Protostellar/planetary disk structure

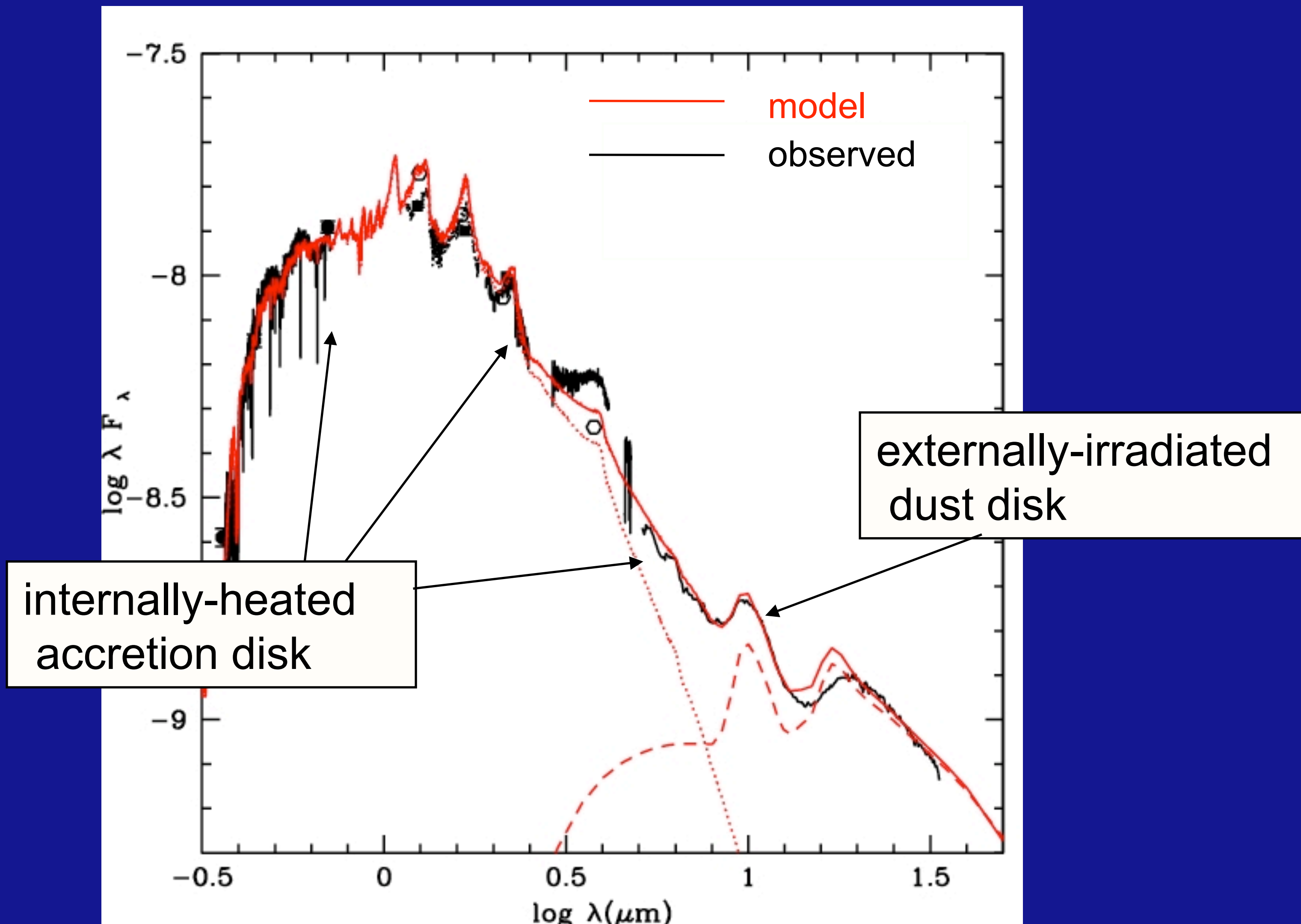
Lee Hartmann
University of Michigan

with much help from Elise Furlan, Melissa McClure, Nuria Calvet, Catherine Espaillat, Paola D’Alessio, Dan Watson and the IRS disk team, Kevin Luhman and the IRAC GTO team...
who cannot be held responsible for its content

Spitzer disk results (low mass stars):

- rapidly-accreting disk- *star formation from (initially) massive disks*
- settling/grain growth: *first step in growing large solid bodies*
- disk "clearing": *limits giant planet formation timescales*
- "transition" disks: *big holes exist @ 1 Myr; we are probably missing a lot...*

FU Ori: 10^{-4} $M_{\odot}$/yr accretion outburst



Zhaohuan Zhu et al. 2007, 2008

FU Ori outburst: accretes 10 M(Jupiter) in ~ 100 yr (from r ≈ 1 AU)

⇒ type of rapid accretion needed to solve the luminosity problem of protostars (and form them) (Evans talk)

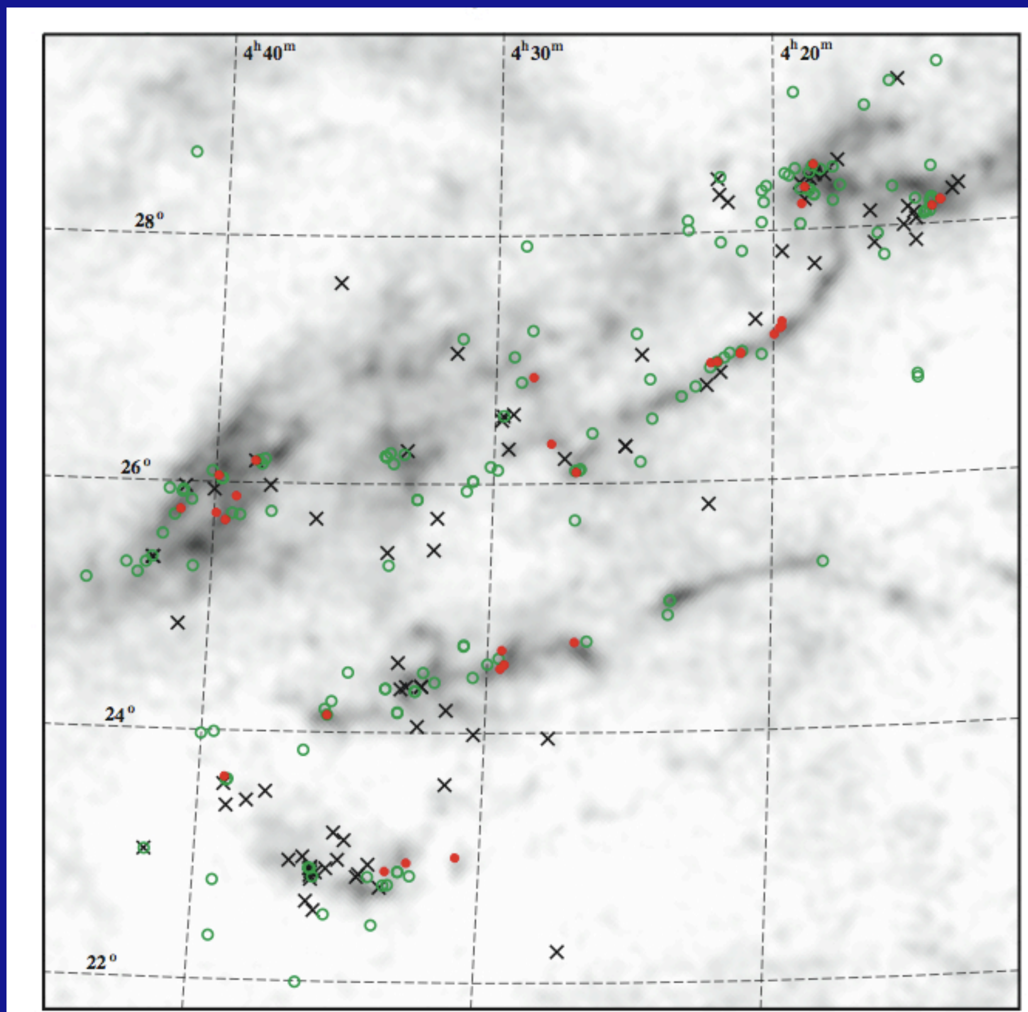
⇒ Spitzer data rule out thermal instability as primary cause of outburst

⇒ implies > 10x the mass of a typical minimum mass solar nebula is present @ r ≈ 1 AU (at least at early age)

