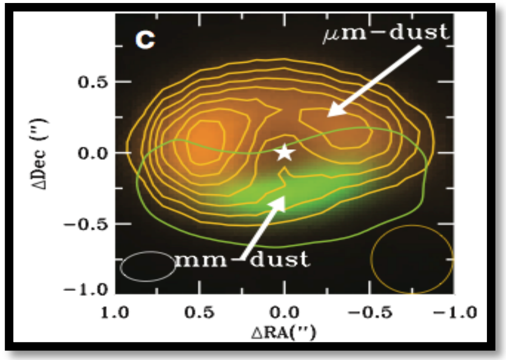
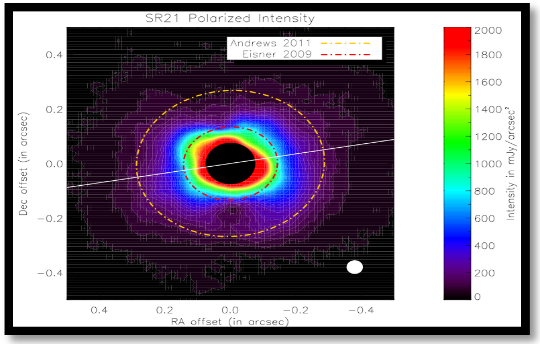
Understanding different observed features of transition disks by modeling dust evolution with one or multiple planets interacting with the disk

IRS 48, Van der Marel et al. (2013)



SR21, Follette et al. (2013)
Pérez et al. (2014)



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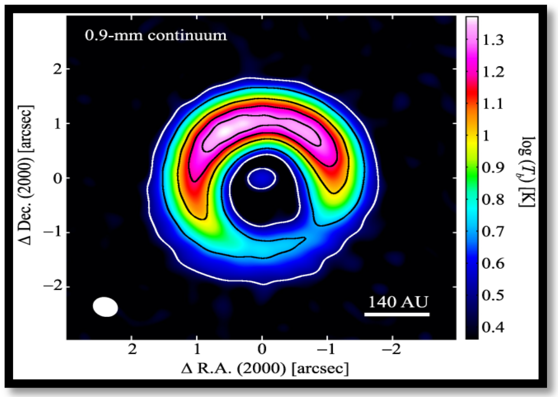
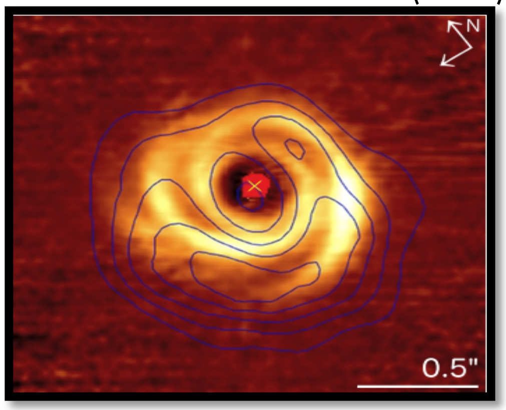
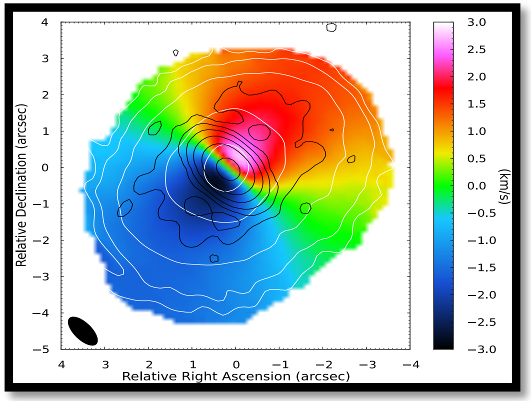
HD 142527, Casassus et al. (2013)
Fukagawa et al. (2013)
Christiaens et al. (2014)
Pérez S. et al. (submitted)



HD135344B, Garufi et al. (2013)
Pérez et al. (2014)
Carmona et al. (2014)



HD100546, Walsh et al. (2014)

