Tracking Planet Footprints in Dusty Disks

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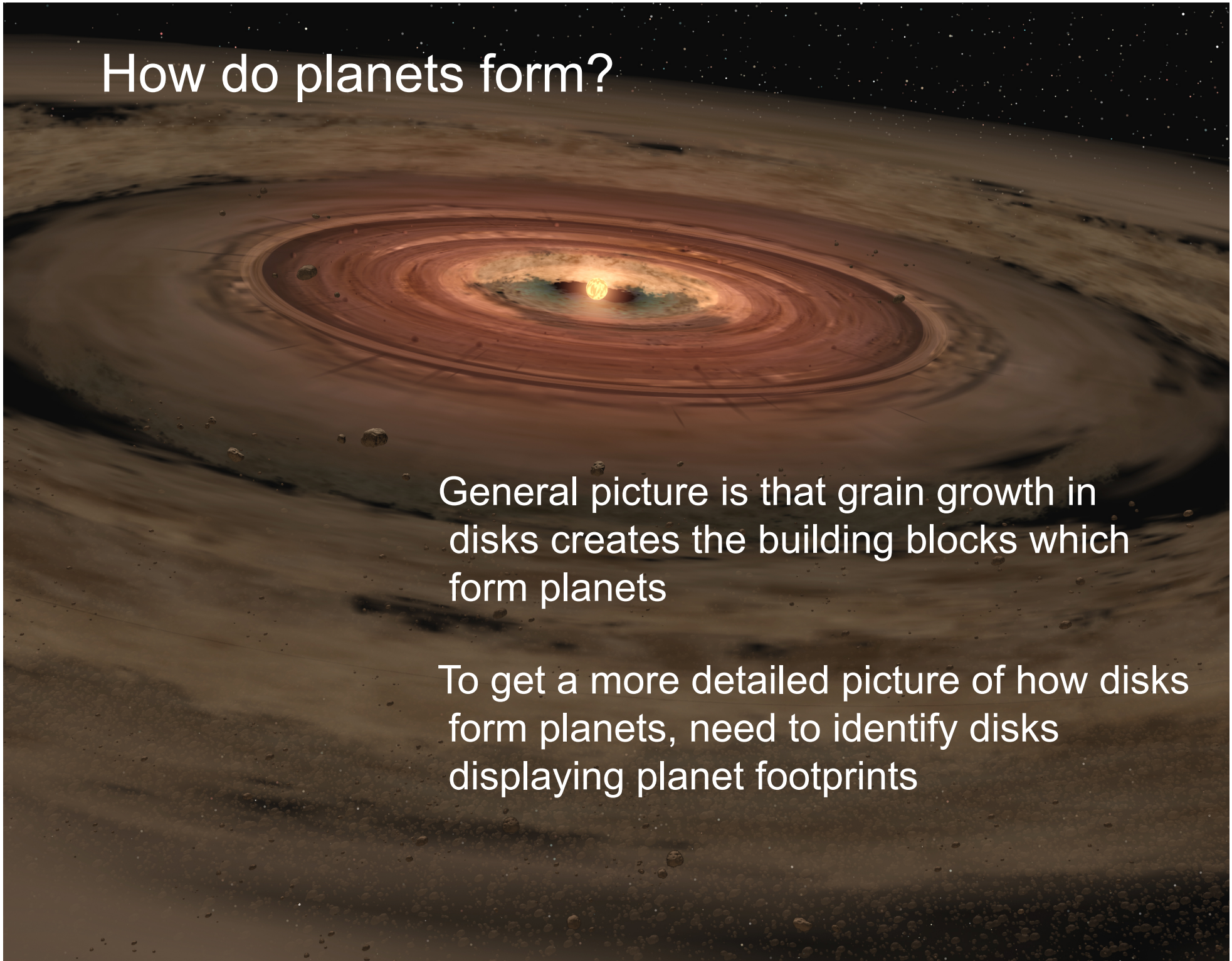
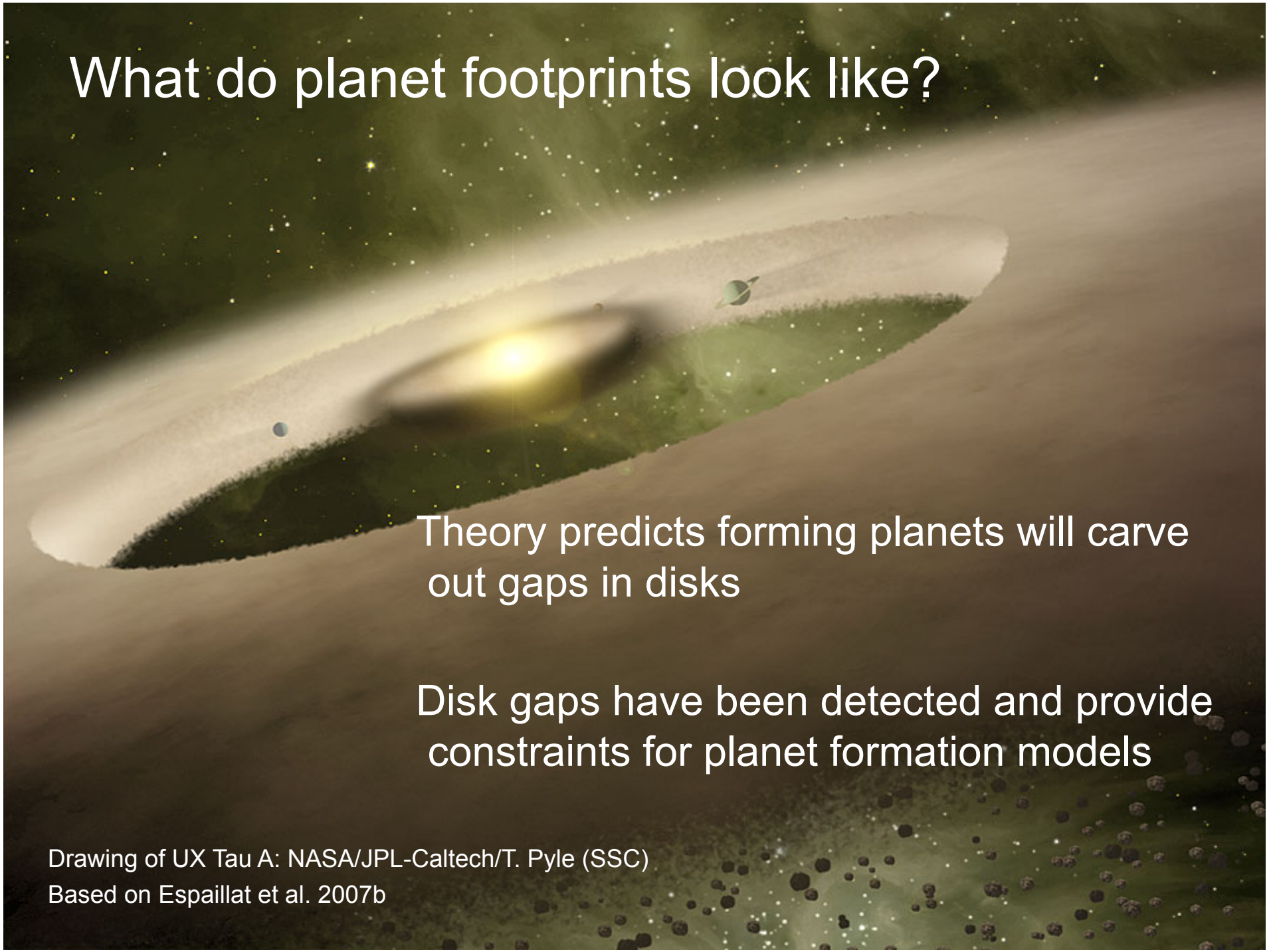
How do planets form?



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

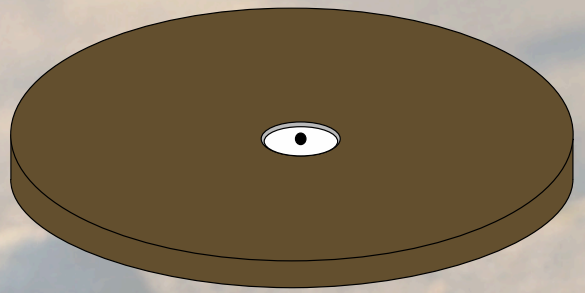
Drawing of UX Tau A: NASA/JPL-Caltech/T. Pyle (SSC)
Based on Espaillat et al. 2007b

Tracking Planet Footprints

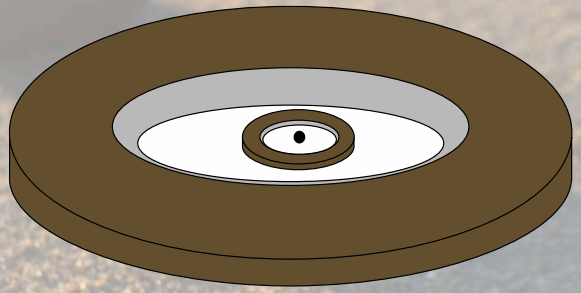
What evidence do we have for planets forming in young disks?

What can disks with holes and gaps tell us about disk evolution and planet formation?

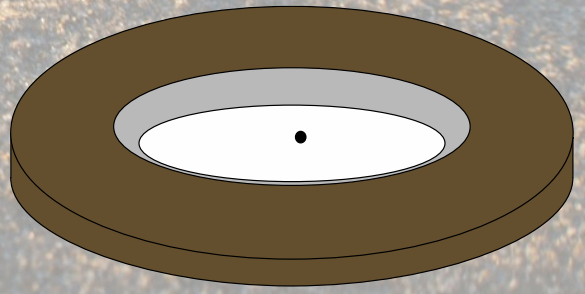
Where do we go from here?



Full disk



Pre-transitional disk



Transitional disk

Espaillat et al. 2014, PPVI

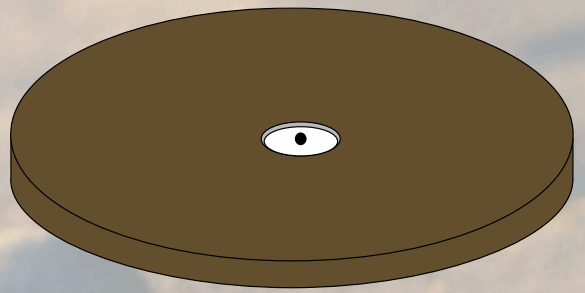
Tracking Planet Footprints

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

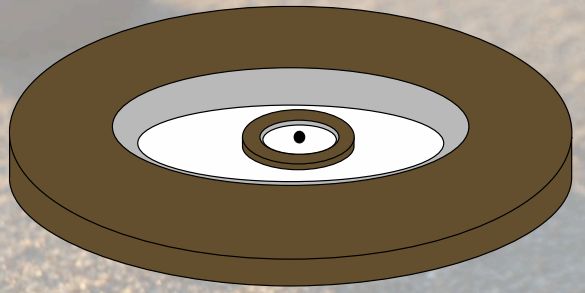
- SEDs and submillimeter images of disk holes and gaps
- theoretical disk clearing mechanisms

What can disks with holes and gaps tell us about disk evolution and planet formation?

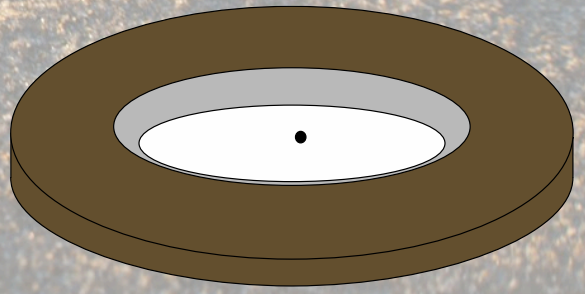
Where do we go from here?



