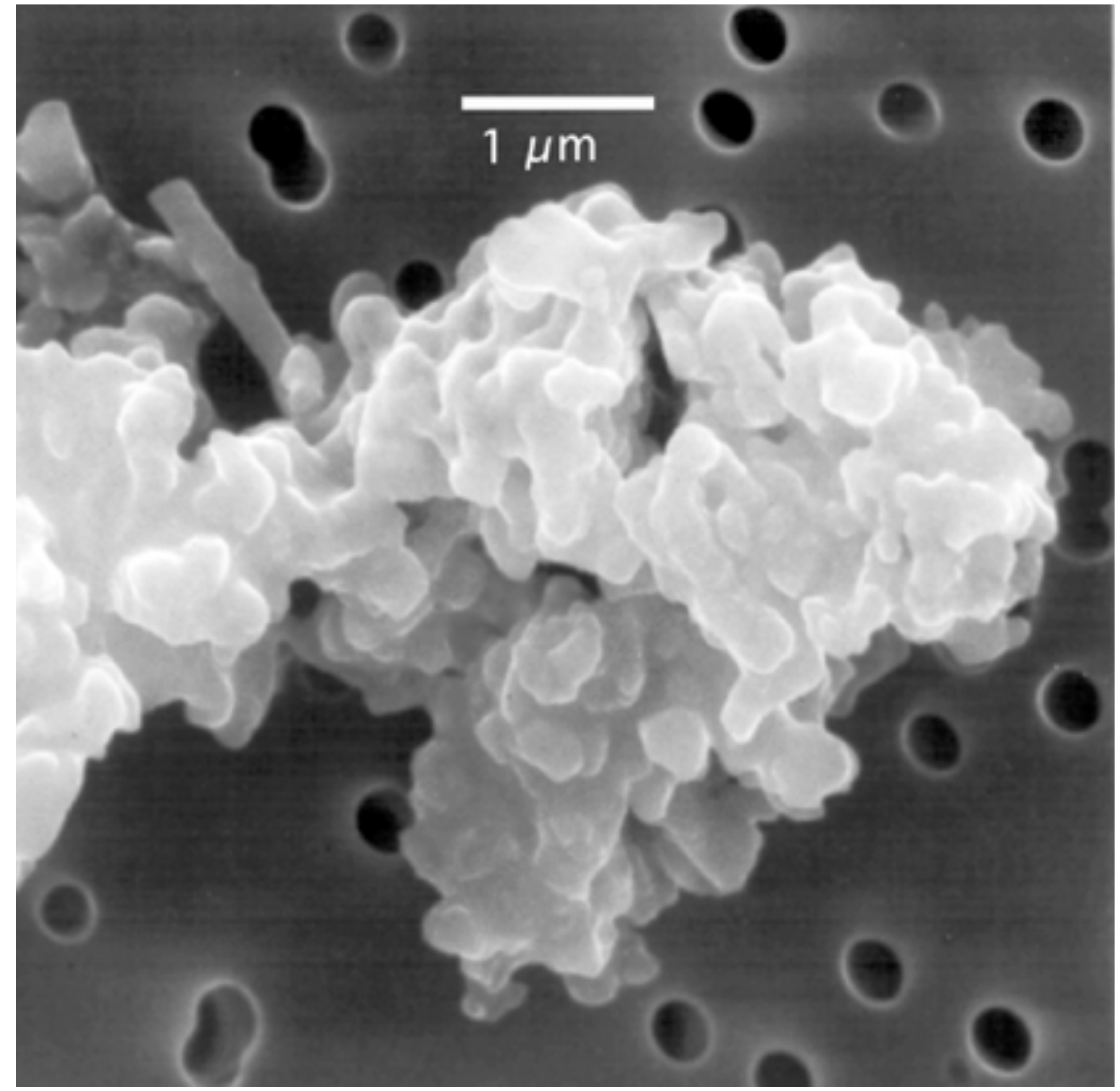
Dust processing in HAeBe disks

Roy van Boekel
MPIA Heidelberg

Overview

- intro, silicates
- origin & initial composition
- main processes at play
- composition from IR spectroscopy
- observable dust in HAe disks:
  - Silicates
  - Carbonaceous species / PAHs

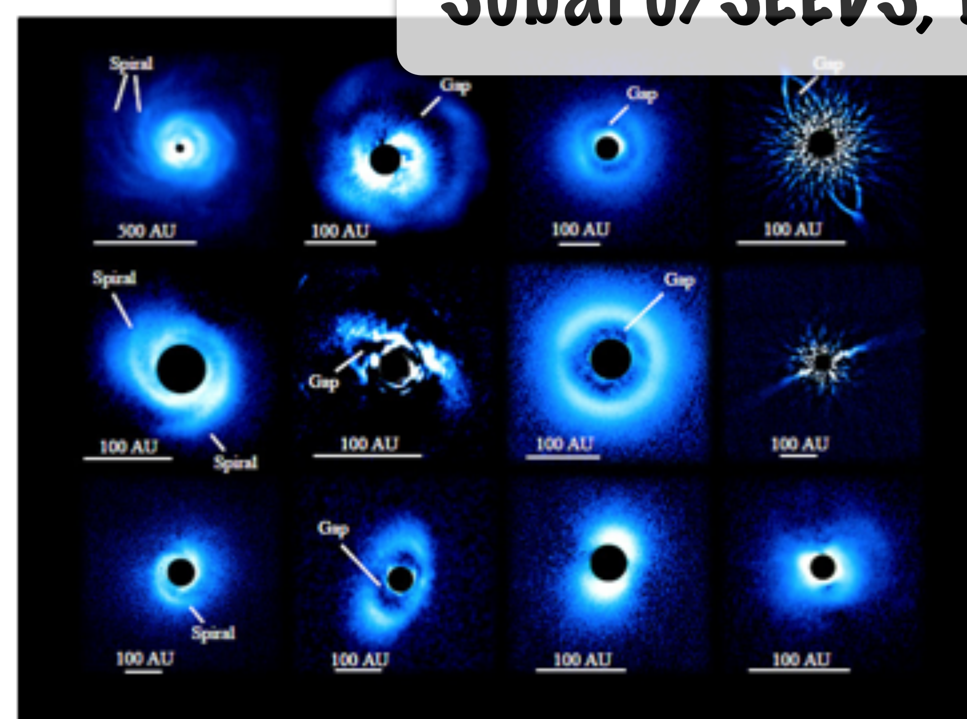


Diagnostics

- "direct" analysis:
  - Earth, Moon, Mars
  - meteorites
  - comets
  - IDPs
  - pre-solar grains ("stardust")
- Spectroscopy:
  - optical: absorption
  - near/mid/far-IR: many spectral features, absorption & emission
  - mm: spectral slope
- Scattering properties:
  - Disk surfaces
  - clouds/cores

Philae / Rosetta, ESA

Subaru/SEEDS, NAO



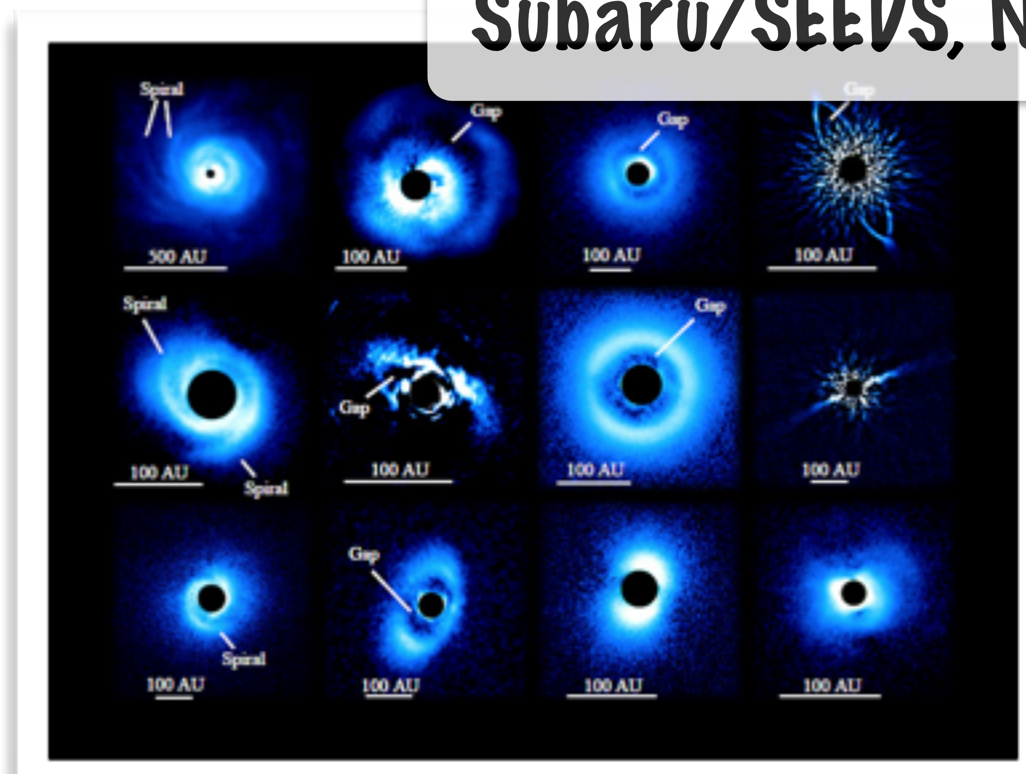
Diagnostics

- "direct" analysis:
  - Earth, Moon, Mars
  - meteorites
  - comets
  - IDPs
  - pre-solar grains ("stardust")

Philae / Rosetta, ESA

- Spectroscopy:
  - optical: absorption
  - near/mid/far-IR: many spectral features, absorption & emission
  - mm: spectral slope

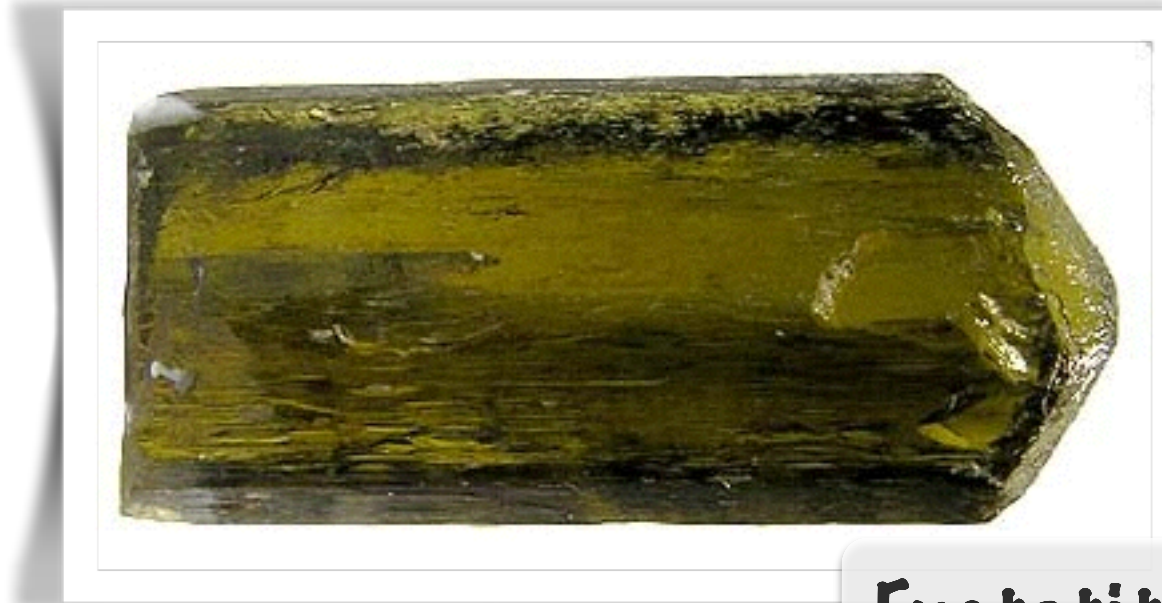
- Scattering properties:
  - Disk surfaces
  - clouds/cores



Subaru/SEEDS, NAO

Main dust components

- **Silicates**
  - Mg/Fe, Si, O
  - amorphous / crystalline forms
- **Carbonaceous**
  - hydrogenated amorphous C
  - "CHON" material (?)
  - graphite, diamonds
  - PAHs
- **Others**
  - Fe, FeS, NiS, SiC
  - Al_2O_3, $MgAl_2O_4$
  - ...



Enstatite

amorphous Carbon

FeS

Main dust components

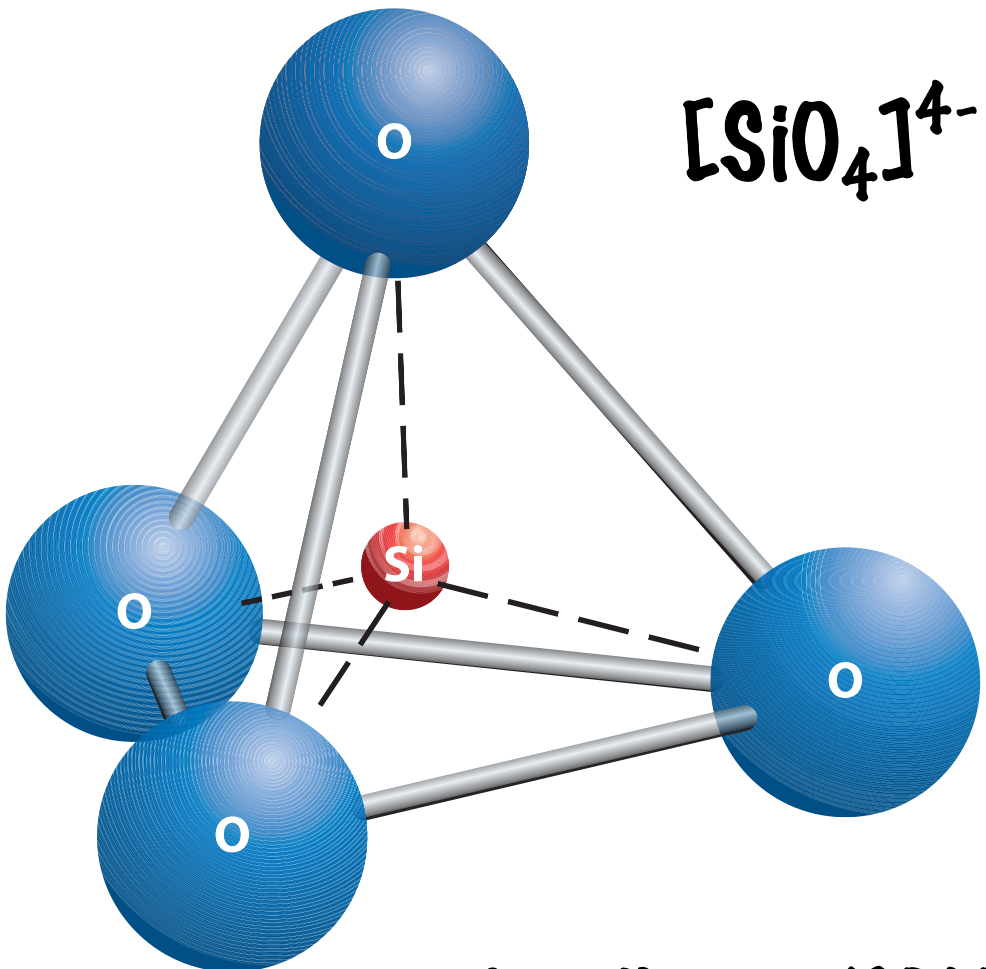
- **Silicates**
  - Mg/Fe, Si, O
  - amorphous / crystalline forms
- **Carbonaceous**
  - hydrogenated amorphous C
  - "CHON" material (?)
  - graphite, diamonds
  - PAHs
- **Others**
  - Fe, FeS, NiS, SiC
  - Al_2O_3, $MgAl_2O_4$
  - ...


Enstatite


amorphous Carbon


FeS

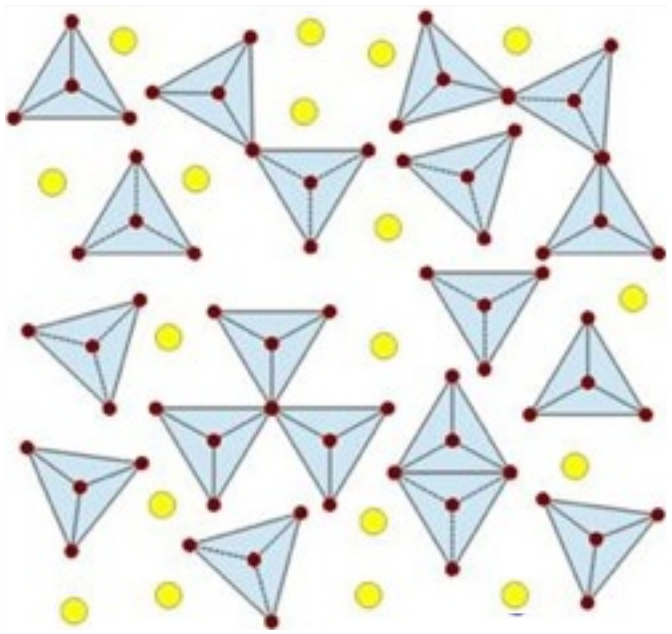
Silicates

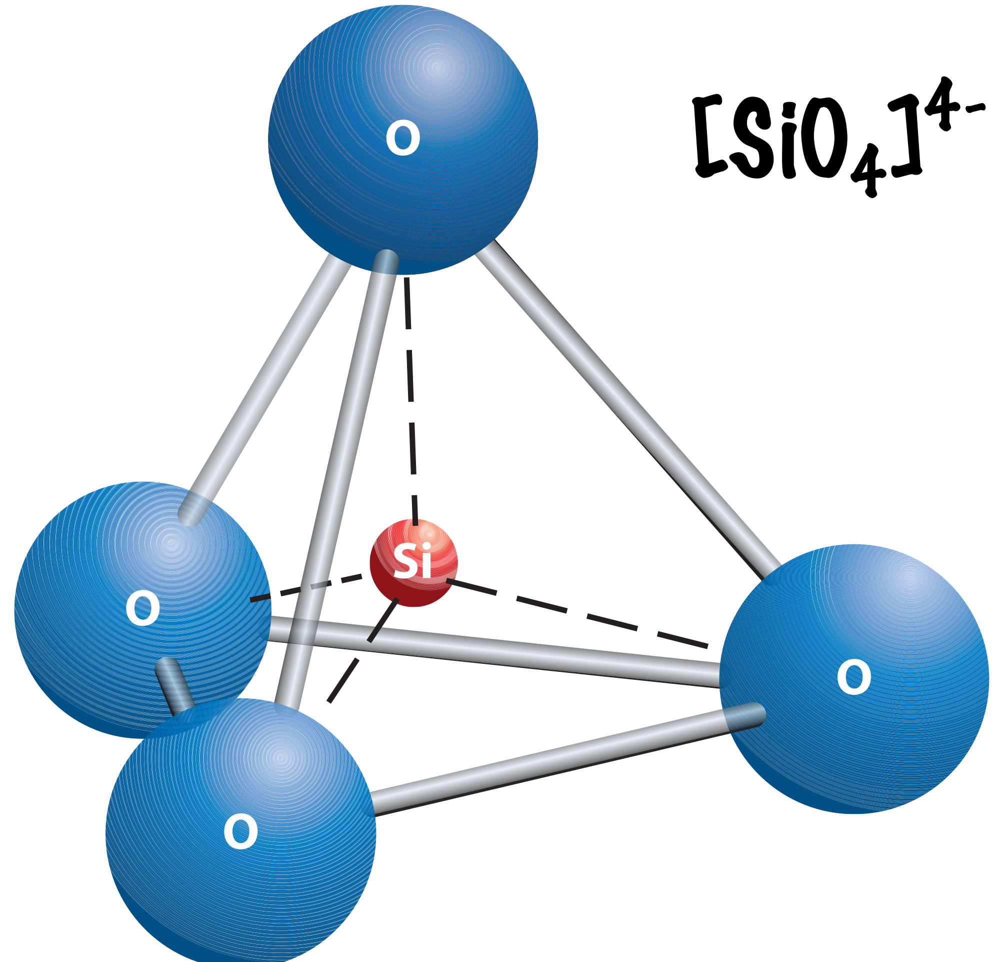


$[SiO_4]^{4-}$

from Henning (2010, ARAA, 48, 21)

Silicates

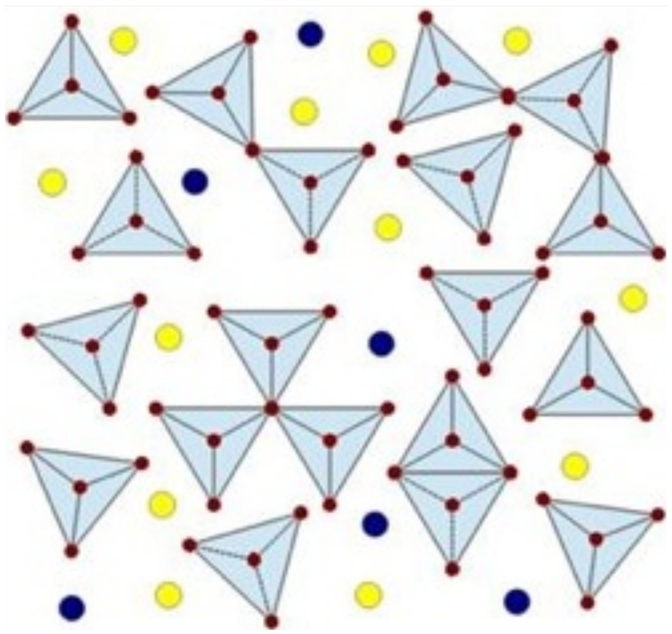


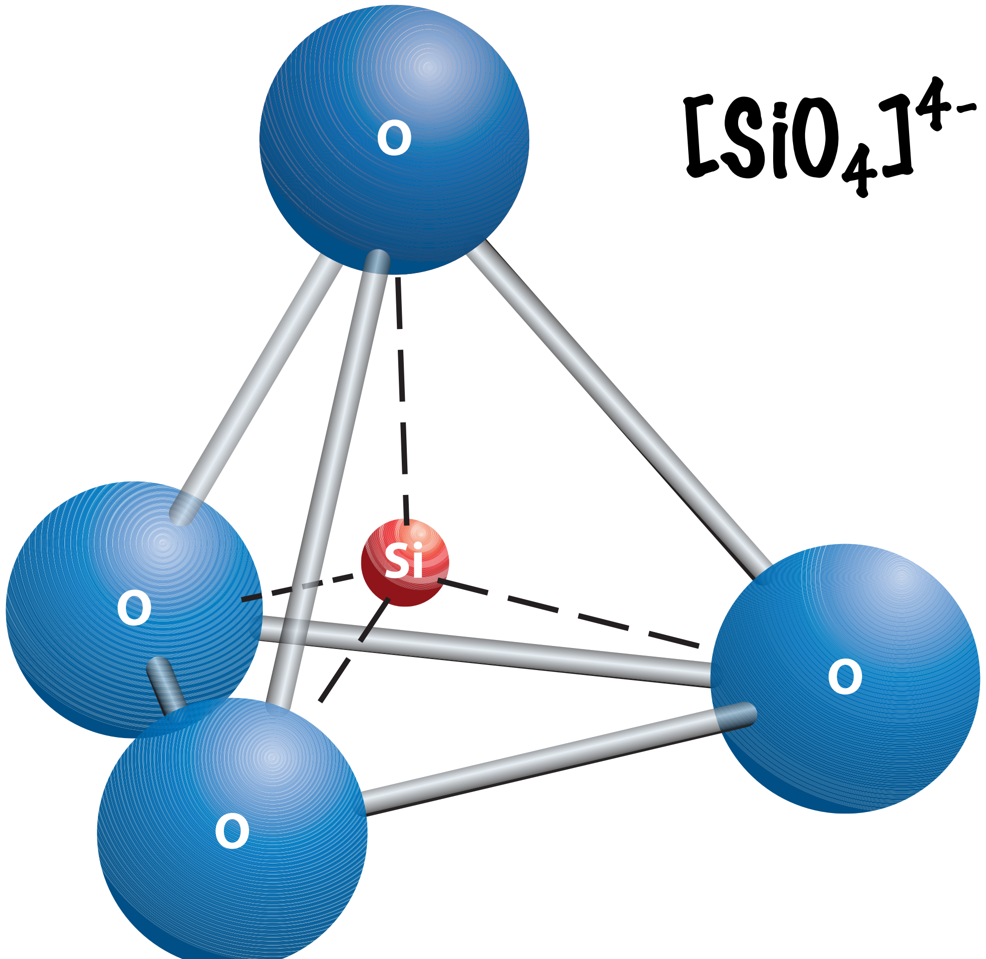


$[SiO_4]^{4-}$

from Henning (2010, ARAA, 48, 21)

Silicates

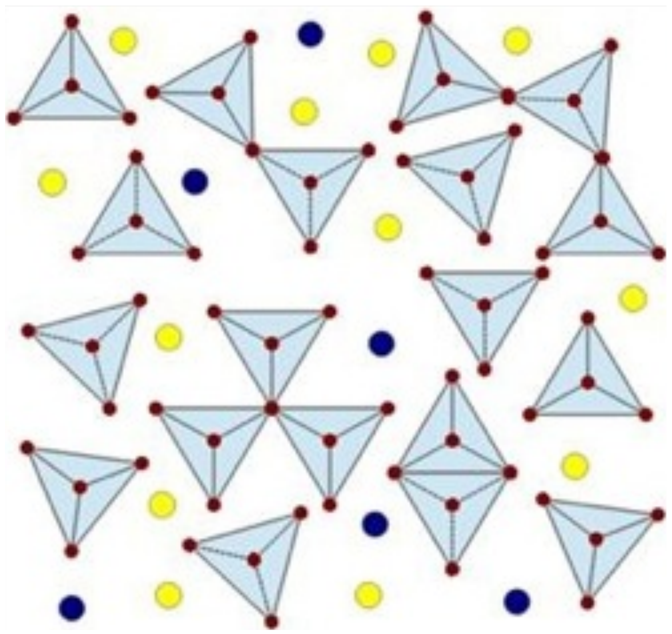




$[SiO_4]^{4-}$

from Henning (2010, ARAA, 48, 21)

Silicates

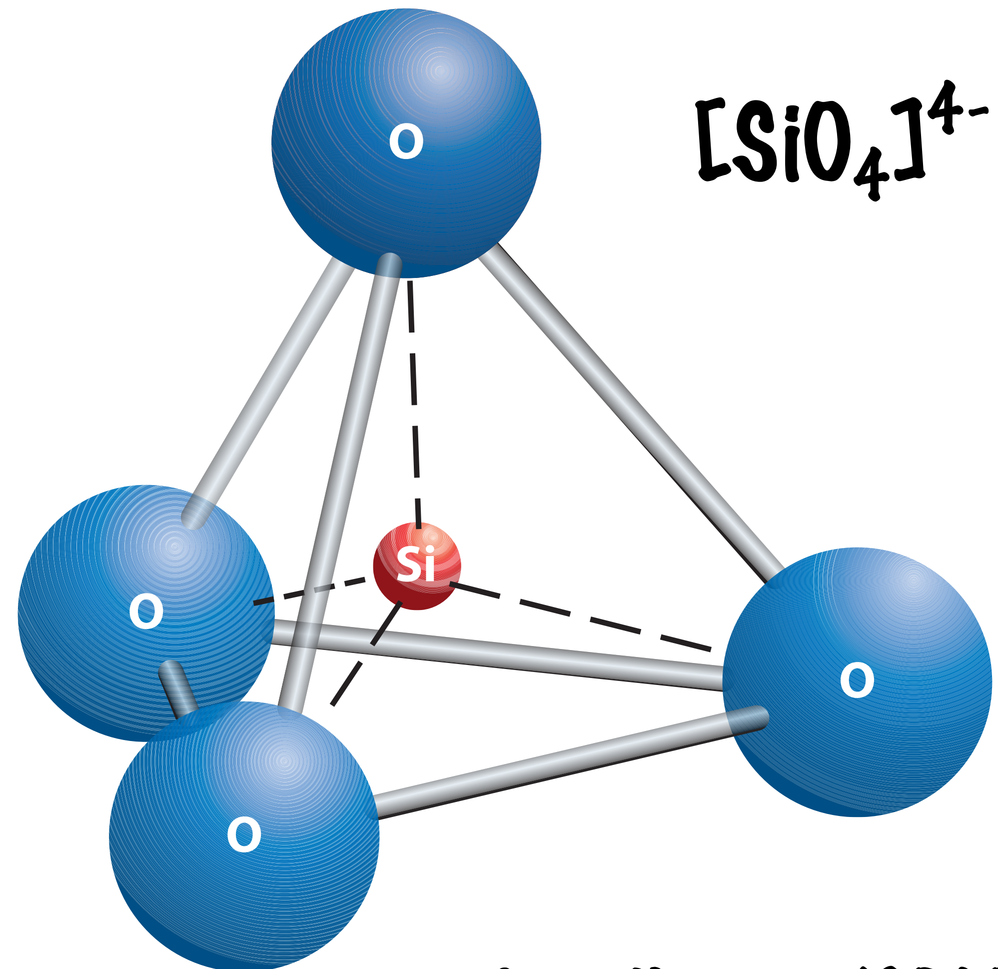


Olivine-type

$Mg_{2x}Fe_{2-2x}SiO_4$

Pyroxene-type

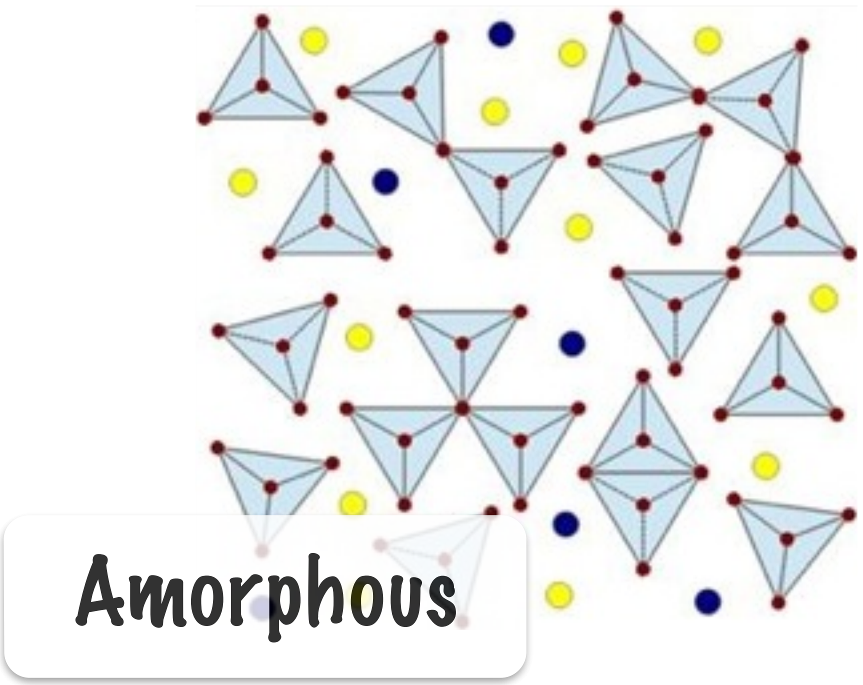
$Mg_xFe_{1-x}SiO_3$

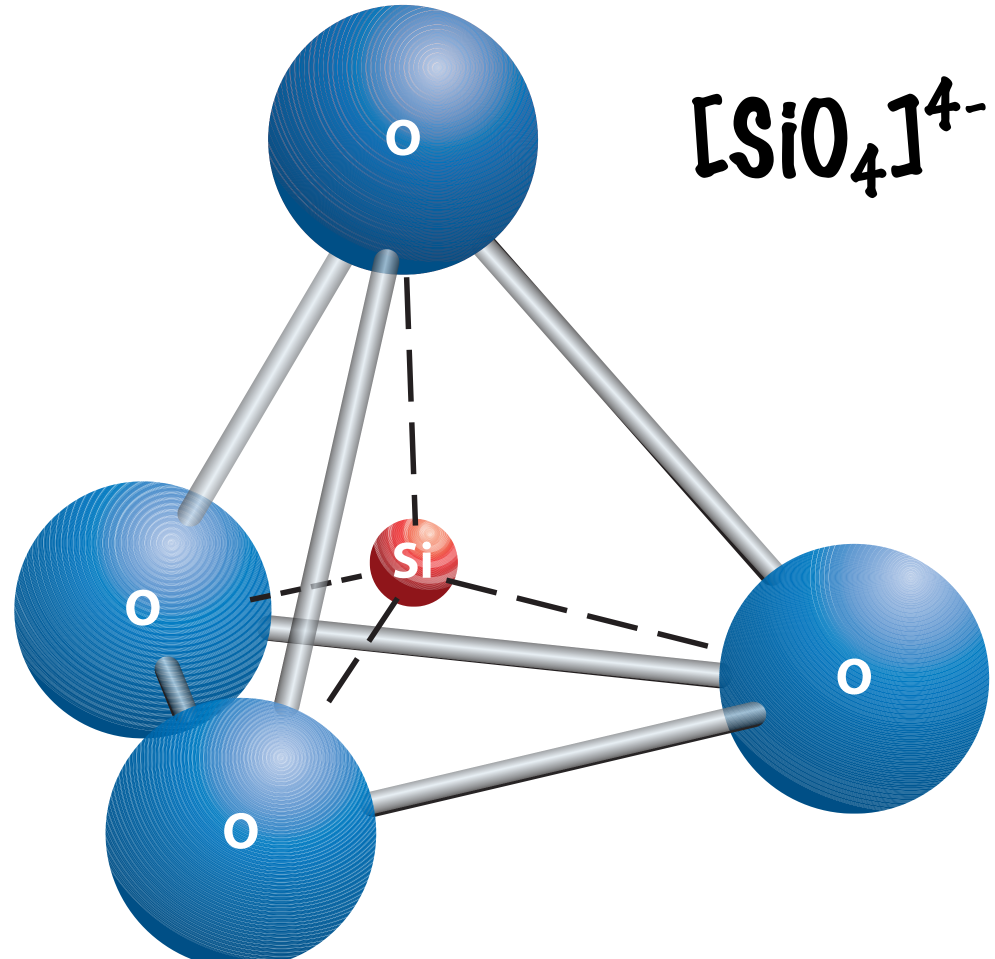


$[SiO_4]^{4-}$

from Henning (2010, ARAA, 48, 21)

Silicates





$[SiO_4]^{4-}$

from Henning (2010, ARAA, 48, 21)

Olivine-type

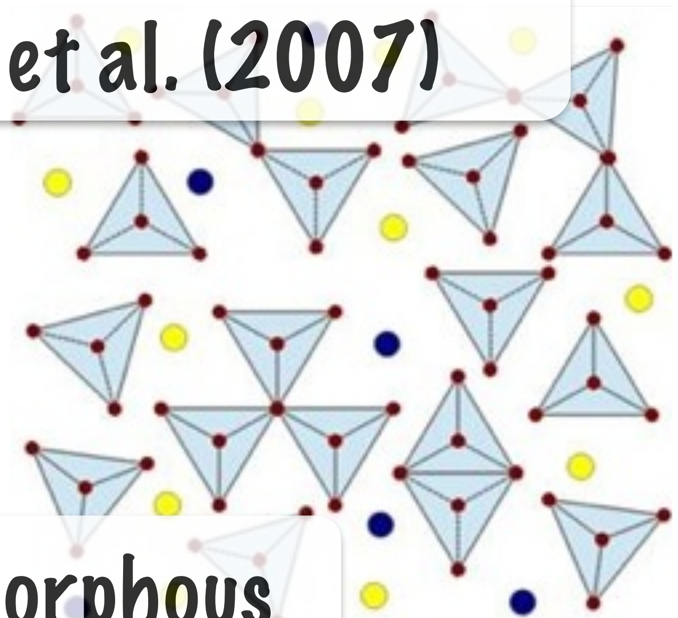
$Mg_{2x}Fe_{2-2x}SiO_4$

Pyroxene-type

$Mg_xFe_{1-x}SiO_3$

Silicates

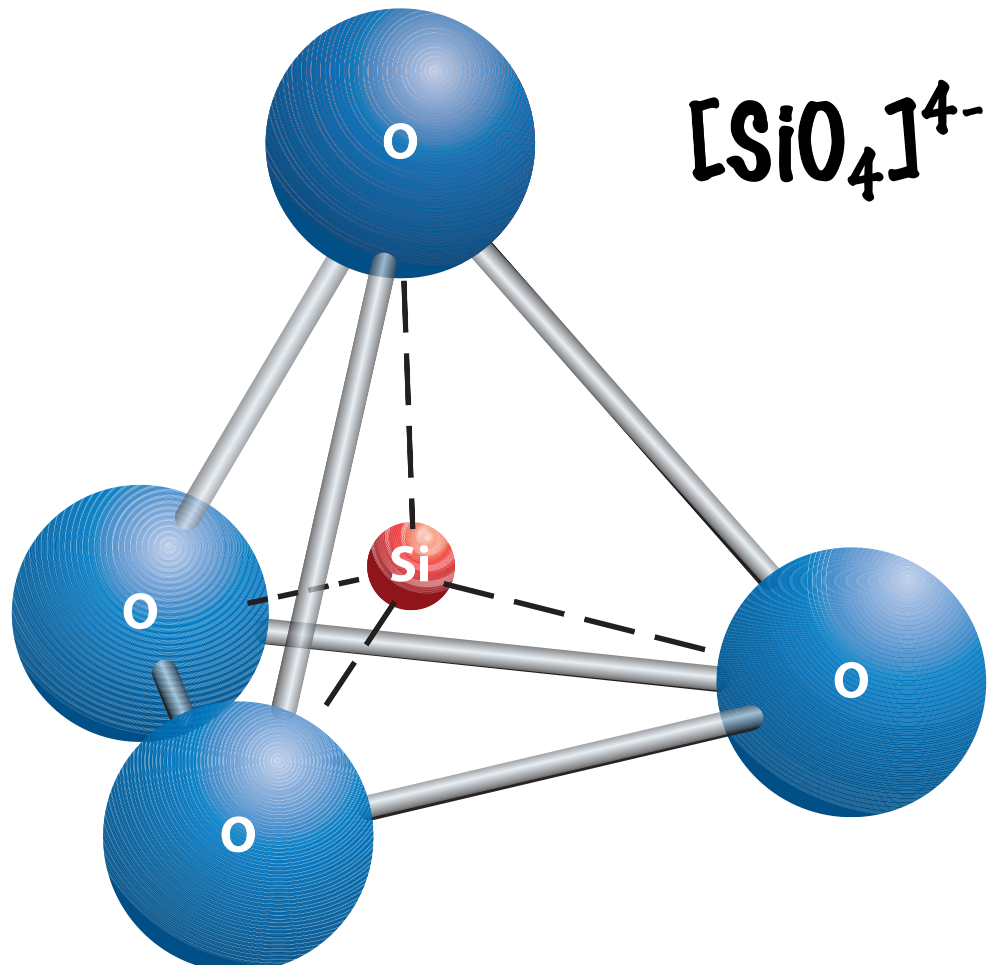
ISM:
Ol-type:Py-type ≈ 1:1
x≈0.5, x≈0.1
Min et al. (2007)



Amorphous

Olivine-type
$Mg_{2x}Fe_{2-2x}SiO_4$

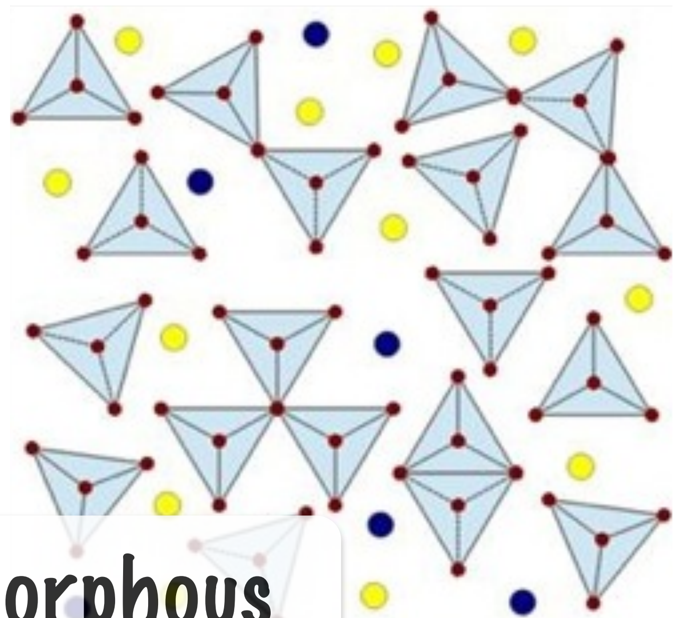
Pyroxene-type
$Mg_xFe_{1-x}SiO_3$



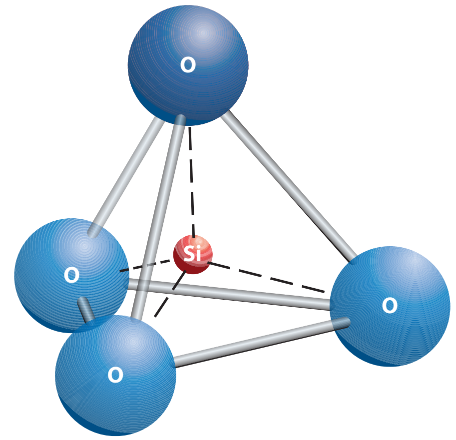
$[SiO_4]^{4-}$

from Henning (2010, ARAA, 48, 21)

