Constraining disk models with (spatially resolved) observations of the inner and outer disk

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CARMA

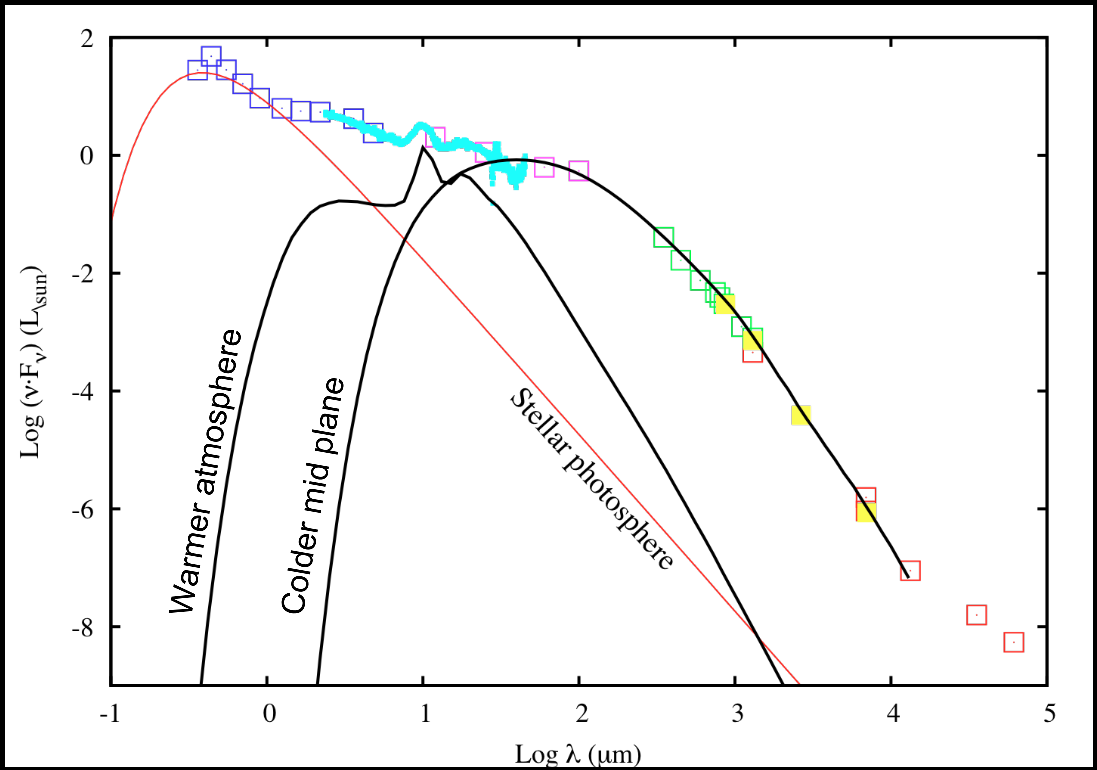
Combined Array for Research in Millimeter-Wave Astronomy

TALK OUTLINE

- Interferometric observations of inner disk structure (<10 AU)
  - challenges for inner disk models

- Spatially resolved observations of the outer disk (>10 AU) through (sub)millimeter interferometry
  - constraining the surface density
  - grain growth and radial dependece of the dust opacity

Disk Structure 101
The spectral energy distribution



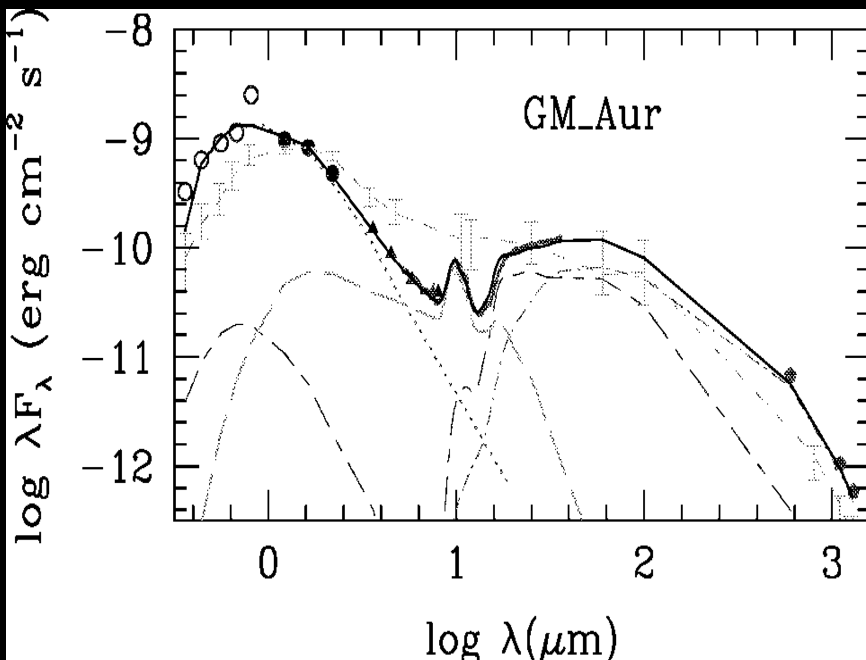
- Disk temperature and radial extent

$$T \propto \sqrt{R}, \quad R_{in} \sim R_*$$
$$R_{out} \sim 10^4 R_* \sim 100 - 500\,\mathrm{AU}$$

- Dust properties in the disk atmosphere
  - sub-micron silicate grains
  - grain structure
- Disk heating and geometrical structure
  - passive flaring disks
- Properties of the dust in the disk mid plane and disk mass (mm)

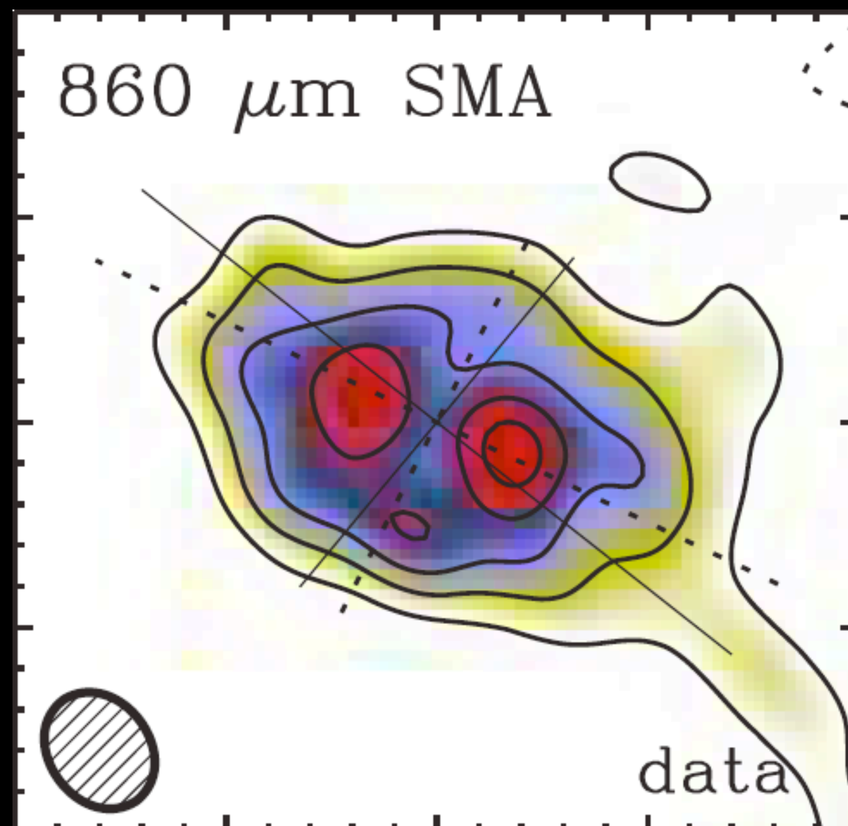
$$F_\nu \propto \nu^\alpha \qquad k_\nu \propto \nu^\beta$$
$$\alpha \approx 2 + \beta$$

Disk Structure 101
The spectral energy distribution

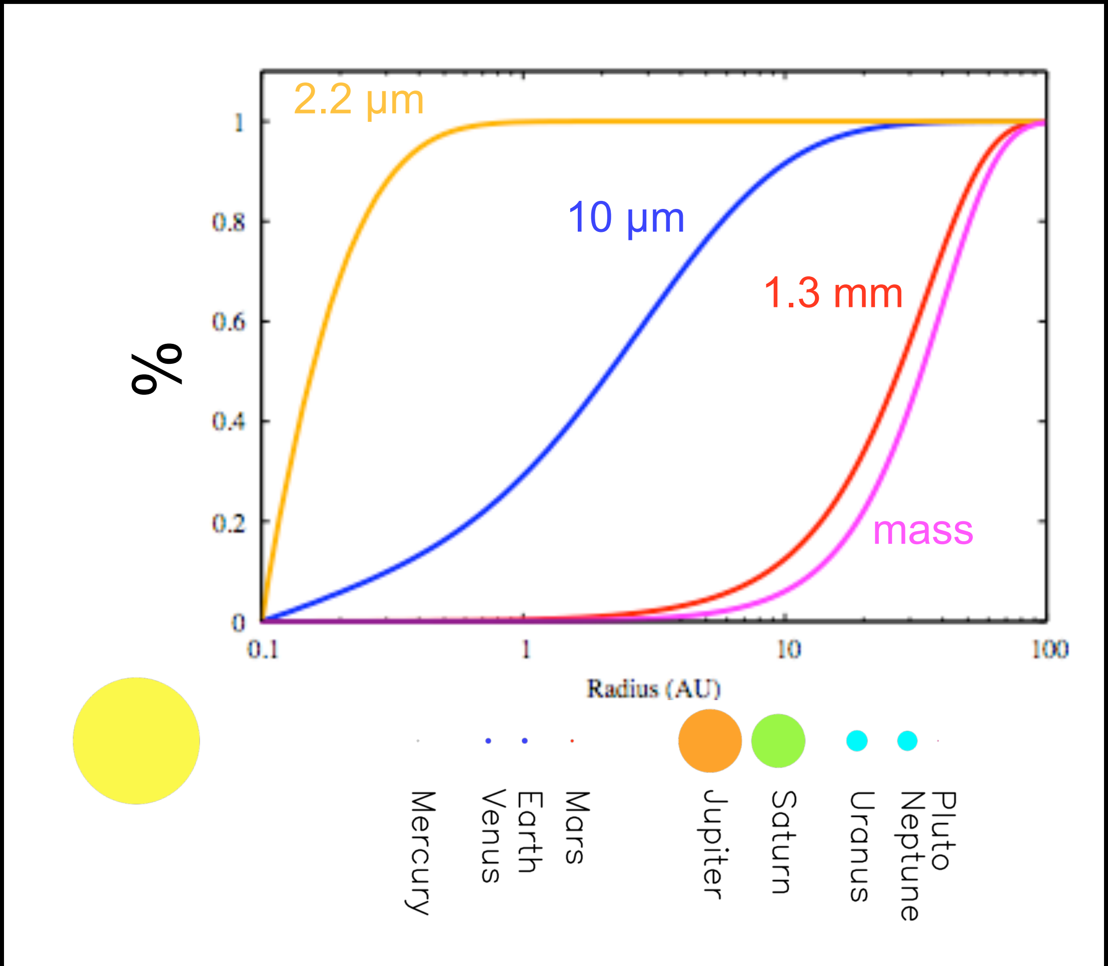


Calvet et al. (2005)

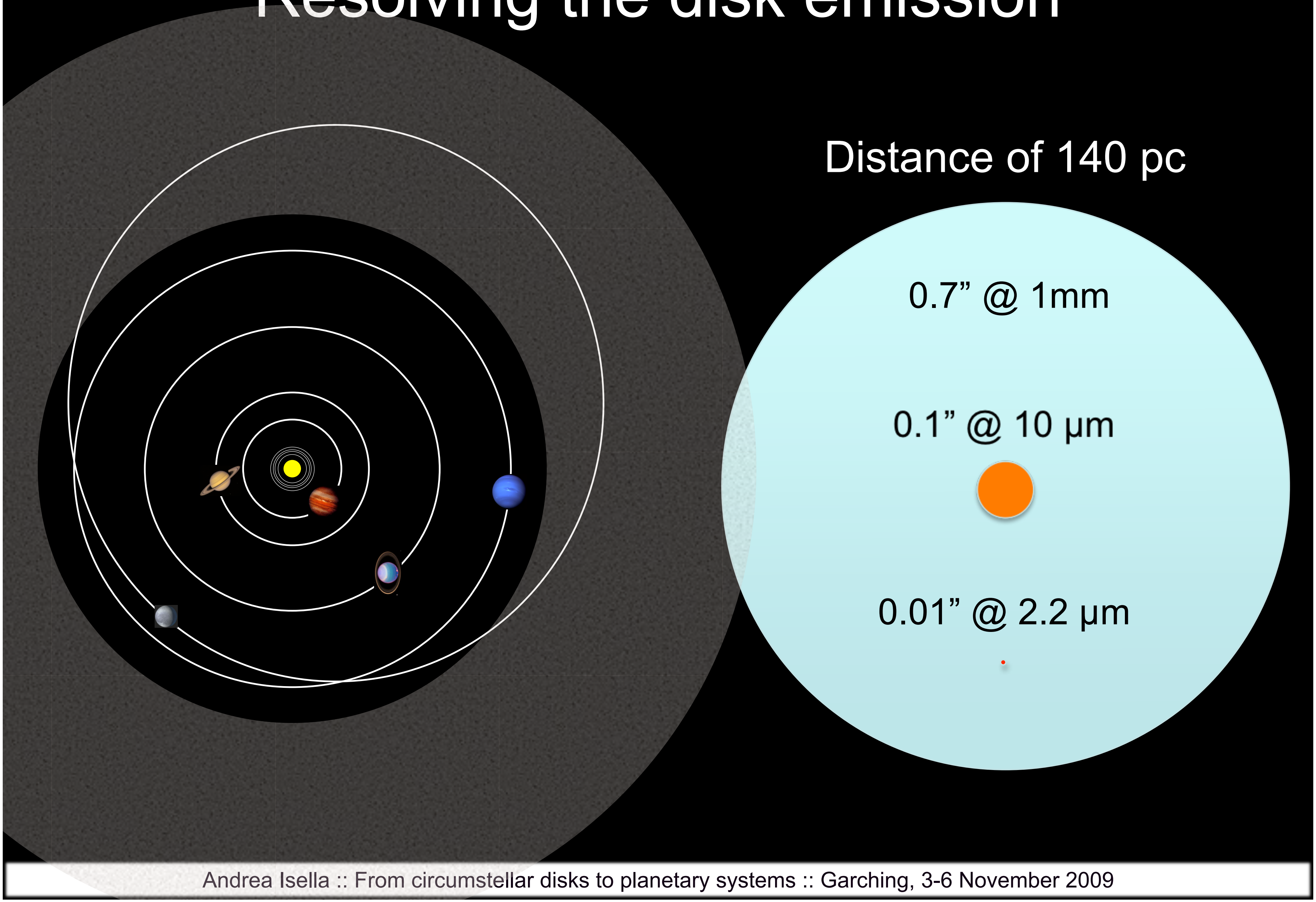
Hughes et al. (2009)



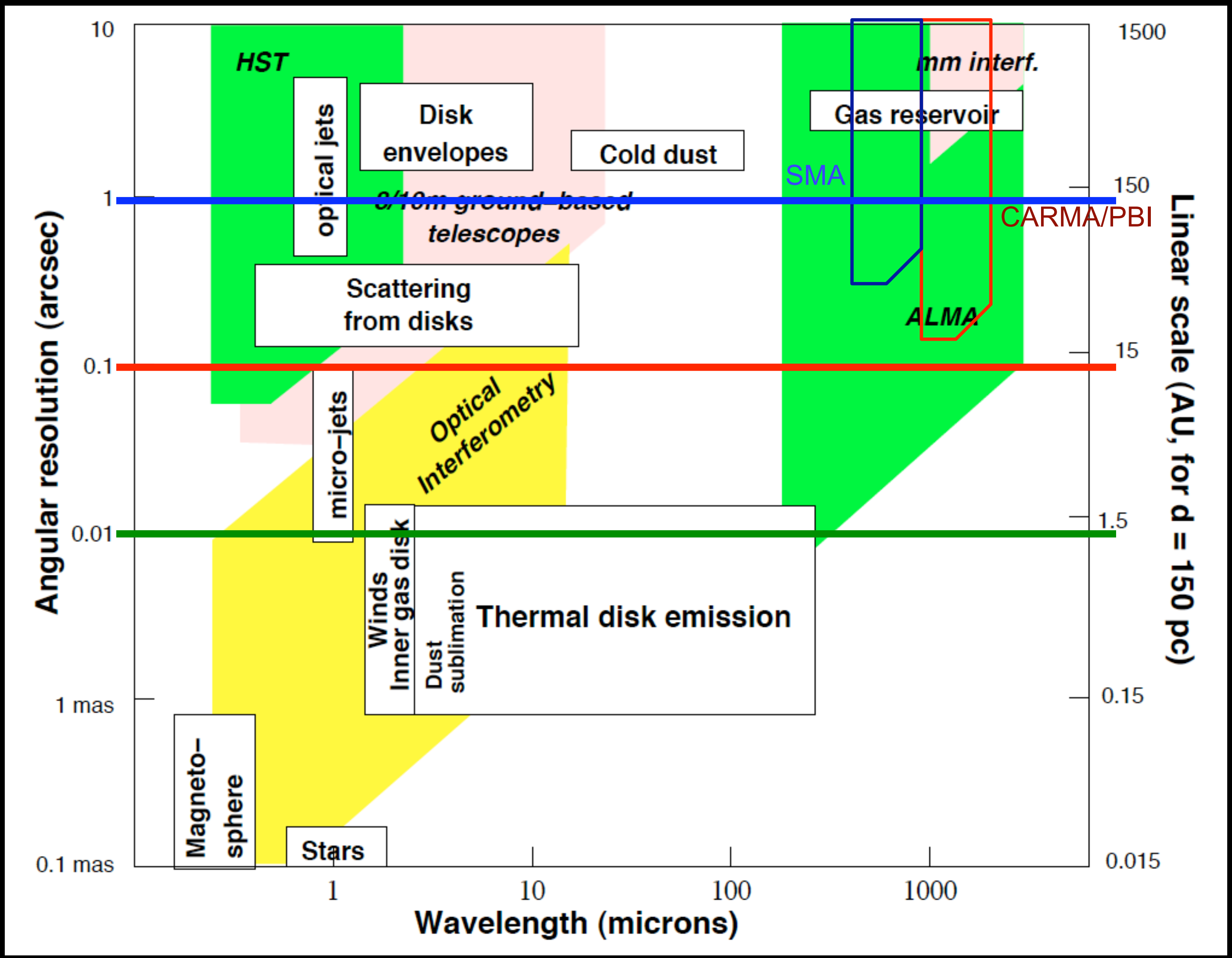
Different wavelengths trace different disk regions



