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„Dark Stars and Planetariums: How to connect current Cosmological Research with Outreach Methods“

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There are times when writing a master's thesis is not recommendable. For example during a pandemic when you can't leave your house. You don't have your usual guidance or access to the Institute and the planetarium, respectively. Additionally, you can't see anybody. As if this was not bad enough, suffering from a depression is throwing a monkey wrench in your plans. Recovering will take every ounce of energy and time. Thinking that you finally made it, the loss of a beloved family member is definitely the last straw. That is really not how I imagined my master studies to be completed.

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Abstract

This thesis aims to display how complex yet fascinating topics from current cosmological research can be presented to the public by using different outreach methods.

The current Concordance Model in cosmology offers an overall framework and stands as the topic for the concept of a new show at the Planetarium of Vienna. In the first part of the show, the formation and evolution of the present-day Universe is traced back until the Era of Reionisation, asking where first stars come from. This connects to part two, which classically follows the Big Bang and the thermal evolution of the Universe back to the first stars. Finally, the show gives an outlook to possible future scenarios of space.

A more precise cosmological focus is laid on Dark Stars (DSs). They are postulated first stars, which are not fuelled by nuclear fusion but by the heating of dark matter annihilation. Since in the early Universe space was not as expanded as it is today, the matter density was higher and *weakly interacting massive particles* (WIMPs) were able to interact and annihilate with each other and thus powering the star until the DM reservoir is depleted. Dark Stars are also able to grow to supermassive scales of $10^6 M_\odot$ and, once they collapse, could be the seeds of supermassive black holes observed today.
Moreover, Dark Stars were translated into an outreach way at the Alexandria Magazin. It is a new Austrian popular scientific journal for young scientists to present their research. The employs basic groundwork explanations that are necessary for a layperson to understand the complex mechanisms behind DSs.

The Standard Model of Cosmology as well as the chosen topic of Dark Stars both serve as examples for different methods adopted in science communication where an simplified yet correct language has to be used in order to inform the interested public.

As the International Astronomical Union (IAU) and its Division J, respectively, were the inspiration for this thesis, a social-media project with the Office for Astronomy Outreach was launched. The IAU is the world's largest astronomical society and influences the public in different ways. Even though the IAU is well known to astronomers, its public awareness is rather low. Consequently, the project, set to present each Division and the Executive Committee, aims to raise the visibility of the IAU.

Science communication in astronomy can be done by scientists or amateur astronomers who are self-taught and work in different public science institutions. They do a very good job and fill in places where scientists are lacking due to different circumstances. Yet, for a profound and correct basis of knowledge scientists with their expertise are essential to boost science communication.

Kurzfassung

In der Astronomie gibt es viele Fragen, die nicht nur Wissenschaftler:innen, sondern auch die breite Öffentlichkeit gleichermaßen faszinieren. Was sind Schwarze Löcher? Wie funktioniert eine Supernova? Was ist der Urknall und was war vor ihm? Gab es überhaupt etwas davor? Die Wissenschaft geht dieser Frage „einfach“ mit Hilfe von jahrelanger Forschung nach. Damit gehört die Kosmologie zu den Gebieten der Astronomie und Astrophysik, die am komplexesten sind. Laiinnen und Laien sind auf die Weitergabe und Vermittlung neuester Forschungsresultate angewiesen. Allerdings können diese nicht in der Fachsprache vermittelt werden, sondern müssen, um klar verständlich zu sein, in eine vereinfachte, populärwissenschaftliche Sprache mit Analogien übersetzt werden.

Ziel dieser Masterarbeit ist es, zu zeigen welche Methoden es in der Öffentlichkeitsarbeit bzw. der Wissensvermittlung gibt, um aktuelle kosmologische Forschung einfach und sachgemäß zu erklären.

Grundgerüst der Kosmologie ist das Standardmodell der Kosmologie, das die Urknalltheorie sowie das ΛCDM-Modell vereint. Hier dient es als Rahmen für eine neue Show im Planetarium Wien. Planetarien haben den Vorteil, dass sie die Phänomene des Weltalls auf eine 360°-Kuppel projizieren können und damit die vorgetragenen Erklärungen audiovisuell unterstützen. Die Vorstellung teilt das Standardmodell auf drei Teile auf. Im ersten Teil wird vom heutigen Universum zurückgegangen bis in die Zeit der ersten Sterne; Teil zwei widmet sich der Entwicklung des Weltalls seit dem Urknall und knüpft mit der Entstehung der ersten Sterne an Teil 1 an; im letzten Teil werden drei der wahrscheinlichsten Szenarien für die Zukunft unseres Universums vorgestellt (Big Rip, Big Crunch, Big Freeze). Die ursprüngliche Idee, dass zum Ende der Masterarbeit eine kurze Sequenz der Show bereits programmiert ist, war auf Grund der Corona-Pandemie nicht umsetzbar. Das Konzept ist ausgearbeitet und angehängt.

Als spezifisches Forschungsthema der Kosmologie wurden Dark Stars ausgewählt. Ihr Name ist irreführend: Es handelt sich nicht um dunkle Sterne, sondern um tatsächlich sehr leuchtkräftige erste Sterne mit einer untypischen Energiequelle. Sie werden nicht, wie üblicherweise, durch die Kernfusion befeuert, sondern durch die Auslöschung, *Annihilation*, von Dunkle-Materie-Teilchen, den WIMPs. Dabei wird genug Energie in Form von hochenergetischen Photonen frei. Beim Kollaps einer protostellaren Wolke stoßen die WIMPs immer öfter zusammen und ihre freigesetzte Energie wirkt als Gegenkraft zur Gravitation, noch bevor die Kernfusion im Inneren des Sterns einsetzen kann. Solange genug Dunkle Materie als „Treibstoff“ zu Verfügung steht, bleibt der Stern im Gleichgewicht. Anschließend kann es kurzzeitig noch zu einer regulären, nuklearen Brennphase kommen, bevor der Stern endgültig an seinem Lebensende ankommt. Supermassereiche Dark Stars könnten dabei direkt zu einem Schwarzen Loch kollabieren und sogar als die bisher ungeklärte Grundlage für supermassereiche Schwarze Löcher dienen.

Dark Stars haben im Rahmen dieser Arbeit auch ihren Weg in die Wissensvermittlung gefunden. Die neue Wissensschaftszeitschrift *Alexandria Magazin* bietet jungen Forscher:innen die Möglichkeit ihr Spezialgebiet vorzustellen. Für den Artikel über die Dark Stars werden zuerst andere wichtige Mechanismen als notwendiges Vorwissen erläutert. Dies umfasst primordiale und allgemeine Sternentstehung/-entwicklung sowie deren Prozesse und Dunkle Materie. Die hier größte Hürde war es, einen Knotenpunkt ins tägliche Leben zu finden bzw. welche Relevanz die vorgestellte Forschung für den Alltag hat.

Warum überhaupt Wissensvermittlung? Prinzipiell aus der einfachen Begründung heraus, dass jede:r das Recht auf lebenslange Bildung und Information hat. Des Weiteren aber auch, dass der Bedarf, die Öffentlichkeit am Laufenden zu halten da ist, wie die Pandemie gezeigt hat. Wissensvermittlung ist immer dann wichtig, wenn einer, mehrere oder alle der folgenden Schlüsselpunkte gegeben sind: Relevanz, Beitrag zur Gesellschaft, sowie Faszination und Interesse. Dabei ergänzen sich Wissenschaftler:innen und die Öffentlichkeit gegenseitig. Eine Forschung, die niemand versteht oder als unsinnig betrachtet wird, verliert wichtige finanzielle Unterstützung. Sind Interesse und Verständnis für die Forschung gegeben und erhalten, werden auch weiterhin die Steuergelder zur Finanzierung der Wissenschaft genutzt. Daher liegt es auch im Interesse der Wissenschaftler:innen Öffentlichkeitsarbeit zu betreiben.

Nicht immer jedoch haben sie die Zeit, Expertise und Möglichkeit, sich damit zu beschäftigen. Wissensvermittlung kann von verschiedenen Personengruppen betrieben werden. Oft von Forscher:innen selber oder auch von Amateuren, wie zum Beispiel Hobbyastronom:innen, die nicht selten in öffentlichen Sternwarten, Planetarien oder Museen arbeiten. Sie erarbeiten sich ihr Wissen aus Interesse selber und bilden sich wiederum bei öffentlichen Vorträgen u.Ä. weiter. Ohne sie wäre das breite Angebot, Forschung vermittelt zu bekommen, nicht zu erhalten. Es ist jedoch wichtig zu sagen, dass ohne die Grundlagen- und Spitzenforschung der Wissenschaftler:innen gar keine Basis gegeben wäre. Sachbücher müssen von Wissenschaftler:innen verfasst werden und Science-Fiction-Werke werden ebenso von ihnen auf die fachliche Genauigkeit überprüft. Obwohl eine Planetariumsshow nicht notwendigerweise von Fachleuten moderiert werden muss, braucht es deren Expertise, um eine Show wissenschaftlich korrekt zu konzipieren. Ausschlaggebend ist hier die Zusammenarbeit von beiden Seiten.

Ein weiteres Projekt dieser Masterarbeit ist der Internationalen Astronomischen Union (IAU) gewidmet, die bei ihrer letzten Generalversammlung 2018 in Wien den Anstoß für das Thema gegeben hat. Die IAU ist der größte Zusammenschluss von Astronom:innen/Astrophysiker:innen der Welt. Mit ihrer Arbeit und Aufbereitung von Forschungsergebnissen tragen sie dazu bei, unser Verständnis vom Weltall aber auch über uns und unsere Welt zu vervollständigen. So bekannt sie in astronomischen Kreisen ist, so unbekannt ist sie meistens für Laiinnen und Laien. Mit Hilfe des Office for Astronomy Outreach der IAU wurde eine Social-Media-Kampagne entwickelt, um die einzelnen Divisions und das Executive Committee vorzustellen. Dabei wählt jede Division verschiedene Mitglieder aus, die sich, ihre Arbeit, ihre Faszination und bereits vorhandene Wissensvermittlung aus ihren Schwerpunkten in kurzen Videos beschreiben. Da das

Filmen, Material sammeln und Zusammenschneiden viel Zeit in Anspruch nimmt und dieses Projekt während des Führungswechsels in der IAU Fahrt aufgenommen hat, wurden bisher noch nicht genug Videos eingesendet, um ein Endprodukt vorzustellen.

Abschließend lässt sich sagen, dass es die Zusammenarbeit von beiden Seiten braucht, um eine gute und sachgemäße Wissensvermittlung anbieten zu können. Einerseits die Wissenschaftler:innen, die ihre Forschung vorantreiben und zur Verfügung stellen. Andererseits, die Öffentlichkeit, die daran interessiert ist, Neues zu erfahren. In der Mitte treffen sich Leute, die selber aus reinem Interesse bereits vorhandene Forschung weitergeben möchten oder Wissenschaftler:innen, die (neben-)beruflich in der Wissensvermittlung tätig sind.

To my Oma who would still be asking me what I am doing today, knowing that the answer would always be the same: learning

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1. Introduction

Astronomy is the most ancient science on Earth and in the Universe. Therefore it amassed knowledge which is nowadays taught at universities. Space, however, is fascinating to all people and hence needs a profound and precise transfer of knowledge.

The motivation for this thesis goes back to the XXX. General Assembly of the International Astronomical Union in Vienna in 2018. At one of Division C's (Outreach, Education and Heritage) panel discussions, delegates from all other Divisions were asked to present their effort for outreach work. All but Division J offered insight into their projects and initiatives. Division J stands for the topics the public is interested in the most: black holes, dark matter, dark energy, the structure of the Universe as well as its beginning and evolution. These topics are among the most complex in cosmology.

Accordingly, a lot of time is invested into their research, time that is rather not spent on engaging with the public. On the other hand, communicating with the public is necessary for research to go on. Taxpayers' money is invested into the funds and grants scientists apply for. If the public does not know about the aim of the researcher they are less likely to spend money on it.

Under the working title *A Cosmologist's Guide to Outreach* this thesis aims to answer the question, "What can Science Communication look like in Cosmology?". Different methods are used, mostly by practical examples and comparative analyses. These showcases serve as possibilities of outreach methods. Accompanying the outreach part is an astronomical field of research: cosmology and more precisely the postulated Dark Stars as first stars in the early Universe. Both are used as research examples that are translated into an easy language such that the interested layperson understands it. On this account the first two Chapters feature more precise explanations of physical processes as it would usually be required for a master's thesis about cosmology. Moreover, technical terms describing the mechanisms are highlighted by italic fonts.

The thesis is structured as follows. In Chapter 2 the Standard Model of Cosmology, the Standard Model of Particle Physics and dark matter are presented as prerequisites to a better understanding for the next section. Chapter 3 is dedicated to Dark Stars as their possible role as first stars. It is mostly a summary of the already existing research. A short part describes the modelling of Dark Stars using the MESA stellar evolution code. After the astronomical components, Chapter 4 introduces outreach in the sense of science communication and its importance for (natural-)scientific research. Here, first examples of engaging with the public are given by the landing of NASA's Perseverance rover and Austria's petition to stay a member of CERN. Both examples give way to a comparison of science communication in the US vs. Austria/Europe.

The heart of the thesis is a self-made concept for a show about cosmology at the Vienna Planetarium (Chapter 5). It features insight into producing a show and what it takes to make it captivating. Chapter 6 focuses on two other outreach methods. The first is a (popular) scientific article for the new Alexandria Magazine written by the author. The second is a Social Media project to raise the public visibility of the IAU. It is a cooperation with the Office for Astronomy Outreach. Chapter 7 presents the conclusions from all previous sections and a short discussion.

2. Crash Courses

Many facts are known about the Universe, much more are unknown. Yet, for both we can make theories and models. Those can be adapted, extended or sometimes even dropped. For the description of the Universe, however, there are some well established theories. In this Chapter the Big Bang Theory, the Standard Model of Particle Physics and dark matter will be presented since they serve as the basis for the Dark Stars theory in Chapter 3. As this thesis serves for both, scientific and outreach reasons, the latter is in need of thorough explanation of background knowledge. For astronomers most topics in this Chapter are very well known but are still described to fulfil a scientific rationale of a master's thesis as well as to make mechanisms understandable for a broader public. Thus, they are here presented as 'crash courses' and serve as an introduction to the field. Technical terms or keywords will be emphasised in italic fonts throughout the thesis.

2.1. Standard Model of Cosmology

Our perception of the Universe has changed a lot since humankind first started to evaluate it, many thousand years ago. Today, there is one widely accepted theory: the Big Bang Theory. It evolved to its acknowledged form in the 20th century. It is the Standard Model of Cosmology and provides a timeline of the evolution of the Universe.

The Big Bang is the postulated beginning of our Universe and with it the beginning of space and time. Its name came mockingly from the English astronomer Fred Hoyle, who was actually a defender of the steady-state Universe. The latter model would opt for an expanding Universe where matter is created homogeneously everywhere at a same rate such that the energy density stays constant, thereby violating energy and mass conservation. The steady-state theory is also contradictory to the observed decrease in energy density due to expansion . Hoyle laughed at the idea that the Universe would just suddenly appear with a "big bang". Even though he was being sarcastic, the term is descriptive enough that the Big Bang Theory (BBT) was made to the *Standard Model of Cosmology*, sometimes also called Concordance Model.

The Big Bang happened everywhere at the same time. Time and space were "creating themselves". Out of a sudden, there was *something*, a hot plasmatic energy state.
Theoretical approaches can be made after 10^{-43} s passed, anything before this time cannot be extrapolated. This boundary is called *Planck scale* or quantum gravity wall. At the Planck scale a *Theory of Everything* (TOE) could possibly apply. During this short era, all fundamental forces (gravity, strong interaction, weak interaction, and electromagnetic interaction, see table 2.2) are considered to be one.

Symmetry breaking	Time [s]	Temperature [K]	Energy [TeV]
Theory of Everything	10^{-43}	10^{32}	10^{16}
Grand Unification	10^{-36}	10^{28}	10^{12}
Electroweak Unification	10^{-12}	10^{16}	1

Table 2.1.: Overview of Symmetry Breaking in the first moments after the Big Bang.

force	range [m]	strength
el.-mgt.	∞	1/137
weak	10^{-18}	$3 \cdot 10^{-7}$
strong	10^{-15}	1
gravity	∞	$5 \cdot 10^{-39}$

Table 2.2.: The four fundamental forces with their ranges and interaction strenghts. Values taken from Wagner, 2014.

First, after the TOE broke down, gravity decoupled from the other forces. Some moments later, at 10^{-36} s and 10^{28} K, the *Grand Unified Theory* (GUT for short) ceases. Here, the weak and the strong interaction were separated. During this epoch another important phase arises. *Inflation* lasted until $\approx 10^{-32}$ s and blew up the Universe with an expansion factor of 10^{26}, which corresponds to a volume increase of 10^{78}. Lastly, at $T = 10^{16}$ K and already reaching a trillionth of a second, the electromagnetic and the weak interaction separated. This is the *electroweak phase transition.* Up to this moment, the temperature was too high for particles to exist in any state other than massless bosons (scalar or vector). After 10^{-12} s, the temperature is low enough for fermions (quarks and leptons, see later fig. 2.5) to become massive. Yet, bound states are not possible; the elementary particles exist in the quark-gluon plasma.

Even though inflation itself lasted only for a short amount of time, the Universe expanded further, but the scale factor a, which gives the relative expansion of the Universe, is not growing exponentially anymore. With this it cooled down further. As the first second of the newborn Universe passes, quarks can be bound into hadrons. Baryons, regular matter, came up, along with antimatter via pair production. For each matter particle an antimatter particle is created, such that there should be equal amounts of both. Yet they are produced at different rates, since there is more matter than antimatter. This *baryon asymmetry* is not yet resolved. The Sakharov conditions for the *baryogenesis* describe the following ingredients (Sakharov, 1991):

- violation of the baryon number B
- no thermal equilibrium for interactions
- CP-violation

At some point the expansion rate became higher than the interaction rate of the particles, they fell out of the thermal equilibrium and started to decouple. This made it possible for protons and electrons to survive, they formed the baryonic matter we still have today. Neutrons decay after 879 s which corresponds to 14 min 39 s (see Serebrov et al., 2018 and Ezhov et al., 2018) and with the formation of deuterium they remain within stable nuclei. Elements heavier than hydrogen formed, mostly helium or isotopes of helium and hydrogen. In very small fractions lithium is produced as well. After three minutes the *Big Bang Nucleosynthesis* came to a halt and the Universe continued to cool down and expand for the next 370,000 years and until today.

Since the beginning, radiation was dominant and particles moved at high speeds. 50,000 years after the Big Bang the density of matter exceeds the density of radiation and the matter-dominated era begins.

Electrons and photons interact with each other since due to the high temperature atoms are stripped of their electrons. They stream in the hot plasma together with photons. Baryonic matter is considered to be made up of mostly electrons. They are coupled to photons by Compton scattering, creating the baryon-photon fluid. The typical interaction rate is given by:

$$\Gamma_\gamma = n_e \sigma_T c_s \tag{2.1}$$

where γ indicates photon, c_s is the sound speed and n_e is the number density of electrons. σ_T is the Thompson cross section for electrons. For nuclei it is negligible. This is the reason that the coupling of photons to matter is dominated by electrons. By now, the Universe is already full of *dark matter* (see Chapter 2.3). It is not yet clear when, where and how it formed. Baryons are drawn towards overdense regions of dark matter falling into potential wells while photons have a high pressure and pull upwards. Also the pressure exerted by the compressed baryons makes them rebound. The mean-free path of photons is:

$$\lambda_\gamma = c\Gamma_\gamma^{-1} \tag{2.2}$$

The baryon-photon fluid flows in and out of the overdensities, being either at a compression in the centre or at the rarefaction at the top of the oscillation. These plasma waves propagate through the Universe at sound speed, which back then was about half the speed of light, c$_{s,rec}$=150 000 000 m/s (today c$_s$=343m/s). The so-called *baryonic acoustic oscillations*, short BAOs, arise from there. All these oscillations can overlap as they travel through space, like a stone thrown into the water which then creates ripples. As the temperature drops further due to expansion, electrons and nuclei are able to 're-combine'. Photons decouple and move without interactions. This happens if:

$$\lambda_\gamma > \frac{c}{\Gamma_\gamma} \quad \text{or} \quad \Gamma_\gamma^{-1} > H^{-1} \tag{2.3}$$

such that the mean free path of the photons is comparable to the Hubble radius.

Recombination did not last for just one second but thousands of years. It happens in a redshift range of $1 + z_{rec}$=1000-1400 ($z_{rec} \approx 1090$), where around 90% of electrons recombined. It was most effective for a temperature of T_{rec} = 3600 K $\simeq$ 0.3 eV. Here, hydrogen is ionized already at 0.3 eV not the typical 13.6 eV, since there are more than enough photons from the high-energy tail of the Planck spectrum. Hydrogen is fully

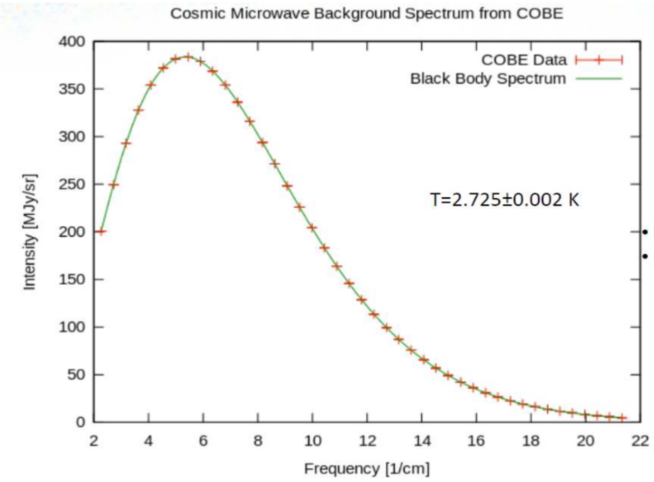

Figure 2.1.: Power spectrum of the Big Bang afterglow as observed by COBE. The peak is located at ≈ 160 GHz; no deviations from a theoretical blackbody spectrum (green line) are visible. The error bars are enlarged seven times to make them visible (orange crosses). Image credit: public domain; based on FIRAS measurements done by Mather et al., 1994 and Fixsen et al., 1996.

ionized at $z > 1400$, helium at $z > 6000$. As a consequence, for redshifts higher than 1400, the Universe is optically thick against Thompson scattering, meaning that the Universe cannot be observed directly. At this point the so-called last-scattering surface for photons can be observed. If there were any fluctuations in the photon temperature, they should be visible in the *cosmic background radiation* until today.

These relics are actually observed. Penzias and Wilson, 1965, were the first to directly measure a signal from the *cosmic microwave background* which would be expected from the Big Bang. At first they thought it was random static, then they pinned it to a pigeon's nest which was found in the Holmdel Horn Antenna. This signal, however, stayed and is detectable at any position in the sky; it is isotropic. In the same journal issue Dicke et al., 1965 reported their own attempts to find cosmic black-body radiation with their own antenna, although they were rather unsuccesful, while Penzias and Wilson struck home with their findings by accident. This afterglow of the hot Big Bang was already predicted by Gamow, 1948 and Alpher and Herman, 1948 roughly twenty years earlier. Over the years the relic temperature of the background radiation has been measured to better accuracy. The measurement of Penzias and Wilson placed the radiation at 3.5 K today.

The next big step was achieved with the COBE (*Cosmic Background Explorer*) satellite, launched in November 1989. Its infrared spectrometer measured $T_{CMB} = 2.725 \pm 0.002K$. Also, COBE found anisotropies in the CMB. One big discovery was the observed power spectrum of the CMB, measured with the Far-Infrared Absolute Spectrometer (FIRAS) . No deviations from a perfect blackbody radiation were found, see fig. 2.1

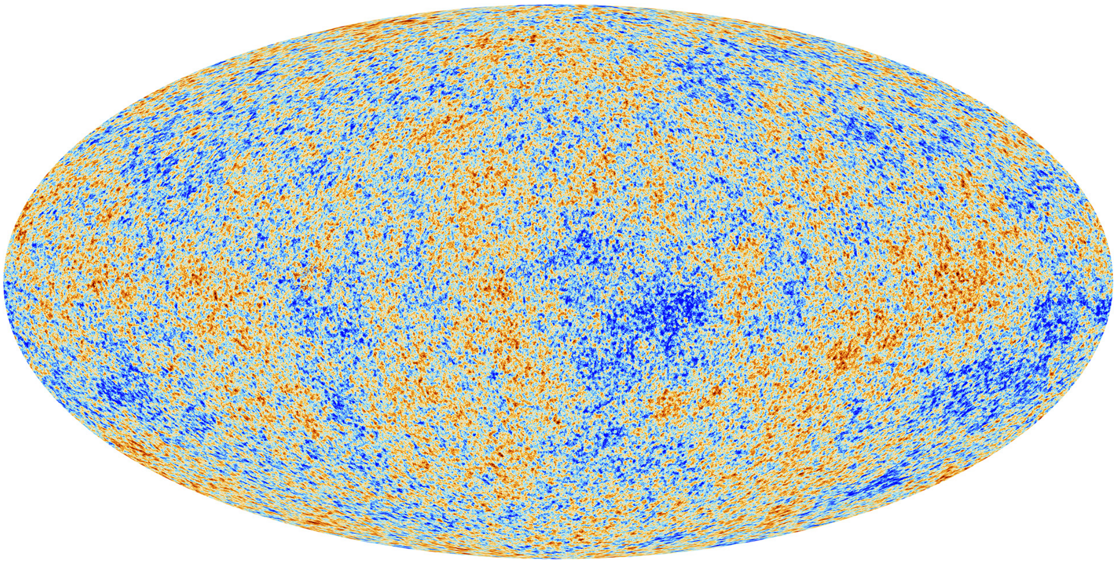

Figure 2.2.: Anisotropies in the Cosmic Microwave Background Radiation as mapped by the Planck Satellite.The dots are different temperature fluctuations (red: hotter, blue: cooler) on top of the mean and correspond to varying densities which later gave way to the formation of bigger structures. ©ESA and the Planck Collaboration et al., 2014.

