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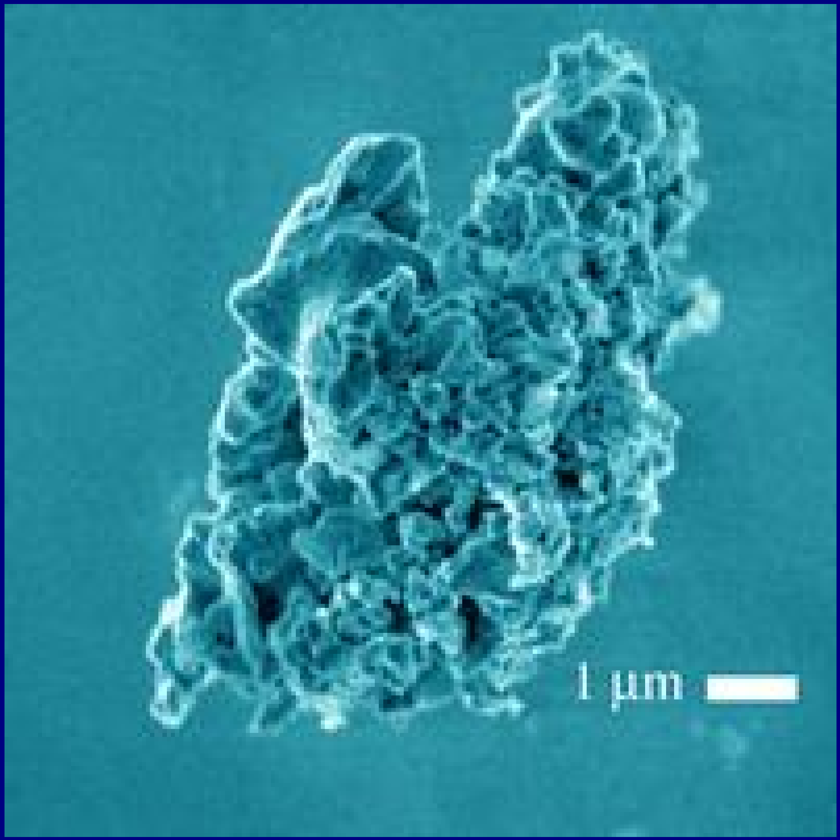
Grain Growth in Protoplanetary Disks

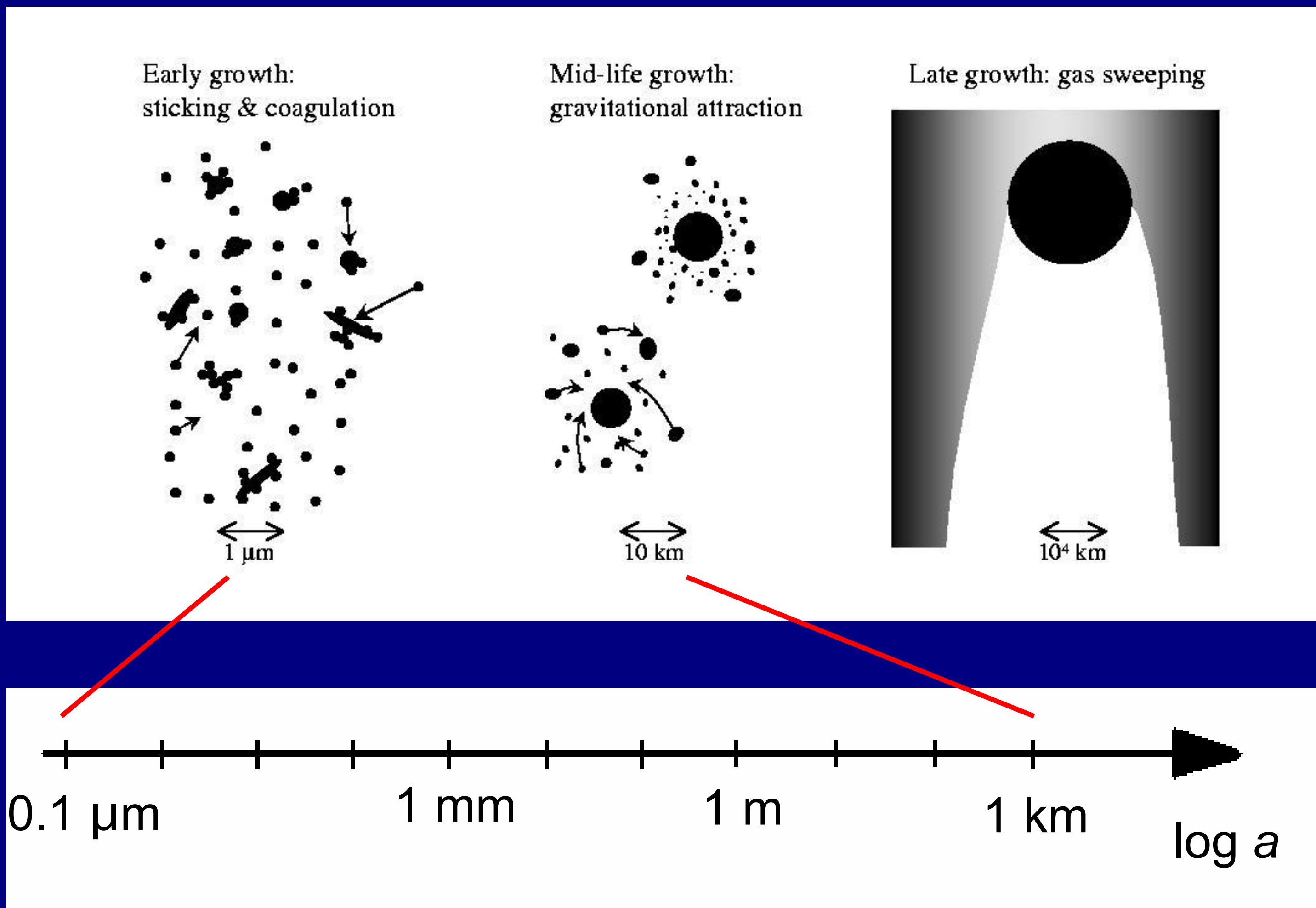
From Infrared to Millimetre Wavelengths



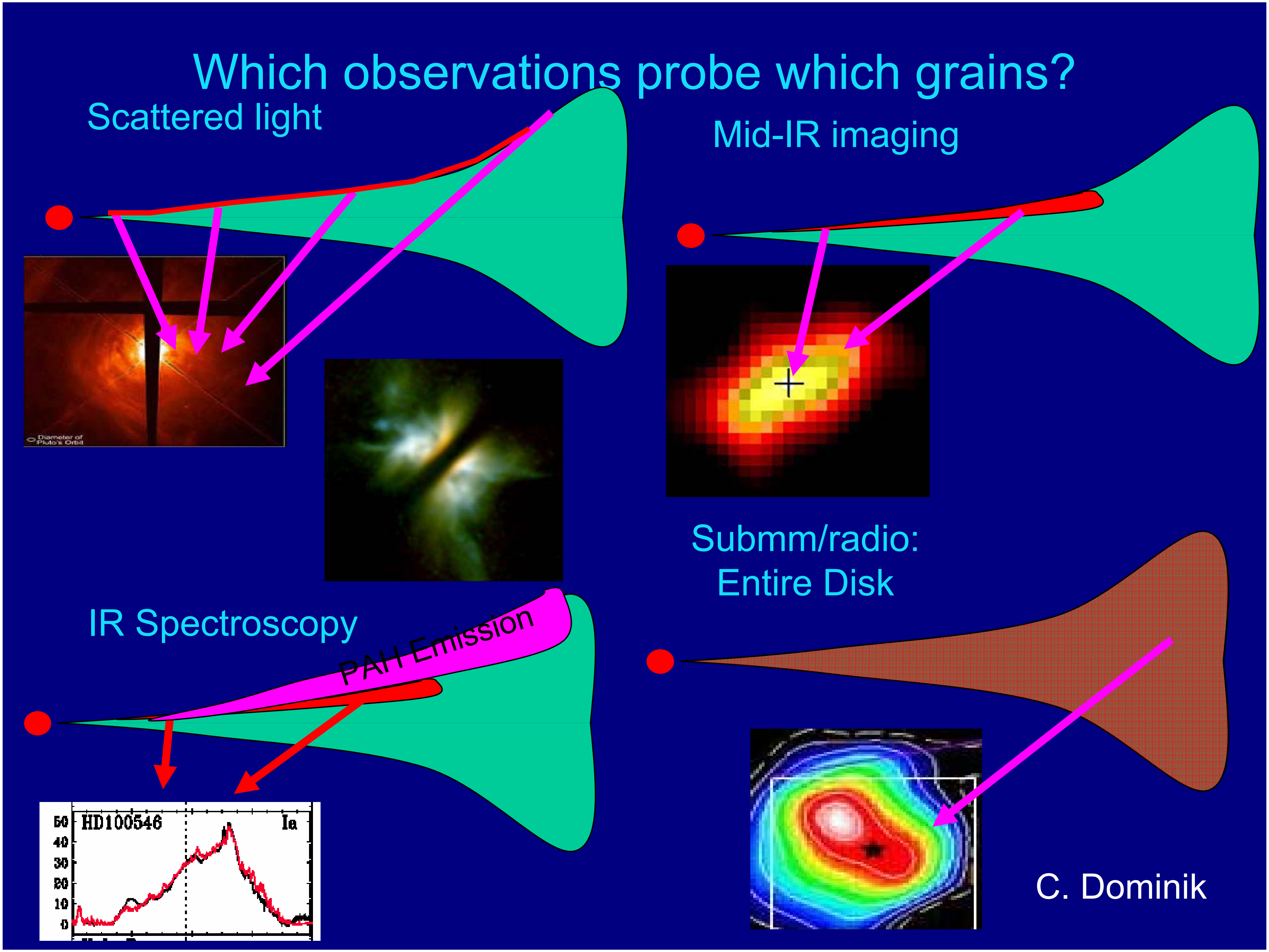
Motivation

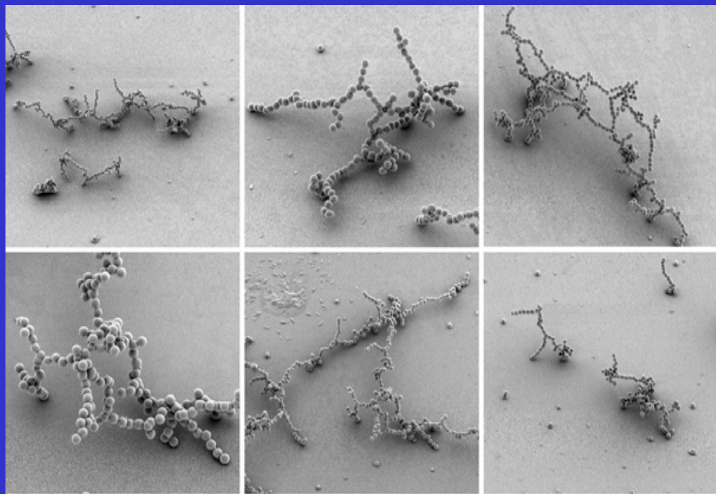
- From molecular cloud dust to planetesimals
- Continuum radiation as an analytical tool
  (Geometry vs. dust opacity)
- Dust affecting disk structure:
  - Dust opacities (Temperature, Convection)
  - Multi-phase fluid system (shear-ind. turbulence)
- Dust affecting disk chemistry and ionization

Road map of planet formation



Beckwith, Henning & Nakagawa (2000)


