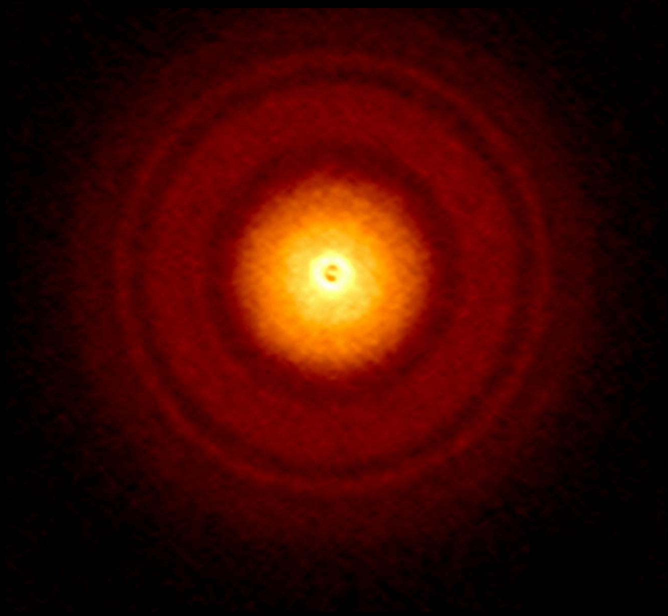
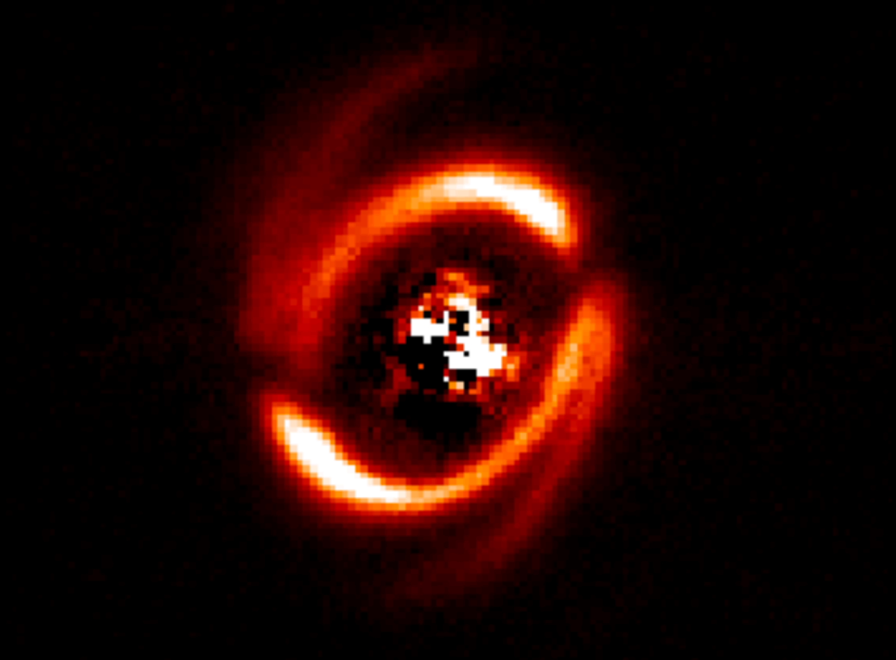
Protoplanetary disks: Searching for the origin of rings, warps & spirals





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Rings, warps and spirals

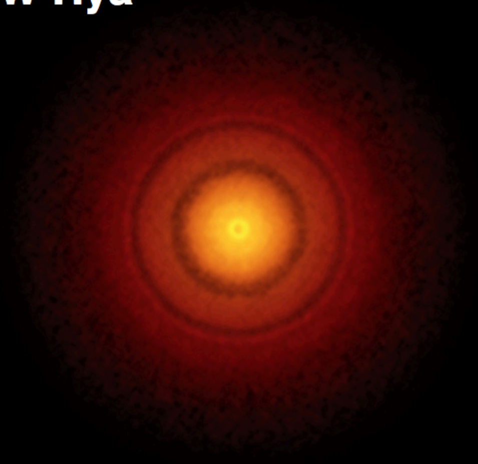
1. Rings in protoplanetary disks
2. Warped ("broken") protoplanetary disks
3. Spirals in protoplanetary disks

Topic 1:

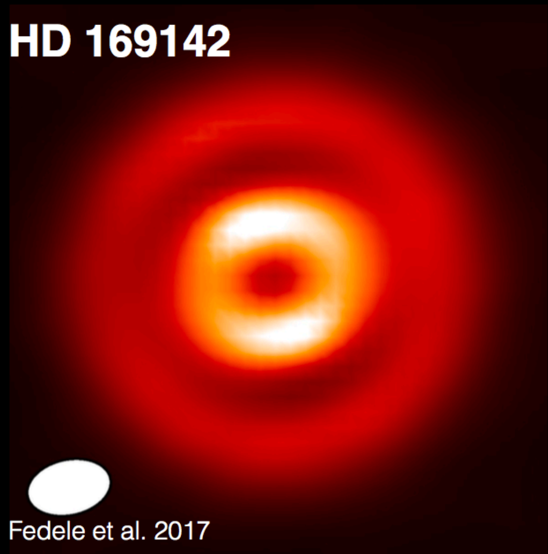
Rings

Protoplanetary disks: Rings & Dust Traps

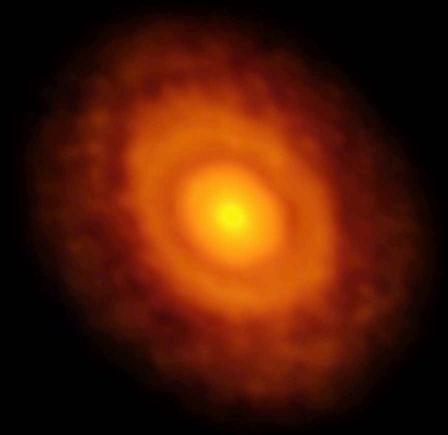
TW Hya



Andrews et al. 2016



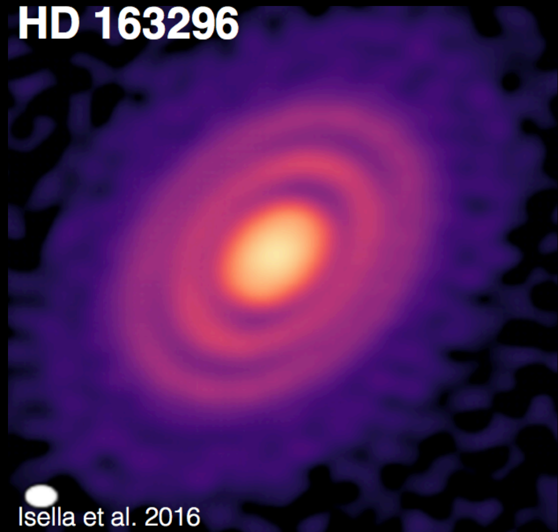
V883 Ori



Cieza et al. 2016

HD 97048

Van der Plas et al. 2016



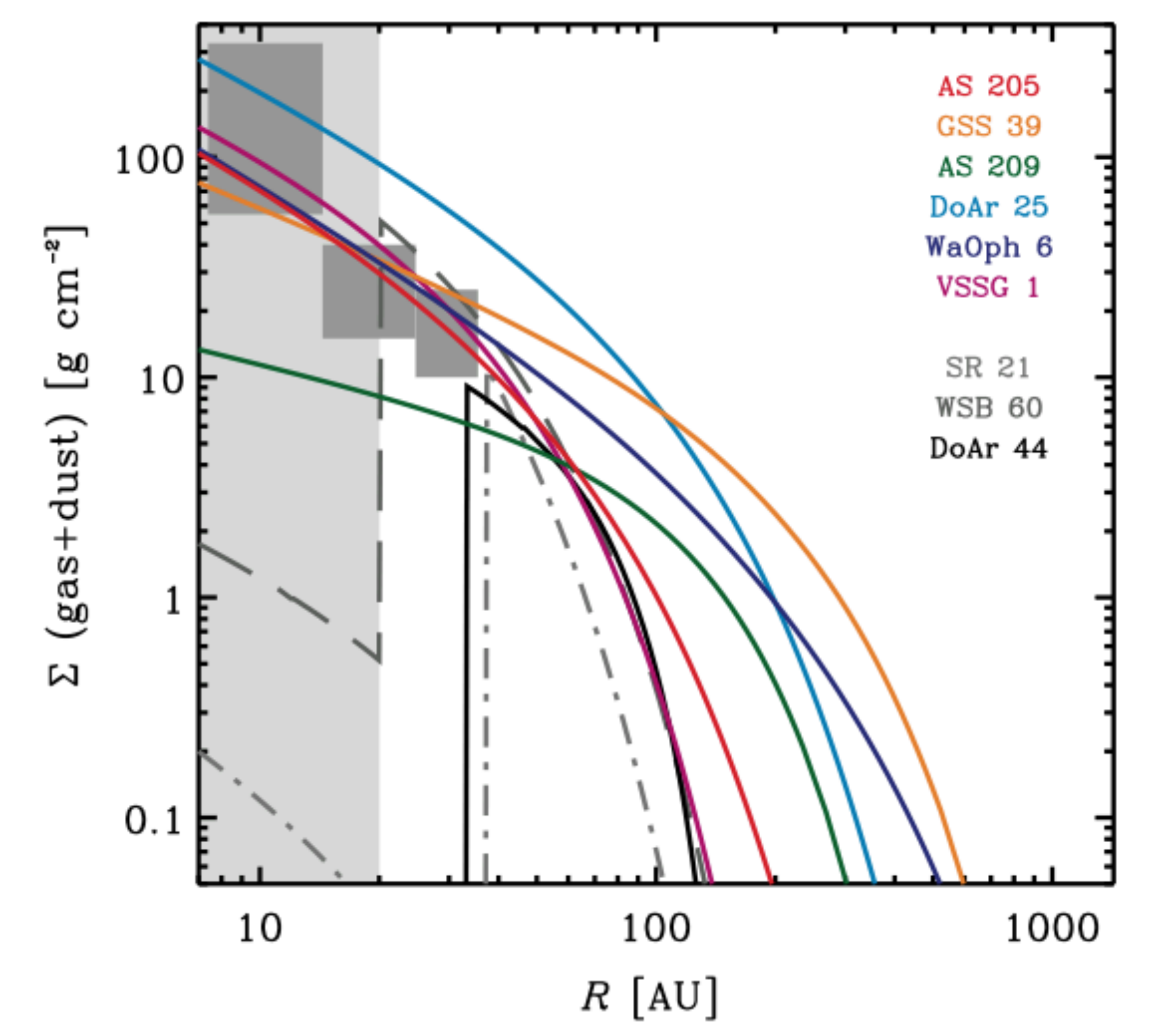
Observations
with ALMA

And stay tuned for the ALMA Large programme data of Andrews, Perez, Dullemond & Isella... Due September 2018

Intermezzo:

The dust drift problem

Radial drift also problem for mm-observations



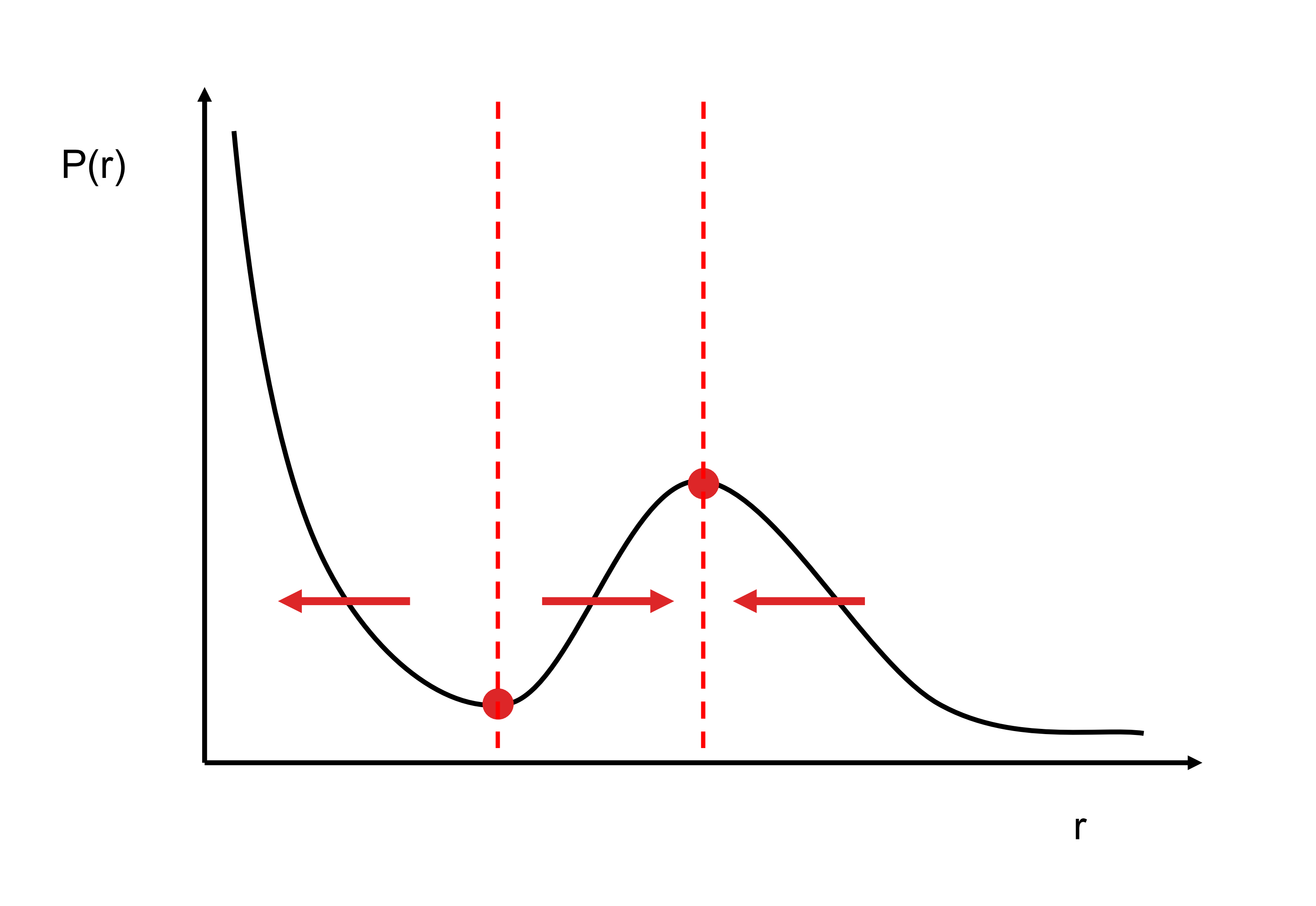
Andrews et al. 2009, 2011

$$t_{\rm drift} \approx 0.25 \left(\frac{R}{100\,AU} \right) \mathrm{Myr}$$

The large dust grains that are observed should have long ago drifted inward.

Why are they still there?

