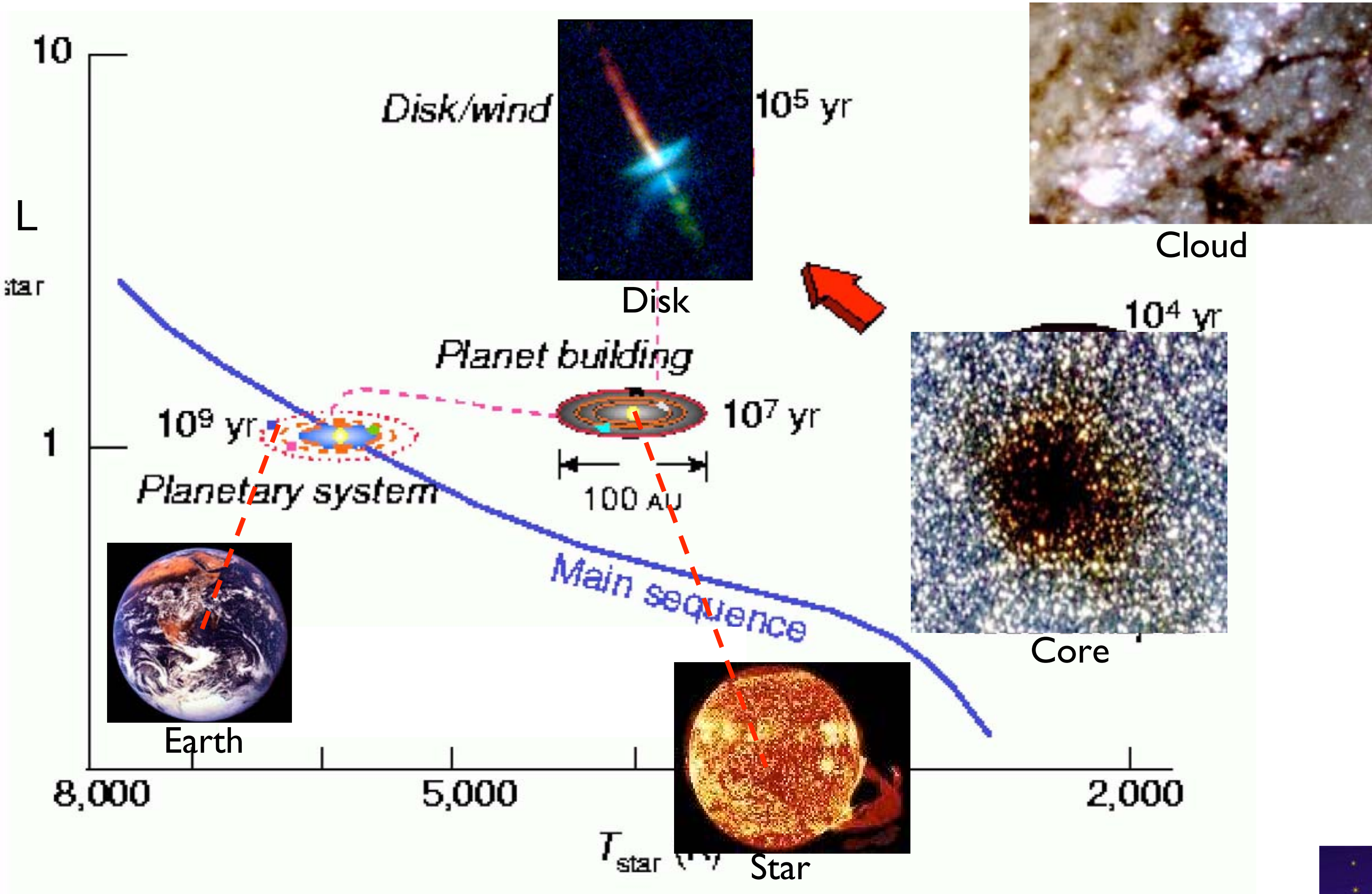
# Setting the Stage for Planet Formation: Grain Growth in Circumstellar Disks

**Leonardo Testi (European Southern Observatory)**

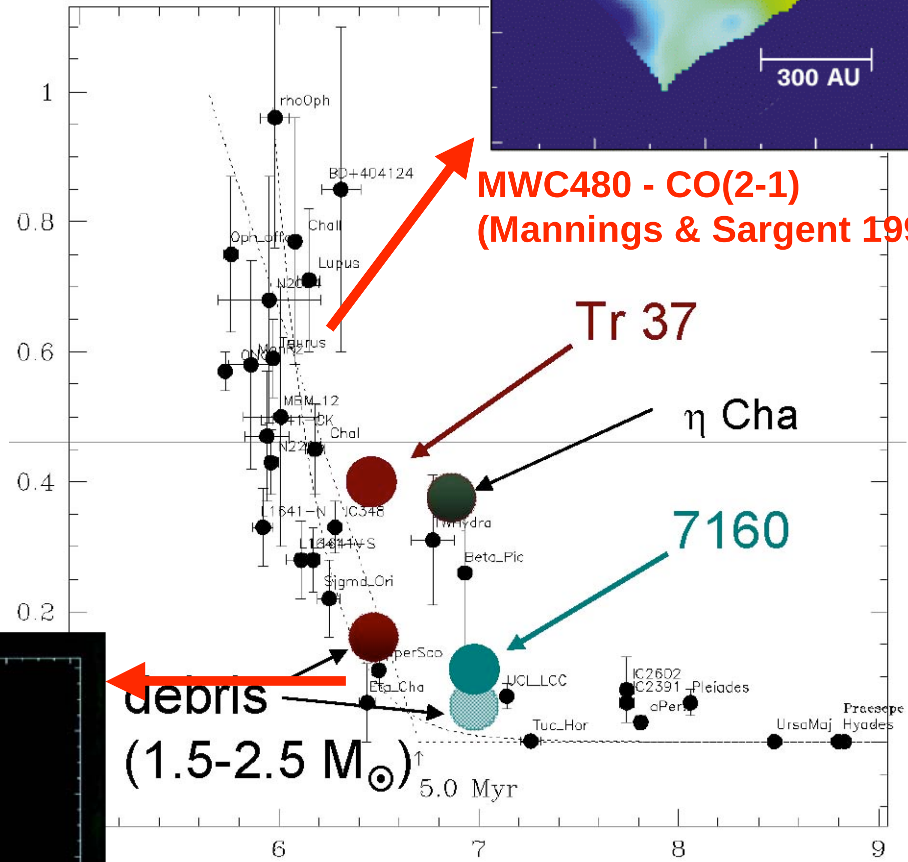
- Disk Evolution
- From Grains to Pebbles
- Do we understand what we observe?
- Wish List for ALMA

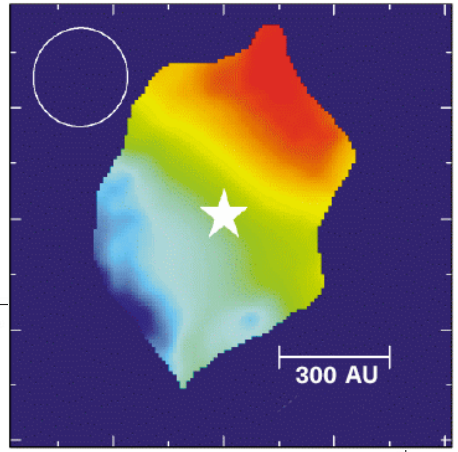
# From Cores to Stars and Planetary Systems



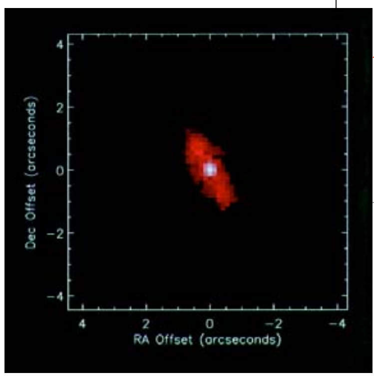
# Disk Evolution

- Evolution of the fraction of infrared excess sources in clusters
- In 1-2Myr 50% of the sources have lost teir inner disk
- Debris disks begin to appear at 5-10Myr



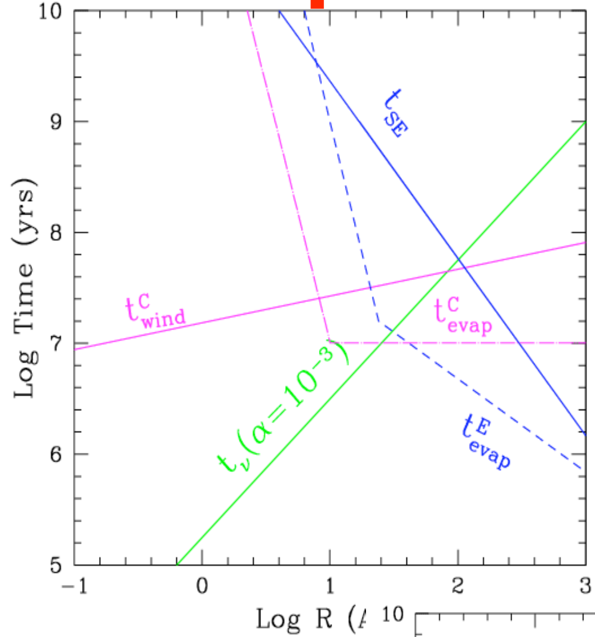

MWC480 - CO(2-1)
(Mannings & Sargent 1998)



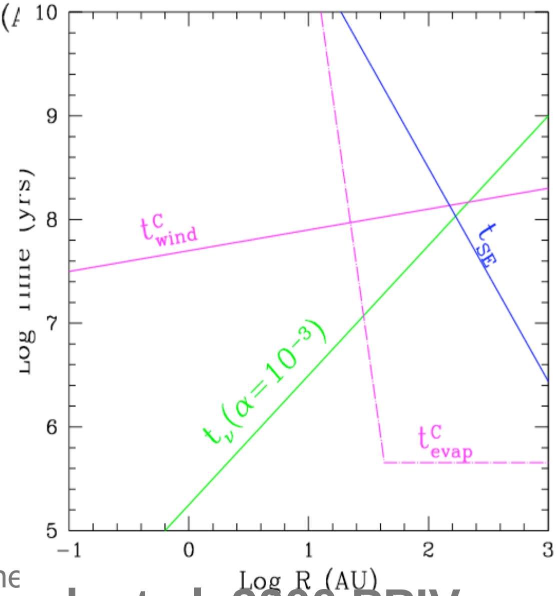

HR4796 - 10-20μm
(Koerner et al. 1998)

# Why do disks dissipate?

- Local effects:
  - viscous evolution
  - photoevaporation
  - wind stripping
  - tidal interactions
  - planet formation



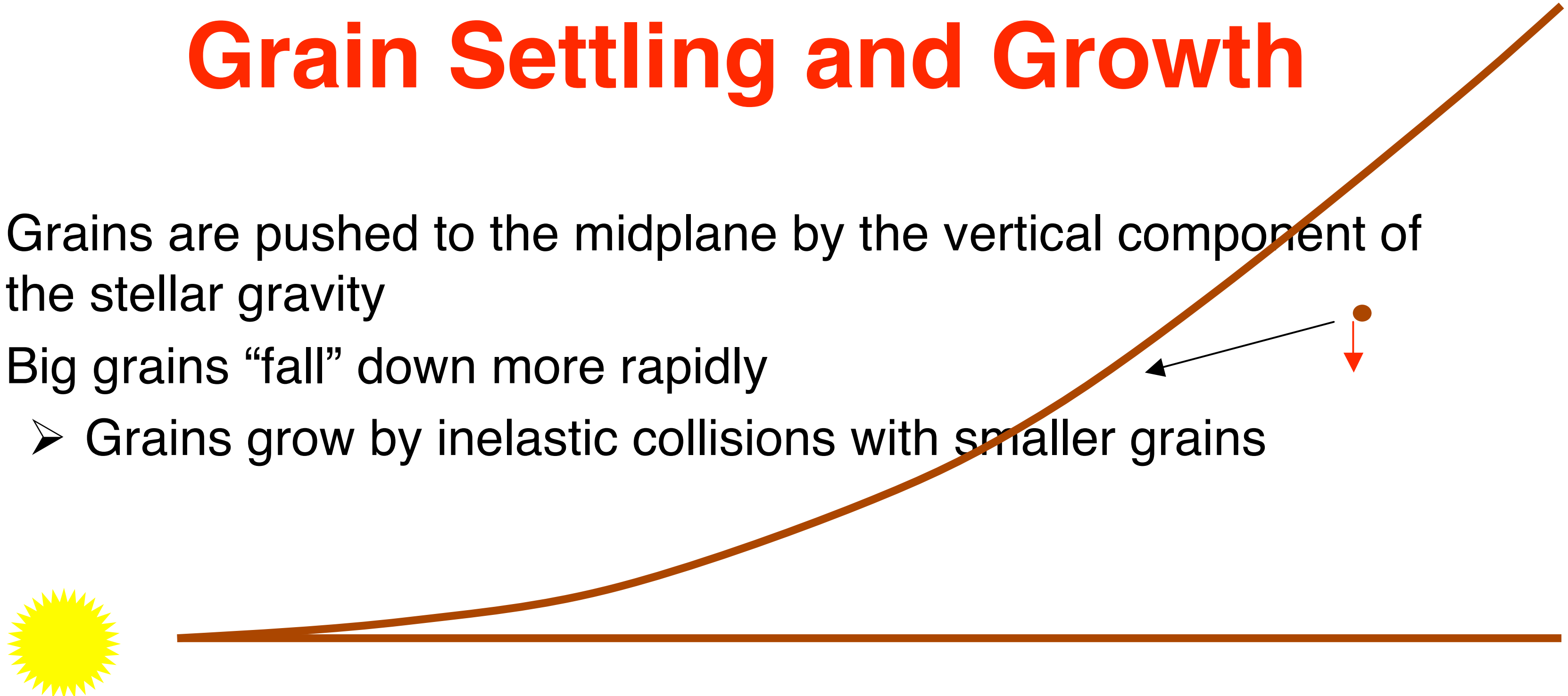

- Environmental effects:
  - stellar encounters in clusters
  - photoevaporation by other stars




