From comets to out-flows

The versatility of the 69 micron band of crystalline olivine

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Bram Acke
Rens Waters
Michiel Min

Content

1. Introduction on minerals and olivine in particular
2. Doing Olivine mineralogy with Herschel/PACS
3. Olivine in evolved stars
4. Olivine in the debris disk β pictoris

1. Introduction: minerals

- What are they?
- Where do we find them?
- How do we find them?
- How are they formed?
- Why are they important for astronomy?

1. Introduction: minerals

- What are they?
- Where do we find them?
- How do we find them?
- How are they formed?
- Why are they im

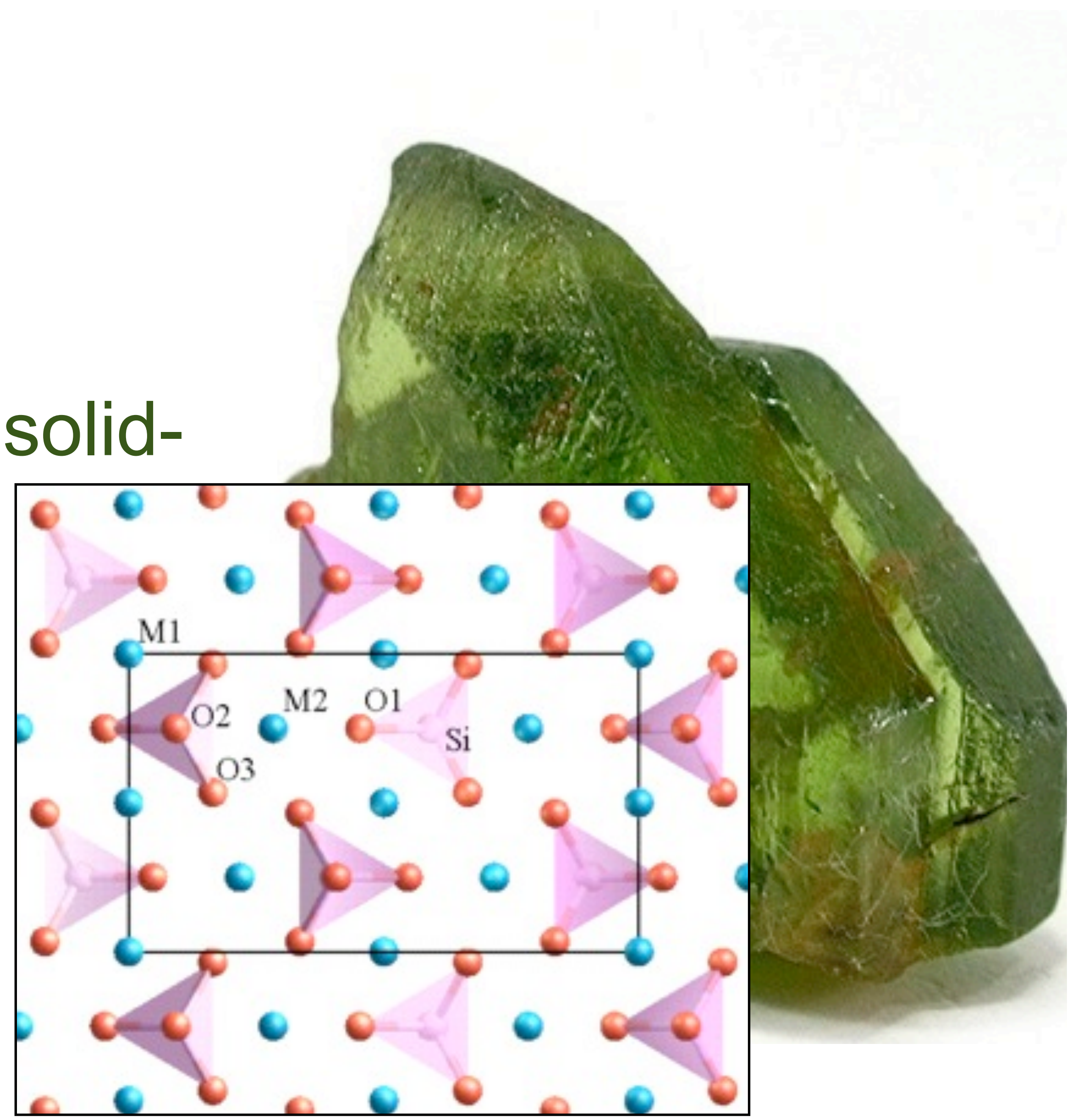
As an example we use the mineral **Olivine**

What is Olivine?

1. Introduction

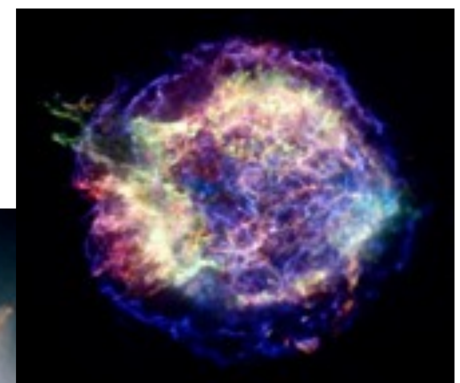
What is Olivine?

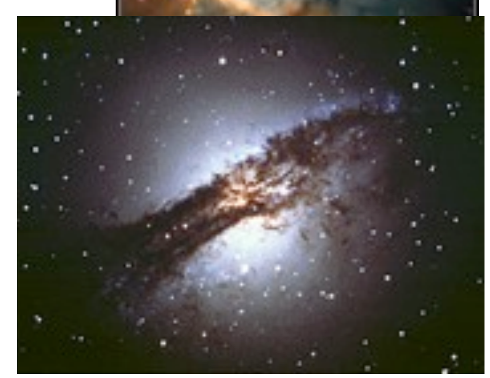
- An ionic compound
- $Mg_{2x}Fe_{2(1-x)}SiO_4$
- $0 \leq x \leq 1$ indicates the solid-solution
- Forsterite $x = 1$
  Fayalite $x=0$
- Mineral = Crystalline
  Glass = Amorphous



1. Introduction

Where do we find olivine?

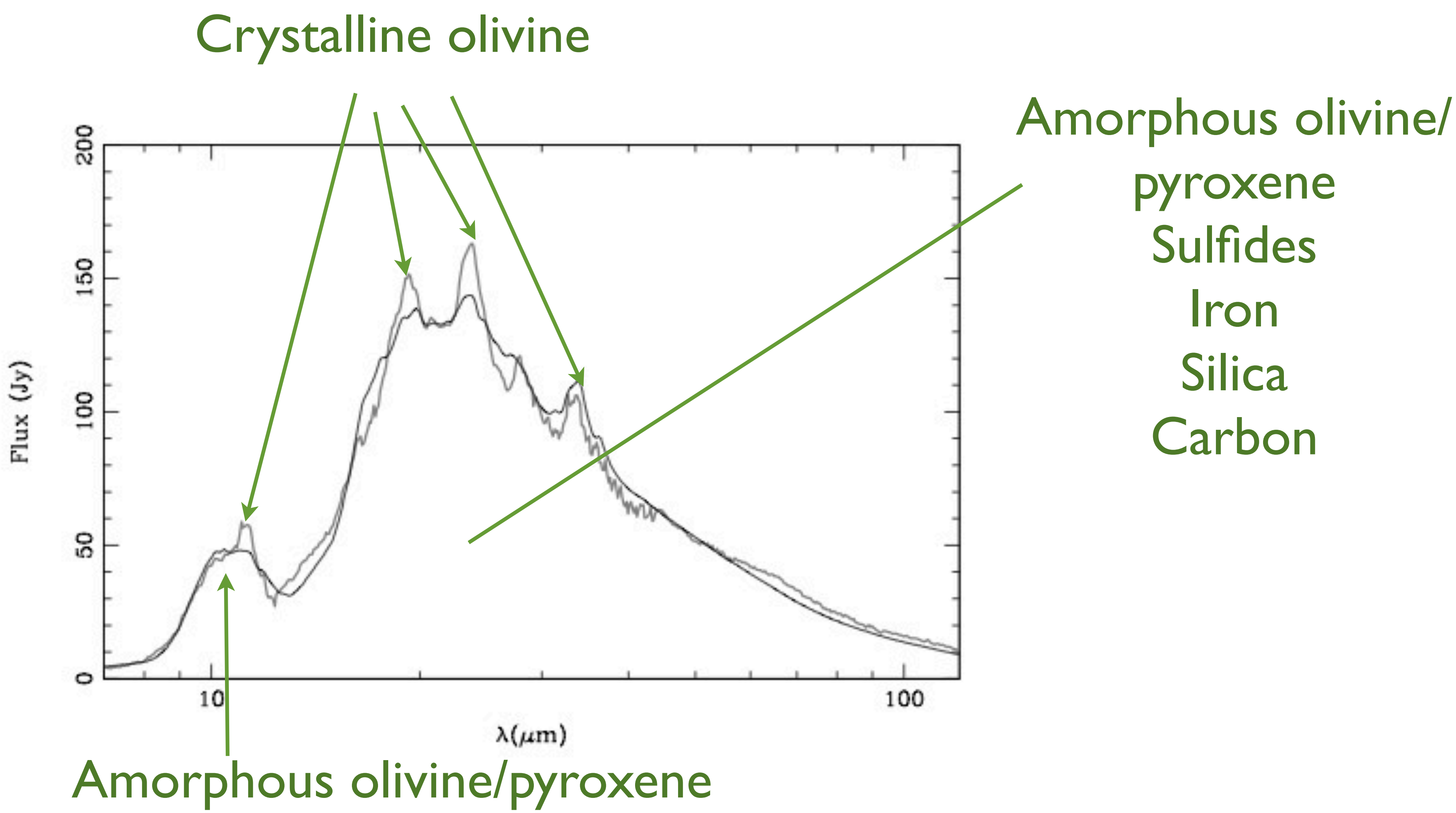


Many more...

1. Introduction

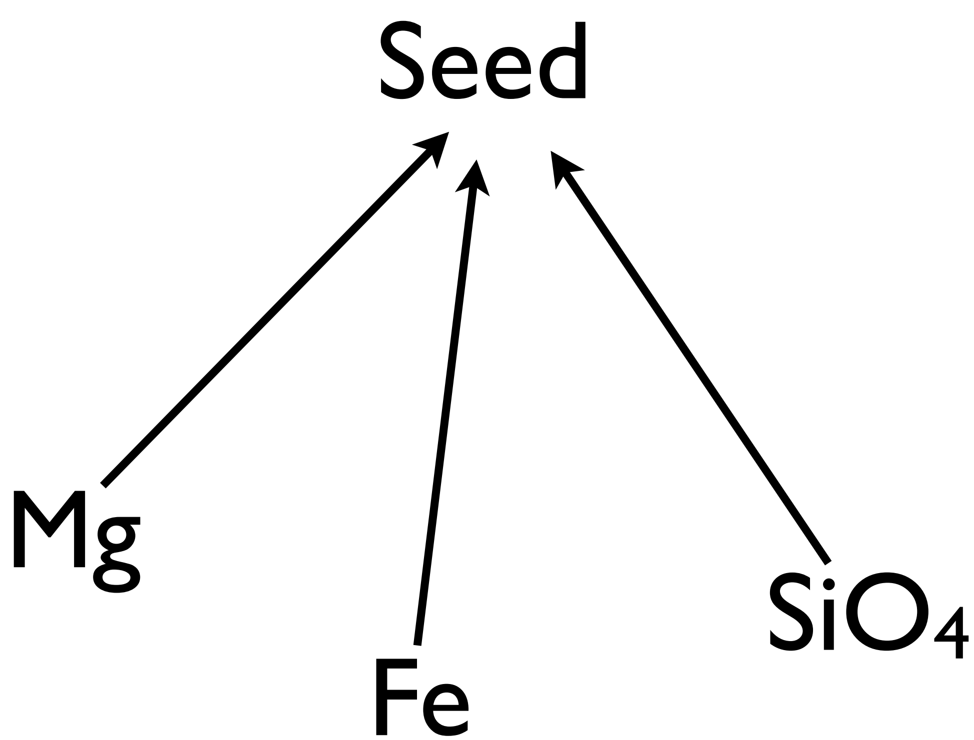
How do we find olivine?

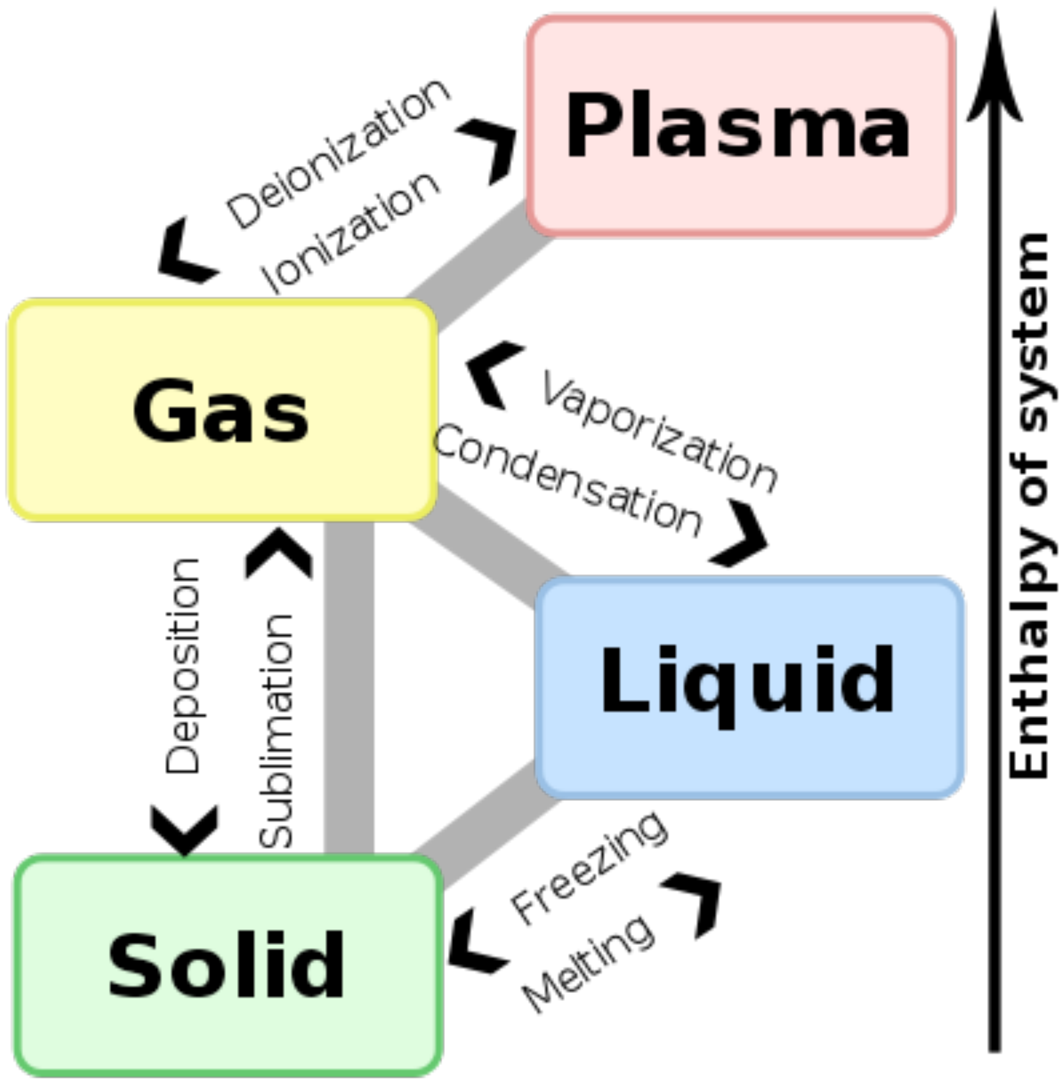


Hale-bopp, Min et al. '05

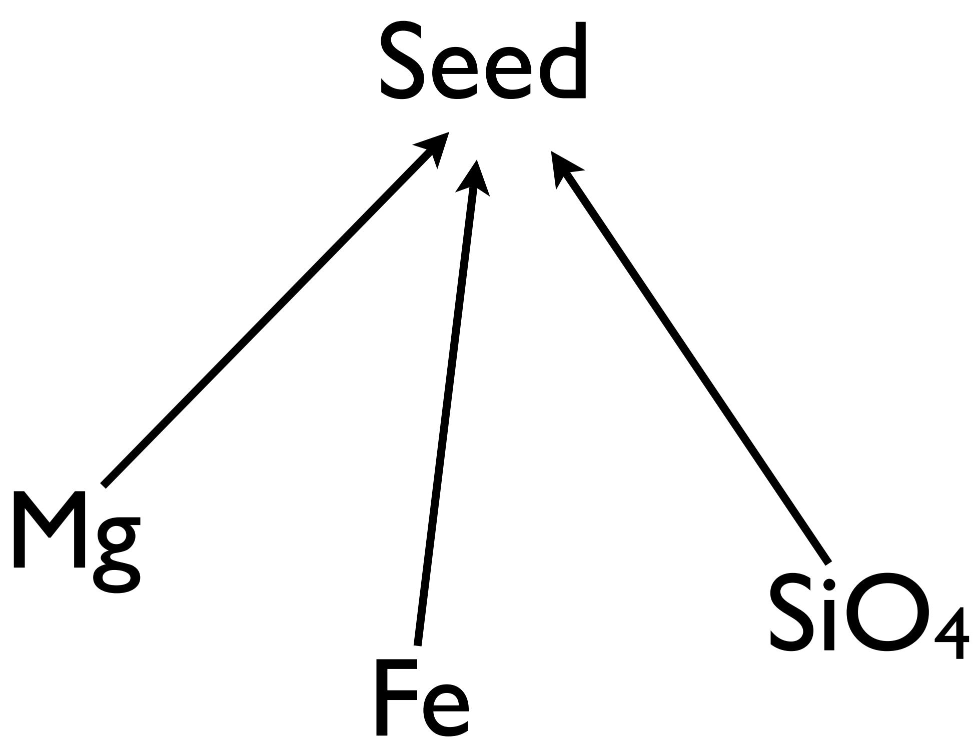
1. Introduction

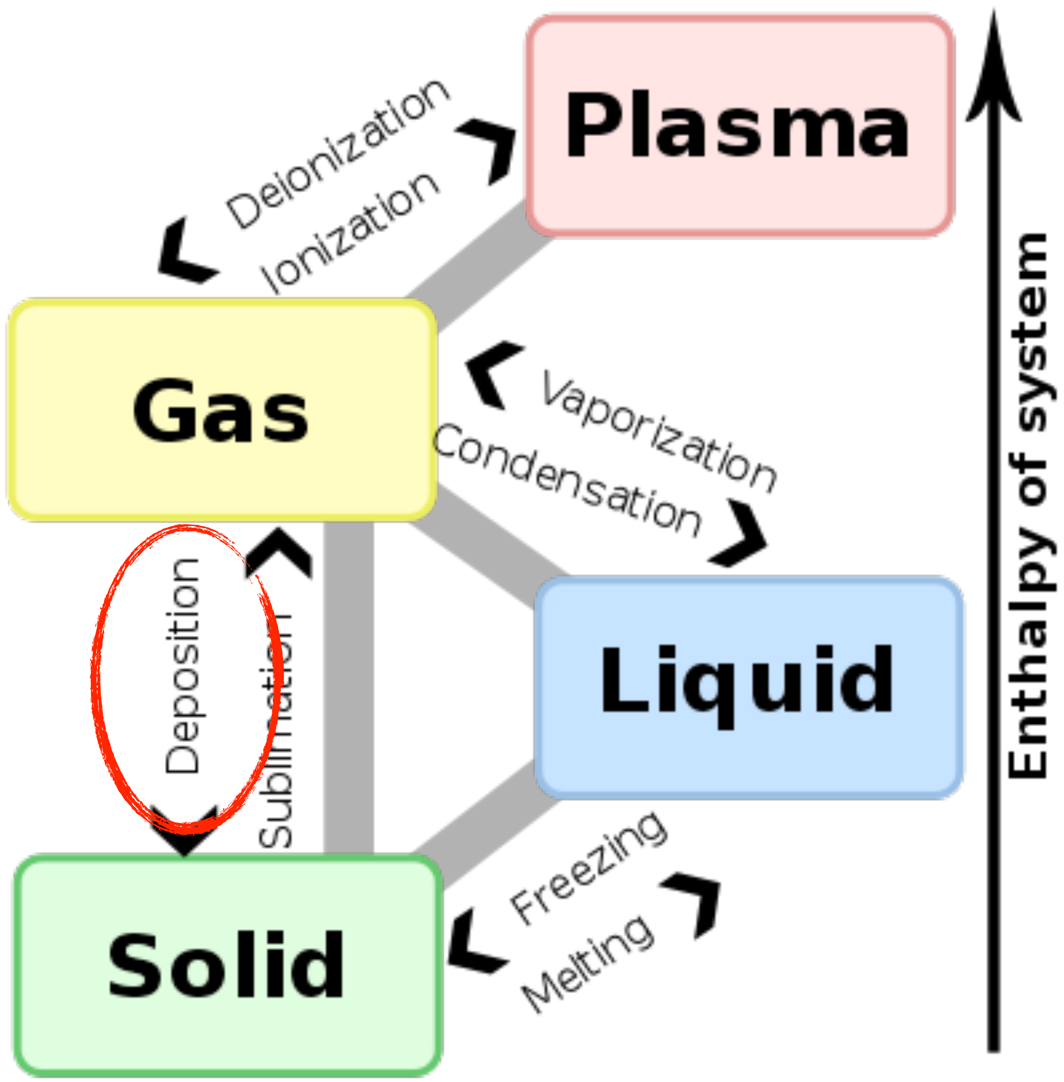
How is olivine formed?





How is olivine formed?





1. Introduction

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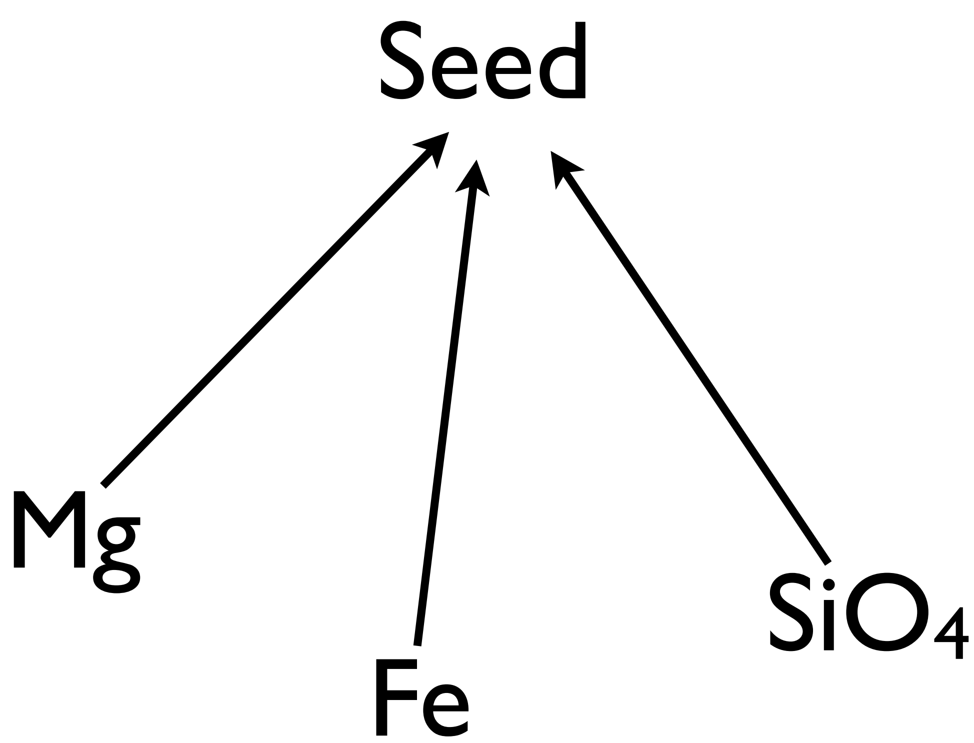

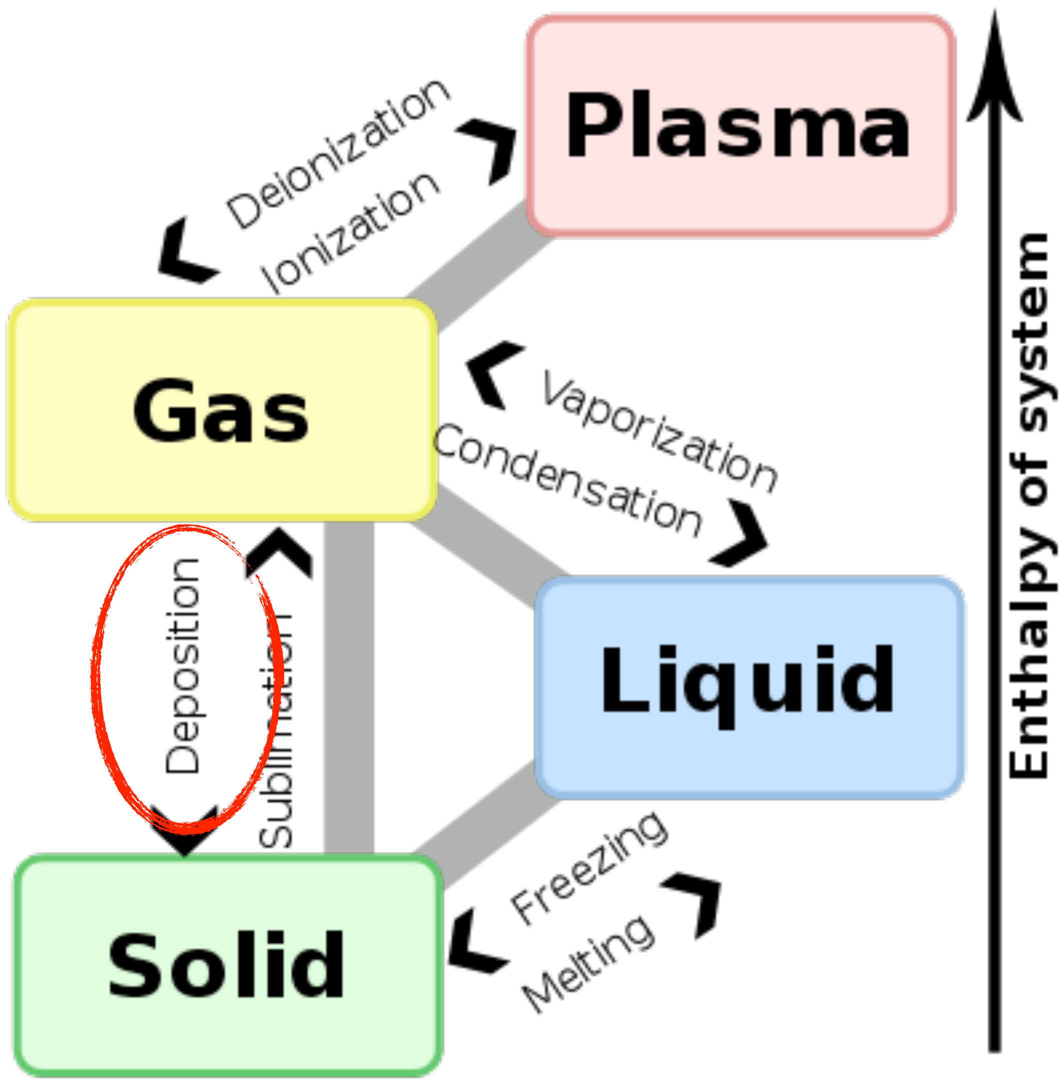

~10^{-10} atm, 1000K

1. Introduction

Why is olivine important?

