Tracking Planet Footprints in Dusty Disks

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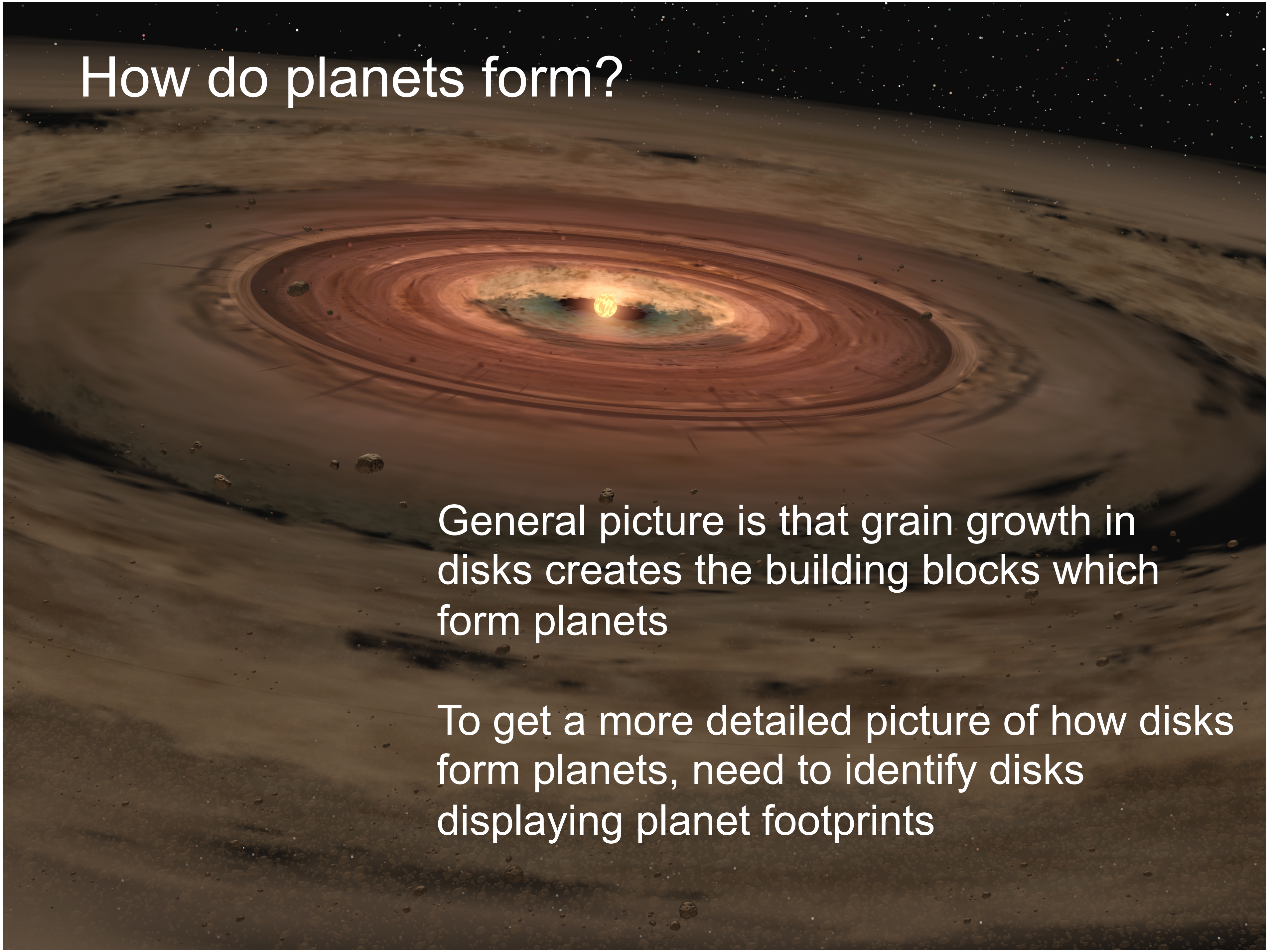
Boston University


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

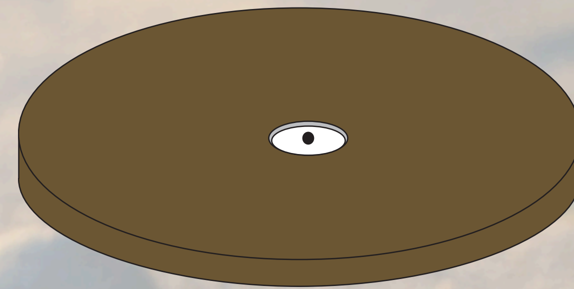
Drawing of UX Tau A: NASA/JPL-Caltech/T. Pyle (SSC)
Based on Espaillat et al. 2007b

Tracking Planet Footprints

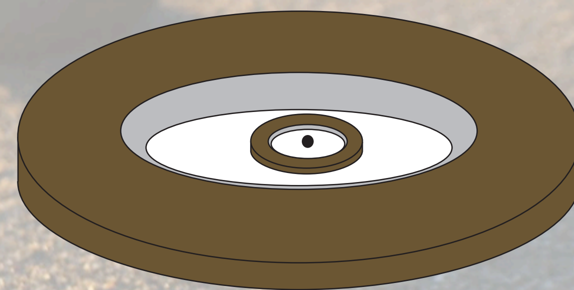
What evidence do we have for planets forming in young disks?

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

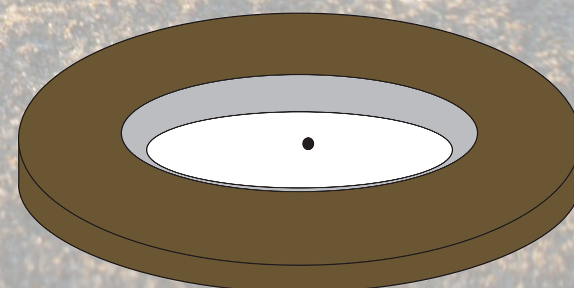
Where do we go from here?



Full disk



Pre-transitional disk



Transitional disk

Espaillat et al. 2014, PPVI

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- full disk overview
- SEDs and images of disk holes and gaps
- theoretical disk clearing mechanisms

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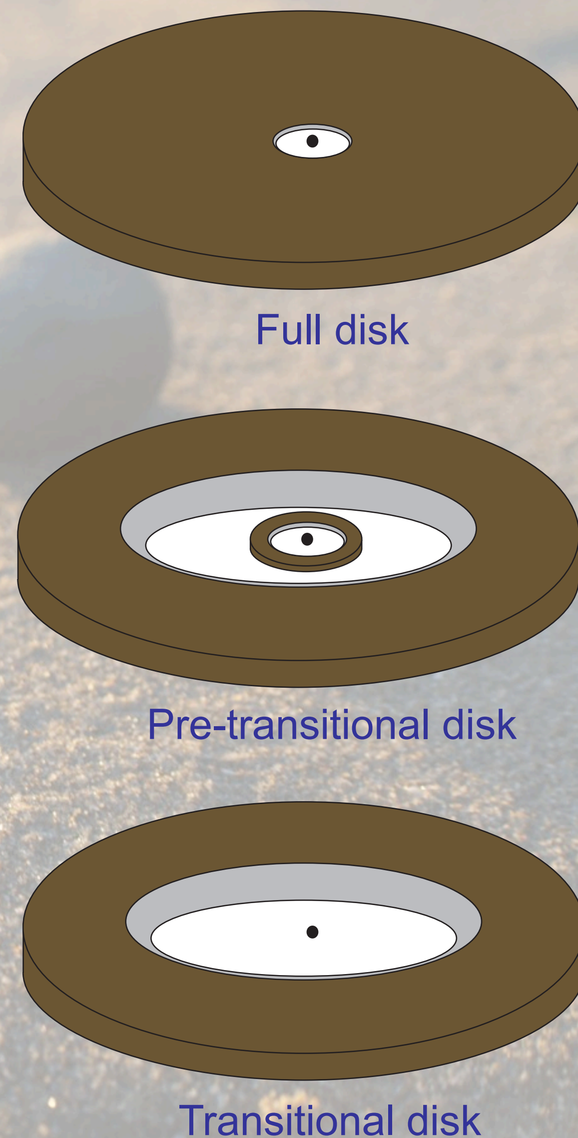
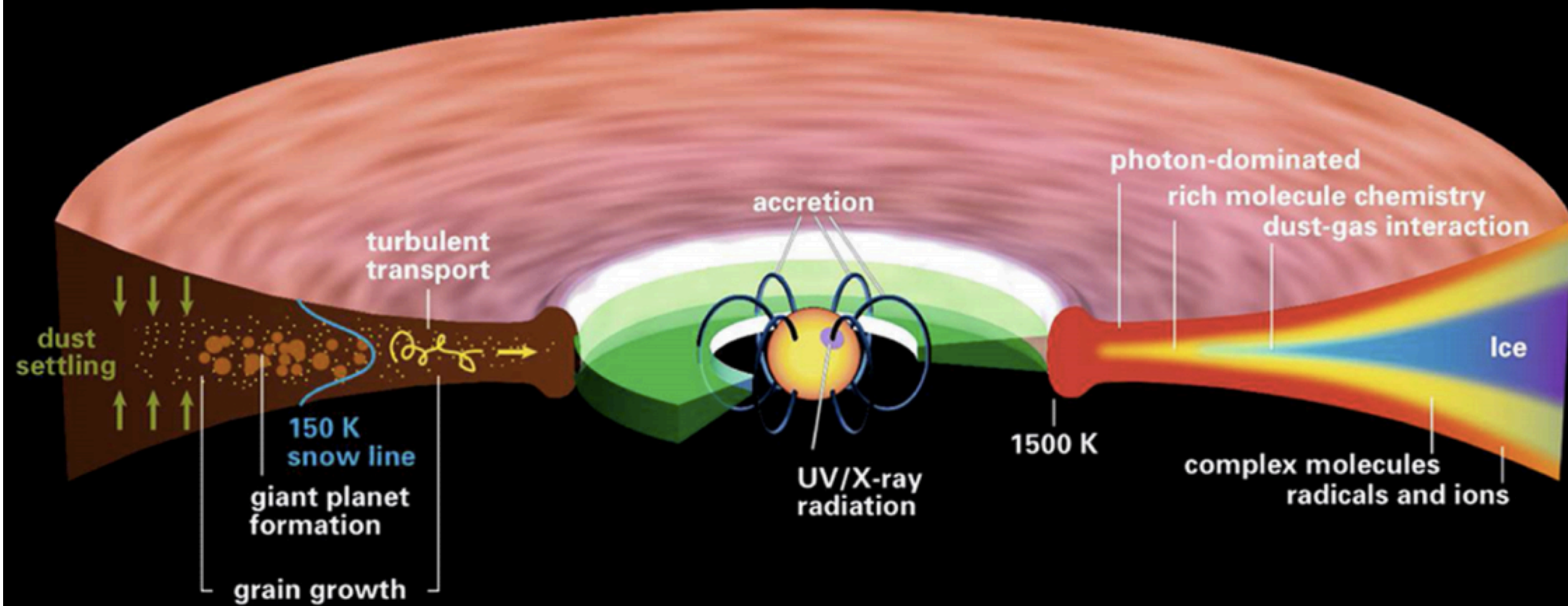


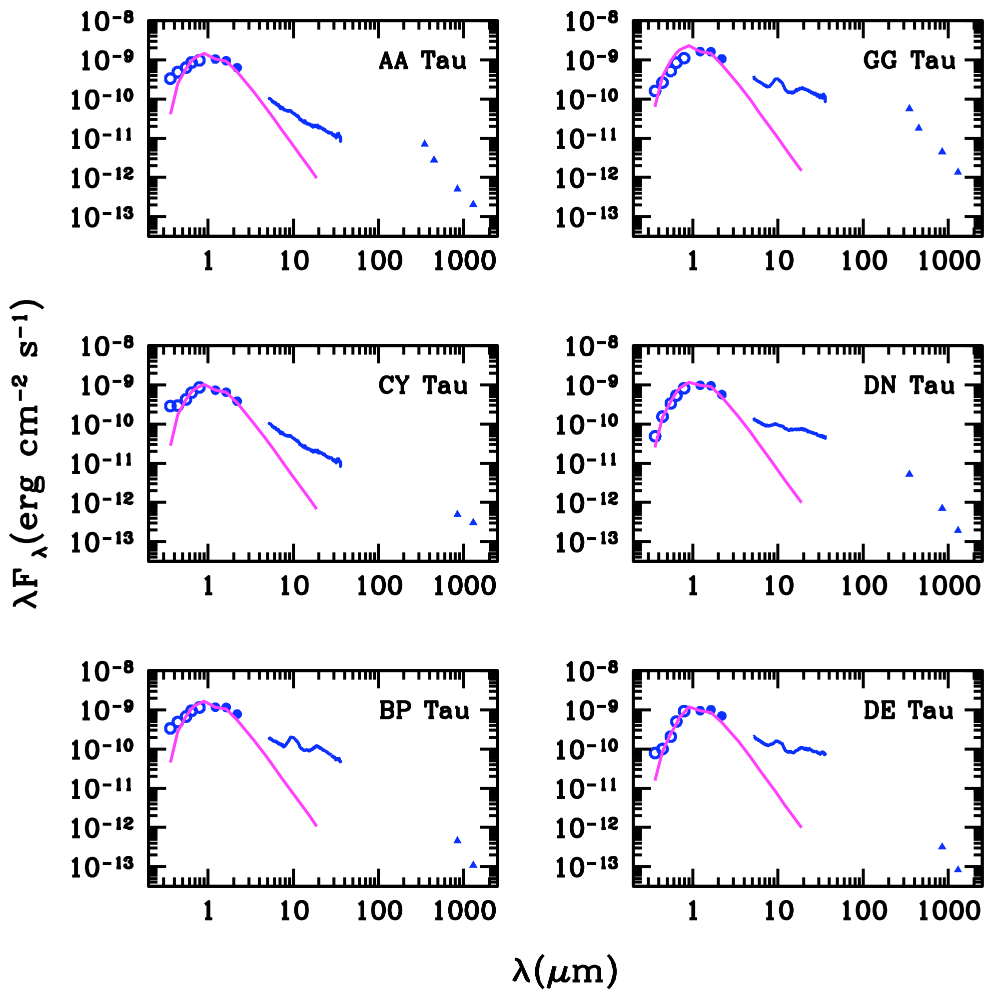
Espaillat et al. 2014, PPVI

Protoplanetary disks have complex structure

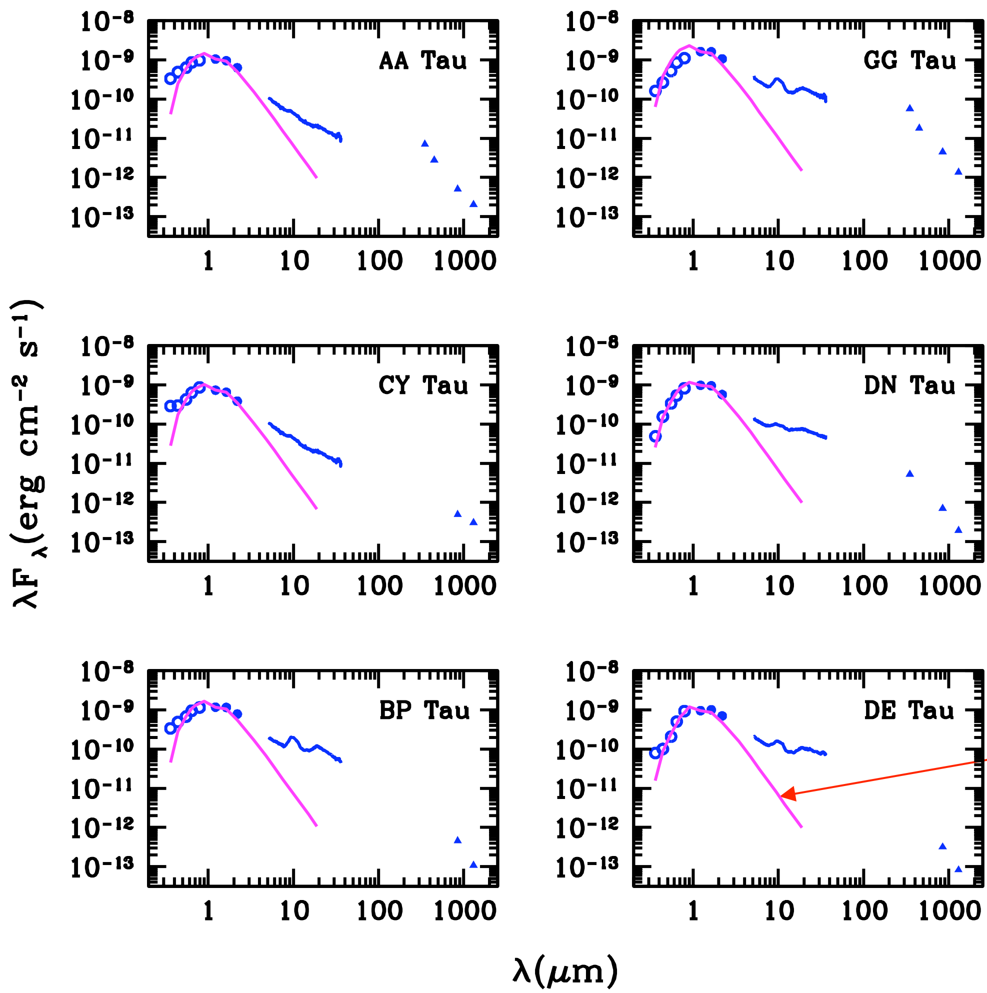


Henning & Semenov 2014

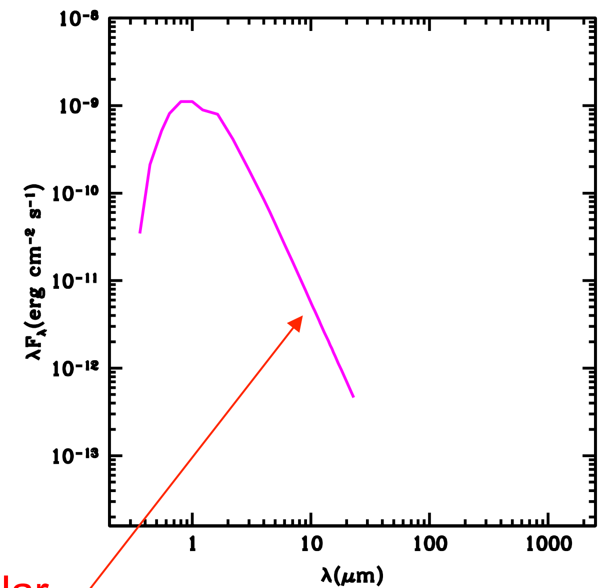
IR excess in SEDs is evidence for dusty disks



IR excess in SEDs is evidence for dusty disks

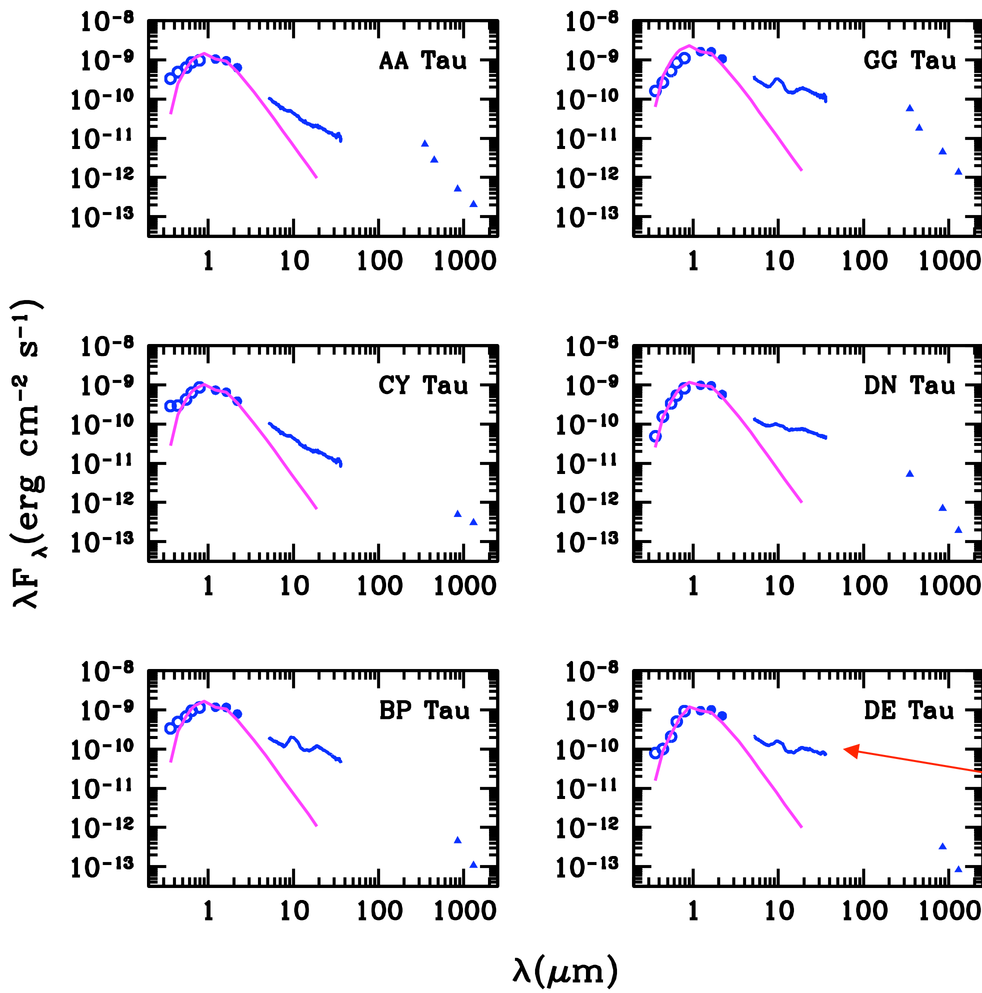


Spectral Energy Distribution of a Star



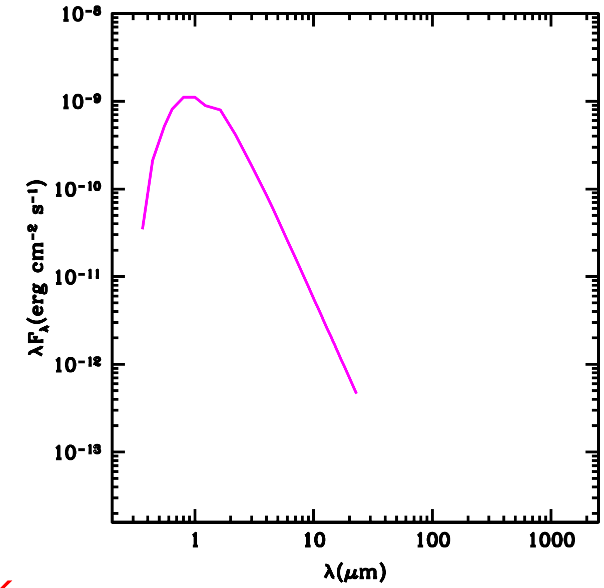
stellar photosphere

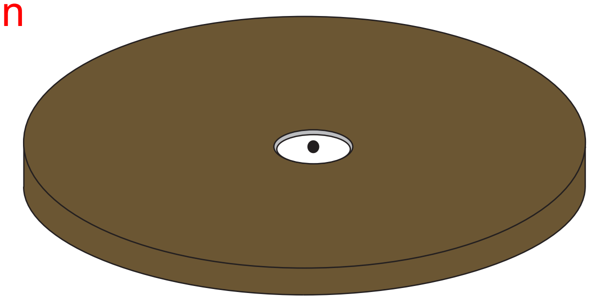
IR excess in SEDs is evidence for dusty disks



