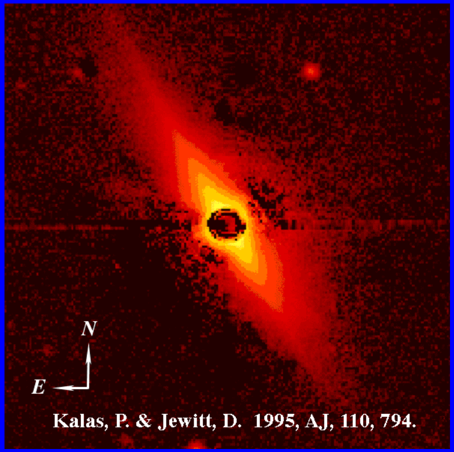
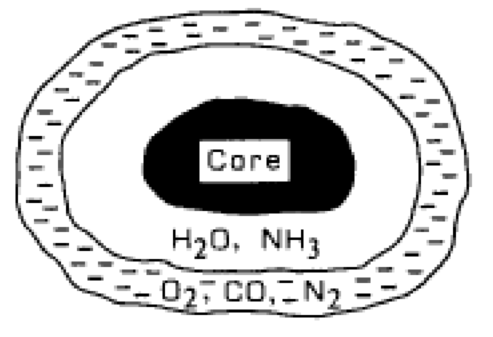
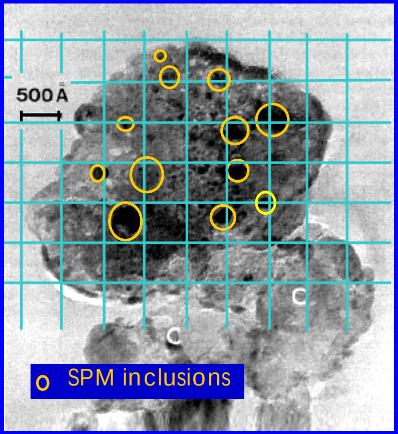


Kalas, P. & Jewitt, D. 1995, AJ, 110, 794.

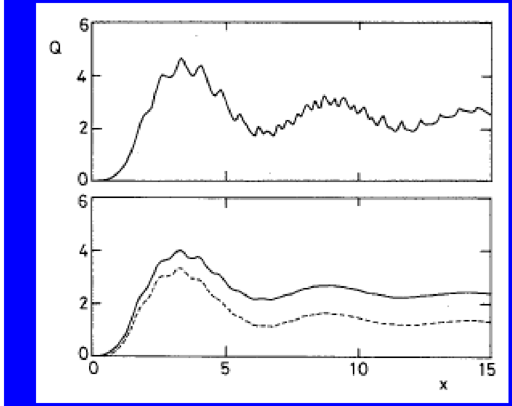


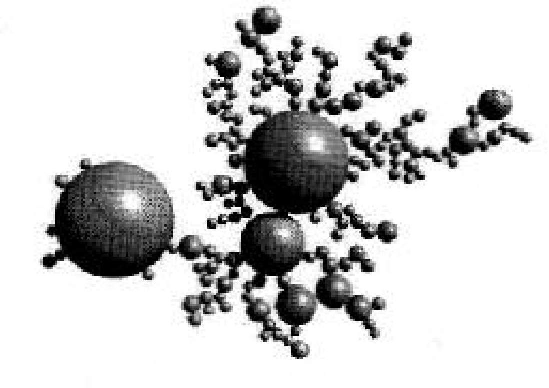


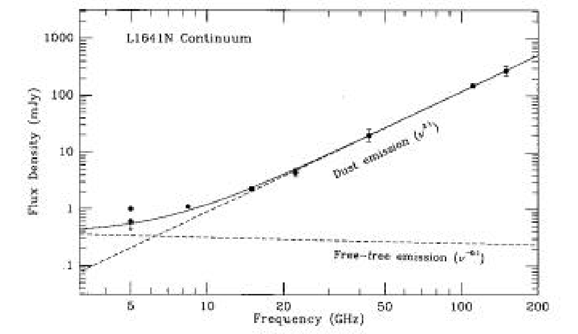
Speck-ulations on Big Dust

Alyssa A. Goodman

Harvard University Astronomy Department







Essential Physical Properties of Dust

- Size Distribution
  - MRN: $N(a) \sim a^{-3.5}$... how often applicable?
- Composition
  - effects emissivity, Q
    - » $Q_{FIR} \sim \lambda^{-\beta}$
      - $\beta=0$ for pure blackbody; $\beta \sim 1$ for amorphous, layer-lattice material; $\beta \sim 2$ for metals & crystalline dielectrics
- Shape (“Fluffiness”, “Compactness”)
  - effects surface area & sticking properties

Size: Which Grains Matter Most?

$$F_\lambda = N\left\{\frac{\pi a^2}{D^2}\right\} \mathbf{Q}_\lambda B_\lambda(T)$$

