Circumstellar disks as observed at millimeter wavelegths

Leonardo Testi (European Southern Observatory)

Silvia Leurini (European Southern Observatory)

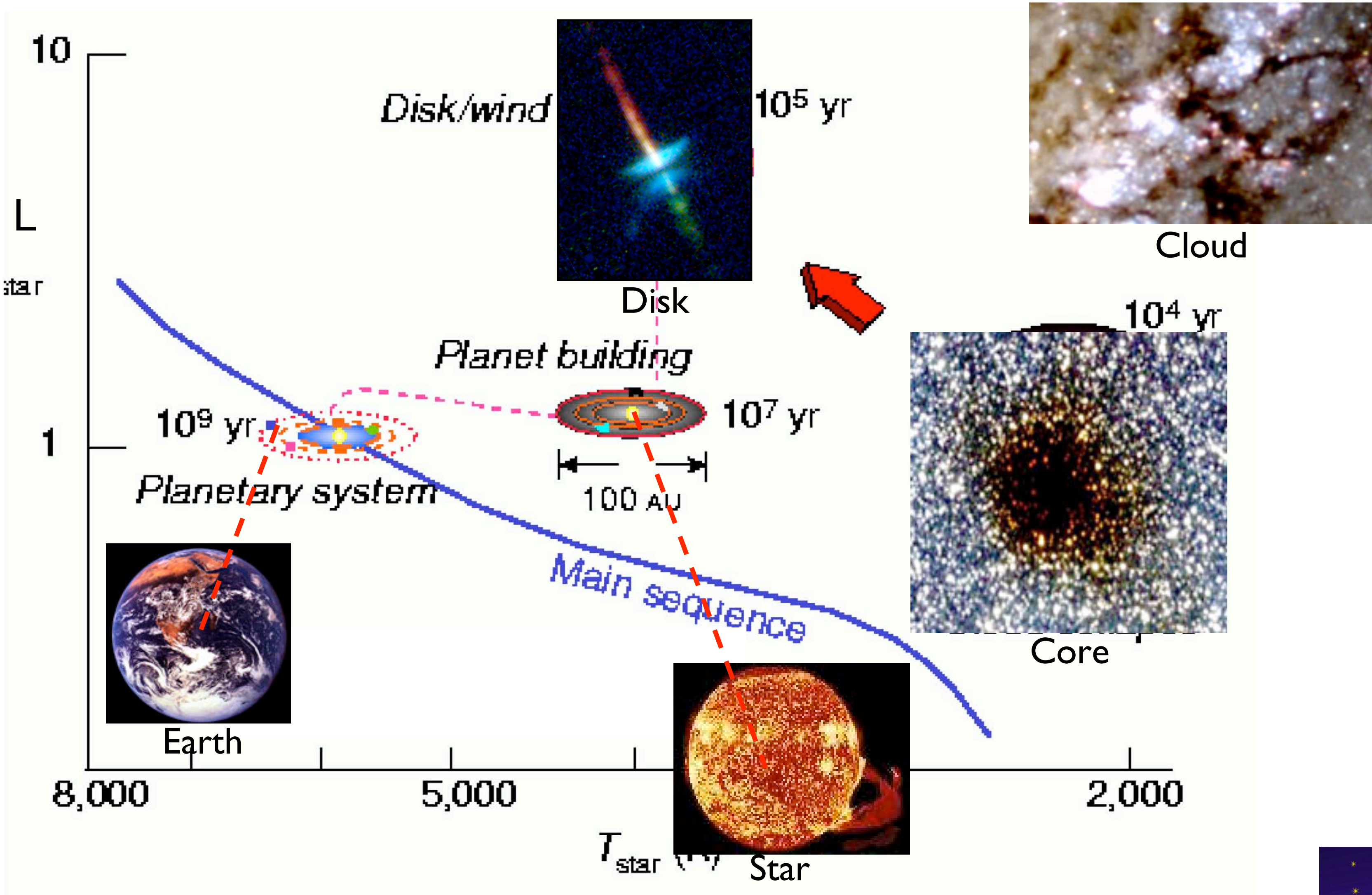
- Introduction - LT
- Disks and Star Formation @ mm-λ - SL
- Disk Evolution & Planet Formation - LT
- Present and Future of mm observations - SL

Disk Evolution & the Initial Steps towards Planet Formation

Leonardo Testi (European Southern Observatory)

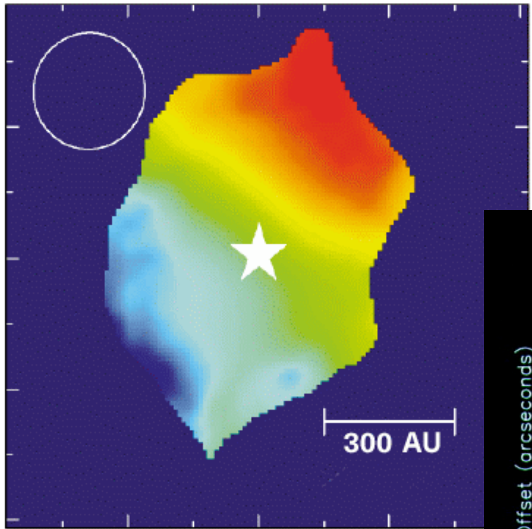
- Disk Evolution
- From Grains to Pebbles
- Observing Planet Formation with ALMA

From Cores to Stars and Planetary Systems

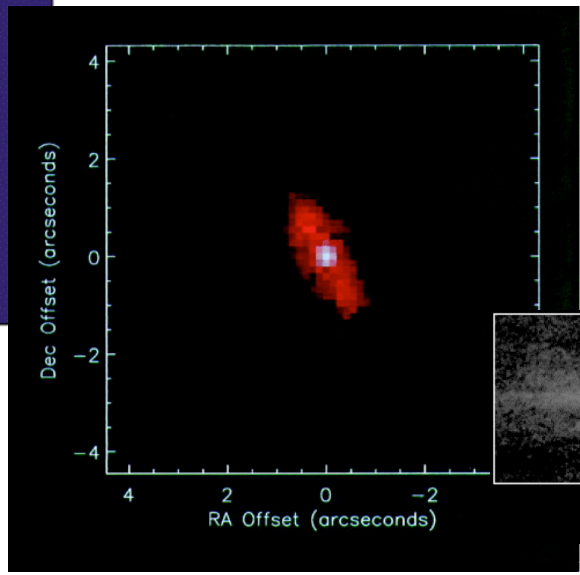


Disk Evolution

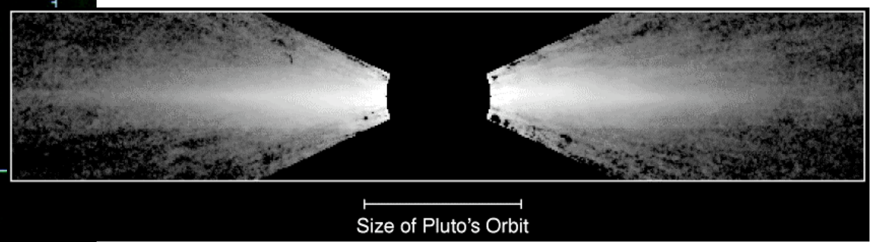
- There is evidence that disk evolution and planet formation systems may occur on timescales of a few million years



MWC 480
Young gaseous disk – 6 Myrs
CO(2-1): Mannings et al 1997

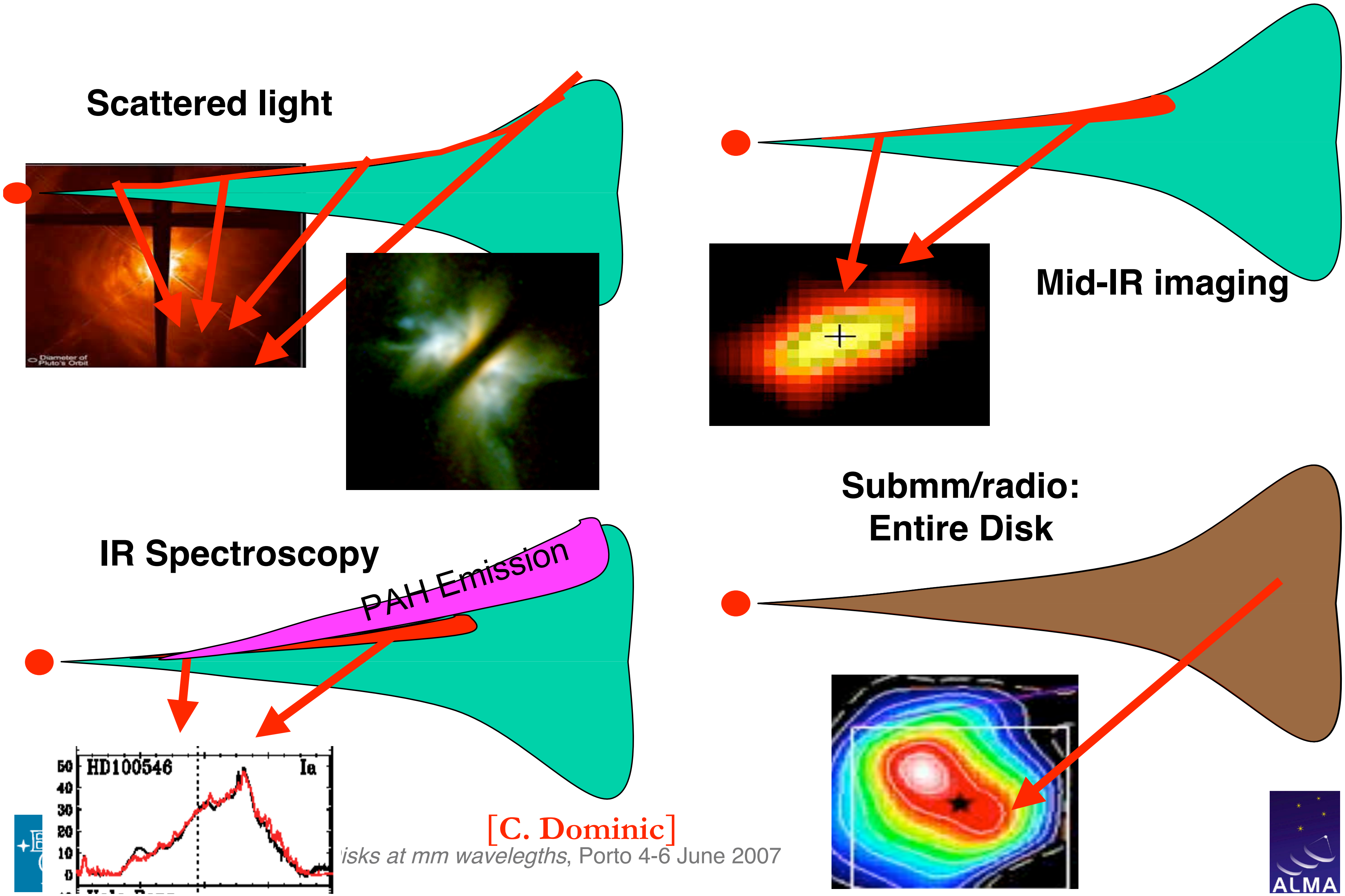


HR 4796 A
Evacuated inner disk – 15Myr
MID-IR: Koerner et al. 1998



ß Pic
Debris disk – 100 Myrs
Scattered light: Burrows et al. 1995

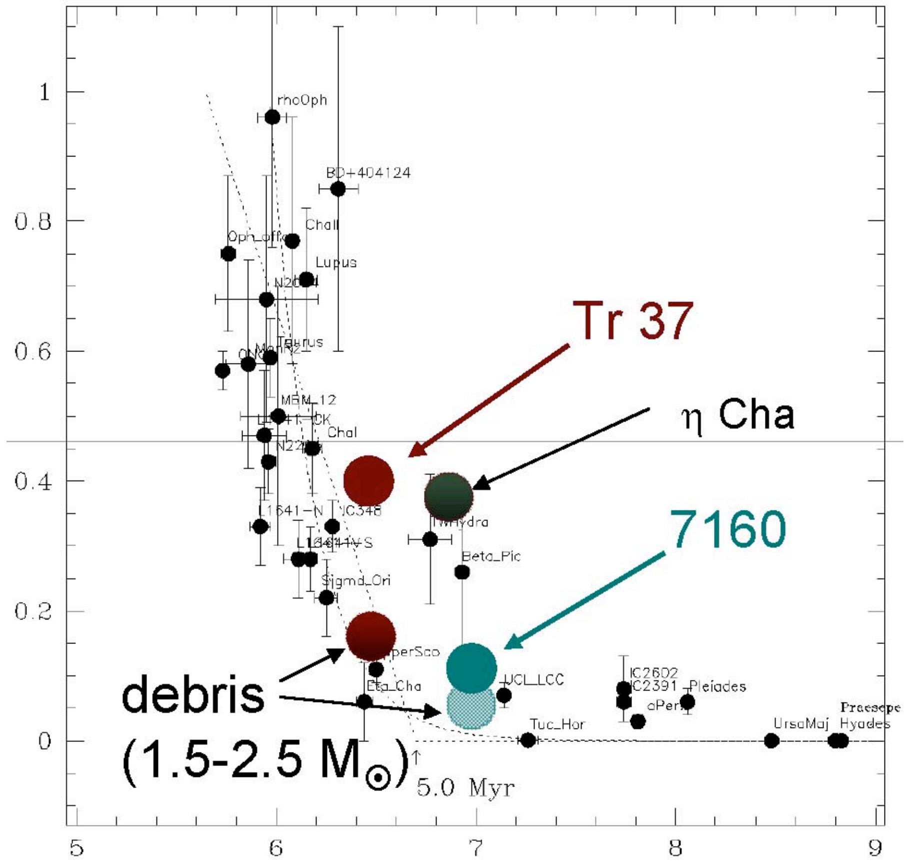
Which observations probe what?



[C. Dominic]

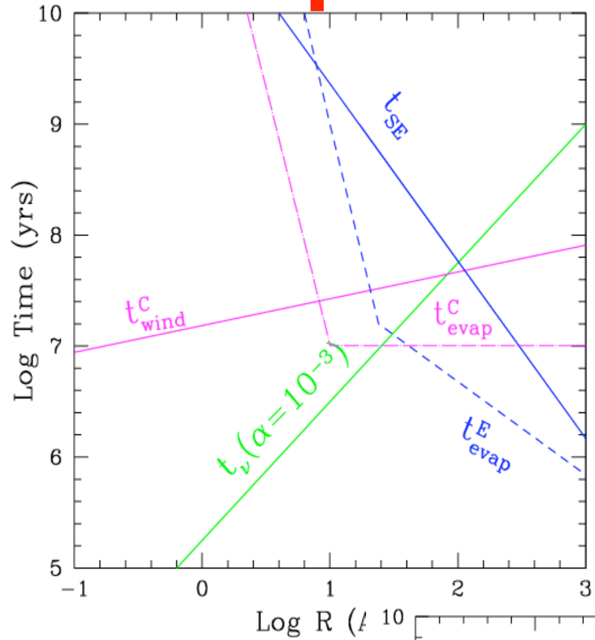
Inner disk clearing

- 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

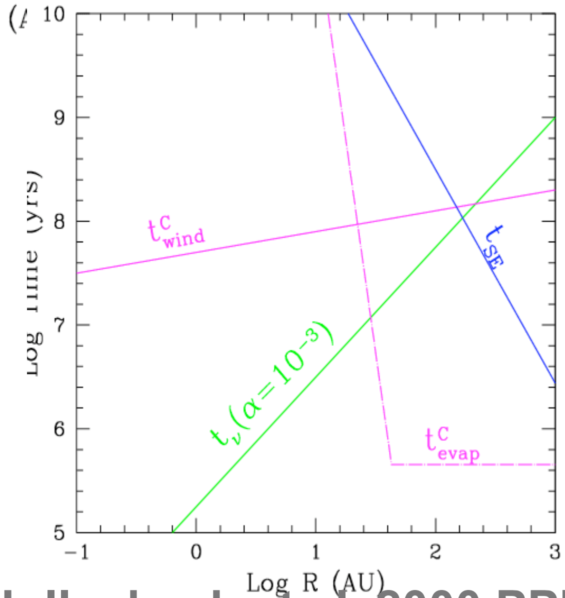


Why do disks dissipate?