A little more than a decade later the *Wilkinson Microwave Anisotropy Probe*, WMAP, followed. It gave an even more detailed picture of the CMB map. While COBE managed to show that the radiation features anisotropies and a clear dipole, WMAP resolved the fluctuations at a more precise level.

Presently, the most accurate mapping of the CMB radiation has been done with the all-sky survey of the Planck satellite (mission end 2013) with an angular resolution of 5-10 arcmin (`http://planck.mpa-garching.mpg.de/Planck/planck.html`). The temperature fluctuations were measured down to 10^{-5} K. COBE already showed that the isotropic CMBR signal is dotted with anisotropies. At the latest since Planck it is clear, that the Universe is full of anisotropies (see fig.2.2). They are thought to stem from random quantum fluctuations that originated before inflation which later blew them up. The pattern of the fluctuations corresponds to a characteristic size, the modes. The decomposition of the temperature map is carried out using spherical harmonics Y_{lm}, that are characterised by a degree l (multipole) and an order m:

$$T(\theta, \phi) = \sum_{l=0}^{\infty} \sum_{m=0}^{m=l} T_{lm} Y_{lm}(\theta, \phi) \tag{2.4}$$

where $l \approx \pi/\theta$ with θ being the angular separation on the sky. For each l there are $2l+1$ modes m.

In addition to these findings, the Planck satellite gave a more detailed view of the

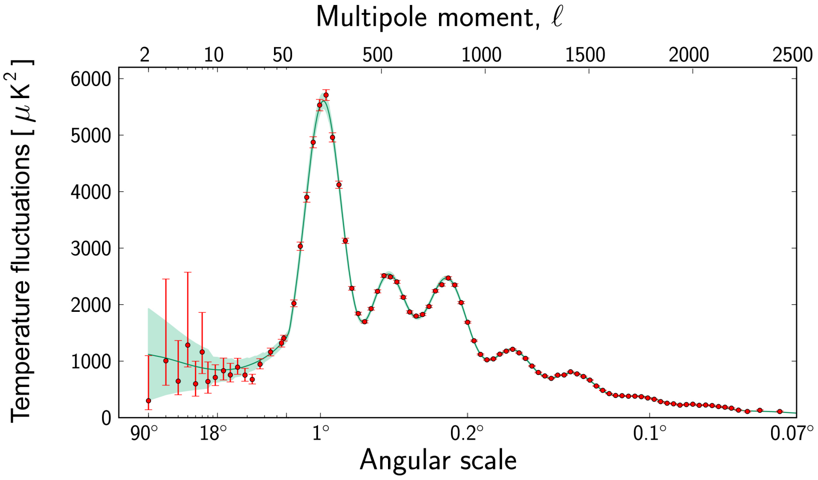

Figure 2.3.: Power spectrum as measured by the Planck satellite. It shows more peaks than WMAP. ©ESA and the Planck Collaboration et al., 2014.

power spectrum of the CMB with additional peaks compared to the previous COBE and WMAP missions. Each peak accounts for different effects and occurrences during the very early Universe, see fig.2.3.

They are caused by the oscillations of the baryon-photon fluid, depending on the rarefactions and the compression into valleys or tops. These sound waves create the temperature fluctuations: An oscillation that has a maximal compression into a valley is hot and has a maximal rarefaction on a hill top where it is cold as a counterpart. It is then followed by a rarefaction in the valley and a compression on the hill and so forth. A compression gives a higher temperature (red dots in the CMB map), rarefactions correspond to lower temperatures (blue dots). The most prominent peak is the first one which gives the total energy content, i.e. the curvature of the Universe and contains the matter density (baryons and DM together). The second peak and the third peak represent the matter content as well. After the third peak, *Silk damping* sets in. It is also called diffusion damping and makes photons travel from hotter regions towards colder regions. Therefore, Silk damping accounts for a more uniform Universe as far as temperature is concerned. Along with other effects, this finally gives way for the formation of bigger structures once they are heavy enough to collapse.

After recombination, the Universe goes dark for one last time. Even though there are many free travelling photons they don't have anything else to interact with. During these *Dark Ages* structures start to form from density perturbations which are linked to the dark-matter potential wells. Here, more and more matter, i.e. hydrogen and helium, accumulate until they can collapse. Two approaches exist for structure formation. First, one evolves the power spectrum from the CMB via a *linear approach*. Then, follows the second approach, the *spherical collapse* (non-linear). Thus overdensities grow into big halos of dark matter and regular matter (primordial gas) which can then collapse and form bigger structures, starting at smaller ones (stars and galaxies), followed by clusters and superclusters. A more detailed description of primordial star formation is given in Chapter 3.1.

Since the era of inflation the Universe has continued to expand. Even though the expansion rate is reduced, the scale factor a of the Universe - a proxy for its size - grows exponentially. This behaviour was only confirmed in 1998 with the "Supernova Cosmology Project" (Perlmutter et al., 1998) via Type Ia Supernovae that are used as standard candles. They found that the Universe is constantly expanding and consequently there has to be a counteracting force opposed to gravity. This outward pressure is now linked to Einstein's cosmological constant Λ. He originally used it in his field equations of General Relativity:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G}{c^4} T_{\mu\nu} - \Lambda g_{\mu\nu} \tag{2.5}$$

or put in words:

curvature = mass distribution - cosmological constant

with G being the gravitational constant, $R_{\mu\nu}$ the Ricci tensor, R the Ricci scalar where both connect to the space-time curvature. $T_{\mu\nu}$ is the energy-momentum tensor and describes the flux of energy and momentum in space-time; and $g_{\mu\nu}$ is the metric tensor which allows to measure distances in space-time.

Einstein used Λ to obtain a calculation for the static model he supported and did not have a clear physical definition for it (Schneider, 2015). For his solution of the field equation Λ was set to zero. With the proof of an expanding Universe, however, the cosmological constant is now used in field theories to describe the vacuum energy density of space and is now close to zero (i.e. *non-zero*):

$$\Lambda = \frac{8\pi G}{c^2} \rho_{vac} \approx 1.9 \cdot 10^{-26} \text{ m/kg} \cdot \rho_{vac} \tag{2.6}$$

or written in terms of density parameters:

$$\Omega_\Lambda = \frac{\Lambda c^2}{3H_0^2} = \frac{8\pi G}{3H_0^2} \rho_{vac} = \frac{\rho_{vac}}{\rho_c} \tag{2.7}$$

where ρ_{vac} is the vacuum density, H_0 is the Hubble constant giving the present-day rate of the expansion and ρ_c as the critical mass density. Today, Ω_Λ is estimated to have a positive value of 0.7 which corresponds to 70% of the energy/mass budget of the Universe. As baryonic matter accounts for only 5% - fig. 2.4 - and dark matter (see Chapter 2.3) makes up 25%, the left-over mass or energy is attributed to the so-called "dark energy". Hence, the cosmological constant and dark energy are thought to be correlated. Together, the concept of the cosmological constant and cold dark matter (CDM, Chapter 2.3) are the

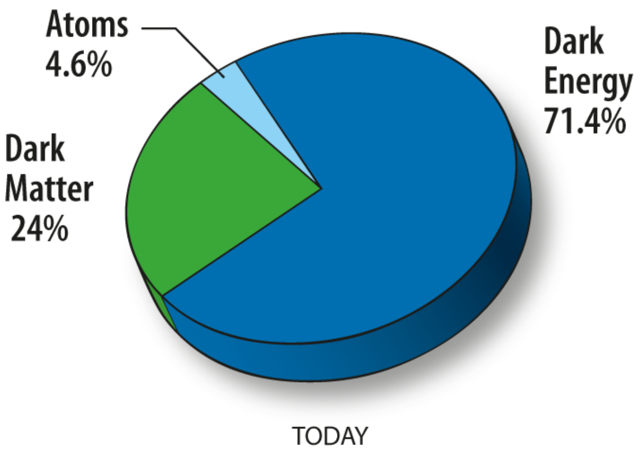

Figure 2.4.: Matter/Energy content of the ΛCDM Universe apportioned by baryonic matter (atoms), dark matter and dark energy in today's Universe. ©NASA

eponyms for the ΛCDM model which complements the Big Bang Theory and consitutes the current Concordance Model.

This outline of the Big Bang model was also used for the topic of the planetarium show described in Chapter 5.1.

2.2. Excursus: Standard Model of Particle Physics

The *Standard Model of Particle Physics* (SM) is complementary to the cosmological theory. It describes the smallest (so far known) building blocks of all matter. This incorporates all elementary particles and the fundamental forces, gravity excluded (see table 2.2). Elementary particles are particles that are not made up of other particles. Among them are the six quarks (up, down, charm, strange, top, bottom) and the leptons (electron, muon, tau and their corresponding neutrinos), see fig. 2.5. Fermions get their name from the Fermi-Dirac statistics, where they have spin-$^1/_2$ and asymmetric wave functions under exchange.

The SM additionally covers the carrier particles, the bosons, for the different fundamental forces. The gluon conveys the strong interaction between the quarks, so they can bundle together and create the rest of the particle zoo which are baryons and mesons (proton, neutron, kaon, pion, ...). Both, the W and the Z bosons carry the weak interaction, e.g responsible for β-decay. The photon carries the force for electromagnetic interactions. These four are the gauge bosons. The newest member is the Higgs boson and is yet the only scalar boson. The particularity of the Higgs or rather the Higgs field is that it gives mass via interaction to elementary particles. Carrier particles follow the Bose-Einstein statistics and have full integer spin. Under exchange they have symmetric wave functions.

As previously mentioned, only gravity does not fit into the Standard Model. It is

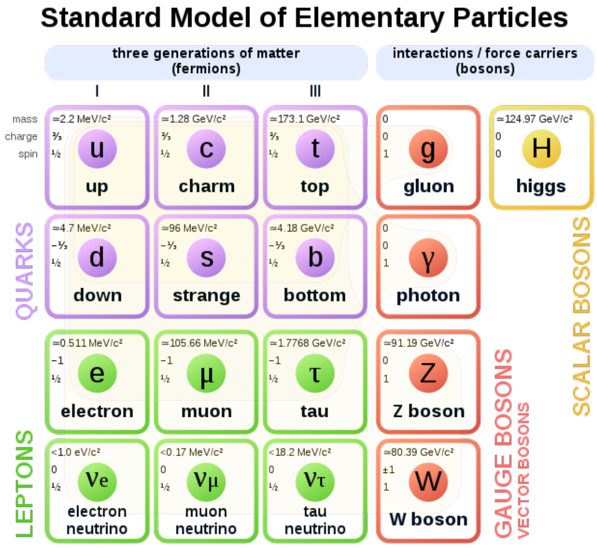

Figure 2.5.: The Standard Model of Particle Physics. The fermions are divided into quarks and leptons and into their three generations. On the right are the carrier particles, the bosons. Image Credit: Commons Wikimedia by MissMJ.

described by *General Relativity* (GR) rather than quantum mechanical theories. Up to this day, no elegant and simple "Theory of Everything" has been found. Attempts to connect both are extending the SM and introducing new physics to it, such as supersymmetry. It is then called *Physics beyond the Standard Model*. In its scope the graviton (the postulated carrier for gravity) could exist. Other approaches are even more exotic and very complex. Two of the main contestants are *String theory* (see Veneziano, 1968 and for a newer approach Green, Schwarz and Witten, 1987) and *Loop Quantum Gravity* (Ashtekar, 1986 and Rovelli and Smolin, 1988).

Even though the Standard Model cannot account for General Relativity at the moment, it deals with relativity in terms of speed or, more precisely, their kinetic energy. It includes *Special Relativity* (SR), set by the most famous formula (Einstein, 1905):

$$E = mc^2 \tag{2.8}$$

In principle, particles are divided into relativistic or non-relativistic ones. The former is the case when a particle's rest mass is zero (m_{rest}=0), e.g. the photon. It moves with the speed of light, such that $v = c$. Also, particle colliders can accelerate particles with non-vanishing mass, $m_{rest} \neq 0$, to velocities near the speed of light, yet never quite reaching c. On the other hand, particles with a non-zero mass can also move at lower velocities ($v \ll c$), these are called non-relativistic (e.g. the proton).

In particle physics (i.e. high-energy physics) the speed of light is often set to $c = 1$, according to natural units, where also electronvolts apply as a typical unit for energy, mass and temperature. In this regime eq. 2.8 is reduced to $E = m$, so energy equals mass, hence a particle's mass is the same as its energy (in units of eV).

2.3. Dark Matter

Dark matter is one of the biggest mysteries in today's science. Even though its nature is not yet known it has become an integral part for the correct description of the Universe's structure and evolution.

The first real studies of dark matter were done in the 1930s by Oort, 1932 and Zwicky, 1933. Oort calculated the movements of the stars in the solar neighbourhood and found that they are moving faster than calculations showed. Consequently, more mass would be needed; Oort thought about "dark matter" as some sort of dim or dark stars (not to be confused with the *Dark Stars* referred in the thesis). A year later in 1933, Zwicky investigated galaxies (at this time still called "nebulae") and galaxy clusters, especially the Coma cluster. His aim was to determine the mass of the cluster by looking at it, more precisely at its luminosity. In principle the mass can be derived with the mass-to-light ratio. Zwicky calculated the velocities of the galaxies and compared them to the observed velocities. He found that for the given mass the measured velocities were far too high to bind the galaxies gravitationally. For a galaxy to be gravitationally bound into a cluster the gravity has to prevail over the escape velocity of the galaxy. Since Zwicky nevertheless observed bound galaxies, he argued that there has to be some additional mass that keeps the galaxies in the cluster.

The next big hint came from Vera Rubin in the 1970s. She observed the orbits and orbital velocities of stars, respectively, in spiral galaxies. Stars in late-type galaxies are rotating around the centre on circular orbits, i.e. stars at small radii need to have higher orbital velocities in order to stay on track against the stronger gravitational force while stars with bigger radii usually rotate slower. This, together with the rotation of the stars in the bulge, which behave like stars in elliptical galaxies, and the rotation of the gas component adds to the rotation curve of a spiral galaxy. In Rubin's observations there were similar results as Oort's: The stars in the outskirts were moving too fast (at a similar speed as the innermost stars) for the observed mass, so that they should be flung out of the galaxies. As this is clearly not the case, Rubin, Ford and Thonnard, 1980 stated that there has to be some additional mass that also spans to bigger distances than the disk component of the galaxy. This mass, which is not visible, would encompass the galaxy as a halo. Today, we call this a *dark matter halo.* Observations show that quite every galaxy (and as a consequence also galaxy clusters) should be surrounded by one.

Dark matter (DM) makes up around 25% of the whole energy-budget in the present-day Universe. Still, only bits and pieces are known about the characteristics of DM itself.

As dark matter does not interact with the electromagnetic field, no light phenomena can occur, therefore it is called *dark.* It is invisible to our eyes and our detectors which capture different regions of the electromagnetic spectrum. Consequently, so far direct detection has not been possible since it is not visible. Indirect tracing, however, provides

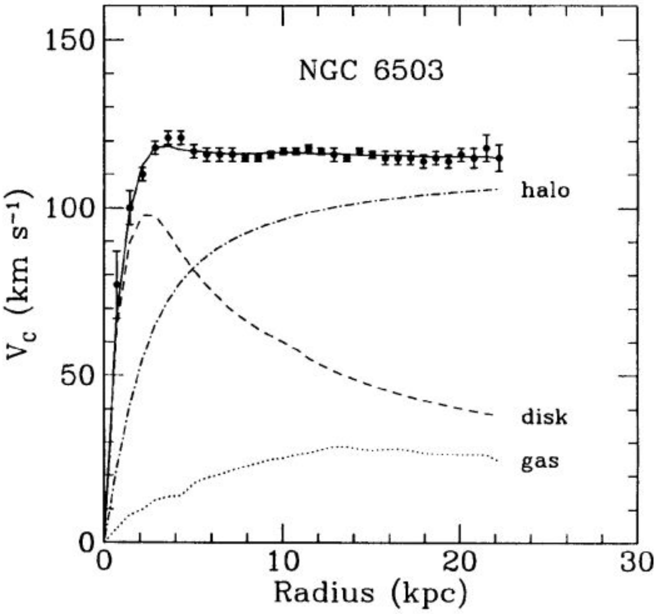

Figure 2.6.: Example of a rotation curve from spiral galaxy NGC 6503. Each curve represents the contribution from different components of the galaxy. Especially the halo contribution (dashed-dotted) is needed to match observed data. Figure taken from Begeman, Broeils and Sanders, 1991,fig.1.

more information. Dark matter exerts a strong gravitational force, hence dark matter particles are thought to be quite massive. Several DM particle candidates have been proposed, the most promiment one is the WIMP, the *weakly interacting massive particle*. As the name suggests, it is massive and interacts via the weak force and gravity. The mass of the WIMP is not yet constrained; it could range anywhere between 10 GeV to 10 TeV.

WIMP Freeze-Out As mentioned before, the exact formation pathway and emergence of dark matter as well as its type is yet of debate. The WIMP, however, matches calculations for the estimate of its abundance today since the earliest times. It fits as neatly as calling it the "WIMP miracle". These dark matter particles χ are thought to be their own antiparticles $\overline{\chi}$, so-called Majorana particles. They can annihilate with each other, creating other particles in cascades or even be created by lighter particles (Jungman, Kamionkowski and Griest, 1996). At very early times, they would have been in thermal equilibrium, where the annihilation and creation are balanced. With the ongoing expansion, the temperature of the Universe sinks to a value that is lower than the mass of the WIMPs and the annihilation rate ultimately drops below the expansion rate. Their interaction rate is then too small for them to uphold an equilibrium and consequently *freeze out* (Schneider, 2015), they decouple. This remaining relic abundance stays constant over time and yields (Begeman, Broeils and Sanders, 1991):

$$\Omega_\chi h^2 \simeq \frac{3 \cdot 10^{-27} cm^3/s}{\langle \sigma \nu \rangle} \tag{2.9}$$

with Ω_χ being the energy density for WIMPs in the present-day Universe and h denotes the Hubble constant (taken in units of 100 km/s/Mpc). For a particle on the weak-interaction scale, like the WIMPs, the corresponding cross section $\langle \sigma \nu \rangle$ would be:

$$\langle \sigma \nu \rangle = 3 \cdot 10^{-26} cm^3/s \tag{2.10}$$

This produces the correct abundance of dark matter in our Universe today of $\Omega_\chi h^2 \sim 0.1$. Therefore, the WIMPs are among the most promising DM candidate and much effort is put into detecting them either directly or indirectly.

However, as the nature of dark matter is yet unclear, many different approaches and ideas have been pursued. For one, it can be divided into three main non-baryonic types, depending on their free-streaming length:

- **Cold Dark Matter (CDM):** It originates from particles that are non-relativistic when they decouple, so CDM particles move slowly ($v \ll c$). CDM clumps on small scales, growing up to large structures. Hence it complements the bottom-up scenario of hierarchical structure formation that is observed and is favoured for the ΛCDM cosmology.
- **Hot Dark Matter (HDM):** It consists of relativistic particles ($v \approx c$) and forms large structures (top-down). An example for HDM would be neutrinos which are nearly massless and therefore relativistic.
- **Warm Dark Matter (WDM):** It is an in-between type of the two above. It would clump on intermediate scales and therefore supresses small-scale structure formation.

Other, more exotic DM types are dark matter as an Bose-Einstein condensate (Hu, Barkana and Gruzinov, 2000) or self-interacting DM (Spergel and Steinhardt, 2000). As stated above, CDM as WIMPs is one of the most promising types of dark matter since it rounds off the observed and predicted bottom-up scenario, where small structures (like stars and then galaxies) form first and grow into larger ones, like galaxy clusters and superclusters. This is supported by mergers of galaxies that are actually observed, either directly by looking at two (or more) colliding galaxies or by relics from previous mergers.

Hot dark matter is more or less discredited. Neutrinos do exist and actually in a non-negligible amount, since without them cosmological simulations do not correctly reproduce today's large-scale structure (e.g. Zennaro et al., 2017 and Nascimento and Loverde, 2021). Yet to the total amount of dark matter, neutrinos as HDM contribute only little. Moreover, a top-down scenario of structure growth is clearly not favoured by observations. Here, matter would have clumped on big scales first, forming superclusters and clusters, which would subsequently fragment into smaller objects (galaxies).

Together, the Big Bang Theory, Standard Model of Particle Physics, dark matter make up the basis to describe the Universe along with Einstein's *Theory of Relativity* (Einstein, 1916).

3. Dark Stars

The main cosmological part of the thesis is the concept of Dark Stars described in this Chapter. Although no own research was done, it serves as a scientific rationale for a master's thesis and good example for current cosmological research.

As stated in Chapter 2, so far recombination was the first time when the Universe was transparent, i.e. became visible. Afterwards photons were free but barely interacting with other particles. Therefore the Universe stayed dark for some 150 million years.

During these Dark Ages, gas accumulated further into the potential wells, giving way to the birth hour of the first luminous objects, the stars. With these bright and energetic objects the *Era of Reionisation* began and the Universe got subsequently transparent again as more and more radiating sources (e.g. quasars) emerged.

3.1. Star Formation in the Early Universe

The basics of star formation are the same for first stars and all following generations: molecular cloud formation, collapse of the cloud and protostellar-disk formation, mass accretion onto pre-stellar core, growth into protostar, nuclear fusion ignition at high enough temperature/density, main-sequence star. There are, however, some differences arising from the lack of heavy elements (*metals*, anything heavier than hydrogen and helium) in the early Universe. The effects of the missing metals onto the first stars are described below.

3.1.1. Molecular Cloud Formation in the Early Universe

At present times star-forming clouds form from neutral hydrogen (HI) regions which then have to turn into molecular clouds, as primarily molecular hydrogen H_2 is able to form stars. H_2 forms when the atomic hydrogen sticks to other molecules, such as graphite or silicates (Barlow and Silk, 1976). This calls for the existence of metals in the Interstellar Medium (ISM), which form during a star's lifetime through *nuclear fusion.* Still on the main sequence, hydrogen is converted into helium, powering the star. Most of the other elements are produced when the star leaves the main sequence on the Hertzsprung-Russel diagram and wanders to the Giant Branch and later, when the core helium burning ignites, to the Asymptotic Giant Branch (AGB), the beginning of its end. Nuclear fusion then burns helium to carbon and massive stars go on to produce metals up to iron. Elements heavier than iron can be produced by *capturing processes* once the stars dies. Then, it sheds its produced metals which enrich the ISM as it propagates as an expanding shock wave.

In the early Universe, once stars begin to form, the Dark Ages end. So up to this point there are no metals (except for the tiniest fractions of lithium and beryllium, which are negligible). The gas filling the Universe is pure hydrogen and helium. Over the last few hundred million years, these gases have been accumulated in potential wells of dark matter, i.e. growing density perturbations, finally becoming primordial halos. Such halos are called minihalos, having a mass of $\sim 10^6\ M_\odot$ and consisting only of H, He and dark matter.

For the formation of molecular hydrogen in the early Universe three pathways exist. Two are two-body reactions, the third one a three-body process, all take place in primordial halos:

$$H + e^- \to H^- \quad \text{then} \quad H^- + H \to H_2 + e^- \tag{3.1}$$

$$H^+ + H \to H_2^+ \quad \text{then} \quad H_2^+ + H \to H_2 + H^+ \tag{3.2}$$

$$H + H + H \to H_2 + H \tag{3.3}$$

The first equation is the associative detachment (AD) reaction (see Kreckel et al., 2010), the second is evaluated as a less efficient and slower process by Tegmark et al., 1997, and the three-body formation (eq. 3.3) was reexamined by Palla, Salpeter and Stahler, 1983. The reactions from eq. 3.1 and eq. 3.2 are dominant at densities below 10^8 cm^{-3} during the atomic phase, when there is barely a trace of molecular hydrogen. Reaction 3.3 takes places for densities $n > 10^8$ cm^{-3}, when no dust grains are available. This is the *molecular phase*, where the primordial gas is completely converted into H_2. Both regimes enable efficient cooling for a primordial cloud to form. The cooling makes the molecules stick together and they condense. Consequently, the whole cloud becomes denser through cooling while it becomes more and more molecular. At densities of $n > 10^{16}$ cm^{-3} the initial conditions for a cloud collapse are ready (Bromm, 2013).

3.1.2. First Star Formation

Once the molecular cloud within the minihalo reaches high enough densities, a dense, self-gravitating core forms in the centre (Abel, Bryan and Norman, 2002). The core undergoes contraction and starts to build up a protostar. It then accretes material around itself which is thought to happen at an accretion rate two orders of magnitude higher than in present galactic star formation (Bromm, 2013). Usually, today, a collapsing cloud is strongly cooled via dust radiation or molecular line emission. The most abundant cooling agent is the CO molecule. Since in the early Universe there are no such complex molecules, H_2 is the only coolant. Even though it suffices to cool the cloud, it is not as strong as line emission. This leads to a higher temperature in the primordial cloud compared to the present and in turn to higher accretion rates.

As expected a protostellar disk forms around the primordial core and the star continues to grow. Contrary to the ideas in the early 2000s (e.g. Abel, Bryan and Norman, 2002), some years later it has been found that due to a strong imbalance in the disk, the latter may fragment (Bromm, 2013 and references therein). Therefore binary or multiple stellar systems may form. However, a 3D simulation from Smith et al., 2012 showed that when heating from dark matter annihilation is considered, the protostellar disk is again stabilised to radii of $\approx$ 1000 AU.

