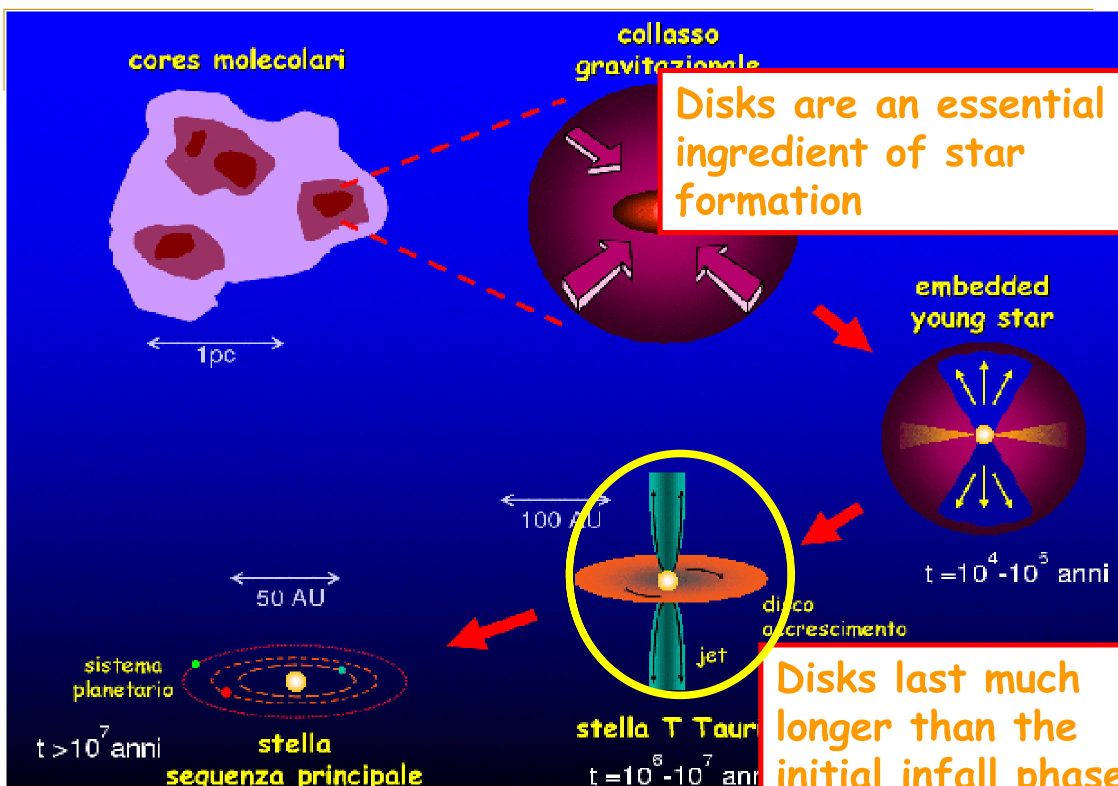
A review of disk obervations

Antonella Natta



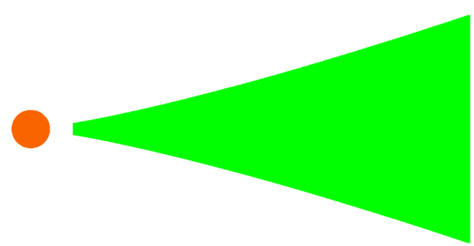
Disks are an essential ingredient of star formation

Disks last much longer than the initial infall phase

Basic ideas about disks

- ★ Viscosity (?) controls angular momentum evolution: matter accretes onto the star, angular momentum is transported outward. With time, the disk mass decreases and its size increases.
- ★ The star dominates the mass of the system. The disk is in Keplerian rotation.

Dust and gas



- ★ Gas and dust are mixed (at least to some degree)
- ★ Dust dominates the opacity
- ★ There is hydrostatic equilibrium (i.e., between stellar gravity and thermal pressure) in the vertical direction

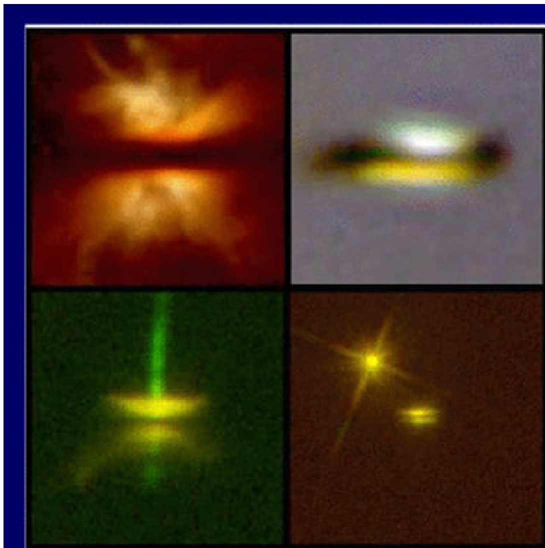
The density decreases steeply ($\exp(-z/H_p)^2$) in the vertical direction

- ★ Disks are flared (α increases with R)

Are disks flared? Some are

★ Flaring is only possible if gas dominates the disk mass

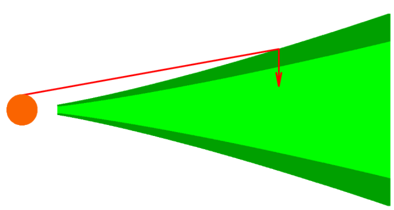
★ Debris disks are geometrically thin

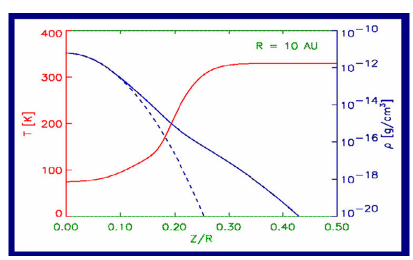


McCaughrean & O'Dell 1996, AJ 111, 1977

Stellar irradiation

★ Disks are heated by viscous dissipation and stellar radiation, which dominates in Pre-MS disks





The disk surface is hotter than the midplane
Emission features may form in the surface

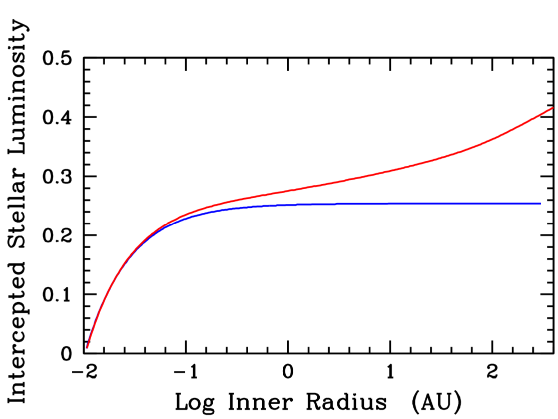
What would we like to know?