- Local effects:
  - viscous evolution
  - photoevaporation by the central star
  - wind stripping
  - tidal interactions (binaries, planets)



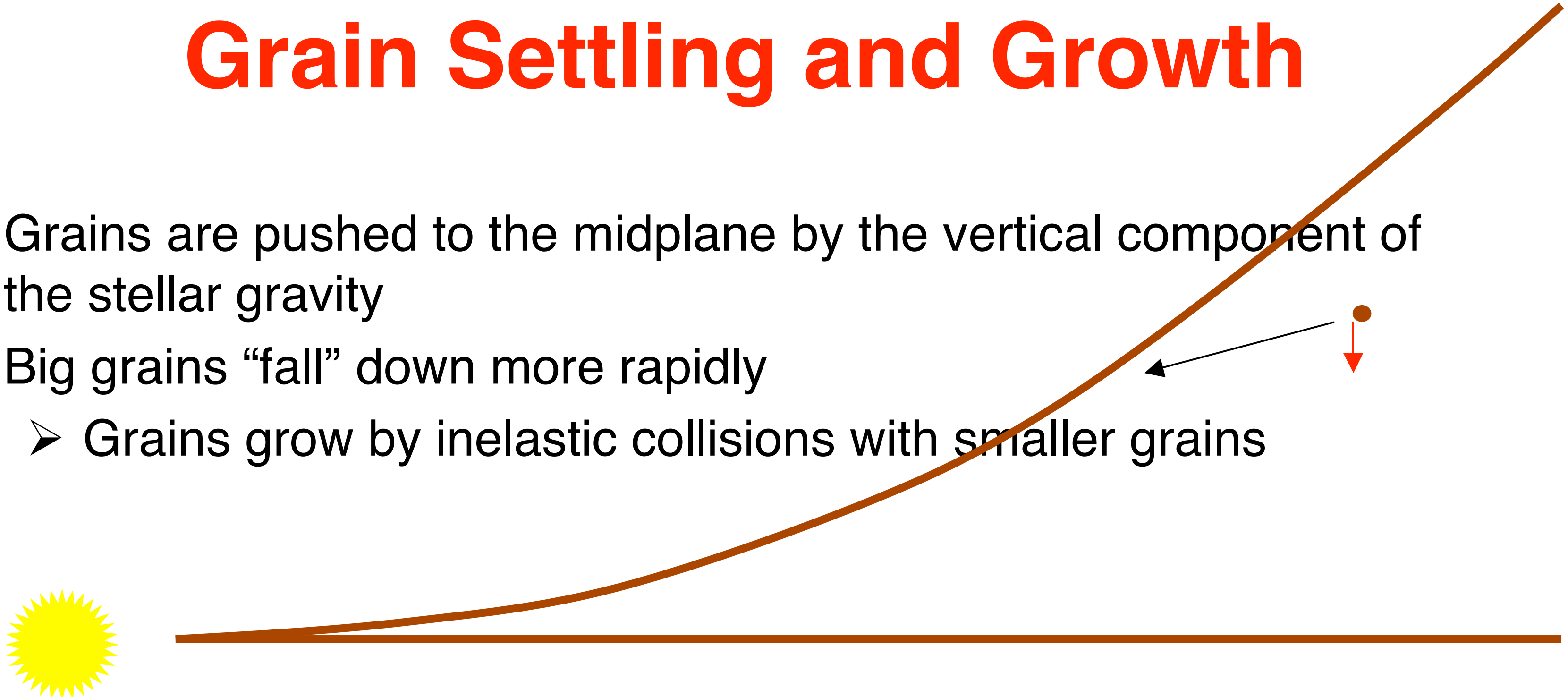
- Environmental effects:
  - stellar encounters in clusters
  - photoevaporation by other stars



Hollenbach et al. 2000 PPIV

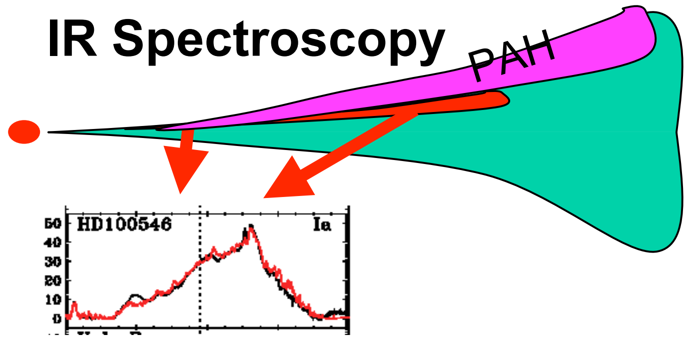
Grain Settling and Growth

- 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

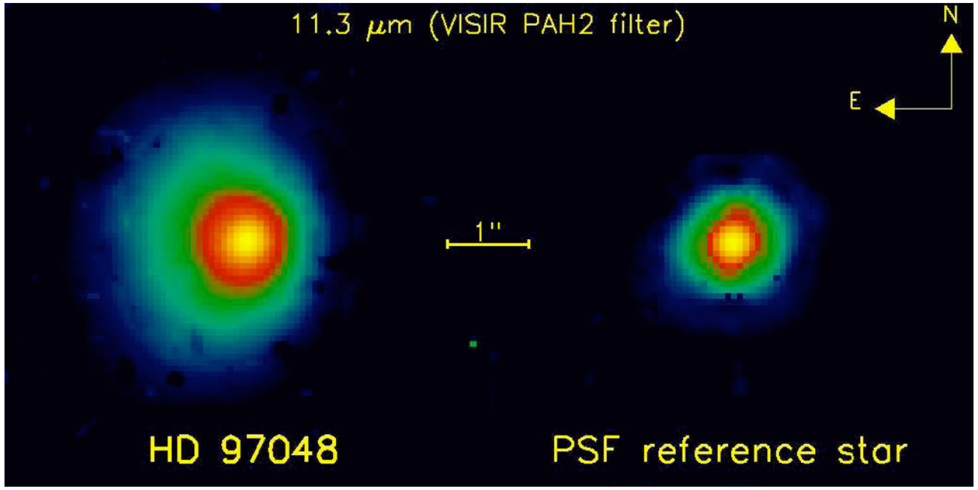


- The process is very fast and rapidly produces a vertical stratification of grain properties
- Turbulence, mixing and destructive collisions have to slow down this process
  - Need to maintain the “flaring” (SED)
  - Big grains are present also in the disk atmosphere

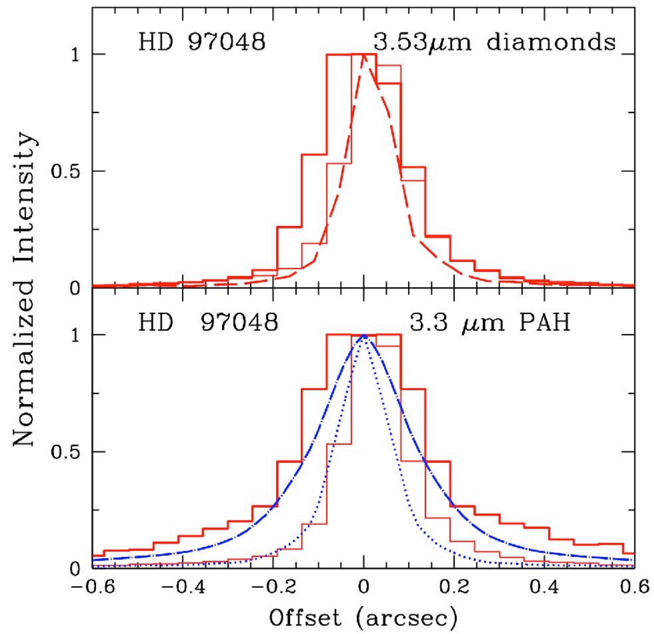
Disk surface



- Small particles are present in the upper layers of flared disks



(Doucet et al. 2006)

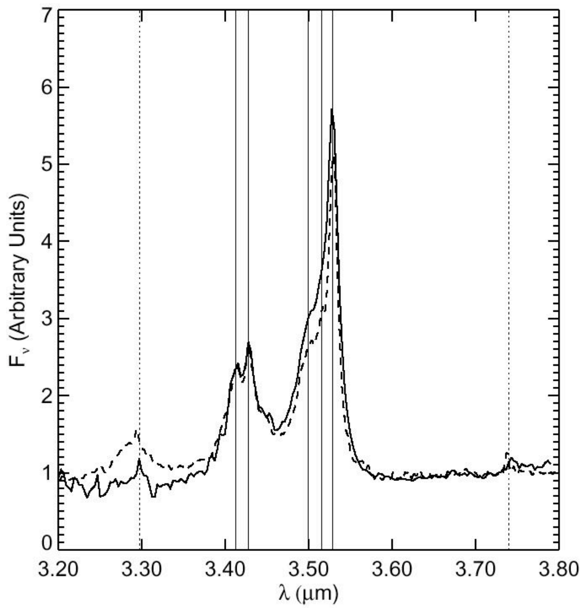


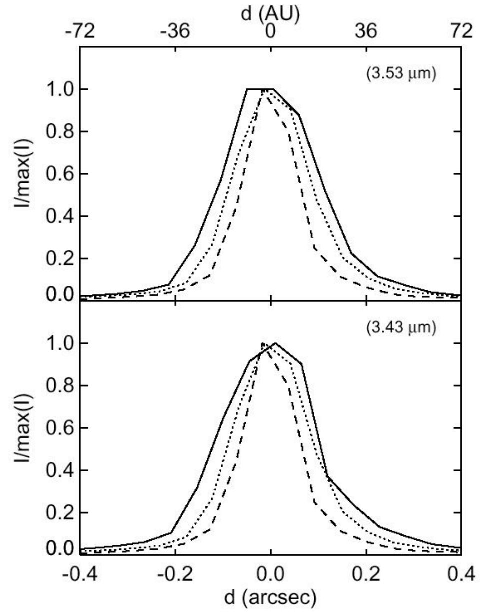
Large Grains: r <=10AU
(nano) Diamonds: r <=15 AU
PAHs: r > 20 AU

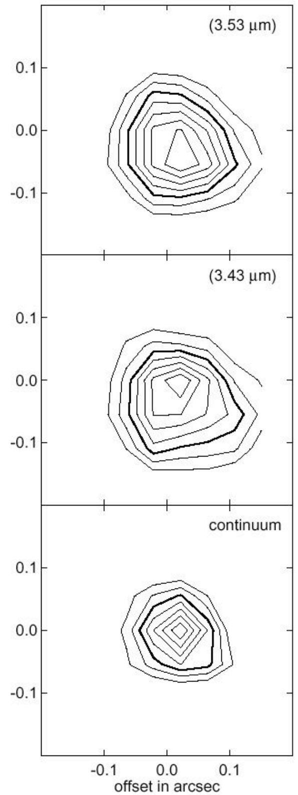
(Habart et al. 2004; 2005)

Diamonds in the HD97048 Disk

- VLT/NACO 0.08 arcsec 3.3μm spectroscopy
- Resolve the spatial location of different dust components



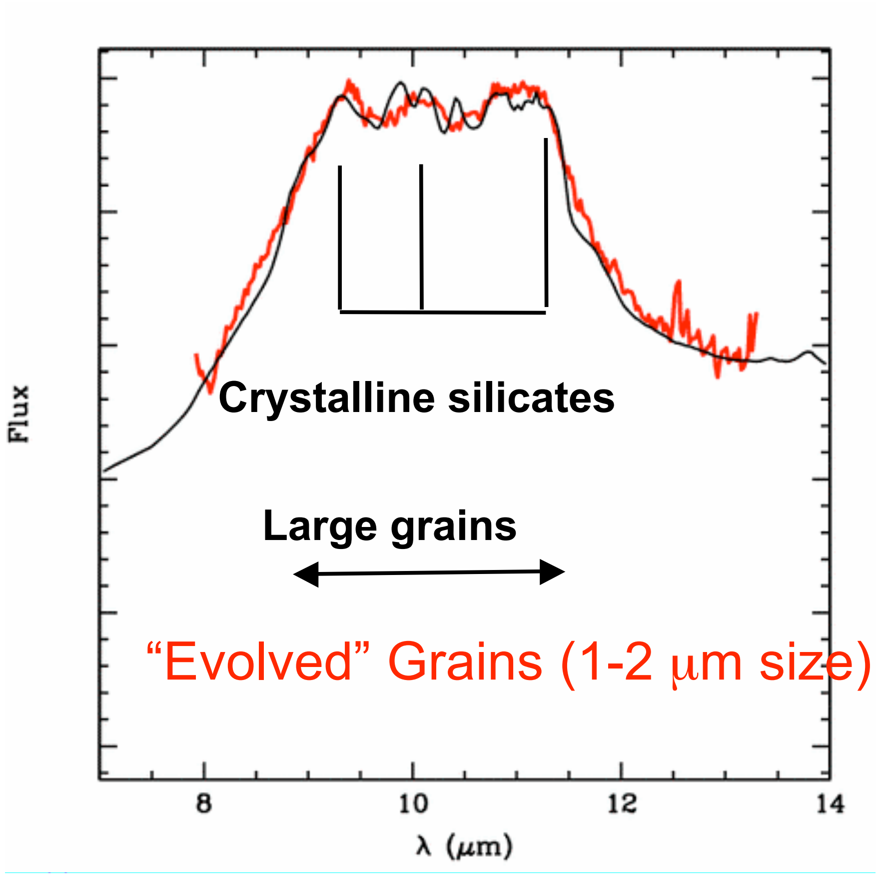




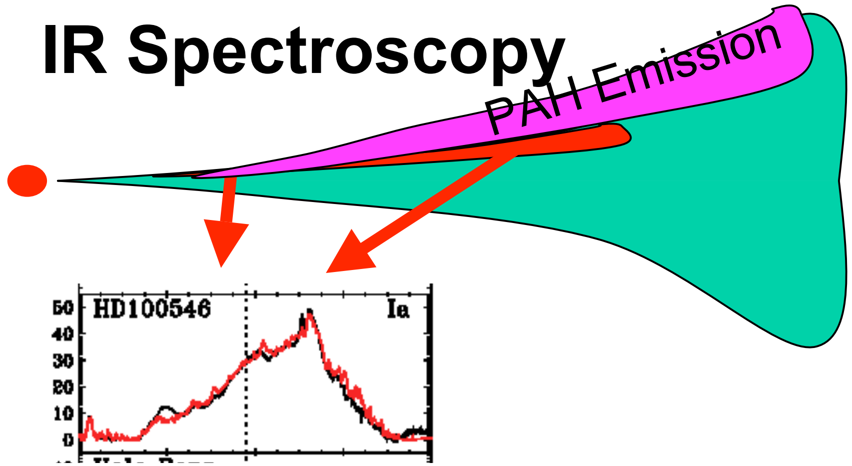
Large Grains: r <=10AU
(nano) Diamonds: r <=15 AU
PAHs: r > 20 AU

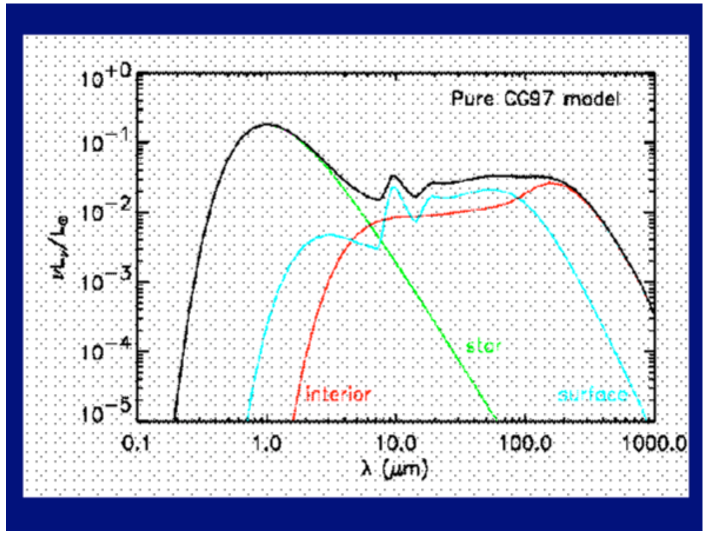
(Habart et al. 2004)

