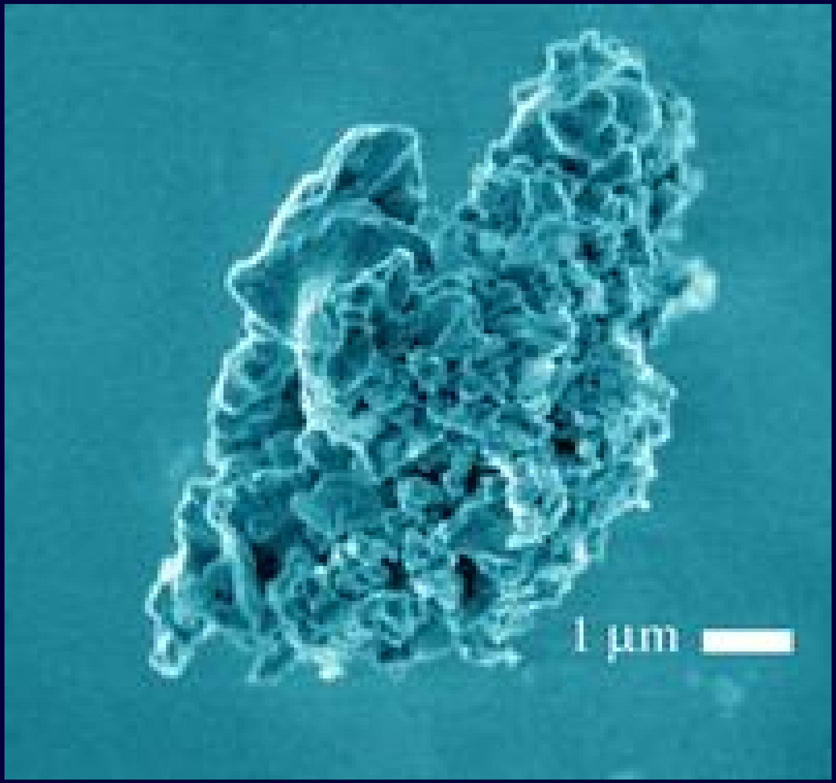
Disk Composition from Spectra

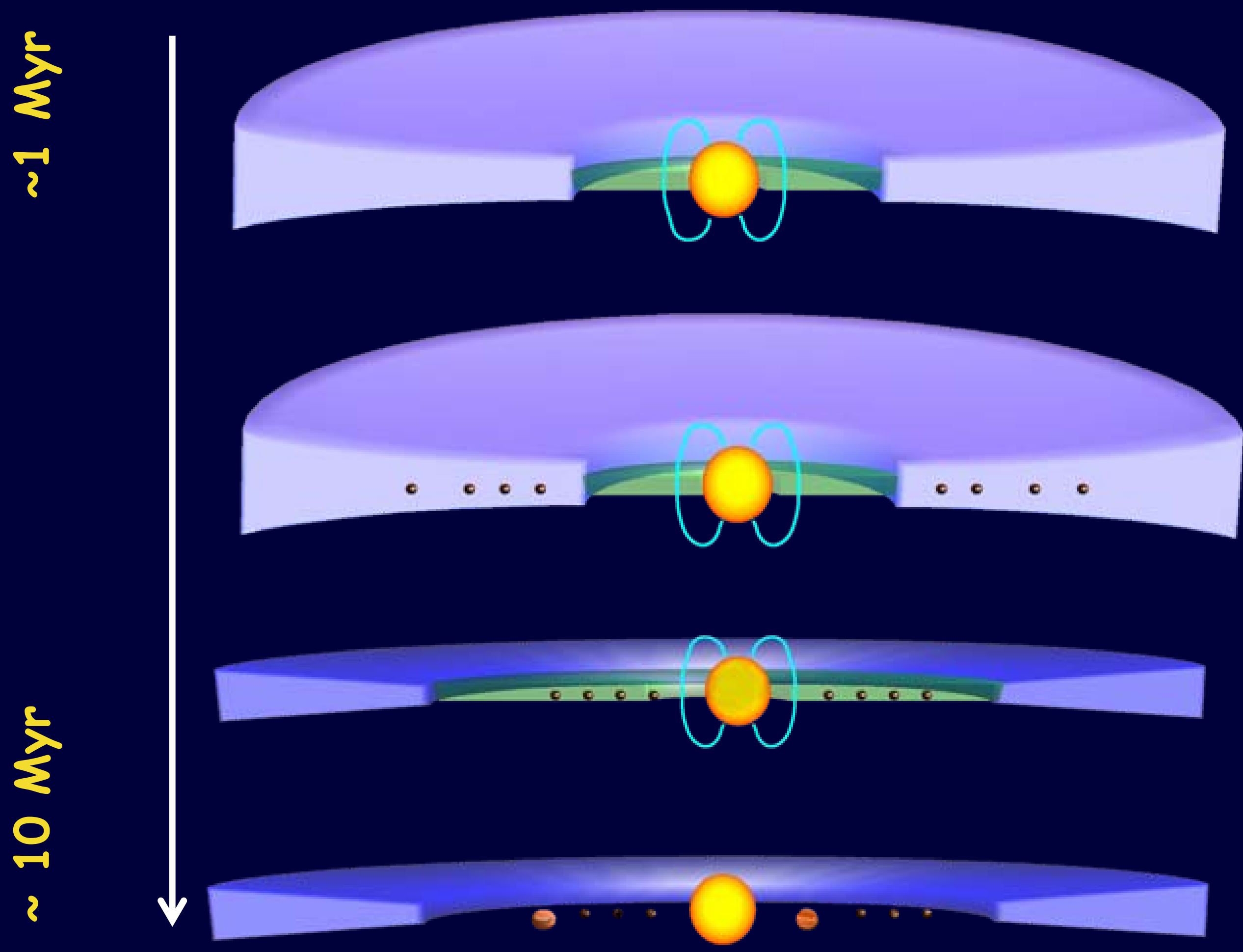


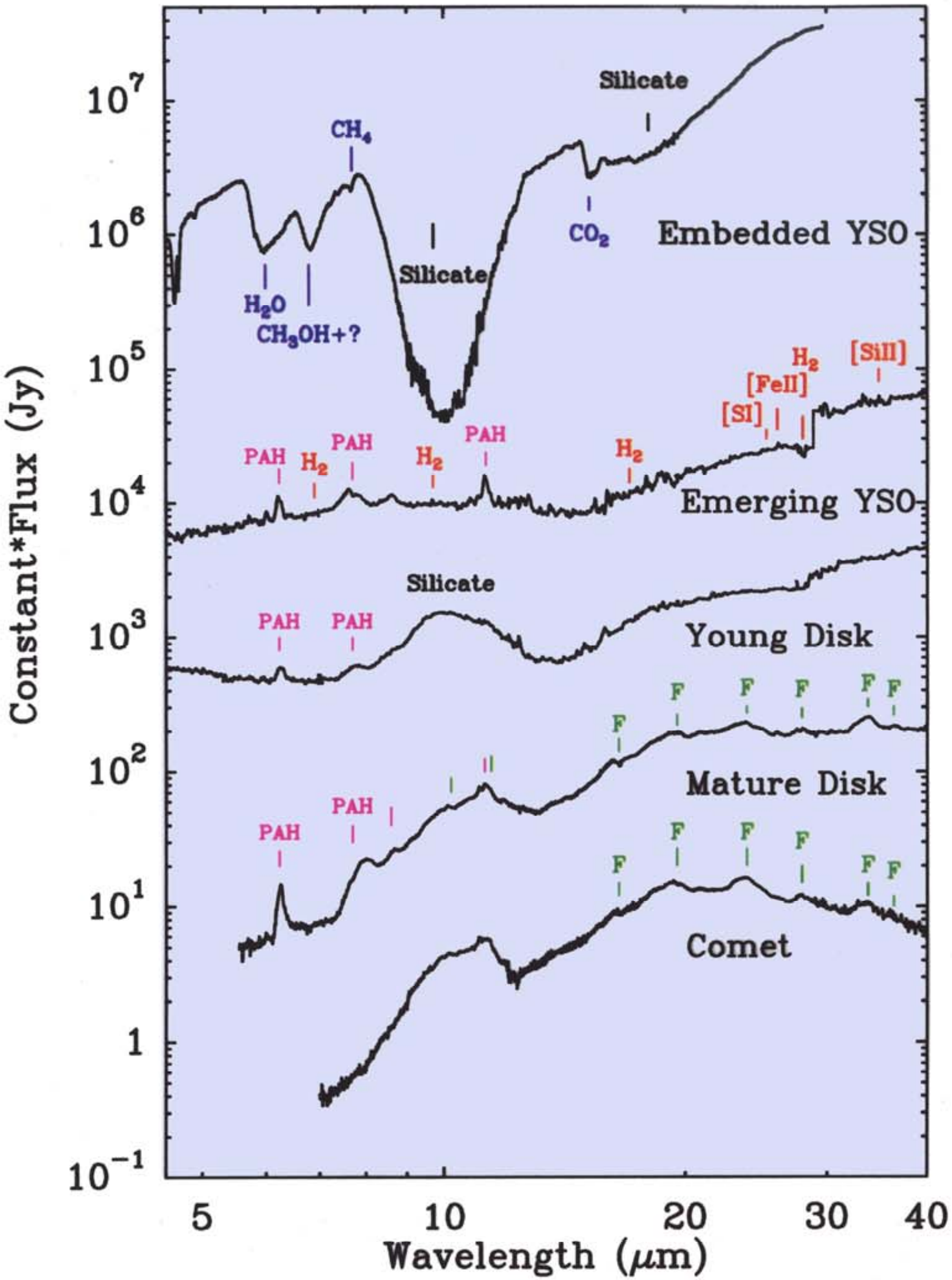
Dust: Motivation

- From molecular cloud dust to planetesimals
- Continuum radiation as an analytical tool

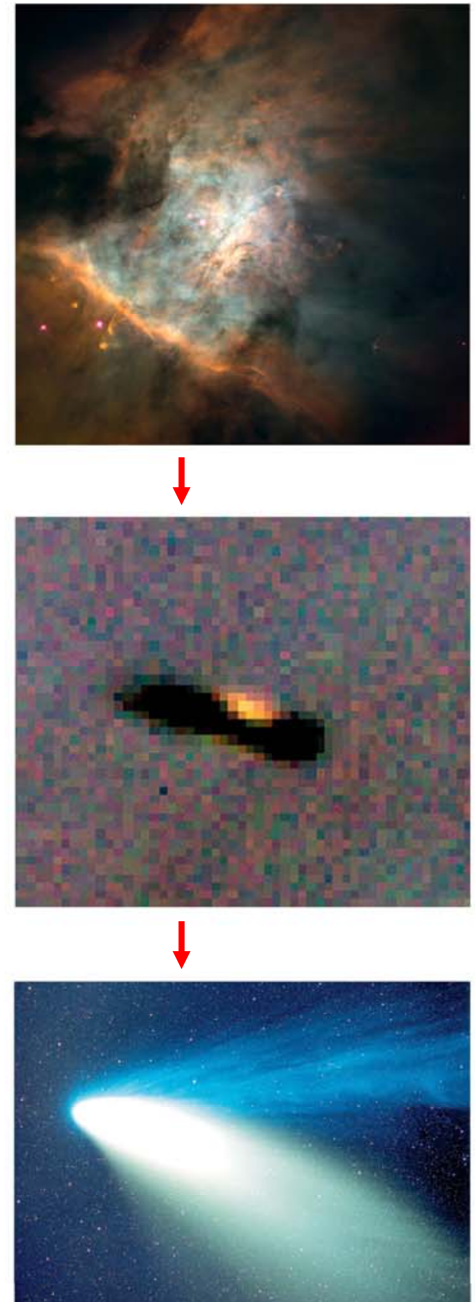
  (Geometry vs. dust opacity)
- Dust affecting disk structure:
  - Dust opacities (Temperature, Convection)
  - Multi-phase fluid system (shear-ind. turbulence)
- Dust affecting disk chemistry and ionisation

Time evolution of protoplanetary disks

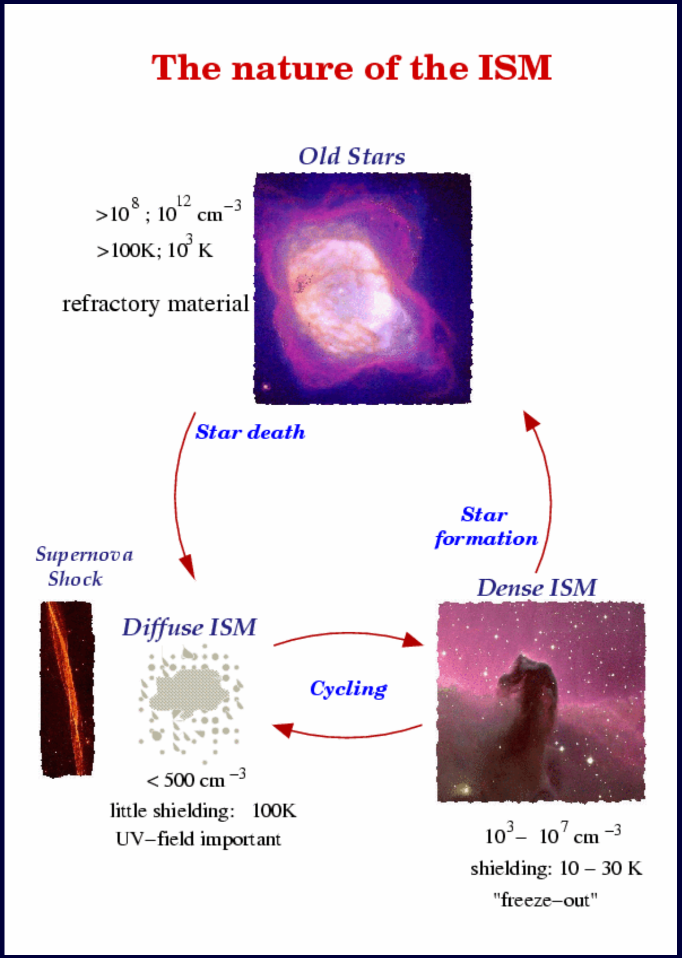




Constant*Flux (Jy)
Wavelength (μm)
5
10
20
30
40
10^{-1}
1
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
Embedded YSO
Silicate
CH_4
CO_2
H_2O
CH_3OH+?
Silicate
Emerging YSO
PAH
H_2
PAH
H_2
PAH
H_2
[SI]
[FeII]
H_2
[SiII]
Young Disk
Silicate
PAH
PAH
Mature Disk
F
F
F
F
F
F
PAH
PAH
Comet
F
F
F
F
F
F



The life cycle of dust



	crystallinity x
Evolved (AGB, PN, RSG)	11-18 %
Evolved (SN)	?
diffuse ISM	<1 %
Star forming regions	small
Herbig Ae/Be, T Tau stars	5-8 %
Debris disks	?
Solar system	Very high

Dust properties: observations

Spectroscopy and Imaging:

IR, optical, UV, mm

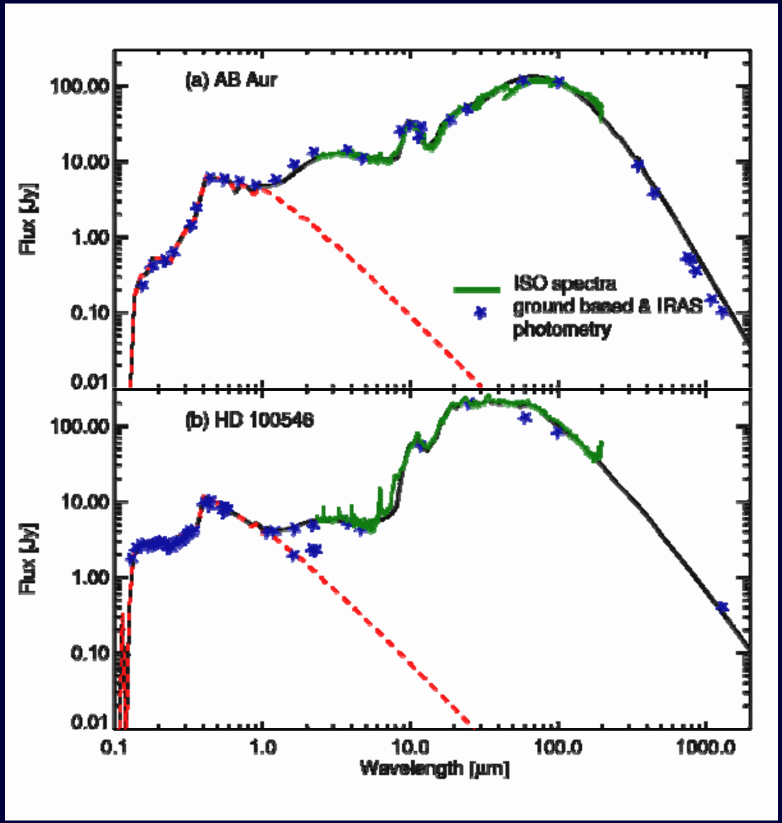
- Composition
  - Degree of dust processing
- Grain shape
- Grain size
- Total dust mass
- Temperature of dust grains
  - Distribution?

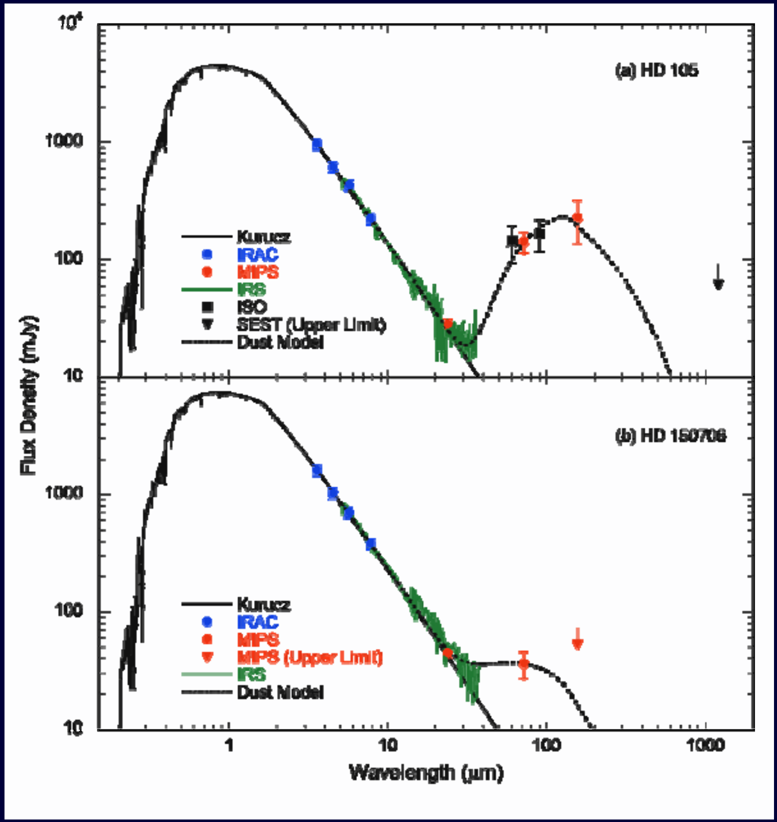
Dust properties: laboratory

- Optical properties of astronomically relevant materials
- Dust condensation experiments
- Dust processing experiments:
  - Annealing
  - Irradiation with particles and high energy photons
- Grains of interstellar/circumstellar origin: IDPs, Chondrules, etc.