Resolving the disk emission

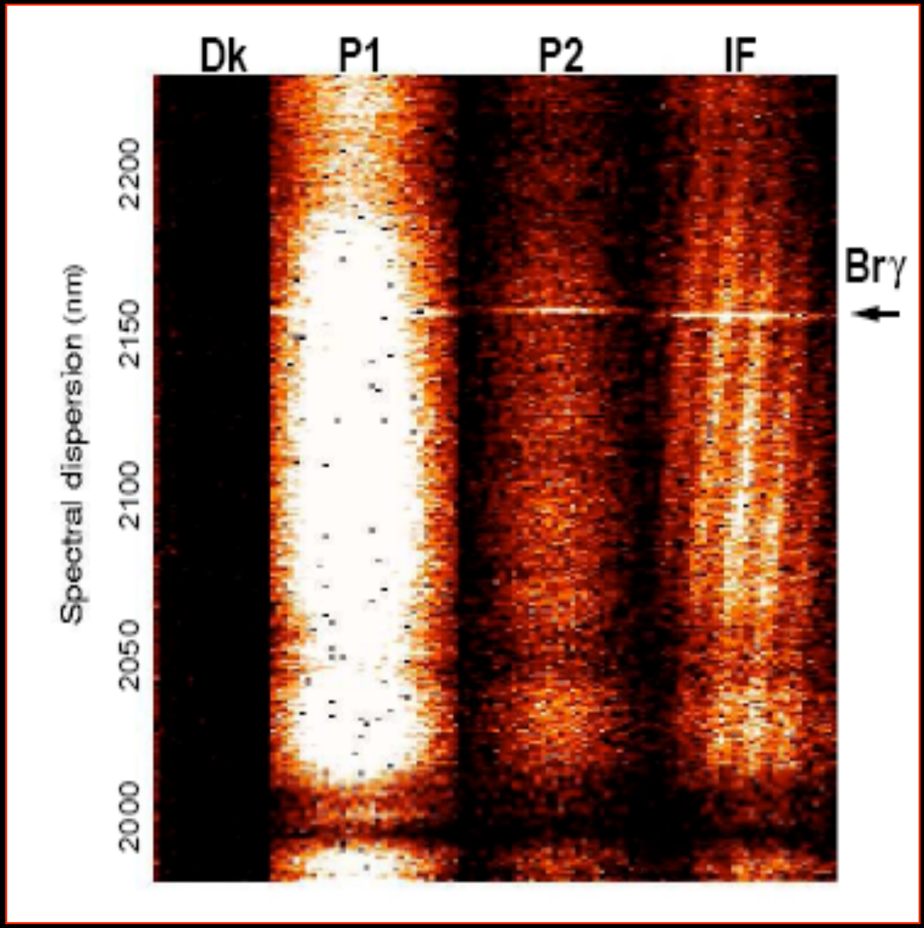


Resolving the disk emission



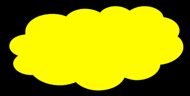
Inner disk – near-IR interferometry

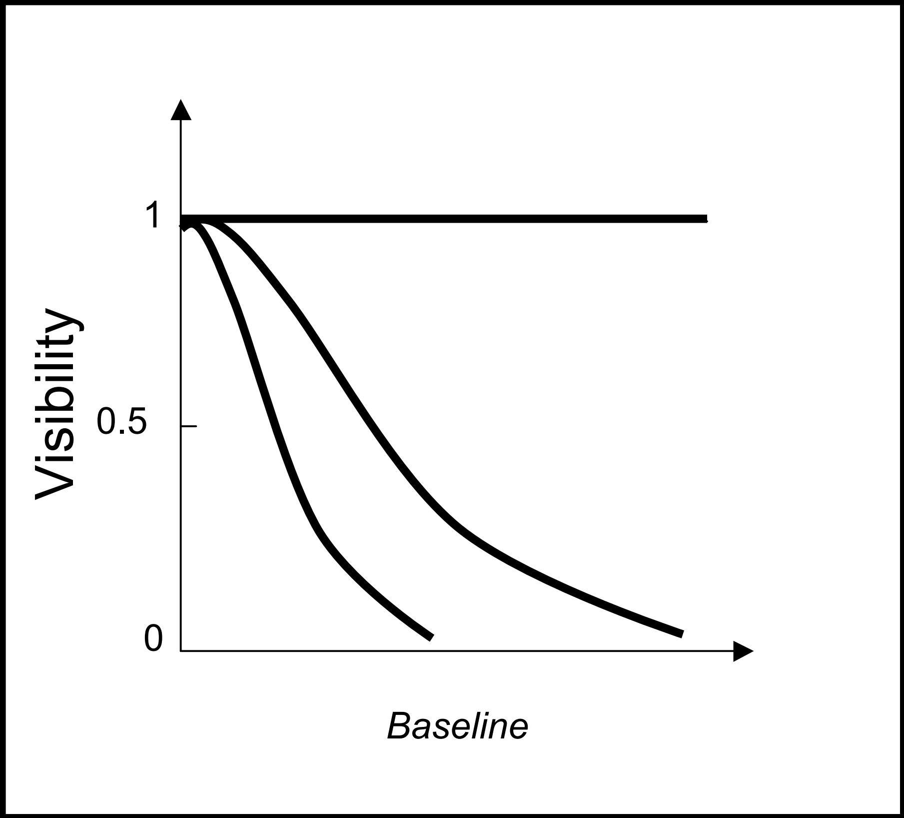
$$\theta \sim \frac{\lambda}{2B}$$



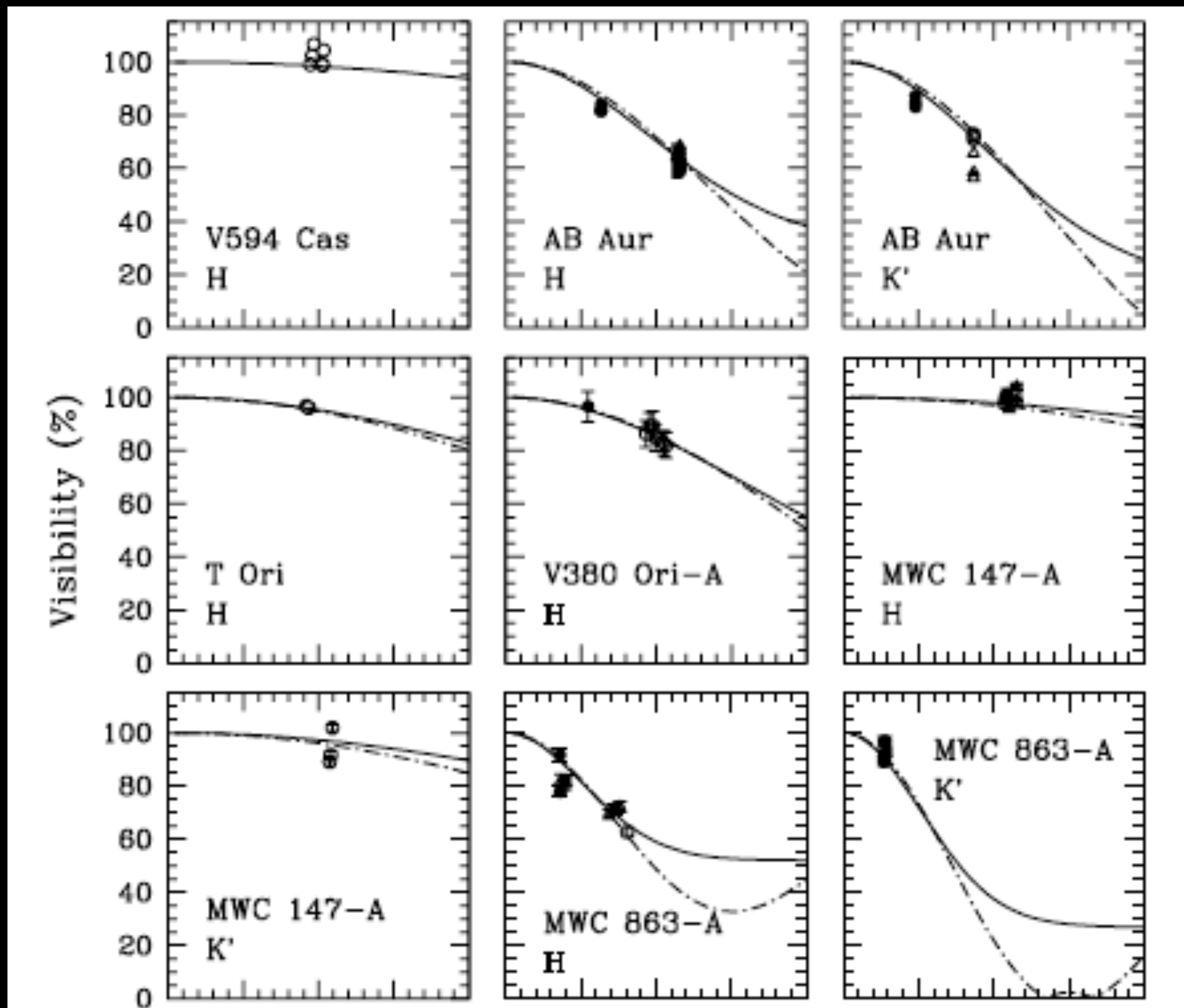
Fringes with AMBER

Inner disk – near-IR interferometry





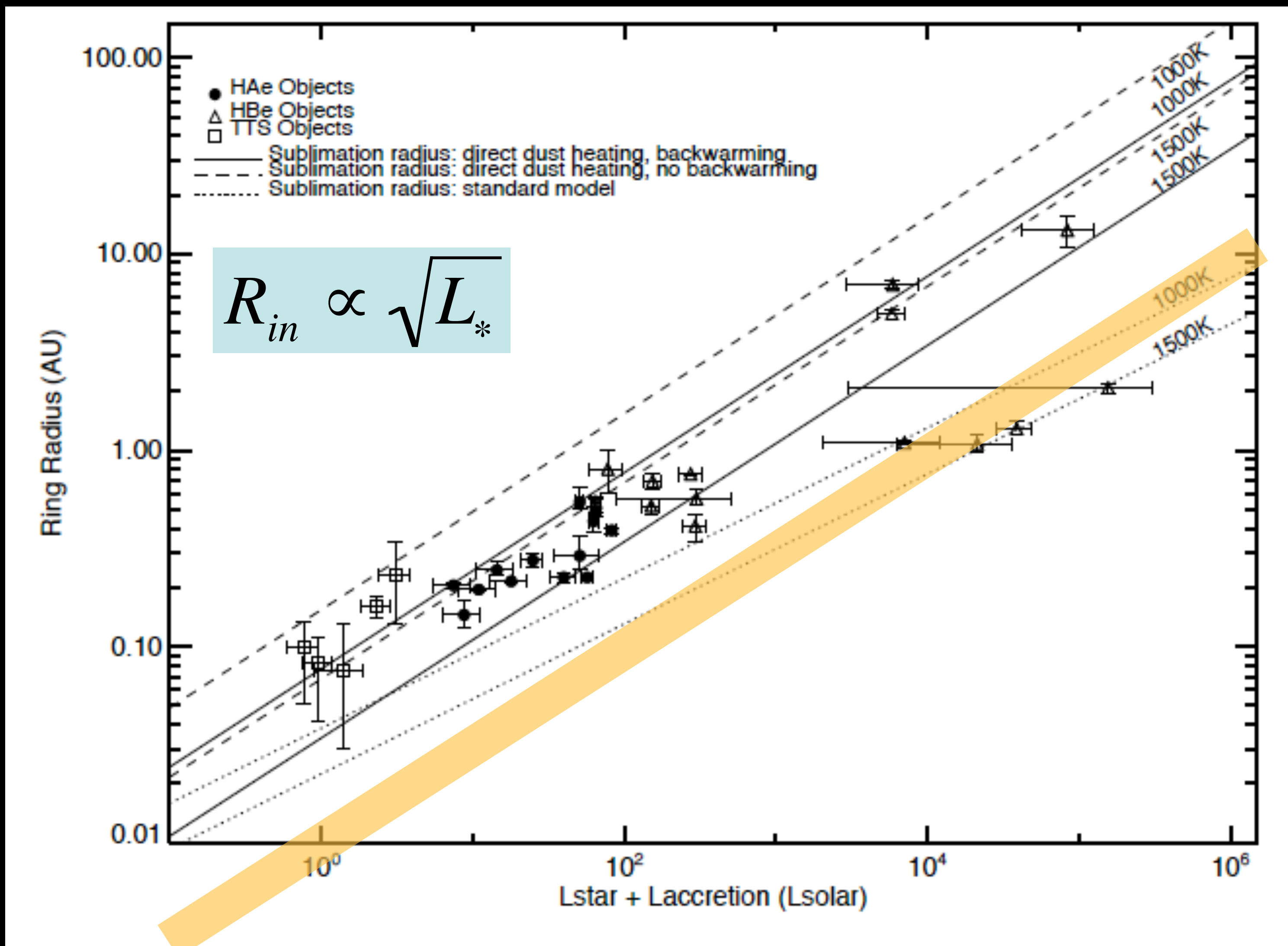
The visibility measures angular scales



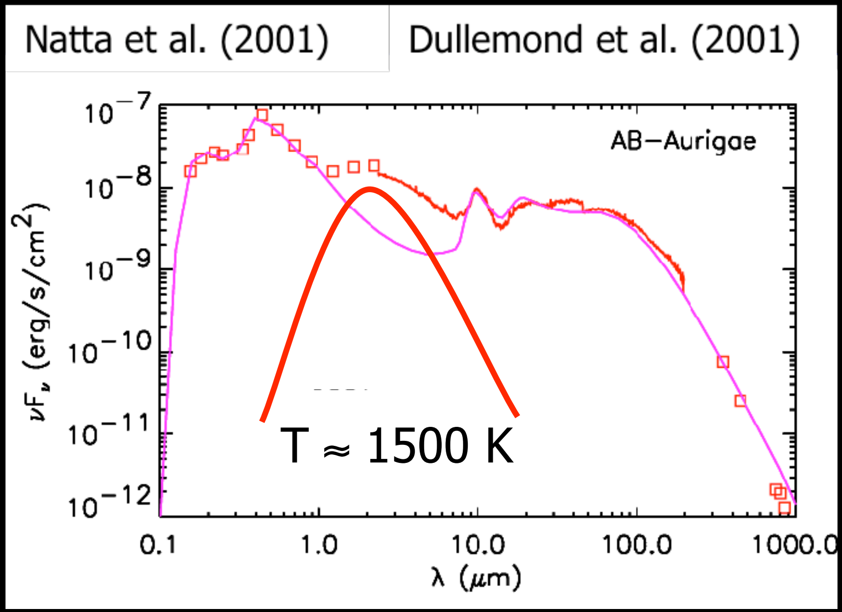
Millan-Gabet et al. (2001)

