Characterizing Planet-Forming Disks Around Young Stars

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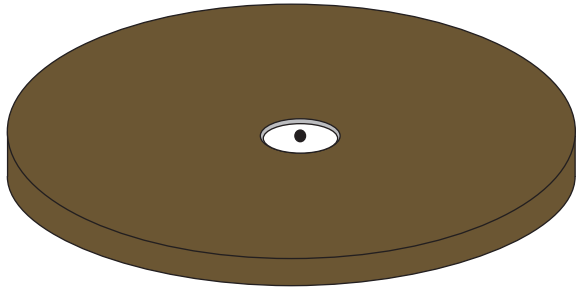
How do planets form?

- Theoretical simulations predict planets clear material around themselves
- Need to look for observational evidence of cleared regions in young disks

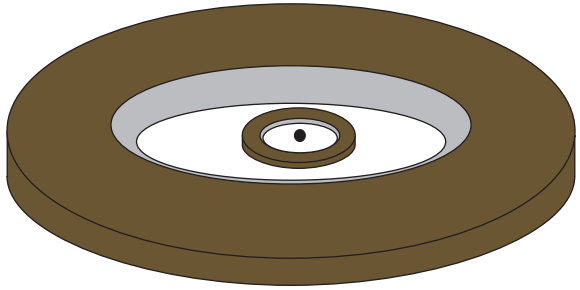
Drawing of UX Tau A: NASA/JPL-Caltech/T. Pyle (SSC)
Based on Espaillat et al. (2007b)

Characterizing disks with holes and gaps

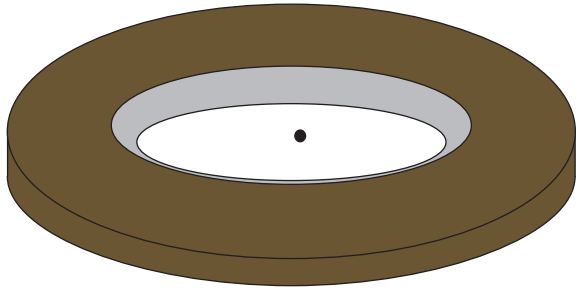
- What do disks with cleared regions look like?
  - Transitional disks
    - Inner holes
  - Pre-transitional disks
    - Cleared-out gap within disk
- What observational constraints can we apply to dust clearing mechanisms?
  - Dust and gas properties



