Observational ISM and Star Formation

This Class (Lecture 16):
Brett Hayes & Duncan Christie

Next Class:
Stacey Alberts & Josh Dolence

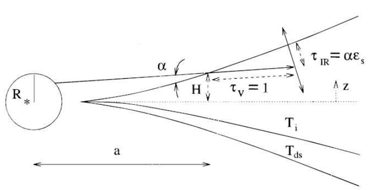
Music: *The Sun is Mass of Incandescent Gas* – They Might Be Giants

Outline

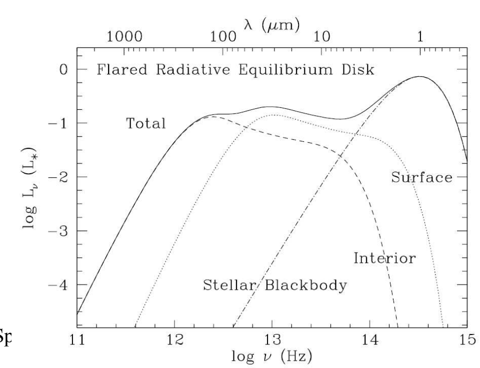
- SED fits (more)
- Inner hole effects?
- Inner rim
- Grain Effects
- SED uniqueness

Disks

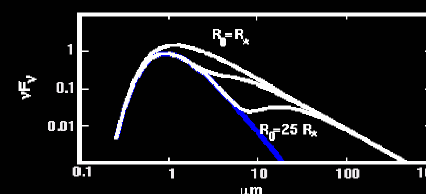
- We have talked about SED fits to different disk geometries
- The first disk models assumed a flat disk, which predicts at longe wavelengths ($\nu F\nu \propto \lambda^{-4/3}$)
  – but few disks obeyed this
- A flared disk can fit more of the disks, but the fit depends on geometry



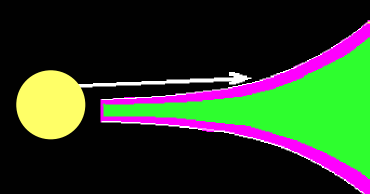
Chiang & Goldreich 1997, ApJ, 490, 368

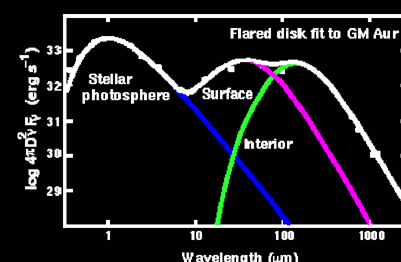


Characterizing Large Disk Samples: SED Models



G.J. van Zadelhoff 2002



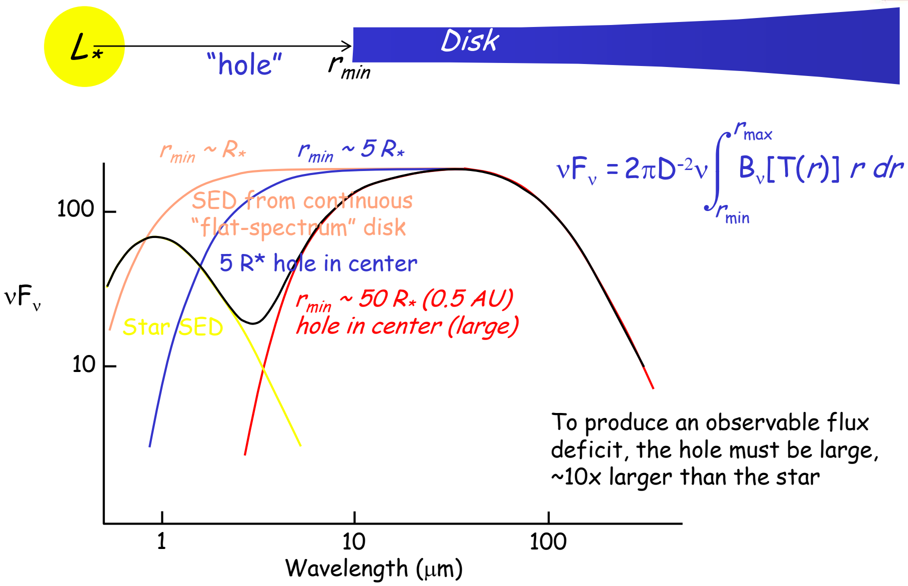


Chiang & Goldreich 1997

IR ➡ disk surface within several 0.1 – several tens of AU
(sub)mm ➡ disk surface at large radii, disk interior.
What determines disk properties (radius, flaring, T)?

http://www.gps.caltech.edu/classes/ge133/slides/lec07_16oct2006.ppt(Geoff Blake)

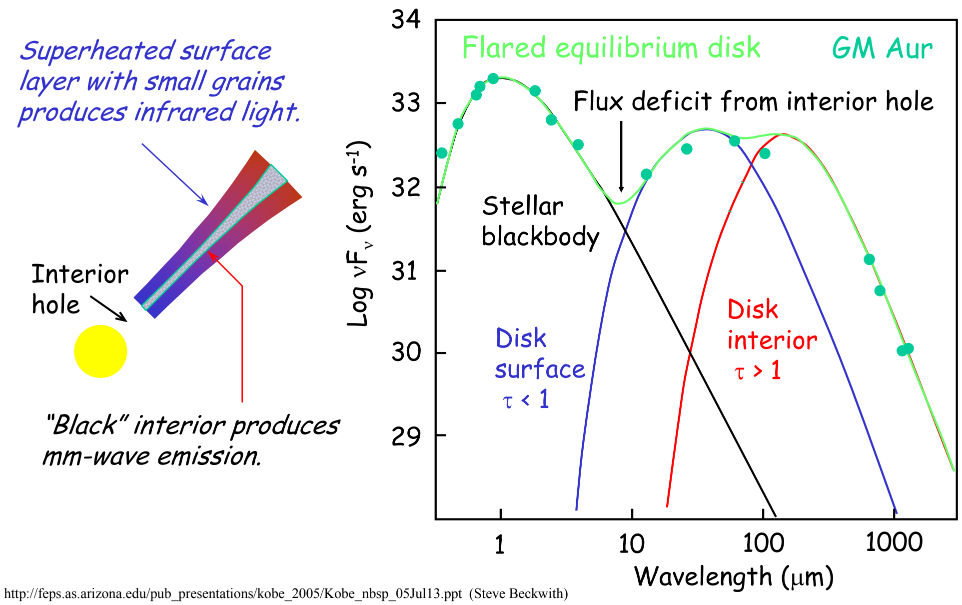
Physical Modification: Holes



To produce an observable flux deficit, the hole must be large, ~10x larger than the star