Disk composition from spectra: Data

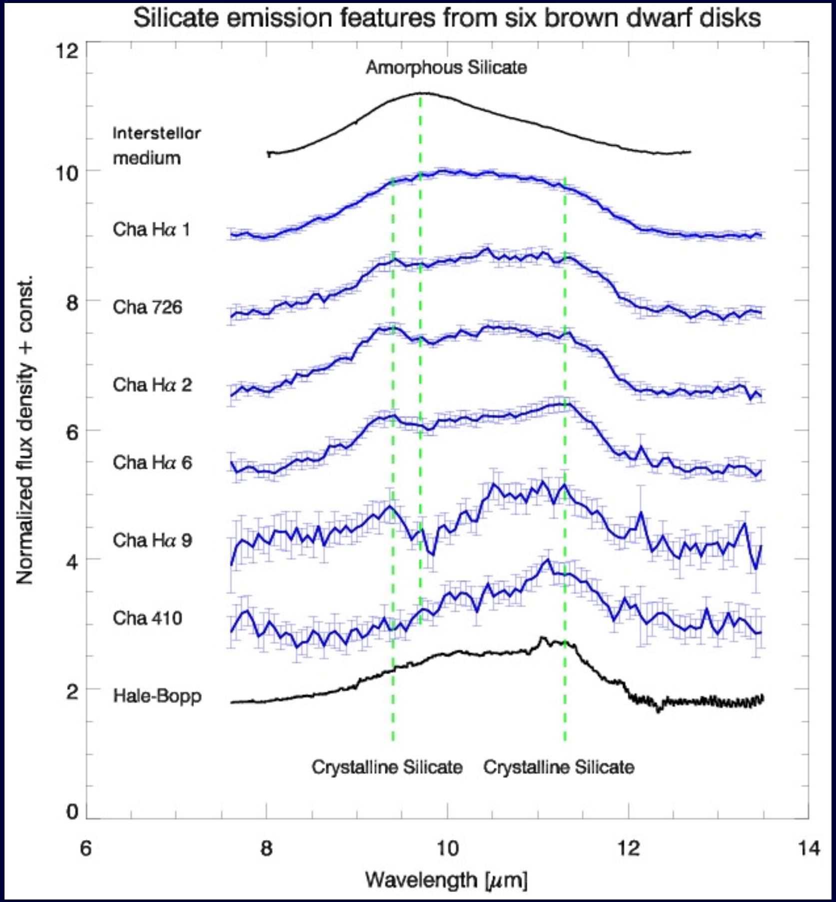
From ISO to Spitzer





(Bouwman et al. 2003, Meyer et al 2004)

Spitzer observations of Brown Dwarf disks



(Apai et al. Science, 2005)

First step: Calibration

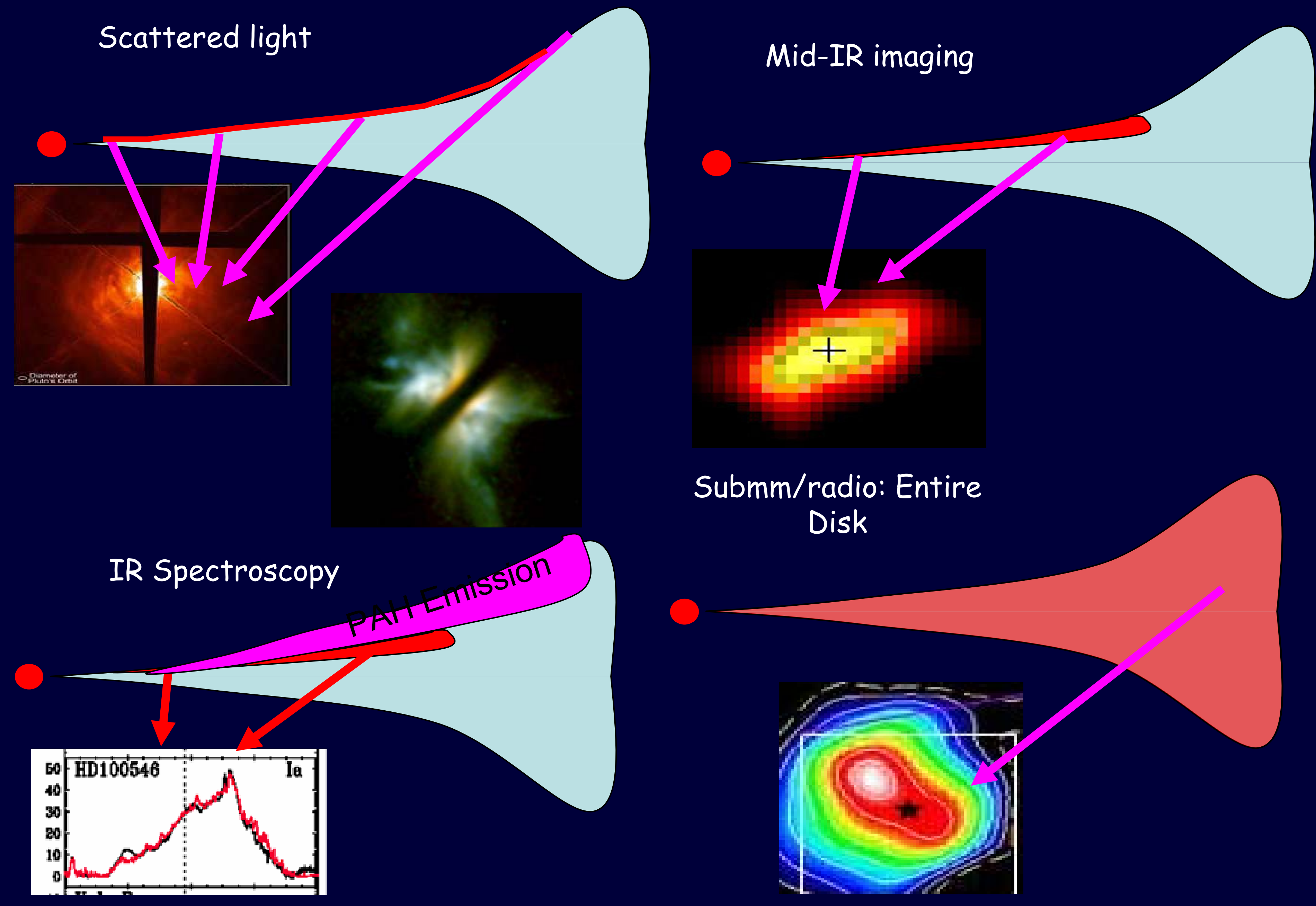
Can you trust features weaker than 1%?

YES! …….if:

- -Spectral response function
- -Flatfielding
- -Instrumental artifacts
- -Throughput corrections
- -non-linearities
- -extended emission

Give a big applause to the SSC and IRS instrument team.

Which observations probe which grains?



Disk composition from spectra: Modeling

What determines the infrared absorption?

- Grain size effects on the opacity
- Shape-dependent opacity effects
  (e.g. graphite needles – Wright 1982)
- Formation of dirty ice mantles
  (Preibisch et al. 1993)
- Formation of fluffy grains
  (e.g. Wright 1987, Ossenkopf & Henning 1994, Stognienko et al. 1995, Quinten et al. 2002)

What determines the infrared absorption?

- Structural transformation
  (e.g. carbon modifications – Jäger, Mutschke, Henning 1998)

- Formation of new dust components
  (e.g. FeS, Fe particles – Henning and Stognienko 1996)

- Temperature dependence of the opacity
  (Henning & Mutschke 1997, Bösch 1978, Agladze et al. 1996, Mennella et al. 1998, Boudet et al. 2005)

Minarology of protoplanetary disks

Structure of silicates

- Most important/common species.
- Defining property : SiO_4-Tetraeder
- Most common sillicates in space:

Olivine: **$(Mg^{2+}, Fe^{2+})_2 SiO_4$**

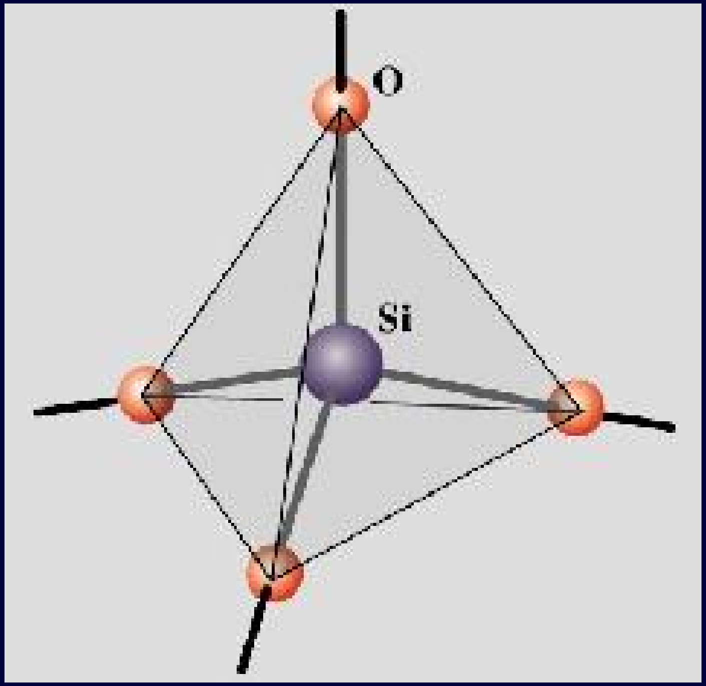
Forsterite Mg_2SiO_4

Fayalite Fe_2SiO_4

Pyroxene: **$(Mg^{2+}, Fe^{2+}) SiO_3$**

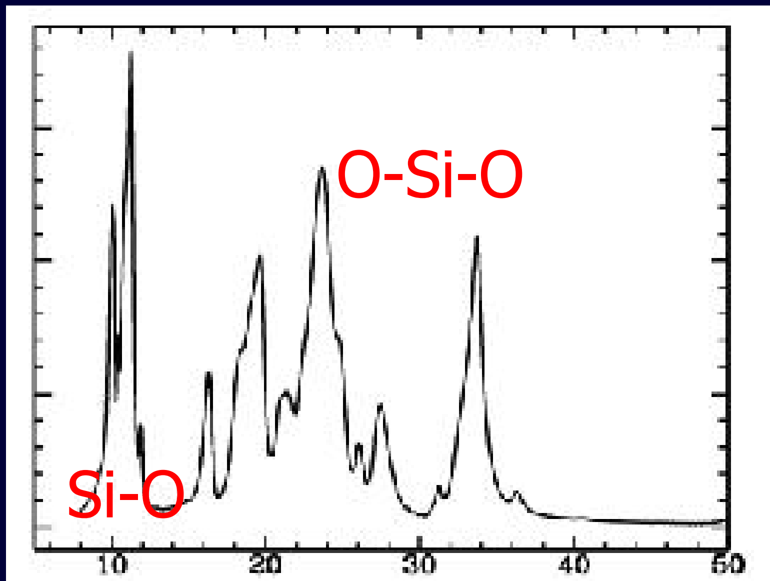
Enstatite $MgSiO_3$

Ferrosilite $FeSiO_3$

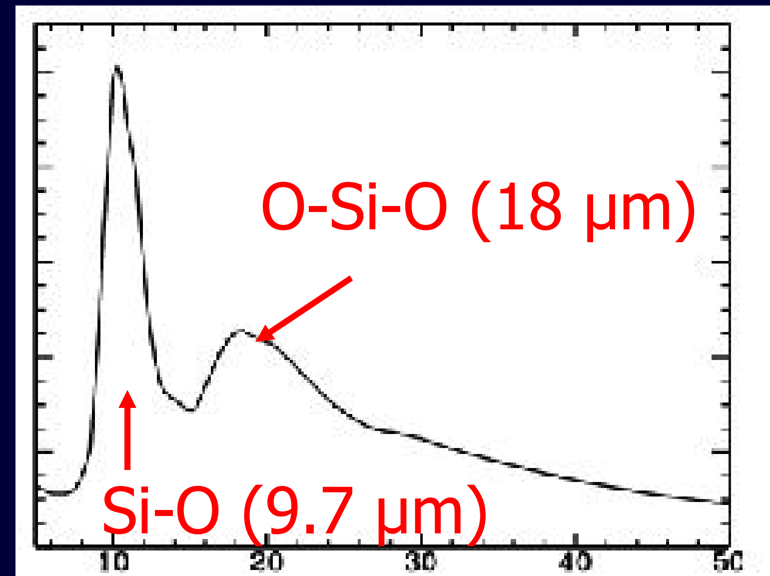


Crystalline

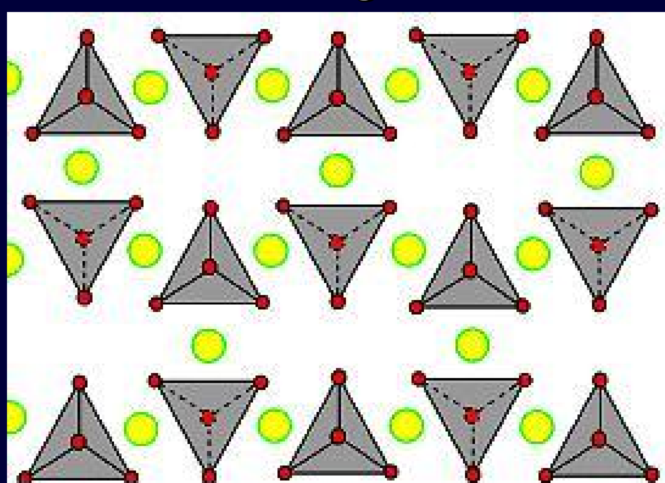
Amorphous

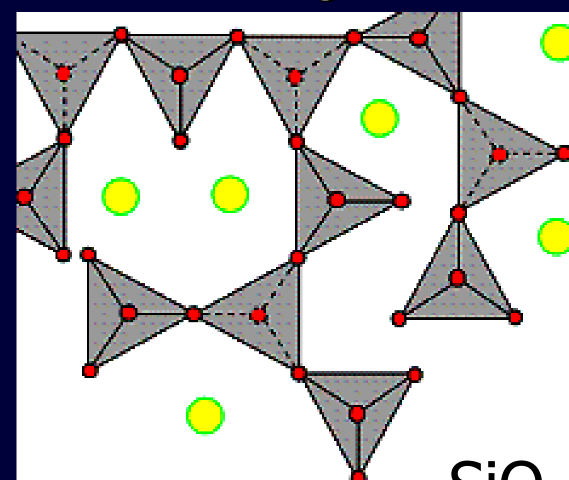


→Wavelength (μm)



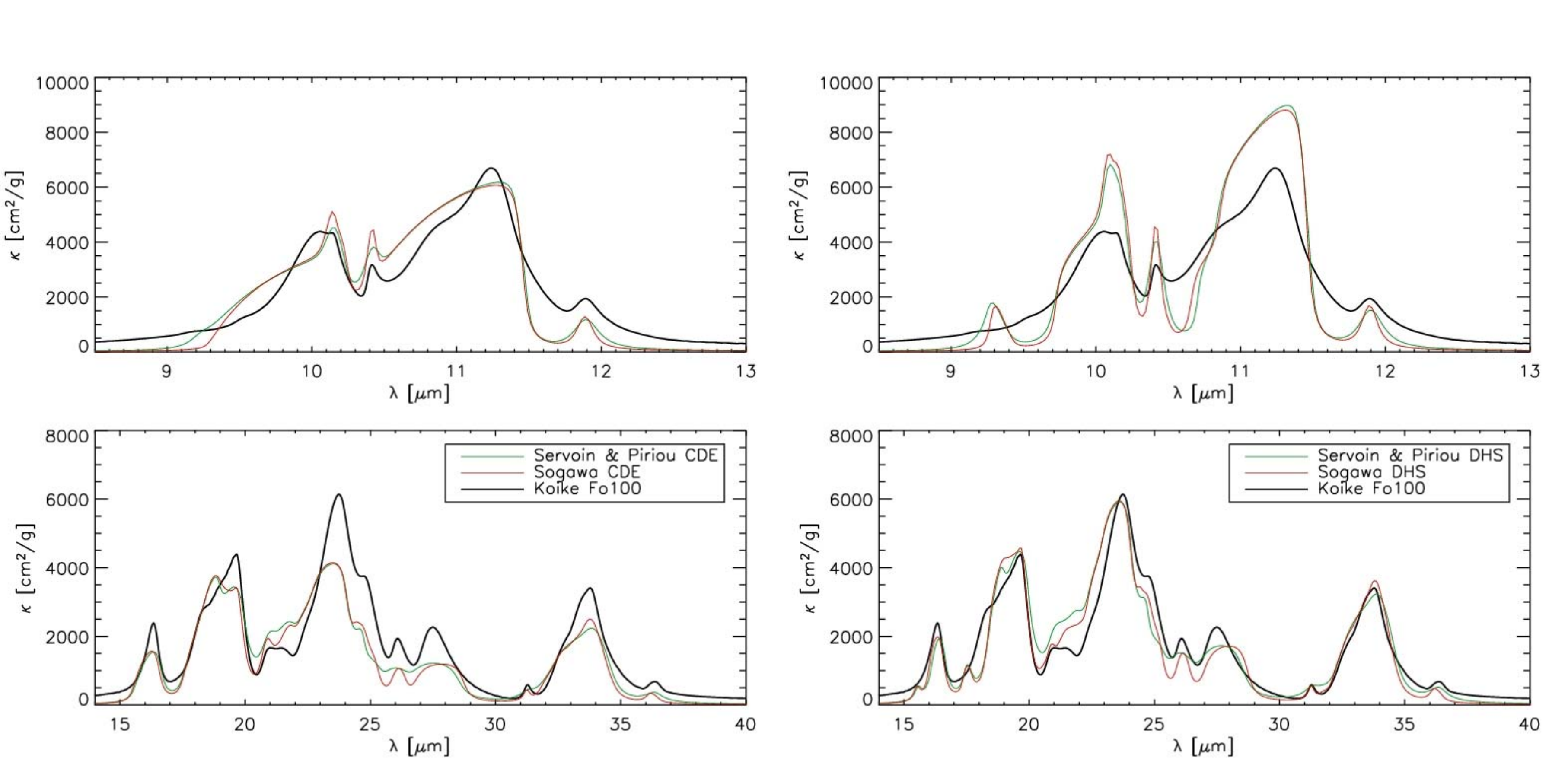
→Wavelength (μm)



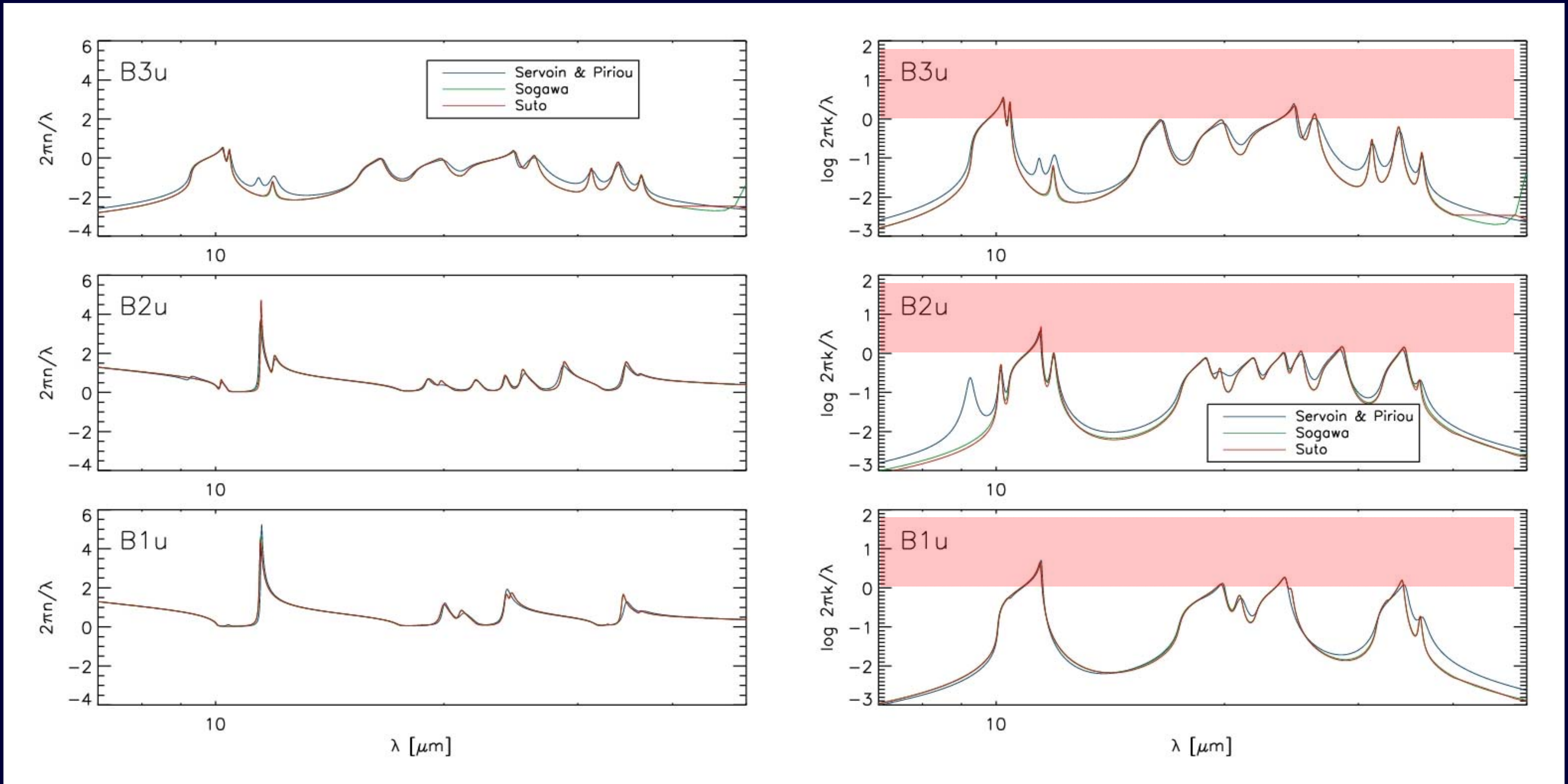


SiO_4

Optical properties of Forsterite



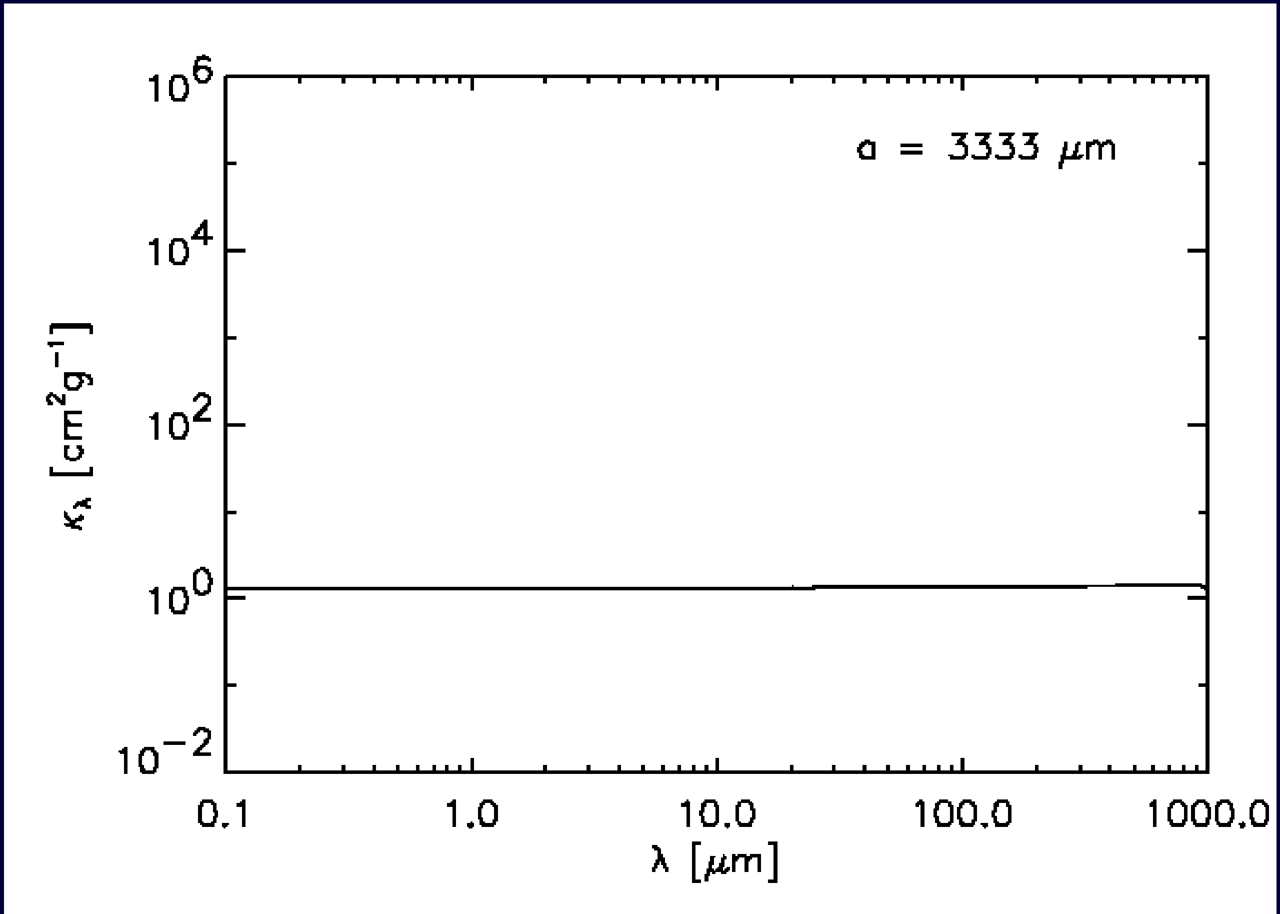
Optical constants of forsterite



Warning: One can already be outside the Rayleigh - limit for a 1 μm sized grain in the strong bands