Full disk



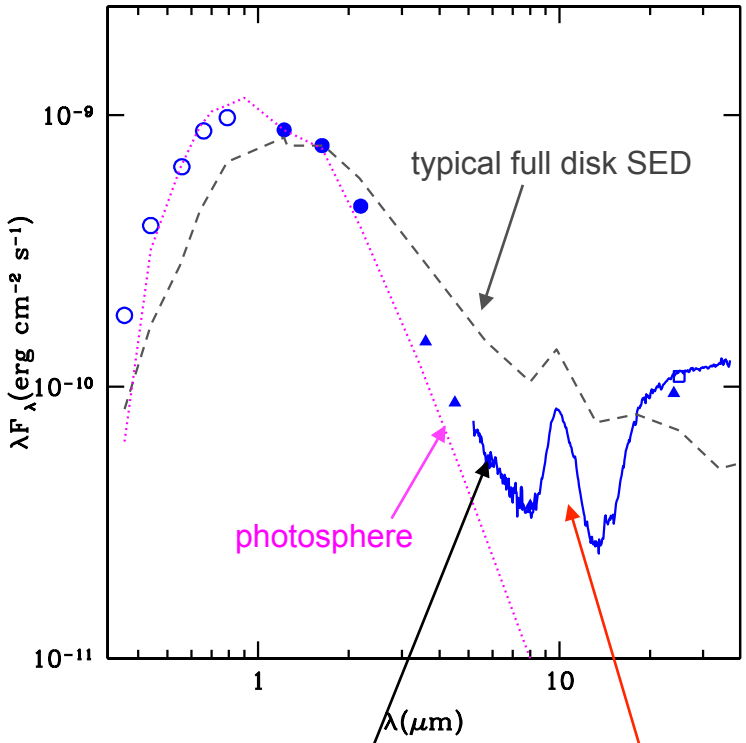
Pre-transitional disk



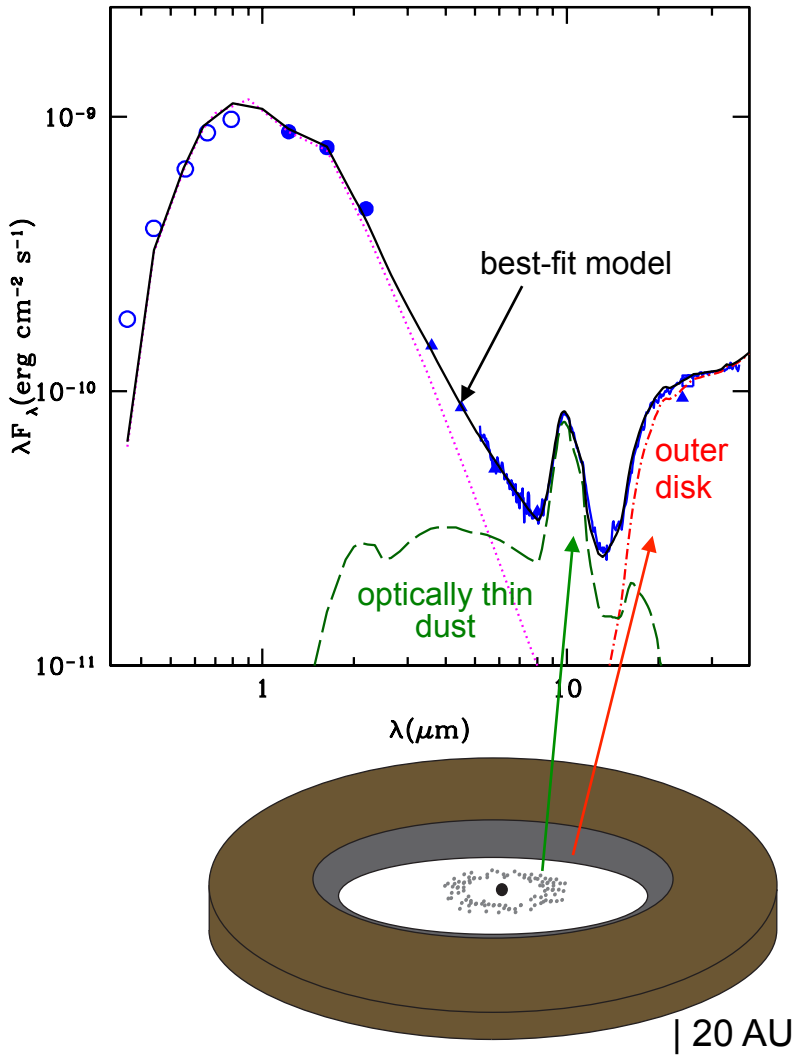
Transitional disk

Transitional disks: optically thick disks with inner holes

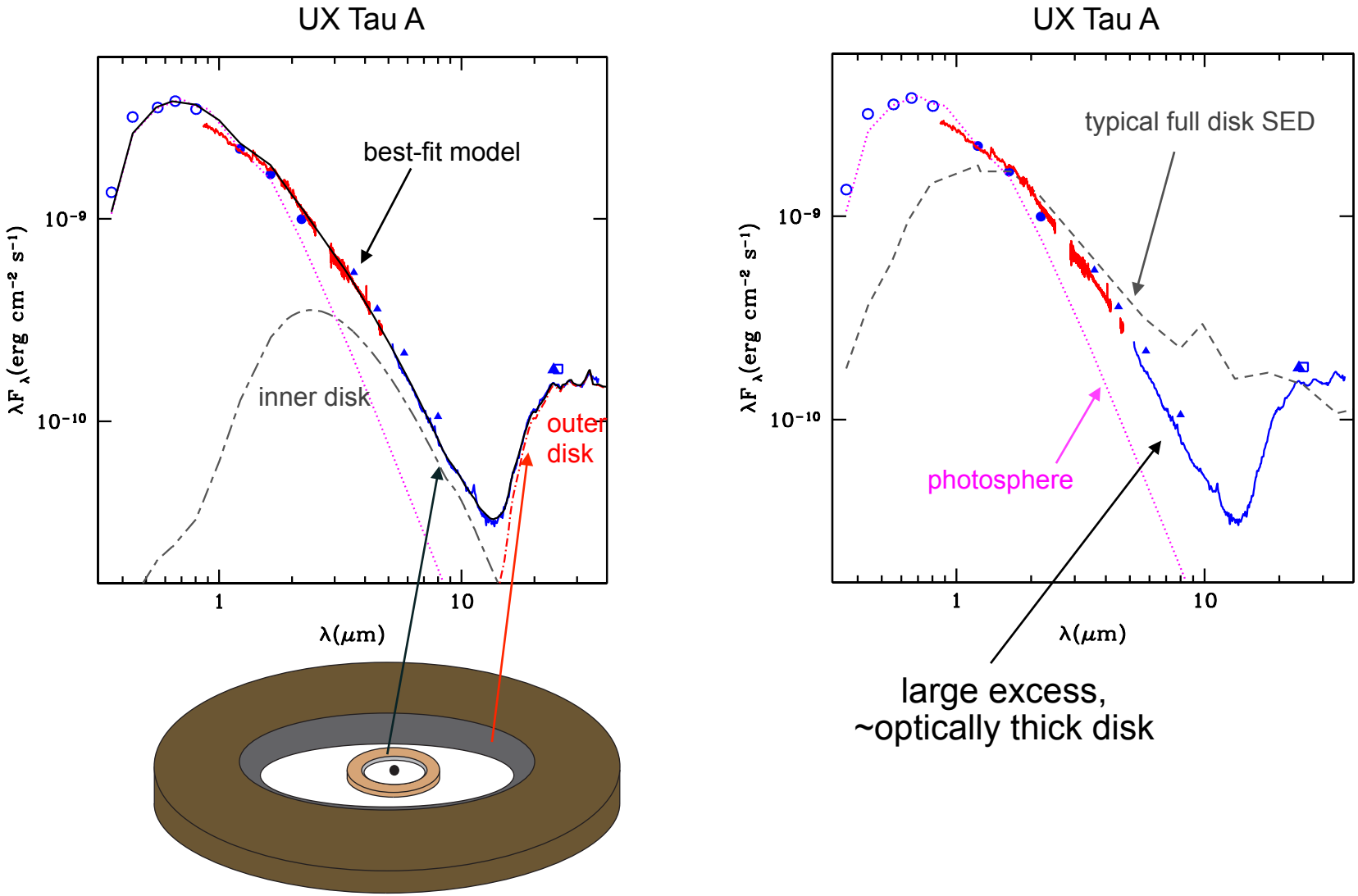
GM Aur



Calvet et al. 2005, Espaillat et al. 2011

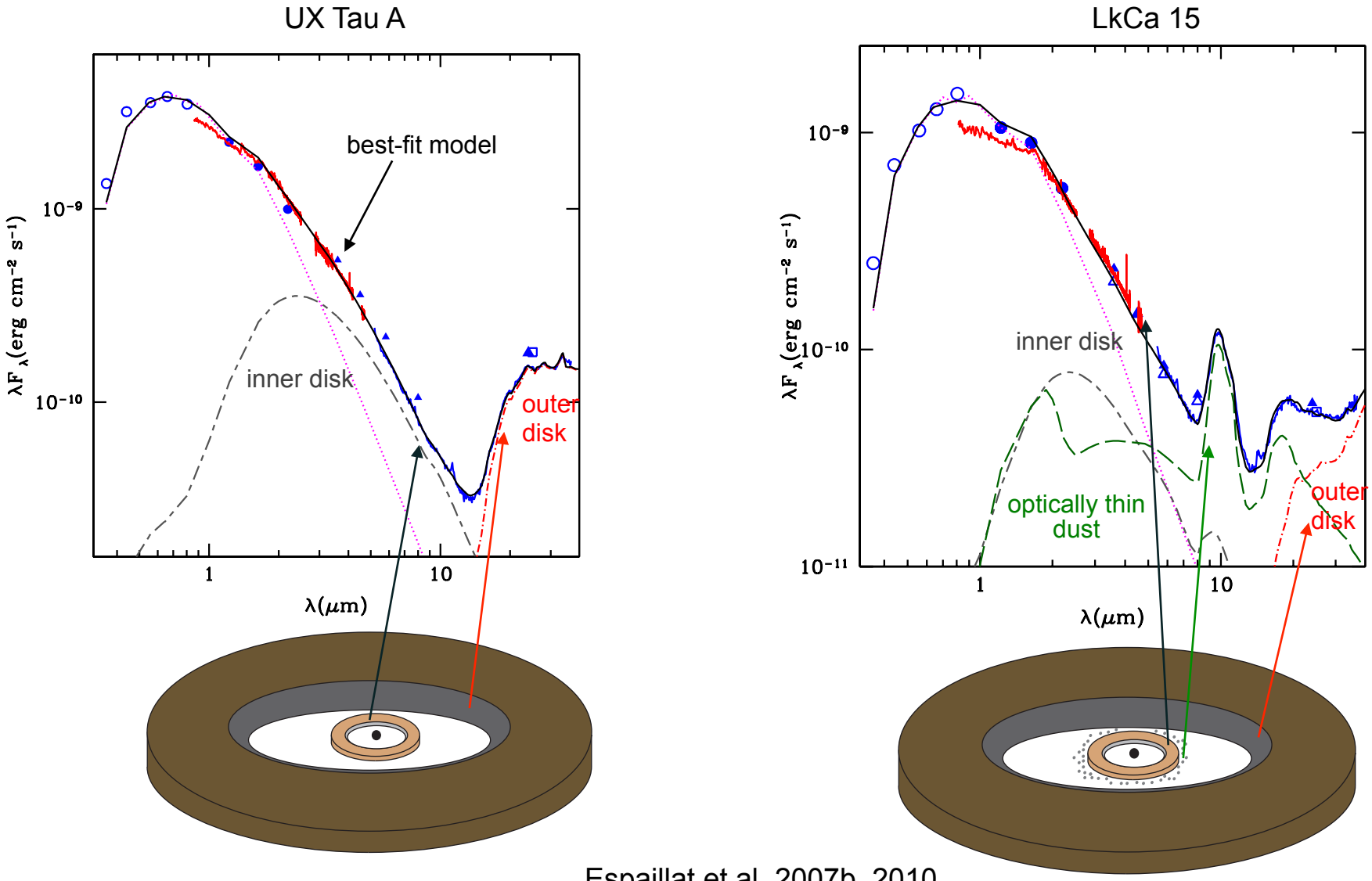


Pre-transitional disks: optically thick disks with gaps



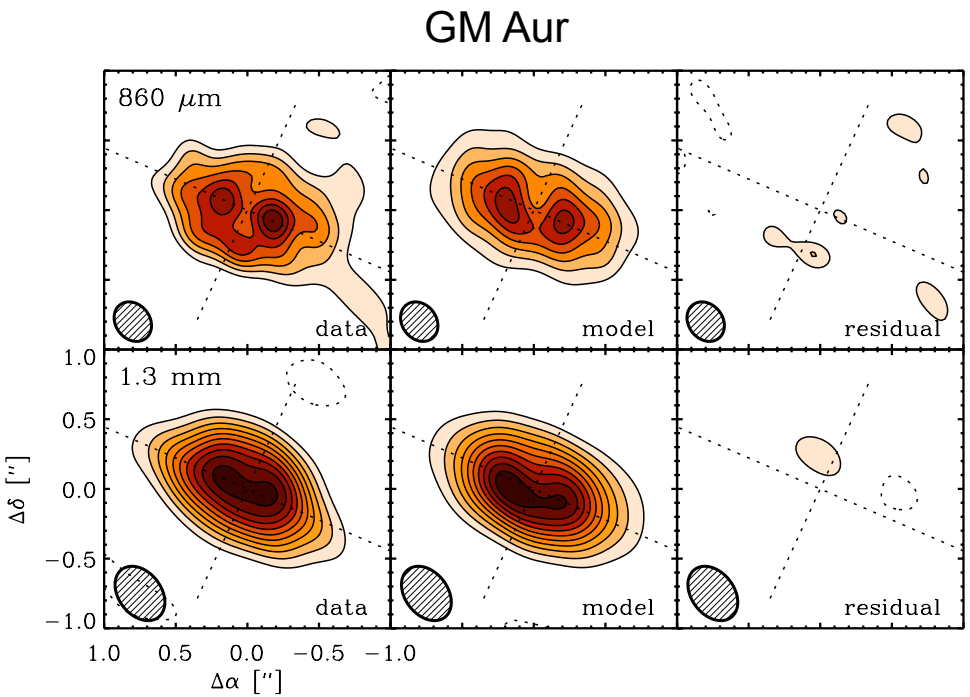
Espaillat et al. 2007b, 2010

Pre-transitional disks: optically thick disks with gaps

