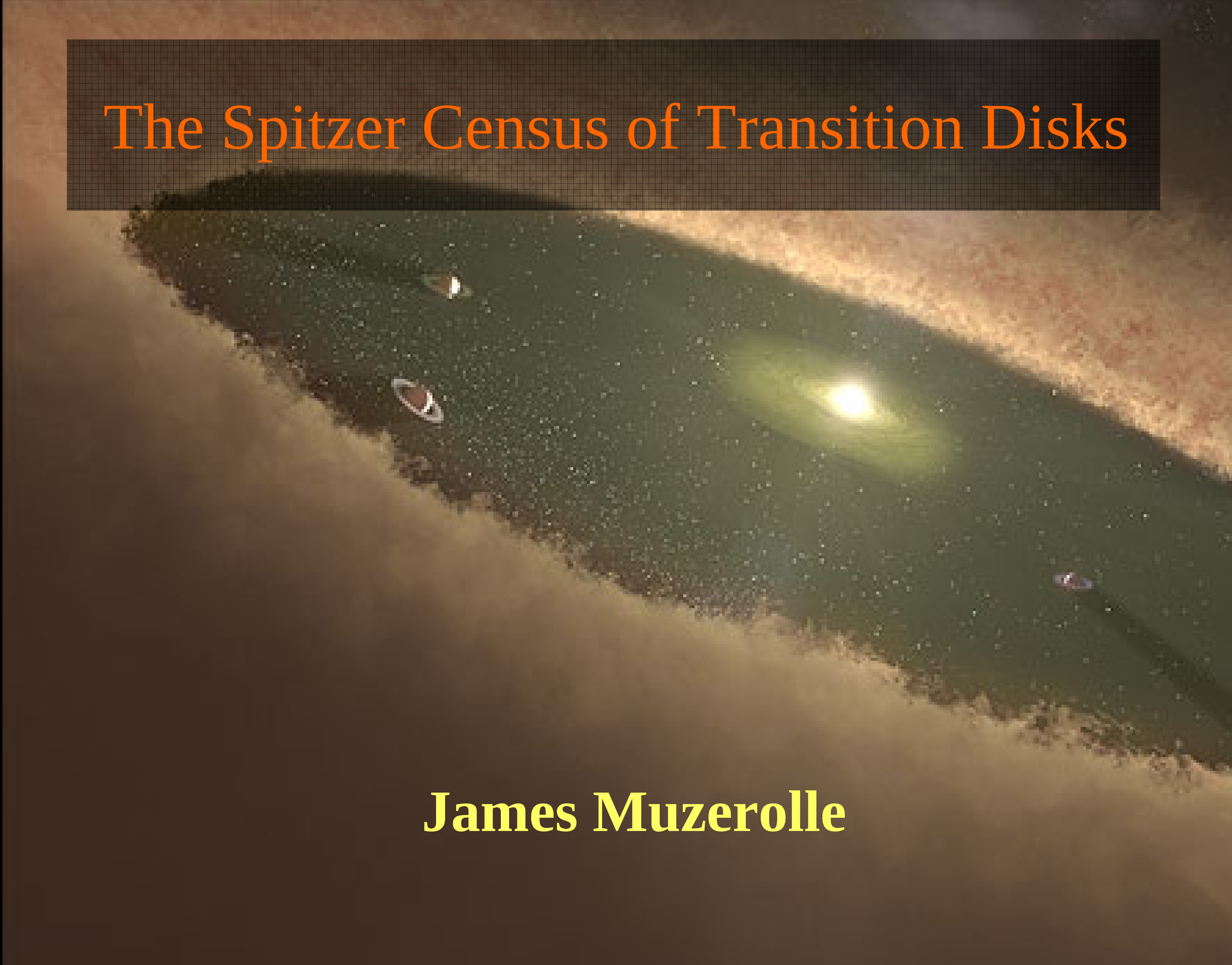
The Spitzer Census of Transition Disks



James Muzerolle

What is a transition disk?

- Optically thick gas-rich disk with AU-scale optically thin or evacuated inner “hole”
  - but can include other types of “evolved” protoplanetary disks!

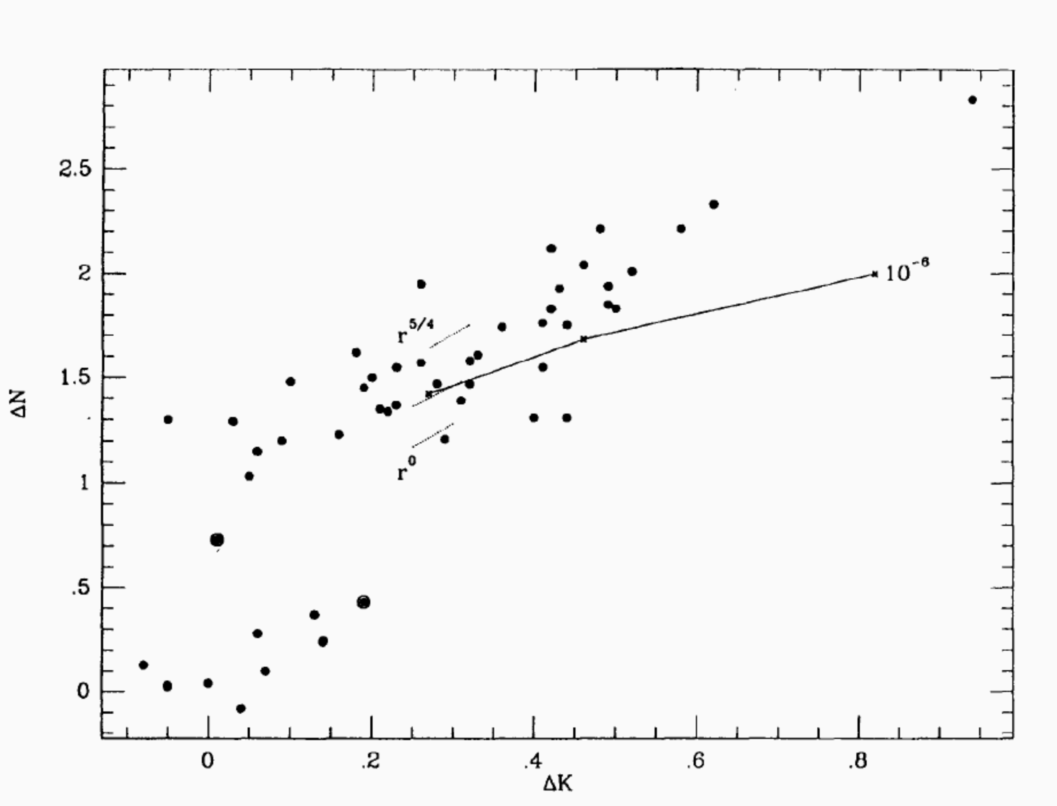
discovery

- Strom et al. (1989) [IRAS]
  - "The presence of IR excesses for λ > 10 μm… and the absence of excess emission at λ < 10 μm… may diagnose *disk clearing* in the inner regions of the disk. If so, these observations may represent the first astrophysical evidence of disks *in transition* from massive, optically thick structures... to low-mass, tenuous, perhaps post-planet-building structures."

- Skrutskie et al. (1990)

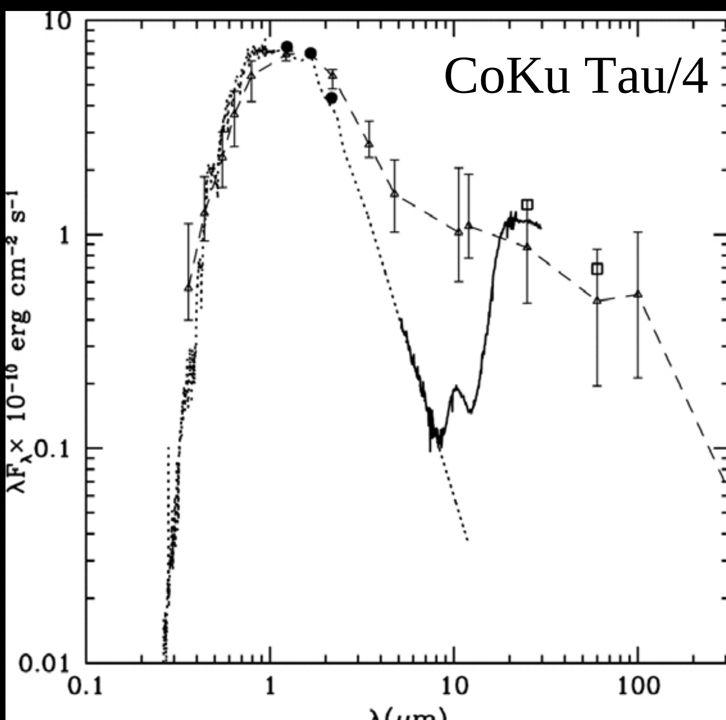
10% of disks (3/33) are optically thin at 10 μm, optically thick at 25 μm