- Evolution AGBs, RSG (e.g. Höfner ’08)
- Young disks & planet formation (e.g. van Boekel et al. ’04)
- Extinction (e.g. Huffman&Stapp ’71)
- ISM/Galaxy evolution (e.g. Spoon et al. ’06)
- Probe of water on Mars (e.g. Fisk et al. ’06)
- etc etc

Content

10′

1. ~~Introduction on minerals and olivine in particular~~
2. Doing Olivine mineralogy with Herschel/PACS
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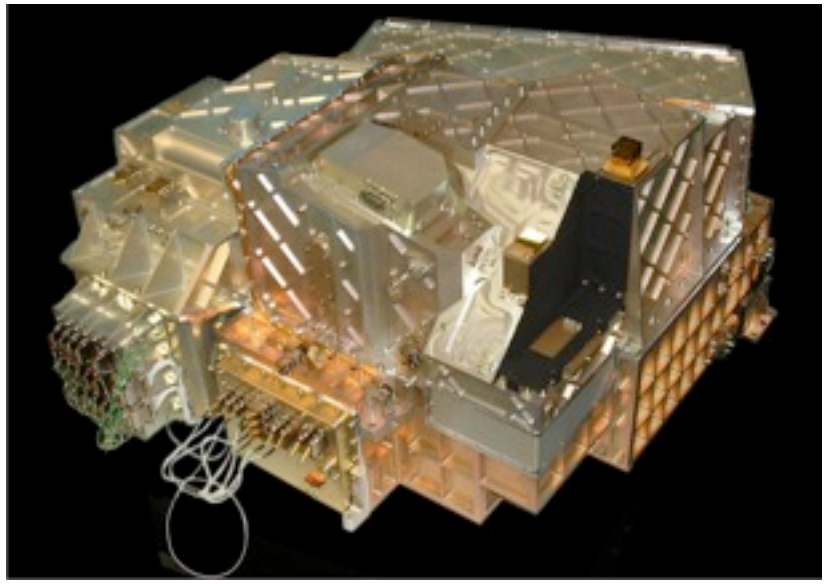
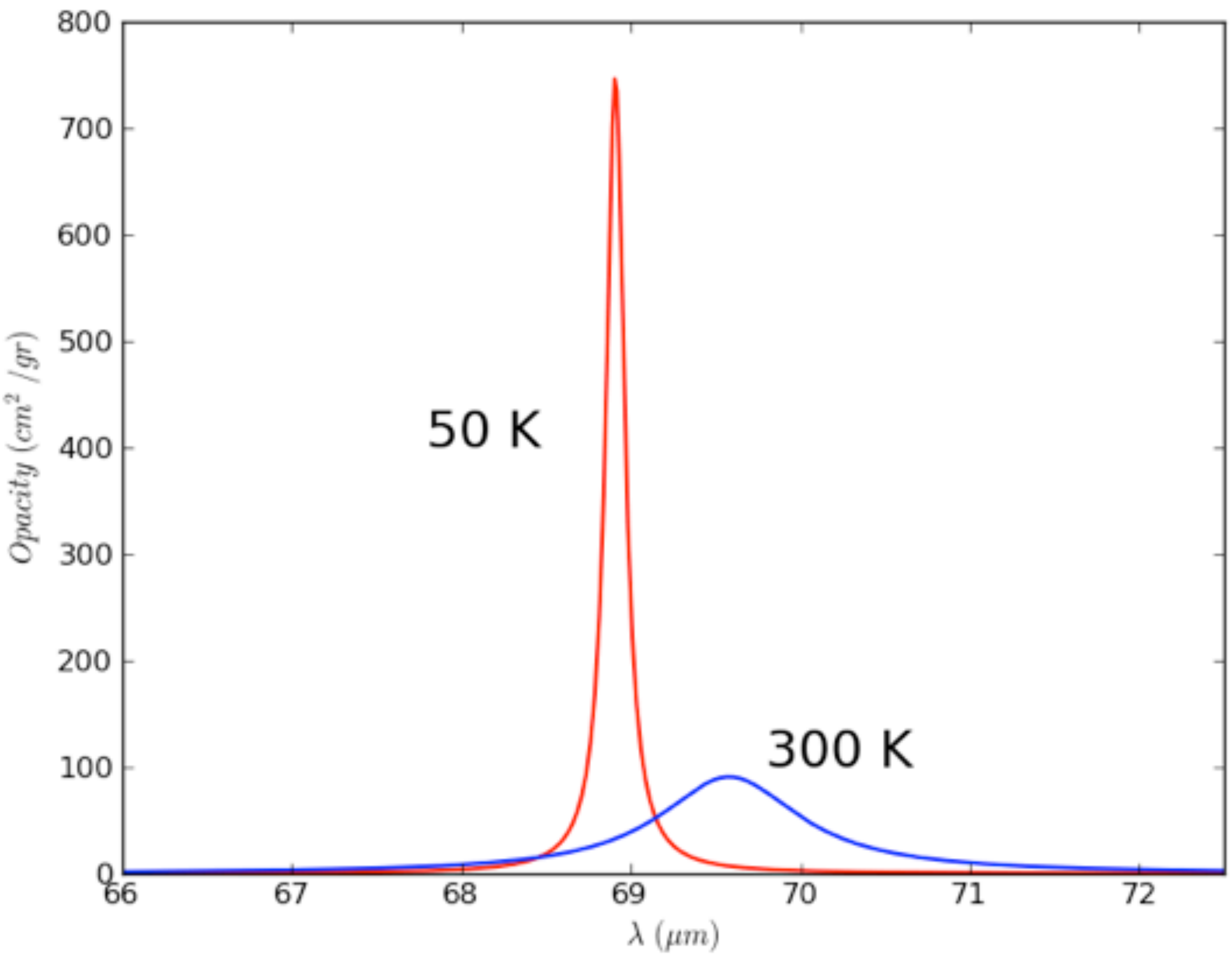
2. Olivine mineralogy with Herschel/PACS

- Limited to the 69 μm band of olivine

- Luckily this band is very useful

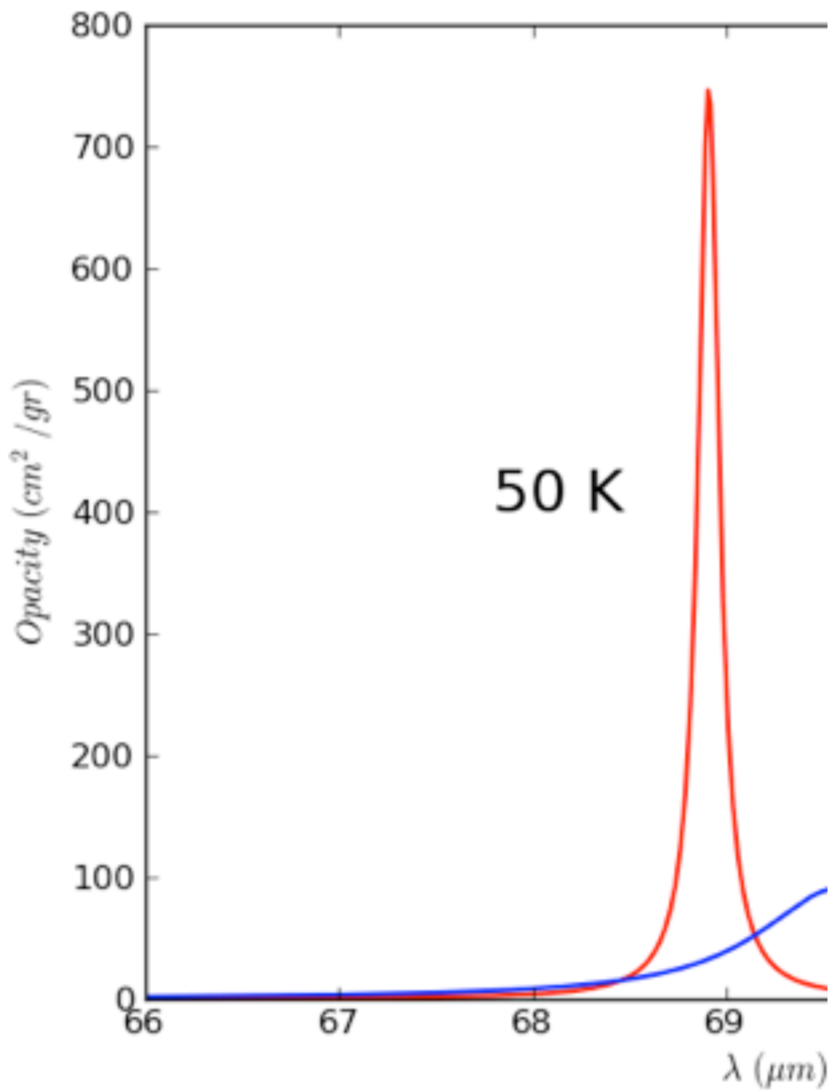


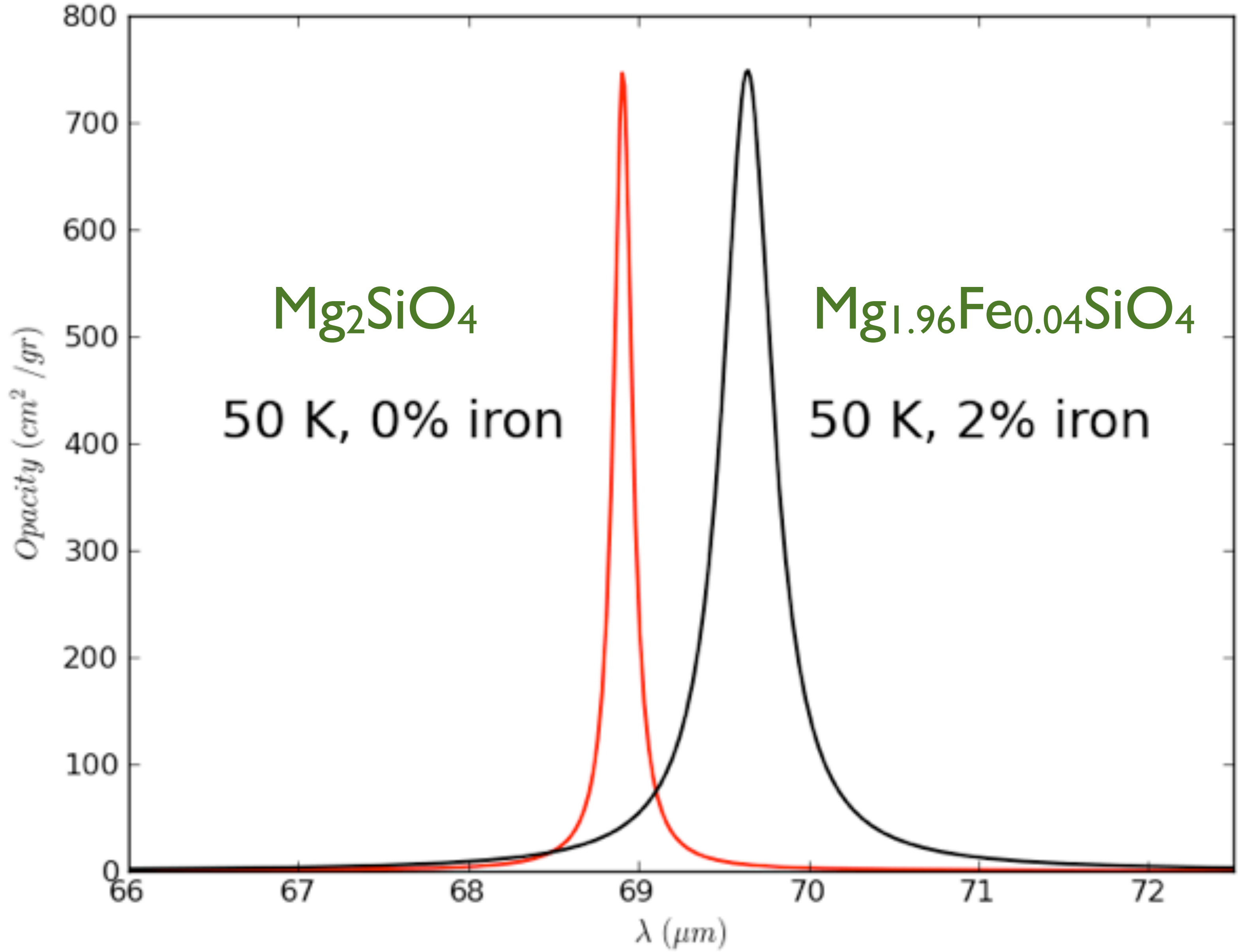
The 69 µm band of olivine



2. Olivine mineralogy

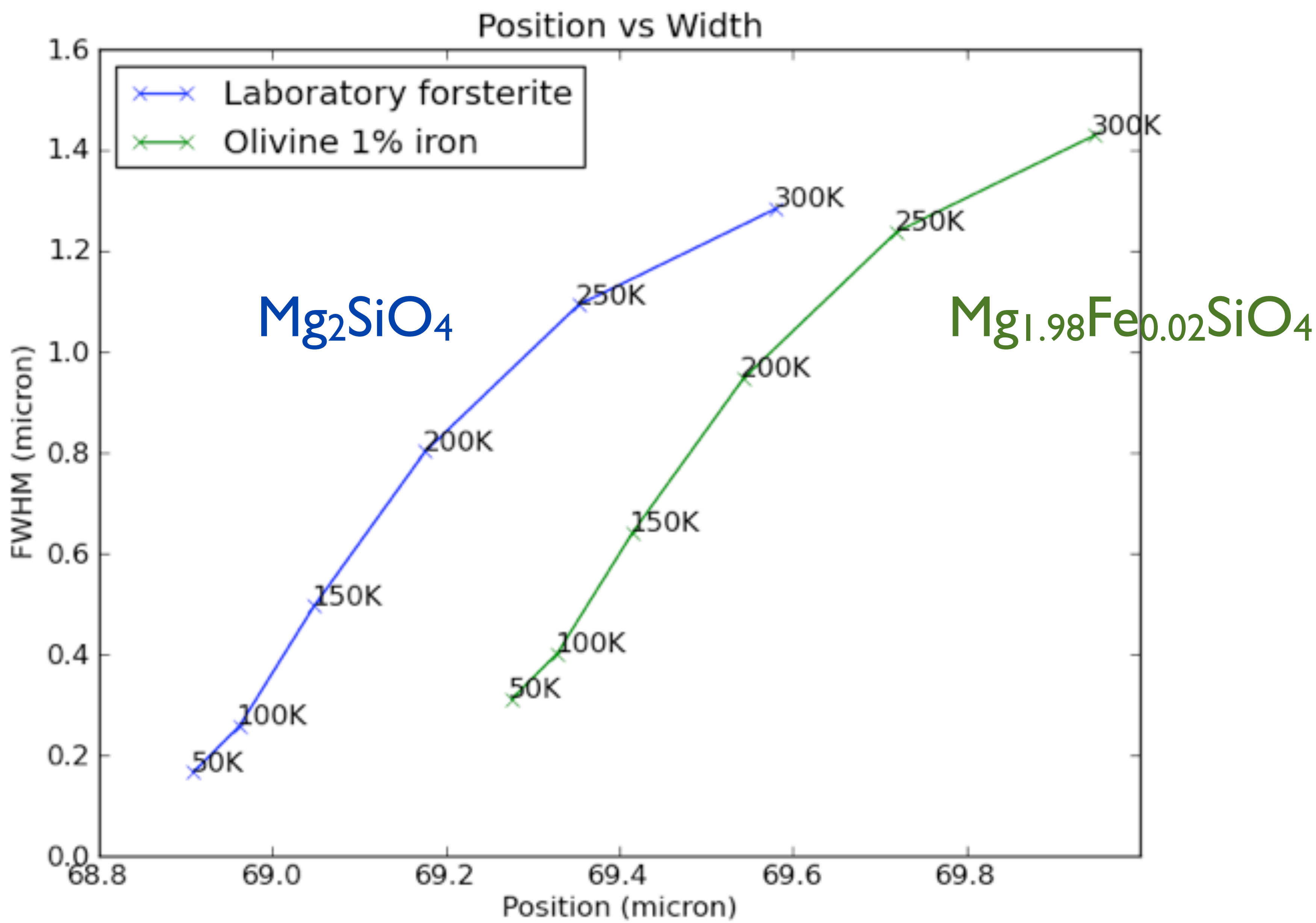
The 69 µm band of olivine





2. Olivine mineralogy

The 69 μm band of olivine



2. Olivine mineralogy

Optical constants: Suto et al 2006, Koike et al. 2003

Next

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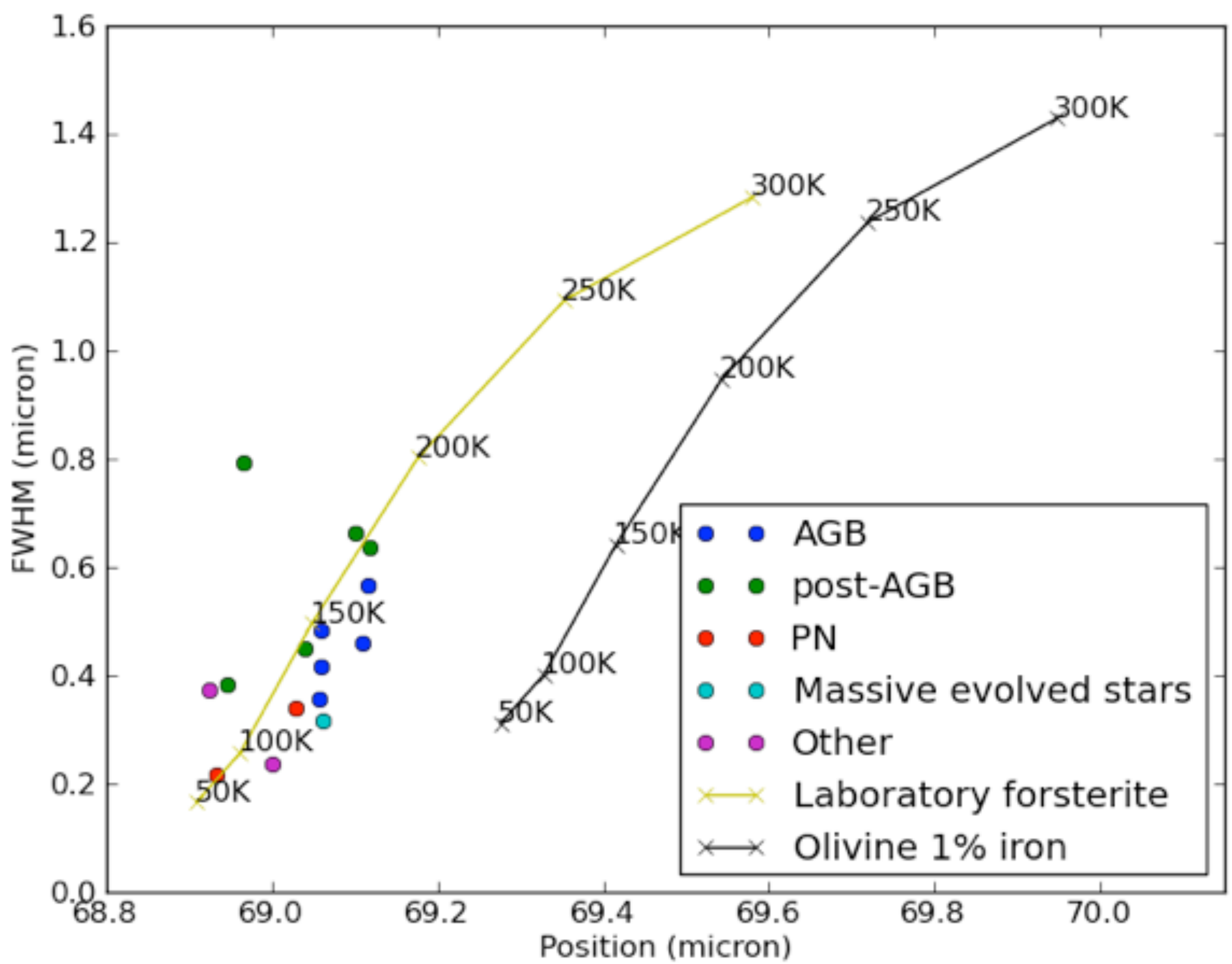
3. Evolved stars

- PACS programs:
  - GT1_jblommae (PI: Joris Blommaert)
  - KPGT_mgroen (MESS) (PI: Martin Groenewegen)
- 38 evolved sources
- AGB, post-AGB, PN, Symbiotic, mixed chemistry, LBV, RSG

69 µm bands in evolved stars

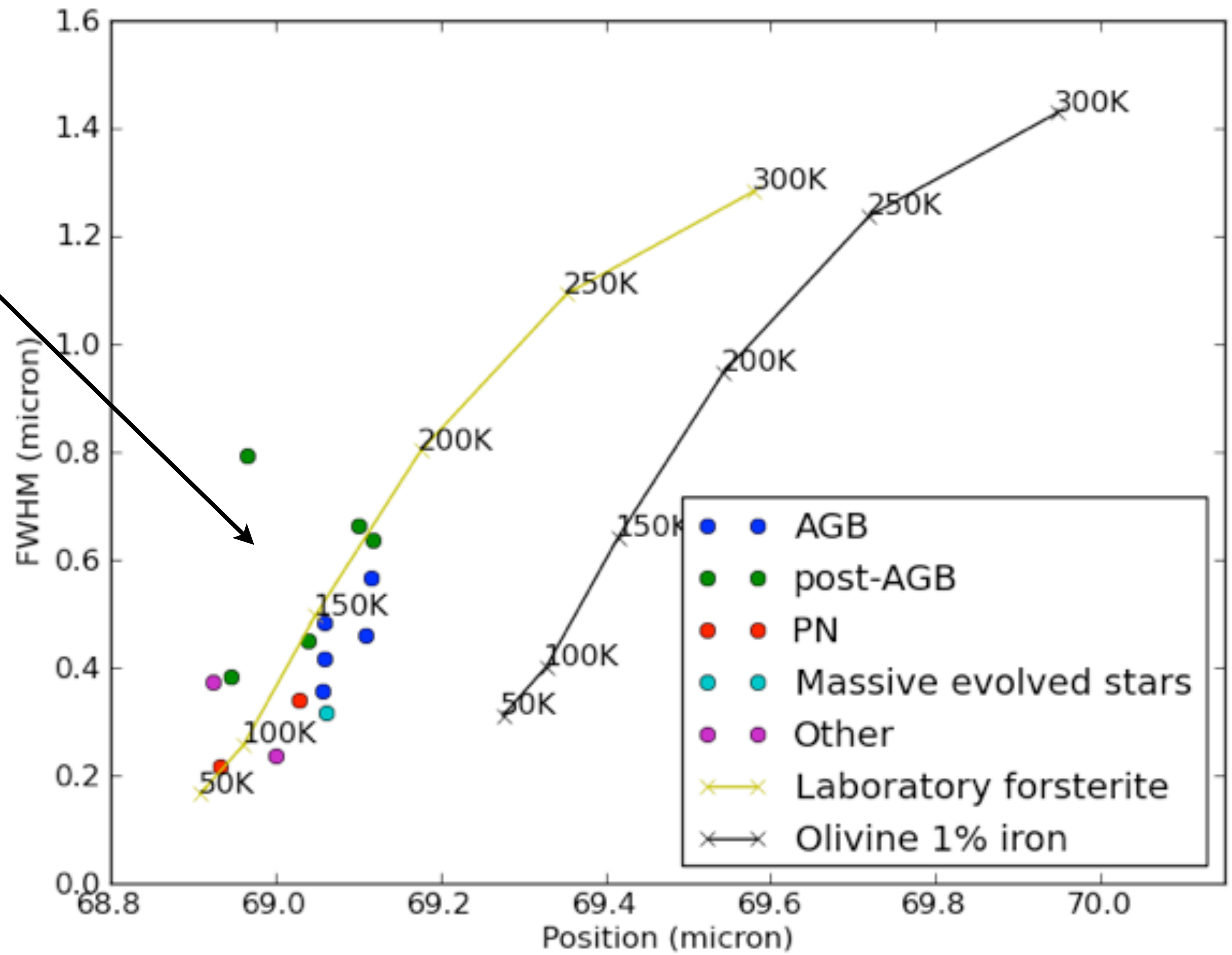


Blommaert, de Vries et al. in prep

3. Evolved stars

69 µm bands in evolved stars

≲0.5% Fe
Cold

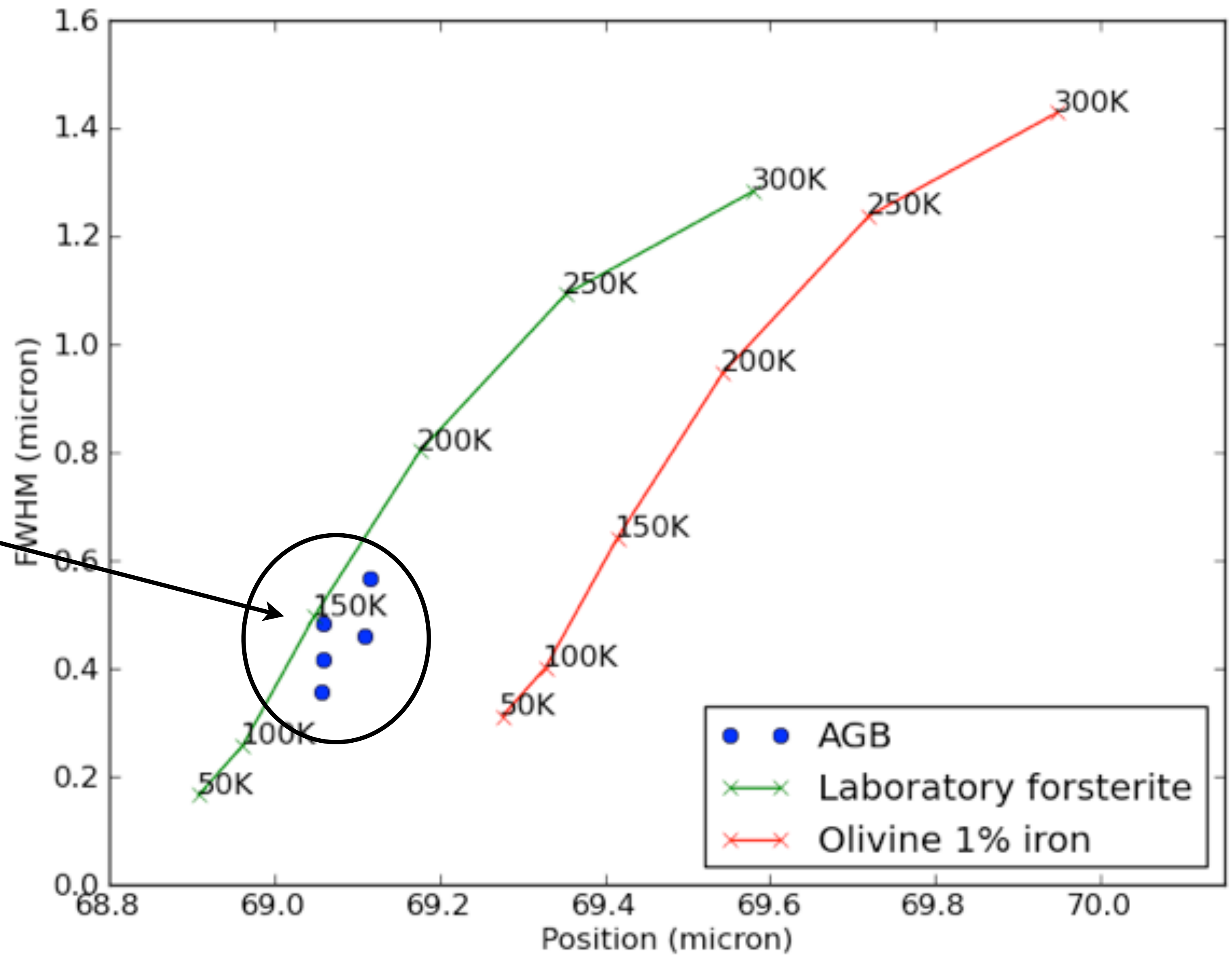


Blommaert, de Vries et al. in prep

3. Evolved stars

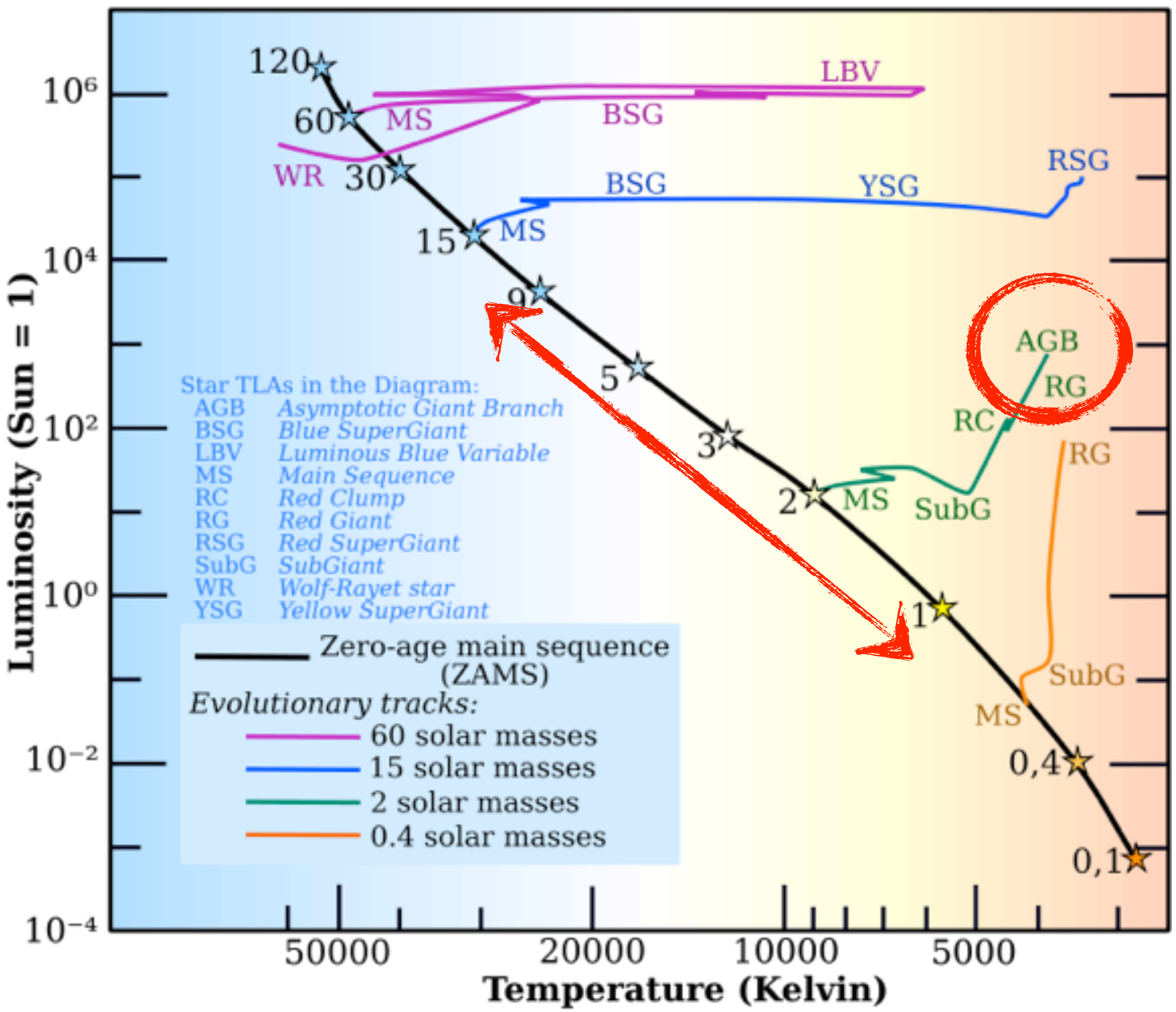
The 69 μm band in evolved stars

AGB outflows



Fun thing!!
We can look into the mineralogy in much more detail now!

