An Observational Perspective of Transitional Disks

James Muzerolle

with **Catherine Espaillat**, Joan Najita, Sean Andrews, Zhaohuan Zhu, Nuria Calvet, Stefan Kraus, Jun Hashimoto, Adam Kraus, Paola D'Alessio

Discovery - IRAS

Strom et al. (1989)

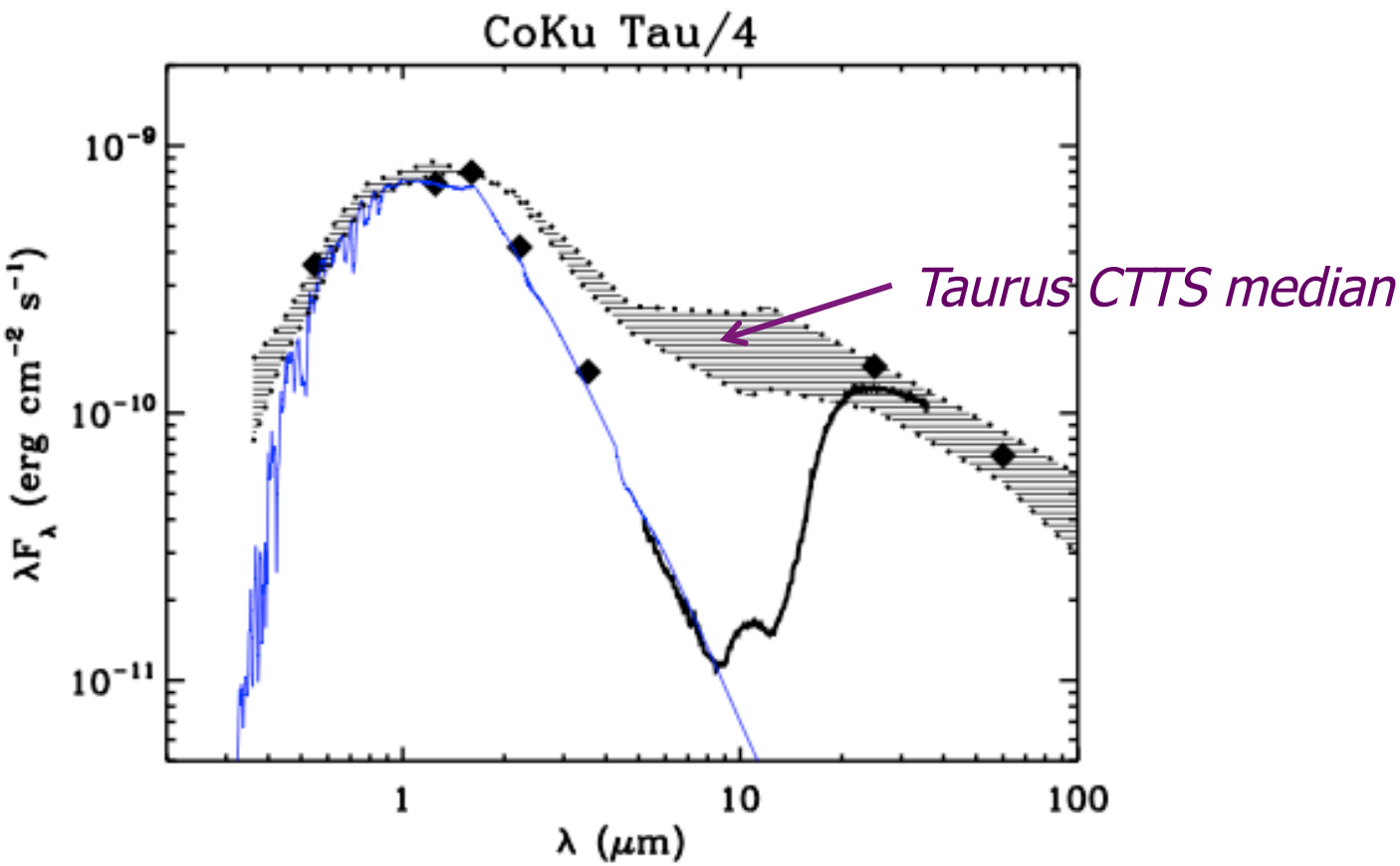
"The presence of IR excesses for $\lambda > 10\ \mu m$… and the absence of excess emission at $\lambda < 10\ \mu m$… may diagnose *disk clearing* in the inner regions of the disk. If so, these observations may represent the first astrophysical evidence of disks *in transition* from massive, optically 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***

Companions/planets? (Marsh & Mahoney 1992, 1993)

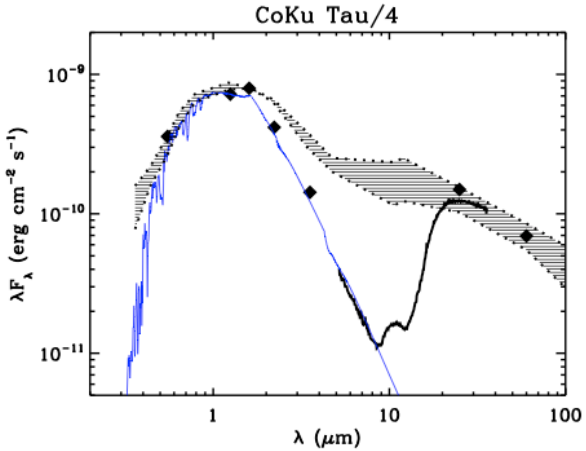
SED evidence of inner clearing



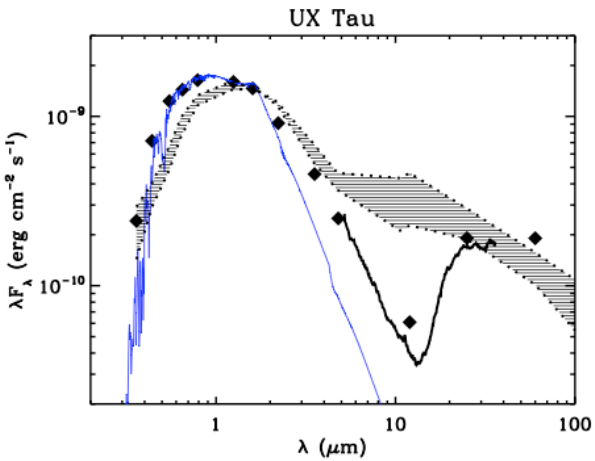
terminology

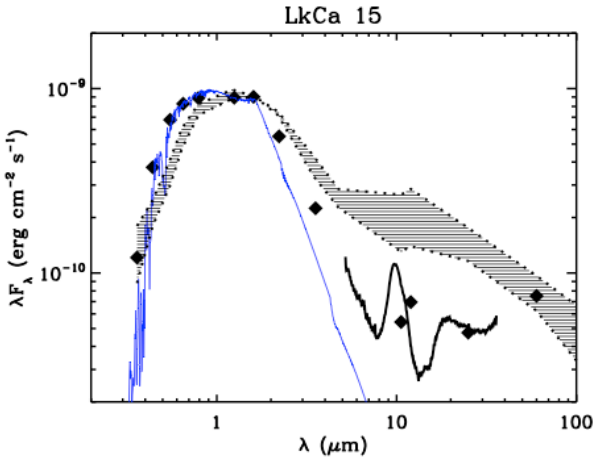
- Transitional disk (TD)
  - weak/zero excess < 10 μm, similar to full disk > 10 μm
  - "classical", "cold disk", inner hole
- Pre-transitional disk (PTD)
  - suppressed NIR excess consistent with opt. thick dust, often with strong 10 μm silicate emission
  - "cold disk", gap
- Weak-excess disk (WTD)
  - Excess significantly less than full disk at all wavelengths
  - "evolved", "homologously depleted", "anemic"

SED classes

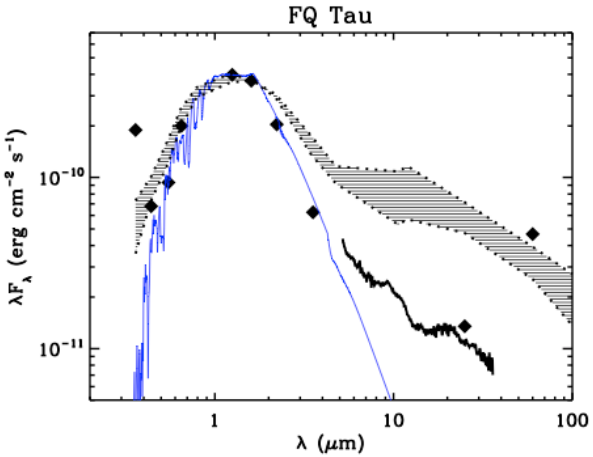


Transitional
(TD)





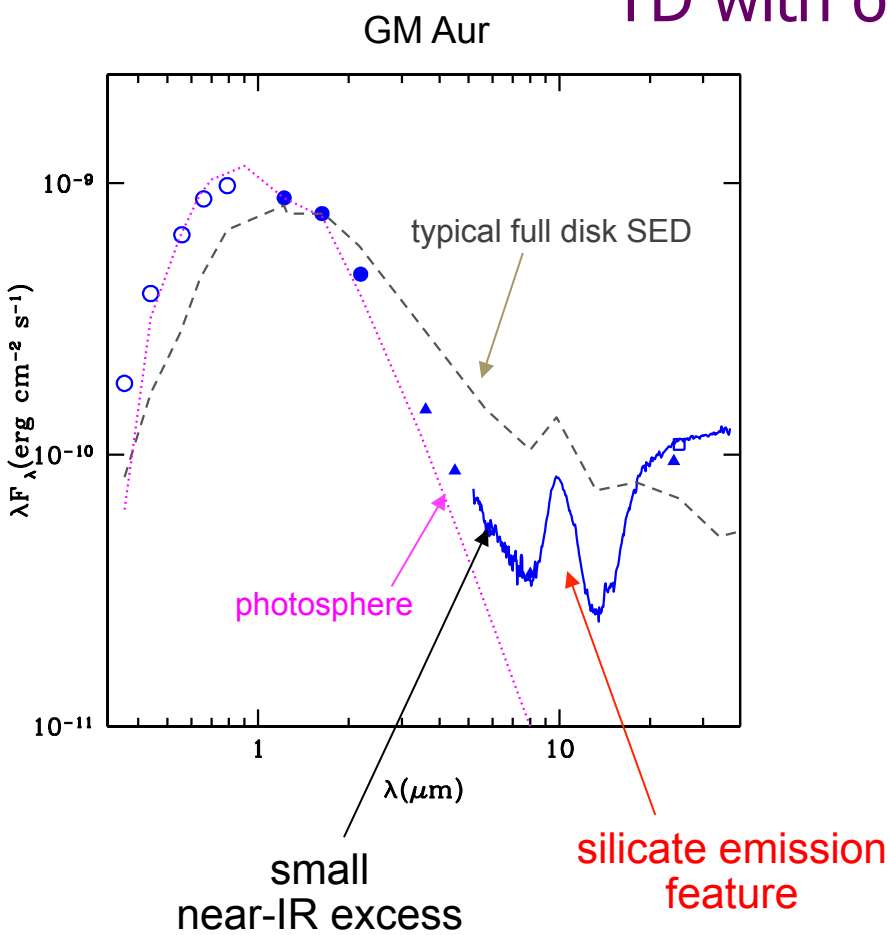
Pre-transitional
(PTD)