Processing of the 10 micron feature



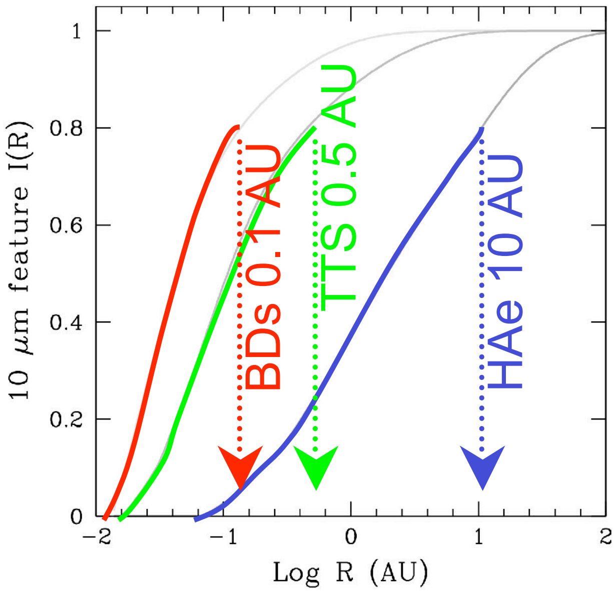
IR Spectroscopy

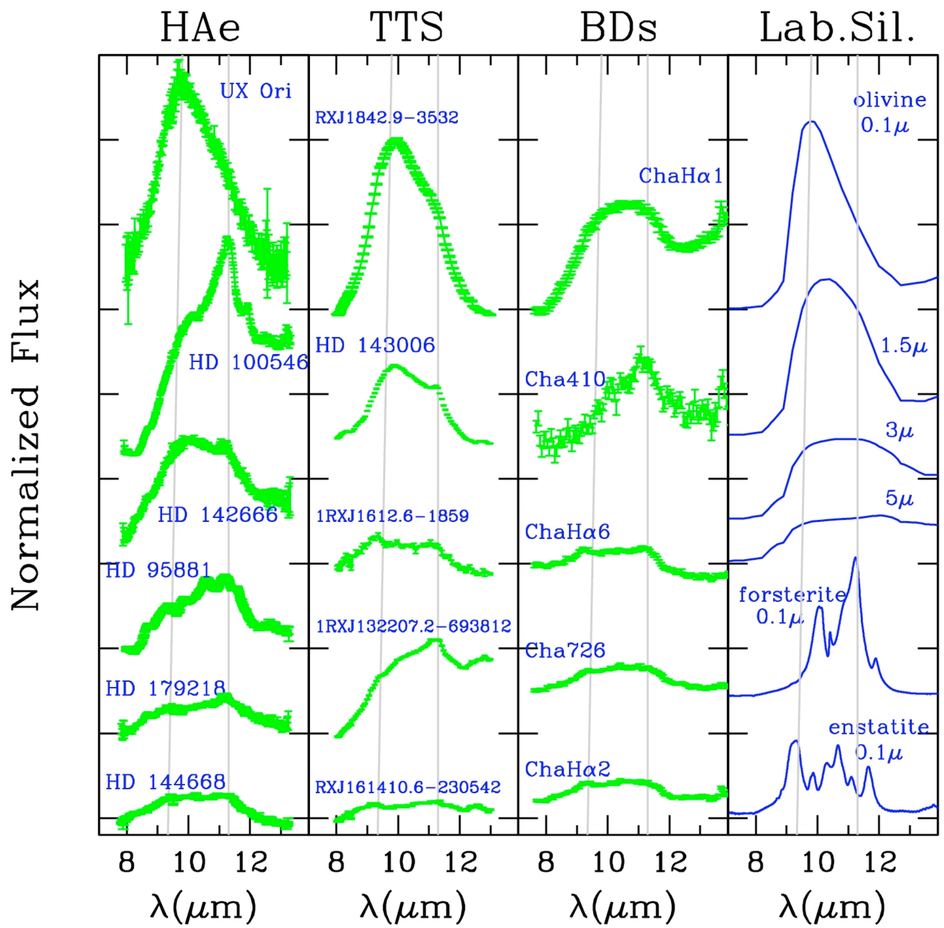




Grain Growth and Crystallization

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

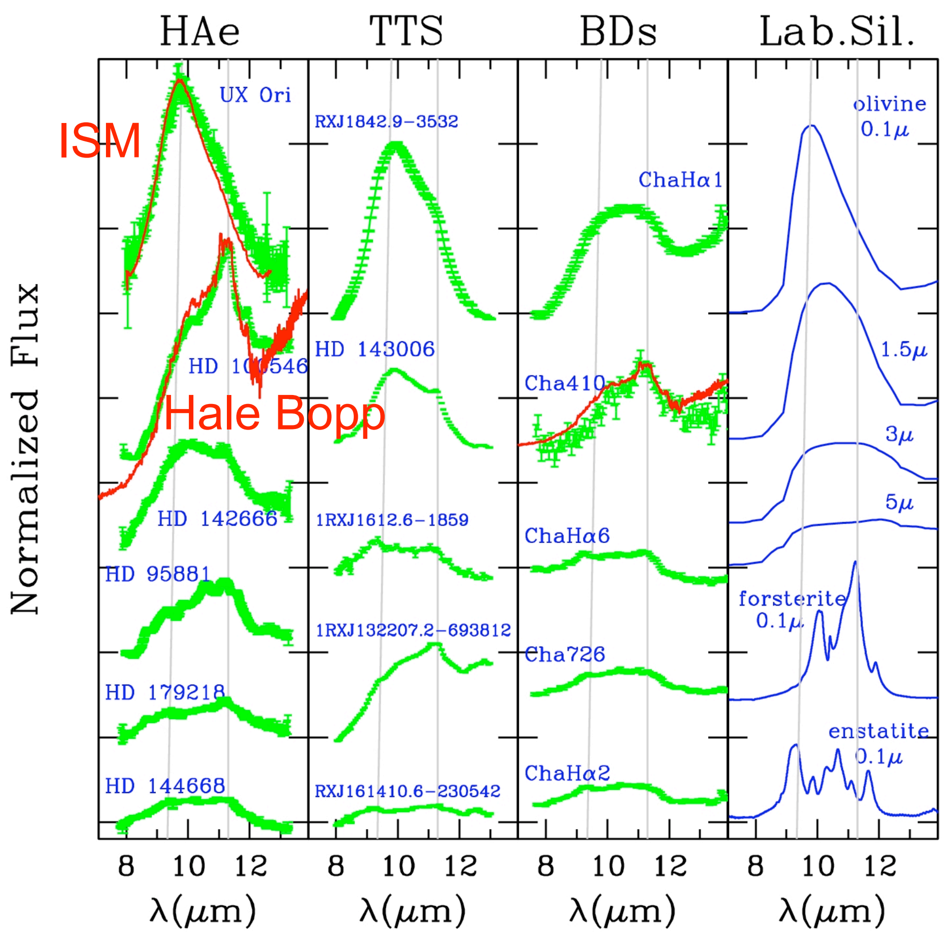




(Data: van Boekel et al. 2005
Bouwman et al. 2005; Apai et al 2005)

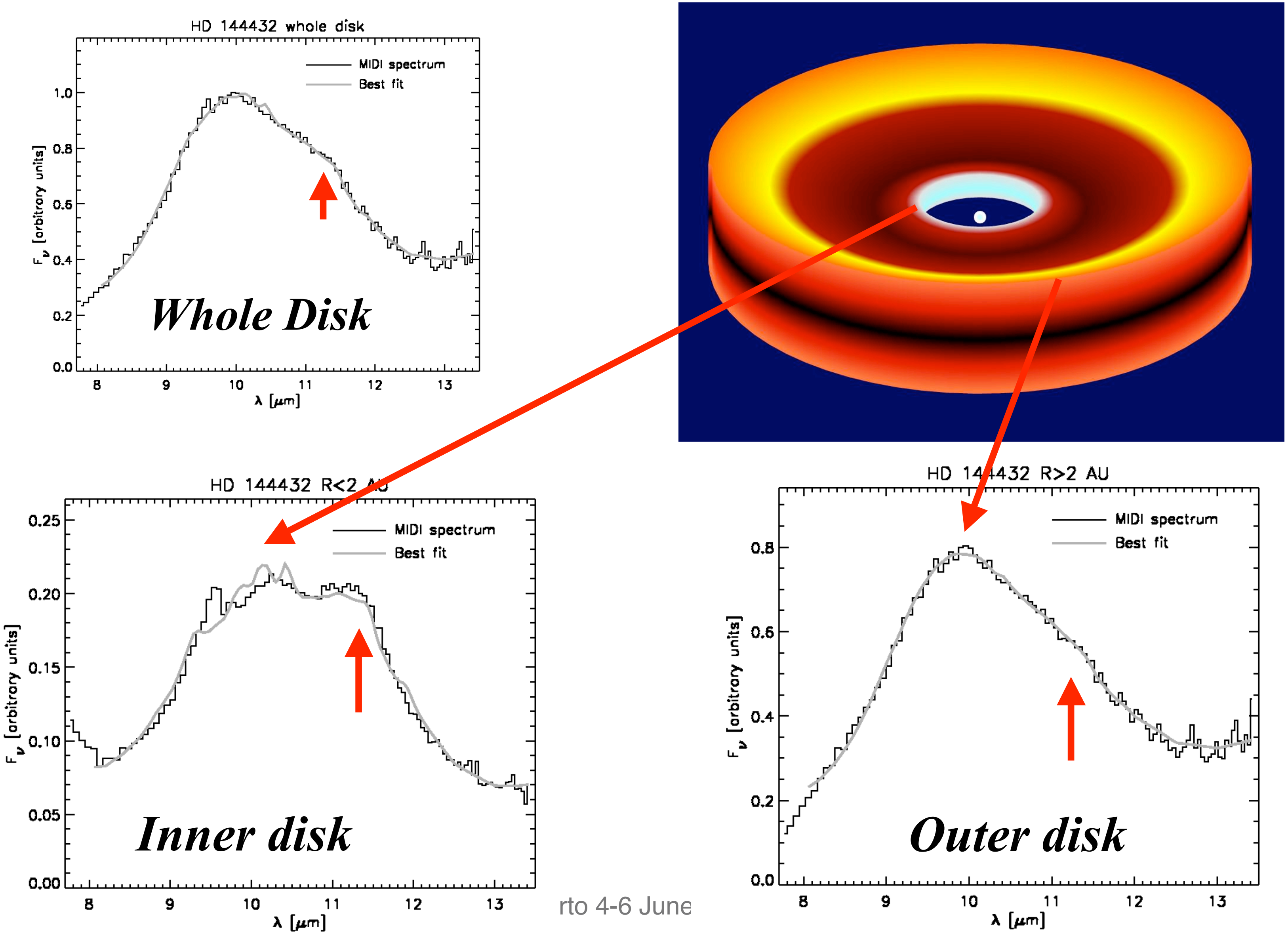
Grain Growth and Crystallization

- 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

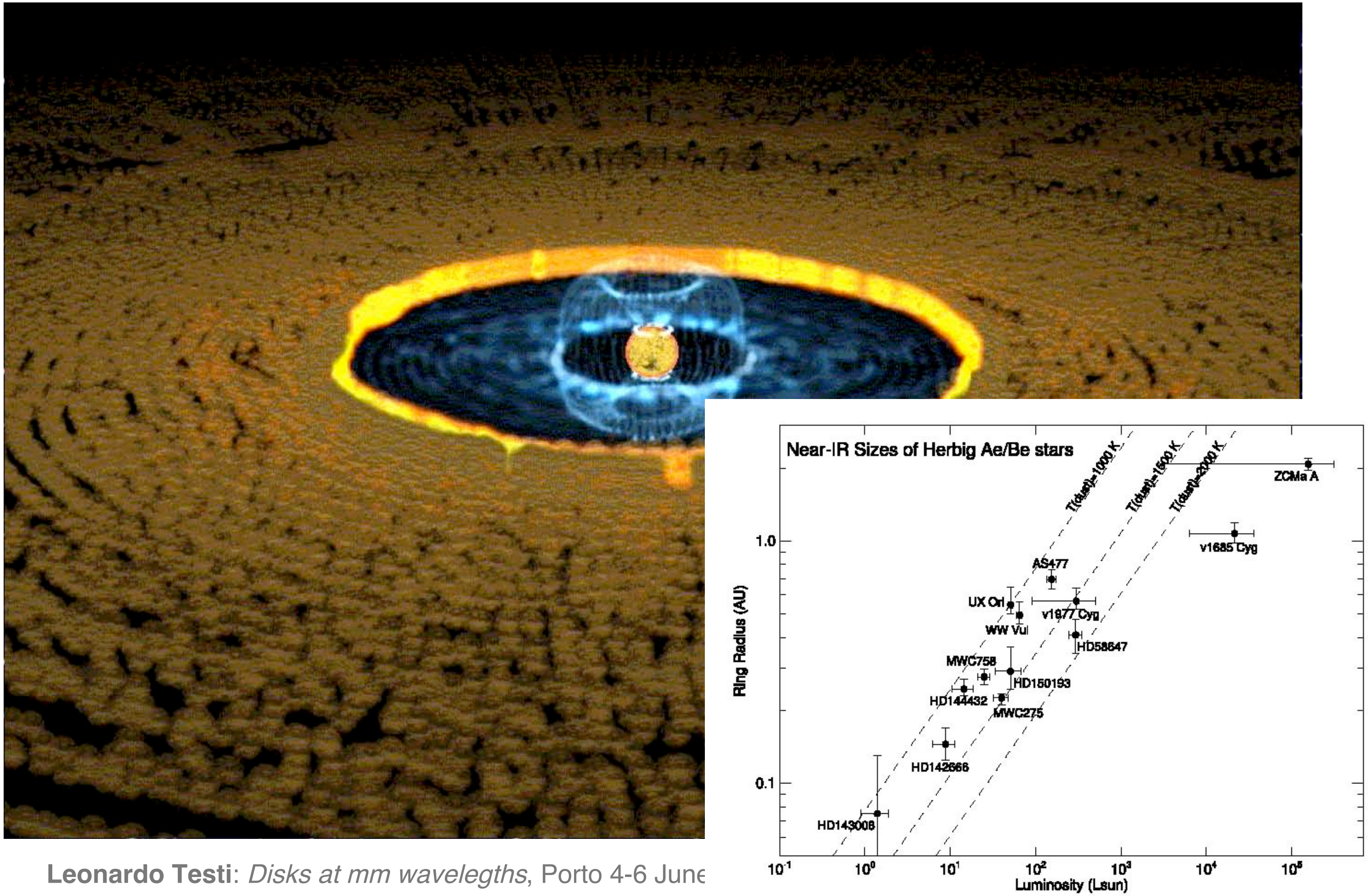


(Data: van Boekel et al. 2005
Bouwman et al. 2005; Apai et al 2005)

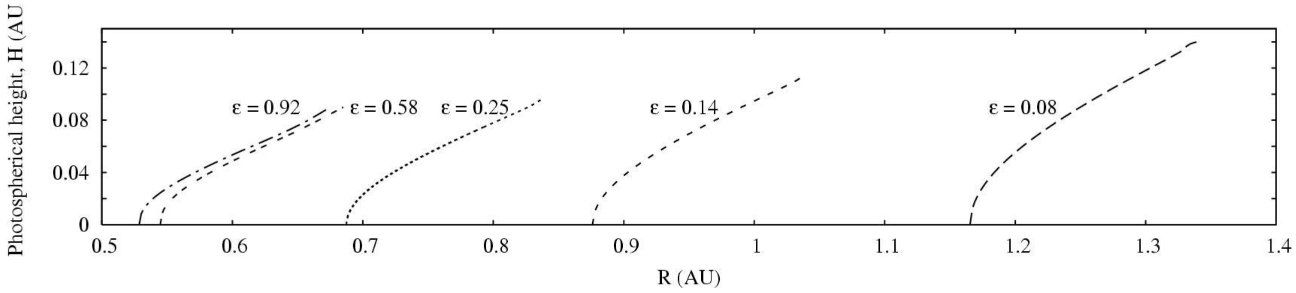
Spatially resolved spect (MIDI)



