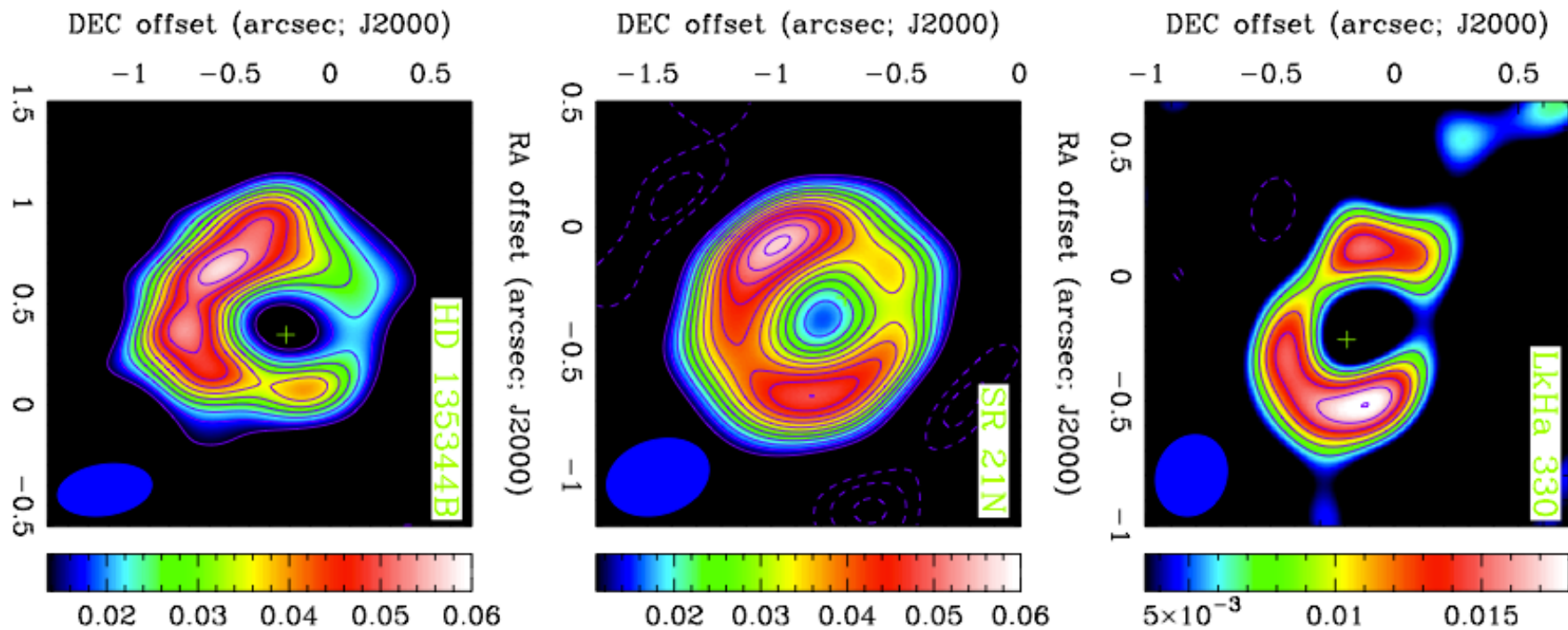
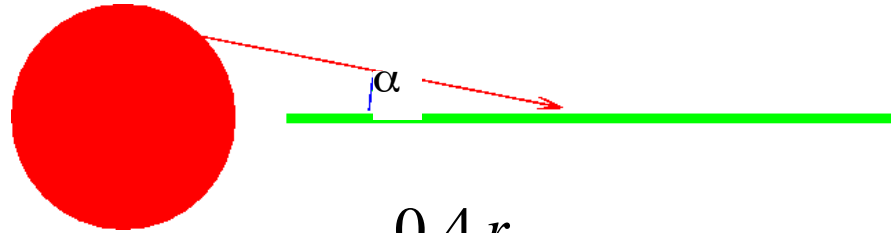


Lecture 11: The Evolution of Disks



Flat irradiated disks



$$\alpha \cong \frac{0.4 r_*}{r}$$

Irradiation flux:

$$F_{\text{irr}} = \alpha \frac{L_*}{4\pi r^2}$$

Cooling flux:

$$F_{\text{cool}} = \sigma T^4$$

$$T = \left(\frac{0.4 r_* L_*}{4\pi\sigma r^3} \right)^{1/4}$$

$$T \propto r^{-3/4}$$

Similar to active accretion disk, but flux is fixed.
Similar problem with at least a large fraction of H Ae and T
Tauri star SEDs.

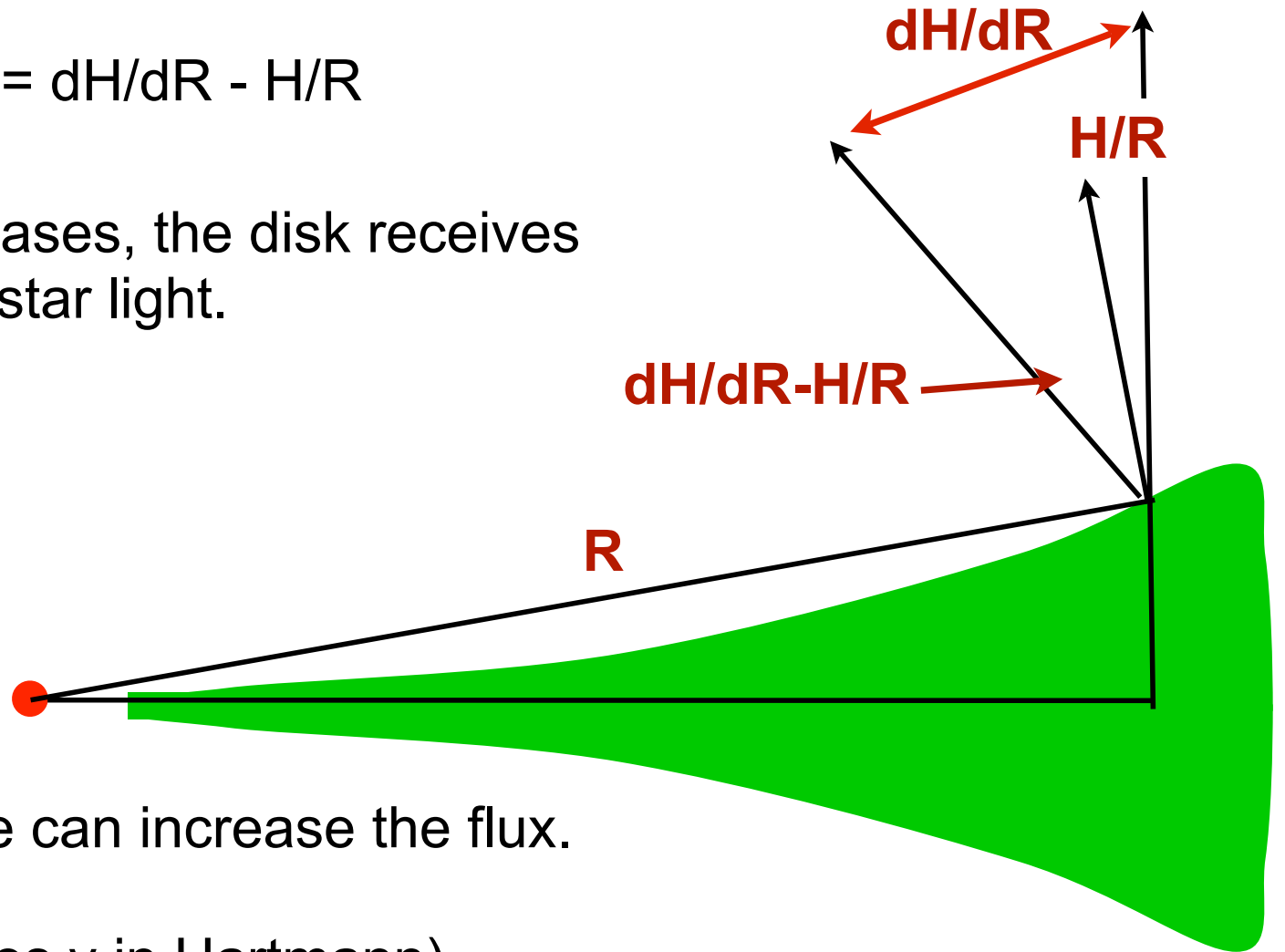
Slide pirated from K. Dullemond

Flared Disk Geometry

$$\sin \alpha = dH/dR - H/R$$

As $\sin \alpha$ increases, the disk receives more “direct” star light.

Flaring geometry:



In this case, we can increase the flux.

(Note $\sin \alpha = \cos \gamma$ in Hartmann)

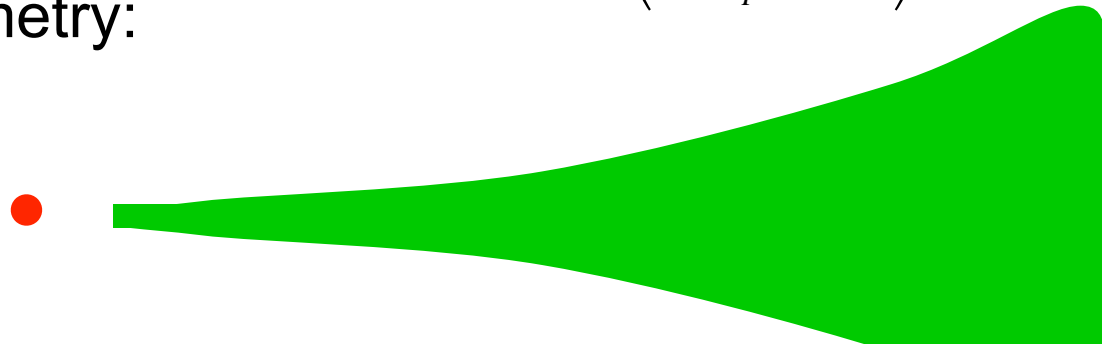
Flared disks: Chiang & Goldreich model

$$h^7 = \left(\frac{k}{\mu m_p GM_*} \right)^4 r^9 \frac{\xi}{\sigma} \frac{\chi L_*}{4\pi}$$

We therefore have:

$$h = C^{1/7} r^{9/7} \quad \text{with} \quad C = \left(\frac{k}{\mu m_p GM_*} \right)^4 \frac{\xi}{\sigma} \frac{\chi L_*}{4\pi}$$

Flaring geometry:

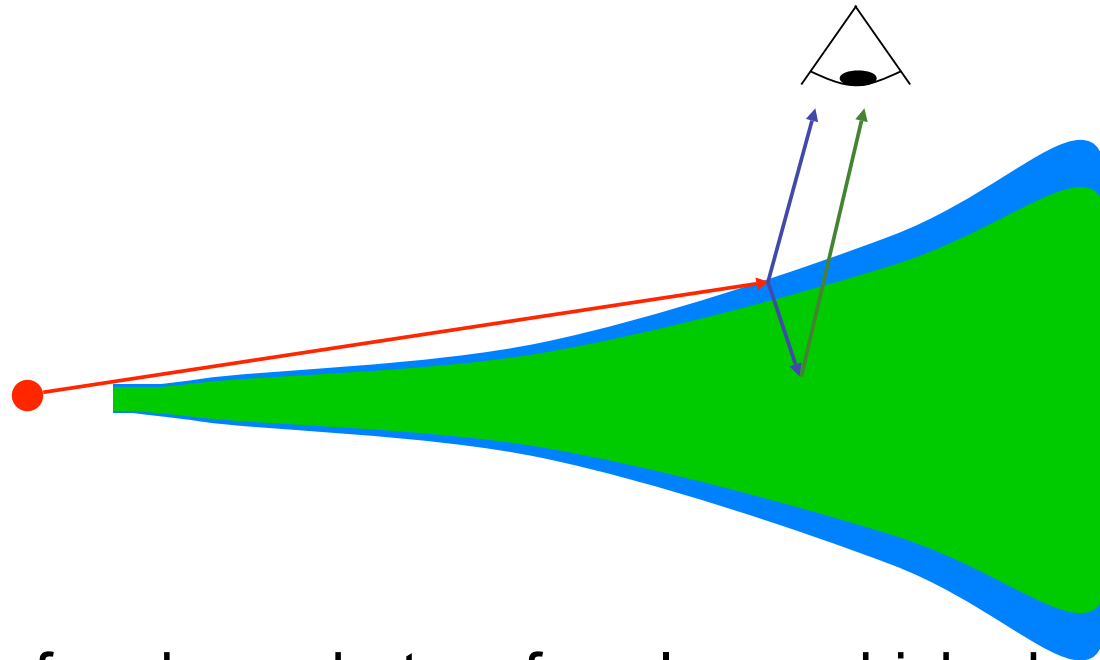


$$h \propto r^{9/7}, T \propto r^{-3/7} \quad (18)$$

Thus, the temperature gradient is much less steep than $T \propto r^{-3/4}$ for flat disks.

Remark: in general χ is not a constant (it decreases with r). The flaring is typically $< 9/7$

The Superthermal Surface Layer



Disk therefore has a hot surface layer which absorbs all stellar radiation. It is optically thick at visible wavelengths, but optically thin in the infrared.

The hot surface emits in the infrared. Half of it is re-emitted upward (and escapes); half of it is re-emitted downward (and heats the interior of the disk).

Slide pirated from K. Dullemond

Why is the atmosphere superthermal?

A few reasons:

- High opacity for visible and UV light, lower opacity for IR light. Creates high temperature for individual grains in optically thin case.
- Geometric: grain cross-section to emitting area is 1/4. Cross section to emitting area for disk is $\sin(\alpha)$.

Disk

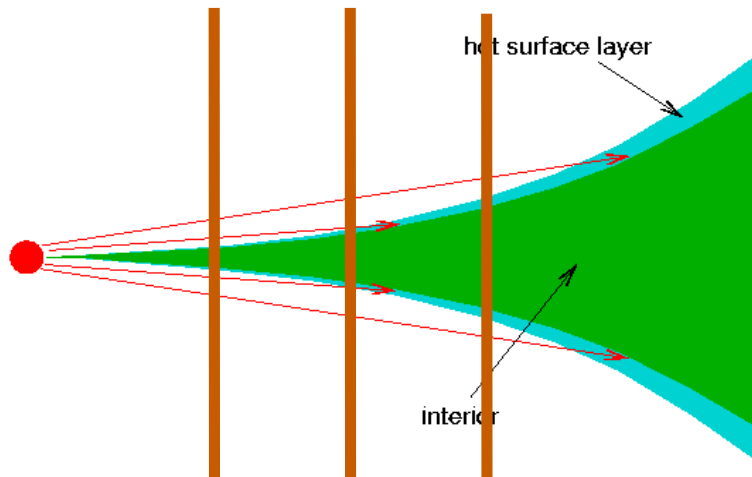
$$T^4 = \sin(\alpha) \frac{L_\star}{4\pi\sigma R^2}$$

Grey grain

$$T^4 = \frac{L_\star}{16\pi\sigma R^2}$$

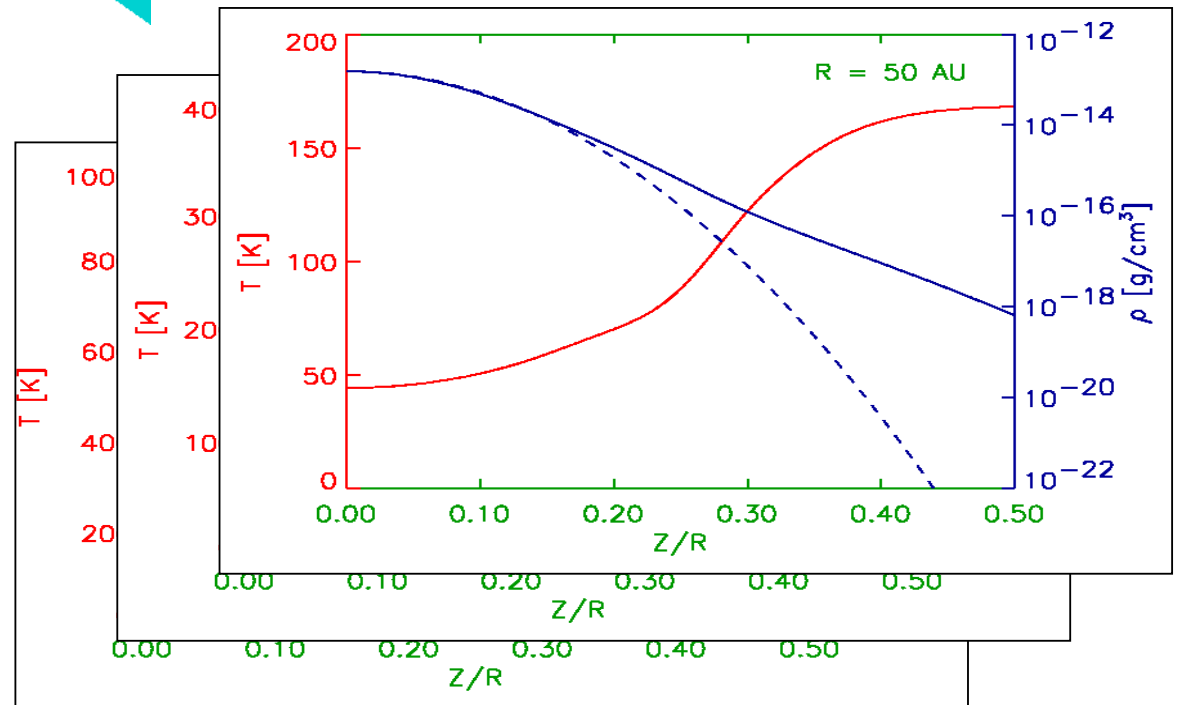
- Atmosphere is optically thin to IR radiation from disk (inner disk can radiate into cold space)

Flared disks: detailed models



← Global disk model...