Once the initial collapse has come to an end, a first protostellar core has formed which is embedded in its host halo. Its exact radius has to be determined. Like with all stars, this depends on the definition. One possibility would be the photosphere, where a star's light is radiated away. For (primordial) protostars, Bromm, 2013 rather settles for a radius where some sort of hydrostatic equilibrium can begin to form. The core mass of the primordial protostars in this early stage is around $\approx 10^{-2} M_{\odot}$.

Still surrounded by the minihalo, the protostar is able to accrete more mass and can therefore grow further. It is expected that the accretion rates for Pop-III stars should have been much higher than for the following generations. Even though H_2 acts as a cooling agent it is not as efficient as present-day molecules and consequently, the formation site, i.e. the cloud is hotter and the infalling gas is faster. While today, stellar nurseries are cooled to roughly 10 K, H_2 can not reach temperatures below 200 K (Bromm, 2013). Additionally, the protostellar disk, which is nearly Keplerian, experiences gravitational torques that drive supplementary mass towards the centre. Following Shakura and Sunyaev, 1973 for the mass accretion in a thin disk (originally calculated for a black hole accretion disk):

$$\dot{M} \simeq 3\pi \nu_{vis} \Sigma \tag{3.4}$$

with $\dot{M}$ being the accretion rate per year, ν_{vis} the viscosity parameter and Σ the mass per unit surface area, Bromm, 2013 estimates a typical mass accretion rate for primordial stars with a protostellar disk to be:

$$\dot{M} \lesssim 10^{-2} M_{\odot} \mathrm{yr}^{-2} \tag{3.5}$$

Therefore, first stars clearly reach higher masses than present-day stars. Bromm, 2013 and references therein find a lower-mass limit to be at $\simeq 1 M_{\odot}$. Theoretically, these Pop-III stars could have survived until today. Upper-mass limits usually yield several hundred solar masses, up to 600 $M_{\odot}$. In some extreme and exotic cases primordial stars may reach a few 1000 $M_{\odot}$ or, as detialed in the next subsections, even $10^6 M_{\odot}$.

3.2. Dark Stars as First Stars

In 2008, Douglas Spolyar, Katherine Freese and Paolo Gondolo postulated a new type of first stars, so-called *Dark Stars* (DS). Their misleading name has nothing to do with them being dark, i.e. not luminous, but it rather points to their unusual power source. Instead of nuclear fusion they are fuelled via WIMP annihilation (Spolyar, Freese and Gondolo, 2008).

If two DM particles (particle χ and antiparticle $\overline{\chi}$) come together they annihilate and energy is set free in particle showers, eventually resulting in photons γ (gamma-rays), electrons e^- and neutrinos ν:

$$\chi\overline{\chi} \rightarrow e^- + \gamma + \nu \tag{3.6}$$

This reaction sufficiently replaces the power from nuclear fusion. Each product yields about 1/3 of the energy: 1/3 from neutrinos, 1/3 from photons and 1/3 from the electrons. Neutrinos will escape and therefore their energy yield will not be deposited in the collapsing cloud. The other two, however, will remain trapped and can deposit their energy such that the fraction $f_Q \simeq 2/3$ of the annihilation energy thermalises the infalling gas and produces the power source for the Dark Star. DM annihilation is therefore a more efficient power source compared to regular nuclear fusion, where not even 1% from the baryonic mass (i.e. hydrogen while on the main sequence) is converted into energy.

3.2.1. Dark Star Formation

In principle the formation of Dark Stars is comparable to regular first stars in the early Universe. At this time, the Universe was much smaller and therefore denser, than it is today. Hence, the dark matter density was higher as well. Primordial gas is made up from hydrogen and helium, it is embedded in a dark matter halo.

As found by Spolyar, Freese and Gondolo, 2008, a Dark Star can only sustain its heating by WIMP annihilation if three criteria are fulfilled. They are crucial for the initial formation of a DS. The criteria are summarised below.

To begin with, we need to know the annihilation rate of the WIMPs. This is given by their cross section:

$$\langle \sigma \nu \rangle = 3 \cdot 10^{-26} cm^3/s \tag{3.7}$$

Mass and energy are equivalent, i.e. the WIMP mass is converted into the annihilation energy. This conversion happens at a certain rate per unit volume such that the heating $\hat{Q}_{DM}$ is:

$$\hat{Q}_{DM} = n_\chi^2 \langle \sigma \nu \rangle m_\chi = \langle \sigma \nu \rangle \frac{\rho_\chi^2}{m_\chi} \tag{3.8}$$

with ρ_χ being the WIMP mass density, n_χ the WIMP number density and m_χ the WIMP mass. The latter is poorly constrained, as no dark matter particle has been found so far. For WIMPs a high mass is expected, in the case here the standard value is $m_\chi = 100$ GeV. The calculations have been done in a range of 10 GeV up to 1 TeV.

The modelling from Spolyar et al., 2009 shows that the WIMP mass or cross section have only a marginal effect on the initial mass (and the existence of DS overall). A smaller annihilation cross section or larger WIMP mass would give a lightly smaller initial DS mass. The outcome of the final stellar mass remains, however, the same regardless the cross section $\langle \sigma \nu \rangle$ and smaller m_χ.

1st criterion - High dark matter density. Looking at eq. 3.8 one can see that the annihilation cross section scales with n_χ^2 as WIMPs have to find an alike since they are their own antiparticles (making them Majorana spinors). This means that the annihilation occurs more often in regions of high DM density. This is the case in the early Universe, where the DM density was higher by $(1+z)^3$ for a given redshift z since space was smaller then. Primordial halos were additionally more packed with DM than most molecular clouds would be today. Dark Stars would form from these clouds in their centres, where the DM density would be highest. Moreover, once such a cloud collapses it pulls in all the matter, deepening the potential well and dark matter would be dragged along, enriching the protostar. This mechanism, the *adiabatic contraction* was described by Blumenthal et al., 1986 and follows the dynamic response of DM due to (baryonic) gas. Spolyar, Freese and Gondolo, 2008 found that the adiabatic contraction works as the best approximation for the modelling of the DM density.

2^{nd} criterion - Annihilation products are trapped inside the star. For low gas densities and when the gas cloud is on the verge of stability, respectively, the annihilation energy gets away by radiation losses. Only when the cloud collapses and the gas densities increase, a part of the annihilation energy is deposited in the gas. This fraction f_Q is divided into three components: 1/3 neutrinos, 1/3 photons and 1/3 charged particles (e^- and e^+, see eq. 3.6). Neutrinos will mostly escape (weakly interacting) without leaving any energy behind. The rest stays trapped in the core, such that $f_Q = 2/3$. This energy is then thermalized and heats the star, i.e. it is the alternative heat/power source for the Dark Stars.

3^{rd} criterion - Dark matter heating/cooling is dominant in the star. Taking the WIMP mass of $m_\chi = 100$ GeV, DM heating becomes the dominant heating mechanism above a threshold of $n > 10^{13}$ cm^{-3}. At this point, DM heating takes over the cooling inside the star and initiates the proto-DS phase. Meanwhile the star has reached a core size of ~17 AU and $M \sim 0.6 M_\odot$.

If all three criteria are fulfilled a Dark Star is created which is gravitationally supported by the released annihilation energy rather than nuclear fusion.

Otherwise, the formation stays the same: once the gas density in the host halo of the Dark Star is high enough it will collapse and start to form a protostellar core with an accretion disk around it. As mentioned in Chapter 3.1 the protostellar disk should be stable against fragmentation if DM annihilation is accounted for. This result from Smith et al., 2012 was further confirmed by Stacy et al., 2014 who evaluated the stabilisation mechanism to the innermost parts of the disk. For a DS to exist it is crucial that the disk does not fragment. A Dark Star should form in the centre of the where the DM density is highest such that there is enough fuel via the WIMP annihilation. Should the disk fragment, the protostar may form more likely outside the central DM peak and would become a regular Pop-III star. Indeed, Stacy et al., 2014 found that even though DM annihilation stabilises the disk against fragmentation, the DM reservoir is only large enough for a few thousand years, thus disfavouring the formation and hence the existence of Dark Stars. Rindler-Daller et al., 2015 disagree with the exclusion of Dark Stars due to depleted DM reservoir in the disk, as DM can still be brought in via capturing of WIMPS that fall in on centrophilic orbits (Freese, Spolyar and Aguirre, 2008 and Iocco, 2008).

A Dark Star is born with a mass of around 1 $M_\odot$ and can then further accrete material

	$\dot{M}$	z	M_{halo}
SMH	$10^{-3} M_{\odot}/\mathrm{yr}$	20	$10^6 M_{\odot}$
LMH	$10^{-1} M_{\odot}/\mathrm{yr}$	15	$10^8 M_{\odot}$

Table 3.1.: Calculations from Rindler-Daller et al., 2015 for different cases. In both cases the WIMP mass is $m_{\chi} = 100$ GeV.

from the surrounding disk as it is the case for regular stars as well. It grows as long as it channels dark matter as its fuel. DSs are found to reach supermassive scales at $\sim 10^7 M_{\odot}$ as found in Freese et al., 2010.

Depending on the formation redshift, the host halo has a different initial mass and hence different mass accretion rates. In Rindler-Daller et al., 2015 they split their formation ways into a small minihalo (SMH) and a large minihalo (LMH), where the minihalo is the host halo from which the DS forms. Depending on the redshift, the formation parameters, accretion rate and host halo mass, vary. For an earlier formation ($z = 20$) the minihalo has a lower mass, hence the stars accrete at a slower rate as there is less mass available (not such strong gravitational pull inwards). If the star forms at later times ($z = 15$), the host halo has more time to grow towards bigger masses. Once accretion started, there is more mass to be accreted per year. See table 3.1 for the exact values.

3.2.2. Modelling of the stars

Stars undergo many phases during their lives. The major stages are the pre-main sequence, the zero-age main sequence, the main sequence, the red-giant branch and the asymptotic giant branch. These phases are connected to timescales (dynamical, thermal, nuclear):

$$\tau_{dyn} \ll \tau_{KH} \ll \tau_{nuc} \tag{3.9}$$

such that the dynamical timescale is the shortest and is related to changes about the inside of the star (travel time), the thermal or Kelvin-Helmholtz timescale denotes the time it takes a star to radiate away its kinetic energy and the nuclear timescale corresponds to the time the star is powered by nuclear fusion of hydrogen in the core (time on main sequence).

Stars and their structure, respectively, can be described using the stellar equilibrium equations:

$$\frac{dP}{dr} = -\rho(r)\frac{GM(r)}{r^2} \qquad \text{hydrostatic equilibrium} \tag{3.10}$$

$$\frac{dM}{dr} = 4\pi r^2 \rho \qquad \text{conservation of mass} \tag{3.11}$$

$$\frac{dL}{dr} = 4\pi r^2 \rho \varepsilon_n \qquad \text{conservation of energy} \tag{3.12}$$

$$\frac{dT}{dr} = -\frac{3\kappa\rho L}{16\pi a c r^2 T^3} \qquad \text{transport of energy} \tag{3.13}$$

Here, the structure equations are expressed in radial not mass coordinates (for a reference see Kippenhahn, Weigert and Weiss, 2012). The hydrostatic equilibrium says that all forces acting on a mass element balance each other such that it will not be accelerated and gravity opposes pressure; ρ is the density, G the gravitational constant, M the mass of the element and r the radius. Eq. 3.11 states that the total mass is equal to the sum of all mass shells arising in a star. In eq. 3.12 the energy produced in a shell is equal to the total luminosity which is radiated away from the shell - which in case for the outermost shell would be the surface of the star. L is the total luminosity and ε_n gives the released nuclear energy. The transport of energy (eq. 3.13) is described by the temperature T, the mean absorption coefficient κ, the radiation density constant a after Stefan-Boltzmann and c is the speed of light. The energy transport can be either radiative, conductive or convective depending on the stellar structure which in turn is determined by the mass of a star (Kippenhahn, Weigert and Weiss, 2012).

The stellar structure equations describe different equilibria: As long as they are sustained the star is stable. If one state is disturbed such that the equilibrium cannot hold anymore, the star undergoes an evolutionary change. The star will try to adjust back into an equilibrium state. The adjustment time depends on the different timescales in eq. 3.9. For example, a transported blob of stellar matter will rise to the surface of the star on the dynamical timescale.

For the Dark Stars it is assumed that they are in hydrostatic and thermal equilibrium once DM heating balances gravity (Spolyar et al., 2009). Although while still accreting infalling matter, the equilibrium is constantly disturbed and re-established on the according timescale. The best approximation for the equilibrium state is shown in the snapshots during the computational modelling. A first approach to study the evolution of Dark Stars was done by Freese and her team by considering a DS to be a polytrope such that its equation of state is

$$P = K\rho^{1+1/n} \tag{3.14}$$

which gives the relation between the pressure P and the density ρ for a given radius. n denotes the polytropic index and K is determined for given mass and radius.

Another approach is via computational modelling using the MESA stellar evolution code (MESA Paxton et al., 2011; Paxton et al., 2013; Paxton et al., 2015; Paxton et al., 2018; Paxton et al., 2019). It is a code that allows to simulate nearly any kind of star

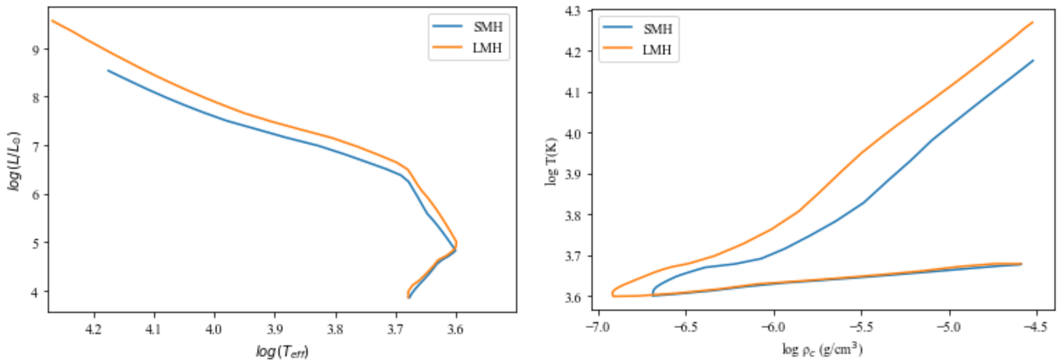

Figure 3.1.: *Left panel:* Reproduction of the HRD for a Dark Star coming from a SMH (blue) or a LMH (orange). *Right panel:* Reproduction of the temperature-density profile. The density is given as the central density of the Dark Star.

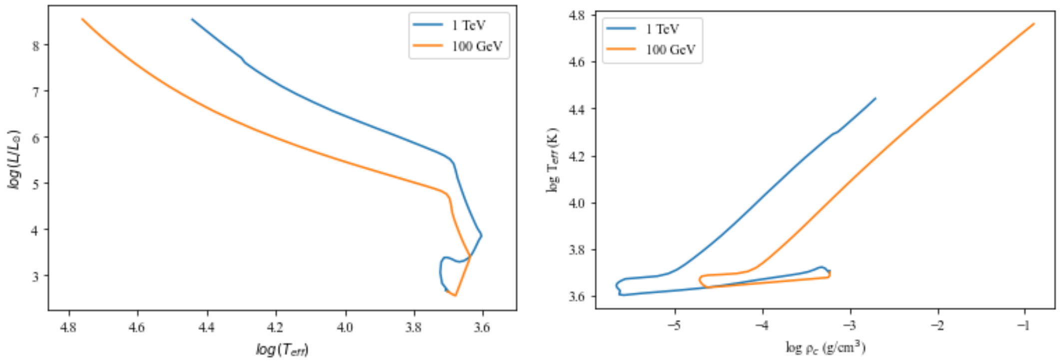

Figure 3.2.: HRD (*left panel*) and density-temperature profile (*right panel*) for fixed halo mass but varying WIMP masses each done for a SMH. In the 100 GeV case the cross section is left at the canonical value of $\langle\sigma\nu\rangle = 3\cdot 10^{-26} cm^3/s$; for the 1 TeV run the cross section was changed to $3\cdot 10^{-29} cm^3/s$.

where the stellar structure equations are solved self-consistently. For this thesis, the DS modelling with MESA was used as well (see Chapter 3.2.2).

In MESA the stellar structure equations are already built in and are solved self-consistently during a run. Of special interest is the evolution of the equation of state (which need not to be a polytrope, see eq. 3.14) which is connected to the hydrostatic equilibrium. Additionally, boundaries and initial values can be set in MESA such as the maximum mass, radius (depending on definition) or the mixing-length parameter α. Regularly, a run starts off by creating a pre-main sequence model, which is then evolved further, where the star starts with nuclear fusion. For DS the central temperature T_c is set low enough to prevent this since DS would be fuelled by DM annihilation. The latter is implemented with the module `other_energy_implicit` which then induces

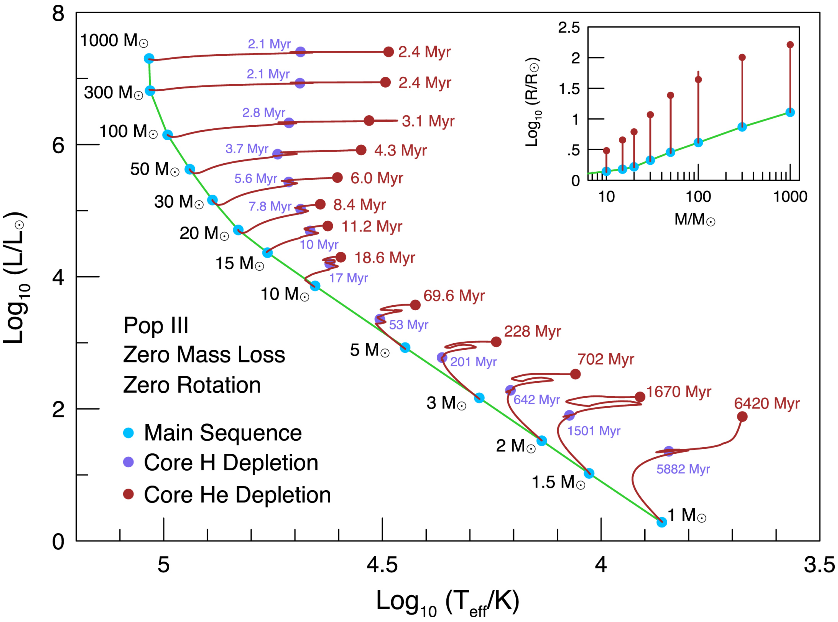

Figure 3.3.: Overview on the HRD evolution of regular Pop-III stars according to their masses. Their respective lifetimes are given as well. Figure taken from Windhorst et al., 2018.

the annihilation energy as thermal support against gravity.

During a run, MESA opens a diagram window featuring a classical Hertzsprung-Russel diagram, luminosity vs. surface temperature, and a second depicting the path on the HRD with density vs. temperature. Runs were done for the case of a small minihalo (SMH) and large minihalo (LMH) as given in table 3.1. The reproduction of the HRD is shown in fig.3.1. The WIMP mass was fixed for both cases at m_χ=100 GeV.

For comparison, other runs were done with a fixed minihalo and different WIMP masses. For these runs the standard WIMP mass of $m_\chi = 100$ GeV as well as $m_\chi = 1$ TeV, both times with the SMH was chosen. In the case of the higher WIMP masses, the annihilation cross section was reduced to $\langle\sigma\nu\rangle = 3 \cdot 10^{-29}$ cm^3/s since the parameters can be traded off, see eq. 3.8. A third run with $m_\chi = 1$ GeV failed due to convergence issues.

Properties of Dark Stars

The investigation of Dark Stars over the past decade has painted a clearer picture about them. Accordingly, basic properties are already known about these peculiar first stars. With their unusual fuel, they also differ from regular Population-III stars.

One thing both have in common are the rather high masses compared to present-day stars. Pop-III stars are thought to range from some solar masses up to 260 $M_\odot$. Supermassive stars could grow to masses above 1000 $M_\odot$. Dark Stars, however, can grow up to masses of 10^6 or even 10^7 $M_\odot$ (see Freese et al., 2010 and Rindler-Daller

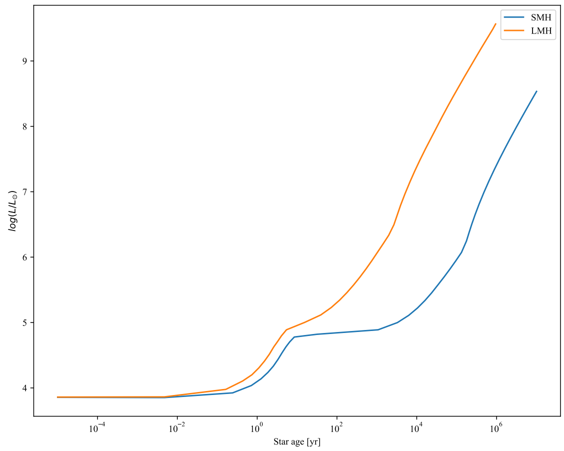

Figure 3.4.: Lifetime of a Dark Star born from a SMH (blue line) and a LMH (orange line). Alongside is the evolution of the luminosity.

et al., 2015). They can reach these high masses during the DM annihilation phase: The Dark Star remains cool enough that no ionising photons are created which could act as a feedback mechanism and stop further accretion. Their luminosity can reach $10^9\ L_\odot$ while having a surface temperature of "only" 10,000 K as visible in fig. 3.1. In contrast, regular first stars have typical surface temperatures of about 50,000 K and may reach 100,000 K at the high mass end (see fig. 3.3).

Overall, this comparison shows that while DSs grow to higher masses and luminosities than regular first stars, the latter are much hotter even at lower masses. This is a consequence of the sizes Dark Stars have. They have radii of ~ 10 AU, which corresponds to the distance Sun-Saturn. Hence, they are giant and also puffy. Another reason is the difference in the power source: While fusion-powered stars produce a large number of ionizing photons, they have an assortment of feedback mechanisms which cut off accretion of material onto the star. Dark Stars barely suffer from feedback and their cooler surface temperatures gives them the opportunity to grow in size (Freese et al., 2010).

Usually, for high surface temperatures, blue or white colours are expected, at least while the star is on the main sequence. The exact colour of any first stars is yet unknown. In case that they should all be massive, they would reach the red-giant phase quickly.

Lastly, the lifetime of first stars is considered to be rather short owing to their high masses since they use up their hydrogen faster. This correlation is visible in fig. 3.3. A typical Pop-III star would live only a few million years. For Dark Stars the evolution would be similar. The models of the MESA runs place the age of a DS at around 10^6 and 10^7 years. Hence, they reach about the same age as regular first stars. Of course, the results vary, depending on the mass.

3.2.3. Final fate of Dark Stars

Dark Stars are massive and therefore they will most likely end as a supernova. Before that, however, they will undergo a phase of nuclear fusion.

Once the dark matter from the adiabatic contraction is used up, they can still get some dark matter particles via capturing processes. Still, at a certain point, DM as a fuel will be depleted. Spolyar et al., 2009 found the cut to be at around 300,000 years and $\sim$850 $M_\odot$ (depending on the WIMP mass). Consequently, the outwards pressure from the released annihilation energy drops and gravity takes over. The DS will contract and density concentration of baryonic matter rises in the centre. Reaching high enough temperatures alongside high pressure, nuclear fusion can set in and starts to power the star anew for a short time. Following the usual evolution, the Dark Star will go through burning cycles (until helium depletion). As it is out of fuel it will become a supernova and, at such high masses, directly collapses into a black hole.

Freese et al., 2010 and Rindler-Daller et al., 2015 study the evolution of supermassive DS, on the ground that orbital dynamics of DM within halos allows the continuous replenishment of DM in the halo centre, enabling a steady fuel for the Dark Star. Since DSs can grow to supermassive sizes they could pose a solution to the problem of supermassive black holes (SMBH). Today, a number of high-z SMBHs is observed, yet it is unclear how they could have grown to their high masses in the given time. SMBH are placed as early as $z \approx 7.1$ (corresponding to 0.77 Gyr after the Big Bang), where a $2{\cdot}10^9 M_\odot$ quasar, more precisley a SMBH, was found by Mortlock et al., 2011. The first stars are thought to form around a redshift of $z \approx 15 - 20$ which is 200 Myr after the Big Bang. As they would collapse only a few million years later, a supermassive black hole would only have roughly 600 million years to grow to such scales. For a regular massive Pop-III star this would not be sufficient, hence supermassive stars are thought to act as seeds for SMBHs.

Especially Dark Stars with their enormously high masses would be great candidates for such seeds. Even if DSs from small minihalos (M$=10^6 M_\odot$) could make it past their nuclear fusion phase, DSs from LMHs would be even better suited. The fact that they form at a lower redshift gives them more time to accrete more matter. Hence the accretion rate is higher and the Dark Stars are therefore more massive. They would directly collapse into a SMBH seed without any fusion phase (Freese et al., 2016) once the DM reservoir is fully depleted.

3.2.4. Observability of Dark Stars

So far, no first stars were directly observed; neither regular nor `"dark"`. There are several reasons as to why they have not been found until today.

1. Massive or supermassive stars have short lifetimes. Hence, they would not have lived until today. Only their final stages, remnants, like black holes or white dwarfs would be visible yet not at high redshifts (see `https://astronomy.swin.edu.au/cosmos/p/Population+III`).