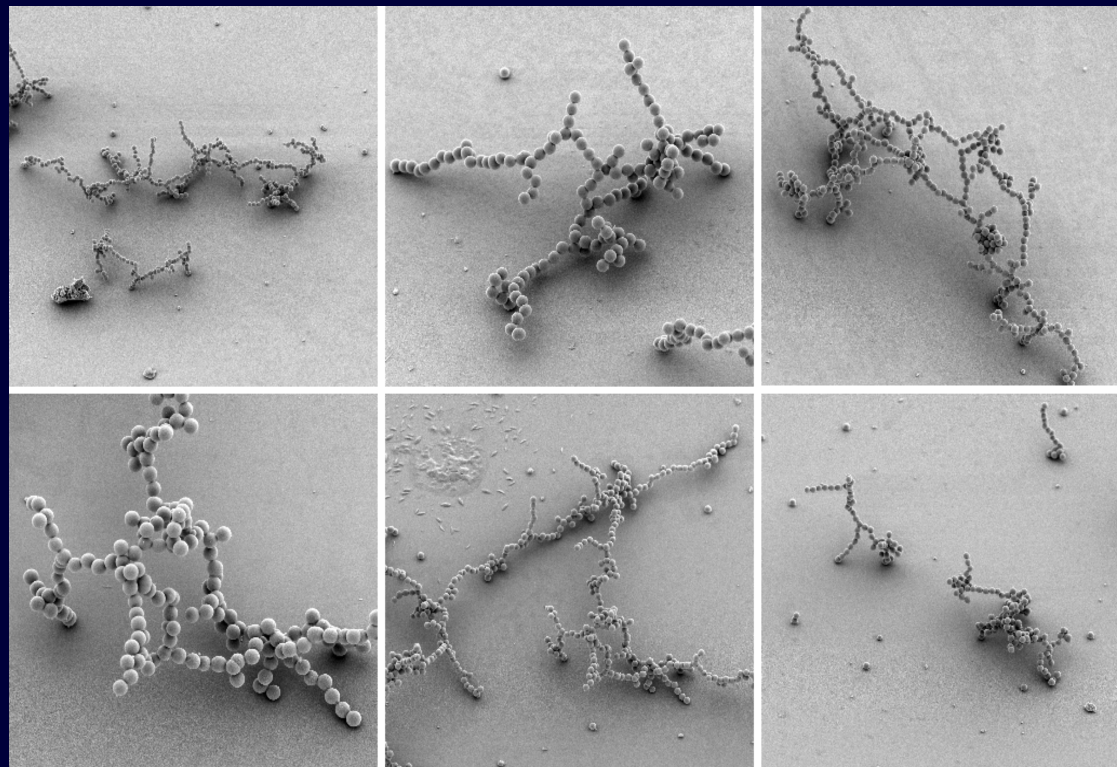
Grain growth: change of opacity

(Absorption opacity)



(Wavelength)

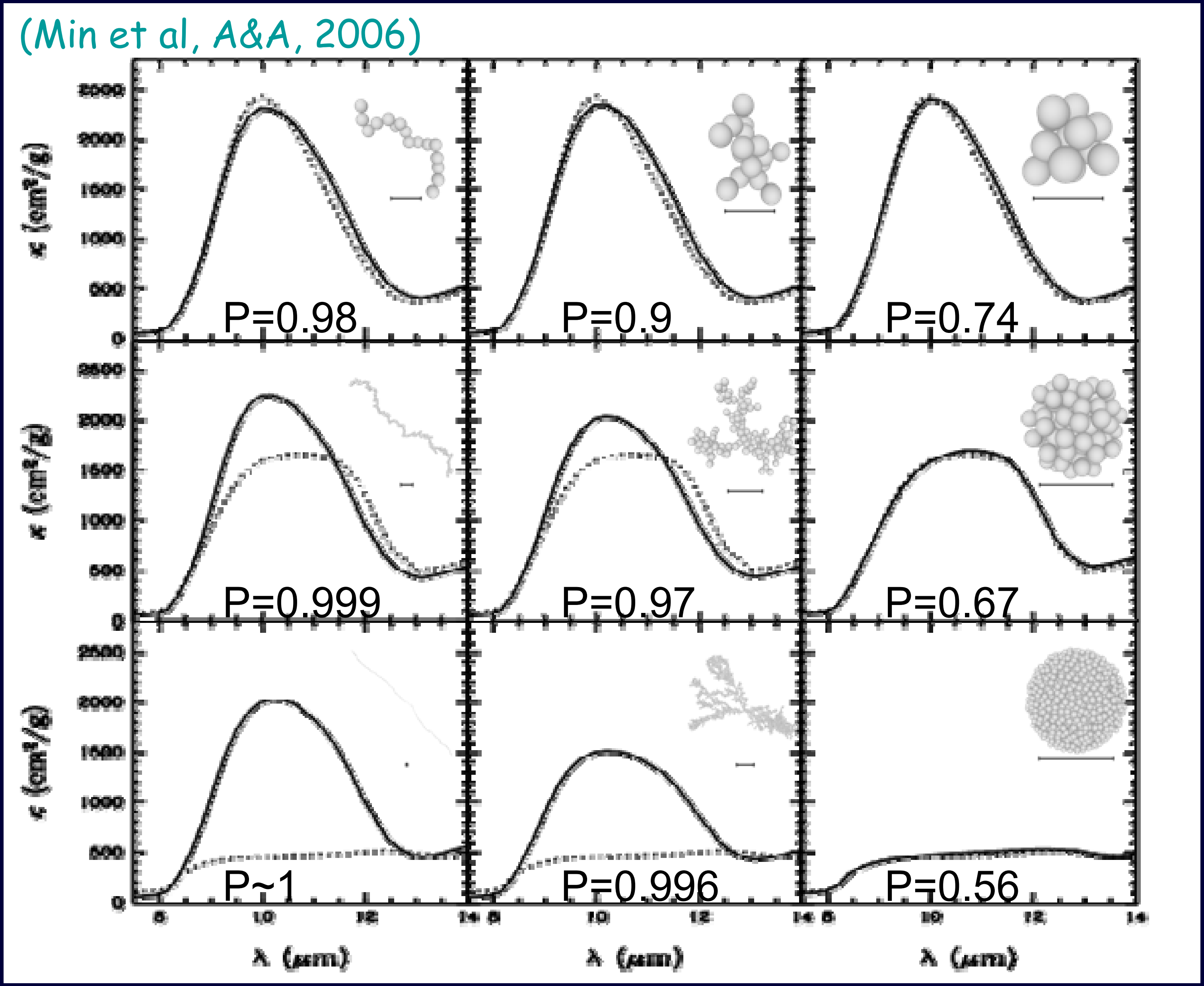
Grain Coagulation



Agglomerates produced by Brownian motion (and most likely by other velocity fields) have open structure (fractal dimensions between 1.4 and 1.9); Mass spectra are quasi-monodisperse

(see, e.g., Blum et al. 2000,
Poppe, Blum and Henning 2000)

Fractal aggregates: silicate feature

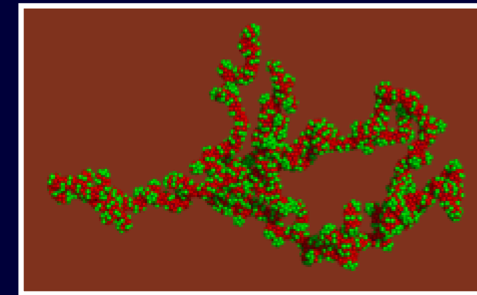


r_V=1 μm

r_V=2 μm

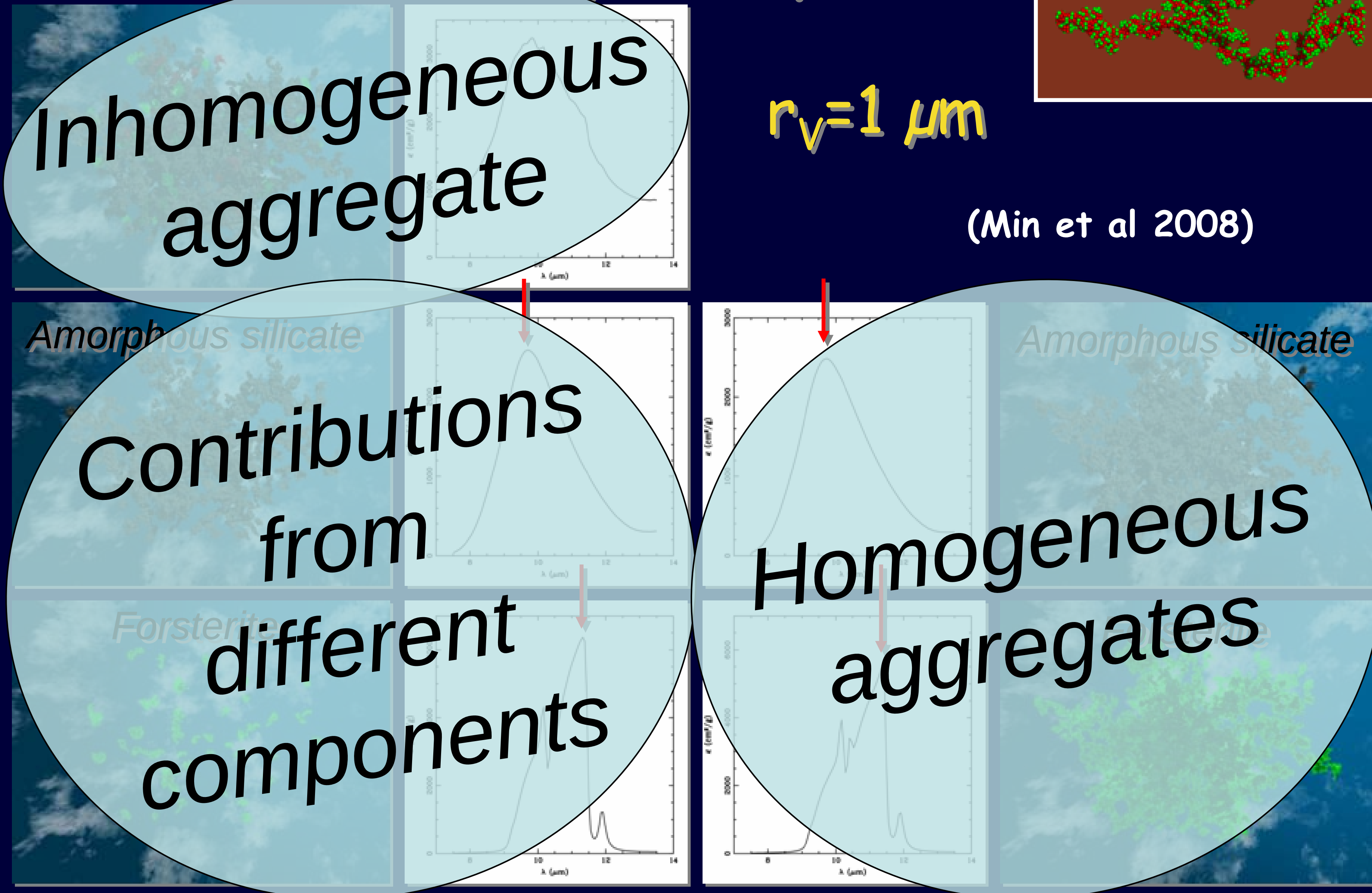
r_V=6 μm

Effective absorption spectra

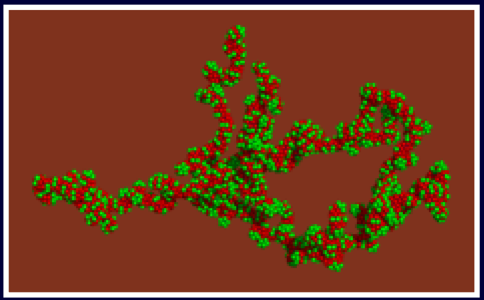


r_V=1 μm

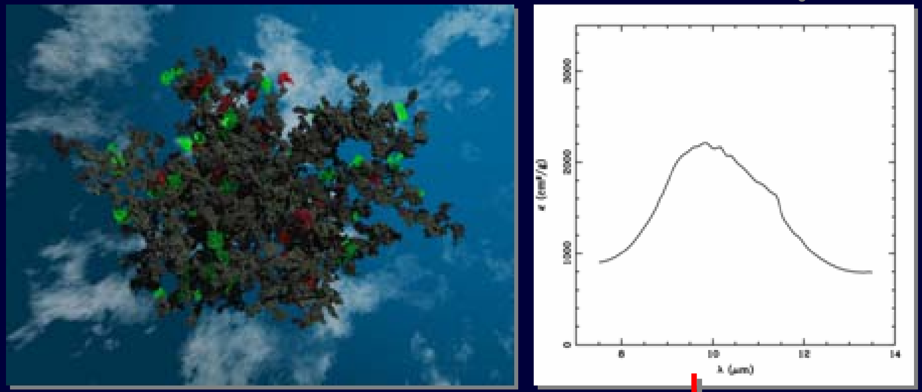
(Min et al 2008)

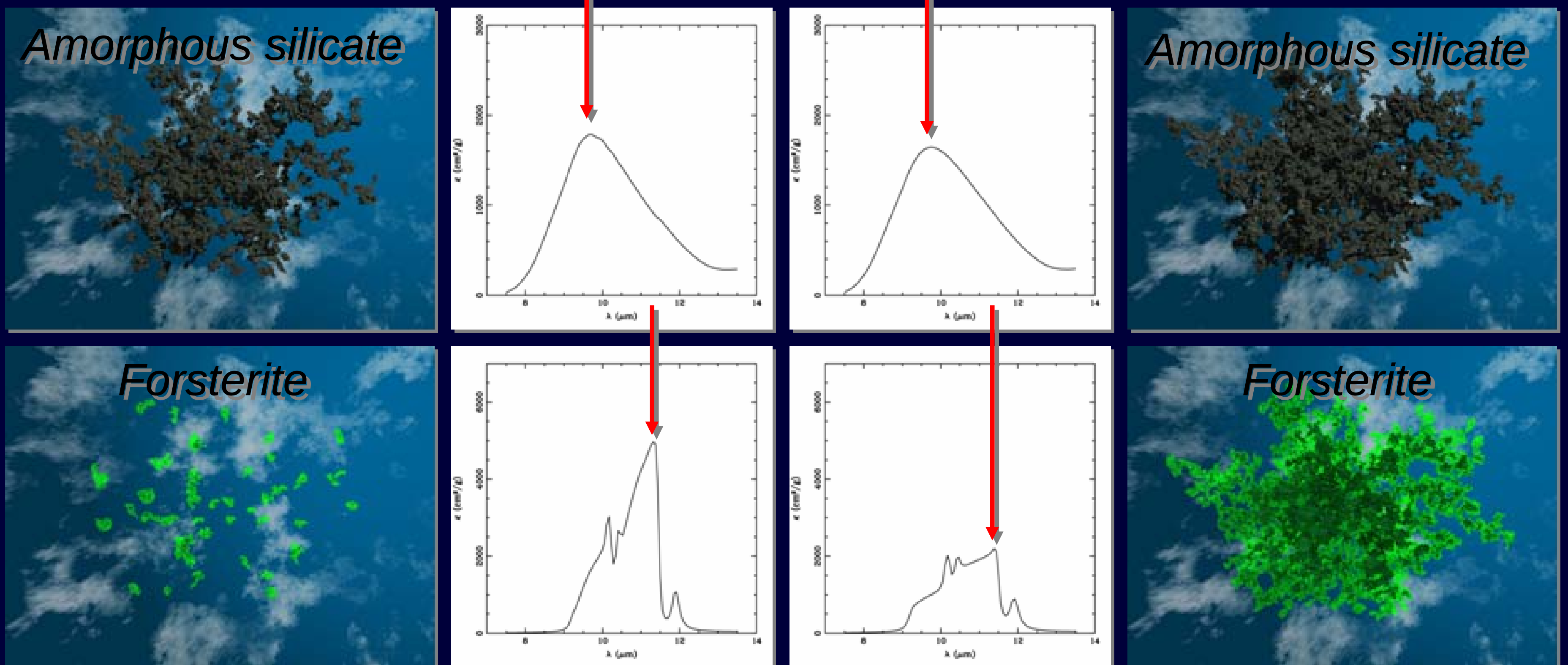


Effective absorption spectra



$r_V = 6\ \mu m$



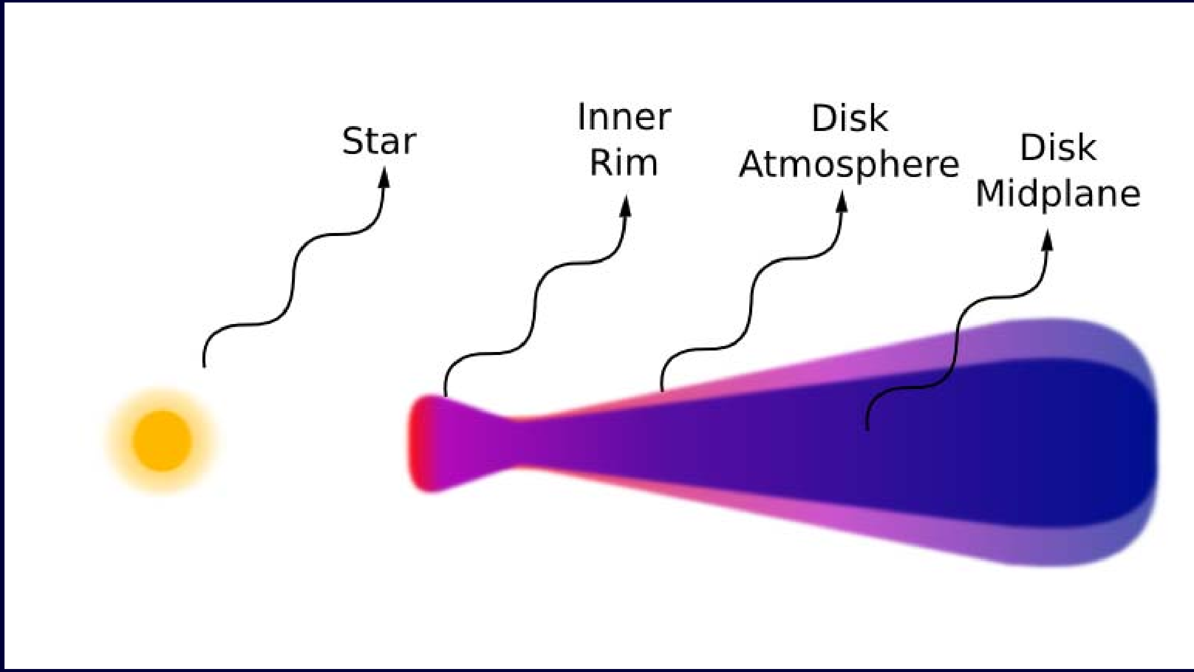


Modeling IR spectra: The Two-Layer Temperature Distribution method

$$F_{\nu,\mathrm{obs}} = F_{\nu,\mathrm{cont}} + \sum_{i=1}^{N}\sum_{j=1}^{M} C_{i,j}\kappa_{i,j}\int_{T_{\mathrm{atm,max}}}^{T_{\mathrm{atm,min}}} \frac{2\pi}{d^2} B_\nu(T_\mathrm{a}) T^{\frac{2-qatm}{qatm}}\, dT$$

$$F_{\nu,\mathrm{cont}} = C_0 \frac{\pi r_\star^2}{d^2} B_\nu(T_\star) + C_1 \int_{T_{\mathrm{rim,max}}}^{T_{\mathrm{rim,min}}} \frac{2\pi}{d^2} B_\nu(T) T^{\frac{2-qrim}{qrim}}\, dT + C_2 \int_{T_{\mathrm{mid,max}}}^{T_{\mathrm{mid,min}}} \frac{2\pi}{d^2} B_\nu(T) T^{\frac{2-qmid}{qmid}}\, dT$$