Silicates



Amorphous



$[SiO_4]^{4-}$

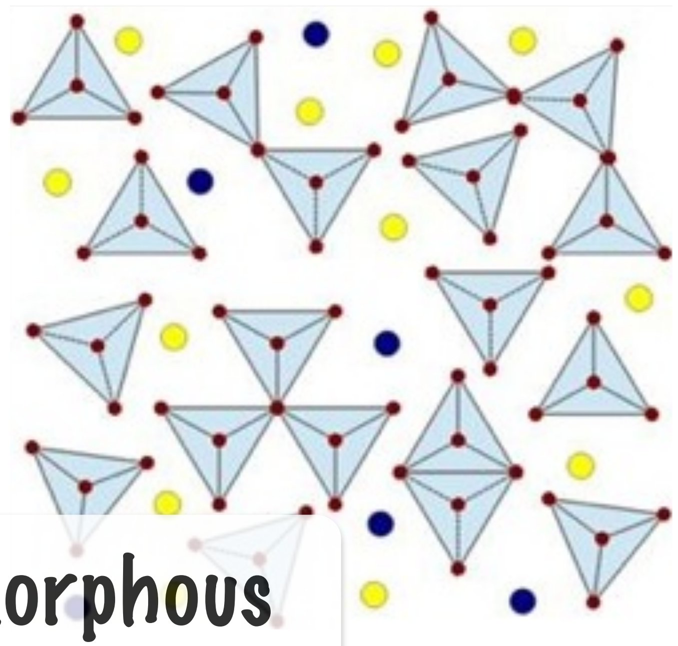
Olivine-type

$Mg_{2x}Fe_{2-2x}SiO_4$

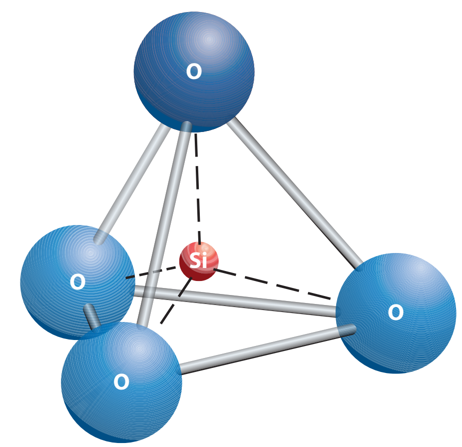
Pyroxene-type

$Mg_xFe_{1-x}SiO_3$

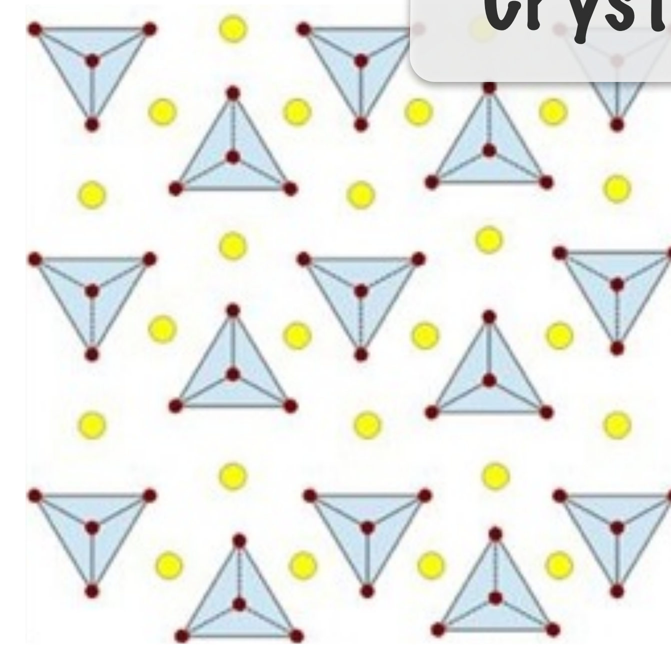
Silicates



Amorphous



$[SiO_4]^{4-}$



Crystalline

Olivine-type

$Mg_{2x}Fe_{2-2x}SiO_4$

Pyroxene-type

$Mg_xFe_{1-x}SiO_3$

Olivines

x=1 forsterite (Mg only)

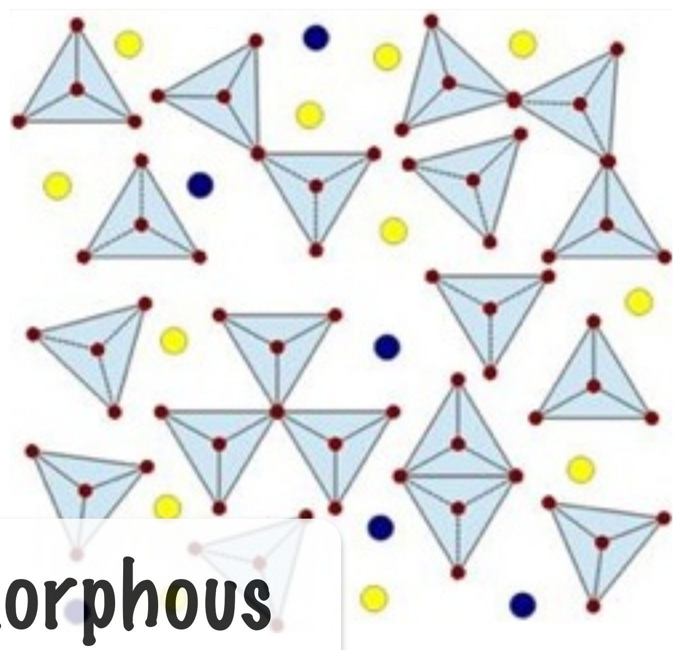
x=0 fayalite (Fe only)

Pyroxenes

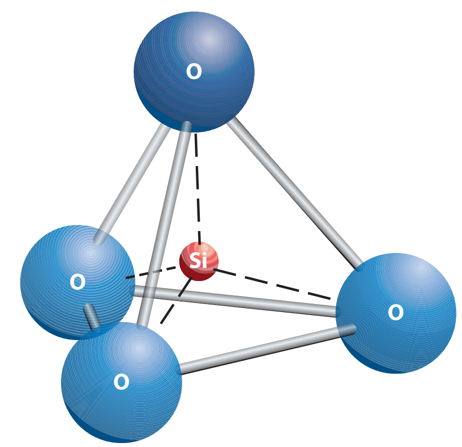
x=1 enstatite

x=0 ferrosilite

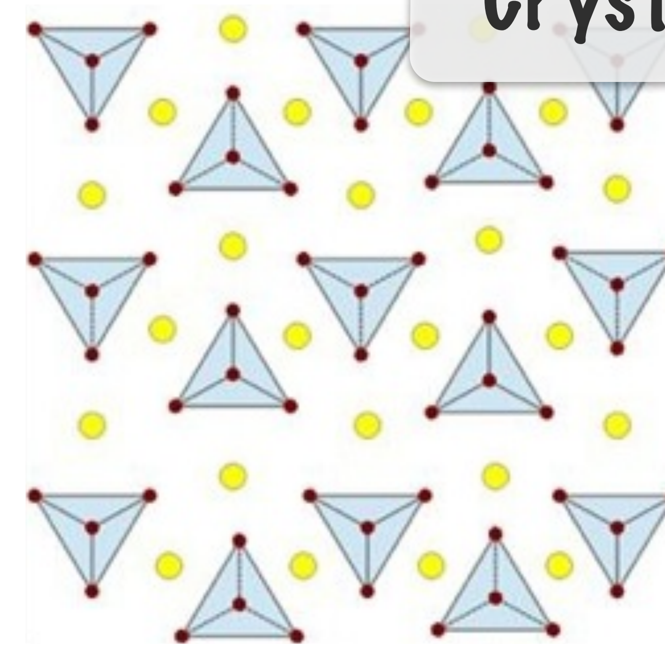
Silicates



Amorphous



$[SiO_4]^{4-}$



Crystalline

Olivine-type

$Mg_{2x}Fe_{2-2x}SiO_4$

Pyroxene-type

$Mg_xFe_{1-x}SiO_3$

Annealing

T > 900 K

Annealing

Olivines

x=1 forsterite (Mg only)

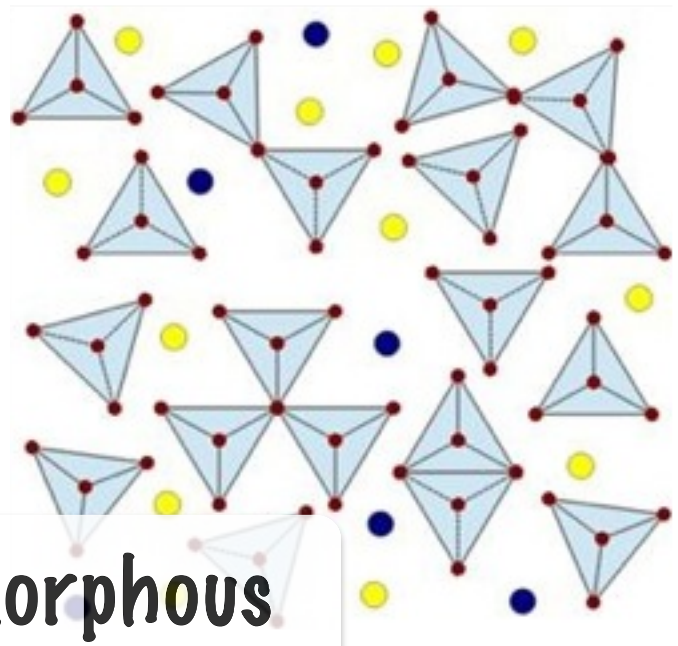
x=0 fayalite (Fe only)

Pyroxenes

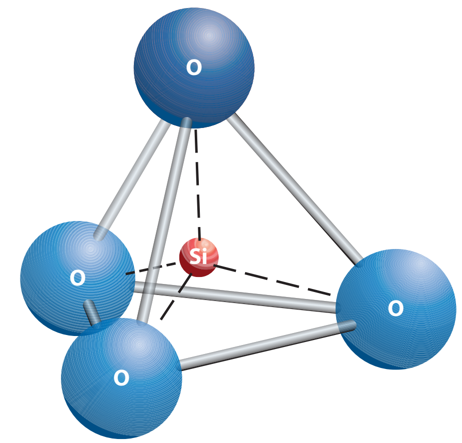
x=1 enstatite

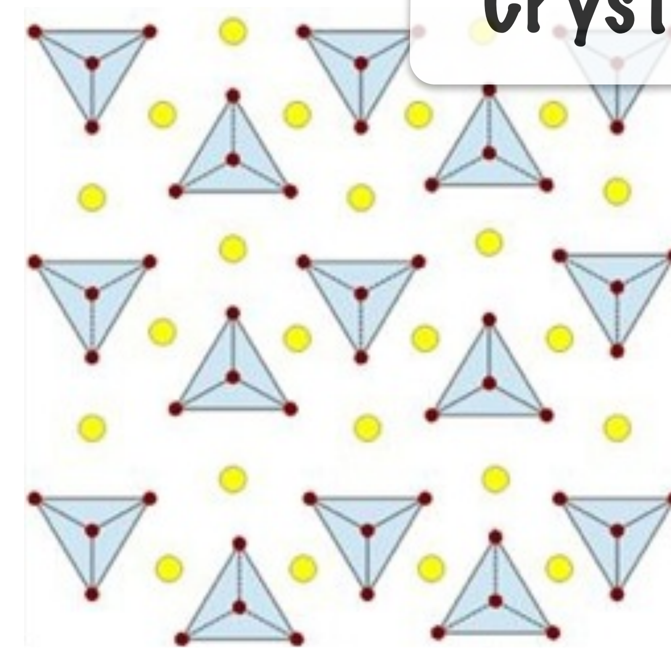
x=0 ferrosilite

Silicates



Amorphous





Crystalline

Olivine-type

$Mg_{2x}Fe_{2-2x}SiO_4$

Pyroxene-type

$Mg_xFe_{1-x}SiO_3$

T=1500 K

Olivines

x=1 forsterite (Mg only)

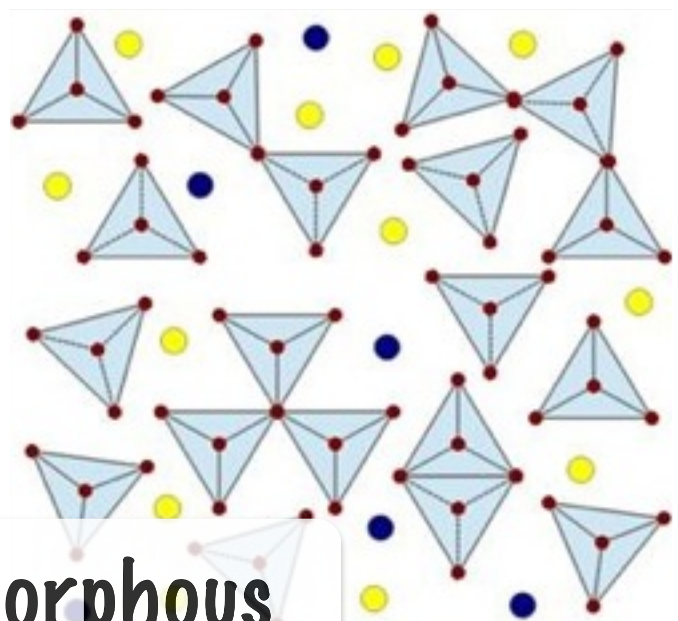
x=0 fayalite (Fe only)

Pyroxenes

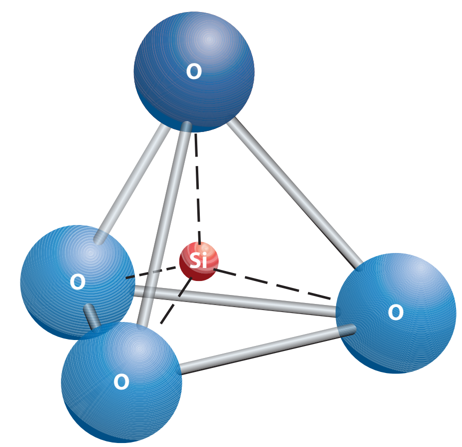
x=1 enstatite

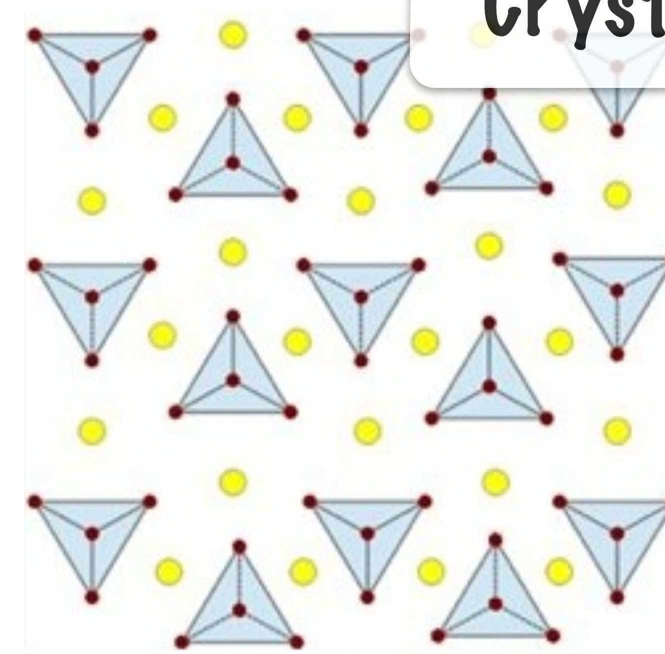
x=0 ferrosilite

Silicates



Amorphous





Crystalline

Olivine-type

$Mg_{2x}Fe_{2-2x}SiO_4$

Pyroxene-type

$Mg_xFe_{1-x}SiO_3$

evapor. & recondens.

evapor. & recondens.

T=1500 K

Olivines

x=1 forsterite (Mg only)

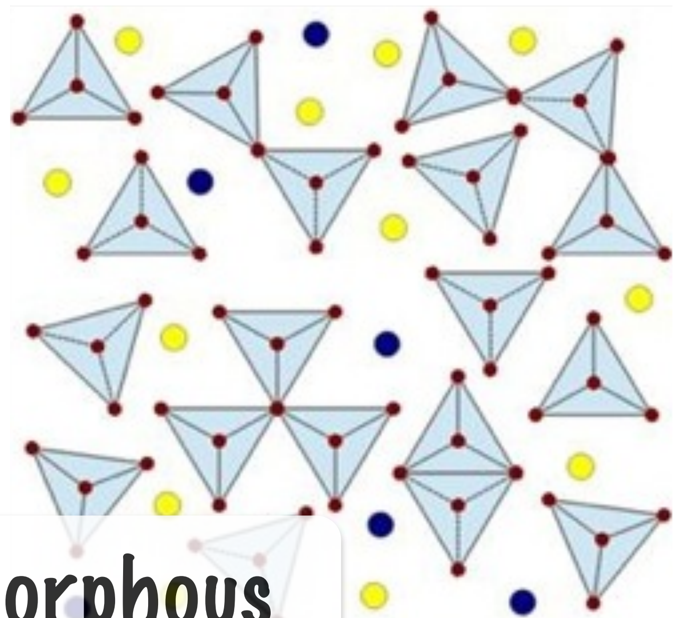
x=0 fayalite (Fe only)

Pyroxenes

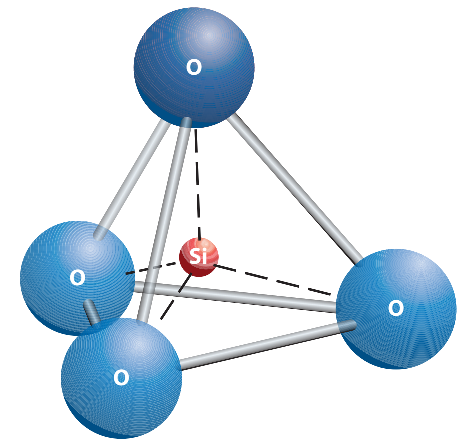
x=1 enstatite

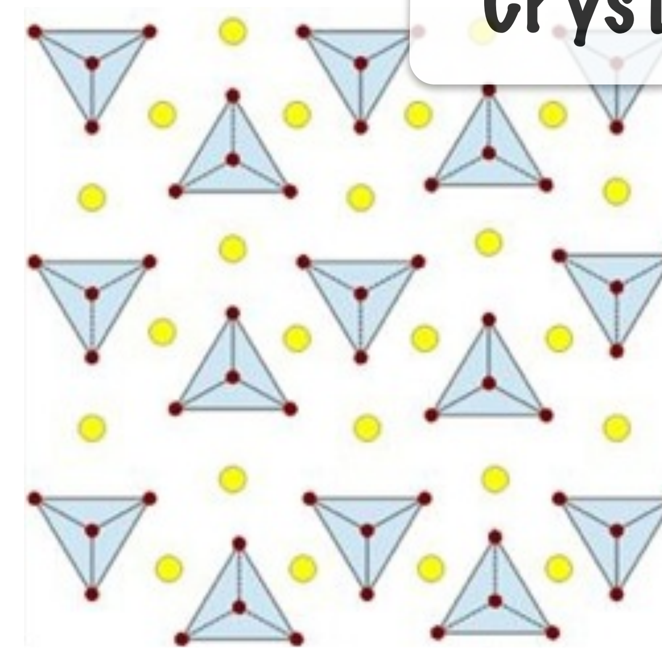
x=0 ferrosilite

Silicates



Amorphous





Crystalline

Olivine-type

$Mg_{2x}Fe_{2-2x}SiO_4$

Pyroxene-type

$Mg_xFe_{1-x}SiO_3$

evapor. & recondens.

evapor. & recondens.

T=1500 K

Olivines

x=1 forsterite (Mg only)

x=0 fayalite (Fe only)

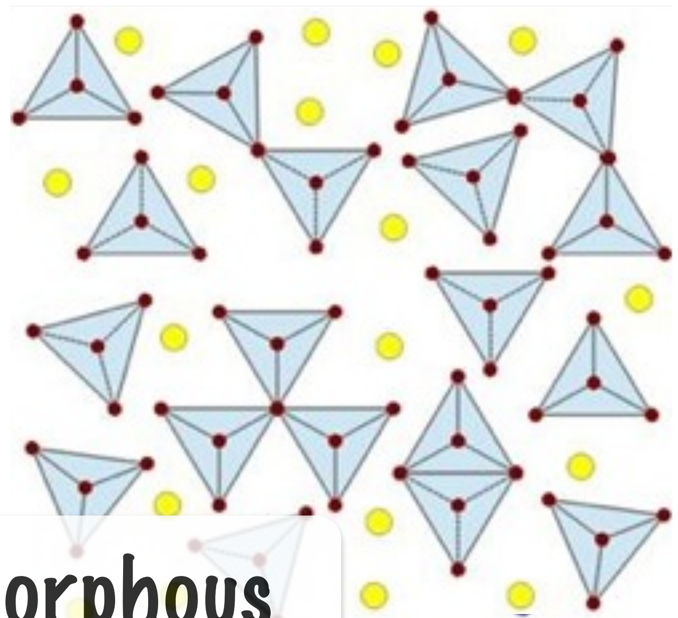
SiO_2

Pyroxenes T=1200 K

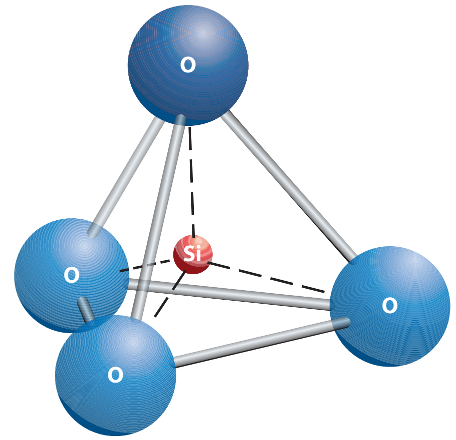
x=1 enstatite

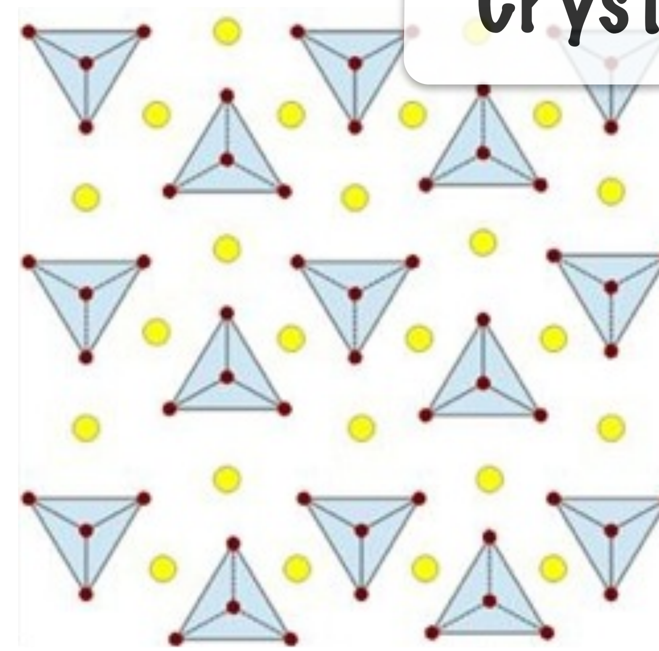
x=0 ferrosilite

Silicates



Amorphous





Crystalline

Olivine-type

$Mg_{2x}Fe_{2-2x}SiO_4$

Pyroxene-type

$Mg_xFe_{1-x}SiO_3$

destruction & re-condens. @ low T

cosmic rays

Olivines

x=1 forsterite (Mg only)

x=0 fayalite (Fe only)

Pyroxenes

x=1 enstatite

x=0 ferrosilite

Origin & initial composition

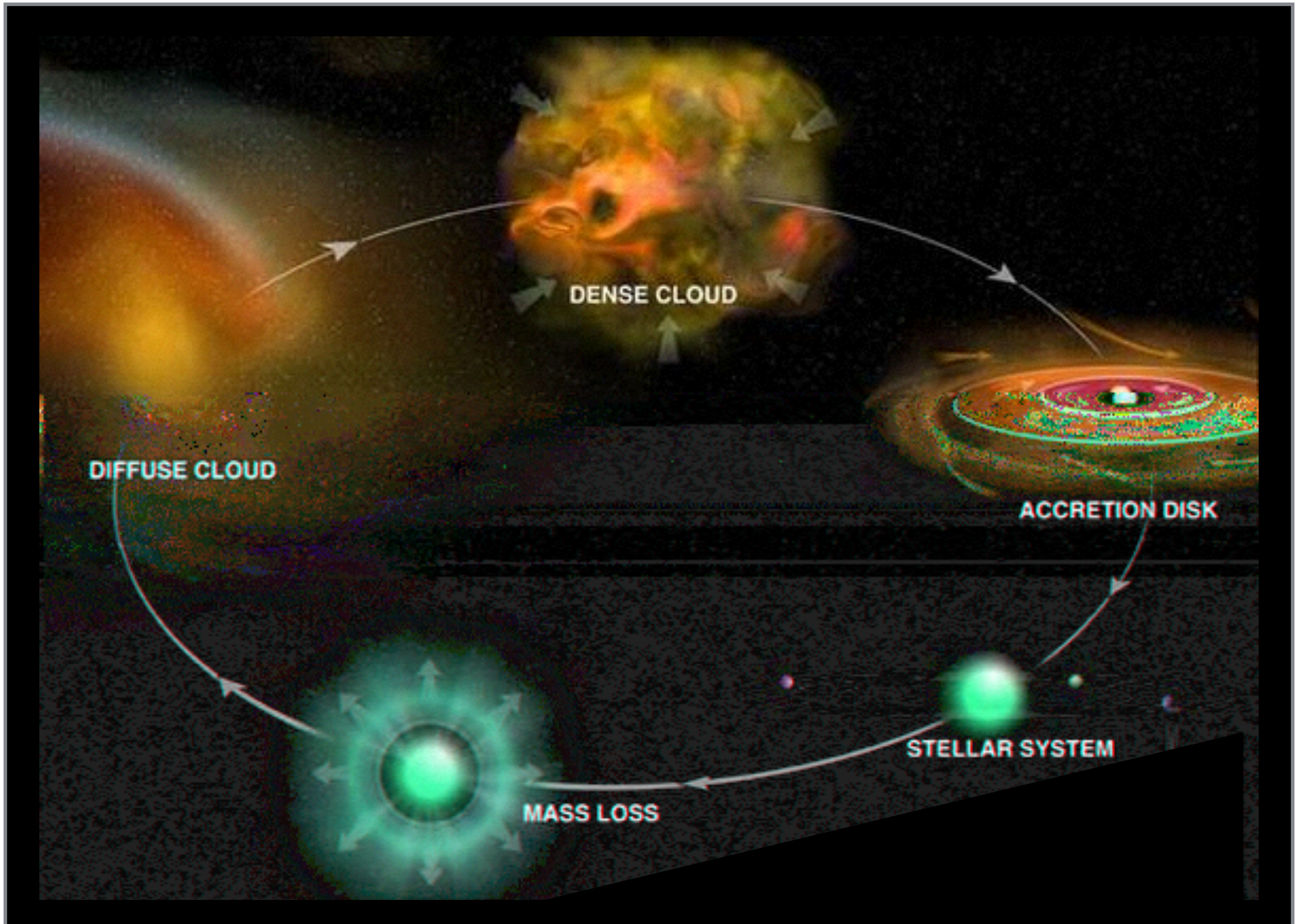


image credit: Bill Saxton, NRAO/AUI/NSF

Origin & initial composition

ISM silicates:
amorphous,
sub-micron sized

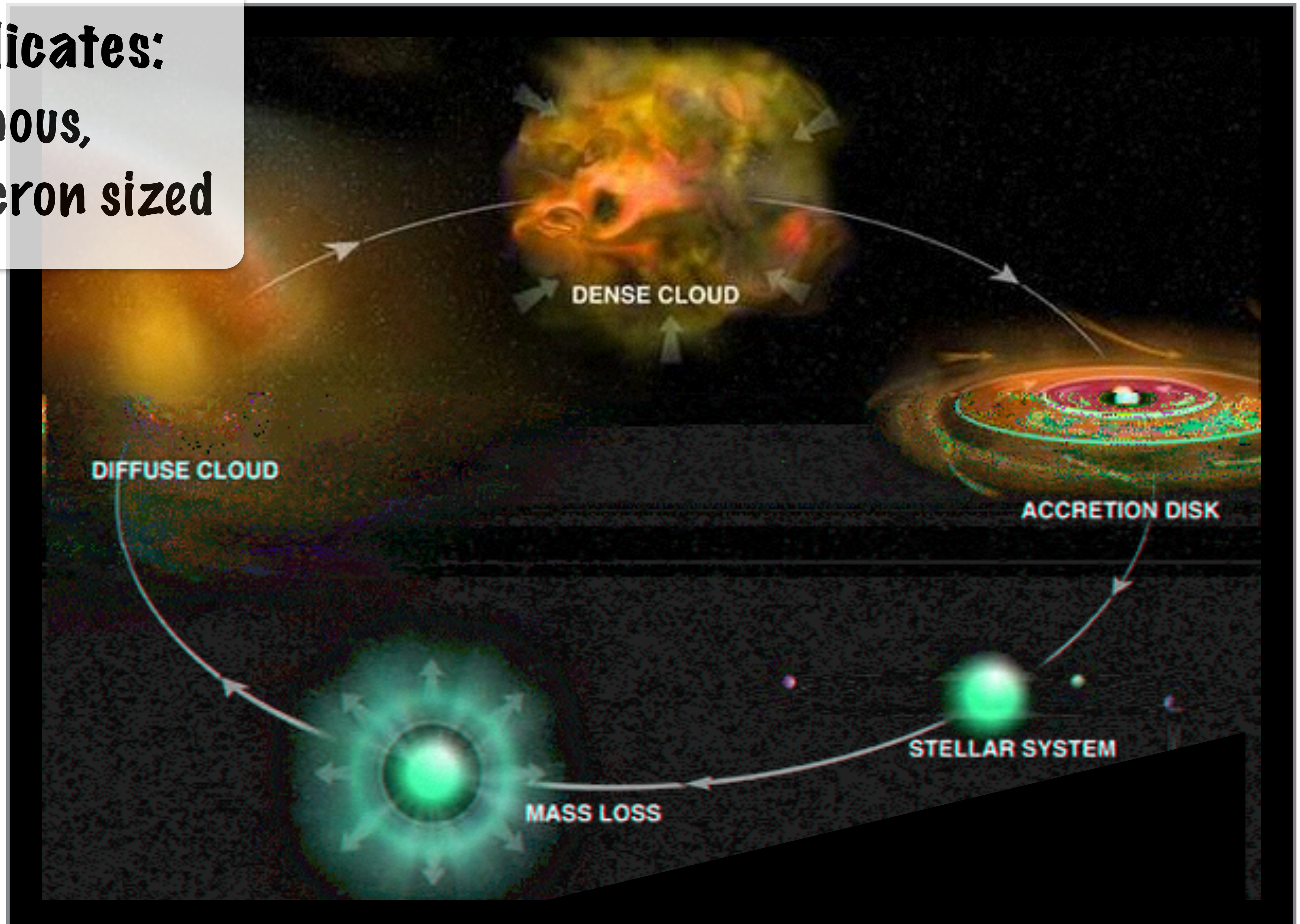
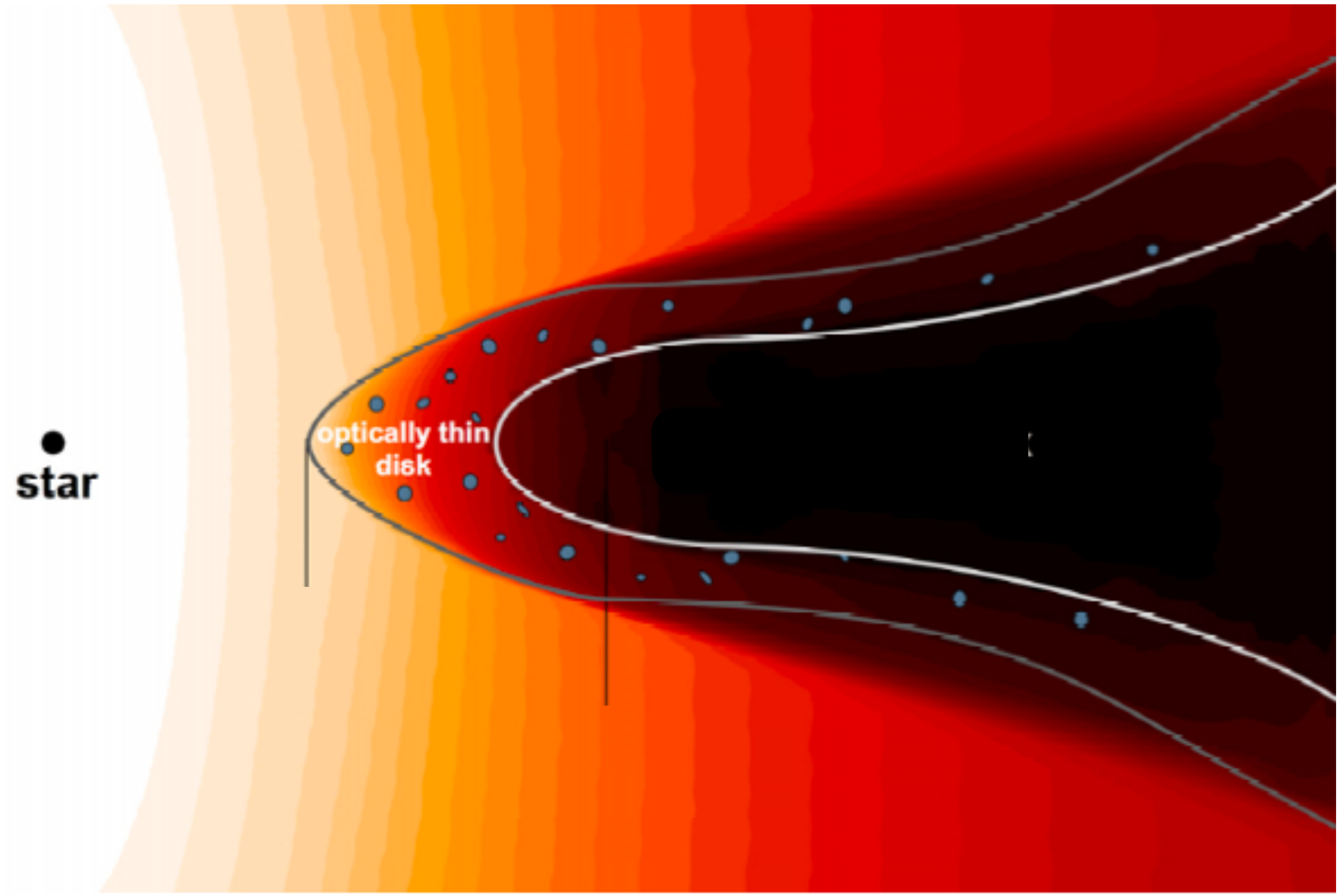