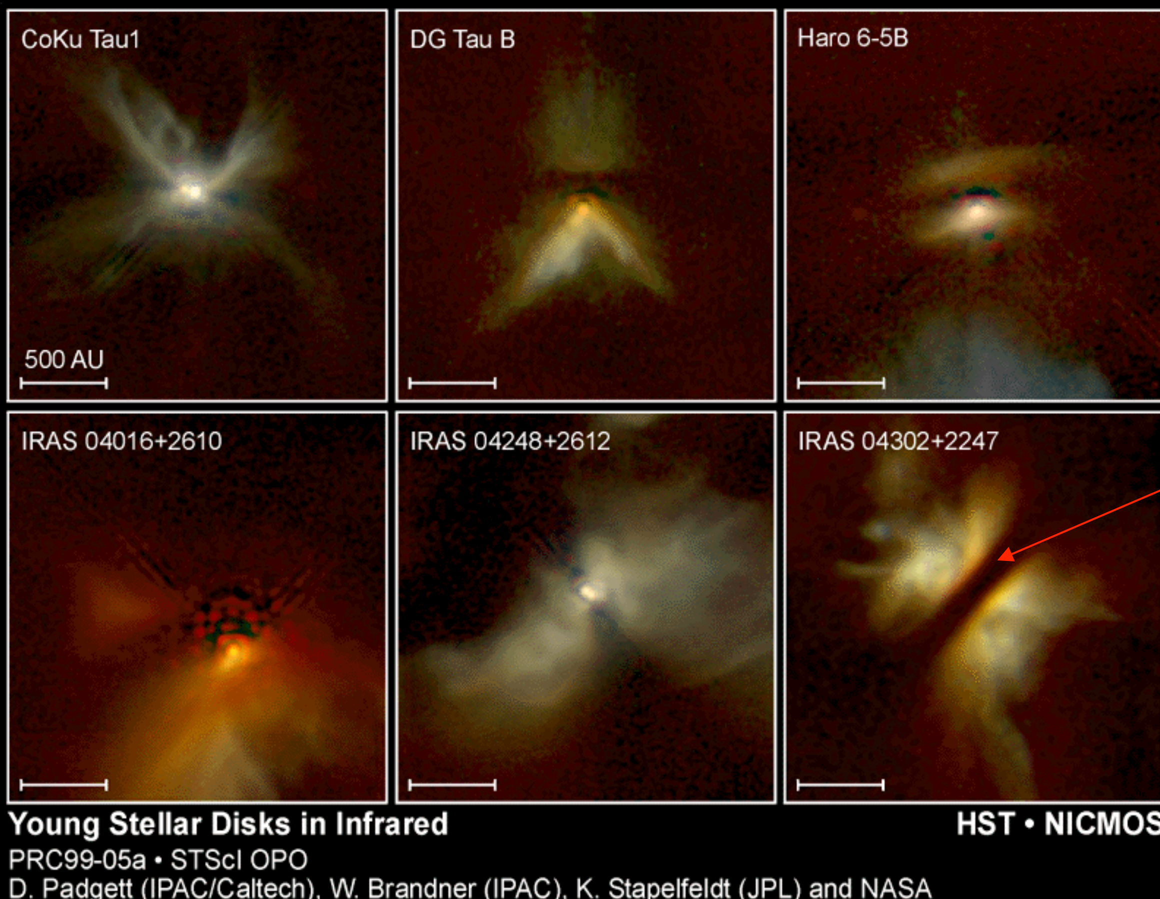
disk emission

Spectral Energy Distribution of a Star



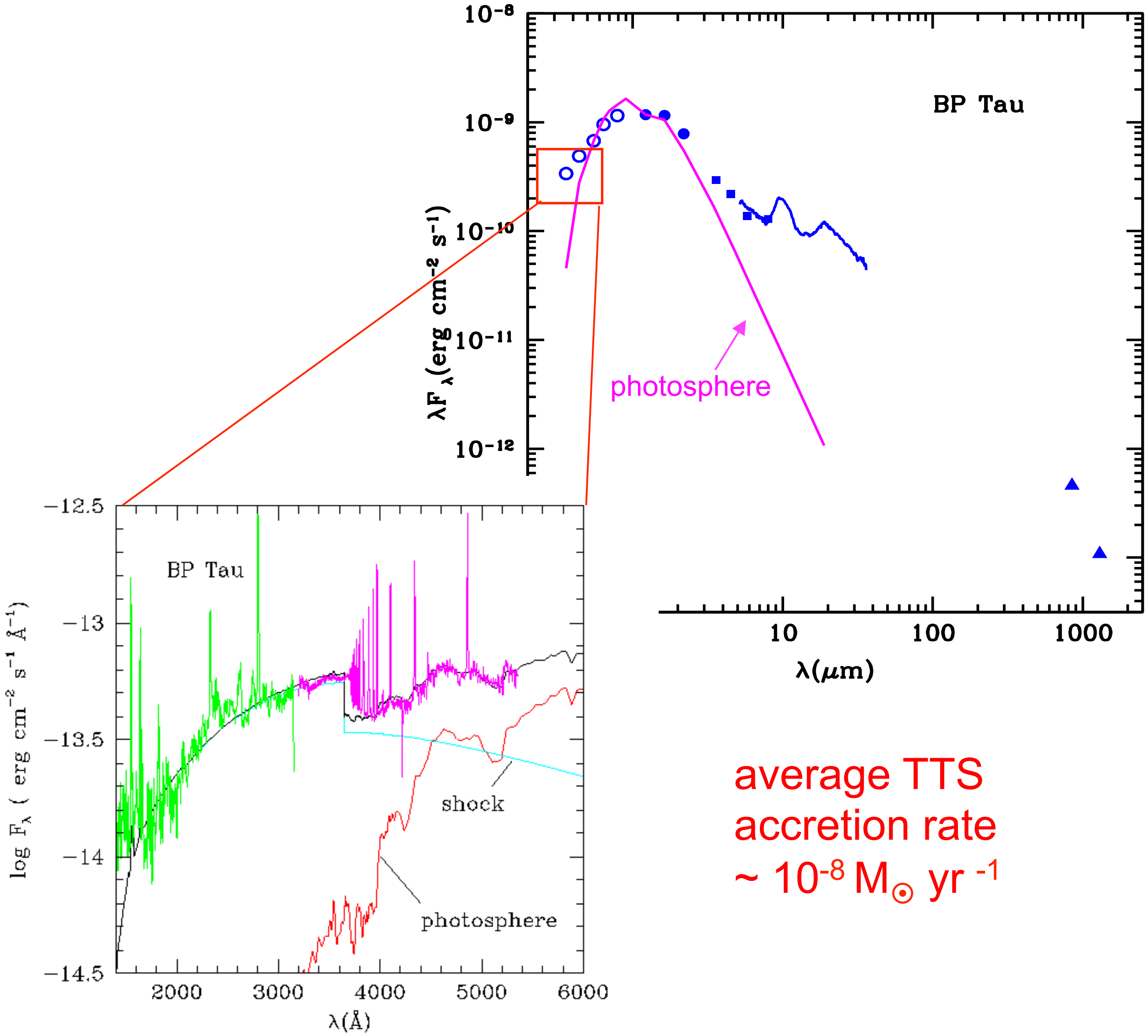


HST imaging confirms dusty disks exist around young stars



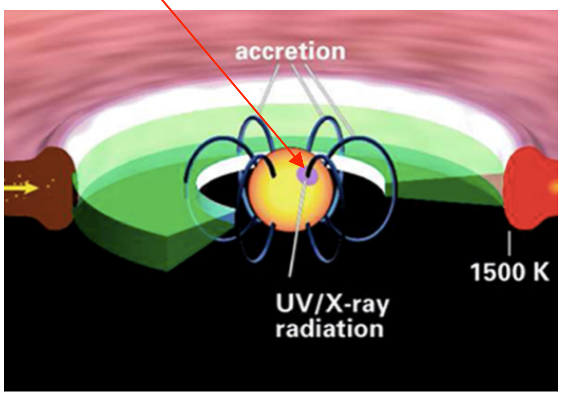
absorption by
dust grains
in disk

UV excess traces gas accretion



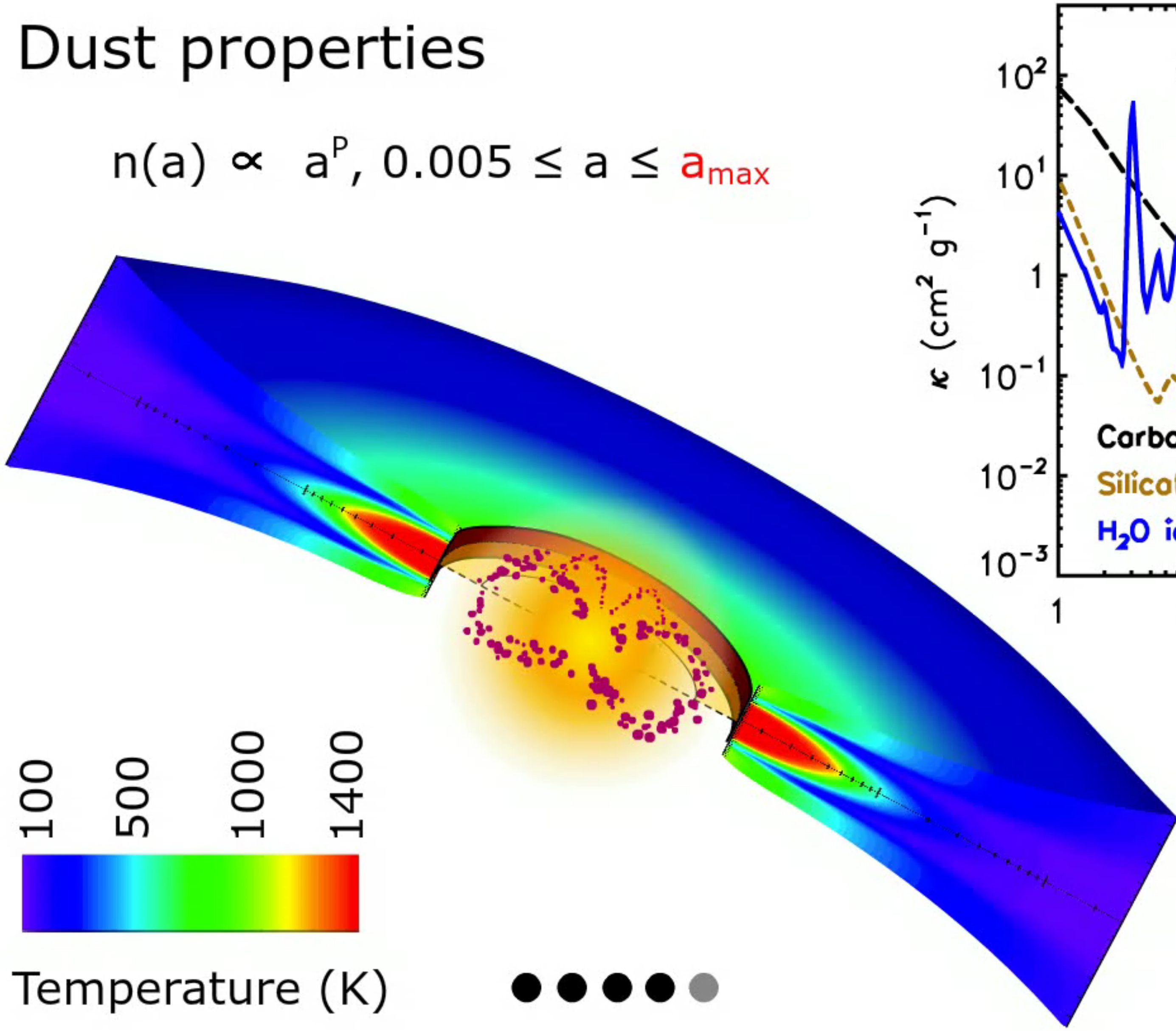
Calvet & Gullbring 1998

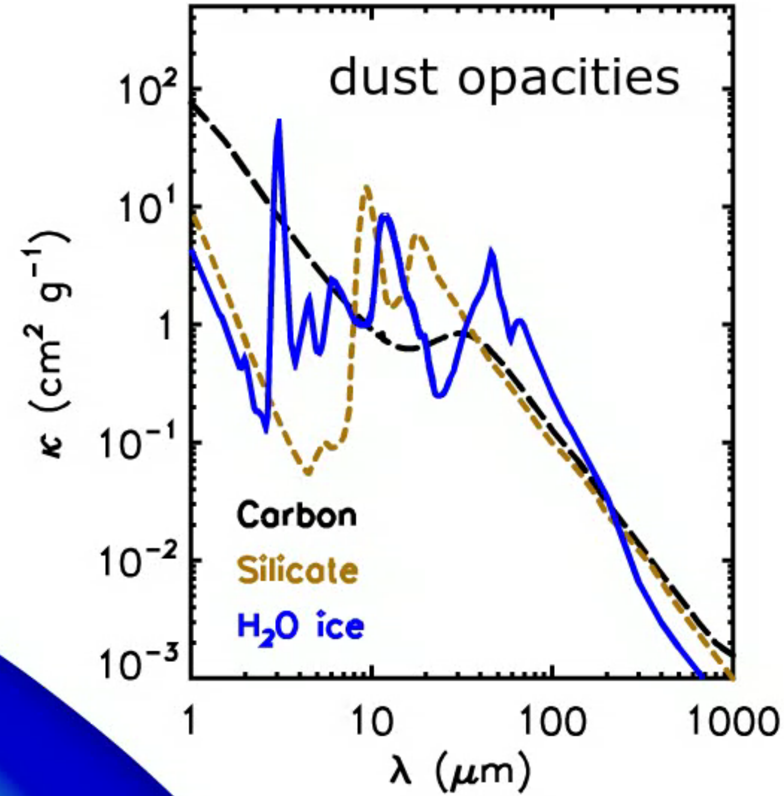
UV excess originates from accretion shock on stellar surface



average TTS accretion rate $\sim 10^{-8}\ M_\odot\ yr^{-1}$

Simulating SEDs to probe disk structure





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

from M. McClure

Tracking Planet Footprints

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

- full disk overview
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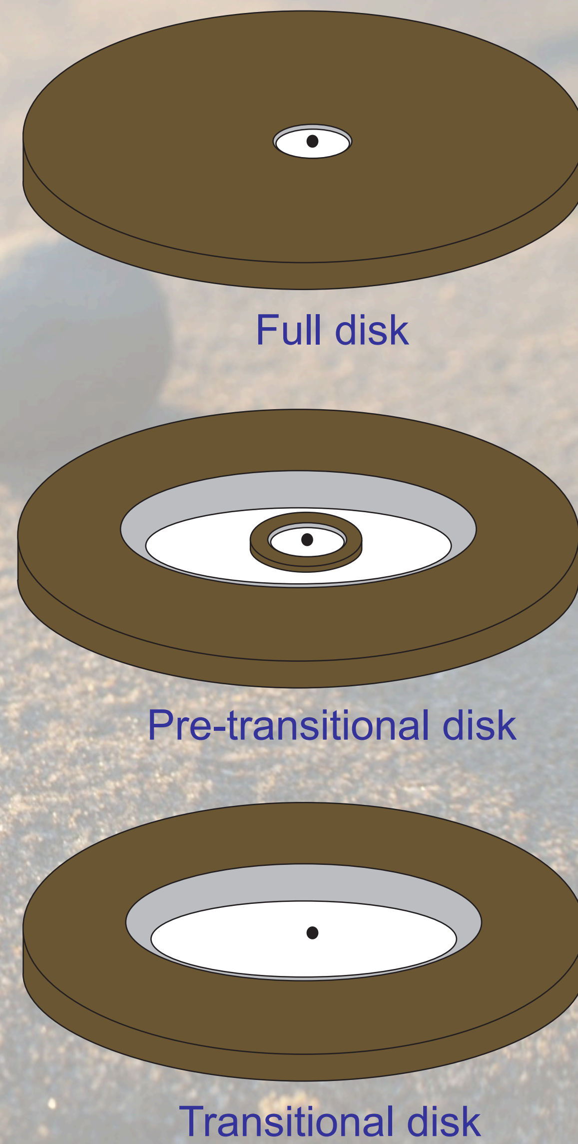
- theoretical disk clearing mechanisms

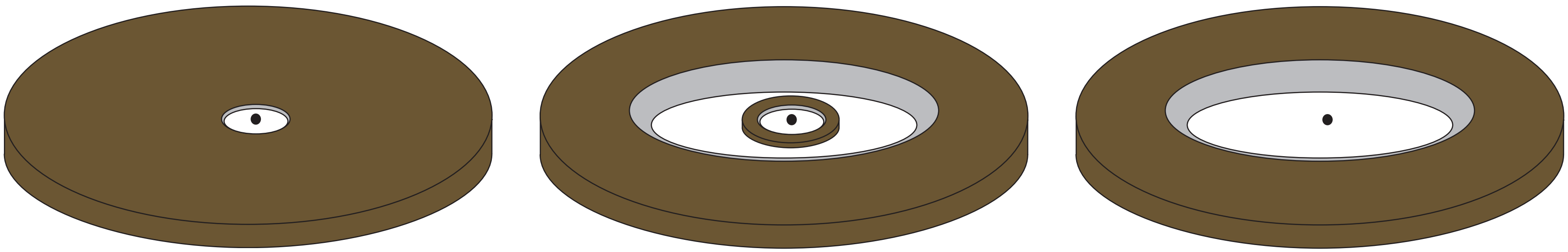
What can disks with holes and gaps tell us about disk evolution and planet formation?

Where do we go from here?



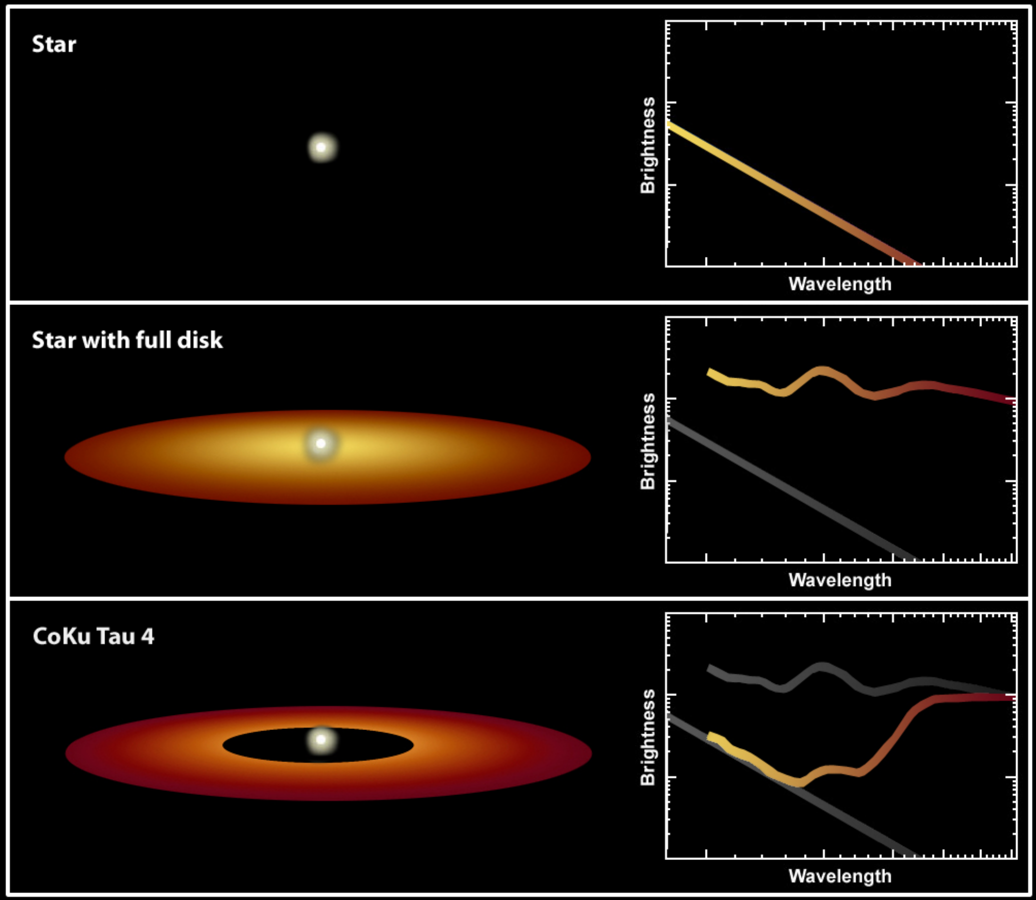
Espaillat et al. 2014, PPVI

Disk structure terminology

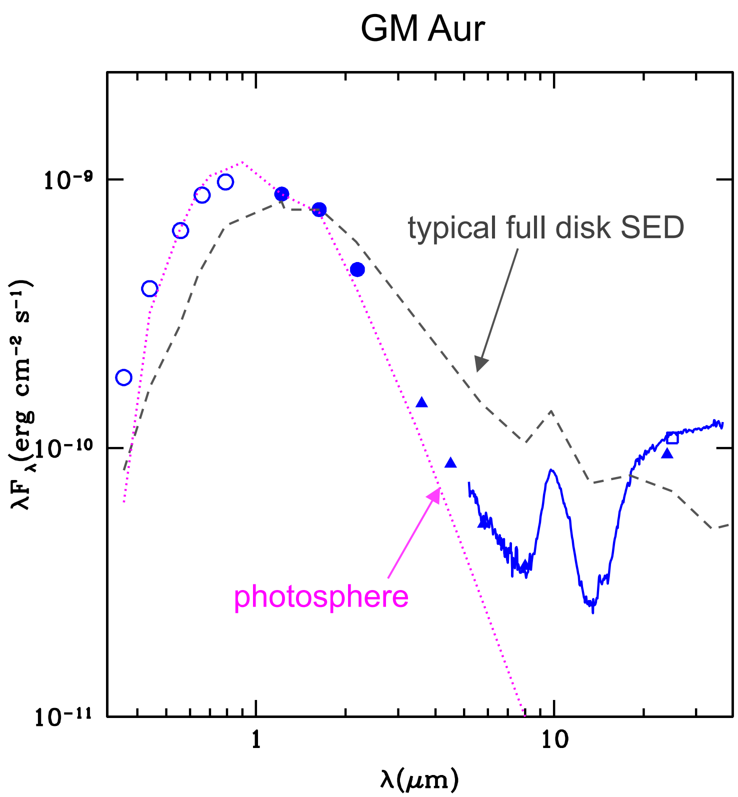


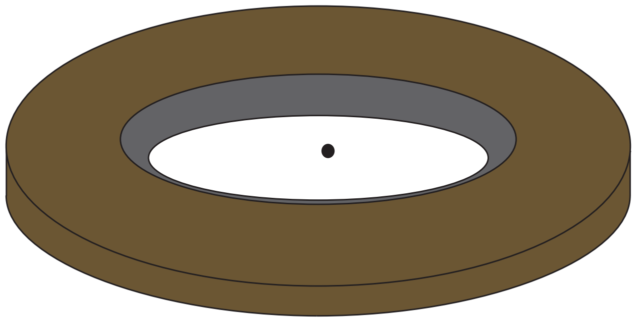
full disk	pre-transitional disk	transitional disk
---	annular **gap**	inner **hole**
	|-------------- cavity or clearing	---------------|
inner wall	inner wall + outer wall	*outer* wall

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

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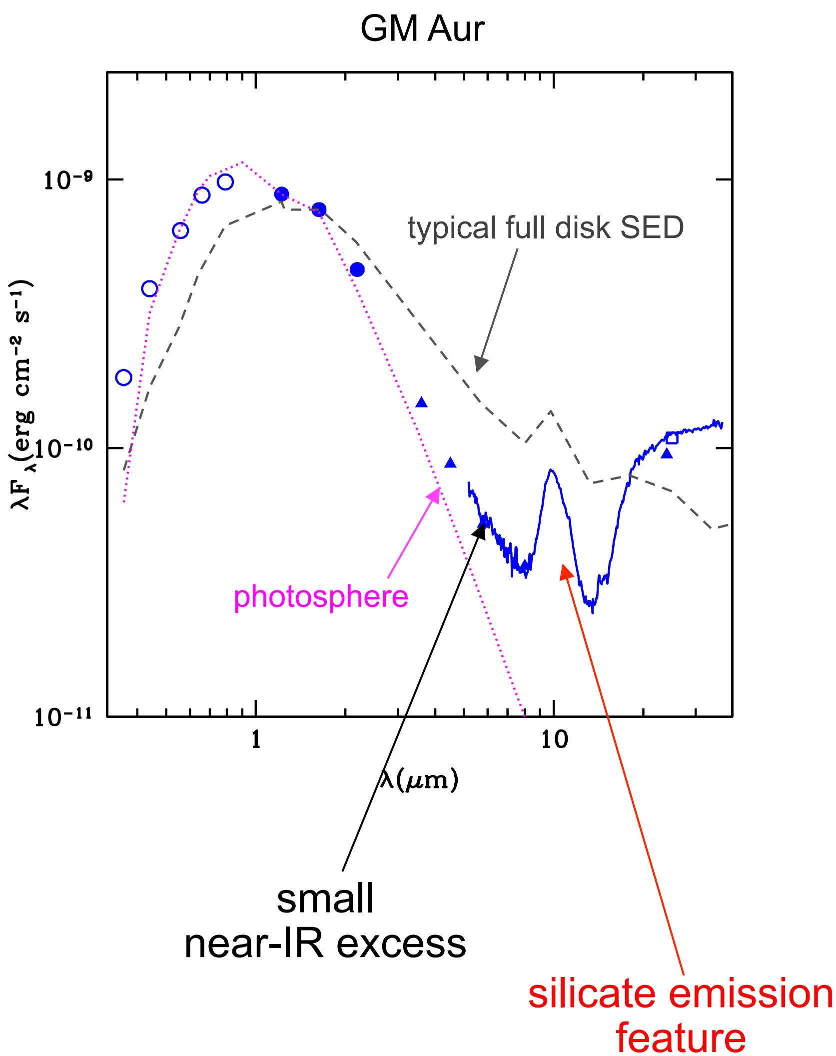