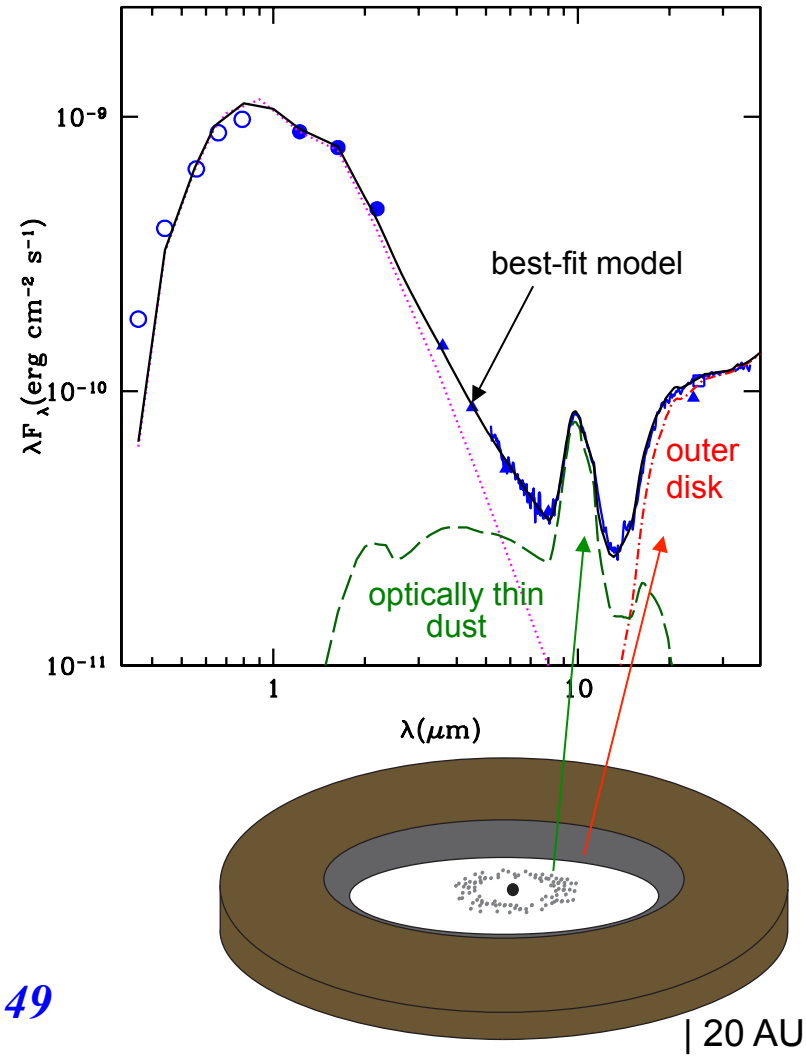


Weak-excess
(WTD)

SEDs & models

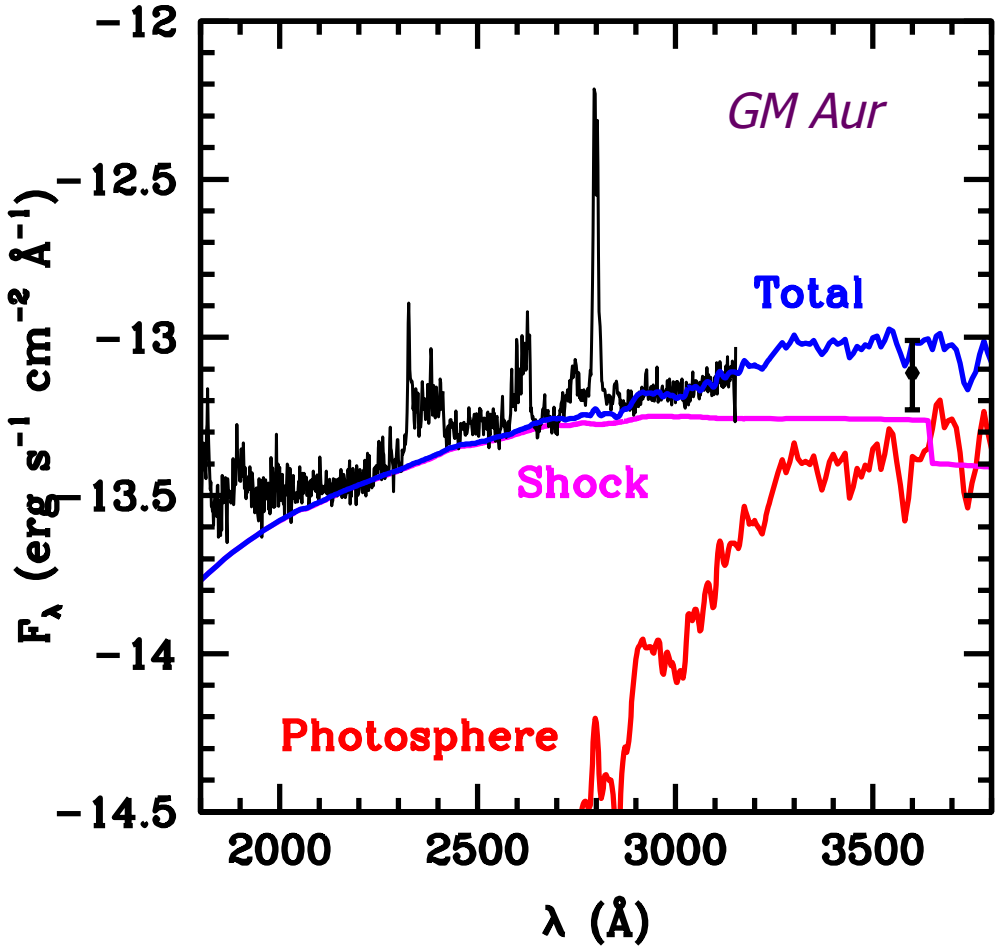
TD with optically thin dust inside hole





Espaillat et al. 2011, ApJ, 728, 49

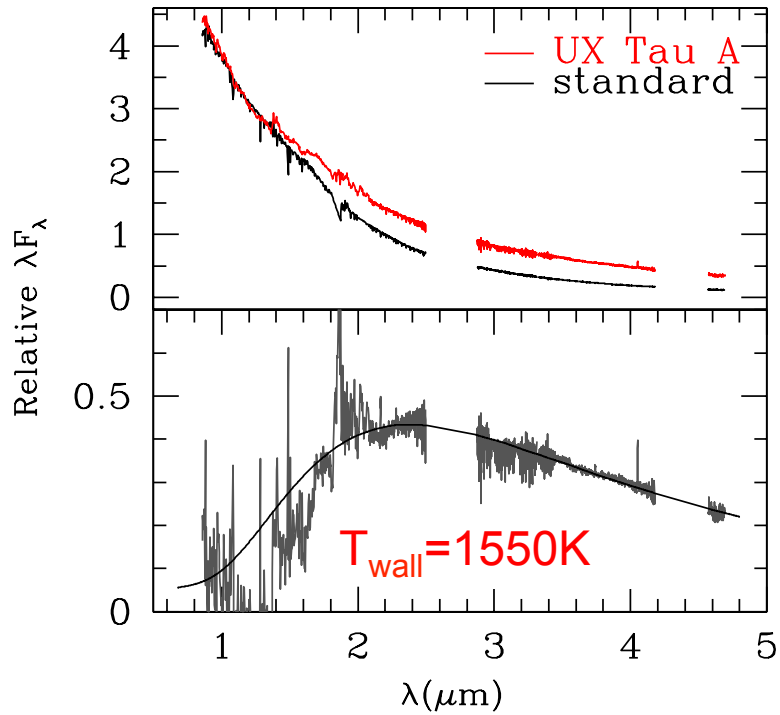
Many TDs continue to accrete at near-typical CTTS levels

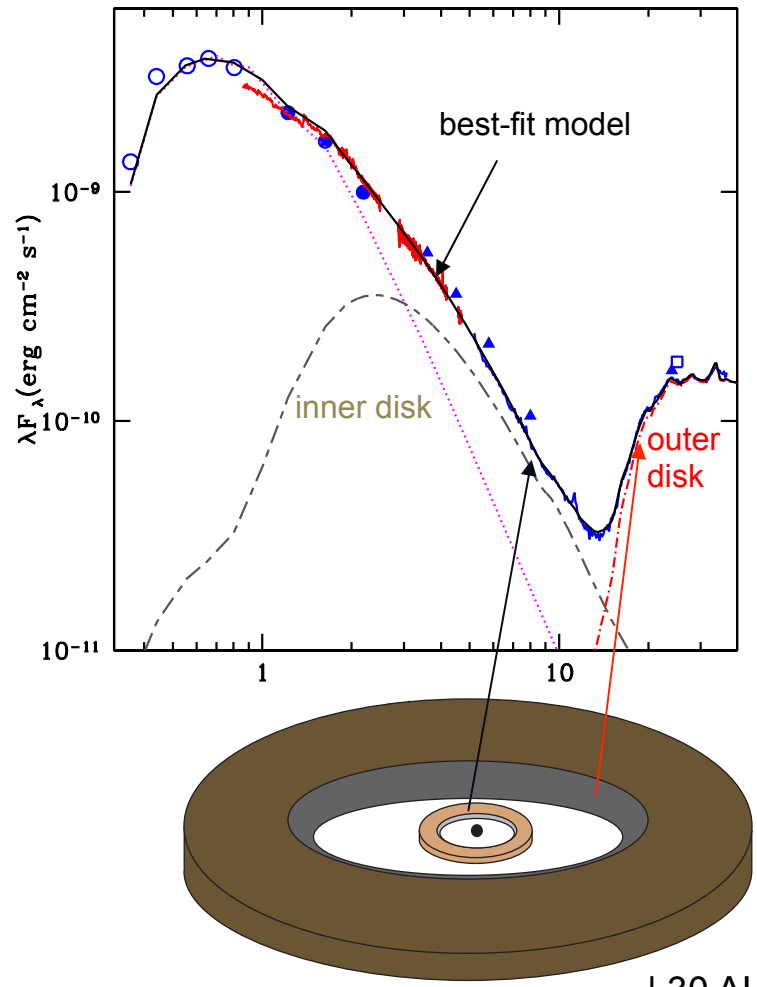


Ingleby et al. 2011, ApJ, 743, 105

TD with optically thick annulus at the sublimation radius:

pre-transitional (PTD)





Espaillat et al. 2010, ApJ, 717, 441

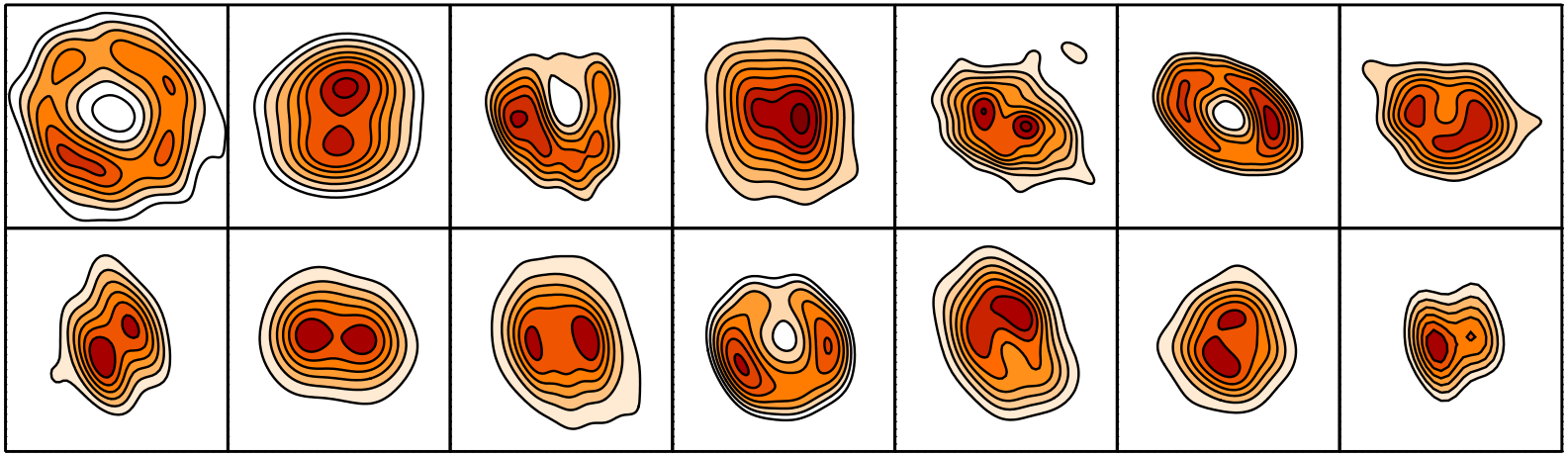
| 30 AU

Imaging – submm cavities

Indicative of large clearing (10s AU)

All bright/massive outer disks (selection effect?)