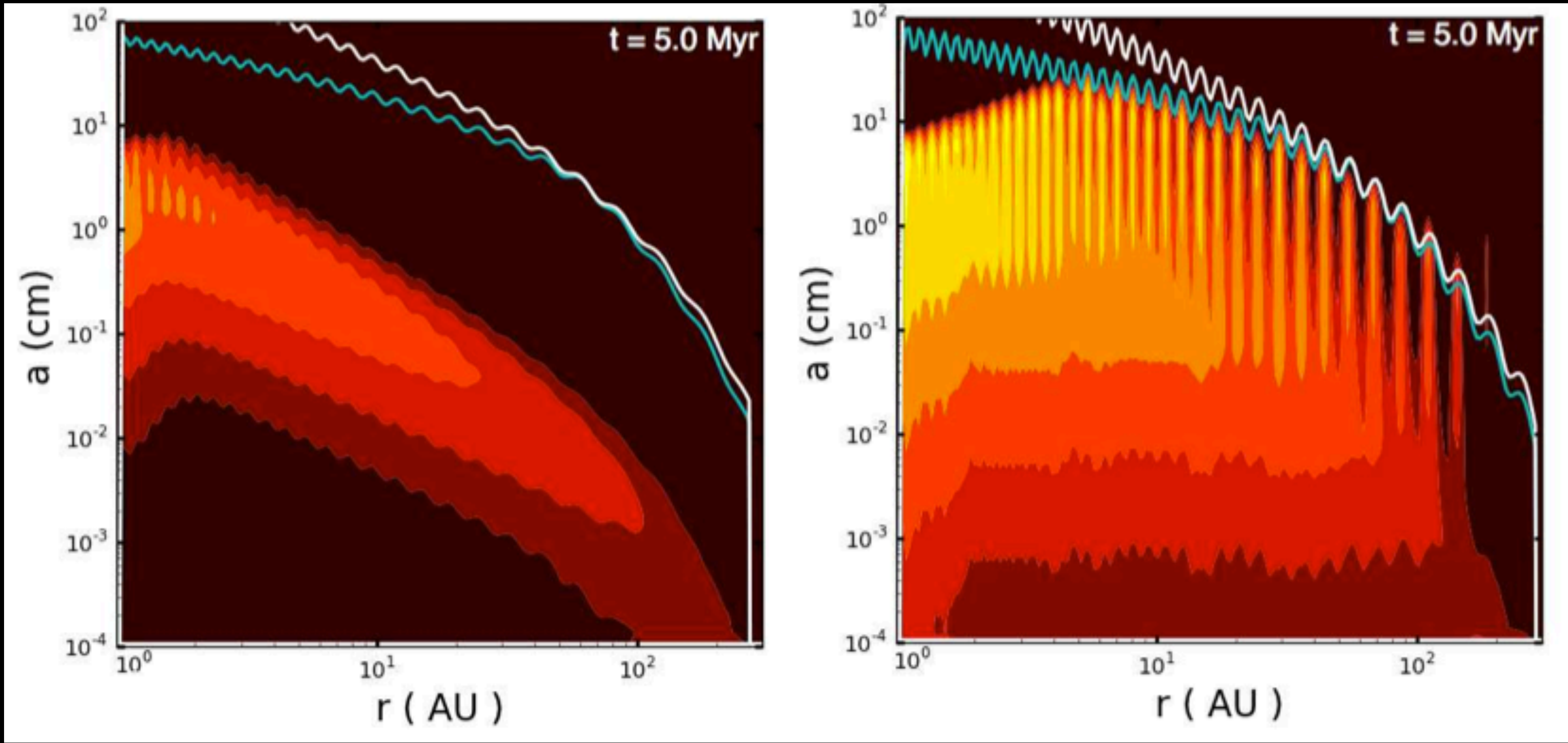
Particles move toward pressure peak



Whipple 1972; Barge & Sommeria 1995; Klahr & Henning 1997; Kretke & Lin 2008; Dzyurkevich et al. 2010; Kato et al. 2010; Johansen et al. 2009; Garaud 2007

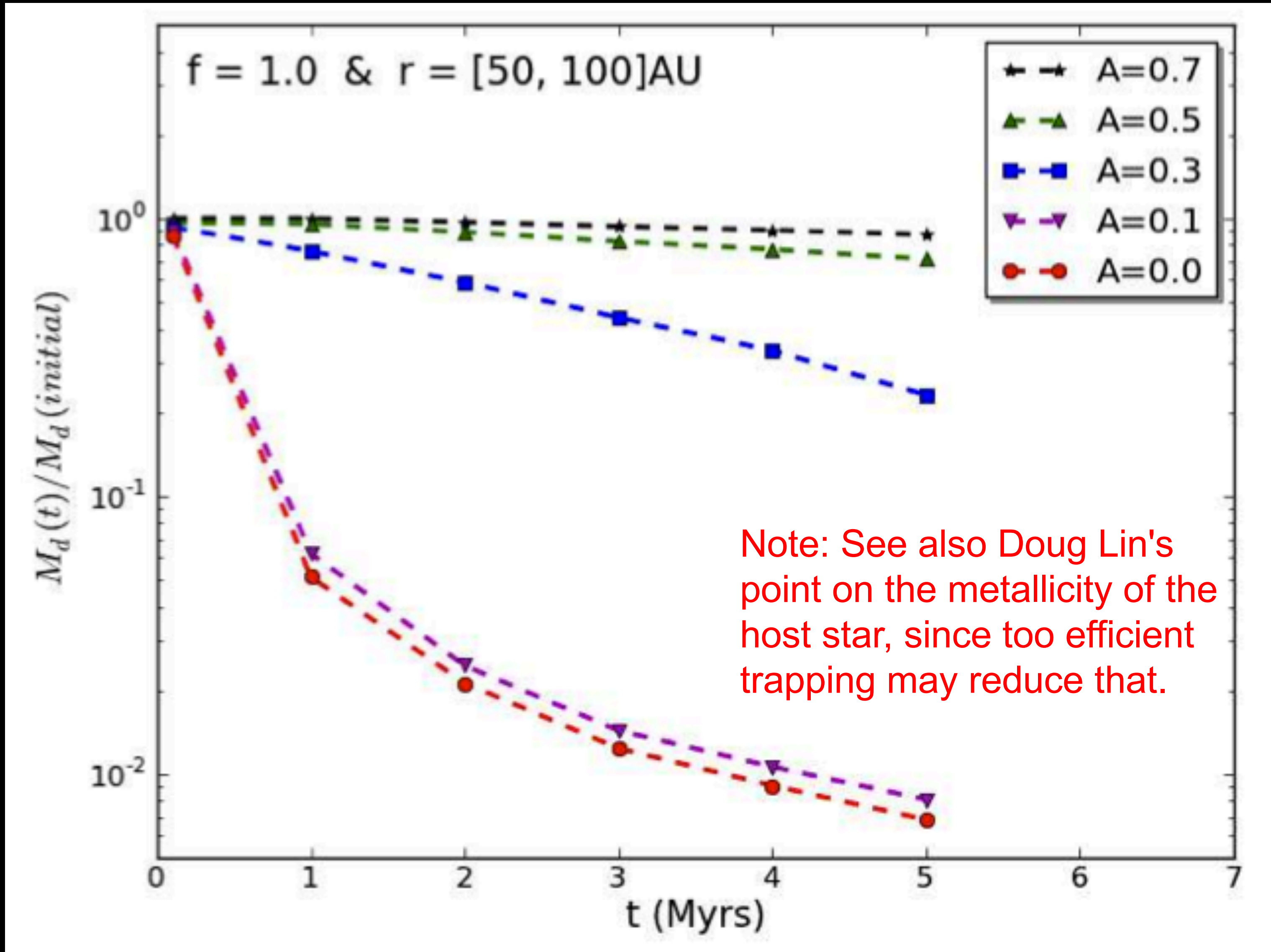
Simple experiment: Lots of small bumps

Weak bumps | Strong bumps



Pinilla et al. 2012

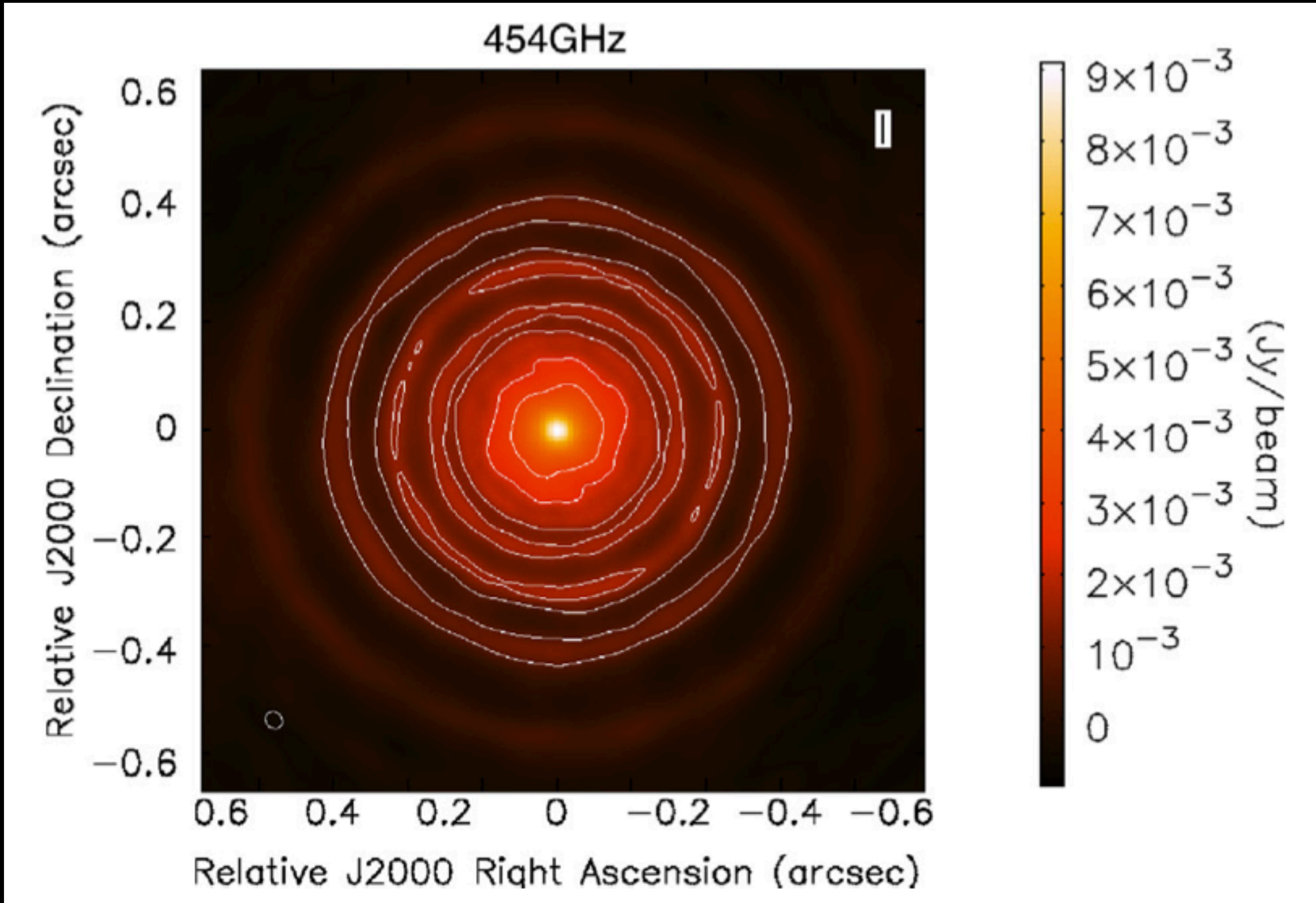
Simple experiment: Lots of small bumps



Pinilla et al. 2012

Simple experiment: Lots of small bumps

ALMA prediction



Pinilla et al. 2012

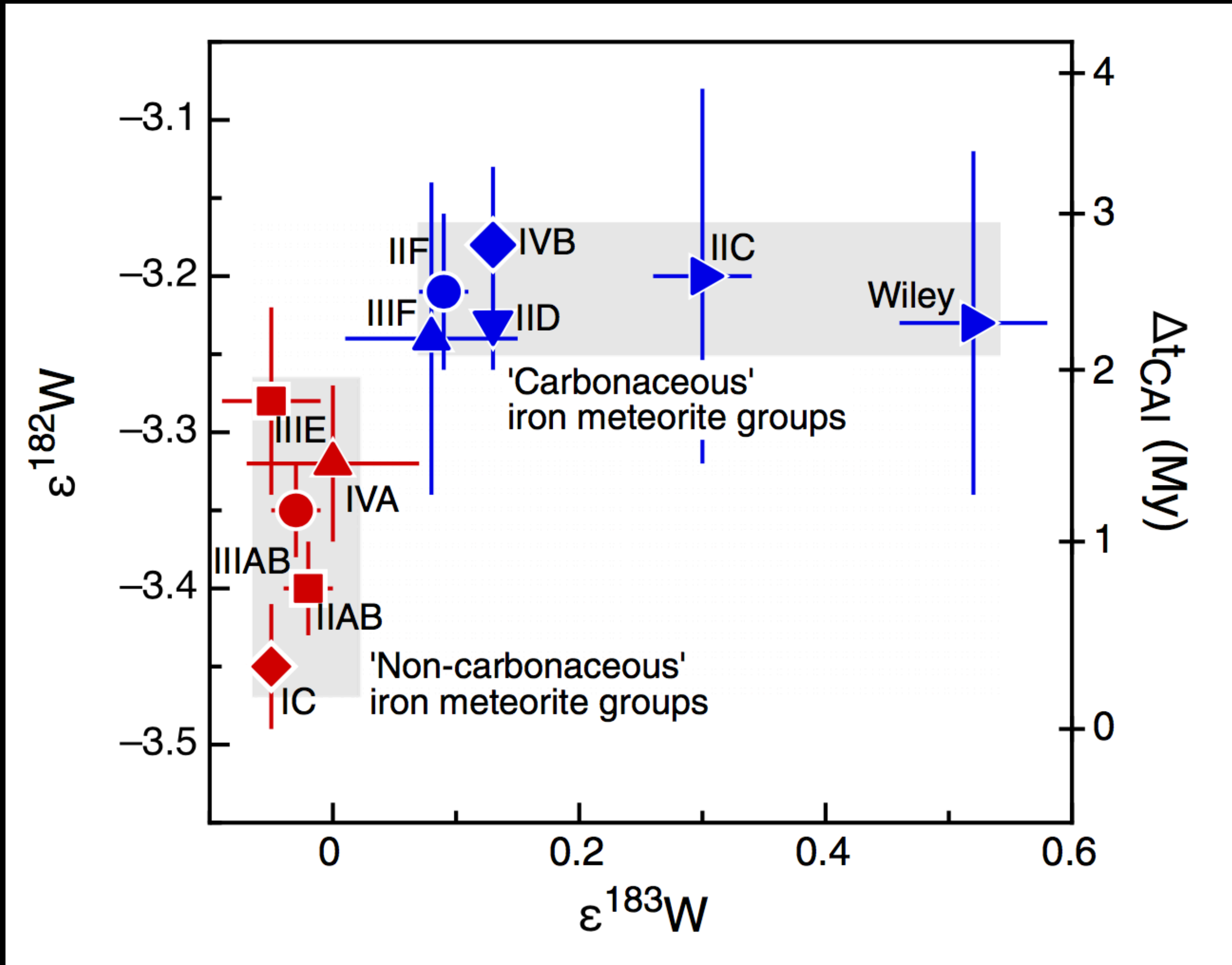
Dust rings are necessary!

- Without some trapping mechanism, most of the dust seen with (sub-)millimeter arrays should not be there anymore.
- Dust trapping in pressure bumps (whatever their origin) keeps the dust in the outer regions.

