Herbig Ae disks at 10 micrometer: disk structure and dust evolution

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Collaborators

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Outline of talk

- Introduction
- I. Geometry of circumstellar disks, flaring vs. self-shadowed
- II. Dust evolution in circumstellar disks
  - “classical” (spatially unresolved) IR spectroscopy
  - Interferometrically resolved spectroscopy
- conclusions

ESO VLT Interferometer

MIDI at the VLTI

- Two-element beam combiner
- Measures spectrally resolved visibilities
- ~8 – 13.5 micron
- Spectral resolution 30 or 250
- maximum spatial resolution 10-20 milli-arcsec
- PI: Christoph Leinert (Heidelberg)

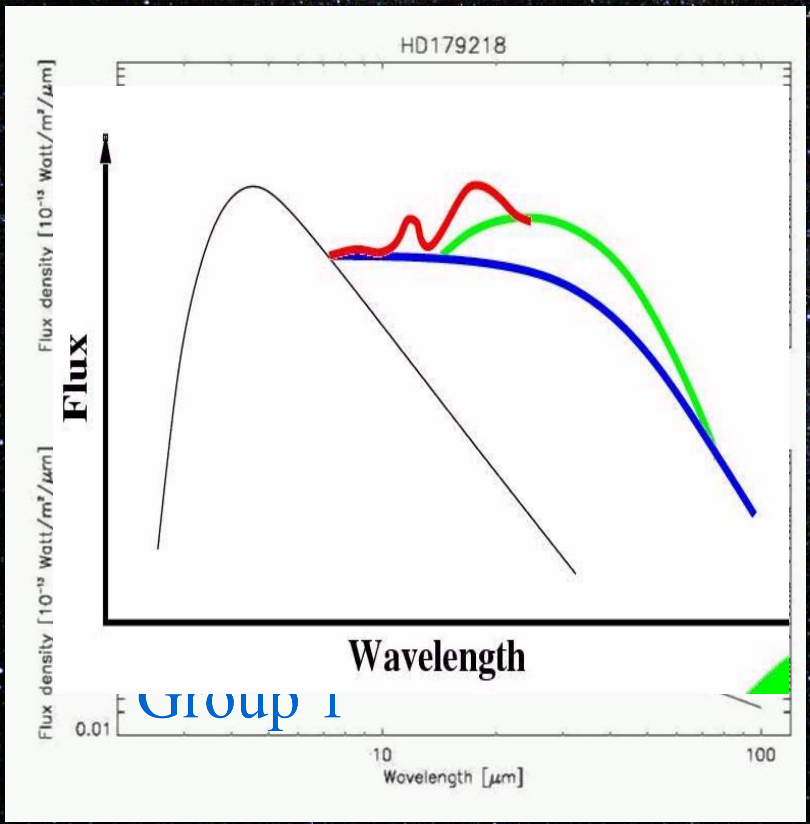
HAe stars

- Intermediate mass PMS stars
- Spectral type early F to late B
- "Class II"
- Passive circumstellar disks that no longer accrete significantly ($\sim 10^{-8}\ M_{\odot}\ yr^{-1}$)
- Ages $\sim 10^{5} - 10^{7}$ yr
- Size and brightness ideal for first science with VLT Interferometer

I. Disk Structure

- Mm interferometry (~100 AU)
- Optical/NIR scattered light (~100 AU)
- High resolution spectroscopy (<1 AU)
- SED modeling (all scales, but indirect)
- Lacking: spatially resolved observations of the dust emission on scales between 0.1 and 100 AU (0.001 – 1 arcsec)
- Large telescope imaging, interferometry

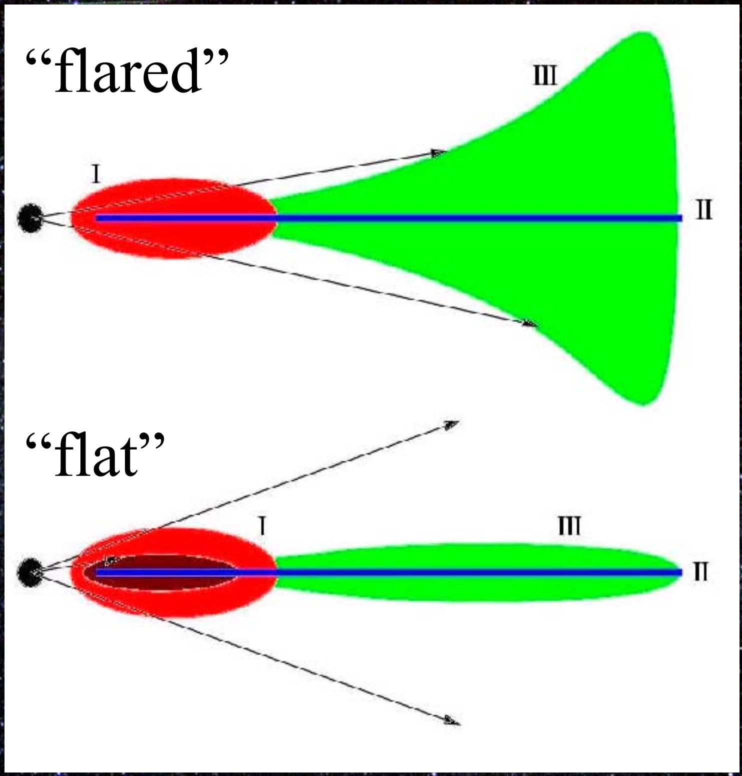
Division into two groups: flaring versus flat (self-shadowed) disks?



Meeus et al. 2001

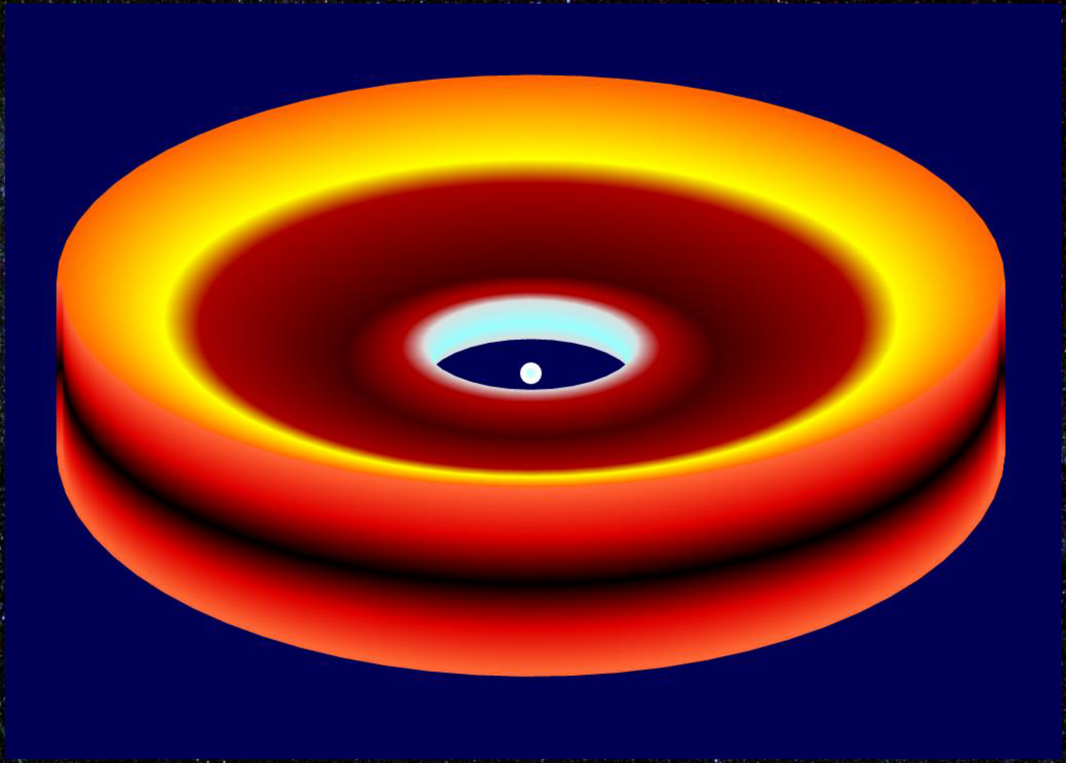
I

II



Flaring disk around 2 $M_\odot$ star

- Inner rim is "puffed-up"
- Causes additional near-IR radiation
- Shadowed region

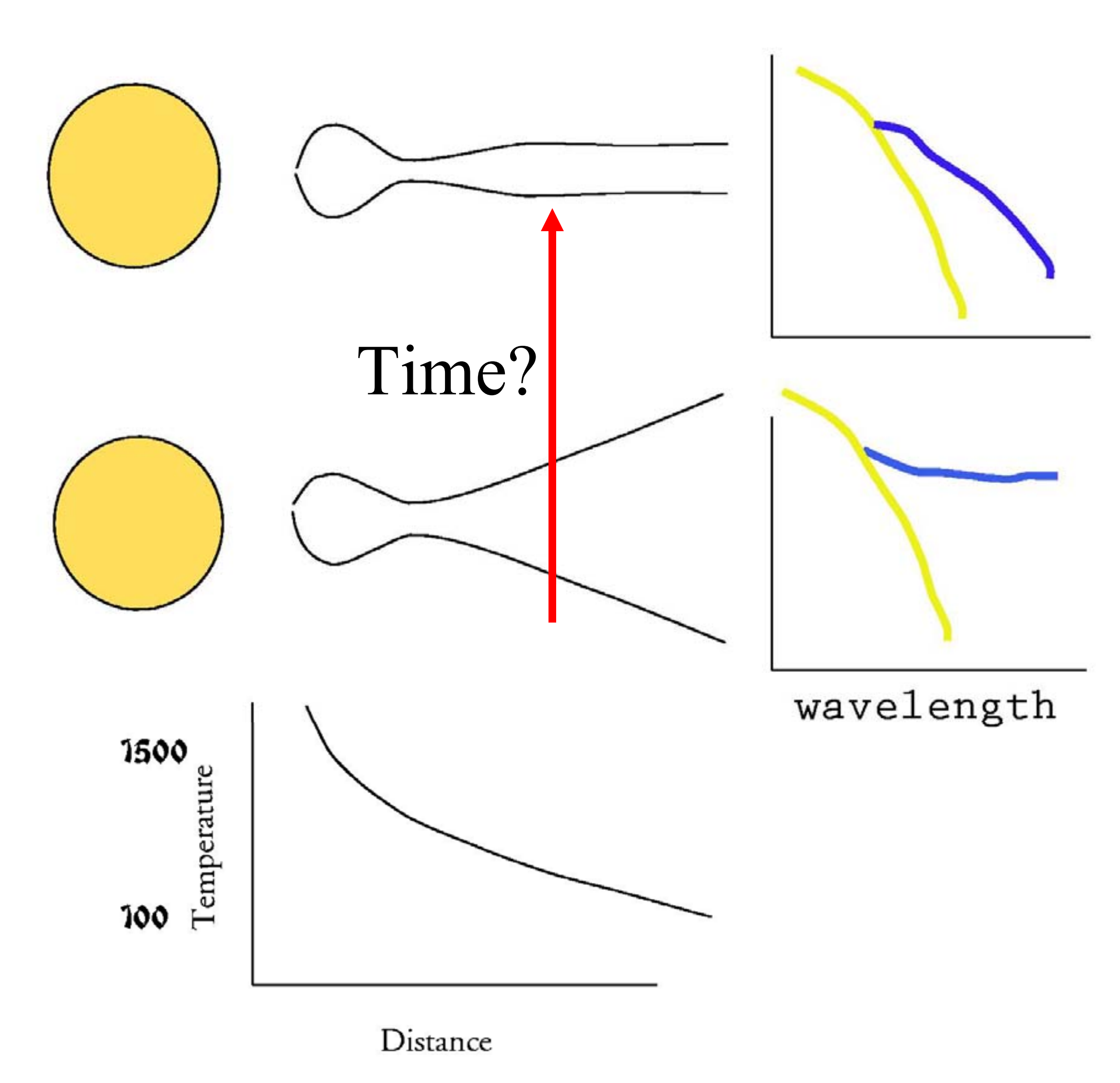


Dullemond, Dominik and Natta

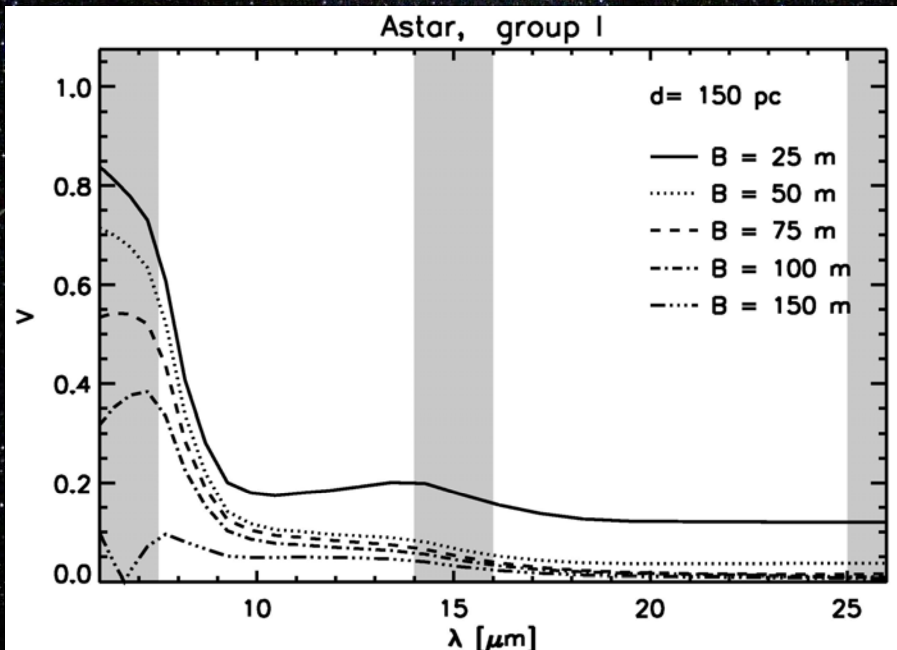
Geometry of protoplanetary disks

- Flaring or flat disks
- Flat disks are self-shadowed
- Evolutionary link?

