Observing Protoplanetary Disks at Long Wavelengths

Kobe International School of Planetary Sciences

“Origins of Planetary Systems”

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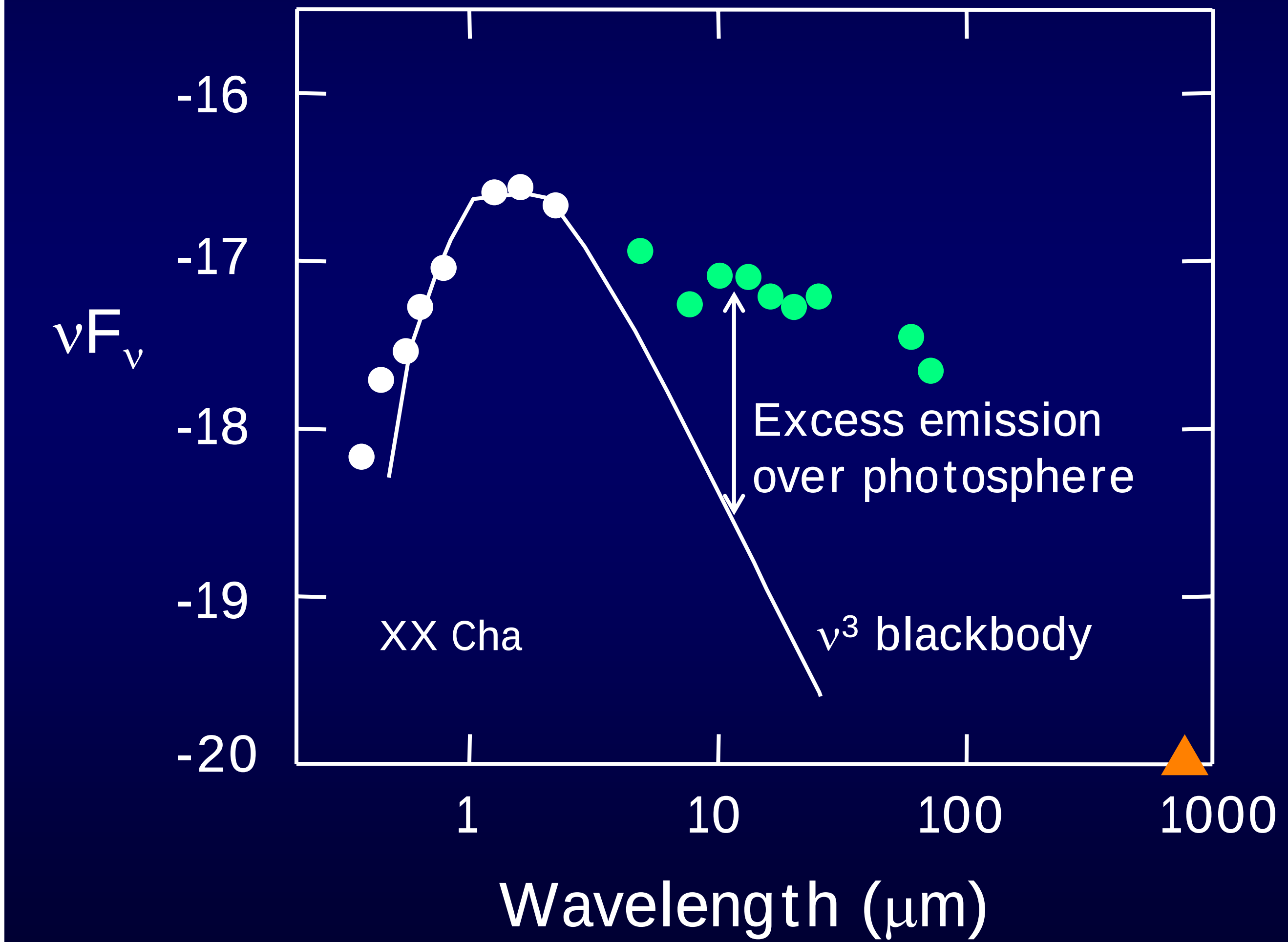
Outline

- The signatures of disks in spectral energy distributions
- Inferring the physical properties of disks from the radiation signatures
  - Unique & degenerate parameters
  - Addition of spatial information
- Disk particles
  - Spectral signatures
  - Size and composition: dust “chemistry”
- Disk dynamical properties
  - Orbital & infall signatures
- Future observations
  - Spatial information (interferometry)
  - High resolution spectra (disk chemistry)

Spectral energy distributions

Adams, Lada, & Shu 1988, *Ap. J.*, **326**, 865.

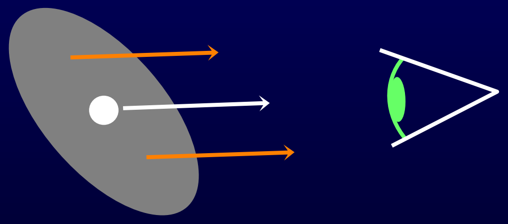


Far IR optical depth:
$\tau \sim 1$ at 100 μm
$\tau \sim 0.01$ at 1 mm

∞ $\tau \geq 100$ at 1 μm
$\Rightarrow A_V \geq 300$

Observed $A_V \sim 3$

∞ clear line of sight
to star and dust.



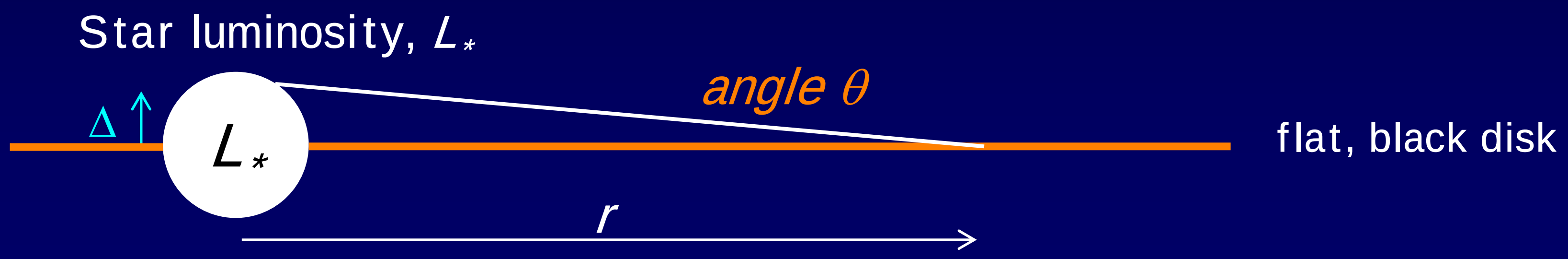
Why does a disk dominate the infrared emission?

Spectral Energy Distributions

(SEDs)

Thin, black disk: "standard theory"

Lynden-Bell & Pringle 1974, *MNRAS*, **168**, 603.
Adams, Lada, & Shu 1988, *Ap. J.*, **326**, 865.



$$\text{Power/area absorbed} \sim \frac{L_*}{4\pi r^2} \sin\theta$$

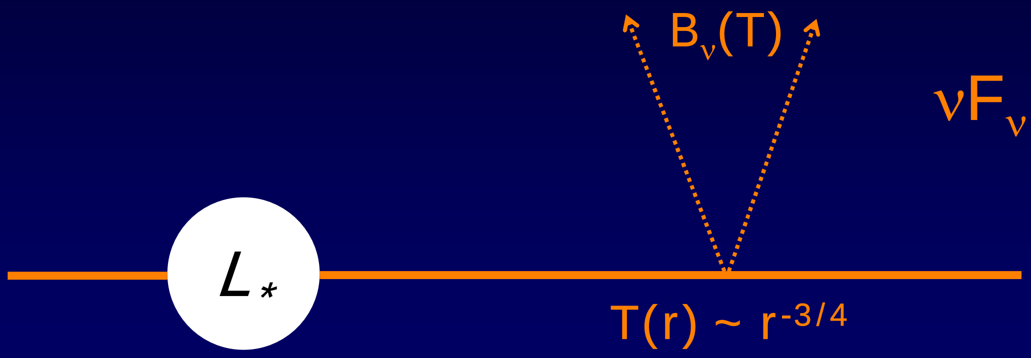
$$\sim \frac{L_*}{4\pi r^2}\frac{\Delta}{r} \sim \frac{L_*}{r^3} \qquad (r \gg \Delta)$$

$$\text{Power/area emitted} = \sigma T^4 \sim \frac{L_*}{r^3}$$

$$\boxed{T(r) \sim r^{-3/4}}$$

Also true for accretion energy.

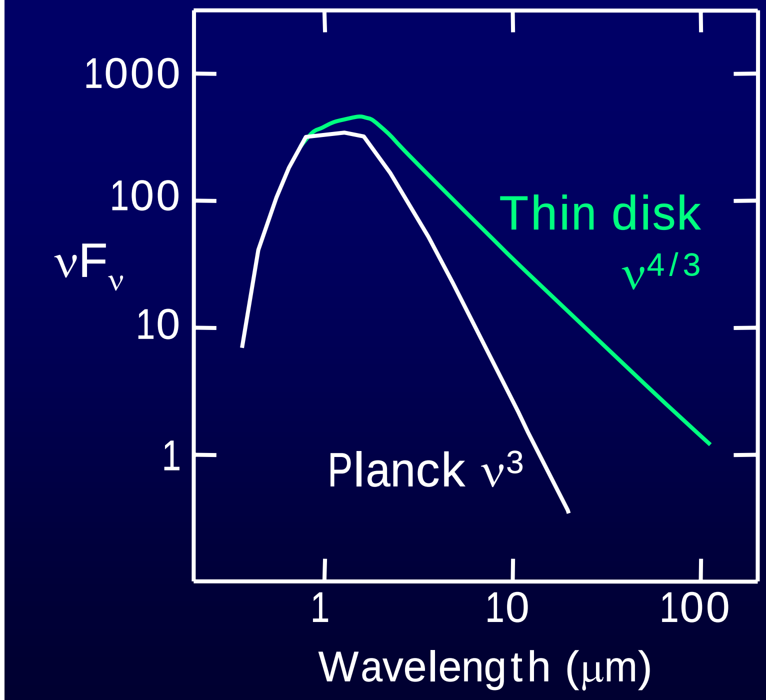
Spectral Energy Distribution (SED)



$$\nu F_\nu = \int_{r_{min}}^{r_{max}} \underbrace{\pi\,\nu B_\nu[T(r)]}_{\text{surface emission}}\ \underbrace{2\pi r\,dr}_{\text{area element}}$$

$$\nu F_\nu = C\,T_0^{8/3}\,\nu^{4/3}\int_{x_{min}}^{x_{max}} \frac{x}{\exp(x^{-3/4}) - 1}\,dx$$

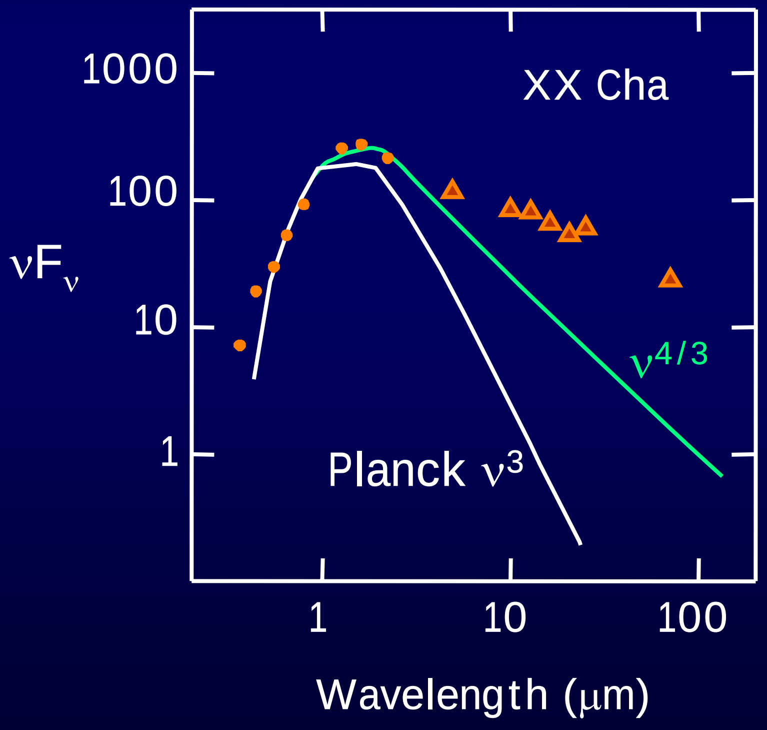
$$\Rightarrow \quad \nu F_\nu \sim \nu^{4/3}$$



Thin disk SED: observations

Adams, Lada, & Shu 1988, *Ap. J.*, **326**, 865.
Beckwith *et al.* 1990, *AJ*, **99**, 924

Thin disk $\nu F_\nu \sim \nu^{4/3}$



The SED from a theoretically thin black disk almost never fits the observations of young stars with excess infrared emission!

- most SEDs flatter than $\nu^{4/3}$
- some SEDs very flat, $\nu F_\nu \sim \nu^0$

Power law $\nu F_\nu \Rightarrow$ power law T(r)

Lynden-Bell & Pringle 1974, *MNRAS*, **168**, 603.
Adams, Lada, & Shu 1988, *Ap. J.*, **326**, 865.

$$T(r) = T_0(r/r_0)^{-q}$$

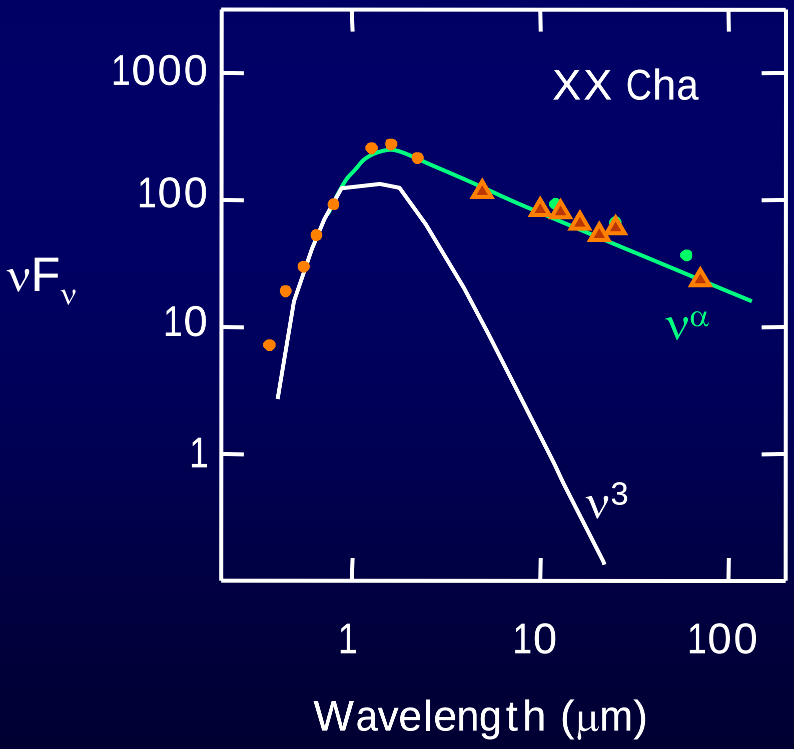
$$\nu F_\nu = \int_{r_{\min}}^{r_{\max}} \pi\, \nu B_\nu[T(r)]\, 2\pi r\, dr$$

$$\nu F_\nu = C\, T_0^{2/q}\, \nu^\alpha \int_{x_{\min}}^{x_{\max}} \frac{x}{\exp(x^q) - 1}\, dx$$

$$\alpha = 4 - 2/q$$

$$\Rightarrow \quad \nu F_\nu \sim \nu^\alpha \sim \nu^{4-2/q}$$

q = 1/2 for a flat SED



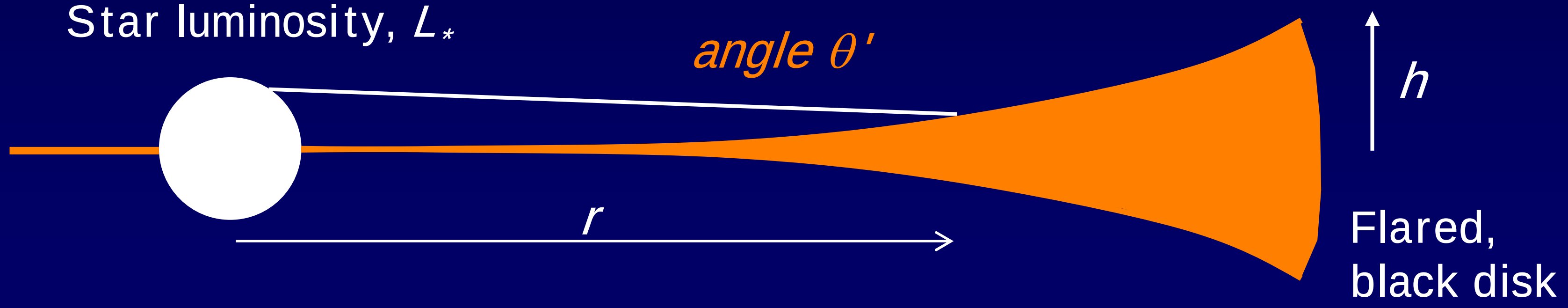
- we can derive q from α
- T(r) uniquely follows from α

How are disks really heated?

- "Standard" flat, black disks with *accretion*:
  - Lynden-Bell & Pringle 1974, *MNRAS*, **168**, 603.
  - Adams, Lada, & Shu 1987, *Ap.J.*, **312**, 788; & 1988, *Ap.J.*, **326**, 865.
- Flaring:
  - Kenyon & Hartmann 1987, *Ap.J.*, **323**, 714.
  - Calvet *et al.* 1994, *Ap.J.*, **434**, 330. (w/ rad. trans. & envelope)
  - Chiang & Goldreich 1997, *Ap.J.*, **490**, 368. (w/ rad. trans., disk only)
- Scattering halo:
  - Natta 1993, *Ap.J.*, **412**, 761.
- Wave-driven accretion heating:
  - Shu *et al.* 1990, *Ap.J.*, **358**, 495.

Geometrical changes: Flaring

Kenyon & Hartmann 1987, *Ap. J.*, **323**, 714.



- gravity ≈ $(z/r)(GM/r^2) \sim r^{-3}$
- absorbed radiation ~ $\sin\theta' \gg \sin\theta$
- $T_{flare}(r) > T_{flat}(r)$, especially at large r

$$\frac{h}{r} \sim r^{2/7}$$

$$T_i(r) \sim r^{-6/15}$$

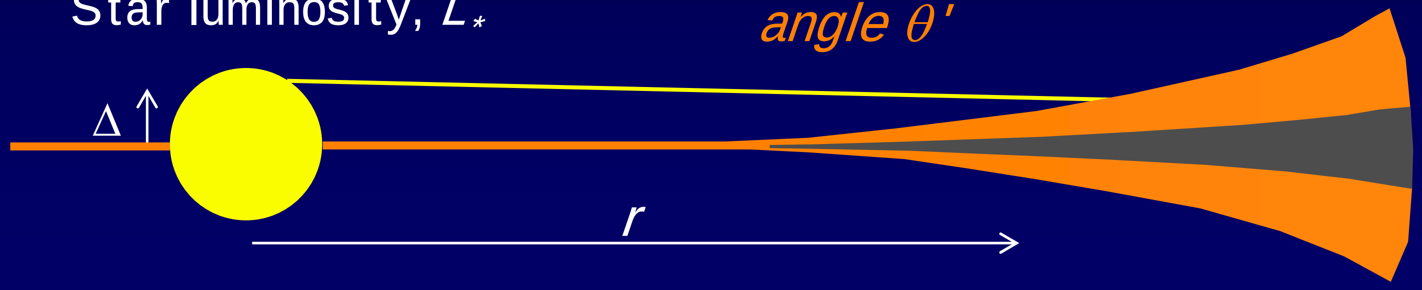
BUT

→ cannot account for *flat* SEDs (6/15 < 1/2)

→ still assumes “black” disk (no radiative transfer)

Radiative transfer

Chiang & Goldreich 1997, *Ap. J.*, **490**, 368.



Star luminosity, L_*

angle θ'

Surface $\tau \sim 1$
in optical

Interior $\tau > 1$
in infrared

- ❖ optical light absorbed $\tau_V \sim 1$, $\tau_{IR} \ll 1$
- ❖ small grains "bare" => $T_{grain} > T_{blackbody}$
- ❖ disk emission $\tau_{IR} < 1$ (5 - 100 μm)

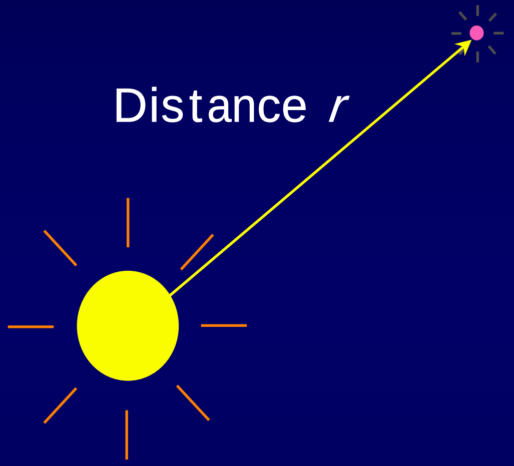
$$\frac{h}{r} \approx 0.9 \left(\frac{r}{209\ AU}\right)^{\frac{13}{45}}$$

Still cannot account for *very flat* SEDs but does fit majority.

$$T_i(r) \approx 21\ K \left(\frac{r}{209\ AU}\right)^{\frac{19}{45}}$$

Prediction: disk surface emission is optically *thin*

Radiative heating: isolated particle



Distance r

Luminosity L

Particle radius a (spherical; rapidly spinning)
Temperature T

Absorbed radiative power: $\pi a^2 \dfrac{L}{4\pi r^2}$

Emitted radiative power: $4\pi a^2 \sigma T^4$

$$T = \left(\frac{L}{16\pi\sigma}\right)^{1/4} r^{-1/2}$$

Using ε_ν for small particles: $T \sim r^{-2/5}$

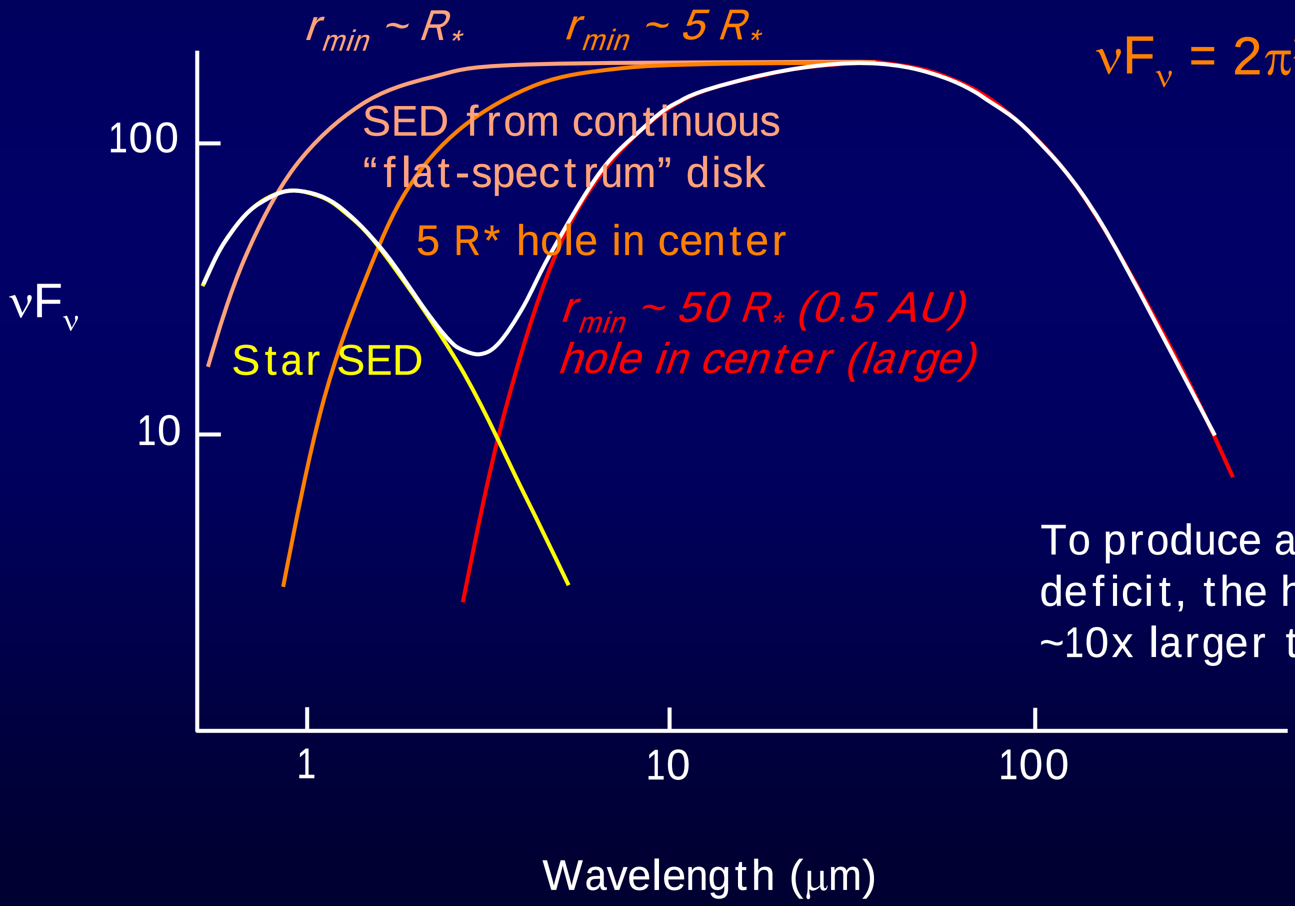
cf L. Spitzer, Jr., *Physical Processes in the Interstellar Medium*, ch. 9.1