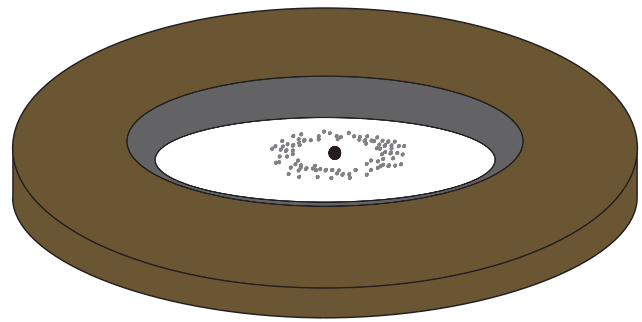

Calvet et al. 2005; Espaillat et al. 2011

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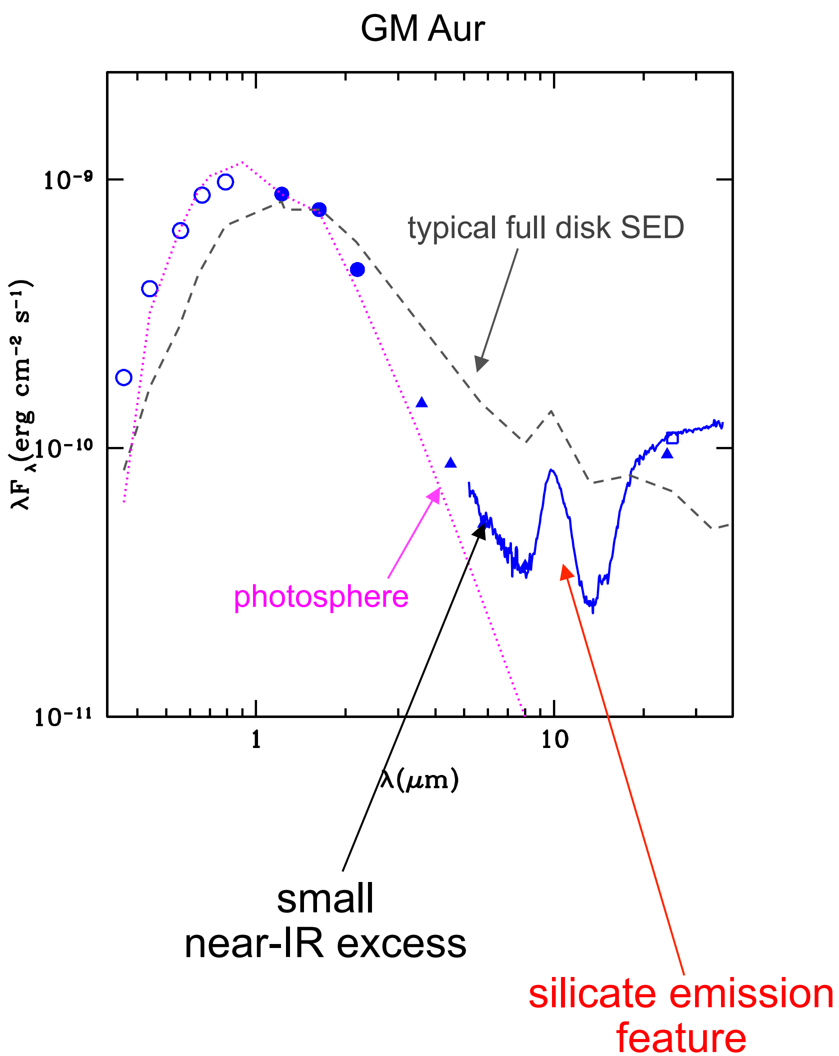
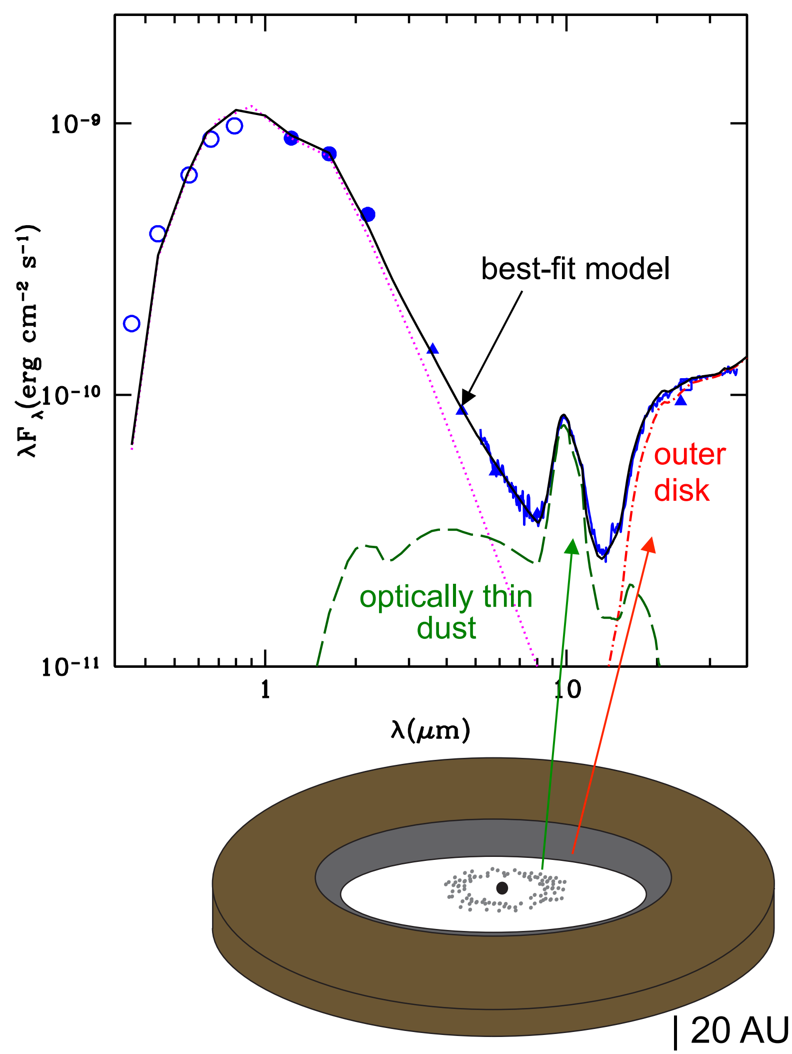
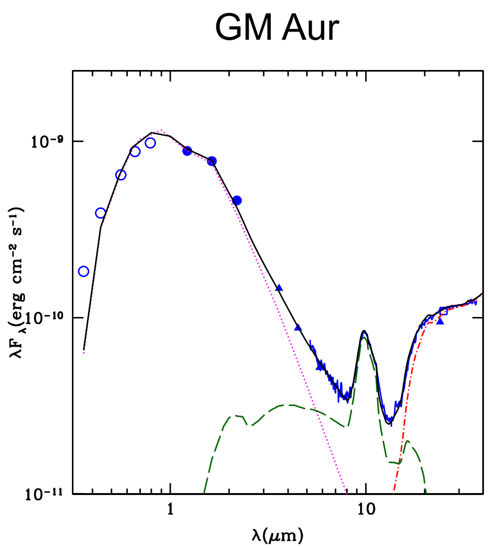
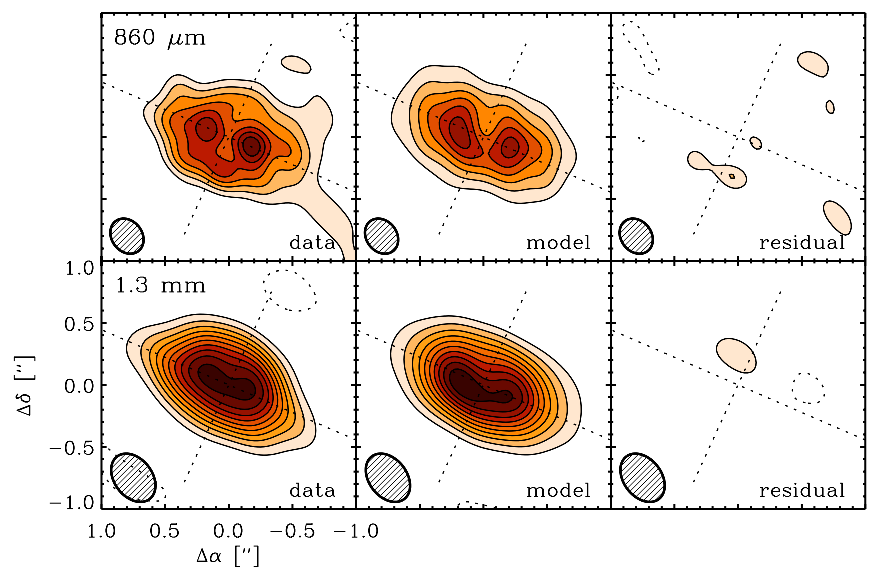


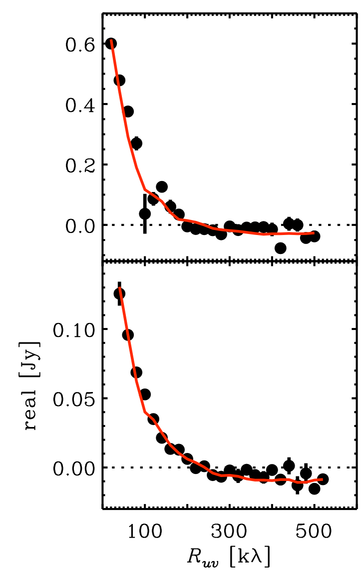


Calvet et al. 2005; Espaillat et al. 2011

Combining submm imaging and SED modeling to confirm disk cavities







best-fit model to observed SED

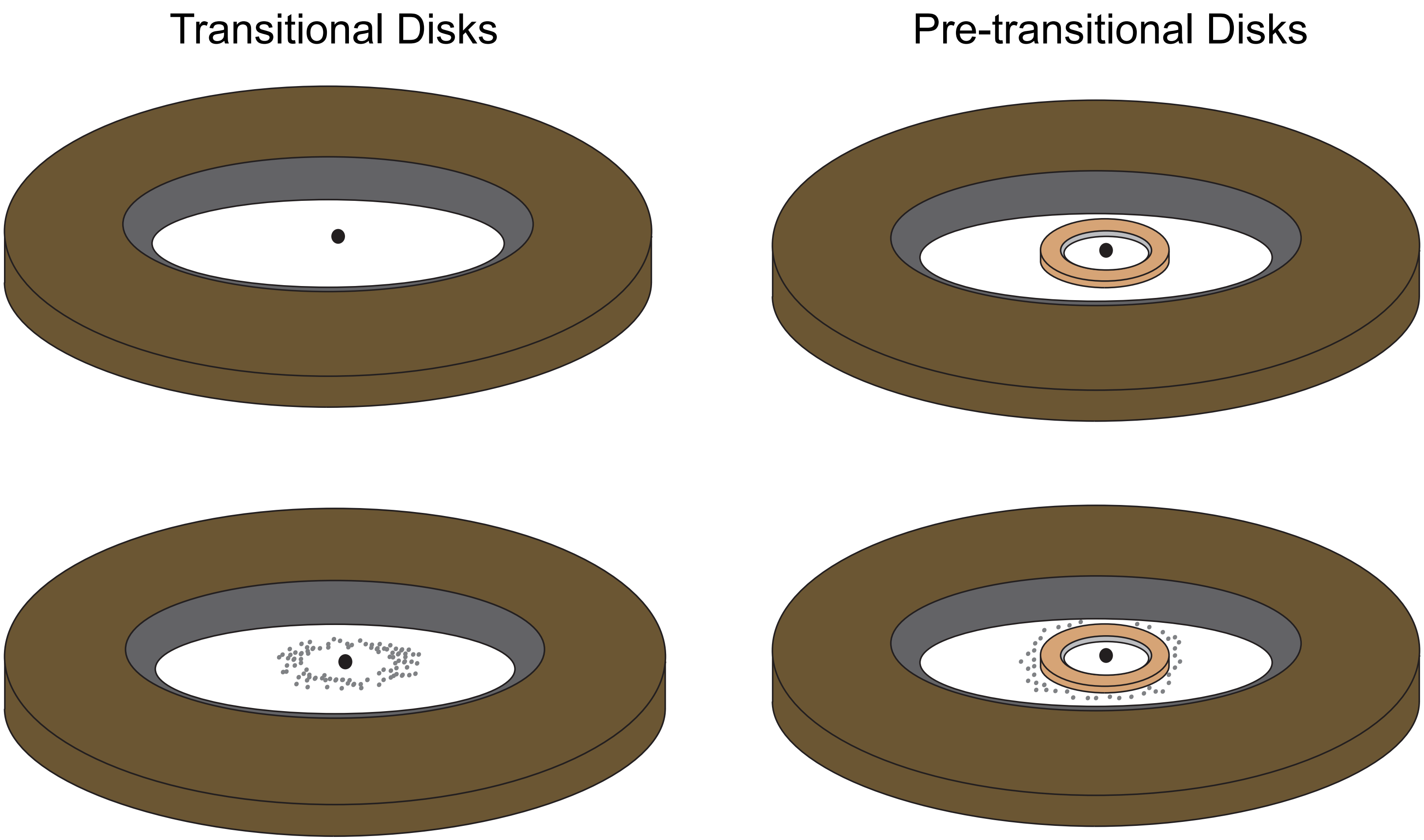
simulated images

&

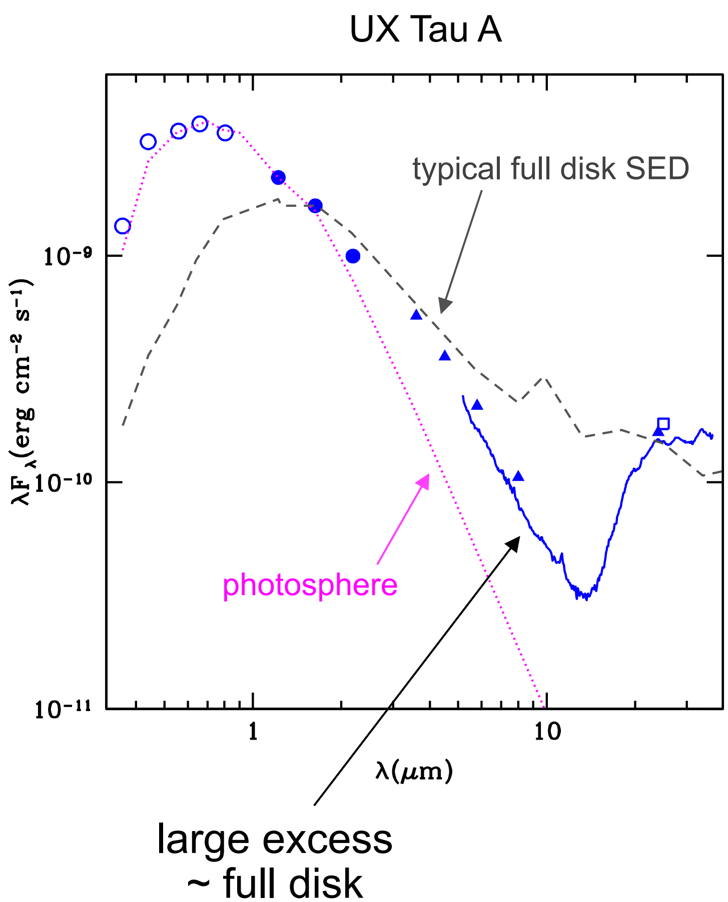
simulated visibilities

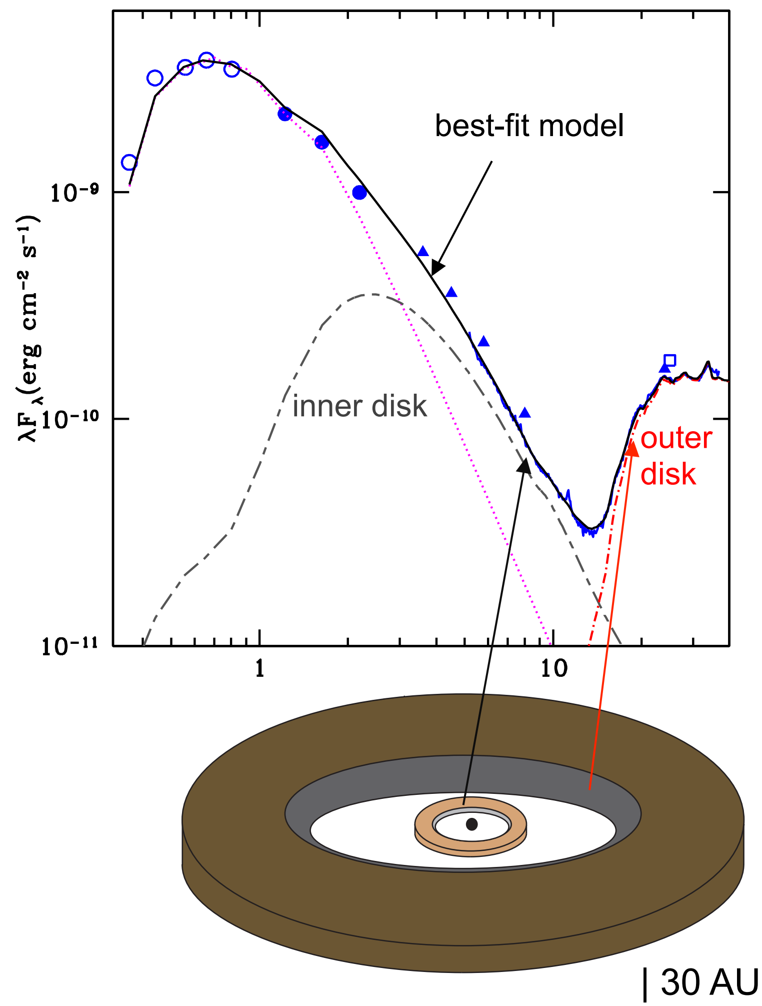
Hughes et al. 2009

In addition to inner holes, annular gaps have been detected



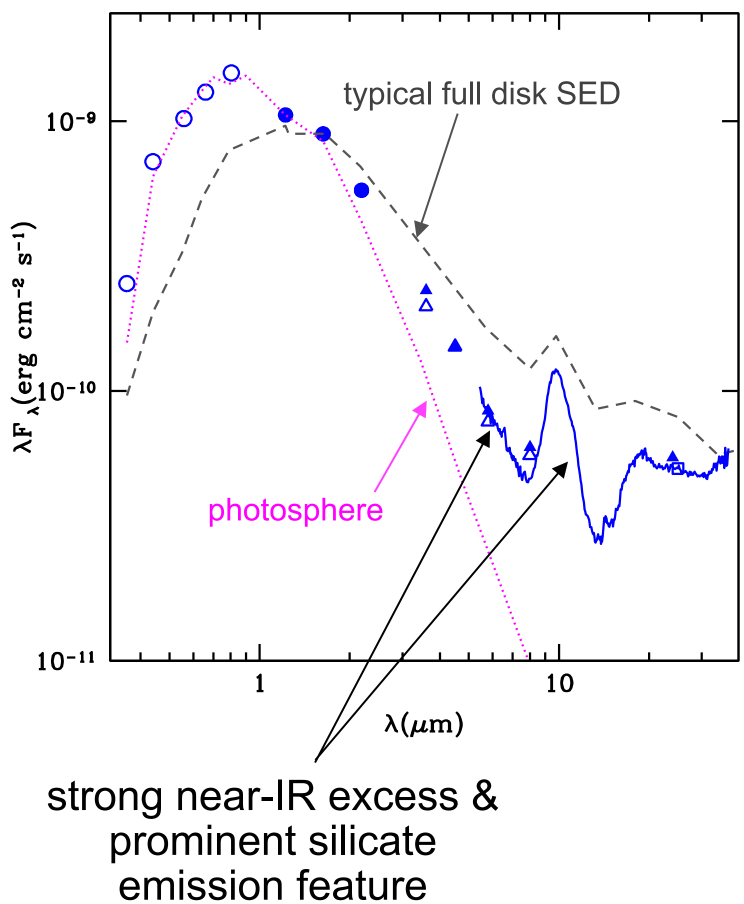
Pre-transitional disks: objects with annular gaps

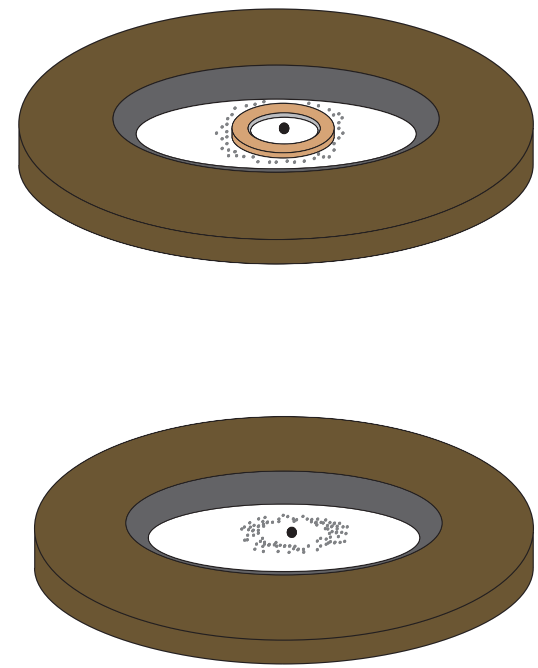




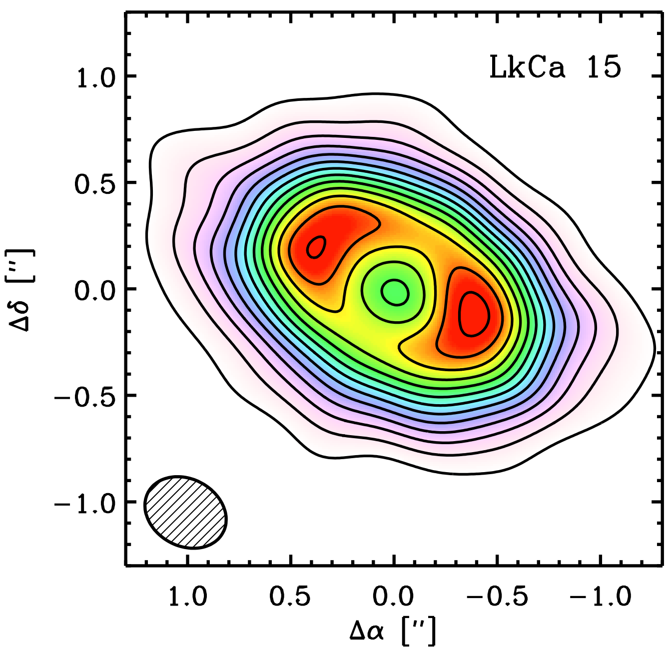
Espaillat et al. 2007b; also Brown et al. 2007

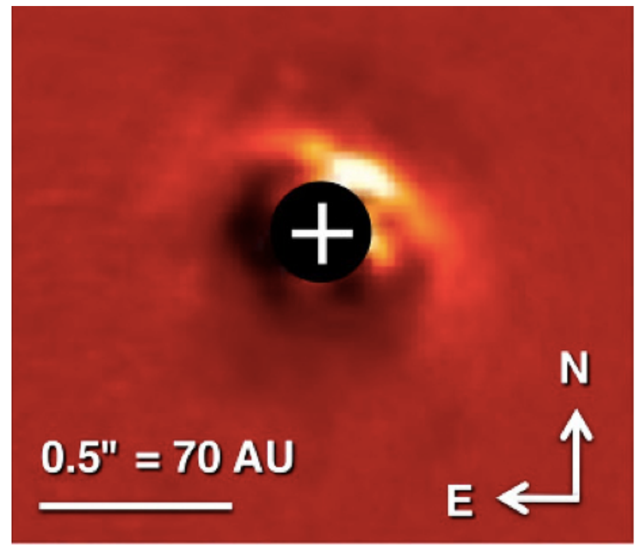
LkCa 15: gap or hole?