2. If first stars would have been in the low-mass range as well, they should still exist

as their lifetime extends to many hundred billion years. By now, however, they would be contaminated by metals either on their own as they dredge up produced elements to their surface or they would have collected metals from the interstellar medium as they travel through it. Both mechanisms would make them appear as Population-II stars, i.e. the second generation of stars which is metal-poor, i.e. not entirely devoid of metals. Nevertheless, current simulations favour massive or supermassive first stars only (see `https://astronomy.swin.edu.au/cosmos/p/Population+III`).

3. Current telescopes and instruments are not sensitive enough to catch light from objects older than a corresponding redshift of z $\approx$ 11. At this redshift the oldest galaxy GN-z11 was found with the Hubble Space Telescope (HST) during the CANDELS/GOODS survey (Oesch et al., 2016). The farther away an object is, the more it will be shifted towards redder colours where higher sensitivities are needed. Though the HST and the Very Large Telescope in the Atacama Desert are among the most powerful telescopes, they are at their limit of observability for such high-redshifted objects.

All hopes in astromomy now lie with the upcoming next generation telescopes: E-ELT (European Extremely Large Telescope), GMT (Giant Magellanic Telescope) and, non-ground based, Euclid and the *James Webb Space Telescope* (JWST). The latter, supposedly, will be launched by the end of this year, 2021. The JWST is an infrared telescope with a bigger wavelength range than the HST and has also a higher sensitivity. One of the goals is to observe the early Universe (`https://www.jwst.nasa.gov/content/about/faqs/facts.html`).

Hence, if regular first stars could be observed, so should be Dark Stars. Many papers have already looked into the detectability of DSs (Freese et al., 2010, Zackrisson et al., 2010 and Ilie et al., 2012). Their conclusion are summed up as follows.

If any type of Dark Stars could be found it would be the supermassive ones at masses of $10^6 M_\odot$ and $10^7 M_\odot$ since they would be luminous enough (up to $10^9 L_\odot$). The NIRCam instrument on the JWST should be capable to observe Dark Stars in all its wavelength bands for exposure times around 10^6 seconds (corresponds to 11.5 days). Zackrisson et al., 2010 found that the HST should already be able to find SMDS of $M = 10^7 M_\odot$ if they existed until z $\approx$ 12. But since no such observations found any Dark Stars in this range, they concluded that they rather did not exist. Yet at a mass range of $10^6 M_\odot$ DSs are still possible, only the Hubble Space Telescope is not sensible enough to resolve them.

Another way to observe Dark Stars and other faint objects, respectively, is done via the drop-out/Lyman-break technique. The Lyman-α line is emitted by hydrogen sources when an electron jumps from a higher energy state (n = 2) back to the ground state (n = 1). When travelling through space this spectral line is absorbed and leaves a break in its continuum flux at 912 Å (91.1 nm) for $z \leq 4$ and at 1216 Å (121 nm) for higher redshifts (Schneider, 2015). The Universe expands and as a consequence emitted light is stretched towards bigger wavelengths λ and hence redder colours; it is *redshifted.* Filters are centred at different frequencies ν and wavelengths, respectively. If now the light passes through the bands, the object is visible for corresponding λ and ν. If it passes through smaller wavelengths or higher frequencies it drops out, i.e. it is not longer visible. Since the absorption wavelength of the Ly-α emitter is known, the redshift can be calculated according to:

$$z = \frac{\lambda_{obs}}{\lambda_{em}} - 1 \tag{3.15}$$

where λ_{obs} is the observed wavelength corresponding to the wavelength of the band and λ_{em} the emitted wavelength.

The JWST will be able to find drop-outs in some of its bands for redshifts up to z $\approx$ 14, which comes near to the formation redshifts of LMH Dark Stars. With this, at least Dark Stars from the high-mass end will be individually detectable while regular first stars are not luminous enough. Yet their light should contribute to the first galaxies with stellar masses of 10^6 to $10^8 M_\odot$ (Freese et al., 2016).

4. Outreach Part I: Introduction

The term *outreach* conveys many different definitions or concepts. The Oxford Dictionary of English describes it as follows:

outreach n. /'aʊt.riːtʃ/ [*mass noun*] an organisation‘s involvement with or influence in the community, especially in the context of religion or social welfare

Following this definition, outreach is a (honorary) service provided by a single person or an organisation to one or more persons in need of this help. This includes social, medical, religious or educational services.

In a broader way outreach is understood as public relations where an organisation offers communication to the public.

The Cambridge English Dictionary provides two other definitions:

outreach /'aʊt.riːtʃ/ ***noun*** an effort to bring services or information to people where they live or spend time

or as stated in the Dictionary of Business English:

outreach /'aʊt.riːtʃ/ ***noun*** the process of an organization building relationships with people in order to advise them, for example about health or financial problems

In both cases, outreach is a commitment from the outreach workers. They want to offer services or knowledge on their own behalf even though they would not have to.

This thesis focuses on outreach as education: The aim is to convey knowledge about a specific scientific field, namely astronomy and astrophysics.

Educational outreach in the sense of scholastic teaching work is not included here. A good example, however, for complex *science education* at an academic level is given by Rindler-Daller, 2020. She describes her lecture about cosmological observations and modelling in which she conveyed the difficulties of cosmological simulations to her students. They had the opportunity to try the simulations themselves using the CLASS code. Beforehand, a thorough introduction into the topic was done on a didactically valuable level.

For the rest of the thesis, outreach is viewed in the context of *science communication*. In this framework, this includes scientific outreach events (workshops or projects), articles, Social Media and transfer of knowledge in a Planetarium.

4.1. Importance of Science Communication

The importance of science, research and innovation appears unquestioned in the academic and knowledge society. All three contributed to today's civilisation and state of technology. Especially medicine, biology, physics and engineering are highly praised for their innovations. Yet the developments in science cannot stand without the support of the public and state financing. Hence, a decent presentation of research aims and results have to be brought to the public and politicians to understand the necessity of new findings.

4.1.1. The Science behind Science Communication

In the past years, science communication has risen to a high significance. As a consequence, it has become a field of research of its own. For a long time, science communication research was rather regarded as communication science. In other words, it was mostly explored from a social science view and researched with didactic and pedagogic approaches. Only slowly over the past years it has become clear that science communication and its research, respectively, has to be evaluated for natural sciences as well.

To make a good science communication certain aspects have to be analysed or rather fulfilled in order to get enough attention. They are presented as three *keywords* below.

Contribution to society is the first keyword. Research and innovations are encouraged if they upgrade our living. Anything that improves our health, prolongs our life, enhances infrastructural changes, strengthens economy or secures sustainability is valued. In return for these developments, research is funded. *Investment* is another keyword. Nothing works without money; fundamental and cutting-edge research are in need of the best technological level and depend on financial support. Funding is mostly given by the state that has its own funds. State money in turn comes from taxpayers' money. Typically, people do not want to spend their tax money on things they render useless. Such objection is easily achieved if people do not understand the purpose of a research.

Therefore, *relevance* is another keyword. If we deem the research to be significant, we rather put our money into it. Even more so, if the necessity is great. The burning issue of the Covid-19 pandemic is an excellent example for relevance. Never before has a vaccine been developed in such a short time. It took the pharmaceutical industry less than a year to find, study, test and produce a vaccine against a virus that keeps the whole world in check. This was possible since both, politics and the public, called for a quick end to the pandemic. During this time the public was provided with facts, figures and insight about the current state of the research. The communication took place on all available channels: TV news, radio, newspapers and Social Media of all kinds. So medical purposes have big relevance and the funding comes in. It has to be admitted that usually it does not proceed at this speed but it was pressing in order to save lives.

Not every scientific field can offer this immediate relevance. In astronomy and physics there are more than enough topics that do not seem to be of significance to the public - unless it is aliens or a potentially hazardous asteroid that flies by near the Earth. Otherwise, why should anyone but astronomers care about the rotation of a star at a distance of 1,500 lightyears? In which way does the breaking of lepton universality contribute daily life? Is it necessary to build yet another radio-telescope array? And "how on earth" are first stars, fuelled by dark matter instead of nuclear fusion, important to an elementary school teacher, your barber, the trash collector or a psychologist?

(Astro-)physicists could simply argue, and actually do so, that all their highly specific research helps to complete the big picture, answer the one and only question: Why are we here?

In order to give public relevance to such topics one has to make them relevant. Not every subject is of an immediate public necessity. Accordingly, other important mechanisms are *fascination* and *interest.* The same spirit that drives scientists to explore their field of research is appealing to others. Yet, not everyone has the possibility to study or the ability to keep up. Still the fascination remains and it can be fed.

At this point science communication enters the stage. First, humans want to understand what is going on around them and they look for answers.

Second, 'Everyone has the right to education. (...) Education shall be directed to the full development of the human personality (...)', as stated by the Universal Declaration of Human Rights of the United Nations (`https://www.un.org/en/about-us/universal-declaration-of-human-rights`). In the context of science communication and its necessity this means that scientists should "simply" convey their results because the public has a right to know about them.

Third, it is in the scientists' own interest to maintain the public's interest in their research. If they cannot make their studies appear appealing and important, the state/the public will rather stop funding them.

Working with fascination is the best way to go, for scientists as well. If you do not like what you are doing why should anyone else? To sum up, science communication is important to both sides. Yet many scientists do not engage in outreach owing to different reasons. One of the main arguments is time. When doing research, every minute is crucial and publications in scientific journals are important. Preparing a popular scientific talk would consume this time. Others may suffer from stage fright. Most important, however, is the problem of language. Researchers' language is so specific that colleagues from a different field could have difficulties understanding them. For interested laypersons it would be even harder.

4.1.2. The people behind it

Science communication and outreach can be done by various people, of various professions. Primarily, the scientists are expected to present their outcome as they know it best. Not all scientists, however, want to engage in science communication, and they do not have to, and not everyone is suited. The latter issue concerns the ability to break down difficult topics and technical terms into a simplified popular language. Moreover, science communication should be exciting, fun, interesting and should arouse interest. Thus, science communication has become a field of research of its own.

Who exactly are the people doing science communication? Bowater and Yeoman, 2013 categorise different groups after a report written by Alison MacLeod from the Wellcome Trust Sanger Institute in 2010. An adaption of the original report from Bowater and Yeoman, 2013 is presented here [1] .

- **Professional Science Communicators** - are people who are employed in museums, science centres or institutes/universities. Sometimes they may be self-employed. They are trained scientists, yet research is not their main occupation. Relevant for this thesis would be employees at a Planetarium or a public observatory.
- **Academic Science Communication Experts** - are specialised academics who Alison MacLeod, 2008, defines as people *'who may have a background in social science or society [...] conduct their own research and run masters degree courses on science and society'*.
- **Science popularisers** - are scientists who gain popularity with the public itself. They write, lecture, broadcast or are in journalism. Their aim is to inspire an ever growing audience about scientific topics. Today this would refer to YouTube channels and podcasts as well.
- **Science Defenders** - their work can be seen as either important or controversial. They are first and foremost scientists who aim at expressing the importance of their very own research, which can be *'controversial or newsworthy'*.
- **Scientists** - engage with outreach in schools or at science events as s sideline to their primary research work. They 'want to give back to the community' via engaging with the public and explain their or other's work.

As a matter of fact, science communicators can belong to more than one group. Whatever the ultimate motive, headlines or goodwill, they all have one common driver: Spark the public's interest with their cool and fascinating science.

4.2. Examples for Science Communication and Outreach

Contribution to the public, investment and relevance steer the symbiosis of science communication on both sides. Over the past years, many exemplary projects, events or initiatives upheld the outreach sector for science. Here, different examples are given that represent at least one of these keywords.

4.2.1. Austria and the CERN Petition

The *Conseil Européen de Recherche Nucléaire*, better known as CERN, in Geneva is a collaboration of different European countries. Here, scientists and engineers work at the world's currently biggest particle accelerator, the *Large Hadron collider* (LHC). First

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[1] The original report is not publicly available and was given after a request of the author by the Wellcome Connecting Science.

agreements and the building of the first experiments happened in the 1950s. At first, Austria did not want to participate, it was still a war-shaken country and money seemed more necessary in other places. Thanks to Fritz Regler and Walter Thirring, two Austrian nuclear scientists, Austria joined the European Organisation for Nuclear Research, which is another name for CERN, in 1959 (Jeitler, 2019).

Member states of CERN pay a sort of membership-fee which goes into the overall budget for all the experiments. In return, students, young scientists and senior researchers from the member states get the opportunity to participate in the studies done at the experiments/detectors in the first row. Another trade-off, which is generated by the investment of local industries, is the direct usage of the findings and innovations. In Austria, MedAustron uses a particle accelerator that was built and developed together with CERN for cancer treatment, thus uniting research and therapy (`https://www.medaustron.at/de/teilchenbeschleuniger`). Moreover, the World Wide Web has its root at CERN, developed by Tim Berners-Lee. Originally the idea was to allow scientific communication between researchers all around the world and offer free access to their findings. It was later put into open access (`https://home.cern/science/computing/birth-web`). In addition to that, CERN is a centre for science communication, offering tours for visitors and schools.

In spring 2009, Austria wanted to exit from the collaboration with CERN. The Federal Ministry for Science claimed that the financial contribution to CERN would not pay off for Austrian scientists and Austria's visibility at the experiments, respectively. Former secretary Johannes Hahn, and the head of the Department for Natural Sciences within the Ministry Daniel Weselka, wanted to broaden Austria's participation in different scientific projects all over Europe and around the world. They did not see reason in putting all the money into one collaboration when Austria's presence seemed secondary (Illetschko and Taschwer, 2009).

This intent caused quite an uproar from the scientists at the Institute of High Energy Physics (HEPHY) of the Austrian Academy of Sciene (ÖAW) in Vienna, which acts as a bridge to CERN. Also, employed researchers from Austria could not understand this move.

Moreover, this was a bad moment for an exit. Some months later, in fall 2009, the Large Hadron Collider, which is the biggest particle collider until this day, would be put into commission. Not only would Austria lose reputation and therefore seem to be an unreliable partner but also the economy would suffer. Up to 35% of the local industries and companies would lose the benefit of the cooperation. Austrian employees in Geneva would have even lost their jobs and the access to research programmes (Grancy, 2009)

The Austrian Physical Society launched the petition "SOS - Save our Science" to prevent Austria's withdrawal. After the first day, more than 6,000 signatures came in (APA, 2009). Eventually, with the help of statements from high-ranked researchers as well as from Nobel prize laureates, about 30,000 signatures from laypersons managed to stop the exit.

The LHC promised to level-up the fundamental research as well as cutting-edge research. It could help to fully explore the Standard Model of Particle Physics (some two years later the Higgs boson was found), expand it (breaking of lepton universality, g-2 factor of the muon) and help us to get a step closer to the answer 'why are we here?'.

Thus the *contribution to society* is very well obvious. Medical improvement and work places would have been lost. It was the fascination of the interested public that exerted pressure on political decision makers in favour of science. *Relevance* overruled and complemented *investment*.

4.2.2. Landing of NASA's Perseverance Rover

Since the "Space Race" in the 1950s and 1960s, broadcasting of spaceflights has been well watched by people all over the world. The Apollo 11 Mission to the Moon had well over 500 million viewers from all over the world (`https://www.mdr.de/zeitreise/mondlandung-grosser-schritt-menschheit-100.html`).

Launches of rockets, satellites and probes as well as landings of some of them on celestial bodies are still televised. Today, of course most of them are provided on social media such as YouTube, Facebook, Twitter and Instagram.

One recent event is the landing of NASA's new Mars rover Perseverance on February 18, 2021. Perseverance has the mission to look for any kind of life on Mars, i.e. microbial traces, and it will collect soil to be tested on-board. Some of it will be stored and shipped back to Earth with a future mission (`https://mars.nasa.gov/mars2020/mission/overview/`). The rover was launched in summer 2020 and, taking the best route, had a six-month journey to our red neighbour. Both, the launch and the landing in the Jezero crater on Mars were broadcasted and made into big television events. Those were featured by two hosts who accompanied the viewers all the time. In between, other correspondents offered peeks into Mission Control Center at JPL (Jet Propulsion Laboratory), talks with experts and guests. In the scope of the mission, a naming contest for the rover was held throughout the US. Students from different levels of education could participate by suggesting a name backed up with an essay as to why the name would fit. The winner of the contest was invited for an interview during the stream as well.

One and half an hour prior to the landing the broadcast started. Its purpose was to give the audience some background information, scientific insights and entertainment to bypass time. Many scientists and engineers working on the mission were being interviewed as they would know best. They explained what was about to happen, what had already happened, clarified some often used technical terms in order to make the audience understand the mission and its steps, respectively, as far as possible.

Up to now (November 2021) the stream scored over 22 million views from all over the world, most of them during the live stream. Other channels offered a live stream as well such that the overall numbers will be higher.

4.2.3. Science Communication in the USA vs. Europe/Austria

Generally, in the US outreach work and science communication are carried out at much larger scales than in Europe. Many universities offer science communication as graduate and postgraduate studies. Nearly every scientific institution has a department for outreach and public relations that offers projects of any kind for the public. Examples are NASA and Fermilab. Not only do they have guided tours, but also workshops, talks and a strong social media presence. They both communicate via Instagram, Twitter and Facebook Accounts, supported with a YouTube channel. On Instagram they inform their followers about ongoing research, do weekly quizzes, advertise merchandise, make historical flashbacks and give-aways.

Such activities do exist in Europe and in Austria, respectively, as well. Yet they do not appear to gain as much attention. Many factors may contribute to this difference. Comparing Europe with the US, one could argue that in the US it is much easier to convey knowledge as all its states speak the same language and it is therefore easier to offer a unified transfer of knowledge throughout the country. Moreover, as English is the leading world language English outreach channels can reach a bigger audience abroad. Still, language should not be an obstacle. Outreach projects can always be translated into the official language of a country that would participate (here: EU member states).

In 2003, a policy briefing from the European Science Foundation (now ESF Science Connect) stated that, following the EU's strategic plan 2000-2010, science communication has to be of greater value and therefore needs more investment (European Science Foundation, 2003). Namely, that the fraction of the Gross Domestic Product (GDP) going into Research and Development (R&D) should increase from 2% to 3% by 2010. On the one hand, this contribution raises Europe's international competitiveness for industries on the global market. On the other hand, more funding is available for an adequate science education and communication.

Comparing Europe's expenditures to the US, back then the US spent 2.6% of their Gross National Product (GNP) for R&D, while Europeans only put 1.9% into it. As such, Europe needed to catch up. As to why this difference is so strong, the European Science Foundation said that "we simply lack a science culture in Europe" and that in the US scientific institutes and organisations "know that they need public and political attention; if not, they will not get any funding for their research".

Following up on the goals for 2000-2010, the new strategic plan for 2010-2020 showed no clear improvement in the European Union (European Commission, 2010). Just as ten years earlier, the goal was still to reach at least 3% of the GDP invested into R&D, only this time by 2020. Indeed, some European countries - such as Austria and Germany - managed to reach the goal and even slightly exceeded the 3% mark, respectively.

As visible in table 4.1 the overall goal for the European countries was not reached, at least by 2019 (for 2020 no data is available yet). Only a handful of European countries touched the mark; most are well below or had even a decrease in their GDP for Research & Development. Consequently the overall European average is still at 2.735%. Whether the strategic plan will be fulfilled with the data of 2020 is rather questionable as the pandemic probably thwarted the efforts for a better science culture.

The United States are still ahead of the game. As mentioned before, their scientific facilities are well aware of the importance of their representation. They are crucially dependent on funding. Answering the question why Americans are more willingly offering

GDP expenditure in [%] per year and country	AUT	EU	US
2001	1.997	1.704	2.648
2010	2.726	1.862	2.735
2019	3.192	2.101	3.067

Table 4.1.: Comparison of selected yearly GDP expenditures for Austria, the European Union (27 member states) and the US. Over the past 20 years there is a clear increase. Value taken from OECD (2021), Gross domestic spending on RD (indicator). doi: 10.1787/d8b068b4-en (Accessed on 08 September 2021).

science communication compared to Europeans would go far beyond the scope of this thesis. A precise evaluation and research would be needed as well as a more profound knowledge of economic systems. Probably the most suitable way would be a cooperation with researchers from social and economic sciences. This opens the possibility of future work in the field of science communication.

5. Outreach Part II: Planetarium

A planetarium is a very specific and elaborate option for science communication. Mostly, when thinking of a planetarium, the average person imagines a rather big round house with a dome on top of it. Inside the dome there would be a bulky, round globe, the projector. That is the classical planetarium as invented by Walter Bauersfeld by order of the optics manufaction Carl Zeiss in Jena, Germany (Krausse, 2006).

In modern planetariums the original Zeiss projectors are often backed up digitally or in some cases they are purely digital. The advantage of digital display is the higher number of possibilities. It is able to show animations of any kind: stars, planets, zoomed-in pictures, atmospheric effects, formation processes, simulations and additional features. A disadvantage, however, is the resolution of the night sky. Where a mechanical projector produces the stars (and other objects) as pin sharp points, a digital "screen" is dependent on its number of pixels and resolution, respectively. 4K resolution makes the stars appear as round halfway sharp smudges. Therefore, in order to be comparable to an analogous night sky it is best to work with digital projectors of 8K.

A planetarium probably accounts for the most vivid visualisation of the Universe and its phenomena. The shows are mostly focused on one general topic, e.g. star formation, planets, the actual night sky, constellations.

In the Vienna Zeiss Planetarium such shows are presented throughout the week for kids as well as for adults. New programmes are produced every one to two years. One missing topic is a show about cosmology, more specifically about the Big Bang and the evolution of the Universe.

As one of the many course instructors responsible for the transfer of astronomical knowledge at Vienna (and previously also in Klagenfurt) Planetarium, I run the shows for the audience. Having found my love for outreach work there and my interest in cosmology, I will be drafting a new show on cosmology. The coding of the programme will be done together with the two software engineers/designers Michael Feuchtinger and Hannes Richter.

The problem with cosmological topics in a planetarium is the display. As it is not something we can observe with our bare eyes, the normal star projector would not be of much use. For the digital projectors (VELVETS) a completely finished animation has to be implemented. Animations take time and computing power. This part is the most challenging.

5.1. Show concept

First, in order to make a show, one needs a general concept, i.e. the structure of it. The big challenge here was to find a new approach to a cosmology show.

Typically, if one tells the story of the Universe, it starts at the beginning, which is the Big Bang. Then it proceeds linearly until today. As this way works best, it is the most commonly used. Therefore it was not considered an option for a new show. Another possibility is to go the other way around: starting today and evolving backwards. This is more of a challenge and one has to be careful in explanations. Also this approach is widely used by now. Another advance in cosmology is to start today and look into the future, constructing how the Universe will evolve and how it will end, should it ever end.

For the show in the Vienna Planetarium something new should be created. The final outcome is a combination of all three paths, each presented in a separate, subsequent part. It is based on the introduction of the Standard Model of Cosmology in Chapter 2.1. A first draft of the storyboard is finished and can be found in Appendix A. Corresponding sequences from the storyboard will be marked in blue.

Part One

A planetarium show typically starts with an intro (pg. 3). Here, a sunset is simulated until all stars (projector shows 3500 stars for the northern hemisphere) appear. This is accompanied by soft background music. The moderation starts with the question "If there are this many stars shining in the Universe, why is it not as bright as a day during the night?". It serves as a catch for the audience's attention as this sentence is followed by turning on the lights, making it blindingly bright. For a beginning Olbers' paradox is explored: If the Universe were static and contained an infinite number of stars, it should be bright during the night. Today, it is well known, that the Universe is not static and expands. During its lifetime of 13.8 billion years it has grown structure, the Cosmic Web. At this point the Cosmic Web is shown on the dome (pg. 4f).

The first part serves as a retracing of the steps it has taken the structure to form itself. It starts with today's structure and breaks down the formation until reaching the first stars. So, this is a sort of "top-down" scenario, showing large structures first, smaller ones in the end. Once the first stars are reached (Era of Reionisation), the next question arises, "Where did the first stars come from?" (pg. 5ff).

Part Two

This part starts with the classic storyline with its beginning at the Big Bang (pg. 8ff). The first second of the Big Bang is explained with three symmetry breakings (TOE, GUT, electroweak phase transition), followed by the primordial nucleosynthesis. Up until recombination the not-yet clear occurrence of dark matter has to be pointed out. The next big stop is at recombination, with a full-dome picture of the CMB-map as shown in Chapter 2, fig. 2.2.

After the last scattering surface, the Dark Ages set in (pg. 11). For simplicity and to make this process more figurative, the Dome lights are switched off as well. Meanwhile, the moderation introduces the structure formation, i.e. smallest fluctuations growing into bigger objects (pg. 11). Towards the end of the Dark-Ages sequence, the Illustris [1] full dome simulation starts: It shows the formation and clustering of primordial gas, which subsequently collapses into first stars and finally grows into today's large-scale structure (pg. 11f). After this scene, the formation of a star, especially a primordial star is shown (cloud collapse, protostellar disk, ignition of nuclear fusion). In this scope, Dark Stars, are presented as well. With this, the storyline connects to the end of part one. At the end, the Cosmic Web is shown once more.

Part Three

This will be only a short chapter in the end. It gives an outlook to the possible future scenarios of the Universe. Those are the *Big Rip*, *Big Freeze* and the *Big Crunch*. They will be featured as a literal "outlook": Shot through a space telescope, they will each pop up with a short explanation.

Big Rip: For this scenario it is assumed that the Universe will continue to expand endlessly. During this process the space between objects (e.g. galaxies), grows larger. We observe this already today but gravity is stronger and keeps the Universe together for now. At a certain point, the expansion will overcome gravity and large structures will be torn apart. All stars, planets and black holes from galaxies will float around individually. Eventually they will be ripped apart into their smallest building blocks and no interactions will be possible anymore. All elementary particles will continue to float through space lonely for all eternity (pg. 13).