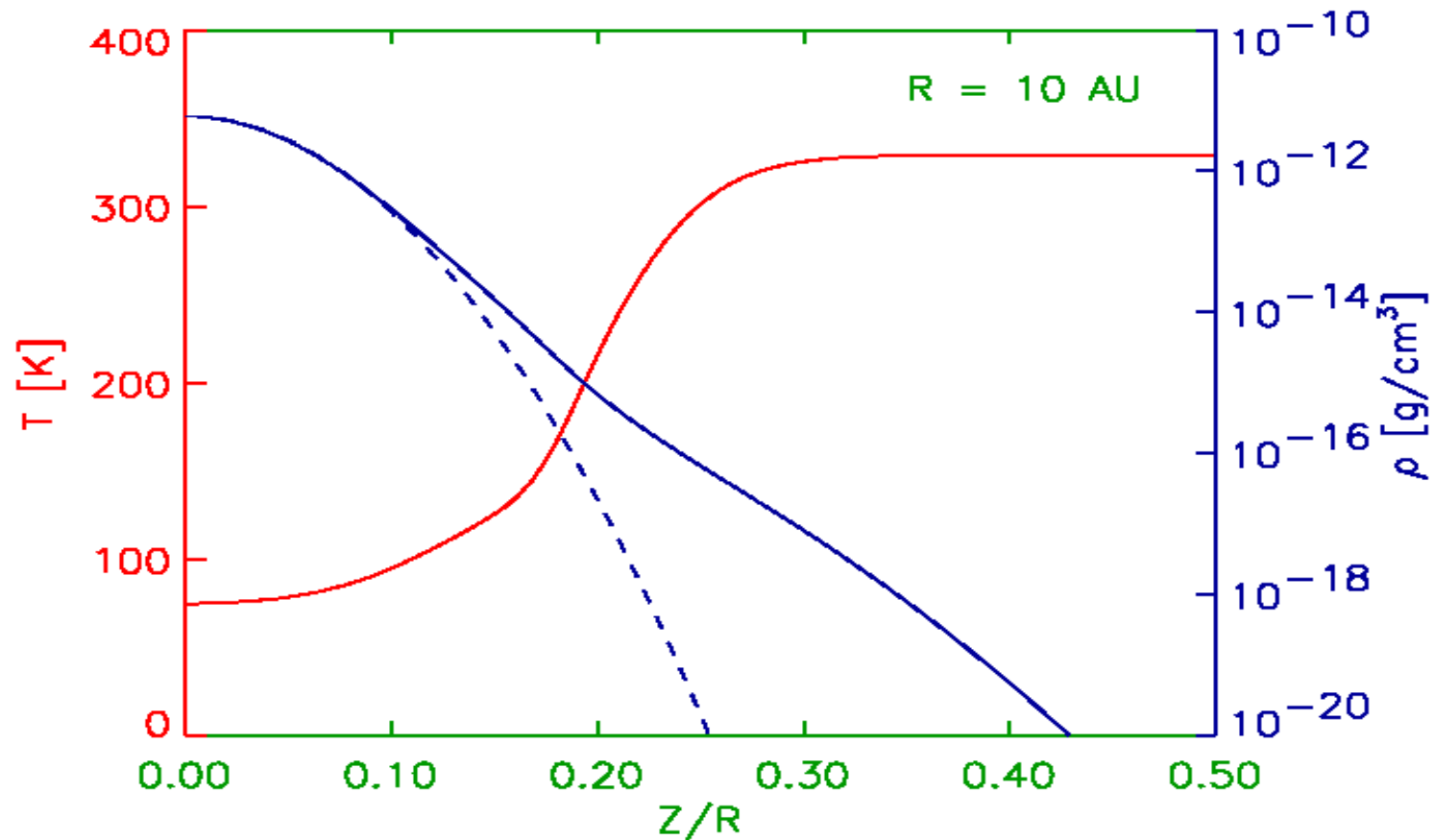
... consists of vertical slices, each forming a 1D problem. All slices are independent from each other.



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Flared disks: detailed models

A closer look at one slice:



Malbet & Bertout, 1991, ApJ 383, 814

D'Alessio et al. 1998, ApJ 500, 411

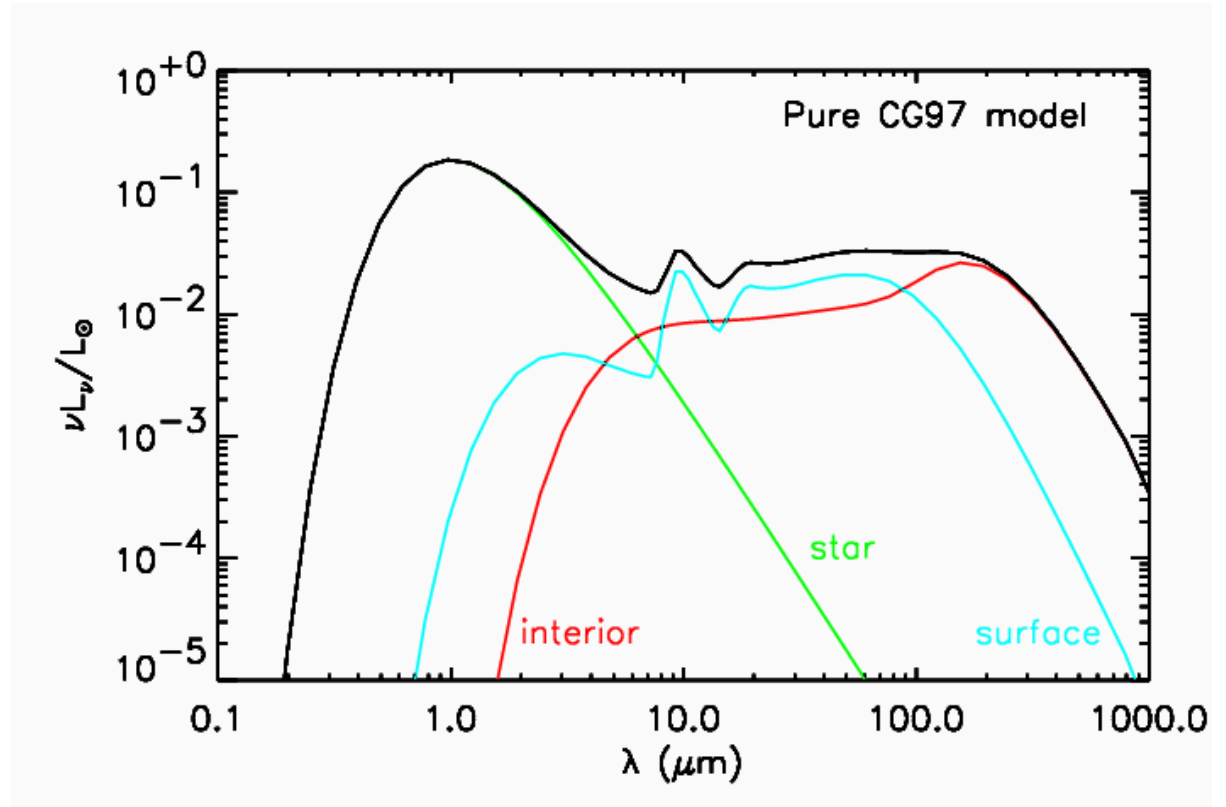
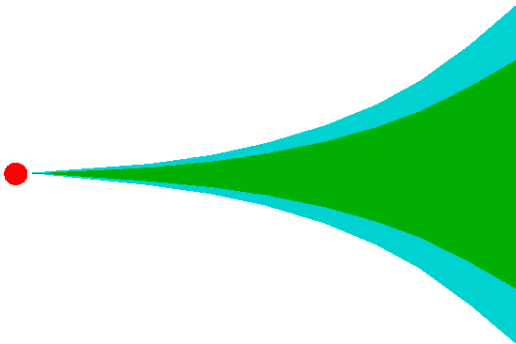
Dullemond, van Zadelhoff & Natta 2002, A&A 389, 464

Slide pirated from K. Dullemond

Chiang & Goldreich: two layer model

Model has two components:

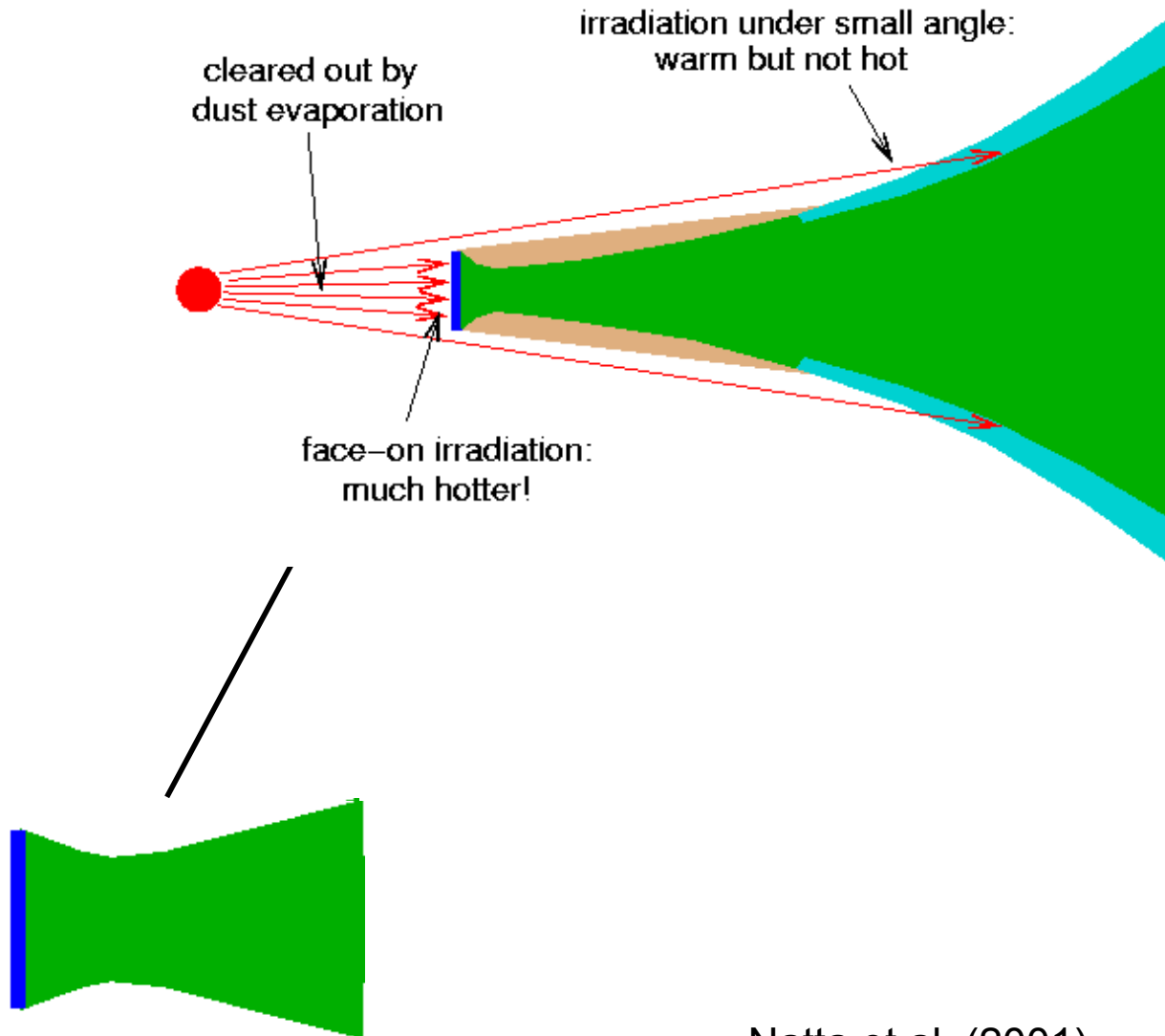
- Surface layer
- Interior



Chiang & Goldreich (1997) ApJ 490, 368

Slide pirated from K. Dullemond

Dust evaporation and disk inner rim



Slide pirated from K. Dullemond

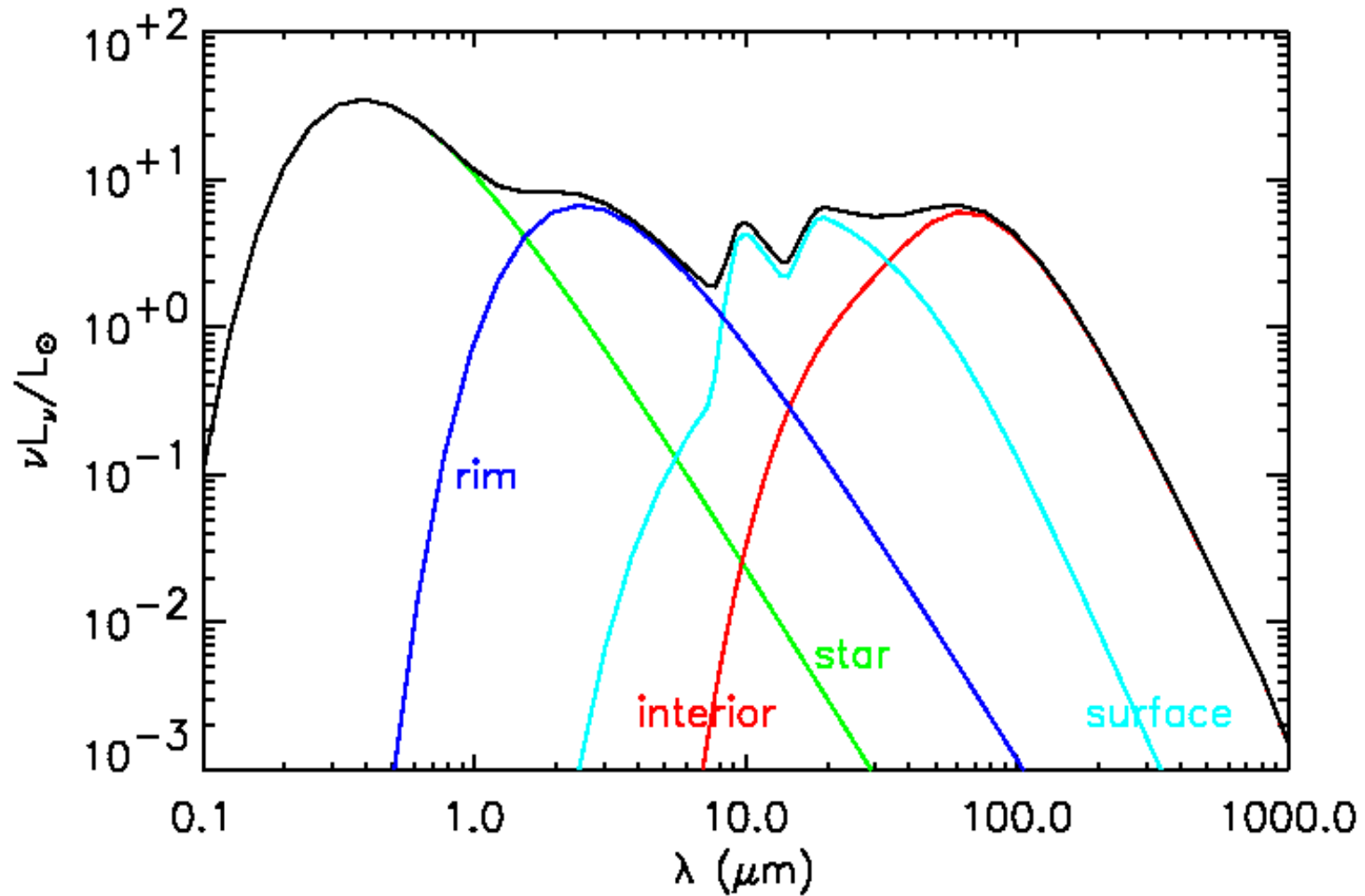
Natta et al. (2001)
Dullemond, Dominik & Natta (2001)

Dust Sublimation

TABLE 1
DUST INGREDIENTS

Composition	Ingredient	ζ_{std}	T_{sub} (K)
ISM	Silicates	0.004	1400
	Graphite	0.0025	1200
P94	Silicates	0.0034	1400
	Organics	0.0041	425
	Troilite	0.0008	680
	Water ice	0.0056	180

