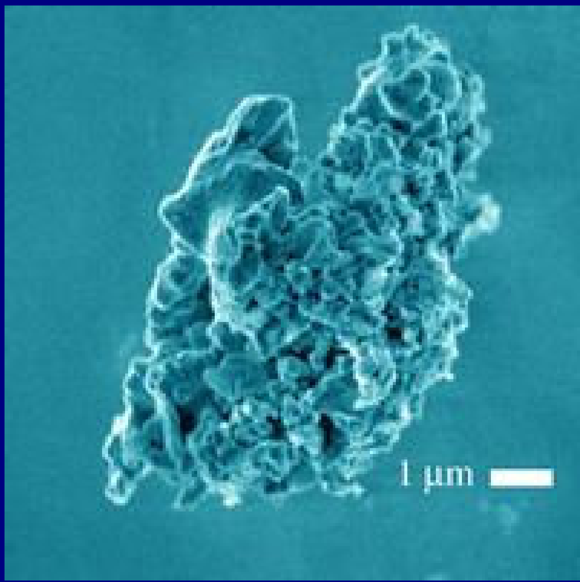
Thomas Henning
Max Planck Institute for Astronomy (MPIA), Heidelberg

Grain Growth in Protoplanetary Disks

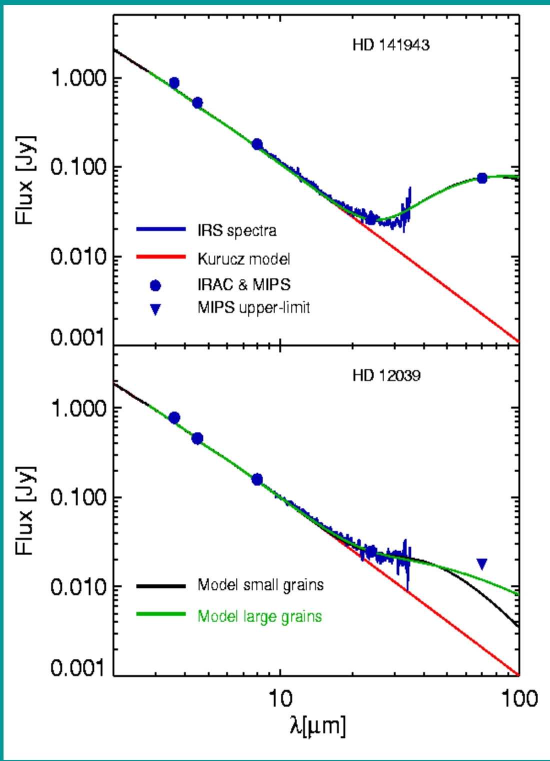


Disks 2006, September 2006, Vidago Palace, Portugal

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

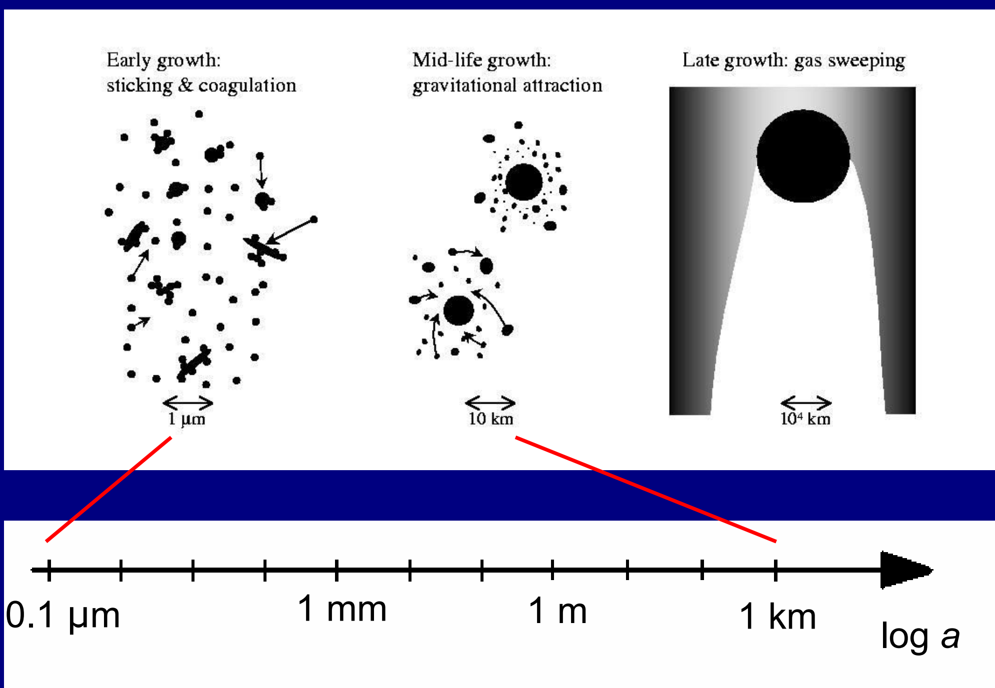
FEPS: Grain Sizes in Debris Disks



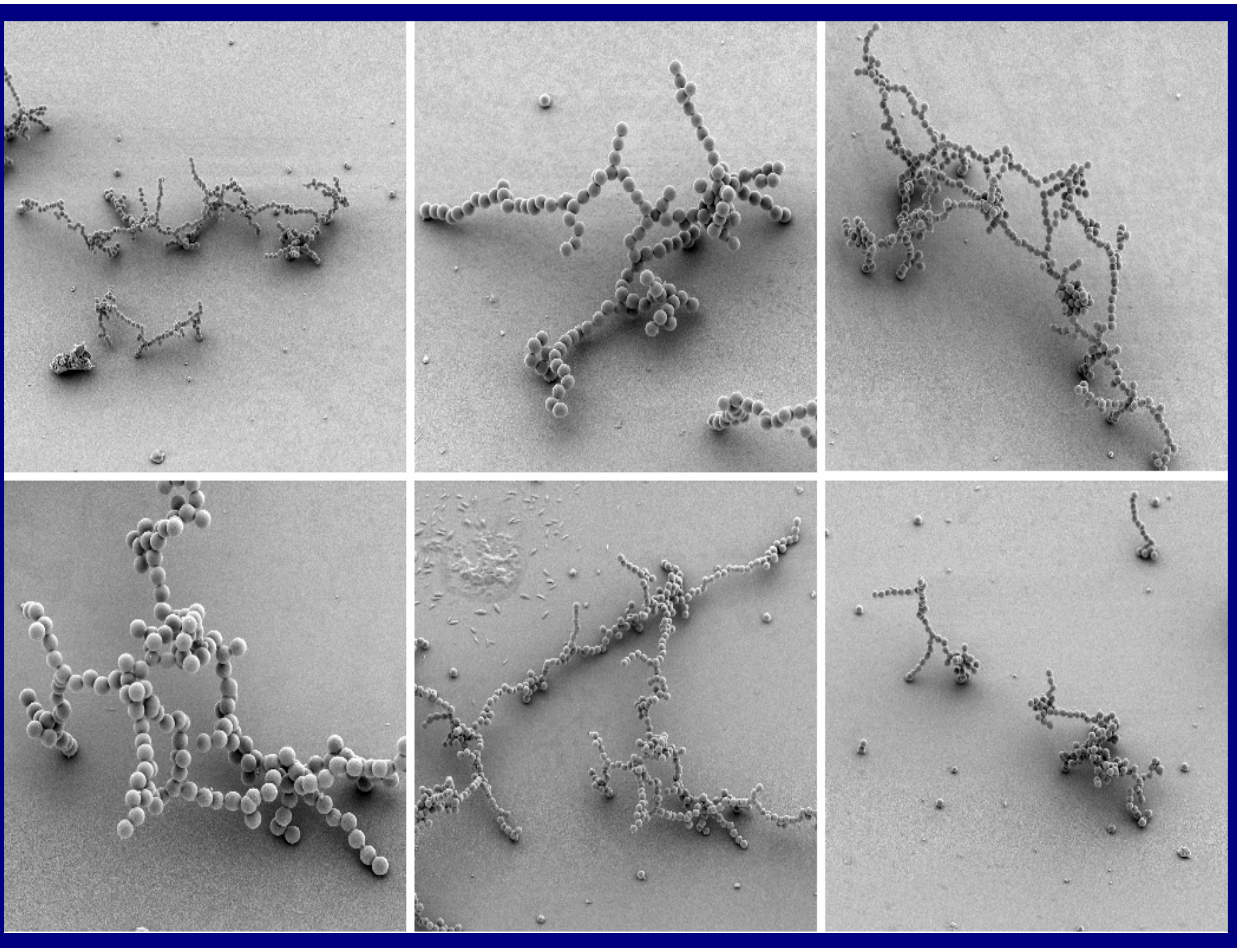
Rin	Rout	Mdust
System located @ 50 pc is unresolv.		
Large (>10μm) grains		
9 AU	42 AU	~8E-9 Msun
System age of 30Myr is much older than blow-out time scale		
Large (>10μm) grains		
4 AU	6 AU	~1E-10 Msun