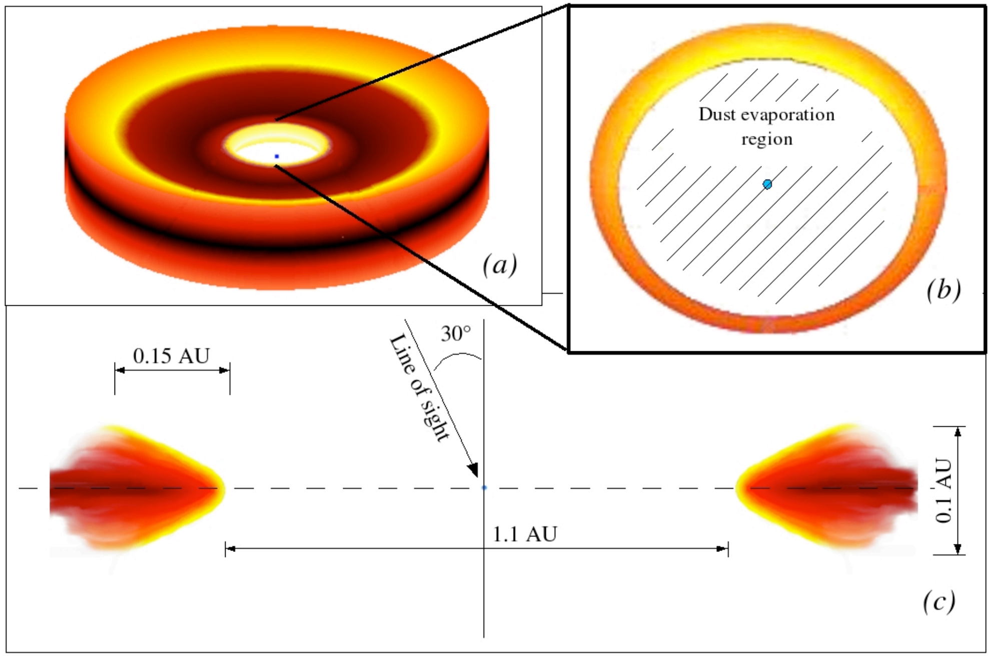
The inner disk



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



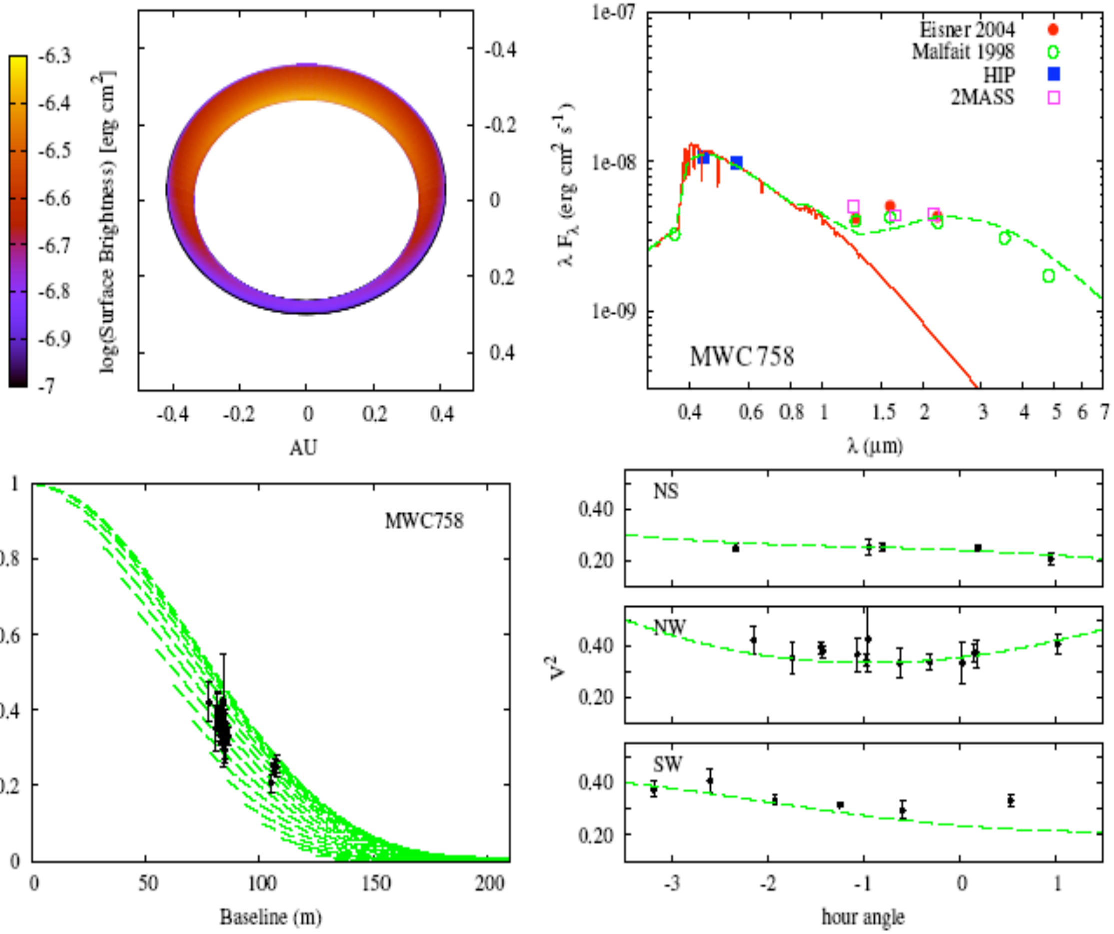
- The rim location and shape depend *only* on the grain properties



(Isella & Natta 2005)

Application to real PTI data

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



χ^2 test on the 3-dimesional space of the parameters

(Isella, Testi & Natta 2006)

Circumstellar disks @ mm-λ

- 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

(sub)mm continuum emission

$$F_\nu = \frac{cos\theta}{D^2}\int_{r_i}^{r_o} B_\nu(T_d)(1-e^{-\tau_\nu})2\pi r dr$$

$T_d \sim r^{-q}$

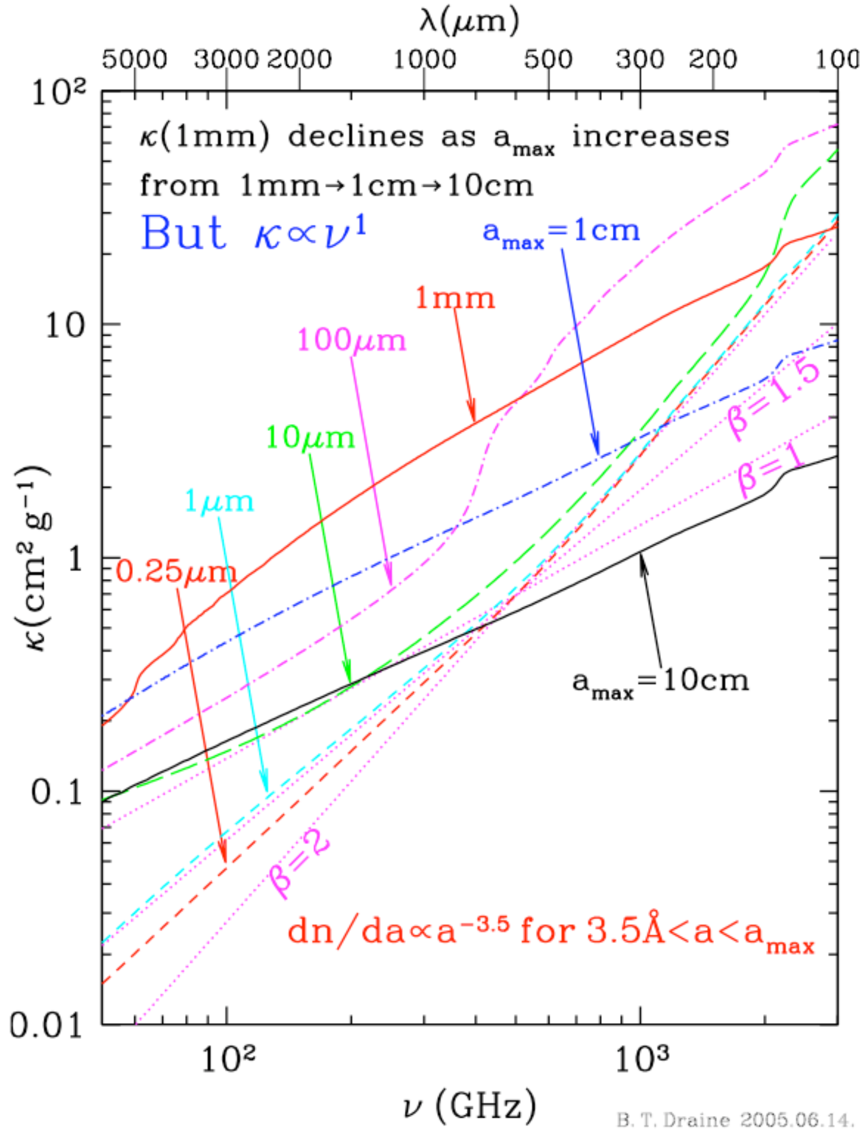
$\tau_\nu \propto \Sigma(r)\kappa_\nu$ $\Sigma(r) \propto r^{-p}$ $\kappa_\nu \propto \kappa_o \nu^\beta$

$\tau_\nu \ll 1$ $T_d \approx const.$

$F_\nu \sim \kappa_\nu\ B_\nu(T_d)\ M_d$

$F_\nu \sim \kappa_\nu\ \nu^2\ T_d\ M_d$

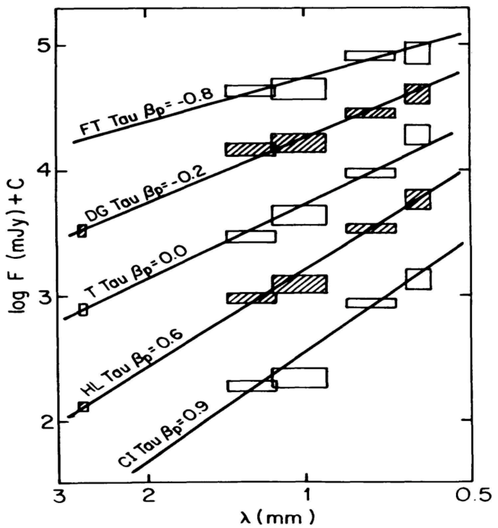
$F_\nu \sim \nu^{2+\beta}$



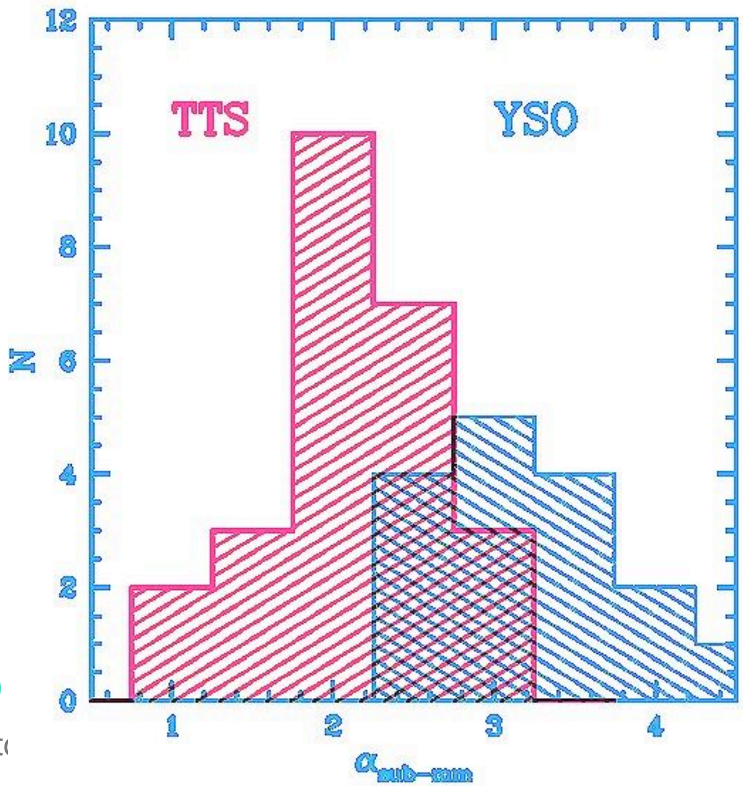
(Draine 2005)

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>>λ)
- $[F_\nu \sim \nu^\alpha; \alpha = 2 + \beta; \kappa_\nu \sim \nu^\beta]$



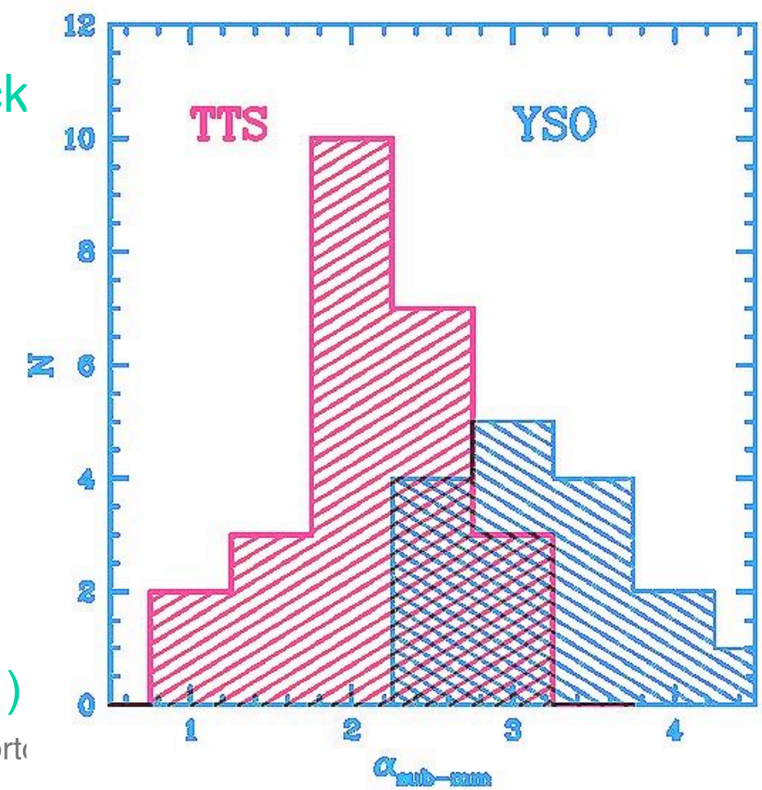
Single dish $\alpha_{sub\text{-}mm}$
(Beckwith & Sargent 1991)



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>>λ).
- [$F_\nu \sim \nu^\alpha ; \alpha = 2 + \beta ; \kappa_\nu \sim \nu^\beta$]

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

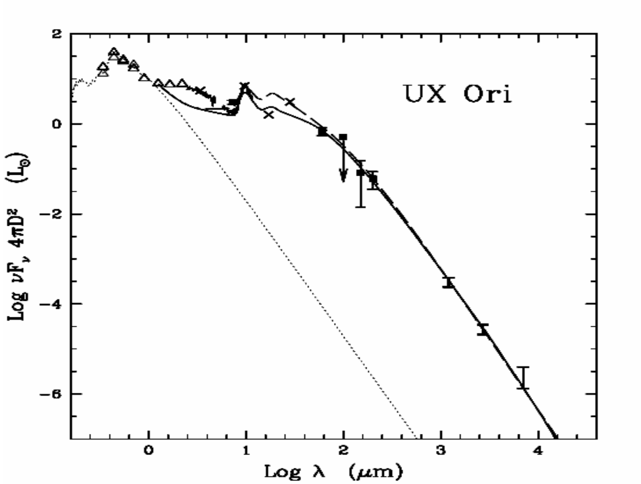


Single dish α_{sub-mm}
(Beckwith & Sargent 1991)

ALMA

Evolved dust in HAe disks

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

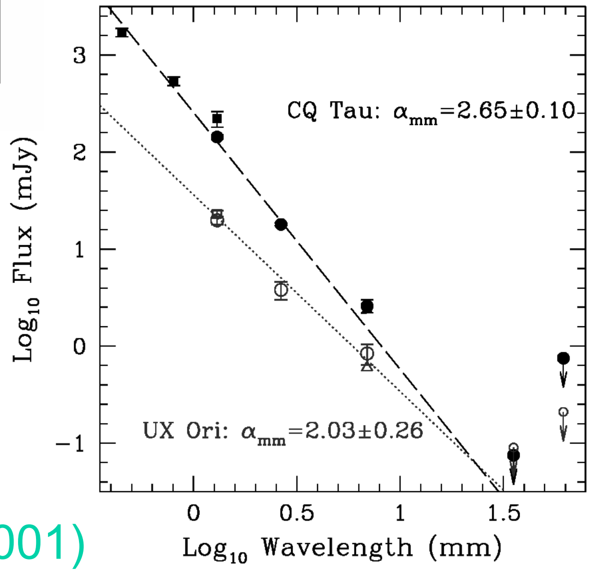


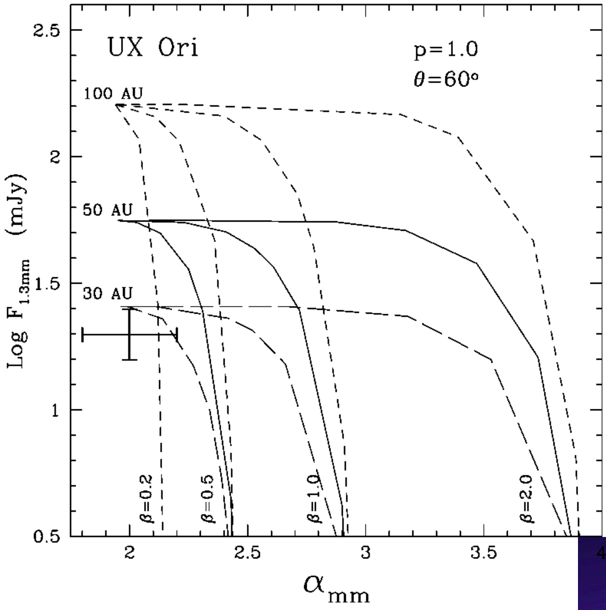
1. **Very small, optically thick, ISM grains disk**
2. **Large disk with very large (few cm size) grains**