⇒ *higher surface densities make growth, migration timescales shorter*

Spitzer: pathfinder for ALMA/JWST era... *statistics!*

IRAC (+ MIPS 24) sensitivity: complete census of disks



Taurus

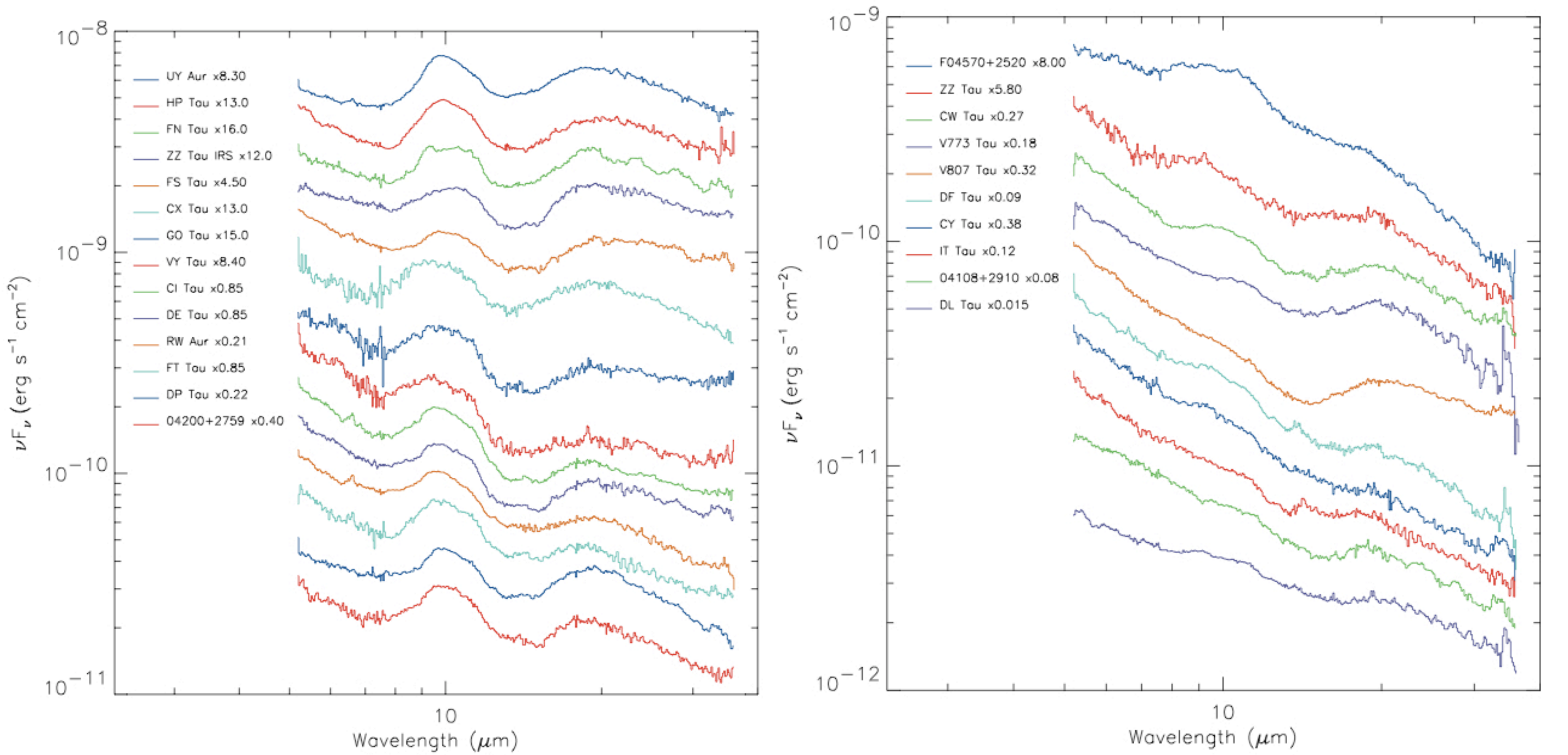
Red = I, protostellar

Green = II, T Tauri (disk)

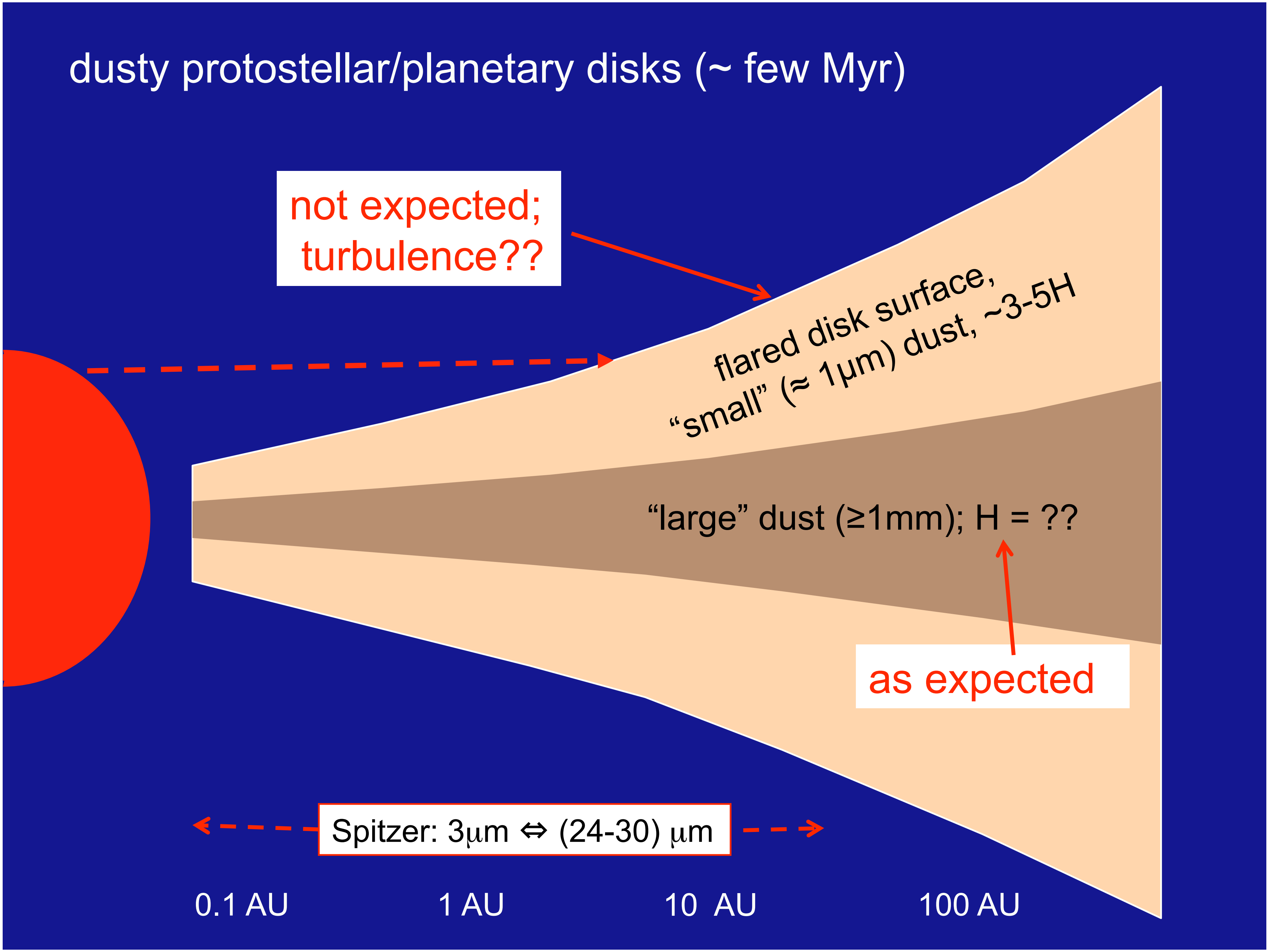
x = III, no disk

Padgett et al., Rebull et al., Luhman et al. 2009

IRS: spectacular sensitivity, wavelength sampling

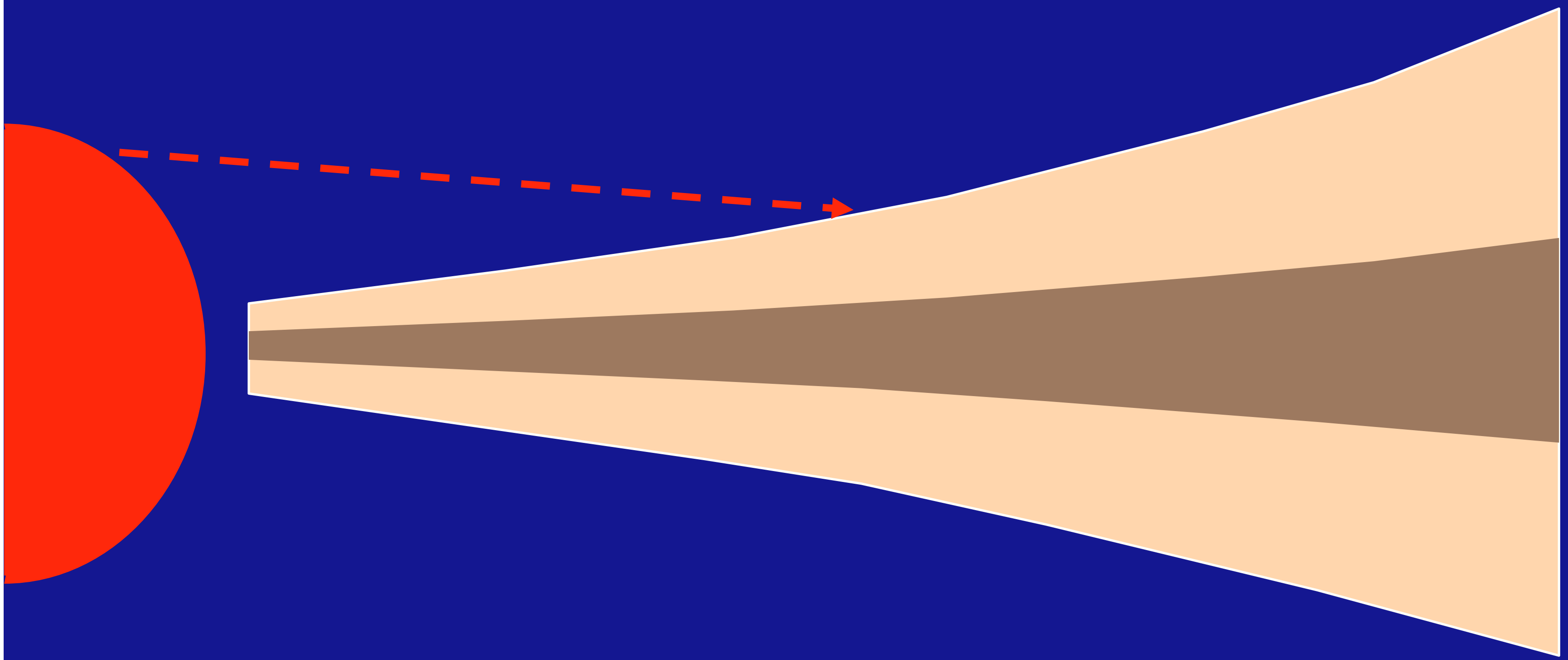


Furlan et al. 2006


dusty protostellar/planetary disks (~ few Myr)
not expected; turbulence??
flared disk surface, "small" (≈ 1μm) dust, ~3-5H
"large" dust (≥1mm); H = ??
as expected
Spitzer: 3μm ⇔ (24-30) μm
0.1 AU
1 AU
10 AU
100 AU