(Hines et al. 2005 ; Bouwman et al. 2006)

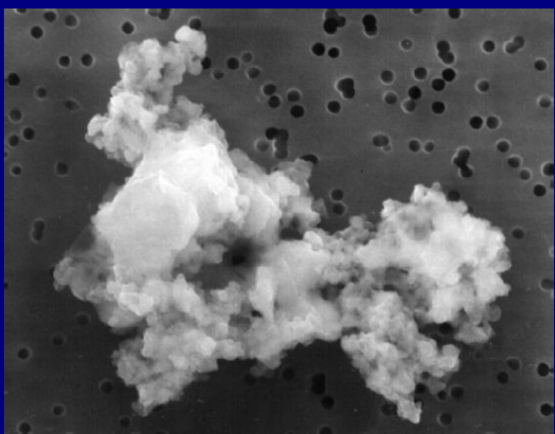
Road map of planet formation

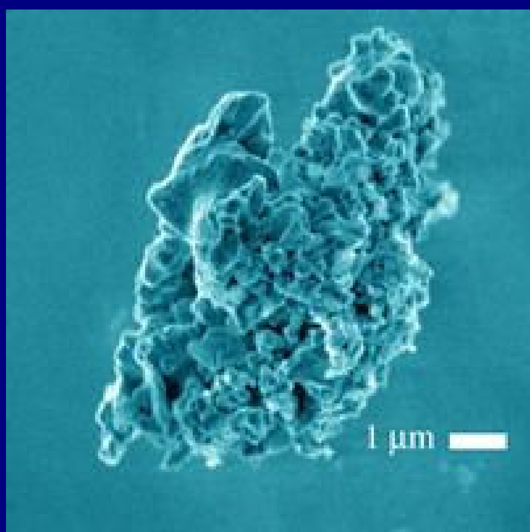


Beckwith, Henning & Nakagawa (2000)

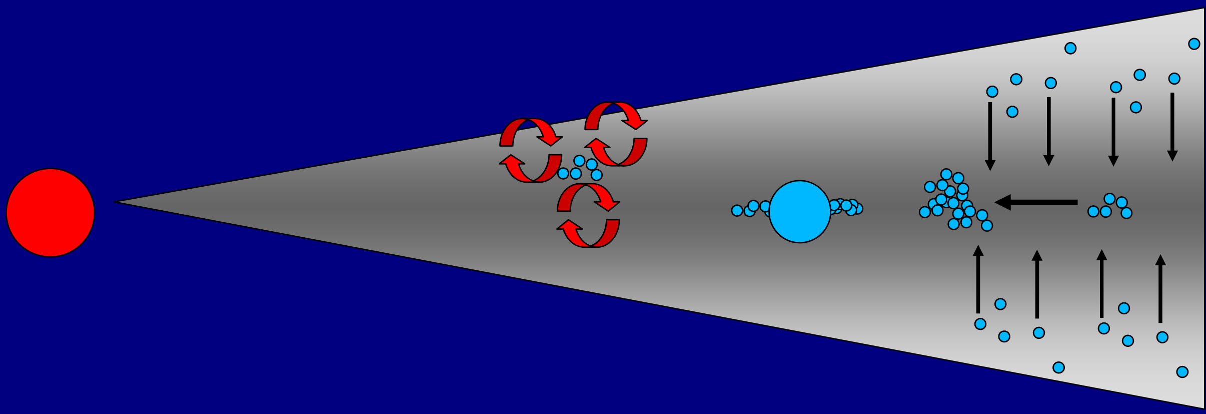


Example porous grains: IDPs





From submicron particles to bigger objects



GROWTH TIME SCALE

$t_g \sim P_K/\sigma \qquad P_K \sim R^{3/2} \quad ; \quad \sigma \sim R^{-2}$

$t_g \sim R^{7/2}$

Growth time differs from outer regions to inner regions.

SETTLING TIME

$$v_z = - z\, \Omega_K^2\, \tau_f$$

$$t_s \sim \frac{\Sigma\,(r)}{\rho_d \cdot a} \ln \frac{z}{z_o}$$

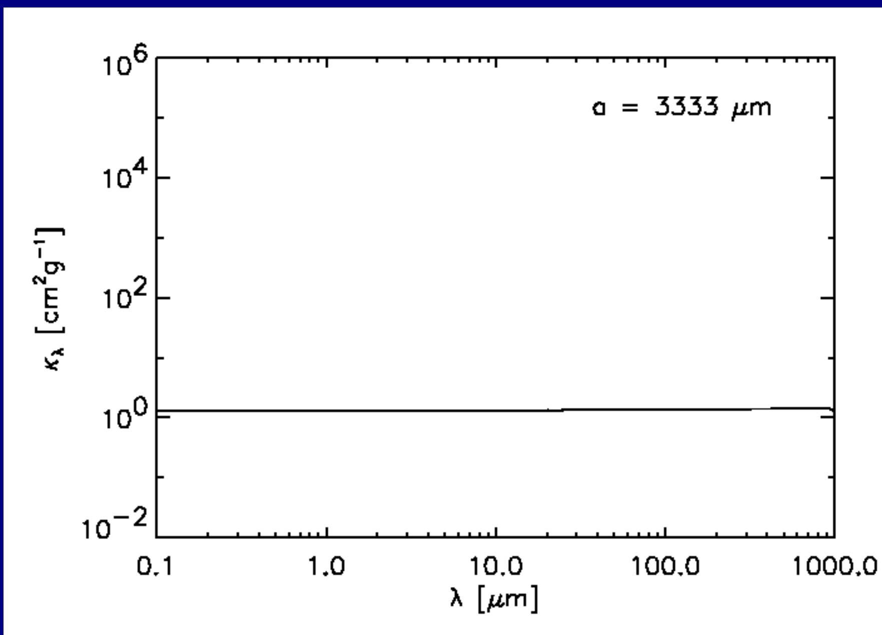
Settling time depends on grain radius for compact spherical particles.

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 + Polariz. + RT modeling
  Menshchikov, Henning & Fischer 1999, Wolf ea. 2003
- Formation of (opacity) gaps
  Koerner et al. 1998, Sicilia-Aguilar et al. (2006)
- 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, 2005, Bouwman ea. 2006

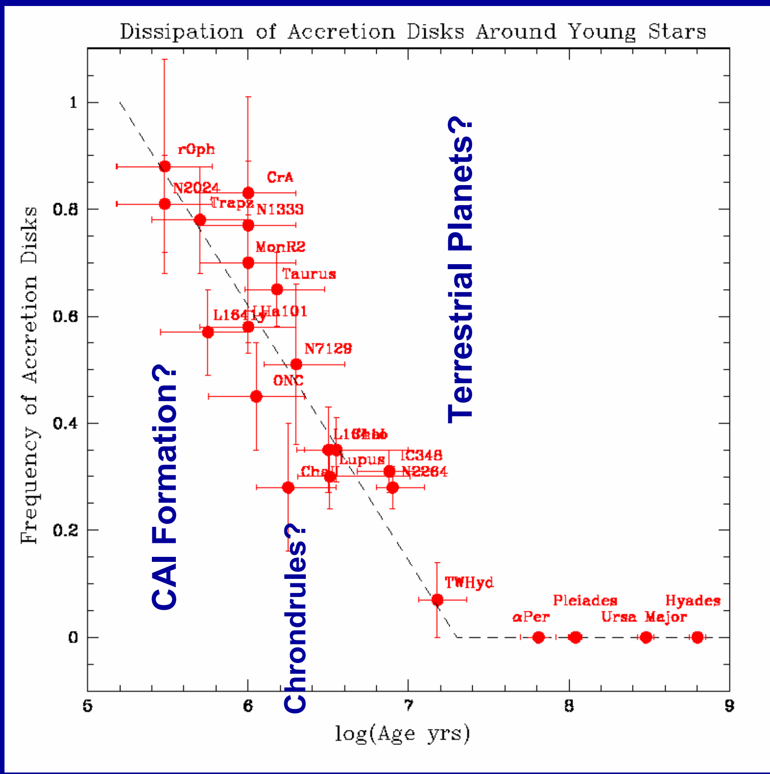
Grain growth: change of opacity

(Absorption opacity)