PdBI 1.2 & 2.7 mm
VLA 7mm and 3.6cm

α_{mm}~2.0; β~0.1
a ≥ 10cm

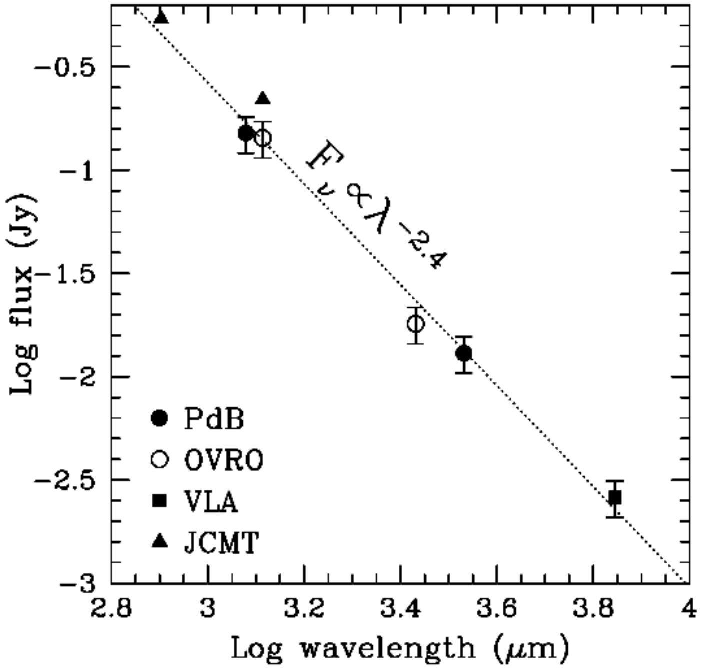
(Testi et al. 2001)





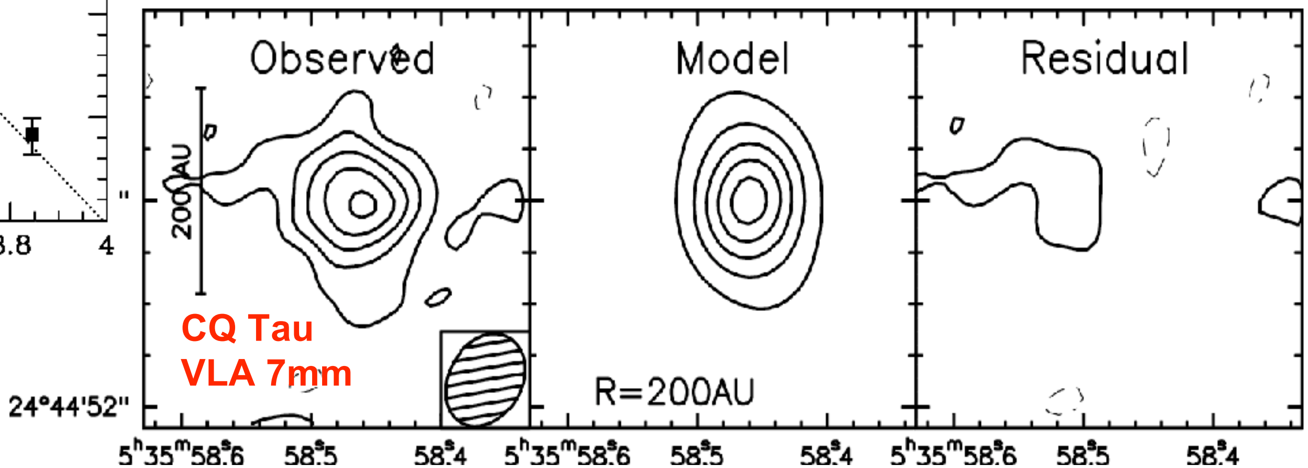
Evolved dust in HAe disks

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



Disk resolved at mm wavelengths:

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



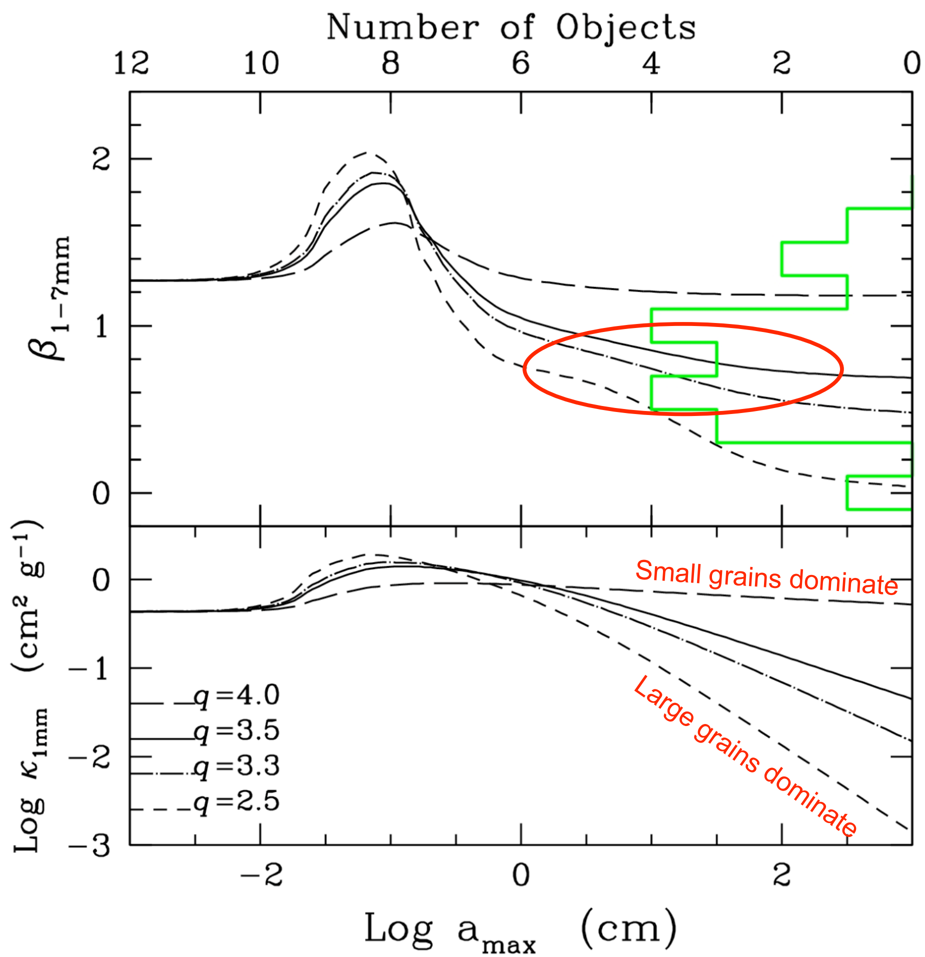
α_{mm}~2.4; p~1.5; β~0.6

(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

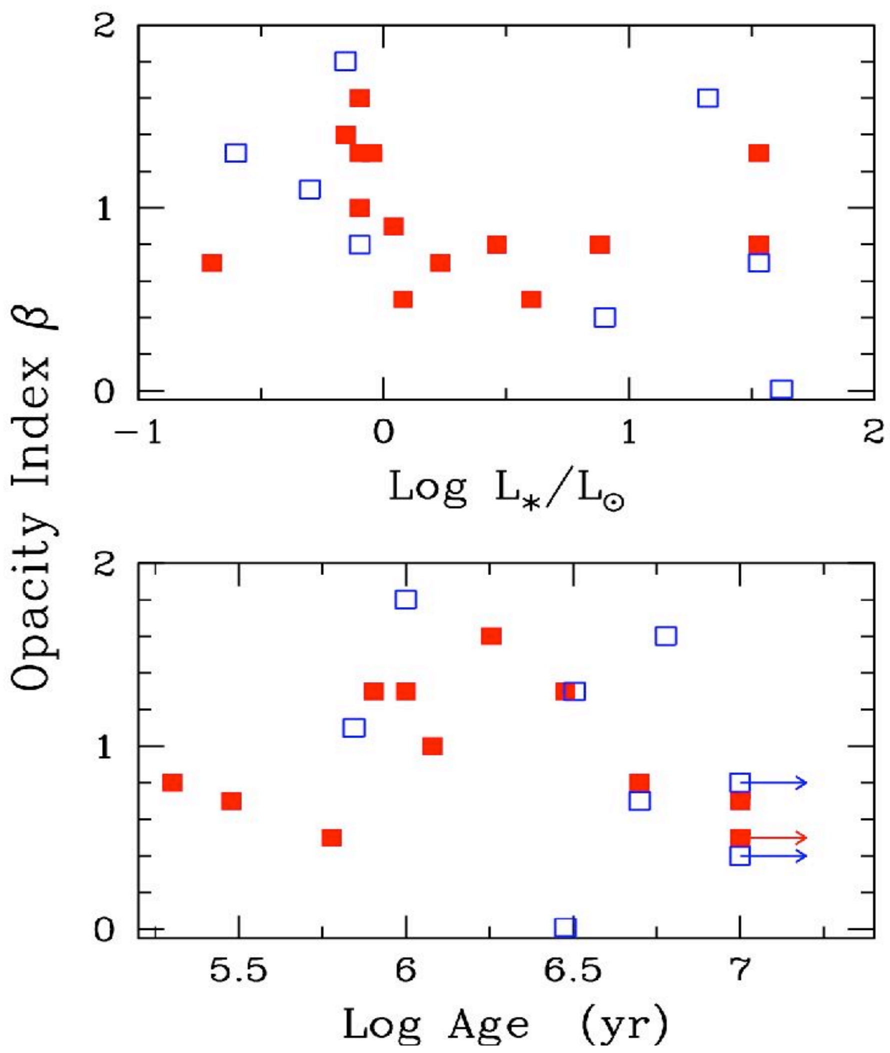


Data:
HAe (Testi et al. 2001; 2003; Natta et al. 2004)
TW Hya (Wilner et al. 2000;Calvet et al. 2002)
TTauri stars (Rodmann et al. 2005)

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

Large grains in HAe and TTS systems

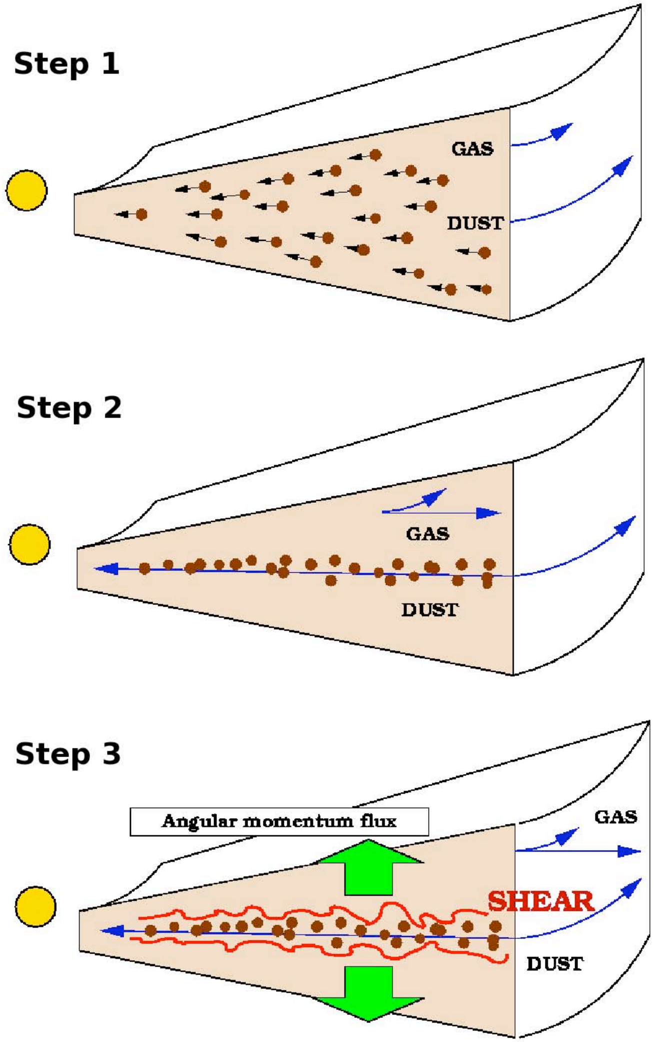
- Values of β range from 1.8 to 0.1 (from ISM grains to pebbles)
- No obvious correlation with stellar properties
- No obvious correlation with age
- No obvious correlation with disk surface grains
- ???
- <u>Caveat</u>: “large disks” small, biased samples



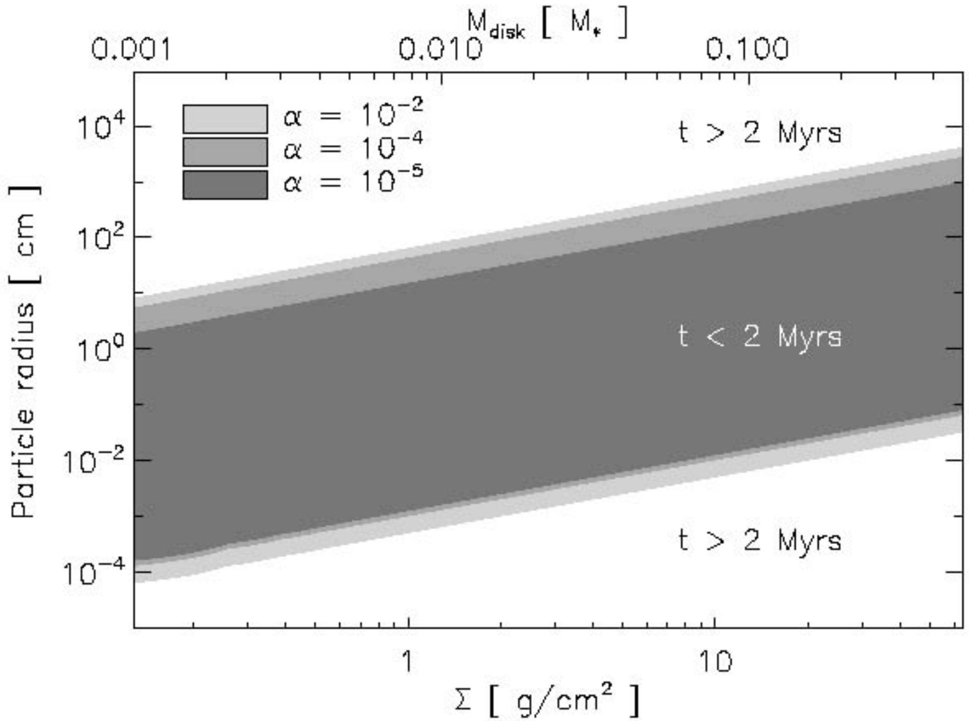
(Natta, LT, et al. PPV)

Data:
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!