transition time ~ **0.3 Myr**

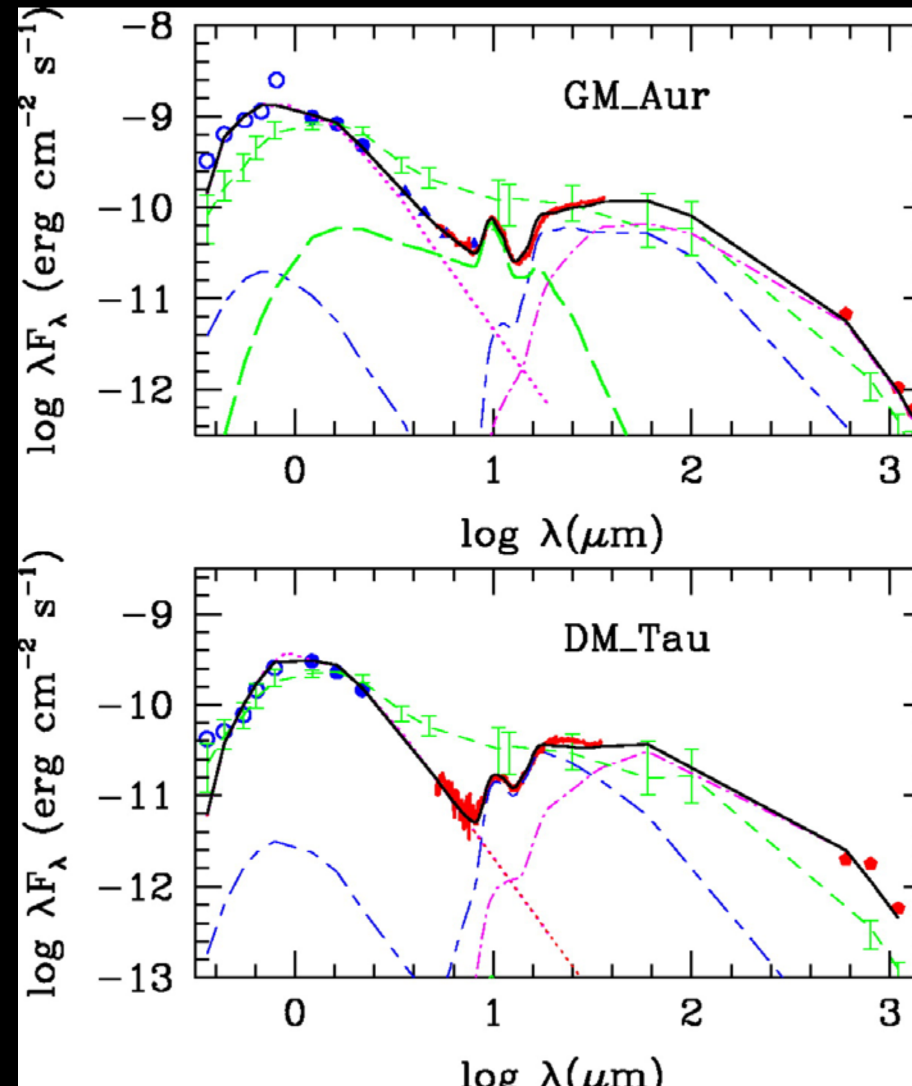


transition disks: *Taurus*

- dust holes ~2-24 AU
- 2/3 still accreting gas
- inner optically thin disk in GM Aur
- CoKu Tau/4 is a circumbinary disk
  (Ireland & Kraus 2008)

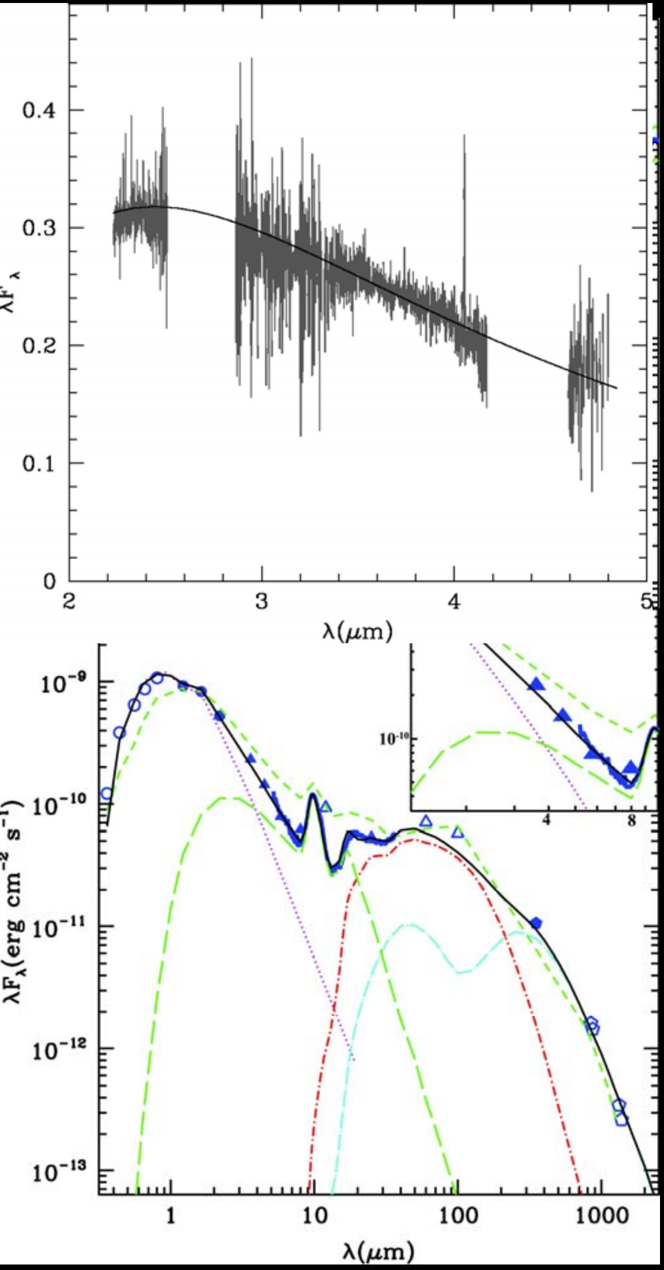


D'Alessio et al. 2005

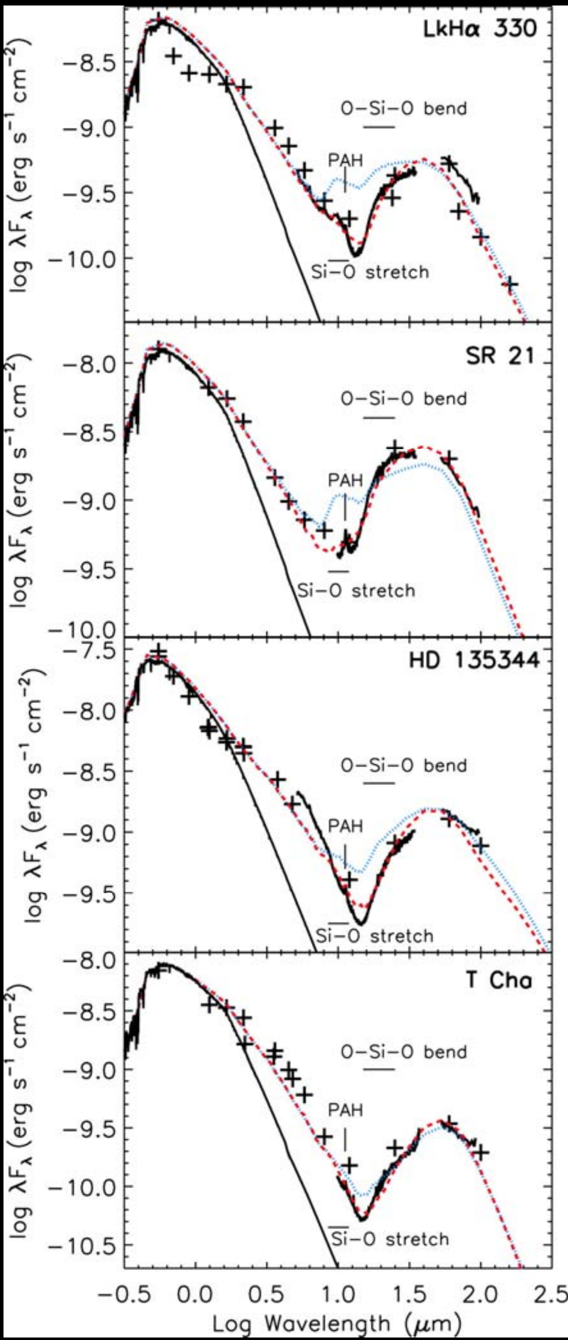


Calvet et al. 2005

disks with large gaps

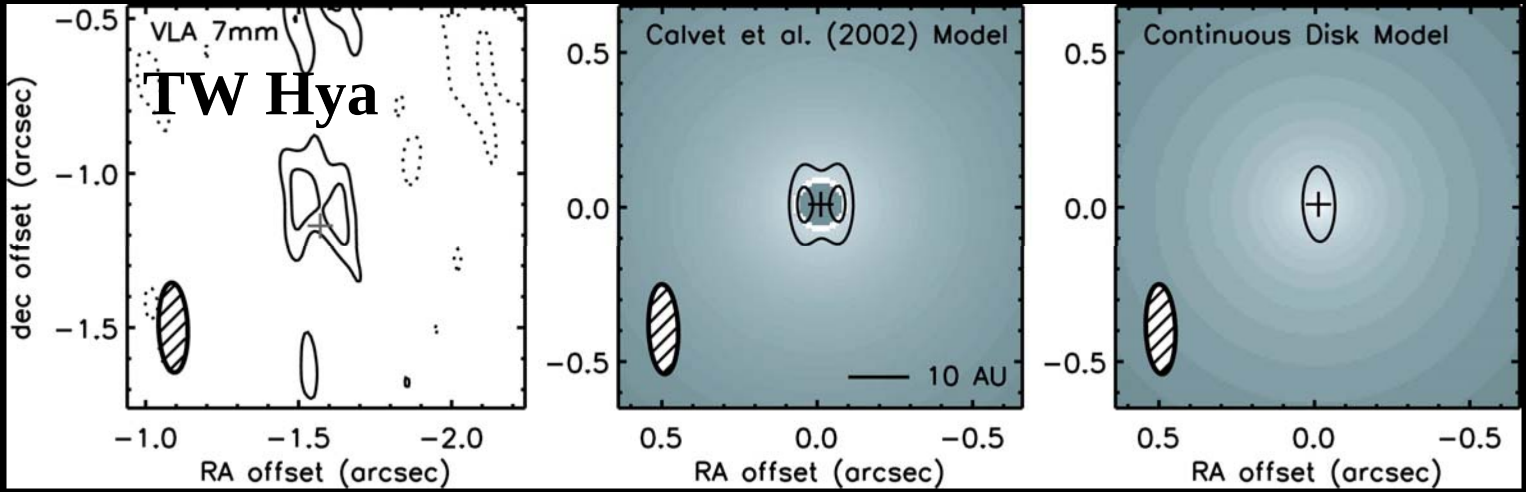


- significant flux deficit at 10-20 microns, but some remaining NIR excess
  - large gap with opt. thick inner (~0.1 AU) and outer (10-50 AU) disk components?
- "pre-transitional" or "cold" disks
- verified for LkCa 15 (see poster #91 by Catherine Espaillat)