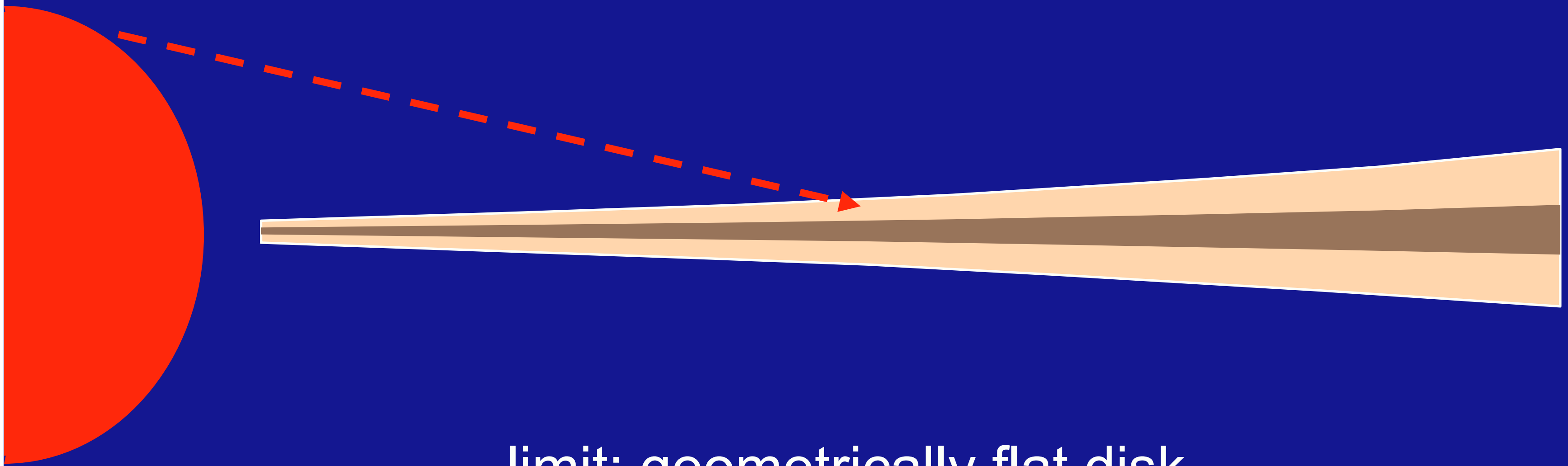
Protostellar/planetary disks (~ few Myr)
dust settles/grows with age;

⇒ less IR excess, less “flared”



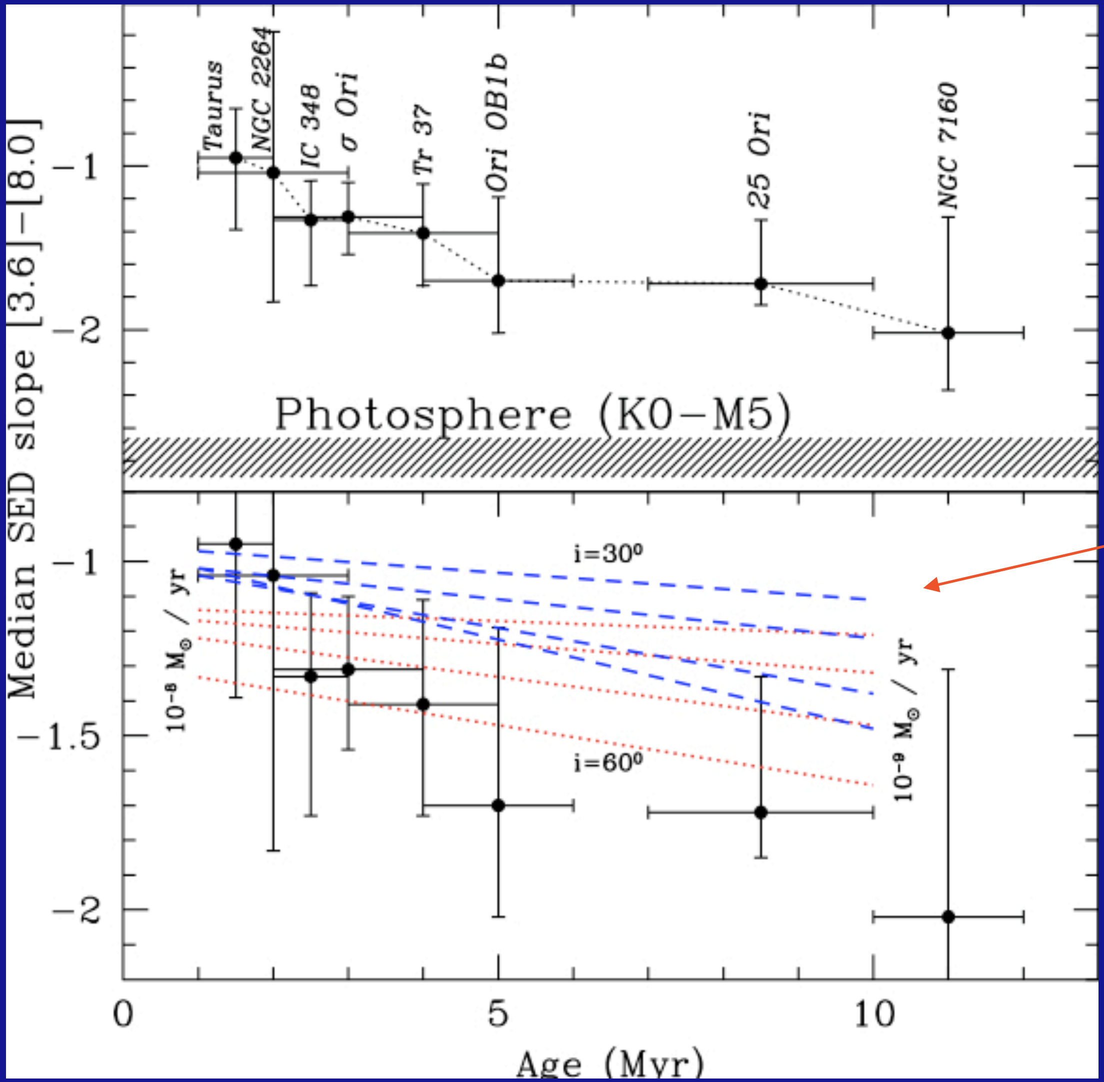
Protostellar/planetary disks (~ few Myr)
dust settles/grows with age;

⇒ less IR excess, less "flared"



limit: geometrically flat disk

Dust evolution



Models for:

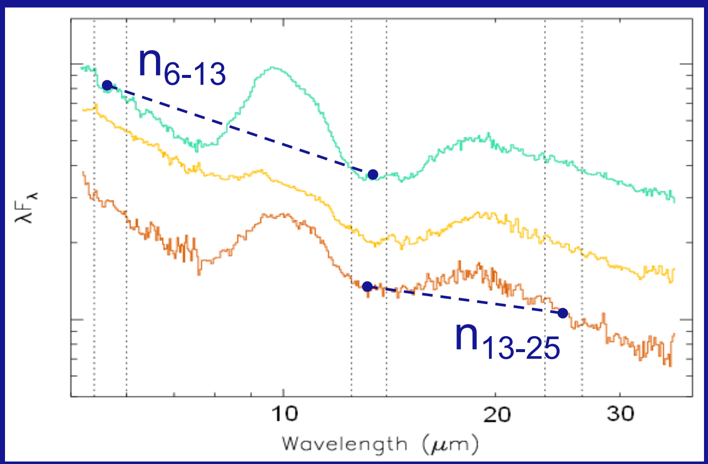
ε (depletion of small dust =
1
0.1
0.01
0.001

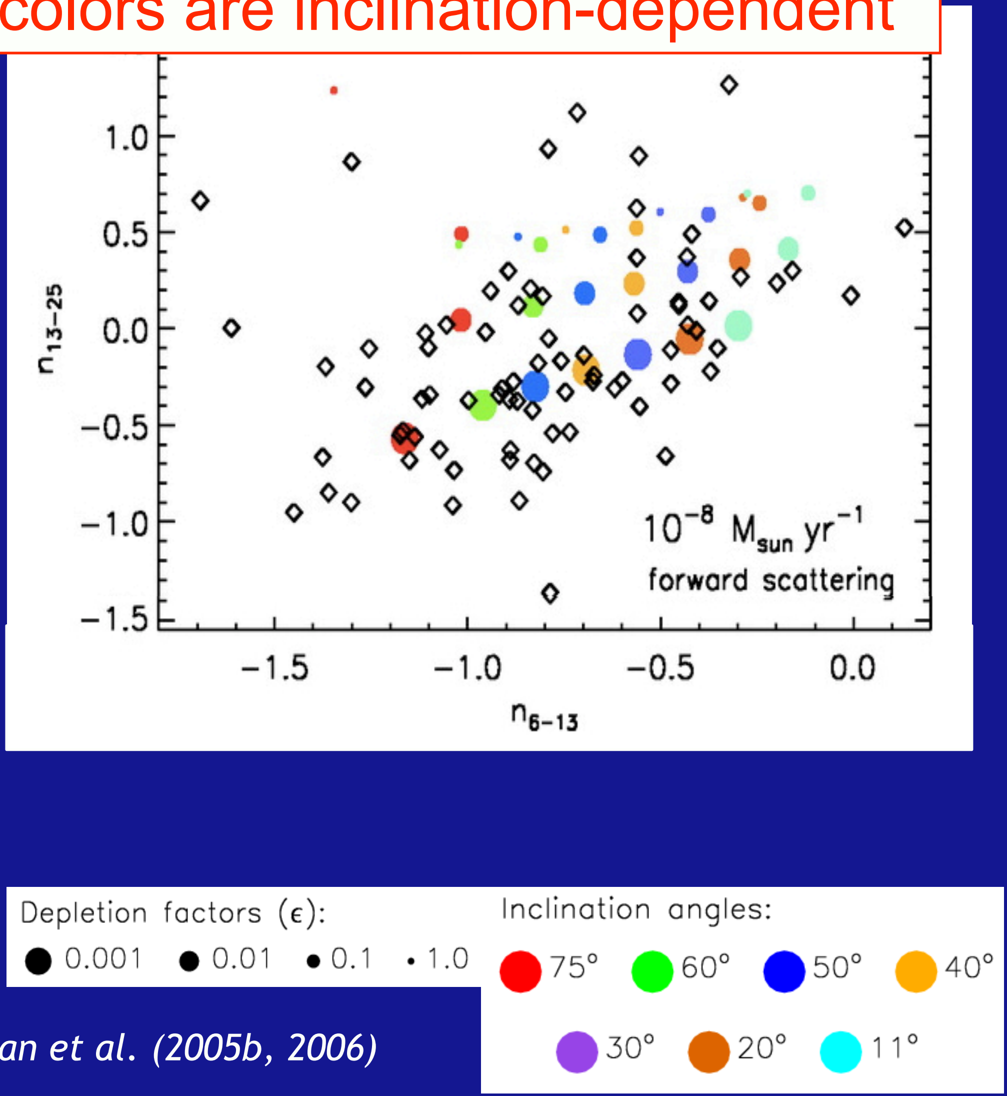
⇒Depletion ~ 0.1% in inner disk upper layers after 5 Myr (Hernandez & IRAC disk team, 2007)