A little bit on AGB stars



A little bit on AGB stars

C/O solar = 0.5

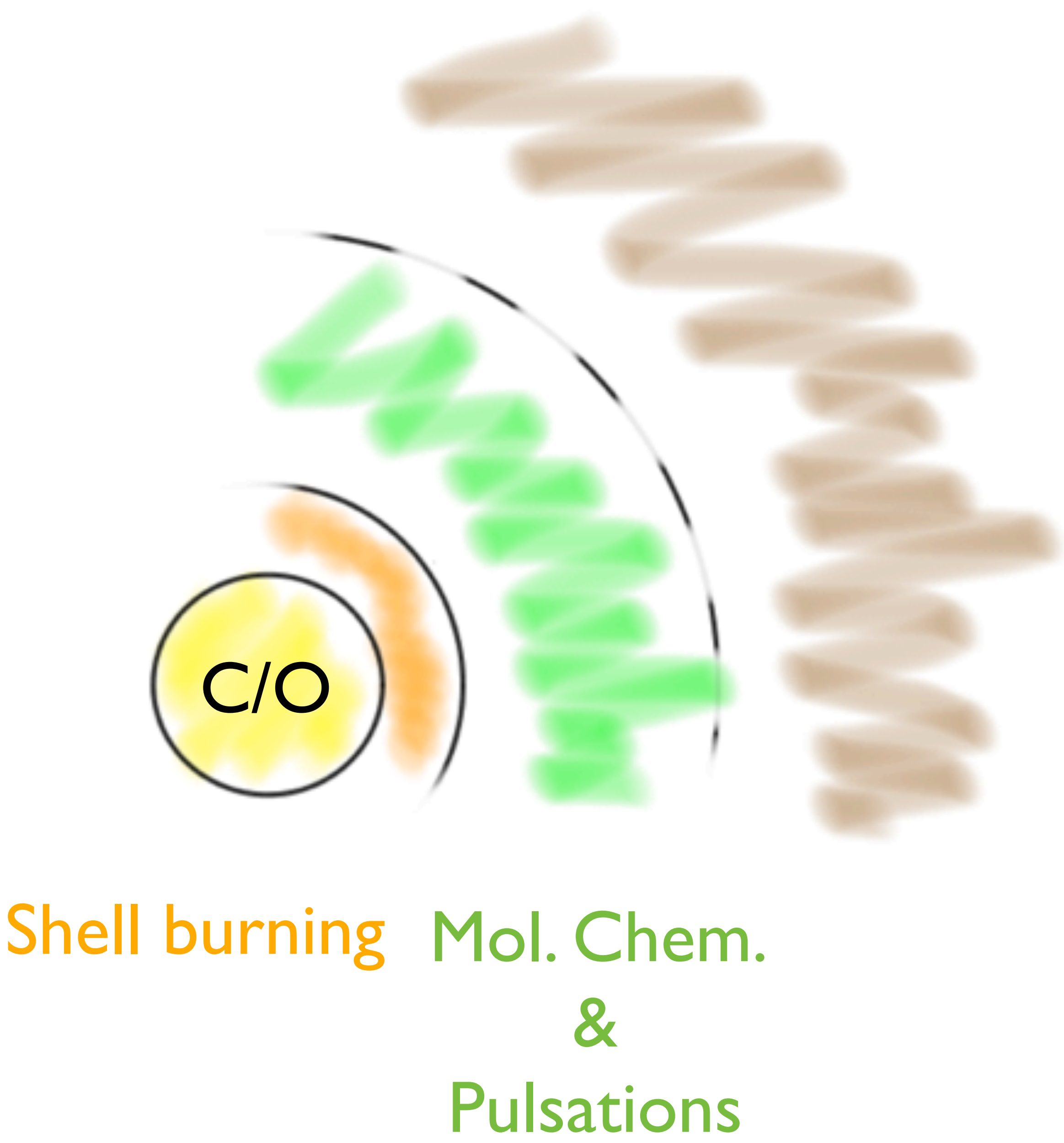
A little bit on AGB stars

Shell burning

C/O solar = 0.5

3. Evolved stars

A little bit on AGB stars



C/O solar = 0.5

3. Evolved stars

A little bit on AGB stars

Shell burning

Mol. Chem. & Pulsations

Dust formation & Acceleration

C/O solar = 0.5

3. Evolved stars

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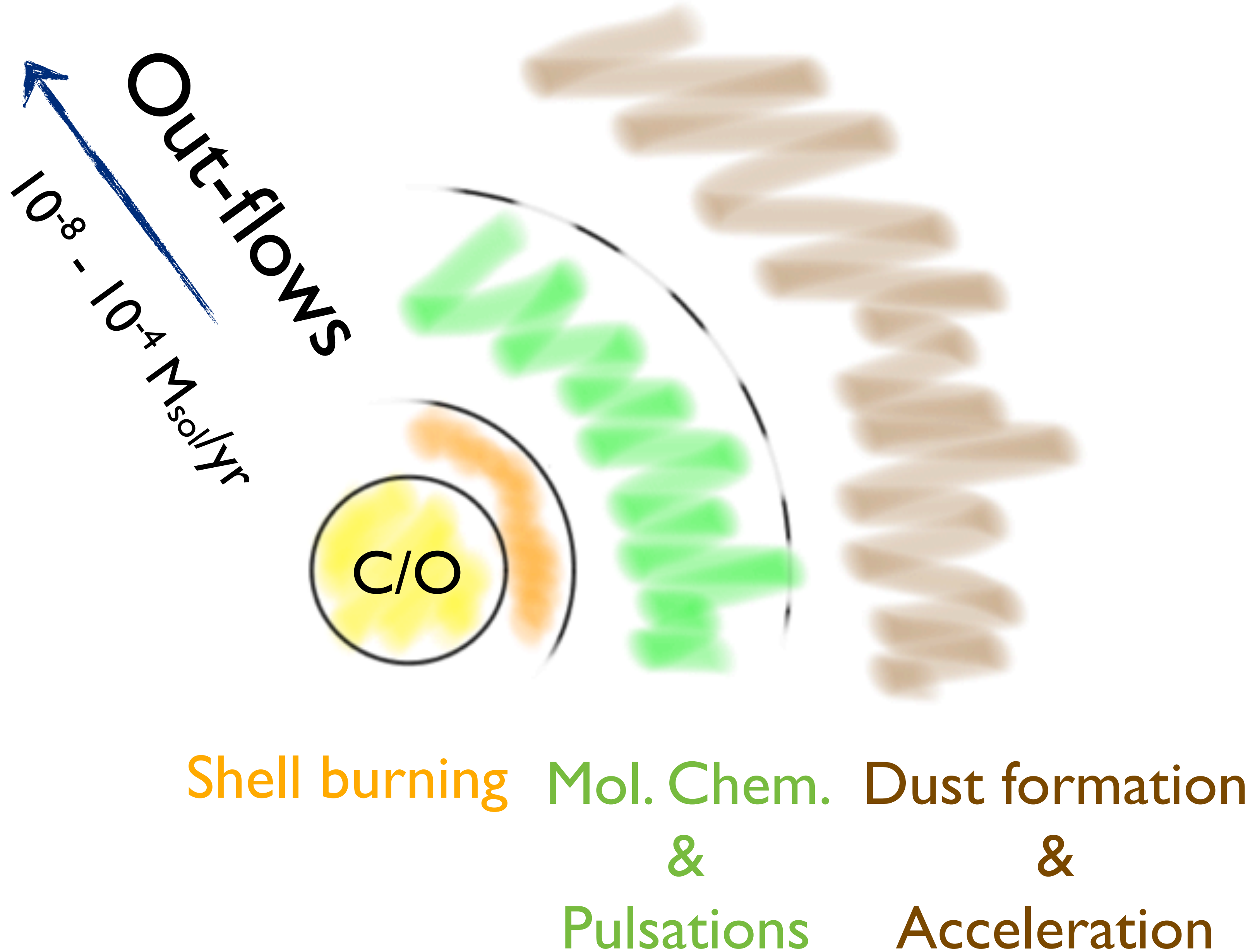

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3. Evolved stars

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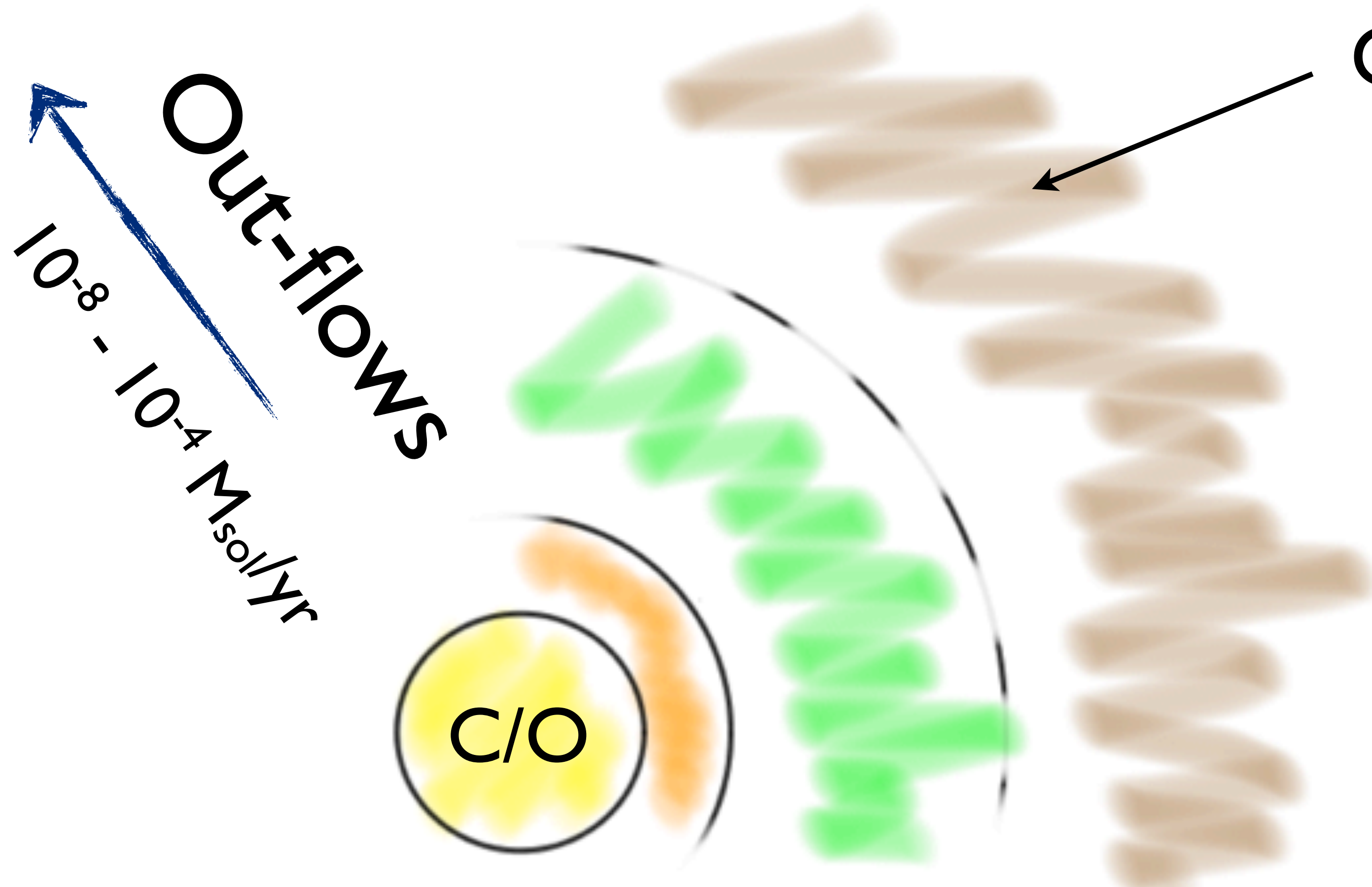


Oxygen chemistry if C/O < 1

Mostly amorphous dust
Minerals if $>10^{-5}$ M_{sol}/yr

C/O solar = 0.5

Shell burning

Mol. Chem. & Pulsations

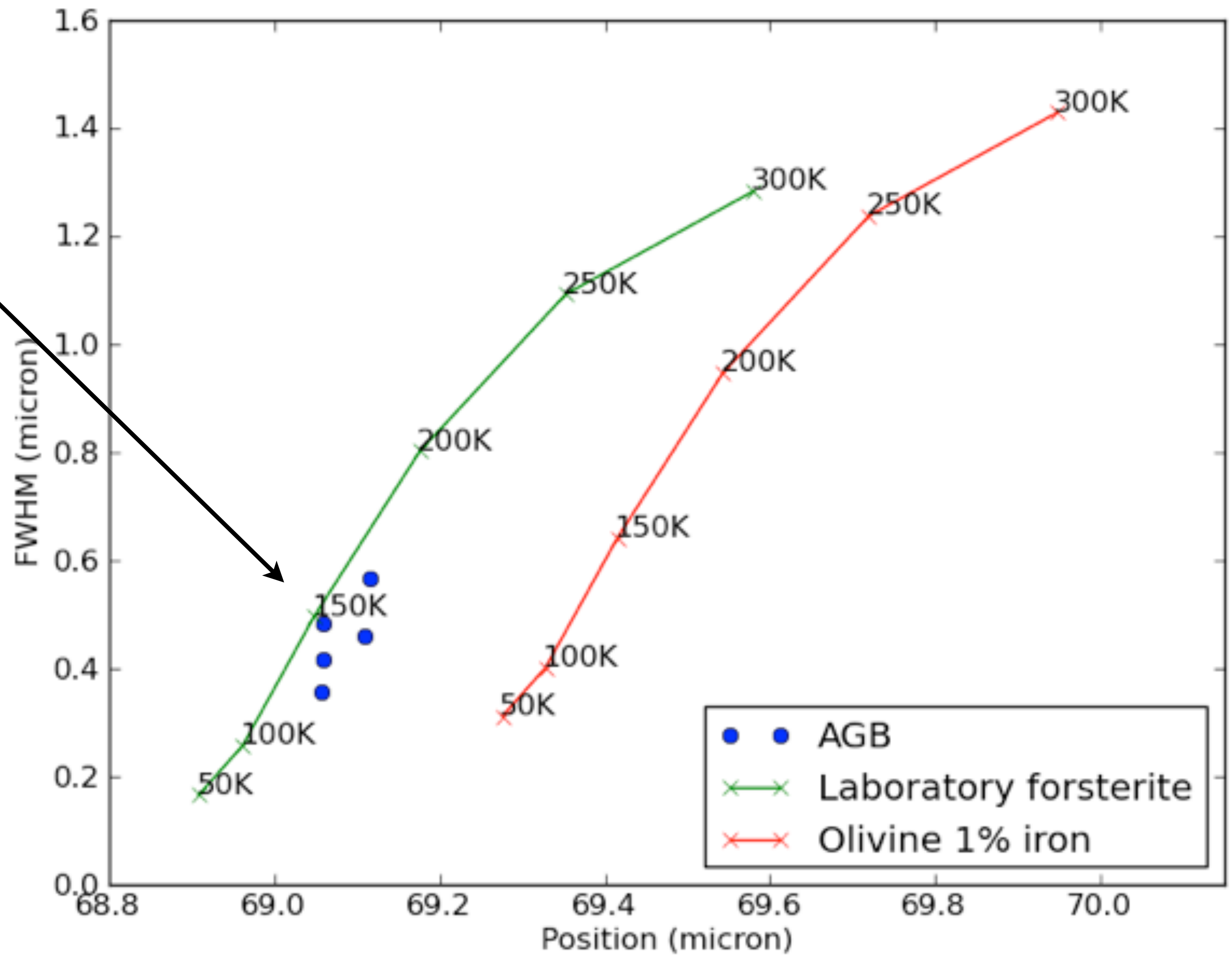
Dust formation & Acceleration

3. Evolved stars

The 69 μm band in evolved stars

≲0.5% Fe

Cold



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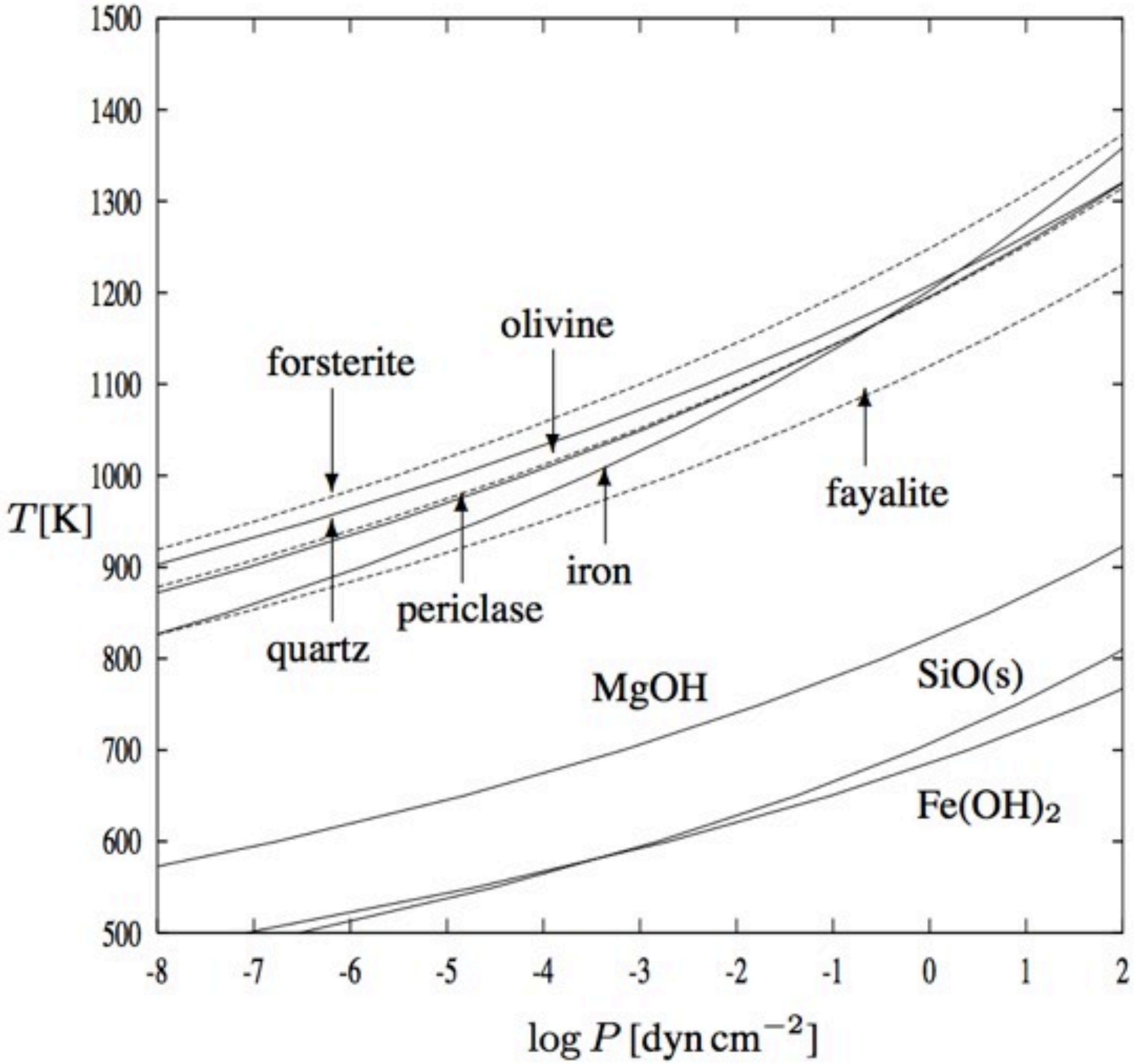
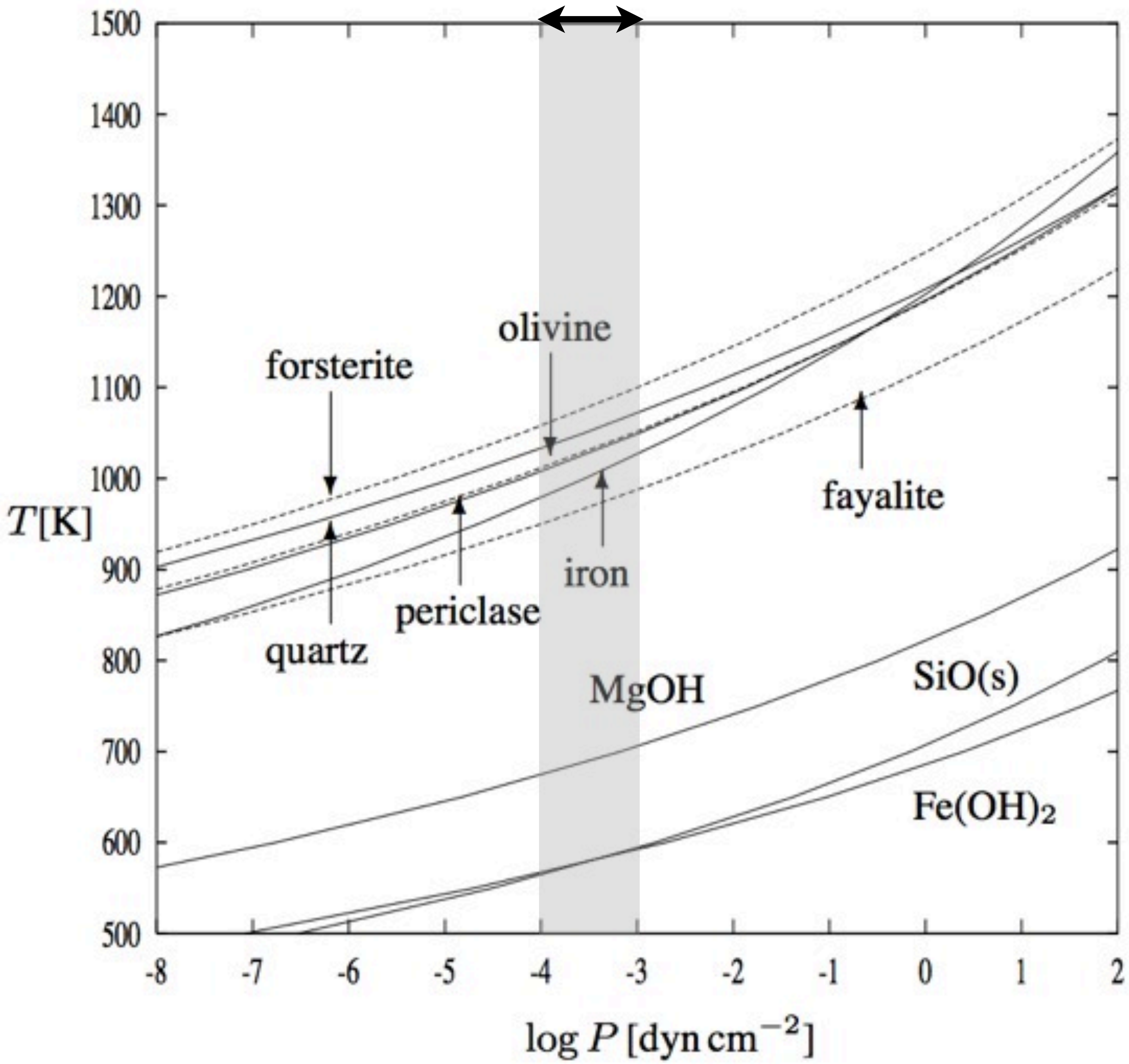
LTE condensation



