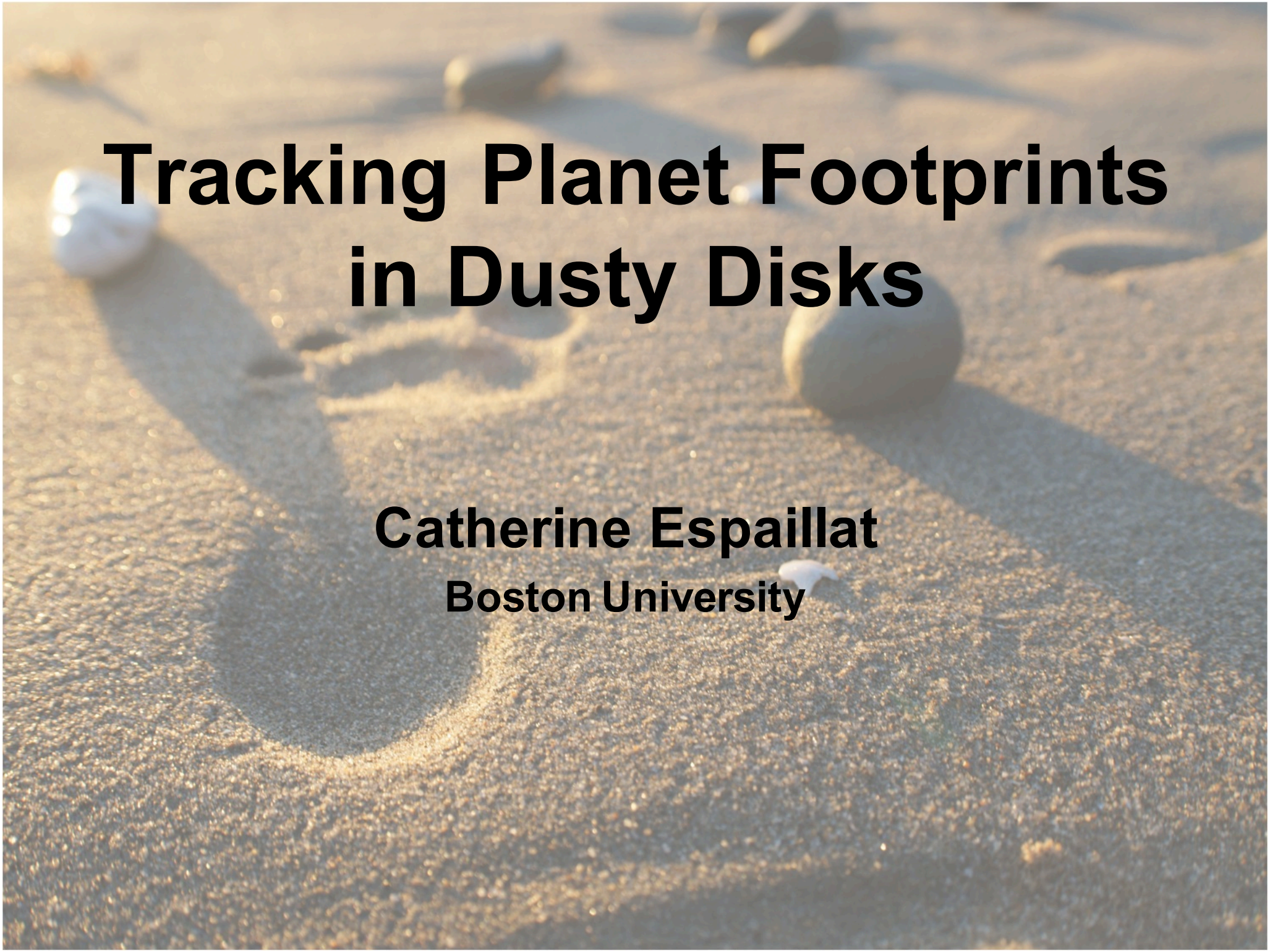
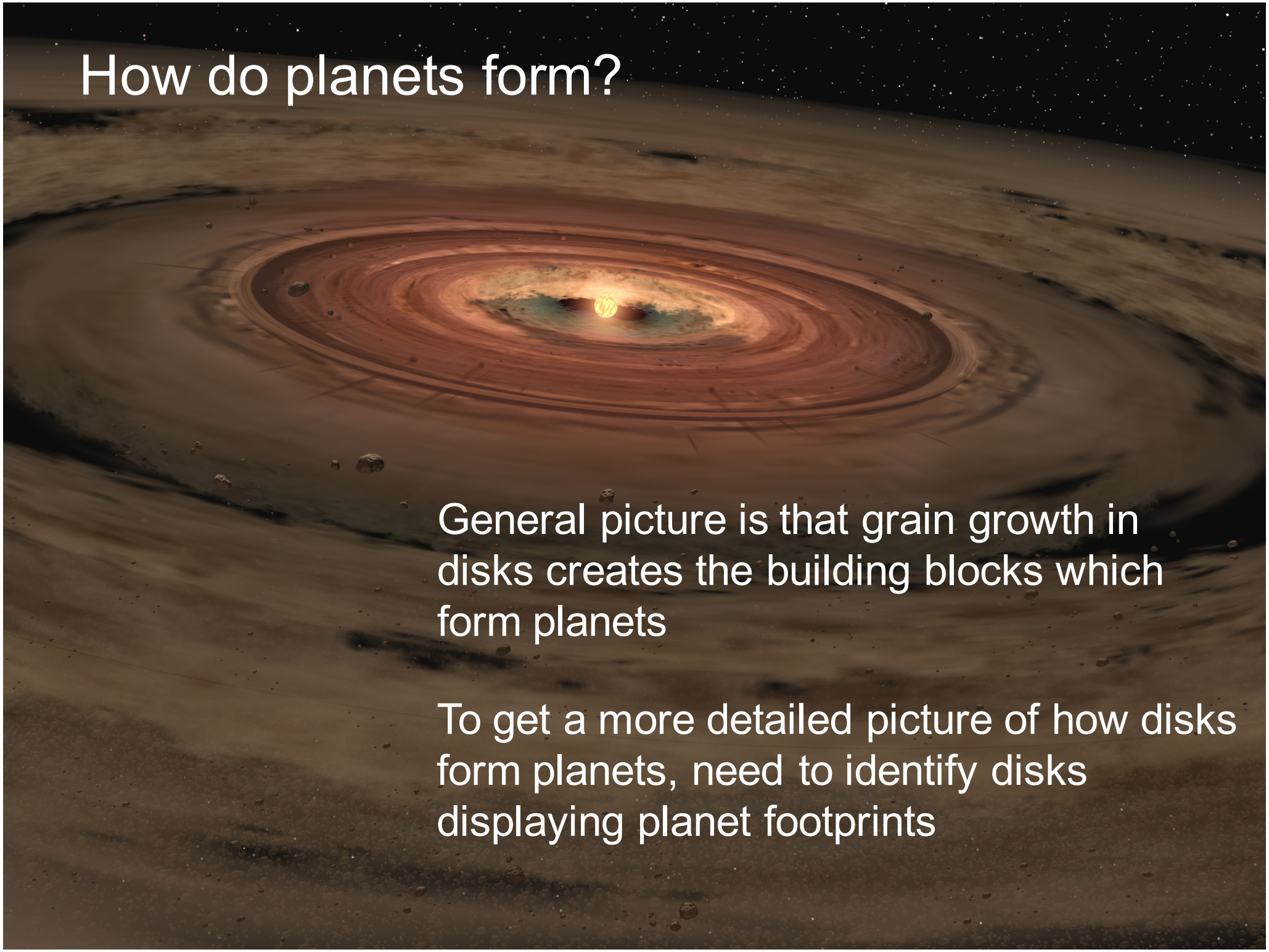


Tracking Planet Footprints in Dusty Disks

Catherine Espaillat

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

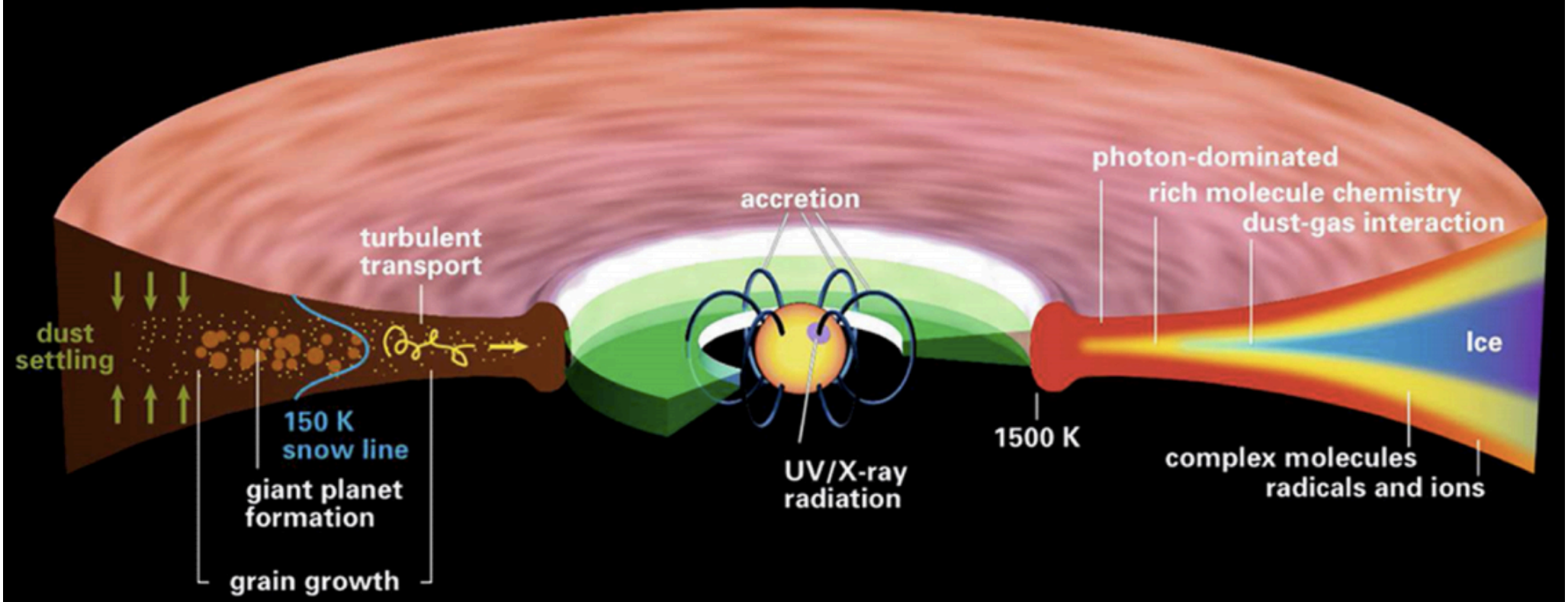
Tracking Planet Footprints

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

How do observations of disks with holes and gaps compare with theoretical simulations of disk clearing?

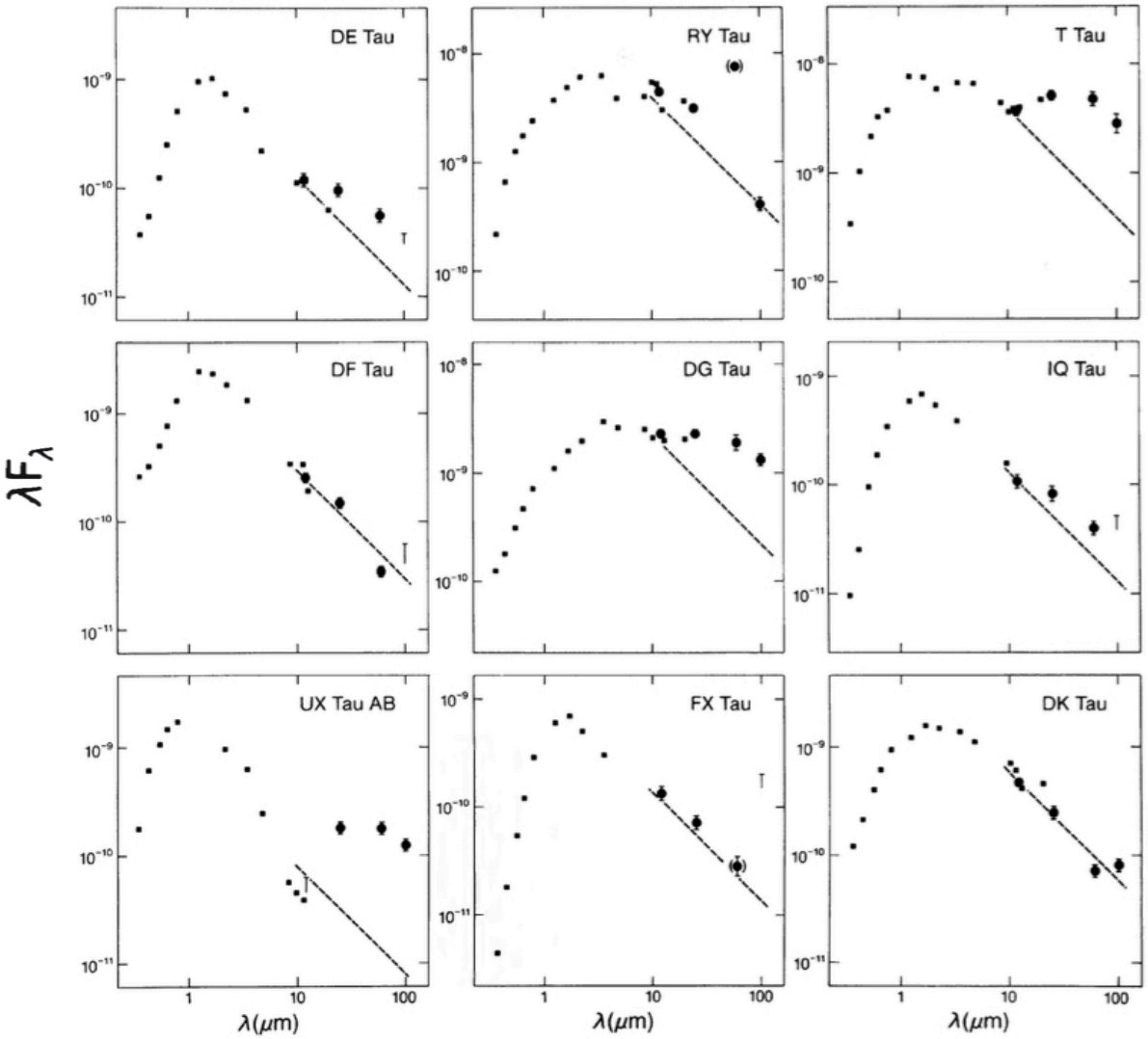
Where do we go from here?

Our current sketch of a protoplanetary disk



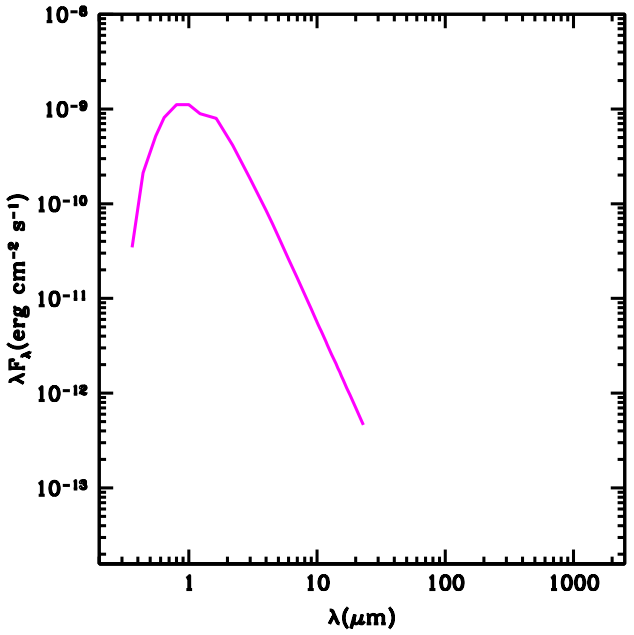
Henning & Semenov 2014

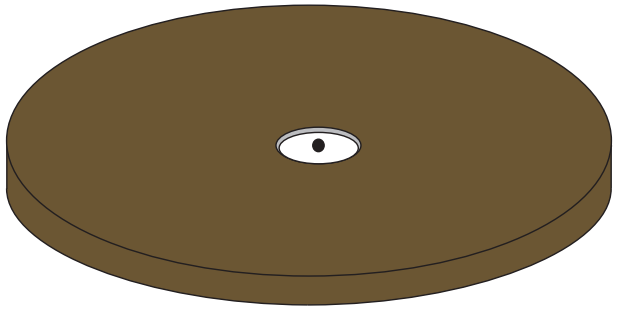
IR excess in SEDs is evidence for dusty disks