Disks in Taurus: IRS Spectral Indices

85 Class II objects

disk colors are inclination-dependent



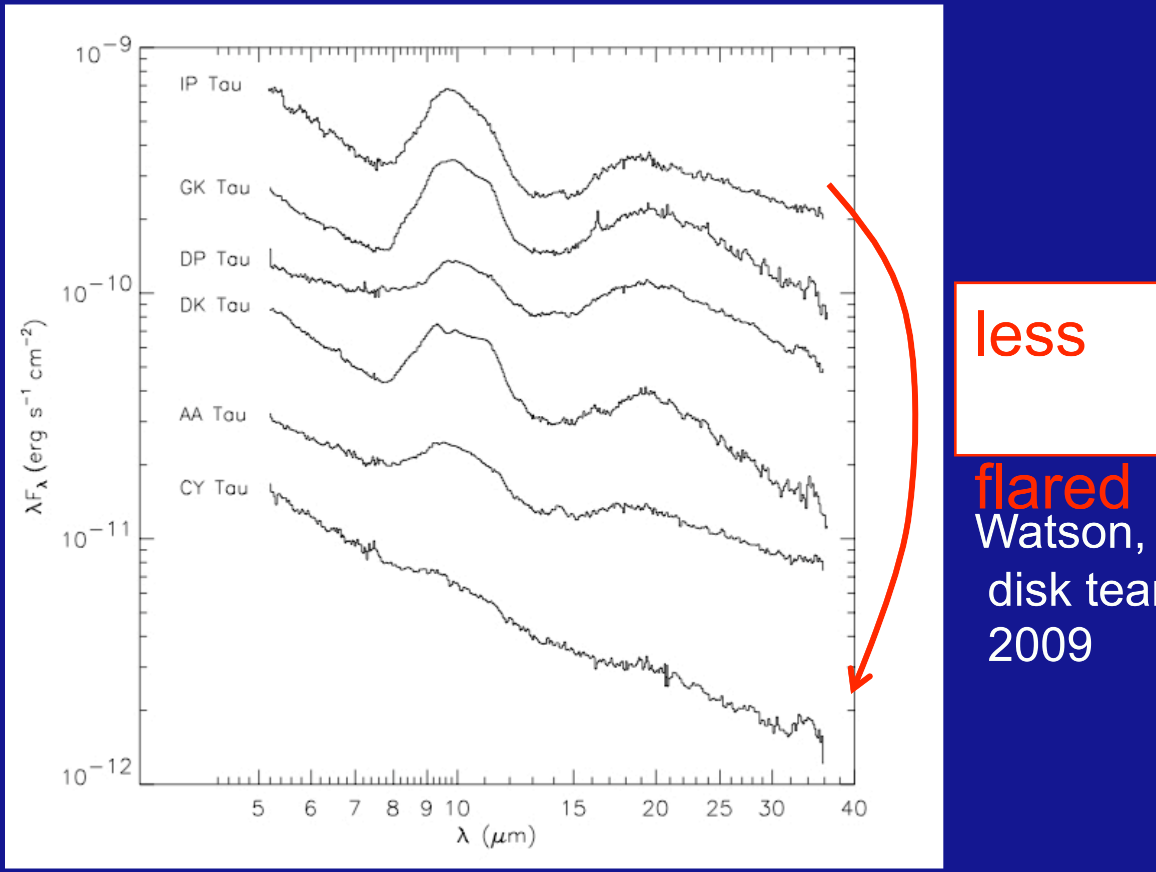


depletion of dust in upper disk layers by factors of 100-1000 @ ages of 1-2 Myr

Furlan et al. (2005b, 2006)

some correlation of disappearance of silicate feature with less "flared" disk; grain growth/settling;

depletions of small dust ≈ $10^{-1} – 10^{-3}$ (important for MRI?)
changes in crystallinity (Bouwman, Sargent , Kessler-Silacci, etc.)



Watson, IRS disk team, 2009

Furlan et al. 2006

Disk "frequency" (small dust @ 10+ AU) decreases over few Myr

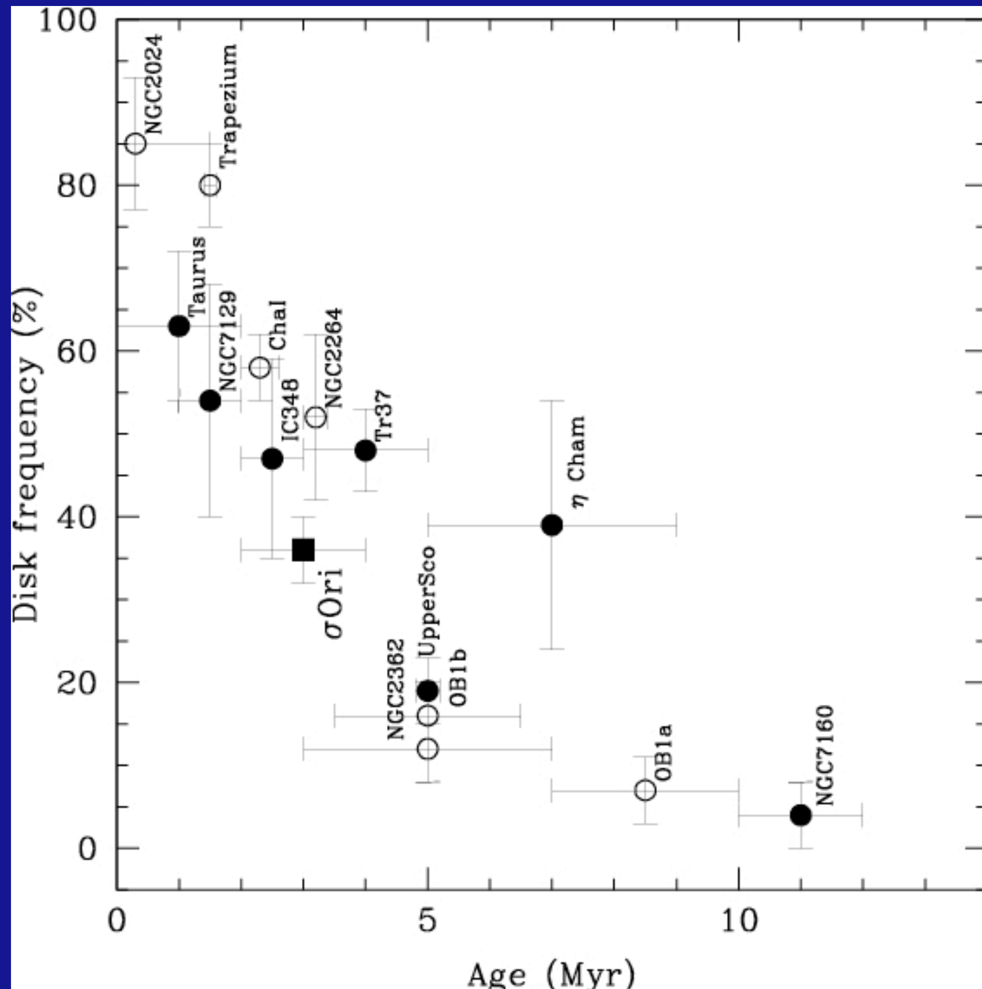
Spitzer contribution: more clusters, more sensitivity, R ⇒ 10+ AU; but not much difference – *GOOD news for warm mission!*

disk clearing AVERAGE timescale shorter than early models of Jupiter formation;

