Issues in modeling SEDs of low mass YSO

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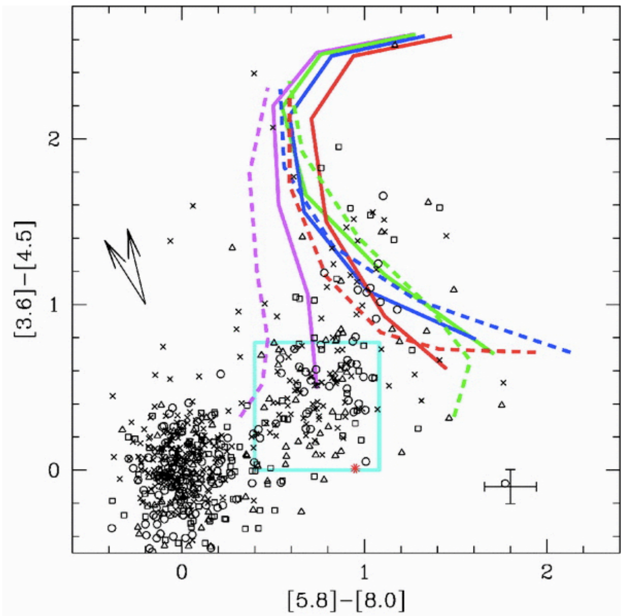
Before Spitzer

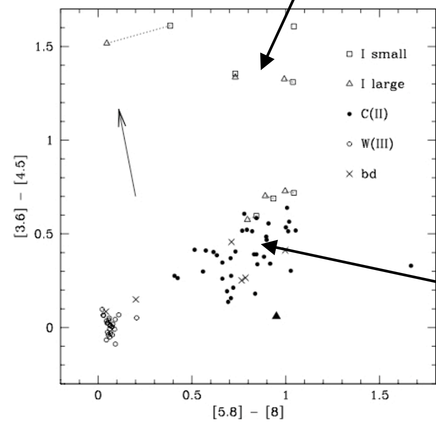
- Grain growth in disks: mm data (Beckwith 1990), median of Taurus (D'Alessio et al 2001)
- Disks in transition: "dips" in SEDs with ground-based near-IR, IRAS (Strom et al. 1989)
- Silicate feature in emission: few ISO (Natta et al. 2000) and ground-based observations (Honda et al. 2003)
- Transitional disks, disks with inner clearing - planets: ground-based near-mid-IR, IRAS (Calvet et al. 2002; Rice et al. 2003)
- Debris disks, secondary dust, evolved from primordial, optically thick disks
- Inner disk frequency and emission decrease with age (Hillenbrand et al., Haisch et al. 2001)

The Spitzer era



Allen et al 2004

Disks around Class I
Posters by Tobin (# 11)
and Zhu (# 43)

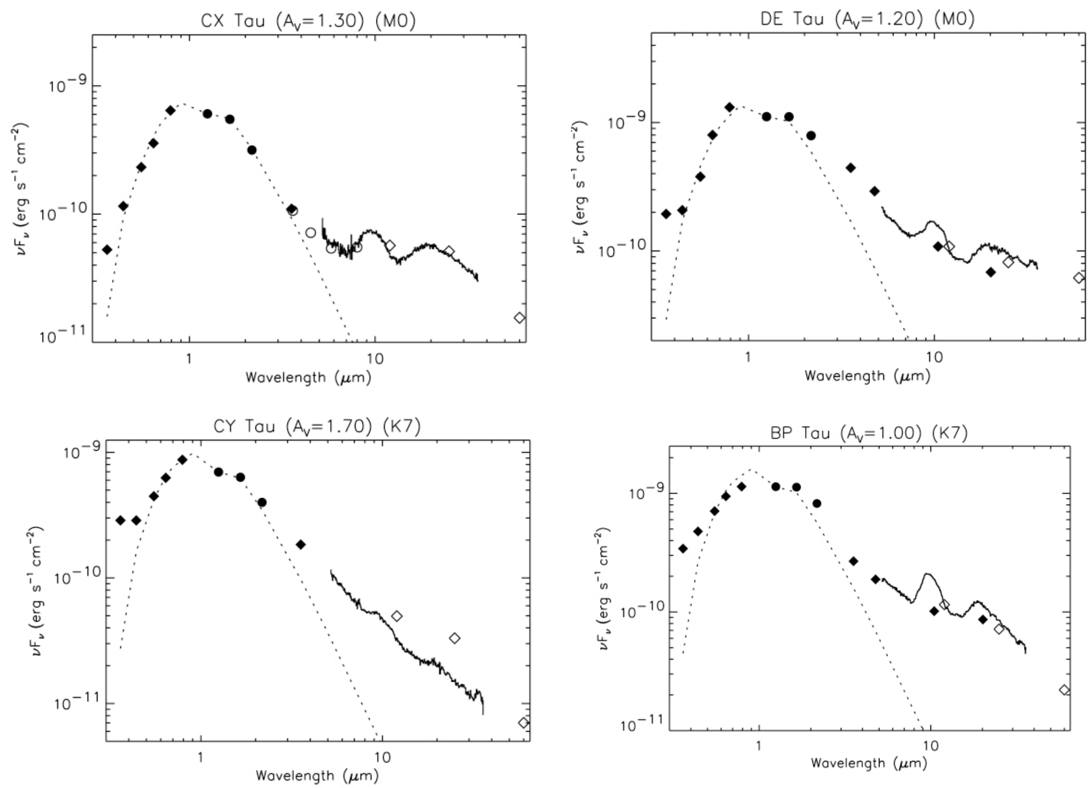


CTTS

Hartmann et al 2005

Except if heavily embedded, Ophiuchus (poster by McClure #61)

SEDs of stars surrounded by disks



Furlan et al 2006

IRAC+IRS+MIPS+2MASS+UBVRI+spectral type
SEDs ready for modeling

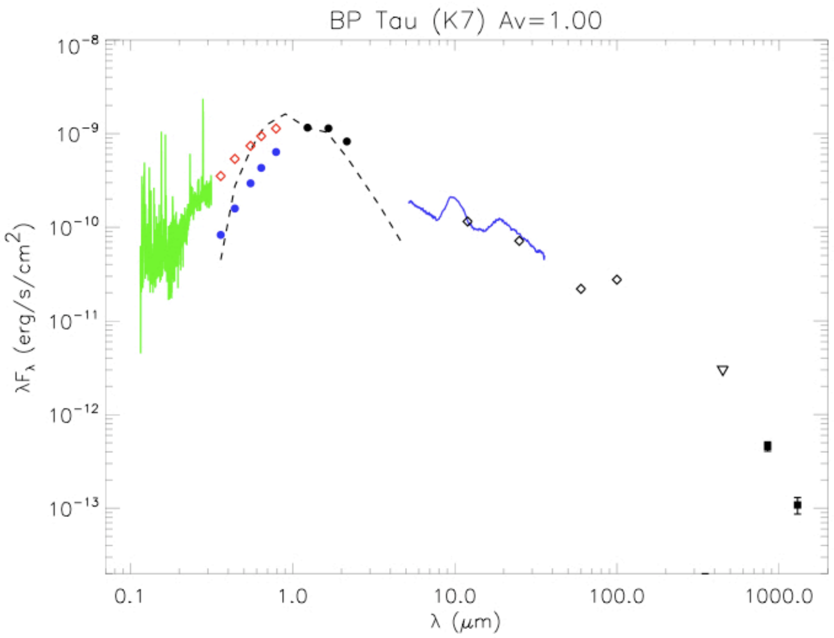
Modeling SEDs

Many approaches and codes available
Sophisticated Montecarlo radiative transfer codes
Irradiated accretion disk models with 1.5 D radiative transfer

Issue: surface density distribution?
Free parameter in many modeling efforts
Hayashi distribution $\Sigma \propto R^{-3/2}$
Or best fit

Physical motivated Σ

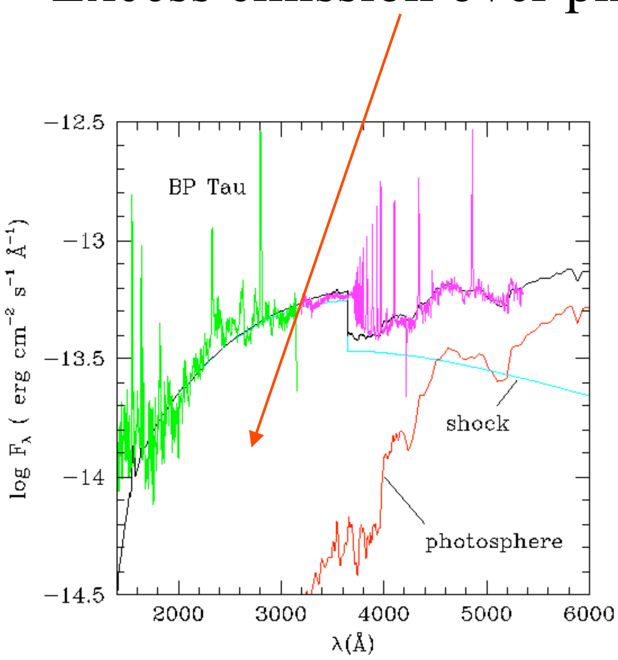
Most stars surrounded by disks are accreting



Calvet & D'Alessio 2009

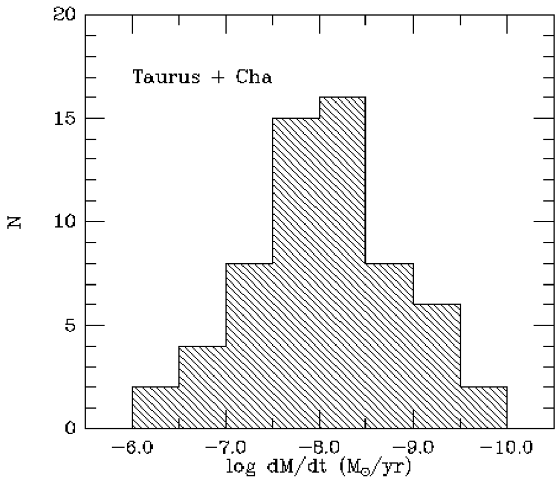
Measurement of mass accretion rate

Excess emission over photosphere $\sim L_{acc} = G\,M\,(dM/dt)\,/\,R$



Ingleby & Calvet 2008

Gullbring et al. (1998)



Link to disk properties

Irradiated accretion disks

$$\Sigma = \frac{\dot{M}}{4\pi\nu}\left[1 - \left(\frac{R_*}{R}\right)^{1/2}\right]$$

$$\nu = \alpha c_s H = \alpha c_s^2/\Omega_K \qquad c_s \propto T^{1/2} \propto R^{-1/4} \qquad \Omega_K \propto R^{-3/2}$$

$$\Sigma \sim 4\left(\frac{\dot{M}}{10^{-8}\frac{\mathrm{M}_\odot}{\mathrm{yr}}}\right)\left(\frac{\alpha}{0.01}\right)^{-1}\left(\frac{T_{100AU}}{10K}\right)^{-1}\left(\frac{R}{100AU}\right)^{-1} \mathrm{gr\ cm}^{-2}$$

Consistent with sub/mm high resolution observations
Andrews & Williams 2007

Viscous disk evolution

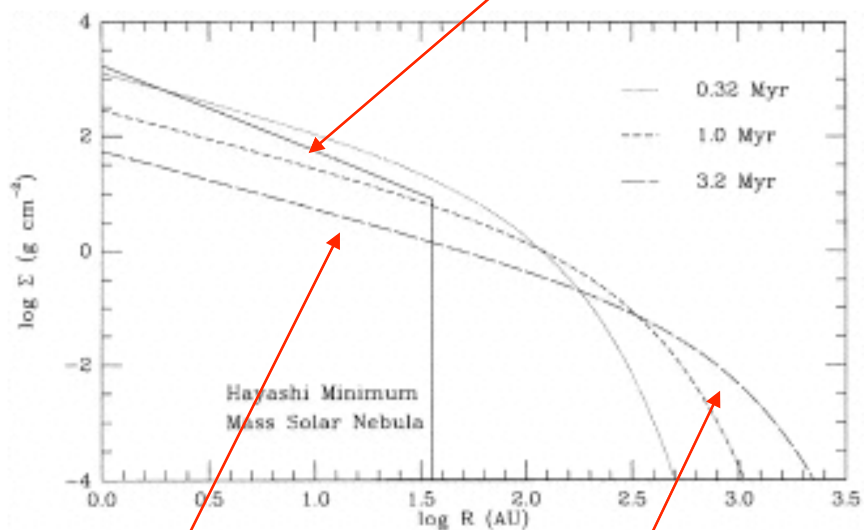
As t increases:

•Transition between dependence 1/R (~ steady disk) and exponential at larger radius

•Disk expands, Σ decreases, the disk mass falls as $1/t^{1/2}$ (lost to the star)

Hartmann 2009

t=0



Σ α 1/R (similar to steady disk)

Exponential cut-off
Poster by Hughes (#56)

Consistent surface density

Surface density not a free parameter

Consistent with dM/dt onto the star

$M_{disk} = \int \Sigma\, 2\pi R\, dR \propto dM/dt\, /\alpha$

$\Rightarrow$ Using M_{disk} as parameter is equivalent to using α

Spitzer/IRS data of Taurus (1-2 Myr)

Silicate emission everywhere

Large range of properties at one age

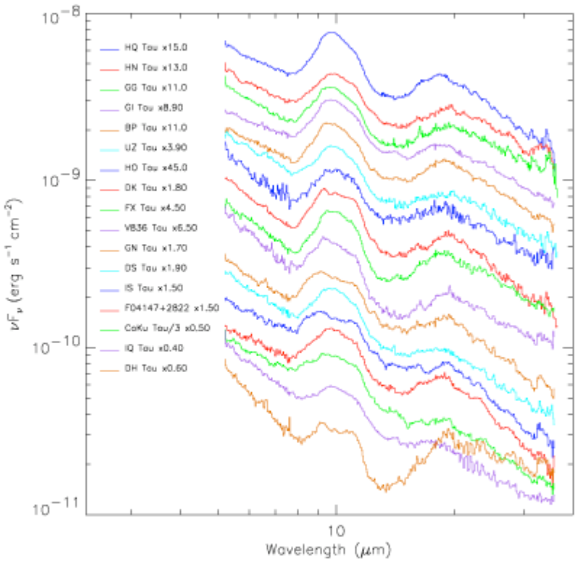


Fig. 5.— Morphological sequence of Class II objects: Group C.

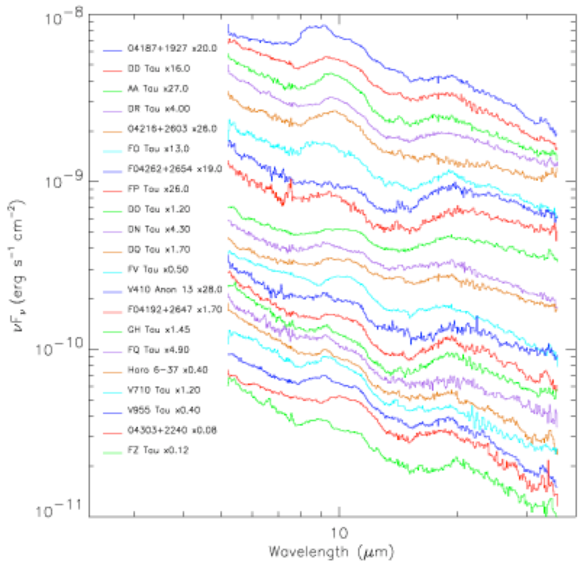
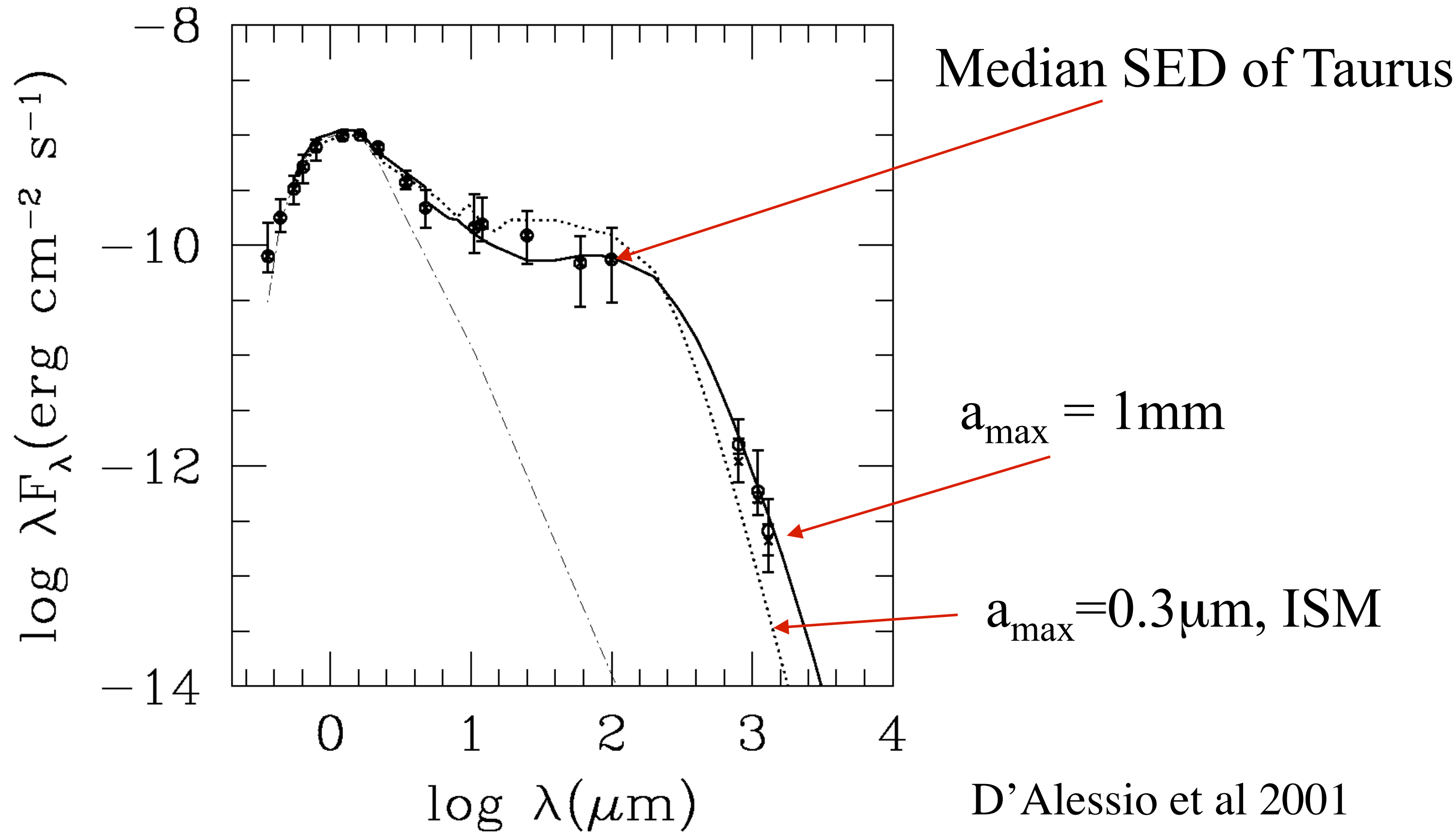


Fig. 6.— Morphological sequence of Class II objects: Group D.