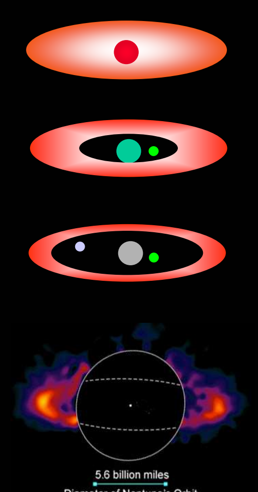
http://feps.as.arizona.edu/pub_presentations/kobe_2005/Kobe_nbsp_05Jul13.ppt (Steve Beckwith)

Flux Deficits

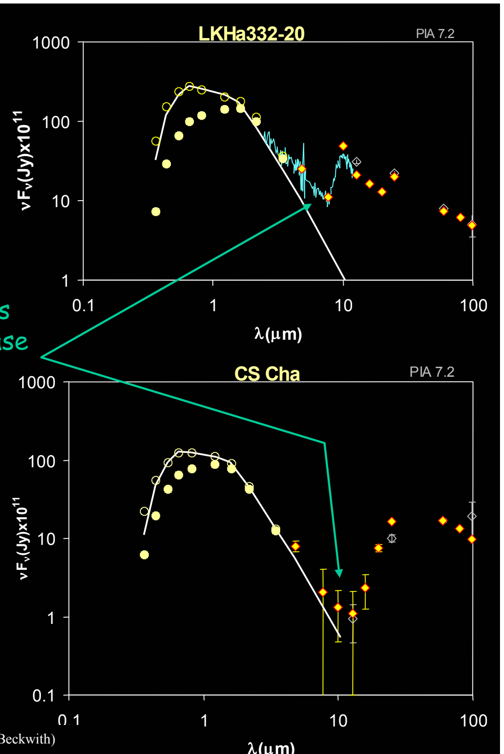


http://feps.as.arizona.edu/pub_presentations/kobe_2005/Kobe_nbsp_05Jul13.ppt (Steve Beckwith)

Evolution of structure



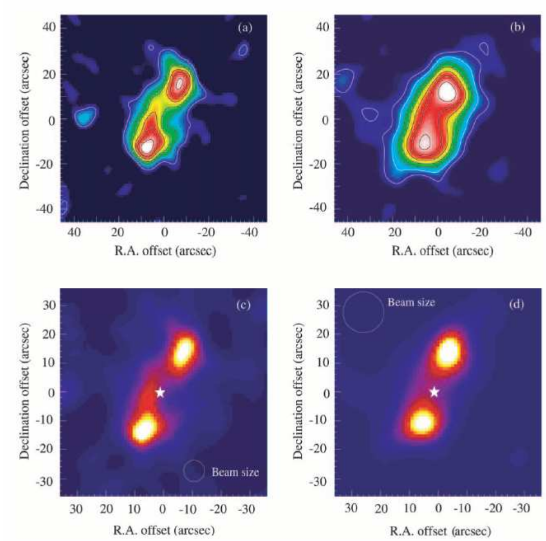
As disks age, the hole sizes should increase



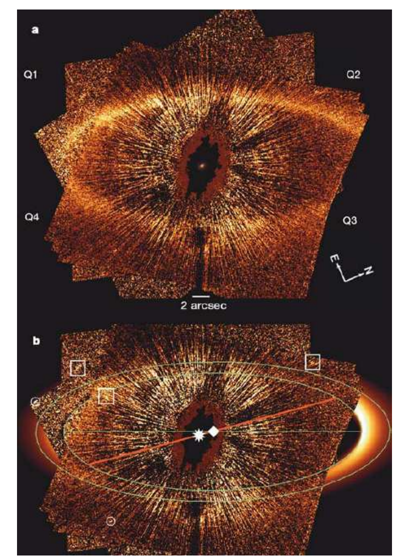
Weinberger *et al.* 1999

http://feps.as.arizona.edu/pub_presentations/kobe_2005/Kobe_nbsp_05Jul13.ppt (Steve Beckwith)