- ★ Density, temperature, ionization, composition of gas as function of R and z
- ★ Density, temperature, composition, size distribution of dust as function of R and z
- ★ Dynamics of both gas and dust

But we do our best!

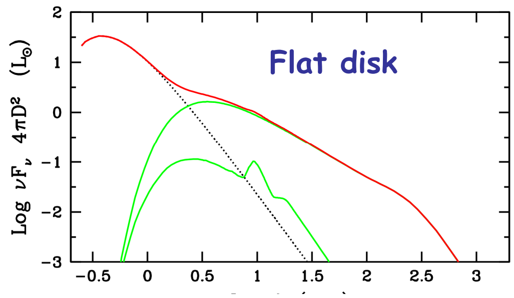
A powerful tool: the SED

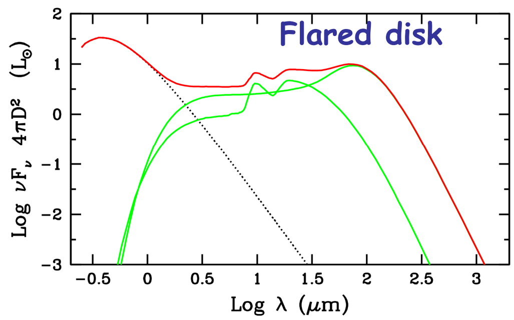
- ★ Disks re-emit the stellar radiation they intercept
- ★ The fraction of L* intercepted by the disk depends on its geometry

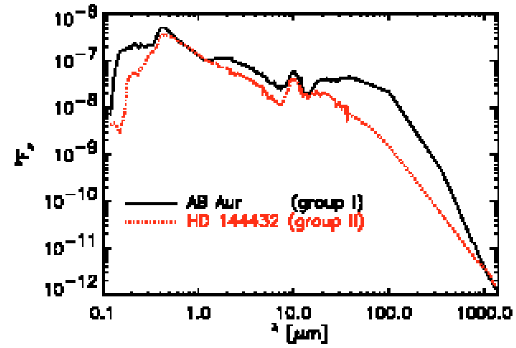


- ✓ 1/4 L* is intercepted within few R* (both flat and flared disks)
- ✓ An additional comparable fraction is intercepted by flared disks at large radii
- ✓ Flared disks intercept and re-emit more stellar light than flat disks