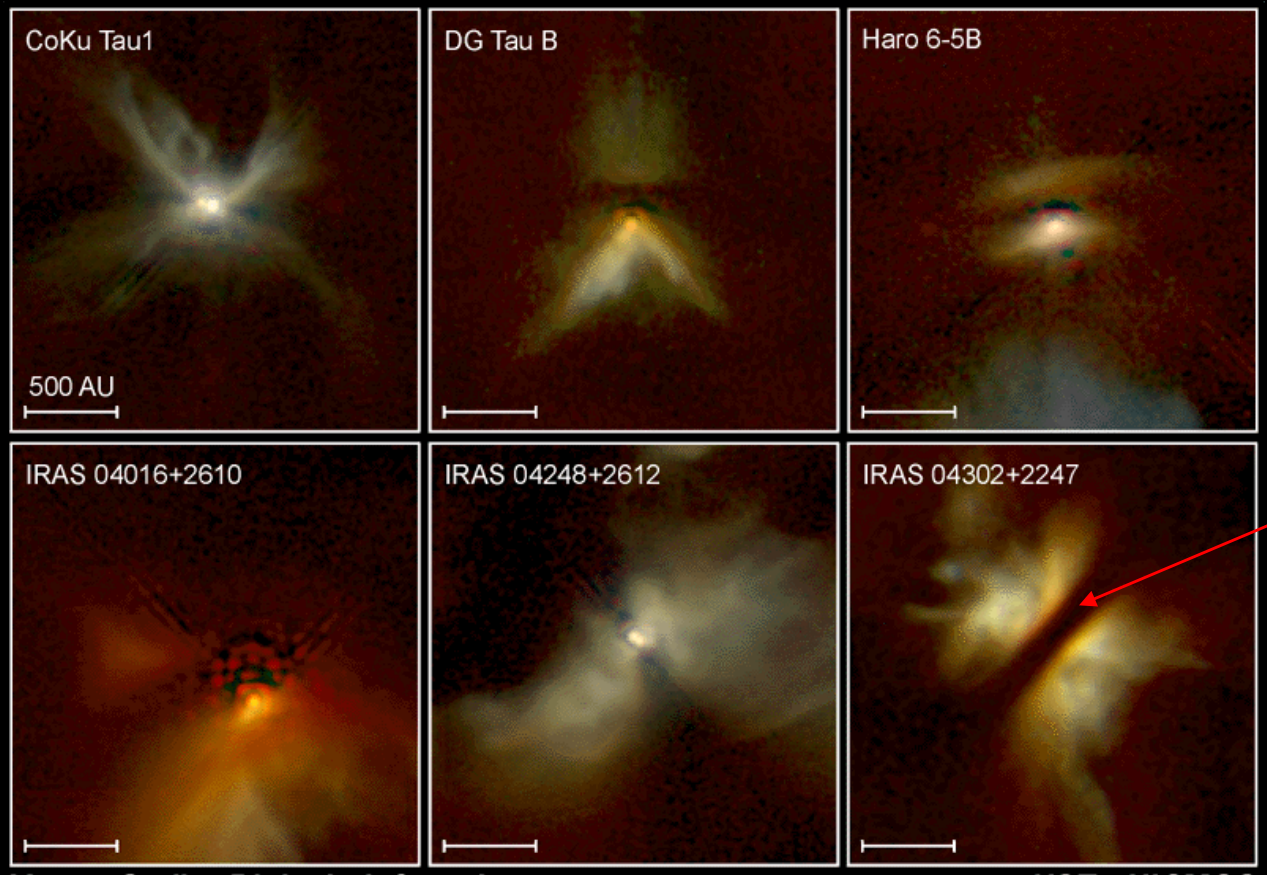
Rucinski et al. 1985

Spectral Energy Distribution of a Star

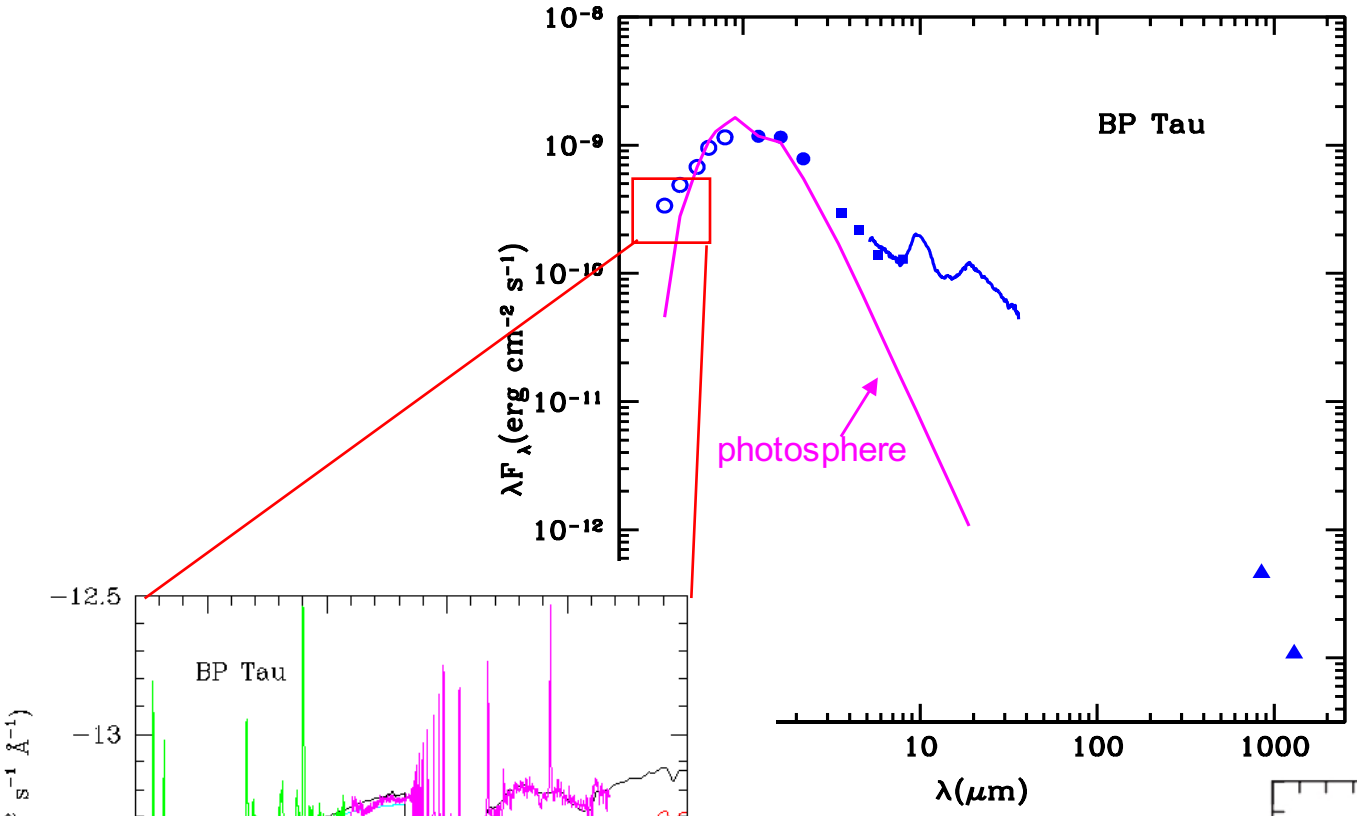


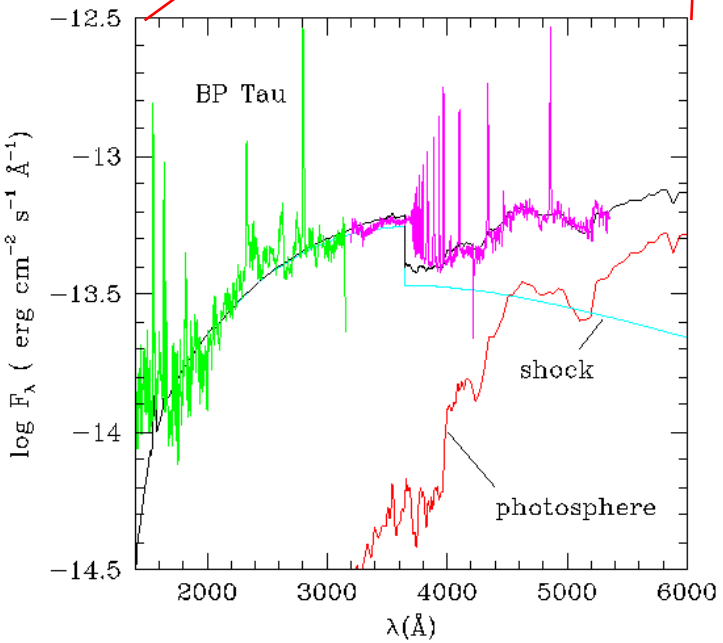


HST imaging confirms dusty disks exist around young stars

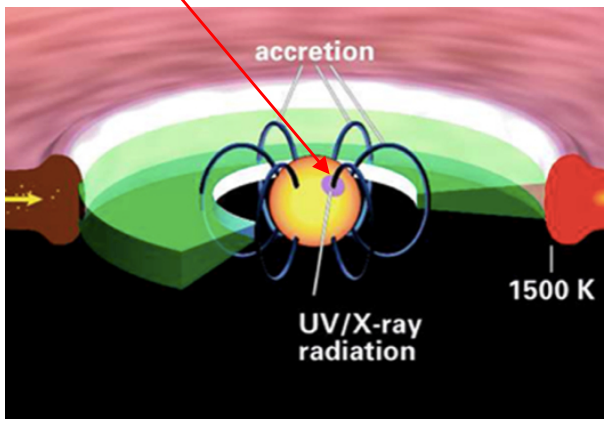


Evidence for gas accretion onto young stars

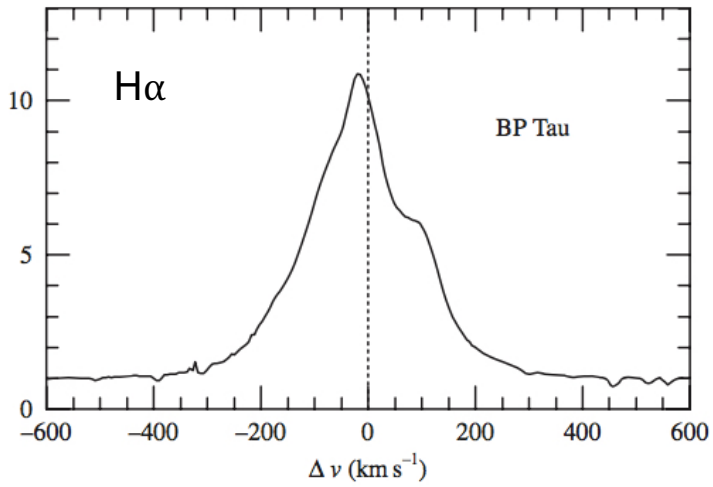




UV excess originates from accretion shock on stellar surface



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

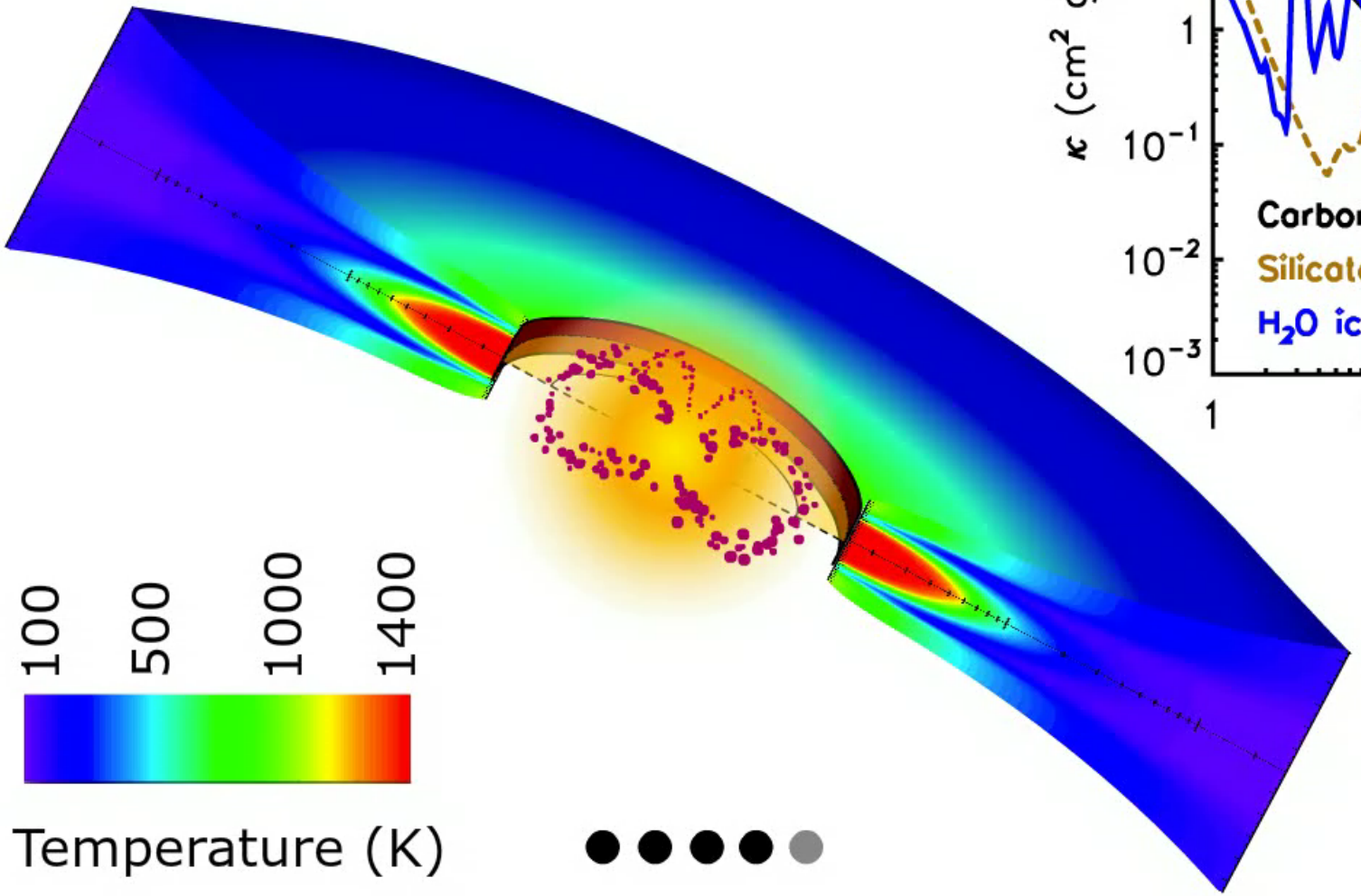


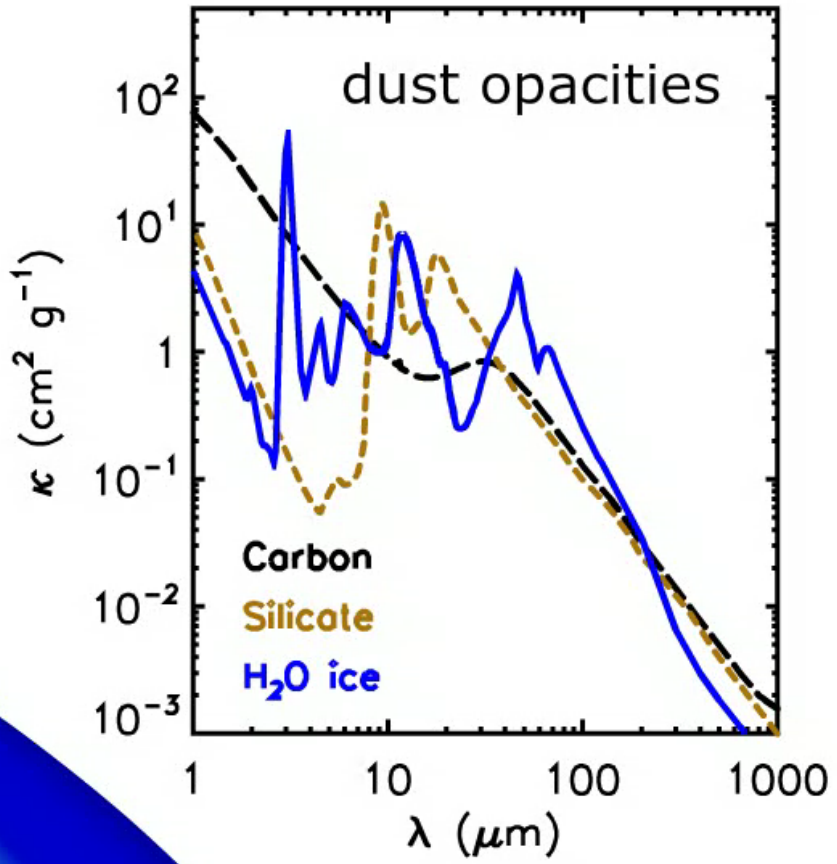
Calvet & Gullbring 1998

Simulating SEDs to probe disk structure

Dust properties

$n(a) \propto a^{P}$, $0.005 \leq a \leq a_{max}$





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

animation from M. McClure

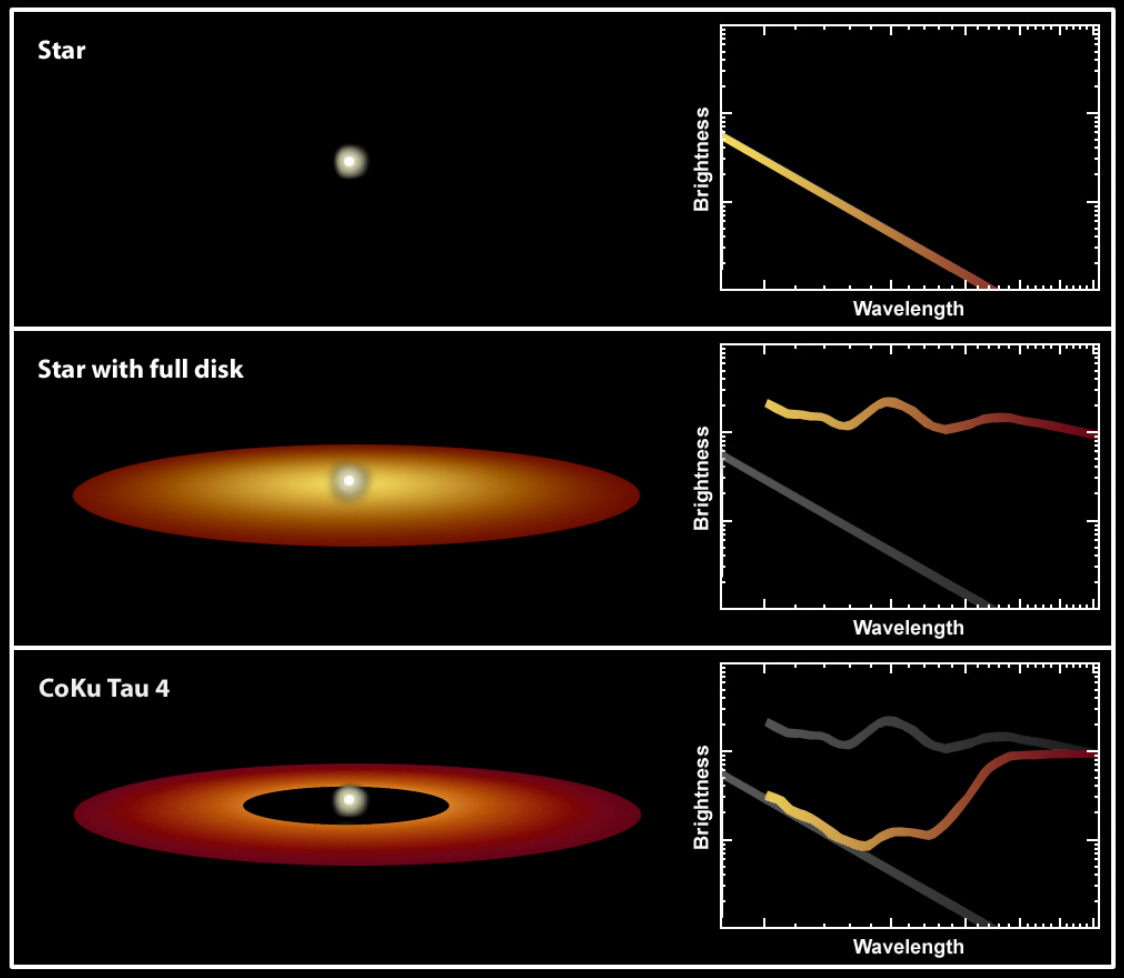
Tracking Planet Footprints

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

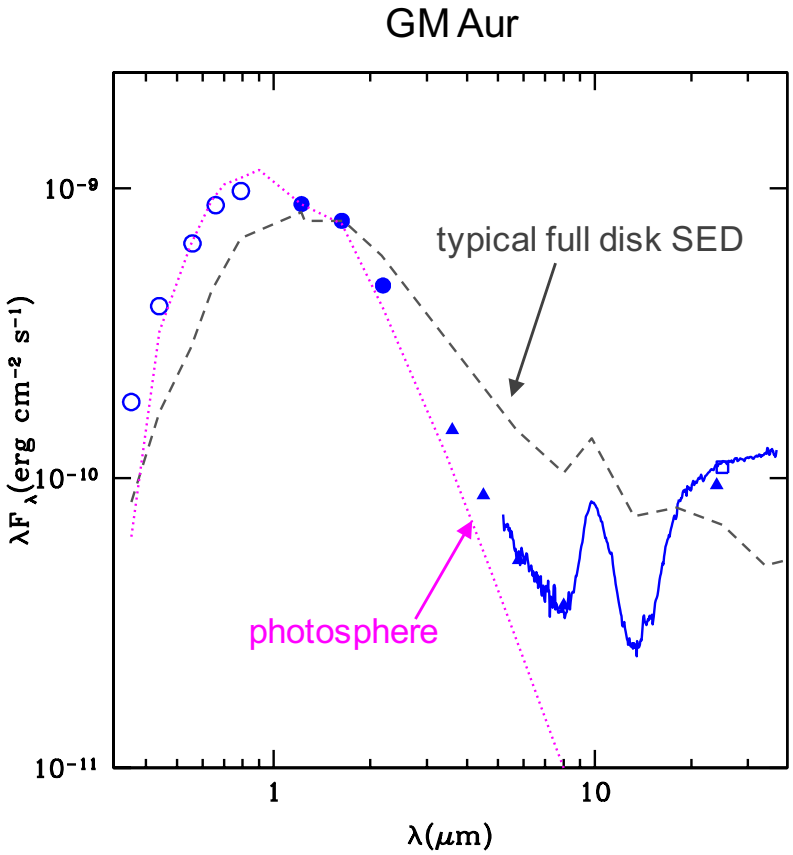
How do observations of disks with holes and gaps compare with theoretical simulations of disk clearing?

