Clear Signs of Dust Grain Growth in Disks Around T Tauri Stars

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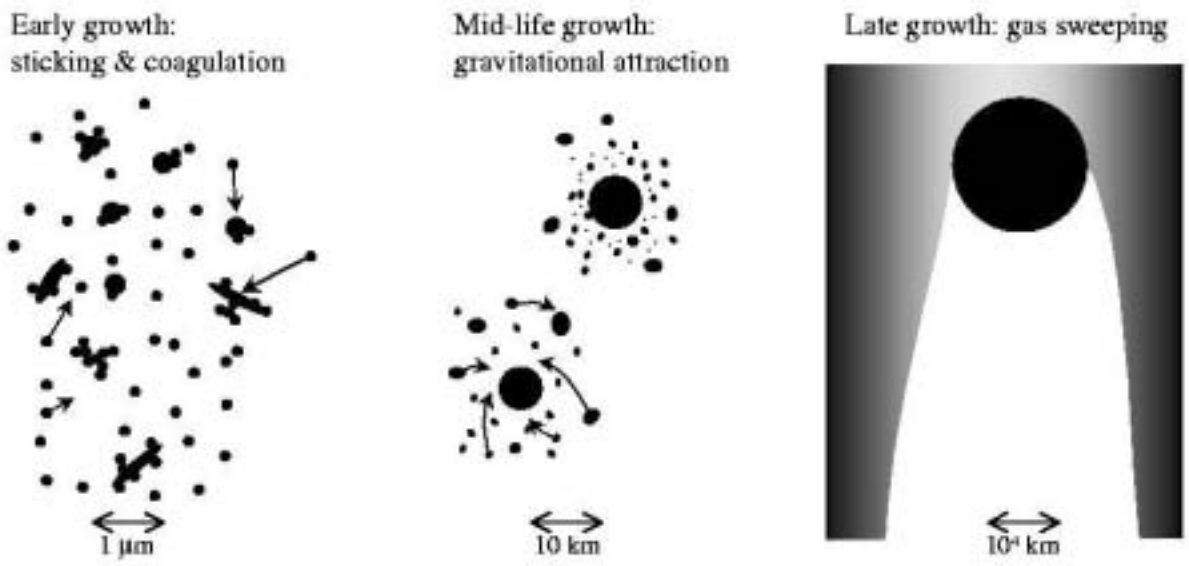
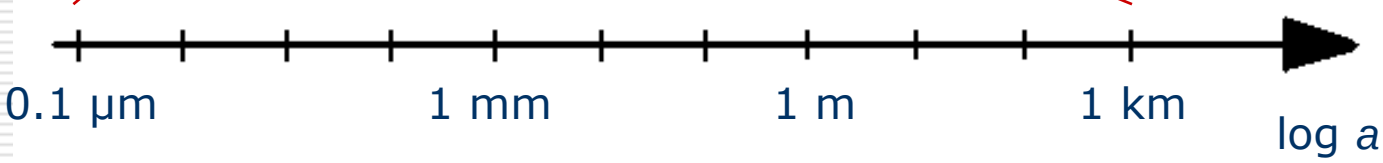
Outline

1. Road map of planet formation
2. How to observe dust grain size?
3. VLA 7-mm observations
4. Derived dust opacity indices
5. Conclusions

1. Road map of planet formation



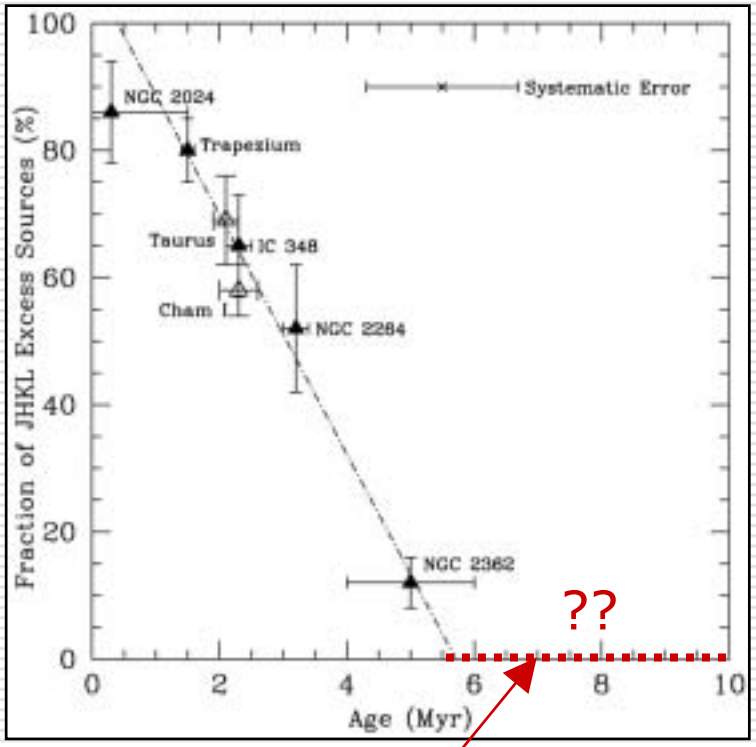
Beckwith et al. (2000)