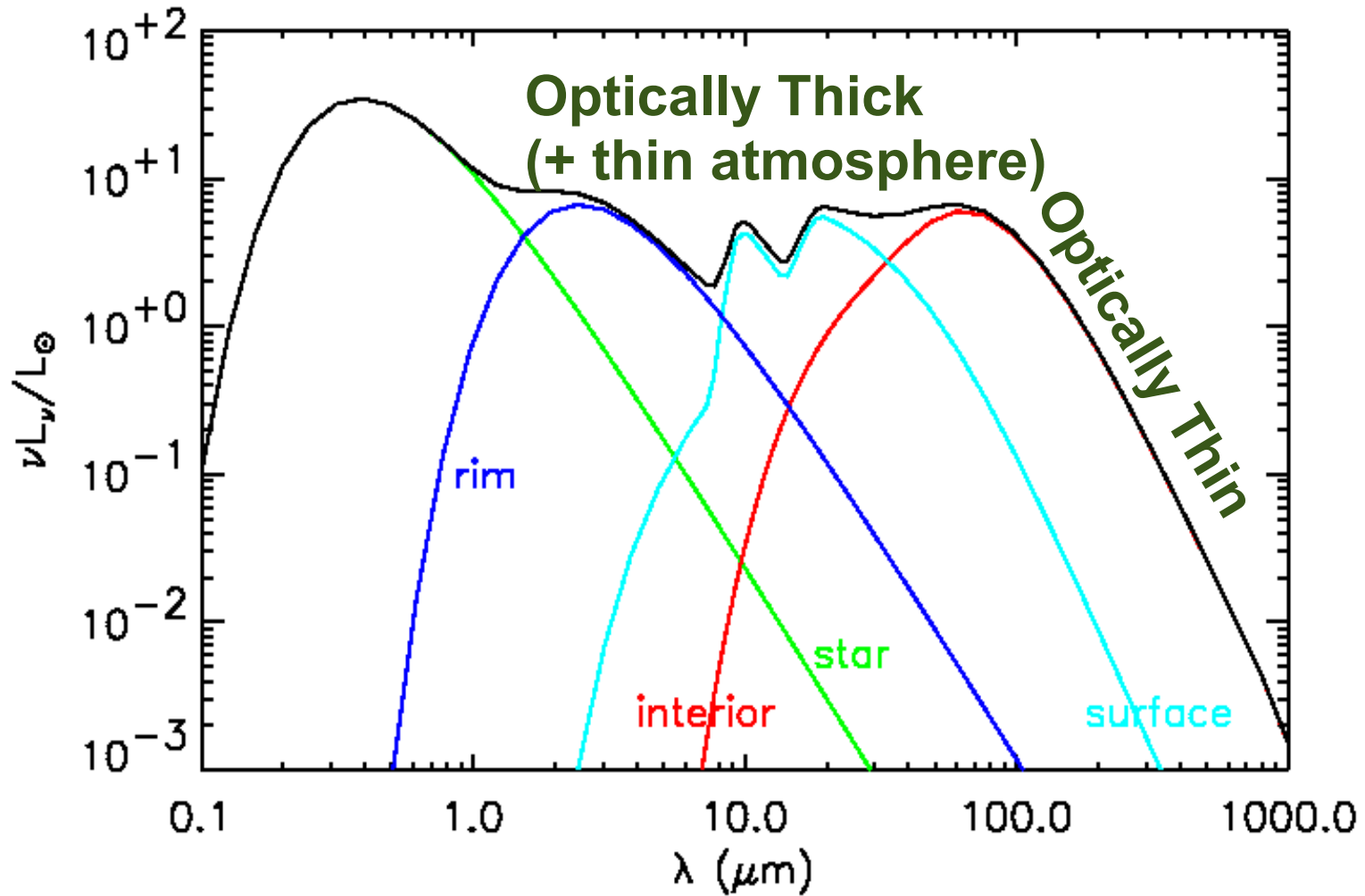
SED of disk with inner rim



Slide pirated from K. Dullemond

Measuring the Masses of Disks

SED of disk with inner rim

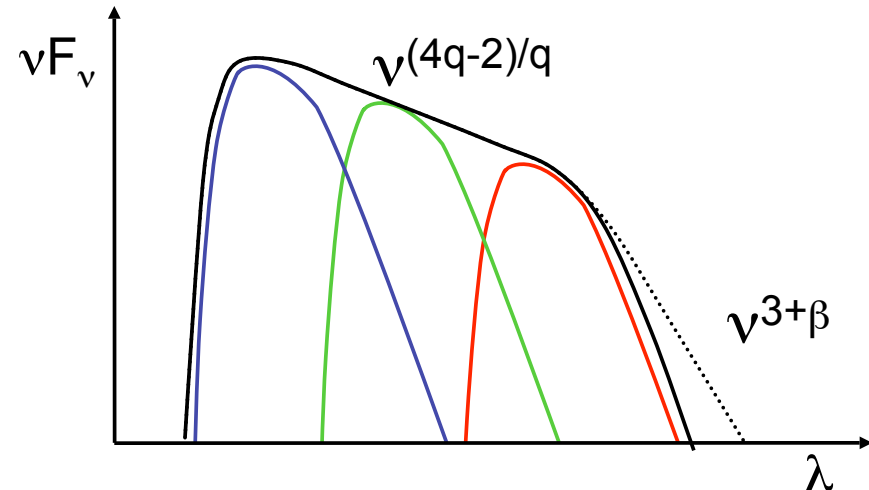


Slide pirated from K. Dullemond

Disk with finite optical depth

If disk is not very optically thick, then:

Multi-color part stays roughly the same, because of energy conservation



Rayleigh-Jeans part modified by slope of opacity. Suppose that this slope is:

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

Then the observed intensity and flux become:

$$I_\nu(r) = (1 - e^{-\tau_\nu}) B_\nu \approx \tau_\nu B_\nu \propto \kappa_\nu B_\nu$$

$$\boxed{\nu F_\nu \propto \kappa_\nu \nu B_\nu \propto \nu^{3+\beta}}$$

Measuring the Masses of Disks

Let us assume that the temperature and surface density follow a power law:

$$T = T_0 \left(\frac{R}{R_0} \right)^{-q} \quad (1)$$

$$\Sigma = \Sigma_0 \left(\frac{R}{R_0} \right)^{-p} \quad (2)$$

Then if $\tau_\nu \ll 1$ then, where $\tau_\nu = \kappa_\nu \Sigma$ where κ_ν is the absorption per mass

$$\nu L_\nu = 4\pi \int_{R_i}^{R_d} \nu B_\nu \kappa_\nu \Sigma(R) 2\pi R dR \quad (3)$$

$$\nu L_\nu = \frac{16\pi^2 k}{c^2} \nu^3 \kappa_\nu \Sigma_0 T_0 R_0^2 \frac{R_d / R_0^{2-p-q}}{(2-p-q)} \quad (4)$$

Measuring the Masses of Disks

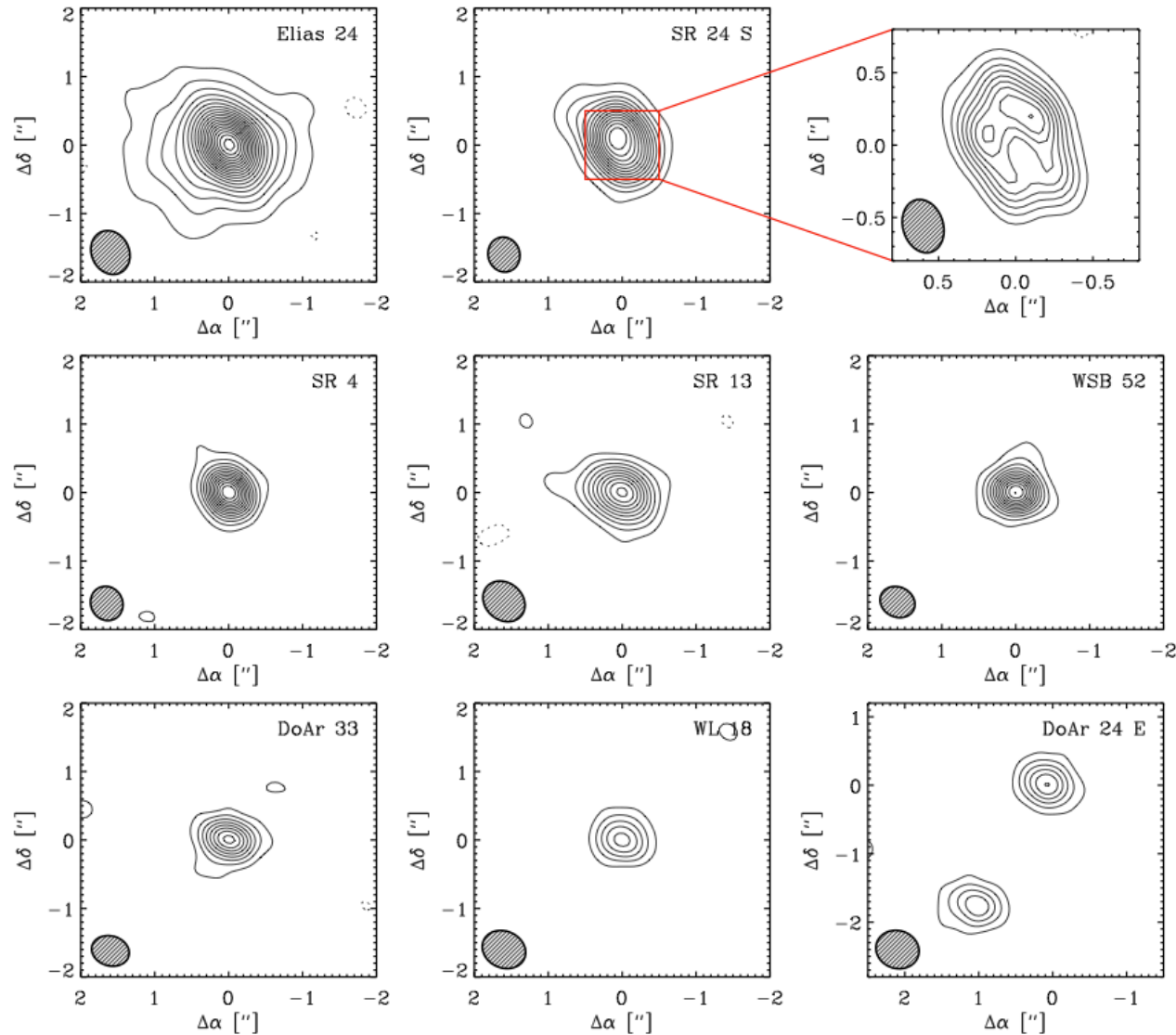
and

$$M_d = \int_{R_i}^{R_d} 2\pi\Sigma R dR = 2\pi\Sigma_0 R_0^2 \frac{R_d/R_0^{2-p}}{(2-p)} \quad (5)$$

which substituting for Σ

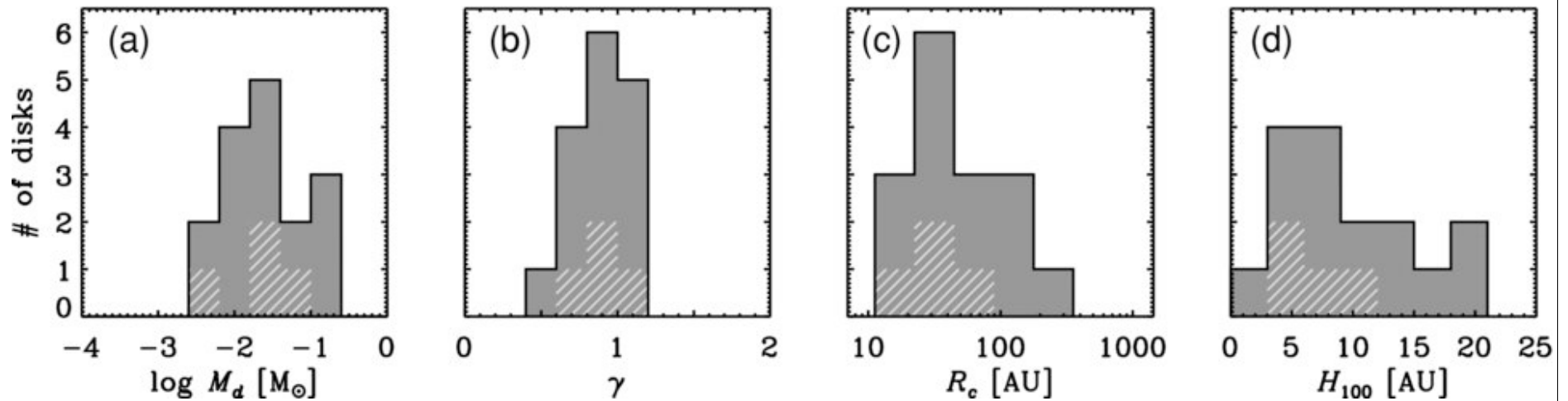
$$\nu L_\nu = \frac{8\pi k\nu^3 \kappa_\nu}{c^2} M_d T_0 \left(\frac{R}{R_0}\right)^{-q} \frac{2-p}{2-p-q} \quad (6)$$

Measuring the Mass of Disks



880 μm , SubmilliMeter Array (SMA) Images, Andrews et al. 2009

Measuring the Masses of Disks

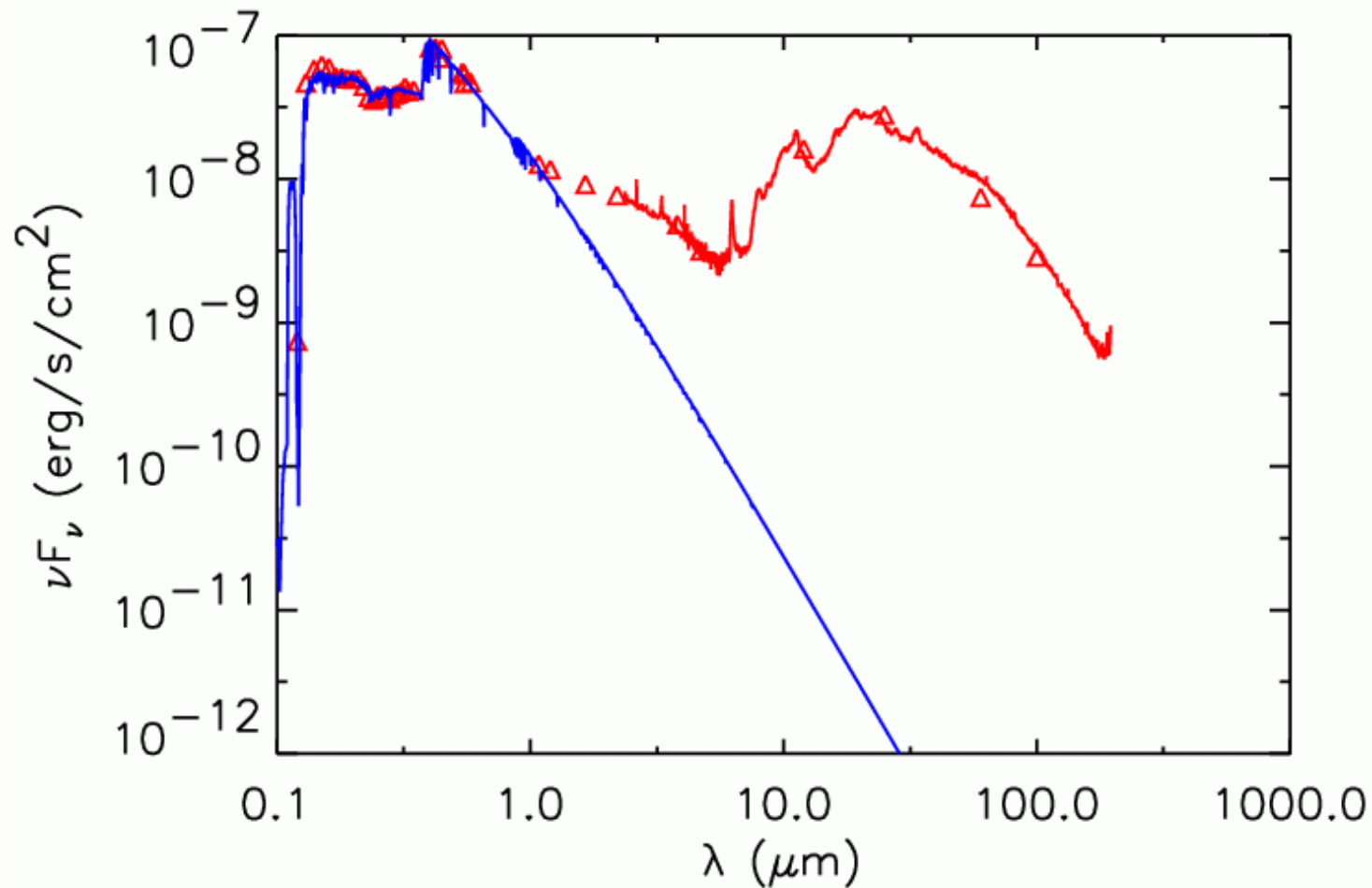


$$\Sigma = (2 - \gamma) \frac{M_d}{2\pi R_c^2} \left(\frac{R}{R_c} \right)^{-\gamma} \exp \left[- \left(\frac{R}{R_c} \right)^{2-\gamma} \right], \quad (1)$$