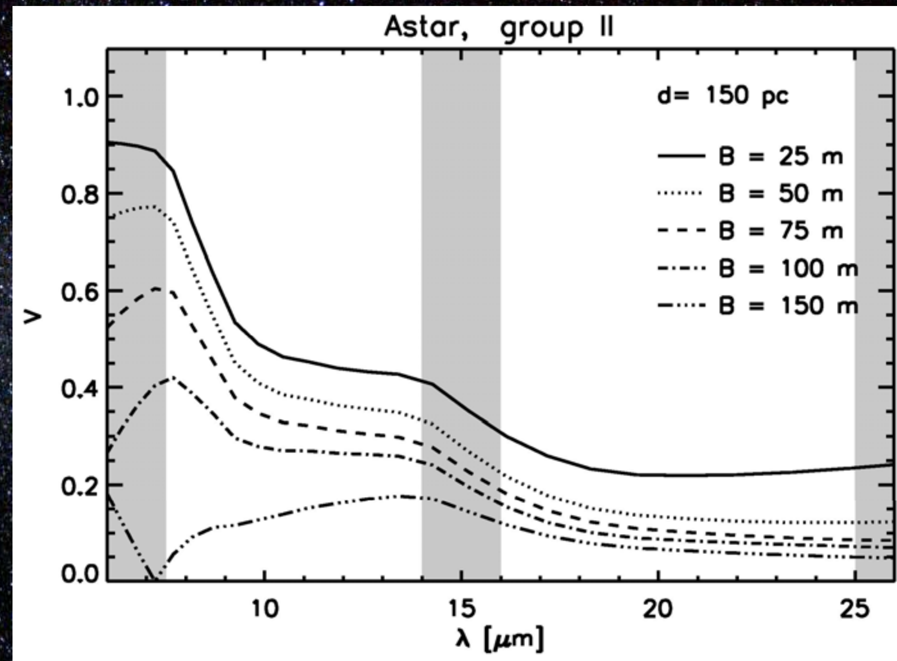
Dullemond (2002), Acke et al. 2004



Visibility simulations: flaring versus self-shadowed



Flaring

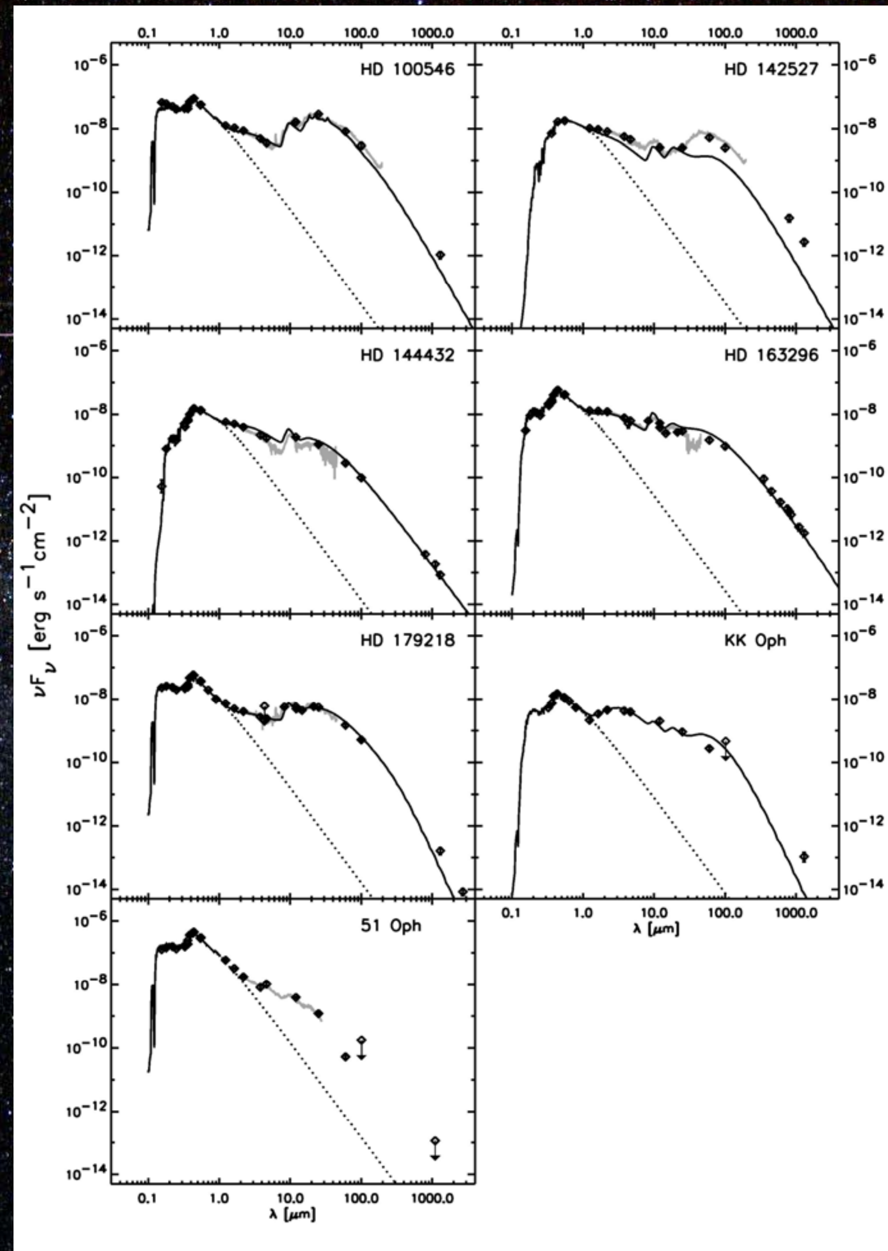


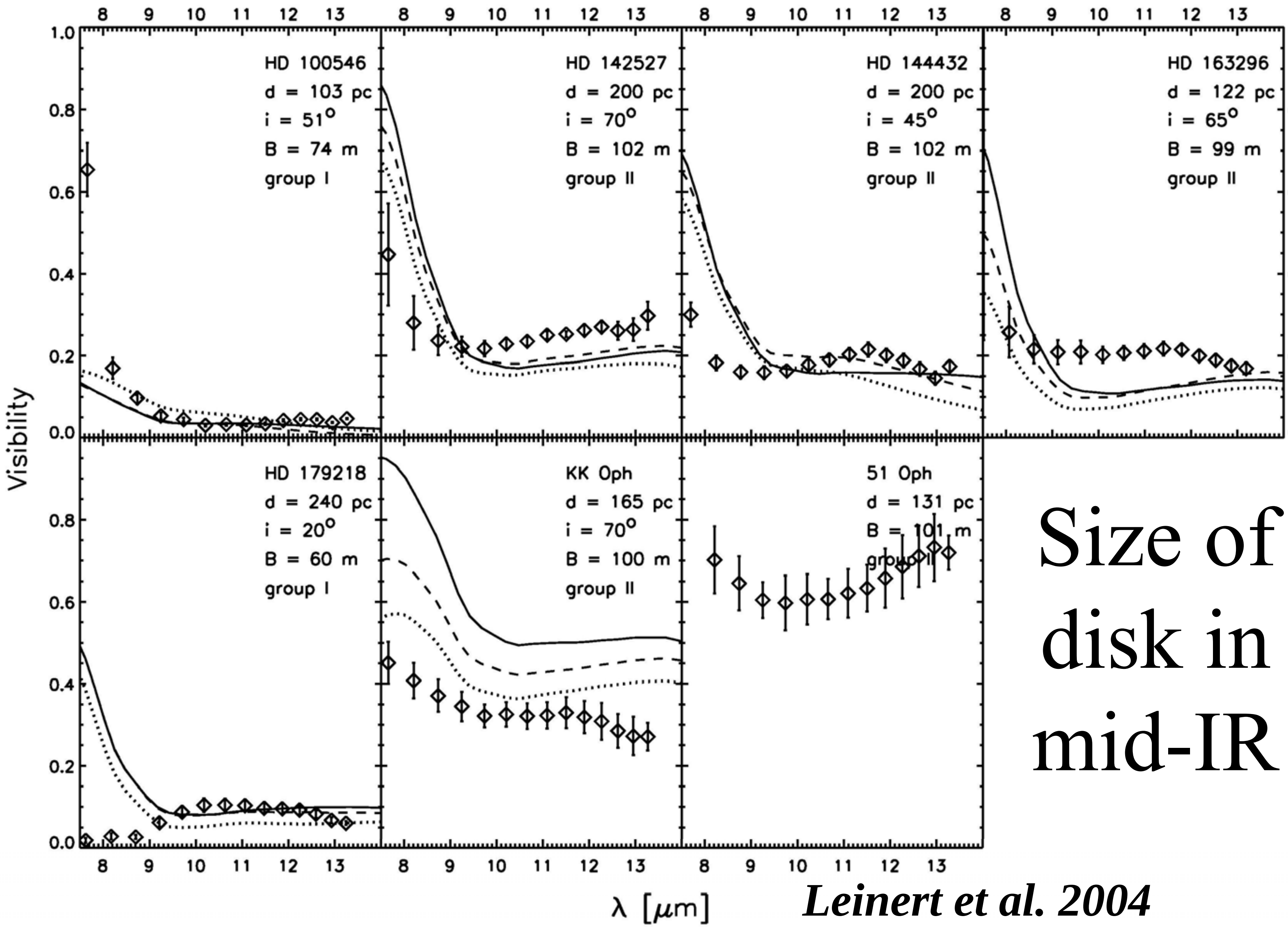
Self-shadowed

Van Boekel, Dullemond et al.

Observed spectra and disk model SED(!) fits to MIDI sample

Dominik et al;
Leinert et al.

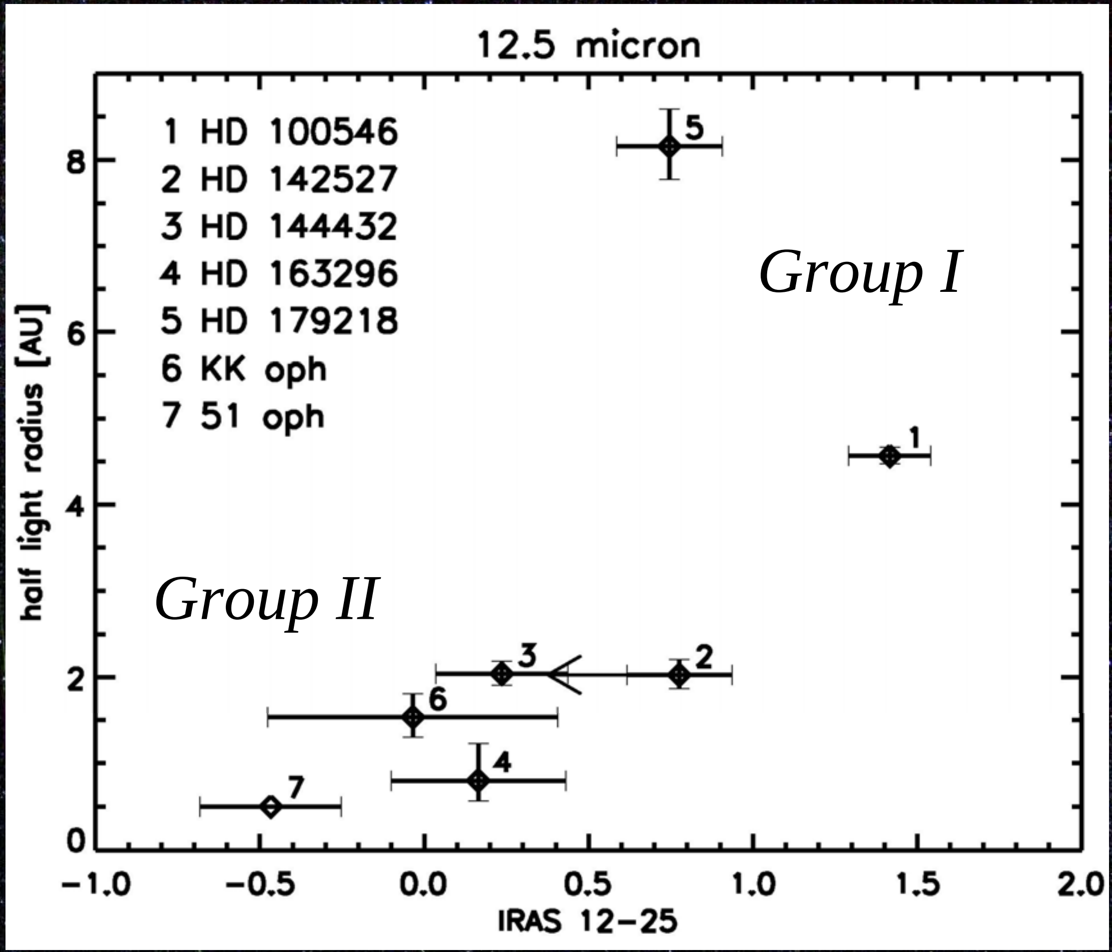




Size of disk in mid-IR

Leinert et al. 2004

IR spectral slope and disk "size"

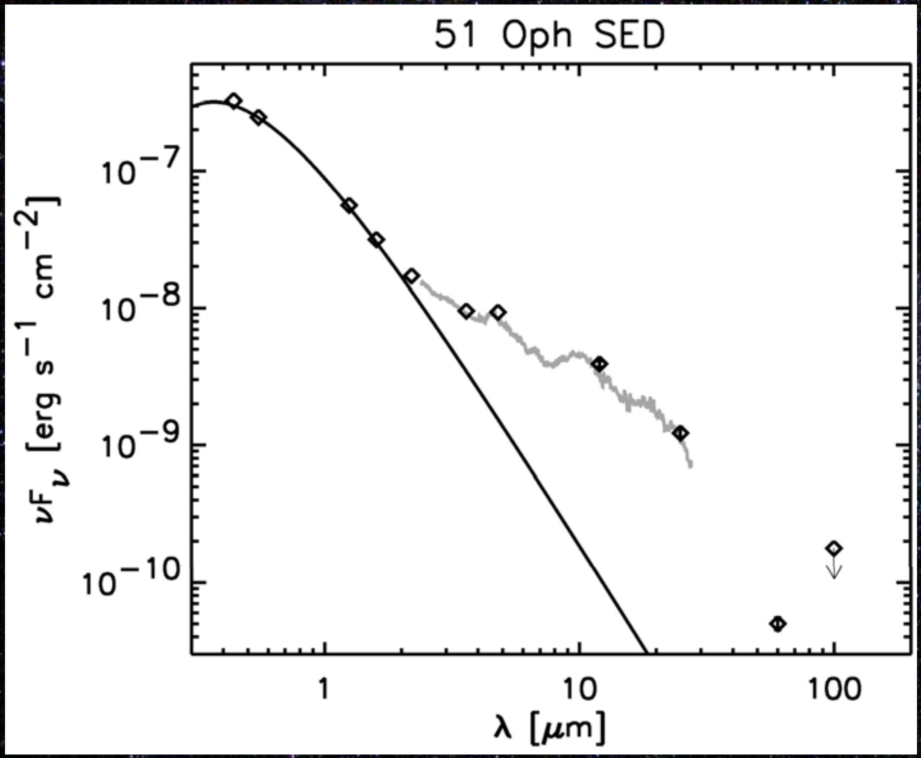


Leinert et al.