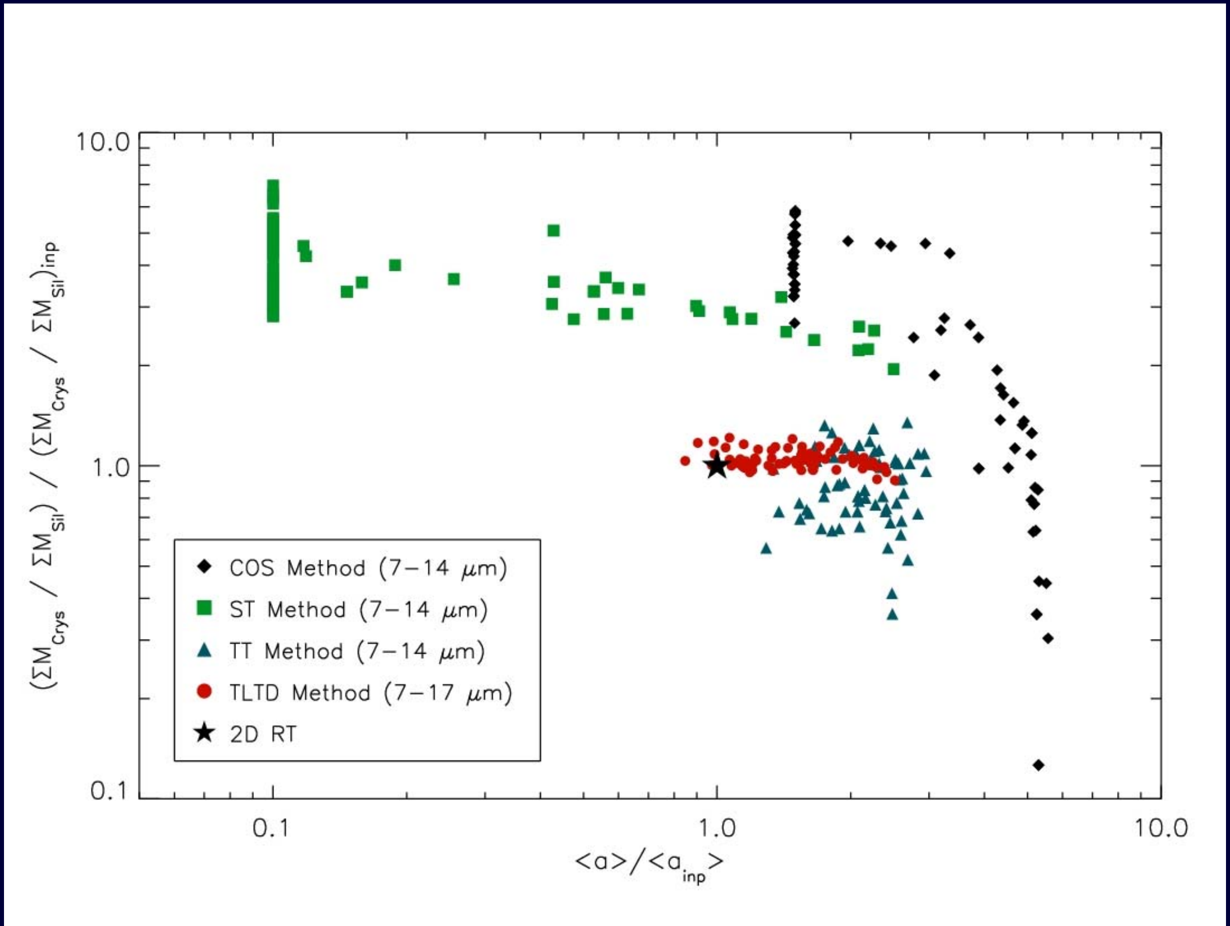
$$T(r) = T_{\mathrm{max}} \left(\frac{r}{r_0}\right)^{-q}$$



Juhasz et al 2008, ApJ in press

Different methods give different results

Relative mass fraction Crystalline silicates



Relative mass averaged grain size

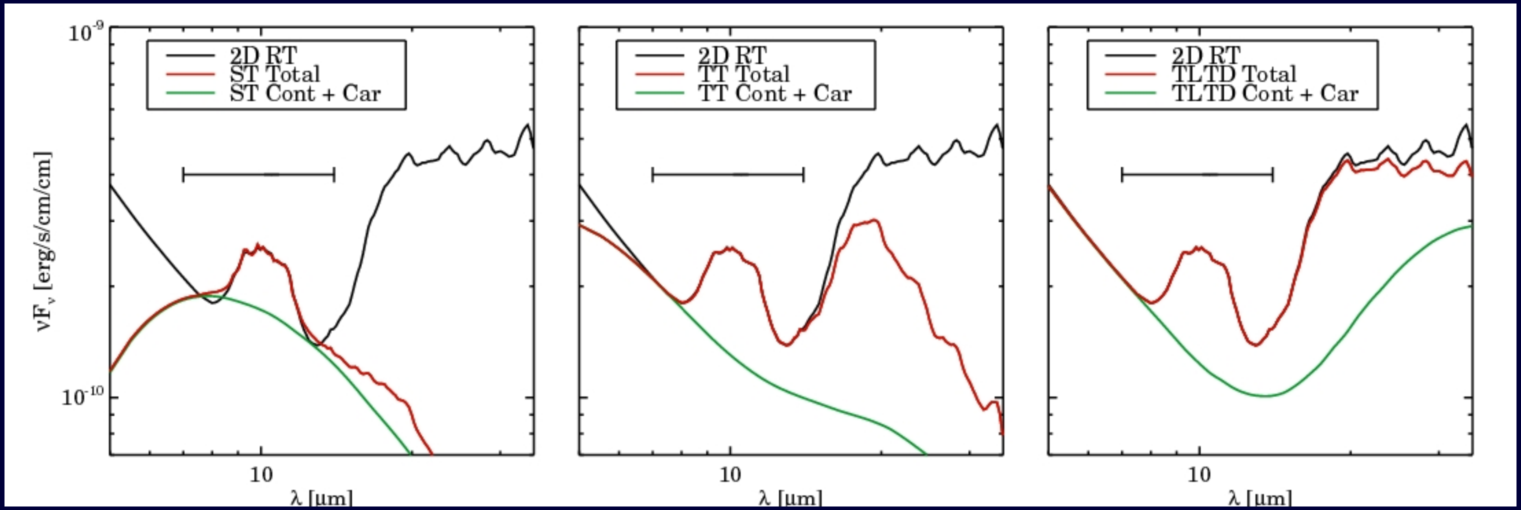
What are the uncertainties?

Assumption: All grains contributing to the 10μm emission feature have the same temperature

Assumption: The continuum below the feature can be described by a Planck-function at a single temperature

Reality: Degeneracy between the optically thick emission of the disk and the optically thin emission of the 'featureless' grains (e.g. carbon)

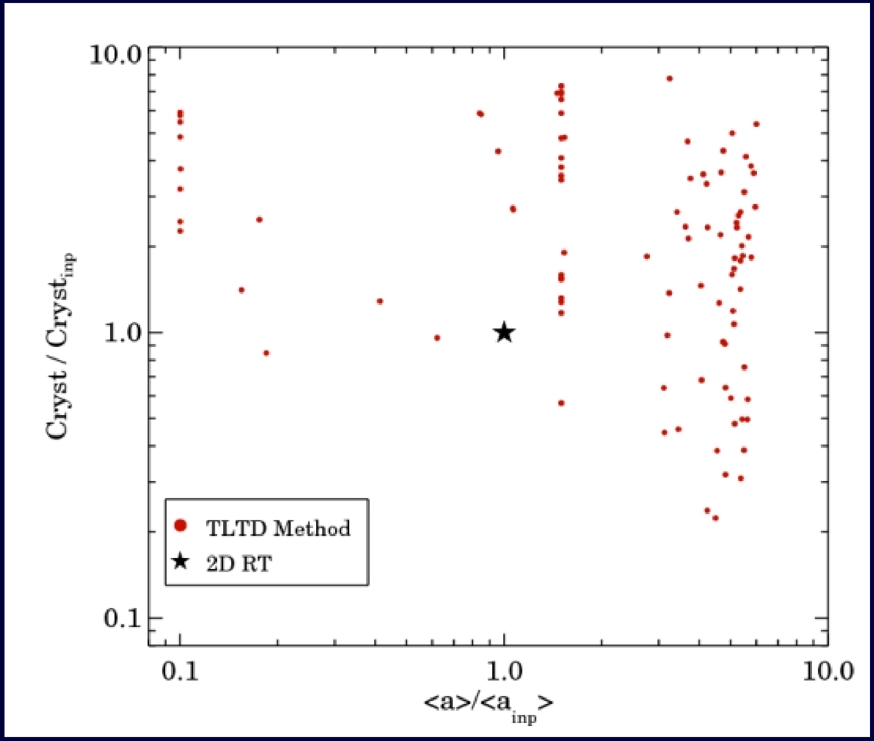
Reality: Degeneracy among the optical data of the used dust species (e.g. large enstatite grains and a linear combination of other dust species)



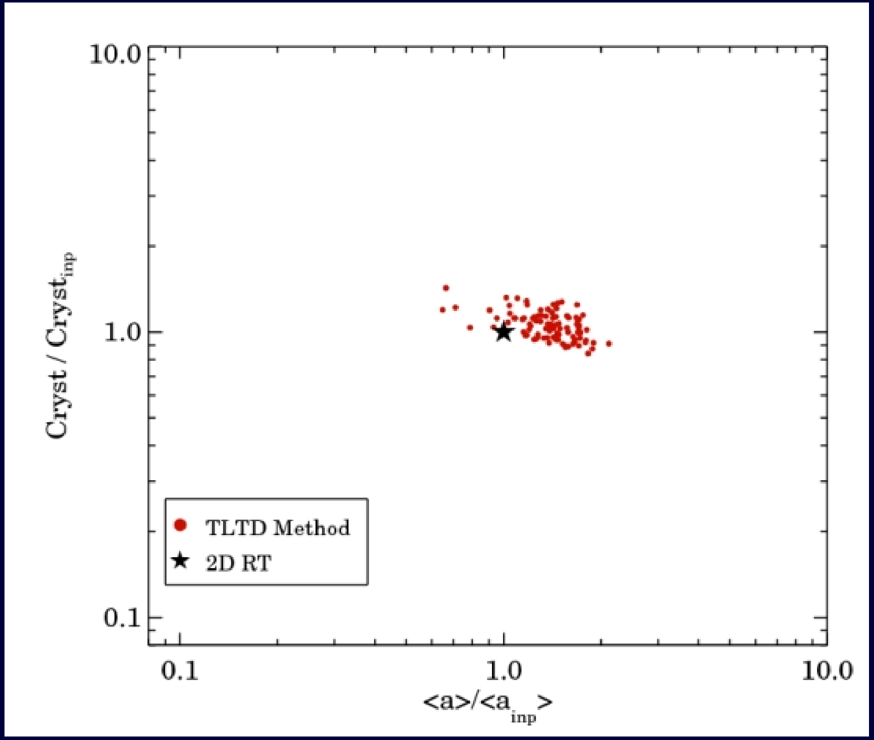
The effect of the signal-to-noise ratio

Relative mass fraction Crystalline silicates

8-13 µm S/N=10



7-17 µm S/N=1000

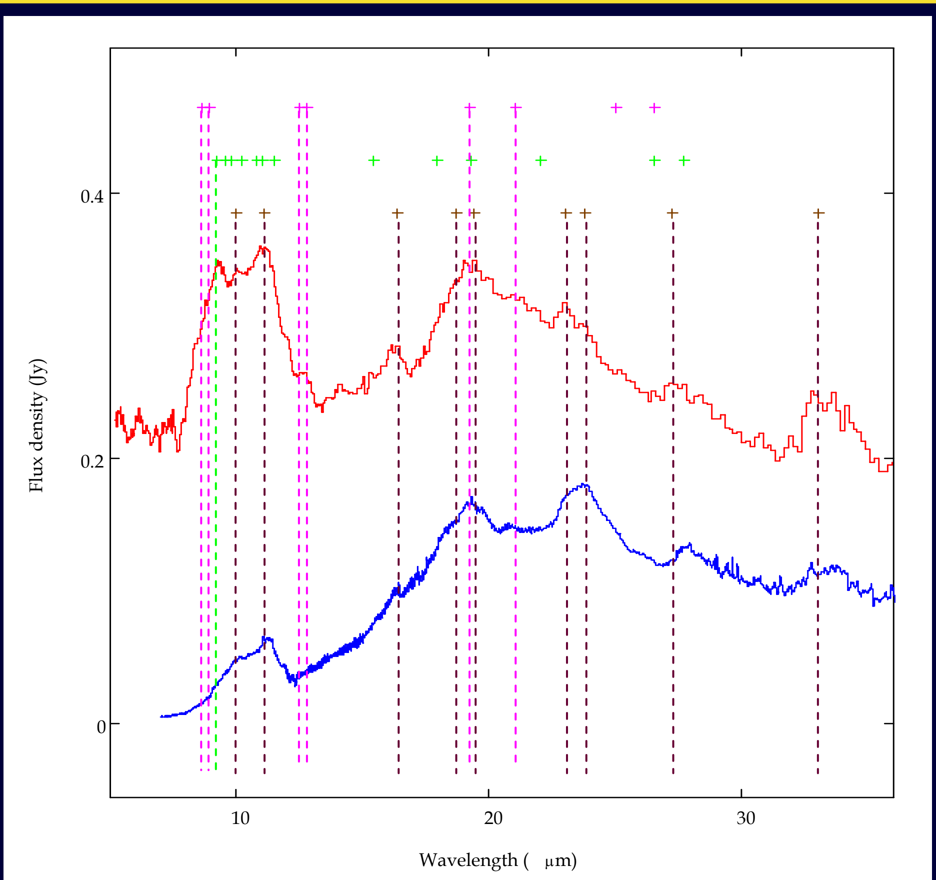


Relative mass averaged grain size

(Juhasz et al. 2008)

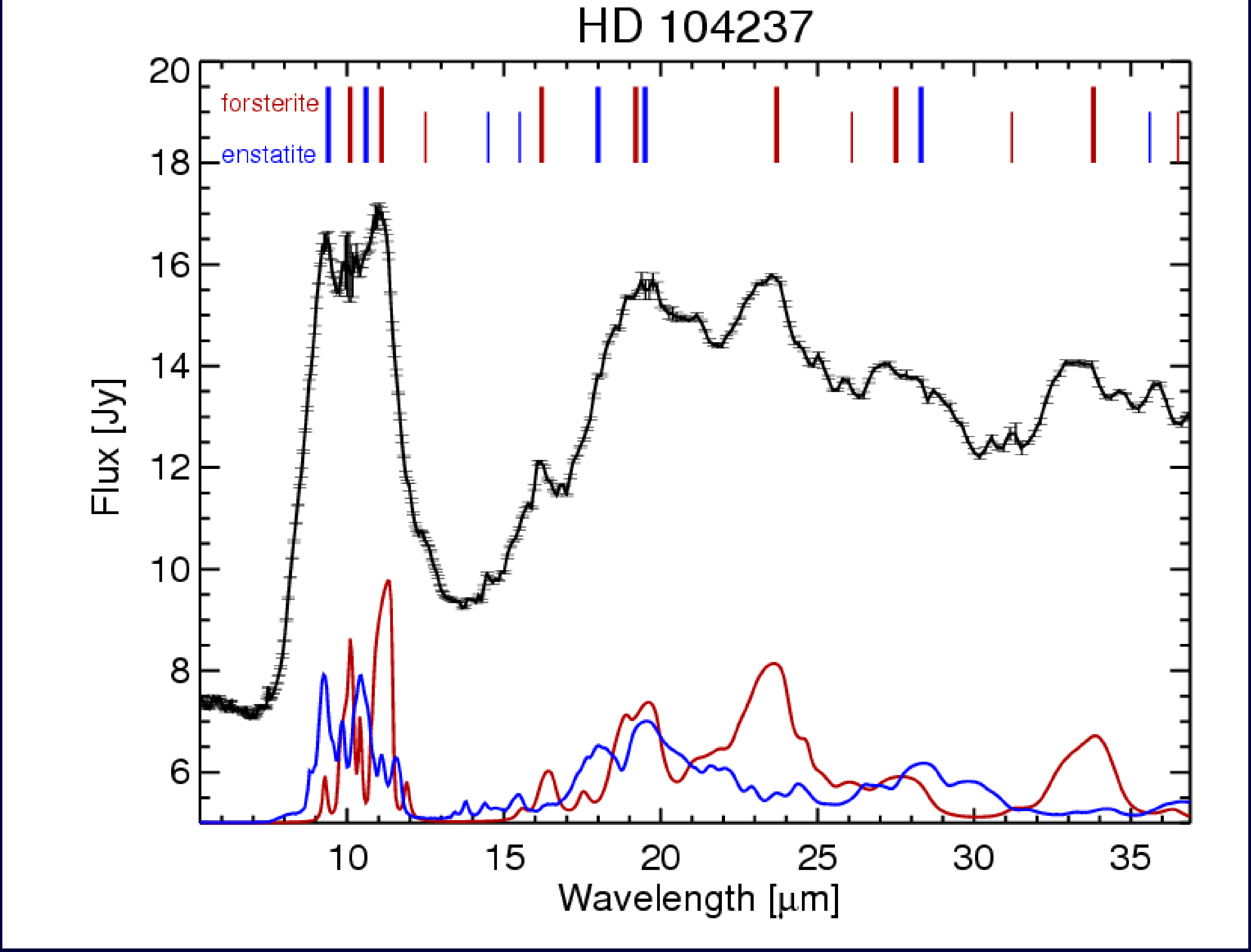
Disk composition from spectra: Observations

Spitzer spectroscopy of Disks

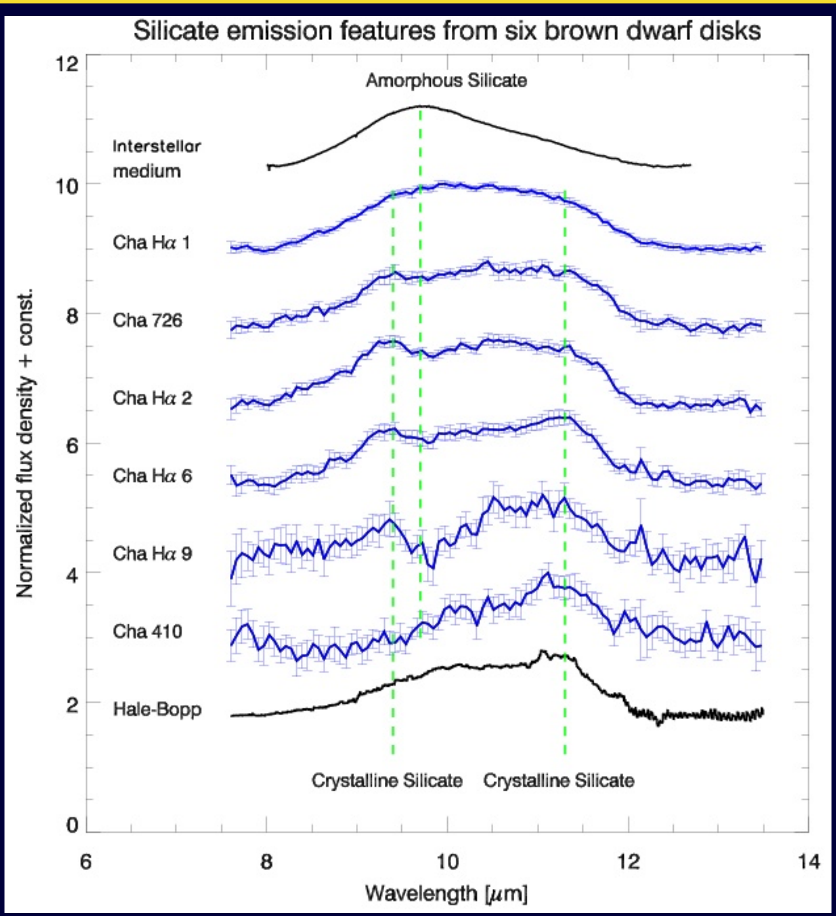


There are about 4000 YSOs within 500 pc of us; we have observed 1894 of them with Spitzer-IRS so far in IRS Disks (through Cycle 4). C2d FEPS and GO add hundreds of objects additionally.

Watson et al, Sargent et al, Furlan et al, Kessler-Silacci et al, Sicilia-Aguilar et al, Bouwman et al, Boersma et al, Merin et al, Quanz et al, Green et al, Geers et al, Luhman et al, Apai et al , Keller et al, Sloan et al, Acke et al, Meeus et al, Beichman et al.