Imaging identifies a large cavity in LkCa15's disk

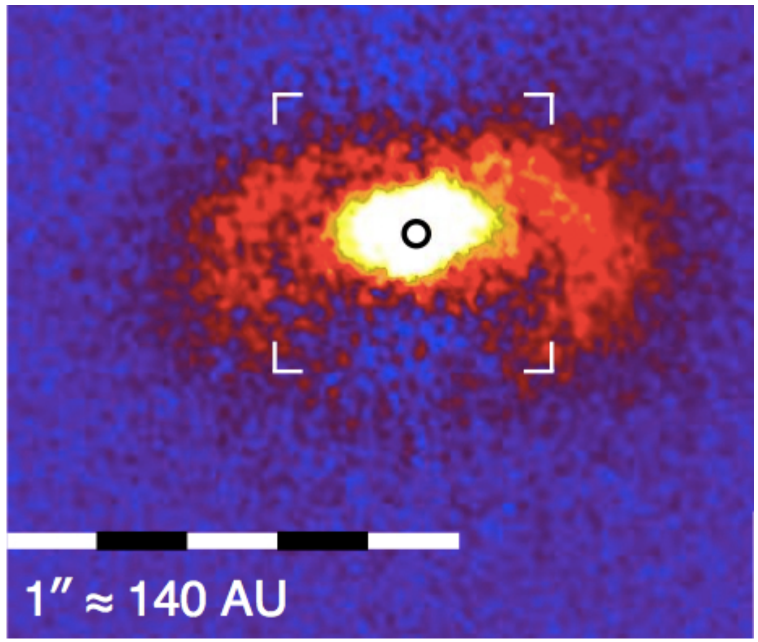




Andrews et al. 2011; also Pietu et al. 2006

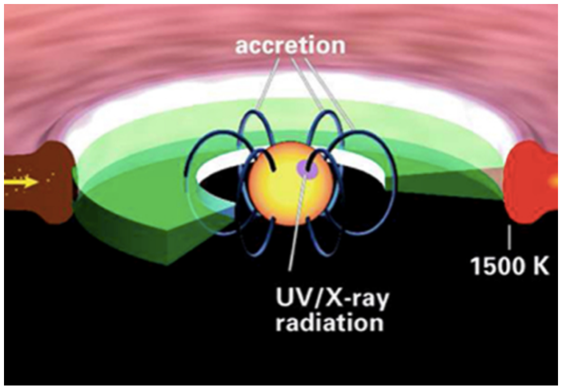
Thalmann et al. 2014

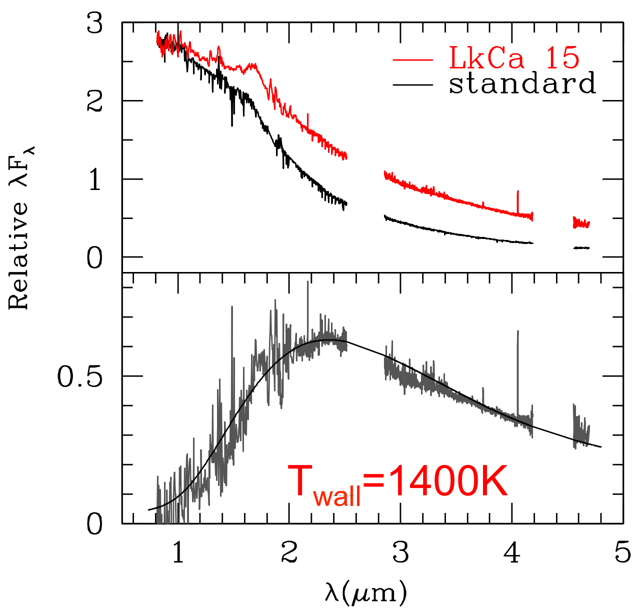
Optical polarimetric imaging identifies small dust within the cavity



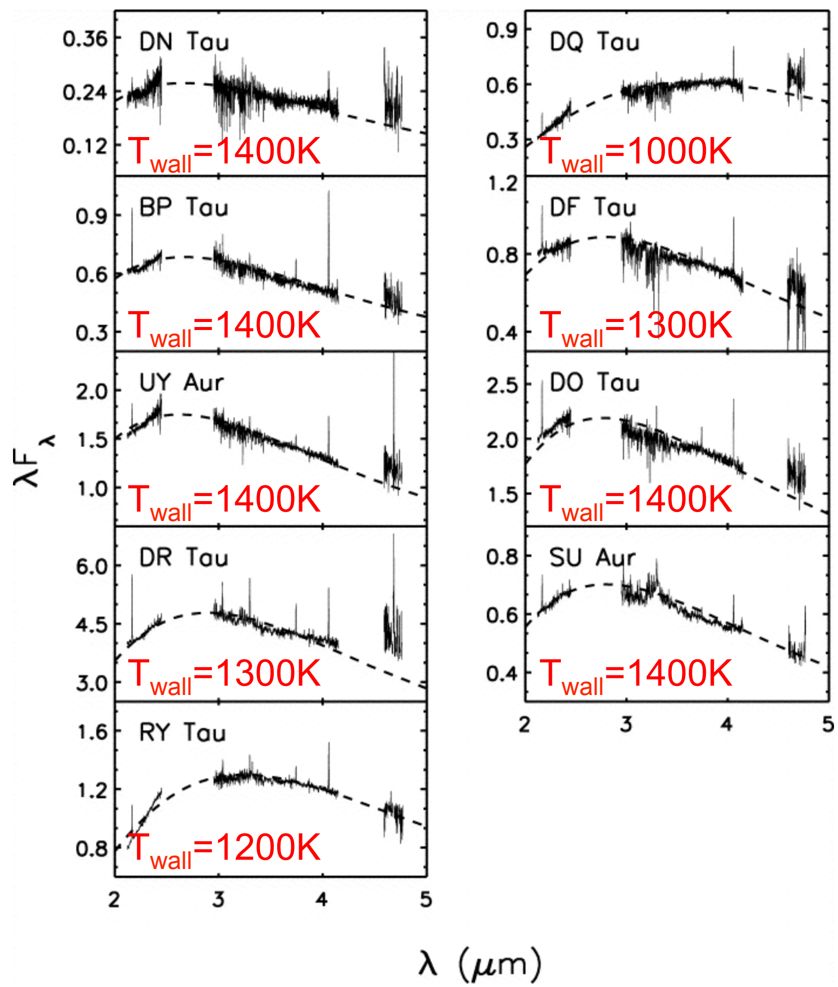
Thalmann et al., submitted, arXiv:1507.03587

LkCa 15's NIR blackbody-like excess points to a gapped disk



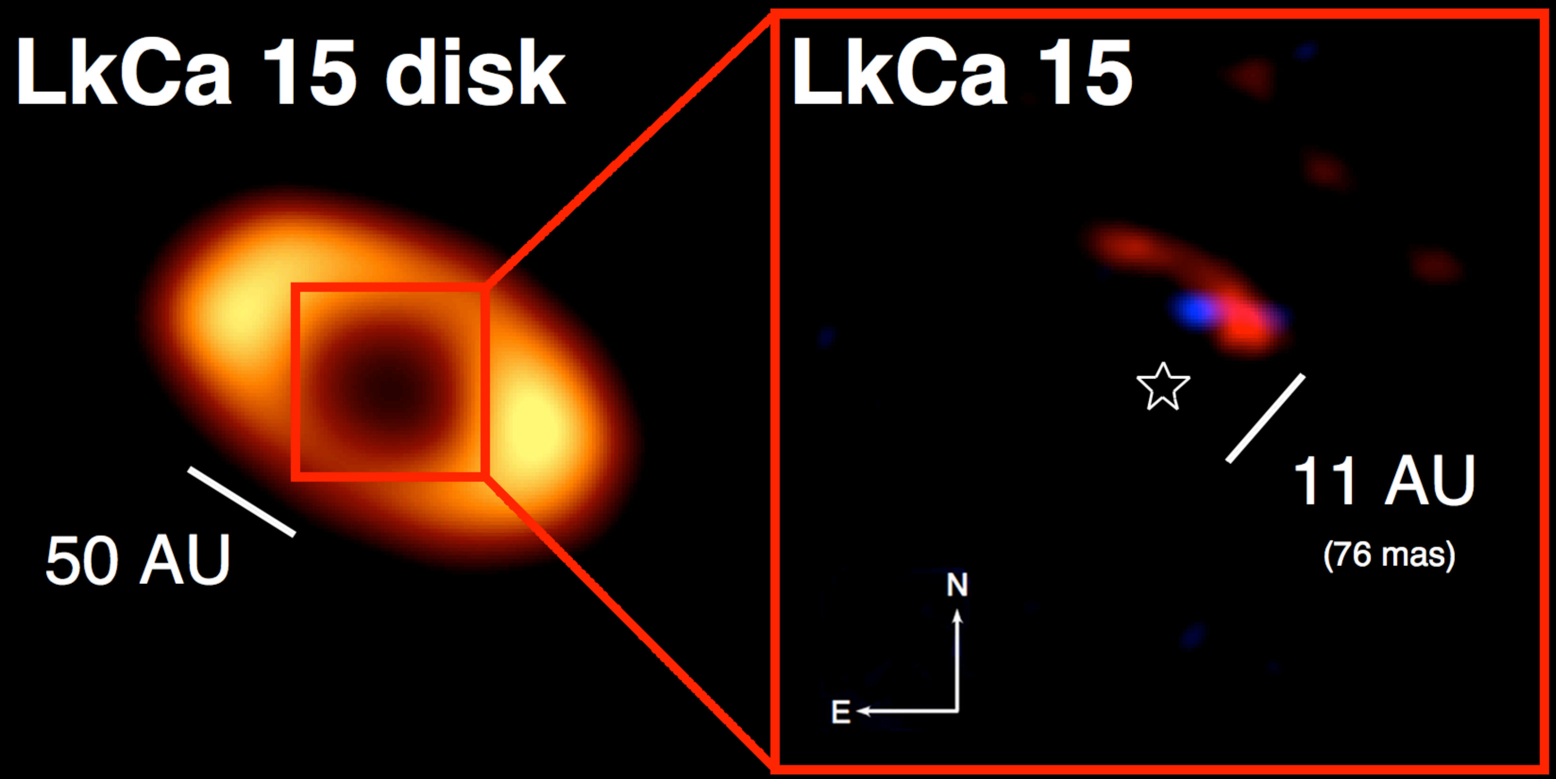


Espaillat et al. 2008a



Muzerolle et al. 2003

A potential protoplanet around LkCa 15

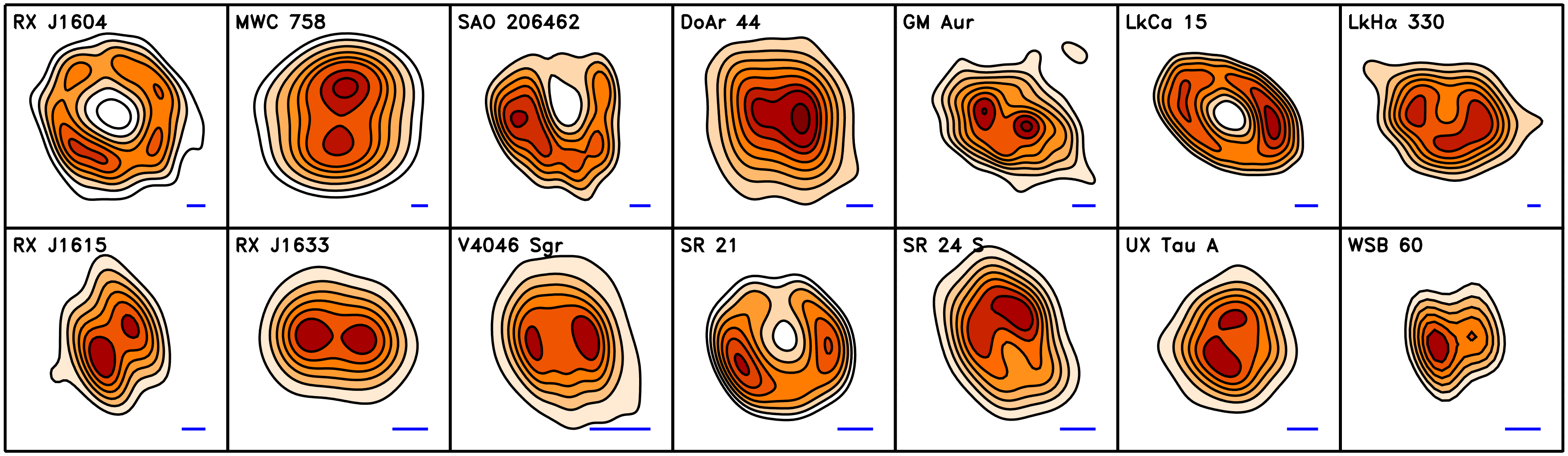


submmm image

IR image

Kraus & Ireland 2011

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

Tracing small dust within submm cavities with NIR polarimetric imaging

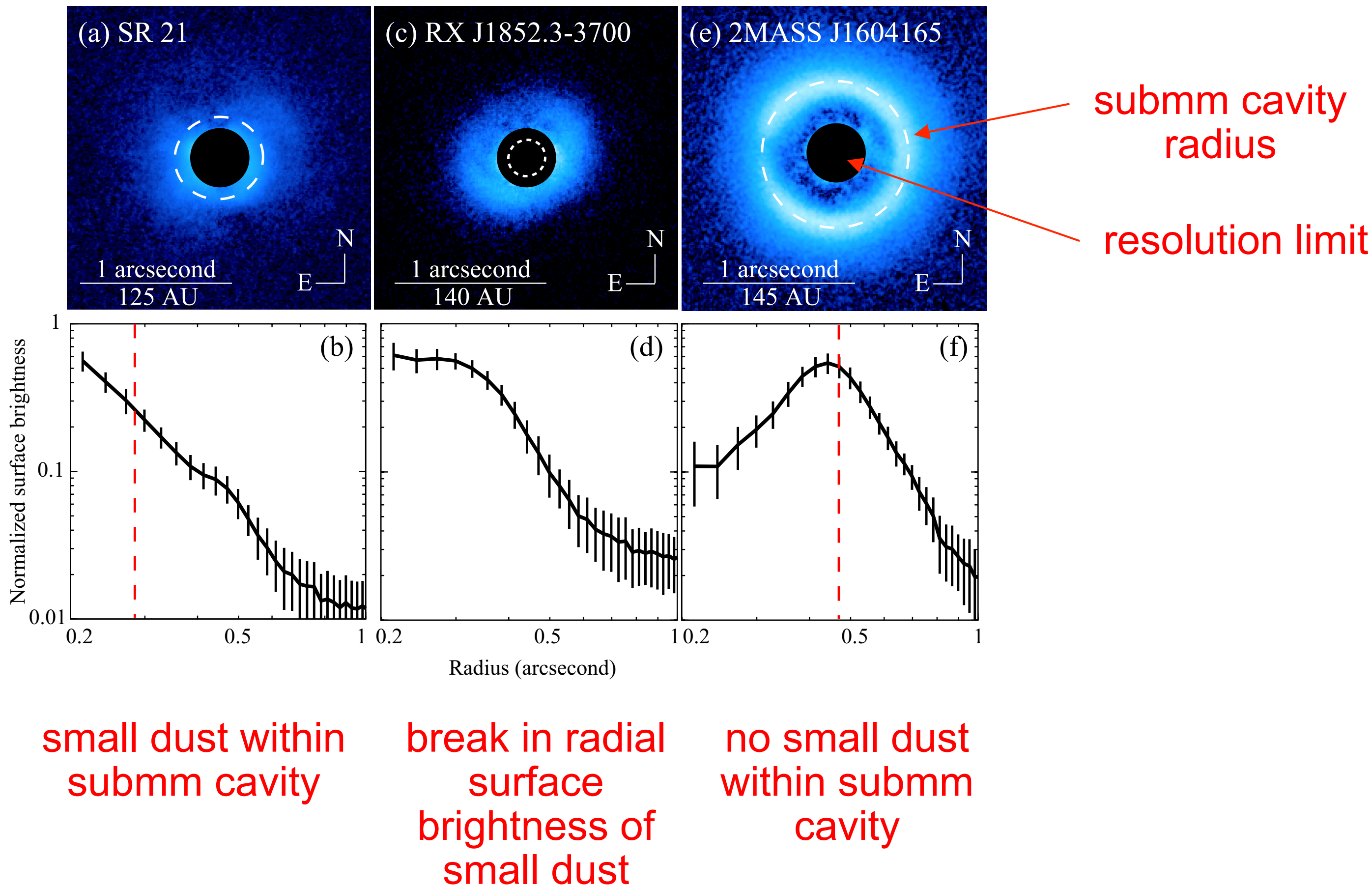
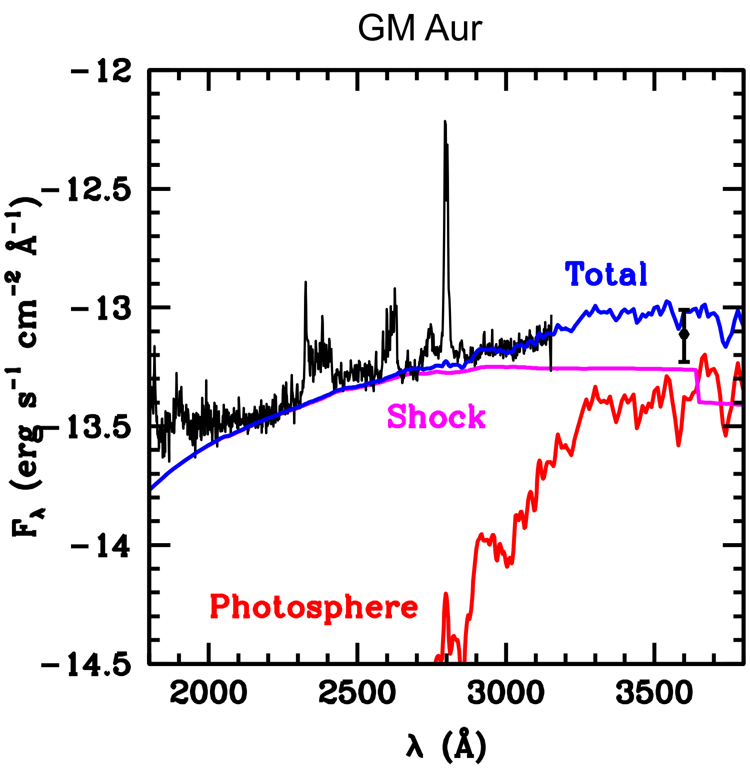
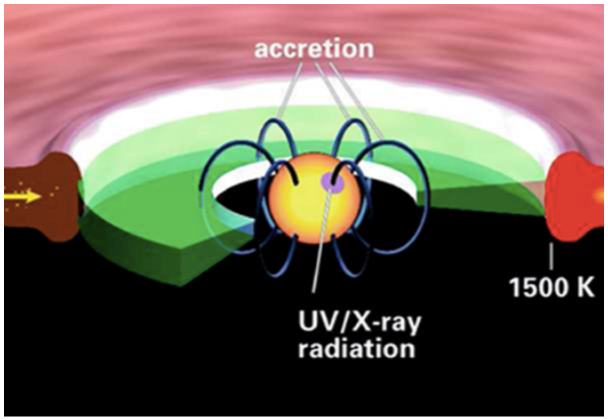


Figure from Espaillat et al. 2014, PPVI; Data from Follette et al. 2013, Kudo et al. in prep, Mayama et al. 2012

Gas can continue to accrete across holes and gaps in dust disk



Accretion Rate ~ 1 x 10^{-8} $M_\odot$ yr $^{-1}$



Ingleby et al. 2013

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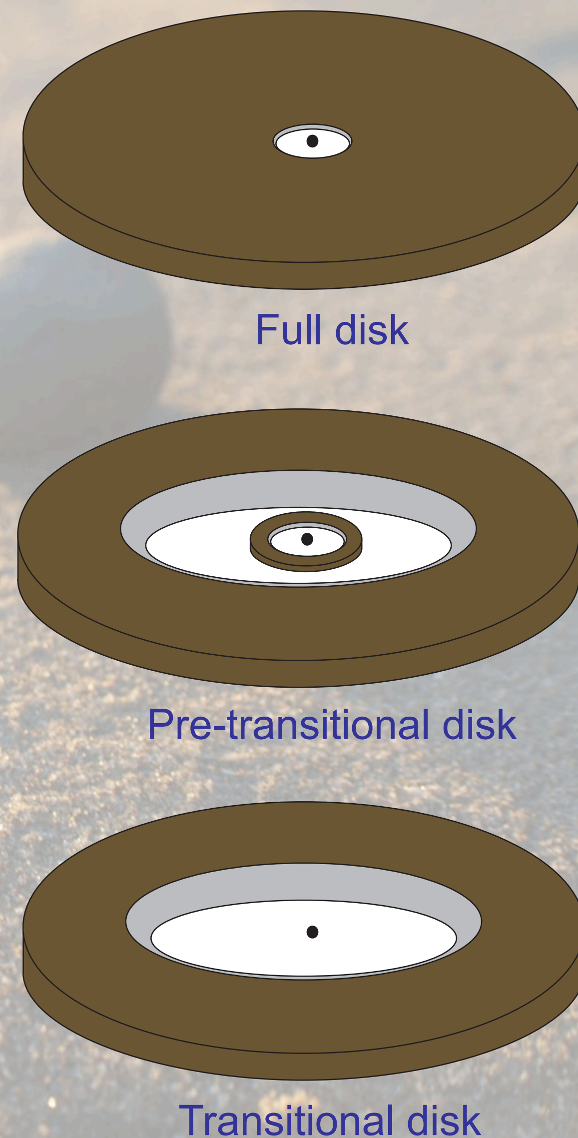
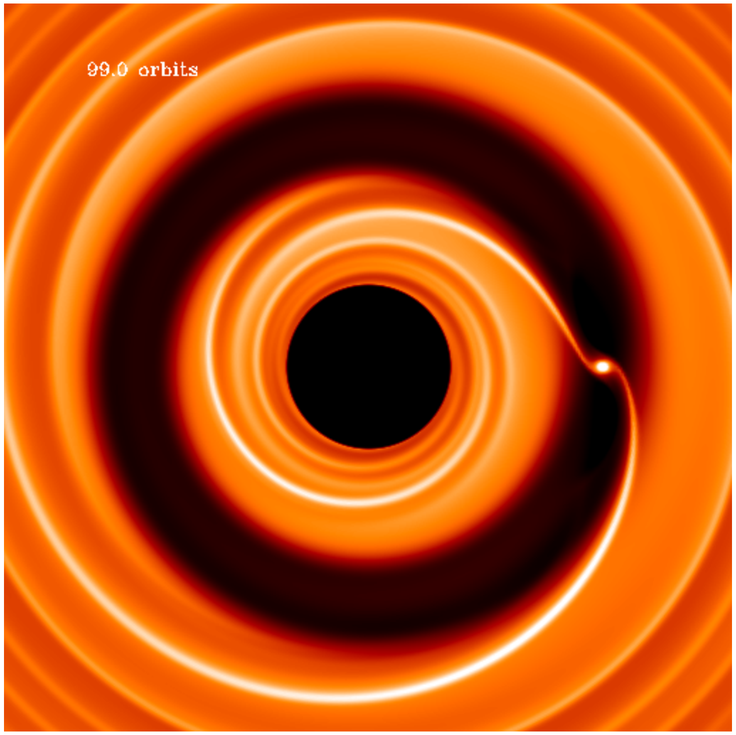


Espaillat et al. 2014, PPVI

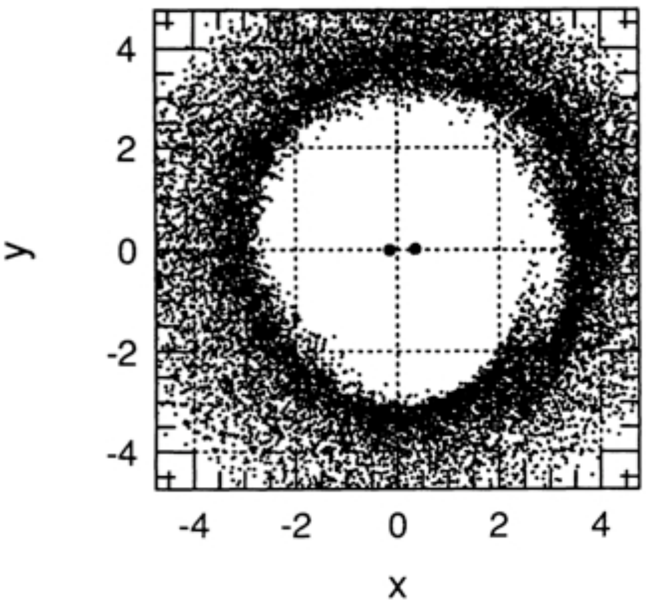
Disk clearing mechanisms: dynamical clearing by planets



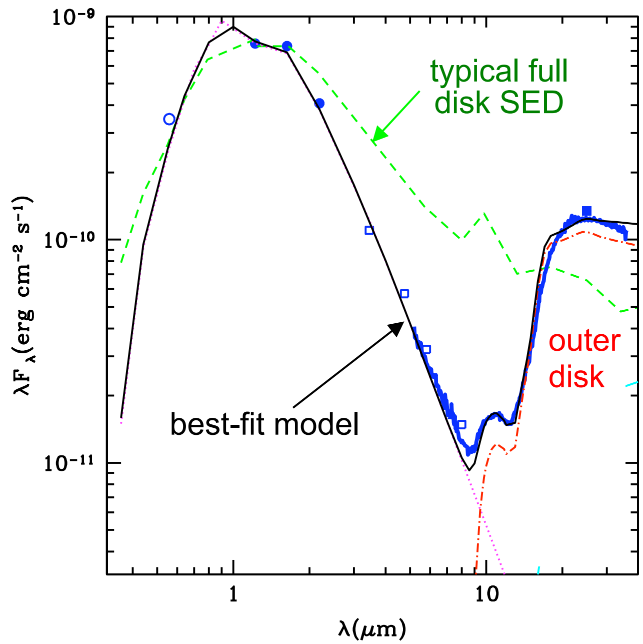
Masset et al. 2002

also Crida et al. 2006; Lubow & D'Angelo 2006; Paardekooper & Mellema 2006; Papaloizou et al. 2007; Pierens & Nelson 2008; Zhu et al. 2011; Kley & Nelson 2012; Baruteau et al. 2014

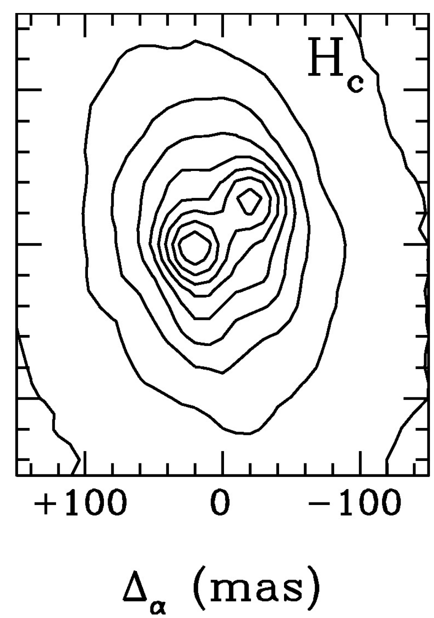
Disk clearing mechanisms:
dynamical clearing by stellar companions



