Proto−planetary disks

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Collaborators

MIDI team (especially Christoph Leinert, Olivier Chesneau, Frank Przygodda, Walter Jaffe, Thomas Henning, Anne Dutrey), ESO VLTI team, Roy van Boekel, Michiel Min, Carsten Dominik, Kees Dullemond, Alex de Koter, Mario van den Ancker

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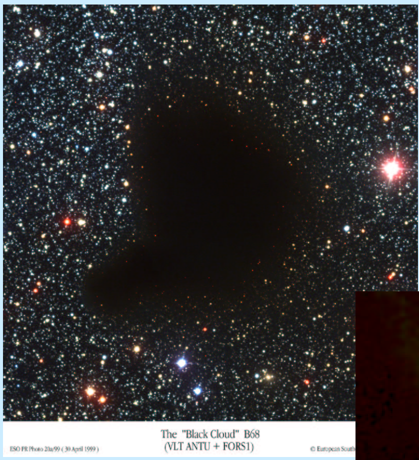
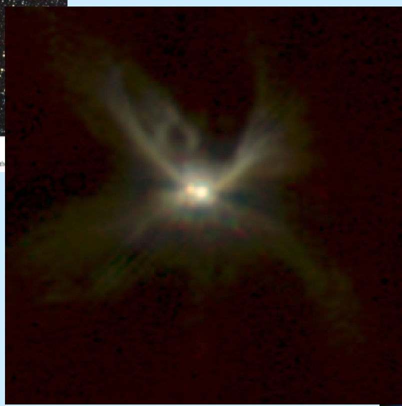
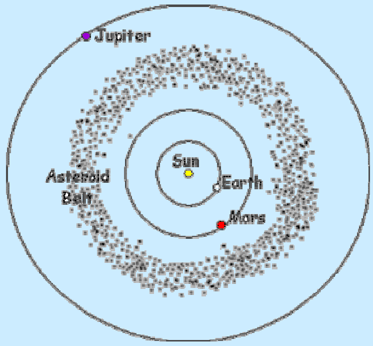
Outline of presentation

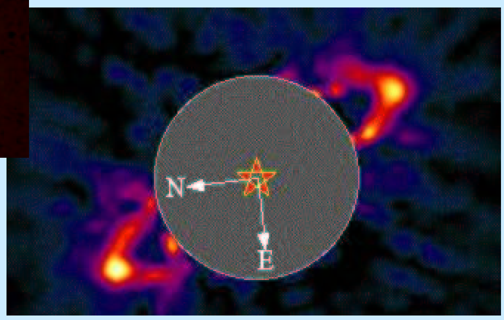
- Introduction, star and planet formation
- Mid−IR diagnostics
- Geometry of disks
- Mineralogy of disks
- Conclusions

Star Formation



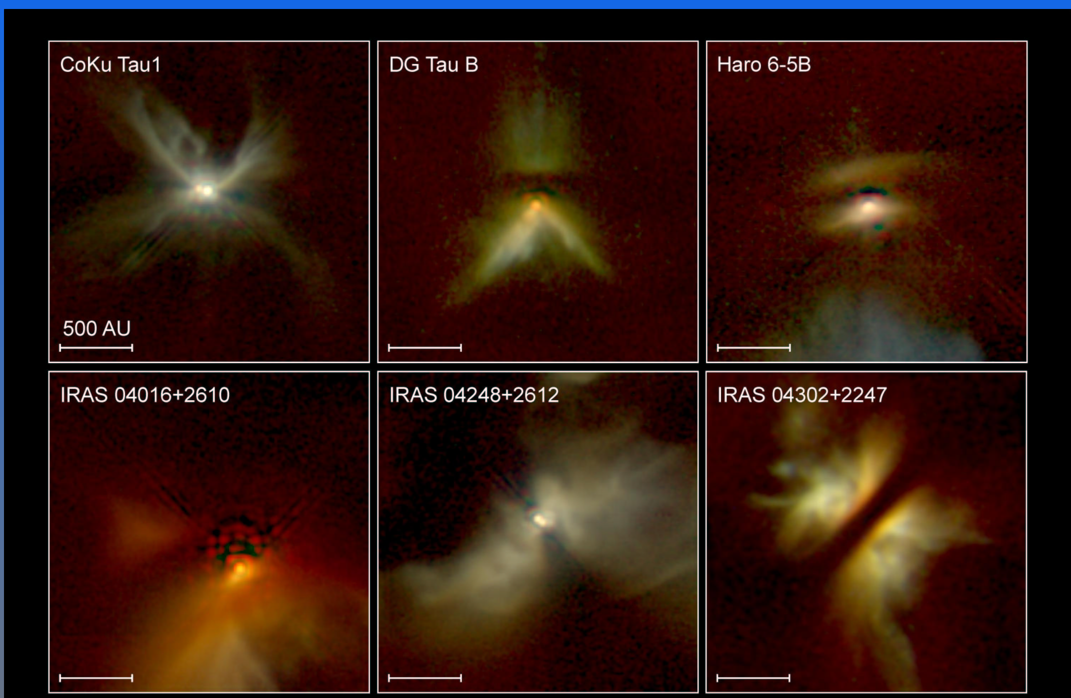




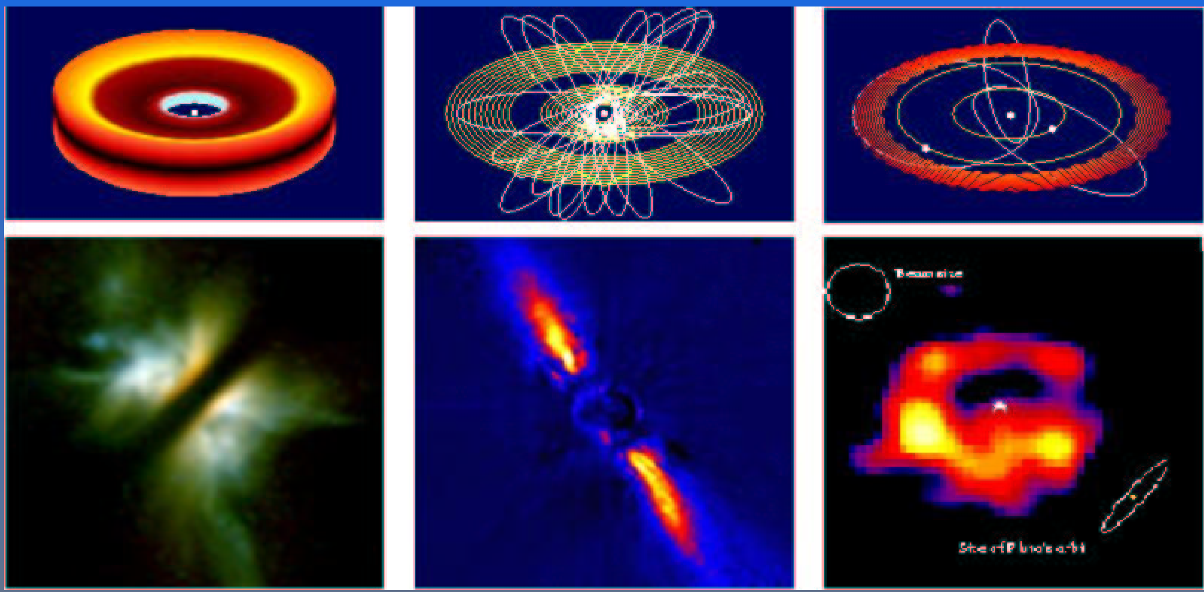


Cloud collapse and star formation

Images of proto−planetary disks



Evolution of proto−planetary disks



Proto−planetary disks

- Dust: building blocks of rocky planets
- Dust particles T = 1500 …. 40 K
- Dust emits thermal infrared radiation
- Spectral structure can be related to chemical composition of dust
- Composition of gas, dust best studied at long wavelengths