image credit: Bill Saxton, NRAO/AUI/NSF

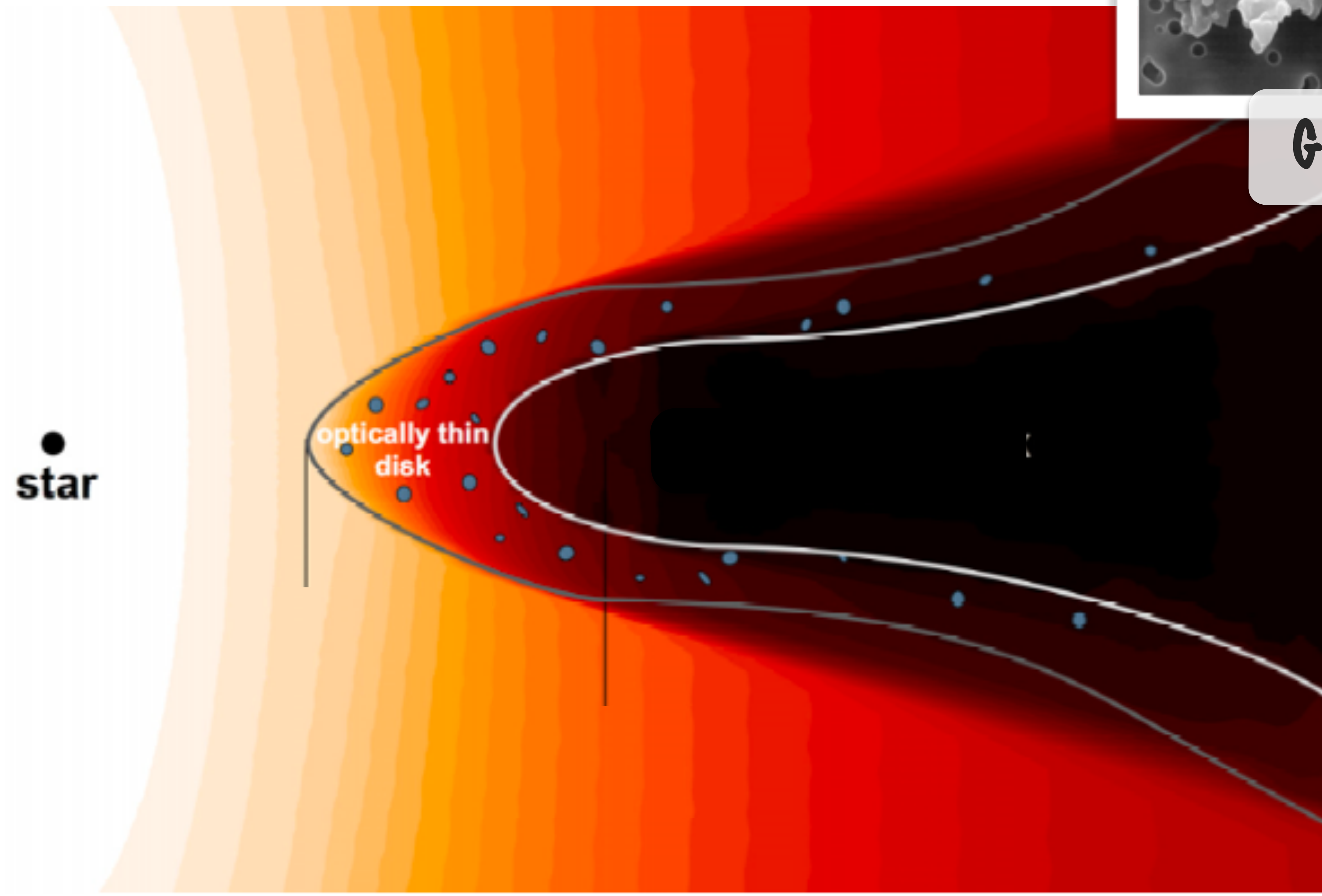
Main processes

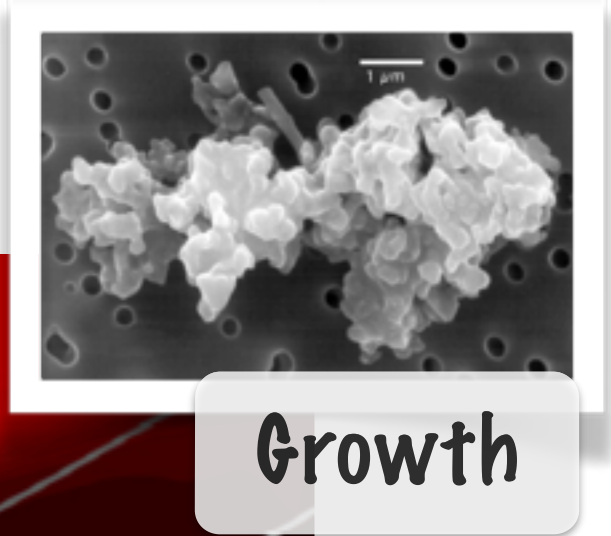
illustration by Kama



Main processes

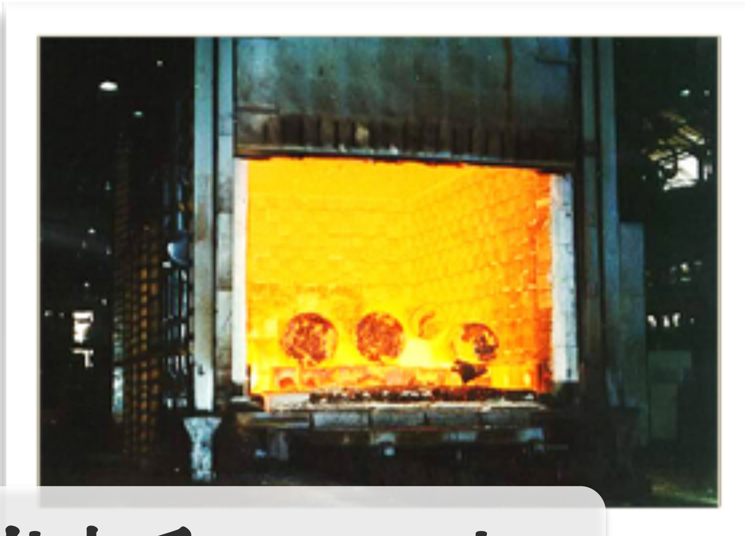
illustration by Kama



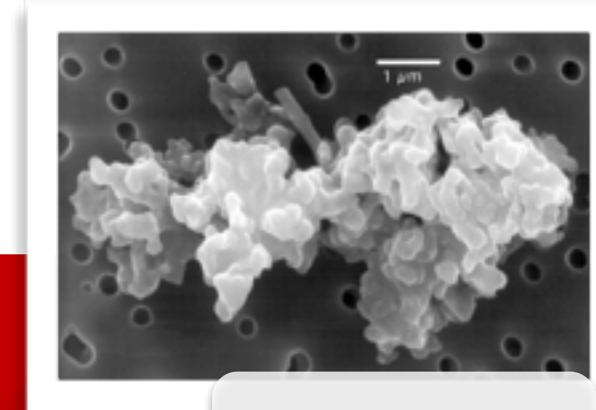


Main processes

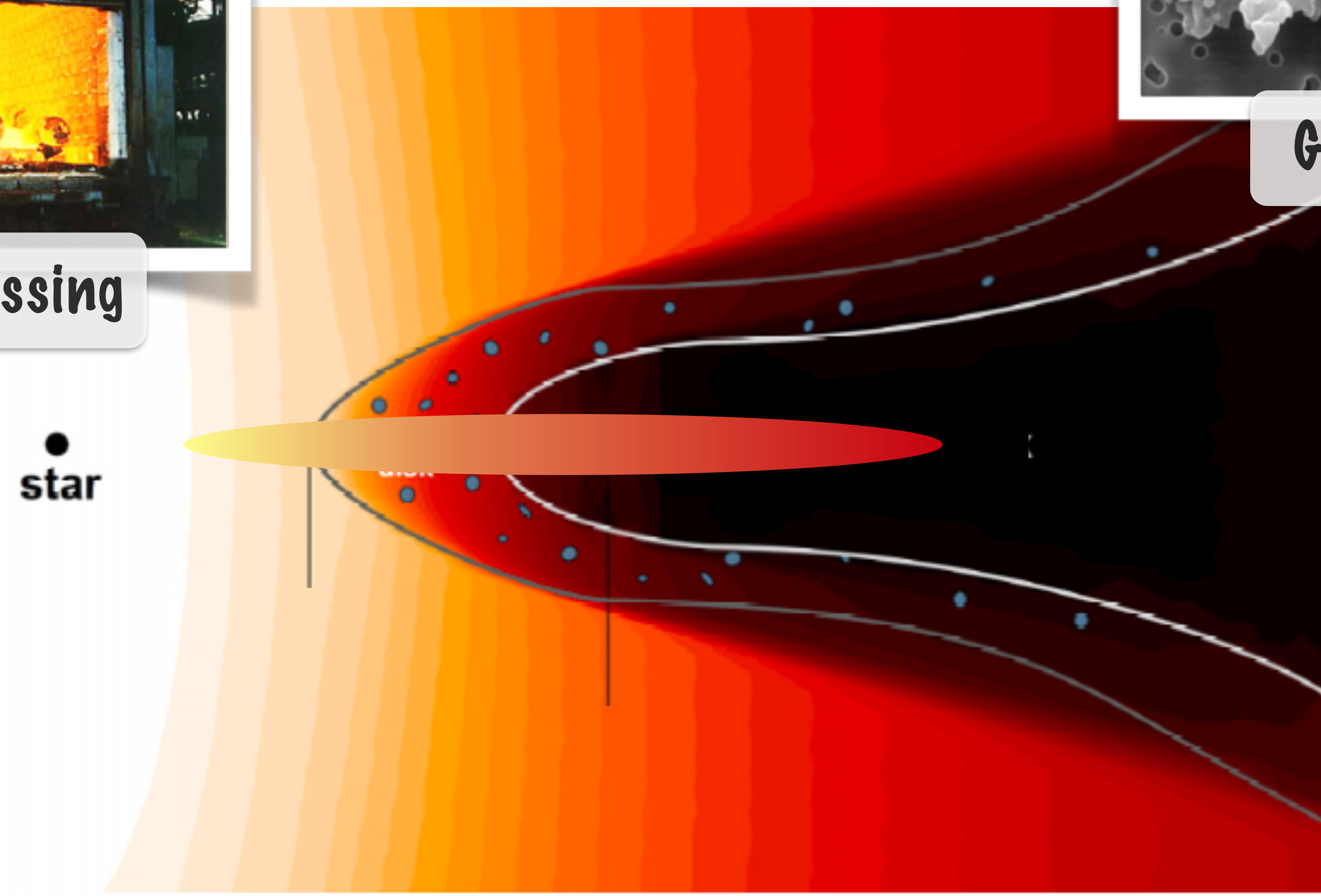
illustration by Kama



High-T processing



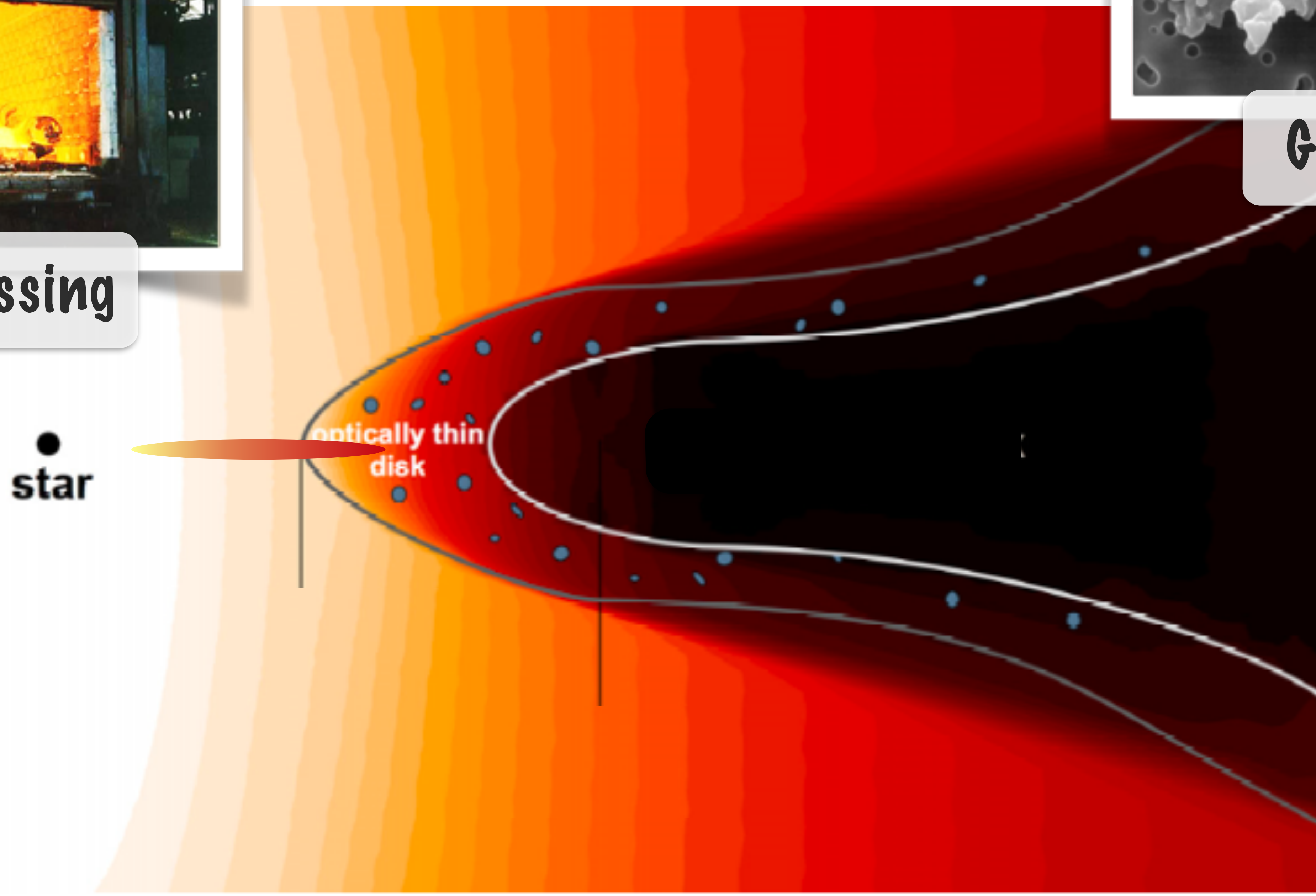
Growth

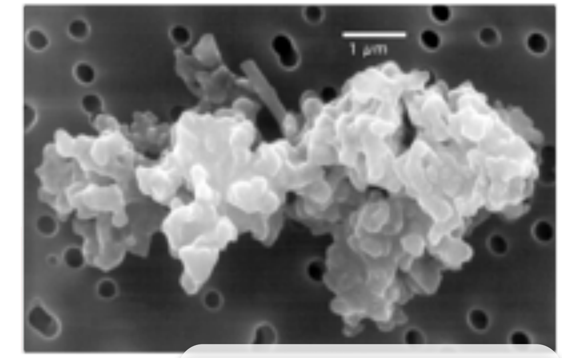


Main processes

illustration by Kama

High-T processing

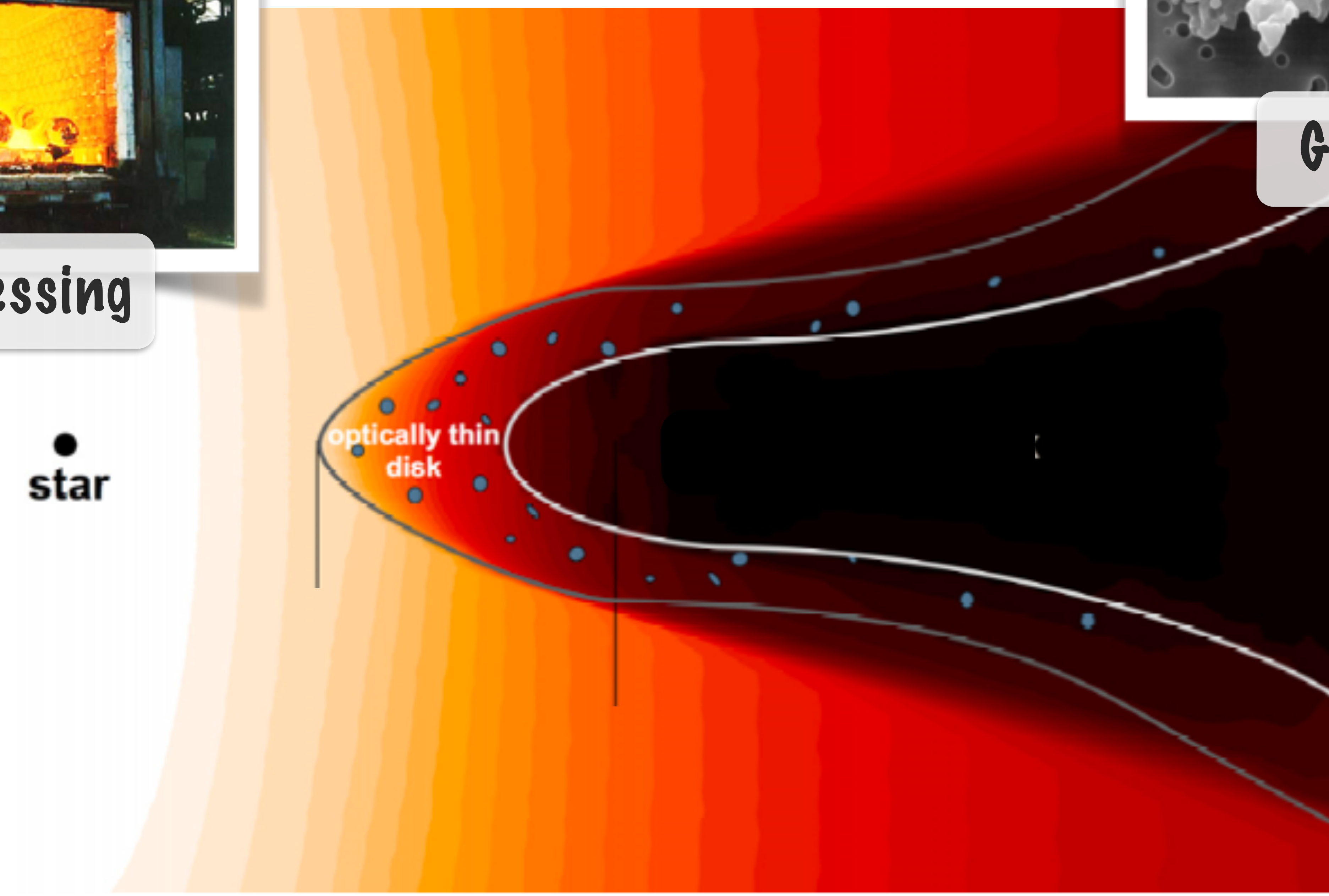


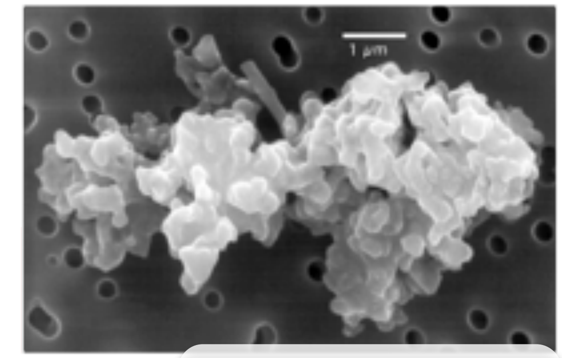


Growth

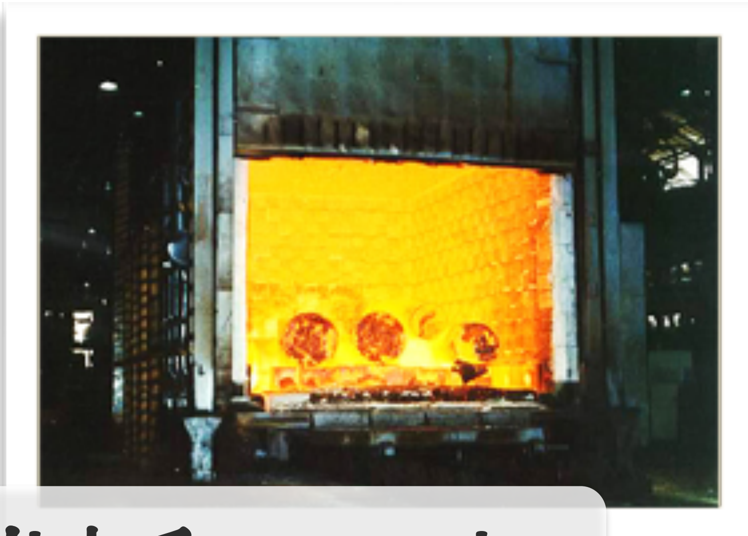
Main processes

illustration by Kama



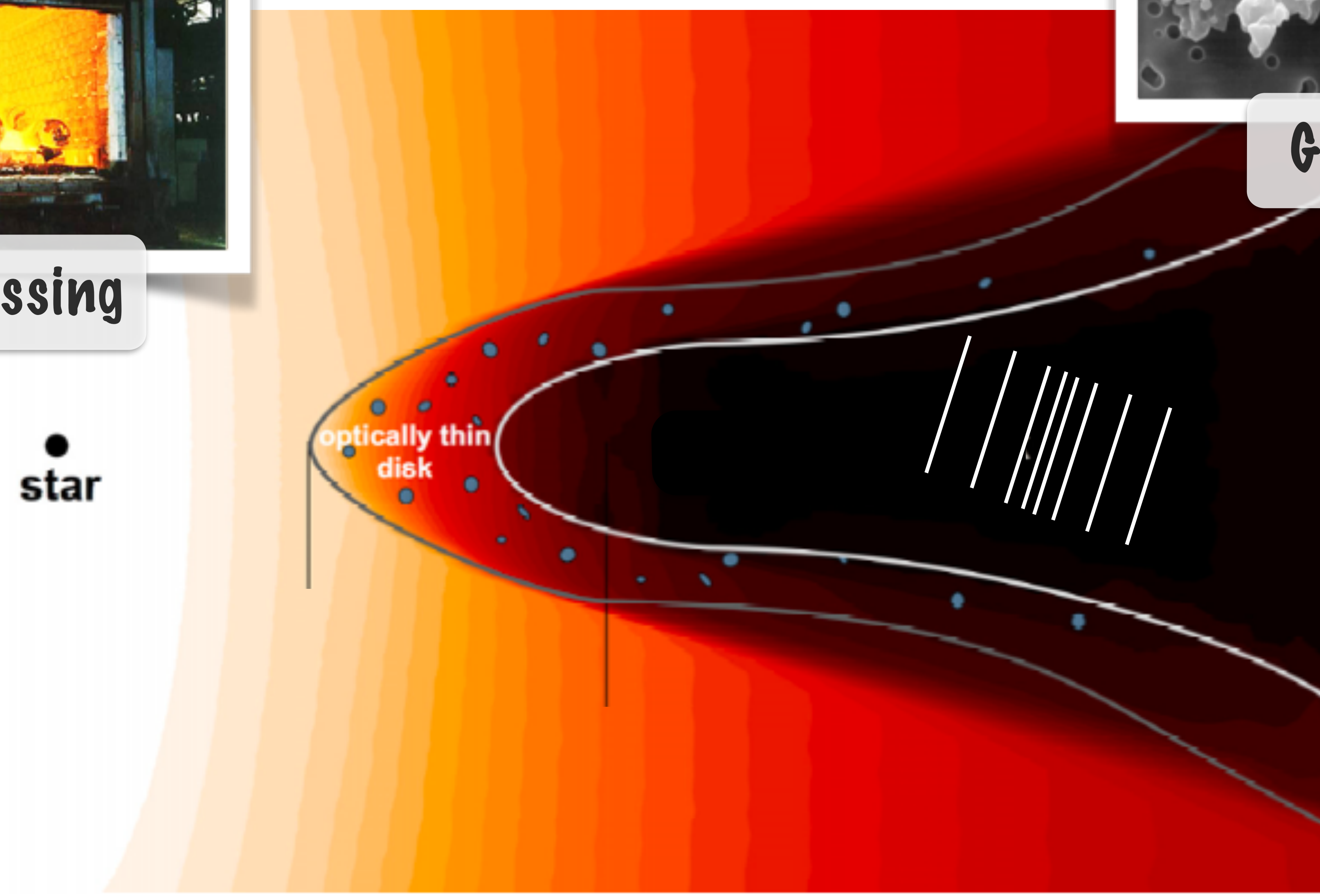


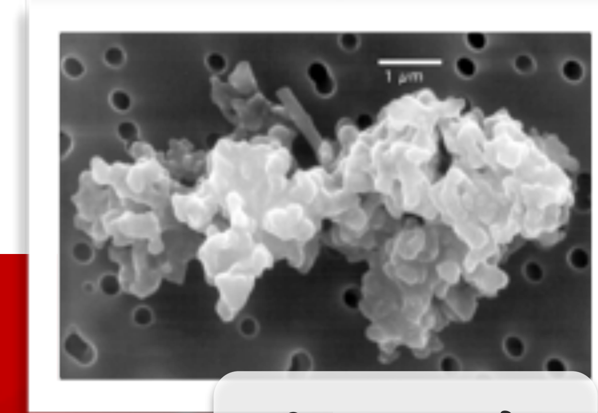
Main processes



High-T processing

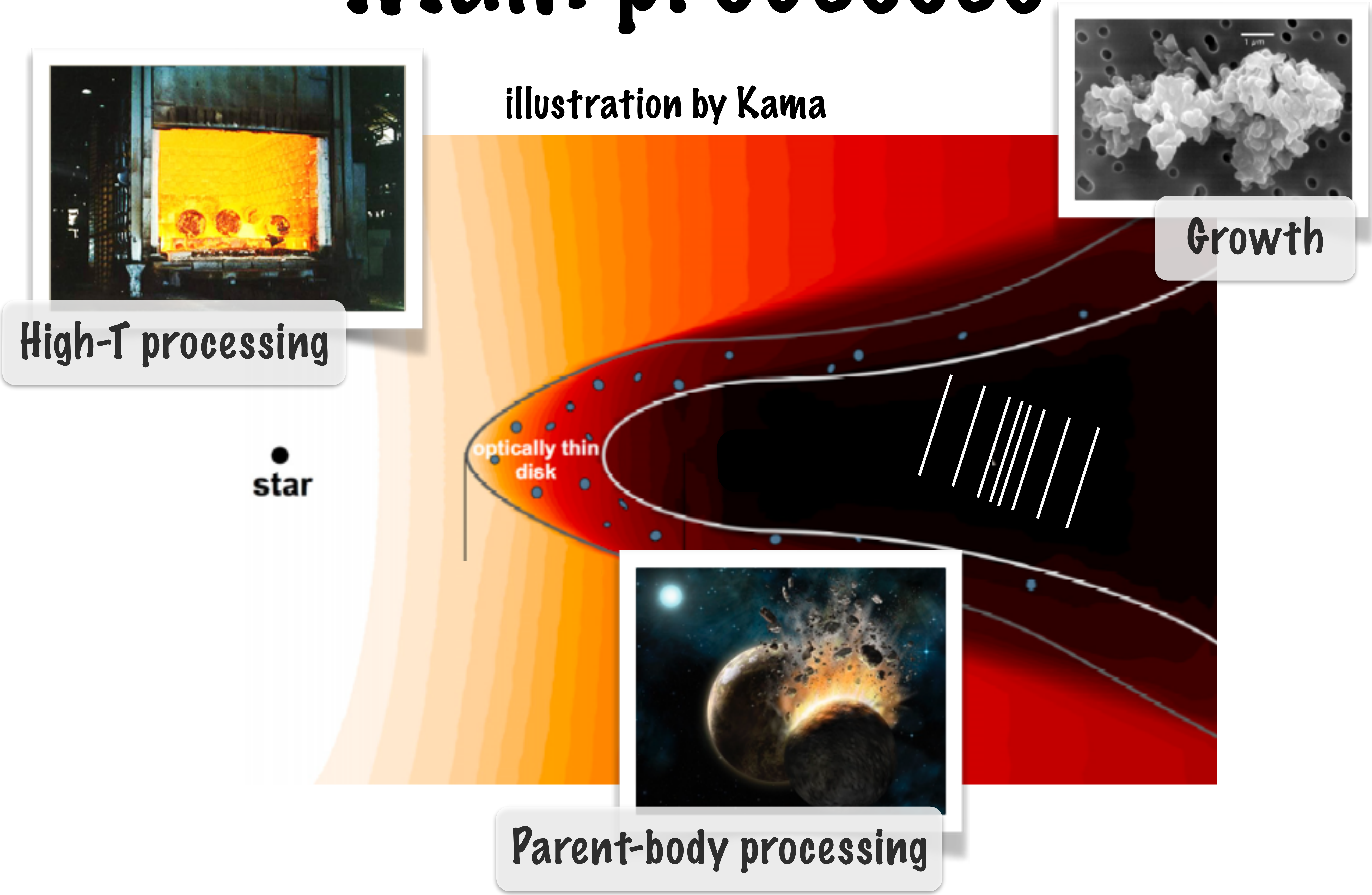
illustration by Kama





Growth

Main processes

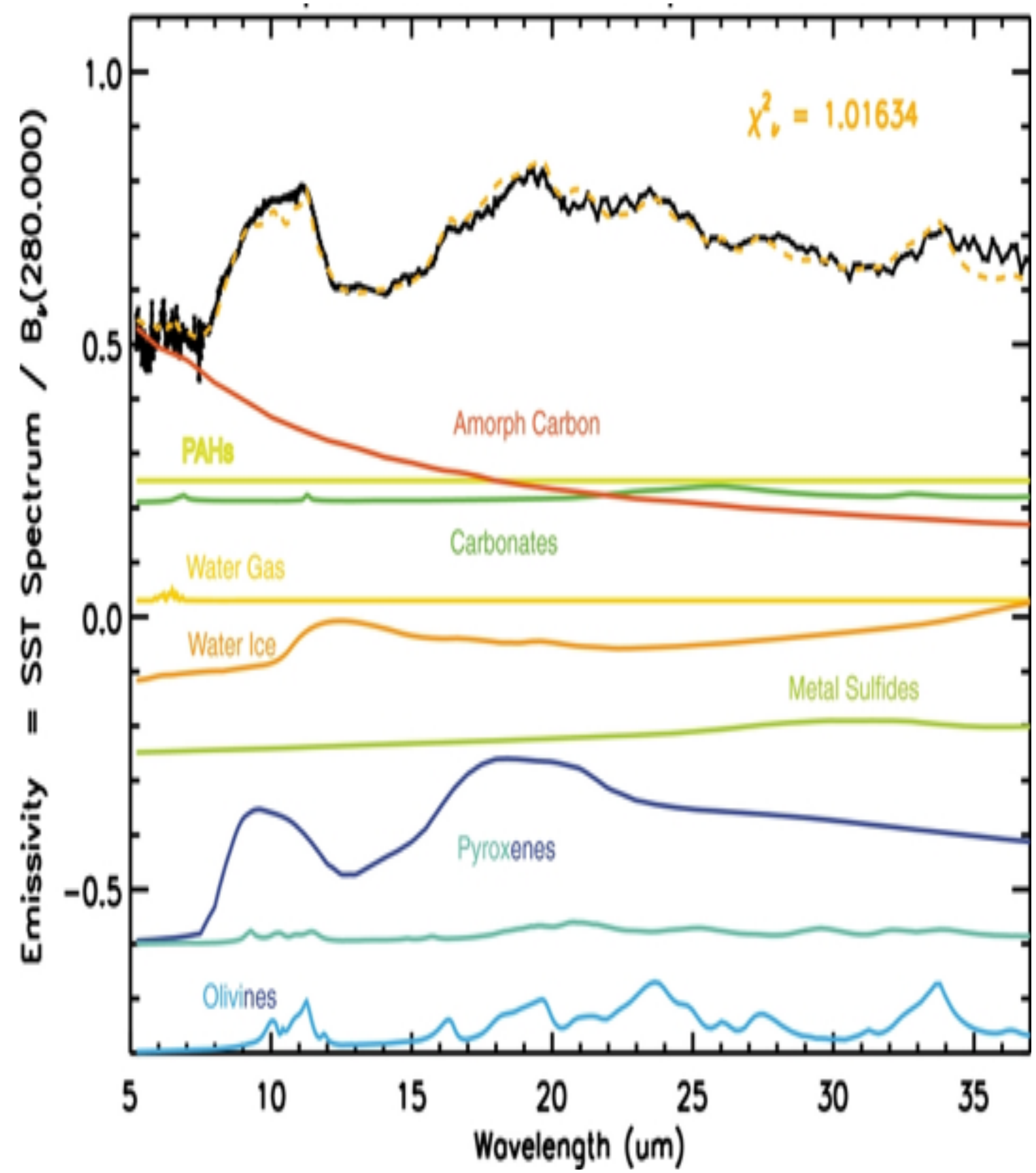


Spectral de-composition

- Opacities of dust species
  - lab measurements of λ-dependent opacities or optical constants
  - optical constants → opacities

- Model to calculate spectra
  - single/two temperature model (e.g. van Boekel et al. 2004, 2005; Bouwman et al. 2008)
  - two-layer Temperature Distribution (Juhasz et al. 2007)
  - full Radiative Transfer disk model (e.g. Mulders et al. 2013)

illustration from Sitko et al. (2011)

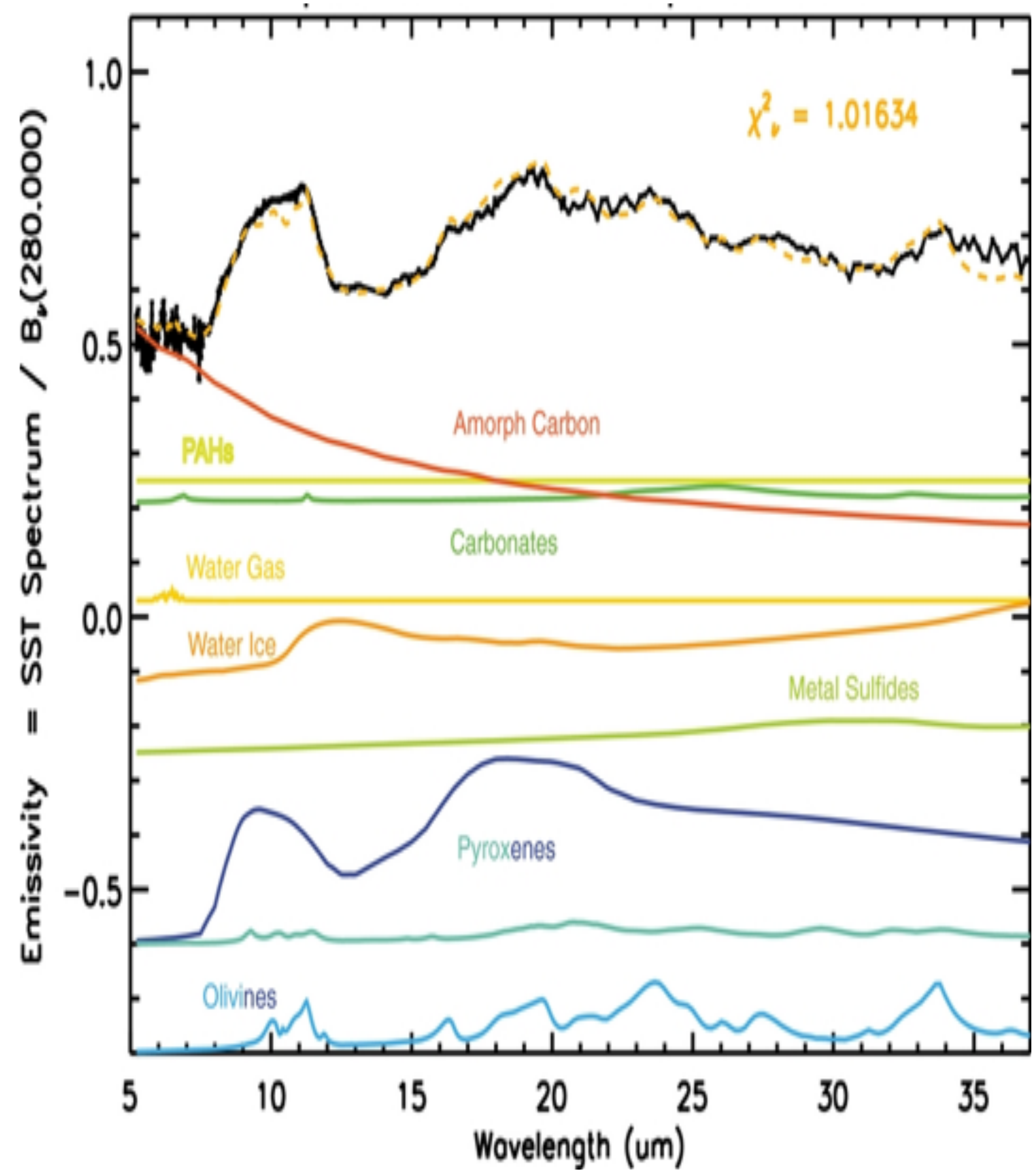


Spectral de-composition

- Opacities of dust species
  - lab measurements of λ-dependent opacities or optical constants
  - optical constants → opacities

- Model to calculate spectra
  - single/two temperature model (e.g. van Boekel et al. 2004, 2005; Bouwman et al. 2008)
  - two-layer Temperature Distribution (Juhasz et al. 2007)
  - full Radiative Transfer disk model (e.g. Mulders et al. 2013)

illustration from Sitko et al. (2011)



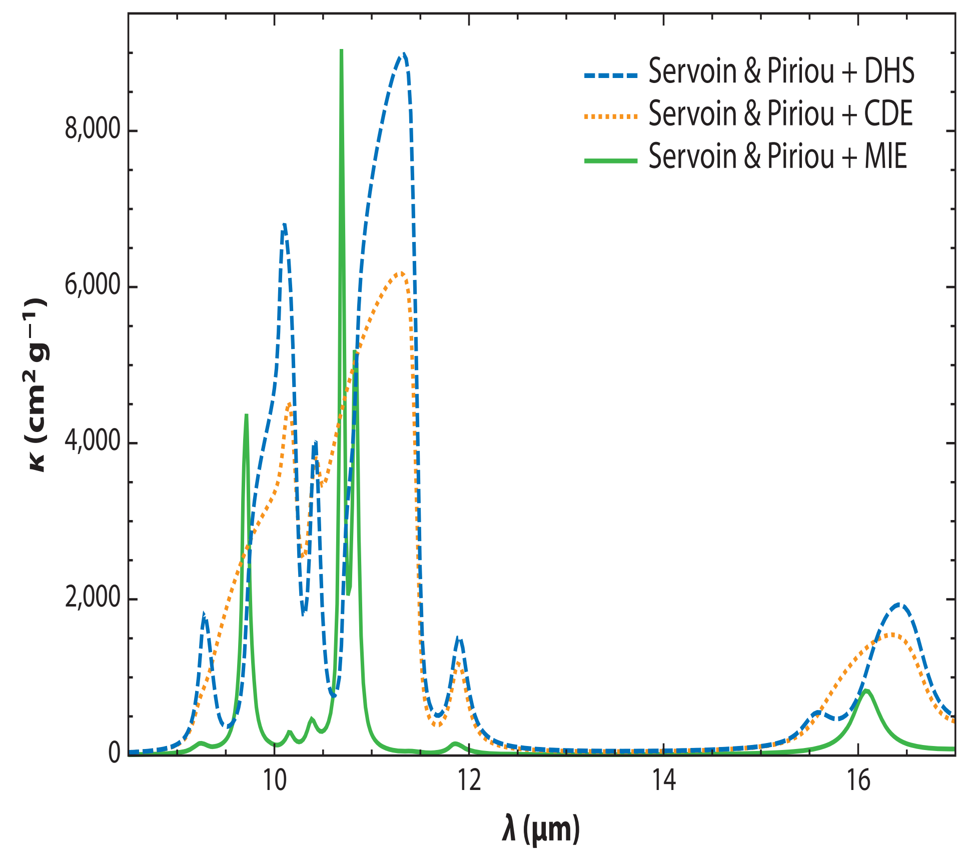
Lab measurements are important!

- Opacities depend on
  - exact composition / impurities
  - particle size / shape / structure
  - temperature

- elaborate measurements!
  - large wavelength range
  - wide range of techniques
  - representative conditions

  - Heidelberg-Jena-St. Petersburg database (Huisken, Jaeger, Dorschner, Mutschke, Henning, et al.)
  - Koike, Suto, Sogawa, Murata, et al.

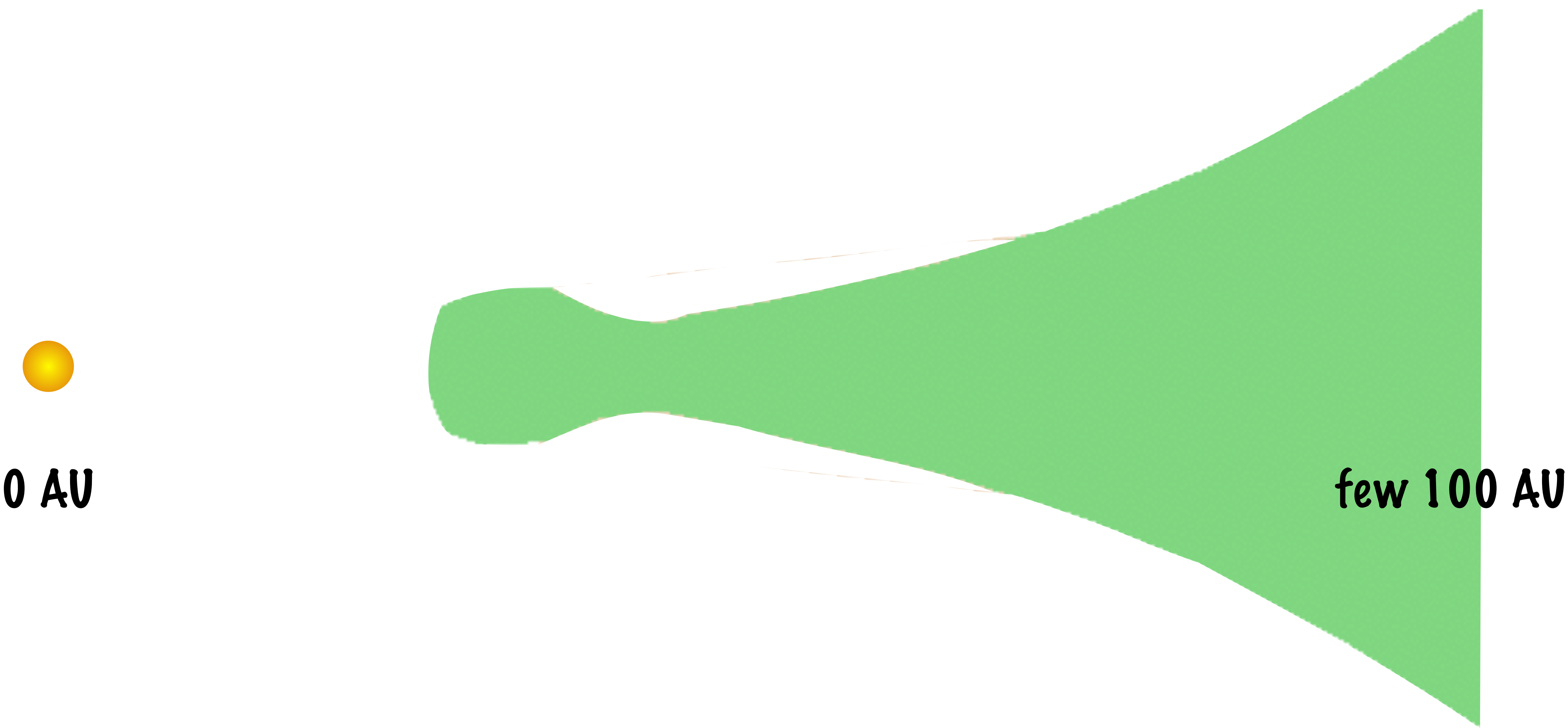
from Henning (2010, ARAA, 48, 21)



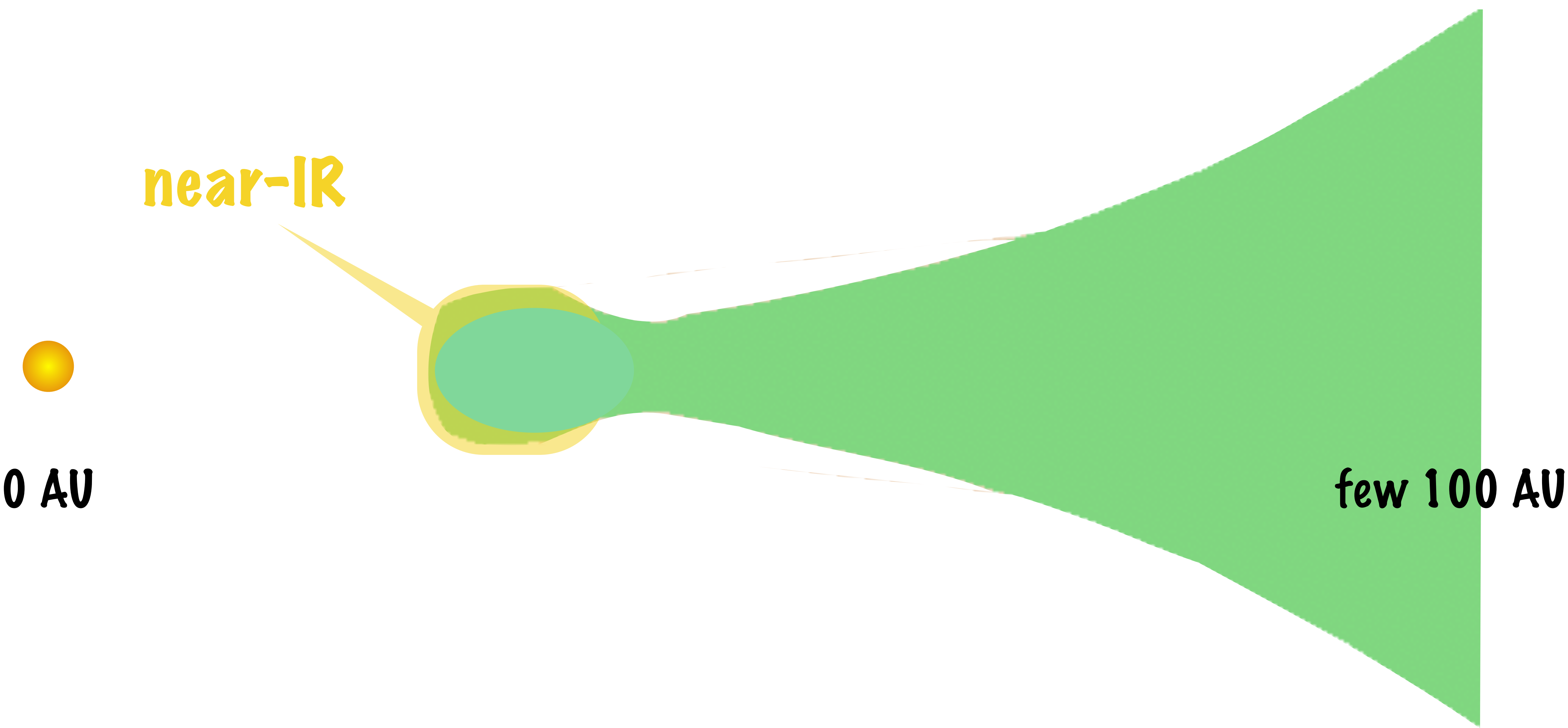
Composition from spectra:
CAVEATS !!!

