Characterizing Planet-Forming Disks Around Young Stars

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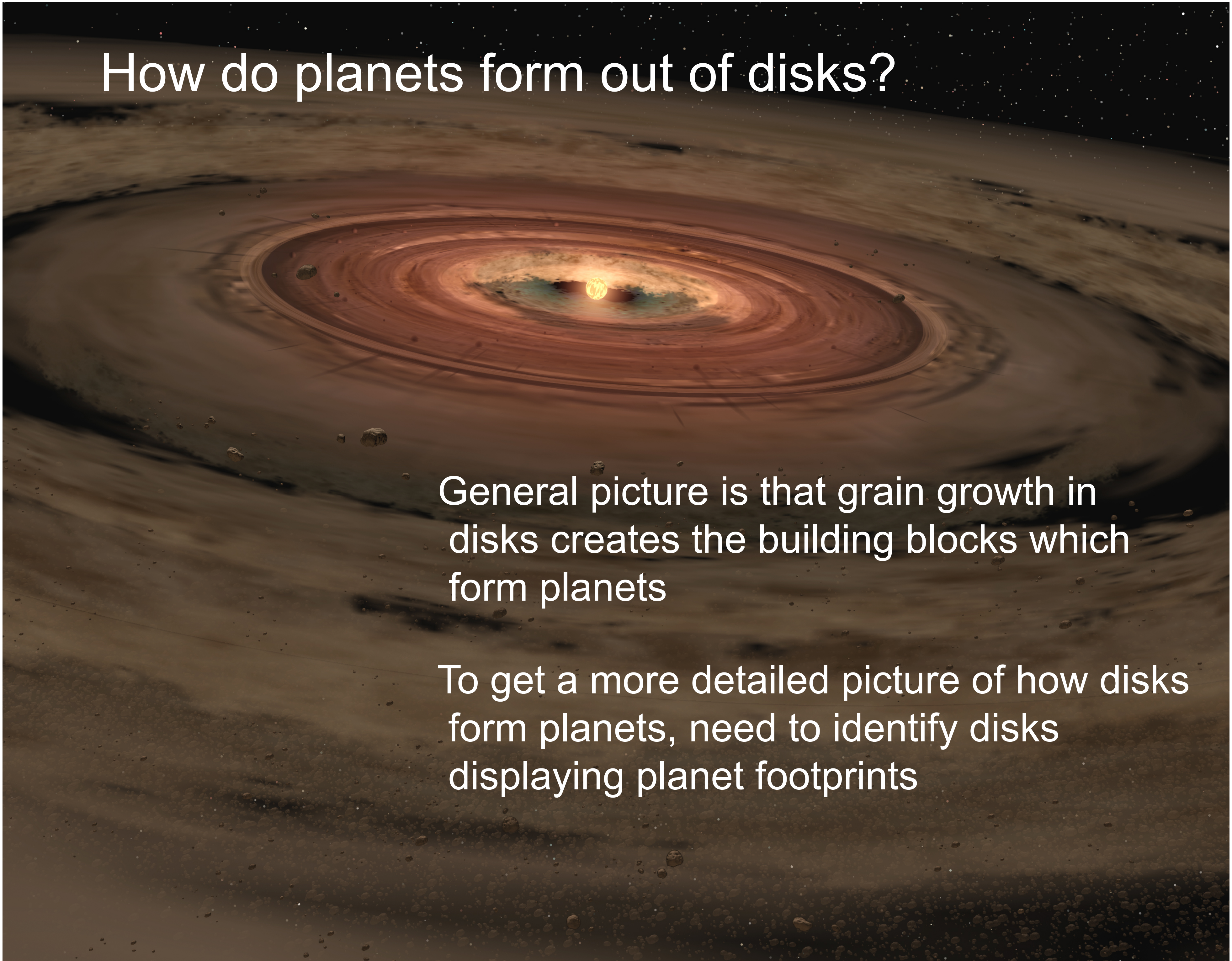
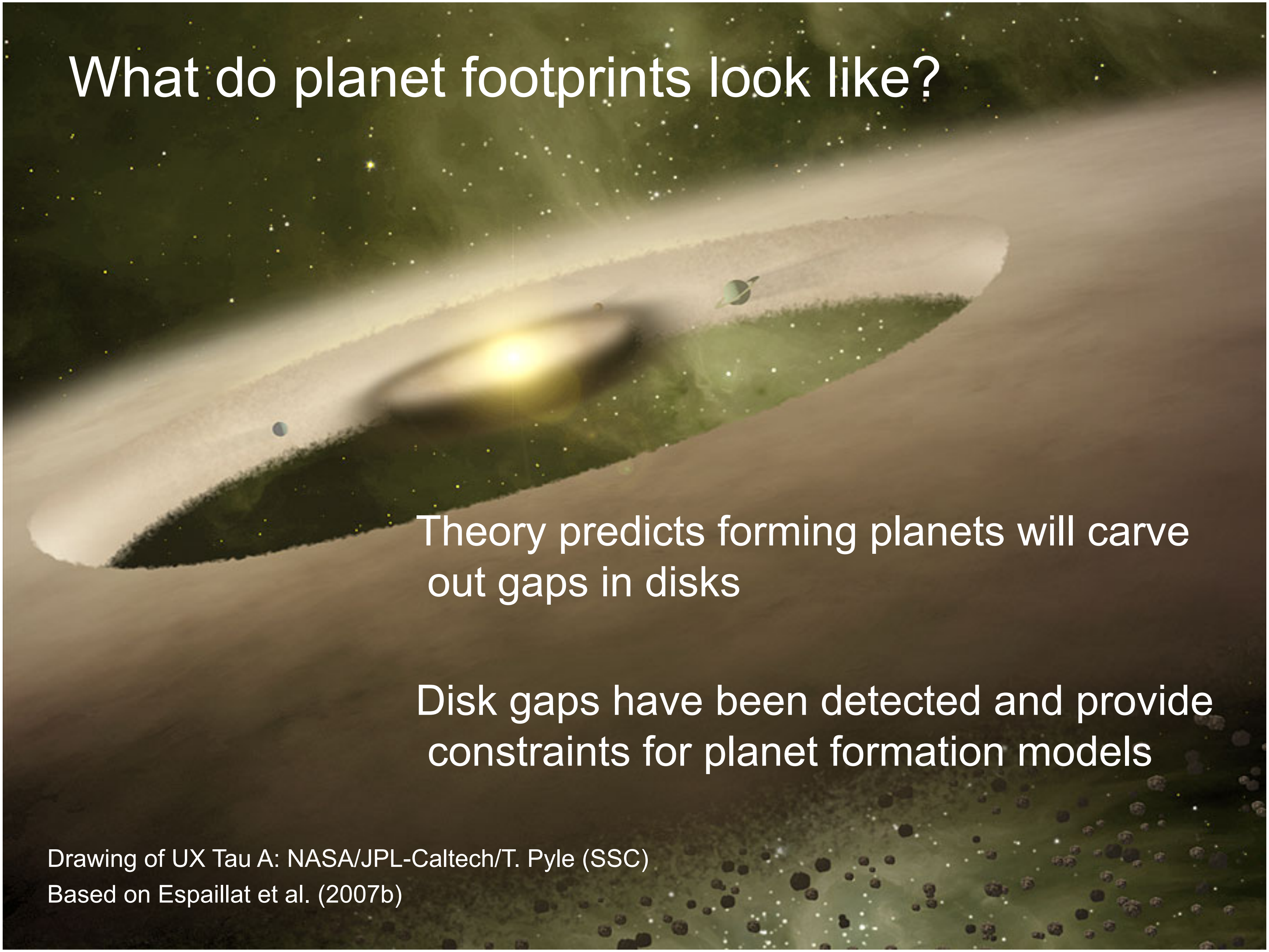
Ben Sargent (RIT), Dan Watson (U Rochester), David Wilner (CfA), Zhaohuan Zhu (Princeton U)



How do planets form out of disks?

General picture is that grain growth in disks creates the building blocks which form planets

To get a more detailed picture of how disks form planets, need to identify disks displaying planet footprints


What do planet footprints look like?
Theory predicts forming planets will carve out gaps in disks
Disk gaps have been detected and provide constraints for planet formation models
Drawing of UX Tau A: NASA/JPL-Caltech/T. Pyle (SSC)
Based on Espaillat et al. (2007b)

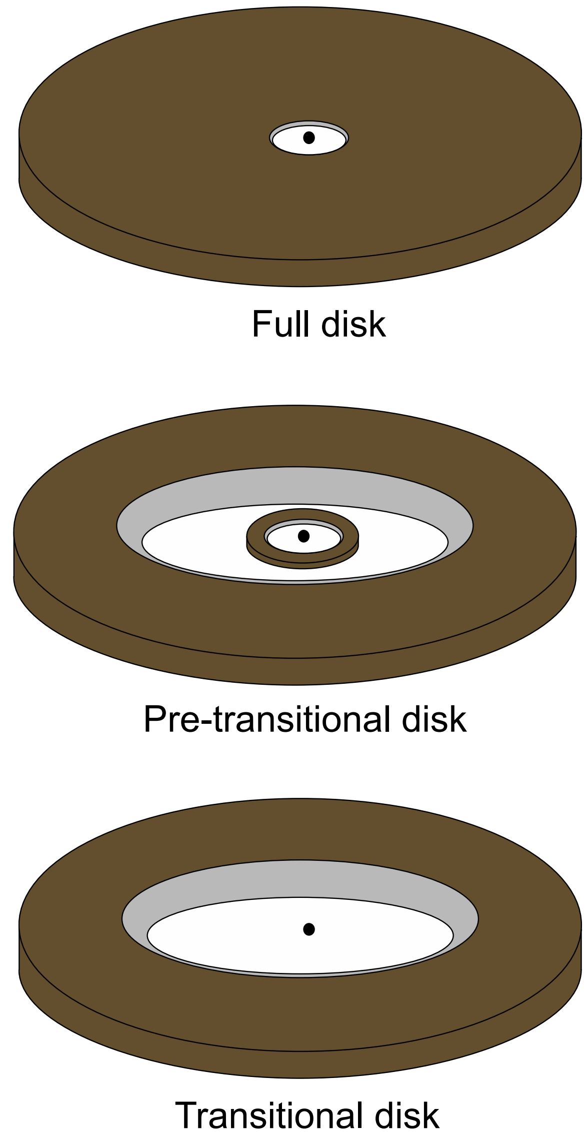
Tracking Planet Footprints

What evidence do we have for planets forming in young disks?

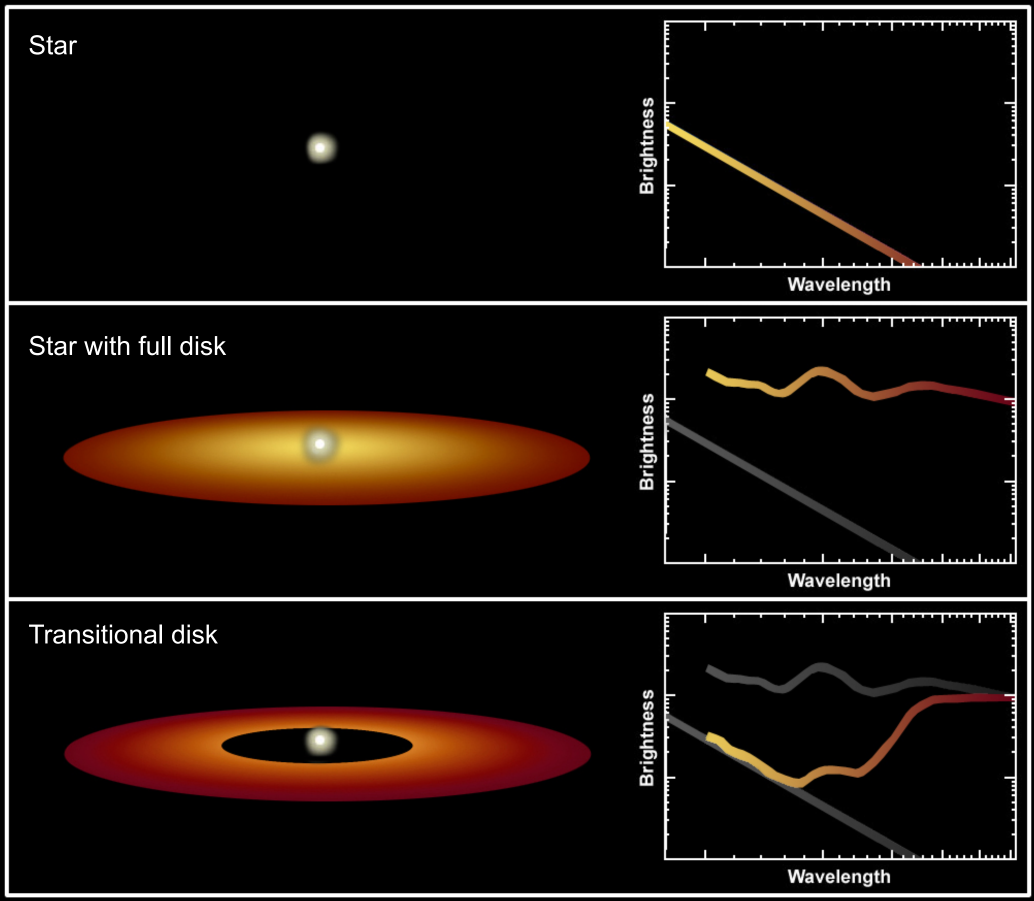
- SEDs & modeling of transitional disks
- SEDs & modeling of pre-transitional disks
- Infrared variability
- Planet imaging searches

What constraints from the observations can we apply to planet clearing models?

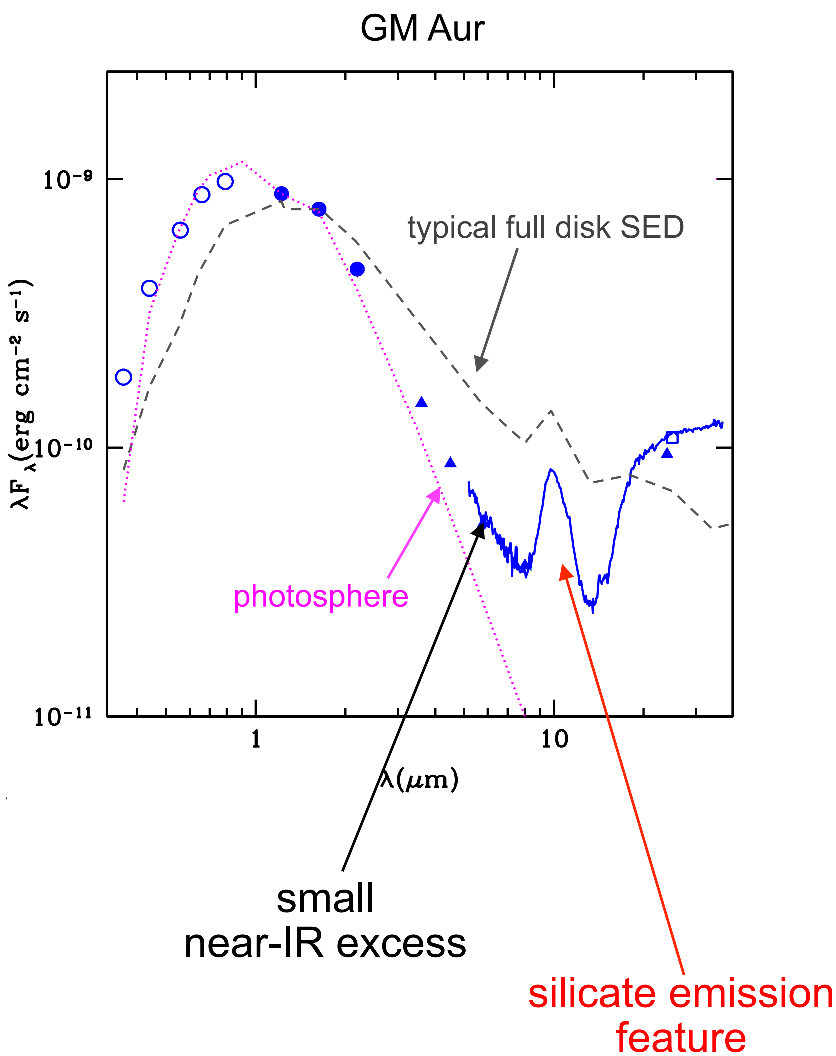
Where do we go from here?