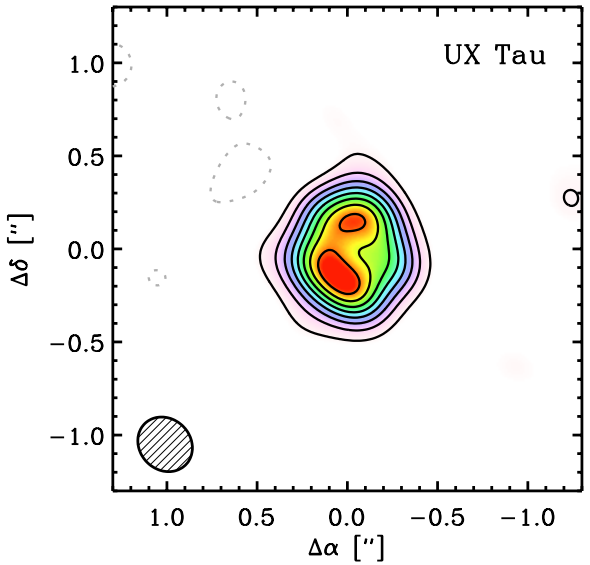


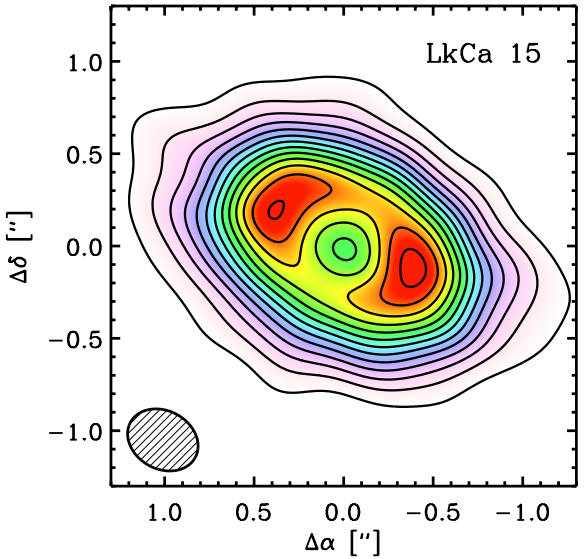
Espaillat et al. 2007b, 2010

Disk cavities have been imaged at millimeter wavelengths



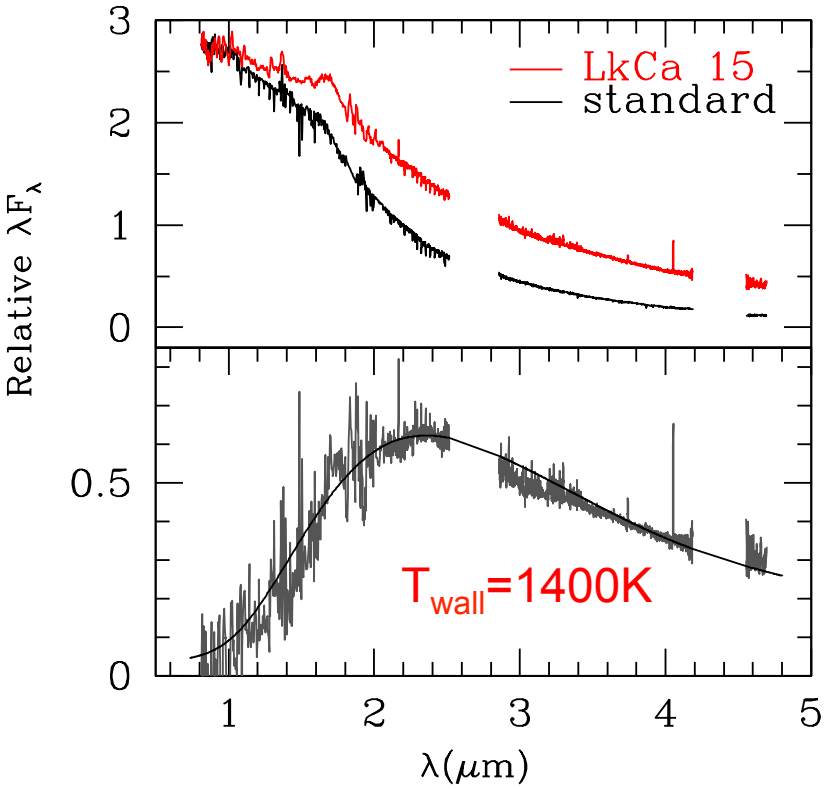
From Hughes et al. 2009; See also Dutrey et al. 2008, Isella et al. 2009, Andrews et al. 2011

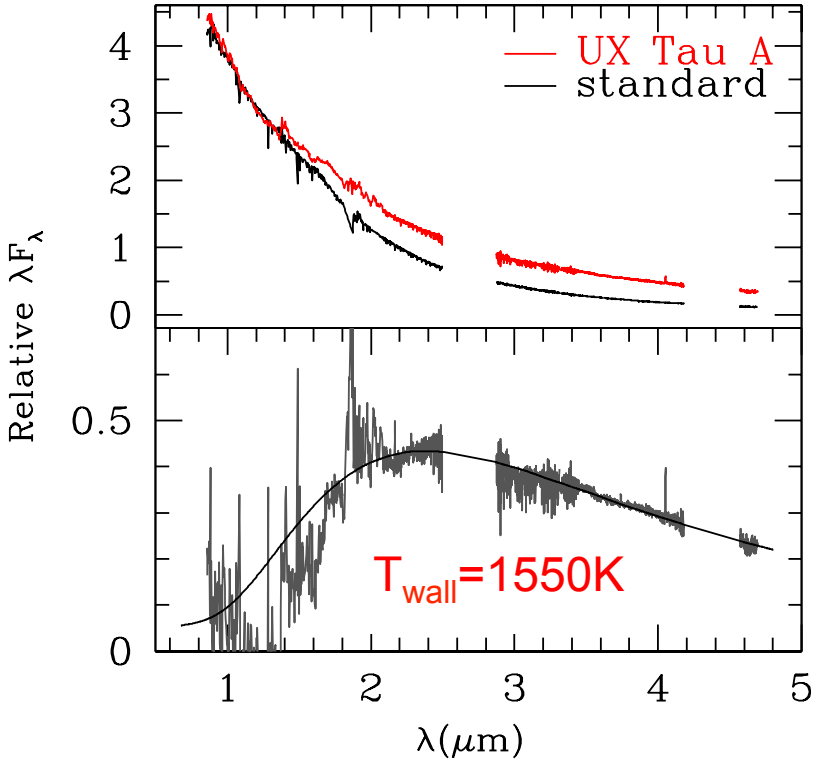




Andrews et al. 2011

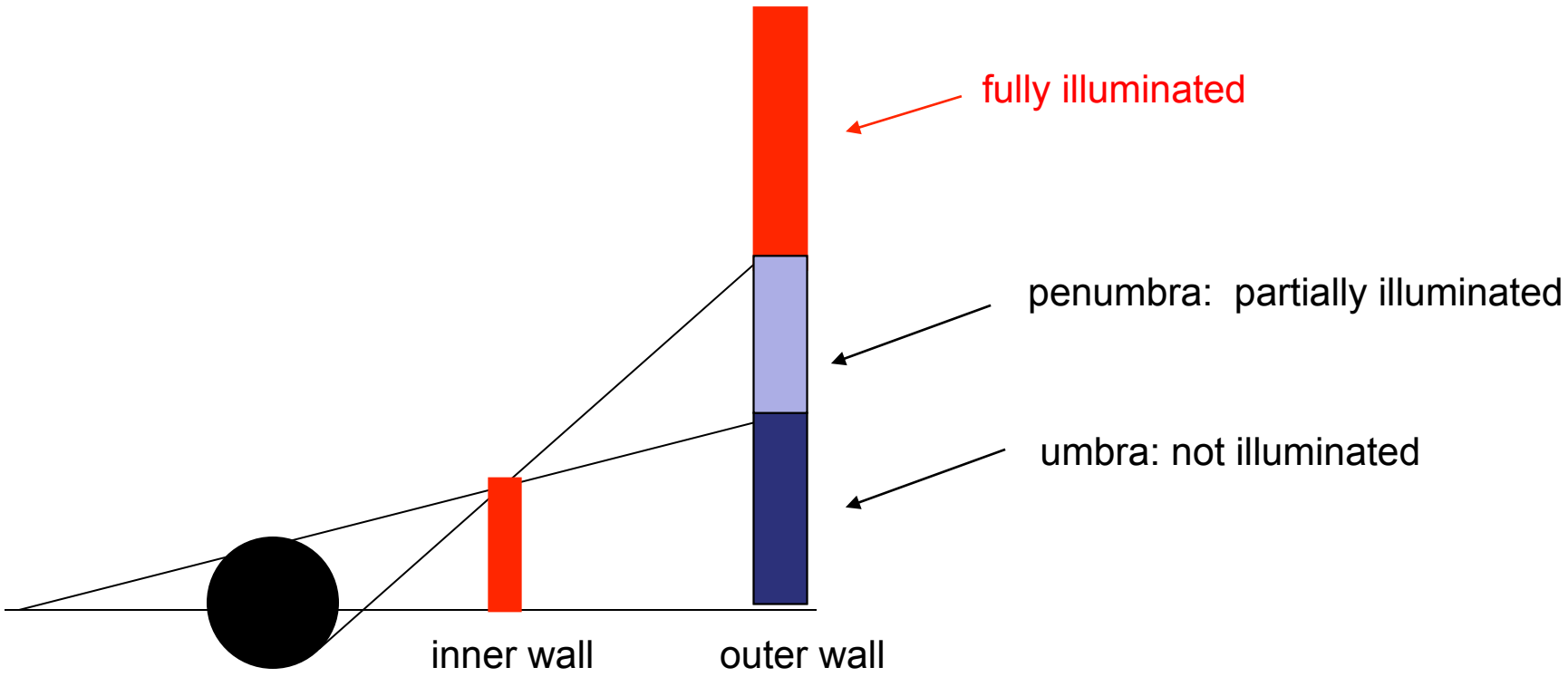
NIR excess indicates an optically thick inner disk





