High Mass star formation

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Collaborators

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Clusters and high mass star formation

- High mass stars form in clusters and hence discussing high mass star formation is equivalent to discussing cluster formation and evolution
- Extinctions are high and so IR and Radio are only effective probes
- Confusion is a problem and distances are typically several kpc
- Outflows and jets at high resolution are often best probes of young high mass YSOs

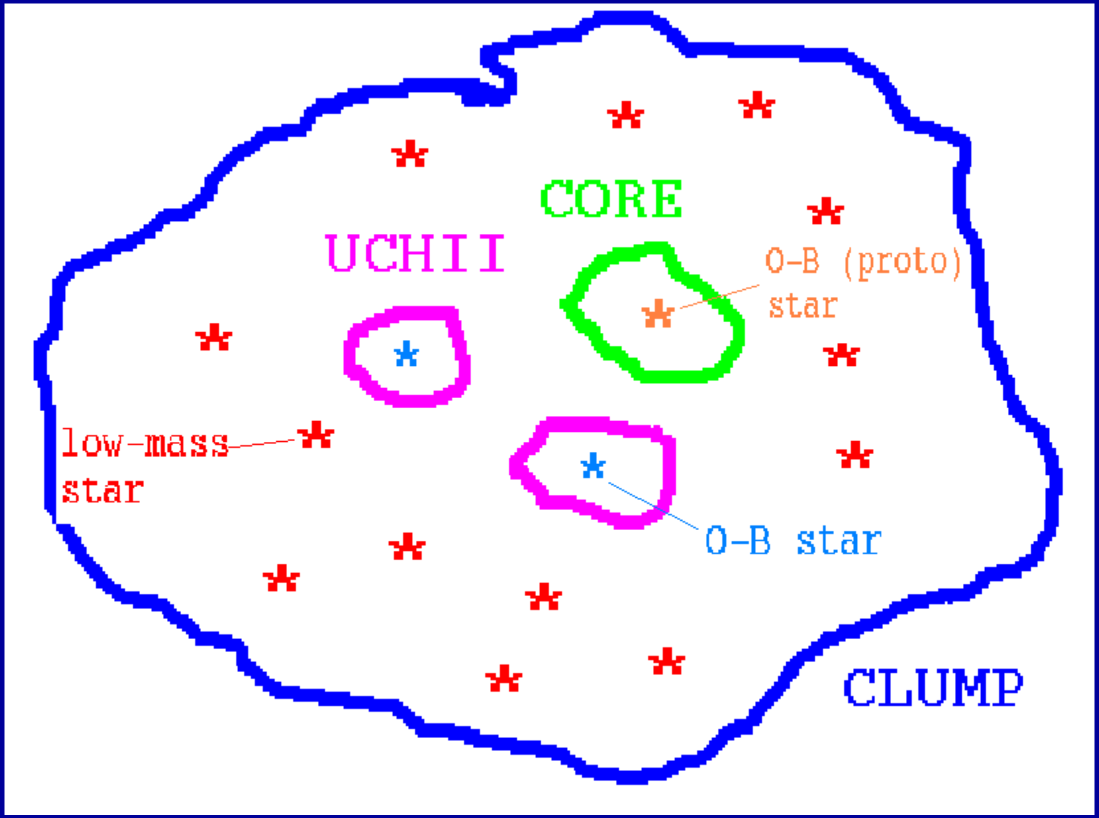
Where do massive stars and clusters form?

Within GMCs (Giant Mol Clouds) of up to few 10^6 solar masses ,size 50 pc, and mean density few hundred cm-3

In parsec scale clumps of mass around a thousand solar masses and density close to 10^5 per cc

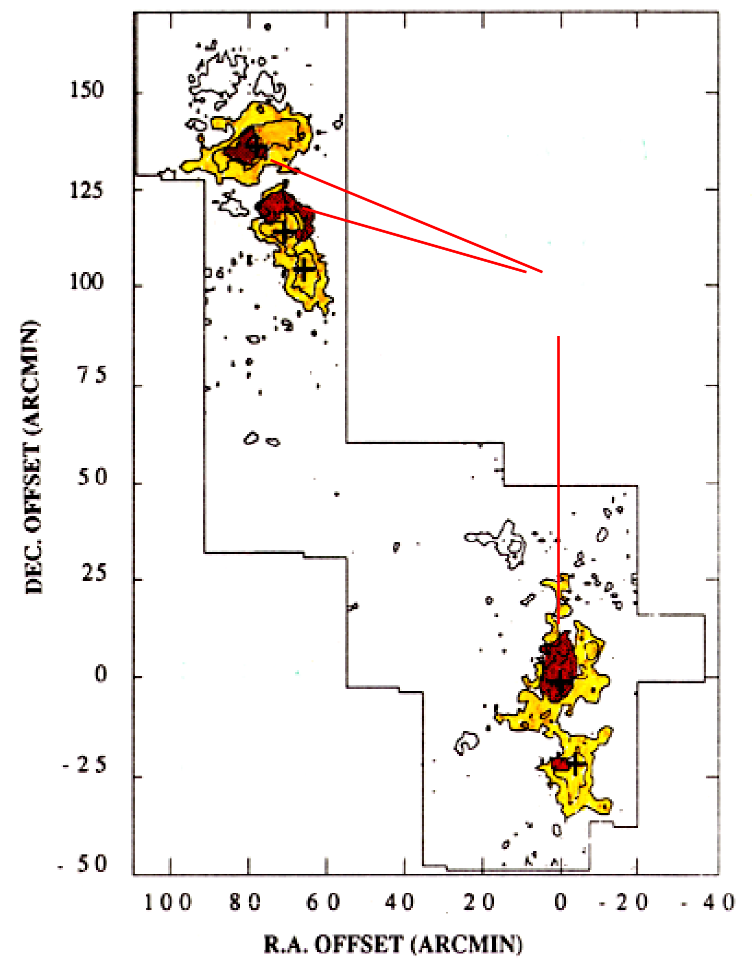
Such clumps are seen in molecular line of high density tracers as well as in Spitzer and MSX images in absorption against background (IRDCs)