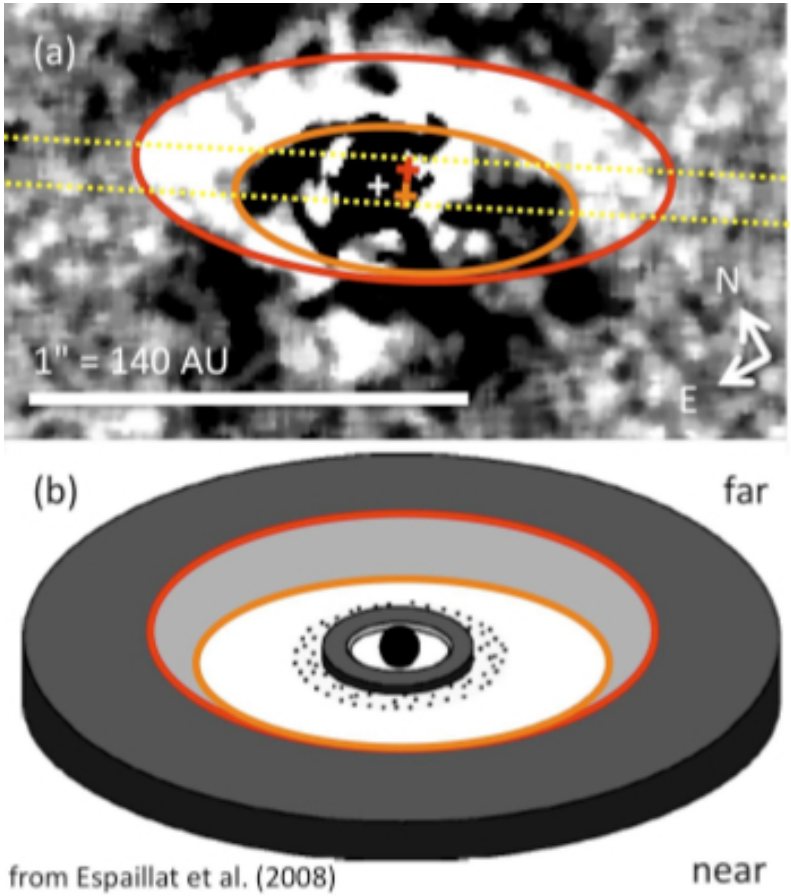
~20% frequency; some do not show MIR SED signature



SMA 880 μm dust continuum images:
Brown et al. 2009; Andrews et al. 2009, 2010, 2011; Hughes et al. 2009; Isella et al. 2010; Cieza et al. 2012; Mathews et al. 2012; Rosenfeld et al. submitted

Imaging – scattered light

SEEDS Subaru H band imaging survey: outer edge of PTD LkCa 15 gap detected



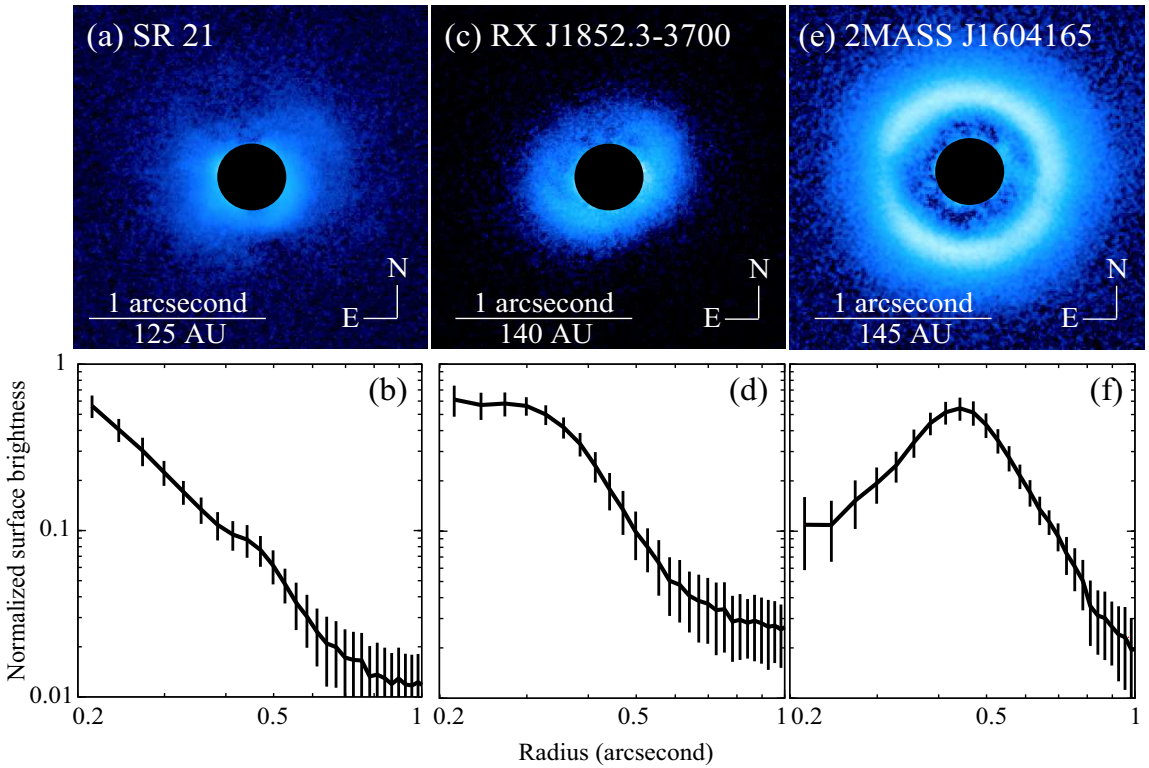
from Espaillat et al. (2008)

Thalmann et al. 2010, ApJ, 718, L87

SEEDS polarimetry survey: 12 TD/PTDs, NIR does not always show gap structure

=> dust filtration? evolution?

smooth profile (3) broken profile (5) cavity (4)



See poster 2B050 Hashimoto et al.

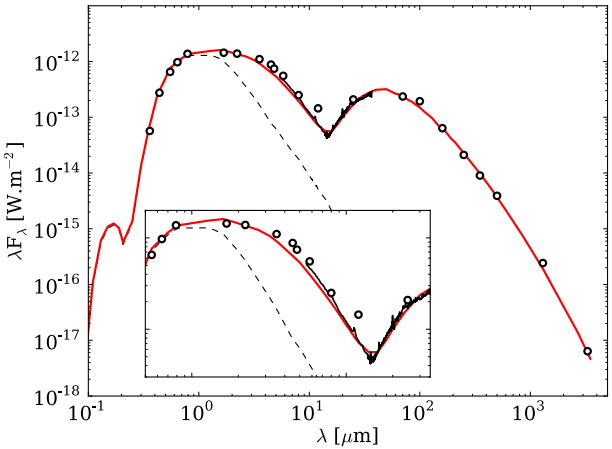
polarized intensity 1.6 μm:

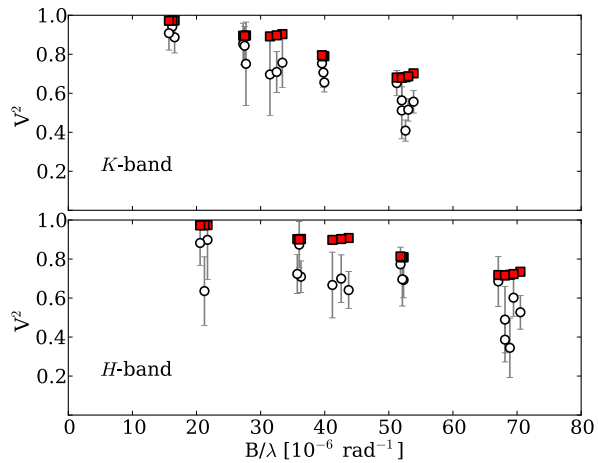
Follette et al. 2013;
Kudo et al. in prep;
Mayama et al. 2012

also VLT/NACO:
Quanz et al. 2011, 2013

Imaging – IR interferometry

Resolving the innermost disk region





T Cha

Inner disk: 0.07-0.11 AU

Outer disk: 12-25? AU

Olofsson et al. 2013, A&A, 552, 4

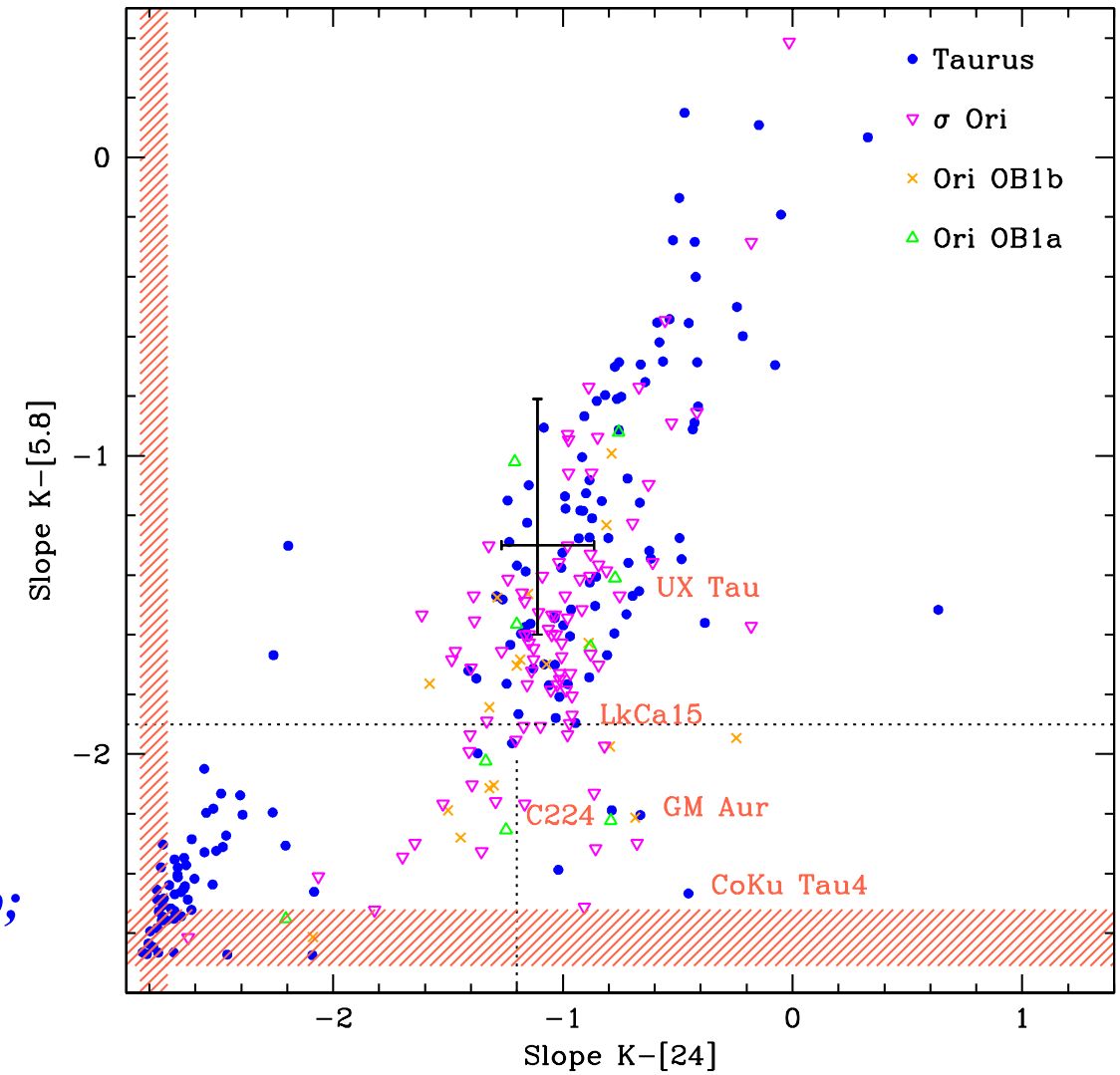
also Arnold et al. 2012 (TW Hya), Kraus et al. 2013 (V1247 Ori), Tatulli et al. 2011 (HD 100546) Cieza et al. 2013 (FL Cha)