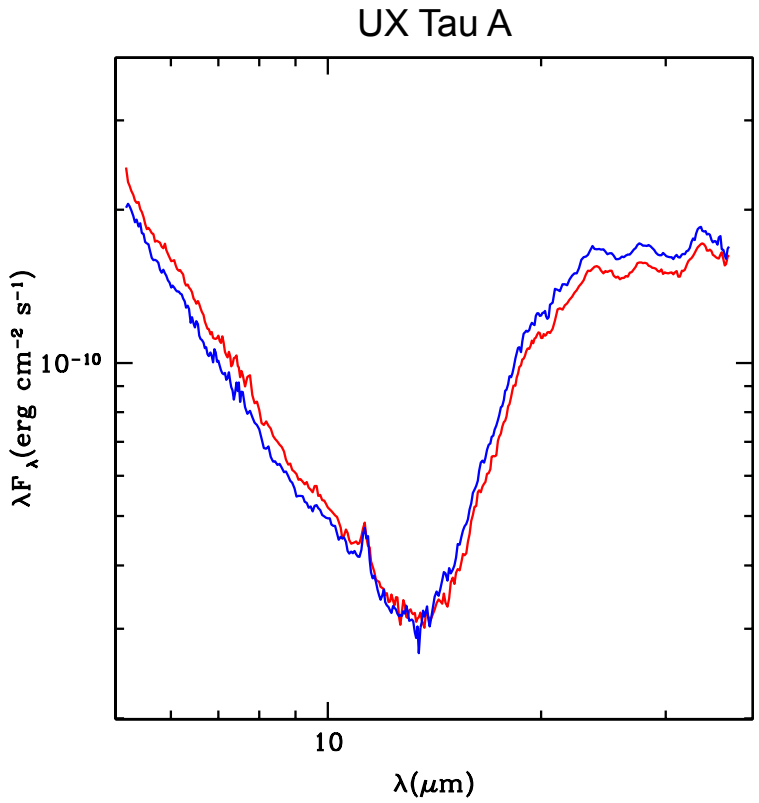
Espaillat et al. 2008, 2010

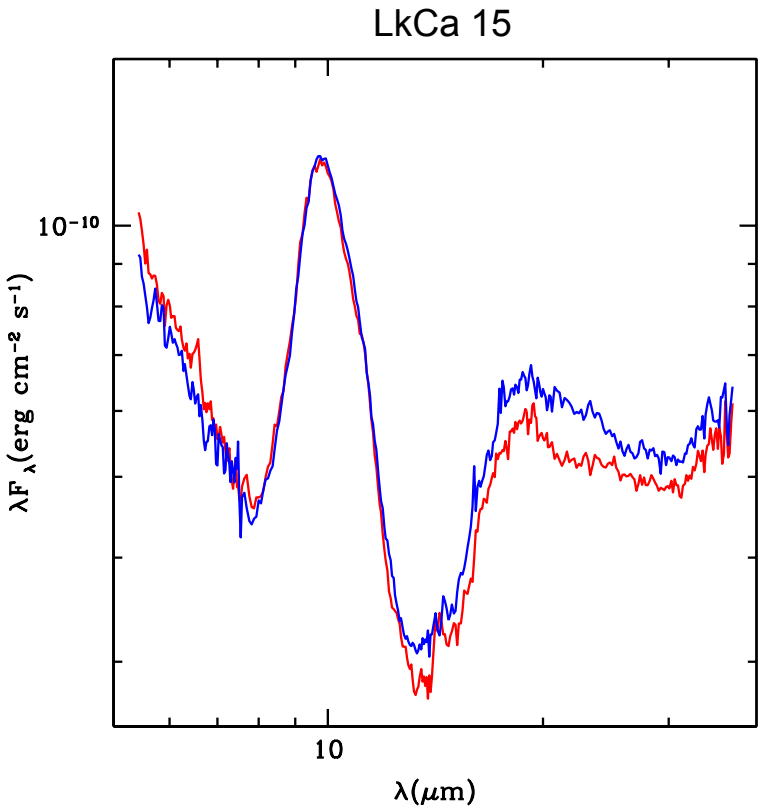
In pre-transitional disks, the inner wall casts a shadow on the outer wall