Heat Death/Big Freeze: It is considered to be the most likely scenario. Expansion will be going on as well but matter will stay intact. It will, however, be used up and dissolve. Hence, there will not be any new material to form stars. Existing stars will be exhausted and will be converted into radiation. Even black holes will decay due to Hawking radiation. The Universe can be considered as a closed system and as such it always strives to a *state of maximal entropy*. It tries to reach a perfect equilibrium. All matter will blend into a uniform material soup and it will stay this way, frozen in its state. Unless a quantum mechanical effect, the *tunnelling*, occurs and starts a new Big Bang (pg. 13f).

Big Crunch/Big Bounce: In the last scenario expansion will not be going on forever. As a matter of fact it will be reversed and the Universe will begin to shrink. Gravity will pull inwards, causing structures to merge. With increasing density in a decreasing space the temperature will rise. It will be hot enough to even "cook" stars. Shortly before everything will be crushed even atoms will disintegrate and black holes would eat each other up, even the Universe itself. Theoretically, the "otherside" of the last black hole could spew out a new Universe. Like a loop, this could happen multiple times, therefore *Big Bounce* (pg. 14).

The explanations for all three scenarios are taken from kurzgesagt's YouTube Video

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[1] for more details see: https://www.illustris-project.org

"Three Ways to destroy the Universe", `https://www.youtube.com/watch?v=4_aOIA-vyBo&t=220s`.

The final extro of the show is yet unclear (pg. 15).

5.2. Production and audio-visual material

In the initial phase of the thesis it was planned, that some 15-20 minutes of the show would be done for a first sneak peek until the final presentation of the thesis. A completely animated show of one hour length takes at least two years of production. Most of the time is used up for the animated videos. They are often simulations brought to a 360° screen. Movement and changes of camera perspective are more laborious than static objects or simple starball projections. In order to make the animation look real, it needs depth and texture. Once the videos are done, they have to be rendered according to the dome system which takes up more time for more intricate animations (file size).

The Planetarium of Vienna does not have employed in-house graphic designers of its own. Hiring one would be too costly. Therefore, the video material will be taken mostly from open-source websites under a Creative Commons license. The European Southern Observatory dedicates a whole media centre on its website to a video archive (`https://www.eso.org/public/videos/archive/category/fulldome/`). Alongside the usual 16:9 videos, there is one collection of full dome videos featuring different objects, phenomena and topics of astronomy (e.g. globular clusters, the Milky Way, supermassive black holes, full-length shows). Some of these videos are to be used for the show done for the thesis.

Music connects to emotion. As such it is crucial for a captivating show. As music is produced by people earning their money with it, audio files often are not free to use therefore permissions to use have to be obtained. The VHS Wien (Volkshochschule Wien) pays a yearly fee which allows to play music for public events (such as planetarium shows). Certain songs are already registered for re-use, new ones can be added.

During the shows music is added in different styles and situations. From the musicology of movie scores, there are many techniques and aims the chosen tracks have. Useful for planetariums are here the *underscoring* and *mood technique*. The first is underlaid quietly to a visual scene or dialogue, it can give a mood or foreshadow; it doubles the narrative. Different from this is the mood technique, where rather than double the feeling it is used to imbue sequences. Its functionality is expressive and underlines certain moods.
At the Vienna Planetarium soundtracks are used to the structure as follows:

1. Music for the inlet and outlet of the audience.
2. Soft music on low volume when the operator talks. Here, audio is not necessary but it suppresses an eerie silence which can be awkward for the audience.
3. Music to highlight passages, either while talking or in video-only sequences. The music builds up and peaks to the climax of the video.

Once all the video and audio material is gathered, the programming (or coding, depending on the dome system) starts. In the case of the Vienna Planetarium this is done with the dome manager interface. The principle of the production with Zeiss' Dome Manager is simpler compared to other softwares e.g. SkySkan Digital Sky 2, where each appearance has to be programmed in a script. Using the Dome Manager one "only needs" to drag the files into the desired plane (horizon, zenith) to the desired moment in the time-line where it should be played and to add the music. The technical details are of course more subtle. If making use of the starball projections, it has to be programmed separately and then added to the main script with time triggers. If all the material is acquired the completion can follow.

Owing to the Covid-19 pandemic and the associated restrictions, like the lockdowns, a programming training of the author was not allowed as no access to the building was given. Generally, most co-workers were not allowed into the building. Moreover, one of the producers left the planetarium so that there is a shortage of staff. Due to these circumstances it has not been possible to produce any part of the show (state: November 5th, 2021).

6. Outreach Part III: Writing and Social Media

Apart from the digital programming and media production at the Planetarium which is a dominant feature of the outreach part, other approaches for science communication have been explored. One is an article for a popular scientific journal, the other is a project with the International Astronomical Union (IAU). Both are described in the next sections.

6.1. Scientific journalism

In the scientific world articles are frequently used to release new results of research. There are many magazines and journals for each field of research. Astronomy (and astronautics) alone comprises more than 70 scientific journals all around the world. Four of the best known are *The Astrophysical Journal*, *Astronomy & Astrophysics*, *Monthly Notices of the Royal Astronomical Society* and *Nature Astronomy.*

The articles, *papers*, published in these journals are directed at the scientific community. For a layperson this style of writing is far too complicated and specific. Popular scientific journals or newspapers offer the public a possibility to delve into newest research findings. In German-speaking countries *P.M. Magazin* or *Spektrum der Wissenschaft* are among the top magazines. For astronomy especially there is e.g. *Sterne und Weltraum* (by Spektrum der Wissenschaft). Newspapers, daily or weekly, offer science sections. *Der Standard*, one of Austria's daily newspapers, adds a short science article nearly every day and once per week provides an extra science section ("Forschung Spezial") about various current topics. Every once in a while a special edition of Forschung Spezial focuses on a specific issue (future Mars and space missions, evolution of nutrition, new methods for reusing or reducing plastic waste, etc).

One of the latest members in Austria's landscape of popular scientific journals is the *Alexandria Magazin*[1]. It focuses on young scientists and students, respectively, from different fields, such as politics, social sciences, natural sciences and many more. Rather coincidentally but perfectly in the scope of this thesis, the author was asked to write an article for the Alexandria magazine about Dark Stars.

Dark Stars are a good example for a very specific field of research. This topic needs a very profound astrophysical knowledge: general stellar formation and evolution, primordial star formation, dark matter, cosmology. The task at hand was to provide a basic understanding

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[1] https://www.alexandria-magazin.at

of these mechanisms and lead over to the scientific topic of dark stars. Of course, the language used should be easy and simplified while not leaving out the scientific rationale.

6.1.1. Writing articles

As mentioned above, scientific journalism encompasses scientific papers and popular scientific articles. They are written by people with different professional backgrounds and have different objectives for heterogeneous readerships.

For scientists the focus clearly is on presenting the whole working process. It is depicted in the structure of a scientific paper: title, abstract, introduction (i.e. background, previous findings), methods, results and conclusion. Many months or often years and much effort have been put into the research. Thus scientists need to highlight the importance of the invested work. Of course, all this is done to present and share new findings, subsequent results or a complete breakthrough. Writing these papers is often a competition against time and other scientists, respectively. Publishing takes time. Once the paper is written it will be refereed by astronomers/astrophysicists from the same special fields as the paper. The peer review starts once the paper is submitted to the publisher, i.e. journal. Often, the article is submitted to arXiv.org database (`https://arxiv.org`) simultaneously. A number of times the reviewer will ask for changes, adaptions or explanations. The revised paper will then be re-submitted once again. Only after the review is finished, the production process and proof-reading starts. Afterwards, the paper is published and available for the public (not always exempt from charges). For astronomical papers there is not only arXiv, but also the *Astrophysics Data System* operated by NASA and the Smithsonian Astrophysical Observatory (`https://ui.adsabs.harvard.edu`). Summed up, scientists strive to present their results based on long-term work and profound research, see fig.6.1.

Journalists on the contrary, look for exciting headlines and readable content. Hence, they often seem to disregard the whole process and focus mainly on the results. Background follows later and the methods are only briefly touched (see fig.6.1, right hand-side). They are, after all, the most complex part of the research. Additionally, most laypersons have little to no interest in data extraction or calculations.

Therefore journalists look for something "spicy". Nevertheless, they have to do extensive research on the presented subject since they should reconstruct the process truthfully. Their objective, however, is to spark interest, gain reads/clicks and inform the public about latest achievements. On this course, they have to use simple explanations and an everyday language. These factors often cost background information or shortened description of processes and methods. Even so, journalists should not oversimplify things as this may falsify information. They have to stay factual and stick to the scientific accuracy. Sustaining the interest of their readers is most relevant to journalists.

When writing a popular scientific article/newspaper report they have to find a reason as to why the reader should read their articles. Scientists do not seek the relevance of their research for an everyday use, but rather to improve research for research's sake. Nevertheless, it has to have a meaningful contribution to the scientific community but it is not bound to "how will this help me in my daily life?" other than "it is awesomely

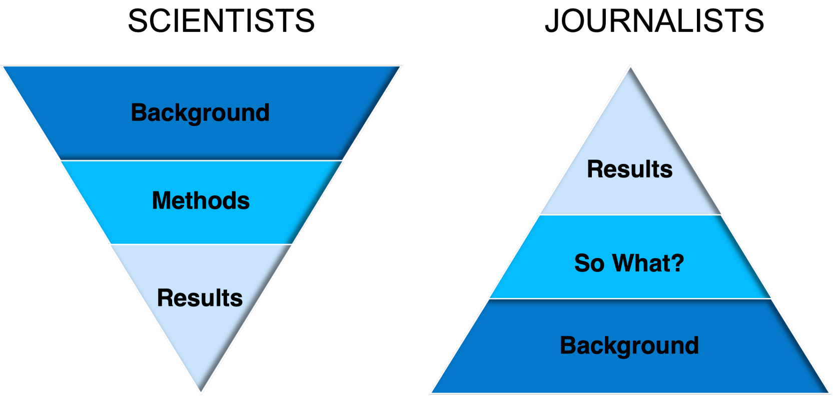

Figure 6.1.: Priorities set by either scientists or journalists in their articles. From *Escape from the Ivory Tower* by Nancy Baron. Copyright ©2010 by Nancy Baron and Island Press. Reproduced by permission of Island Press, Washington, DC.

interesting". Even though the latter will be sufficient for laypersons who are already keen on the topic, a popular scientific article should aim not only to keep the already existing fanbase but also to gain the curiosity of others.

6.1.2. Knowledge Transfer at the Alexandria Magazine

At the Alexandria magazine there is a default structure and layout given by the editorial office. In principle, the articles are essays. The article starts off with a proposition or hypothesis, followed by a short justification why this topic is relevant to the public or the reader. It should relate to the daily life. The main body consists of pro and contra arguments which are supported by actual results. This demands accurate journalistic research and correct citing. It serves as an approach towards the main message and problem. Methods can be explained in this part as well. In the end, a conclusion should offer a solution, new questions, future outlooks and personal statements. An info-box is dedicated to the author's personal information.

An article should have a length of about 10,000 symbols, spacing included. Mechanisms, statistics and images accompany the text with figures for easier understanding. For an example, see fig. 6.2, where an artistic illustration of the power source of a Dark Star vs. a regular star is shown. Additionally, an article can have up to three info-boxes with supplementary information, that would take too long or deviate from the main topic in the running text, that explains technical terms.

The article on "Dark Stars - Licht am Anfang des Universums" (Fenkart, 2021; see appendix A) is divided similarly to the structure in Chapters 2 and 3 of this thesis with different introductions into the necessary topics. These have to be explained beforehand to a layperson such that the Dark Stars can be understood. In the following the structure

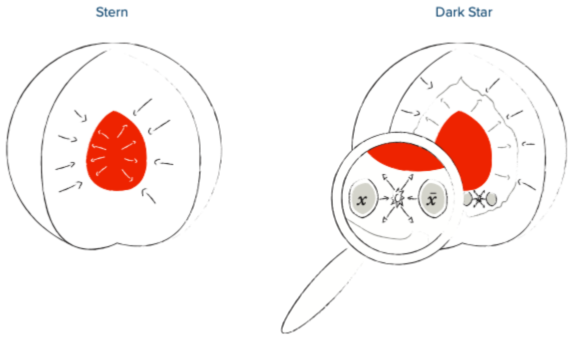

Figure 6.2.: Comparison of the structure and power source, respectively, in a regular star (left) and a Dark Star (right). Note, that this is only an artistic illustration that supports the understanding of DM annhililation. ©Alexandria Magazin, illustrated by Rika Vestjens after a scheme provided by the author.

of the article is described, supported by excerpts from the publication referenced to the according Chapter, marked in blue, in this thesis.

Every article starts with a reference point as to "why this is important" and an introduction into reading:

> Sterne erscheinen uns selbstverständlich, jedoch sind sie vergänglich, wenn auch auf astronomischen Zeitskalen. Darüber hinaus sind nicht alle Sterne gleich, schon gar nicht gleich alt, groß oder heiß.

The first section explained the evolution of a star during its lifetime. More precisely, how stars are born, what happens once they exist and how they die. This encompasses star formation, starting with molecular clouds in the ISM, collapse, nuclear fusion and death for either a low-mass or massive star.

> Solange ein Stern Wasserstoff in seinem Kern als Treibstoff zur Verfügung hat, ist er erneut in einem Gleichgewicht. Die Kernfusion erzeugt dann Druck nach außen, und die Gravitation zieht nach innen. Dieser Zustand bleibt über einige Millionen bis zu vielen Milliarden Jahren bestehen. Je mehr Masse ein Stern hat, desto kurzlebiger ist er. Das liegt an den enormen Temperaturen, die bei hohem Druck den Wasserstoff schneller aufbrauchen als bei einem Stern, der wenig Masse hat. Ist das Gasreservoir einmal verbraucht, kommt der Stern an sein Lebensende.

The next Chapter compared primordial to present-day star formation and evolution, where the main difference is the lack of metals in the early Universe (Chapter 3.1):

> In den ersten 200 Millionen Jahren nach der Entstehung des Universums durch den Urknall gab es nur selten Phasen, in denen es etwas zu sehen gab. Auch wenn es beinahe seit dem Beginn des Kosmos Photonen (Lichtteilchen) gab, können wir erst etwas sehen, wenn sie mit Teilchen oder anderen Objekten wechselwirken. Erst mit der Entstehung der Sterne wurde das Universum dauerhaft sichtbar.

Finally, dark matter was explained similar to Chapter 2.3.

> Im Lauf der letzten Jahrzehnte hat sich gezeigt, dass in der Astrophysik nichts mehr ohne die sogenannte Dunkle Materie funktioniert. Sie heißt dunkel, weil sie nicht sichtbar ist, genauer: Sie interagiert nicht mit Photonen und ist daher nicht über typische Lichtphänomene nachweisbar.

Once all the prerequisites were described, the central matter of Dark Stars and their observability followed. At this point the explanation is already very similar to the description of Dark Stars in Chapter 3.2 of the thesis as enough knowledge was conveyed by now. This passage from the article is not taken from the main body but from the caption of one of the figures comparing Dark Stars to regular stars:

> Bei Dark Stars kommt es nicht zur Kernfusion. Bei der Entstehung von Dark Stars werden Dunkle-Materie-Teilchen und -Antiteilchen stärker zusammengequetscht, sie annihilieren immer öfter. Die dadurch freiwerdende Energie hält den Stern im Gleichgewicht, noch bevor die Kernfusion einsetzen kann.

This part also included the role of Dark Stars as possible seeds for supermassive black holes (Chapter 3.2.3) and a short notion on the detectability of Dark Stars (Chapter 3.2.4). The conclusion gives yet again a connection to life on Earth and the mysteries that are still unsolved. It is a vague outlook into the future, paraphrased into an open end:

> Unsere Ozeane und das Universum haben eine Gemeinsamkeit: Obwohl wir die Weltmeere seit Jahrtausenden sehen und seit vielen Jahrhunderten auch erkunden, ist uns erst ein Bruchteil davon bekannt. Ähnlich ist es mit dem Universum, auch von ihm kennen wir nur einen Bruchteil.

The full article (first version), can be found at the end of the thesis, in Appendix A.

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6.2. IAU Social Media Project

As mentioned in the Introduction, the inspiration for this master thesis was the IAU General Assembly in 2018. The International Astronomical Union is the biggest association of astronomers worldwide, having a total of 11,478 active members, junior members included. It is well known among astronomers but less so to the broad public. Most people do not know that there is a connected astronomical (or any scientific) society. In order to make their importance understood, the audience in the Planetarium is told "those are the people who decided that Pluto is not a planet anymore". Obviously, this statement carries a slightly cynical or even negative undertone.

The IAU does much more, ever since it was established in 1919. Two years later, in 1921, the first General Assembly was held where one of the first things was to settle on some norms. For example, clear definitions of constellations on the night sky in order to avoid confusion with the nomenclature. Each culture has different legends and therefore different constellations. An Asian and European astronomer may look at the same star, yet it would bear two or more names. Today, there are 88 official constellations for nomenclature and orientation.

For the public many concerns are of less importance: the variability period of some low-magnitude star, the spectrum of a dwarf galaxy or the formation of polycyclic aromatic hydrocarbons. It is barely known that the IAU, or more precisely, Commission A3 Fundamental Standards (part of Division A), sets and adapts the reference frames for not only celestial matters (ICRS - International Celestial Reference Systems) but also for terrestrial purposes. This affects the accuracy of our coordinate systems and as a consequence all navigation.

Today it is quite easy to get the public's attention by means of communication. We have a large variety of social media channels. Thus the IAU has accounts on several services, namely Twitter, Facebook and YouTube with approximately 13,000 , 18,000 and 2000 followers. Yet, the feedback, i.e. the numbers of likes, shares or comments are rather moderate, ranging roughly between 17-51 likes per posting.

In order to try to raise the public's awareness of the IAU, the author launched a project together with the IAU Office for Astronomy Outreach (OAO), the coordinator from the OAO Izumi Hansen, and since August 2021, Lina Canas, head of the OAO.

The aim is to present the IAU - its people, its work - to the public. Therefore, we make use of short videos for each Division and the Executive Committee.

The idea for the layout of the videos is to start with a title slide naming the Division with the official webpage image of the Division as a background. All participating members from the Division are given the same set of eight key questions they should answer. Not every question would have to be answered and they should not reply to them directly but rather blend them into a short presentation about themselves. The questions serve as guidelines. Additionally, each Division has a special question, a take-home message, that focuses on their scientific rationale. In the video, each question would be shown to the viewer on a black screen and then followed by the responses from the Division members. At the end, a compilation of B-roll shots (supplemental or back-up material that is not used for the main footage) will round it up. The B-roll features the astronomers while working on their research projects or while conducting outreach work. Also, pictures from previous gatherings would fit in here. Just as for the planetarium show the videos would be accompanied by music. An example for the proposal is attached in the Appendix A.

Getting footage for the videos proved to be hard. 2021 should have been the year of the 31st General Assembly of the IAU, held in Busan, Korea. Even though the Covid-19 situation has improved slightly in some places, restrictions are still too prohibitive to hold a grand international conference. Nevertheless, the elections for the posts of presidents, vice-presidents and secretaries had to happen in order to stick to the three-year legislature. Starting in late-spring/early-summer the Divisions and the Executive Committee were busy preparing the handovers. The Business Meetings were held online in the middle of August 2021. Therefore, up until now only one video was sent in. It seems though, that the willingness of the invited Divisions (Division C and J) as well as the Executive Committee to participate is very high. As such the deadline for the videos was postponed to a date after the business meetings.

7. Conclusion

The Covid-19 pandemic is a perfect, ongoing example for the importance of science communication. While governmental services try to educate the public about the facts and figures of the corona-virus and the vaccine through all available social channels, corona-virus sceptics and anti-vaxxers use the same media to spread their non-scientific views. Misinformation can do a lot of harm. Hence, it is crucial that people with an academic background in their respective fields of research communicate their knowledge to the public. After all, it is a topic that has everyone's attention.

In astronomy, one crucial scientific decision resounded throughout all lands: in 2006 Pluto's degradation to a dwarf planet by the IAU. It was broadcasted through all analogous and digital media. People had to rethink their knowledge about the solar system and understand this change. As a matter of fact, it is still a frequently asked question by adults and children as well.

The advances in technology and theoretical (astro-)physics revolutionised our perception of the Universe over the past decades. The Big Bang theory stands as the present Concordance Model and is complemented with the concepts of dark matter and dark energy. Similarly, the Standard Model of Particle Physics rounds off the whole theory. Yet, both are not completely solved. It is still unclear when and how exactly dark matter arose and what its true nature is. Dark energy and the baryon asymmetry are open questions as well. One of the biggest problems is the compatibility of general relativity and quantum mechanics, which has particle physicists find new theories beyond the Standard Model. In case there will be new findings, they will certainly not only thrill scientists but also make their way into the news and popular scientific magazines as well. In 2021 there were some pioneering results, such as the exact determination of the muon g-2 factor at Fermilab (Abi et al., 2021), the breaking in the lepton flavour universality at CERN's LHCb experiment (LHCb collaboration et al., 2021), or the follow-up publication of the first-ever direct image of a black hole by the Event Horizon Telescope Collaboration, where they now published the magnetic-field line arrangement of the black hole in the galaxy M87 (Event Horizon Telescope Collaboration et al., 2021a and Event Horizon Telescope Collaboration et al., 2021b).

For astronomy and cosmology the next breaking results are expected to come with the JWST. It will shed new lights on the early Universe and with it, on Dark Stars. If they are found they will reveal details about the nature of dark matter, as DM is their fuel instead of nuclear fusion. The existence of Dark Stars is not unlikely in the early Universe. Space was smaller than today and therefore had a higher matter density; which holds for dark and baryonic matter alike. Stars are formed from molecular clouds which at a redshift of around $z \approx 20$ consisted of primordial gases (hydrogen and helium) as well as dark matter. When collapsing, the DM is streaming towards the centre of the emerging protostar alongside H and He. Due to the contraction, matter is compressed and its density rises, making dark matter particles collide more often. In a ΛCDM Universe the most likely candidates are the *weakly interacting massive particles* (WIMPs). They are thought to be Majorana fermions, i.e. they are their own antiparticle and annihilate upon colliding. This annihilation releases energy in the form of photons and heat. The energy is released outwards and starts to act as a counterforce, a pressure, against gravity. As a consequence the Dark Star reaches an equilibrium state before the core can assemble enough mass (hence also heat and pressure) to ignite nuclear fusion. As long as there are enough WIMPs for annihilation, the star stays stable.

Due to the absence of metals in the early Universe and the unusual heating, a DS is able to accrete mass onto itself, making it grow to supermassive scales. Hence, DSs can reach masses up to 10^6 or even $10^7 M_\odot$. The typical luminosity of such a DS is at around $10^{10} L_\odot$, while their surface temperature settles at 10,000 K. With radii of ≈ 10 AU, they are called giant and "puffy", possibly giving them a rather red colour.

Should the JWST launch in the upcoming months, first results on whether Dark Stars actually exist will be published in a few years. Up to this moment further theoretical inquiries can be made. There are still open questions:

- **Lifetime.** The precise lifetime of Dark Stars depends on different factors, such as dark matter fuel, replenishment of DM, a nuclear fusion phase and the mass. Under ideal conditions, a DS could live for a few billion years.

- **Particle shower.** Many interactions can lead to the creation of new (elementary) particles: scattering, decay events or annihilation. Upon this, the newly created particles can interact again, thus triggering a *particle shower*. So far, for Dark Stars the postulated interaction products are high-energy photons γ, electrons e^- and the associated electron neutrinos ν_e. The exact pathway and products from the primary and secondary showers however, depend on the detailed WIMP model.

- **Dark Matter type.** The current model of Dark Stars is based on a ΛCDM cosmology, taking the WIMPs as the most prominent candidates of cold dark matter. Even though the latter reconstructs our Universe quite well, it fails to solve the *cusp-core problem* for low-mass galaxies, the *missing satellites problem* and the *too-big-to-fail problem*. Hence, other dark matter types are considered (Bose-Einstein condensate, self-interacting DM, fuzzy DM). Whether or how another DM type would influence the existence and evolution of Dark Stars could be researched in future work.

The first and the second point could be explored using the MESA stellar evolution code, changing the parameters in the inlist files and modify the module `other_energy_implicit` to the properties of other DM types. For the exact results of the particle-shower products the 2-body interaction has to be calculated with the integration of partial differential equations and the corresponding cross sections.

Mostly, the thesis focuses on outreach methods, more precisely on science communication. It is done in order to inform the public about current scientific results and to make them understand complex research. The latter is a crucial point for the funding of research: Part of the tax payers' money goes into Research & Development. But if the public does not see, or rather does not understand the research, they will not want to see science supported with further money.

Moreover, laypersons would often enough want to know about the ongoing research for the same reasons scientists delve into their research: they both are fascinated by it. And fascination should be encouraged and fed. To underline the importance and justification of science communication four key phrases were introduced: *relevance*, *contribution to society*, *investment* and *fascination and interest.* Each of them is reason enough that science communication is and should be done.

There are different methods in science communication to facilitate a transfer of knowledge. A very straight-forward way are public talks and popular-scientific articles. For this thesis the main outreach spotlight is on the knowledge transfer at planetariums. While talks are often accompanied with presentation slides that offer (audio-)visual material, a planetarium captures the attention with full dome projections. All the different phenomena in the Universe are envisioned on a 360° screen and a worker/educator orally guides through the show.