(Wavelength)

NIR Excess Fraction (< 0.1 AU) vs. Cluster Age



No detectable inner disks for ages > 10 Myr

Haisch et al. 2001; see also Carpenter et al. (2005) for millimeter emission

Time Scales For Grain Evolution

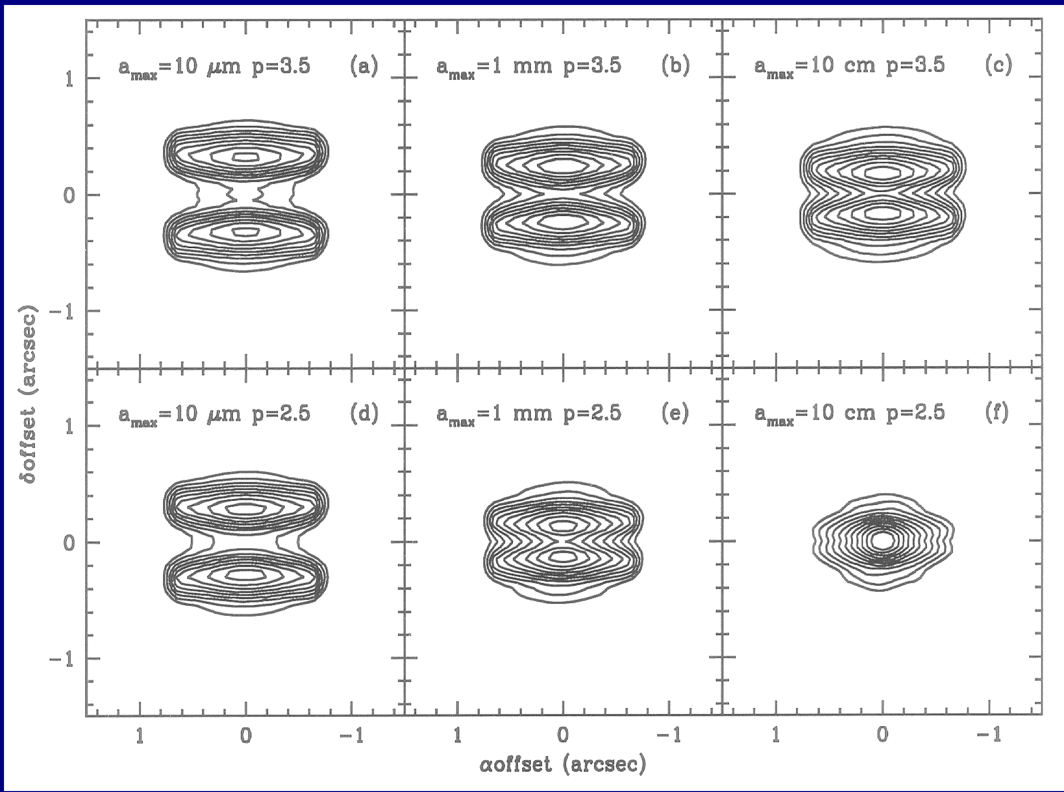
t ≤ 5 -10 × 10^6 yrs
(from infrared excess emission)

(1) Dust grains 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 →100Myr) by collisional shattering of lager bodies)

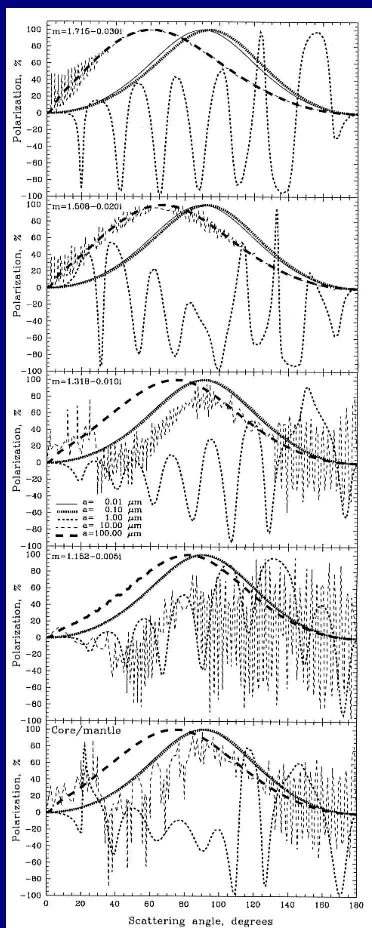
Images of edge-on disks at λ = 0.814μm for dust mixtures



D'Alessio et al. (2001)

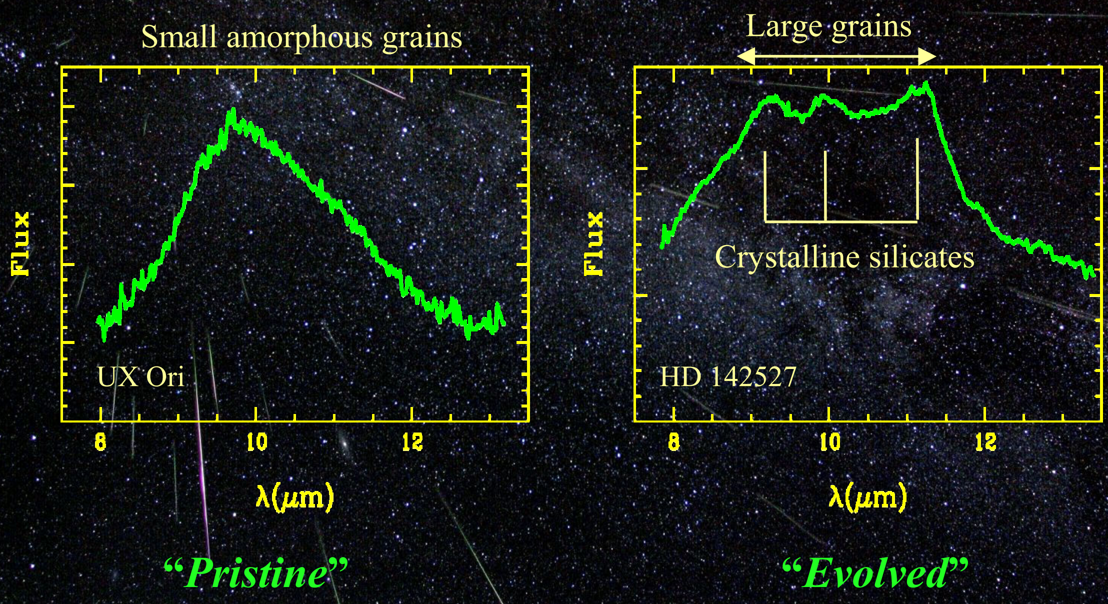
Polarization

Grain sizes from 0.01 – 100 microns



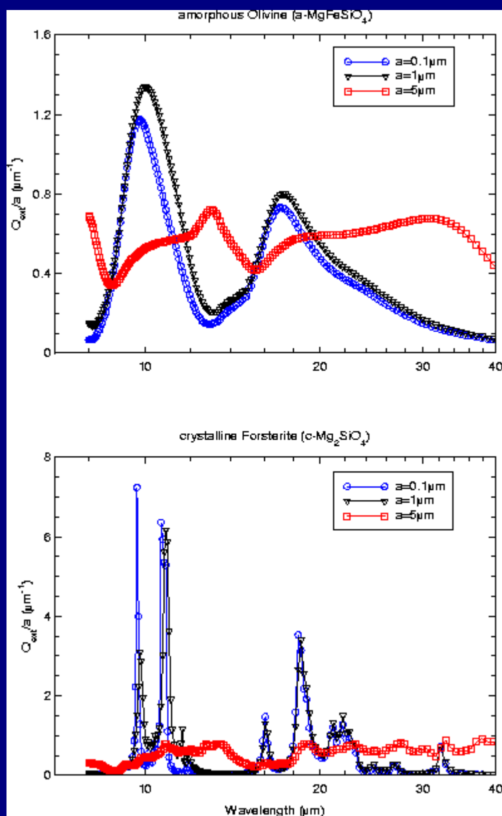
Voshchinnikov and Krügel (1999)