Full disk



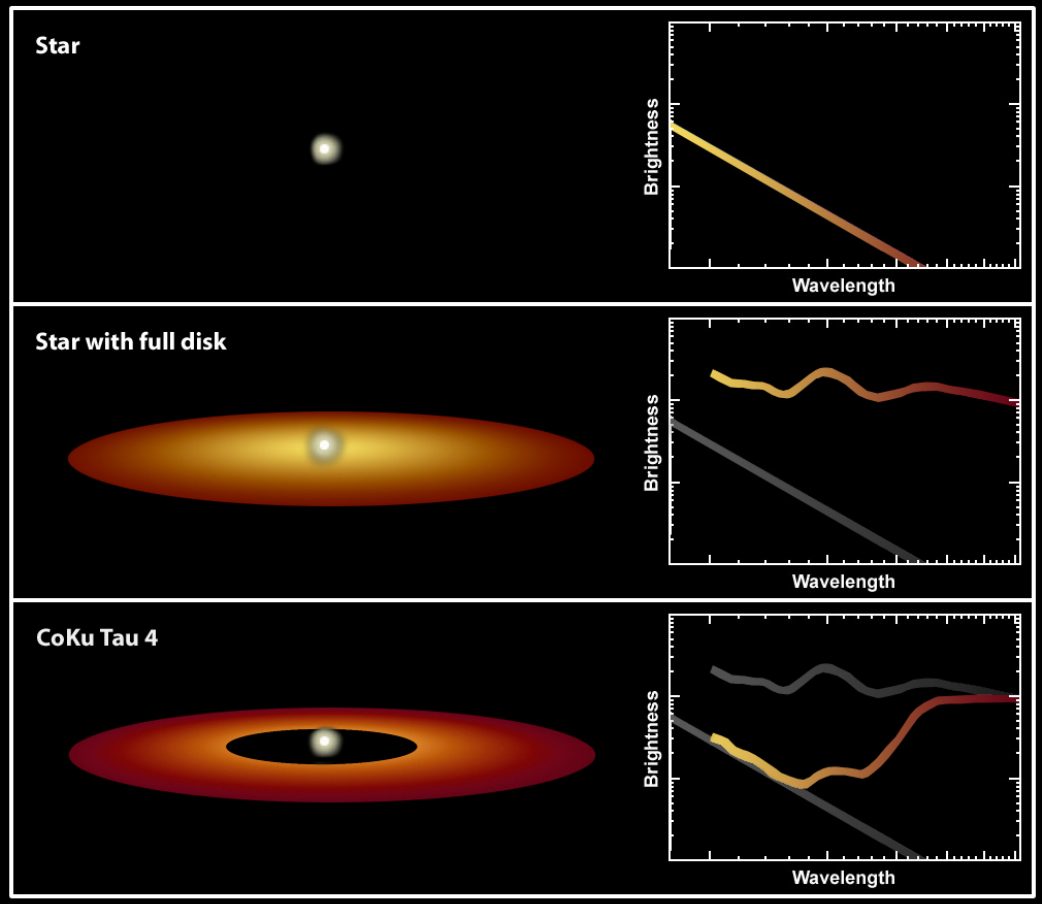
Pre-transitional disk



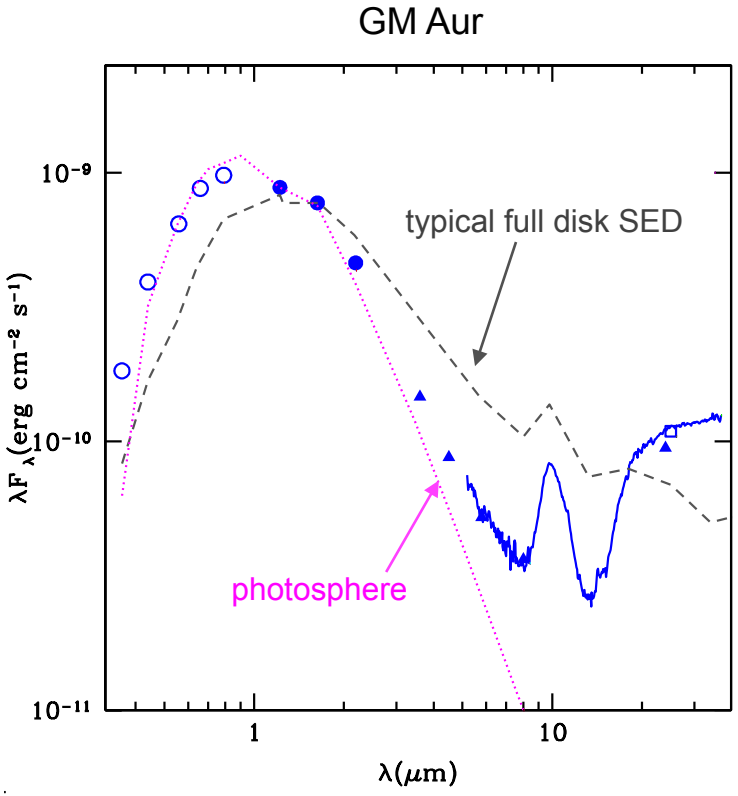
Transitional disk

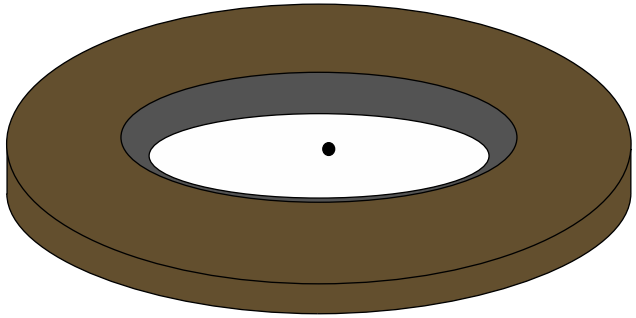
Espaillat et al. 2014, PPVI

Transitional disks have IR dips in SED, indicating an inner disk hole



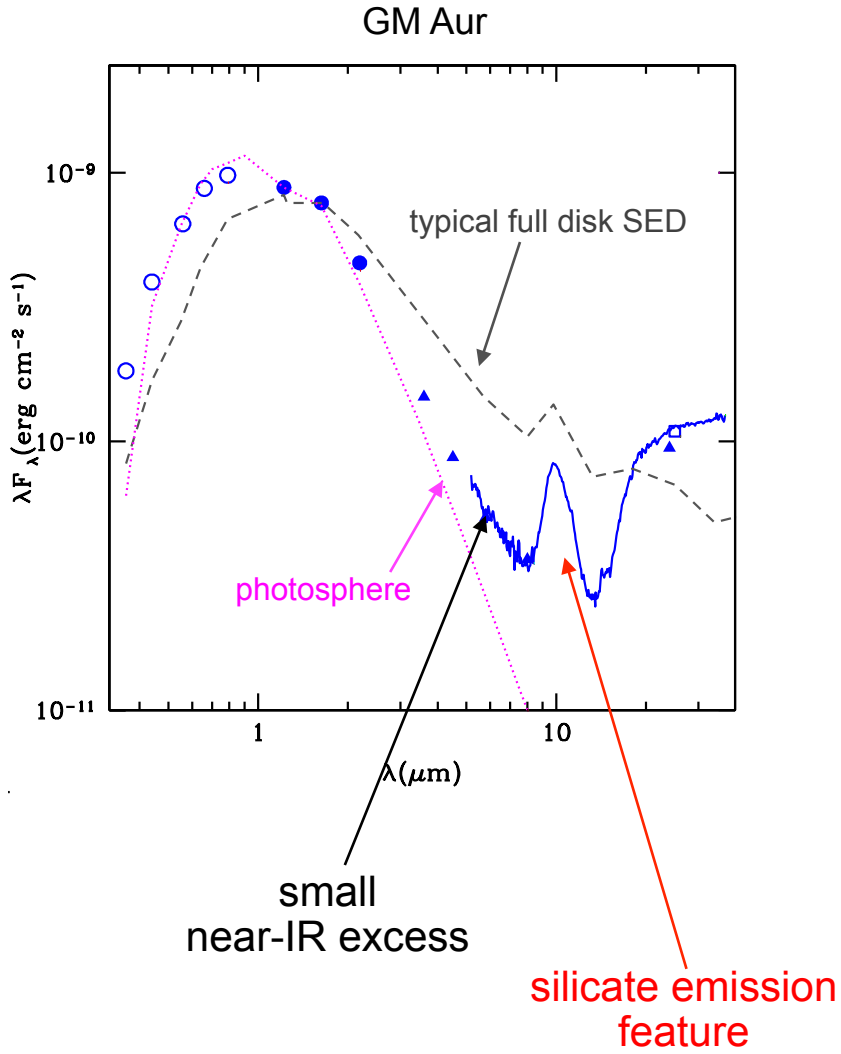
Some inner holes contain small, hot dust

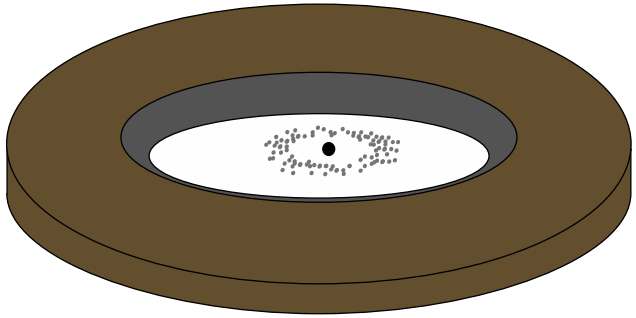




Calvet et al. 2005; Espaillat et al. 2011

Some inner holes contain small, hot dust





Calvet et al. 2005; Espaillat et al. 2011

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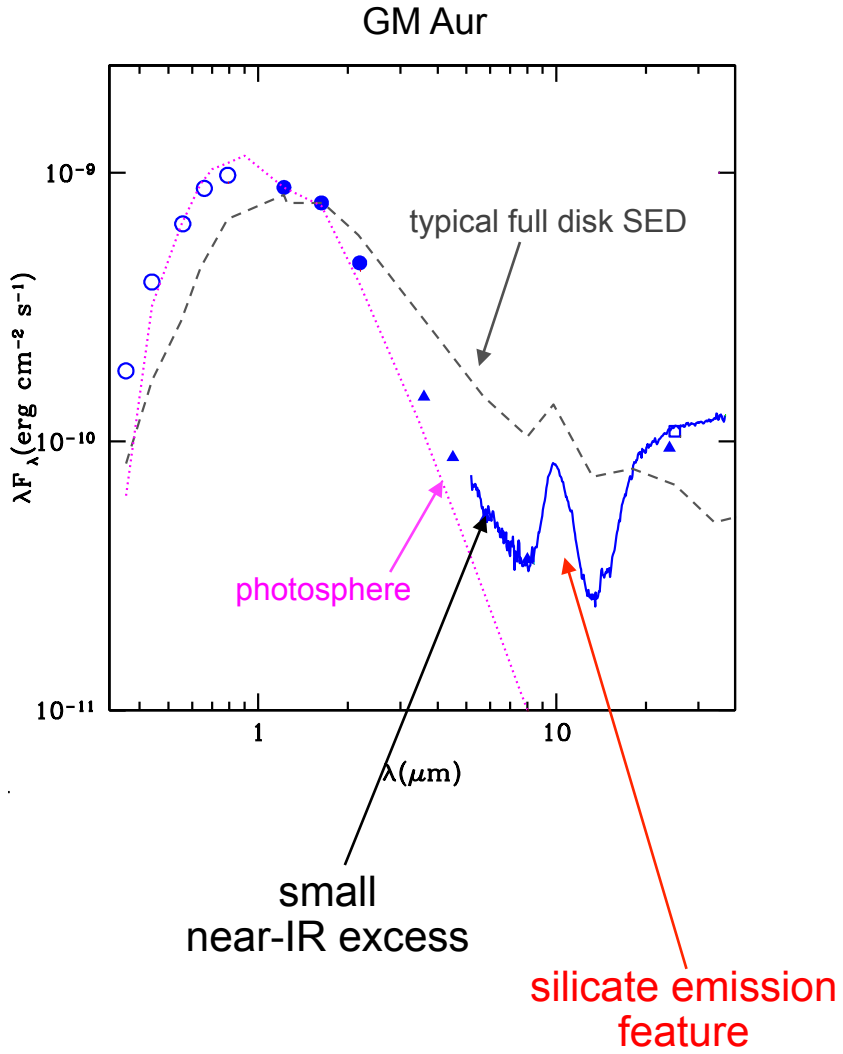
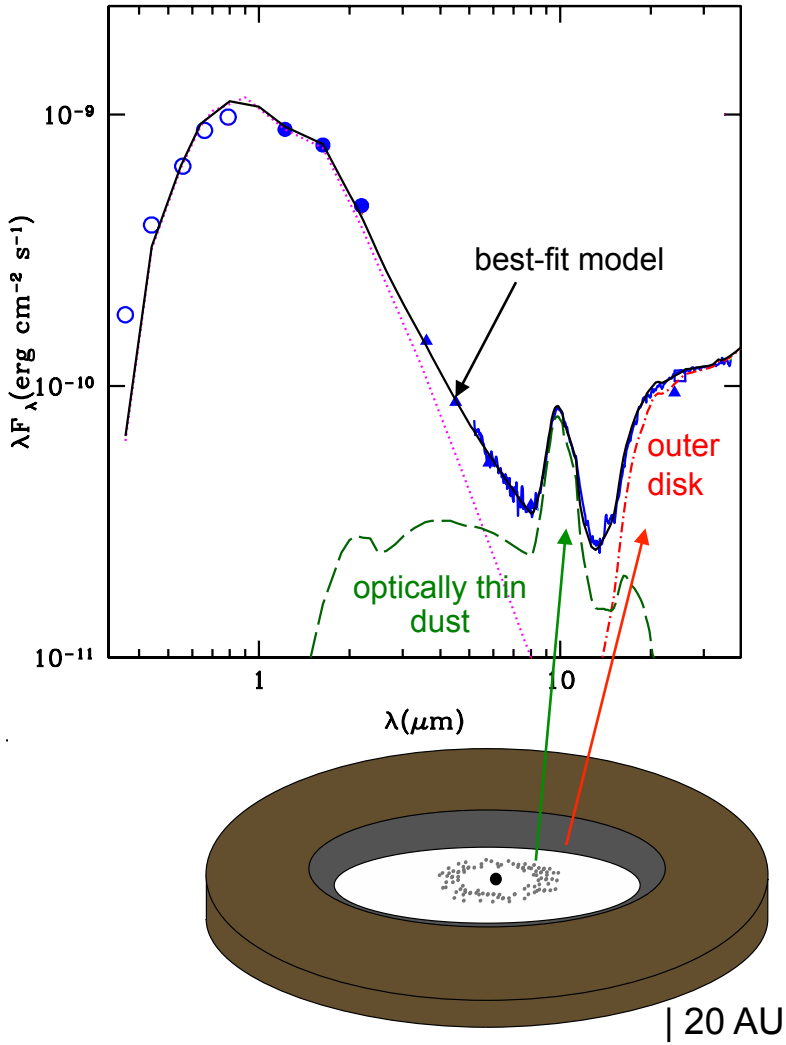