Hollenbach et al. 2000 PPIV

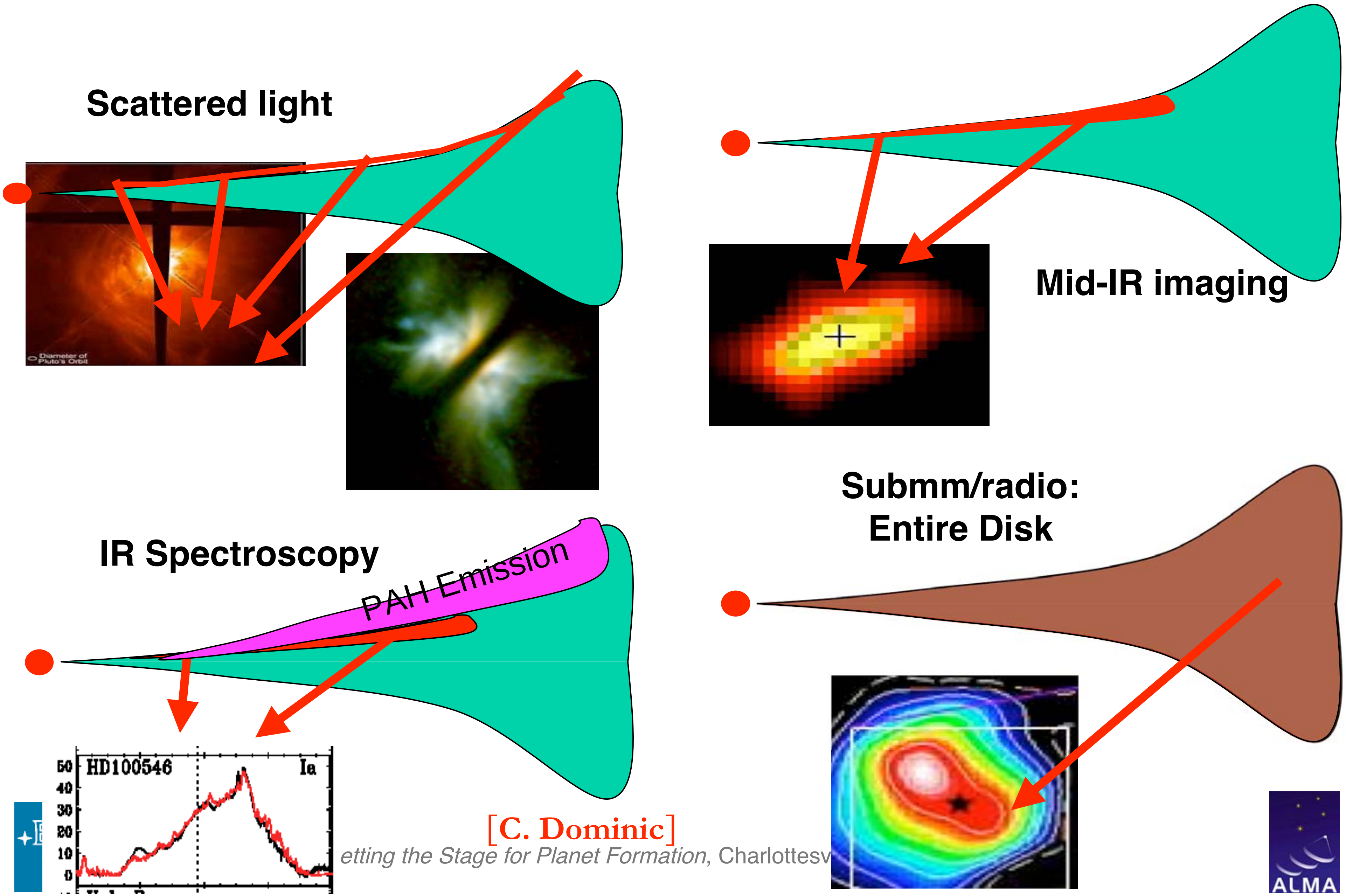
# Grain Settling and Growth

- Grains are pushed to the midplane by the vertical component of the stellar gravity
- Big grains "fall" down more rapidly
  - Grains grow by inelastic collisions with smaller grains



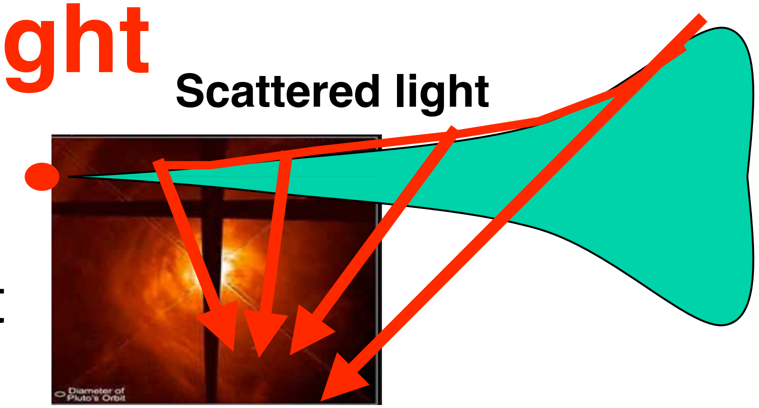
- The process is very fast and rapidly produces a vertical stratification of grain properties
- Turbulence, mixing and destructive collisions have to slow down this process
  - Need to maintain the "flaring" (SED)
  - Big grains are present also in the disk atmosphere

# Which observations probe what?

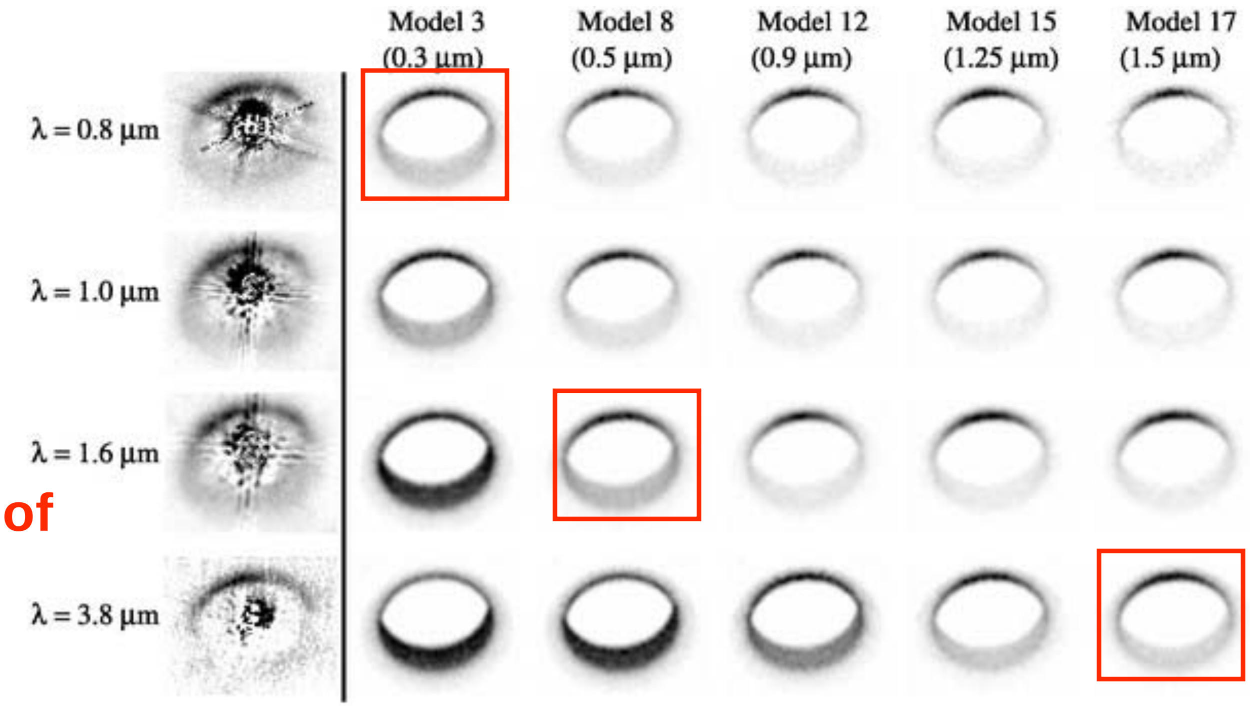



[C. Dominic]

# Scattered Light




- Multi-wavelenght high angular eresolution images of scattered light
- Probe different layers of the disk surface

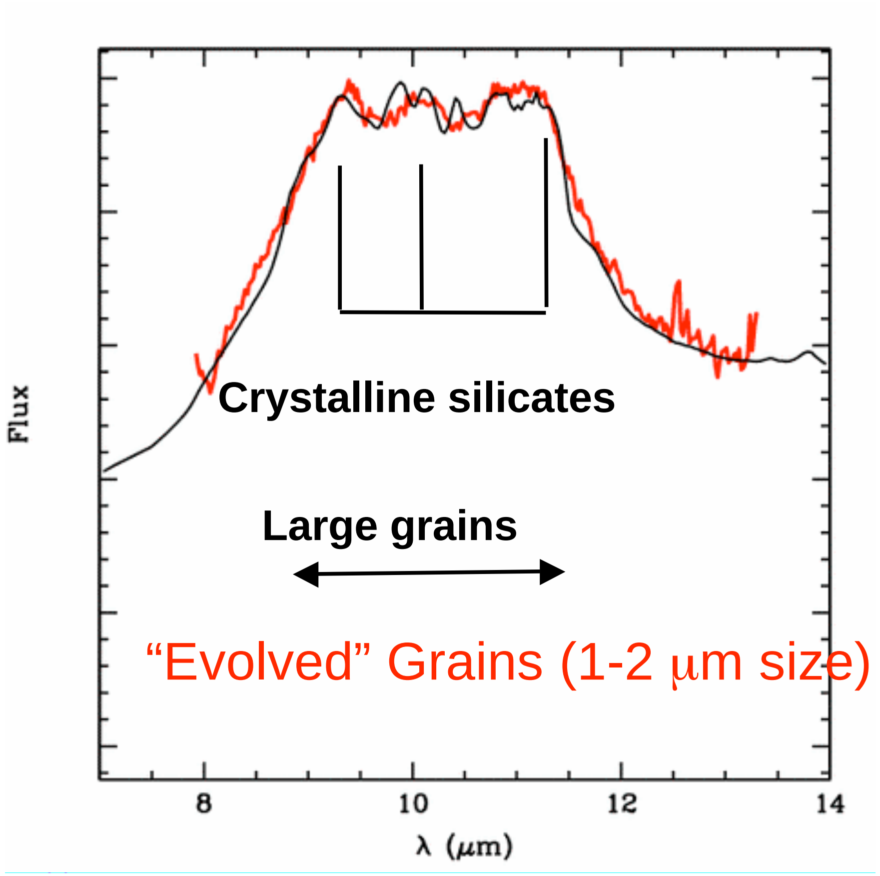



**Clear Evidence for:**

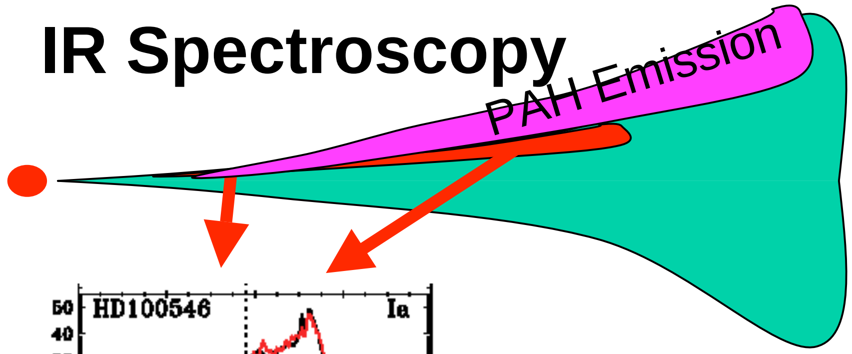
- **Presence of Large Grains in the Disk Surface**
- **Vertical Stratification of Grain Sizes**