Planet formation

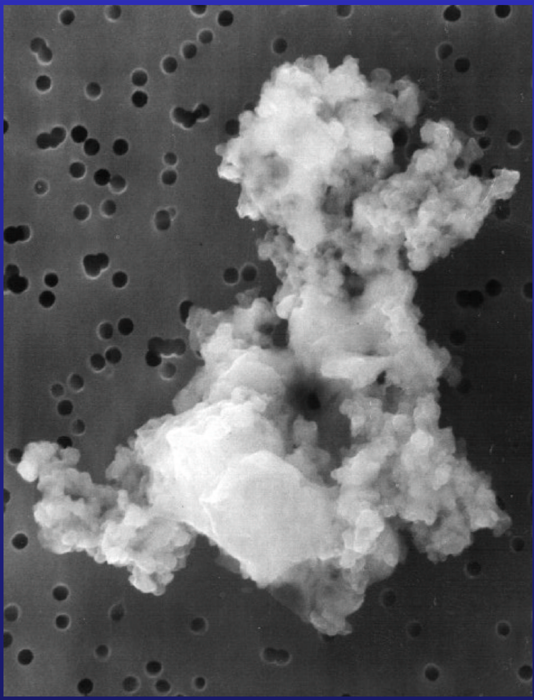
- Dust originates from interstellar space
- Properties of dust change in disk:
  - grain growth
  - heating and chemical processing
- Compare dust properties from interstellar space to dust in proto−planetary disks

Proto−planetary disks

- What is gas and dust composition of disks?
- How does composition evolve with time?
- What is the geometry of the disk?
- Can we observe planet formation?
- How does planet formation depend on stellar mass?

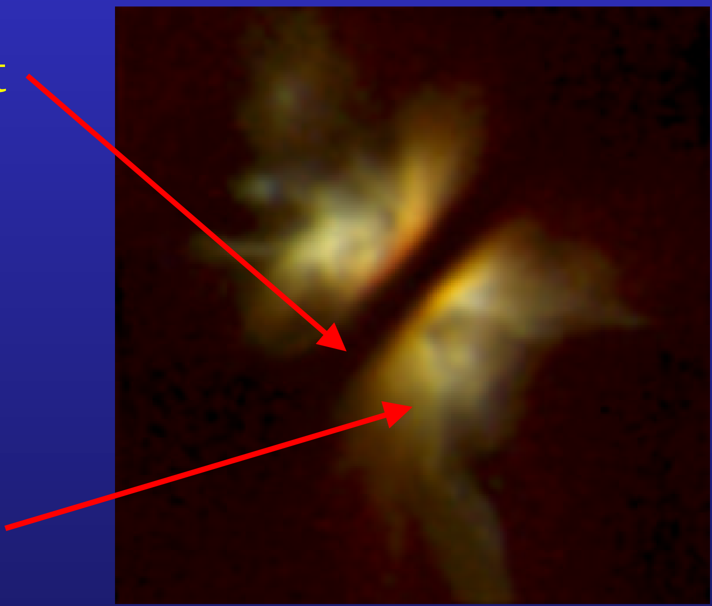
Dust growth: planet formation

- Gas−rich disk: small relative velocities of grains
- Grains stick
- Slowly size grows
- Eventually gravitational growth

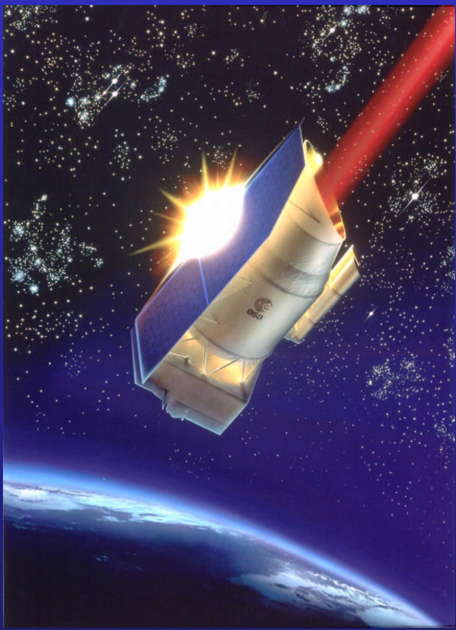


Dust

- Absorbes light → heats up, thermal IR emission
- Scatters light → bright halo in optical



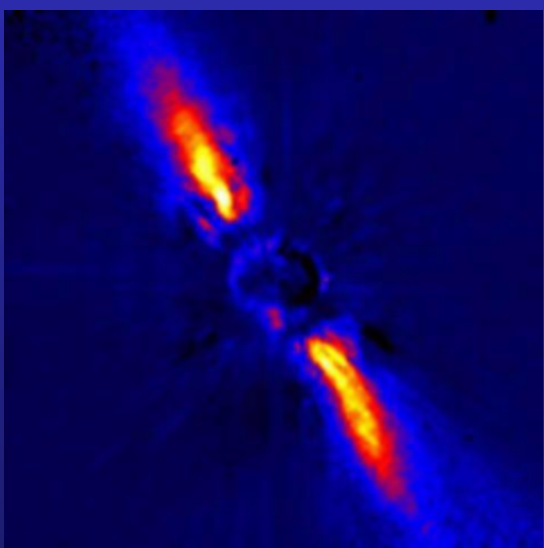
Study of dust disks



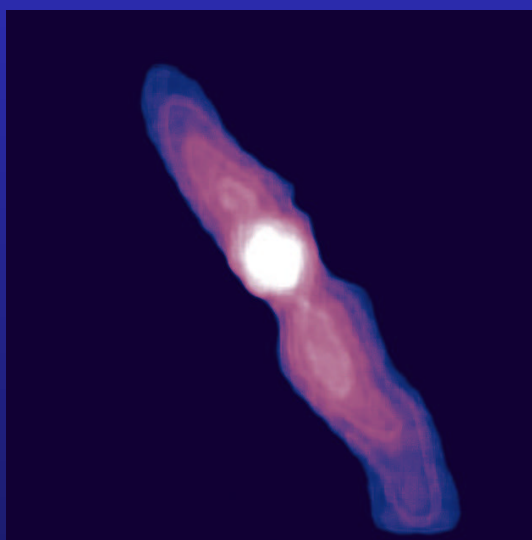
Infrared Space Observatory

Very Large Telescope Interferometer

Beta Pictoris



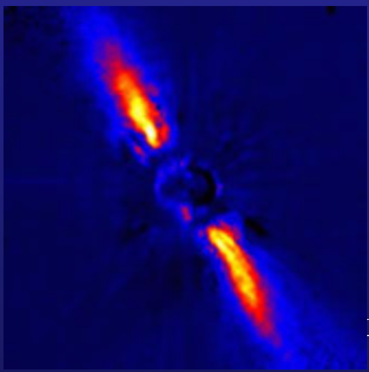
Near−IR: scattered light

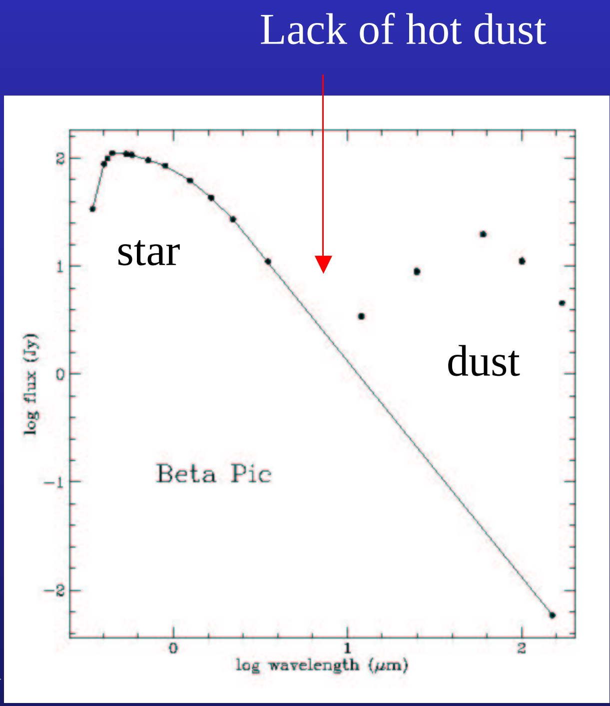


Mid−IR: thermal emission

Disk Gaps: planets?