1atm ~ 1e6 dyn cm^{-2}
1 dyn cm^{-2} ~ 0.1Pa

Gail & Sedlmayr 1999

LTE condensation



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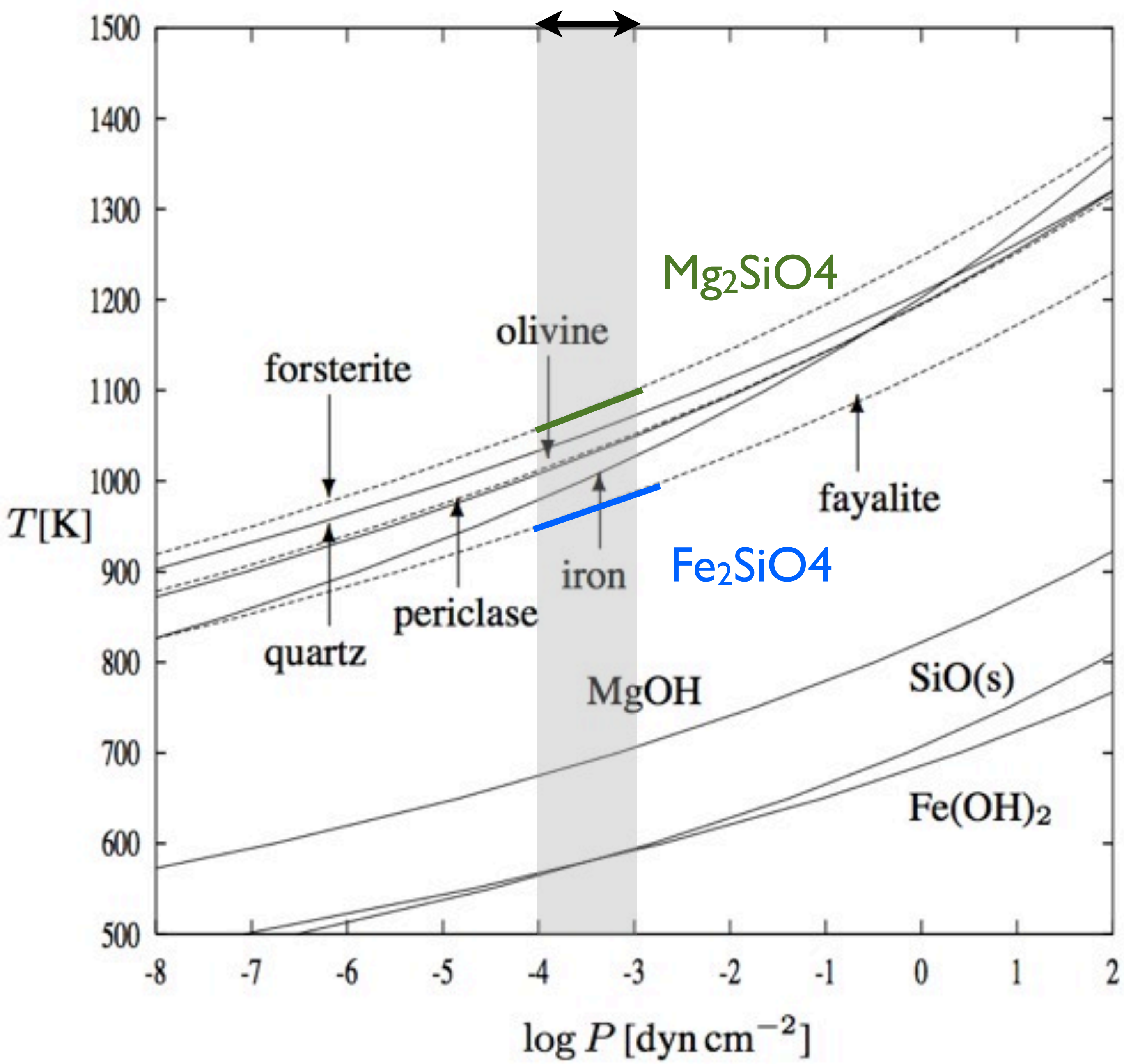

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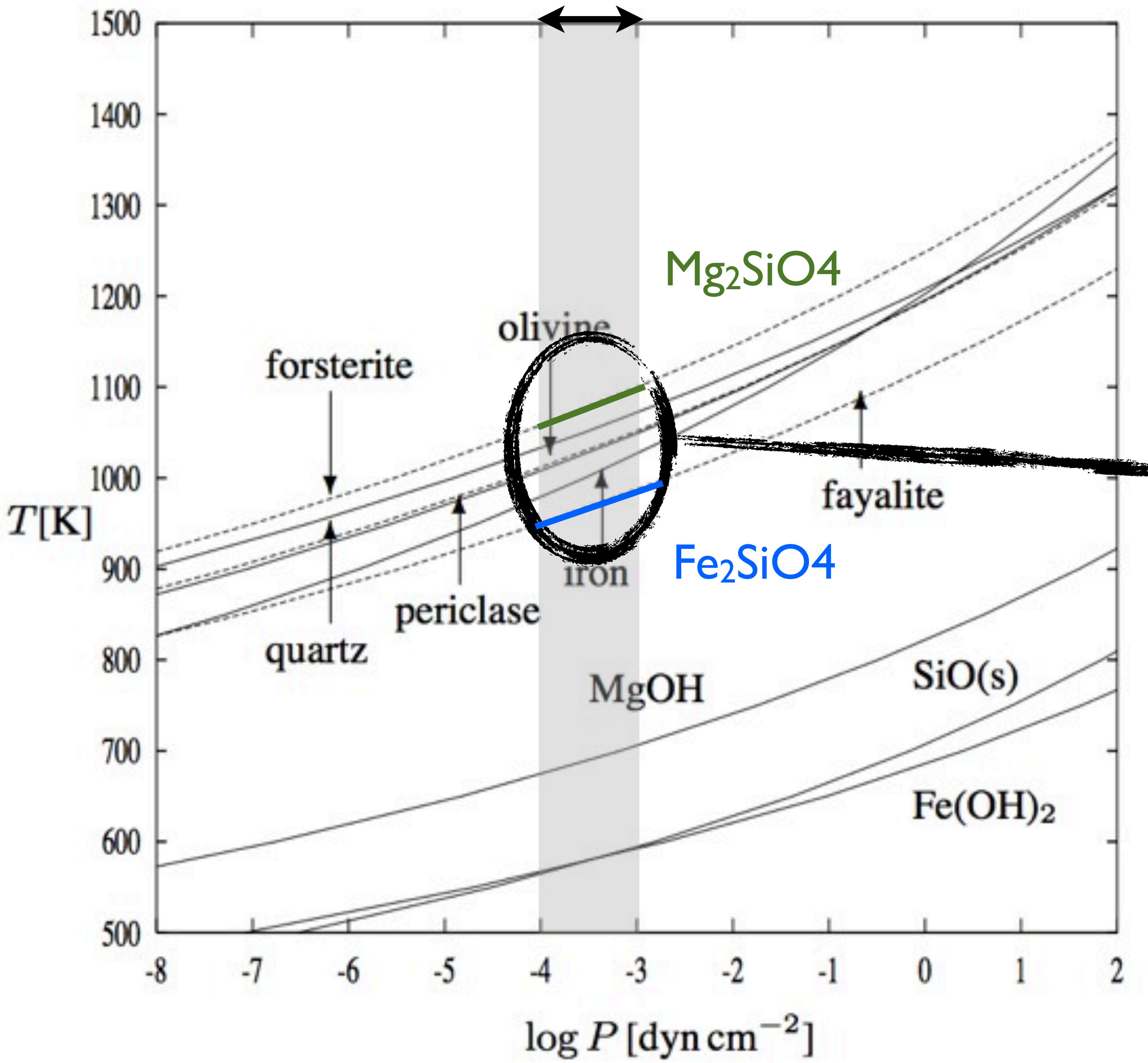


$Mg_{2x}Fe_{2(1-x)}SiO4$

1050K: x=1

...

1000K: x=0.5

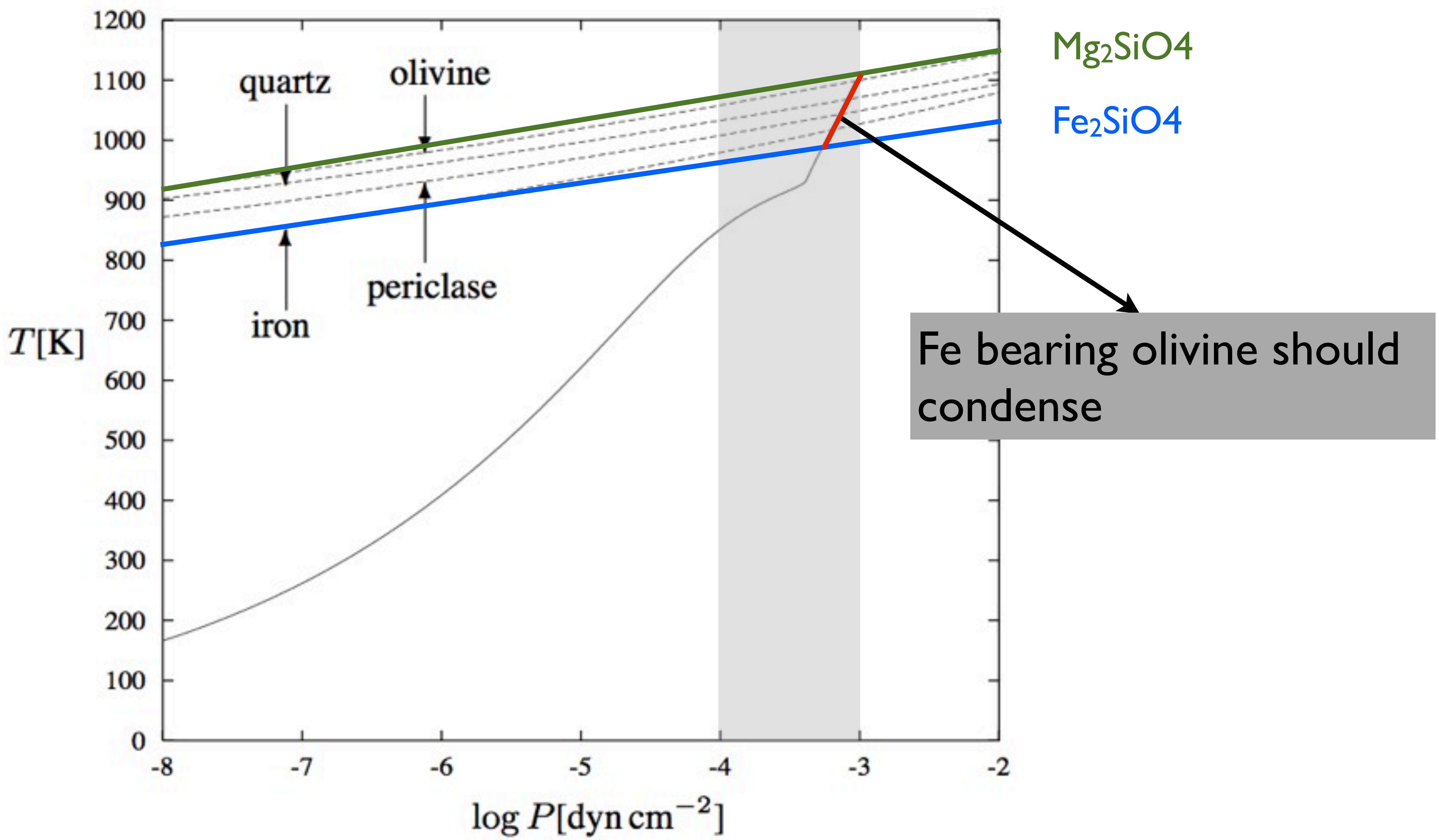
...

950K: x=0

1atm ~ 1e6 dyn cm^{-2}
1 dyn cm $^{-2}$ ~ 0.1Pa

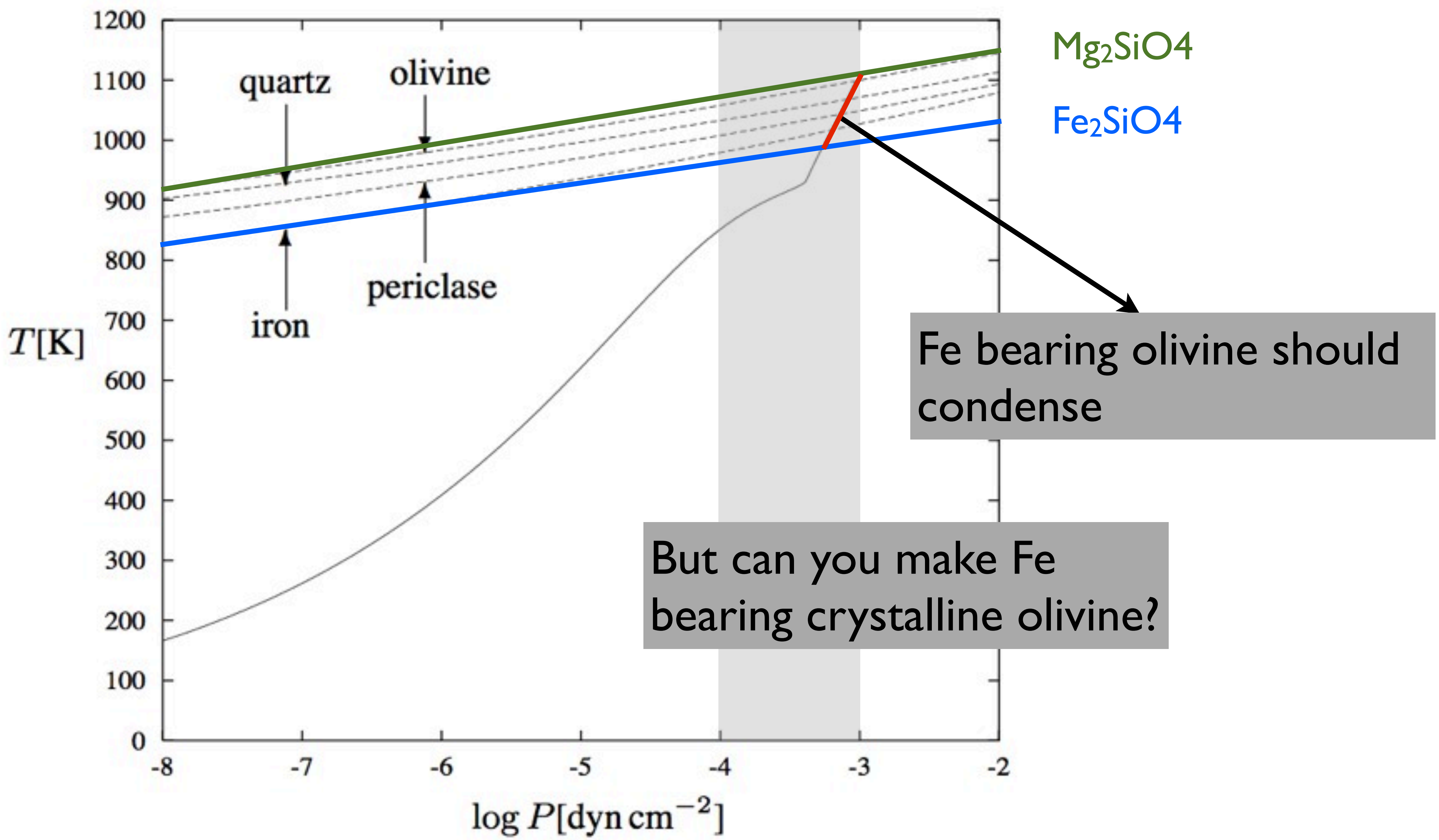
Gail & Sedlmayr 1999

Cooling track



10^{-5} Msol/yr, Gail & Sedlmayr 1999

Cooling track



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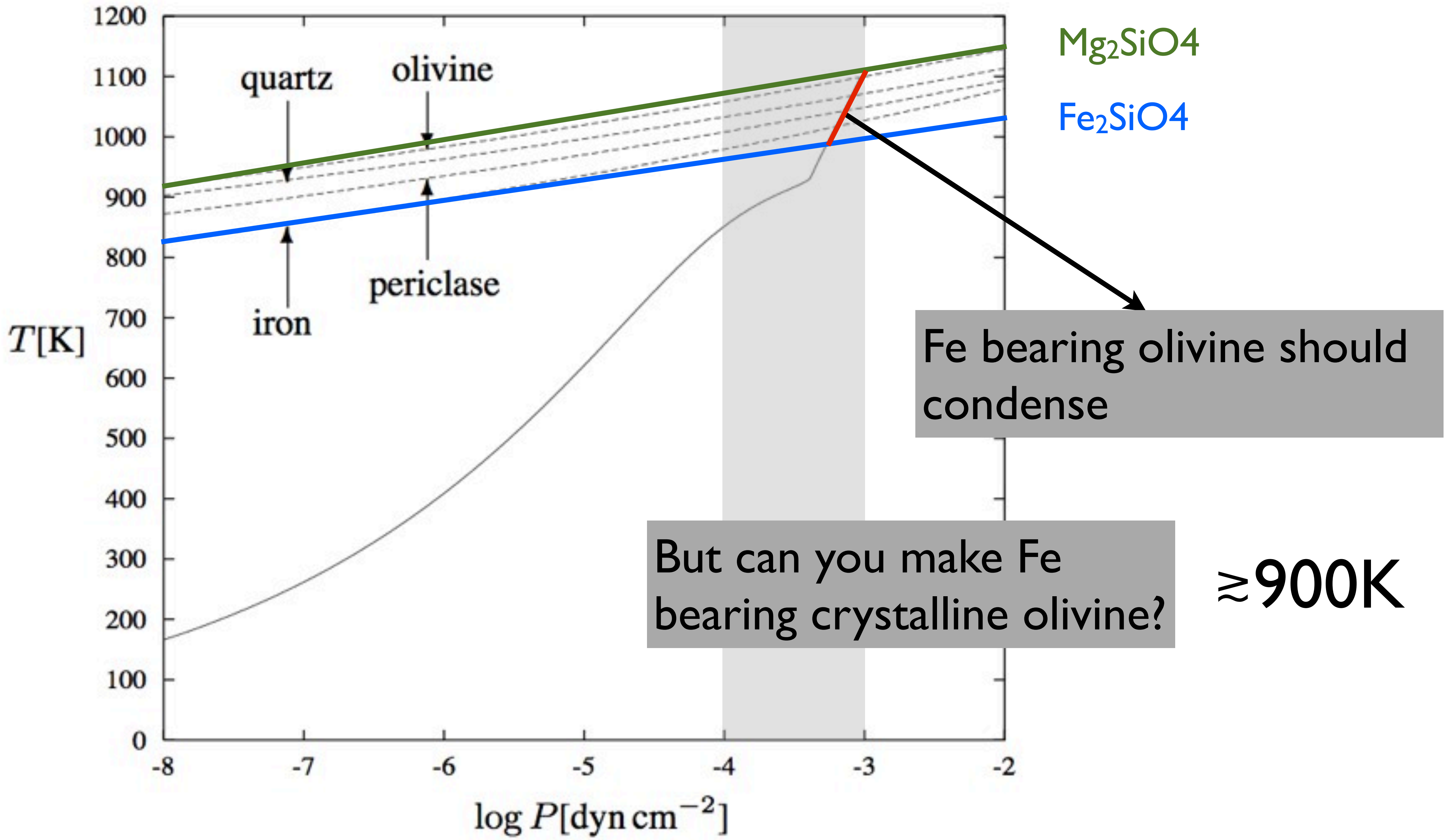
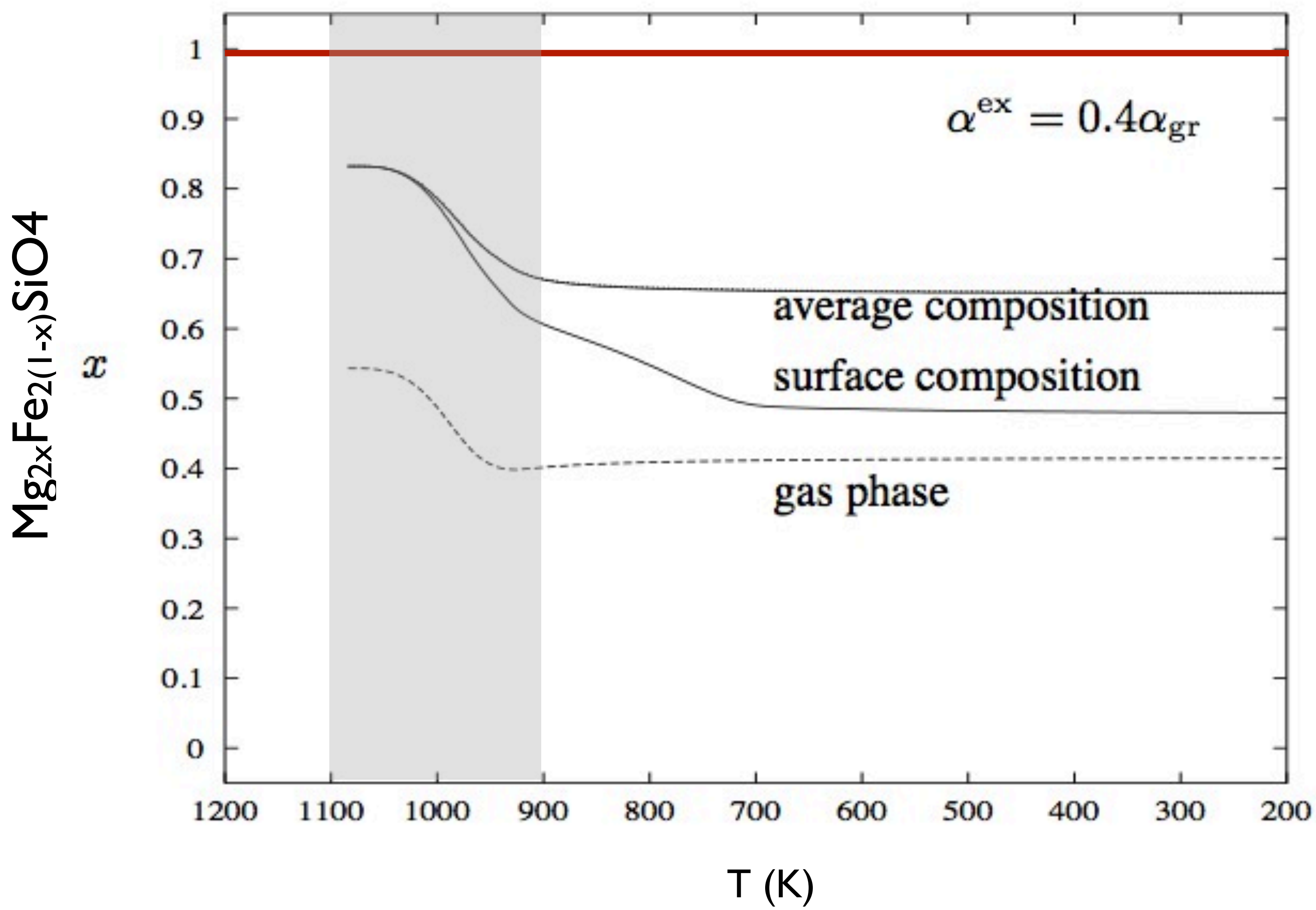