Artymowicz & Lubow 1994

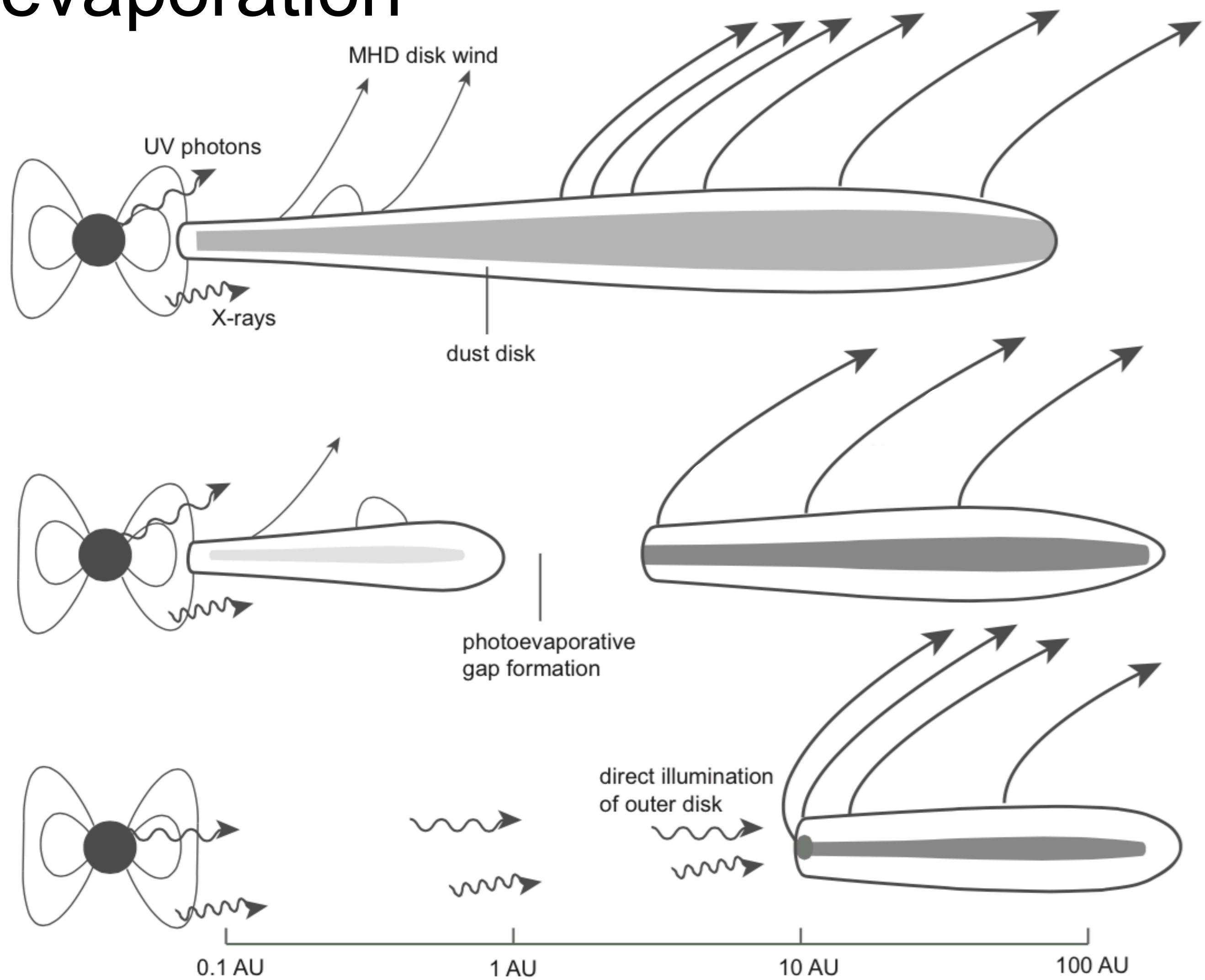


D'Alessio et al. 2005



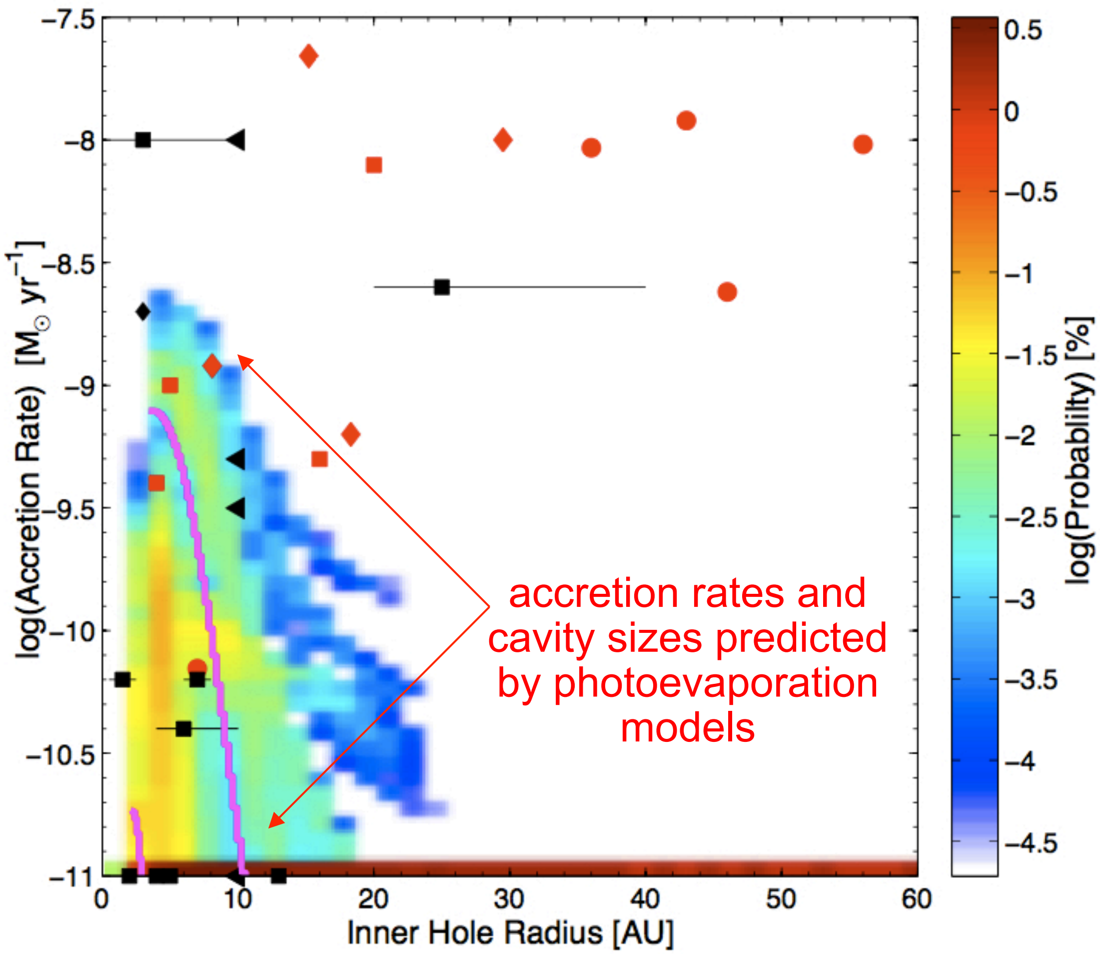
Ireland & Kraus 2008

Disk clearing mechanisms: photoevaporation



Adapted from Alexander et al. 2015; see also Hollenbach et al. 1994; Clarke et al. 2001

Photoevaporation models cannot explain accreting objects with large inner cavities



Owen et al. 2011

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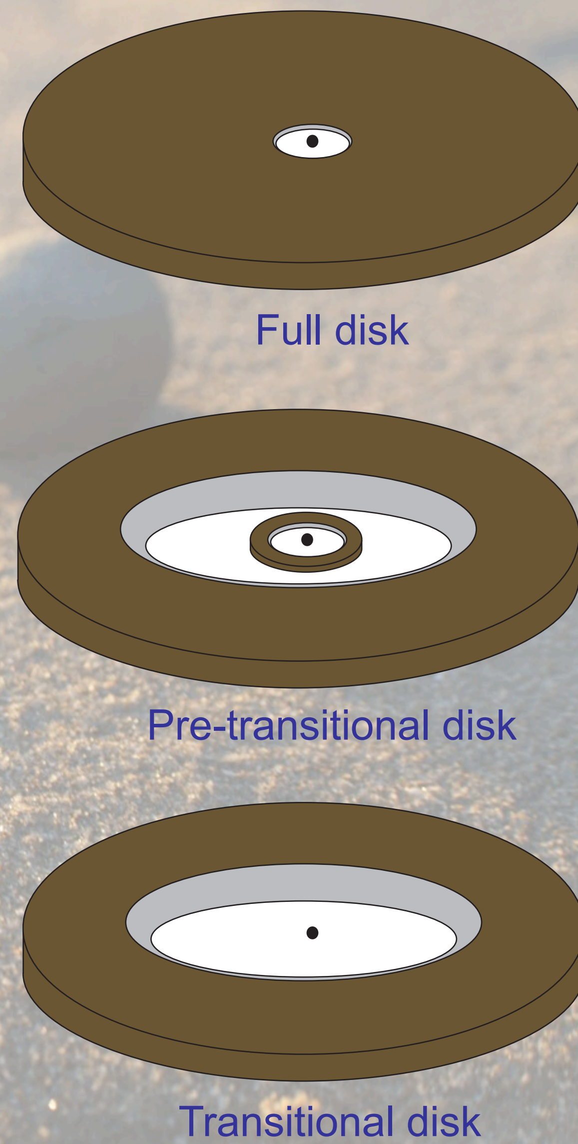
What can disks with holes and gaps tell us about disk evolution and planet formation?

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

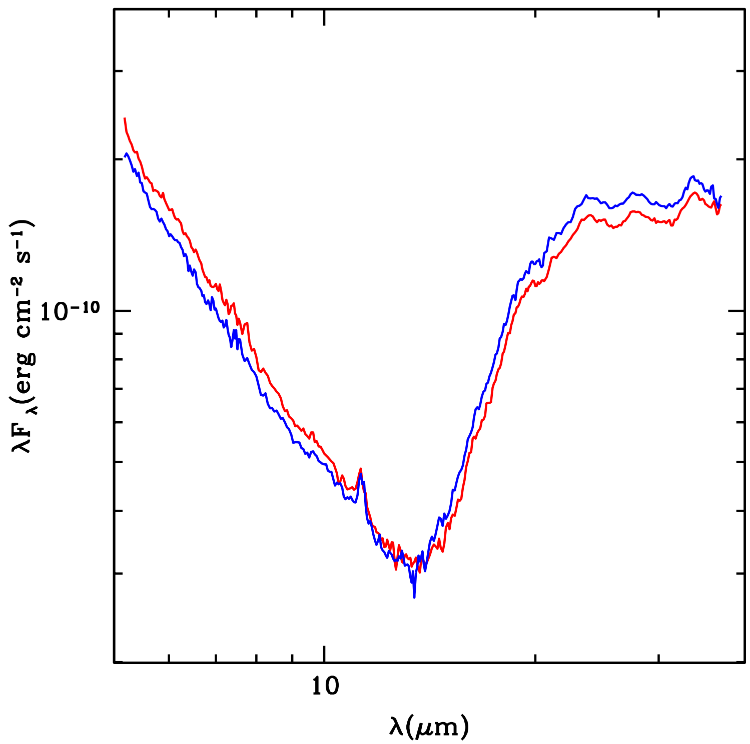
Where do we go from here?

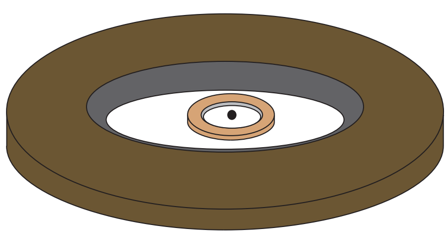


Espaillat et al. 2014, PPVI

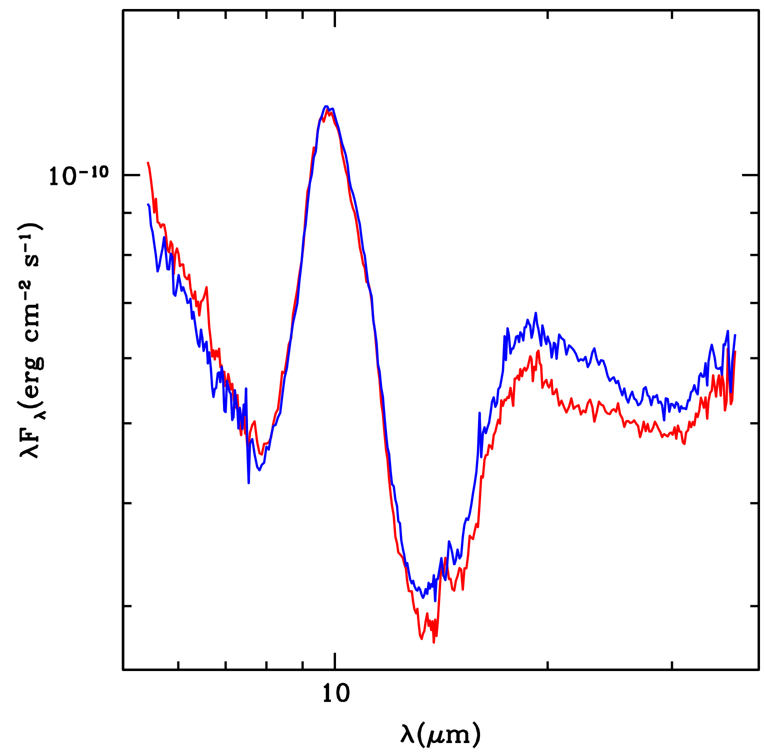
Pre-transitional disks have variable "see-saw" IR emission

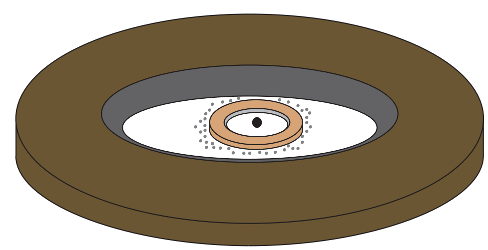
UX Tau A





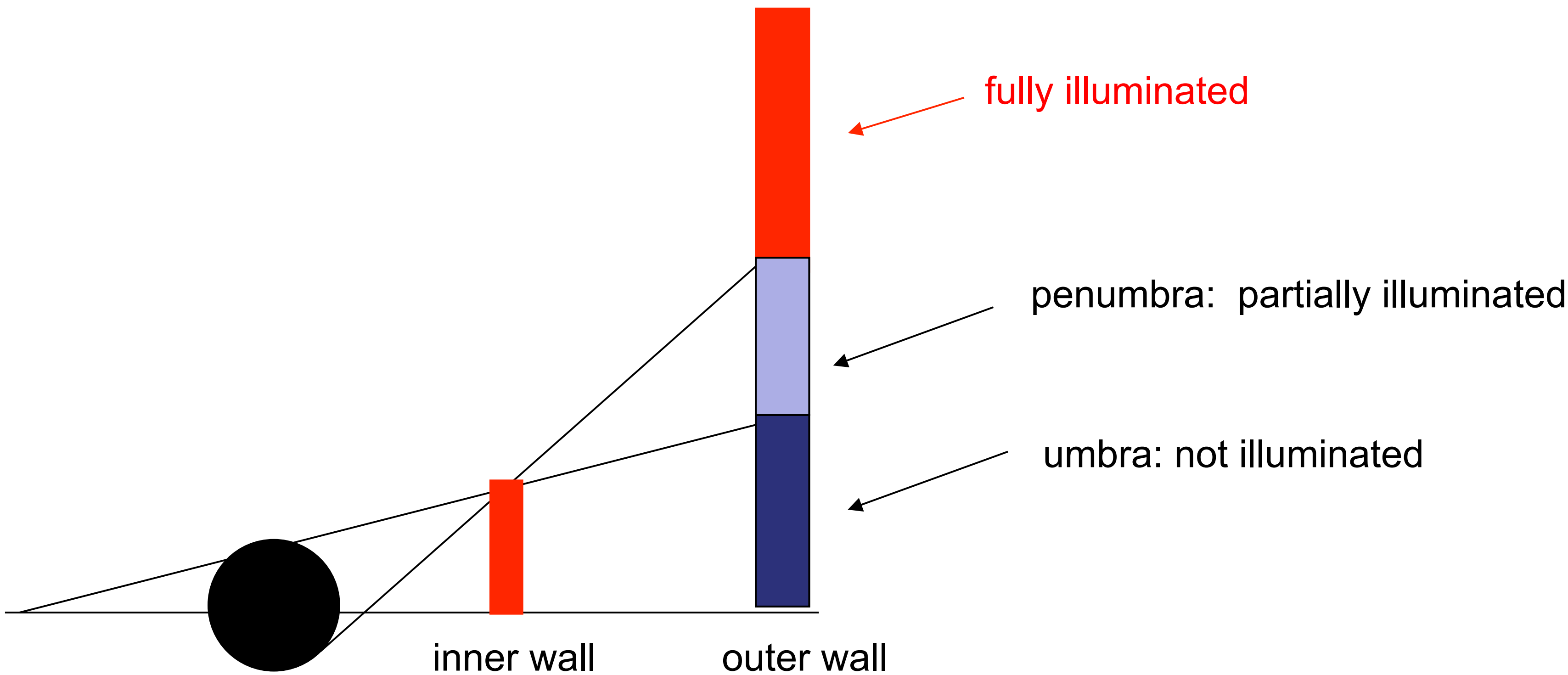
LkCa 15





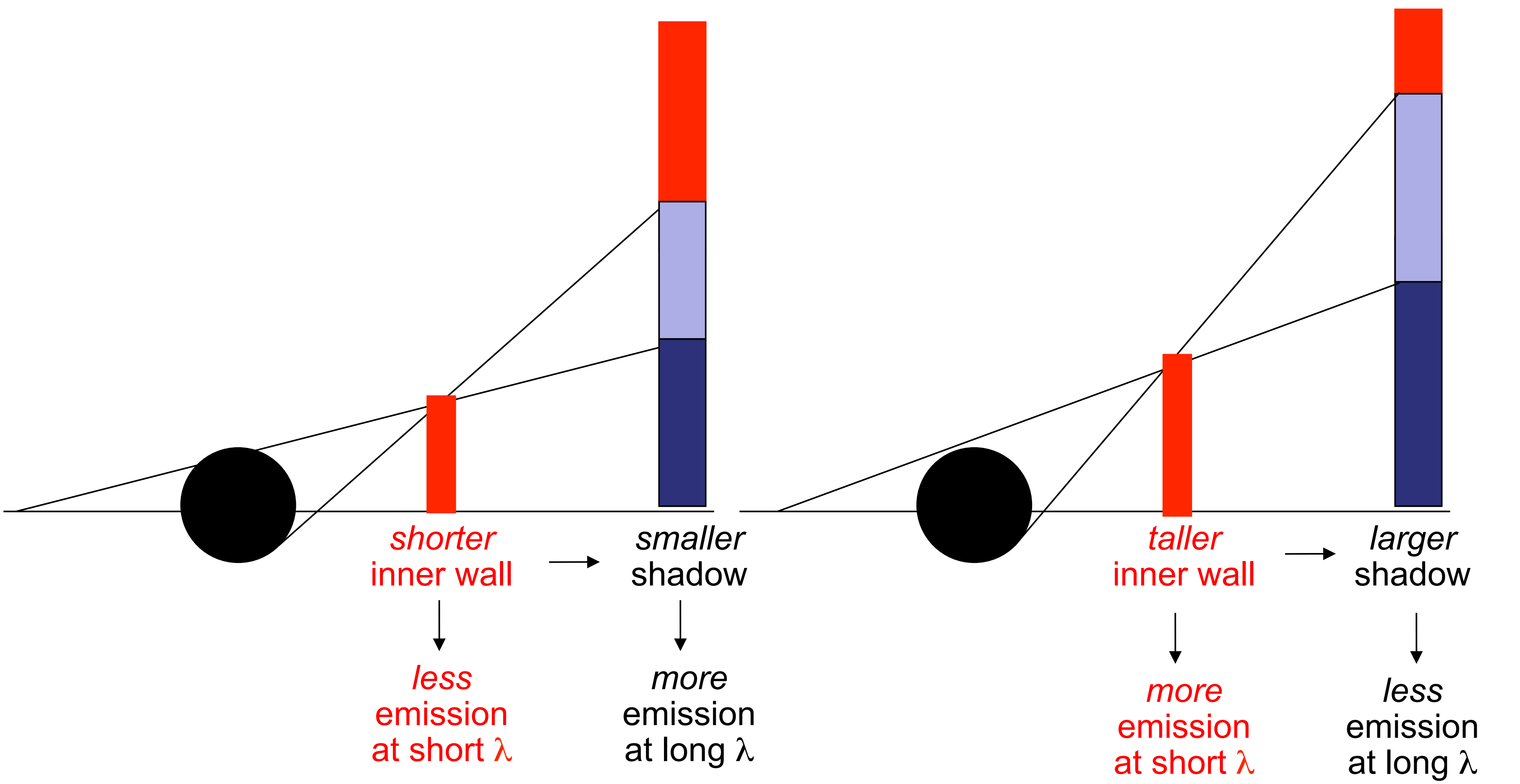
Espaillat et al. 2011; also Muzerolle et al. 2010, Flaherty et al. 2012

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



Espaillat et al. 2010

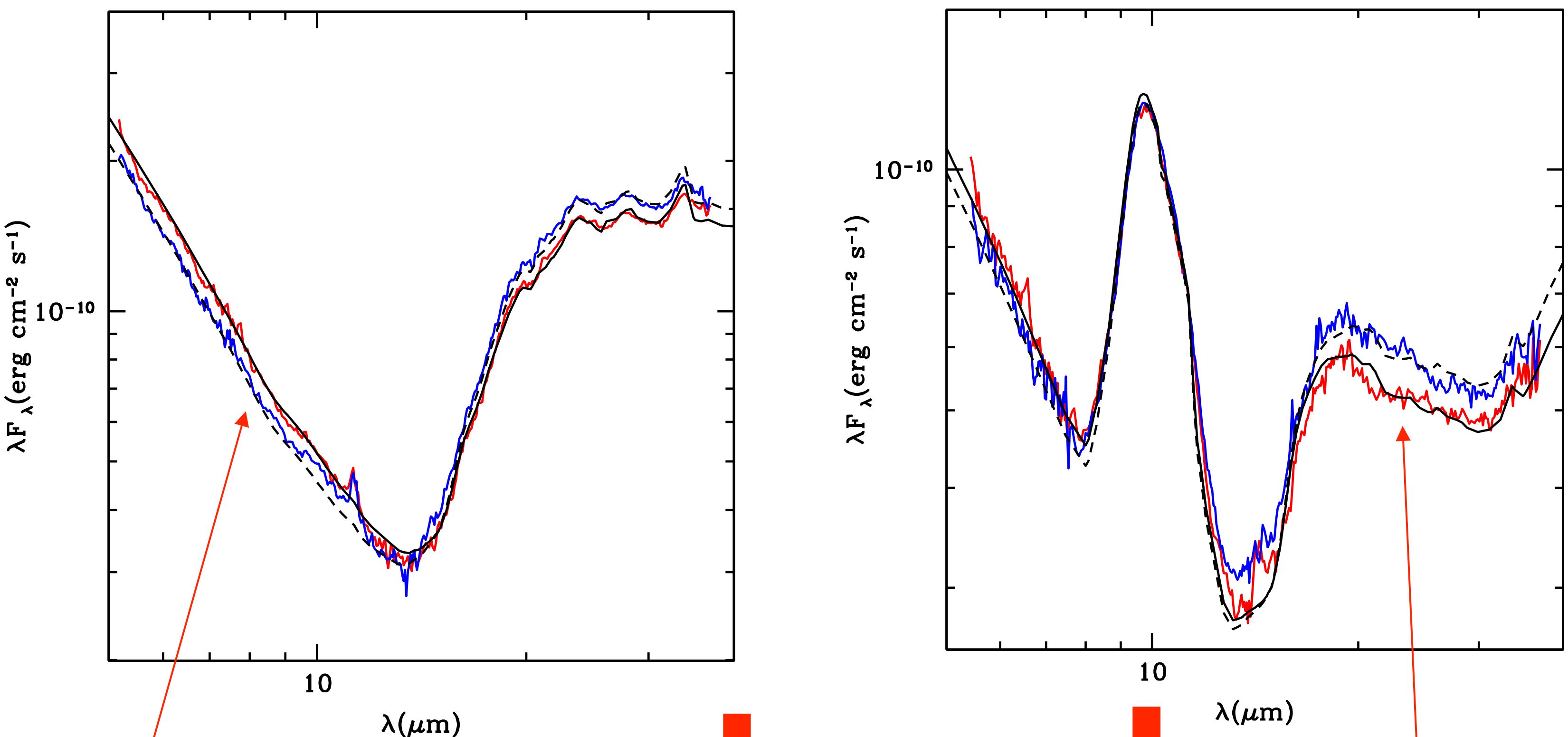
Changing the height of the inner wall changes the shadow on the outer wall

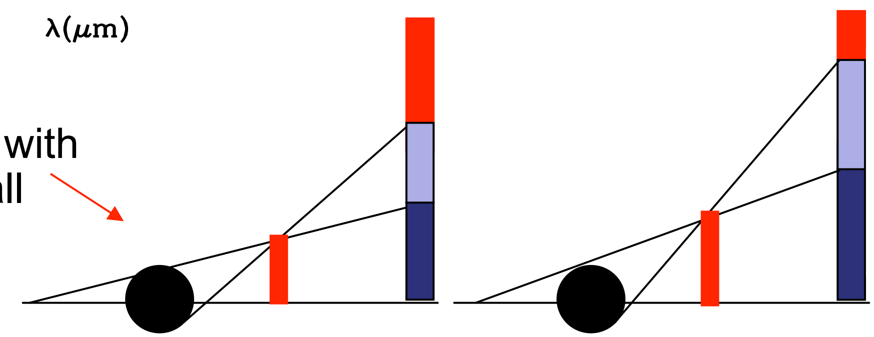


Can fit each SED by changing the height of the inner wall

UX Tau A

LkCa 15





broken line: model with shorter inner wall

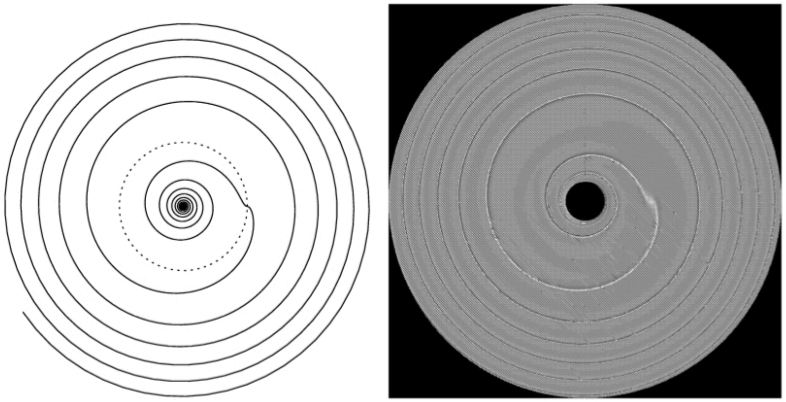
solid line: model with taller inner wall