- Planets clear orbit
- dust removed
- Lack of emission in part of IR spectrum



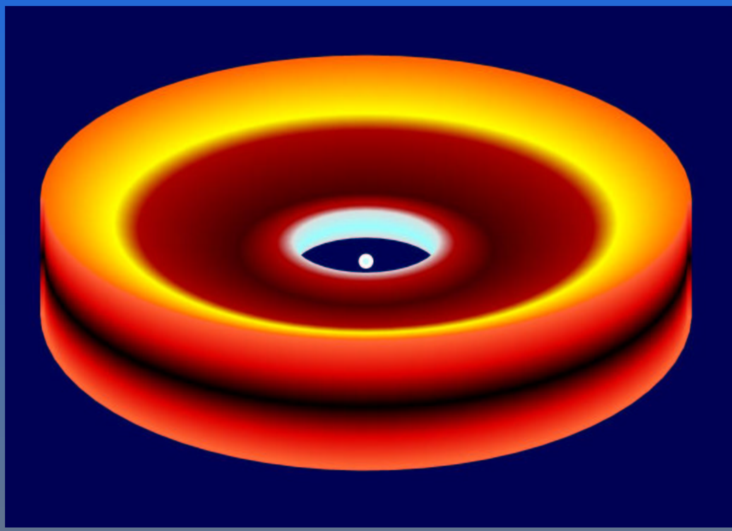


Herbig Ae/Be Stars (HAEBEs)

- Intermediate mass pre−main sequence stars
- Surrounded by remnant accretion disk
- Concentrate on late Be, Ae stars:
  - Point sources (< 1.0 arcsec) at 10 micron
  - mid−IR emission likely from disk only
- Disk mass typically 0.001−0.1 Msun (from millimeter photometry and imaging)

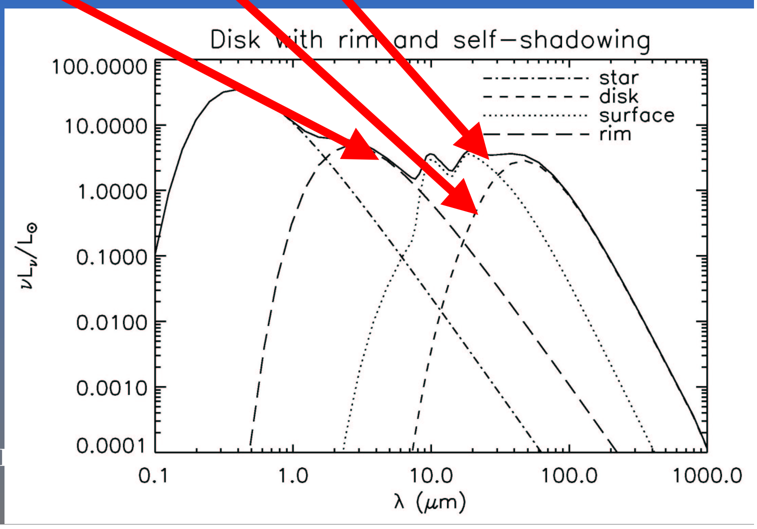
Flaring disk around 2 solar mass star

- Inner wall is “puffed−up”
- Causes additional near−IR radiation
- Shaded region



Dullemond, Dominik and Natta

Passively heated disks

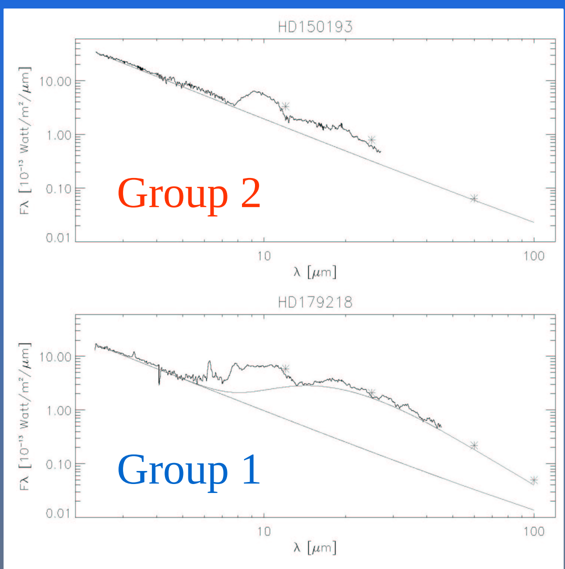


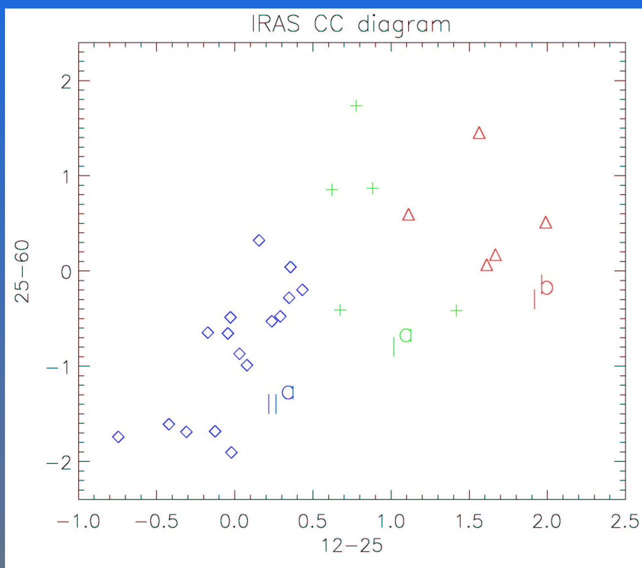
Dullemond, Dominik and Natta (2001 ApJ)

DDN model fits SEDs

Dullemond et al. 2001

Division into two groups: flaring versus flat disks?

