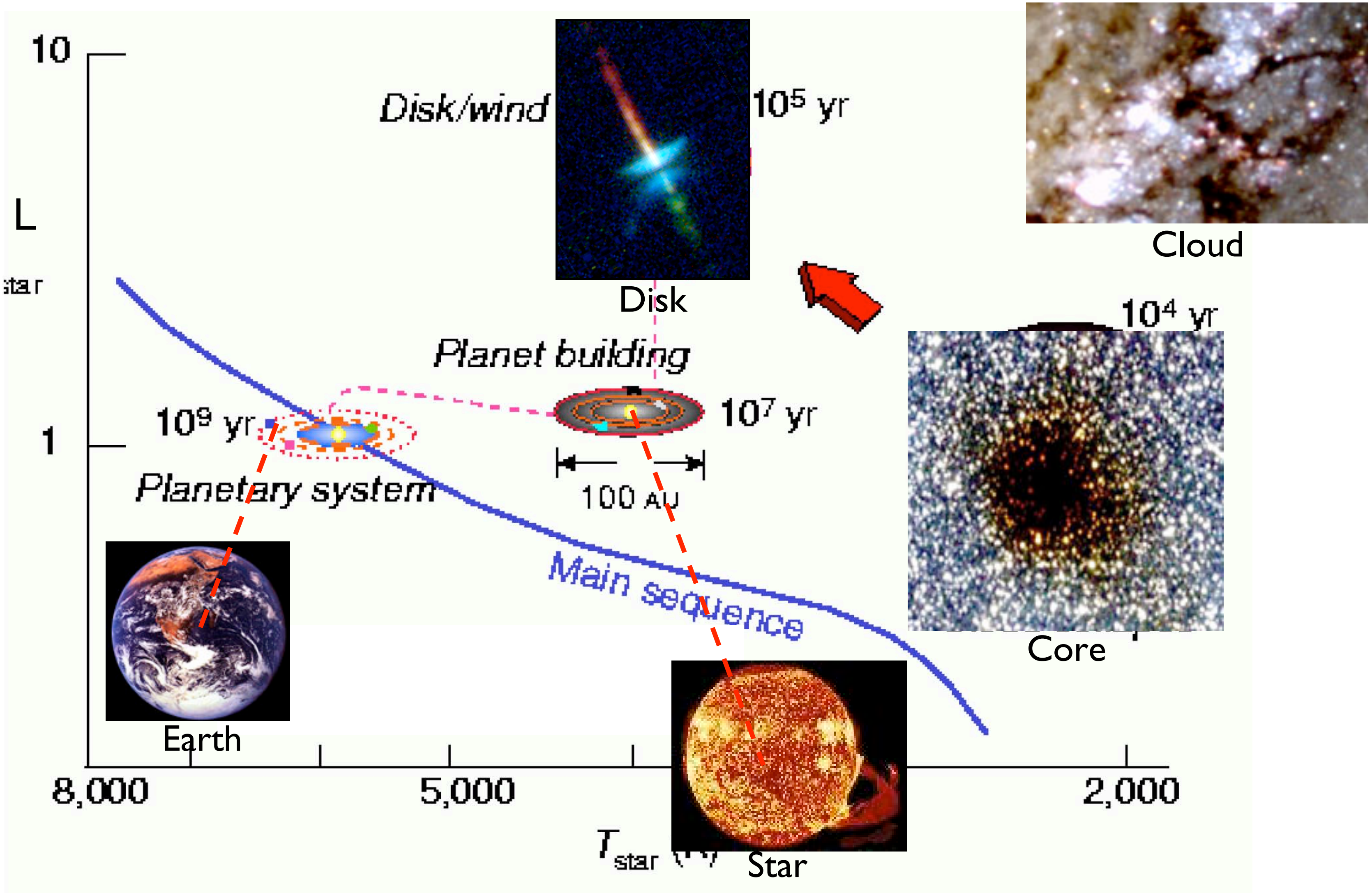
Circumstellar disks and the dawn of planetary systems

Leonardo Testi (European Southern Observatory)

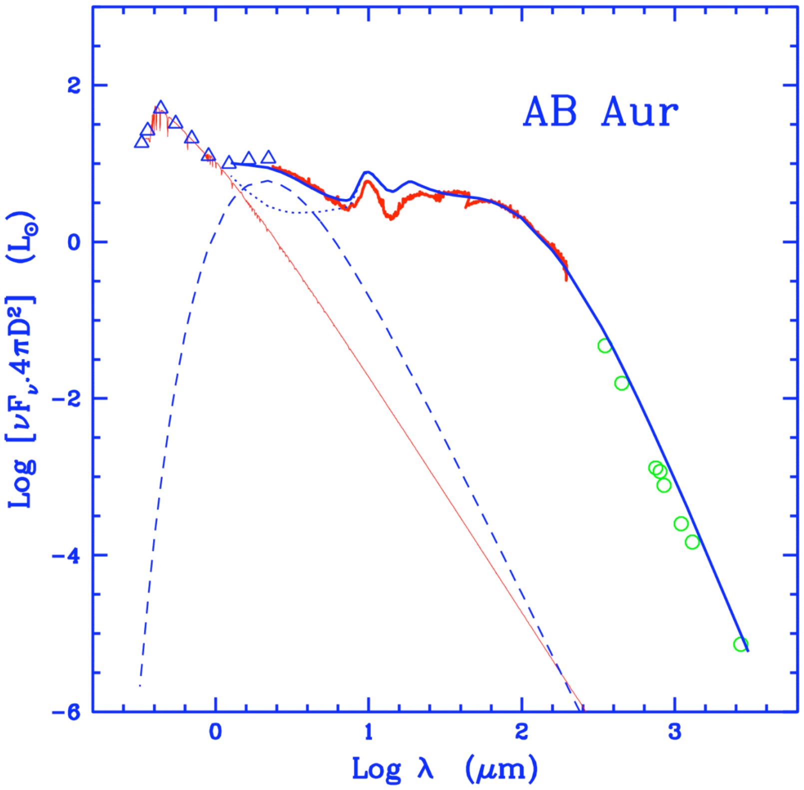
- Structure of Circumstellar Disks
- The role of disks in the formation of stars
- Evolution & Fist Steps towards Planet Formation

From Cores to Stars and Planetary Systems

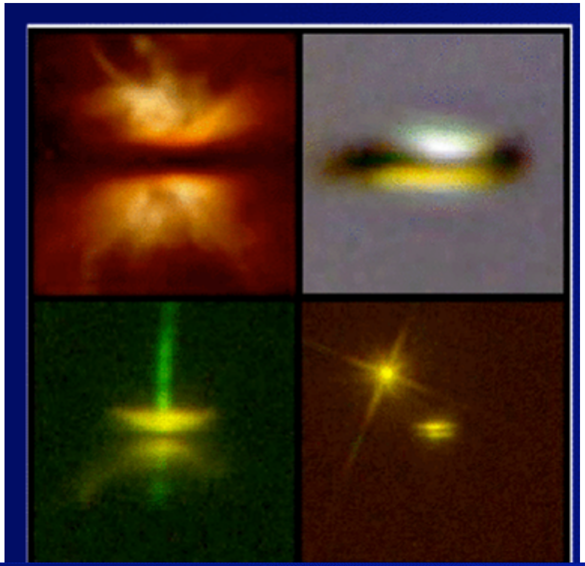


SED and Infrared Excess

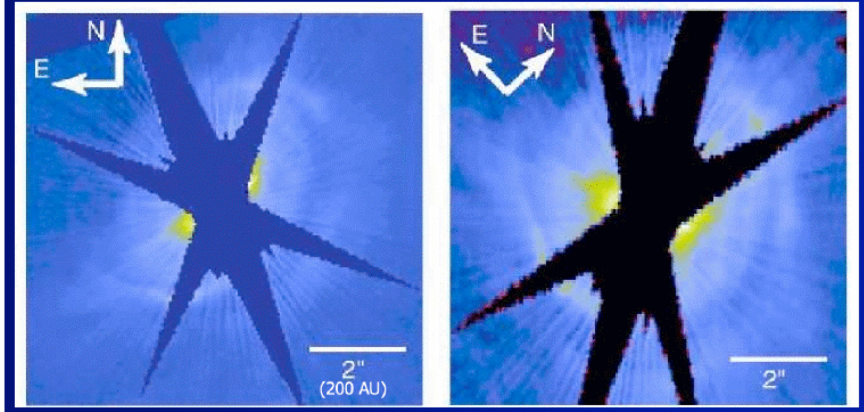
- Cirsumstellar disks in the PMS phase are optically thick (except at λ≥mm)
- Disks dominate the emission beyond 1-2μm
- The shape of the SED depends on the disk structure



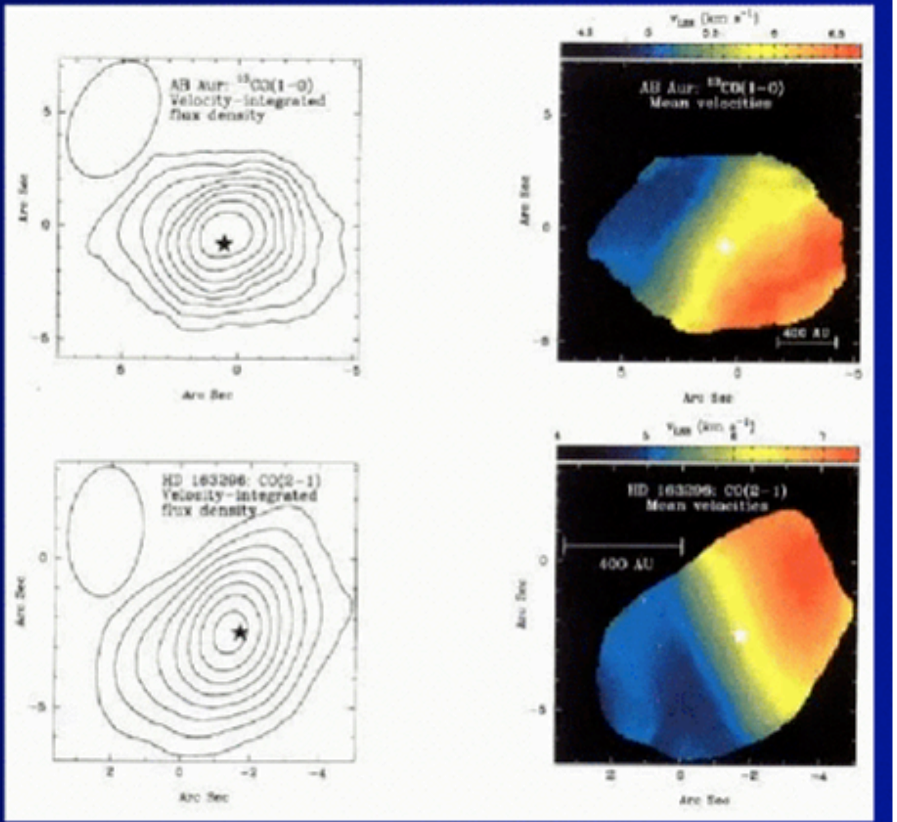
Disks at different wavelengths



HD 100546 in the visual (0.2-1.0 μm)



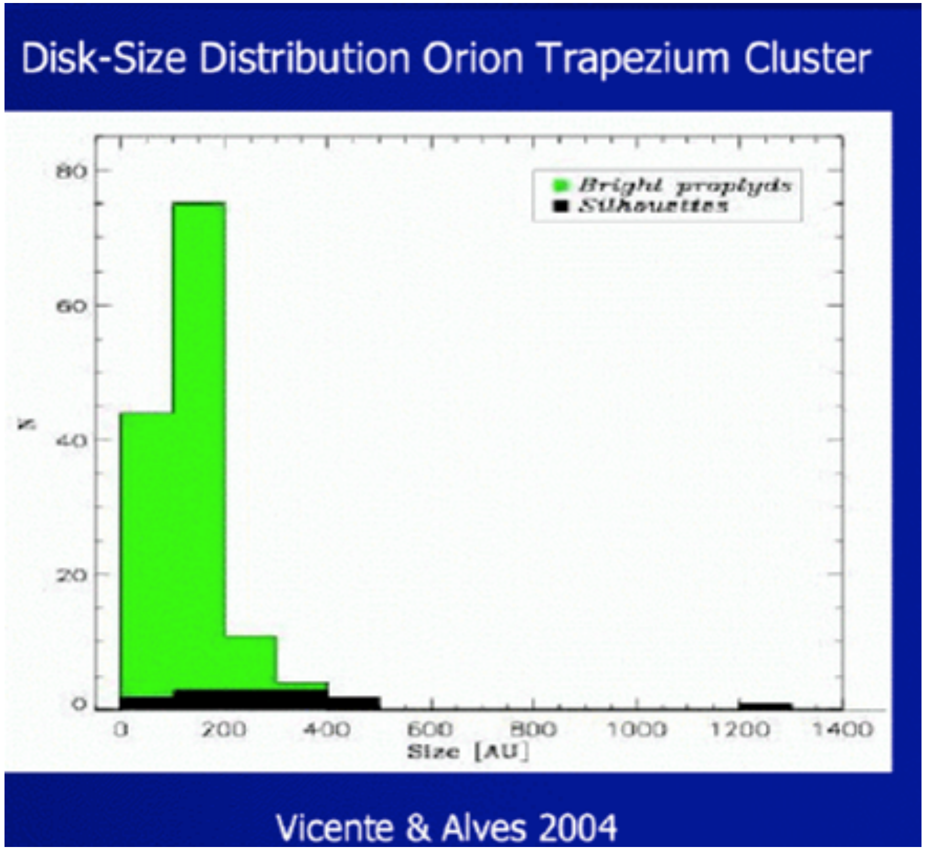
Grady et al. 2001, AJ 122, 3396



Mannings & Sargent 1997, ApJ 490, 792

Physical sizes

- Few hundred AUs
  - From scattered light
  - Mm continuum
  - CO mm lines



Disk-Size Distribution Orion Trapezium Cluster

Vicente & Alves 2004

Masses: (sub)mm continuum emission

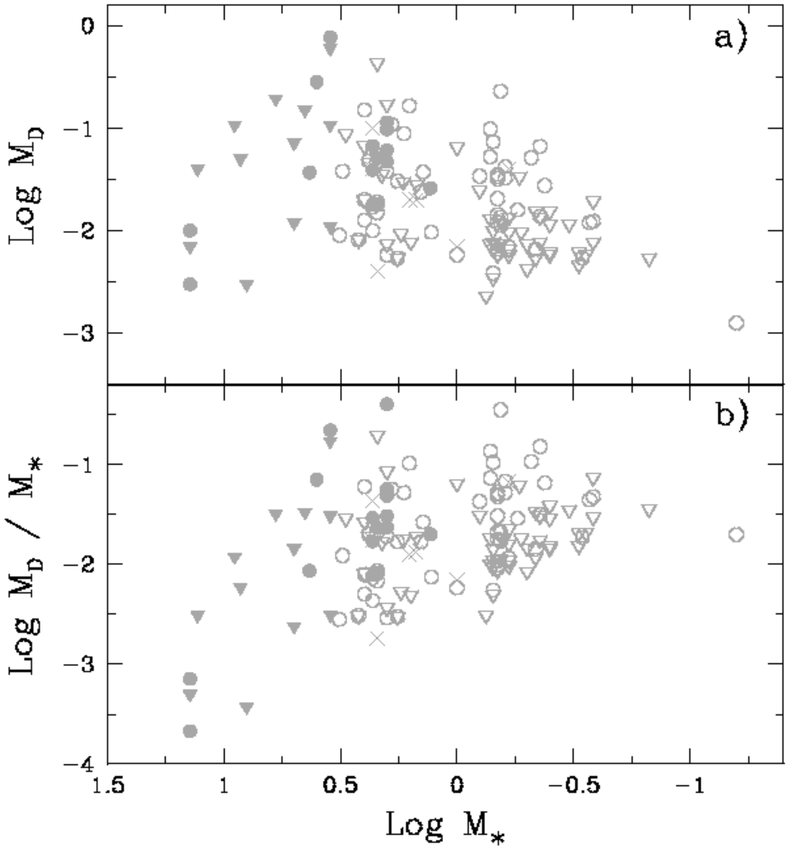
- $M_D \sim 0.01\text{-}0.1$ Msun
- M_D/Mstar ~ 0.03

- $F_{1mm} \sim B_n(T)\, k_{1mm}\, M_D$

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

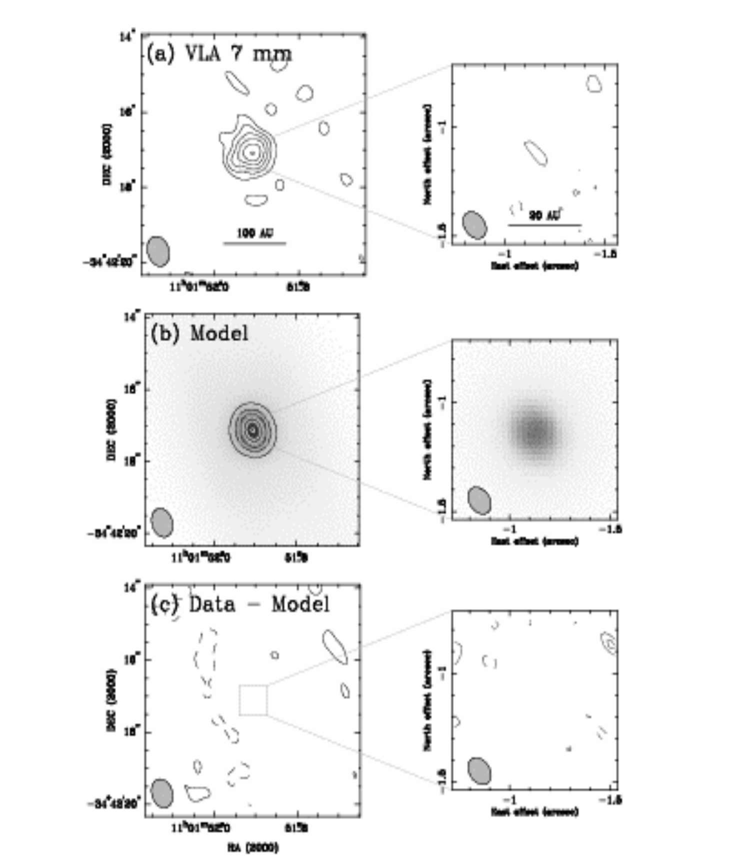
$$\mathrm{T}_d \sim r^{-q}$$

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



Radial density profiles

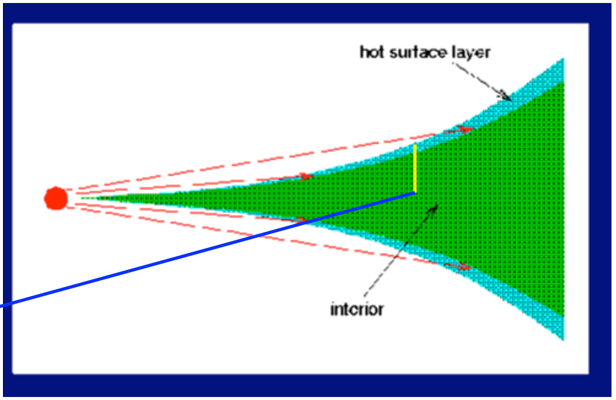
- High resolution mm continuum observations allow to derive the dust column density as a function of radius

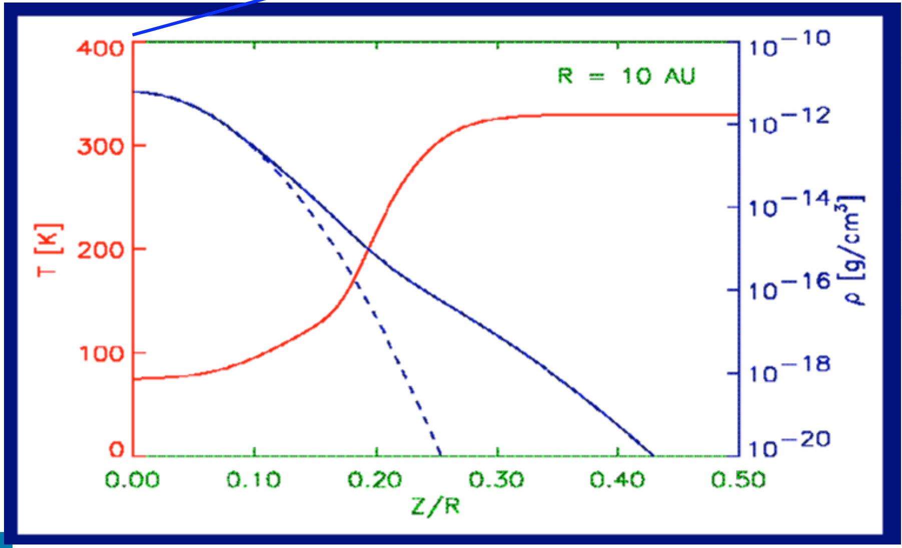


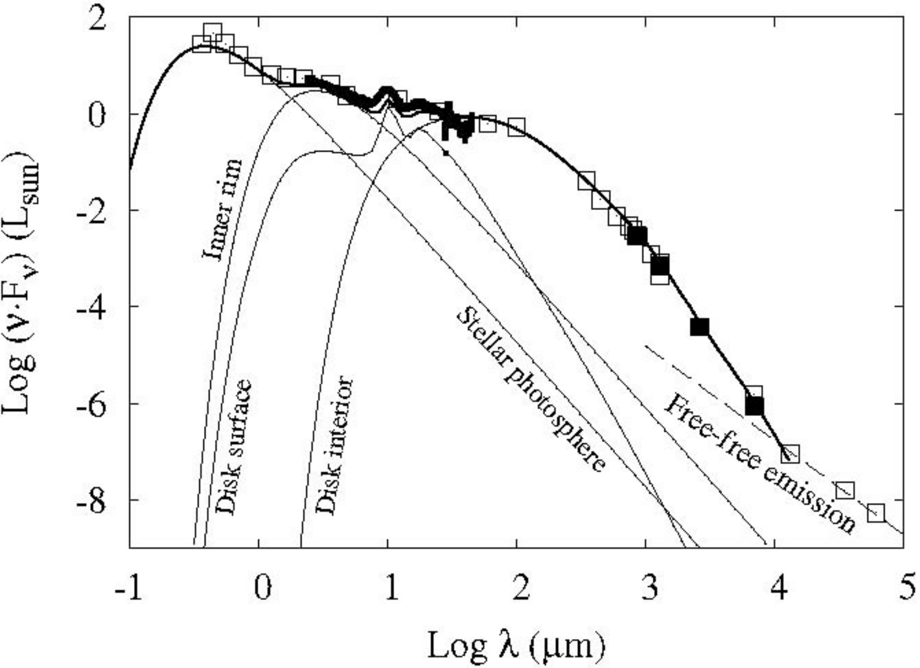
VLA 7mm
$T \sim r^{-q}$; $q \sim 0.5$
$\Sigma \sim r^{-p}$; $p \sim 1.0$
(Wilner et al. 2000)