Andrews et al. 2010

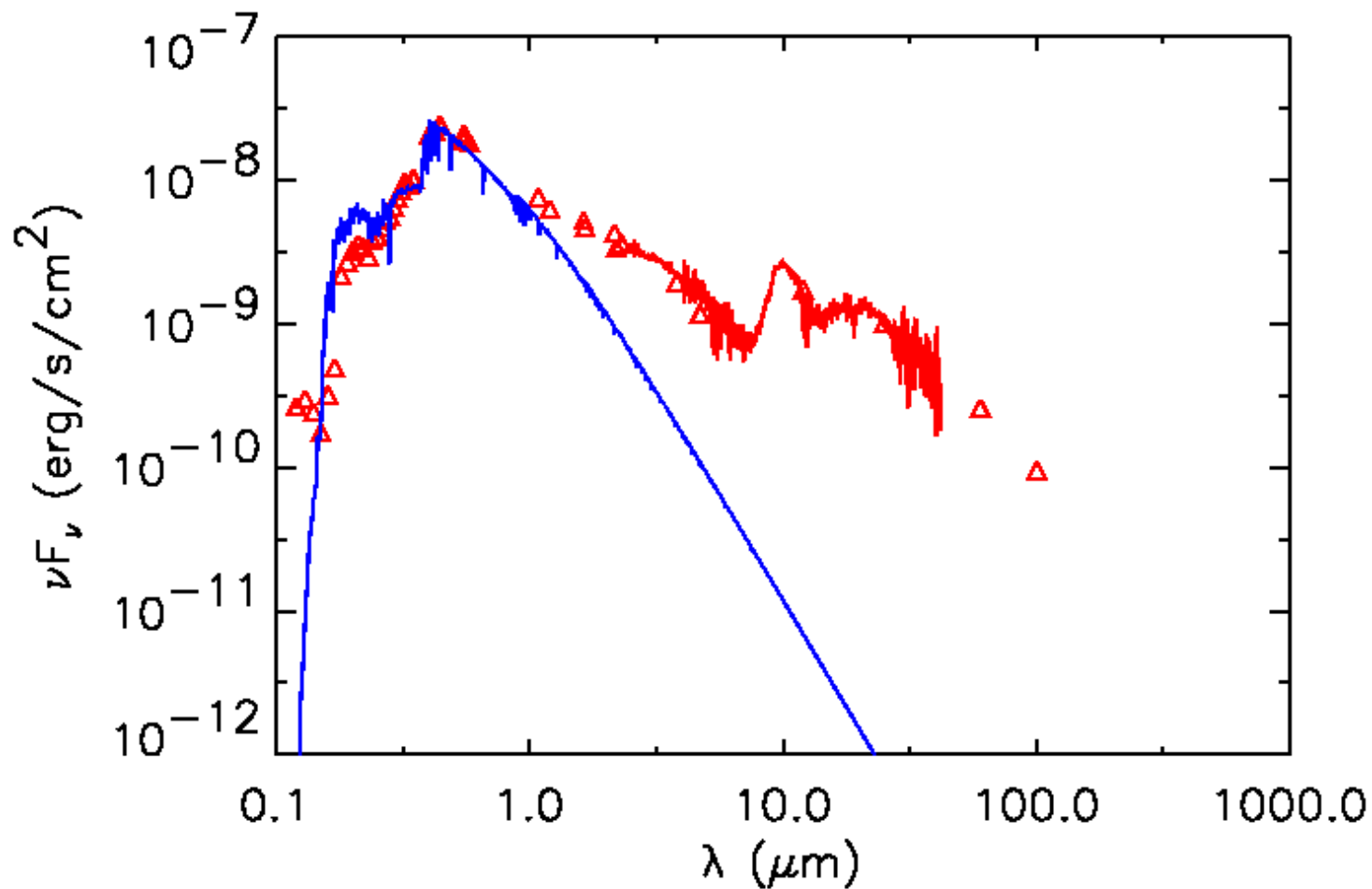
Disk Evolution

Example: HD100546



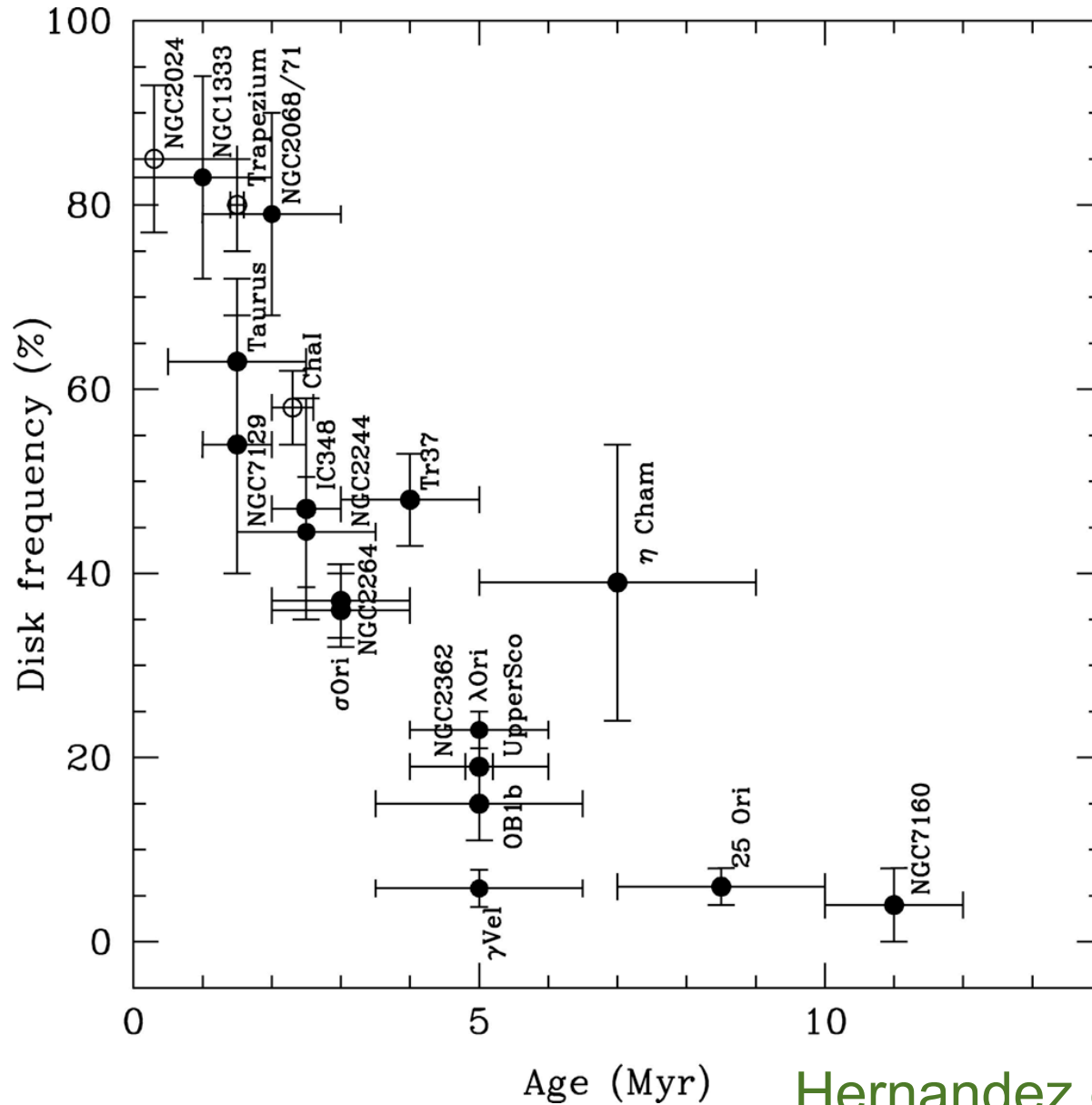
Must have weak inner rim (weak near-IR flux),
but must be strongly flaring (strong far-IR flux)

Example: HD 144432



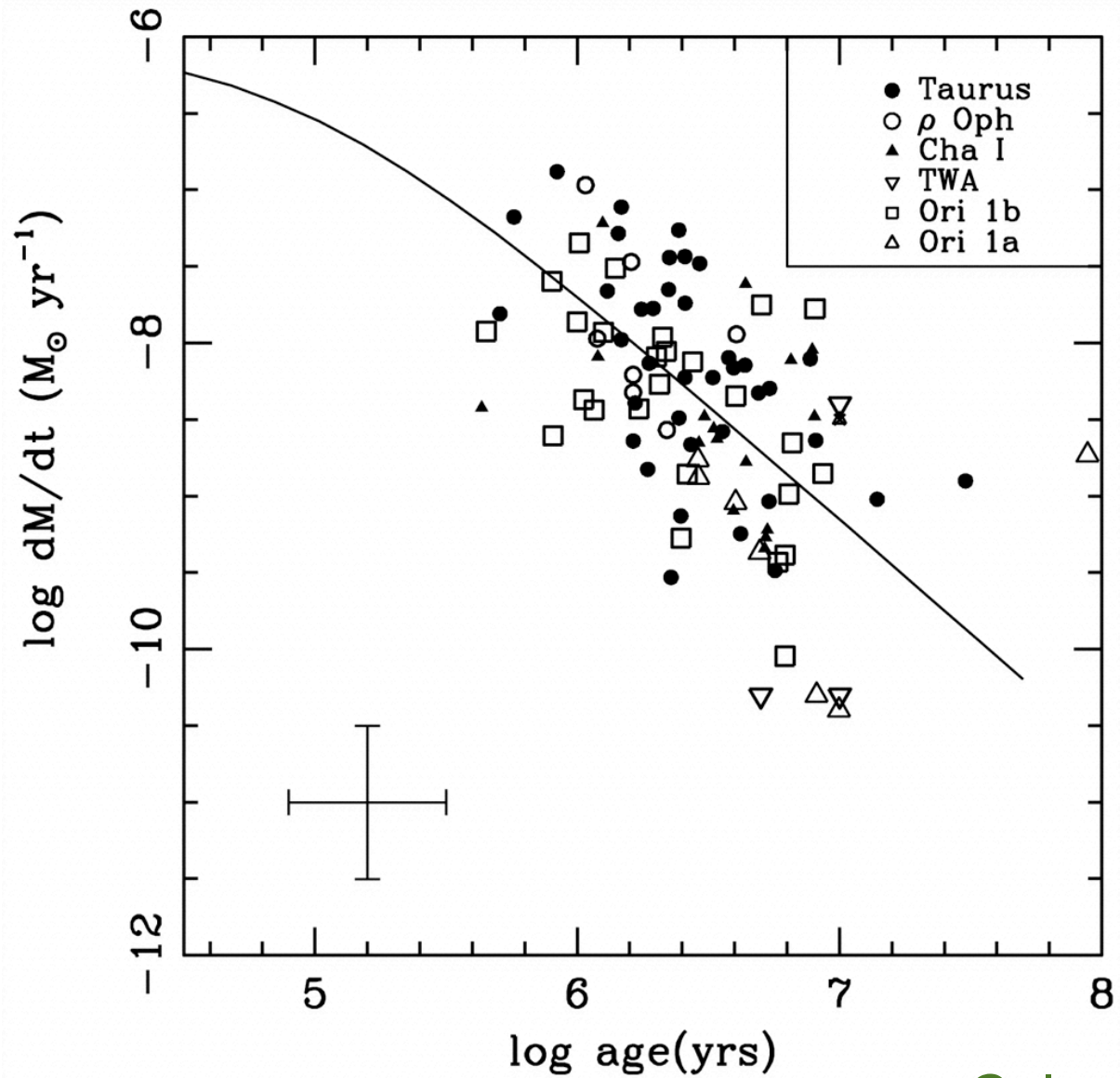
Must have strong inner rim (strong near-IR flux), but either small or non-flaring outer disk (weak far-IR flux)

Disk Evolution I: the disappearance of gas disk in 5 Myr



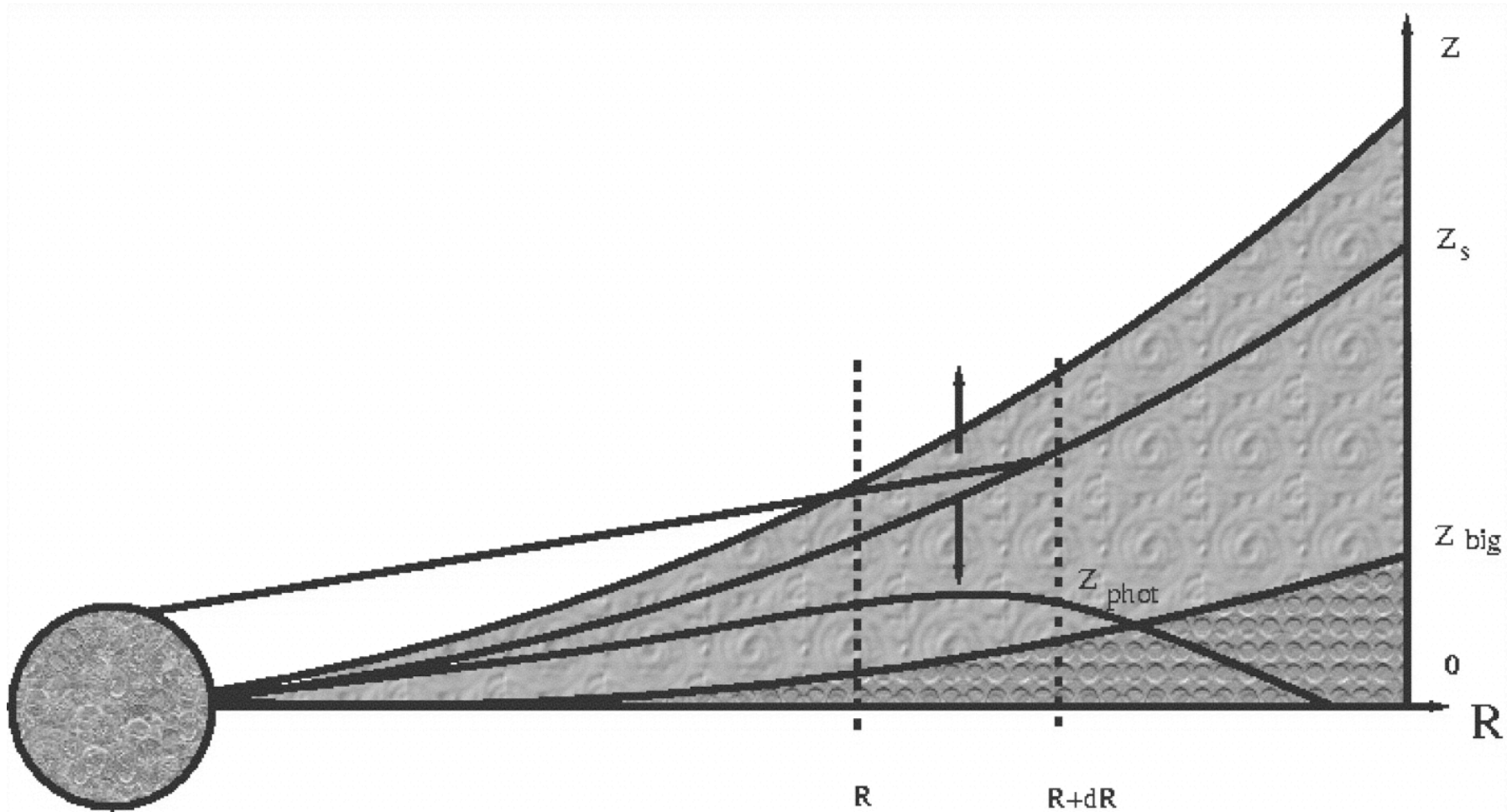
Hernandez et al. 2008

Disk Evolution I: the disappearance of gas disk in 5 Myr



Calvet et al. 2005

Disk Evolution II: Evidence for Dust Settling



Dust Grain Distribution

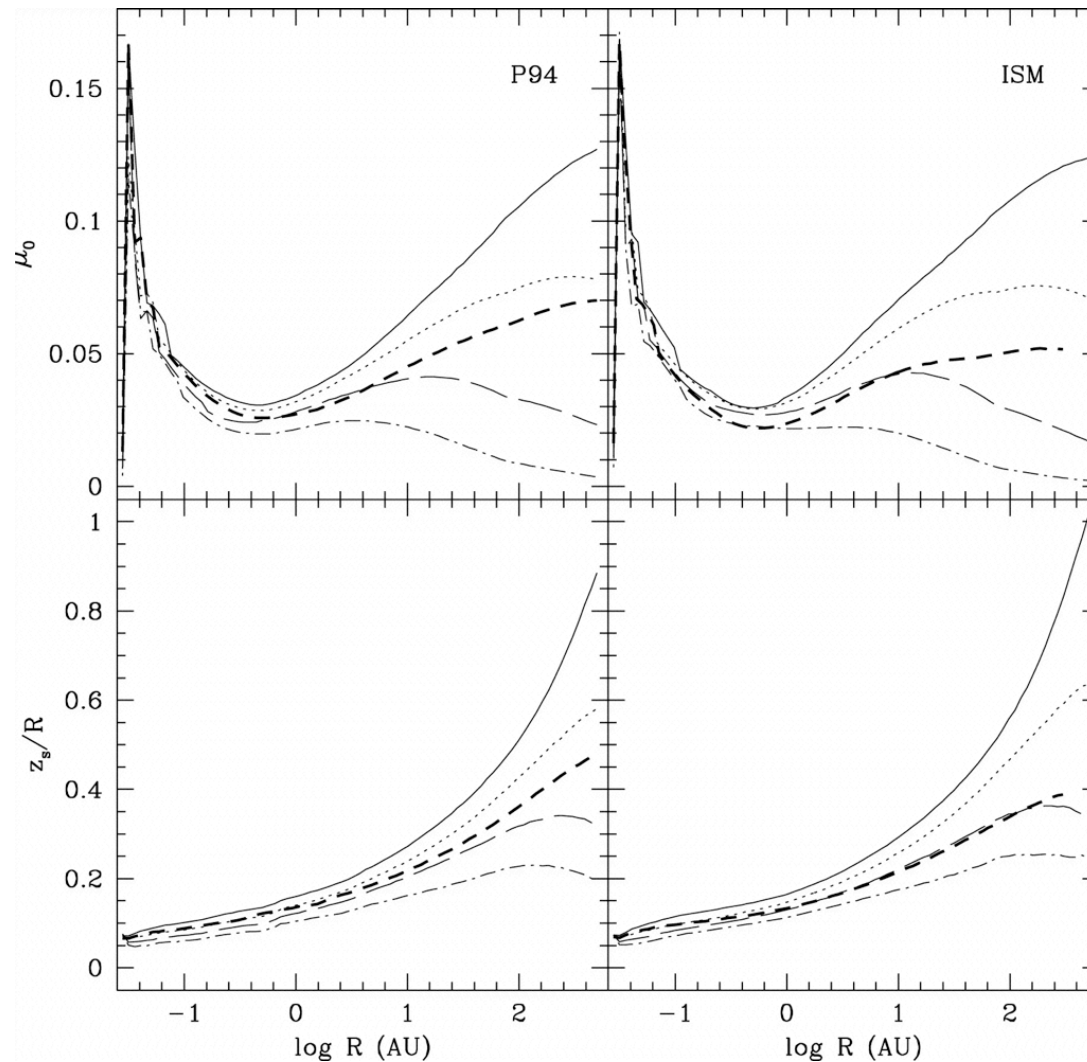
There is a distribution of grain sizes: from 0.001 μm to 1 μm in the ISM