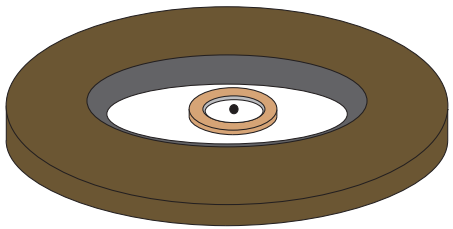


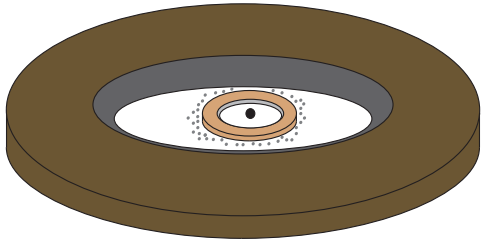
Espaillat et al. 2010

Pre-transitional disks have variable "seesaw" IR emission



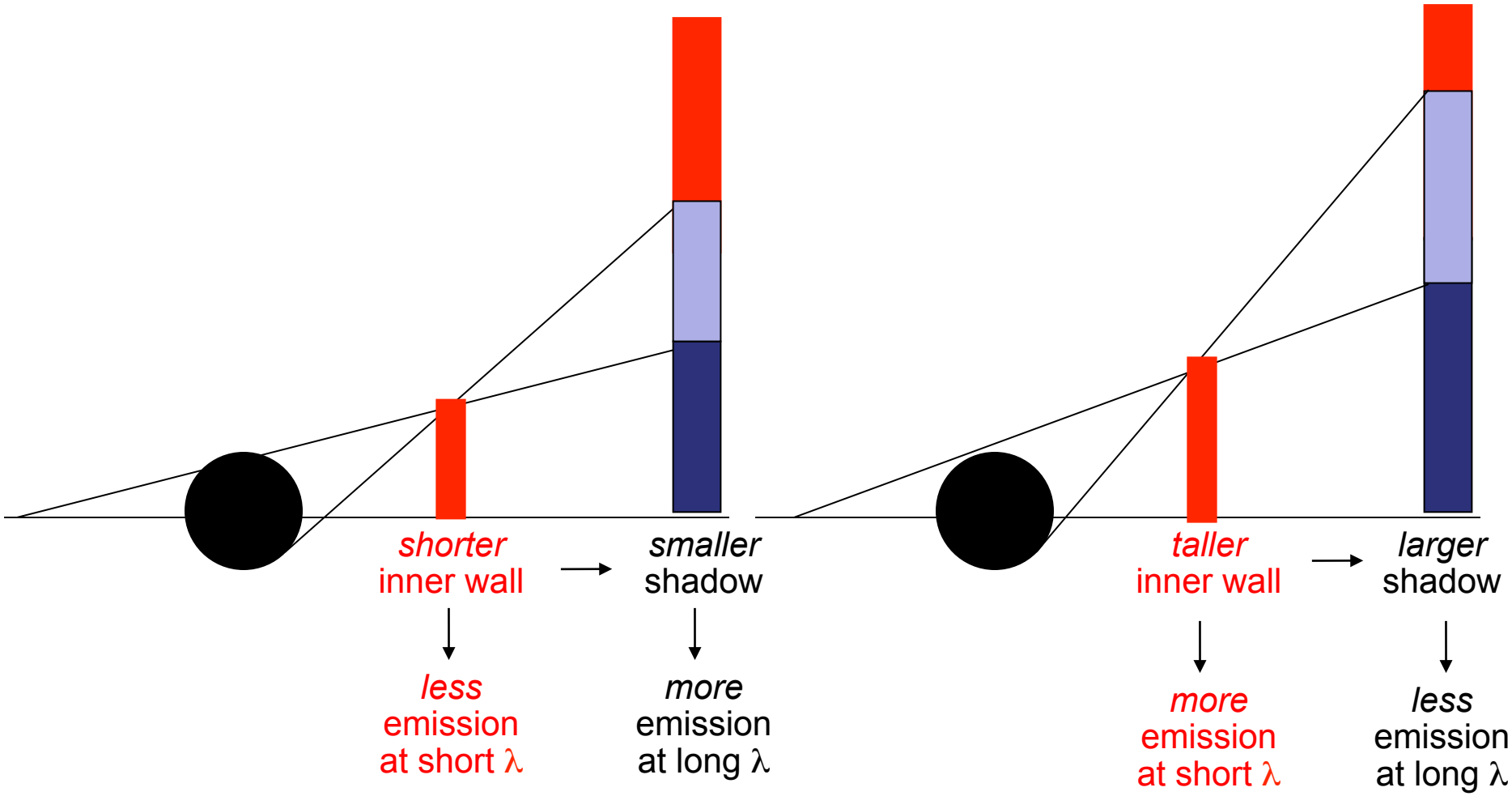




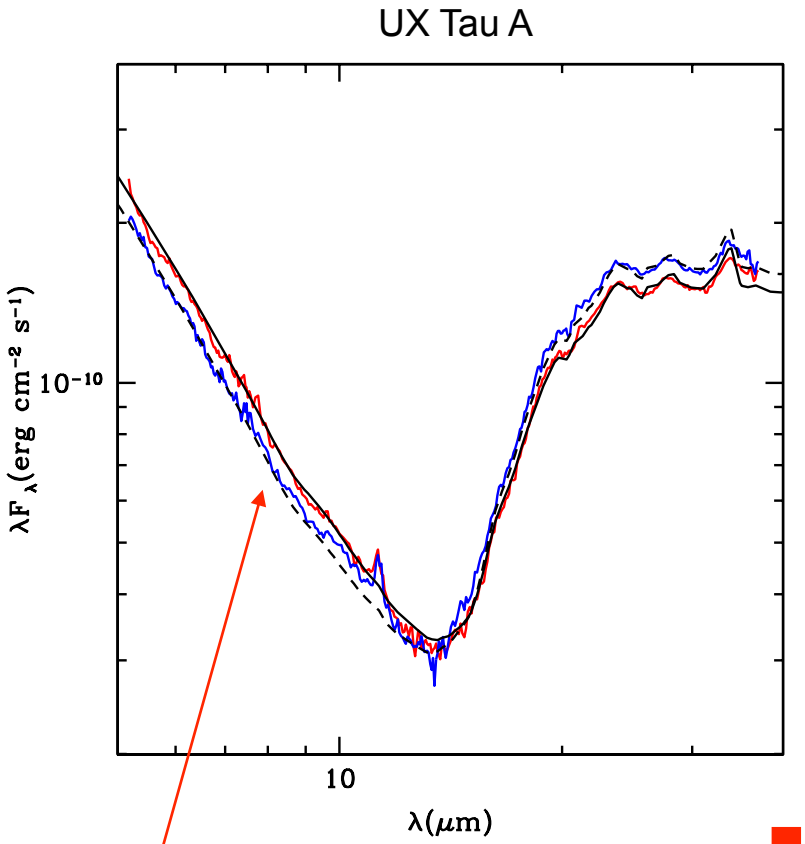


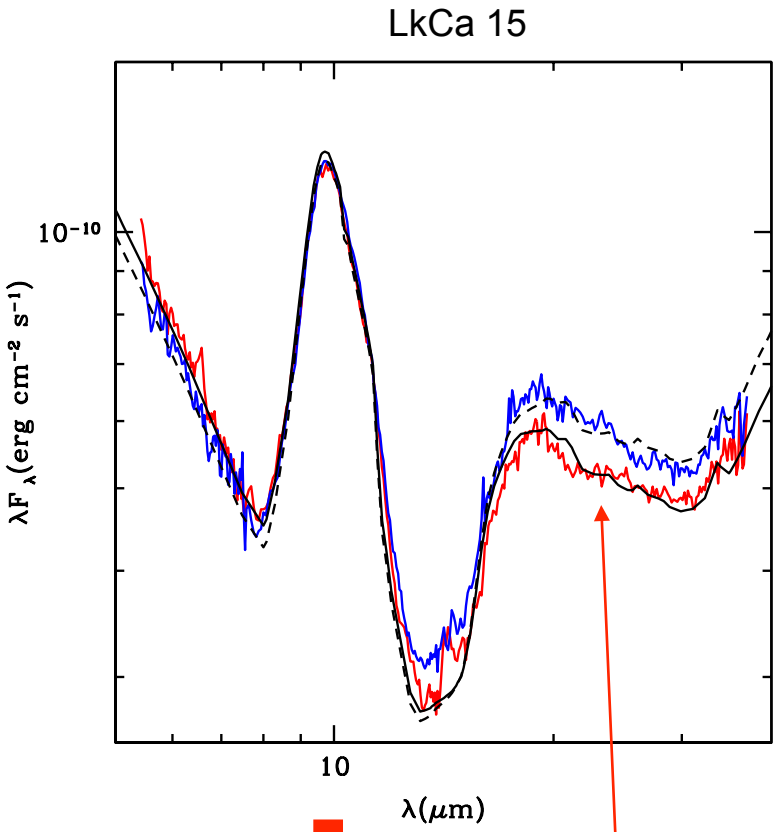
Espaillat et al. 2011; see also Muzerolle et al. 2010

Changing the height of the inner wall affects the shadow on the outer wall



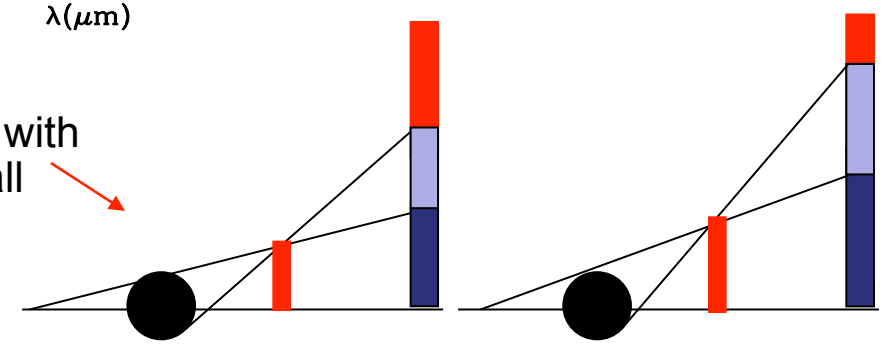
Can fit each SED with disk models by changing inner wall's height





broken line: model with shorter inner wall

solid line: model with taller inner wall



Espaillat et al. 2011

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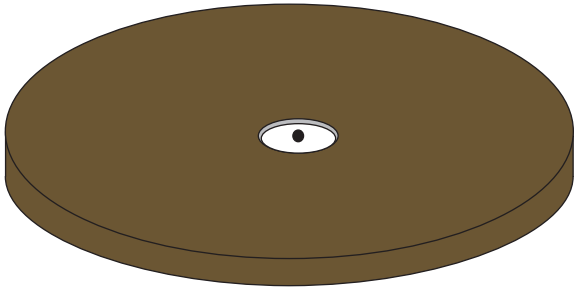
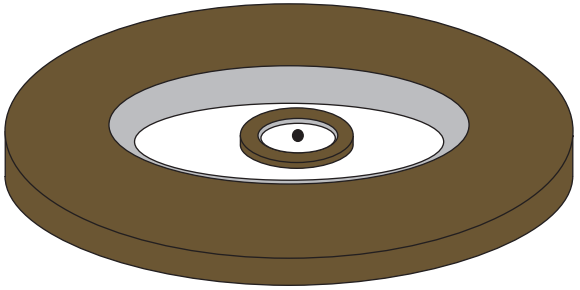
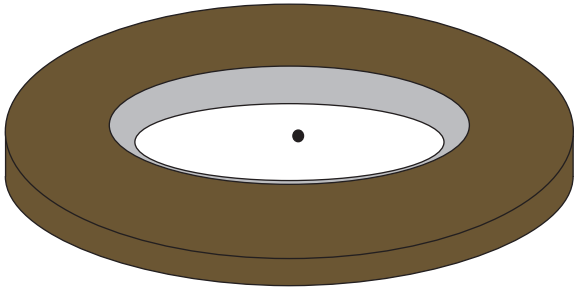