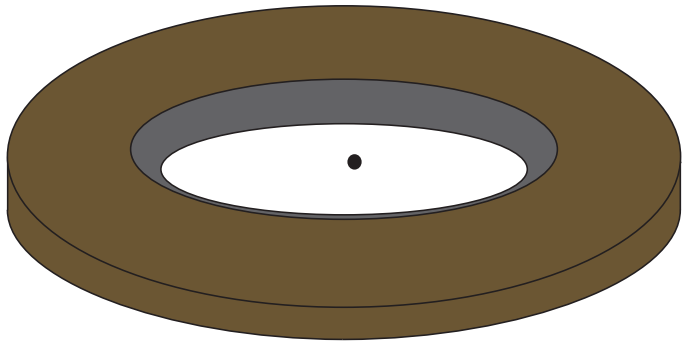
Where do we go from here?

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



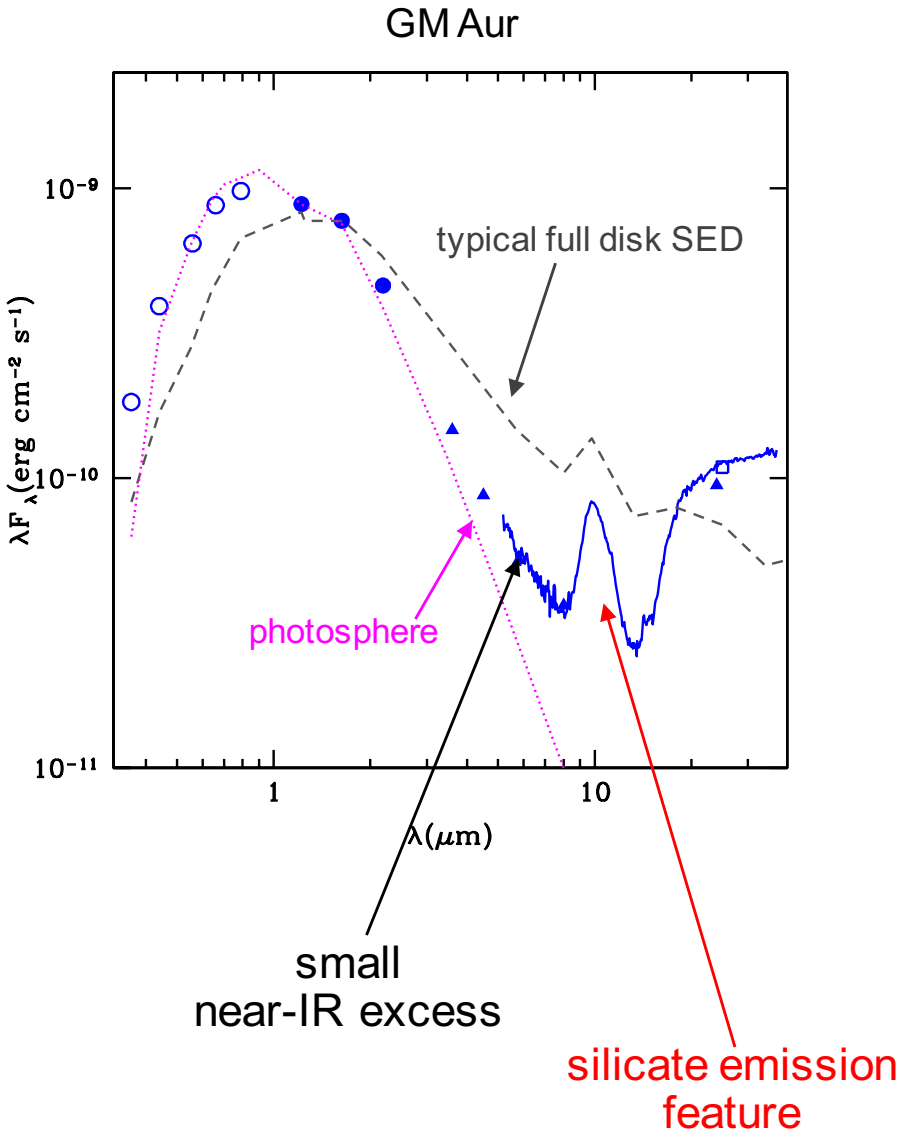
Some inner holes contain small, hot dust

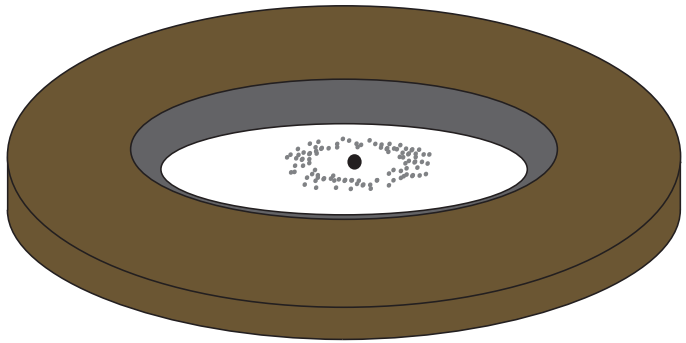




Espaillat et al. 2008, 2011

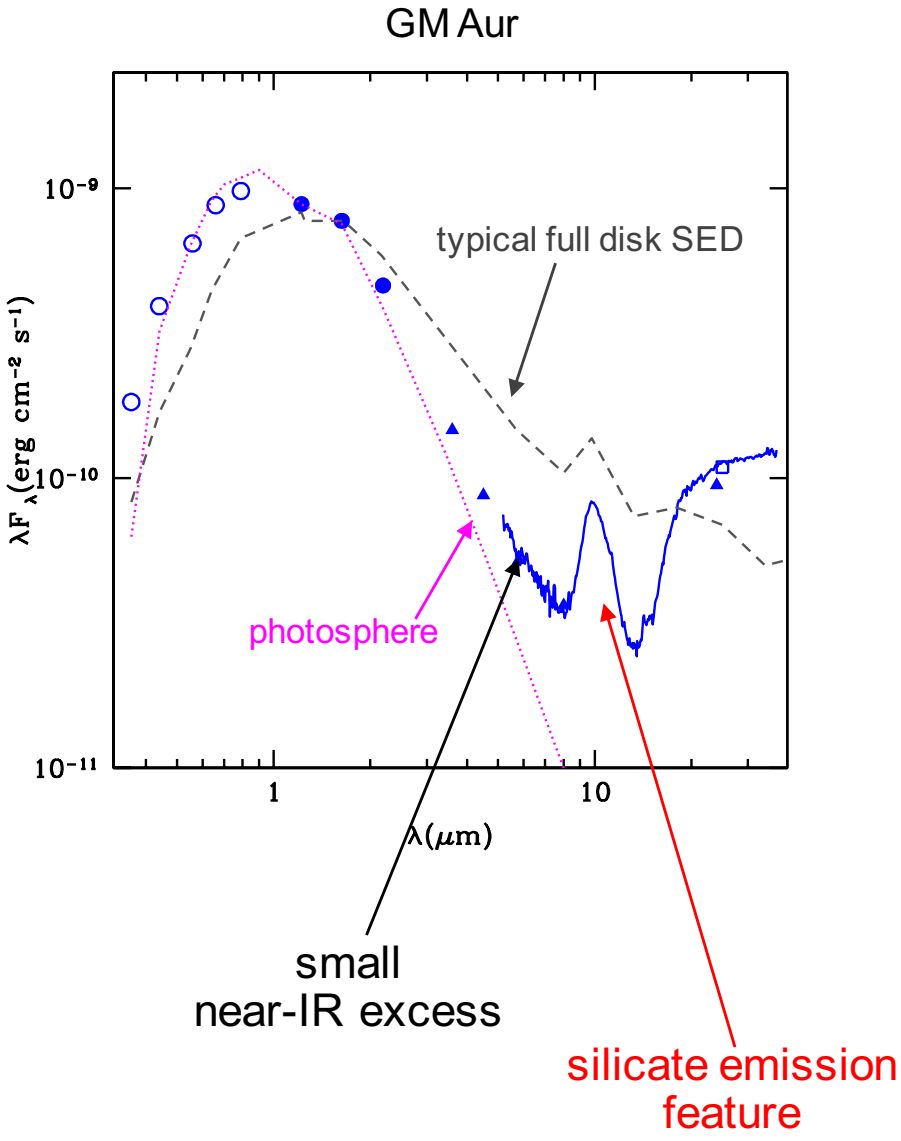
Some inner holes contain small, hot dust

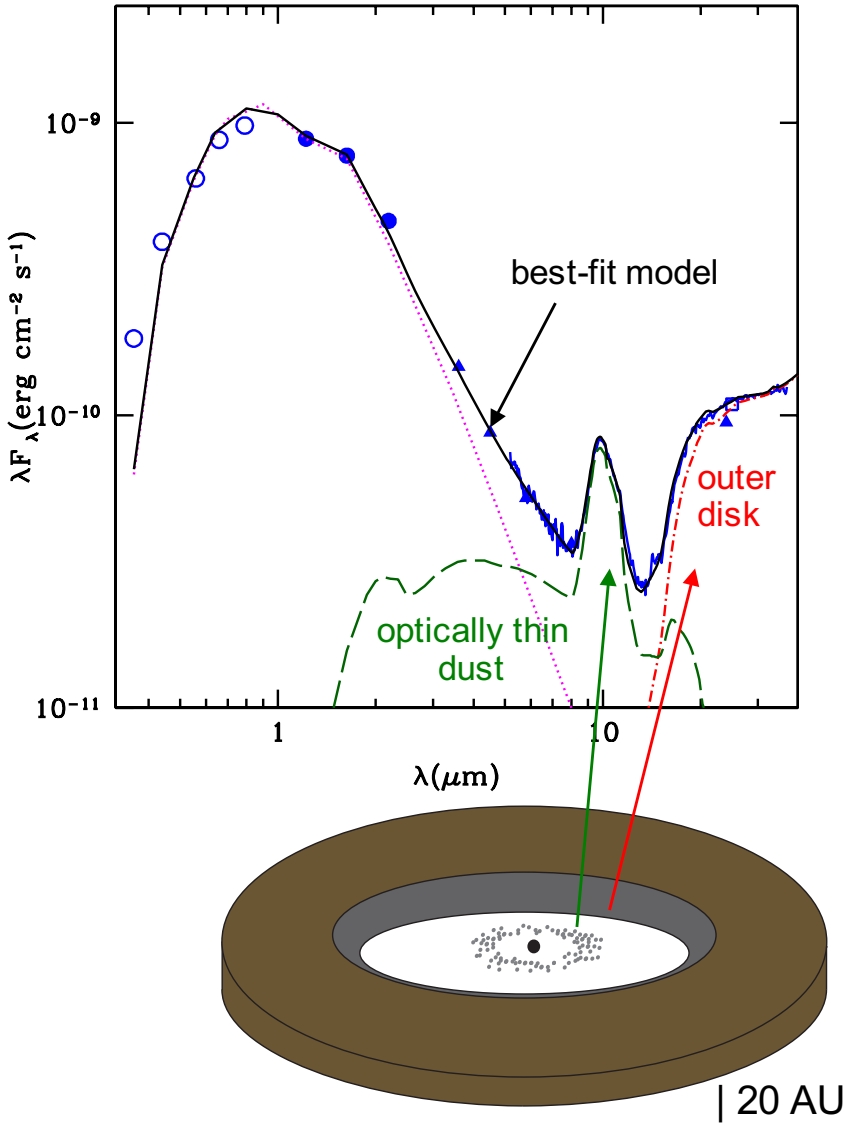




Espaillat et al. 2008, 2011

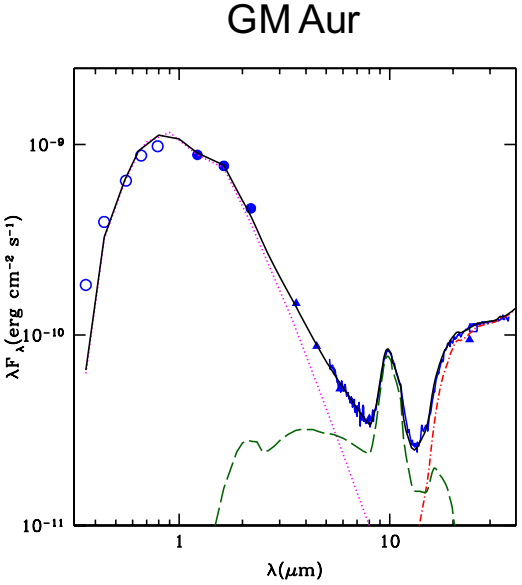
Some inner holes contain small, hot dust

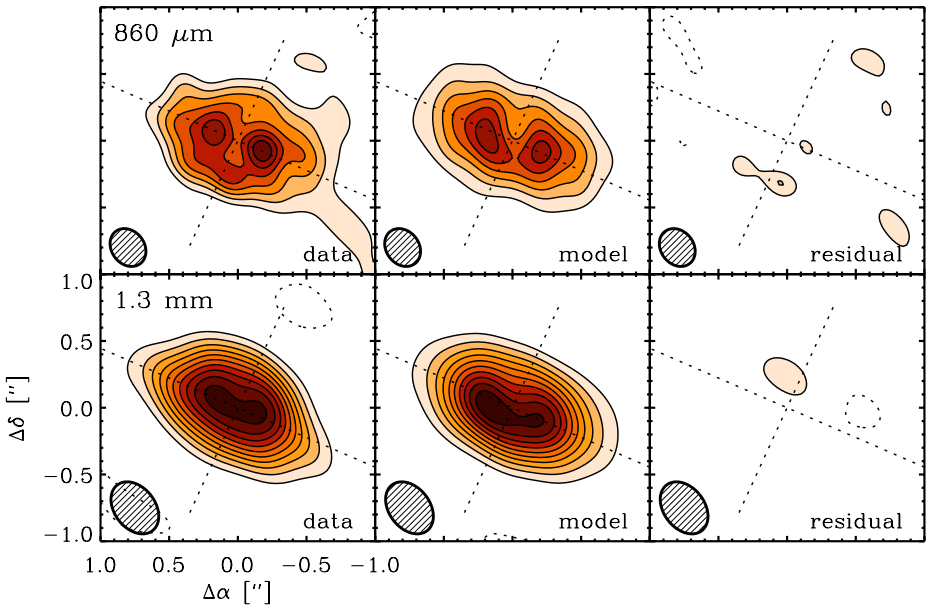


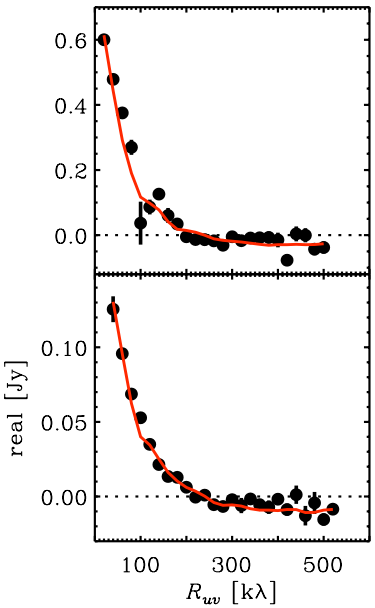


Espaillat et al. 2008, 2011

Combining submm imaging and SED modeling to confirm disk cavity of GM Aur



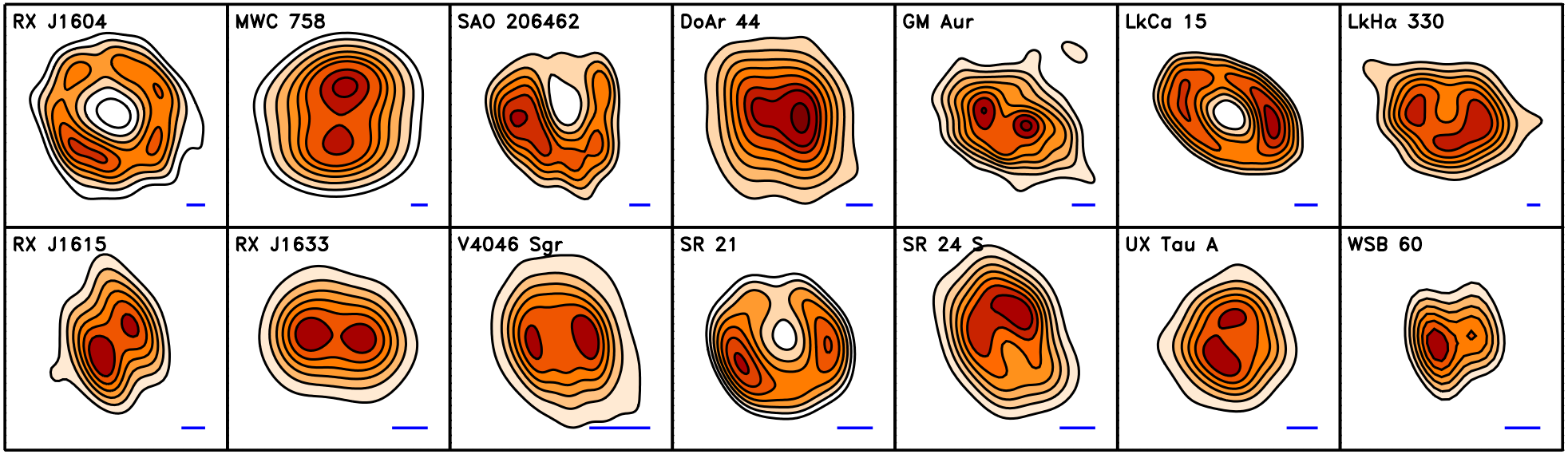




best-fit model to observed SED → simulated images & simulated visibilities

Hughes et al. 2009

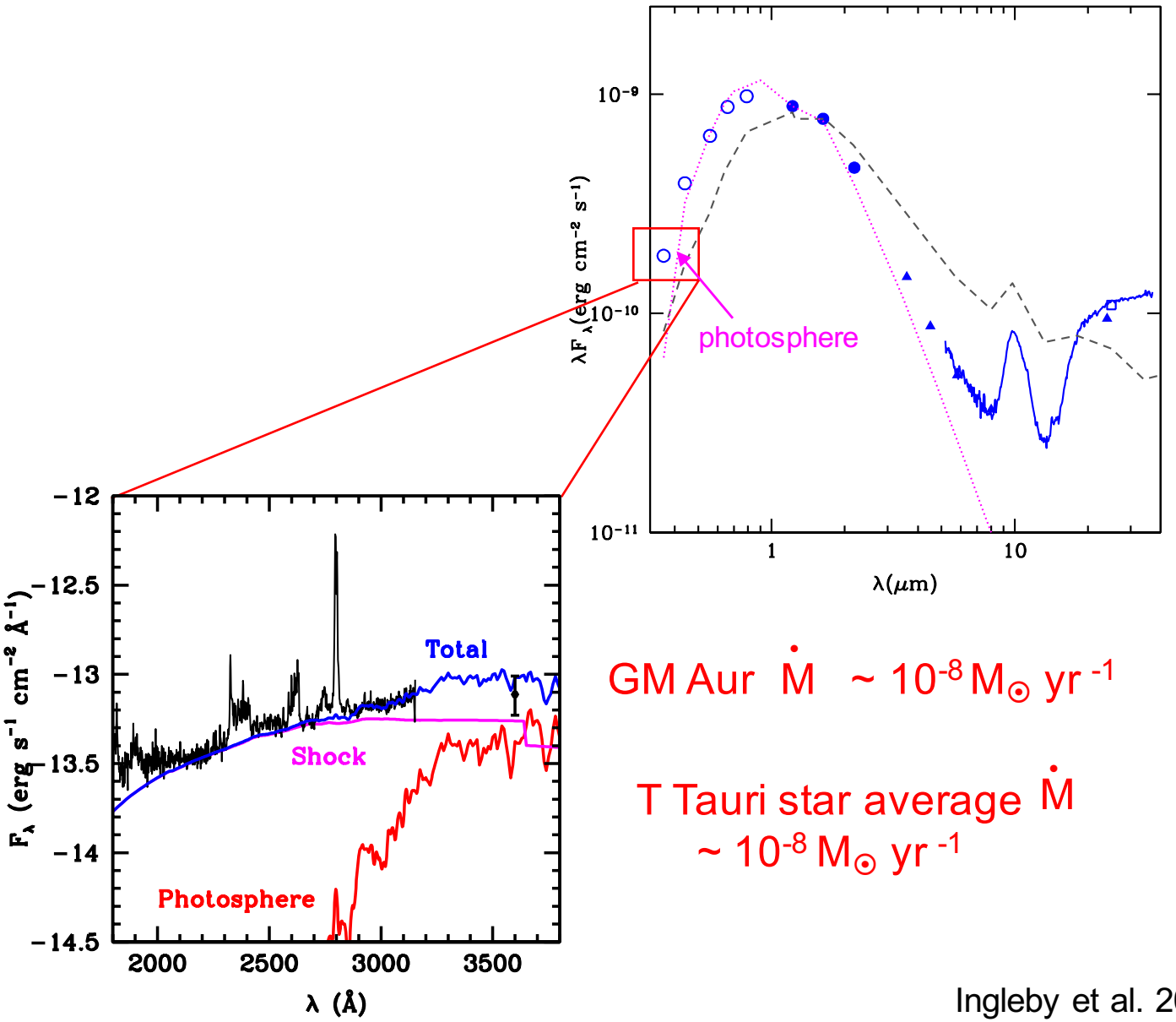
Several disk cavities now confirmed via submm interferometric imaging