Dust processing at 10 micron

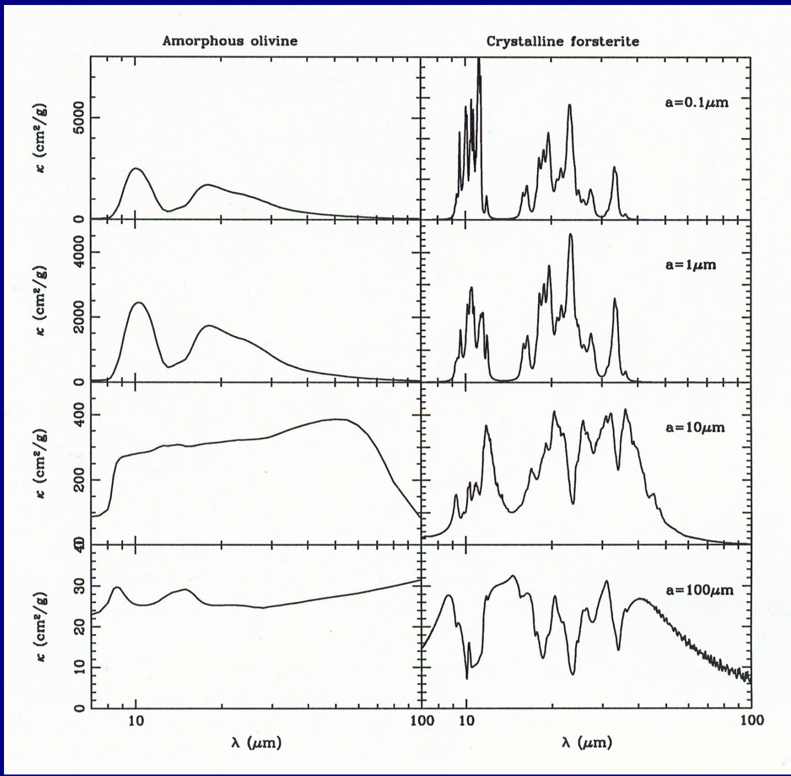


Zoom-in to mid-infrared

Dust Opacity: Effects of Size and Composition shown at R=100
(Henning et al. 2000)

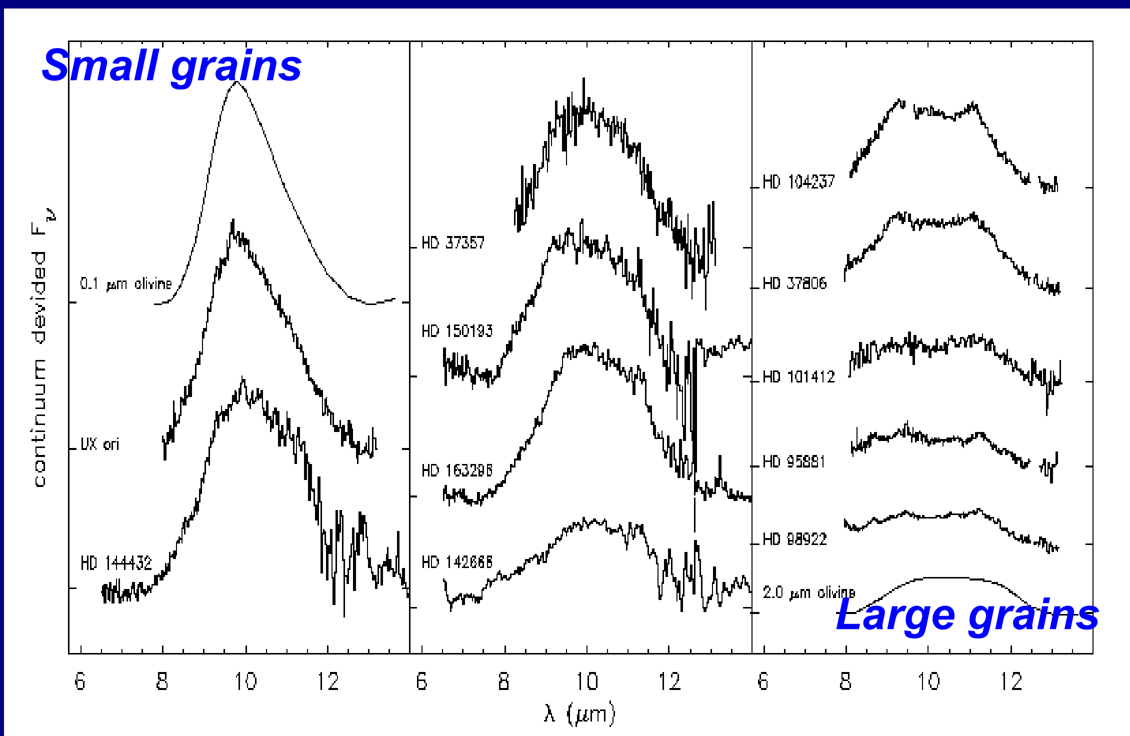


Grain Sizes – Crystalline vs. amorphous grains



Min et al. 2004

Evidence for Grain Growth



Grains grow to micron sizes …

v. Boekel et al. 2003

Evidence for Grain Growth -T Tauri Disks

Small grains

F. Przygodda et al.: Evidence for grain growth in T Tauri disks L45

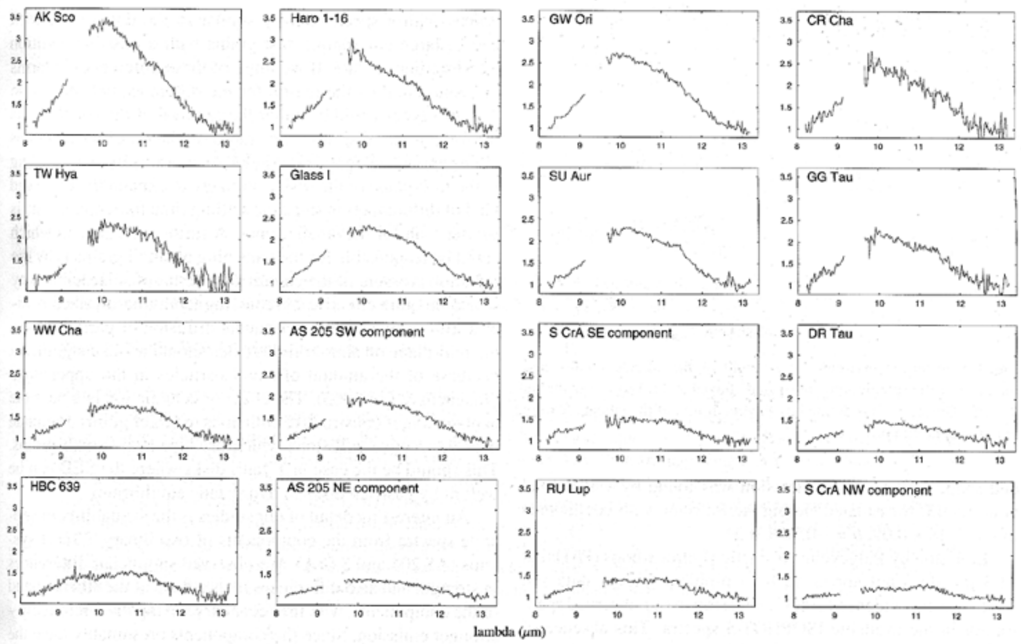


Fig. 2. Continuum normalized spectra of our sample ordered by the strength of the silicate feature. The shape of the feature is showing a correlation with the strength. Stronger features have a triangular shape with a pronounced peak near 9.8 μm while weaker features are more plateau-like. The gap from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

Przygodda et al. 2003

Large grains

Grain Growth and Dust Settling

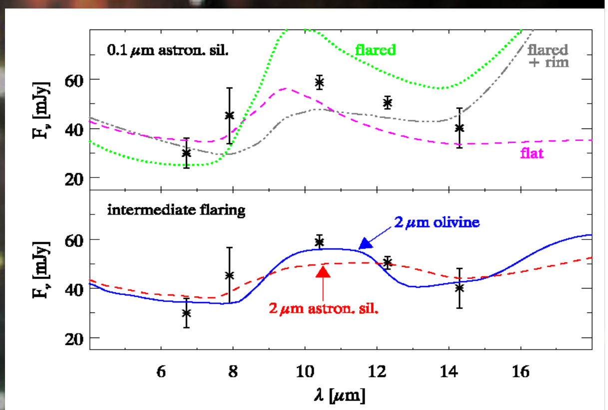
CFHT BD Tau 4 - Gemini (Apai et al. 2004)