timescales range over an order of magnitude

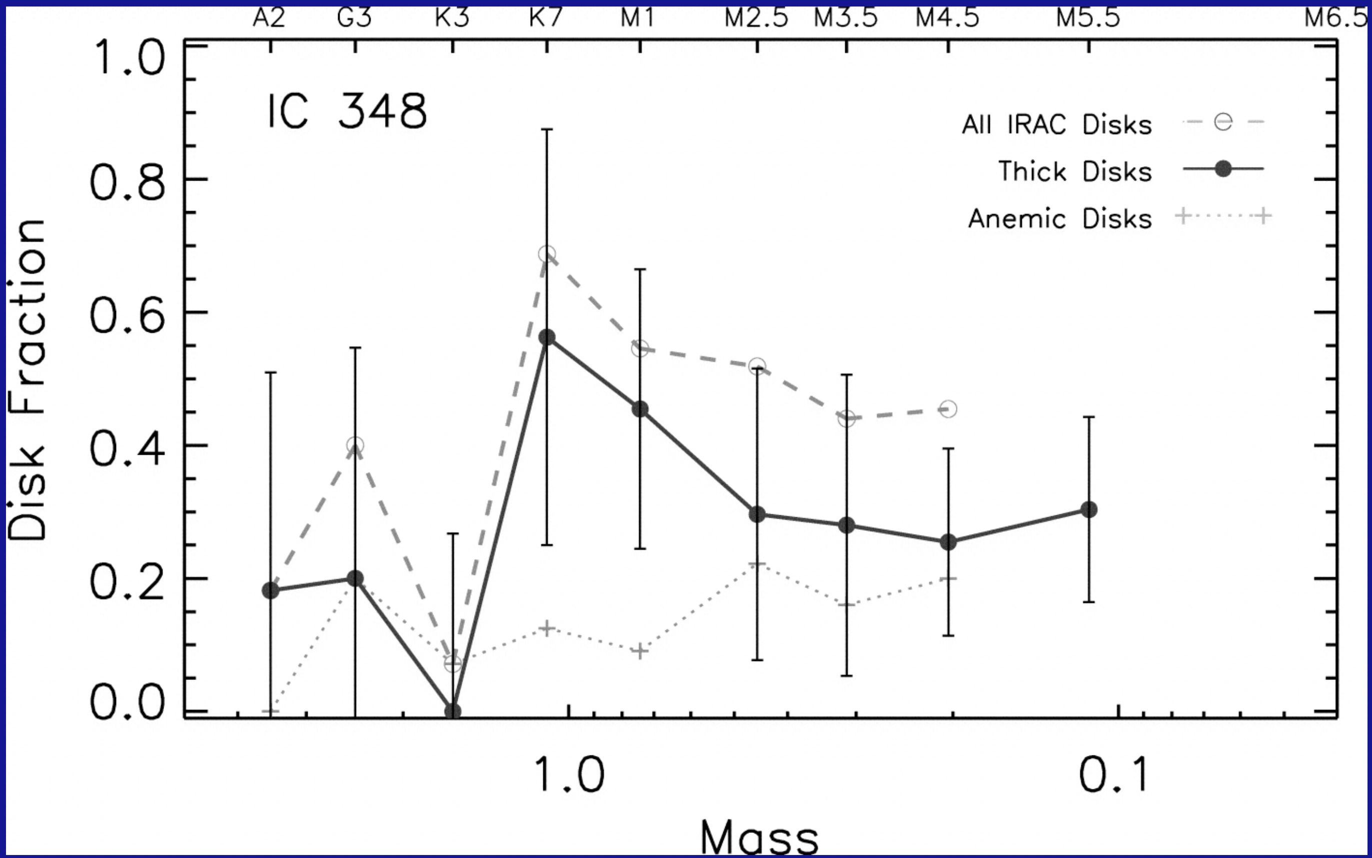
⇒ initial conditions

close binary companions reduce inner disk emission: Cieza et al. 2009



Hernandez et al. 2007

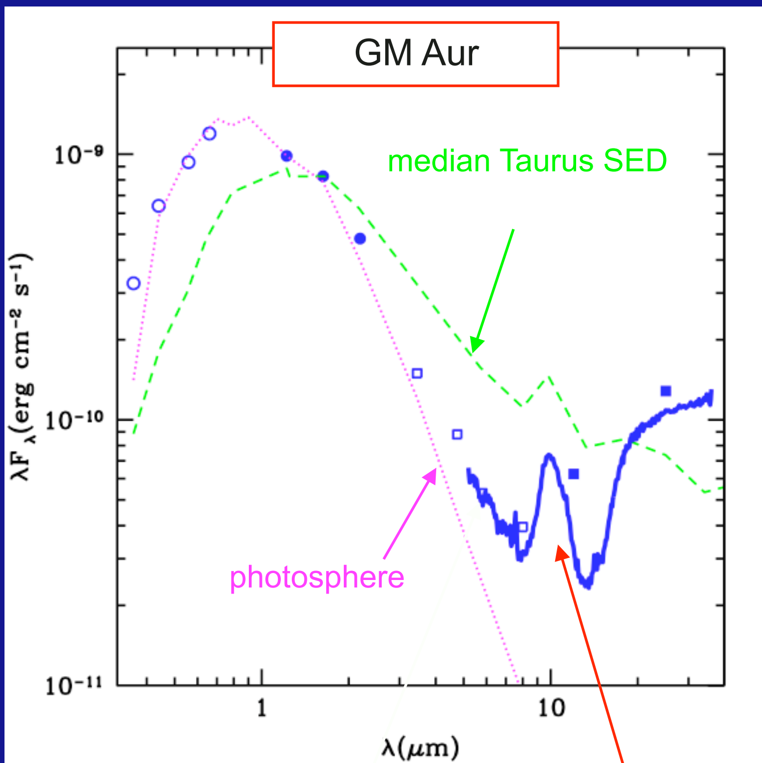
Disk frequencies decrease rapidly above 1 $M_\odot$



Lada et al. 2006

Disk evolution timescales much faster at higher masses (consistent with dM/dt increasing with M_*)

Transitional Disks: Optically Thick Disks with Inner Holes

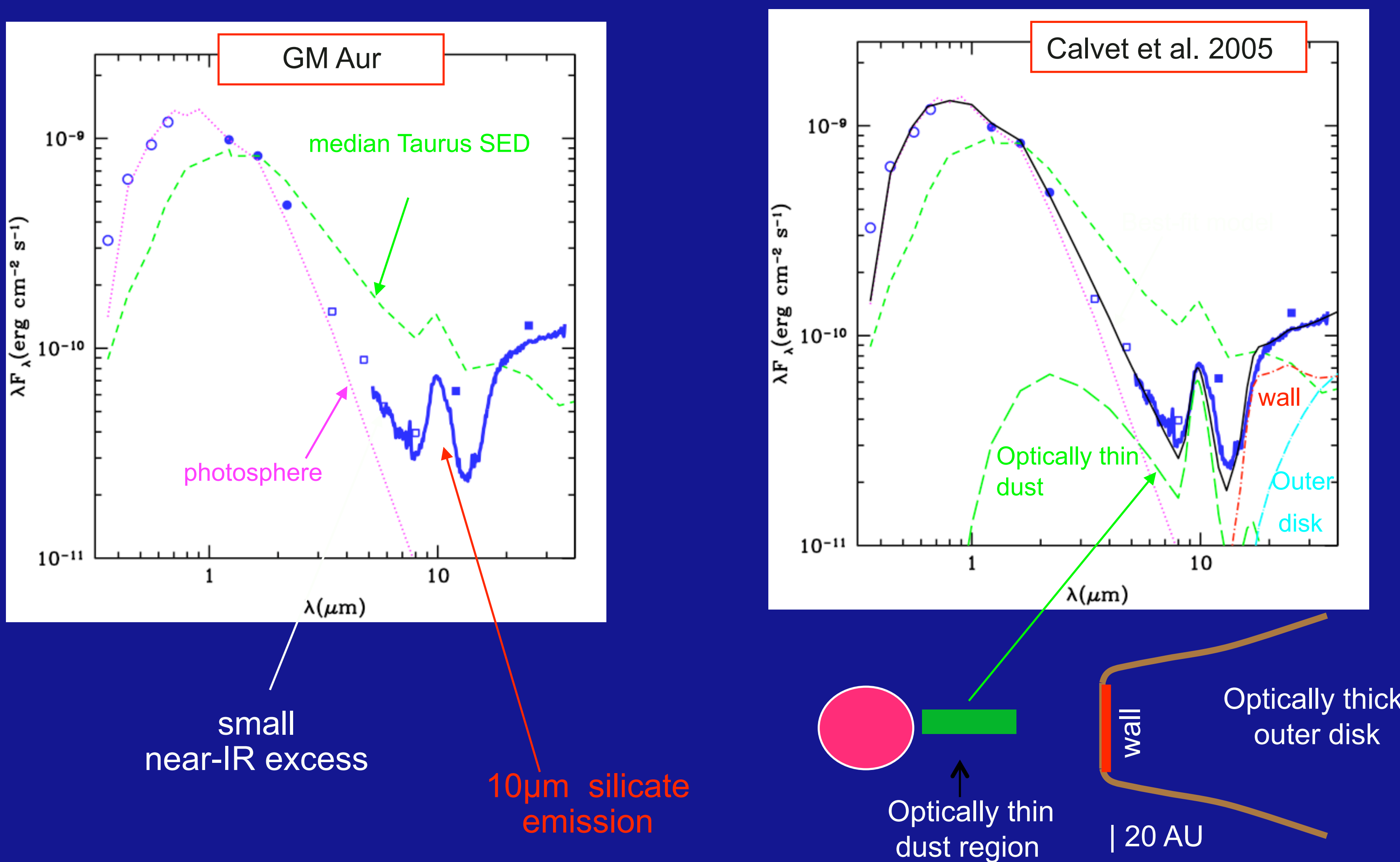


small
near-IR excess

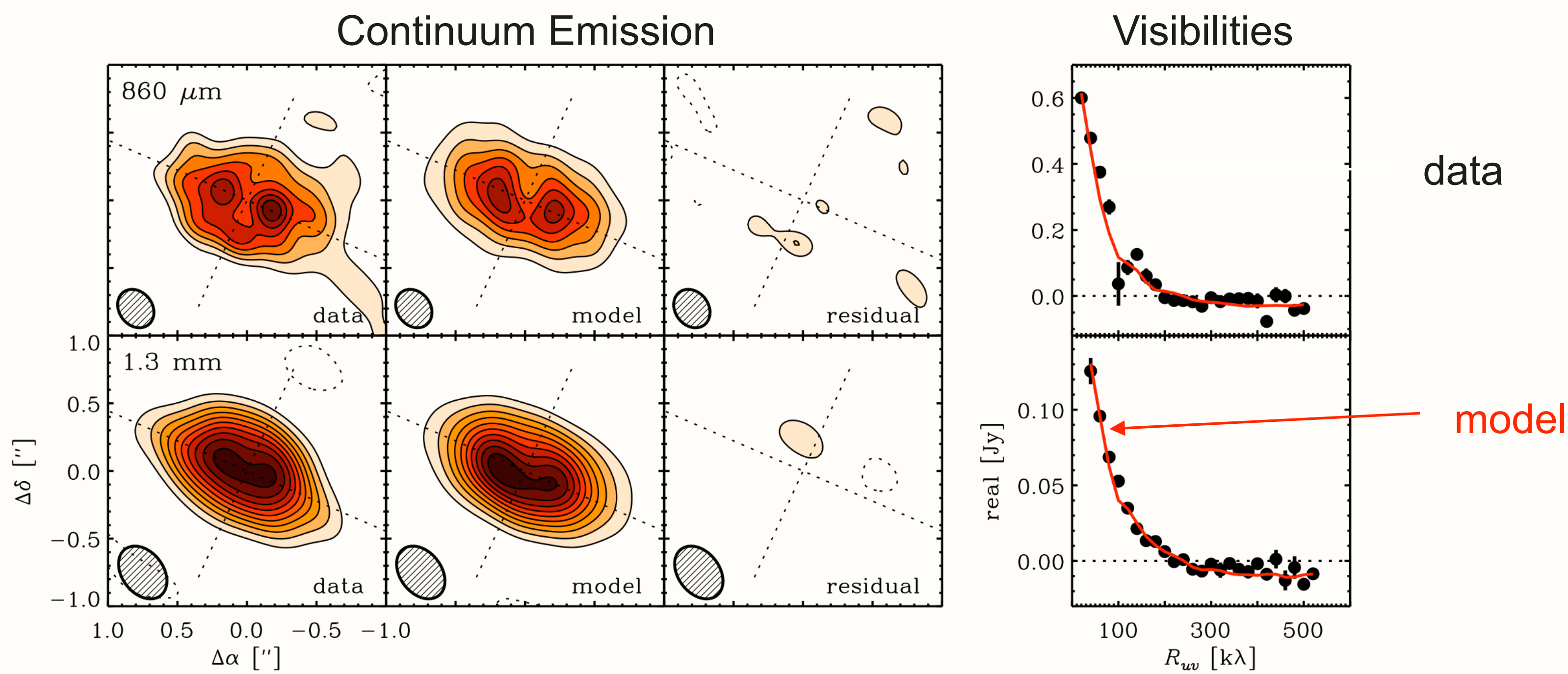
10µm silicate
emission

- SEDs show little or no emission at $\lambda < 8\ \mu m$
  - ~photospheric (+ little dust)
- SEDs show substantial emission at $\lambda > 20\ \mu m$
  - optically thick disk
- objects with NO inner excess ⇒ more likely binary clearing of inner disk (i.e., CoKu Tau 4)
- objects with some warm dust emission – and typically, inner disk gas (CO) and accretion onto central star – more likely to be planets(?)