- Uncertainties in opacities
- Dust properties vary with location in disk
- Need to know/model density + Temperature Structure
- We "see" only minor fraction of dust mass

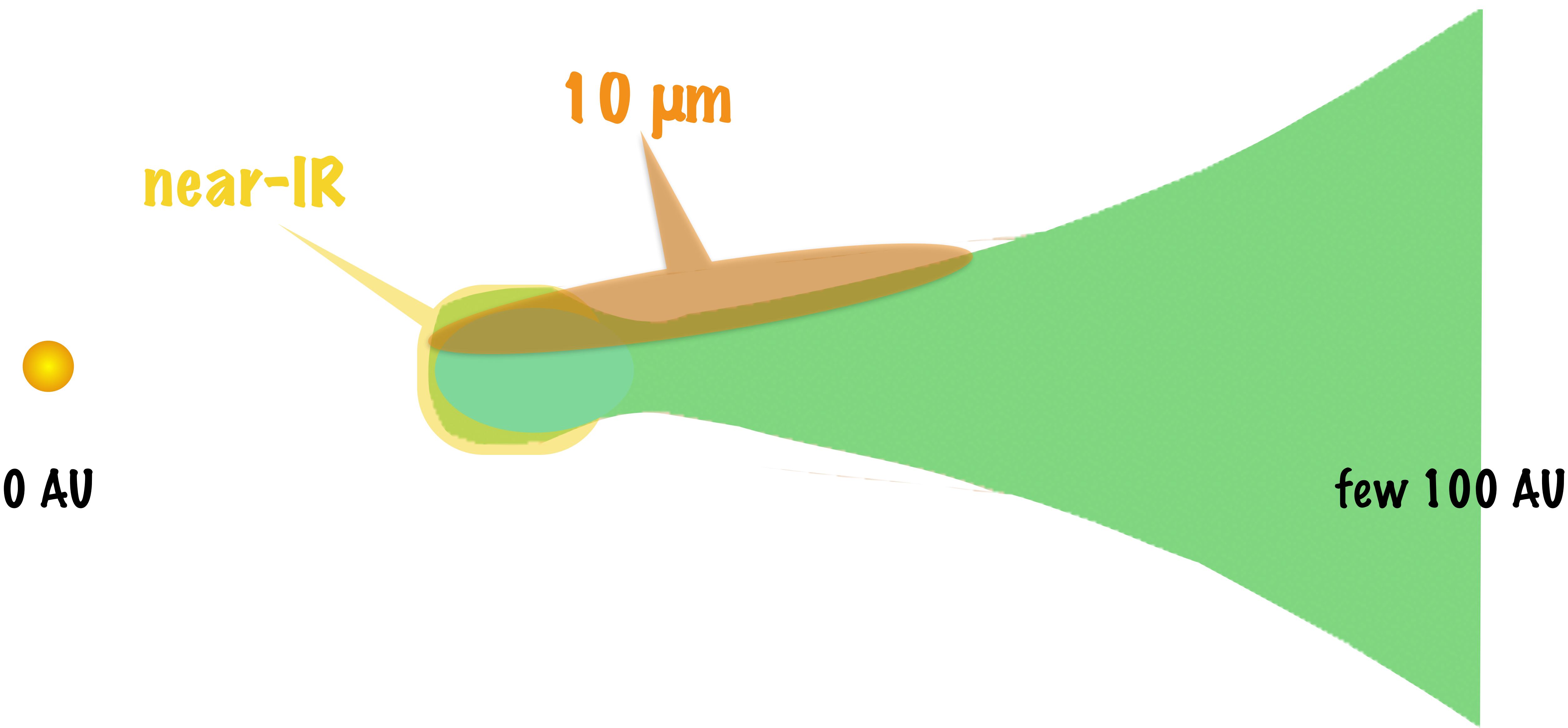
which regions do we see?



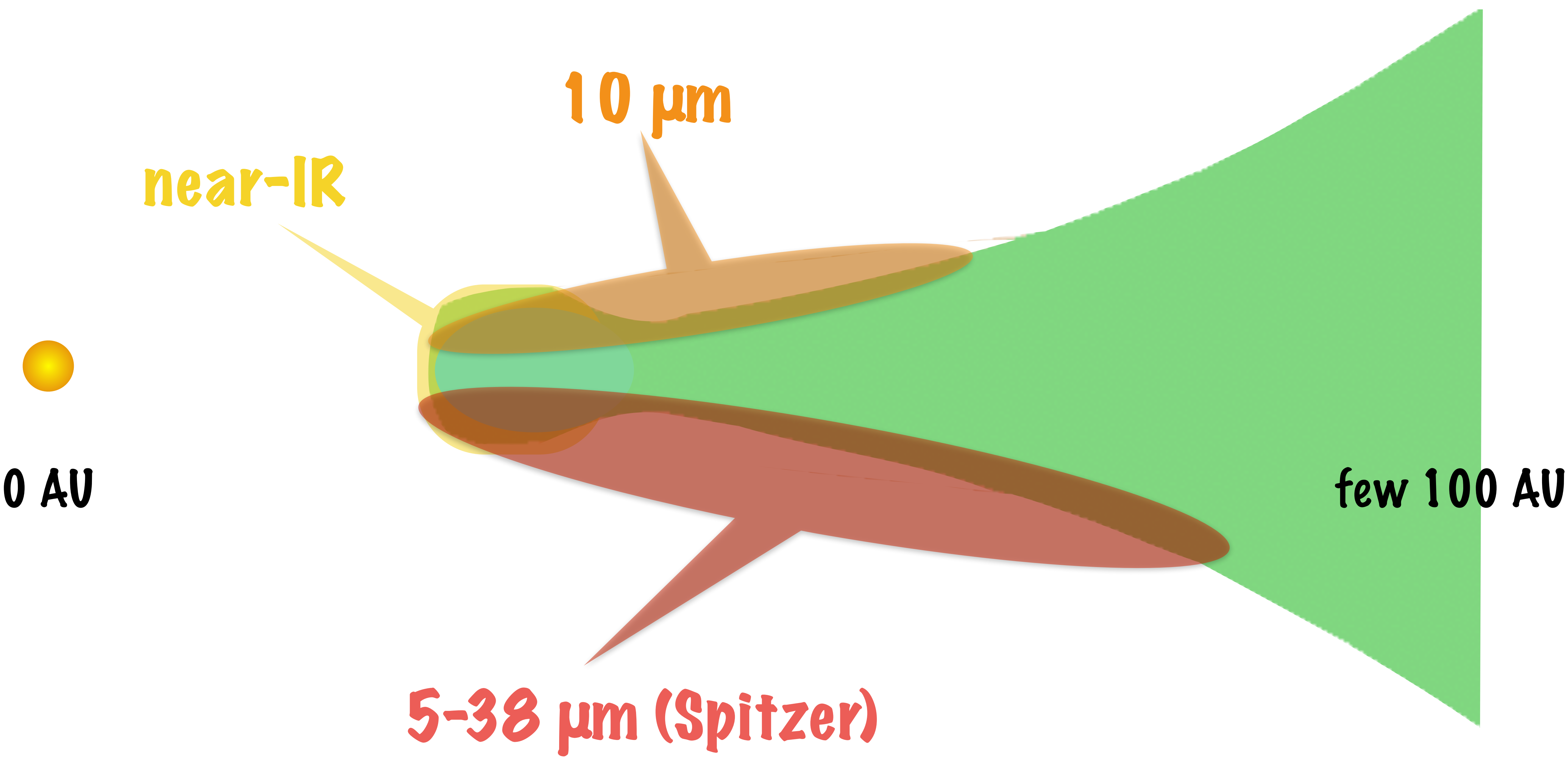
which regions do we see?



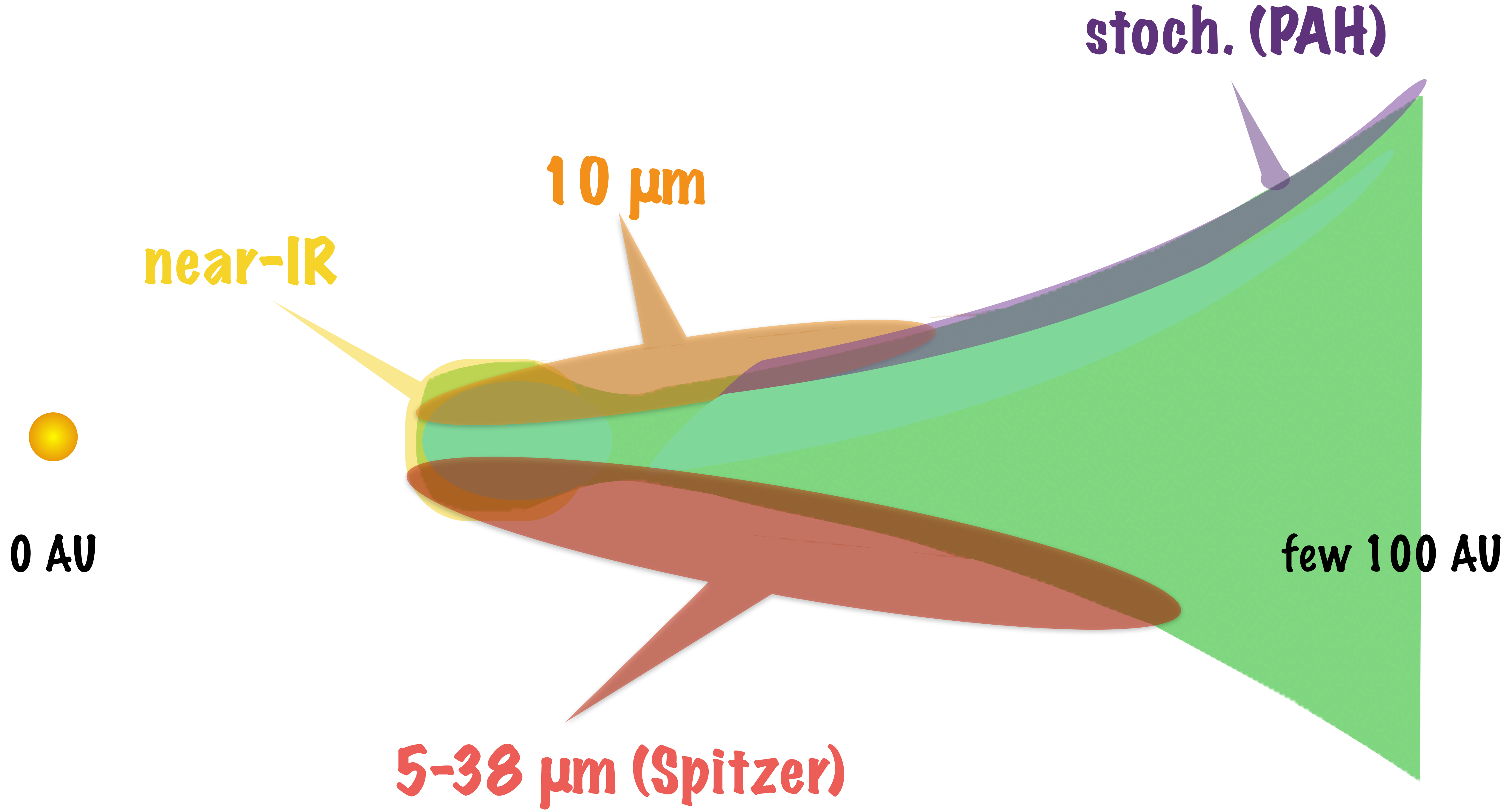
which regions do we see?



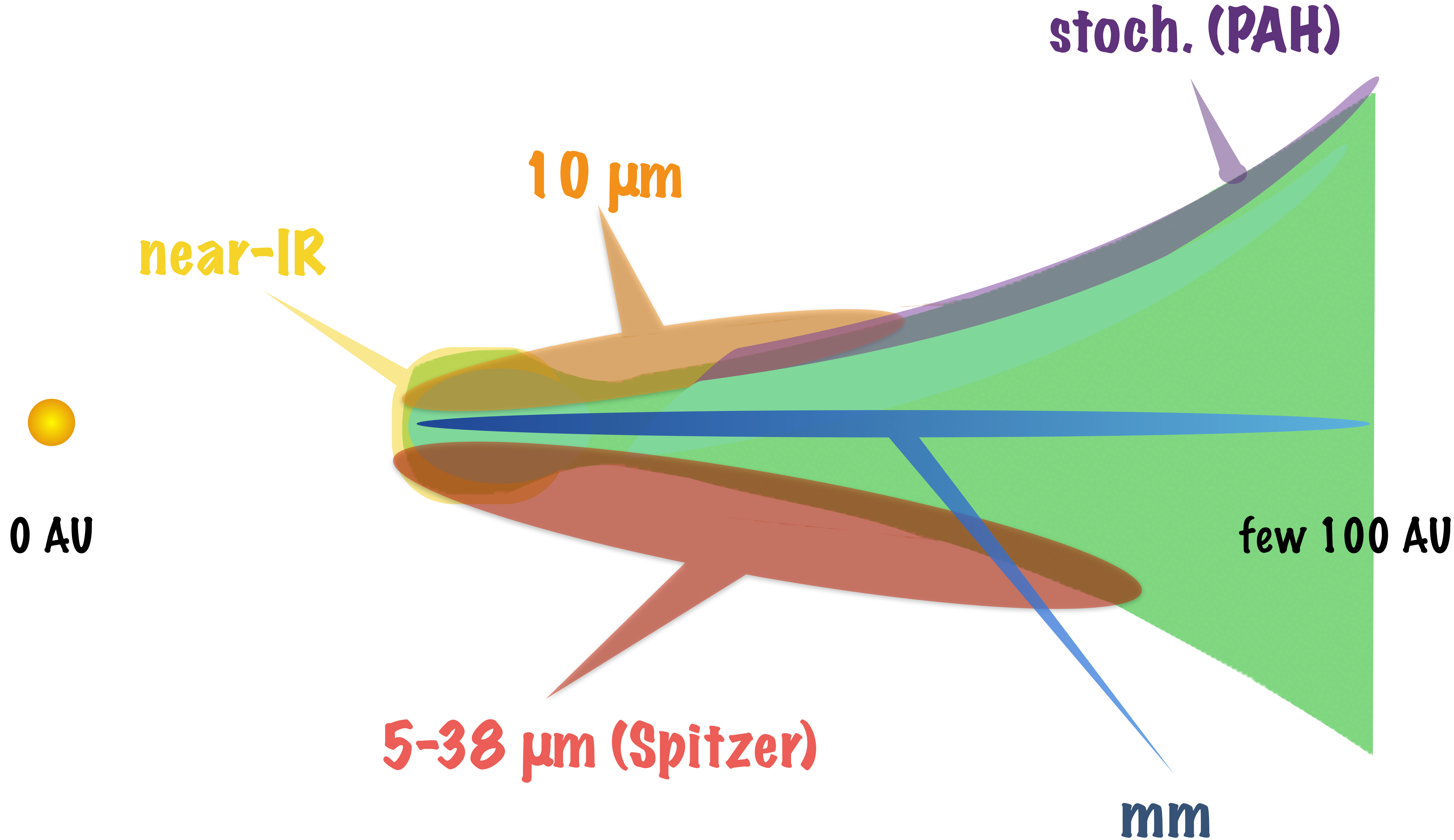
which regions do we see?



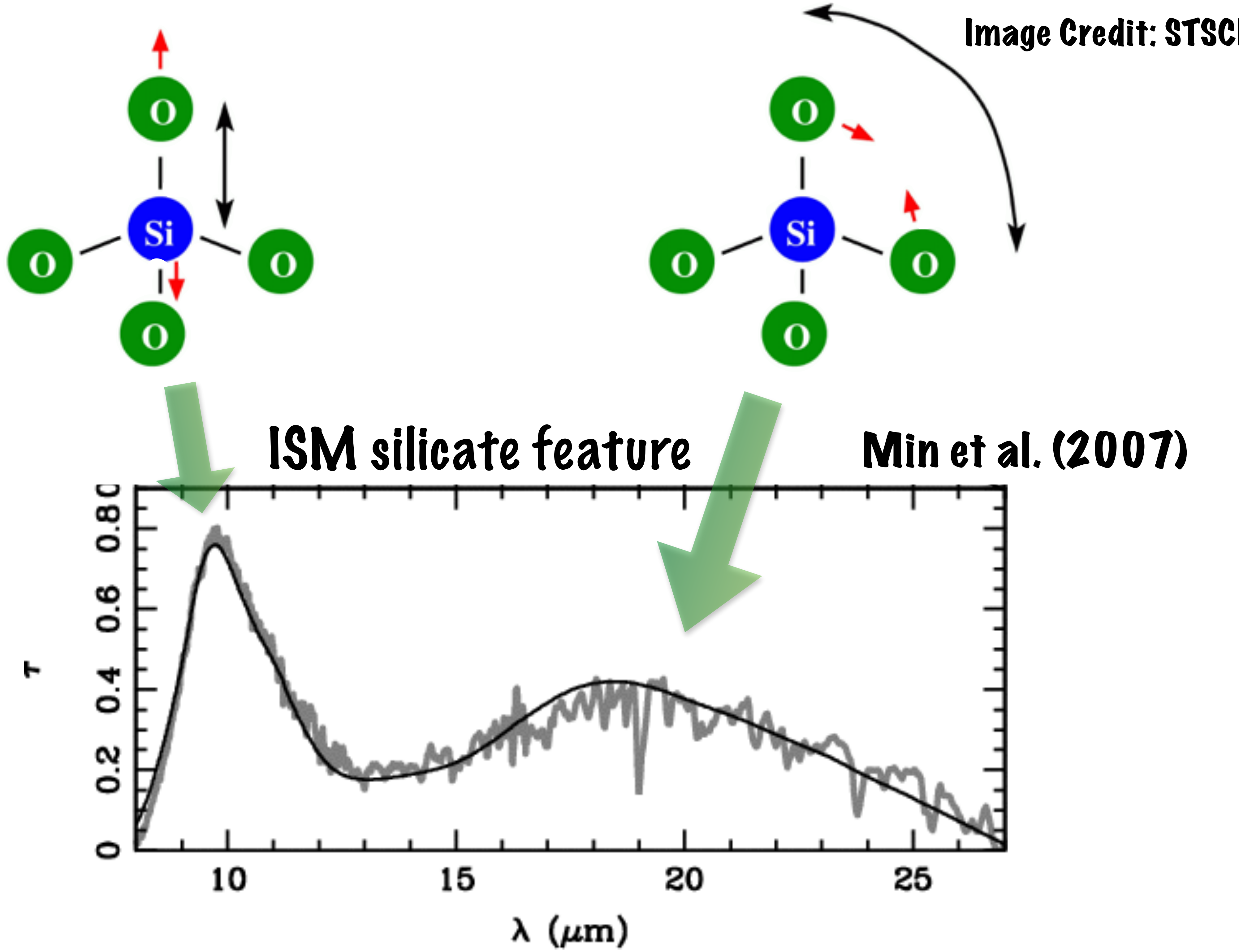
which regions do we see?



which regions do we see?

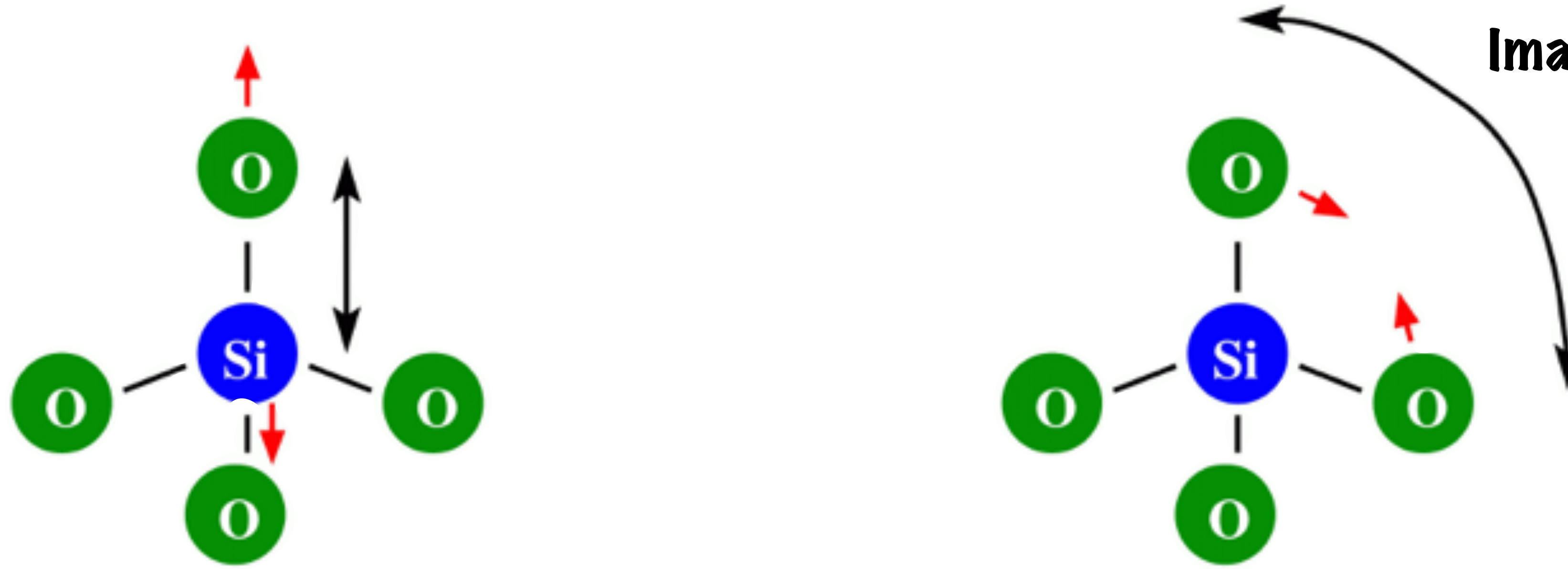


Silicates spectroscopy



Silicates spectroscopy

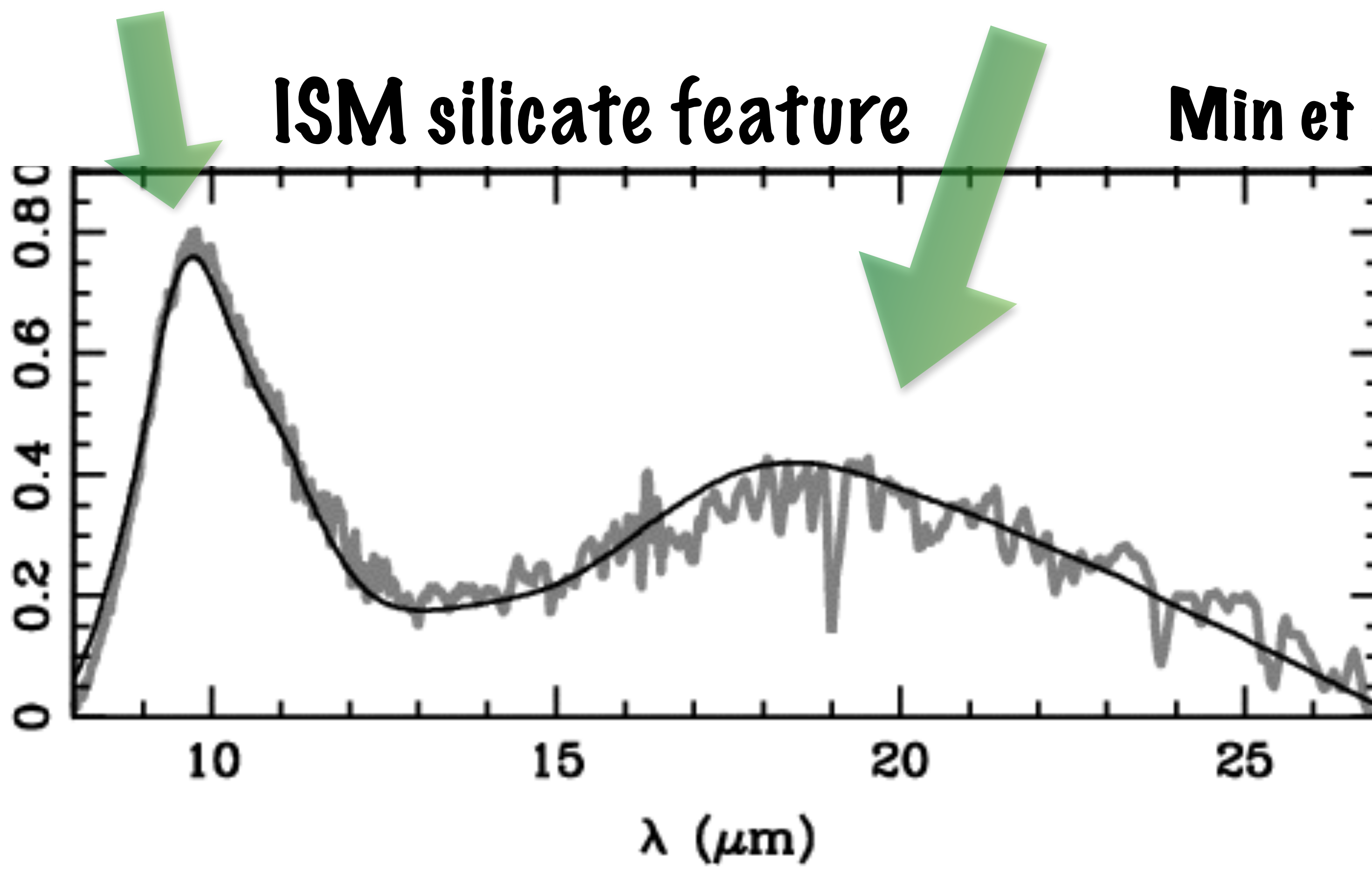
Image Credit: STSCI



ISM silicate feature

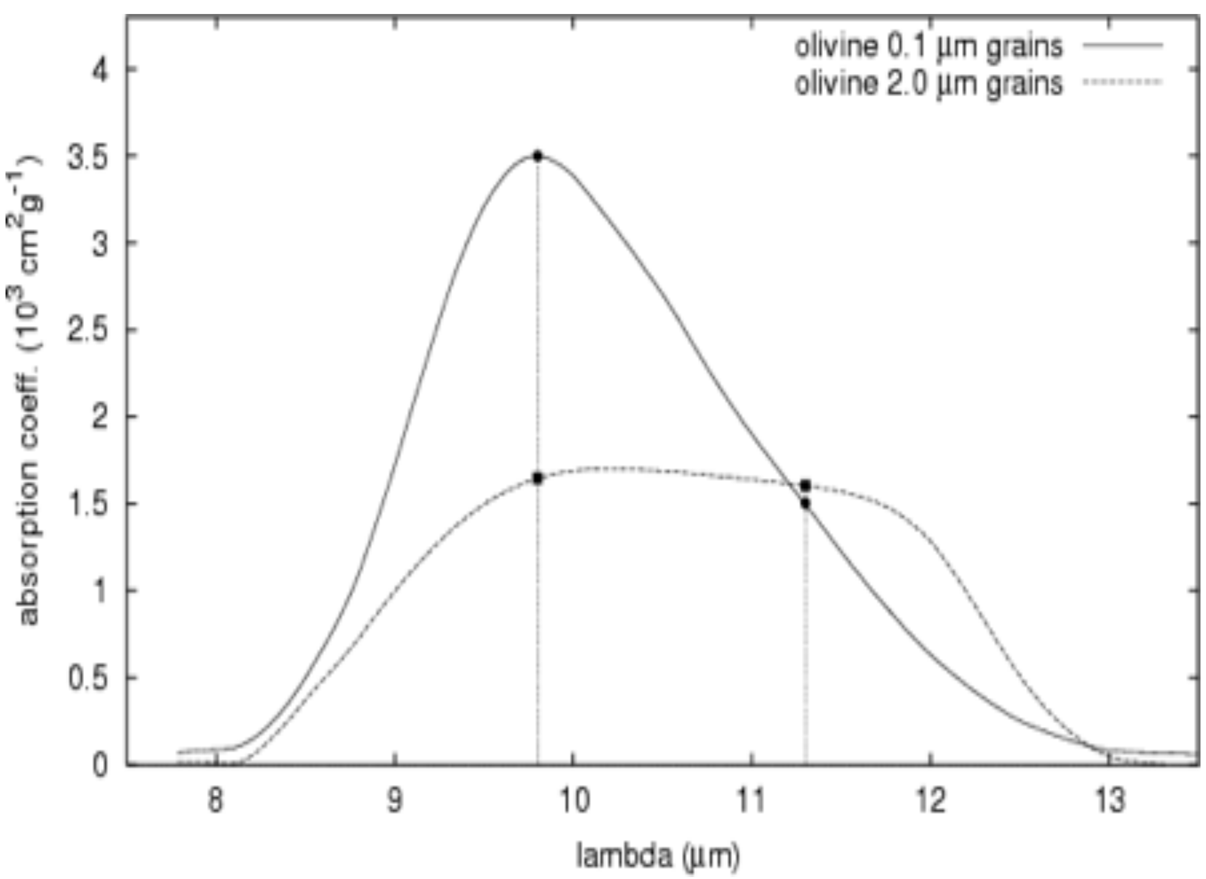
Min et al. (2007)

ISM:
amorphous
sub-micron sized

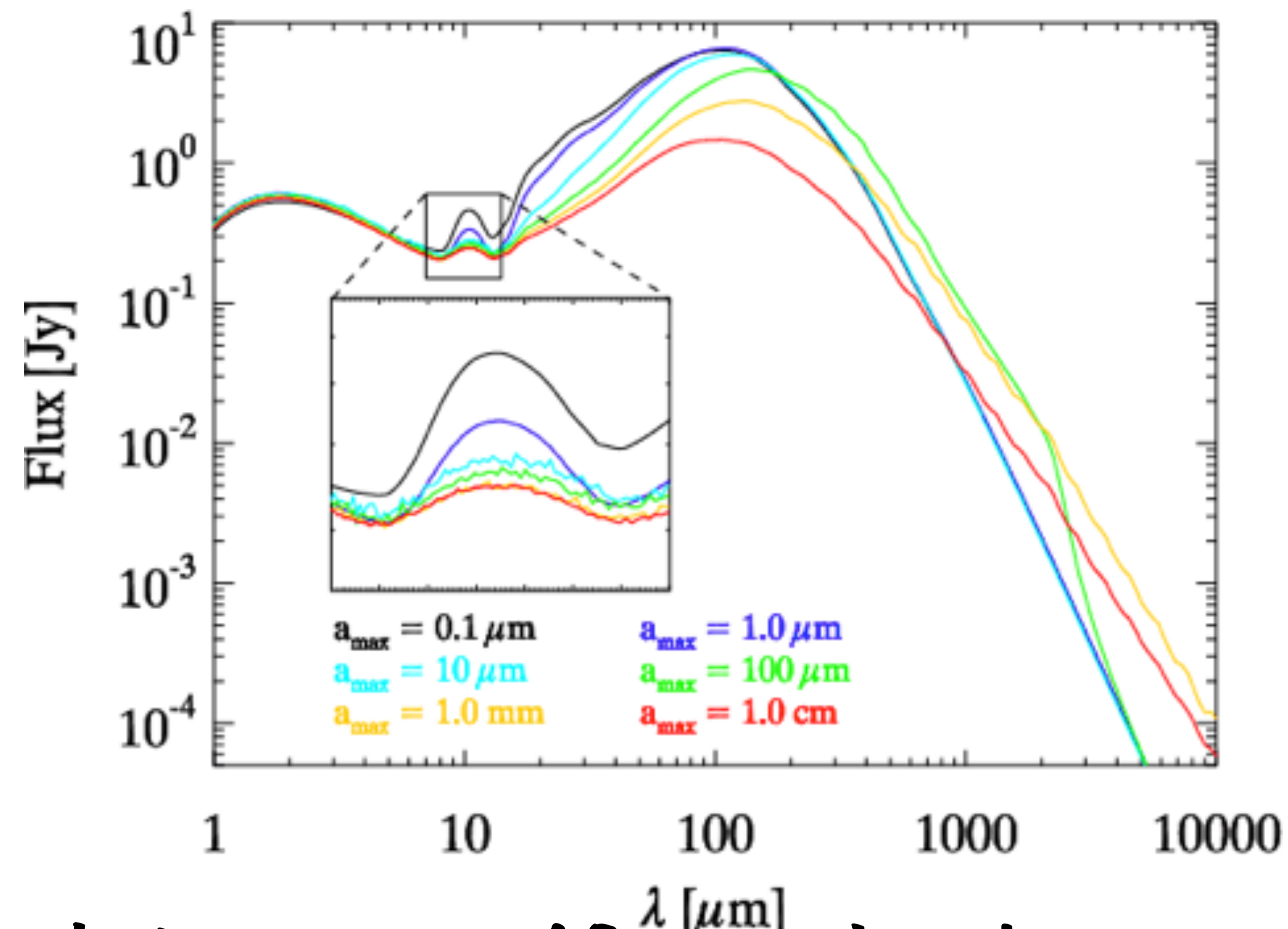


Silicates - grain growth

e.g. Bouwman et al. (2001)
Voschinnikov & Henning (2008)



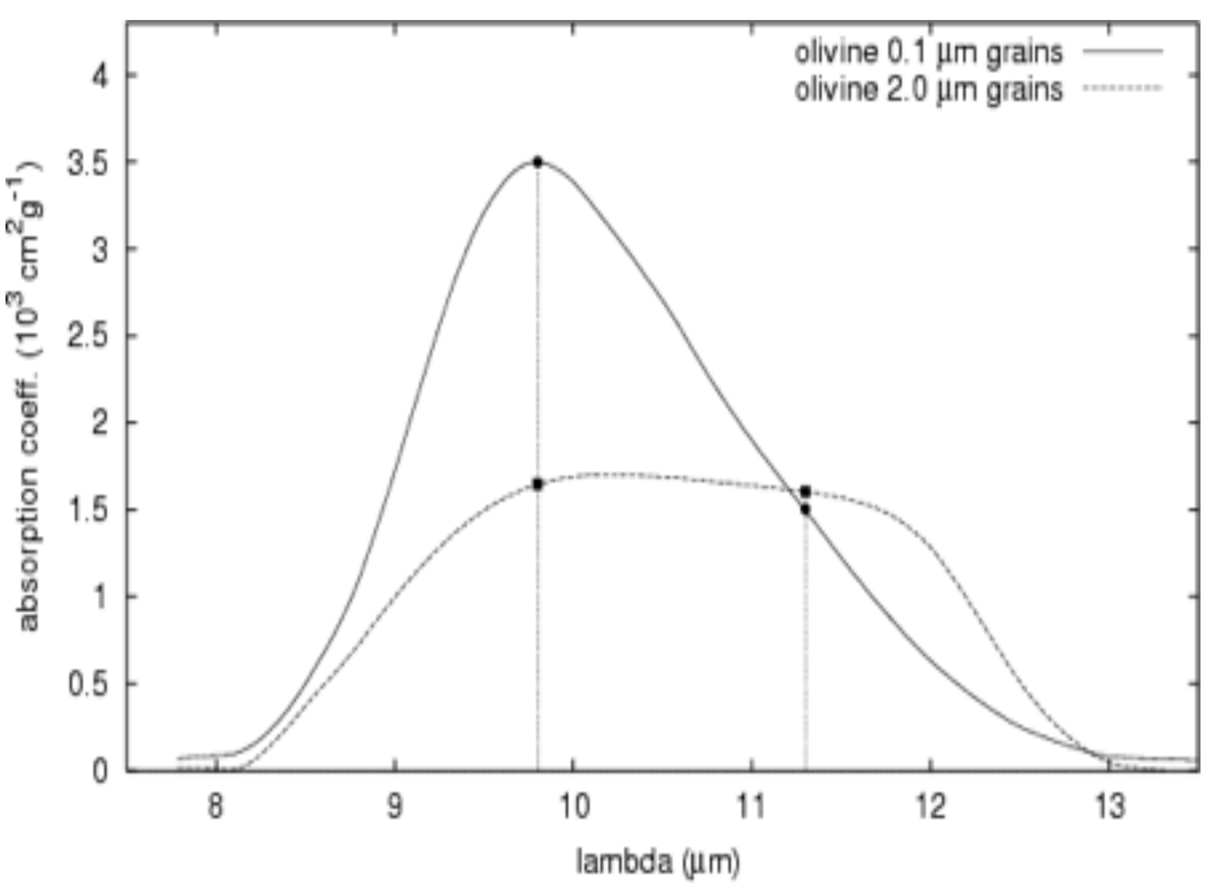
Lommen et al. (2010, A&A, 515, 77)



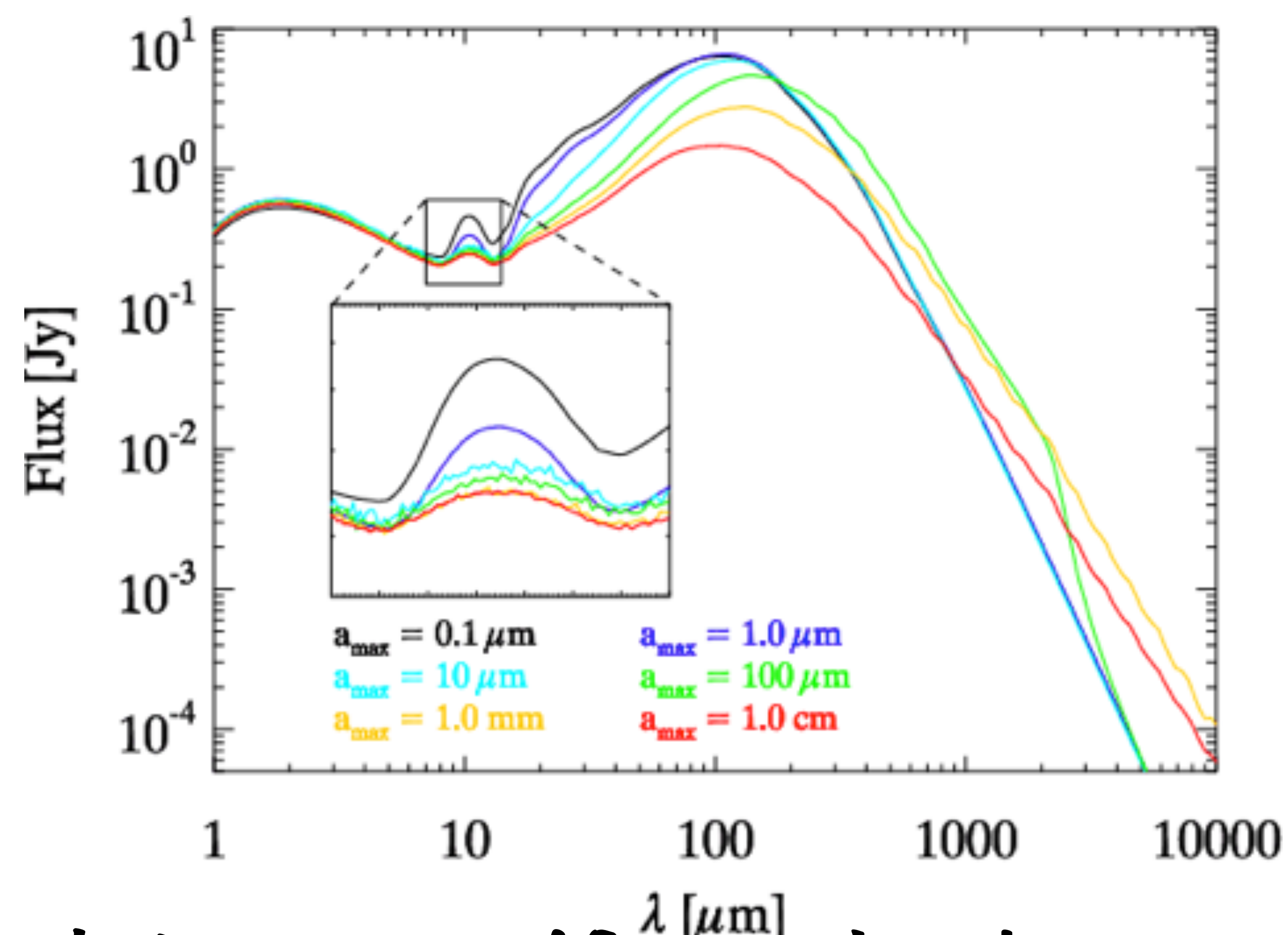
Observed correlation between growth signatures at 10 µm and mm!
Acke et al. (2004, A&A, 422, 621)

Silicates - grain growth
or porosity / shape irregularities ?

e.g. Bouwman et al. (2001)
Voschinnikov & Henning (2008)



Lommen et al. (2010, A&A, 515, 77)