The SED: disk geometry

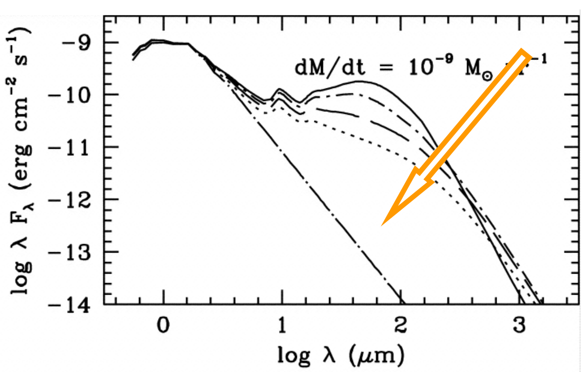




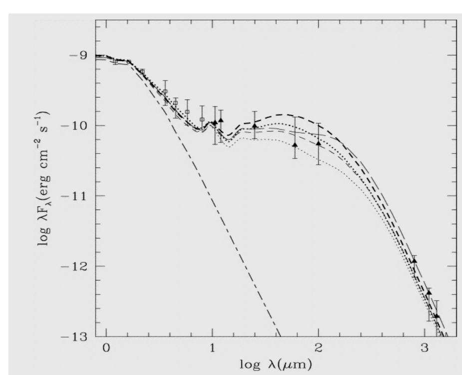


- Some fully flared disks
- Very few flat disks
- A lot of intermediate cases

Dust growth and settling



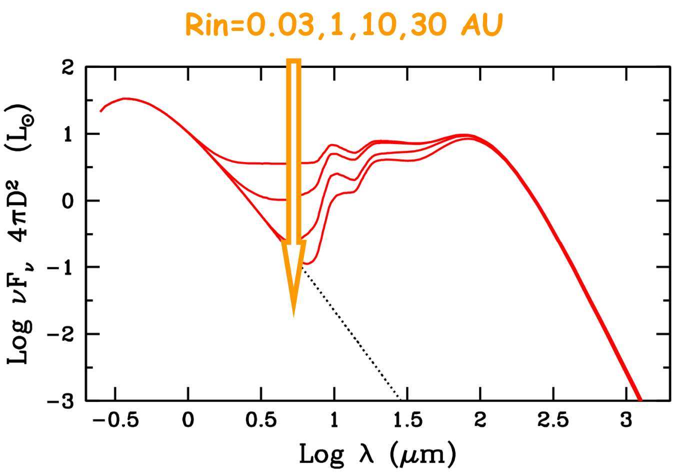
Median TTS in Taurus

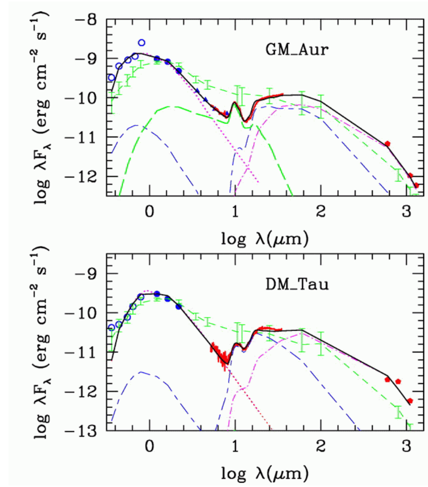


- Grain size increases
- Opacity to L_* decreases
- Less heating, less IR

D'Alessio et al. 2006
Dullemond & Dominik 2005

Inner holes: transition objects



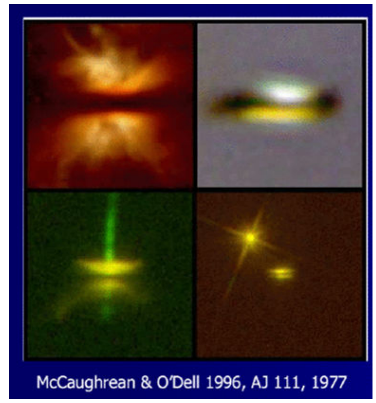


Calvet et al. 2005

Summary

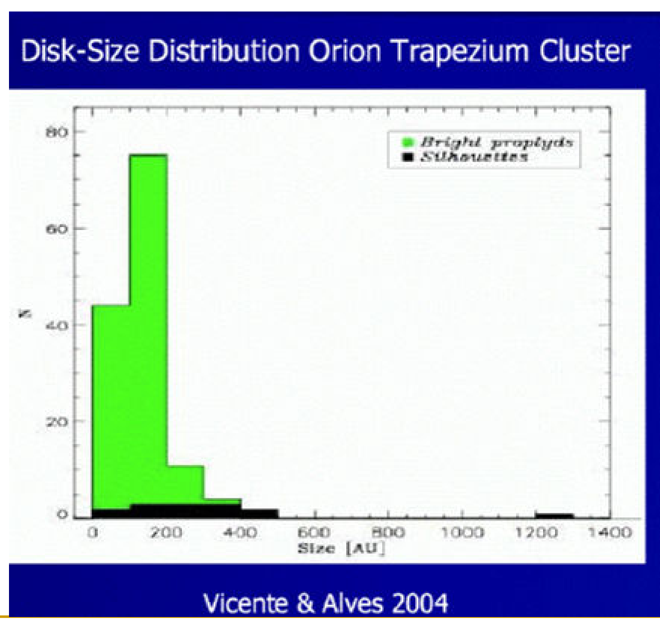
- Pre-MS disks are flared, to varying degree (SEDs)
  - Grain growth and settling

Disk sizes



- ★ Hundreds of AUs
  - In scattered light
  - Dust millimeter emission
  - Images in CO mm lines
- ★ Different techniques will give different sizes
  - Scattered light and CO probe a thin layer on the disk surface
  - Dust millimiter continuum probes the bulk of the dust in the disk midplane

The physical size is not the FWHM brightness



HD 163296

Grady, 2000,2005

PA = 140° ± 5° (130°)

Incl = 60° ± 5° (58°)

Rout = 450AU

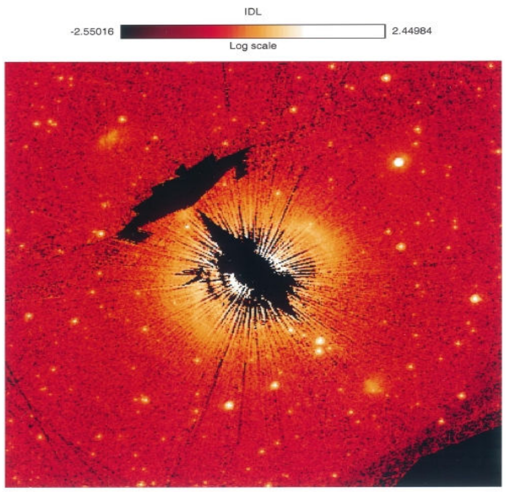


FIG. 2*a*

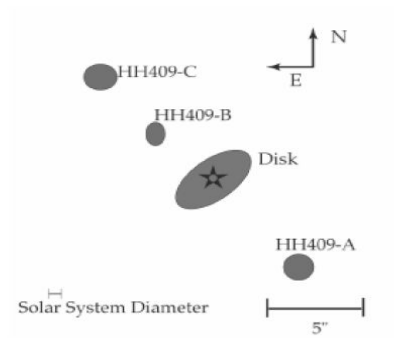
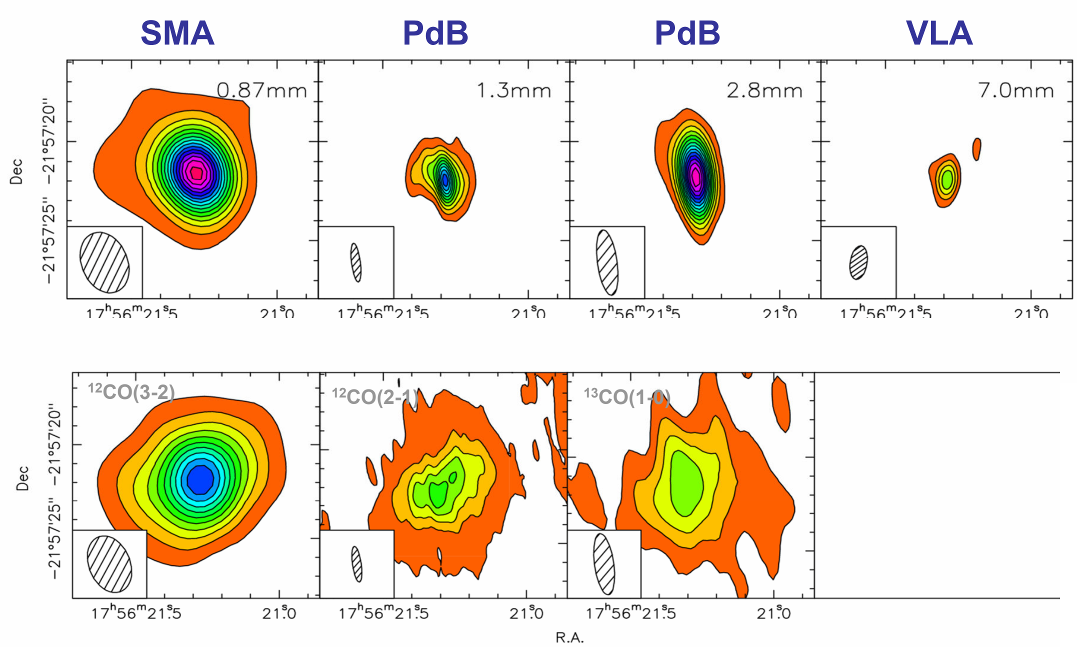