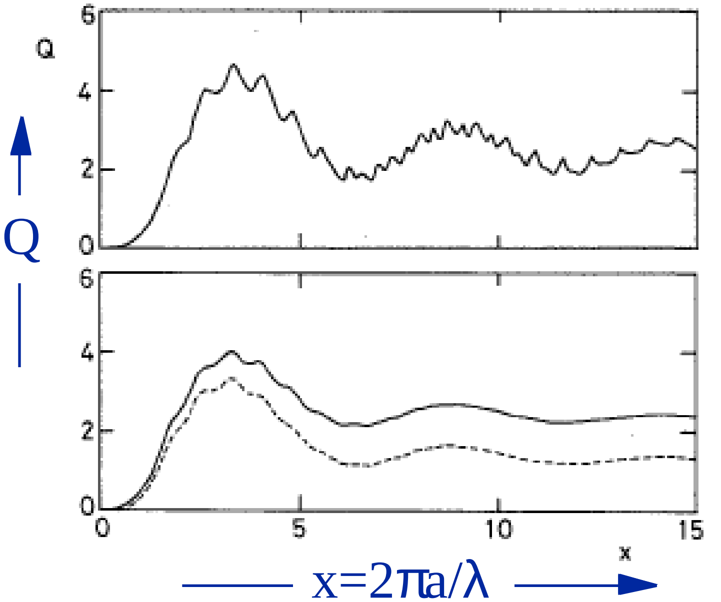
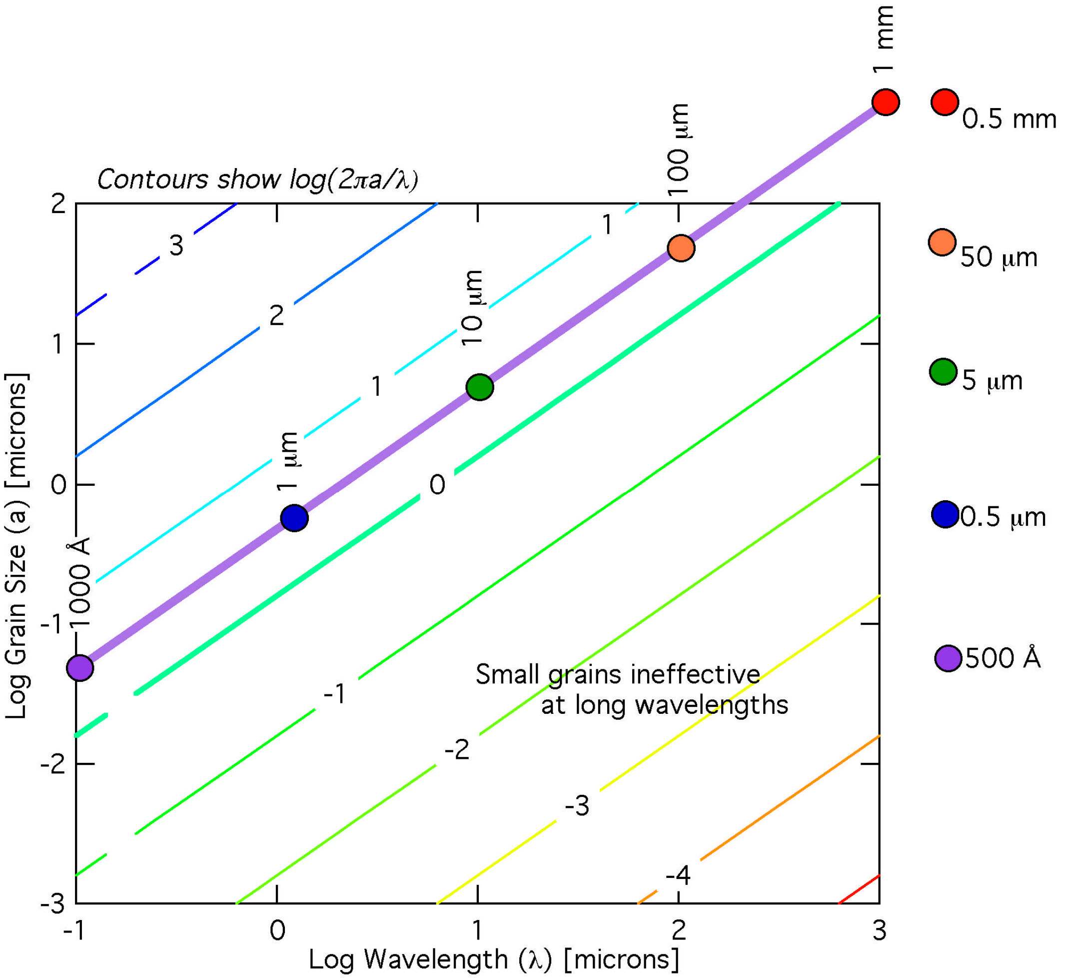


Figure 3.1 Plots of efficiency factors Q_{ext} and Q_{sca} against x for spheri
grains. Upper frame: $m = 1.6 - 0.0i$; $Q_{ext} = Q_{sca}$. Lower frame: $m = 1.6 - 0.$
solid curve is Q_{ext}, dashed curve is Q_{sca}.