See posters:
2B048 (Menu)
2B049 (Maaskant)
2B051 (Kraus)

Demographics

Spitzer photometric selection

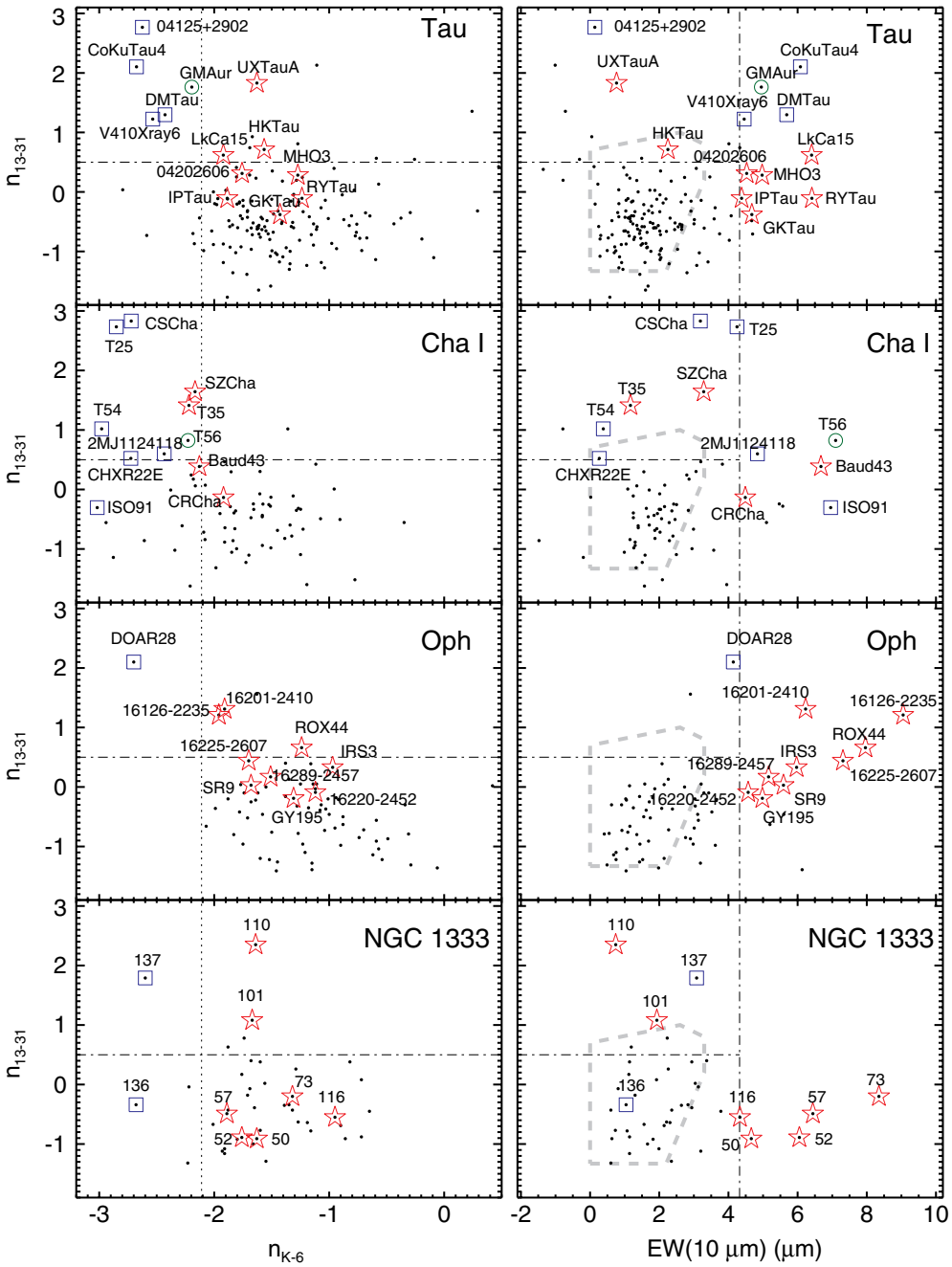
NIR vs MIR colors or spectral slopes



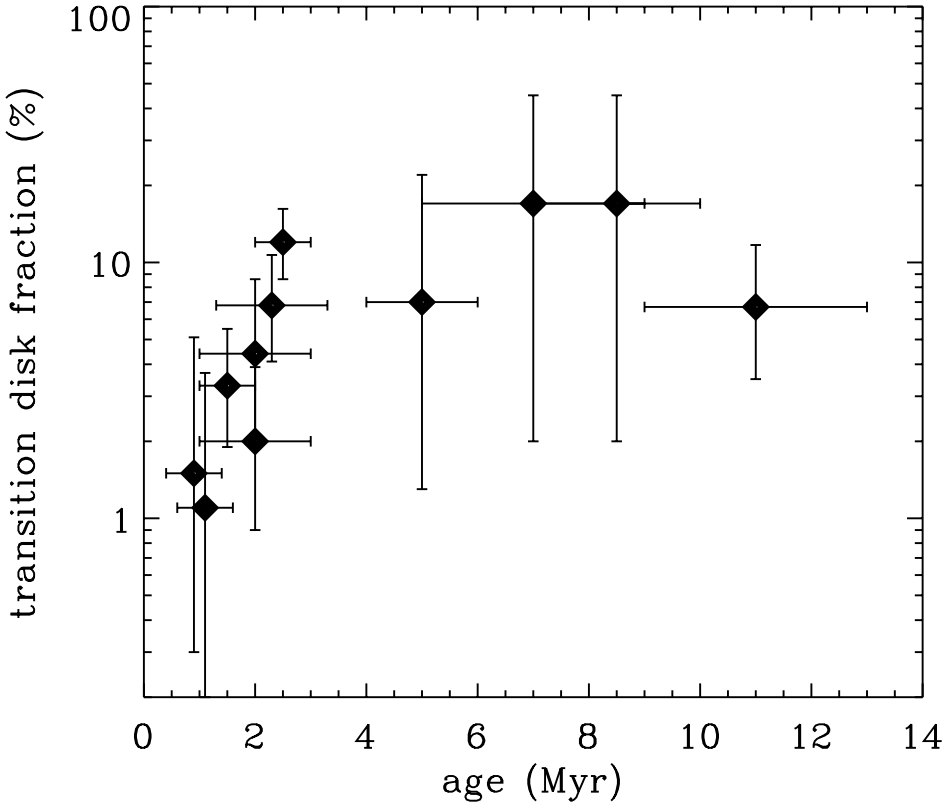
Hernandez et al. 2007ab; Luhman et al. 2010

Spectral slope selection misses some candidates

-> PTDs with strong silicate emission



Kim et al. 2013, ApJ, 769, 149



data from Muzerolle et al. 2010, McClure et al. 2010, Oliveira et al. 2010, Furlan et al. 2011, Manoj et al. 2011, Arnold et al. 2012, Luhman & Mamajek 2012

Frequency –

N_{TD}/N_{disk} ranges from ~1-20%, possibly age-dependent

the clearing timescale debate:

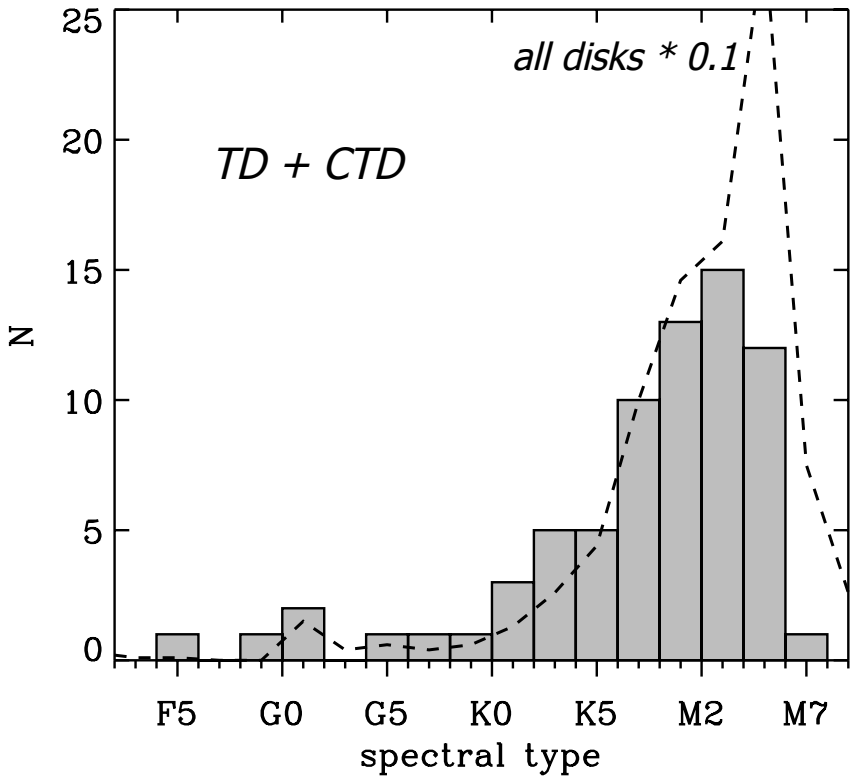
short, ~0.2 Myr (e.g. Luhman et al. 2010)

long, ~few Myr (e.g. Sicilia-Aguilar & Currie 2011)

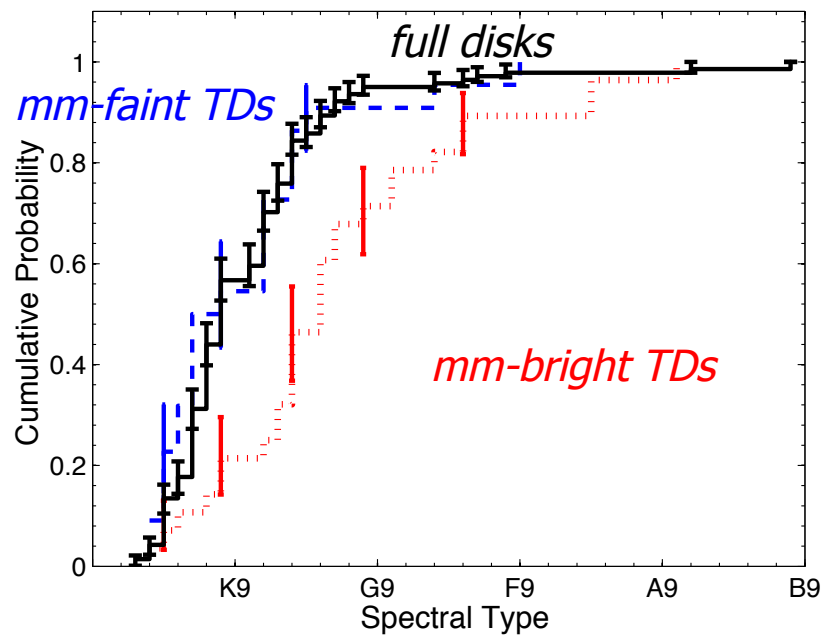
depends on sample selection!