“Flared” disks

- Two components:
  - An optically thin surface layer (atmosphere)
  - A cool, optically thick inner layer which contains most of (~all) the mass

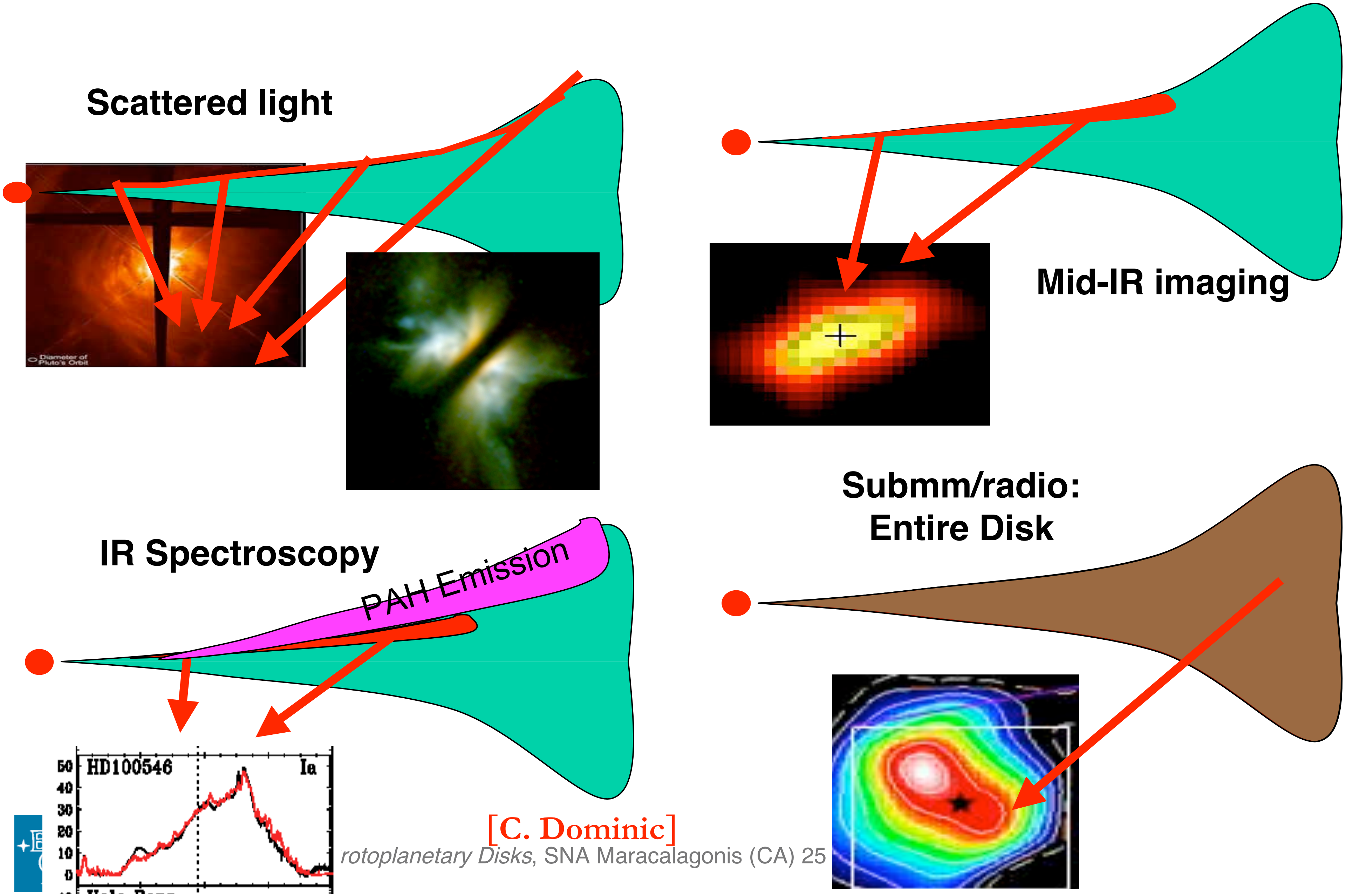






(Isella et al. 2007)

Which observations probe what?



Scattered light

Mid-IR imaging

IR Spectroscopy

Submm/radio:
Entire Disk

[C. Dominic]

Molecular gas

- Gas has to dominate the disk mass
  - From geometry : **H/R ~ 0.1 at 1 AU**

$$\frac{1}{\rho}\frac{\partial p}{\partial z} \sim \frac{p}{\rho z} = -\frac{GM_* z}{R^3}$$

$$\rho(z) = \rho(0)\ exp(-z^2/2H^2)$$

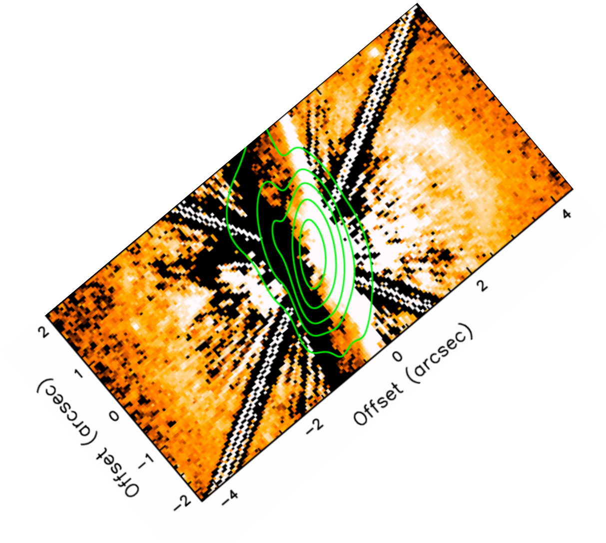
$$H/R = (T_d/T_g)^{1/2}\ (R/R_*)^{1/2}$$

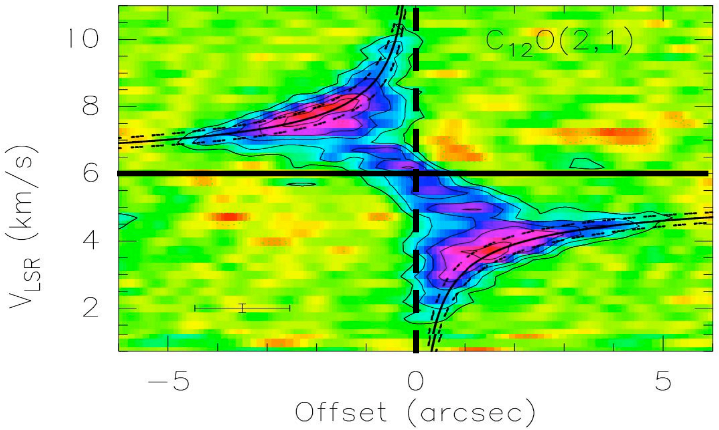
$$T_g = \frac{GM_*\mu}{kR_*}$$

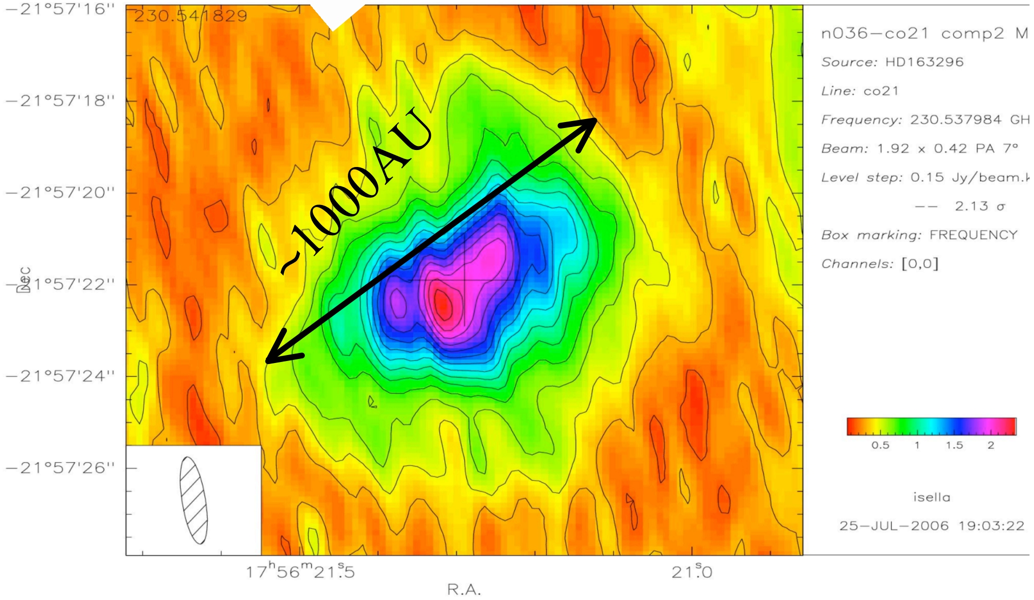
- Direct measurements:
  - Cold gas CO, … (outer disk)
  - Warm gas H_2, CO, H_2O(?) (inner disk)
  - Indirect: Accretion and Jets

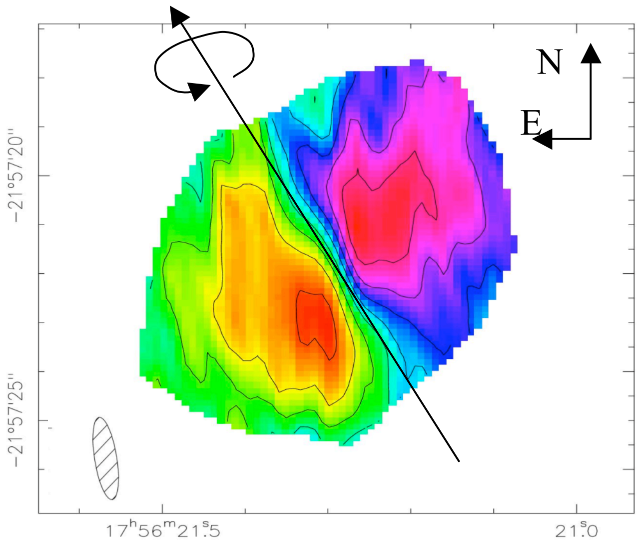
Outer disks structure and kinematics

HD163296





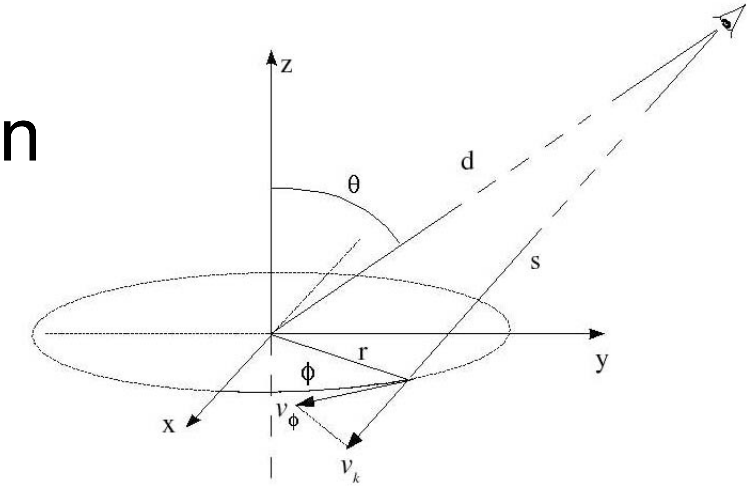




(Isella et al 2007)

Molecular gas

- Calculation of the CO emission assuming thermalised gas



$$I_\nu = \int_0^\infty S_\nu(s) e^{-\tau_\nu}(s) K_\nu(s) ds$$

$$\tau_\nu(s) = \int_0^s K_\nu(s')ds' \qquad K_\nu^d(s) = \rho(s)\cdot k_\nu \qquad K_\nu^{CO}(s) = n_l(s)\cdot\sigma_\nu(s)$$

$$n_l(s) = \chi_{CO}\frac{\rho(s)}{m_0}\cdot\frac{g_l\, e^{-E_l/\mathrm{k}T_{CO}(s)}}{Z(T_{CO}(s))}$$

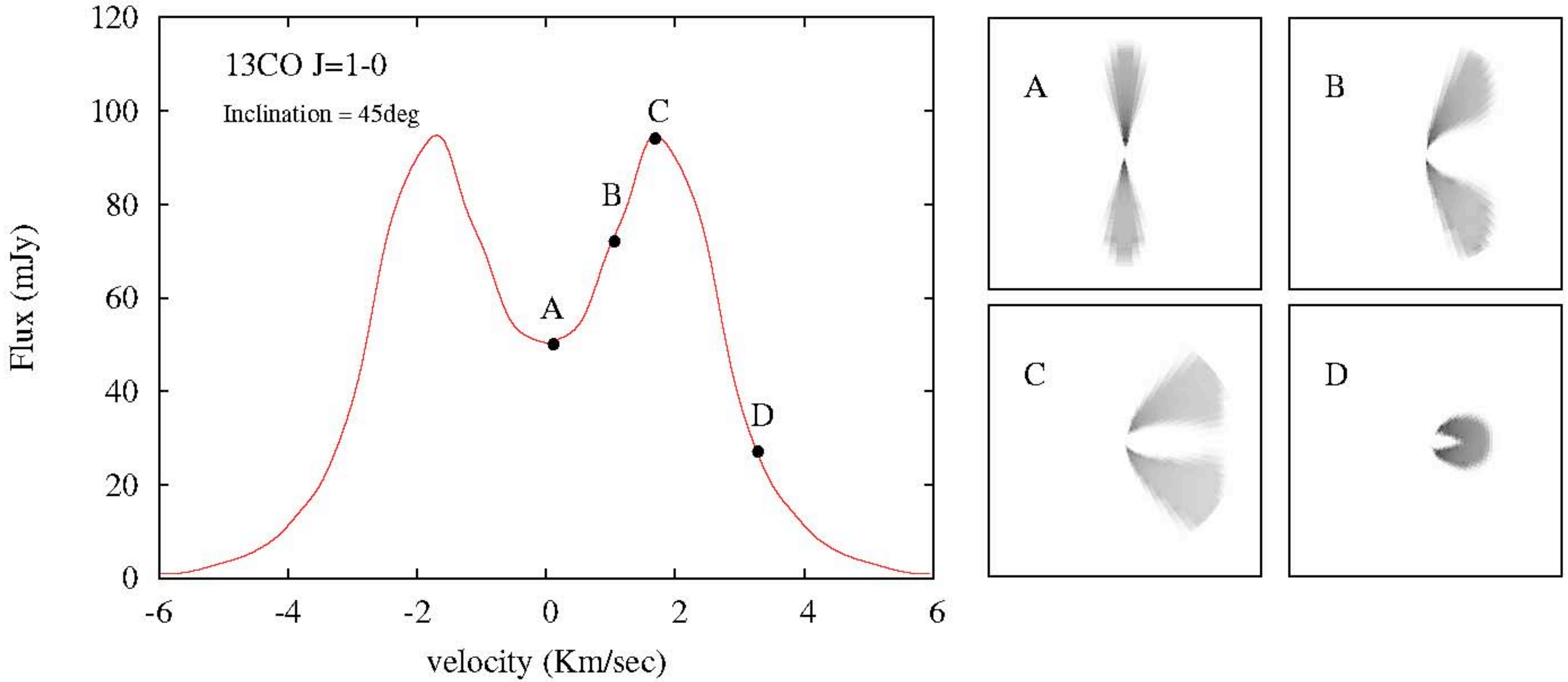
$$S_\nu(s) = B_\nu(T_{CO}(s)) = \frac{2\mathrm{h}\nu^3}{\mathrm{c}^2}\frac{1}{\exp(\mathrm{h}\nu/\mathrm{k}T_{CO}(s))-1}$$

$$T_{CO}(r) = T_{CO}(r_0)(r/r_0)^{-q}$$

(Isella et al. 2007)

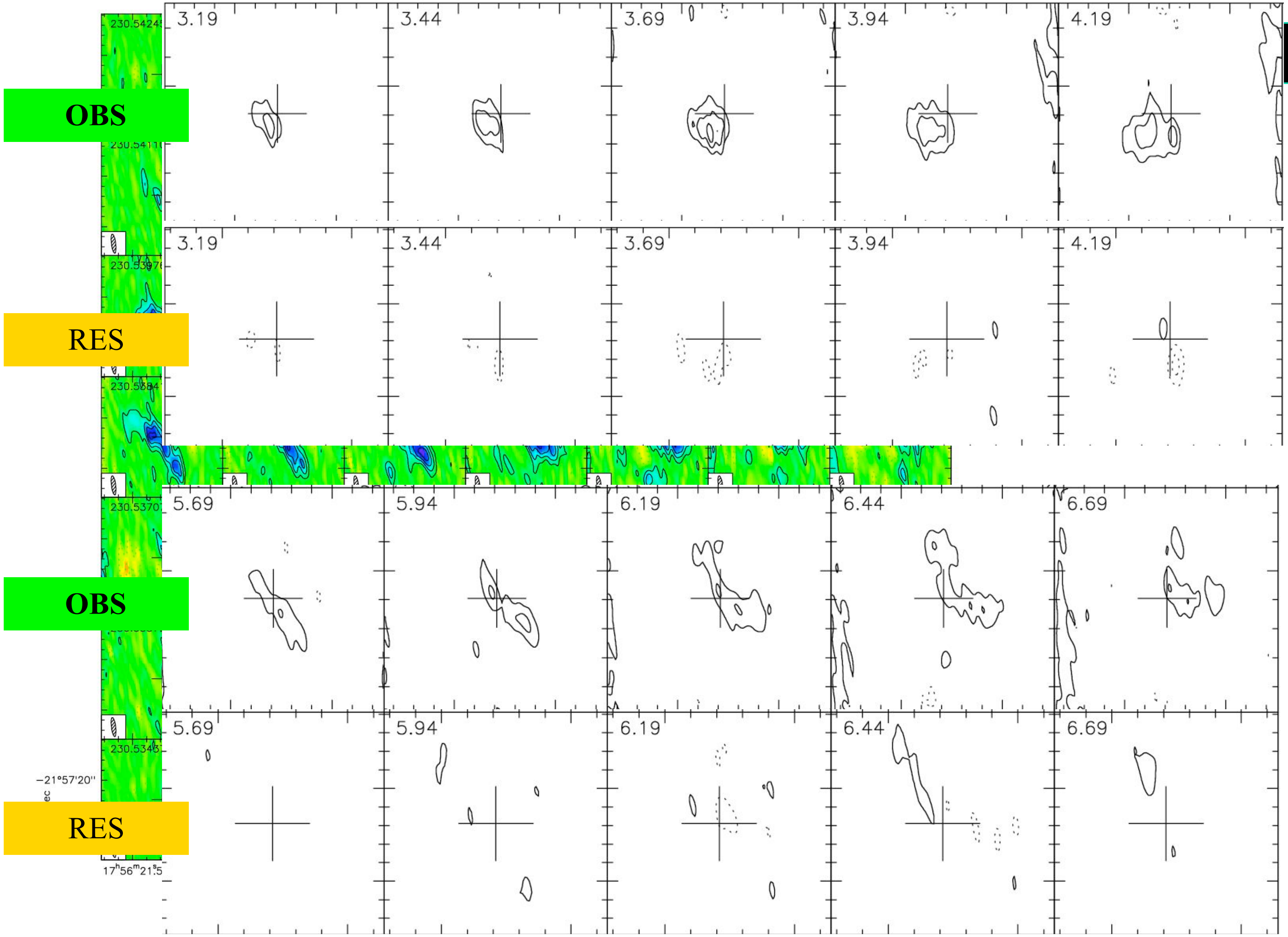
Molecular gas

- Simulated CO profiles and maps



(Isella et al. 2007)