- Good side effects:
  - Concentration of dust → conditions for planet formation
  - Isolated reservoirs → compositional reservoirs

To mix or not to mix

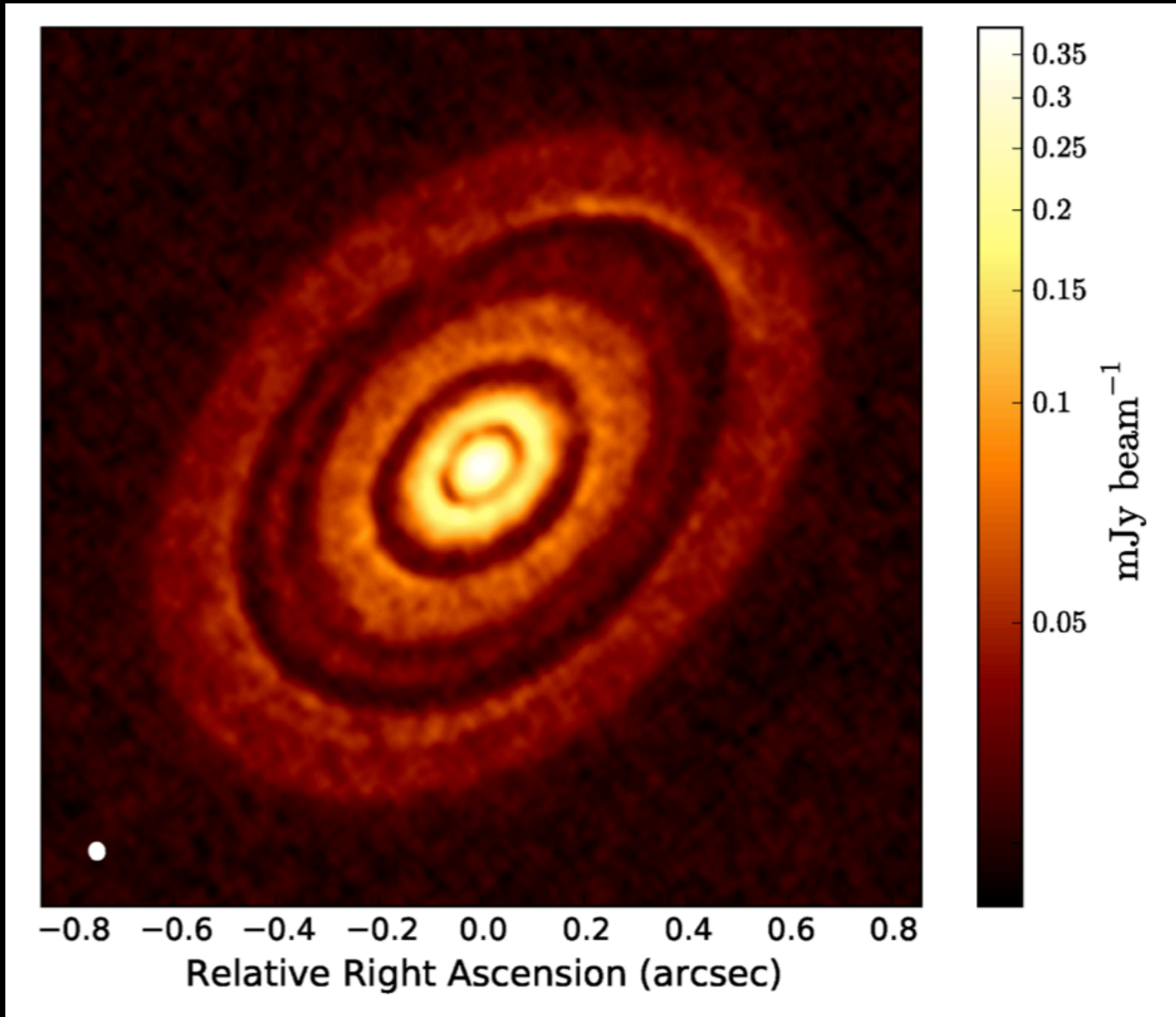
Solar System had distinct reservoirs already early on.
Could this be related to the rings we see in protoplanetary disks?



Kruijer, Burkhardt, Budde & Kleine (2017)

What is the origin
of these rings/traps?

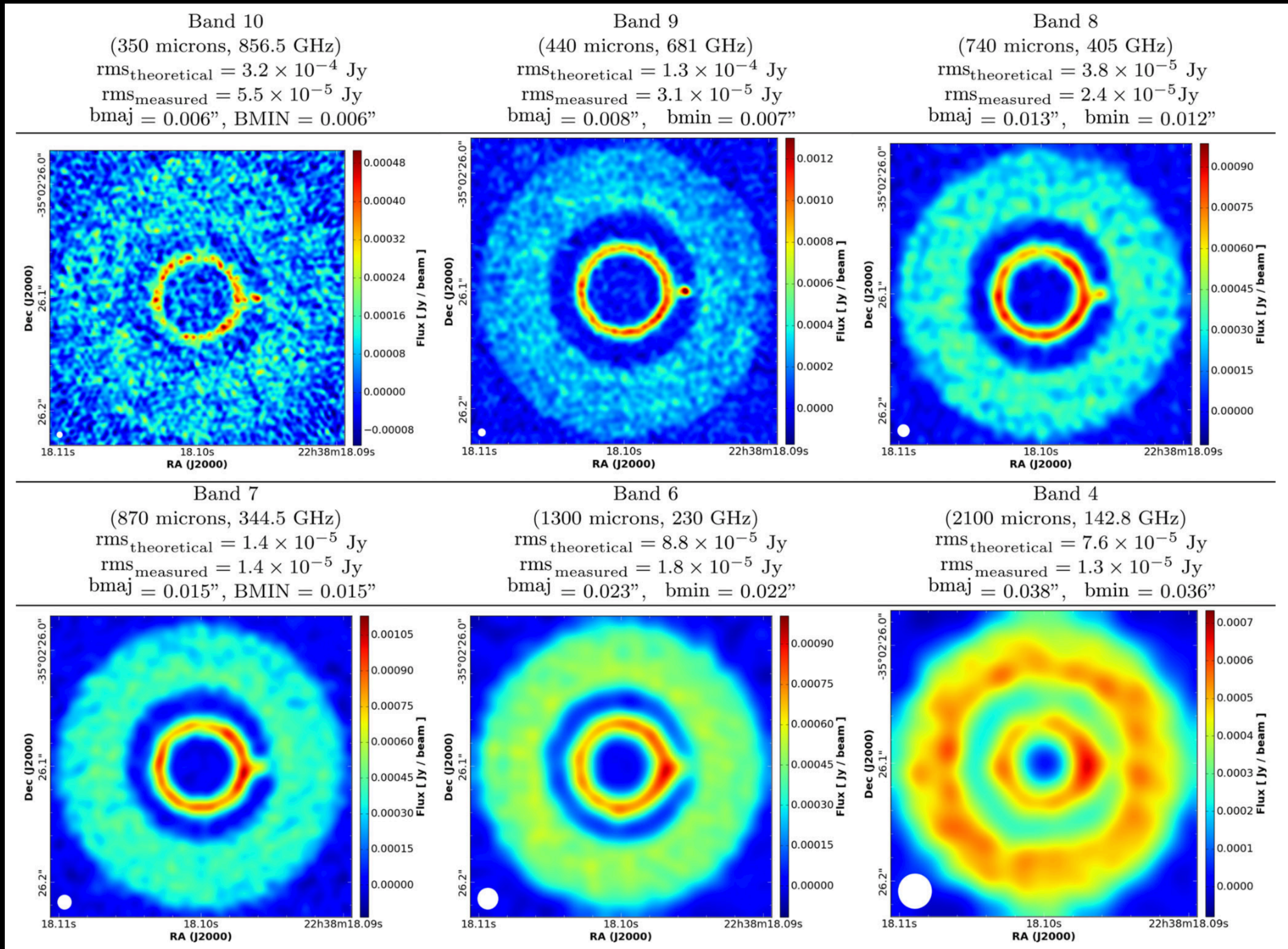
Are these planet gaps?



Dipierro et al. 2015

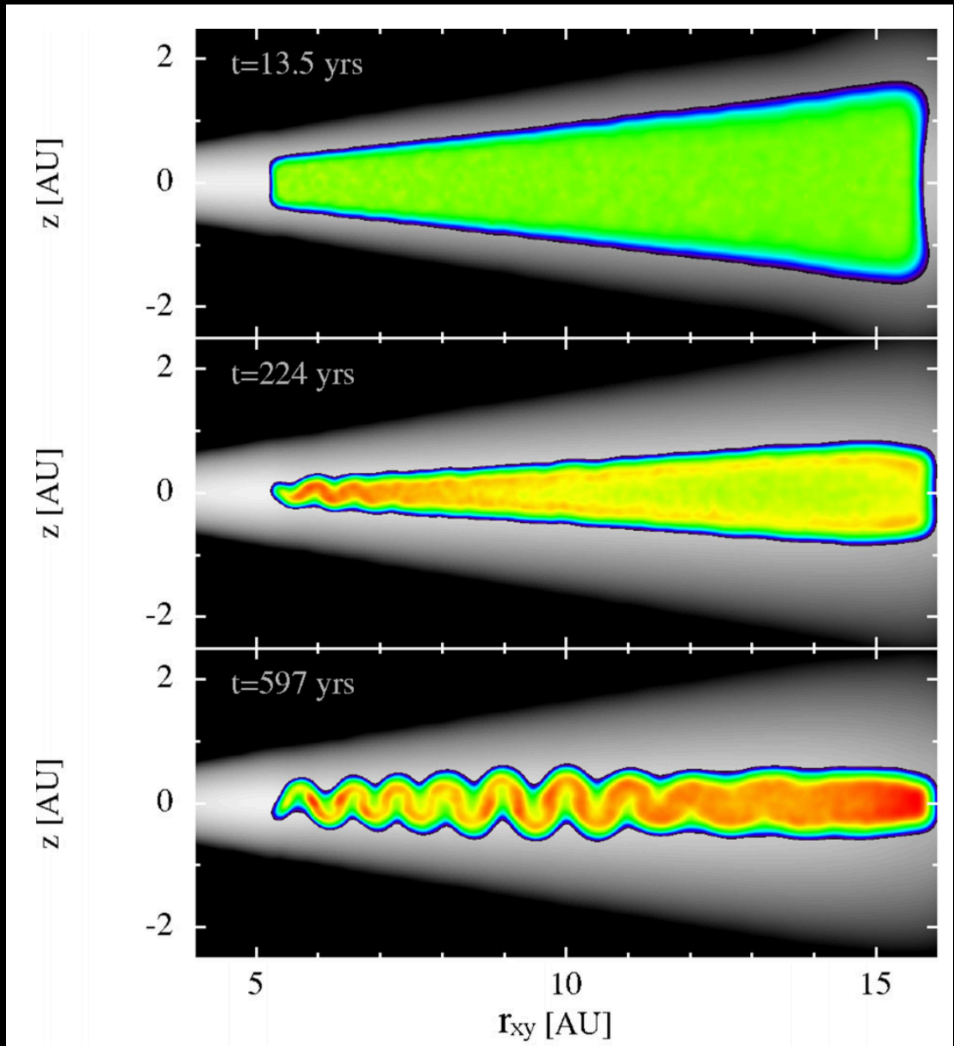
Kanagawa et al. 2015; Picogna & Kley 2015; Akiyama et al. 2016; Boley 2017 and more...

If planets, shouldn't we see the CPD?

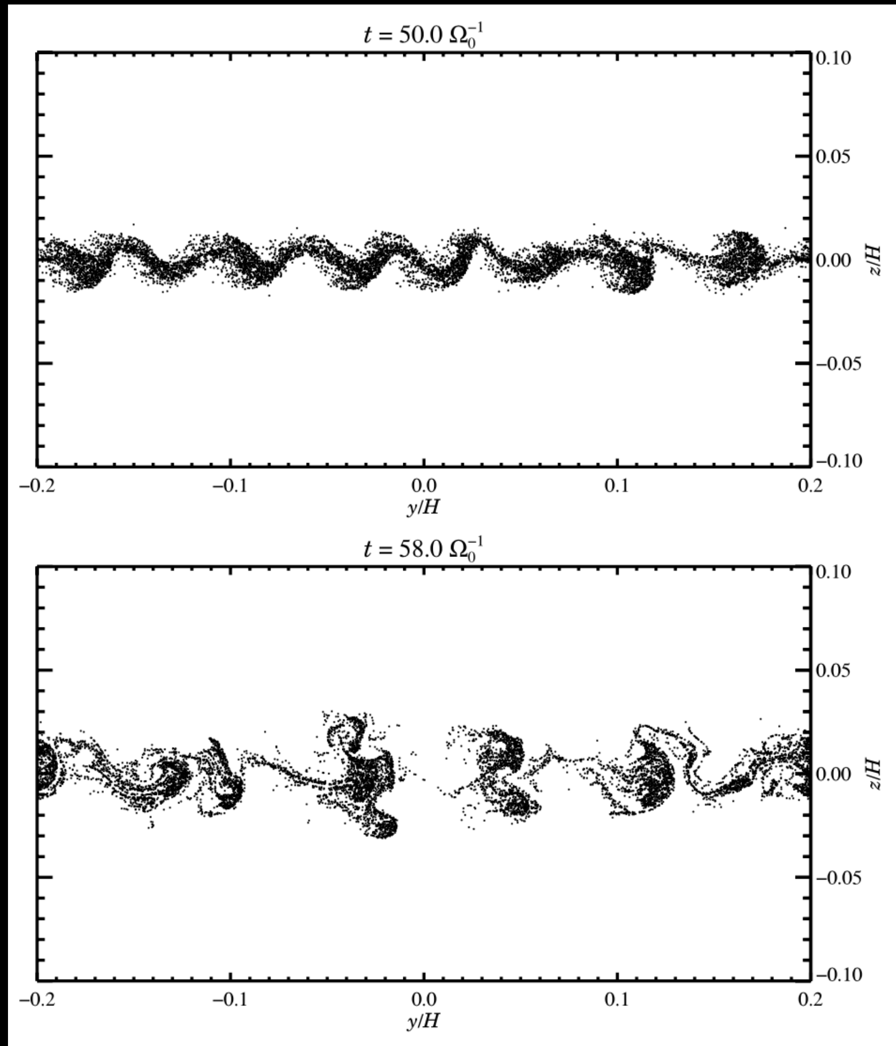


Szulagyi & Mordasini 2017

Toroidal vortex model

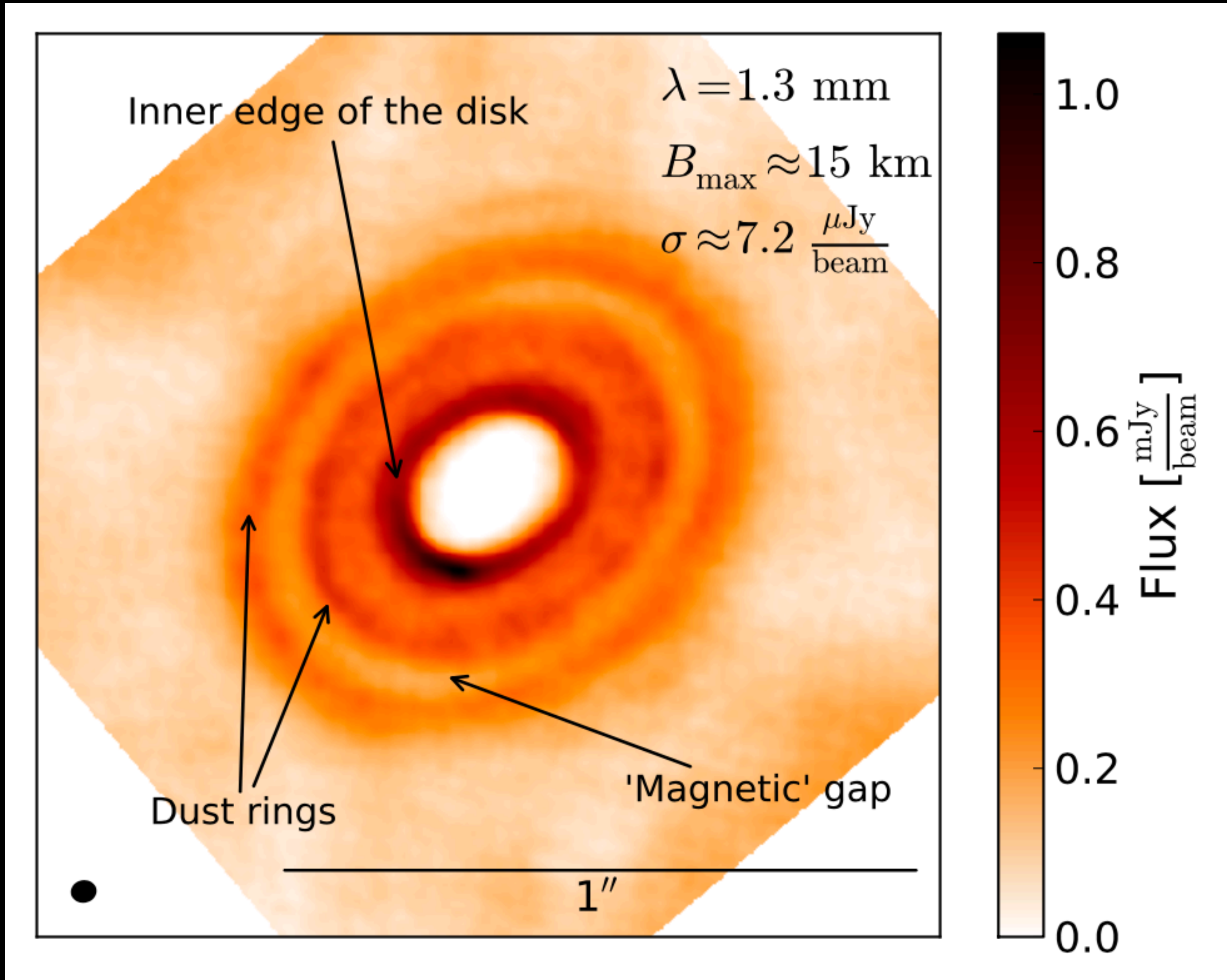


Loren-Aguilar & Bate (2015)