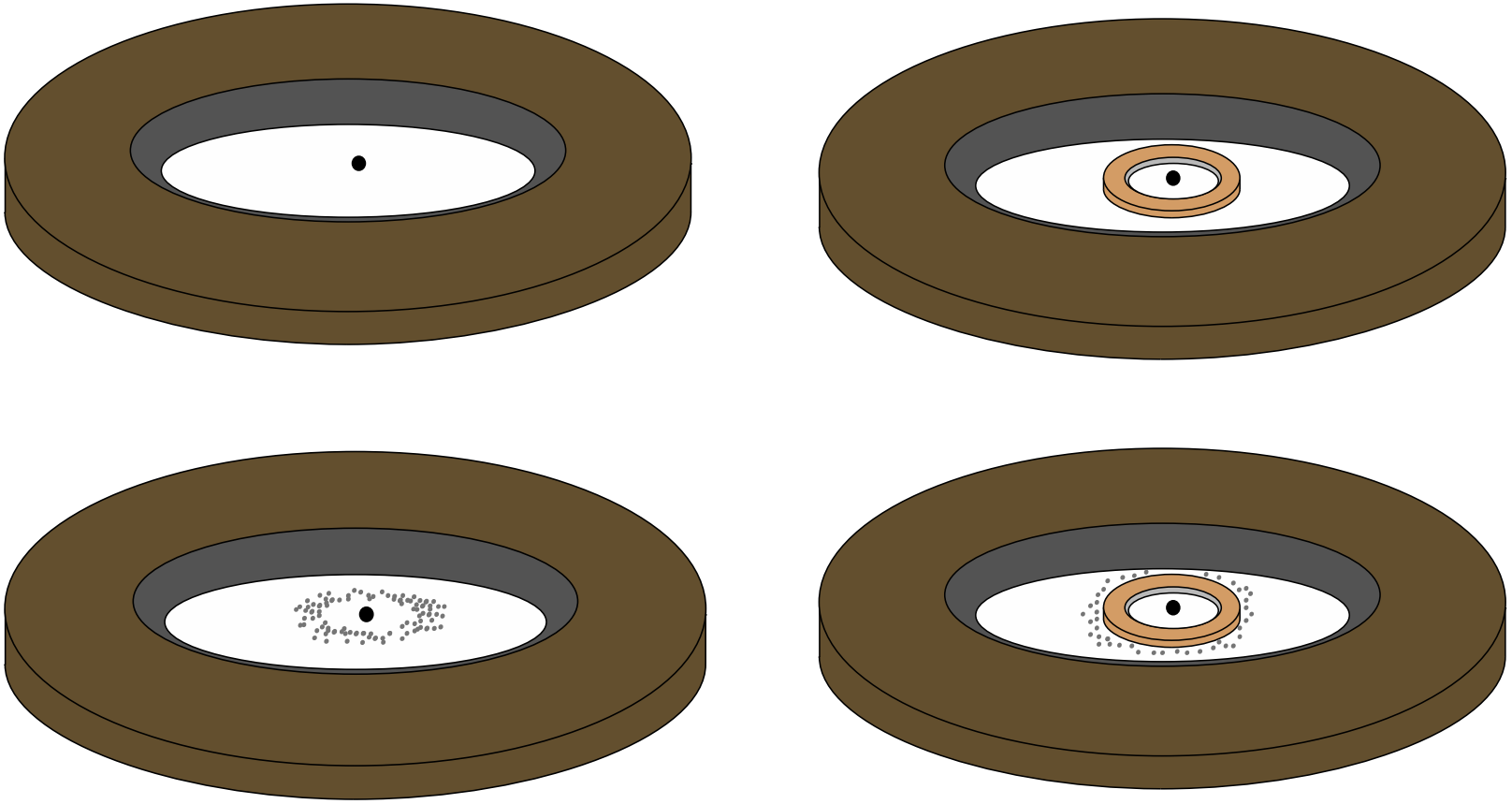


Calvet et al. 2005; Espaillat et al. 2011

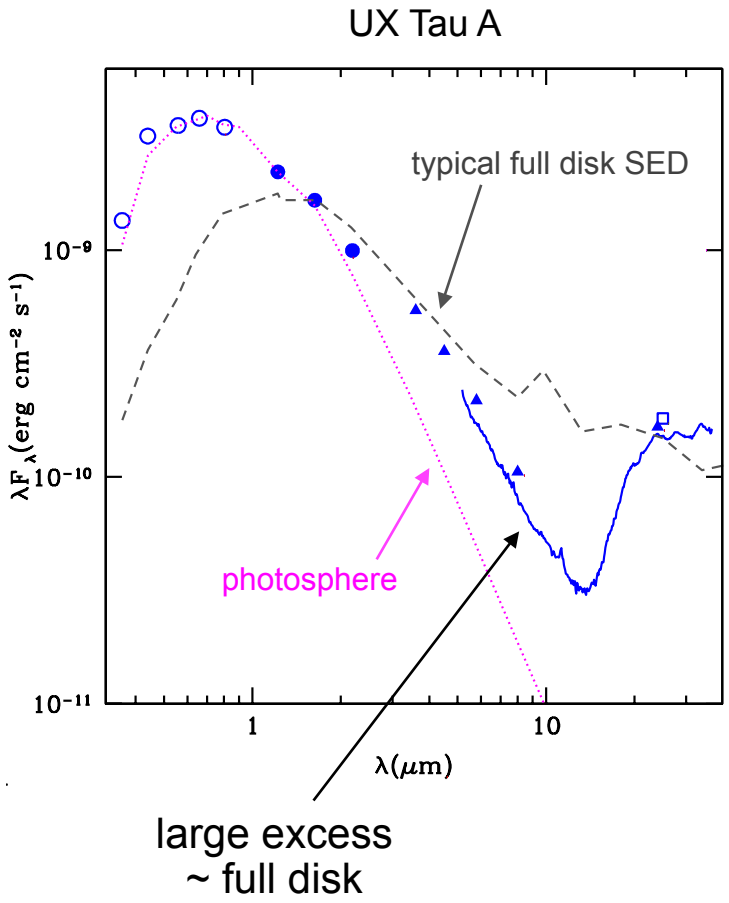
In addition to inner holes, annular gaps have been detected

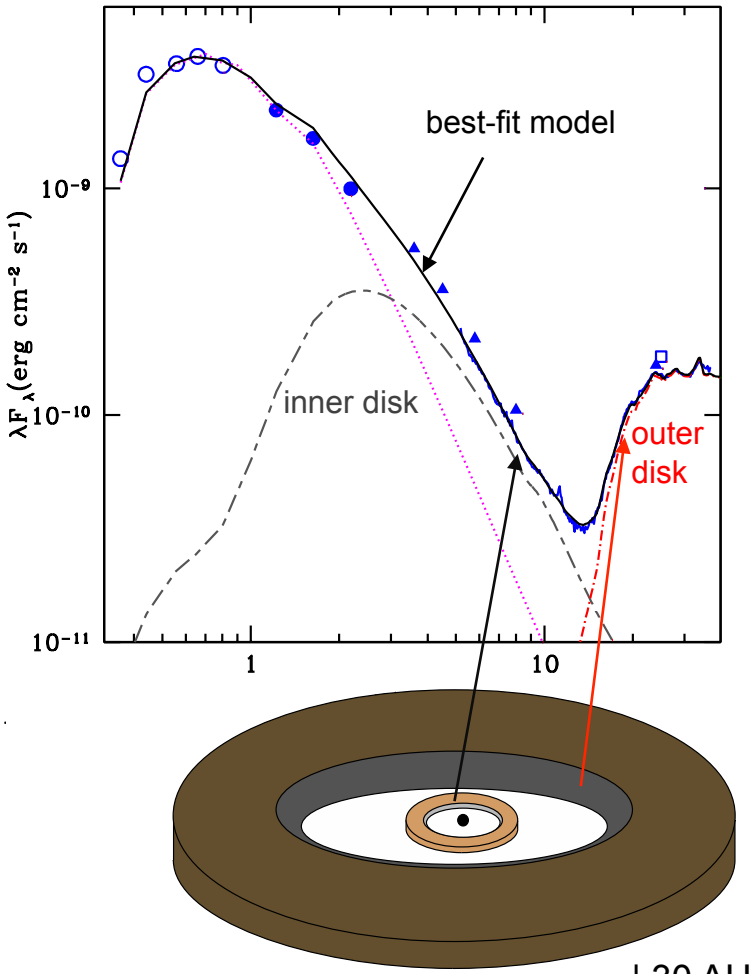
Transitional Disks

Pre-transitional Disks



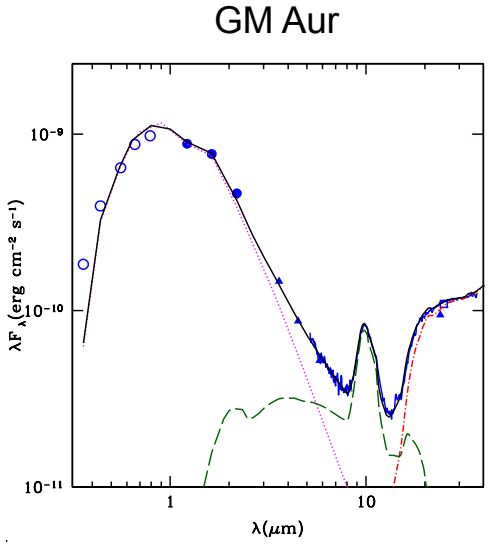
Pre-transitional disks: objects with annular gaps

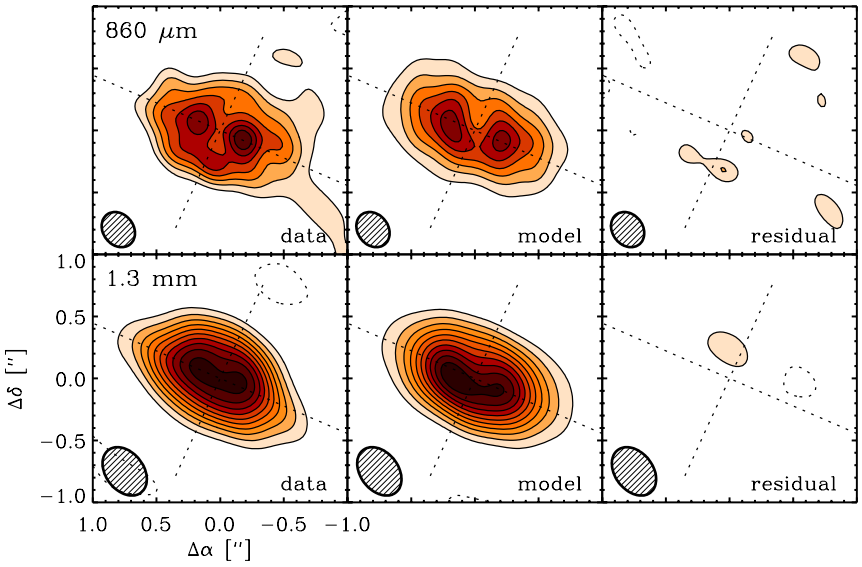


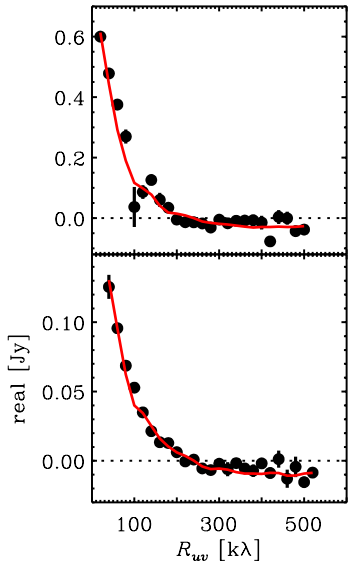


Espaillat et al. 2007b; also Brown et al. 2007

Combining submm interferometric imaging and SED modeling to confirm disk cavities