At the Vienna Planetarium there was no show about cosmology in the programme before 2020. The centrepiece of this thesis is the concept for a new show that explain the Current Concordance Model of Cosmology, i.e. the Big Bang theory as described in Chapter 2.1. It is split into three parts: Part 1 goes backward in time, starting at the present-day structure in the Universe until the first stars; Part 2 moves forwards since the Big Bang and has a bigger focus on first stars; Part 3 shows possible future scenarios of our Universe. For a show about cosmology with all its theoretical and mathematical framework, one has to find the right balance of previously offered knowledge and new content. For the latter to be clear, the basics has to be sufficient but not overwhelming as a show typically only lasts for one hour. In the early stages of the thesis (March 2020), the idea was to not only present a concept but also present a sequence of about 10 minutes from the show. Unfortunately, owing to the restrictions of the Covid-19 pandemic, no programming was possible.

Directly focusing on the issue of Dark Stars is the article written for the Alexandria Magazine (Fenkart, 2021). Just as for the show, the article has to give insight into different explanations that are needed for a layperson to understand Dark Stars. The fundamentals here are primordial as well as present-day star formation and evolution (from birth to death of a star), nuclear fusion and capturing processes, dark matter and its annihilation in case of WIMPs. Only after this knowledge is conveyed in a simple yet scientifically correct language, Dark Stars themselves come into the spotlight. Articles at the Alexandria Magazine start with a justification as to "Why this is important" to the reader and should connect to something of the daily life. This was the most challenging part of the article since Dark Stars themselves "only" contribute to the big jigsaw puzzle, trying to answer the question "Where do we, where does the Universe come from?". They mainly fulfil the keywords *fascination and interest*.

A third outreach project in the scope of this thesis is done with the Office for Astronomy Outreach (OAO) of the International Astronomical Union to raise the visibility in the public of the latter. In short videos, different members of each Division as well as the Executive Committee will present their work and love they have for astronomy. Shooting, gathering material, rendering and cutting the videos takes time and due to the Business Meetings in the summer 2021 as well as the overworked yet understaffed OAO the videos are still in the making.

Chapter 4.1.2 presents who the people doing science communication are. Mostly, it is people who are scientists themselves. Not all scientists can or want to to outreach, therefore many amateur astronomers work at museums, planetariums or public observatories. They do a very good job and gain a high level of expertise by working out and learning about astronomy and astrophysics by themselves. Without them many public scientific institutions would not be able to fulfil the mission of educating the public. This may pose the question why this thesis is even necessary.

It is important to say that even though amateur astronomers are excellent at their outreach work, it is crucial that scientists actually present their research and offer a steady stream of new results. Regardless their technical terminology, scientists are the ones who give the basis for any kind of knowledge transfer. They research it, prove it, present it. A popular scientific book as well an article has to be written by a scientist , or at least have the explanations or comments of a researcher in it. It is the same for any science-fiction movies; they need a verified scientific basis. The science behind it is and has to be checked by scientists who work with producers to be as accurate as possible.

At planetariums, many are amateurs who guide the shows. Nevertheless, professionals are needed for profound and correct explanations. The shows are made and/or re-checked by scientists such that the ever-fascinating and complex Universe is depicted correctly.

Finally, as stated above, it needs the collaboration from different sides: researchers offering and supervising input for science communication, an interested audience willing to learn more and professional science communicators (scientists or amateurs) who convey the broad spectrum of knowledge.

Bibliography

Abel, Tom, Greg L. Bryan and Michael L. Norman (Jan. 2002). “The Formation of the First Star in the Universe”. In: *Science* 295.5552, pp. 93–98. DOI: `10.1126/science.295.5552.93`. arXiv: `astro-ph/0112088 [astro-ph]`.

Abi, B. et al. (2021). “Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm”. In: *Phys. Rev. Lett.* 126 (14), p. 141801. DOI: `10.1103/PhysRevLett.126.141801`. URL: `https://link.aps.org/doi/10.1103/PhysRevLett.126.141801`.

Alpher, Ralph A. and Robert C. Herman (Dec. 1948). “On the Relative Abundance of the Elements”. In: *Physical Review* 74.12, pp. 1737–1742. DOI: `10.1103/PhysRev.74.1737`.

APA (2009). *Tausende unterzeichnen Petition gegen CERN-Ausstieg.* URL: `https://www.diepresse.com/478541/tausende-unterzeichnen-petition-gegen-cern-ausstieg`. (last accessed: 5.11.2021).

Ashtekar, Abhay (1986). “New Variables for Classical and Quantum Gravity”. In: *Phys. Rev. Lett.* 57 (18), pp. 2244–2247. DOI: `10.1103/PhysRevLett.57.2244`. URL: `https://link.aps.org/doi/10.1103/PhysRevLett.57.2244`.

Barlow, M. J. and J. Silk (July 1976). “H_2 recombination on interstellar grains.” In: *Astrophysical Journal* 207, pp. 131–140. DOI: `10.1086/154477`.

Begeman, K. G., A. H. Broeils and R. H. Sanders (Apr. 1991). “Extended rotation curves of spiral galaxies : dark haloes and modified dynamics.” In: *Monthly Notices of the Royal Astronomical Society* 249, p. 523. DOI: `10.1093/mnras/249.3.523`.

Blumenthal, G. R. et al. (Feb. 1986). “Contraction of Dark Matter Galactic Halos Due to Baryonic Infall”. In: *Astrophysical Journal* 301, p. 27. DOI: `10.1086/163867`.

Bowater, Laura and Kay Yeoman (2013). *Science communication : a practical guide for scientists.* eng. 1. publ.. Chichester: Wiley. ISBN: 9781119993131.

Bromm, Volker (Nov. 2013). “Formation of the first stars”. In: *Reports on Progress in Physics* 76.11, 112901, p. 112901. DOI: `10.1088/0034-4885/76/11/112901`. arXiv: `1305.5178 [astro-ph.CO]`.

collaboration, LHCb et al. (2021). *Test of lepton universality in beauty-quark decays.* arXiv: `2103.11769 [hep-ex]`.

Dicke, R. H. et al. (July 1965). “Cosmic Black-Body Radiation.” In: *Astrophysical Journal* 142, pp. 414–419. DOI: `10.1086/148306`.

Einstein, A. (Jan. 1905). “Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig?” In: *Annalen der Physik* 323.13, pp. 639–641. DOI: `10.1002/andp.19053231314`.

Einstein, A. (1916). “Die Grundlage der allgemeinen Relativitätstheorie”. In: *Annalen der Physik* 354.7, pp. 769–822. DOI: `https://doi.org/10.1002/andp.19163540702`. eprint: `https://onlinelibrary.wiley.com/doi/pdf/10.1002/andp.19163540702`. URL: `https://onlinelibrary.wiley.com/doi/abs/10.1002/andp.19163540702`.

European Commission (2010). *EUROPE 2020 - A European strategy for smart, sustainable and inclusive growth.* URL: `https://ec.europa.eu/eu2020/pdf/COMPLET%20EN%20BARROSO%20%20%20007%20-%20Europe%202020%20-%20EN%20version.pdf`. (last accessed: 8.11.2021).

European Science Foundation (2003). *Science Communication in Europe (Policy Briefing).* URL: `http://archives.esf.org/fileadmin/Public_documents/Publications/ESPB20.pdf`. (last accessed: 8.11.2021).

Event Horizon Telescope Collaboration et al. (Mar. 2021a). "First M87 Event Horizon Telescope Results. VII. Polarization of the Ring". In: *Astrophysical Journal Letters* 910.1, L12, p. L12. DOI: `10.3847/2041-8213/abe71d`. arXiv: `2105.01169 [astro-ph.HE]`.

Event Horizon Telescope Collaboration et al. (Mar. 2021b). "First M87 Event Horizon Telescope Results. VIII. Magnetic Field Structure near The Event Horizon". In: *Astrophysical Journal Letters* 910.1, L13, p. L13. DOI: `10.3847/2041-8213/abe4de`. arXiv: `2105.01173 [astro-ph.HE]`.

Ezhov, V. F. et al. (June 2018). "Measurement of the Neutron Lifetime with Ultracold Neutrons Stored in a Magneto-Gravitational Trap". In: *Soviet Journal of Experimental and Theoretical Physics Letters* 107.11, pp. 671–675. DOI: `10.1134/S0021364018110024`.

Fenkart, Sanje (July 2021). "Dark Stars - Licht am Anfang des Universums". In: *Alexandria Magazin* 2, pp. 44–47.

Fixsen, D. J. et al. (Dec. 1996). "The Cosmic Microwave Background Spectrum from the Full COBE FIRAS Data Set". In: *Astrophysical Journal* 473, p. 576. DOI: `10.1086/178173`. arXiv: `astro-ph/9605054 [astro-ph]`.

Freese, Katherine, Douglas Spolyar and Anthony Aguirre (Nov. 2008). "Dark matter capture in the first stars: a power source and limit on stellar mass". In: 2008.11, 014, p. 014. DOI: `10.1088/1475-7516/2008/11/014`. arXiv: `0802.1724 [astro-ph]`.

Freese, Katherine et al. (June 2010). "Supermassive Dark Stars: Detectable in JWST". In: *Astrophysical Journal* 716.2, pp. 1397–1407. DOI: `10.1088/0004-637X/716/2/1397`. arXiv: `1002.2233 [astro-ph.CO]`.

Freese, Katherine et al. (June 2016). "Dark stars: a review". In: *Reports on Progress in Physics* 79.6, 066902, p. 066902. DOI: `10.1088/0034-4885/79/6/066902`. arXiv: `1501.02394 [astro-ph.CO]`.

Gamow, G. (1948). "The Origin of Elements and the Separation of Galaxies". In: *Phys. Rev.* 74 (4), pp. 505–506. DOI: `10.1103/PhysRev.74.505.2`. URL: `https://link.aps.org/doi/10.1103/PhysRev.74.505.2`.

Grancy, Alice (2009). *CERN-Ausstieg: Arbeitsplätze und Projekte gefährdet.* URL: `https://www.diepresse.com/479026/cern-ausstieg-arbeitsplatze-und-projekte-gefahrdet`. (last accessed: 5.11.2021).

Green, Michael B., John H. Schwarz and Edward Witten (1987). *Superstring theory. Volume 1 - Introduction.*

Hu, Wayne, Rennan Barkana and Andrei Gruzinov (2000). "Fuzzy Cold Dark Matter: The Wave Properties of Ultralight Particles". In: *Phys. Rev. Lett.* 85 (6), pp. 1158–1161. DOI: `10.1103/PhysRevLett.85.1158`. URL: `https://link.aps.org/doi/10.1103/PhysRevLett.85.1158`.

Ilie, Cosmin et al. (May 2012). "Observing supermassive dark stars with James Webb Space Telescope". In: *Monthly Notices of the Royal Astronomical Society* 422.3, pp. 2164–2186. DOI: `10.1111/j.1365-2966.2012.20760.x`. arXiv: `1110.6202 [astro-ph.CO]`.

Illetschko, Peter and Klaus Taschwer (2009). *Entsetzen über Österreichs CERN-Ausstieg.* URL: `https://www.derstandard.at/story/1241622199541/entsetzen-ueber-oesterreichs-cern-ausstieg`. (last accessed: 5.11.2021).

Iocco, Fabio (Apr. 2008). "Dark Matter Capture and Annihilation on the First Stars: Preliminary Estimates". In: *Astrophysical Journal Letters* 677.1, p. L1. DOI: `10.1086/587959`. arXiv: `0802.0941 [astro-ph]`.

Jeitler, Manfred (2019). *Seit 60 Jahren dabei: Österreich am CERN.* URL: `https://www.derstandard.de/story/2000108183027/seit-60-jahren-dabei-oesterreich-am-cern`. (last accessed: 13.5.2021).

Jungman, G., M. Kamionkowski and K. Griest (Mar. 1996). "Supersymmetric dark matter". In: 267, pp. 195–373. DOI: `10.1016/0370-1573(95)00058-5`. arXiv: `hep-ph/9506380 [hep-ph]`.

Kippenhahn, Rudolf, Alfred Weigert and Achim Weiss (2012). *Stellar Structure and Evolution.* Springer. DOI: `10.1007/978-3-642-30304-3`.

Krausse, Joachim (2006). *Wissen in Bewegung - 80 Jahre Zeiss-Planetarium Jena.* First Edition. Ernst Abbe Stiftung.

Kreckel, H. et al. (July 2010). "Experimental Results for H_2 Formation from H^- and H and Implications for First Star Formation". In: *Science* 329.5987, p. 69. DOI: `10.1126/science.1187191`.

Mather, J. C. et al. (Jan. 1994). "Measurement of the Cosmic Microwave Background Spectrum by the COBE FIRAS Instrument". In: *Astrophysical Journal* 420, p. 439. DOI: `10.1086/173574`.

Mortlock, Daniel J. et al. (June 2011). "A luminous quasar at a redshift of z = 7.085". In: *Nature* 474.7353, pp. 616–619. DOI: `10.1038/nature10159`. arXiv: `1106.6088 [astro-ph.CO]`.

Nascimento, Caio Bastos de Senna and Marilena Loverde (Aug. 2021). "Neutrinos in N -body simulations". In: 104.4, 043512, p. 043512. DOI: `10.1103/PhysRevD.104.043512`. arXiv: `2102.05690 [astro-ph.CO]`.

Oesch, P. A. et al. (Mar. 2016). "A Remarkably Luminous Galaxy at z=11.1 Measured with Hubble Space Telescope Grism Spectroscopy". In: *Astrophysical Journal* 819.2, 129, p. 129. DOI: `10.3847/0004-637X/819/2/129`. arXiv: `1603.00461 [astro-ph.GA]`.

Oort, J. H. (Aug. 1932). "The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems". In: *Bulletin Astronomical Institute of the Netherlands* 6, p. 249.

Palla, F., E. E. Salpeter and S. W. Stahler (Aug. 1983). "Primordial star formation - The role of molecular hydrogen". In: *Astrophysical Journal* 271, pp. 632–641. DOI: `10.1086/161231`.

Paxton, B. et al. (2011). "Modules for Experiments in Stellar Astrophysics (MESA)". In: *Astrophysical Journal Supplement* 192, 3, p. 3. DOI: `10.1088/0067-0049/192/1/3`. arXiv: `1009.1622 [astro-ph.SR]`.

Paxton, B. et al. (2013). "Modules for Experiments in Stellar Astrophysics (MESA): Planets, Oscillations, Rotation, and Massive Stars". In: *Astrophysical Journal Supplement* 208, 4, p. 4. DOI: `10.1088/0067-0049/208/1/4`. arXiv: `1301.0319 [astro-ph.SR]`.

Paxton, B. et al. (2015). "Modules for Experiments in Stellar Astrophysics (MESA): Binaries, Pulsations, and Explosions". In: *Astrophysical Journal Supplement* 220, 15, p. 15. DOI: `10.1088/0067-0049/220/1/15`. arXiv: `1506.03146 [astro-ph.SR]`.

Paxton, B. et al. (2018). "Modules for Experiments in Stellar Astrophysics (MESA): Convective Boundaries, Element Diffusion, and Massive Star Explosions". In: *Astrophysical Journal Supplement* 234, 34, p. 34. DOI: `10.3847/1538-4365/aaa5a8`. arXiv: `1710.08424 [astro-ph.SR]`.

Paxton, Bill et al. (2019). "Modules for Experiments in Stellar Astrophysics (MESA): Pulsating Variable Stars, Rotation, Convective Boundaries, and Energy Conservation". In: *Astrophysical Journal Supplement* 243.1, 10, p. 10. DOI: `10.3847/1538-4365/ab2241`. arXiv: `1903.01426 [astro-ph.SR]`.

Penzias, A. A. and R. W. Wilson (July 1965). "A Measurement of Excess Antenna Temperature at 4080 Mc/s." In: *Astrophysical Journal* 142, pp. 419–421. DOI: `10.1086/148307`.

Perlmutter, S. et al. (Jan. 1998). "Discovery of a supernova explosion at half the age of the Universe". In: *Nature* 391.6662, pp. 51–54. DOI: `10.1038/34124`. arXiv: `astro-ph/9712212 [astro-ph]`.

Planck Collaboration et al. (2014). "Planck 2013 results. I. Overview of products and scientific results". In: *A&A* 571, A1. DOI: `10.1051/0004-6361/201321529`. URL: `https://doi.org/10.1051/0004-6361/201321529`.

Rindler-Daller, T. (May 2020). "Understanding CMB physics through the exploration of exotic cosmological models: a classroom study using CLASS". In: *European Journal of Physics* 41.3, 035602, p. 035602. DOI: `10.1088/1361-6404/ab6c6b`. arXiv: `1908.05042 [physics.ed-ph]`.

Rindler-Daller, T. et al. (Feb. 2015). "Dark Stars: Improved Models and First Pulsation Results". In: *Astrophysical Journal* 799.2, 210, p. 210. DOI: `10.1088/0004-637X/799/2/210`. arXiv: `1408.2082 [astro-ph.CO]`.

Rovelli, Carlo and Lee Smolin (1988). "Knot Theory and Quantum Gravity". In: *Phys. Rev. Lett.* 61 (10), pp. 1155–1158. DOI: `10.1103/PhysRevLett.61.1155`. URL: `https://link.aps.org/doi/10.1103/PhysRevLett.61.1155`.

Rubin, V. C., Jr. Ford W. K. and N. Thonnard (June 1980). "Rotational properties of 21 SC galaxies with a large range of luminosities and radii, from NGC 4605 (R=4kpc) to UGC 2885 (R=122kpc)." In: *Astrophysical Journal* 238, pp. 471–487. DOI: `10.1086/158003`.

Sakharov, Andrei D (1991). "Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe". In: *Soviet Physics Uspekhi* 34.5, pp. 392–393. DOI: `10.1070/pu1991v034n05abeh002497`. URL: `https://doi.org/10.1070/pu1991v034n05abeh002497`.

Schneider, Peter (2015). *Extragalactic Astronomy and Cosmology: An Introduction.* DOI: `10.1007/978-3-642-54083-7`.

Serebrov, A. P. et al. (2018). "Neutron lifetime measurements with a large gravitational trap for ultracold neutrons". In: *Phys. Rev. C* 97 (5), p. 055503. DOI: `10.1103/PhysRevC.97.055503`. URL: `https://link.aps.org/doi/10.1103/PhysRevC.97.055503`.

Shakura, N. I. and R. A. Sunyaev (June 1973). "Reprint of 1973A&A....24..337S. Black holes in binary systems. Observational appearance." In: *Astronomy and Astrophysics* 500, pp. 33–51.

Smith, Rowan J. et al. (Dec. 2012). "Weakly Interacting Massive Particle Dark Matter and First Stars: Suppression of Fragmentation in Primordial Star Formation". In: *Astrophysical Journal* 761.2, 154, p. 154. DOI: `10.1088/0004-637X/761/2/154`. arXiv: `1210.1582 [astro-ph.CO]`.

Spergel, David N. and Paul J. Steinhardt (2000). "Observational Evidence for Self-Interacting Cold Dark Matter". In: *Phys. Rev. Lett.* 84 (17), pp. 3760–3763. DOI: `10.1103/PhysRevLett.84.3760`. URL: `https://link.aps.org/doi/10.1103/PhysRevLett.84.3760`.

Spolyar, Douglas, Katherine Freese and Paolo Gondolo (Feb. 2008). "Dark Matter and the First Stars: A New Phase of Stellar Evolution". In: *Physical Review Letter* 100.5, 051101, p. 051101. DOI: `10.1103/PhysRevLett.100.051101`. arXiv: `0705.0521 [astro-ph]`.

Spolyar, Douglas et al. (Nov. 2009). "Dark Stars: A New Look at the First Stars in the Universe". In: *Astrophysical Journal* 705.1, pp. 1031–1042. DOI: `10.1088/0004-637X/705/1/1031`. arXiv: `0903.3070 [astro-ph.CO]`.

Stacy, Athena et al. (June 2014). "The mutual interaction between Population III stars and self-annihilating dark matter". In: *Monthly Notices of the Royal Astronomical Society* 441.1, pp. 822–836. DOI: `10.1093/mnras/stu621`. arXiv: `1312.3117 [astro-ph.CO]`.

Tegmark, Max et al. (Jan. 1997). "How Small Were the First Cosmological Objects?" In: *Astrophysical Journal* 474, p. 1. DOI: `10.1086/303434`. arXiv: `astro-ph/9603007 [astro-ph]`.

Veneziano, G. (Sept. 1968). "Construction of a crossing-simmetric, Regge-behaved amplitude for linearly rising trajectories". In: *Nuovo Cimento A Serie* 57.1, pp. 190–197. DOI: `10.1007/BF02824451`.

Wagner, Paul (2014). *Einführung in die Physik*. ger. 3., erw. Aufl.. Wien: Facultas.WUV. ISBN: 9783708911441.

Windhorst, Rogier A. et al. (Feb. 2018). "On the Observability of Individual Population III Stars and Their Stellar-mass Black Hole Accretion Disks through Cluster Caustic Transits". In: *Astrophysical Journal Supplement* 234.2, 41, p. 41. DOI: `10.3847/1538-4365/aaa760`. arXiv: `1801.03584 [astro-ph.GA]`.

Zackrisson, Erik et al. (Sept. 2010). "Observational constraints on supermassive dark stars". In: *Monthly Notices of the RAS* 407.1, pp. L74–L78. DOI: `10.1111/j.1745-3933.2010.00908.x`. arXiv: `1006.0481 [astro-ph.CO]`.

Zennaro, M. et al. (Apr. 2017). "Initial conditions for accurate N-body simulations of massive neutrino cosmologies". In: *Monthyl Notices of the Royal Astronomical Society* 466.3, pp. 3244–3258. DOI: `10.1093/mnras/stw3340`. arXiv: `1605.05283 [astro-ph.CO]`.

Zwicky, F. (Jan. 1933). “Die Rotverschiebung von extragalaktischen Nebeln”. In: *Helvetica Physica Acta* 6, pp. 110–127.

A. Appendix

Below, the article on Dark Stars (Fenkart, 2021) which was published in the Alexandria Magazine is presented, see Chapter 6.1.2. Note that the article is featured on different pages in the pre-print version given here (pg. 42-45) and the published printed version (pg. 44-47).

It is then followed by the storyboard of the show conceptualized for the Vienna Planetarium. In Chapter 5.1, the show was referenced to the according Chapters in the cosmological part and pages from the storyboard.

The last document is one of the proposals to the IAU Divisions for the Social Media project. Here, the proposal for Division J with its own take-home message is attached.

DARK STARS
LICHT AM ANFANG DES UNIVERSUMS

WARUM DAS WICHTIG IST

Das Universum zu beobachten ist inzwischen nicht mehr schwer: Sonne runter, Licht aus, Teleskop raus. Dabei blicken wir durchaus mehrere Milliarden Jahre zurück in die Vergangenheit. Allerdings ist die Frühzeit des Universums ungefähr so schwer nachvollziehbar wie der exakte Entstehungszeitpunkt der ersten Mehrzeller. Dark Stars könnten nun Aufschluss über die Natur der ersten Sterne geben.

Text von Sanje Fenkart

Wenn wir in wolkenlosen Nächten gen Himmel blicken, erwarten wir, dass uns viele Hundert bis ein paar Tausend Sterne entgegenfunkeln. In Wien sind es ungefähr 200, während man am Land, fernab der Lichtverschmutzung, über 3.000 Sterne und sogar die Milchstraße, unsere Heimatgalaxie, als ein leuchtendes Band sieht. Sterne erscheinen uns selbstverständlich, jedoch sind sie vergänglich, wenn auch auf astronomischen Zeitskalen. Darüber hinaus sind nicht alle Sterne gleich, schon gar nicht gleich alt, groß oder heiß. Jeder ist besonders. Und obwohl die Astronomie ihren Namen vom griechischen αστρον (astron), Stern, und νομος (nomos), Gesetz, hat, sind sie uns immer noch ein Rätsel. Vor allem die allerersten Sterne, die unser Universum erleuchtet haben.

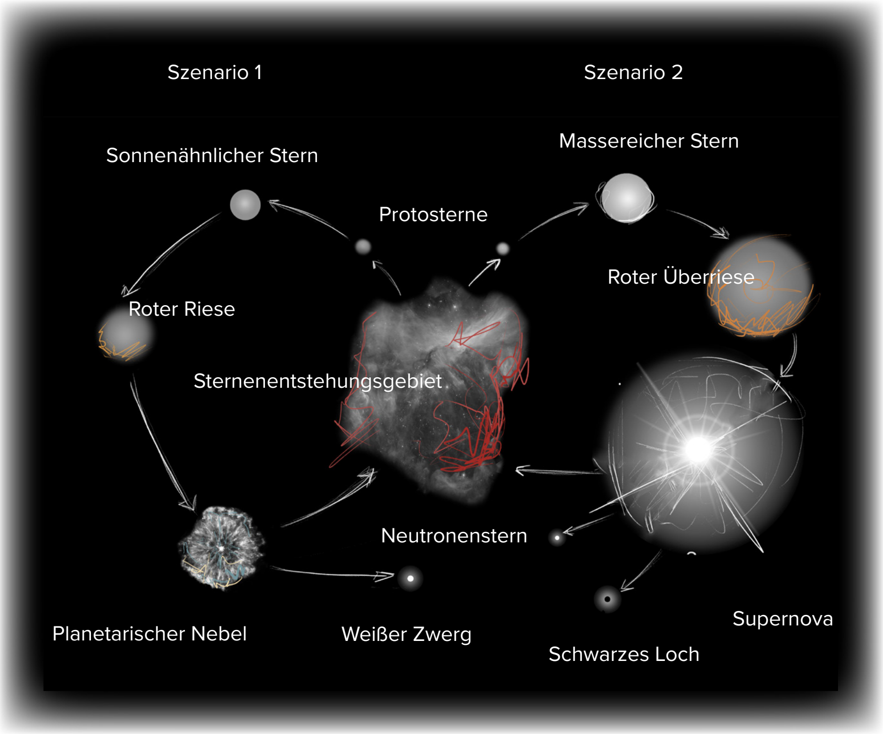
EIN STERNENLEBEN

Sterne haben ein Leben, sie werden geboren, sie altern, sie sterben. Nur beträgt ihre Lebensspanne meist Milliarden von Jahren. Sterne werden aus Molekülwolken geboren, nebelartige Ansammlungen von Wasserstoff, dem häufigsten Gas im Weltall. Die Gaswolken füllen den Bereich zwischen Sternen aus, sie bilden das sogenannte interstellare Medium, kurz ISM. Sie können mehrere Lichtjahre groß sein und alle möglichen Formen annehmen. Im Normalfall befinden sich Molekülwolken im Gleichgewichtszustand, das heißt, dass sich alle Kräfte ausgleichen. In diesem Fall wirkt ein nach außen gerichteter Druck, der durch die Bewegung der Wasserstoffmoleküle zustande kommt, gegen die nach innen strebende Gravitation. Gravitation, Anziehungskraft, wirkt immer zwischen Körpern und ist dort sehr stark, wo sich viel Masse befindet. Bei Gaswolken ist das der Mittelpunkt. Solange die beiden Kräfte gleich stark sind, bleibt die Wolke eine Wolke.