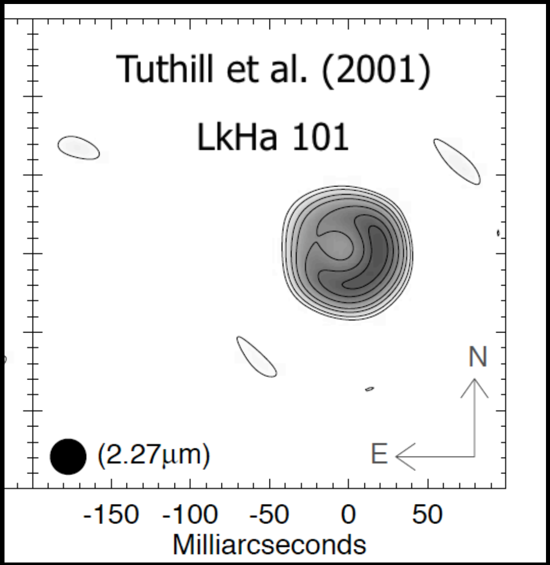
Inner disk radius & dust sublimation

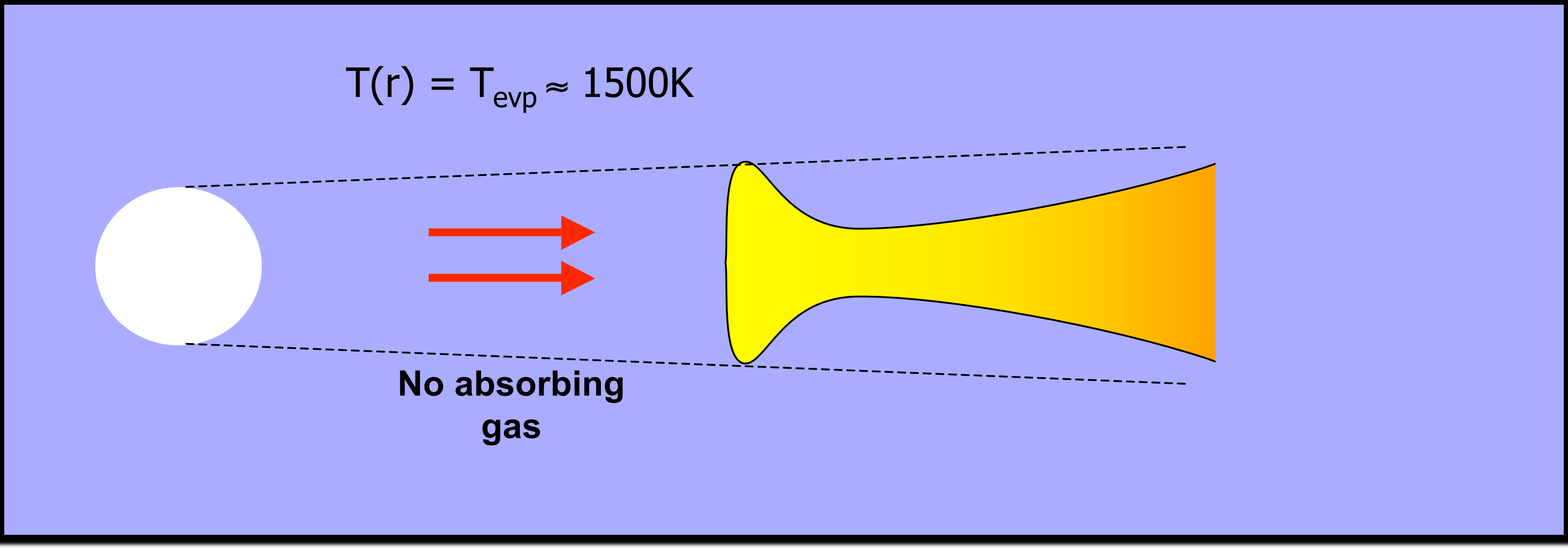
Millan-Gabet et al. (2001, 2008)



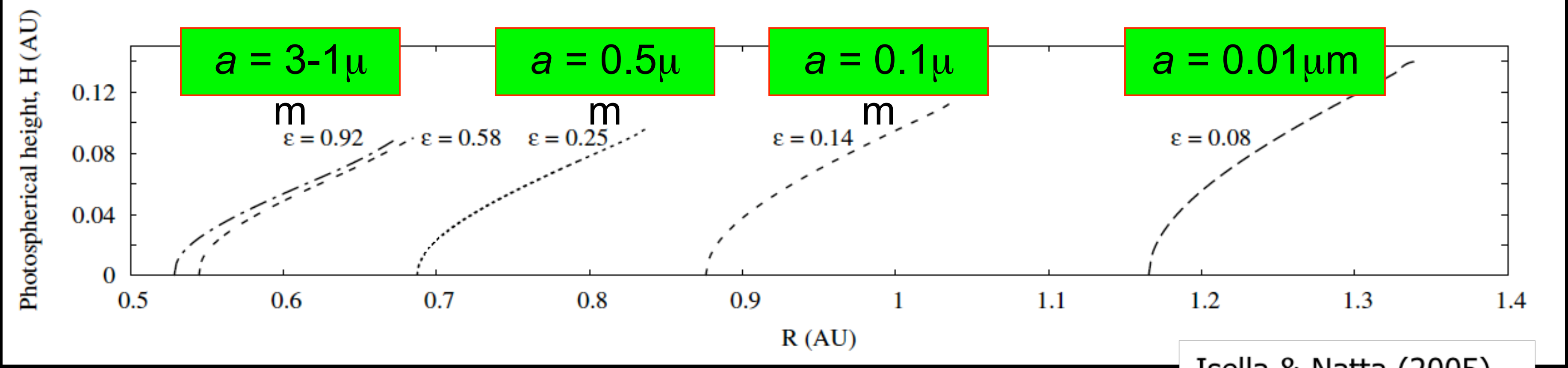
“Puffed-up” inner rim



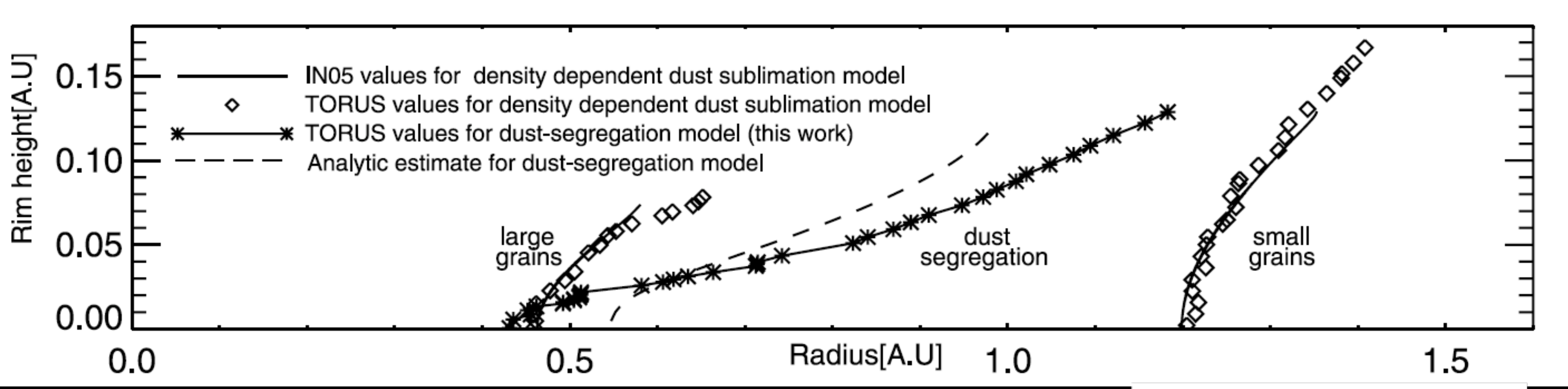




“Puffed-up” inner rim



Isella & Natta (2005)



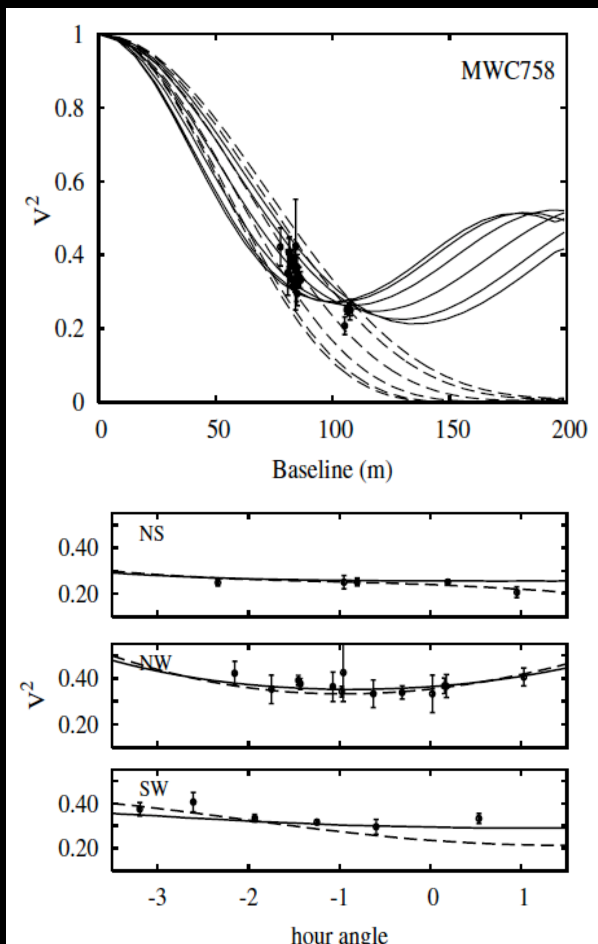
Tannirkulam et al. (2007)

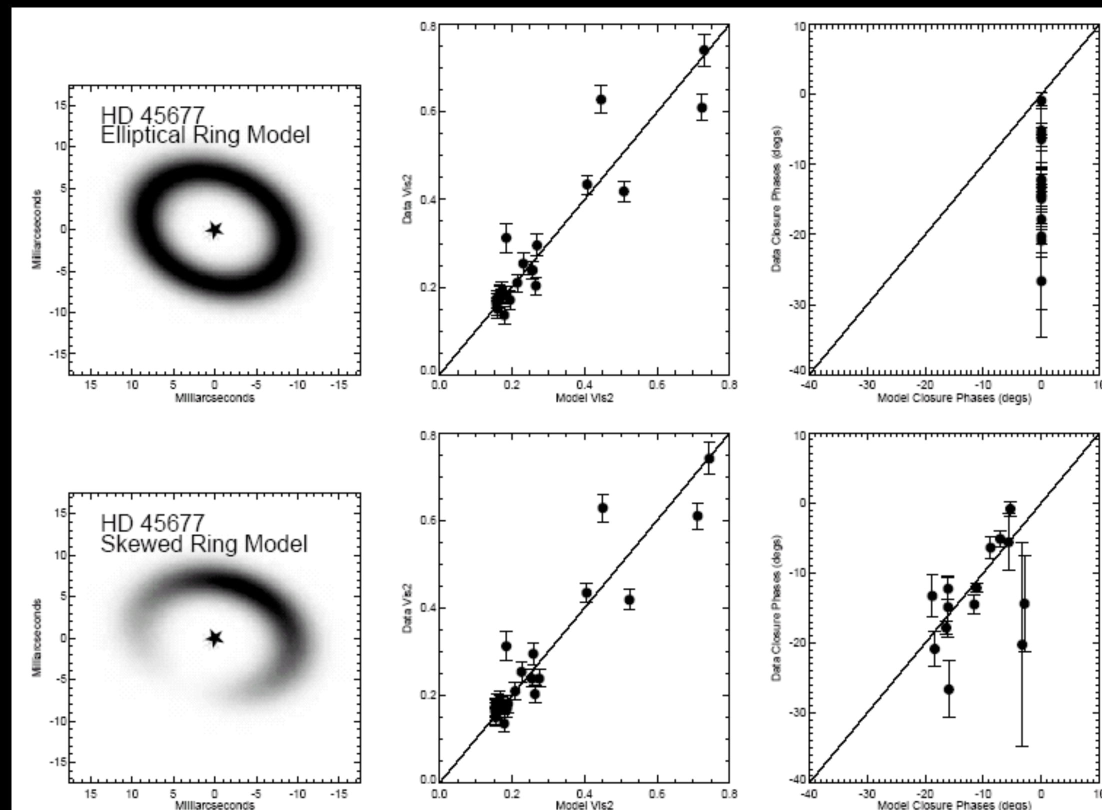
See also Vinkovic et al. (2006), Kama et al. (2009)

Agreement with the observations

Eisner et al. (2004, 2005)
Isella et al. (2006)

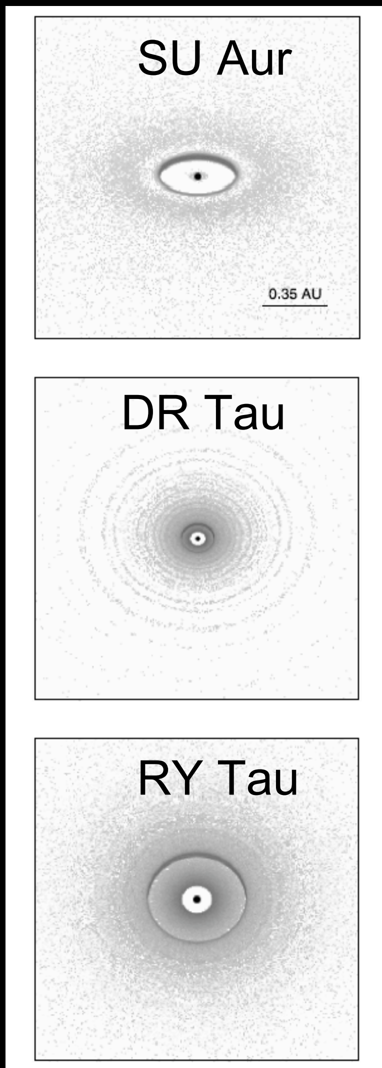
Monnier et al. (2006)

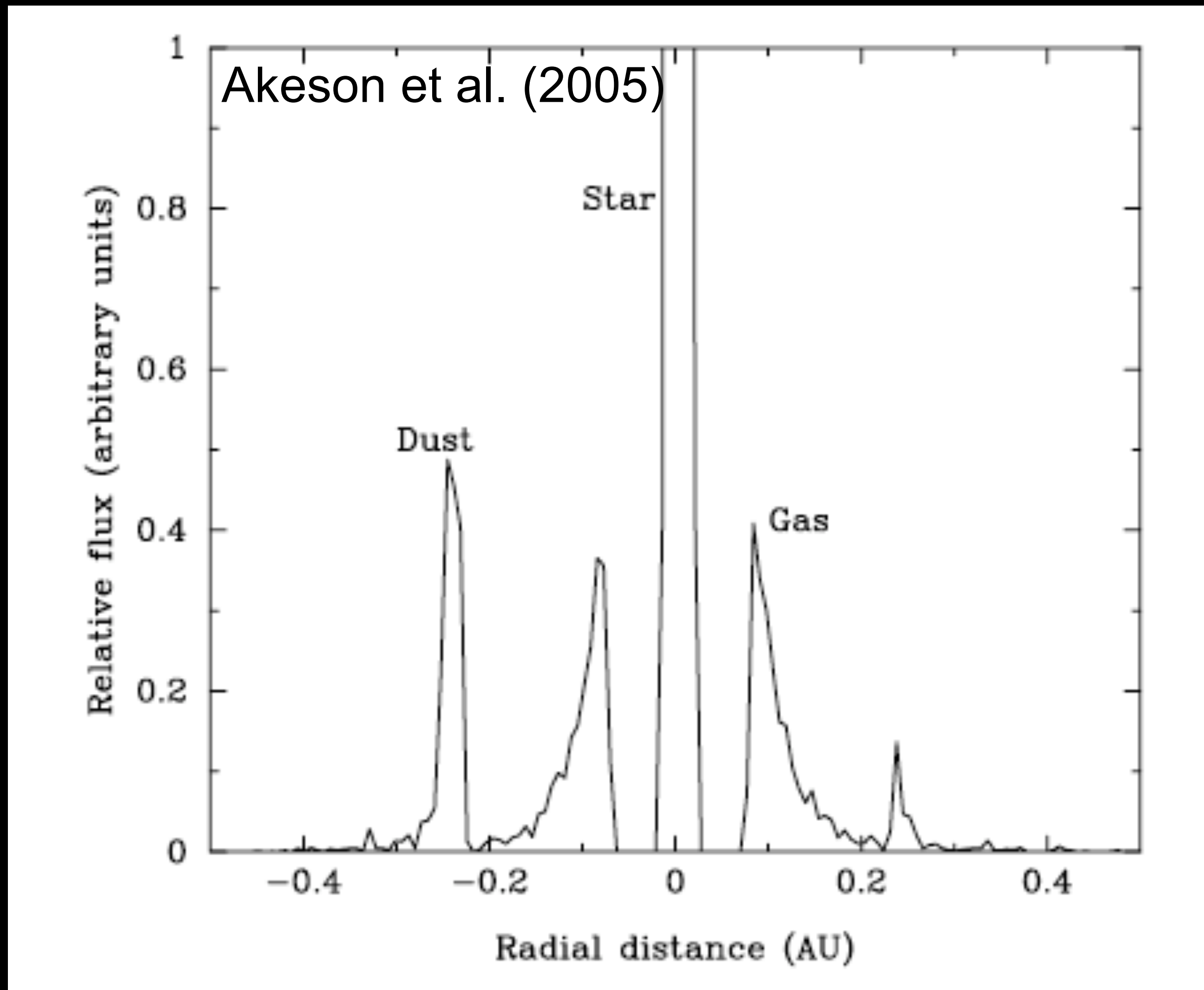




But ….