Structure of circumstellar disks

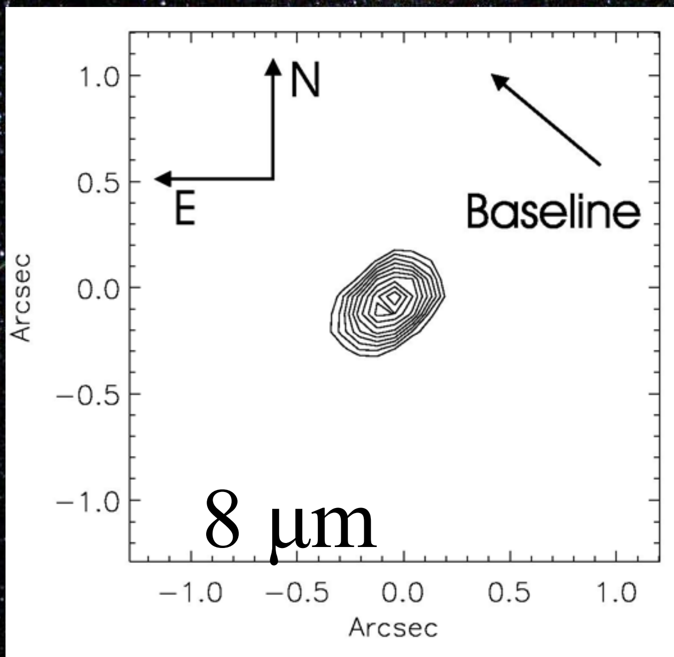
- Q: Is the observed difference in SED (group I, group II) caused by a difference in disk geometry (flaring, flat)? MIDI: “YES”
- Current generation of models reproduce first measurements reasonably
- Much work ahead modeling individual sources
- Measurements at multiple baselines

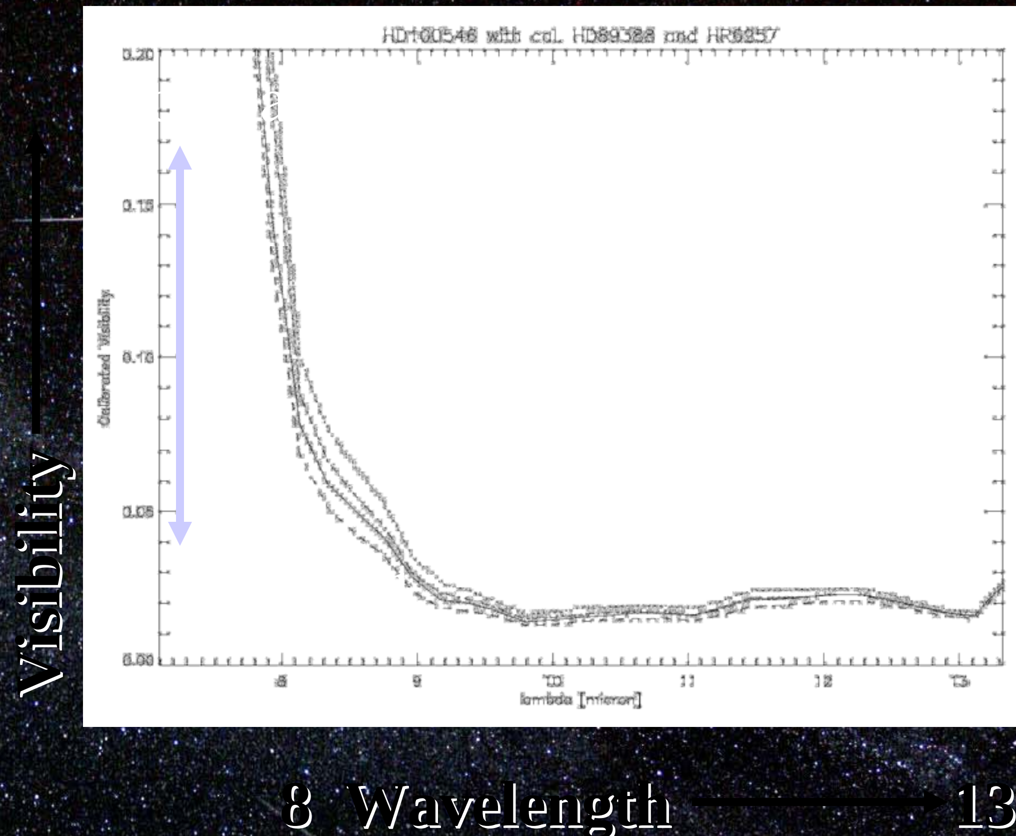
51 Oph: very different disk structure



- Gas-phase molecules in near-IR
- puffed-up inner rim missing
- Disk covering angle only 4 deg
- Very compact @ 10 micron!

VLTI observations at 10 μm of HD100546 using MIDI





- Emission almost fully resolved on a scale of 20 milli-arcsec (!)
- “Wall” at ~10 AU? Bouwman et al. 2003, Liu et al 2004

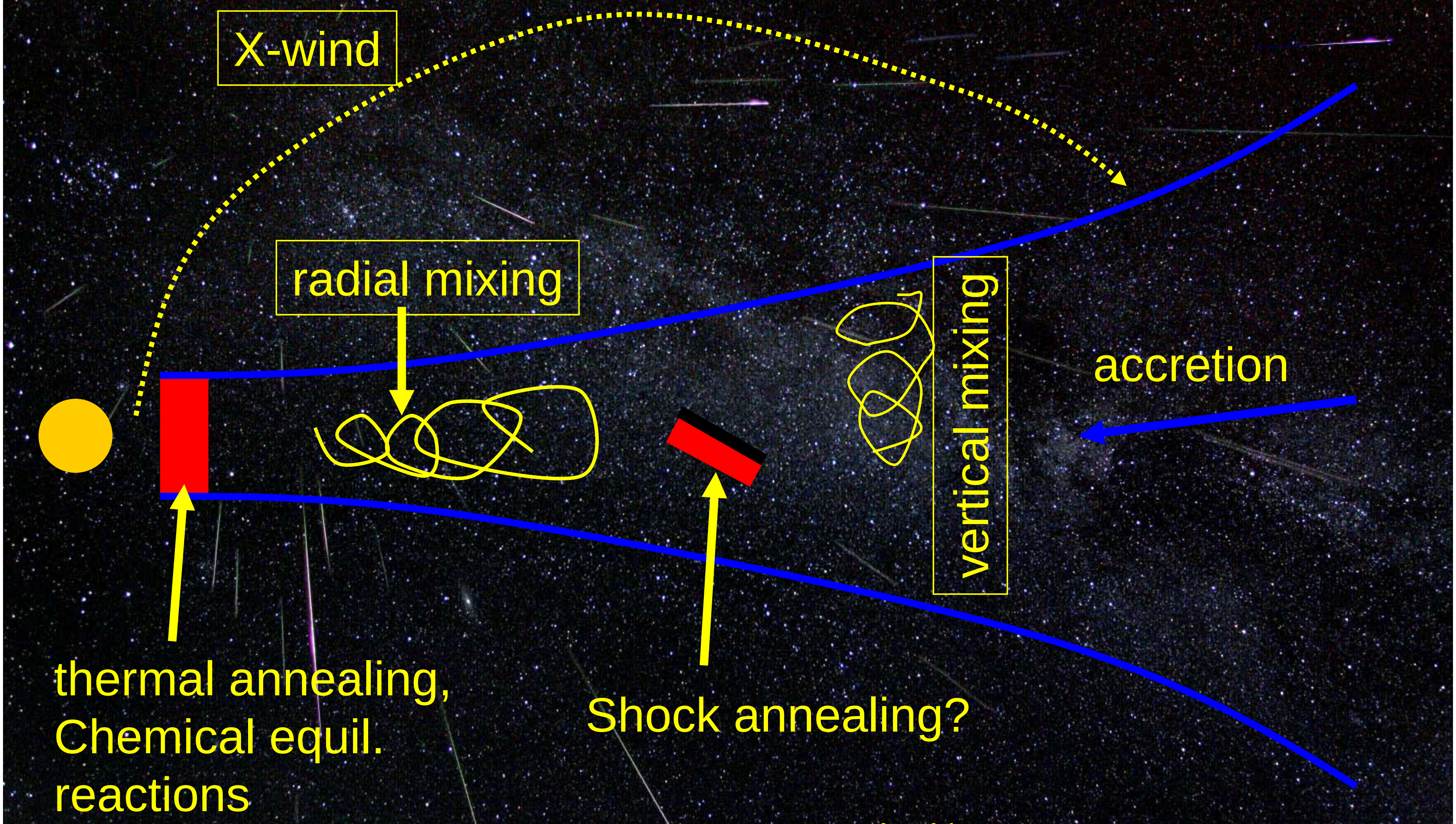
II Dust processing

- From “pristine” (sub-micron sized, amorphous grains, ISM) dust to “evolved” (micron sized grains, partly crystalline, comets) dust.
- How?
- Where?
- When?

Processing of silicates: amorphous → crystalline

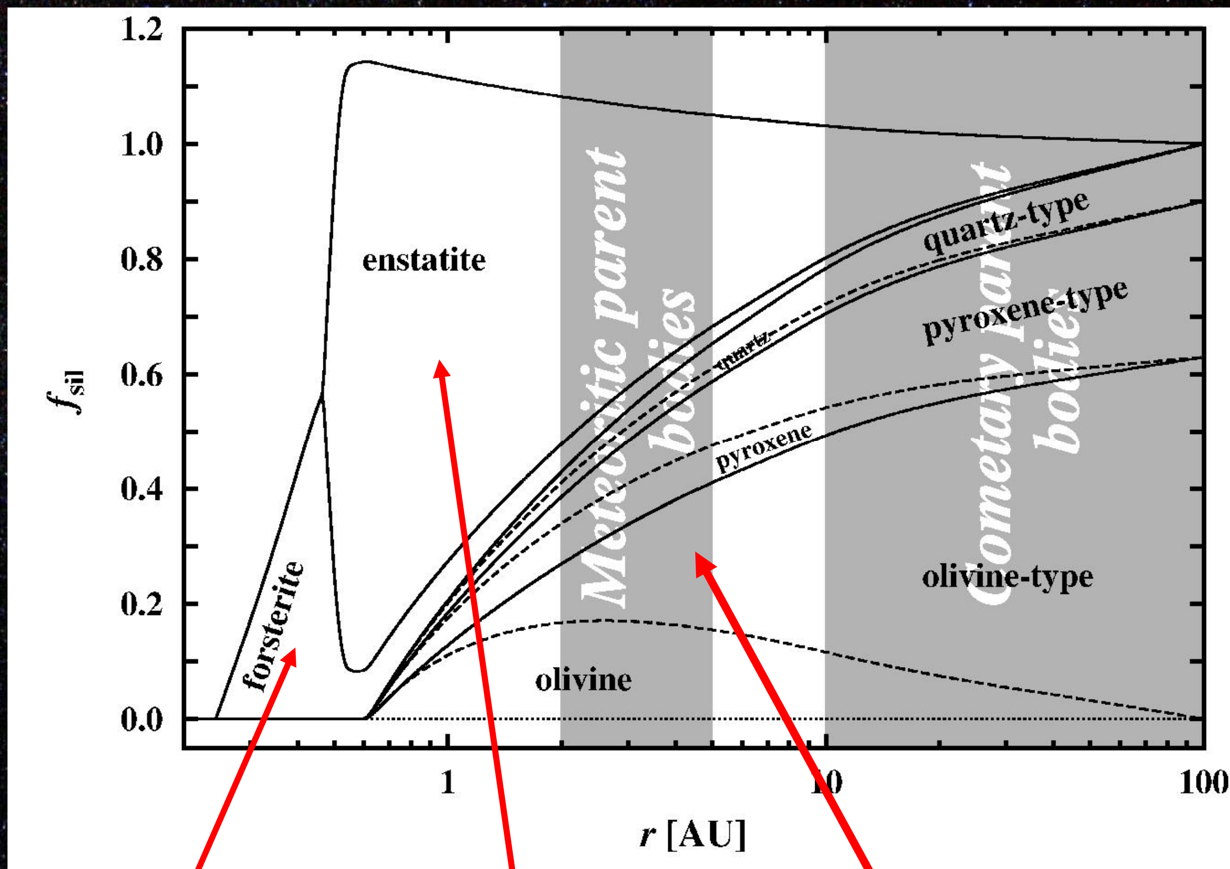
- Vaporisation, recondensation above about 1400-1500 K (forsterite, Mg-rich)
- Chemical equilibrium reactions T > 1100 K
  - conversion of forsterite to enstatite
- Thermal annealing of amorphous ISM silicates, Fe-rich (?) T > 900 K
- Annealing in shocks?