Full disk

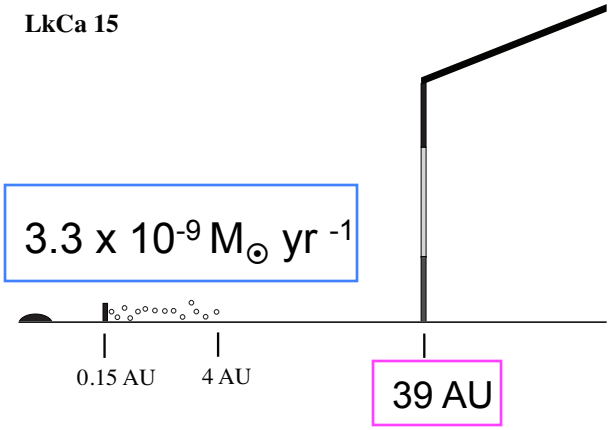


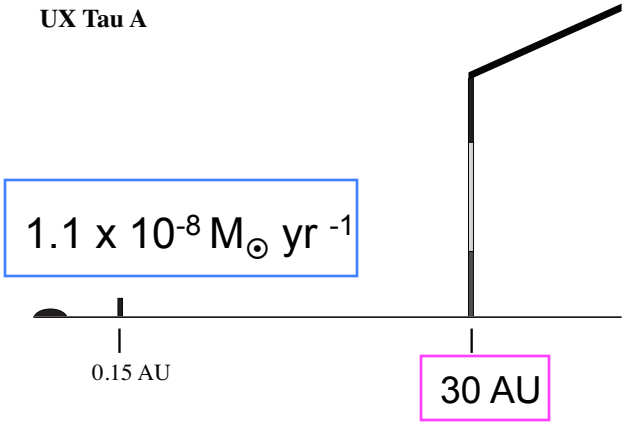
Pre-transitional disk



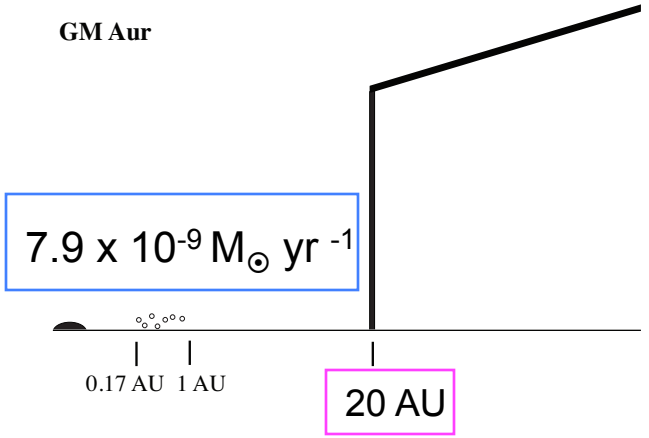
Transitional disk

Extracting constraints for disk clearing models

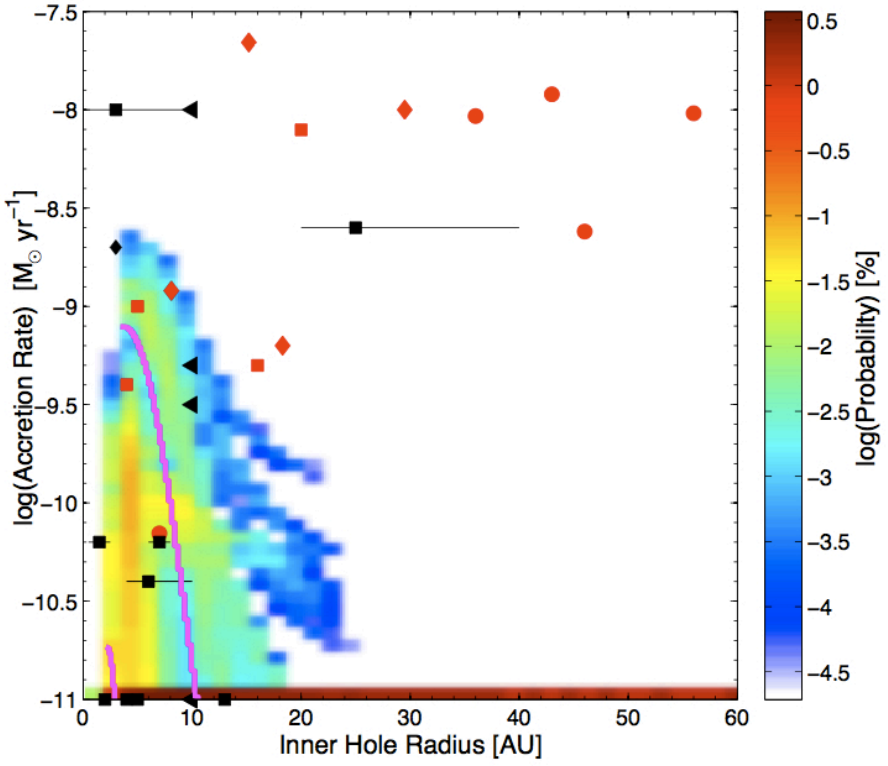




average TTS accretion rate
~ 10^{-8} $M_\odot$ yr^{-1}
Hartmann et al. 1998



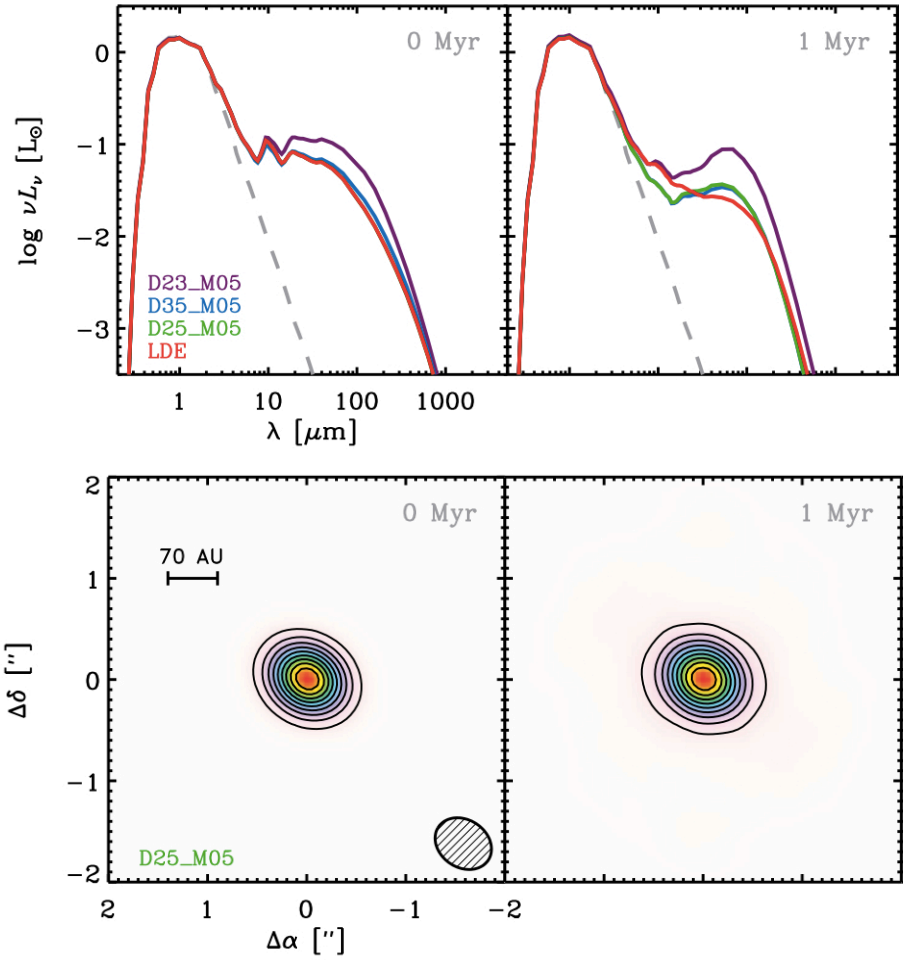
Photoevaporation models cannot explain accreting objects with large disk holes