Disk Exercises

- Calculate the “typical” disk radii (distance from the star) sampled by different wavelengths:
  - $\lambda(\mu m) = 1, 2, 4, 10, 100$
  - $L_* = 0.2, 1, 5\ L_{sun}$
  - Vary assumptions about temperature ($T \sim r^{-1/2}$, $T \sim r^{-2/5}$, etc.)
  - What areas of a disk do different search techniques sample?
- Set up a model calculation of an SED using the tools of the last few slides and show how the SED varies with different model parameters (r_{min}, r_{max}, q)
  - Use MathCad, Mathematica, C, or a similar program to make numerical calculations easy
  - Vary disk inclination to the line-of-sight

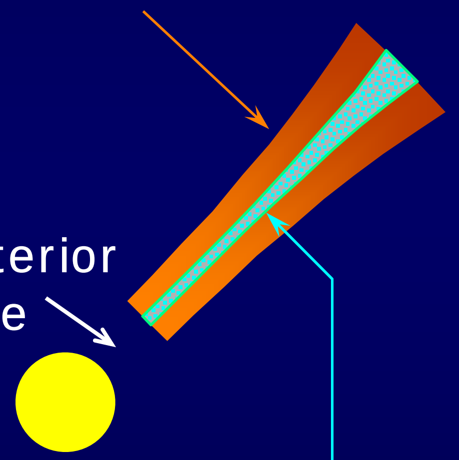
Physical Modification: Holes

$$\nu F_\nu = 2\pi^2\nu \int_{r_{\min}}^{r_{\max}} B_\nu[T(r)]\; r\, dr$$



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

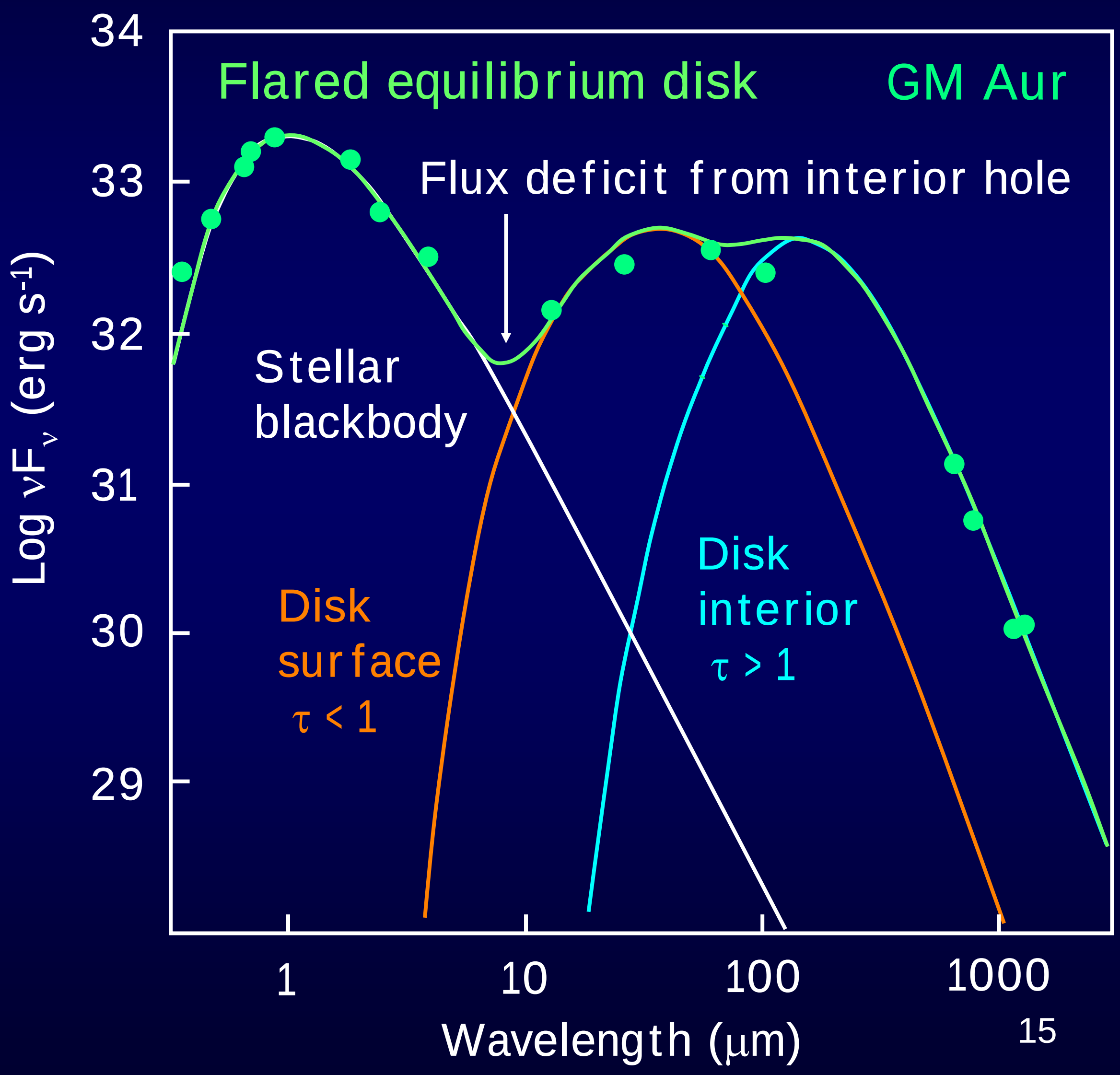
Inner holes produce flux deficits



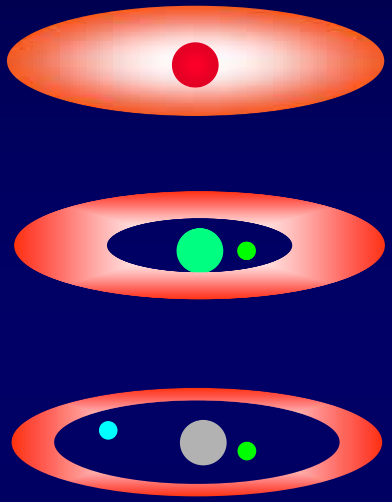
Superheated surface layer with small grains produces infrared light.

Interior hole

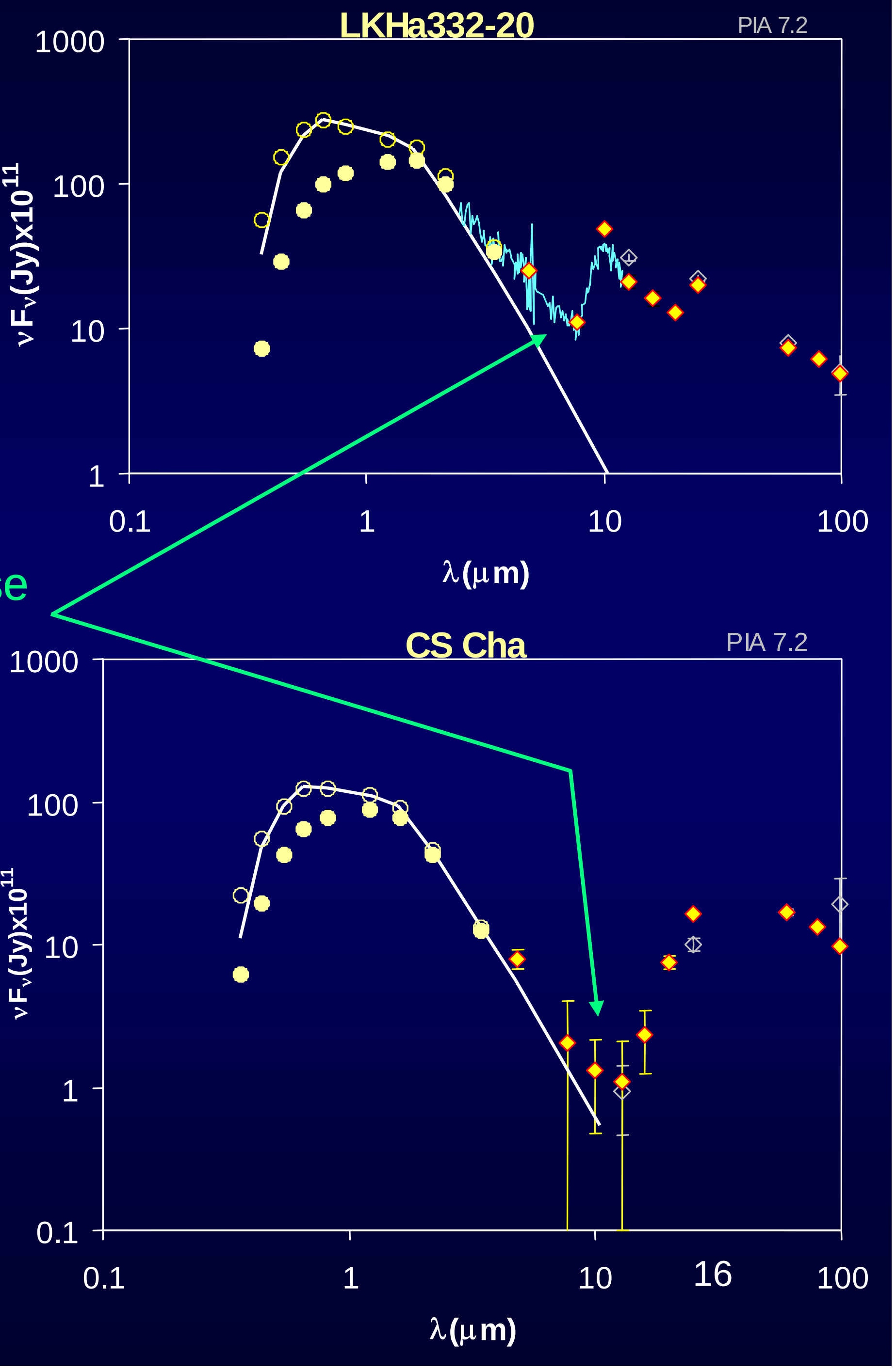
"Black" interior produces mm-wave emission.



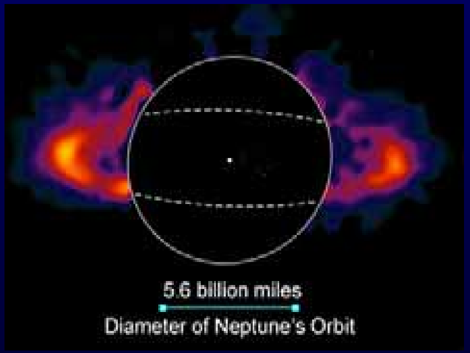
Evolution of structure



As disks age, the hole sizes should increase

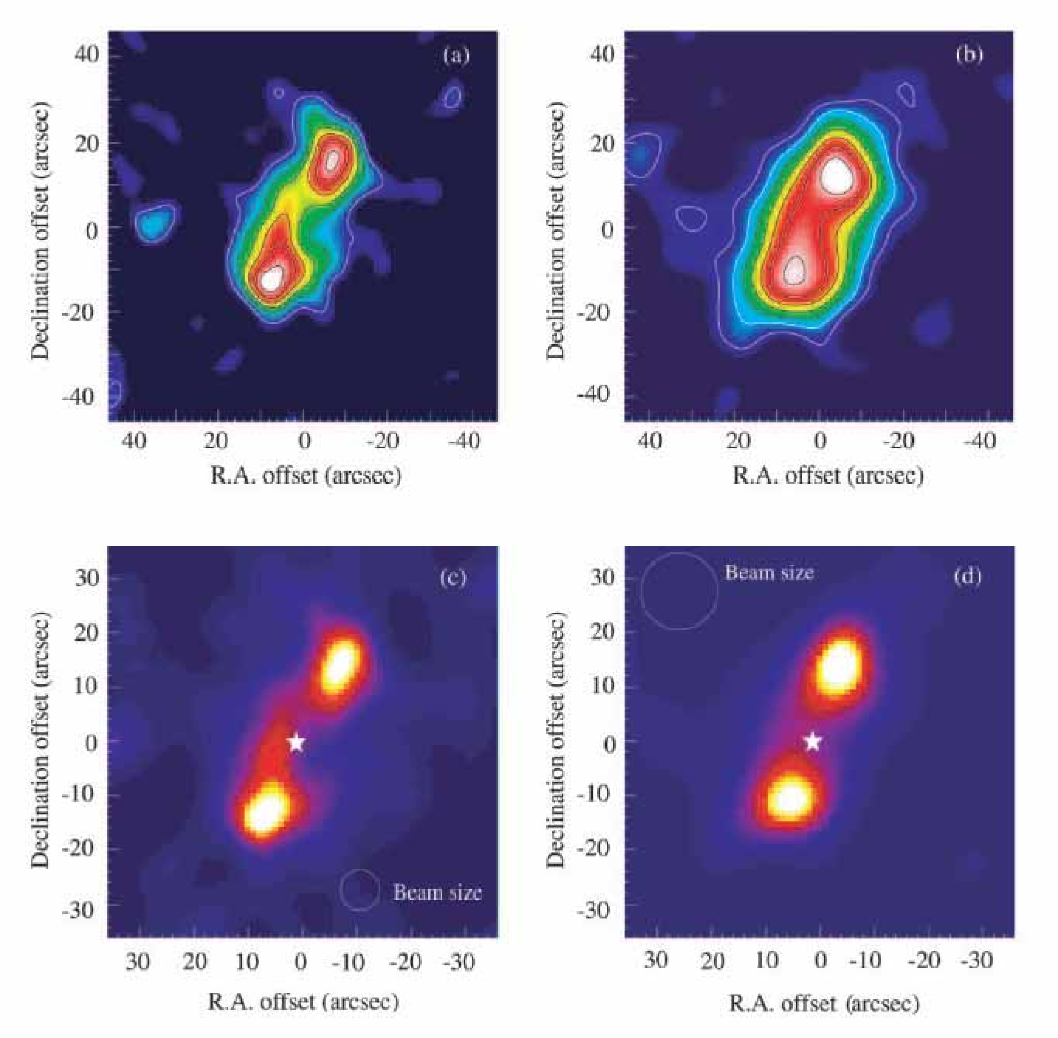


HR4796

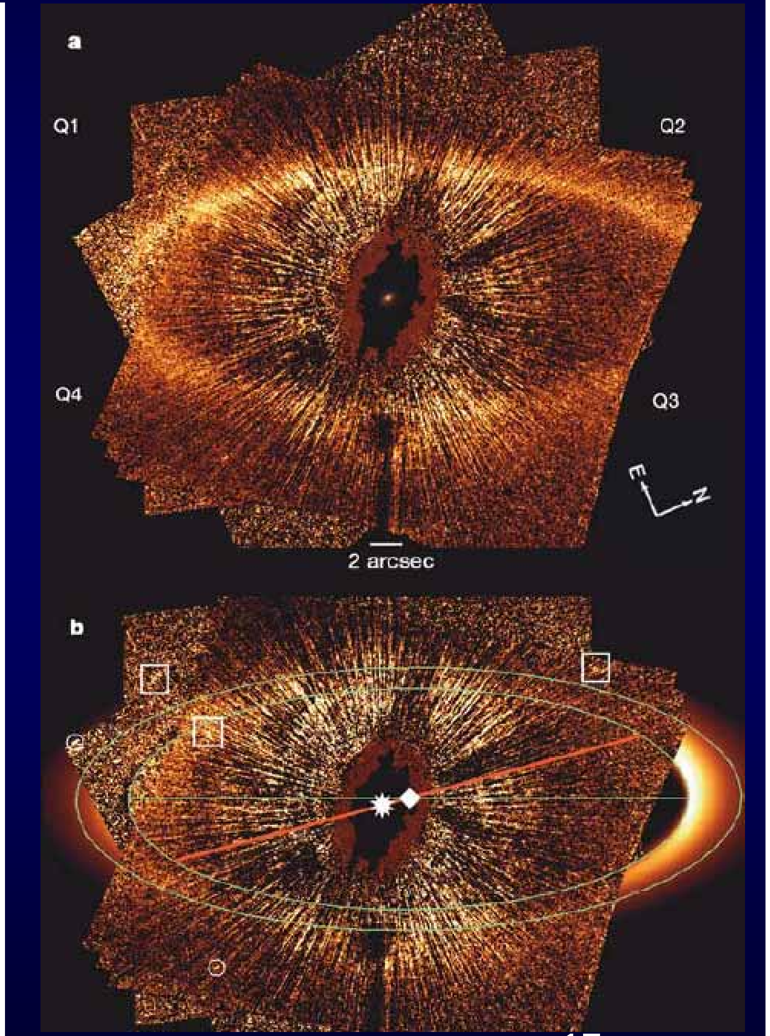


Weinberger *et al.* 1999, *ApJ Let*, **525**, L53

Fomalhaut: Ring Emission



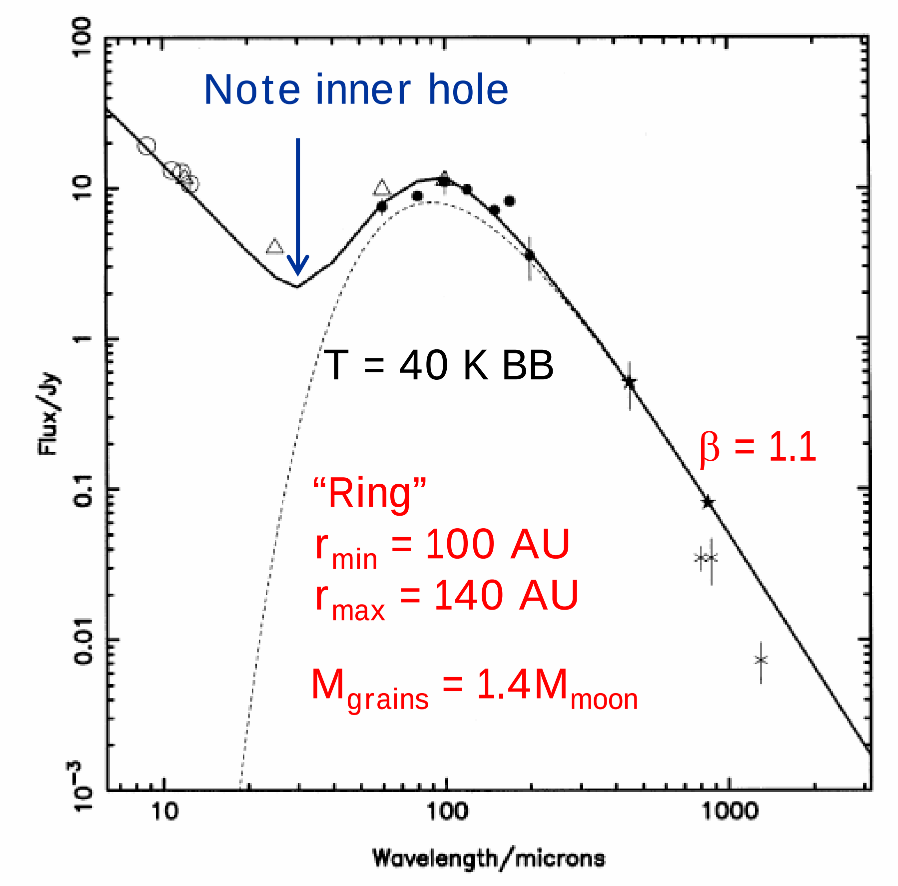
Holland *et al.* 2003, *ApJ*, **582**, 1141



Kalas et al. 2005, *Nature*, **435**, 1067

Vega-type stars: Fomalhaut

Dent *et al.* 2000, *MNRAS*, **314**, 702



Note inner hole

T = 40 K BB

β = 1.1

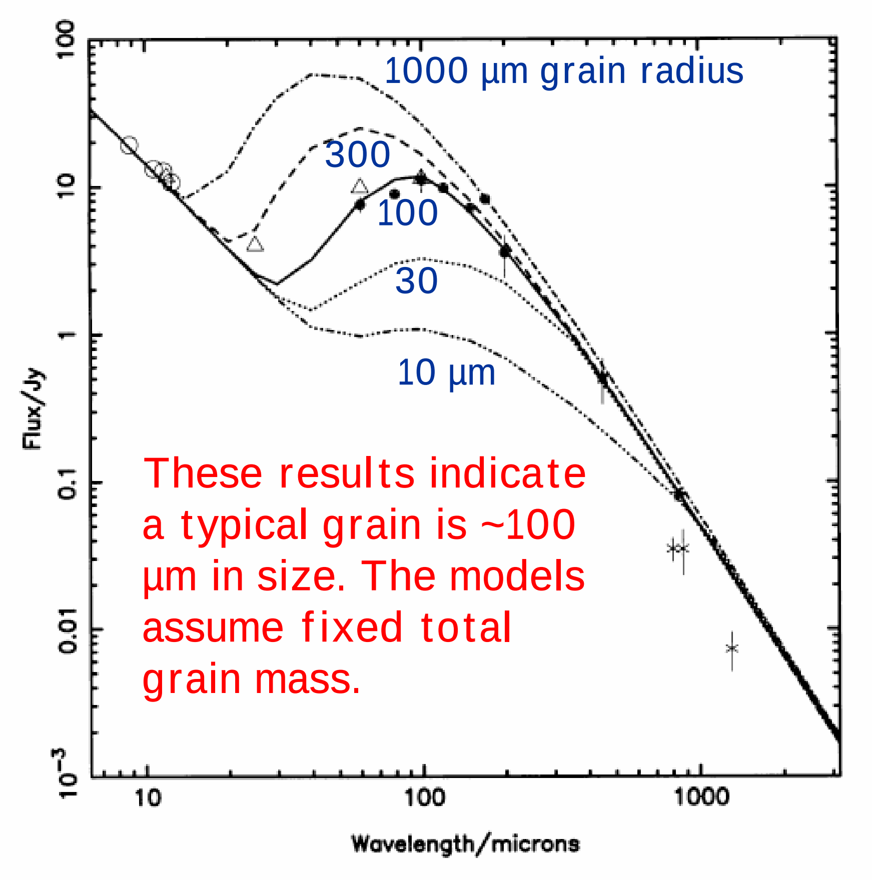
"Ring"

r_{min} = 100 AU

r_{max} = 140 AU

M_{grains} = 1.4M_{moon}

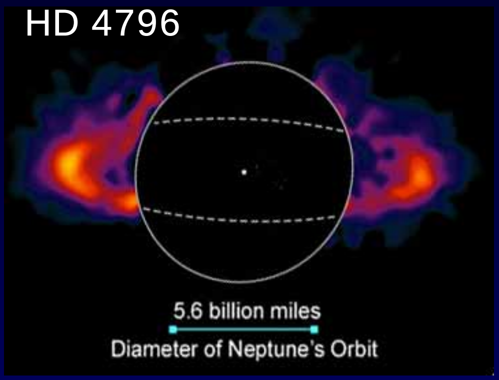
Figure 1: Best fit



These results indicate a typical grain is ~100 µm in size. The models assume fixed total grain mass.