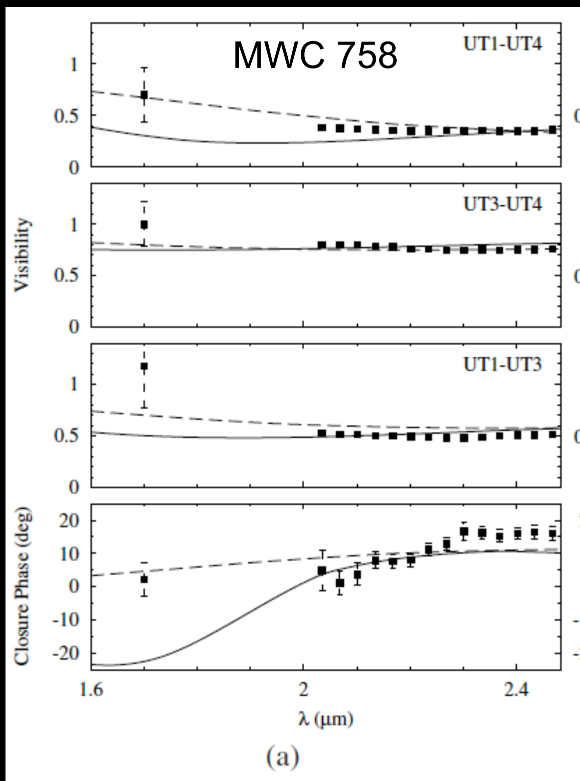
The "puffed-up" inner rim is not enough



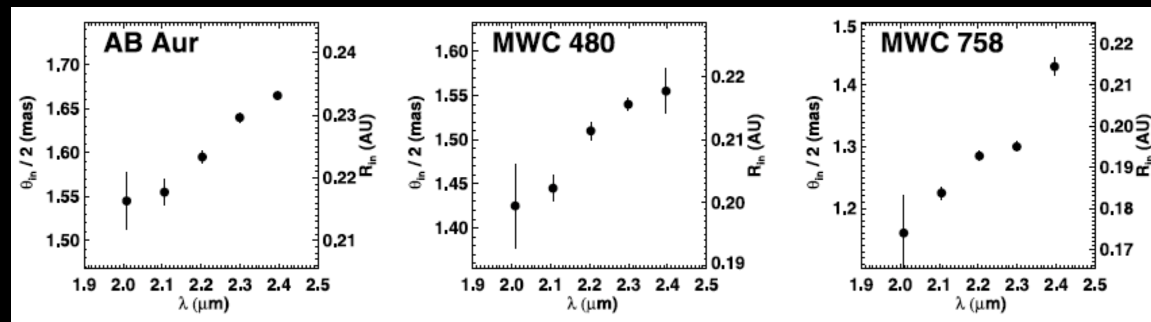


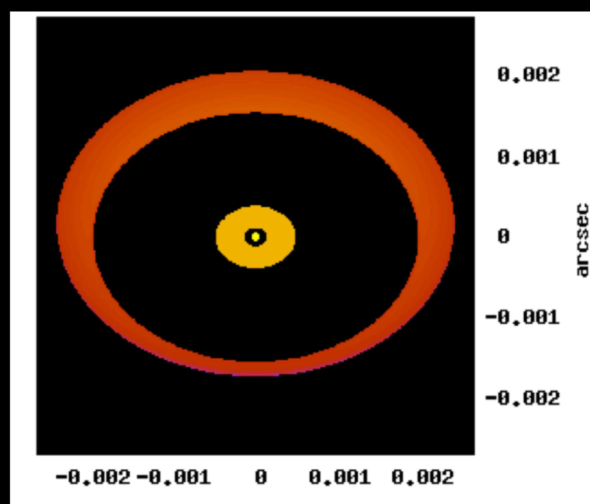
Evidence of hot material inside the rim

Isella et al. (2008)

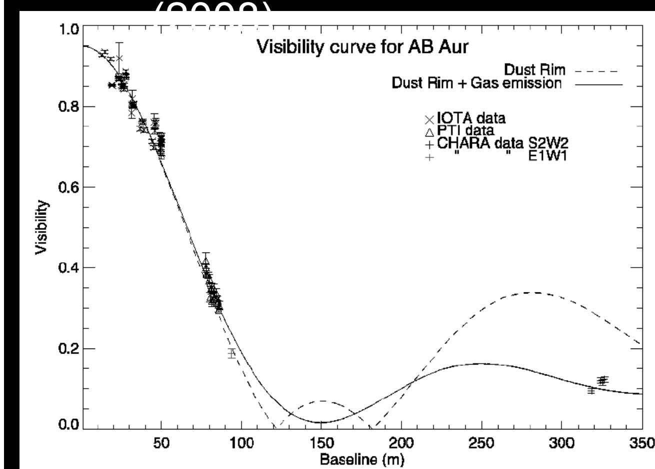


Eisner et al. (2007)





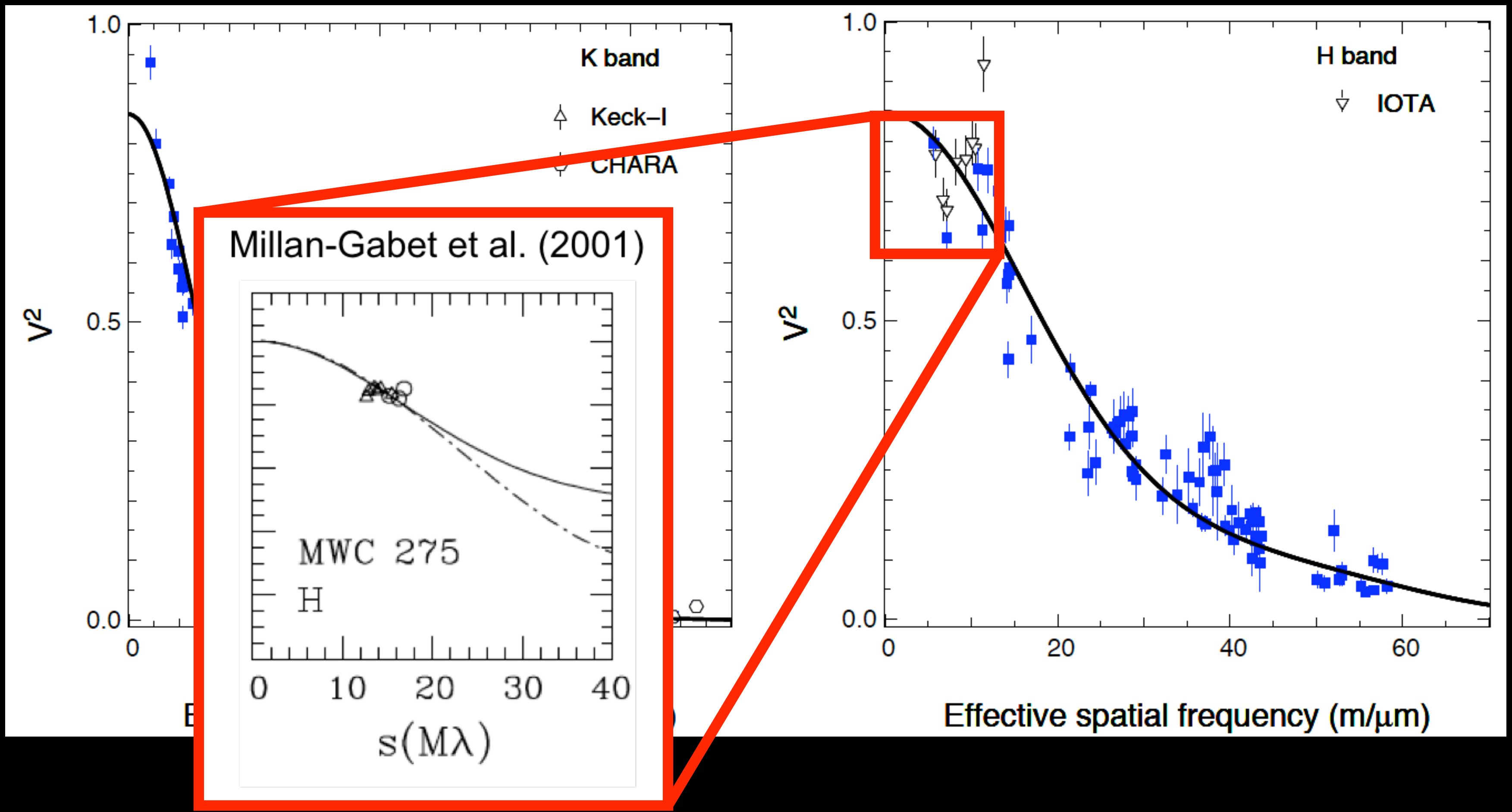
Tannirkulam et al. (2008)



Evidence of hot material inside the rim

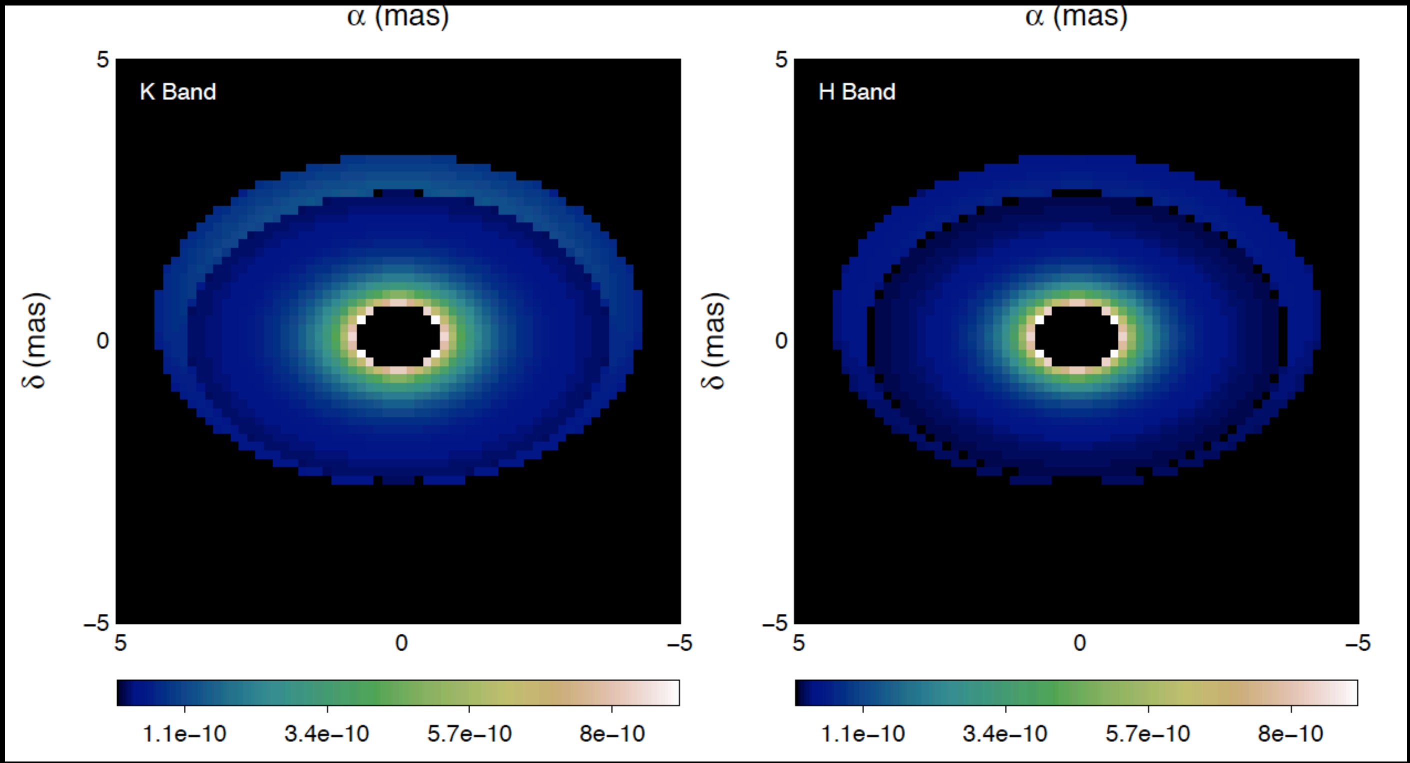
Benisty et al. (2009, A&A in press) – Tannirkulam et al (2008)

HD 163296



Spatially resolved spectroscopy of the inner disk

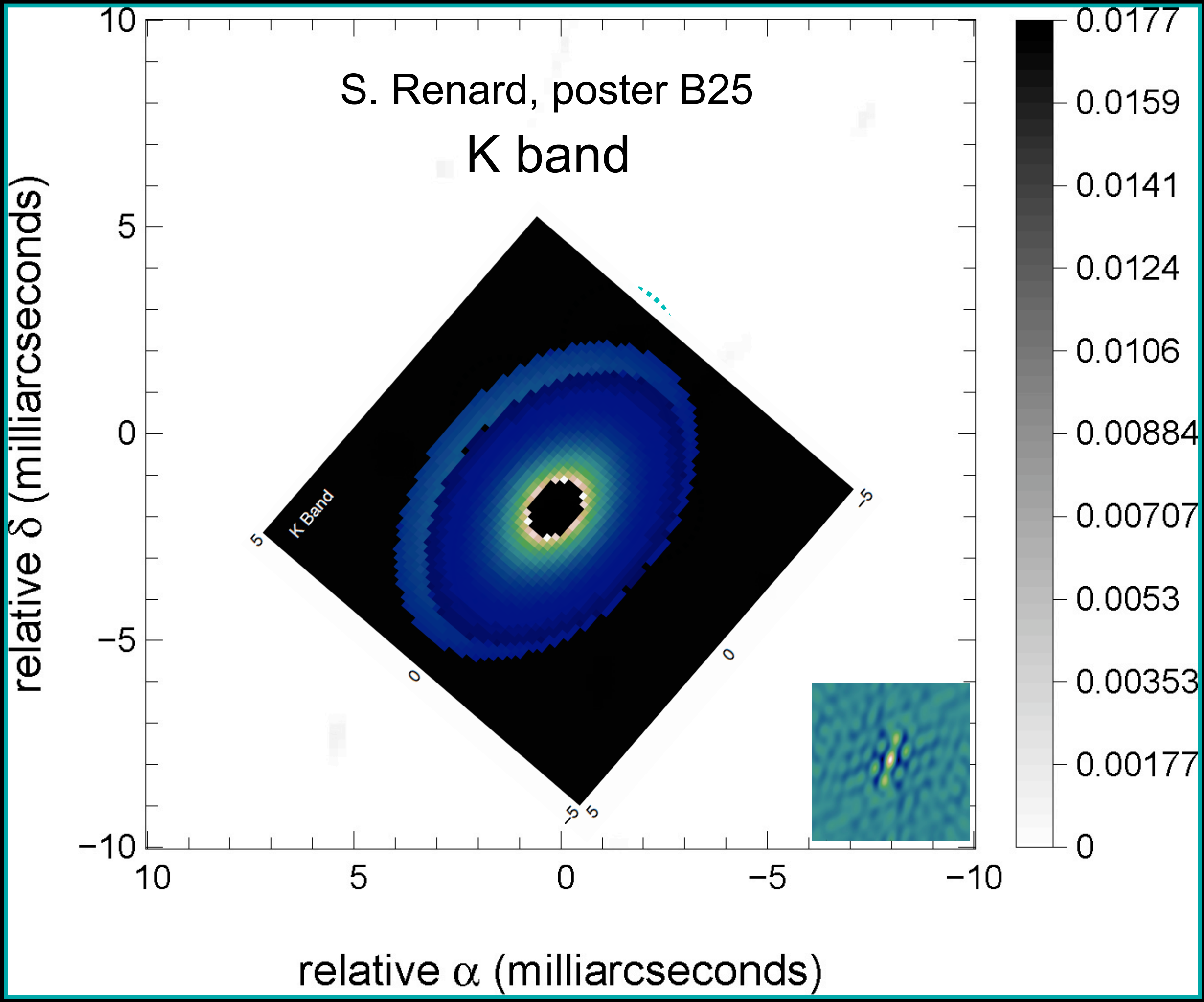
Benisty et al. (2009)



What is the nature of the material within the dust sublimation radius?