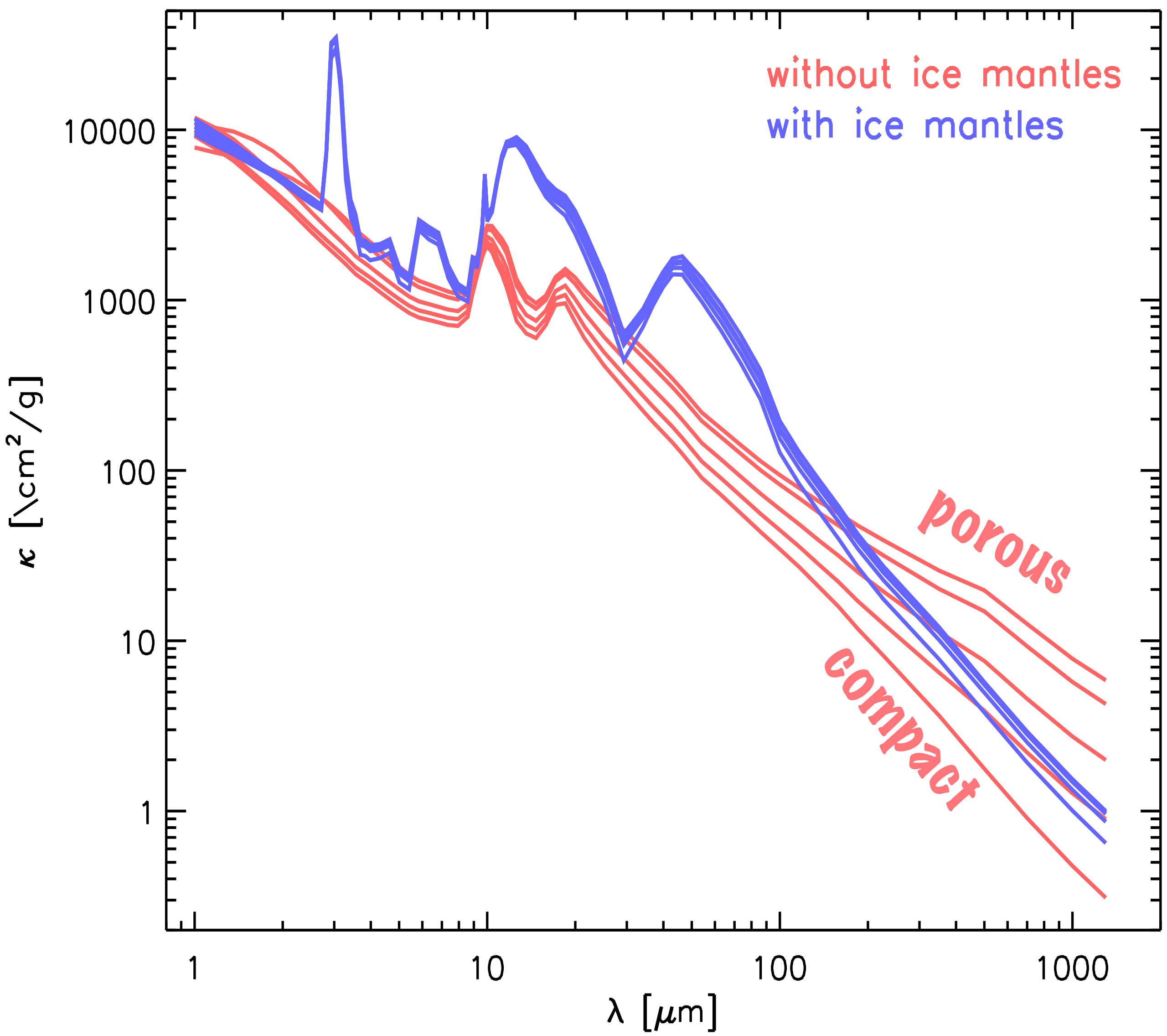


Observed correlation between growth signatures at 10 µm and mm!
Acke et al. (2004, A&A, 422, 621)

mm slope, porosity, ice mantles

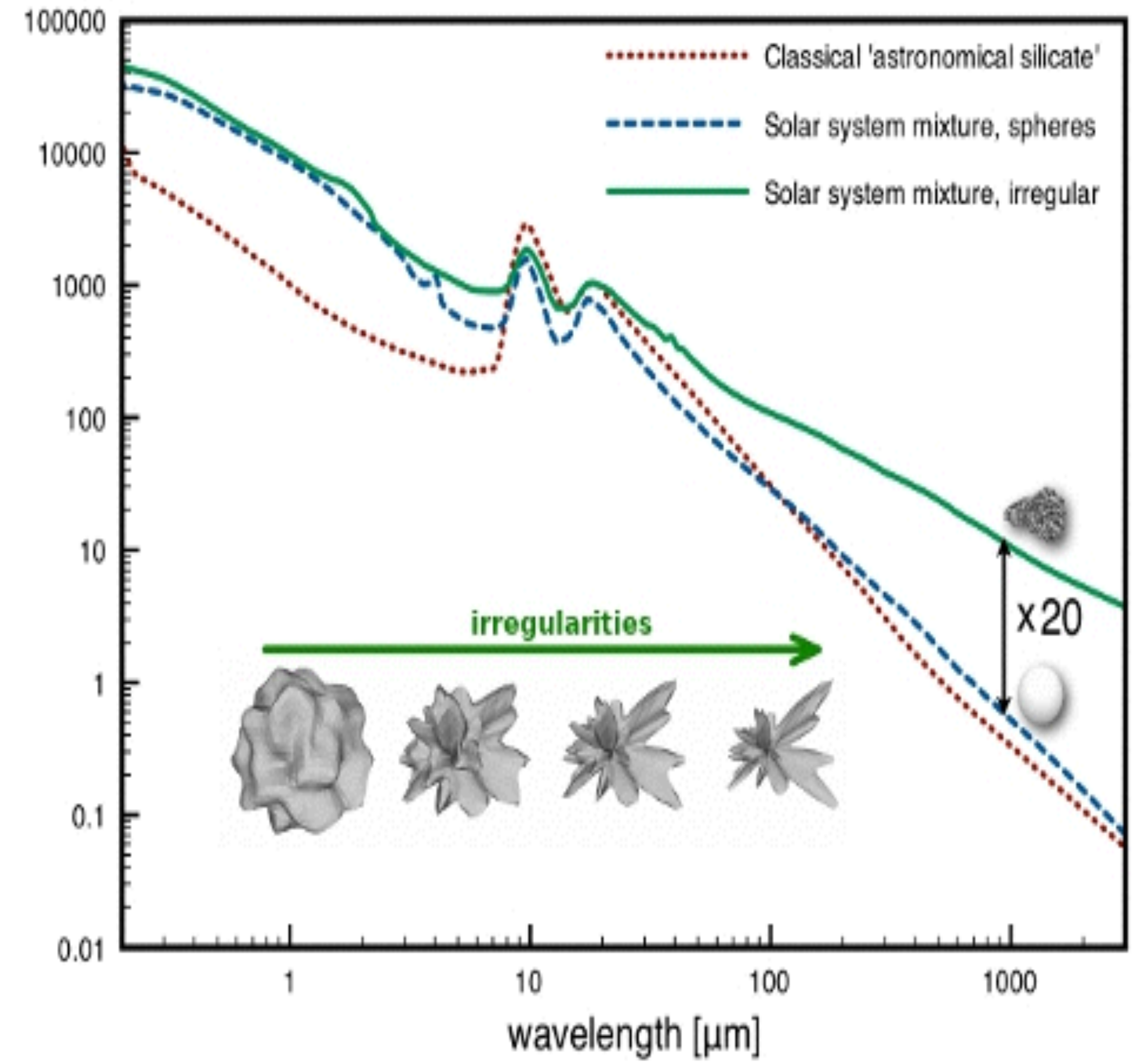
Porosity, ice mantles

Ossenkopf & Henning (1994)



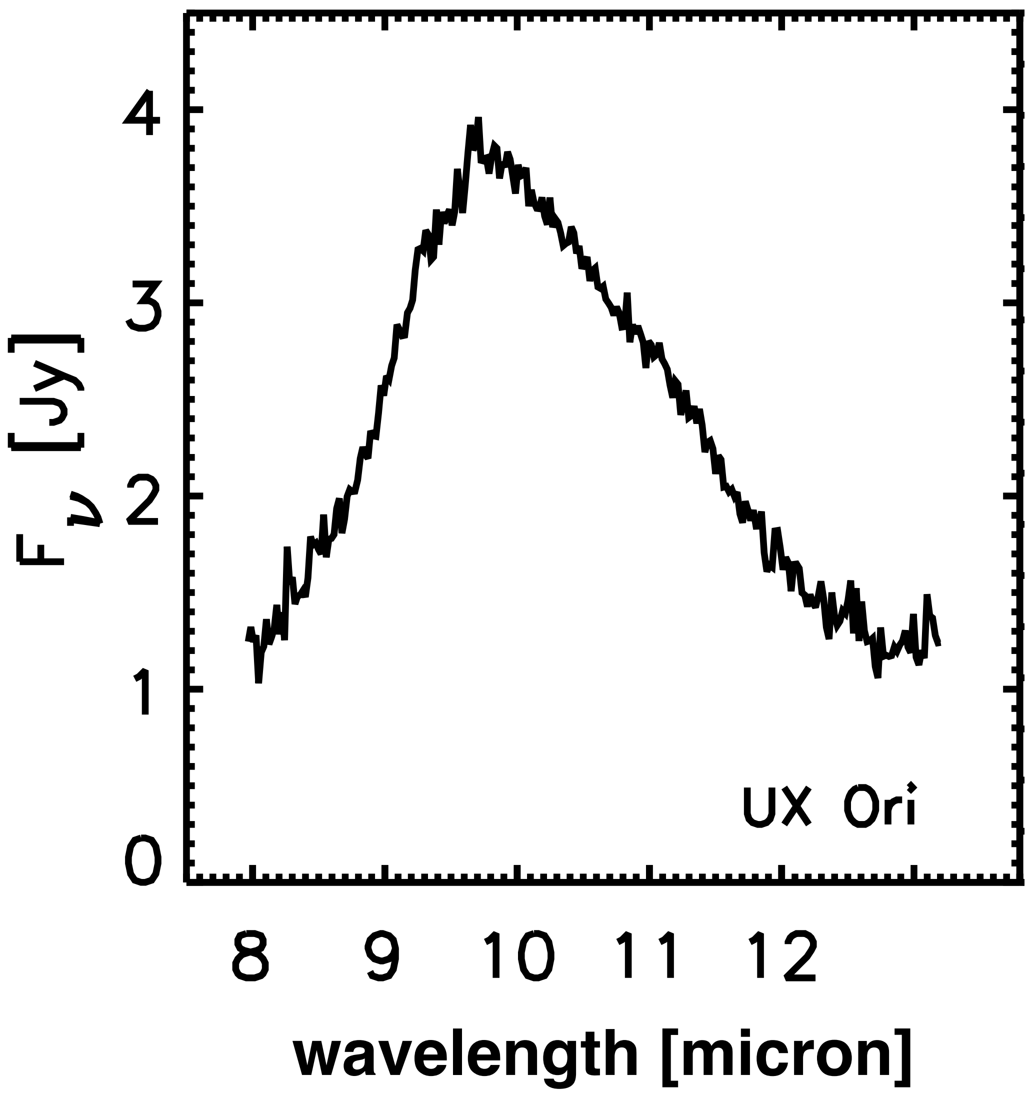
shape irregularities

Min et al. (2006, 2014 in prep)

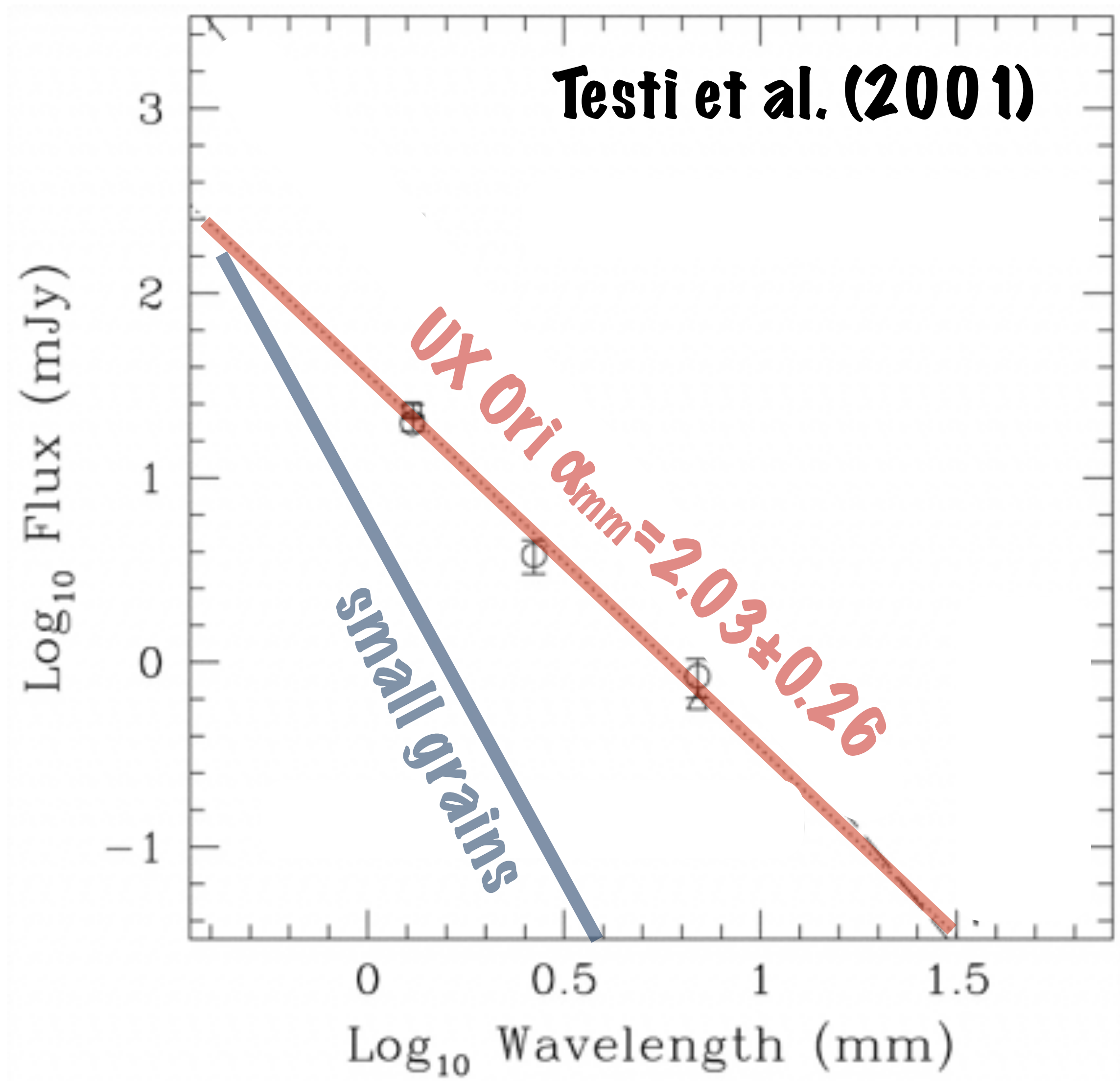


disk surface vs. midplane

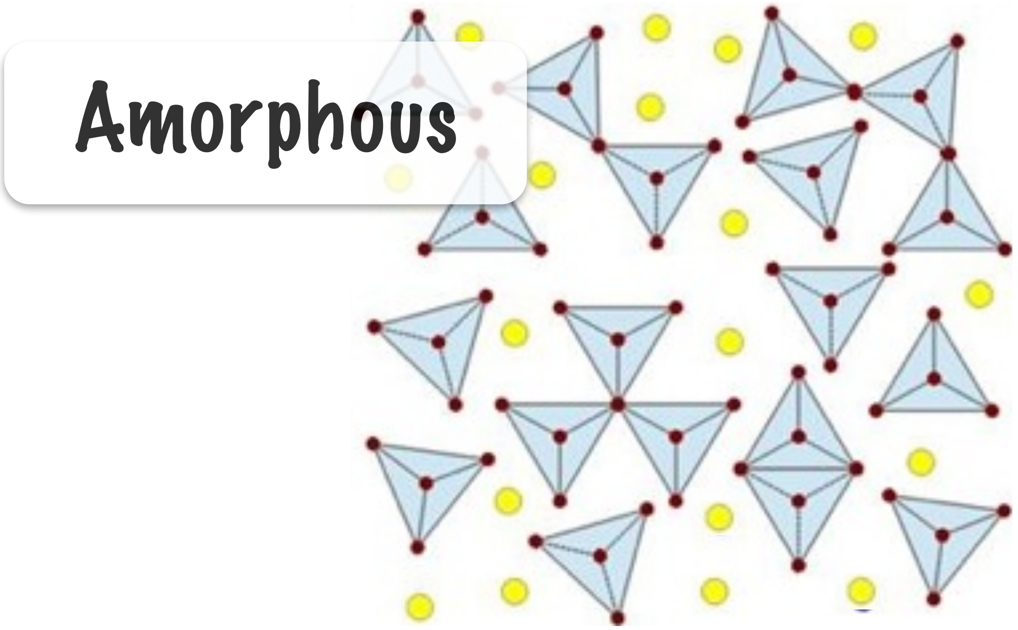
surface layer:
particles ≲ 1 μm

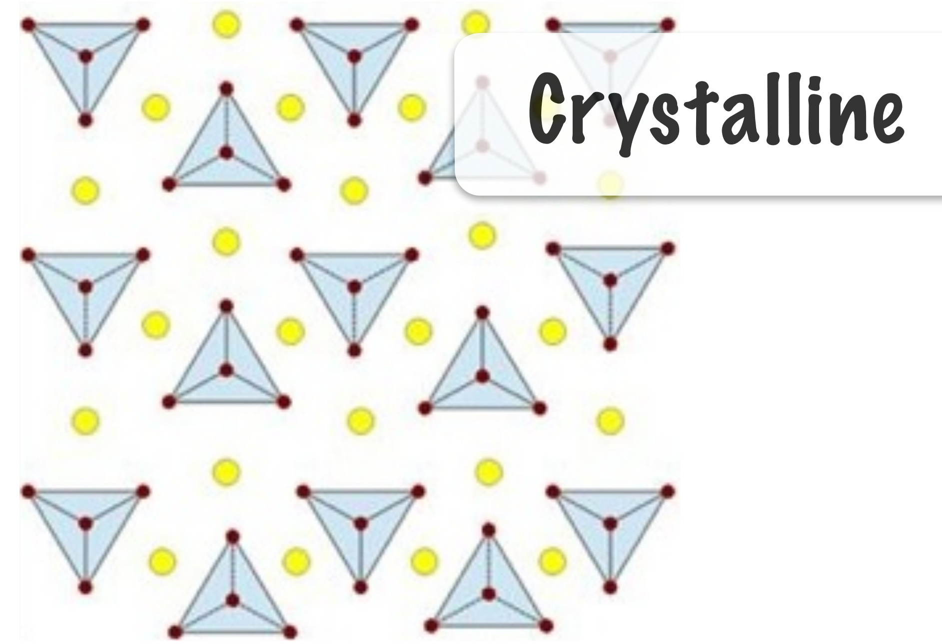


mid-plane:
particles ≳ 10^5 μm

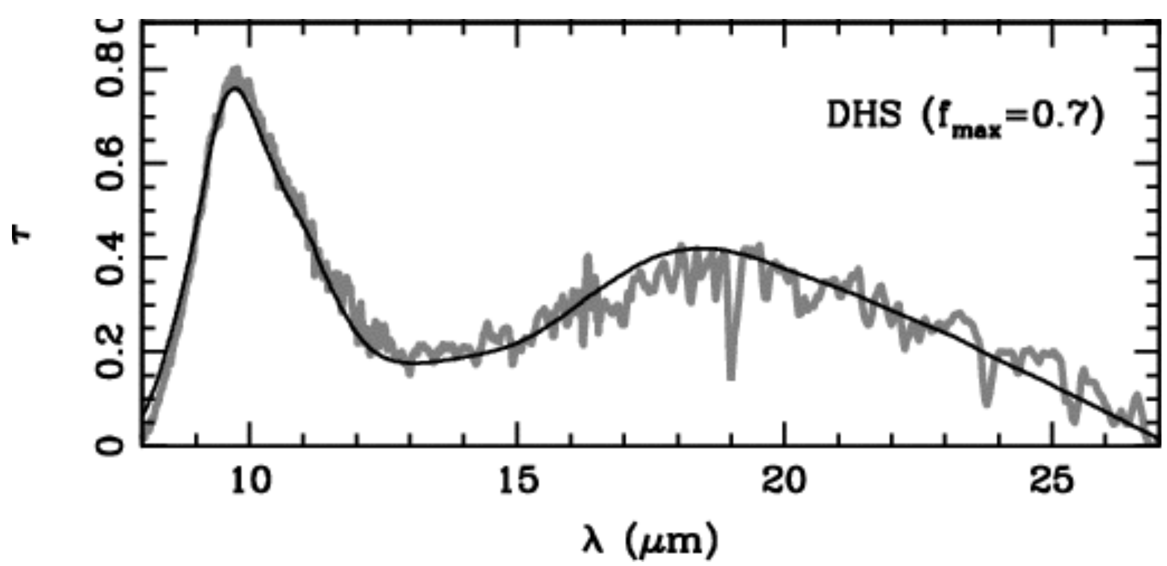


Silicates - crystallisation

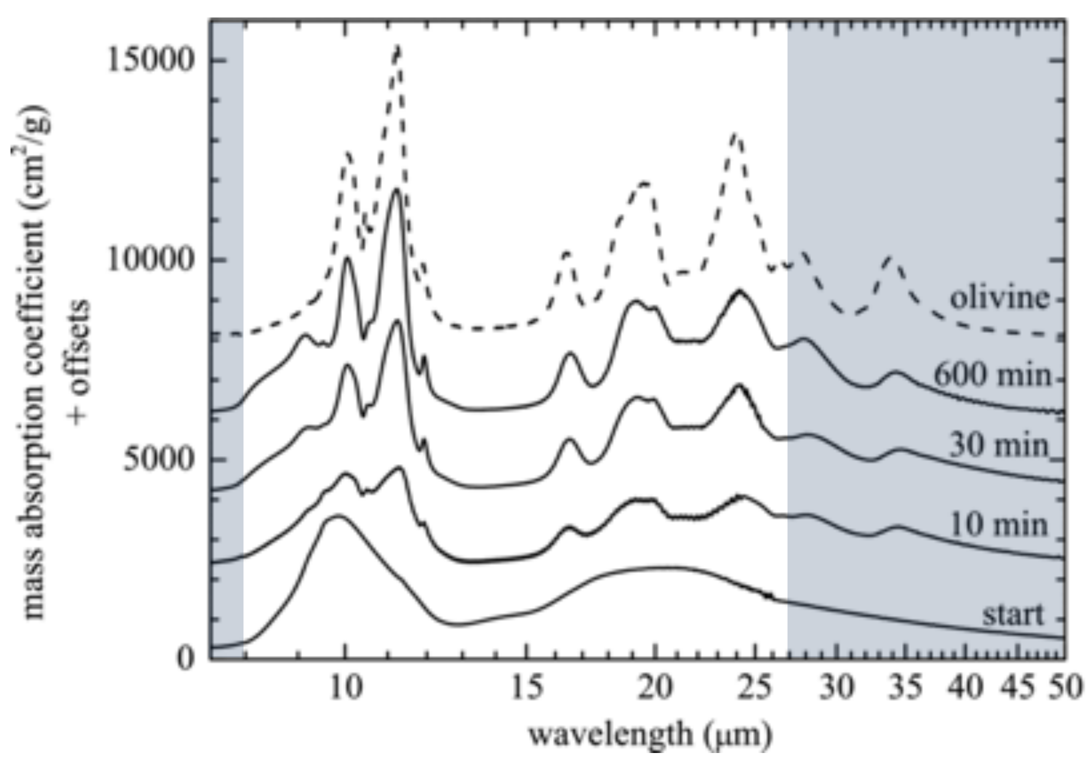




Min et al. (2007, A&A, 462, 667)

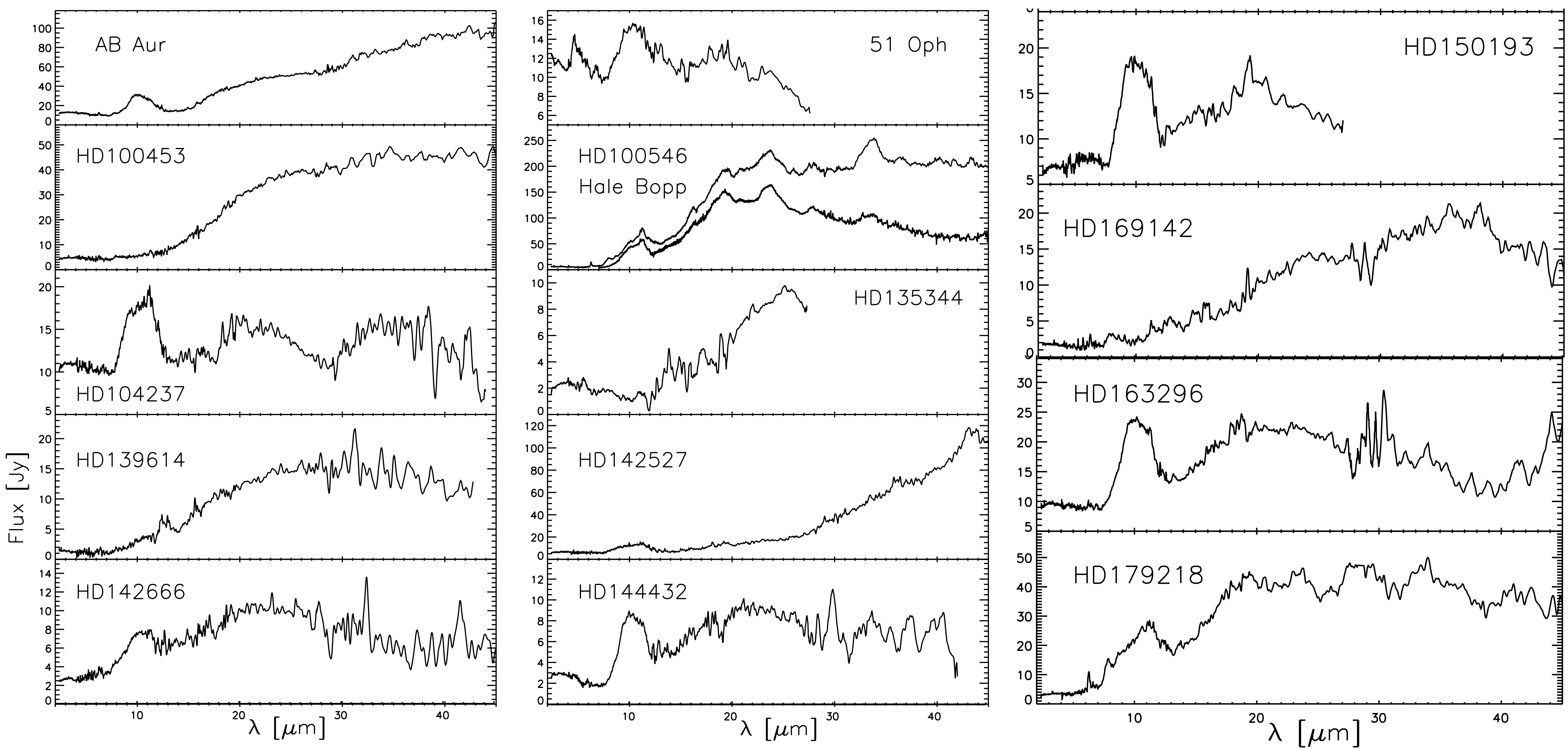


Murata et al. (2009, ApJ, 696, 1612)



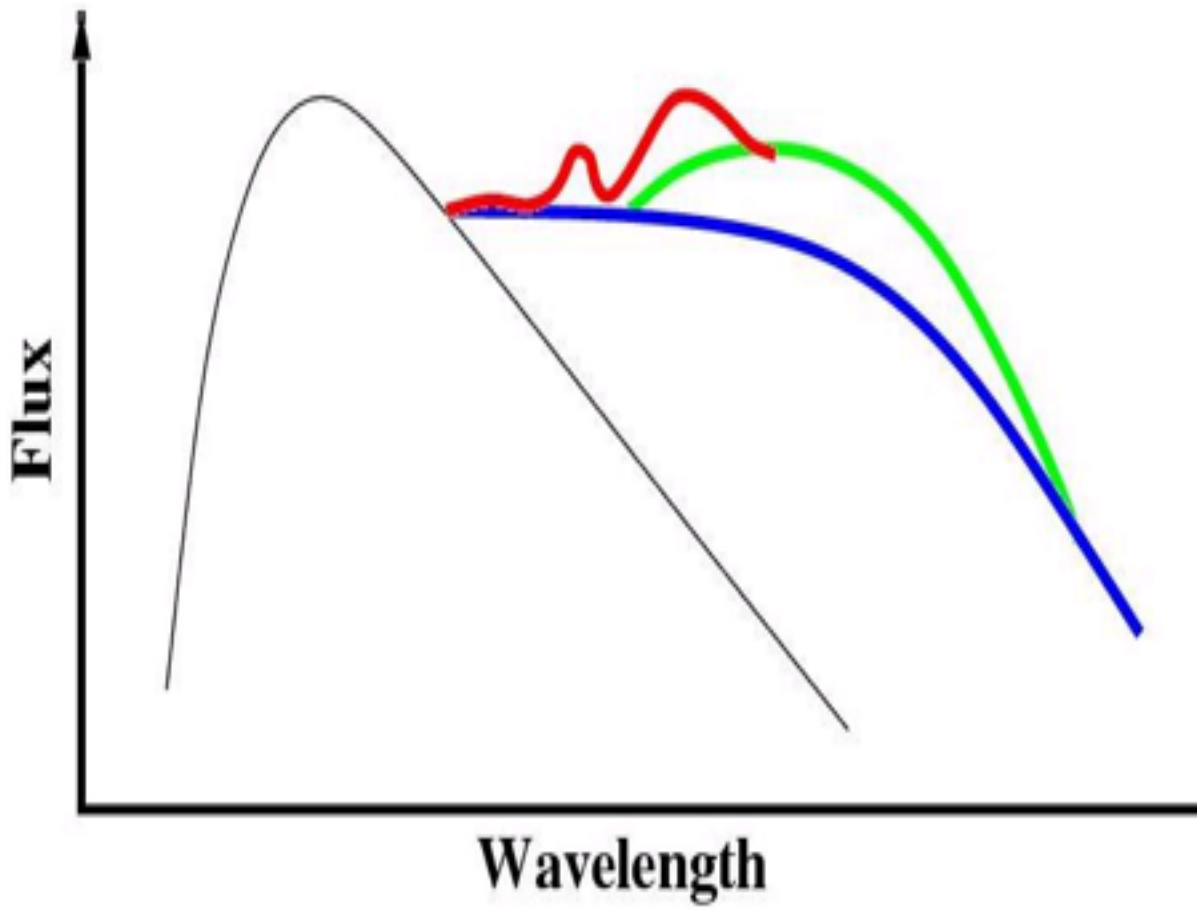
ISO: "the big punch"

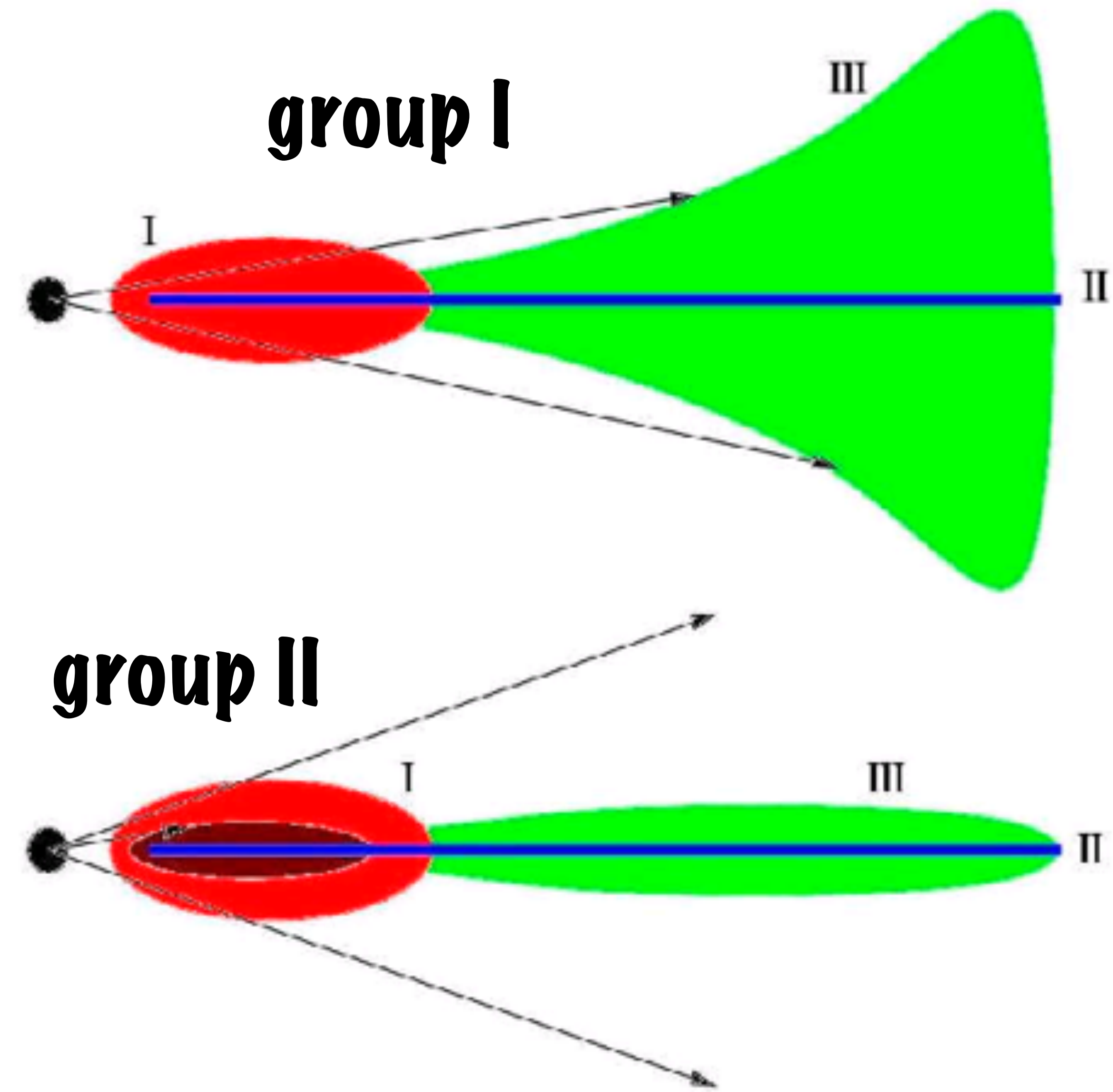
Meeus et al. (2001, A&A, 365, 476)



ISO: "the big punch"

Meeus et al. (2001, A&A, 365, 476)



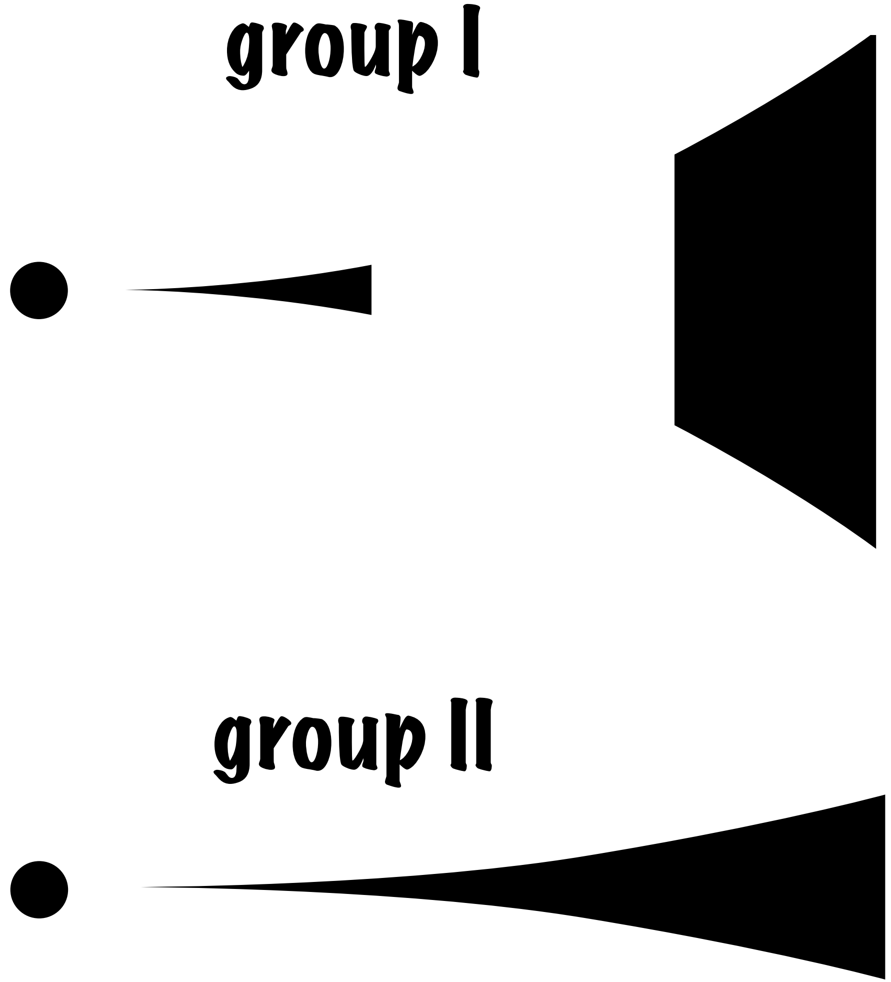


Disk Geometry

Maaskant et al. (2013, A&A, 555, 64)

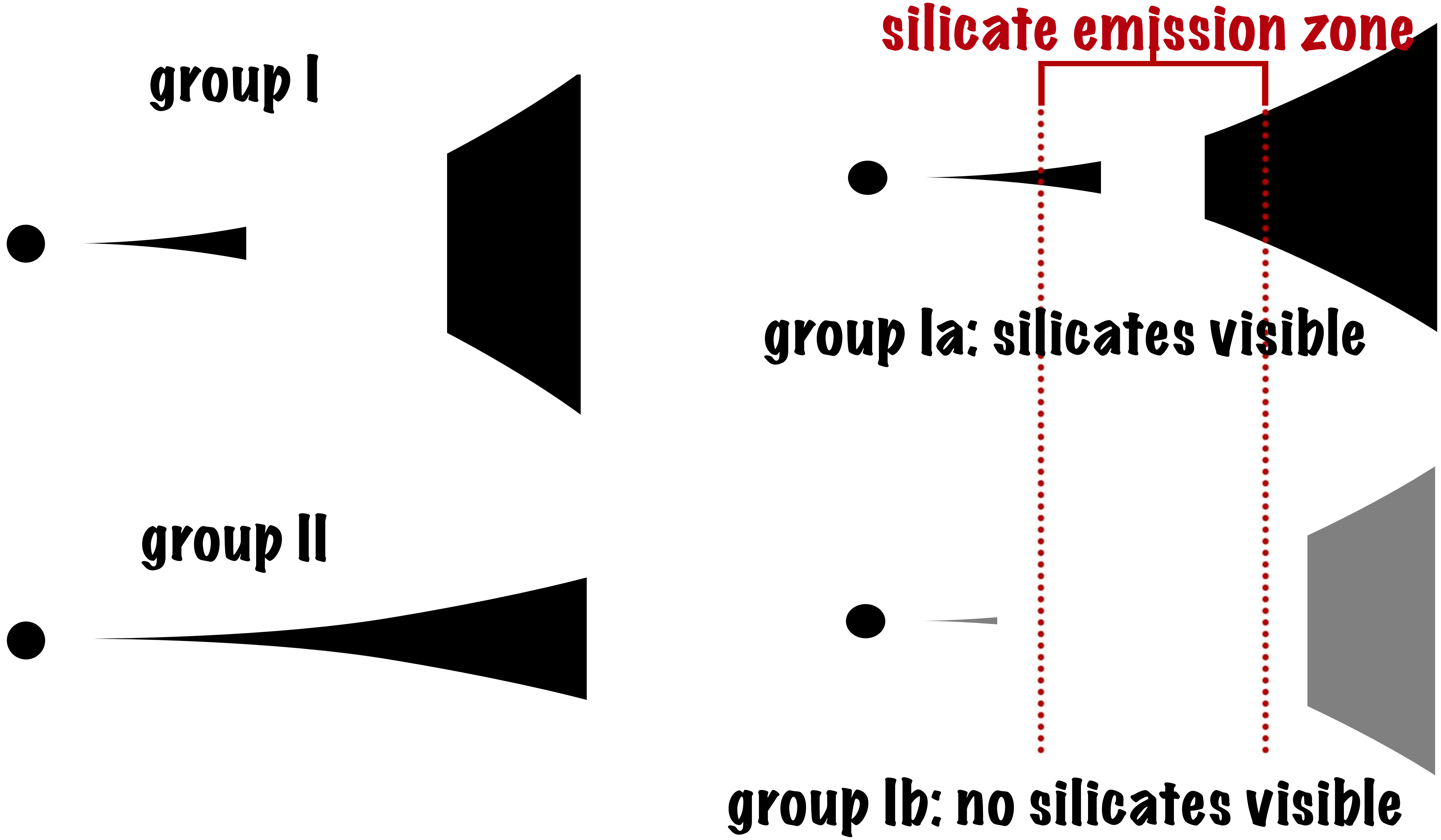
group I

group II



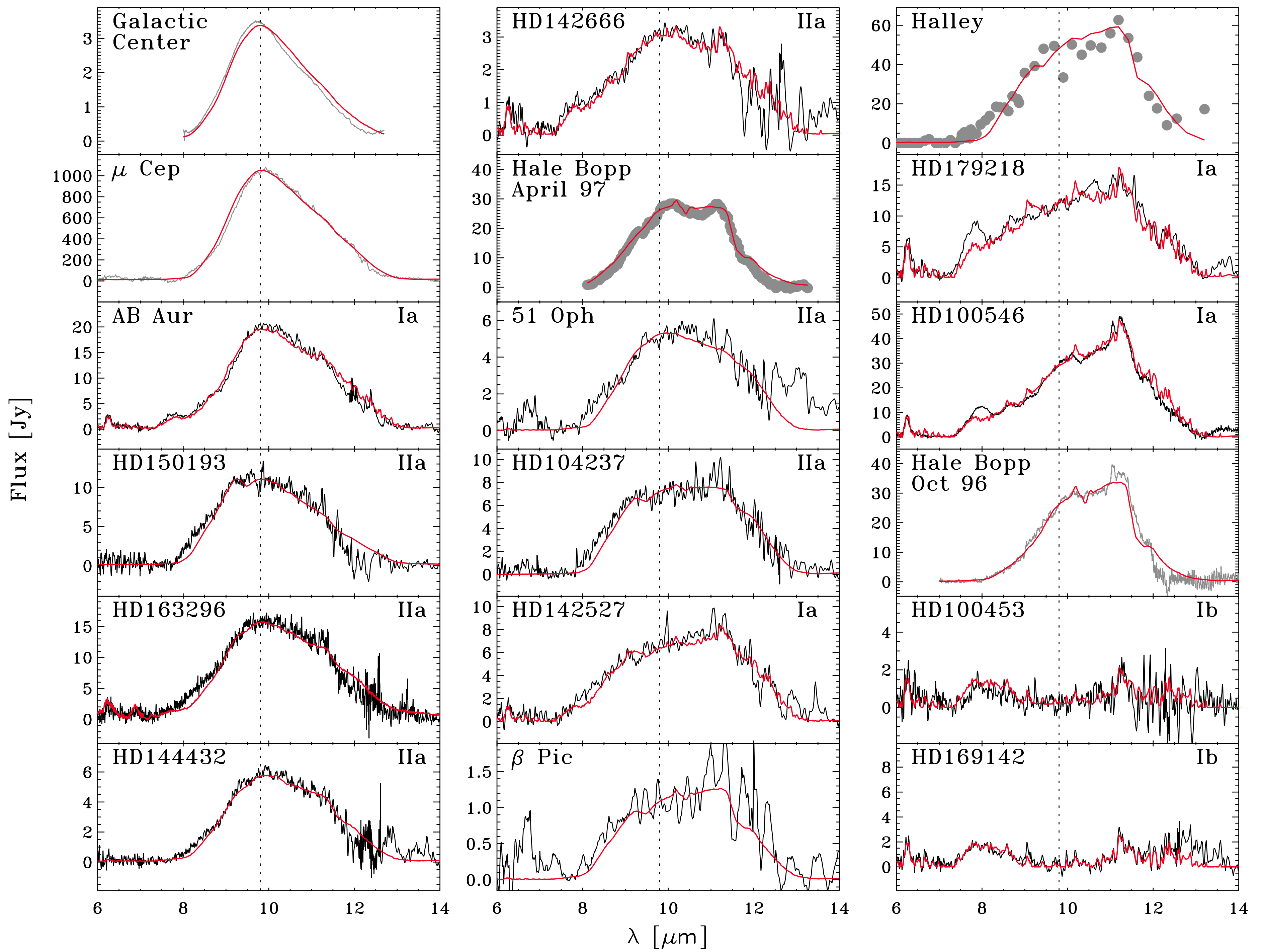
Disk Geometry

Maaskant et al. (2013, A&A, 555, 64)