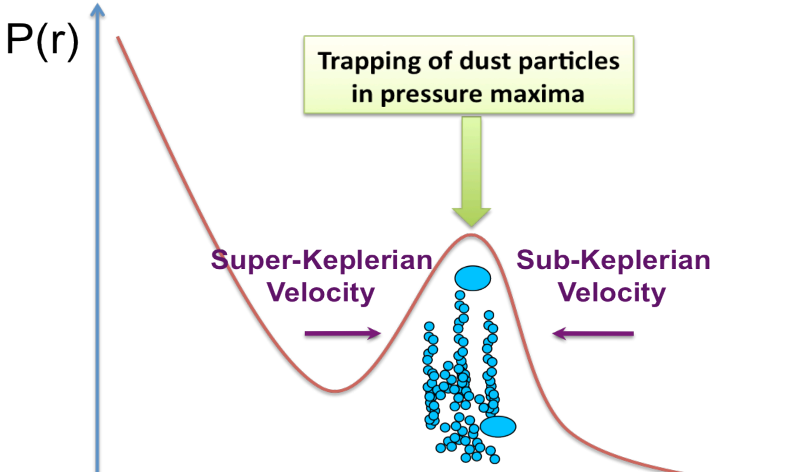


Outline

- Brief introduction: particle trapping.
- Models:
  - hydrodynamical models of planet-disk interactions.
  - dust evolution models.
  - radiative transfer.
- Applications: HD135344B *(A. Garufi talk)* , IRS48 *(N. van der Marel talk)*, HD100546 & SR21, and spectral index of transition disks (this talk).
- Conclusions

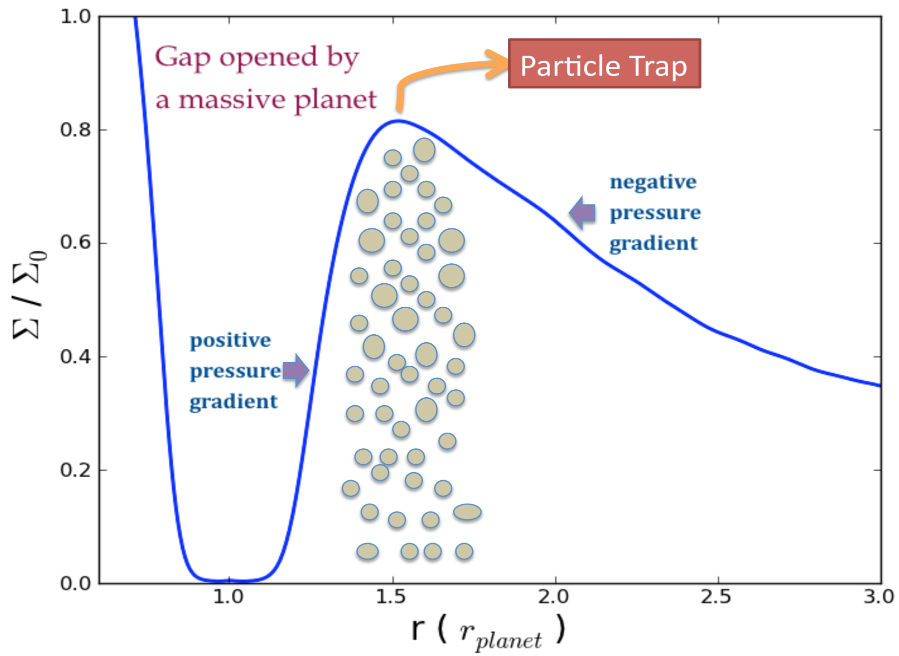
Introduction

Transition disks are excellent candidates to study particle trapping



e.g. Klahr & Henning (1997) ; Fromang & Nelson (2005); Johansen et al. (2009); Pinilla et al. (2012a)

A huge pressure bump is formed at the outer edge of a gap carved by a massive planet,



Particle Traps

- Dead Zones
- Evaporation Front
- Giant Planets
- MRI effects

Models

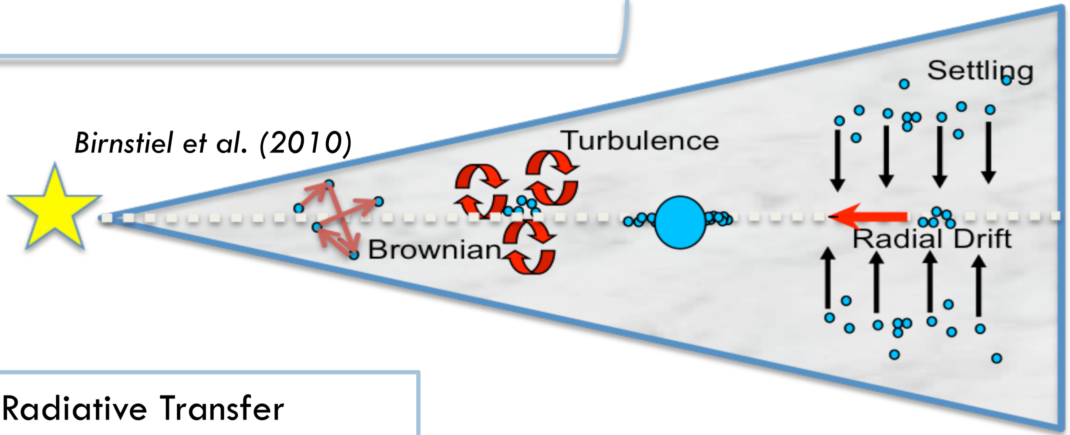
Models: Combination of gas/dust evolution and radiative transfer