FIG. 2*b*

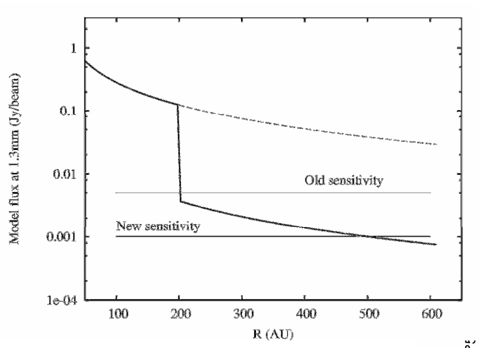
FIG. 2.—(*a*) 20″ × 20″ composite image of HD 163296 combining the data from the three orientations. The image is logarithmically scaled and oriented with north up and east to the left. Radial streaks in the image are due to differences in the PSF at the epoch of observation and in the calibration data (*HST*'s "breathing"). Dark, irregularly shaped polygons are voids produced by the intersection of the wedge structure in the three observations. The region of the most severe PSF residuals, interior to 1″.5, has been digitally masked out in this composite image. (*b*) Cartoon of the HD 163296 disk + knot system showing the orientation of the disk and the position of the knots relative to the disk.

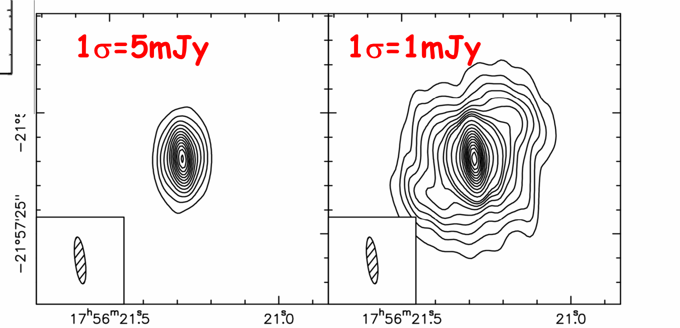
HD 163296



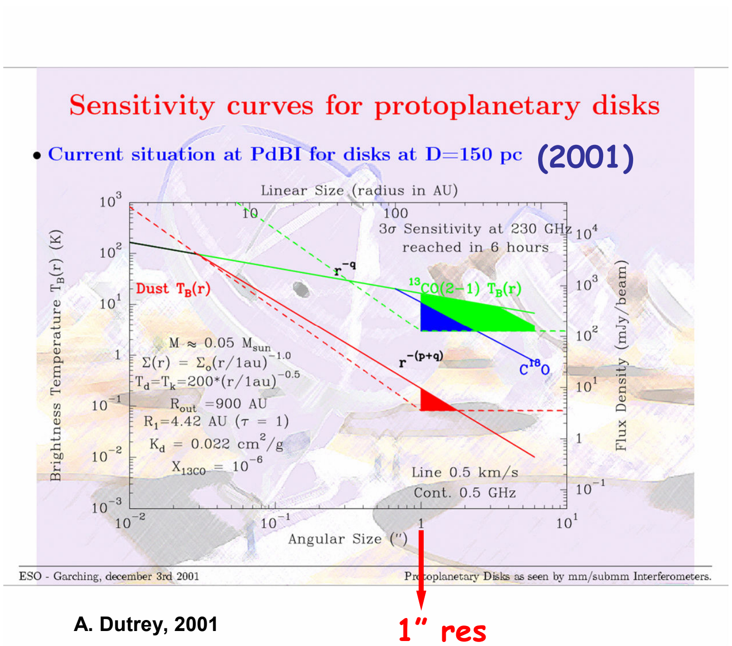
[Isella et al., 2006]

How big an object looks depends on your sensitivity





Why CO seems bigger than dust?



A. Dutrey, 2001

CO mm lines are brighter than dust continuum (much more optically thick)

Other molecules/isotopes have weaker lines→ disks will look smaller than in the continuum

How to proceed if you have data from mm interferometers?

- mm interferometers have sufficient coverage of the UV plane to allow image reconstruction ….
- But it is much safer to compare observations to model predictions in the UV plane, i.e., one needs to compute model-predicted intensity maps and "observe" them with the same setup as the data
- From a $\chi 2$ analysis, one can check the capability of models to reproduce the observations and constrain model parameters
  - R_{disk}
  - Surface density profile $\Sigma(R)$
  - Inclination and PA

Pre-MS disks are big

DM Tau	0.5 Msun	850 AU
GM Aur	0.8 Msun	500 AU
LkCa15	1 Msun	500-600 AU
MWC 480	2 Msun	450 AU
HD163296	2.4 Msun	550 AU
AB Aur	2.3 Msun	1000 AU
HD 34282	2 Msun	800 AU

Any information on Σ ?

- From mm interferometric maps, it seems that

$$\Sigma \propto R^{-1}$$

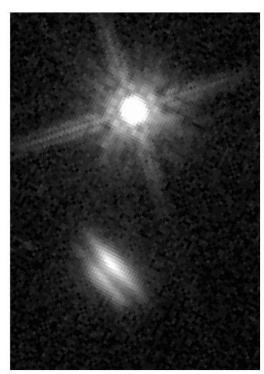
(for R>20-30AU)

⬇

All the mass is in the outer disk

A sharp outer edge?