M. Benisty's talk!

Image reconstruction



Flaring Vs Self-shadowing

Dullemond et al. (2004), Meeus et al. (2001)

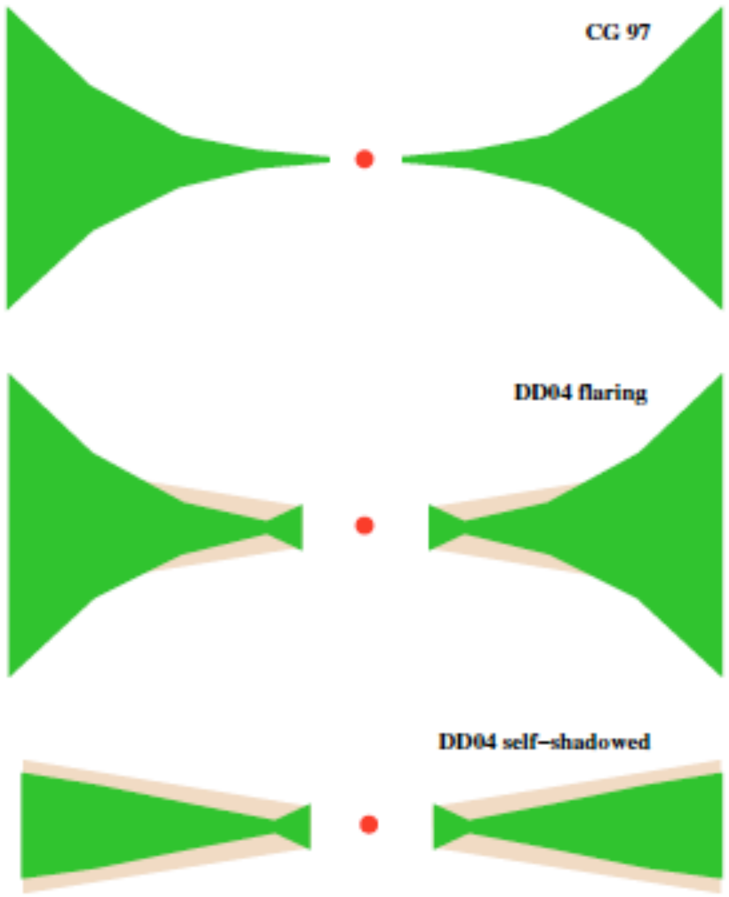
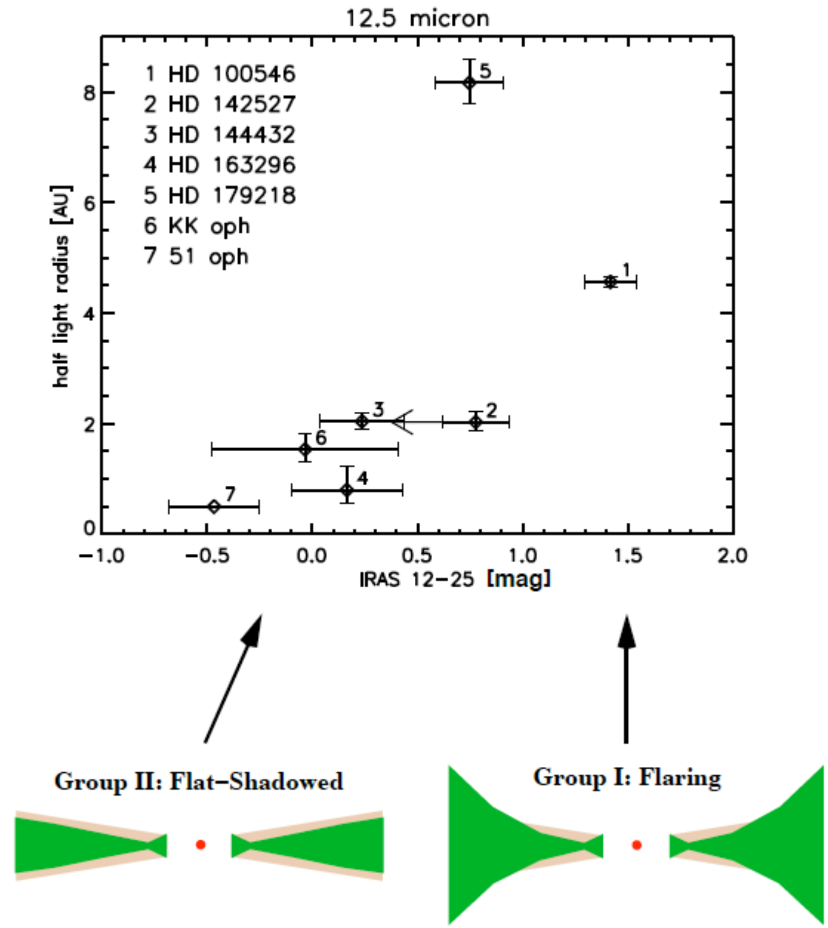
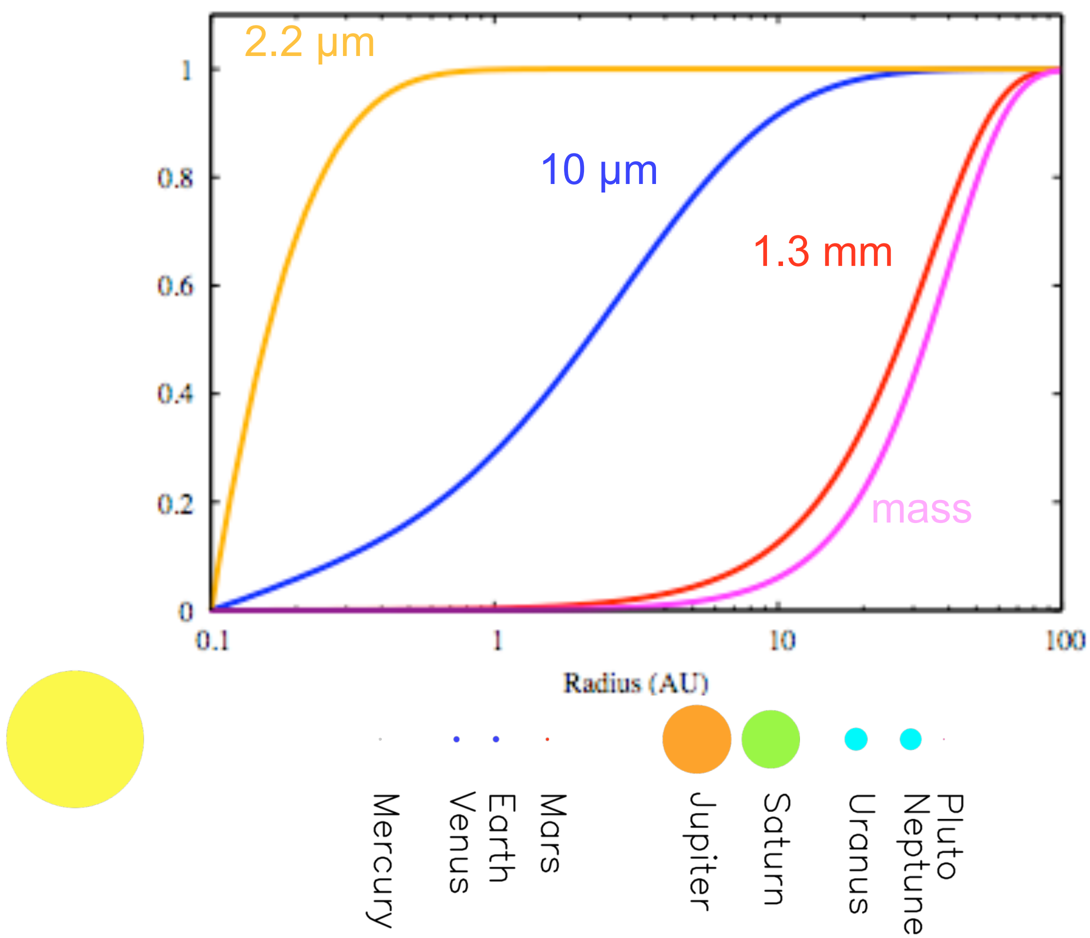


Fig. 1. A schematic representation of the geometries of the disk models studied in this work. The shadow cast by the inner rim is shaded light.

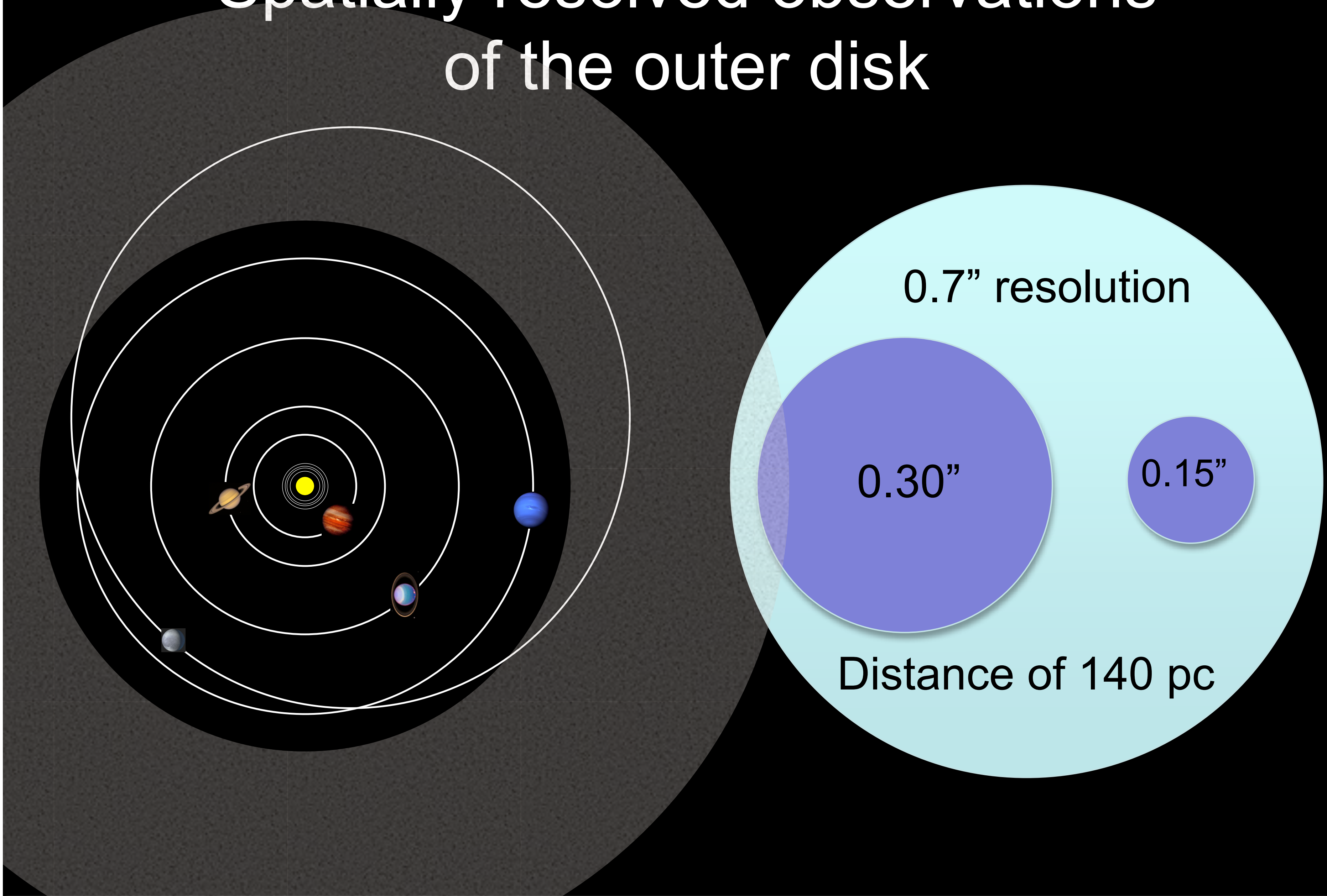


Millan-Gabet et al. (2008)

Disks @ mm wavelengths

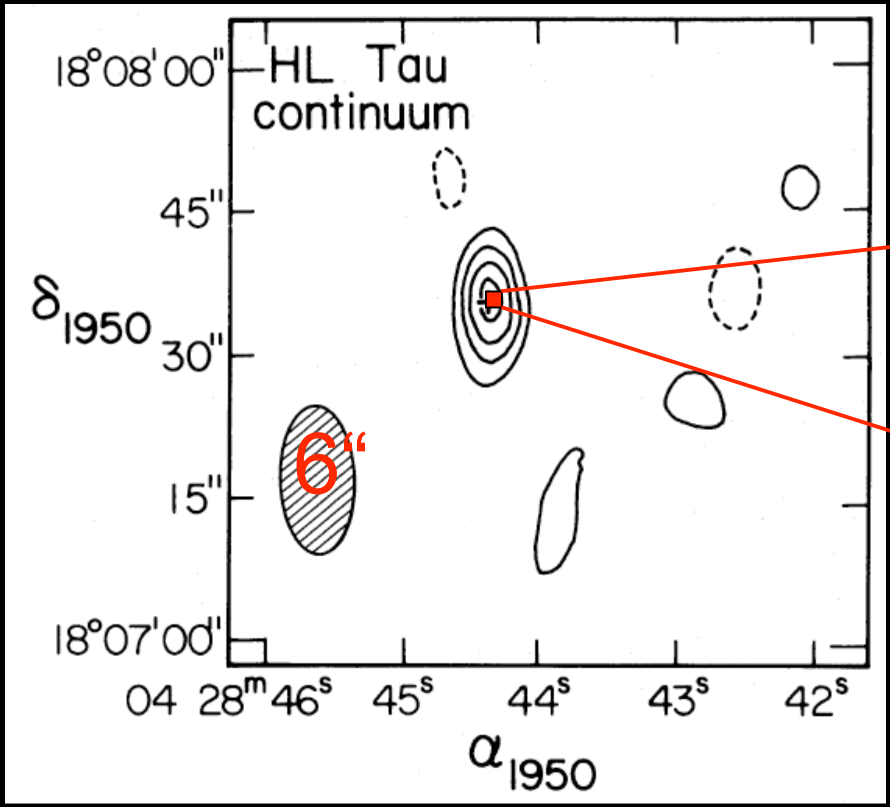


Spatially resolved observations of the outer disk



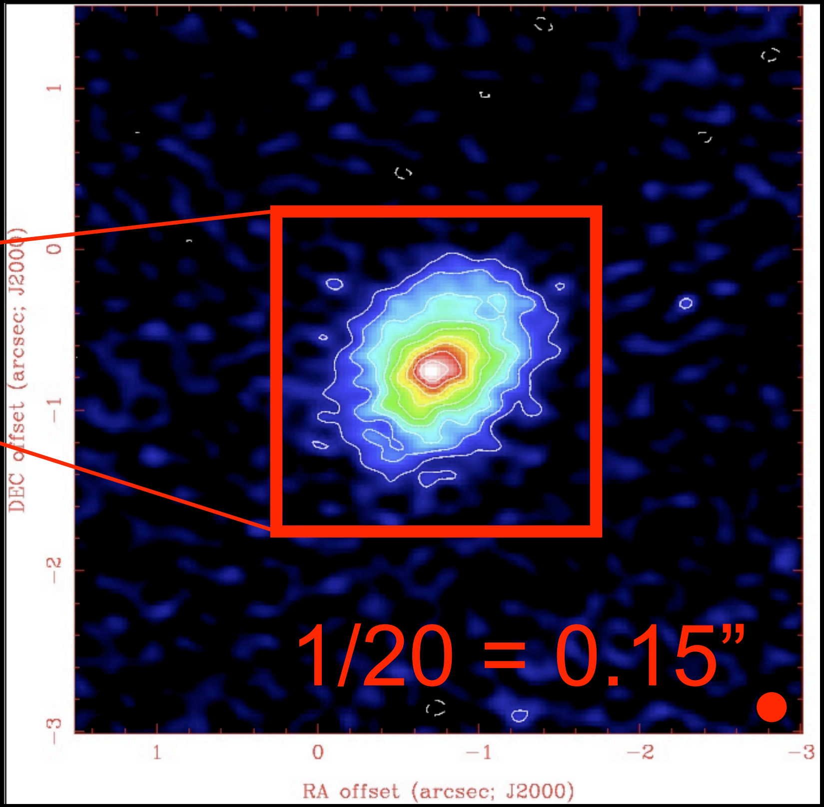
Spatially resolved observations of the outer disk

OVRO



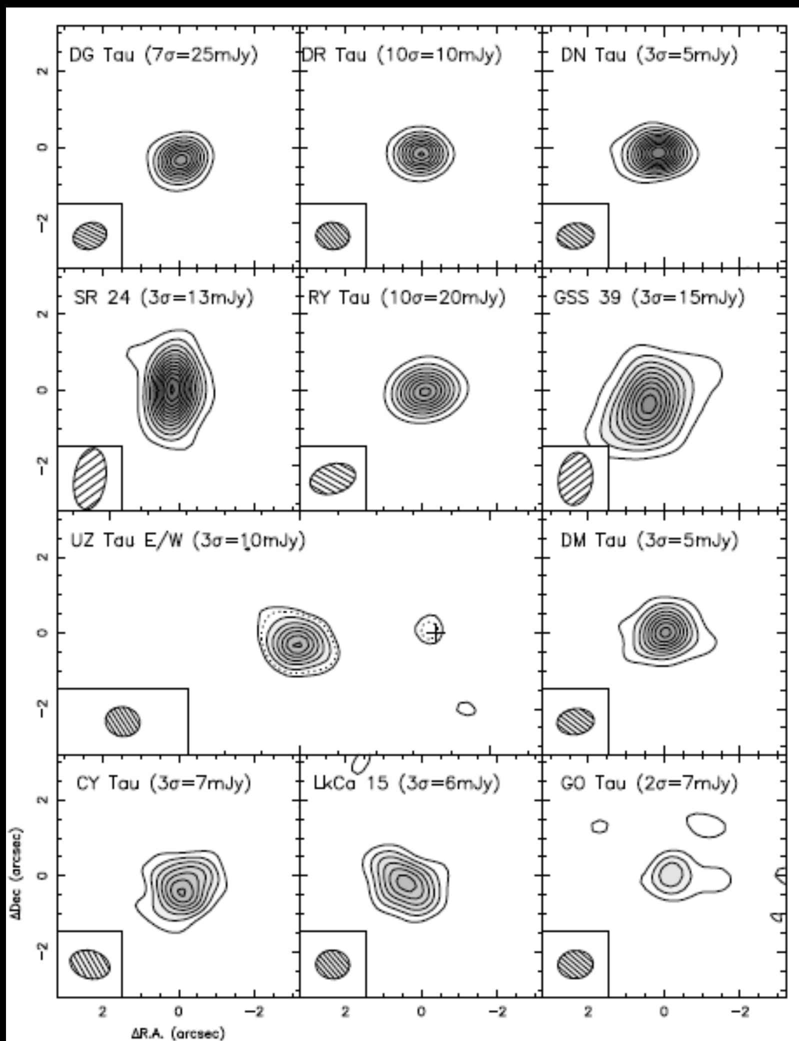
Sargent & Beckwith (1987)

CARMA = OVRO + BIMA



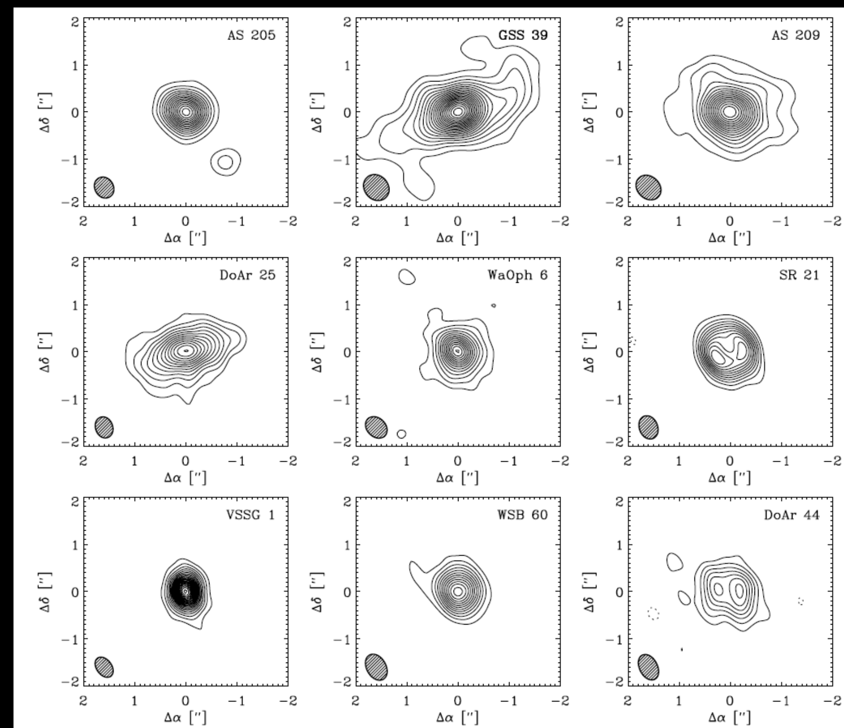
Kwon et al. (in prep.)