2D Hydrodynamical simulations of planet-disk interactions using FARGO (Masset, 2000)

Quasi-steady state is reached
(≤ 1000 orbits ≈ 10^{-2}- 10^{-1}Myr)
Azimuthally average

Dust Evolution Models
(radial direction)

Birnstiel et al. (2010)



Radiative Transfer
Modeling (e.g. RADMC, MCMax)

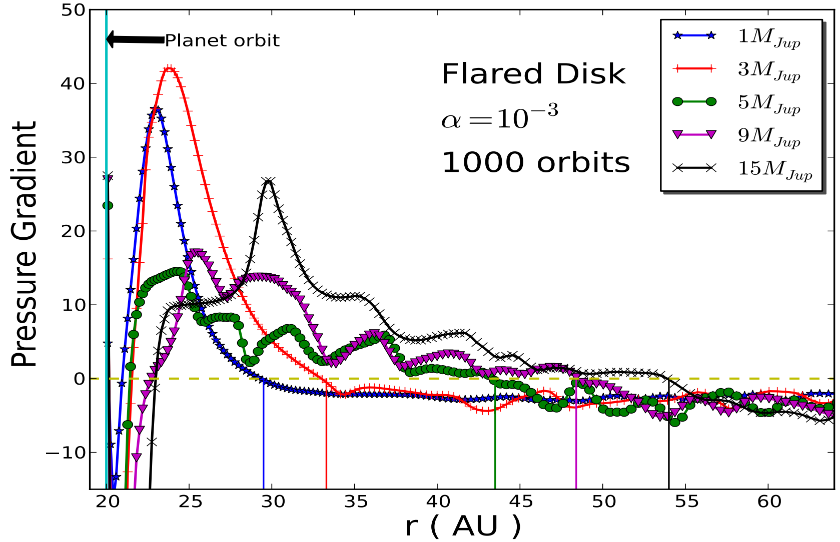
Talk to me for details of the models ☺ More than happy to explain them to you

Direct comparison between models and available observations

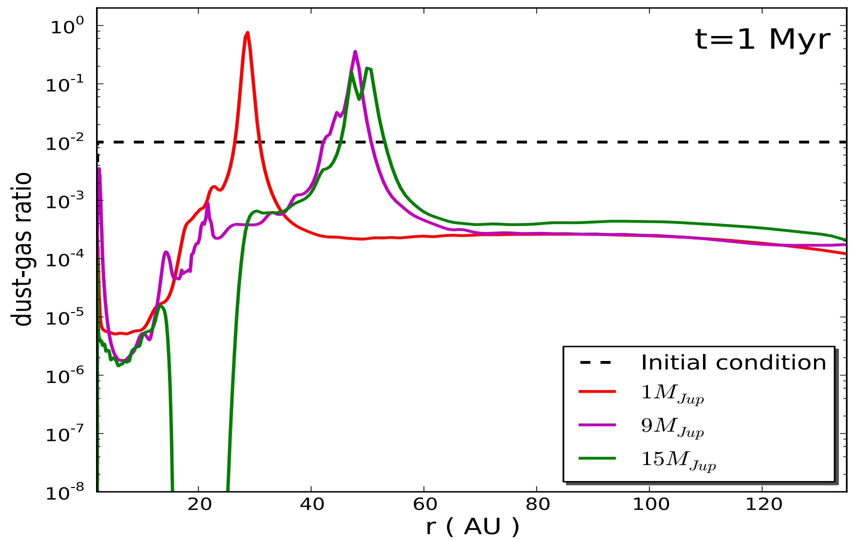
Results & Applications

Previous Results I

<u>Pressure Gradient:</u> location of pressure maxima depends on the mass of the planet