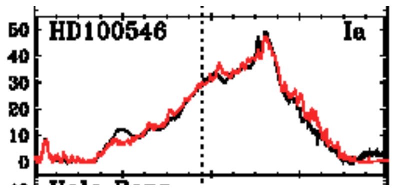
(Duchene et al. 2006)

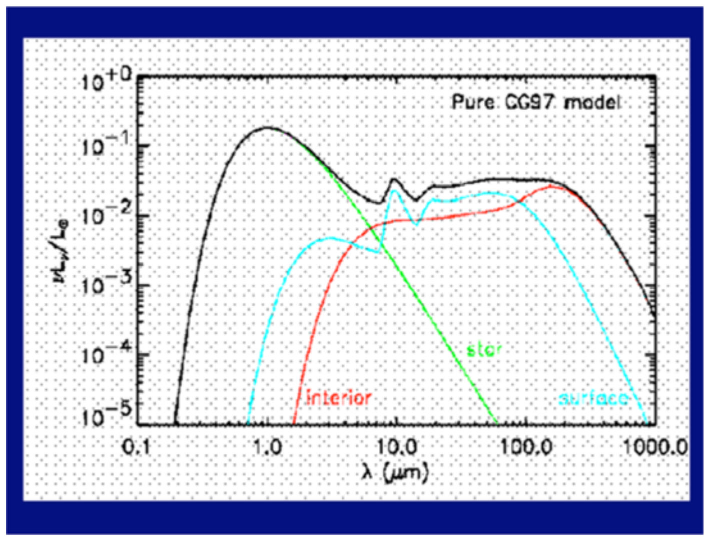
# Processing of the 10 micron feature




## IR Spectroscopy

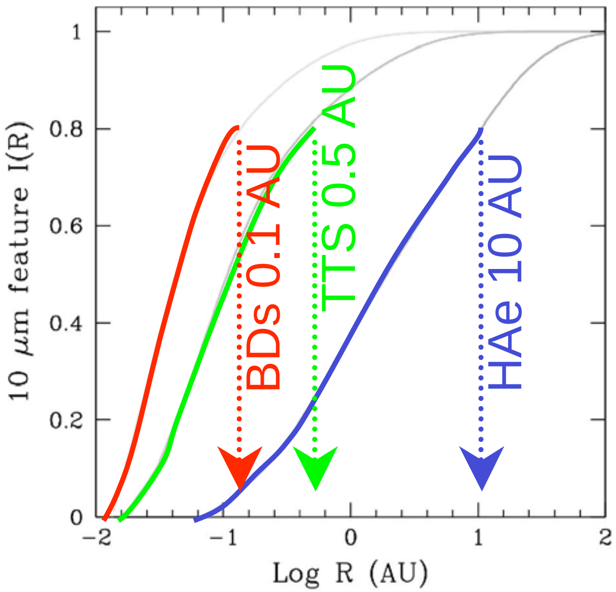


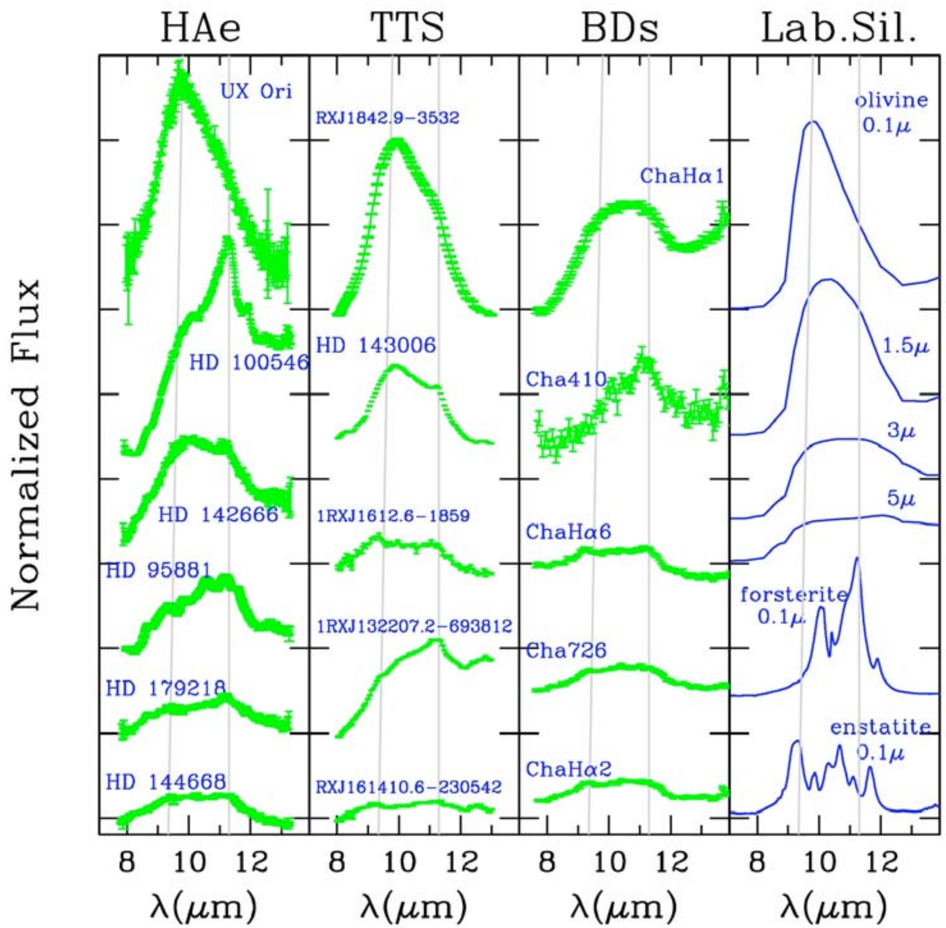



# Grain Growth and Crystallization

- Full range of profiles in disks around HAeBe, TTS and young BDs

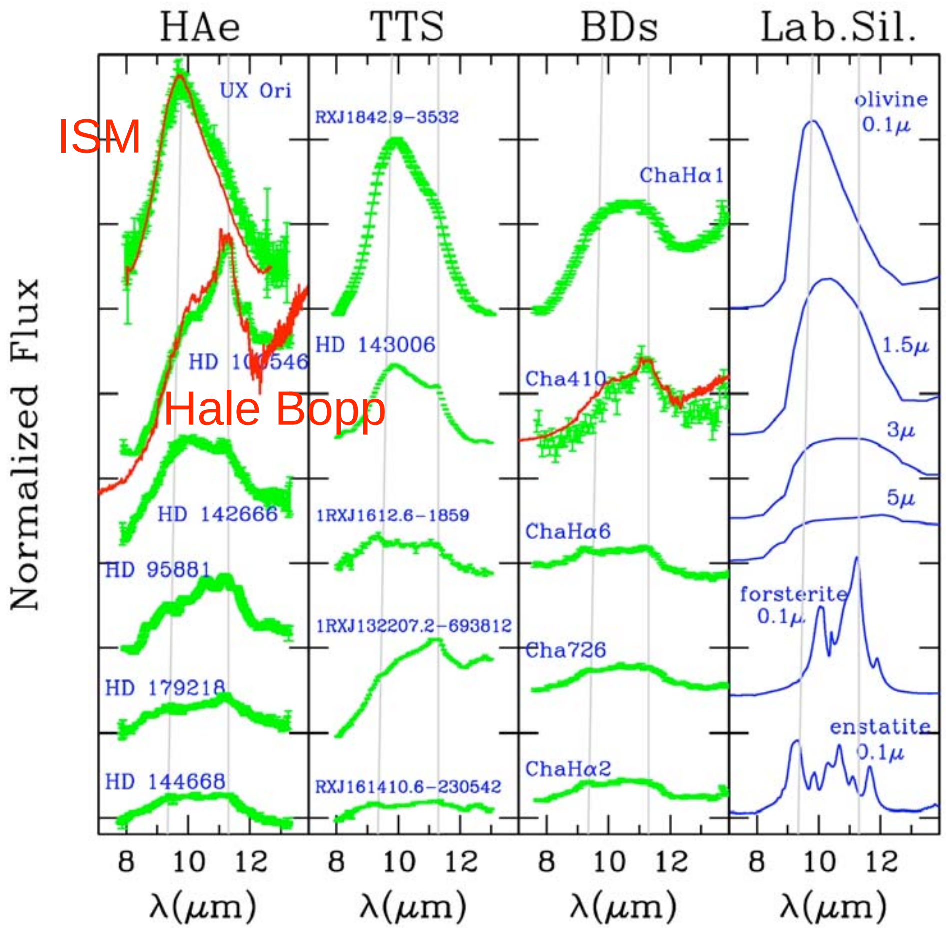



(Data: van Boekel et al. 2005
Bouwman et al. 2005; Apai et al 2005)

# Grain Growth and Crystallization

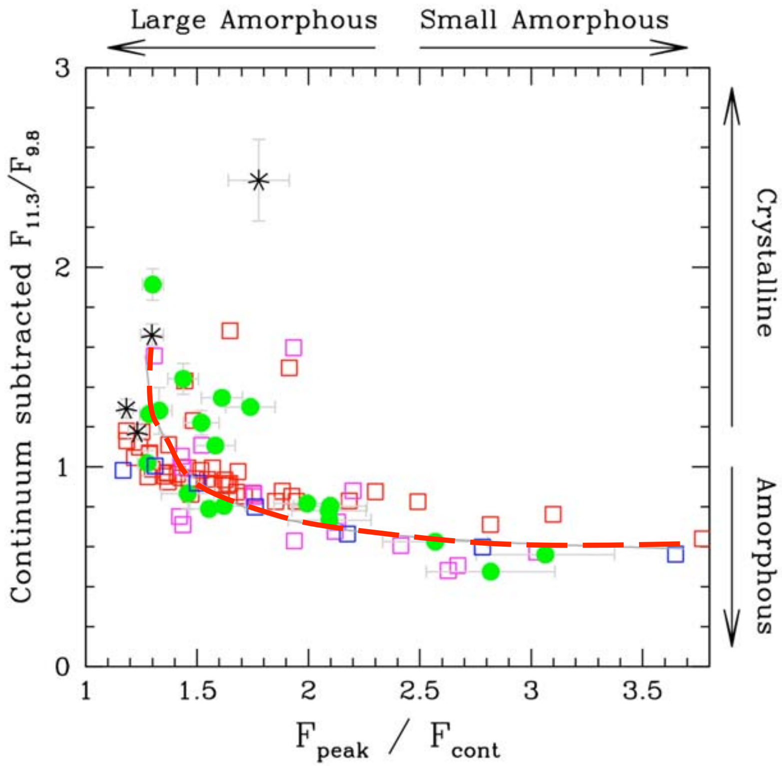
- Full range of profiles in disks around HAeBe, TTS and young BDs
- Grain sizes: from ISM to a few μm (not sensitive to larger grains)
- Mineralogy: from Amorphous to Crystalline




(Data: van Boekel et al. 2005
Bouwman et al. 2005; Apai et al 2005)