Extinction law suggests

$dn/da = k a^{-3.5}$ where a is the grain radius and n is the density of grains with radius a .

a_{max} is 0.03 μm in ISM - most mass in larger grains

Disk Evolution II: Evidence for Dust Settling

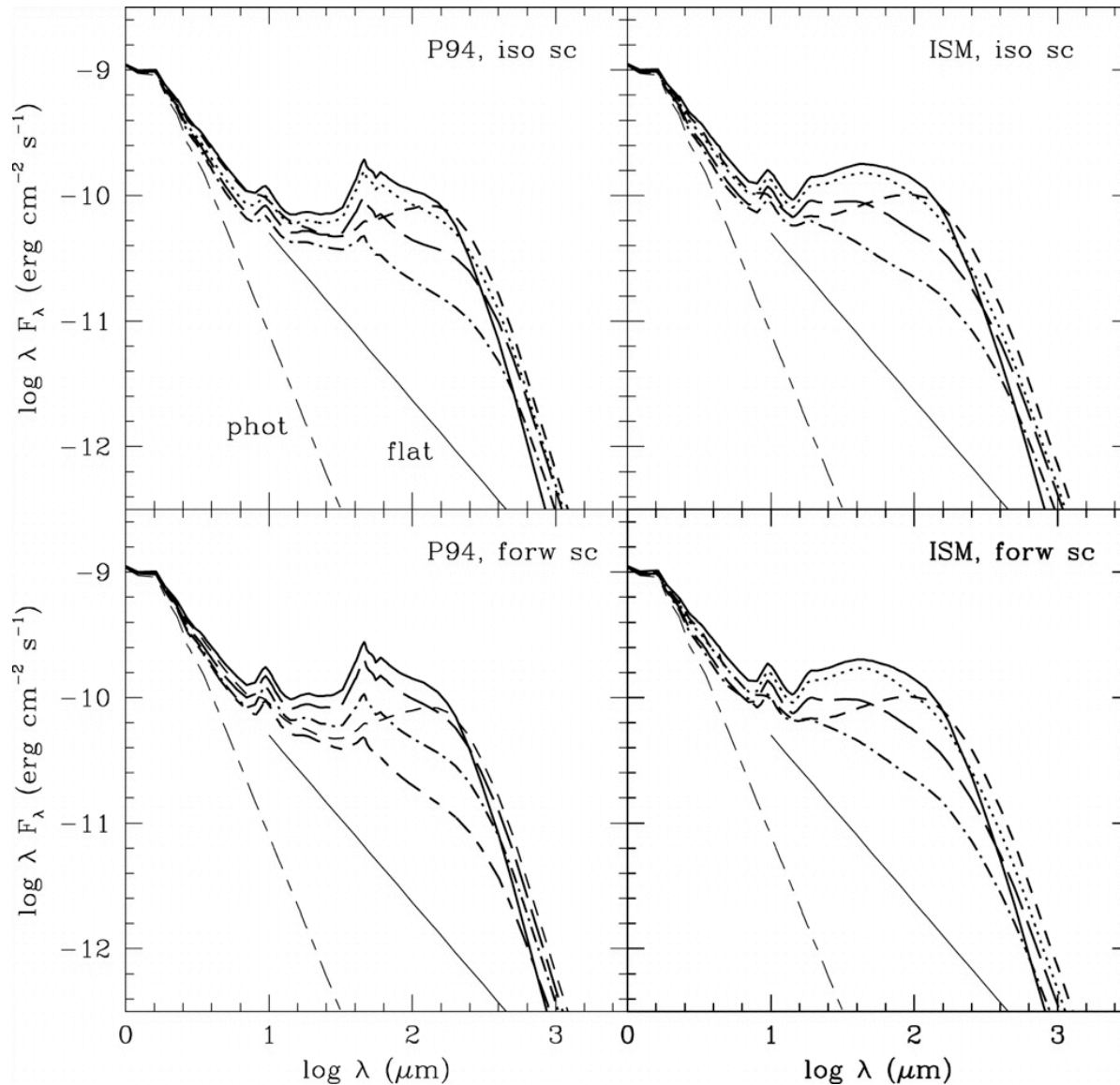


solid: $\epsilon = 1$
dotted: $\epsilon = 0.1$
long-dash: $\epsilon = 0.01$
dot-dash: $\epsilon = 0.001$
thick dash: well mix
with $a_{\max} = 1$ mm

ϵ = abundance of small grains ($< 0.25 \mu\text{m}$) grains/normal
abundance of small grains

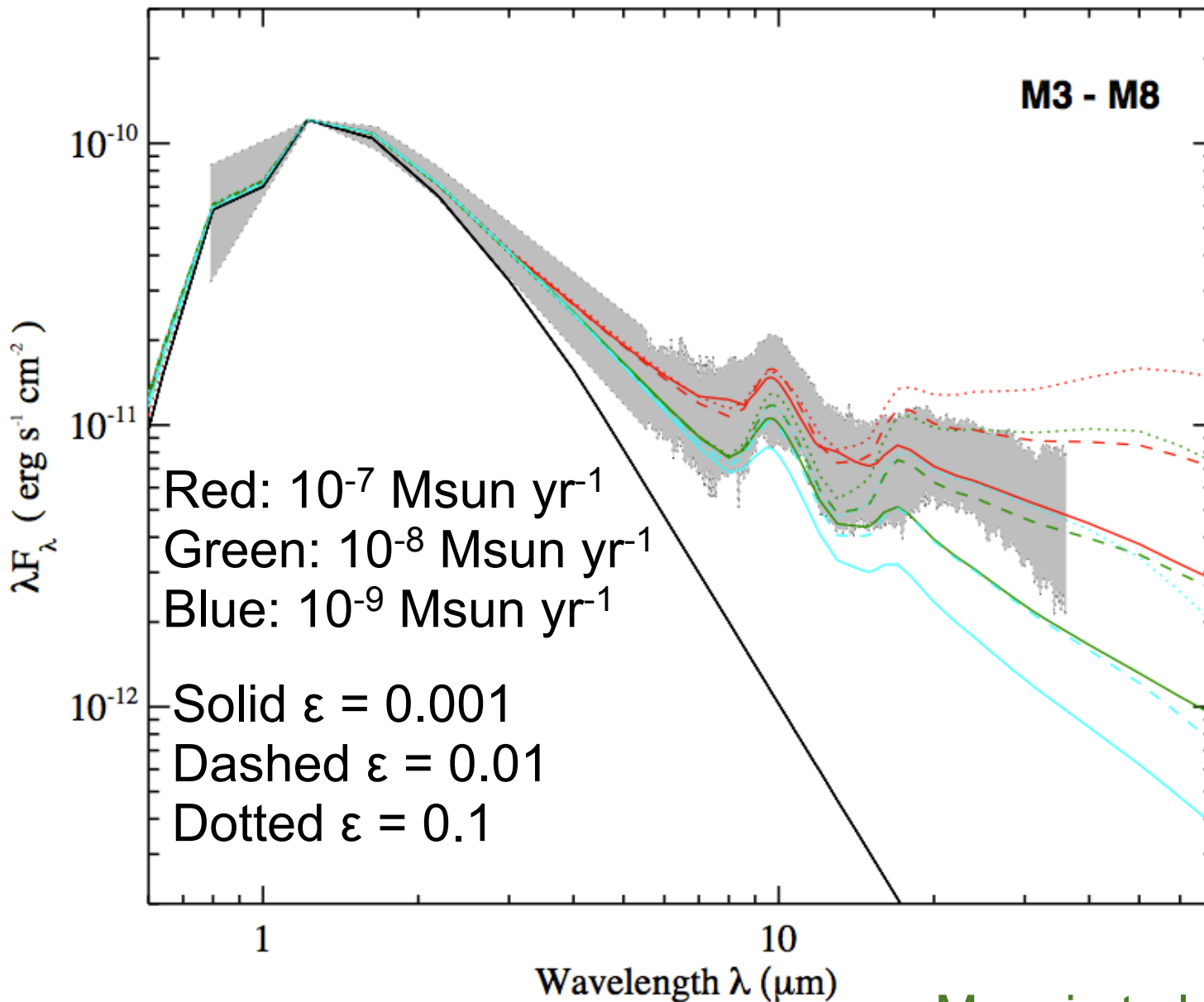
D'Alessio et al. 2006

Disk Evolution II: Evidence for Dust Settling



solid: $\epsilon = 1$
dotted: $\epsilon = 0.1$
long-dash: $\epsilon = 0.01$
dot-dash: $\epsilon = 0.001$
thick dash: well mix
with $a_{\text{max}} = 1$ mm

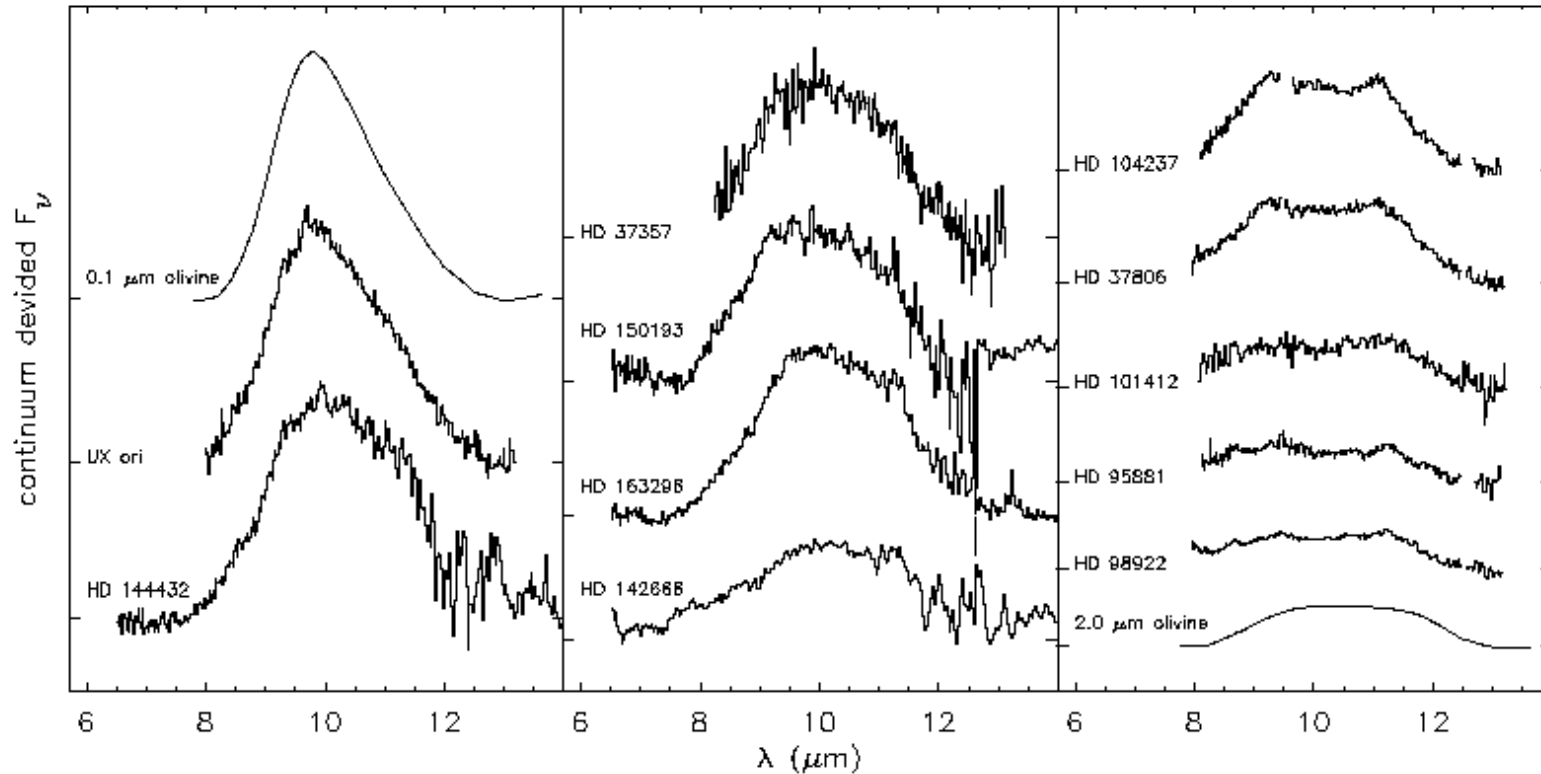
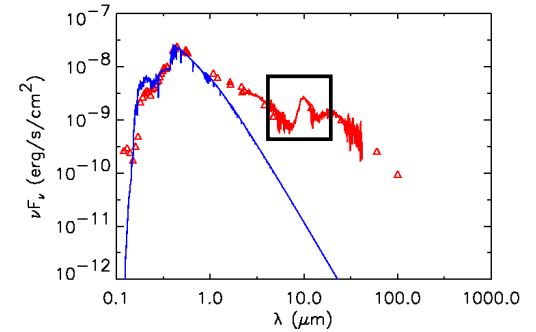
Disk Evolution II: Evidence for Dust Settling



Manoj et al. 2011

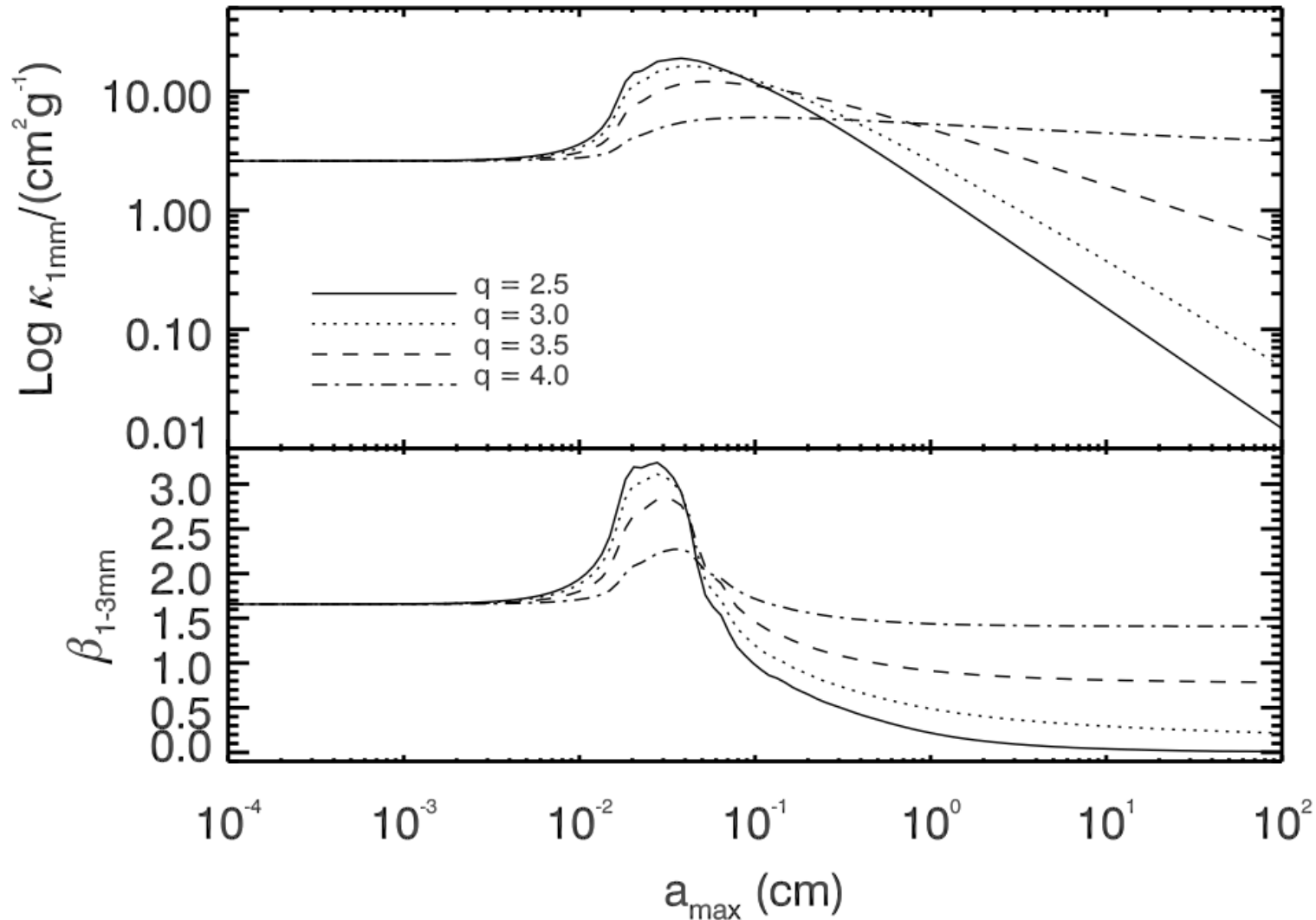
Disk Evolution III: Evidence for Grain Growth

The 10 micron silicate feature shape depends strongly on grain size. Observations show precisely these effects. Evidence of grain growth.