Stellar mass dependence

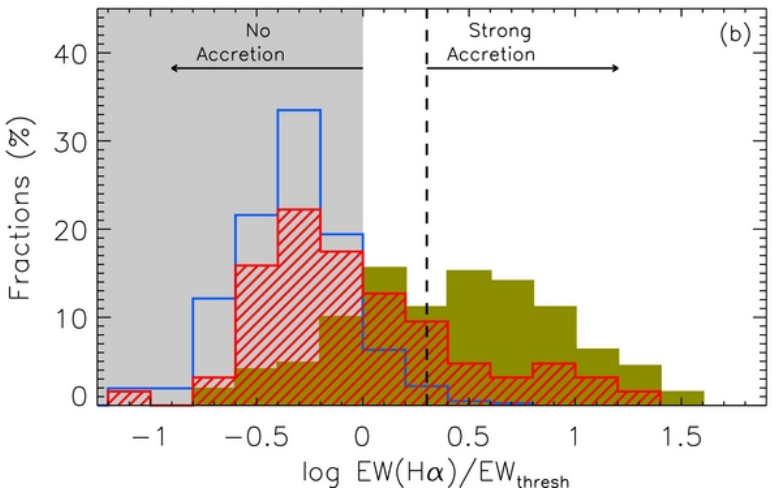
-TDs underrepresented around lower-mass stars

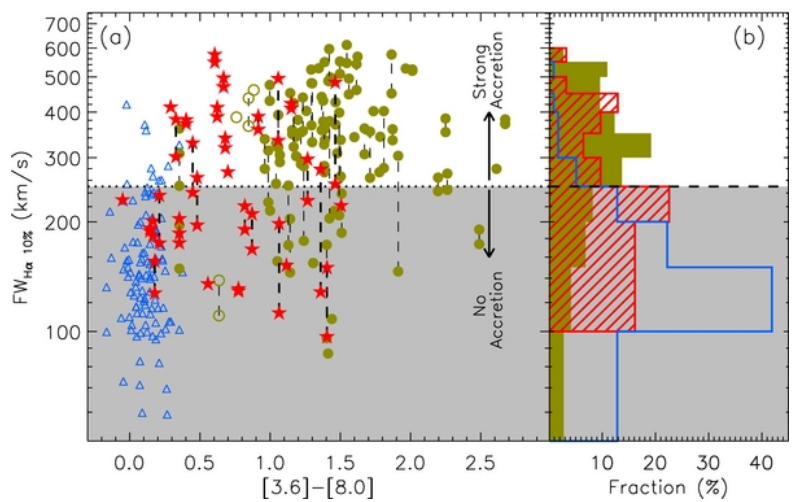


data from Muzerolle et al. 2010, McClure et al. 2010, Oliveira et al. 2010, Furlan et al. 2011, Manoj et al. 2011, Arnold et al. 2012, Luhman & Mamajek 2012



Owen & Clarke 2012, MNRAS, 426, 96



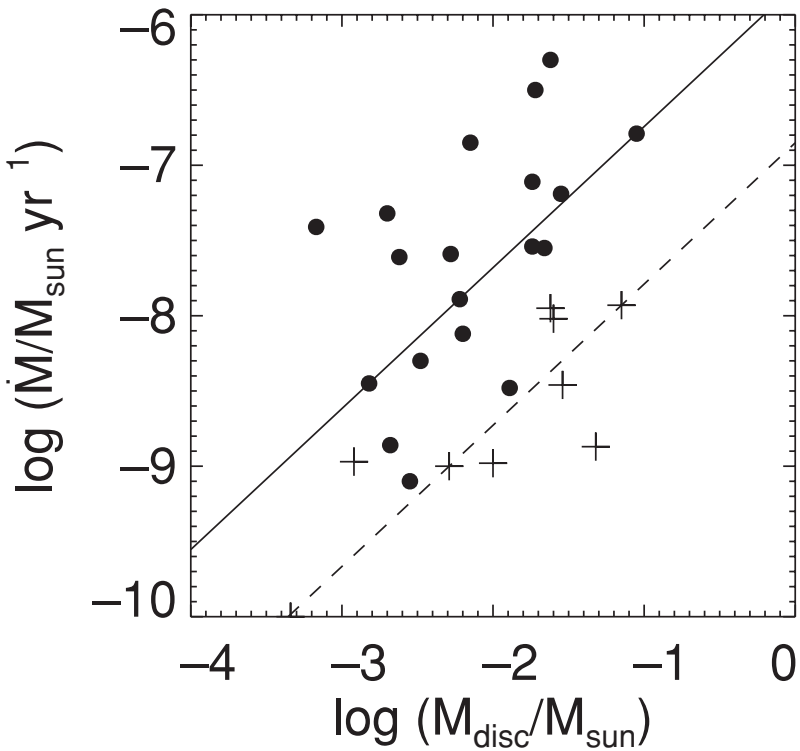


Fang et al. 2013, ApJS, 207, 5

Accretion in TDs:

less frequent than in CTTSs?

lower accretion rates?

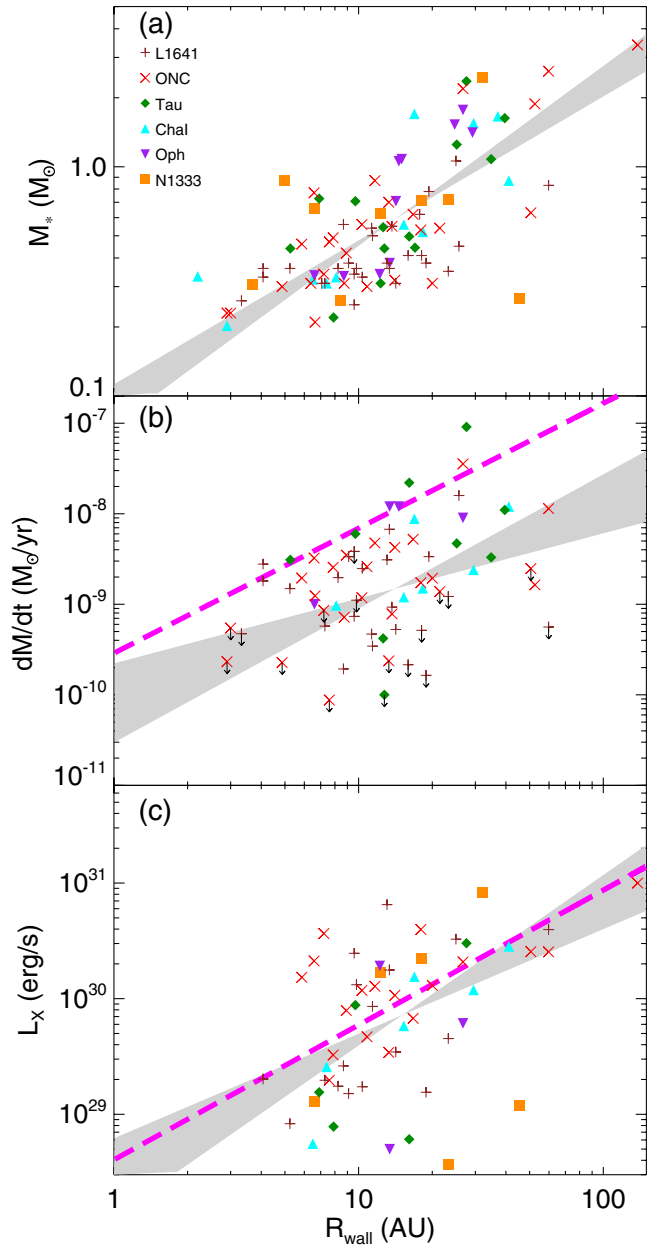


Najita et al. 2007, MNRAS, 378, 369

The Mdot vs Mdisk plane:

TDs in Taurus tend to have larger Mdisk, smaller Mdot than single CTTSs

Results in other regions are mixed; depends critically on the accretion tracer

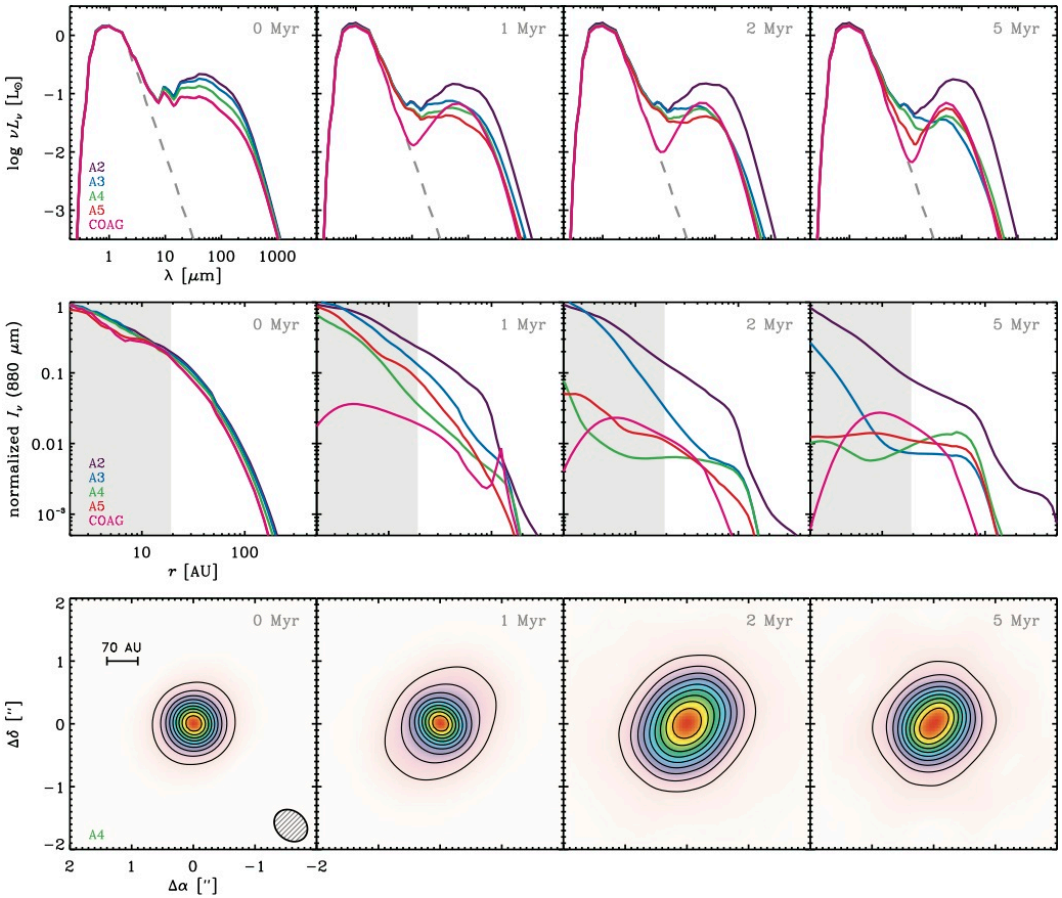


correlation between M*, R_{hole}

no correlation between L_x or Mdot and R_{hole} after accounting for M_* dependence