Crystallization and Mixing



C. Dominik

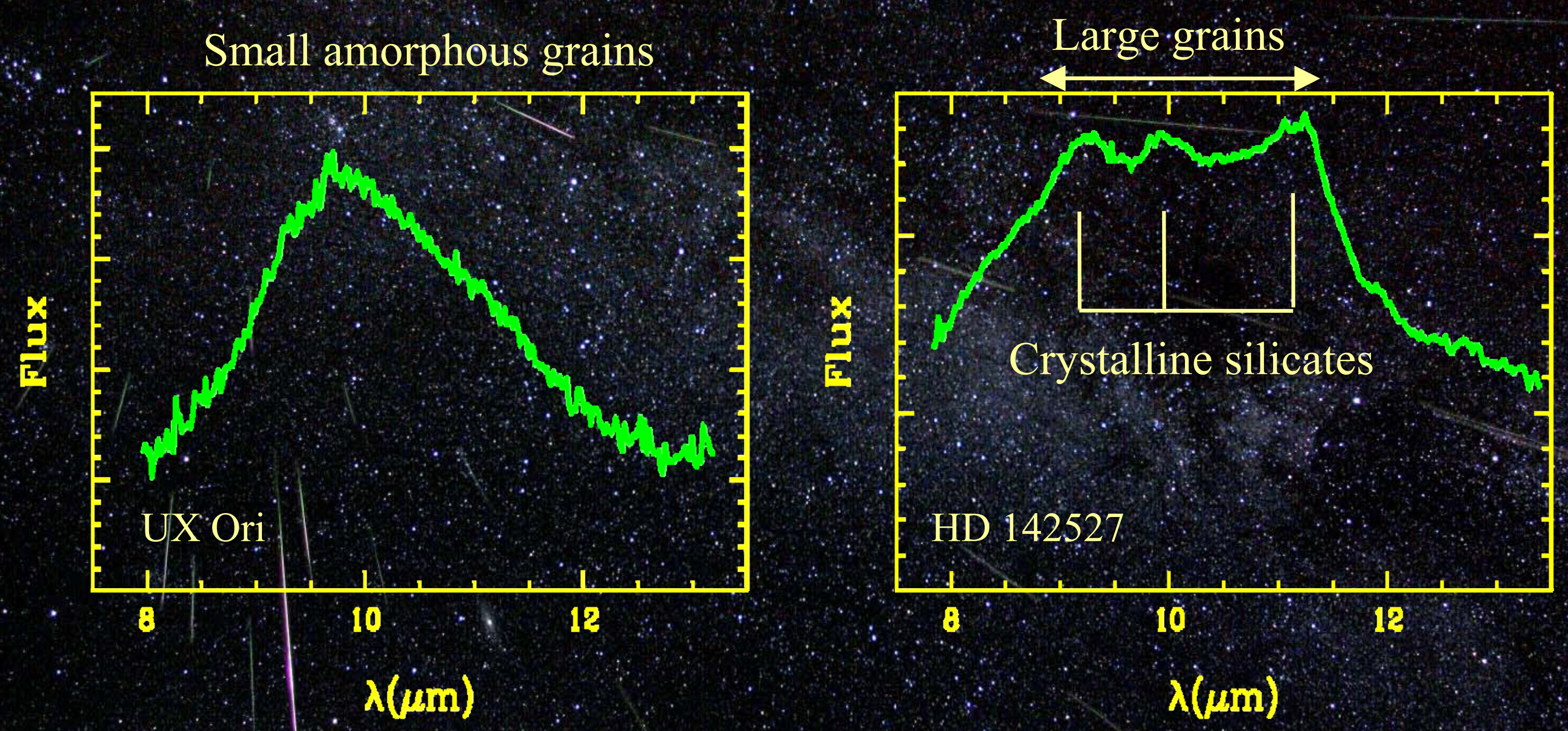
Distribution of silicates



Forsterite Enstatite

Fe-rich amorphous olivines,pyroxenes

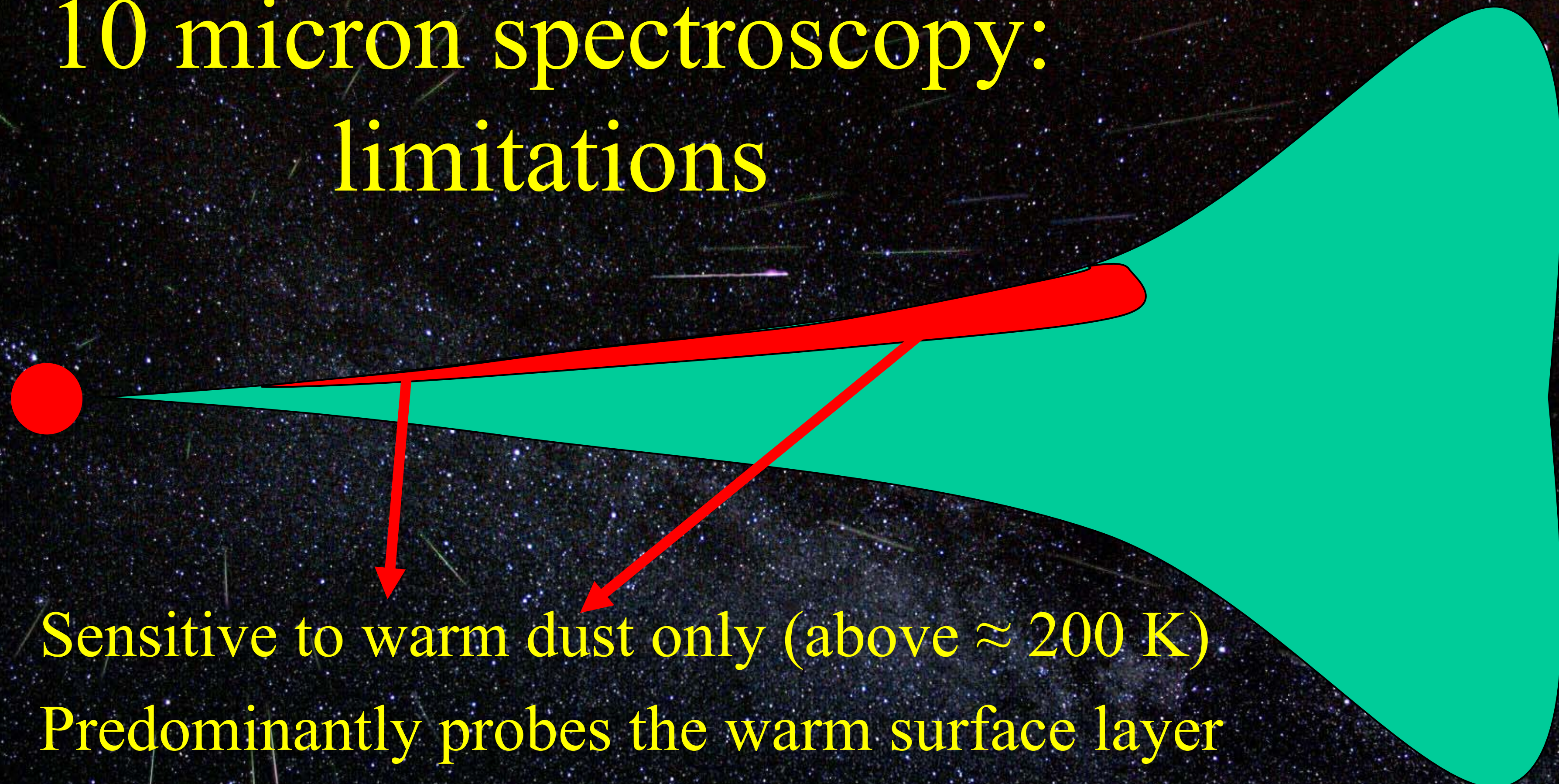
Dust processing at 10 micron



"Pristine"

"Evolved"

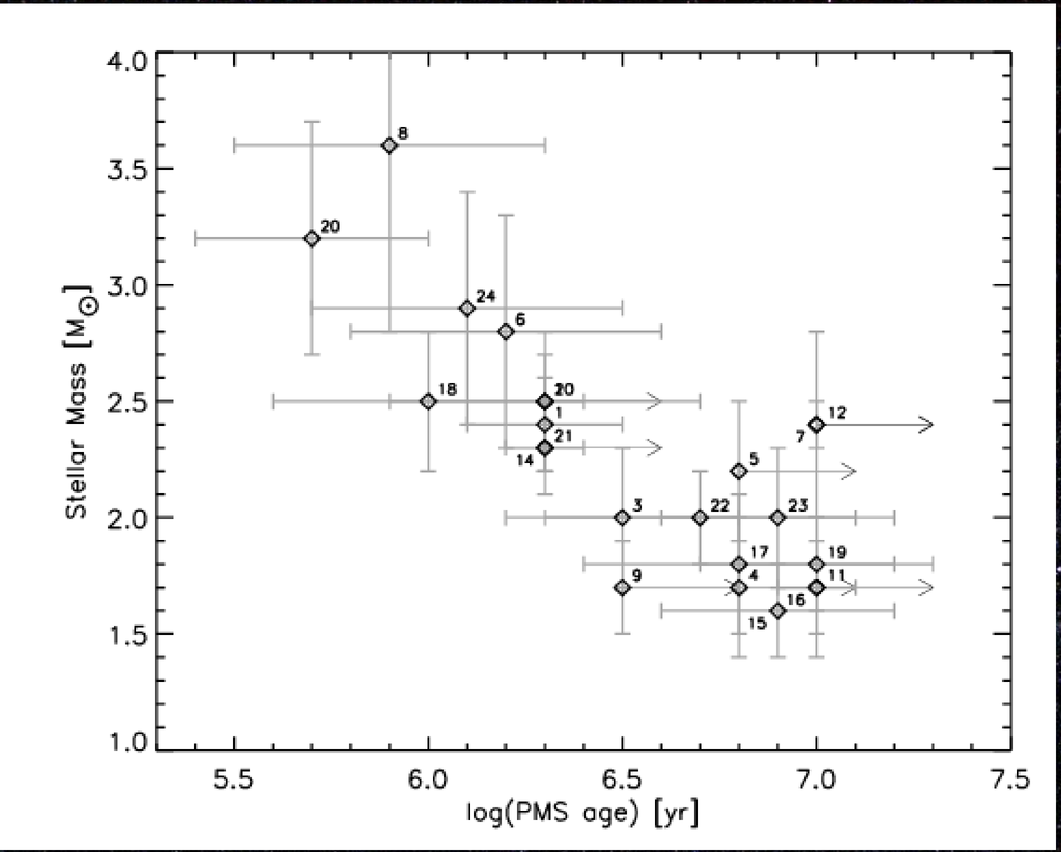
10 micron spectroscopy: limitations



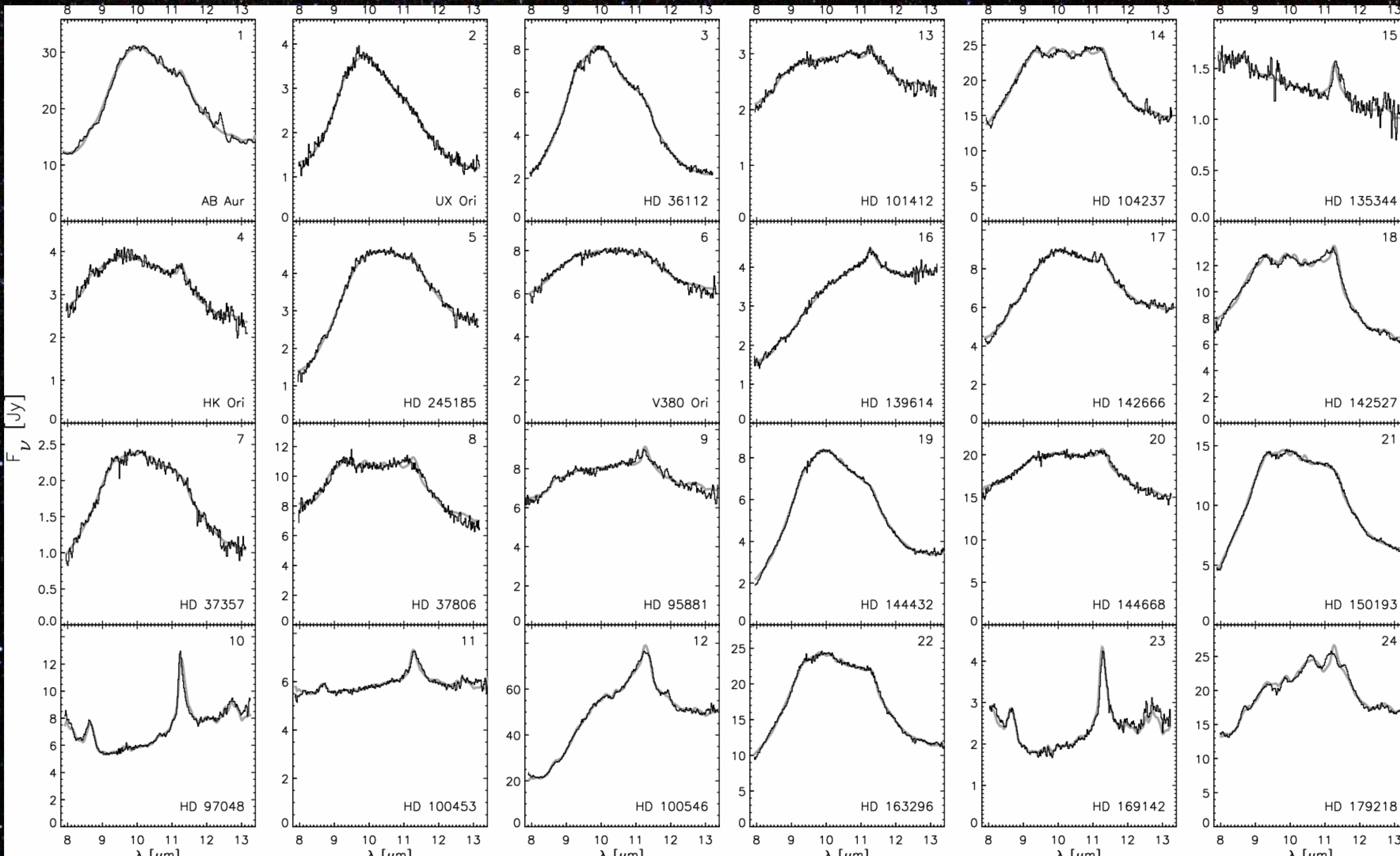
- Sensitive to warm dust only (above ≈ 200 K)
- Predominantly probes the warm surface layer
- Sensitive to grain sizes upto a few micron
- Small wavelength range (~ 8 – 13.5 micron): little information about temperature distribution of dust

10 micron survey (spatially unresolved)