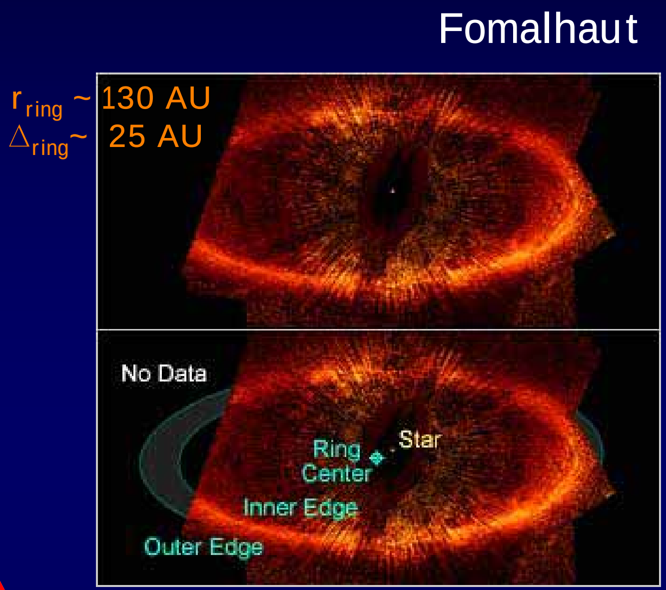
Figure 6: varying grain size

Modification 2: Gaps & Rings

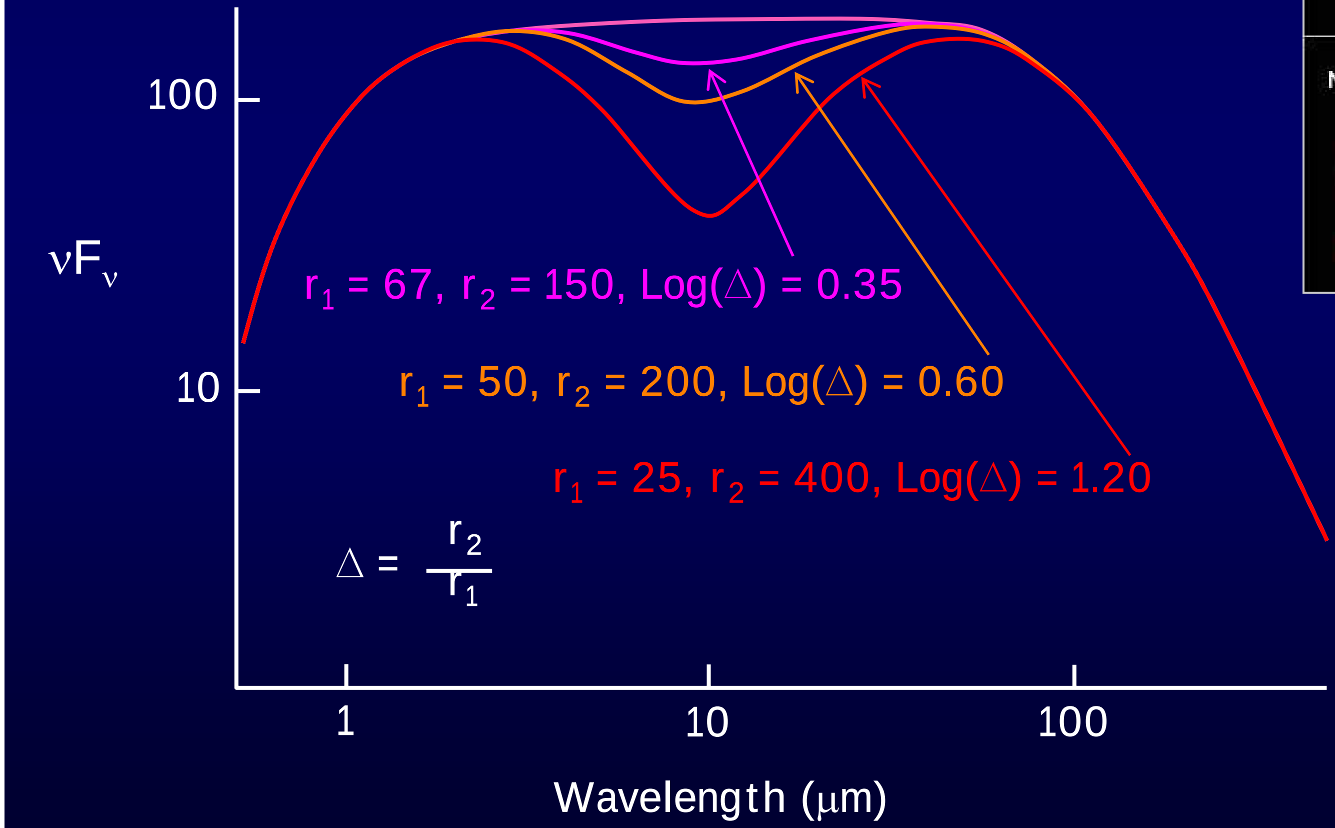


Weinberger *et al.* 1999

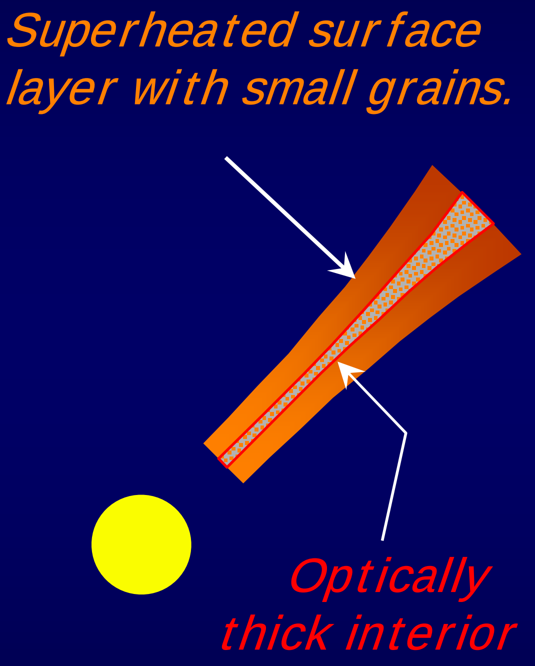
Gaps must be large to cause observable changes to the SEDs



Kalas, Graham, Clampin 2005

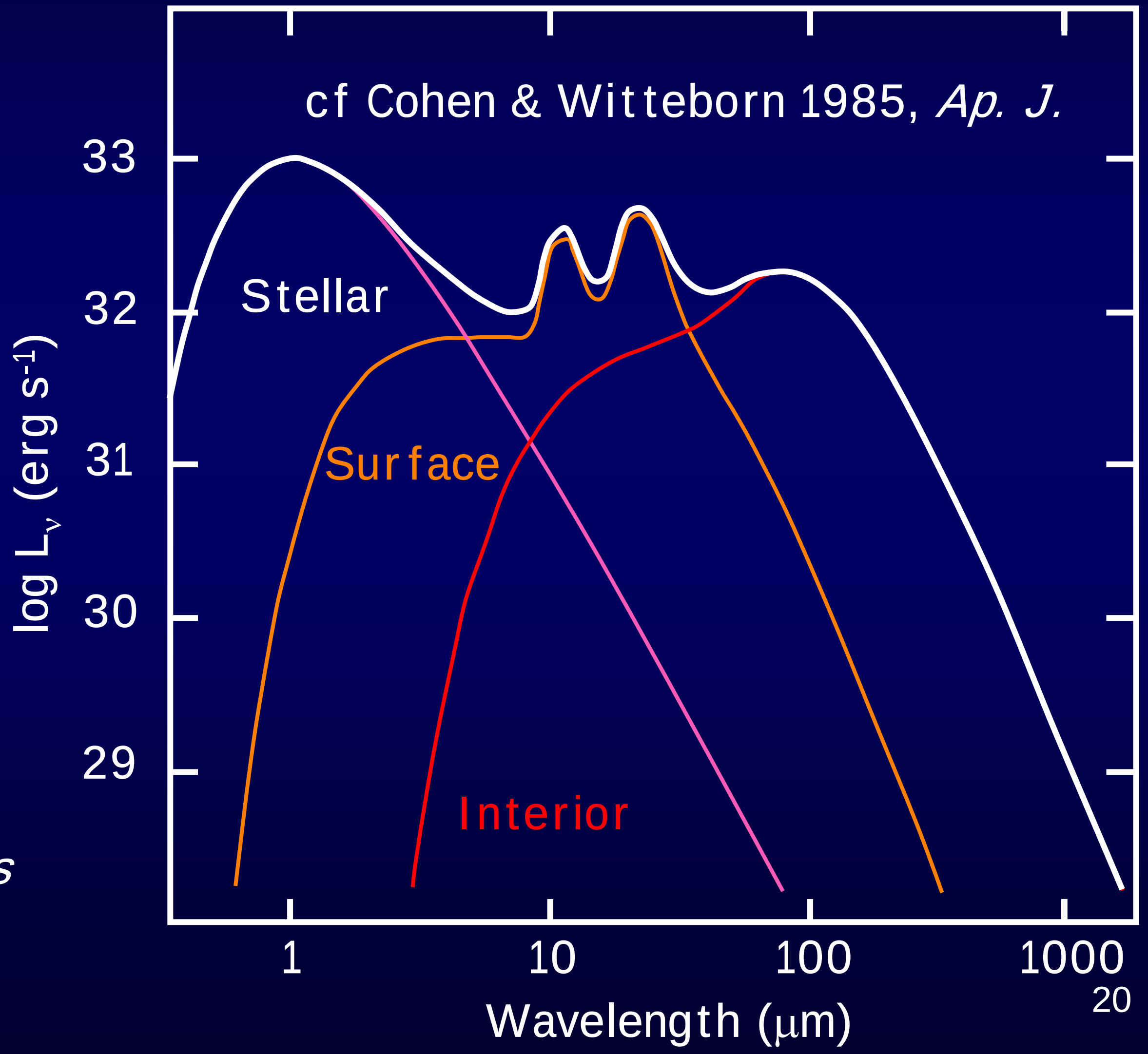


Optically thin, $dT/dr > 0$ $\Rightarrow$ *Emission* features



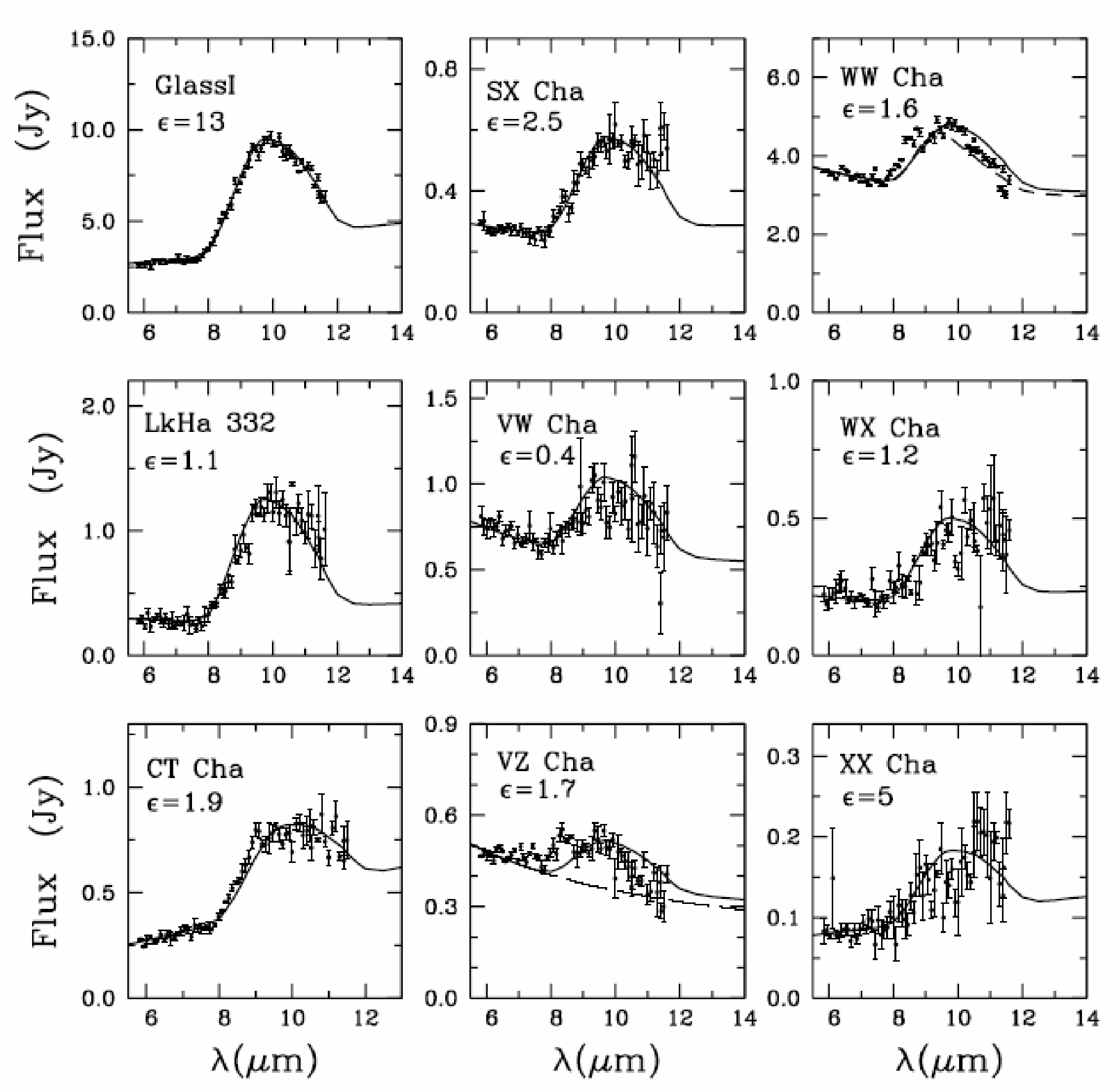
Surface layer τ_1:
dust emission features (face-on orientation).

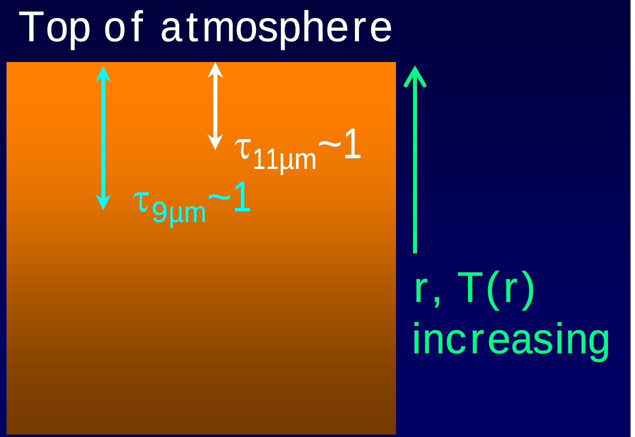
Chiang & Goldreich 1997, *Ap. J.*, **490**, 368.



Silicate emission confirms $\tau<1$ atmospheres

Fits: 1.2 µm pyroxene grains, CG97 model





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

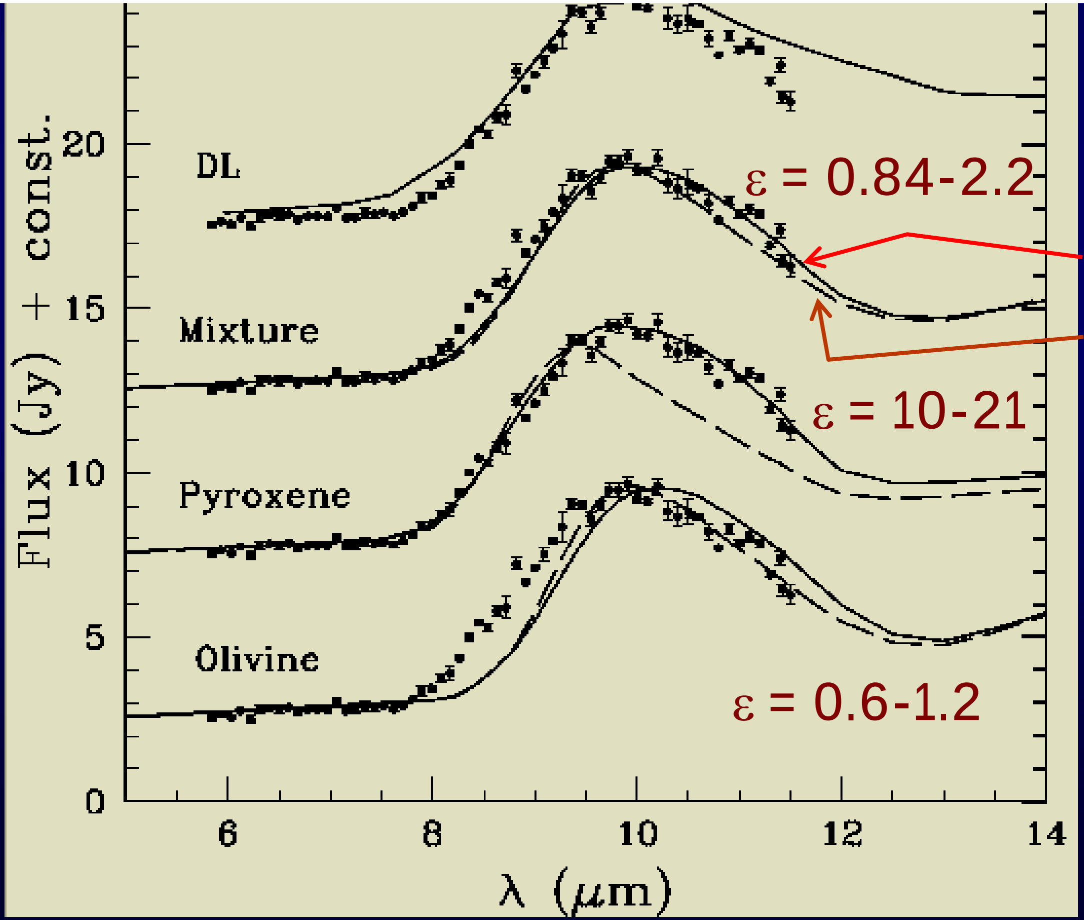
Natta, Meyer, & Beckwith 2000, *ApJ*, **534**, 838

10 μm emission: Mineralogy

Natta, Meyer, & Beckwith 2000, *ApJ, 534, 828.*

Grain sizes ~ 1 μm (from ε)
Some evidence for features at 8.5 and 11.3 μm:
crystalline silicates

$\varepsilon \equiv \sigma_{10}/\sigma_{mix}$



ε = 0.84-2.2

ε = 10-21

ε = 0.6-1.2

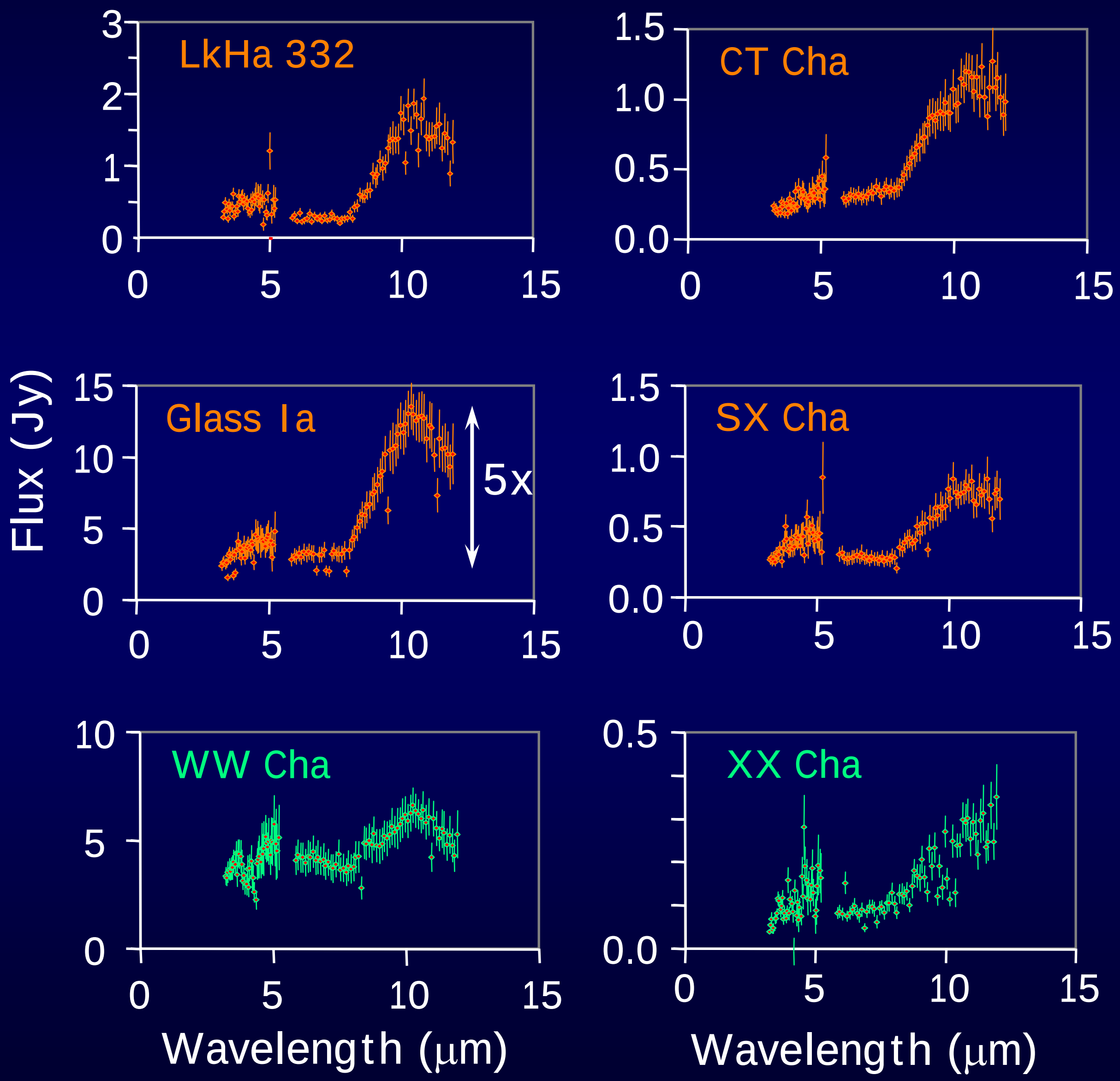
DL silicates

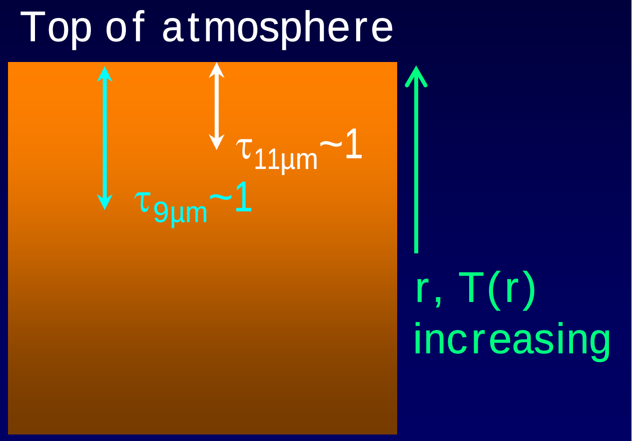
1 μm 0.5:0.5 olivine/pyroxene
0.1 μm 0.3:0.7 olivine/pyrox.