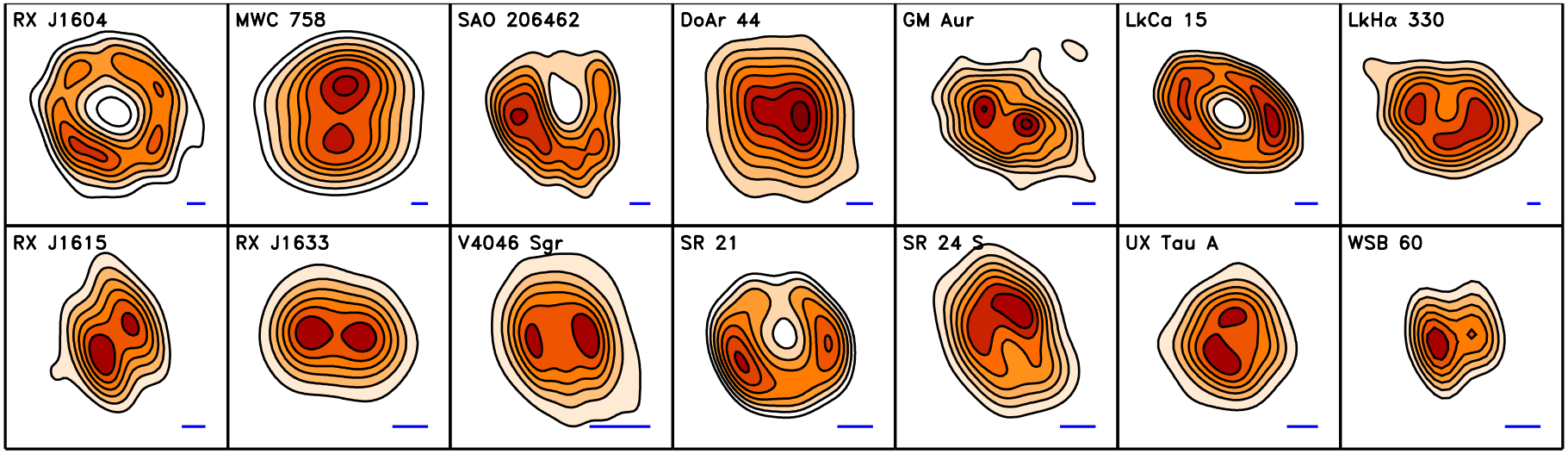




best-fit model to observed SED → simulated images & simulated visibilities

Hughes, Andrews, Espaillat et al. 2009

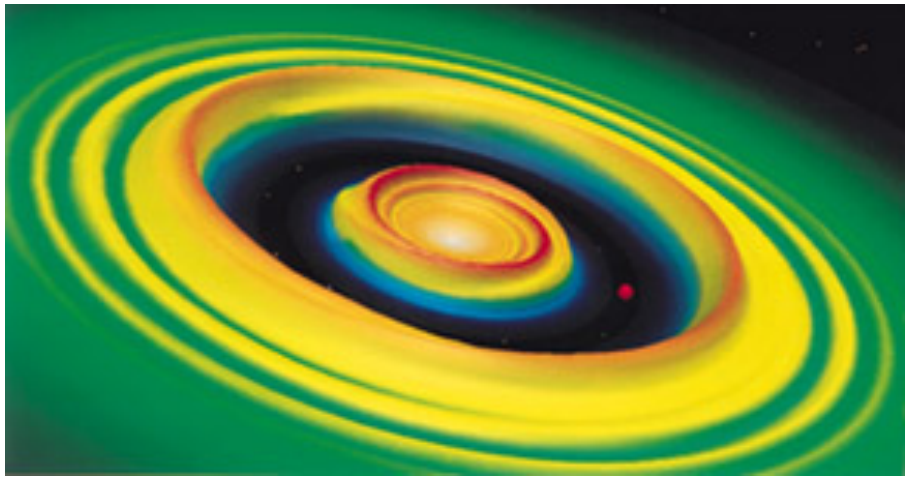
Several disk cavities now confirmed via submm interferometric imaging

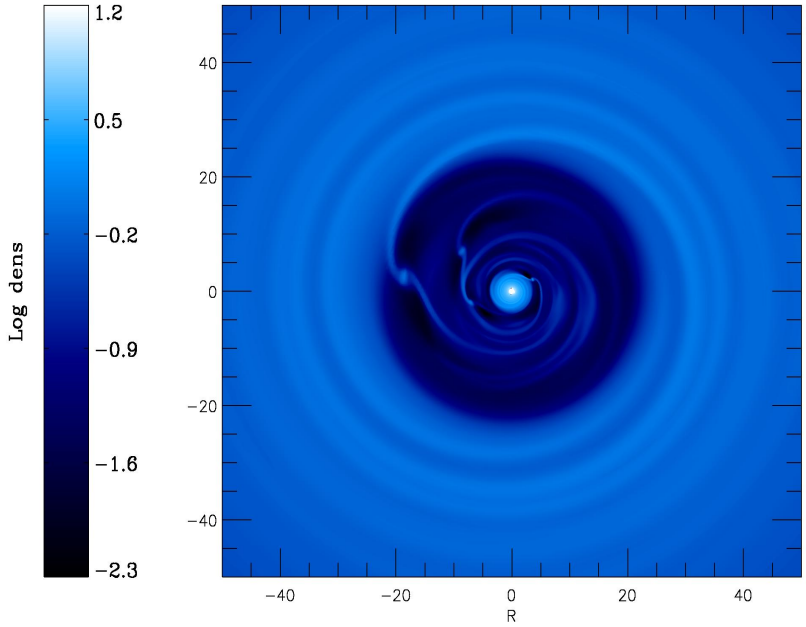


also AB Aur (*Pietu et al. 2005*), TW Hya (*Hughes et al. 2007*), SAO 206462 (*Brown et al. 2009*), RY Tau (*Isella et al. 2010a*), DM Tau (*Andrews et al. 2011*), IRS 48 (*Brown et al. 2012*), HD 142527 (*Casassus et al. 2013*), Sz 91 (*Tsukagoshi et al. 2014*)

Figure from Espaillat et al. 2014, PPVI; Data from Mathews et al. 2012 Isella, et al. 2010, Brown et al. 2009, Andrews et al. 2009, Hughes et al. 2009, Andrews et al. 2011b, Brown, et al. 2008, Cieza et al. 2012, Rosenfeld et al. 2013, Andrews et al. 2010