Outer disks structure and kinematics



OBS

RES

OBS

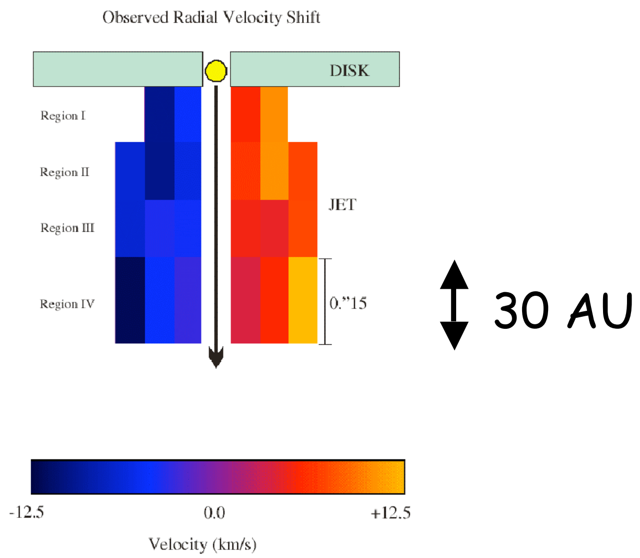
RES

HD163296

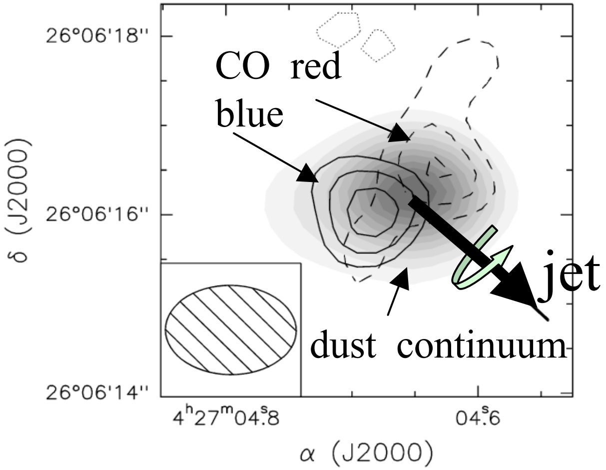
(Isella et al. 2007)

Gas properties and evolution

- Kinematics
  - Disk-outflow interaction
  - Possible evidence for non keplerian motions
- Physical properties
  - Temperature, density structure
  - Abundance, gas to dust ratio
- Chemical properties
  - Formation of complex molecules
  - Chemical differentiation in different regions of the disk



(Bacciotti et al 2002)



(Testi et al.2002)

Gas properties and evolution

- Kinematics
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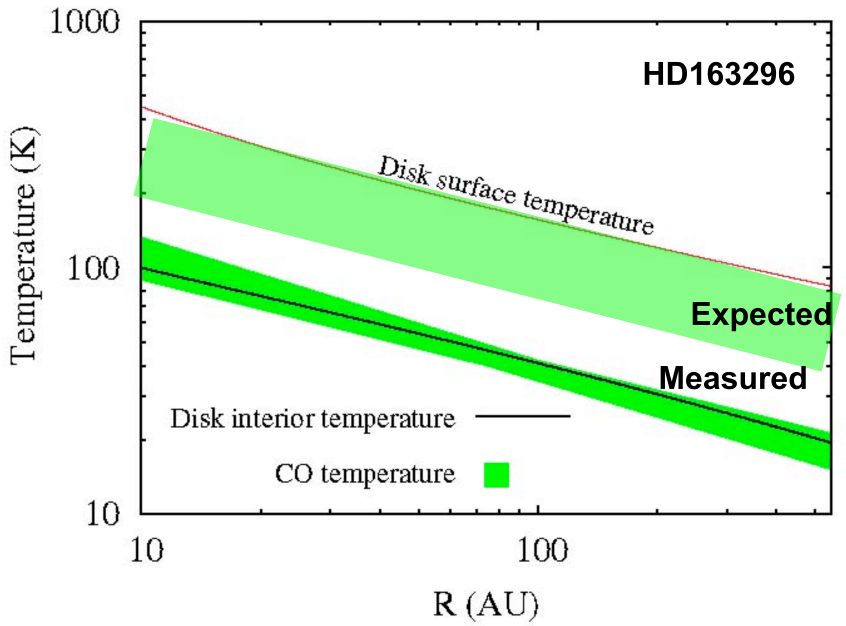


CO isotopes depletion factors:

$^{13}CO \Rightarrow \sim 10$ $([^{13}CO]/[H_2] \sim 10^{-7})$

$C^{18}O \Rightarrow >60$

Disks and the formation of stars

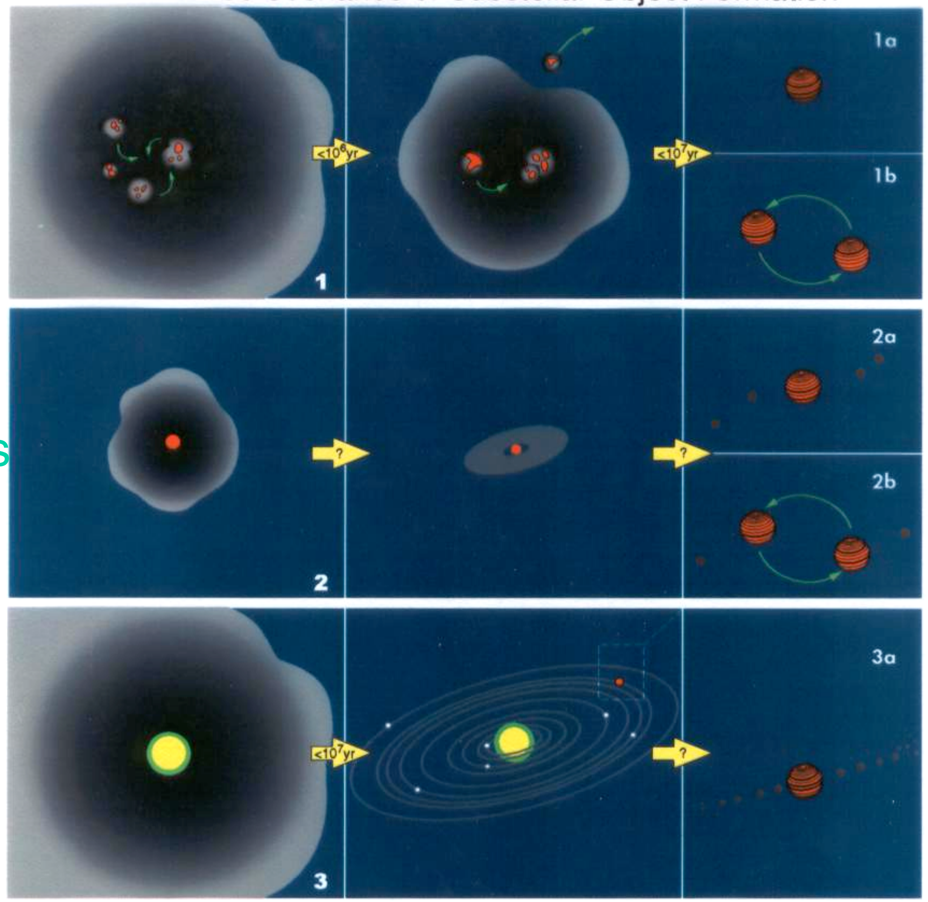
- Disks are formed in the early stages of core collapse and are an essential ingredient of the standard paradigm for star formation

- Disk-star interaction during pre-main sequence evolution
  - Disk accretion
  - Outflows and winds

- Is this paradigm applicable to the least and most massive stellar objects?
  - Formation of Brown Dwarfs
  - Formation of Massive Stars

Origin of Brown Dwarfs

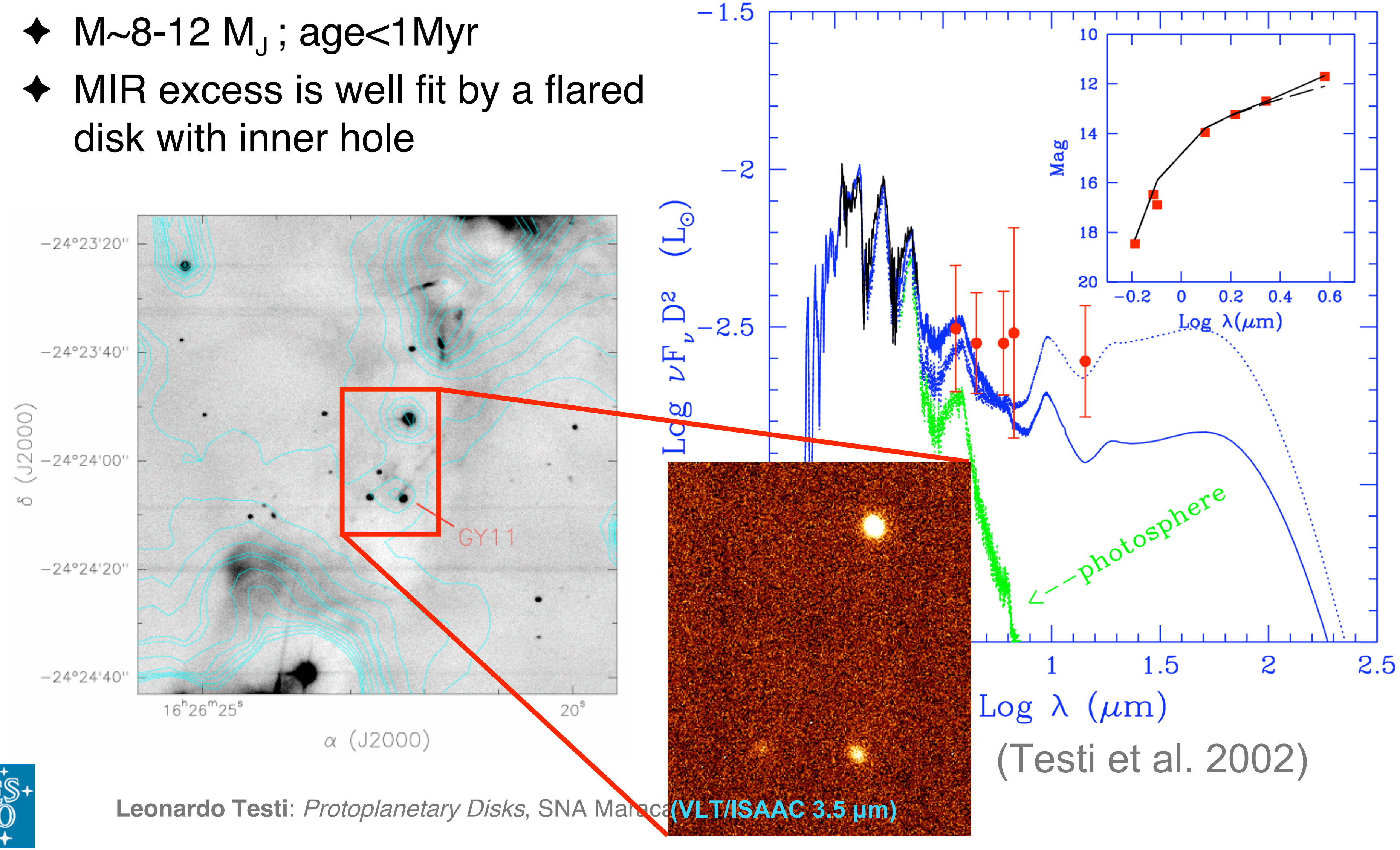
- ✦ Dynamical interaction in small (proto-)stellar systems result in the ejection of stellar embrios
  - ➢ No or very short-lived disk
  - ➢ Single or low-mass binaries
- ✦ Standard core collapse and disk accretion scenario
  - ➢ High fraction of long lived active disks
  - ➢ Similar properties a more massive TTs systems
- ✦ Formation in protoplanetary disks and subsequent dynamical ejection
  - ➢ No disks
  - ➢ No multiples



Three Scenarios of Substellar Object Formation

Disks in Brown Dwarfs

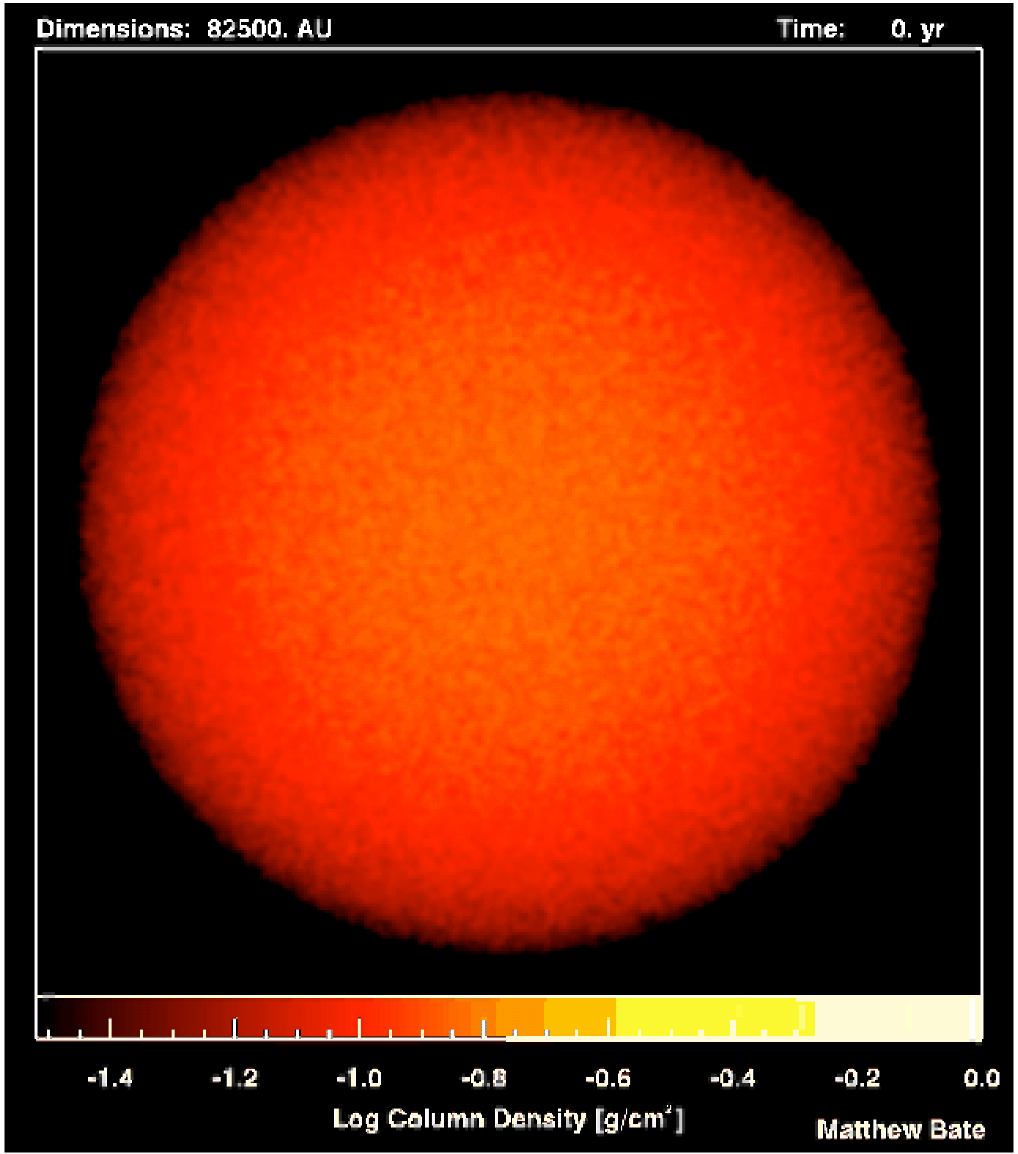
- GY11 in ρ-Oph
- M~8-12 M_J ; age<1Myr
- MIR excess is well fit by a flared disk with inner hole



(Testi et al. 2002)

Numerical simulations

- Collapse of a turbulent cloud core (simplified)
- Resolution ~20AU
- Formation of a small cluster

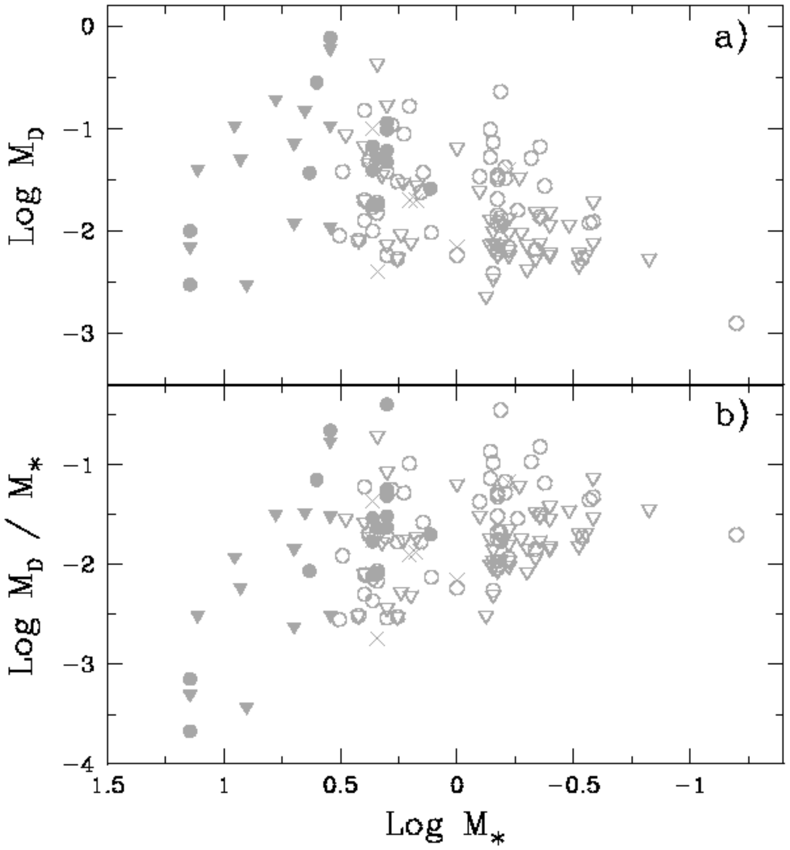


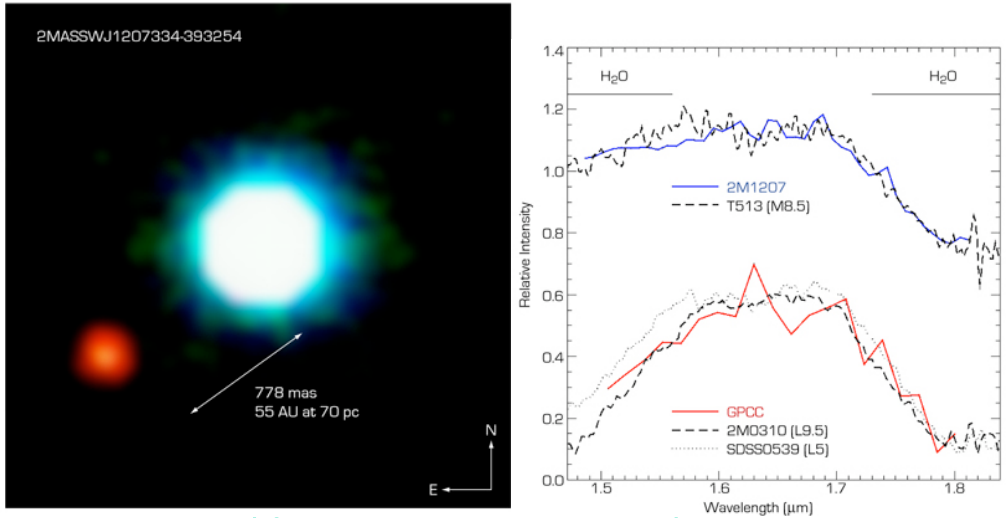
(Bate et al. 2004)

Disk masses

- $M_D \sim 0.0001\text{-}0.001$ Msun
- $F_{1mm} \sim B_n(T)\, k_{1mm}\, M_D$

- 0.1-0.3 mJy @ 150pc





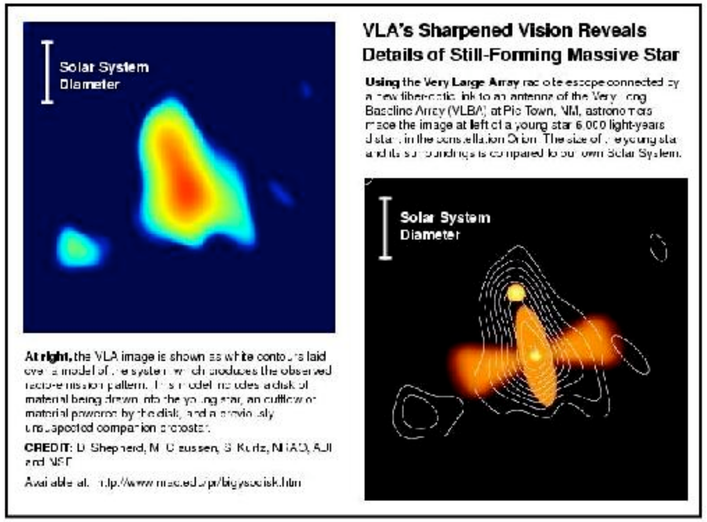
(Chauvin et al. 2004)

Planet or binary?