Fomalhaut: Ring Emission



Holland *et al.* 2003



Kalas et al. 2005

Vega-type stars: Fomalhaut

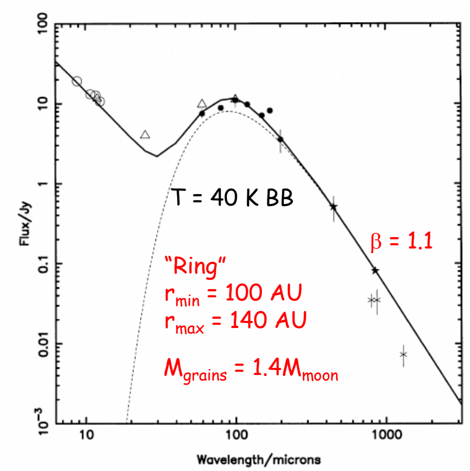


Figure 1: Best fit

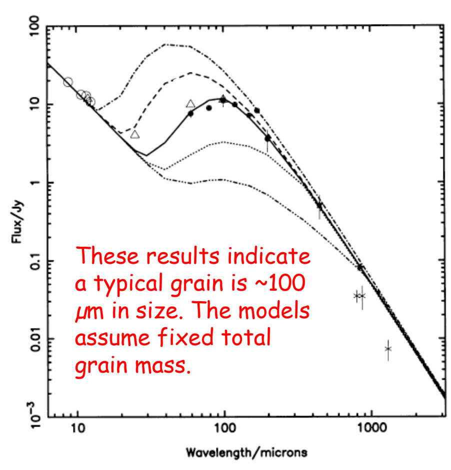
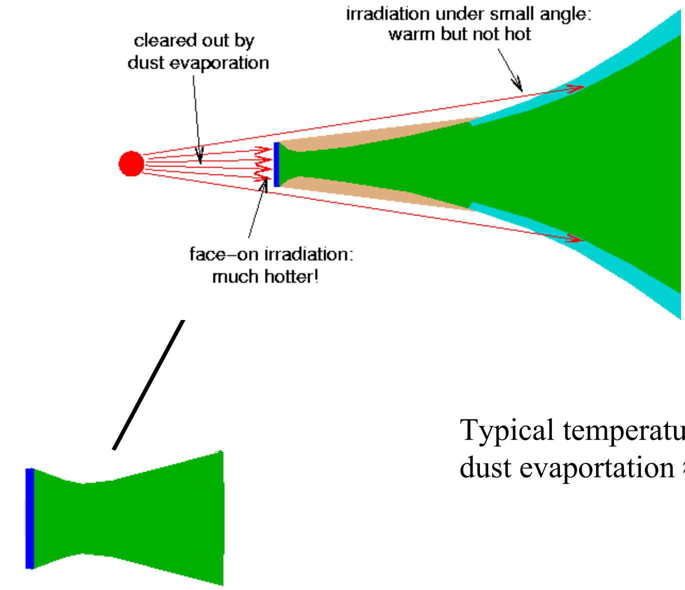


Figure 6: varying grain size

Dent *et al.* 2000

http://feps.as.arizona.edu/pub_presentations/kobe_2005/Kobe_nbsp_05Jul13.ppt (Steve Beckwith)

Dust Evaporation at Inner Rim

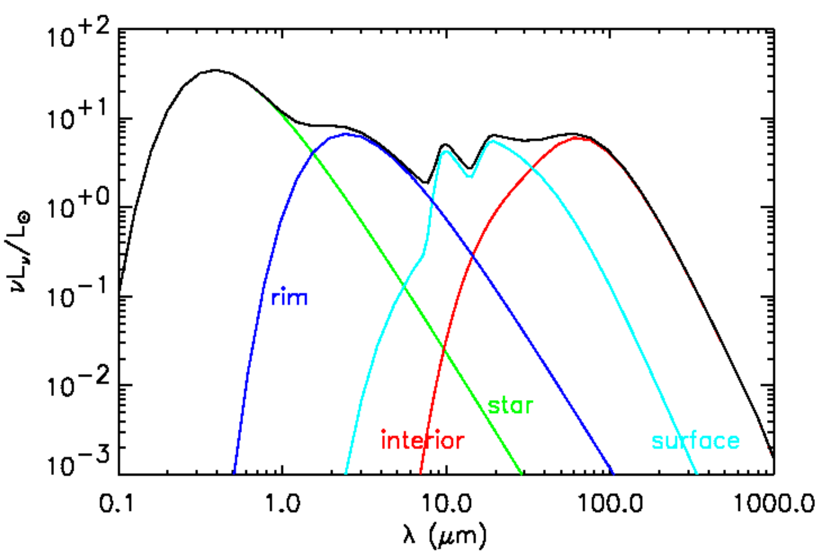


Typical temperature for dust evaportation ≈ 1500 K

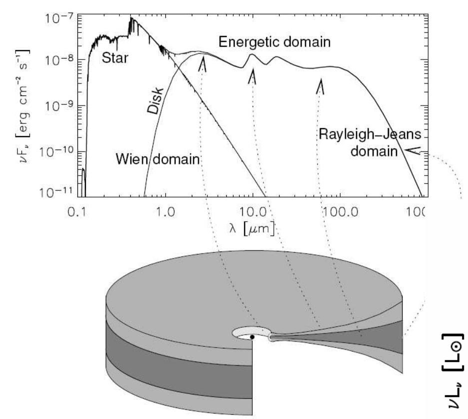
http://www.mpia-hd.mpg.de/homes/dullemon/lectures/starplanet/index.html

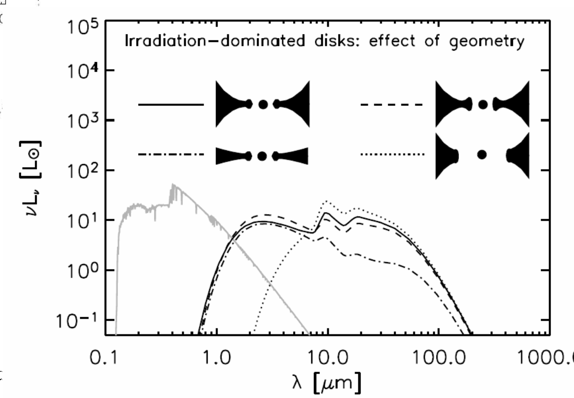
Natta et al. (2001)
Dullemond, Dominik & Natta (2001)