Which observations probe which grains?
Scattered light
Diameter of Pluto's Orbit
Mid-IR imaging
Submm/radio:
Entire Disk
IR Spectroscopy
PAH Emission
HD100546
Ia
50
40
30
20
10
0
C. Dominik



Grain Coagulation

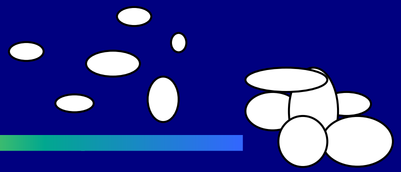
(see, e.g., Blum et al. 2000, Poppe, Blum and Henning 2000)

- **Micron- to centimetre-sized grains and agglomerates stick at the typical relative velocities occurring in protoplanetary disks; Particles reach sticking treshold (about 1 m/s) for particle sizes of about 0.1 m**

- **Grains couple with $\tau_f \propto m/\sigma_s \rho_g v_{th}$ to the gas**

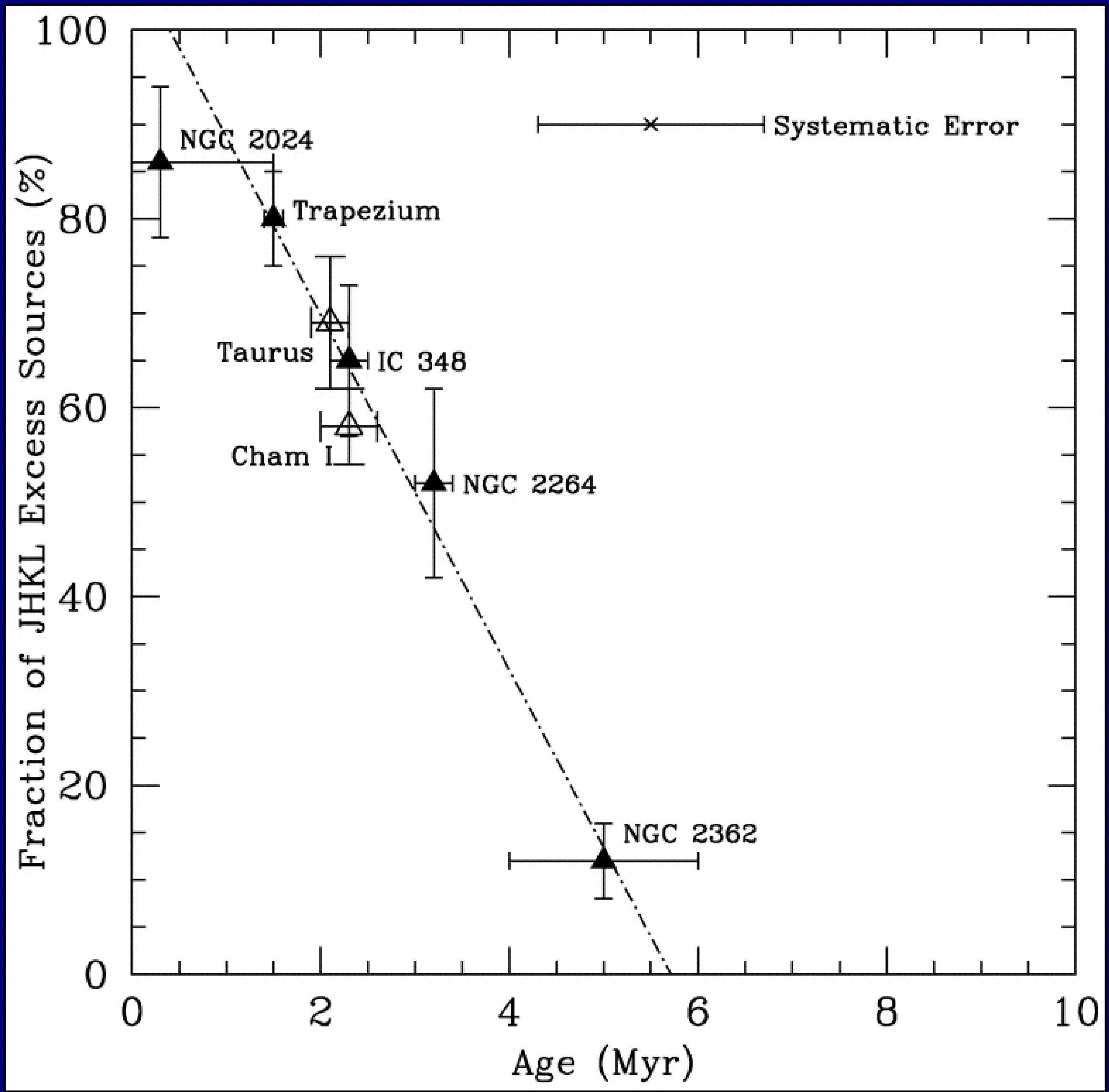
- **Agglomerates produced by Brownian motion (and most likely by other velocity fields) have open structure (fractal dimensions between 1.4 and 1.9); Mass spectra are quasi-monodisperse**

Evidence for grain growth



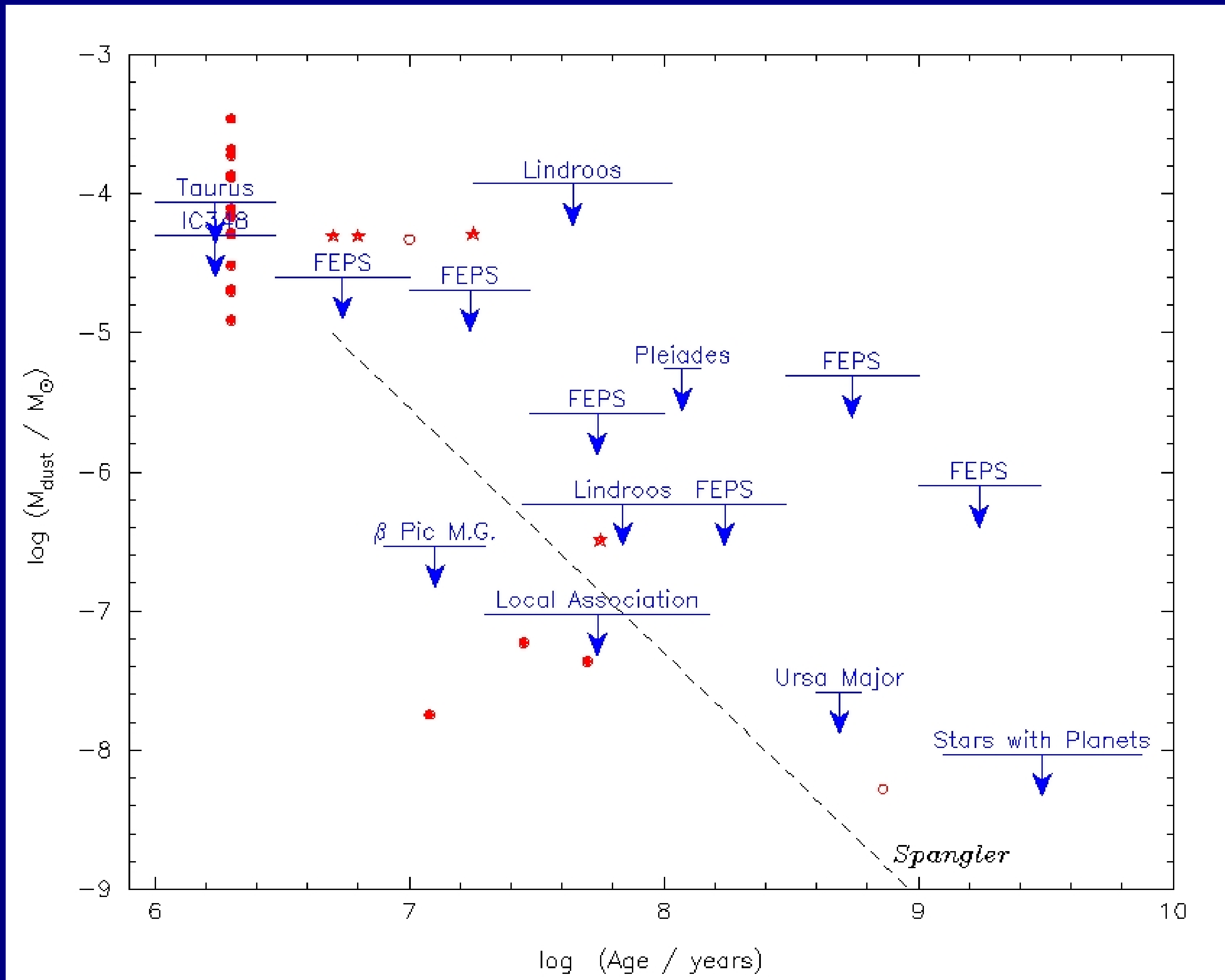
- Decrease in NIR and submm emission
  Haisch ea. 2001, Carpenter ea. 2005
- Flatter SEDs at millimetre wavelengths
  Mannings & Emerson 1994, Koerner ea. 1995, Dutrey ea. 1996
  Testi ea. 2003, Natta ea. 2004, Pietu ea. 2003, Rodmann ea. 2005
- Gray opacities in the disk region + RT modeling
  Menshchikov, Henning & Fischer 1999, Wolf ea. 2003
- Formation of (opacity) gaps
  Koerner et al. 1998
- Geometrically flattened disks
  D´Alessio et al. 2001, Dullemond & Dominik 2004
- Wavelength-independent disk size ?
  Throop et al. 2001; Shuping et al. 2003
- Infrared spectroscopy
  Bouwman ea. 2001, Meeus ea. 2001, van Boekel ea. 2003,
  Przygodda ea. 2003, van Boekel ea. 2004

Disk lifetimes (1)



Haisch et al. (2001)

Disk lifetimes (2)



Carpenter et al. (2005)

Time Scales For Grain Evolution

$t \leq 5 \times 10^6$ yr
(from infrared excess emission)

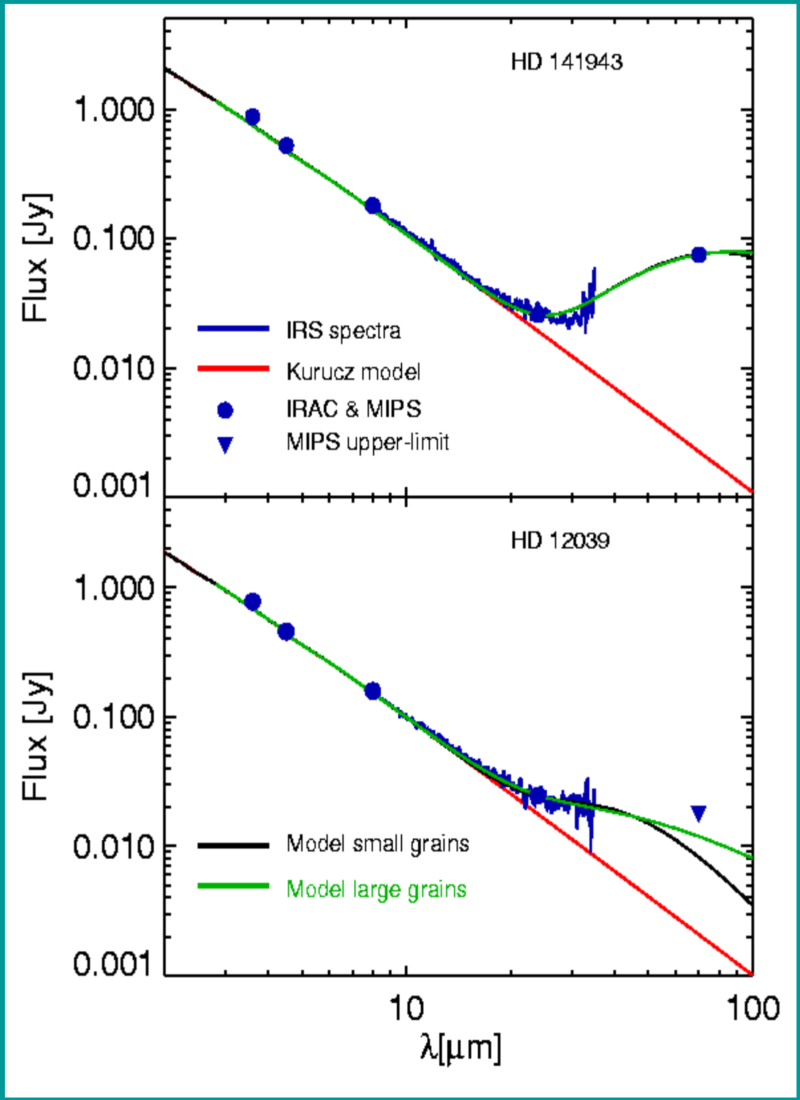
→

(1) Dust grains have been thoroughly removed from circumstellar disks.