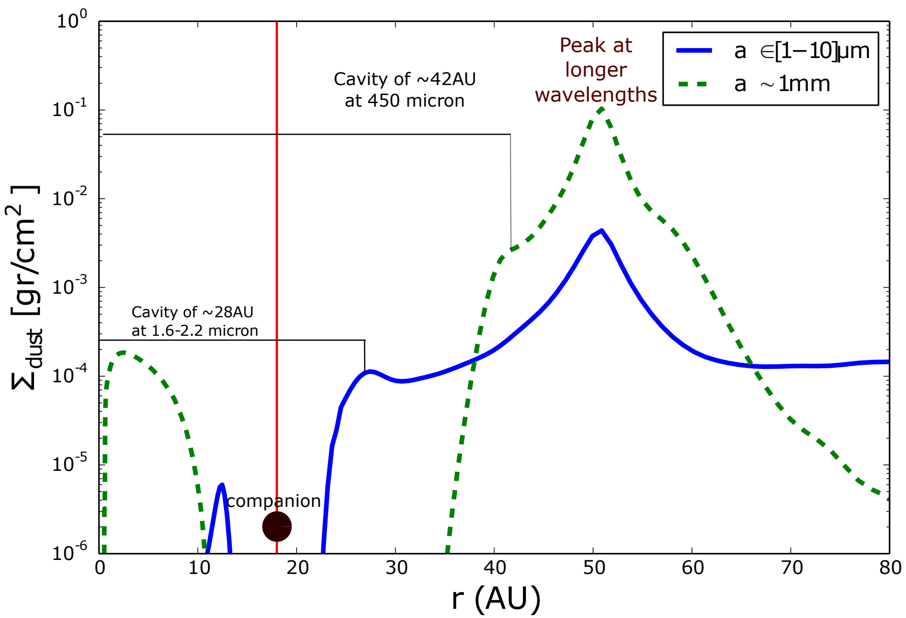
<u>Dust Filtration</u>: also depends on the mass of the planet



Pinilla, P.; Benisty M. & Birnsitiel T. (2012b)

Previous Results II

Segregation of particles in the radial direction

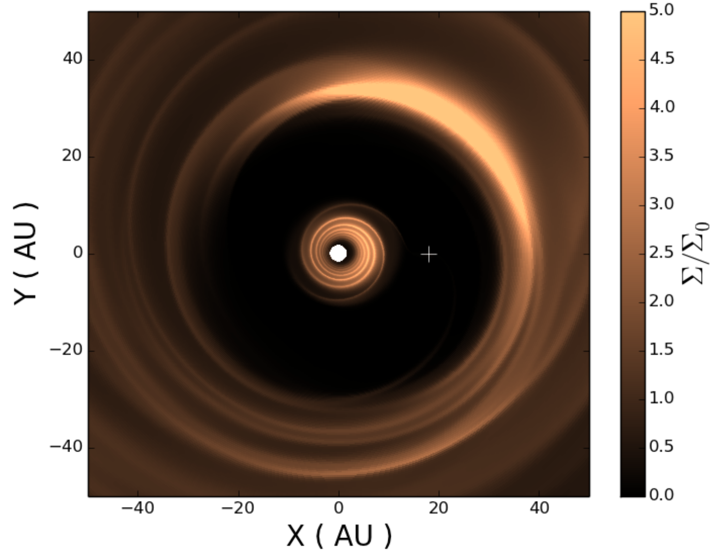


Example of observations: HD135344B

(A. Garufi's talk)

See also *de Juan Ovelar et al. (2013)*

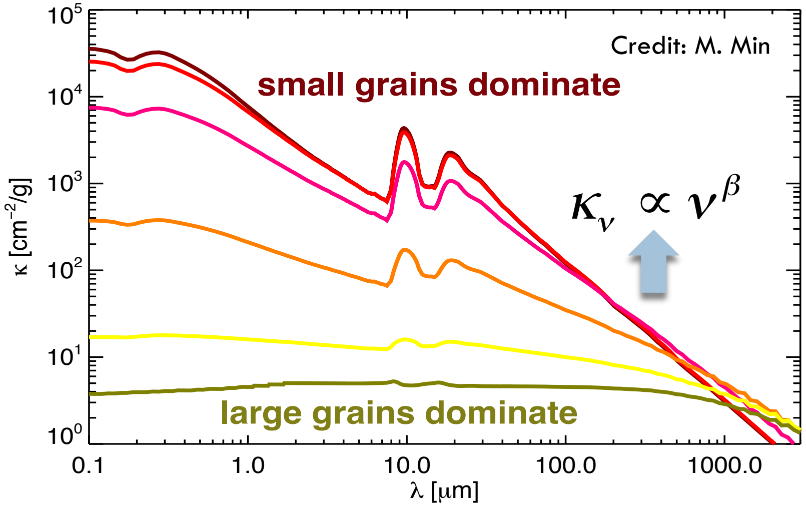
Vortices may also form and create strong azimuthal contrast at mm-wavelengths (e.g IRS 48 and HD142527)



See also: *Ataiee et al. (2013), Birnstiel et al. (2013), Fung et al. (2014), Zhu et al. (2014)*