Espaillat et al. 2011

Potential causes of MIR variability in pre-transitional disks

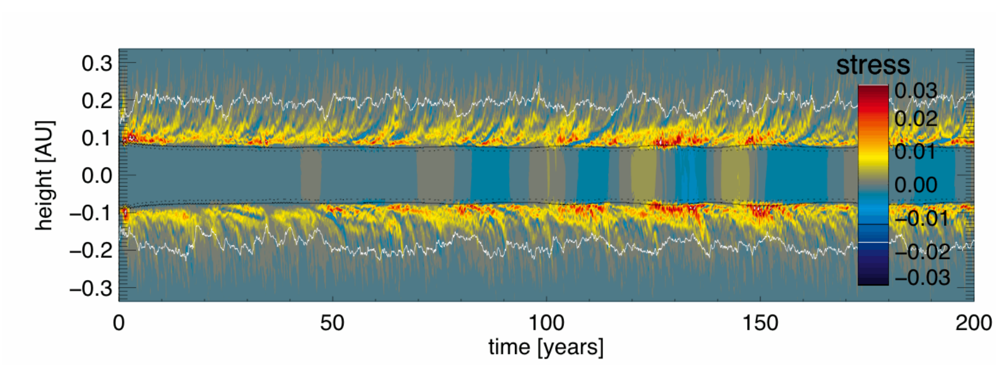
Planet-disk interaction

Flaherty et al. 2011



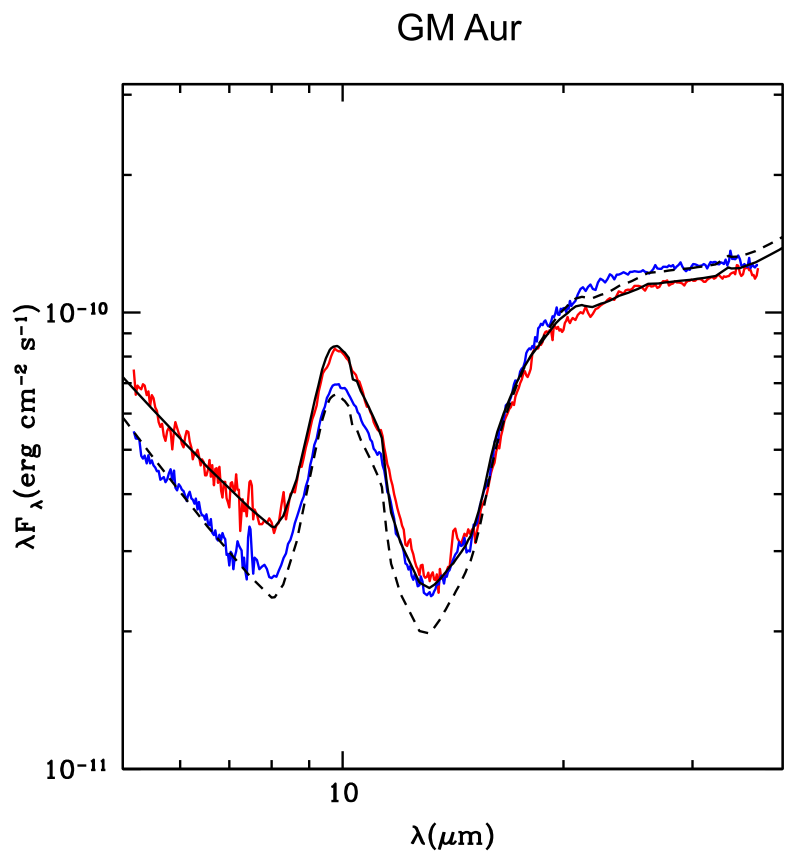
Ogilvie & Lubow 2002

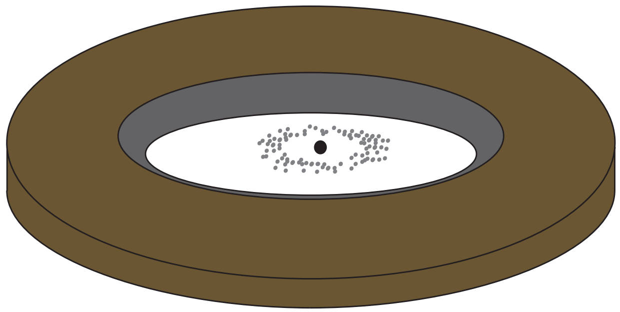
Turbulence from MRI



Hirose & Turner 2011

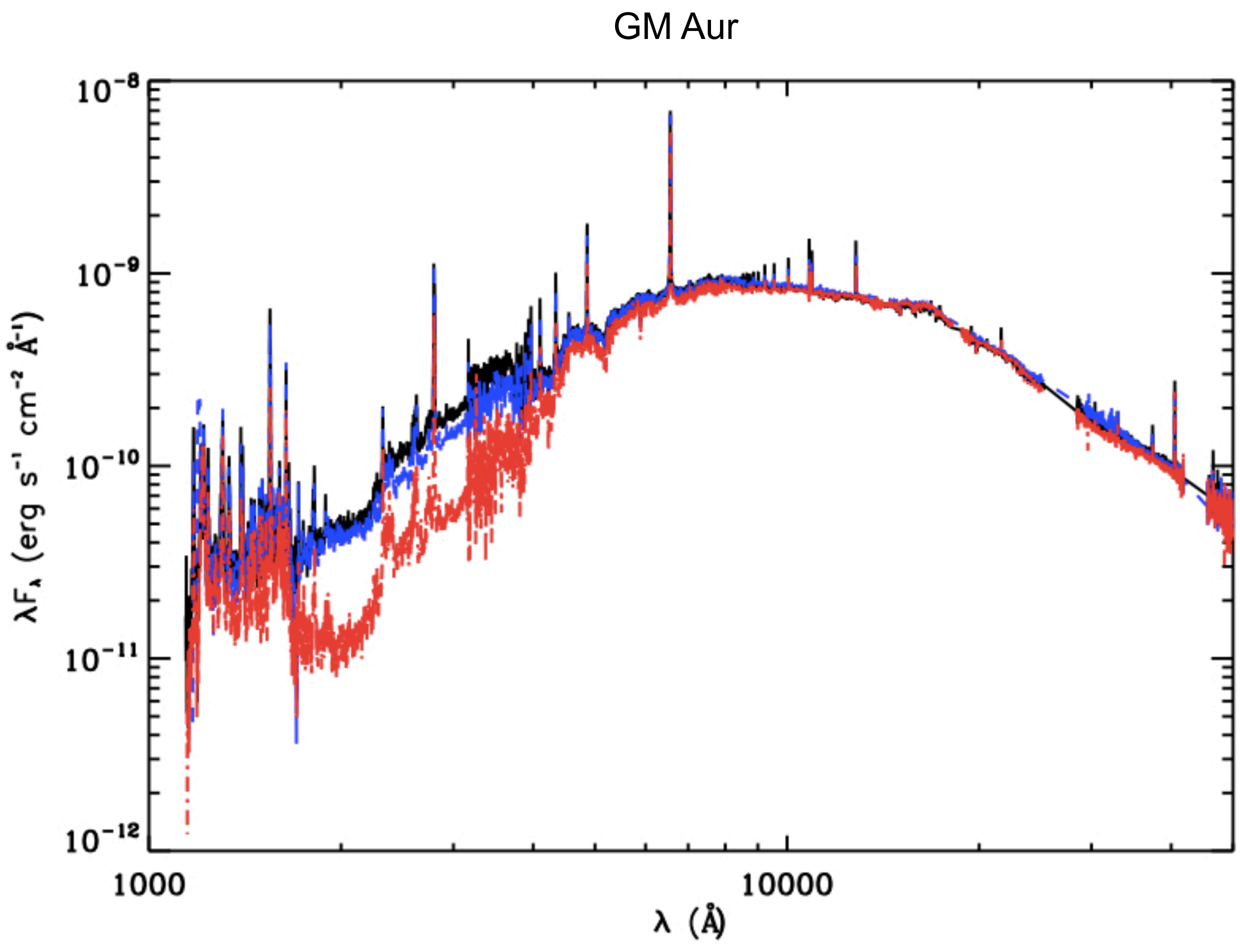
MIR variability in transitional disks





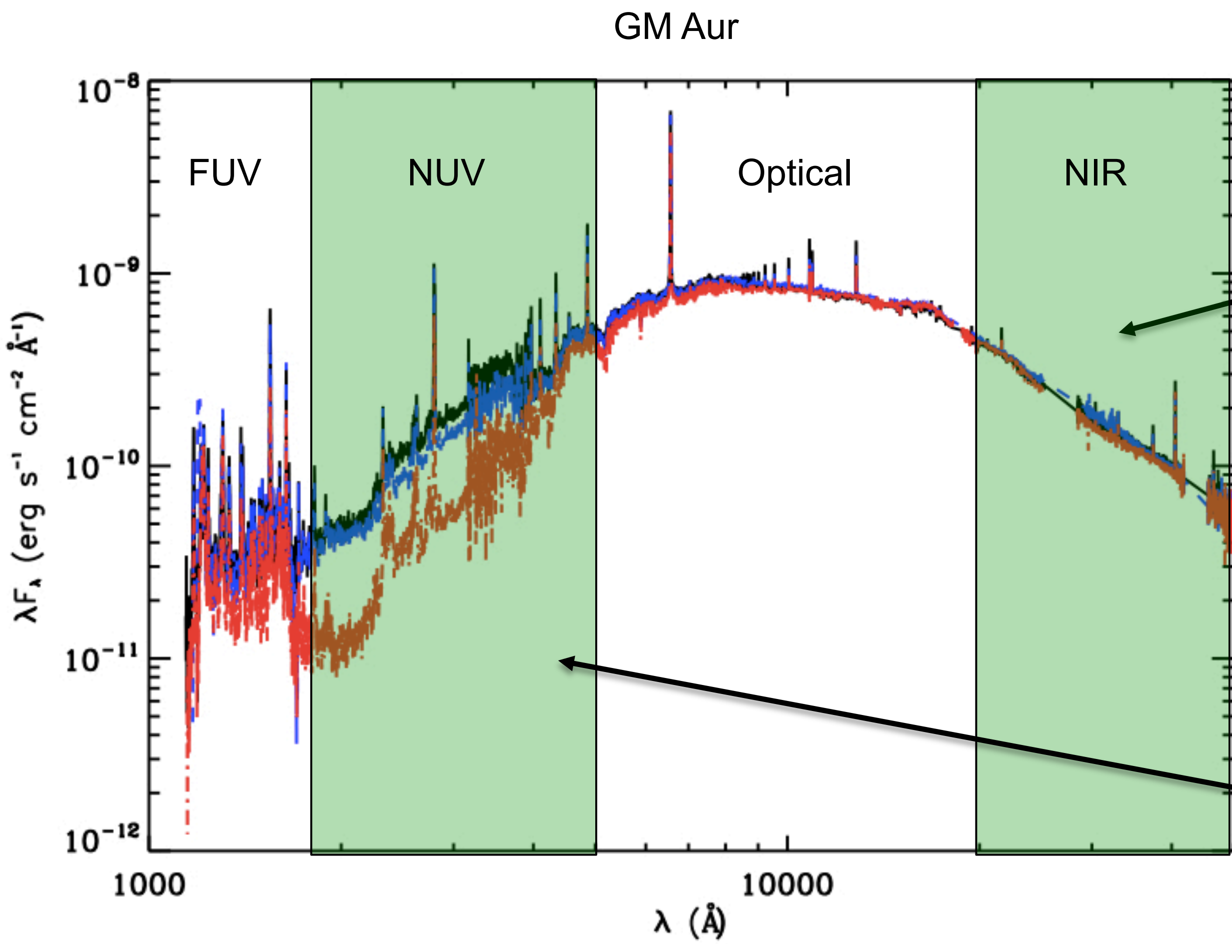
Espaillat et al. 2011

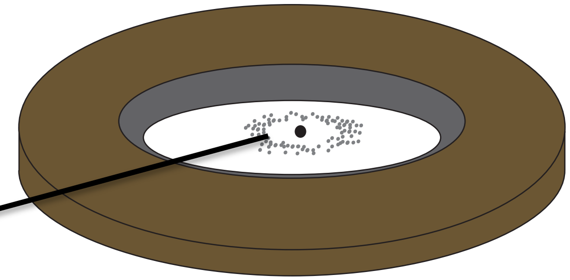
FUV-NIR variability in GM Aur

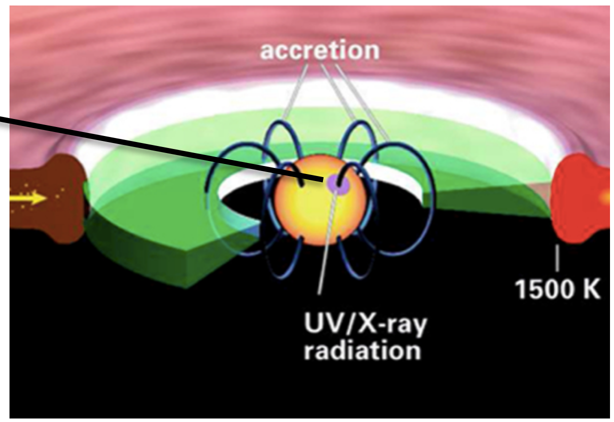


Ingleby, Espaillat et al. 2015

FUV-NIR variability in GM Aur



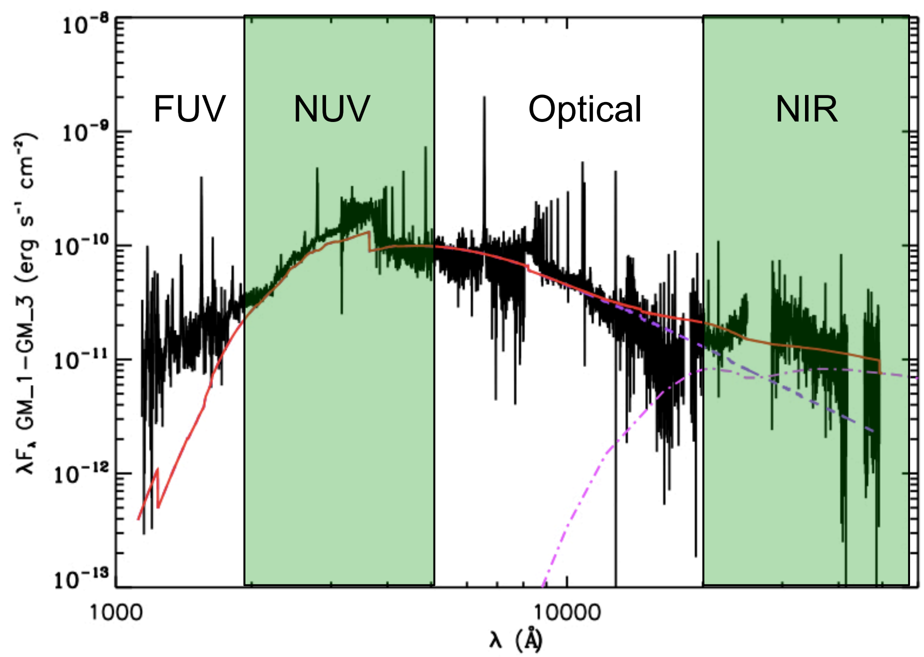




Ingleby, Espaillat et al. 2015

Decrease in FUV-NIR emission of GM Aur

Excess in Observation #1 over #3



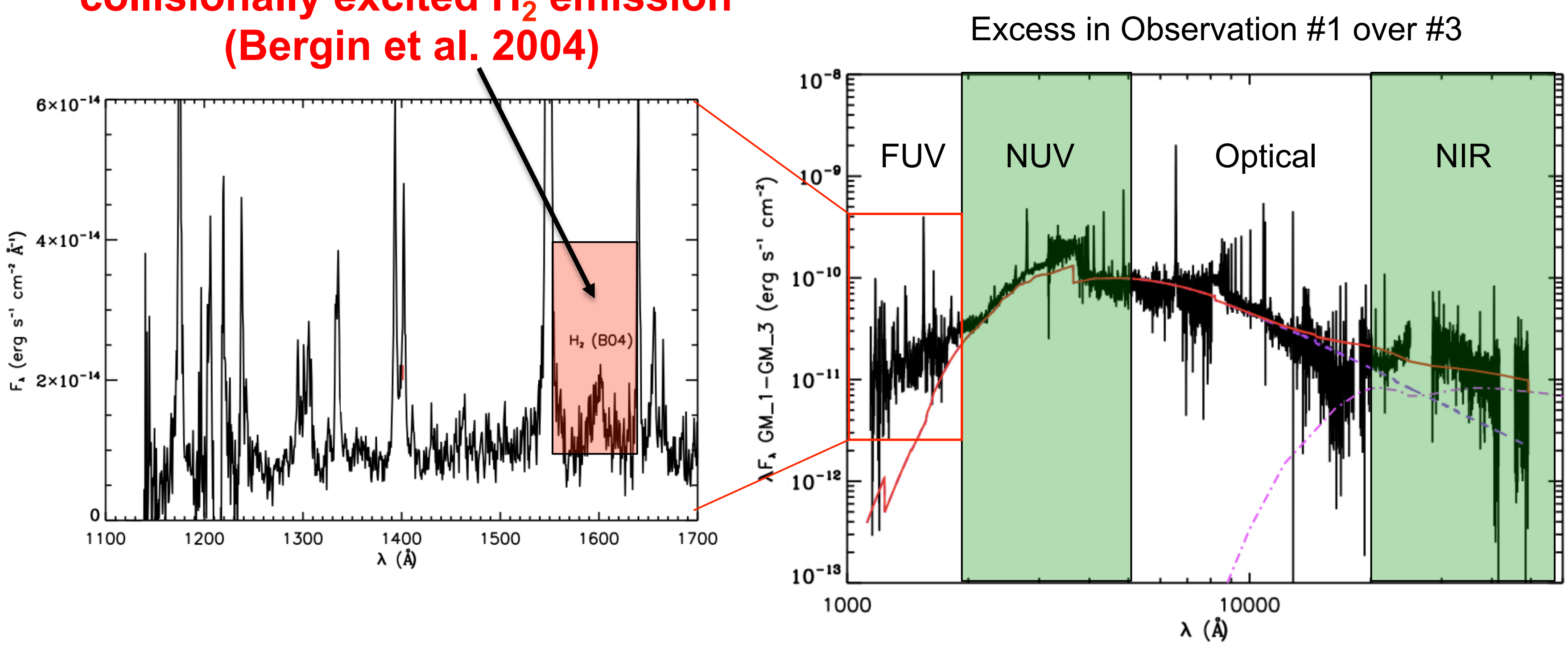
accretion rate decreases

dust mass in inner disk decreases

Ingleby, Espaillat et al. 2015

Decrease in FUV-NIR emission of GM Aur

collisionally excited H_2 emission (Bergin et al. 2004)



H_2 gas density decreases

accretion rate decreases

dust mass in inner disk decreases

Ingleby, Espaillat et al. 2015

Interpreting the FUV-NIR emission

lower NUV

lower NIR

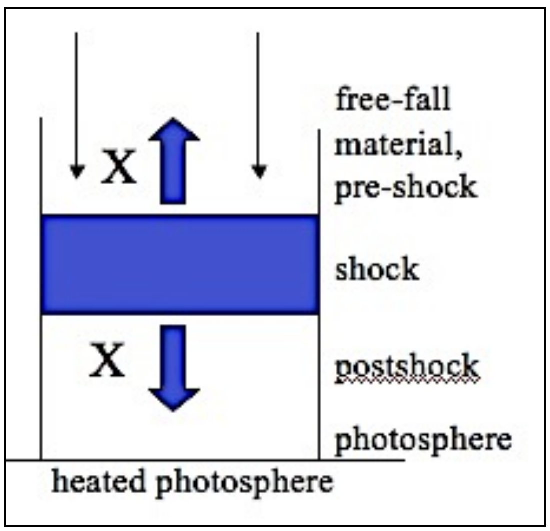
weaker
1600Å H_2

Interpreting the FUV-NIR emission

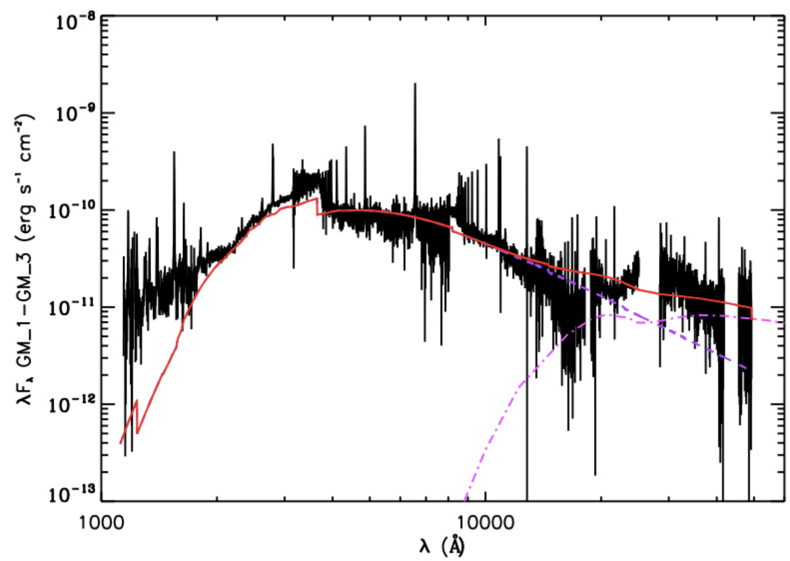
lower NUV → decreased accretion rate → less dense accretion column

lower NIR

weaker
1600Å H_2



Energy $\propto$ density x v^3

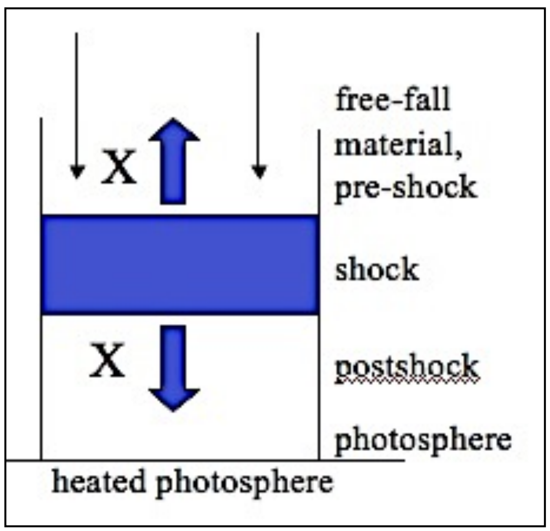


Interpreting the FUV-NIR emission

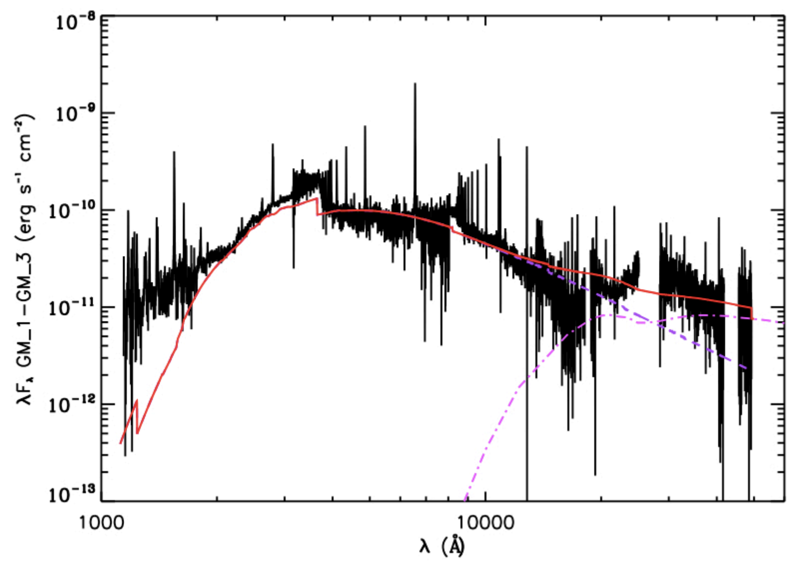
lower NUV → decreased accretion rate → less dense accretion column