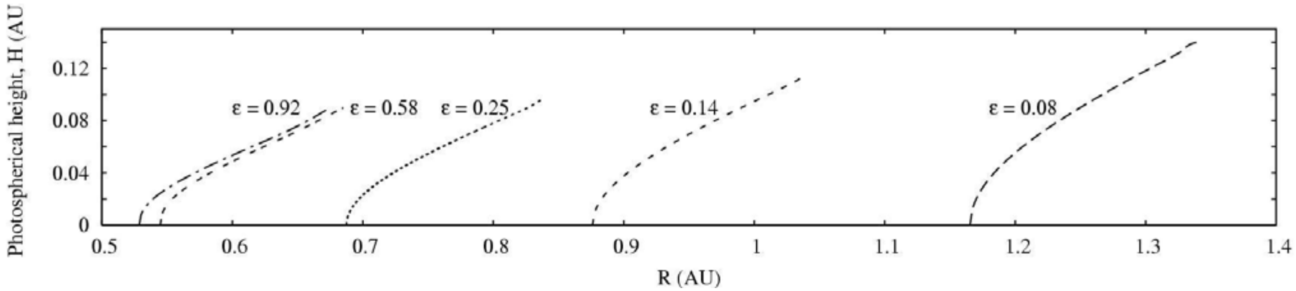
# Grain Growth and Crystallization

- Larger grains have a lower peak to continuum ratio
- Mixtures with a high fraction of crystalline grains have a larger 11.3 to 9.6 ratio
- All types of mixtures in all type of systems

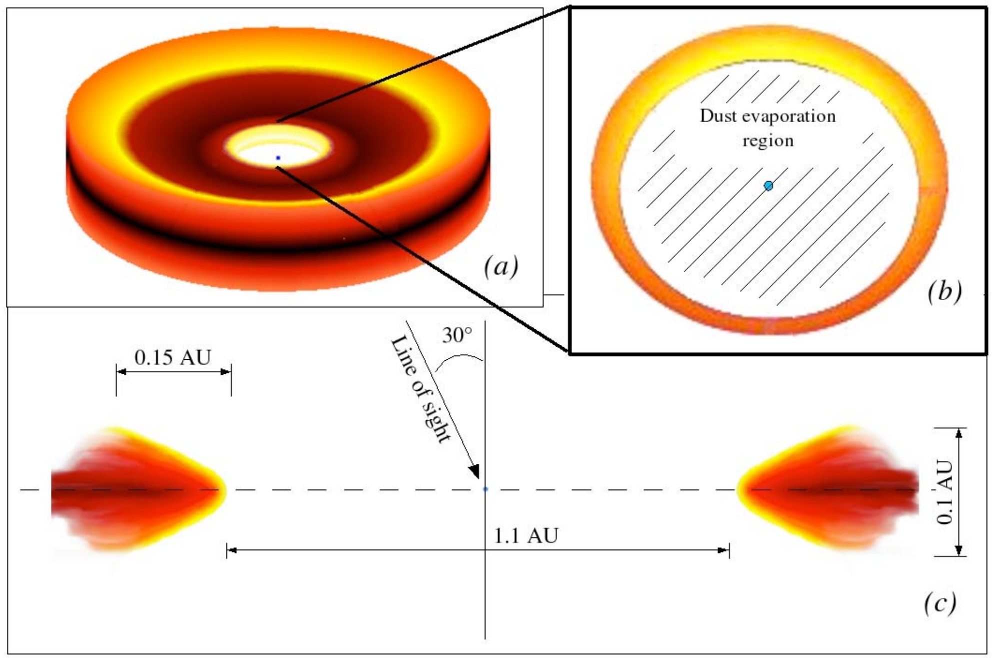



(Data: van Boekel et al. 2005; Kessler-Silacci et al. 2005; Przygodda et al. 2004 Bouwman et al. 2005; Apai et al 2005)

# Dust in the very inner disk: a job for near-IR interferometry



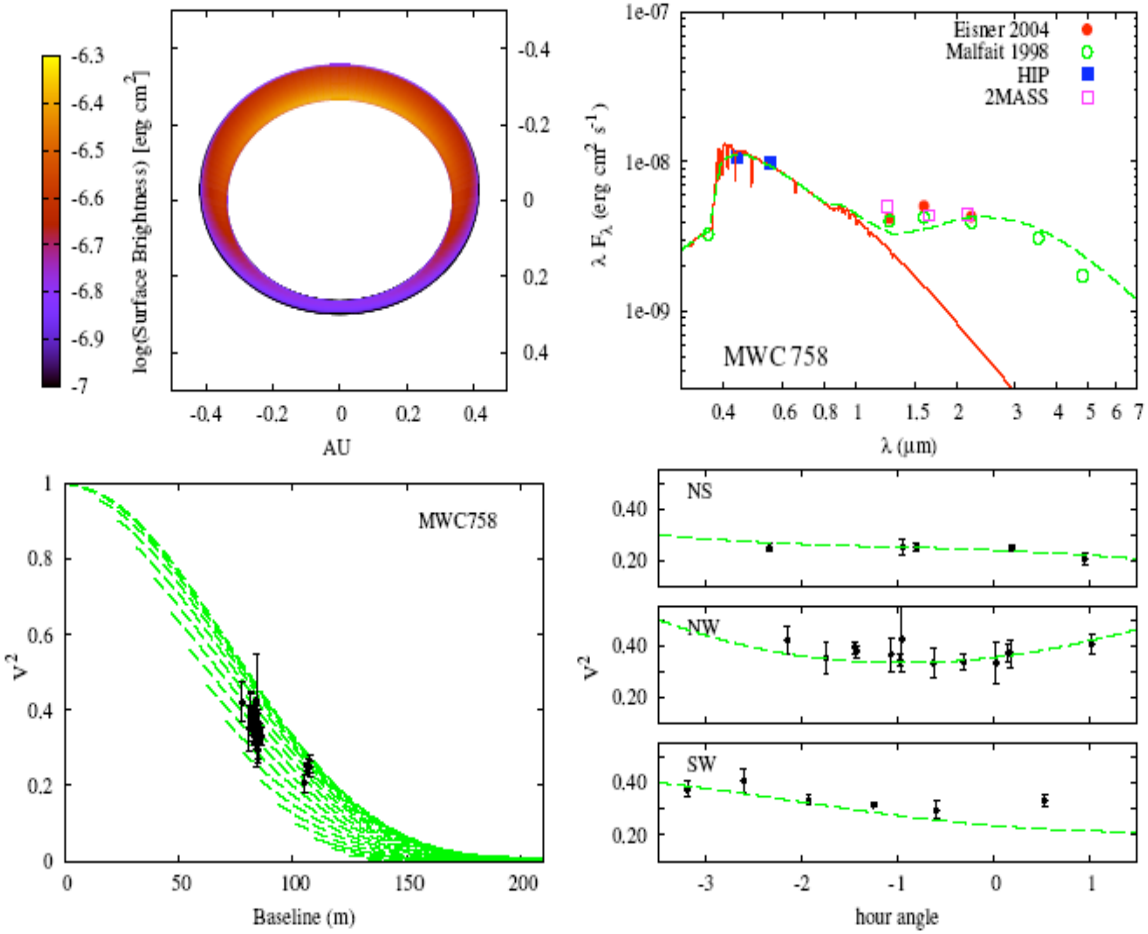

- The rim location and shape depend *only* on the grain properties




(Isella & Natta 2005)

# Application to real PTI data

| MWC 758 | **Incl = 40° -- PA = 145° -- *a* = 1.2 μm ($R_{in}$ = 0.32AU)** |
|---|---|




$\chi^2$ test on the 3-dimesional space of the parameters

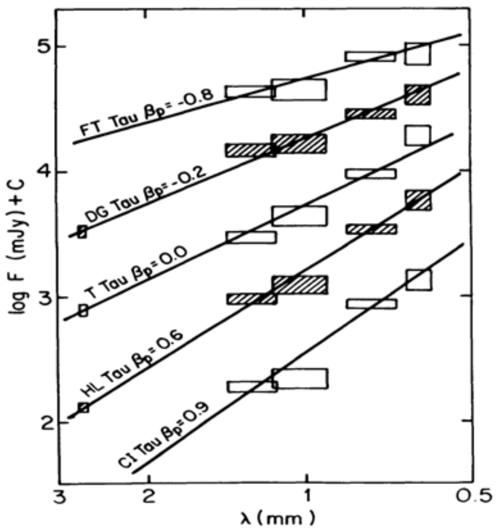
(Isella, Testi & Natta 2006)

# Circumstellar disks @ mm-$\lambda$

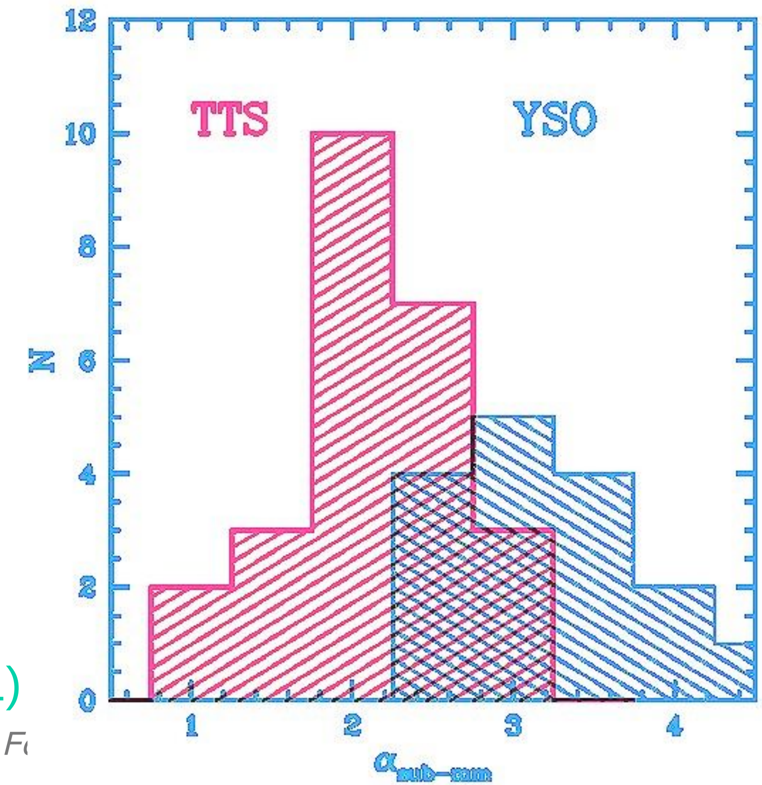
- At long wavelegths the thermal emission from dust grains in circumstellar disks becomes optically thin
- mm observations are a powerful (in most cases the only) probe of the dust population on the disk midplane
- The observed millimeter spectral energy distribution depends “only” on the number, temperature and emissivity of dust grains
  - Assuming a grain mixture at a defined temperature, the measured flux at a given wavelength is proportional to the total dust mass
  - Measuring the continuum emission from dust grains at several wavelengths we can set constraints also on the combination of the dust properties ad the disk structure
  - With the aid of appropriate disks models and of spatially resolved images of disks it is possible to constrain the geometry and physical properties of the dusty disks

# Evolution of dust in disks

- Search for the presence of large (cm-size) grains
- The basic idea is to search for mm spectra that approach the black body spectrum
  - limit for optically thick disk or grey dust (size>>$\lambda$)
- $[F_\nu \sim \nu^\alpha; \alpha=2+\beta; \kappa_\nu \sim \nu^\beta]$




Single dish $\alpha_{sub-mm}$
(Beckwith & Sargent 1991)