ISM: $N(a) \sim a^{-3.5}$

Grain Size Distribution in the ISM

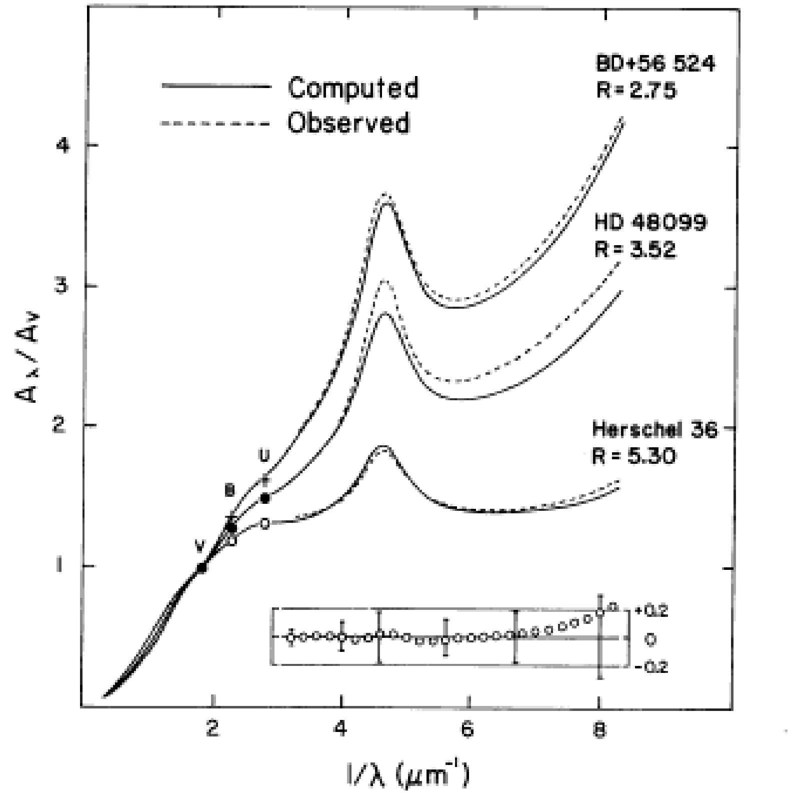


FIG. 4.—Same as Fig. 3 except for the UV portion of the mean R_V-dependent extinction law from eq. (4). The data at U, B, and V from Fig. 3 are also plotted. Again, the "error" bars in the lower inset represent the computed standard deviation of the data about the best fit of $A(\lambda)/A(V)$ vs. R_V^{-1} with $a(x) + b(x)/R_V$. The open symbols in the inset represent the difference between $A(\lambda)/A(V)$ from eq. (4) and the average curve of Seaton (1979) for $R_V = 3.2$. The only serious deviation occurs for $x > 7\ \mu m^{-1}$ (see text).

Cardelli, Clayton & Mathis 1989.

– $N(a) \sim a^{-3.5}$

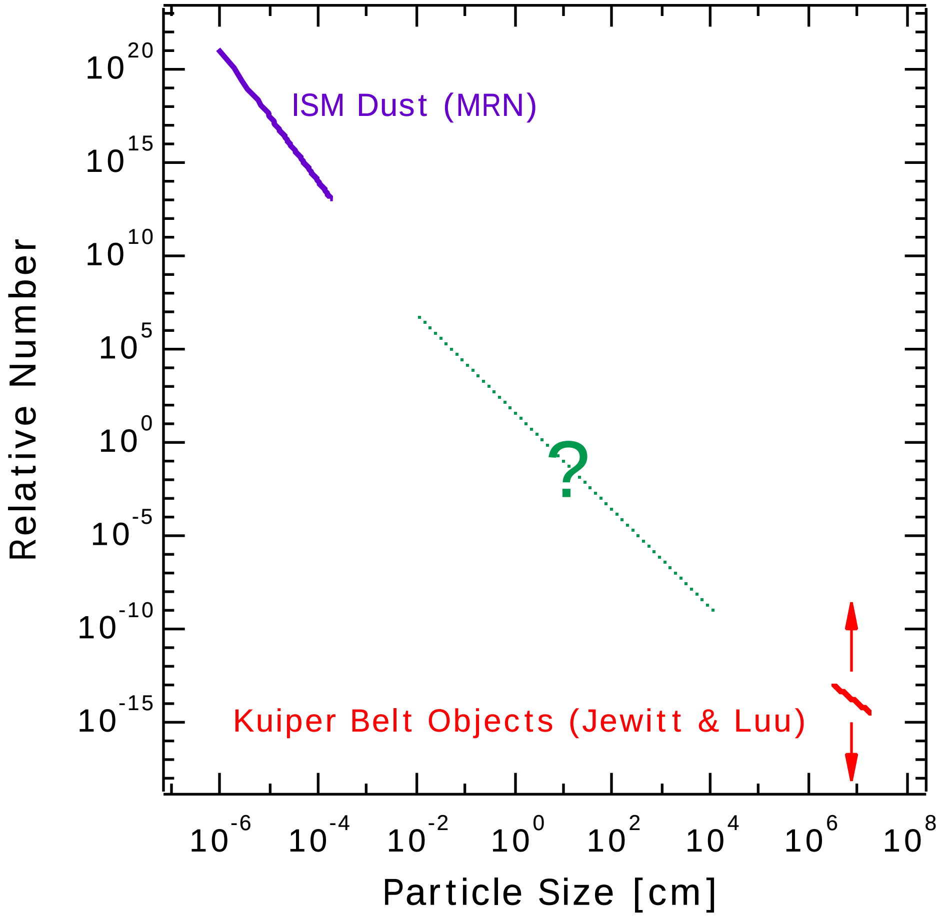
(Mathis, Rumpl & Nordseick 1977)

– BUT both slope and upper & lower size cutoffs can effect R_V observed

– R_V is observed to vary substantially in ISM!!

(recall: $A_V = R_V\, E(B-V)$)

Size Distributions: What’s In-Between?



? Asteroids, Interplanetary Dust, “Big” Interstellar Dust

SEDs & Mass Determination

Flux at λ for N particles of size a:

$$F_\lambda = N\left\{\frac{\pi a^2}{D^2}\right\}Q_\lambda B_\lambda(T) \qquad B_\lambda(T) = \frac{2hc^2}{\lambda^5}\,\frac{1}{\exp\left(hc/\lambda kT\right)-1} \qquad Q_{\mathrm{FIR}} \quad \lambda^{-\beta}\begin{cases}\beta=0 & \text{blackbodies}\\ \beta=1 & \text{amorphous, lattice-layer materials}\\ \beta=2 & \text{metals \& crystalline dielectrics}\end{cases}$$

Flux at λ for a distribution with N_a particles of each size a:

$$F_\lambda(obs) = \sum_{\text{grain distribution}} N_a\left\{\frac{\pi a^2}{D^2}\right\}Q_{\lambda,a}B_\lambda(T)$$

(Note: same flux can be achieved using different combinations of size distribution and emissivity law!)