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

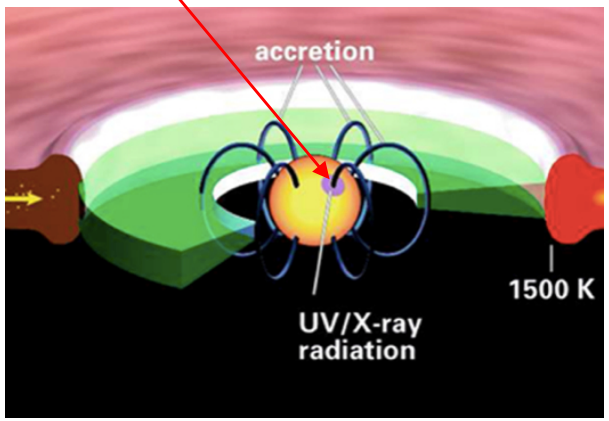
Gas can continue to accrete across cavity in dust disk



GM Aur $\dot{M}$ ~ 10^{-8} $M_\odot$ yr^{-1}

T Tauri star average $\dot{M}$
~ 10^{-8} $M_\odot$ yr^{-1}

UV excess originates from accretion shock on stellar surface

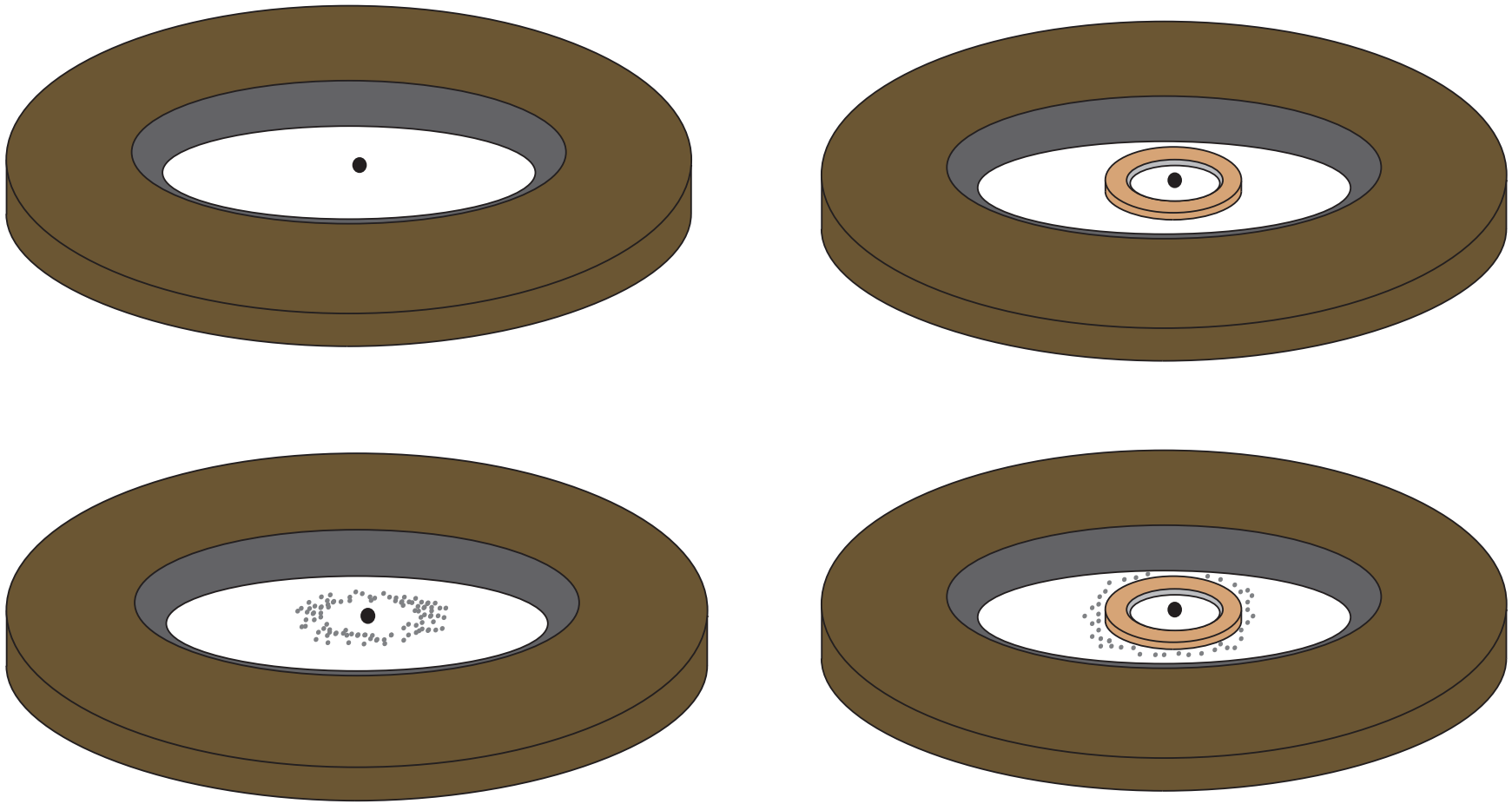


Ingleby et al. 2013, Espaillat et al. in preparation

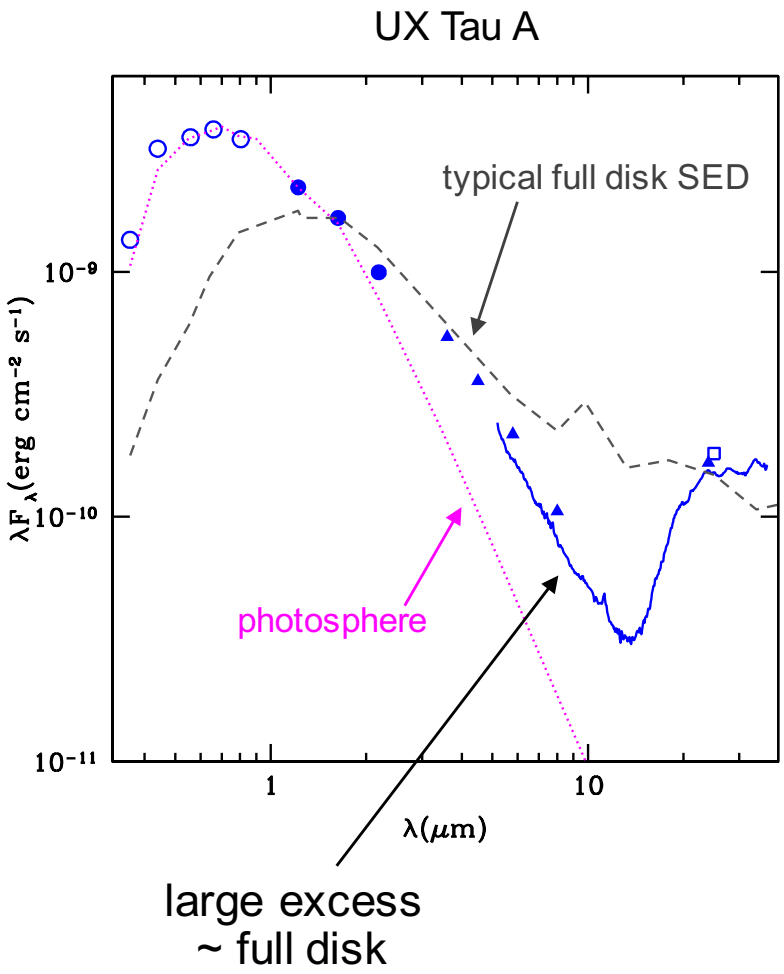
In addition to inner holes, large annular gaps have been detected

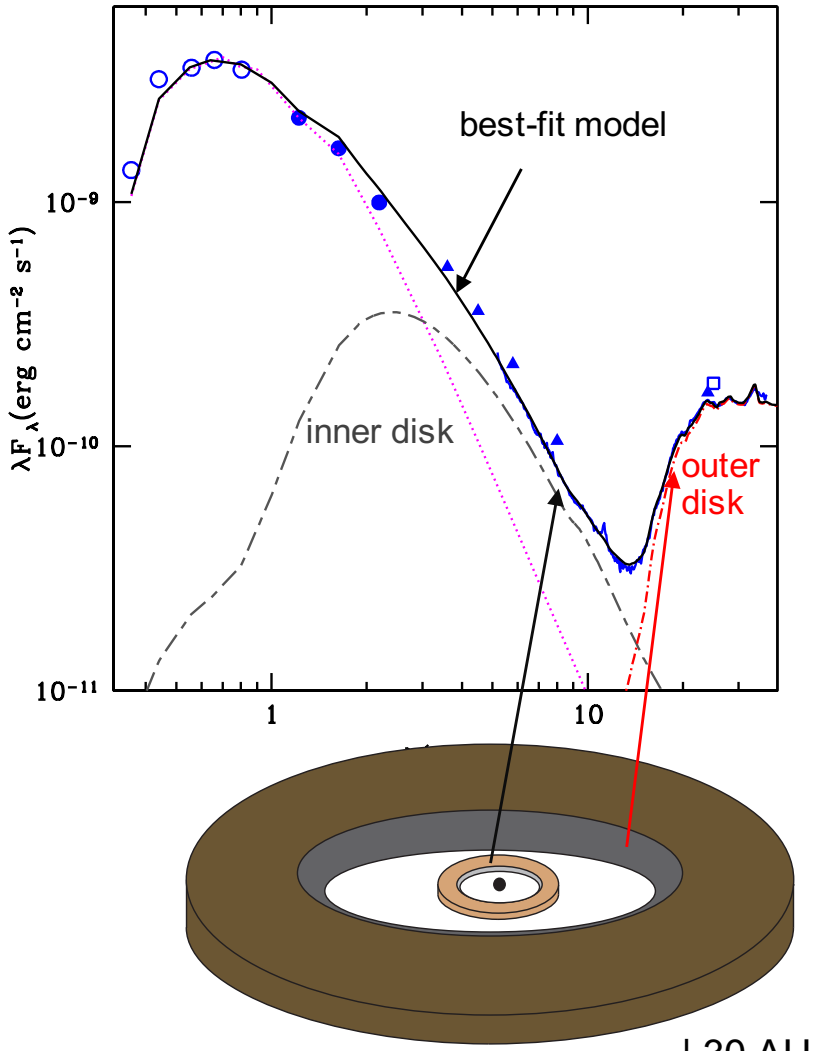
Transitional Disks

Pre-transitional Disks



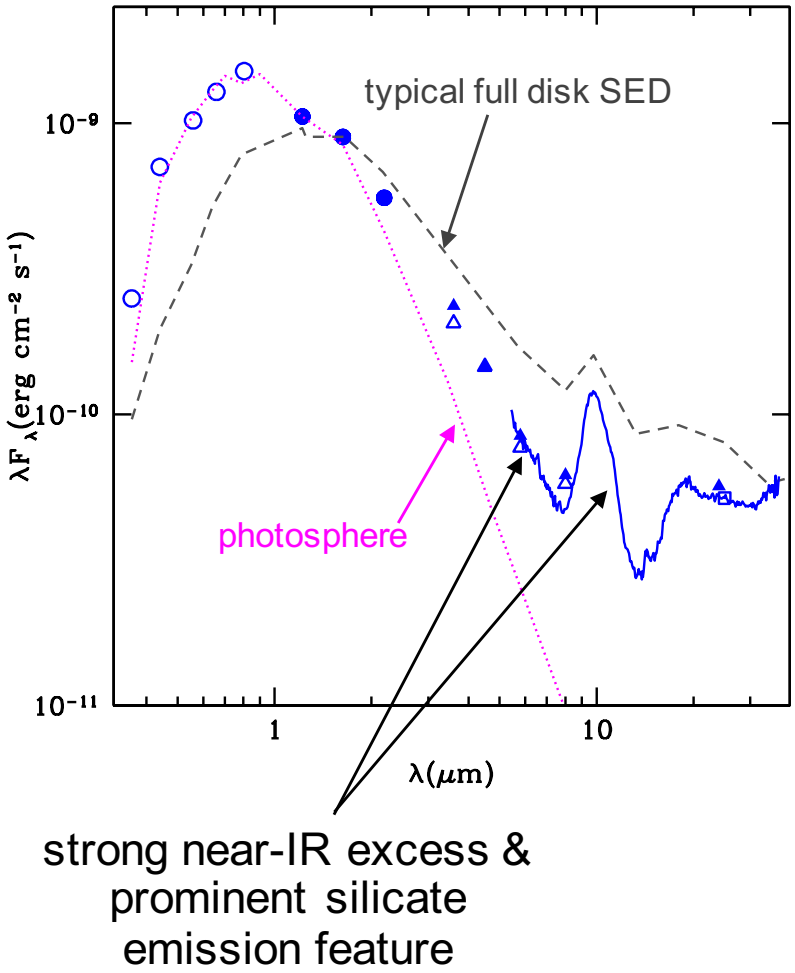
Pre-transitional disks: objects with large, annular gaps



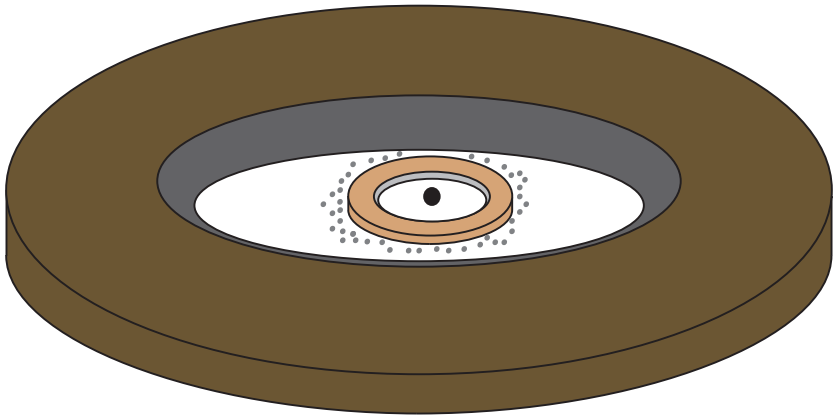


Espaillat et al. 2007b

LkCa 15's gap is filled with optically thin dust

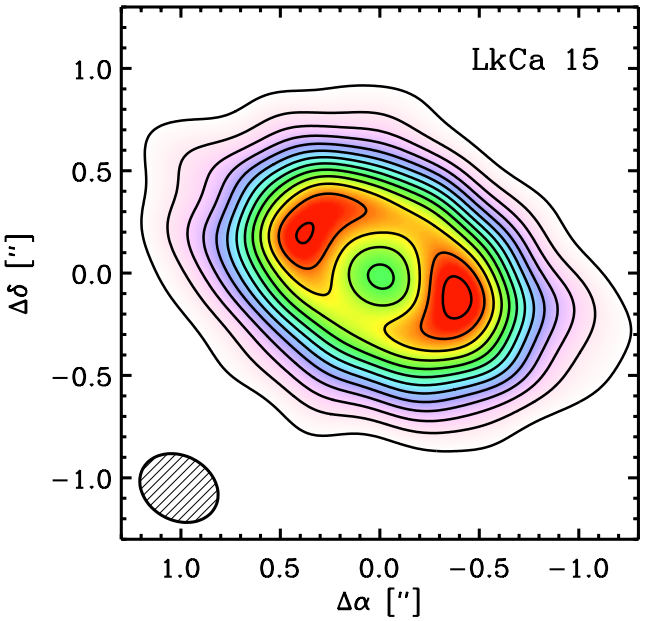


strong near-IR excess & prominent silicate emission feature



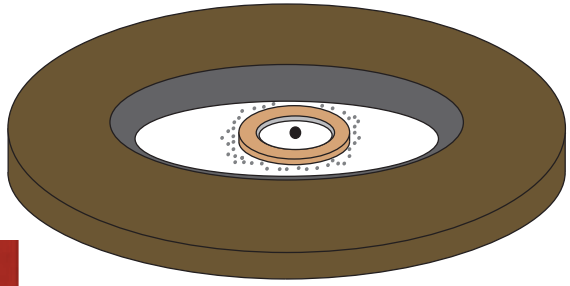
Espaillat et al. 2011

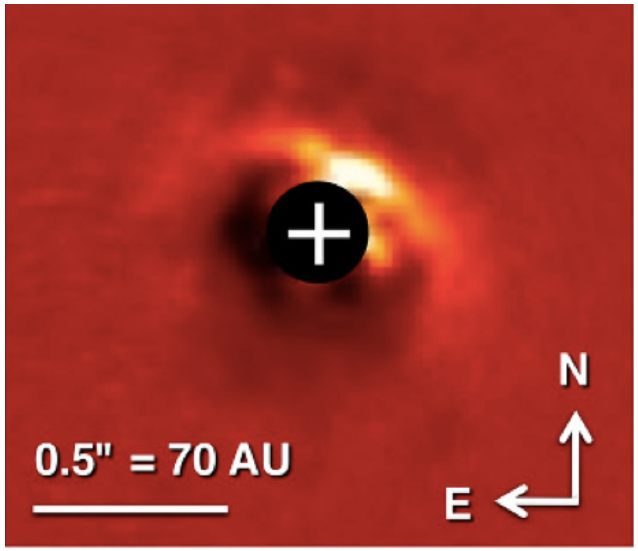
Resolving structure in LkCa15's disk



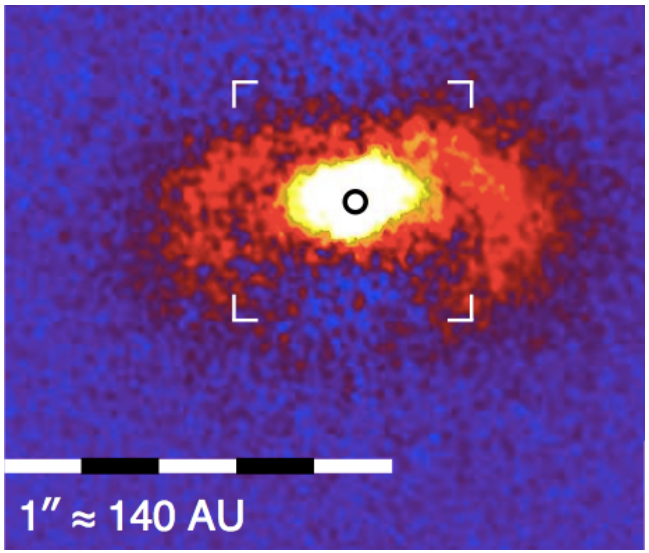
Andrews et al. 2011

(also Pietu et al. 2006)