SED of disk with inner rim

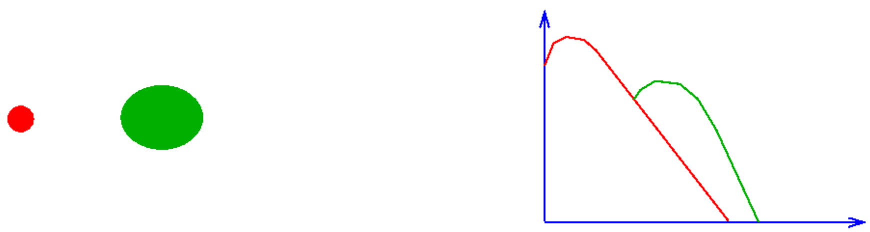


Geometry Matters

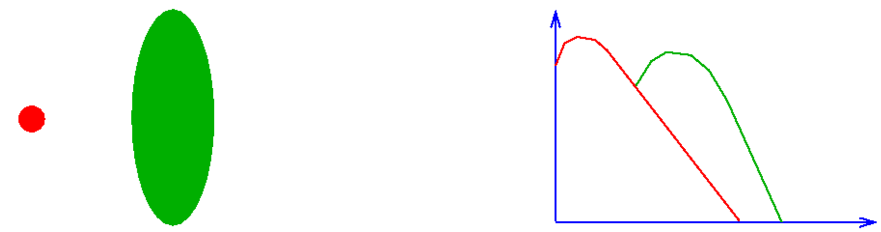




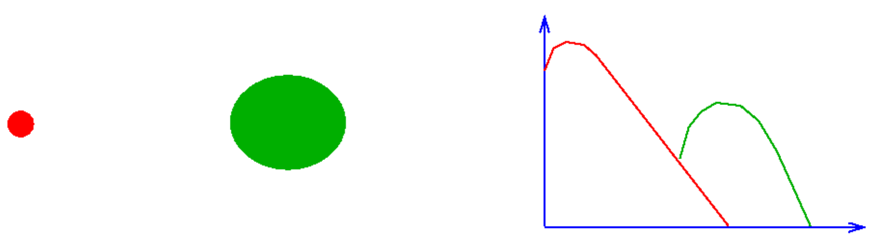
Covering Fraction



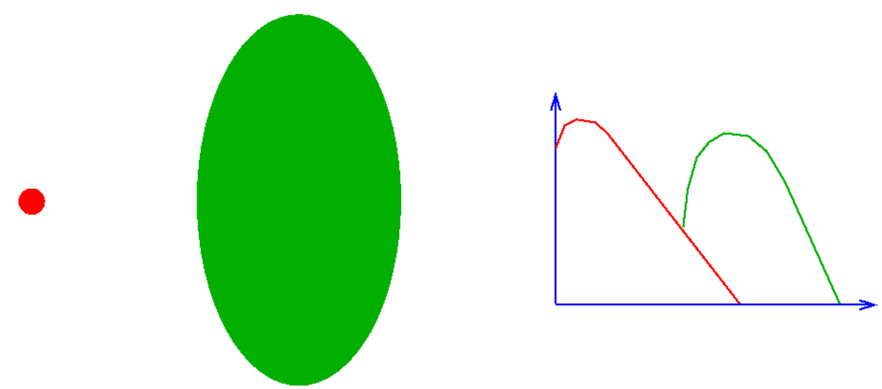
Covering Fraction



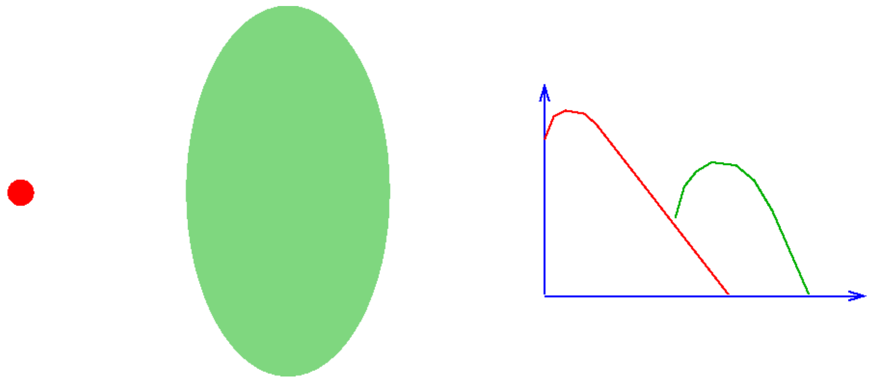
Covering Fraction



Covering Fraction

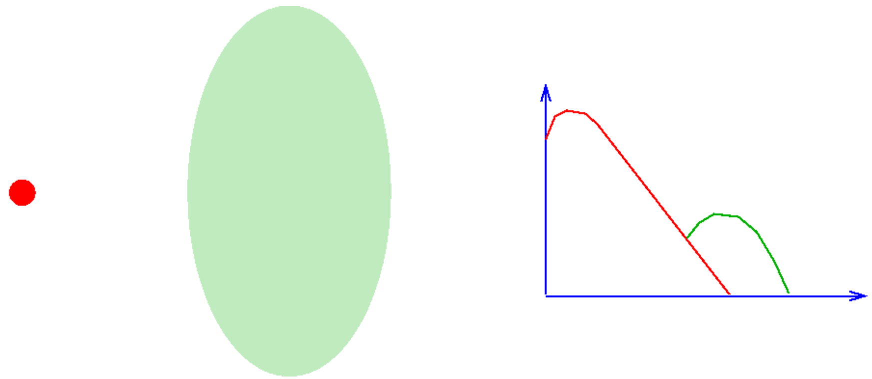


Covering Fraction



Astronomy 596 Spring 2007

Covering Fraction



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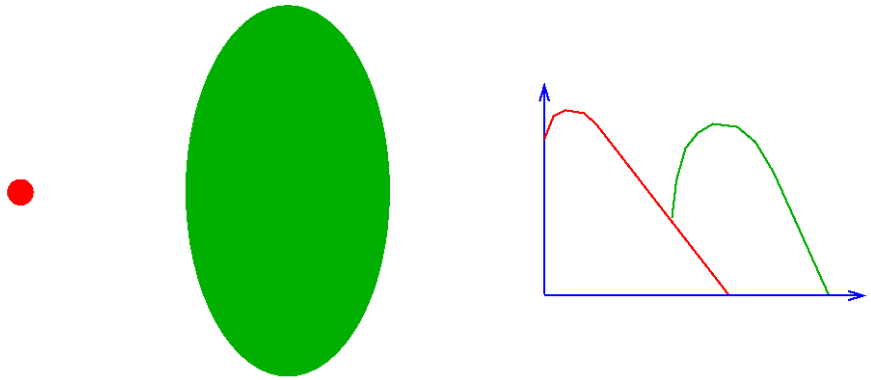
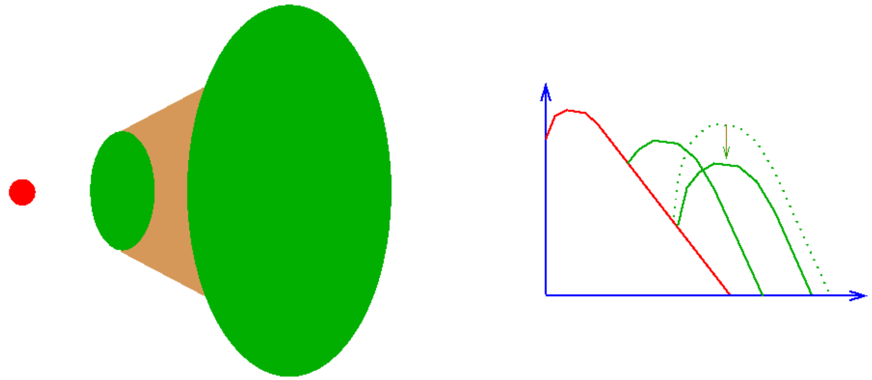
Covering Fraction



Astronomy 596 Spring 2007

Covering Fraction



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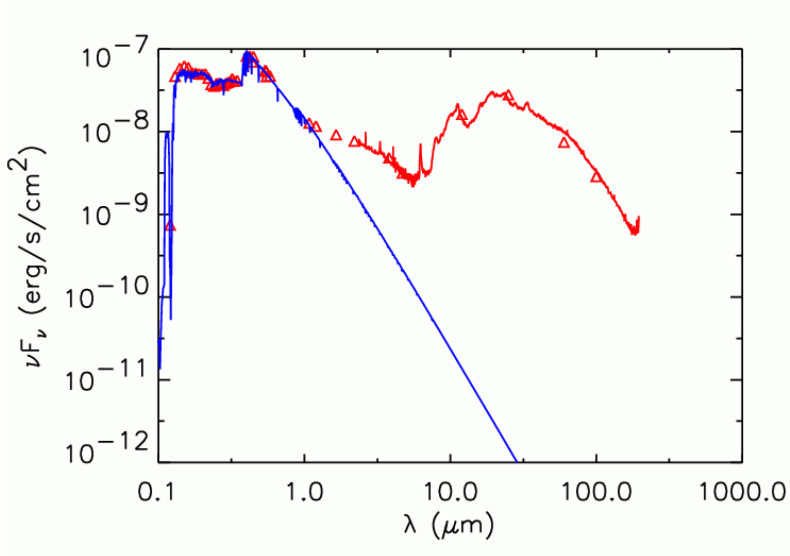