Mass determination:

$$M_{dust} = \frac{4sF_\lambda D^2}{3B_\lambda(T_{dust})}\left\{\frac{a}{Q_\lambda}\right\}$$

Using "appropriate average" of a/Q_λ.

$$M_{dust}(true) = \sum_{\substack{\text{grain \& }\\ \text{temperature distribution}}} \frac{4sF_\lambda D^2}{3B_\lambda(T_{dust})}\left\{\frac{a}{Q_{\lambda,a}}\right\}$$

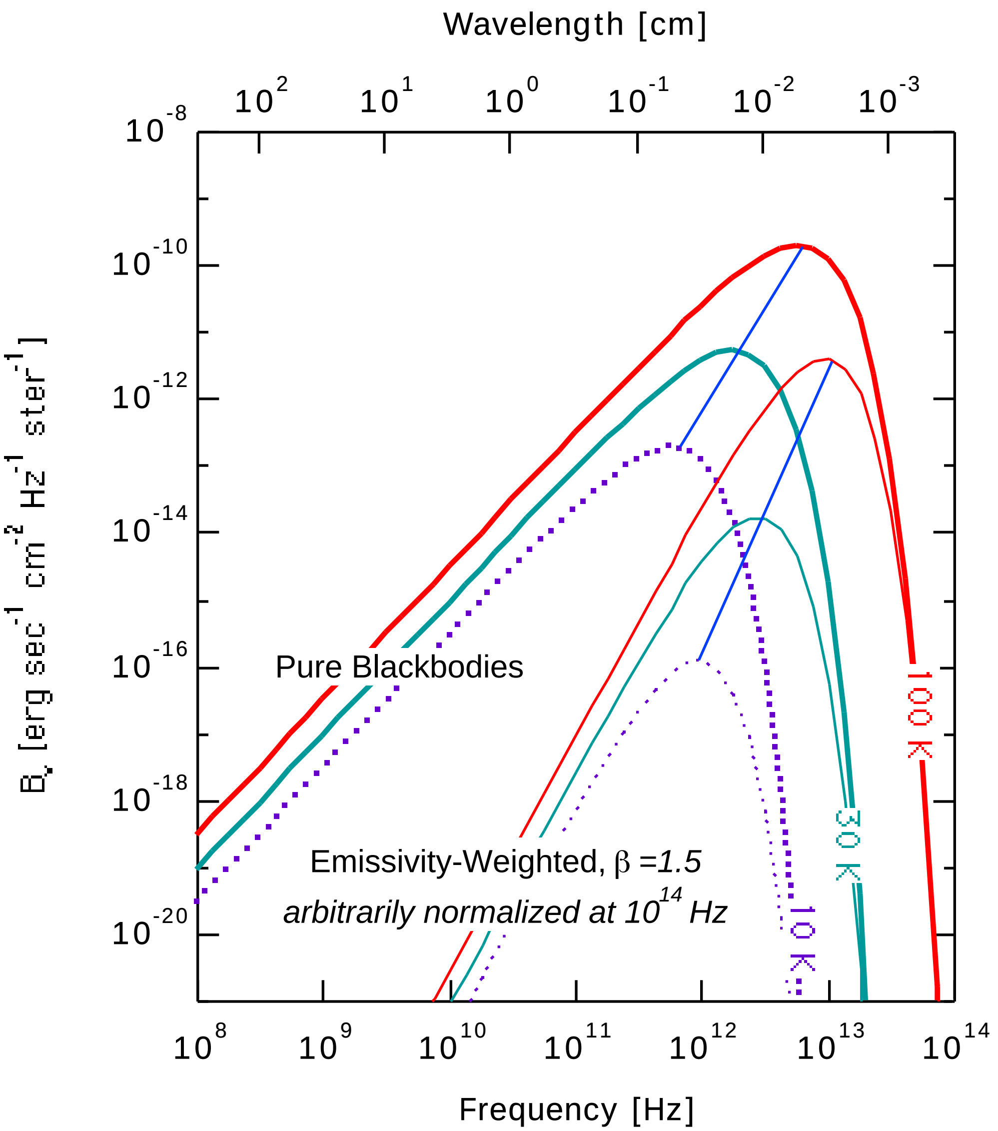
"Wien's Law":

$$\lambda_{\mathrm{peak}} \approx 3000\left[\frac{5}{\beta+5}\right]T^{-1}$$

Peak flux moves to longer λ for smaller β.

N = number of grains
a = "typical" grain size
D = distance from observer
T_{dust} = dust temperature
Q = emissivity
s = density of grain material

Composition: Changes β



- Maximum emissivity is for pure blackbody, $\beta=0$
- SED peaks move to longer λ for smaller β
- Decreasing β gives you more flux at any λ, so...

  overestimating β will mean more mass required to produce observed flux

- *WARNING: In theory, β is only a property of individual grains, but in “practice” it has come to include size distribution*