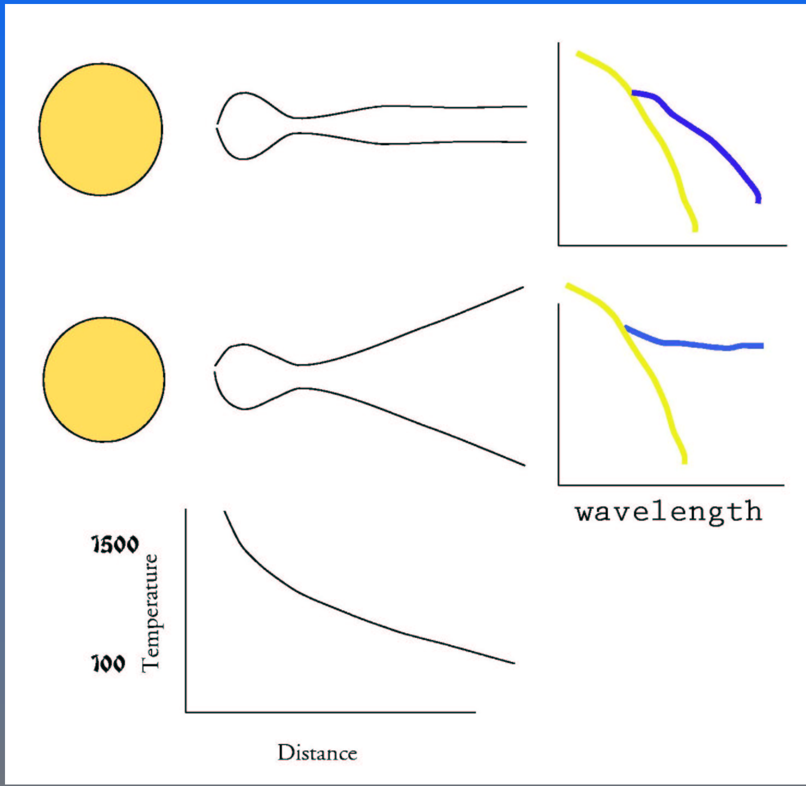




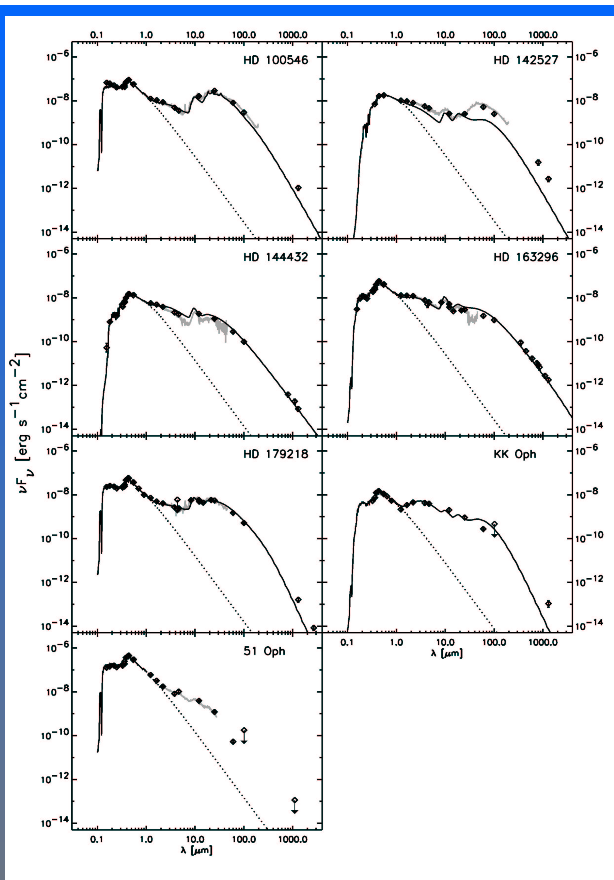
Geometry of protoplanetary disks

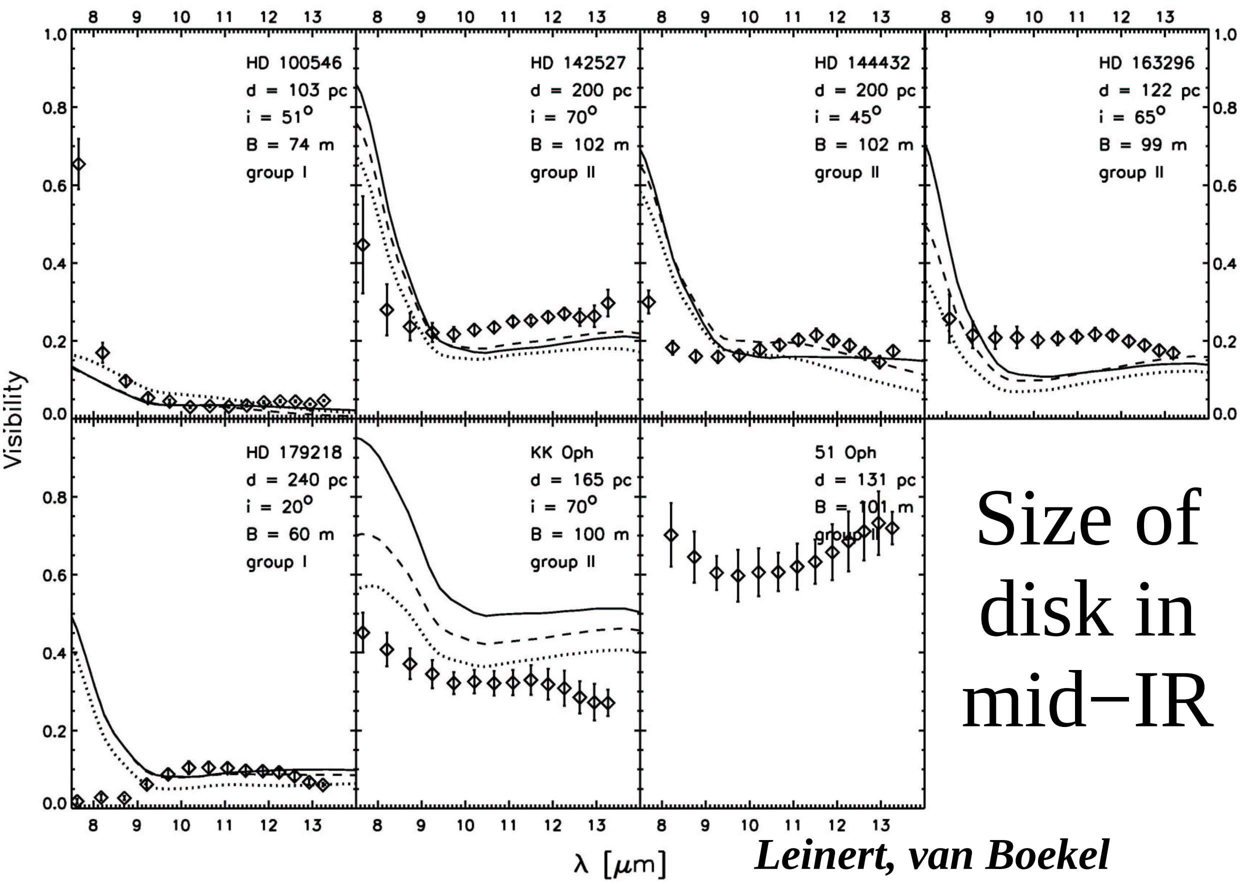
- Flaring or flat disks
- Flat disks are self−shadowed
- Evolutionary link?

Dullemond (2002)