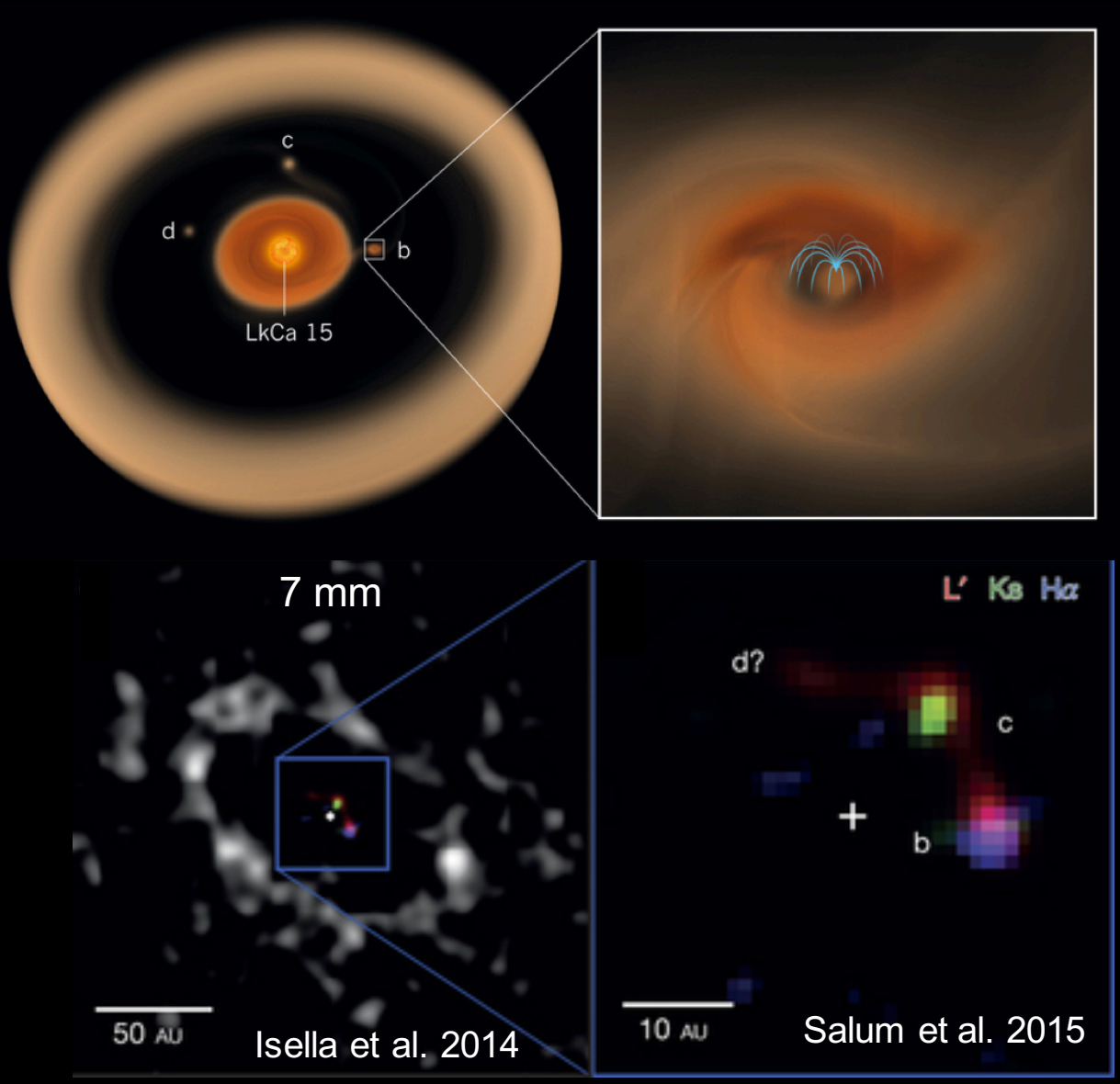


Thalmann et al. 2014

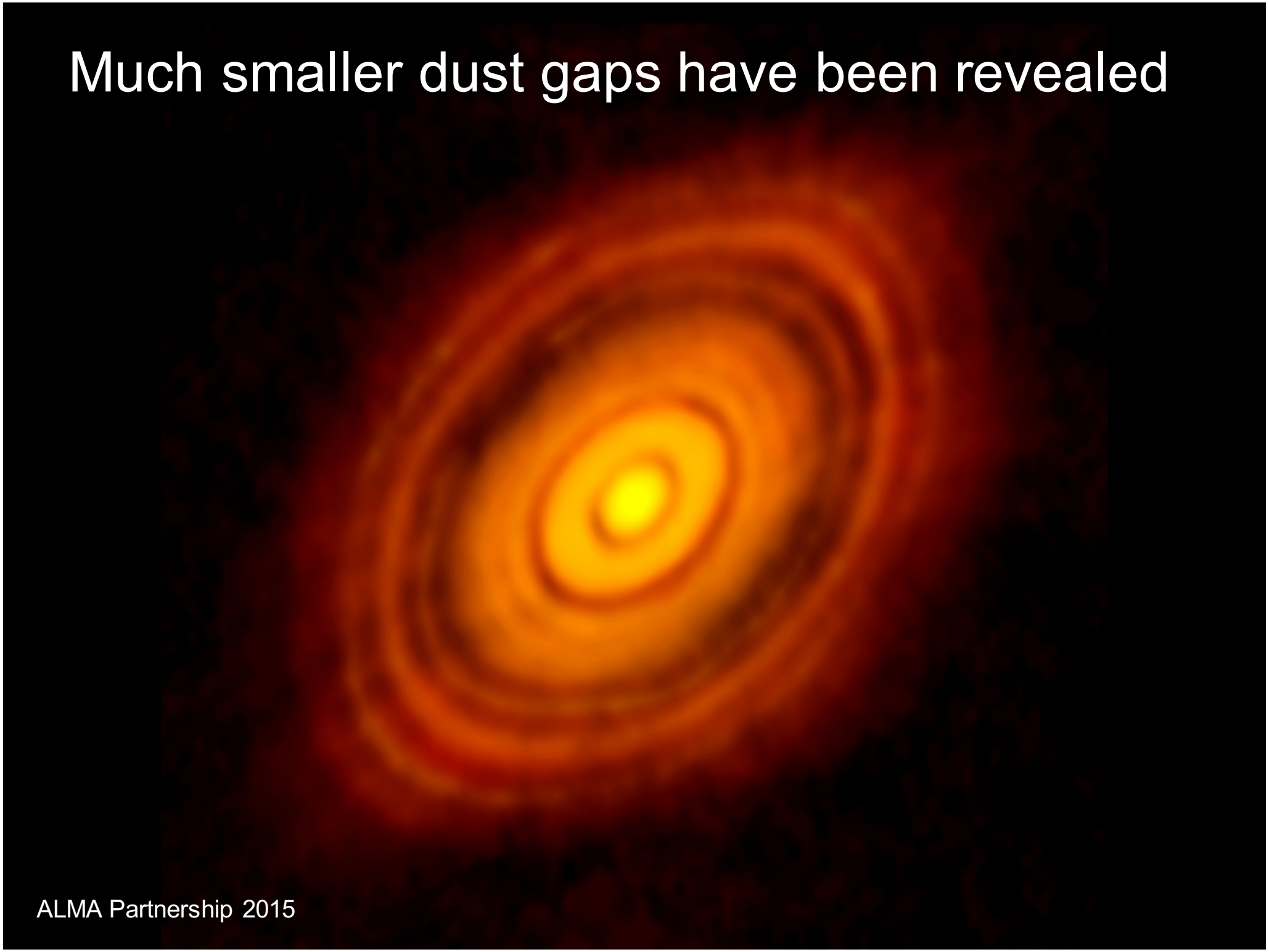


Thalmann et al. 2015

At least one protoplanet around LkCa 15

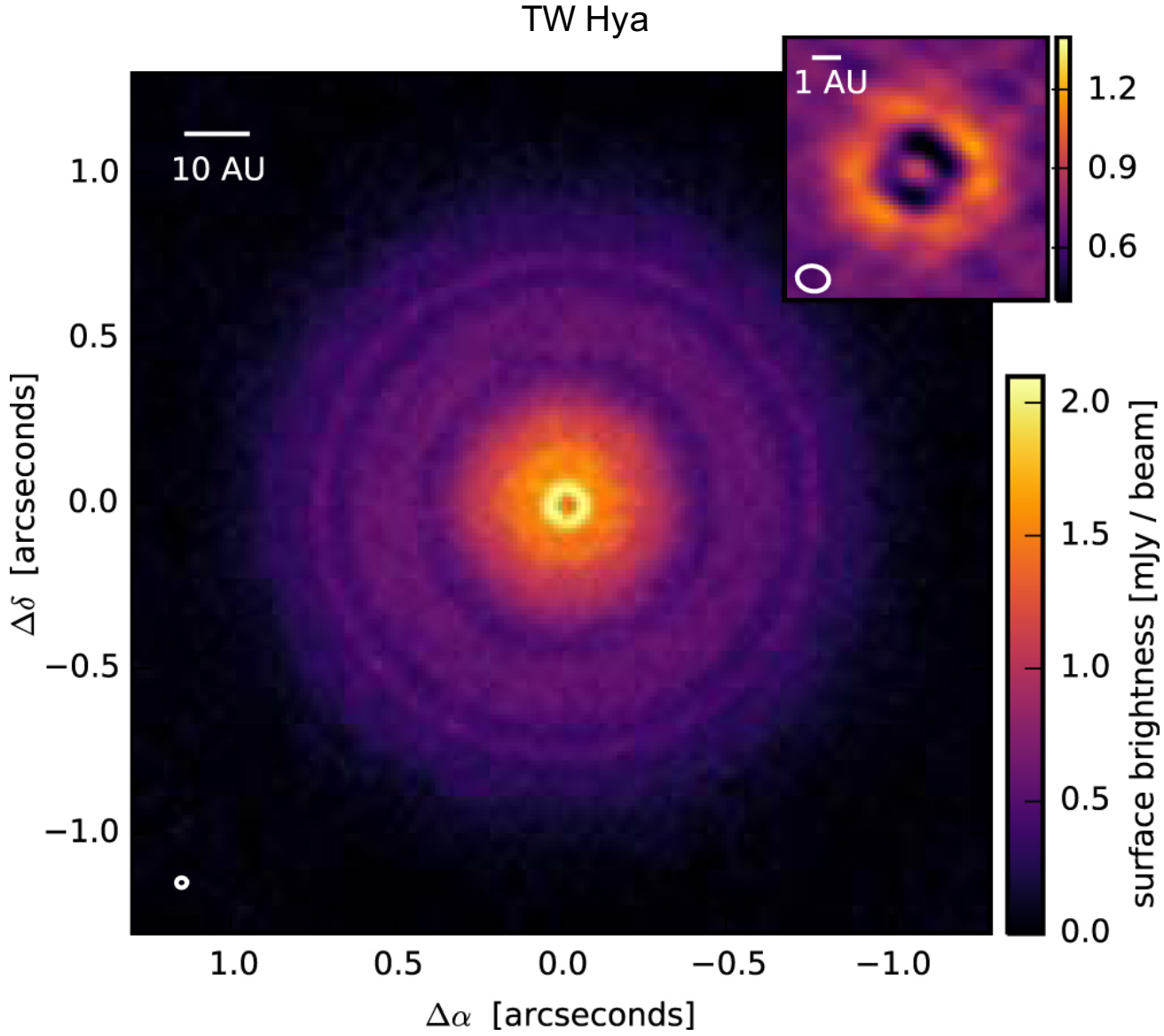


Much smaller dust gaps have been revealed



ALMA Partnership 2015

Small dust gaps also seen in at least one other protoplanetary disk



Andrews et al. 2016

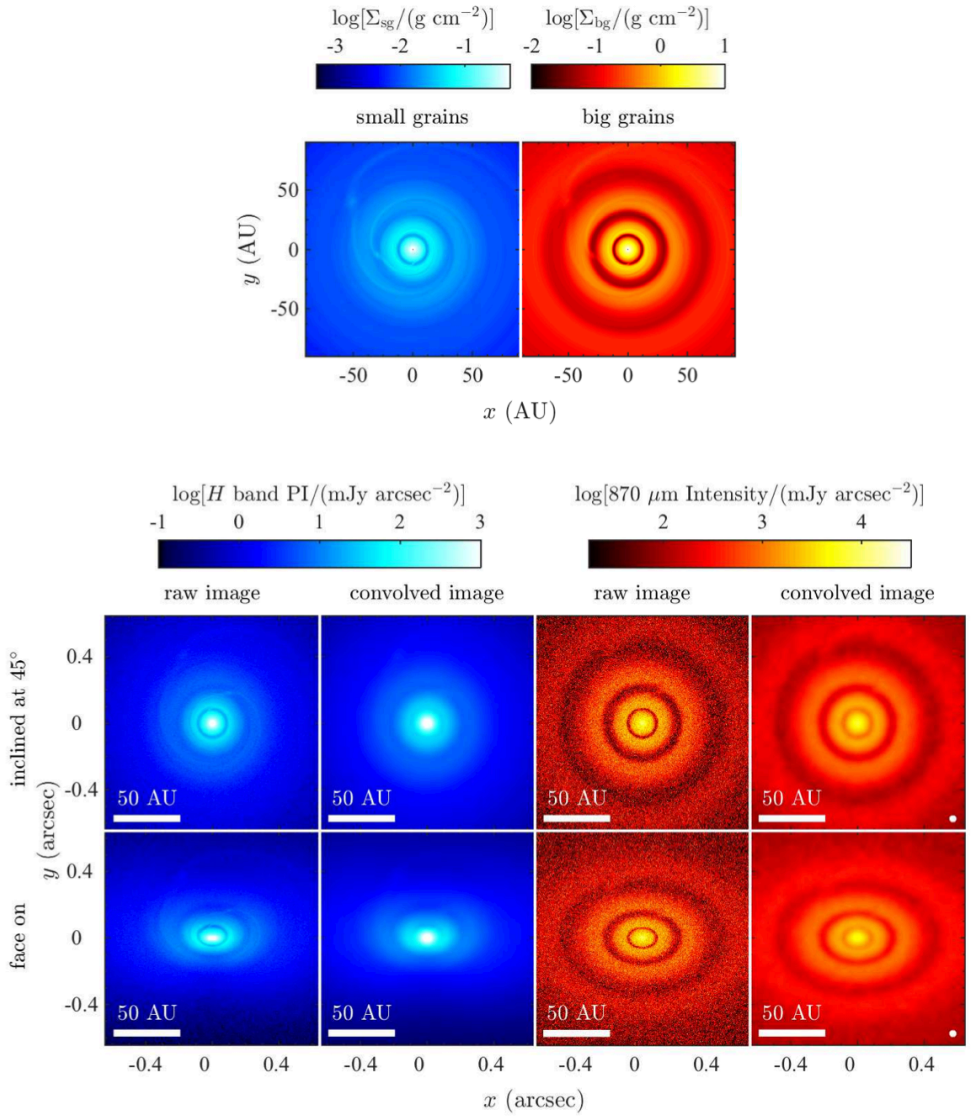
Tracking Planet Footprints

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

How do observations of disks with holes and gaps compare with theoretical simulations of disk clearing?

Where do we go from here?

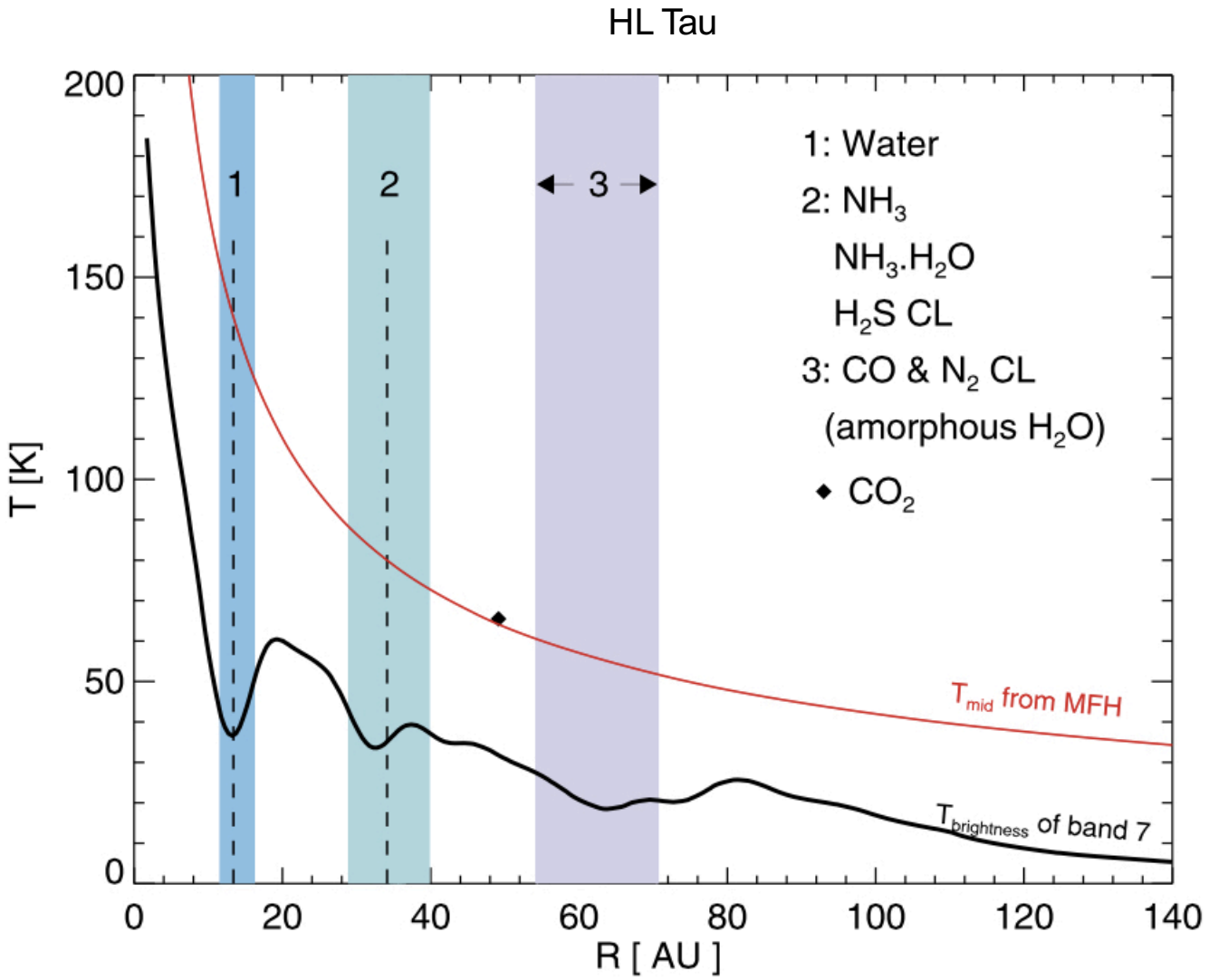
Multiple planets can form multiple small gaps