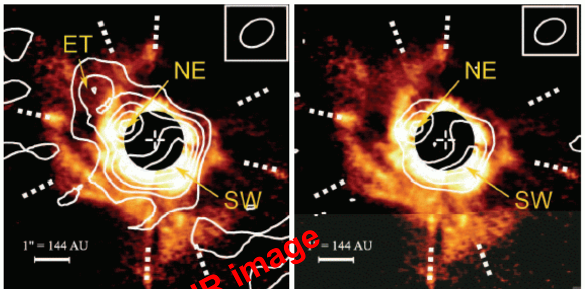
- In silhouette disks in Orion there is evidence of a sharp outer edge (McCaughrean & O'Dell 1996)



- Same in HK TauB (Stapelfeldt et al. 1998), etc.
  - Origin unclear

Structures in disks: AB Aur

SMA, 850 mic continuum (contours)



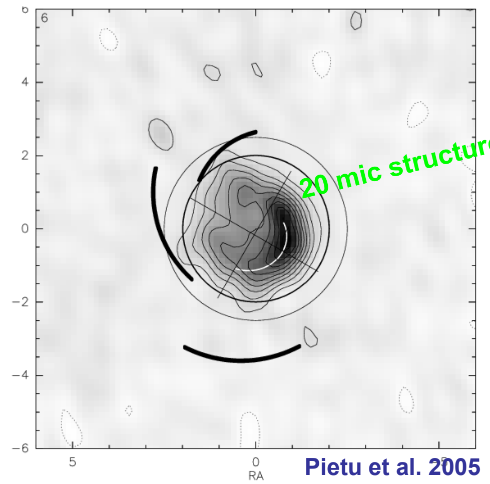
Subaru AO near-IR image
Fukagawa et al 2004

Lin et al. 2006

Fig. 1.— Left: Dust continuum with natural weighting superposed on the Subaru near-IR image. The angular resolution is 0″.91 × 0″.72. Contours start from 2σ (or 5.5mJy beam $^{-1}$) with a spacing of 2σ. Right: The dust continuum without inner 30kλ data points on the UV plane superposed on the Subaru image. The angular resolution is 0″.95 × 0″.66. Contour spacing is 2σ (or 5.6mJy beam^{-1}). Note that the central part of the near-IR image has been suppressed with an occulting mask. The SMA dust image shows a definite depression in the center.

Don't get excited too soon

PdB, dust 1.4mm continuum



Pietu et al. 2005

Summary

- Pre-MS disks are flared, to varying degree (SEDs)
  - Grain growth and settling
- Disks are large, R ~ a few hundreds AU
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- We are beginning to see structures in disks

Disk mass: how?

★From mm dust emission (optically thin) one can derive the dust mass

$$F_\nu = \frac{\cos\theta}{D^2} \int_{R_0}^{R_D} B_\nu(T_d)(1 - e^{-\tau_\nu})\, 2\pi R$$

$$\tau_\nu = \frac{1}{\cos\theta} \kappa_\nu \Sigma(R)$$

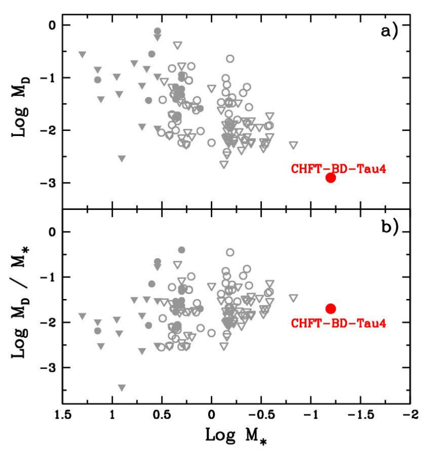
If $\tau_\nu \ll 1$:

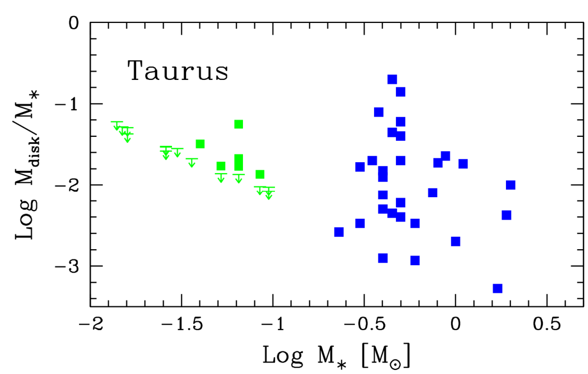
$$F_\nu \propto \kappa_\nu \times B_\nu(T_d) \times M_d$$

Dust opacity

Characteristic dust temperature

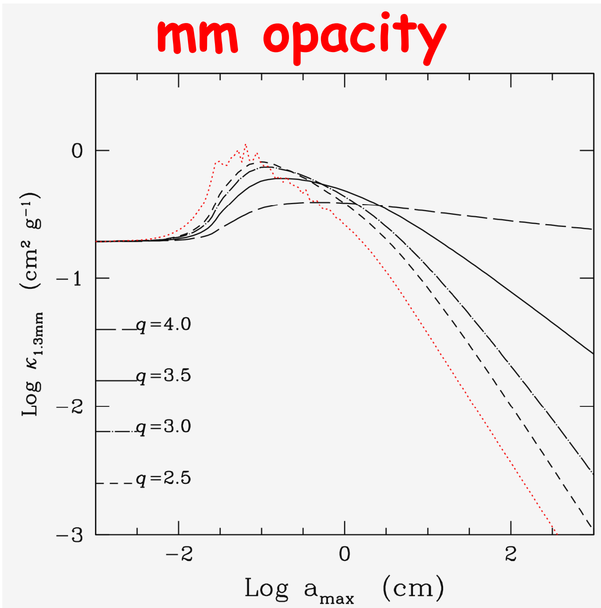
★From the dust mass, the total mass assuming a gas-to-dust ratio = 100 (!!)