Johansen, Henning & Klahr (2006)

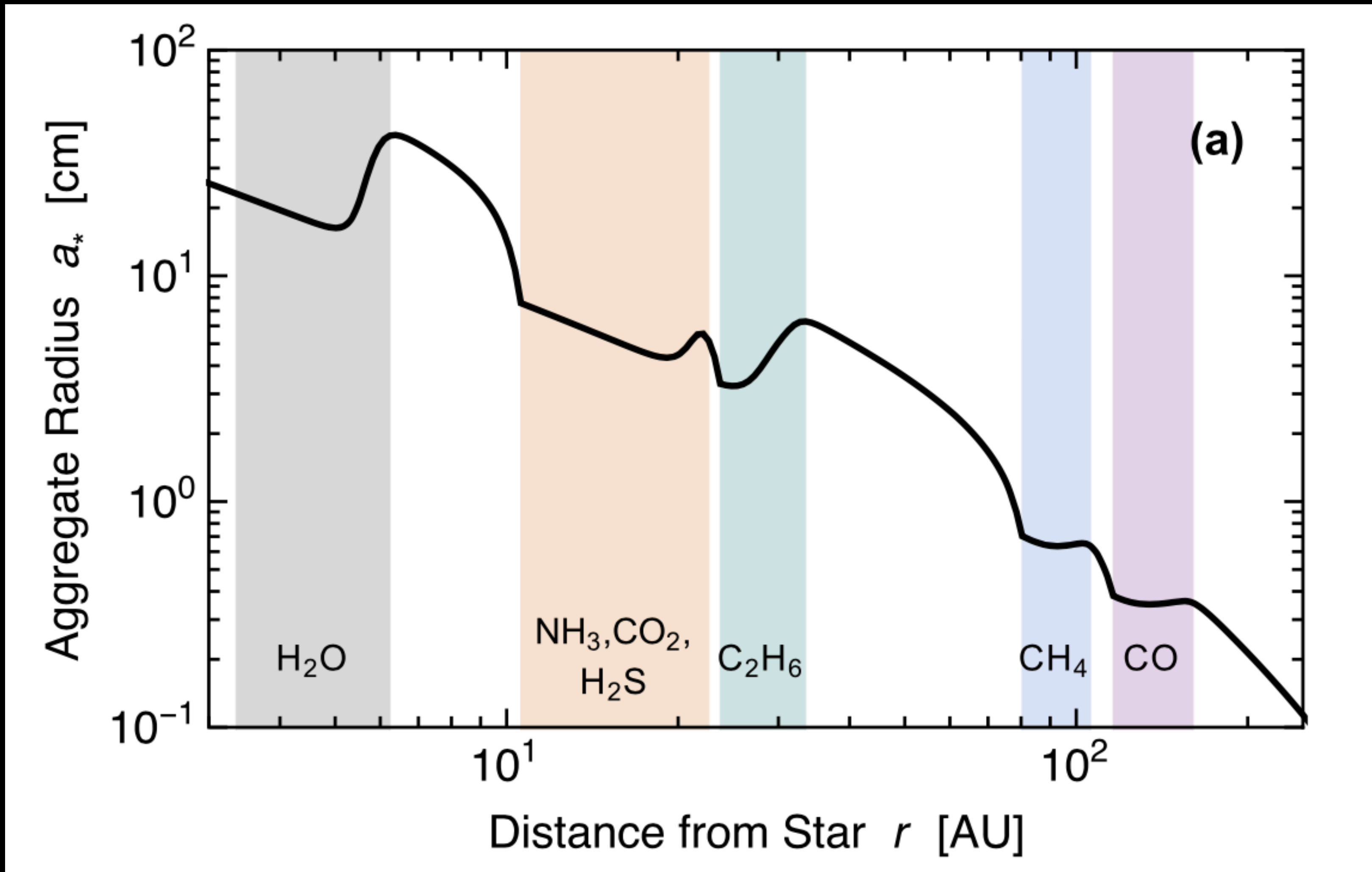
Zonal flows in MRI disks



Ruge, Flock et al. (2016)

Johansen 2009; Dzyurkevich et al. 2010; Uribe et al. 2011; Dittrich et al. 2013; Flock et al. 2015

Ice lines

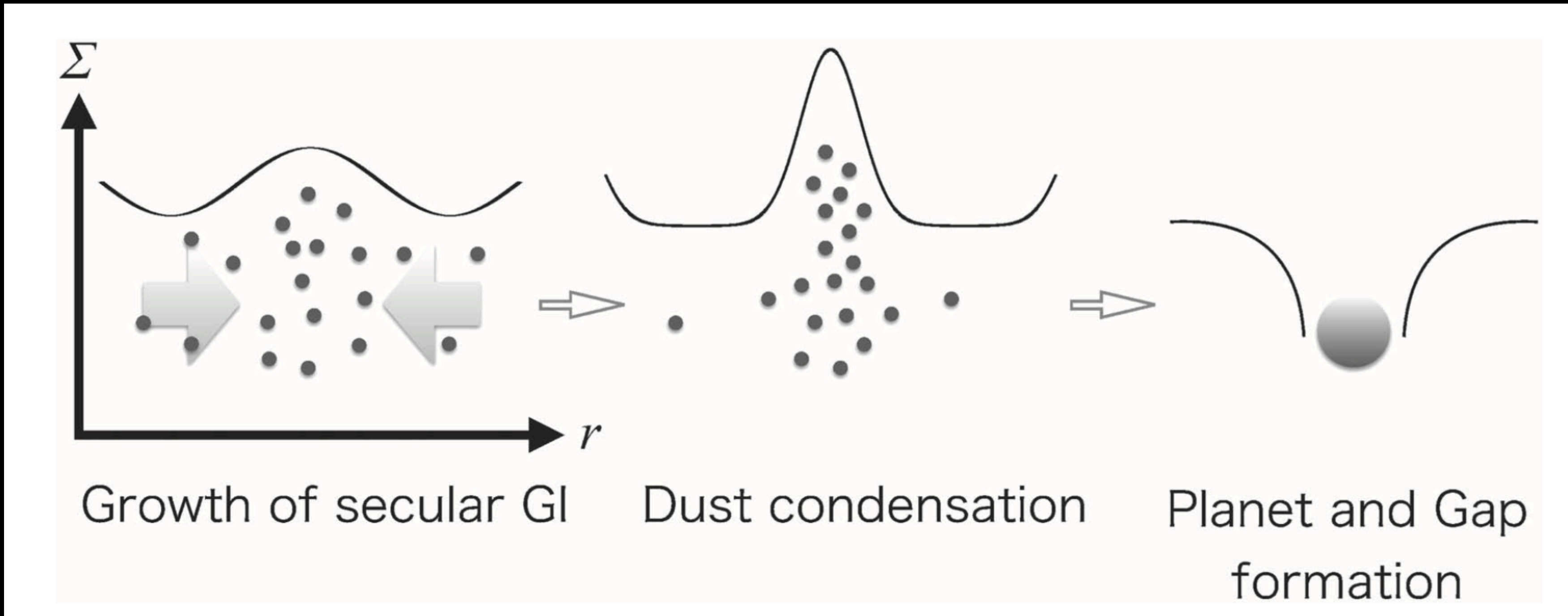


Okuzumi et al. 2016
Zhang et al. 2015

Secular GI in pebble population

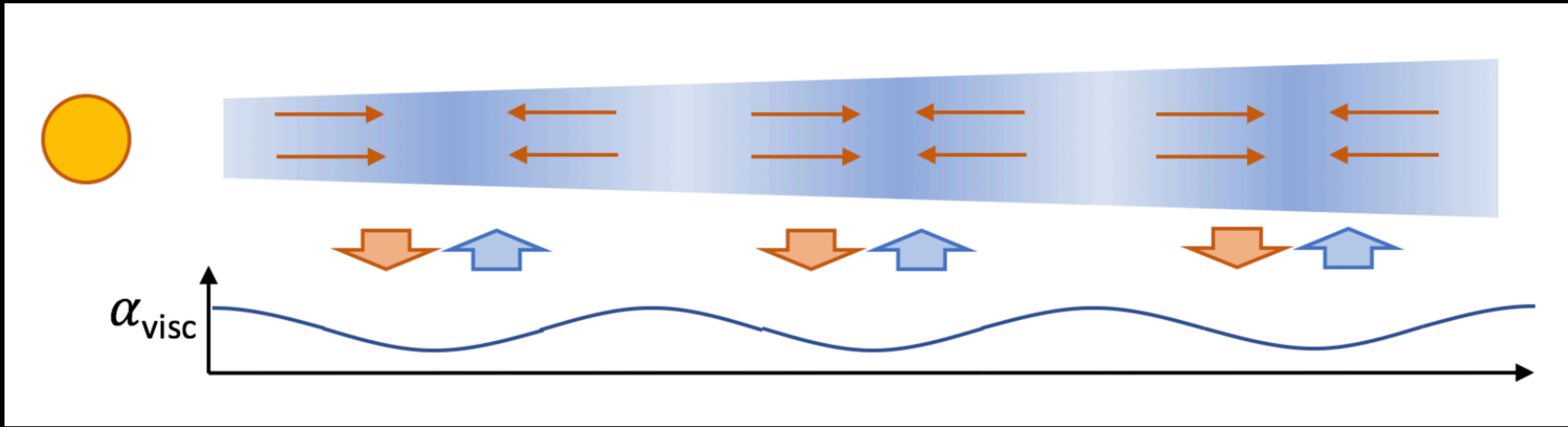
Secular GI in pebble population: Shariff & Cuzzi (2011), Youdin (2011), Takahashi & Inutsuka (2014)

Key: Slow gravitational contraction, mediated by the gas.



Takahashi & Inutsuka (2016)

Viscous ring instability driven by dust



Main ingredients:

1. Gas pressure bump attracts dust
2. Dust makes disk 'deader' → reduces ν
3. Viscous disk wants to keep $\Sigma\nu$ constant
4. So reduced ν means increasing Σ
5. This strengthens pressure bump
6. Goto 1

Dullemond & Penzlin (2018)

Viscous ring instability driven by dust

Equations (simplified form):
Coupled conservation equations for gas and dust:

$$
\begin{aligned}
\frac{\partial \Sigma_{\mathrm{g}}}{\partial t} + \frac{1}{r_0}\frac{\partial}{\partial x}\left(\Sigma_{\mathrm{g}} v_{x\mathrm{g}}\right) &= 0, \\
\frac{\partial \Sigma_{\mathrm{d}}}{\partial t} + \frac{1}{r_0}\frac{\partial}{\partial x}\left(\Sigma_{\mathrm{d}} v_{x\mathrm{d}}\right) &= \frac{1}{r_0^2}\frac{\partial}{\partial x}\left(\mathcal{D}_{\mathrm{d}}\Sigma_{\mathrm{g}}\frac{\partial}{\partial x}\left(\frac{\Sigma_{\mathrm{d}}}{\Sigma_{\mathrm{g}}}\right)\right),
\end{aligned}
$$

Dullemond & Penzlin (2018)

Viscous ring instability driven by dust

Equations (simplified form):
Radial velocity for gas and dust:

Gas velocity:

$$v_{x\mathrm{g}} = -\frac{3}{\Sigma_{\mathrm{g}} r_0} \frac{\partial(\Sigma_{\mathrm{g}} \nu)}{\partial x},$$

Dust velocity:

$$v_{x\mathrm{d}} = \frac{1}{1+\mathrm{St}^2} v_{x\mathrm{g}} + \frac{1}{\mathrm{St}+\mathrm{St}^{-1}} \frac{c_{\mathrm{s}}^2}{\Omega_{\mathrm{K}} r_0} \frac{\partial \ln \Sigma_{\mathrm{g}}}{\partial x}.$$

Dullemond & Penzlin (2018)

Viscous ring instability driven by dust

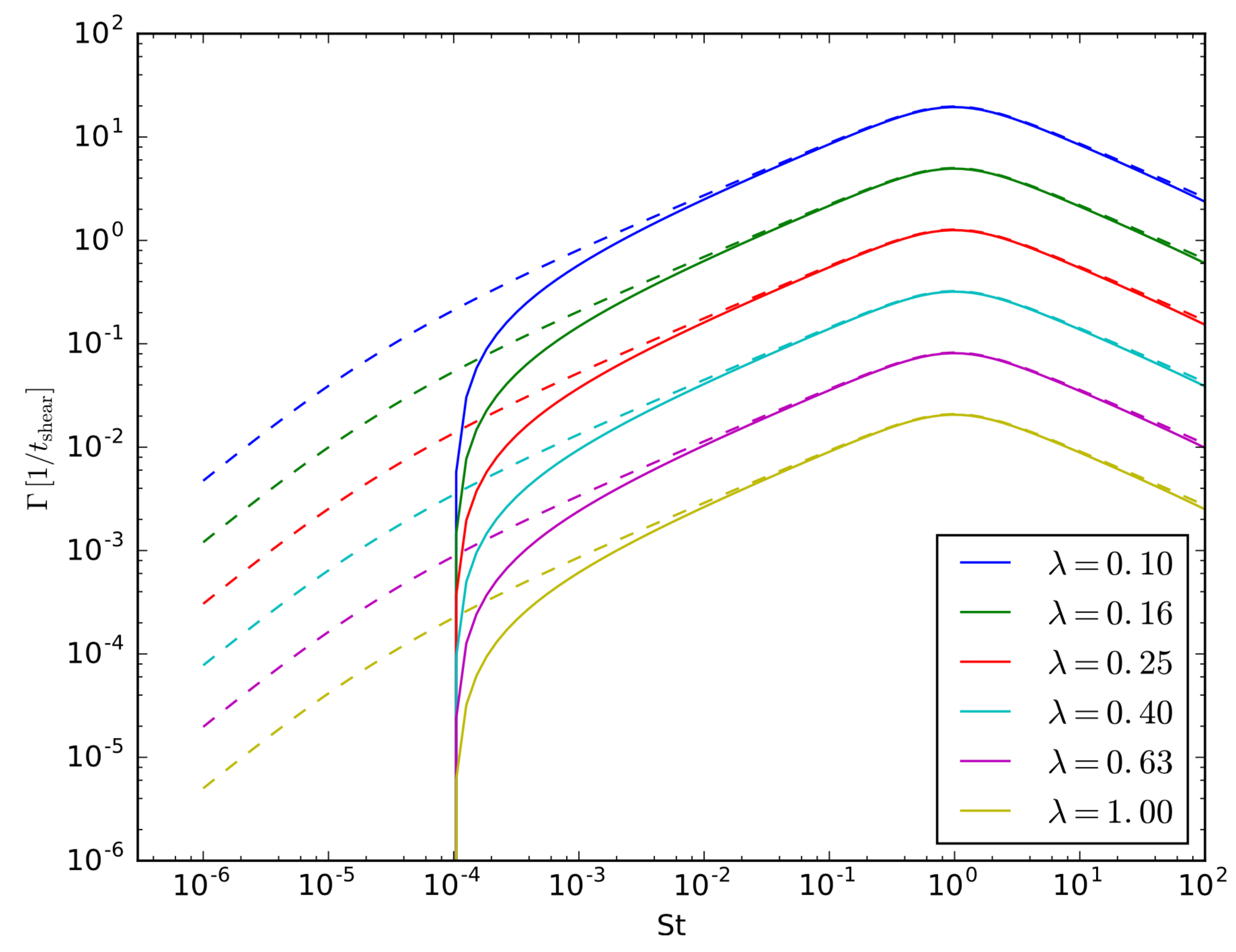
Key ingredient: *High dust → low alpha*

$$\alpha = \alpha_1 \left(\frac{\Sigma_{\rm d}}{\Sigma_{\rm d1}}\right)^{\phi_{\rm d}} \left(\frac{\Sigma_{\rm g}}{\Sigma_{\rm g1}}\right)^{\phi_{\rm g}},$$