Kim et al. 2013, ApJ, 769, 149

Grain growth



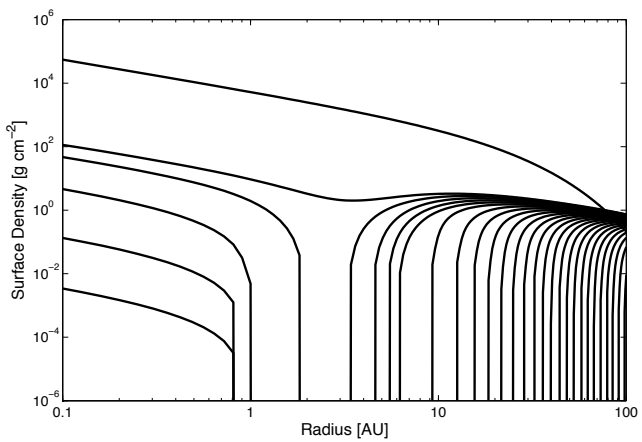
Can reproduce SEDs but not large submm cavities

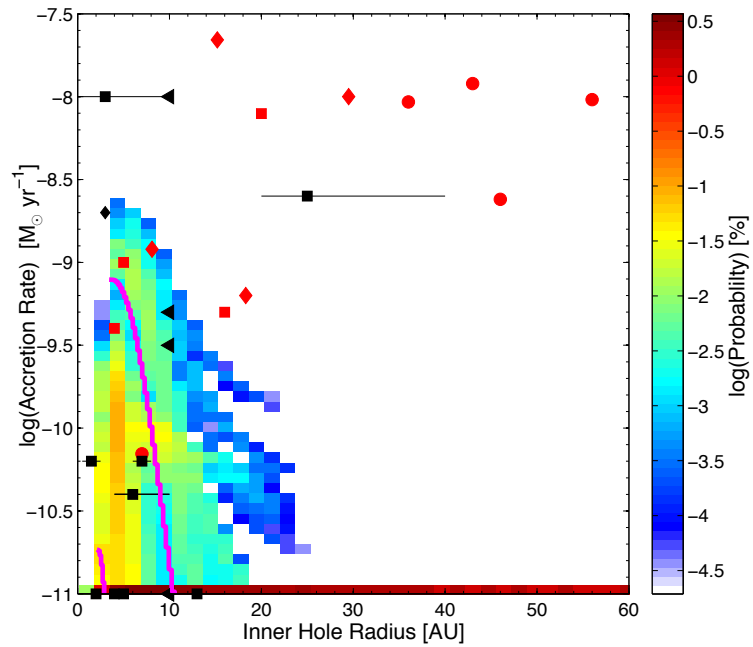
Birnstiel et al. 2012, A&A, 544, A79

UV/X-ray photoevaporation

Models predict a strong correlation between Lx and R_hole, Mdot

Vast majority are non-accreting objects with large holes



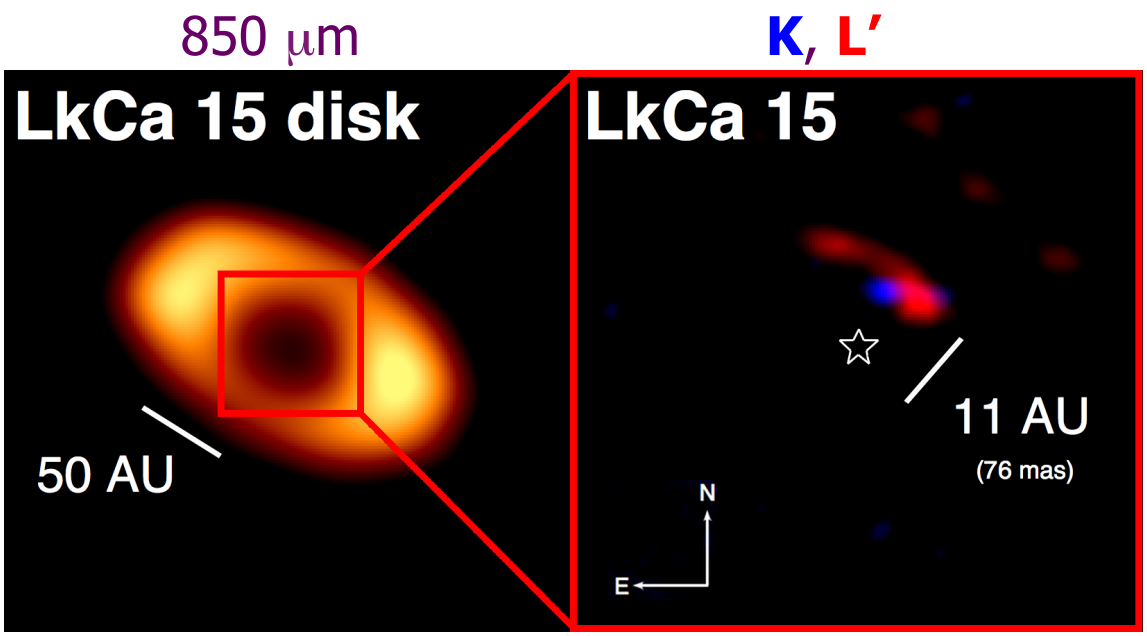


Owen et al. 2011, MNRAS, 412, 13

Do young giant planets create TDs?

At least one imaged within the gap of a PTD

-but cannot account for the measured hole radius

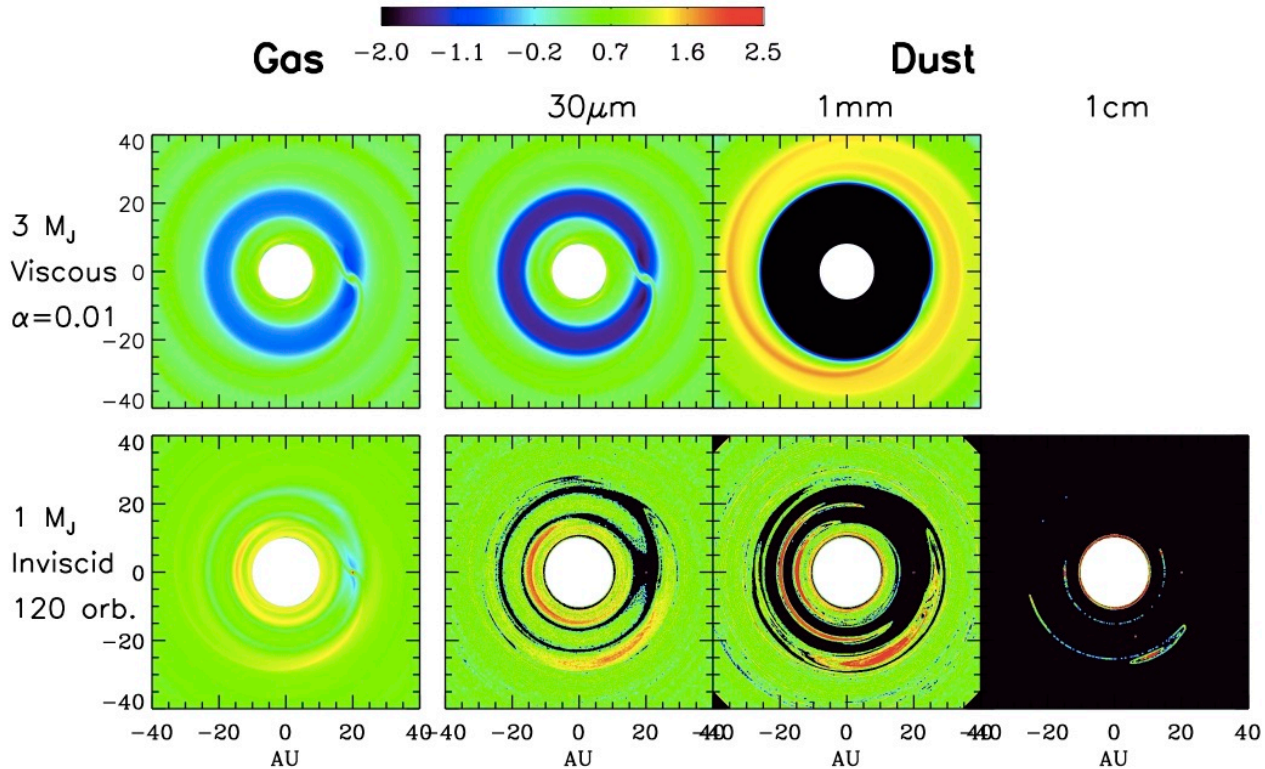


Kraus & Ireland 2012, ApJ, 745, 5
also Huelamo et al. 2011 (T Cha)
Cieza et al. 2013 (FL Cha)

Simulations of gaps with giant planets

dust filtration: gas pressure at outer edge prevents mm particles from accreting into the inner disk

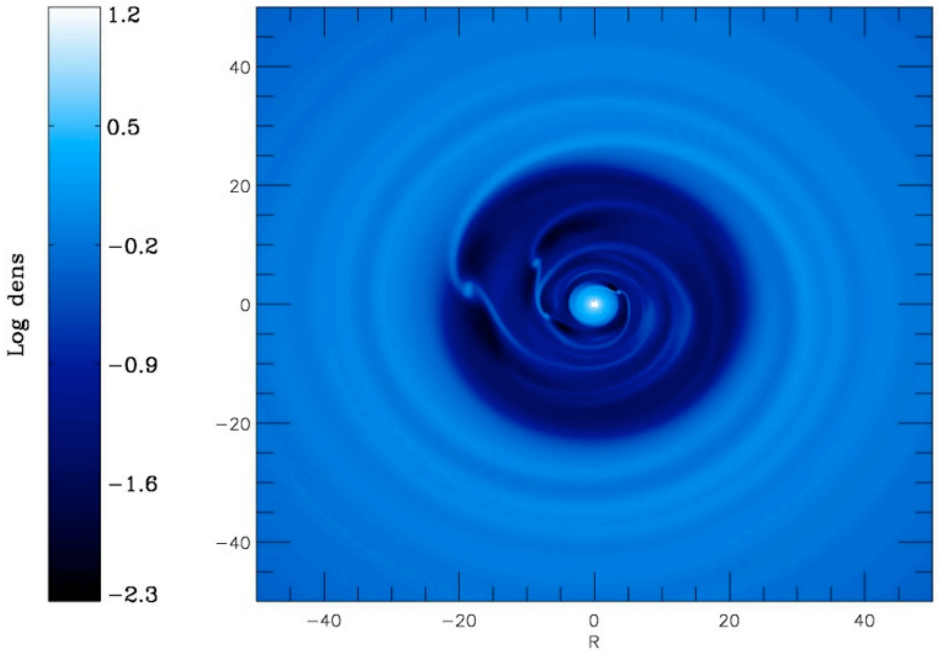
could explain submm cavities, but small grains can pass through the gap



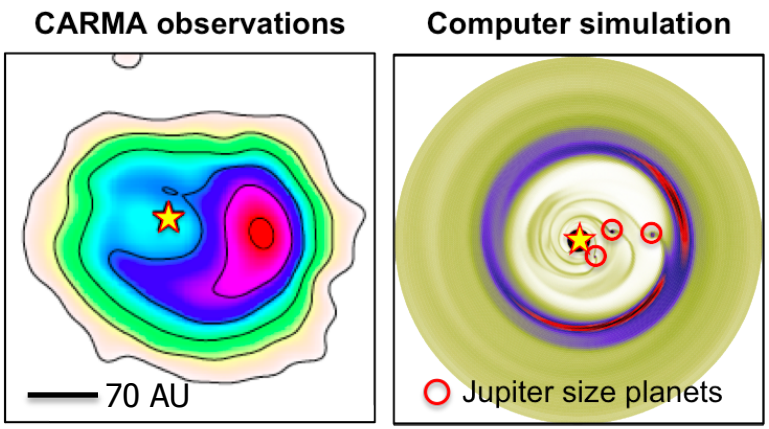
also Rice et al. (2006)
Pinilla et al. (2012)

See poster 2S055
Zhu et al.