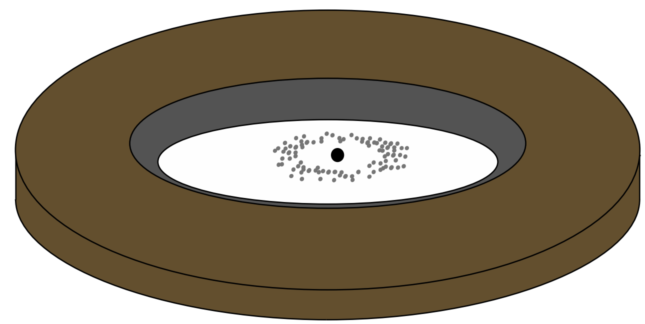


Transitional disks have dips in IR SED



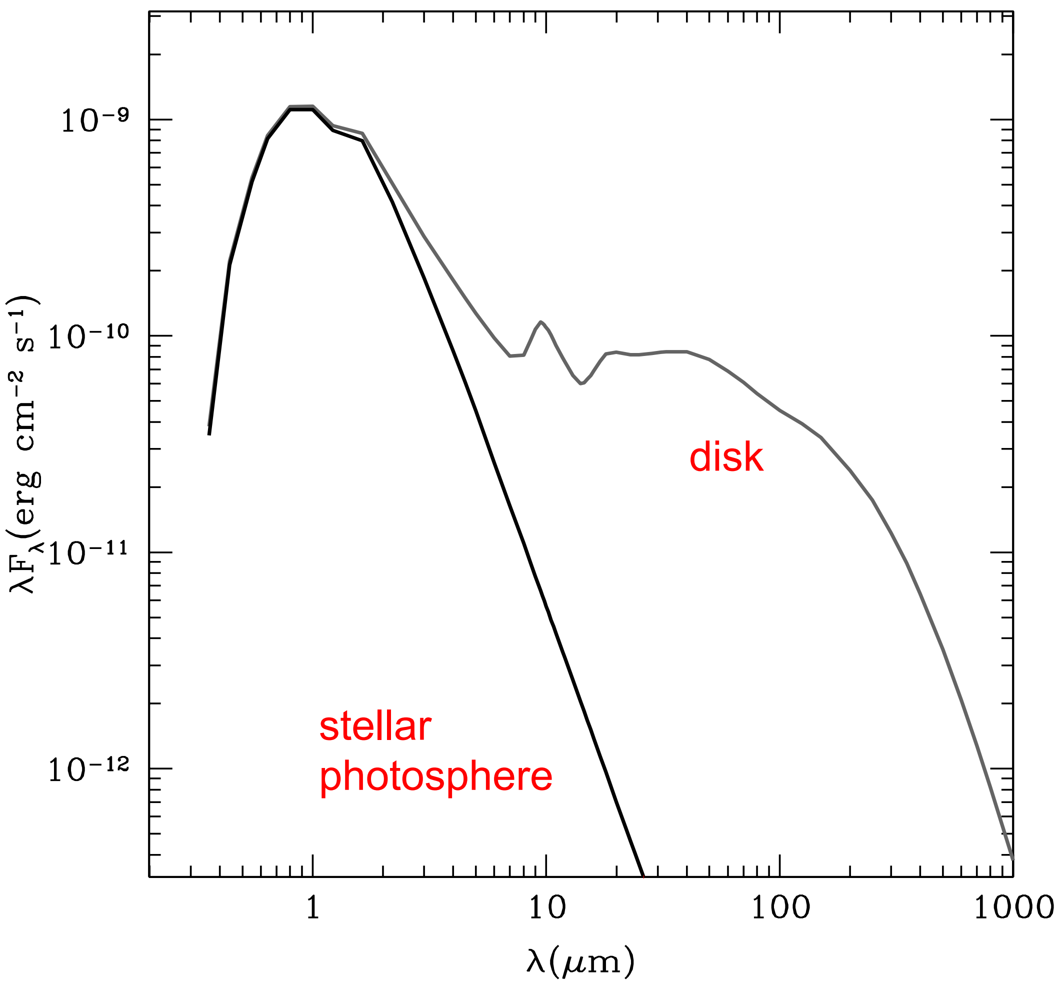
Some inner holes contain small, hot dust





Calvet et al. 2005; Espaillat et al. 2011

Simulating SEDs to probe disk structure



D' Alessio et al. 1998, 1999, 2001, 2005, 2006

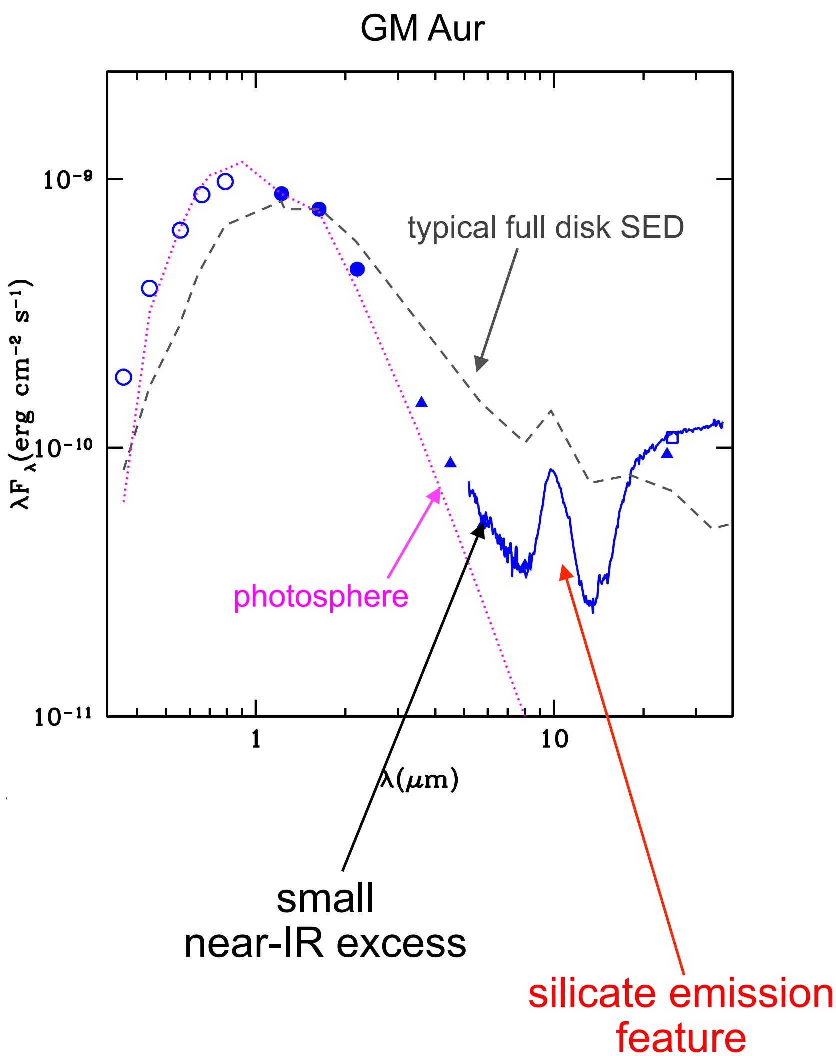
Assumptions:

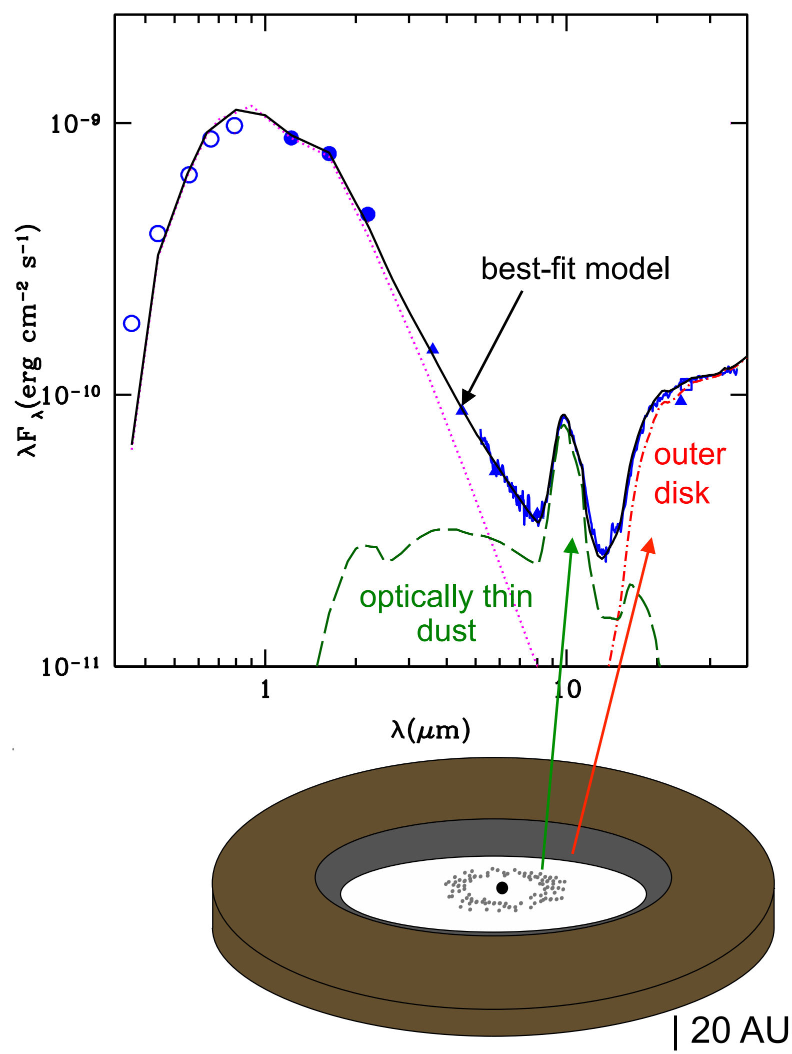
- Steadily accreting
- Geometrically thin
- Vertical hydrostatic equilibrium
- Dust and gas are thermally coupled

Input parameters:

- Stellar properties
  - luminosity, radius, & effective temperature
- Mass accretion rate
- Shakura & Sunyaev viscosity parameter (α)
- Dust properties

Some inner holes contain small, hot dust

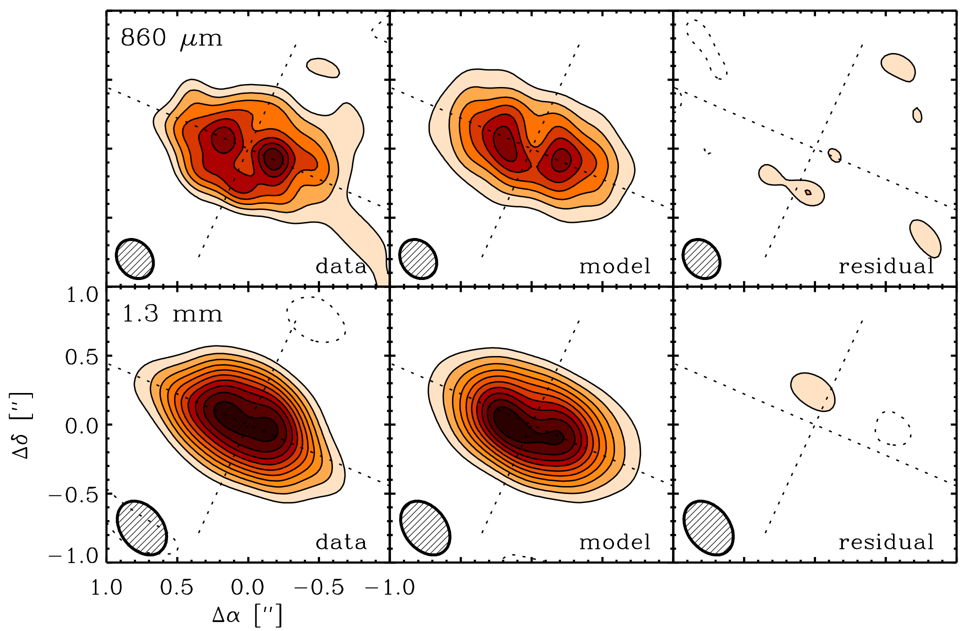




Calvet et al. 2005; Espaillat et al. 2011

Inner holes confirmed via millimeter interferometric imaging

Continuum Emission of GM Aur

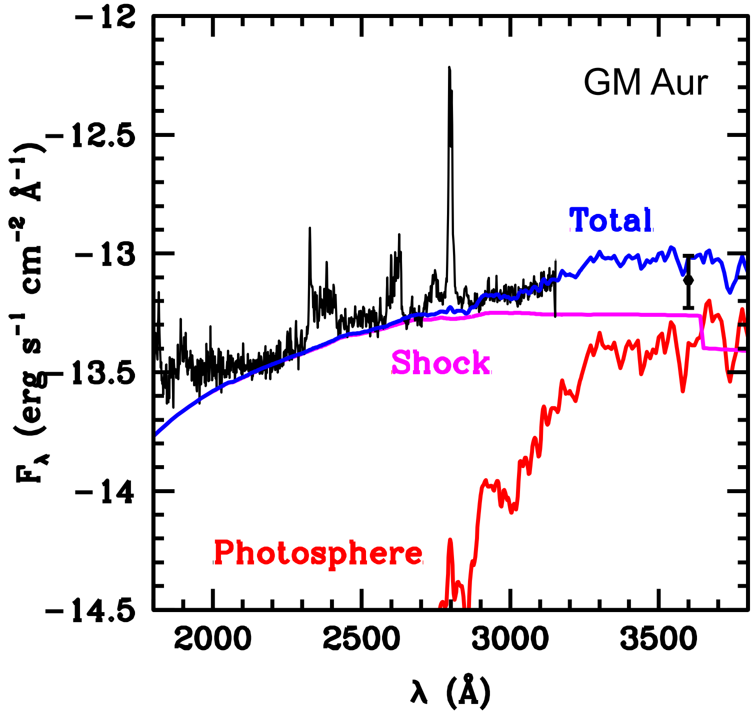


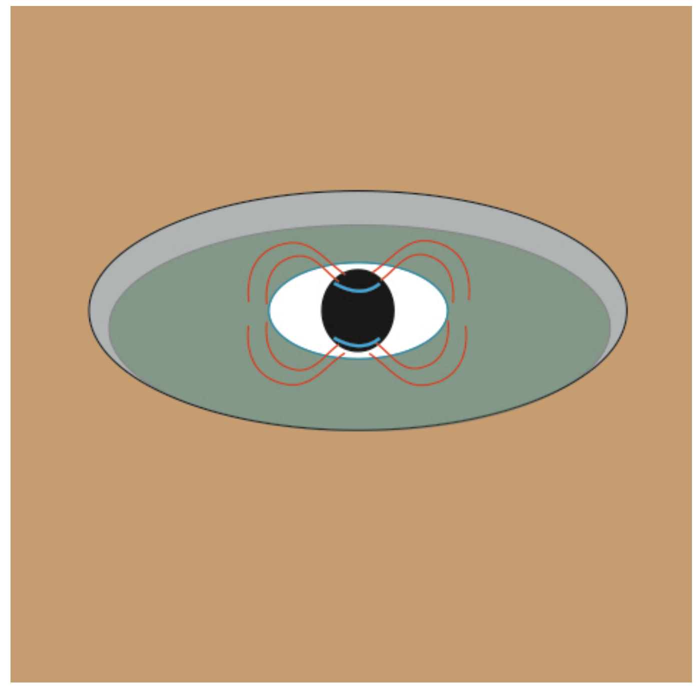
Hughes, Andrews, Espaillat et al. 2009; see also Dutrey et al. 2008;

talks by S. Casassus, M. Fukgawa, A. Isella, F. Menard, N. van der Marel

Gas can continue to accrete across inner hole

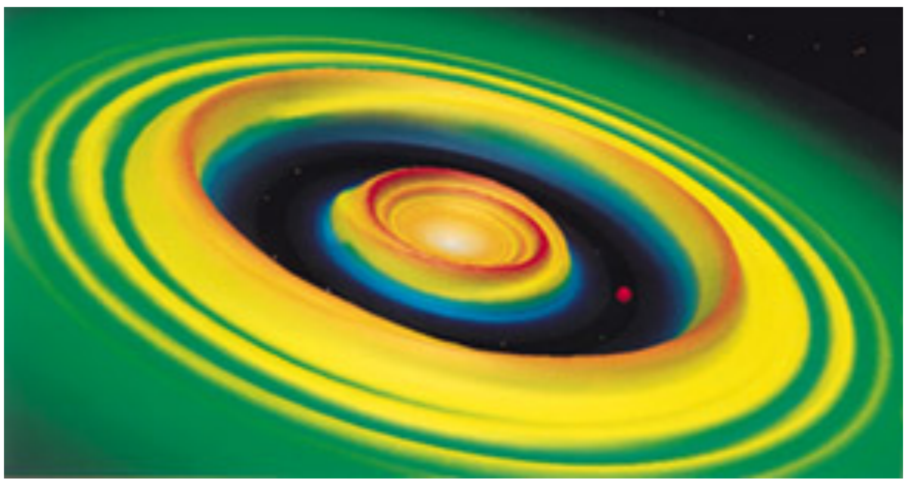
$8 \times 10^{-9}\, M_\odot\, yr^{-1}$

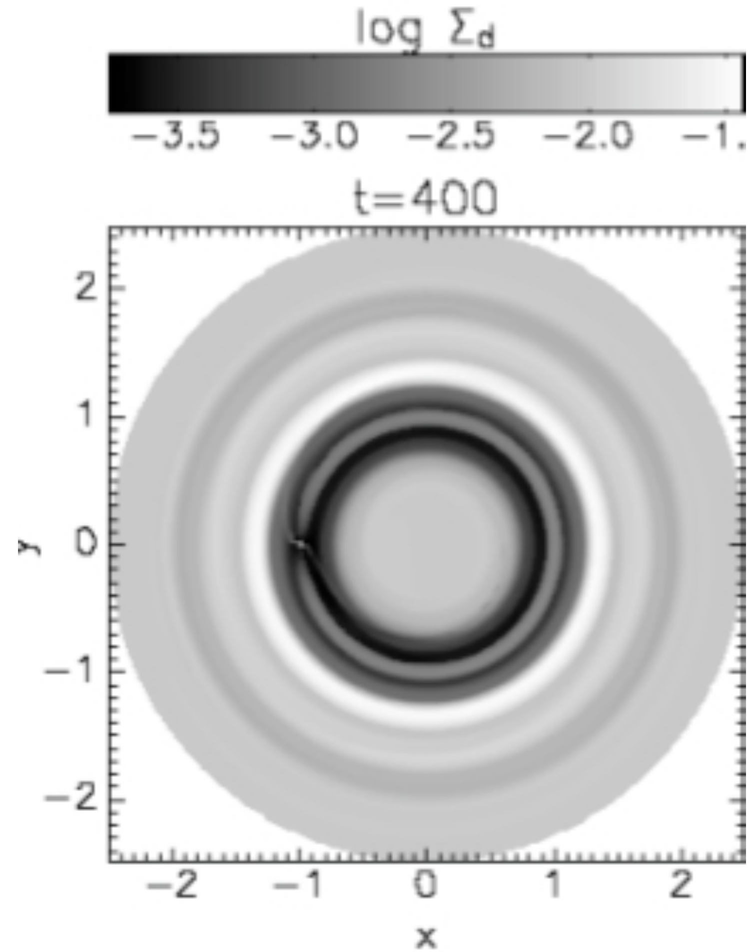




Ingleby et al. 2011; talk by S. Casassus, poster 4 by S. Bruderer

Disk clearing mechanisms: planets



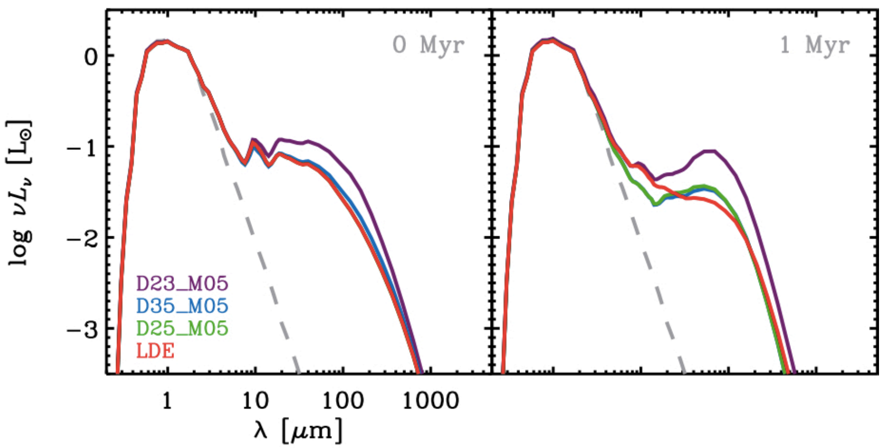


Bryden et al. 1999

Paardekooper & Mellema 2004

Disk clearing mechanisms: grain growth

Theoretical Predictions



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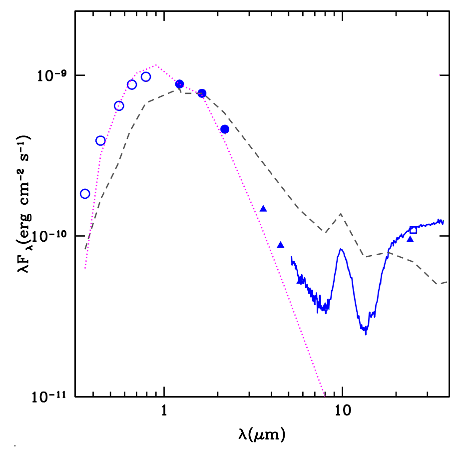
Observations of GM Aur