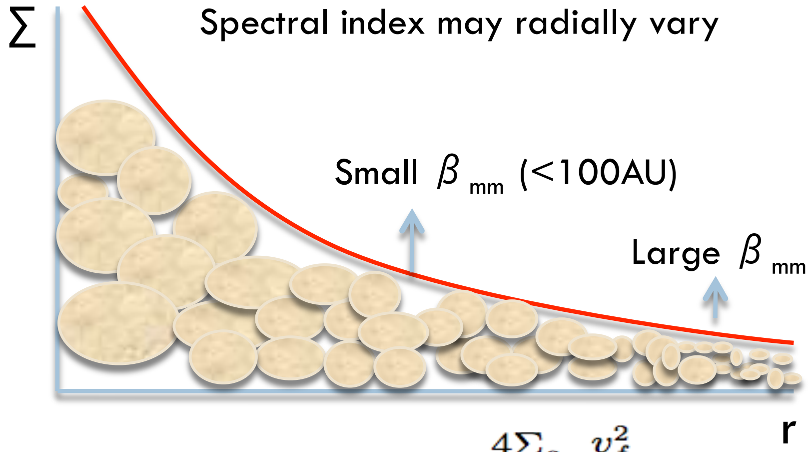
New Implications: spectral index of transition disks

Size dependence of the dust opacity



If $\beta \leq 1$, dust grain have grown to sizes > 1mm

Spectral index may radially vary

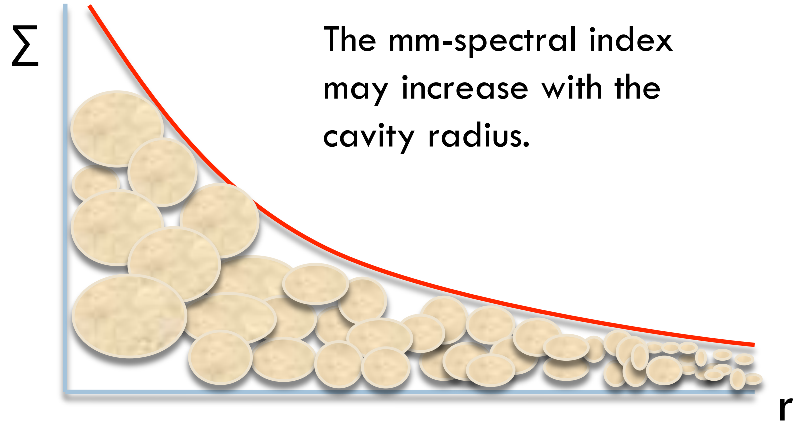


$$a_{\max} \simeq \frac{4\Sigma_g}{3\pi\alpha\rho_s}\frac{v_f^2}{c_s^2}$$

Variations of the opacity index have been resolved for some classical disks (e.g. Guilloteau et al. 2011, Perez et al., 2012 & Trotta et al. 2013)

Transitions disks: A change in the cavity radius impacts the spatially integrated spectral index

The mm-spectral index for transition disks

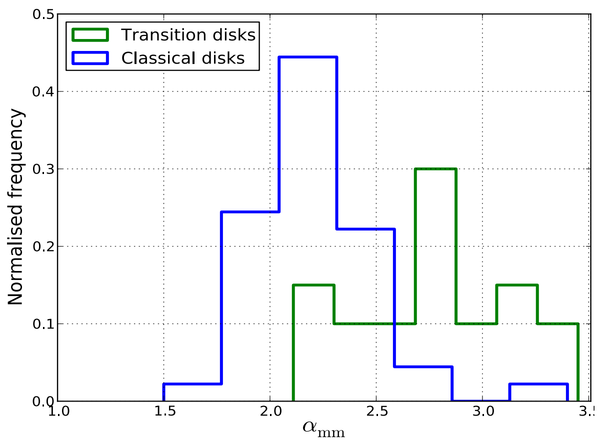


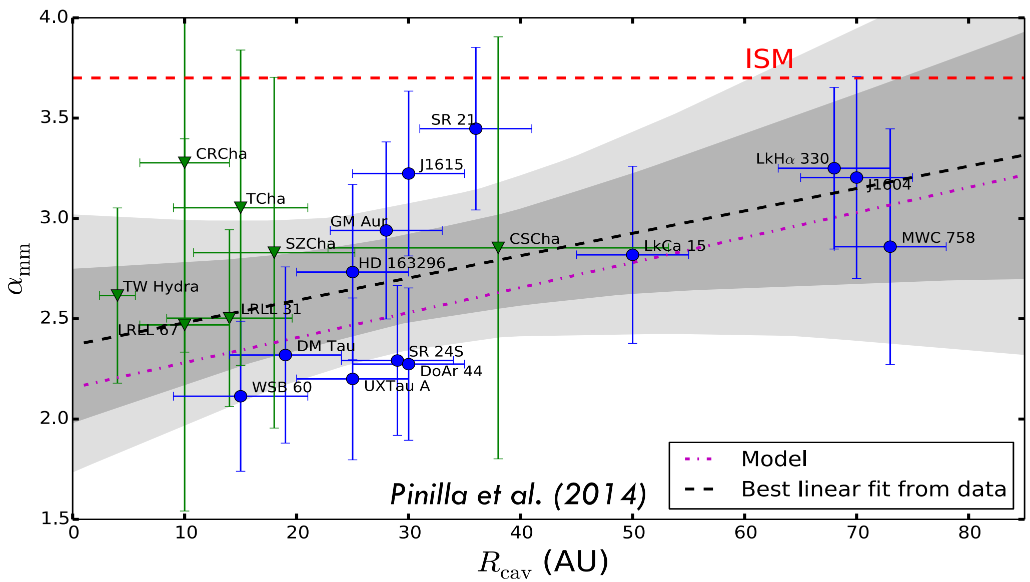
The mm-spectral index may increase with the cavity radius.