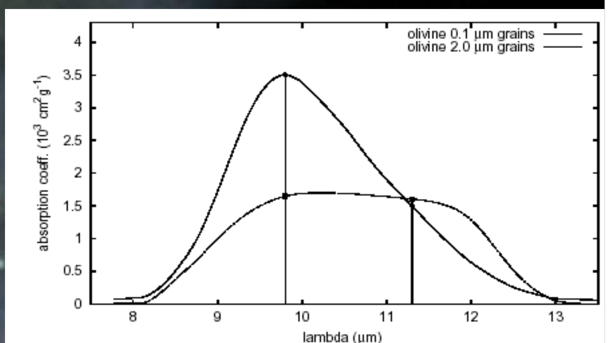
The most complete SED

-Broad and weak silicate emission feature
-Continuum slope between flared and flat disk model predictions
Model with reduced flaring is necessary

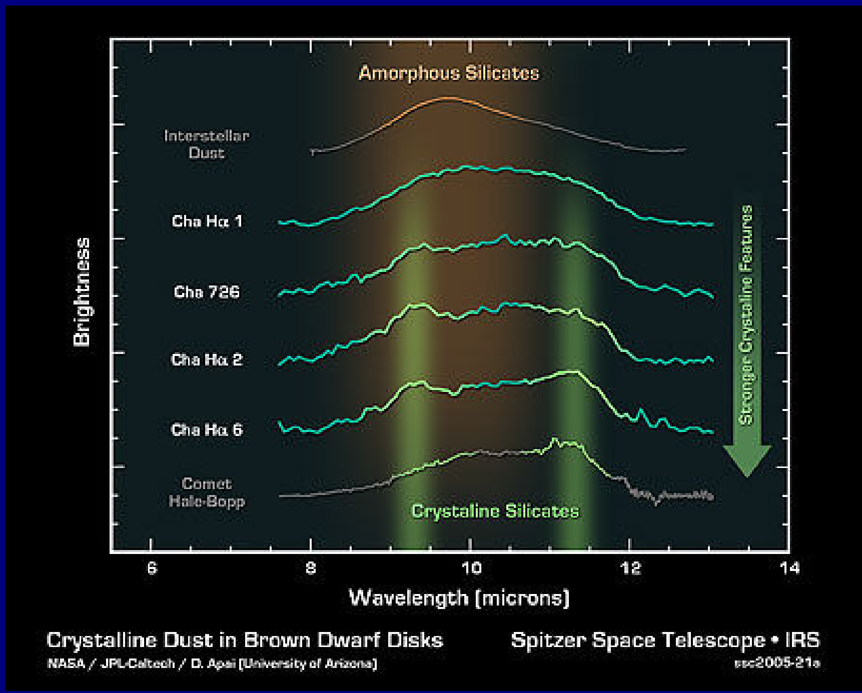
Conclusions:
- **Grain growth** to ~2μm sizes
- Dust grains sediment

Same processes in disks around low-mass stars!





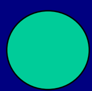
Grain Growth and Brown Dwarfs



Apai et al. (Science, 2005)

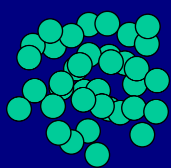
Aggregate Geometry

- compact



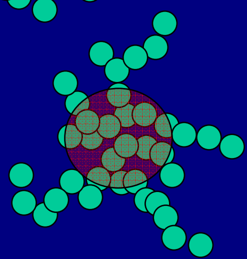
D =3

- porous
  - PCA



D =3

- fractal
  - CCA

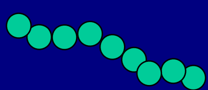


D ~ 2

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

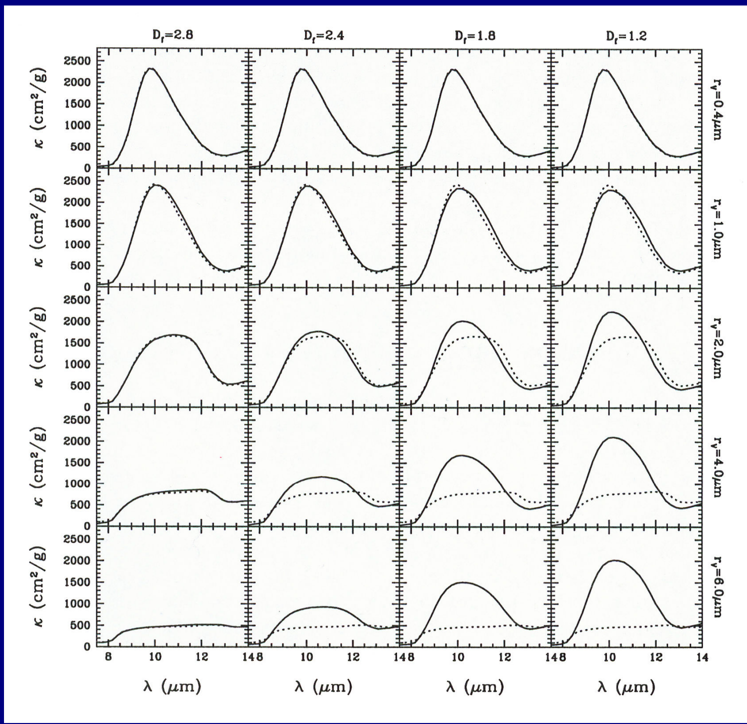
Fractal Dimension D

- quasi-linear



D ~ 1

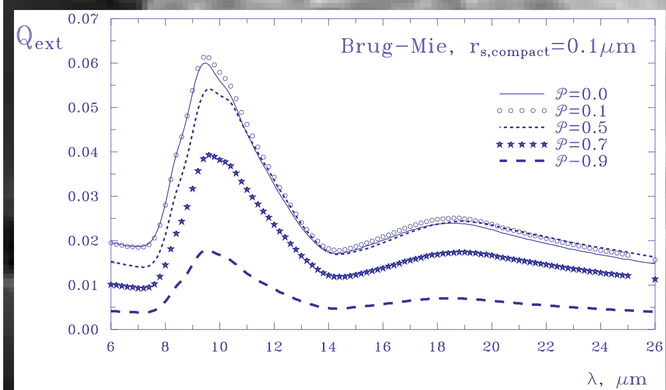
Silicate Emission Feature for Fractal Aggregates



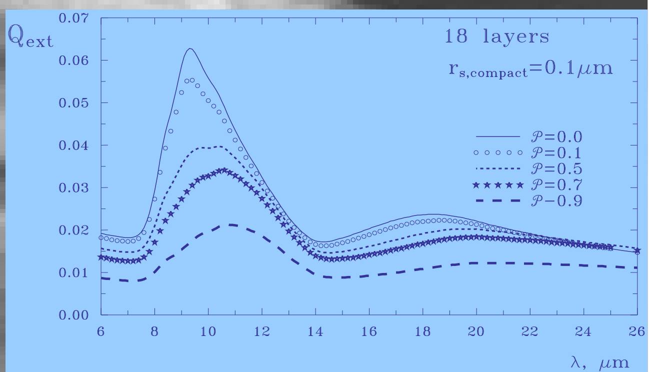
Min et al. 2006; see also Henning & Stognienko 1993

Silicate feature

small size (Rayleigh) inclusions



inclusions of different sizes



Voshchinnikov, Ilin, Henning, Dubkova, 2006

How to observe grain sizes with millimeter/centimeter observations?

- Flux density from a disk viewed face-on

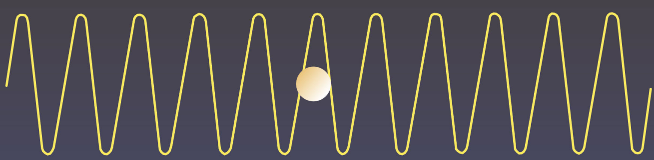
$$F_\nu = \frac{1}{D^2}\int_{R_{\rm in}}^{R_{\rm out}} B_\nu(T(r)) \times \{1 - e^{-\tau(\nu,r)}\} \times 2\pi r {\rm d}r$$

$$\tau(\nu) \propto \kappa(\nu) \propto \nu^\beta$$

- Optically thin disk; Rayleigh-Jeans regime

$$F_\nu \propto \nu^2 \tau(\nu) \propto \nu^2 \kappa(\nu) \propto \nu^{(2+\beta)}$$

MM-waves interact with all atoms



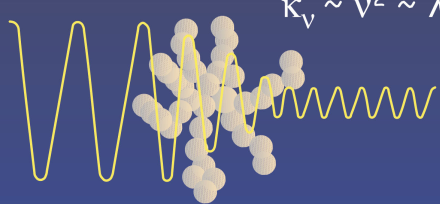
Particle size << wavelength
$\Rightarrow$ coupling ~ $\lambda^{-\beta}$
1st order: size independent, wave sees every atom