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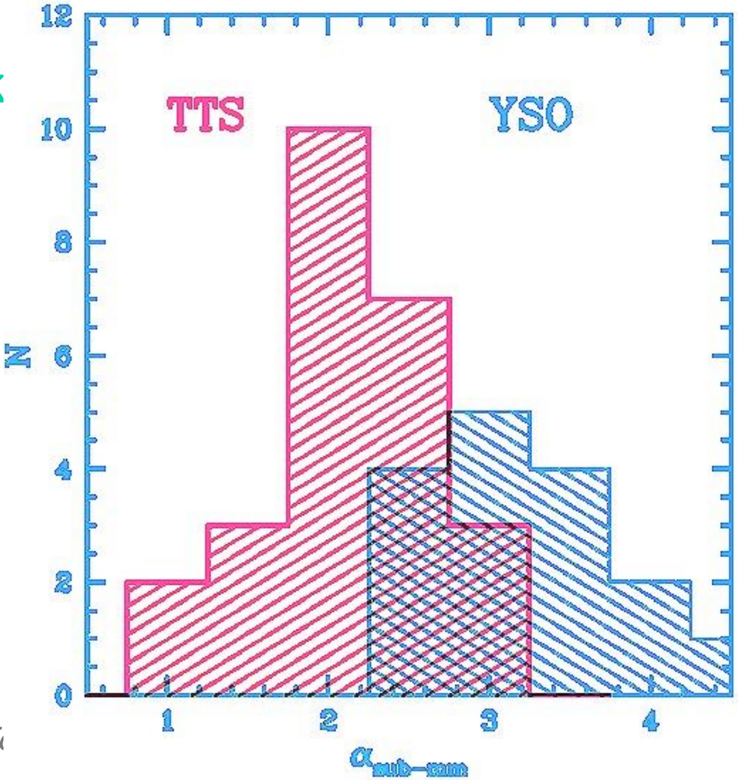
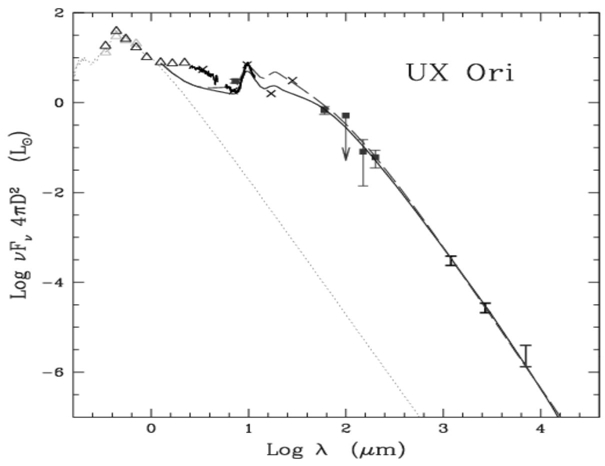
- Disks may be optically thick
- Need to go to longer $\lambda$
- Worrie about free-free
- Need to resolve disks
- Need to use disk models




Single dish $\alpha_{sub-mm}$
(Beckwith & Sargent 1991)

# Evolved dust in HAe disks

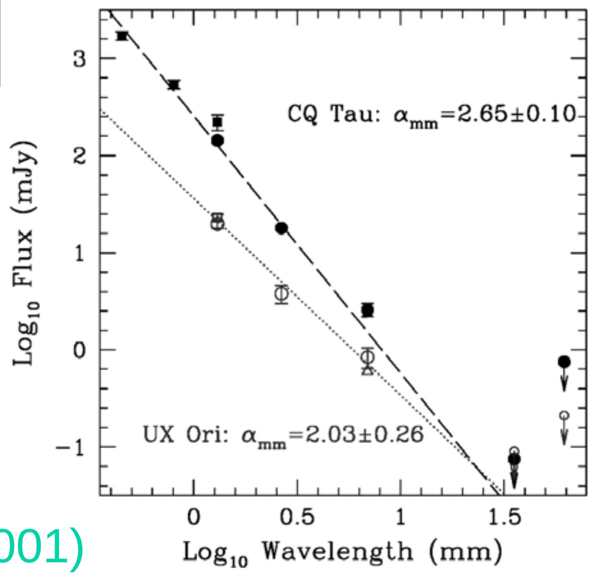
- 1 to 7 mm observations with OVRO/PdBI and the VLA

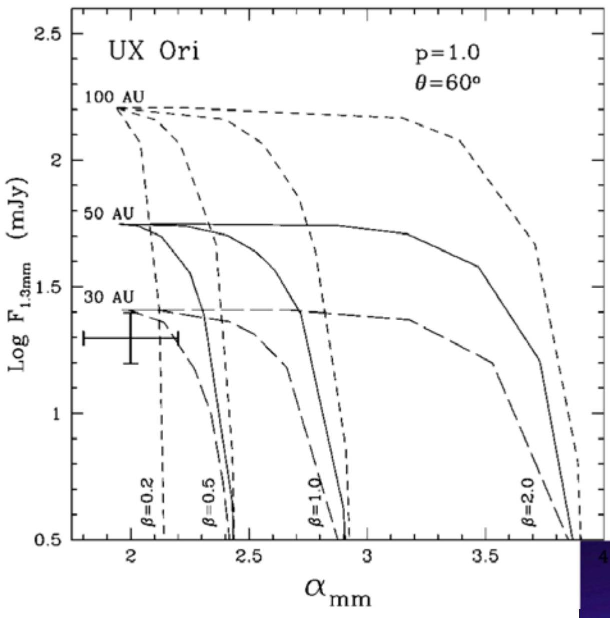



1. **Very small, optically thick, ISM grains disk**
2. **Large disk with very large (few cm size) grains**

PdBI 1.2 & 2.7 mm
VLA 7mm and 3.6cm

$\alpha_{mm}$~2.0; β~0.1
a ≥ 10cm




(Testi et al. 2001)

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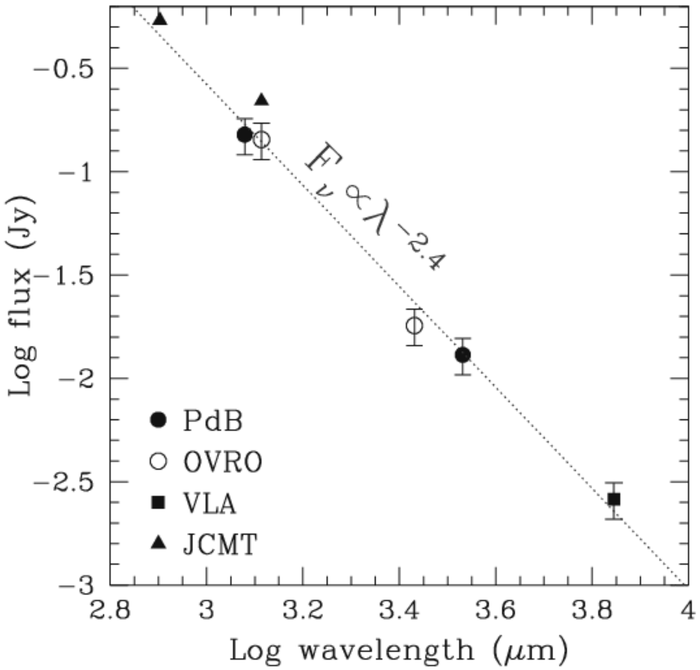
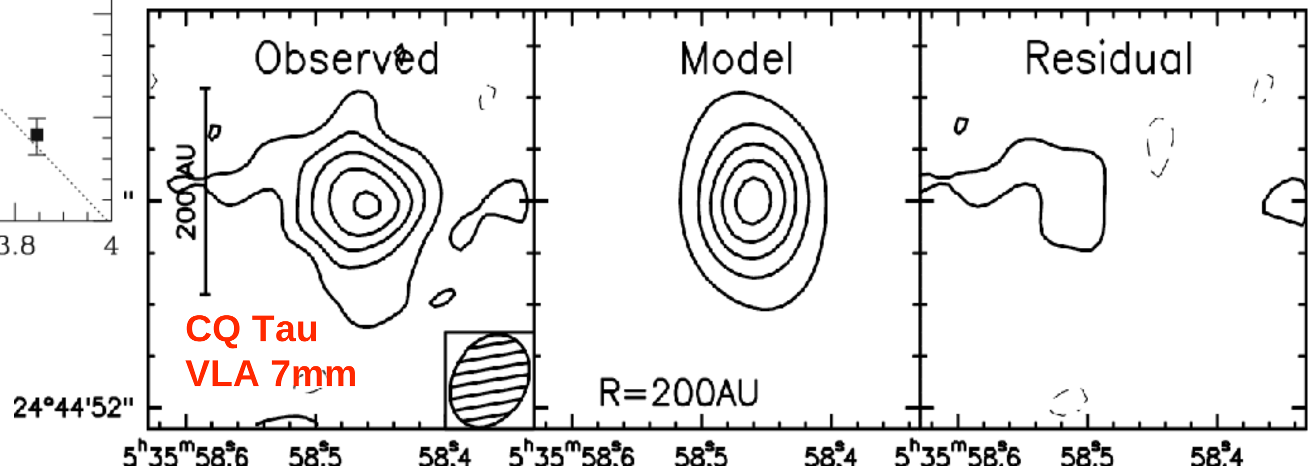



**Disk resolved at mm wavelengths:**

- **Disk size**
- **Surface density profile**
- **Dust emissivity index**



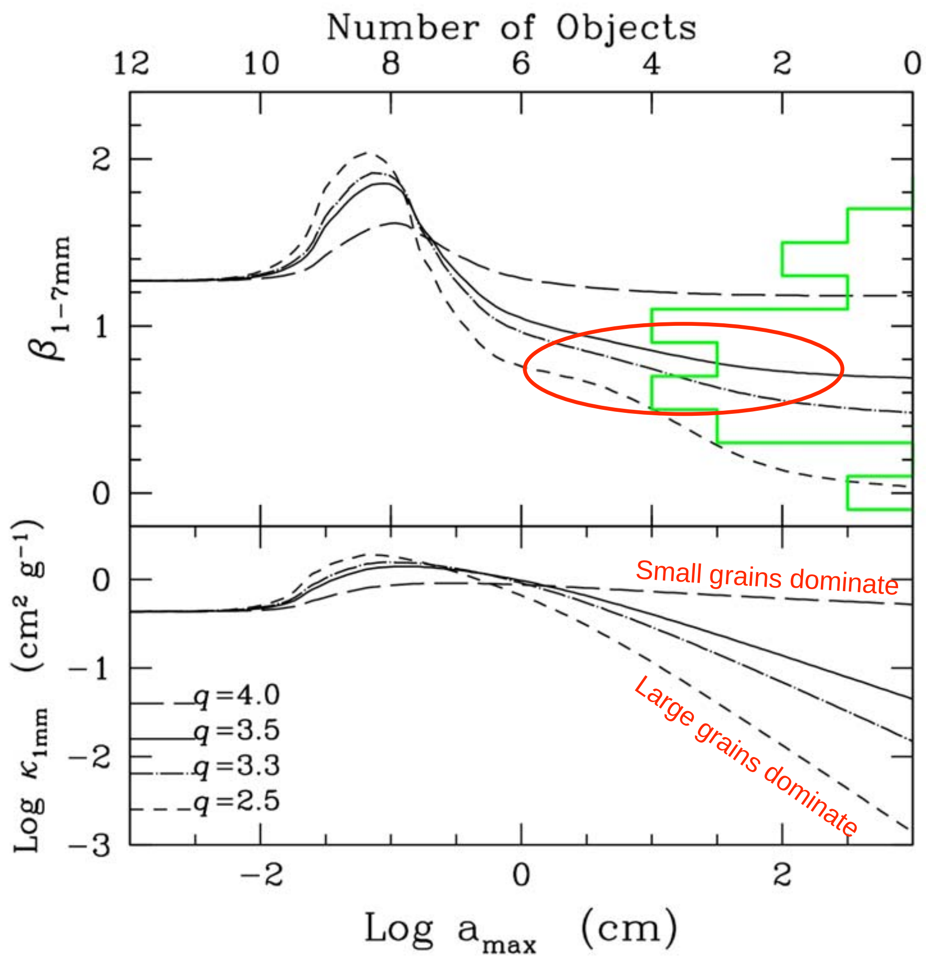

$\alpha_{mm}$~2.4; p~1.5; β~0.6

(Testi et al. 2003)

# β, grain sizes, k and disk masses

- Grain size distributions with very large upper cutoff explain the observed low values of β
- Opacity and mass is dominated by the upper end of the distribution

- Using the appropriate dust opacity coefficients: $M_{dust} \sim 10^{-2/-3} M_{sun}$ => original disk mass 0.1-1 $M_{sun}$
- Size distribution need to be cut at "observed" size