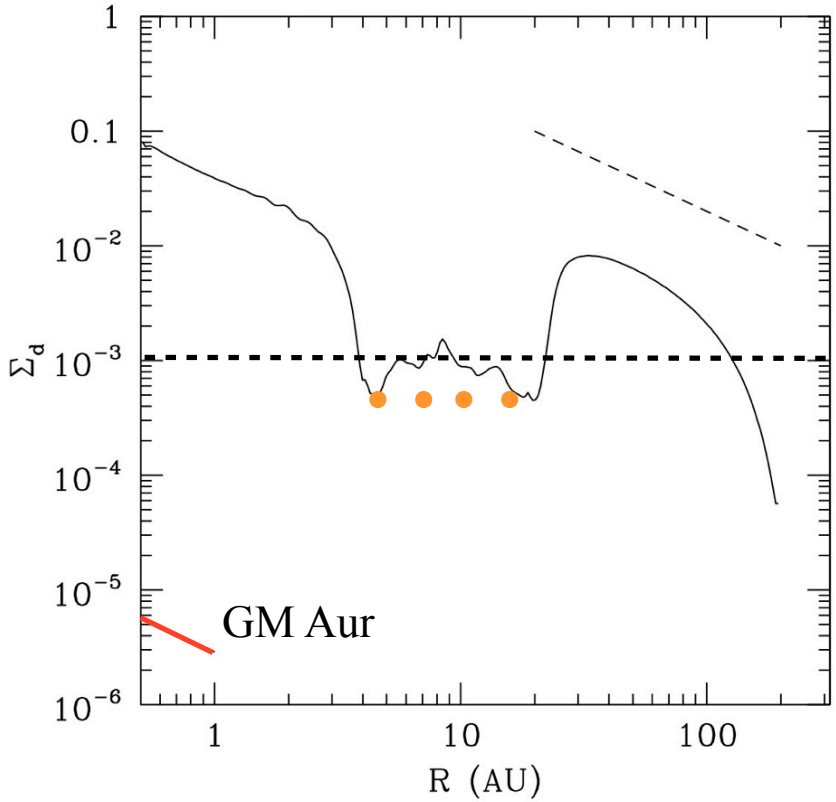
Need multiple planets to clear multi-AU gaps

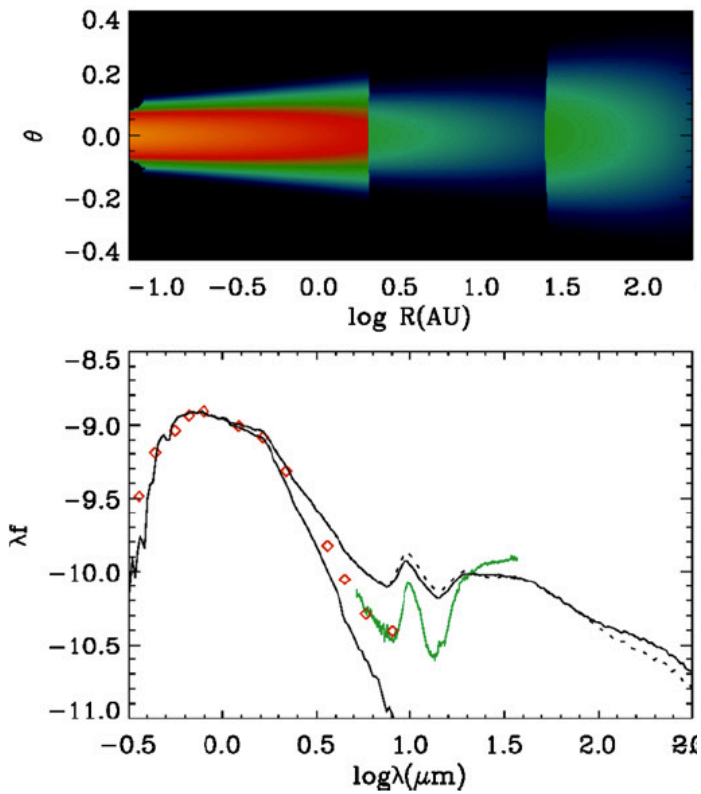


Zhu et al. 2011, ApJ, 729, 47
also Dodson-Robinson & Salyk (2011)



Isella et al. 2013, ApJ, accepted



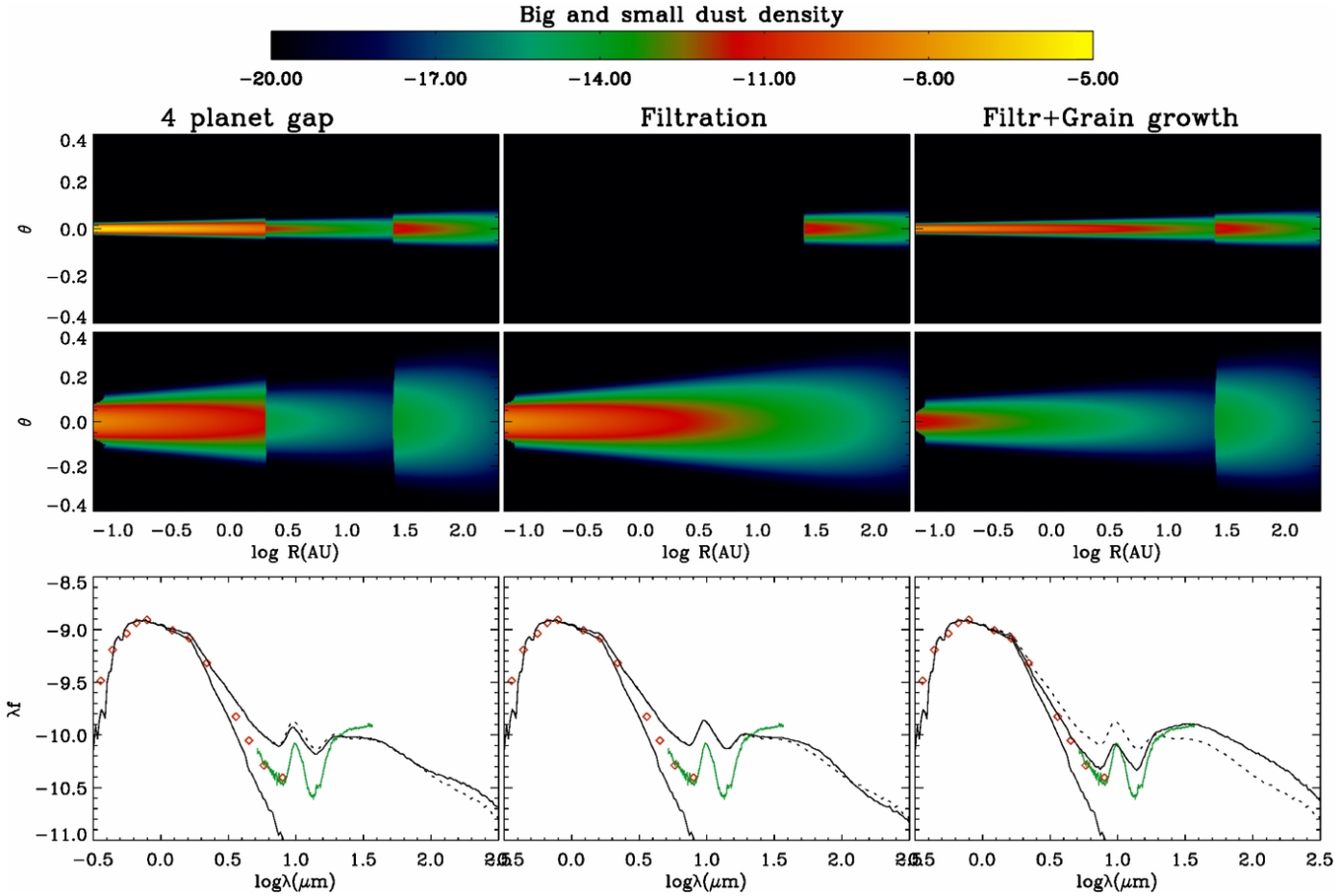


Zhu et al. 2012

Get larger gap, but inner disk still not affected

$\kappa_{10\mu m}$=10 cm^2/g, the inner disk is optically thick

-> need depletion of order 10^3 – 10^5!



Zhu et al. 2012, ApJ, 755, 6

To explain moderate accretion rates and NIR deficits, must add other physics

=> "filtration" plus grain growth?

Future prospects

ALMA

- complete census of submm cavities
- find smaller gaps – lower-mass planets?
- measure masses/sizes of evolved/WTDs

JWST

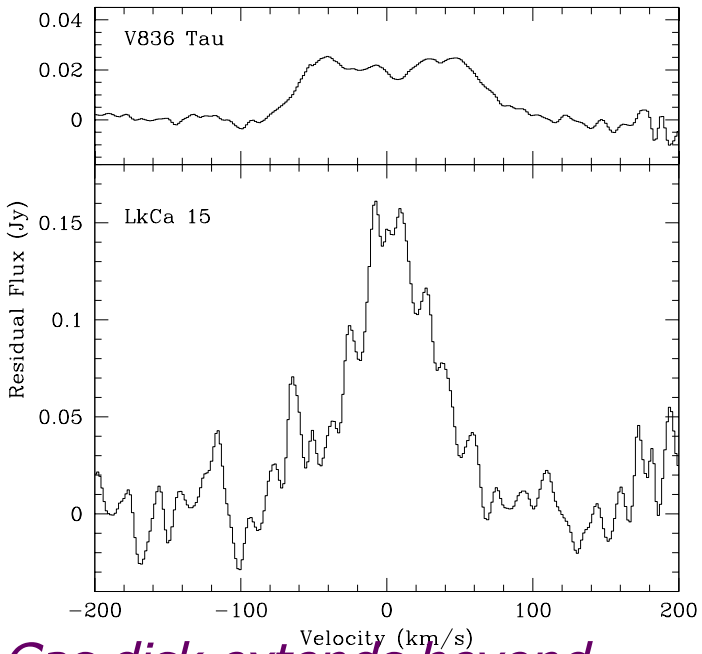
- MIRI IFU spectroscopy – gas, dust distribution
- NIRISS NRM interferometry – planets? MIR gap sizes?
- Imaging, MOS spectroscopy – increase SED/Mdot samples, explore extreme environments

VLTI/MATISSE, GMT, TMT….

Extras

Gas tracers of the inner disk

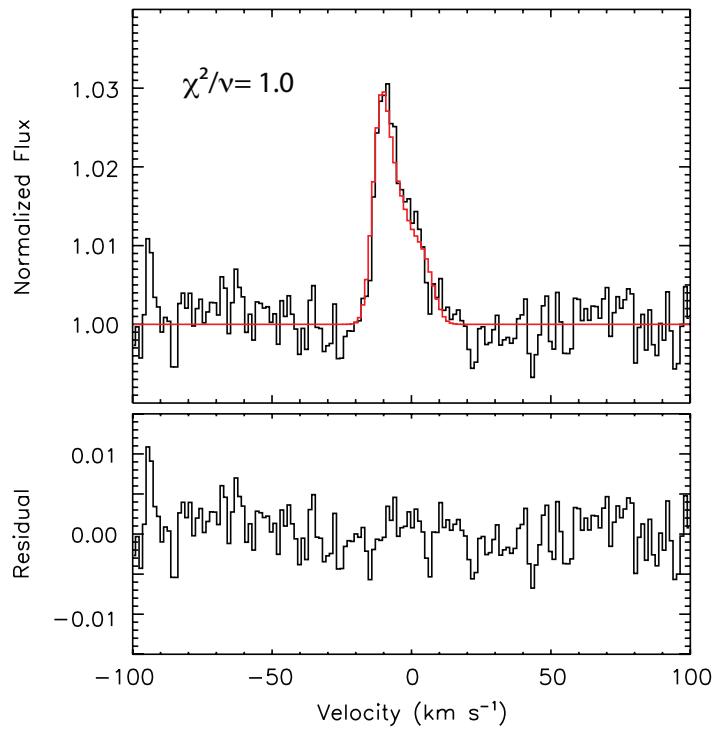
truncation at ~0.4 AU



Gas disk extends beyond inner dust annulus

Najita et al. 2008, ApJ, 687, 1168

Eccentric gas disk?