Furlan et al. 2006

Dust properties from SED: Grain growth



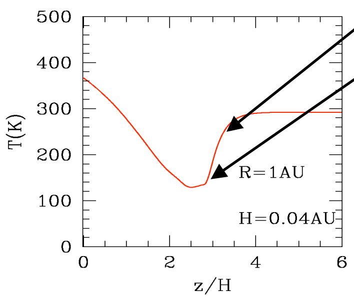
D'Alessio et al 2001

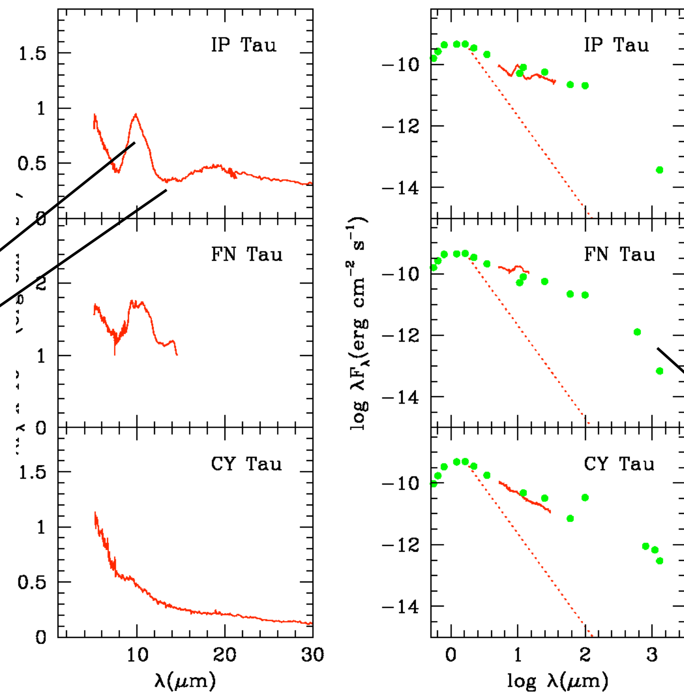
Spitzer/IRS spectra of T Tauri stars

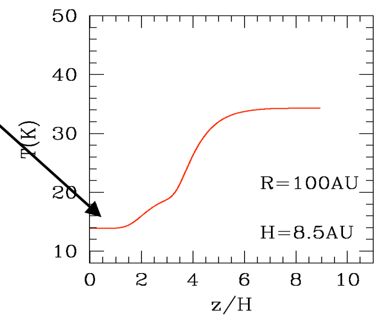
Dust growth and settling

silicate feature emission ⇒ small grains

mid-IR,mm⇒ large grains

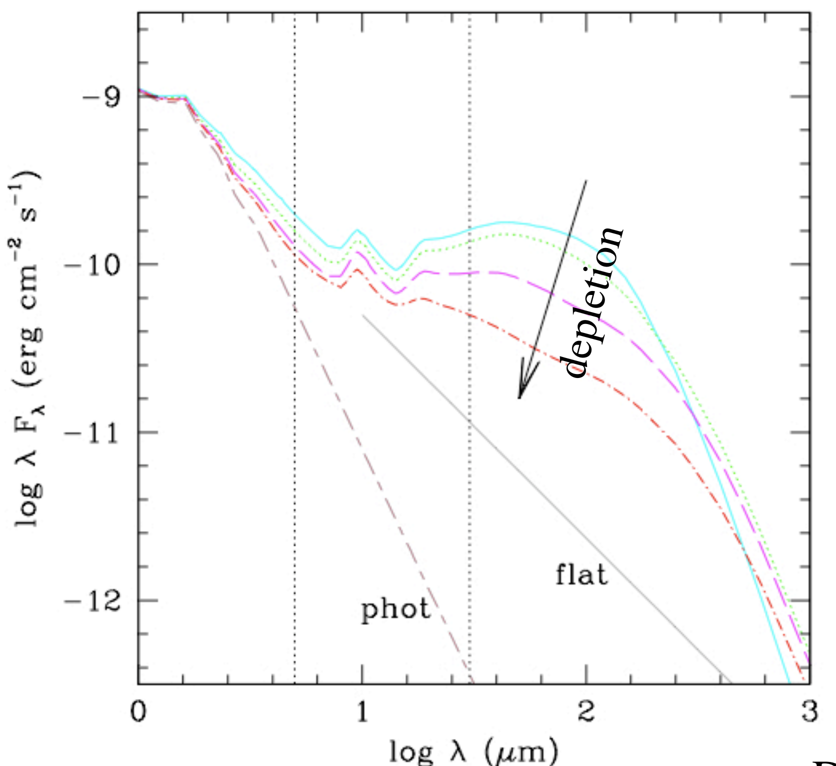






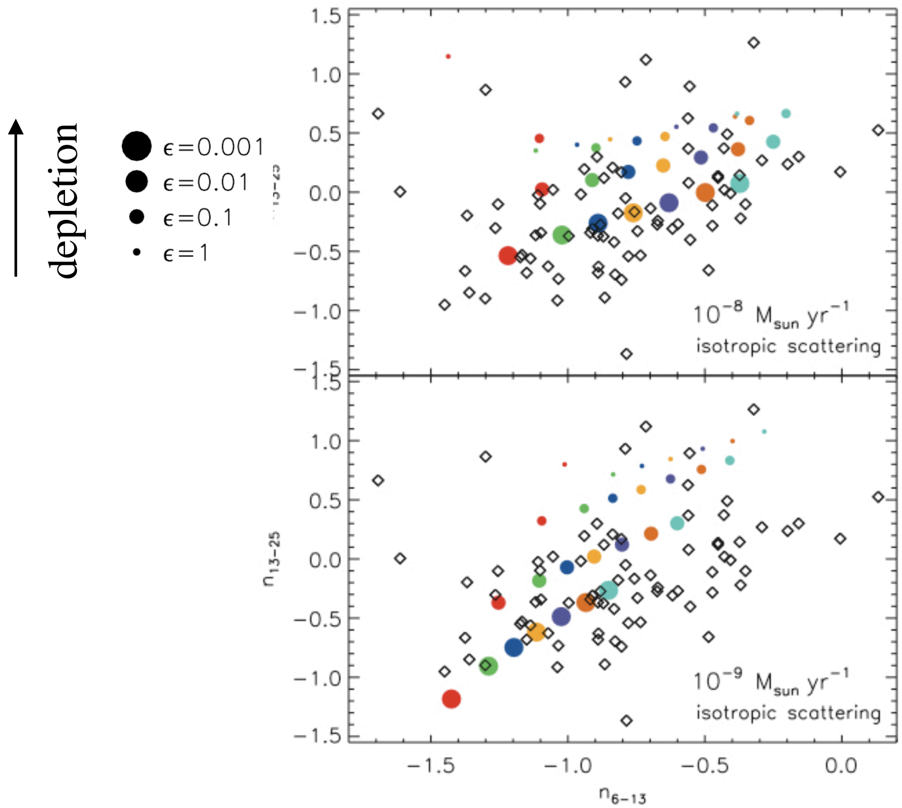
Effects of dust settling in SED

Effects of dust settling conspicuous in IRS range



D'Alessio et al 2006

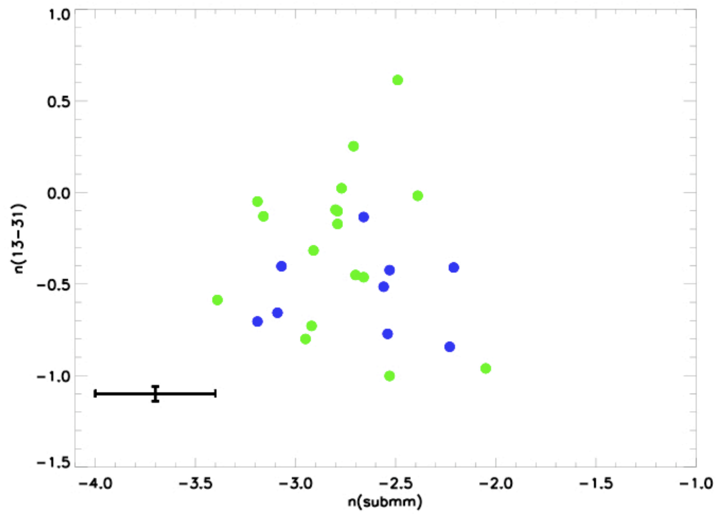
Dust settling in Taurus disks



Taurus disks consistent with 1 - 0.1% dust depletion (relative to standard dust -to-gas mass ratio) in upper layers

Furlan et al. 2006, and Furlan's talk

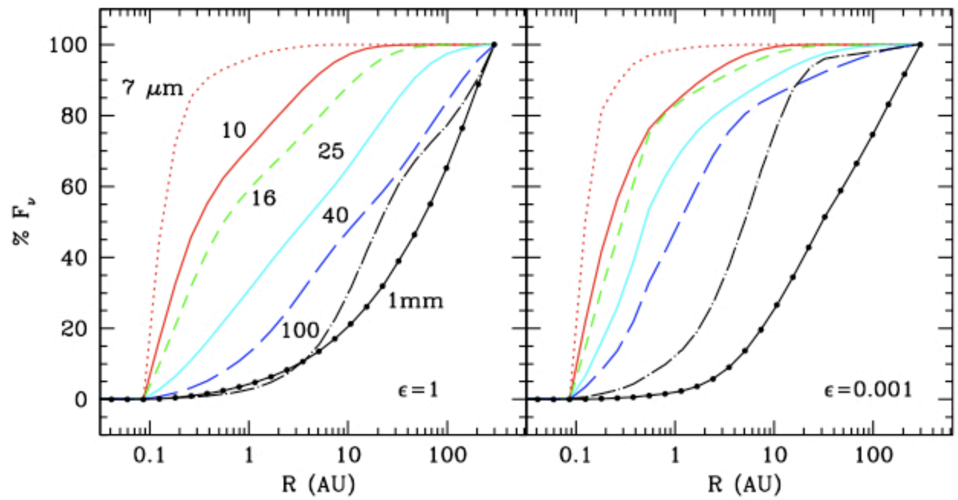
Dust settling toward midplane



No correlation between mid -IR slope and sub/mm slope (poster by Crockett #45)

Where does the flux come from?

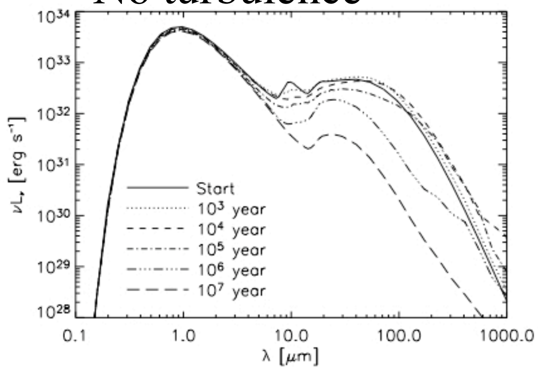
Cumulative flux for different wavelengths



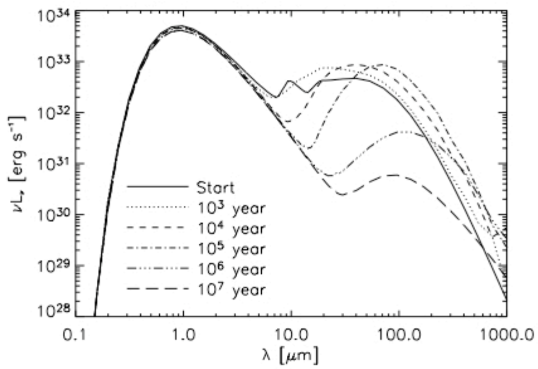
Most mid-IR from < 10 AU in settled disks
Sub/mm from outer disk
⇒Shorter evolutionary timescales for dust in inner disk
Consistent with theoretical expectations

No agreement with theoretical predictions otherwise

No turbulence



With turbulence



Dullemond & Dominik 2005
Rapid disappearance of small grains
Turbulence enhances problem
No silicate emission
No near IR excess

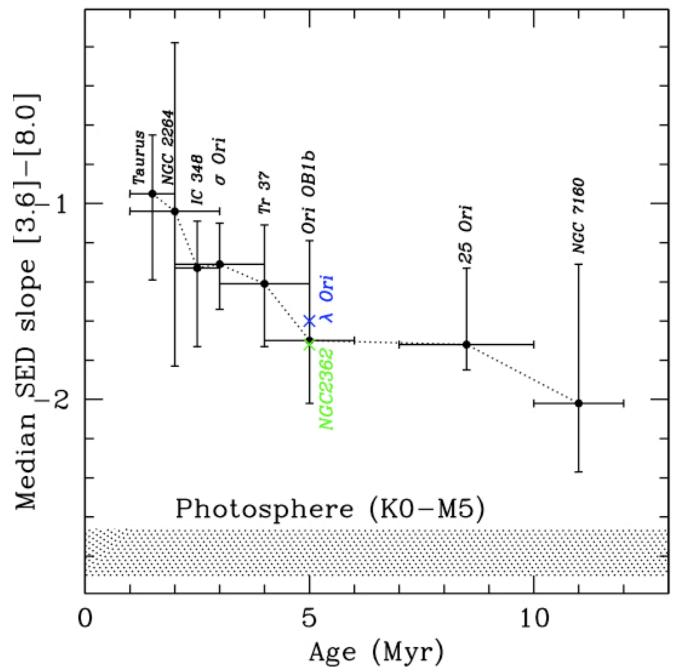
Fragmentation of aggregates

Disk evolution

Median and quartiles

Age not the only parameter
 determing evolution
Initial conditions?
 metallicity?

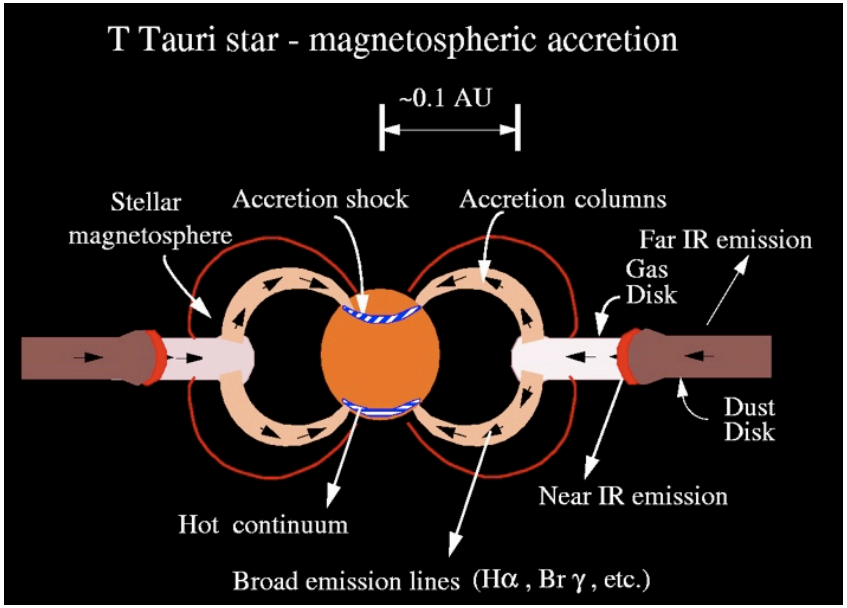
What is happening to the
 disks?