Disks and High-Mass Protostars

- There is evidence that also high-mass protostars are surrounded by massive (accretion?) disks
- Examples:
  - **G192** (Shepherd et al. 2001)
  - **IRAS 20126+4104** (Cesaroni et al. 1997/1999/2005)
  - **G24/G31** (Beltran et al. 2004/2005)

G192: 7mm cont
40 mas resol
VLA+PT



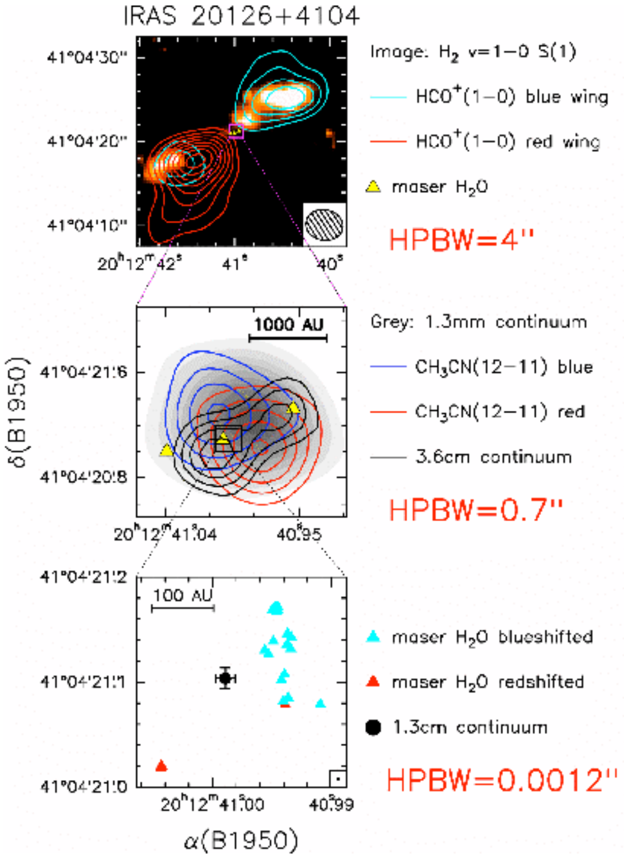
VLA's Sharpened Vision Reveals Details of Still-Forming Massive Star

Using the **Very Large Array** radio telescope connected by a new fiber-optic link to an antenna of the Very Long Baseline Array (VLBA) at Pie Town, NM, astronomers made the image at **left** of a young star 6,000 light-years distant, in the constellation Orion. The size of the young star and its surroundings is compared to our own Solar System.

At right, the VLA image is shown as white contours laid over a model of the system which produces the observed radio-emission pattern. This model includes a disk of material being drawn into the young star, an outflow of material powered by the disk, and a previously unsuspected companion protostar.

CREDIT: D. Shepherd, M. Claussen, S. Kurtz, NRAO, AUI and NSF

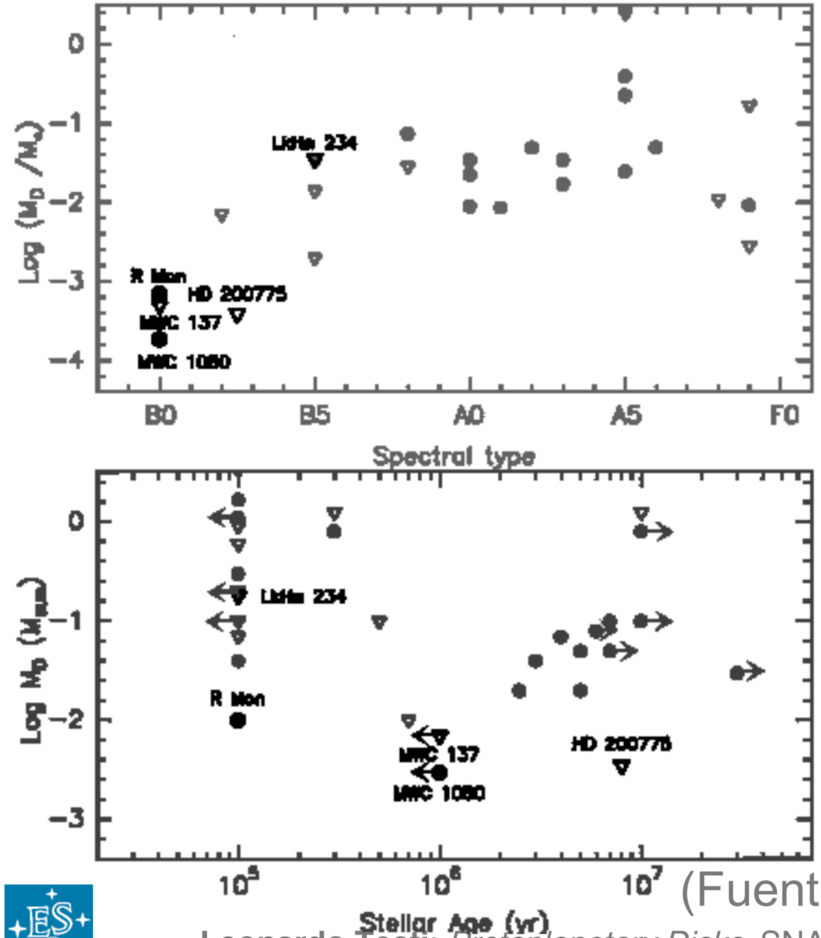
Available at: http://www.nrao.edu/pr/bigysodisk.htm

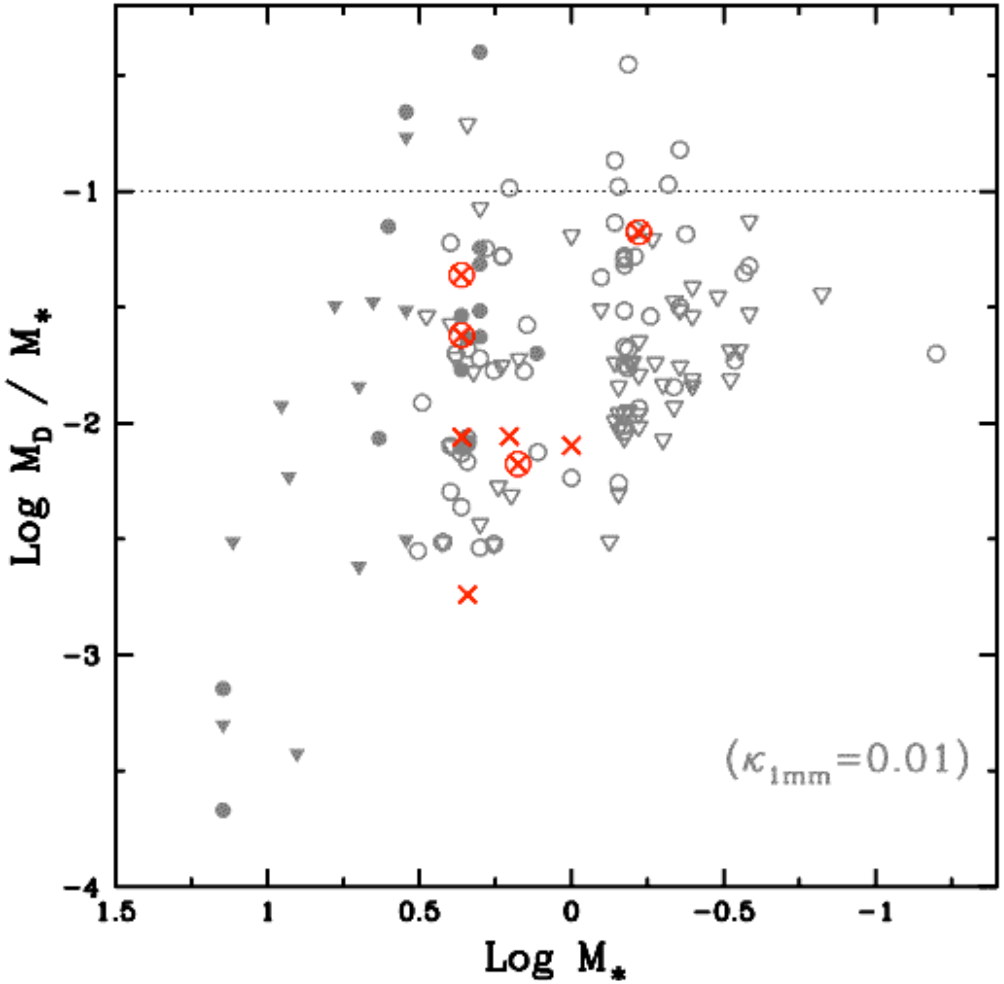


I20126: CH_3CN
PdBI

Disks around massive stars

- Disk masses derived from mm continuum observations

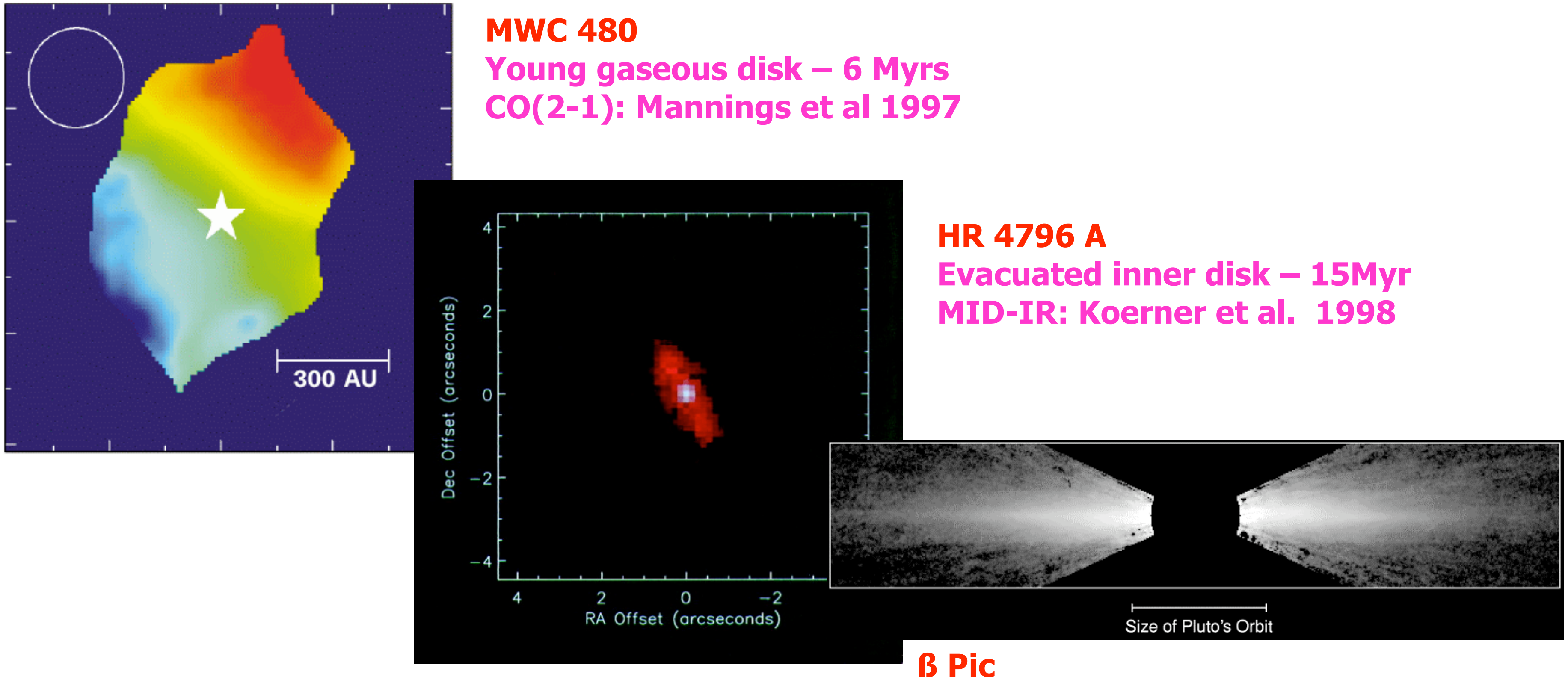




(Fuente et al. 2003)

Disk Evolution

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



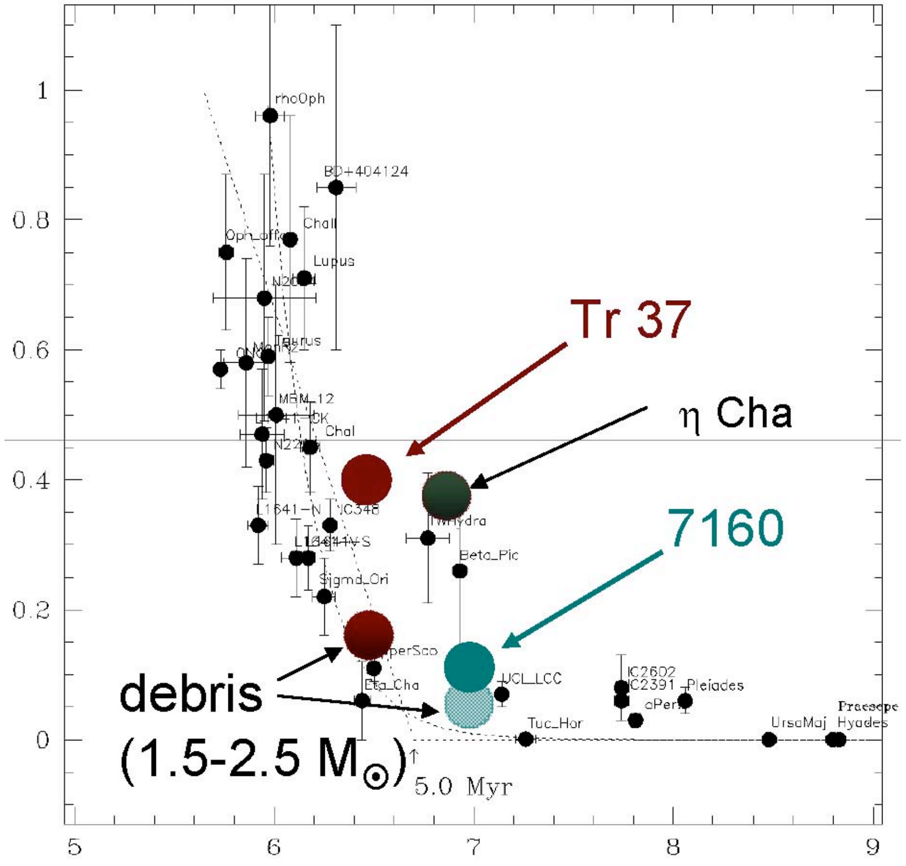
MWC 480
Young gaseous disk – 6 Myrs
CO(2-1): Mannings et al 1997

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

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



Tr 37

η Cha

7160

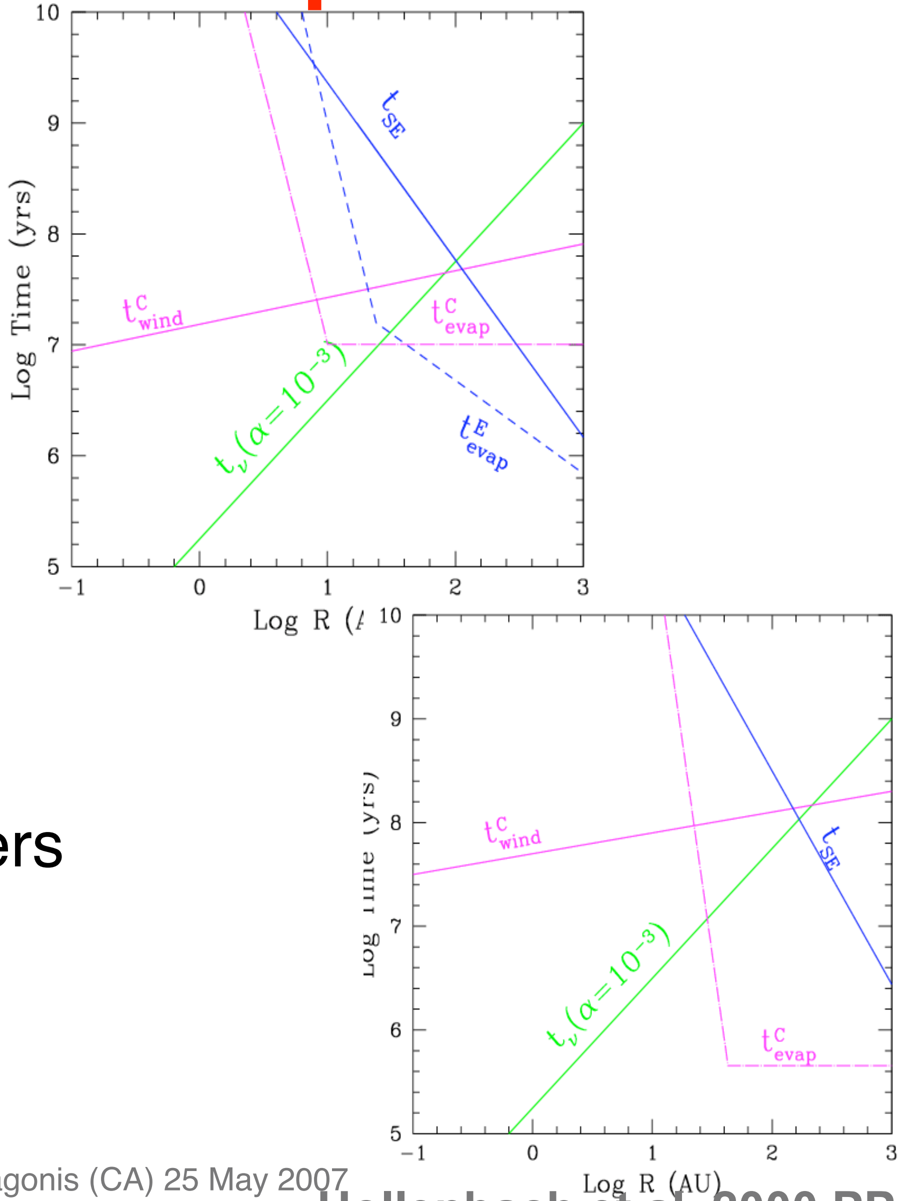
debris
$(1.5\text{-}2.5\ M_\odot)$

Leonardo Testi: *Protoplanetary Disks*, SNA Maracalagonis (CA) 25 May 2007

Why do disks dissipate?

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

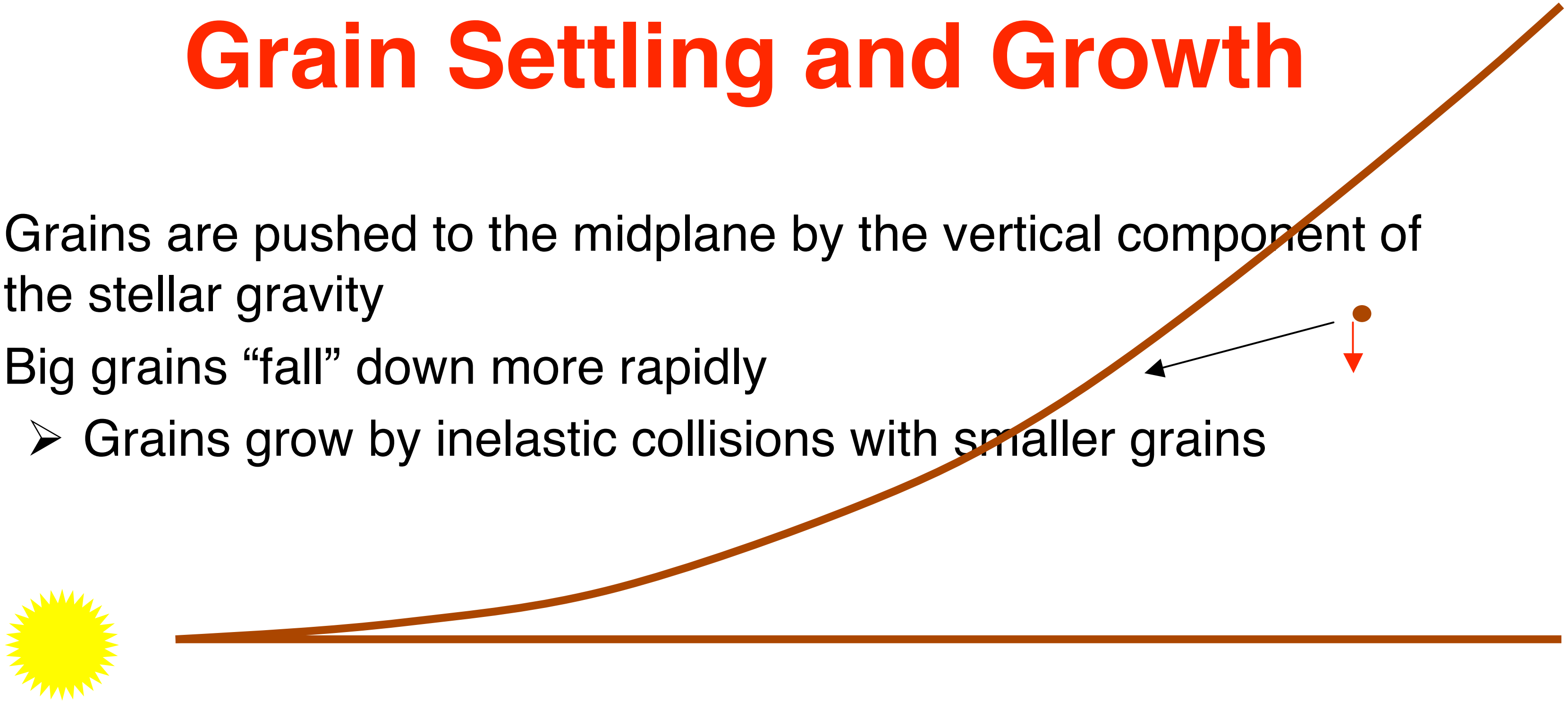
- Environmental effects:
  - stellar encounters in clusters
  - photoevaporation by other stars