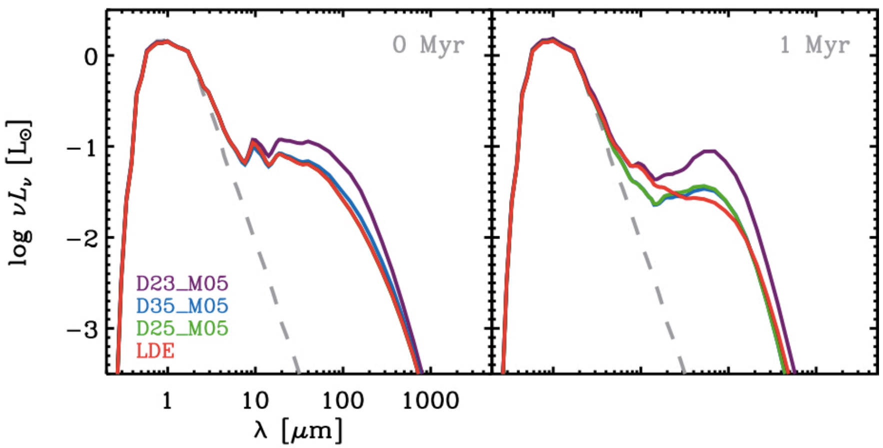


Birnstiel, Andrews, & Ercolano 2012; talk by T. Birnstiel

Disk clearing mechanisms: grain growth

Theoretical Predictions

Observations of GM Aur



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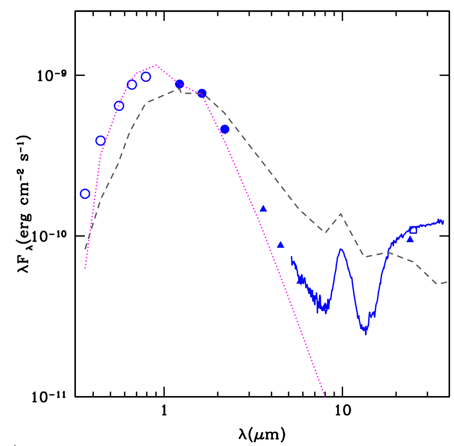

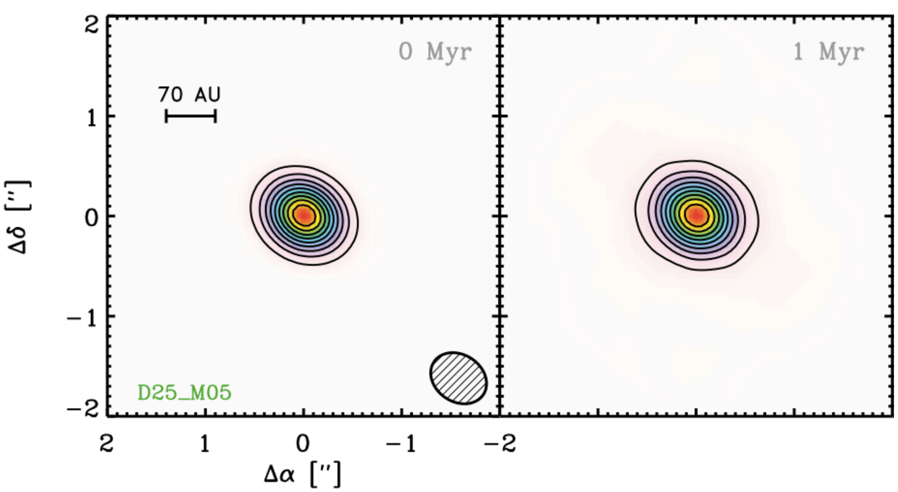

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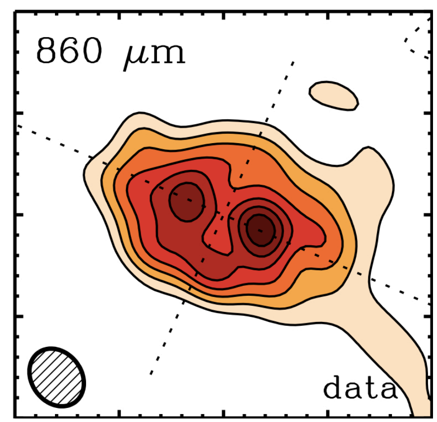
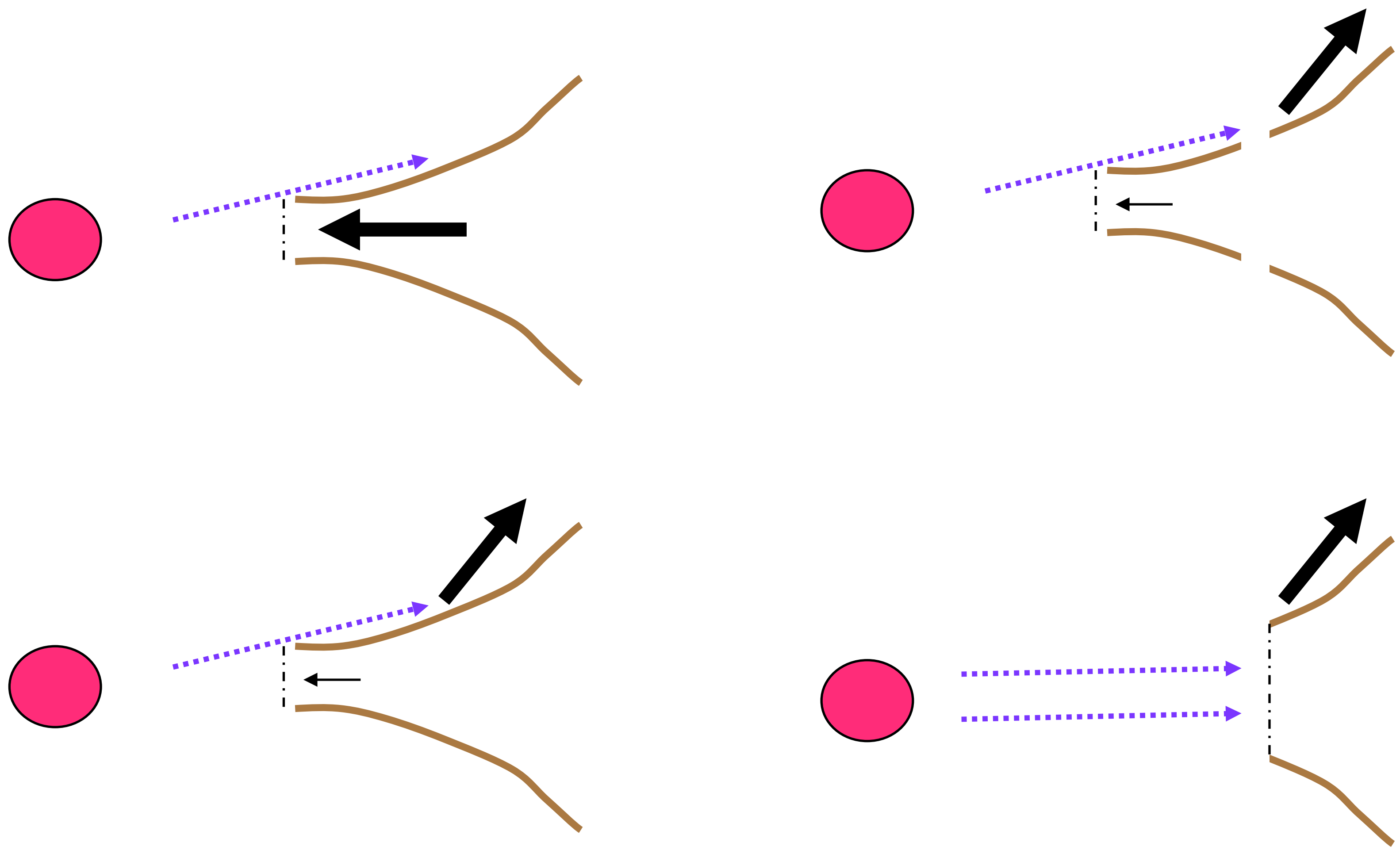


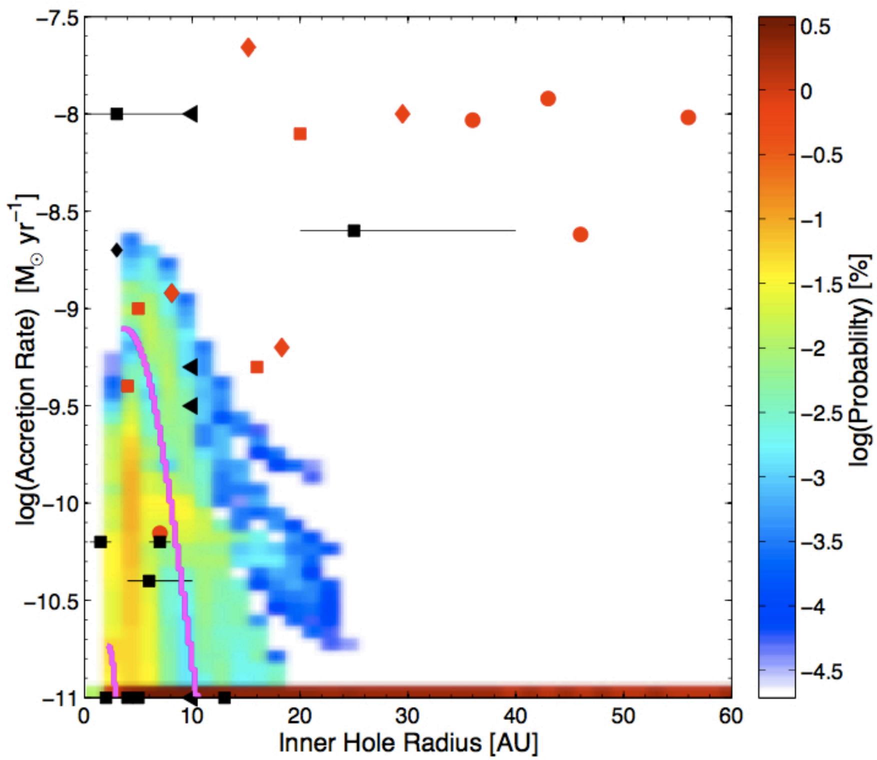
Birnstiel, Andrews, & Ercolano 2012; talk by T. Birnstiel

Disk clearing mechanisms: photoevaporation



Hollenbach et al. 1994; Clarke et al. 2001; Gorti & Hollenbach 2009; Ercolano, Clarke, & Drake 2009; Owen et al. 2009; talks by U. Gorti, B. Ercolano

Photoevaporation models cannot explain accreting objects with large inner holes



Owen et al. 2011

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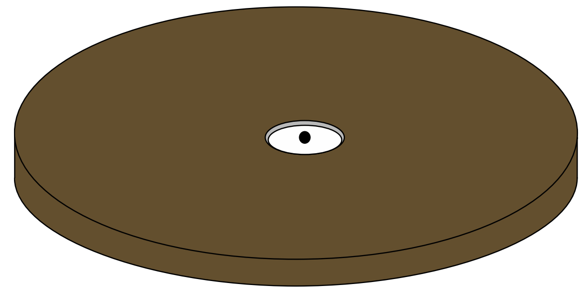
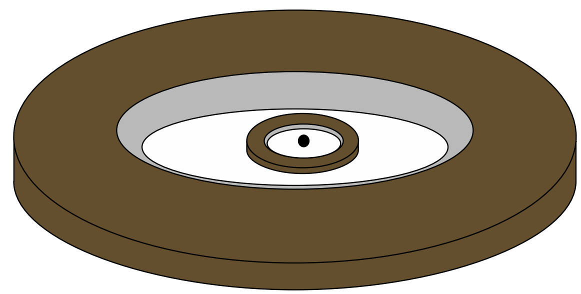
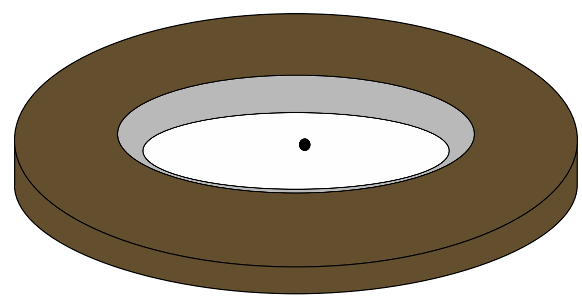