CARMA survey @ 1.3 mm
0.4”-0.8” resolution



Isella, Carpenter, & Sargent (2009)

SMA survey @ 0.85 mm
0.3”-0.5” resolution

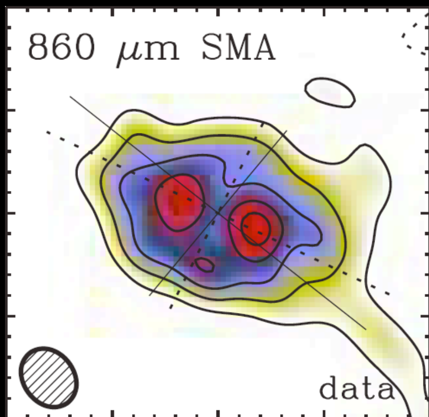


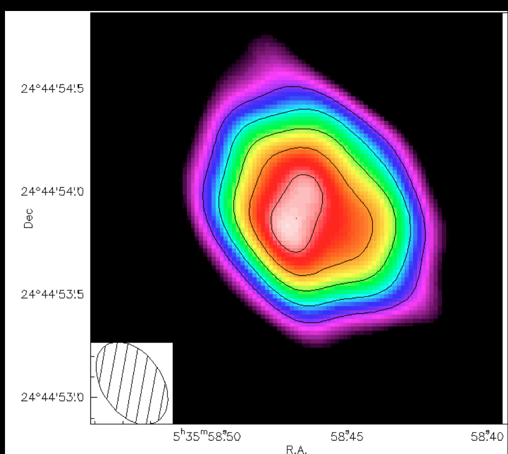
Andrews, Wilner, Hughes,
Qi, Dullemond (2009)

All disks resolved

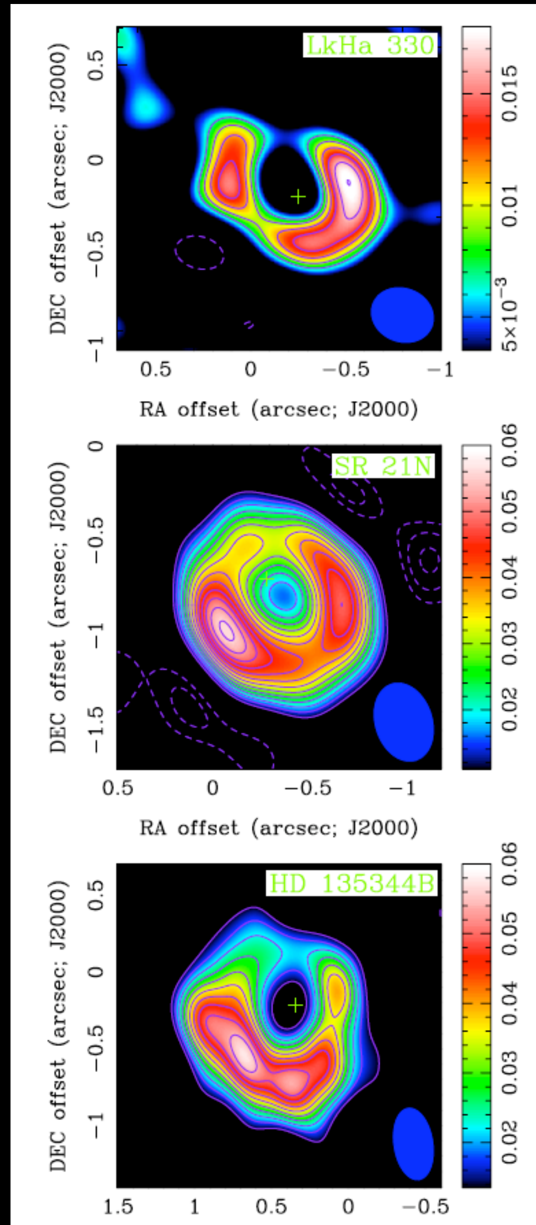
Disks @ 0.3” resolution

GM Aur, Hughes et al. (2009)





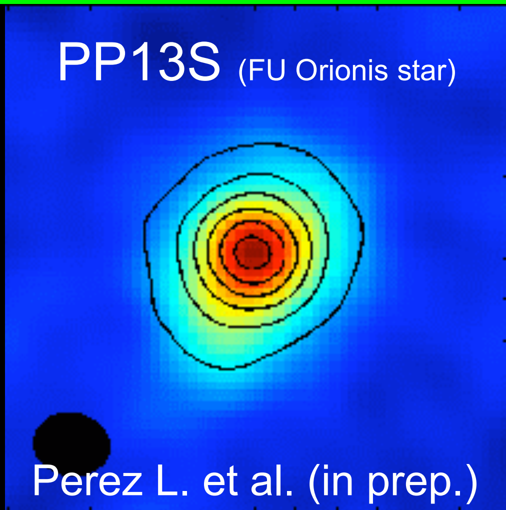
CQ Tau
Banzatti A, Poster A5

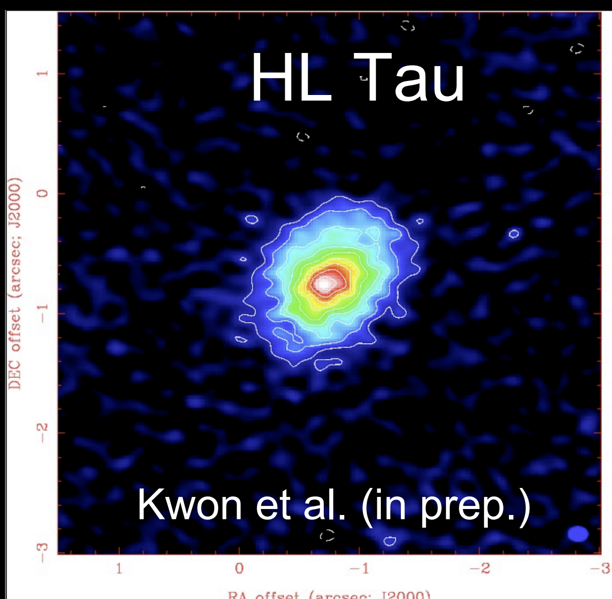


Brown et al. (2009)

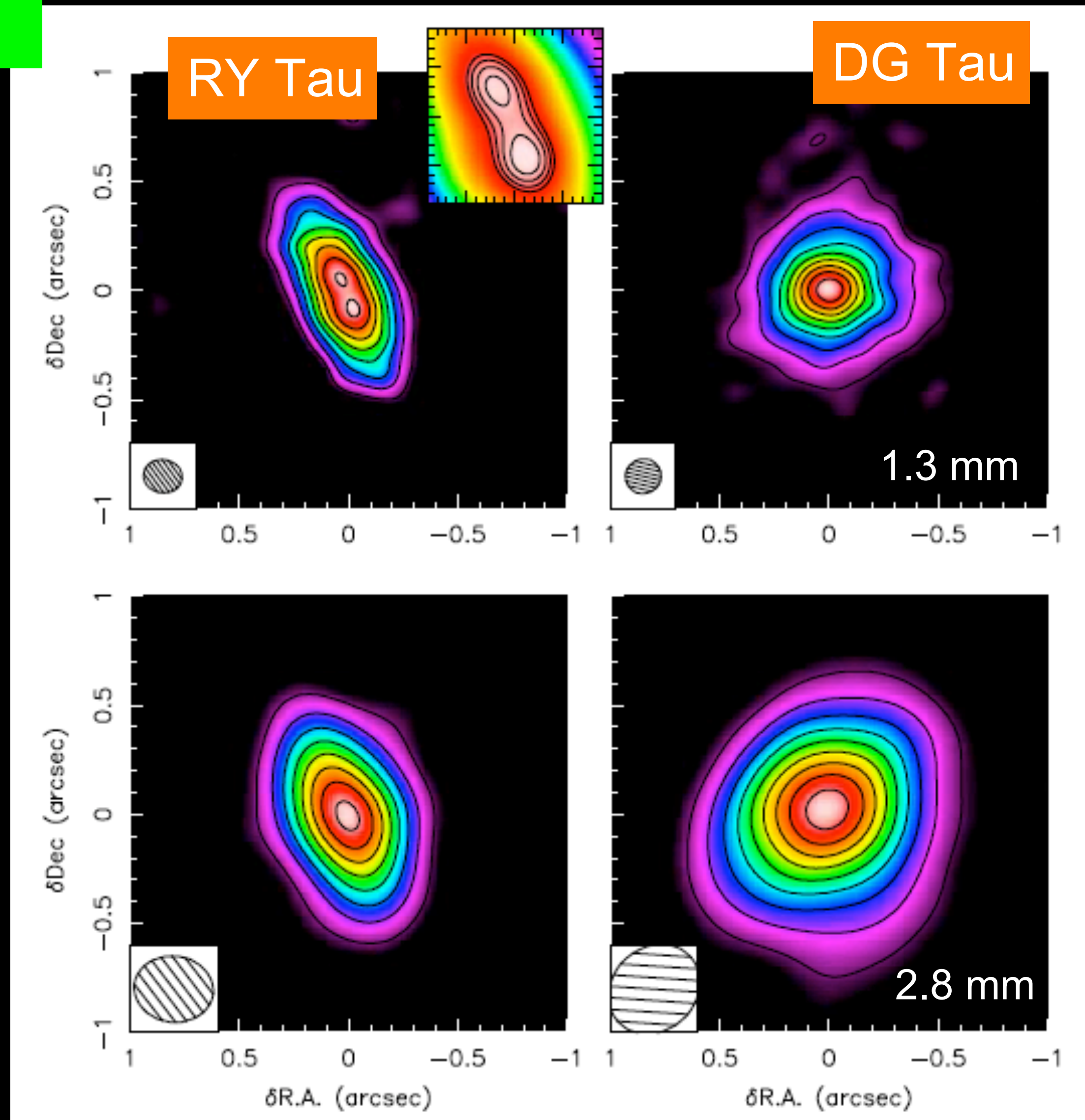
Perez L., in prep.

Disks @ 0.15” resolution
CARMA 230 GHz





Isella, Carpenter & Sargent (in prep.)



Constraining the disk surface density

$$F_\nu(R) \propto \Sigma(R) \times k_\nu(R) \times T(R)$$

Lynden-Bell & Pringle 1974

Similarity solution for the disk surface density of a keplerian viscous disk

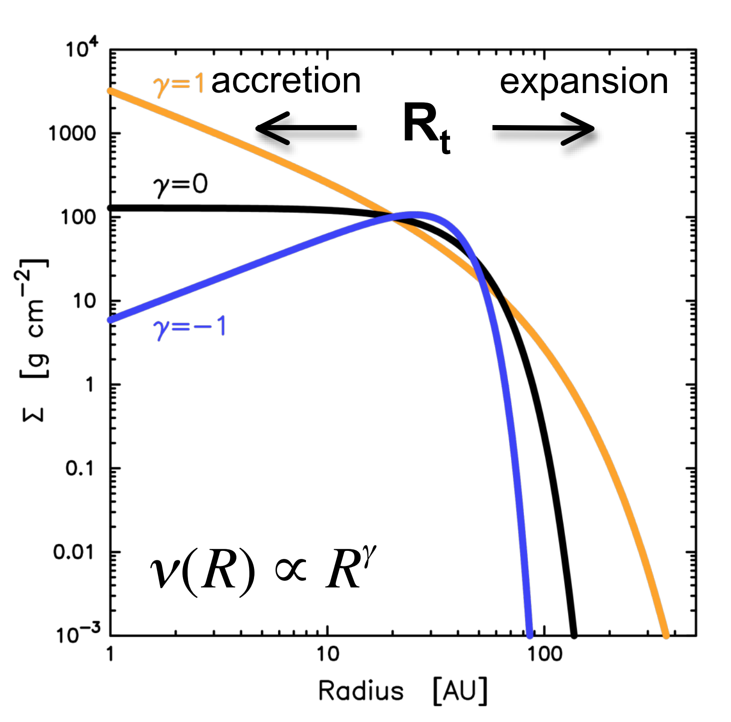
$$\Sigma(R,t) = \Sigma_t \left(\frac{R_t}{R}\right)^\gamma \times \exp\left\{-\frac{1}{2(2-\gamma)}\left[\left(\frac{R}{R_t}\right)^{(2-\gamma)} - 1\right]\right\}$$

$$R_{in} < \Sigma(R) < \infty$$

$$R_{90\%} \sim 4R_t$$

$$R_t(t) \propto (t/t_s)^{1/(2-\gamma)}$$

$$M_d(t) \propto (t/t_s)^{-1/(2(2-\gamma))}$$



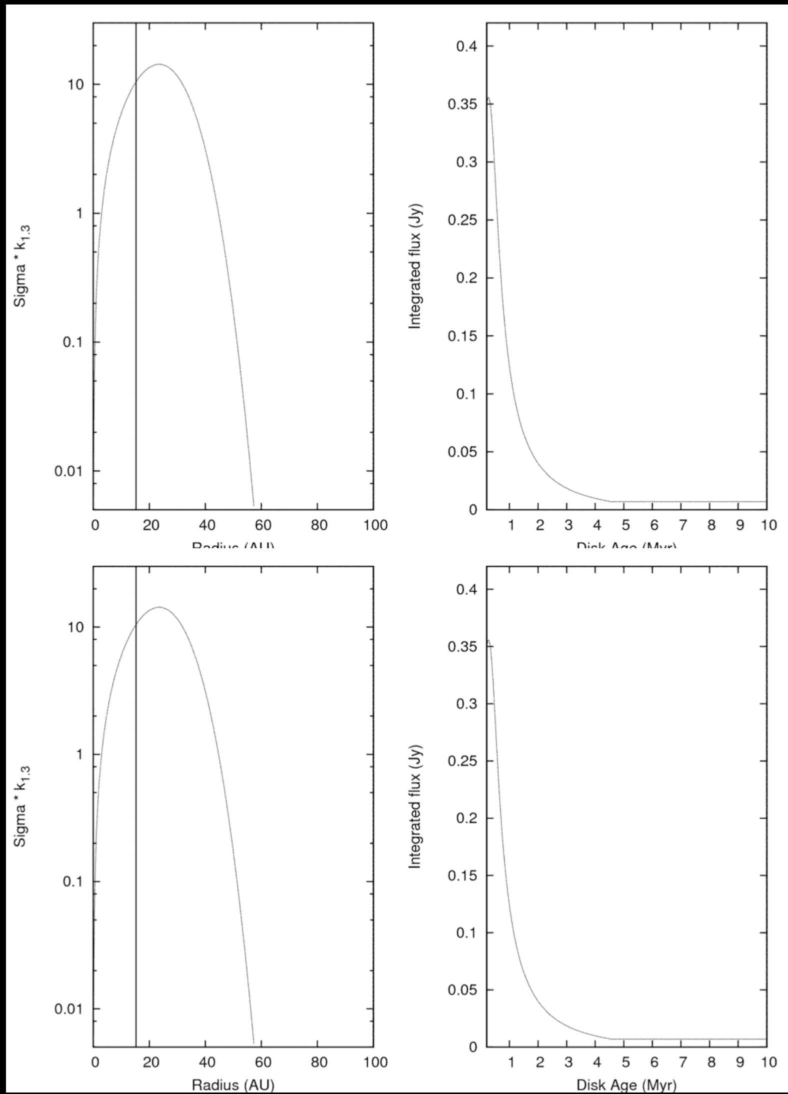
Hughes et al. (2008)
Isella et al. (2009)
Andrew et al. (2009)