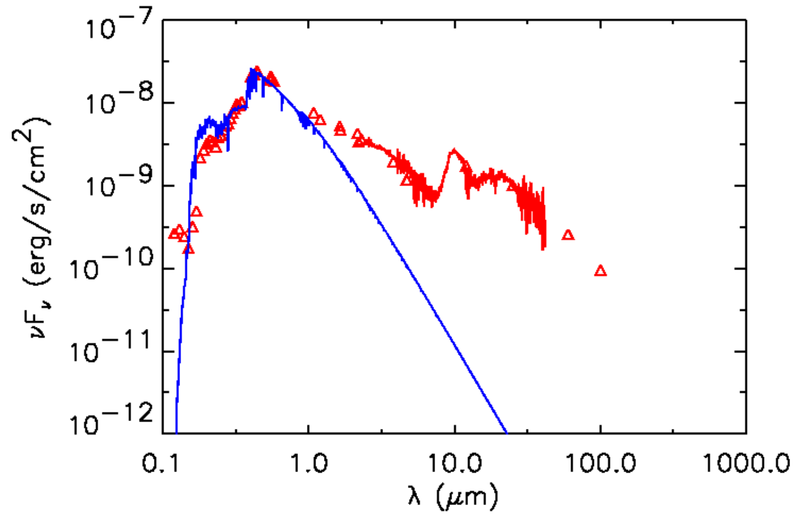
Example: HD100546



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

http://www.mpia-hd.mpg.de/homes/dullemon/lectures/starplanet/index.html (Kees Dullemond)

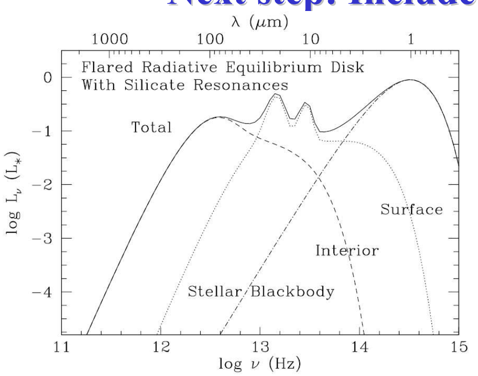
Example: HD 144432



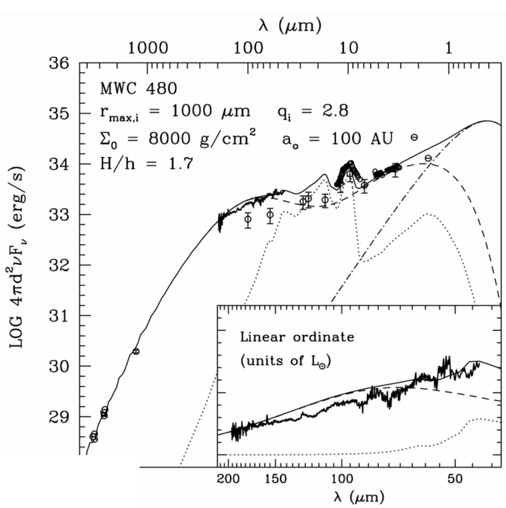
Must have strong inner rim (strong near-IR flux), but either small or non-flaring outer disk (weak far-IR flux)

http://www.mpia-hd.mpg.de/homes/dullemon/lectures/starplanet/index.html (Kees Dullemond)

Next step: Include Grain Opacities



The grains in disk surfaces are not perfect black- or greybodies, but instead have wavelength dependent emissivities.