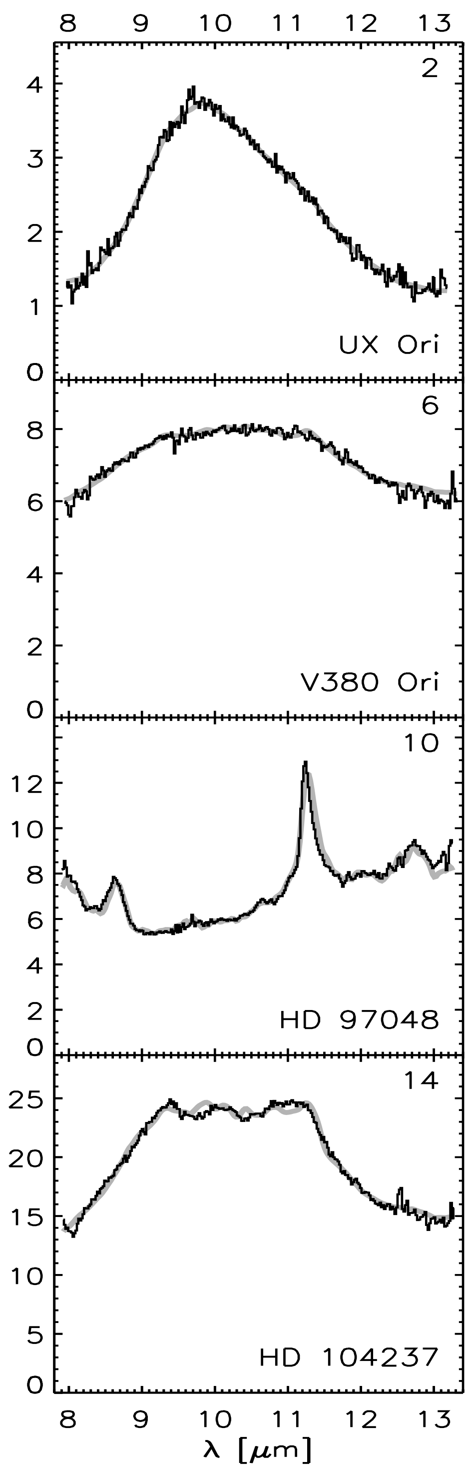
ISO: "the big punch"

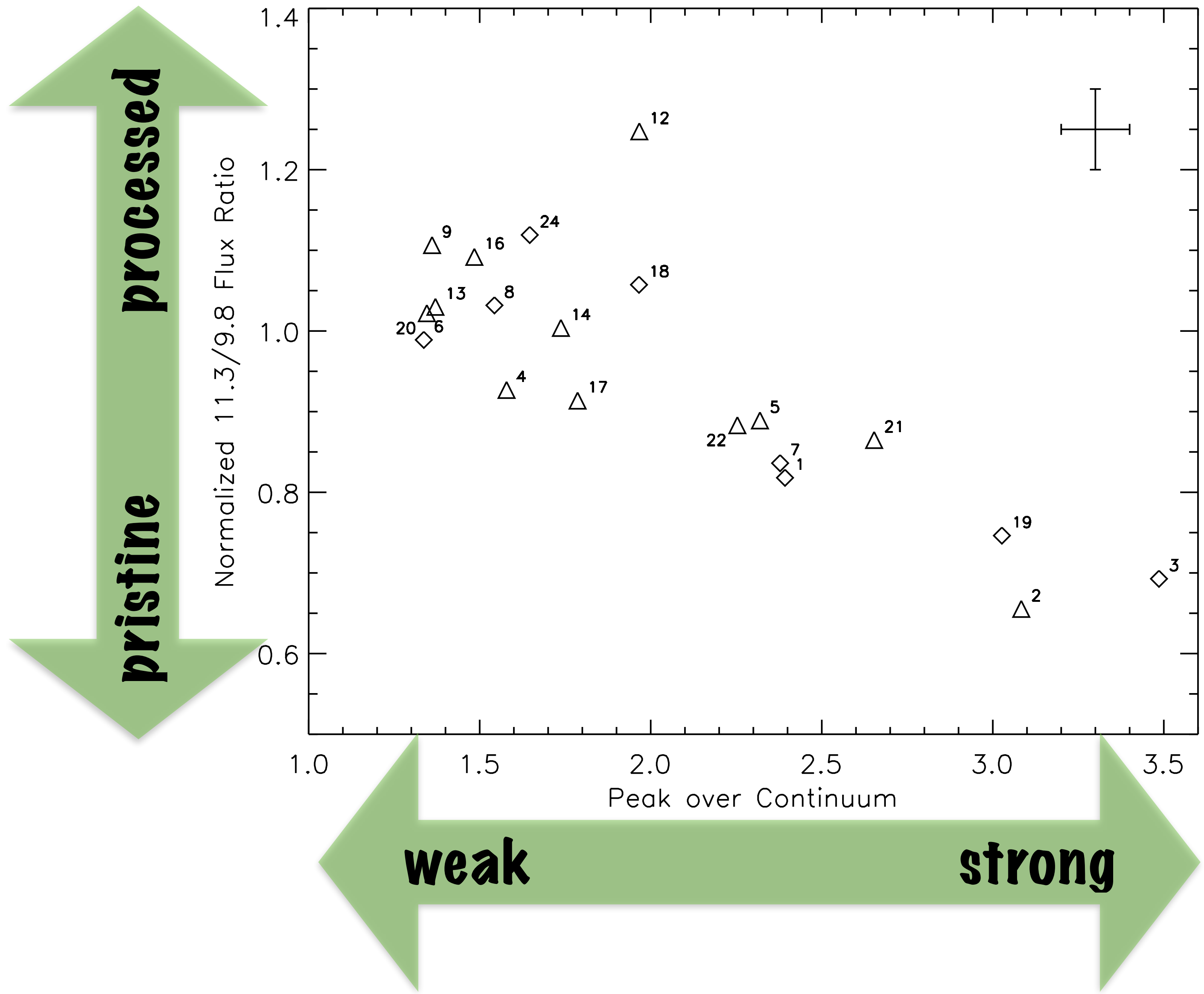
Bouwman et al. (2001, A&A 375, 950)



advancement from ground

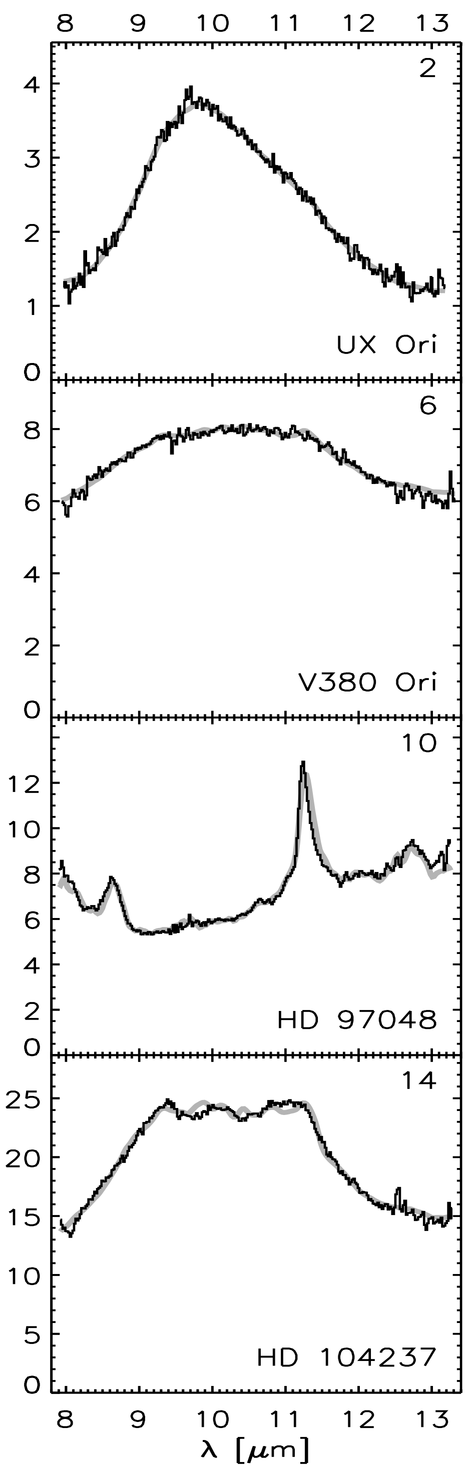
van Boekel et al. (2003, 2005)

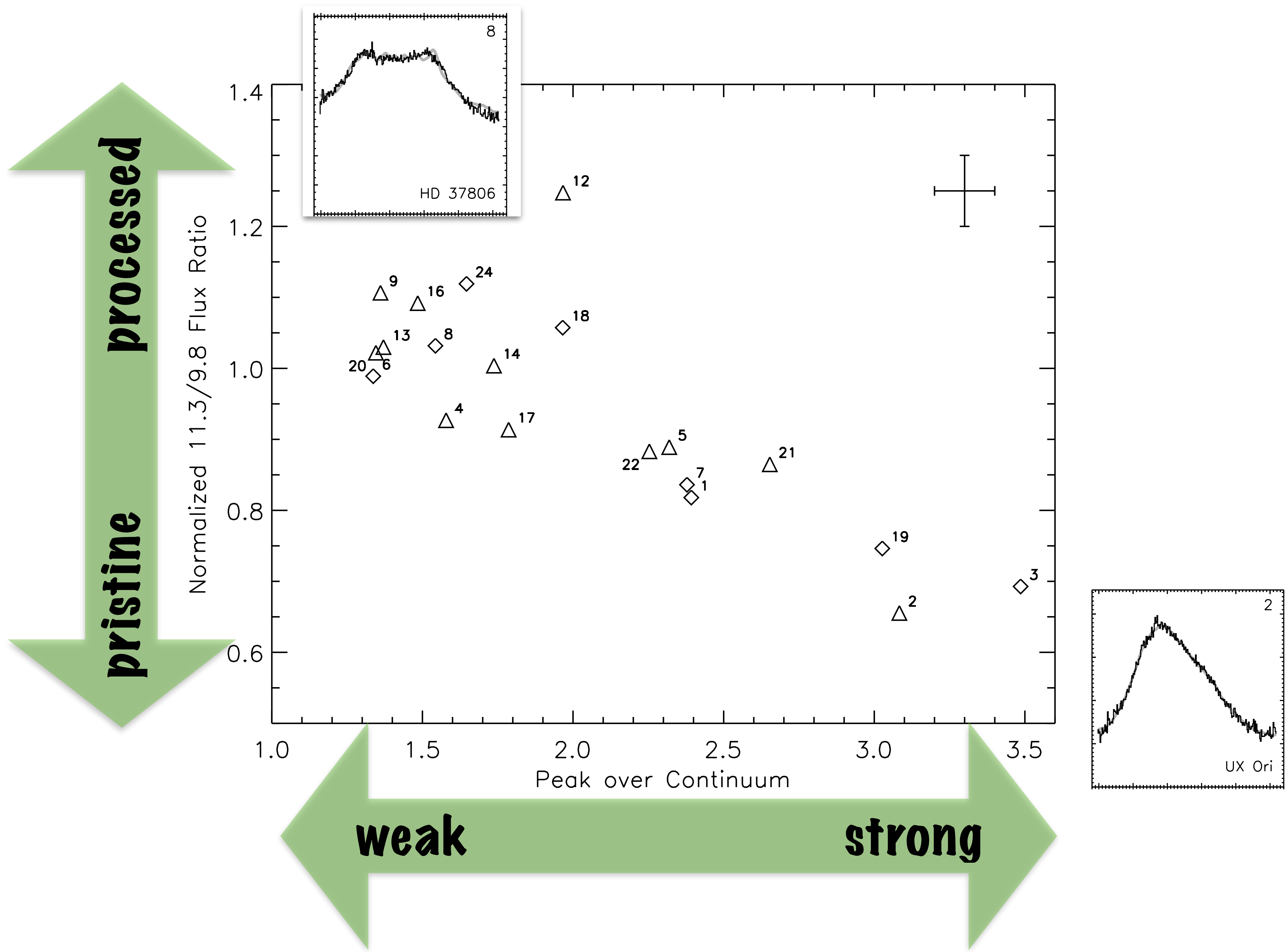




advancement from ground

van Boekel et al. (2003, 2005)

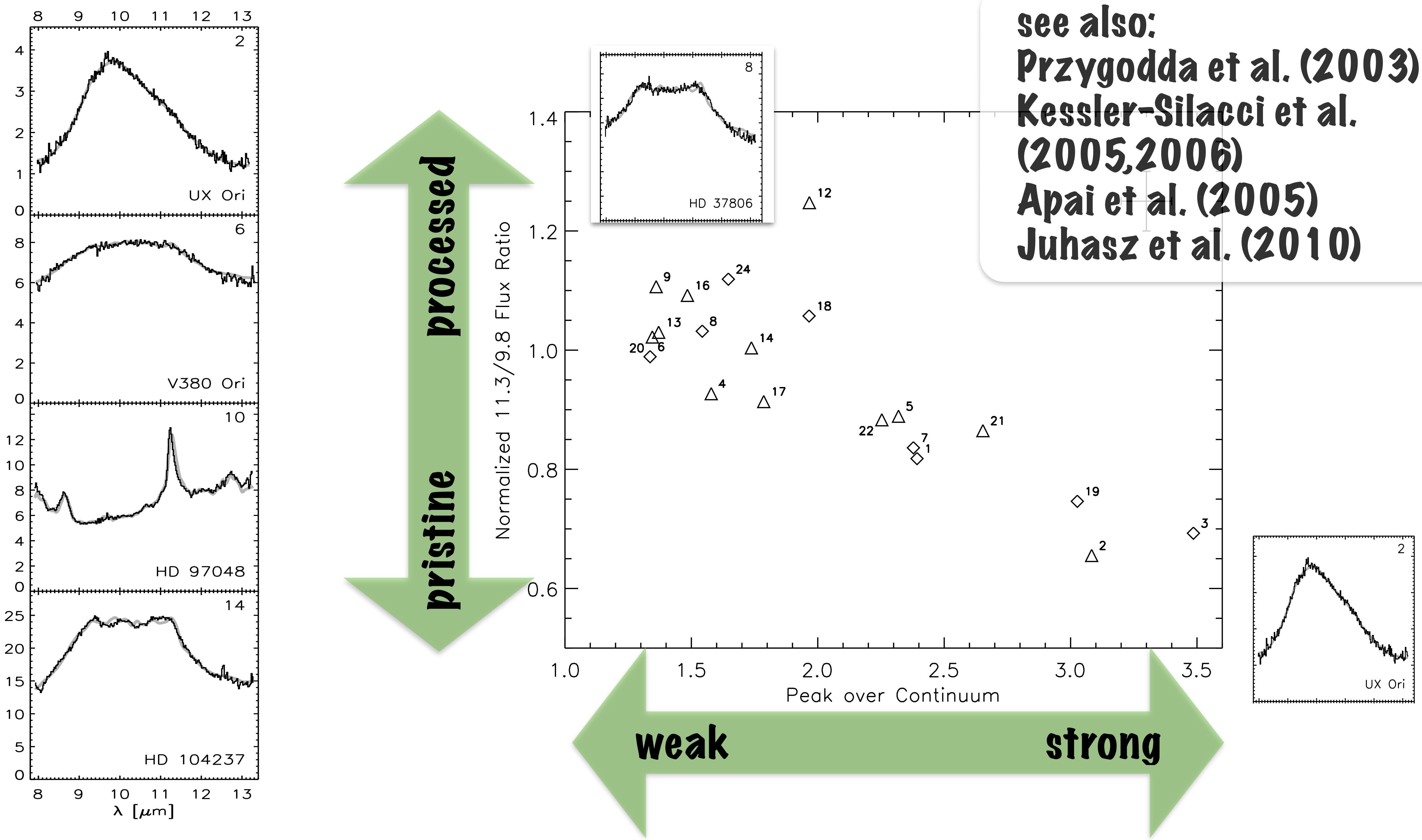




advancement from ground

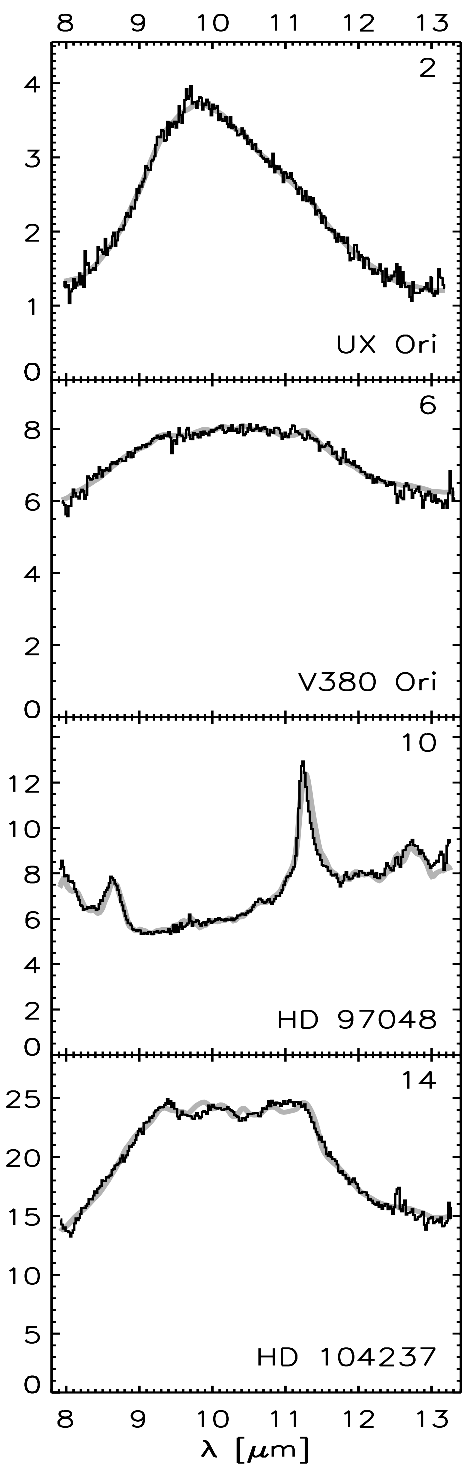
van Boekel et al. (2003, 2005)

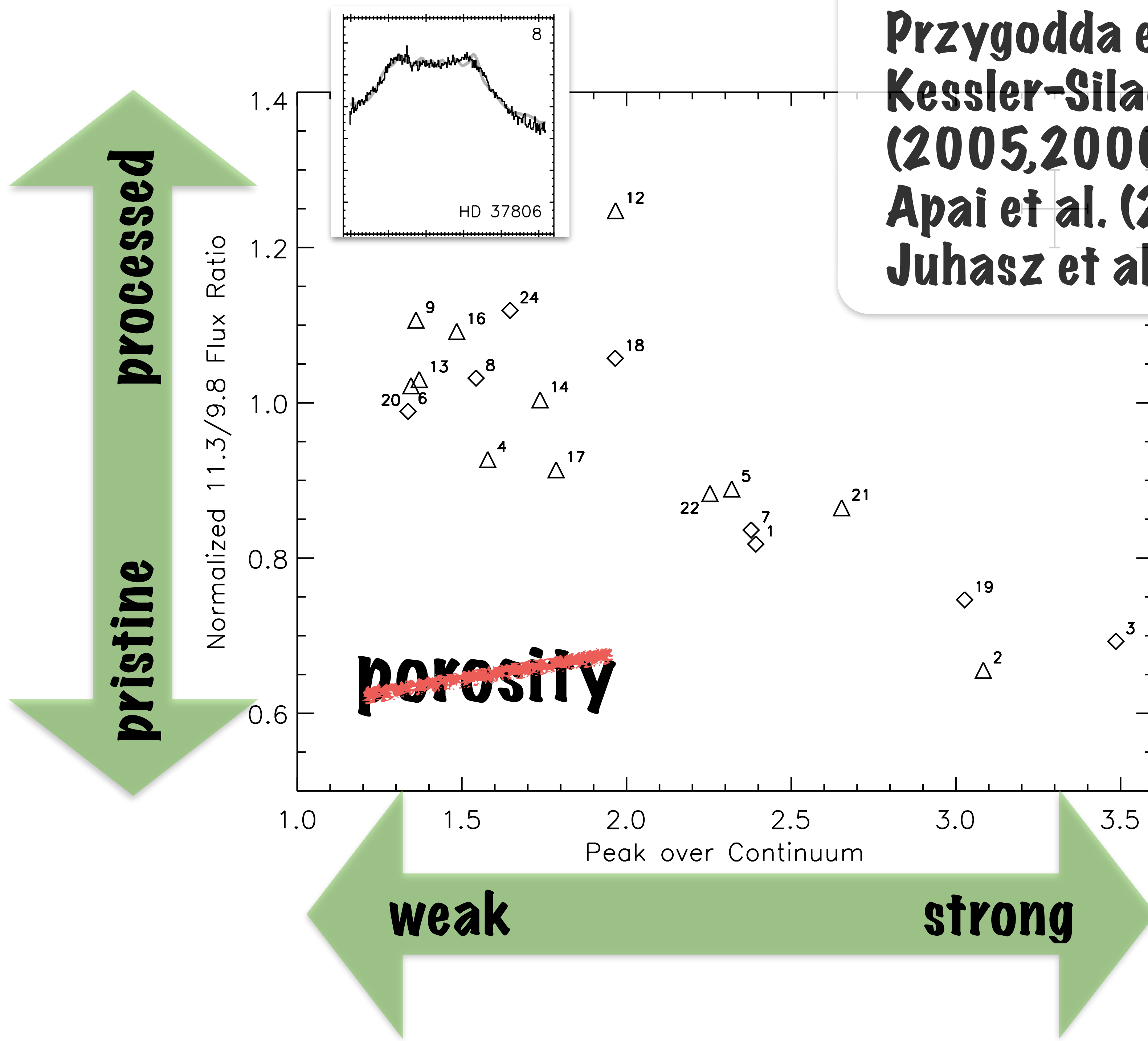
see also:
Przygodda et al. (2003)
Kessler-Silacci et al. (2005,2006)
Apai et al. (2005)
Juhasz et al. (2010)

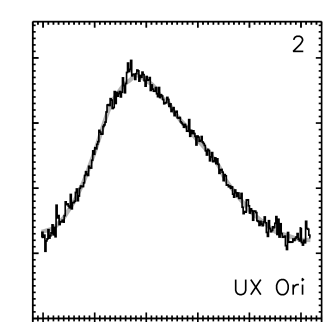


advancement from ground

van Boekel et al. (2003, 2005)

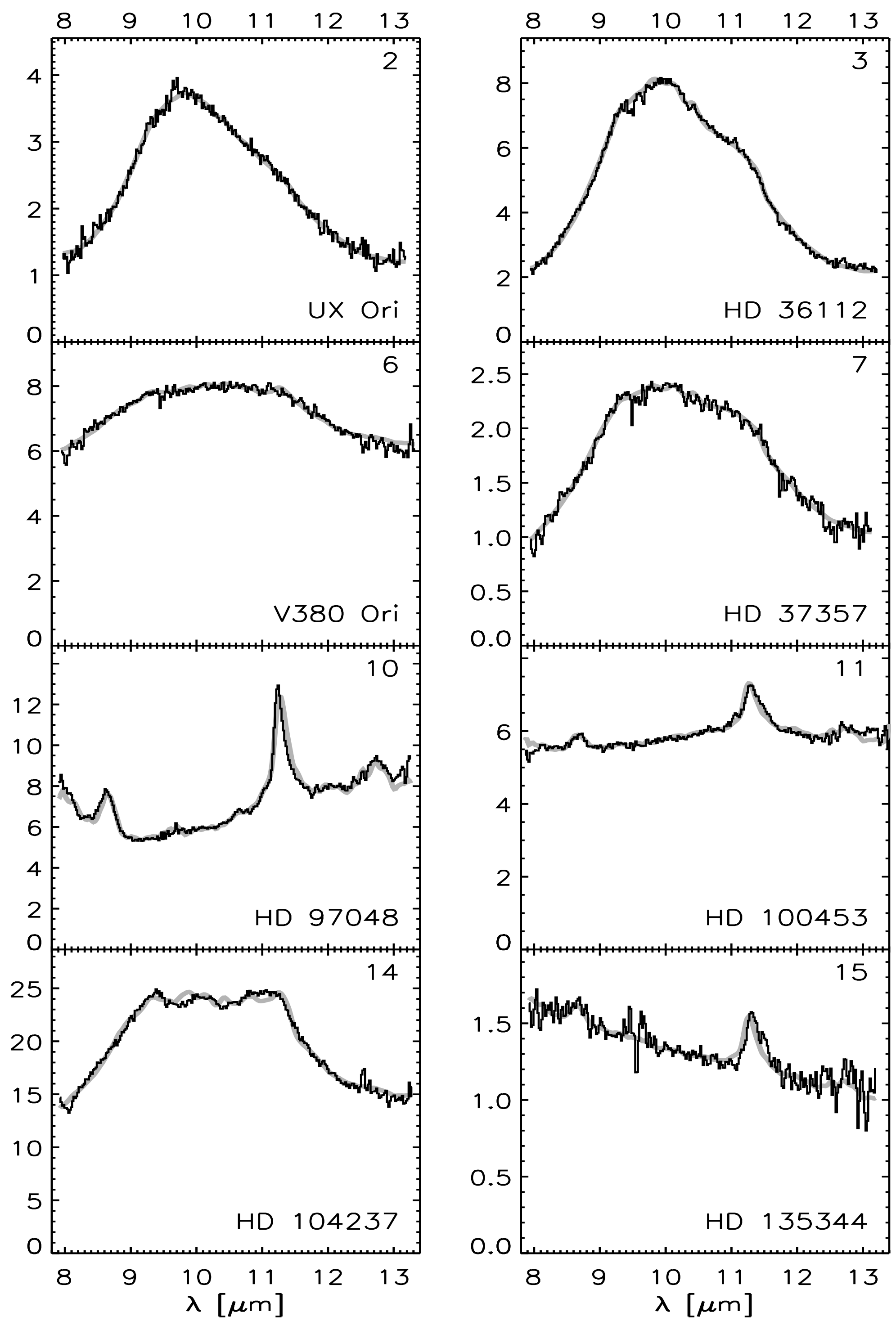




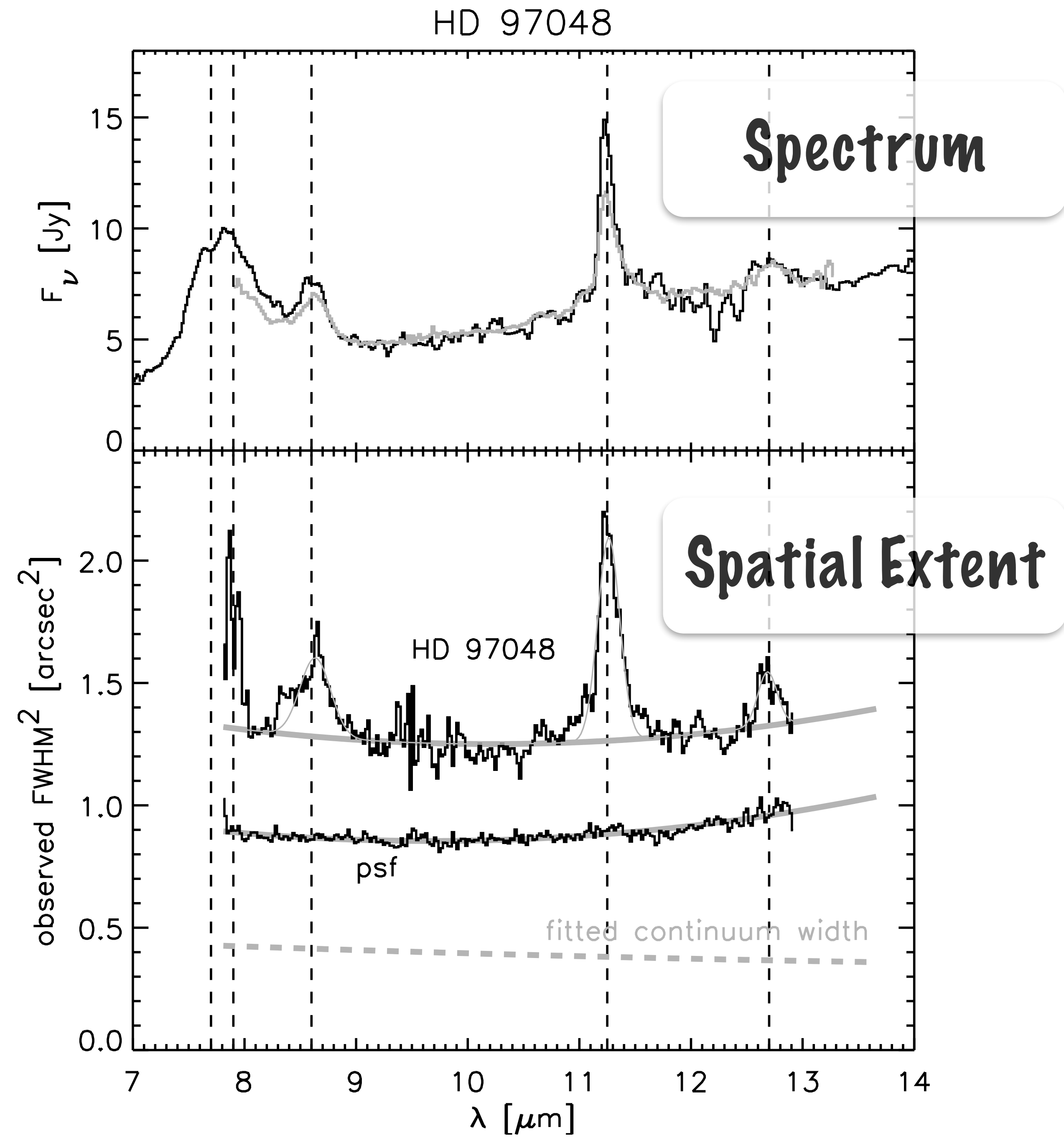


see also:
Przygodda et al. (2003)
Kessler-Silacci et al. (2005,2006)
Apai et al. (2005)
Juhasz et al. (2010)

advancement from ground



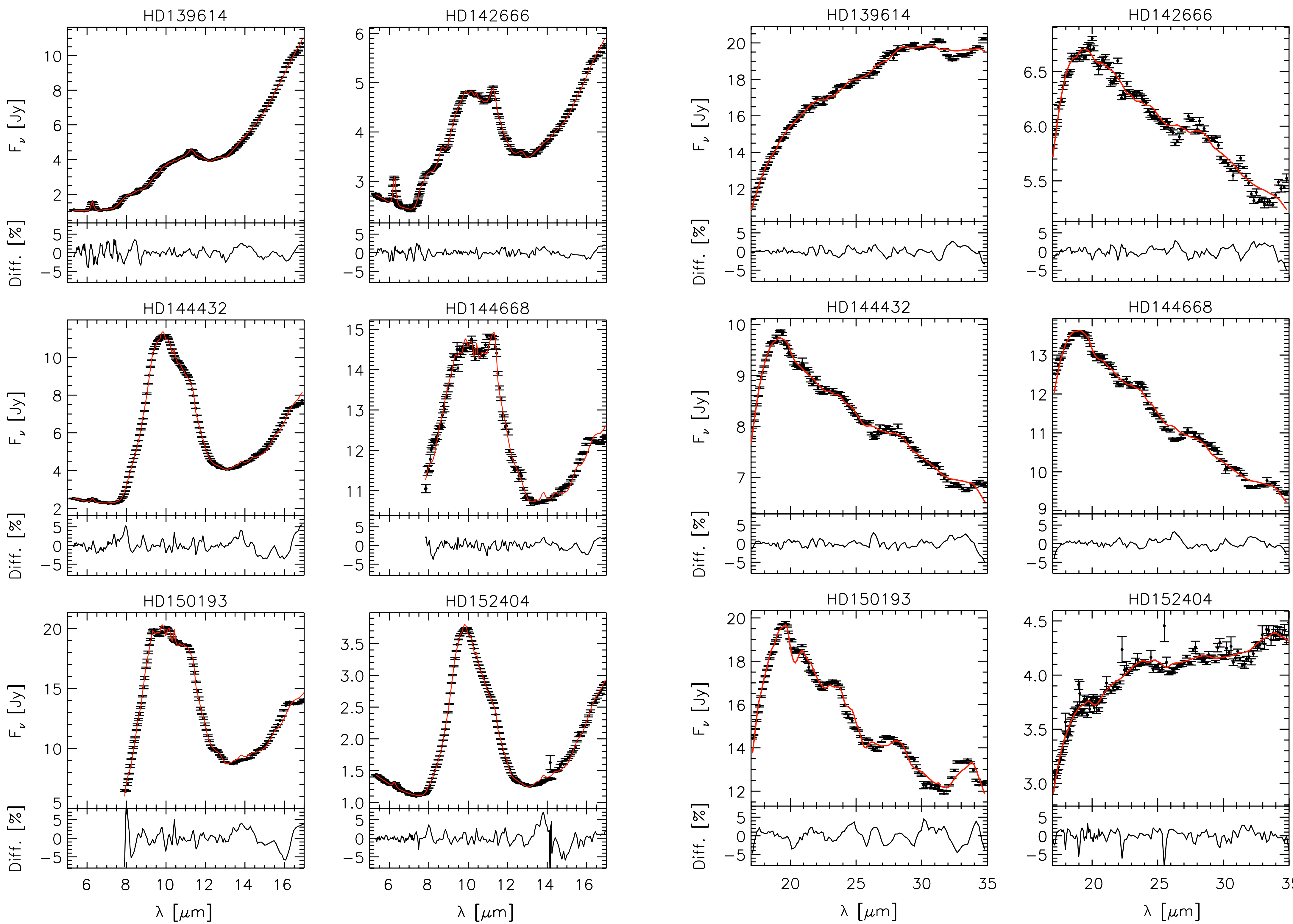
van Boekel et al. (2003, 2005)



van Boekel et al. (2004, A&A, 418, 177)