KS two-sided test: very low probability (≪ 1%) that the two samples are similar.

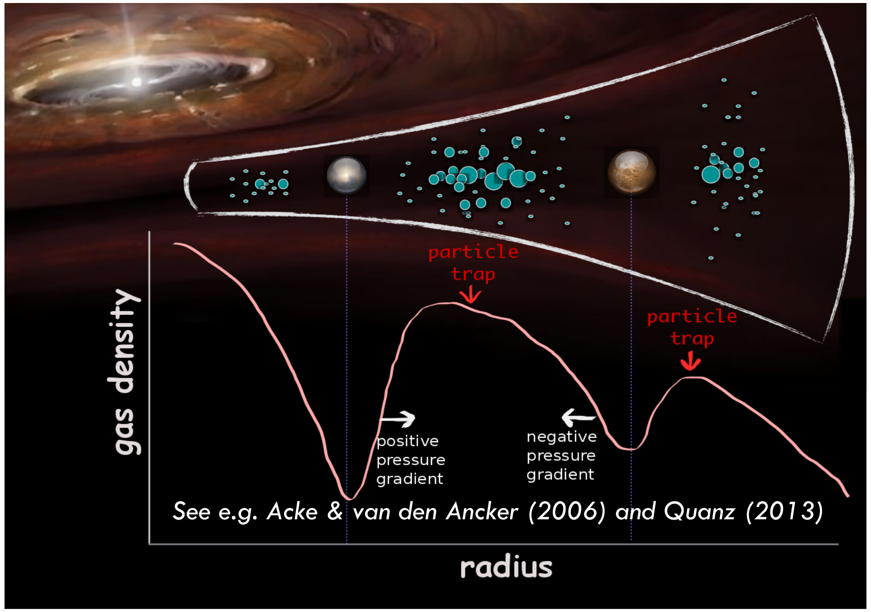
We predict a positive trend between Rcav and α mm. Multi-wavelength observations with high angular resolution are needed to prove our predictions

We gather and compare the spectral index of 20 transition disks, with available data of classical disks





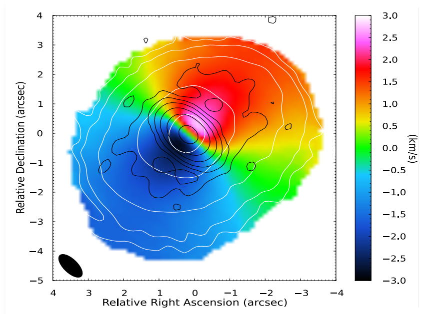
Multiple planets? A beautiful example HD 100546

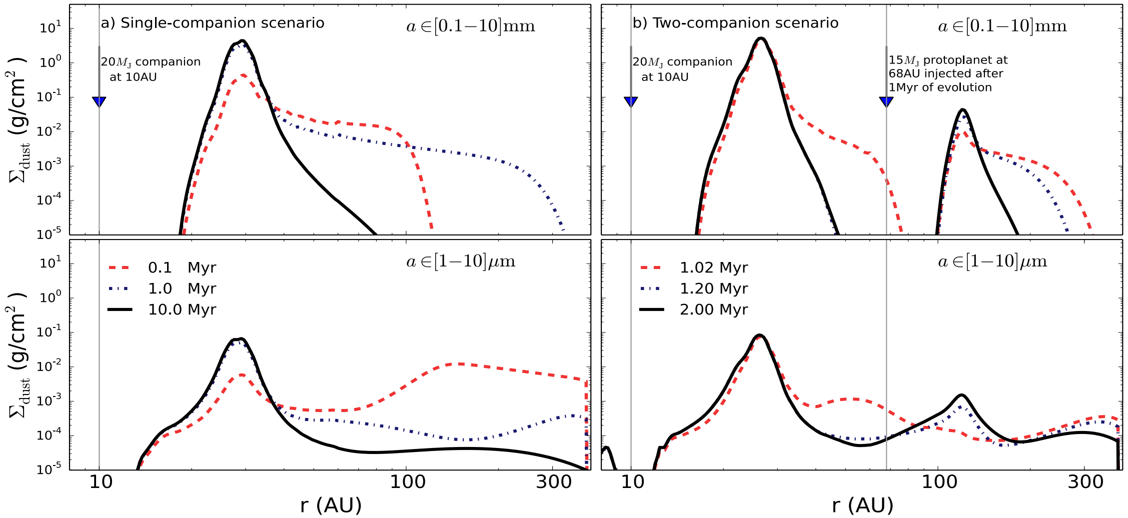


Open question:
Can we constrain the age of the outer planet by dust evolution models?