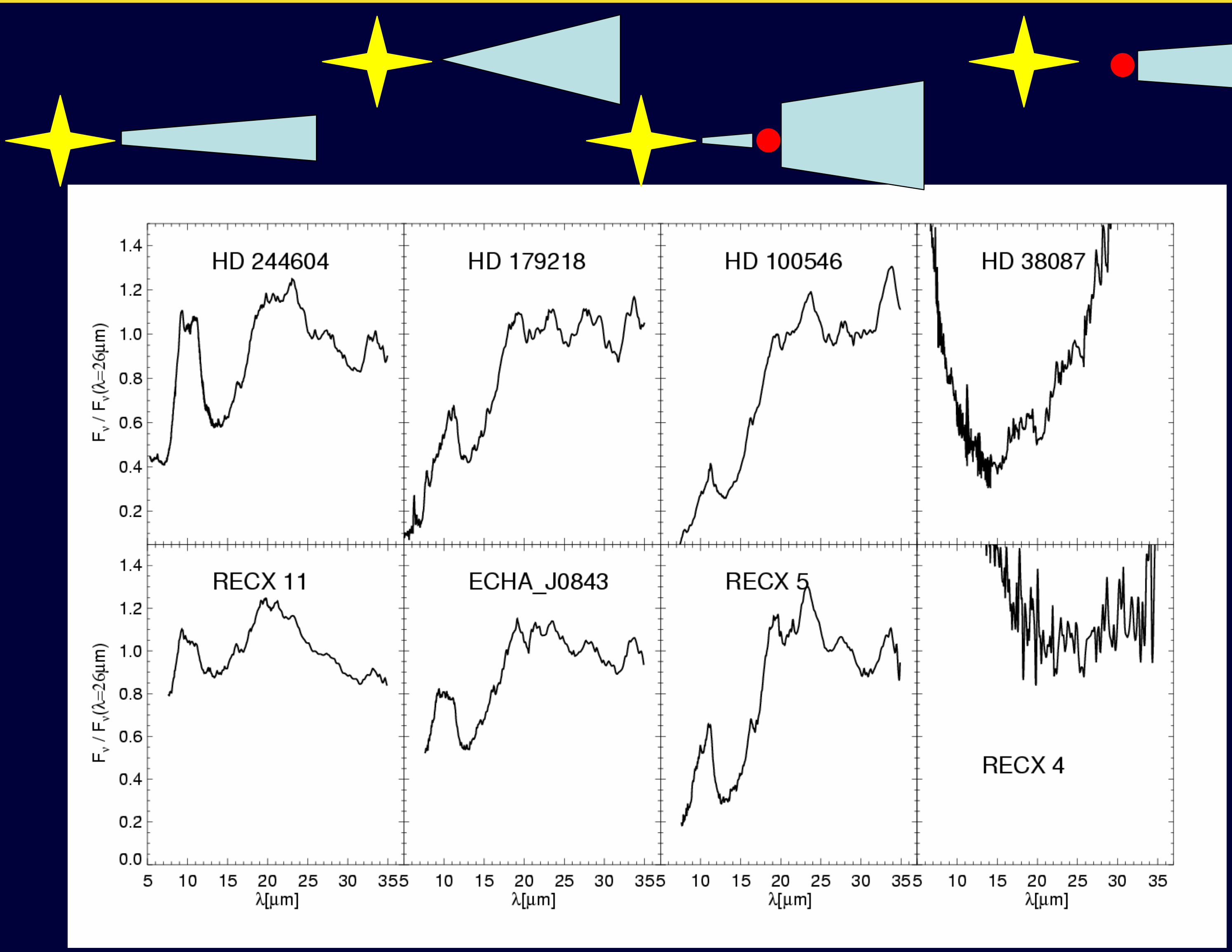

HD 104237
forsterite
enstatite
Flux [Jy]
Wavelength [μm]
20
18
16
14
12
10
8
6
10
15
20
25
30
35

Spitzer observations of Brown Dwarf disks



(Apai et al. Science, 2005)

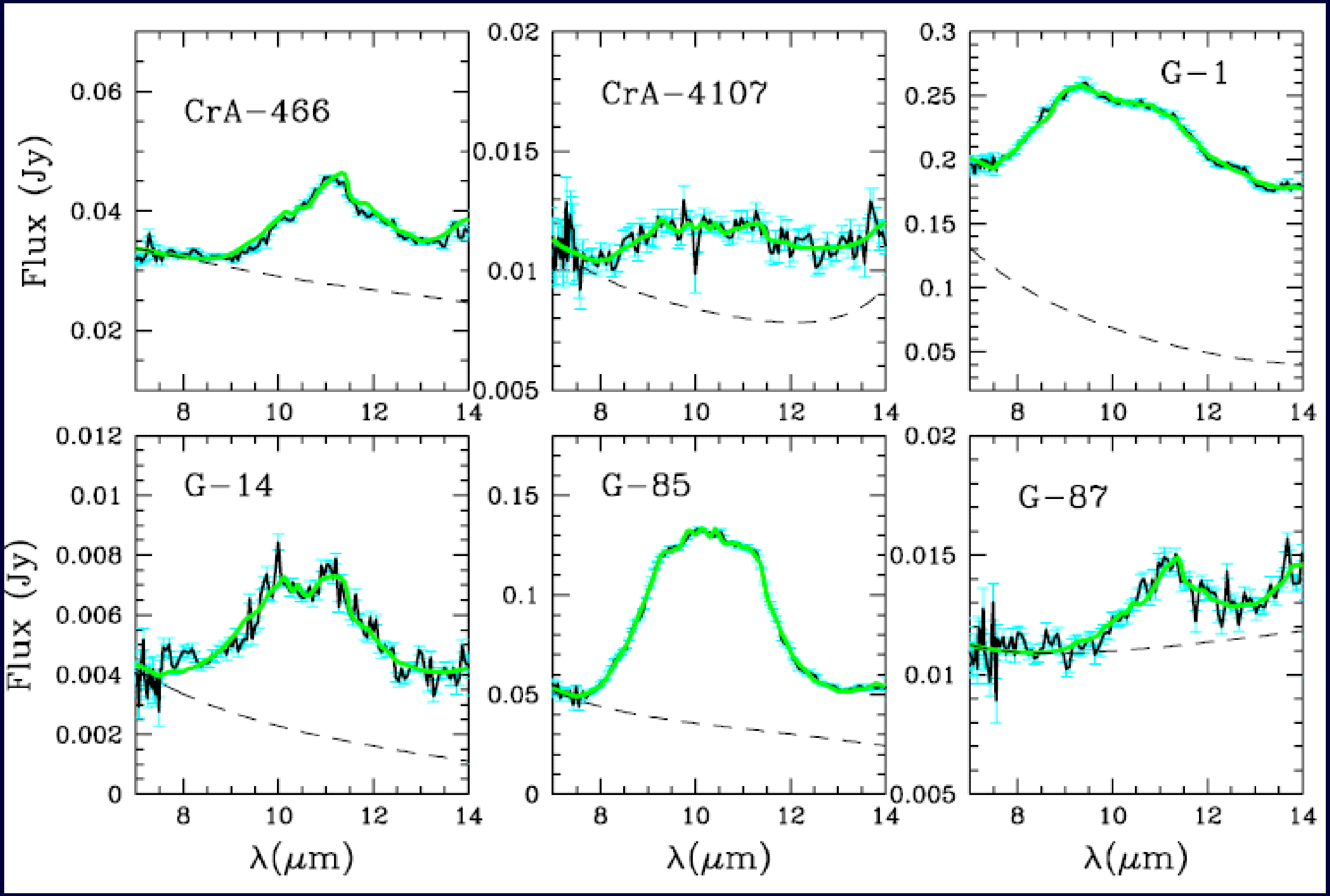
The evolution of planet forming disks



HAE

Mstar

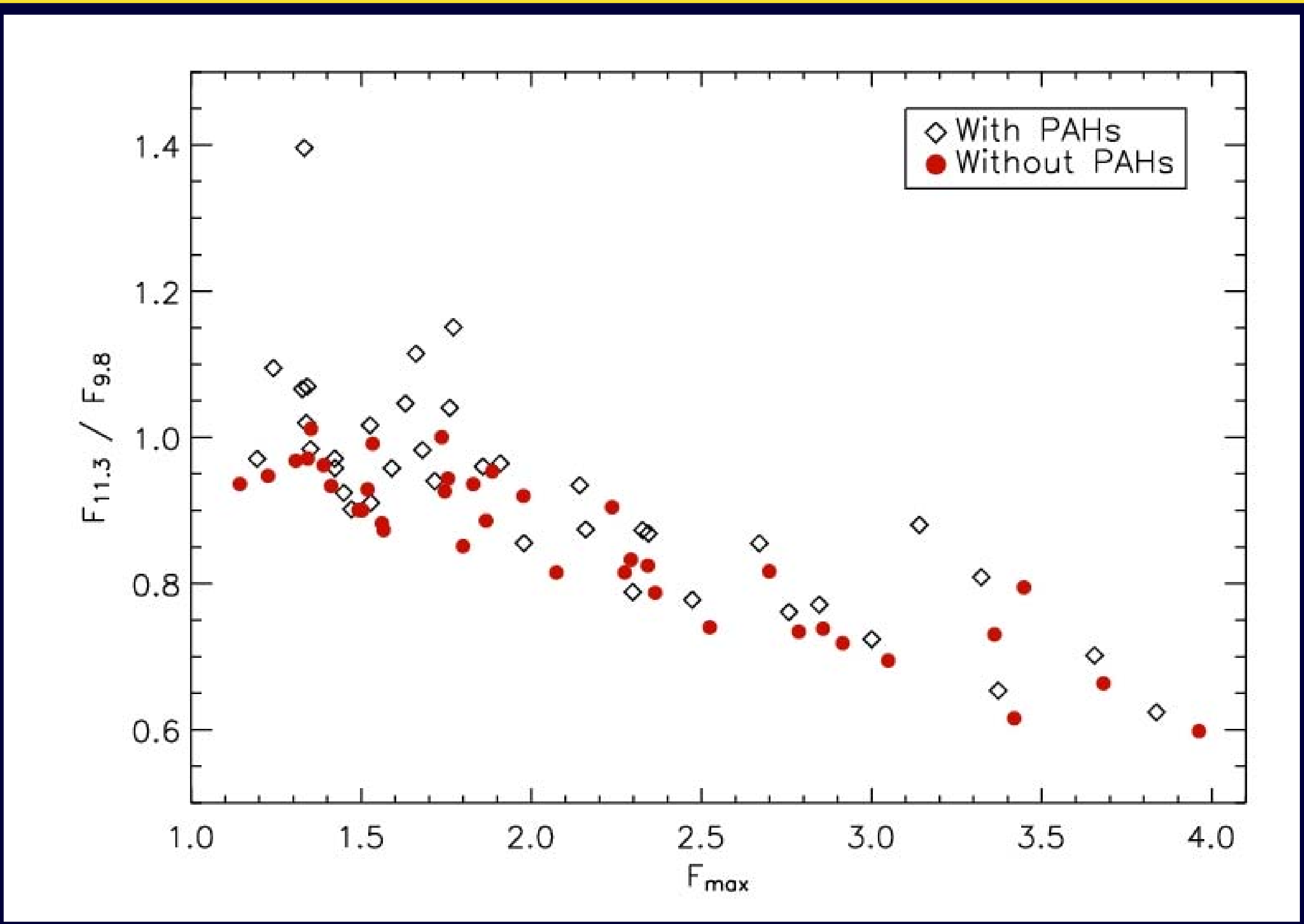
Spitzer observations of TT disks



(Sicilia-Aguilar et al, 2008)

Growing dust grain in Protoplanetary Disks

F11.3/F9.8



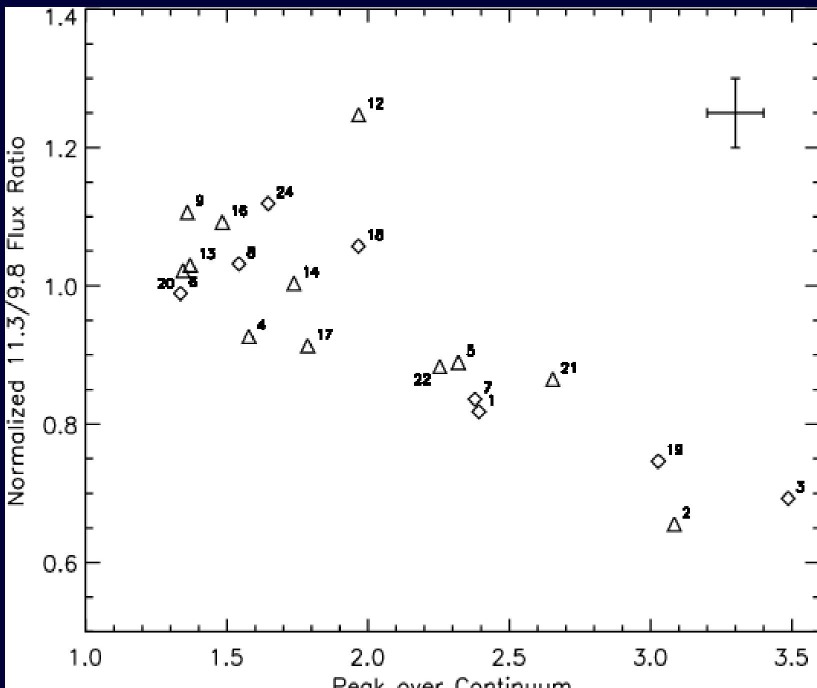
Peak over continuum 10µm band

The shape and strength of the 10 micron silicate feature

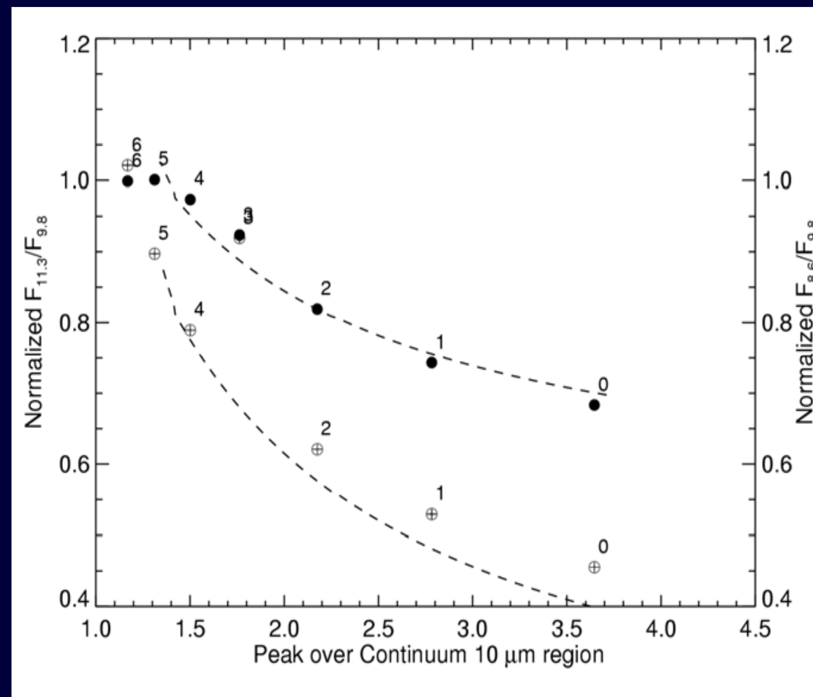
HAEBE

FEPS TTS sample

F11.3/F9.8



Peak over continuum 10µm band



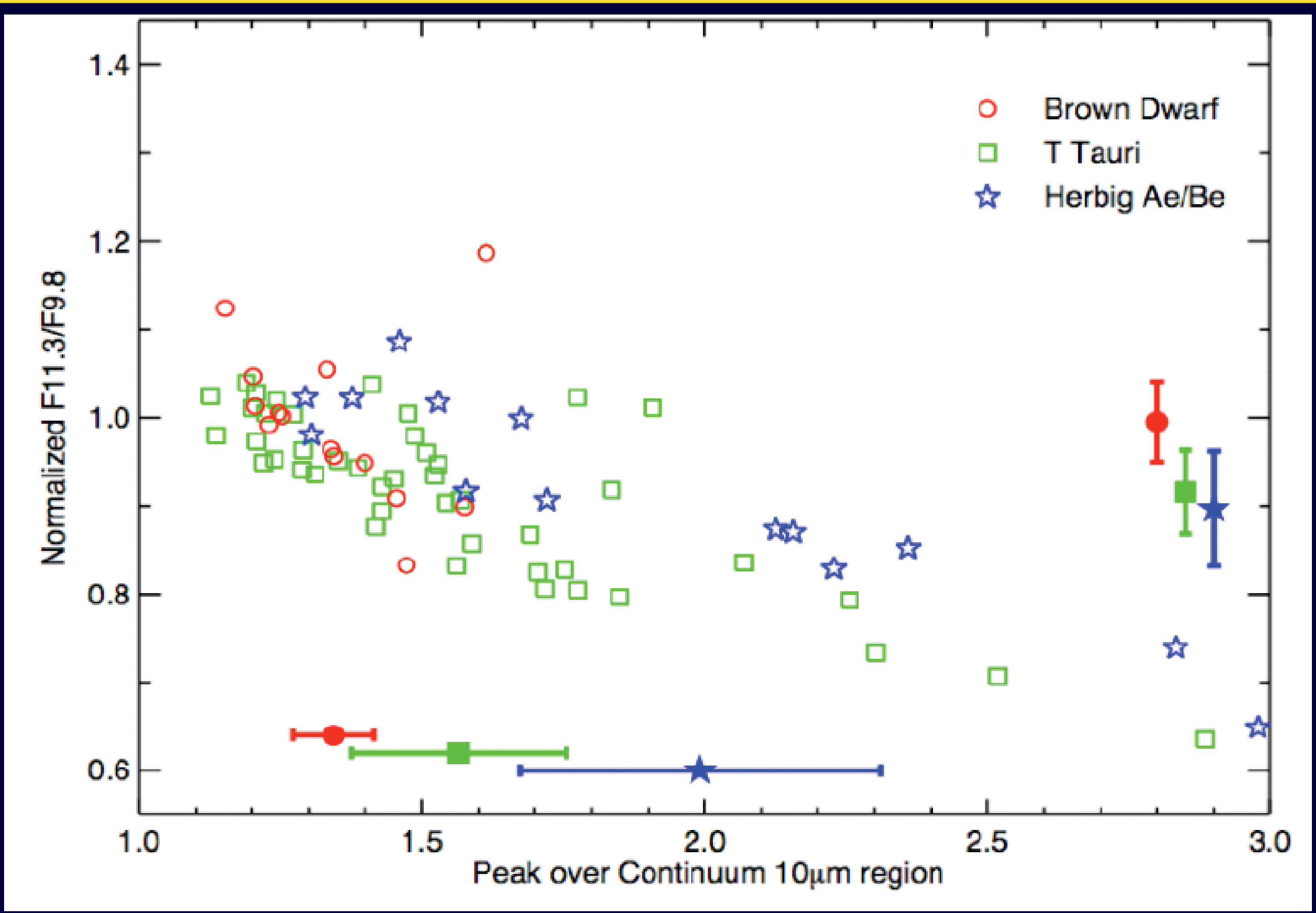
F8.6/F9.8

- Band strength and shape determined by grain size

(van Boekel et al, 2005; Bouwman et al, 2006, sub.)

Comparison between stellar types

F11.3/F9.8

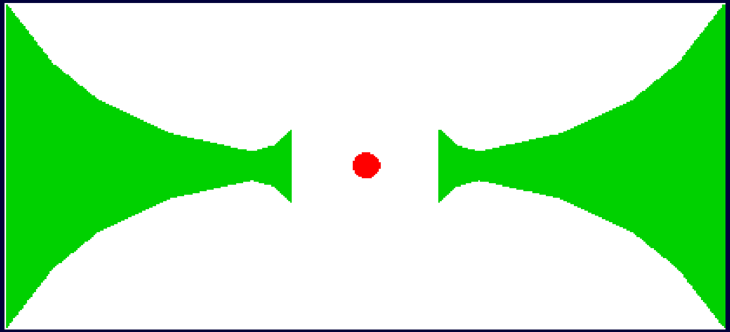


Peak over continuum 10μm band

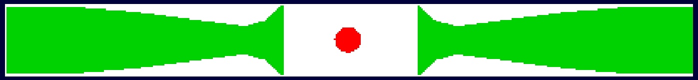
Pascucci et al 2008, See also poster

Disk geometries proposed for Herbig Ae/Be stars

Group I:flaring
strong FIR excess



Group II:flattened
weak FIR excess



self-shadowing disk or Grain settling?