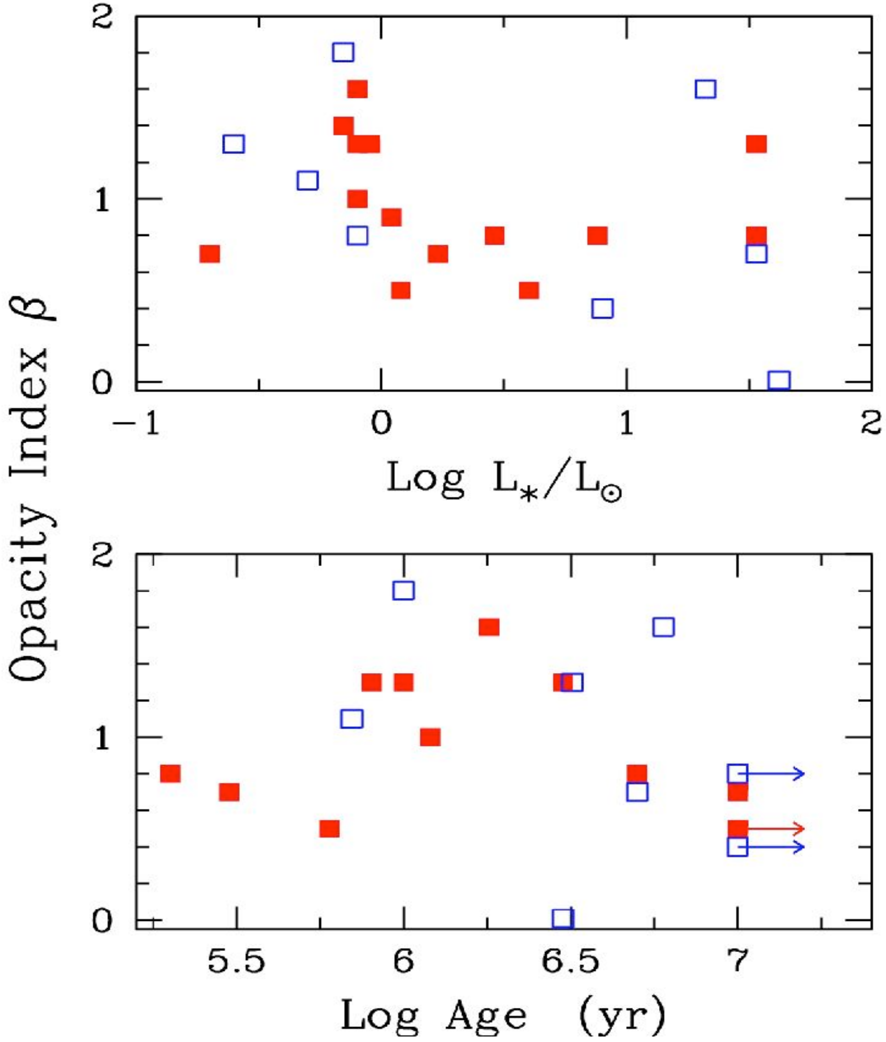



Data:
HAe (Testi et al. 2001; 2003; Natta et al. 2004)
TW Hya (Wilner et al. 2000;Calvet et al. 2002)
TTauri stars (Rodmann et al. 2005)

(Natta & LT 2004; Natta, LT, et al. PPV)

# Large grains in HAe and TTS systems

- Values of β range from 1.8 to 0.1 (from ISM grains to pebbles)
- No obvious correlation with stellar properties
- No obvious correlation with age
- No obvious correlation with disk surface grains
- ???
- <u>Caveat</u>: “large disks” small, biased samples




(Natta, LT, et al. PPV)

Data:
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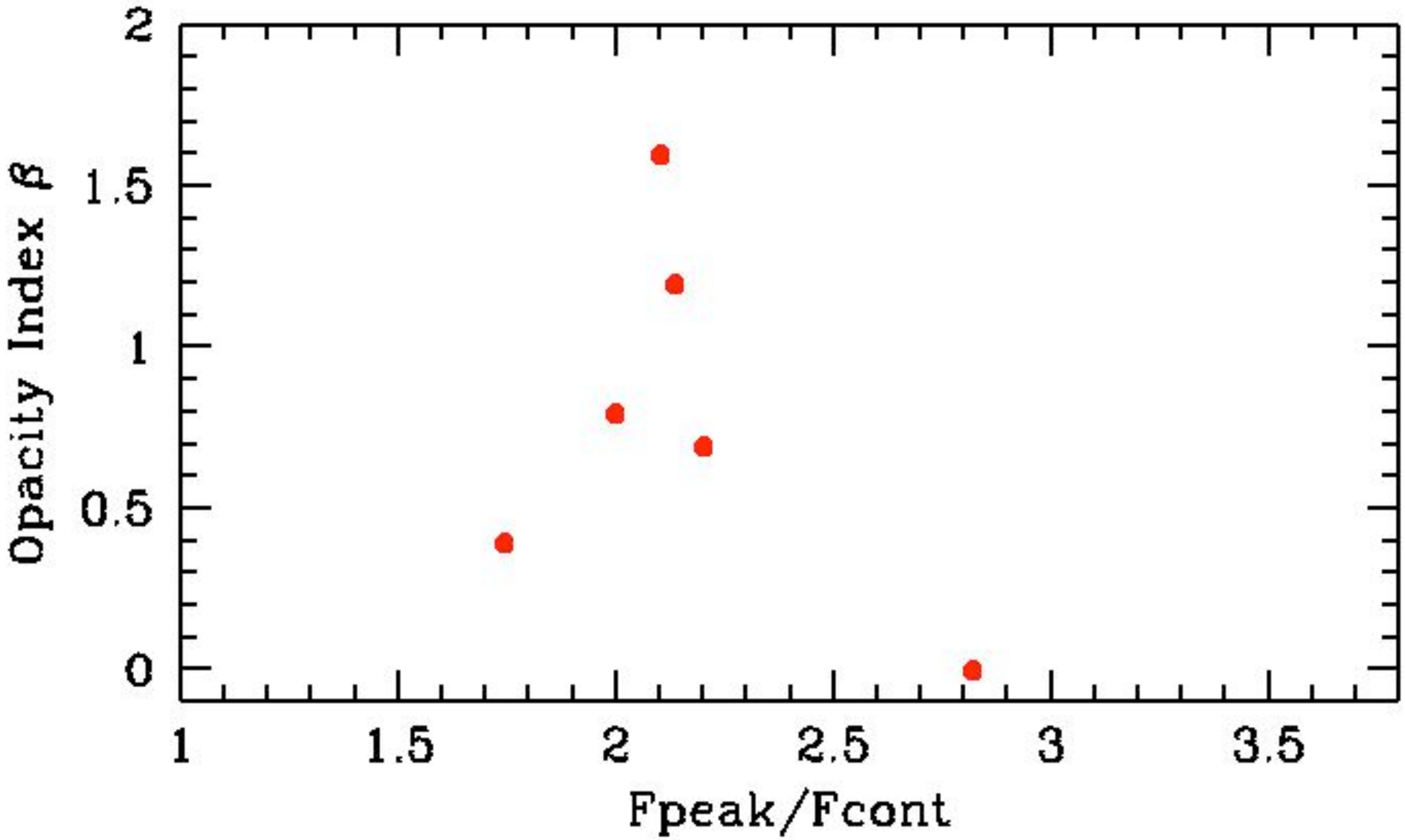
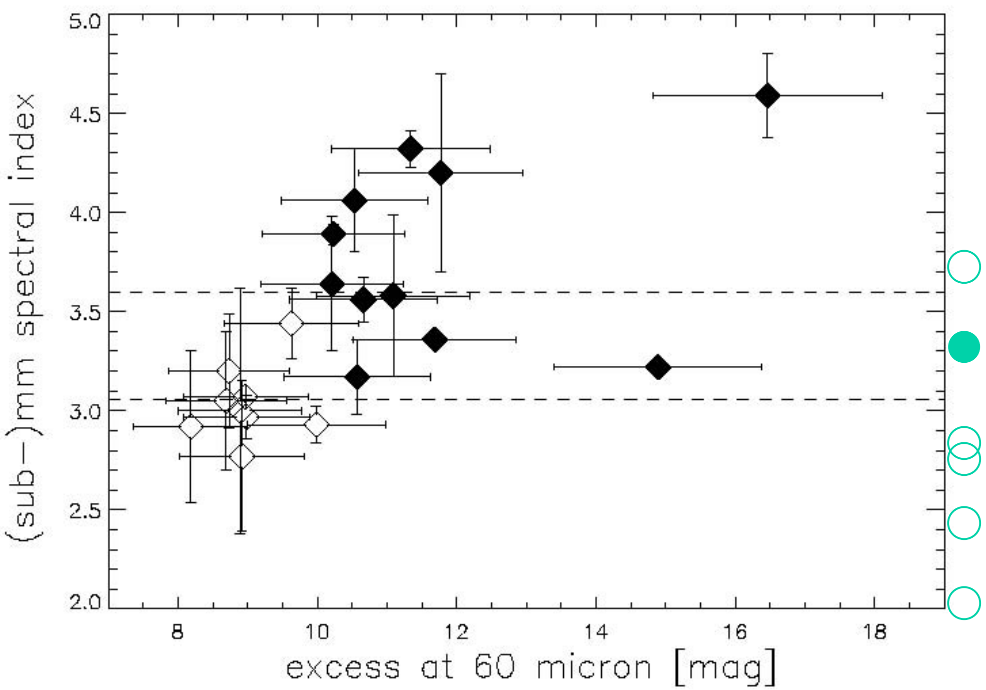
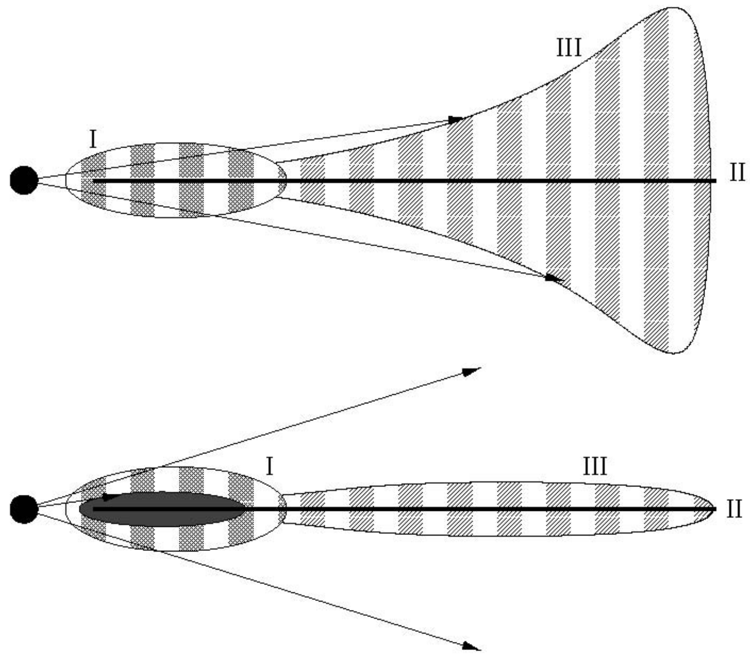
# Midplane Dust vs Surface Dust




- Caveat: MIR and (sub)mm are sampling different regions of the disk!

# Midplane dust vs Disk Properties




- Possible correlation between midplane dust properties and the disk structure
- Caveat: most of these spectral indices are derived from limited, single dish data!