Transitional Disks:
Optically Thick Disks with Inner Holes



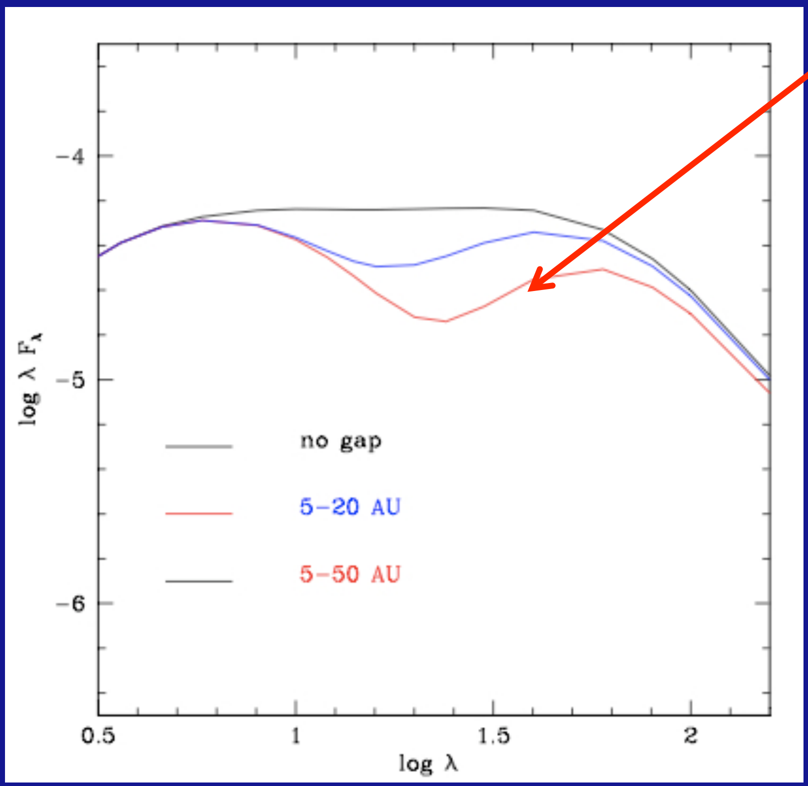
SMA Millimeter Imaging of GM Aur's Hole



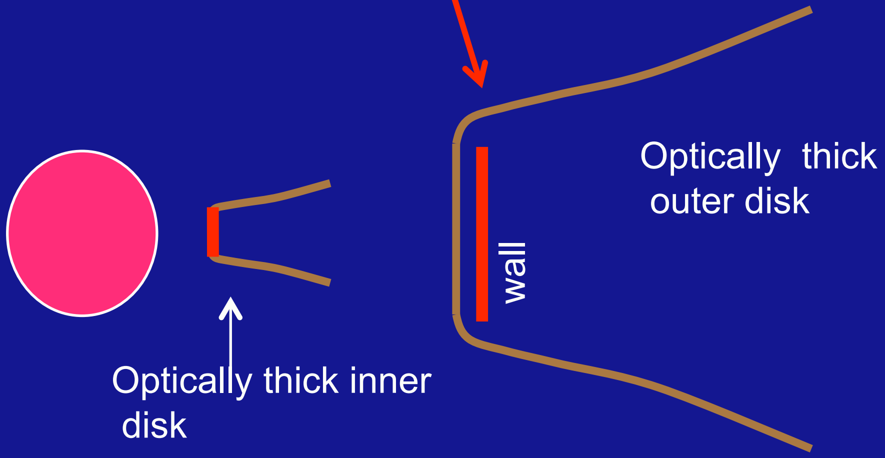
inner hole ~ 24 AU

Hughes et al. 2009

gaps must be BIG –
more like holes – to be
detected in SEDs

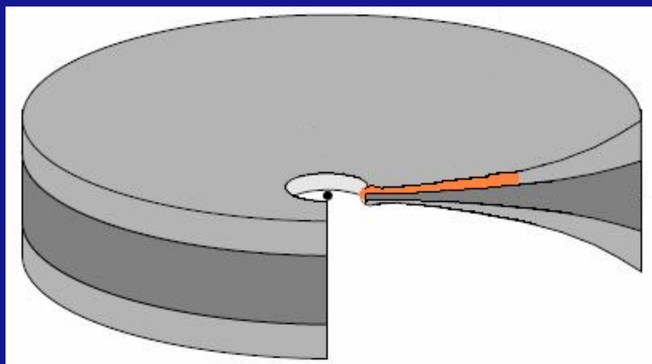


toy model ignores wall
heating, which fills in SED

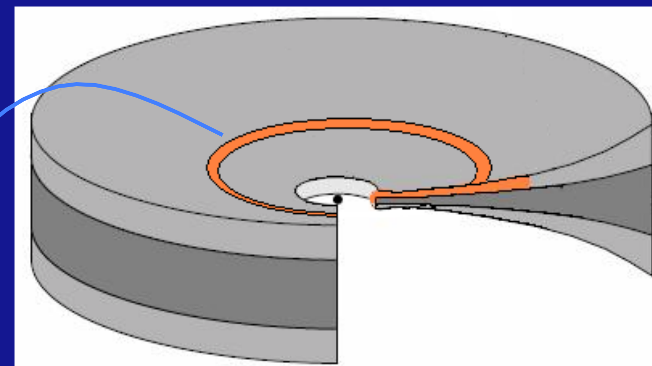


interpretation made more complicated (or less obvious)
by presence of silicate emission