Parameterized form (because we do not know exactly how)

Dullemond & Penzlin (2018)

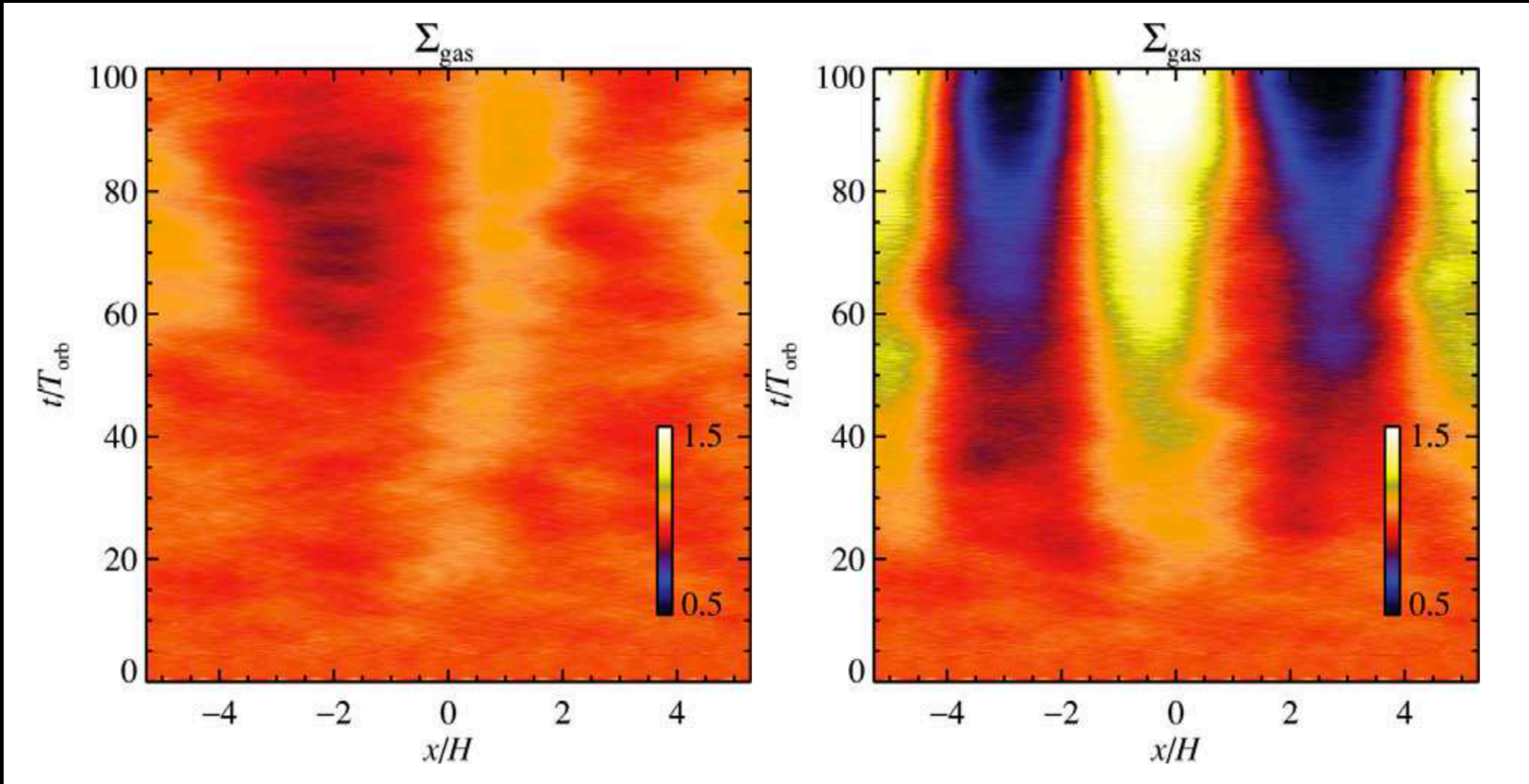
Viscous ring instability driven by dust



Dullemond & Penzlin (2018)

Viscous ring instability driven by dust

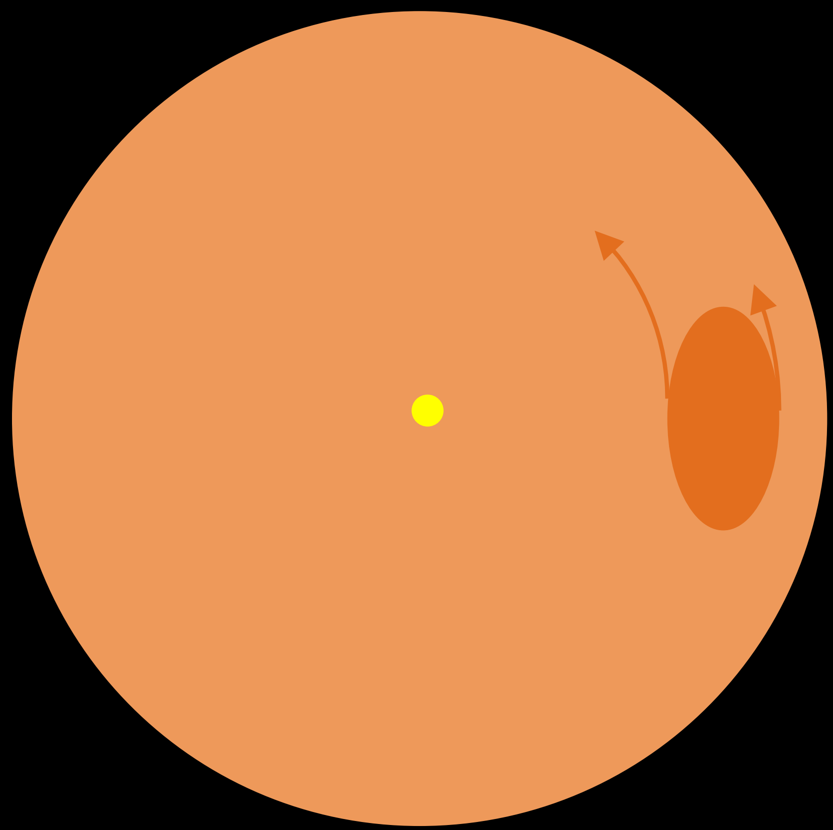
Similar effect found in MHD + dust models



Johansen, Kato & Sano (2011)

To create rings: instability must be slow

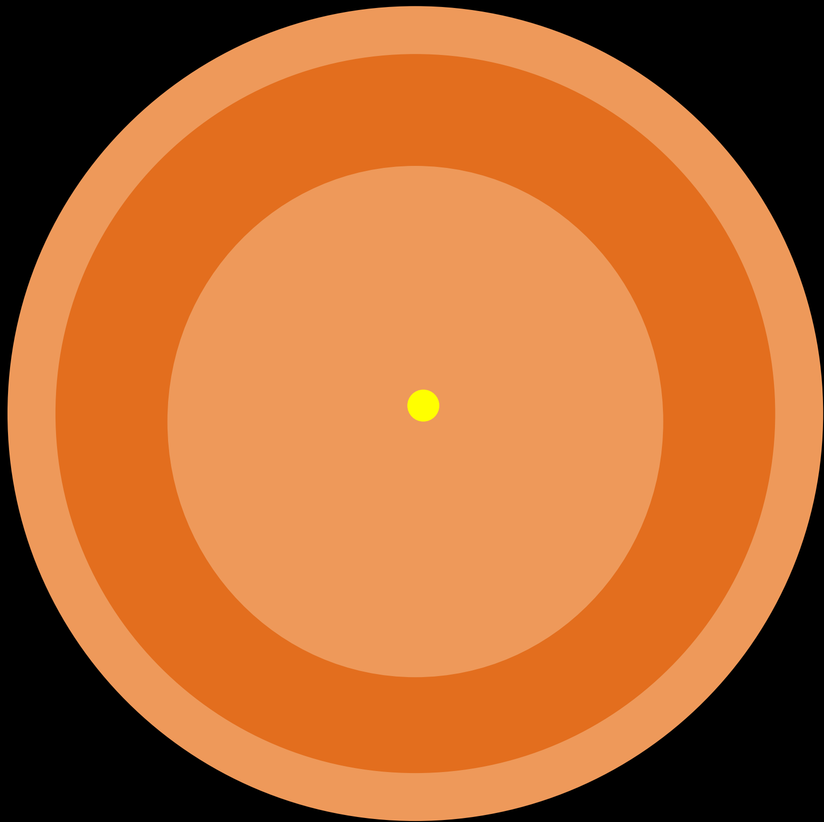
Slow enough that any local bumps shear out to become rings



If not: the instability will create blobs and arcs, but not grand design rings

To create rings: instability must be slow

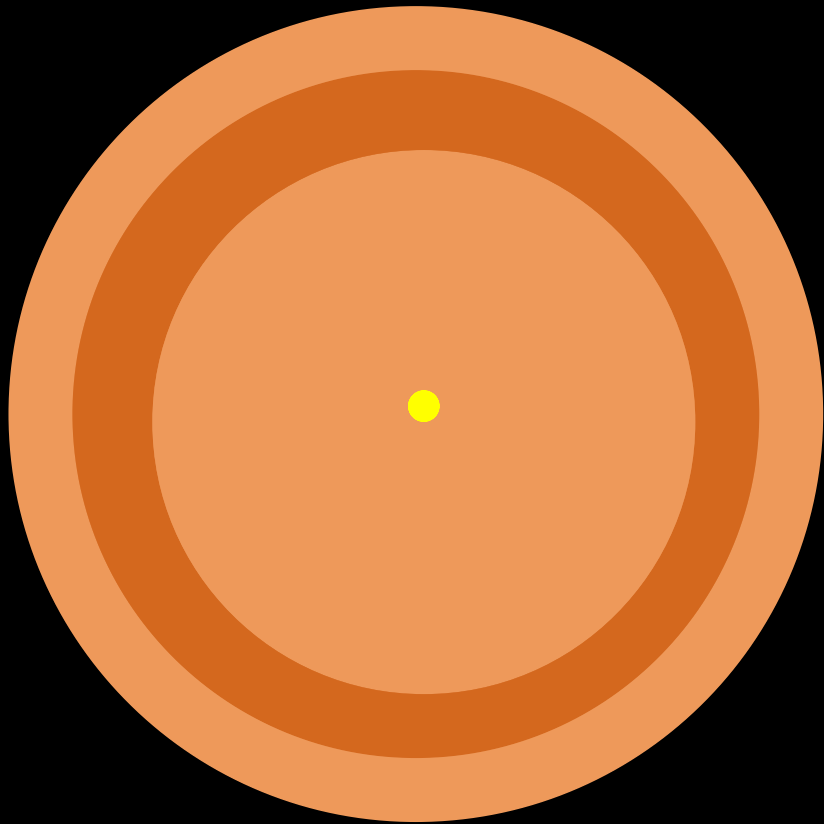
Slow enough that any local bumps shear out to become rings



If not: the instability will create blobs and arcs, but not grand design rings

To create rings: instability must be slow

Slow enough that any local bumps shear out to become rings



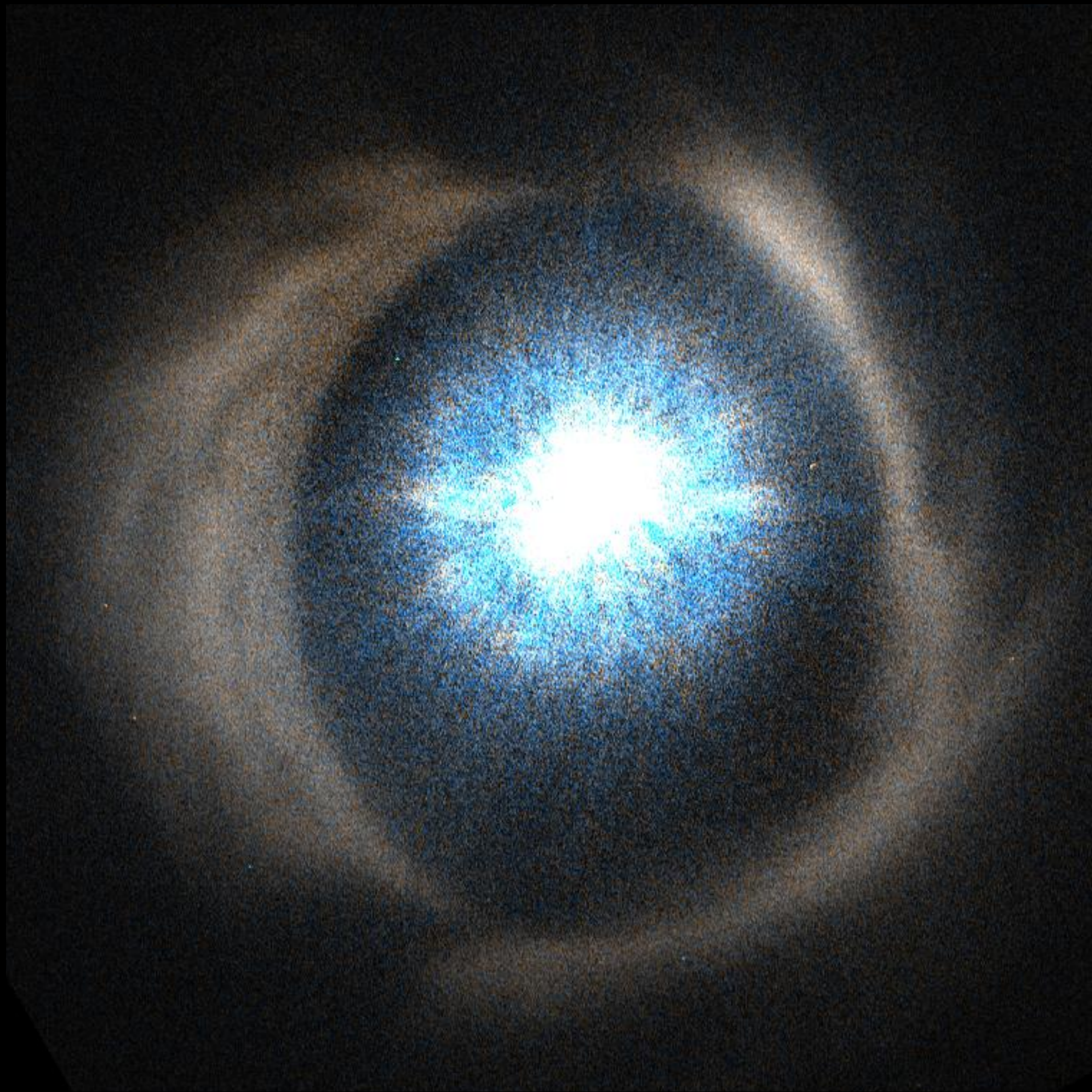
If not: the instability will create blobs and arcs, but not grand design rings