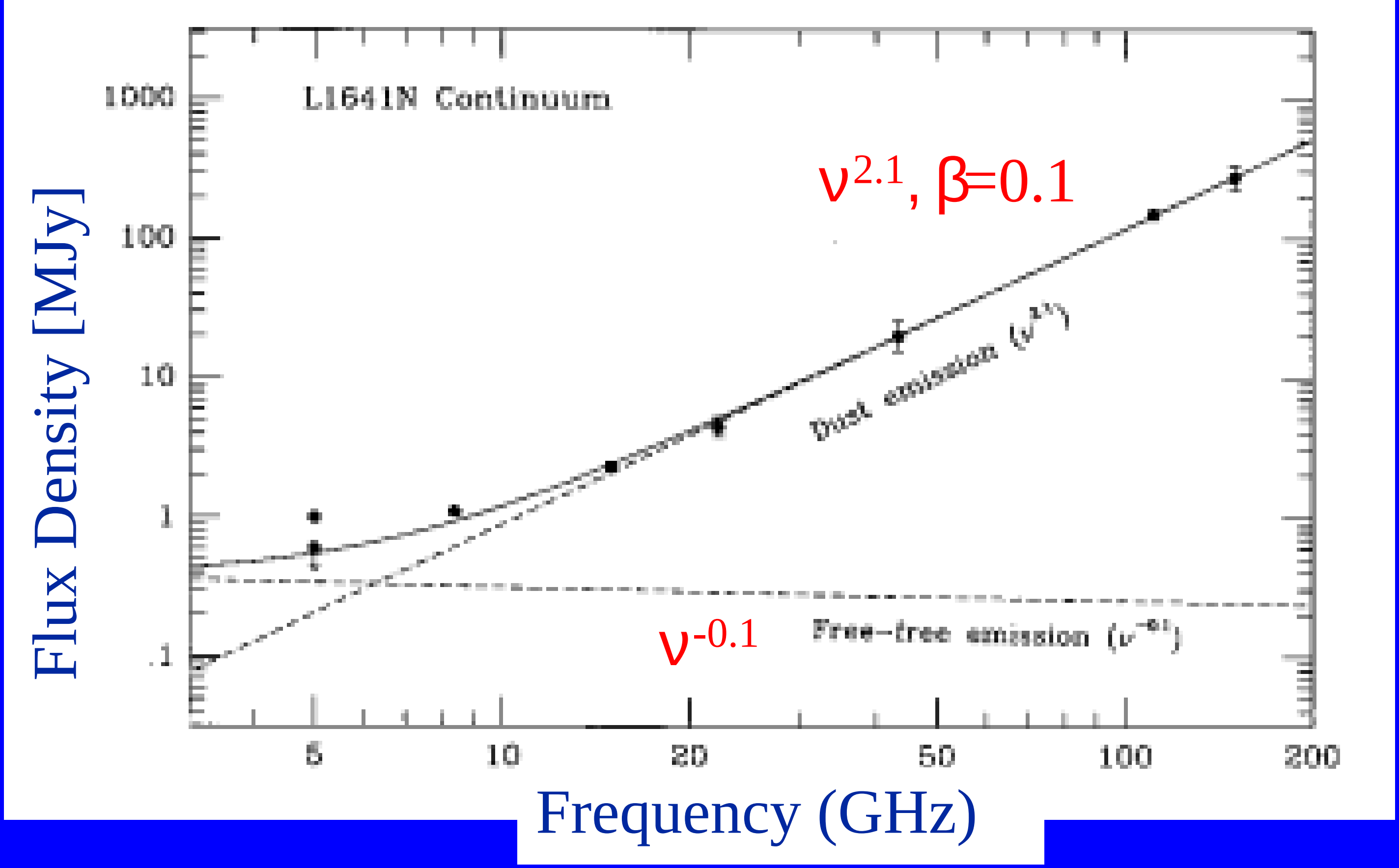
Essential Physical Properties of Dust

- Size Distribution
  - MRN: $N(a) \sim a^{-3.5}$... how often applicable?
- Composition
  - effects emissivity, Q
    - » $Q_{FIR} \sim \lambda^{-\beta}$
      - β=0 for pure blackbody; β~1 for amorphous, layer-lattice material; β~2 for metals & crystalline dielectrics
- Shape (“Fluffiness”, “Compactness”)
  - effects surface area & sticking properties

Evidence for Grain Growth in Cirucumstellar Environments

- Modification of "β", a.k.a. "dust opacity index"
  - opacity ~ $\kappa_\nu \sim (\lambda_o/\lambda)^\beta \sim (\nu/\nu_o)^\beta$
  - ISM: $\beta \sim 2$
  - Disks around Young Stars: $\beta << 2$
    - » more opacity at longer wavelengths in disks than ISM
    - » (e.g. TTS Disks $\beta \sim 0.6$; Mannings & Emerson 1994, see also Beckwith & Sargent 1991)
  - Low β's are easily Inconsistent with $N(a) \sim a^{-3.5}$

The Data: Low-β and Free-Free



Chen, Zhao & Ohashi, 1995

Disk Masses from SEDs Uncertain by ~ x100

Plots show χ^2 for disk masses derived from fits of Mannings & Emerson (1994)