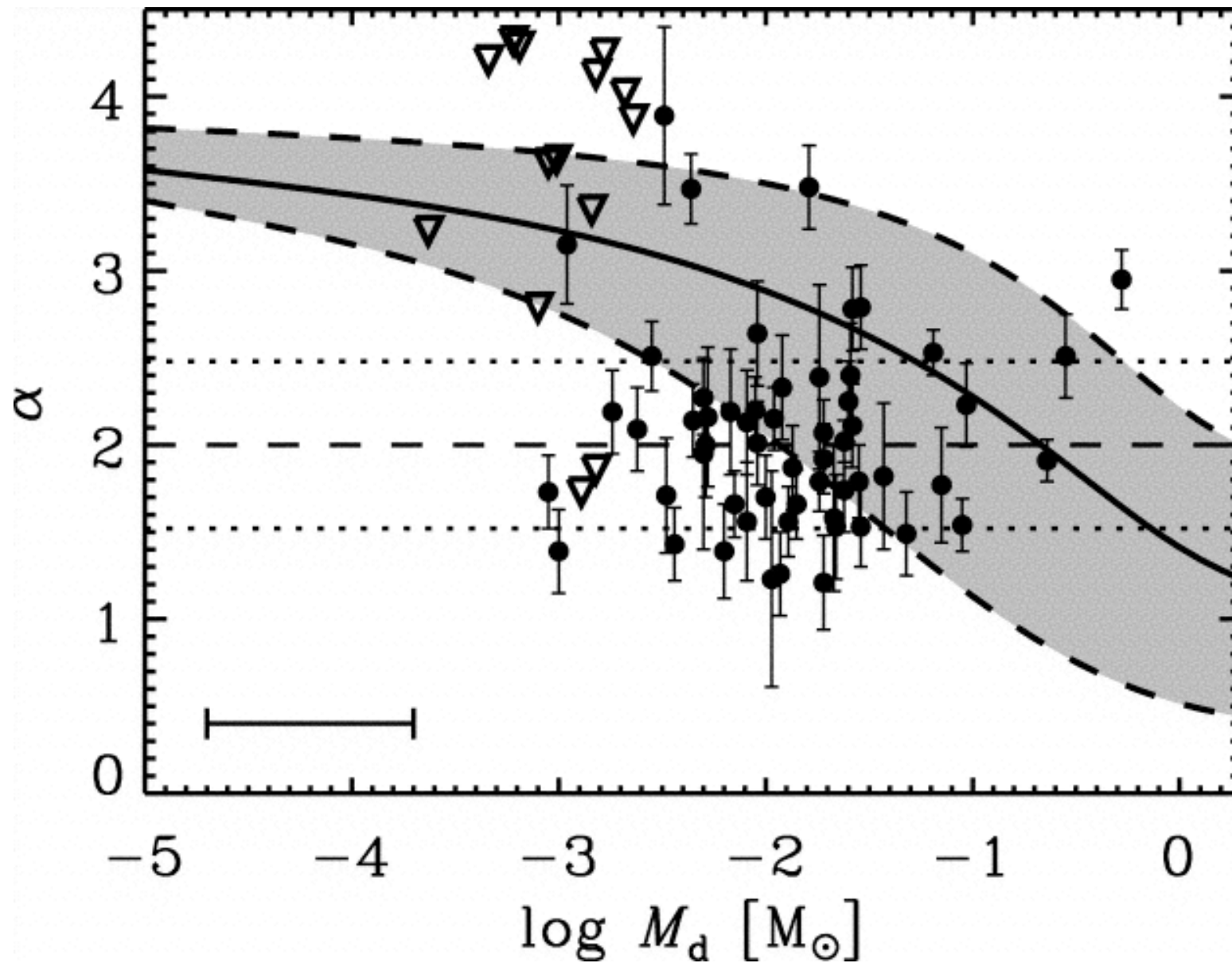
van Boekel et al. 2003

Disk Evolution II: Evidence for Grain Growth

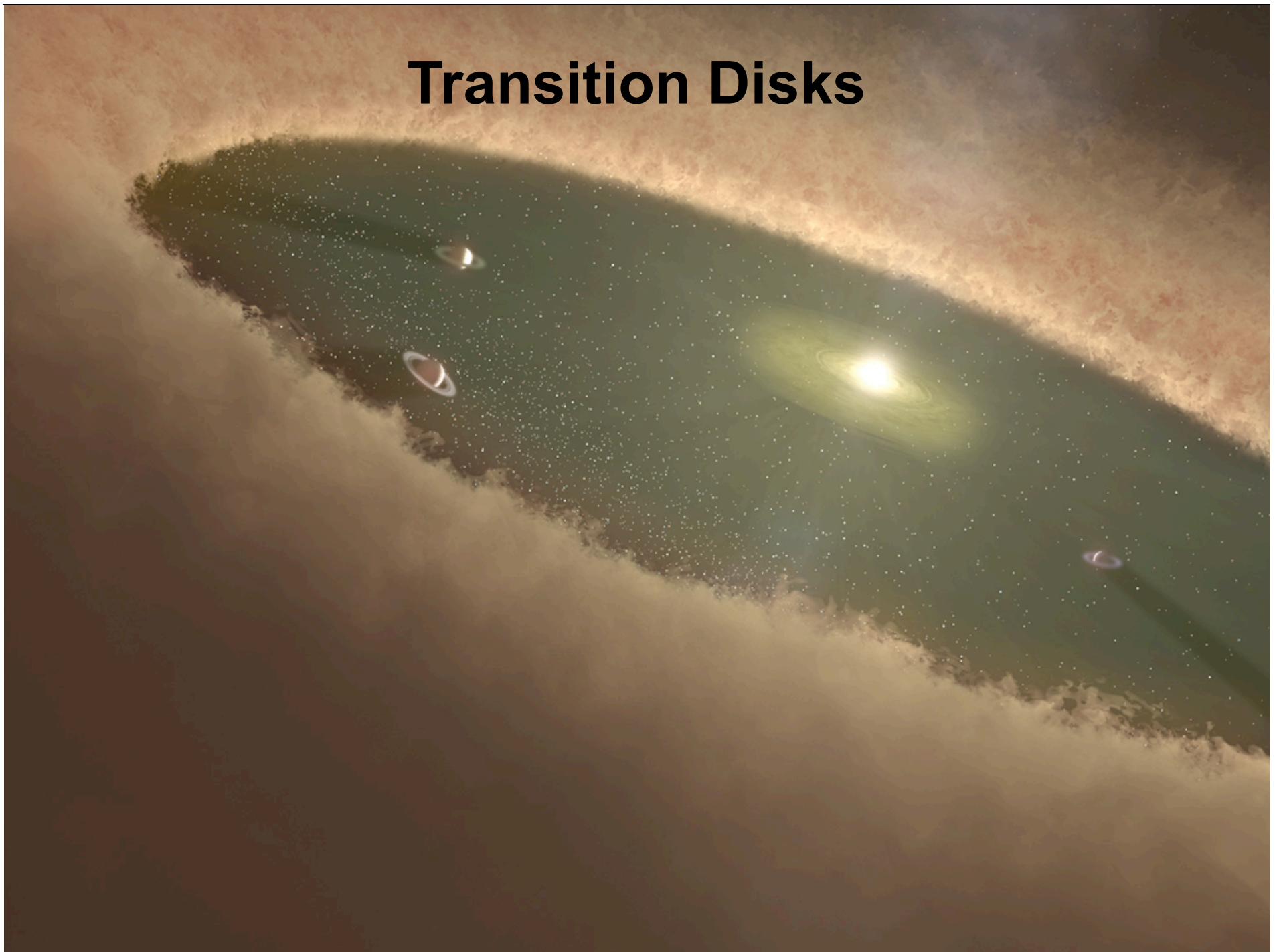


millimeter opacity: $\kappa_{\nu} = 0.1(\nu/10^{12} \text{ Hz})^{\beta} \text{ g cm}^{-2}$

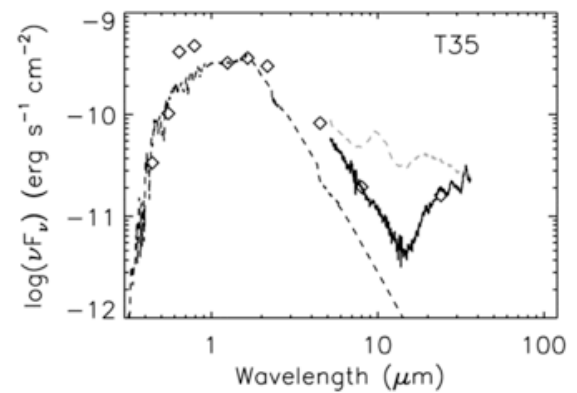
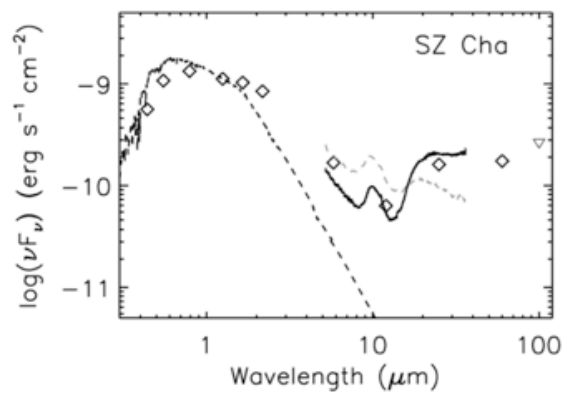
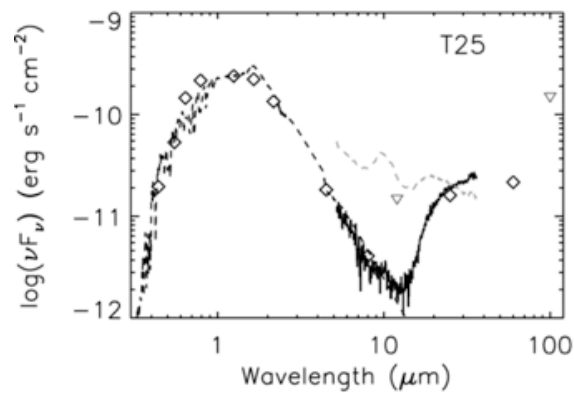
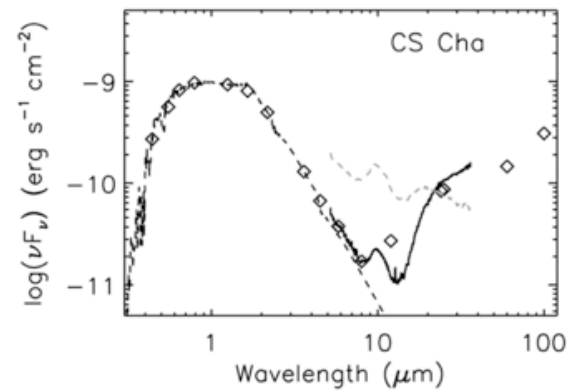
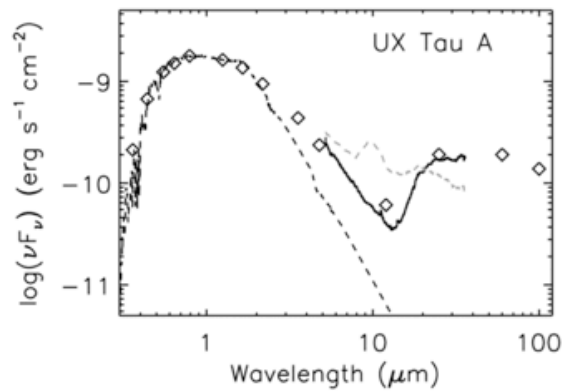
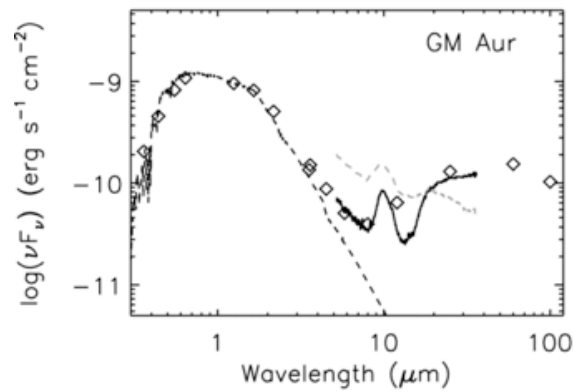
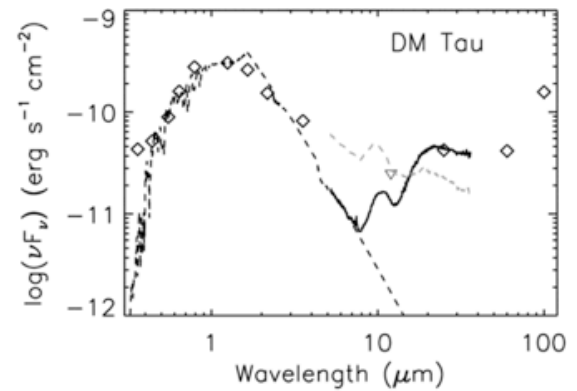
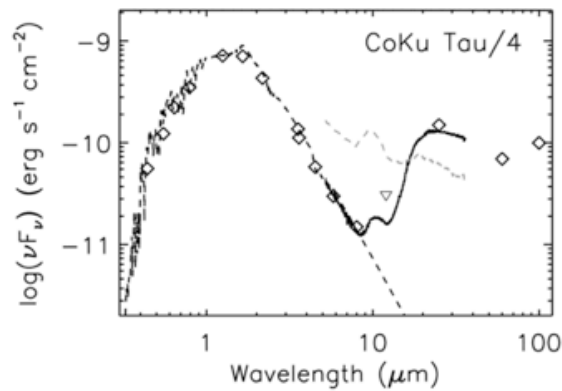
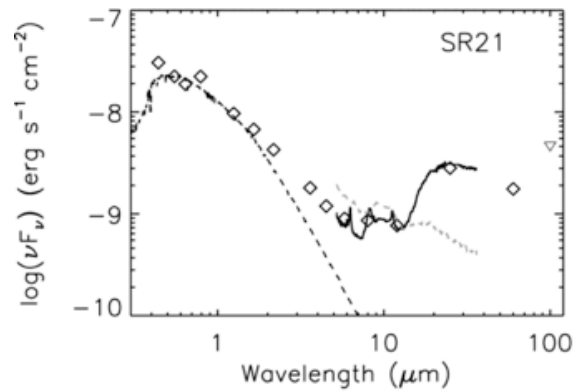
Disk Evolution III: Evidence for Grain Growth



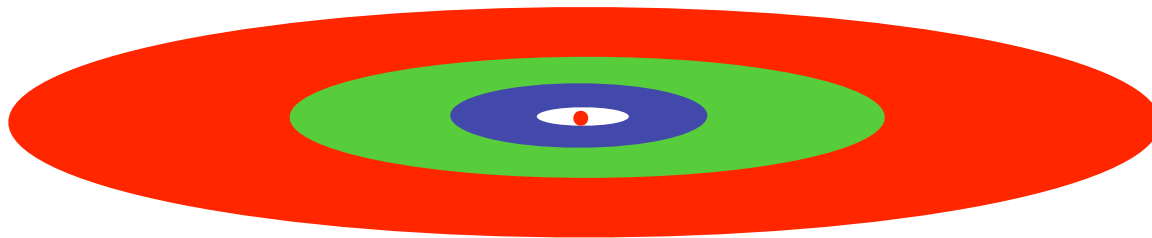
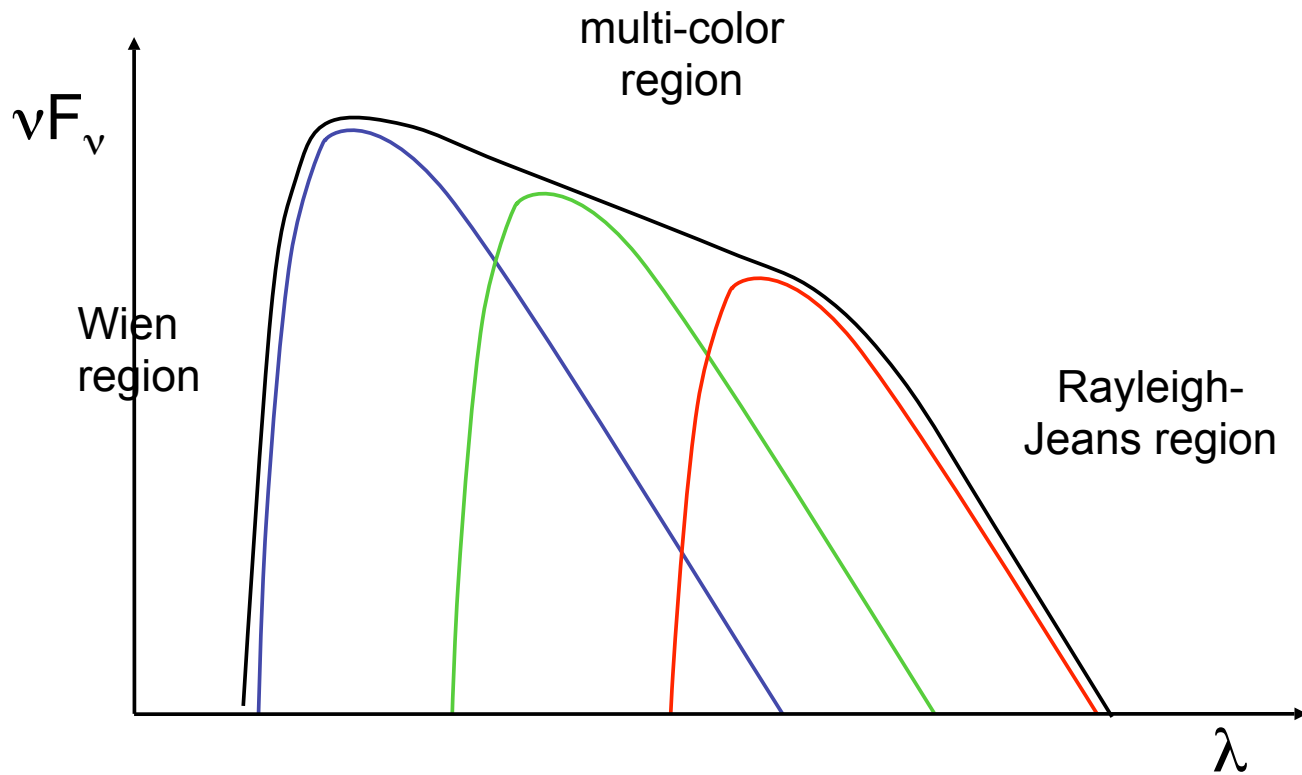
Transition Disks