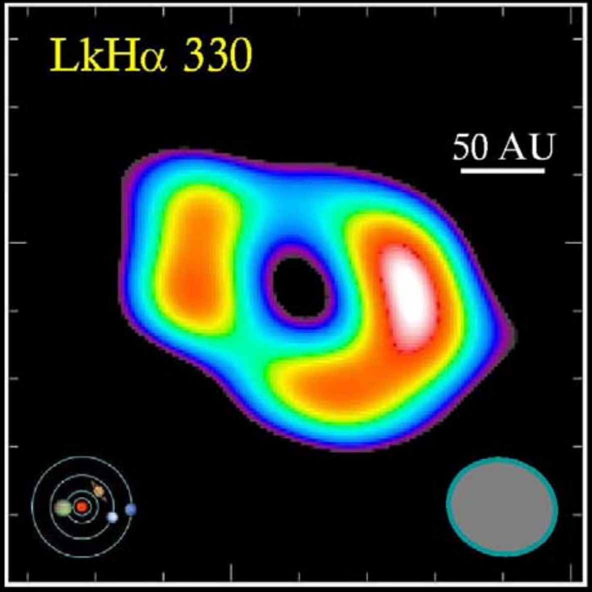
Espaillat et al. 2007, 2008

Brown et al. 2007



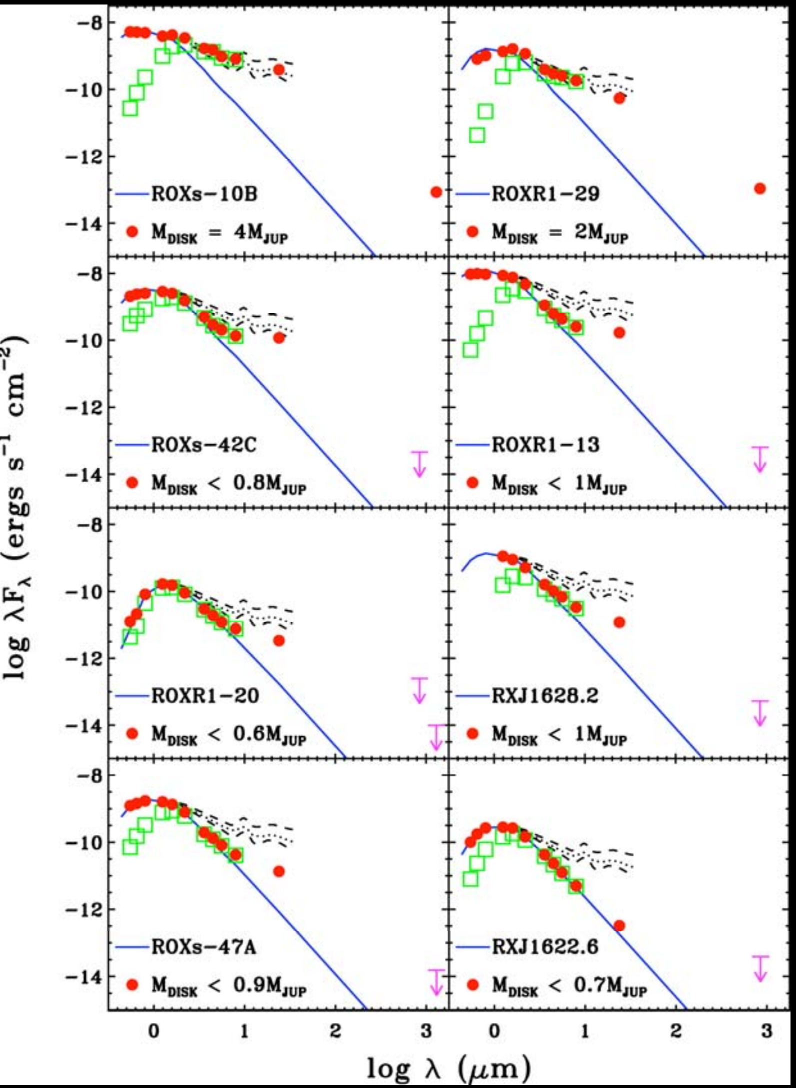
Hughes et al. 2007

spatially-resolved inner holes

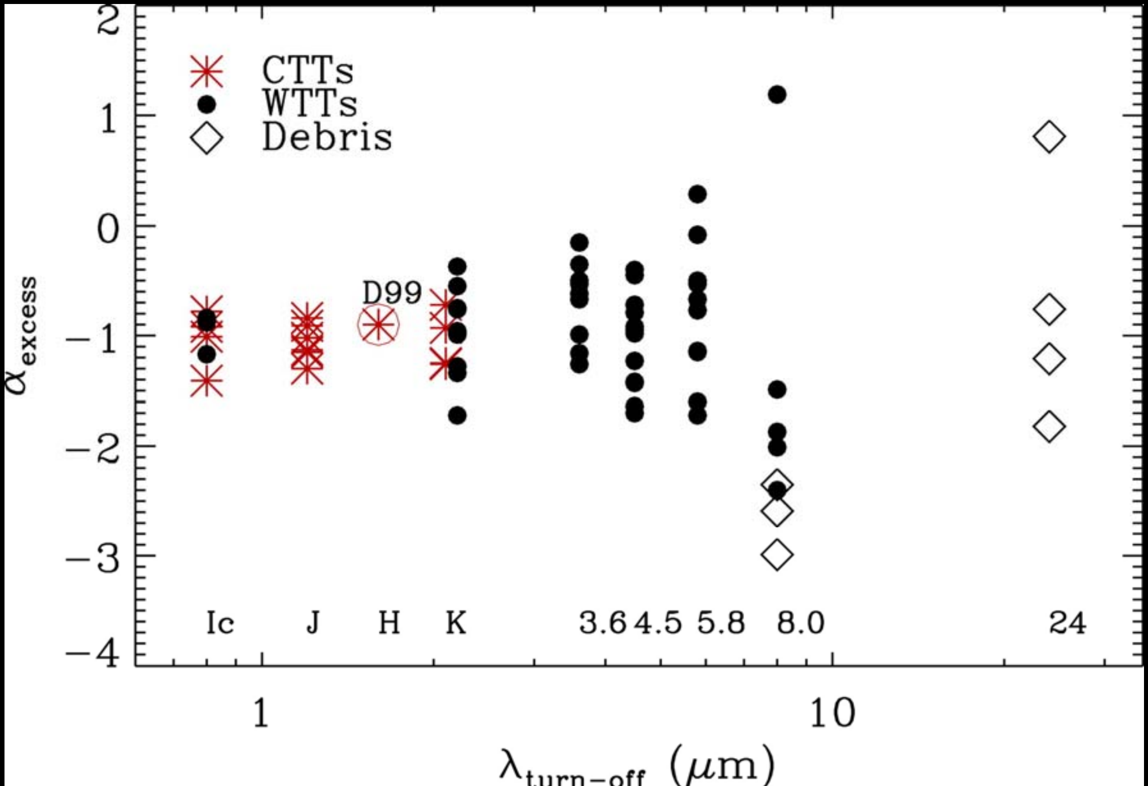


Brown et al. 2008

c2d survey: WTTS diversity

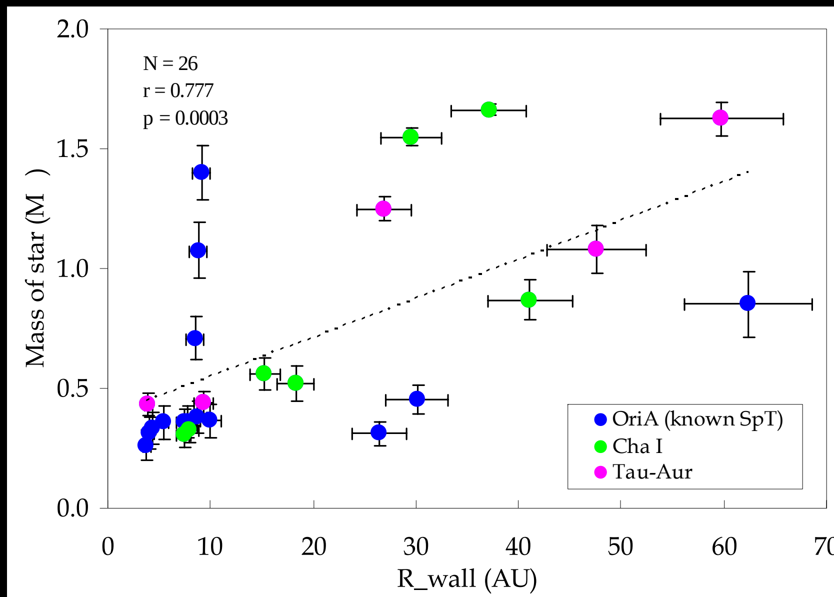


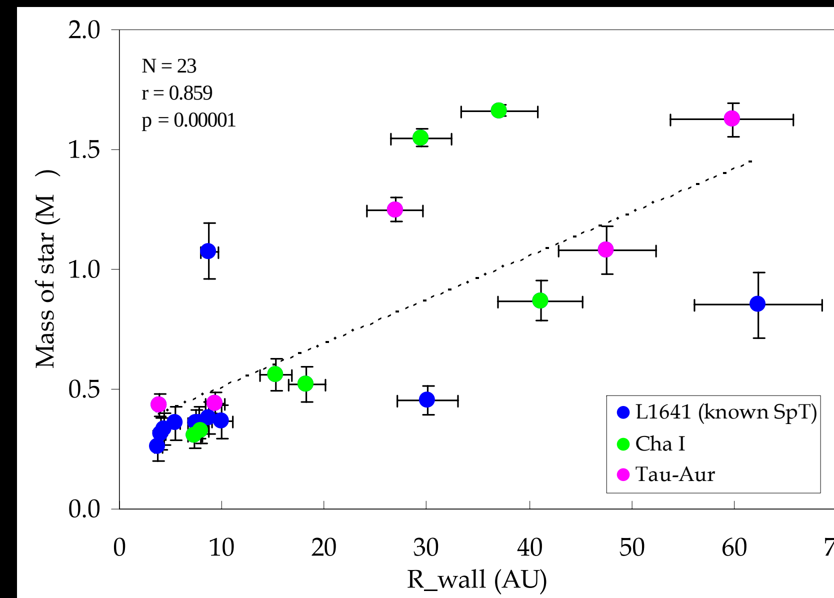
- Survey of > 230 “WTTS” (Cieza et al. 2007)
  - wide age range, some may still be accreting?
- wide range of SED shapes
- turn-off wavelength vs. spectral slope trends indicate multiple evolutionary pathways?