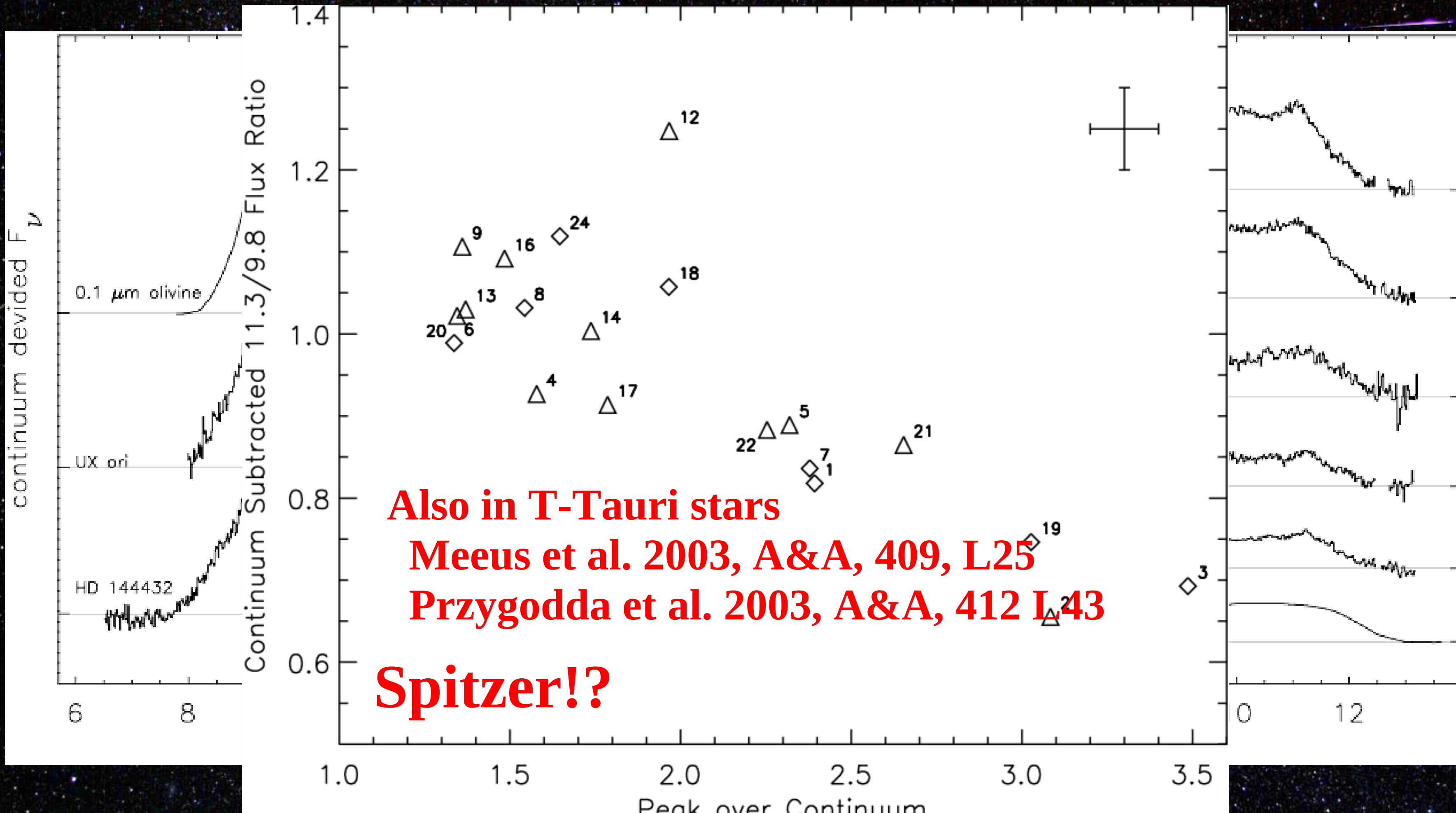
- 24 stars
- 1.5 - 3.5 $M_{\odot}$
- $10^5 - 10^7$ yrs
- Age-mass relation
- ESO 3.6/TIMMI2
  7.8-13.4 micron
  R=160
  SNR 20-100



The sample star spectra



Shape vs. strength of silicate feature



Also in T-Tauri stars

Meeus et al. 2003, A&A, 409, L25

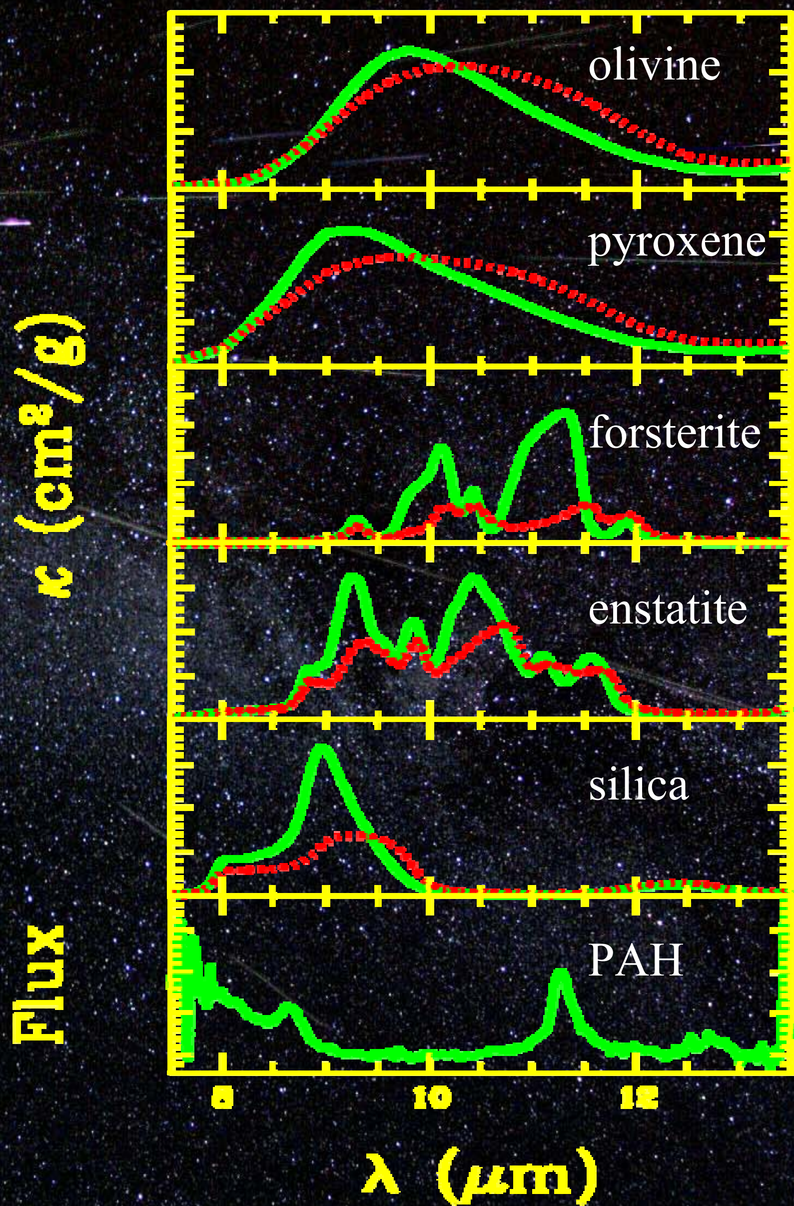
Przygodda et al. 2003, A&A, 412 L43

Spitzer!?

Van Boekel et al. 2003, A&A, 400, L21

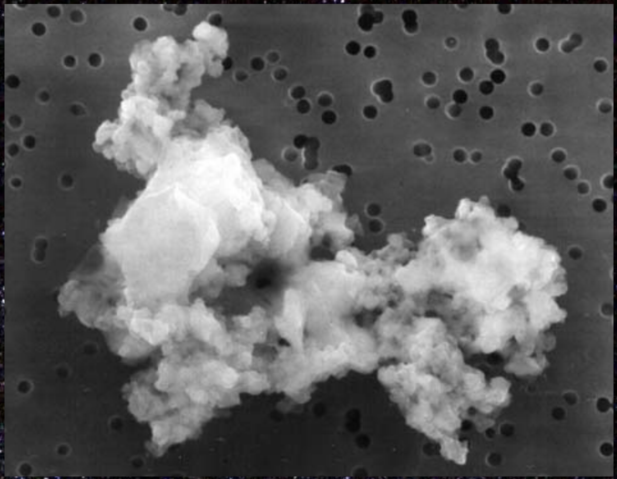
Compositional fits

- Optically thin model
- Olivine, Pyroxene, forsterite, Enstatite, Silica, PAH
- Distribution of hollow spheres (DHS)
- 0.1 µm (“small”) and 1.5 µm (“large”) grains
- Single temperature (Uniform composition)



Distribution of Hollow Spheres (DHS)

(Michiel Min)



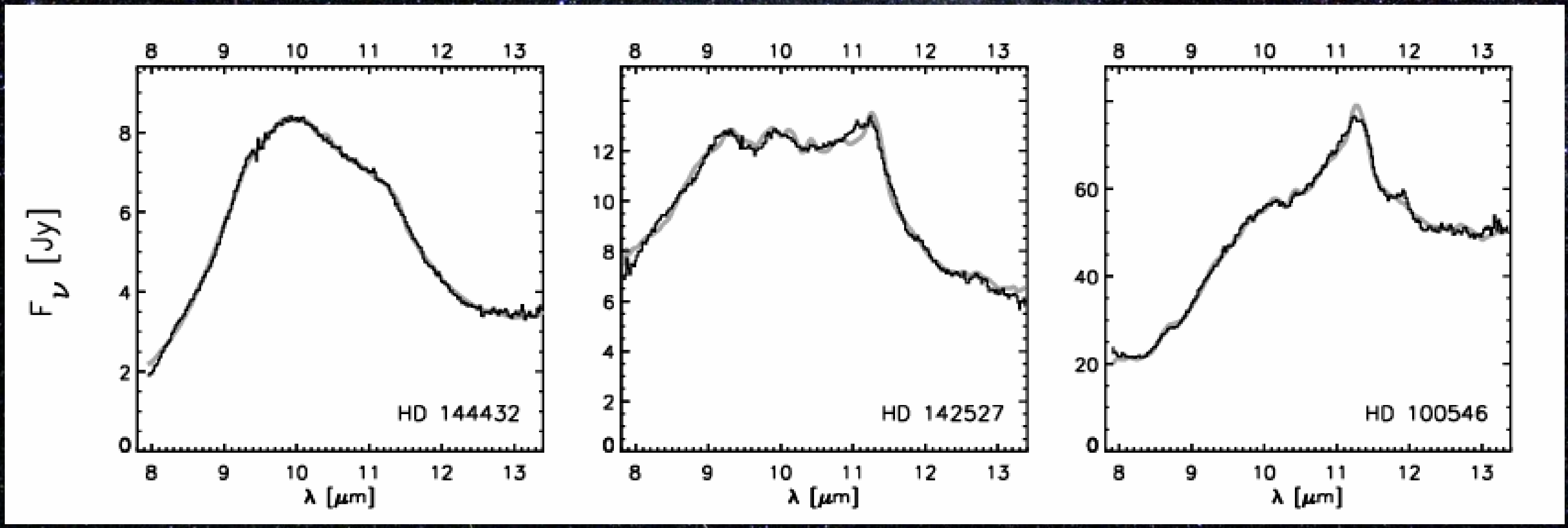
- Spherical grains with central cavity
- Average over the volume fraction occupied by the inner cavity, keeping the mass of the particles constant.
- *Statistical approach to model realistic, irregular dust particles*
- Allows opacities of large grains (outside Rayleigh limit) to be calculated.
- Min, Hovenier & De Koter 2003, A&A, 404, 35
  Min, Hovenier & De Koter 2005, A&A, in press,
  astro-ph/0503068

'Shake the box'

Make a linear least square fit to obtain:

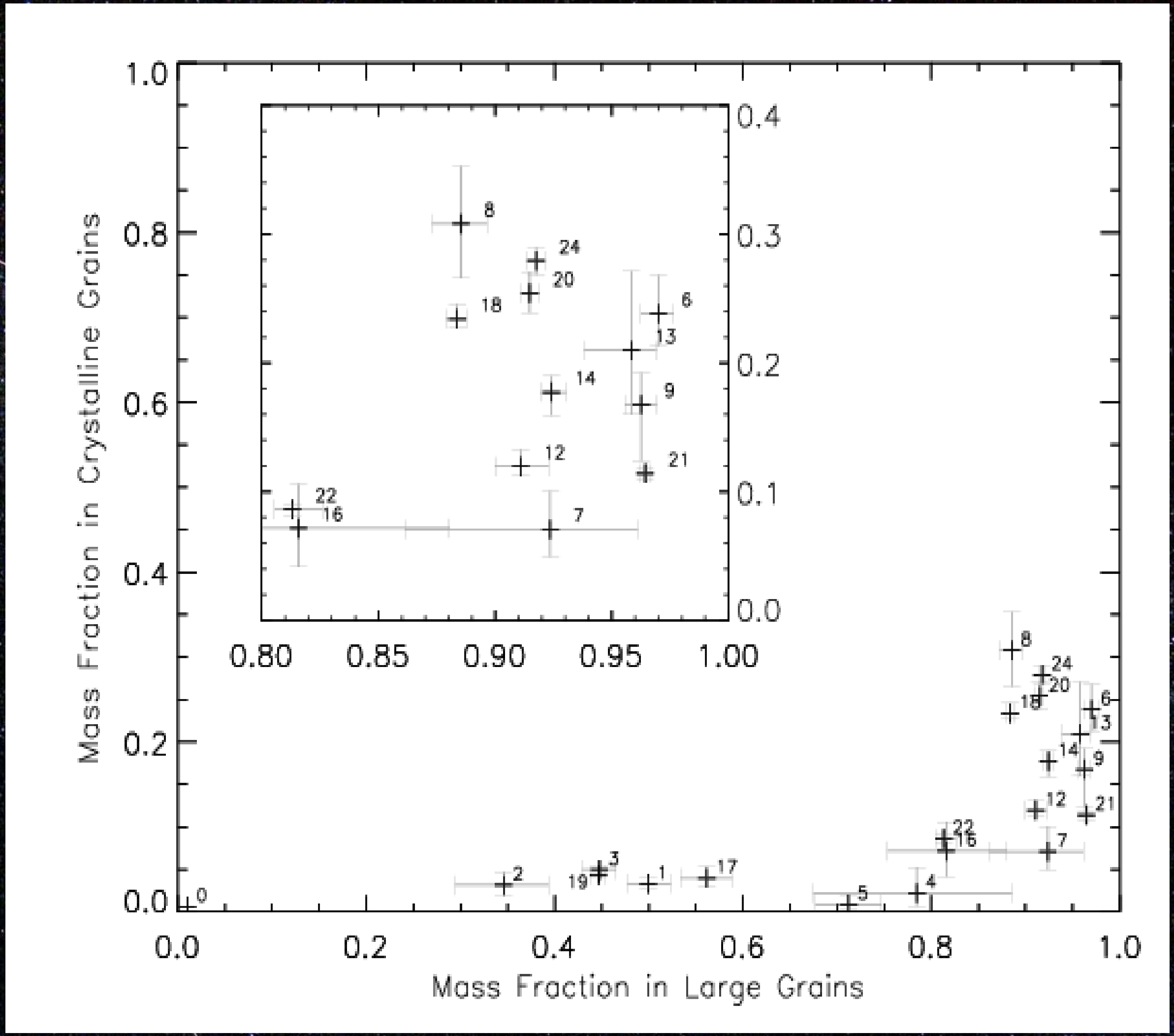
✗ The abundances of all dust species (growth, crystallinity)