High-mass star forming region



0.5 pc

Embedded Clusters: Basic Observational Data

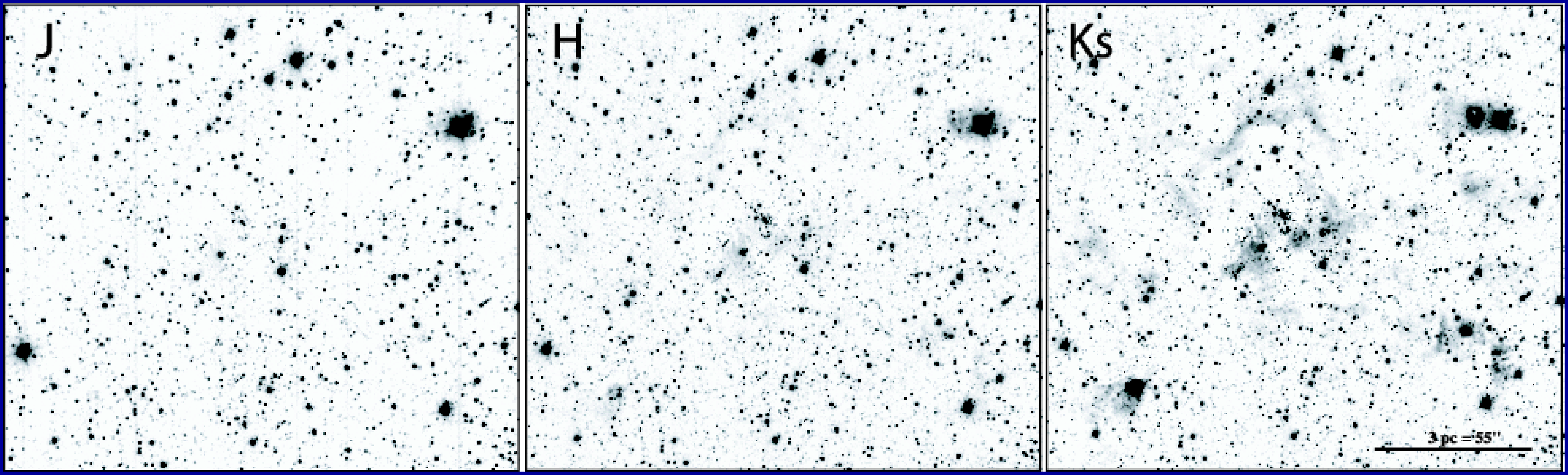


Stellar Inventory of GMCs:

Most Stars form in *Embedded Clusters*

Infrared surveys of GMCs reveal:
70-100% of all embedded YSOs confined to embedded clusters .

Clusters seen in NIR towards W49 at 8 kpc (Homeier and Alves)



Cluster with 50 stars above 20 solar masses (10^4 solar masses in all)

HIGH-MASS STAR FORMATION: PROBLEMS

Observational difficulties

Rare: located at **high distances** (~ 5 kpc)
Rapid evolution towards the Zero-Age Main Sequence
Formation in **clusters**: confusion

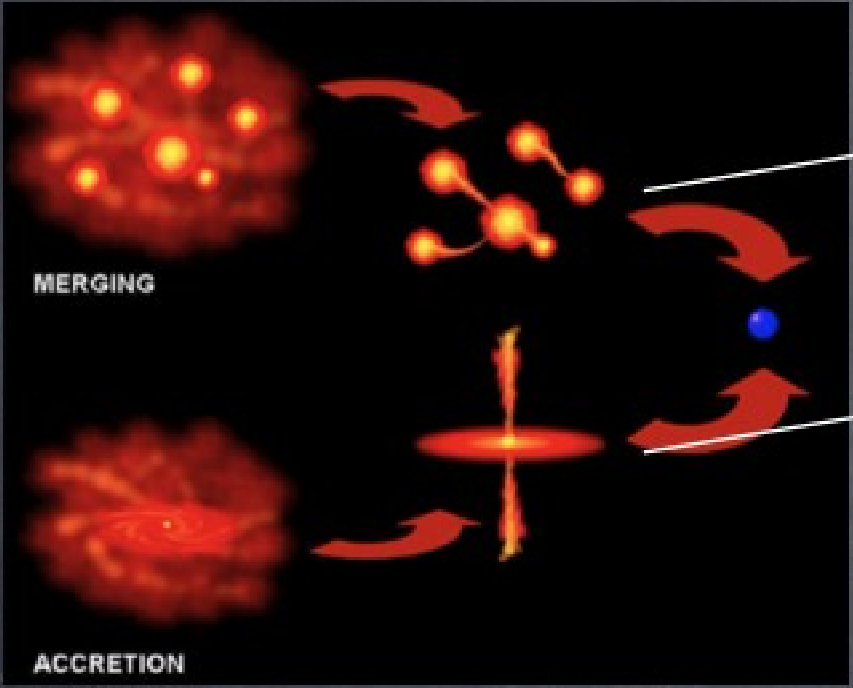
Theoretical problem

Stars with **$M \geq 8\ M_{sun}$** reach the ZAMS while still accreting: radiation pressure should halt accretion process

↓

MASSIVE STARS SHOULD NOT FORM (?!)