1.2 μm pyroxene
0.1 μm pyroxene

1.2 μm olivine
0.1 μm olivine

Silicate emission confirms $\tau<1$ atmospheres

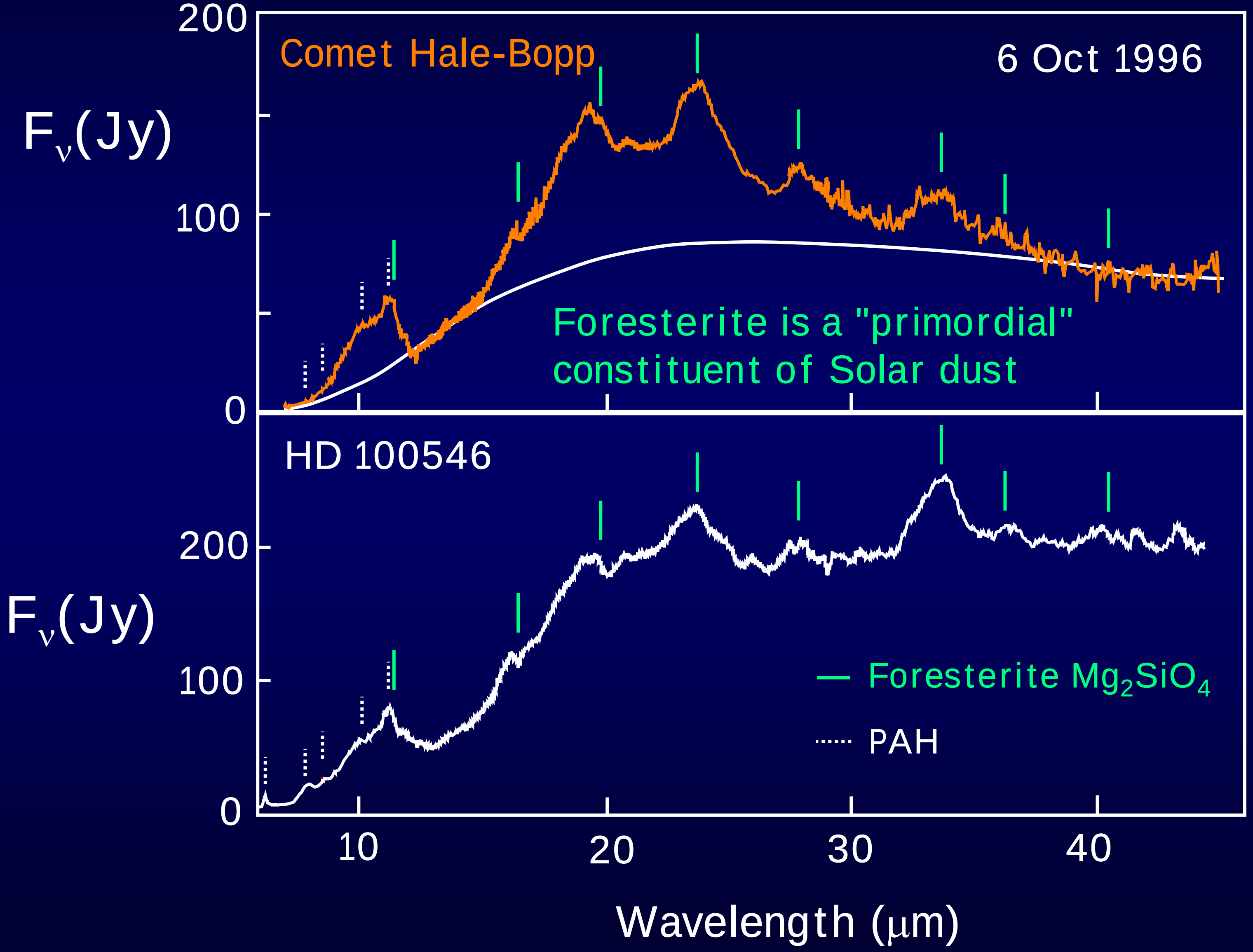




Emission features indicate optically thin emission from in an atmosphere with vertically *increasing* temperature gradients

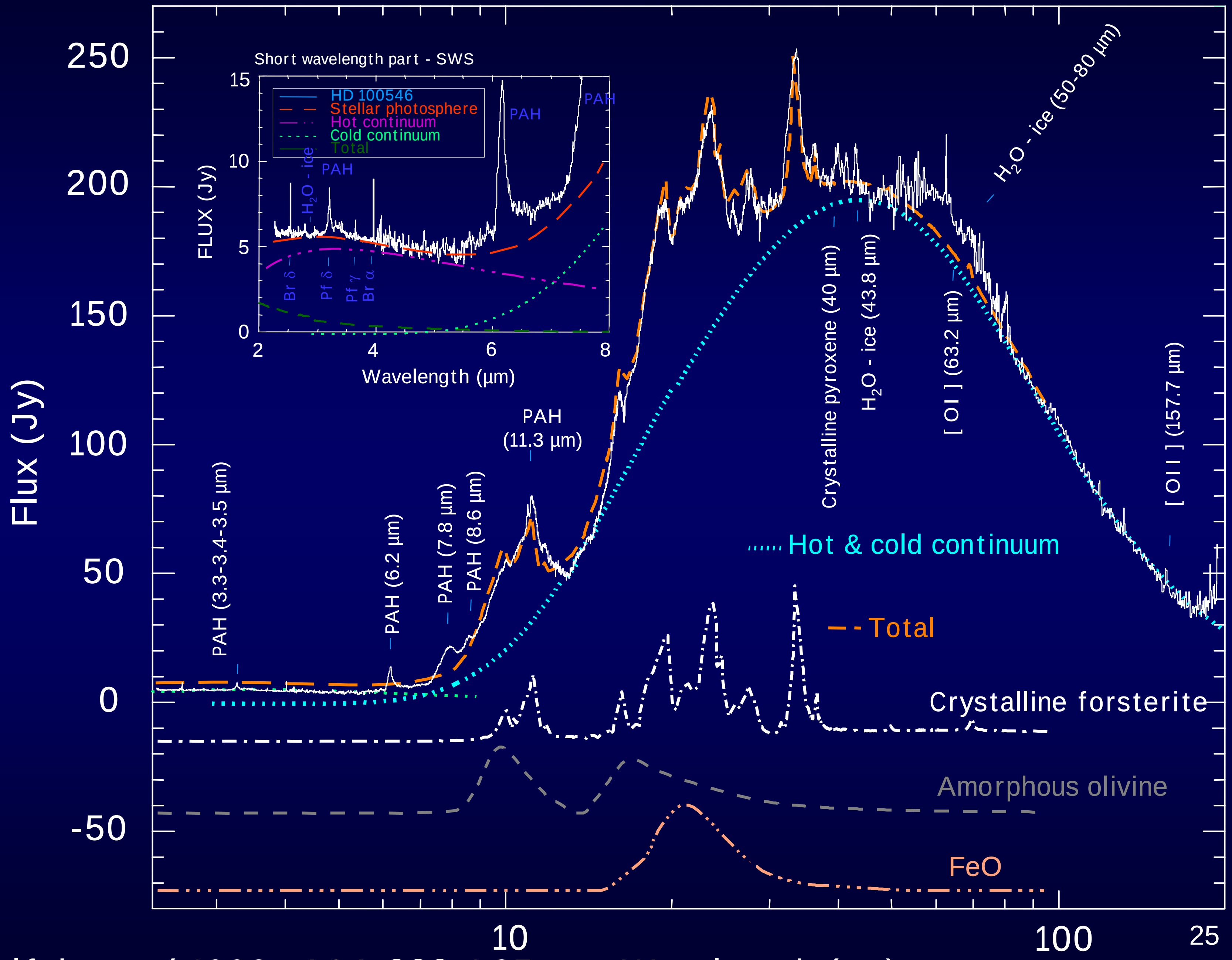
Natta, Meyer, & Beckwith 2000, *ApJ*, **534**, 838

Waelkens *et al.* 1996, *A&A*, **315**, L245.



Foresterite is a "primordial" constituent of Solar dust

HD 100546 - SWS and LWS : all components

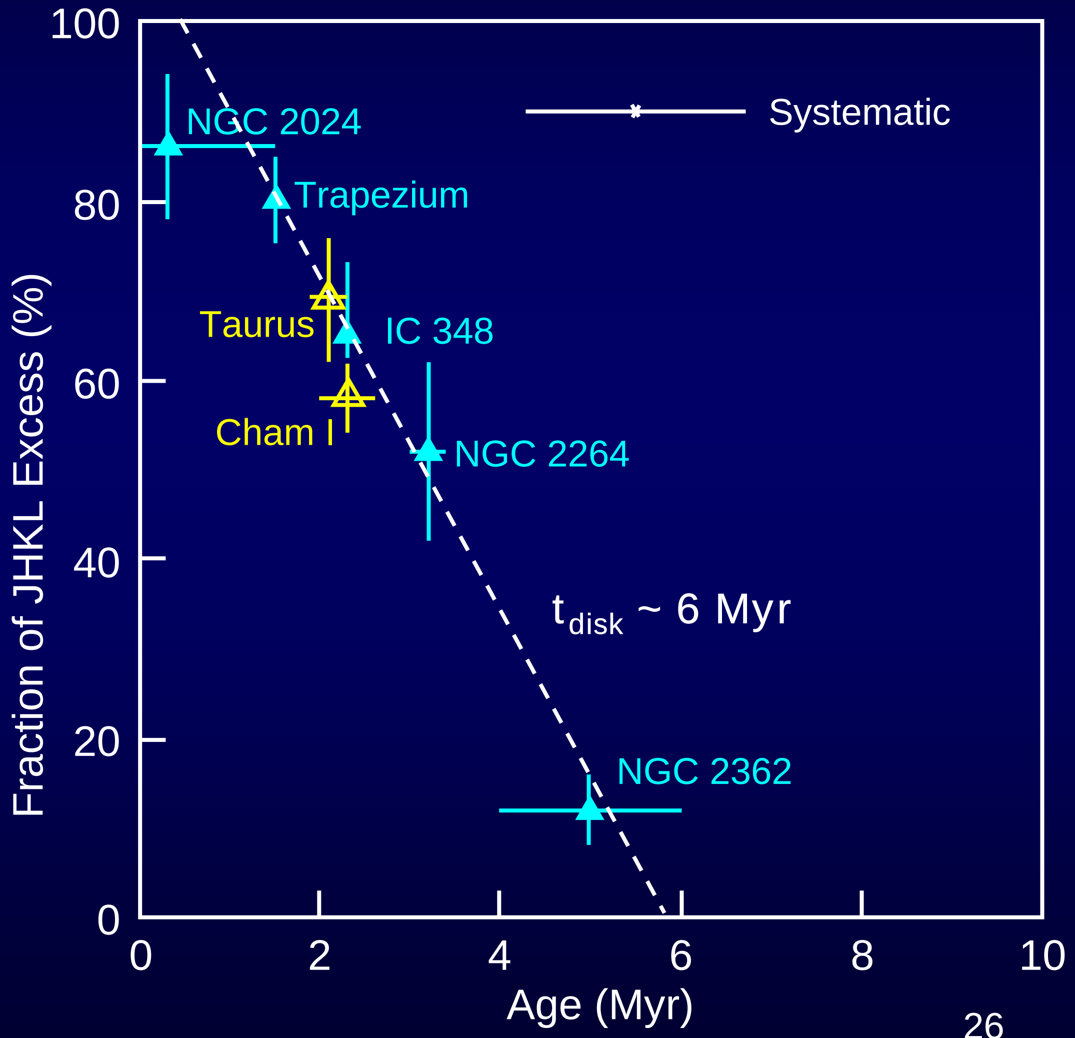


Malfait *et al.* 1998, *A&A*, **332**, L25

Near- IR Disk Lifetimes

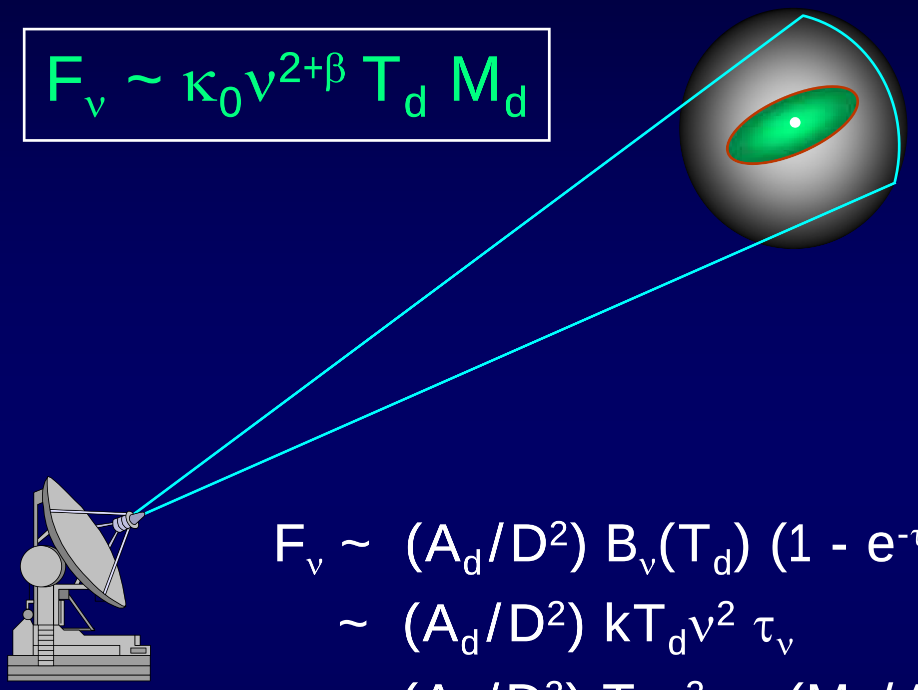
- L-band (3.4 μm) light used as disk proxy
  - 900 K
  - ≥10^{20} gm of dust
  - Inner disk (TBD)
- Disk lifetime ~6 Myr
- Principal uncertainty driven by NGC 2362
- Are outer and inner disk lifetimes the same?

Haisch, Lada, Lada 2001, *ApJL*, **553**, L153.



How do we observe disk mass?

$$\boxed{F_\nu \sim \kappa_0 \nu^{2+\beta}\, T_d\, M_d}$$



Beckwith *et al.* 1990, *AJ*, **99**, 924
Beckwith 1999, “OSPS”, p. 579.

We want to observe where the disk is transparent (to see *all* the material)

For long enough wavelengths (λ > 200 μm), the dust $\tau < 1$.

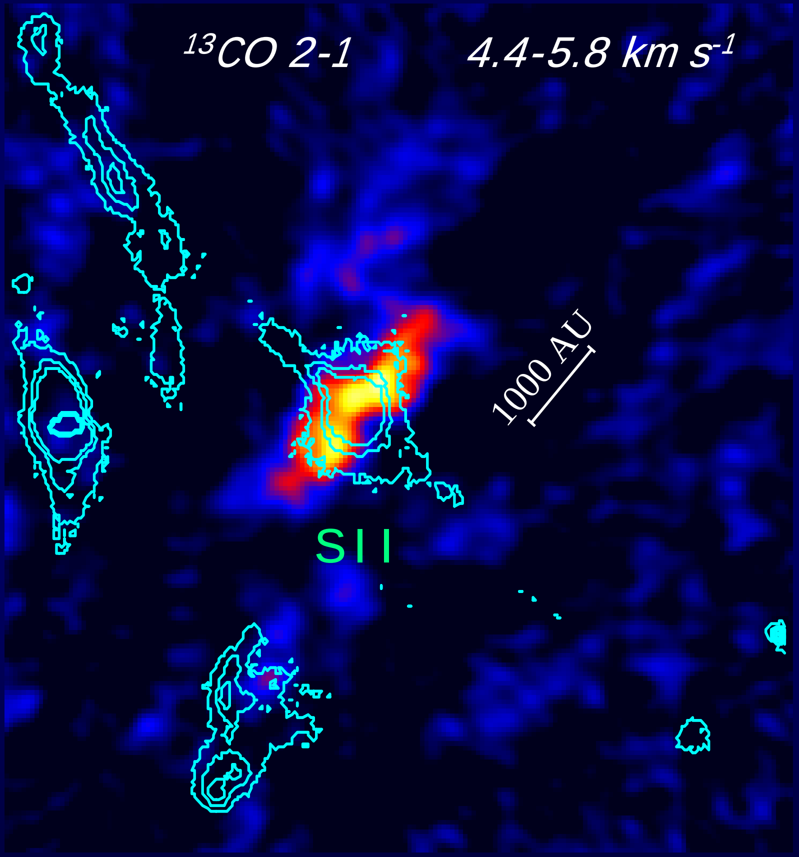
$$\begin{aligned} F_\nu &\sim (A_d/D^2)\, B_\nu(T_d)\, (1 - e^{-\tau}) \\ &\sim (A_d/D^2)\, kT_d \nu^2\, \tau_\nu \\ &\sim (A_d/D^2)\, T_d \nu^2\, \kappa_\nu\, (M_d/A_d) \\ &\sim D^{-2}\, T_d\, \nu^2\, \kappa_\nu\, M_d \end{aligned}$$

$A_d \equiv$ disk projected area
$D \equiv$ distance to source
$T_d \equiv$ disk particle temperature
$\tau_\nu \equiv$ optical depth at ν
$M_d \equiv$ mass of disk
$\kappa_\nu \equiv$ mass opacity (cm^2 g^{-1})

$$\kappa_\nu \sim \kappa_0\, (\nu/\nu_0)^\beta$$

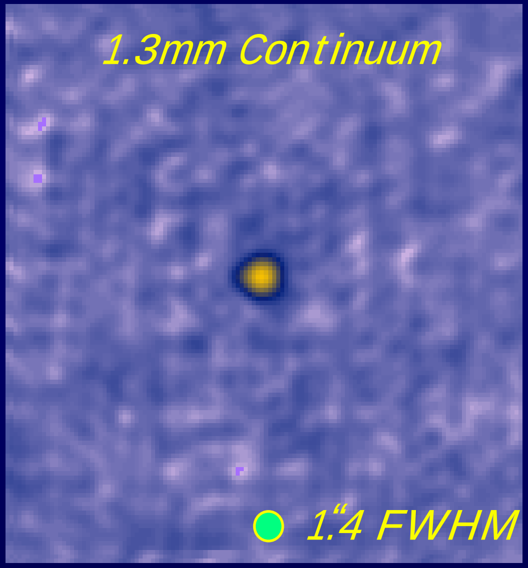
$$M_d = 0.03\ M_{sun}\ \frac{F_\nu}{1\ \mathrm{Jy}} \left(\frac{D}{100\ \mathrm{pc}}\right)^2 \left(\frac{\lambda}{1.3\ \mathrm{mm}}\right)^3 \frac{50\ \mathrm{K}}{T}\ \frac{0.02\ \mathrm{cm}^2\ \mathrm{gm}^{-1}}{\kappa_{1.3\mathrm{mm}}}$$

mm-wave continuum is easily seen



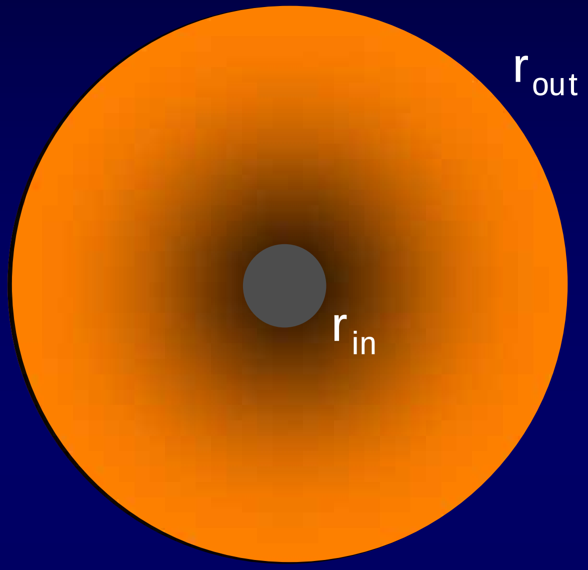
Mundt *et al.* 1990, *A&A*, **232**, 37.

HL Tau



Koerner & Sargent 1995,
Ap.SS., **223**, 169
and unpublished data.

$T(r)$ & $\Sigma(r)$ govern where F_ν originates



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

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

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

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

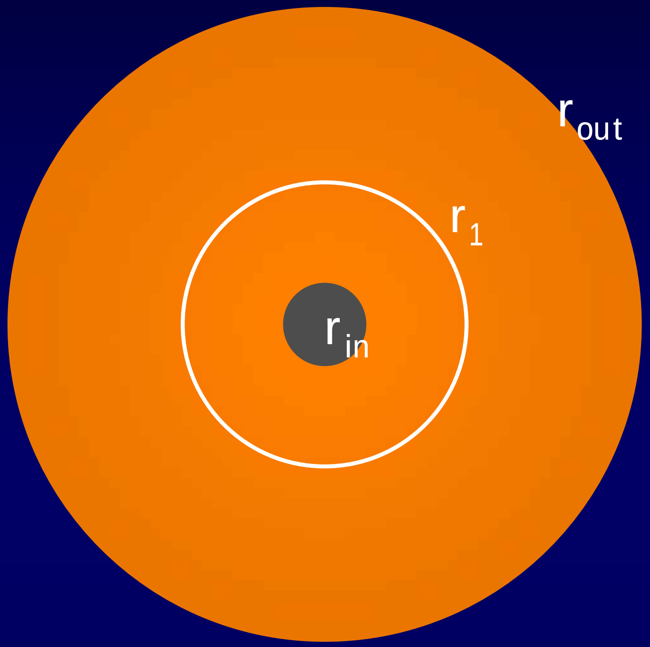
$\Sigma(r) \sim r^{-p}$ $\quad 0 < p < 2$

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

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

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

Inner Parts May Have $\tau >> 1$



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

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

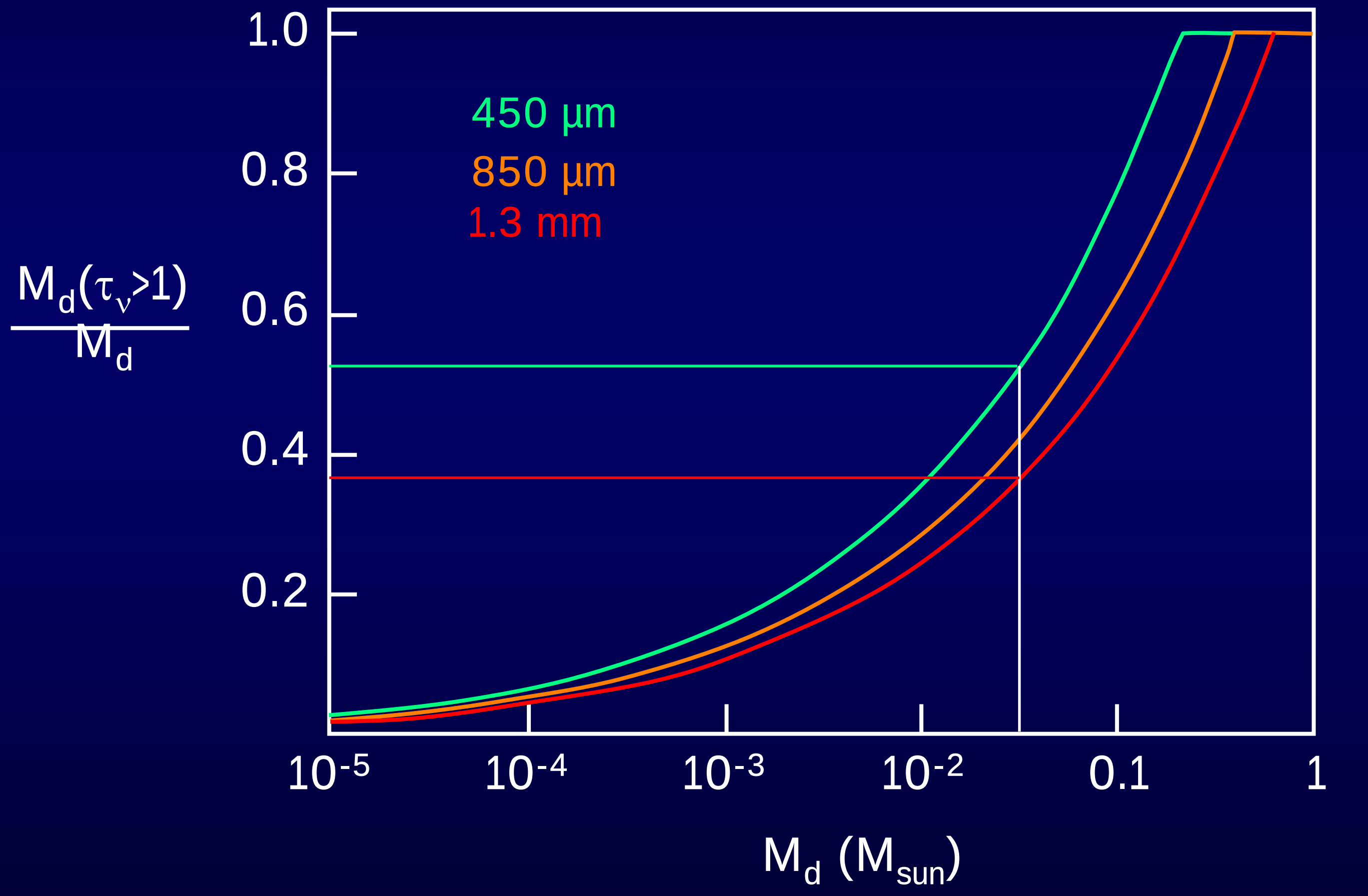
$$+ \int_{r_1}^{r_{out}} k\,T(r)\,\nu^2\,\kappa_\nu\Sigma(r)\,2\pi r\,dr \qquad (\tau < 1)$$

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.)