✗ The average temperature of the dust grains



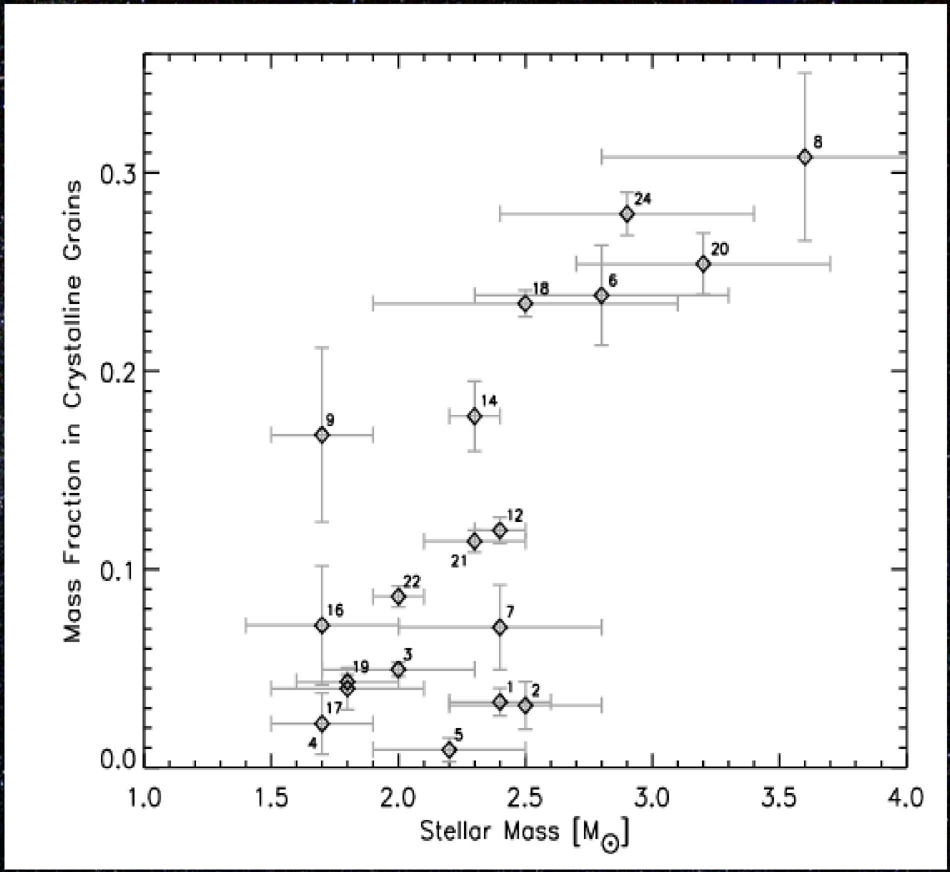
Results (I): growth & crystallization

- All stars have grain growth, most stars dominated by large grains
- *All* highly crystalline sources have much grain growth



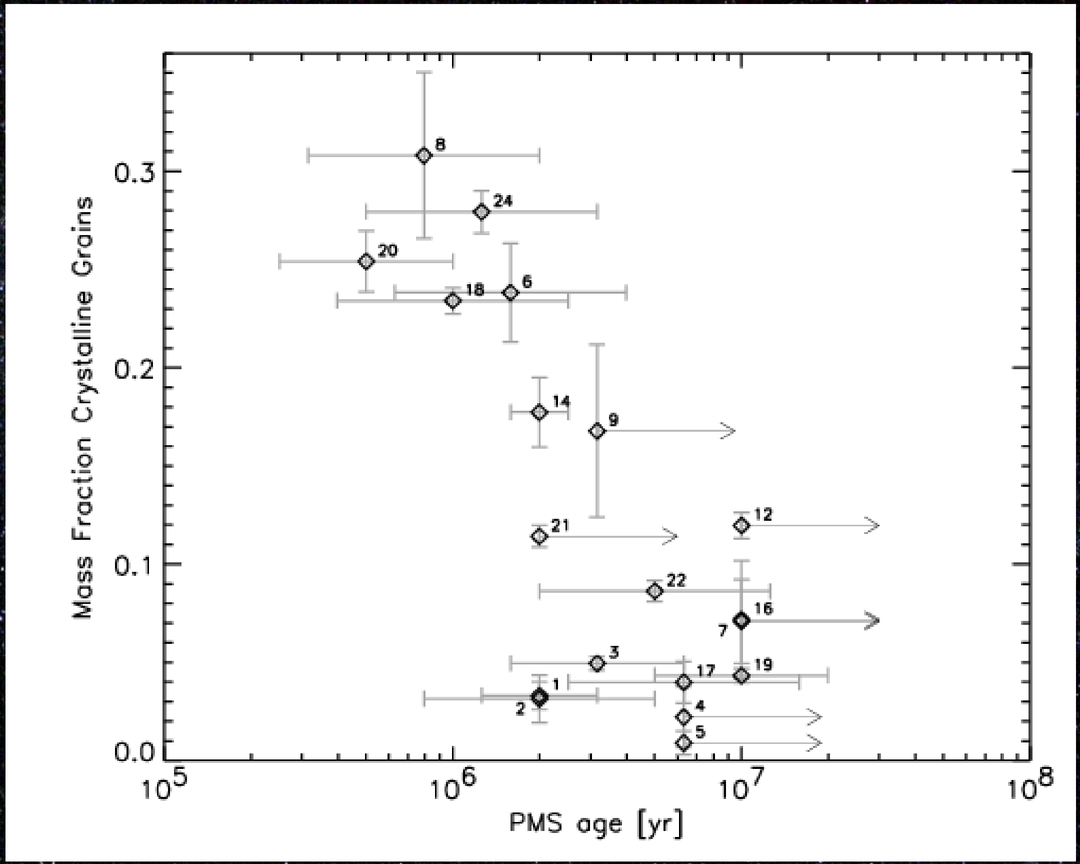
Results (II): crystallization vs stellar mass

- More massive stars ($M>2.5\ M_{\odot}$, $L>60\ L_{\odot}$) show highest crystallinity
- Below $2.5\ M_{\odot}$ ($60\ L_{\odot}$) no relation between mass, crystallinity

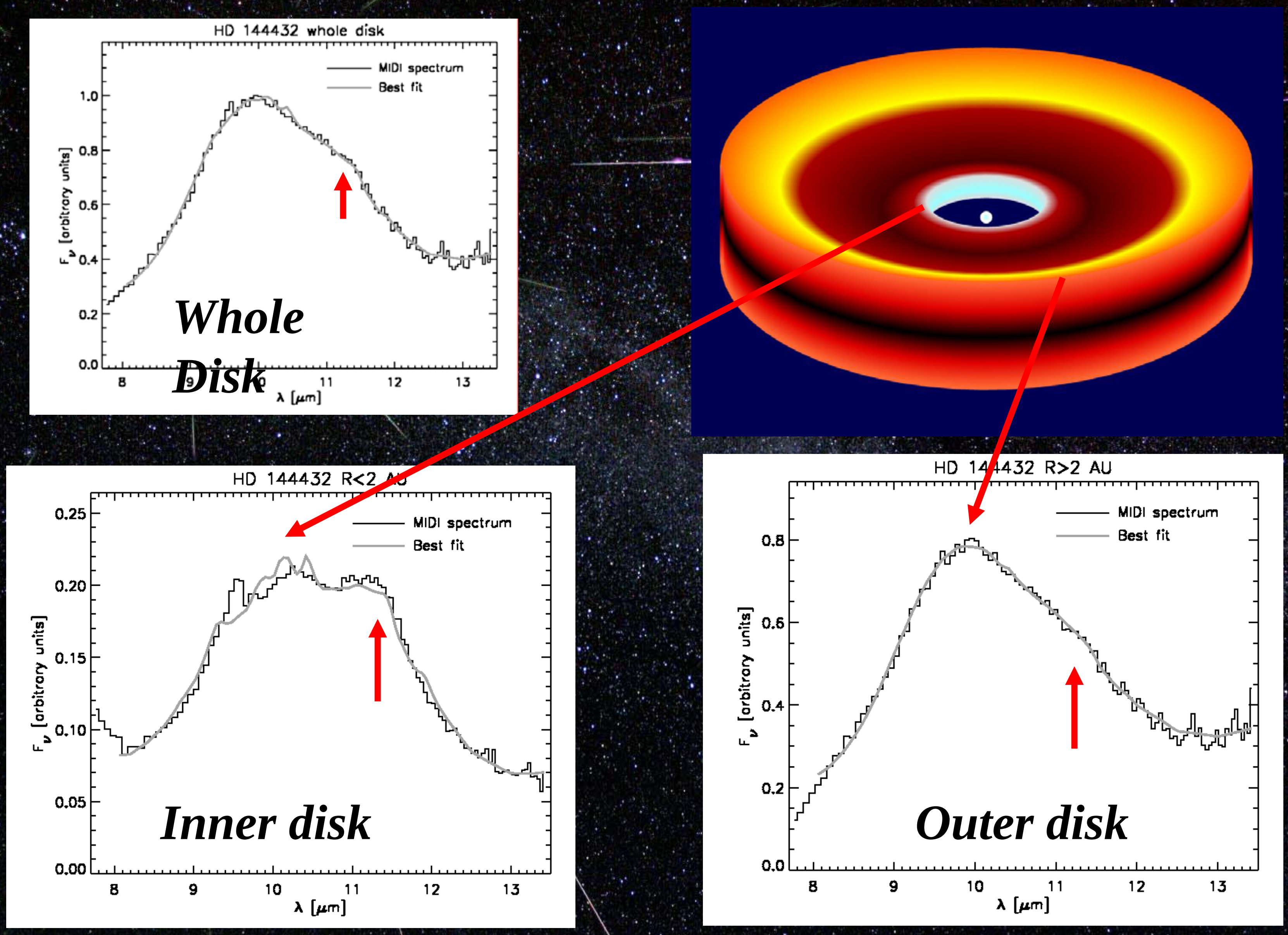


Results (III): crystallization vs PMS age

- Young stars are also most massive (most luminous) ones
- Below 2.5 $M_\odot$ no obvious relation
- Suggests that crystallization happens in early (active?) phase

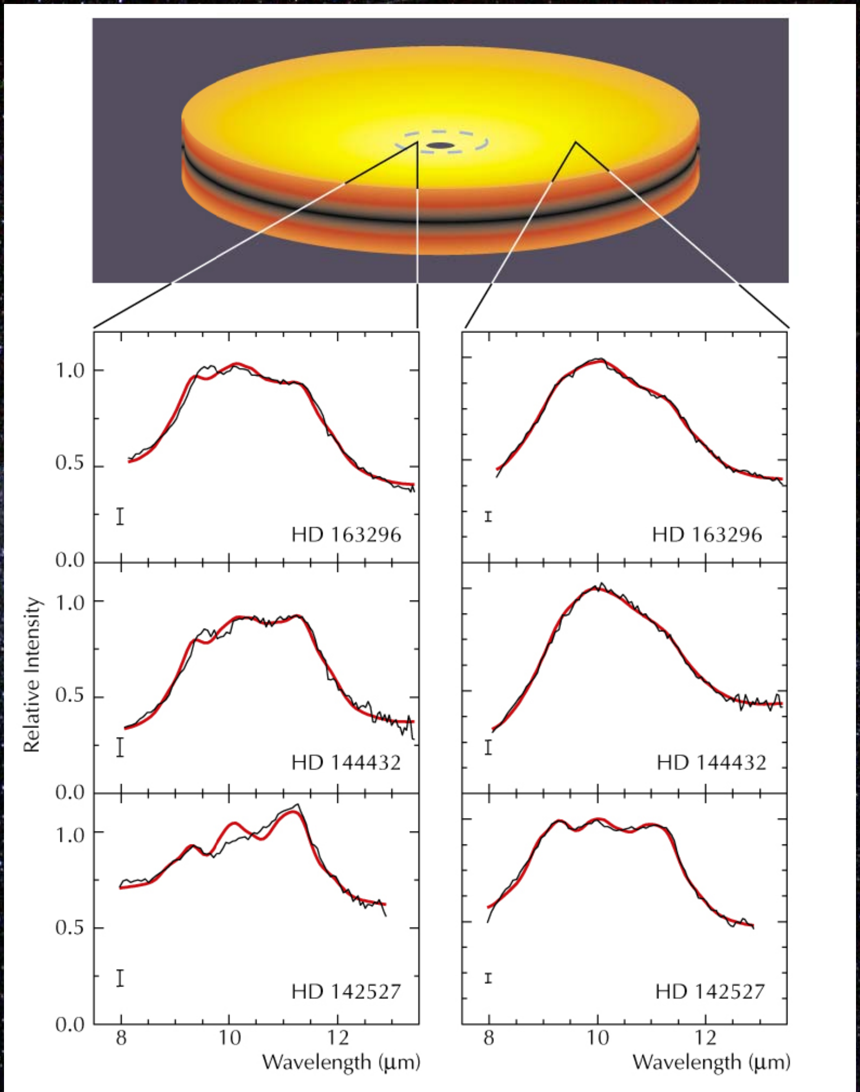


Spatially resolved spectroscopy (MIDI)