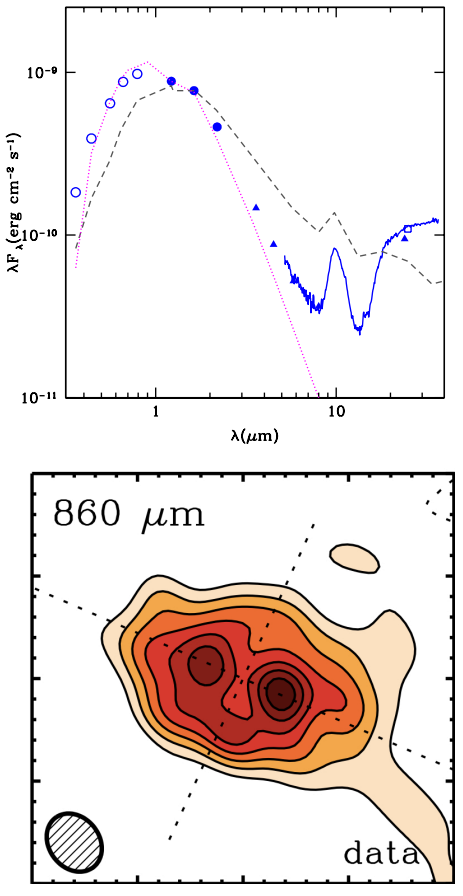
Owen et al. 2011

Grain growth models cannot explain TD/PTD SEDs and sub-millimeter images

Theoretical Predictions

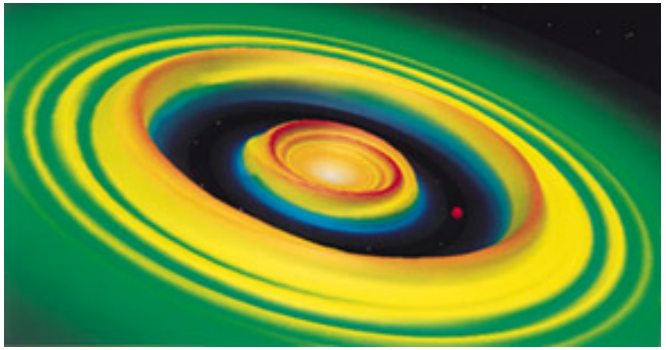


Observations of GM Aur

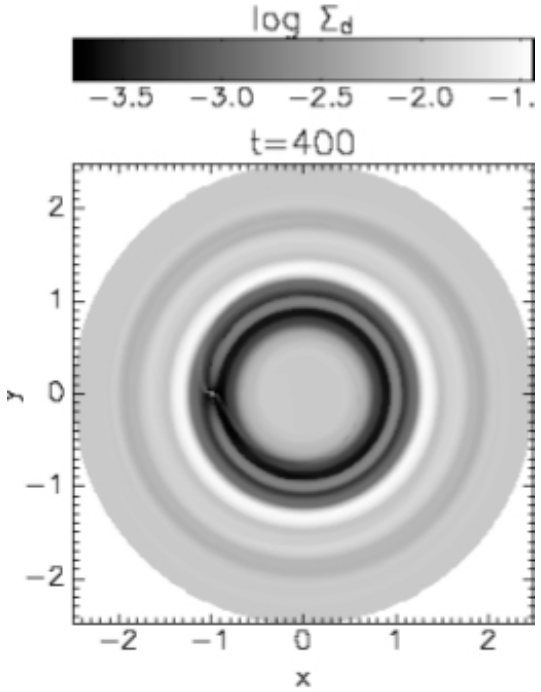


Birnstiel, Andrews, & Ercolano 2012

Planet formation models predict clearings in disks



Bryden et al. 1999

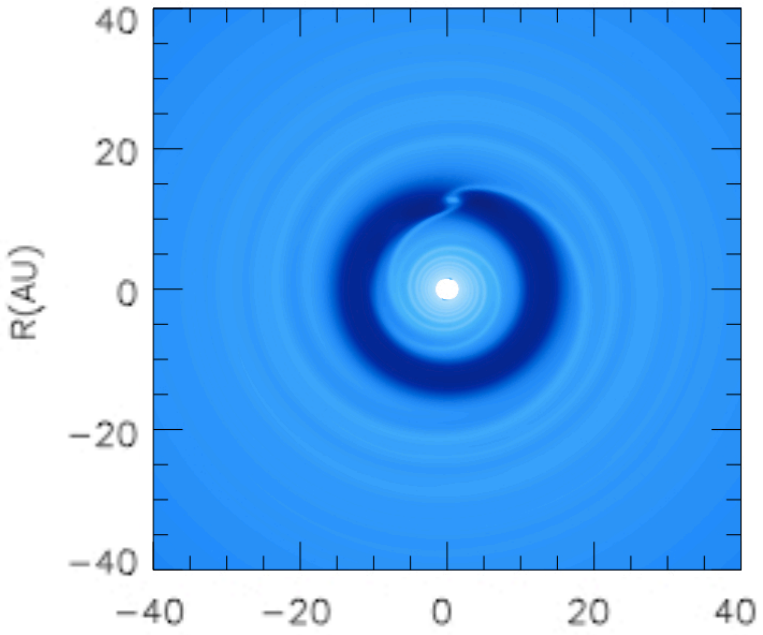


Paardekooper & Mellema 2004

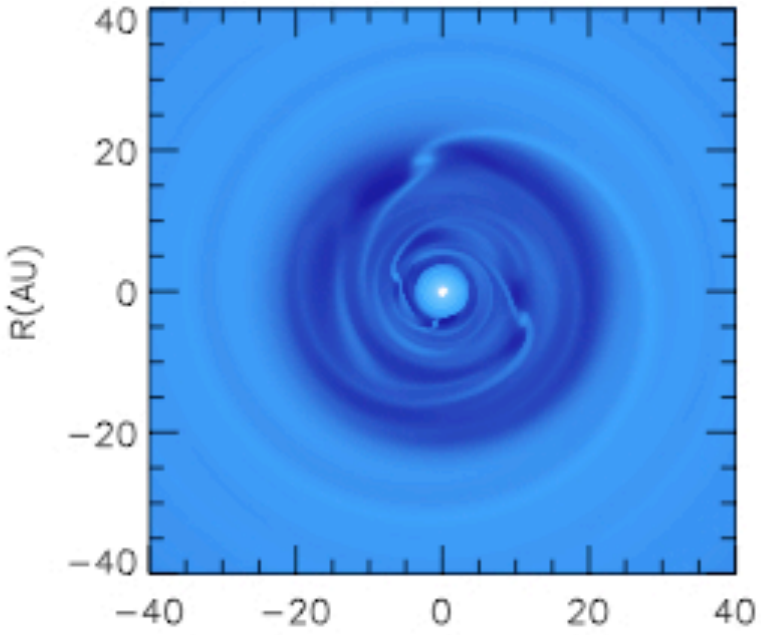
See also Goldreich & Tremaine, 1980; Ward, 1988; Paardekooper & Mellema, 2004; Quillen et al., 2004; Lubow & D'Angelo 2006; Varniere et al., 2006; Zhu et al. 2011; Dodson-Robinson & Salyk 2011

Multiple planets open a large disk gap

One Planet

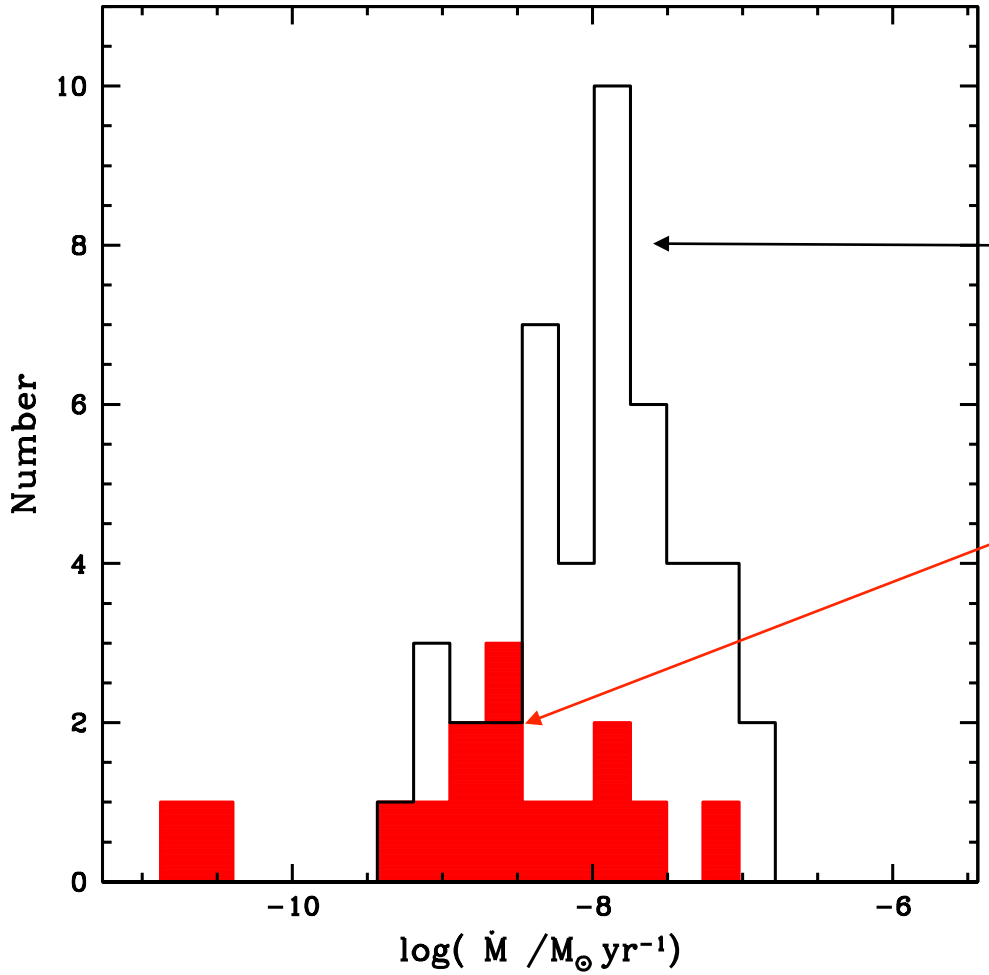


Four Planets



Zhu et al. 2011

Mass accretion rates of TD/PTD are lower than full disks, but still significant



Full Disks:
$1.3 \times 10^{-8}\ M_\odot\ yr^{-1}$

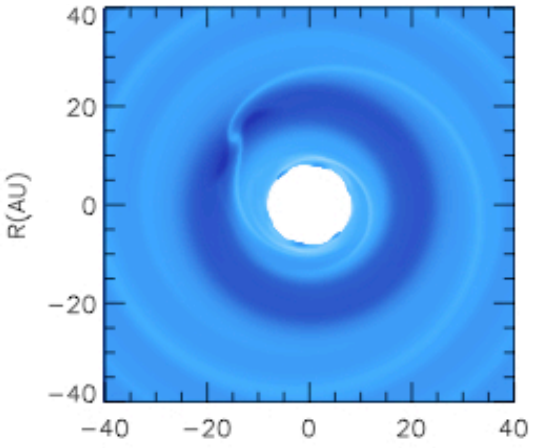
Pre-transitional & Transitional Disks:
$3.1 \times 10^{-9}\ M_\odot\ yr^{-1}$