Dust growth and/or disk dissipation

- **NIR young-cluster surveys: Disks lost within ~10 Myr**
  - ➔ Disk accretion/dissipation
  - ➔ Growth of dust particles
  - ➔ ... or both together

- **Observational tests**
  - ➔ Molecular line observation to trace gas disk evolution
  - ➔ Infrared dust spectroscopy
  - ➔ Resolved dust continuum observations at millimetre wavelengths



Haisch et al. (2001)

Spitzer Legacy Program:
Formation and Evolution of Planetary Systems

2. How to observe dust grain size?

- Flux density from a disk viewed face-on

$$F_\nu = \frac{1}{D^2}\int_{R_{\rm in}}^{R_{\rm out}} B_\nu(T(r)) \times \{1 - e^{-\tau_\nu(r)}\} \times 2\pi r \mathrm{d}r$$

- Optically thin disk; Rayleigh-Jeans regime

$$F_\nu \approx \frac{1}{D^2}\int_{R_{\rm in}}^{R_{\rm out}} 2k_{\rm B}T\,\nu^2/c^2 \times \tau_\nu(r) \times 2\pi r \mathrm{d}r$$

- Introduce mass opacity coefficient $\kappa_\nu \propto \nu^\beta$

$$F_\nu \approx \frac{2k_{\rm B}\nu^2}{c^2D^2}\kappa_\nu \int_{R_{\rm in}}^{R_{\rm out}} T(r)\Sigma(r) \times 2\pi r \mathrm{d}r \approx \frac{2k_{\rm B}\langle T\rangle \nu^2}{c^2D^2} \times M_{\rm dust}\kappa_\nu$$

Size-dependent opacity index

- Mass opacity frequency-dependent

$$F_\nu \propto \nu^2 \times \kappa_\nu \propto \nu^{2+\beta} \equiv \nu^\alpha$$

- For small (compact) grains with $a \ll \lambda$ (ISM dust)

$$\beta = 2 \Rightarrow F_\nu \propto \nu^4$$

$$\kappa_\nu = (2\ldots4)(\lambda/1.3\mathrm{mm})^{-2} \times 10^{-3}\,\mathrm{cm}^2\mathrm{g}^{-1}$$

Hildebrand (1983)
Draine & Lee (1984)
Ossenkopf & Henning (1994)

- Grey opacity if $a \gg \lambda/2\pi$ ($a \gg 1$ mm for $\lambda = 7$ mm)

$$\beta = 0 \Rightarrow F_\nu \propto \nu^2$$

- mm-sized particles somewhere in between

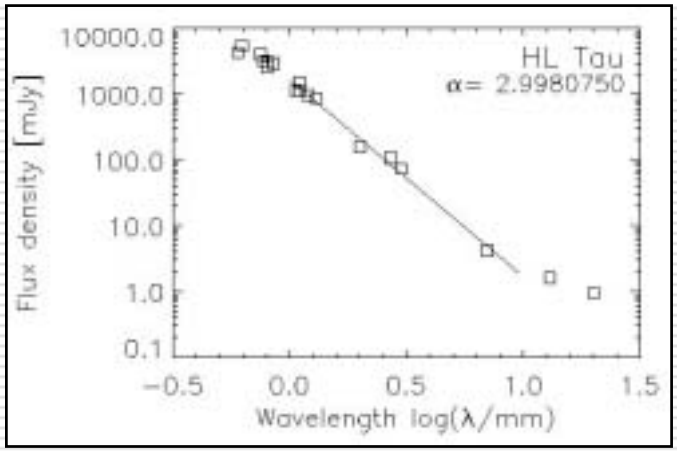
$$0 < \beta < 2 \Rightarrow F_\nu \propto \nu^{2\ldots4}$$