The special feature of these models is the puffed-up hot inner rim of the disk

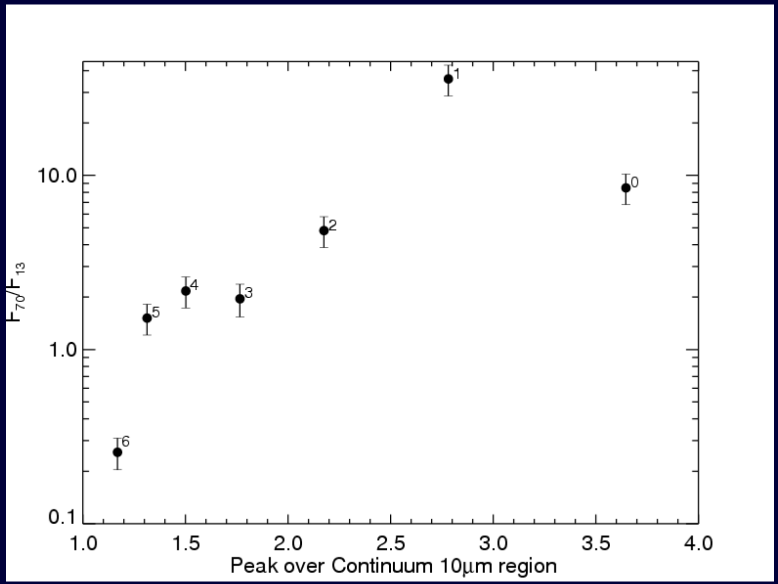
(Dullemond, Dominik & Natta 2001; Dominik, Dullemond, Waters & Walch 2003; Dullemond & Dominik 2004)

Grain size and disk flaring

TTS

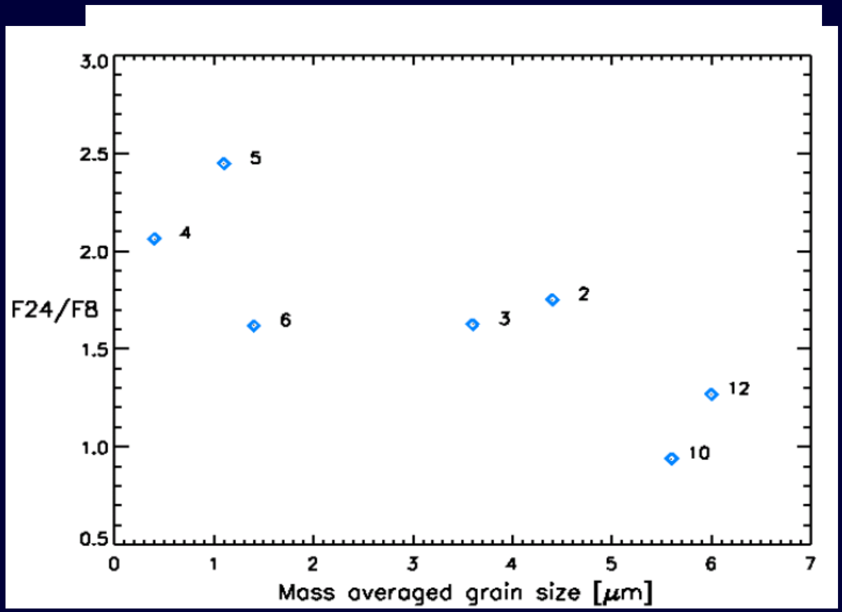
← Flatter

F70/F13



←Grain size

M stars



← Flatter

←Grain size

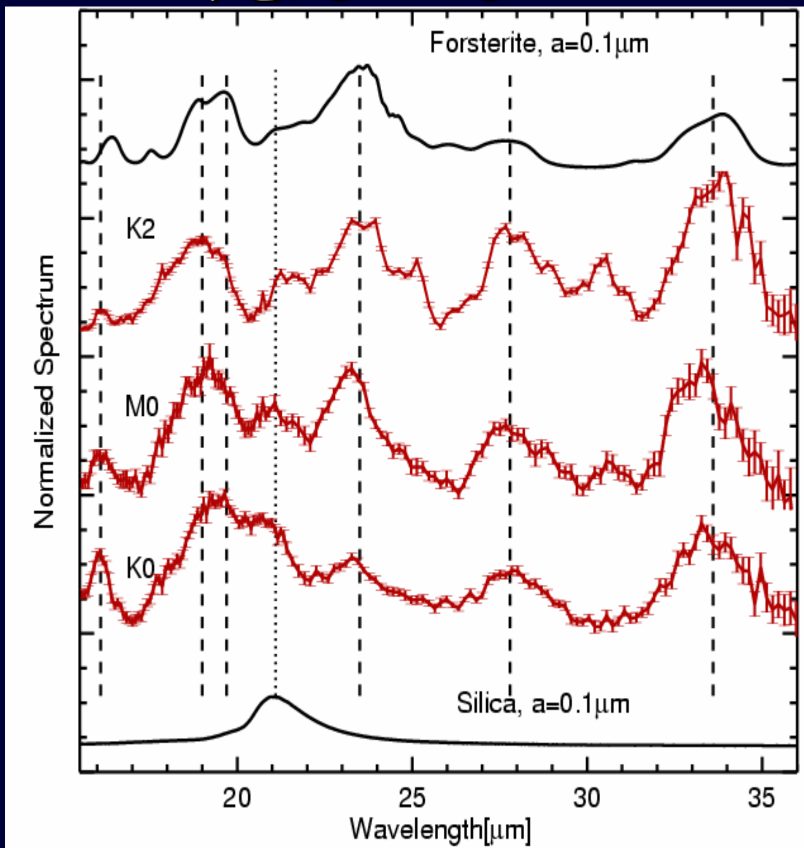
- Grain settling determines observed disk flaring

See also Acke et al. for mm correlation and Poster by Meeus et al

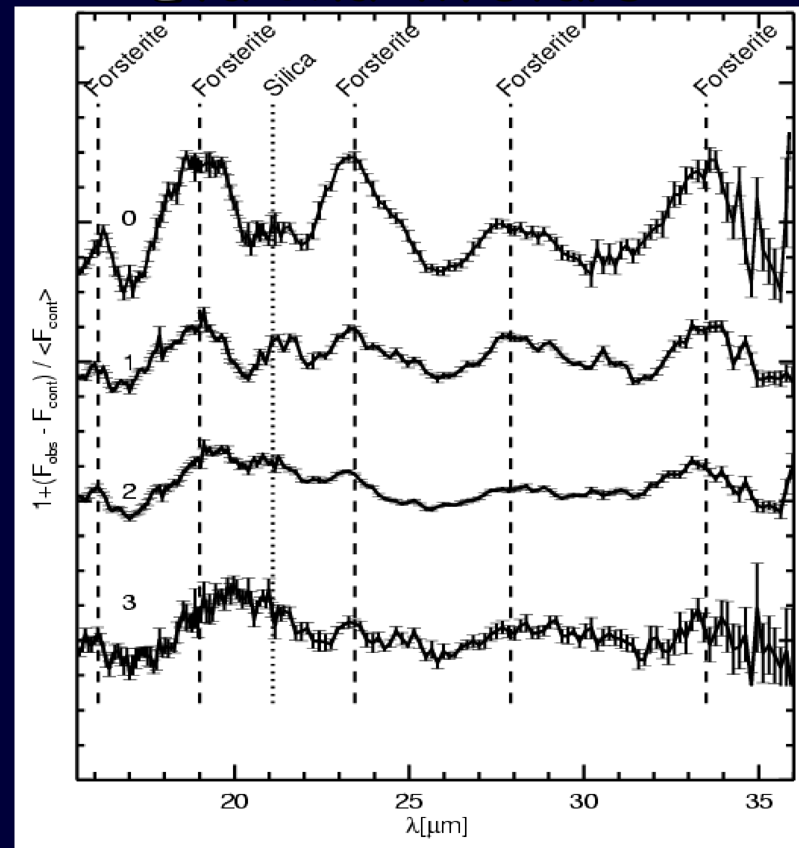
Crystalline silicates in protoplanetary discs

Continuum normalised spectra

FEPS:TTS

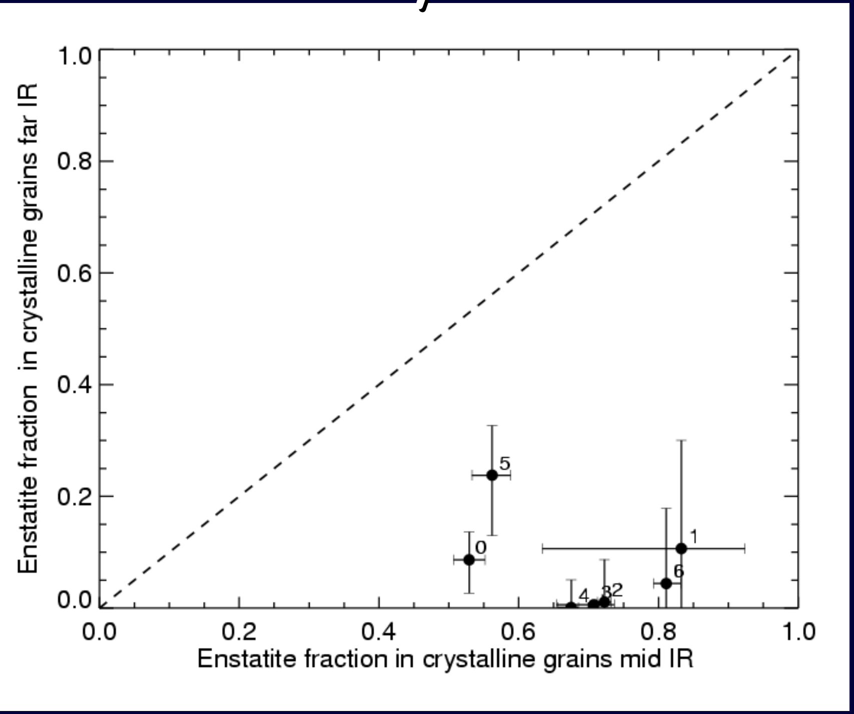


Eta Cha: M stars



The origin of crystalline silicates: annealing or condensation?

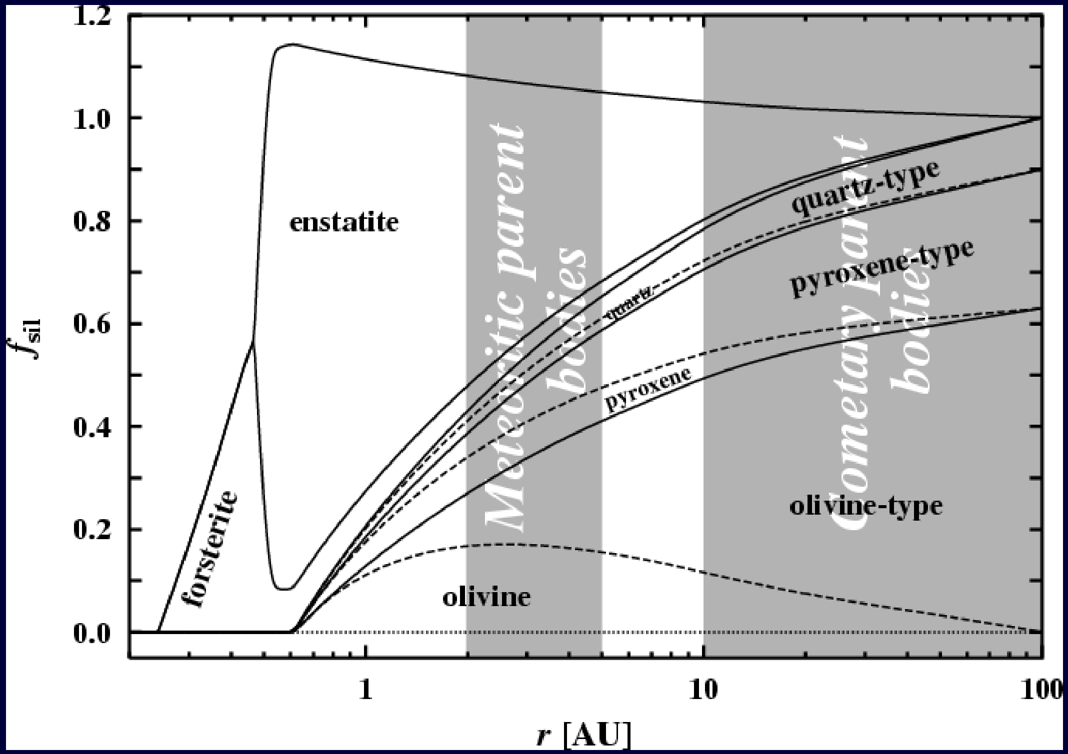
TTS systems



♦*Enstatite dominates in the inner (~1AU) disk, Forsterite in the outer (5-10AU) disk!!*

(Bouwman et al 2008; see also van Boekel et al. 2005)

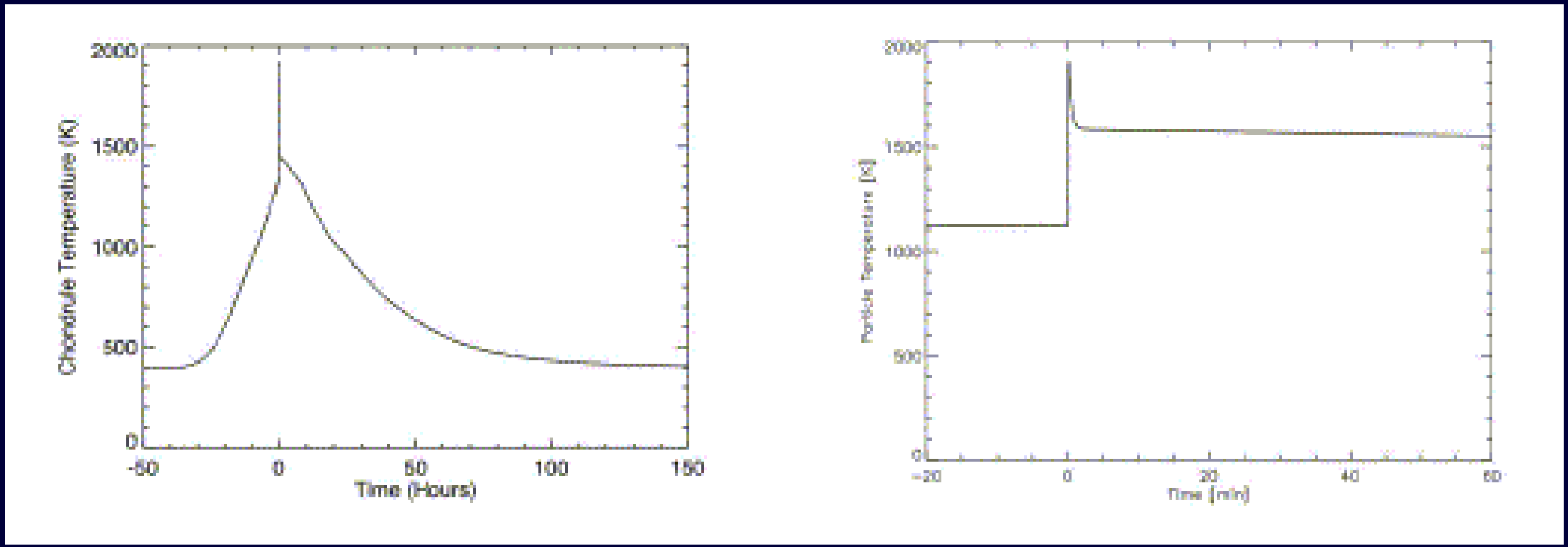
Dust disk models



- Accretion disk model
- Detailed dust mixture
- Annealing
- Evaporation + re-condensation
- Coagulation
- Radial mixing

(e.g. Gail 2004, Keller & Gail 2004, Wehrstedt and Gail 2003, see also Keller et al. and Brocklee-Morvan et al.)

Shock heating of Chondrules



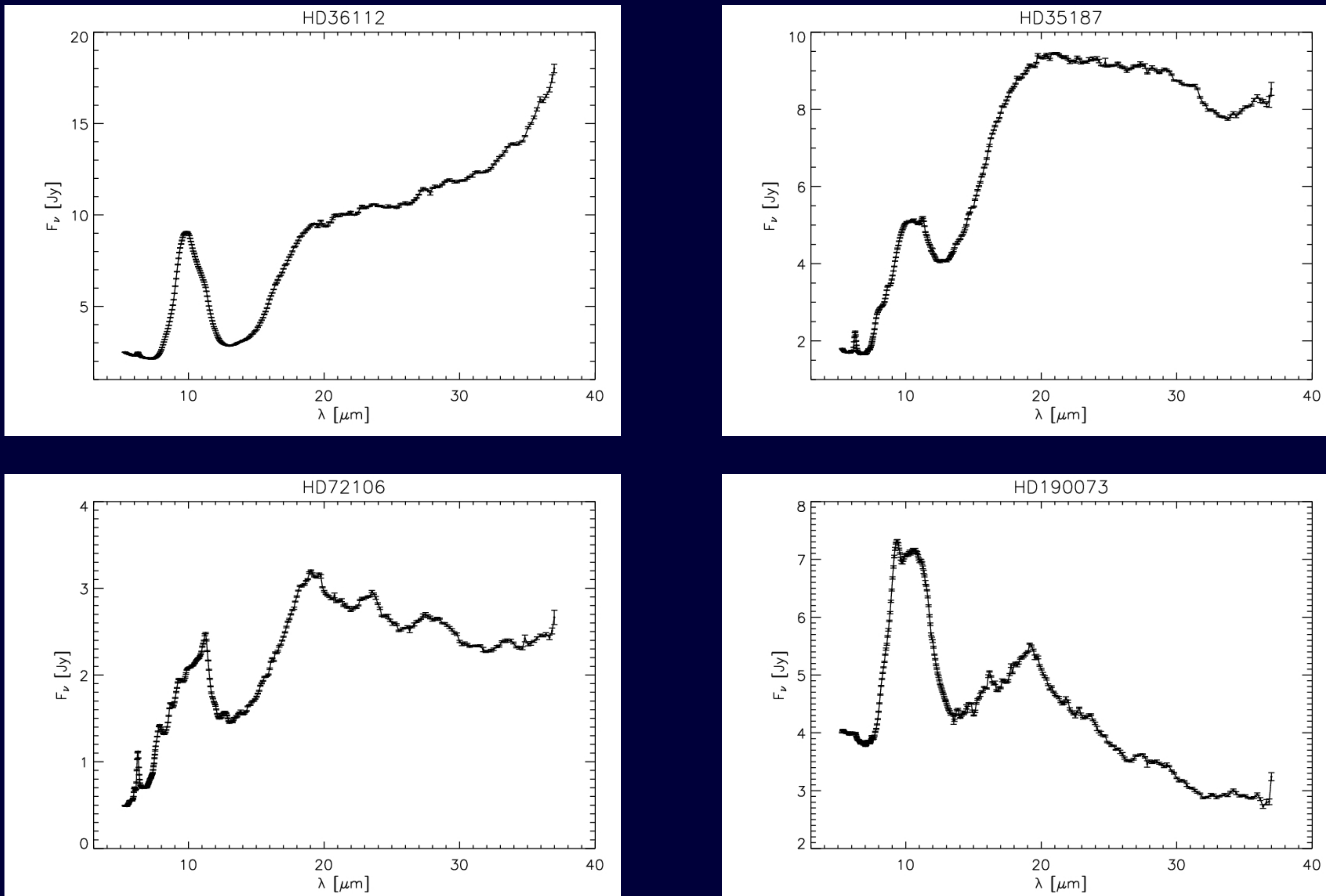
(Desh et al, 2005)

$\rho=10^{-9}$ gr cm^{-3}, a=300μm, v=8km s^{-1}

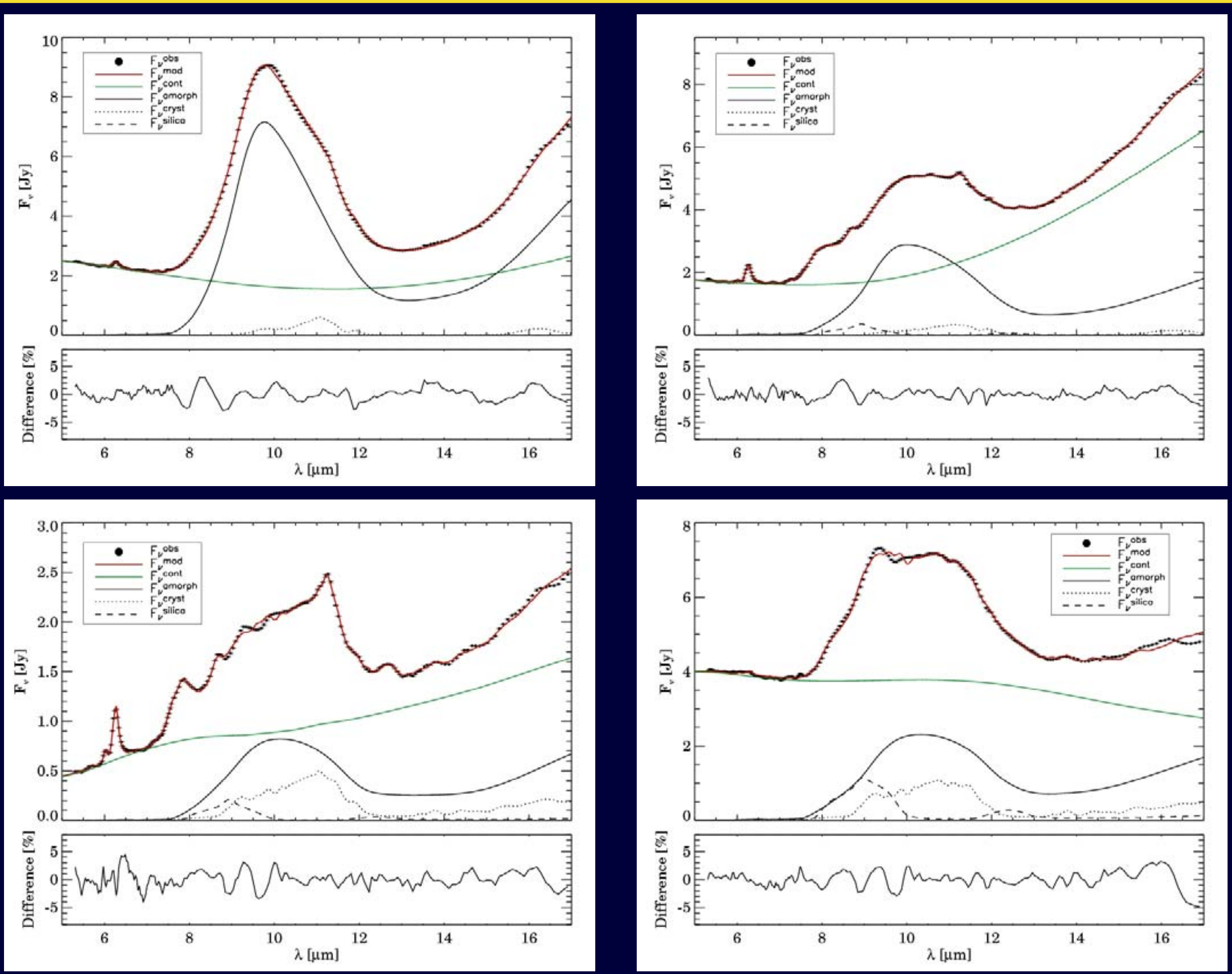
Spitzer study of Haebe stars

- Sample selection: Use targets identified in The et al 1994, van de Ancker 1998, Malfait et al. 1998, Sylvester et al 1996
  - Spectral type A, B or F
  - Near or far IR excess
  - Luminosity class III-V
  - Emission lines
- Checked the Spitzer data archive for all objects from the above studies observed with Spitzer (GTO, Legacy, Acke & Bouwman).
- Checked for misclassified objects (ABG stars, Classical Be stars, debris disks etc.
- Found ~50 HAEBE systems without extended emission i.e. emission only from disk.