Dong, Zhu, & Whitney 2015

also Meru et al. 2015, Tamayo et al. 2015, Dipierro et al. 2015, Gonzalez et al. 2015

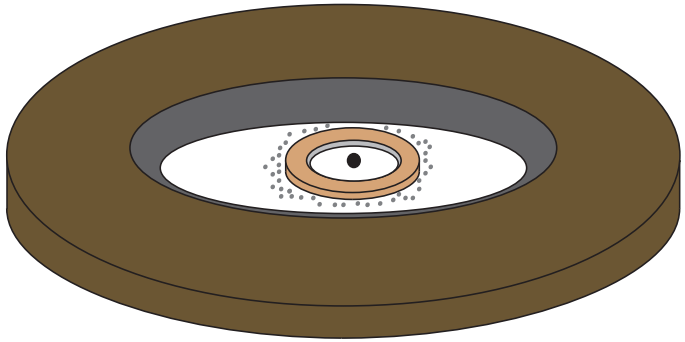
Condensation fronts can lead to dust gaps



Zhang et al. 2015

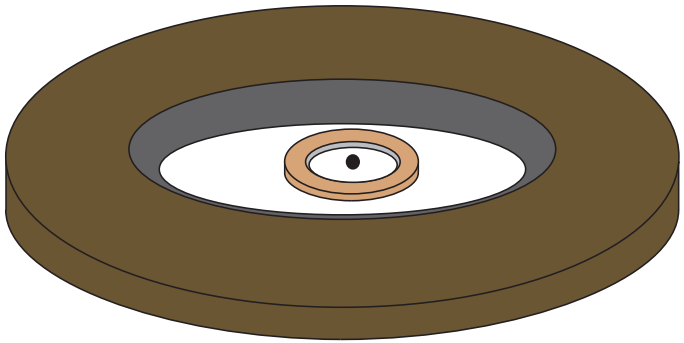
Explaining large holes and gaps in disks

LkCa 15



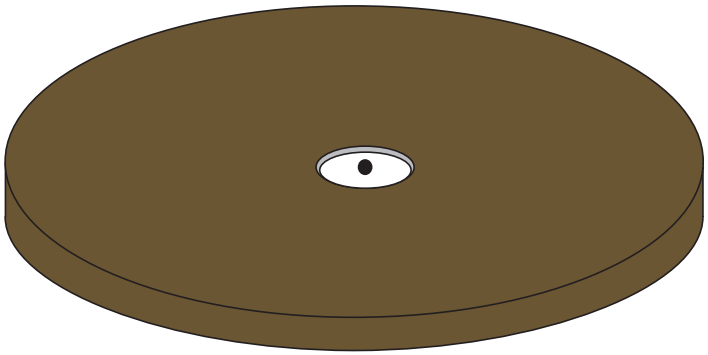
$3 \times 10^{-9}\ M_\odot\ yr^{-1}$ | 40 AU

UX Tau A



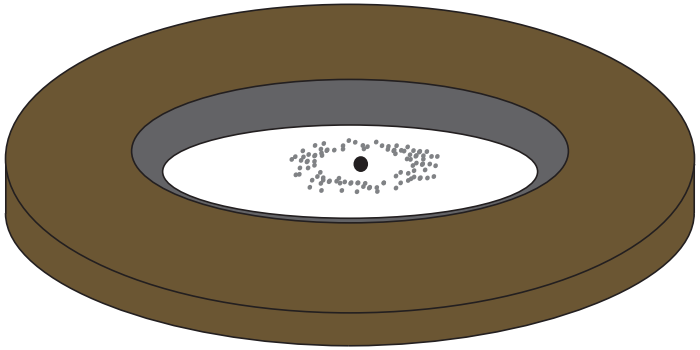
$1 \times 10^{-8}\ M_\odot\ yr^{-1}$ | 30 AU

Full disk



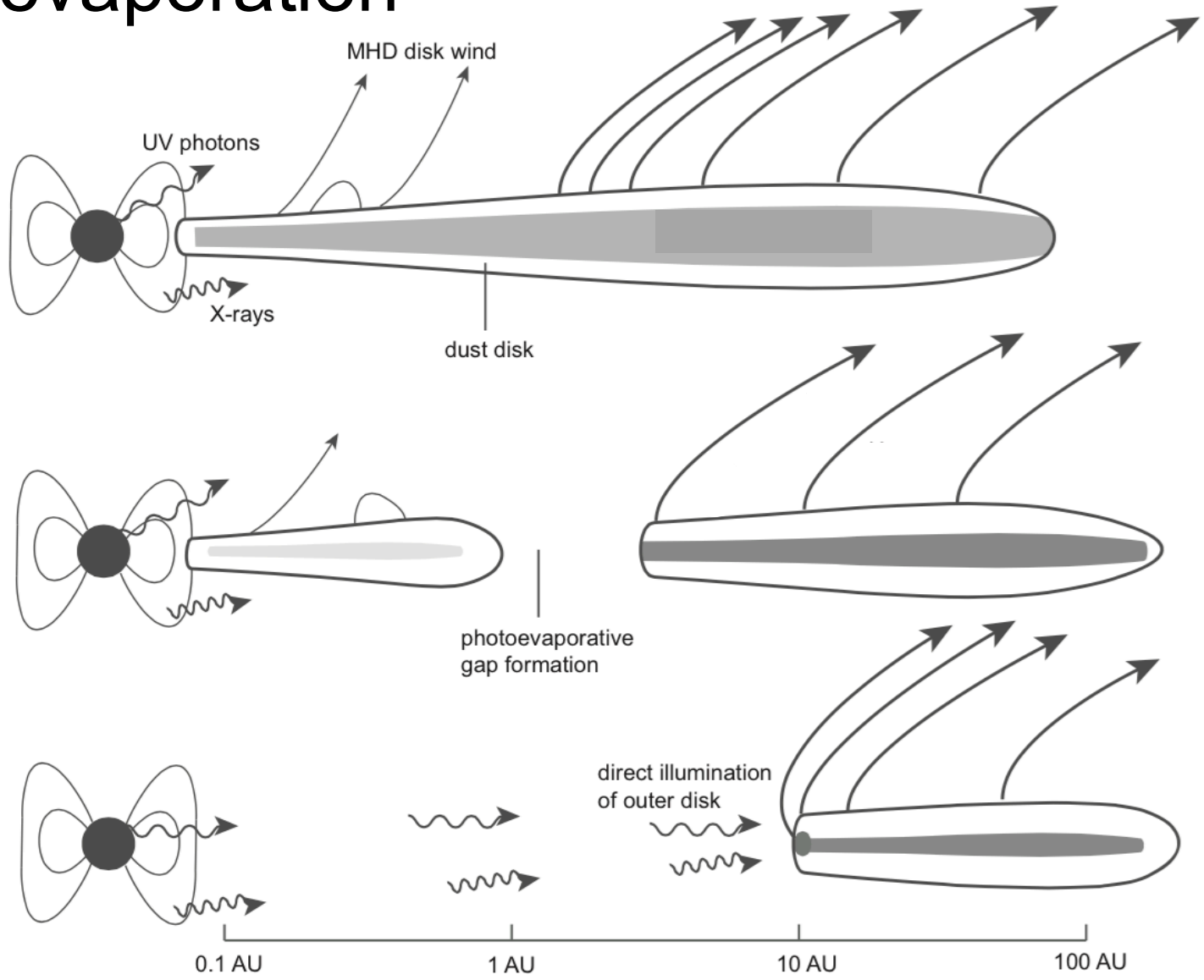
$1 \times 10^{-8}\ M_\odot\ yr^{-1}$

GM Aur



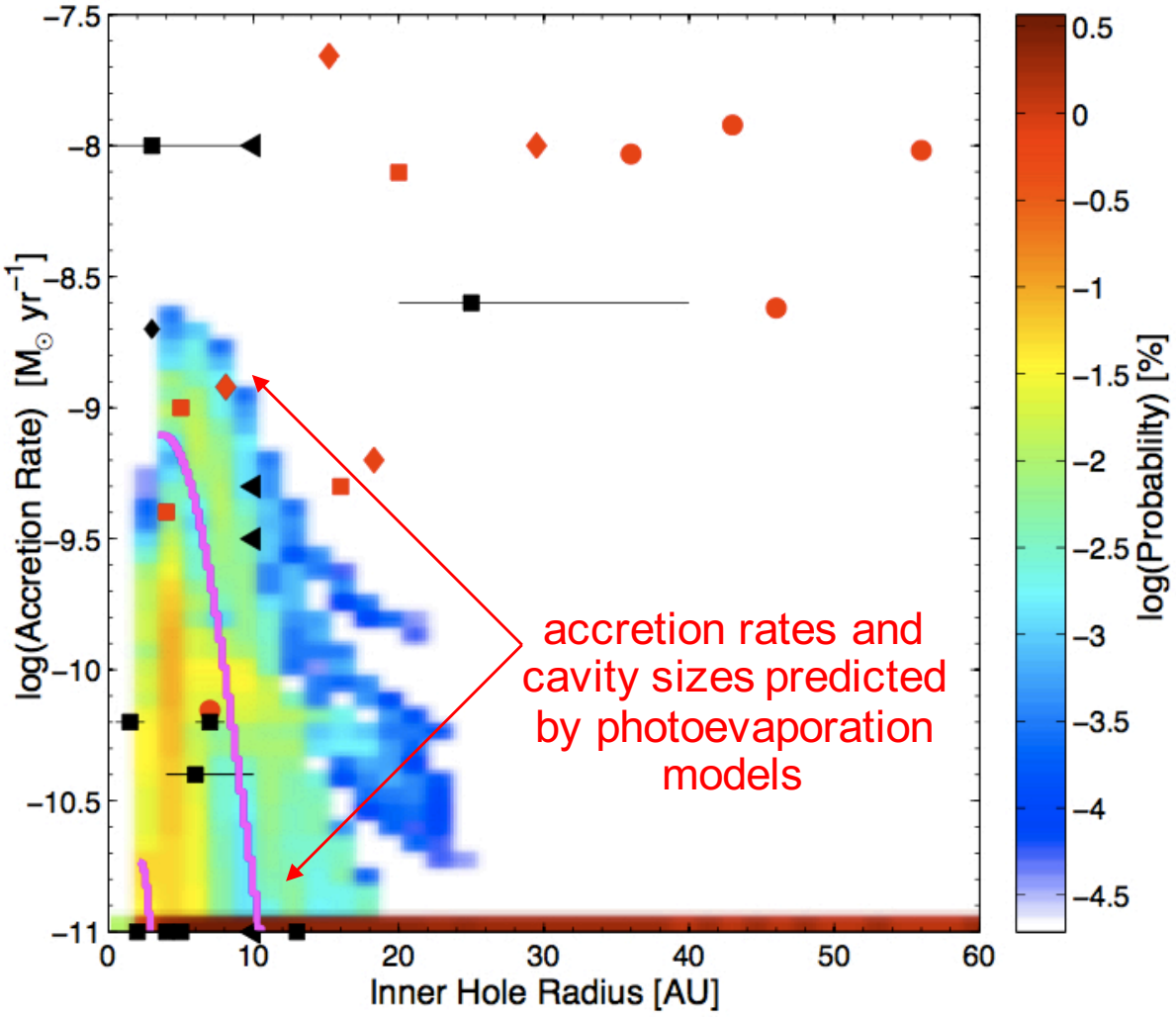
$8 \times 10^{-9}\ M_\odot\ yr^{-1}$ | 20 AU

Disk clearing mechanisms: photoevaporation



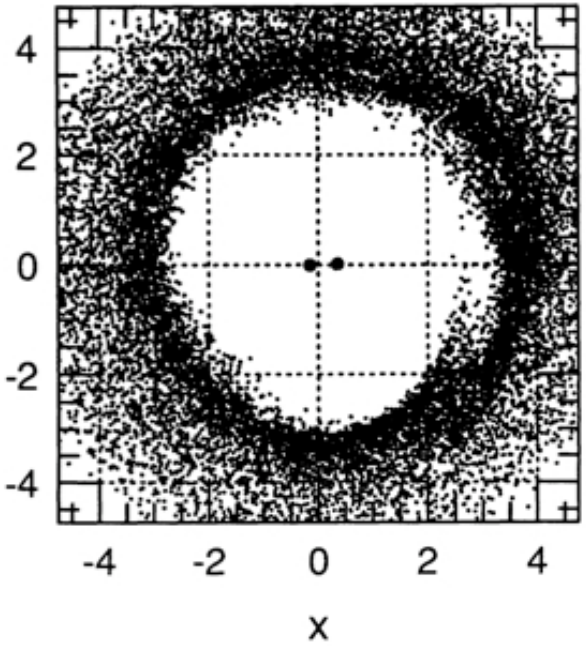
Adapted from Alexander et al. 2015; see also Hollenbach et al. 1994; Clarke et al. 2001

Difficult to explain accreting objects with large inner cavities using photoevaporation

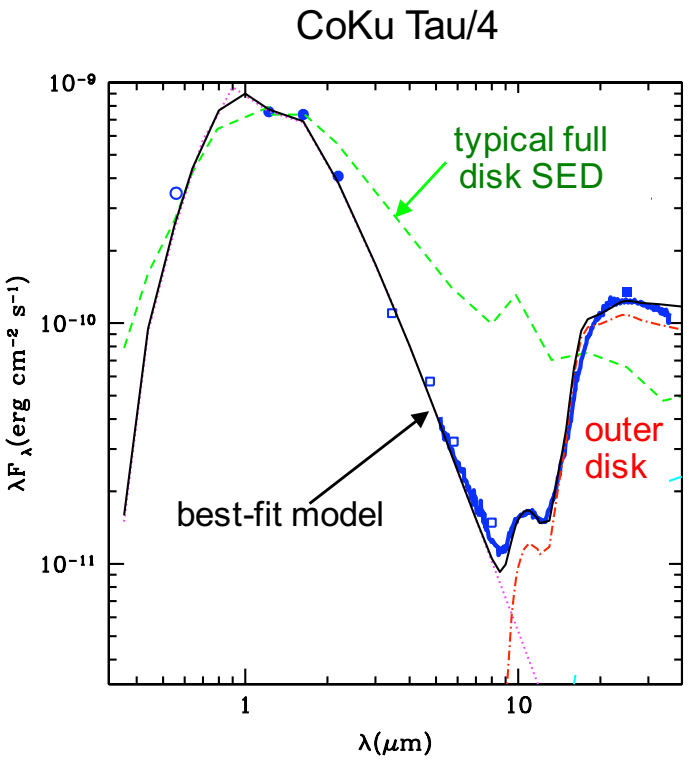


Owen et al. 2011

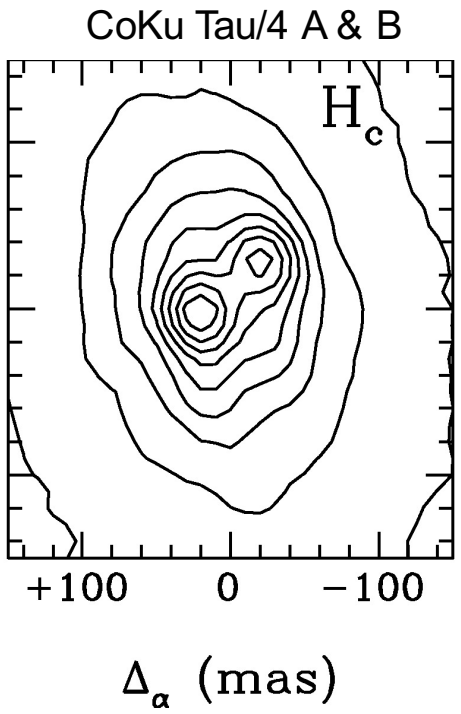
Disk clearing mechanisms: dynamical clearing by stellar companions



Artymowicz & Lubow 1994

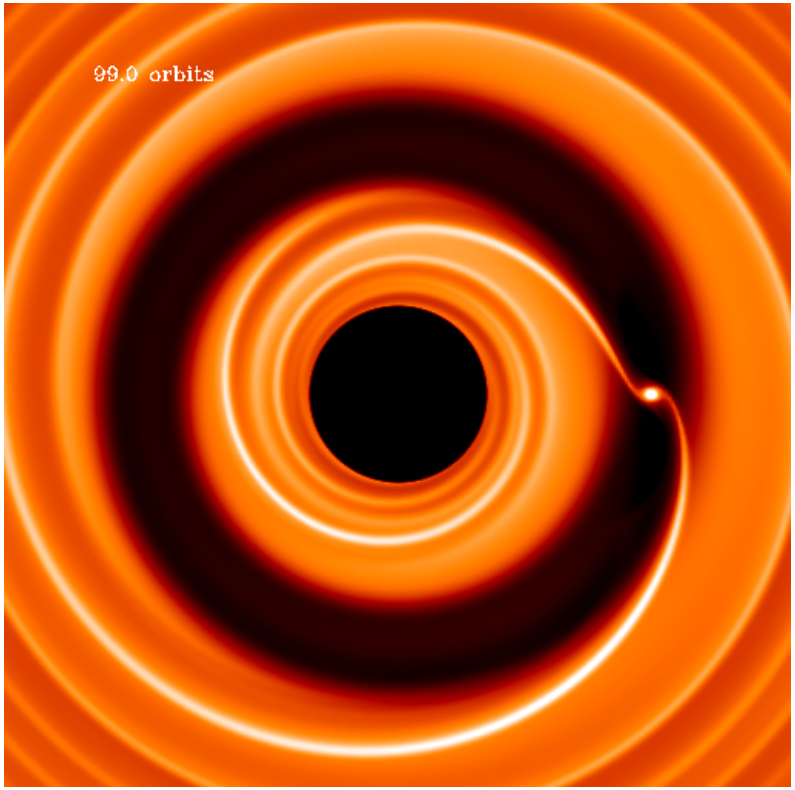


D'Alessio et al. 2005



Ireland & Kraus 2008

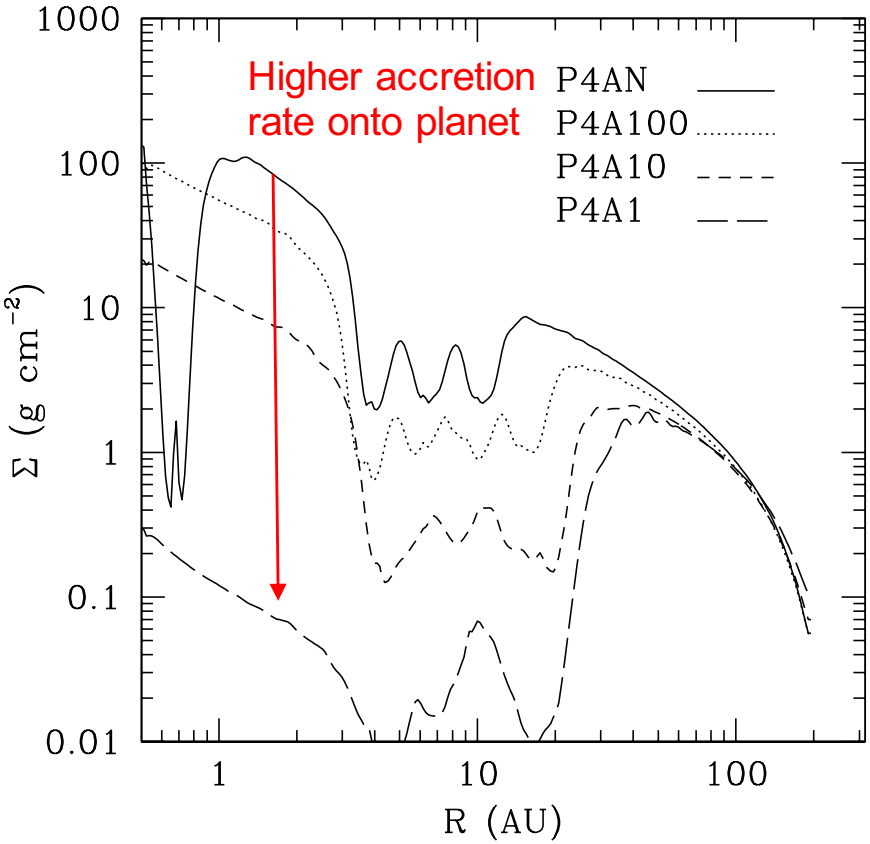
Disk clearing mechanisms: dynamical clearing by planets