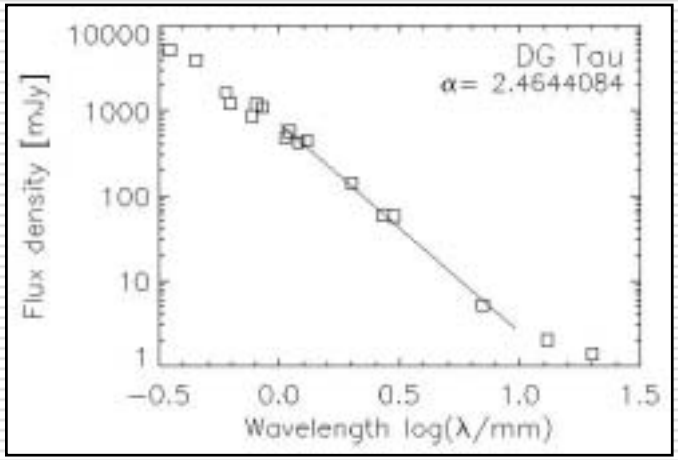
Recipe

- Resolve disk at mm wavelength
- Measure spectral slope α in Rayleigh-Jeans part of SED
- **Two possibilities to account for shallow SED (small α):**
  (i) optically thick disk & any β
  (ii) optically thin disk & low β
- Resolved (large) disks render (i) improbable/unphysical

➔ Opacity index $\beta \approx \alpha - 2$

- Low-mass star TW Hya: Calvet et al. (2002)
- 3 intermediate-mass stars: Testi et al. (2003) Natta et al. (2004)



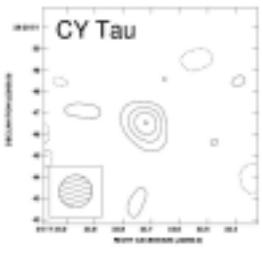


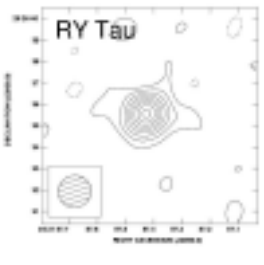
3. VLA 7-mm observations

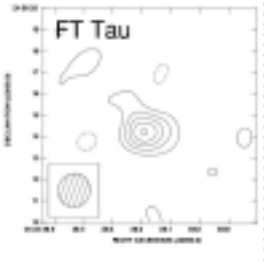
- 14 low-mass PMS stars in Taurus-Auriga region
- 7-mm observations at VLA in D configuration
  - ☹ low spatial resolution (~1.5” beam at 7 mm)
  - ☺ high sensitivity (~0.2 mJy)
- 11 secure detections ($\sigma \geq 5$)
- Additional observations at 1.3, 2.0, and 3.6 cm