Spitzer Spectra of Herbig Ae/Be stars

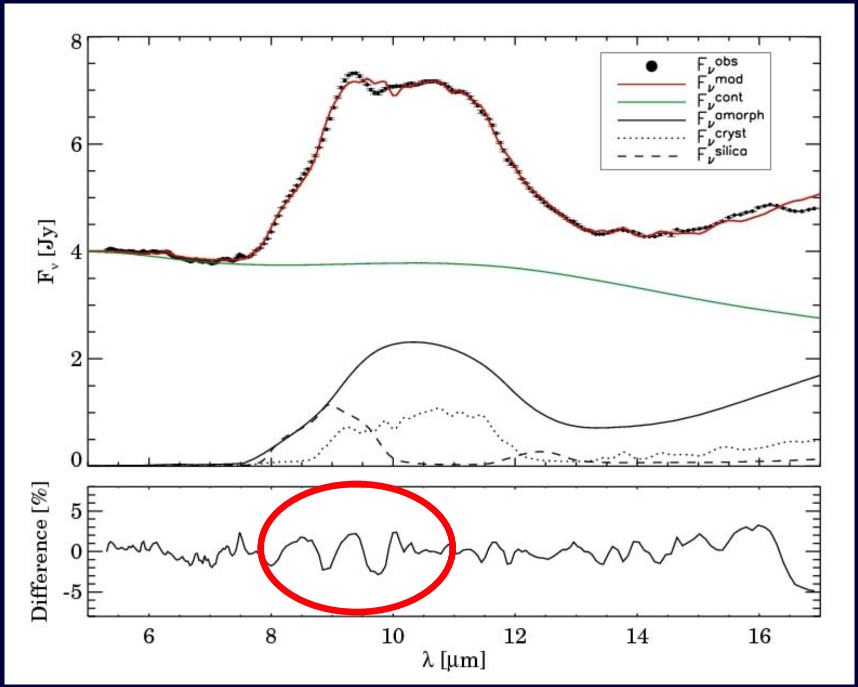


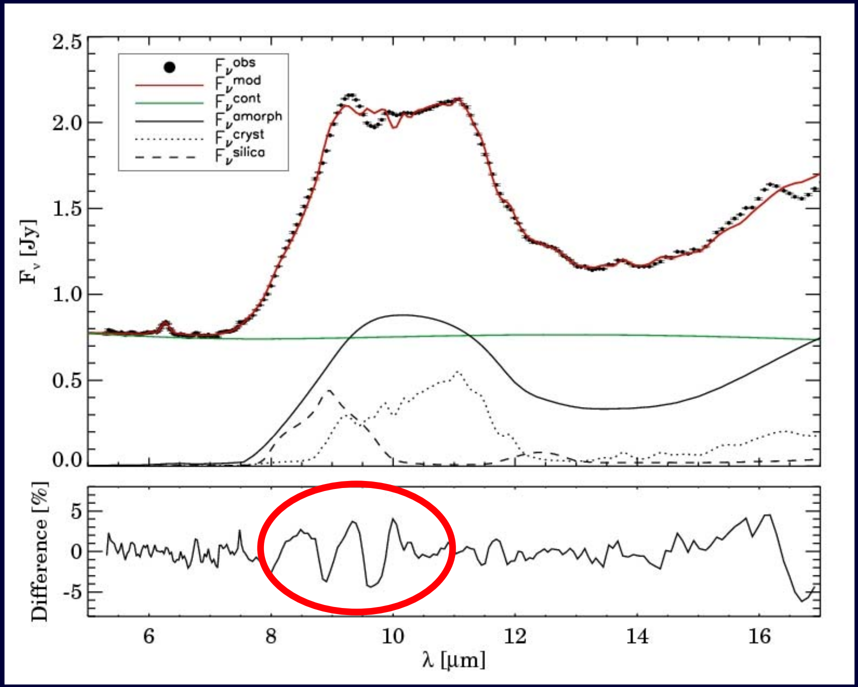
Modeling Herbig Ae/Be stars



Juhasz in prep

Problems at 9.4 μm

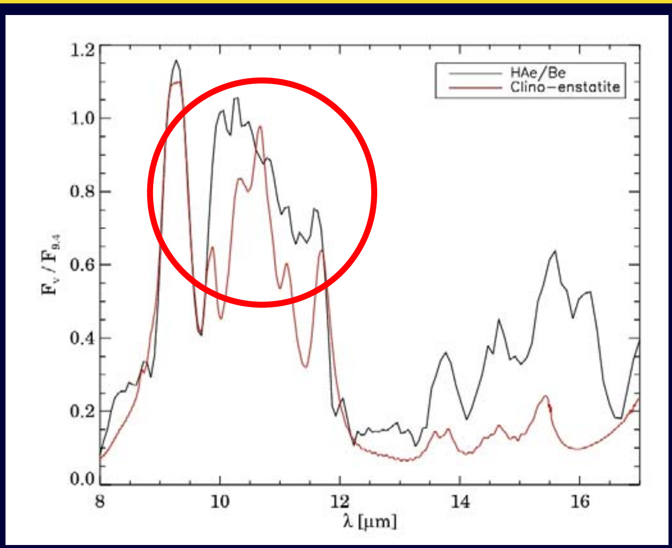


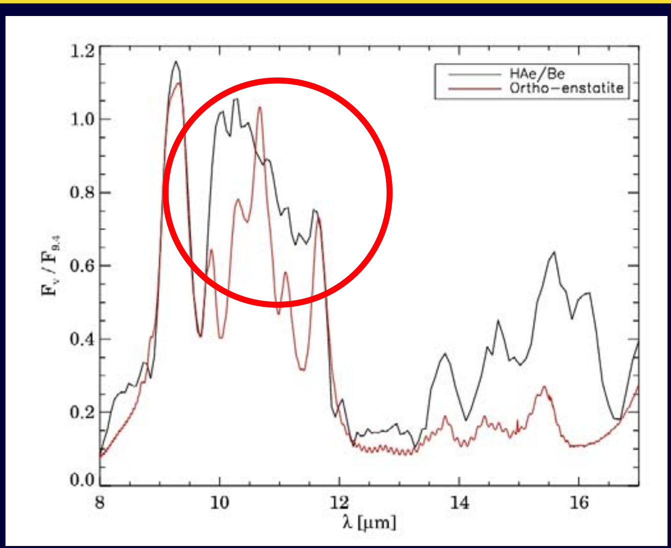


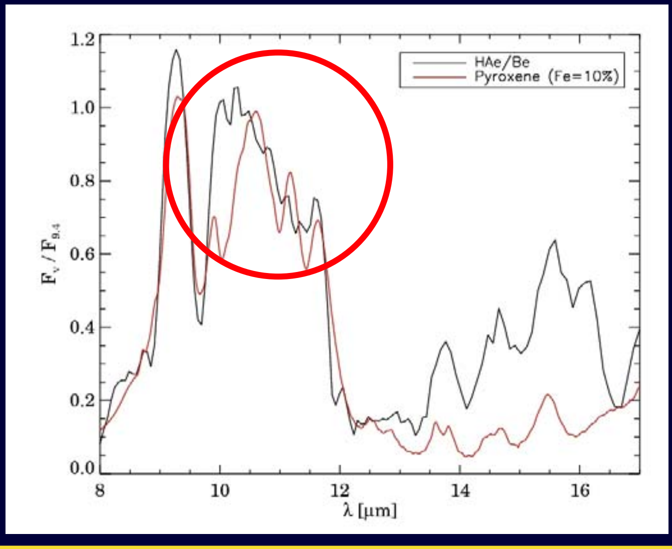
- 10 μ m silicate complex is smooth, lacking typical 'spiky' substructure, but one single and strong band is present at ~9.4 μ m
- The ~9.4 μm region has a major contribution to the χ^2

Problems at 9.4 µm - Pyroxene residuals

F_{obs} - Cont - F_{Am} - F_{Sil} - F_{Fors}



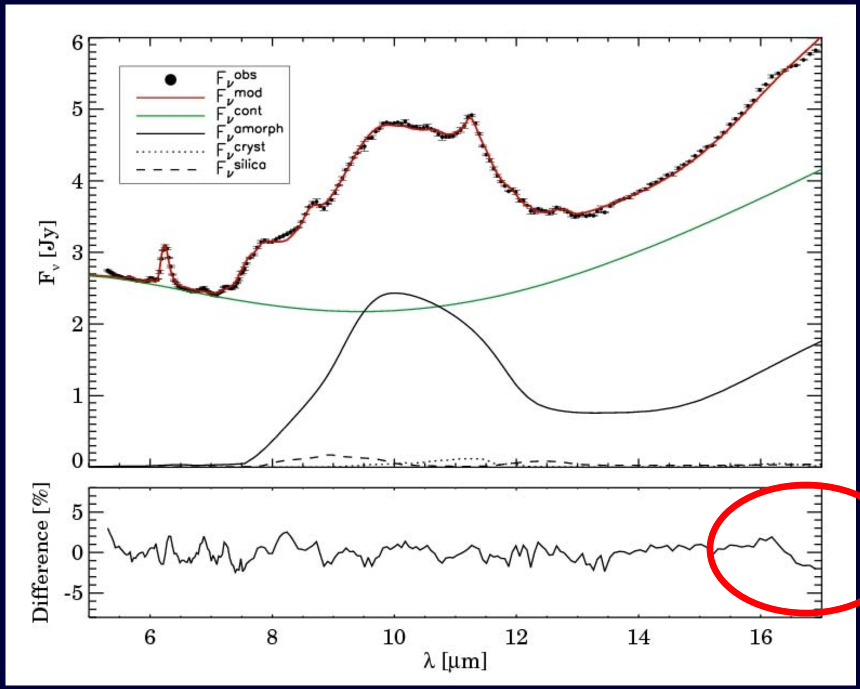


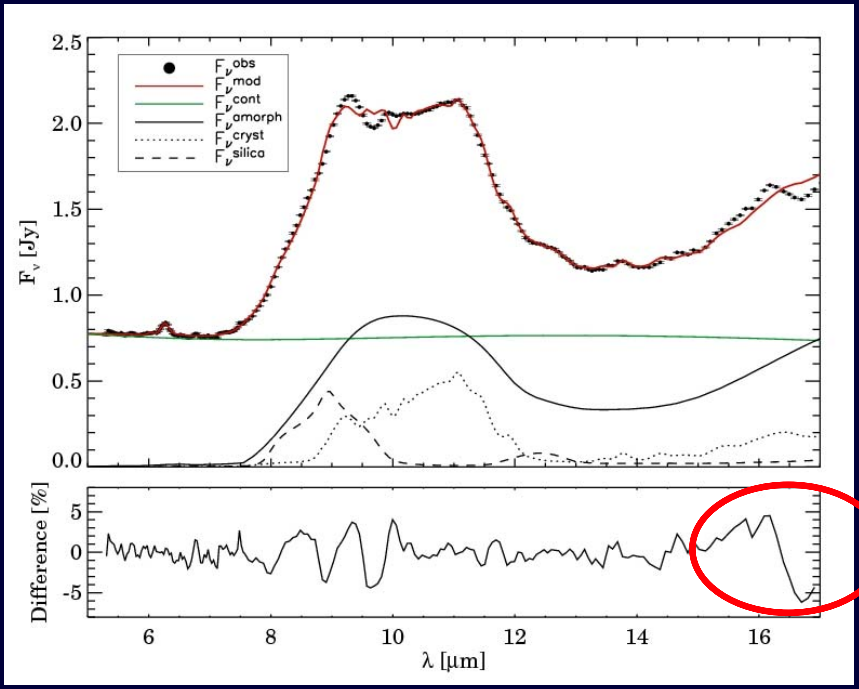


Q_{abs} curves from Chihara et al. 2002

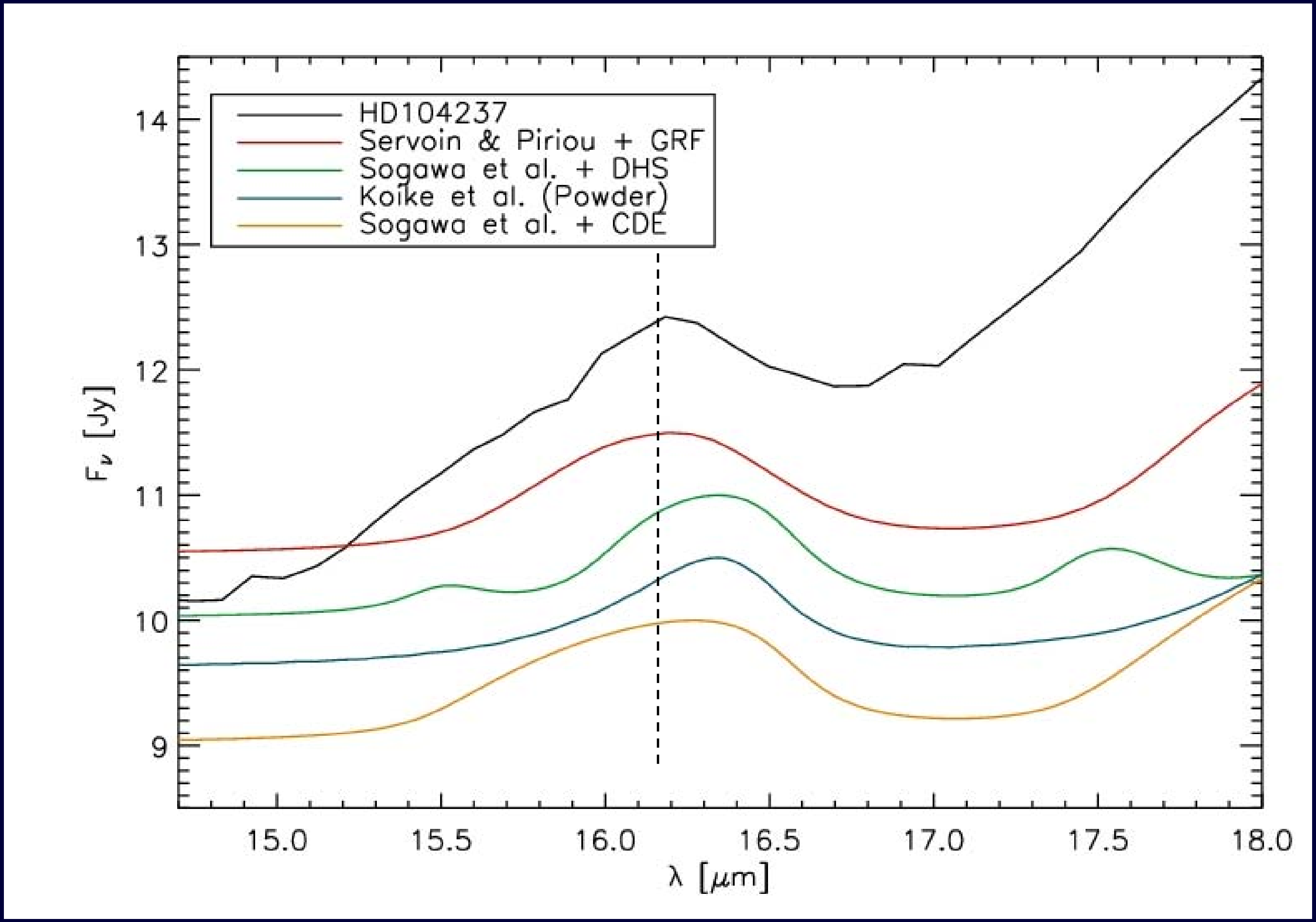
Although the strength of the 9.4 um feature can be well fitted by ortho- or clino-enstatite their sharp peaks between 10 and 12 µm increase the χ^2 substantially

Problems at 16 μm



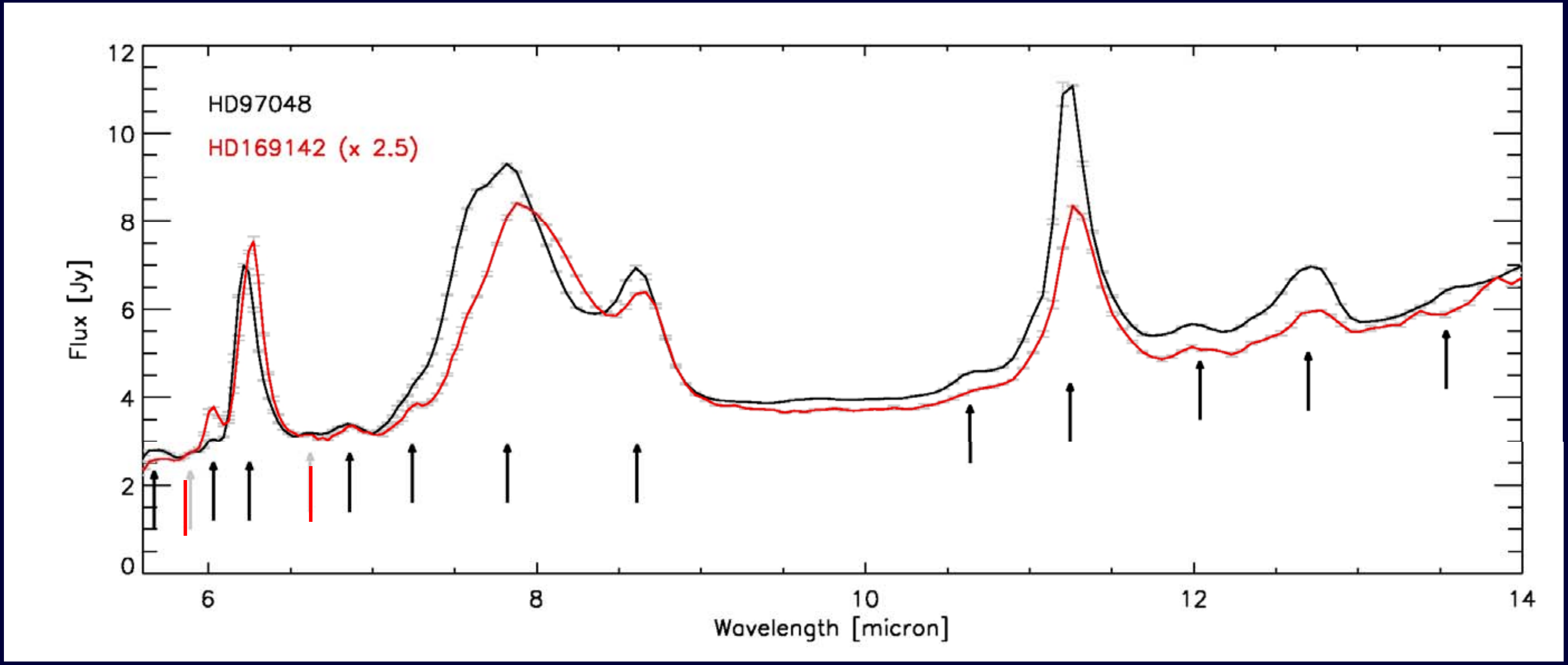


Problems with the Forsterite band at 16 µm



Disk composition from spectra: Observations of PAH bands

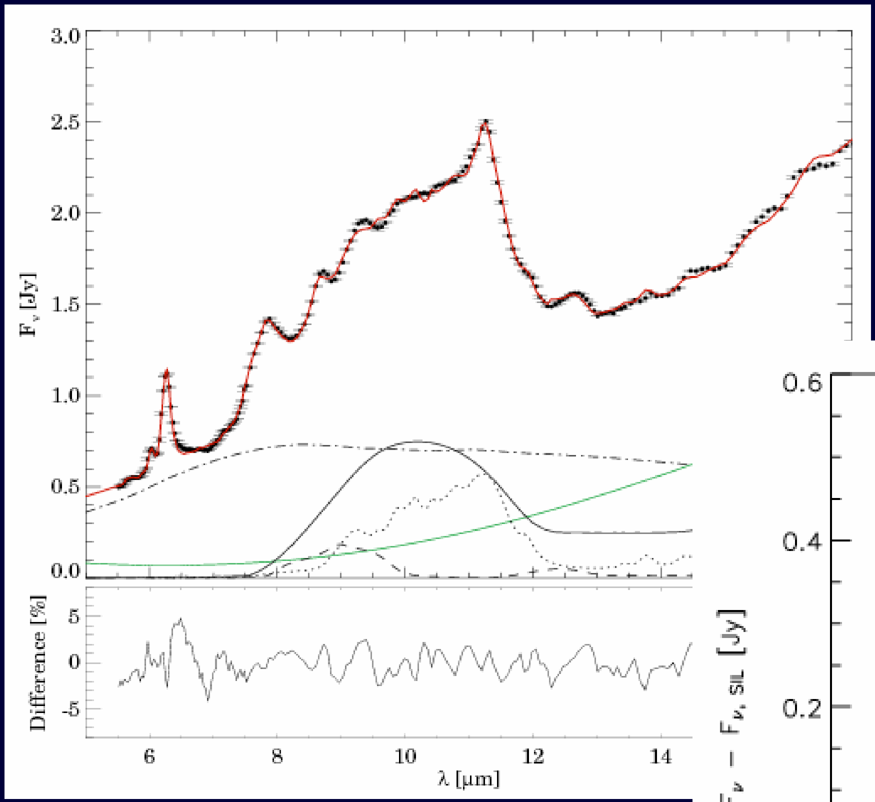
PAH emission from protoplanetary disks



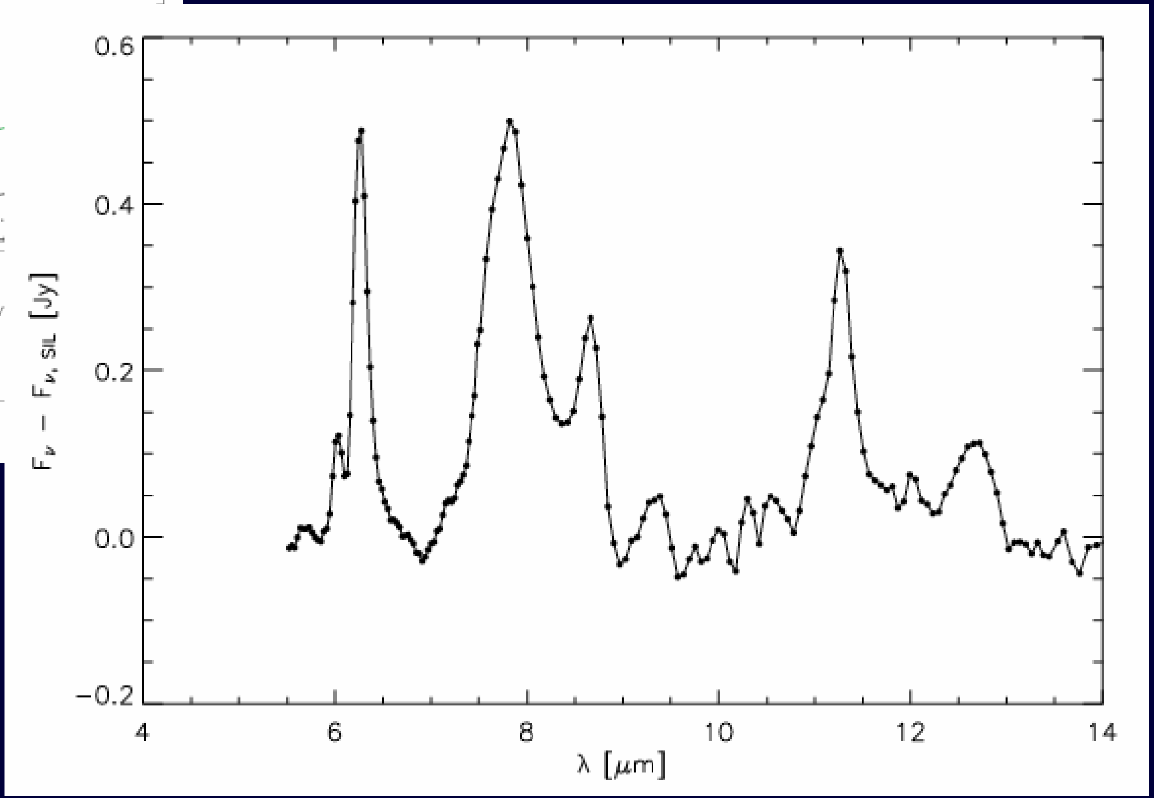
Acke et al in prep. (and poster), Sloan etal 2005, Keller etal 2008, Boersma et al 2008, Geers et al (C2D)