PROPOSED SCENARIOS

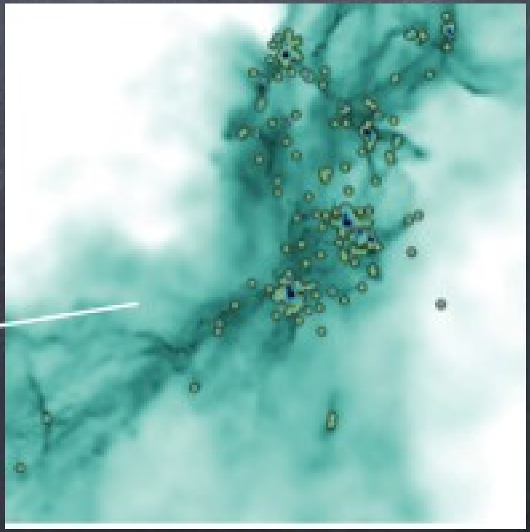


Courtesy of Luca Carbonaro

Stellar Mergers
discs/outflows
deeply altered

Core Accretion
well defined disc-
outflow systems

Competitive Accretion
massive stars at
cluster centre



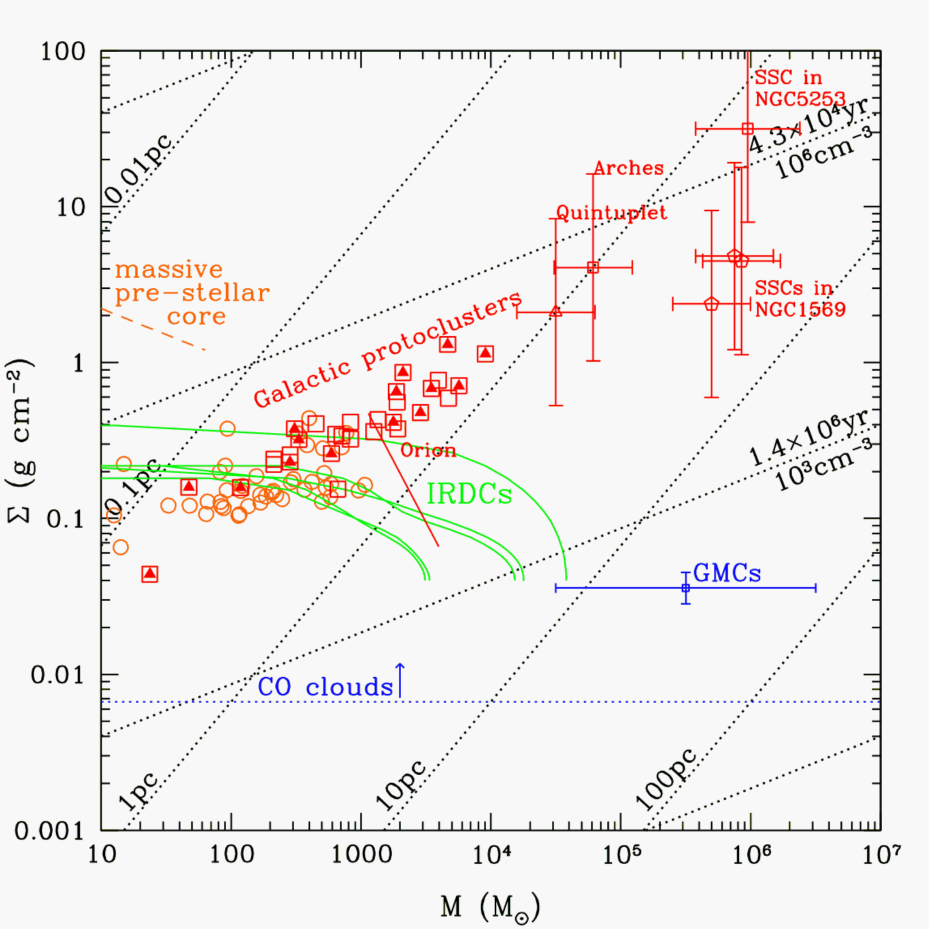
From Zinnecker & Yorke 2007

Forming high mass stars requires disks

- A variety of studies have shown that forming a high mass star requires accretion via a disk which shields accreting material from radiation
- This causes radiation to emerge along disk axis (probably together with a jet)
- One also needs high accretion rates (10^{-3} solar masses per year)

The Mass vs Column Density Diagram

Clusters and Clouds compared (J.Tan)



How does one evolve from cloud to cluster

Millimeter continuum surveys

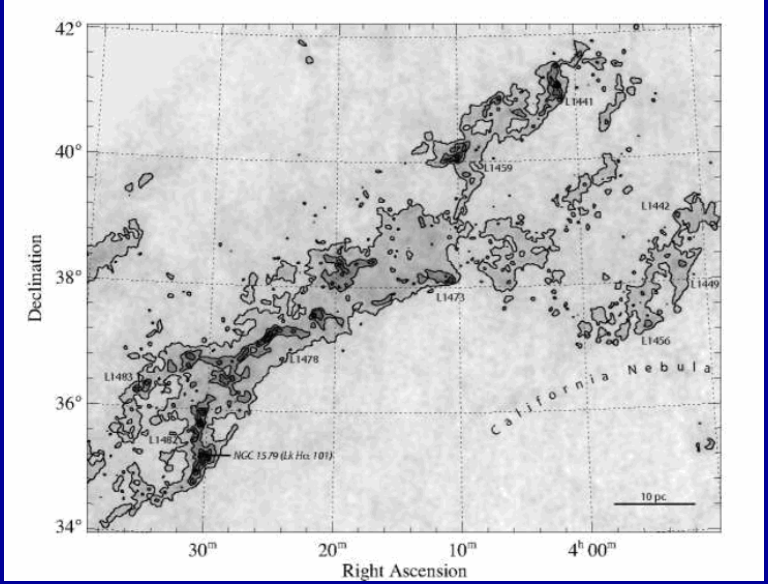
Mm continuum emission by dust is a good probe of the pc sized clumps that give rise to clusters and OB stars

At mm wavelengths, dust emission is typically optically thin and intensity is proportional to N(H2)