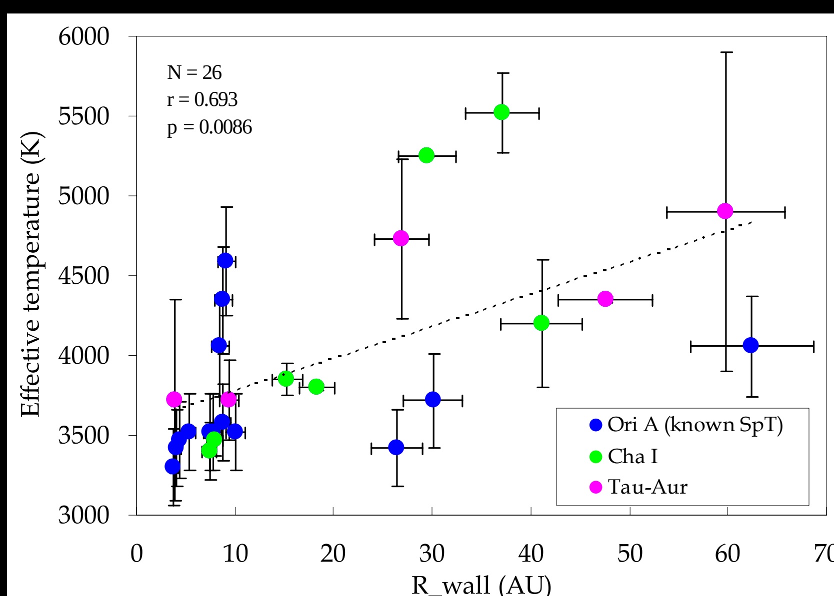


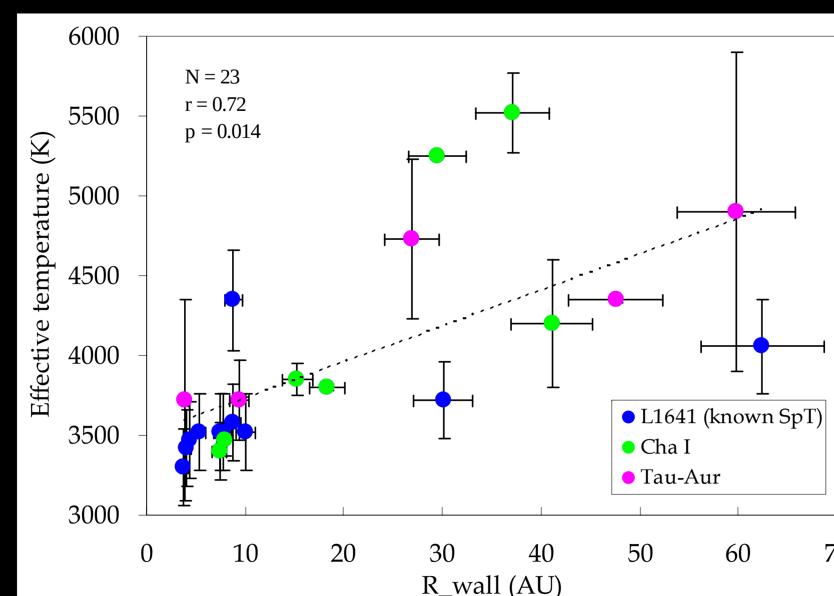
Statistical trends: Cha I, Orion IRS study