Full disk

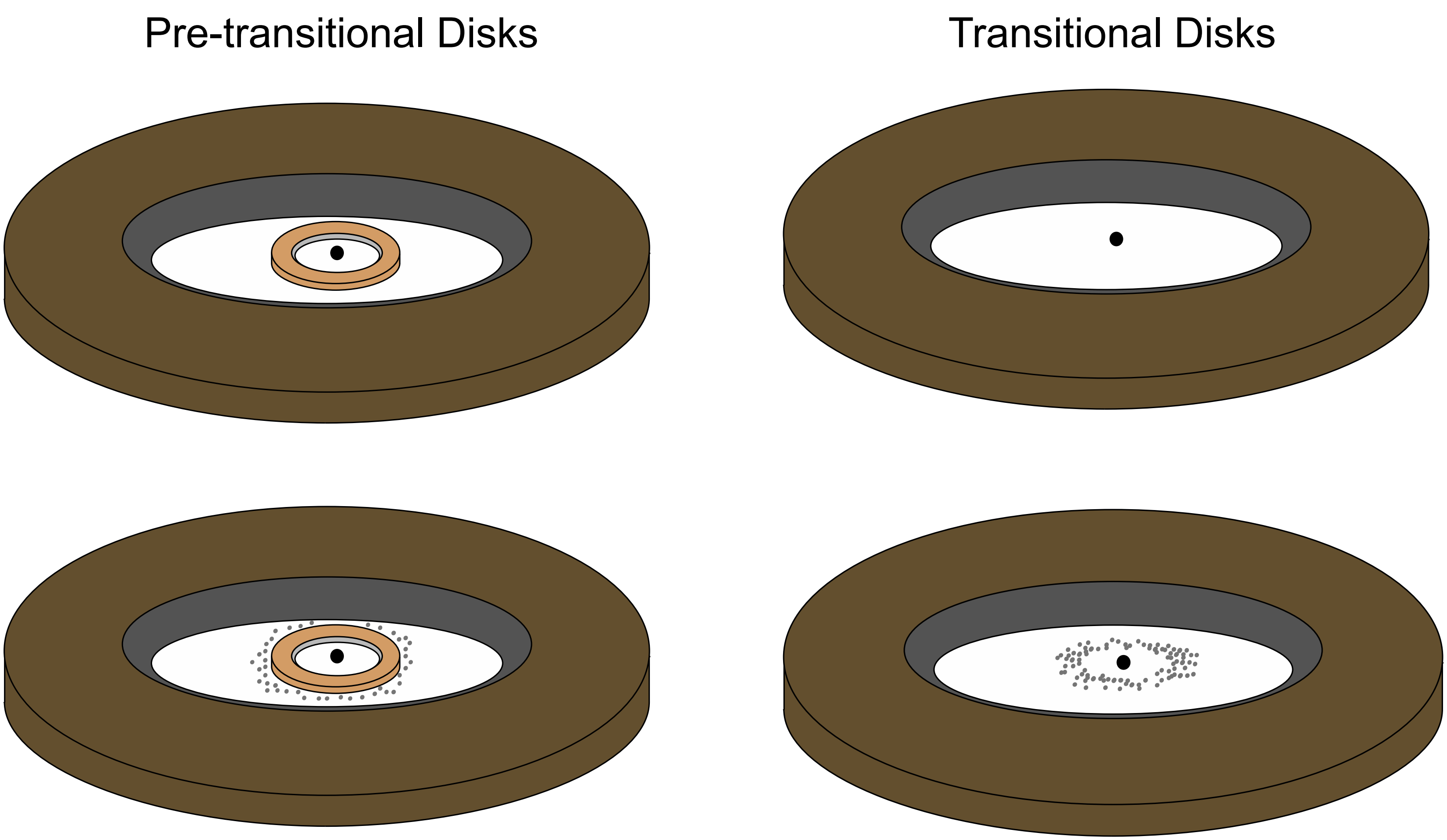


Pre-transitional disk

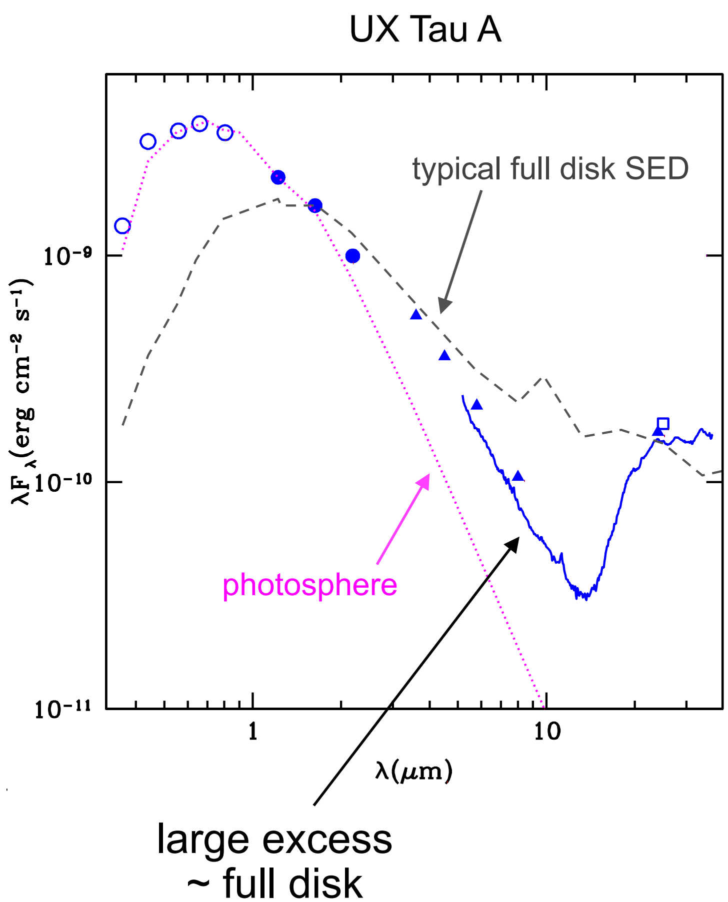


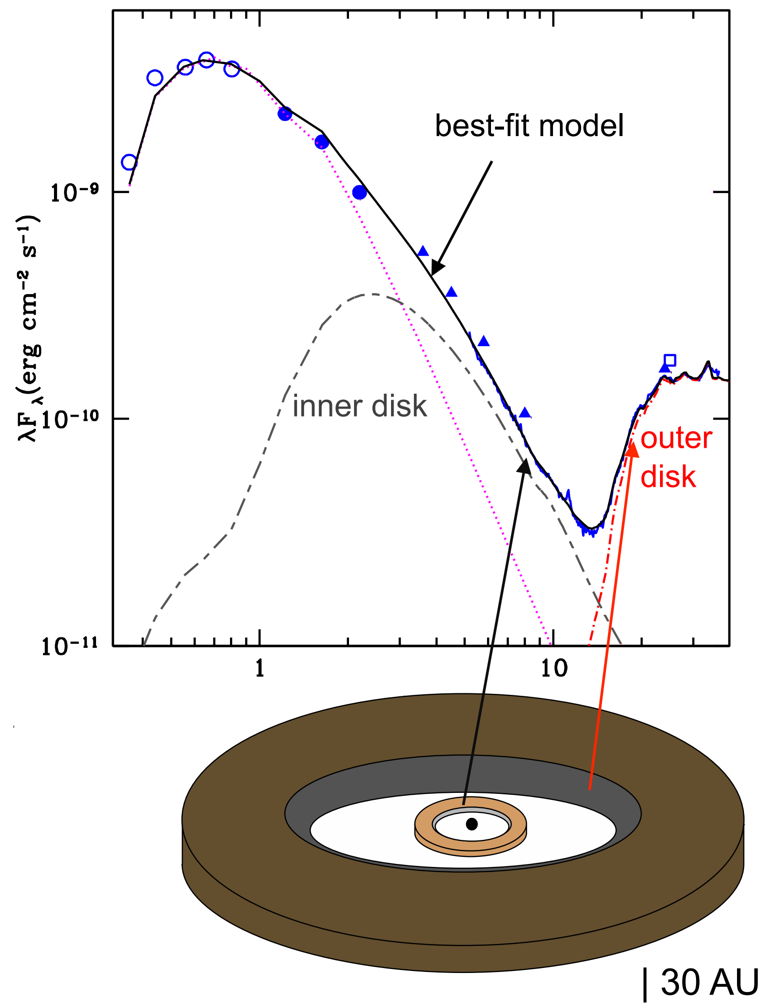
Transitional disk

In addition to inner holes, annular gaps have been detected



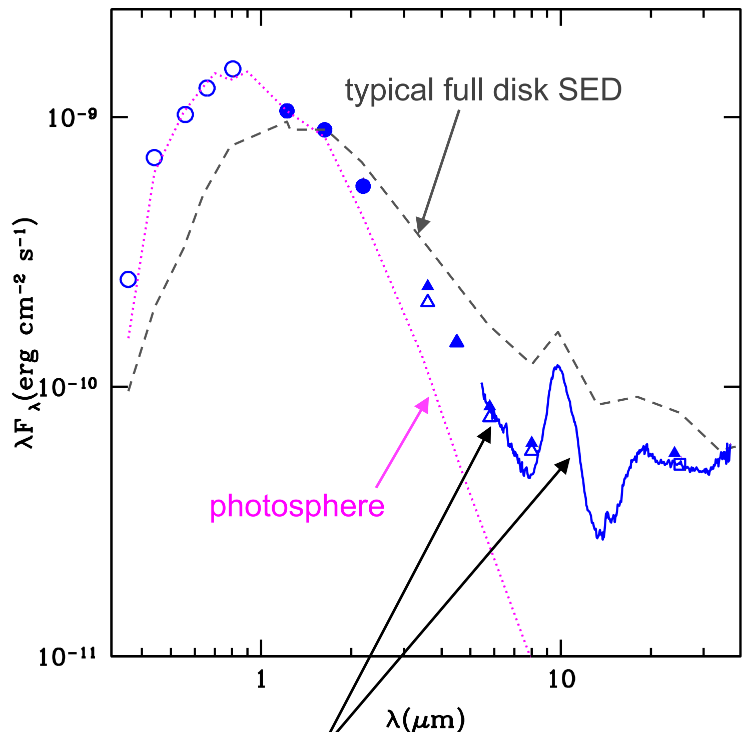
Pre-transitional disks: objects with annular gaps



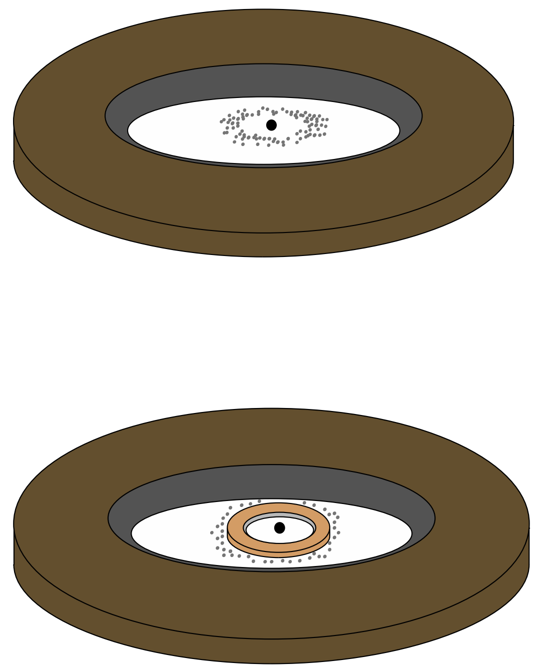


Espaillat et al. 2007b

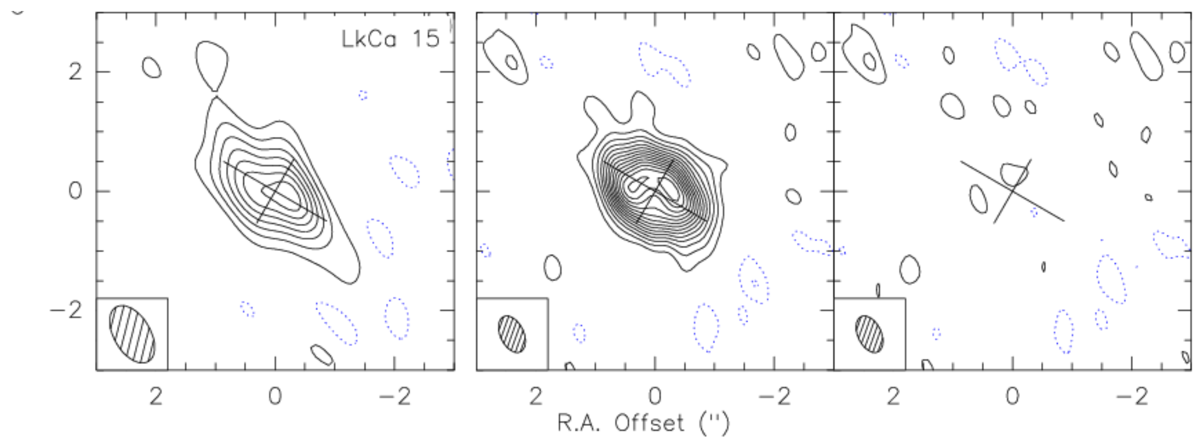
Identifying planet footprints in LkCa 15



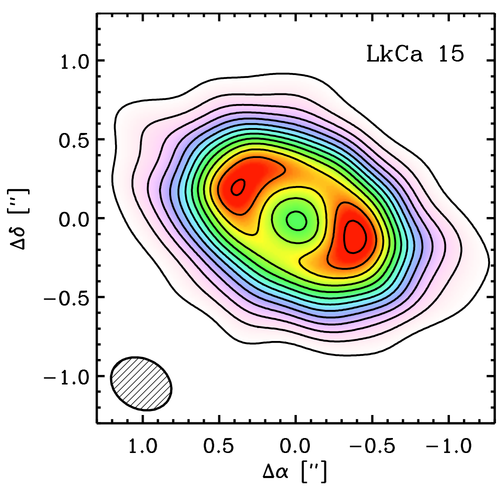
strong near-IR excess &
prominent silicate
emission feature



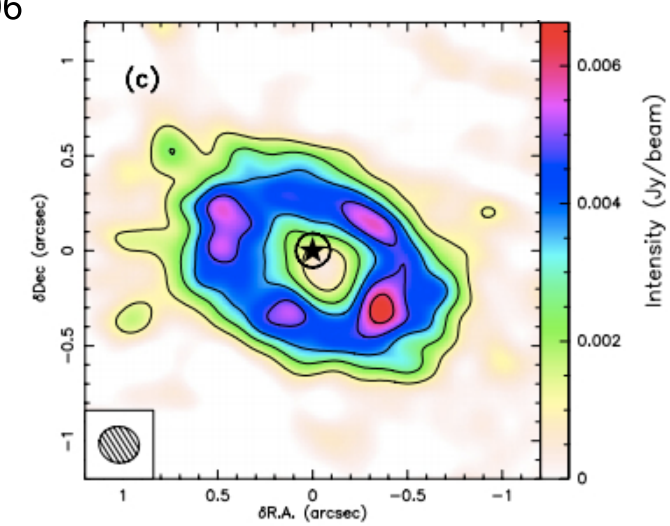
Millimeter imaging confirms a large clearing in LkCa 15's disk



Pietu et al. 2006

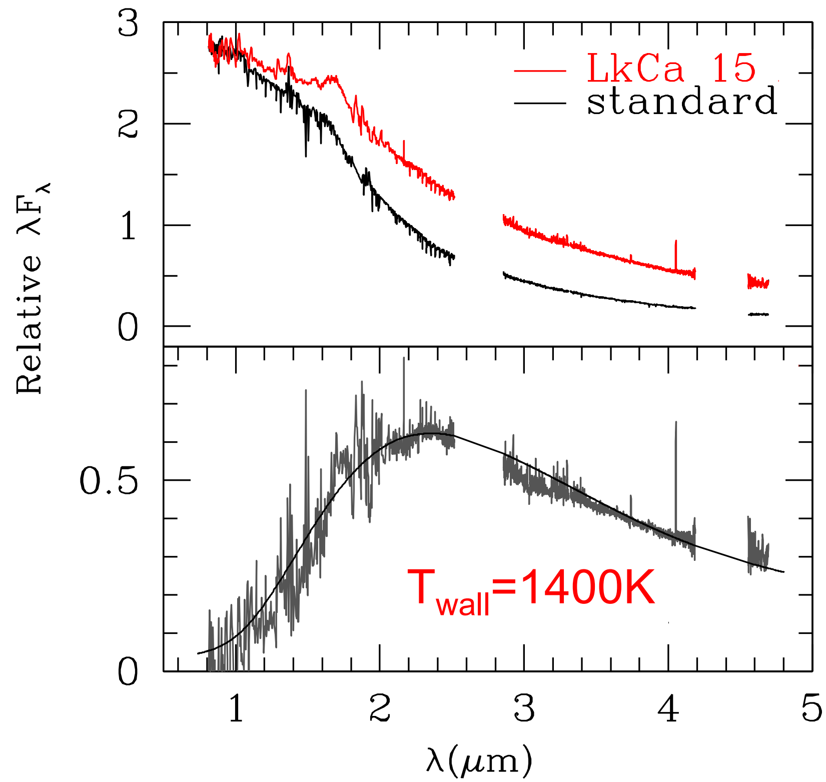


Andrews, Wilner, Espaillat et al. 2011



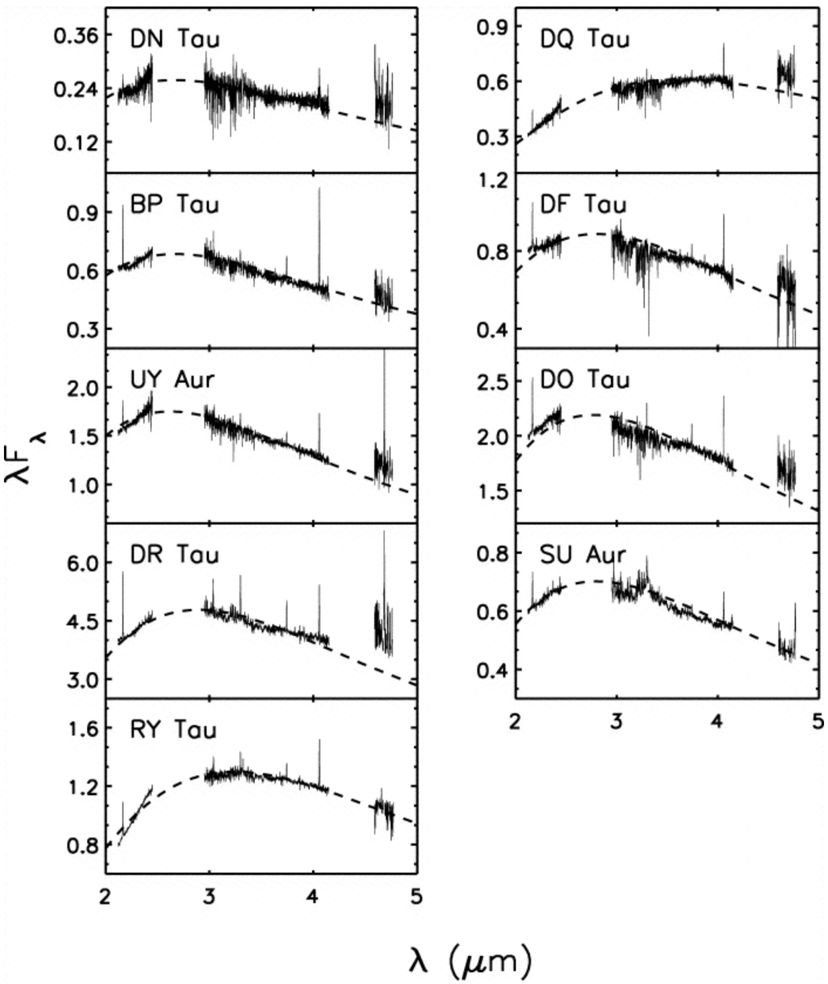
Isella, Perez, & Carpenter 2012

Extracting the NIR excess of LkCa 15 to probe the innermost disk

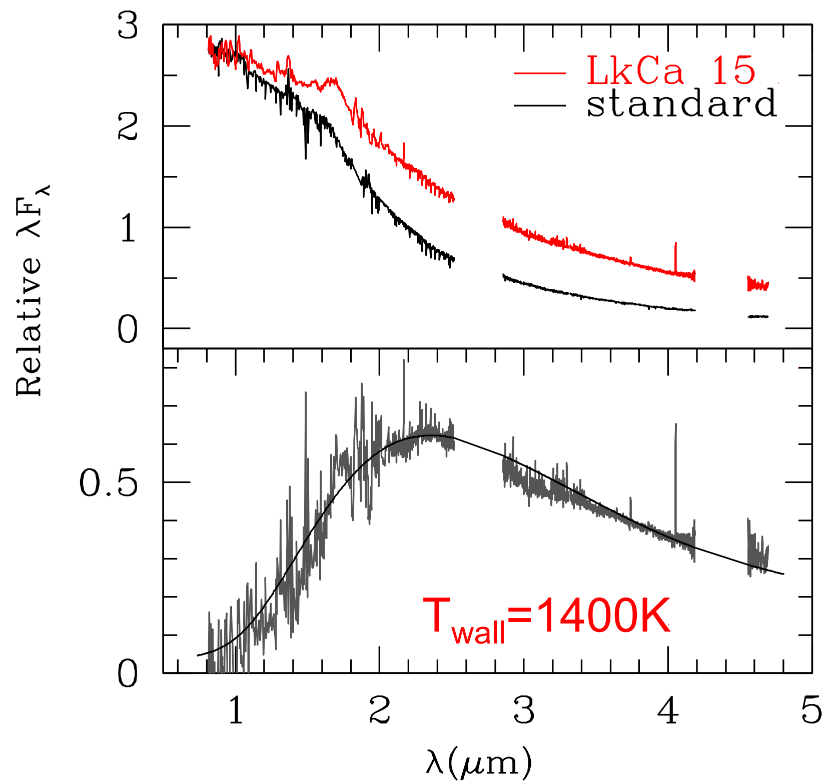


Espaillat et al. 2008a

NIR blackbody-like excess is also observed in full disks



Muzerolle et al. 2003



Espaillat et al. 2008a

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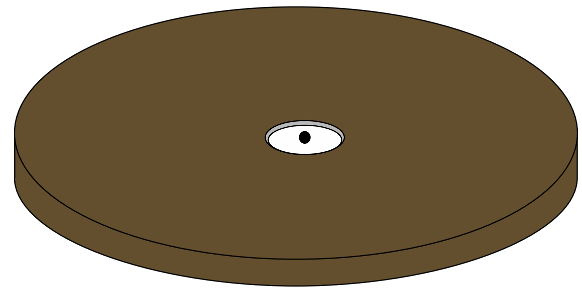
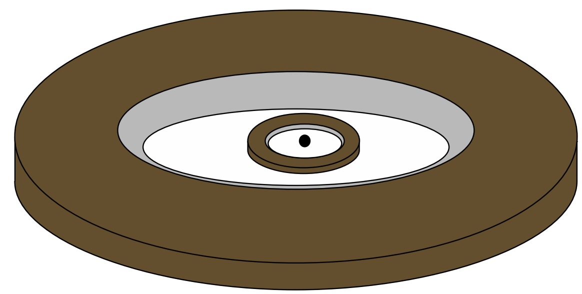
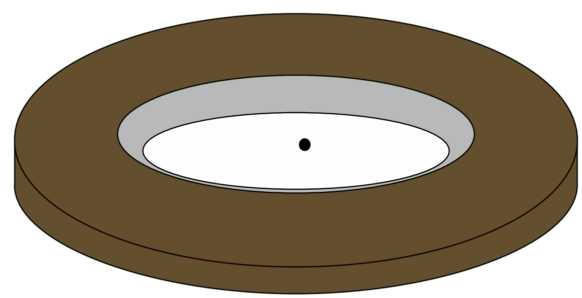