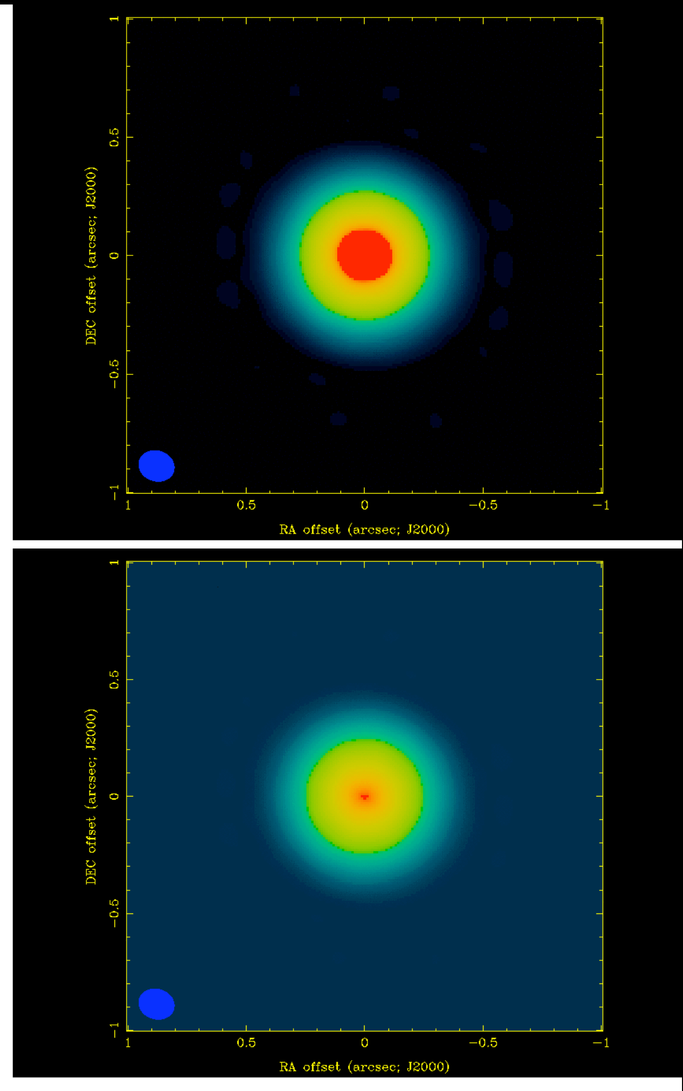
Viscous disk evolution

γ=-1

R_1= 30 AU

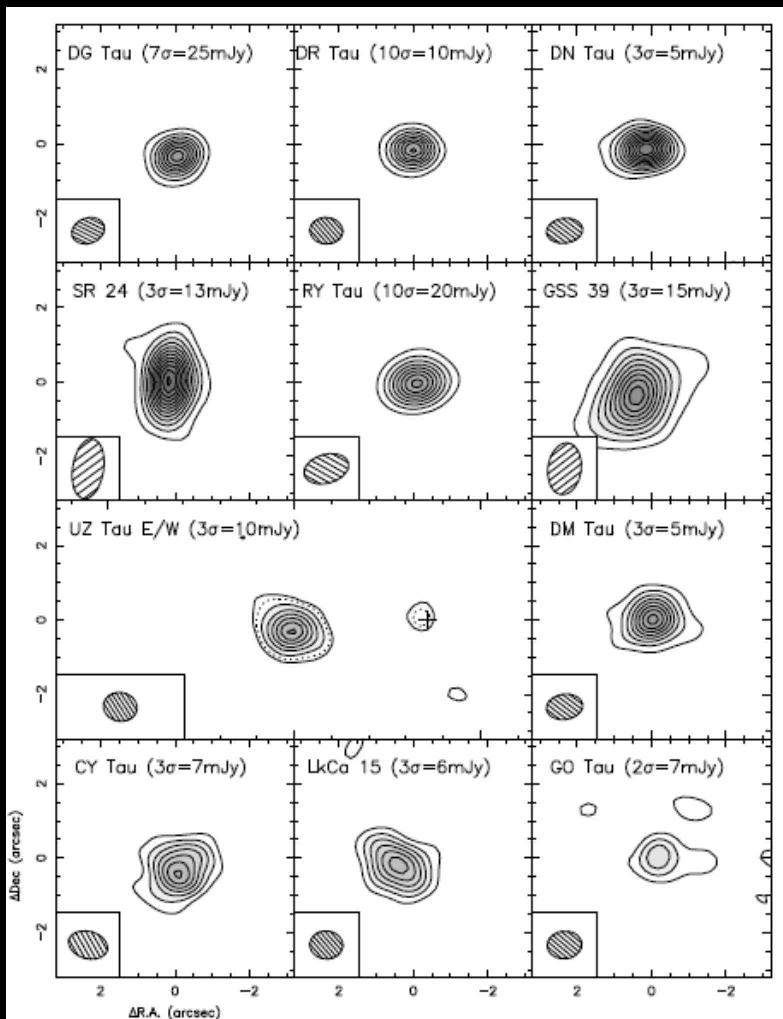
M_0 = 0.05 $M_\odot$



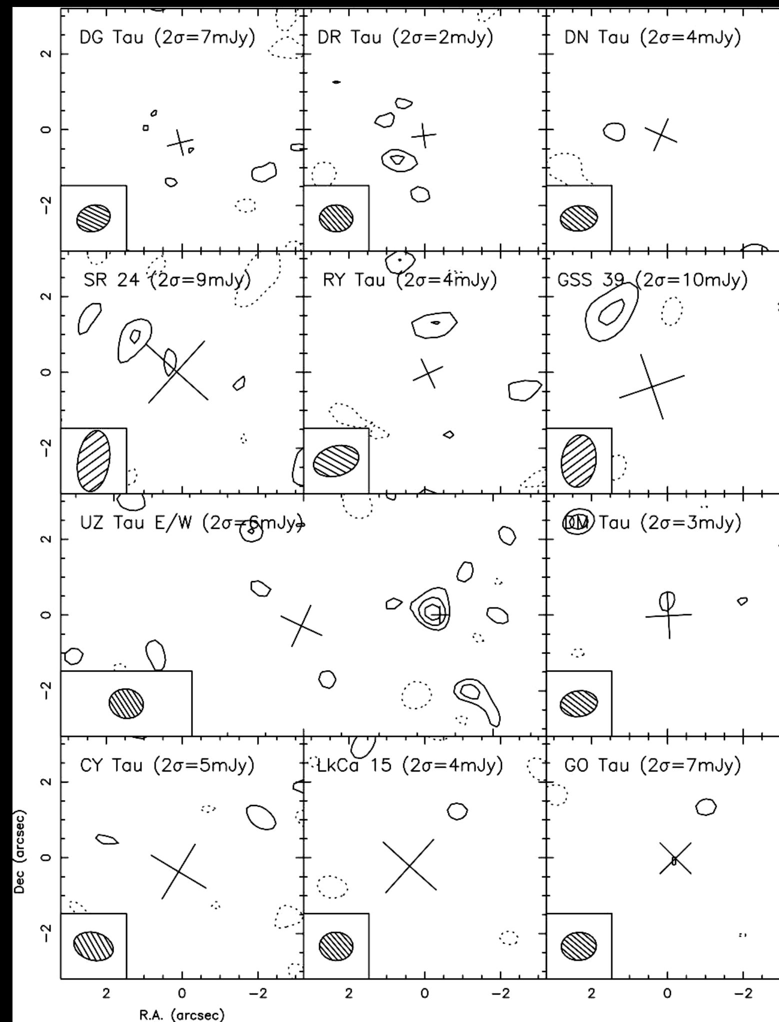


Observations Vs Models

Observations

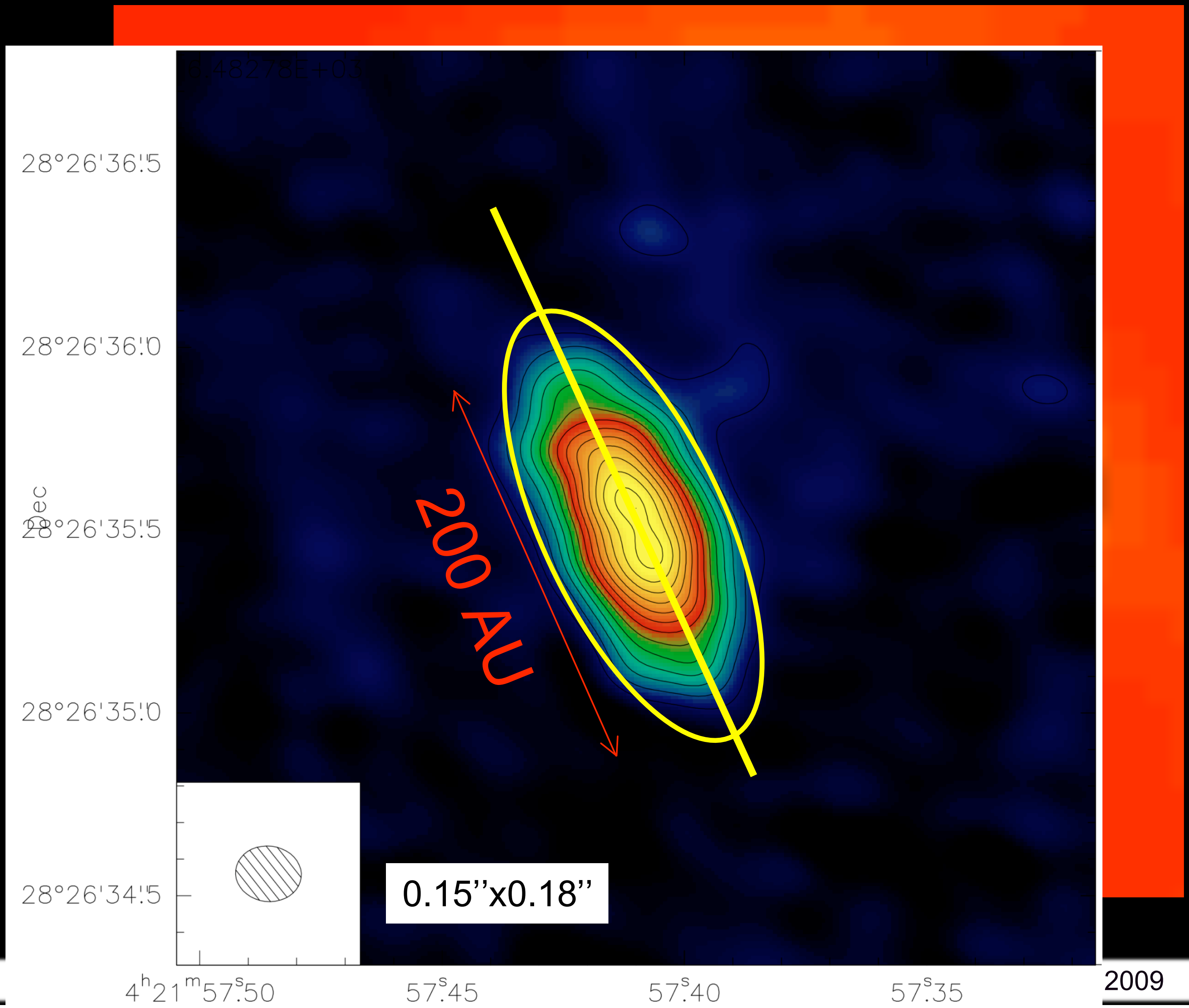


Observations - Model



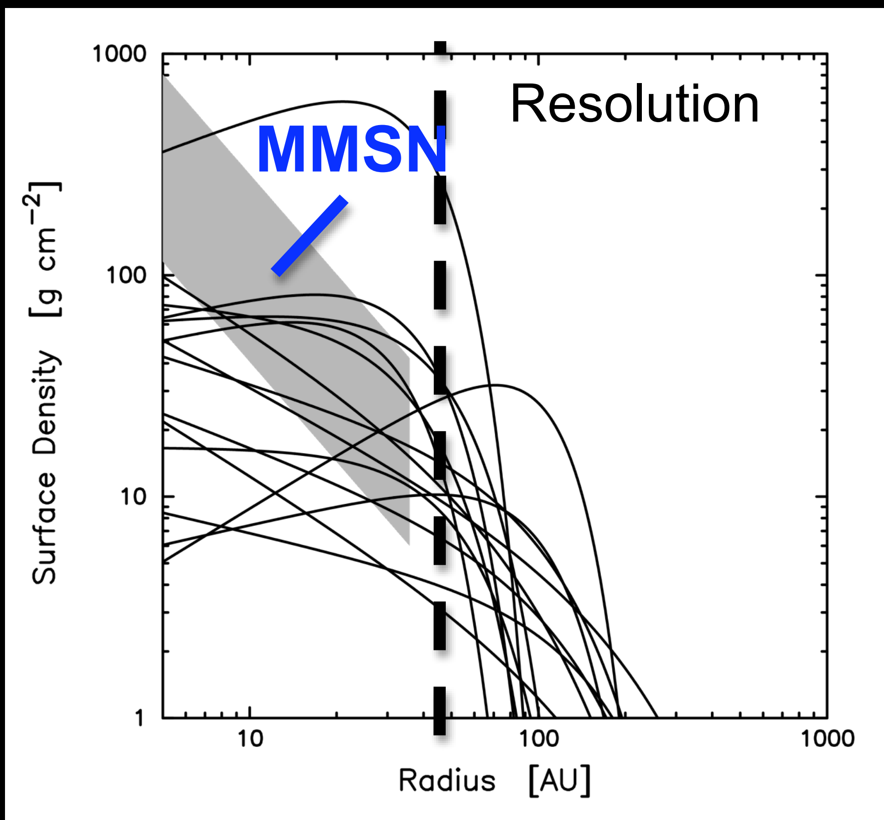
Isella et al. (2009)

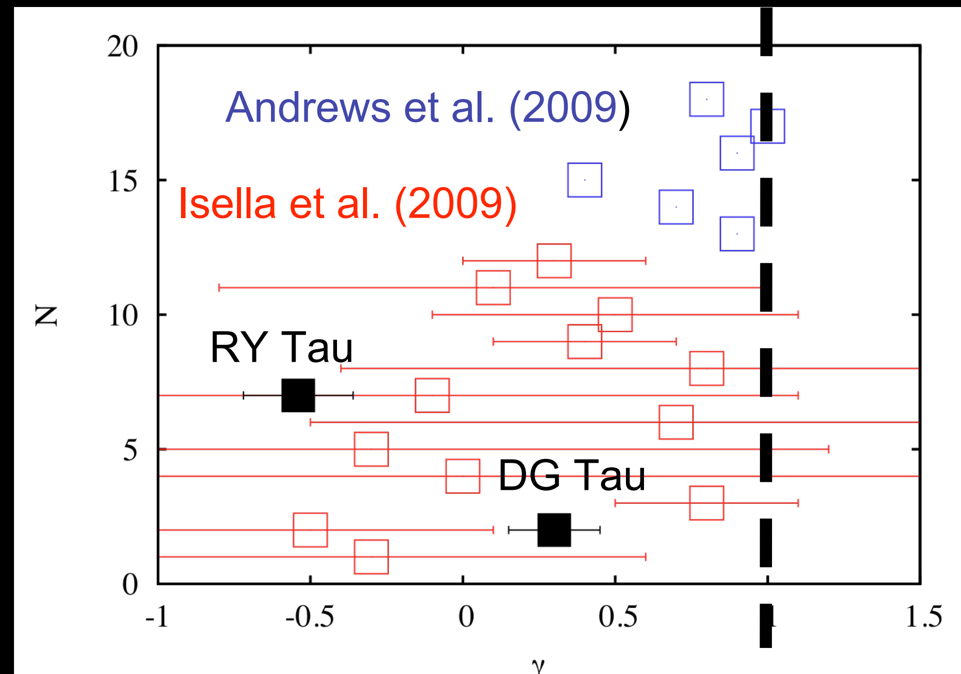
Example: RY Tau



Surface density

Isella et al. (2009)





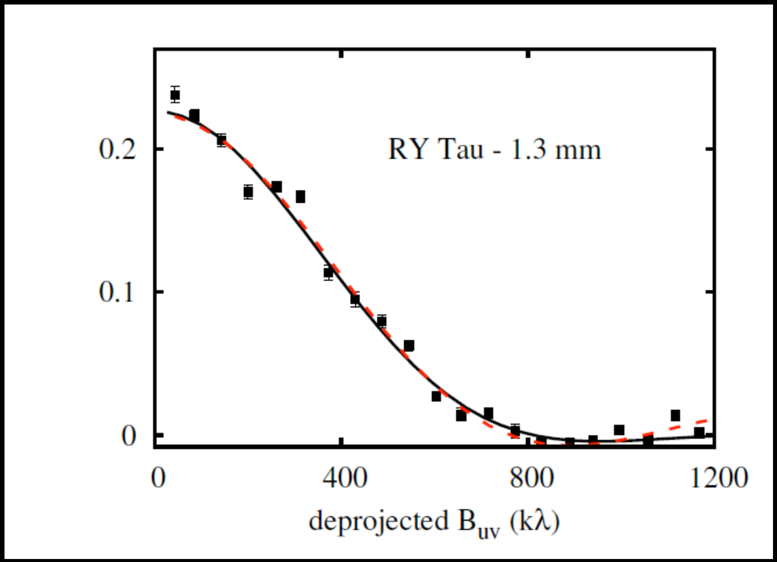
$$\nu = \alpha c_s H.$$

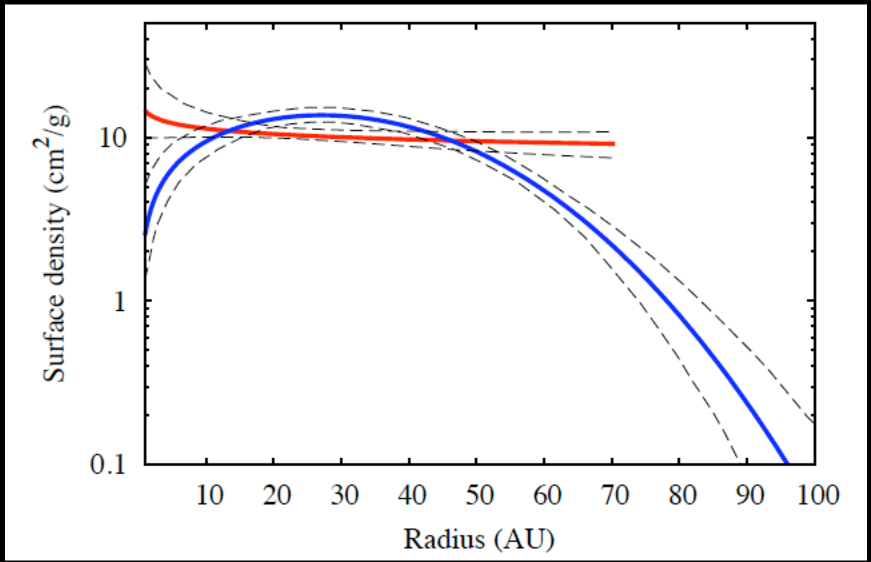
$$\alpha \sim R^{(\gamma-3/2)} \times T^{-1}(R) \sim R^{(\gamma-1)}$$

MMSN = Minimum Mass Solar Nebula

α decreases with the radius

Disentangling surface density models





Isella et al. , in prep.