Hernandez et al. 2008
 and Hernandez’ talk

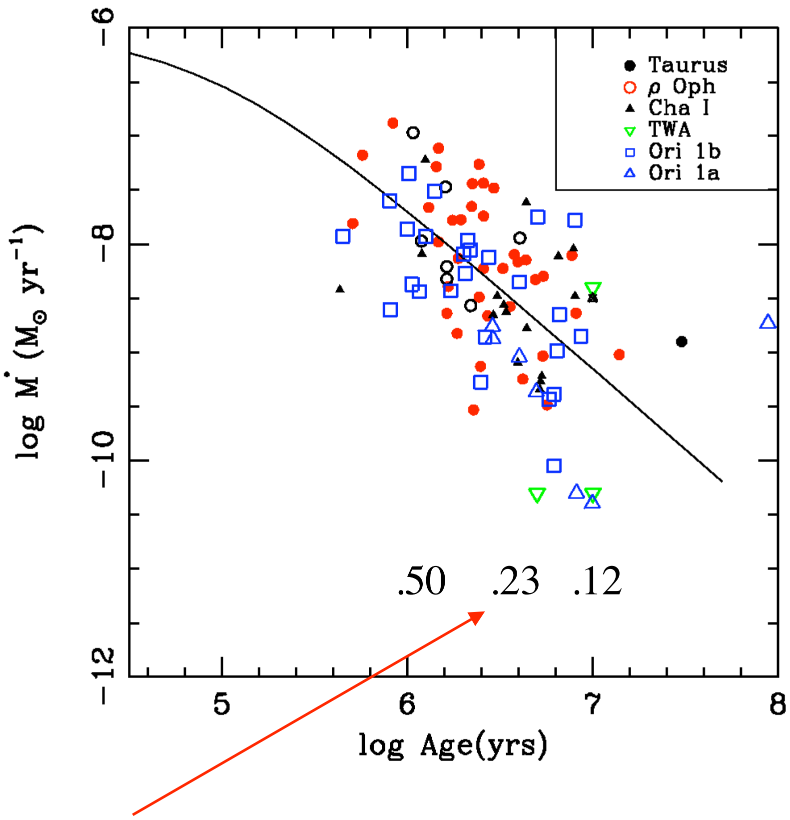
Inner disk

- •Stellar magnetic field truncates disk at a few stellar radii , B ~ few kG (Johns -Krull & Valenti, 2005)
- •Material falls onto star along magnetic field lines.
- •Sharp transition dust/gas (Natta et al 2001; Dullemond et al 2001), emission from walll dominates near-IR
- •Inner gas disk, optically thin



Inner gas disk may not be thin in Herbig's stars (poster by Tannirkulam #65), but probably is in CTTS (poster by Ingleby # 46)

Mass accretion rate decreases with time

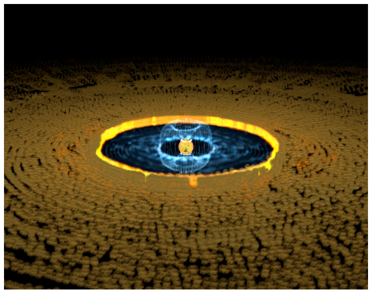


Hartmann et al. (1998), Muzerolle et al. (2001), Calvet et al. (2005)

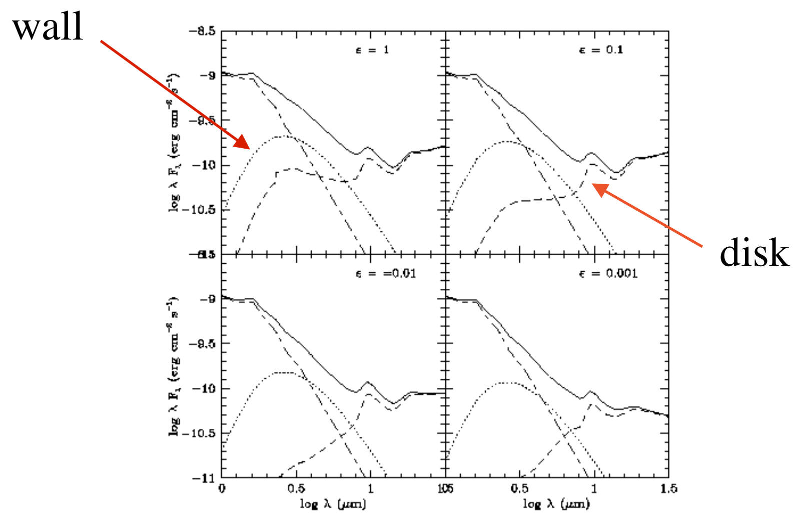
Fraction of accreting objects decreases with time: not explained by viscous evolution

Evolutionary effects

Inner disk:

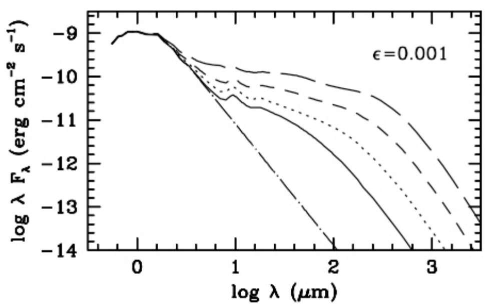


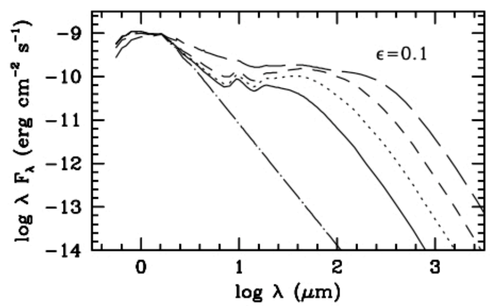
Art by Luis Belerique
& Rui Azevedo



Slope becomes stepper as:

•Degree of settling increases



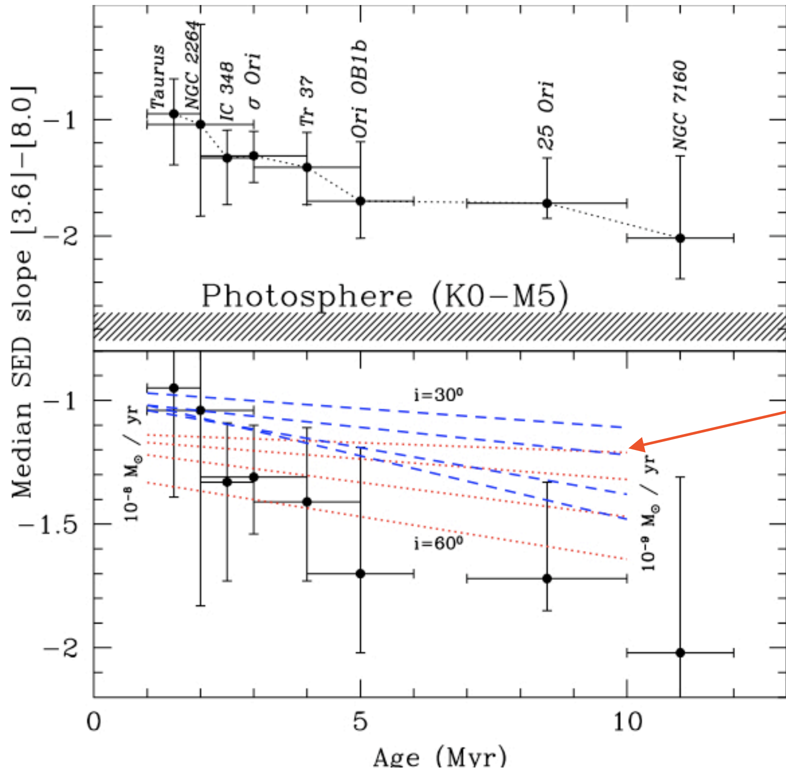


•Accretion rate decreases

log dM/dt= -10, -9, -8, -7

Σ decreases

Dust evolution



Models for:

ε
1
0.1
0.01
0.001

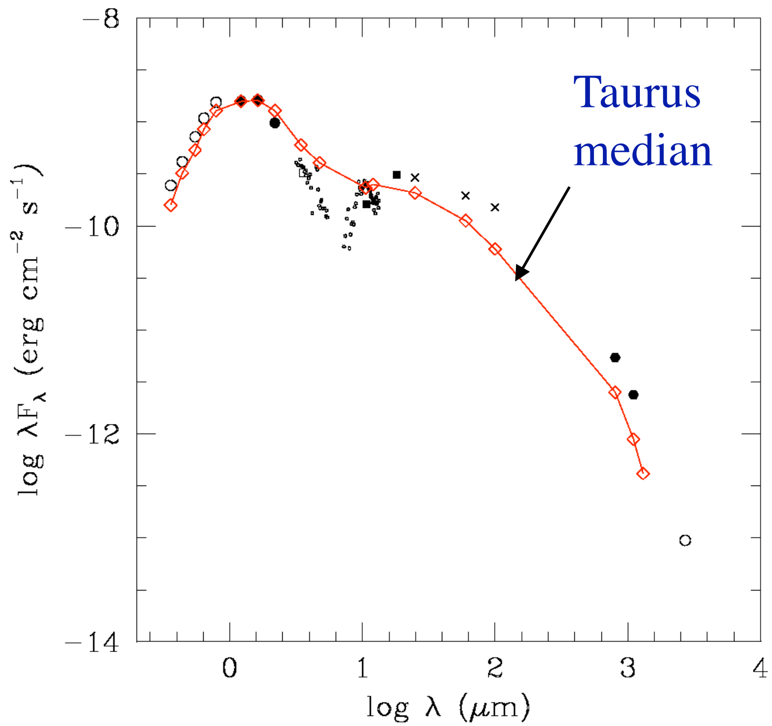
⇒Depletion < 0.1% in inner disk upper layers after 5 Myr (Hernandez et al 2007)

Transitional disks

Strom et al. 1989, inner disk clearings and disks in transition

TW Hya, 10 Myr old

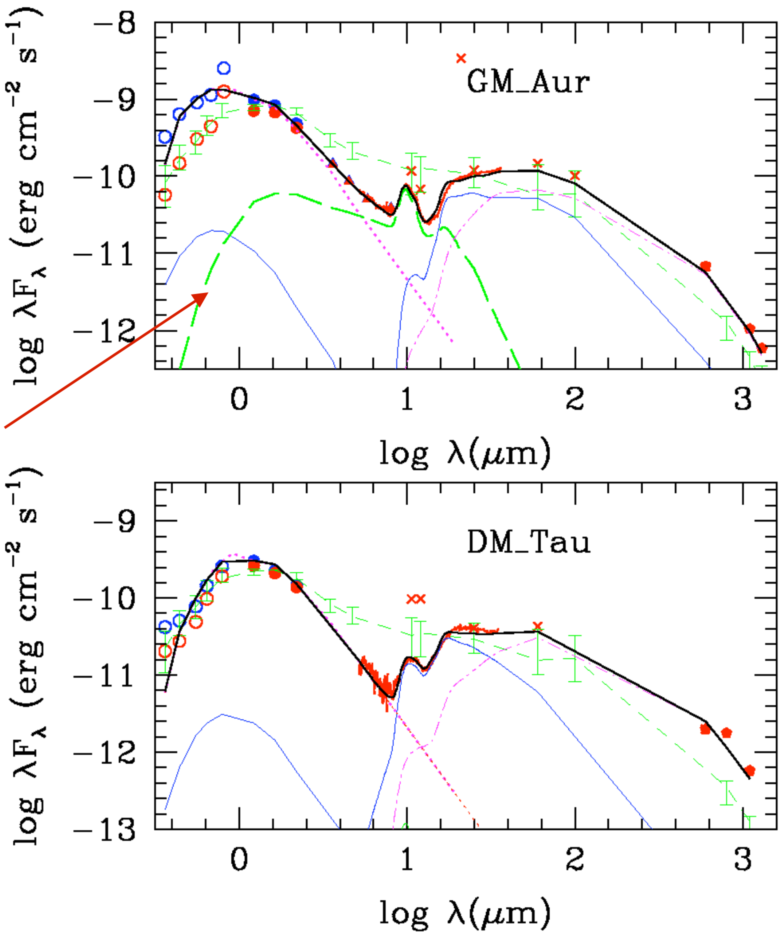
- Near to mid-IR flux deficit relative to Taurus median
- Sharp rise
- Flux at longer λ consistent with optically thick emission



Muzerolle's talk

Calvet et al 2002

Transitional disks in Taurus



Optically thin material

$R_w \sim 24$AU
outer disk + inner disk with little dust + gap
(~ 5-24AU)