Full disk



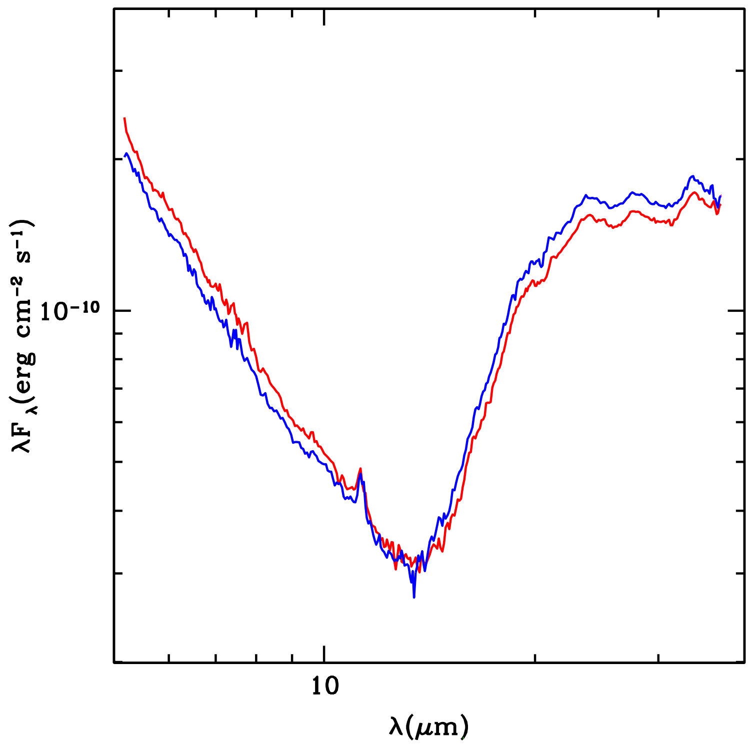
Pre-transitional disk



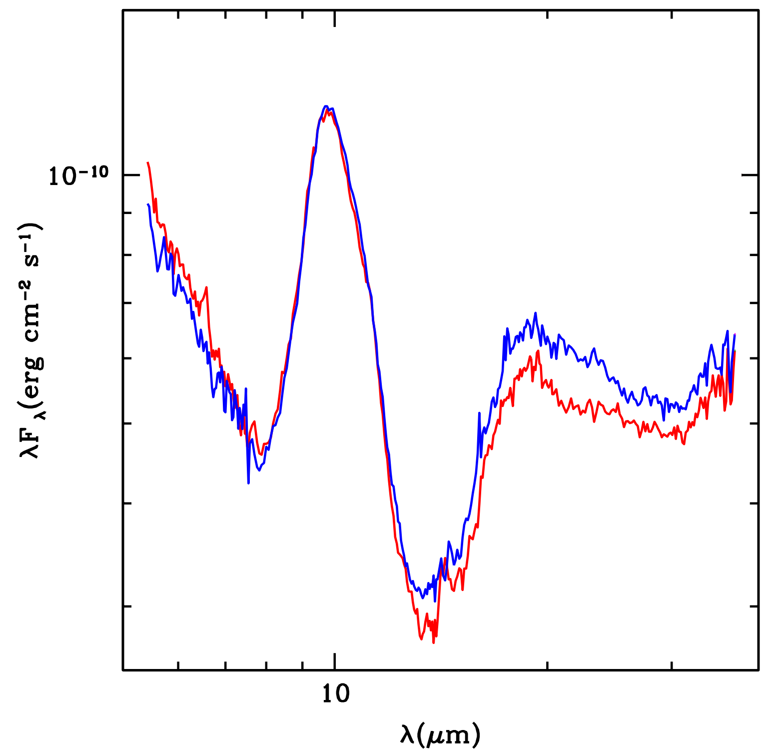
Transitional disk

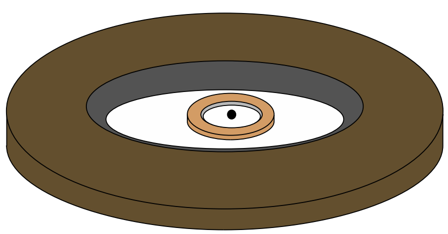
Pre-transitional disks have variable "see-saw" IR emission

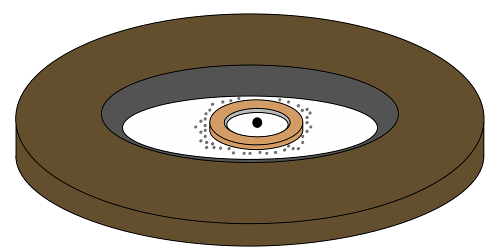
UX Tau A



LkCa 15

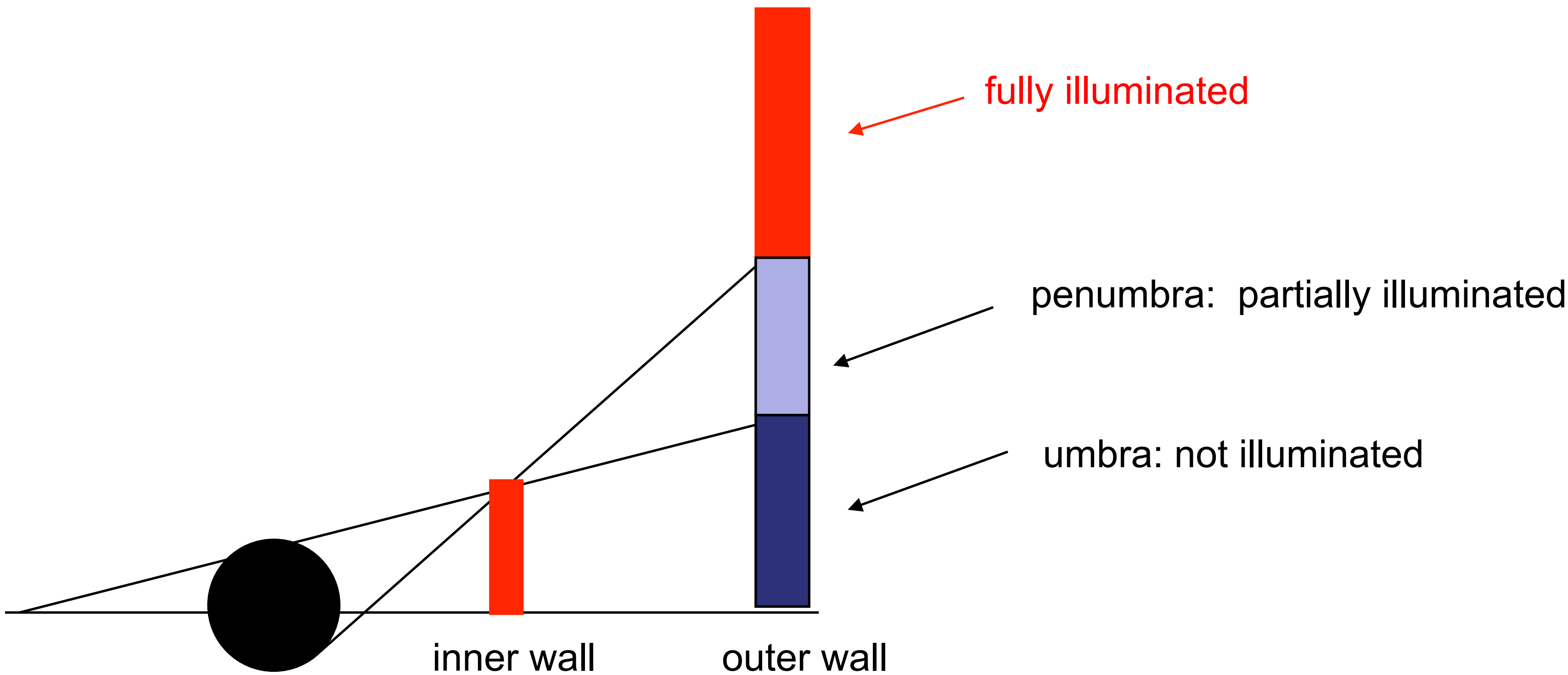






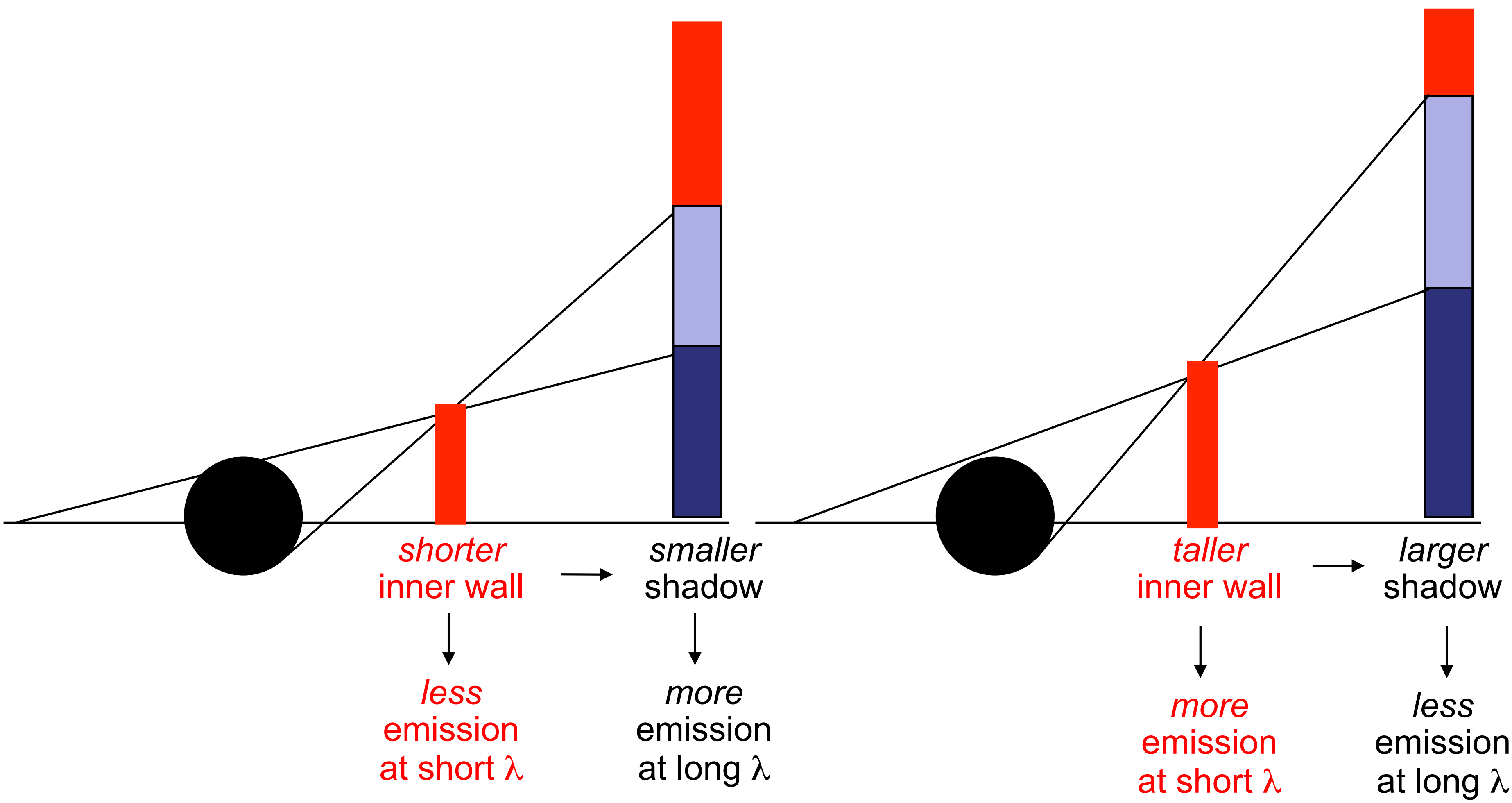
Espaillat et al. 2011; see also Muzerolle et al. 2009, Flaherty et al. 2012

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

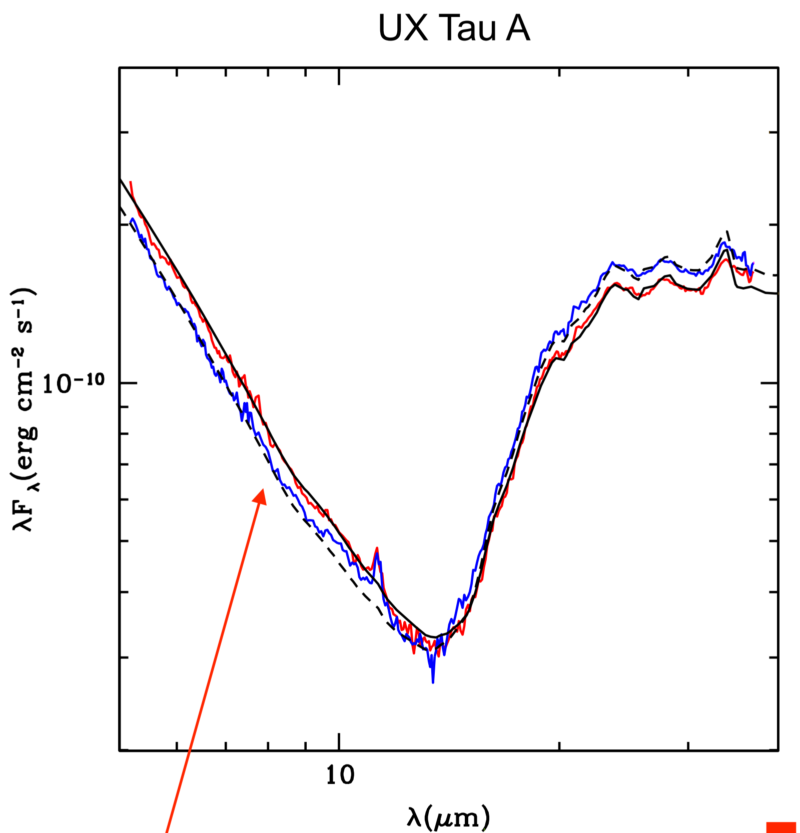


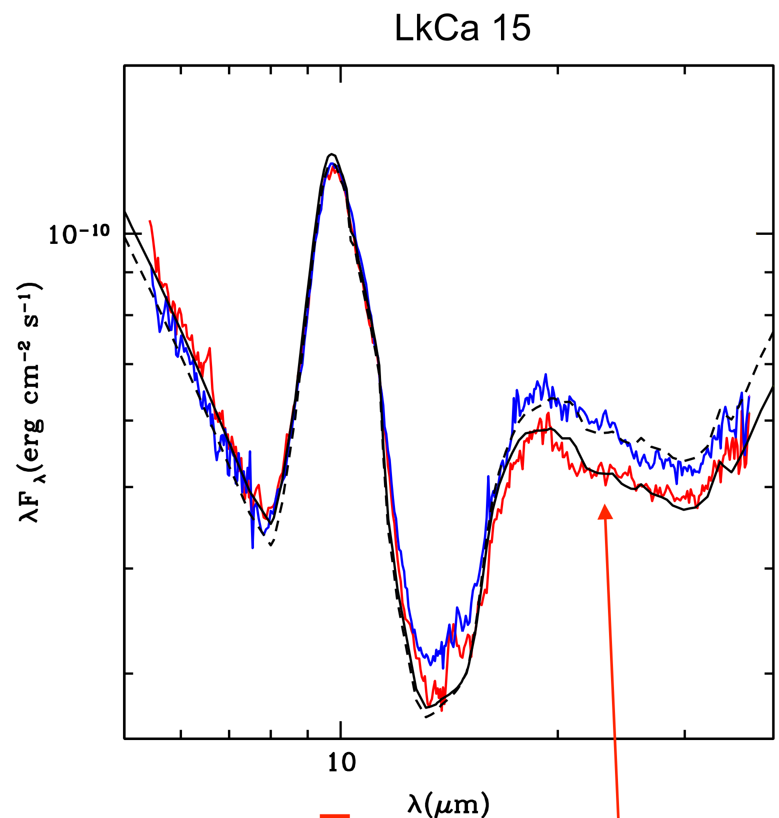
Espaillat et al. 2010

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

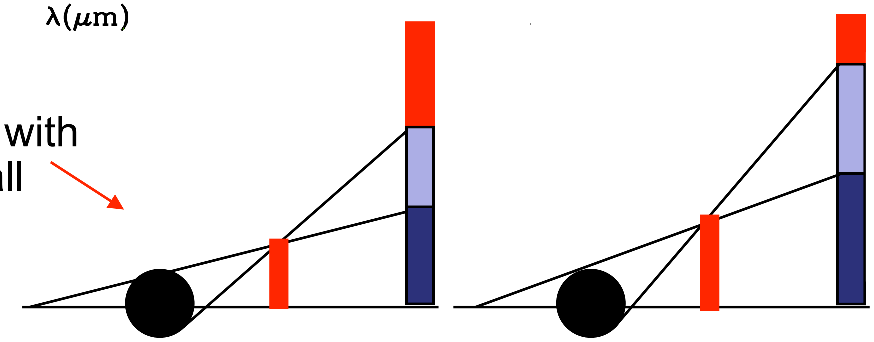


Can fit each SED by changing inner wall's height with time





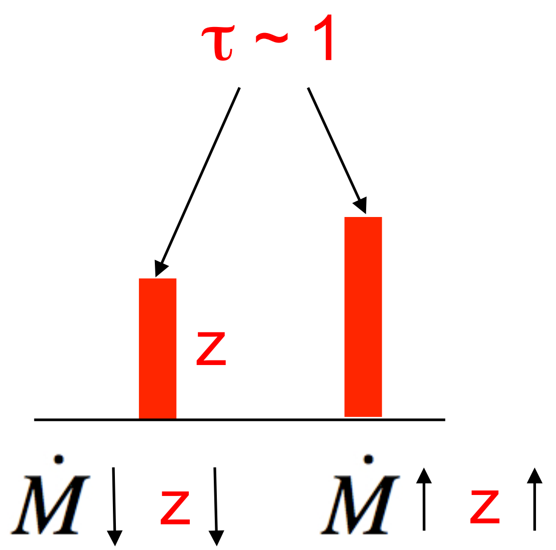
broken line: model with shorter inner wall



solid line: model with taller inner wall

Espaillat et al. 2011

IR variability cannot be explained with variable accretion rates



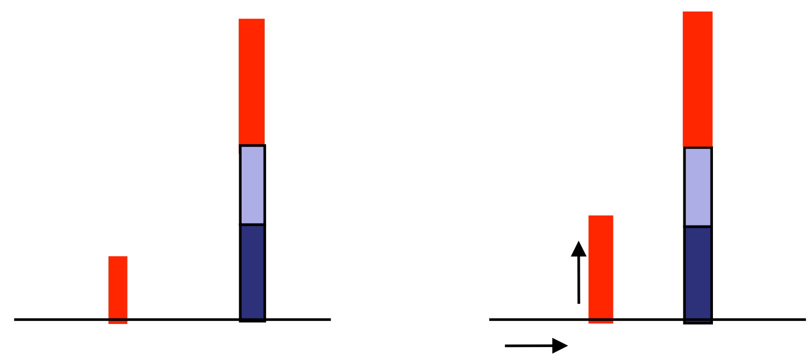
A higher accretion rate leads to a taller inner wall