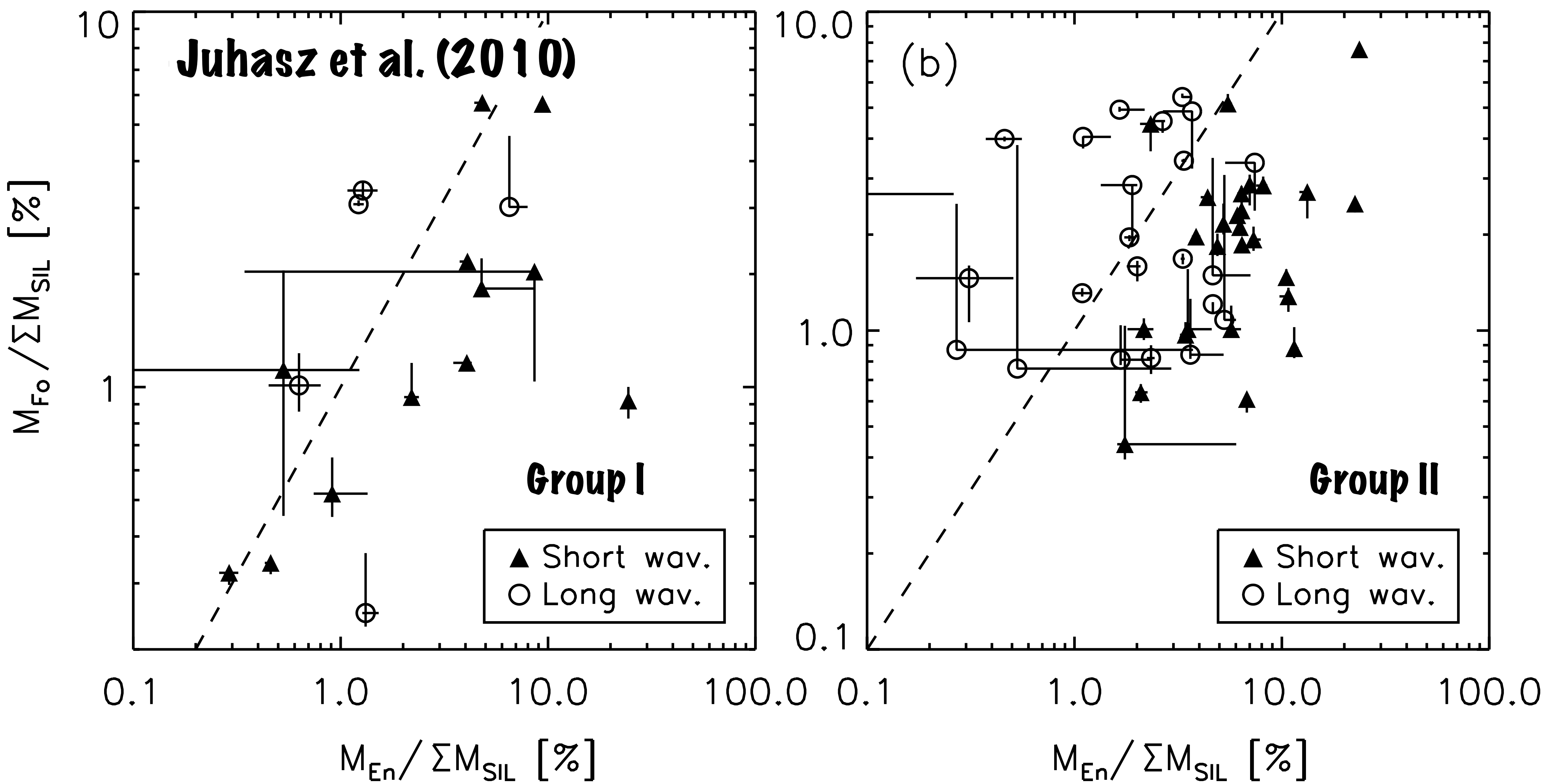
hammering it home with Spitzer

Juhasz et al. (2010, ApJ, 721, 431)



warm enstatite & cool forsterite

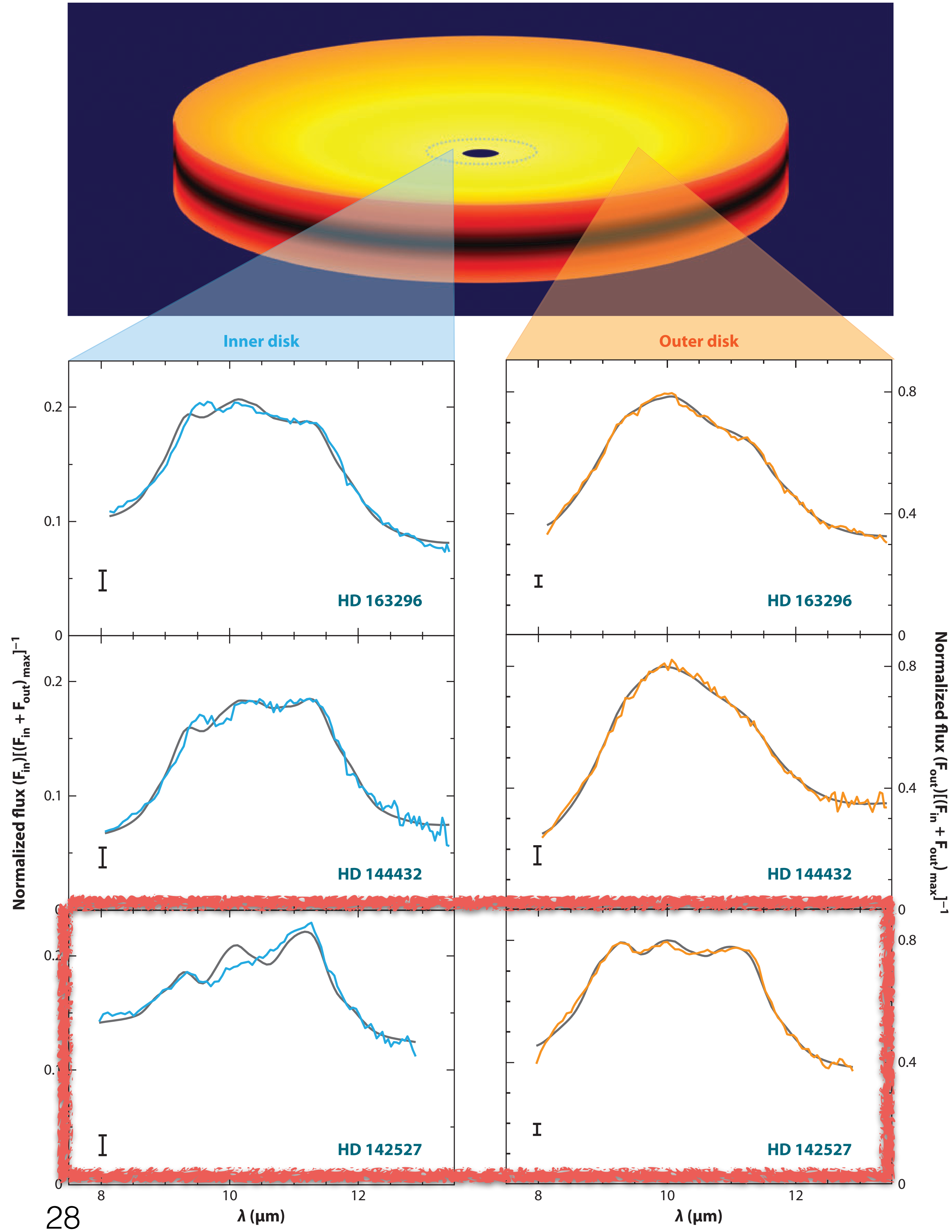
- fit to 5-17 μm region: pyroxene dominates (enstatite)
- fit to 17-35 μm region: olivine dominates (forsterite)



spatial distribution

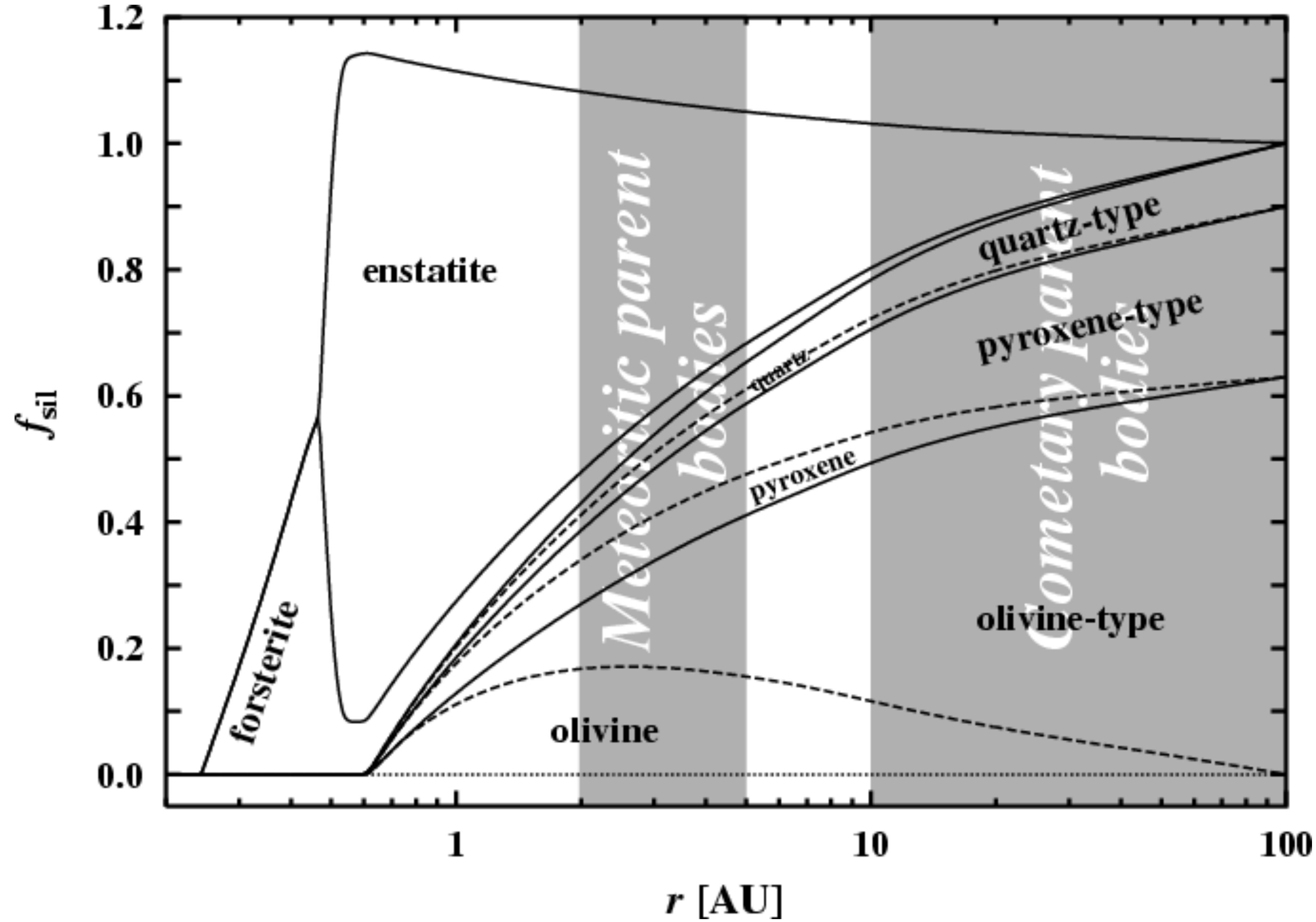
- Very innermost region (sub-AU scale):
  - higher crystallinity
  - larger grains
  - forsterite-dominated
- Further out (≈1-10 AU)
  - lower crystallinity
  - smaller grains
  - enstatite-dominated

van Boekel et al. (2004)



spatial distribution

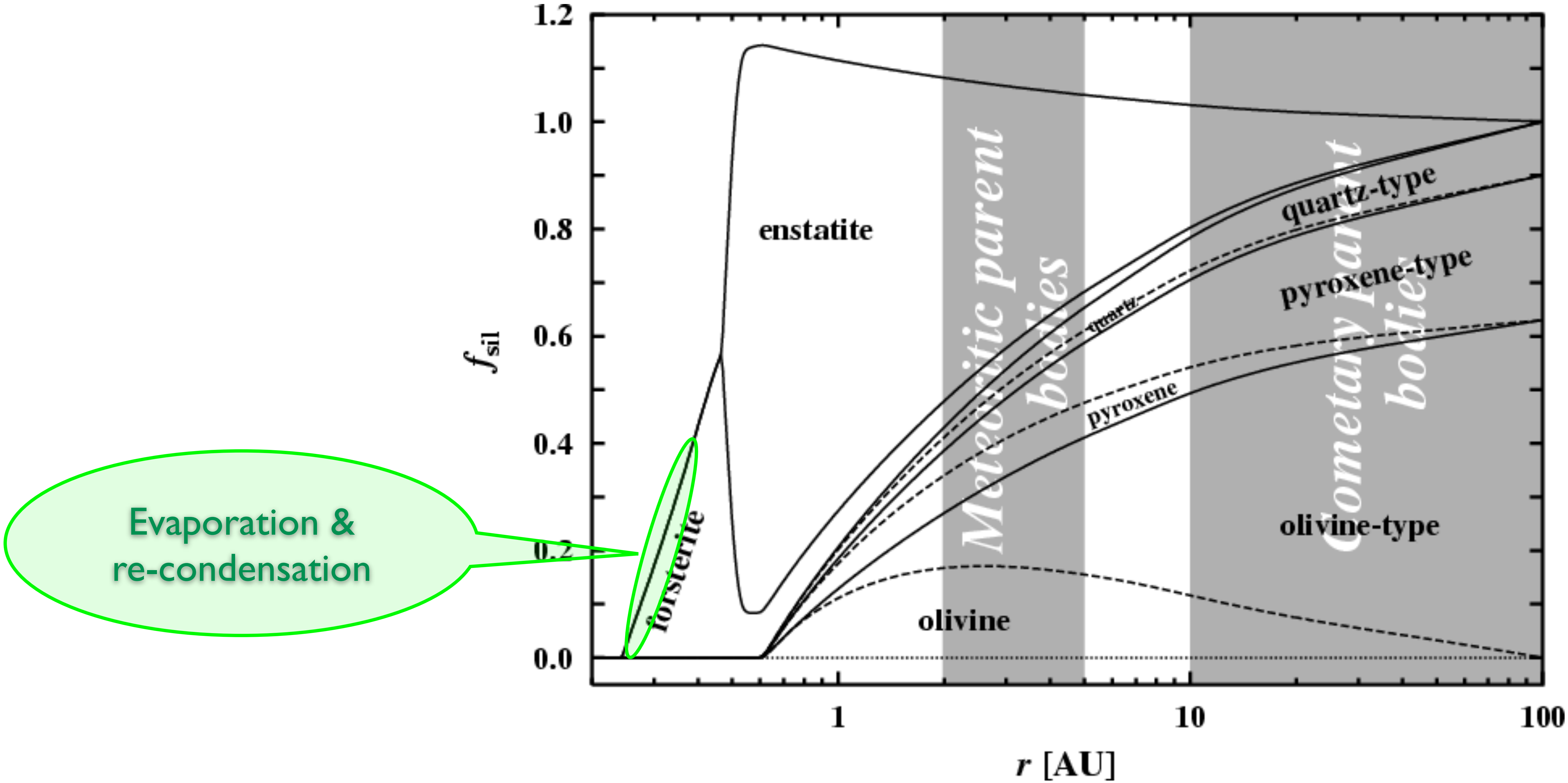
Gail (2004, A&A, 413, 571)



* reaction of solid states with H_2 yields SiO gas and H_2O gas allowing inter-grain transport of Silicon and Oxygen; see Gail et al. (2004) for a detailed description

spatial distribution

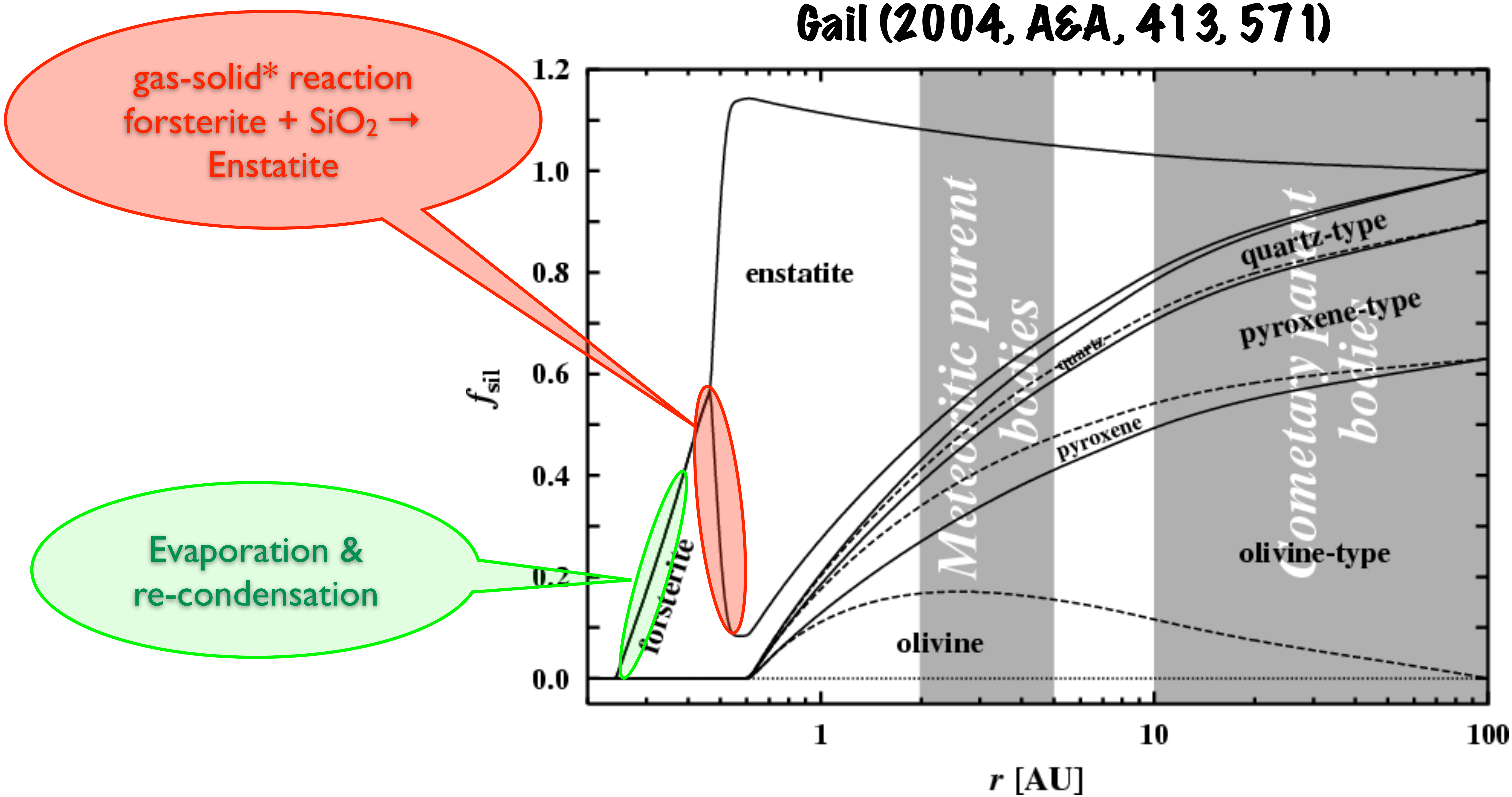
Gail (2004, A&A, 413, 571)



* reaction of solid states with H_2 yields SiO gas and H_2O gas allowing inter-grain transport of Silicon and Oxygen; see Gail et al. (2004) for a detailed description

spatial distribution

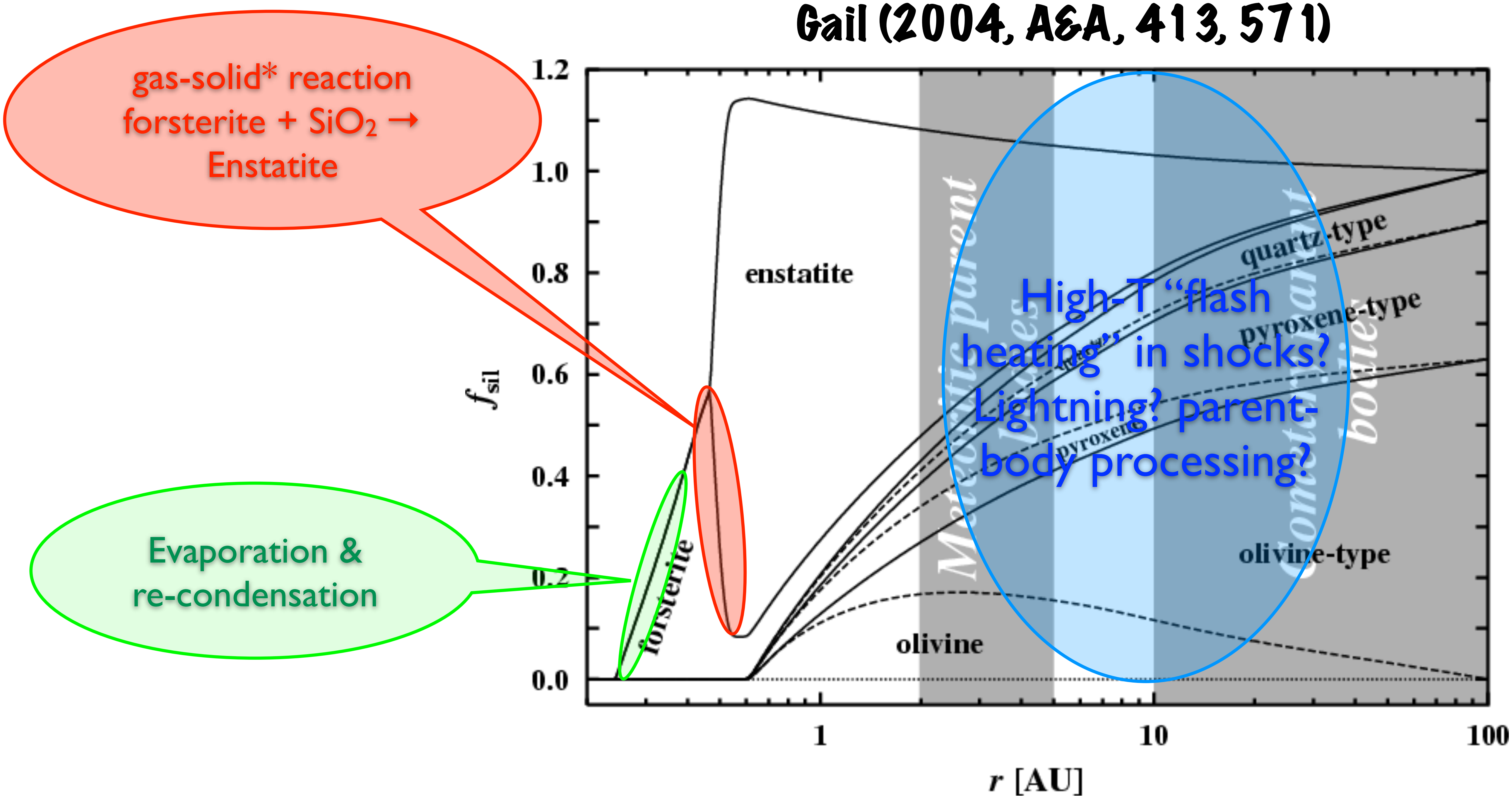
Gail (2004, A&A, 413, 571)



* reaction of solid states with H_2 yields SiO gas and H_2O gas allowing inter-grain transport of Silicon and Oxygen; see Gail et al. (2004) for a detailed description

spatial distribution

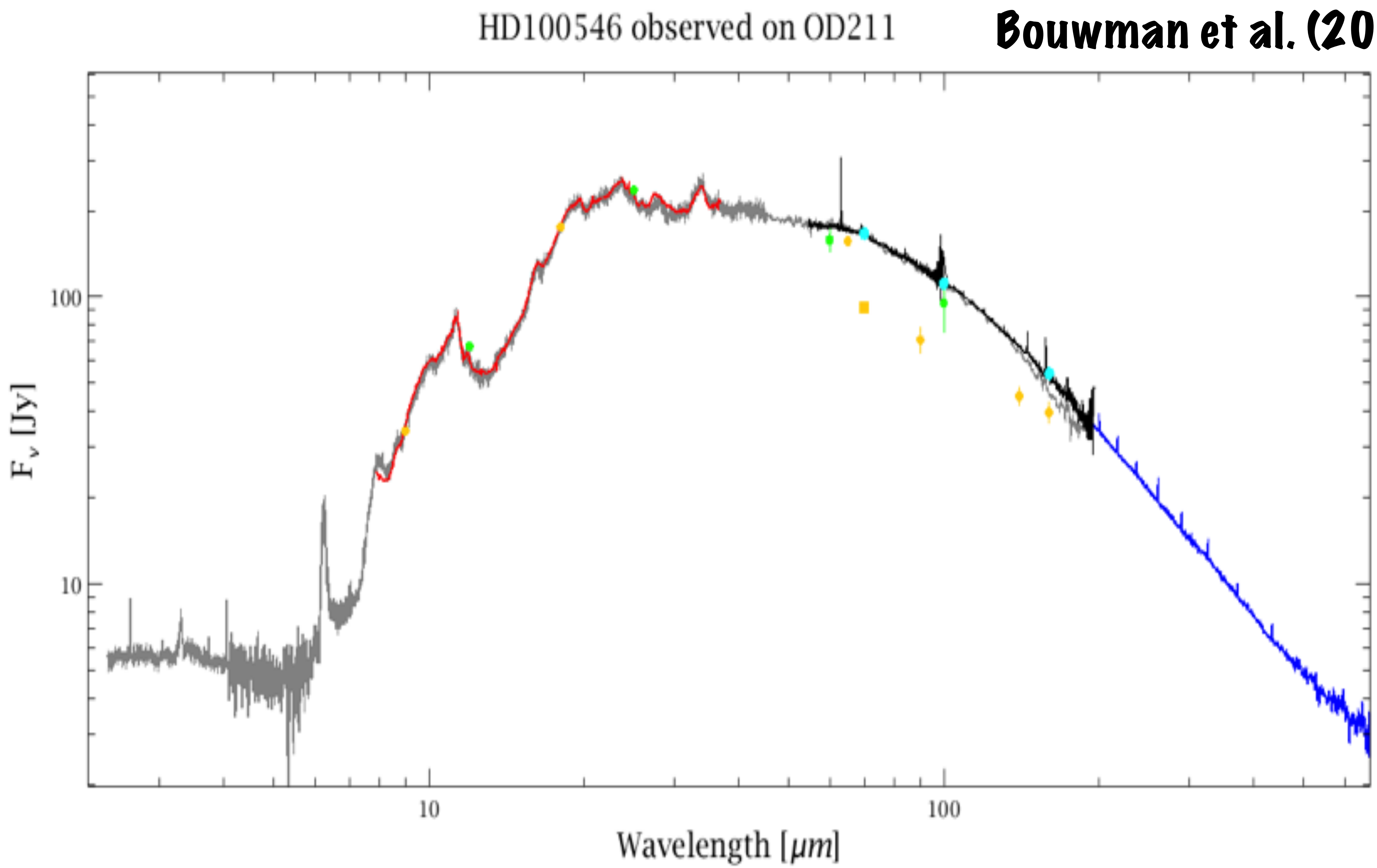
Gail (2004, A&A, 413, 571)



* reaction of solid states with H_2 yields SiO gas and H_2O gas allowing inter-grain transport of Silicon and Oxygen; see Gail et al. (2004) for a detailed description

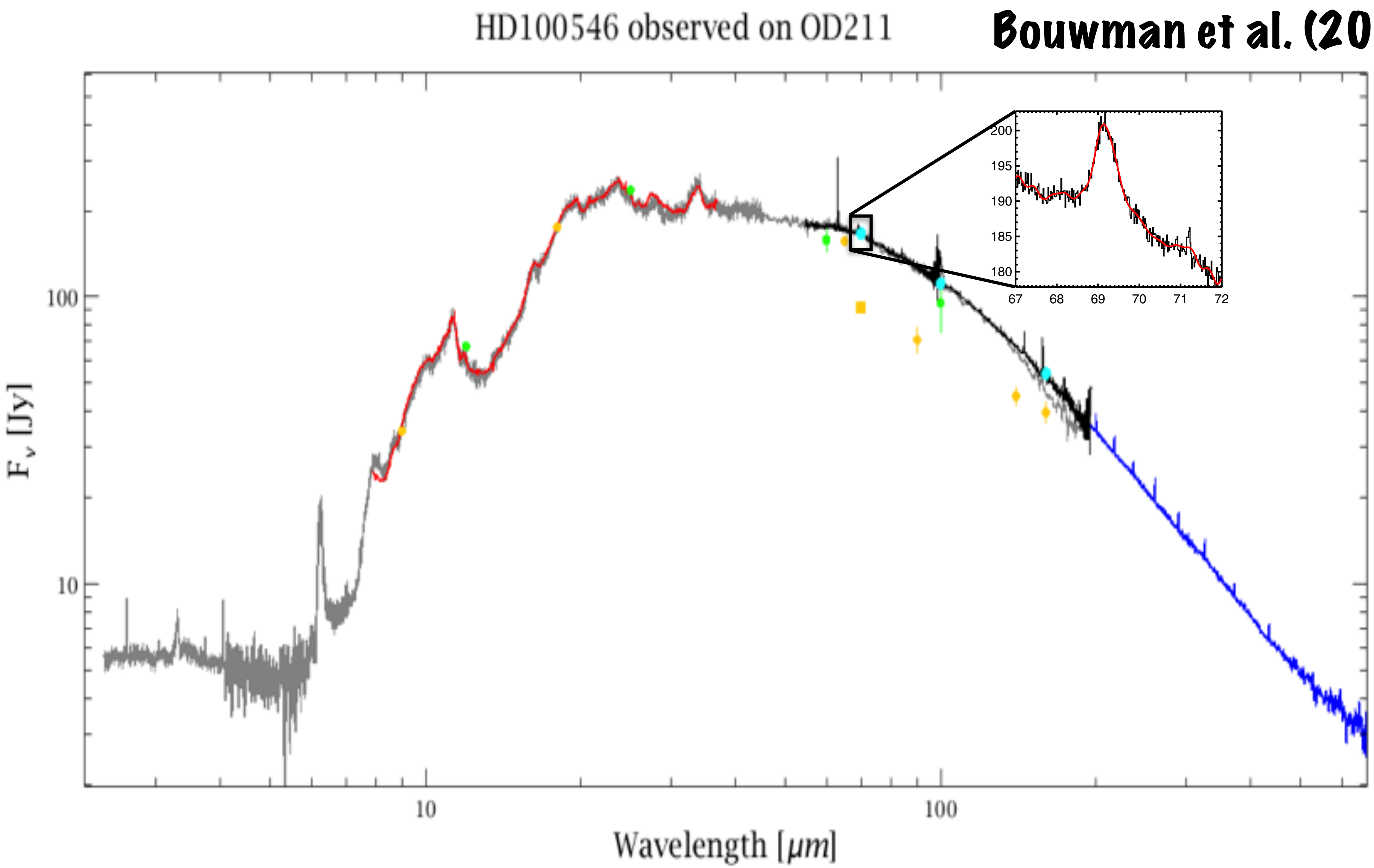
even cooler stuff: Herschel

Bouwman et al. (2014)



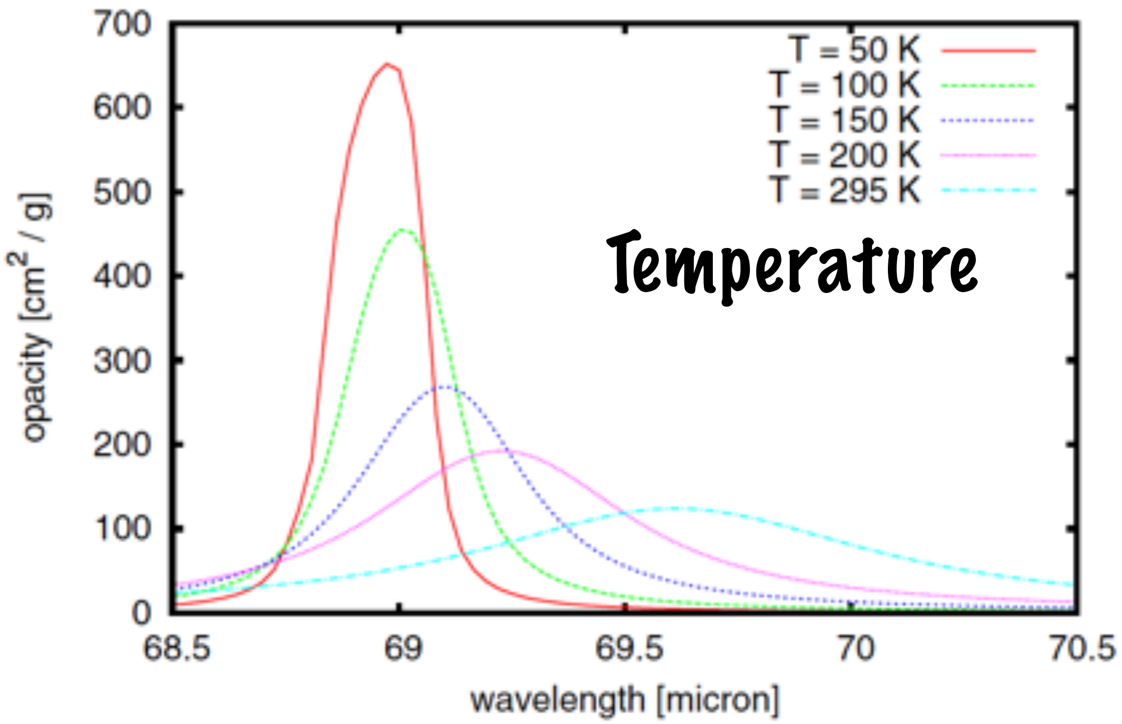
even cooler stuff: Herschel

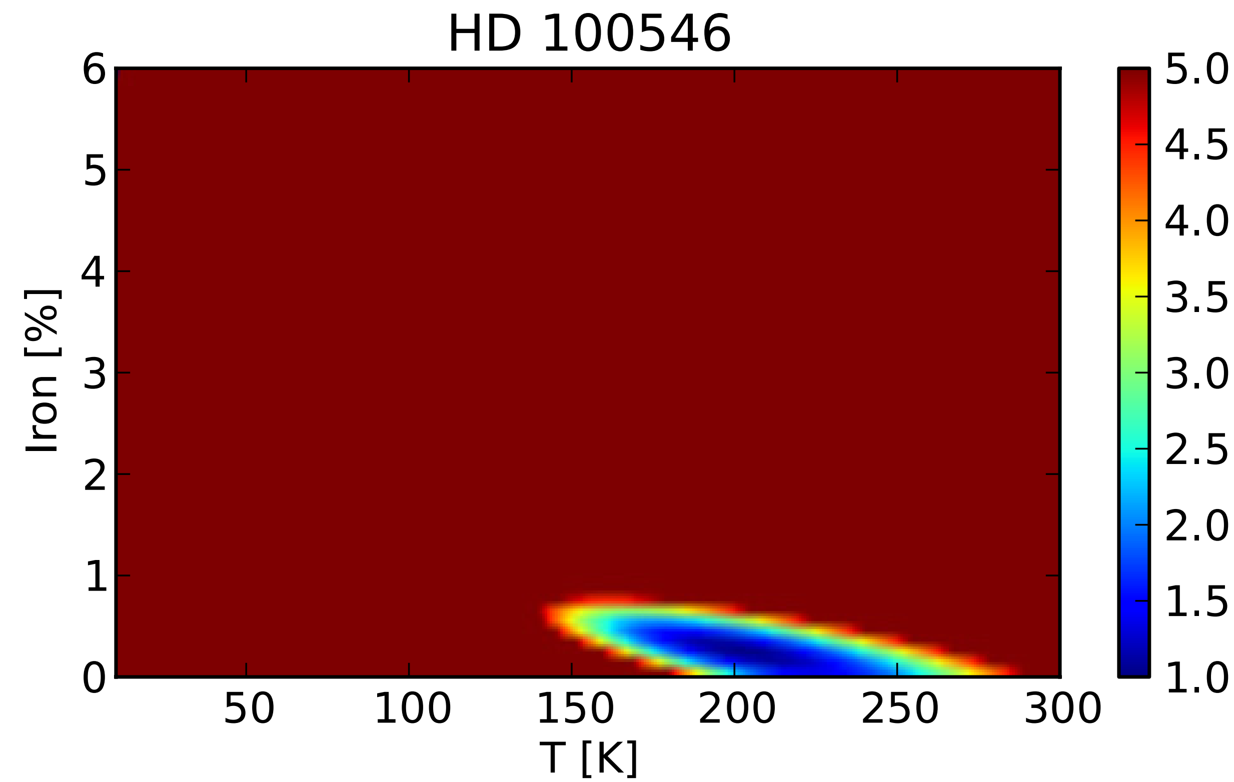
Bouwman et al. (2014)

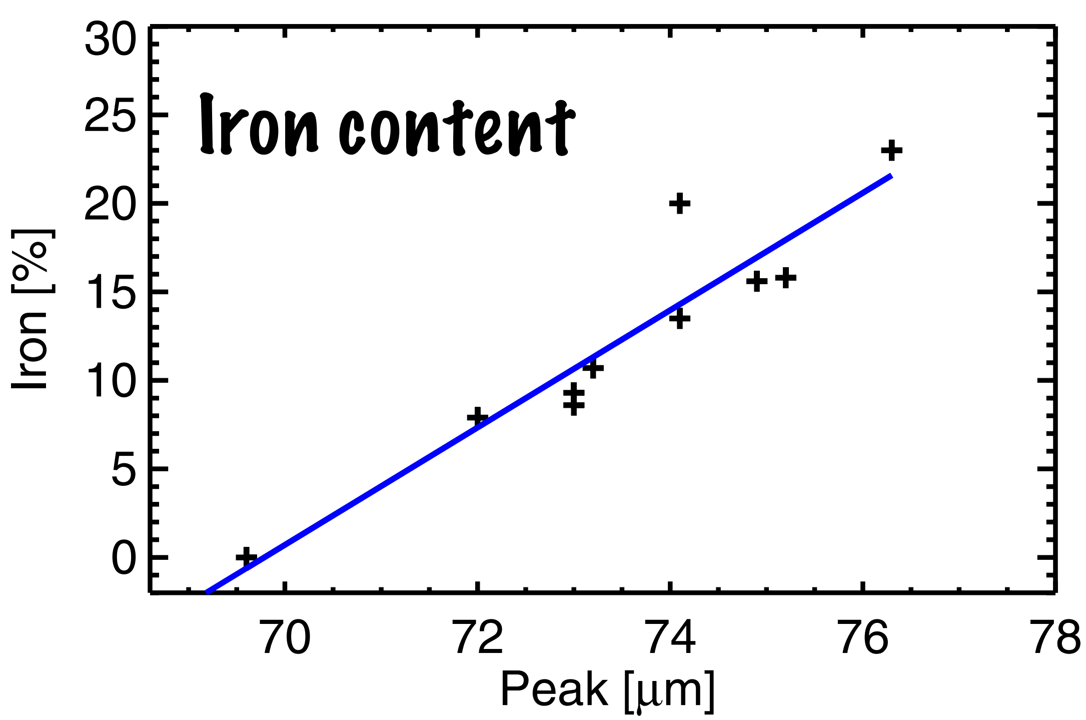


69 µm olivine band

Sturm et al. (2013, A&A, 533, 5) Maaskant et al. (2014, submitted)





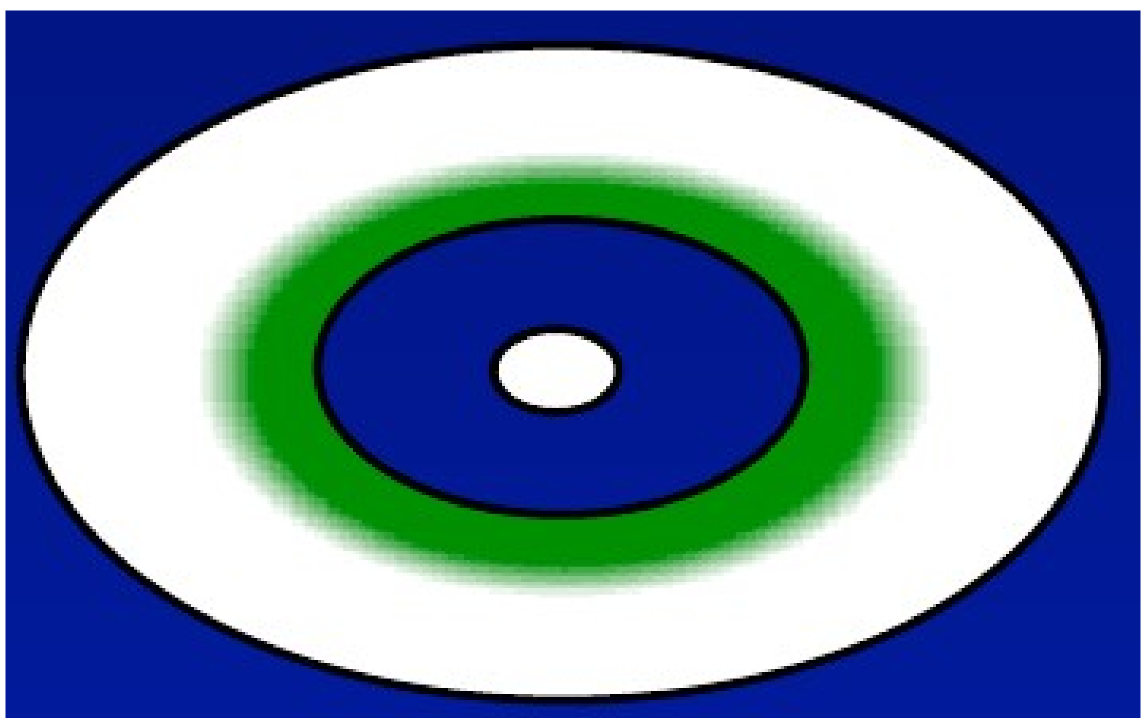


In sample of 8 HAe stars: 7 have ≲1% Fe,

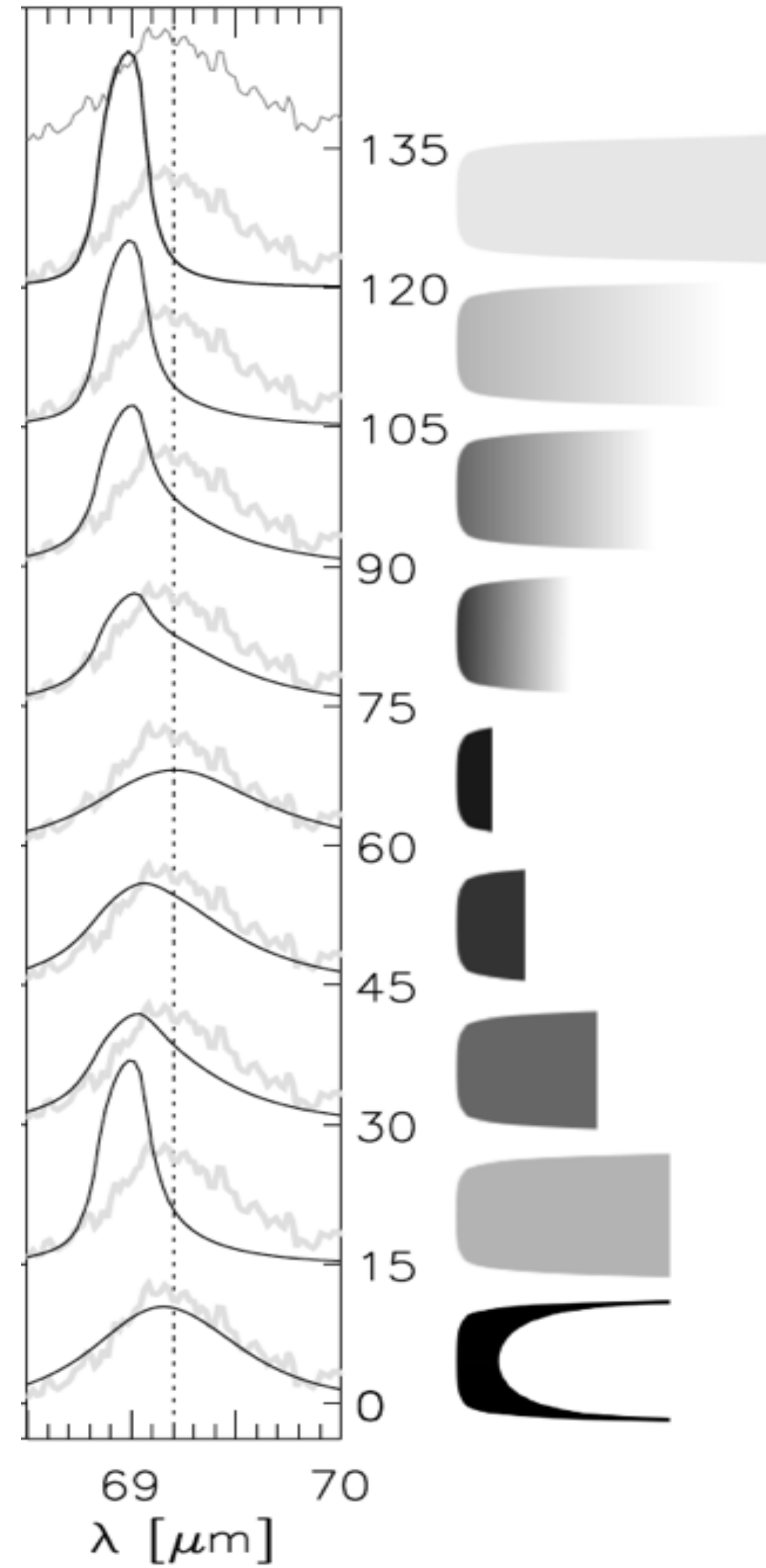
1 has ≈3% Fe (AB Aur) but low SNR

69 μm band in HD 100546

Mulders et al. (2011, A&A, 531, 93)