Spatial distribution of the dust

- Crystalline grains concentrated in central disk regions
- Outer disks can be "pristine" while inner disks are "evolved".
- In disks with low crystallinity, crystals seem restricted to innermost disk region
- In disks with high crystallinity, crystals are present also further out.
- HD 142527: inner disk mostly forsterite, further out more enstatite

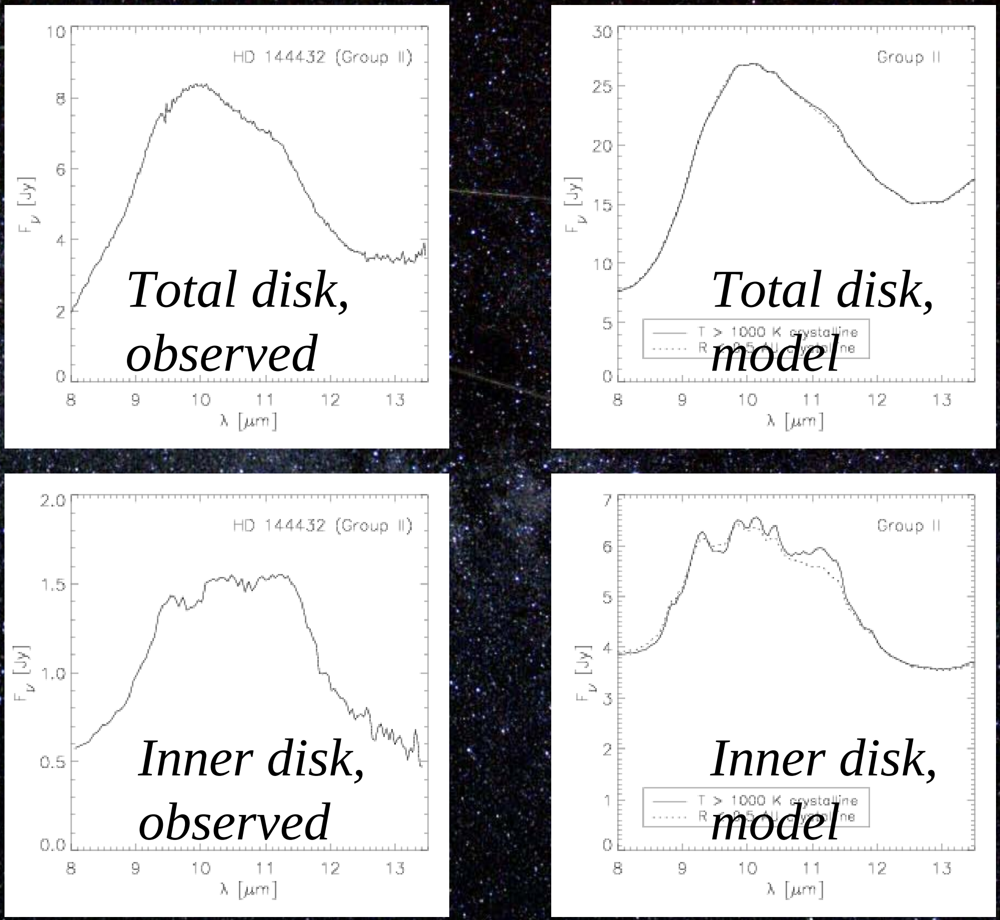


MIDI @ VLTI Nature, **432**, 479

Disk model with non-uniform composition

Joke Meijer

- 2D radiative transfer, self consistent vertical structure
- Mixture of carbon and silicates
- T > 1000 K crystalline, T < 1000 K amorphous, no radial mixing
- For more crystalline disks, include radial mixing
- See poster by Meijer, Dullemond et al.



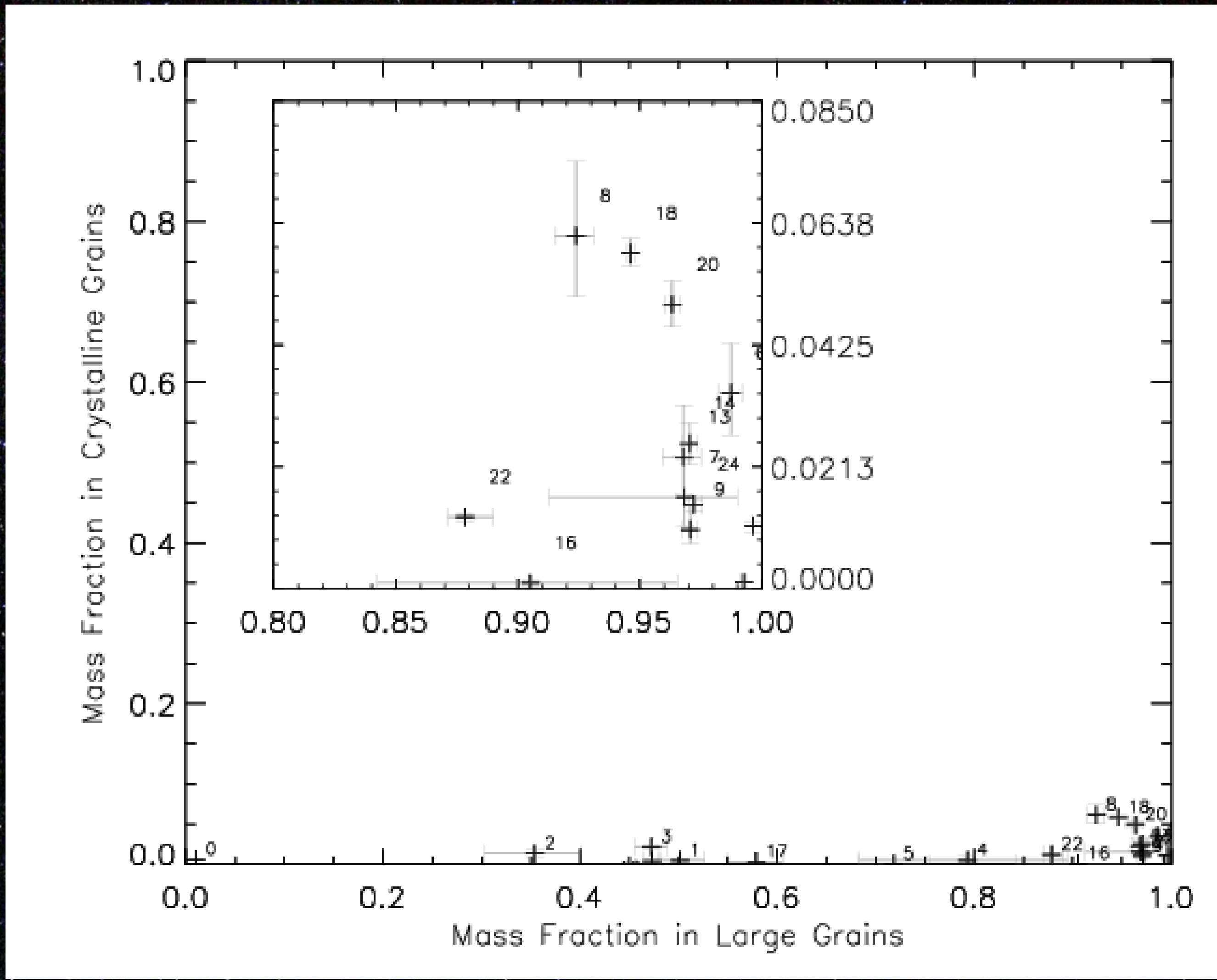
VLTI/MIDI observations of HAe stars

- Inner disks (~1 AU) have:
  - higher fraction of silicates is crystalline (40-100%)
  - larger silicate grains than further out
- more forsterite in inner disk, more enstatite further out in HD142527
- *Consistent* with:
  - Chemical equilibrium processing+ thermal annealing in inner disk
  - Radial mixing to move crystals to larger distance
- What causes large star-to-star differences?

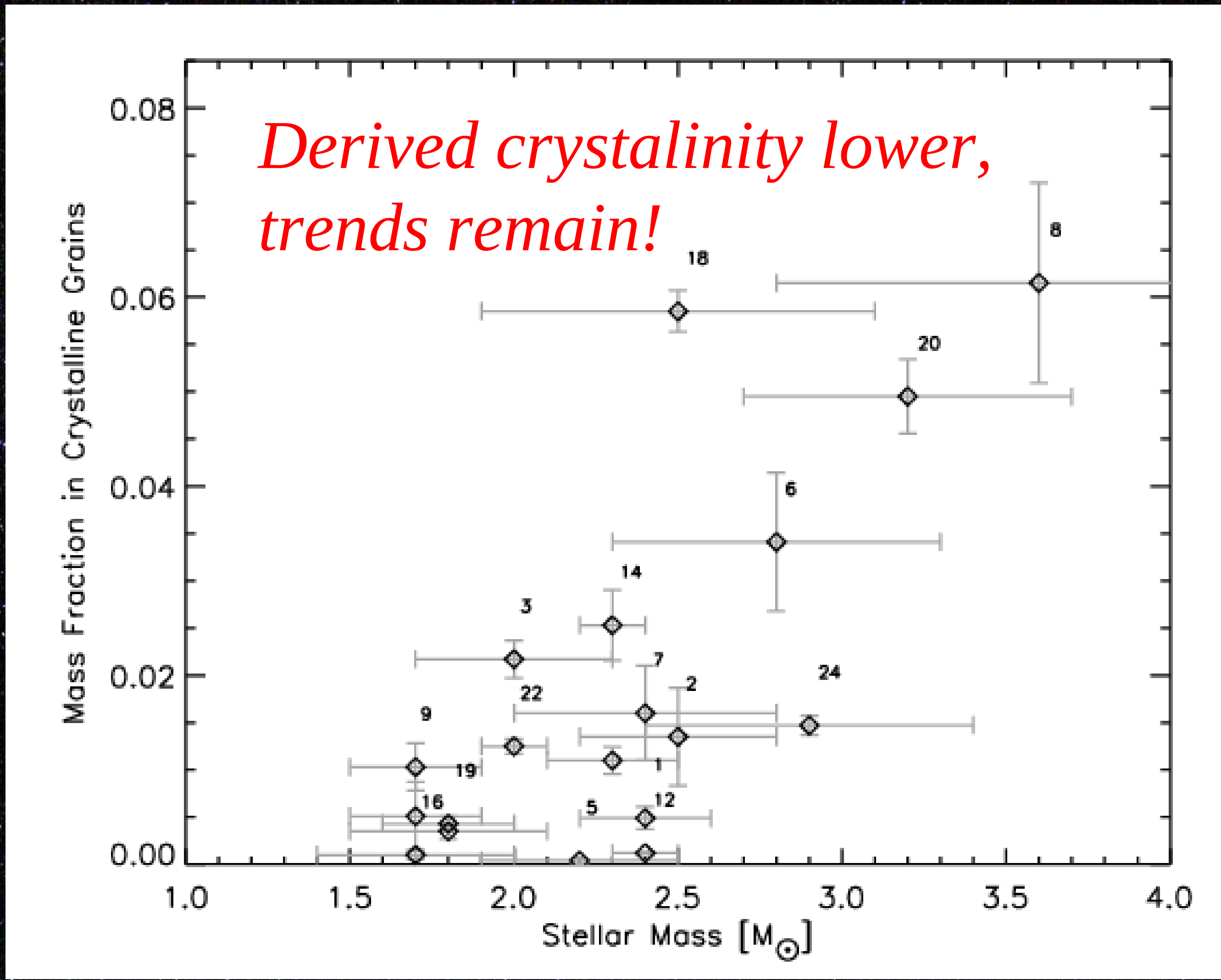
Consequences for spatially unresolved analysis?

- Composition not homogeneous,
- Crystalline silicates hotter than amorphous silicates (more so in low crystallinity sources than in highly crystalline sources)
- Simple test: fit full disk spectra, demand that $T_{crystalline} > 1000$ K
- See if trends remain

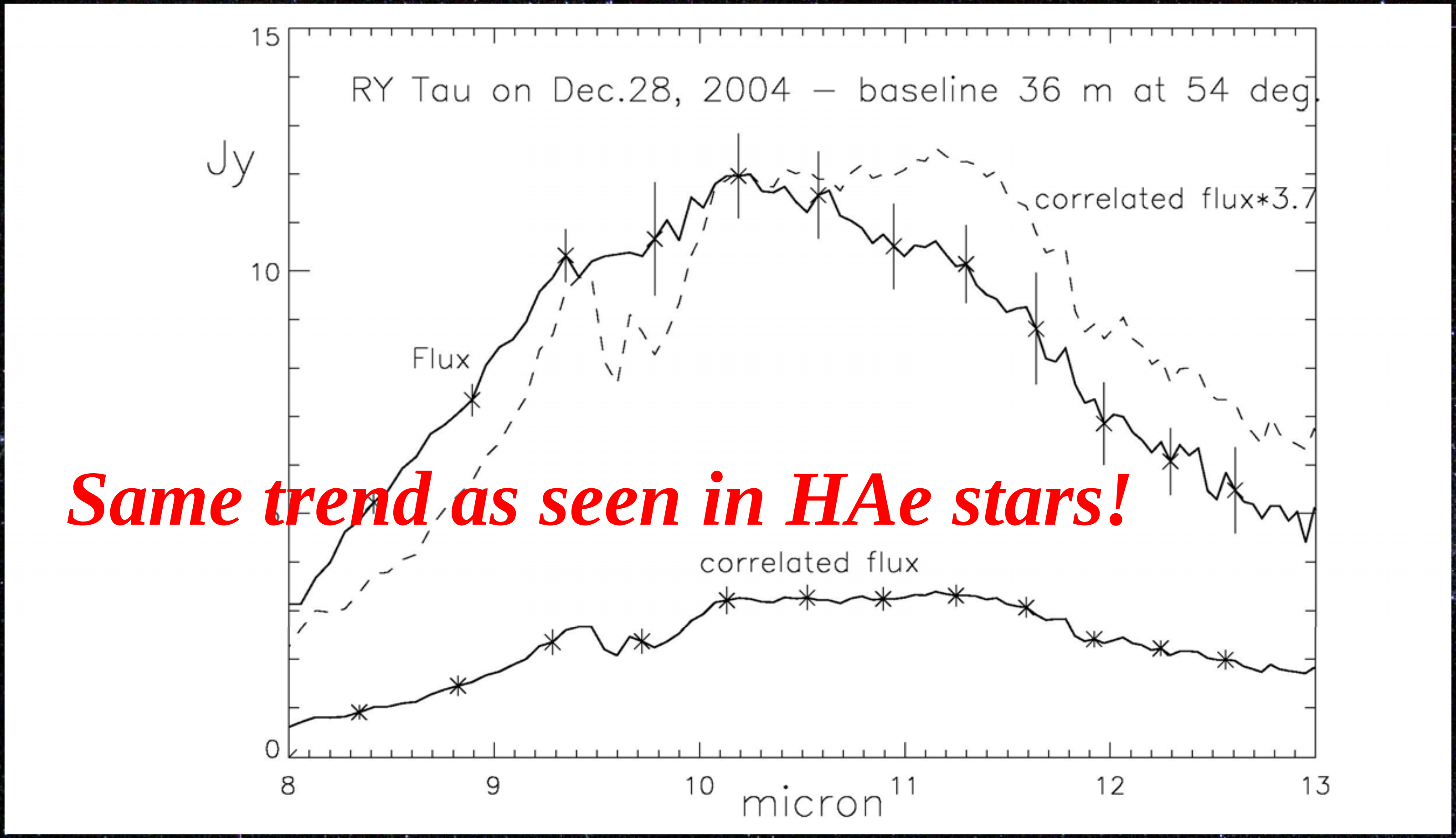
growth & crystallization, $T_{crystalline}$ > 1000 K



Crystallization vs M_*, $T_{crystalline}$ > 1000 K



MIDI observations of T Tau stars



Same trend as seen in HAe stars!