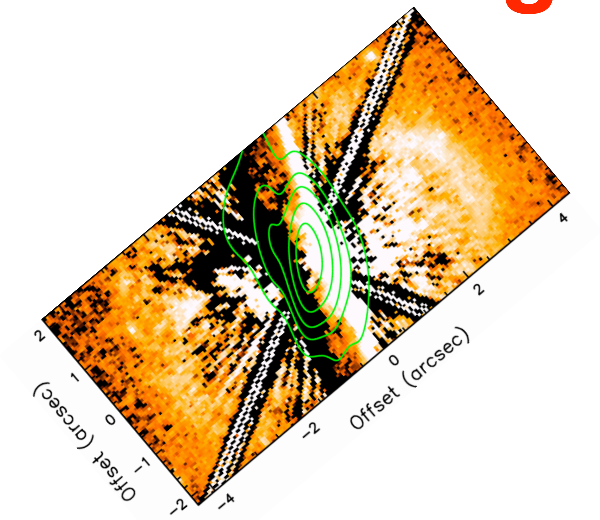
(Brauer et al. 2007)

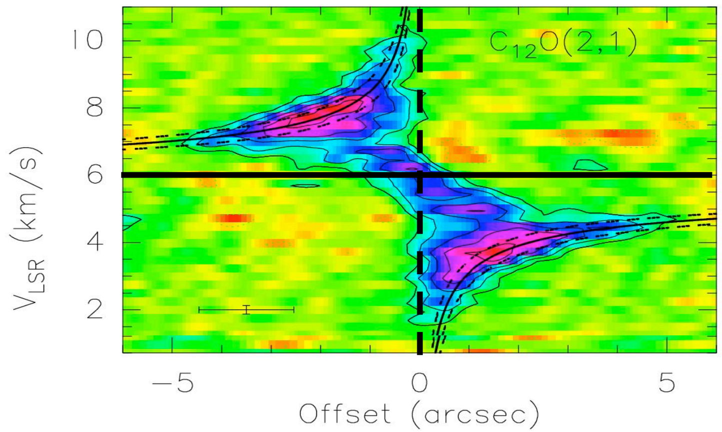


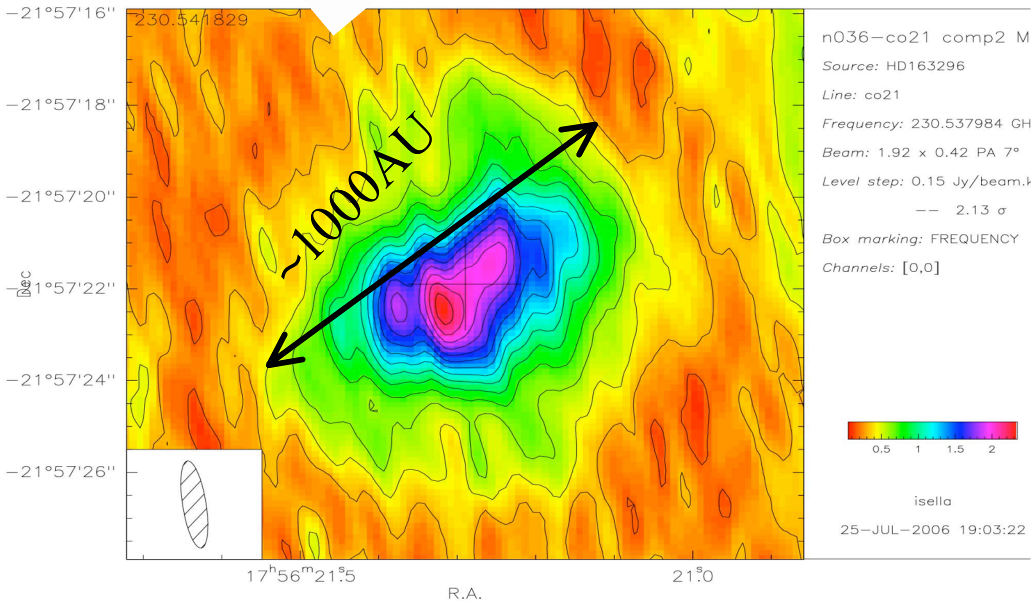
- Radial drift of mm-cm size particles at r~100AU can be very fast
- Viscosity, porosity, gas/dust ratio
- Trapping in disk patterns
  - Vortices, spiral arms…

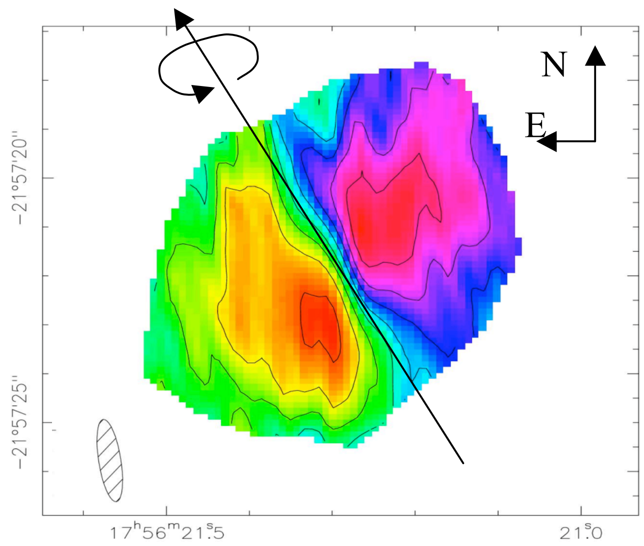
Resolving the disk properties

HD163296



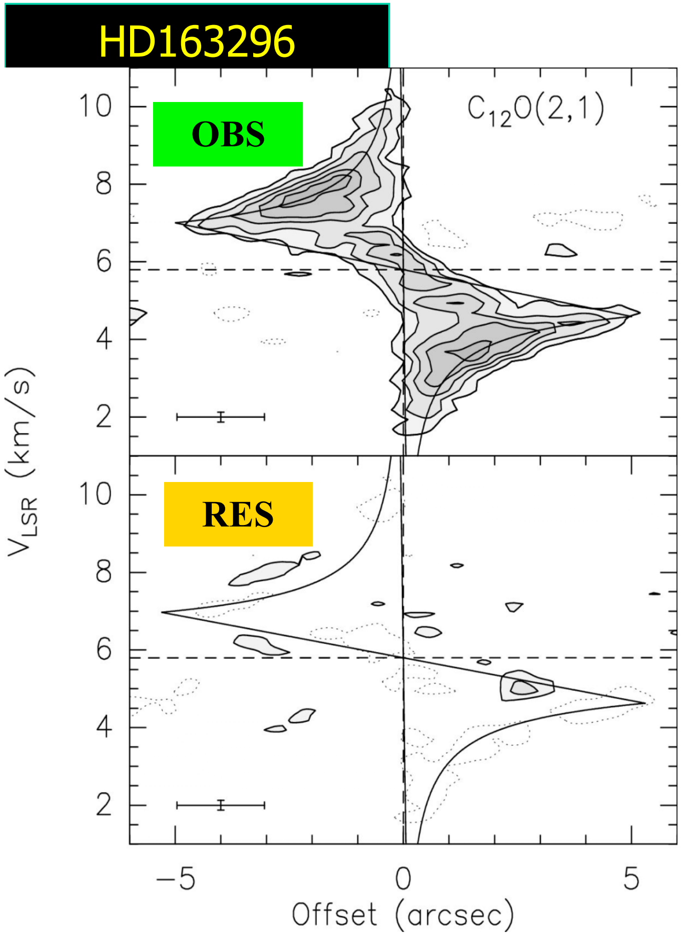




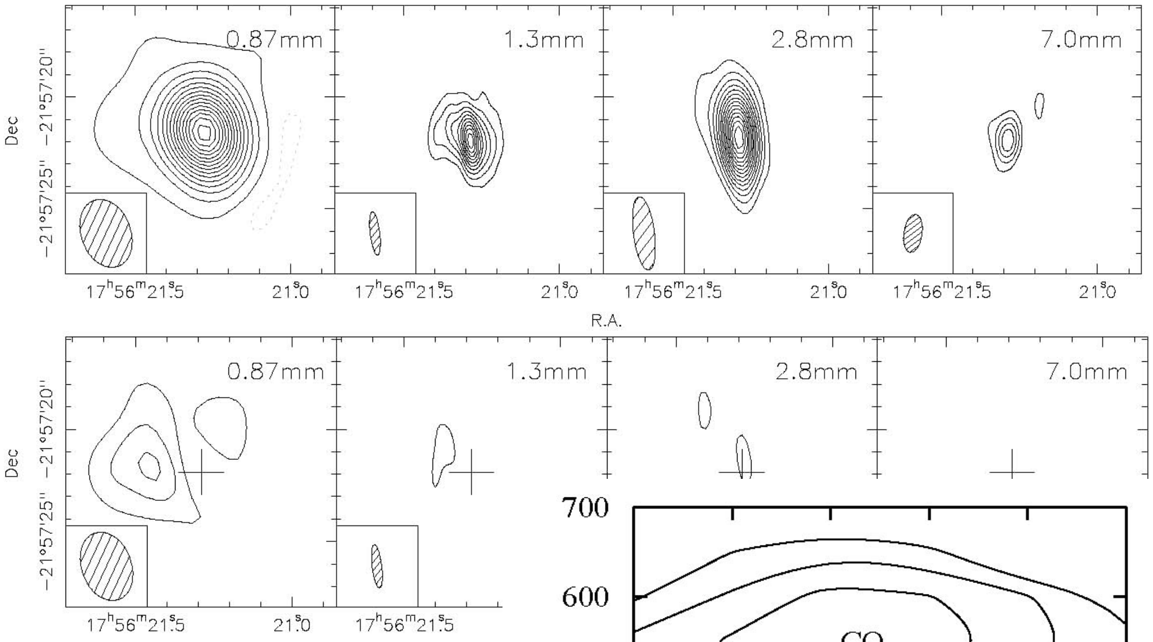


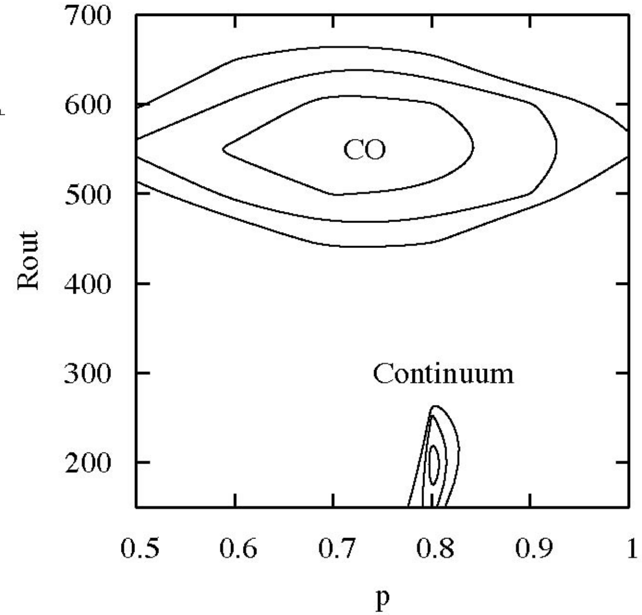
(Isella et al 2006)

Resolving the disk properties



(Isella et al 2006)





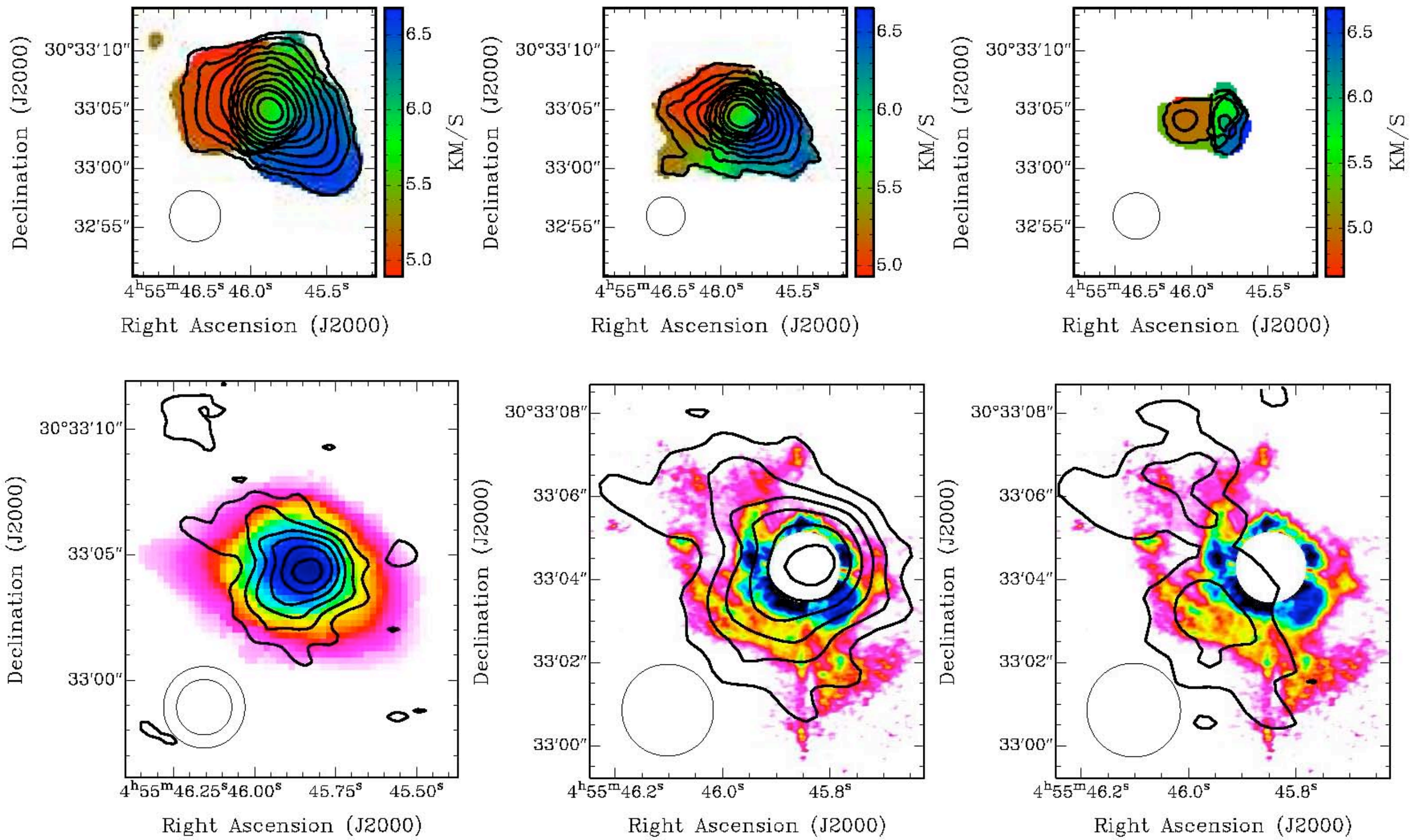
Dust properties

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

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

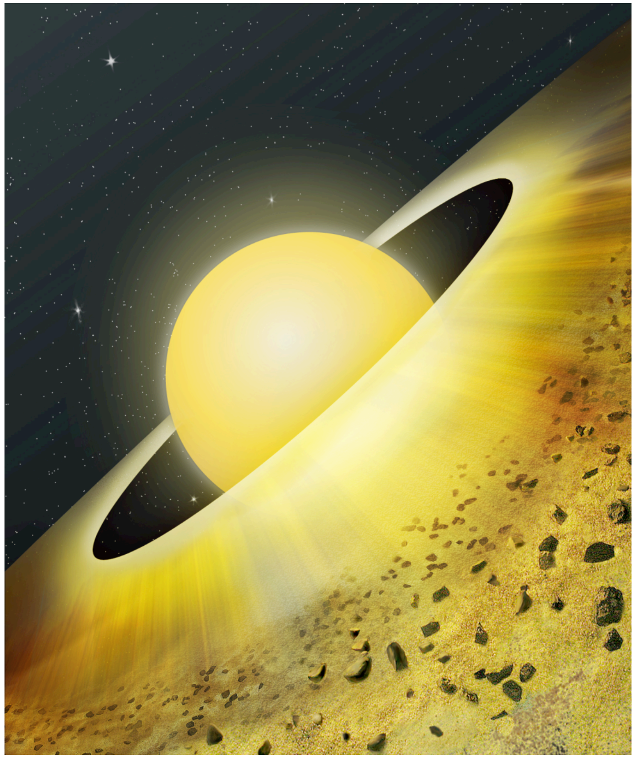


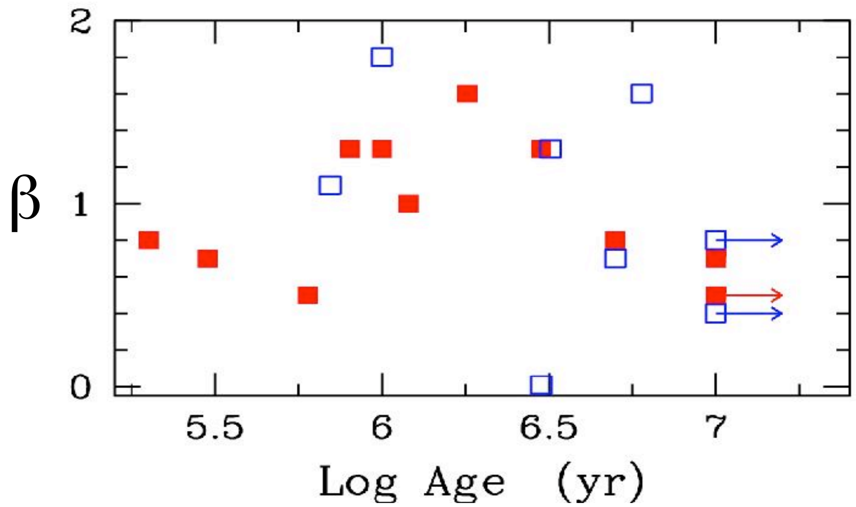
OVRO 2.7mm
(Corder et al. 2005)