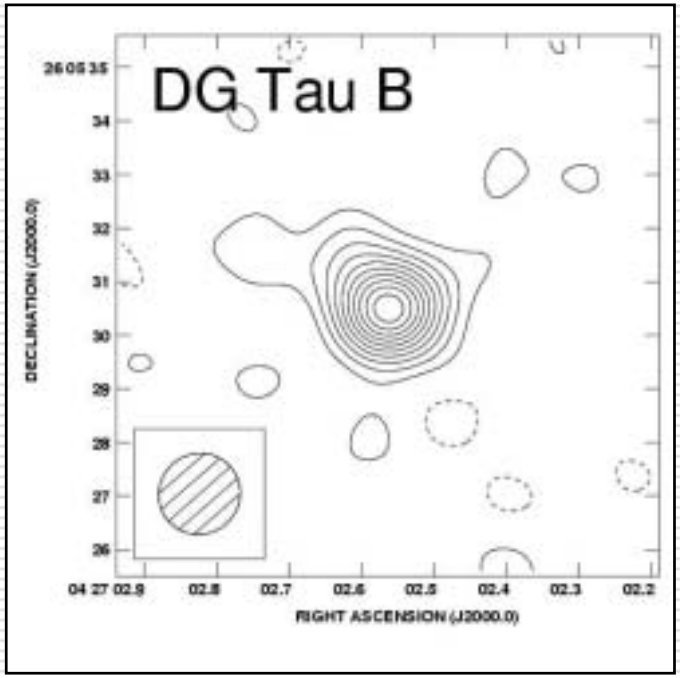
NRAO

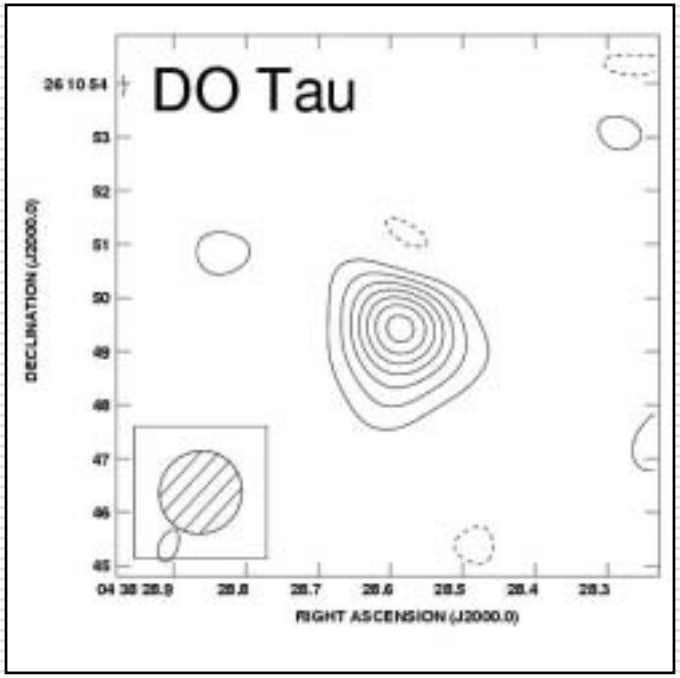
7-mm maps

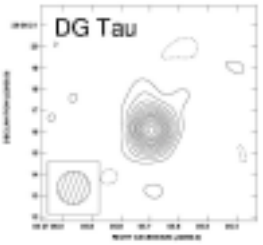

CY Tau

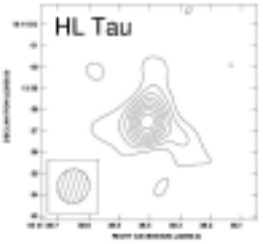

RY Tau

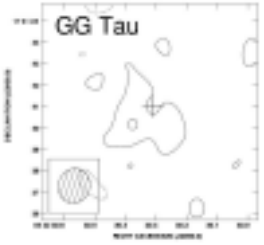

FT Tau

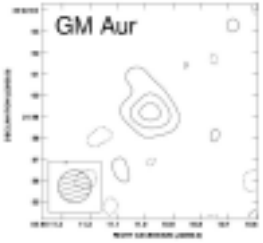

DG Tau B
DECLINATION (J2000.0)
RIGHT ASCENSION (J2000.0)

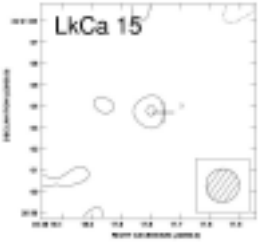

DO Tau
DECLINATION (J2000.0)
RIGHT ASCENSION (J2000.0)