Topic 2: Warps

Tilted inner disks in TD sources:

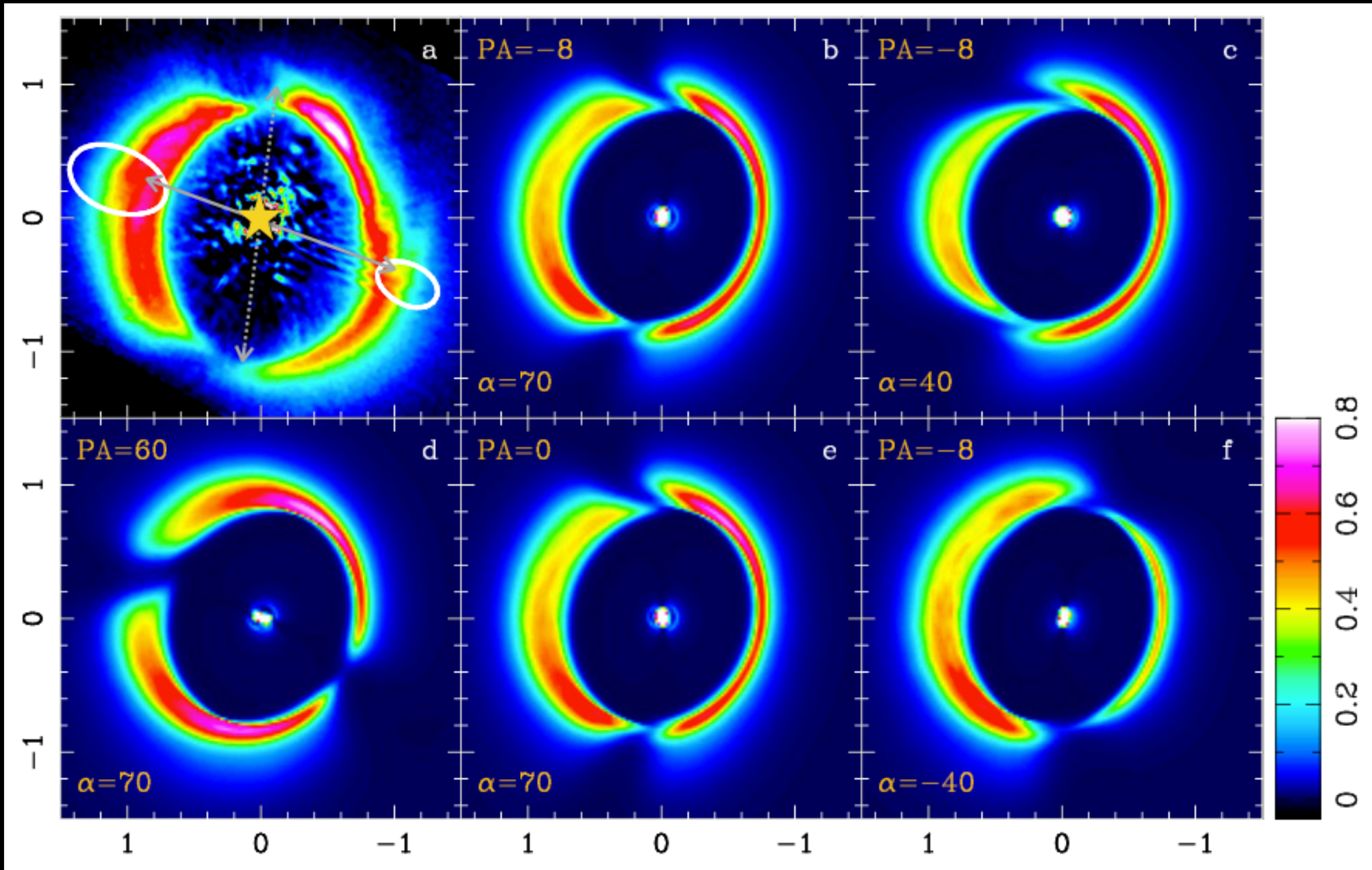
The “cloud capture” model

The Transition Disk HD 142527



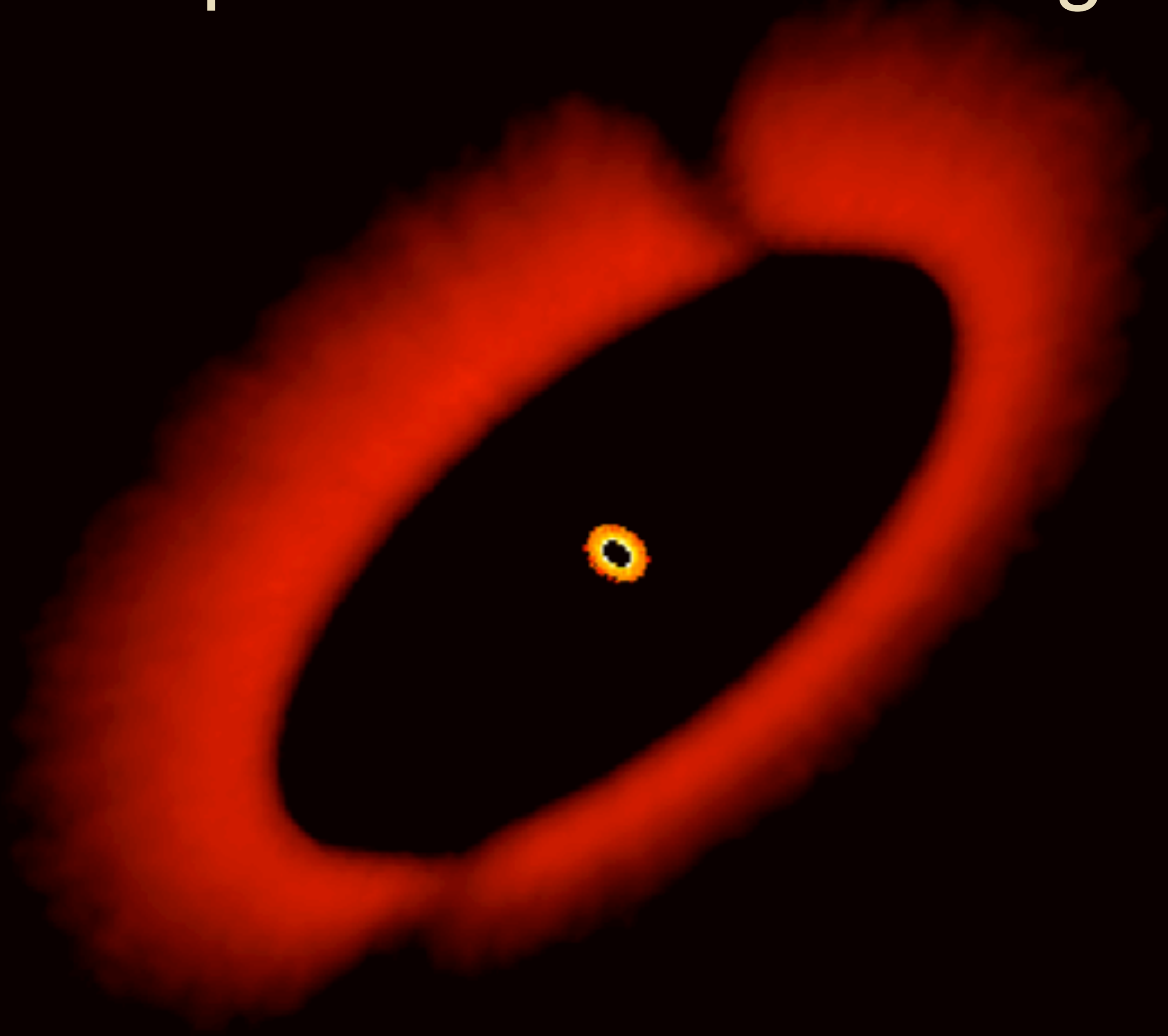
VLT-SPHERE image of HD 142527

HD 142527: A tilted inner disk



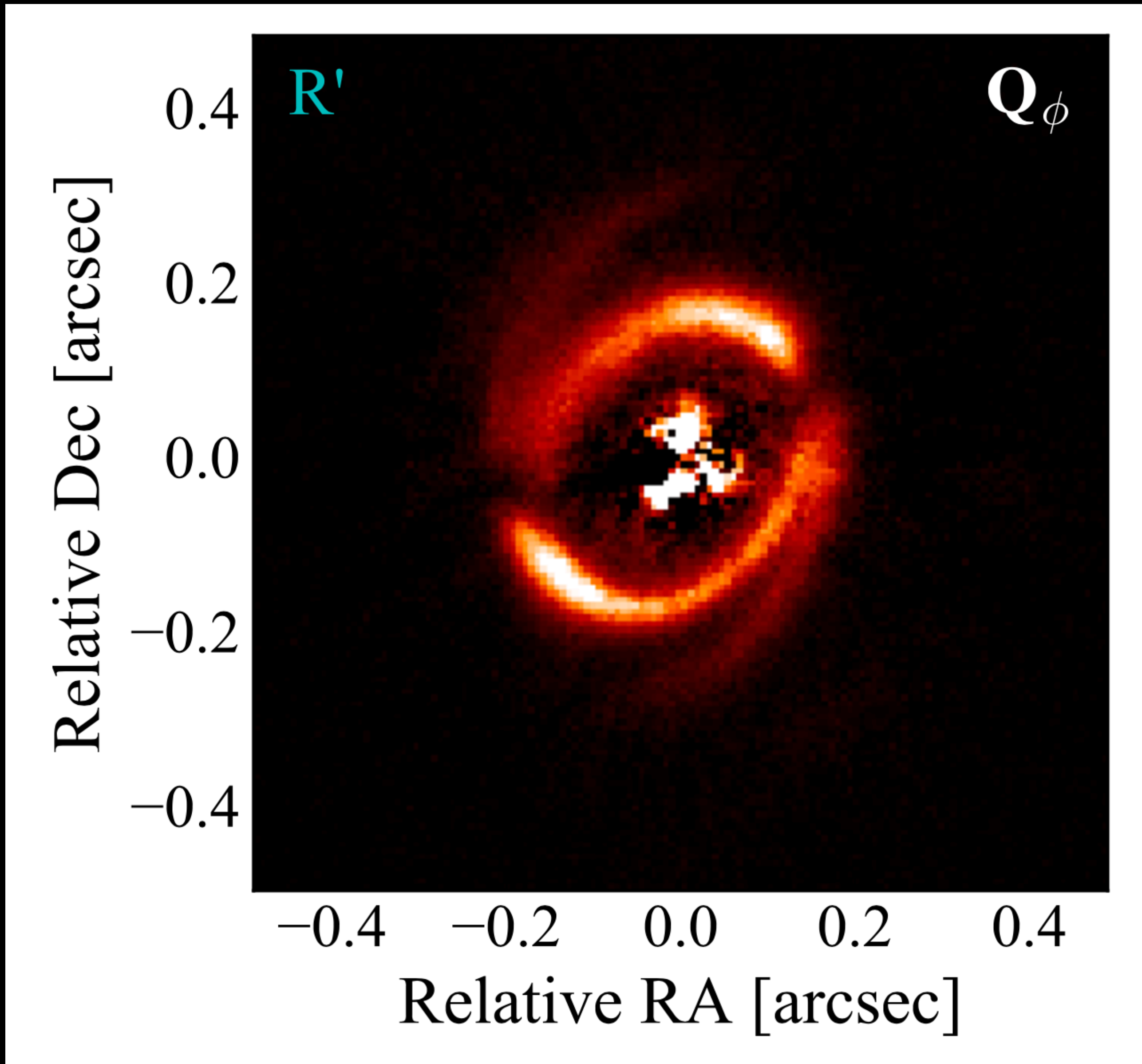
Marino et al. 2014

Close-up from another viewing angle



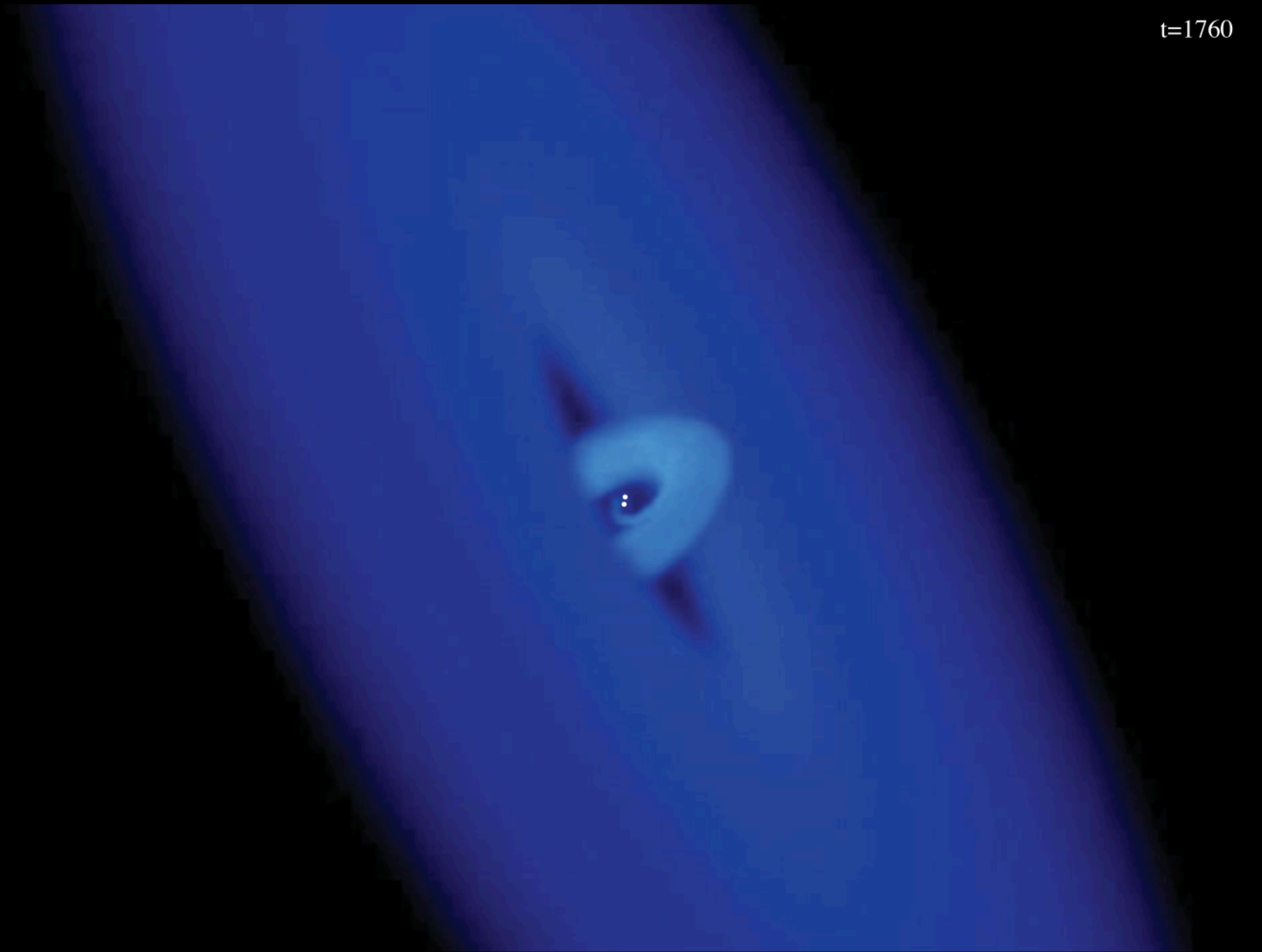
Star is removed for clarity
Model shown here is not optimized for HD142527