Observed spectra and disk model fits

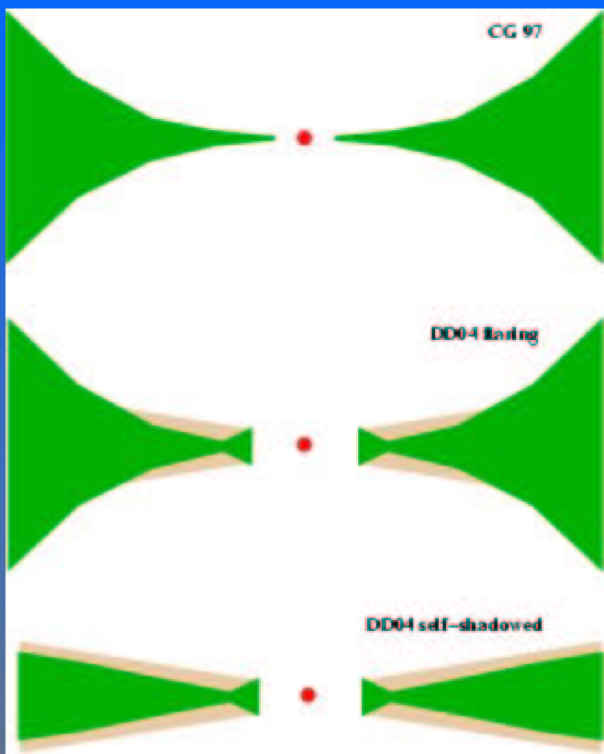




Size of disk in mid−IR

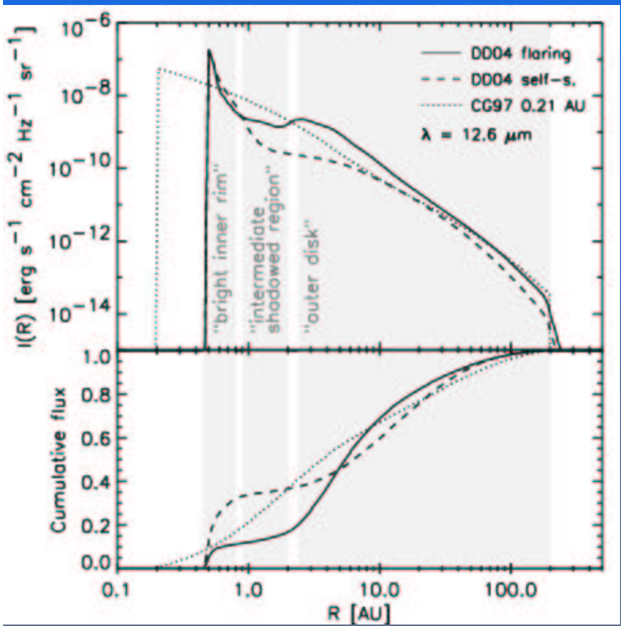
Leinert, van Boekel

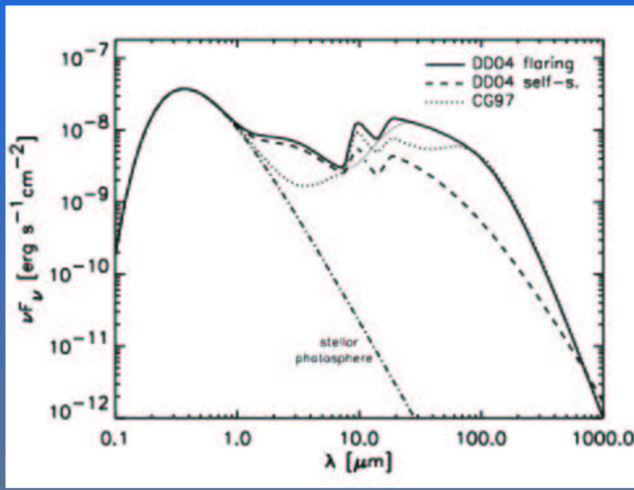
Different disk geometries



Van Boekel, Dullemond, Dominik

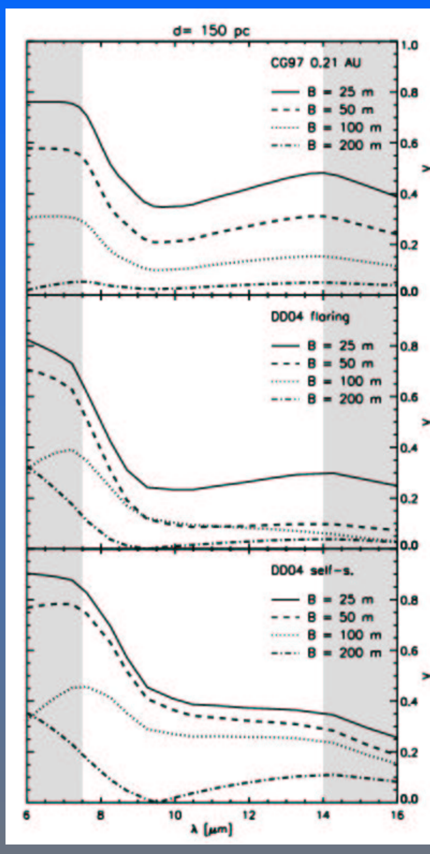
Intensity distribution and spectrum



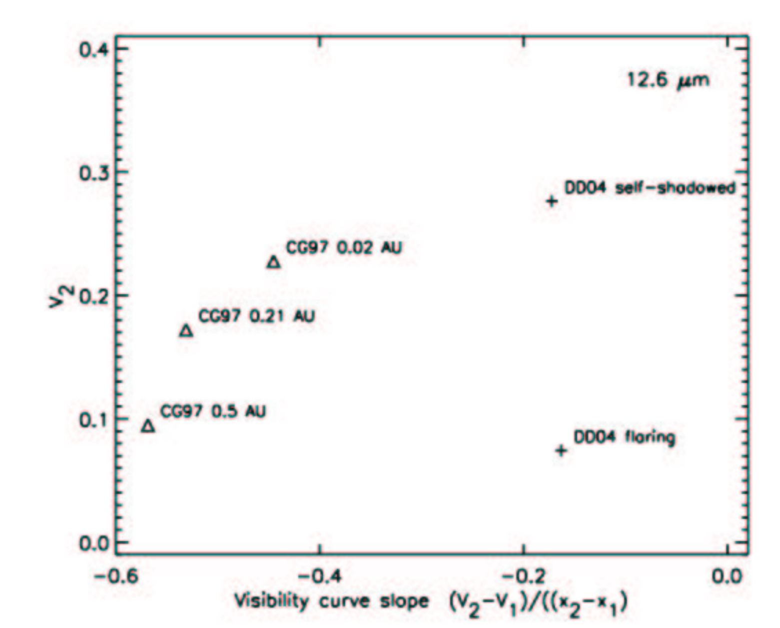


Visibilities for different disk geometries

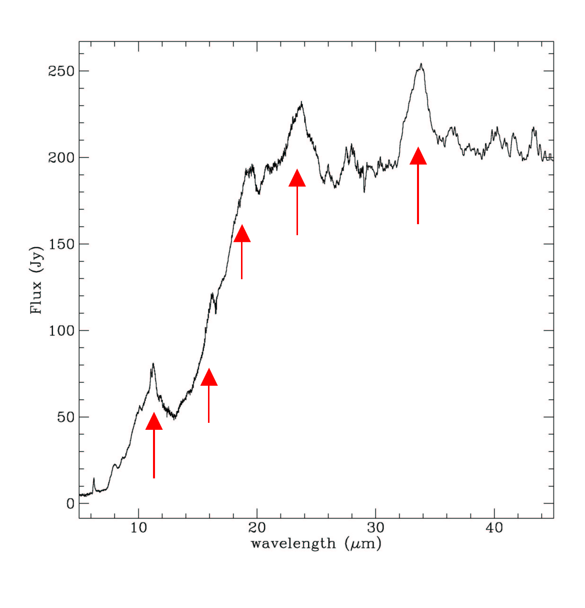
Van Boekel et al



Distinguishing between models



HD 100546: a young star with *crystalline* silicates!



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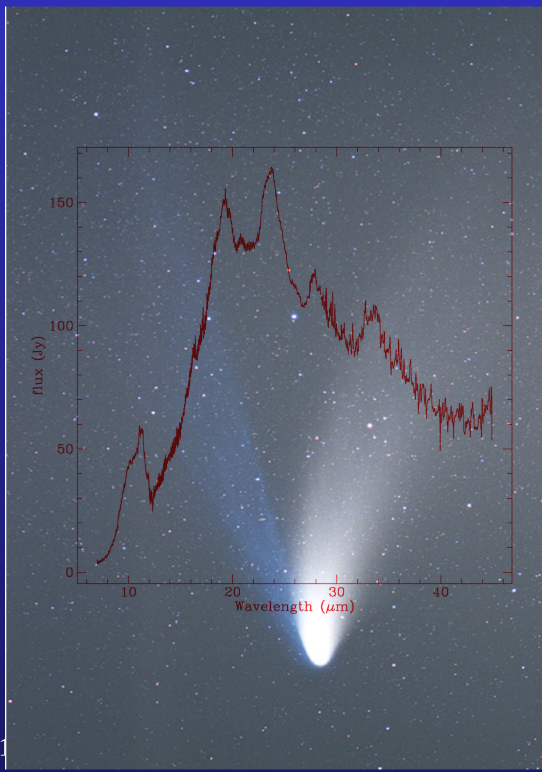
Comet Hale−Bopp

- Highly crystalline silicates
- Formed in proto−solar cloud
- Strong mixing in proto−solar disk!