Disk clearing mechanisms: dynamical clearing by planets

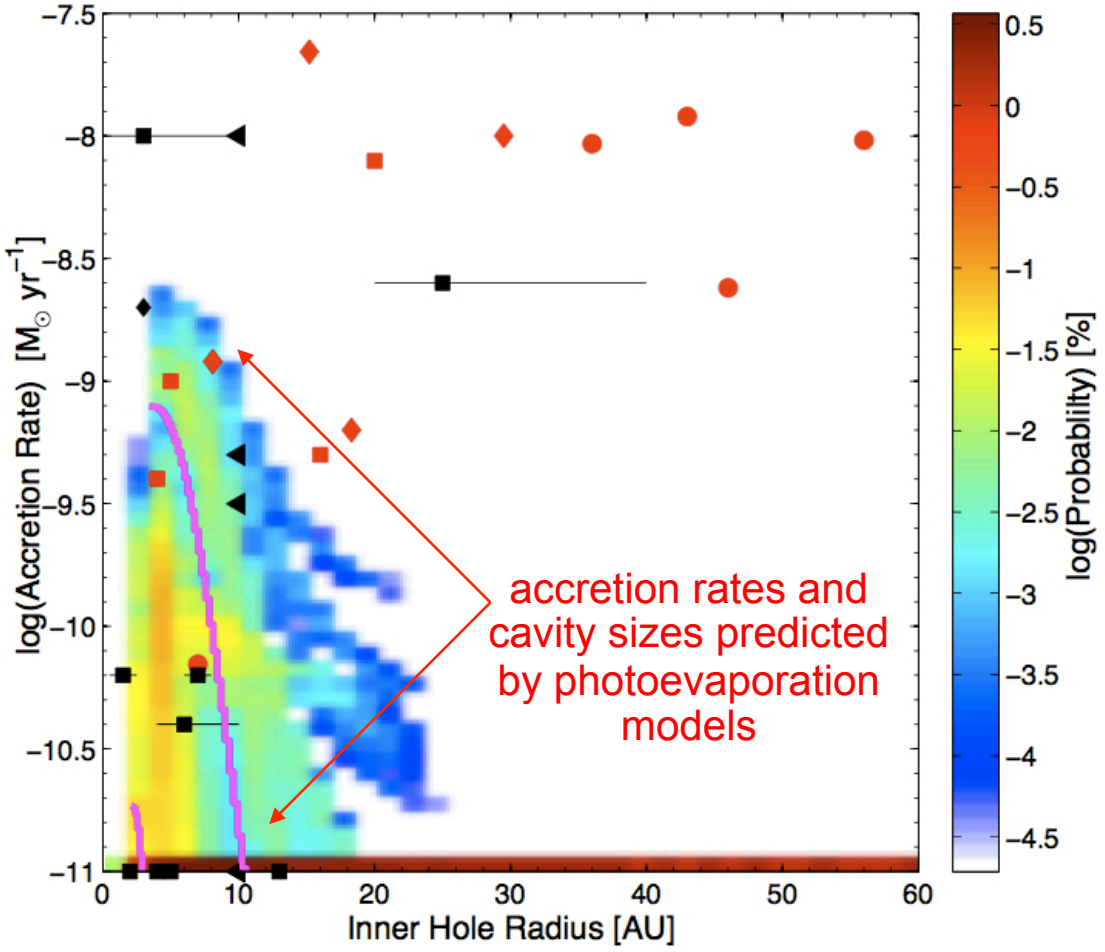




Bryden et al. 1999

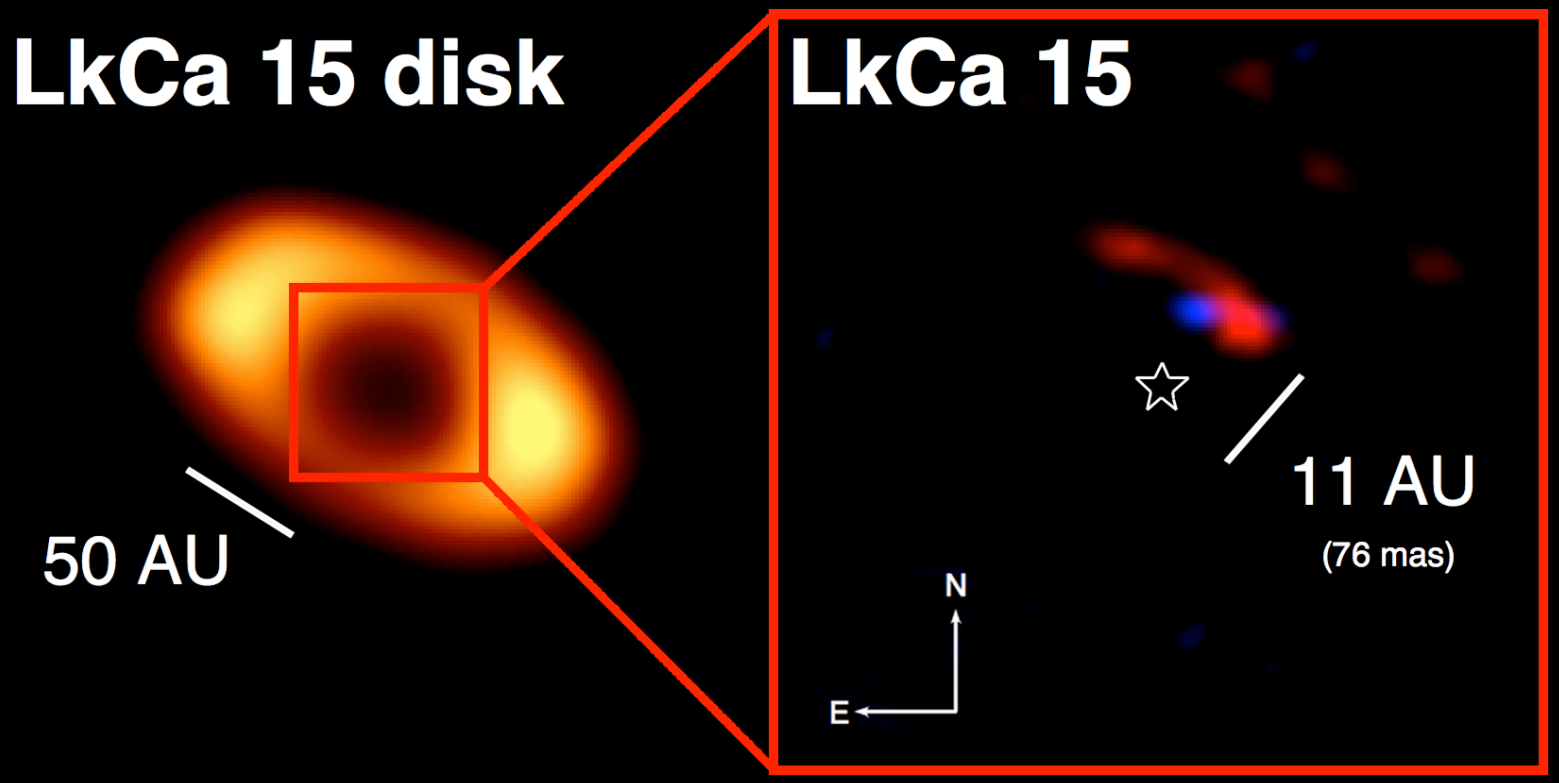
Zhu et al. 2011; see talk by Z. Zhu

Disk clearing mechanisms: photoevaporation



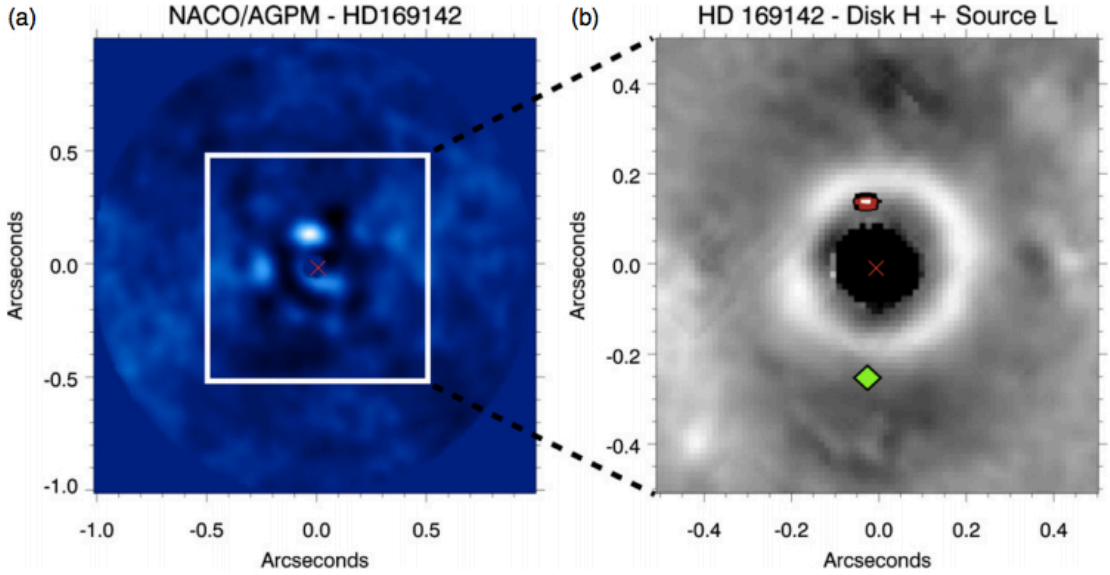
Owen et al. 2011

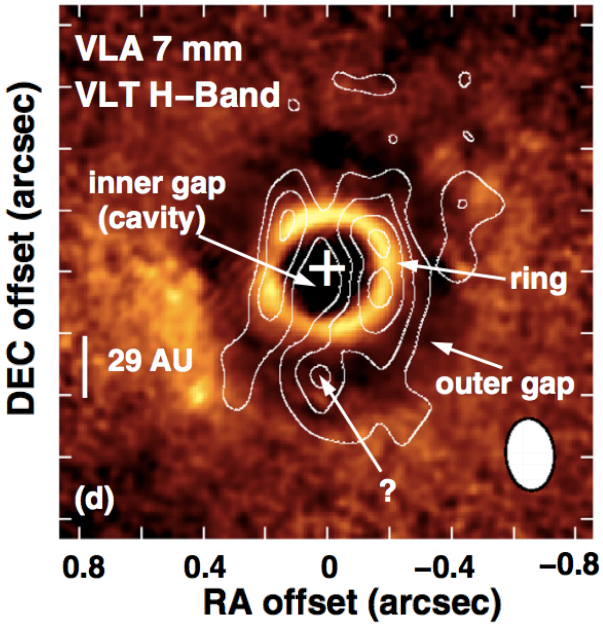
A possible protoplanet around LkCa 15



Kraus & Ireland 2011

A possible protoplanet around HD 169142





Reggiani et al. 2014, also Biller et al. 2014; see talk by S. Quanz

Osorio et al. 2014

Tracking Planet Footprints

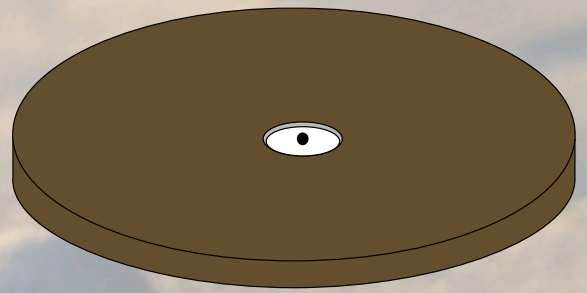
What evidence do we have for planets forming in young disks?

- SEDs and submillimeter images of disk holes and gaps
- theoretical disk clearing mechanisms

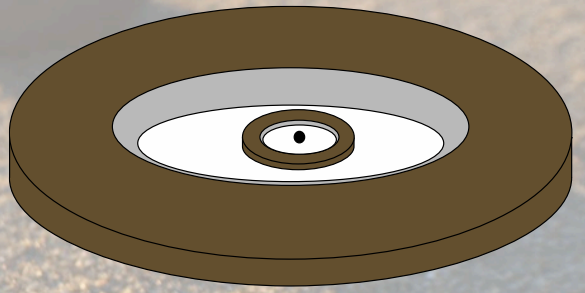
What can disks with holes and gaps tell us about disk evolution and planet formation?

- variable dust & gas properties
- spatial distributions of disk gas and dust

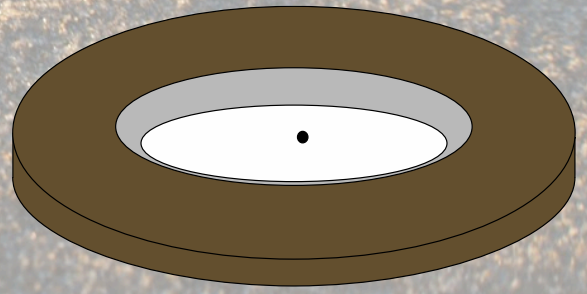
Where do we go from here?



Full disk



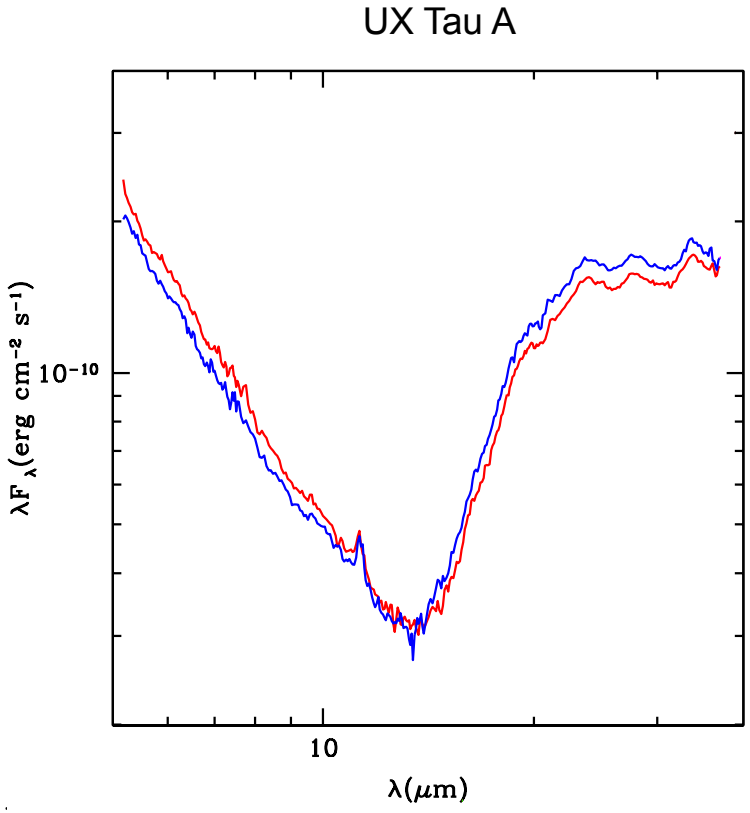
Pre-transitional disk

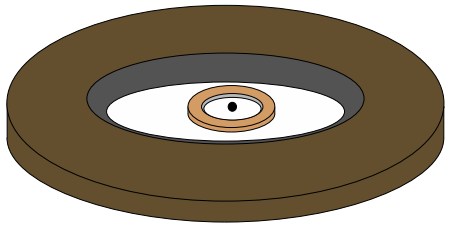


Transitional disk

Espaillat et al. 2014, PPVI

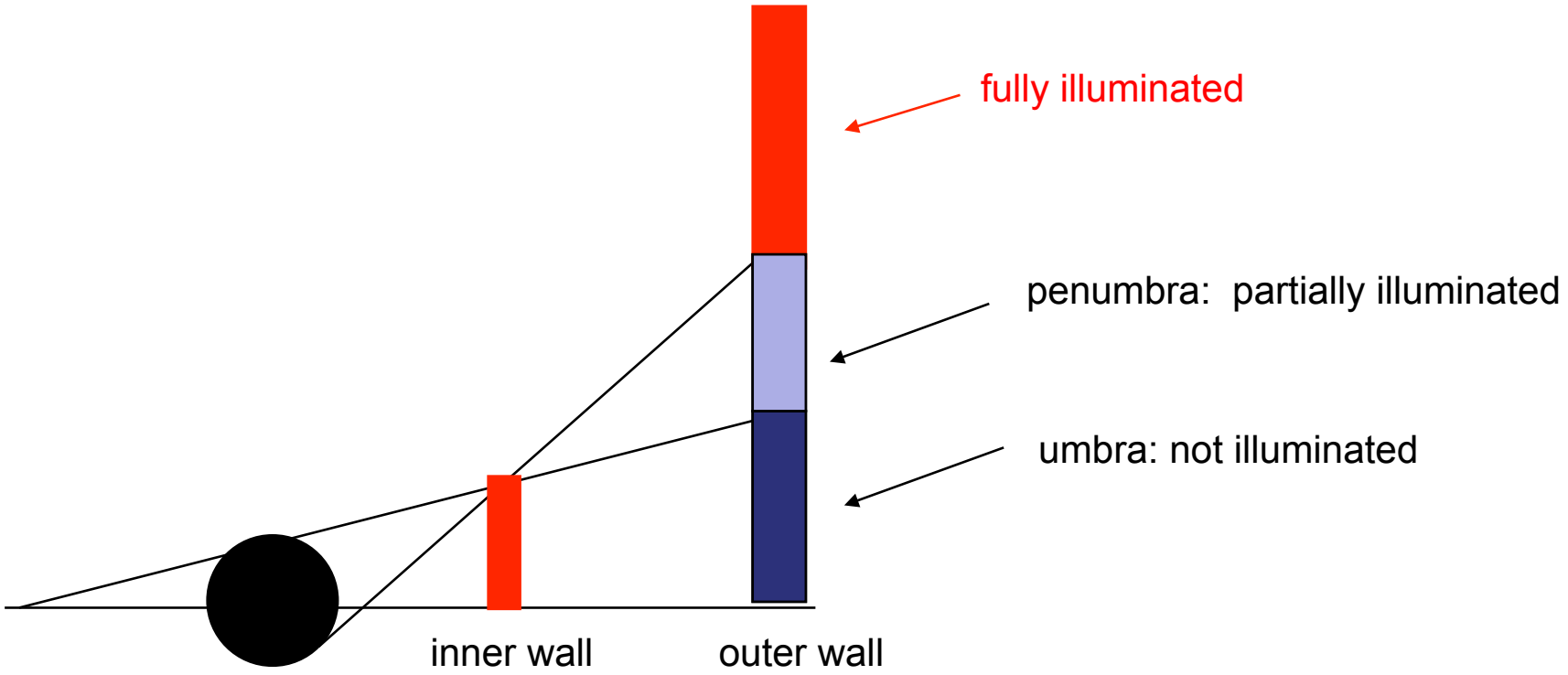
Pre-transitional disks have variable "see-saw" MIR emission





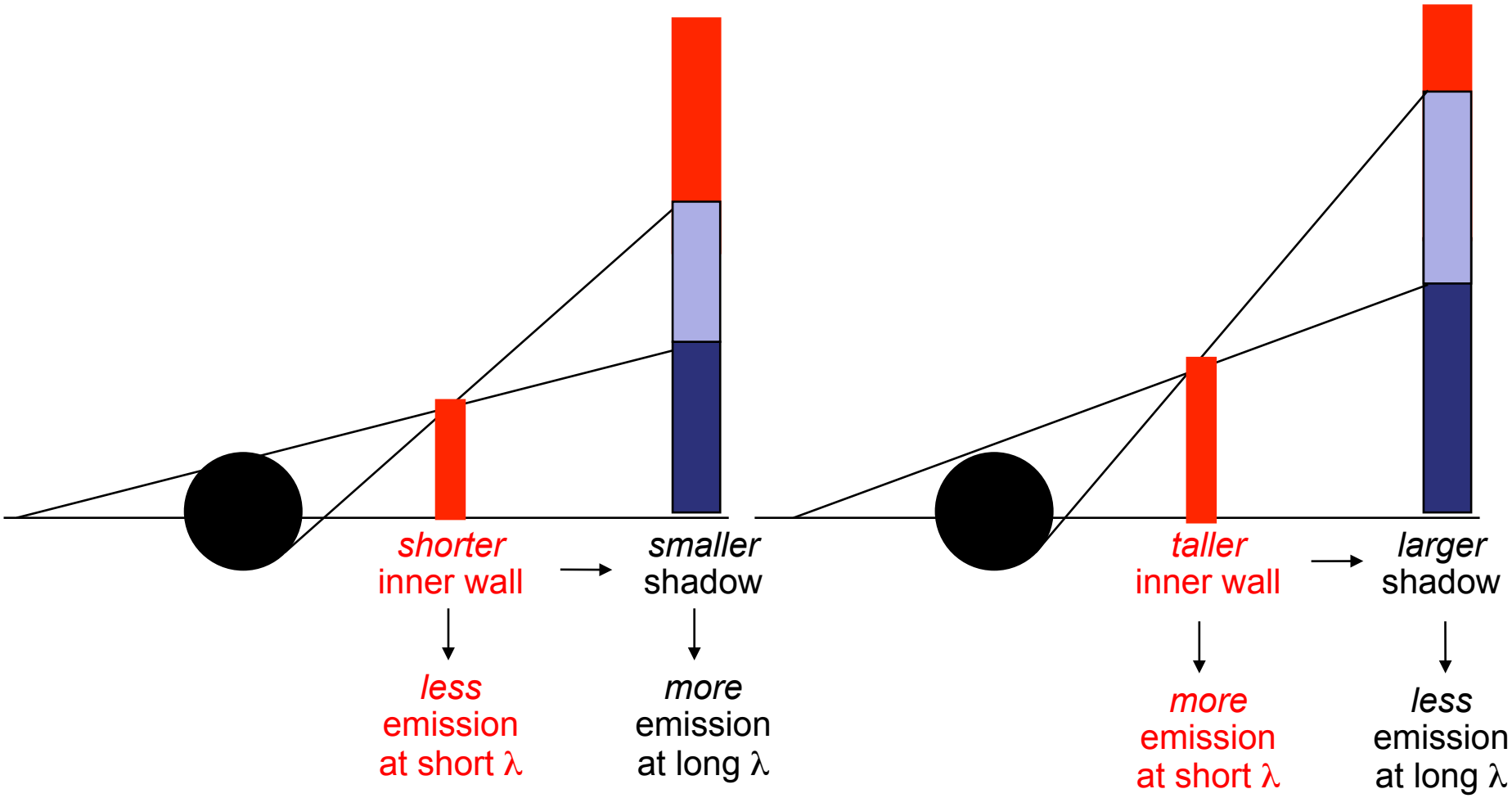
Espaillat et al. 2011; also Muzerolle et al. 2010, Flaherty et al. 2012