Insulators: absorption by lattice resonances

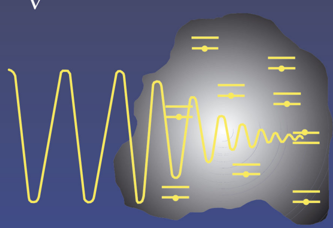
$\kappa_\nu \sim \nu^2 \sim \lambda^{-2}$ Lorentz "tail"

Conductors: "antenna" growth, absorption by free electrons

$\kappa_\nu \sim \nu^2 \sim \lambda^{-2}$ plasma skin depth



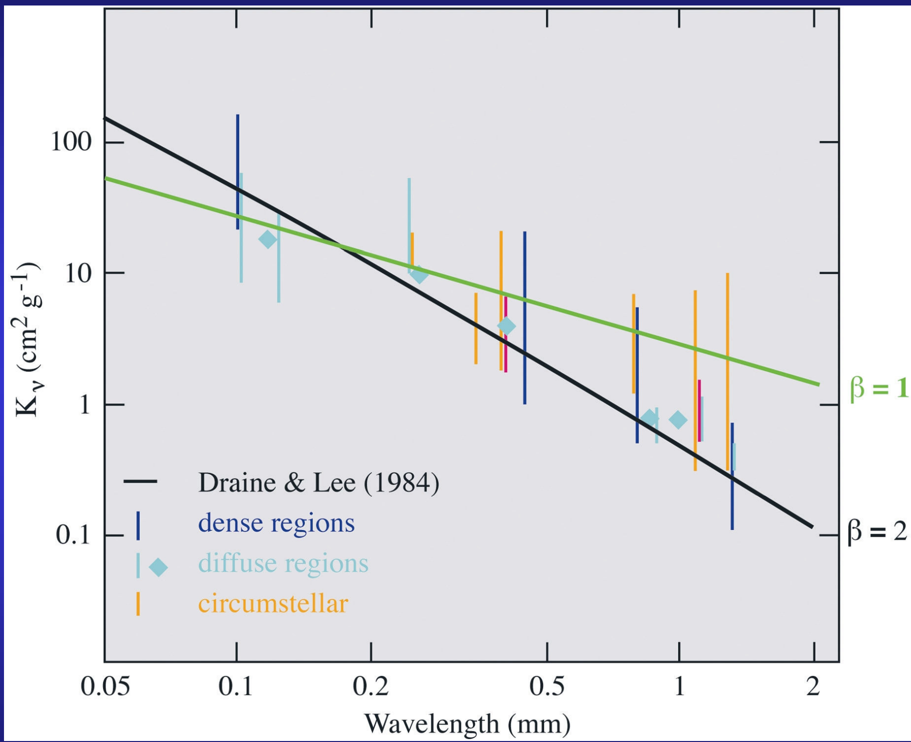
Fe, graphite



Olivines (silicates): Mg_2SiO_4

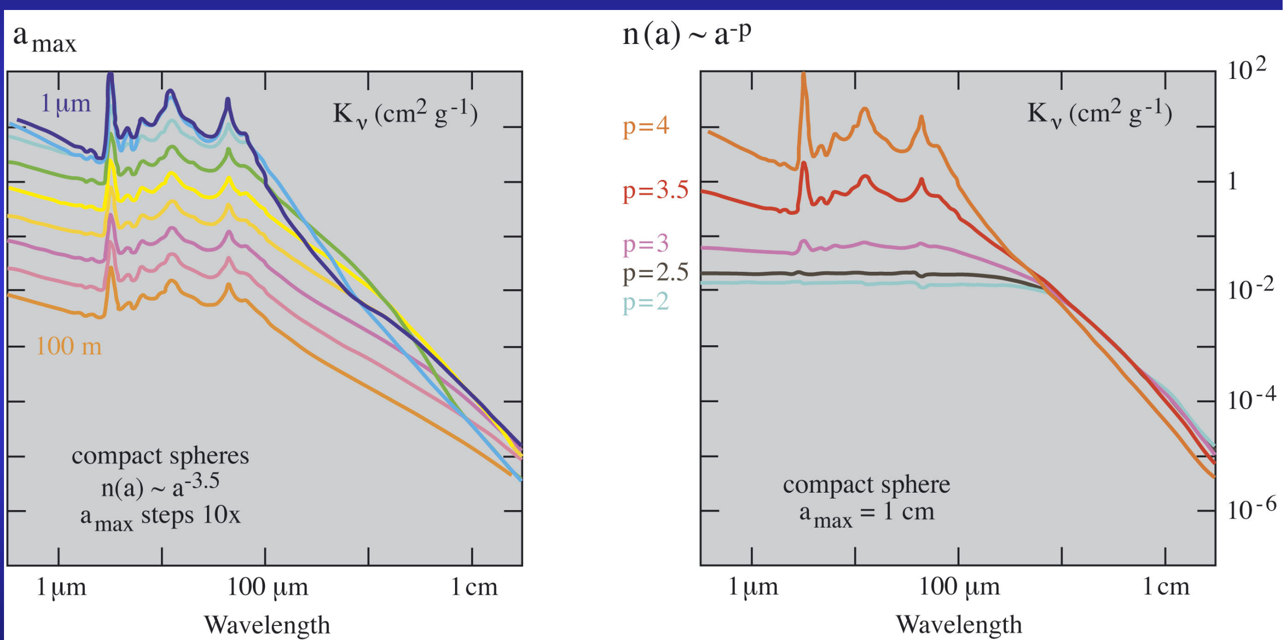
Disks

Interstellar Opacities



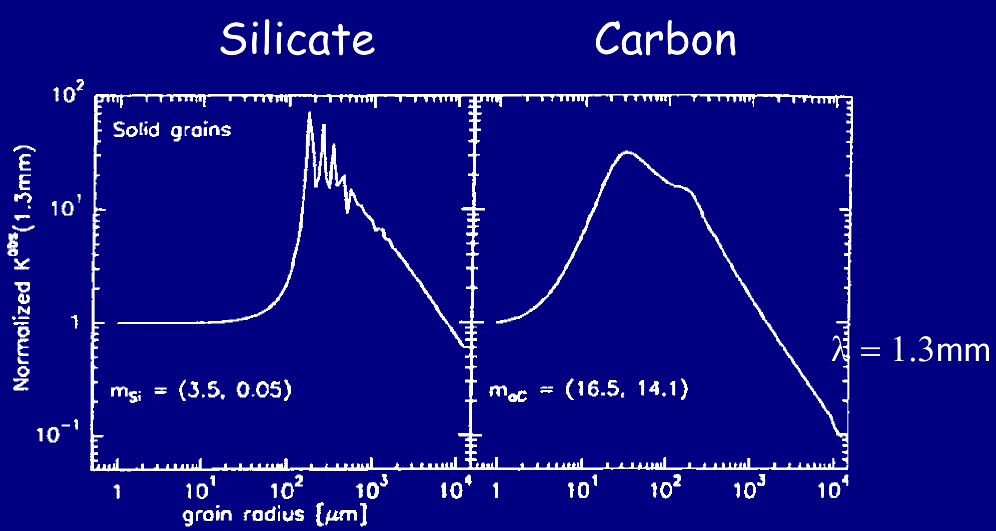
Henning et al. (1995)

Grain Size does alter opacity



Miyake and Nakagawa (1993)

Mm opacity as a function of size



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

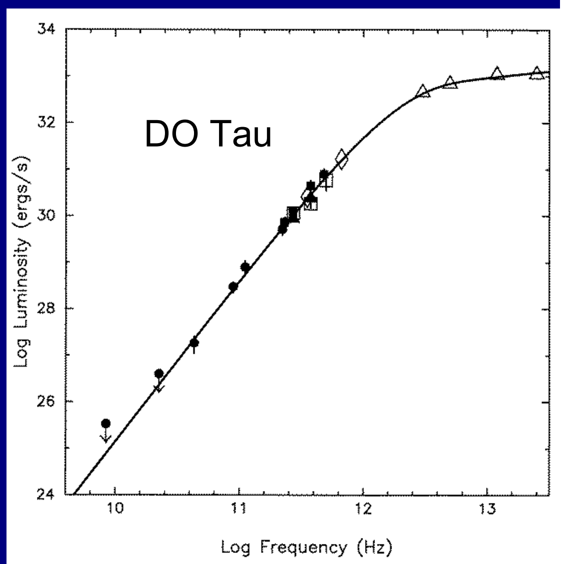
Very small grains: $\kappa(\nu,a)$ independent of a