≳900K

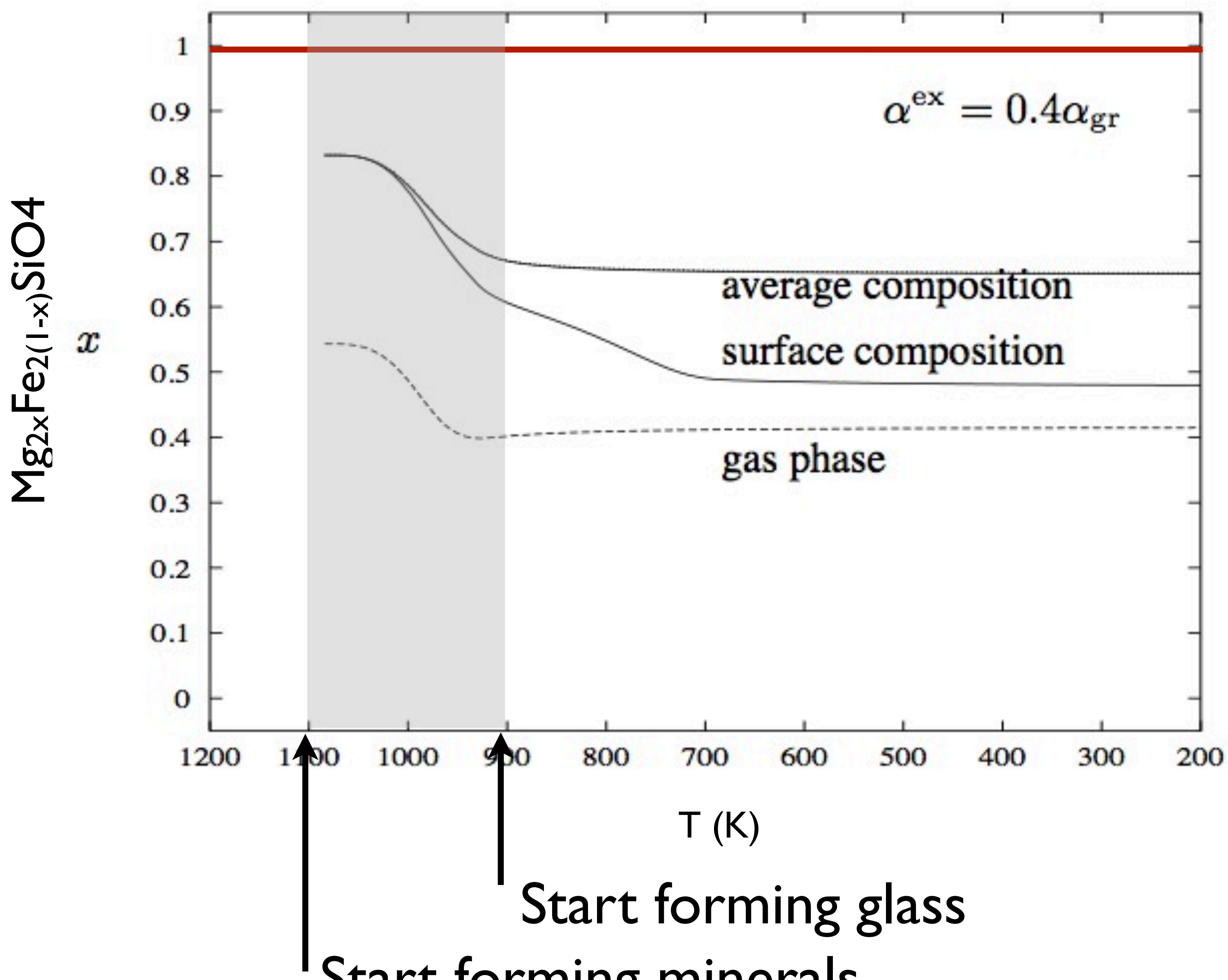
10[-5] Msol/yr, Gail & Sedlmayr 1999

Cation exchange & growth



Gail & Sedlmayr 1999

Cation exchange & growth



Gail & Sedlmayr 1999

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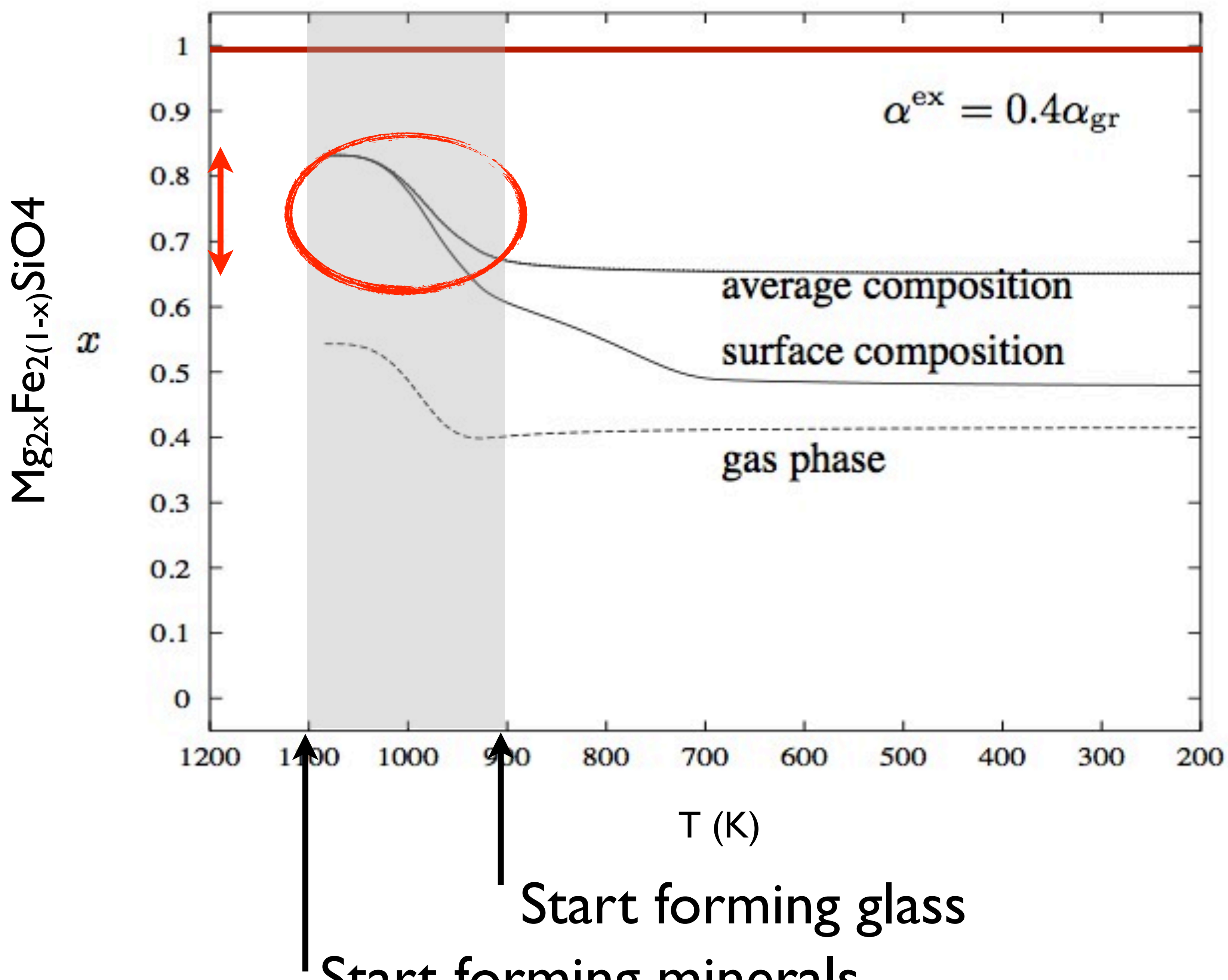
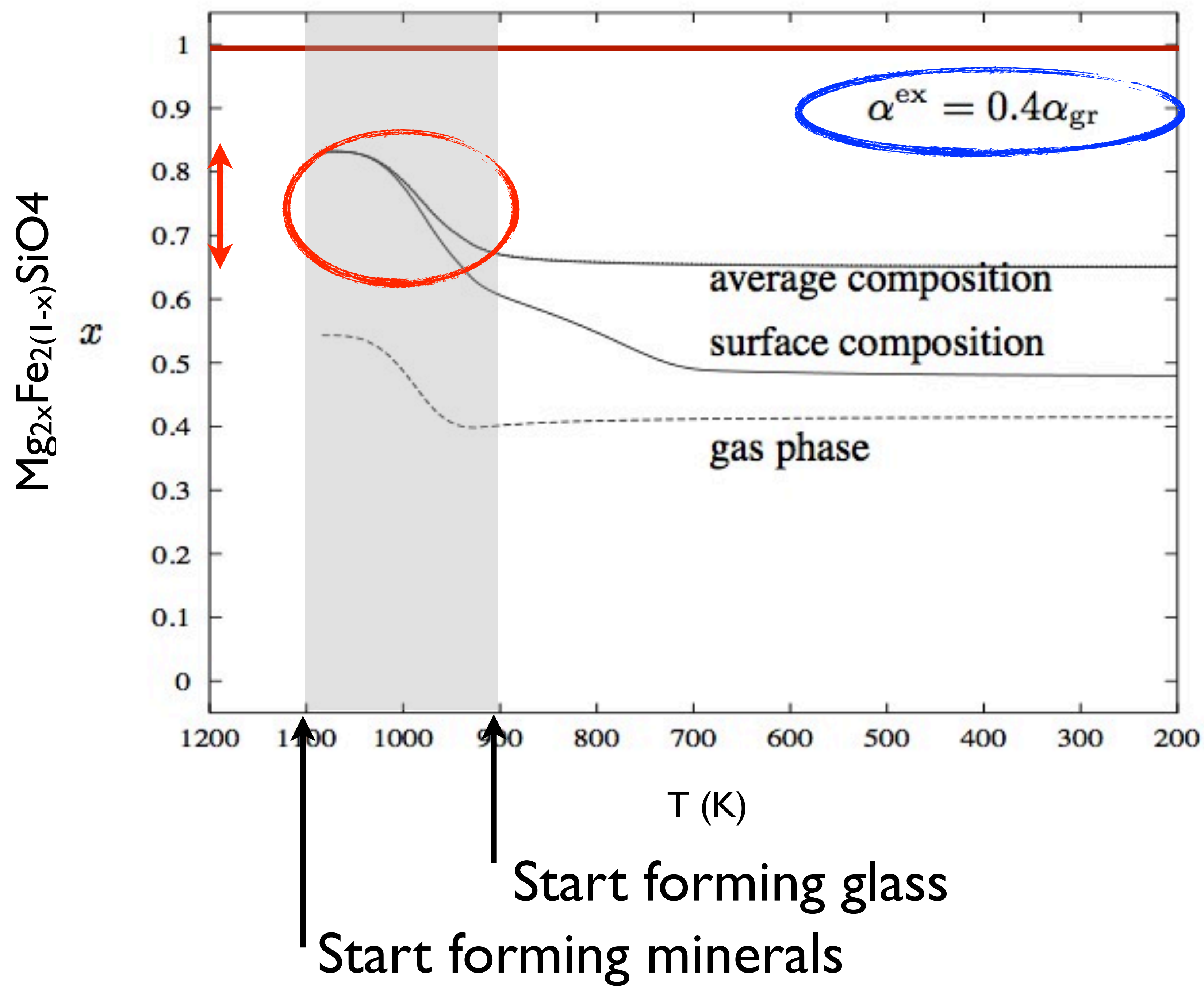


Gail & Sedlmayr 1999

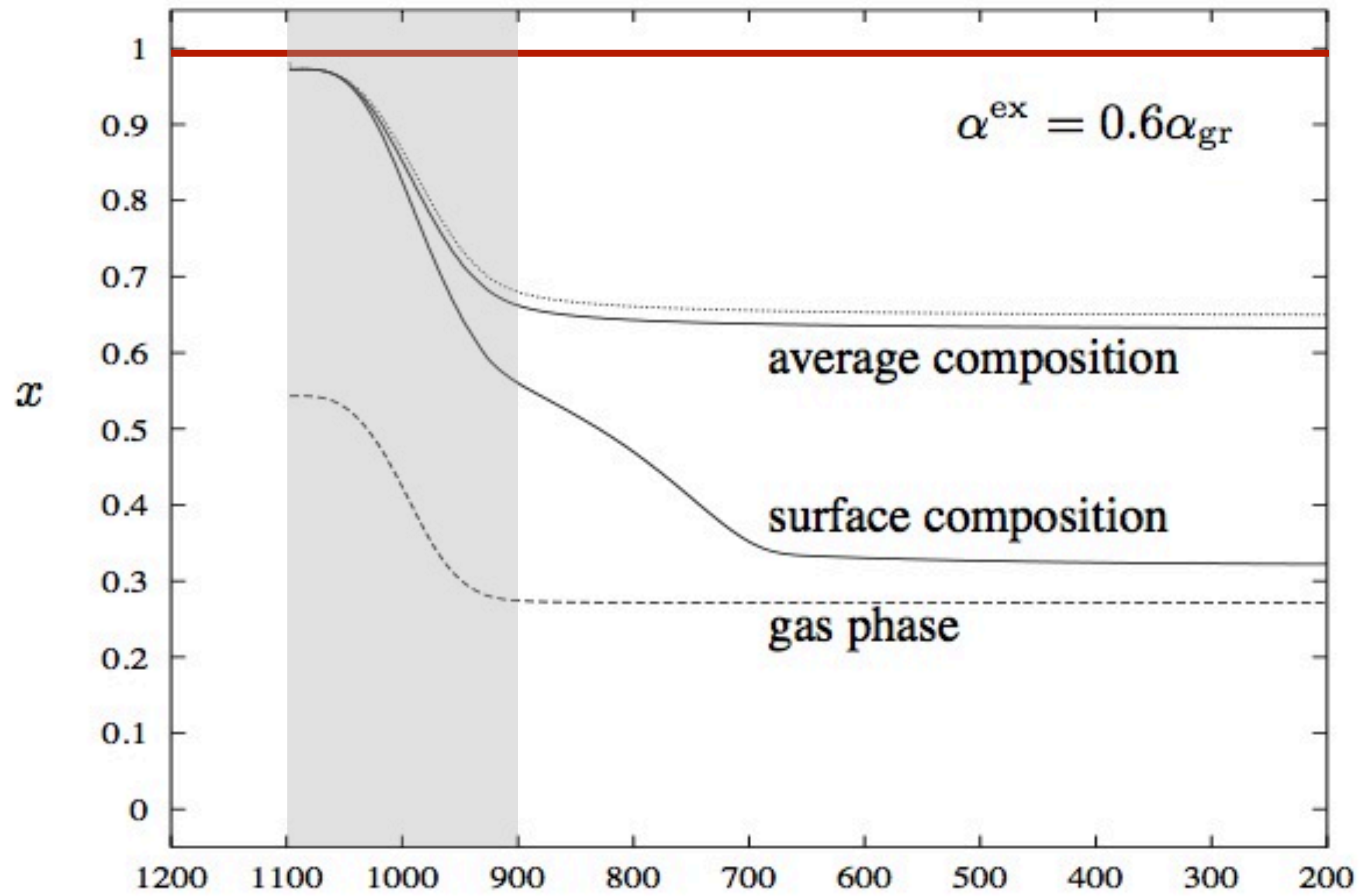
Cation exchange & growth



Cation exchange coef.
vs
Grain growth

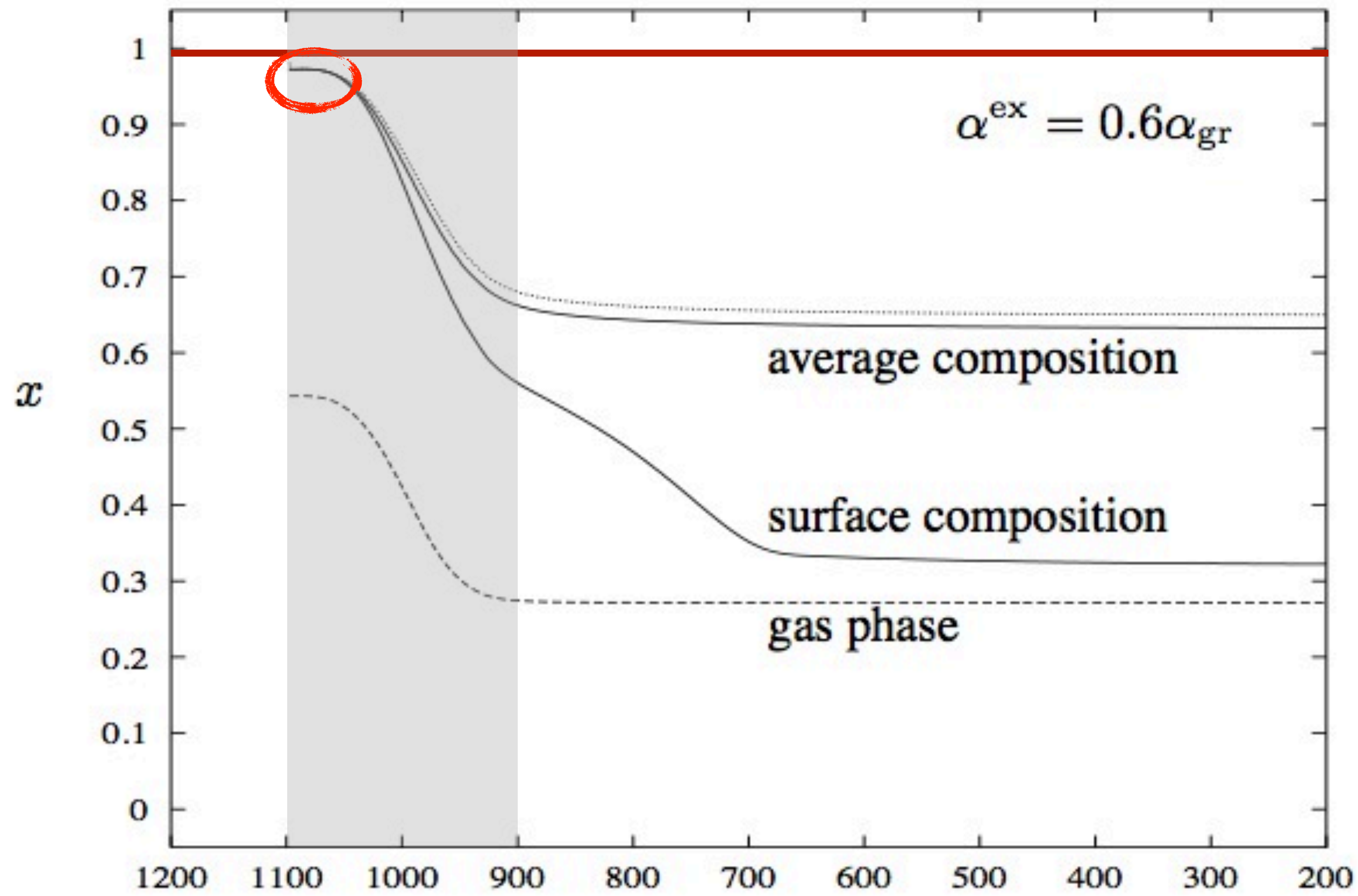
Gail & Sedlmayr 1999

Increasing exchange



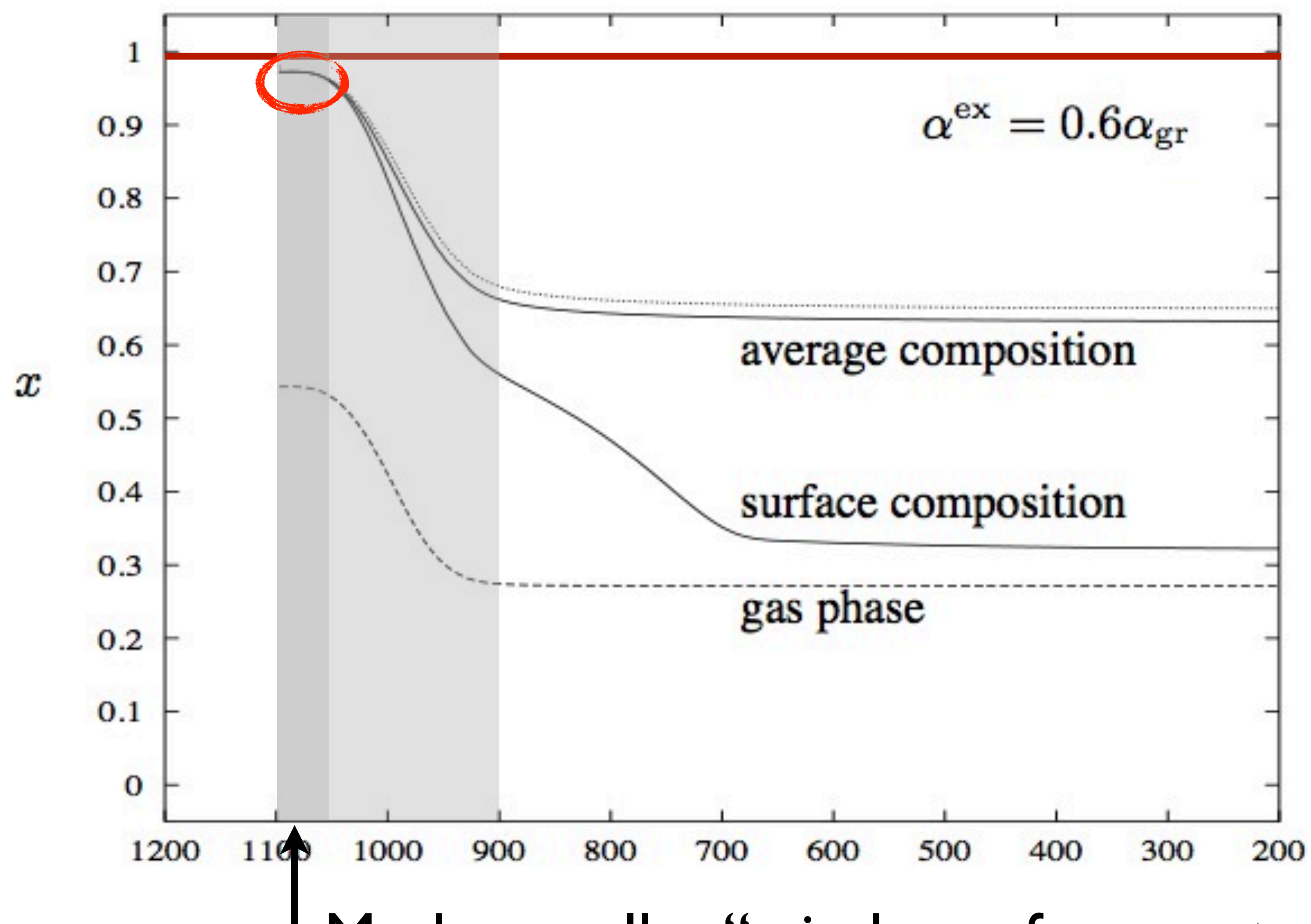
Gail & Sedlmayr 1999

Increasing exchange



Gail & Sedlmayr 1999

Increasing exchange



Maybe smaller "window of opportunity"

Gail & Sedlmayr 1999

Conclusions

- AGB stars form pure forsterite ($\lesssim$0.5% Fe)
- We can now compare observations precisely to models
- This puts constraints on modeling

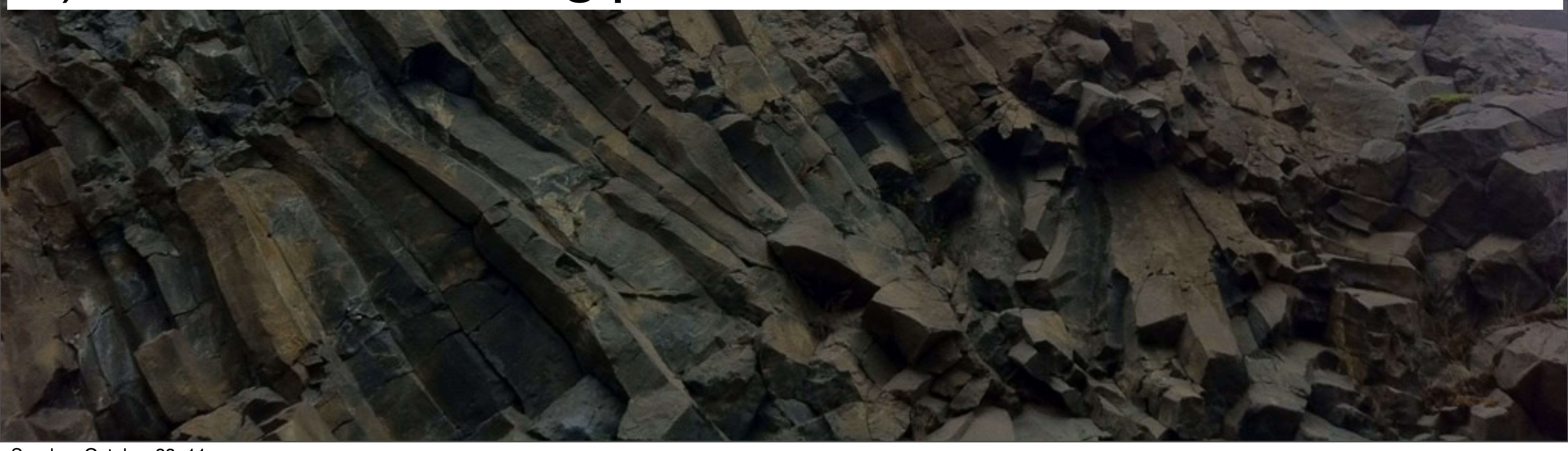
Discussion

- Modeling dependent on many parameters
- Exchange coef.
- Mass-loss rate
- When you form crystalline/amorphous (grains growth, diffusion,etc)
- Out-flow velocities

INTERMEZZO

26'

A) Reflects the small scale crystalline structure
B) Effect due to rapid cooling of lava
C) Surface weathering due to contact with the atmosphere
D) Due to the cooling process in contact with water



Next

30'

1. ~~Introduction on minerals and olivine in particular~~
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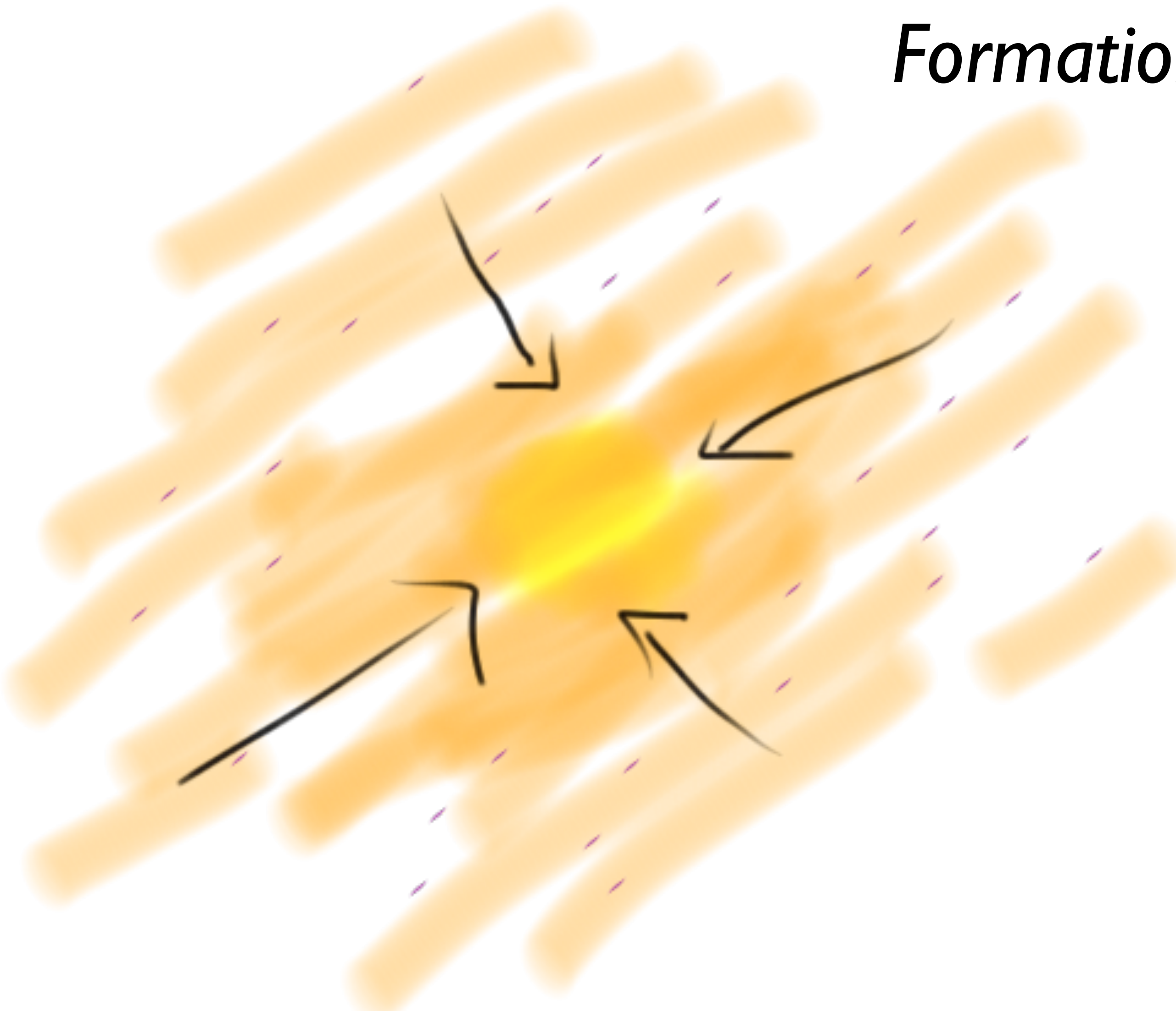
4. Olivine in the debris disk β pictoris

Debris Disks



Formation of a new star

Accretion of amorphous dust and gas from the ISM

Debris Disks

Proto-planetary disk phase

Dust and gas rich disk

Dust growth

Formation/annealing of crystalline grains

Radial mixing (?)