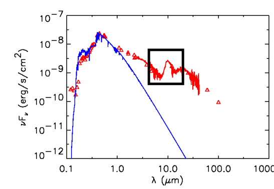


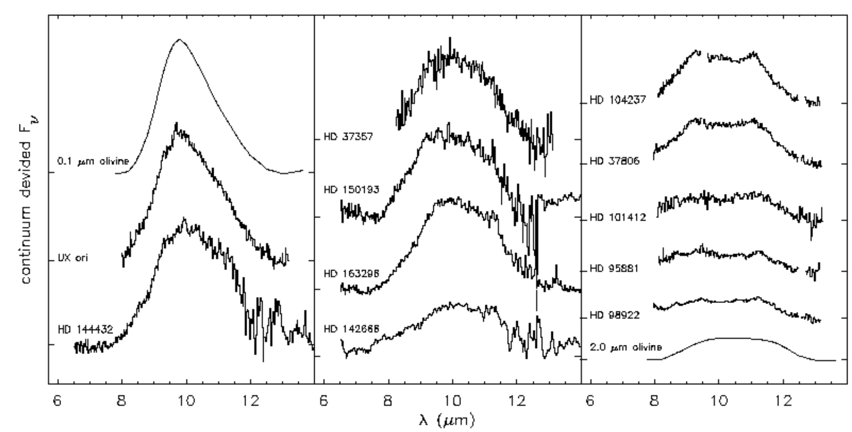
Predicts silicate *emission* bands for the SiO stretching and bending modes at 10/18 µm.

http://www.gps.caltech.edu/classes/ge133/slides/lec07_16oct2006.ppt (Geoff Blake)

Measuring Grain Sizes

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



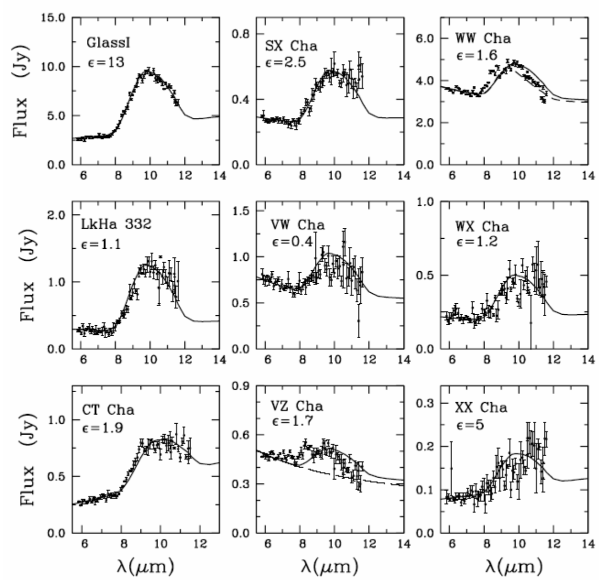


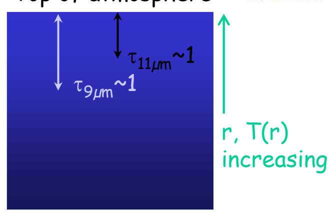
van Boekel et al. 2003

Mar 13, 2007

Silicate Emission: Disk Atmosphere

Fits: 1.2 μm pyroxene grains, CG97 model

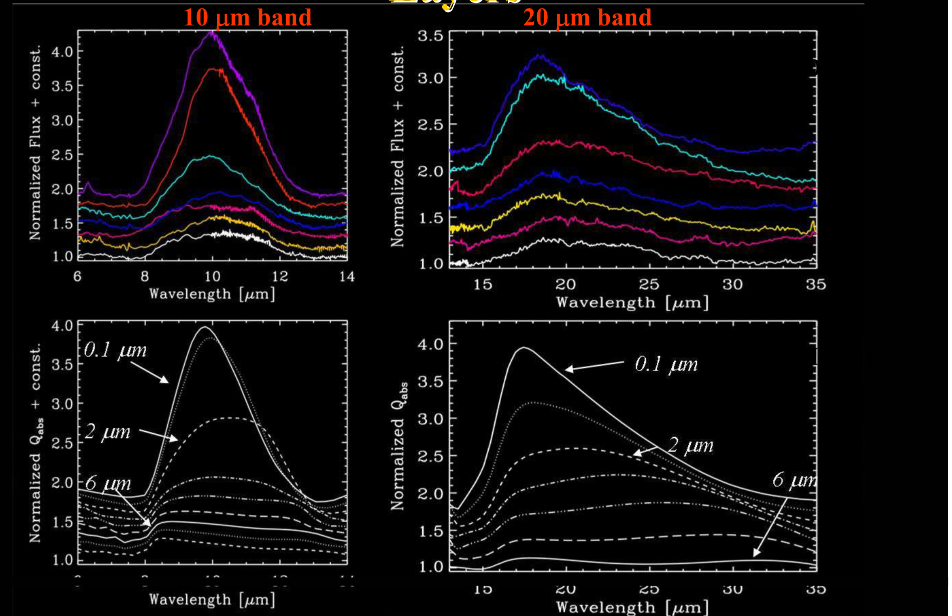




Emission features indicate optically thin emission from in an atmosphere with vertically *increasing* temperature gradients