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

Krügel & Siebenmorgen (1994)

Grain size from mm observations

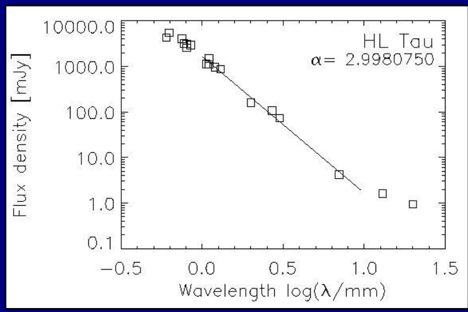
- **T Tauri star DO Tau**
  Koerner et al. (1995): ß=0.6±0.3
- **Low-mass star TW Hya**
  Calvet et al. (2002) ß=0.7
- **Intermediate-mass stars:**
  Testi et al. (2003) CQ Tau: ß=0.5-0.7
  Natta et al. (2004): ß=0.4-1.5
- **Wilner et al. (2005) cm observations TW Hya**

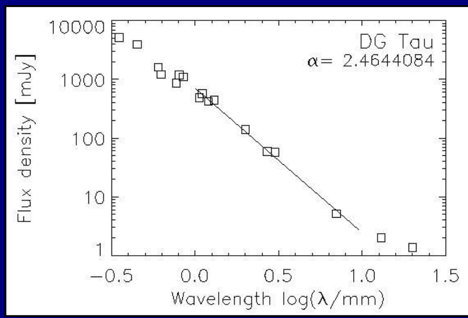


Grain size from mm observations

- 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

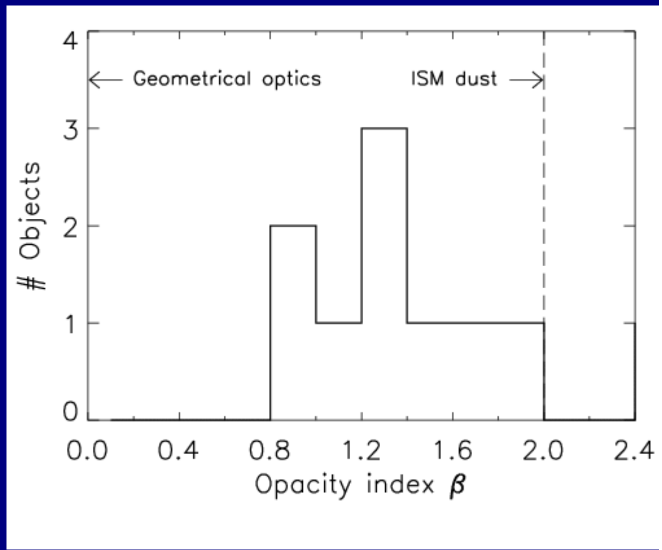
(Rodmann, Henning, Chandler et al. 2005)

- 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 (σ≥5)
- Additional observations at 1.3, 2.0, and 3.6 cm

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

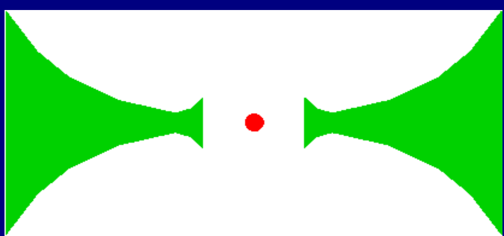
Rodmann et al. 2005



Grains grow to centimeter sizes …

Disk geometries proposed for Herbig Ae/Be stars

Group I
strong FIR excess



flaring disk

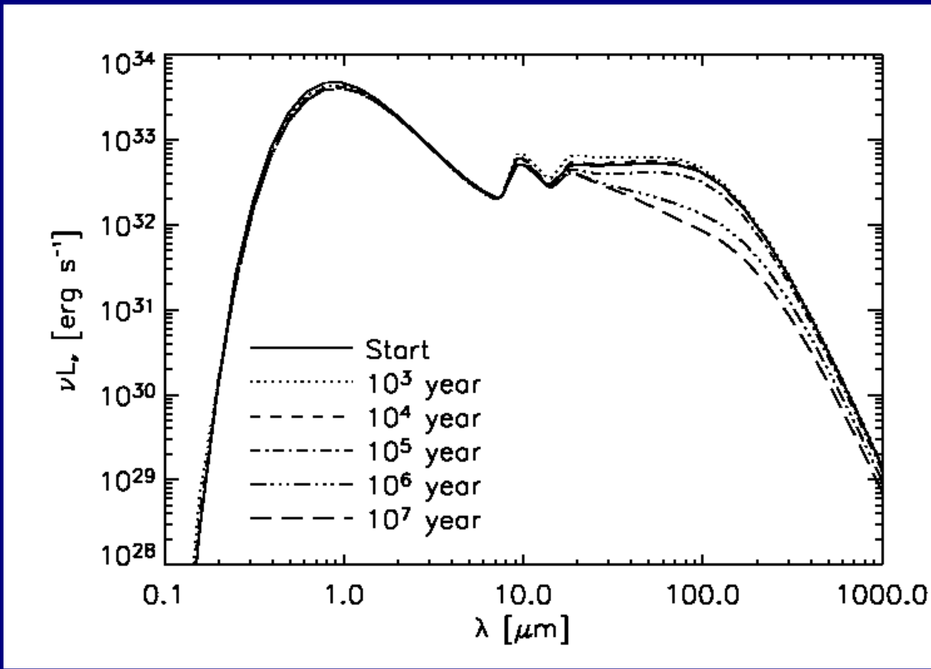
Group II
weak FIR excess

self-shadowing disk

The special feature of these models is the puffed-up hot inner rim of the disk

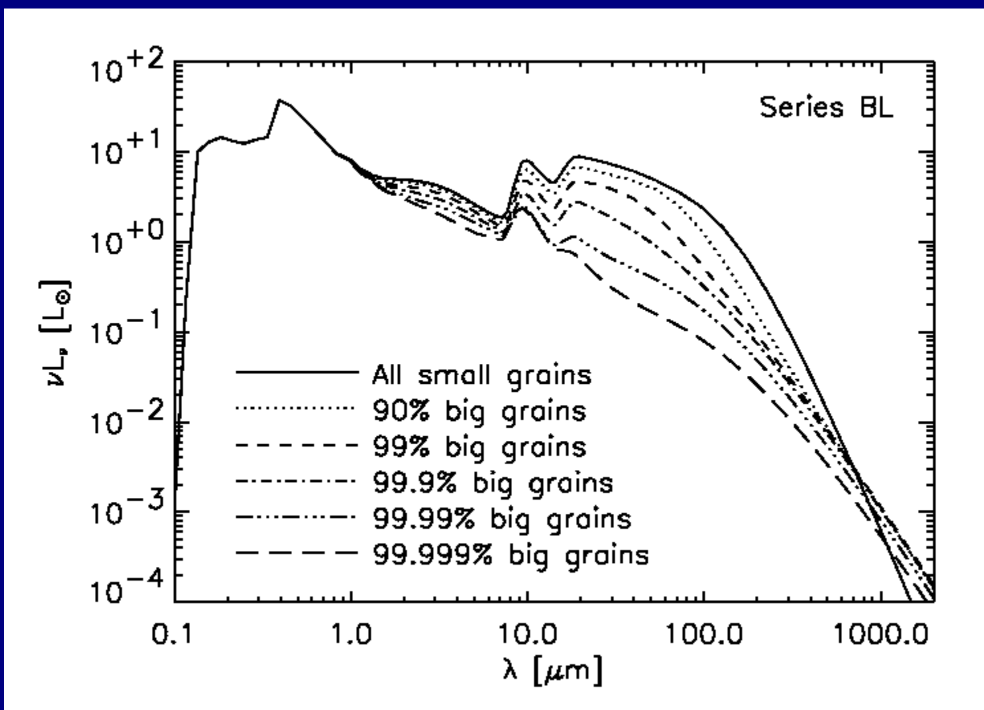
Meeus et al. 2001; Dullemond, Domink & Natta 2001; Dominik, Dullemond, Waters & Walch 2003; Dullemond & Dominik 2004