Emission at short λ increases

$$\boxed{R_{wall}} \propto (L_* + L_{acc})^{0.5}$$

$$L_{acc} \sim GM_* \boxed{\dot M} / R_*$$

$\dot M \uparrow$ R ↑



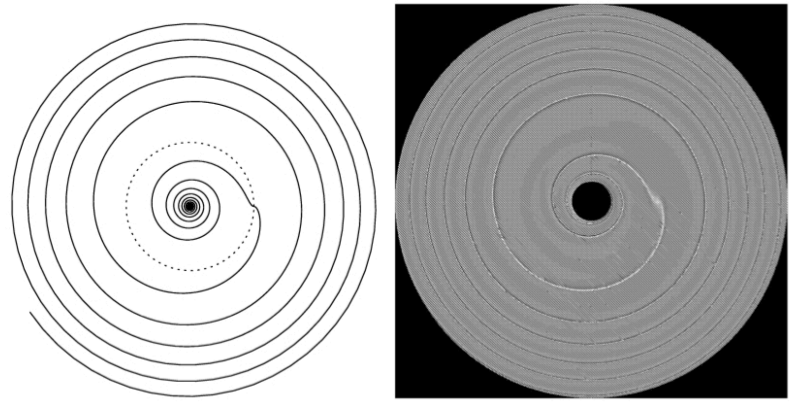
A higher accretion rate also leads to a larger wall radius

Emission at long λ does not change

Potential causes of IR variability in pre-transitional disks

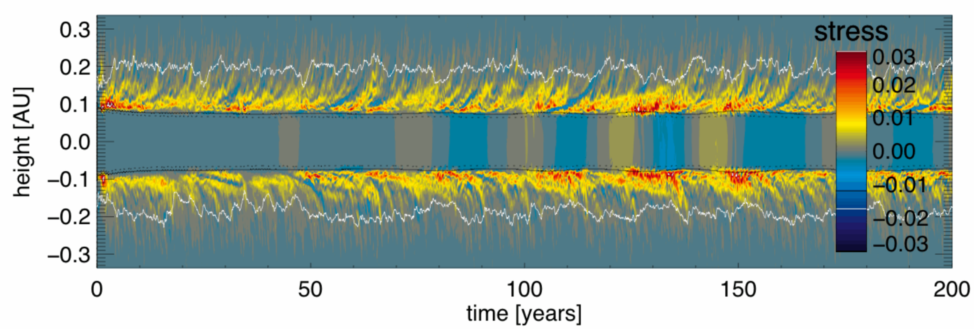
Planet-disk interaction

Flaherty et al. 2011



Ogilvie & Lubow 2002

Turbulence from MRI



Hirose & Turner 2011

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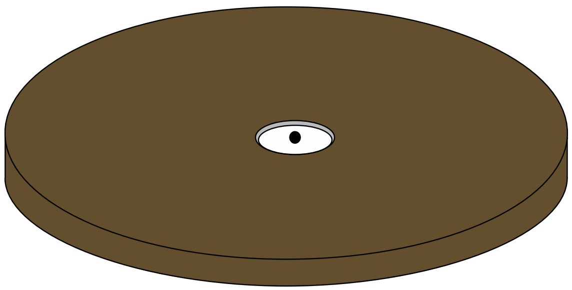
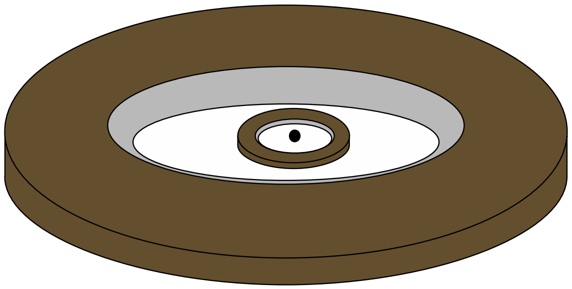
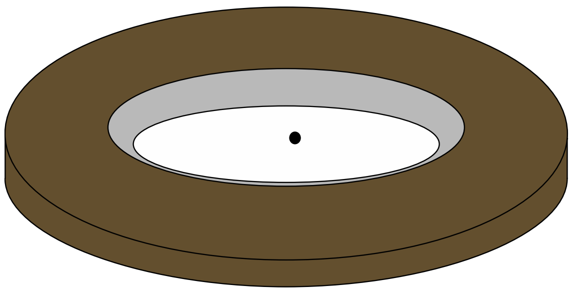


Full disk

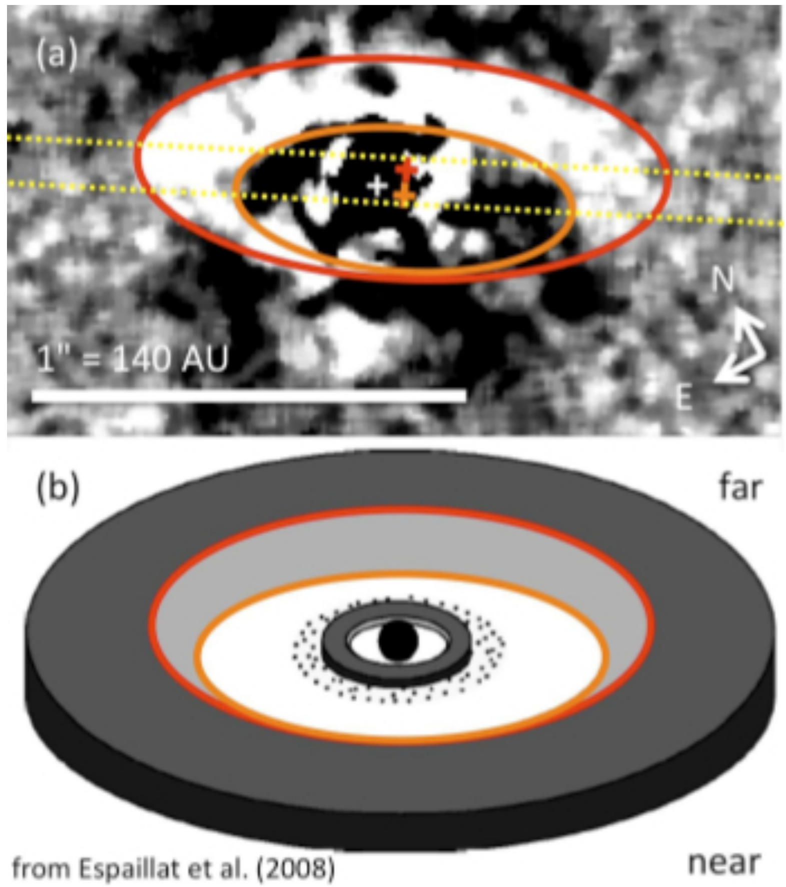


Pre-transitional disk



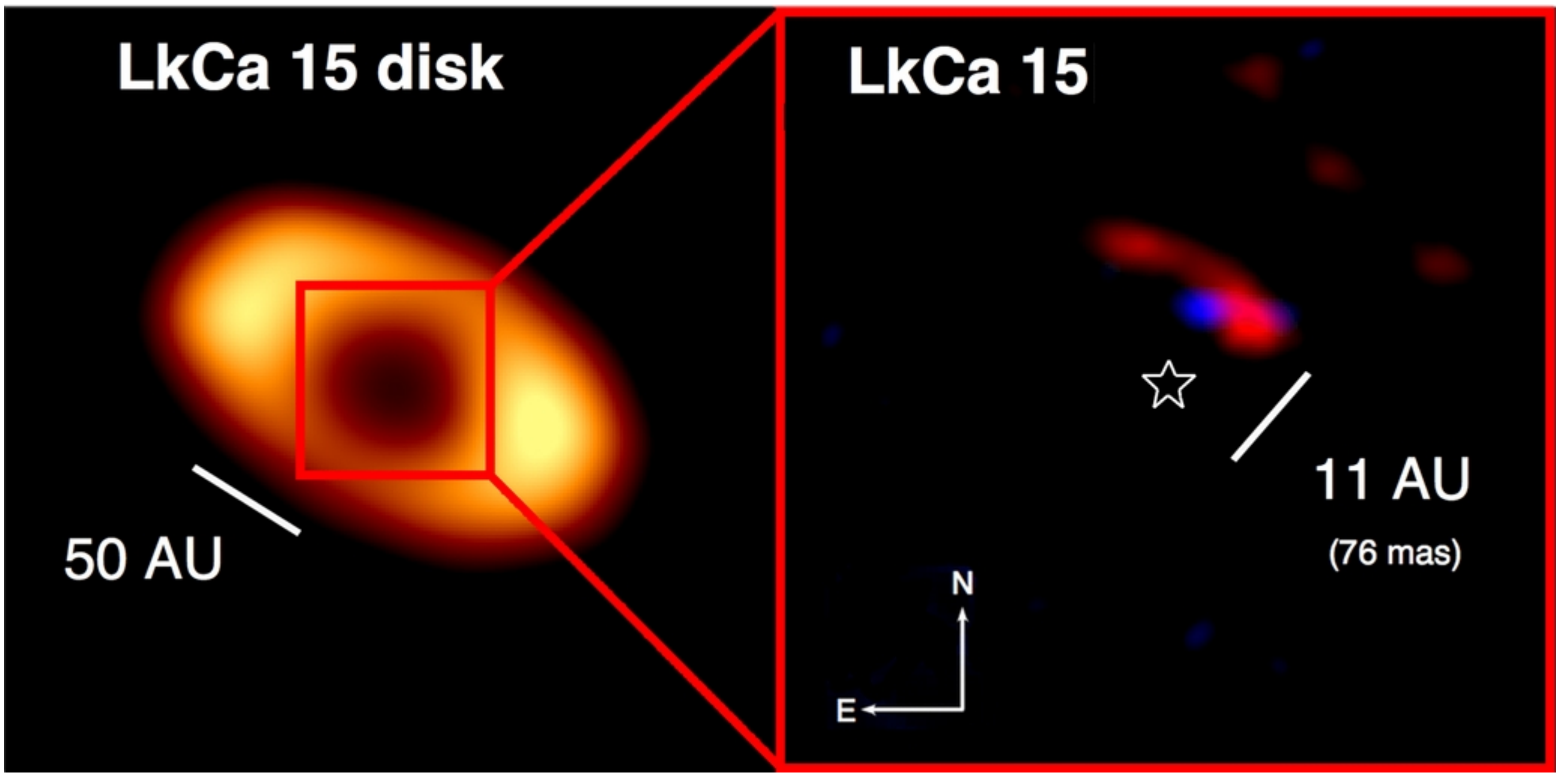
Transitional disk

NIR image of LkCa 15's outer wall



Thalmann et al. 2010

A possible protoplanet has been detected: LkCa 15 b



Kraus & Ireland 2011

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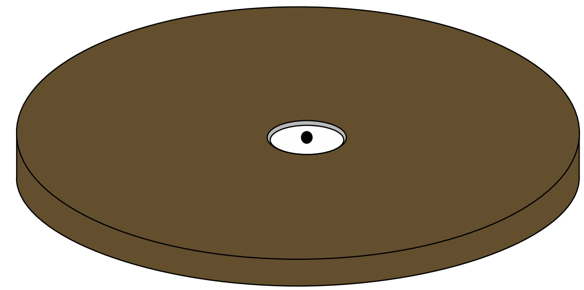
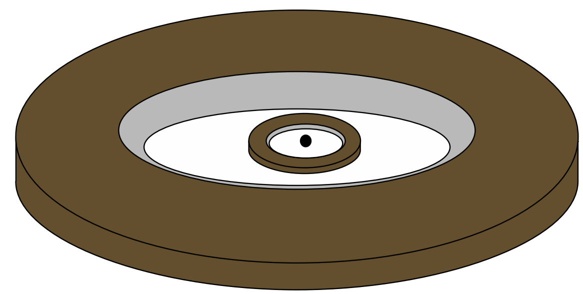


Full disk



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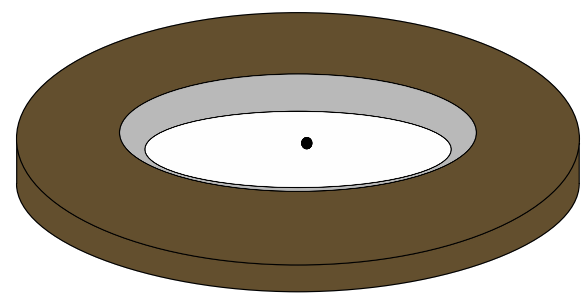
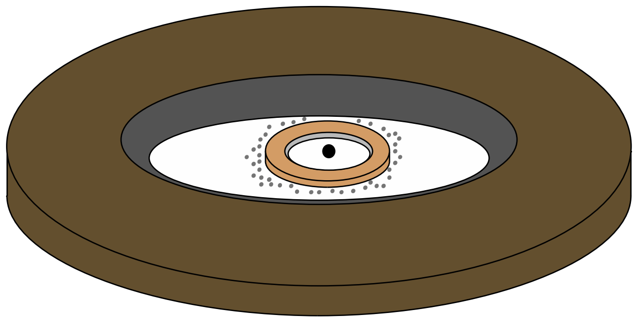


Transitional disk

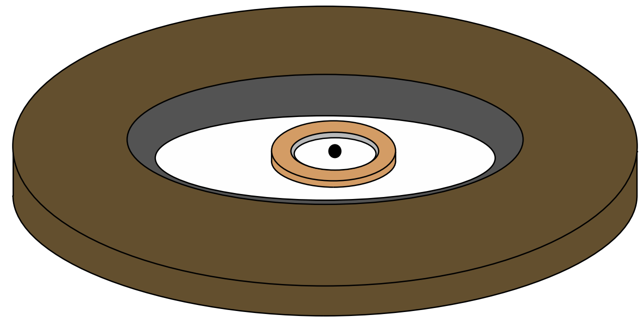
Extracting observational constraints to build a physical model

LkCa 15



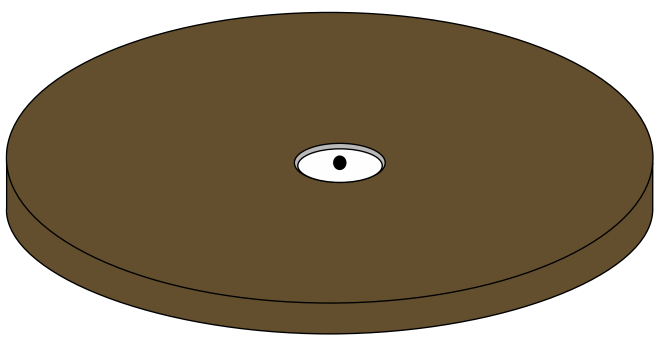
$3 \times 10^{-9}\ M_\odot\ yr^{-1}$ | 40 AU

UX Tau A



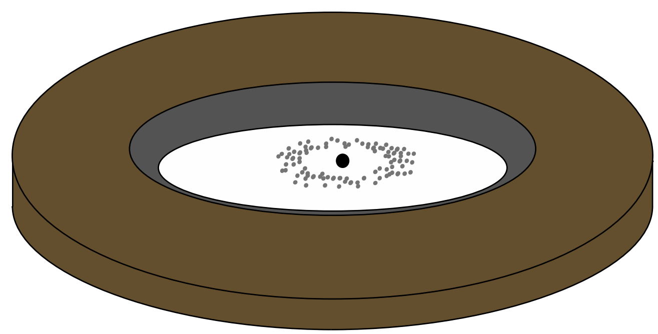
$1 \times 10^{-8}\ M_\odot\ yr^{-1}$ | 30 AU