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

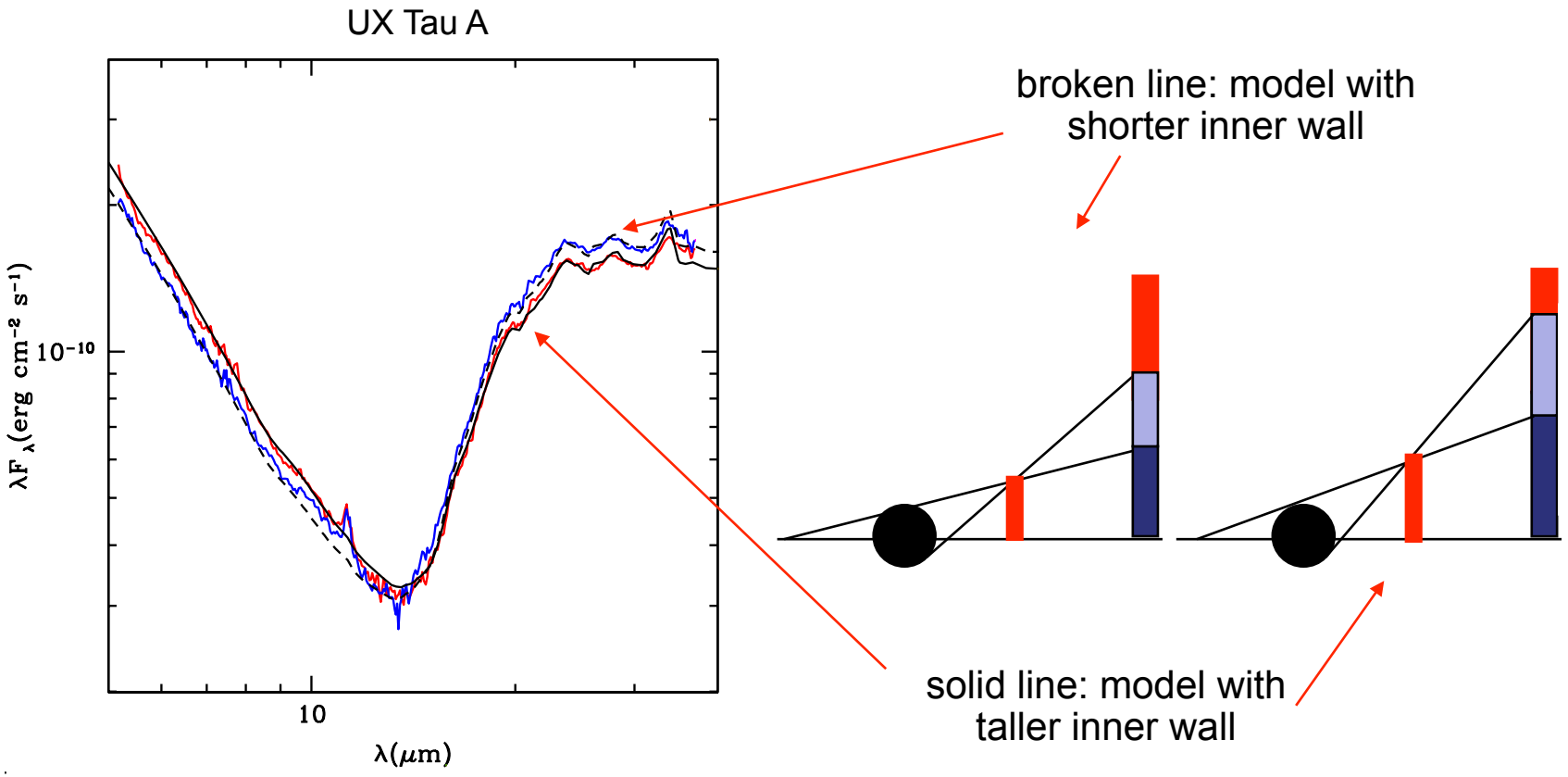


Espaillat et al. 2010

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

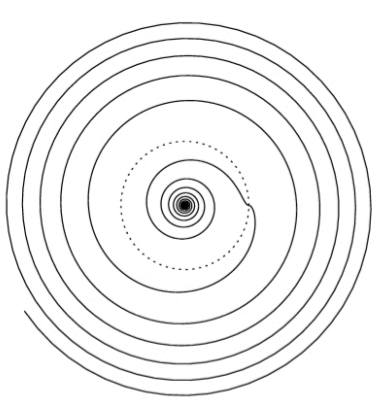


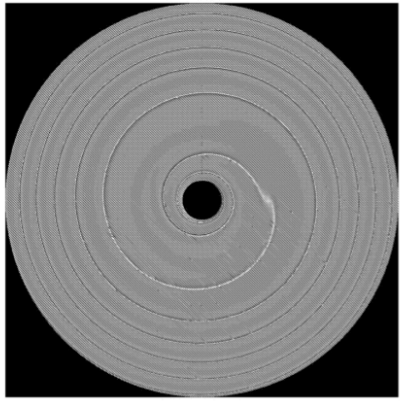
Espaillat et al. 2011

Potential causes of MIR variability in pre-transitional disks

Planet-disk interaction

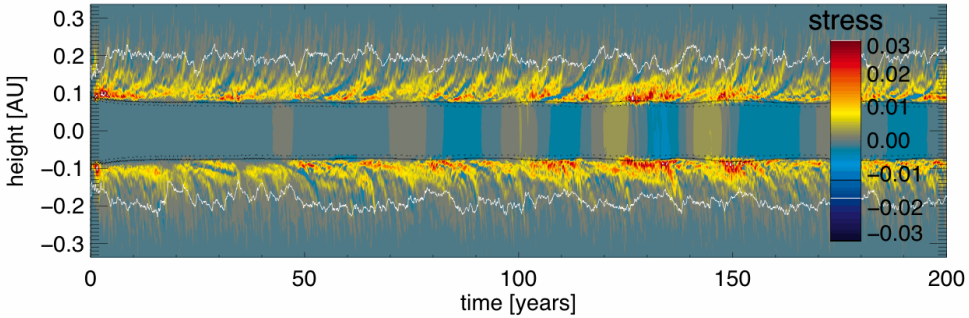
Flaherty et al. 2011





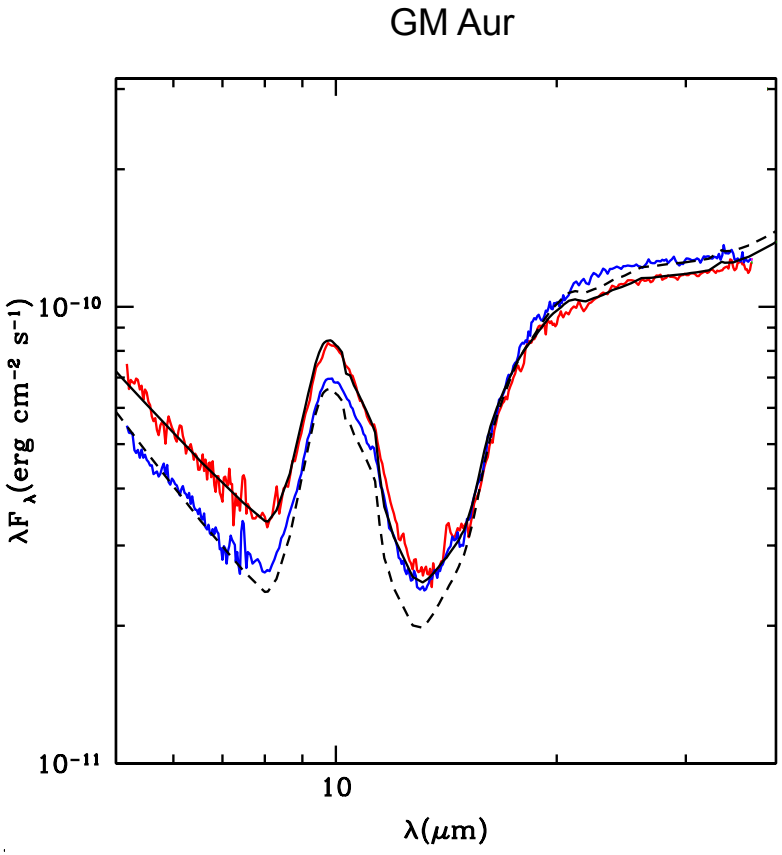
Ogilvie & Lubow 2002

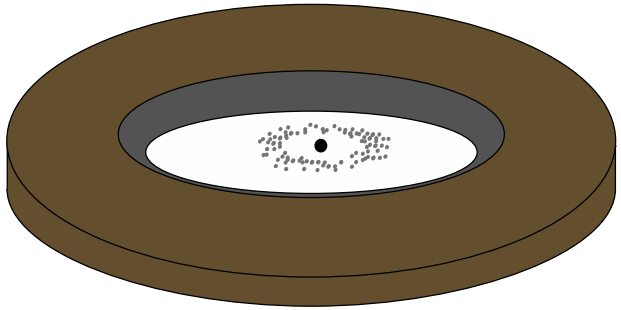
Turbulence from MRI



Hirose & Turner 2011; talk by N. Turner

MIR variability in transitional disks

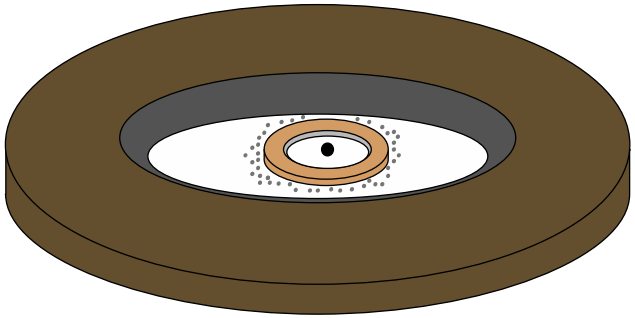




Espaillat et al. 2011

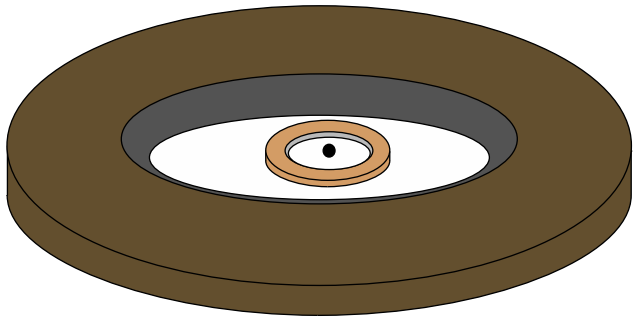
Extracting observational constraints to inform physical models

LkCa 15



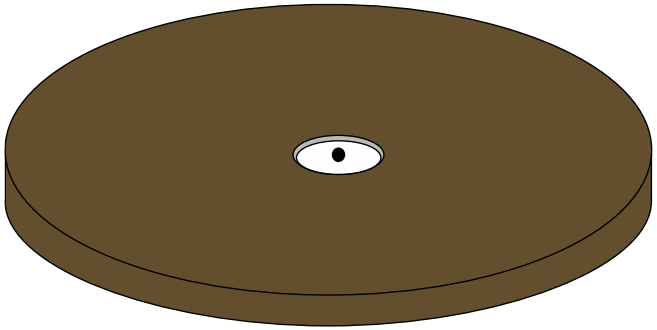
$3 \times 10^{-9}\ M_{\odot}\ yr^{-1}$ | 40 AU