Extinction Surveys

In the NIR using background stars (Lada et al) and determining reddening

In the MIR using background galactic dust
small particle emission
(using Spitzer, MSX images
(IR Dark Clouds or IRDCs)



Lada, Lombardi, Alves : NICER map of California cloud (Extinction in K-band)

Yields mass distribution over clump

Mass determination of molecular clouds

3 Main Techniques

- From dust column density in emission (mm) or absorption (extinction)
- Virial Mass from molecular line width and size assumes GM^2/R of order $0.5\ M\sigma_v^2$
- Molecular line luminosity (e.g. using $C^{18}O$) calibrated empirically or based on assumed abundance

Different Mass determinations have different drawbacks

- Virial Mass has problem that it neglects e.g. magnetic field, system may not be virialised
- Mass using $C^{18}O$, HCN, CS is doubtful due to abundance variations, excitation etc
- Methods using dust emission/extinction must assume dust size distribution, dust-to-gas ratio

Hence best to compare results from different techniques

What insights from galactic SF

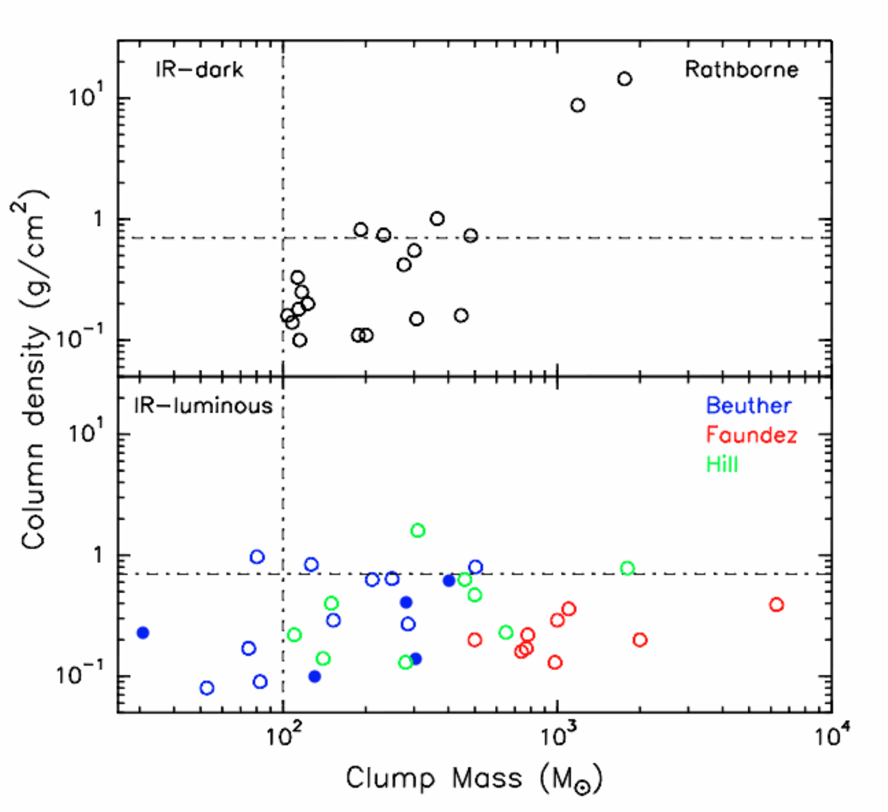
- One can study the internal (protostar scale) structure of the parsec scale “clump” (including kinematics)
- One can study the outflows and jets which are the most evident initial signature of a protostar
- One can study parameters like L/M as a function of clump parameters as a guide to the Schmidt-Kennicut law

Study by Lopez-Sepulcre et al.

- Aim is to have an “unbiased” sample of clumps in order to check if star formation rate depends, e.g., on column density of progenitor clump
- Looks for evidence of outflow, inflow, rotation
- Uses IRAM 30m observations of HCO+, HCN, SiO, $C^{18}O$
- Check the Krumholtz-McKee contention that there is a column density limit of 0.7 gm cm^{-2} for high mass SF
- Compare star formation in IRDCs and IR luminous regions

Lopez-Sepulcre et al. Sample

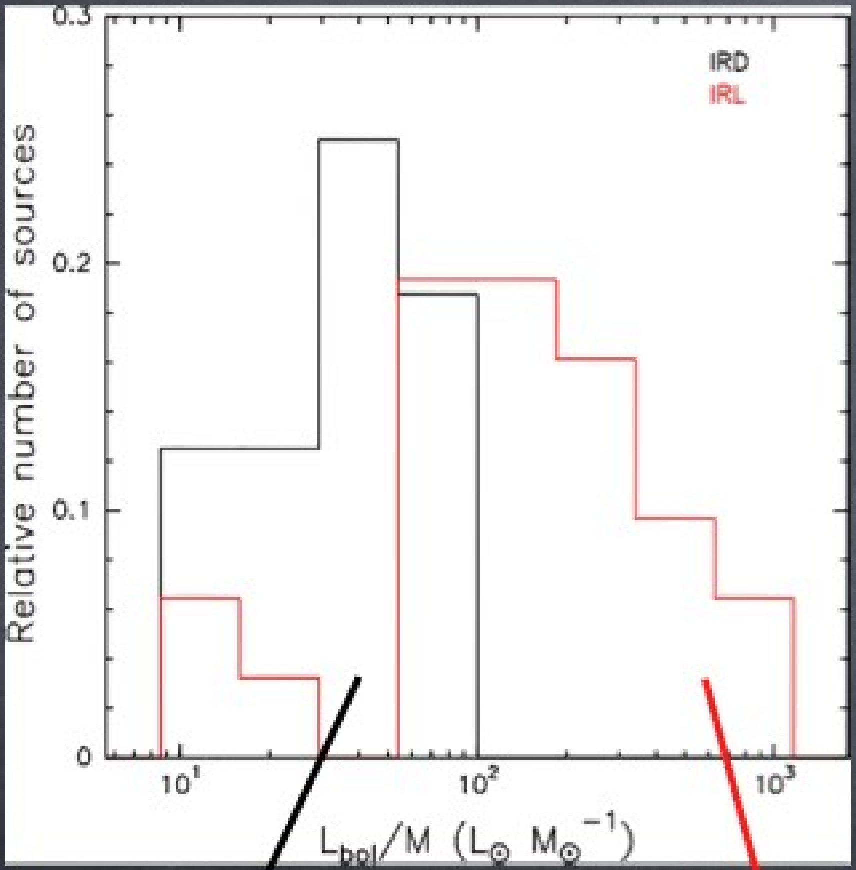
- 18 IRDCs from Rathborne et al.
- 31 Clumps with high-mass protostellar objects from various authors
- Aim is to check whether star formation is more prevalent in certain parts of the Mass-Column Density diagram