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

Optical depth effects

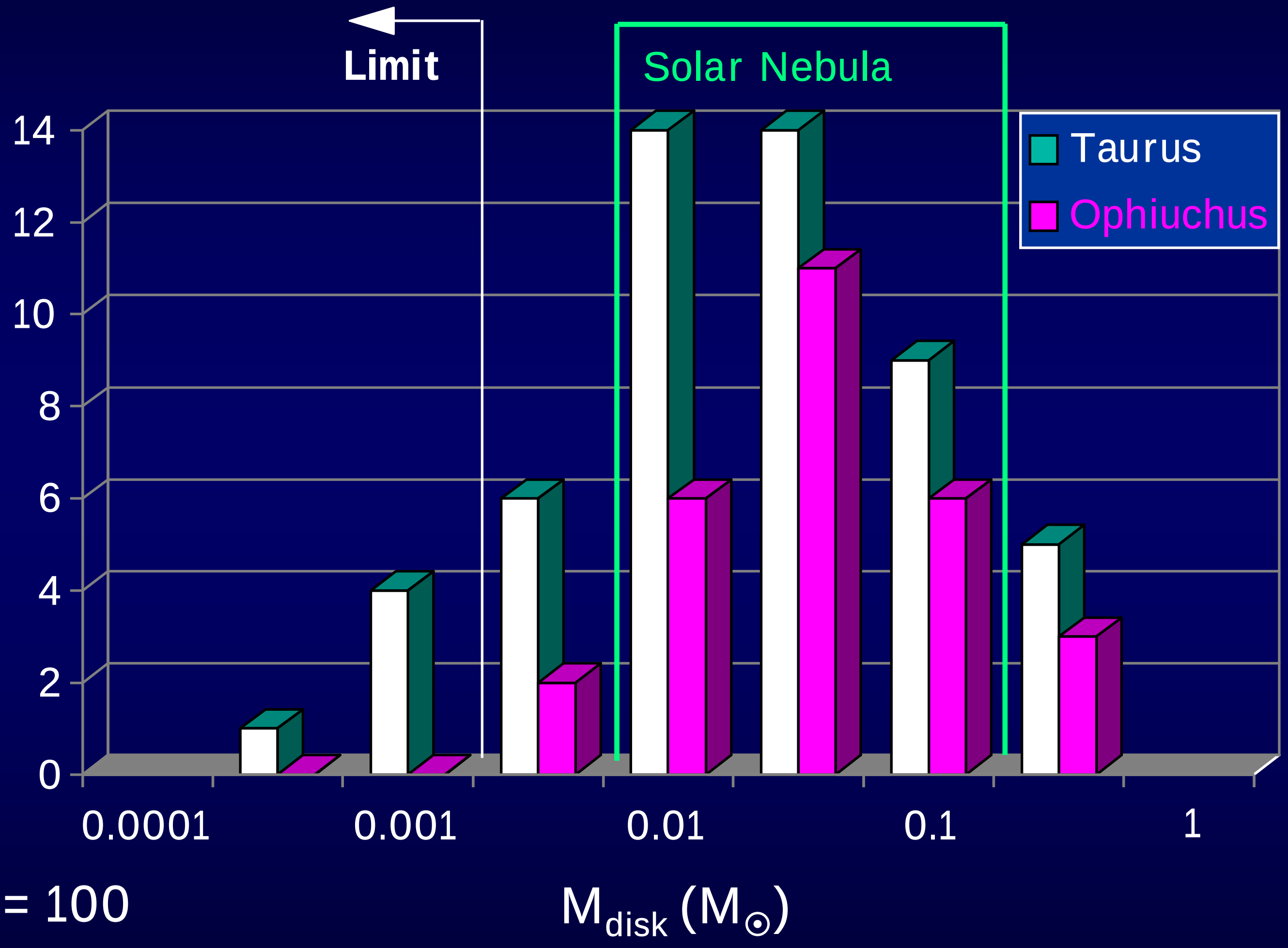
Andrews & Williams 2005, astro-ph 0506187 (June 2005)



Degeneracy of Parameters: mm-waves

- Compare mm-wave spectral indices, β, for opaque ($\tau >> 1$) and transparent ($\tau \ll 1$) disks at $\lambda \sim 1$ mm
  - What are the limiting cases?
- Estimate the relative contributions of optically thick and optically thin parts of a disk to mm-wave light
  - Assume a surface density law: $\Sigma(r) \sim r^{-p}$
  - Find the radius, $r_{\tau=1}(\lambda)$, where $\tau(\lambda) = 1$
  - What happens to relative contributions of thick/thin emission as wavelength varies?
  - Show how this degeneracy makes it impossible to derive the dust spectral index, β, uniquely from an SED
  - How can one use spatial resolution to overcome this problem?

Disks *can* build planets



Beckwith
& Sargent

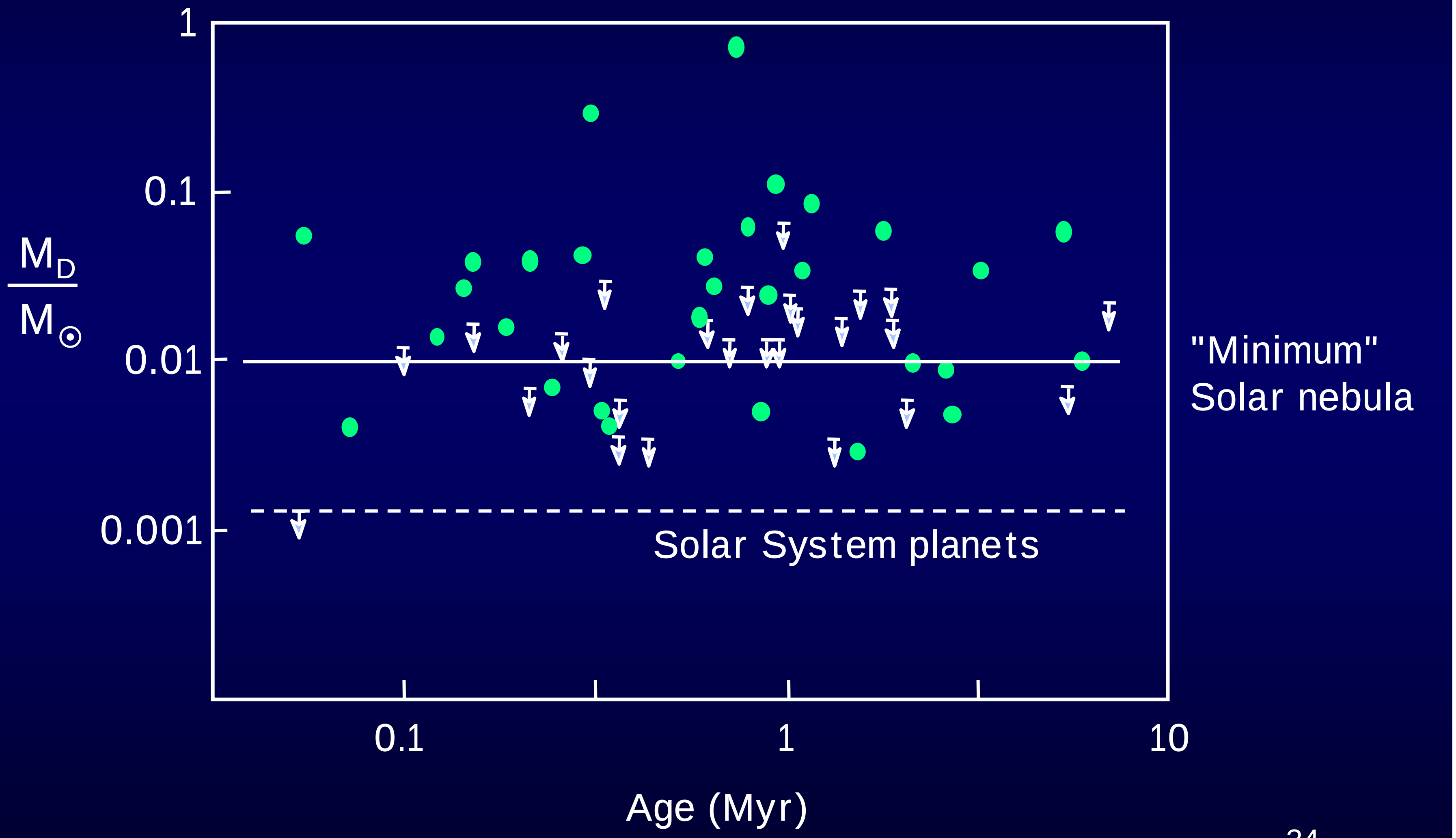
Andre &
Montemerle

assumes
gas/dust = 100

similar mass distribution for NGC 2071 by E. Lada 1998
but *not* Orion HST disks (E. Lada *et al.*, Bally *et al.*, unpublished)

Mass Evolution of Young Disks

BSCG 1990, *AJ.*, **99**, 924.



Disk Mass

Andrews & Williams 2005, astro-ph 0506187

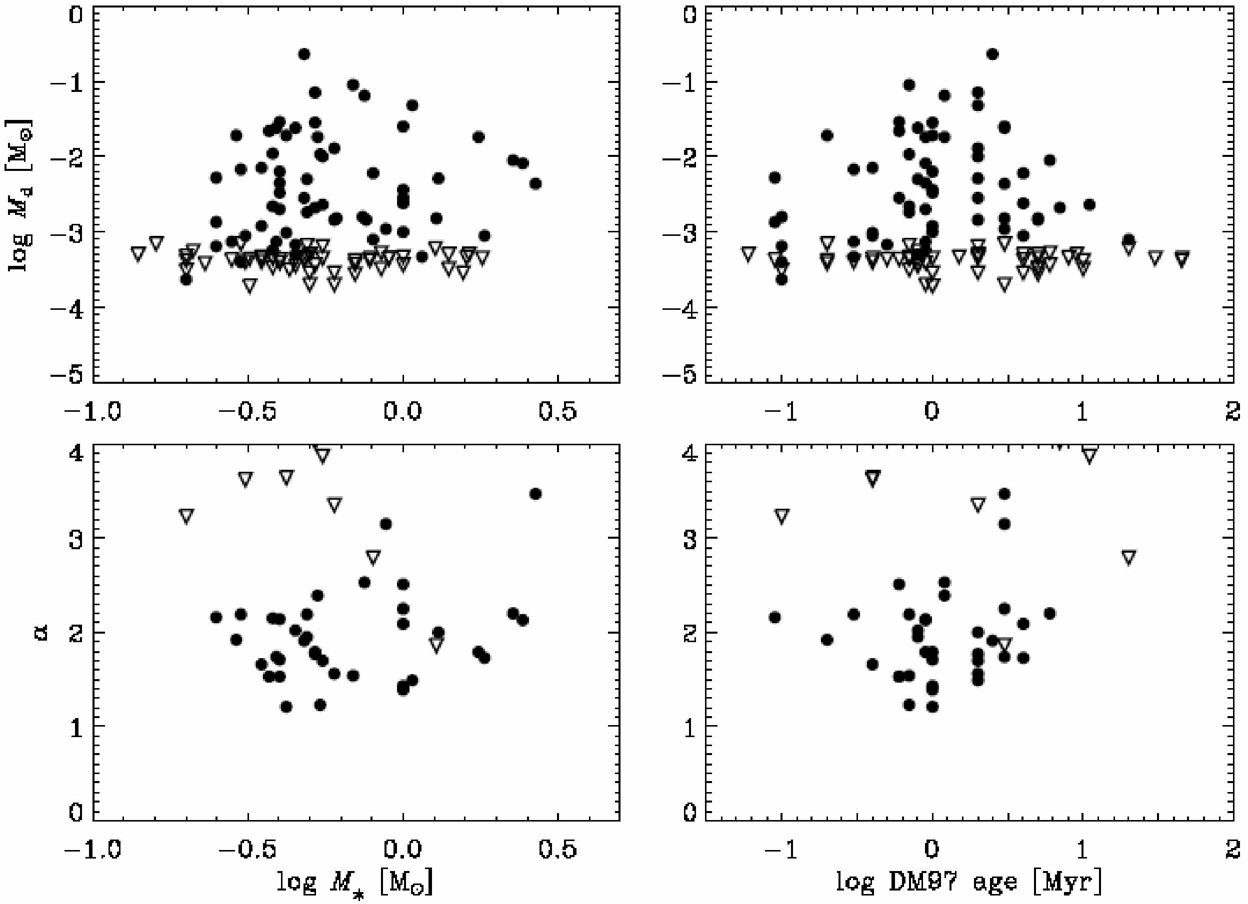
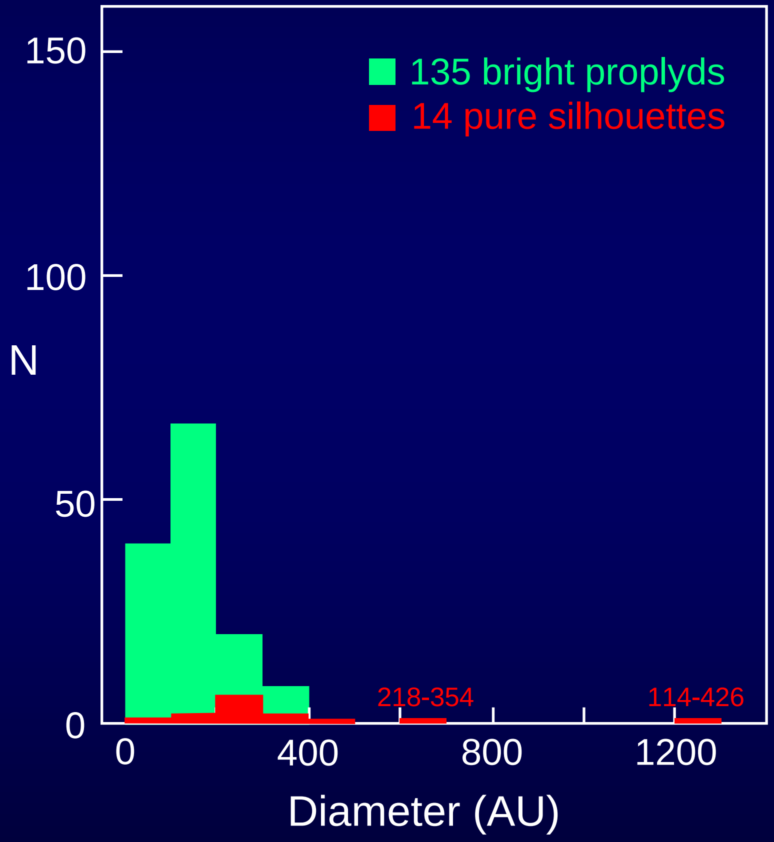
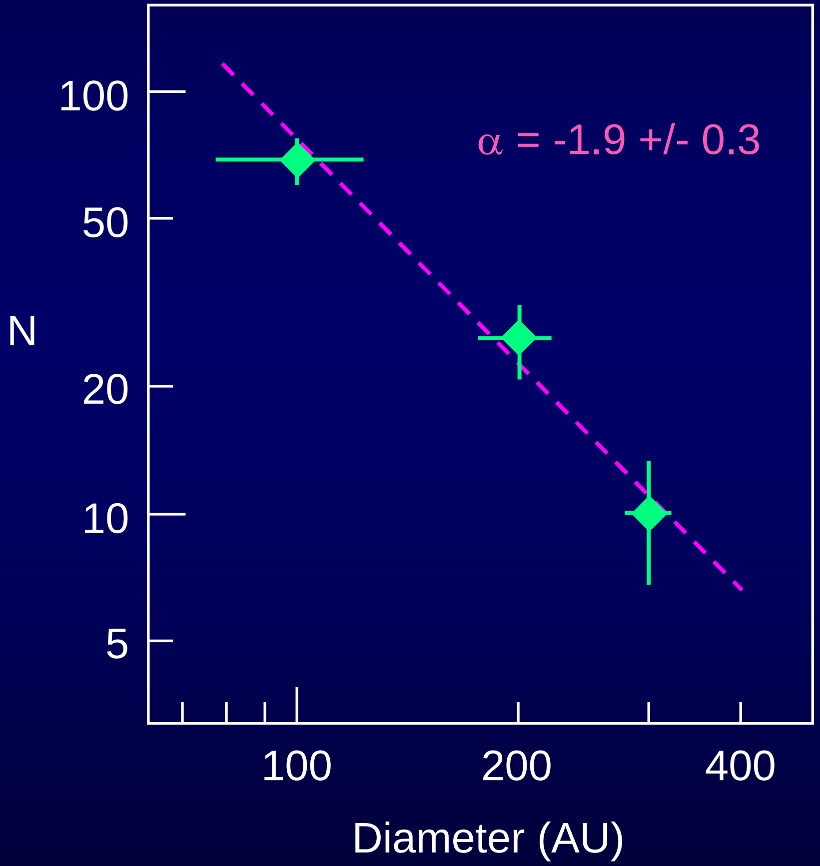


Fig. 9.— Plots showing the relationships between disk masses or submillimeter continuum slopes and stellar masses or ages. Filled circles are detections and open triangles are 3-σ upper limits.

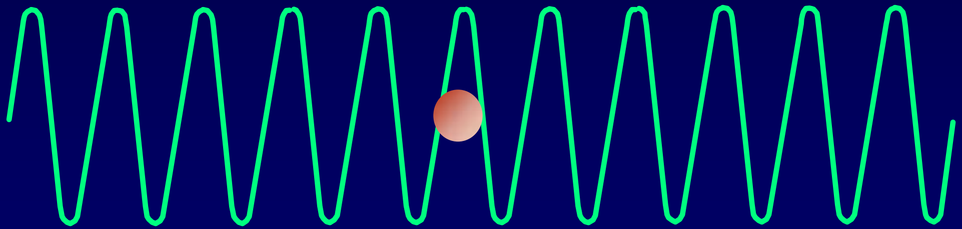
Distribution of Disk Radii: Orion

Vicente & Alves 2005, astro-ph 0506585 (2005)





MM-waves interact with *all* atoms



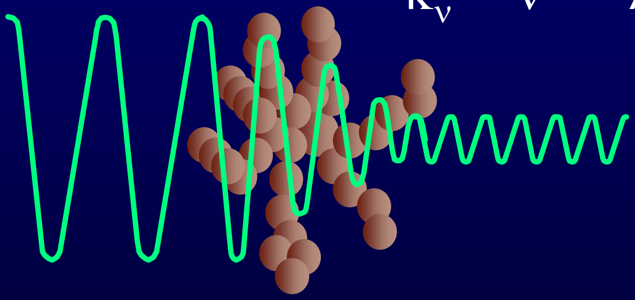
Particle size << wavelength

$\Rightarrow$ coupling $\sim \lambda^{-\beta}$

1st order: size independent,
wave sees every atom

Conductors: “antenna” growth,
absorption by free electrons

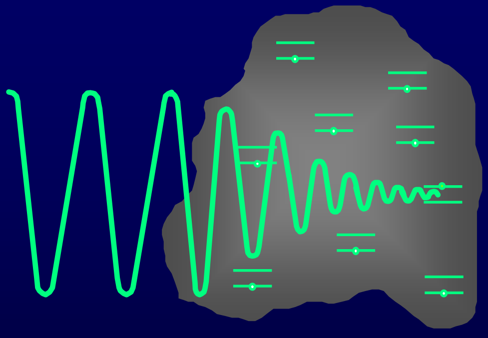
$\kappa_\nu \sim \nu^2 \sim \lambda^{-2}$ plasma
skin depth



Fe, graphite

Insulators: absorption by
lattice resonances

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

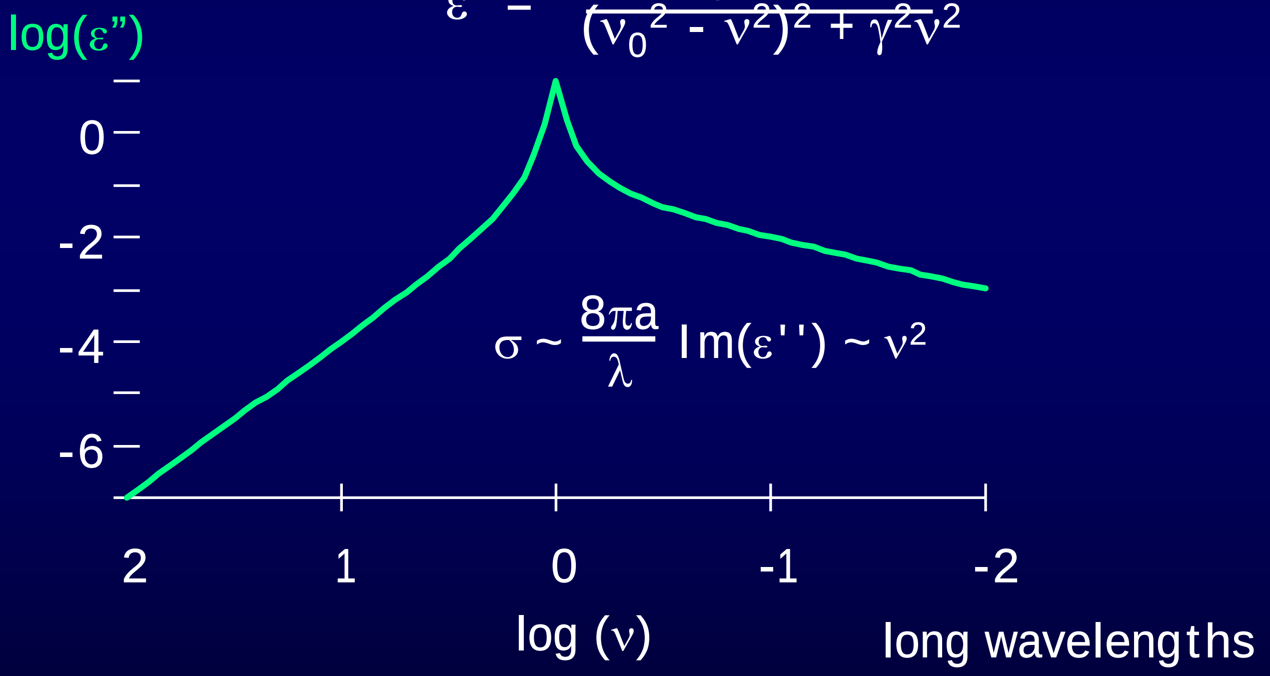


Olivines (silicates):
Mg_2SiO_4, $[Mg,Fe]Si_2O_5$

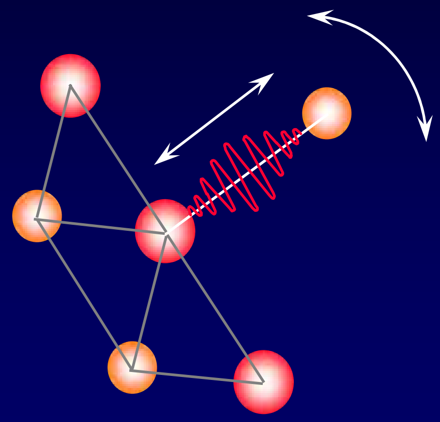
Absorption in Insulators

Lattice resonances

$$\varepsilon'' = \frac{\nu_p^2\ \gamma\ \nu}{(\nu_0^2 - \nu^2)^2 + \gamma^2\nu^2}$$



$$\sigma \sim \frac{8\pi a}{\lambda}\ \mathrm{Im}(\varepsilon'') \sim \nu^2$$



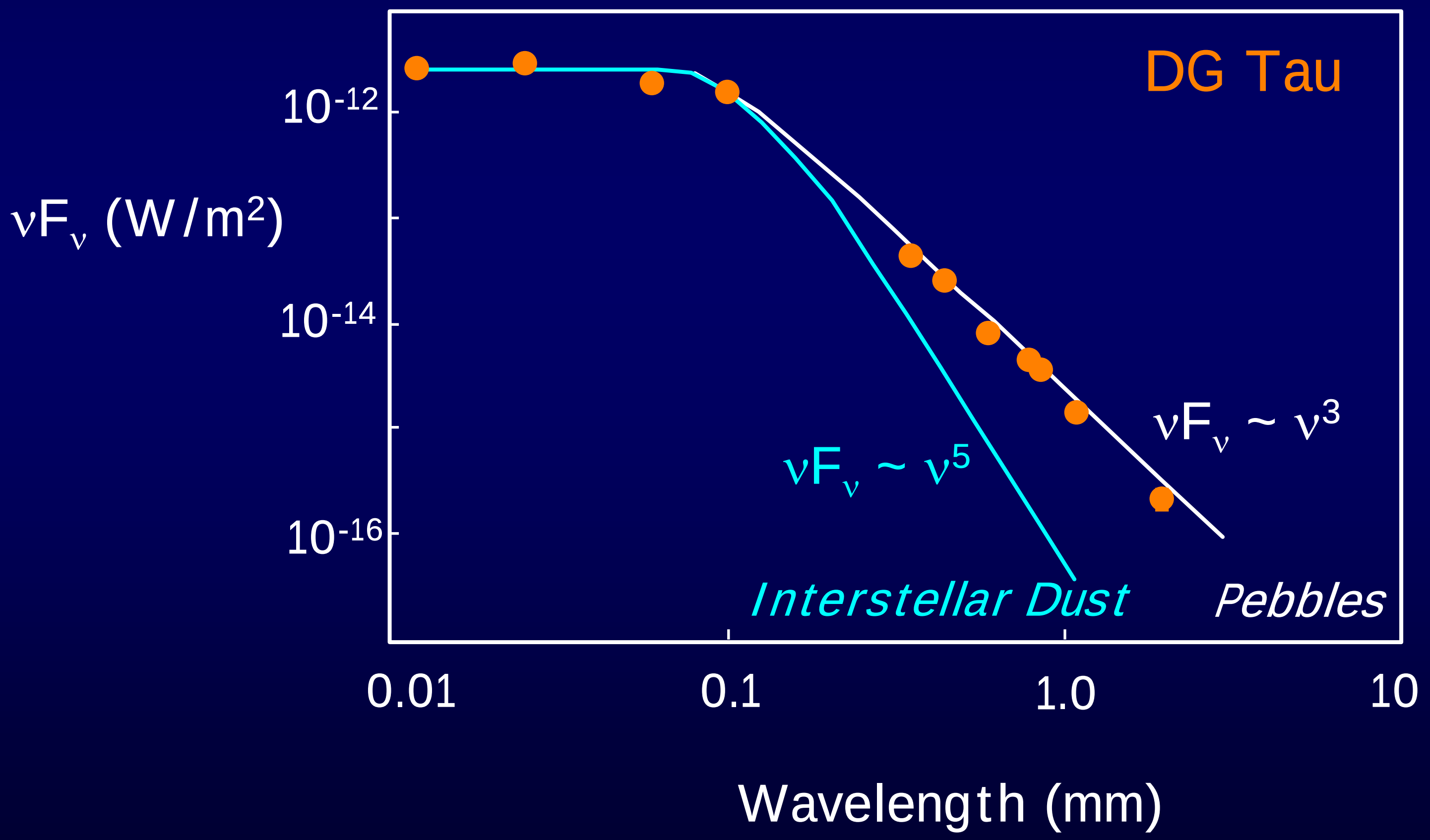
Vibrational modes

$\sim 1 – 30\ \mu m$

$$\kappa_\nu \sim \sigma(\nu)\ /\ m_p$$
$$\sim \nu^2$$

Particle Emissivity in Disks

Beckwith & Sargent 1991, *Ap. J.*, **381**, 250.
Mannings & Emerson 1994, *MNRAS*, **267**, 361