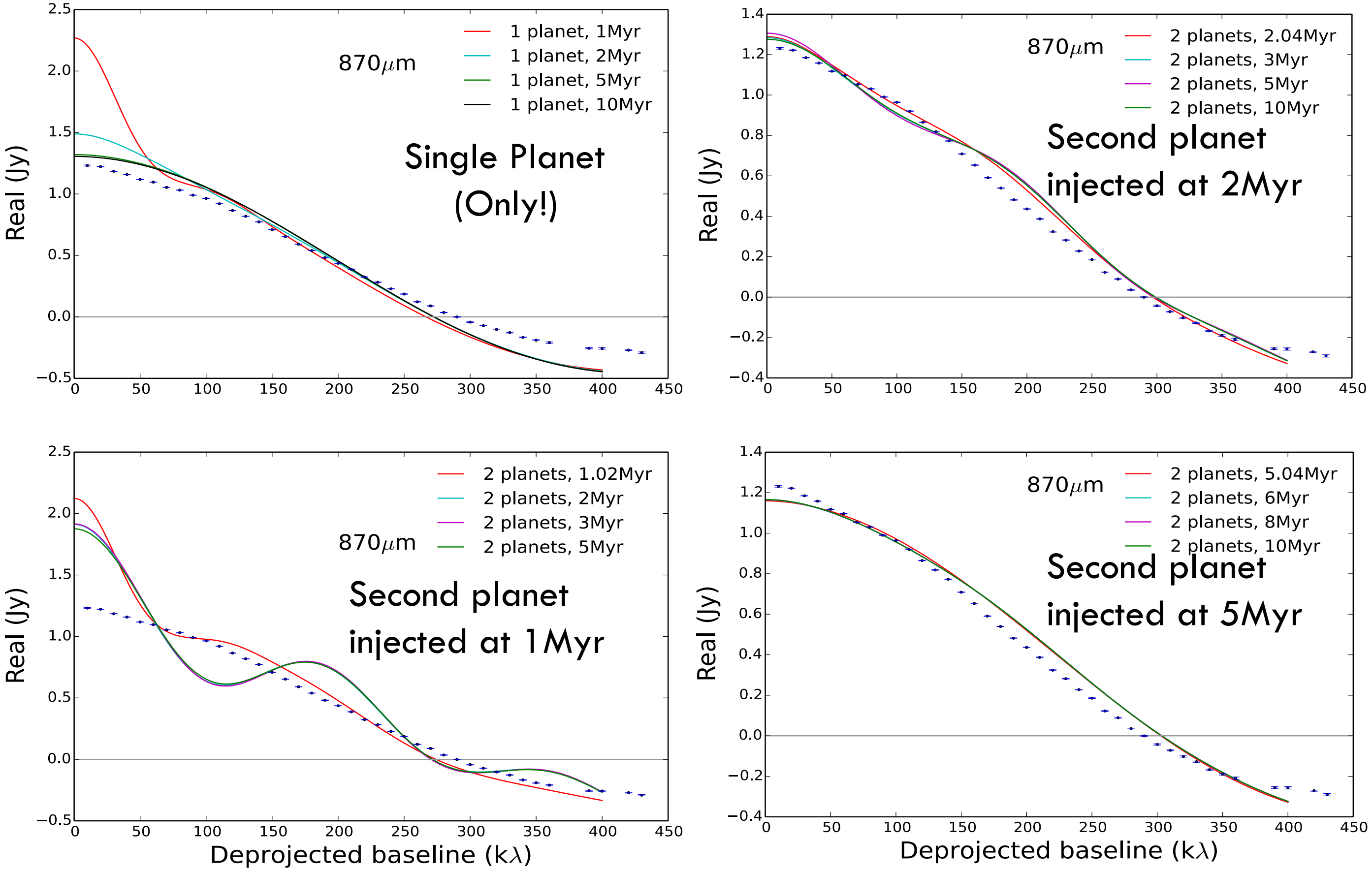
The two rings-like emission supports the idea of particle trapping by two massive planets embedded in the disk!