Luminosity to gas Mass ratio

- L/M: of interest for comparison with extragalactic star formation
- L is a measure of star formation rate and so L/M is a measure of gas exhaustion timescale or (dM/dt)/M
- L/M should be a proxy for evolution or “time” since L should increase and M decrease with time

L/M HISTOGRAM



IR-dark: **smaller L/M values**

IR-luminous: **larger L/M values**

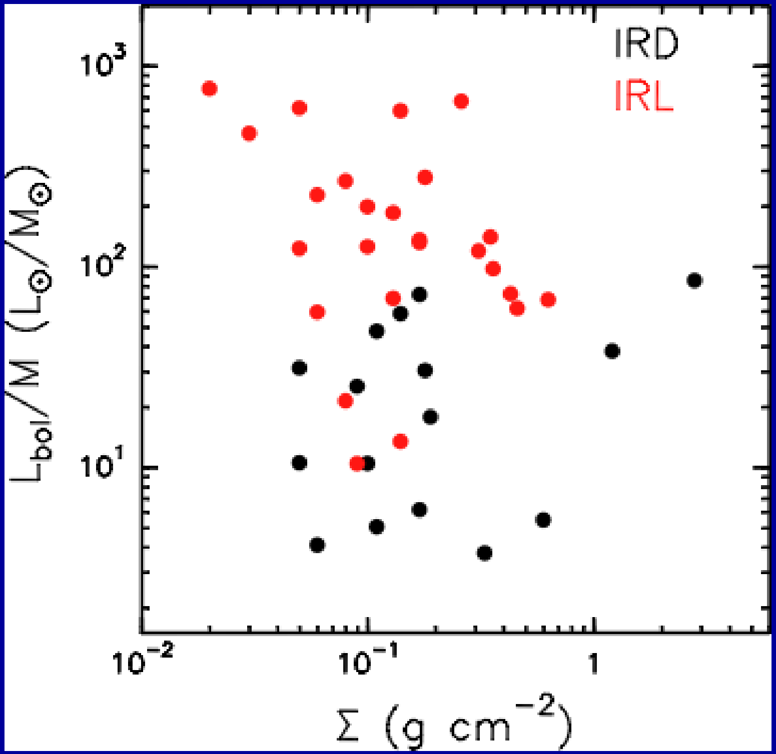
L/M: rough measure of time or evolutionary state

Distance-independent quantity

L/M indicator of evolution or external pressure

- If L/M was sensitive to the external triggering pressure, one would expect a dependence on column density

In fact, no dependence is observed. Hence L/M is mainly a measure of age



Conclusions from Lopez Sepulcre et al.

- L/M may be measures of “age” or evolutionary state
- L/M values not greatly different than for “W49 like objects” (I.e. time scales similar)
- Evidence for an increase in star formation rate above a limit of 0.3 gm/cm^2

And what can one say about extragalactic star formation

- It is certainly more spectacular as a look at images of 30 Doradus in the LMC tell us
- But there is evidence that it in many ways is just a scaled up version of galactic star formation

Simplified View of Extragalactic Star Formation

- Based upon :
  - Assuming local IMF is valid everywhere (use IR luminosity as tracer of star formation rate)
  - Assuming for the SF efficiency some version of the Schmidt Law

AMAZING IF TRUE !

The Schmidt Law

- The Schmidt Law for the star formation rate (SFR) has many forms:

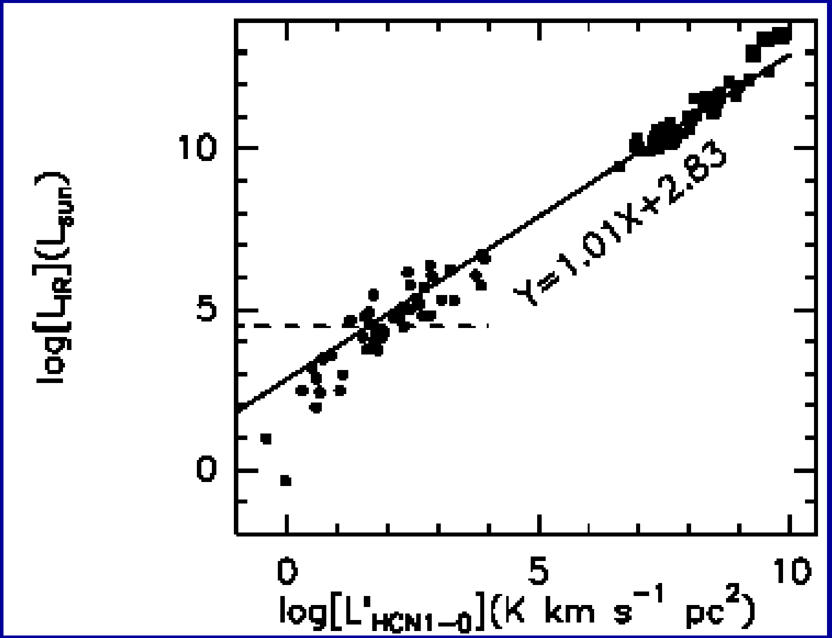
$$SFR = d\Sigma/dt \sim \Sigma^p \text{ with } p=1\text{-}2$$