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

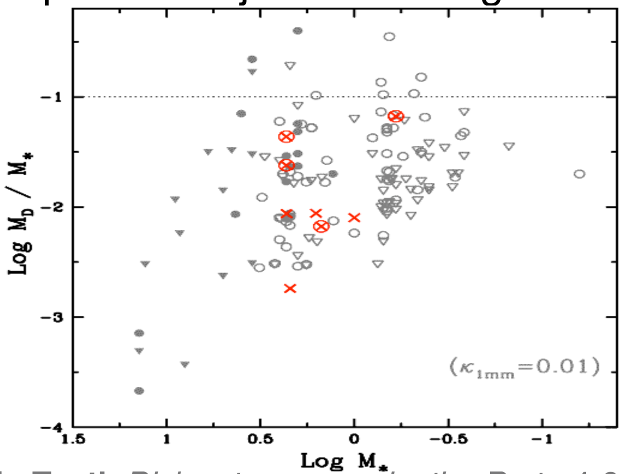


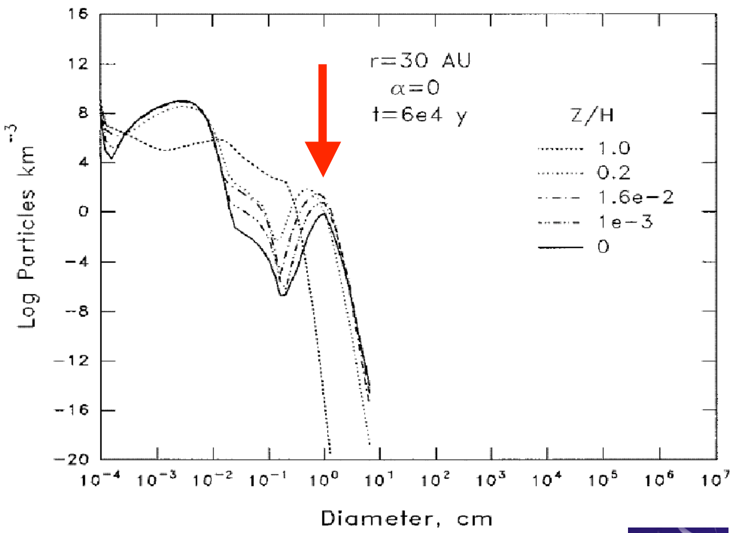


State of the Art & Future Directions

- 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

- 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
- Growth to pebbles is very fast, but converting a significant mass to 1m-size planetesimals seems more difficult (or requires more time)
  - Or perhaps we are just observing the odd beasts?





State of the Art & Future Directions

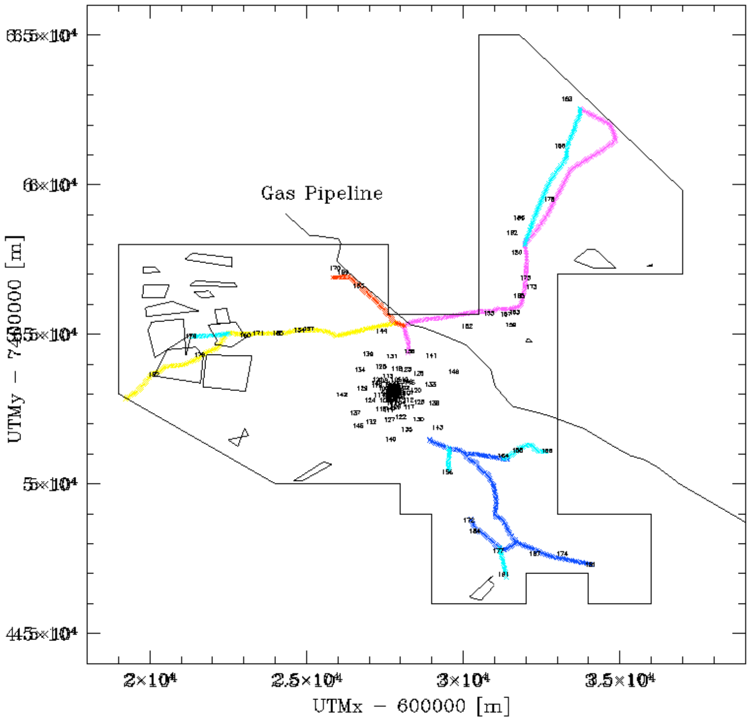
- Grains grow and settle in disks around all type of PMS objects
- Grain evolution can be very fast as we see highly processed grains around objects of all ages between 1 and 10 Myr
- It is difficult to derive a consistent picture of grain evolution because different observations probe different regions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

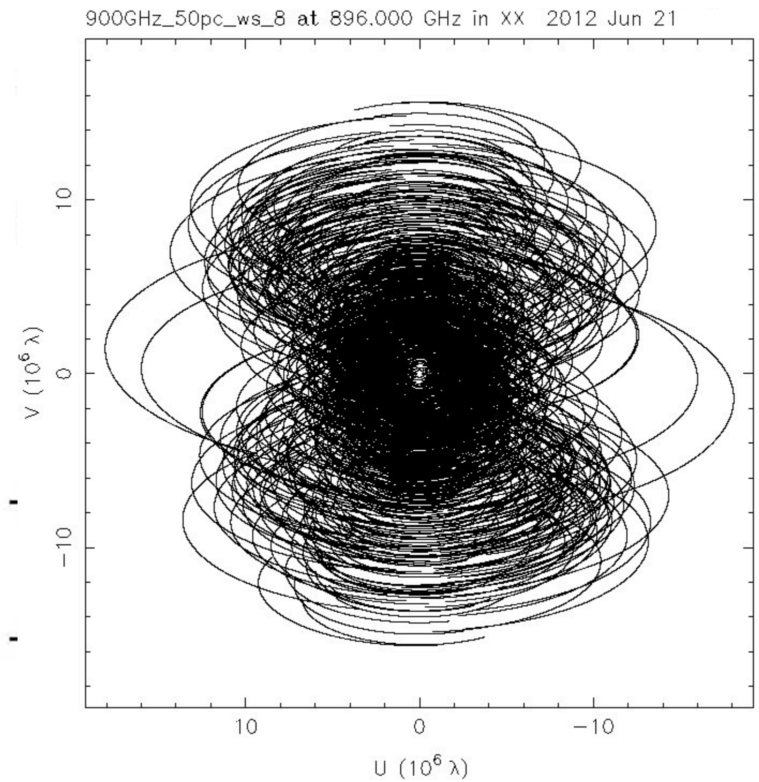
- Most of the dust mass is contained in “pebbles”
  - Large bodies, if present, do not dominate the solid mass of the disk up to 5-10 Myr
- Growth to pebbles is very fast, but converting a significant mass to 1m-size planetesimals seems more difficult (or requires more time)
  - Or perhaps we are just observing the odd beasts?

- 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

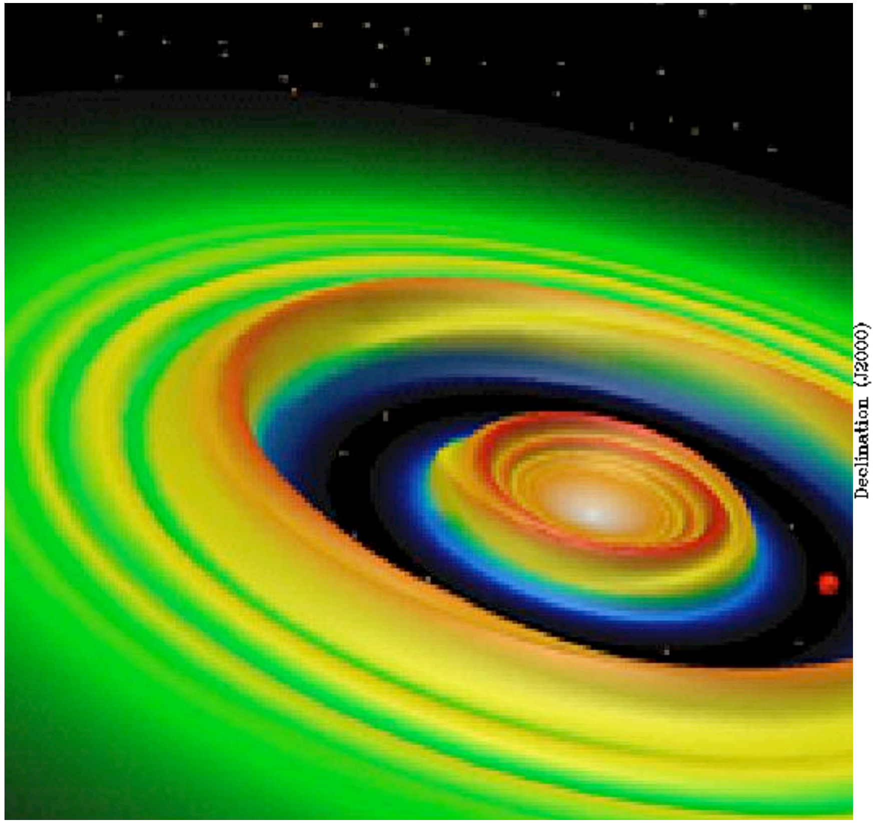
mm Interferometers (u,v) coverage

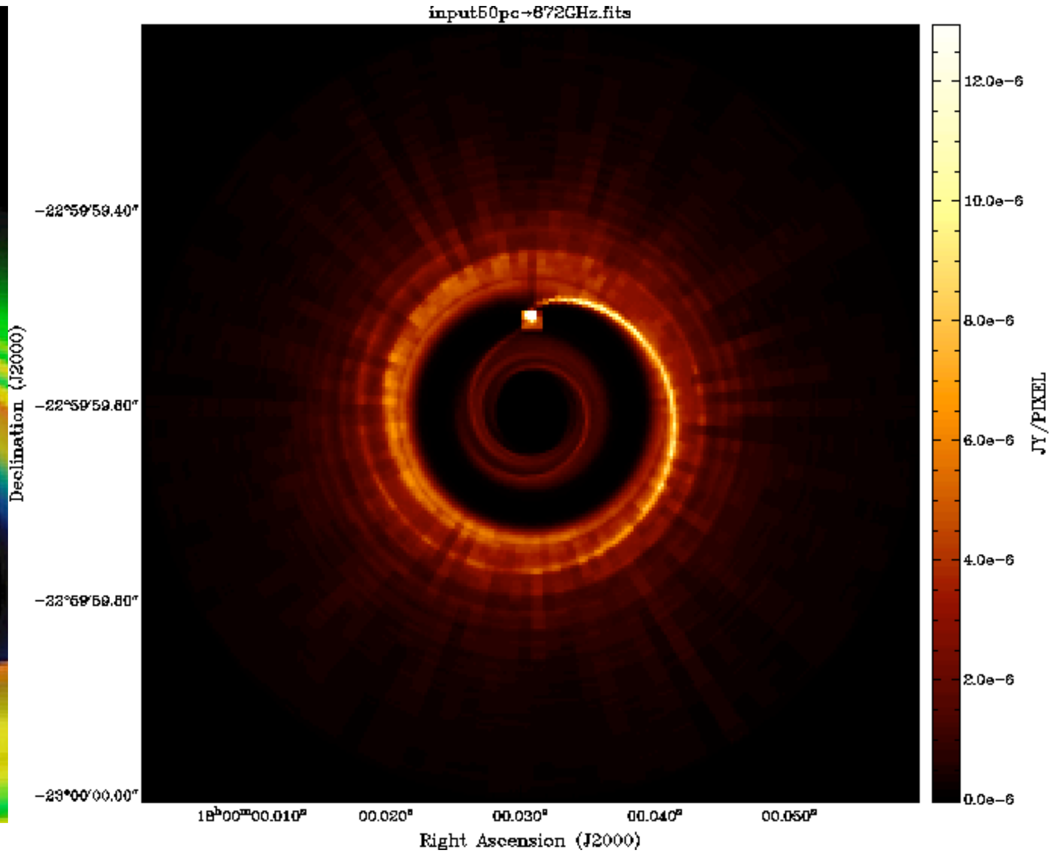
- Current mm interferometers offer typically ~10^4 visibility measurements in several hours, the VLA delivers ~10^5 visibilities per hour
- ALMA will improve by almost two orders of magnitude