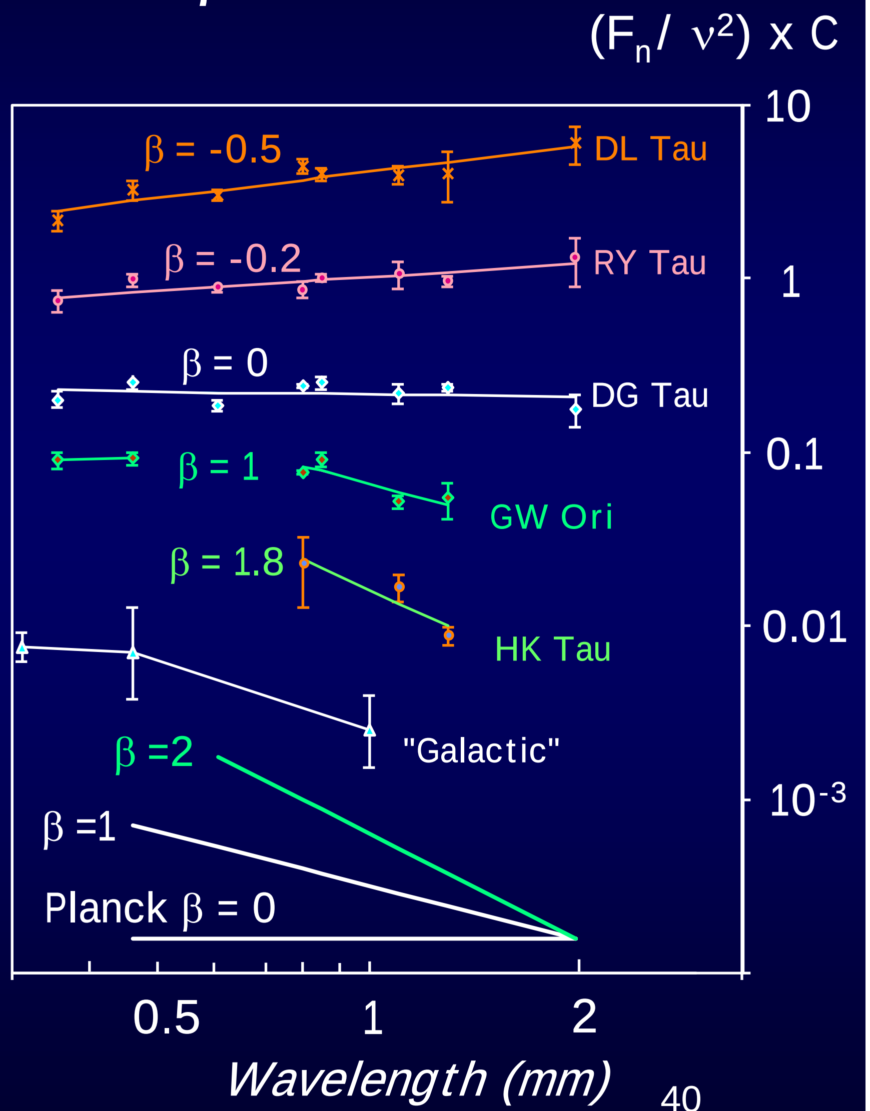
Spectral Index: β

$$F_\nu \sim \kappa_\nu \, (M_{dust}/A) \, B_\nu(T)$$
$$\kappa_\nu = \kappa_0 \, (\nu/\nu_0)^\beta$$

- Opacity index β
  - Interstellar dust: $\beta = 2$
  - Planetesimals: $\beta = 0$
  - Observed: $-0.5 < \beta < 2$

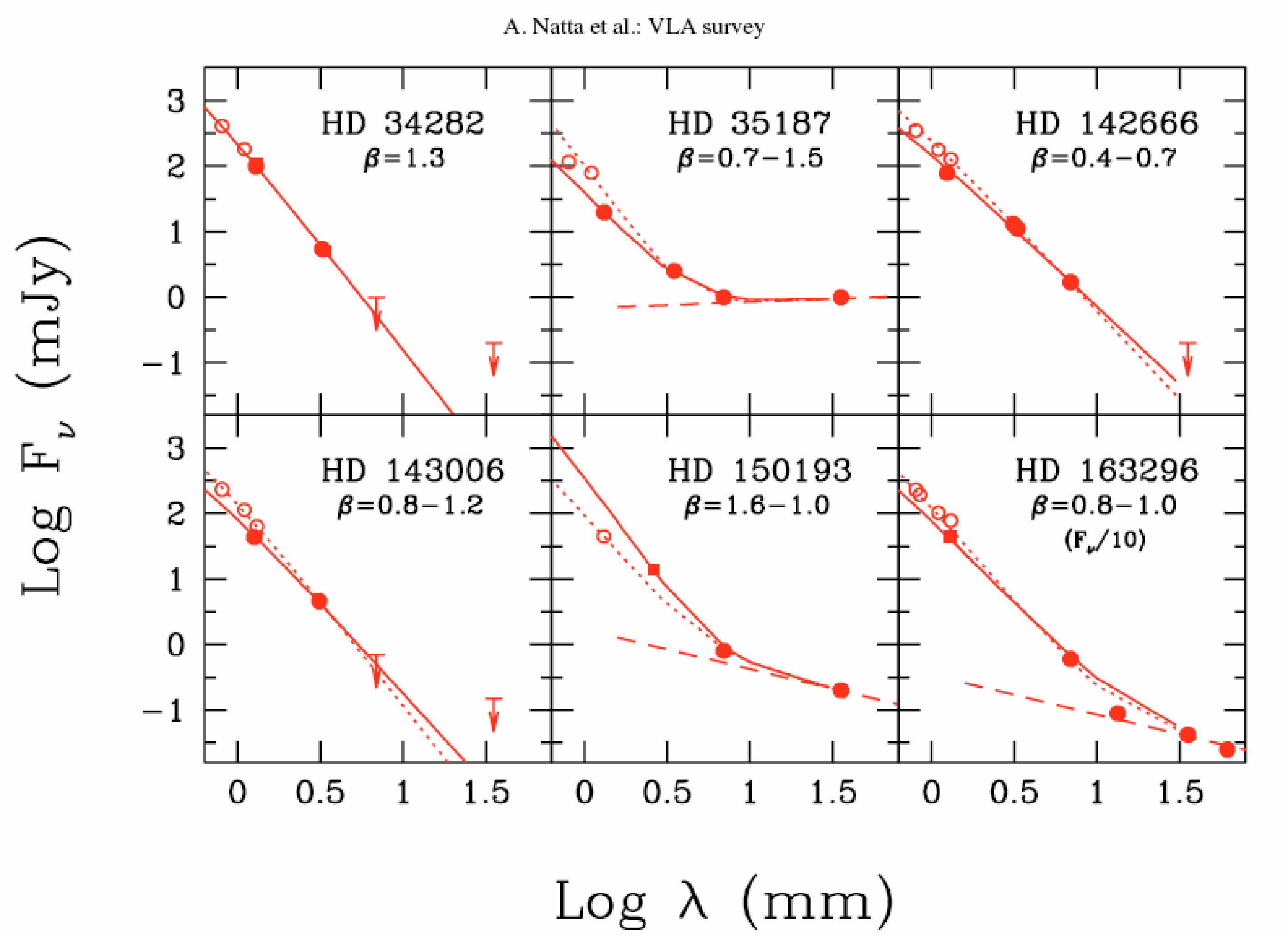
Adams *et al.* 1990
Beckwith & Sargent 1991
Mannings & Emerson 1994

Latest work by:
Lay et al. 1994 (0.85 mm CSO-JCMT)
Willner et al. ASI poster (7 mm VLA)



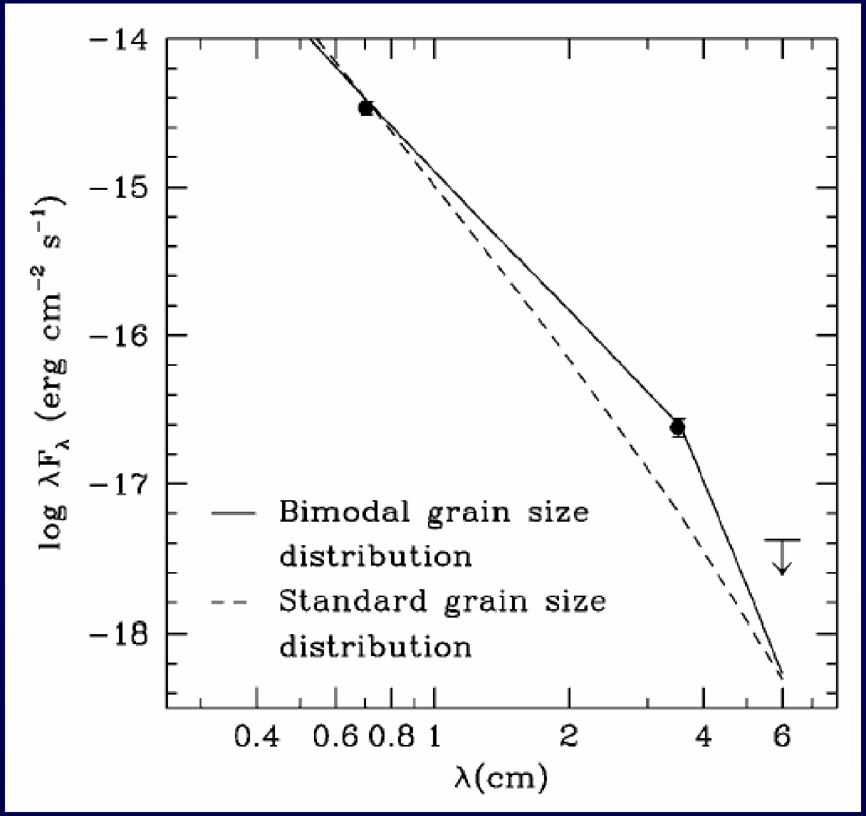
Radio Wavelength Emissivity

Natta et al. 2004, *AA*, **416**, 179



See also: Andrews & Williams 2005, astro-ph 0506187

TW Hydra: 3.5cm dust emission

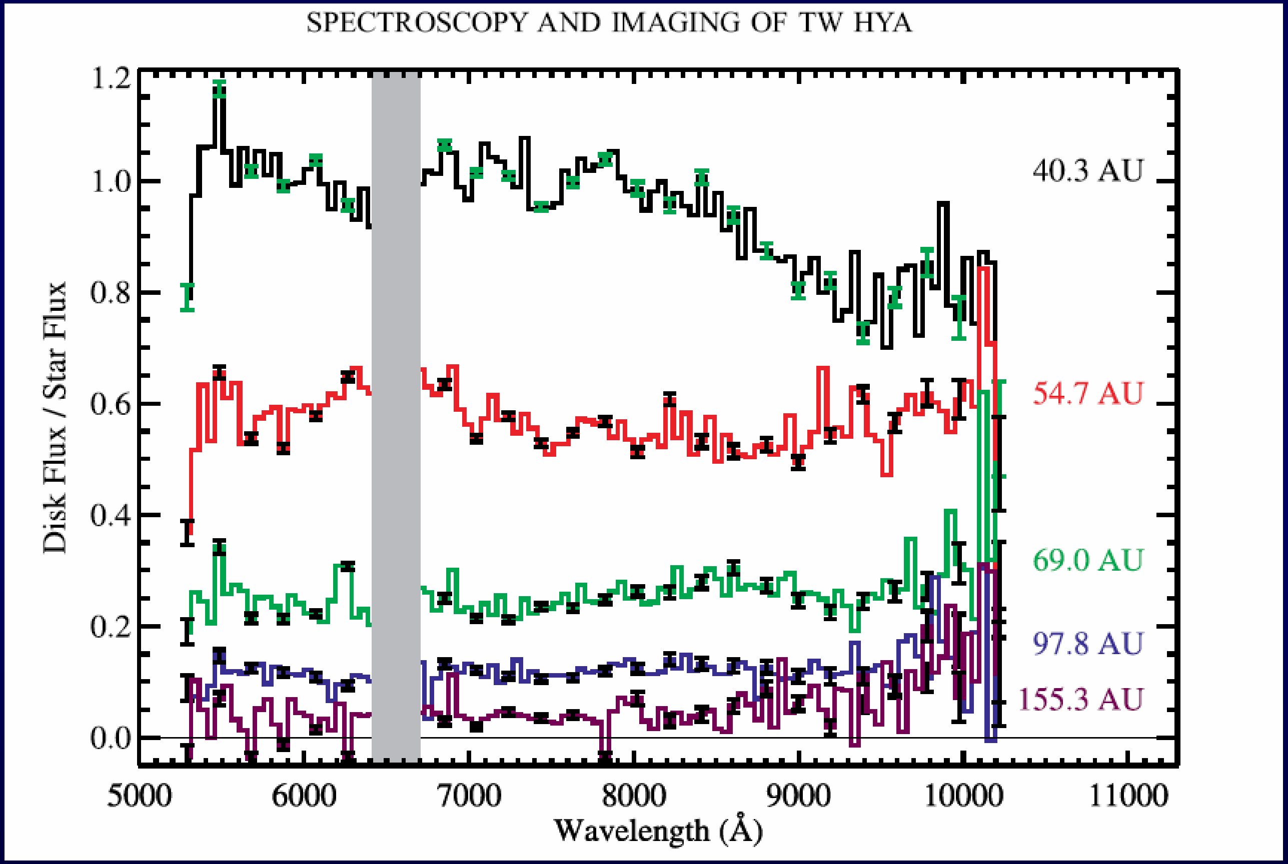


Wilner *et al.* 2005, *ApJL*, **626**, L109

- Very long wavelengths sensitive to centimeter-size grains
- Must rule out synchrotron & free-free (plasma) emission
- Large grains out to tens of AU
- Assumed disk mass ~$0.1M_{sun}$

Spatially Resolved Spectra: TW Hydra

Roberge *et al.* 2005, *ApJ*, **622**, 1121



The scattered light from the disk is essentially gray from ~50 AU to ~150 AU.

This result argues for relatively large (>1 μm) scattering particles

Numerical Models: TW Hydra

No. 2, 2002 DEVELOPING GAP IN PROTOPLANETARY DISK 1011

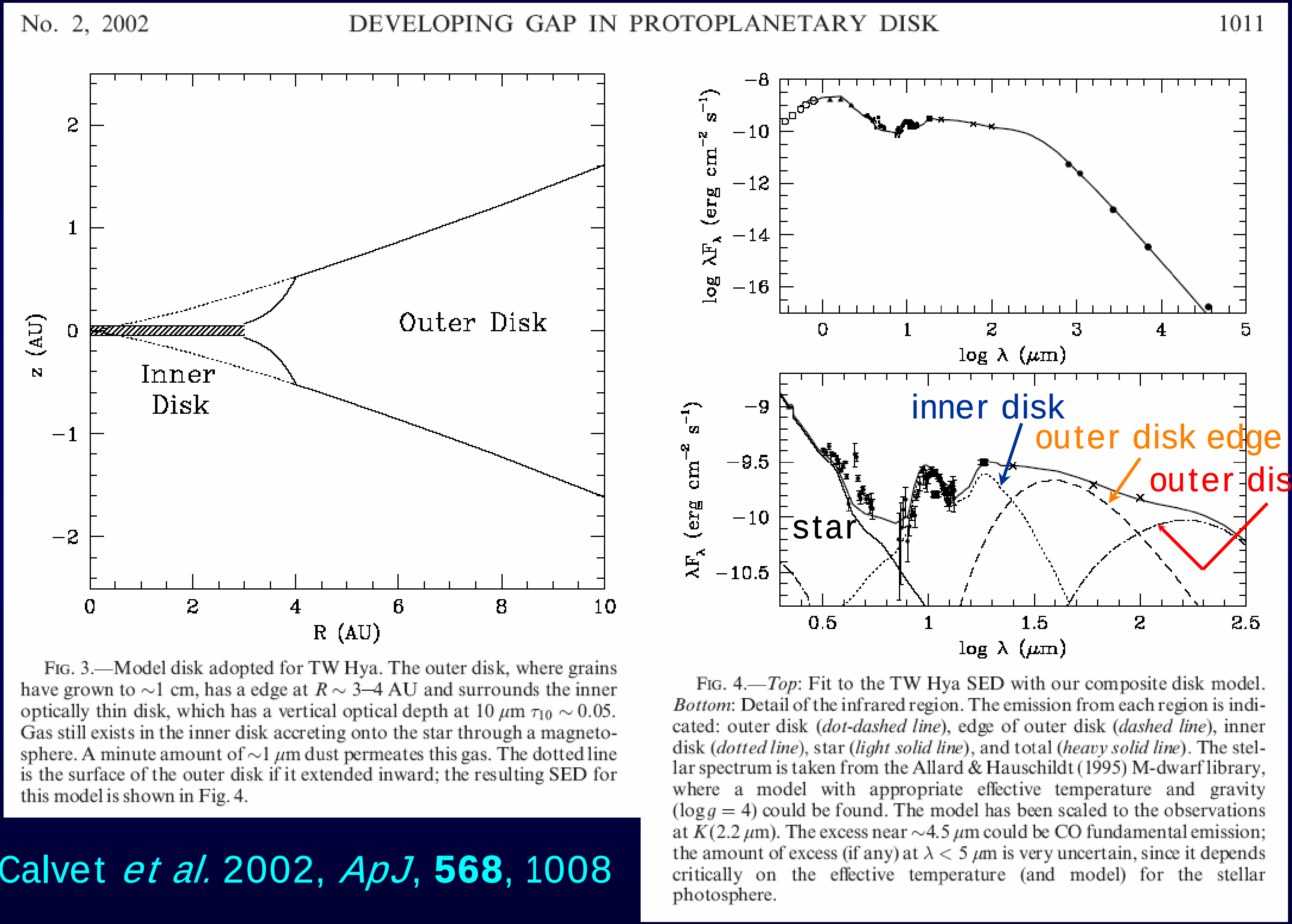


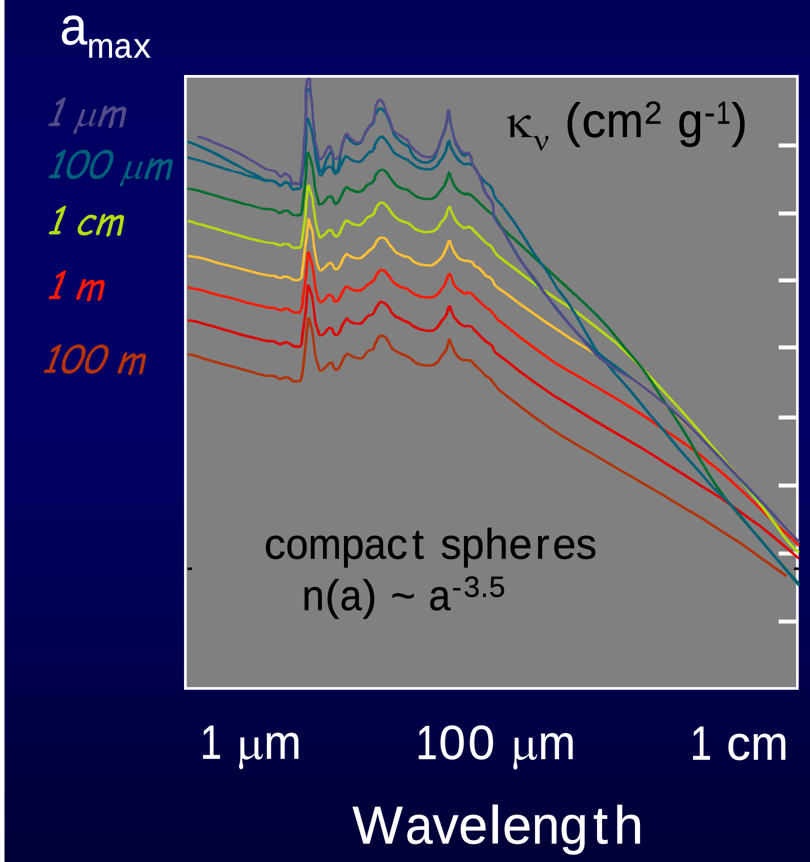
FIG. 3.—Model disk adopted for TW Hya. The outer disk, where grains have grown to ~1 cm, has a edge at $R \sim 3$–4 AU and surrounds the inner optically thin disk, which has a vertical optical depth at 10 μm $\tau_{10} \sim 0.05$. Gas still exists in the inner disk accreting onto the star through a magnetosphere. A minute amount of ~1 μm dust permeates this gas. The dotted line is the surface of the outer disk if it extended inward; the resulting SED for this model is shown in Fig. 4.

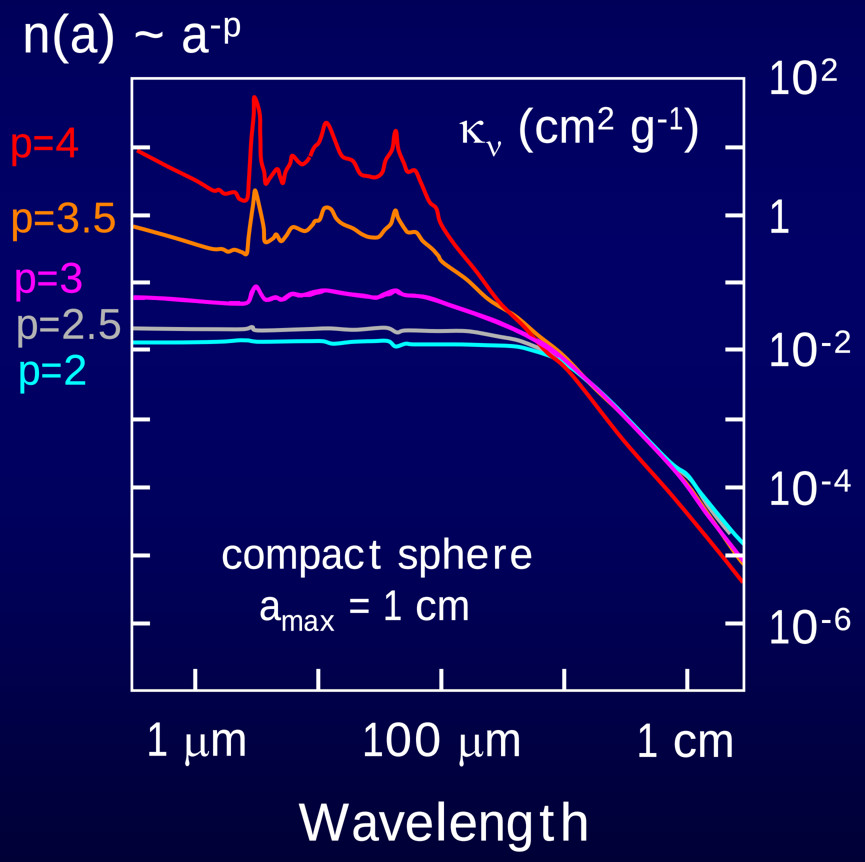
FIG. 4.—*Top*: Fit to the TW Hya SED with our composite disk model. *Bottom*: Detail of the infrared region. The emission from each region is indicated: outer disk (*dot-dashed line*), edge of outer disk (*dashed line*), inner disk (*dotted line*), star (*light solid line*), and total (*heavy solid line*). The stellar spectrum is taken from the Allard & Hauschildt (1995) M-dwarf library, where a model with appropriate effective temperature and gravity ($\log g = 4$) could be found. The model has been scaled to the observations at K (2.2 μm). The excess near ~4.5 μm could be CO fundamental emission; the amount of excess (if any) at $\lambda < 5$ μm is very uncertain, since it depends critically on the effective temperature (and model) for the stellar photosphere.