Another example: HD 100453



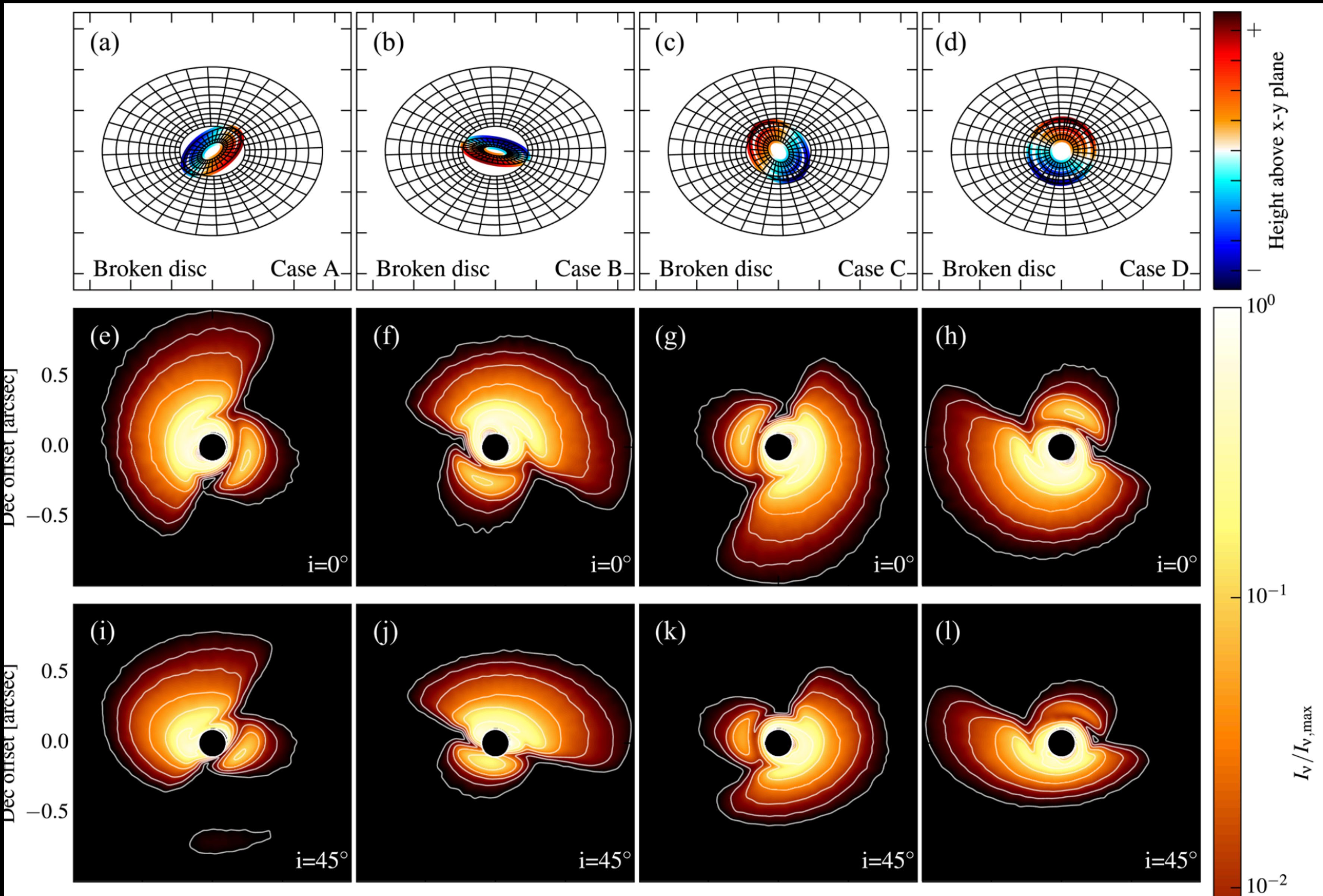
Benisty et al. (2017)

Inclined inner binary: breaking the disk



Facchini, Lodato & Price (2013)

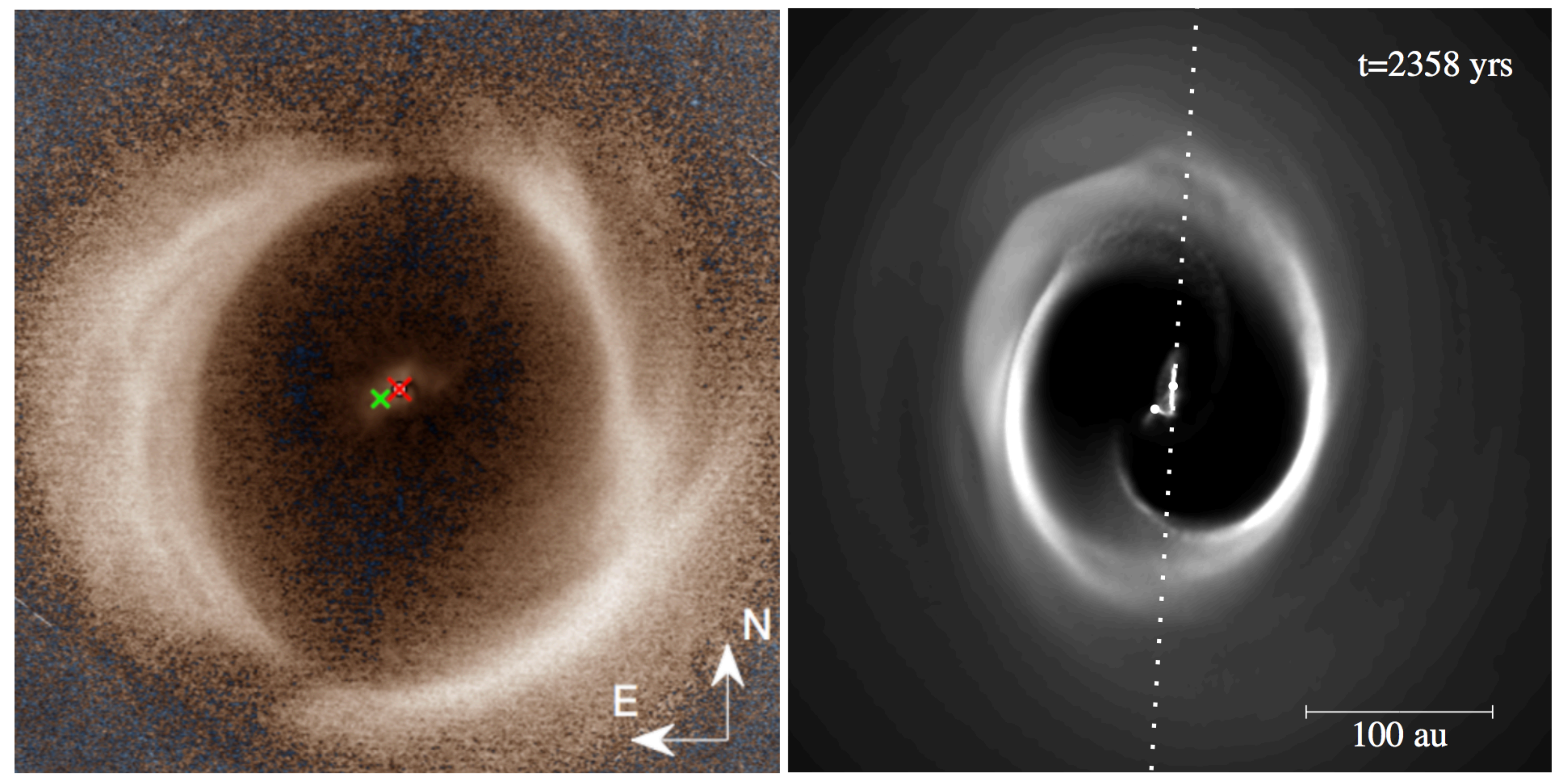
Broken disks in scattered light



Facchini, Juhasz & Lodato (2018)

TDs: "just" circumbinary disks?

HD 142527



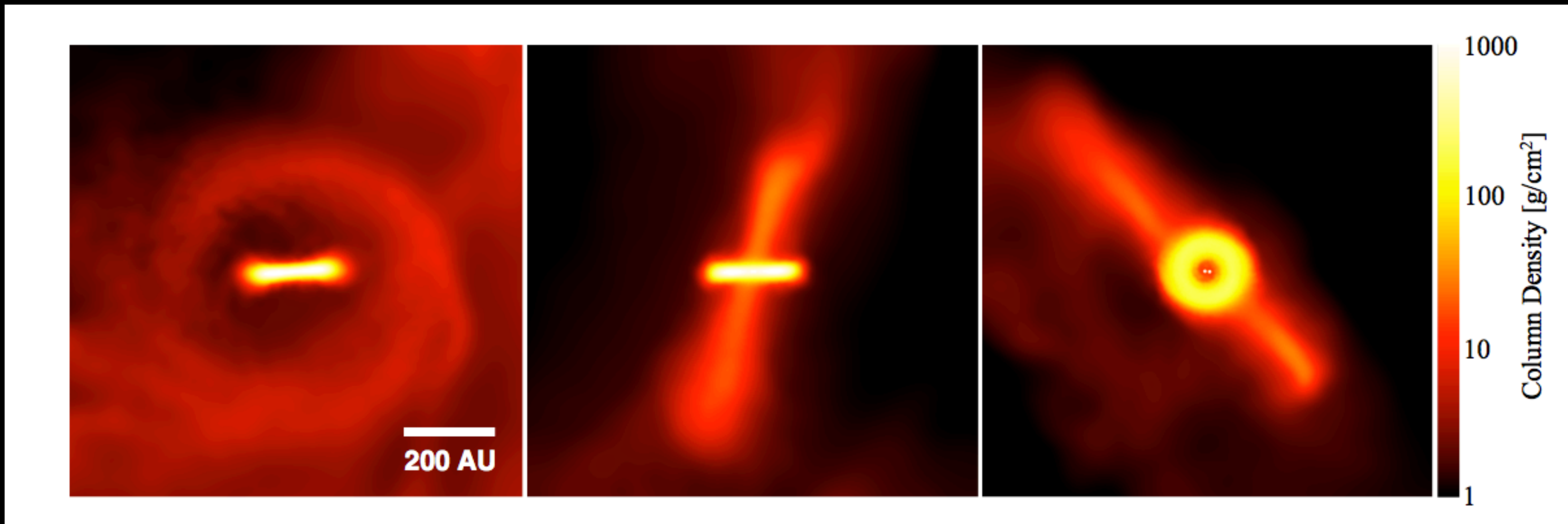
Price et al. (2018)

So why binary misaligned with disk?

- Misaligned binary appears to be able to explain misaligned inner/outer disk, but:
- If star and disk are related (star forming from disk), then why are they misaligned?

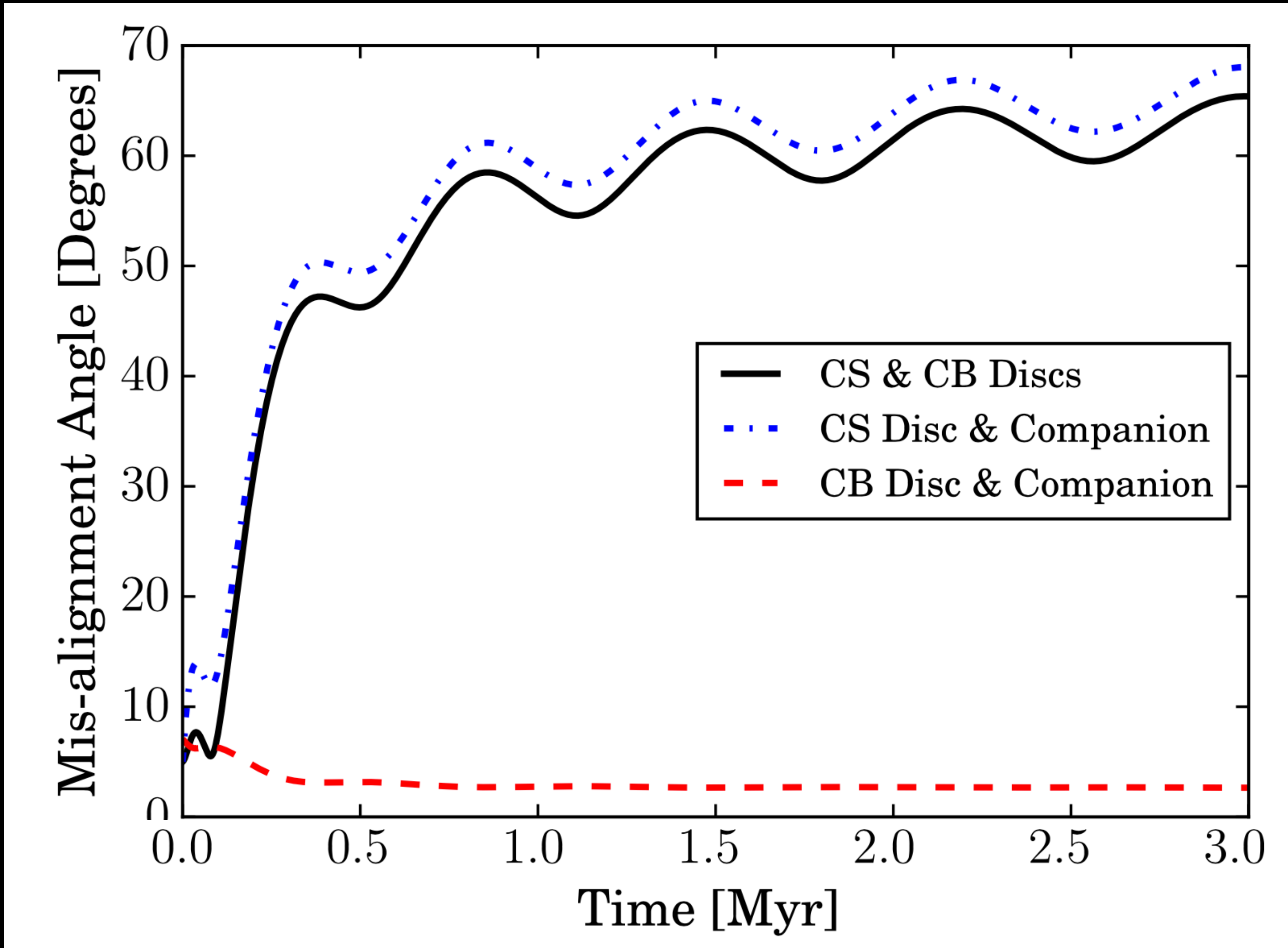
Maybe due to "messy" star formation?