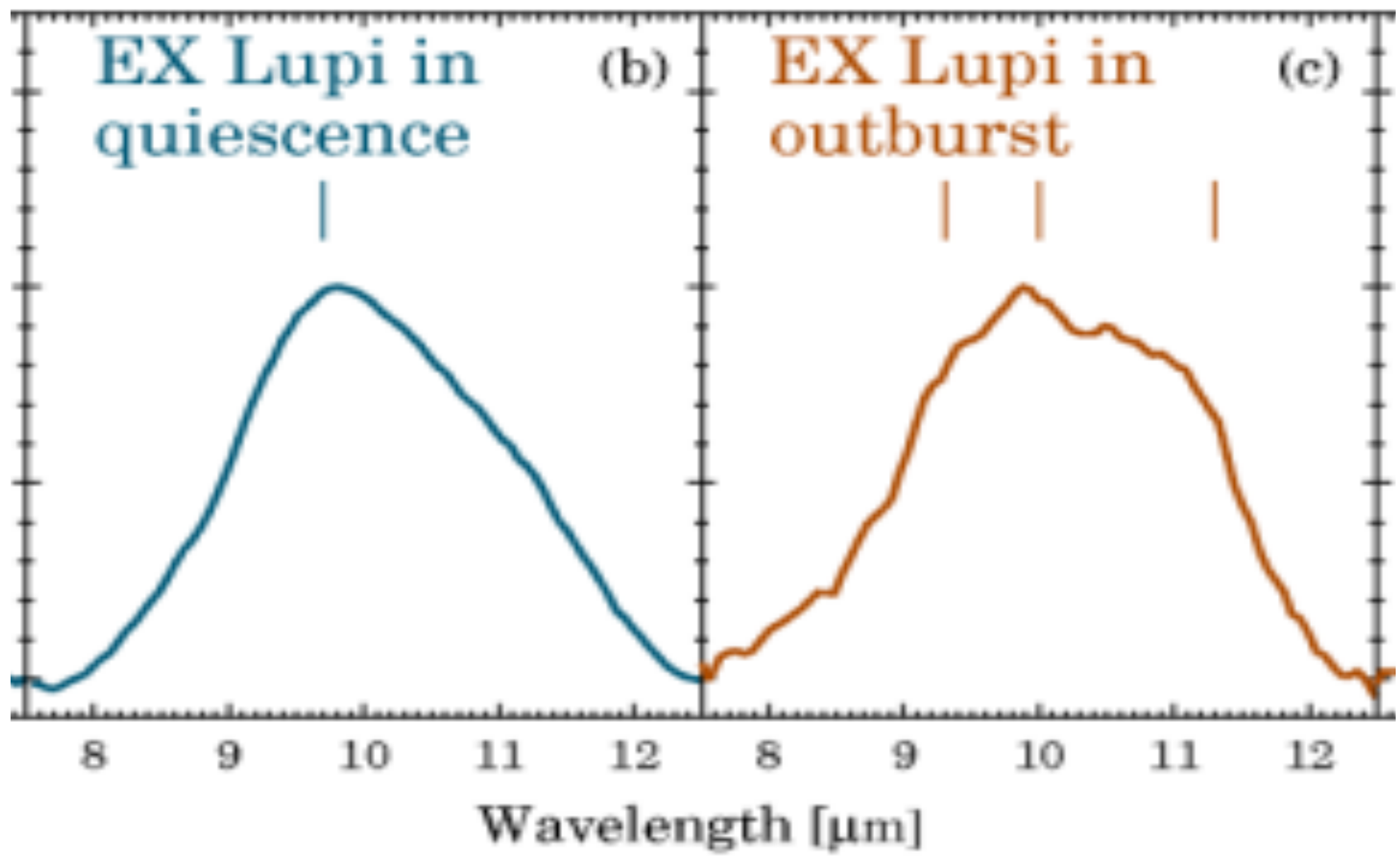


Fe/(Fe+Mg) = 0.003



real-time crystallization

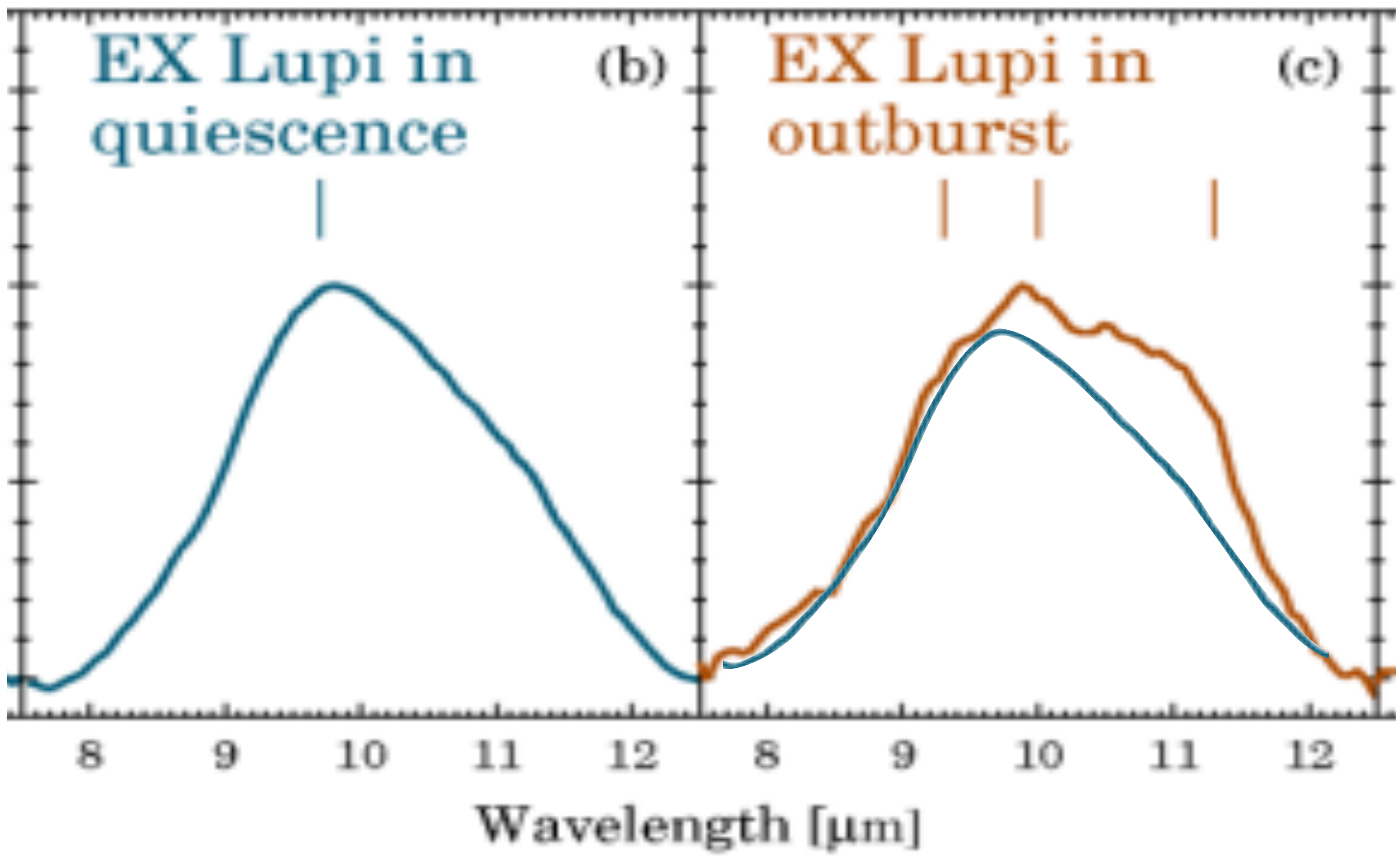
Abraham et al. (Nature, 459, 224)



less/not relevant in HAEBEs because of high photospheric luminosity (cannot get factor 10-100 increase in Lbol in accretion outburst)

real-time crystallization

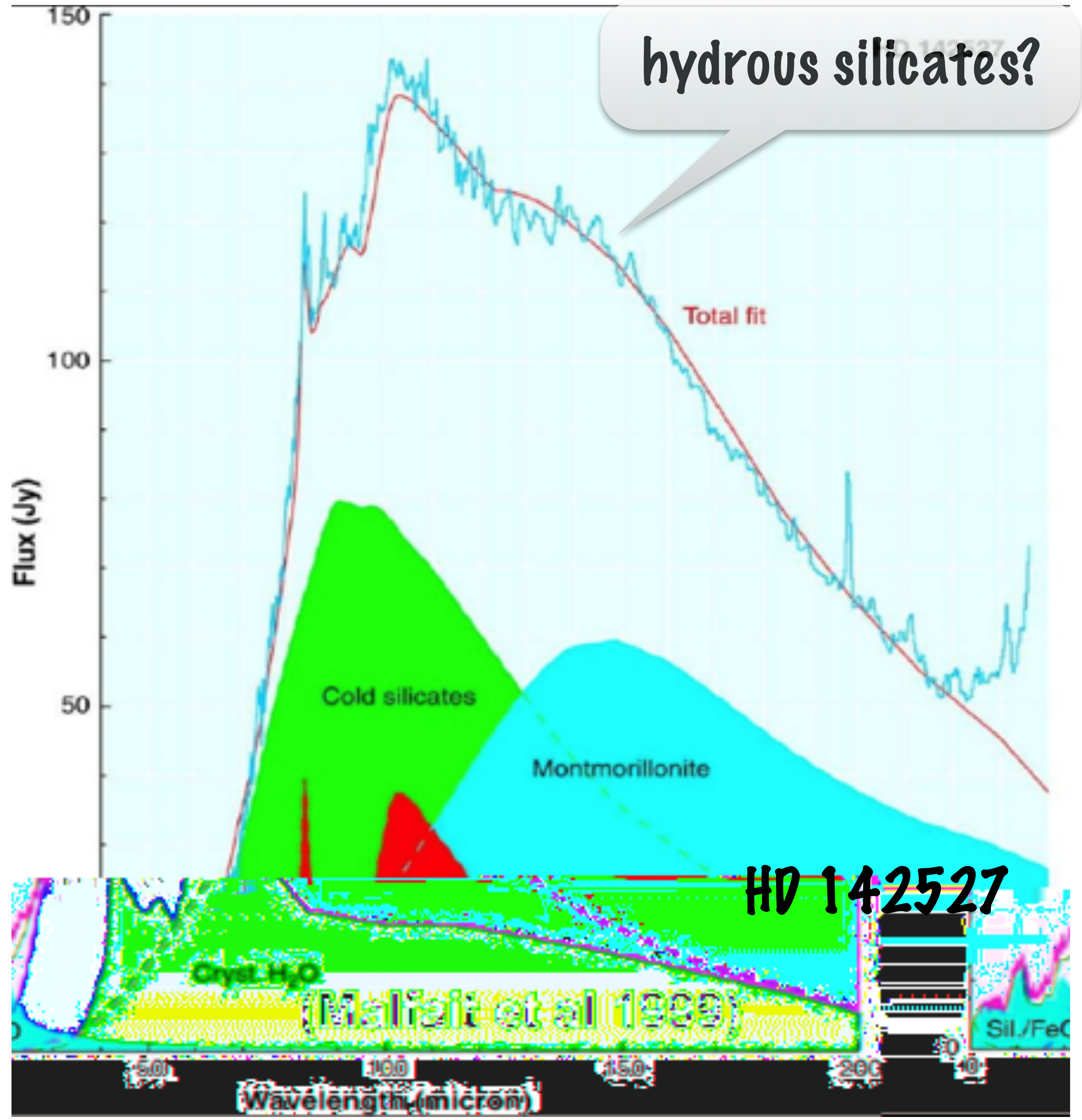
Abraham et al. (Nature, 459, 224)



less/not relevant in HAEBEs because of high photospheric luminosity (cannot get factor 10-100 increase in Lbol in accretion outburst)

Parent-body processing?

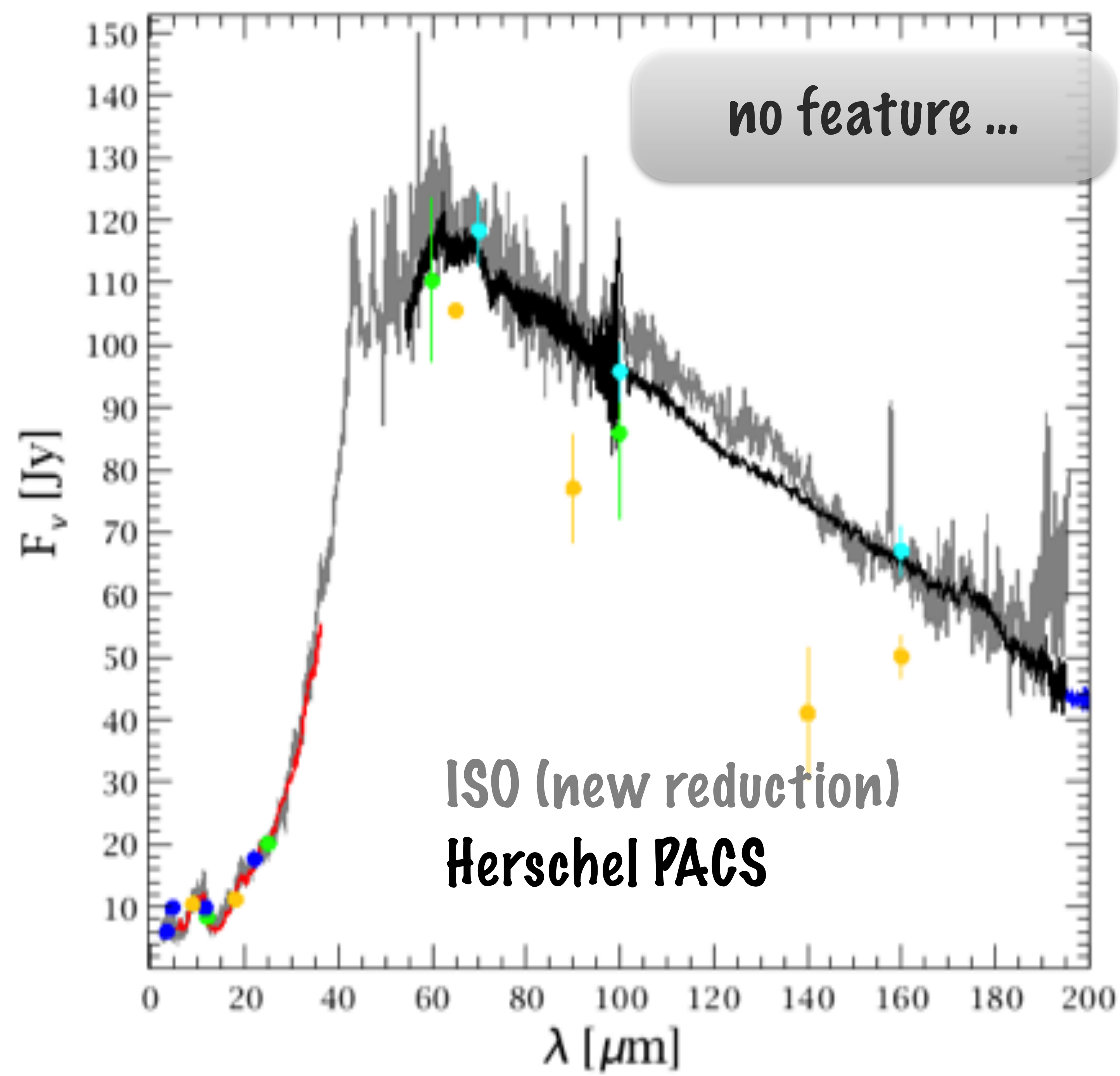
- dust → planetesimals → large bodies
- high T / high P / differentiation / liq. water
- collisions → 2nd gener. dust
- tracer: hydrous silicates
- tentative evidence from ISO
- not confirmed with Herschel
- no evidence for parent-body processing (so far ...)



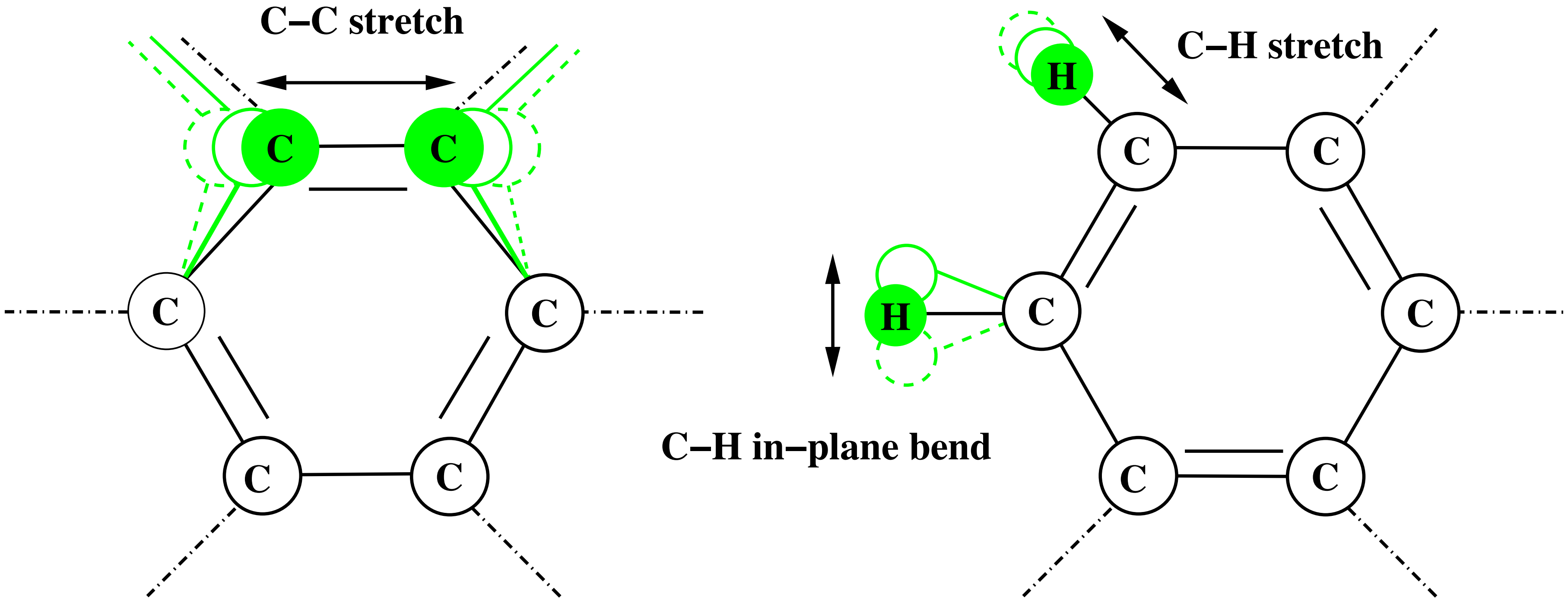
Parent-body processing?

- dust → planetesimals → large bodies
- high T / high P / differentiation / liq. water
- collisions → 2nd gener. dust
- tracer: hydrous silicates
- tentative evidence from ISO
- **not confirmed with Herschel**
- **no evidence for parent-body processing (so far ...)**

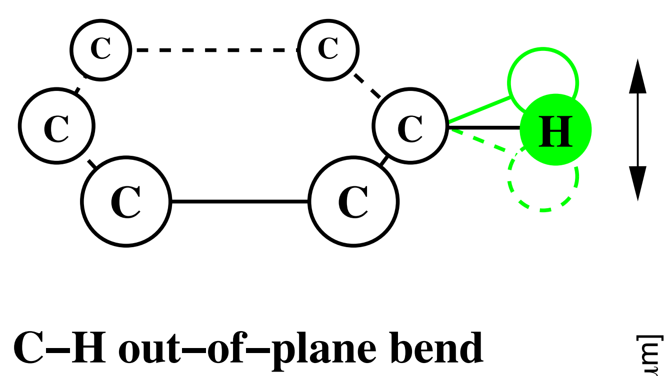
Min et al. 2014 (in prep)

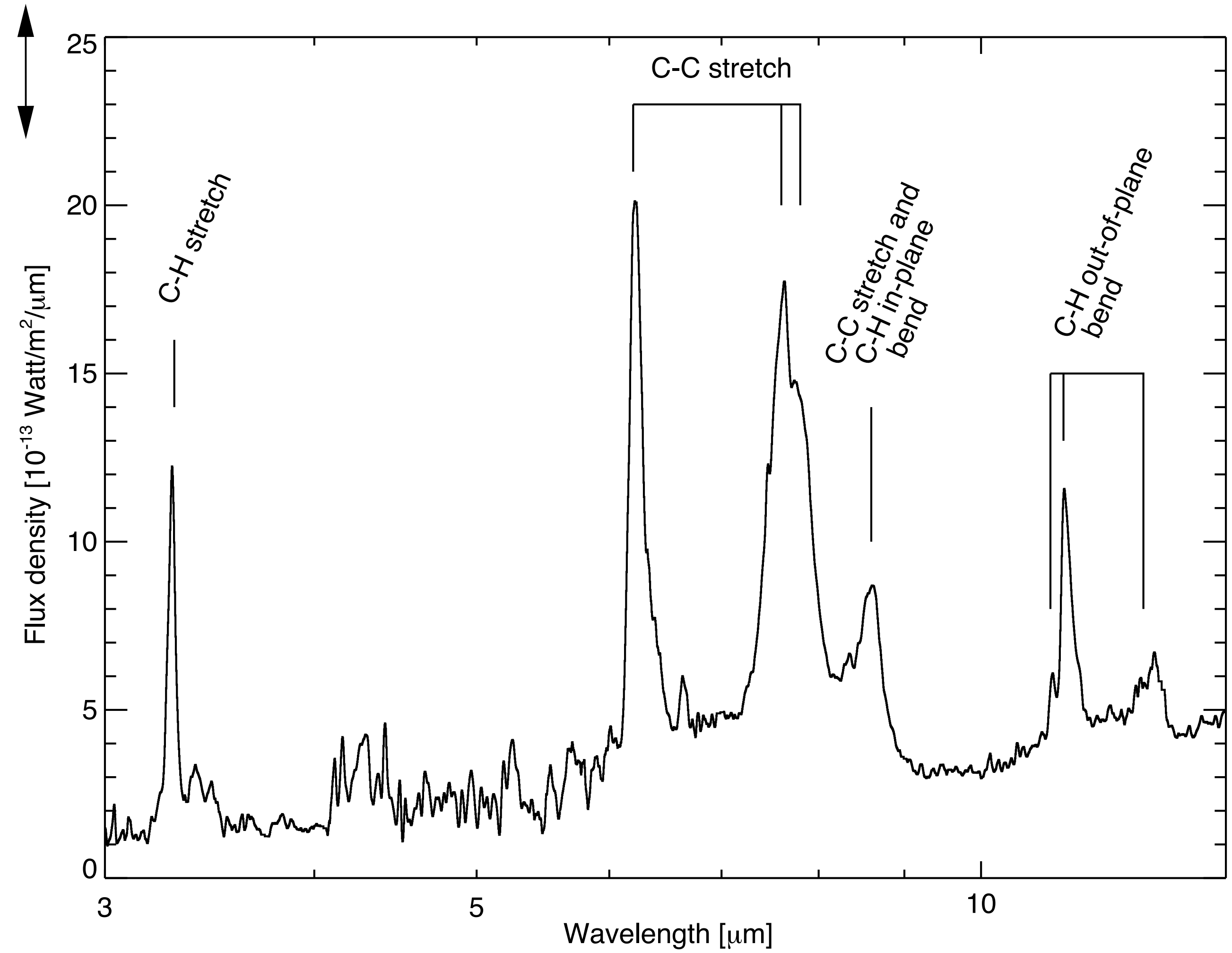


PAHs



Peeters (2002)





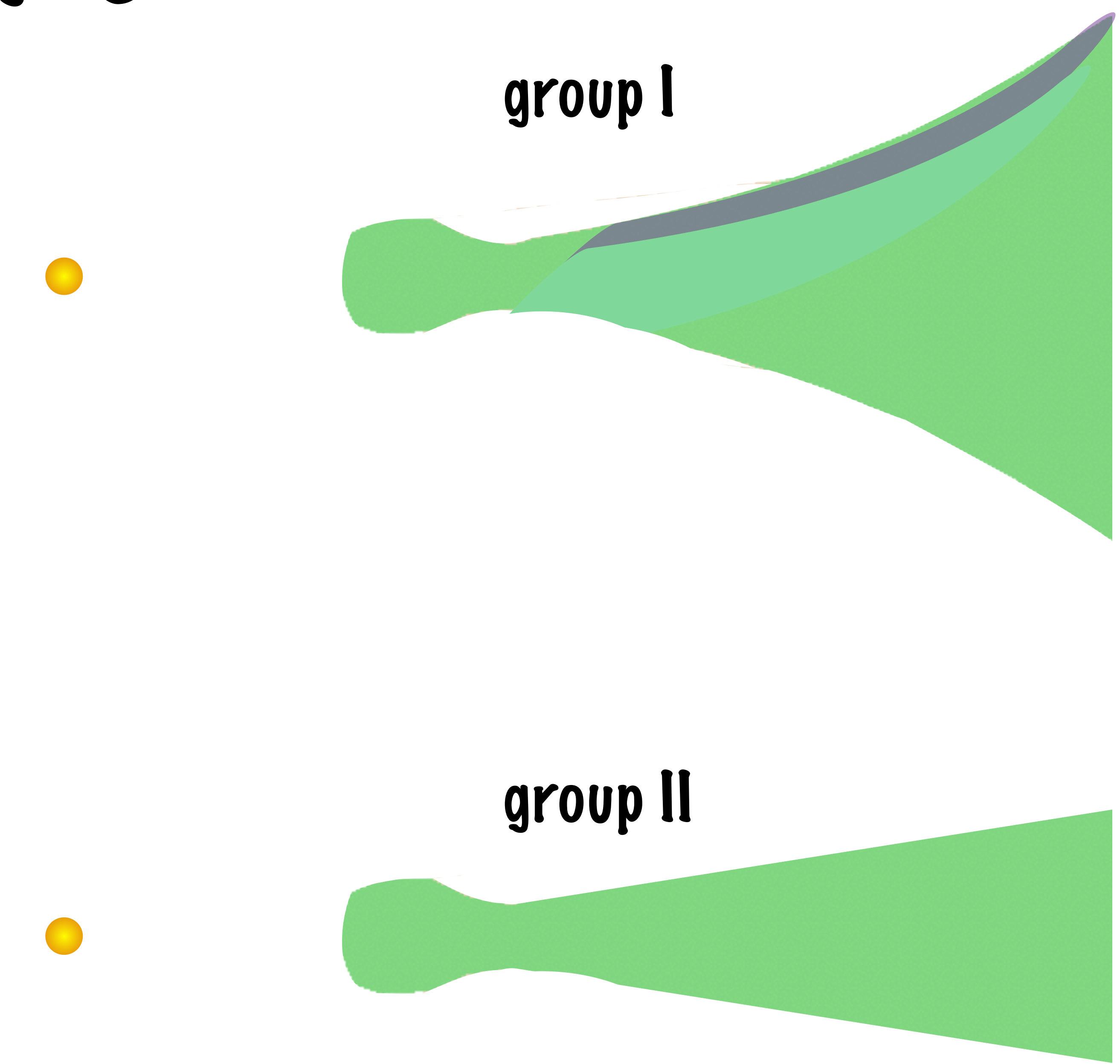
Band shapes & strengths depend on:

- size of molecule
- ionization state
- H-atoms at edges
- ring/chain structure

PAHs

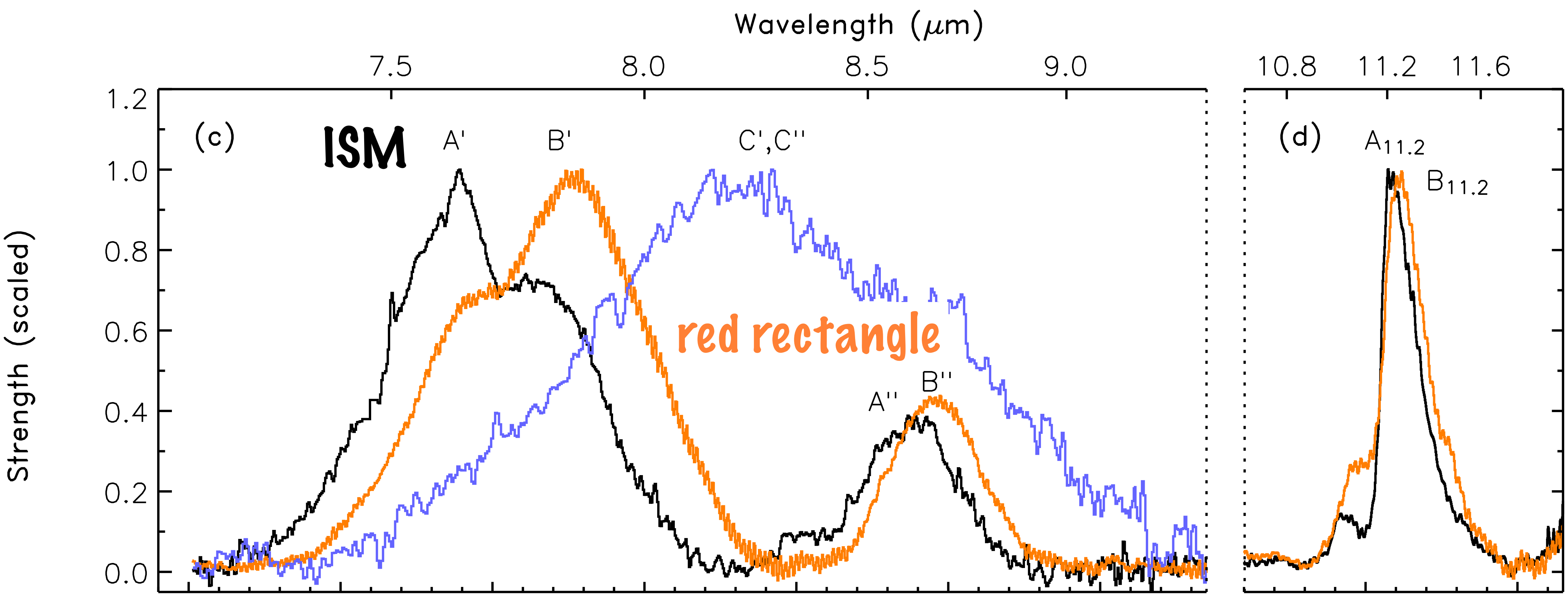
- UV-excitation
- Stochastic heating
- Disk geometry important
  - "group I" strong PAHs
  - "group II" weak PAHs, mostly

    (e.g. Acke & van den Ancker, 2004, 426, 151; Acke et al. et al. 2010, ApJ, 718, 558)



PAHs

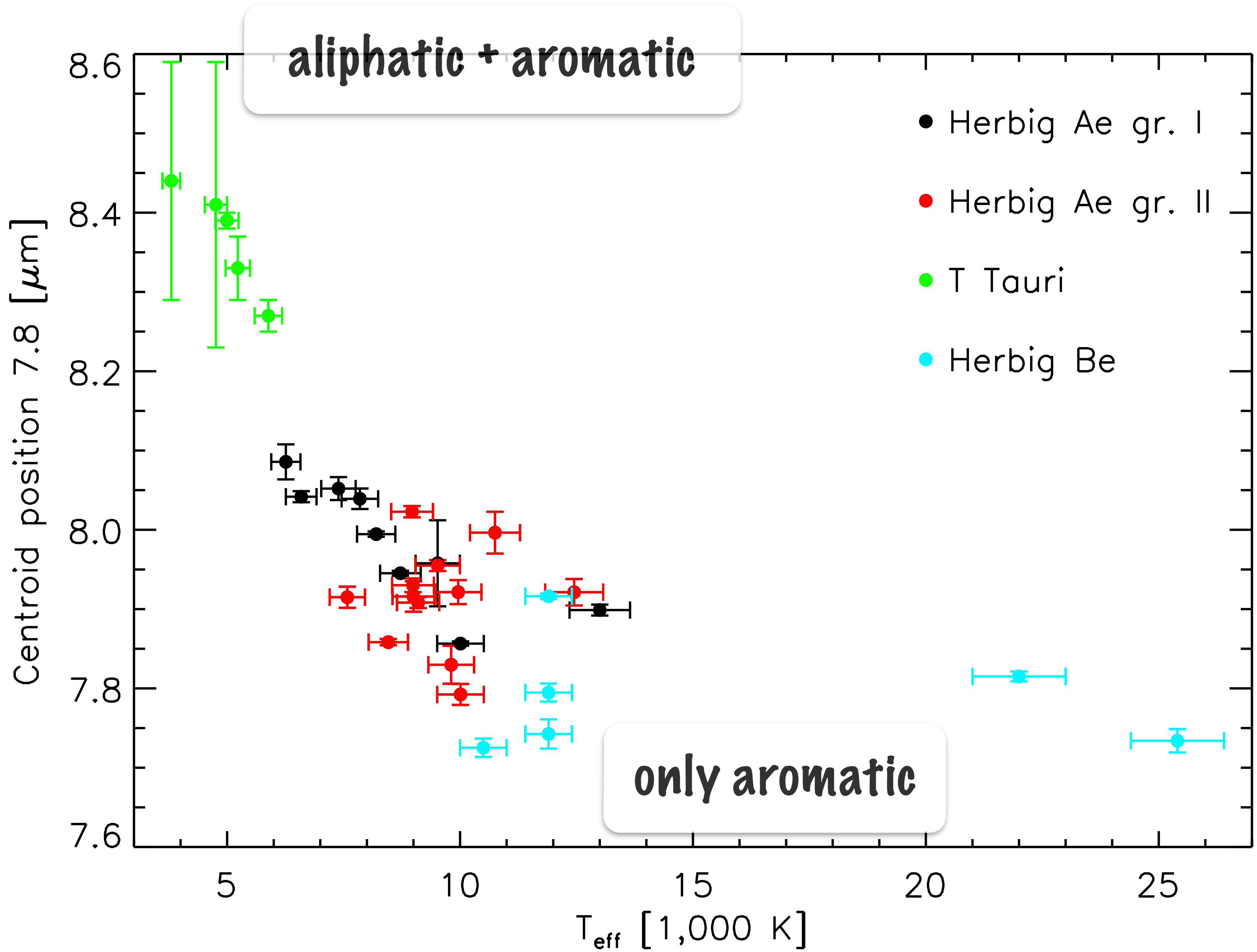
- Abundant in ISM
- Depleted/Absent in class 0 objects
  (Van Dishoeck & van der Tak 2000; Geers et al. 2009)
- visible in most HAe stars, shapes from A' to B'
  (Peeters, 2002, Acke & v/d Ancker 2004, Acke et al. 2010)



Peeters (2011)

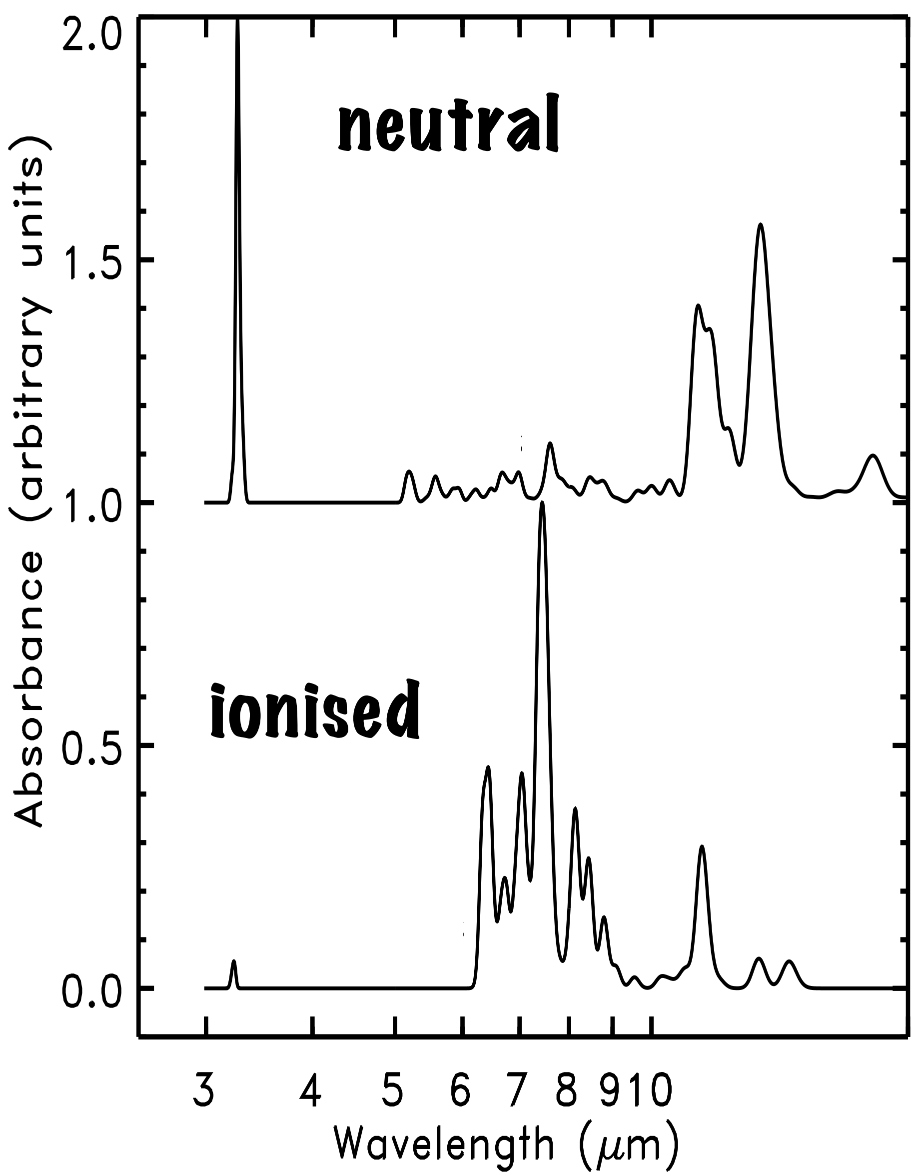
Dependence on UV field

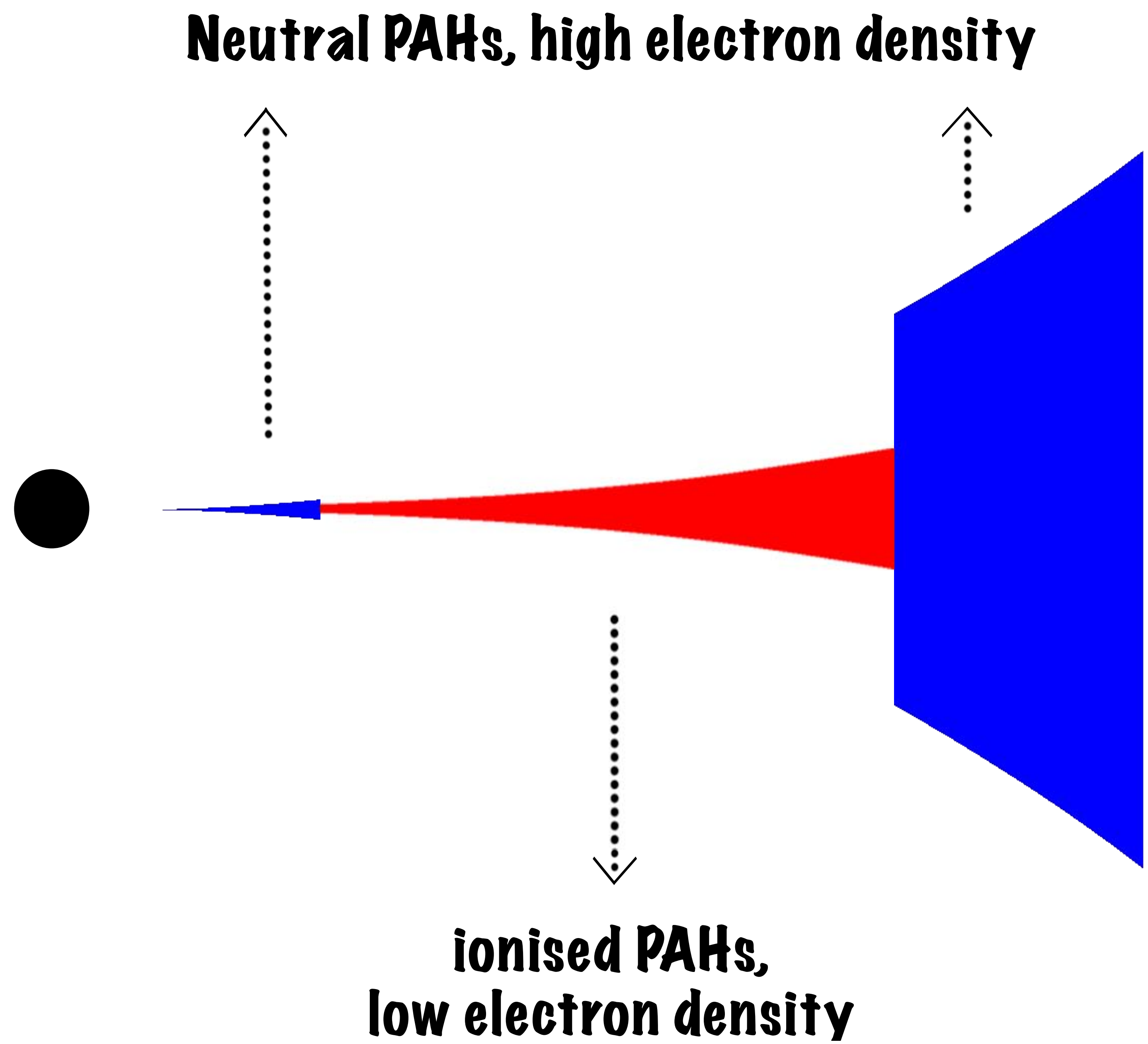
Acke et al. (2010, ApJ, 718, 558)



PAHs in transition disks

Maaskant et al. (2014, A&A 563, A78)





Conclusions

- Grain growth is ubiquitous ?
- Crystallization:
  - cold crystalline silicates very Fe-Poor, warm/hot ones probably as well
  - evaporation & re-condensation at inner disk edge
  - outward transport & gas-solid reaction → radial transport important in central few AU!
  - non-equilibrium processes at large radii, likely evaporation & re-condensation
- no evidence for parent-body processing yet
- PAHs frozen in cores, partially released in disks?
- PAH Chemistry driven by stellar UV-field

Limitations

IR spectroscopy:

- composition: only species with spectral features
- growth: only limited range of particle sizes, or porosity?
- only "surface layer", small fraction of total dust

mm observations:

- no spectral features, no direct composition info
- grain size, porosity, ice mantles all affect spectral slope

END