(2) Grains have been evolved into larger bodies (reduced effective radiating surface).

(Replenishment of grains in disks around Vega-type stars ($t \rightarrow$ 100Myr) by collisional shattering of lager bodies)

FEPS: Grain Sizes in Debris Disks

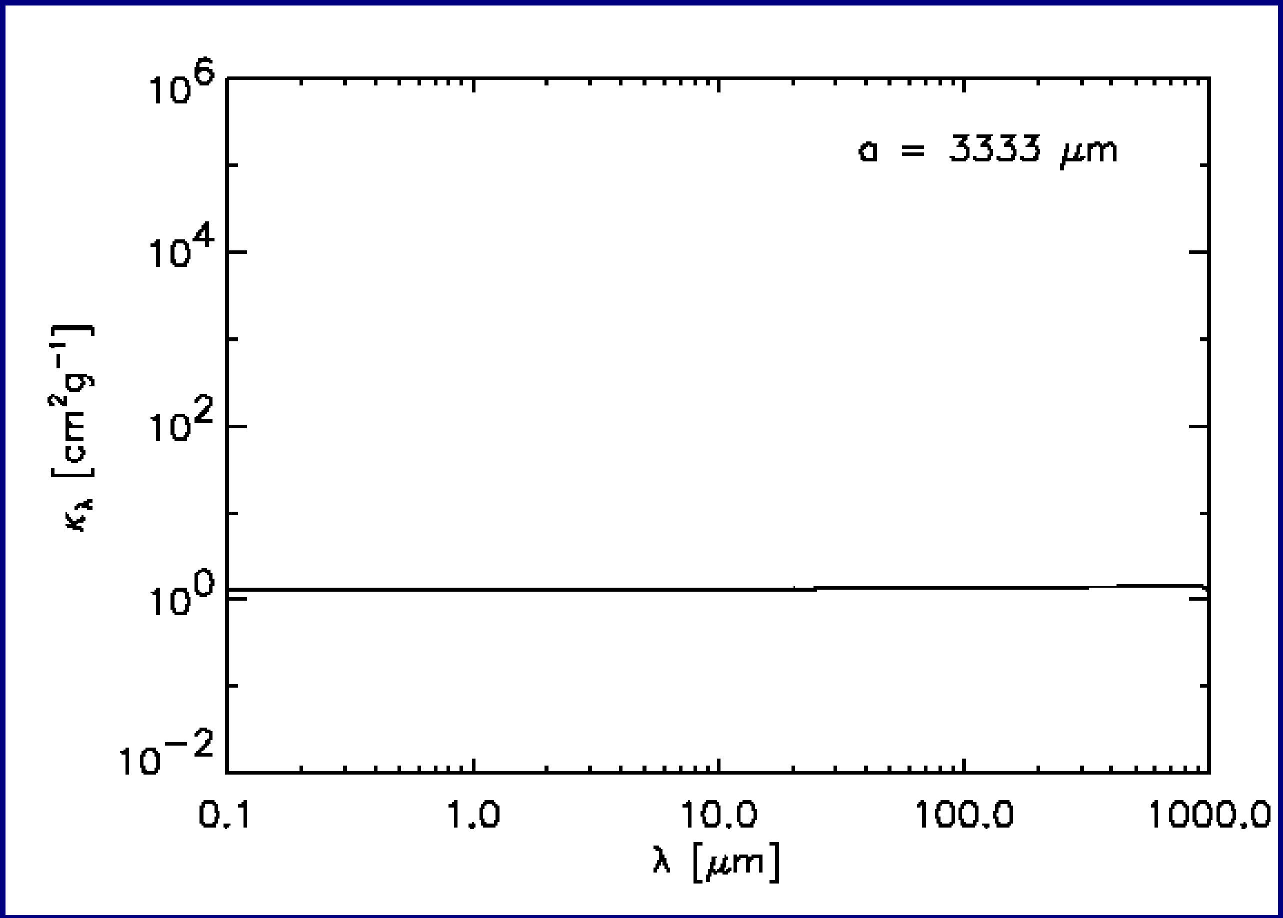


Rin	Rout	Mdust
System located @ 50 pc is unresolv.		
Large (>10μm) grains		
9 AU	42 AU	~8E-9 Msun
System age of 30Myr is much older than blow-out time scale		
Large (>10μm) grains		
4 AU	6 AU	~1E-10 Msun

(Hines et al. 2005 ; Bouwman et al. 2005)

Grain growth: change of opacity

(Absorption opacity)



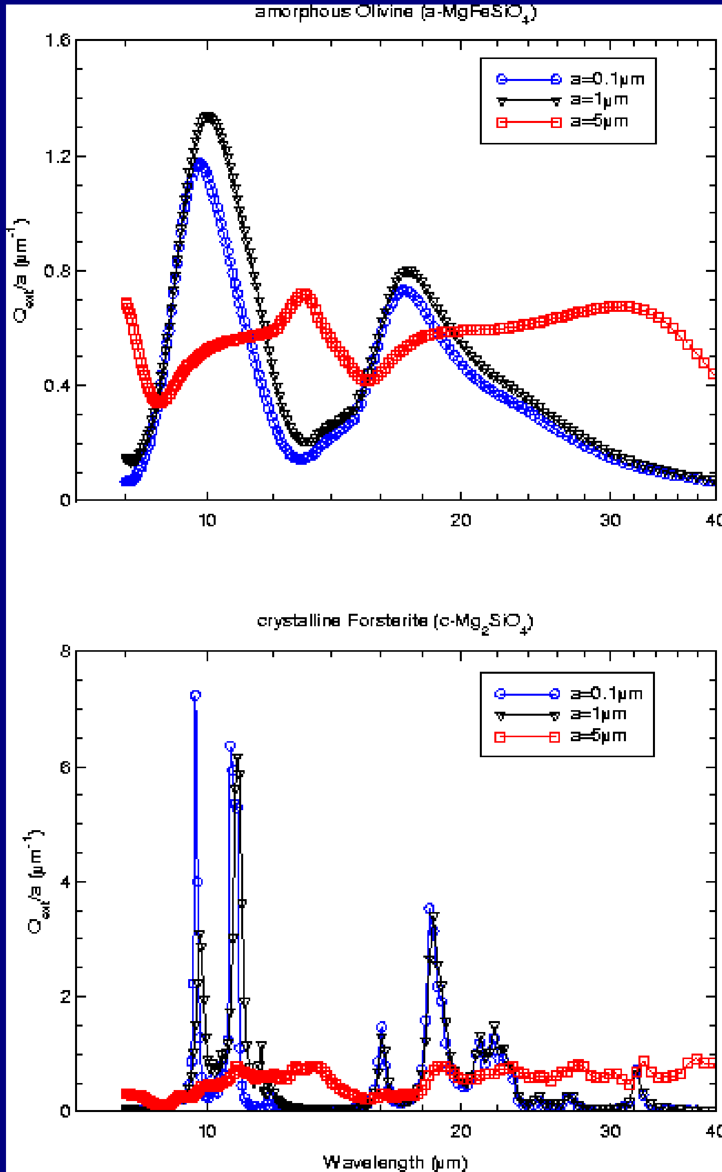
(Wavelength)

Zoom-in to mid-infrared

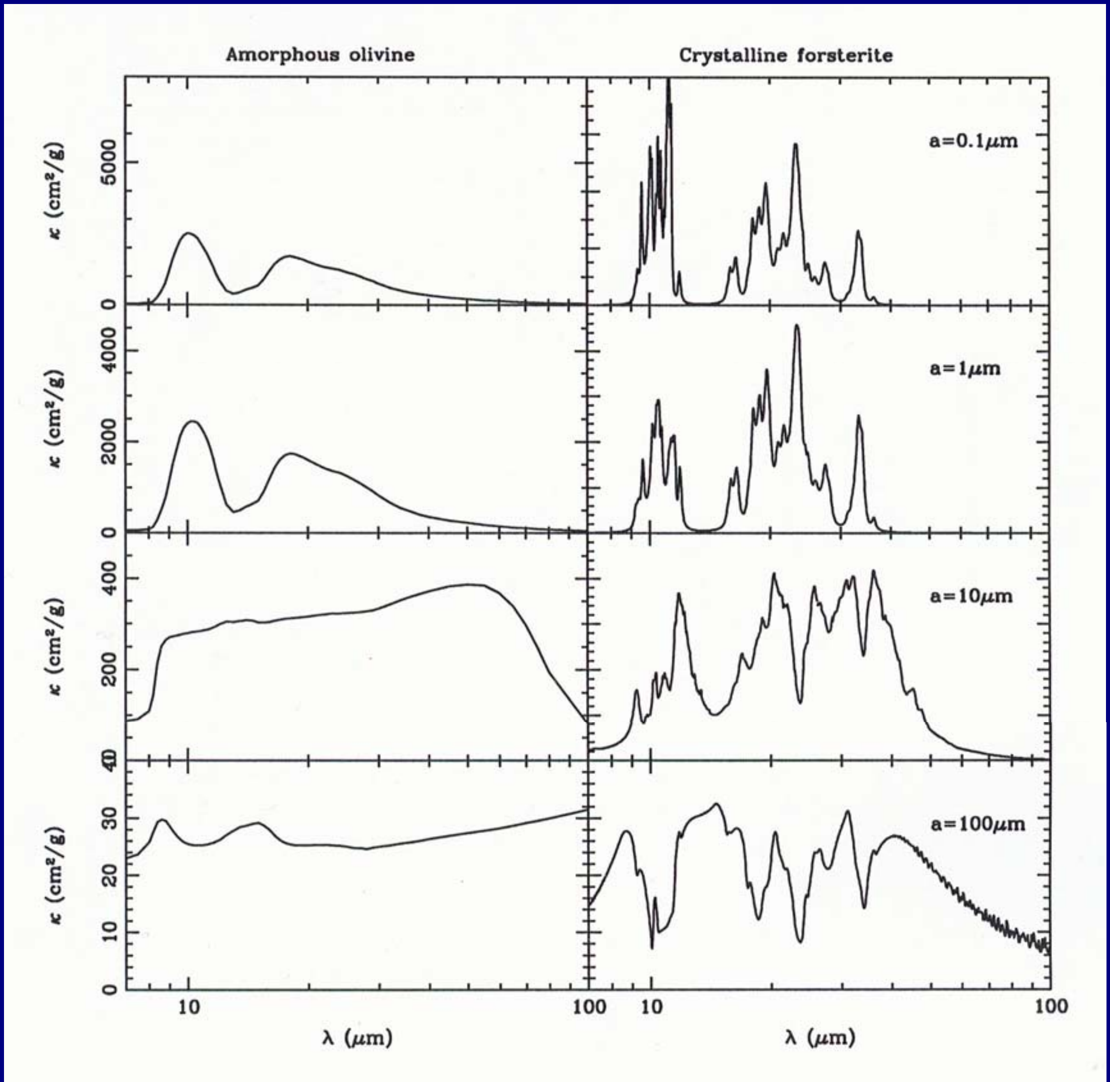
Dust Opacity: Effects of Size and Composition shown at R=100