Walsh et al. (2014)





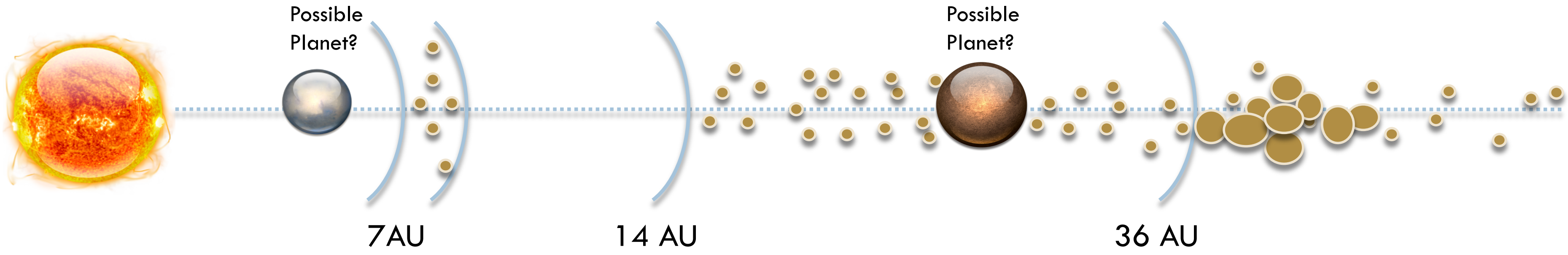
Hinting the age of the planet in HD100546



Models reveal that the outer planet in HD100546 should be injected in the disk after > 2 Myr of dust evolution under the presence of a inner companion

Pinilla et al. (in prep)

Another example of multiple planets: SR21



Narrow gas ring
(Pontoppidan et al, 2008)
Dust ring - Pionier instrument
(Benisty, priv. comm.)

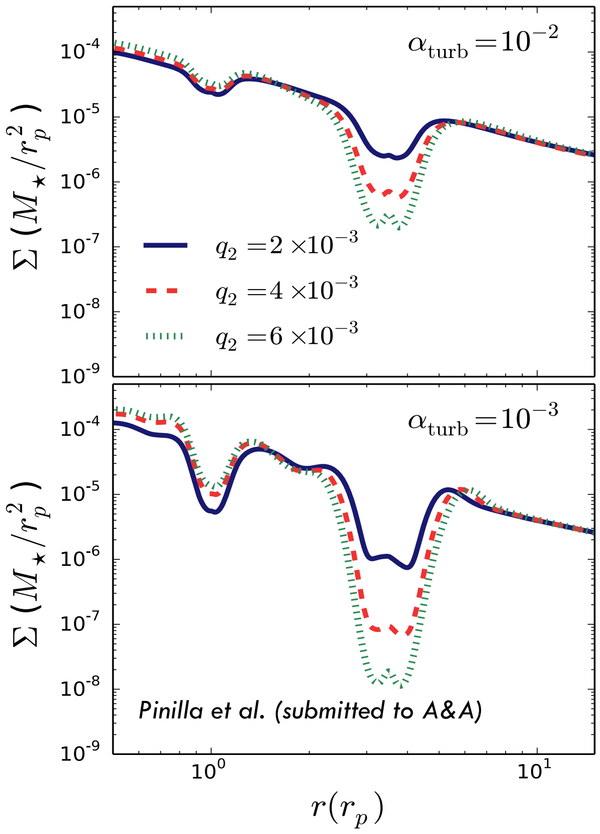
Smooth polarized radial intensity (~ r^{-3})
Follette et al. (2013)

mm-cavity radius at 36 AU,
low-contrast asymmetry
Andrews et al. (2011), Pérez et al. (2014)

Questions:

1. What produce the inner ring at 7AU?
2. How to have a smooth distribution of small grains from 14 AU?
3. How to create the asymmetry?

Two planets models



Questions:

1. What produce the inner ring at 7AU?
   A potential planet at ~5AU.
   1Mjup planet is enough to form a ring of gas and dust at ~7AU.

2. How to have a smooth distribution of small grains from 14 AU?
   The outer planet cannot be very massive. High diffusion of particles i.e. when disk viscosity is $\alpha \sim 10^{-2}$ helps to have a smooth distribution of small grains. Less spatial segregation between small and large grains. Can be also the case of of HD169142? See Osorio *et al.* (2014)

3. How to create the asymmetry?
   In such cases, vortex formation is very unlikely.
   Disk eccentricity? Spiral arms?

Conclusions

- The integrated spectral index in higher for transition disks than for regular protoplanetary disks.
- For transition disks, there is a high probability of a positive relation between the spectral index and the cavity size.
- Observations of HD100546 reveal a two-ring like emission consistent with tapping by two companions. The outer companion must be younger than the inner companion.
- To have a smooth distribution of small grains while large grains are located at pressure maxima, high turbulence is needed. In such cases, long-lived vortices are unlikely to exist.

THANK YOU!