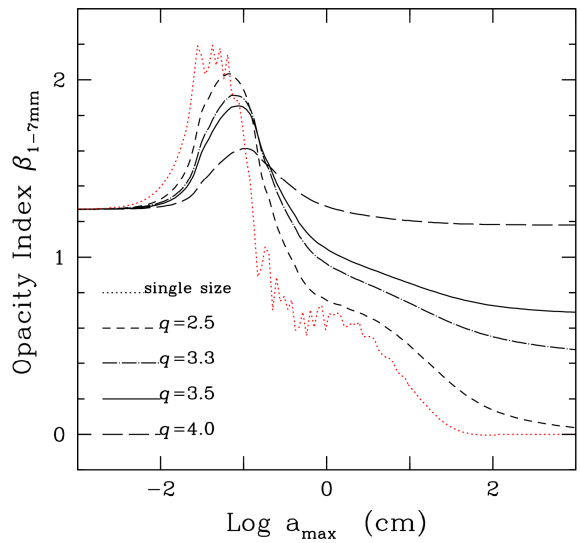


Mdisk ~ 0.001- 0.1 Msun if k(1mm)~1 cm^2/g

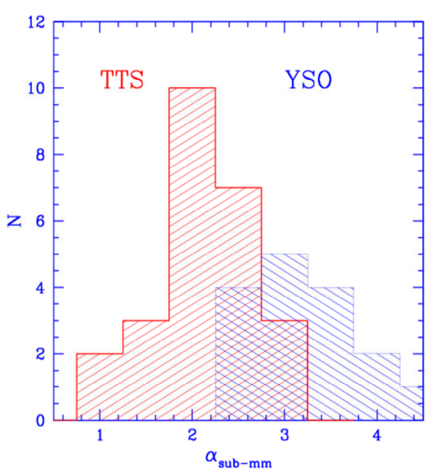
The problem of dust opacity



β_{1-7mm} $(\kappa \sim \lambda^{-\beta})$



We know grains in the ISM -Why worry for disks?



Beckwith & Sargent 1991

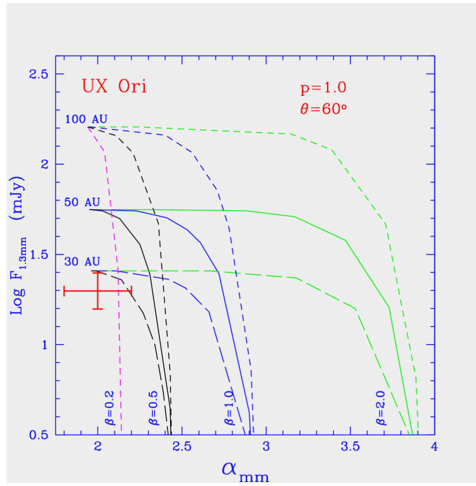
- At mm wavelengths, disks have flatter SEDs than ISM grains would predict
  - If tau<<1, F_ν☸ B_ν k_ν ☸$\lambda^{-\alpha}$;

α=2+$\beta \sim 4$ (ISM)

- But are grains really different?
  - If tau>>1, F_ν☸ B_ν☸ λ^{-2}

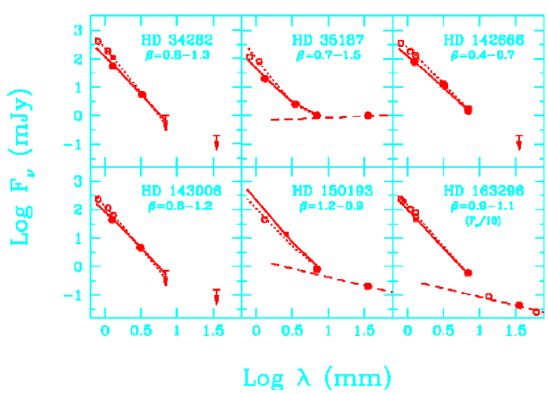
What happens if we increase the mass of a disk of fixed size Rd?

- ✓ α_{mm} decreases from ~ 2+β to ~ 2
- ✓ F_ν increases to reach a constant value $\propto R_d^2$
- ✓ We need R_d!

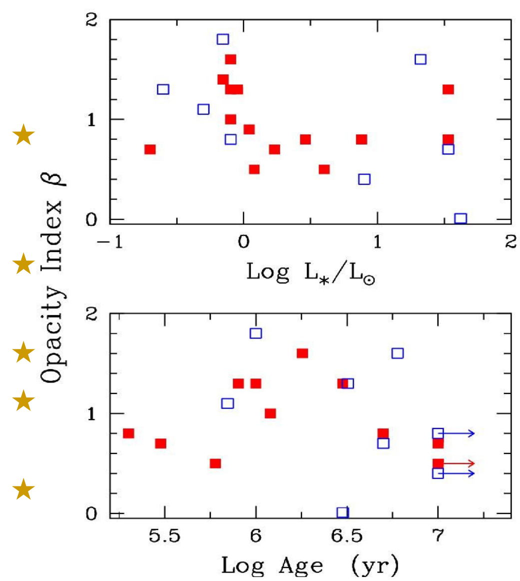


αmm=spectral index between 1.3 e 7 mm

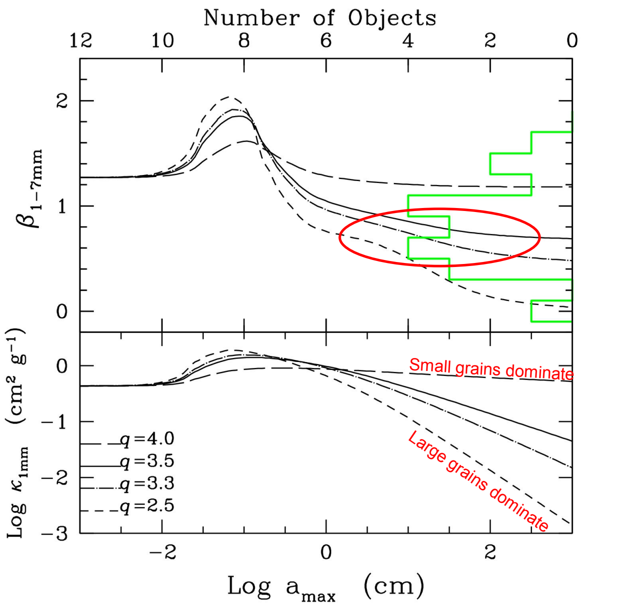
Several disks are resolved at mm wl with interferometers