Natta, Meyer, & Beckwith 2000, *ApJ*, **534**, 838

Grain Emission/Growth in Disk Surface Layers

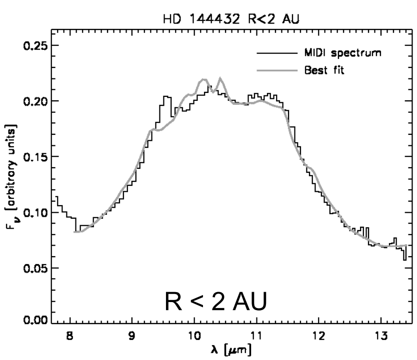


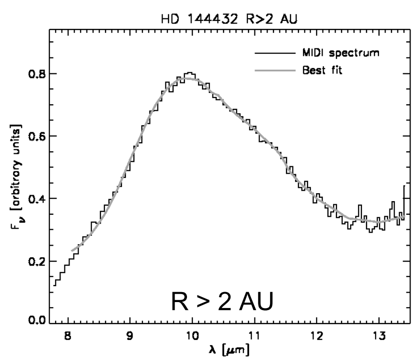
Kessler-Silacci et al. 2006

Grain Sizes in the Inner Disk

Resolving inner disk region with...

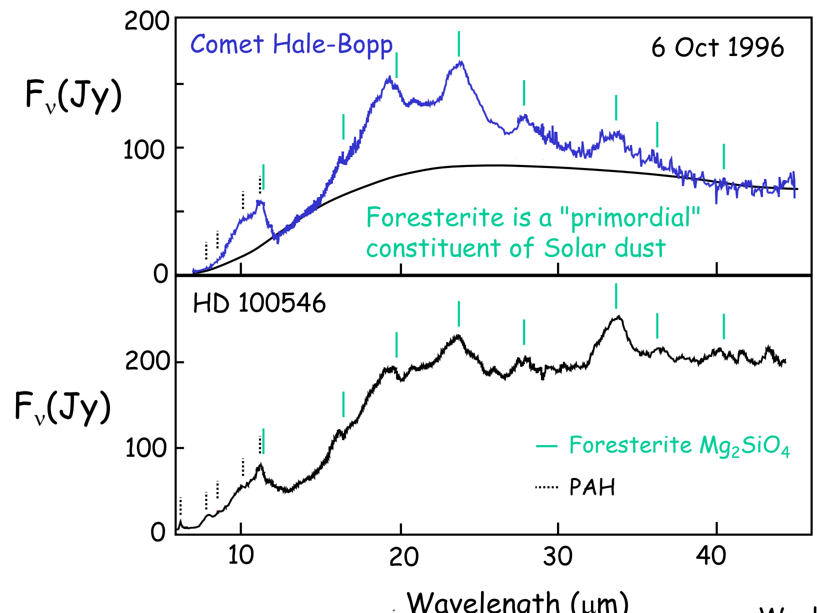
...infrared interferometry





van Boekel et al. 2004

Disk to Comet Comparison

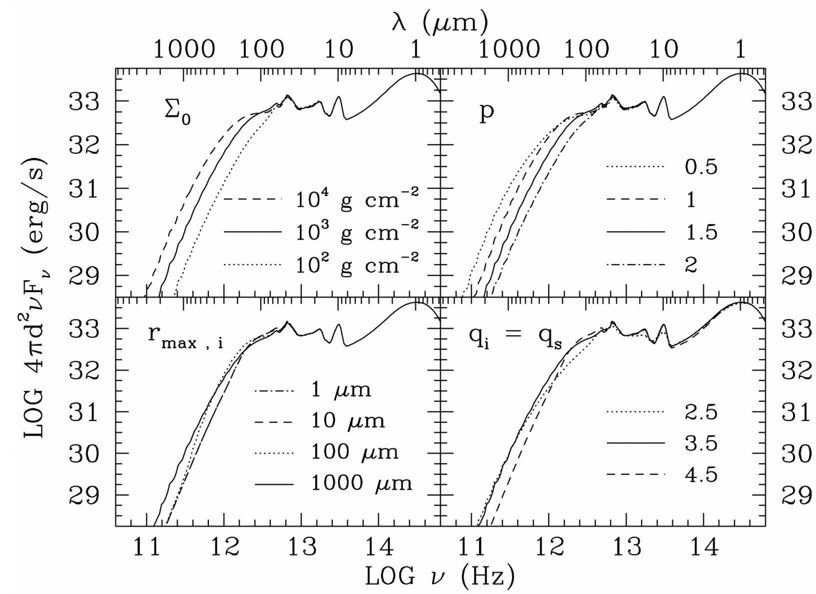


Waelkens *et al.* 1996

SEDs Are Not Unique

- Tend to add many variables for fits of usually few data points.
- Various factors can mimic relative contributions of thick/thin emission as wavelength varies.
- This degeneracy makes it impossible to derive the dust spectral index, β, uniquely from an SED
- But one can use spatial resolution to overcome this problem.

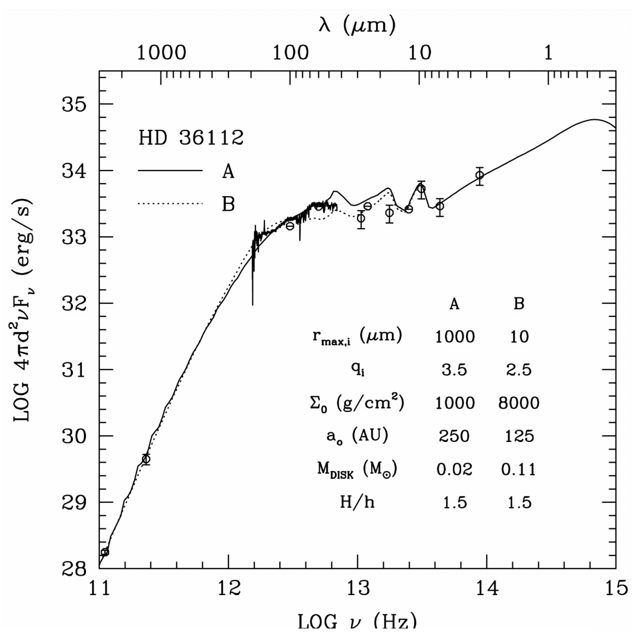
How unique are these models?