Kommt es zu einer Störung, zerfällt dieses Gleichgewicht zu Gunsten der Schwerkraft und die Wolke kollabiert. In ihrem Mittelpunkt sammelt sich immer mehr Wasserstoffgas an, dieses wird dadurch immer weiter verdichtet, womit auch die Temperatur ansteigt. Irgendwann entsteht daraus ein Protostern; sobald seine innere Temperatur mehrere Millionen Grad Celsius erreicht, kann er mit der Kernfusion beginnen: Wasserstoff wird in Helium umgewandelt, es wird Energie frei, die wir in Form von Licht sehen und im Falle unserer Sonne, die ebenso ein Stern ist, als Wärme spüren (Kippenhahn et al., 2012).

LICHTJAHR

Licht breitet sich als Welle aus und hat dabei eine gewisse, endliche Geschwindigkeit. Diese beträgt 300.000 km/s. Ein Lichtjahr misst, anders als der Name andeutet, kein Zeitintervall, sondern ist eine Längeneinheit, nämlich die Entfernung, die das Licht in einem Jahr zurücklegen kann. Die Distanz ergibt sich folgendermaßen: 365 (Tage) · 24 (Stunden) · 60 (Minuten) · 60 (Sekunden) · 300.000 km/s = 10 Billionen Kilometer. Bis zu unserem nächsten Nachbarstern Proxima Centauri sind es 4.2 Lichtjahre.



Quelle (in Anlehnung an): NASA and the Night Sky Network

Sterne haben ebenfalls einen Lebenszyklus: Geboren aus Gaswolken leuchten sie Jahrmillionen, um dann, je nach Masse, als planetarischer Nebel zu enden, oder in einer Supernova zu verglühen. So entstehen neue Gaswolken und der Zyklus beginnt von vorne.

CAPTURING-PROZESSE

Elemente können in Sternen zusätzlich durch sogenannte Einfangprozesse entstehen. Das Grundprinzip besteht darin, dass der Atomkern ein neues Teilchen hinzubekommt. Beim *neutron capturing* wird ein neutrales Neutron eingefangen, das den Kern instabil macht. Über einen weiteren Zerfall (β-Zerfall) wird das neue Atom wieder stabil. Hier unterscheidet man zwischen dem s-Prozess (für slow, langsam) und dem r-Prozess (rapid, schnell). So entstehen sukzessive weitaus schwerere Elemente als Eisen. Auch über *proton capturing* können bereits schwere Elemente ein weiteres Proton bekommen, was wiederum ein neues Element hervorbringt.

Solange ein Stern Wasserstoff in seinem Kern als Treibstoff zur Verfügung hat, ist er erneut in einem Gleichgewicht. Die Kernfusion erzeugt dann Druck nach außen und die Gravitation zieht nach innen. Dieser Zustand bleibt über einige Millionen bis zu vielen Milliarden Jahre bestehen. Je mehr Masse ein Stern hat, desto kurzlebiger ist er. Das liegt an den enormen Temperaturen, die bei hohem Druck den Wasserstoff schneller aufbrauchen als bei einem Stern, der wenig Masse hat. Ist das Gasreservoir einmal verbraucht, kommt der Stern an sein Lebensende.

Dabei gibt es zwei verschiedene Szenarien. Im ersten Szenario bläht sich in massearmer Stern auf und verliert seine äußeren Schichten durch mehrmaliges Zusammenziehen und Wiederaufblasen. Währenddessen werden im Kern immer wieder neue Elemente erzeugt. Am Ende bleibt vom Stern bloß ein heißer, leuchtschwacher Kern übrig, ein weißer Zwerg. So wird es auch unserer Sonne ergehen, allerdings erst in etwa fünf Milliarden Jahren. Noch befindet sie sich in der Midlife-Crisis.

Das zweite Szenario entsteht bei einem massereichen Stern, der die acht- bis zehnfache Masse der Sonne erreichen kann. Bei so einem Stern geht das Ganze schneller. Sobald die Gravitation die stärkere Kraft ist, kollabiert der Stern im Bruchteil einer Sekunde, nur um gleich darauf als Supernova zu explodieren. Dabei werden im selben Moment alle Schichten weggeschleudert. Dieses Ereignis ist so energiereich und hell, dass es bei großen und nahen Sternen sogar tagsüber zu sehen sein würde (Kippenhahn et al., 2012).

Alle natürlich vorkommenden Elemente, die wir heute bei uns auf der Erde kennen, werden in Sternen hergestellt. Bei massearmen Sternen entstehen vor dem Kollaps nach Helium noch Kohlenstoff und Spuren von einigen anderen Elementen. Massereiche Sterne produzieren zusätzlich Sauerstoff, Neon, Magnesium, Silizium und letztendlich Eisen. Schwerere Elemente können nicht in den Brennphasen erzeugt werden und entstehen unter anderem bei der Explosion durch *Capturing-Prozesse*. All diese Elemente werden wieder in das interstellare Medium abgegeben und reichern somit das Gas für die nächsten Sterne an (Kippenhahn et al., 2012).

So läuft das bei allen Sternen ab. Schon immer. Doch die allerersten Vertreter ihrer Art unterschieden sich eindeutig von ihren jüngeren Nachkommen, die wir heute beobachten.

ERSTE STERNE

In den ersten 200 Millionen Jahren nach der Entstehung des Universums durch den Urknall gab es nur selten

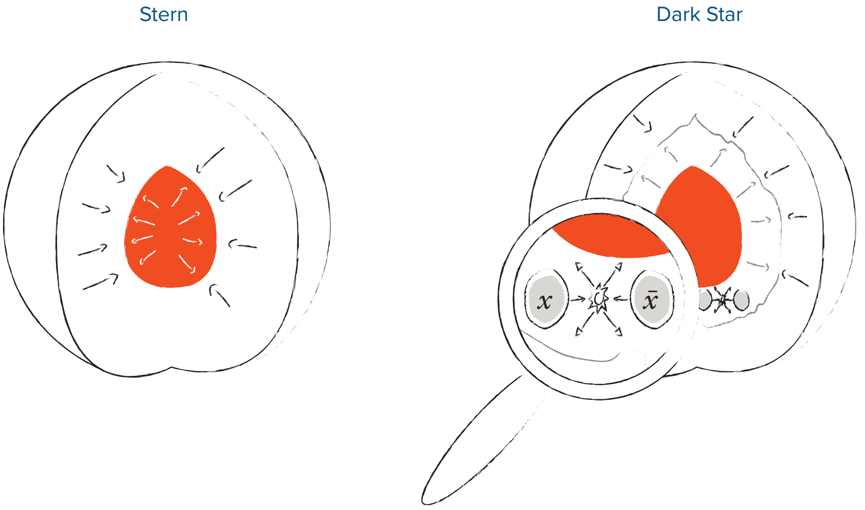
Phasen, in denen es etwas zu sehen gab. Auch wenn es beinahe seit dem Beginn des Kosmos Photonen (Lichtteilchen) gab, können wir erst etwas sehen, wenn sie mit Teilchen oder anderen Objekten wechselwirken. Erst mit der Entstehung der Sterne wurde das Universum dauerhaft sichtbar. Die erste Generation (Population-III-Sterne) wurde ebenso aus Gaswolken geboren wie die Sterne heute. Einziger Unterschied: Dieses primordial genannte Gas bestand hauptsächlich aus Wasserstoff und Helium (Freese et al., 2016). Es gab also noch keine anderen Metalle (für Astronom:innen ist jedes Element schwerer als Helium ein „Metall“). Durch das Fehlen der schweren Elemente und Staubpartikel musste molekularer Wasserstoff (H_2) Heiz- und Kühlprozesse ausgleichen und kompensieren. Dadurch konnten die Gaswolken schneller kollabieren, die entstehenden Protosterne waren in der Lage, mehr Gas auf sich anzusammeln, zu akkretieren (Volonteri, 2010; Bromm, 2013). Damit waren die ersten Sterne sehr massereich, hell und heiß. Und auf Grund ihrer extrem hohen Masse lebten sie durchschnittlich zwei Millionen Jahre. Daher existieren sie heute nicht mehr, denn seit den ersten Sternen sind gut 13 Milliarden Jahre vergangen (Bromm, 2013).

CRASHKURS: DUNKLE MATERIE

Im Lauf der letzten Jahrzehnte hat sich gezeigt, dass in der Astrophysik nichts mehr ohne die sogenannte Dunkle Materie funktioniert. Sie heißt dunkel, weil sie nicht sichtbar ist, genauer: Sie interagiert nicht mit Photonen und ist daher nicht über typische Lichtphänomene nachweisbar. Es gibt allerdings indirekte Beobachtungen. Bereits in den 1930er Jahren fanden Jan Hendrik Oort (1932) und Fritz Zwicky (1937) erste Hinweise auf Dunkle Materie. In ihren Berechnungen zur Bewegung der Sterne in der Milchstraße und bei Massenbestimmungen für Galaxienhaufen passten ihre Ergebnisse nicht mit den Beobachtungen zusammen: Es fehlte Masse, um diese Strukturen gravitativ zusammenhalten zu können. In den 1980er brachte die US-amerikanische Astronomin Vera Rubin weitere Indizien vor, die für die Dunkle Materie sprachen. Sie bemerkte, dass die Sterne im Außenbereich der Milchstraße zu schnell unterwegs sind, die beobachtete vorhandene Masse würde nicht ausreichen, um die Sterne an die Galaxie zu binden. Daher muss auch hier eine zusätzliche Masse vorhanden sein, die die Fliehkräfte wieder ausgleichen kann (Rubin et al., 1980). Auch durch viele andere Berechnungen und Simulationen zeigt sich, dass das Universum ohne Dunkle Materie nicht seine heutige Form hätte annehmen können. Dunkle Materie ist häufiger als die sichtbare, baryonische Materie. Letztere macht alle Sterne, Galaxien, Planeten, jegliches Gas und Staub aus, trägt zum Gesamtenergiebudget des Universums jedoch nur 5% bei.

DARK STARS

Dunkle Materie könnte nicht nur die Form von Galaxien erklären, sondern auch eine Rolle bei der Entstehung der ersten Sterne gespielt haben. Vor knapp 13 Jahren wurde die Theorie der *Dark Stars* entwickelt (Spolyar et al., 2008). Als Dark Stars werden jene ersten Sterne bezeichnet, die nicht durch die Energie der


Stern

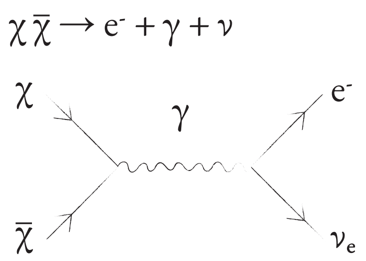
Dark Star

Bei regulären Sternen besitzt der Kern nur 2% des Volumens, aber 50% der Masse, daher zieht die Schwerkraft nach innen. Ihr wirkt der Gasdruck entgegen, der durch die Kernfusion von Wasserstoff zu Helium entsteht. Die beiden Kräfte halten den Stern im Gleichgewicht, er dehnt sich nicht aus und fällt nicht zusammen. Bei Dark Stars kommt es nicht zur Kernfusion. Bei der Entstehung von Dark Stars werden Dunkle Materie-Teilchen und -Antiteilchen stärker zusammengequetscht, sie annihilieren immer öfter. Die dadurch freiwerdende Energie hält den Stern im Gleichgewicht, noch bevor die Kernfusion einsetzen kann.

ah!

ANTITEILCHEN

Zu jedem Teilchen existiert ein Antiteilchen, daher gibt es *Materie* und *Antimaterie*. So ist dem Proton das Antiproton oder dem Elektron das Positron zugeordnet. Teilchen und Antiteilchen haben dieselbe Masse und Lebensdauer, sie können sich durch ihre Ladung unterscheiden. Das Elektron zum Beispiel ist negativ, das Positron positiv geladen. Beim Zusammenstoß von Teilchen und Antiteilchen löschen sie sich gegenseitig aus, sie *annihilieren*, und erzeugen dabei unter Freisetzung von Energie neue Teilchen sowie Photonen.



Dunkle Materie-Teilchen und -Antiteilchen vernichten sich unter Freisetzung von Energie gegenseitig. Diese Reaktion kann wie hier in einem Feynman-Diagramm dargestellt werden.

Kernfusion leuchteten, sondern durch die Zerstörung von Dunkle Materie-Teilchen und -Antiteilchen. Dieser Vorgang wird Annihilation genannt. Treffen zwei solche Teilchen aufeinander, löschen sie sich gegenseitig aus.

Dabei wird so viel Energie frei, dass diese Paarvernichtung die Kernfusion ersetzen könnte. Dark Stars könnten so wie normale Population-III-Sterne aus primordialen Gaswolken entstanden sein. Diese sind neben Wasserstoff und Helium voll von Dunkle-Materie-Teilchen. Beim Kollaps der Wolke wird auch die Dunkle Materie mitgezogen, während ein Protostern geboren wird. Die Teilchen werden also auf immer kleineren Raum gezwungen und stoßen so öfter zusammen. So oft, dass die nach außen wirkende Energie der Gravitation Einhalt gebietet, bevor die Kernfusion starten kann. Und obwohl der Anteil der Dunklen Materie im Stern nur 0.1% der Masse ausmachen würde (der Rest sind Wasserstoff und Helium), reicht das völlig, um den Stern im Gleichgewicht zu halten (Freese et al., 2016).

Dark Stars wären übrigens nicht dunkel gewesen: Sie könnten mehrere zehn Millionen Mal heller geleuchtet haben als unsere Sonne, im Durchschnitt wären sie aber „nur“ 10.000° C kühl gewesen (Freese et al., 2016). Manche könnten sogar das Millionenfache der Sonnenmasse erreicht haben. Diese supermassereichen Dark Stars wären an ihrem Lebensende nicht nur als Supernova explodiert, sondern hätten auch zu supermassereichen primordialen Schwarzen Löchern werden können.

Dürften, könnten, wären. Dark Stars sind bisher reine Hypothese, es gibt noch keinerlei Beweise für diese Himmelskörper. Für normale erste Sterne übrigens auch nicht, deren Existenz ist allerdings gewiss. Das Problem liegt (bei beiden) an der Beobachtbarkeit. Primordiale Sterne, mit oder ohne Dunkle-Materie-Annihilation, sind mit unseren aktuellen Teleskopen einfach nicht zu finden. Über Rückstände von Metallen im ISM könnte man Hinweise auf sie finden. Eine große Komplikation ist das Licht dieser Sterne, das uns erreicht. Ein Lichtsignal ist eine elektromagnetische Welle, die im Laufe der Zeit durch die Expansion des Universums in die Länge gezogen wird. Blaues Licht hat eine kleinere Wellenlänge, doch wenn sich der Raum ausdehnt oder sich ein Objekt von uns wegbewegt, wird diese Welle auseinandergezogen. Damit wird sie ins Rötliche verschoben, bis hin ins Infrarote. Für dieses schwache, weit entfernte Signal sind unsere derzeitigen Instrumente nicht sensibel genug. Die größte Hoffnung liegt nun auf dem James Webb Space Telescope (JWST), das im Herbst 2021 starten soll. Ein zusätzliches Problem beim Nachweis von Dark Stars ist die Tatsache, dass wir über die Eigenschaften der Dunkle-Materie-Teilchen nicht viel wissen. Das erschwert die Detektion. Nichtsdestotrotz, sollten sehr leuchtkräftige, massereiche Dark Stars tatsächlich existiert haben, wären sie mit dem JWST beobachtbar (Freese et al., 2016).

ZURÜCK IN DIE ZUKUNFT

Unsere Ozeane und das Universum haben eine Gemeinsamkeit: Obwohl wir die Weltmeere seit Jahrtausenden sehen und seit vielen Jahrhunderten auch erkunden, ist uns erst ein Bruchteil davon bekannt. Ähnlich ist es mit dem Universum, auch von ihm kennen wir nur einen Bruchteil. Damit stehen die Chancen gleichermaßen gut und schlecht, in Zukunft noch weiter in die Vergangenheit blicken zu können als heute. Vielleicht können wir irgendwann die Spuren der ersten Sterne im Universum entdecken und sie hinreichend erforschen. Dann können wir überprüfen, ob es Dark Stars tatsächlich gegeben hat. Das spannende daran: Wenn wir sie studieren könnten, würden sie uns womöglich mehr über die Dunkle Materie verraten.

Wann und ob es dazu kommen wird, steht allerdings noch in den Sternen.

WISSENSCHAFTLER:IN
SANJE FENKART

studiert Astronomie an der Universität Wien und schreibt derzeit an ihrer Masterarbeit. Außerdem arbeitet sie am Planetarium und den Sternwarten Wien als Science Educator für Shows und Führungen. Vor allem die Kosmologie, also die Entstehung und Entwicklung des Universums, fasziniert sie in ihrer Komplexität und Vielfalt. Gemeinsam mit der immer noch ungeklärten Dunklen Materie macht sie ihr Spezialgebiet aus.

AUSGEWÄHLTE LITERATUR

Freese, K., Rindler-Daller, T., Spolyar, D., & Valluri, M. (2016). *Dark stars: a review. Reports on Progress in Physics, 79*(6), 066902.

Kippenhahn, R., & Weigert, A. (2012). *Stellar Structure and Evolution*. Springer Science & Business Media.

Spolyar, D., Freesse, K., & Gondolo, P. (2008). Dark matter and the first stars: a new phase of stellar evolution. *Physical Review Letters, 100*(5), 051101.

Für das vollständige Quellenverzeichnis besuche unsere Website www.alexandria-magazin.at/magazin/quellenverzeichnis-warum-wir-streiten.php oder scanne den QR-Code am Anfang des Heftes.

	Intro Herzlich Willkommen im Planetarium Wien! Mein Name ist...., ich werde SIe heute durch die nächste Stunde begleiten. Vor sich können Sie den Sternenhimmel bewundern. So sieht er bei uns auf der Nordhalbkugel aus. Was glauben Sie, wie viele Sterne das hier gerade sind? (*schätzen lassen)*. Solch eine Pracht kann man am besten fernab von jeglichen Großstädten bestaunen, wenn uns die Lichtverschmutzung nicht stört. Also am besten in den Bergen, am Land, in der Wüste oder auch 1823 in Bremen. Stellen Sie sich vor, Sie sind ein bereits bekannter Astronom im 19. Jhd und Sie blicken fasziniert in die sternenklare Nacht. Und da beginnen Sie sich plötzlich zu fragen, wieso es bei dieser schieren Unzahl an Sternen, die alle leuchten und ihr Licht uns erreicht, es nicht auch nachts taghell ist? KLICK Vor lauter Himmel die Sterne nicht sehen, so würde es uns vorkommen. 1823 ist der deutsche Astronom Heinrich Wilhelm Olbers genau dieser Frage nachgegangen, wieso es nachts tatsächlich trotz der vielen Sterne so dunkel ist. Daher sprechen wir hier auch vom Olberschen Paradaxon KLICK. Olbers meinte zunächst, dass die Gaswolken, die den Raum zwischen den Sternen füllen, das Licht einfach schlucken würden. KLICK Wiliam Herschel widersprach ihm da. Wäre dem so, dann würde das intergalaktische Medium das Licht zwar schlucken, sich aber auch gleichzeitig immer weiter aufheizen und der Himmel würde ausgefüllt mit diesem Licht strahlen. Das absorbierte Licht wäre also gleich stark wie das abgegebene, das emittierte. KLICK Letztendlich geklärt wurde dies über die Kosmologie. Die Überlegung, dass es durch Sternenlicht auch nachts hell wäre, würde nur dann funktionieren, wenn das Universum unendlich alt, unendlich groß und statisch, also unveränderlich, wäre. Es hätte immer dieselbe Größe und würde sich nicht verändern. KLICK Auch Albert Einstein setze sich stark für dieses Weltbild ein. Um 1930 häuften sich die Belege, vor allem durch Edwin Hubble und Georges Lemaître, dass sich das Universum ausdehnt. Somit änderte sich die Kosmologie. Sie ist ein Teilbereich der Astronomie und beschäftigt sich mit der Entstehung, der Entwicklung und der Struktur des Universums selbst. Ihre Anfänge finden sich zwar bereits in Babylon, wirklich Fahrt aufgenommen hat sie erst in den letzten 100-150 Jahren und zählt heute zu den wichtigsten und komplexesten Gebieten der aktuellen Astronomie. KLICK Sie beruht auf mathematischen Theorien, die sich furchtbarer Formeln bedienen, sie wird gestützt durch Beobachtungen die wir mit Teleskopen und Satelliten anstellen. Heute ist das Urknallmodell die anerkannteste Theorie zur Entstehung des Universums. Damit können wir	PD: SIgnation Planetarium PD: Sonnenuntergang simulieren bis Fix #100 PD: Musik (kommt noch) PD: Licht ganz hell PD: Panorama Wald (bei Nacht?) PD: Porträt Olbers (2x: NO, SW) PD: Porträt Herschel (2x: SO, NW) PD: Licht überblenden, rötlich/orange PD: zurück zu Sternenhimmel #100 PD: Porträt Einstein PD: abblenden und Porträt Hubble+Lemaître PD: (hoffentlich als Video) Formeln aufschreiben, durchlaufen lassen....ALMA Panorama ...verlasse Erde: Umlaufbahn mit Satelitten ...zoom bis Cosmic Web (Solaris Video Neu)	

	die Geschichte des Universums seit seiner Geburt bis zum heutigen Tag nachvollziehen **Teil 1: Back in time (top-down)** Large-Scale structure (…wirken lassen). So sieht das heutige, uns bekannte Universum aus. Dieses Bild ergibt sich aus Simulationen, also es ist kein echtes Foto. Es ist ein Ausschnitt des beobachtbaren Universums und zeigt die Verteilung der sichtbaren (je nach Bild) (und der dunklen) Materie. Sichtbare Materie beschreibt nichts weiter als Objekte, die wir sehen können, weil sie mit dem Licht wechselwirken und daher für uns direkt beobachtbar sind. Dazu zählen Galaxien, Sterne, Planeten, Gaswolken und Staub. Sie stellt nur 5% des Gesamtenergiebudgets dar. Wenn man genauer hinsieht, bemerkt man, dass die sichtbare Materie unregelmäßig im Raum verteilt ist. Sie sammelt sich entlang von leuchtenden Bändern, die wir Filamente nennen. Dazwischen befinden sich schwarze Flecken, die wir Voids nennen, also Leere. Was genau dort ist, ist noch unklar. Materie gibt es dort nicht, selbst die Dunkle Materie ist hier kaum vorhanden. Sie werden aber stark von der Dunklen Energie beeinflusst. Gemeinsam bilden sie das kosmische Netz. Dunkle Materie nimmt 27% des Energiebudgets ein. Was genau sie ist, bleibt unklar. Wir können sie nicht direkt beobachten, da sie keine Wechselwirkung mit Licht aufweist, daher bezeichnen wir sie als „dunkel". Jedoch können wir sagen, dass sie existiert, da wir ihren gravitativen Einfluss, also über ihre Schwerkraft, auf die normale Materie beobachten können. Mit den normalen Gesetzen der Physik würde dies nicht ausreichen. Außerdem könnten wir die heutige Strukturentwicklung des Universums ohne die Dunkle Materie gar nicht erklären. Sie ist ausschlaggebend für die Entstehung ganz früher, kleiner Unregelmäßigkeiten der Dichte, die später zu den heutigen Großobjekten wurden. Sie beeinflusst auch heute noch die Bewegung von Himmelskörpern und hält ganze Galaxien zusammen. Die restlichen knapp 70% des Massenbudgets werden von der Dunklen Energie eingenommen. Sie ist sogar noch rätselhafter als DM und teilweise sogar unter Wissenschaftler:innen umstritten. Allerdings ist die praktisch, da sie uns eine Möglichkeit bietet, wie man sich die beschleunigte Expansion des Weltalls erklären kann. Wie ist dieses große Netzwerk an Materie nun überhaupt entstanden? Viele Forschungsgruppen gehen dieser Frage nach. Über Theorien, Hypothesen, Vorhersagen, Beobachtungen, Rechnungen und Simulationen wird versucht, die Geschichte unseres Kosmos aufzuarbeiten.	PD: Cosmic Web	