Axes: Mass vs. β

Typical β~0.6

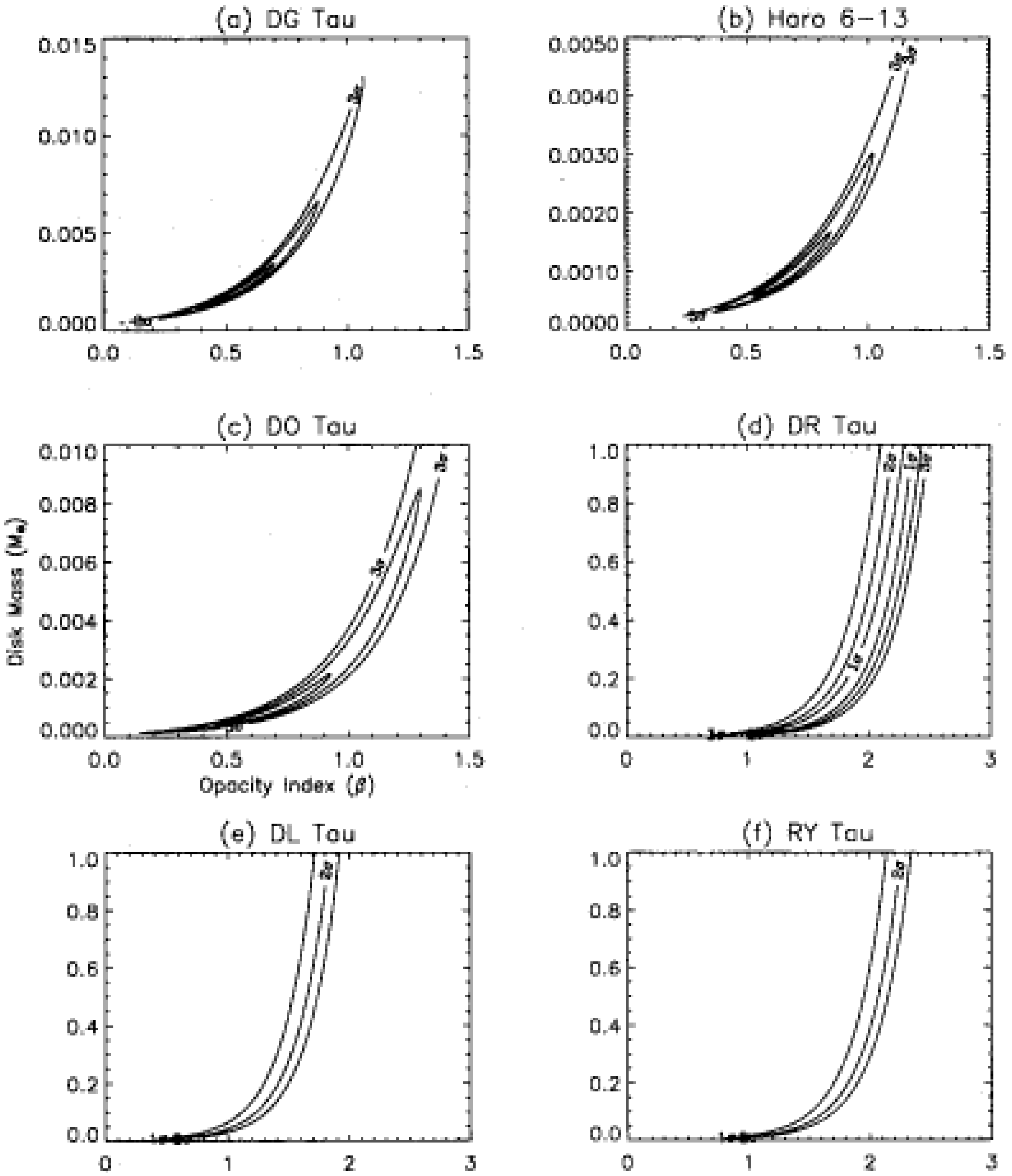


Figure 3. Contour plots of confidence intervals in χ^2 (relative to the global minimum χ^2) versus opacity index (β) and disc mass (M_D). Contours are drawn for $\Delta\chi^2$ of 1, 4 and 9, corresponding to 1, 2 and 3σ confidence levels respectively. (a) DG Tau, (b) Haro 6-13, (c) DO Tau, (d) DR Tau, (e) DL Tau, (f) RY Tau.

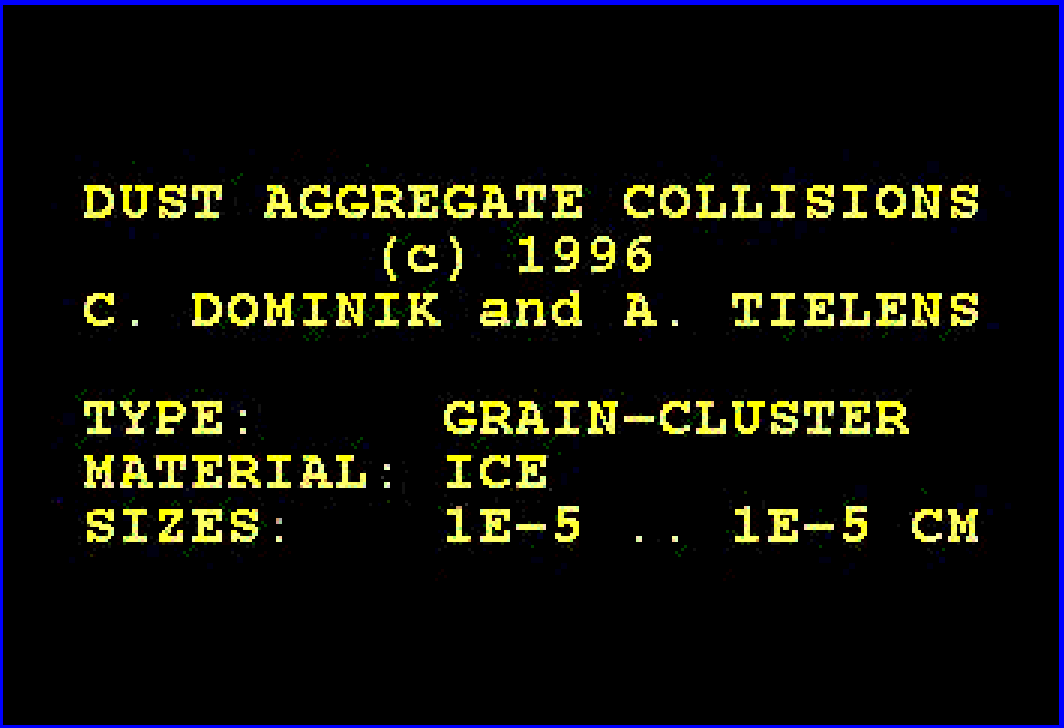
How (Big) Solids are Formed

- More Obvious Scenario: Direct Coagulation of Material, *in-situ* (Goldreich & Ward 1973; Cameron 1975, etc.)
- Less Obvious Scenarios: Mixtures of Materials formed in Hot/Cold Environments, on Varying Timescales
    - e.g. as accomplished through star/disk-formation/ outflow process (see F. Shu et al.)
- or... some of both?

Making Big Dust(balls) by Coagulation

- *Requirements*
  - – substantial rate of low-speed collisions
  - – “sticky” material (ices good)
  - – melting & other exotic possiblities
- *Dangers*
  - – equilibrium established short of “big” dust
  - – evaporation & destruction by high *T* & *hν*
    - » within several A.U. of forming stars
  - – destruction by high-speed collisions
    - » e.g. infall, supersonic turbulence, etc.