(Henning et al. 2000)

Database for optical constants
Henning et al. (1999)

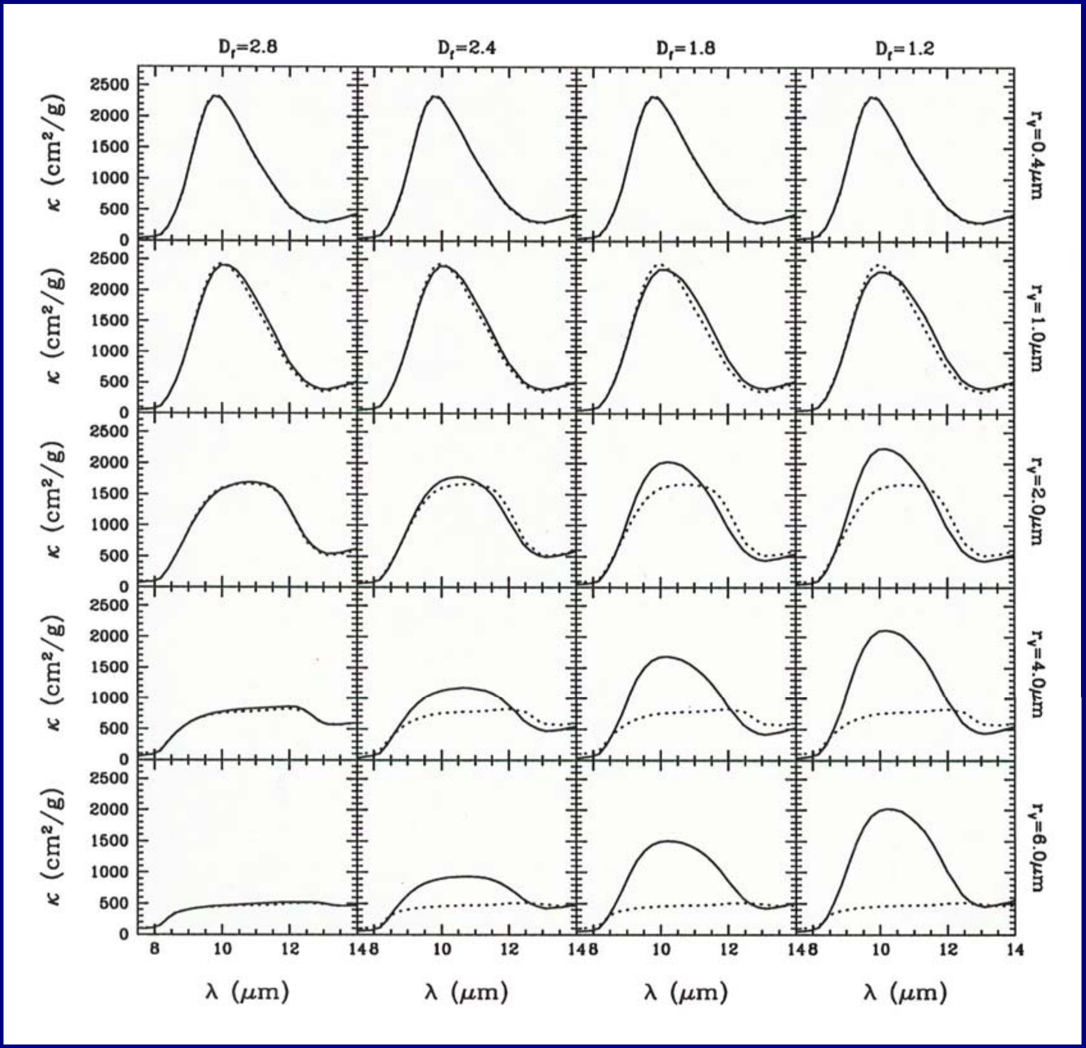


Grain Sizes – Crystalline vs. amorphous grains



Min et al. 2004

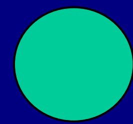
Silicate Emission Feature for Fractal Aggregates



Min et al. 2005, submitted; see also Henning & Stognienko 1993

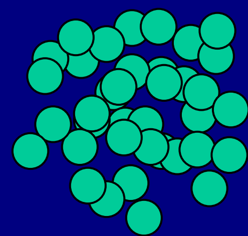
Aggregate Geometry

- compact



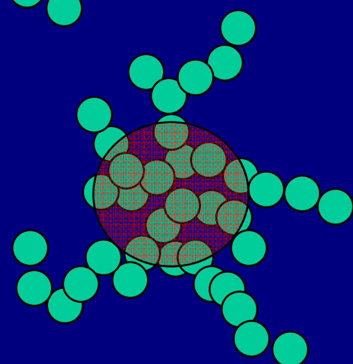
D =3

- porous
  - PCA



D =3

- fractal
  - CCA

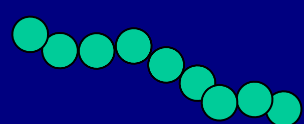


D ~ 2

$$M(s) \propto s^D$$

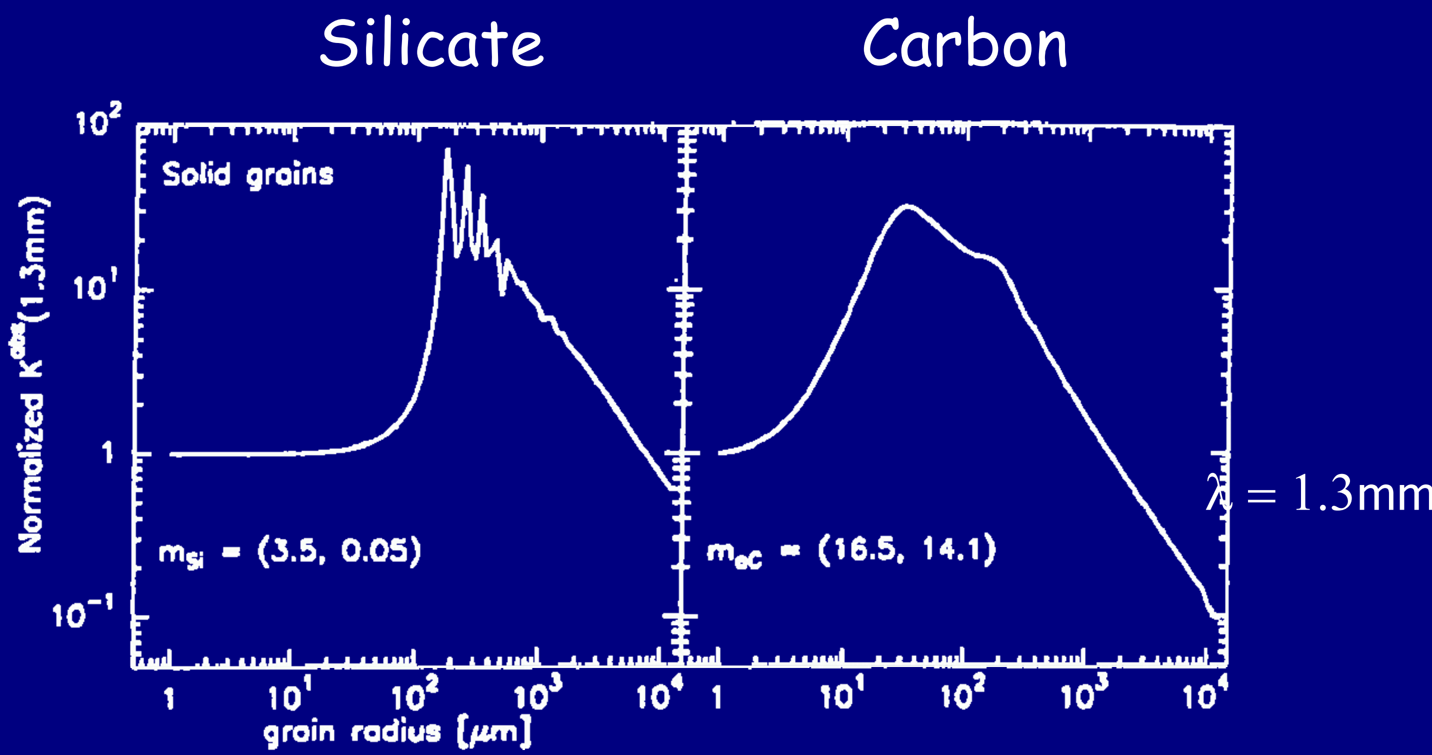
Fractal Dimension D

- quasi-linear



D ~ 1

Mm opacity as a function of size



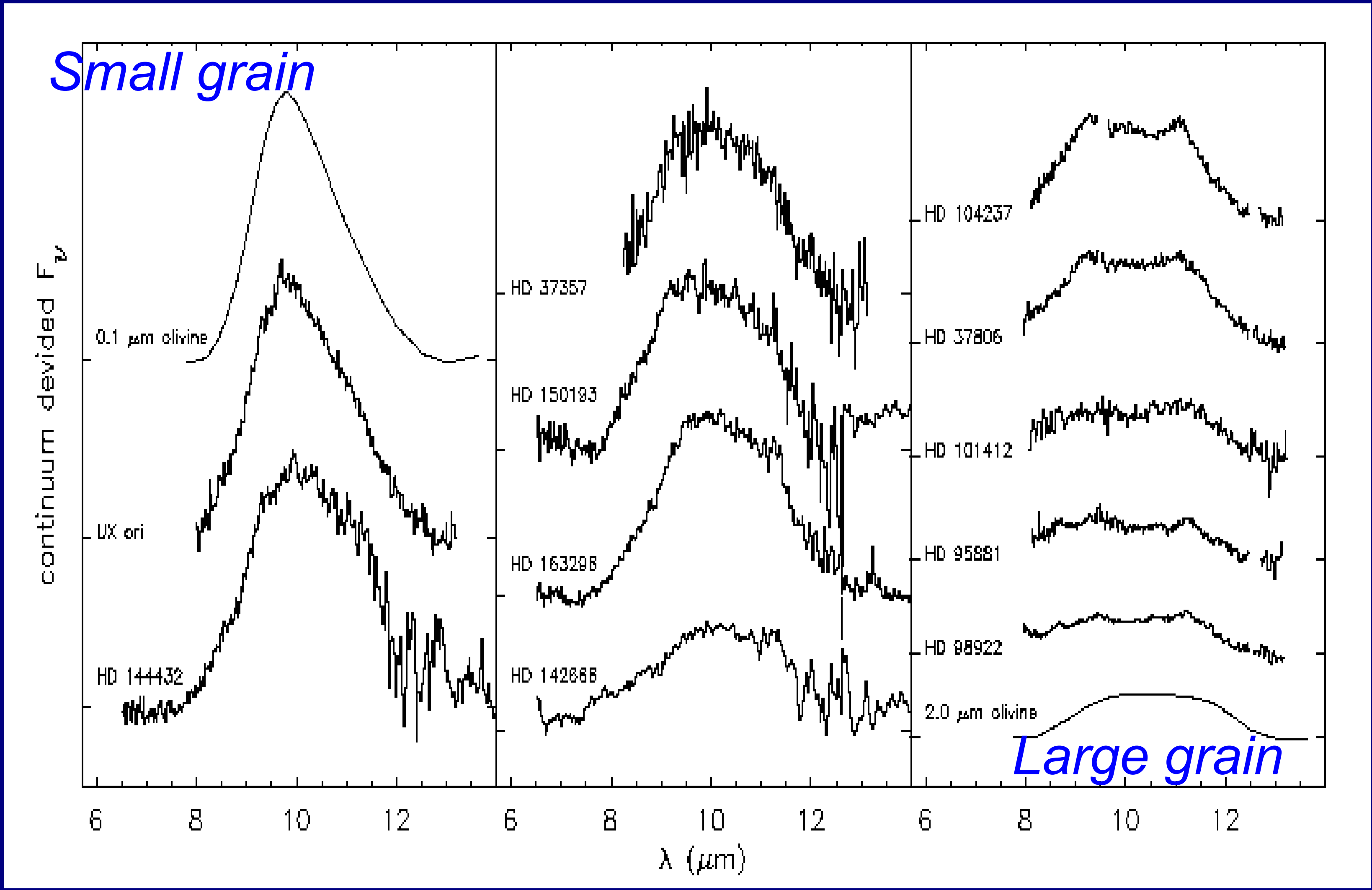
$$\frac{\pi a^2 Q(\nu,a)}{\frac{4\pi}{3} \rho_d a^3}$$