Alternatively : $d\Sigma/dt \sim \Sigma/\, t(SF)$

Where Σ is column density and $t(SF)$ is timescale for star formation

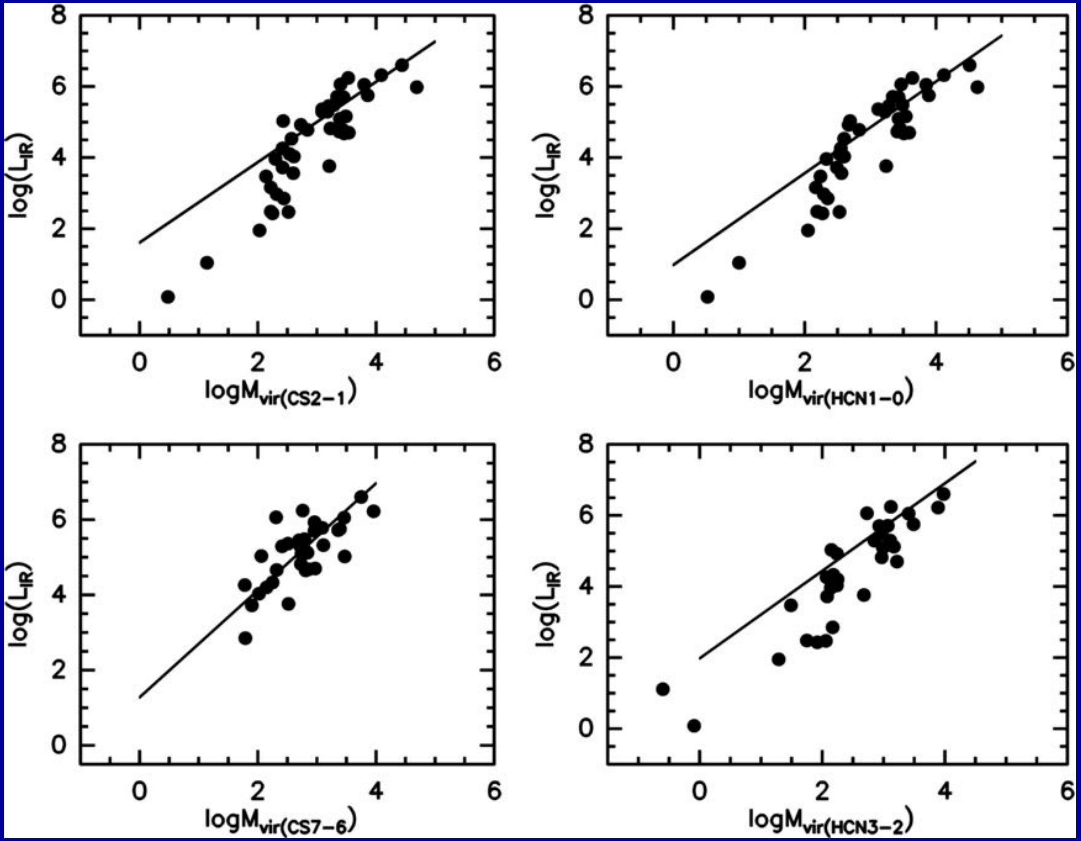
Galactic Extragalactic connection

- That there is a connection is clear from the various correlations found between star formation and molecular line luminosity (most recently from Wu et al)



- The HCN luminosity tracks the IR luminosity with the same relationship for galactic and extragalactic SFR

Different lines give similar result for galactic clouds



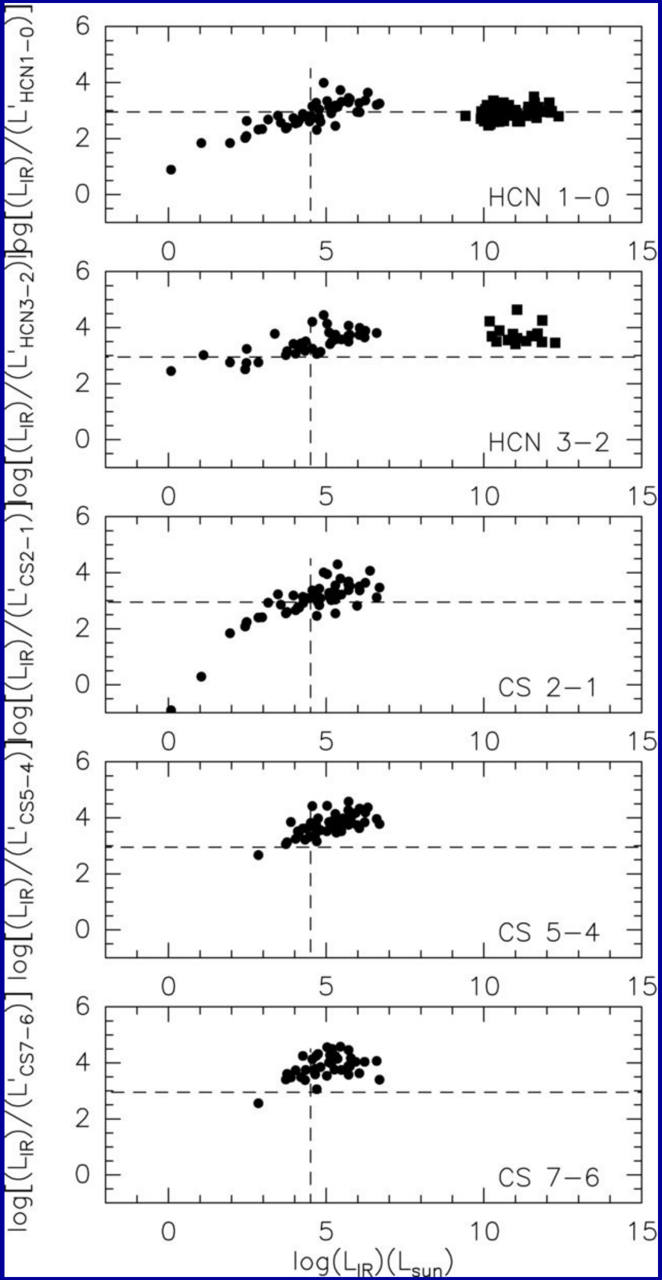
Thus dependence does not depend on tracer