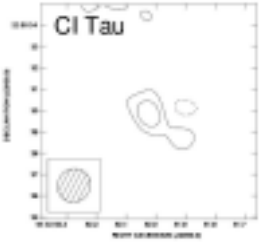

DG Tau

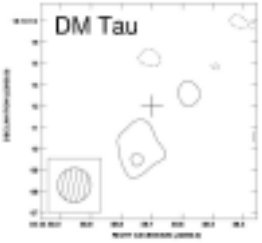

HL Tau

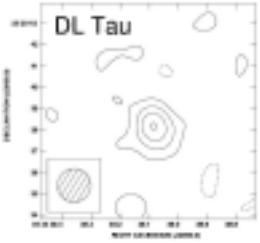

GG Tau

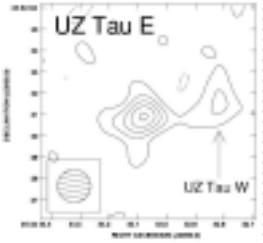

GM Aur


LkCa 15


CI Tau

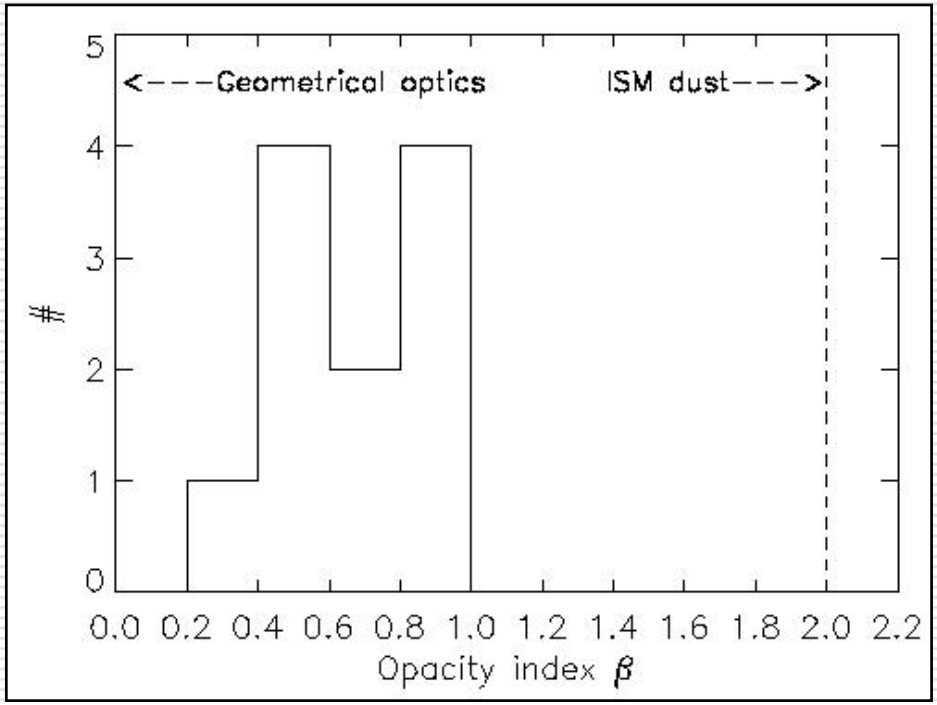

DM Tau

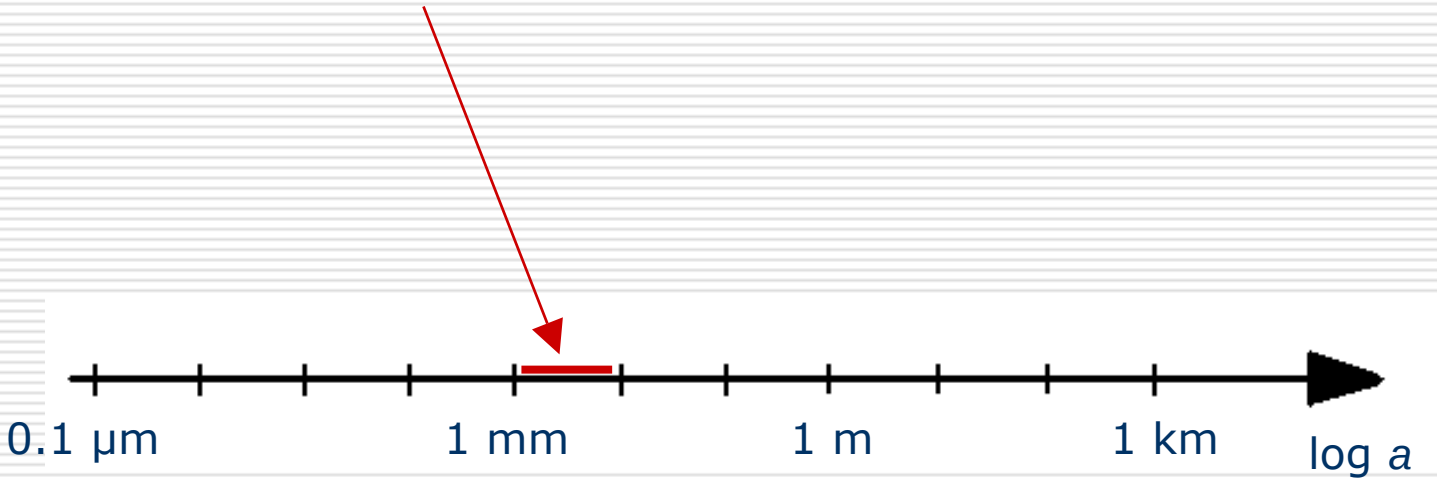

DL Tau


UZ Tau E
UZ Tau W

4. Dust opacity indices

- All detected disks spatially resolved (6 fully, 5 part.)
- Spectral indices $\alpha < 3$
- Opacity indices $\beta = \alpha - 2 < 1$
- Small corrections:
  Rayleigh-Jeans &
  free-free emission



5. Conclusions

- 11 disks around low-mass PMS stars in Taurus-Auriga resolved at 7 mm
- Spectral slopes indicate presence of mm-sized dust grains
- Fast particle growth within first 1 Myr
- ... almost half way on the road to planetesimals