UX Tau A



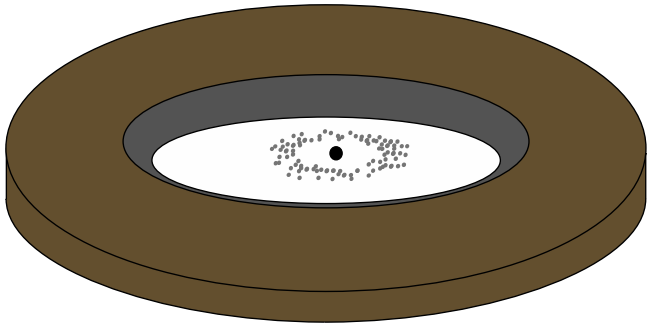
$1 \times 10^{-8}\ M_{\odot}\ yr^{-1}$ | 30 AU

Full disk



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

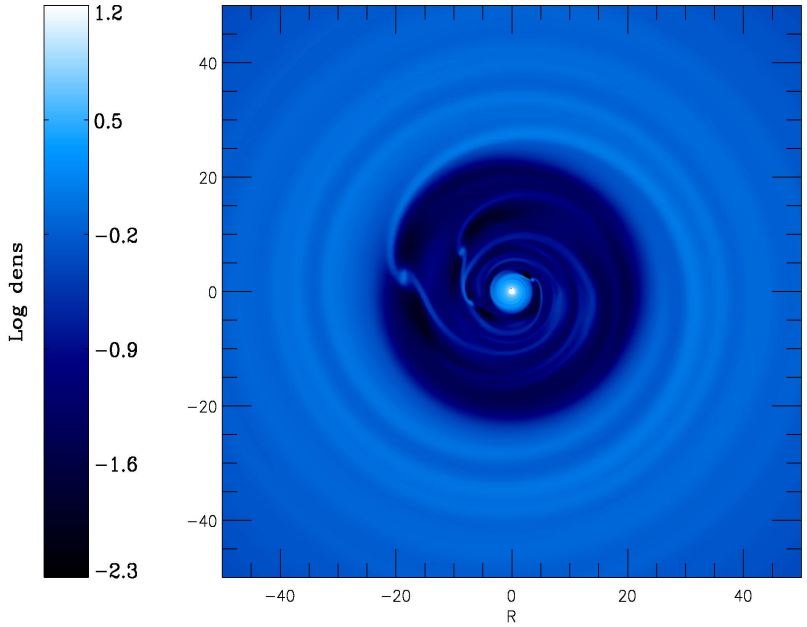
GM Aur



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

Multiple planets cannot explain all aspects of the observations

Multiple planets can create large gaps



However, predicted accretion rate of ~10^{-11} $M_\odot$ yr^{-1} is lower than observed

Zhu et al. 2011; talk by Z. Zhu

Dust filtration can lead to different gas and dust distributions

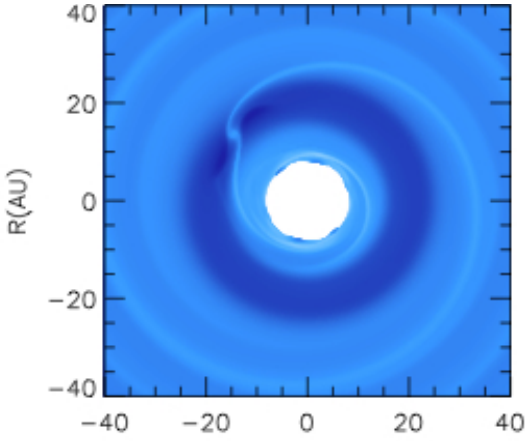
Gas Distribution

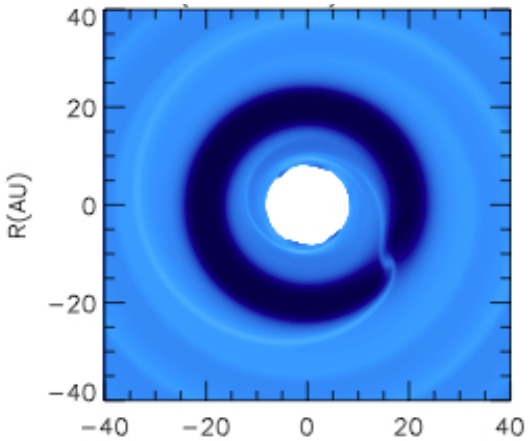
Small Dust Distribution

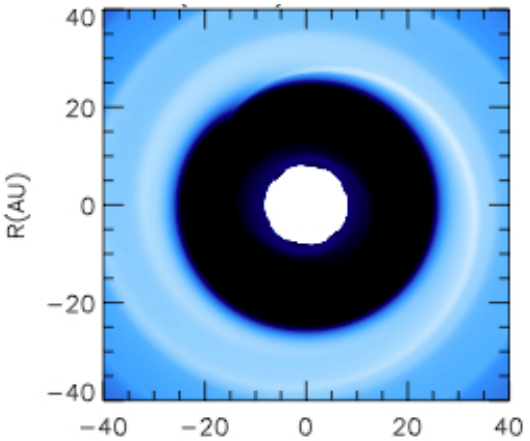
(< 10 microns)

Large Dust Distribution

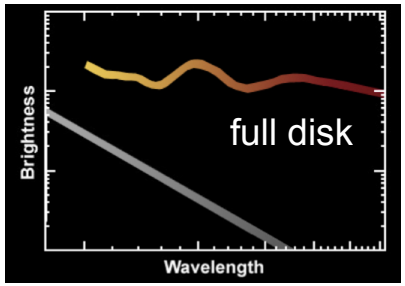
(~ 1mm)

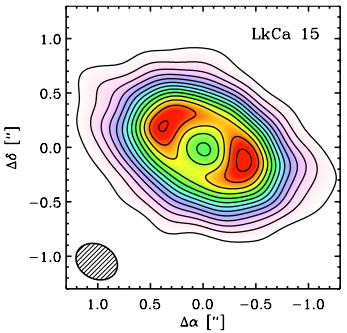






$\sim 10^{-9}\ M_{\odot}\ yr^{-1}$

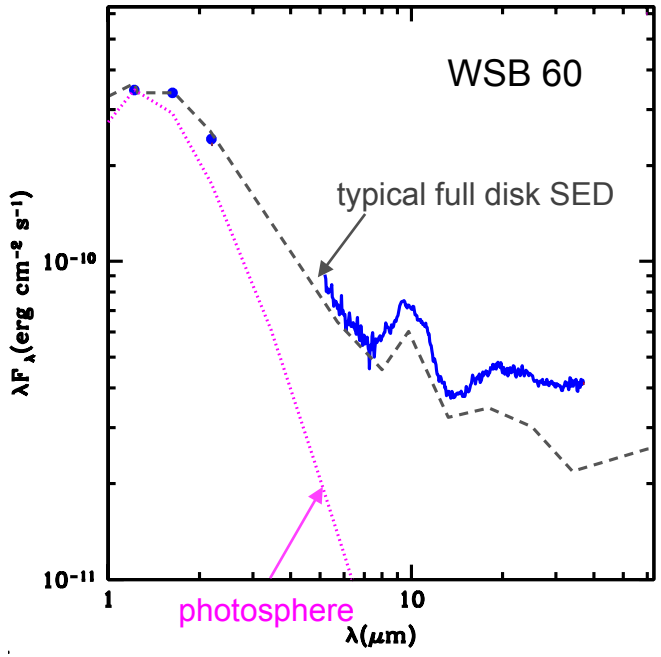




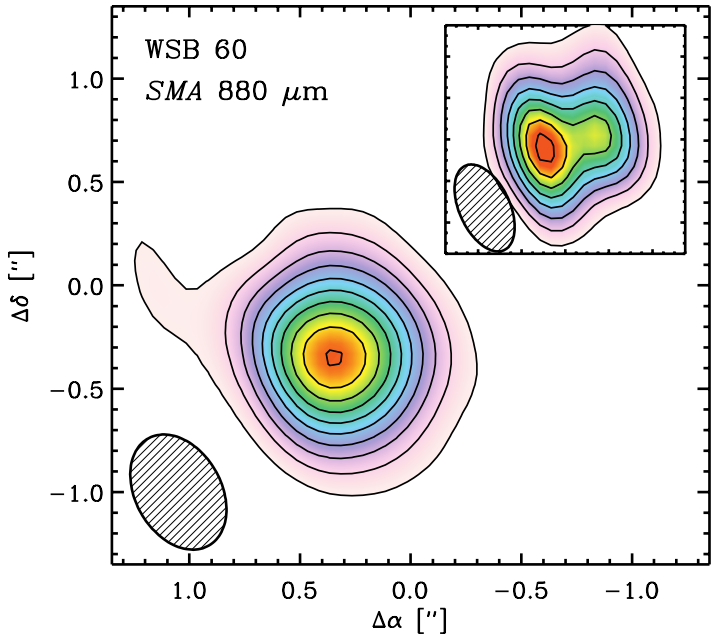
Zhu et al. 2012; talk by Z. Zhu

Possible evidence of earliest stages of gap opening via dust filtration

Full disk SED

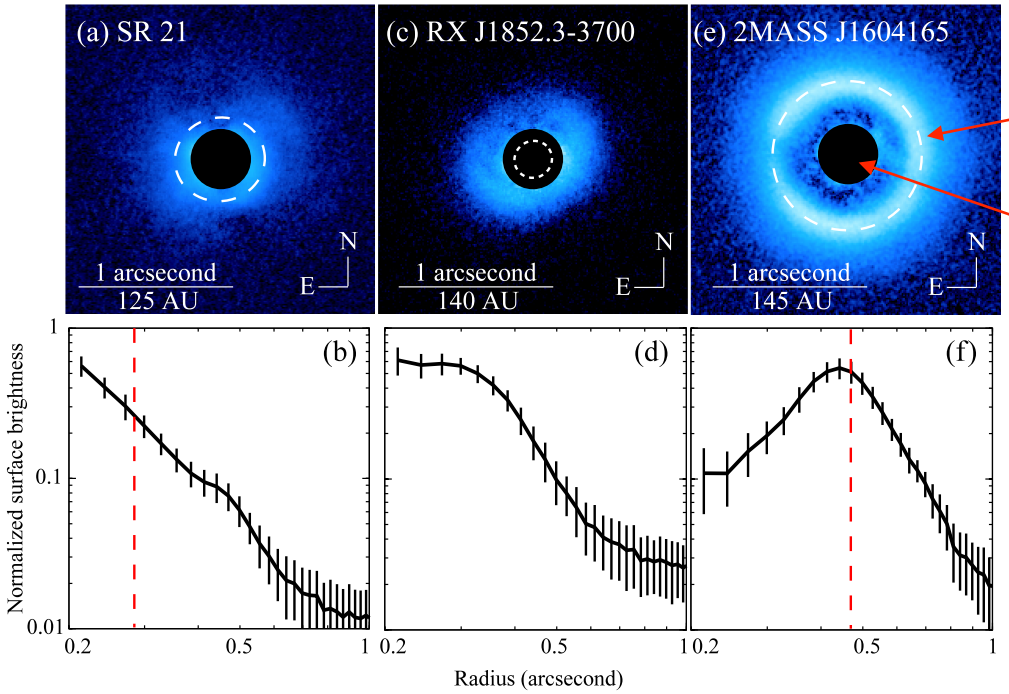


Cavity seen in submm



Andrews et al. 2011

Tracing small dust within submm cavities with NIR polarimetric imaging



submm cavity radius

resolution limit

small dust within submm cavity

break in radial surface brightness of small dust

no small dust within submm cavity

Figure from Espaillat et al. 2014, PPVI; Data from Follette et al. 2013, Kudo et al. in prep, Mayama et al. 2012

Tracking Planet Footprints

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

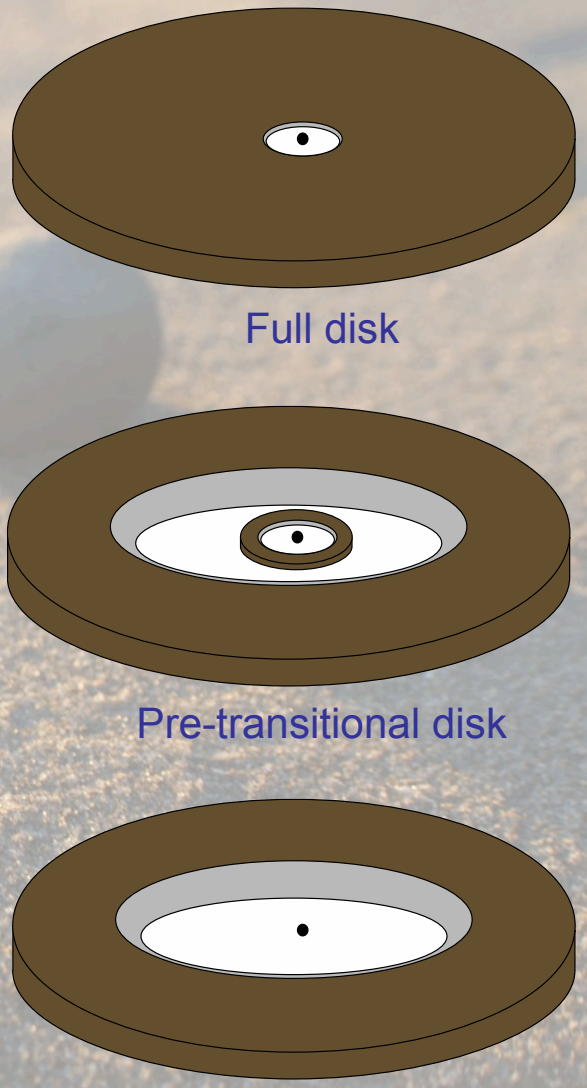
- SEDs and submillimeter images of disk holes and gaps
- theoretical disk clearing mechanisms

What can disks with holes and gaps tell us about disk evolution and planet formation?