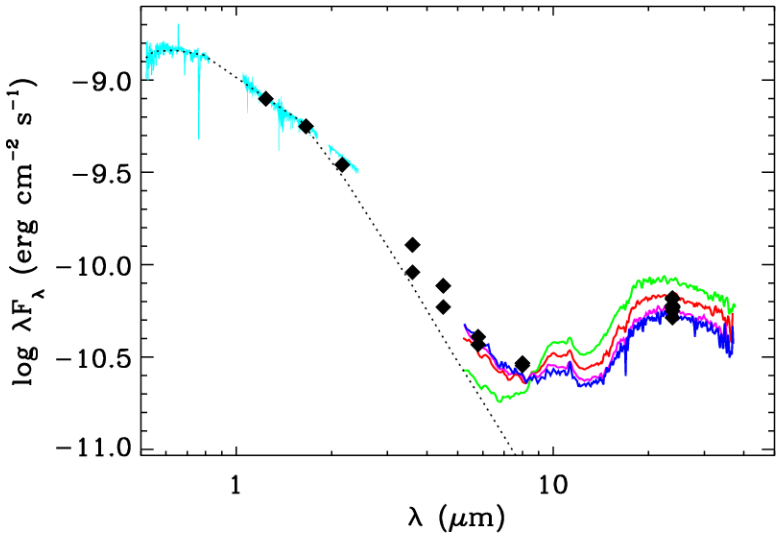
Liskowsky et al. 2012, ApJ, 760, 153

also Salyk et al. (2007, 2009)
Pontoppidan et al. (2008)

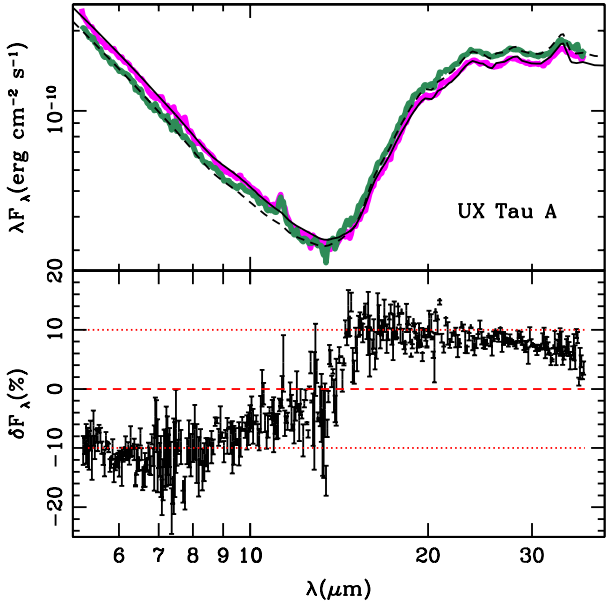
Variability

As with typical CTTS, TDs vary across the spectrum

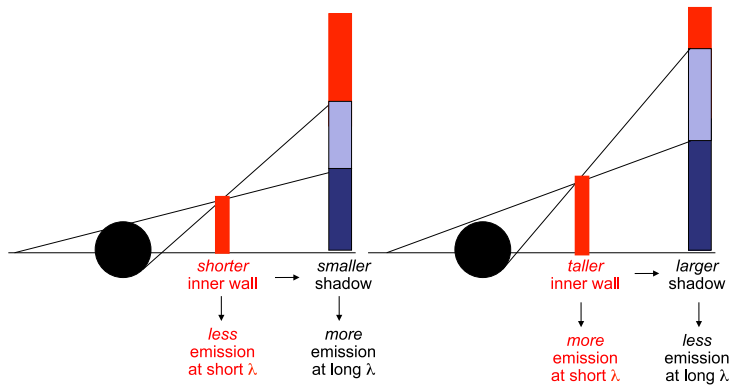
"see-saw" variability: changes in inner disk structure lead to variable illumination of outer disk



Muzerolle et al. 2009



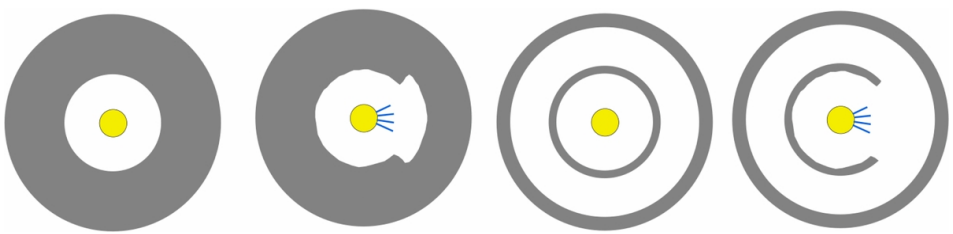
Espaillat et al. 2011



Espaillat et al. 2011

Mechanisms:

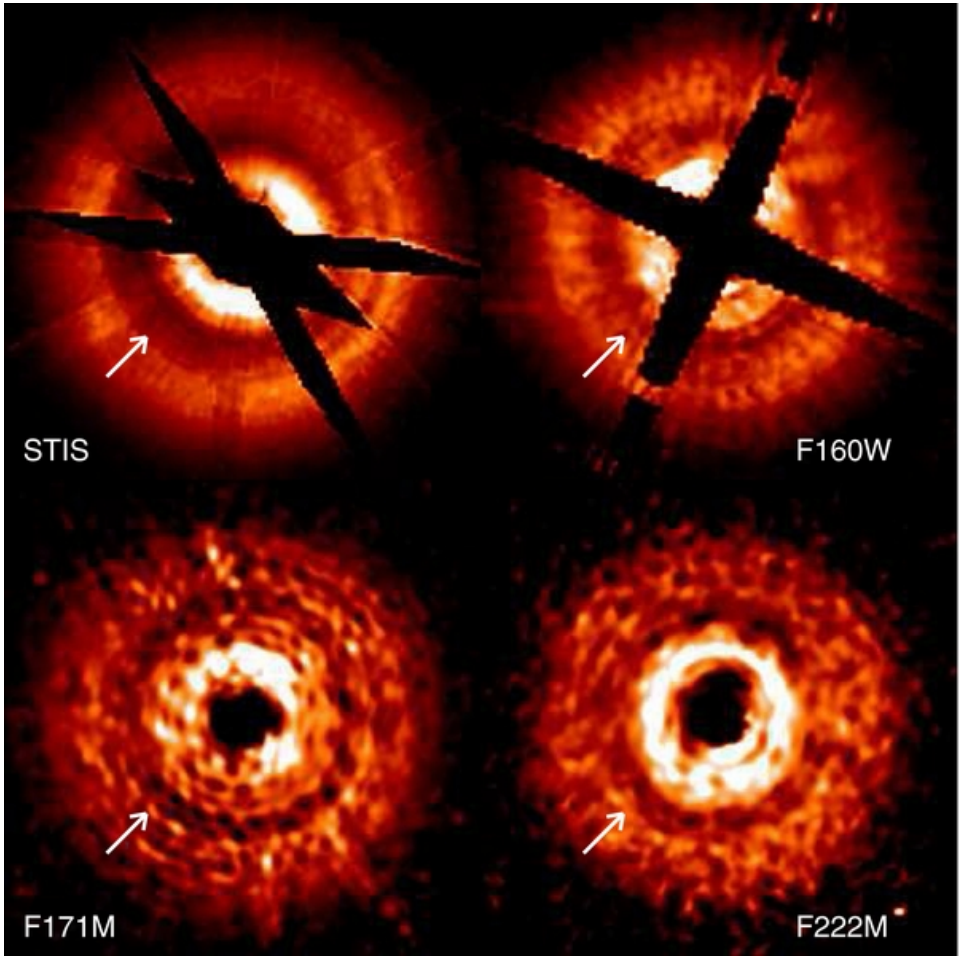
Variable height of inner annulus - driven by companion?



Flaherty et al. 2013, AJ, 145, 66

Variable irradiation by localized accretion shocks

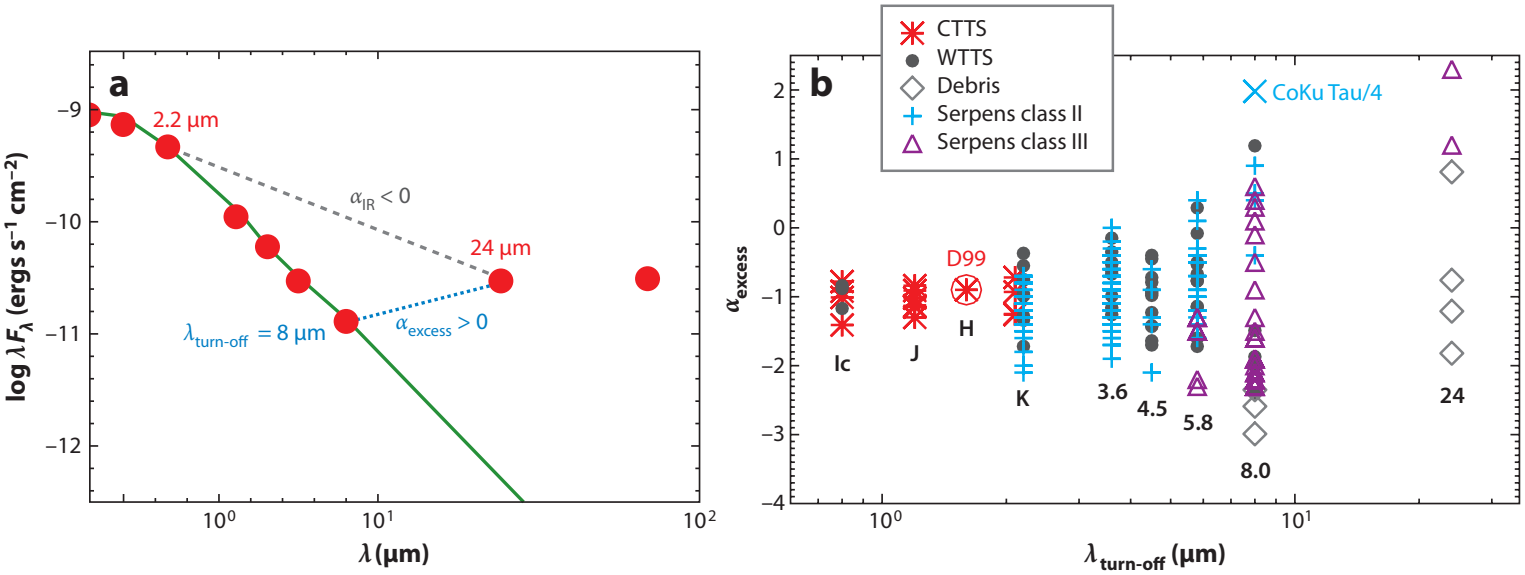
HST/STIS observations of TW Hya: gap at ~80 AU, more distant than ~5 AU inner hole seen in MIR, mm



Debes et al. 2013, ApJ, 771, 45

Spectral slope, excess turn-off wavelength

-a range of values, multiple evolutionary pathways?



Williams & Cieza 2011, ARAA, 49, 67