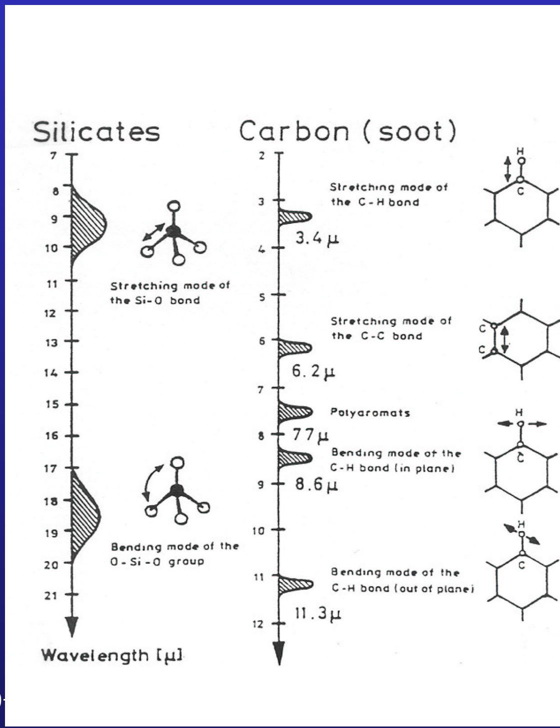


Crystalline silicates in young stars

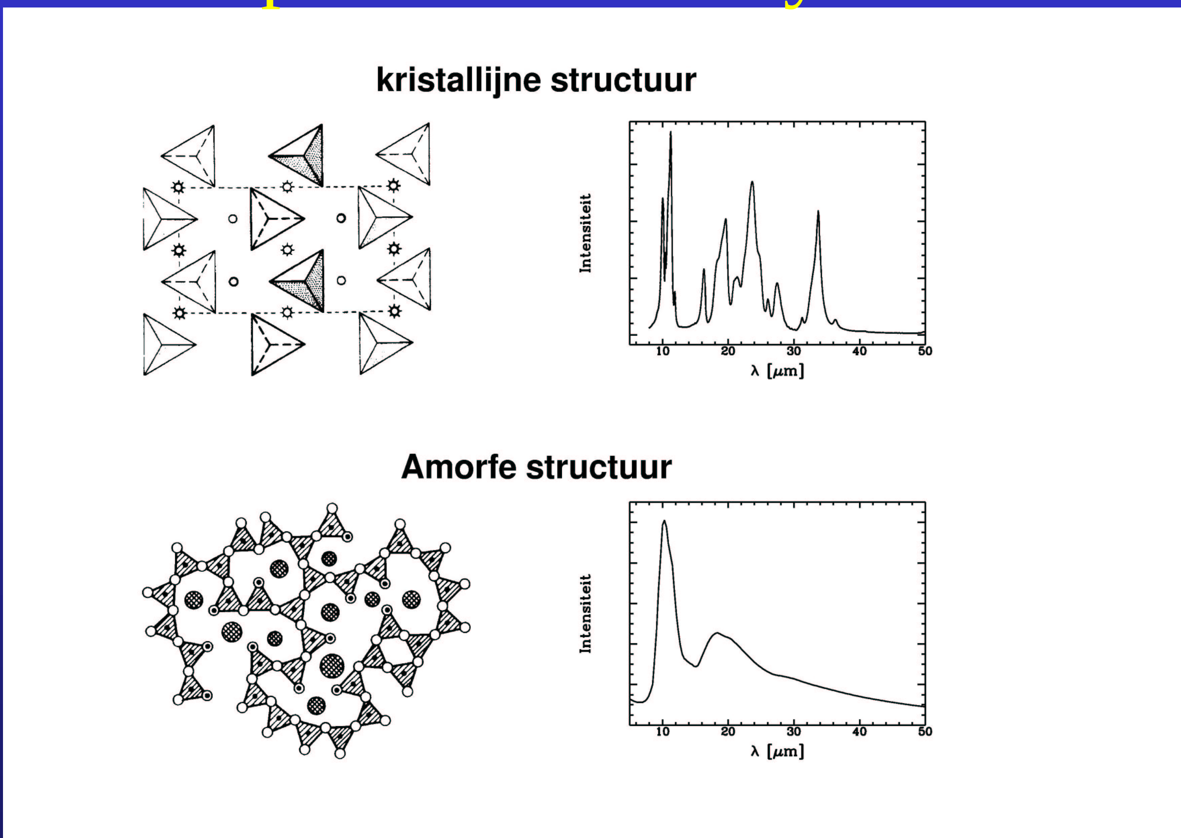
- Insterstellar space: silicates are amorphous
- Crystallisation in proto−planetary disk!
- Heating of amorphous silicates to T=1000K may crystallise grains
- Lots of *cold crystals:* mixing...

Solid state emission bands

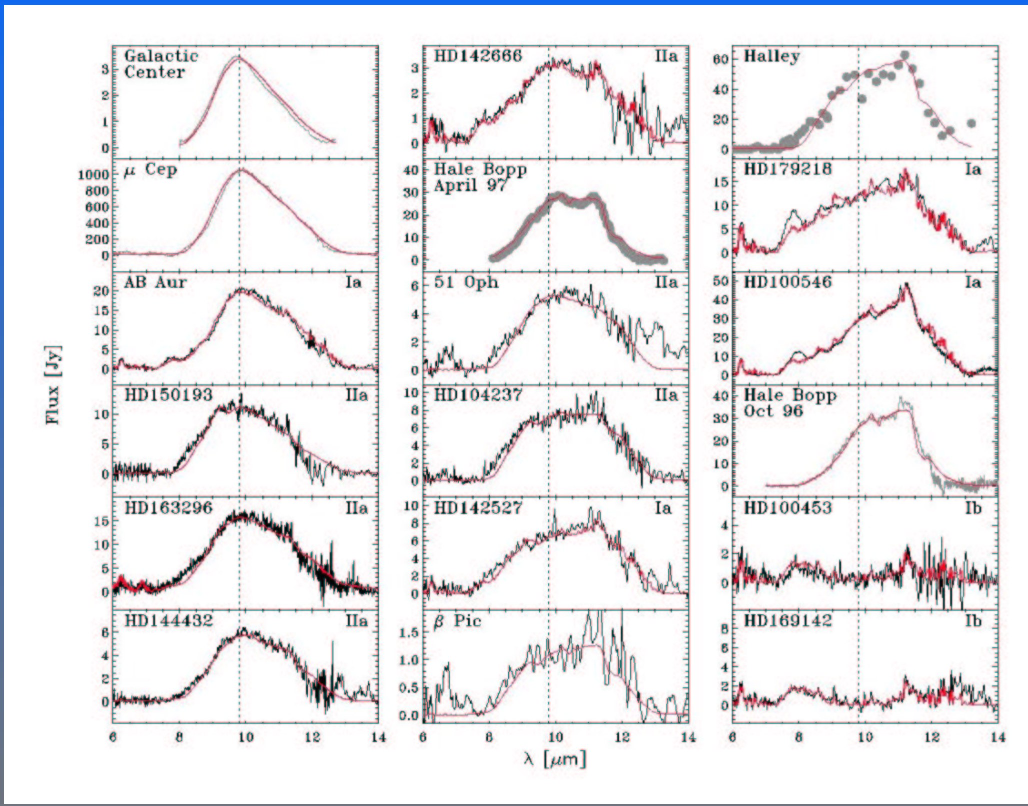
- Molecular bonds in solid show resonances
- Characteristic of chemical composition and lattice structure
- Important diagnostic of dust composition!