Calvet *et al.* 2002, *ApJ*, **568**, 1008

Grain size does alter opacity

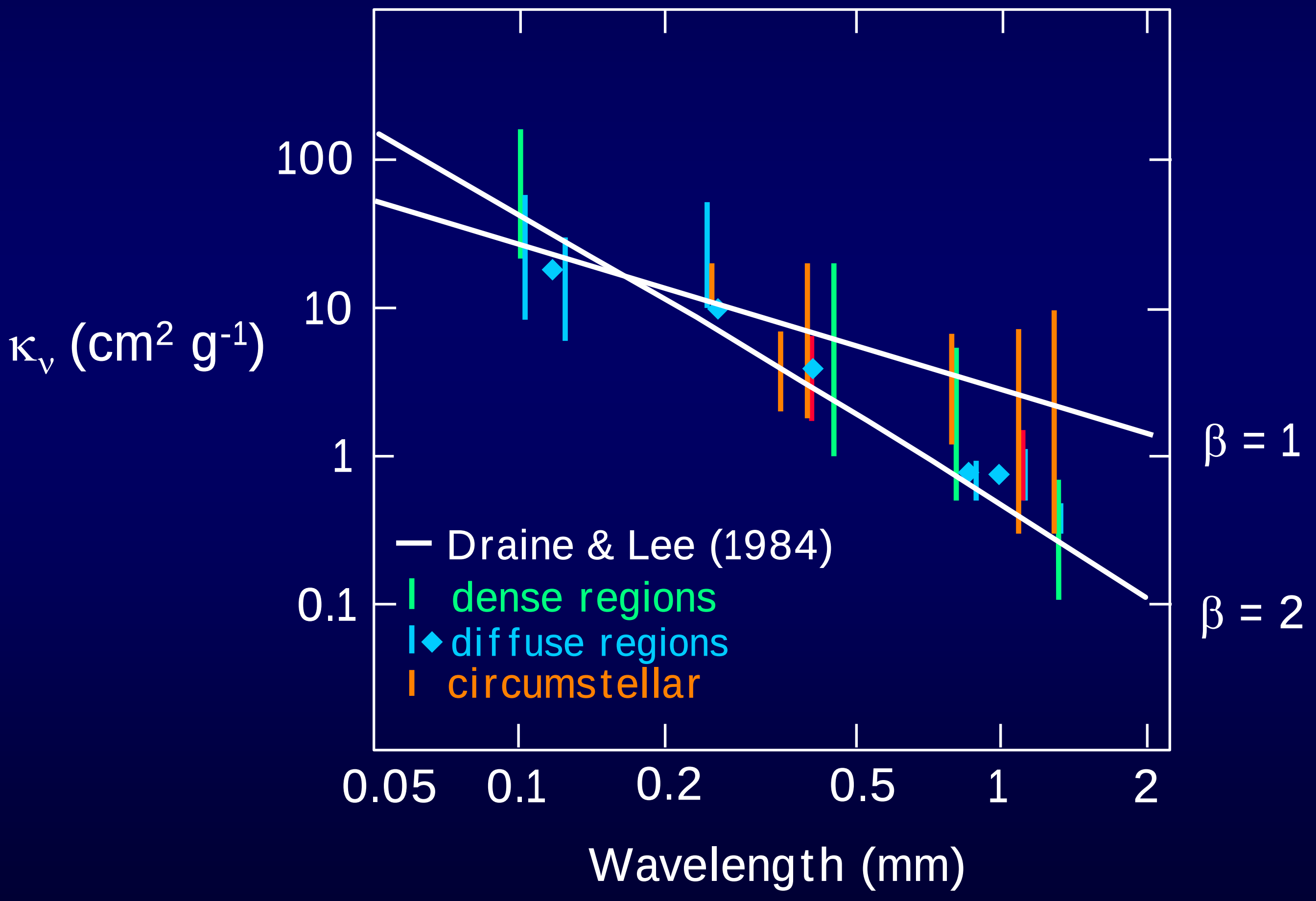
Miyake & Nakagawa 1993, *Icarus*, **106**, 20.





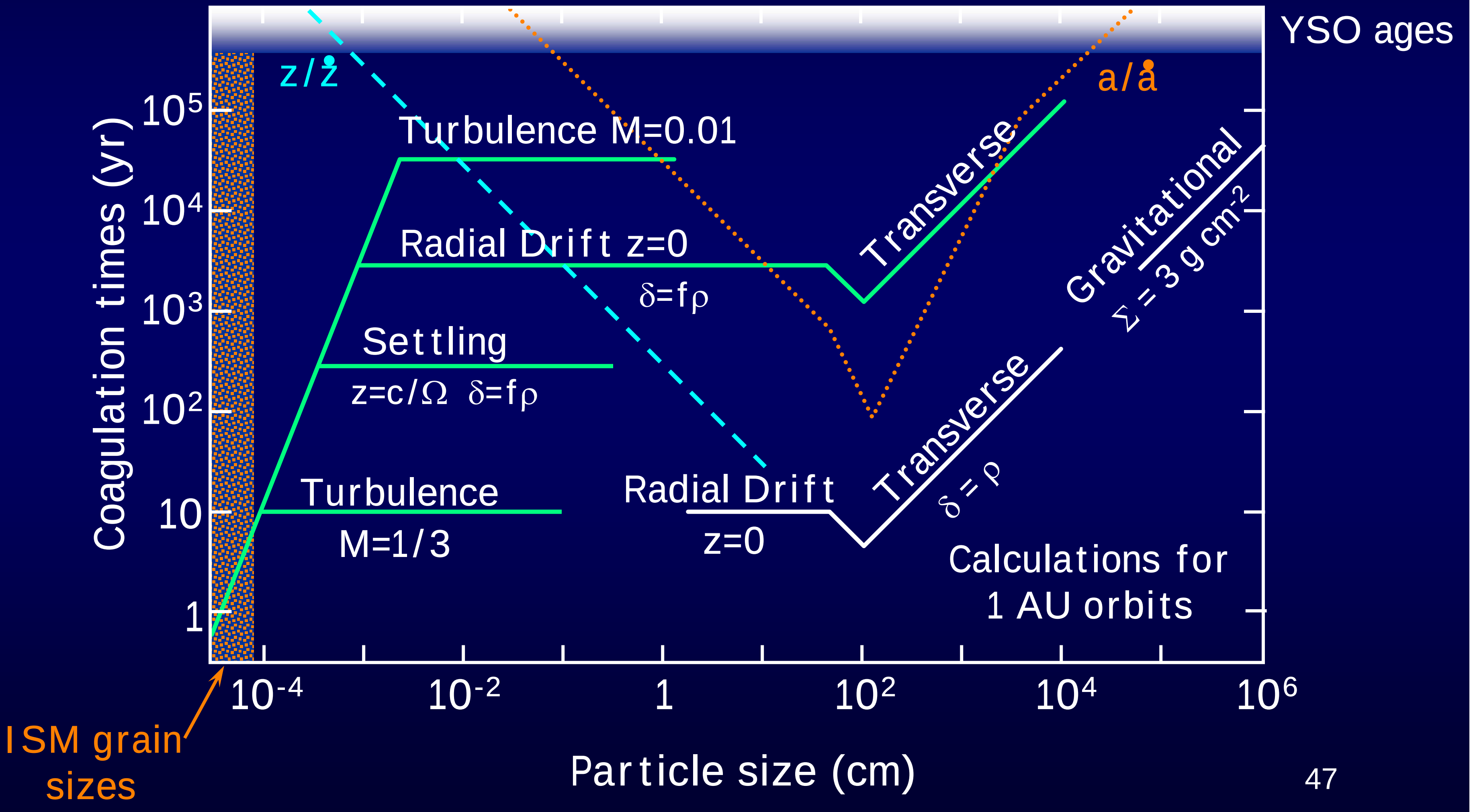
Interstellar opacities are uncertain

Henning, Michel, & Stognienko 1995, *Plan. & Sp. Sci.*



Particles grow quickly

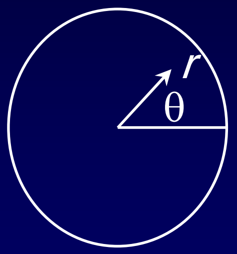
Weidenschilling, S. J. 1988, *Meteorites & Early Solar Sys.*
Chokshi *et al.* 1993, *Ap. J.*, **407**, 806,
Blum *et al.* 1999, *EM&P*, **80**, 285 (lab experiments)



Disk dynamics: what is the velocity field?

Keplerian velocity field is clear signature.

Velocity gradients & gravity

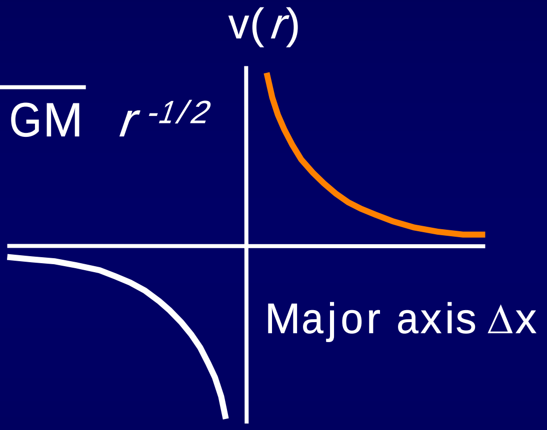


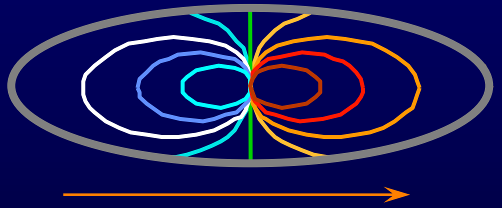
Circular disk viewed at
high inclination angle

Pure Keplerian rotation

$v_\phi(r) = \sqrt{GM}\; r^{-1/2}$

$v_r(r) = 0$



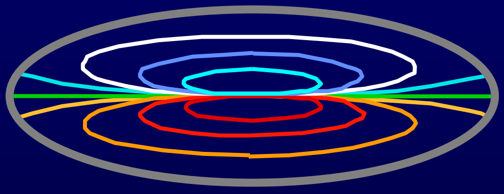


velocity gradient

Pure radial infall

$v_r(r) = \sqrt{2GM}\; r^{-1/2}$

$v_\phi(r) = 0$

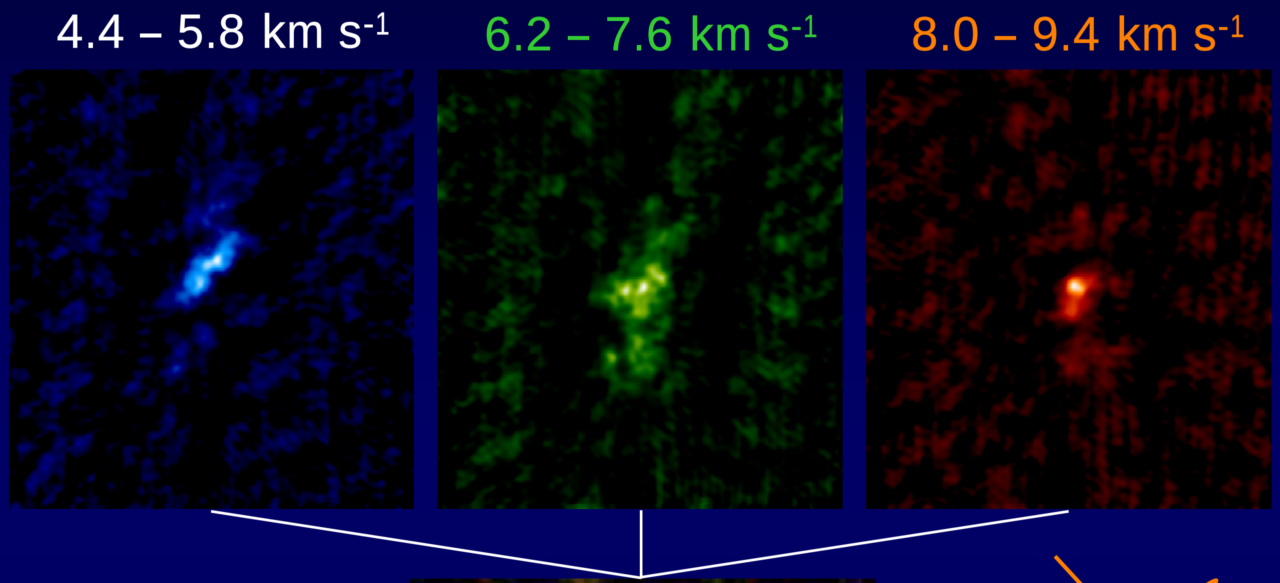


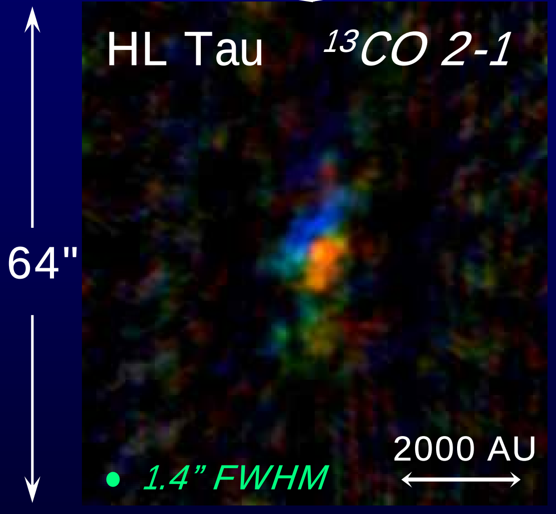
velocity gradient ↓

Dutrey *et al.* 1994, *A&A,* **286**, 149.
Saito *et al.* 1995, *Ap. J.*, **453**, 384

Hayashi et al. 1993, *Ap. J. Lett.*, **418**, L71.

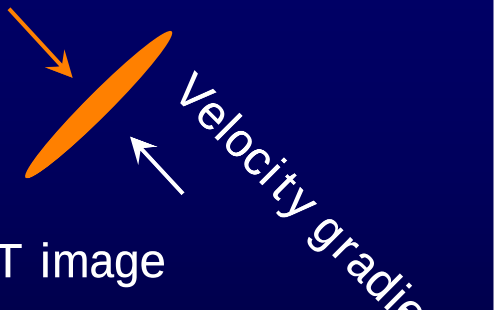
Gas Dynamics in HL Tau: mostly infall



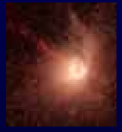


HL Tau shows an *infalling* disk.

Hayashi *et al*. 1993,
Ap. J. Lett., **418**, L71.
Koerner & Sargent 1995,
Ap.SS., **223**, 169
and unpublished data.

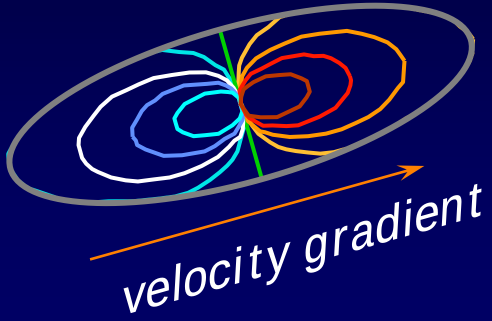


HST image

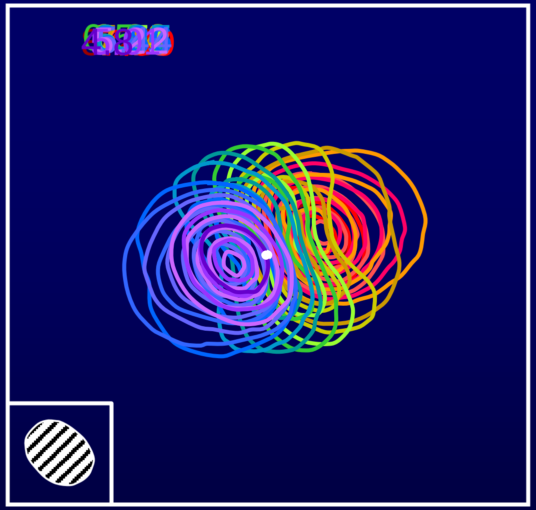


GG Tau system: a rotating disk

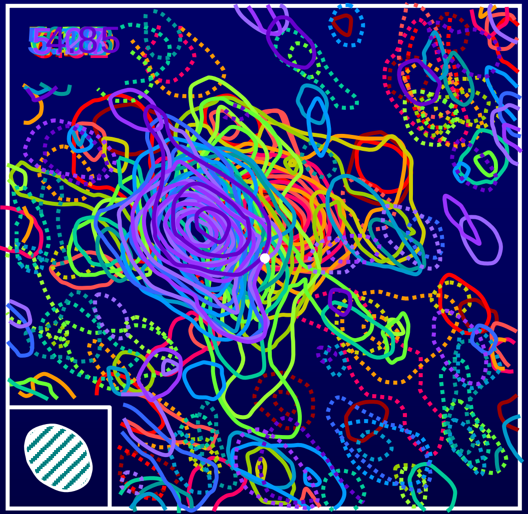
Dutrey *et al.* 1994, *A&A,* **286**, 149



^{13}CO J=1-0

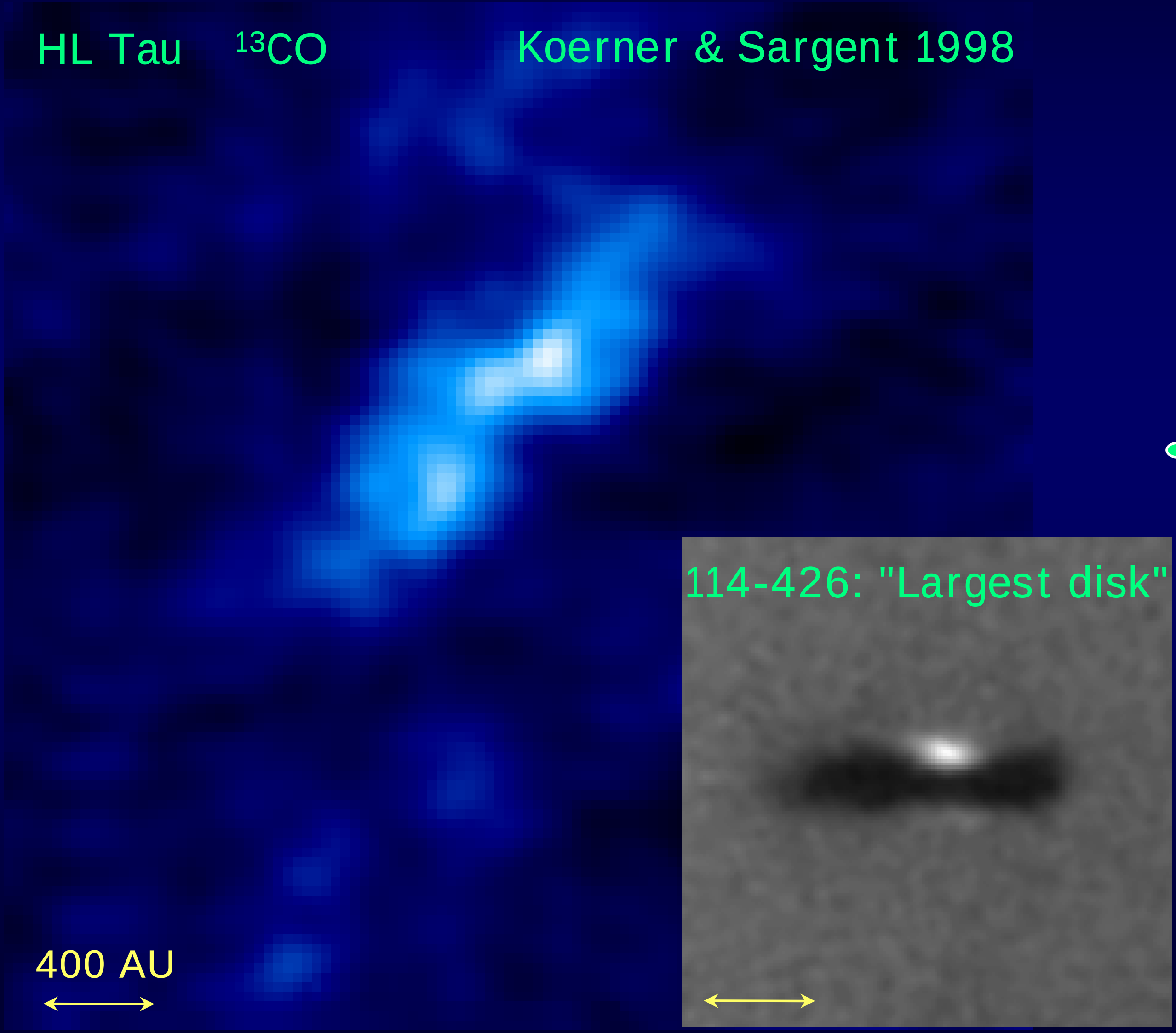


Model calculation



Observed velocity map

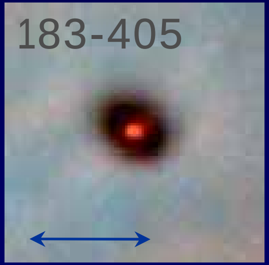
To see real* disks, need high resolution



HL Tau ^{13}CO Koerner & Sargent 1998

114-426: "Largest disk"

McCaughrean
& O'Dell 1996



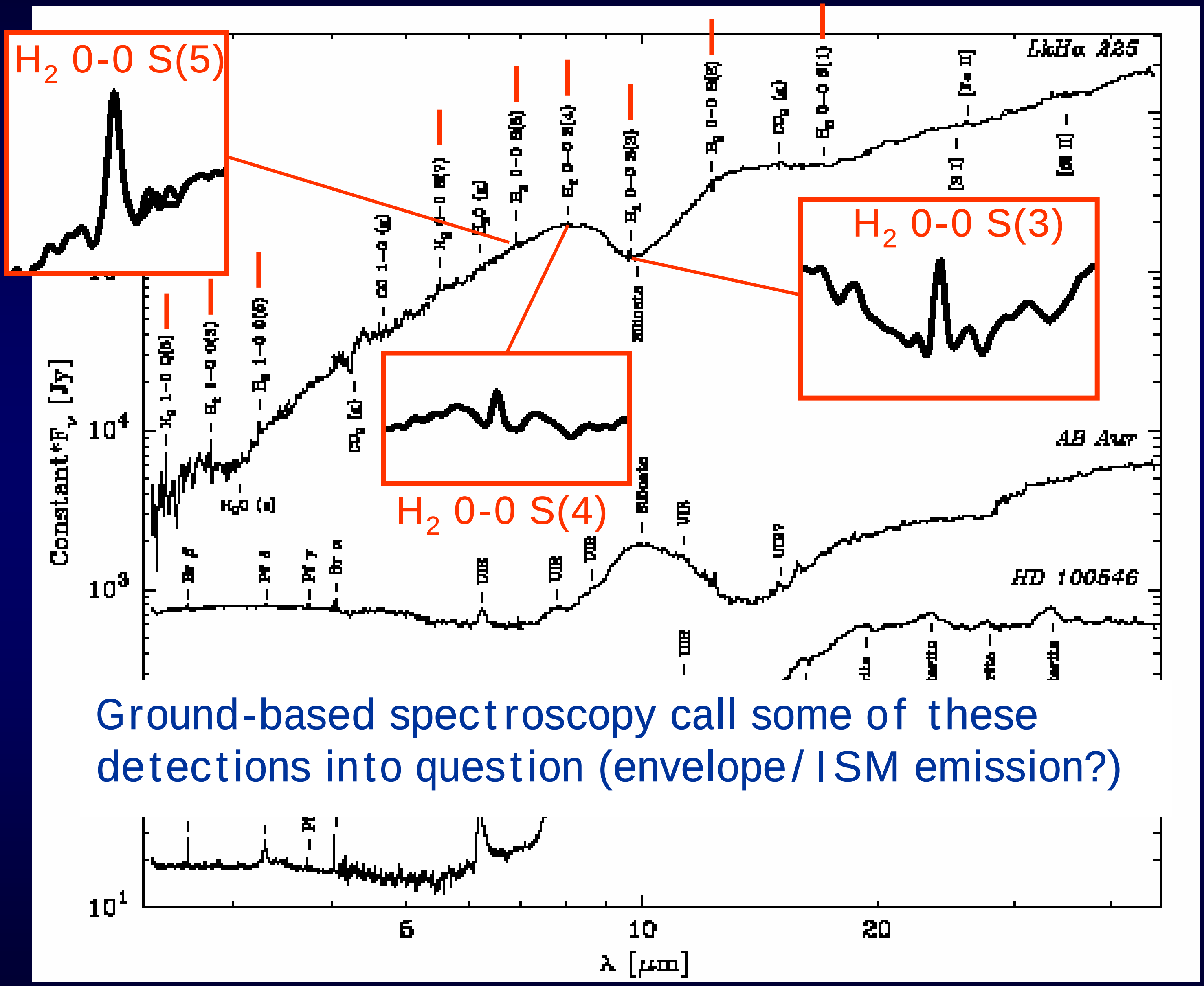
● Solar System

Burrows *et al. 1996*

Future Observations

- Use high spatial resolution to break degeneracies
  - ALMA: resolution of mm-wave emission to tens of AU
  - VLT/Keck/LBTI: resolution of thermal IR emission to ~1 AU
- Use spectral resolution to analyze disk atmospheres and grain/gas composition
  - Spitzer spectra of disks
  - SOFIA spectra in far infrared
  - ALMA for molecular abundances in disk interiors on few x 10 AU scales