Hollenbach et al. 2000 PPIV

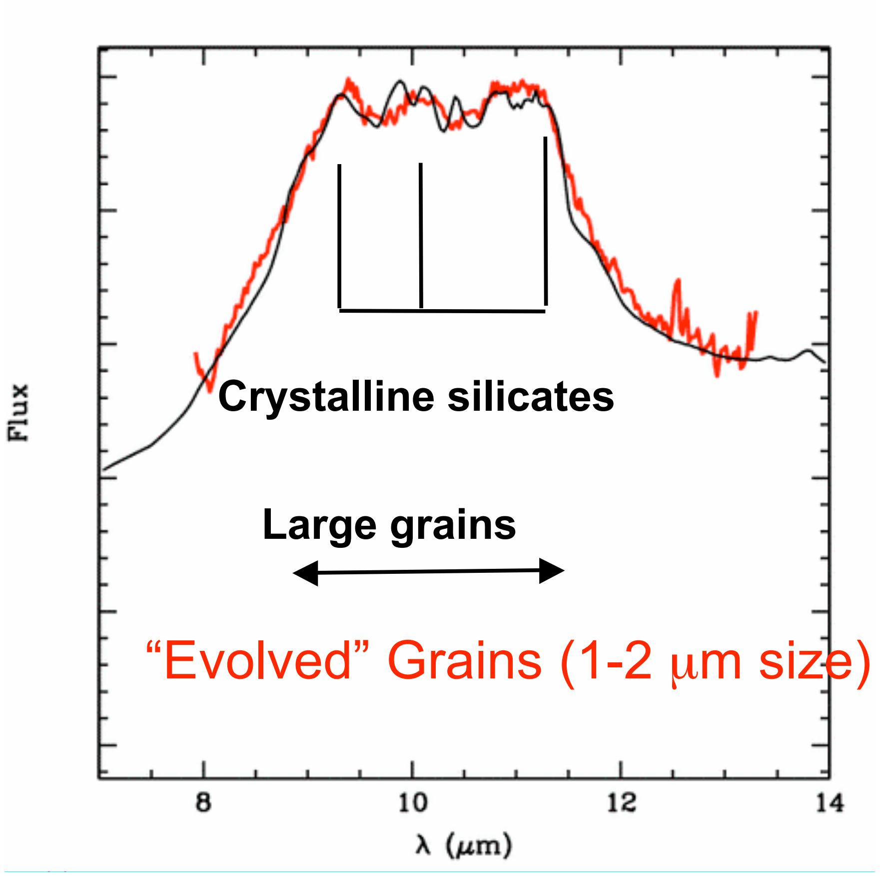
Grain Settling and Growth

- 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

Processing of the 10 micron feature

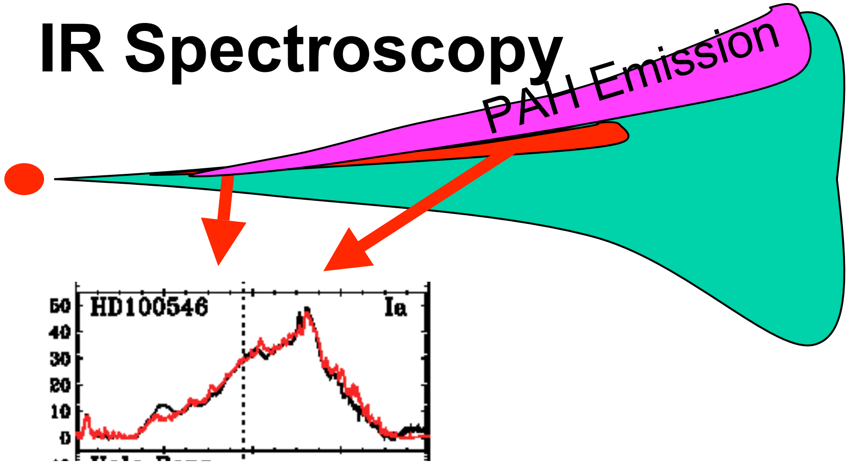


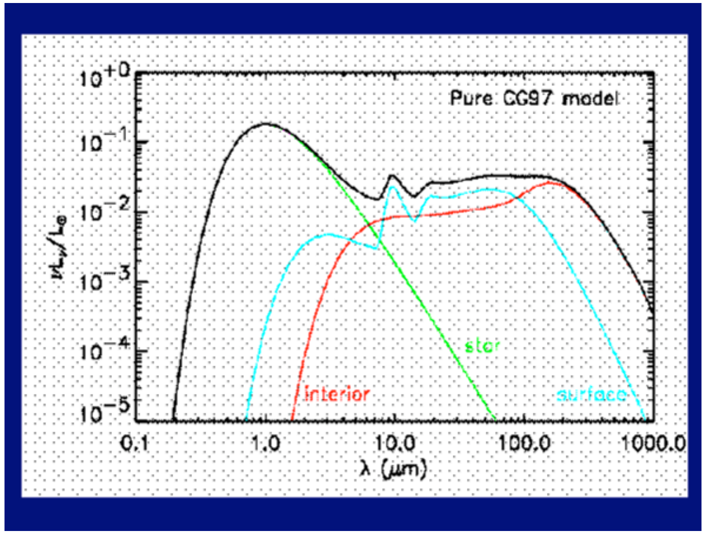
Crystalline silicates

Large grains

“Evolved” Grains (1-2 μm size)

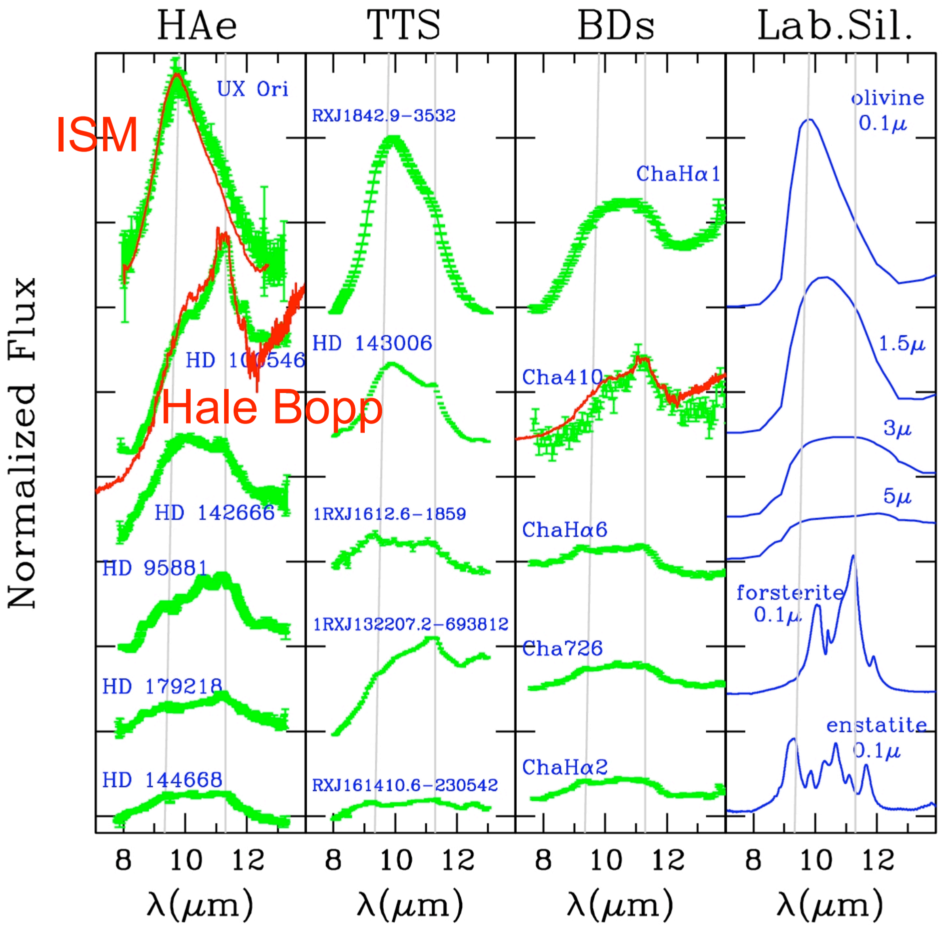
IR Spectroscopy





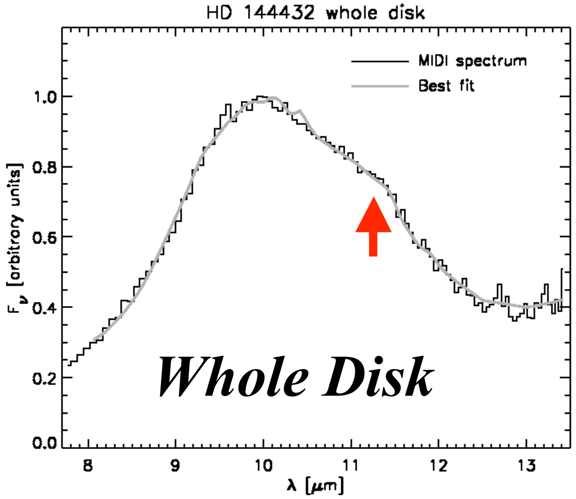
Grain Growth and Crystallization

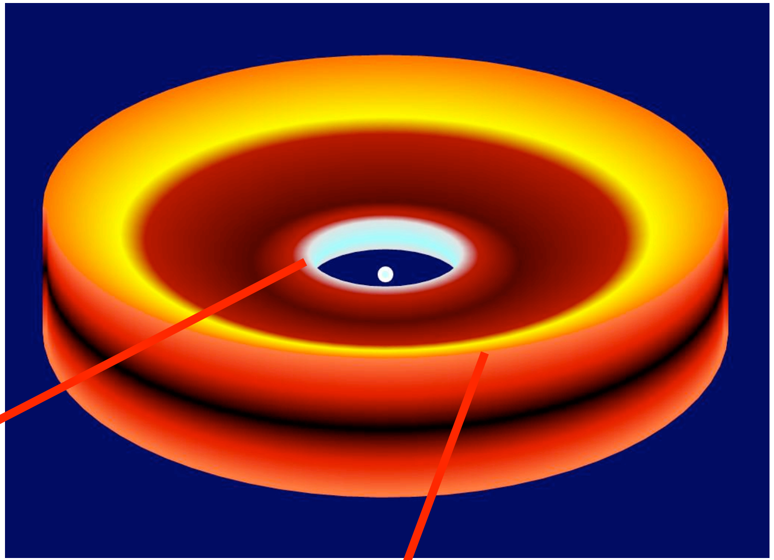
- Full range of profiles in disks around HAeBe, TTS and young BDs
- Grain sizes: from ISM to a few μm (not sensitive to larger grains)
- Mineralogy: from Amorphous to Crystalline

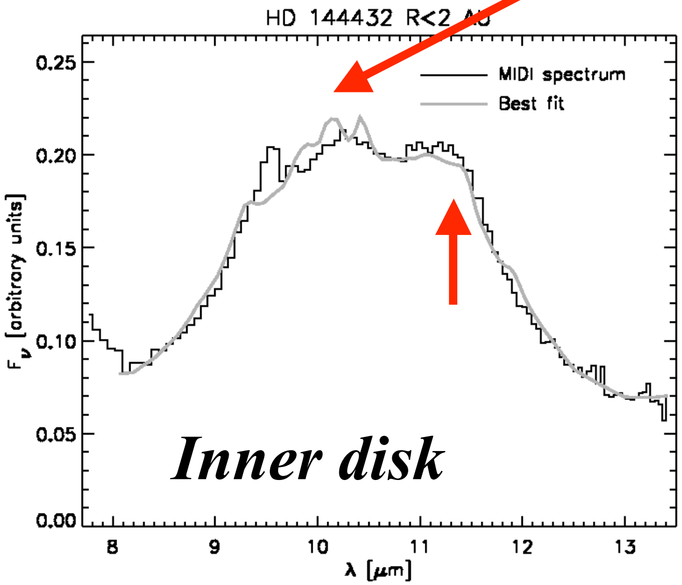


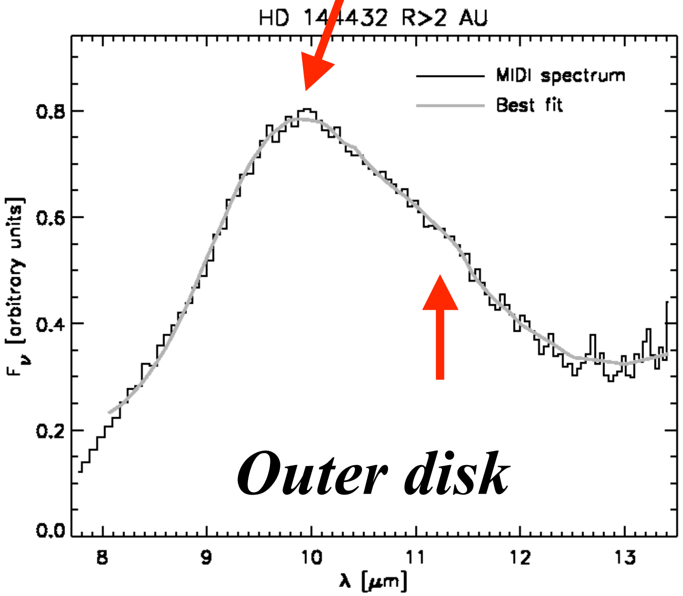
(Data: van Boekel et al. 2005
Bouwman et al. 2005; Apai et al 2005)

Spatially resolved spect (MIDI)



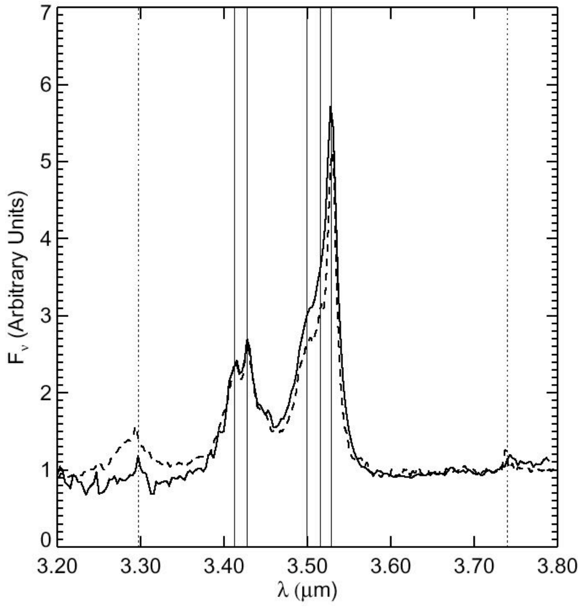


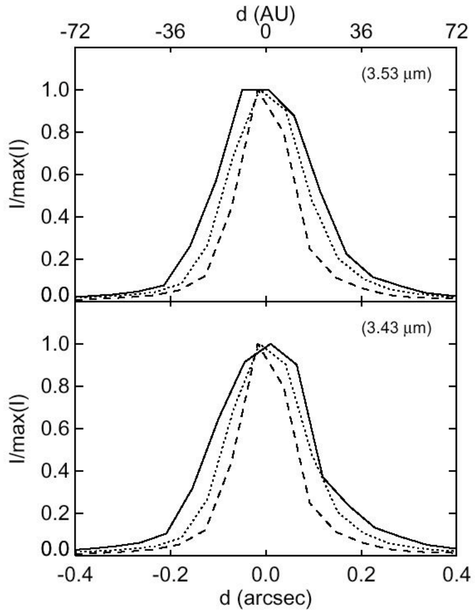


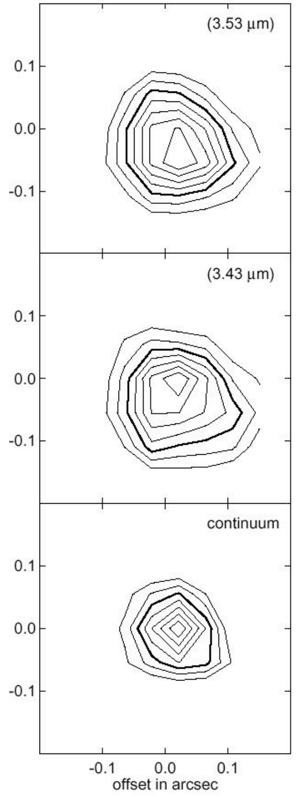


Diamonds in the HD97048 Disk

- 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)

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

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

$$T_d \sim r^{-q}$$

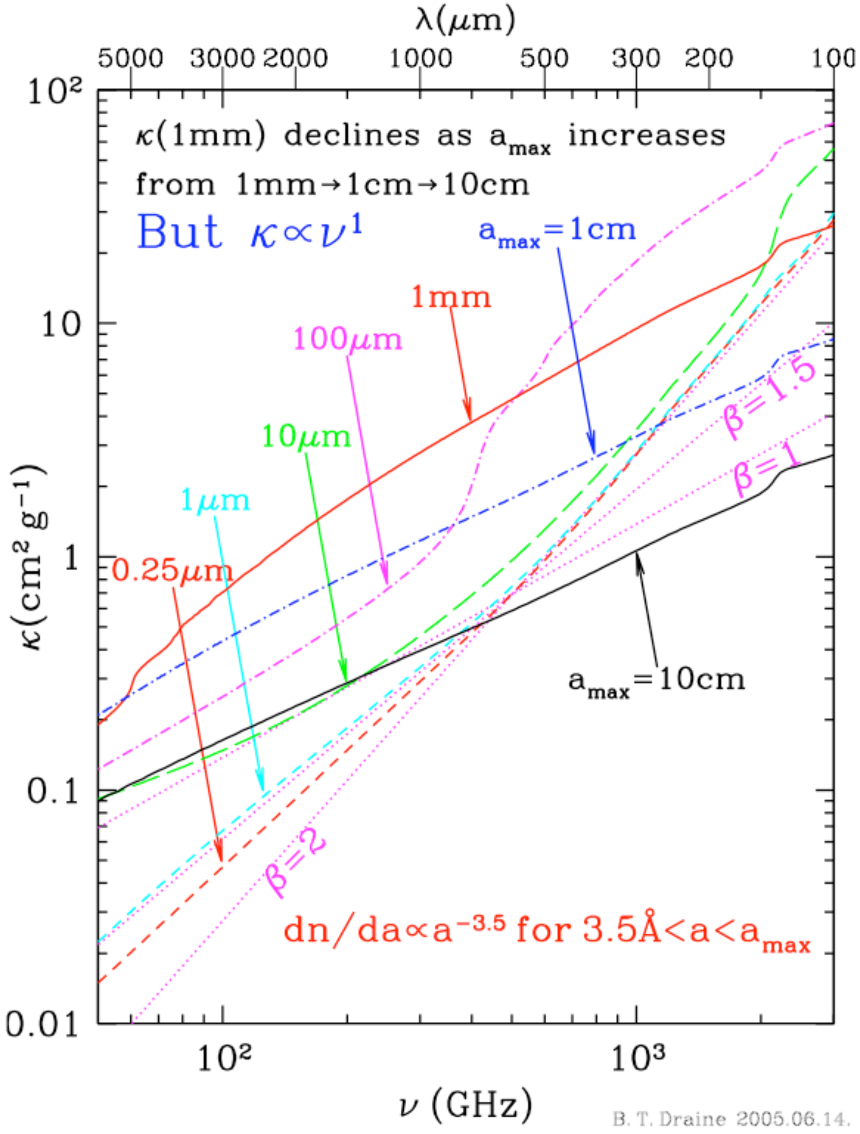
$\tau_\nu \propto \Sigma(r)\kappa_\nu$ $\Sigma(r) \propto r^{-p}$ $\kappa_\nu \propto \kappa_o \nu^\beta$

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

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

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

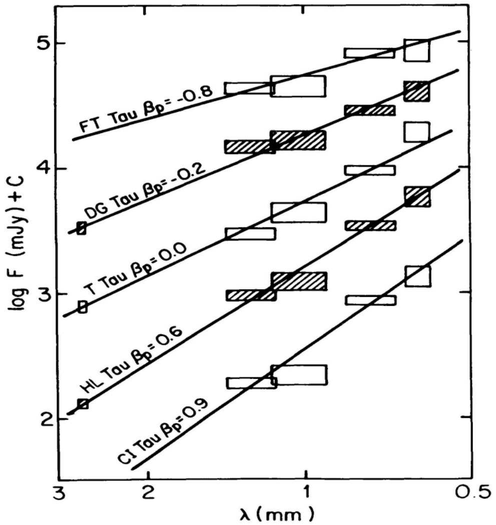
$F_\nu \sim \nu^{2+\beta}$



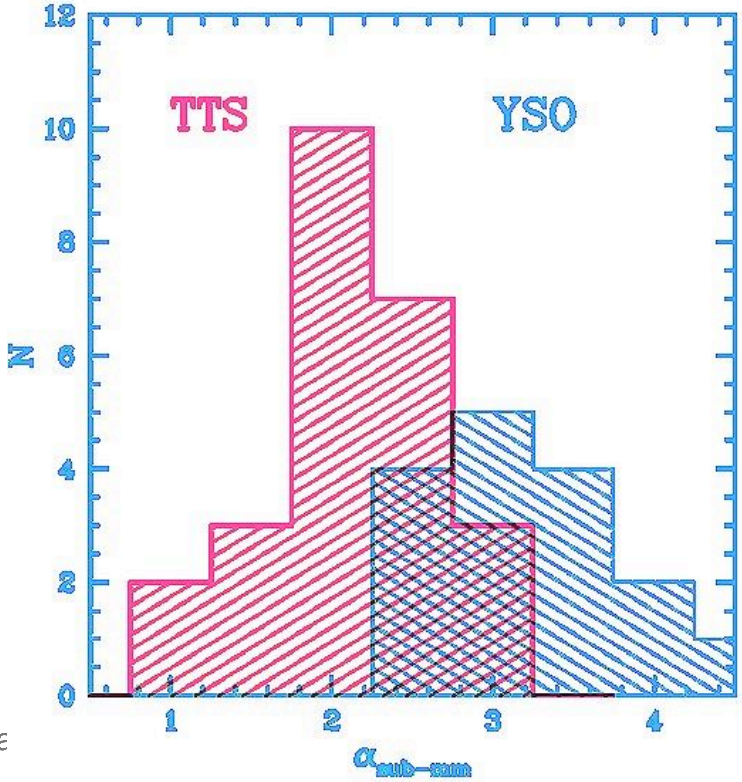
(Draine 2005)