Very small grains: $\kappa(\nu,a)$ independent of a

Very large grains: $\kappa(\nu,a) \sim a^{-1}$

Krügel & Siebenmorgen (1994)

Evidence for grain growth



v. Boekel et al. 2003

Evidence for grain growth

Small grains

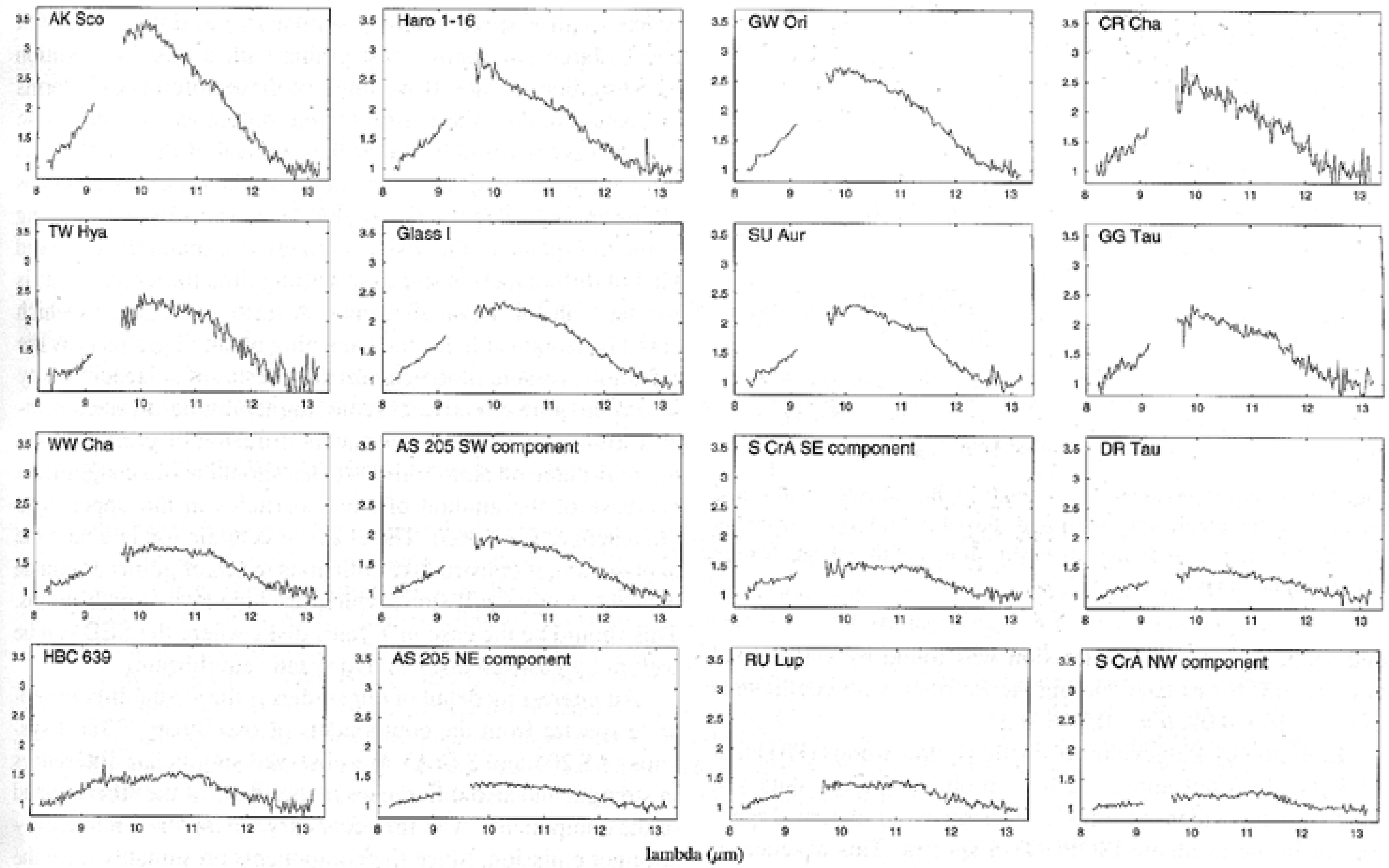
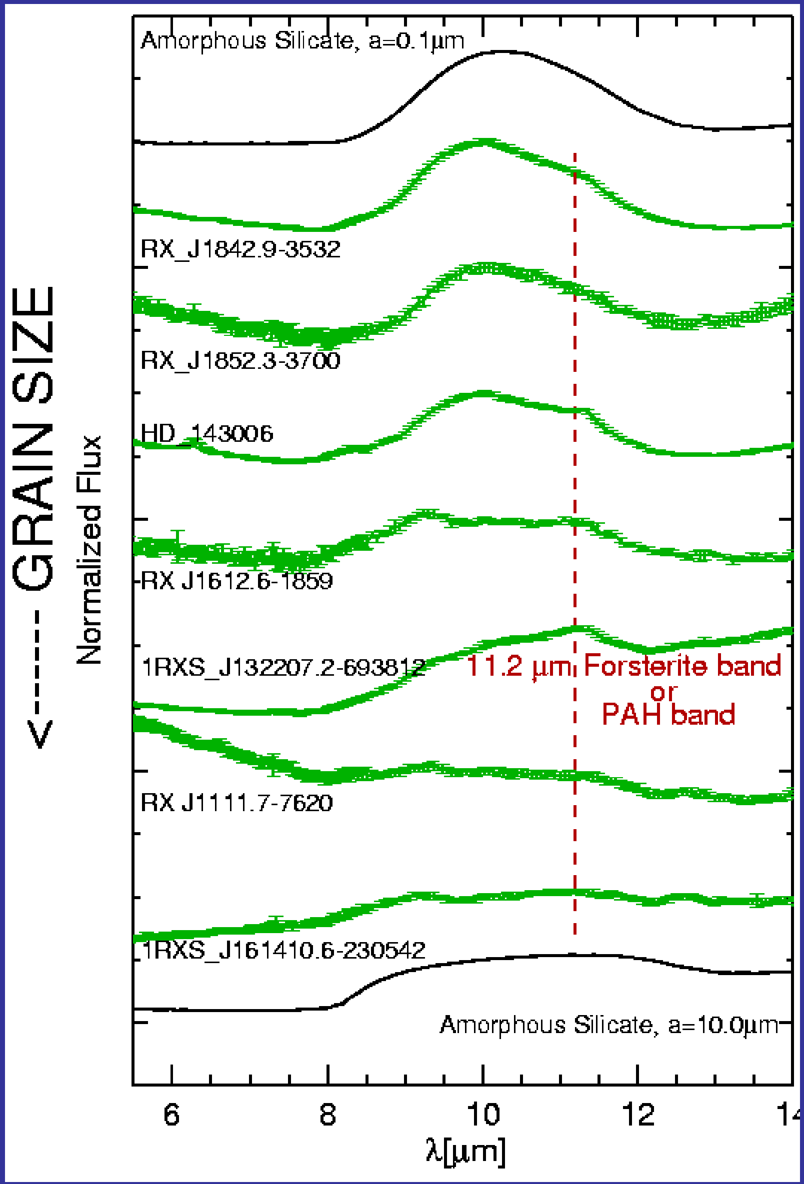


Fig. 2. Continuum normalized spectra of our sample ordered by the strength of the silicate feature. The shape of the feature is showing a correlation with the strength. Stronger features have a triangular shape with a pronounced peak near 9.8 μm while weaker features are more plateau-like. The gap from 9.15 to 9.65 μm in most of the spectra is caused by a broken channel of the TIMMI2 detector.

Large grains

Przygodda et al. 2003

FEPS: Grain Growth in TTS Disks



4 Myr

3-10 Myr

3-10 Myr

0.8 Myr

18 Myr

5 Myr

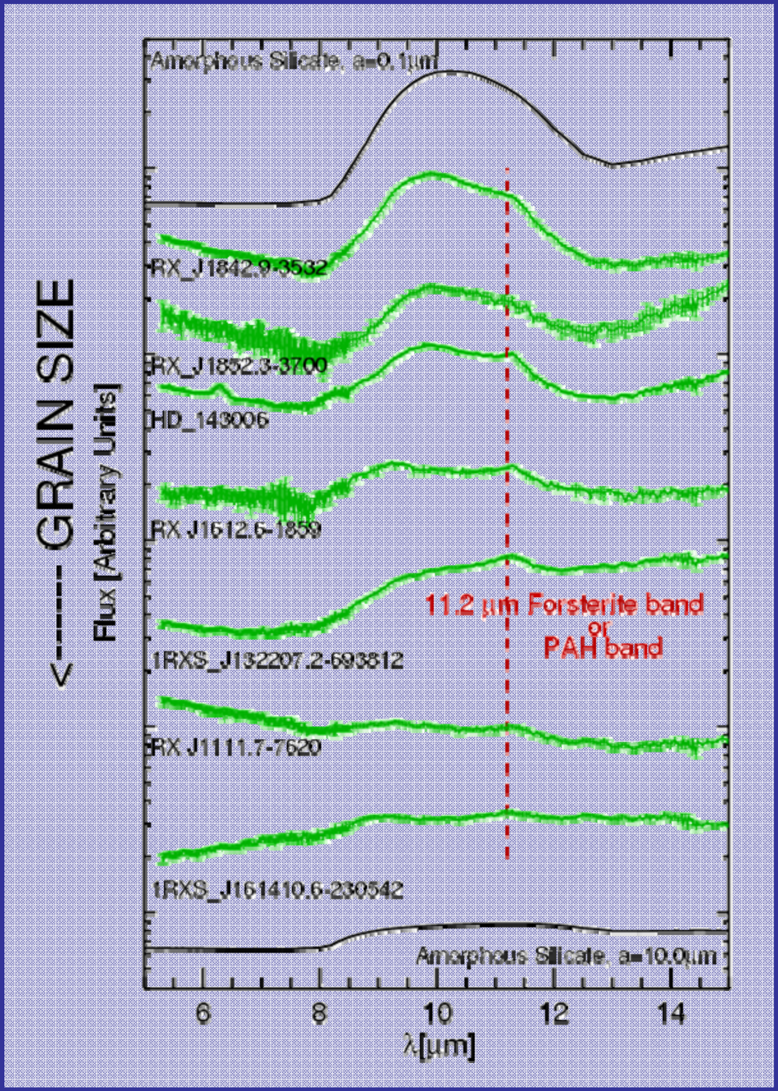
0.3 Myr

- Clear evidence for grain growth of amorphous silicate from ISM sized grains (0.1 **µ**m) to larger, 10**µ**m sized grains
- Presence of crystalline silicates and PAH molecules
- No correlation between stellar age and grain size (other dependencies, uncertain ages??)