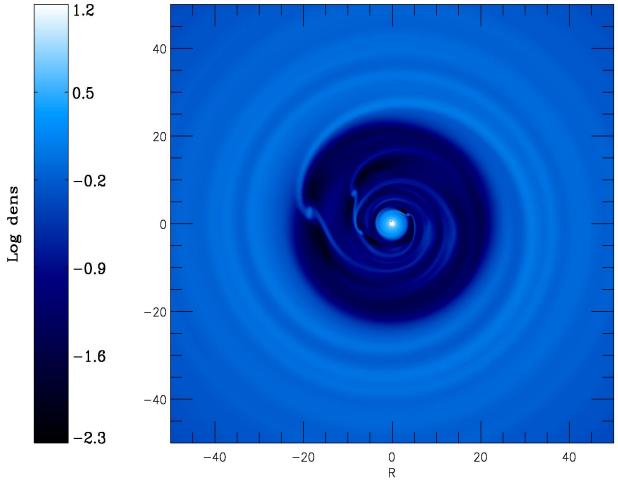


Masset et al. 2002

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

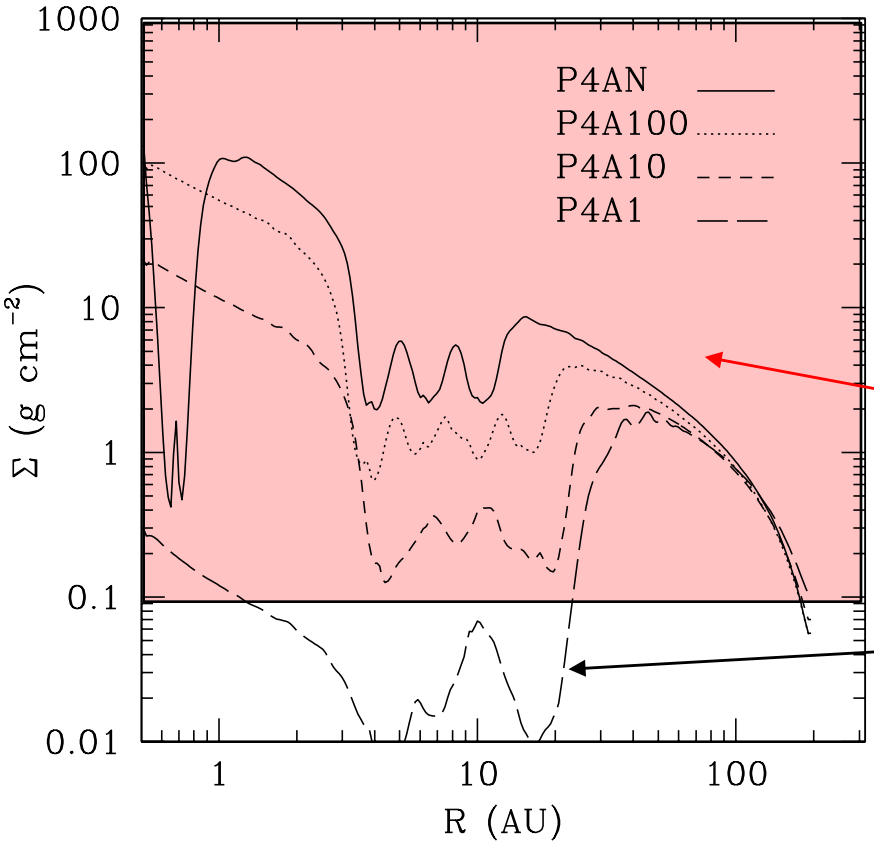
Multiple giant planets open a large gap

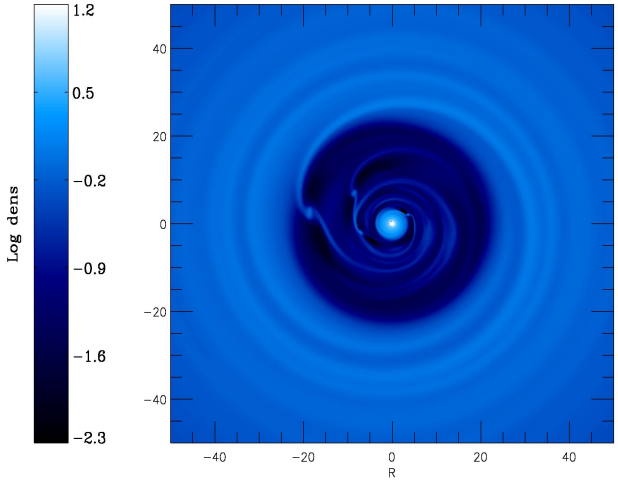




Zhu et al. 2011

Multiple giant planets open a large gap





optically thick,

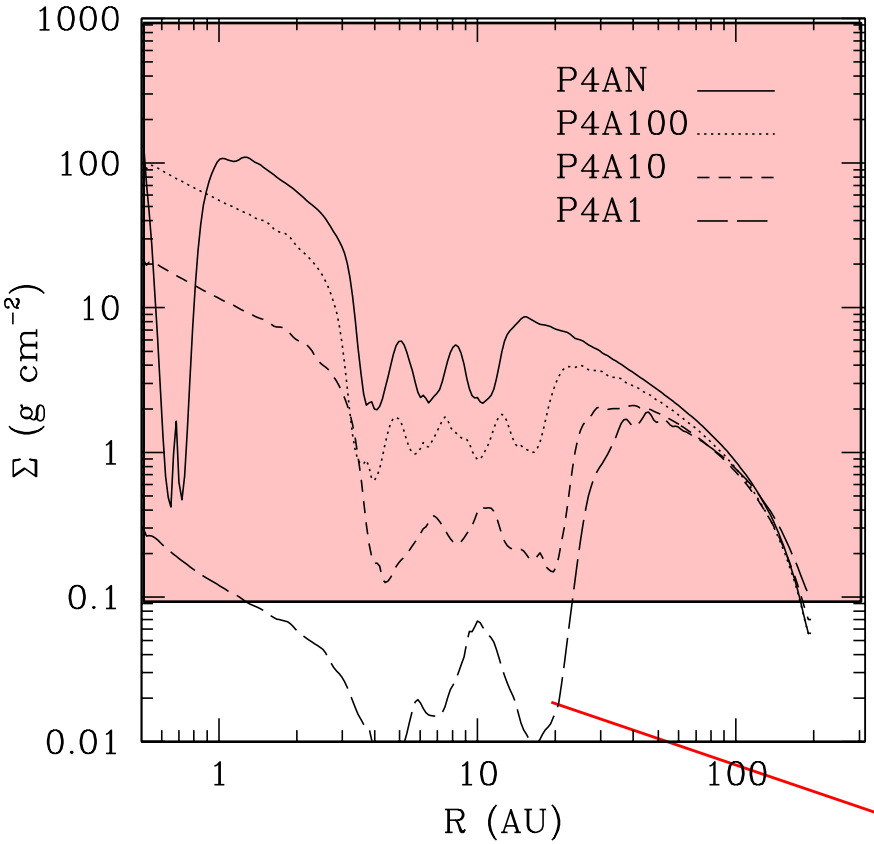
no dip in SED

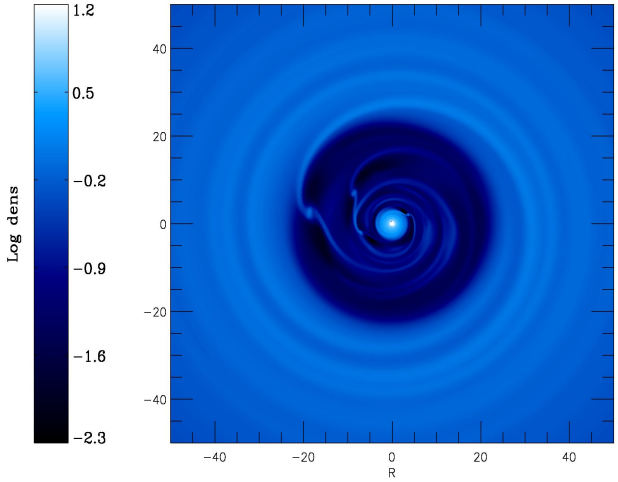
optically thin,

leads to dip in SED

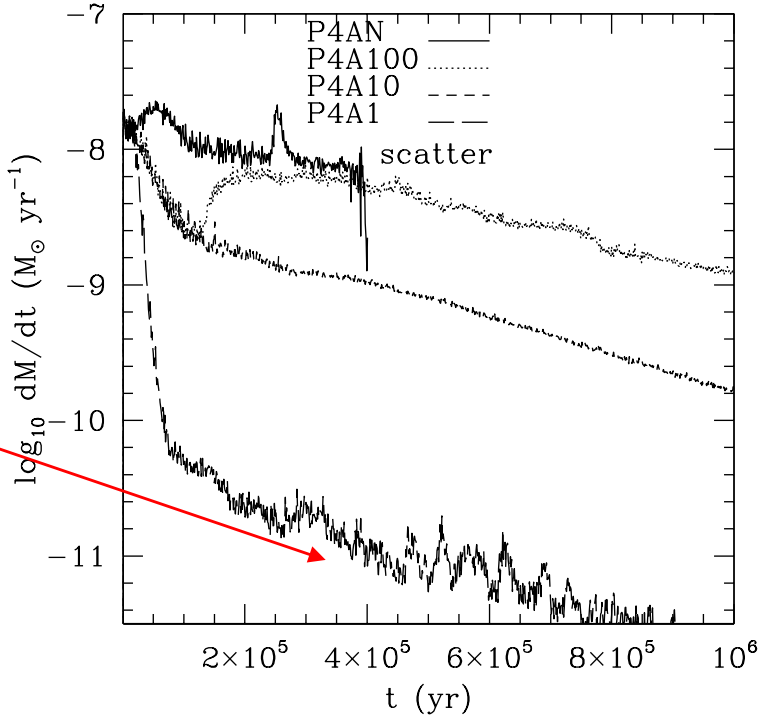
Zhu et al. 2011

Multiple giant planets open a large gap





Accretion Rate onto the Star



Zhu et al. 2011

Dust filtration can lead to different gas and dust distributions

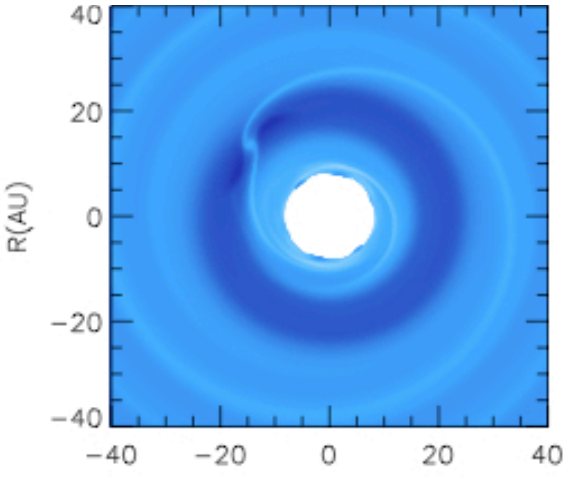
Gas Distribution

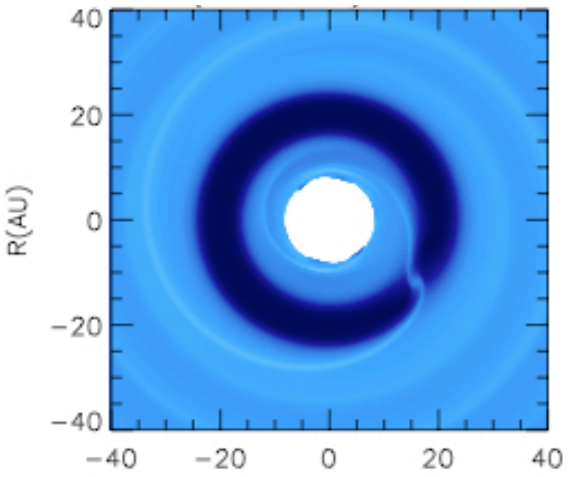
Small Dust Distribution

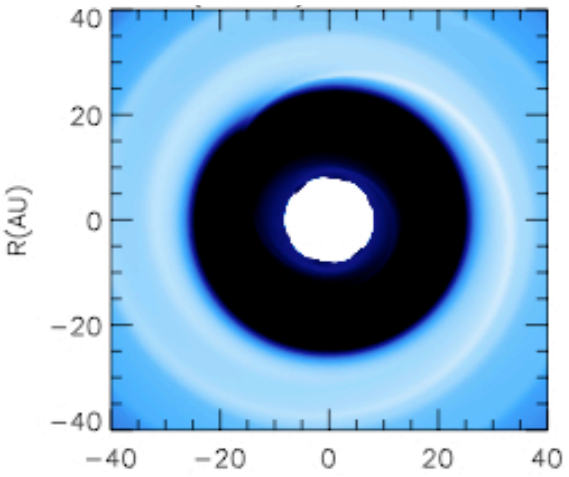
(< 10 microns)

Large Dust Distribution

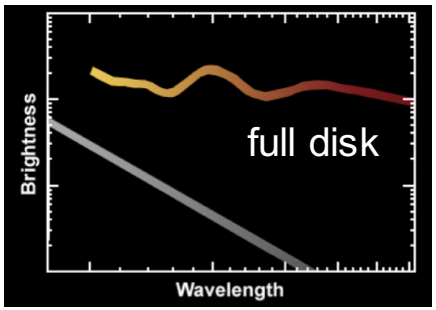
(~ 1mm)

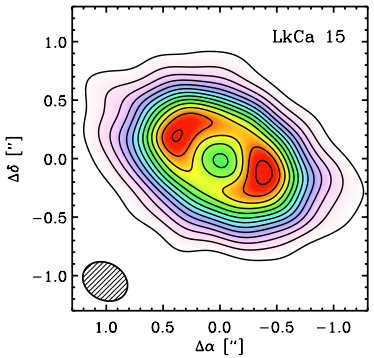






$\sim 10^{-9}\ M_{\odot}\ yr^{-1}$



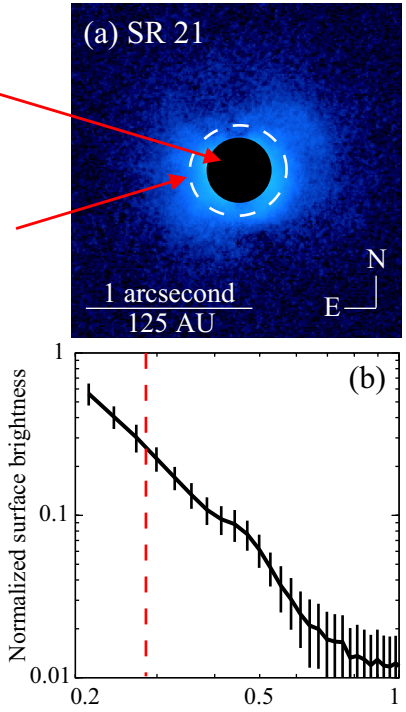


Zhu et al. 2012

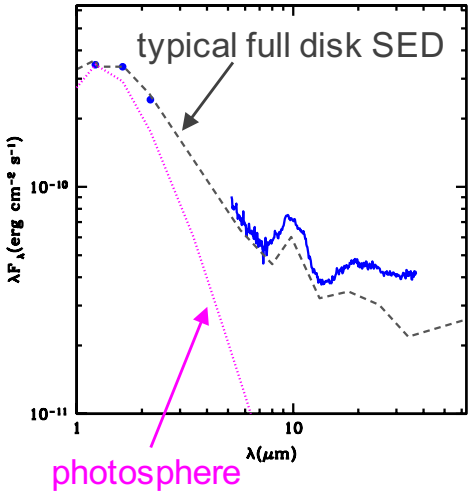
Disks with submm cavities and NIR emission from inner disk

resolution limit

submm cavity radius



small dust within submm cavity



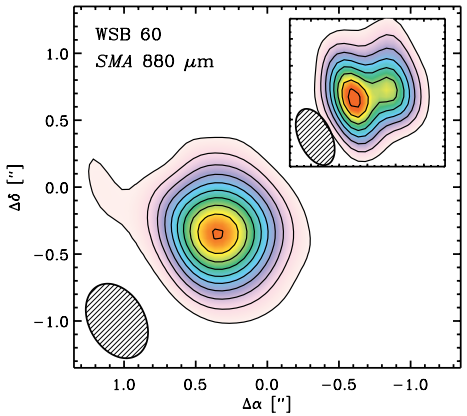


Figure from Espaillat et al. 2014, PPVI; Data from Follette et al. 2013, Kudo et al. in prep, Mayama et al. 2012

Andrews et al. 2011

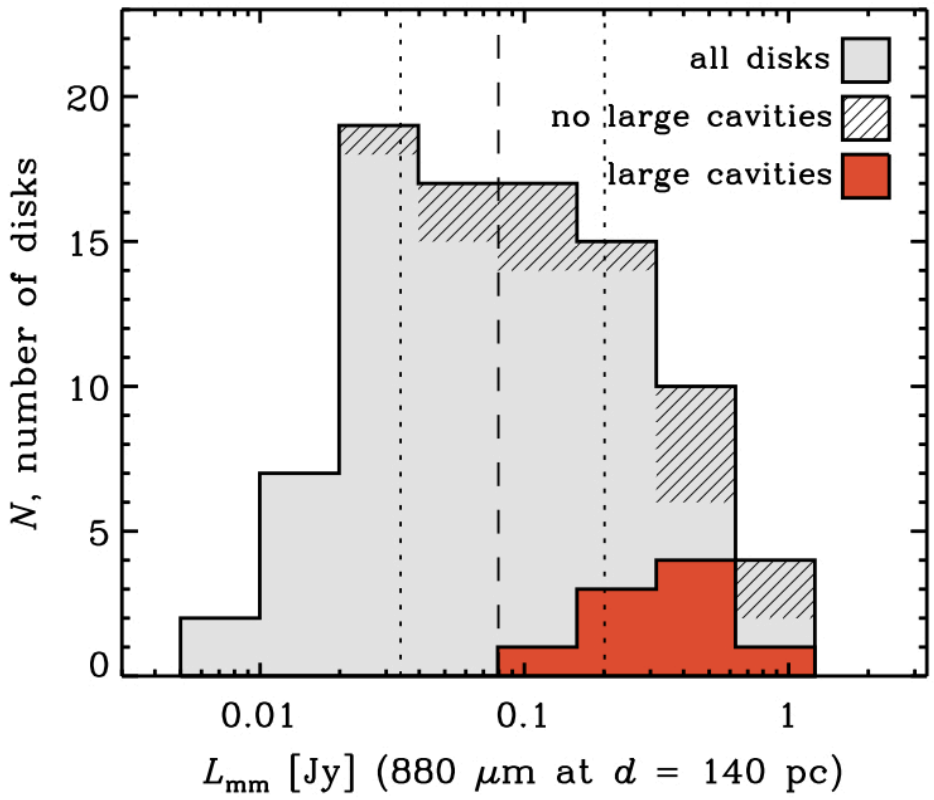
Tracking Planet Footprints

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

How do observations of disks with holes and gaps compare with theoretical simulations of disk clearing?