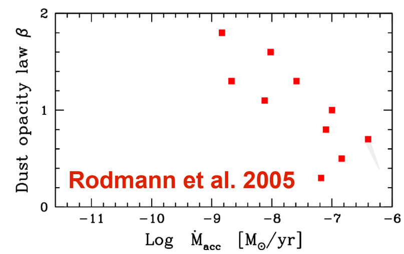


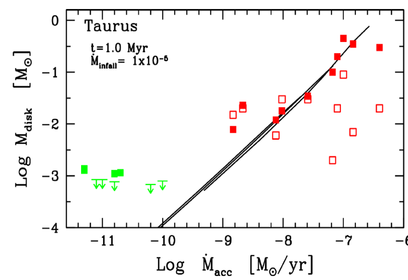
HAe (Testi et al. 2001; 2003; Natta et al. 2004)
TW Hya (Wilner et al. 2000;Calvet et al. 2002)
TTauri stars (Rodmann et al. 2005)



"conventional" disk masses need to be revised to take into account the dust properties true masses can be much larger







Summary

- ★ Pre-MS disks are flared, to varying degree (SEDs)
  - Grain growth and settling
- ★ Disks are large, R ~ a few hundreds AU
- ★ The surface density decreases roughly as 1/R
- ★ We are beginning to see structures in disks
- ★ Disk masses are very poorly known
  - Estimates in the literature are likely underestimated

★ A "typical" disk does not have M=0.01 Msun, R=100AU, Σ☸1/R$^{1.5}$

Dynamics in viscous disk

- ★Keplerian rotation: $v_\varphi=(GM_*/R_*)^{1/2}$
- ★Radial drift toward the star: $v_R \sim \alpha c_s H/R$
- ★No vertical motions: $v_z=0$

- ★Turbulence?

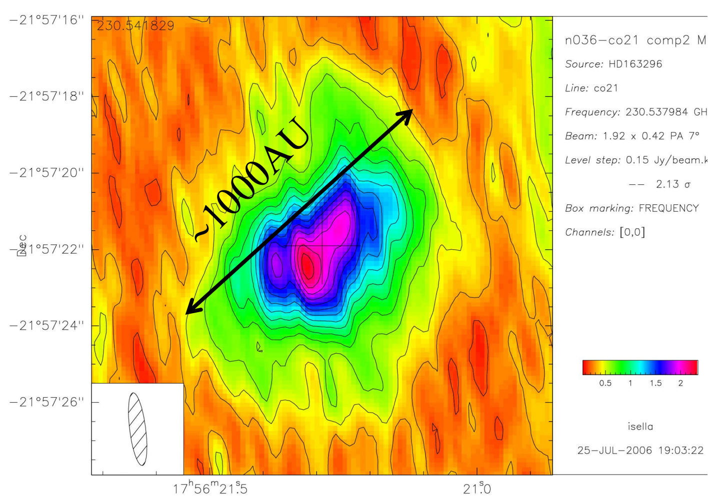
Table 1: TYPICAL VELOCITIES

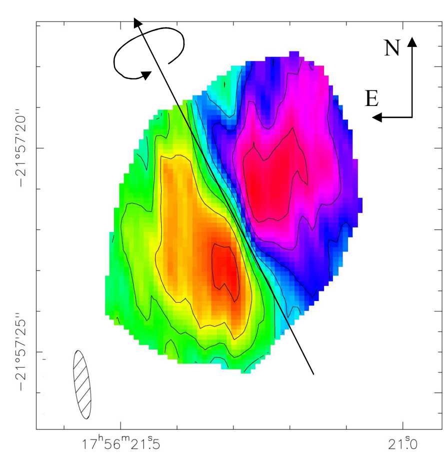
R	v_ϕ (km s^{-1})	c_s (km s^{-1})	v_R (m s^{-1}!)
$R_\star$	360	6	100
1 AU	30	1	30
100 AU	3	0.1	3

Rotation from CO mm lines: a velocity gradient across the major axis

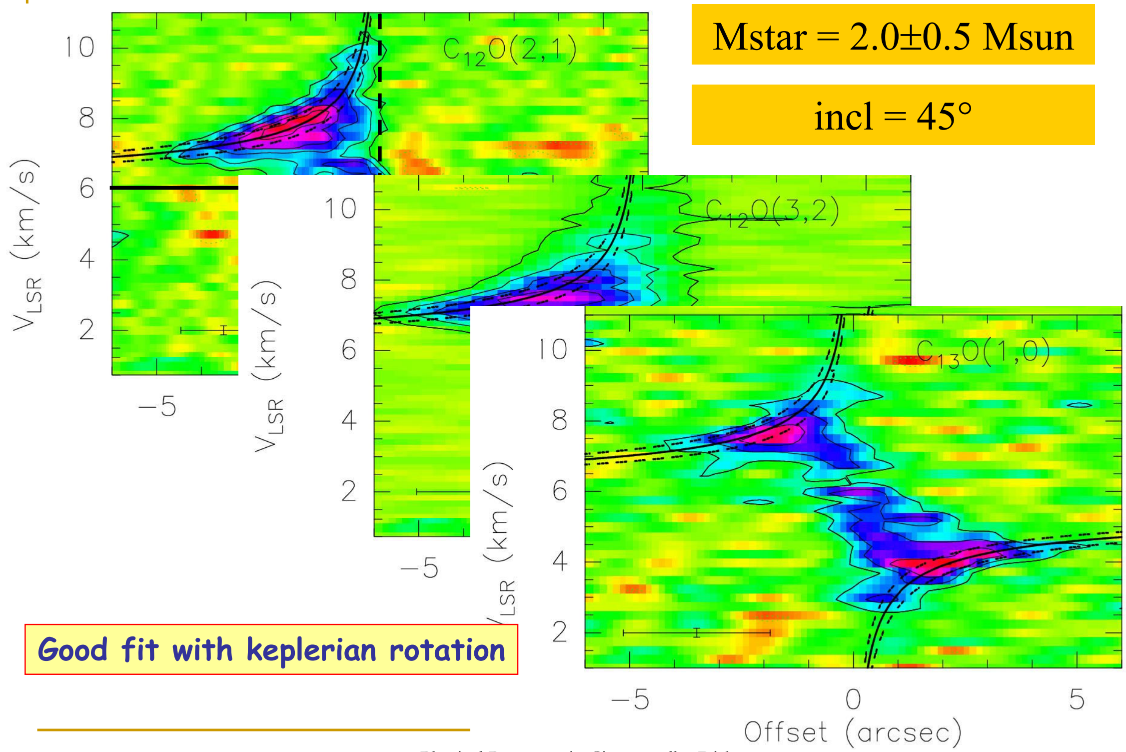
HD163296 : 12CO J=2-1

[Isella et al. 2006]