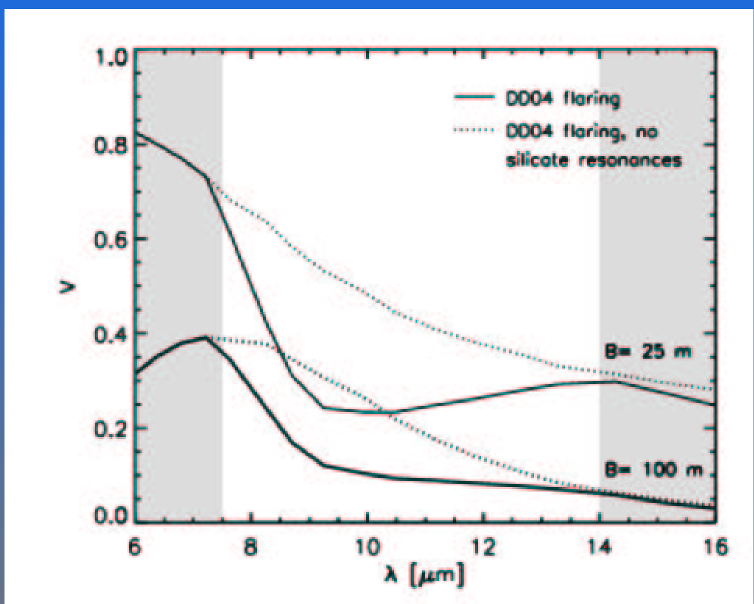
Amorphous versus Crystalline



ISO sample fits

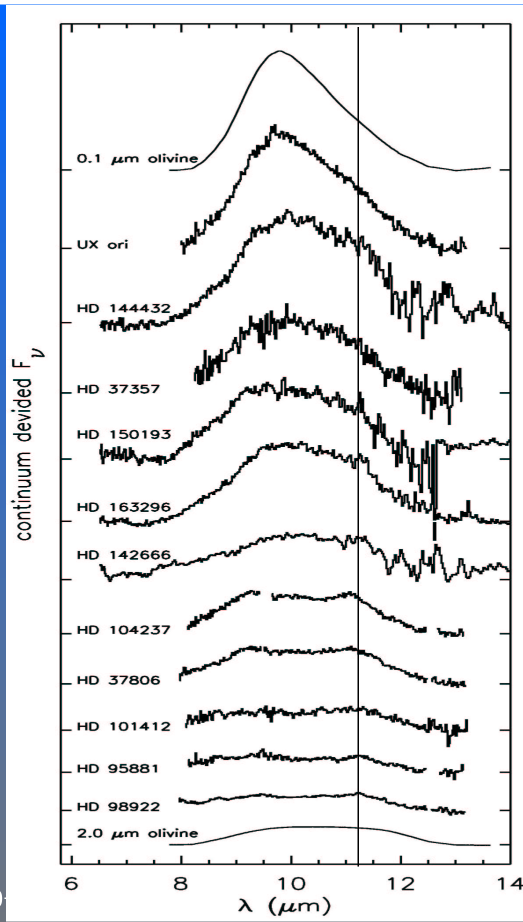


Effect of mineralogy on visibilities…



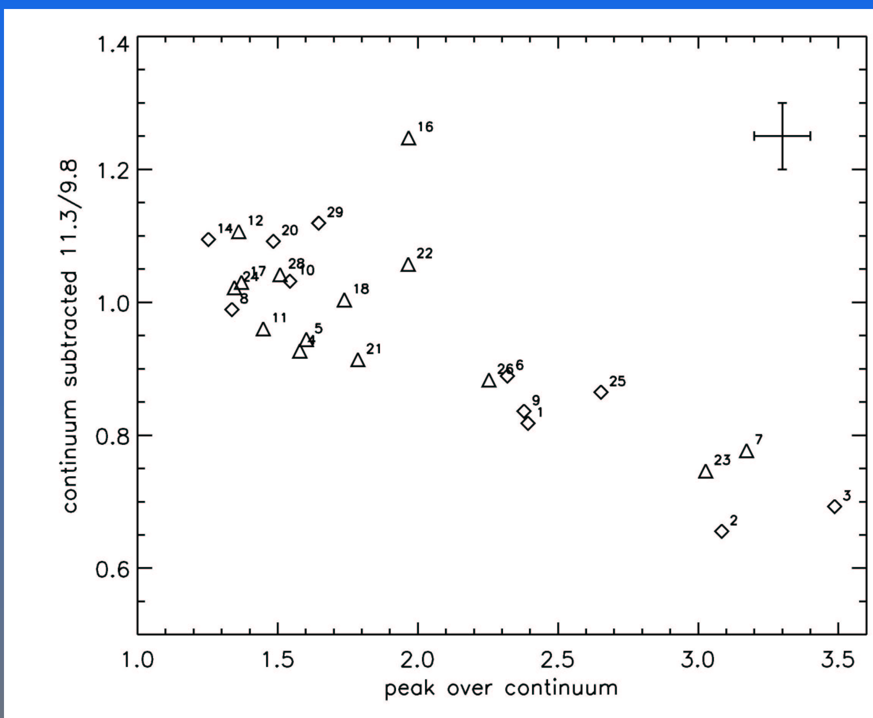
Ground−based 10 μm spectra of Herbig Ae stars

- Shape and strength are correlated
- Removal of small amorphous silicates
- May be due to coagulation
- Forsterite peak appears