(Ake et al. 2004; Meeus et al. 2001)

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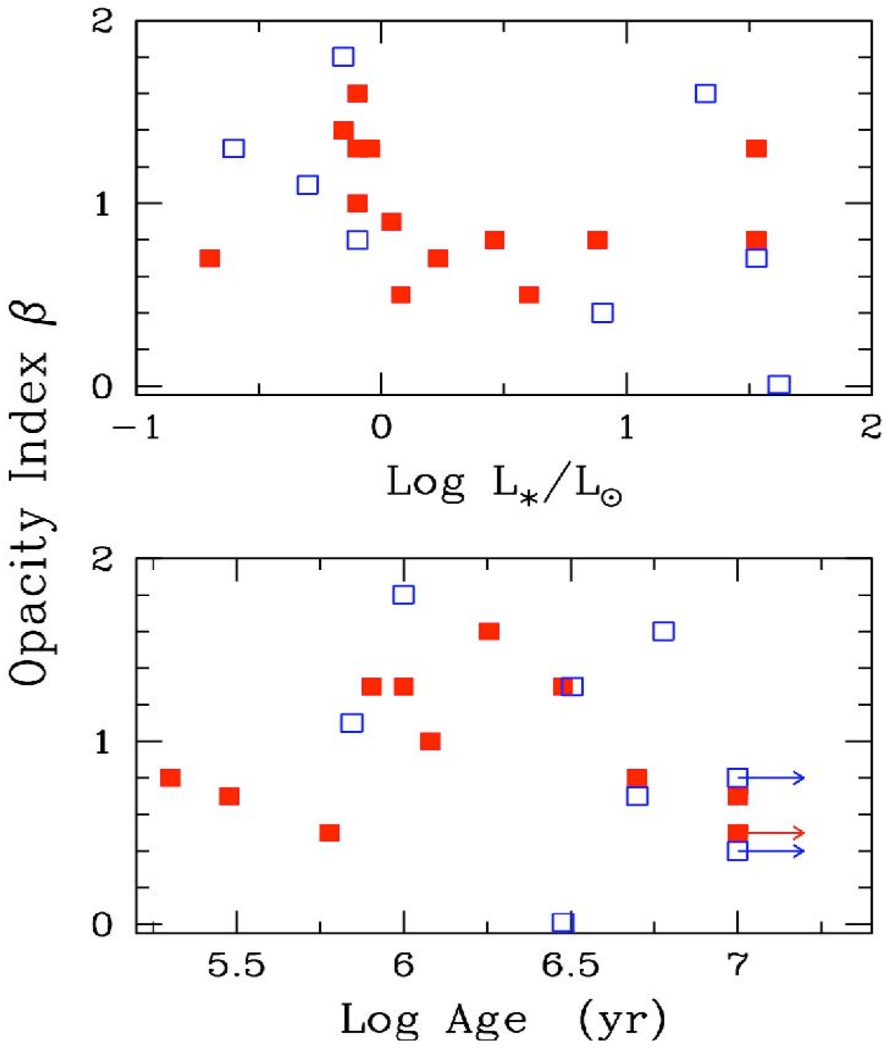
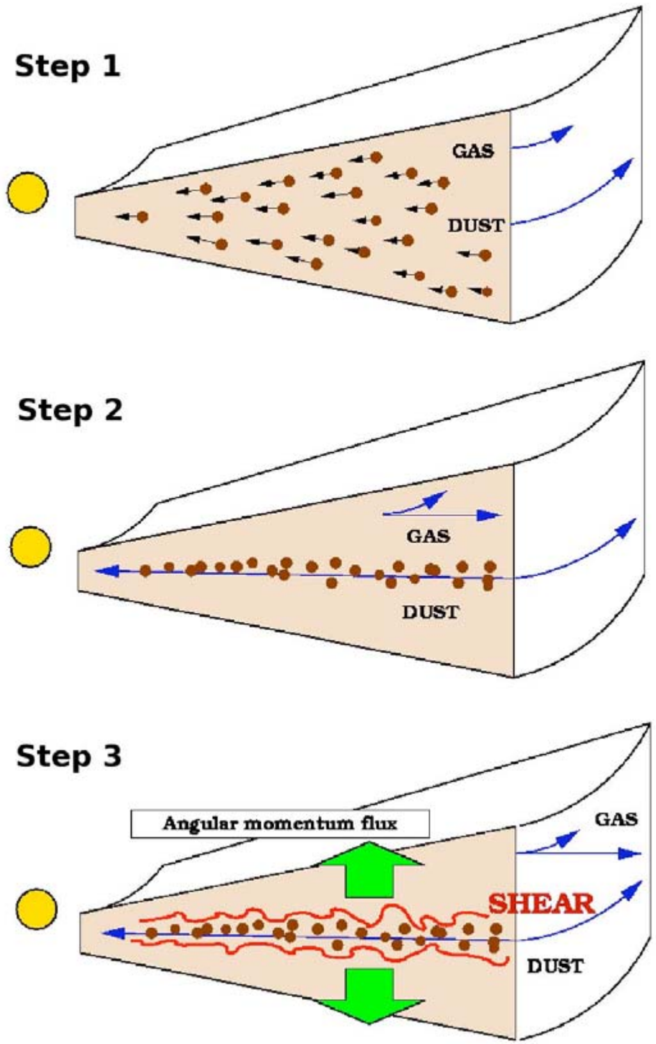


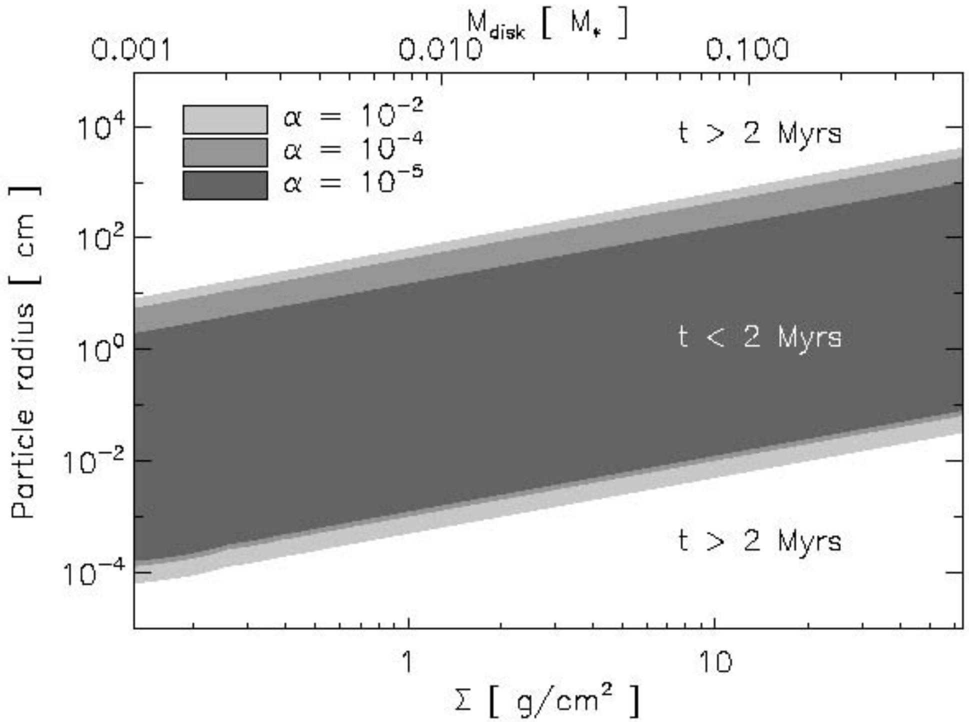

(Natta, LT, et al. PPV)

Data:
HAe (Testi et al. 2001; 2003; Natta et al. 2004)
TW Hya (Wilner et al. 2000;Calvet et al. 2002)
TTauri stars (Rodmann et al. 2005)

# Pebbles should not survive in disks!



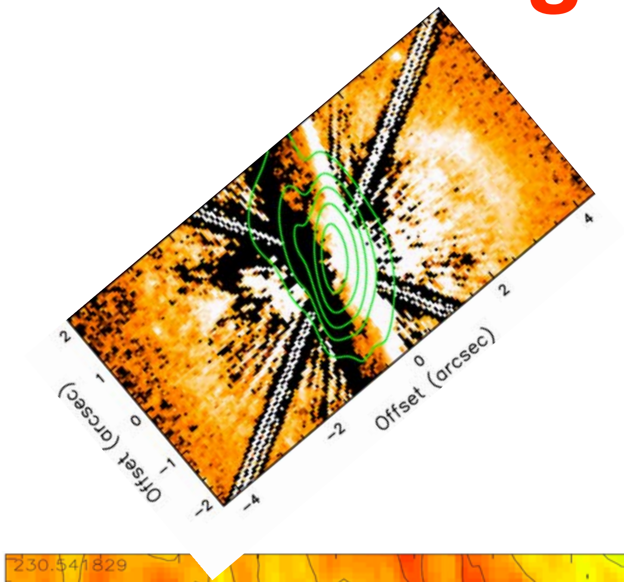

(Brauer et al. 2007)

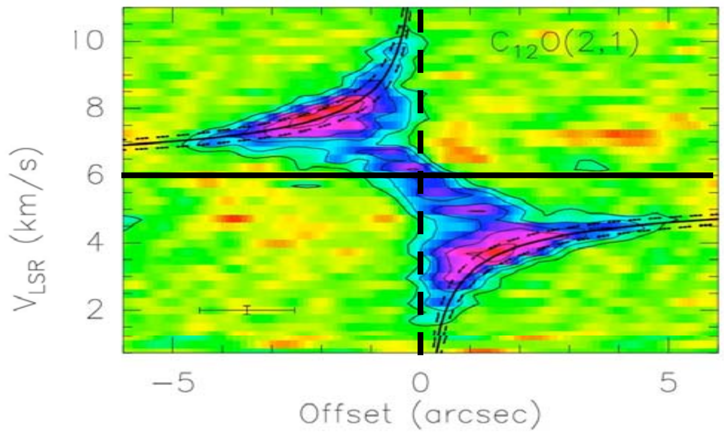


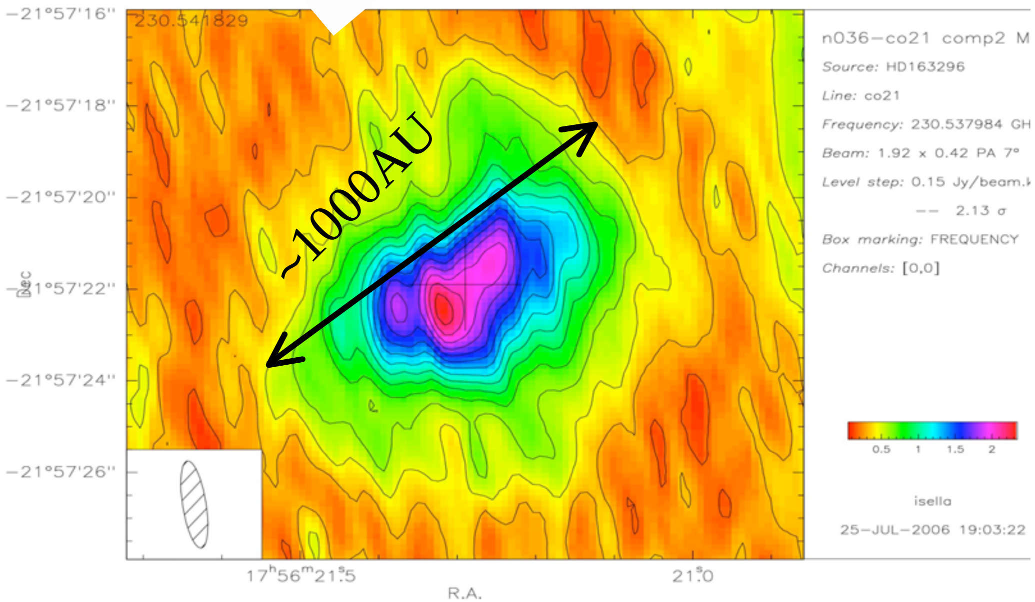

- Radial drift of mm-cm size particles at r~100AU can be very fast
- Viscosity, porosity, gas/dust ratio
- Trapping in disk patterns
  - Vortices, spiral arms…