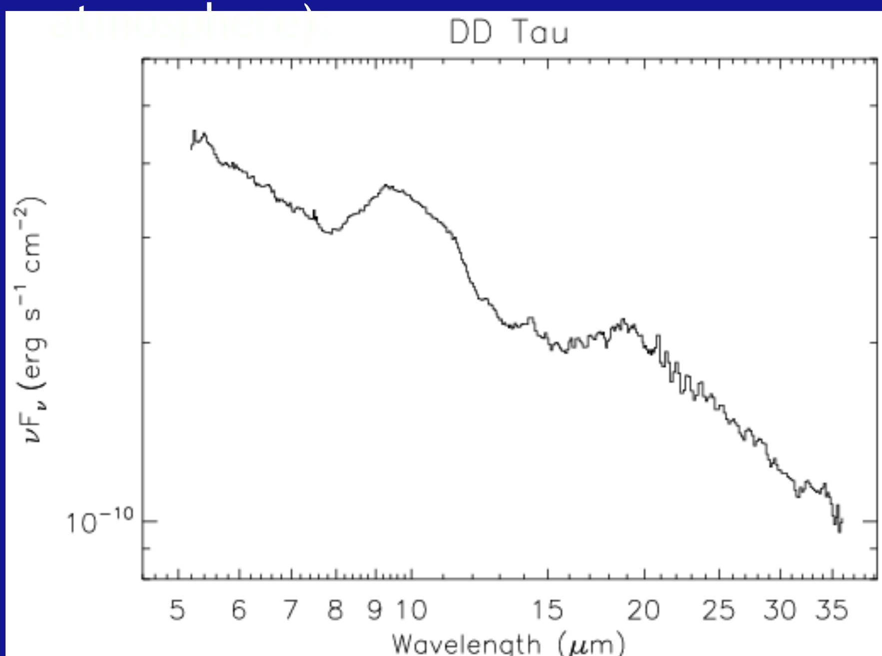
Formation of Disk Gaps

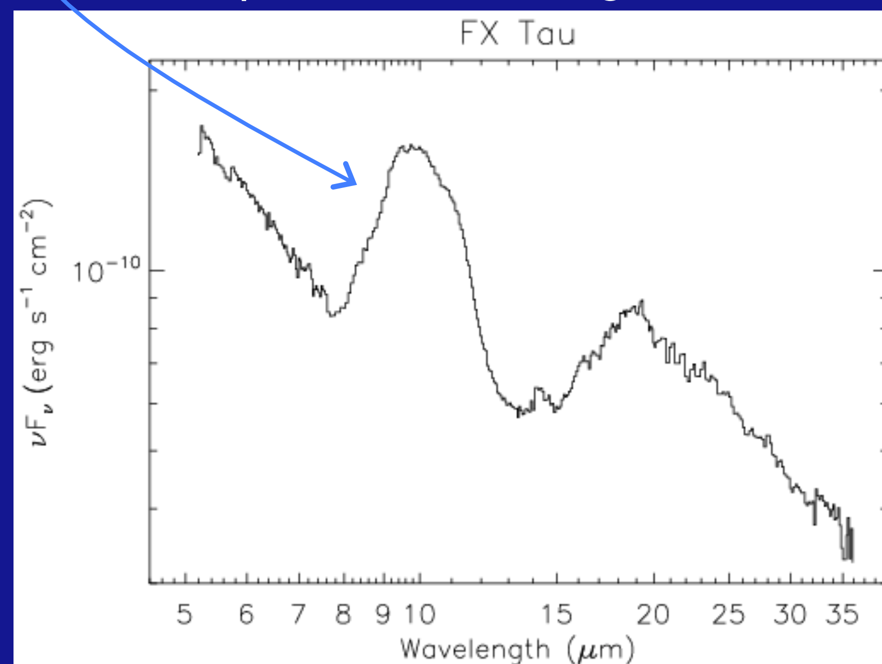


full accretion disk (10 μm silicate feature generated in disk

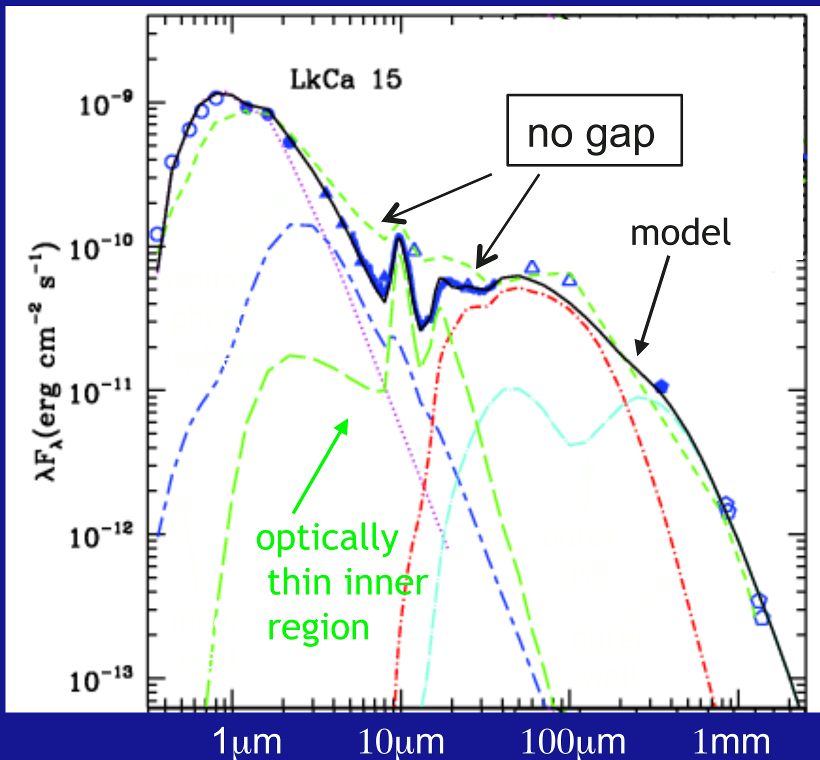


inner disk gap forming, filled with optically thin dust that increases the 10 μm feature strength:





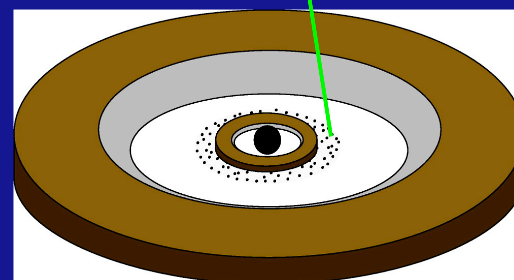
“Pre-Transitional Disk”: LkCa 15



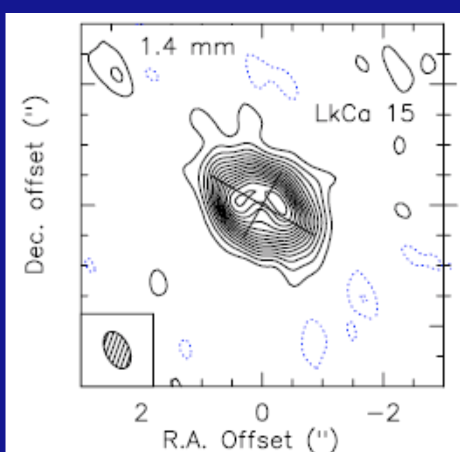
inner wall: 0.12-0.15 AU

outer wall: 56 AU

optically thin inner region: 0.15-5 AU, 4×10^{-11} $M_\odot$

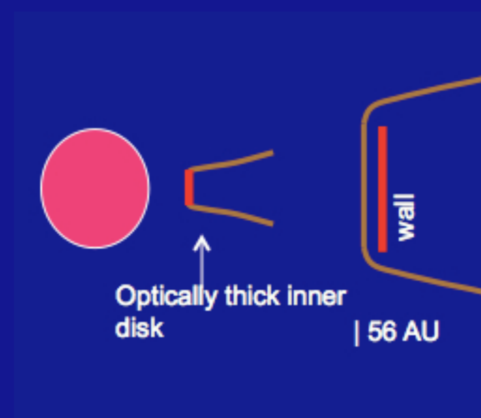


Espaillat et al. (2007b)



1.4 mm image
⇒ ~ 50 AU
inner cavity

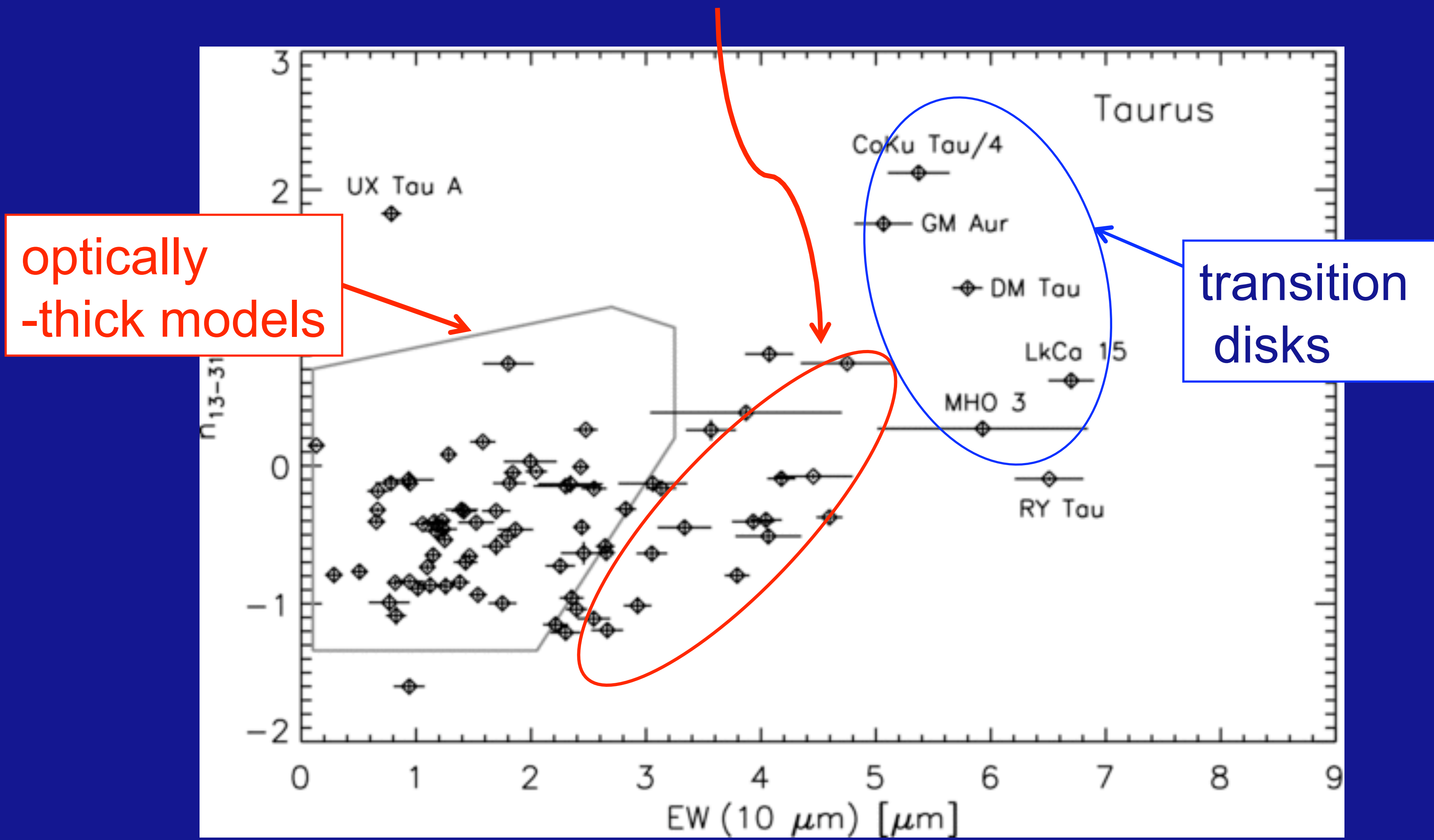
Pietu et al. (2006)