IR Luminosity versus virial mass

Wu et al 2010

Extragalactic “clouds” seem to behave analogously to galactic clouds

- Above Lir of 3 10^4L(sun) , Lir/L(HCN) constant
- Does not depend on excitation
- Suggests a unit “subcluster” of a few hundred solar masses



Conclusions on extragalactic star formation

- Extragalactic star formation may well be just galactic on a larger scale
- One finds that the star formation rate (represented by L(IR)) is proportional to the mass of dense(>10^4) gas represented by L(HCN) (strange!)
- But we do not understand what determines the efficiencies and timescales
- The assumption that Star Formation Rate is proportional to L(IR) depends on IMF universality (!)

Future of this topic

Requires interferometry and all these objects will be redone with ALMA (0.1 arc sec. or 200 AU at 2 kpc)

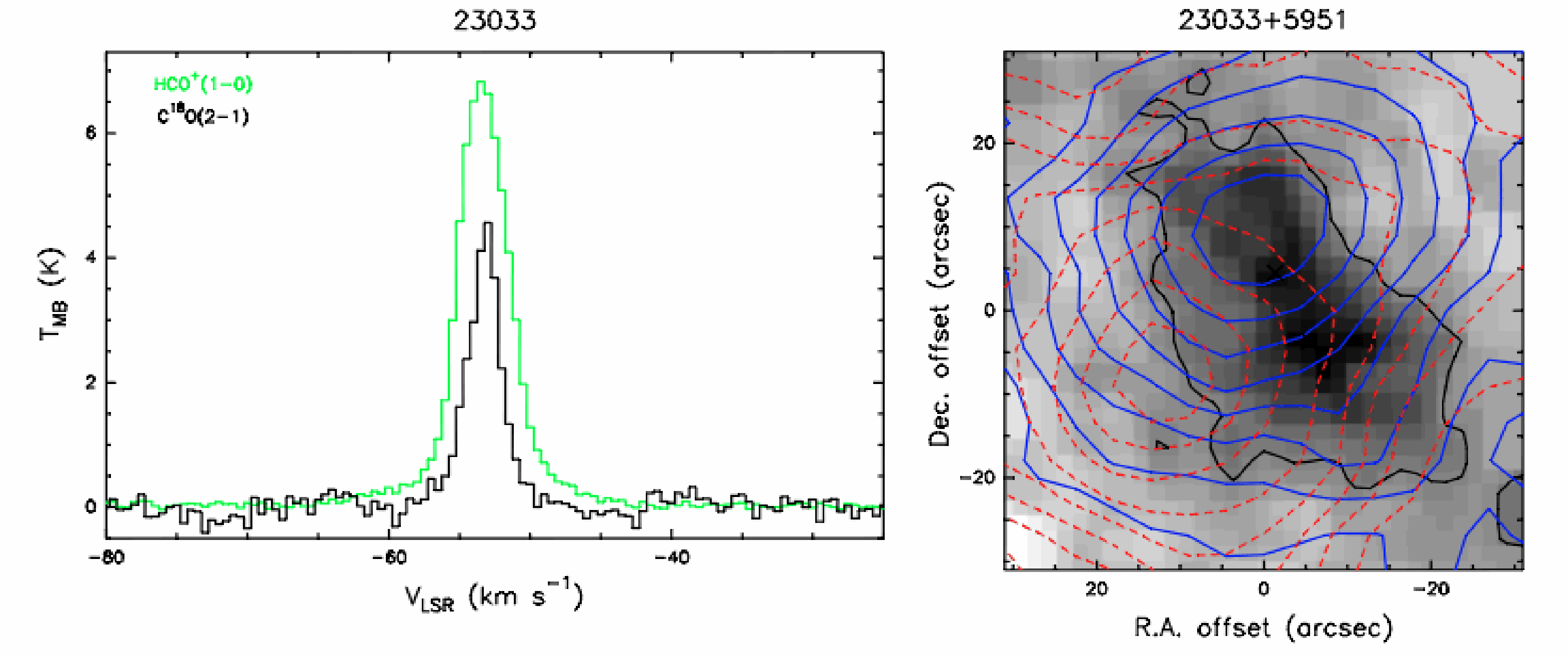
This will perhaps allow the identification of the protostar which is origin of flows

One needs tracers of the low mass stars in embedded clusters (perhaps from X-rays or radio)

Reliable distance estimates are needed from VLBI and near IR spectral types combined with photometry