Full disk



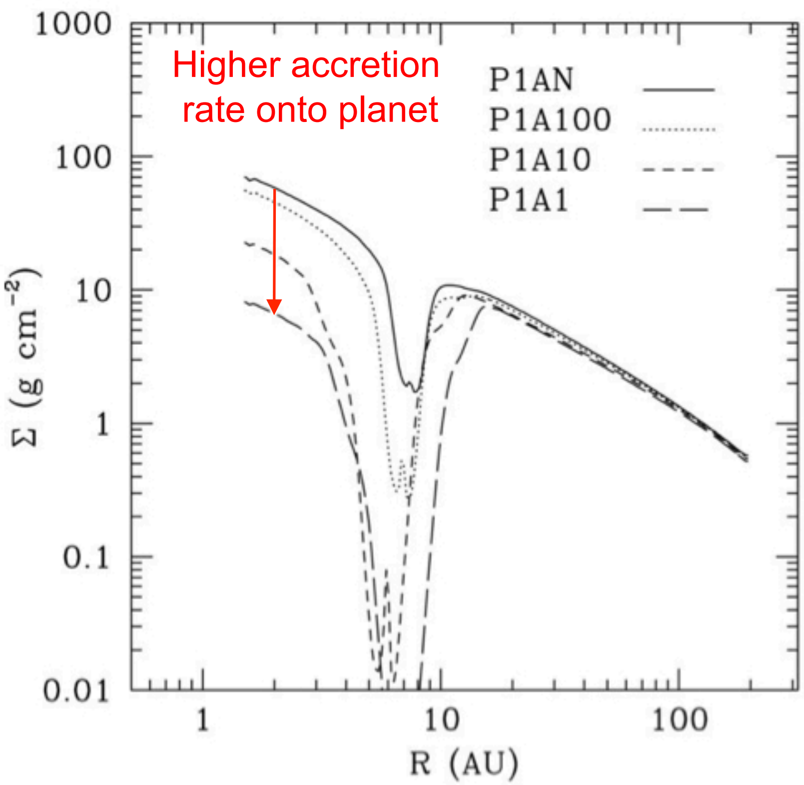
$1 \times 10^{-8}\ M_\odot\ yr^{-1}$

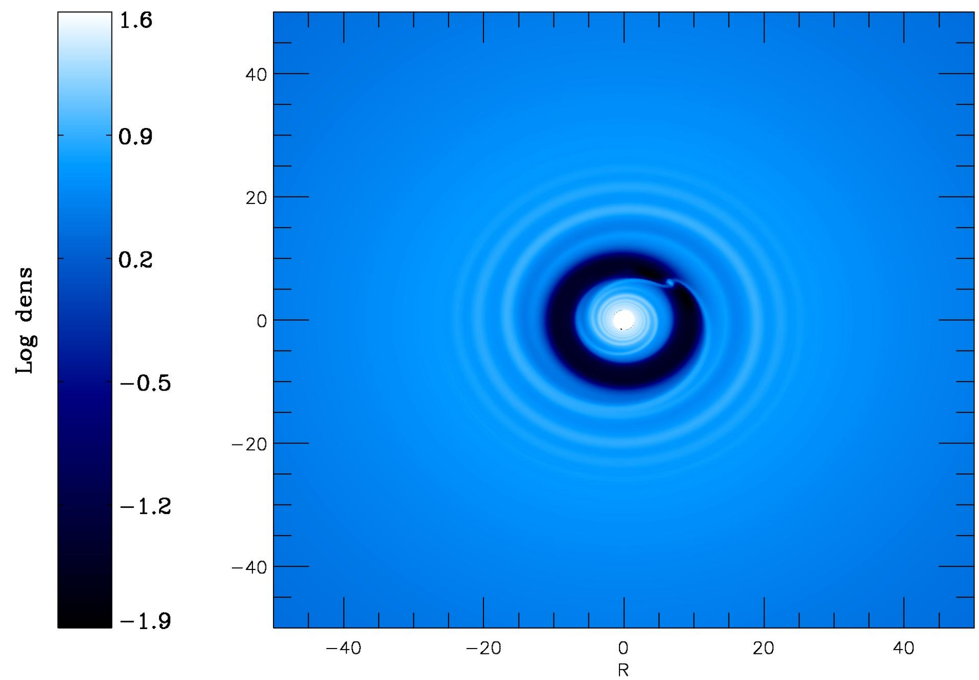
GM Aur



$8 \times 10^{-9}\ M_\odot\ yr^{-1}$ | 20 AU

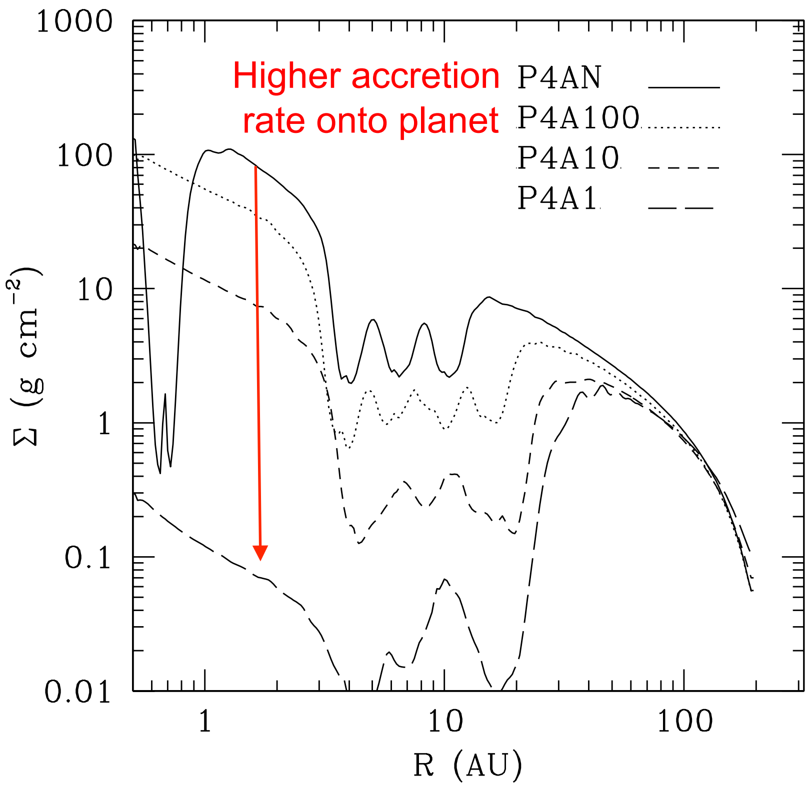
A single planet opens a small annular gap

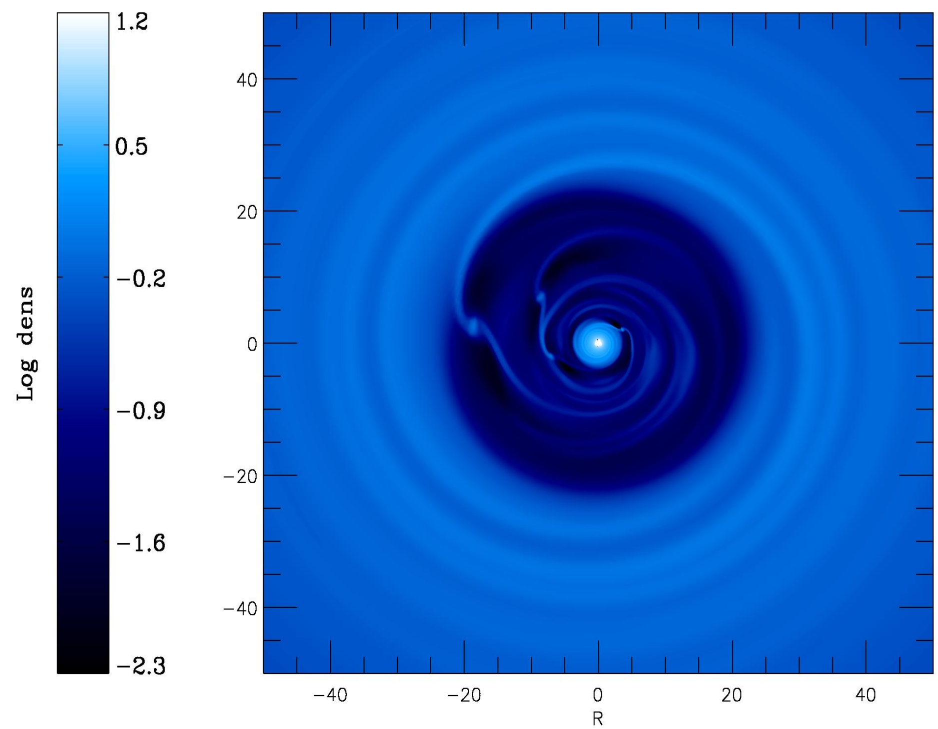




Zhu et al. 2011

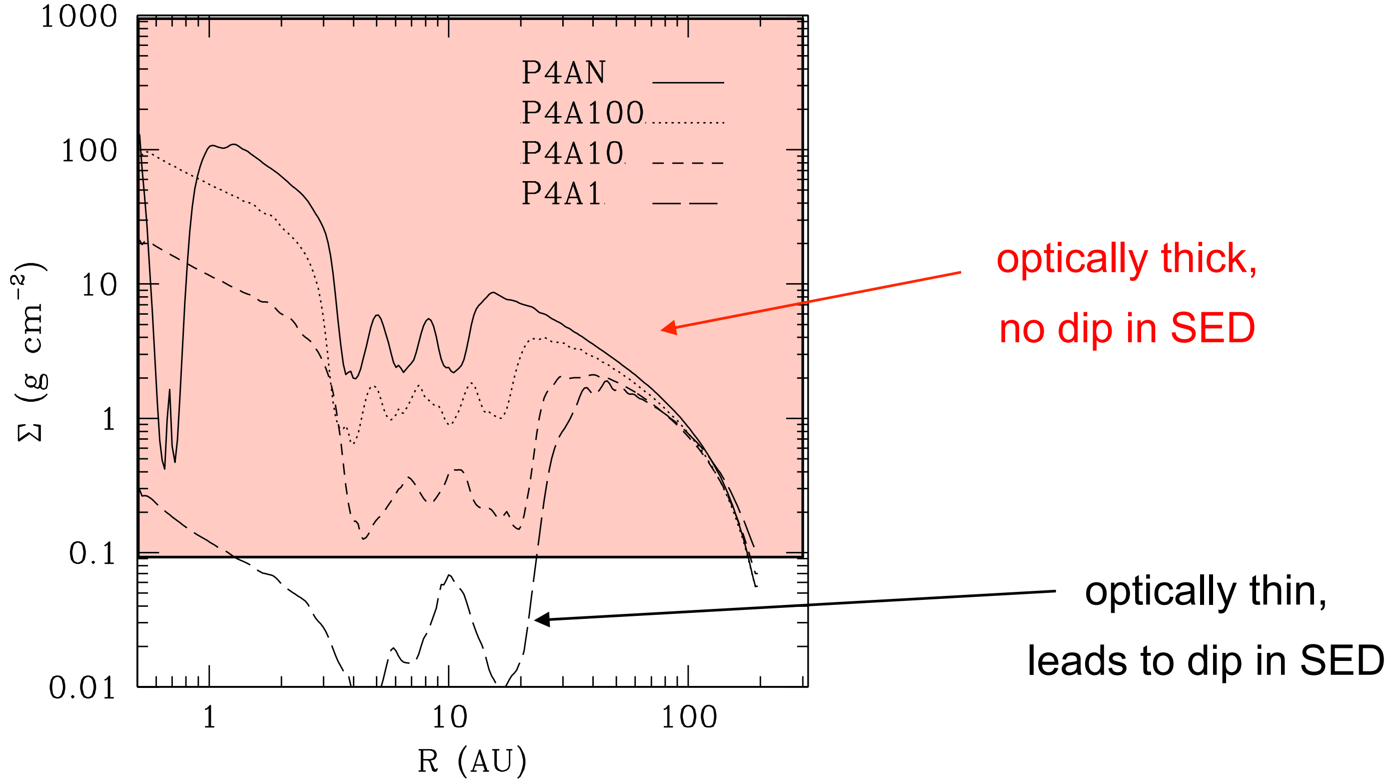
Multiple planets open a large annular gap





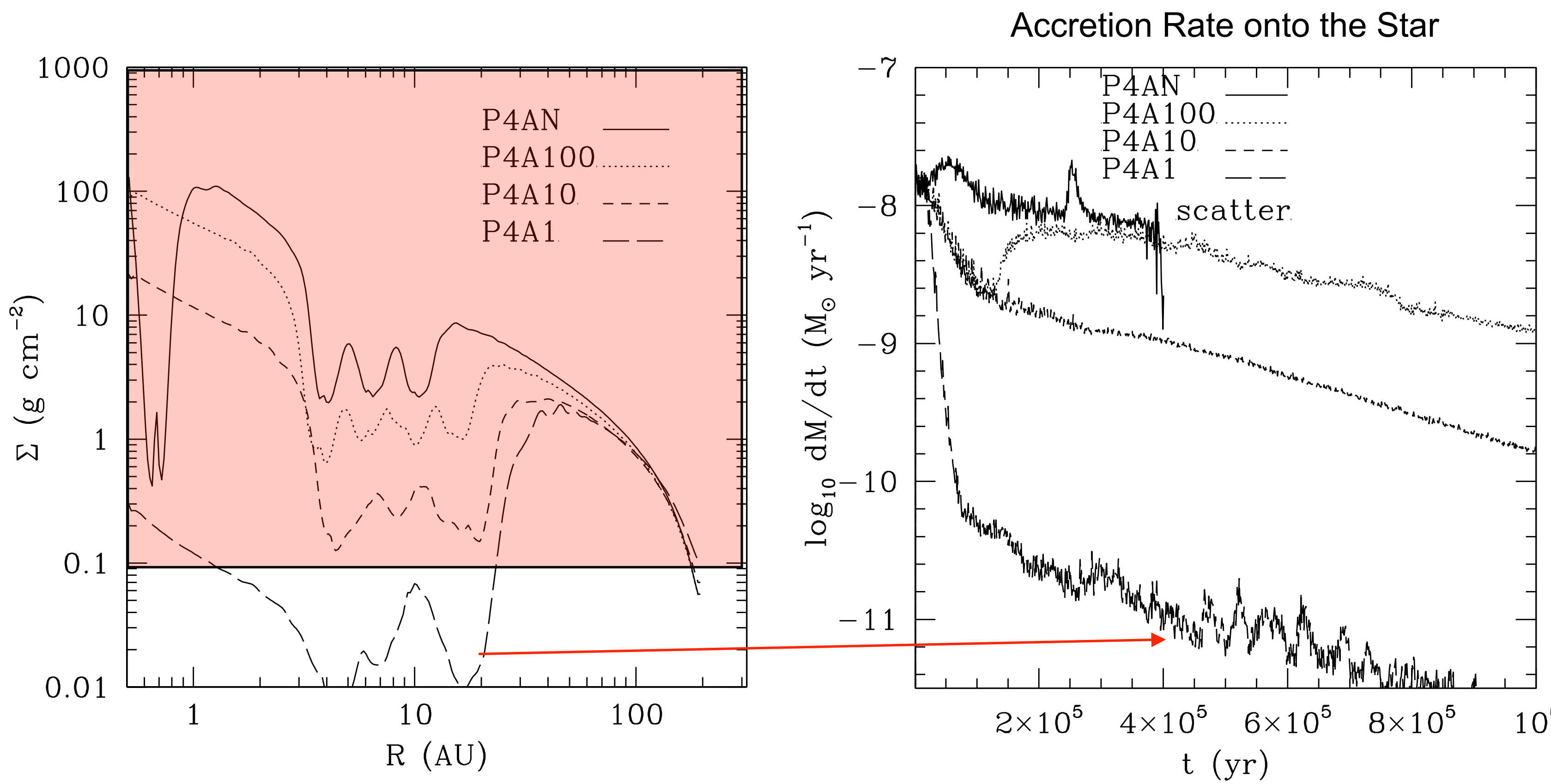
Zhu et al. 2011; see also Dodson-Robinson & Salyk 2011

The gaps must be deep enough to be detectable in SEDs



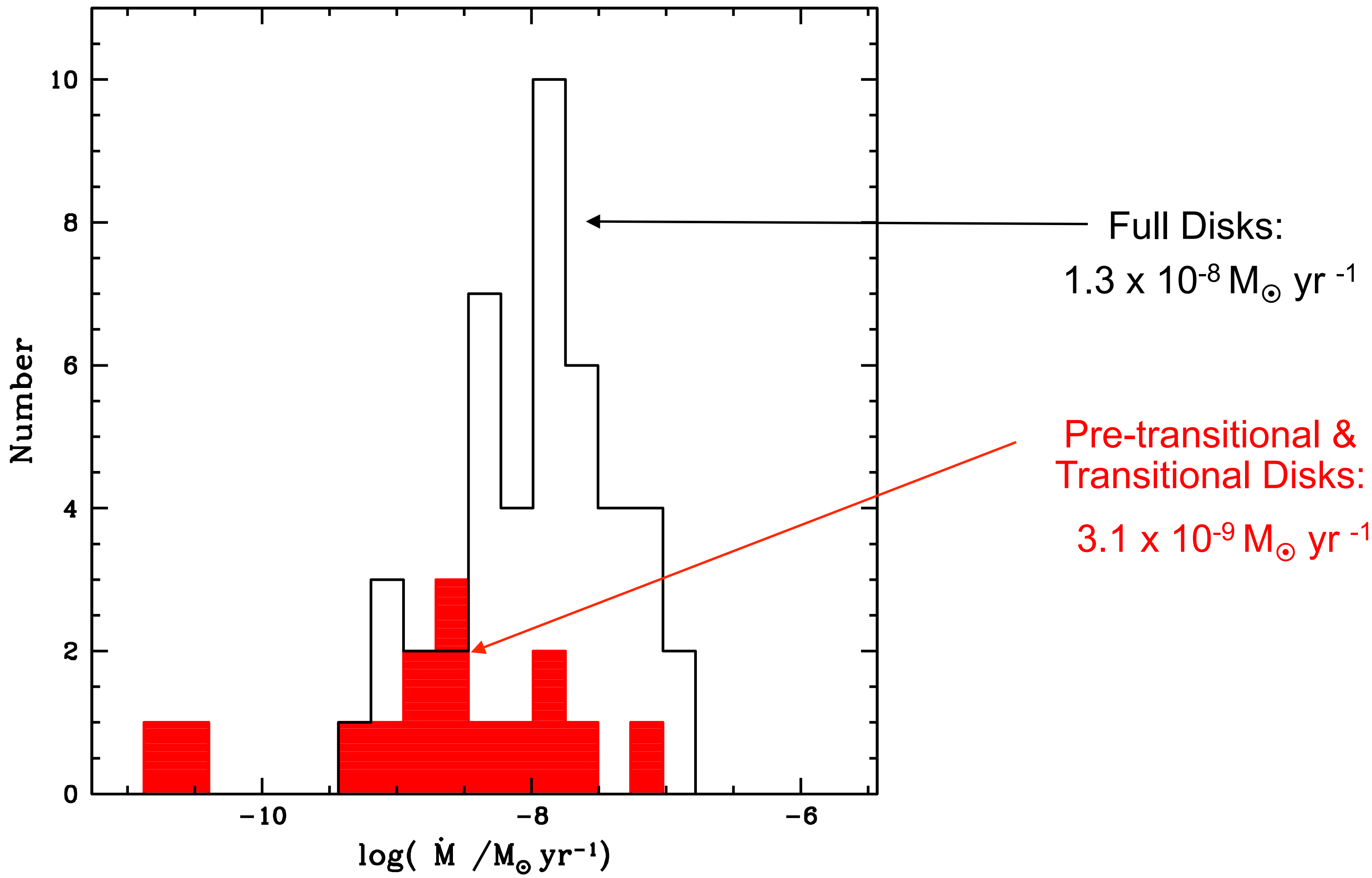
Zhu et al. 2011

Multiple planets significantly decrease the accretion rate onto the star



Zhu et al. 2011

Mass accretion rates of TD & PTD are lower than full disks, but still substantial



Espaillat et al. 2012; see also Najita et al. 2007, Kim et al. 2013

Single planet and dust filtration lead to different gas and dust distributions

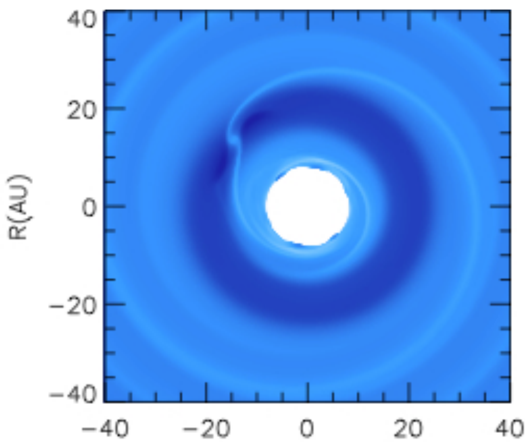
Gas Distribution

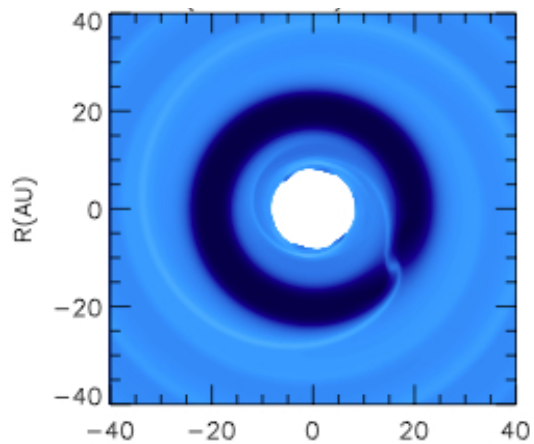
Small Dust Distribution

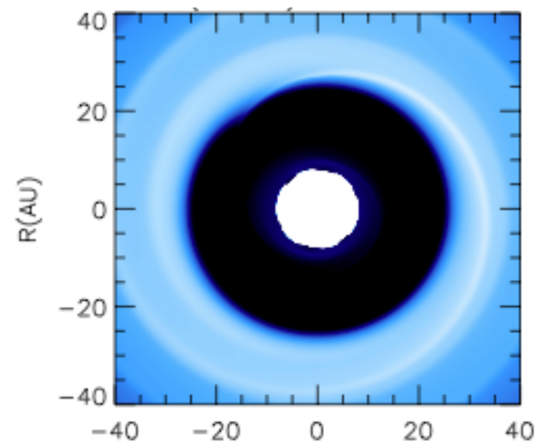
(< 10 microns)