Leinert

Conclusions

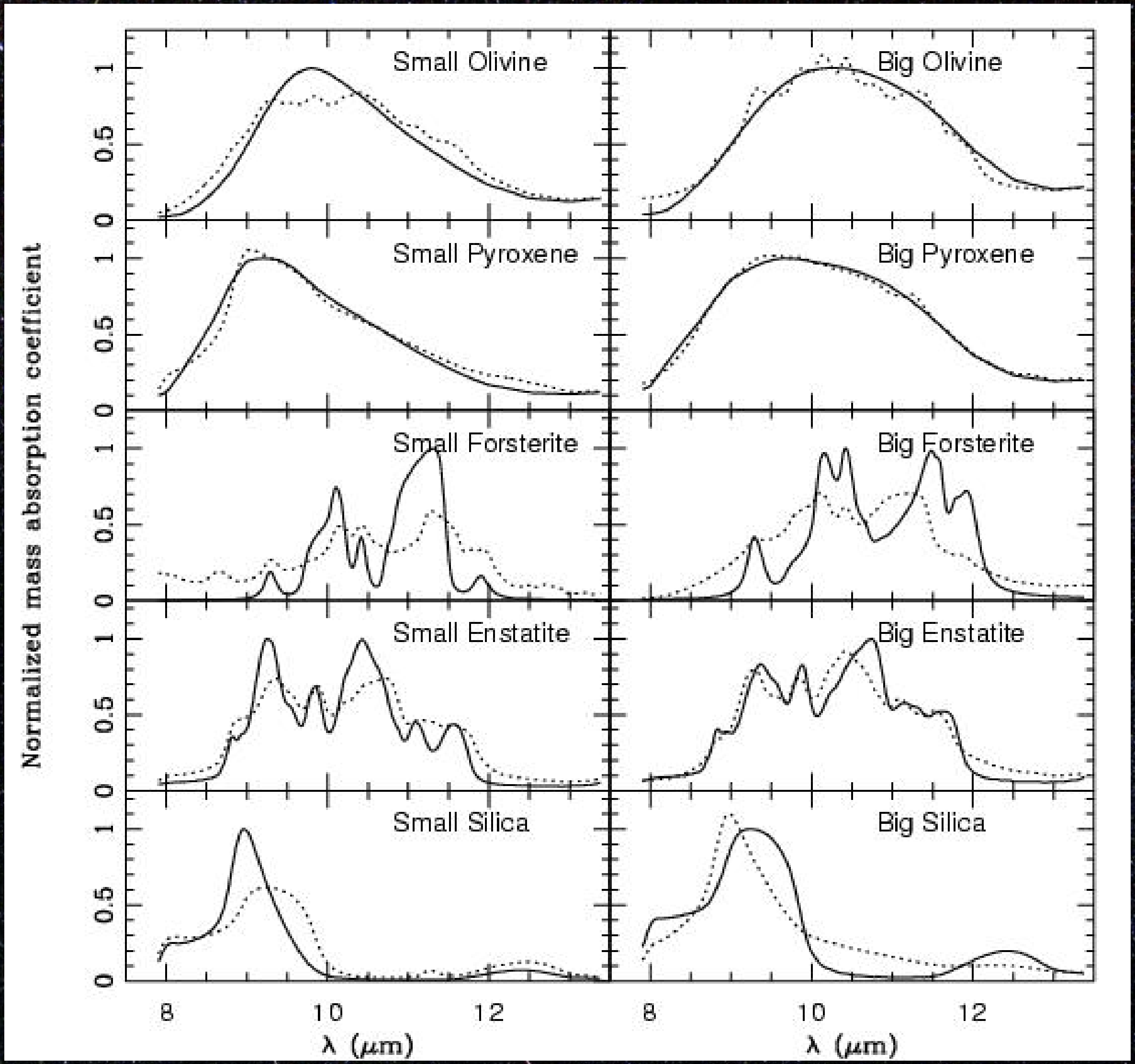
- Current generation of disk models yields qualitative agreement with spatially resolved thermal IR emission
- Need for detailed fitting of individual sources, multiple baselines
- Refinement/reconsideration of disk models

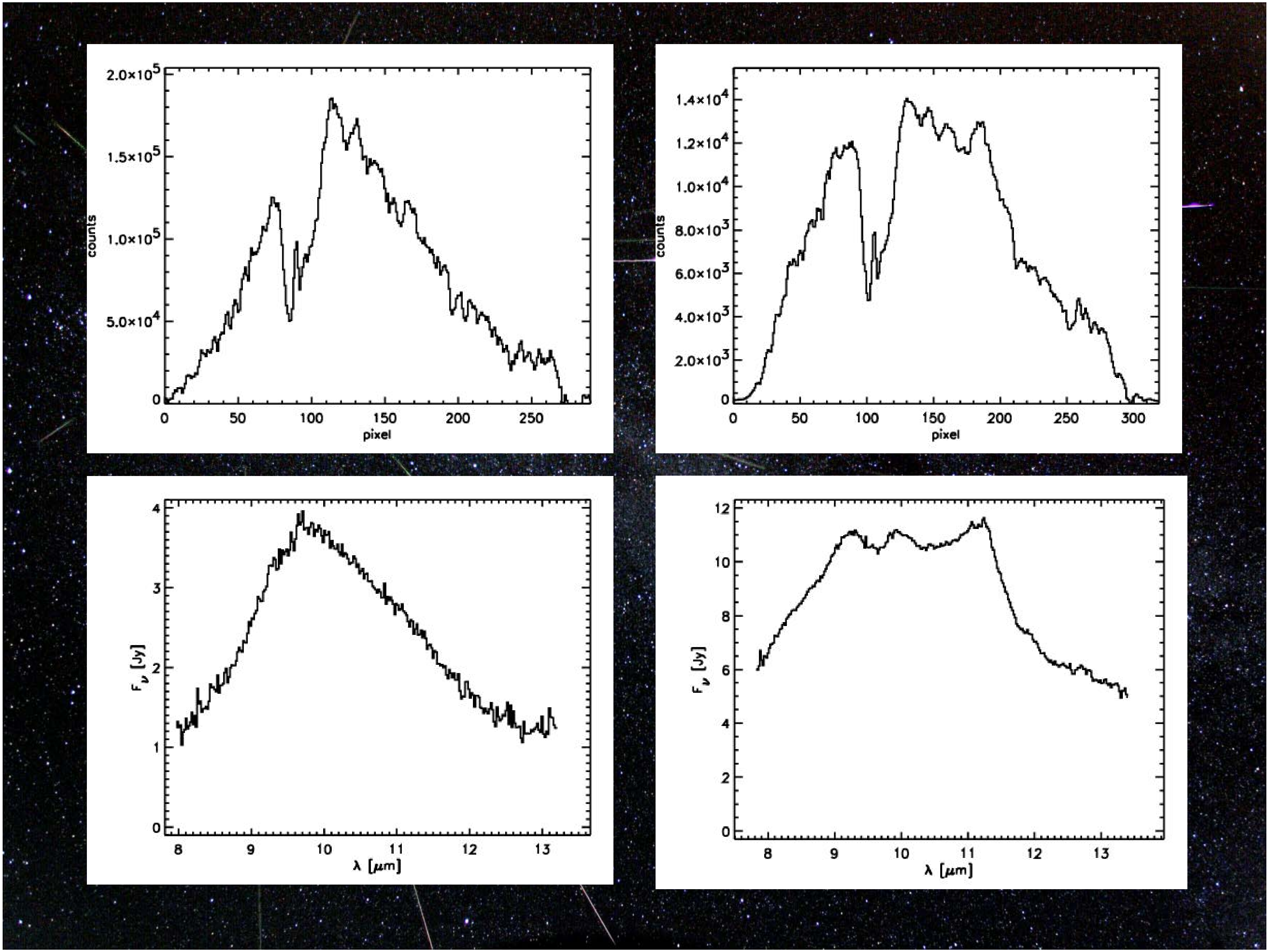
- Growth is “easy”, happens “everywhere” (< 10-20 AU)
- Crystallization in innermost disk regions, subsequent radial transport outward, efficiency varies
- Crystallization (radial mixing) happens predominantly in active or early passive disk phase.

Would you like to compare?

- To obtain “DHS” opacities, please send a request to Michiel Min (mmin@science.uva.nl)
- Min, Hovenier & De Koter 2005, A&A, in press,
  astro-ph/0503068

Degeneracies





counts
pixel
counts
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F_ν [Jy]
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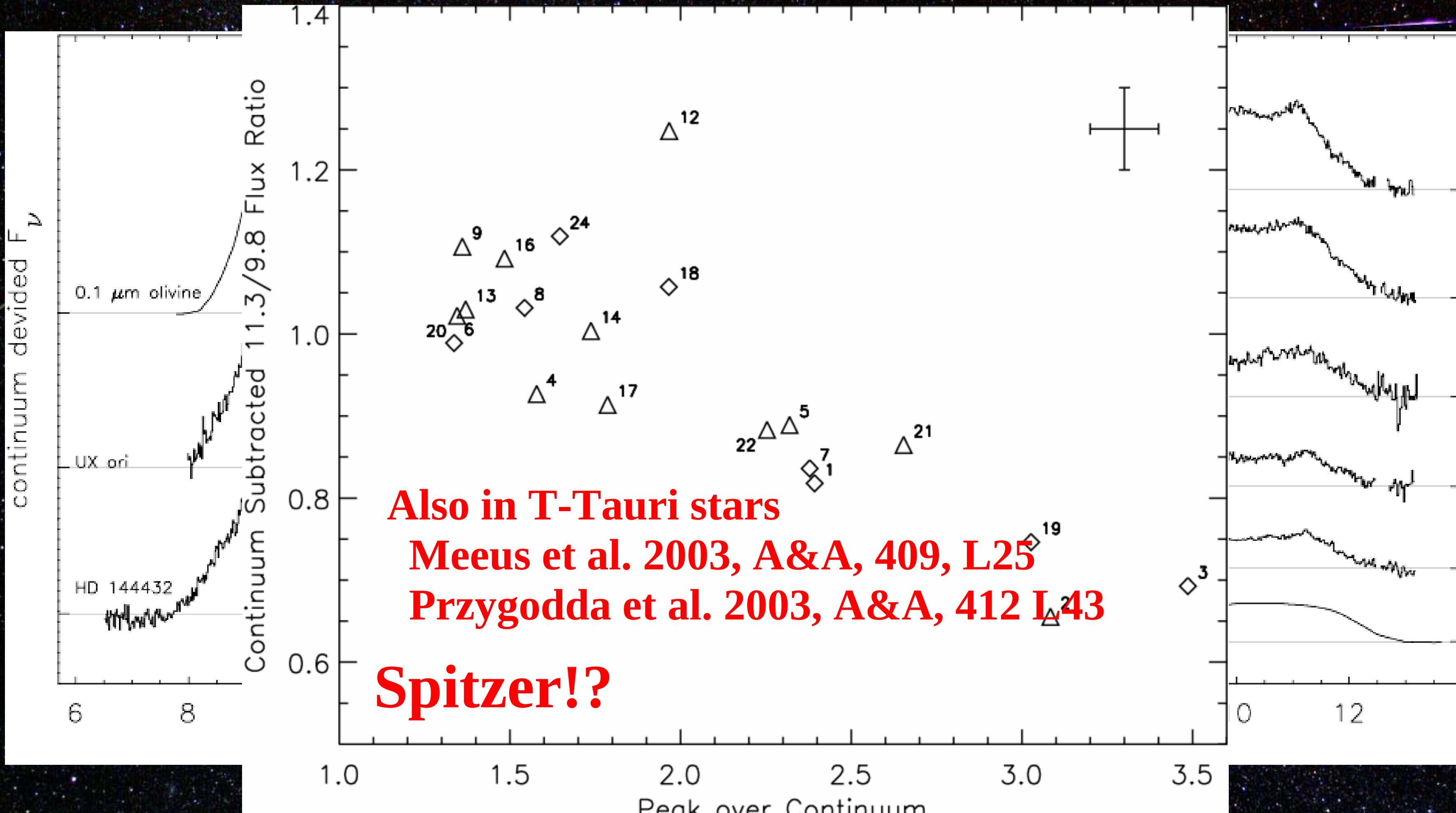
F_ν [Jy]
λ [μm]

Shape vs. strength of silicate feature



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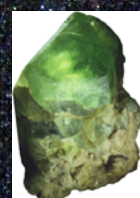
Dust species

Amorphous Olivine

Amorphous Pyroxene

Crystalline Forsterite



Crystalline Enstatite

Silica

PAH