4. β Pictoris

Debris Disks

Debris disk phase

Devoid of gas

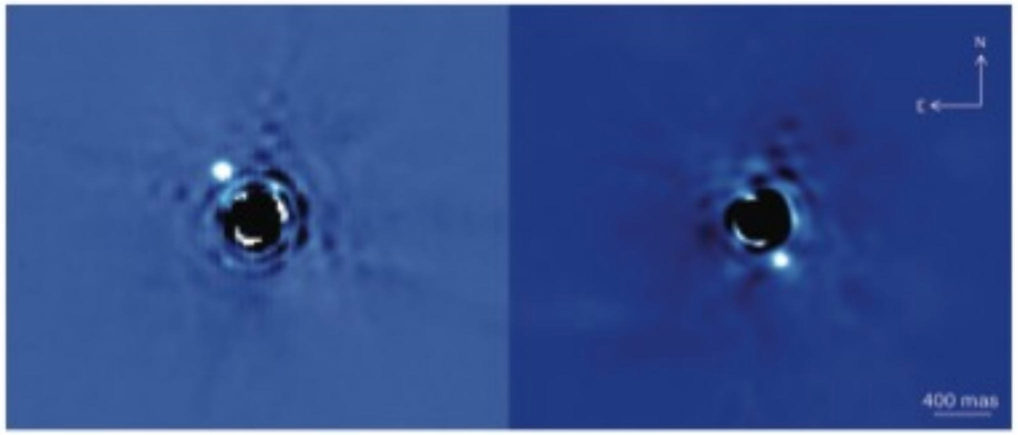
Low life-time small dust particles

Large planetesimal bodies and possibly planets

New population of small dust grains

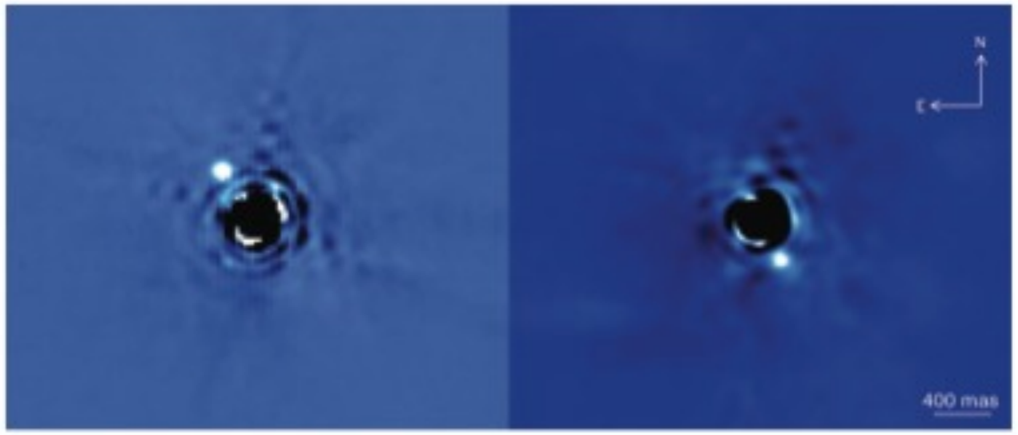
4. β Pictoris

β pictoris



Lagrange et al. 2010

β pictoris



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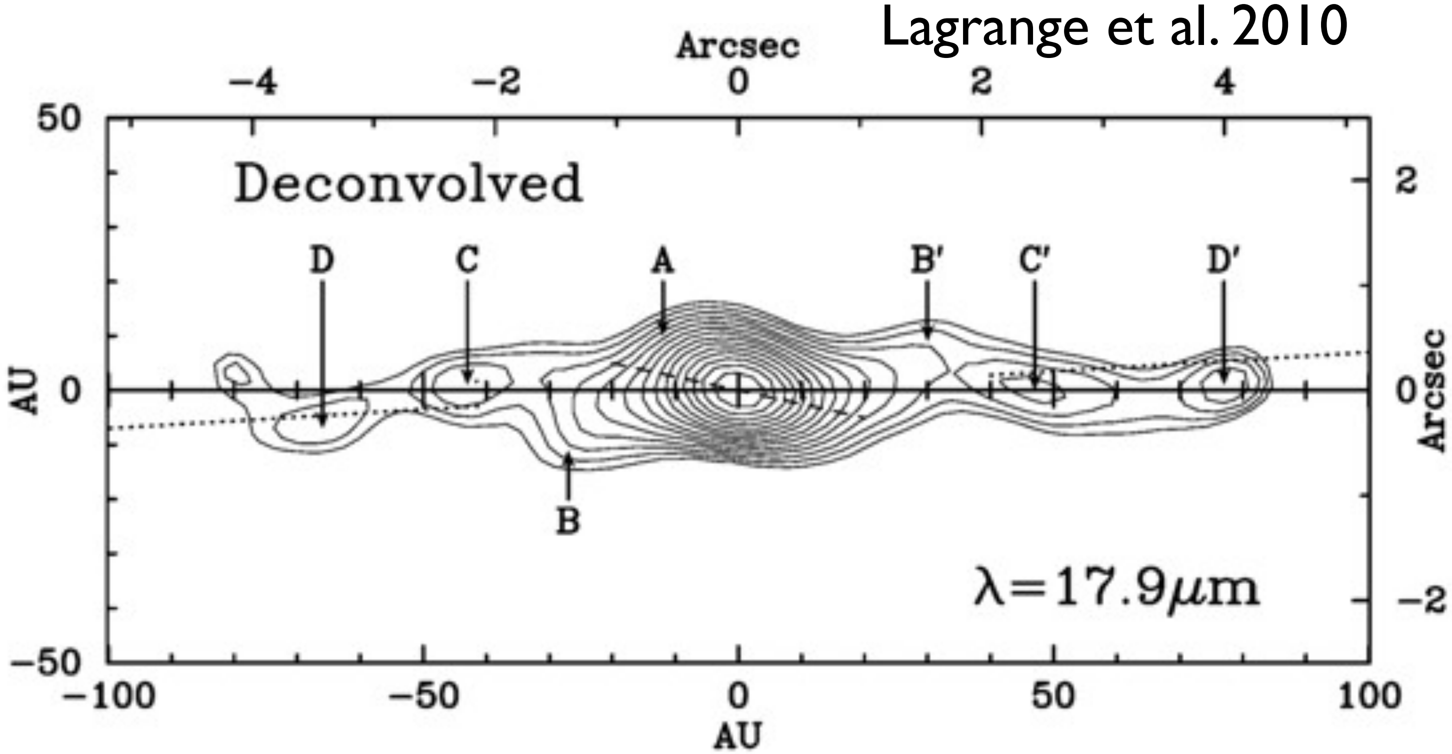
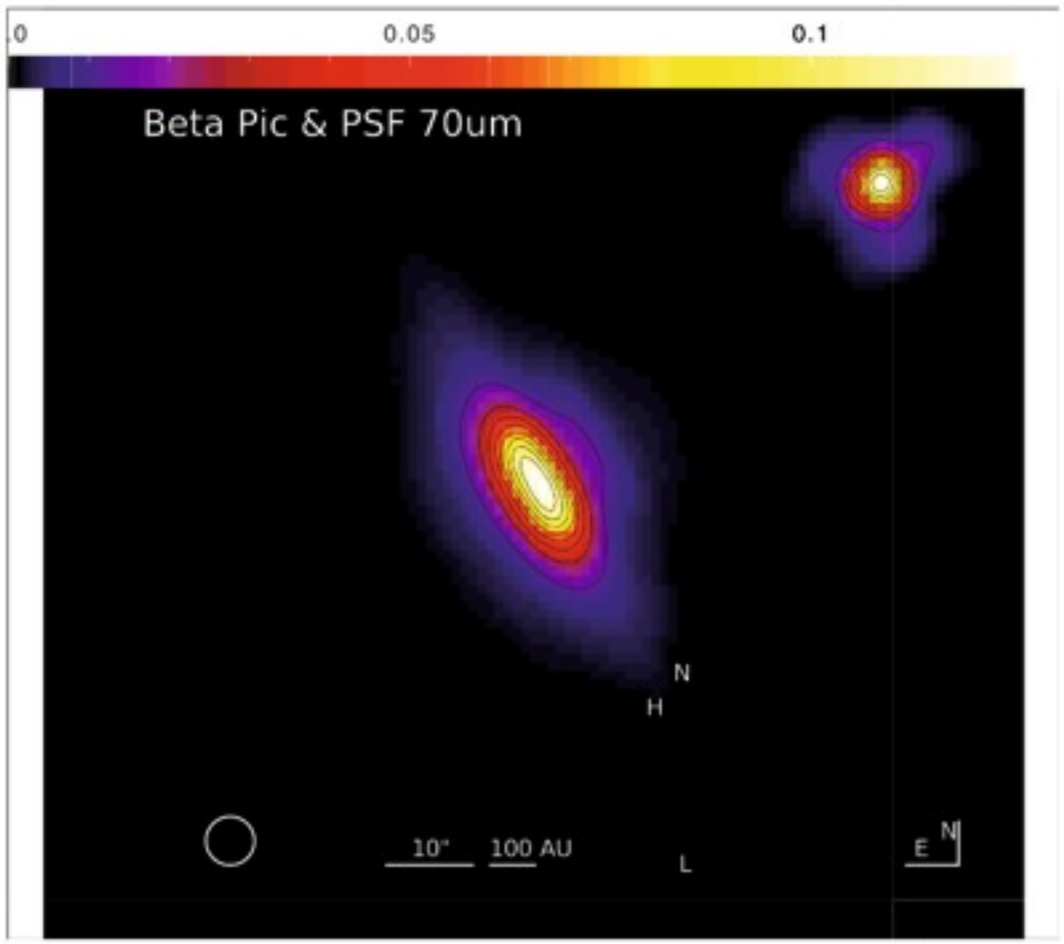
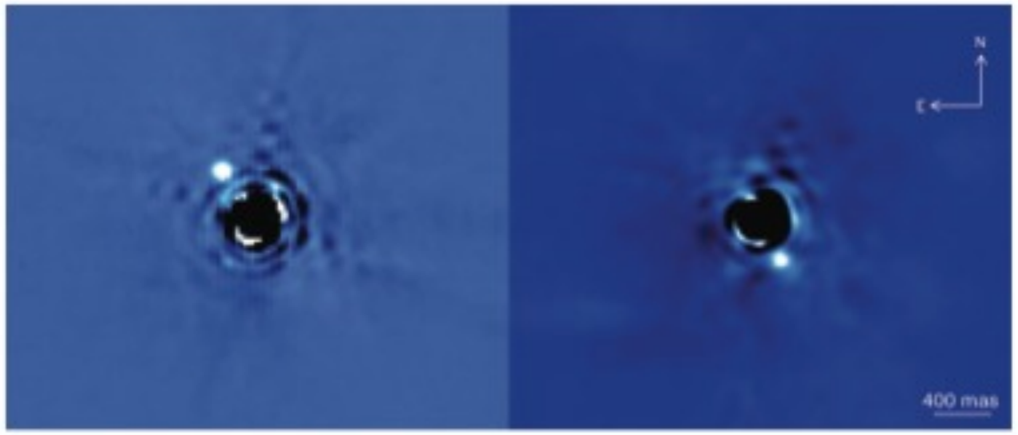


Wahhaj et al 2003

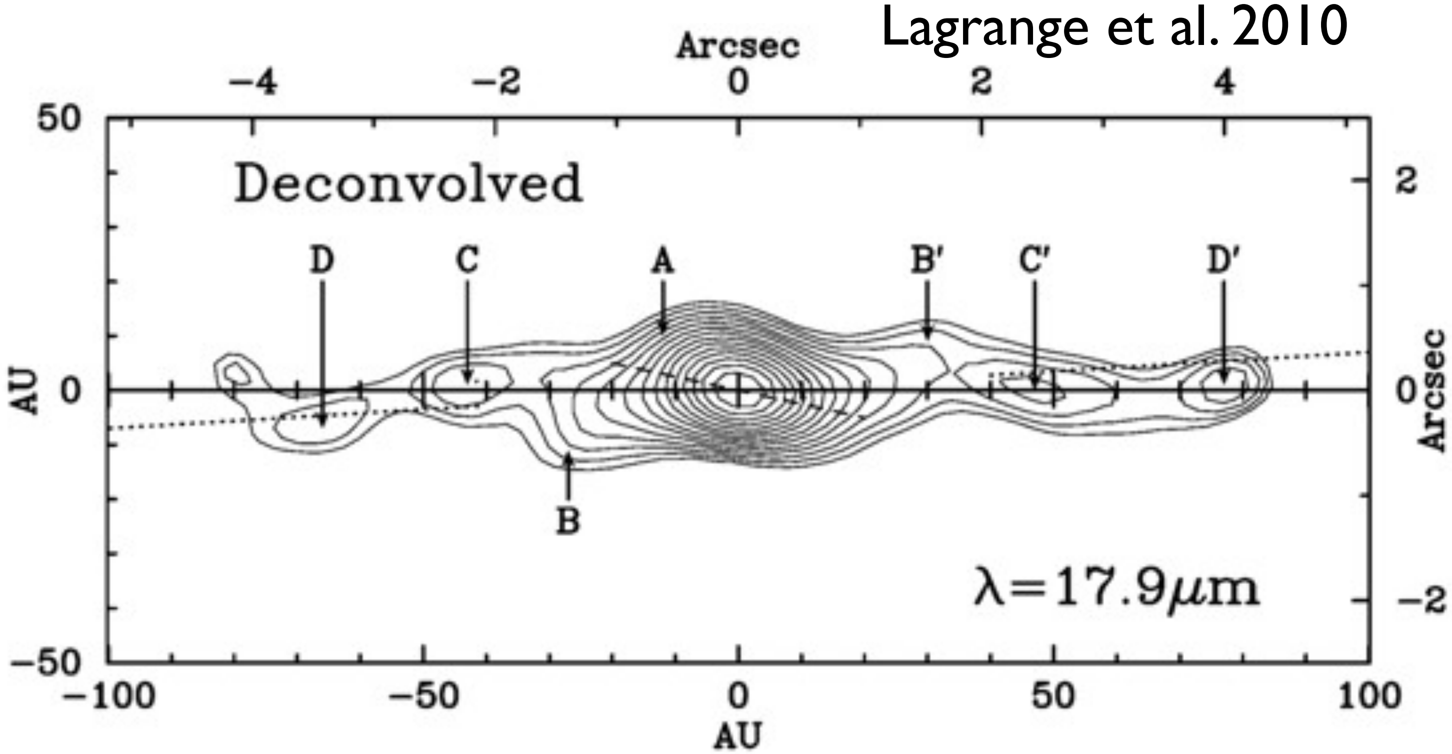
β pictoris



Vandenbussche et al, 2010

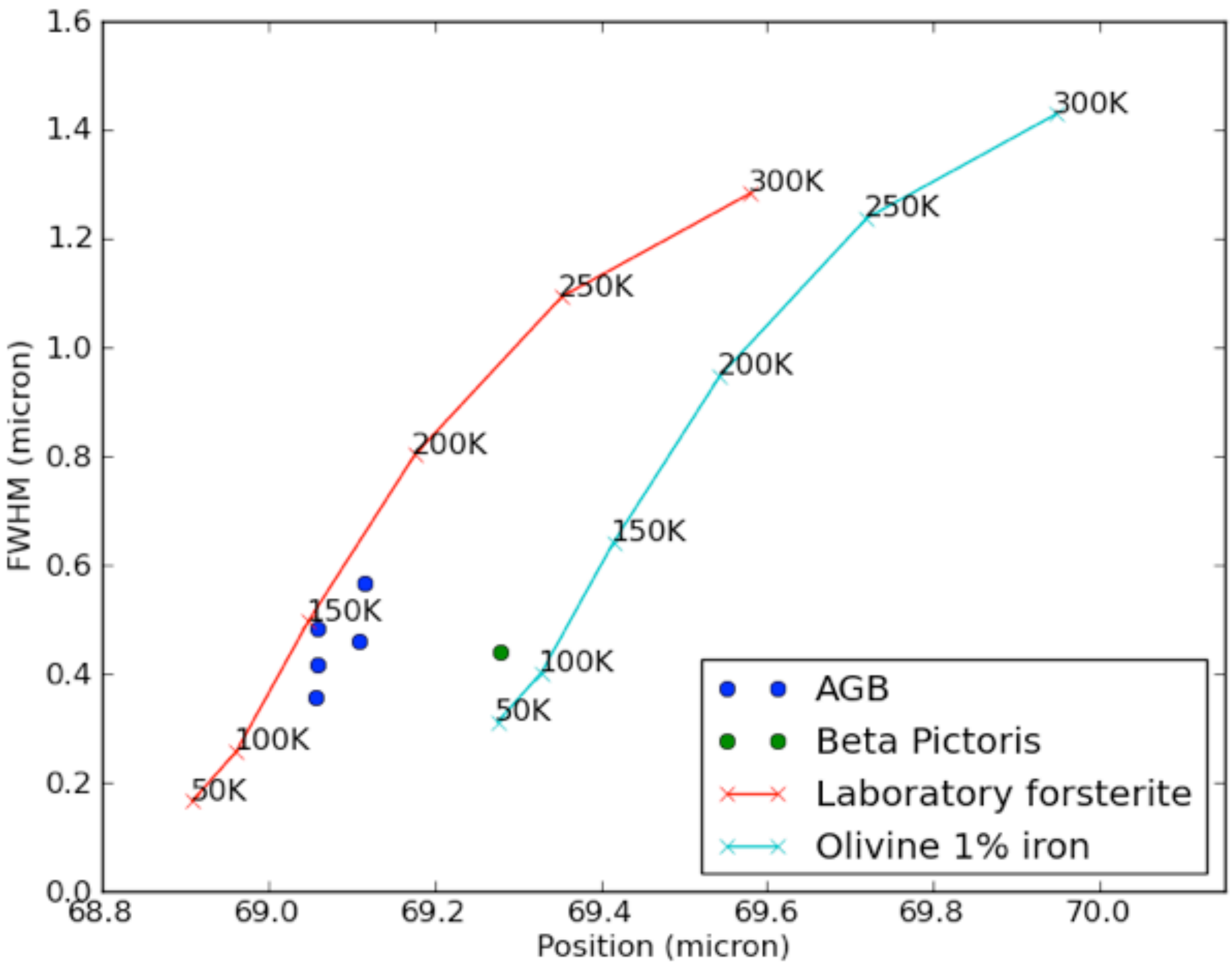


Lagrange et al. 2010



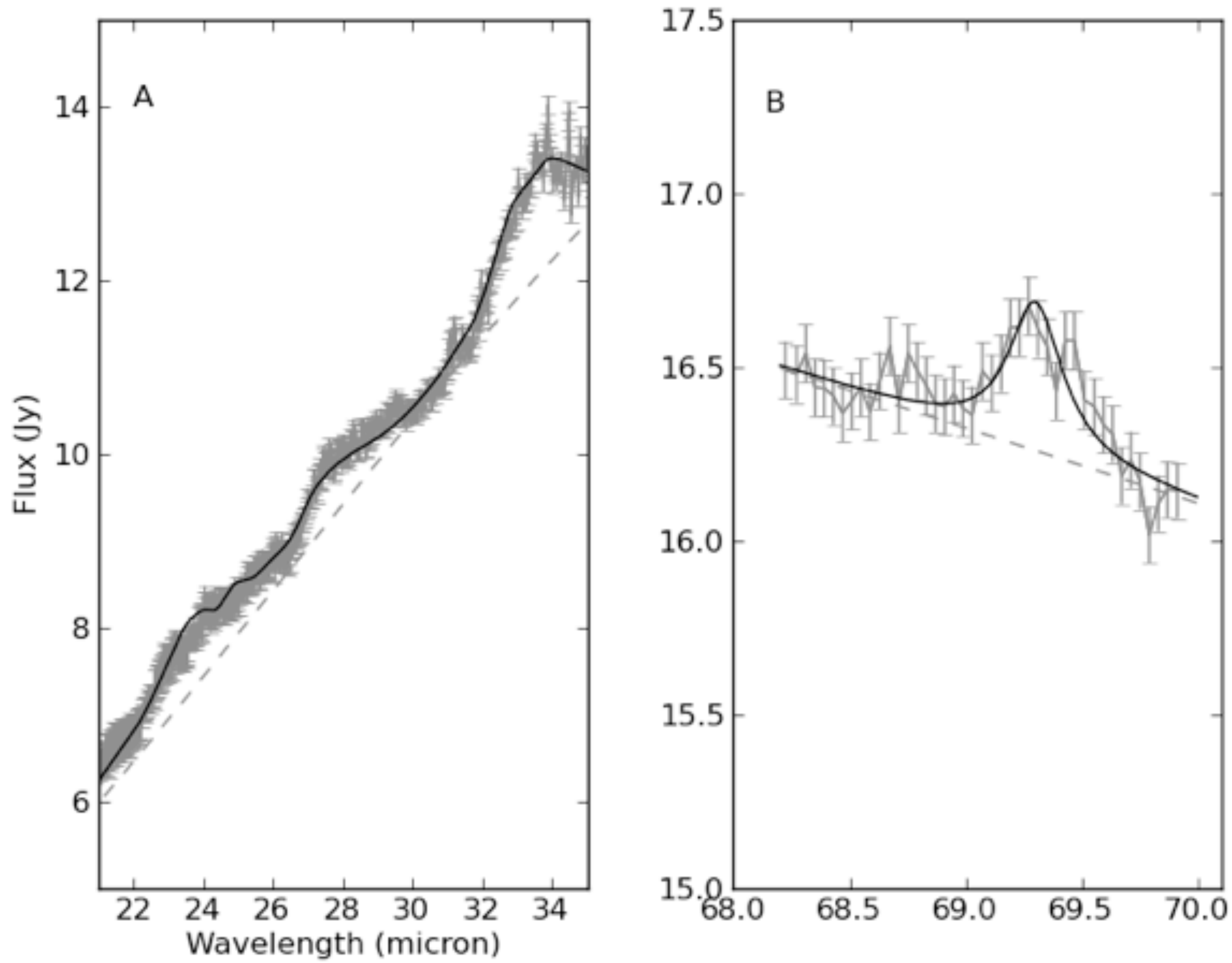
Wahhaj et al 2003

Olivine in the debris disk β Pictoris



4. β Pictoris

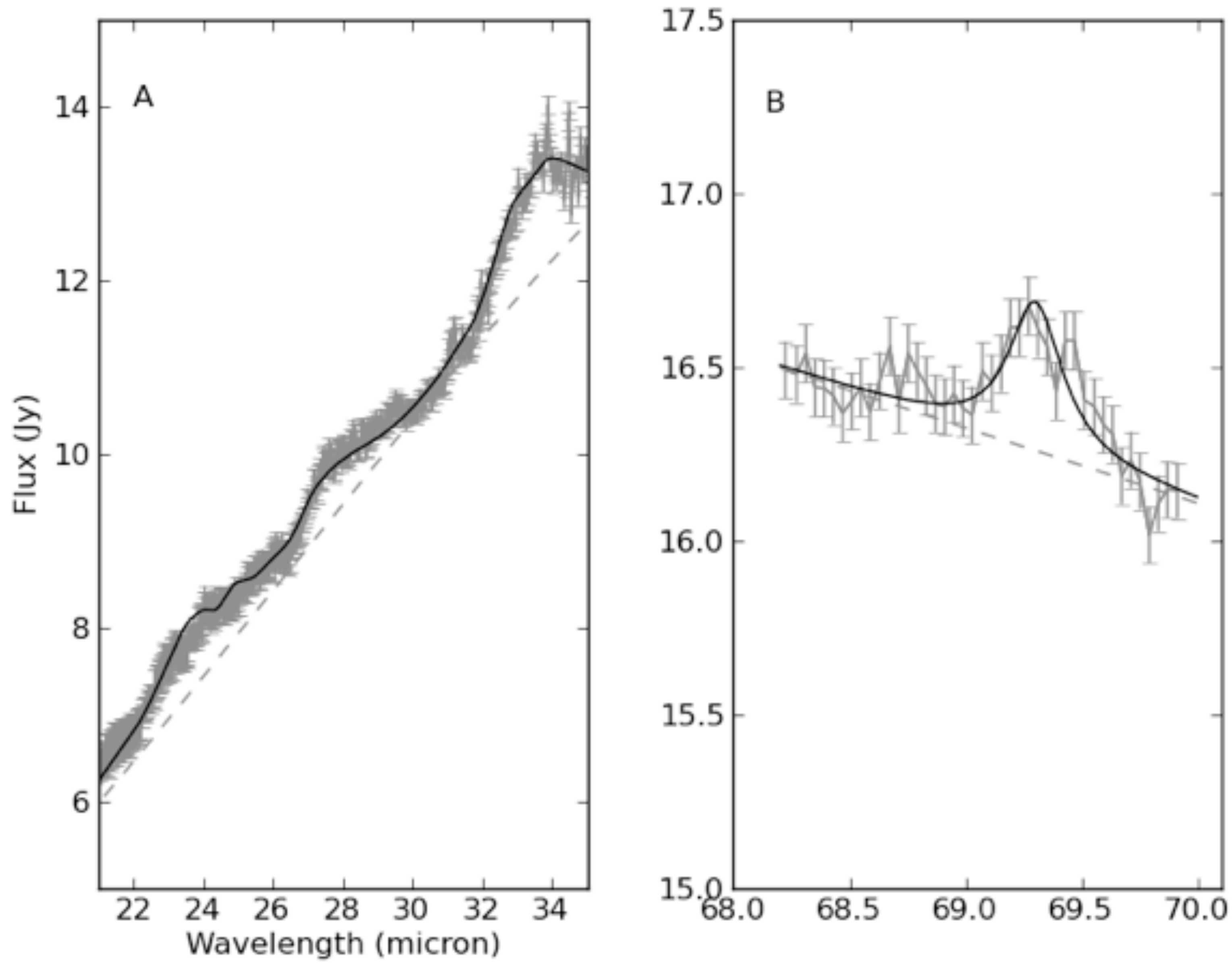
Fitting



de Vries, Acke, et al. submitted

4. β Pictoris

Fitting



1.0±0.1% Fe

de Vries, Acke, et al. submitted

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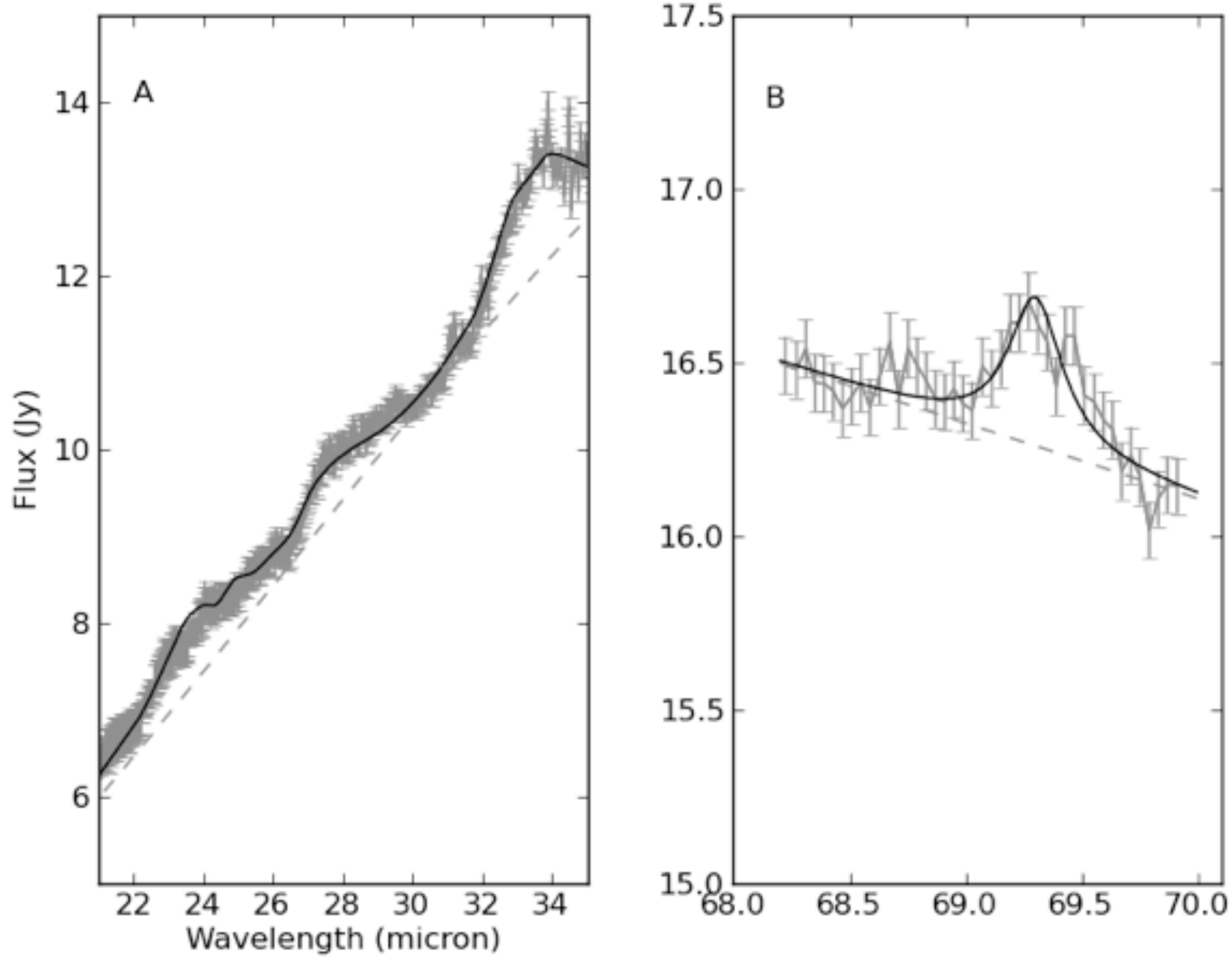


1.0±0.1% Fe

45±20 AU

de Vries, Acke, et al. submitted

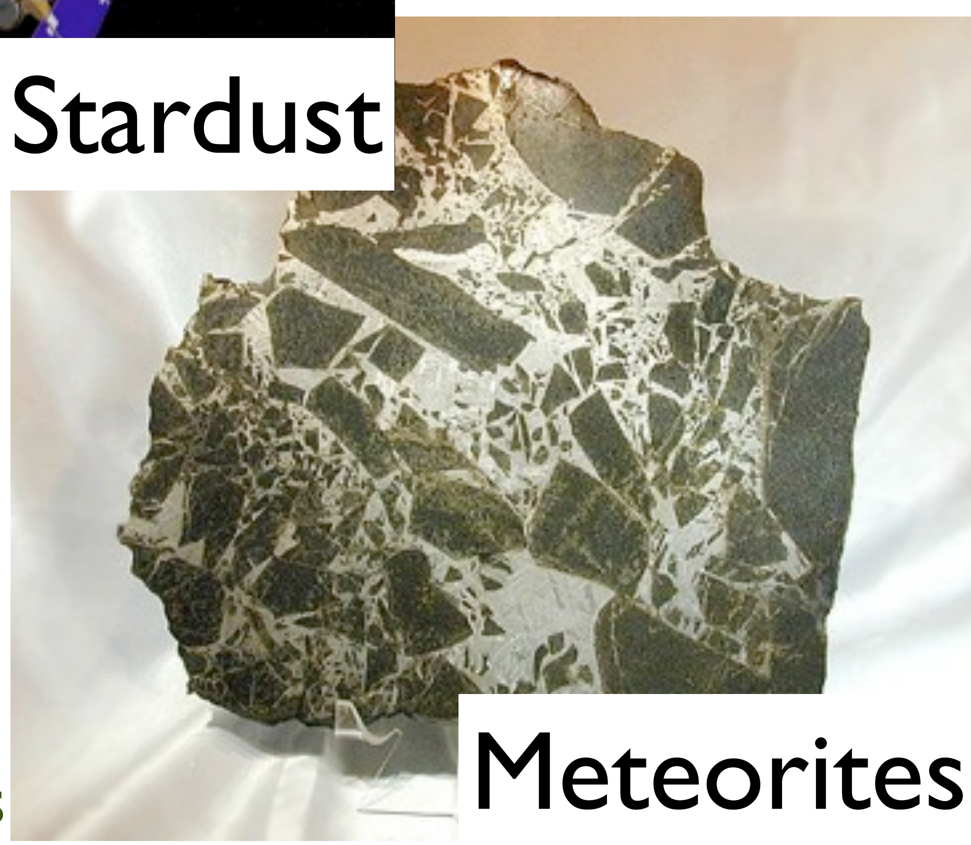
4. β Pictoris

Solar System

- How does this compare to the Solar System?