Large Dust Distribution

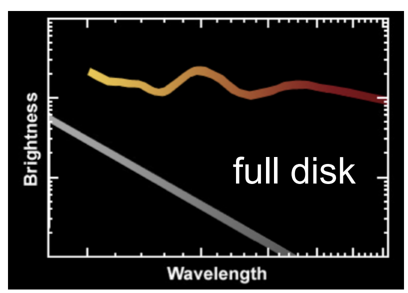
(~ 1mm)

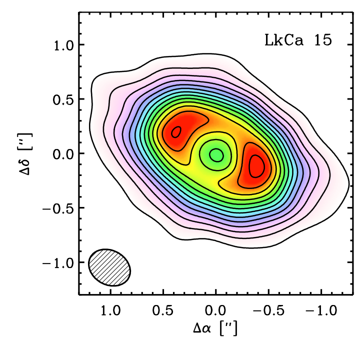






$\sim 10^{-9}\ M_{\odot}\ yr^{-1}$

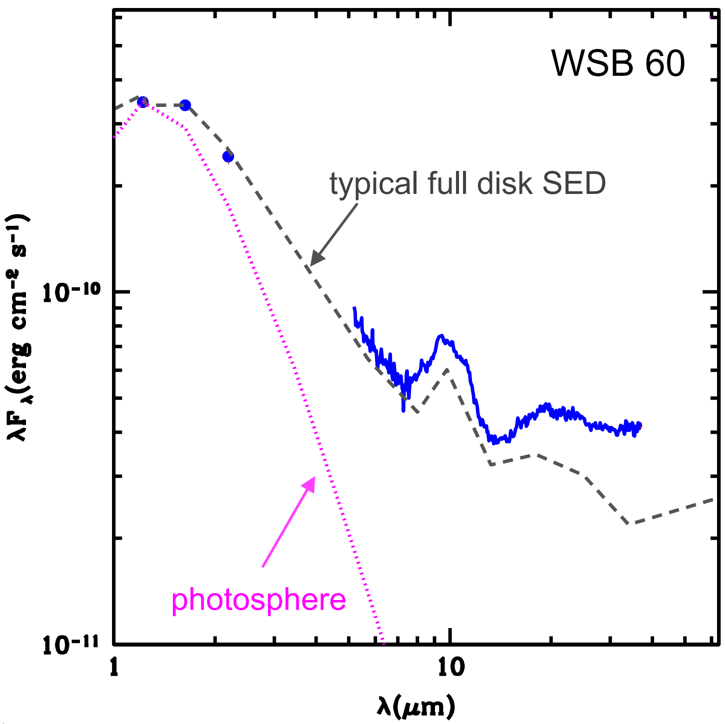




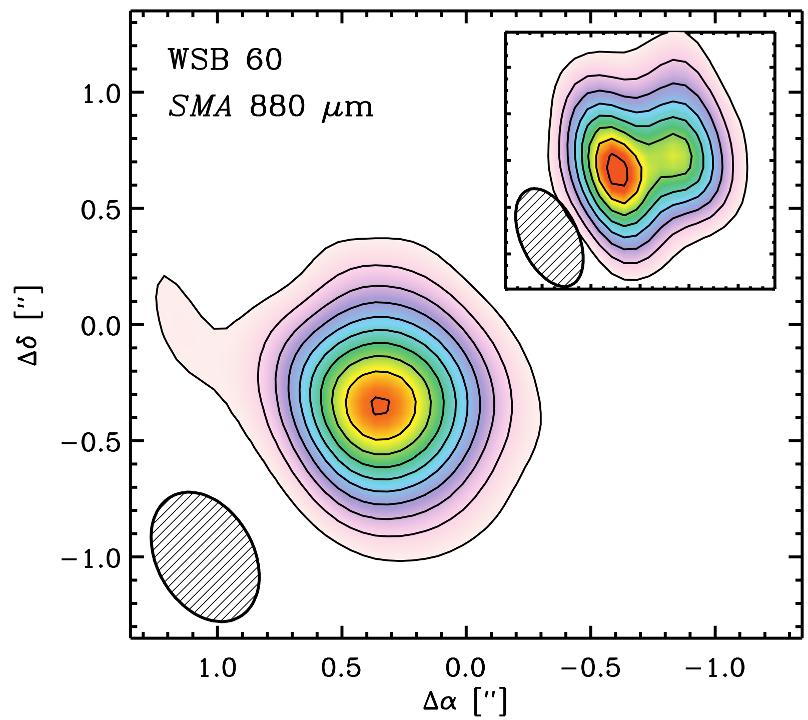
Zhu et al. 2012; talk by R. Dong

Earlier stage of gap opening by planets?

Full disk SED



Clearing seen in millimeter



Andrews, Wilner, Espaillat et al. 2011

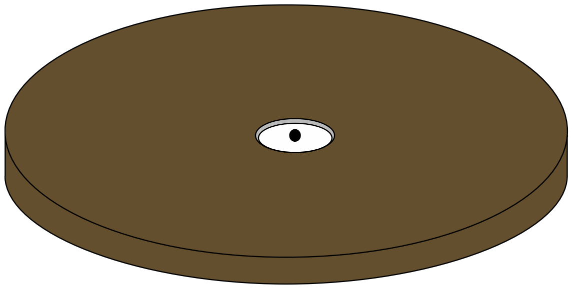
Tracking Planet Footprints

What evidence do we have for planets forming in young disks?

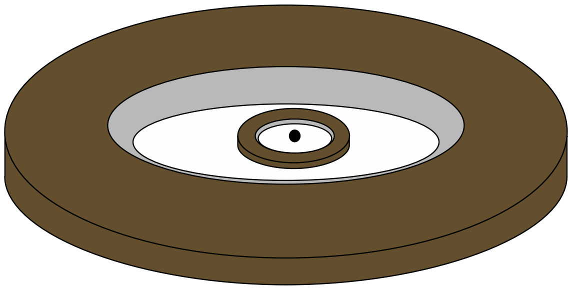
- SEDs & modeling of transitional disks
- SEDs & modeling of pre-transitional disks
- Infrared variability
- Planet imaging searches

What constraints from the observations can we apply to planet clearing models?

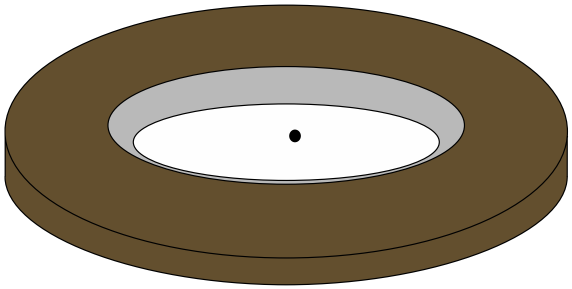
Where do we go from here?



Full disk

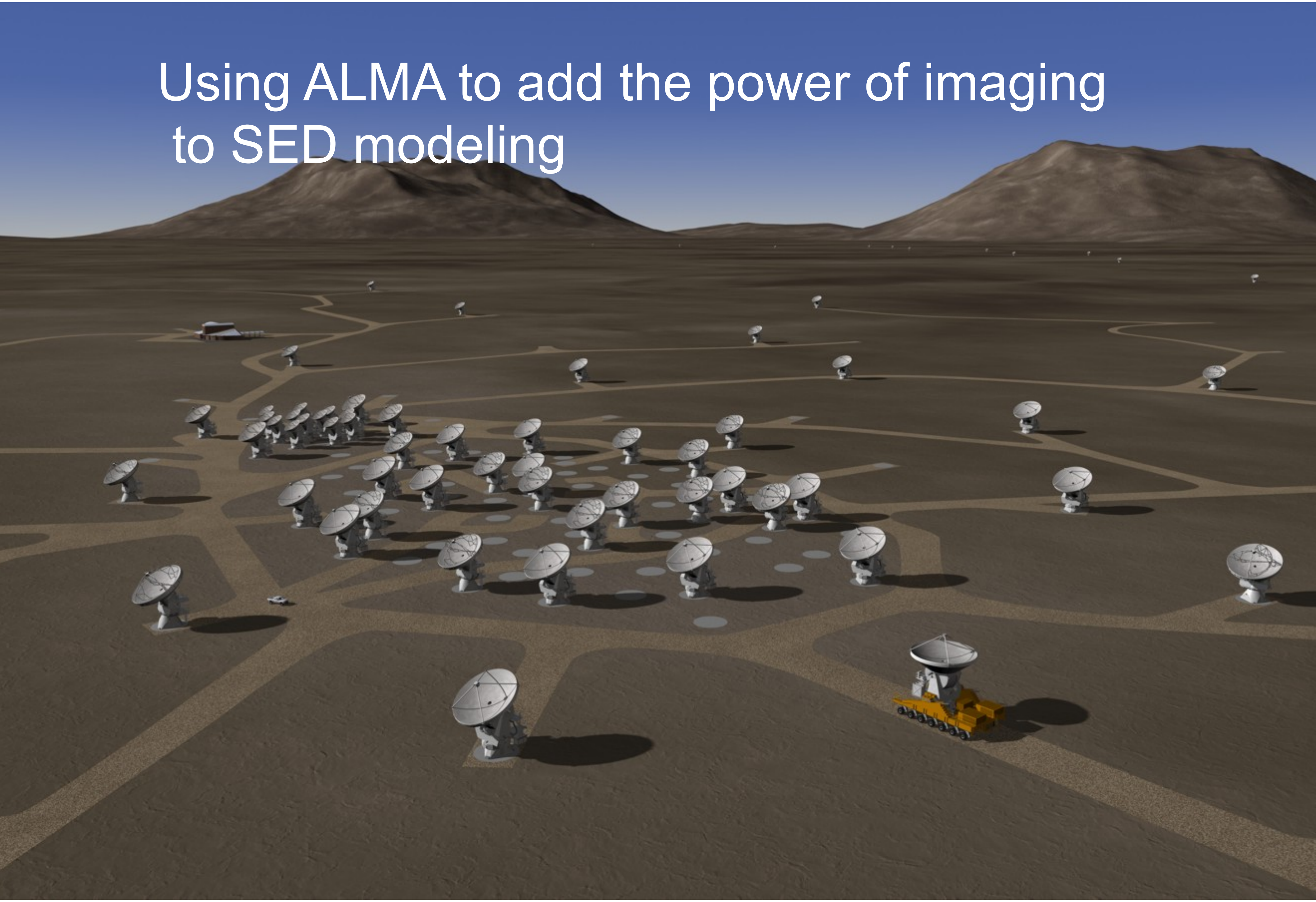


Pre-transitional disk



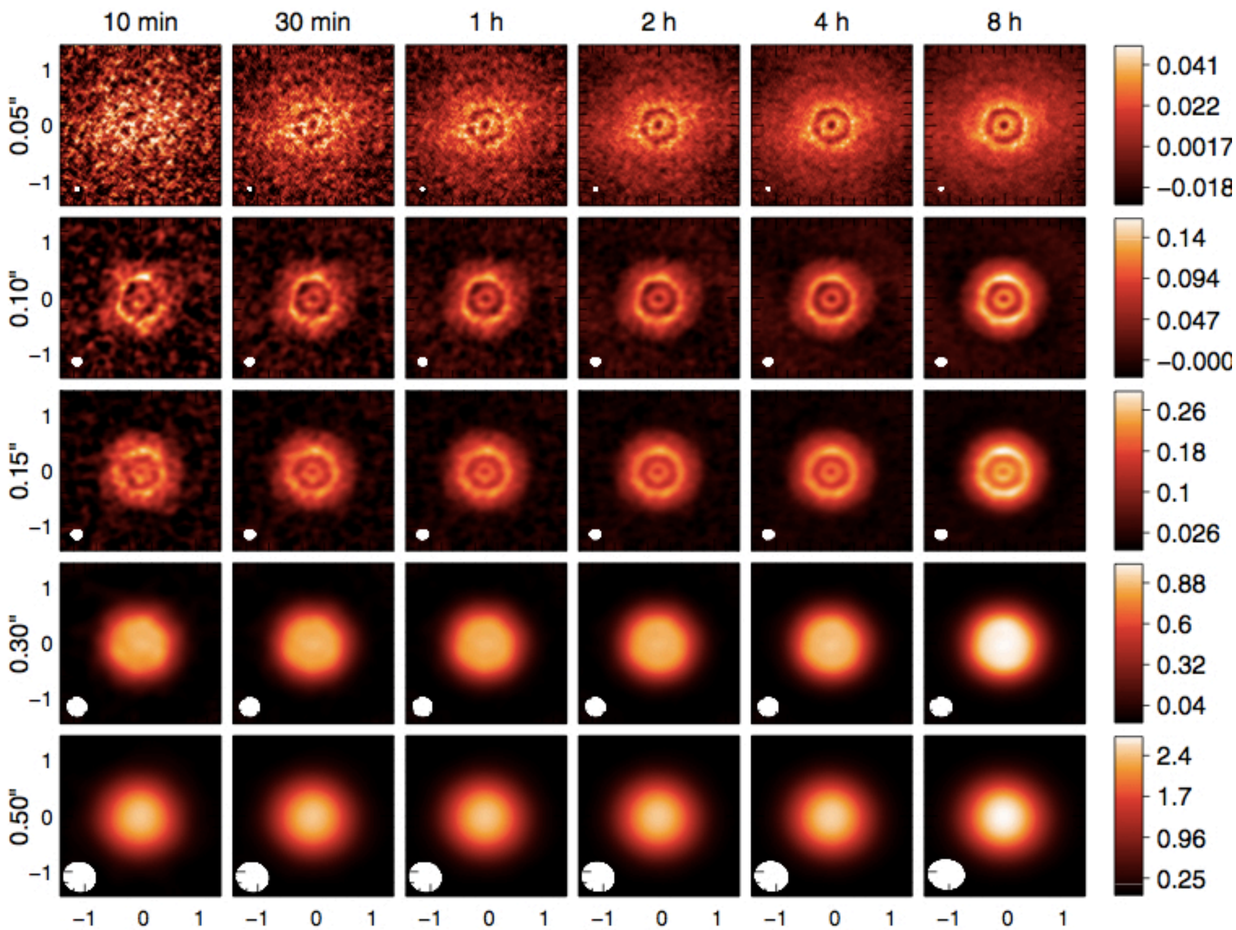
Transitional disk

Using ALMA to add the power of imaging to SED modeling



ALMA will image small gaps in disks

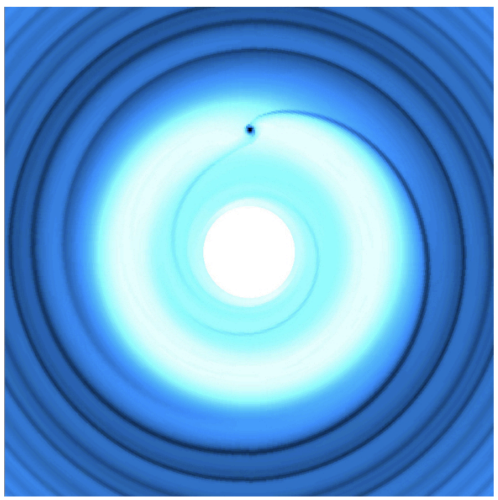
Simulated ALMA images of a disk gap spanning 35 - 50 AU



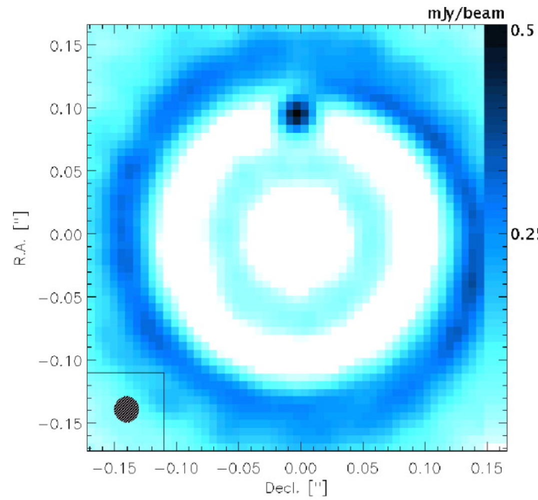
Gonzalez et al. 2012; poster 25 by S. Maddison

ALMA will image gas giant planets in disks

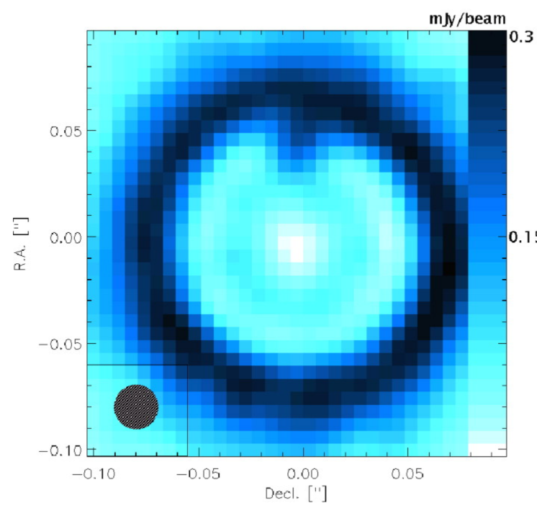
1 Jupiter-mass planet
located 5 AU from star



Simulated images



at 50 pc



at 150 pc

Wolf & D'Angelo 2005; talks by S. Wolf & H. Jong-Condell


What do planet footprints look like?
Drawing of UX Tau A: NASA/JPL-Caltech/T. Pyle (SSC)
Based on Espaillat et al. (2007b)