see also poster #92 by Kyoung Hee Kim



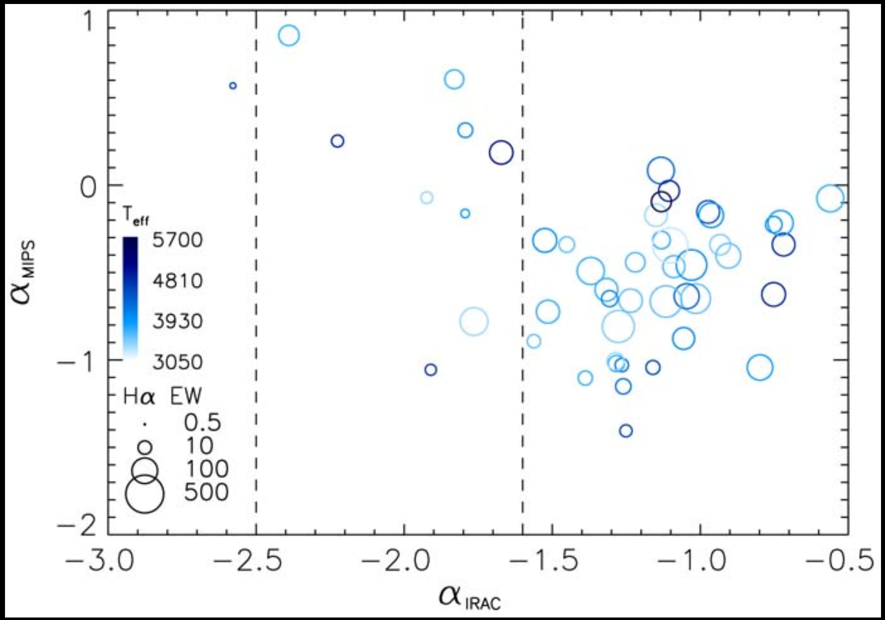


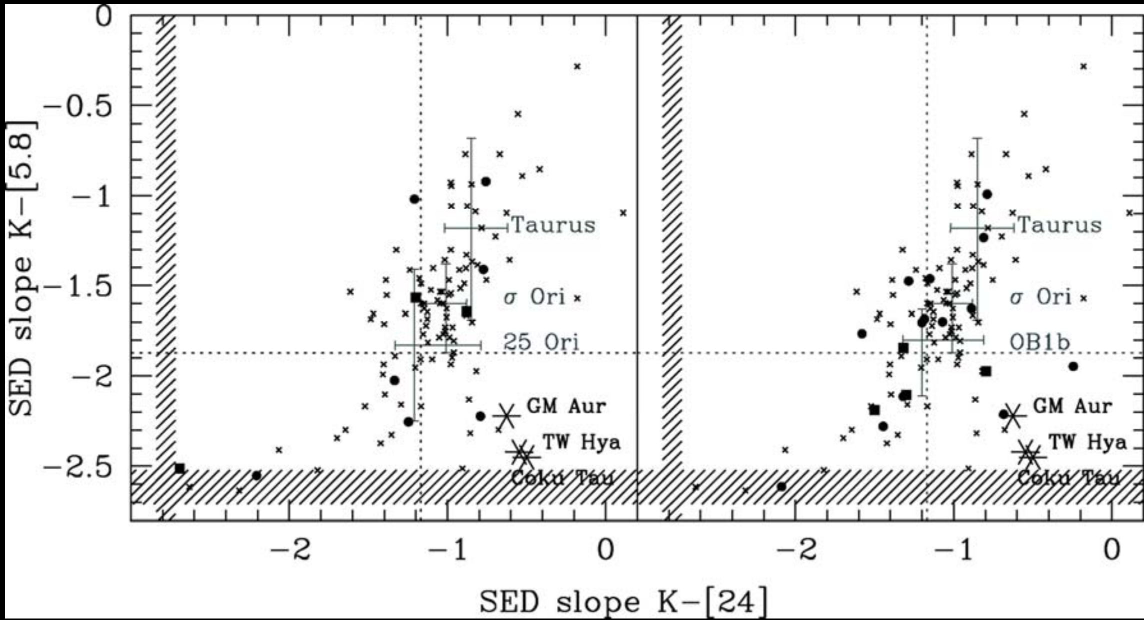




Spitzer statistics: source selection

- candidates from short, long-wavelength spectral slopes





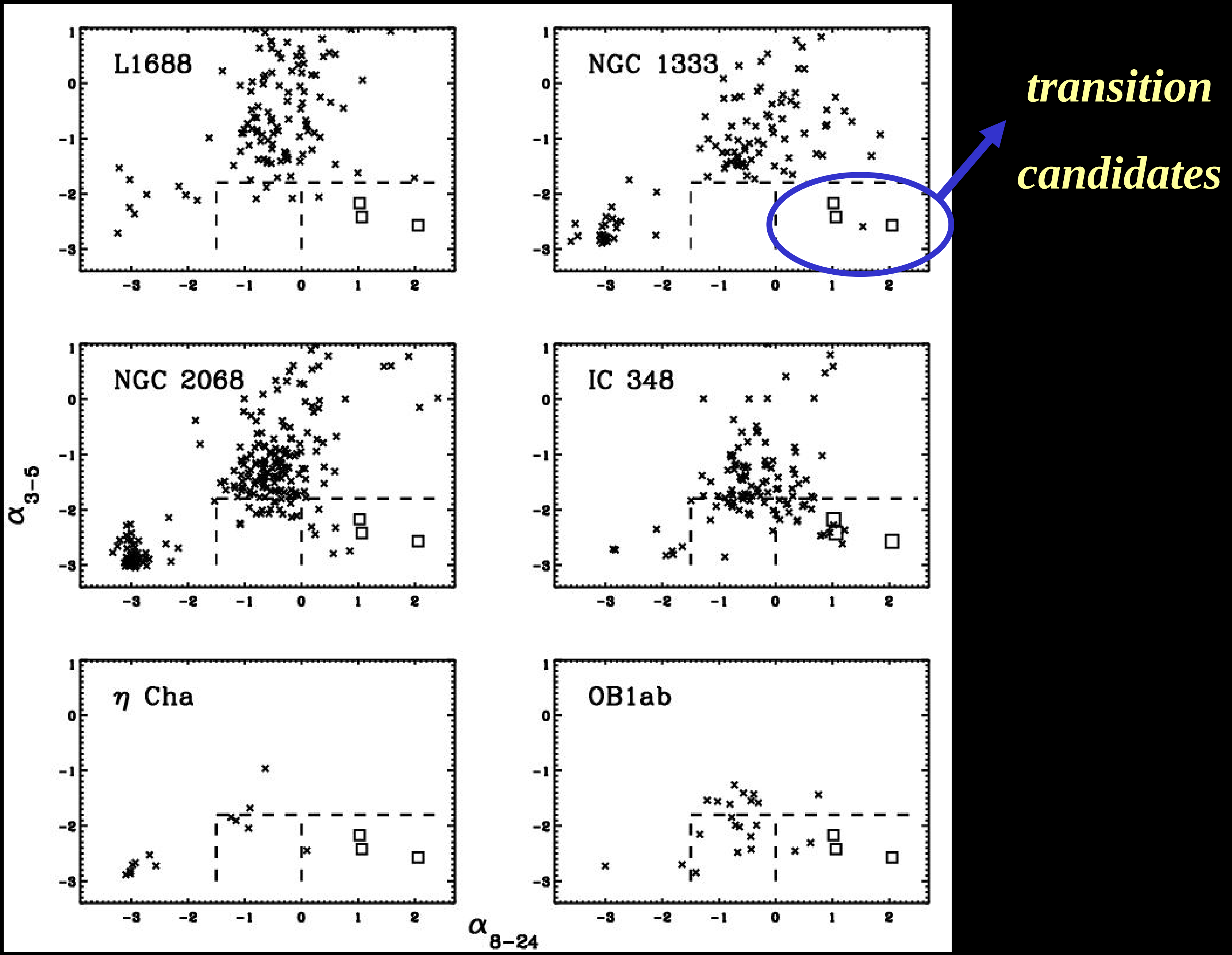
NGC 2068/2071, t~2 Myr

Flaherty & Muzerolle 2008

Orion OB1ab associations, t~5, 10 Myr

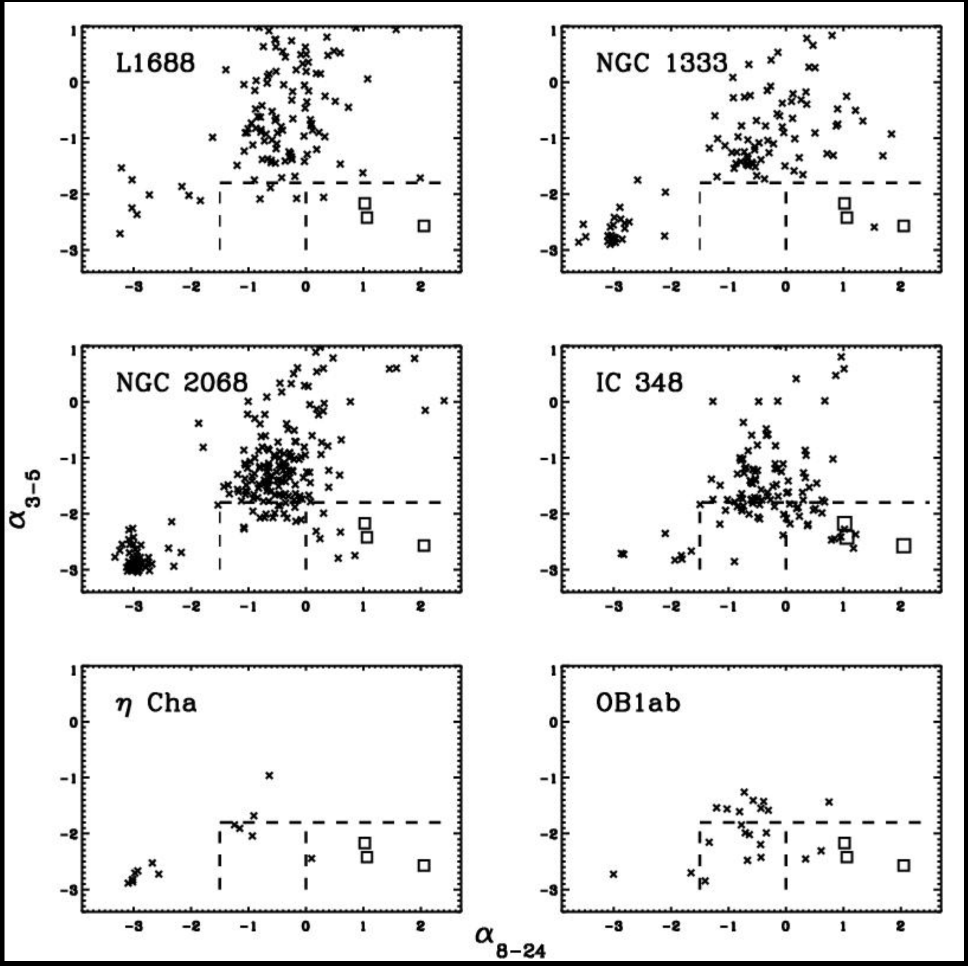
Hernandez et al. 2007

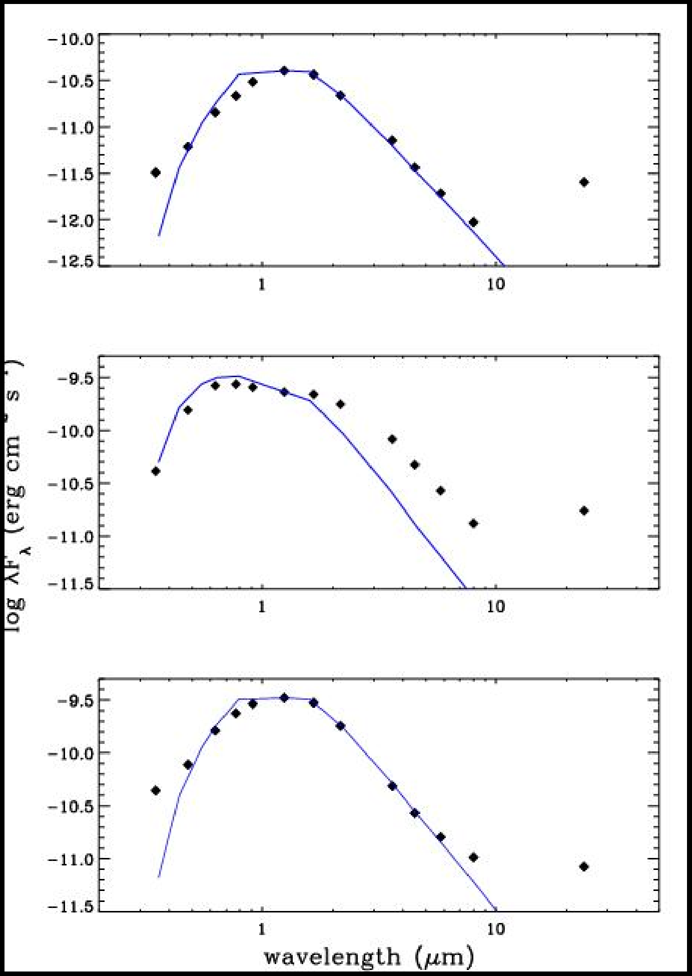
Spitzer statistics: clusters/associations



Transition candidates

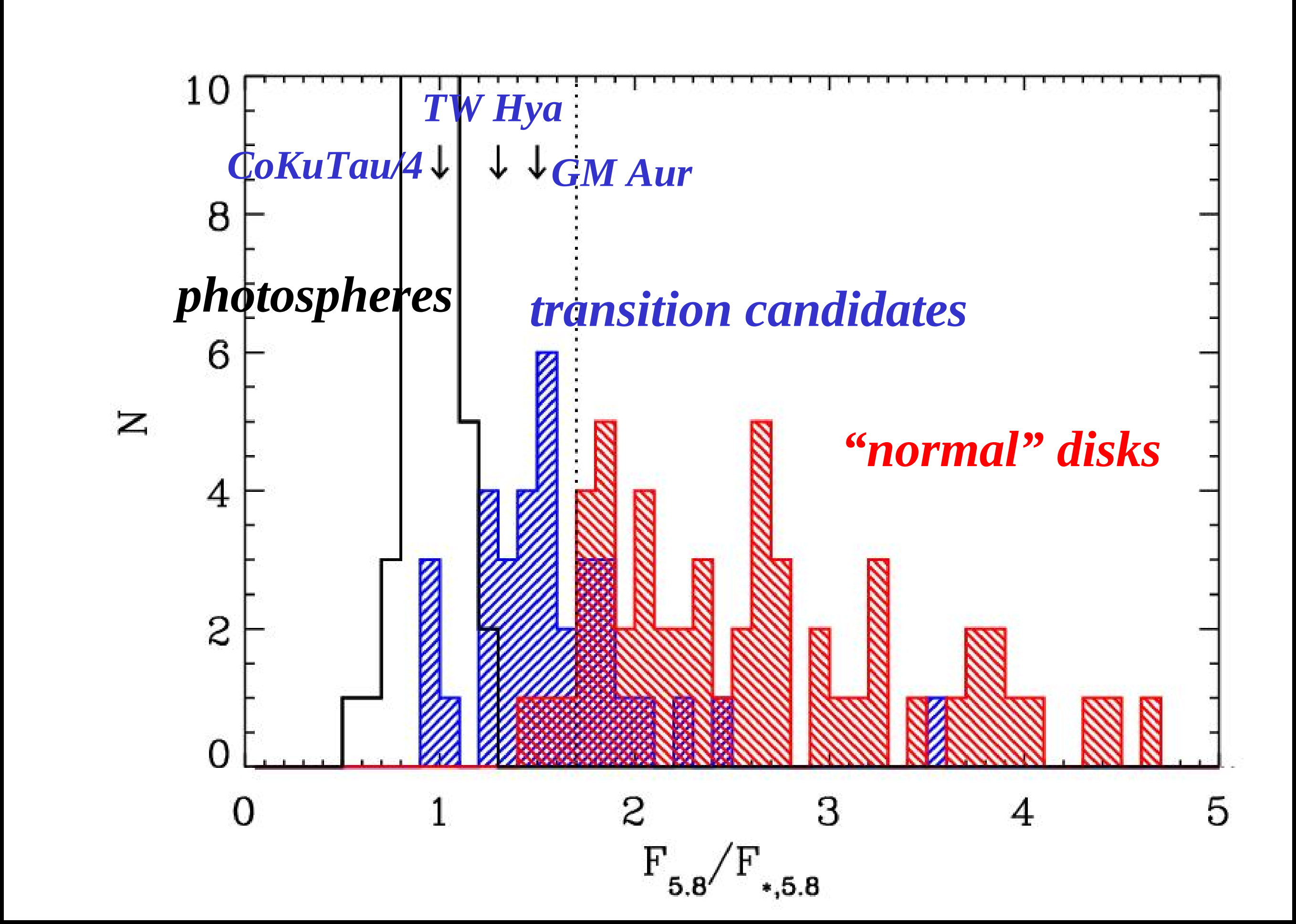
- 3 flavors:
  - weak/zero IRAC excess, strong MIPS-24 excess (canonical transition disk)
  - moderate IRAC excess, strong MIPS-24 excess (pre-transition disk)
  - weak/zero IRAC excess, weak MIPS-24 excess (“weak” or “evolved” disk)