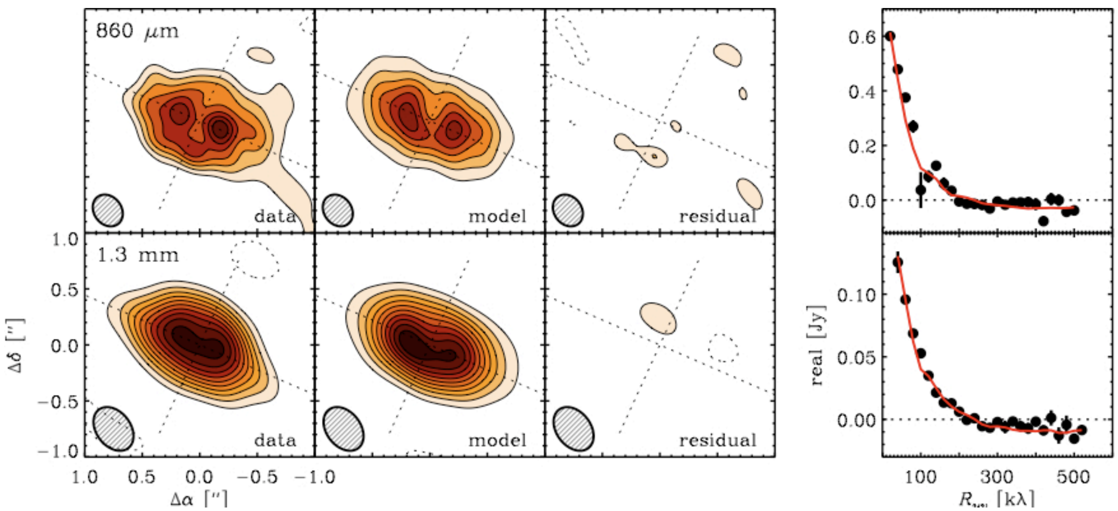
$R_w \sim 3$ AU
only external disk

Both accreting

Calvet et al 2005

Imaging of holes with sub/mm interferometry

IRS spectra finely maps disk structure

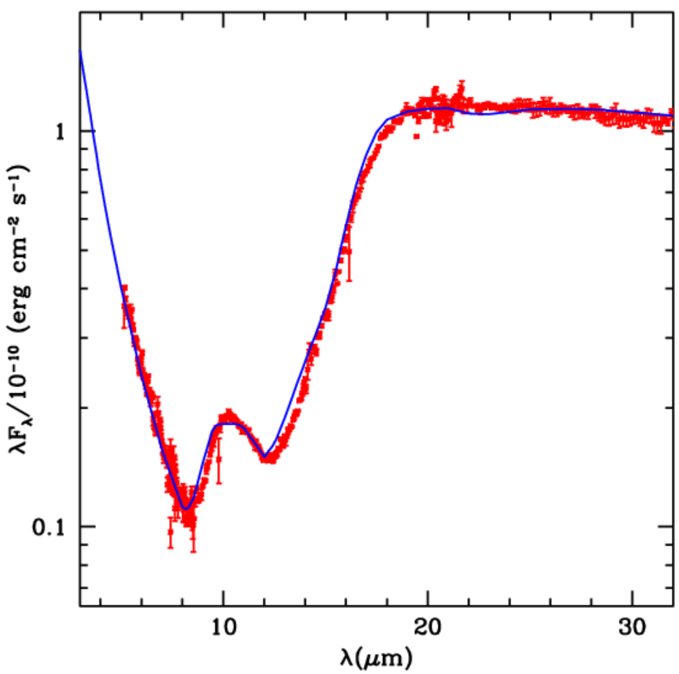


GM Aur

Wilner, Andrews' talks

Circumbinary disks

CoKu Tau 4, ~ 10 AU
~ 2 Myr



Forrest et al. 2004;
D'Alessio et al. 2005

Binary system
(Ireland & Kraus 2008)
Other cases
HD98800 Furlan et al. 2007
Hen3-600A Uchida et al 2004

Check for companions

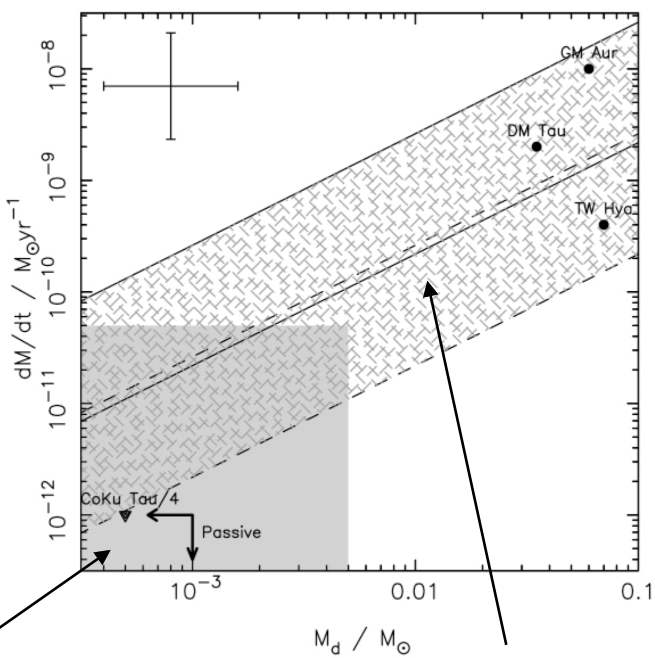
Tidal interactions clear inner disks

Kraus' talk
Interesting variability
Poster by Nagel (#37)

What agent clears the inner disk regions?

Planets most likely

Alexander & Armitage 2007



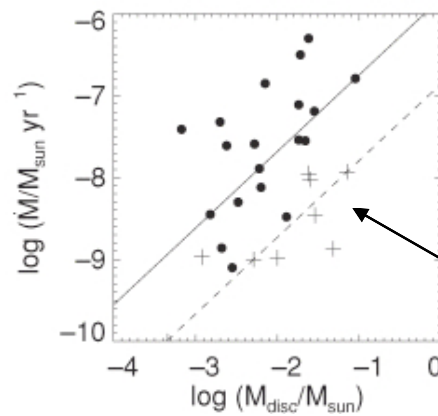
Photoevaporation

Planet

Alexander's talk

Lubow & d'Angelo 2006:

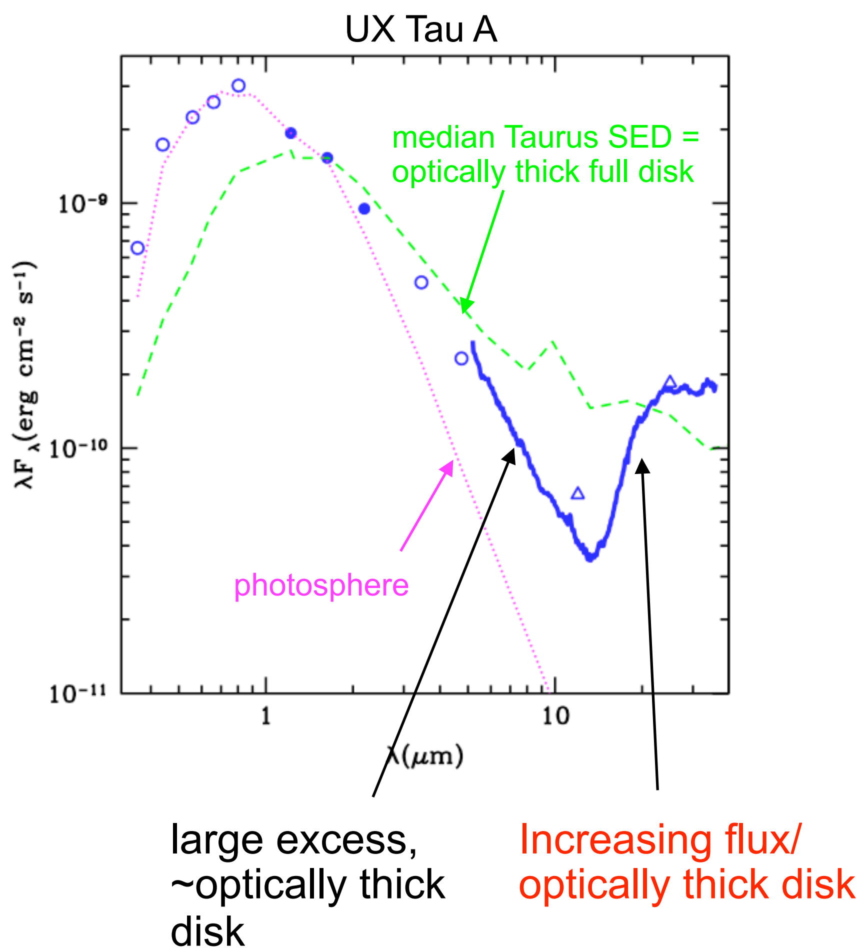
- Disks more massive than expected from $(dM/dt)_*$
- Some mass of outer disk into planet
- $(dM/dt)_*$ not indicative of M_{disk} in TD $\Leftrightarrow$ low α



Transitional disks

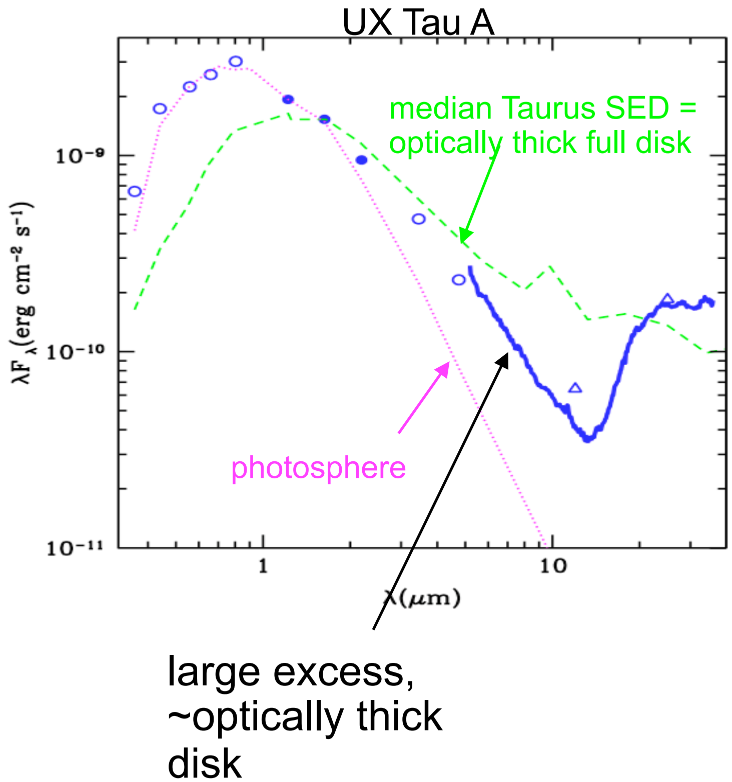
Najita, Strom, & Muzerolle 2007

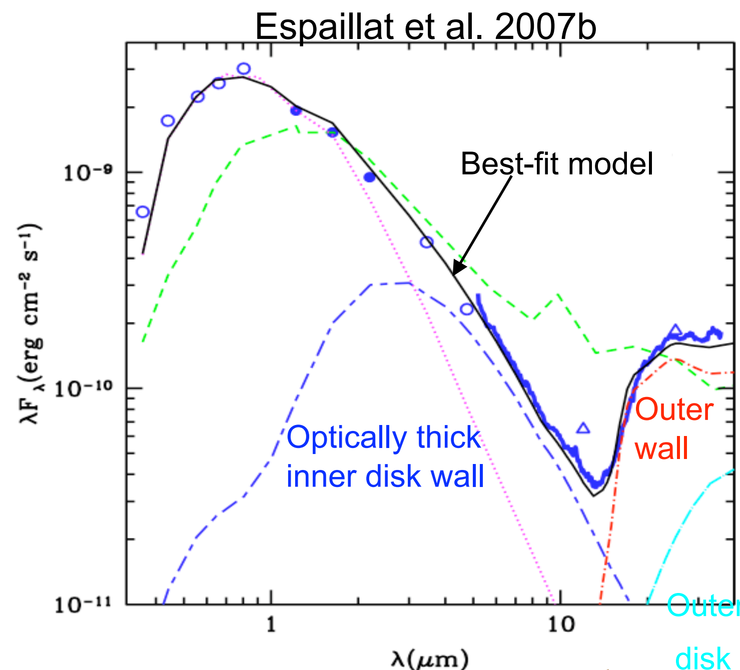
Pre-Transitional Disks: optically thick disks with gaps