(FEPS et al. in prep)

(see poster by Bouwman et al.)

The first FEPS results : From T Tauri to debris disks



- Sample of stars with ages of ~1 to 10Myr
- Clear evidence of grain growth from 0.1 to 10 µm
- Detection of crystalline silicates
- Confirmation of PAH emission around HD143006

(Bouwman et al. in prep)

How to observe grain size?

- Flux density from a disk viewed face-on

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

- Optically thin disk; Rayleigh-Jeans regime

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

$$\kappa_\nu \propto \nu^\beta$$

- Introduce mass opacity coefficient

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

Size-dependent opacity index

- Mass absorption coefficient is frequency-dependent

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

- For small (compact) grains with *a*<<λ (ISM dust)

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

$$\kappa_\nu = (2...4)(\lambda/1.3\mathrm{mm})^{-2} \times 10^{-3}\,\mathrm{cm}^2\mathrm{g}^{-1}$$

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

- Grey opacity if a>>λ/2π (a>>1 mm for λ=7 mm)

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

- mm-sized particles somewhere in between

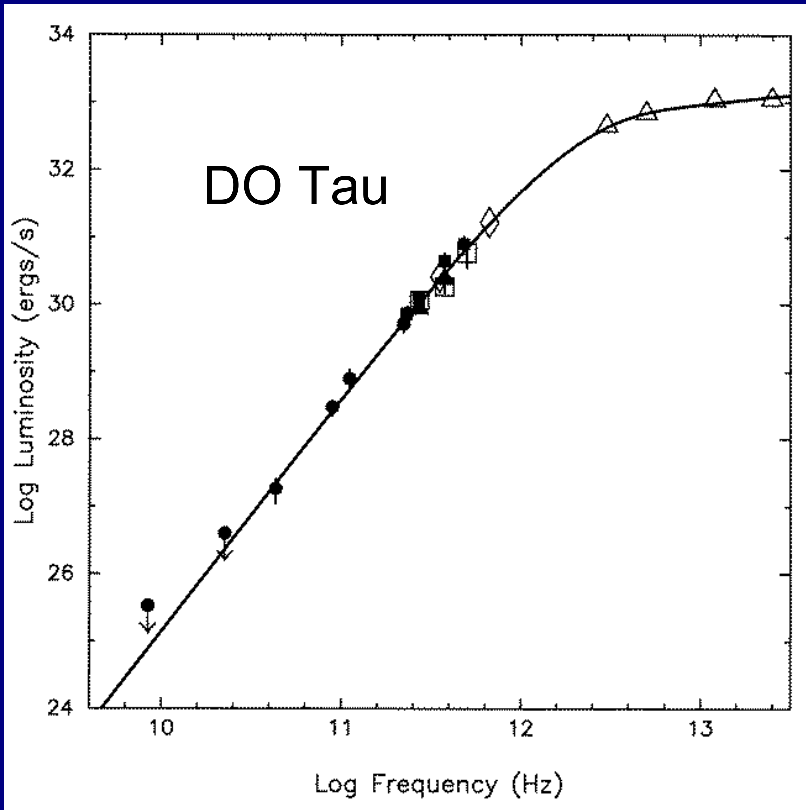
$$0 < \beta < 2 \Rightarrow F_\nu \propto \nu^{2...4}$$

Grain size from mm observations

- **T Tauri star DO Tau**
  Koerner et al. (1995): ß=0.6±0.3

- **Low-mass star TW Hya**
  Calvet et al. (2002) ß=0.7
  Wilner et al. (2005) centimeter obs.

- **Intermediate-mass stars:**
  Testi et al. (2003) CQ Tau: ß=0.5-0.7
  Natta et al. (2004): ß=0.4-1.5



Grain size from mm observations

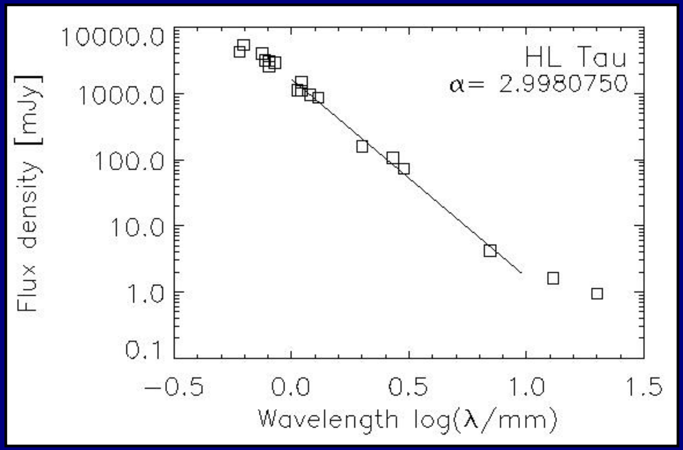
- Correct for radio free-free emission
- Measure spectral slope *α* in Rayleigh-Jeans part of SED
- **Two possibilities to account for shallow SED (small α):**

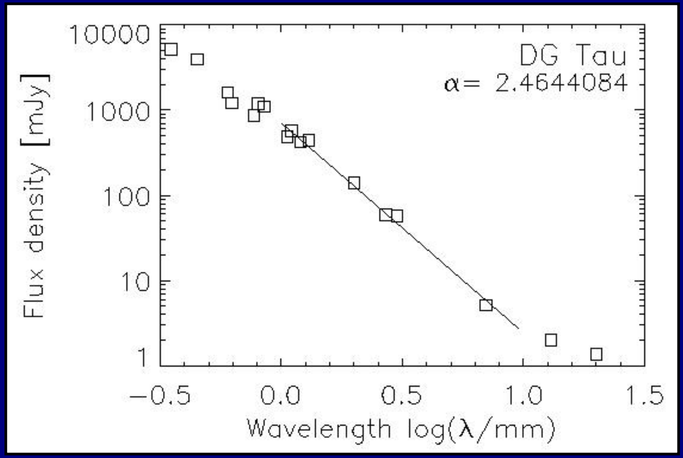
  (i) optically thick disk & any β

  (ii) optically thin disk & low β

  Resolved (large) disks render (i) improbable/unphysical

➔ Opacity index *β* ≈ *α*–2





VLA 7-mm observations

(Rodmann, Henning, Chandler et al. 2005)

- 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)
- 10 secure detections ($\sigma \geq 5$)
- Additional observations at 1.3, 2.0, and 3.6 cm

Grain size from mm observations

- Correct for radio free-free emission
- Measure spectral slope α in Rayleigh-Jeans part of SED

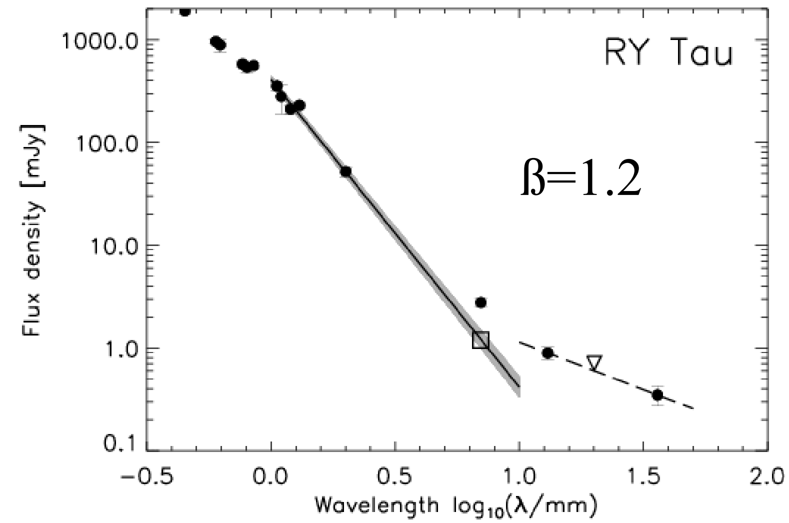
- **Two possibilities to account for shallow SED (small α):**