Spitzer IRS spectra of Herbig Ae stars: PAH

HD72106



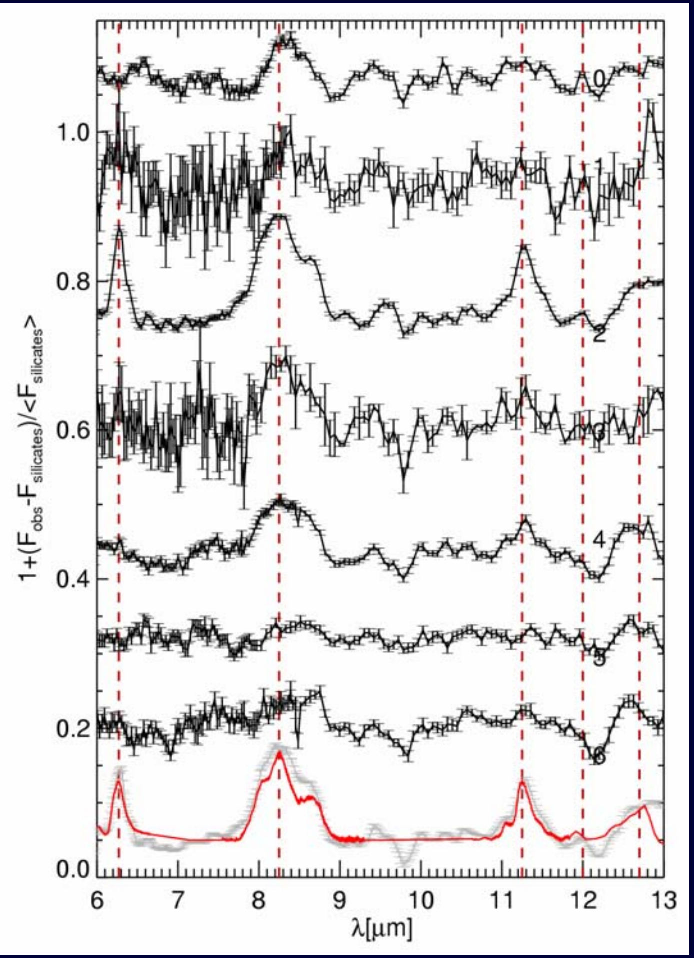
Silicate subtracted residual



Acke et al in prep.

FEPS: PAH emission in TTS systems

Normalized Flux

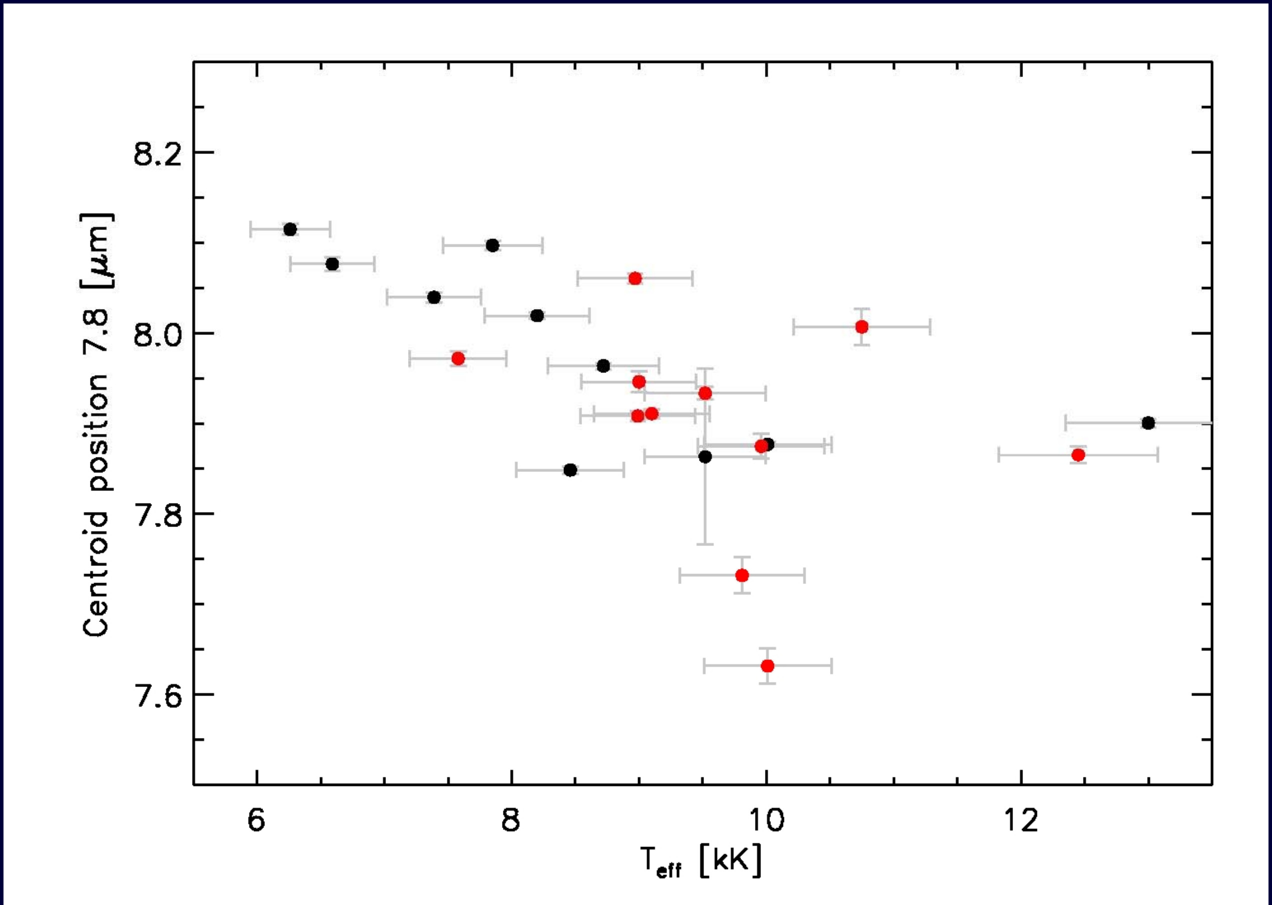


Wavelength

(Bouwman et al. 2008)

- Sample of G to late K type stars
- 5/7 show 8.2 micron band
- 1 source shows strong 6.2 and 11.2 bands
- Also 8.6 and 12.1 and 12.7 micron bands
- Xray Chemistry?? Ionization of PAH molecules

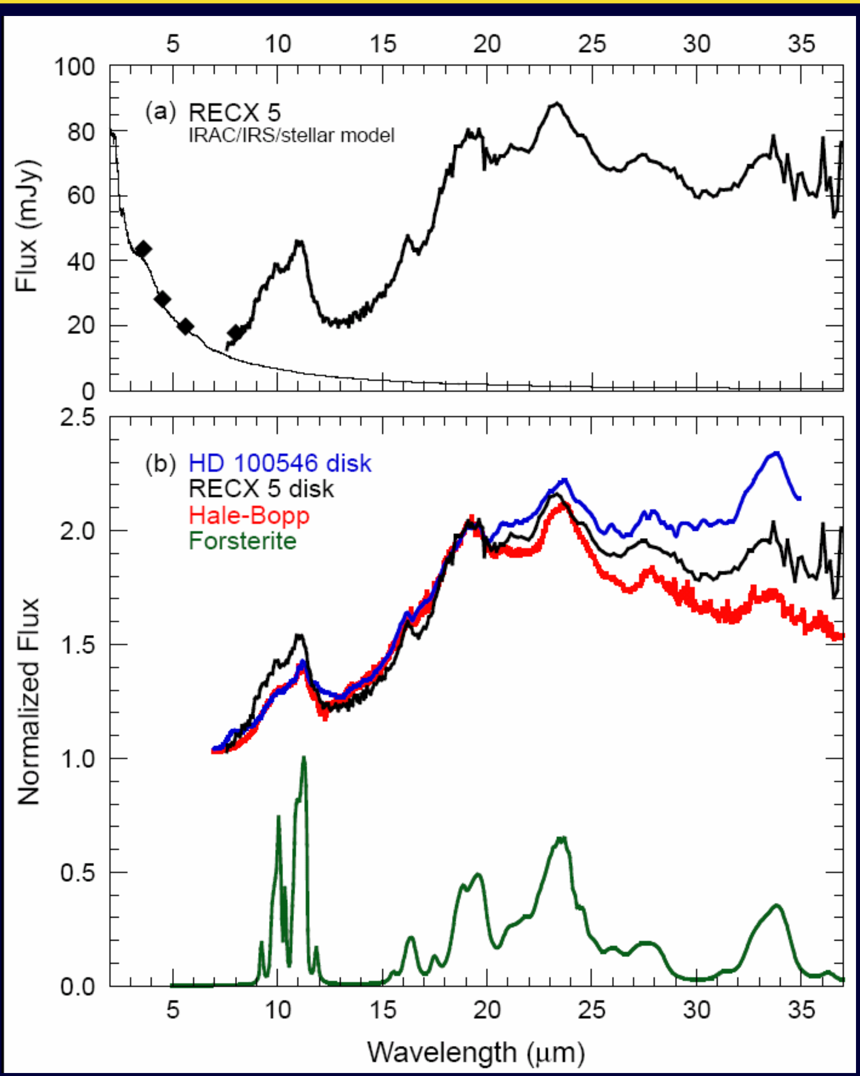
PAH processing

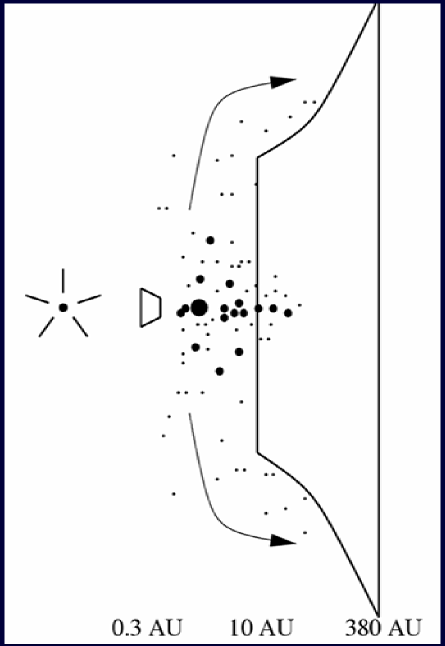


Keller at al 2008, Acke et al in prep

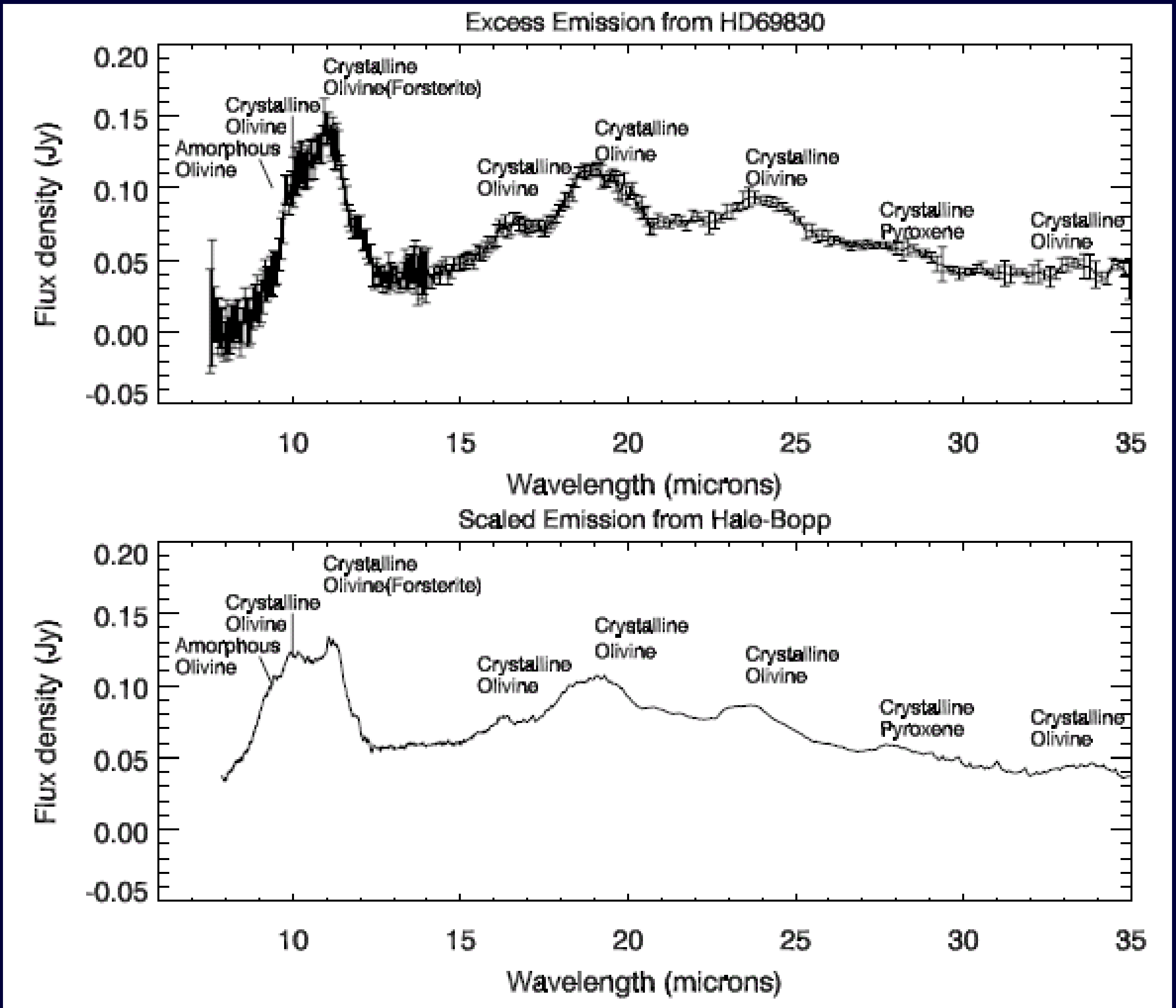
Disk composition from spectra: links to the solar system

Comparison between disk around a M5 star, a B9star and the Sun



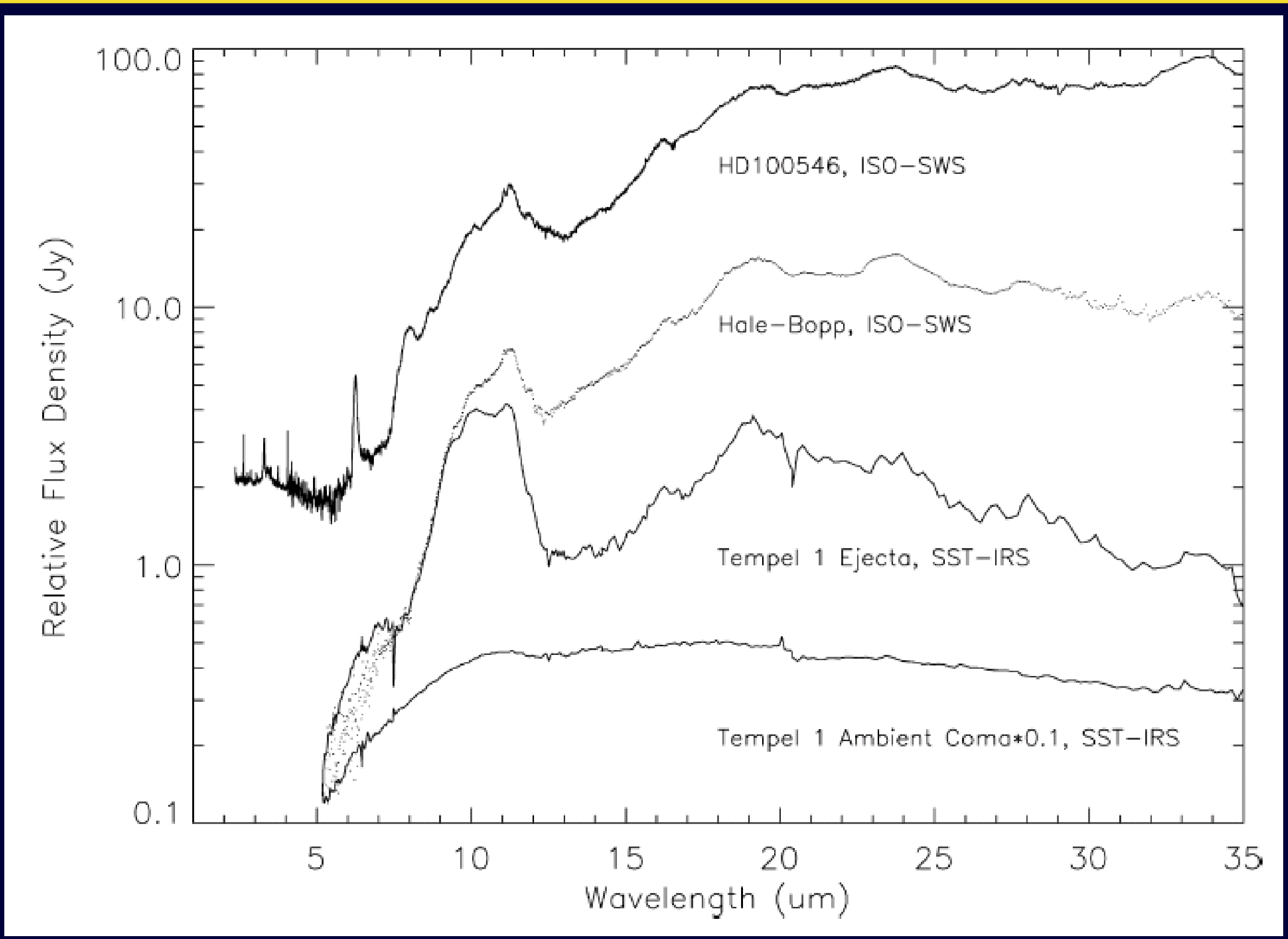


Comets in HD69830



Beichman et al 2005

Cometary spectra: tracing different epochs and compositions



Lisse et al 2005,2007

Conclusions:

- Spitzer is providing IR spectra for objects spanning a wide range of masses, environments and ages.
- Interpreting IR spectra requires detailed dust models and lab measurements.
- Dust processing in disks is not limited to specific types of sources.
- Dust growth and settling.
- Formation of crystalline silicates: High temperature processing in the inner disk. Radial mixing? Shocks?
- Interactions between the dust and planets?. Comparison to the proto-solar nebulae (Comets)
- Time-scales? Multiple processes working at different time-scales