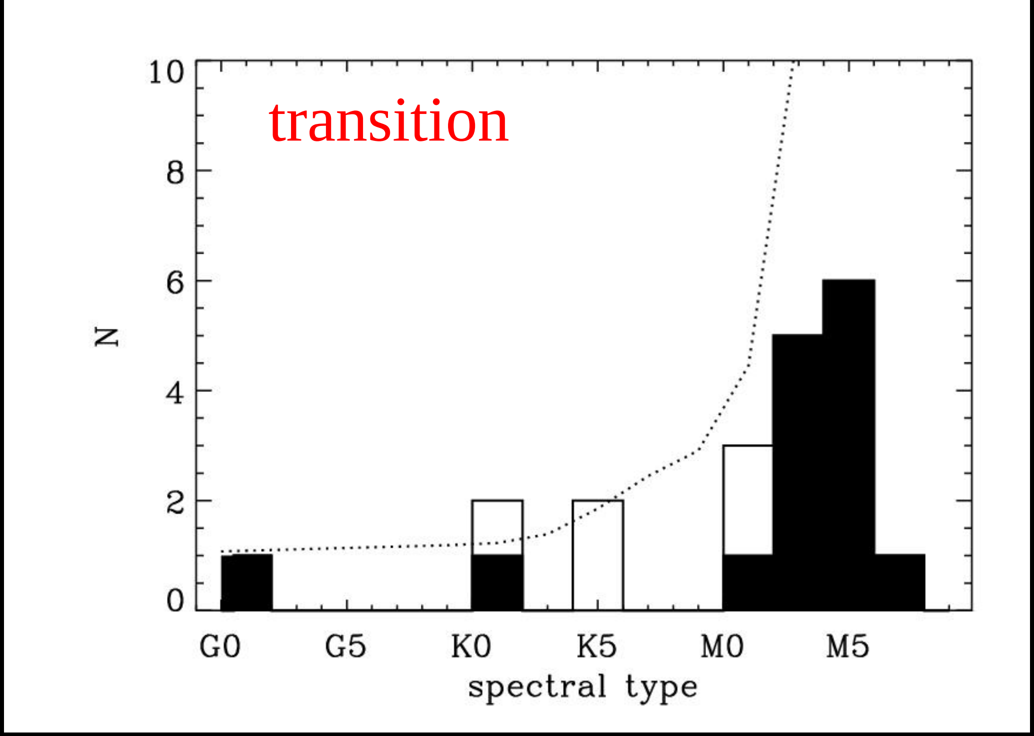
Transition candidates

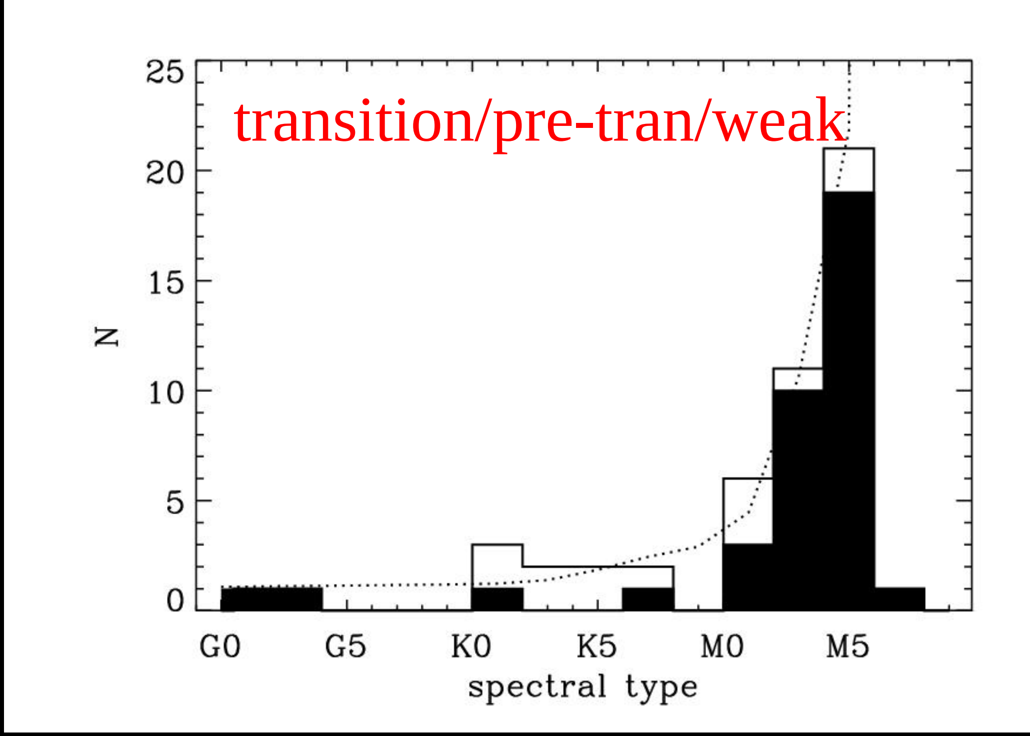
- cull excess sources by measuring 5.8 flux excess relative to expected photospheric emission



Muzerolle et al. 2008

Spectral type distribution



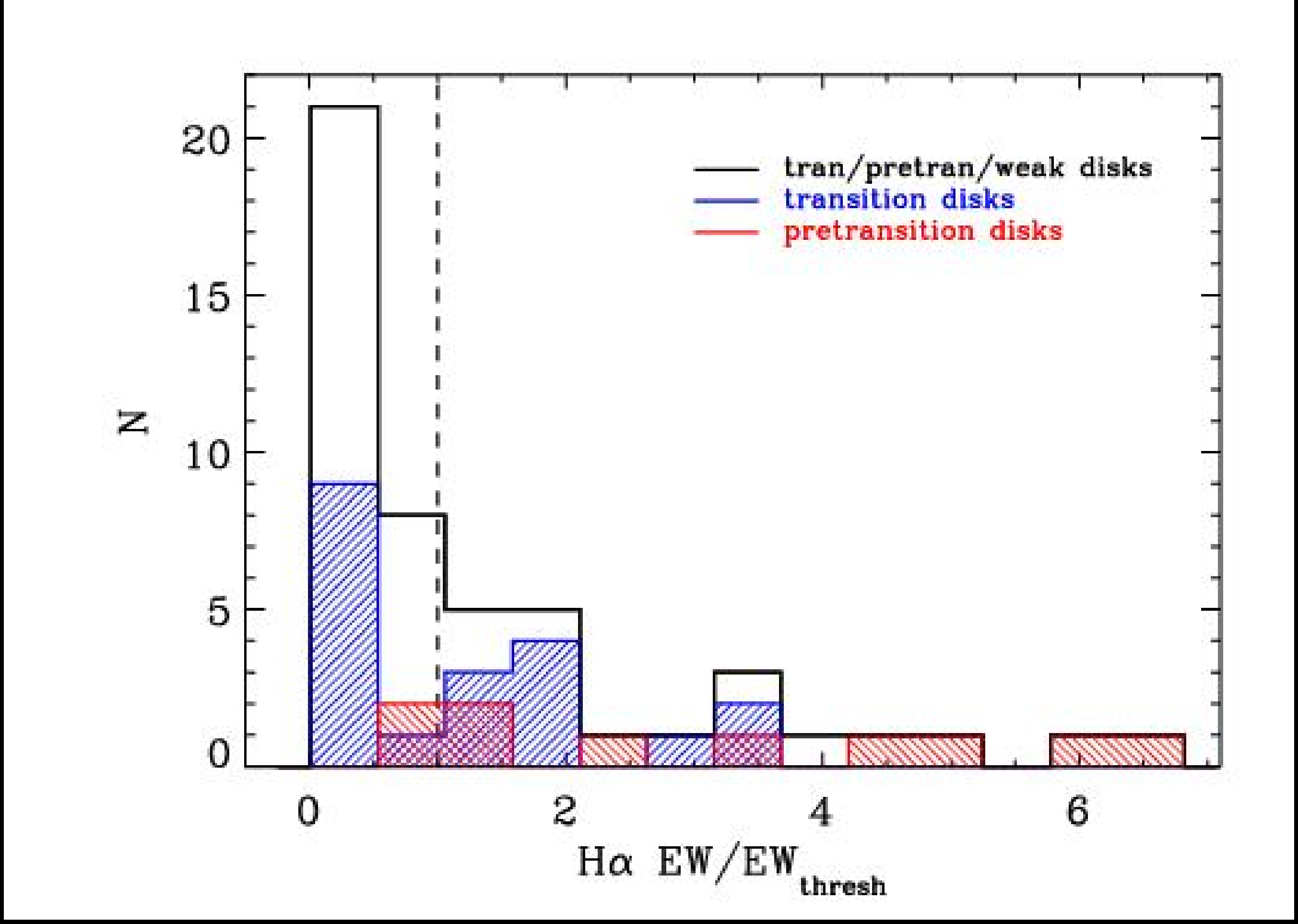


Muzerolle et al. 2008

transition disks less frequent around M stars?