Source with outflow in HCO+

- C18O(2-1) marks "undisturbed" clump gas



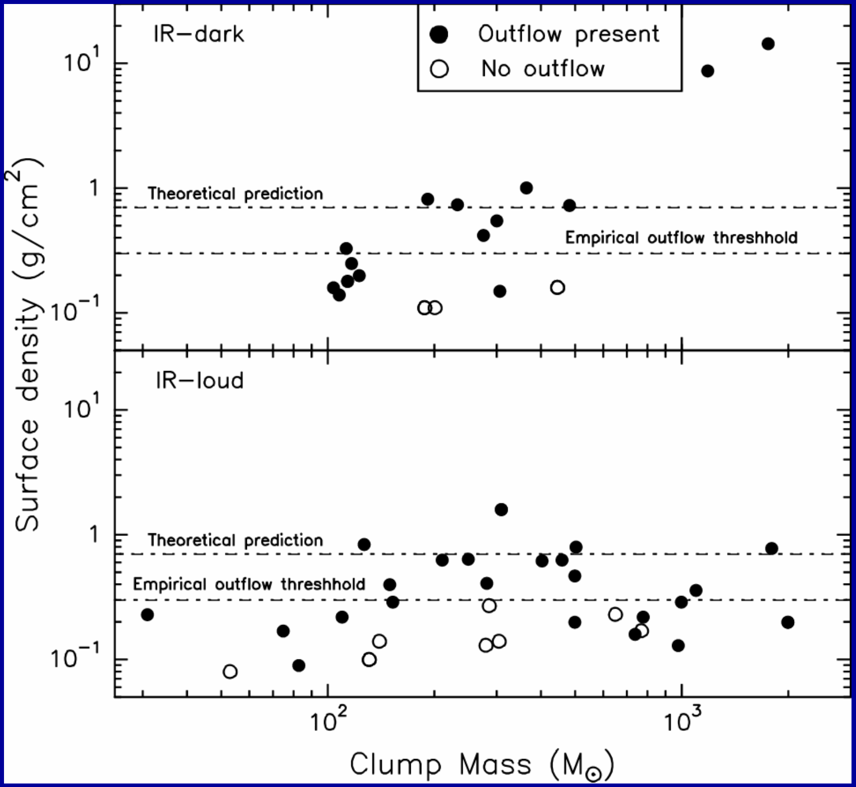
Outflows correlate with surface density??

All objects with no outflows have clump surface density below a threshold of 0.3 g cm-2 (theoretical prediction for high-mass SF is 0.7 gm cm-2)

Is this credible ?

Needs testing with other outflow tracers (CO, SiO)

SiO detected in most regions
Including IRDCs

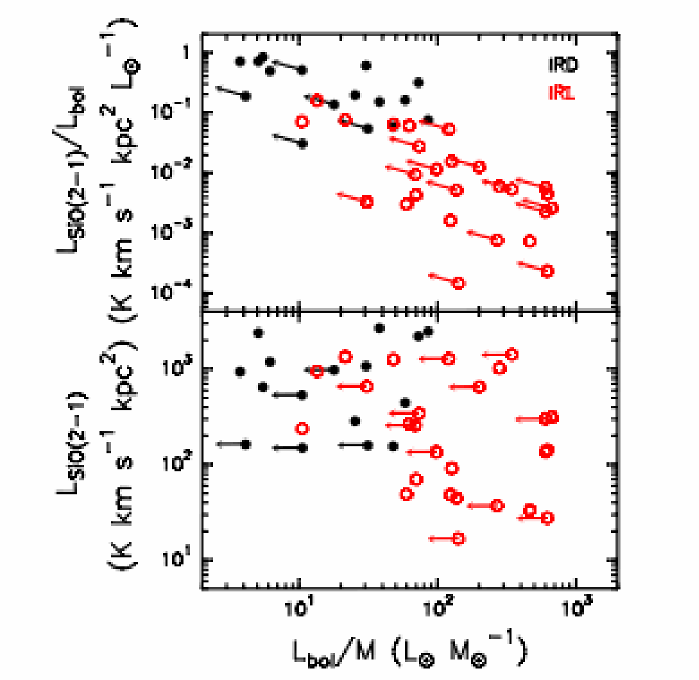


SiO as outflow tracer

- SiO traces C-shocks where gas streams past charged dust grains and releases Si into gas phase
- How much Si gets sputtered depends on binding energy but clearly a small fraction in practise
- No confusion with ambient gas in contrast to CO, HCO+ etc

SiO luminosity versus L/M

- Anti-Correlation SiO against L/M ?

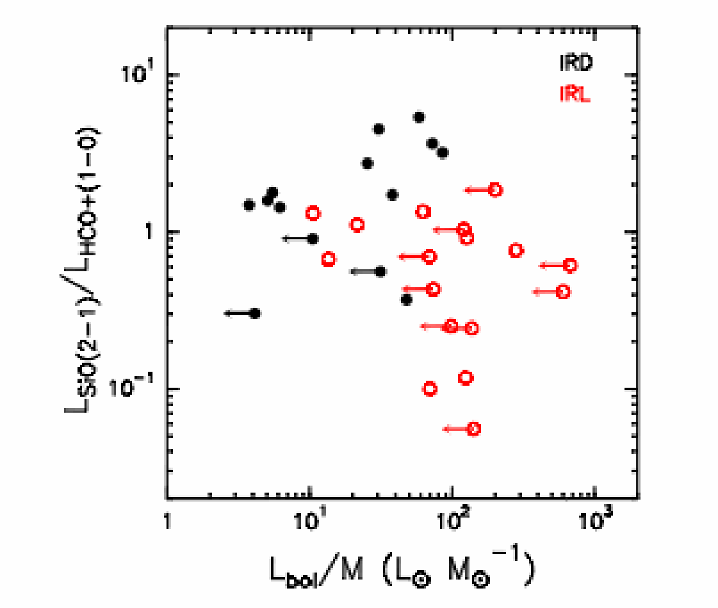


Top panel shows D independent
quantities L(SiO)/L
And bottom panel just L(SiO)

Note slight cheat in
Plotting L(SiO/L versus
L/M

What does SiO depend on

- SiO luminosity is a measure of outflow mass times SiO abundance. One test is to compare with other outflow tracer such as HCO+.



Slight trend for fall-off of SiO luminosity with L/M suggests fall-off of SiO Abundance with L/M

SiO as evolution indicator

- Lopez-Sepulcre et al. results suggests one can use SiO as evolution indicator
- Strong SiO is a sign of youth
- Quantifying this will be a challenge