Effect of dust settling on SED

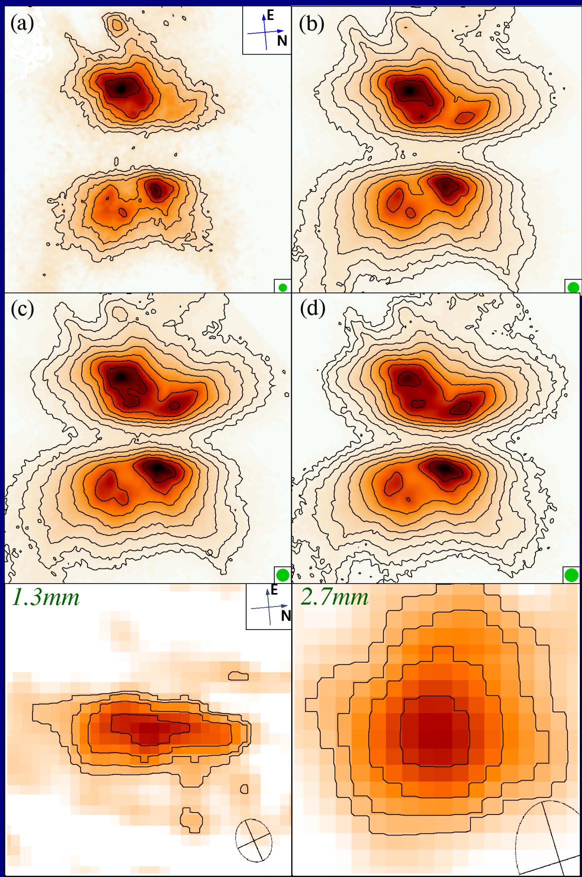


Dullemond & Dominik (2004),
See also Miyake & Nakagawa (1995), Tanaka et al. (2005),
D' Alessio et al. (2006)

Growth of grains: effect on SED



Dullemond & Dominik 2004



„Butterfly Star" in Taurus

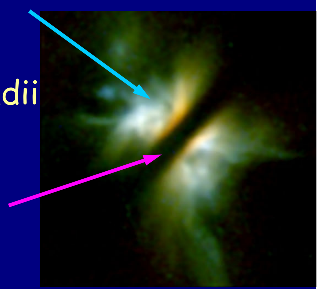
Wolf, Padgett, & Stapelfeldt 2003

High-resolution near-infrared images (HST) + mm maps (OVRO)

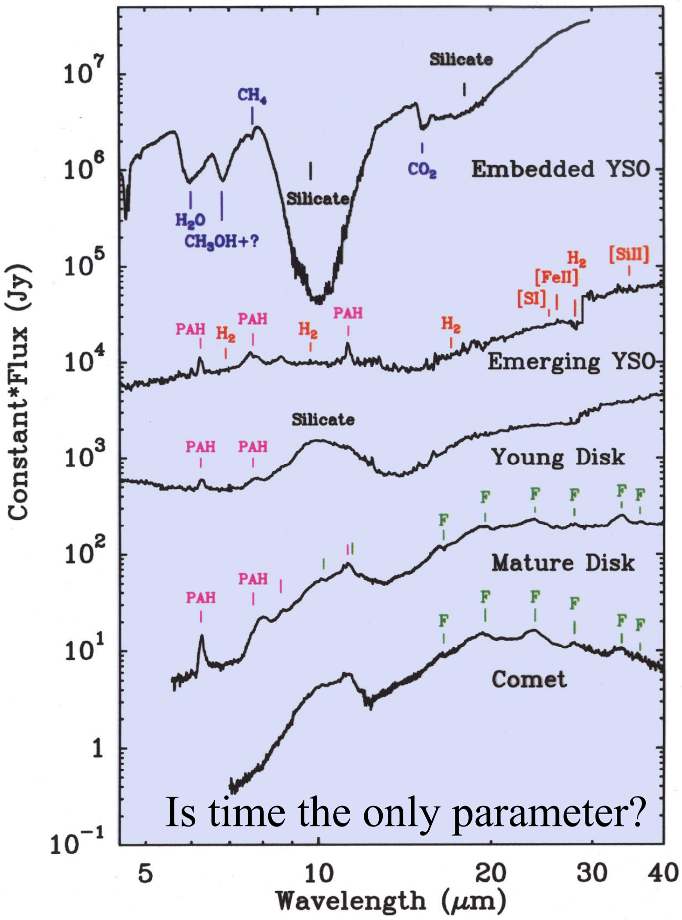
↓

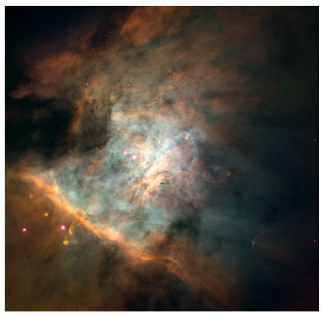
Confirmation of **different dust evolution scenarios** in the circumstellar shell and disk:

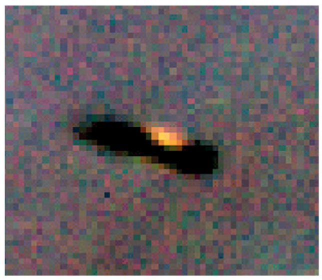
1. Interstellarer dust (< 1mu) in the shell
2. Dust grains with radii up to 0.1mm in the circumstellar disk!



Similar reasoning for HL Tau: Men'shchikov, Henning, Fischer (1999)



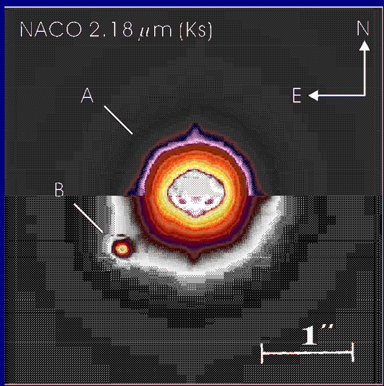




Evolution with Time – The Problems

- Age determination in PMS phase
- Short Transition Period
- Environmental factors (binarity, …)

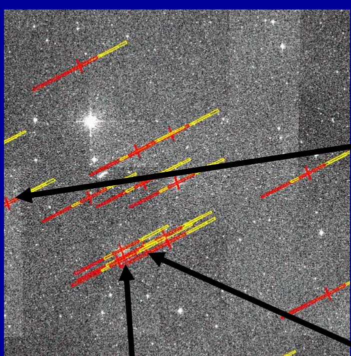
Example: HD 100453

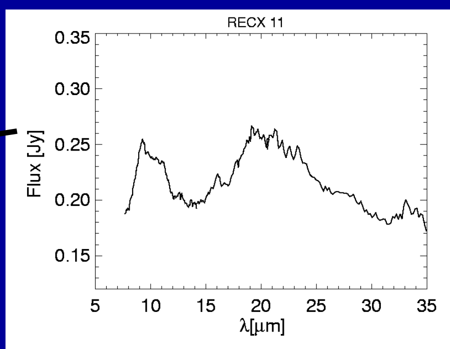


Chen, Henning ea. 2005

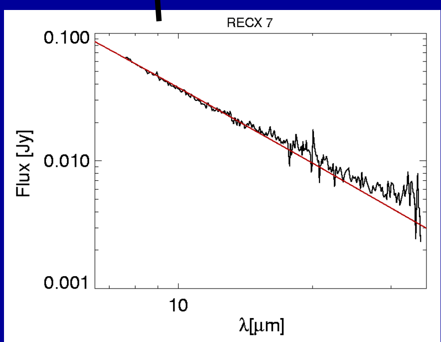
Spectrum has no feature

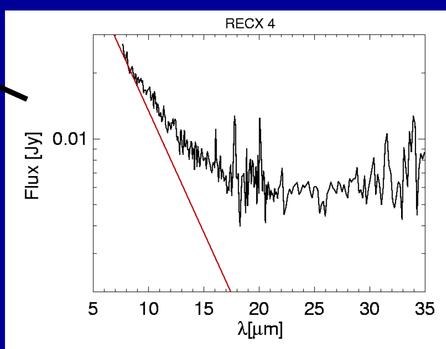
The 9Myr old Eta Cha cluster





Silicate processing





Inner hole formation and grain growth

Disk dispersion in close binary

Bouwman ea. (2006)

Summary

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

Reviews:

- **Beckwith, S.V.M., Henning, Th., Nakagawa, Y.: PPIV. 2000.**
- **Henning, Th., Dullemond, C., Dominik, C., Wolf, S. , In: Klahr, H., Brandner, W. (eds.): Planet Formation. 2006.**
- **Natta, A., Testi, L., Henning, Th. et al. PPV. 2006.**

Open questions

- Gravitational instability of dust sublayer?
- What is the structure of agglomerates produced by sedimentation ?
- What happens when “particles” reach the size of about 0.1m ?
- How important are destruction processes?
- What is the relation between crystallinity and grain size?