lower NIR → less dust mass in inner disk → less emitting dust

weaker 1600Å H_2 → lower gas density → less emitting gas



Energy $\propto$ density x v^3



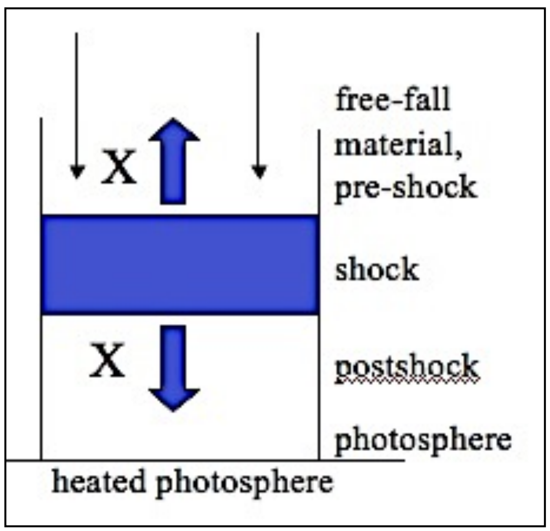
Interpreting the FUV-NIR emission

lower NUV → decreased accretion rate → less dense accretion column

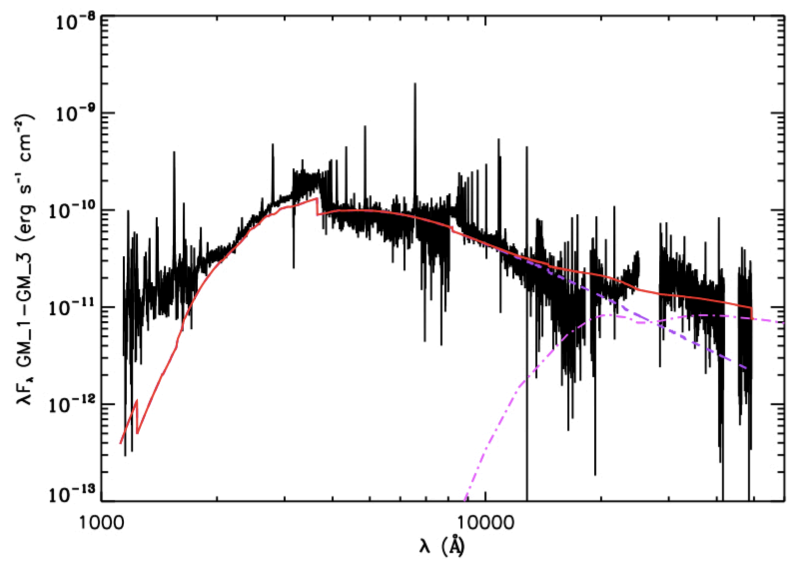
lower NIR → less dust mass in inner disk → less emitting dust

weaker 1600Å H_2 → lower gas density → less emitting gas

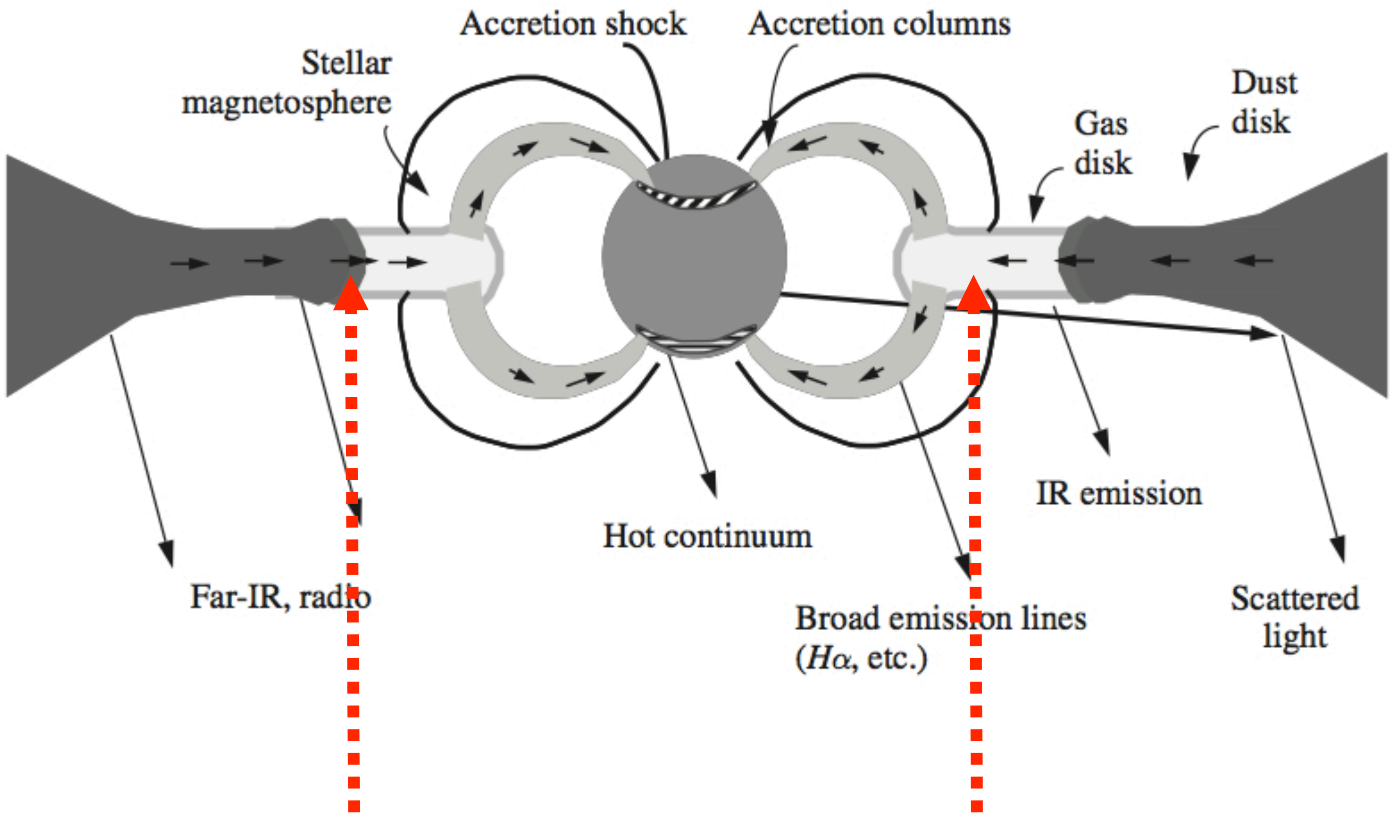
less emitting dust / less emitting gas → coexist in disk



Energy $\propto$ density x v^3



Comparing the locations of dust and gas



dust destruction radius
R_{dust} ~ 10 R_{star} (0.08 AU)

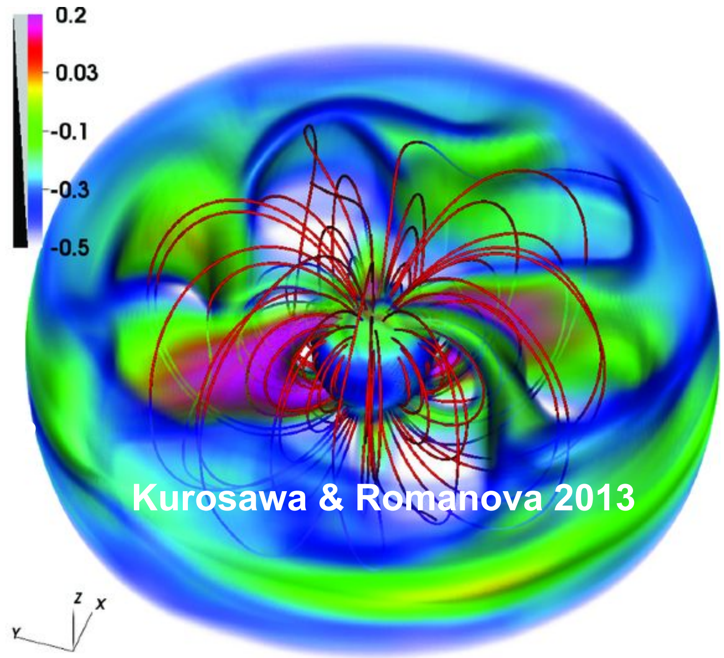
magnetospheric truncation radius
R_{mag} ~ 5 R_{star} (0.04 AU)

corotation radius
R_{cor} ~ 8.5 R_{star} (0.07 AU)

Hartmann 2008

Tracing the star-disk connection

Inhomogeneities in the inner disk → Less mass loading onto star



GM Aur's NUV, NIR, and 1600Å H_2 feature all decrease in strength.

– Points to decrease in the density of the accretion column and inner disk.

Tracking Planet Footprints

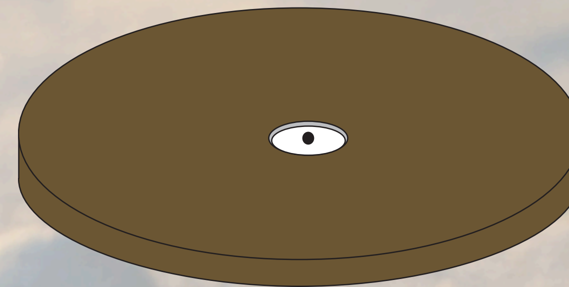
What evidence do we have for planets forming in young disks?

- full disk overview
- SEDs and images of disk holes and gaps
- theoretical disk clearing mechanisms

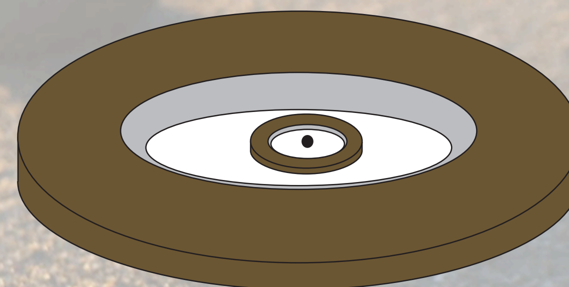
What can disks with holes and gaps tell us about disk evolution and planet formation?

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

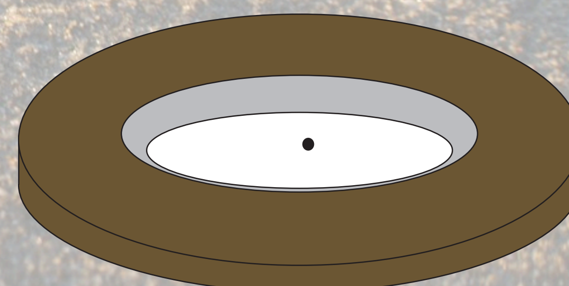
Where do we go from here?



Full disk



Pre-transitional disk

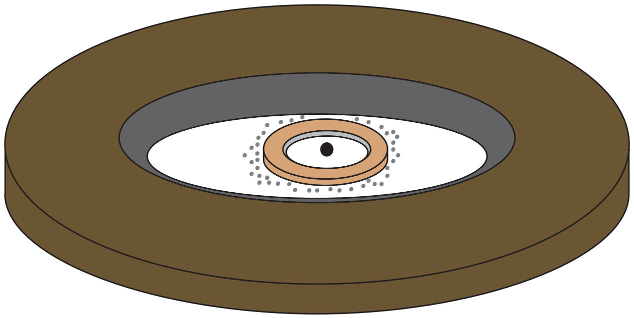


Transitional disk

Espaillat et al. 2014, PPVI

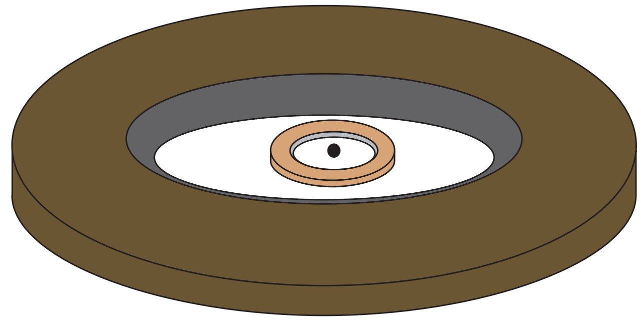
Extracting observational constraints to inform physical models

LkCa 15



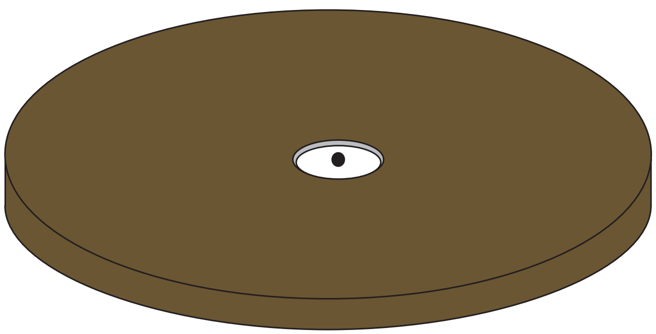
$3 \times 10^{-9}\ M_\odot\ yr^{-1}$ | 40 AU

UX Tau A



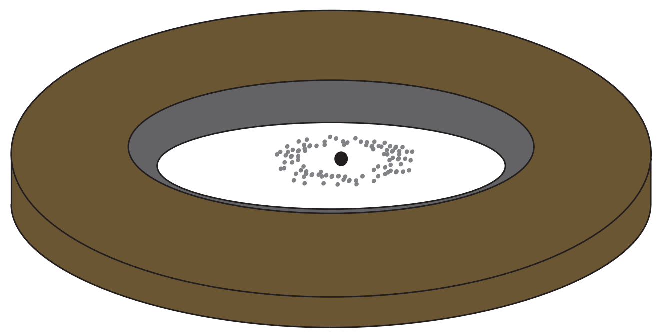
$1 \times 10^{-8}\ M_\odot\ yr^{-1}$ | 30 AU

Full disk



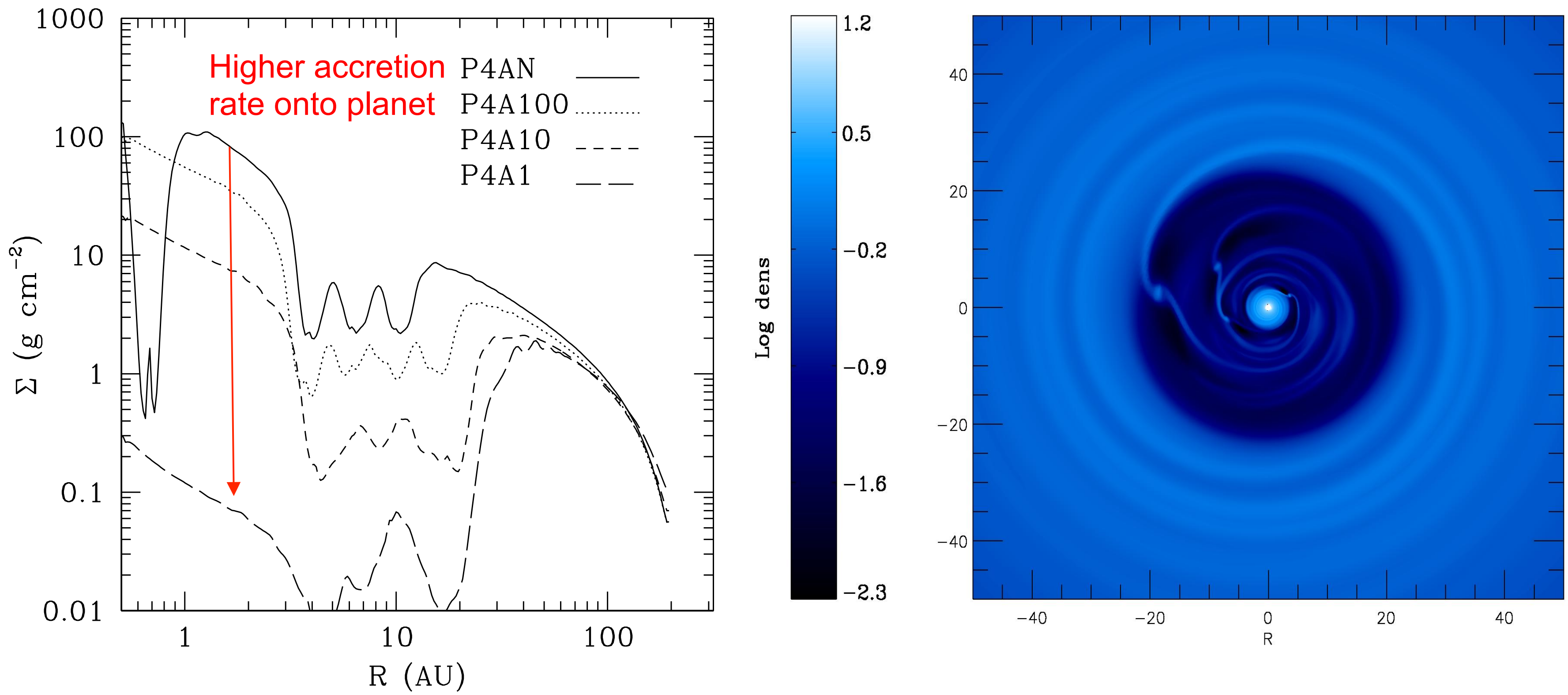
$1 \times 10^{-8}\ M_\odot\ yr^{-1}$

GM Aur



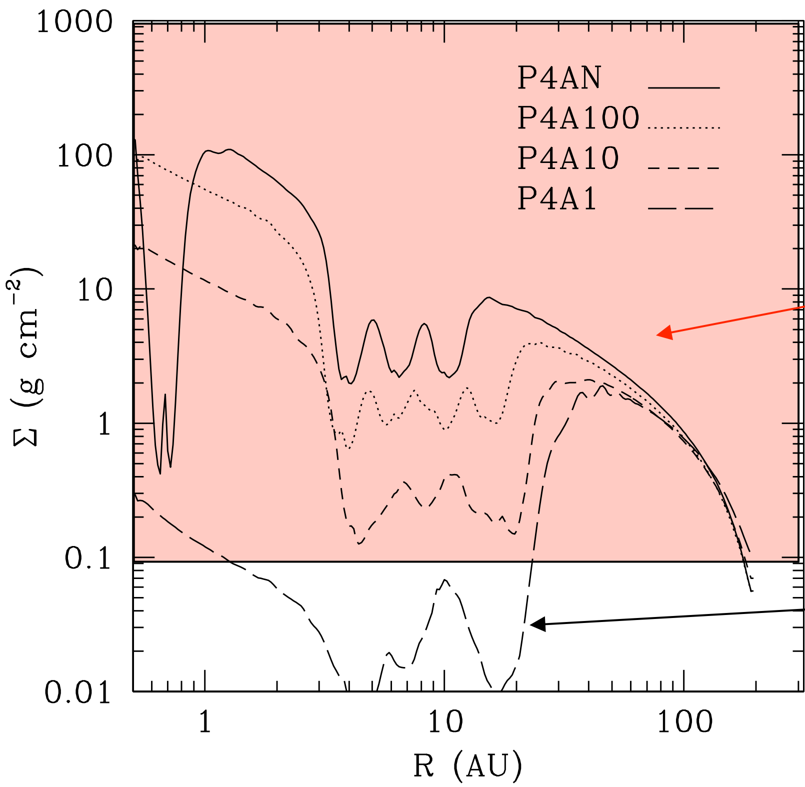
$8 \times 10^{-9}\ M_\odot\ yr^{-1}$ | 20 AU

Multiple planets open a large annular gap



Zhu et al. 2011

The gaps must be deep enough to be detectable in SEDs

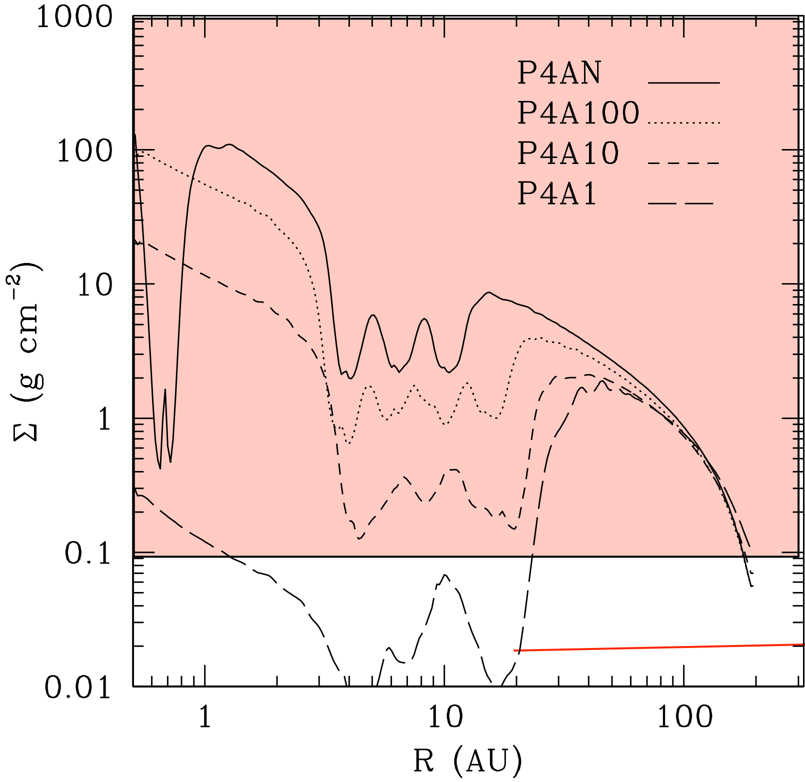


optically thick, no dip in SED

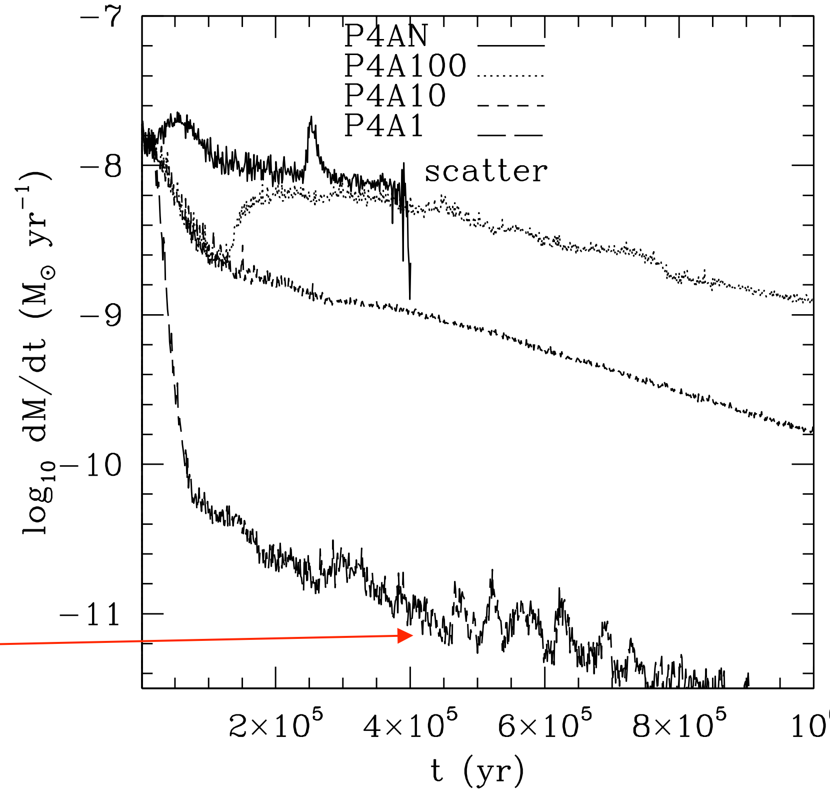
optically thin, leads to dip in SED

Zhu et al. 2011

Multiple planets significantly decrease the accretion rate onto the star



Accretion Rate onto the Star



Zhu et al. 2011

Dust filtration can lead to different gas and dust distributions

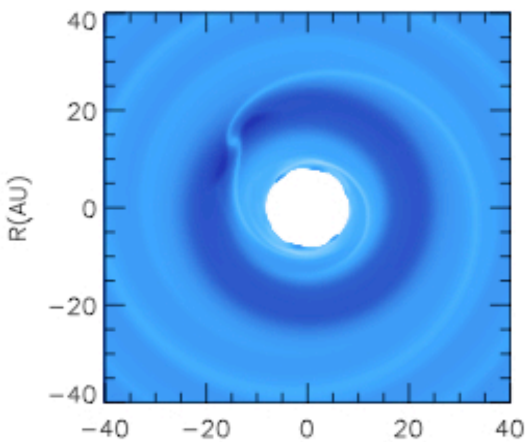
Gas Distribution

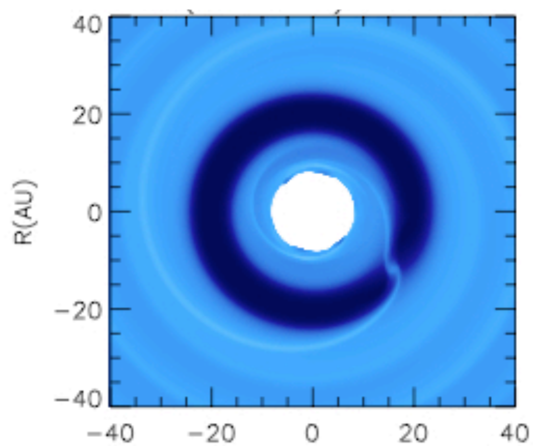
Small Dust Distribution

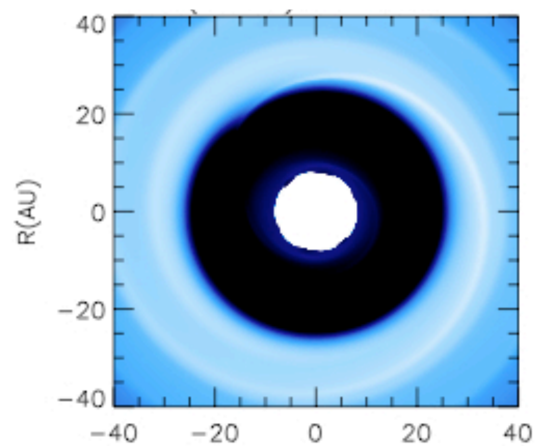
(< 10 microns)