Similarity solution

i (°)	PA (°)	R_t (AU)	γ	Σ_t (g/cm^2)	χ^2_r
66±2	24±3	26.7±1.2	-0.54±0.18	2.6±0.2	1.0896

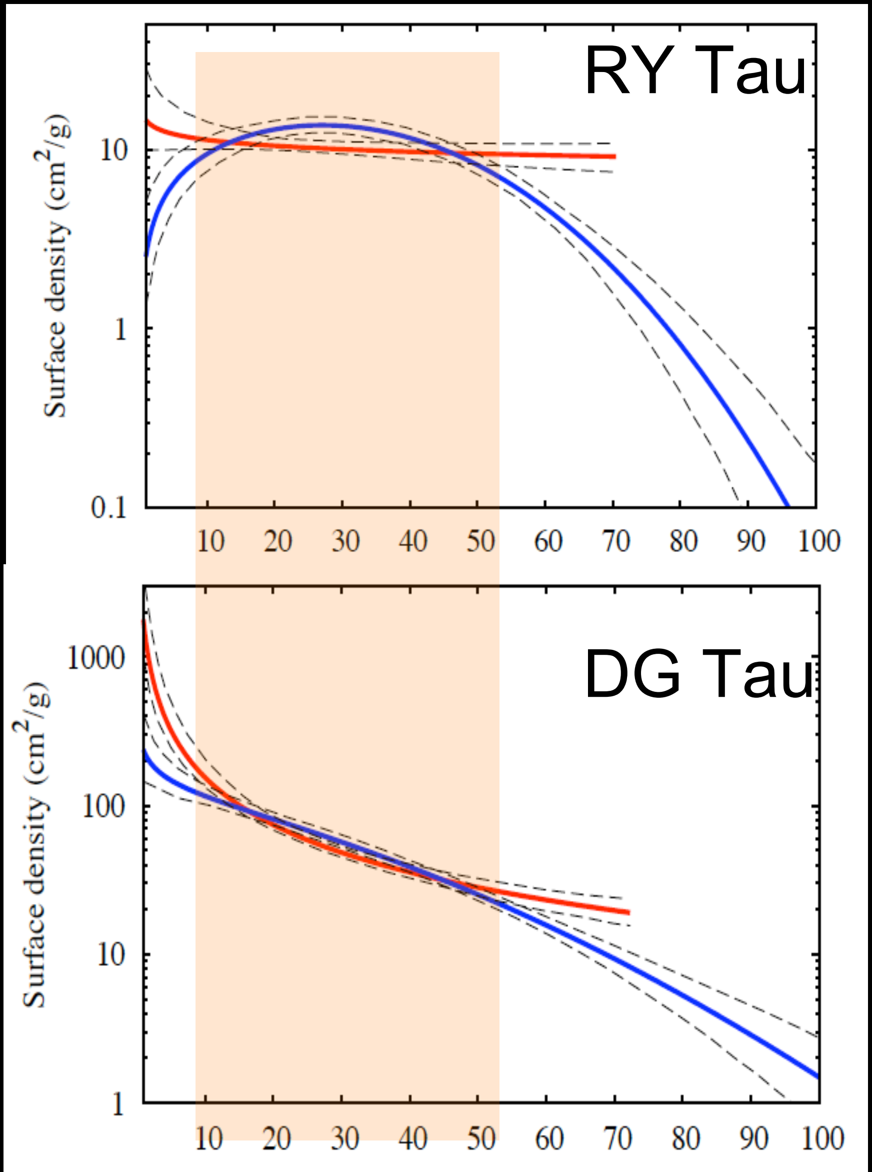
Power law, $\Sigma \propto R^{-p}, \quad R_{in} < R < R_d$

i (°)	PA (°)	R_d (AU)	p	Σ_{40} (g/cm^2)	χ^2_r
66±2	24±3	70.6±3.9	0.12±0.15	1.9±0.6	1.0897

Disentangling surface density models

Power law

Similarity solution

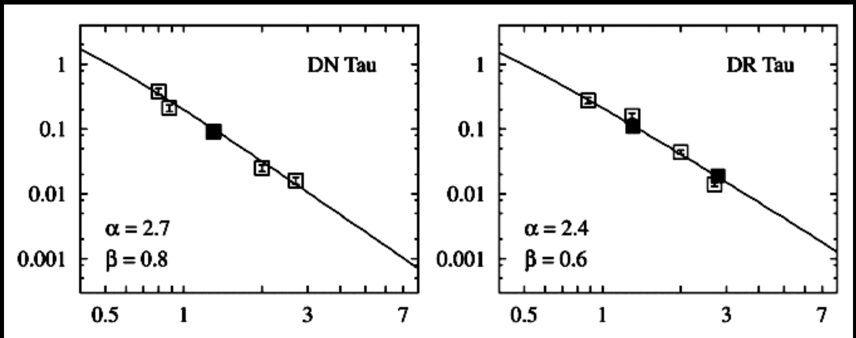


Isella et al. , in prep.

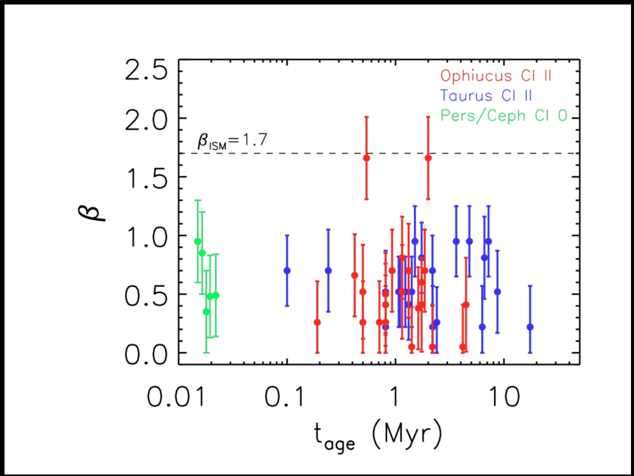
Grain growth

See, Natta et al. (2007), PPV review

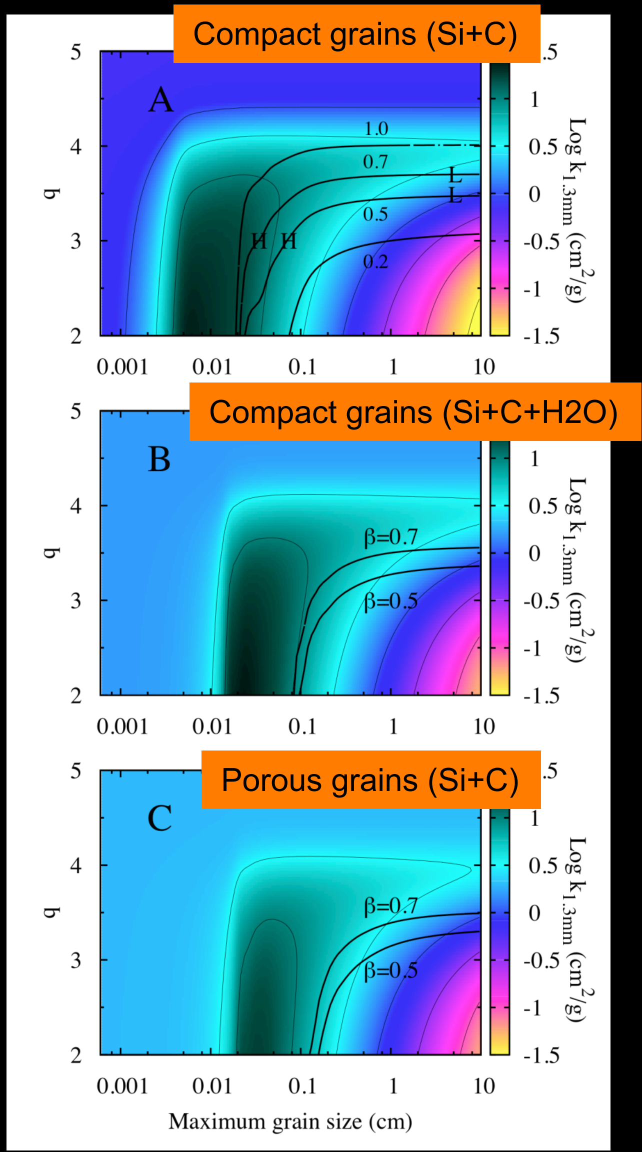
$$k_\nu \propto \nu^\beta \rightarrow F_\nu \propto \nu^{2+\beta+\Delta\beta}$$



Wavelength (mm)



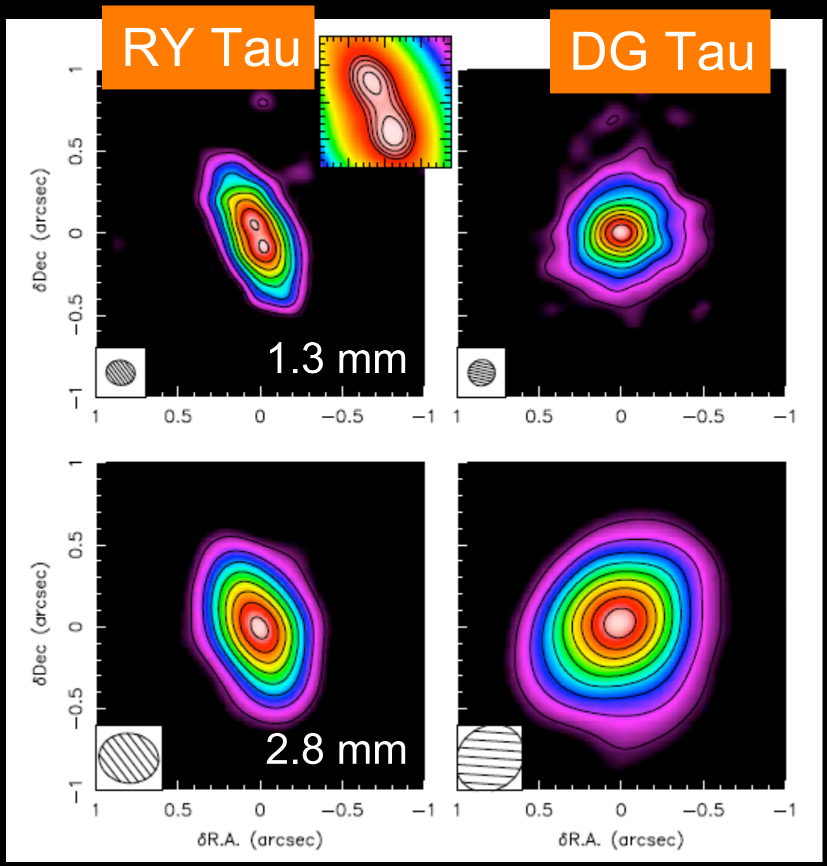
Ricci et al. (2009), A&A submitted



Isella et al. , in prep.

Does the dust opacity vary with radius?

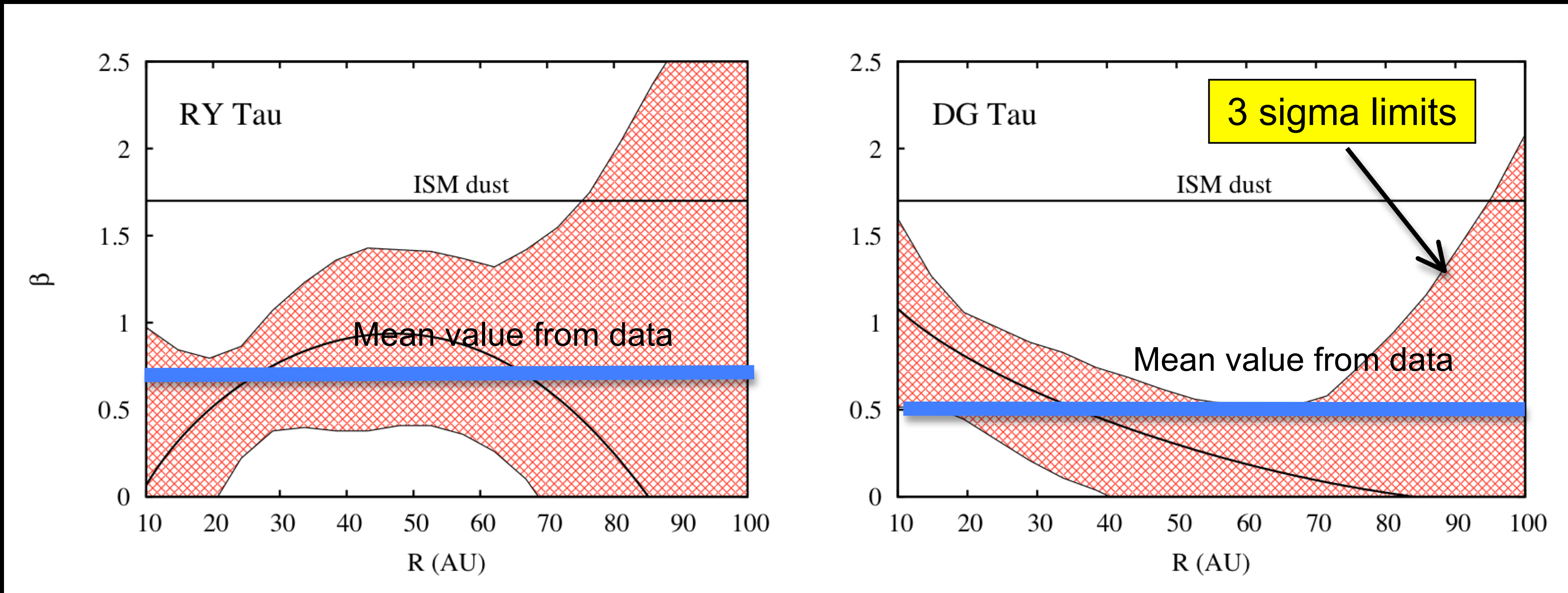
$$F_\nu(R) \propto B_\nu(T,R) \cdot \Sigma(R) \cdot k_\nu(R)$$



$$k_{1.3}(R) = k_{2.8}(R)\left(\frac{2.8}{1.3}\right)^{\beta}$$

$$\frac{F_{1.3}(R)}{F_{2.8}(R)} \propto \frac{k_{1.3}(R)}{k_{2.8}(R)} \propto \left(\frac{2.8}{1.3}\right)^{\beta(R)}$$

Does particle opacity vary with radius?



Isella et al. , in prep.

- β is lower than found for the interstellar medium
- No evidence for radial gradient in β

Summary

Inner disk – 1 to 10 AU

1. The “puffed-up” inner rim model reproduces the K-band emission and it is in agreement with the disk structure inferred from mid-infrared interferometry
2. But, an additional component is required to fit the H band data. The nature of this component is still uncertain

Outer disk > 10 AU

1. From the constrain of the surface density it appears that $\gamma < 1$. This implies that α decreases with the radius.
2. @ 0.15” resolution we can constrain the surface density between 10 and 50 AU.
3. Actual observations does widely constrain the radial variation of the slope of dust opacity β. In DG Tau and RY Tau β is smaller than 1.7, between 20 and 70 AU.

Thank you