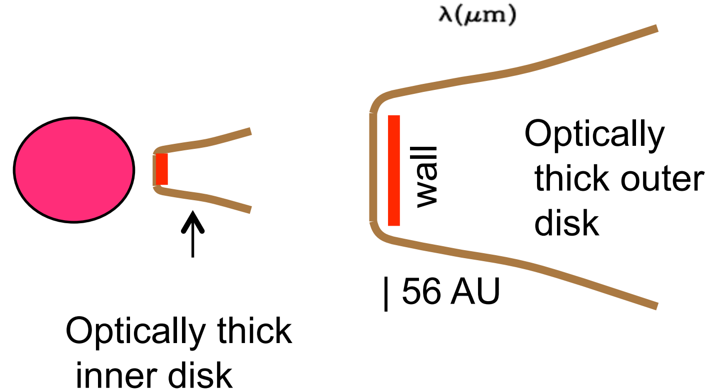


Espaillat et al. 2007; Brown et al. 2007

Pre-Transitional Disks: optically thick disks with gaps



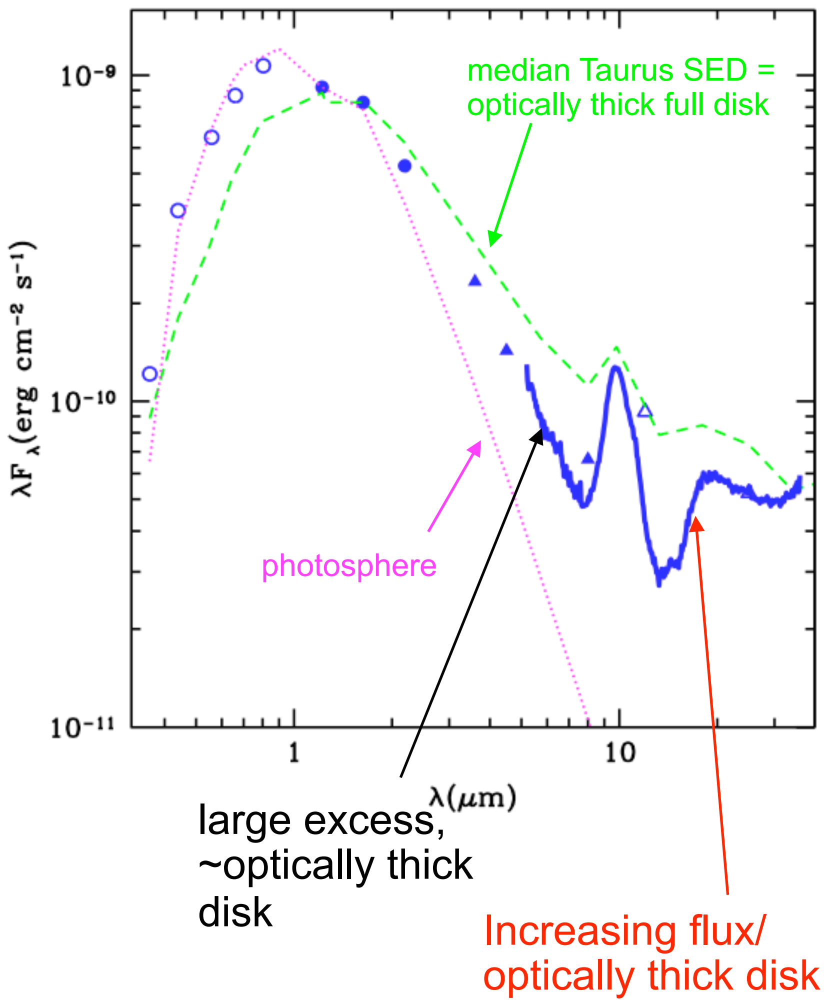




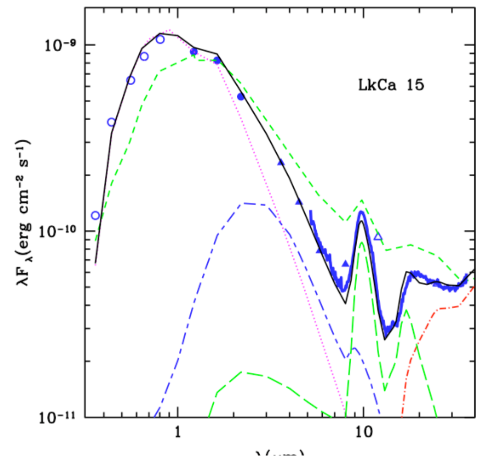
Pre-Transitional Disk of LkCa 15

- Truncated outer disk at 46 AU (Pietu et al. 2006)
- Binary? No companion $M > 0.1\ M_{sun}$ 3-22 AU (Ireland & Krauss 2008) or larger separations (White & Ghez 2001)

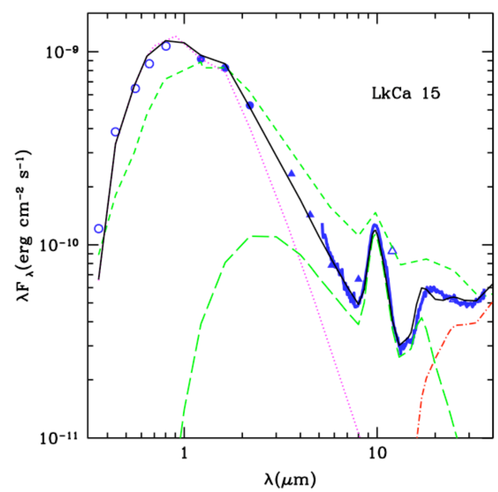
Pre-Transitional Disk of LkCa 15



Two alternatives:



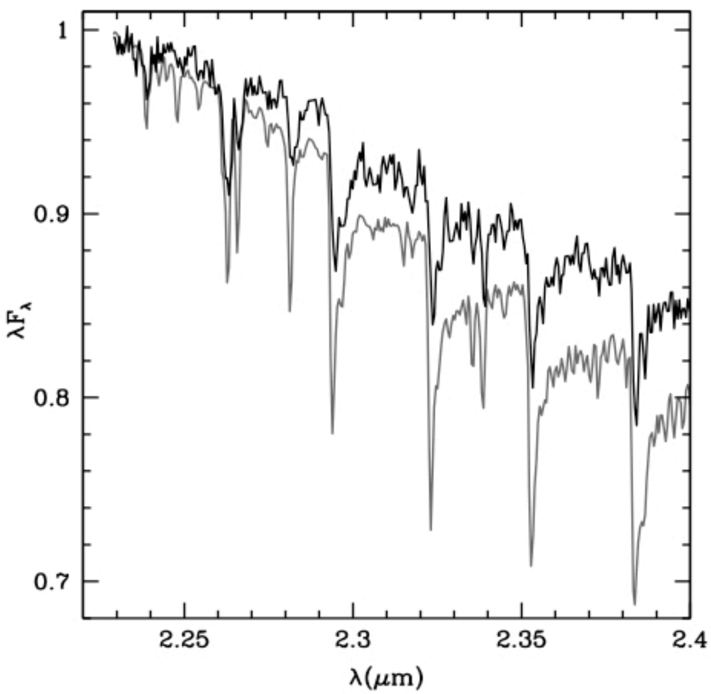
thick

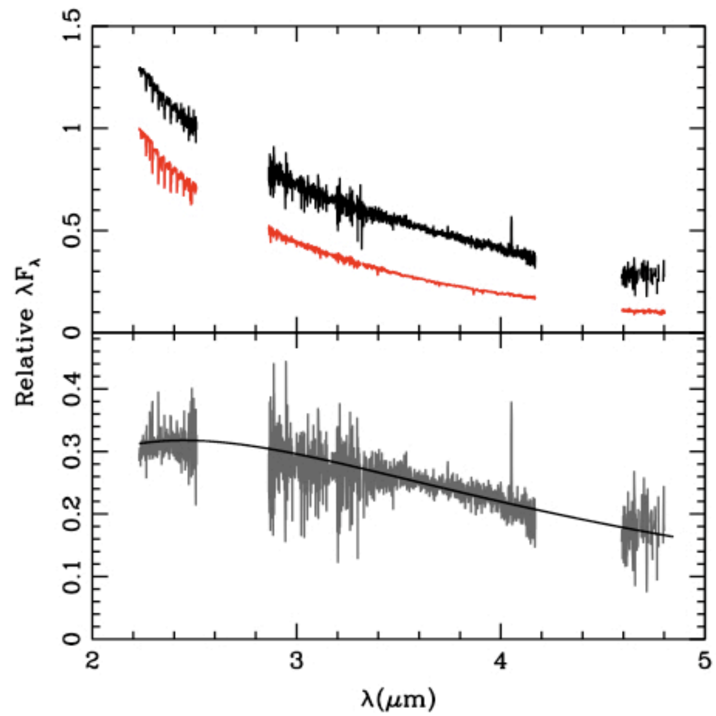


thin

Detailed near-IR spectrum of pre-transitional disk LkCa 15

Blackbody at T ~ 1500K

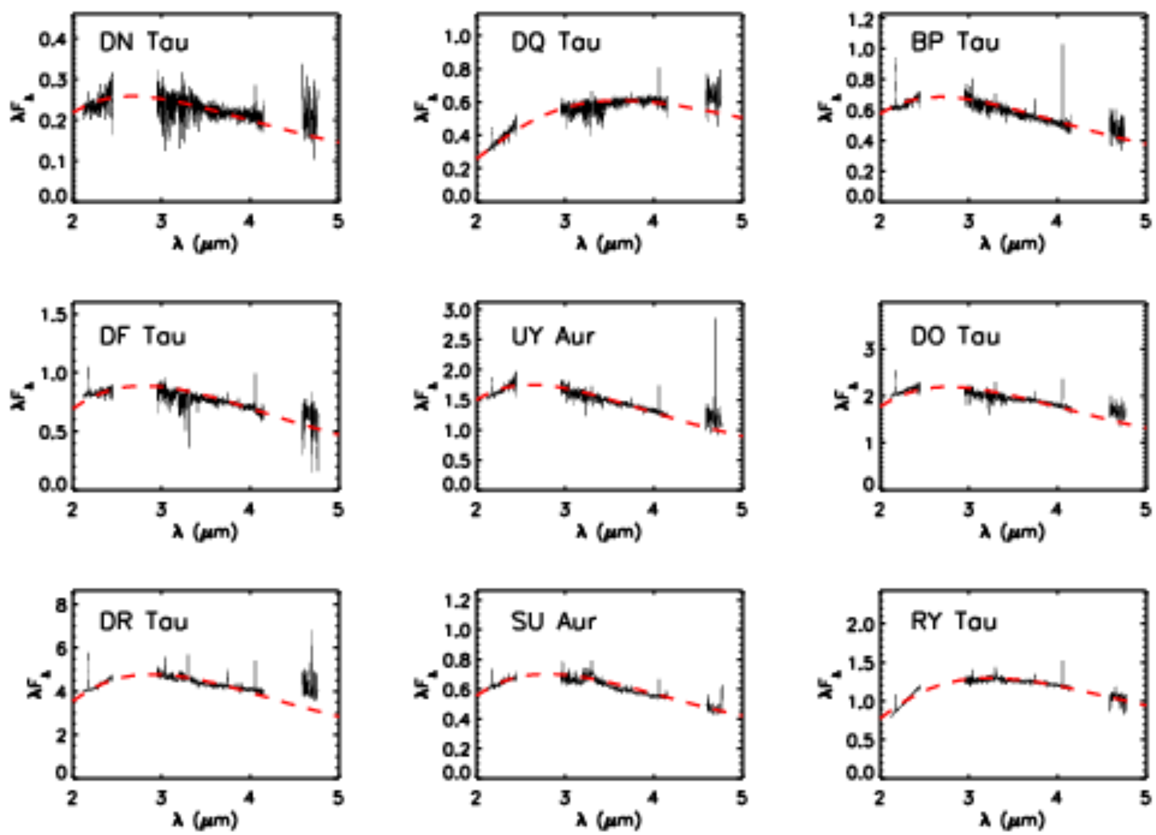




2-5 mm SpeX spectrum

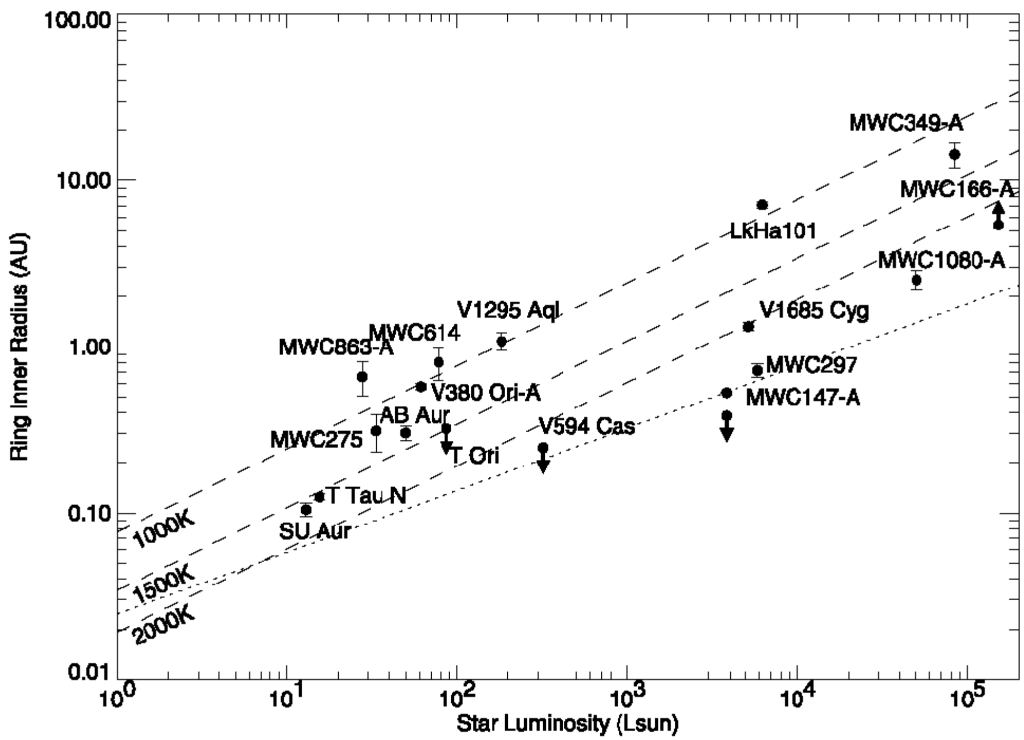
Espaillat et al. 2008,
Poster by Espaillat #91

Blackbody-like near-IR excess between 2-5 mm in full disks of CTTS



Muzerolle et al. 2003

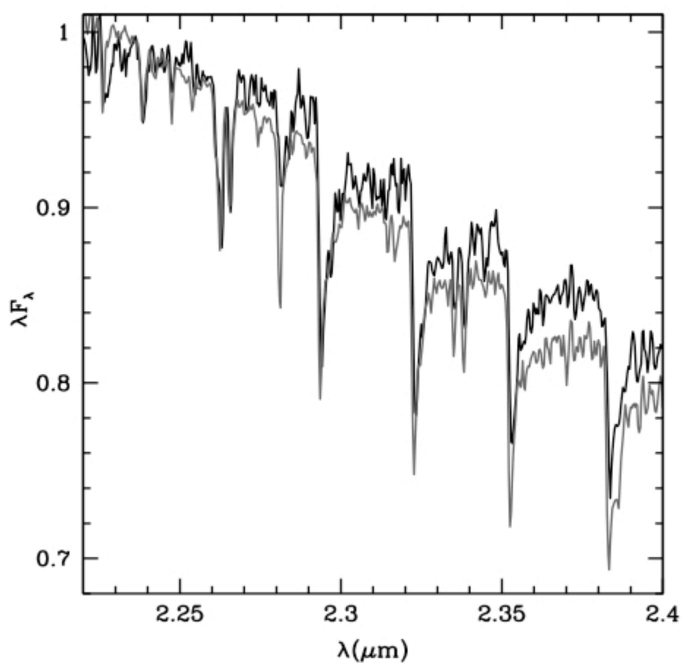
Dust-gas Transition

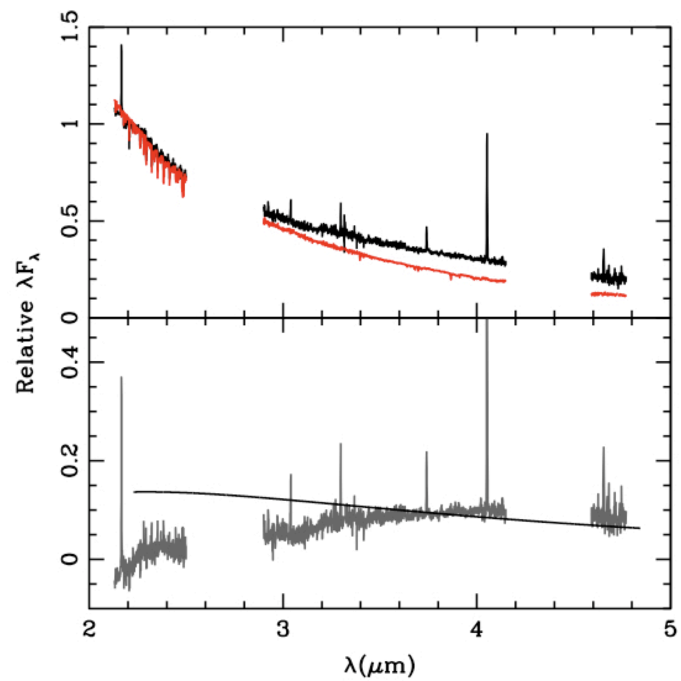


Monnier & Millan-Gabet 2002

Detailed near-IR spectra of transitional disks

No hot optically thick gas!





Poster by Espaillat #91

Implications

Direct detection of gap in optically thick disk

Points to planet formation (Rice et al. 2003, 2007; Quillen et al. 2004; Alexander & Armitage 2007)

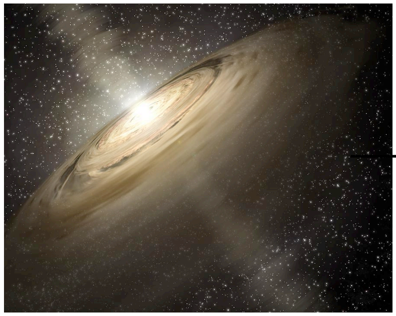
Suggests evolutionary sequence:

Gap opening (pre-TD) → inner disk clearing (TD)

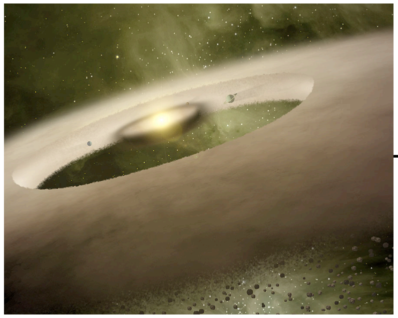
If so, evidence against inside-out clearing mechanisms: photoevaporation (Clarke et al. 2001; MRI erosion of wall (Chiang & Murray-Clay 2007)

How the inner disk becomes optically thin? Rapid dust evolution?

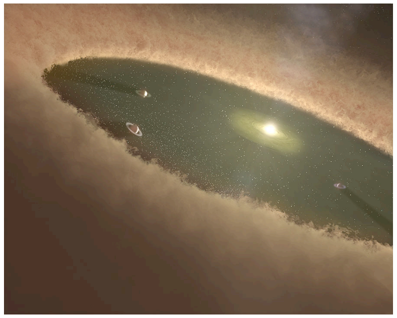
"Full" optically thick disk



Disk Gaps:Pre-transitional disks



Inner Disk Holes: Transitional disks



What have we learned

Three types of disks.

Full disks: they evolve by decreasing their mass and mass accretion rate as the original dust growths and settles toward the midplane.

The median emission of disks in a population decreases with age, large spread. Age is not the only factor.

Disk frequency decreases with age

Pre-transitional disks: disks with gaps

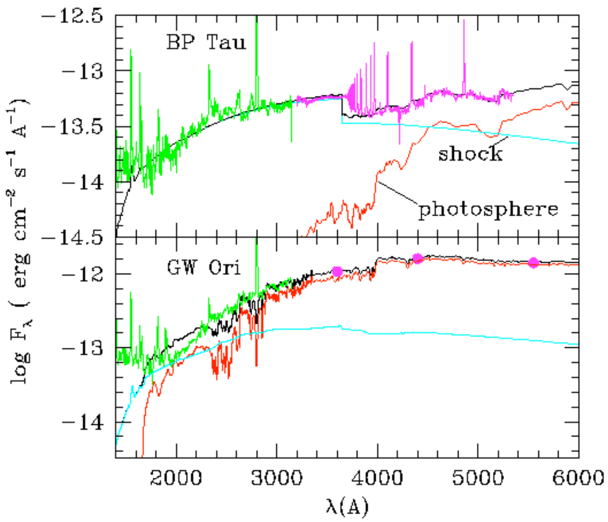
Transitional disks: disks with inner cleared regions

What is the causal relationship between these types?

“Full” disks | Disk Gaps:Pre-transitional disks | Inner Disk Holes: Transitional disks