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



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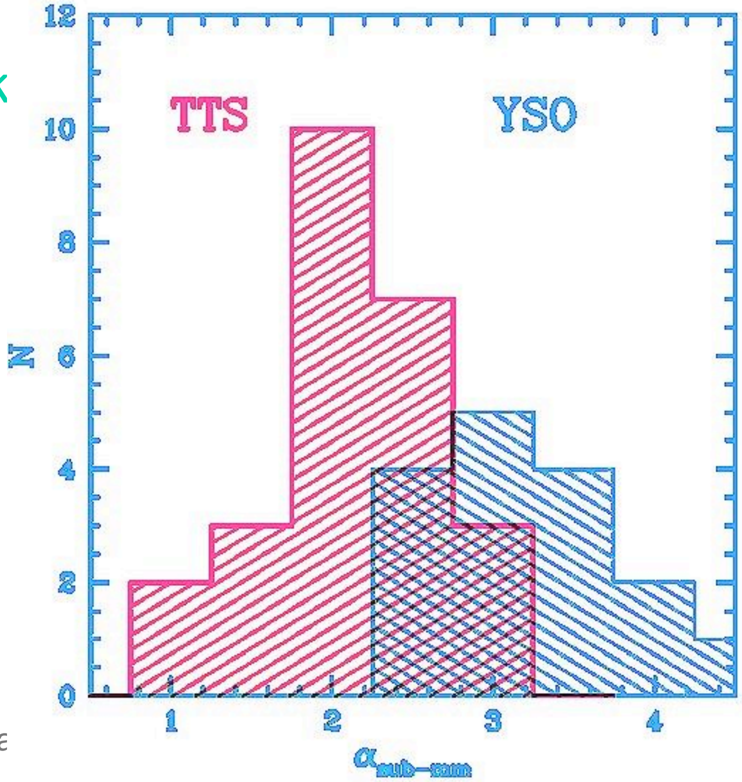
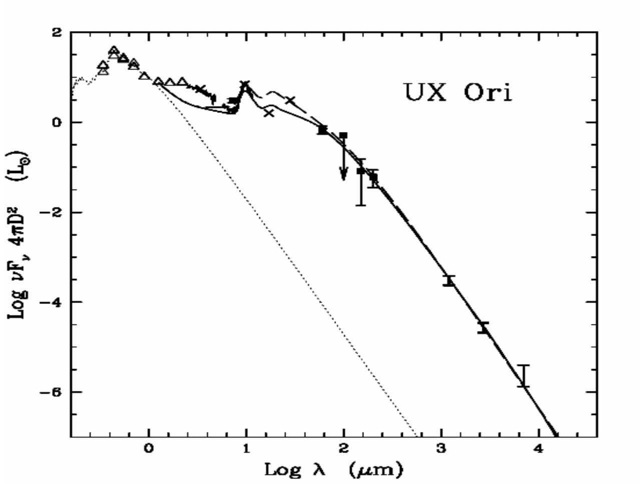
- Disks may be optically thick
- Need to go to longer λ
- Worrie about free-free
- Need to resolve disks
- Need to use disk models



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

Evolved dust in HAe disks

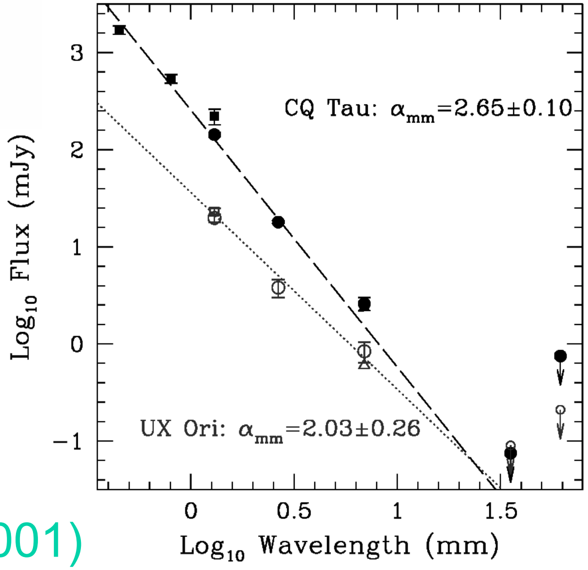
- 1 to 7 mm observations with OVRO/PdBI and the VLA

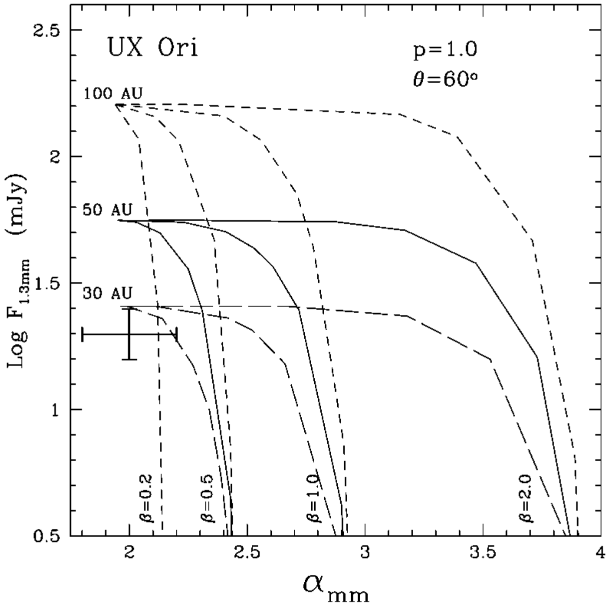


1. **Very small, optically thick, ISM grains disk**
2. **Large disk with very large (few cm size) grains**

PdBI 1.2 & 2.7 mm
VLA 7mm and 3.6cm

$\alpha_{mm}\sim2.0$; $\beta\sim0.1$
$a \geq 10$cm





(Testi et al. 2001)

Evolved dust in HAe disks

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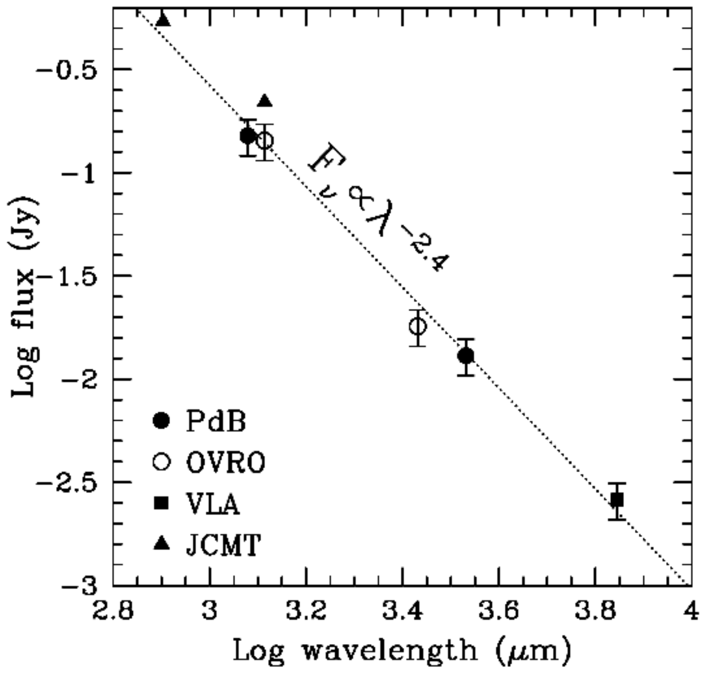
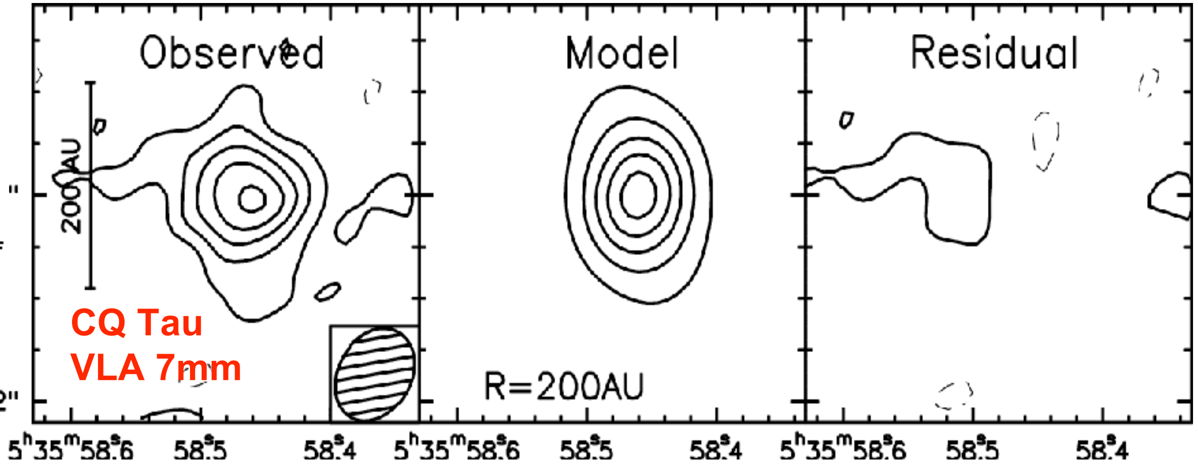


Disk resolved at mm wavelengths:

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



CQ Tau
VLA 7mm

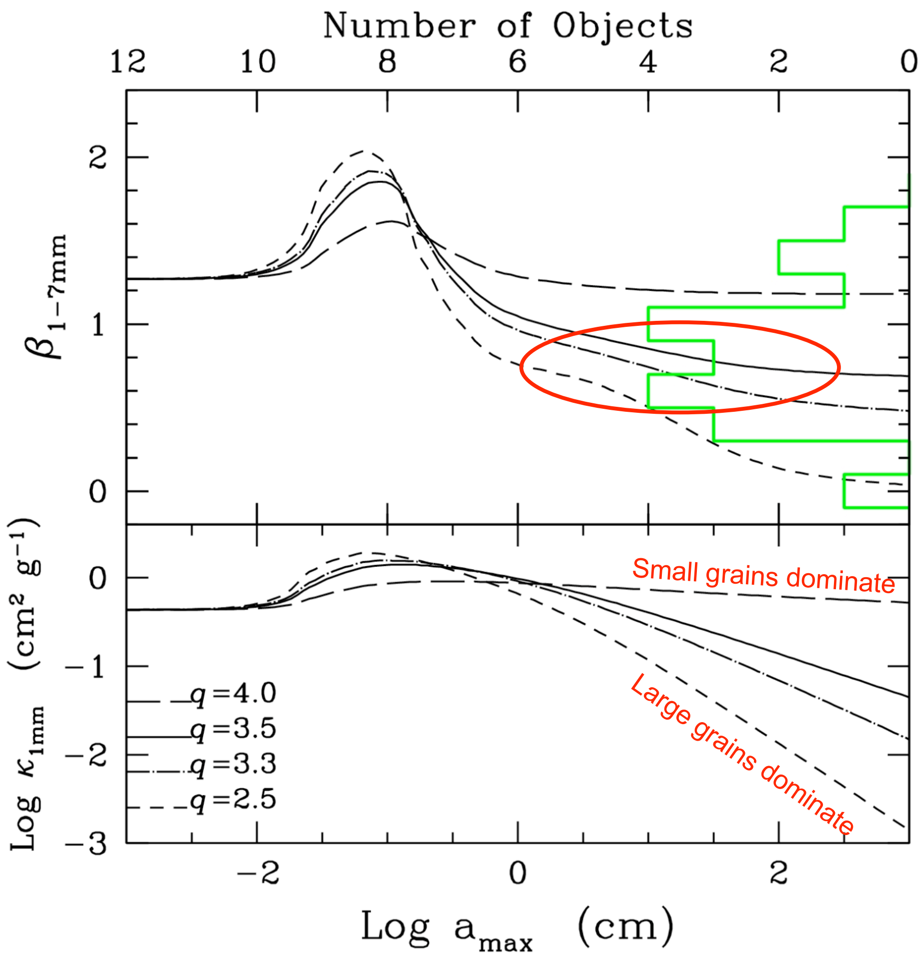
α_{mm}~2.4; p~1.5; β~0.6

(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

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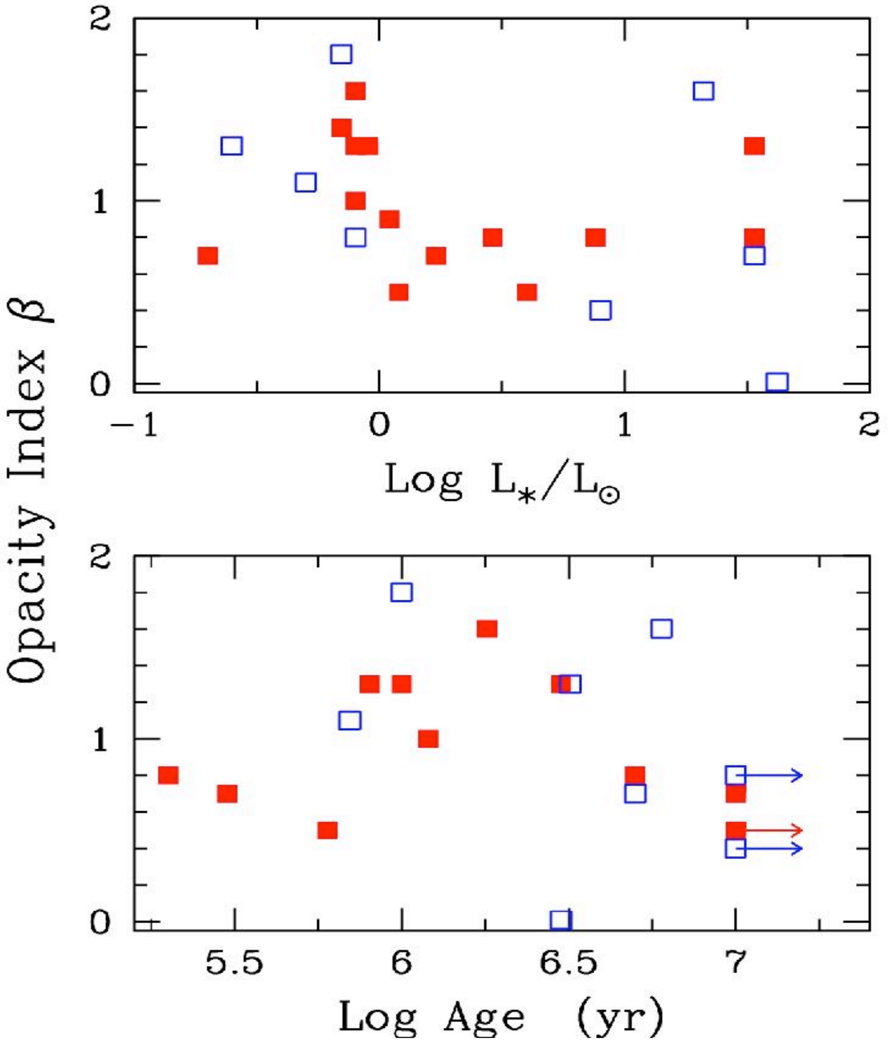
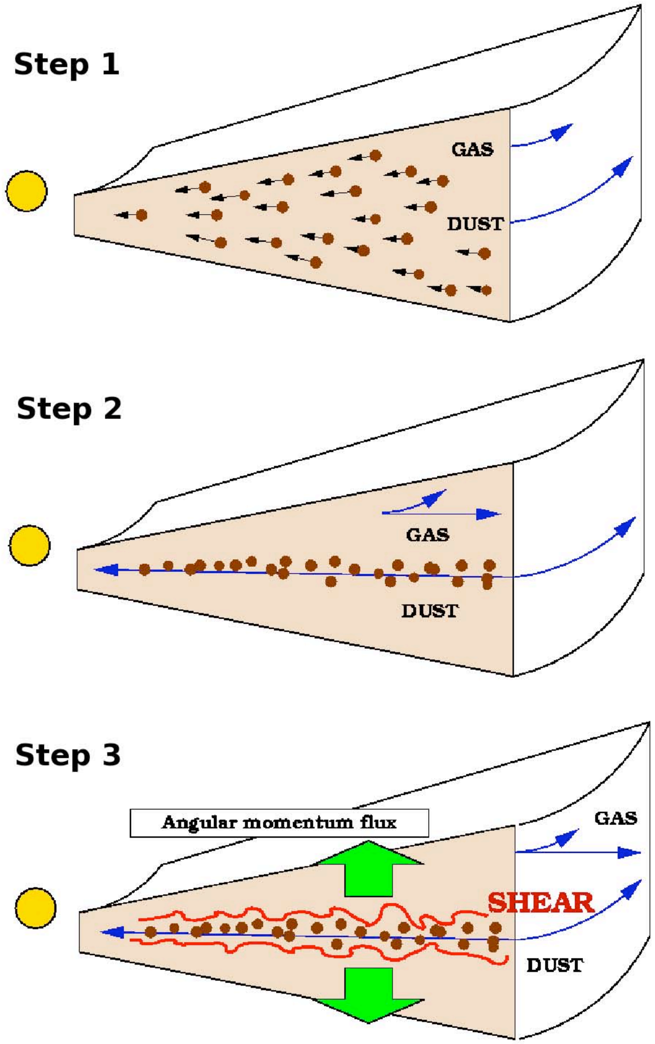
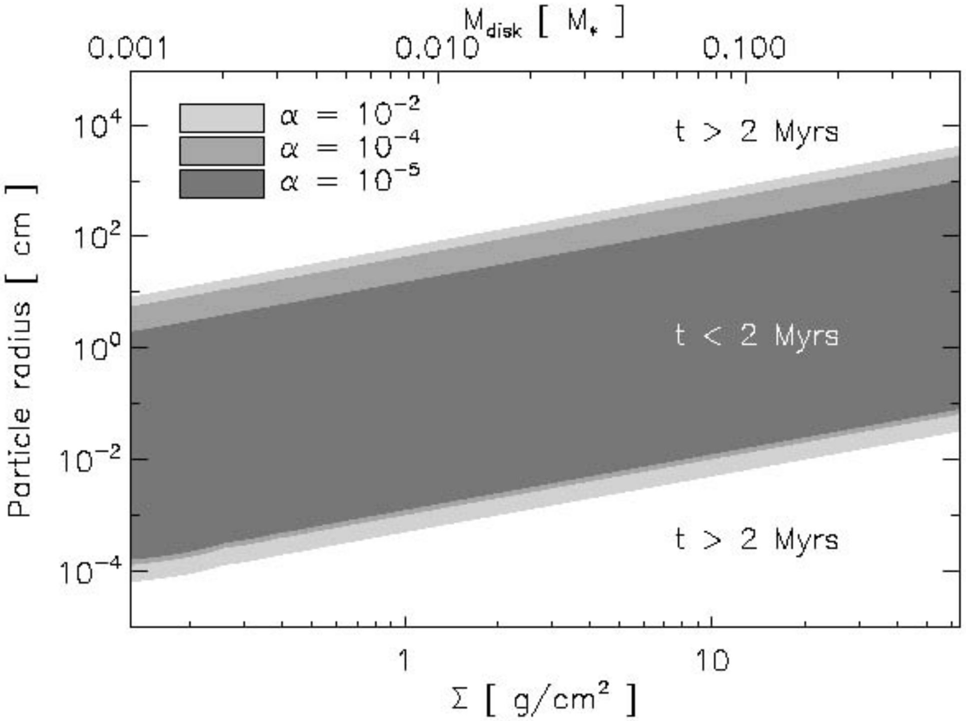


(Natta, LT, et al. PPV)

Pebbles should not survive in disks!