- variable dust & gas properties
- spatial distributions of disk gas and dust

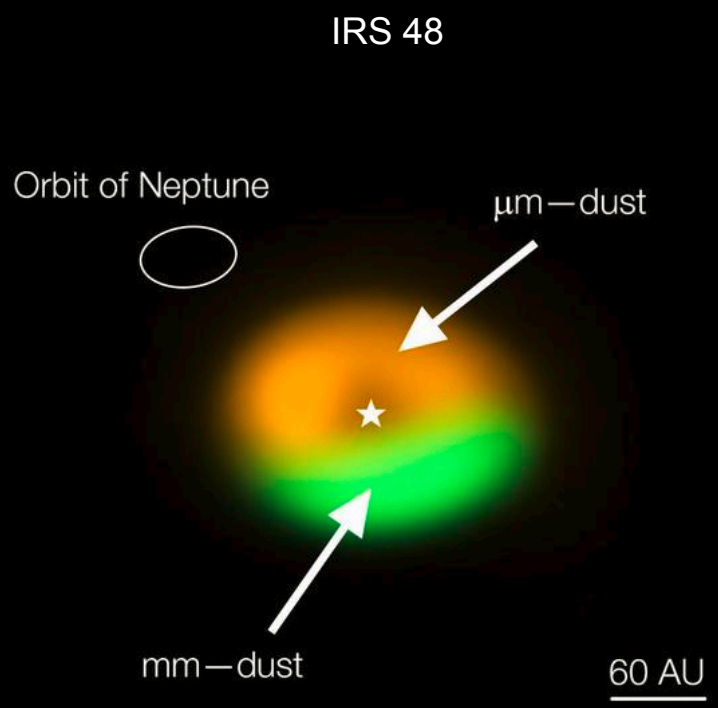
Where do we go from here?

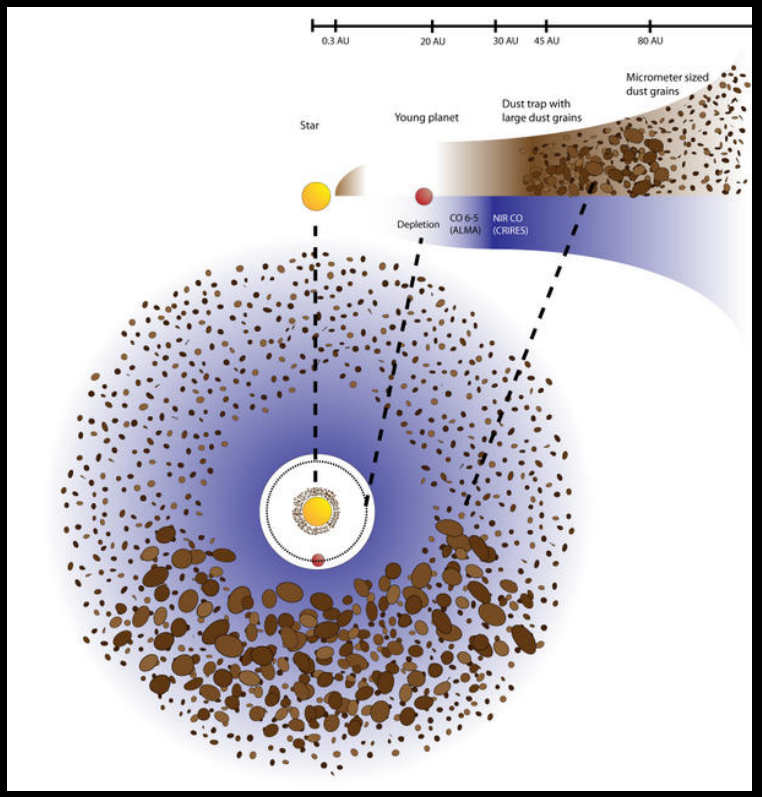
- spatially resolving the dust and gas distributions in (pre-)transitional disks
- identifying more, and smaller, disk gaps



Espaillat et al. 2014, PPVI

ALMA has revealed dust asymmetries

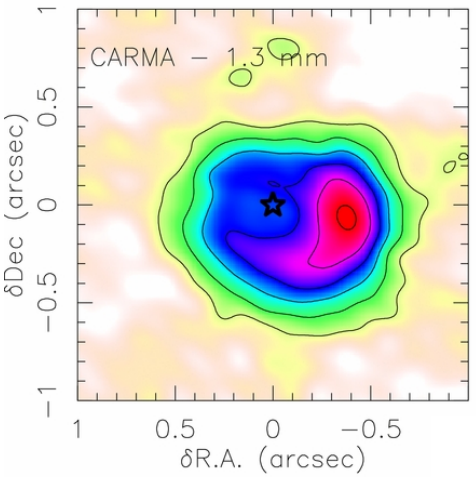




van der Marel et al. 2013

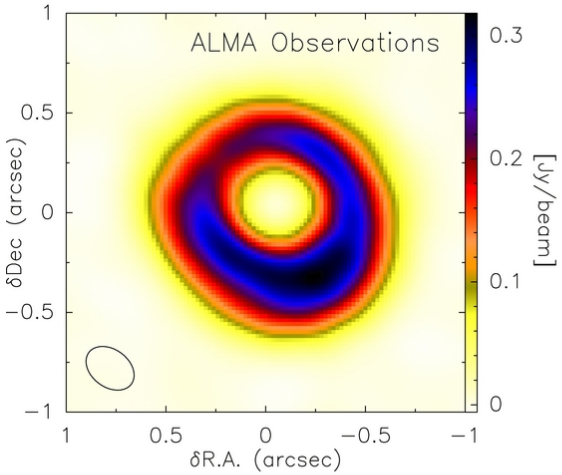
Additional dust asymmetries seen in transitional disks

LkHα 330

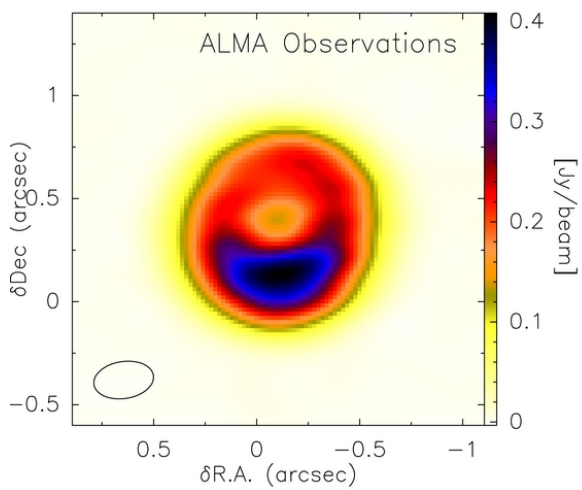


Isella et al. 2013

SAO 206462



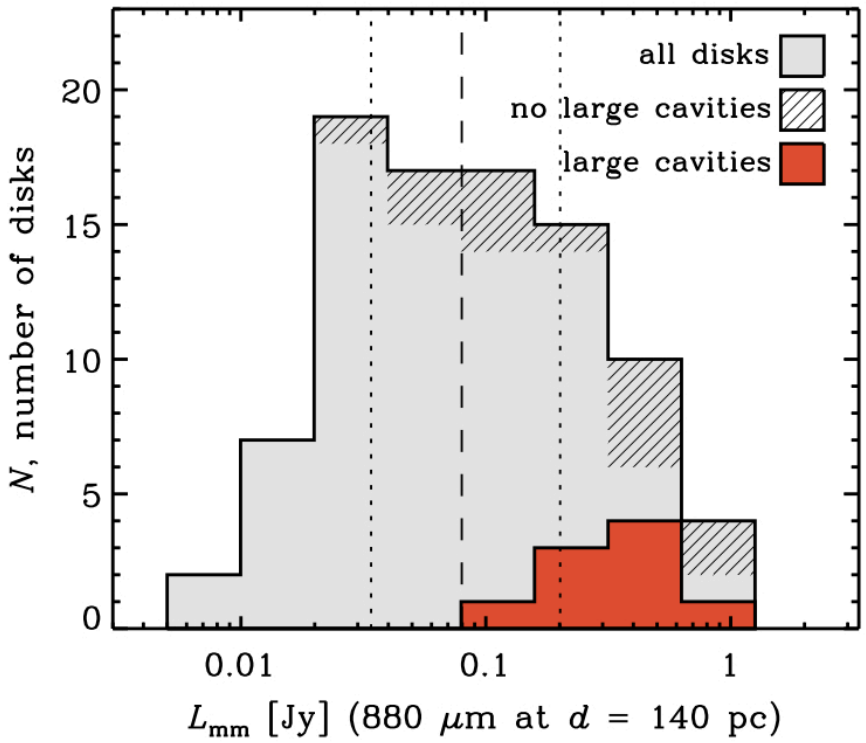
SR 21



Perez et al. 2014

also Casassus et al. 2013; Fukagawa et al. 2013; Pineda et al. 2014

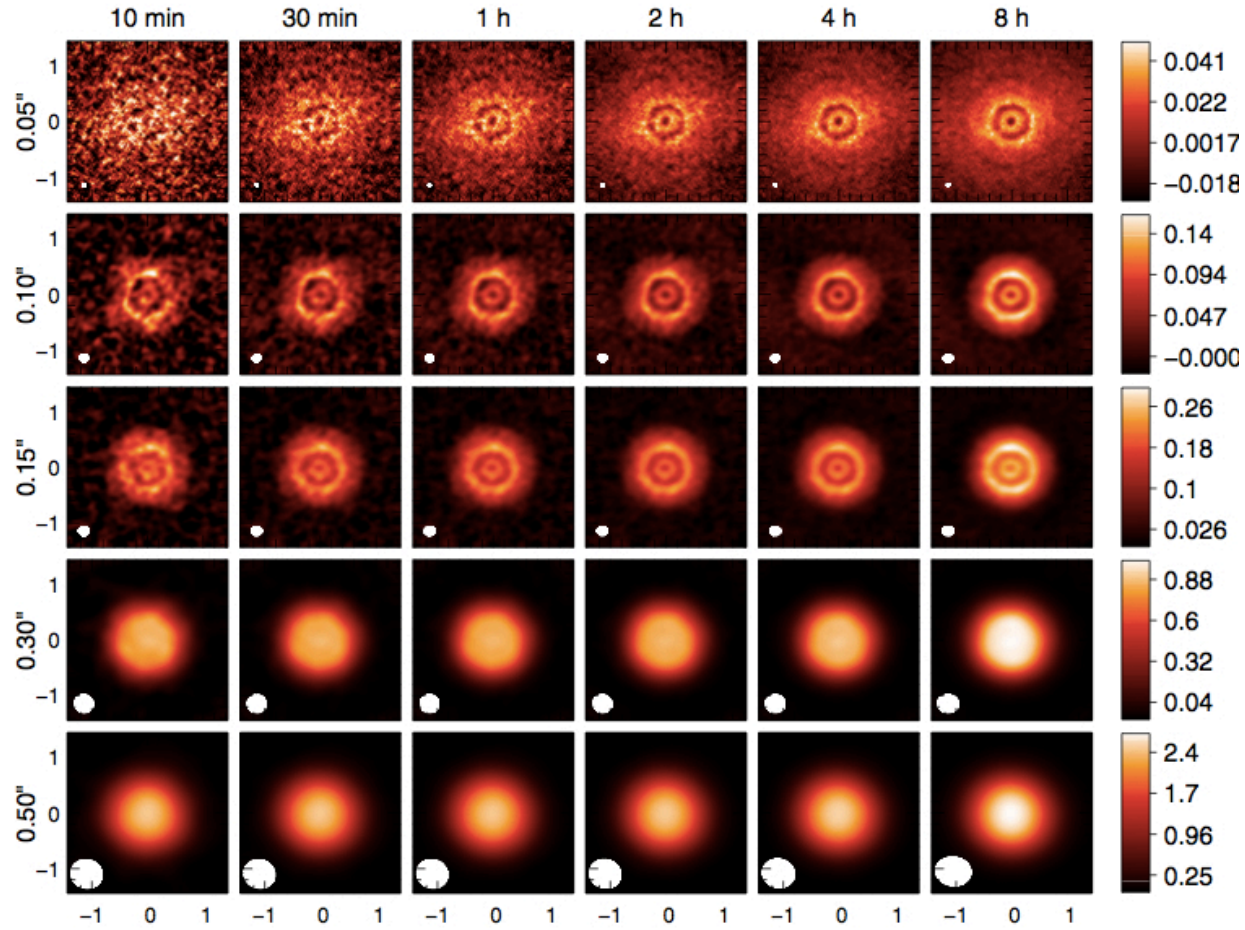
Identifying new, fainter (pre-)transitional disks



Andrews et al. 2011

Imaging smaller disk gaps

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



Gonzalez et al. 2012

What do planet footprints look like?

Drawing of UX Tau A: NASA/JPL-Caltech/T. Pyle (SSC)
Based on Espaillat, Calvet, *D'Alessio* et al. (2007b)