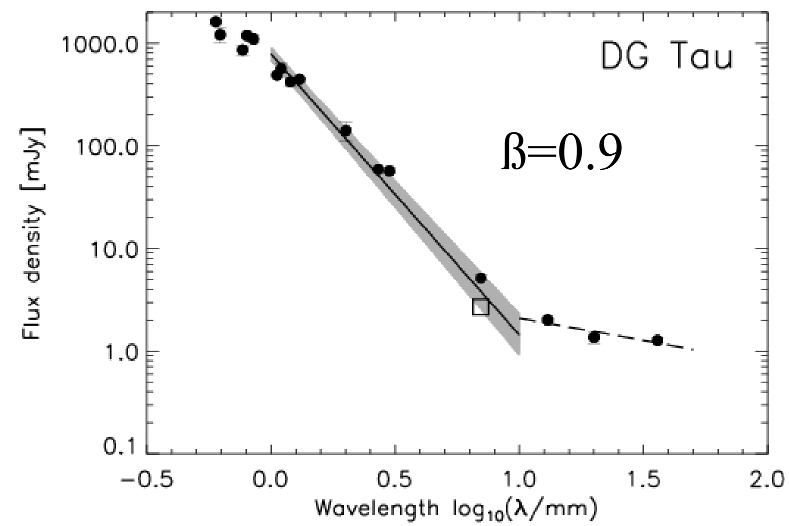
  (i) Optically thick disk & any β

  (ii) Optically thin disk & low β

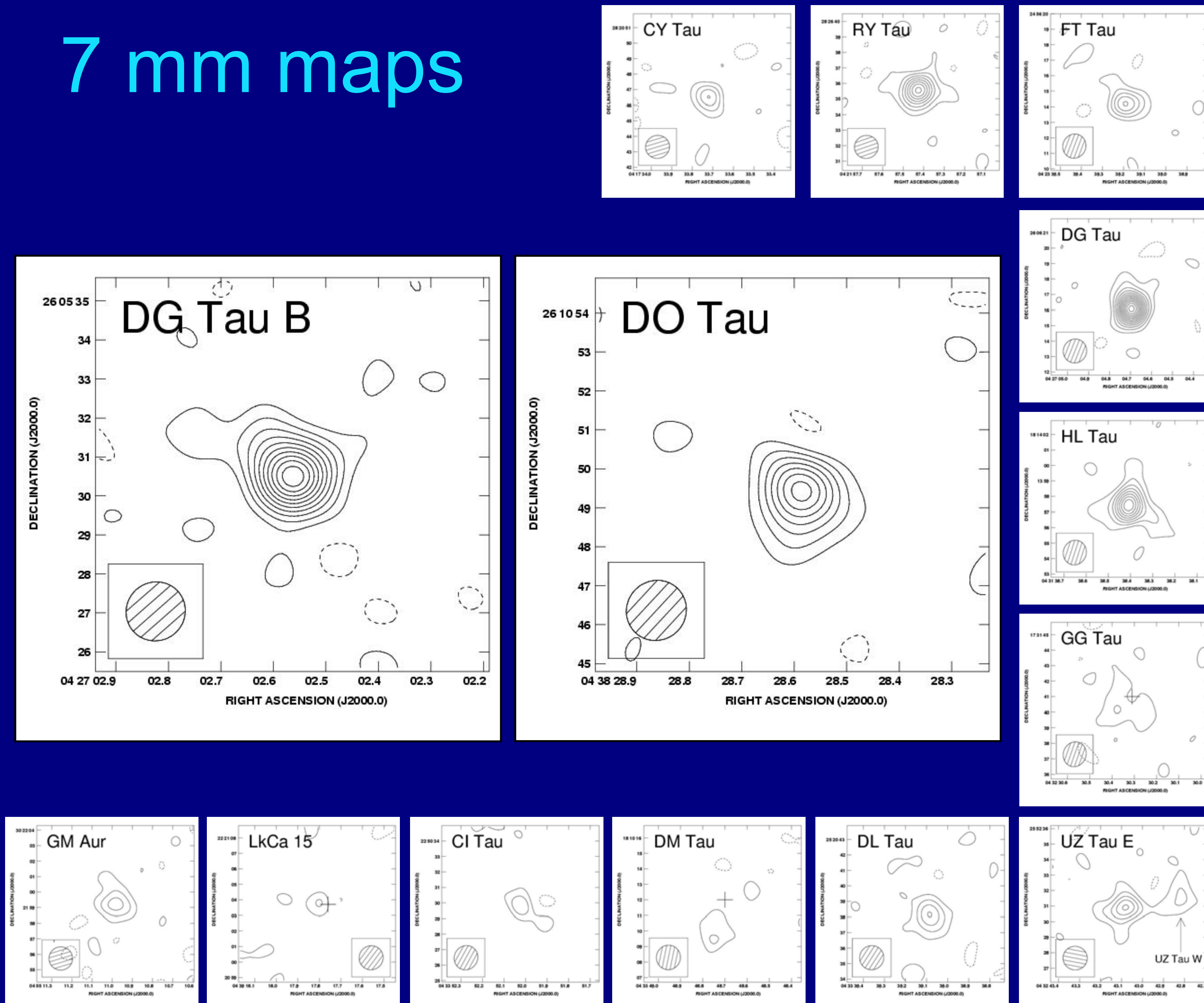
  Resolved (large) disks render (i) improbable/unphysical

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





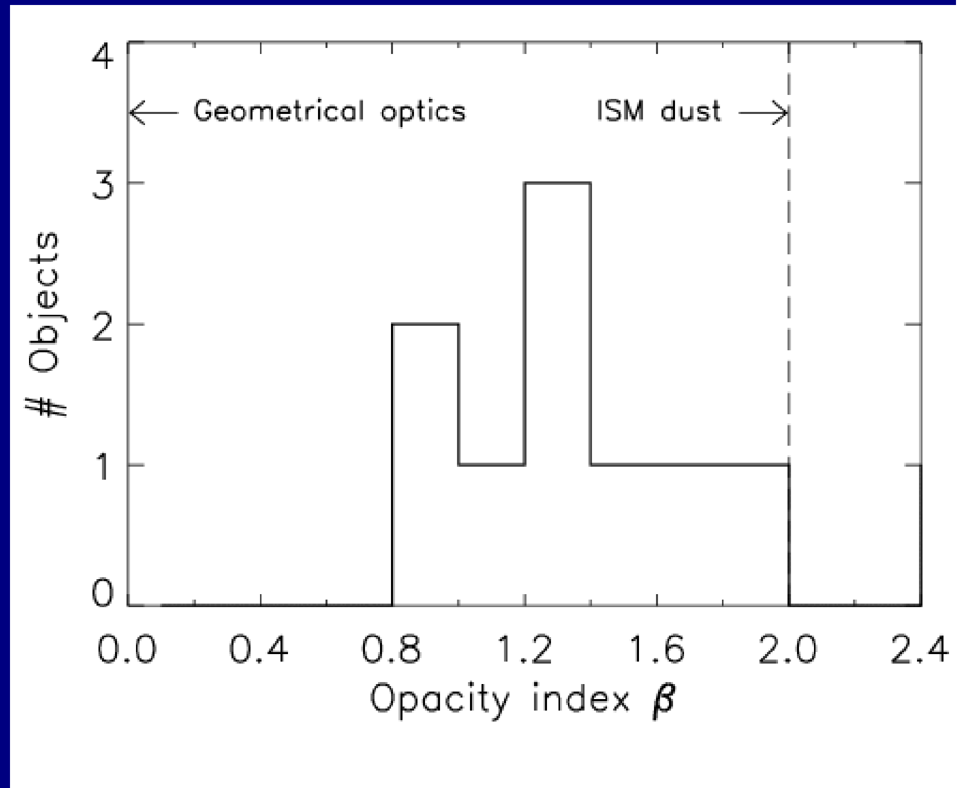
7 mm maps


CY Tau
RY Tau
FT Tau
DG Tau
DG Tau B
DO Tau
HL Tau
GG Tau
GM Aur
LkCa 15
CI Tau
DM Tau
DL Tau
UZ Tau E
UZ Tau W
DECLINATION (J2000.0)
RIGHT ASCENSION (J2000.0)
26 05 35
04 27 02.9
26 10 54
04 38 28.9

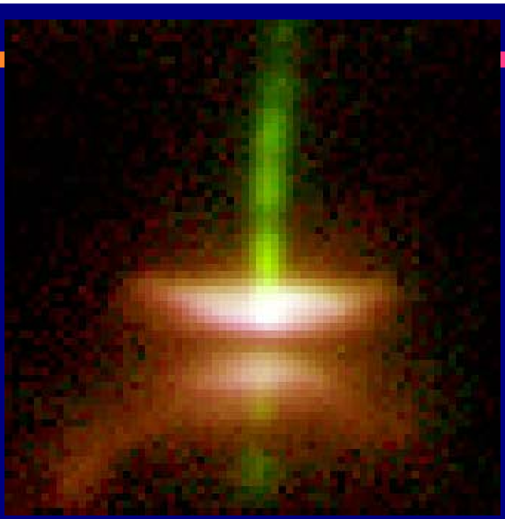
Dust opacity indices

- All detected disks spatially resolved (7 fully, 3 part.)
- Spectral indices $\alpha < 4$
- Opacity indices $\beta = \alpha - 2 < 2$
- Small corrections: Rayleigh-Jeans & free-free emission

Rodmann et al. 2005



Dust models for Accretion Disks



Pollack et al: 1994, ApJ 421, 615

- Olivine ([Fe, Mg]$_2$ SiO$_4$), orthopyroxene ([Fe, Mg] SiO$_3$), volatile and refractory organics, water ice, troilite (FeS), and metallic iron
- κ (1 mm) = 5 x 10^{-3} cm^{2}g^{-1} (gas + dust)

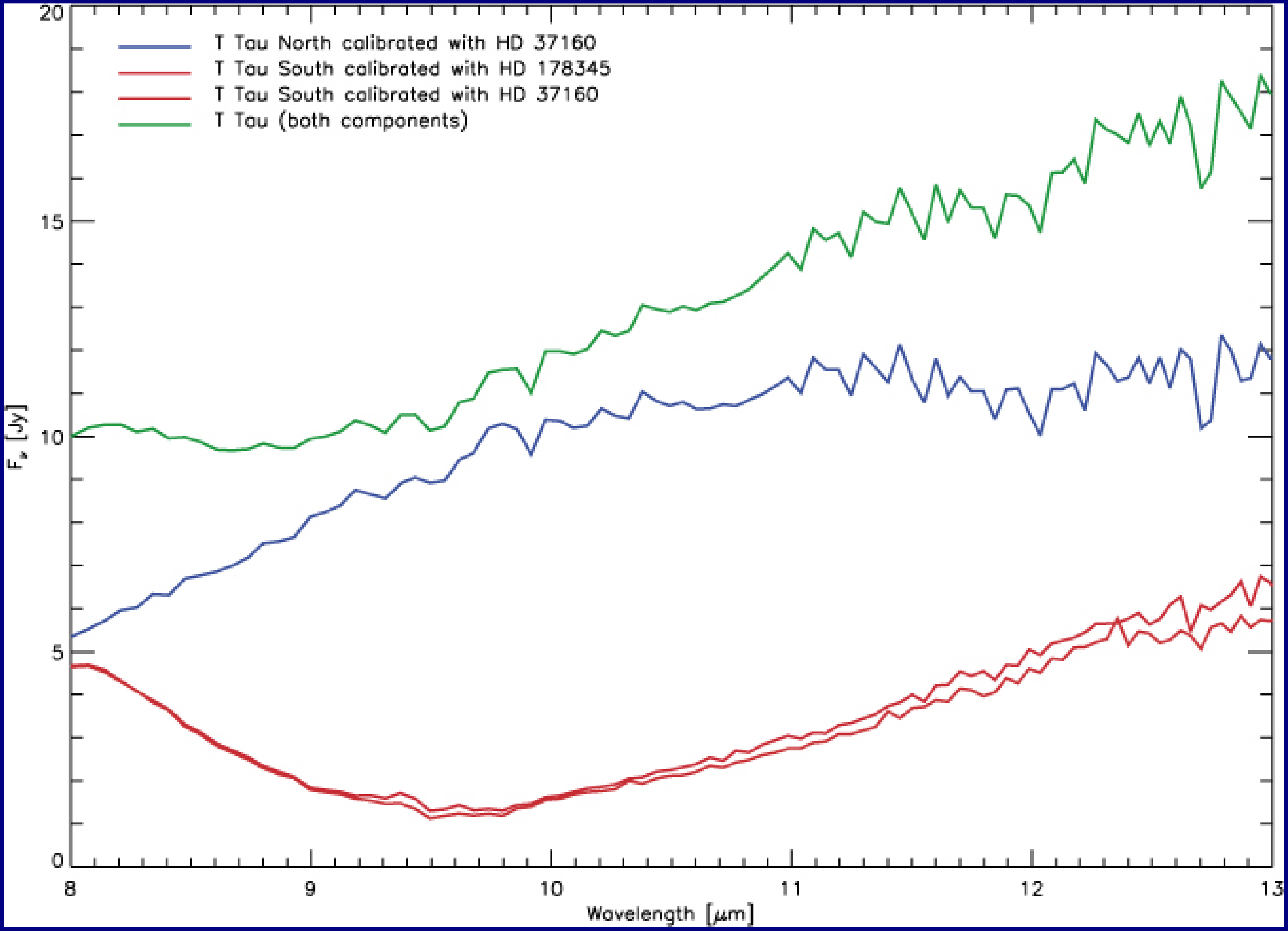
Krügel & Siebenmorgen: 1994, AA 288, 929

- Fluffy grains composed of subparticles of astronomical silicate and amorphous carbon with an admixture of frozen ice
- κ (1.3 mm) = 2 x 10^{-2} cm^{2}g^{-1} (gas + dust)