	Top-Down +Simulationen		
	KLICK Die leuchtenden Punkte entlang der Filamente sind nicht Sterne, wie es beim Anblick unseres Nachthimmels gewohnt sind, sondern es sind Galaxien, Ansammlungen von mehreren Hundertmilliarden Sternen. Die dicken, hellen Knotenpunkte weisen auf Haufen und Superhaufen hin, kleinere sind Galaxiengruppen und einzelne Lichtpunkte stellen alleinstehende Galaxien dar.	PD: Cosmic Web weiterdrehen und langsam reinfliegen	
	KLICK Solche einzelne Galaxien sind eher selten, die meisten, wie unsere Milchstraße, befinden sich in Gruppen. Diese können wiederum Teil von Haufen und die ein Teil von Superhaufen sein. Solche Cluster können mehrere hundert oder sogar tausend Galaxien beinhalten. (Ein Beispiel dafür wäre der Virgo-Cluster mir 1300, dessen Teil wir sind). Die Gravitation, jene Kraft, die das Universum zusammenhält, bindet auch die Galaxien in Haufen zusammen.	PD: Haufen überblenden (HUDF, Abell, Virgo?)	
	KLICK Die nächstkleineren Strukturen sind Gruppen. Unsere Milchstraße befindet sich in der *lokalen Gruppe*. Sie ist sozusagen unsere galaktische Nachbarschaft. Ihr Durchmesser beträgt etwas 6 Millionen Lichtjahre und bindet ca. 70 Galaxien aneinander. Die beiden größten sind unsere eigene Milchstraße und die Andromeda-Galaxie, die wir bei idealen Beobachtungsverhältnissen sogar mit freiem Auge am Sternenhimmel entdecken können.	PD: Andromeda +Milkyway	
	KLICK Beide, auch die Milchstraße, sind Spiralgalaxien. Unsere Heimatgalaxie besteht aus ca. 200 Mrd. Sternen sowie aus Gas und Staub. Aus dem Gas können laufend neue Sterne entstehen. Das führt dazu, dass wir hier hauptsächlich junge, leuchtstarke Sterne haben, die sich mit ihrer bläulichen Farbe zu erkennen geben.	PD: Video Milchstraße	
	Alter (muss nicht vorkommen)		
	KLICK Aber es gibt auch alte Sterne, die man in der Mitte, im Bulge findet oder in Kugelsternhaufen, die um unsere Galaxie kreisen. Die Sterne, die dort wohnen, sind gut und gern bis zu 11 Milliarden Jahre alt sind. Damit schätzt man, dass die Milchstraße ungefähr 12 Mrd. Jahre alt sein dürfte. Klingt nach uralt, vor allem, wenn man bedenkt, dass das Universum 13,8 Milliarden Jahre alt ist. Tatsächlich sind aber die meisten Galaxien zwischen 10-13.4 Milliarden Jahre alt. Damit liegt unsere Sterneninsel eigentlich schön in der Mitte.	PD: Kugelsternhaufen	

	Galaxienentstehung KLICK Der genaue Entstehungsweg von Galaxien ist noch nicht perfekt ausgereift, jedoch ist die führende Theorie das „Bottom-up“-Szenario, also von unten nach oben, von klein auf groß. (Mitreden bei Simulation, erklären). Zuerst entstanden kleine Massenansammlungen, *Dichtestörungen*, im sonst so ebenmäßigen Universum. Daraus wurden größere Flecken aus DM-Halos und Gas, aus denen Sterne geboren wurden. Galaxien gehören zu den letzten Strukturen, nur Cluster und Supercluster sind später durch Verschmelzungsprozesse verschiedener Art entstanden.	PD: Aquarius-Simulation oder PD: Illustris mit Übergang auf Millenium Run oder auch ganz anders, wenn es nicht passt, weil top-down	
	KLICK Galaxien konnten durch schon vorhandene Sphären aus dunkler und gewöhnlicher Materie geboren werden, aus sog. Halos. Beginnt das Gas in solchen Halos abzukühlen, sinkt es in die Mitte ab, wo es immer dichter wird und außerdem zu einer Scheibe abflacht. In dieser Scheibe selber verklumpt das Gas an einzelnen Stellen erneut. Diese Klumpen fallen in sich zusammen, sie kollabieren, und sie bilden Sterne. Über mehrere Millionen bis Milliarden Jahre sammeln sich so immer mehr Leuchtpunkte in der Galaxie an.	PD: Deep-Sky-Sternentstehung (vielleicht umgeformt)	
	Überleitung KLICK Die Sterne in Galaxien, gehören aber nicht zur ersten Generation von Sternen. Noch vor der Zeit der Galaxien sind sie einzeln entstanden. Ebenso aus Halos, aus primordialen (ganz frühen, ursprünglichen), Halos.	PD: Entweder was auch immer da is lassen oder fade zu Fix #100	
	Doch woher bekamen diese Sterne ihr Gas, die sie für ihre Entstehung brauchen?		
	(Part 1 Ende)		

	Part 2: Urknallmodell, Bottom-Up-Szenario “Am Anfang (…) war es wüst und leer; und es lag Finsternis auf der Tiefe; und Gott sprach: es werde Licht und es ward Licht.“ So beginnt die Bibel mit Genesis (dem ersten Buch Mose). Ganz so war es nicht, aber doch. Wir wissen zwar nicht, was punktgenau am Anfang war, jedoch beginnt für uns das Universum mit dem Urknall. Ein kleiner, heißer und dichter Zustand, der plötzlich Raum und Zeit erschuf; und das (*ATEMPAUSE, ganz wichtig , Leute*) überall zugleich in alle Richtungen. KLICK In den Bruchteilen der ersten Sekunde (42 Nachkommastellen) lösten sich die vier Grundkräfte – Gravitation, elektromagnetische Kraft, schwache und starke Wechselwirkung – phasenweise voneinander ab. Zu Beginn waren sie nicht zu unterscheiden, nun sind sie unabhängig. Beim Billionstel einer Quadrillionstel Sekunde setzt die Inflation ein und dauert stolze 10^{-32} Sekunden an. Die Inflation bläht das Universum rasant auf, in dieser kurzen Zeit um fast das Tausendfache an, von rund 17 cm auf 170 m. Danach nimmt die Ausdehnung des Weltalls weiter ihren Lauf. Nukleosynthese Während der ersten Momente ist es im Universum zu heiß, um stabile Atomkerne zu bilden. Protonen und Neutronen schwirren als hochenergetische Teilchen gemeinsam mit Elementarteilchen, wie zB. Elektronen und Quarks in der heißen Ursuppe umher. Die Strahlung, also Photonen – Licht – dominiert. Teilchen und ihre dazugehörigen Antiteilchen löschen sich fröhlich gegenseitig aus. Drei Minuten nach dem Urknall ist das Universum so weit abgekühlt durch die Ausdehnung, dass die Teilchen miteinander verschmelzen und erste stabile Atomkerne bilden können. Diese bestehen aus einem positiven Proton und einem elektrisch neutralen Neutron. In der sogenannten *primordialen Nukleosynthese* entstehen die ersten Elemente, allem voran Wasserstoff und Helium, sowie ihre Isotope (zB. Deuterium). Elektronen können dabei noch nicht an den Kern koppeln. Als heißes Gas schwirren die einzelnen Teilchen – Elektronen, Kerne, Photonen – herum. Dichtefluktuationen & Dunkle Materie	PD: dunkel lassen PD: Hell (ja, noch mal)	Fact Box: Grundkräfte mit Reichweite, stärke, bsp Temperatur-&Energieskalen Zeitleiste Inflation und TOE/GUT Link zu Inflation dazu Isotope

	Die Expansion geht weiter und damit nehmen die Dichte und die Temperatur in Weltall ab. Über die nächsten Zehntausend Jahre nimmt die Stärke der Strahlung langsam ab. Materie gewinnt die Oberhand und ab diesem Zeitpunkt beginnen sich kleine, dichte Regionen zu bilden, die eine starke Anziehungskraft ausüben. Hier wird der Einfluss der Dunklen Materie das erste Mal ausschlaggebend. Wie und wann sie genau entstanden ist, bleibt bisher unklar. Allerdings machte sie damals gleich 85% der Materie aus.		
	Baryon-Photon-Fluid &BAOs (kann weggelassen werden) An das heiße Plasma, das sogenannte Baryon-Photon-Fluid, sind Schwallwellen gekoppelt. Kommen sie bei diesen dichten Regionen (Dunkler Materie) vorbei, werden sie von deren Gravitation nach unten (in die Potentialtöpfe) gezogen. Vor allem die Baryonen möchten sich hier ansiedeln; die Welle sackt ab. Das Licht möchte jedoch frei bleiben und übt einen entgegengesetzten Druck aus; die Welle geht wieder nach oben. Damit entsteht eine Schwingung, die sich mit der damaligen Schallgeschwindigkeit (knapp 60% der Lichtgeschwindigkeit). Ist die Anziehungskraft stark genug, werden die Teilchen in die Überdichte gesaugt und sammeln sich dort gemeinsam mit der dunklen Materie an. Diese *baryonischen akustischen Oszillationen* werden langsamer, je mehr sich das Universum ausbreitet.		Baryonen: Astro vs. PP BAOs im Leistungsspekrum
	(falls ausgelassen hier weiter) Rekombination & CMB Lange Zeit passiert nichts weiter, bisher war das Universum praktisch undurchsichtig. Obwohl es genug Lichtteilchen, die Photonen, gibt, können wir sie mit unseren Teleskopen nicht sehen. Ihr Licht wird von der Umgebung „geschluckt", das Universum erscheint uns nebelig. 380 000 Jahre nach dem Urknall ändert sich das für einen kurzen Moment. Bei der Rekombination, wie man in der Astronomie die folgende Epoche nennt, ist das Weltall auf 4000 K abgekühlt, aus dem nun kühleren Plasma wird ein Gas, das hauptsächlich aus Wasserstoff und Helium besteht. Elektronen können sich nun mit Protonen und Neutronen verbinden und bilden damit erstmals neutrale Atome. Dabei werden Photonen entsendet.	PD: CMB-Foto	
	KLICK Der Großteil kann nun ungestört durch die Gegend reisen, das Universum wird in einem Schnappschuss sichtbar. Wir beobachten das junge Weltall zum ersten Mal.	Oder erst hier PD: CMB-Foto	
	Durch die Expansion bis zum heutigen Tag, ist allerdings die Wellenlänge der damals emittierten Photonen in die Länge gezogen worden und damit ins Rote verschoben. Dadurch messen wir heute auch nur noch eine Resttemperatur von gerade mal 2.7K (-270°C). Das nennen wir die *kosmische Hintergrundstrahlung*. Gemessen wurde sie mit dem Welttraumteleskop Planck. Diese Hintergrundstrahlung ist im Prinzip eine Temperaturkarte. Rote Flecken zeigen Orte mit leicht erhöhter		Planck-Facts, CMB Facts

	Temperatur, blaue etwas Kühlere. Egal in welche Richtung wir blicken, dieses Relikt aus früher Zeit ist überall präsent und beobachtbar. (falls BAOs): ungefähr zur gleichen Zeit, wie zur Rekombination, bricht ein anderer Prozess ab. Die Schwingungen des Baryon-Photon-Fluid werden zum Zeitpunkt der Rekombination (*last-scattering surface*) in ihrer Bewegung „eingefroren“; egal ob sie gerade ganz weit draußen sind, ganz in den dichten Regionen oder irgendwo dazwischen. Wichtig sind die Punkte, wo die Schwingung mit den Baryonen komplett in eine Dichteregion gefallen ist. Aus diesen entwickeln sich über die nächsten 200 Millionen Jahre die Halos, die wir für die Entstehung erster Sterne brauchen. (falls ohne BAOs): Zum Zeitpunkt dieses Schnappschusses fällt auch ein Teil der normalen Materie in die überdichten Regionen und bleibt dort gefangen. Aus ihnen werden über die nächsten 200 Millionen Jahre die Halos heranwachsen, die wir für die ersten Sterne brauchen.		

	Dark Ages KLICK Während diese Zeit vergeht, erscheint uns das Universum als dunkel, daher auch die Bezeichnung der „Dark Ages“. Obwohl Licht frei strömen kann, hat es nichts, womit es wechselwirken könnte. Außerdem bewirken die neutral geladenen Atome, dass Licht geschluckt/absorbiert werden kann. Unseren Blicken verborgen bilden sich inzwischen die Halos aus primordialem Wasserstoff und Helium, sowie der Dunklen Materie immer weiter aus. First Stars KLICK Sobald die Bedingungen reif sind, können diese Halos in sich zusammenfallen. Normalerweise ist so ein Halo im Gleichgewicht: Gravitation zieht nach innen, ein Druck durch Teilchenbewegung im Gas zeigt nach außen. Wird dieser Zustand gestört, ist die Gravitation die dominierende Kraft. Das Gas fällt in Richtung Zentrum und wird dort durch immer weiter einfallendes Gas zusammengedrückt. Ein Protostern entsteht. Dieser sammelt weiterhin Gas aus der Umgebung an, bis ein Zentrum so heiß und dicht wird, dass die Gesetze der Physik überbrückt werden. Die Kernfusion setzt ein: der junge Stern verbrennt bei Temperaturen von über 10 K Wasserstoff zu Helium und wird das bis an sein Lebensende fortführen. Die dabei erzeugte Energie wird als Licht und Wärme freigesetzt. Damit sind die ersten Sterne geboren. Diese nennt man (aus unerfindlichen Gründen) Population-III-Sterne. Unsere heutigen, wie z.B. die Sonne, sind Pop-I-Sterne Typisch für Pop-III-Sterne ist, dass sie sehr massereich (sehr schwer) und dadurch auch extrem hell sind. Sie sind sogar massereicher als die meisten Sterne, die wir heutzutage kennen. Während wir heute Schwergewichte bereits mit 25 Sonnenmassen kennzeichnen, nimmt man für primordiale Sterne durchaus mehrere Hundert Sonnenmassen an. Eines haben sie jedoch gemeinsam: je mehr Masse sie haben, desto kürzer leben sie. Bei hoher Masse sind der Druck und damit die Temperatur im Kern extrem hoch. Dadurch wird dort der vorhandene Wasserstoff sehr viel schneller bei der Kernfusion aufgebraucht als in einem massearmen Stern. Normalerweise kommen Sterne auf Lebenszeiten von ein paar zehn Millionen bis mehrere Hundertmilliarden Jahren. Erste Sterne erreichen durchschnittlich gerade Mal zwei Millionen Jahre. Sie gehen in katastrophalen Explosionen, in Supernovae, zugrunde. KLICK Durch dabei freigesetzten Druckwellen fallen weitere Halos in sich zusammen und es entstehen, wie in einer Kettenreaktion (naja) weitere Sterne und im Verlauf Galaxien und Haufen	PD: ein paar frei fliegende Photonen zeigen und dann langsam abblenden und dunkel lassen PD: irgendeine Musik dazu? entweder PD: Sternentstehung Simulation (ausschmücken mit Halo oder PD: Illustris/Clues-Simulation starten bald pausieren oder: kombinieren und übreblenden PD: Musik zu Illustris “Leaving“ Armaggedon PD: Illustris (weiter)laufen lassen	Kollaps: wenn Dichte kritische Dichte übersteigt Anm: Im Fließtext fehlt noch die Sache mit Metallen!

	Reionisation Die Geburt der ersten Sterne leitet die letzte wichtige Phase in der Kosmologie ein, die *Reionisation*. Wenn die Sterne als Supernovae ihre äußeren Hüllen durchs All schleudern, setzten sie auch irre viel hochenergetische Strahlung frei. Diese trifft auf einzelne (neutrale) Wasserstoffatome und wenn die Voraussetzungen passend sind, wird ein Elektron im Atom angeregt und es gibt ein Photon ab. Das umgebende Gas wird dadurch positiv geladen, es wird ionisiert. Da es vor der Rekombination schon mal eine Phase ionisierten Plasmas gab, sprechen wir hier von der Re-Ionisation. Dieser Prozess führt dazu, dass die freien Photonen (21-cm) nun ungestört, also ohne absorbiert zu werden, durch das Weltall reisen können. Das Universum wird durchsichtig und wir können es beobachten. Je mehr Sterne und Galaxien entstehen und je mehr energiereiche Strahlung vor allem aus den Kernregionen der Galaxien frei wird, desto eher wir das Universum transparent. Ende Part II Und immer noch, expandiert das Universum, Galaxien tauchen auf und verschmelzen miteinander, wachsen, bilden ganze Gruppen, werden zu Haufen und Superhaufen. Bis wir wieder am heutigen Tag ankommen und das komische Netz als unsere großräumige, kosmische Nachbarschaft betrachten können.		Energiezustand Wasserstoffatom, 21-cm-Linie, Ionisierung, Lyman-Alpha Anm: Quasare

	Part 3: Zukunft des Universums KLICK Die Geschichte unseres Universums zu entwirren ist voll im Gange. Sie ist komplex und wirft für jede neue Erkenntnis ein weiteres Rätsel auf. Noch viel komplizierter sind Vorhersagen für die Zukunft unseres Kosmos. Für viele Milliarden Jahre dürfte es noch ähnlich aussehen wie heute: mit verschmelzenden Galaxien, vielen neugeborenen und ebenso vielen sterbenden Sternen. Doch auch dies sollte irgendwann sein Ende nehmen, oder? Bisher gibt es drei gängige Theorien, die in der Kosmologie debattiert werden. (falls zu lang, nur kurz alle drei erwähnen, vielleicht ein zwei Sätze und Heat Death als Wahrscheinlichste hervorheben)	PD: Erde bei Nacht von außen Anflug auf Hubble (oder anderes Weltraumteleskop), durch Röhre/Spiegel raus und beim Blick hinaus Blobs/Fenster einblenden, wo die drei Szenarien nacheinander ablaufen	
	Big Rip KLICK Beim „großen Zerreißen“ wird angenommen, dass sich das Universum weiterhin brav ausbreitet. Damit wird auch (so bereits schon heute) der Raum zwischen den Galaxien und generell zwischen Himmelskörpern immer größer. Noch hält die Gravitation alle Strukturen zusammen. Doch irgendwann dürfte der außen gerichtete Druck der Expansion die Abstände so stark auseinandergezogen haben, dass die Anziehungskraft dem nicht mehr standhalten kann. Als erstes würden Galaxien zerfallen. Sterne, Planeten und schwarze Löcher (i.e. AGNs) wären als Einzelobjekte unterwegs. Aber auch sie werden früher oder später zerrissen und in ihre Bauteile zerlegt. Selbst Atome können der Expansion nicht mehr standhalten und sie werden zu freien Elementarteilchen, wie in den ersten Bruchteilen nach dem Urknall. Der Raum wäre irgendwann so groß, dass nichts mehr miteinander wechselwirken kann. Die Expansion wäre mit Überlichtgeschwindigkeit unterwegs. Alle Teilchen würden bis in alle Ewigkeiten einsam und allein umherfliegen.	PD: Big Rip	
	Wärmetod (Heat Death/Big Freeze) KLICK Die bisher wahrscheinlichste Theorie bedient sich auch wieder einer anhaltenden Ausdehnung. Jedoch bleibt hier die Materie intakt; sie braucht sich allerdings auf und wird nach und nach in Strahlung umgewandelt. Alle Gaswolken, notwendig für Sternentstehung, werden erschöpft sein, jegliche Sterne und ihre Überreste zerfallen zu Strahlung, selbst schwarze Löcher verdampfen (Hawking-Strahlung). Das Universum kann als ein abgeschlossenes System angesehen werden, das den Gesetzen der Physik (den Gesetzen der Thermodynamik!) unterliegt. So ein System strebt immer den „Zustand der maximalen Entropie“ an. Was nichts weiter bedeutet, als dass es zu einem gleichförmigen Gleichgewichtszustand wird. Das passiert auch schon, wenn Sie sich einen Kakao mit einem wundervollen Berg aus Schlag richten und gestört durch ein Telefonat darauf vergessen. Nach einer gewissen Zeit werden der Schlag und der Kakao zu einer gleichmäßigen, vermischten Masse geworden sein. Das gleiche würde mit dem Weltall passieren. Nur auf größeren Längen- und Zeitskalen und mit vielen verschiedenen Zutaten.	PD: Big Freeze	

	Ist dieser Zustand erreicht, wäre das Universum also uniform: physikalisch perfekt, klinisch tot. Eigentlich würde es dann so verbleiben. Es sei denn, rein theoretisch, setzt ein quantenmechanischer Vorgang, das Tunneln ein und aus dem Nichts (das ja auch Etwas ist) könnte ein neuer Urknall entstehen. Big Crunch/Big Bounce **KLICK** Im letzten Szenario würde die Expansion noch für lange Zeit anhalten. An einem gewissen Punkt würde sie sich allerdings umkehren. Die Gravitation, nach innen in gerichtet, würde das Universum wieder zusammenziehen. Zunächst würden Strukturen einfach miteinander verschmelzen und dichter werden. Ein kleineres Universum bedeutet aber auch einen Anstieg der Temperatur. Es würde so heiß werden, dass sich die Umgebung so sehr aufheizt, dass sie sogar Sterne „zerkochen“ könnte. In den Minuten vor dem „großen Zusammenkrachen“ würde auch Atome zerfallen. Supermassive schwarze Löcher würden sich gegenseitig verschlingen und zu guter Letzt sich und das Universum selbst auch. Aus dem heraus könnte es (auf der „anderen Seite“ des SL) zu einem neuen Urknall kommen, durch den sich das neugeborene Universum wieder ausdehnt und das ganze Spiel würde von Neuem beginnen. Daher redet man hier auch vom „Big Bounce; das Universum ist bisher immer wieder entstanden und wird immer wieder zusammenfallen. Eine Art Jojo-Effekt.	PD: Big Crunch	

	Extro KLICK Auch wenn der Big Freeze aktuell nach dem wahrscheinlichsten Szenario klingt, zu Hundertprozent kann man es nicht bestätigen. Erleben werden wir es sowieso nicht. Aber wer weiß schon, was in den nächsten Milliarden Jahren oder vielleicht schon morgen passieren wird? (damit Ende, bzw. weiteres Extro noch unklar)	PD: Sternenhimmel Fix #100 oder PD: Cosmic Web	

Raising the public profile of the IAU

Sanje Fenkart

June 2021

The International Astronomical Union is the largest international society for professional astronomers with representation in over 100 countries. As part of my master's thesis and in collaboration with the IAU Office for Astronomy Outreach, I am requesting your help to create videos that easily allow the public to learn more about the role and importance of the IAU in astronomy. The main goal of the videos is to raise broader public awareness of the work of the IAU, its purpose and relevance for society.

The videos will address the IAU structure, its divisions, members, aims and connection to the public across the various Scientific Bodies. We plan to feature members from around the world, accounting for as many different gender, gender identity or expression, race, colour, national or ethnic origin, religion or religious belief, age, marital status, sexual orientation, disabilities, and veteran statuses as possible. Once completed, these videos will be shared on the Facebook, Twitter, and Youtube accounts associated with the IAU.

Questions and video shooting

As a contributor to this project, we would like you to film answers to the following questions. These questions should be thought of as guidelines. They can be answered in any order. Please answer questions 0 and 1. Answering all other questions is optional.

0. Start off with a greeting phrase in your mother tongue/first language.
1. What is your name, in which division (commission/working group) are you, where are you working, where are you right now (while shooting)? What is your position within the Division (meber, president, member of SC, Phd)?
2. In your own words, what are the topics (scientific objectives) of your division?
3. What fascinated you about astronomy and astrophysics in the first place? Why did you choose your specific field of research?
4. What makes your Division unique among the IAU Divisions?
5. How does the work of your Division affect the science of astronomy?
6. How does the work of your Division affect the public? Why is it important?
7. What vision do you have for the future of the Division? What do you hope the Division will accomplish in the future?
8. What take-home message do you have for the public about your Division?

For the videos itself, please:

- Record yourself with a camera (mobile phone, computer/laptop, regular camera, professional camera).
    - If the situation allows it, let someone else film.
- Film yourself in landscape format, ideally with a ratio of 16:9 (usually corresponds to a resolution of 1920x1080).

    - Most smartphones should offer this quality. Otherwise pick your highest resolution.
- Please film at your regular work place (institute, faculty, office, observatory, etc.), if possible.
    - Otherwise, please film yourself somewhere you are comfortable (your home office, a quiet yard, etc.).
    - You can record yourself at different places; please state where you are if you do this.
    - Please, film within the health and safety measures of your region due to the Covid-19 pandemic.
- If possible, please film B-roll of yourself. B-roll will be added in between speeches to show viewers how you do your work. They provide additional visuals to the video and keep the video interesting.
    - These can be filmed at your workplace, home office, or else relevant to your work.
    - Examples of this type of film can be glimpses of your computer screen (showing astronomical research/content), shots of you calling a colleague, shots of you speaking with a colleague in-person or digitally, etc. For examples see:
      https://www.youtube.com/watch?v=5DoB0M-d8H8
      https://www.youtube.com/watch?v=FnOBKUNsZVI&t=58s
      https://www.youtube.com/watch?v=sFqLGhcP4iI
      Note that these examples only serve as an orientation for B-roll shots.
    - Please, film within the health and safety measures of your region due to the Covid-19 pandemic.
    - If filming other people, please inform them of the purpose of this footage and receive their permission to be filmed and have the footage shared with the public. Please send us their email address so that we can confirm that we have their permission to share footage of them.

If you have pictures of you and/or your Division of past meetings, conferences or projects that you are comfortable releasing under a Creative Commons license, please send them to us as well. If you do not have permission to share the photo, please connect us with the photographer so we can receive permission to share the photo. Like B-roll, these will be cut into speeches to provide visual action to what is being said.

I would ask each Division to address a special main message. Here is yours:

Extragalactic astronomy and especially cosmology deal with some of the most complex topics in astrophysics. How do you look past boundaries in order to understand the very beginning? What makes the intangible tangible in your everyday and in the public's everyday?

Please send the videos to the email address to a01503318@unet.univie.ac.at or sanje.fenkart@gmail.com by the beginning of July.

Regards, Sanje Fenkart.
Institute for Astronomy, Vienna.