Espaillat et al. 2012; also Najita et al. 2007

Dust filtration cannot explain small dust distribution

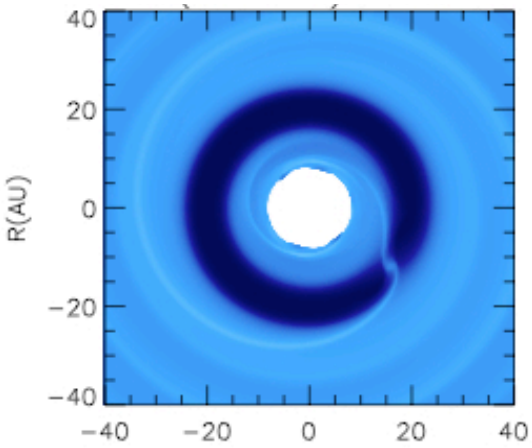
Gas

Distribution



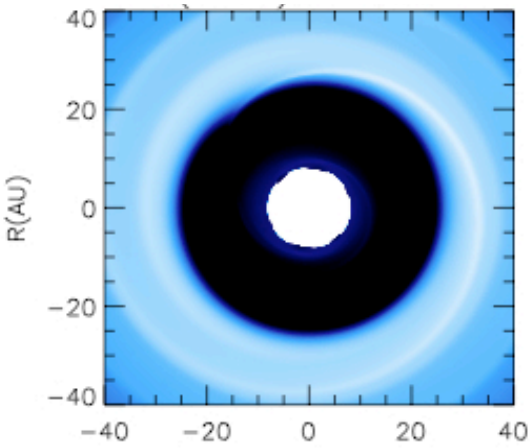
Small Dust Distribution

(<30 microns)



Large Dust Distribution

(~ 1mm)

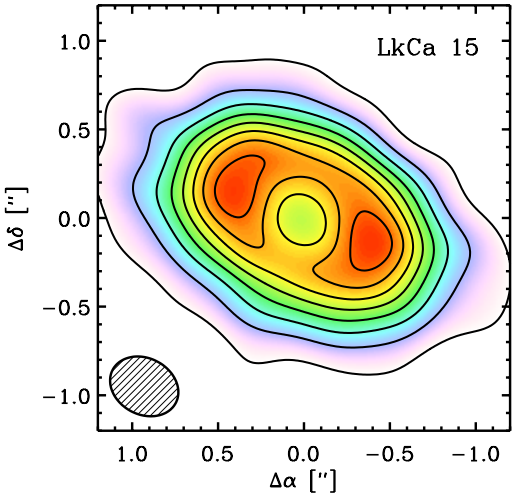


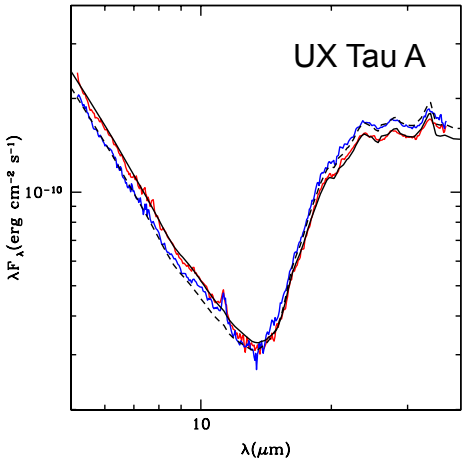
Zhu et al. 2012

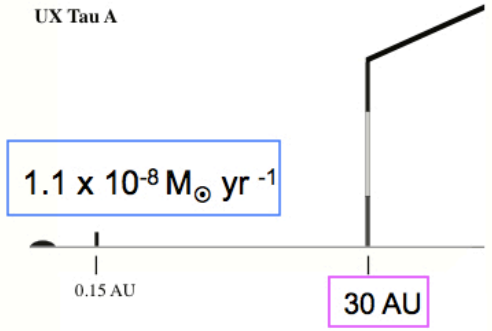
Characterizing planet-forming disks around young stars

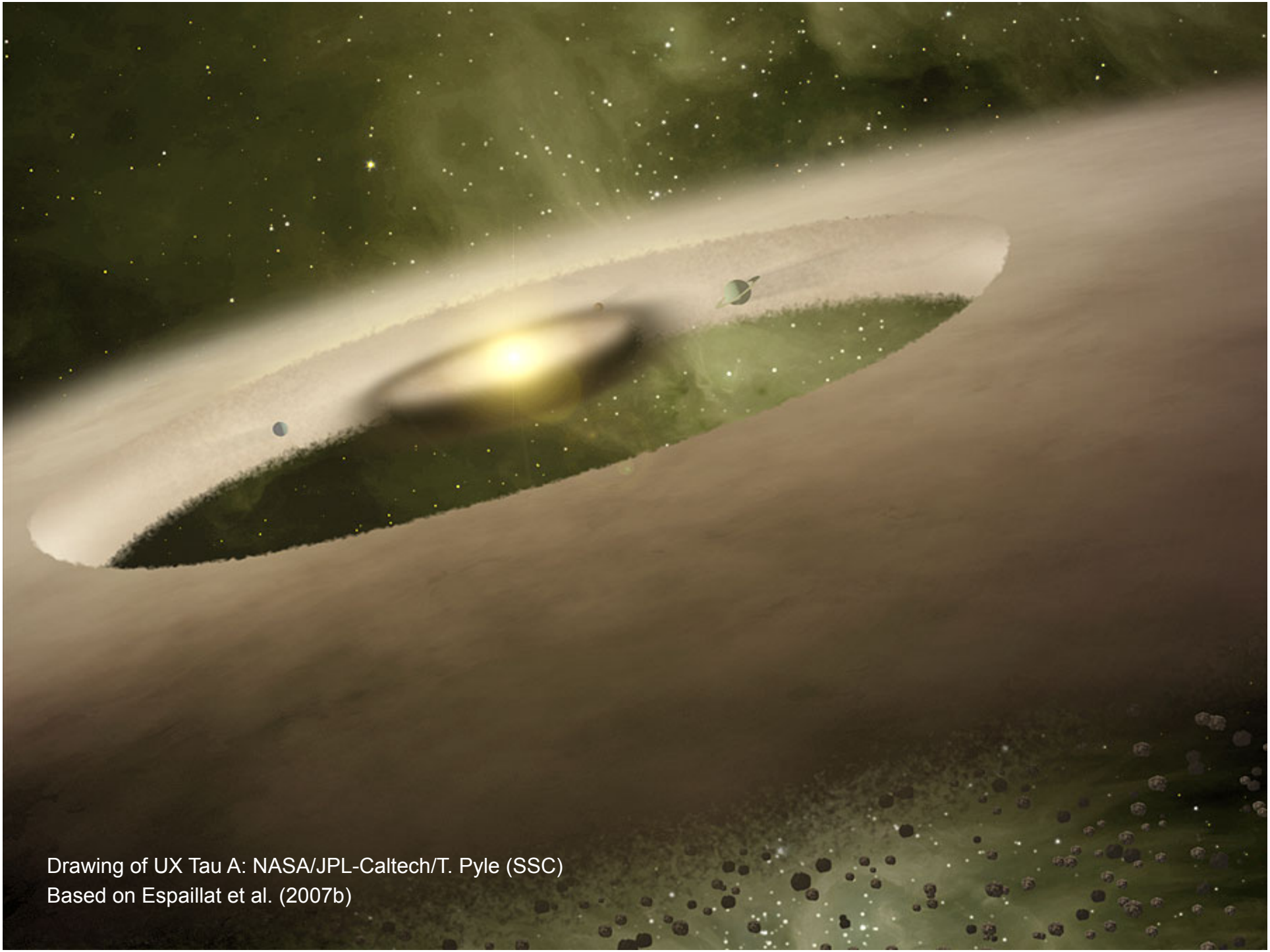
- We have detected gaps and holes in disks
  - holes/gaps identified through SED modeling
  - confirmed with NIR and millimeter images
  - disks with gaps display seesaw IR variability

- We can extract constraints from the observations for planet formation theories
  - large gaps in the dust disk are accompanied by substantial gas accretion rates onto the star









Drawing of UX Tau A: NASA/JPL-Caltech/T. Pyle (SSC)
Based on Espaillat et al. (2007b)