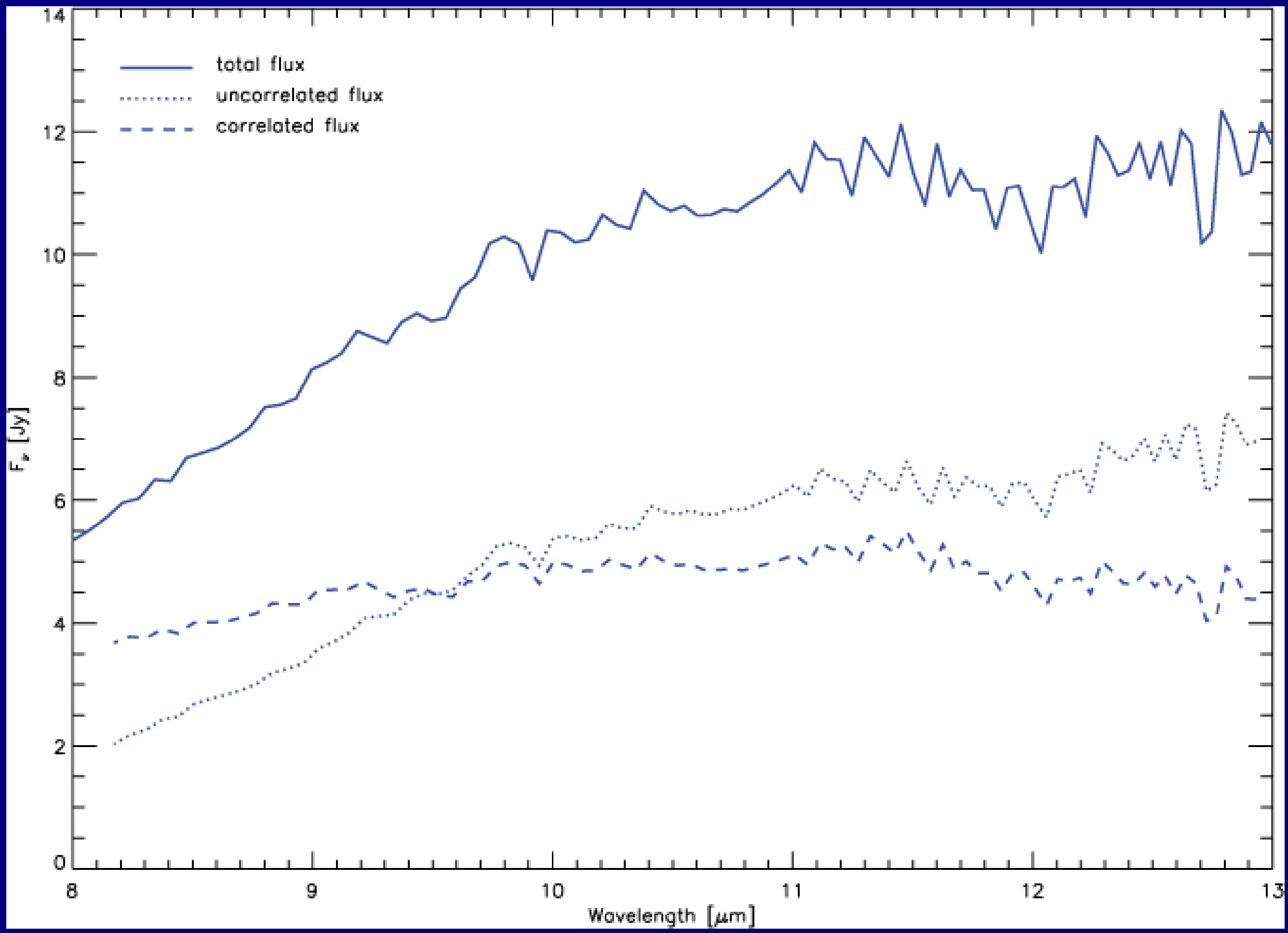
Henning & Stognienko: 1996, AA 311, 291 (Semenov et al. 2003)

- Improved optical data and agglomeration models, Role of Fe
- κ (1.3 mm) = 10^{-2} cm^{2}g^{-1} (gas + dust, Fe-rich silicates)

T Tauri North and South



T Tauri North

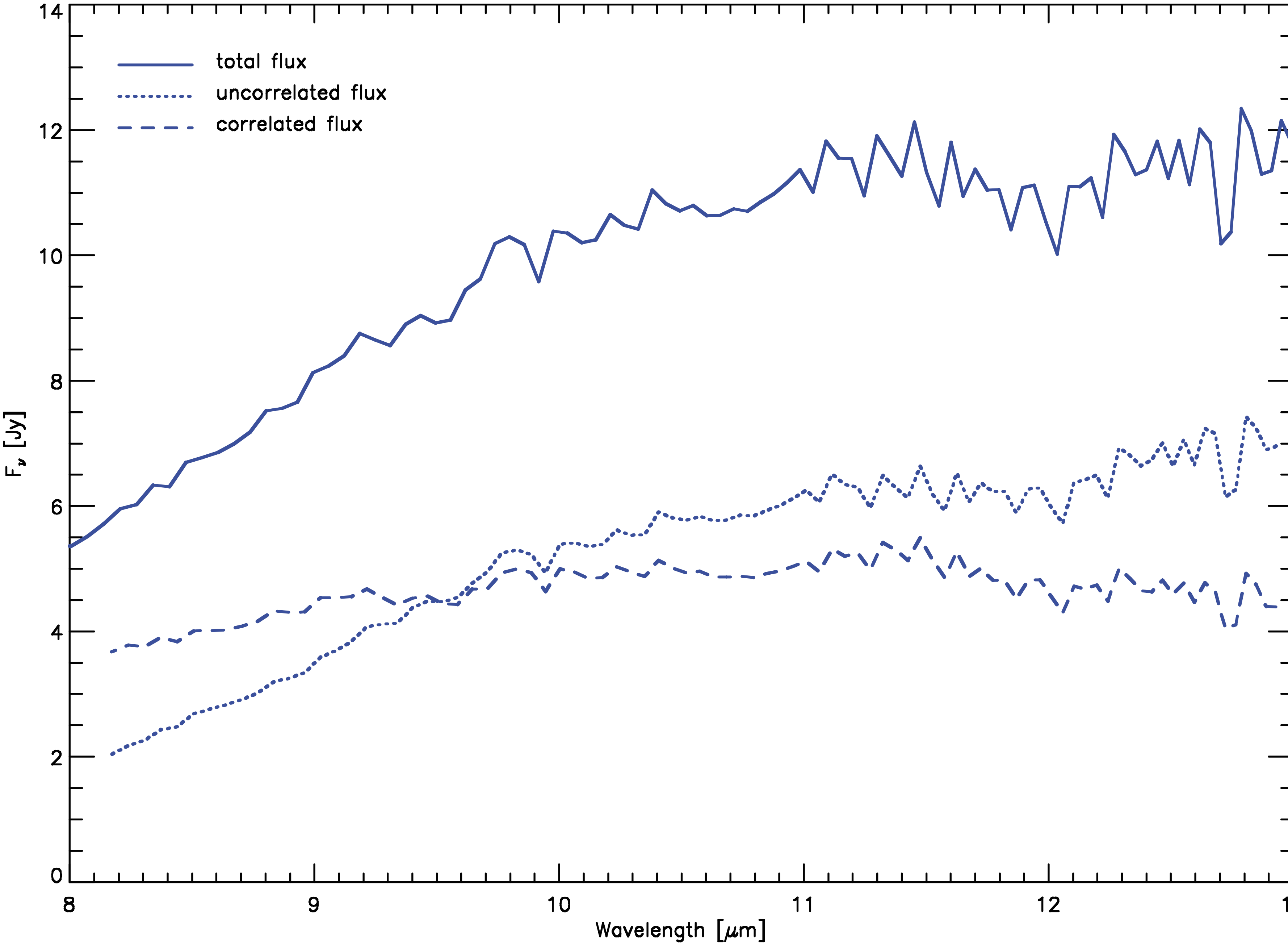


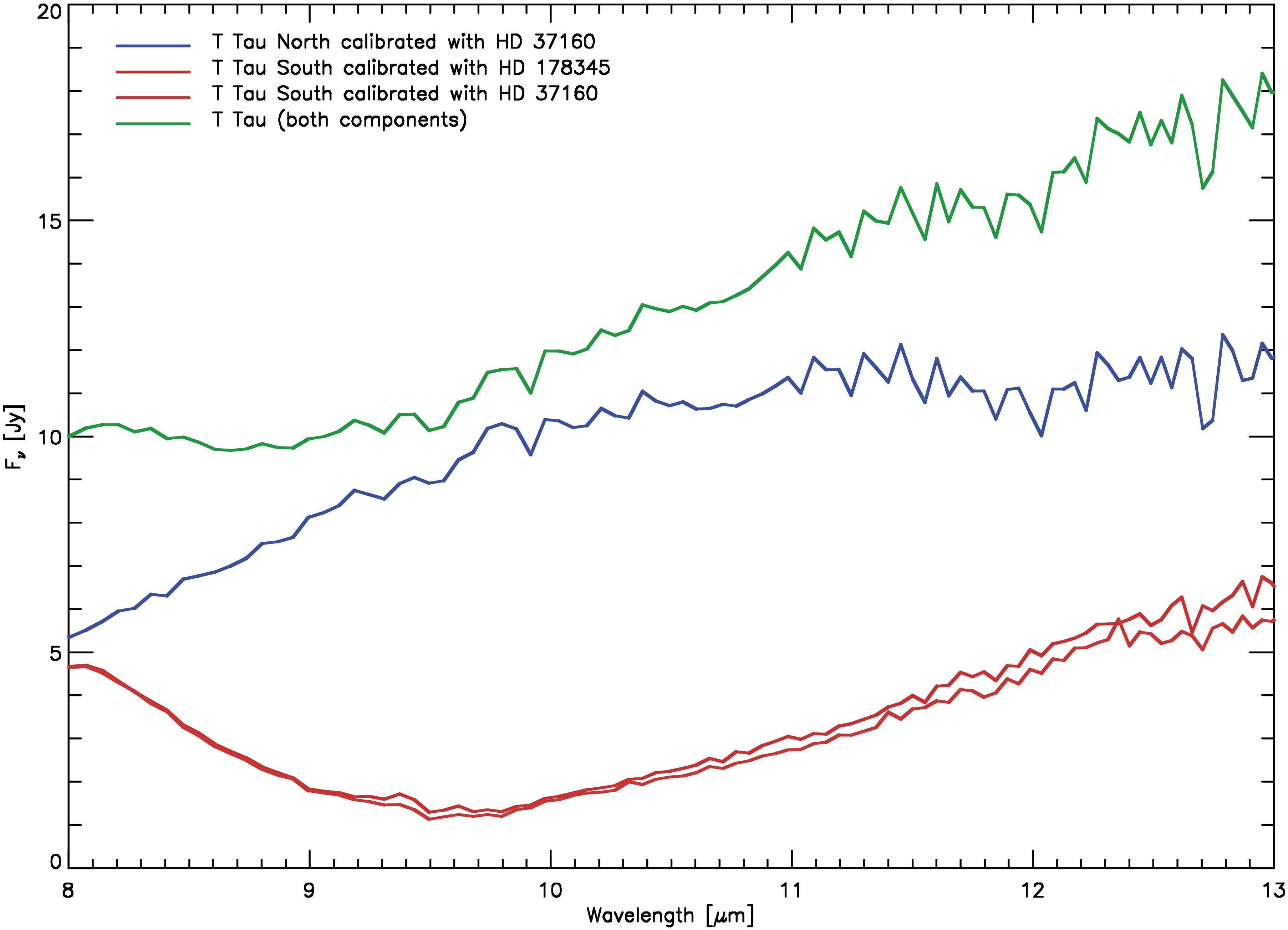
MIDI GTO Science Team

Summary

- Grains in protoplanetary disks grow
- Evidence for micron-sized and millimetre- to centimeter-sized grains
- Spatially resolved data are becoming available

Review: Henning, Dullemond, Dominik, Wolf (2005)


total flux
uncorrelated flux
correlated flux
F_ν [Jy]
Wavelength [μm]
0
2
4
6
8
10
12
14
8
9
10
11
12
13



T Tau North calibrated with HD 37160
T Tau South calibrated with HD 178345
T Tau South calibrated with HD 37160
T Tau (both components)
20
15
10
5
0
F_ν [Jy]
8
9
10
11
12
13
Wavelength [μm]