Disk Evolution IV: Transition Disks

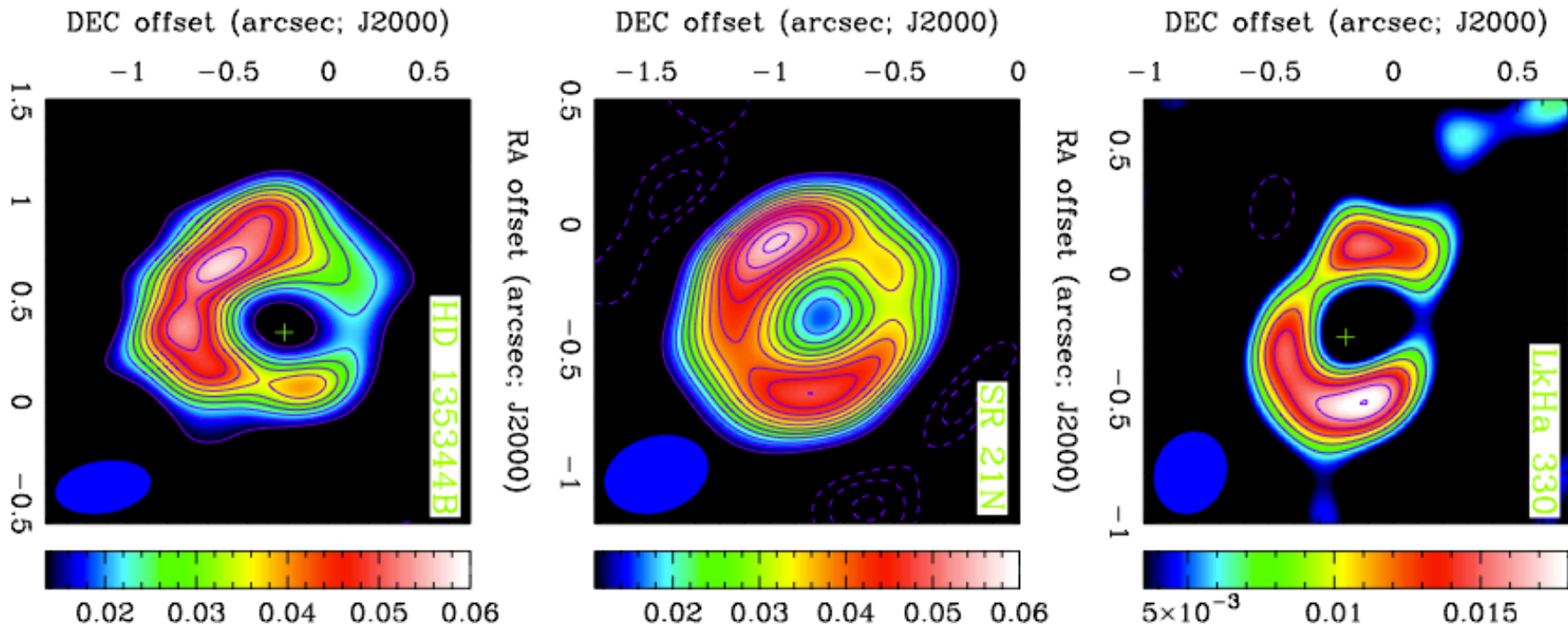


Multi-color blackbody disk SED



Slide pirated from K. Dullemond

Millimeter Imaging of Transition Disks



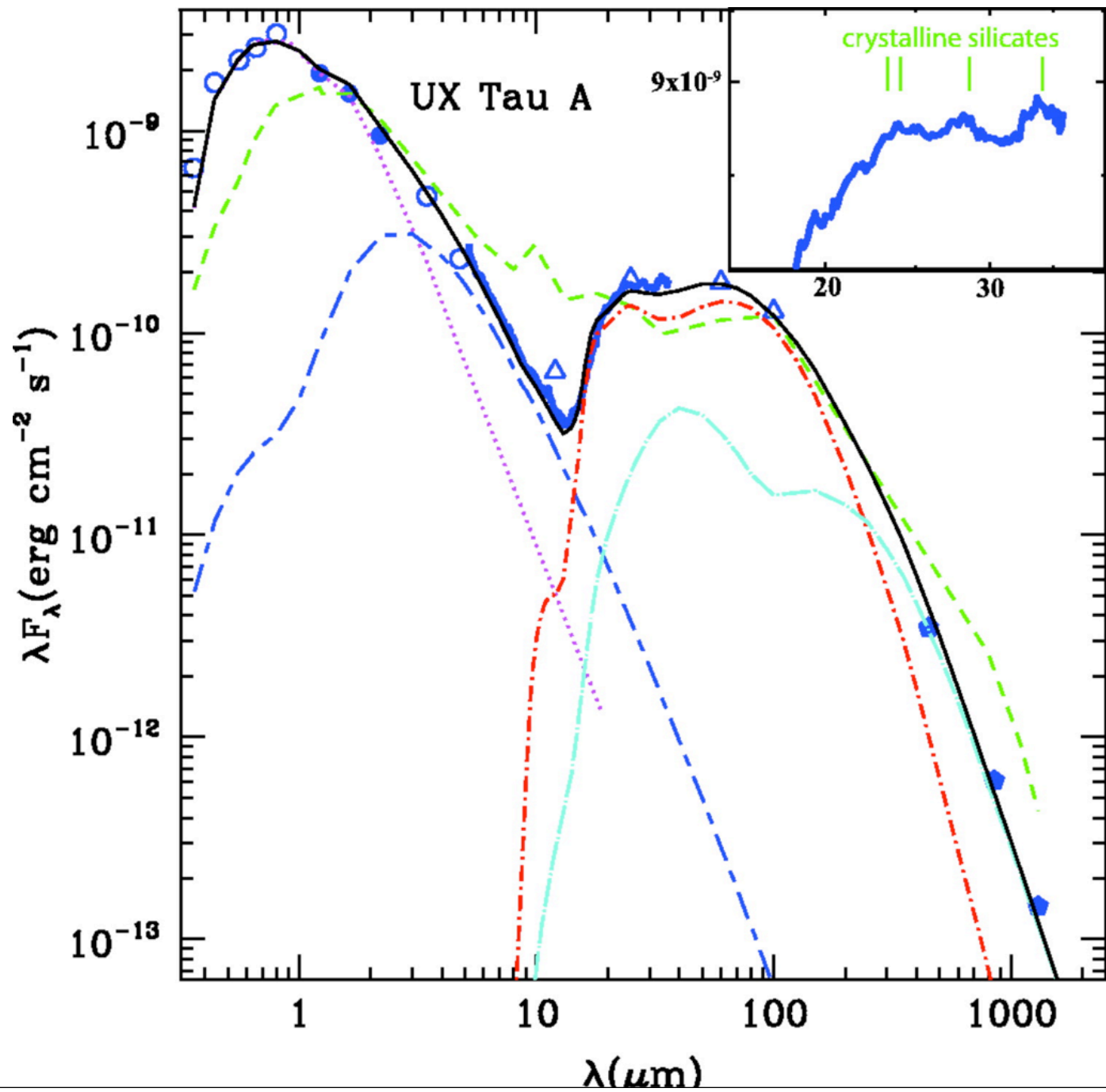
Andrews et al. 2009

Holes can Also be Created by Binary Stars

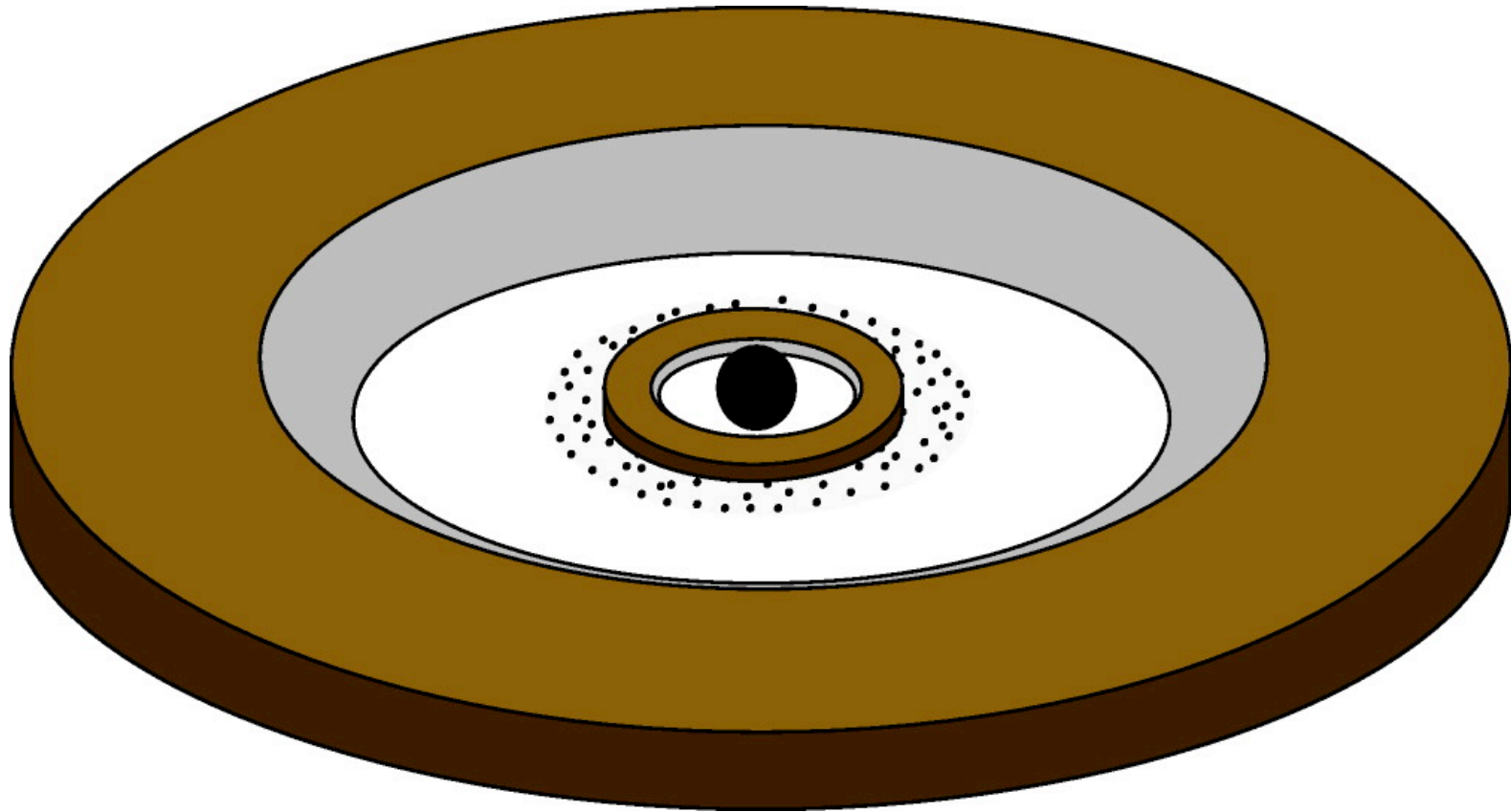


Disk Evolution V: Gaps in Disks

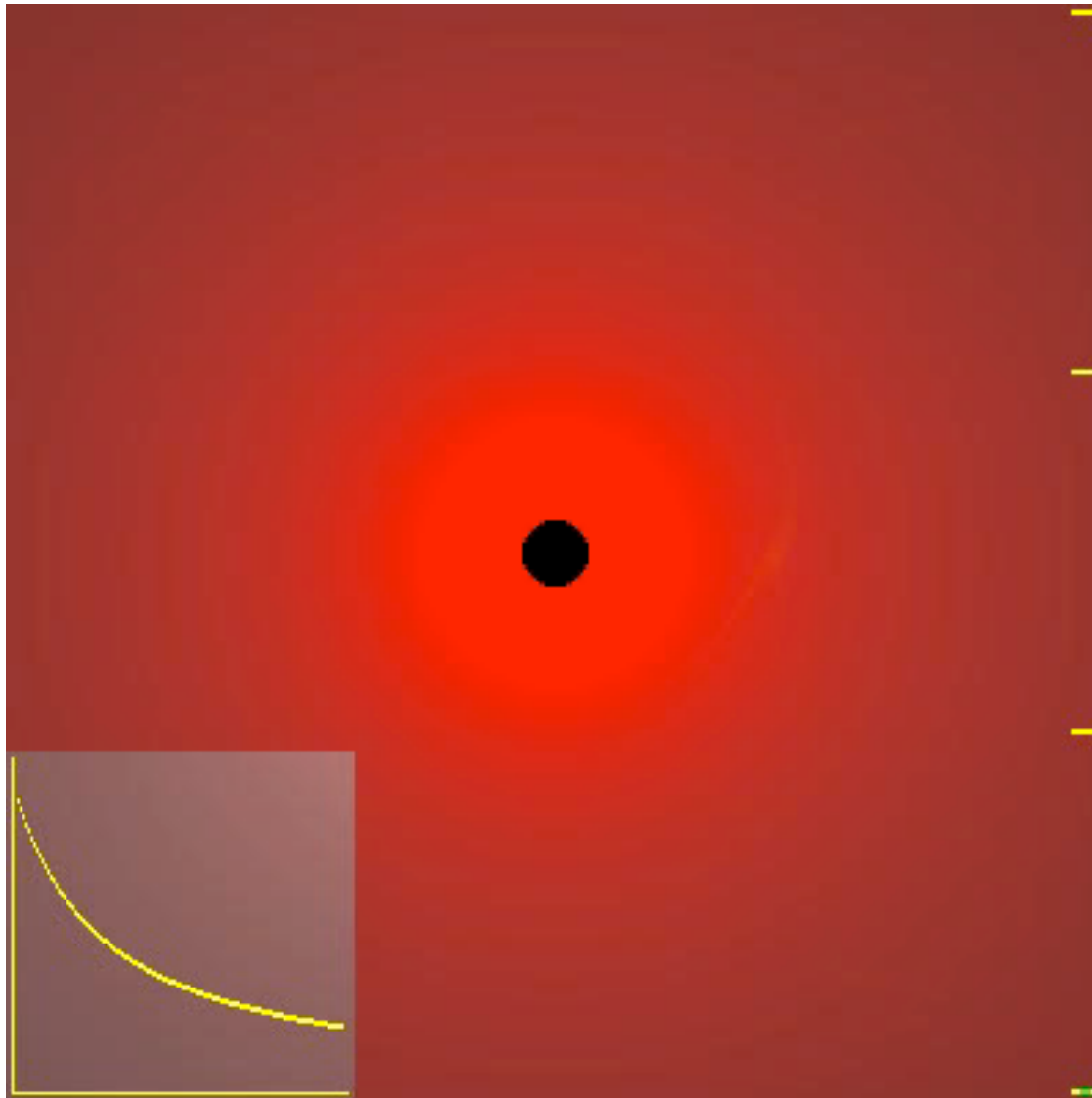




The Gap Model for UX Tau



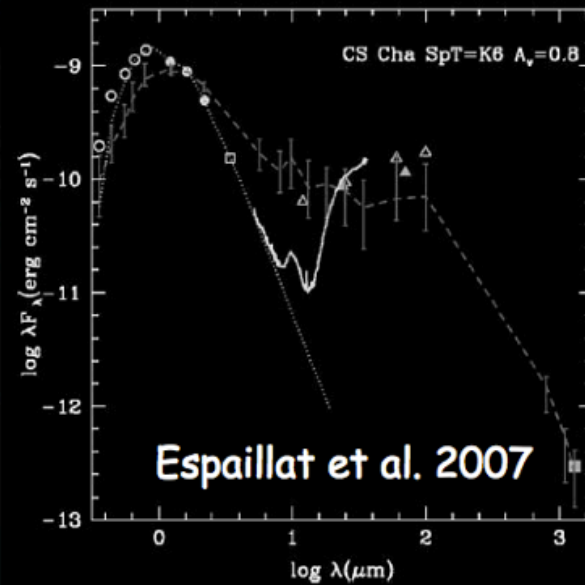
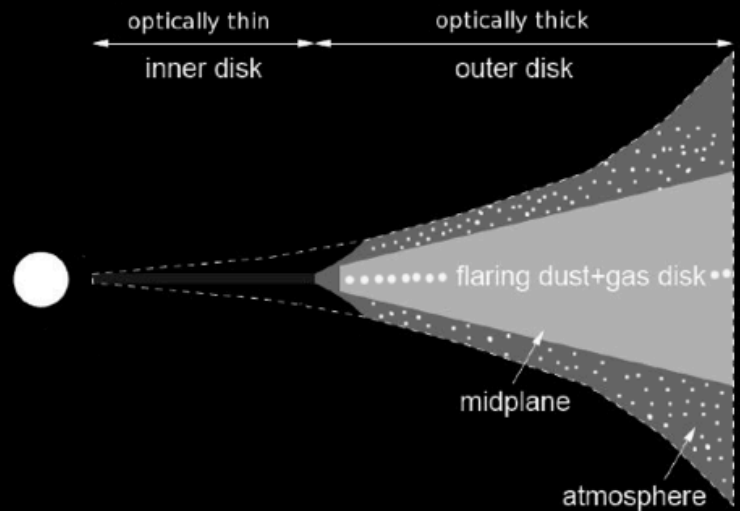
Clearing by Planet in Disks



Phil Armitage web site

Disk Evolution V: Debris Disks

Transitional Disk



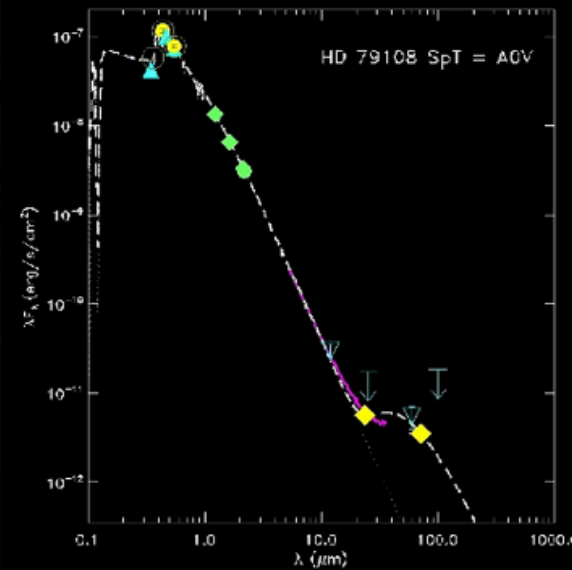
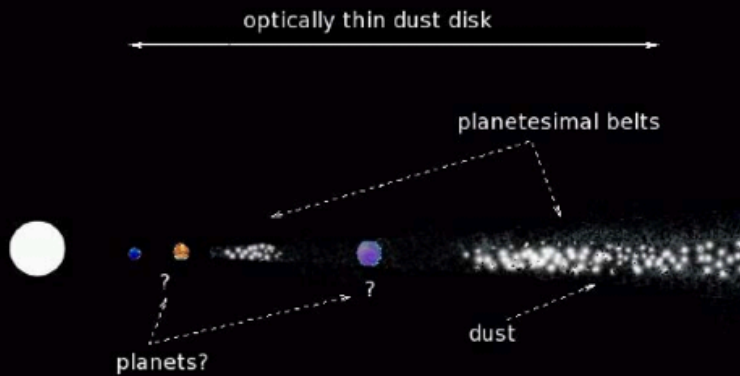
age $\sim 10^6 - 10^7$ yr

Lack of NIR excess, a lot of gas in the outer disk

$f \sim 10^{-1} - 10^{-2}$

$\sim 50\%$ shows signs of acc.