Single Particle: Aggregate of Similar Particles



DUST AGGREGATE COLLISIONS
(c) 1996
C. DOMINIK and A. TIELENS

TYPE: GRAIN-CLUSTER
MATERIAL: ICE
SIZES: 1E-5 .. 1E-5 CM

Ice

Recall:

cm/s	km/s
100	0.001
1000	0.01
10000	0.1
100000	1

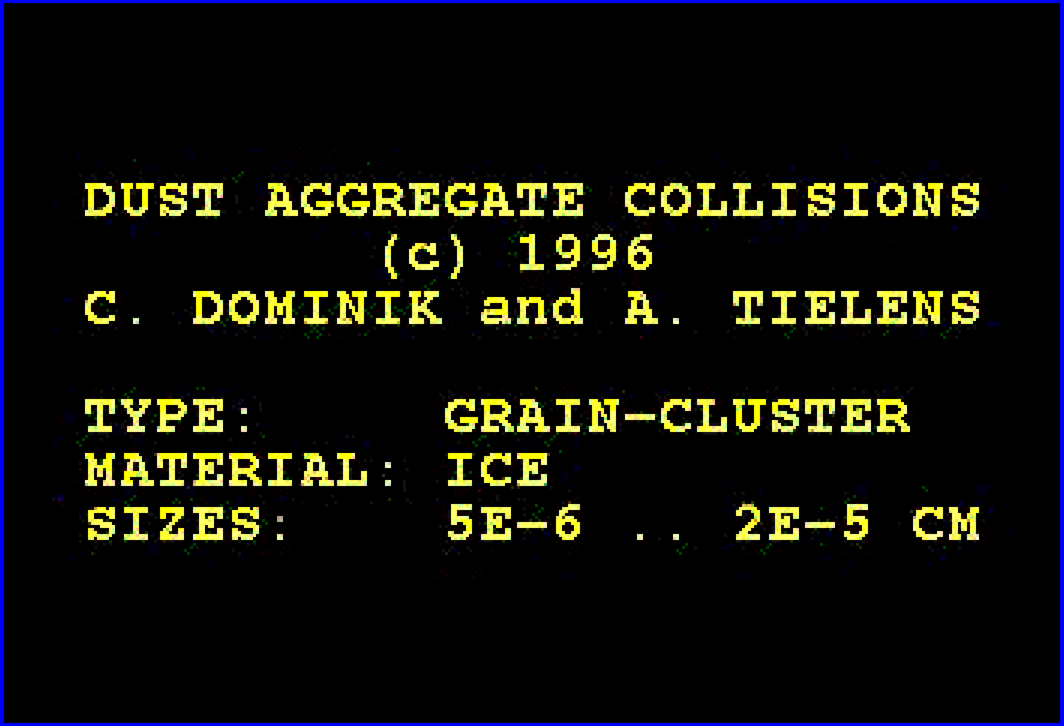
Single Particle :Aggregate of Similar Particles

```
DUST AGGREGATE COLLISIONS
        (c) 1996
C. DOMINIK and A. TIELENS

TYPE:      GRAIN-CLUSTER
MATERIAL:  QUARTZ
SIZES:     1E-5 .. 1E-5 CM
```

Quartz

Single Particle: Aggregate of MRN-like Particles

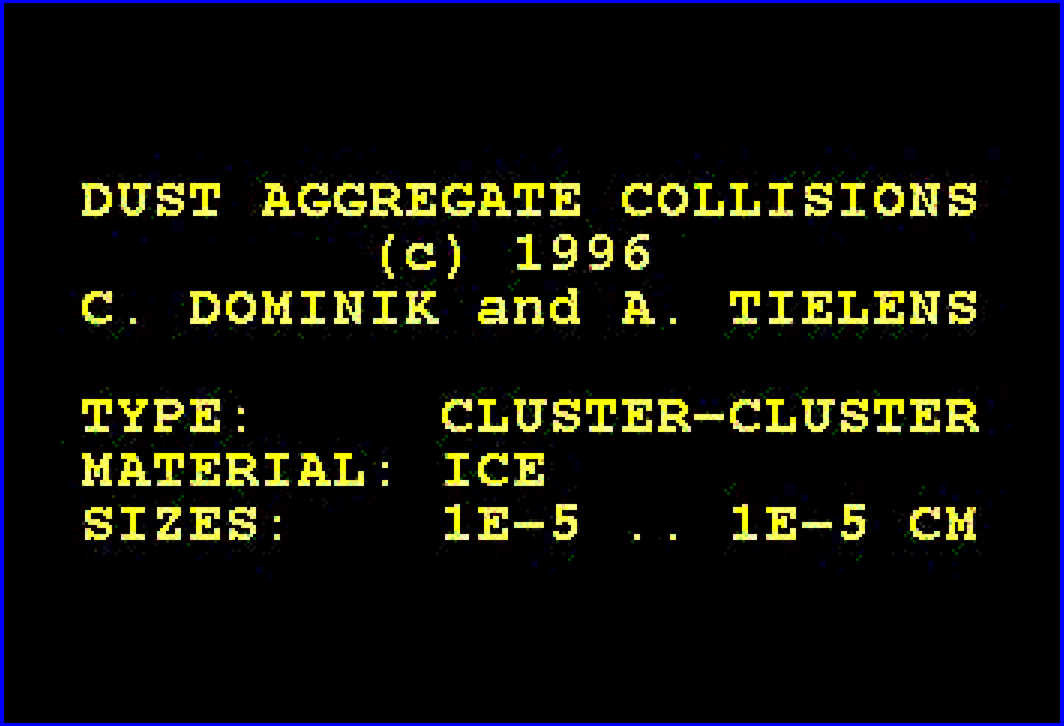


```
DUST AGGREGATE COLLISIONS
        (c) 1996
C. DOMINIK and A. TIELENS

TYPE:      GRAIN-CLUSTER
MATERIAL:  ICE
SIZES:     5E-6 .. 2E-5 CM
```

Ice

Aggregate:Aggregate
(Each made of like particles)



```
DUST AGGREGATE COLLISIONS
        (c) 1996
C. DOMINIK and A. TIELENS

TYPE:     CLUSTER-CLUSTER
MATERIAL: ICE
SIZES:    1E-5 .. 1E-5 CM
```

Ice

Grain Growth in Cores?