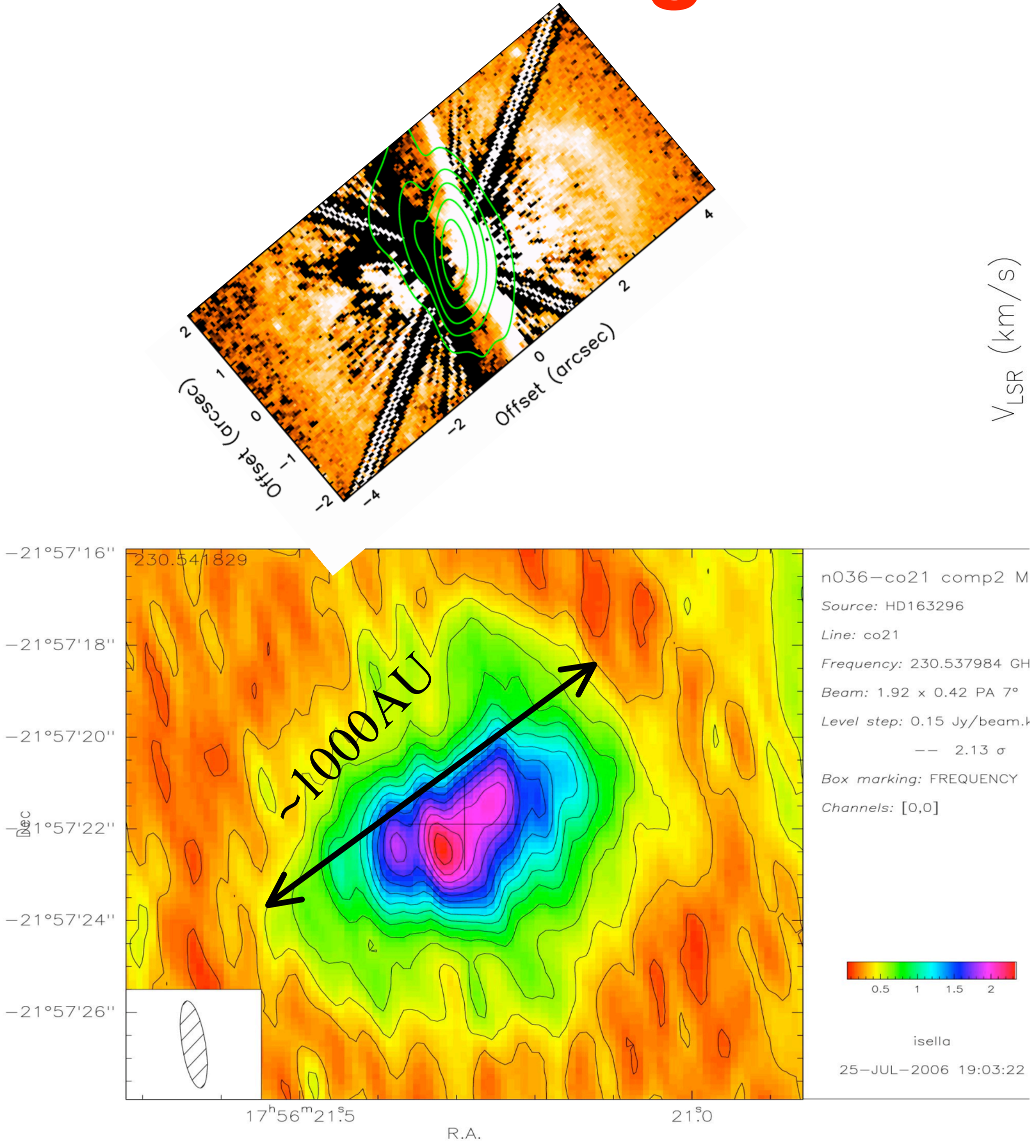
(Brauer et al. 2007)

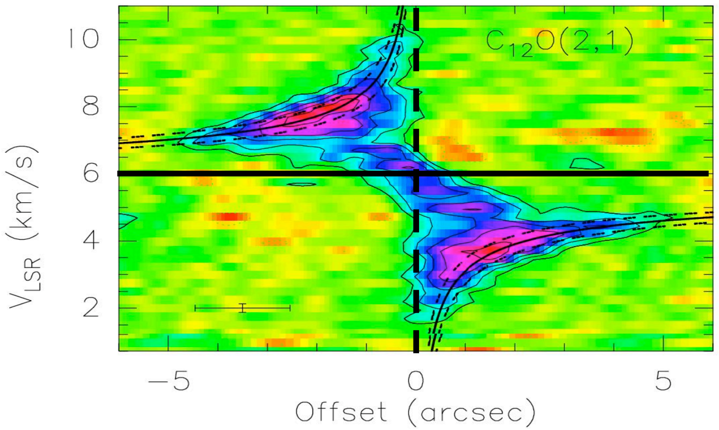


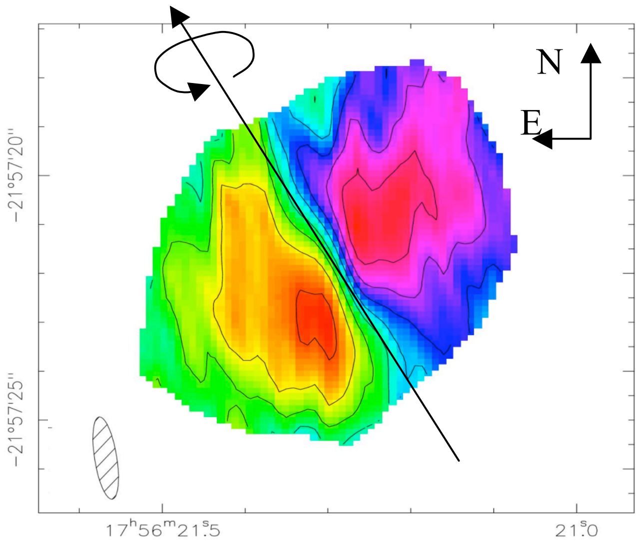
- ✦ Radial drift of mm-cm size particles at r~100AU can be very fast
- ✦ Viscosity, porosity, gas/dust ratio
- ✦ Trapping in disk patterns
  - ➢ Vortices, spiral arms…

Resolving the disk properties

HD163296

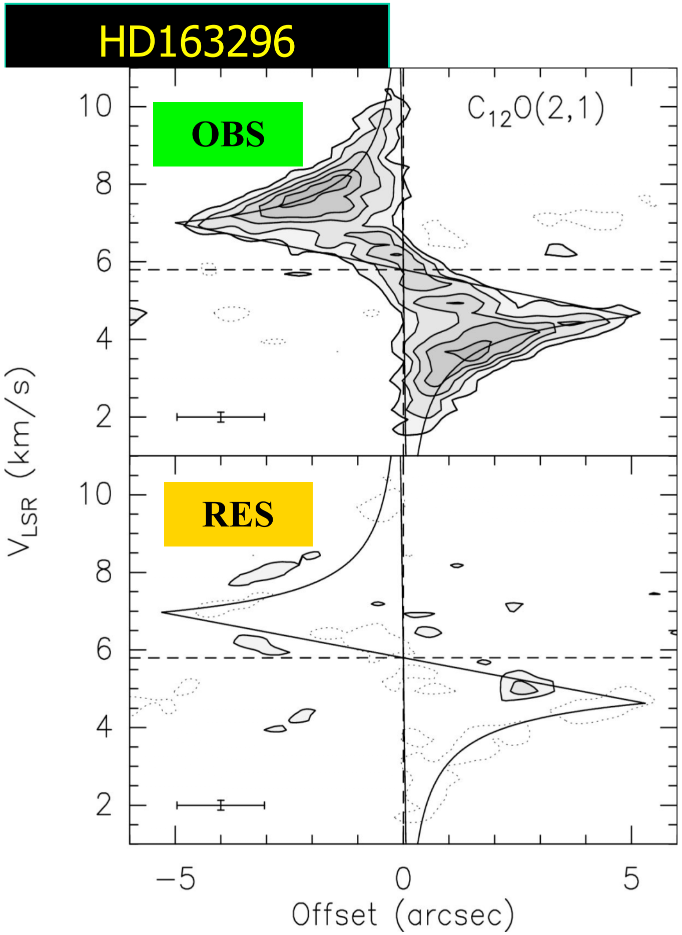




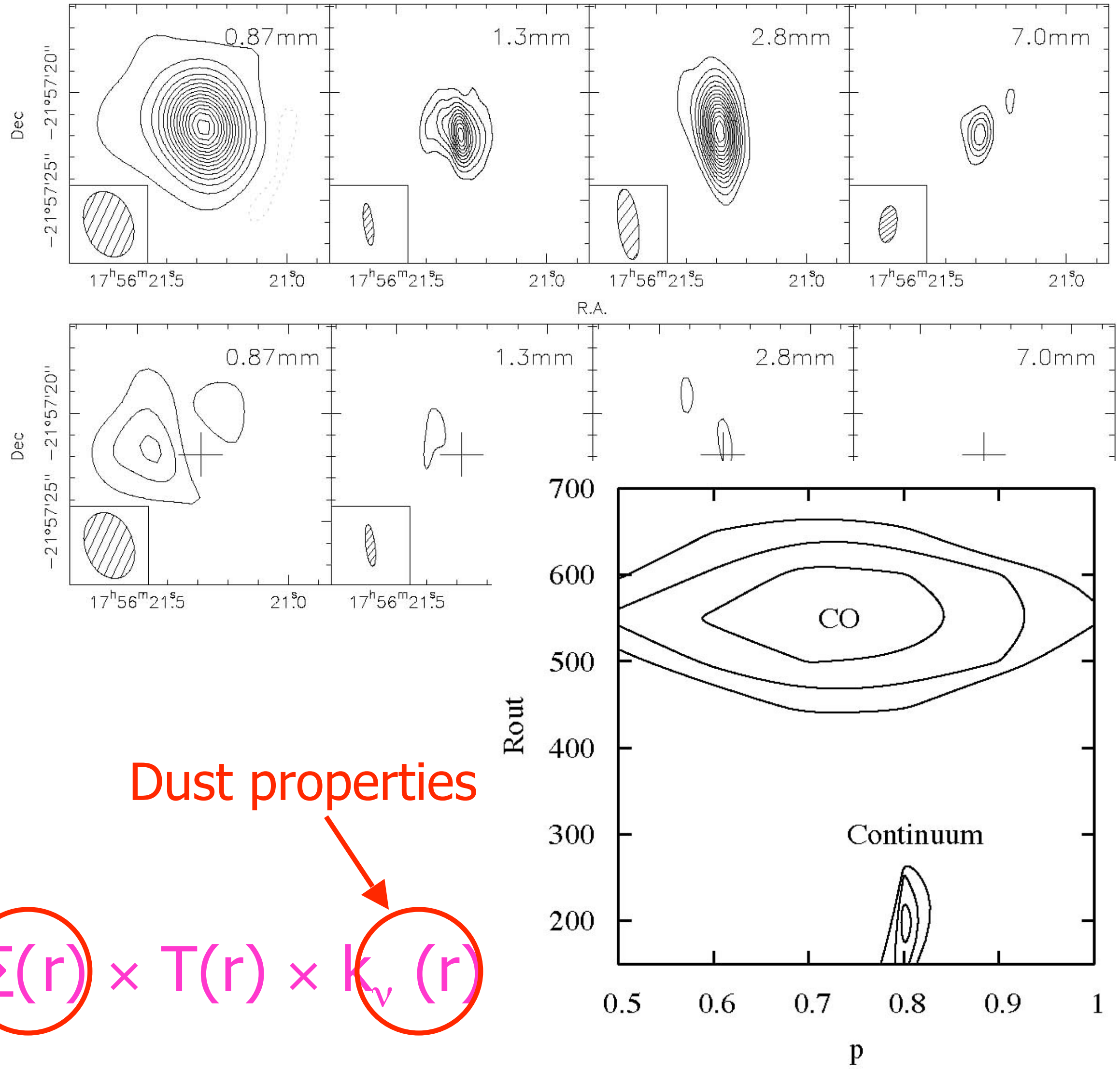


(Isella et al 2006)

Resolving the disk properties



(Isella et al 2006)



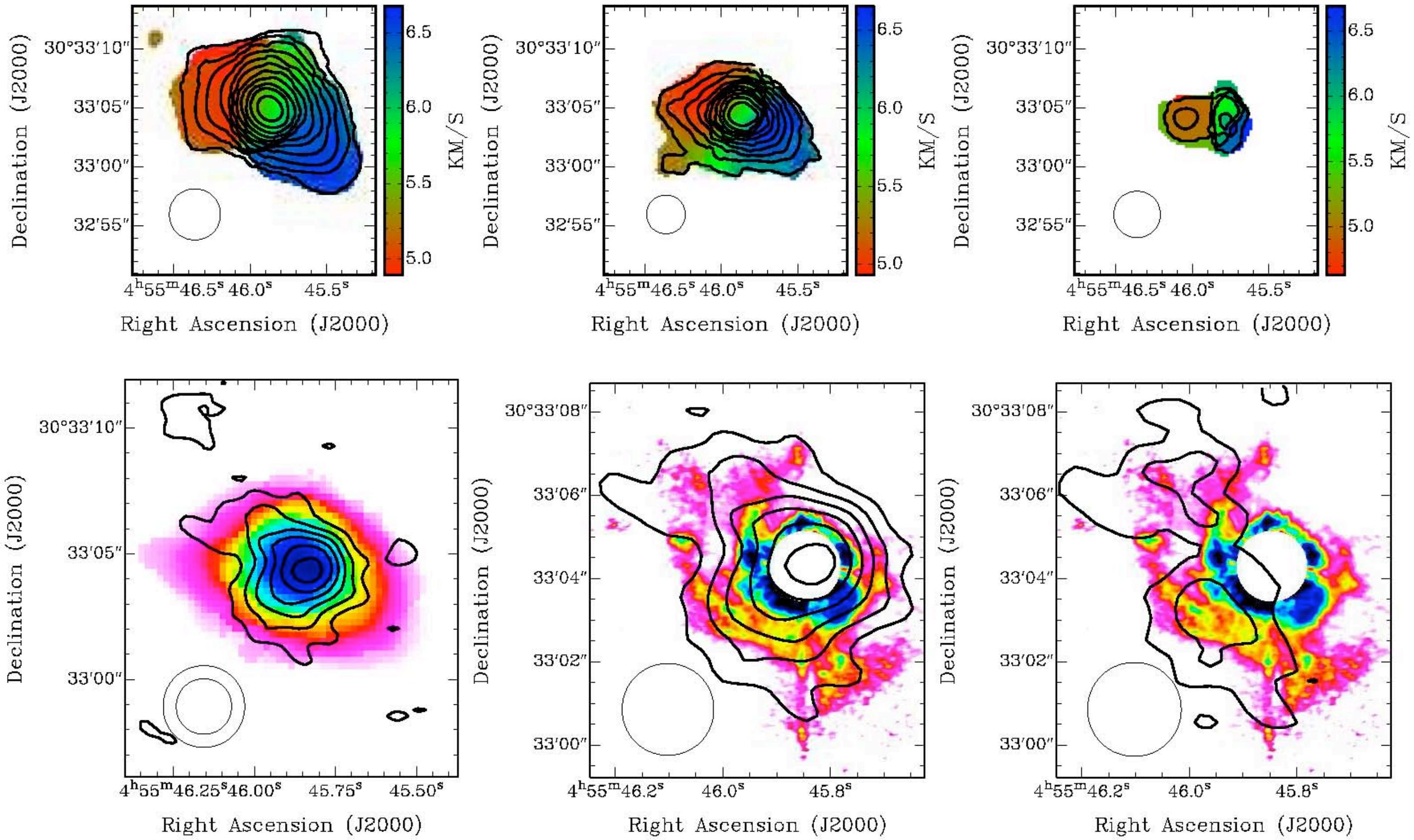
Dust properties

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

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

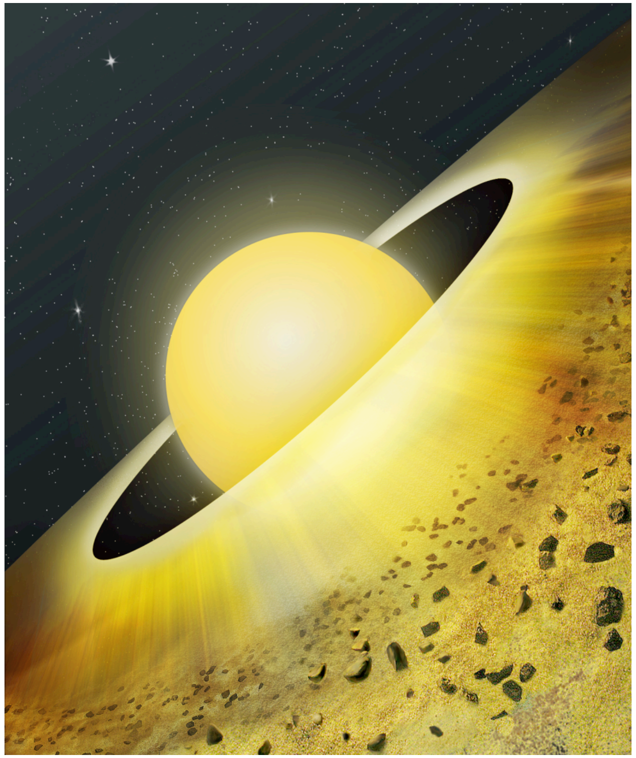


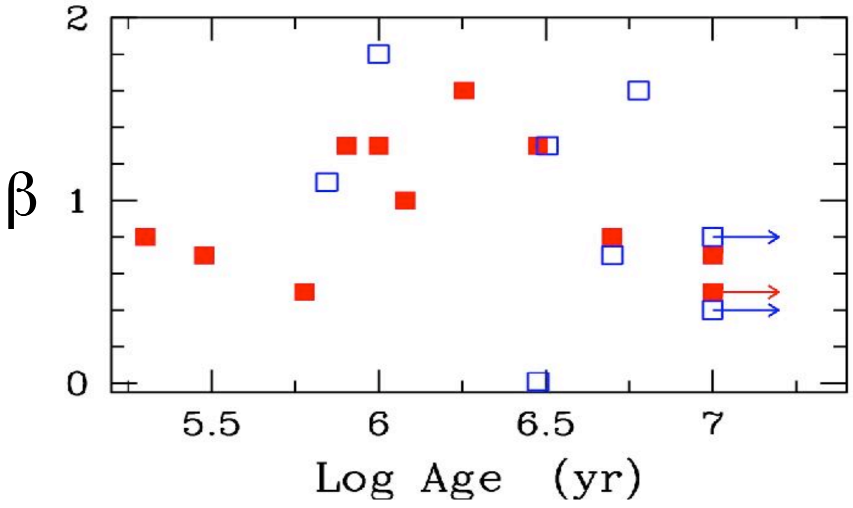
OVRO 2.7mm
(Corder et al. 2005)

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





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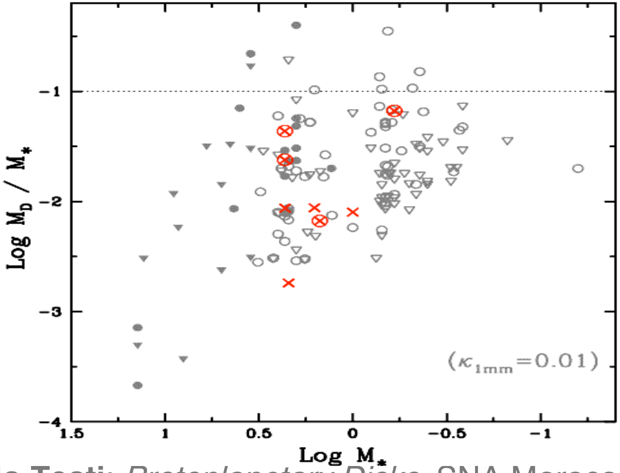
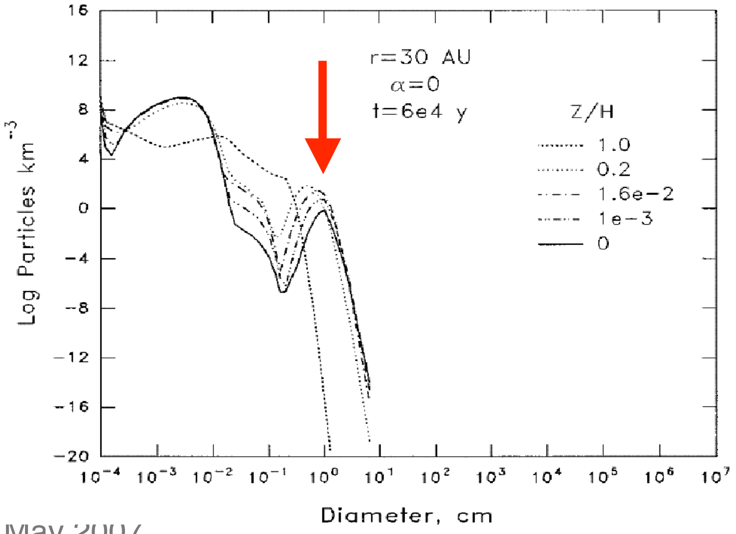
  - Large bodies, if present, do not dominate the solid mass of the disk up to 5-10 Myr
- Growth to pebbles is very fast, but converting a significant mass to 1m-size planetesimals seems more difficult (or requires more time)
  - Or perhaps we are just observing the odd beasts?