Accretion activity

- Use EW(Ha) as a *rough* tracer
- Percentage of disks that are actively accreting:
  - 60% (transition)
  - 80% (pre-tran)
  - 20% (weak/evolved)



Muzerolle et al. 2008

Age trend

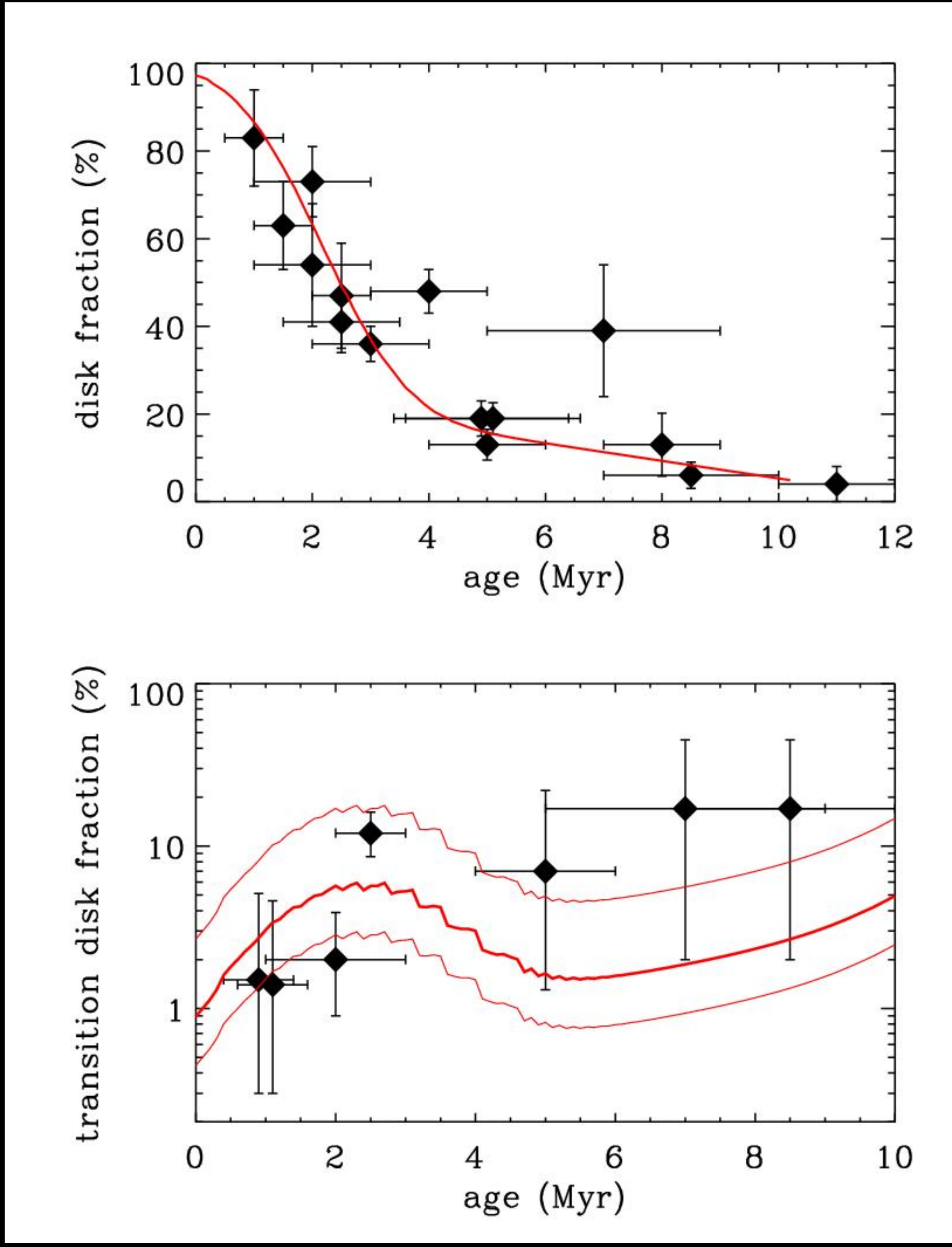
- Transition phase appears even at t <~ 1Myr