Some, but not too much.

Weidenschilling & Ruzmaikina (1994) find "...weak turbulence results in few collisions and preserves [original particle size distribution, while] strong turbulence tends to produce net destruction, rather than ...growth]"

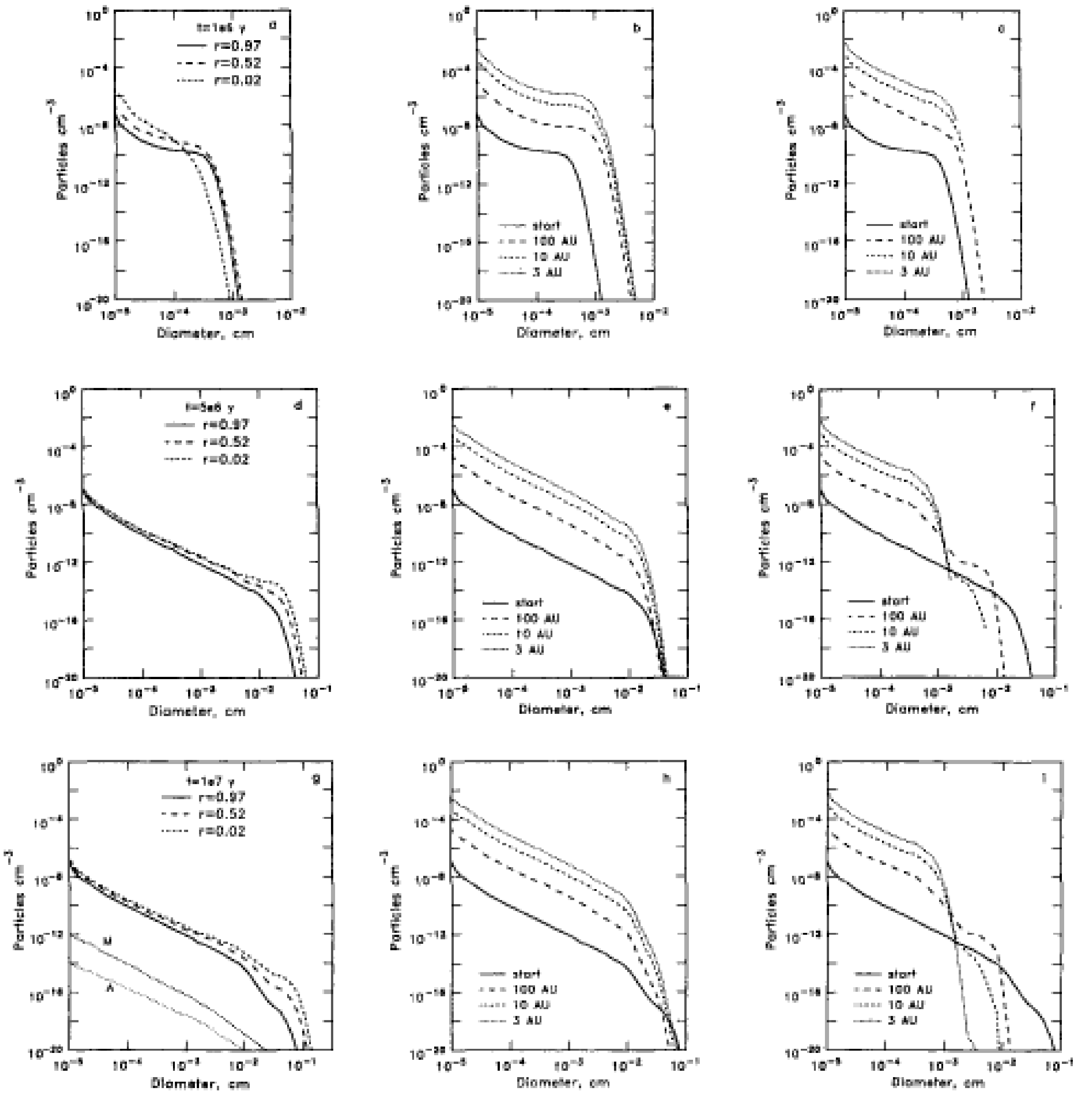


FIG. 4.—(a–i) Results for the nominal cloud model. The plots show size distributions expressed as numbers of particles per logarithmic diameter interval $2^{1/3}$. Plots give results for three values of r in the static cloud, after evolution times of 10^6 yr (a), 5×10^6 yr (d), and 10^7 yr (g). Plots (b), (e), and (h) show the size distribution produced by collapse of the outermost zone, for assumptions of weak turbulence; (c), (f), and (i) are similar, but for strong turbulence (see text).

For a Proper Model of Big Dust around YSOs...

- *We'd need, all as functions of 3D position (and time)...*
  - "Initial" Size Distribution
  - Velocity Distributions (of dust and gas)
    - » including effects of binaries & shocks
  - Temperature Distribution
    - » including effects of "cloud surface" heating, transient grain heating & shocks
  - Composition Distribution
    - » e.g. more ices in colder regions?
  - Serious Dedication & Brilliance

Observations to Constrain a Model

- Total Flux at a given wavelength
- Integrated (unresolved) SED
- Spatially resolved SED
- Spatially resolved multi-λ polarimetry
- Spatially resolved maps of ice features
- Record in meteorites, comets & asteroids

Questions to Consider

- *How to make big dust?*
  - How long does it last in a given environment?
- *How to best detect big dust?*
- *How much big dust makes how much of a difference in:*
  - SEDs
  - mass calculations
  - chemistry
  - ISM