Debris Disk



age $\geq 10^7$ yr

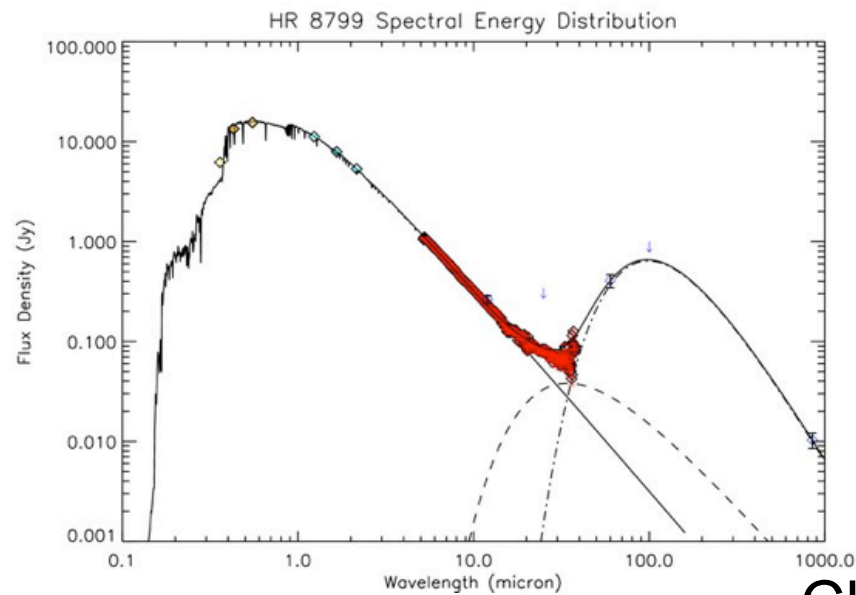
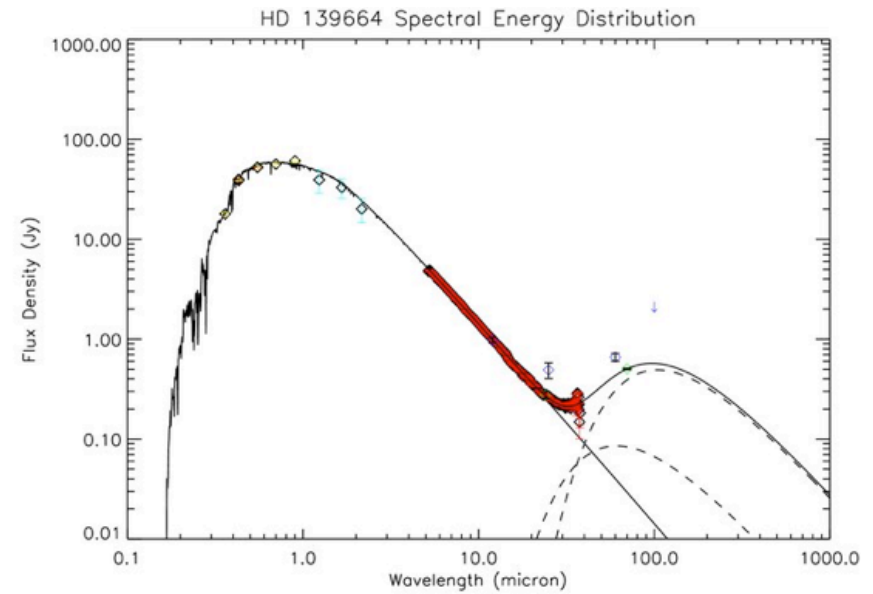
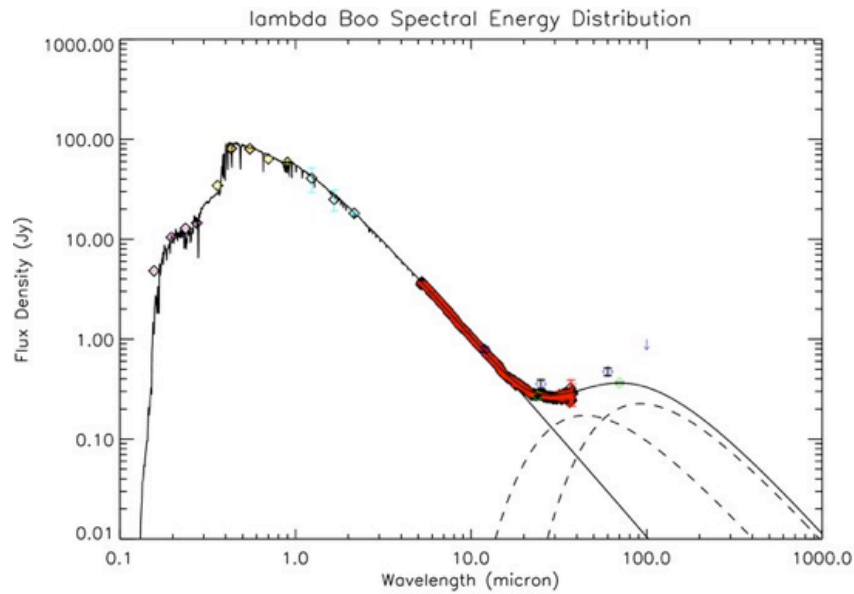
No or very little gas

$f < 10^{-3}$

$f \equiv L_{\text{IR}}/L_*$

Taken from talk by Kate Su

SEDs of Debris Disks

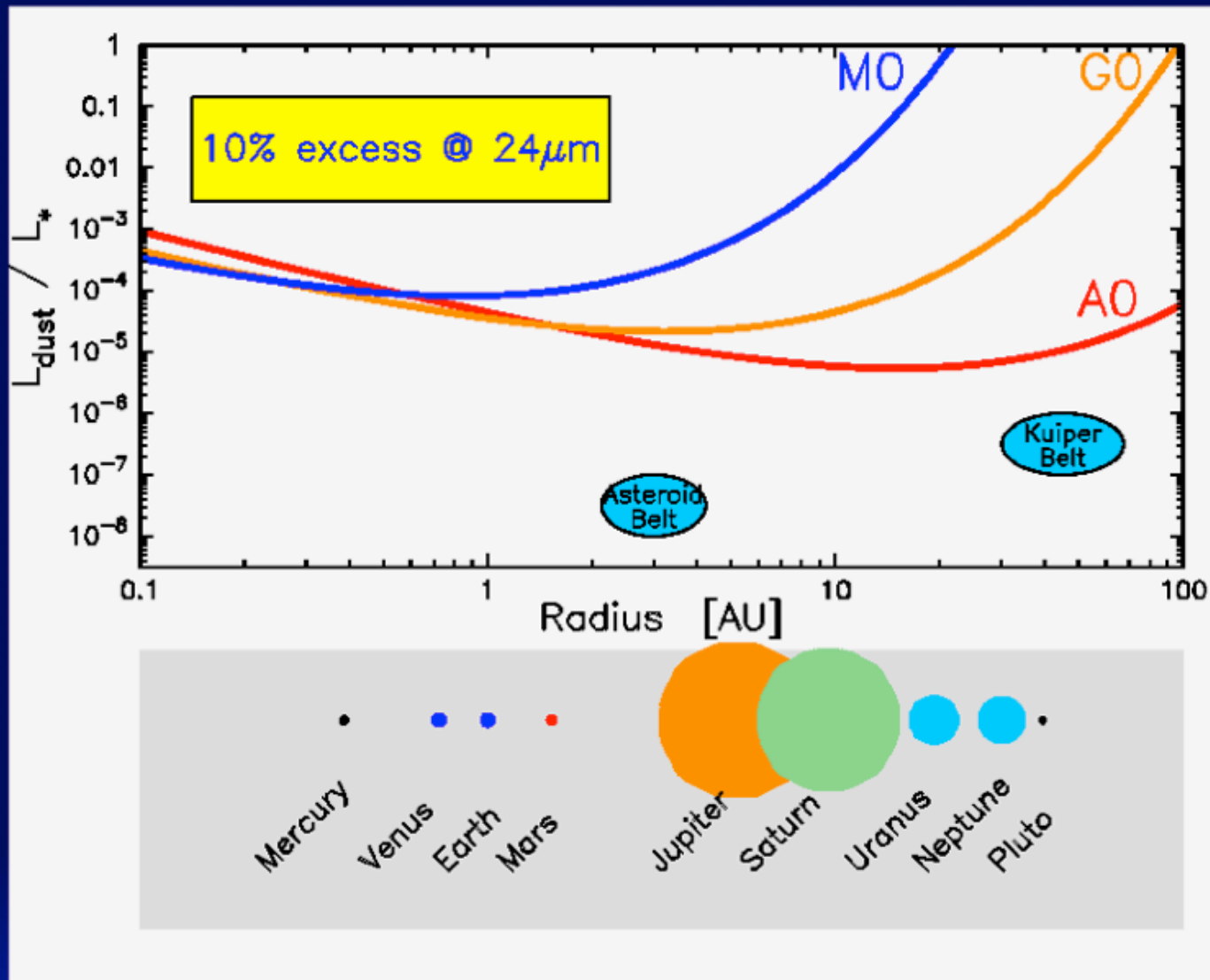


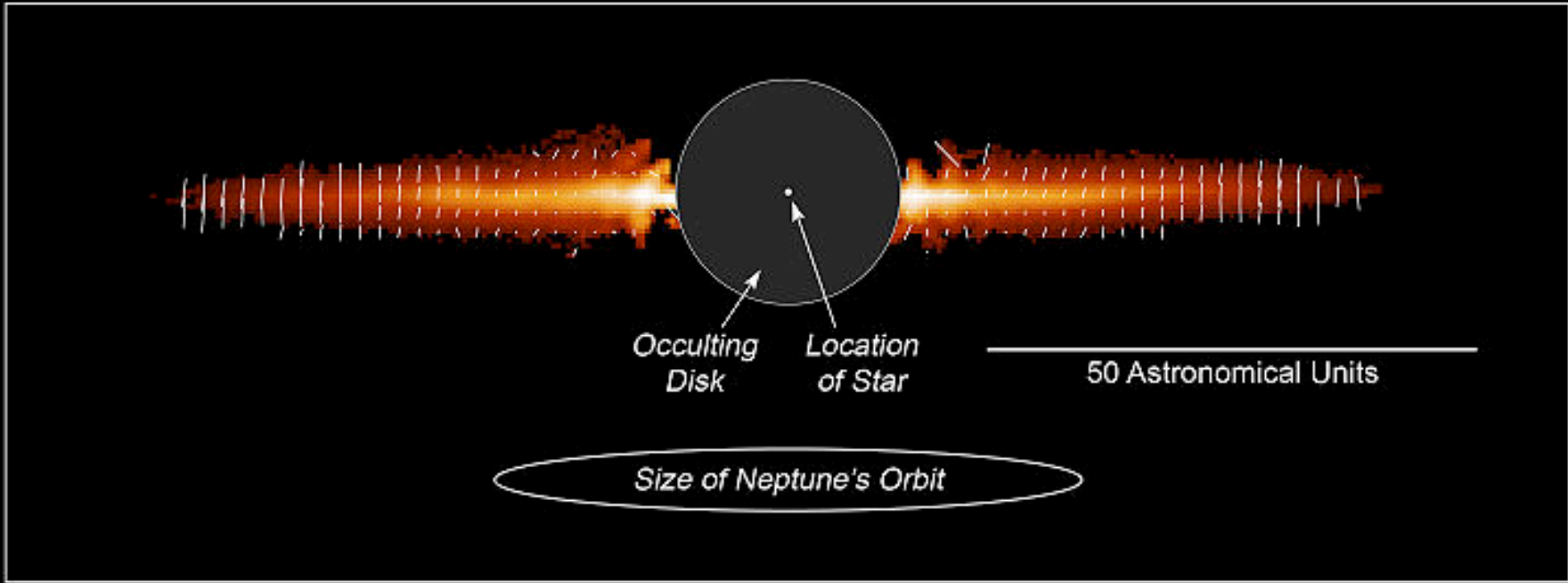
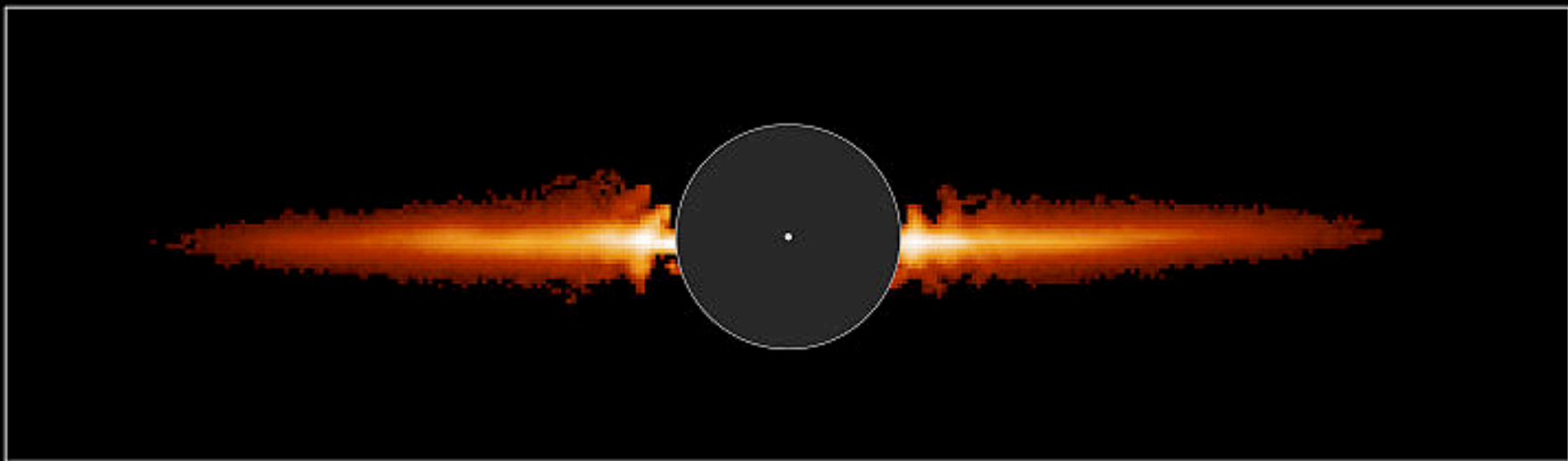
Chen et al. 2009

Why “Debris” Disk?

- Poynting Robertson effect creates a drag that causes larger grains to fall into Sun on timescales of thousands of years.
- Small grains blown out by wind.
- New grains must continually be created by collisions between planetesimals (kilometer sized bodies).

Sensitivity to Debris: MIPS 24 μm





AU Microscopii Debris Disk
Hubble Space Telescope • ACS/HRC



HD69830 System

Summary

- Young pre-main sequence stars are surrounded by disks of gas and dust. Small dust grains make disks optically thick.
- Disappearance of gas disks happens quickly, 1/2 of stars lose their disks in 2-3 Myr, almost all in 10 Myr.
- Evolution of disks includes settling of dust and collision of dust to form larger grains.
- Evidence of dust settling and growth apparent in SEDs, silicate features, and sub-millimeter part of the spectrum.
- Holes and gaps are observed in disks, these may be created by planets, binaries or photoevaporation.
- After the gas disk is dispersed, we are left with debris disks, which are disks of small dust grains (which produce IR-excess) produced in collisions of large planetesimals (which aren't observed).