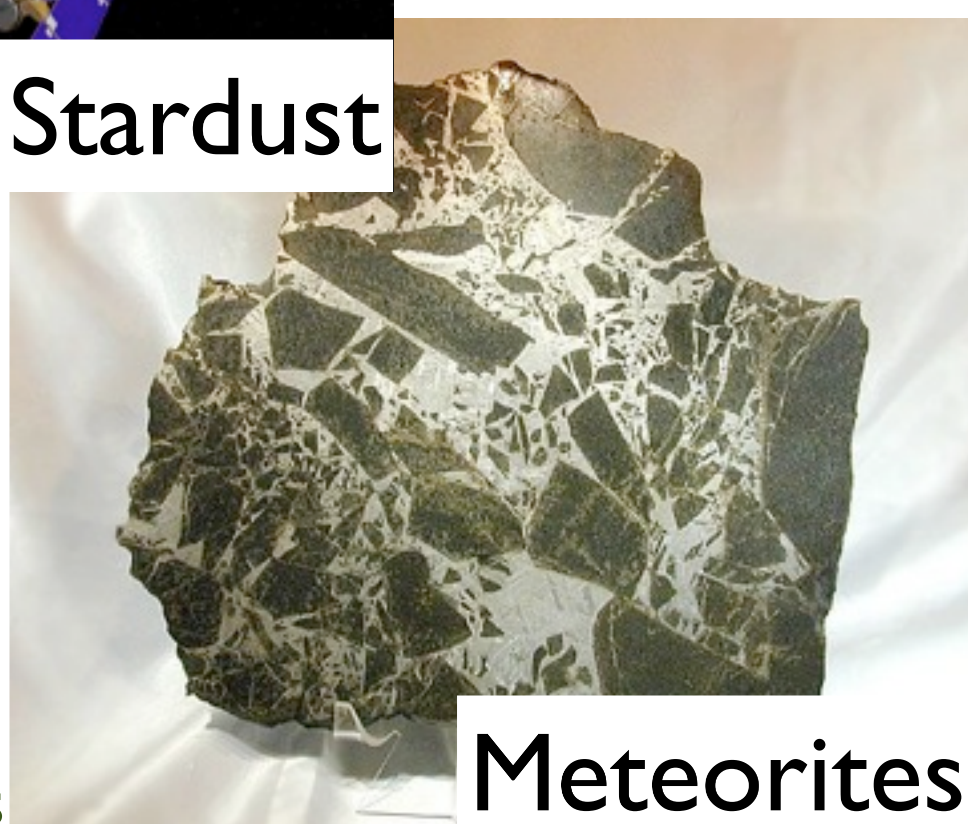
Mineralogy

Mineralogy

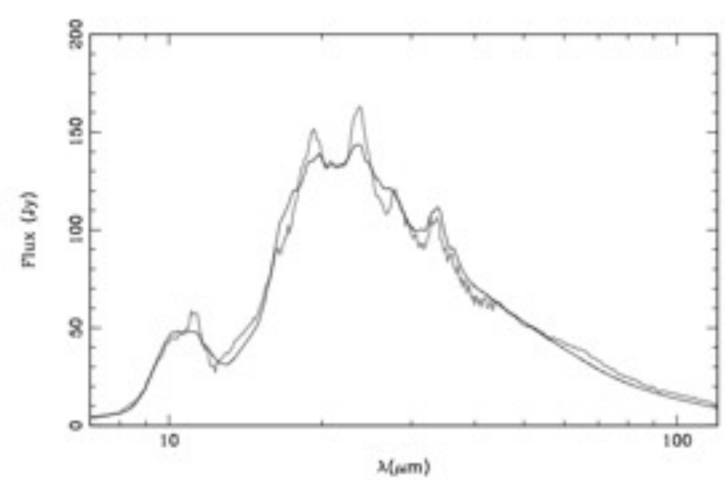


Mineralogy

Stardust



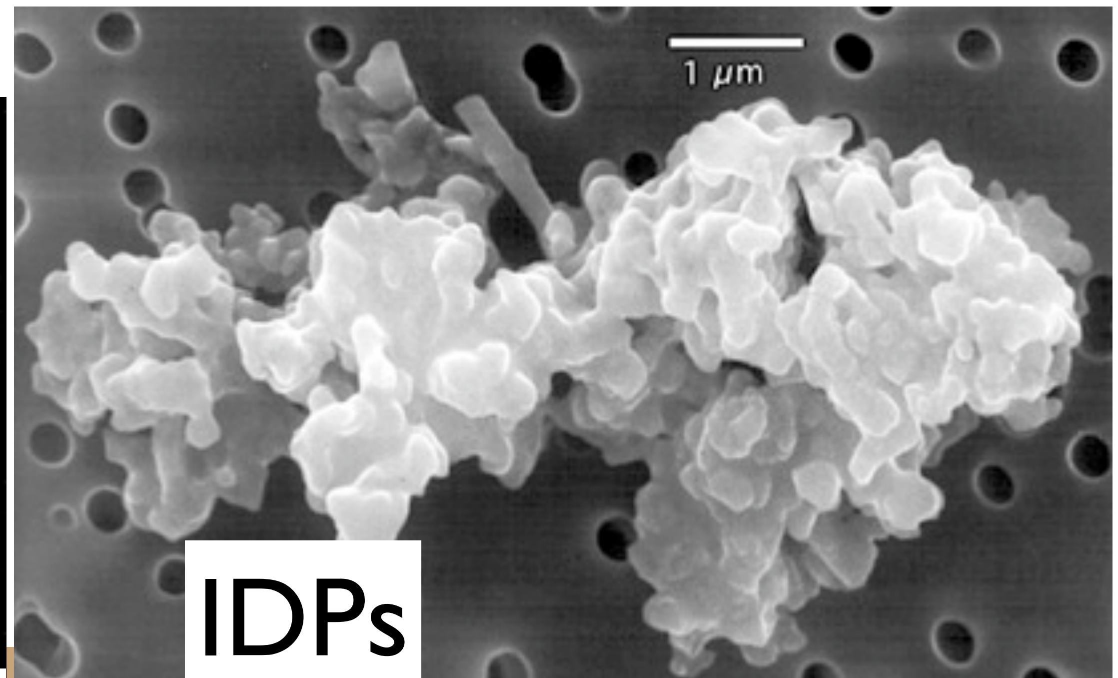
Meteorites



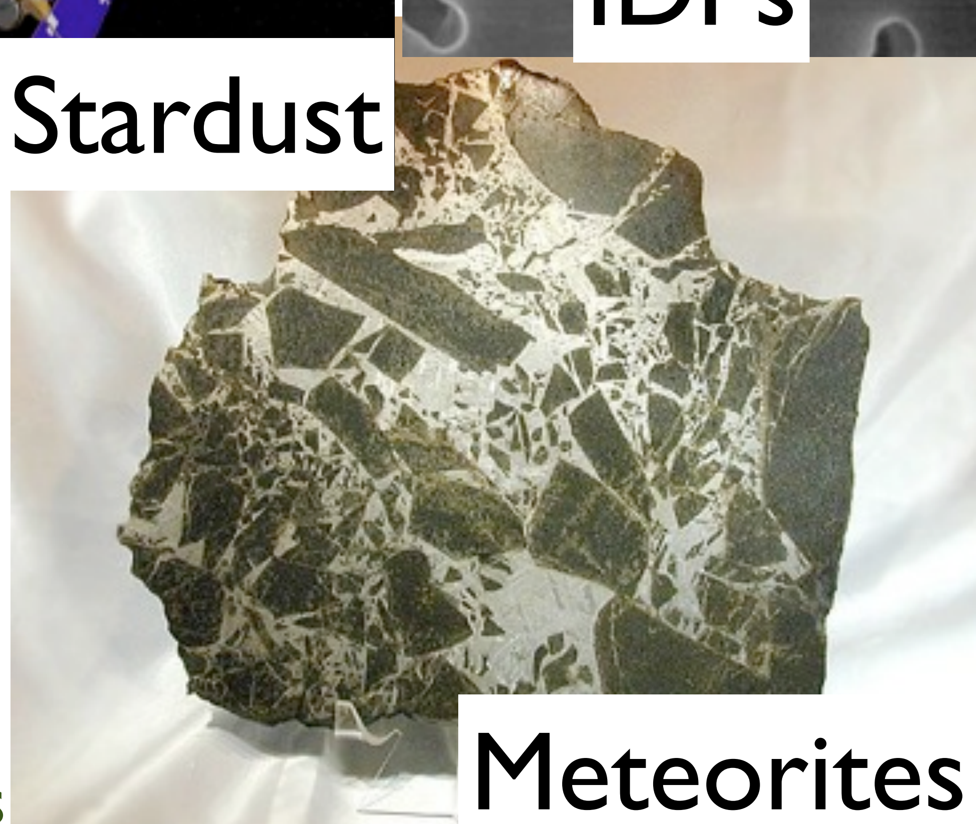
Spectra

Mineralogy

Stardust



IDPs



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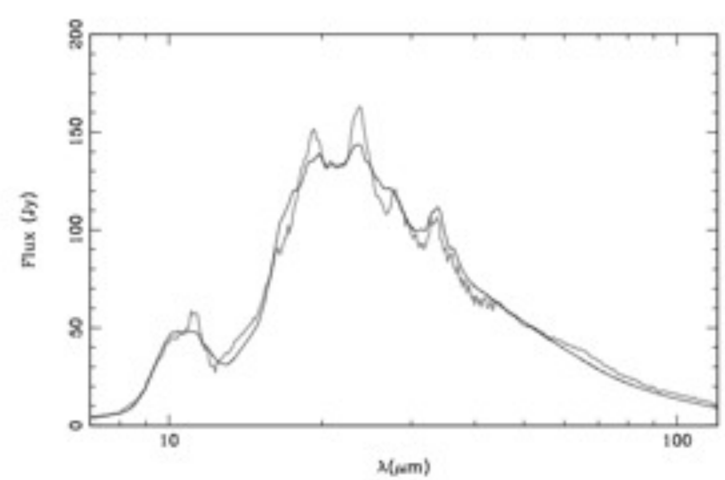
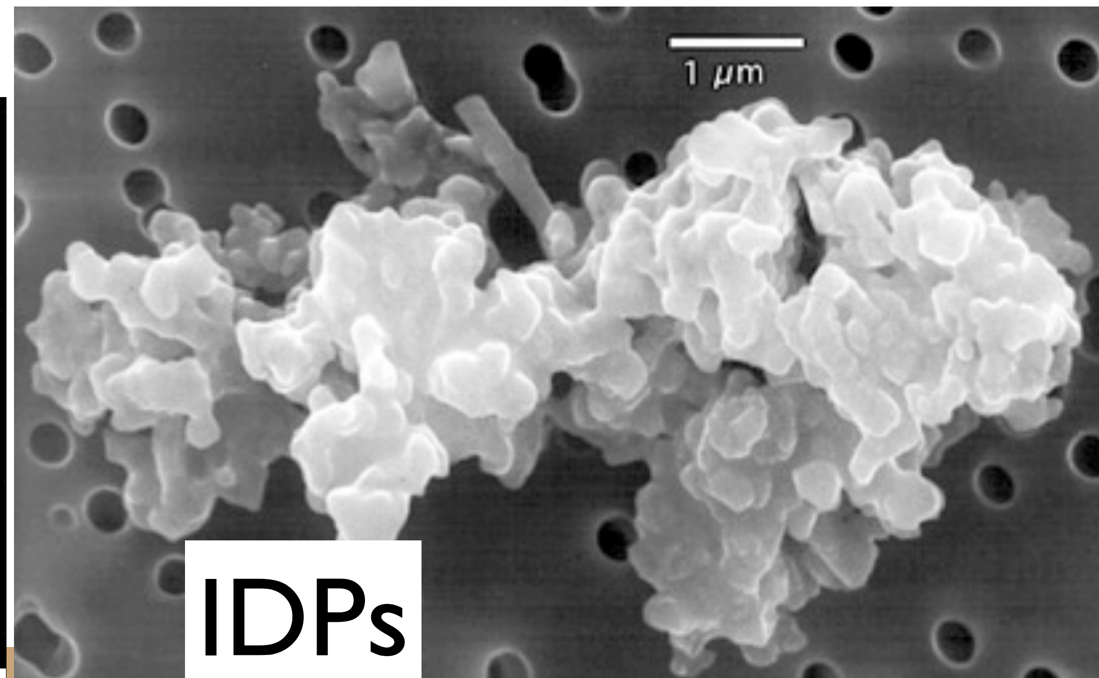