near-infrared excess fit with a 1600 K blackbody ⇒ inner wall emission

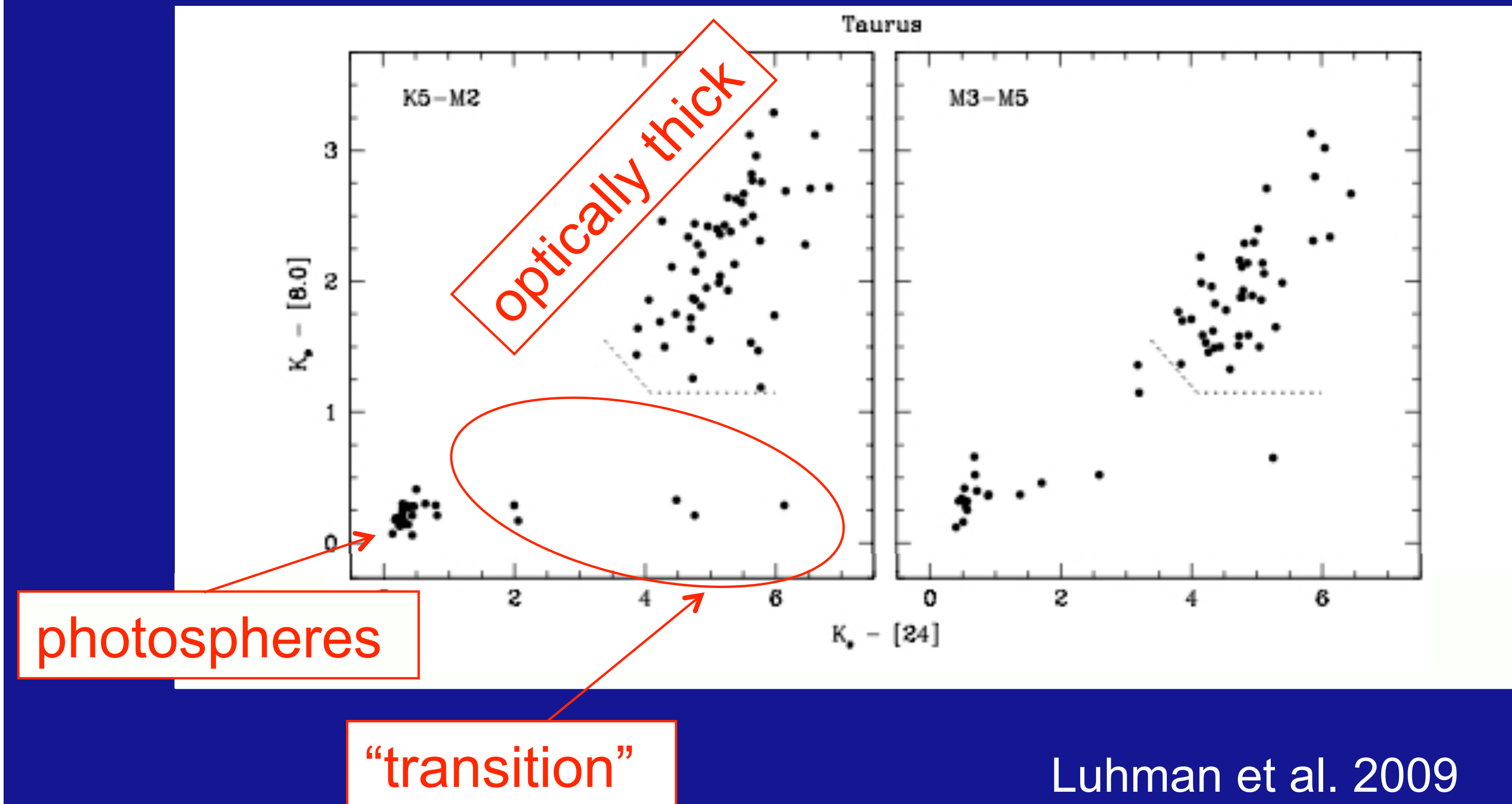
Espaillat et al. (2008)

model problem or incipient clearing?



Furlan et al. 2009

IRAC + MIPS surveys: statistics of transition

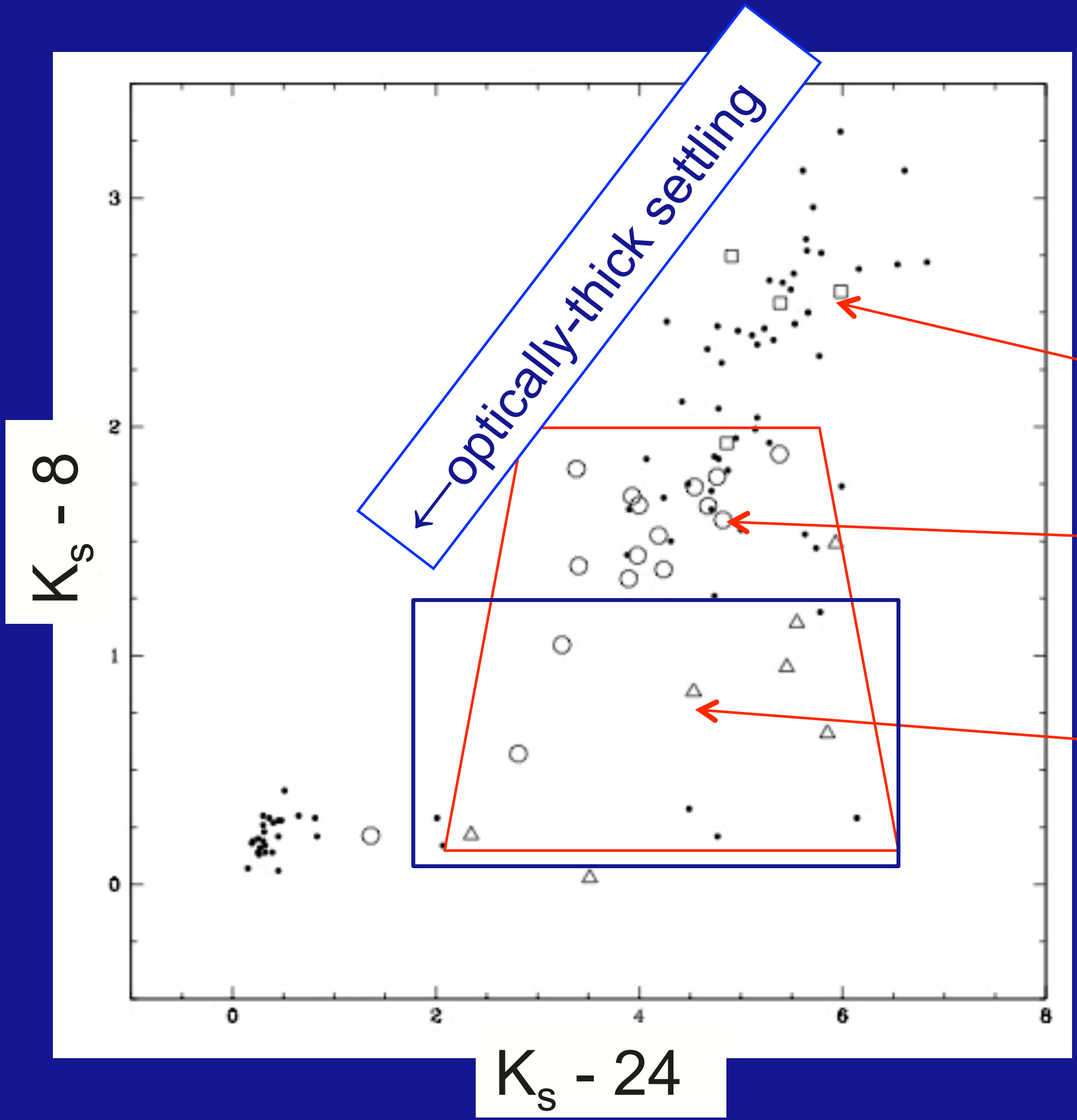


Luhman et al. 2009

so-called "transition" disks ≈ 10-15% of optically -thick disks: infer thick⇒thin timescale is short

- not surprising, *except over wide range of radii*

Are timescales for “transition” long?



dots: Taurus K5-M2: Luhman et al. 2009

from Currie et al. 2009:
open squares: N2362 “primordial” disks

open circles: “evolved” / homologously settled

open triangles: N2362 “transitional” disks

RED: Currie et al. “transitional disks”

BLUE: everyone else

We find that the disk statistics of N2362 (5 Myr) aren't very much different than Taurus (≈ 2 Myr) WHEN THE SAME CRITERIA are used for "transitional disks".

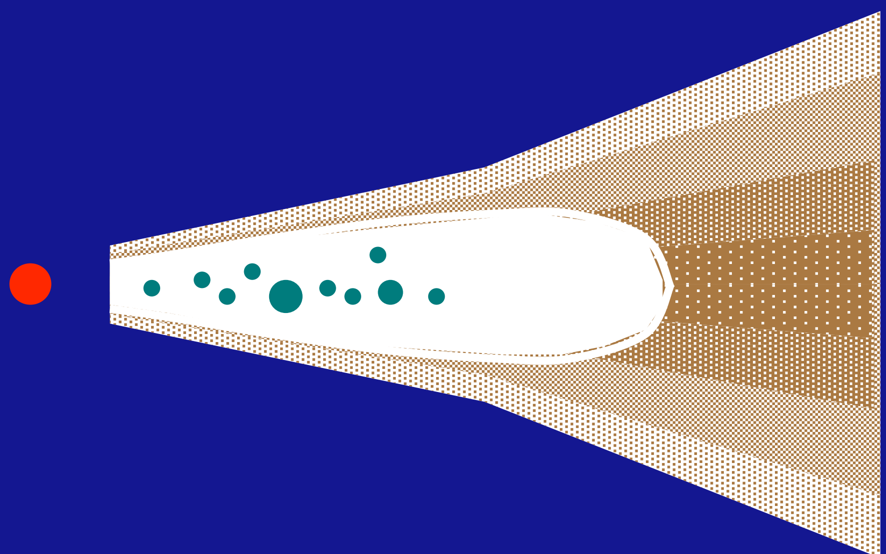
Should "homologously depleted" or "primordial evolved", optically-thick disks be counted as "transition" objects?

For: settling does increase with time (as previously known)

Against:

- settled (flat) disk ≠ "transition" disks with *flared* (i.e., not very settled) outer disk *(Currie et al. also say different evolutionary path)*
- we *cannot* tell if optically thick, geometrically flat disks are "homologously depleted"
- "primordial" disks... are there any?? (regenerate small dust?)

Substantial evolution – gap clearing, formation of large solid bodies – is probably occuring “right under our noses” at ages as low as 1 Myr. In this sense “evolution” is “slow” – Myrs, *in agreement with overall clearing timescales.*



BUT: making fine distinctions via SEDs of optically-thick disks is dangerous:

settling not necessarily homologous

and settling ≠ “transition”

Less confusion, safer if we only distinguish optically thin vs. thick (+ maybe “pre-transitional”?)

Summary

•Disk frequencies (dust emission) not very different from 3μm ⇒ 24μm ⇒ evolution similar from 0.1 to ~ 10 AU

• decay time for optically thick emission ≈ 3 Myr (but varies by 10x)

• > 1 M(sun) stars – faster disk evolution

• Small dust in upper disk layers: turbulent support or regeneration?

• Evidence for dust settling/growth, increasing with age (depletions ~ 0.1-0.001)

•"Transitional disks (holes, gaps)" ~10% @ 1-2 Myr

•⇒ We only detect **BIG** gaps... some evidence for smaller holes ("pre-transitional disks")

• Massive inner disks needed to explain star formation and FU Ori outbursts...