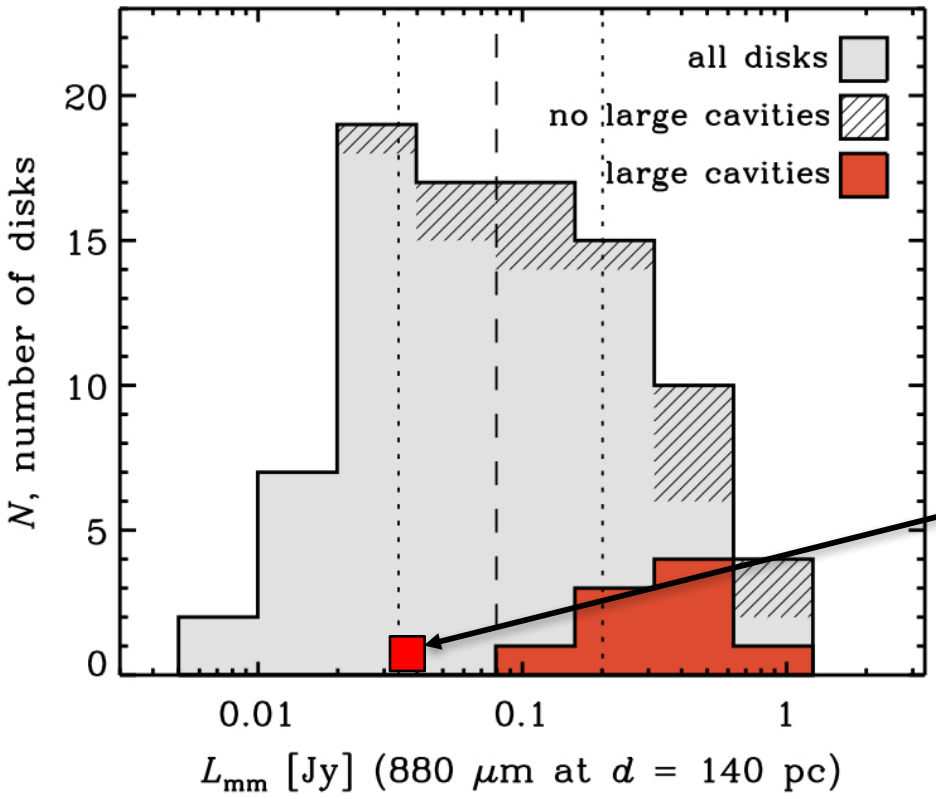
Where do we go from here?

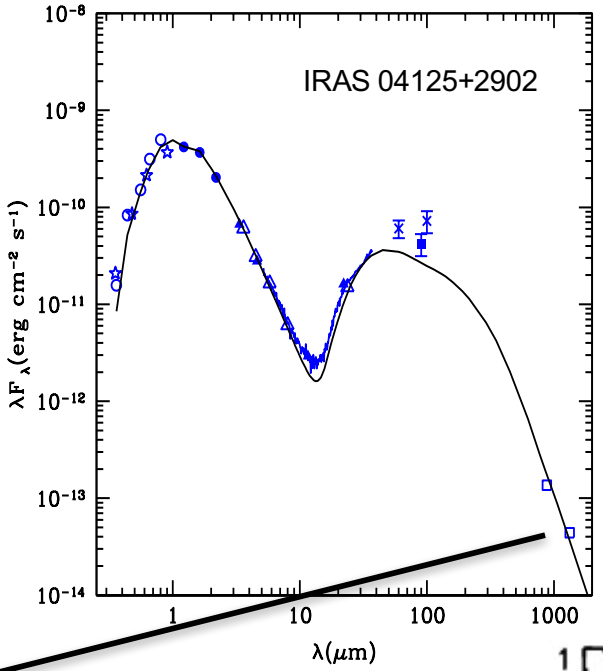
Identifying new disks with large cavities

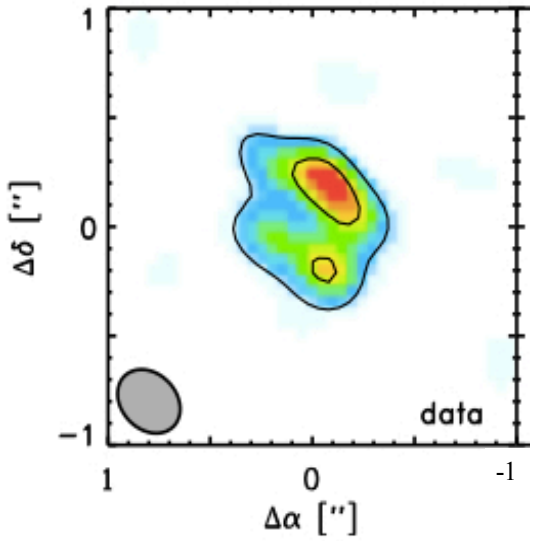


Andrews et al. 2011

Identifying new disks with large cavities



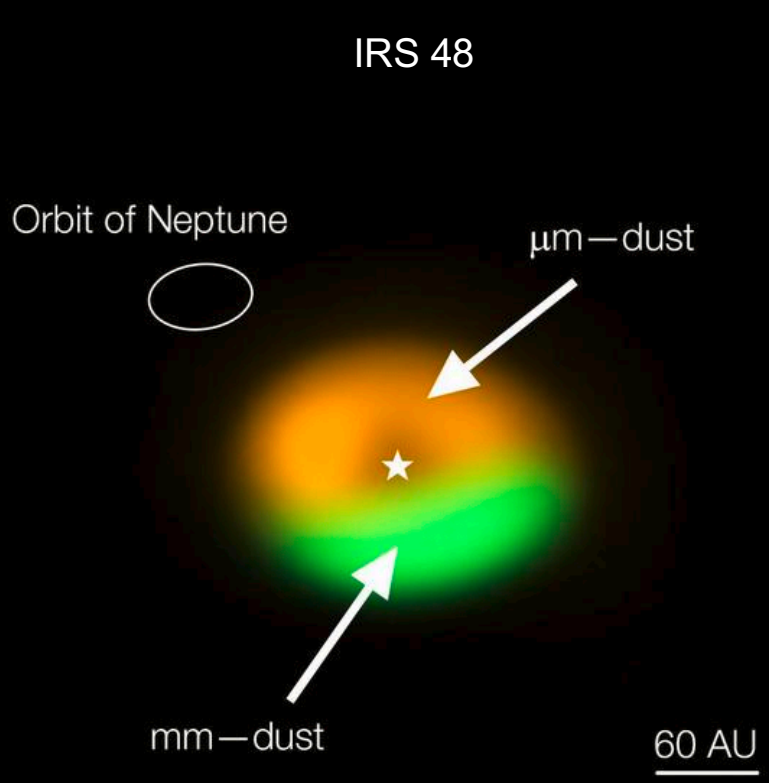


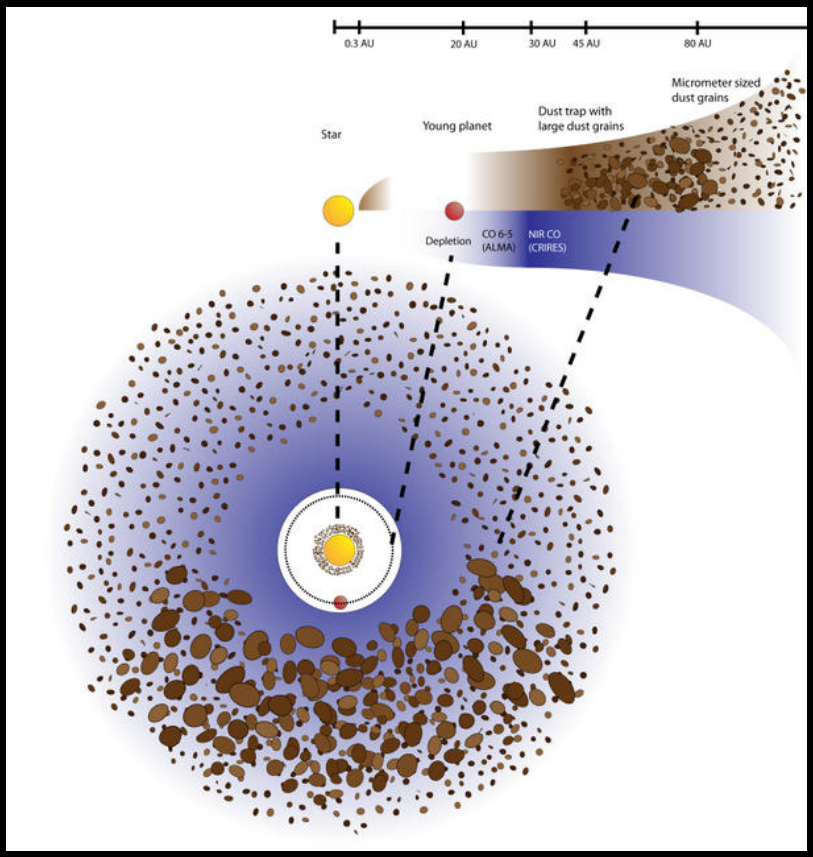


Andrews et al. 2011

Espaillat et al. 2015

ALMA has revealed dust asymmetries in disks

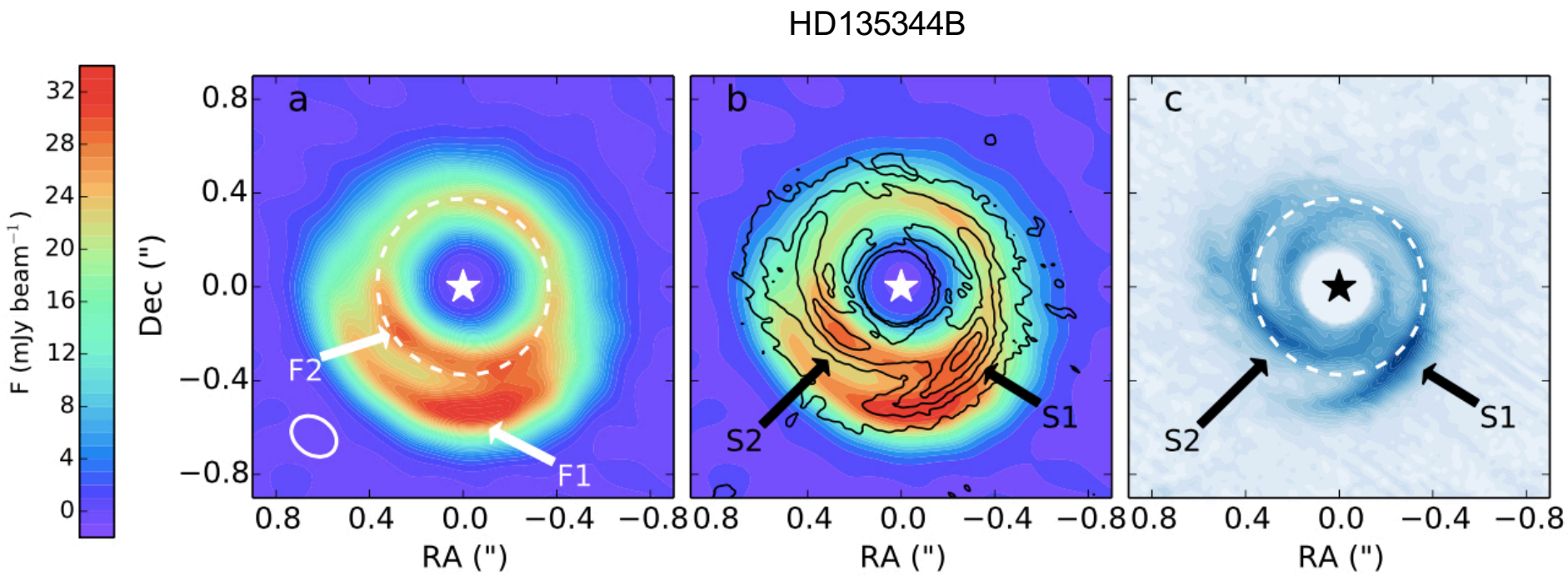




van der Marel et al. 2013

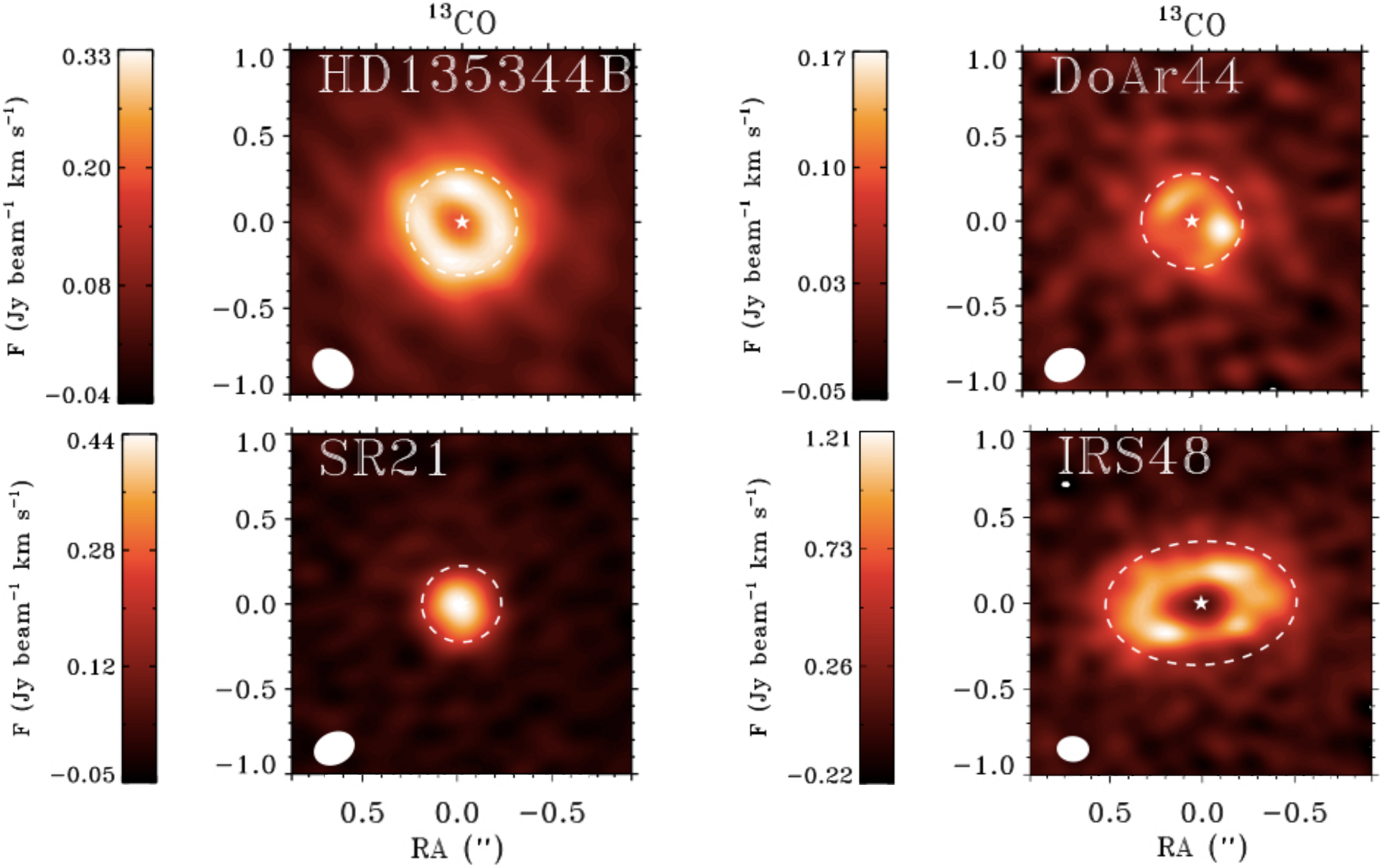
also Casassus et al. 2013; Fukagawa et al. 2013; Isella et al. 2013; Perez et al. 2014; Pineda et al. 2014

At least one asymmetry resolved into spiral structure



van der Marel et al. 2016, Garufi et al. 2013

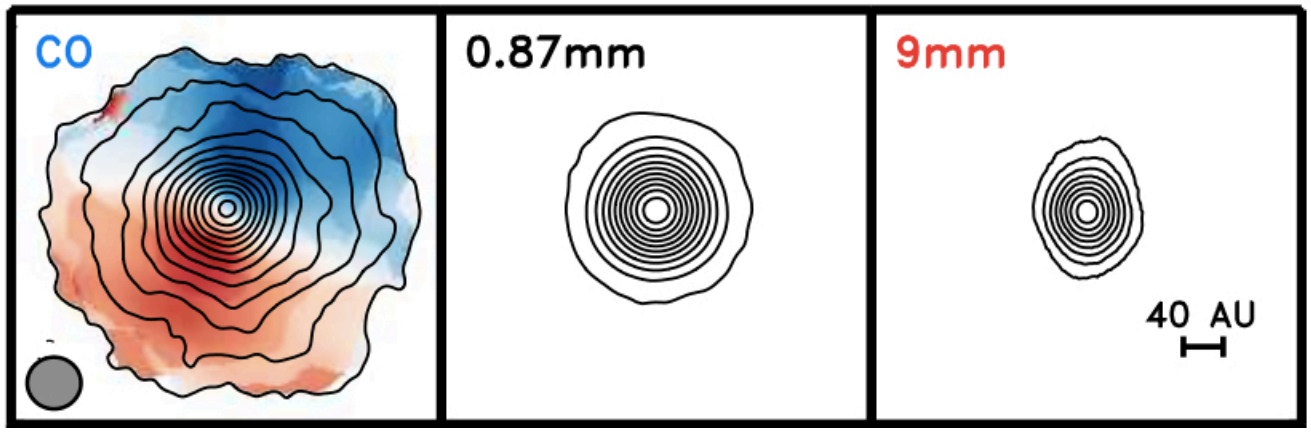
Gas seen within dust cavities with ALMA



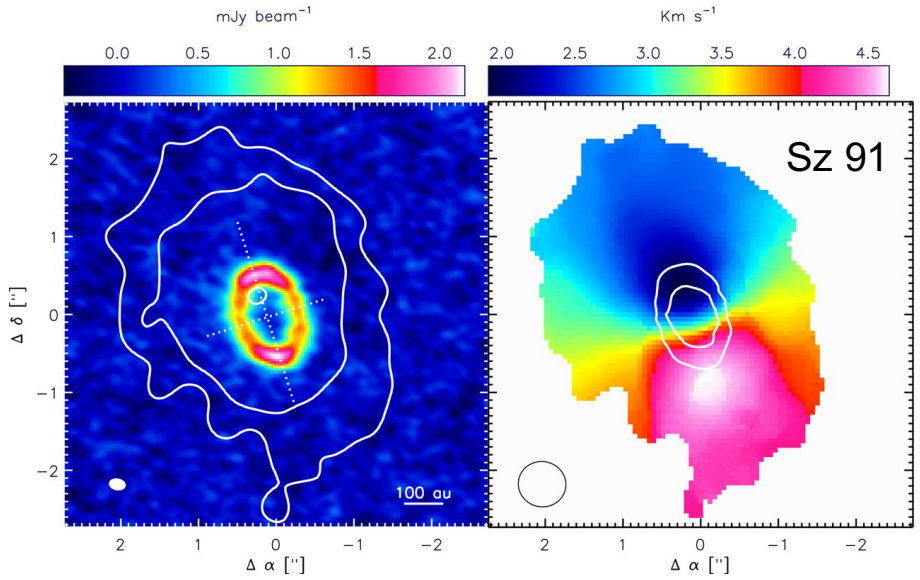
van der Marel et al. 2015

Evidence for dust grain radial drift

TW Hya



Andrews et al. 2012, 2015; Menu et al. 2014



Canovas et al. 2016

What do planet footprints look like?