Large Dust Distribution

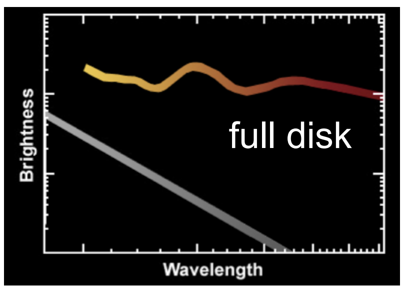
(~ 1mm)

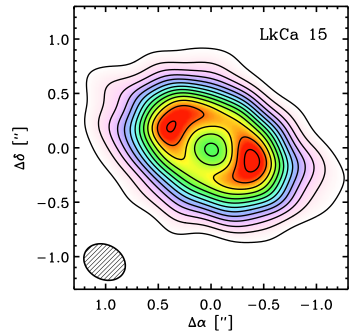






$\sim 10^{-9} M_{\odot}$ yr $^{-1}$

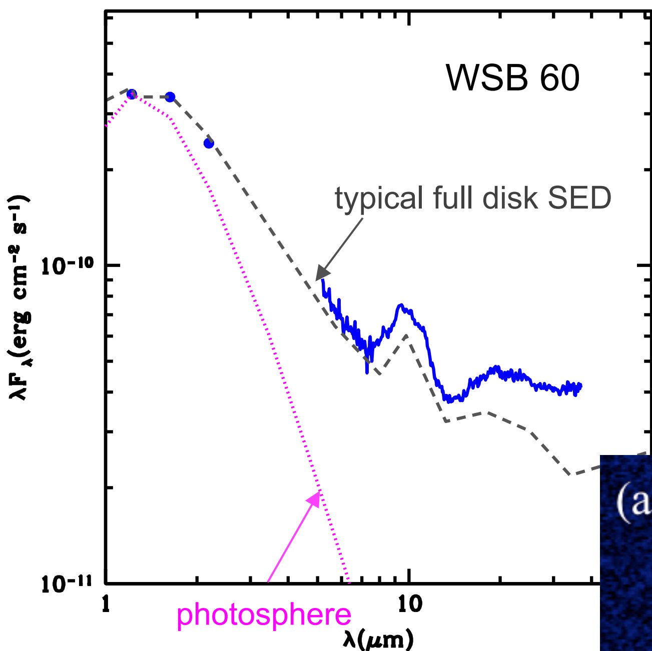




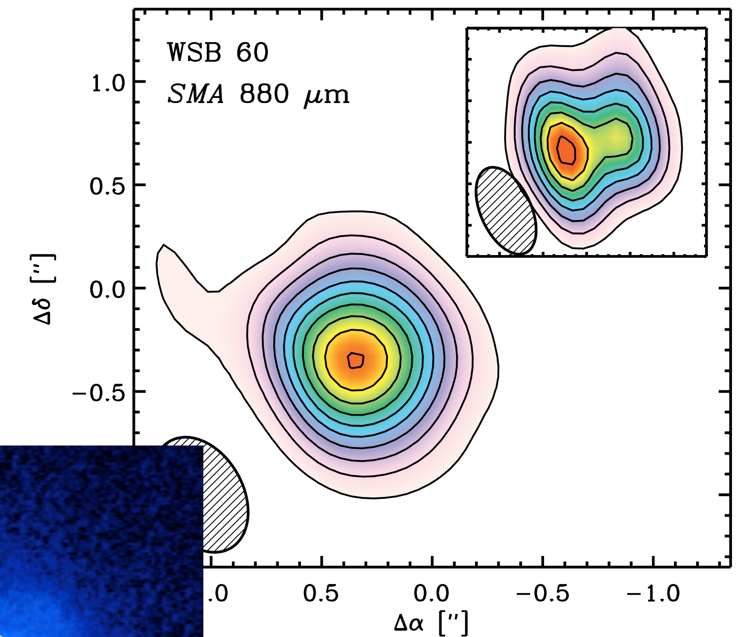
Zhu et al. 2012

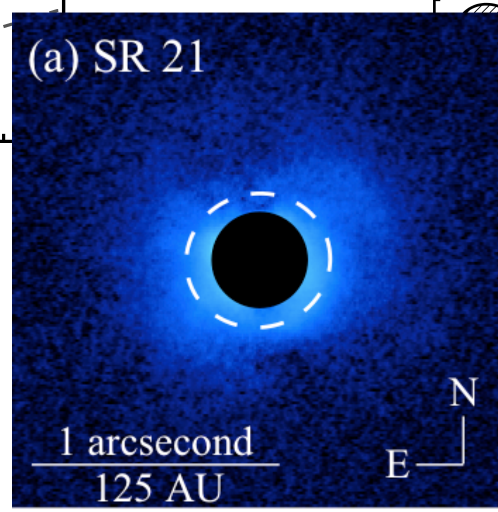
Possible evidence of earliest stages of gap opening via dust filtration

Full disk SED



Cavity seen in submm





Andrews et al. 2011

Tracking Planet Footprints

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

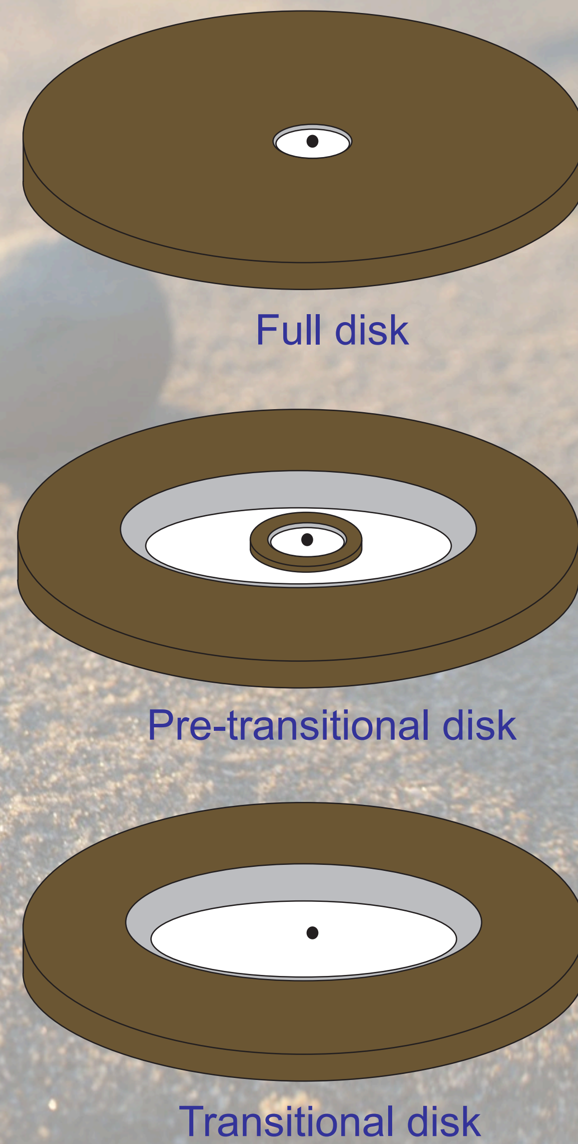
- full disk overview
- SEDs and images of disk holes and gaps
- theoretical disk clearing mechanisms

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

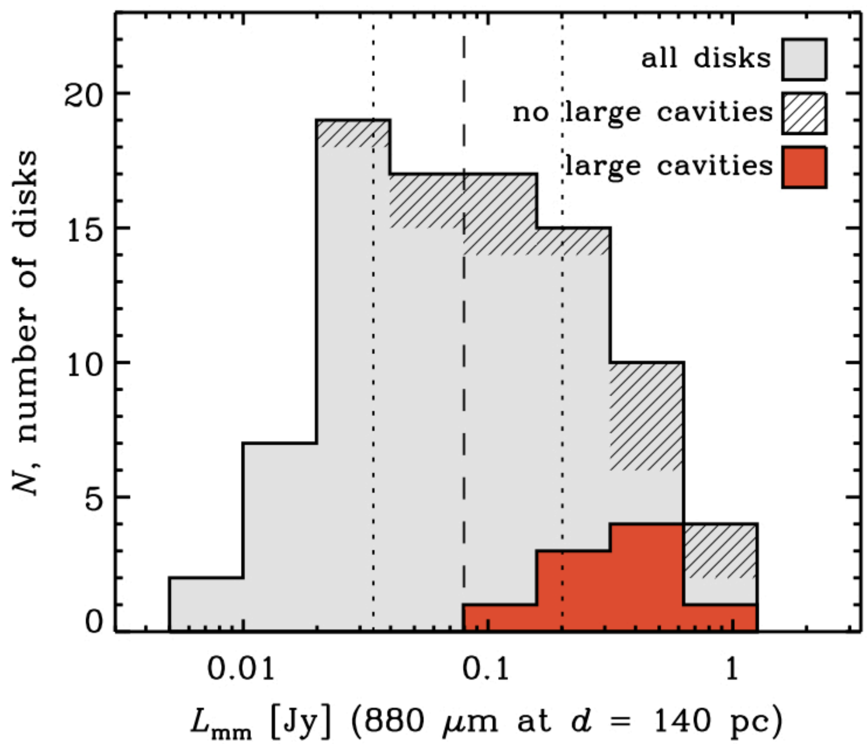
Where do we go from here?

- identifying more disks with cavities
- spatially resolving disk structure



Espaillat et al. 2014, PPVI

Identifying new, fainter (pre-)transitional disks



Andrews et al. 2011

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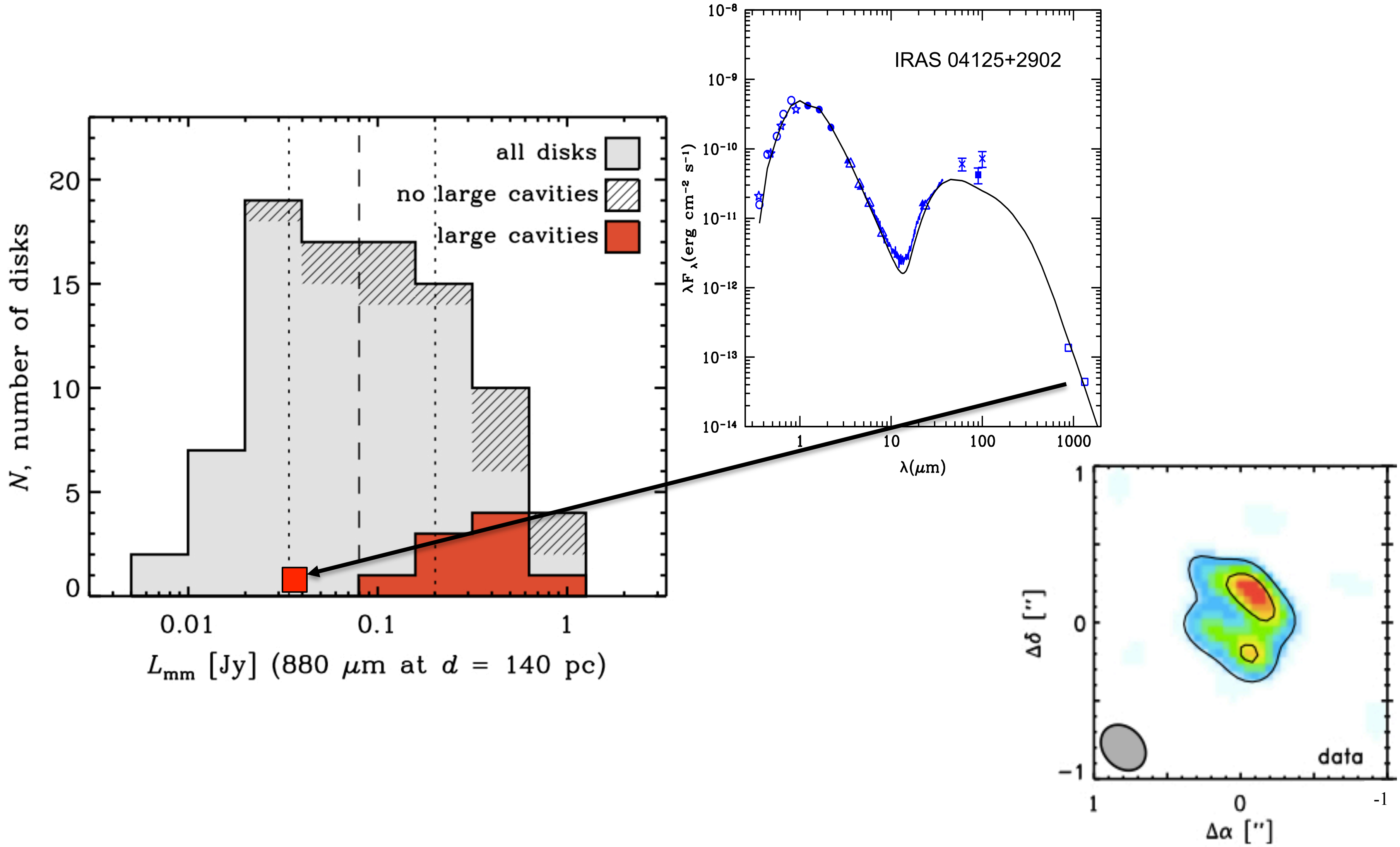
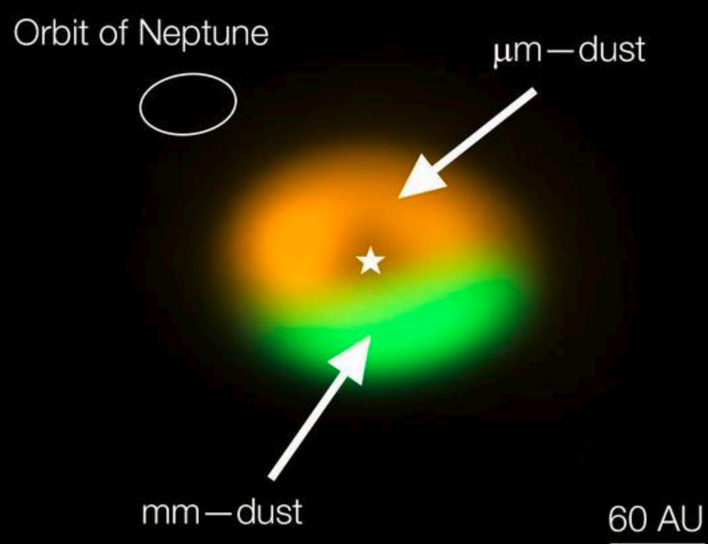


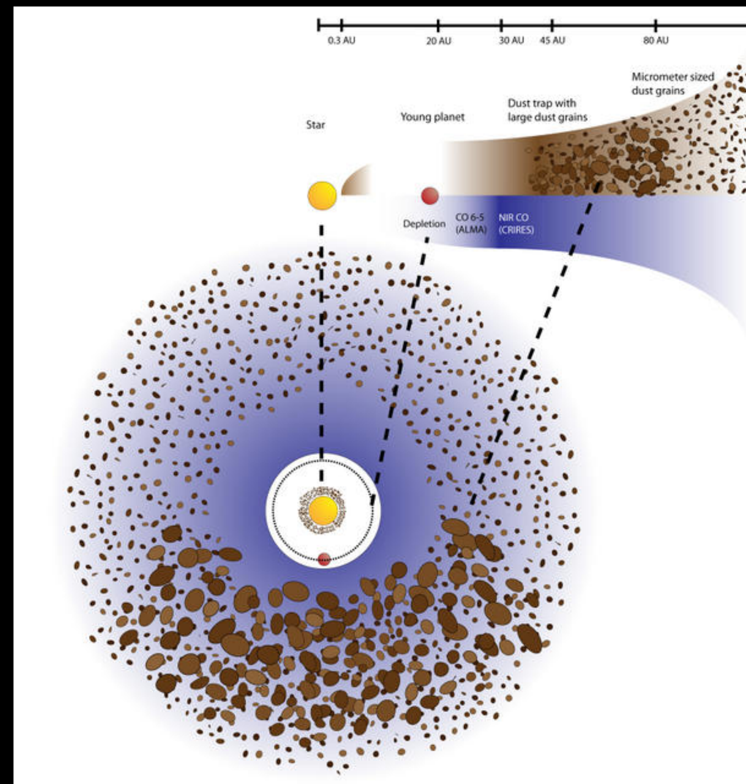
Andrews et al. 2011

Espaillat et al. 2015

ALMA has revealed dust asymmetries

IRS 48

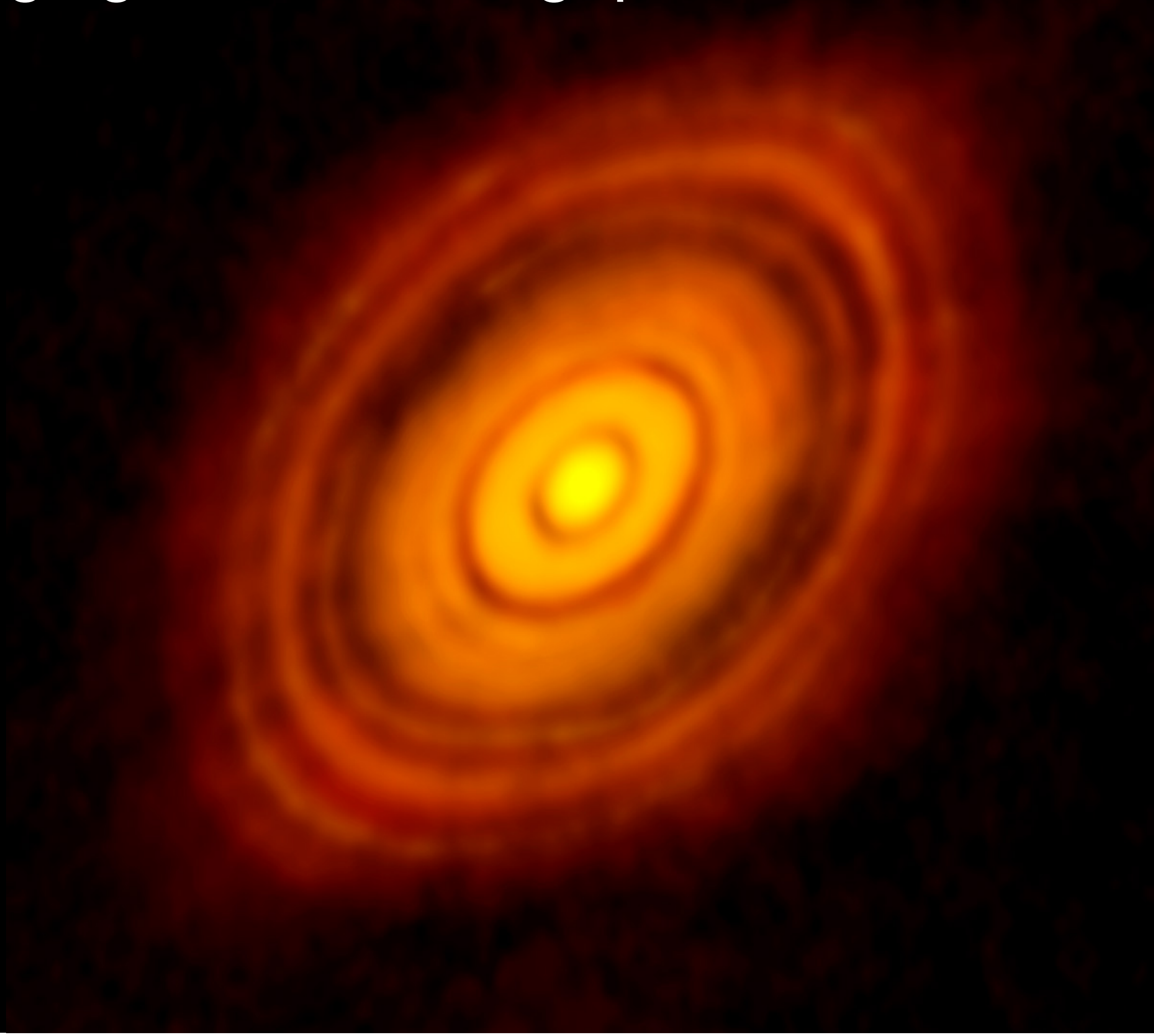




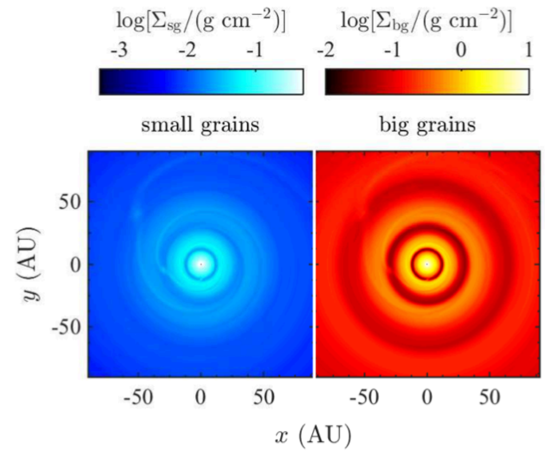
van der Marel et al. 2013

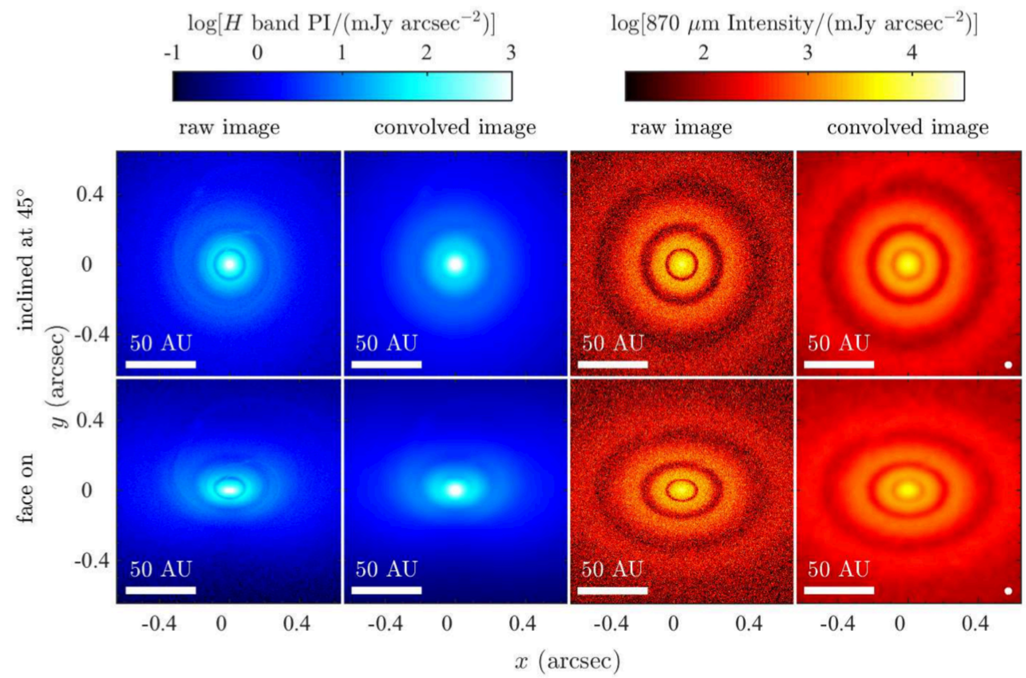
also Casassus et al. 2013; Fukagawa et al. 2013; Isella et al. 2013; Perez et al. 2014; Pineda et al. 2014

Imaging smaller disk gaps…



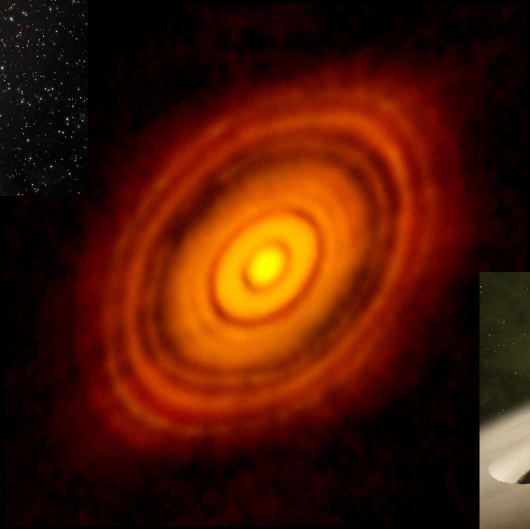
Planets can open small disk gaps

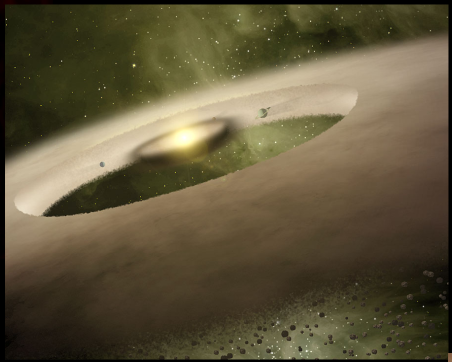


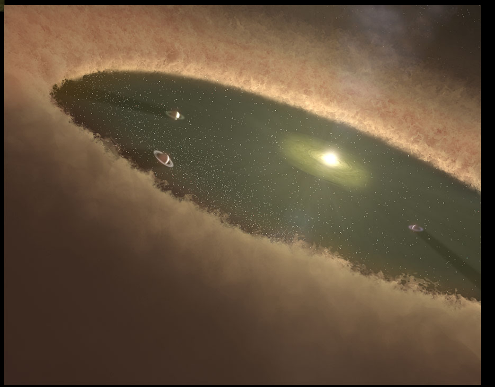


Dong, Zhu, & Whitney 2015; Meru et al. 2015

Linking disk evolution and planet formation







What do planet footprints look like?