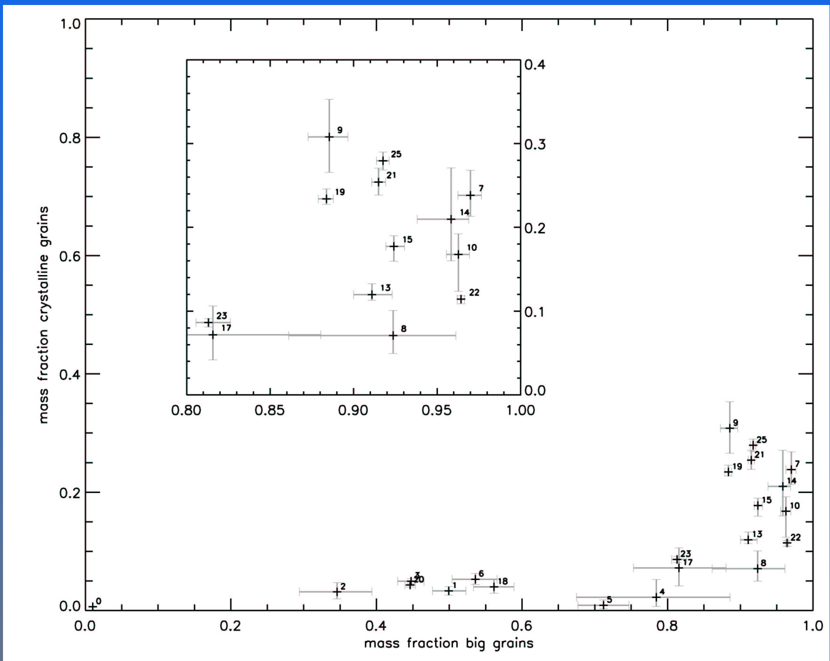


Van Boekel

Shape and strength of silicate feature



Crystallinity versus grain size



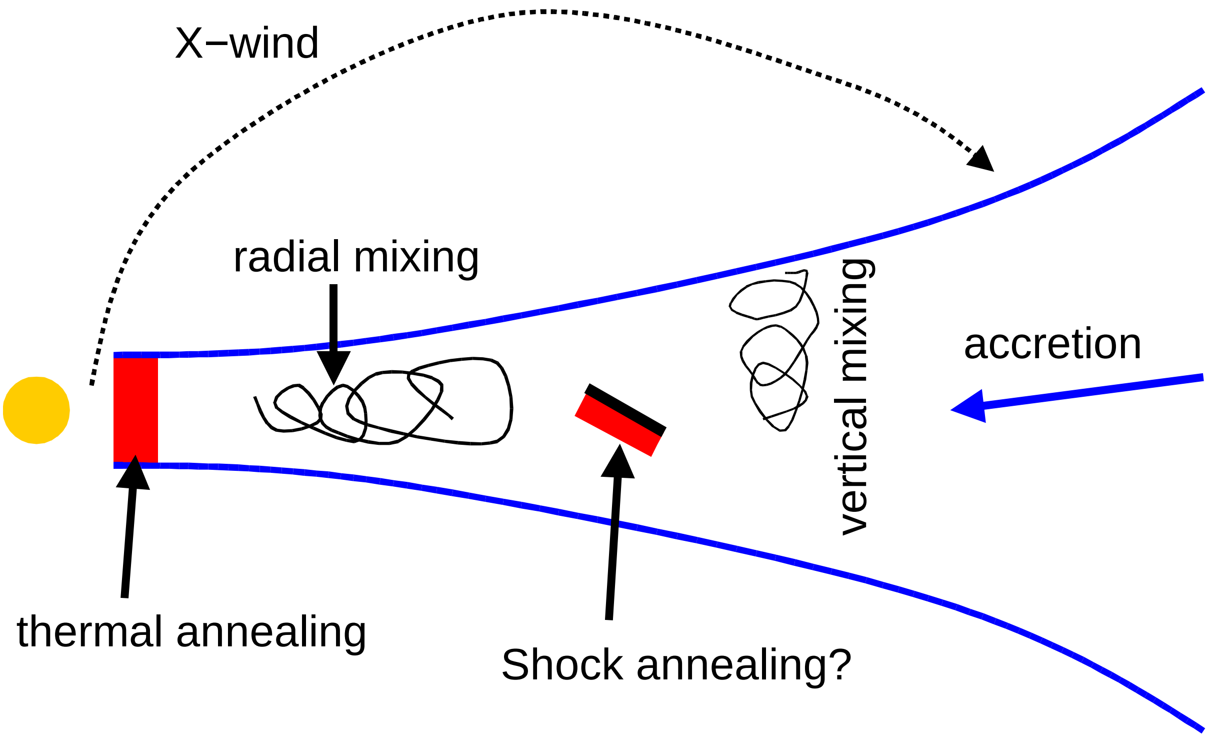
Grain size

- All stars show substantial removal of sub−micron sized grains
- Crystallisation is > 10 % when average grain size is dominated by 2 μm sized grains
- Crystals then also tend to be large (~2 μm)
- Coagulation is easier than crystallisation (density versus temperature)
- Crystallisation of the “current” grain population

Grain size

- Stars without 10 μm silicate emission tend to be old (~ 10^7 yrs)
- Simplest explanation: removal of silicate grains smaller than 3−5 μm on that timescale
- PAHs remain visible in spectrum: small grains survive in outer disk

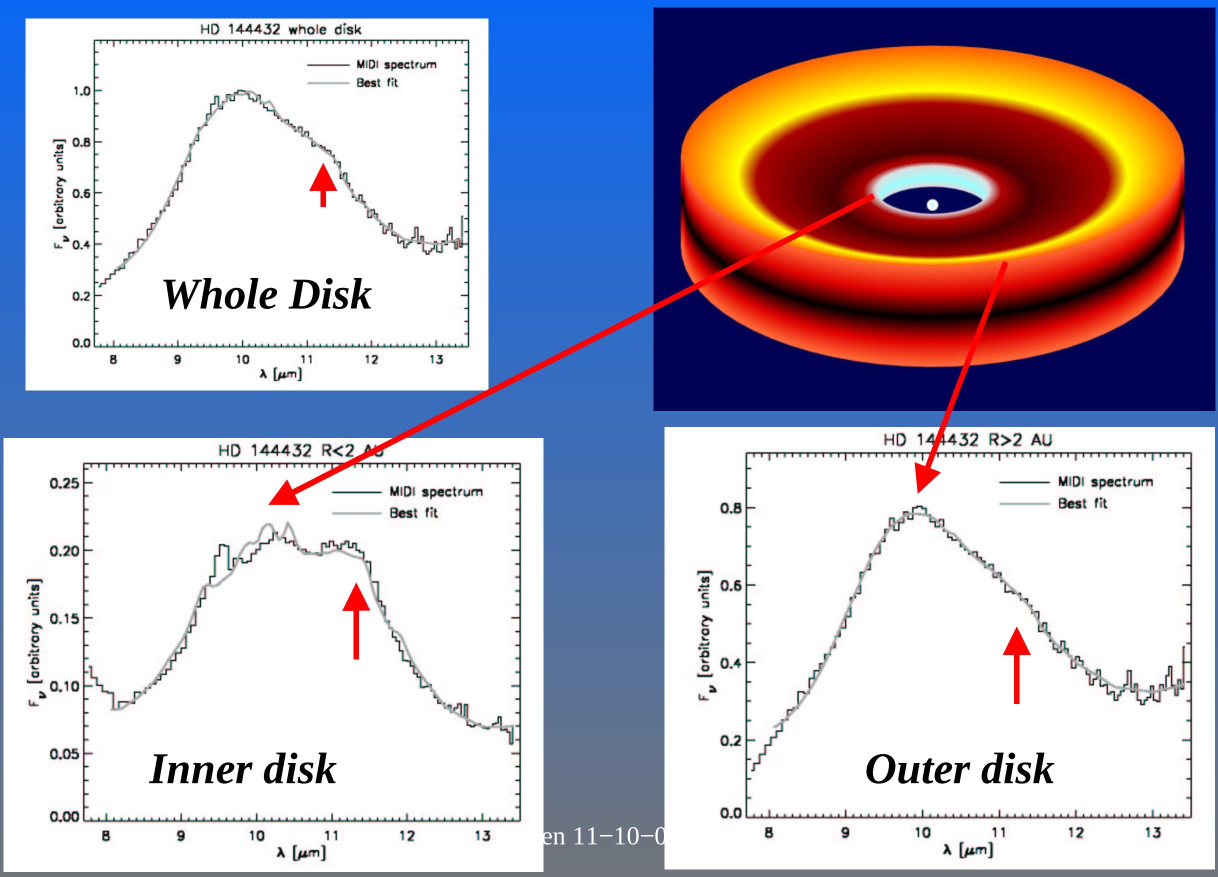
Crystallization and Mixing



MIDI observations of HAeBe stars

- Data presented were taken June 2003
- Baseline used 102 meters (UT1−UT3)
- Spatial resolution 20 milli−arcsec
- Spectrally dispersed fringes, R = 30
- Allows to determine 10 μm spectra of inner 2 AU of nearby HAeBe stars

Spatially resolved spectroscopy



VLTI/MIDI observations of HAeBe stars

Van Boekel et al.

MIDI spectra of HAeBe stars compared to comets and ISM

VLTI/MIDI observations of HAeBE stars

- Inner disks (< 2 AU) have:
  - larger silicate grains
  - higher fraction of silicates is crystalline (40−100%)
- more forsterite in inner disk, more enstatite further out
- *Consistent* with:
  - Chemical equilibrium processing+ thermal annealing in inner disk
  - Radial mixing to move crystals to larger distance

Origin of crystalline silicates

- Inner disk: chemical equilibrium and thermal annealing
- Large star−to−star variations in outer disk crystallinity:
  - No obvious correlation with age of star
  - Requires large range in efficiency of mechanisms that cause crystallisation of outer disk: radial mixing, shocks, X−wind,….

Conclusions

- VLTI has a large potential for proto−planetary disk studies
- Parameter space is large:
  - Disk geometry
  - Disk mineralogy
- Requires large data sets on multiple baselines