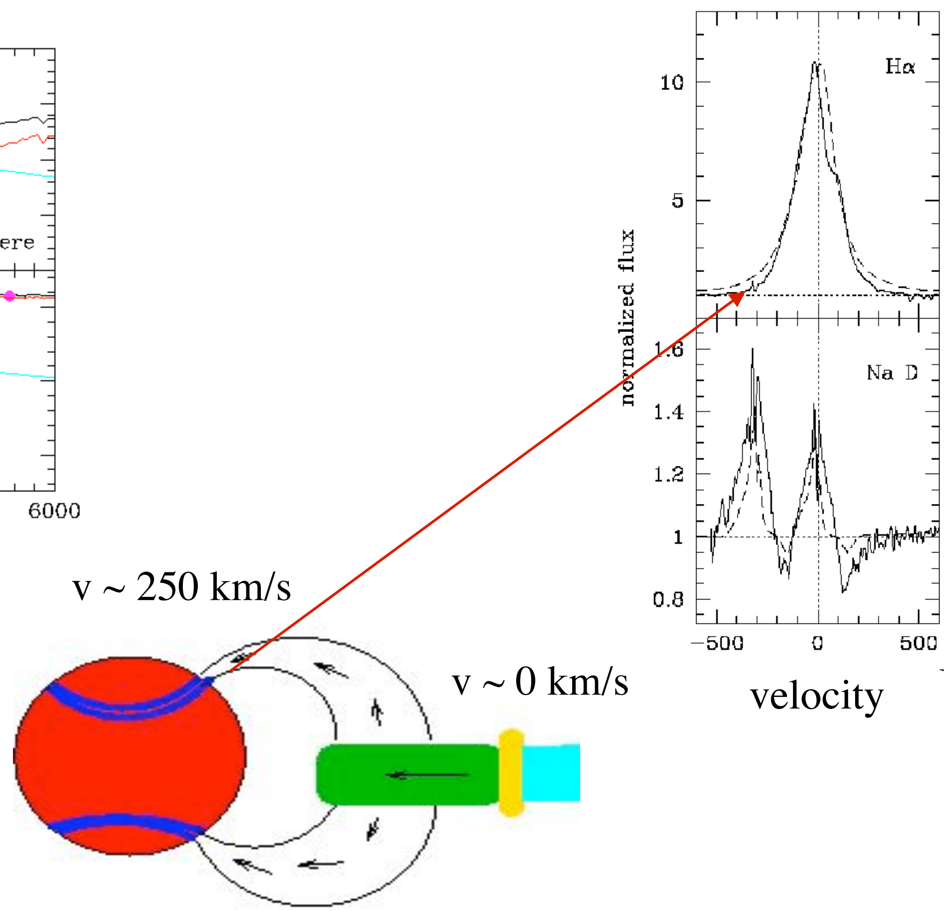
Evidence for magnetospheric accretion

Excess emission/veiling



Broad emission lines

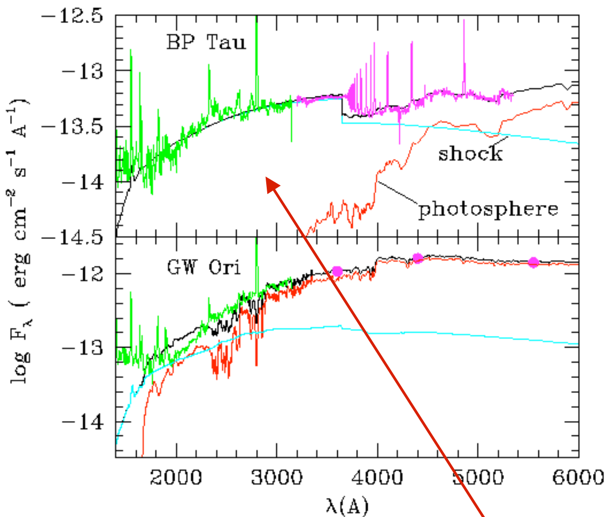
Muzerolle et al. 1998, 2001



Evidence for magnetospheric accretion

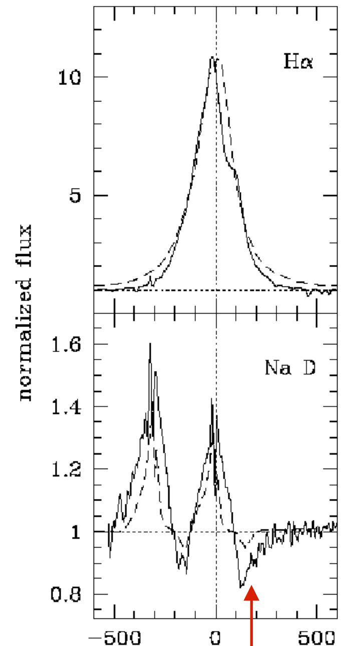
Excess emission/veiling

Calvet & Gullbring 1998



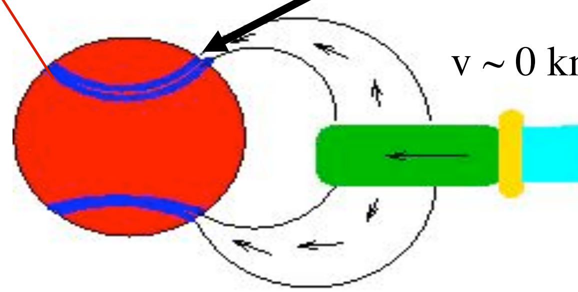
Broad emission lines

Muzerolle et al. 1998, 2001



v ~ 250 km/s

v ~ 0 km/s

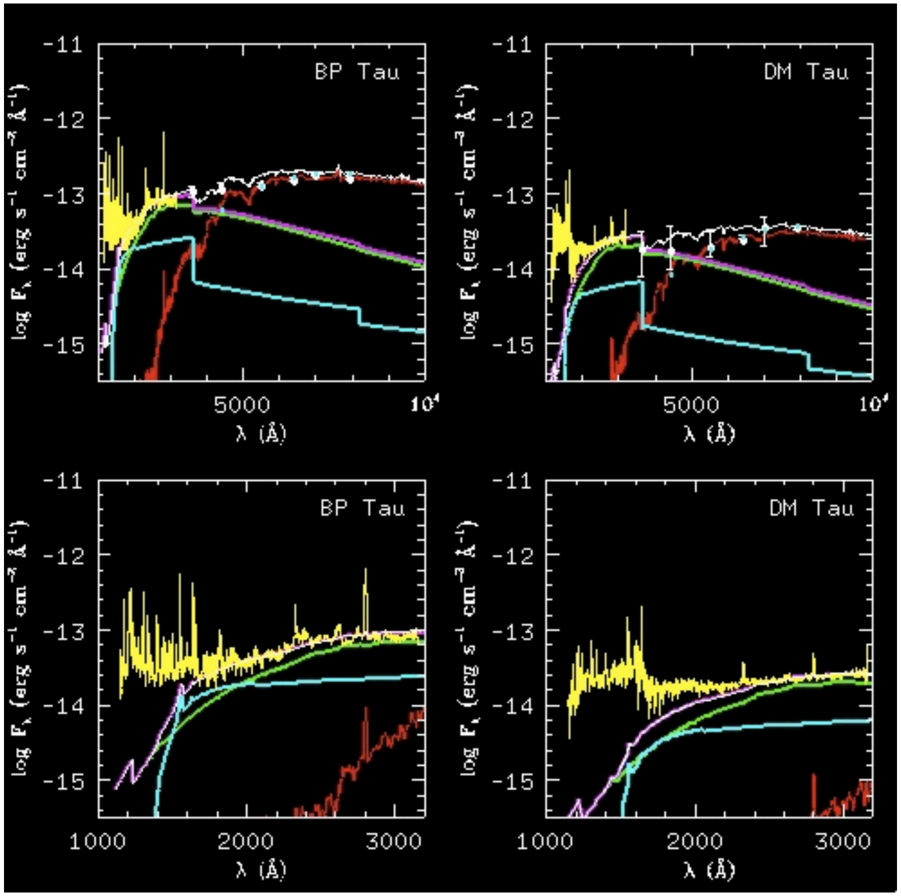


Redshifted absorption if right inclination

BP Tau and DM Tau

BP Tau:
M= 0.79 M_{solar}
L= 1.34 L_{solar}
R=2.39 R_{solar}
Age= 1.53 Myrs

DM Tau:
M=0.47 M_{solar}
L=0.36 L_{solar}
R=1.48 R_{solar}
Age= 2.82 Myrs



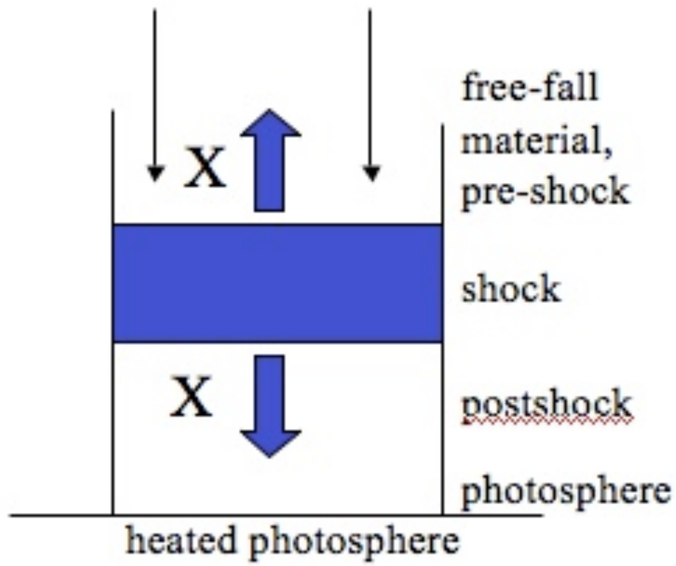
Ingleby & Calvet 2008

Magnetospheric Accretion

- Material reaches photosphere at almost the free fall velocity

$$v_{ff} = 307 km/s \left(\frac{M}{M_{solar}}\right)^{\frac{1}{2}} \left(\frac{R}{2R_{solar}}\right)^{\frac{-1}{2}} \left(1 - \frac{R}{R_i}\right)^{\frac{1}{2}}$$

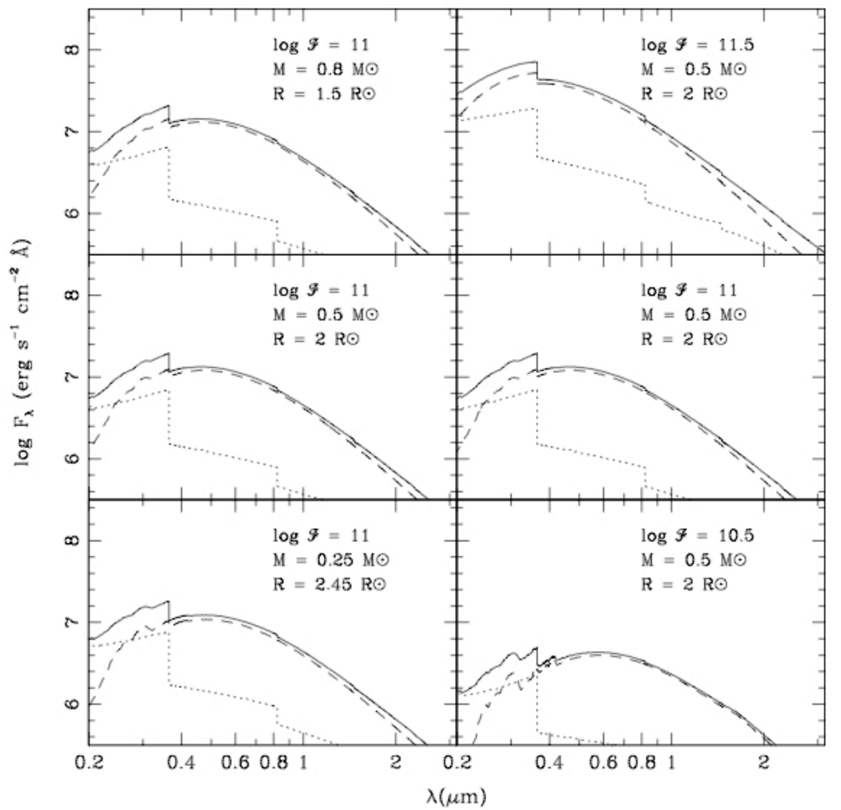
- R_i = radius where magnetic field truncates the disk = 5R
- Emission is characterized by F and f
- F = total energy in column
- f = filling factor



$$T_s = 8.6 \times 10^5 K \left(\frac{M}{0.5 M_{solar}}\right) \left(\frac{R}{2R_{solar}}\right)^{-1}$$

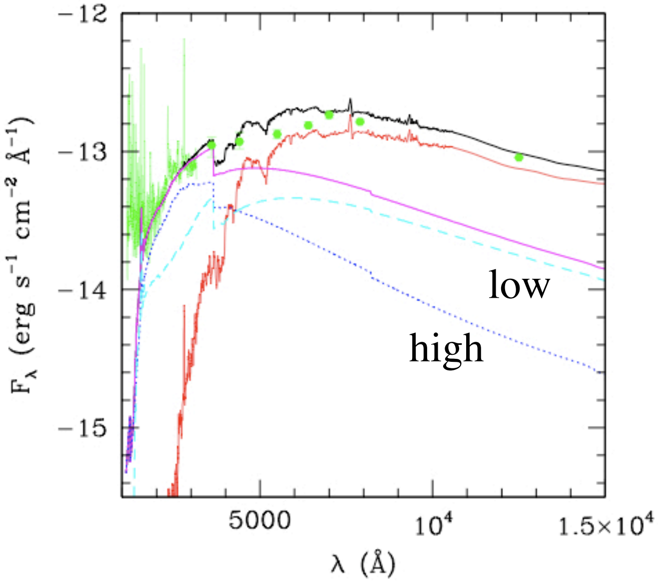
Calvet & Gullbring, 1998

Accretion shock model: heated photosphere emission



$L_{hp} \sim 3/4\ L_{acc}$

Multiple accretion columns



Two column model:
F_{high} = 3 x 10^{11} erg/cm^2/s
f_{high} = 0.7%
F_{low} = 2 x 10^{10} erg/cm^2/s
f_{low} = 11%

dM/t $_{high}$ ~ 2 x 10^{-8} M_{sun}/yr
dM/dt $_{low}$ ~ 2 x 10^{-8} $M_{sun/}$yr

dM/dt $_{tot}$ ~ 4 x 10^{-8} M_{sun}/yr

BP Tau: r_J ~ 0.3 (Edwards et al. 2006)

Single column: dM/dt ~ 3 x 10^{-8} M_{sun}/yr