Spectra

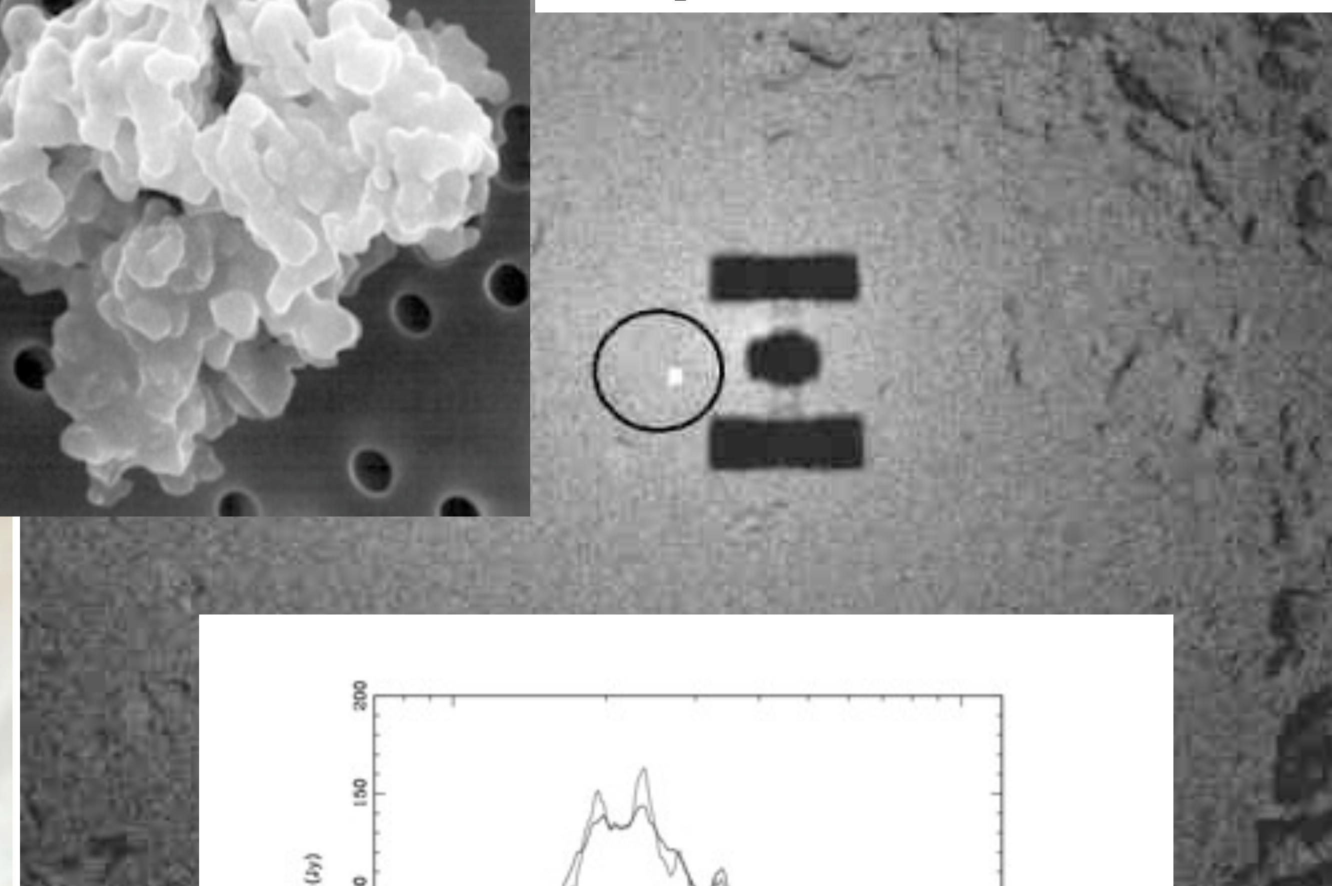
Mineralogy

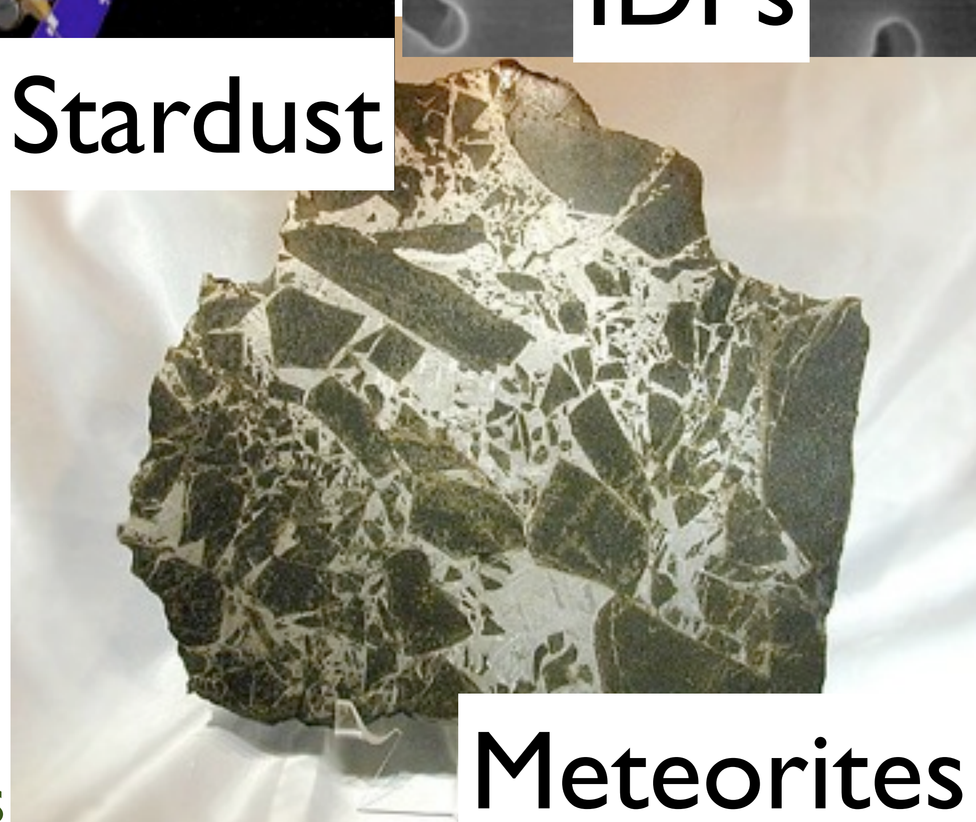
Stardust



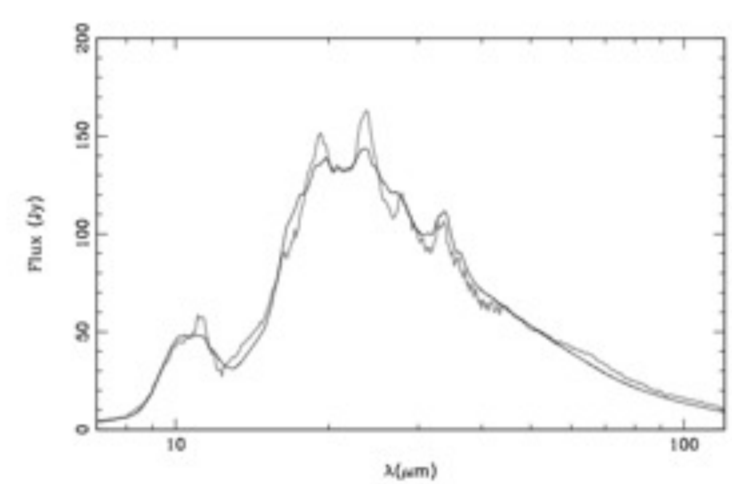
IDPs

Hayabusa mission





Meteorites



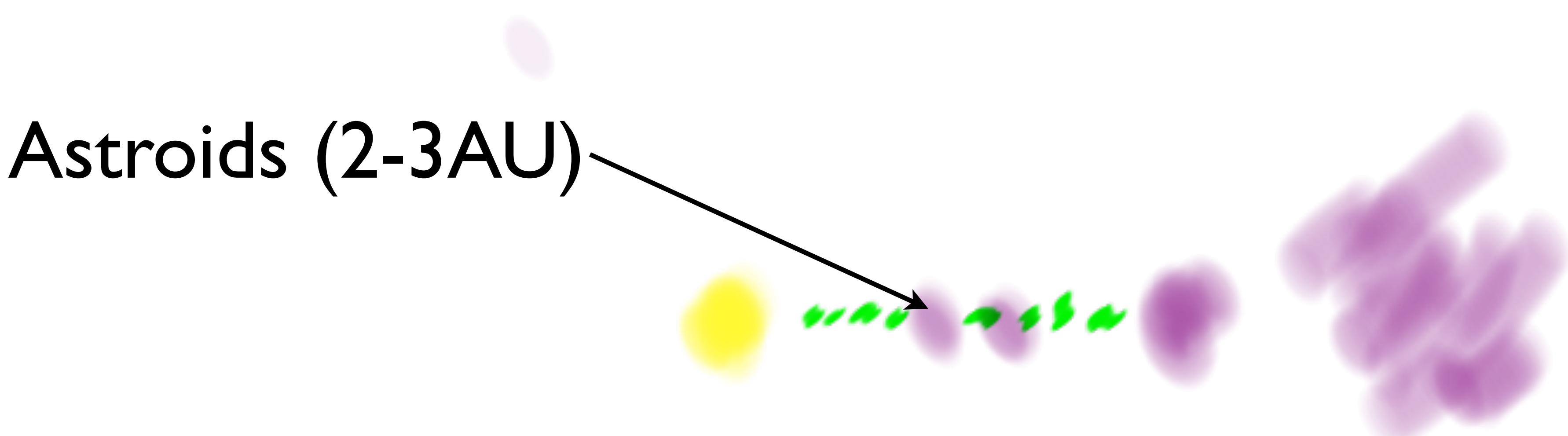
Spectra

Population

Solar System

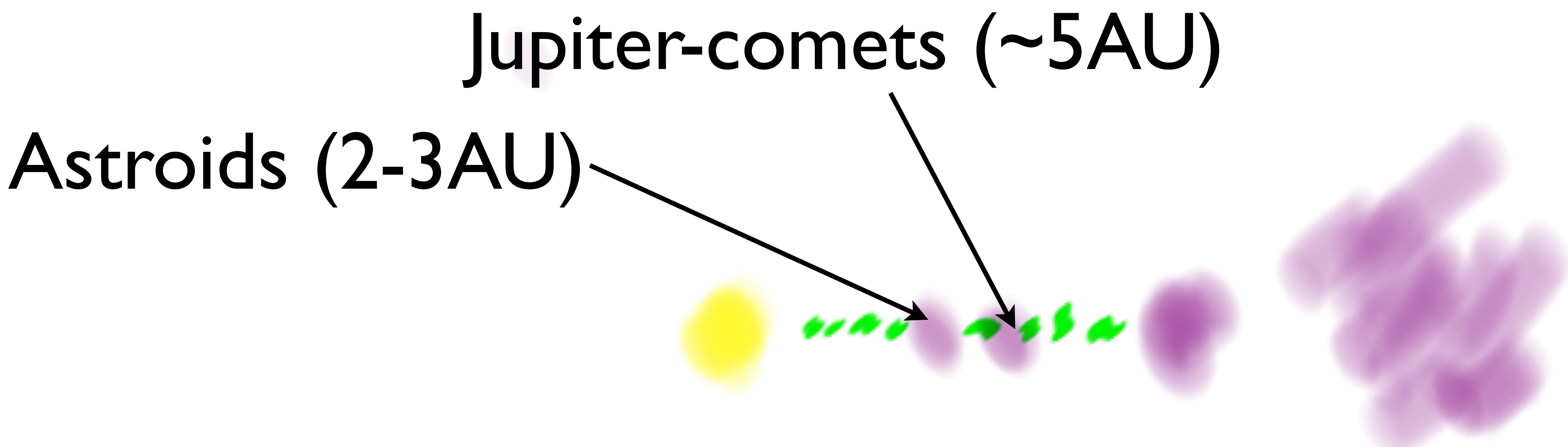
Population

Solar System



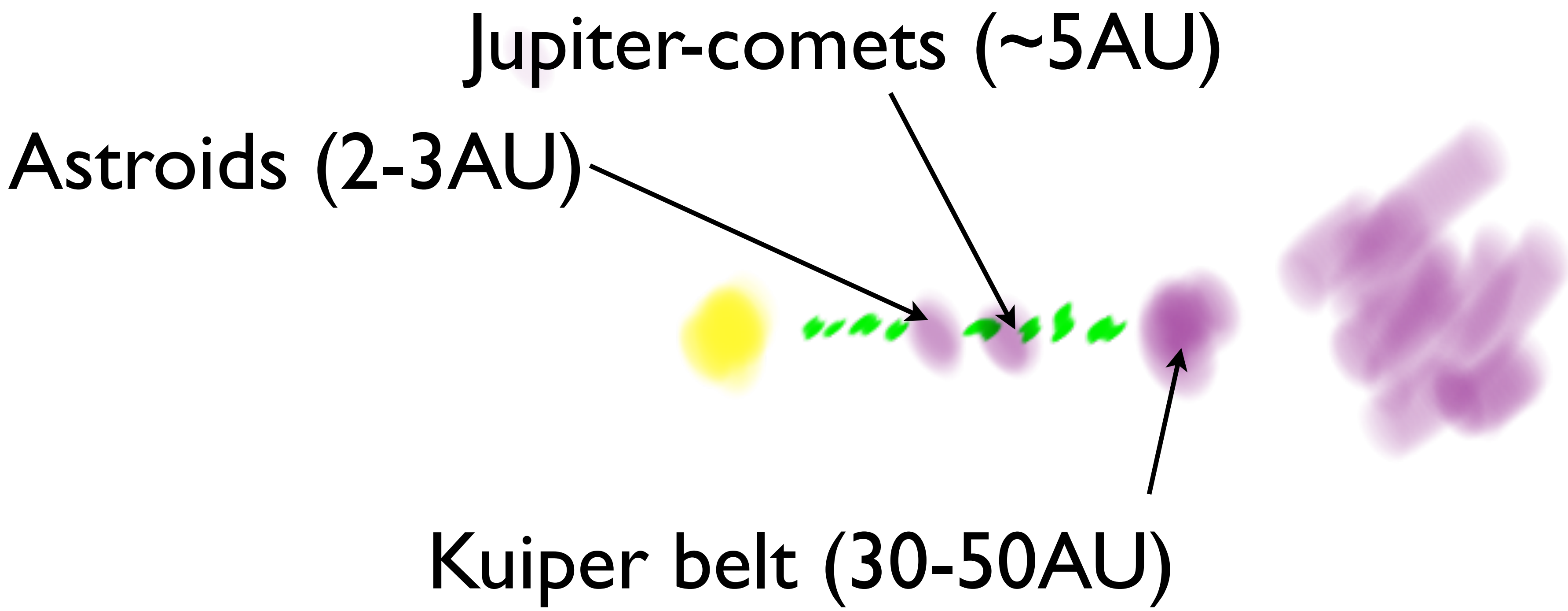
Population

Solar System



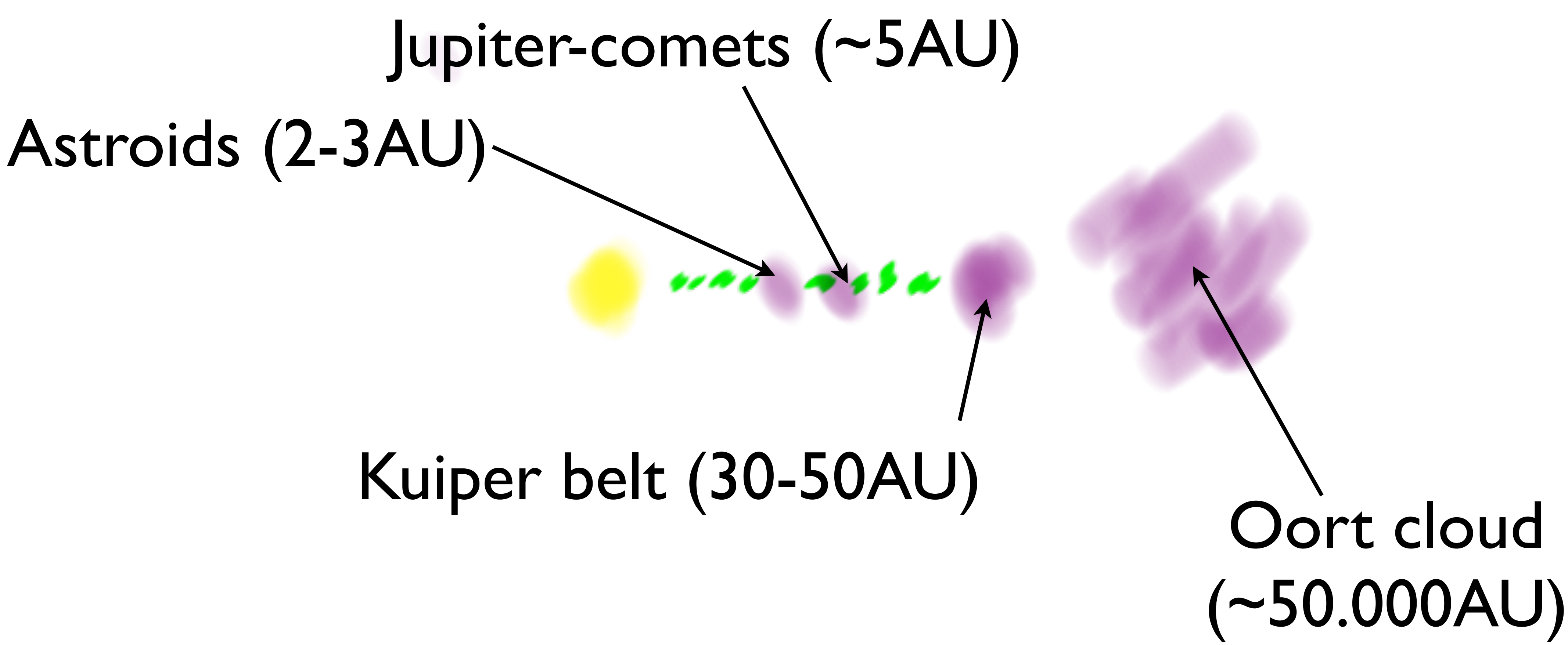
Population

Solar System



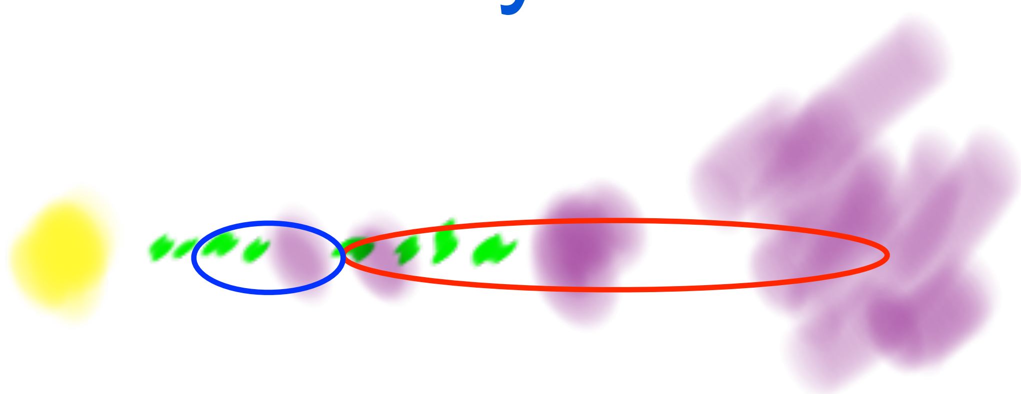
Population

Solar System



Two-groups

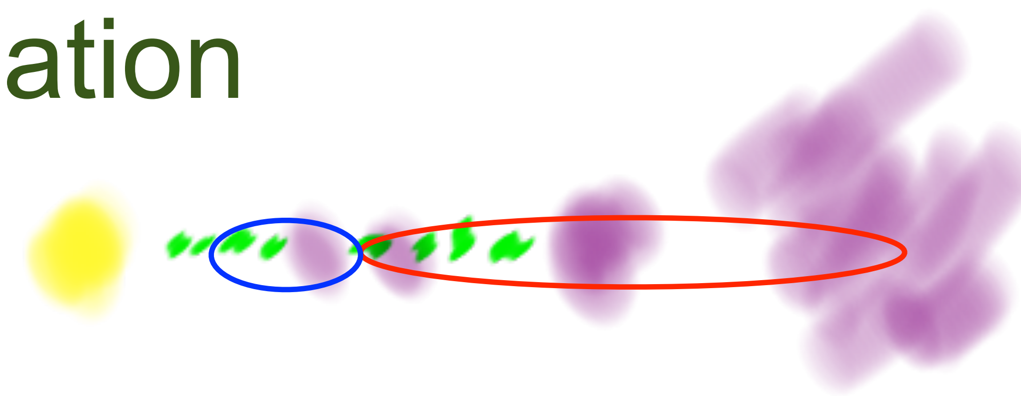
- Chondrites, IDPs, cometary: x~0.99
- Astroids & Ordinary chondrites: x~0.7



Equilibration

- Equilibrated vs Un-equilibrated

- Equilibration is a parent body effect
- Body must be large
- Heating up to 200-500K
- Decay, gravity, EM-radiation



Conclusion I

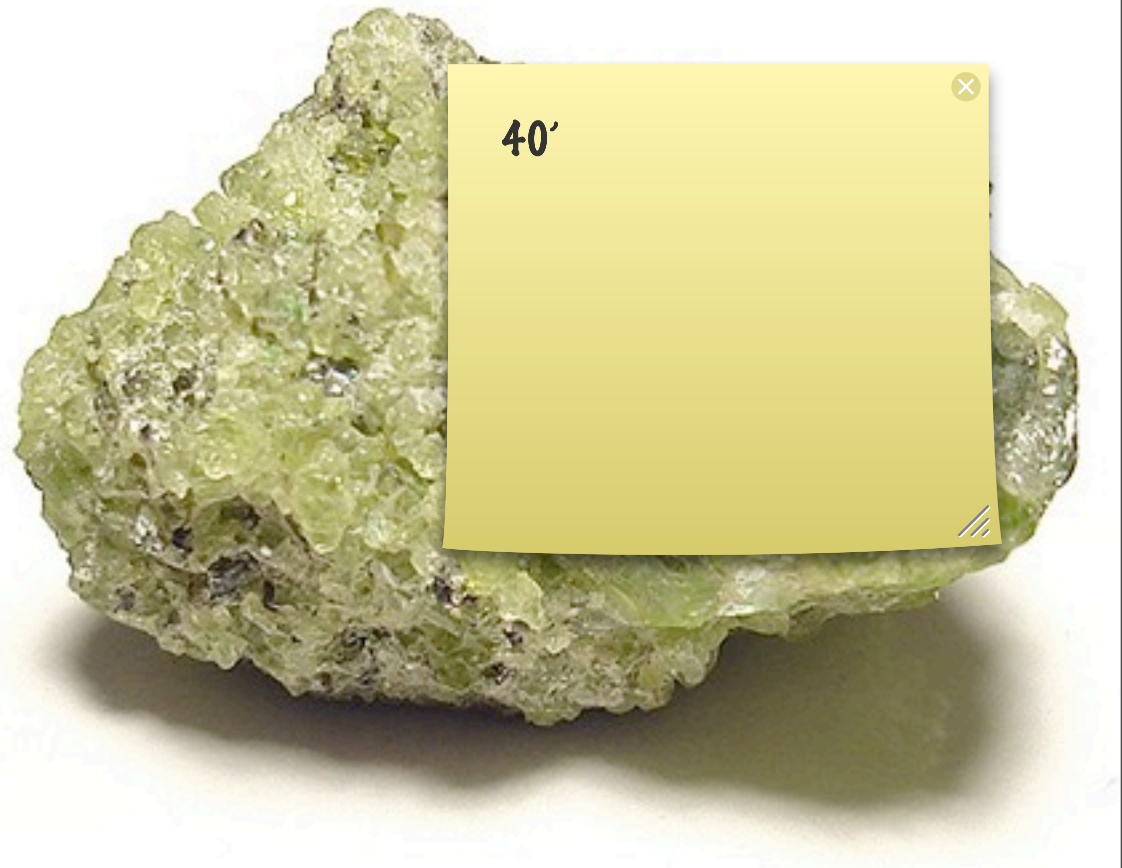
- β Pictoris has un-equilibrated olivine
- β Pictoris’ olivine pre-dates planet formation
- The parent bodies are small and cold
- SS and β Pictoris olivine has the same composition

Summary I

- The 69 μm band enables us to do precise mineralogy
- Gas-condensation in AGBs gives very pure forsterite (≲0.5% Fe)
- This puts constraints on the models

Summary II

- Olivine in β Pictoris is un-equilibrated
- In composition and location the olivine compares to un-equilibrated SS bodies
- Pre-planet formation olivine contains ~1% Fe
- This composition can be obtained with gas-phase condensation or annealing



Thanks!

A lot of credit goes to:

Bram Acke, Joris Blommaert, Rens Waters, Michiel Min, Bart Vandenbussche, Christoffel Waelkens

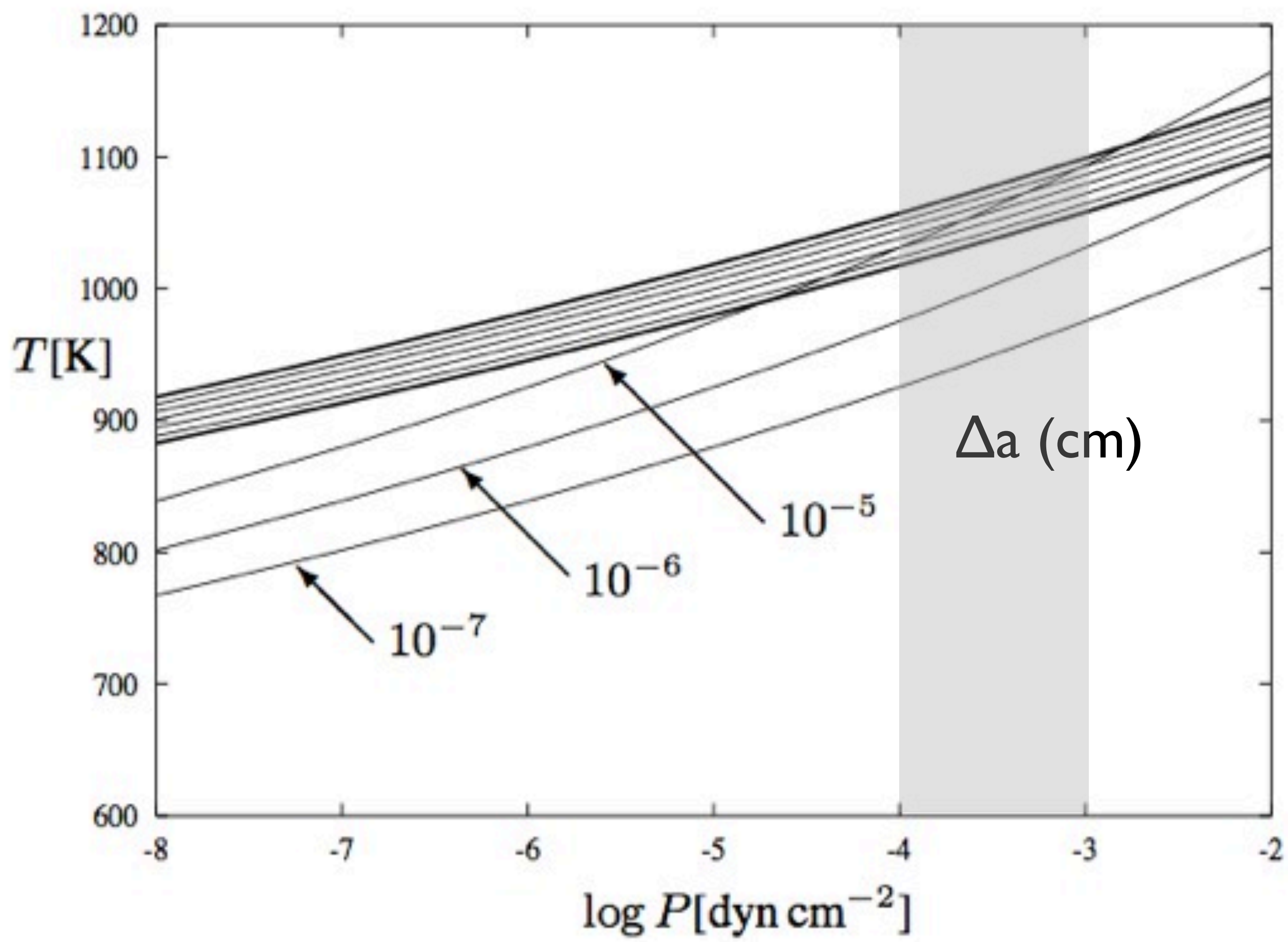
Crystalline vs amorphous

$$\tau_{\mathrm{growth}} = \Delta a \left| \frac{\mathrm{d}a}{\mathrm{d}t} \right|^{-1}$$

$$\tau_{\mathrm{annealing}} = \frac{(\Delta a)^2}{D}$$

Gail & Sedlmayr 1999

Crystalline vs amorphous



$$\tau_{\text{growth}} = \Delta a \left| \frac{da}{dt} \right|^{-1}$$

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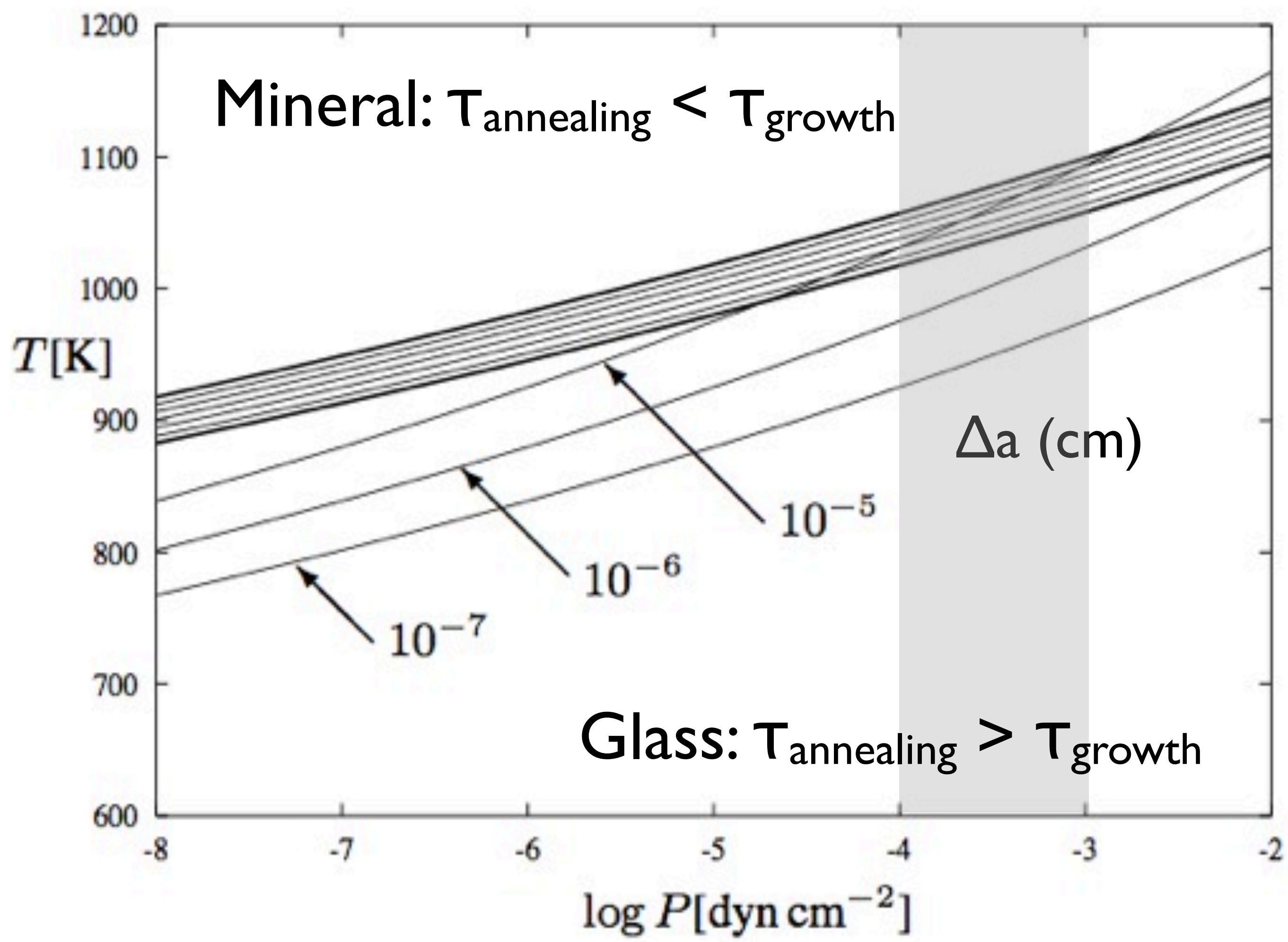
Gail & Sedlmayr 1999

Crystalline vs amorphous

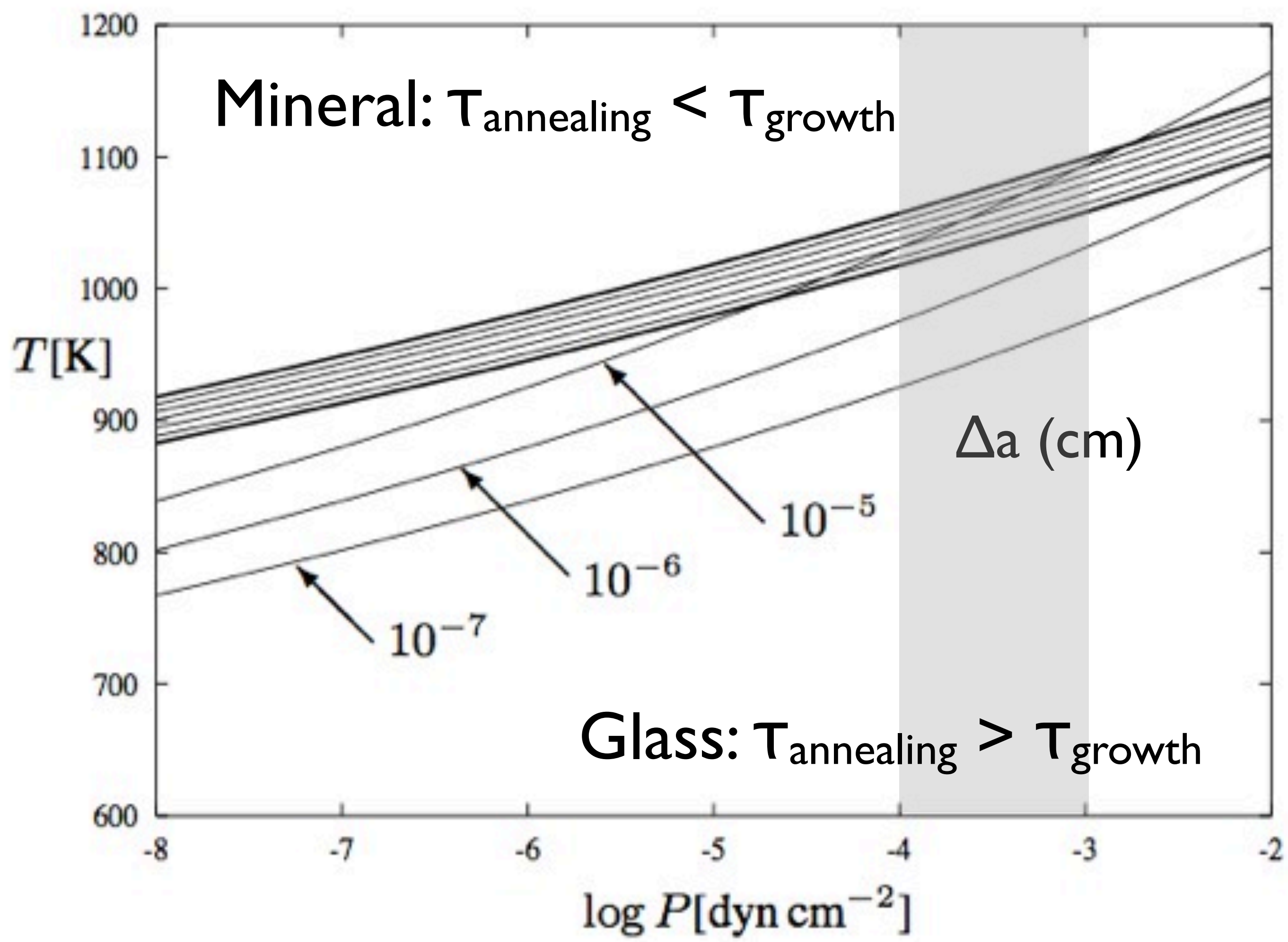


$$\tau_{\rm growth} = \Delta a \left| \frac{{\rm d}a}{{\rm d}t} \right|^{-1}$$

$$\tau_{\rm annealing} = \frac{(\Delta a)^2}{D}$$

Gail & Sedlmayr 1999

Crystalline vs amorphous

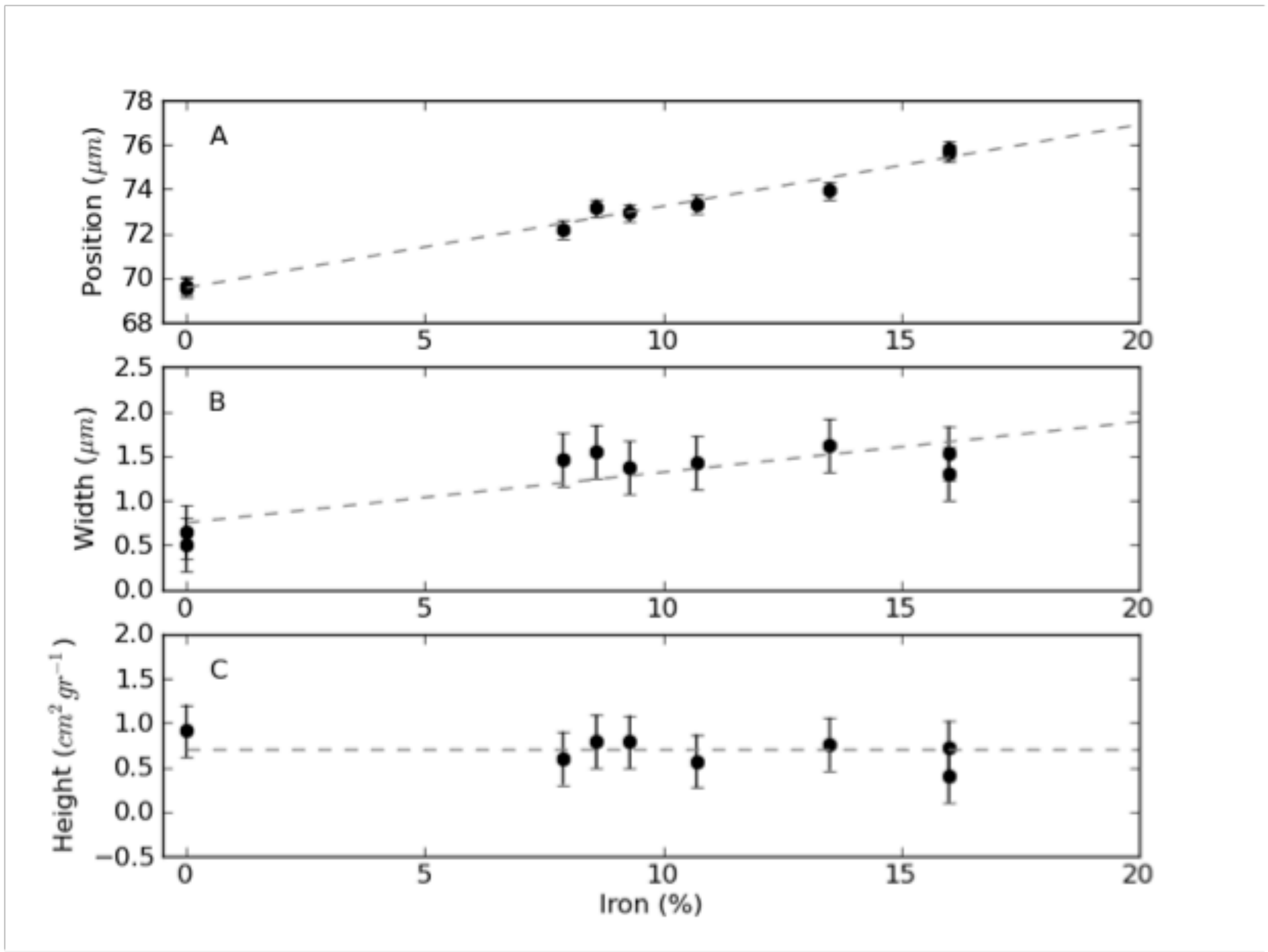


$$\tau_{\rm growth} = \Delta a \left| \frac{{\rm d}a}{{\rm d}t} \right|^{-1}$$

$$\tau_{\rm annealing} = \frac{(\Delta a)^2}{D}$$

Crystalline at ≳900K

Gail & Sedlmayr 1999



Optical constants: Suto et al 2006, Koike et al. 2003