… <30 μm.

http://www.gps.caltech.edu/classes/ge133/slides/lec07_16oct2006.ppt (Geoff Blake)

How Bad are these Model Degeneracies?

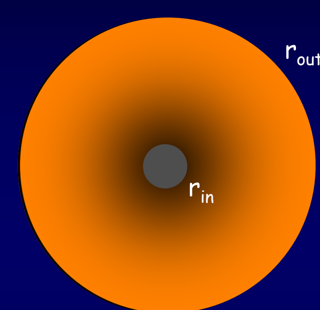


Bad! Note that for these two limiting cases the disk size differs by a factor of two, and the masses by a factor of nearly six!

Can be broken with resolved images at longer wavelengths.

http://www.gps.caltech.edu/classes/ge133/slides/lec07_16oct2006.ppt (Geoff Blake)

T(r) & Σ(r) Determine F_ν



$$F_\nu \sim D^{-2} \int_{r_{in}}^{r_{out}} B_\nu[T(r)]\,(1-e^{-\tau(r)})\,2\pi r\,dr$$

$$F_\nu \sim D^{-2} \int_{r_{in}}^{r_{out}} k\,T(r)\,\nu^2\,\underbrace{\kappa_\nu \Sigma(r)}_{\tau_\nu(r)}\,2\pi r\,dr$$

$T(r) \sim r^{-q}$ $3/4 < q < 1/2$

$\Sigma(r) \sim r^{-p}$ $0 < p < 2$

$\kappa_\nu \sim \nu^\beta$ $\beta \sim 2$

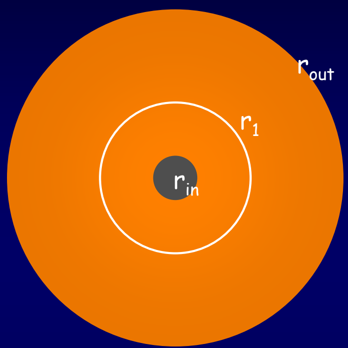
$$F_\nu \sim \nu^{2+\beta} \kappa_0 \int_{r_{in}}^{r_{out}} r^{1-q-p}\,dr \quad \sim \kappa_0 \nu^{2+\beta} r^{2-q-p}$$

p = 3/2, q = 3/4 $F_\nu(1\text{ mm}) \sim r_{in}^{-1/4}$

p = 1, q = 1/2 $F_\nu(1\text{ mm}) \sim r_{out}^{1/2}$

http://feps.as.arizona.edu/pub_presentations/kobe_2005/Kobe_nbsp_05Jul13.ppt (Steve Beckwith)

Inner Disk May Have $\tau \gg 1$



$$F_\nu \sim \int_{r_{in}}^{r_{out}} B_\nu[T(r)]\,(1-e^{-\tau(r)})\,2\pi r\,dr$$

$$F_\nu \sim \int_{r_{in}}^{r_1} k\,T(r)\,\nu^2\,2\pi r\,dr \qquad (\tau > 1)$$

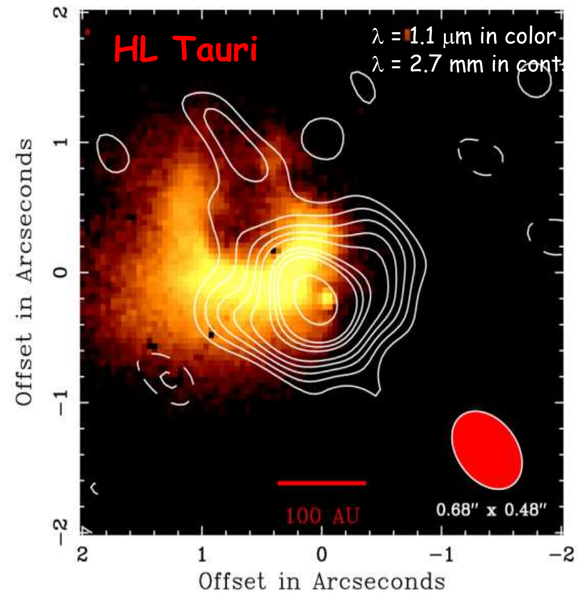
$$+ \int_{r_1}^{r_{out}} k\,T(r)\,\nu^2\,\kappa_\nu \Sigma(r)\,2\pi r\,dr \qquad (\tau < 1)$$

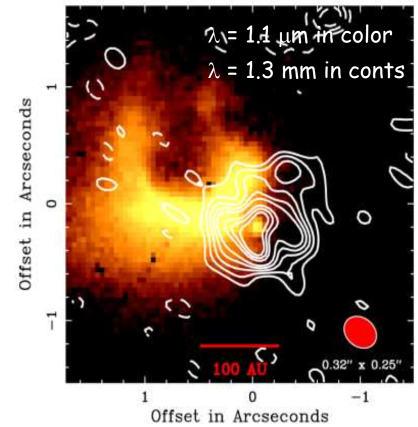
$$F_\nu \sim T(r_1)\,\nu^2\,\pi r_1^2 + \kappa_\nu\,\Sigma(r_{out}) T(r_{out})\,\nu^2\,\pi r_{out}^2$$

The radius at which the disk appears optically thick is a function of κ_ν, hence wavelength. The changing ratio of optically thick/optically thin regions with wavelength offsets the changes from κ_ν itself, thus causing a degeneracy of parameters (makes it difficult to derive β uniquely.)

http://feps.as.arizona.edu/pub_presentations/kobe_2005/Kobe_nbsp_05Jul13.ppt (Steve Beckwith)

Tracing the Bulk Material





Stapelfeldt et al. 1995; Looney et al. 2000