  ~1% of stars

  → fast? $10^4 - 10^5$ yrs

- fraction increases with age

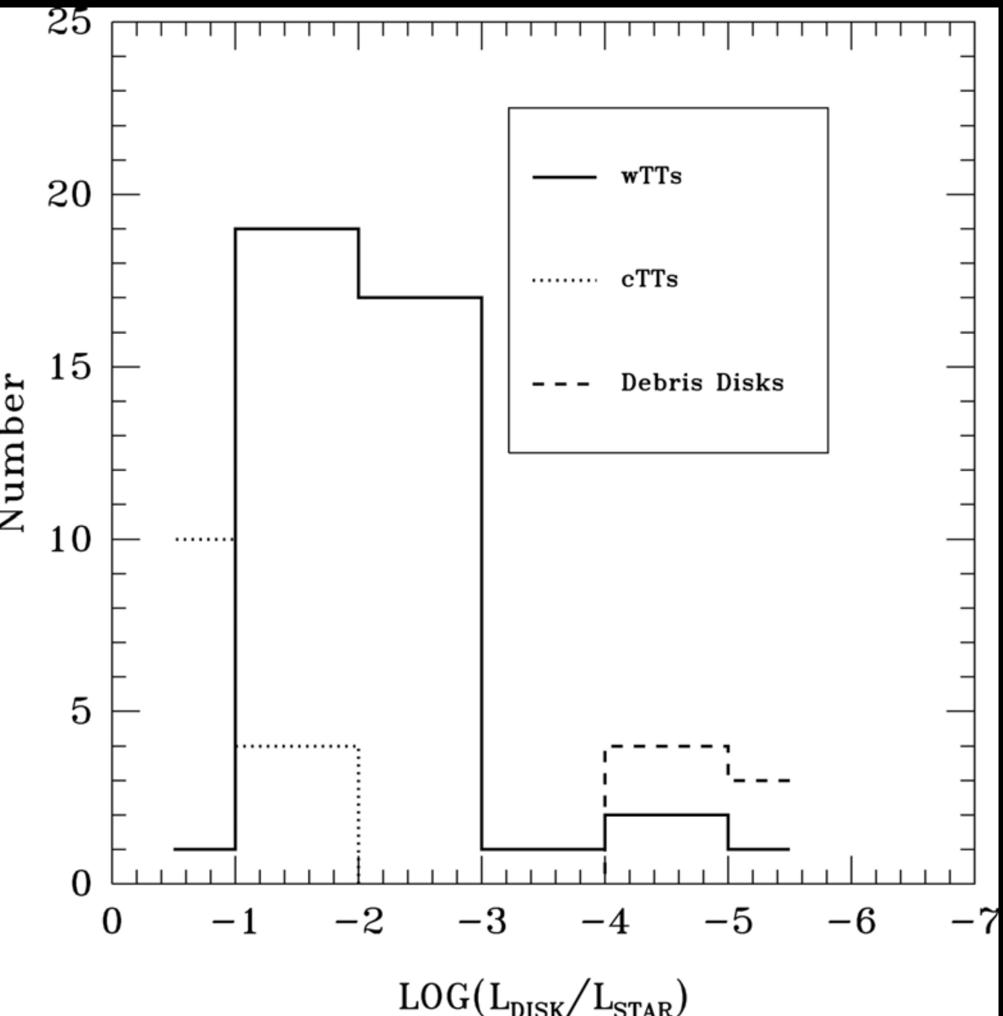
  ~5-15% at 3-10 Myr

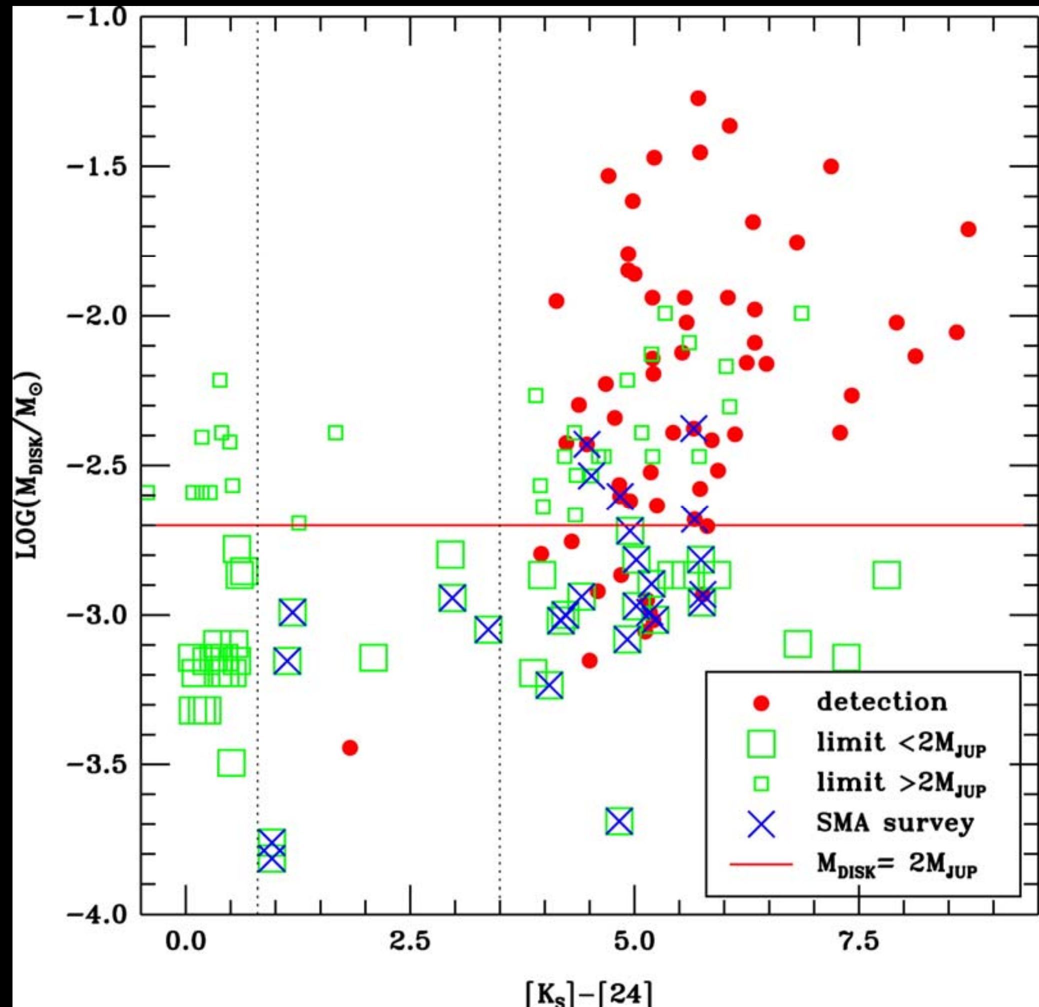


Muzerolle et al. 2008

Dust, gas content

- Optically thick/thin transition
- Poster #86 (Lucas Cieza)

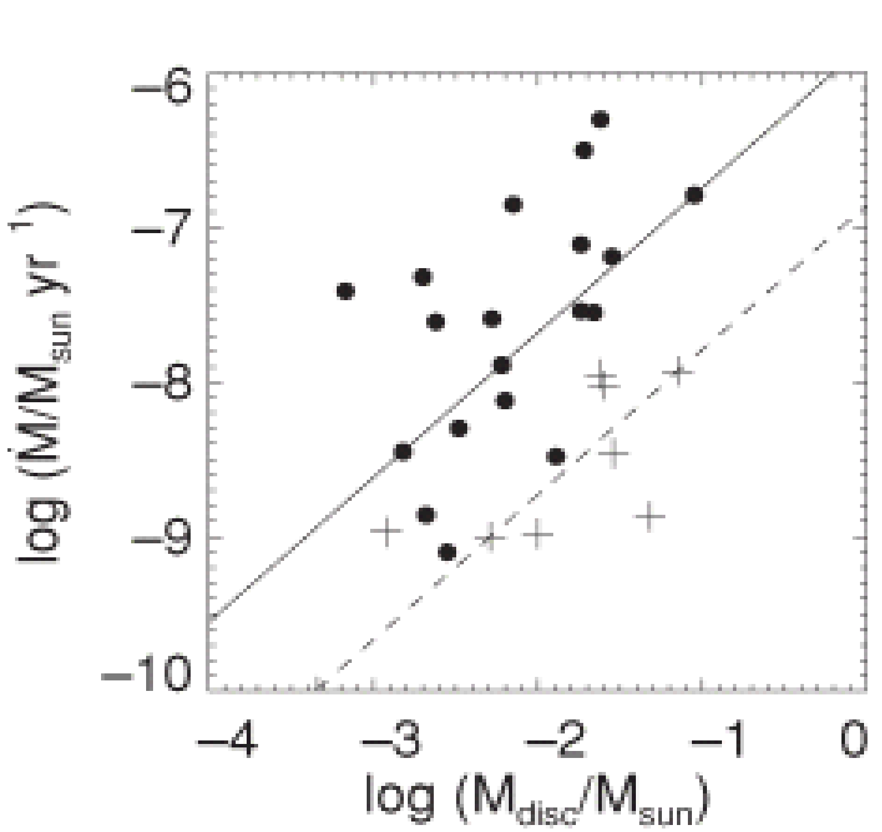




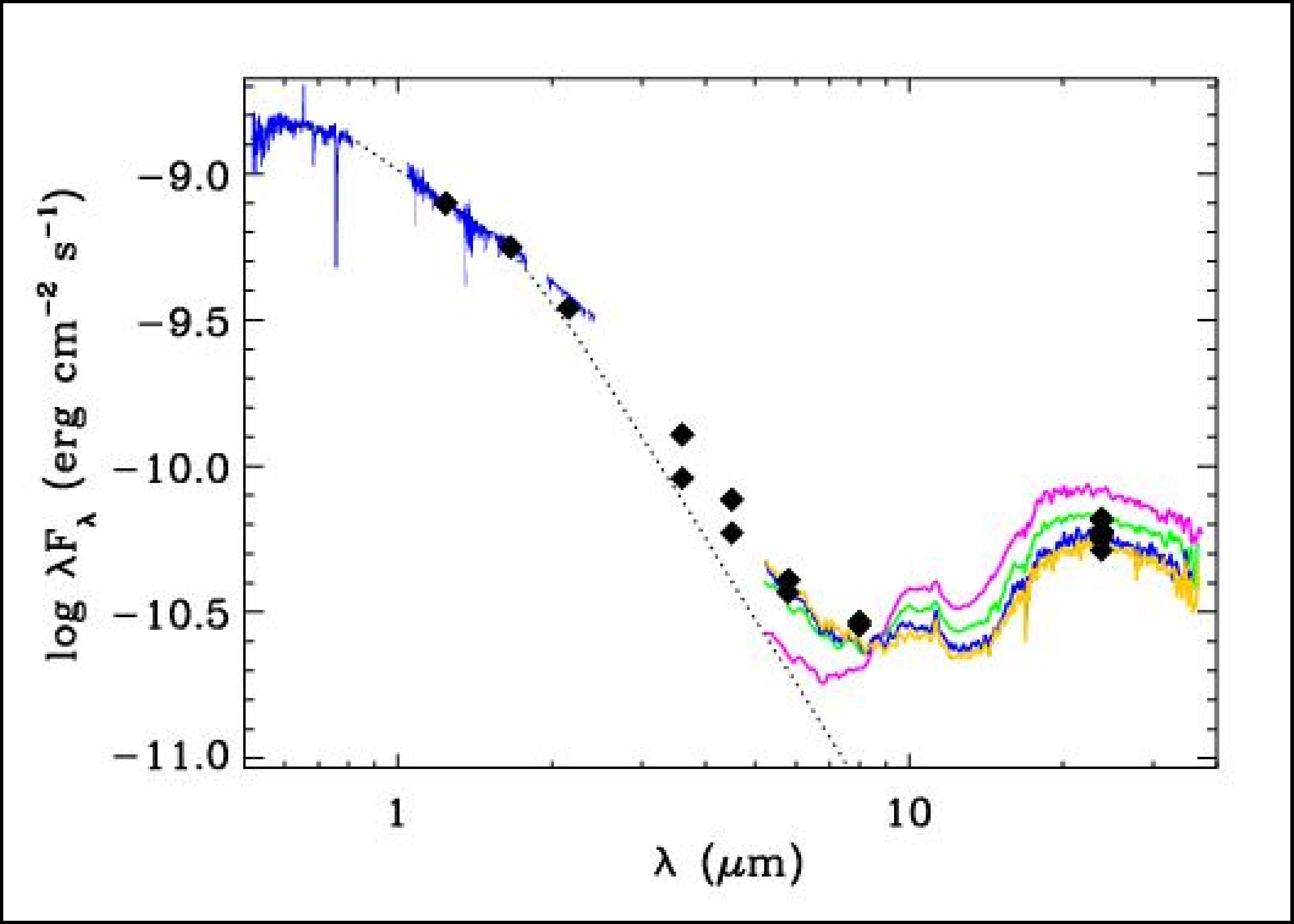
Dust, gas content

- disk mass, accretion rate as diagnostics
  - need more Mdot, Mdisk!!

Najita et al. 2007



mid-IR variability: LRLL 31



See poster #54 (Kevin Flaherty)

Dispersal mechanisms

- Photoevaporation
  - can only explain a few transition disks (no accretion, low disk mass)
  - best/only way to remove cold gas in outer disks?
  - new models including FUV lead to more efficient mass loss at large disk radii (*Gorti & Hollenbach*)
  - Need more constraints on TTS chromospheric ionizing flux (probably ok? *Herczeg)*

Dispersal mechanisms

- Stellar companions
  - CoKu Tau/4
  - Awaiting a thorough survey in the relatively unexplored 5-15 AU range (*Kraus)*
- Planet formation
  - Still circumstantial, except perhaps TW Hya??

Open questions

- Is planet formation really related to the clearing of gas disks (at large radii), or does gas disk dispersal limit the timescale for (giant) planet formation
- How many transitional disks host massive planets, and what is the long-term fate of such systems?
- How well can/do we understand the high-energy (X-ray & UV) flux from T Tauri stars?
- Is there really a single evolutionary path for all (gas) disks?
- How significant is the population of binary "transitional" disks, and how should we treat it?

Open questions

- How to maintain inner optically thick annulus?
  - Evaporation of solid bodies moving in via gas drag
  - Look for gas-phase diagnostics at evaporation front?

Future prospects

- Measurements of mass accretion rates, disk masses for larger samples
- (M)HD modeling to explore accretion, dust mixing/settling, effects of sharp edges
- High-resolution spectroscopy of molecular and atomic gas (Phoenix, CRIRES, EXES?)
- 50-100 micron constraints on larger inner holes (SAFIRE, etc)
- Resolve inner hole structure, direct detection of giant planets (ALMA, GMT, ELT)