HD163296 : position - velocity diagrams

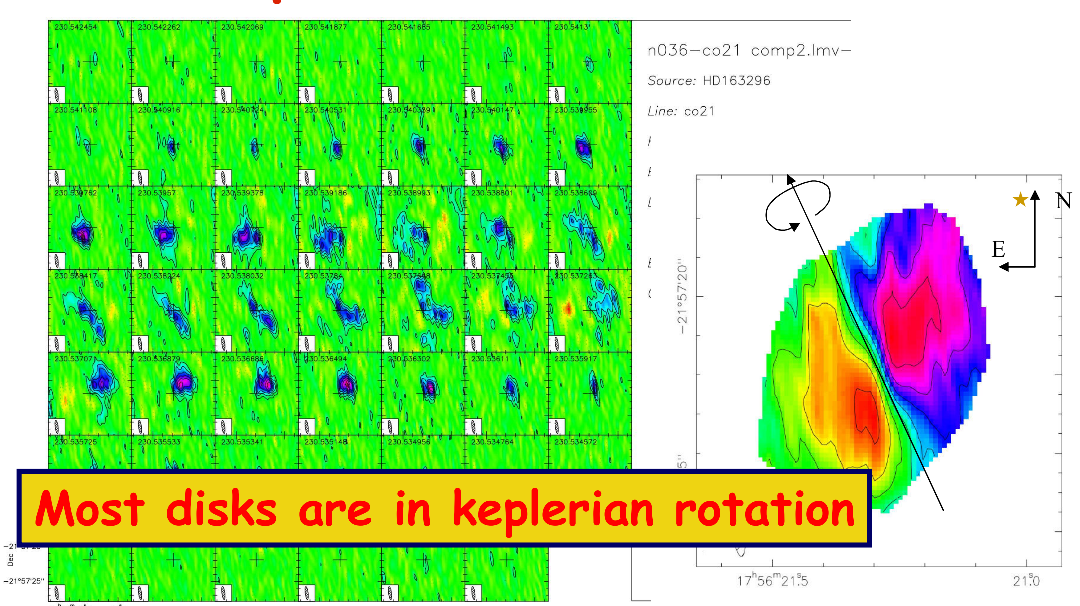


Mstar = 2.0±0.5 Msun

incl = 45°

Good fit with keplerian rotation

Fits to channel maps (better in the UV plane)



Most disks are in keplerian rotation

Departures from keplerian rotation

- Some evidence of non-keplerian rotation in AB Aur (Pietu et al. 2005)

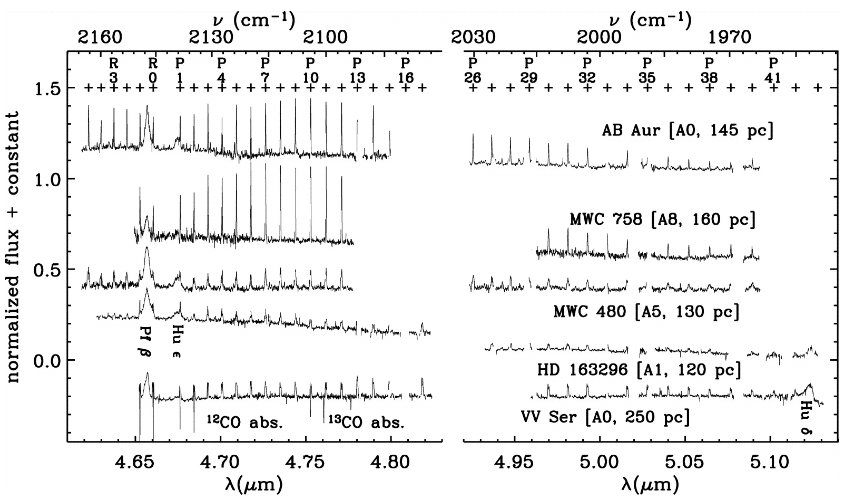
$V \propto R^{0.41 +/- 0.01}$

- Not true in other disks (e.g., HD163296)

Keplerian rotation in the inner disk from near-IR vibrational CO lines

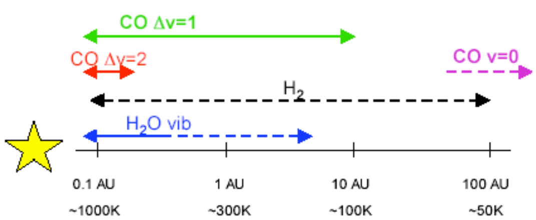
V=1-0 at 4.8μm

V=2-1 at 2.4μm

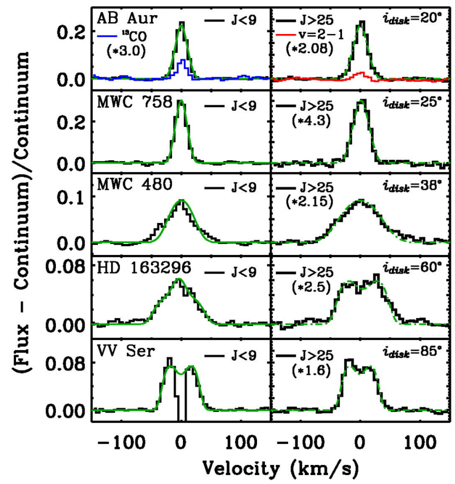


Blake et al. 2004, Brittain et al. 2005, Najita, Carr et al. 2001, 2003

Keplerian rotation in the inner disk from near-IR vibrational CO lines



Courtesy of J. Najita (*NOAO*)



- ★ Formation on the disk surface or in the inner, dust-free disk
- ★ Consistent with keplerian rotation in the inner disk

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- ★ We are beginning to see structures in disks
- ★ Disk masses are very poorly known
  - – Estimates in the literature are likely underestimated
- ★ Evidence of keplerian rotation in the inner and outer disk
  - – Some evidence of deviations (AB Aur)