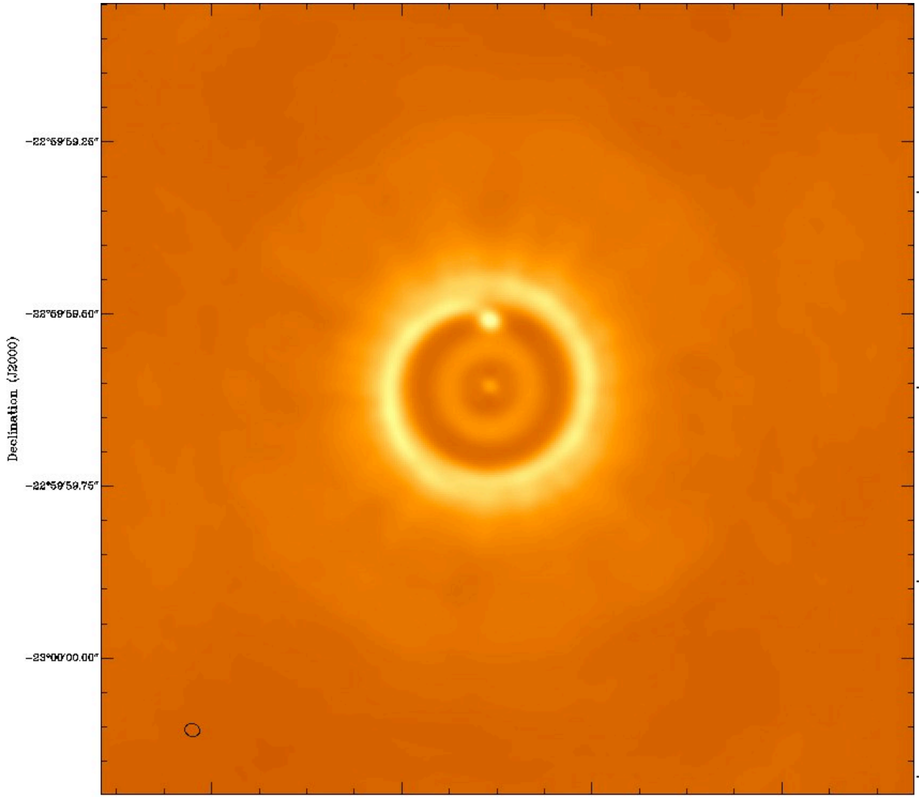
Late stages of planet formation

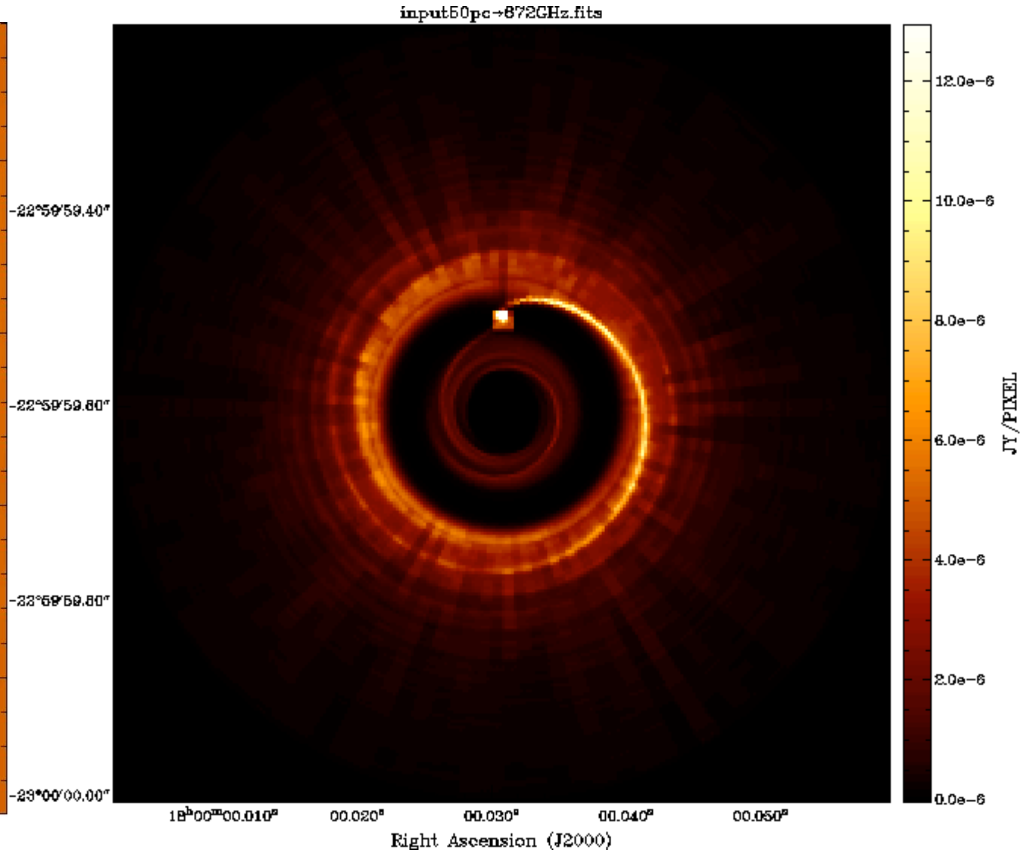




- Simulations of giant protoplanets in circumstellar disks

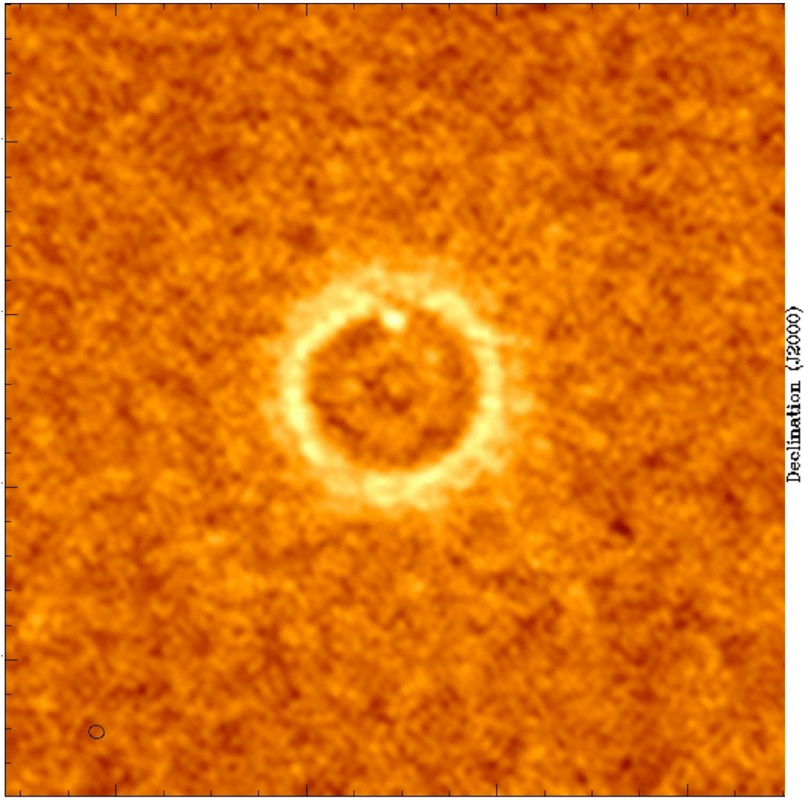
Late stages of planet formation

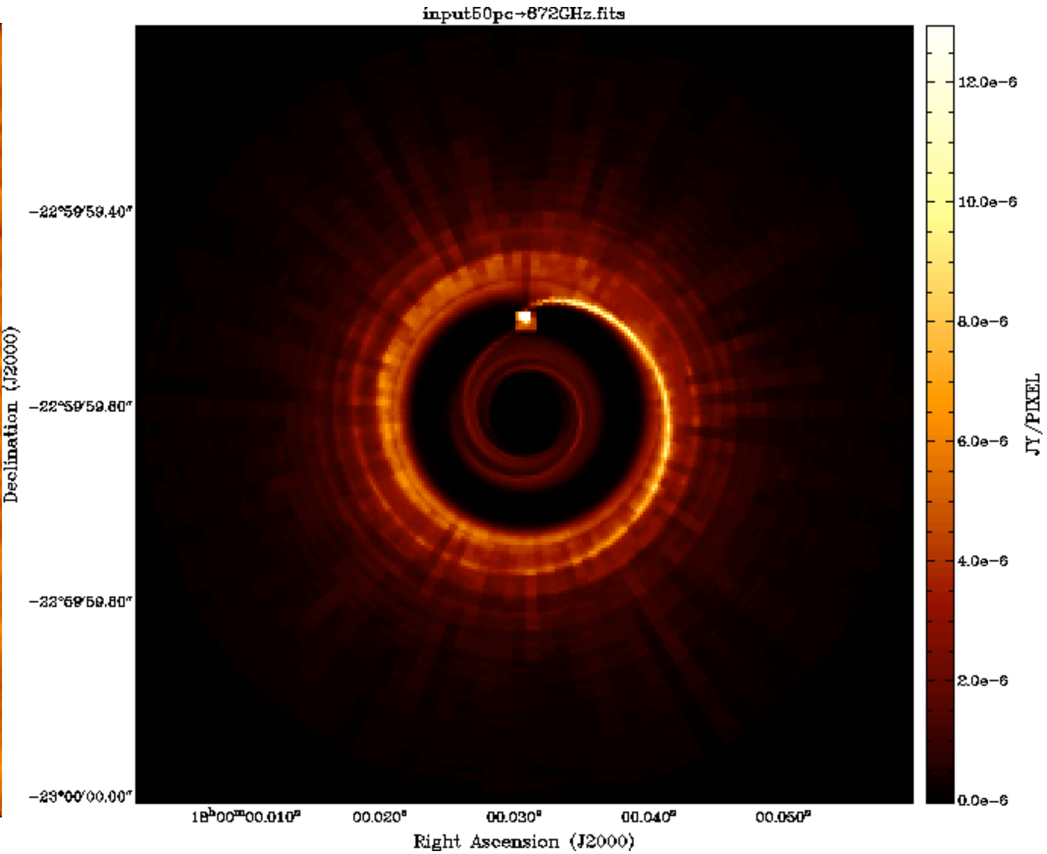




- Simulations of giant protoplanets in circumstellar disks
- ALMA 650GHz Y1 8h

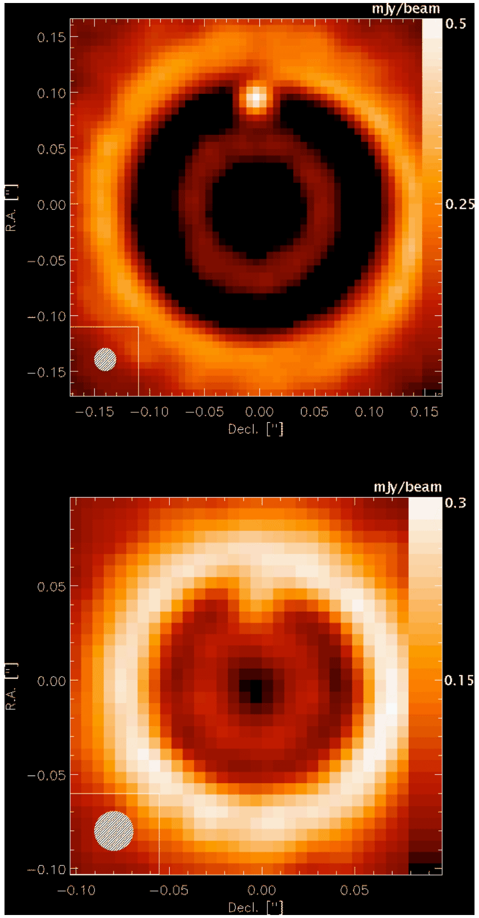
Late stages of planet formation





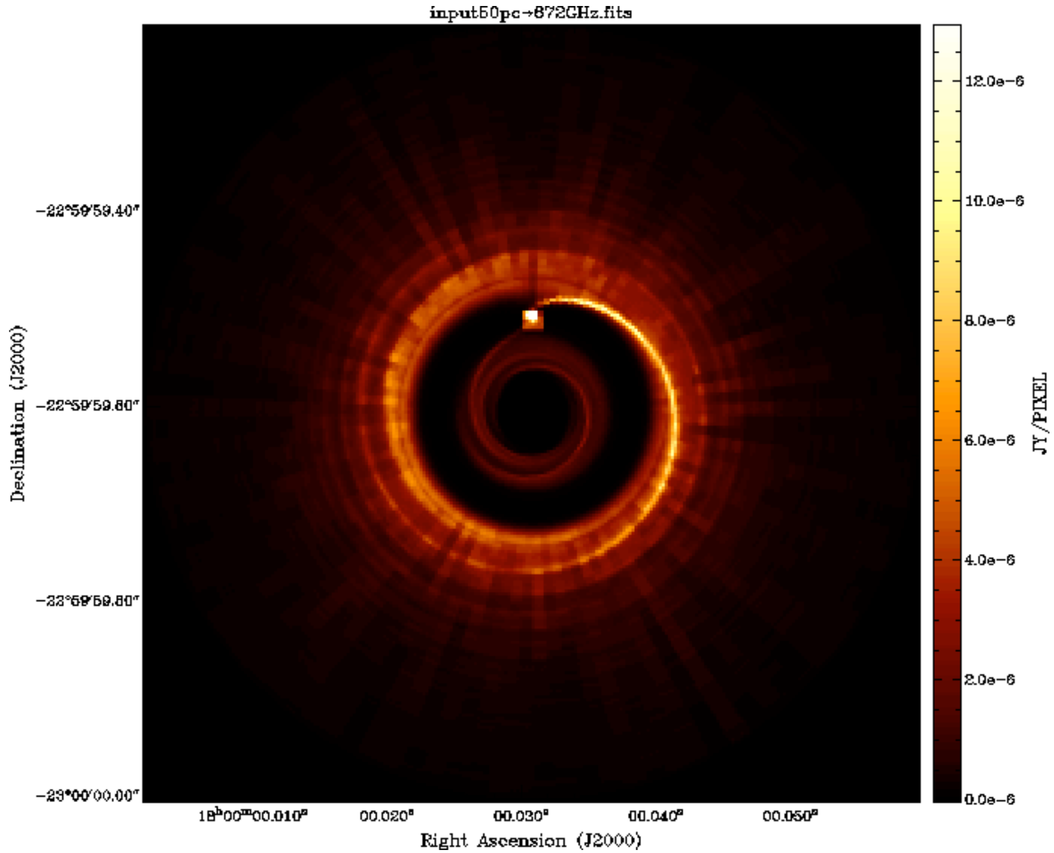
- Simulations of giant protoplanets in circumstellar disks
- ALMA 650GHz Y1 8h
- NB. 50pc distance! (though experiment even with ALMA)

Late stages of planet formation



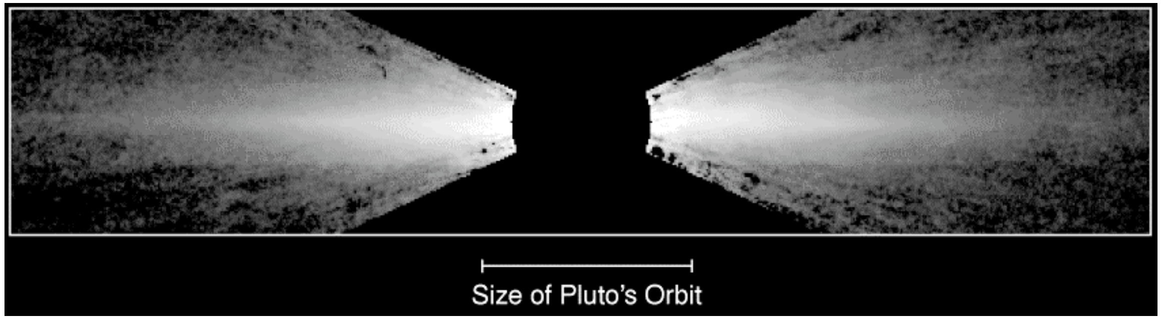
50pc

100pc

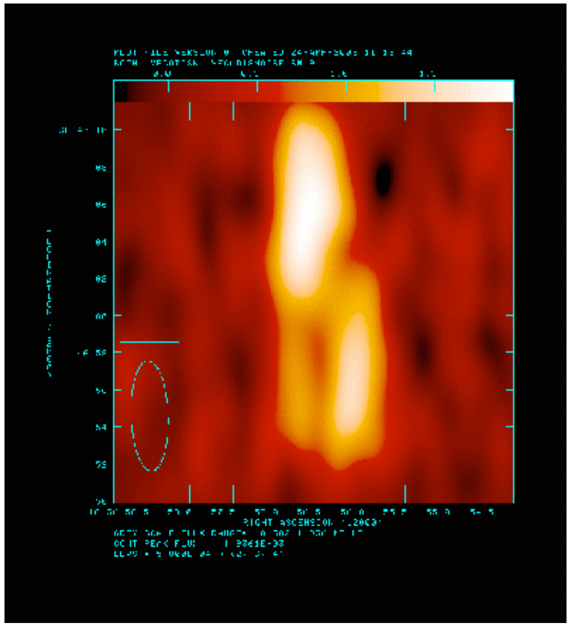


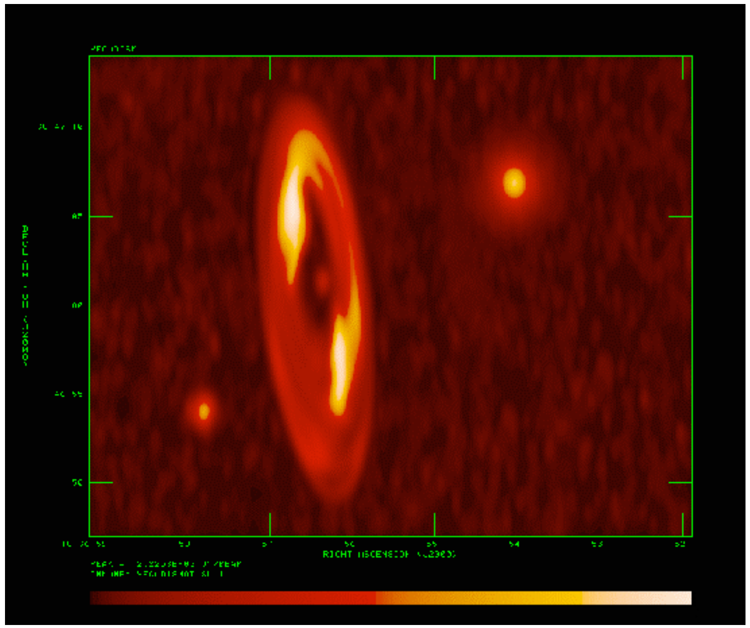
- Simulations of giant protoplanets in circumstellar disks
- ALMA 650GHz Y1 8h
- NB. 50pc distance! (though experiment even with ALMA)

Debris disks



- Simulations of the observations of a disk similar to that around Vega as observed with PdB and with ALMA





Circumstellar Disks @ mm-λ

- Disks and the formation of stars
  - Disk structure, chemistry
  - Disk-jet interaction: removal of angular momentum and accretion
  - Formation of Brown Dwarfs and massive stars

- Disk evolution and planet formation
  - Chemical evolution, prebiotic molecules
  - Evolution of dust and formation of planetesimals
  - Giant protoplanets and gaps in disks

- Debris disks
  - Secondary dust properties
  - Dust-planets interactions