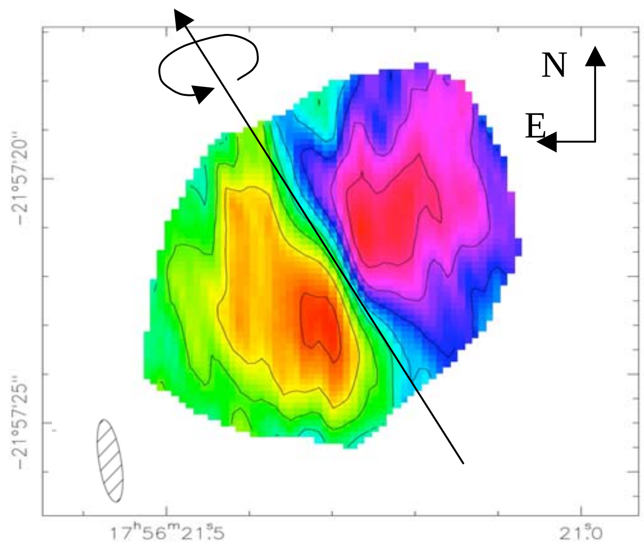
# Resolving the disk properties

HD163296



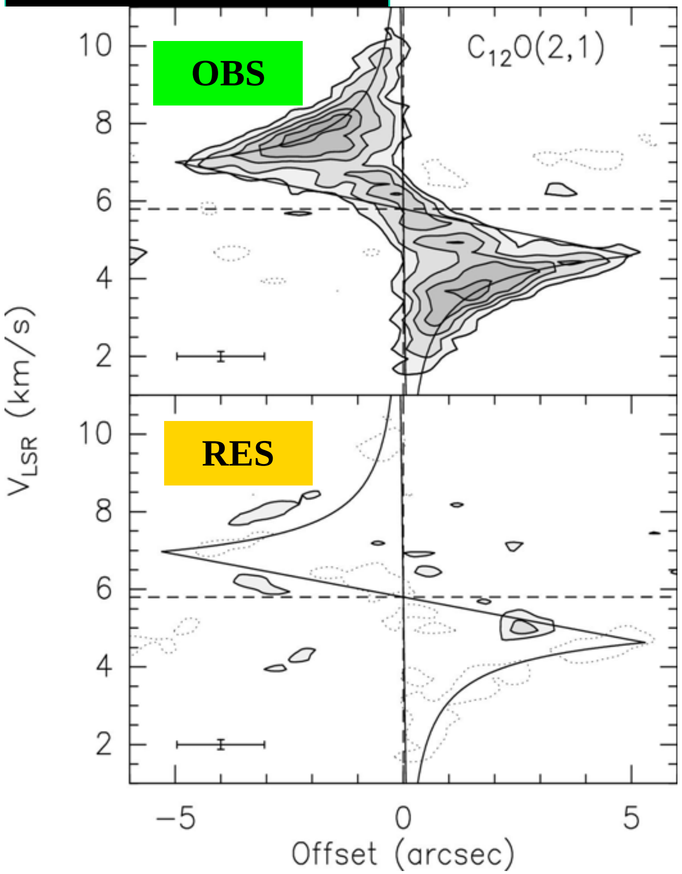



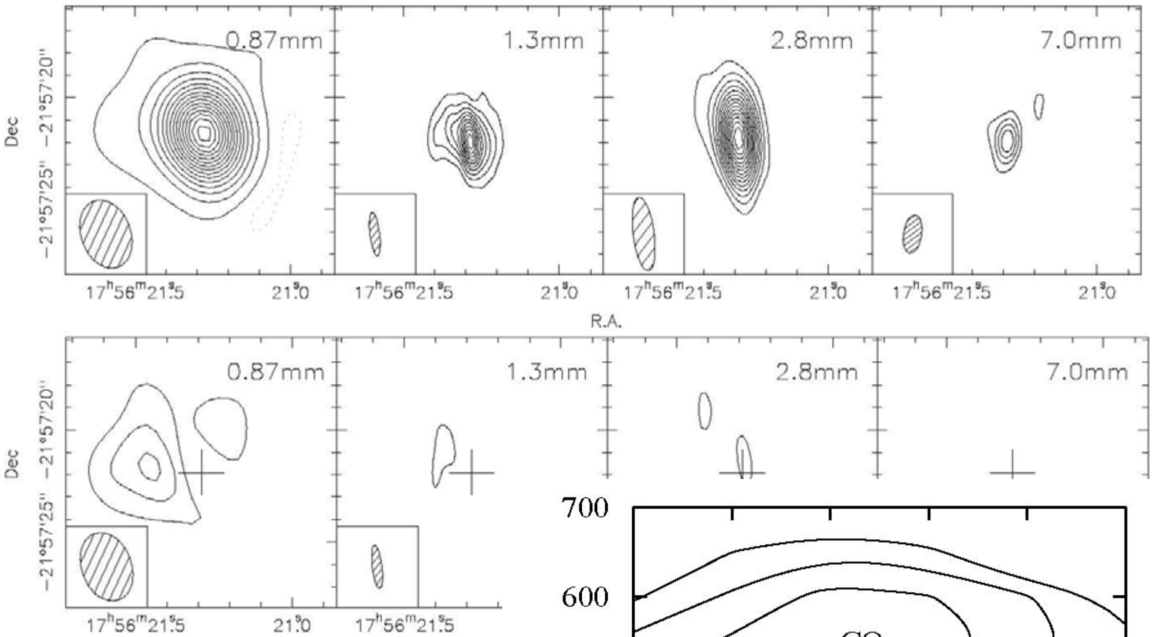



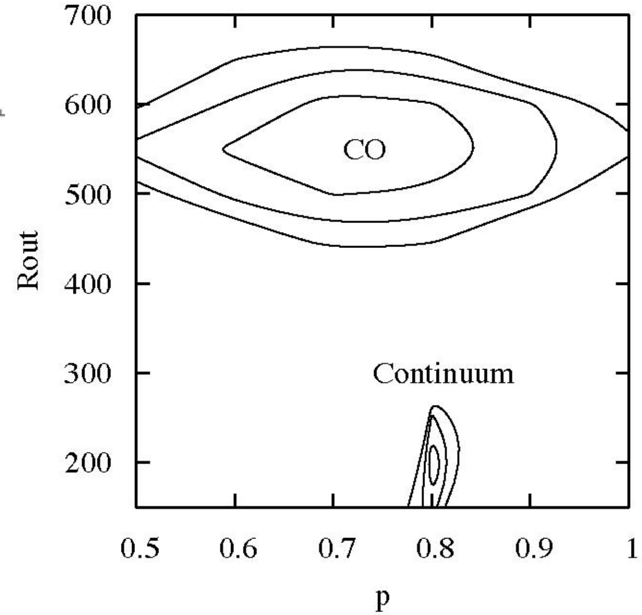

(Isella et al 2006)

# Resolving the disk properties

HD163296




(Isella et al 2006)

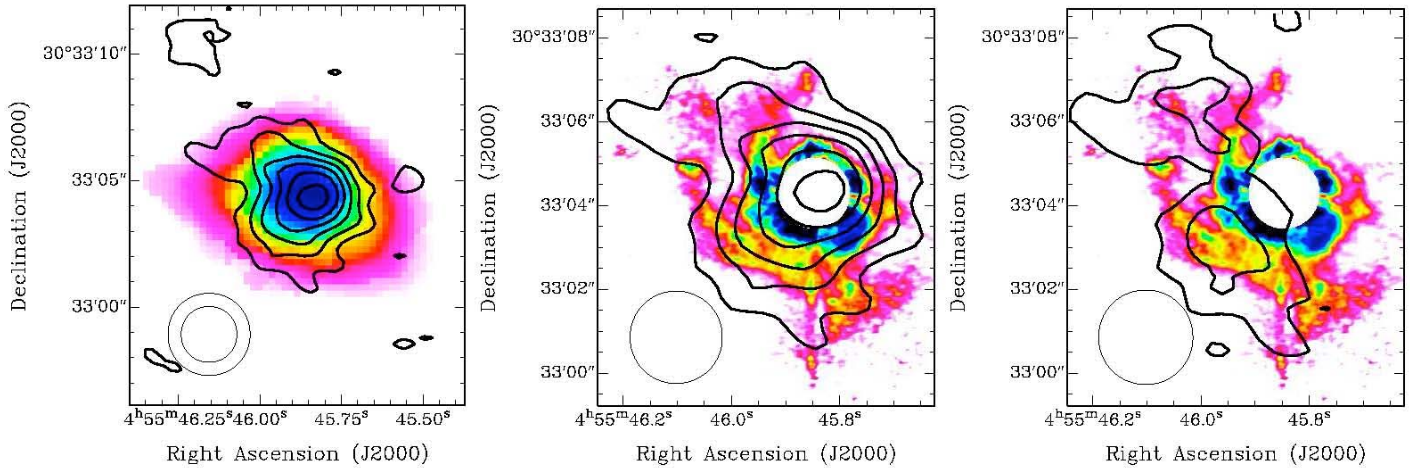
Dust properties

$$F_\nu(r) \sim \Sigma(r) \times T(r) \times k_\nu(r)$$

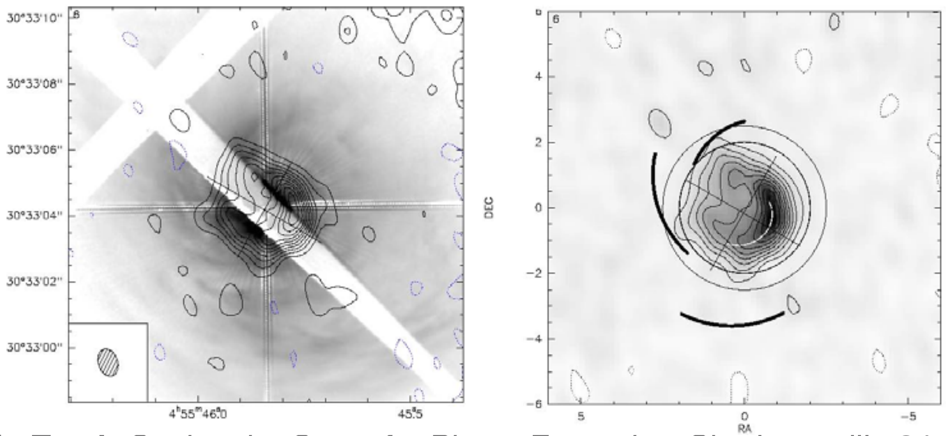
Disk structure

# Spiral structure in AB Aur

- Detection at mm wavelengths confirm that the spiral structure seen in scattered light correspond to a density contrast in the disk



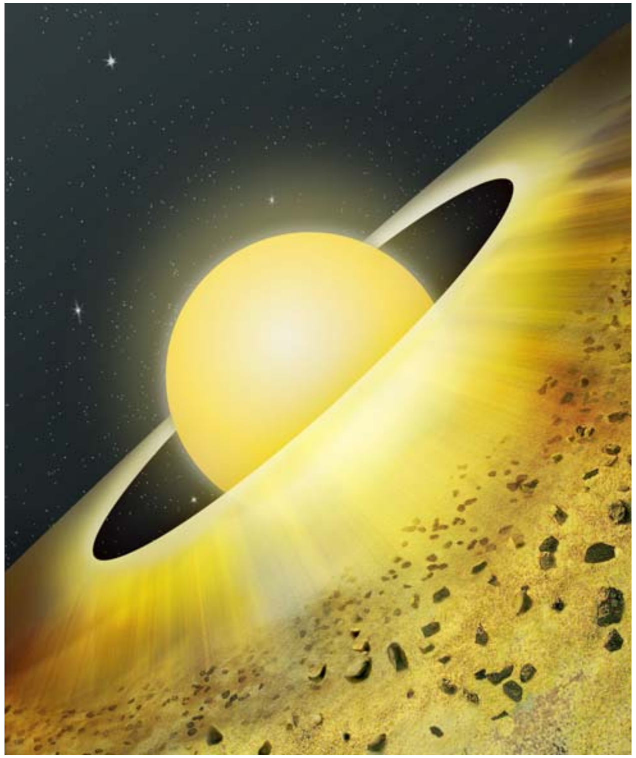

OVRO 2.7mm
(Corder et al. 2005)

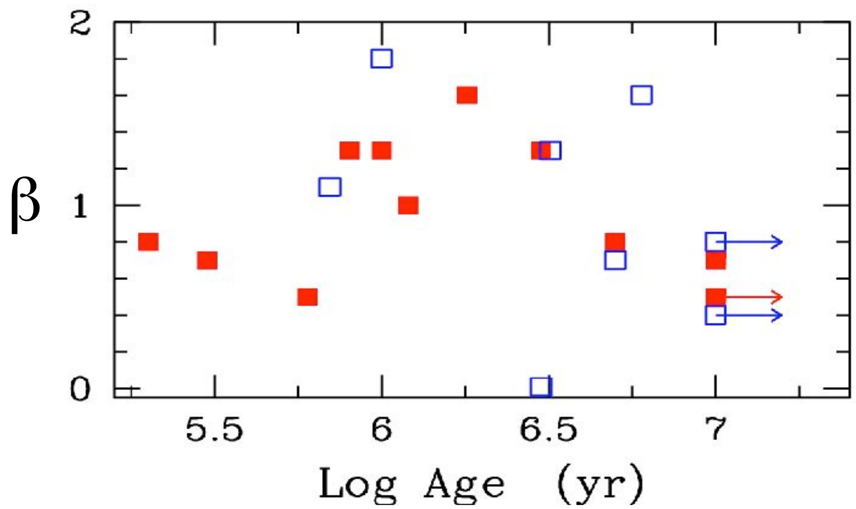



Also confirmed by PdBI and SMA Observations (Pietu et al. 2005; Lin et al. 2005)

# State of the Art & Future Directions

- Grains grow and settle in disks around all type of PMS objects
- Grain evolution can be very fast as we see highly processed grains around objects of all ages between 1 and 10 Myr
- It is difficult to derive a consistent picture of grain evolution because different observations probe different regions of the disks and samples are still small





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- Most of the dust mass is contained in “pebbles”
  - Large bodies, if present, do not dominate the solid mass of the disk up to 5-10 Myr
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  - Or perhaps we are just observing the odd beasts?

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- Timescale for settling and growth: is dust evolution occurring in Class I phase?
  - Early planet formation?
- Large grains should be dragged to the central star on very short timescales, why do we see them at all?
  - Resolve the radial dependence of Grain Growth in disks