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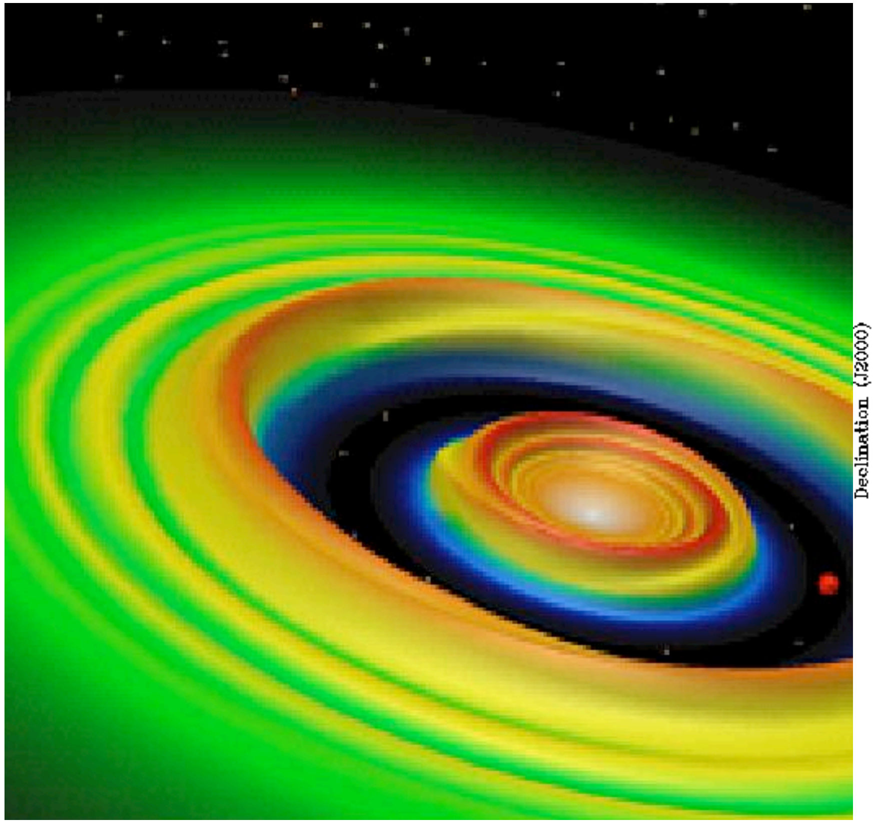
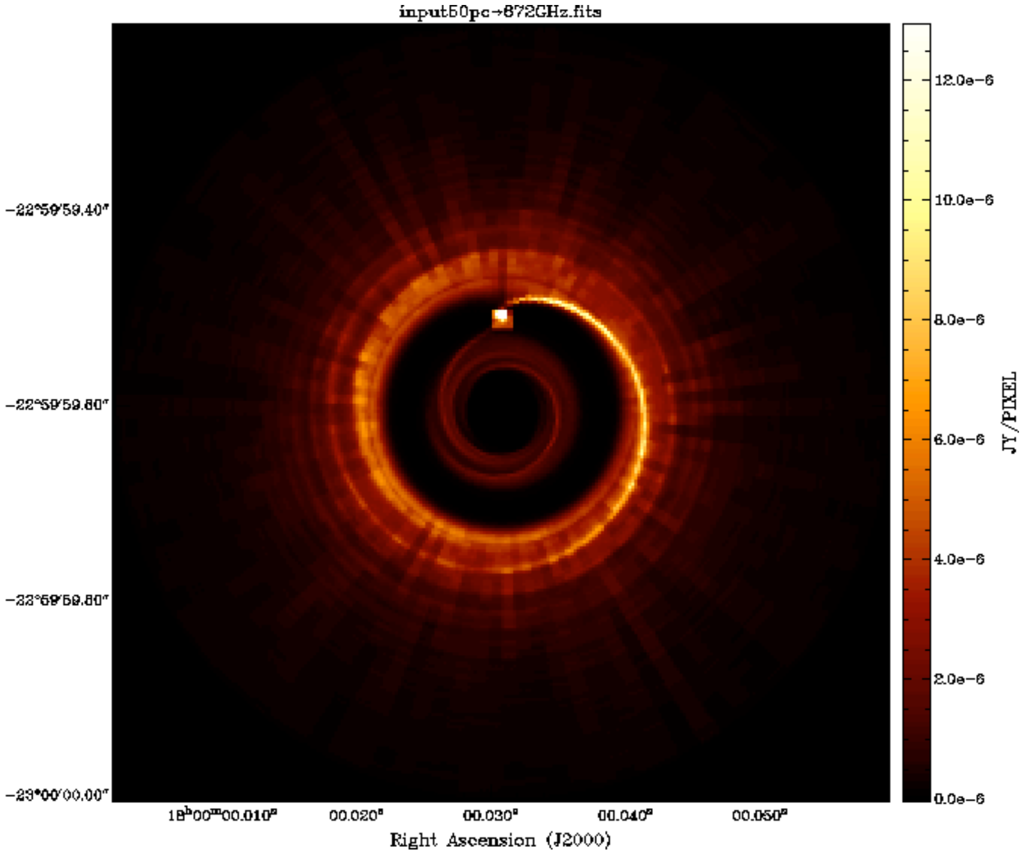
- Timescale for settling and growth: is dust evolution occurring in Class I phase?
  - Early planet formation?
- Large grains should be dragged to the central star on very short timescales, why do we see them at all?
  - Resolve the radial dependence of Grain Growth in disks

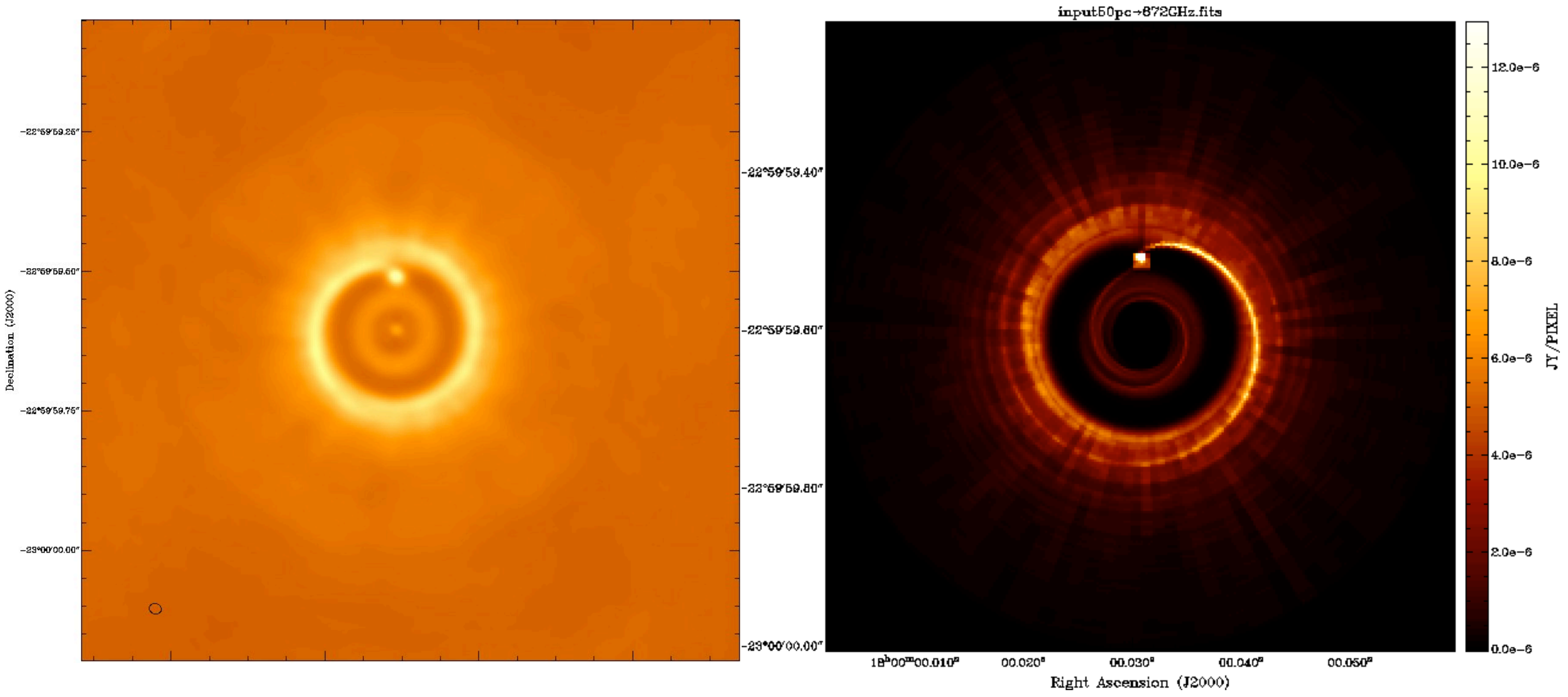
Late stages of planet formation





- Simulations of giant protoplanets in circumstellar disks

Late stages of planet formation



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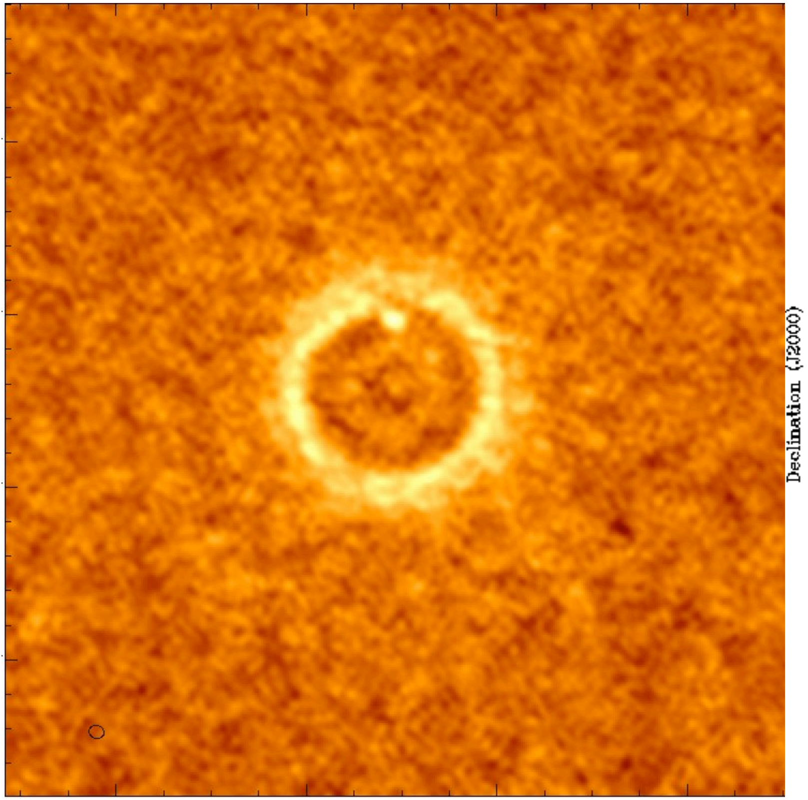

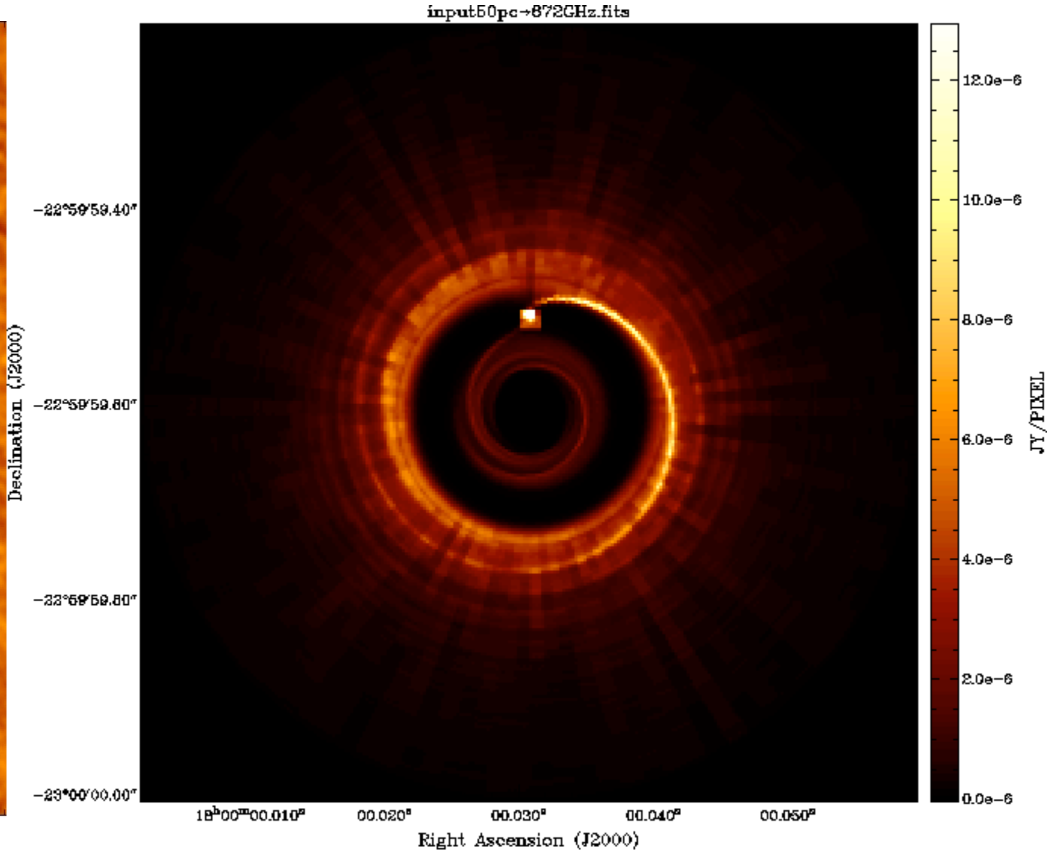

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- NB. 50pc distance! (though experiment even with ALMA)

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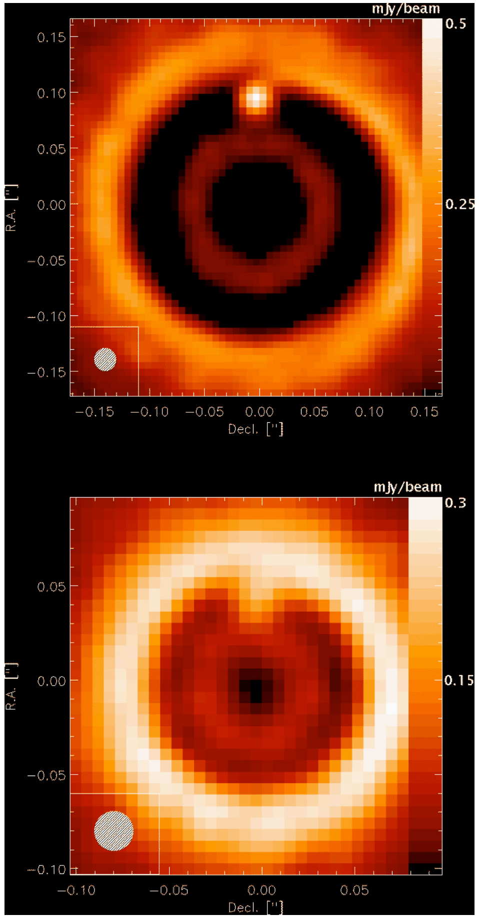
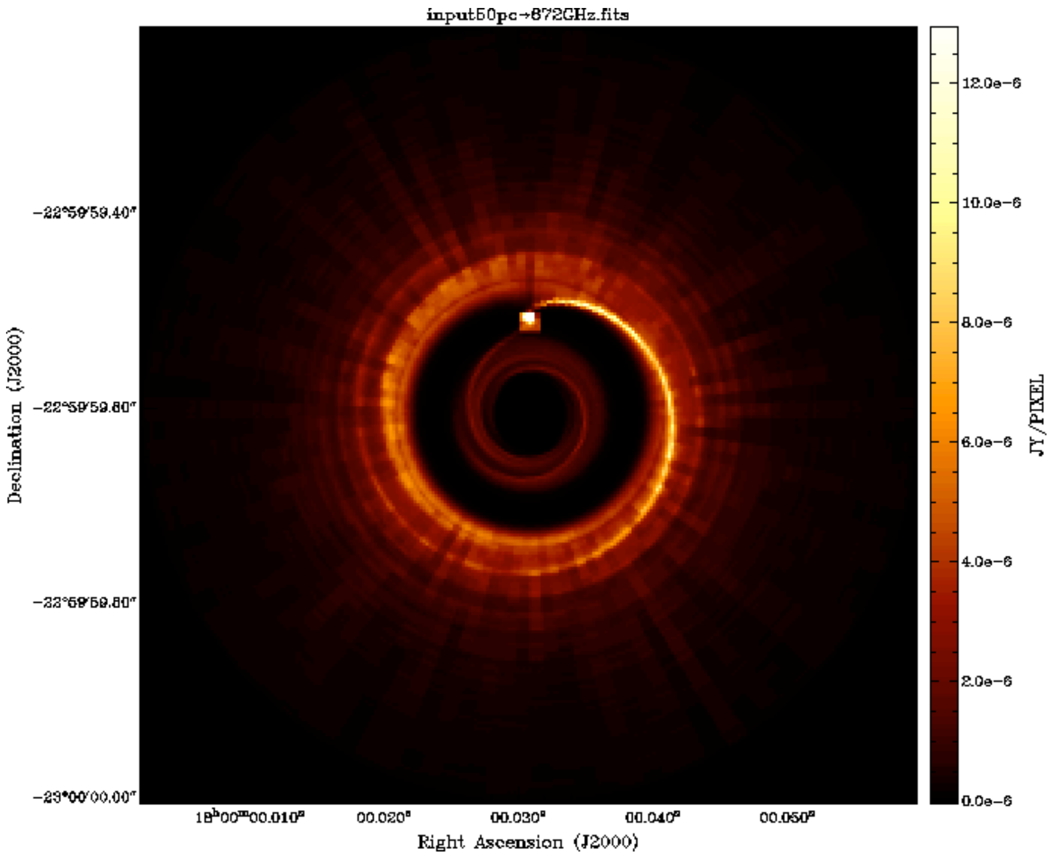


50pc

100pc



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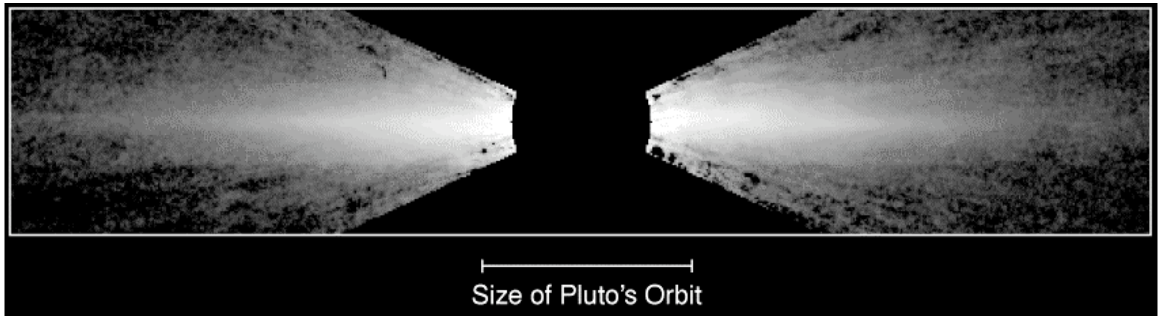
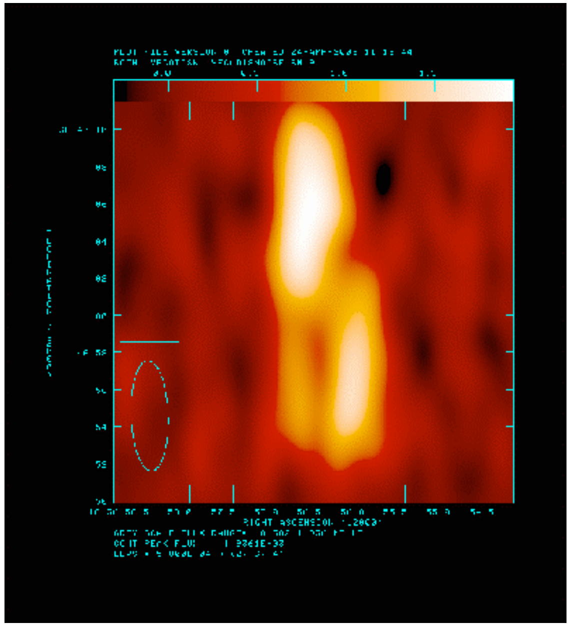
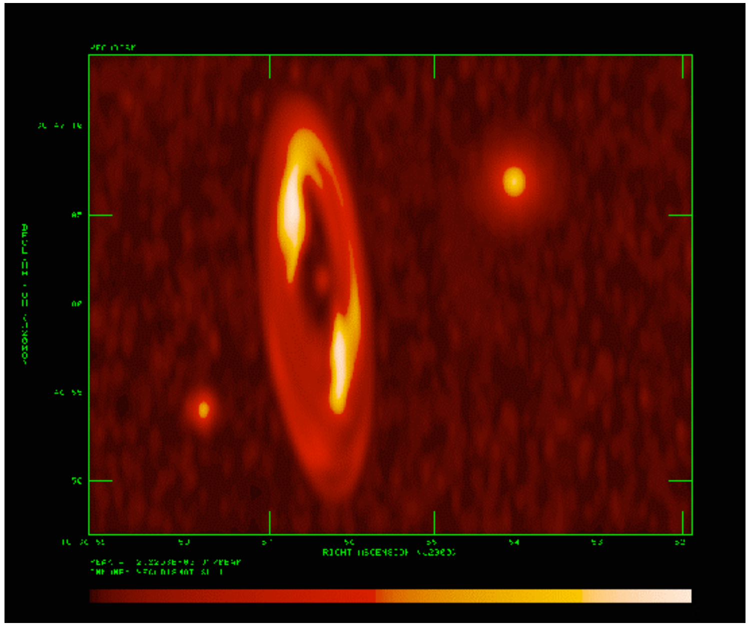
Debris disks



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





ALMA & Circumstellar Disks

- 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