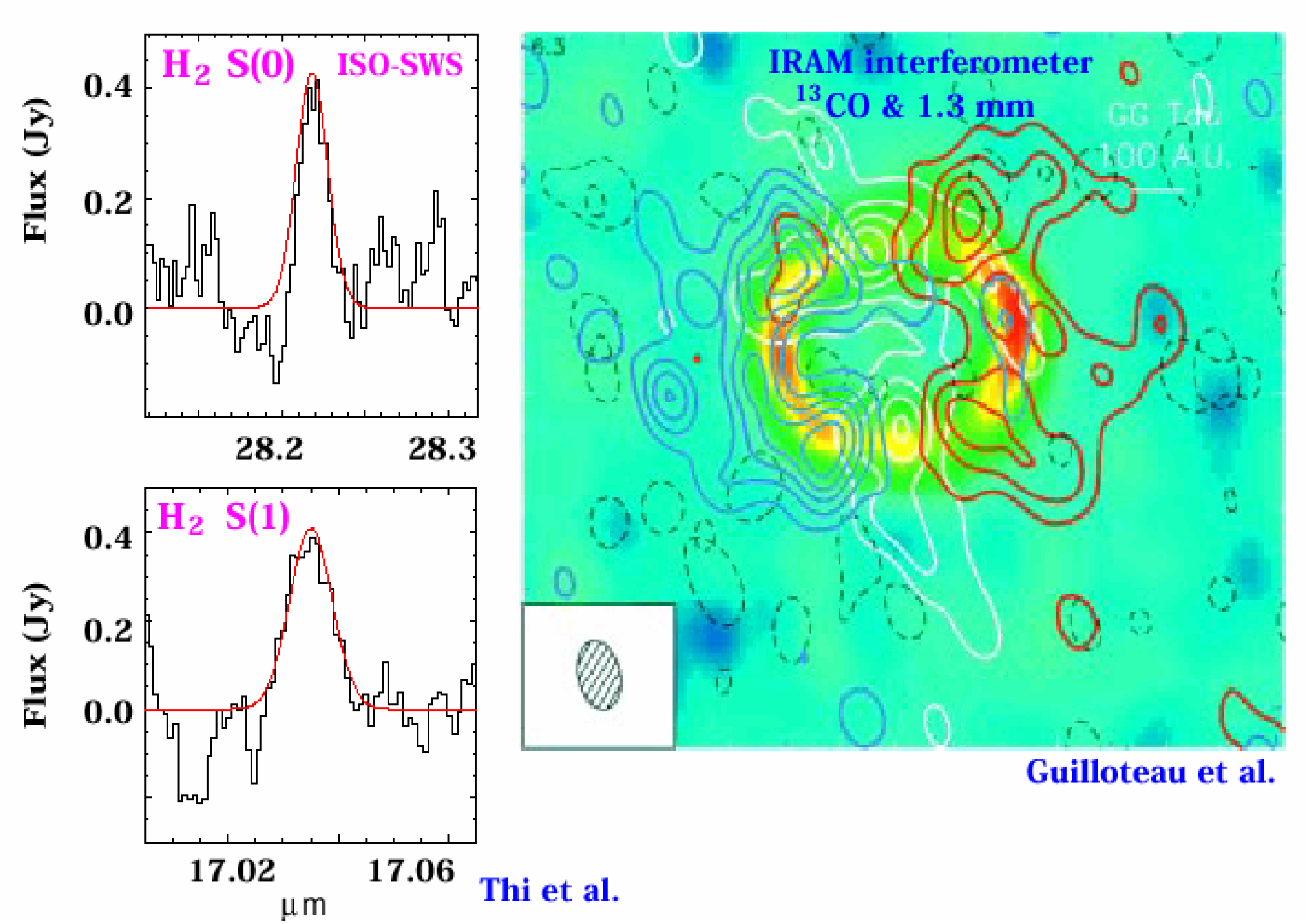
van den Ancker 2000, astro-ph 0005060



Ground-based spectroscopy call some of these detections into question (envelope/ISM emission?)

H_2 in the GG Tau Disk

Thi *et al.* 1999, *Ap.J.Lett.*, **521**, L63

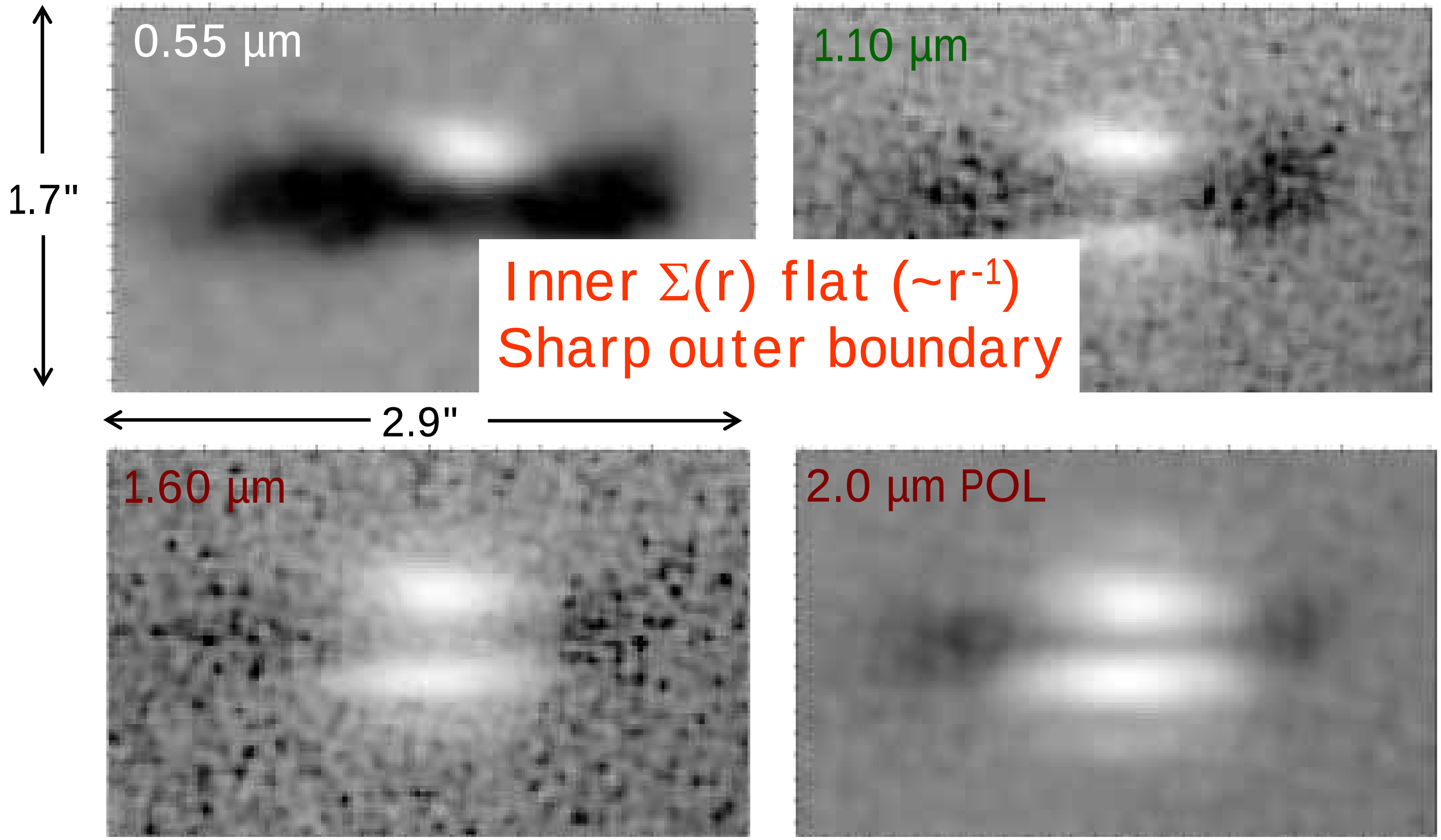


Guilloteau et al.

Thi et al.

Disk boundaries appear to be sharp

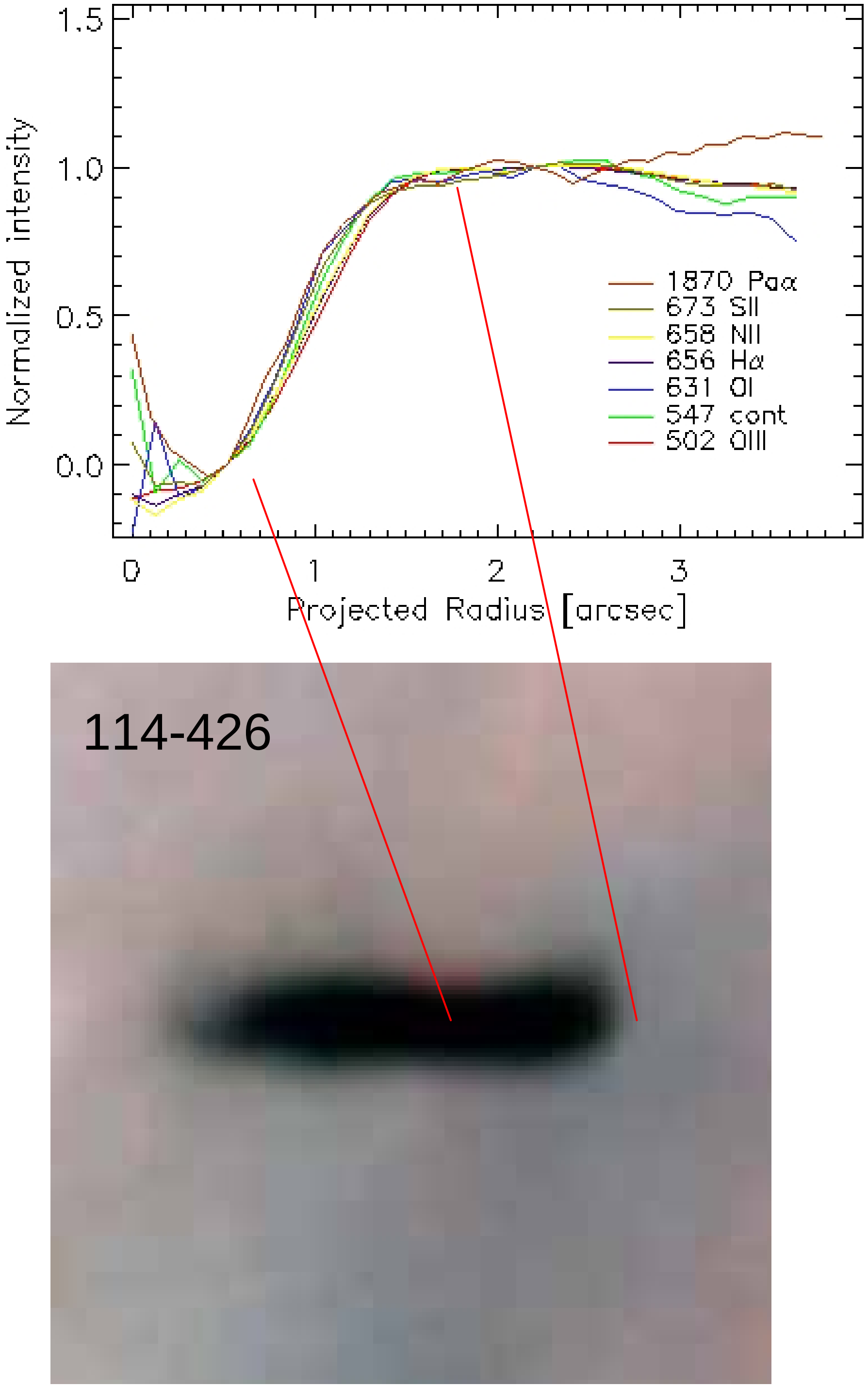
O'Dell & Wen 1992, *Ap.J.*, **387**, 229.

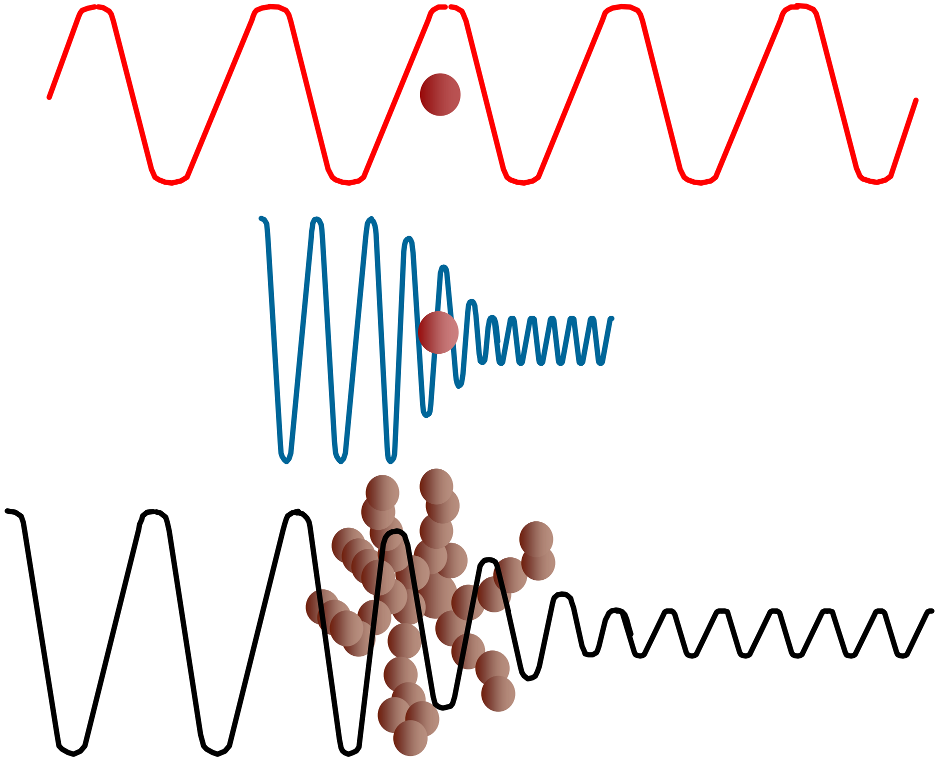


Inner $\Sigma(r)$ flat ($\sim r^{-1}$)
Sharp outer boundary

McCaughrean *et al.* 1998, *ApJL*, **492**, L157.

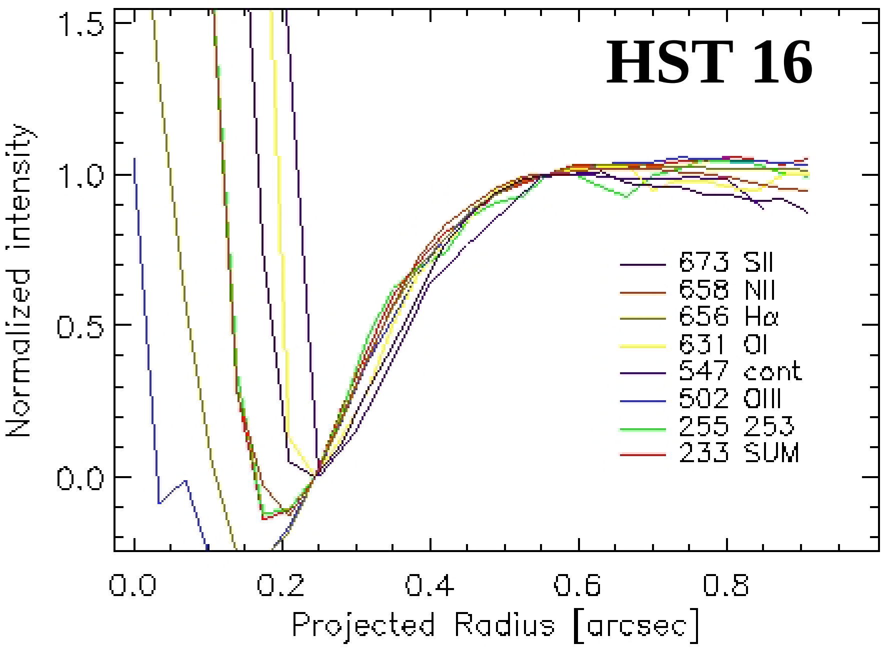
Achromatic extinction

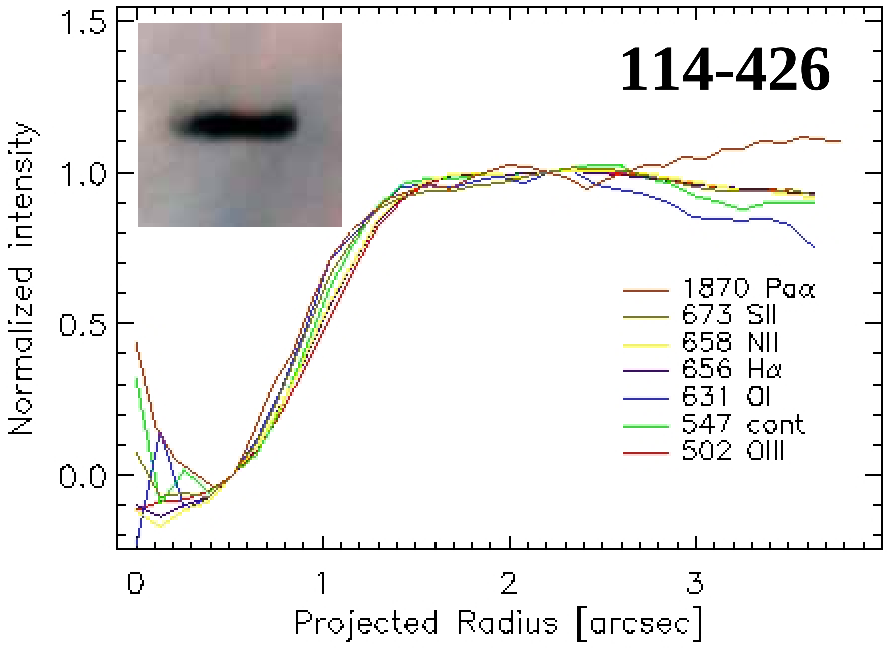


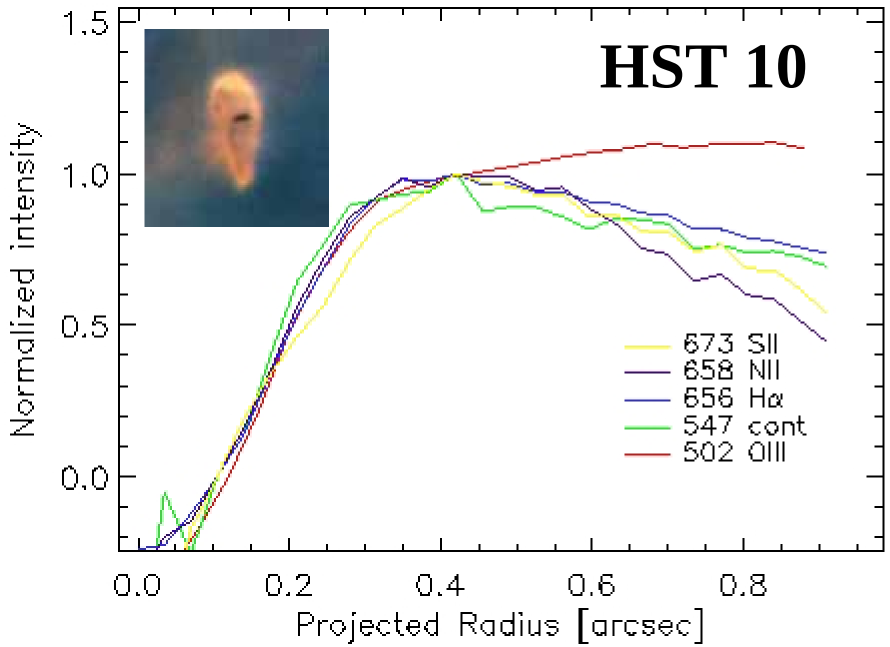


Interpretation: the particles have grown to pebbles or rocks.

Throop *et al.*, *Science*, April, 2001





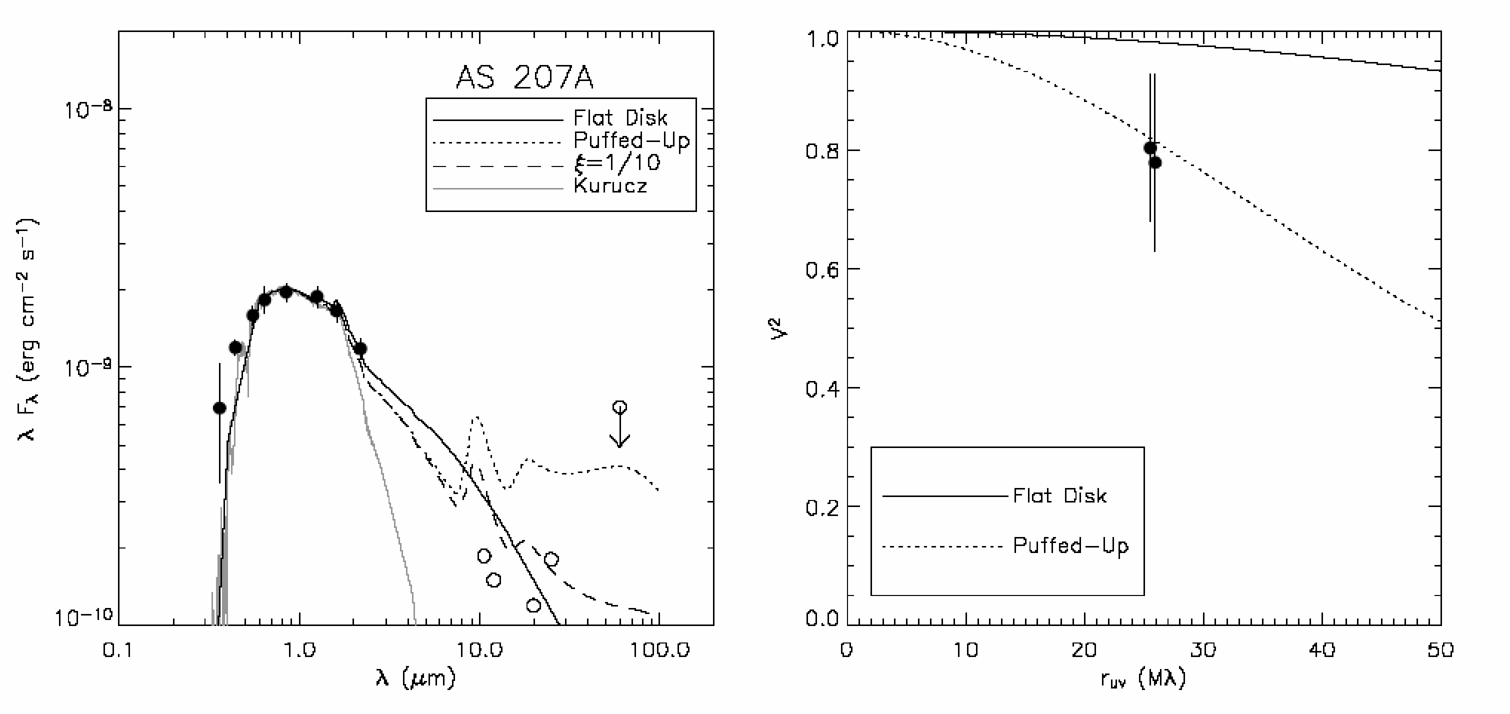


Grain size > Wavelength

Throop *et al.*,
Astro-ph 0104445

Keck interferometer observations at 2 μm

Eisner *et al.* 2005, *ApJ*, **623**, 952



For AS 207A, V2508 Oph, and PX Vul, simple flat accretion disk models suggest much smaller sizes (when fitted to SEDs) than those determined interferometrically. Models incorporating puffed-up inner walls and flared outer disks provide better fits to our V^2 and SED data than the simple flat disk models. This is consistent with previous studies of more massive Herbig Ae stars (Eisner et al. 2004; Leinert et al. 2004) and suggests that truncated disks with puffed-up inner walls describe lower mass T Tauri stars in addition to more massive objects.

Summary Lessons

- Our understanding of disk atmospheres is compatible with observed SEDs
- We can measure sizes, temperature distributions, masses, and some features (holes, gaps) with reasonable certainty
- Parameter degeneracies that affect interpretations may be resolved with high angular resolution
  - ALMA for mm-wave disk “interiors”
  - IR-interferometry for inner disks, holes, and surfaces
- Spectra and SEDs show good evidence for:
  - Grain growth leading to small rocks
  - Constituents similar to proto-Solar nebula
  - Gas entrained with dust
  - Disks bound to stars