Angular momentum axis of infalling matter may change during the star formation process



Bate 2018

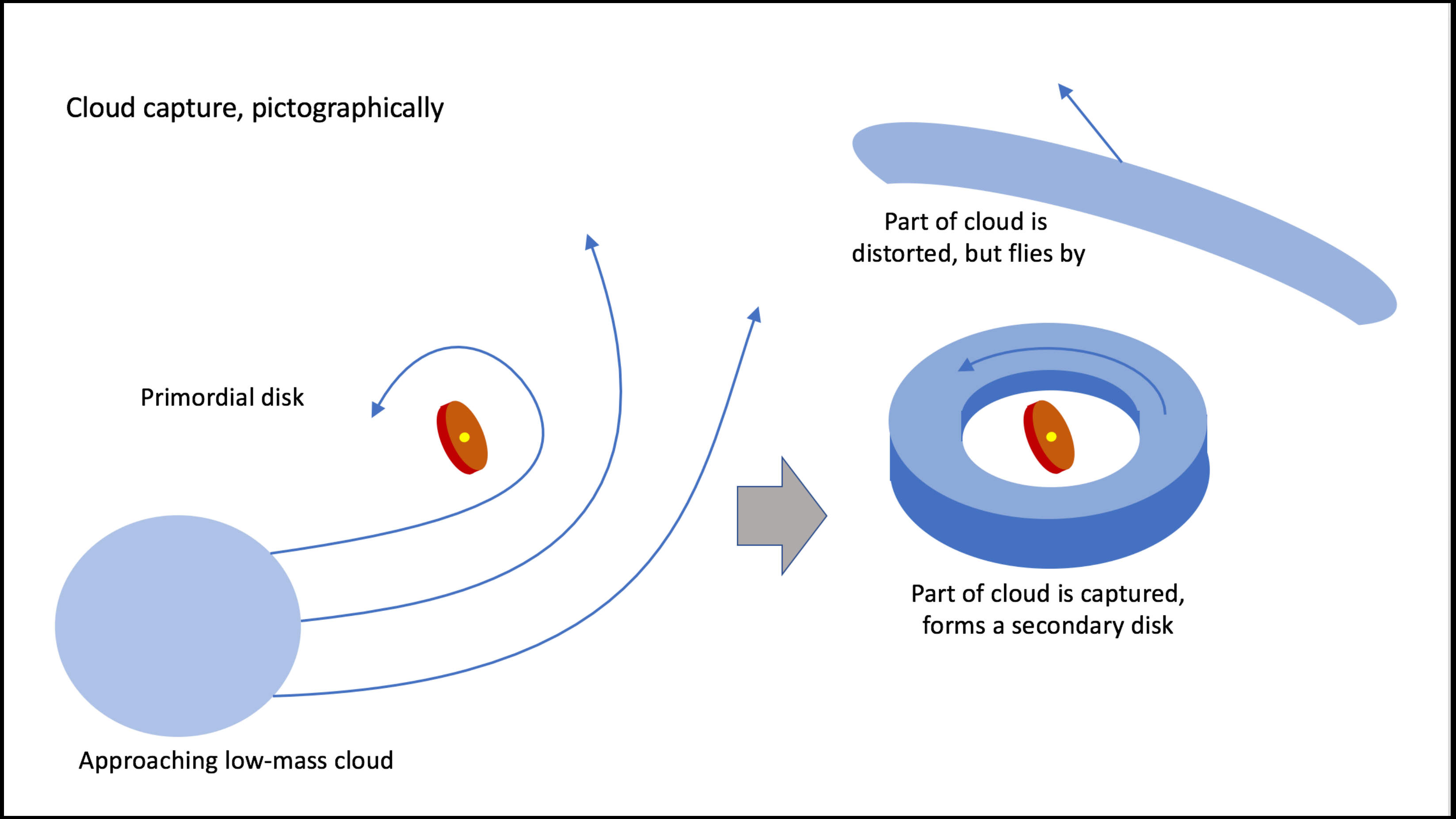
Secular resonance induced tilt



Owen & Lai (2017)
See also Matsakos & Königl (2017)

Or could it be late gas capture?

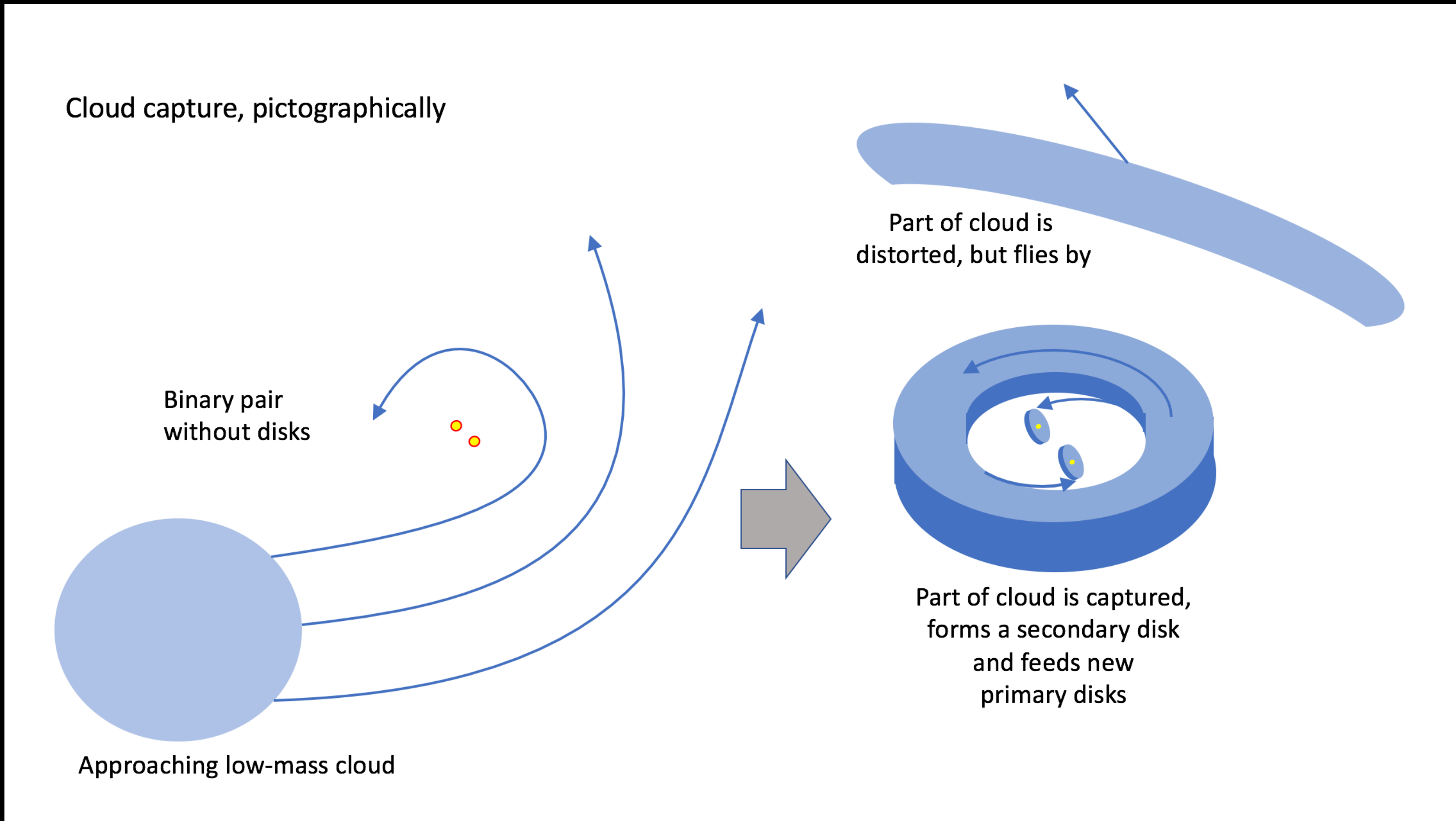
- Maybe the star has captured a cloudlet, which formed a new disk around the system.
  - Possibility 1: Star has a primordial disk



Dullemond, Fukagawa, Oehl, Kramer submitted (2018)

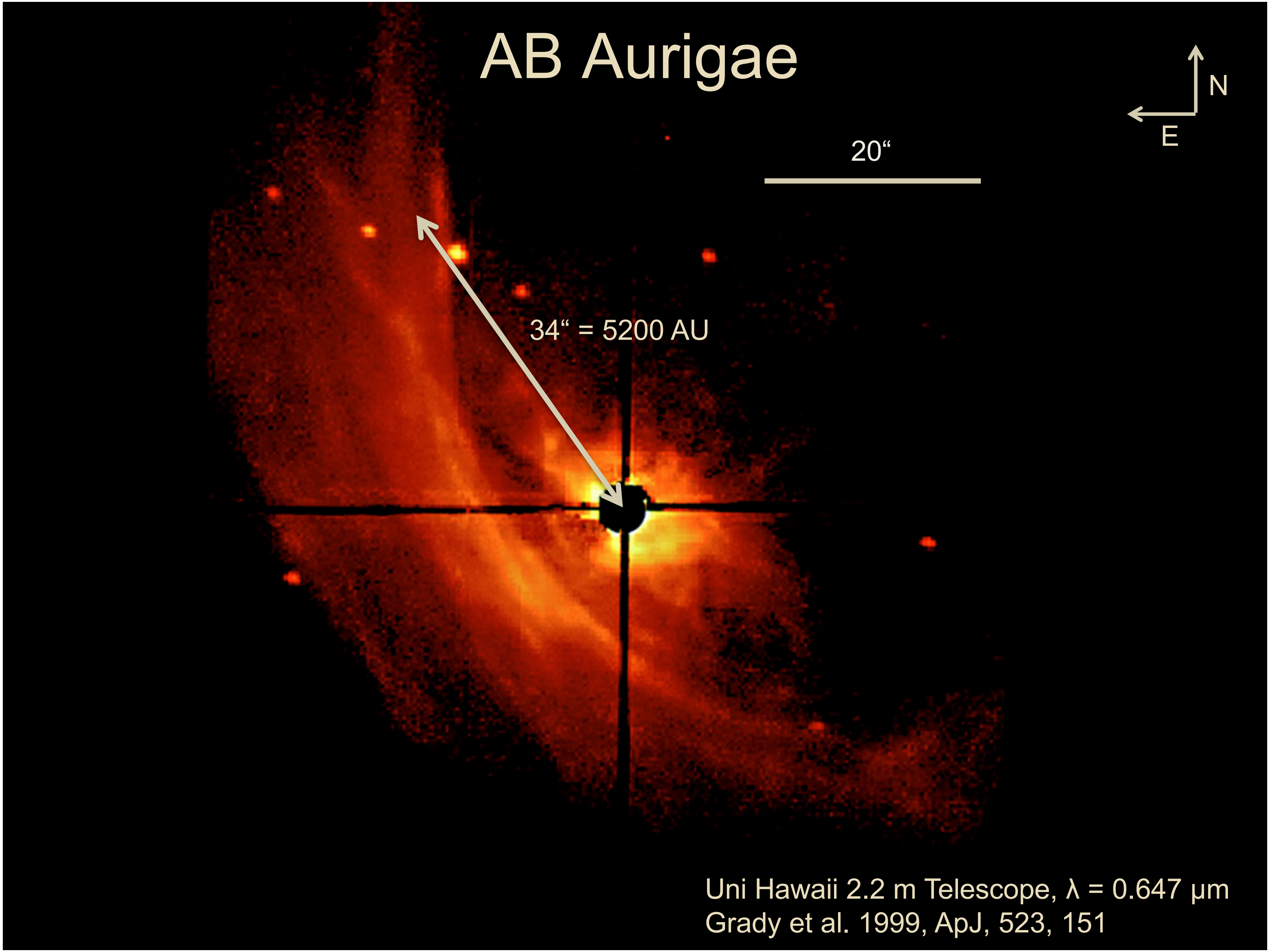
Or could it be late gas capture?

- Maybe the star has captured a cloudlet, which formed a new disk around the system.
  - Possibility 2: Binary star



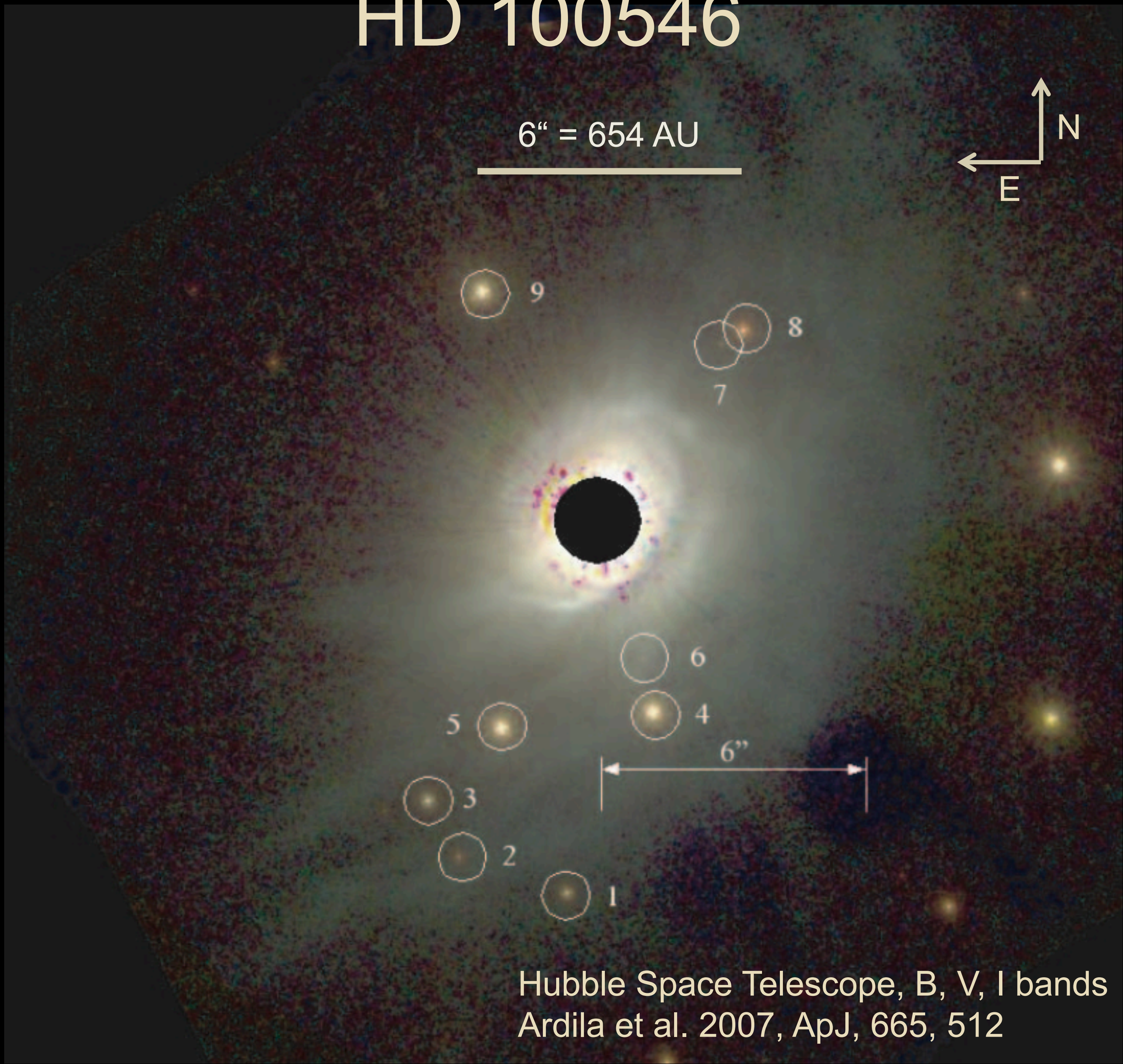
Dullemond, Fukagawa, Oehl, Kramer submitted (2018)

AB Aurigae



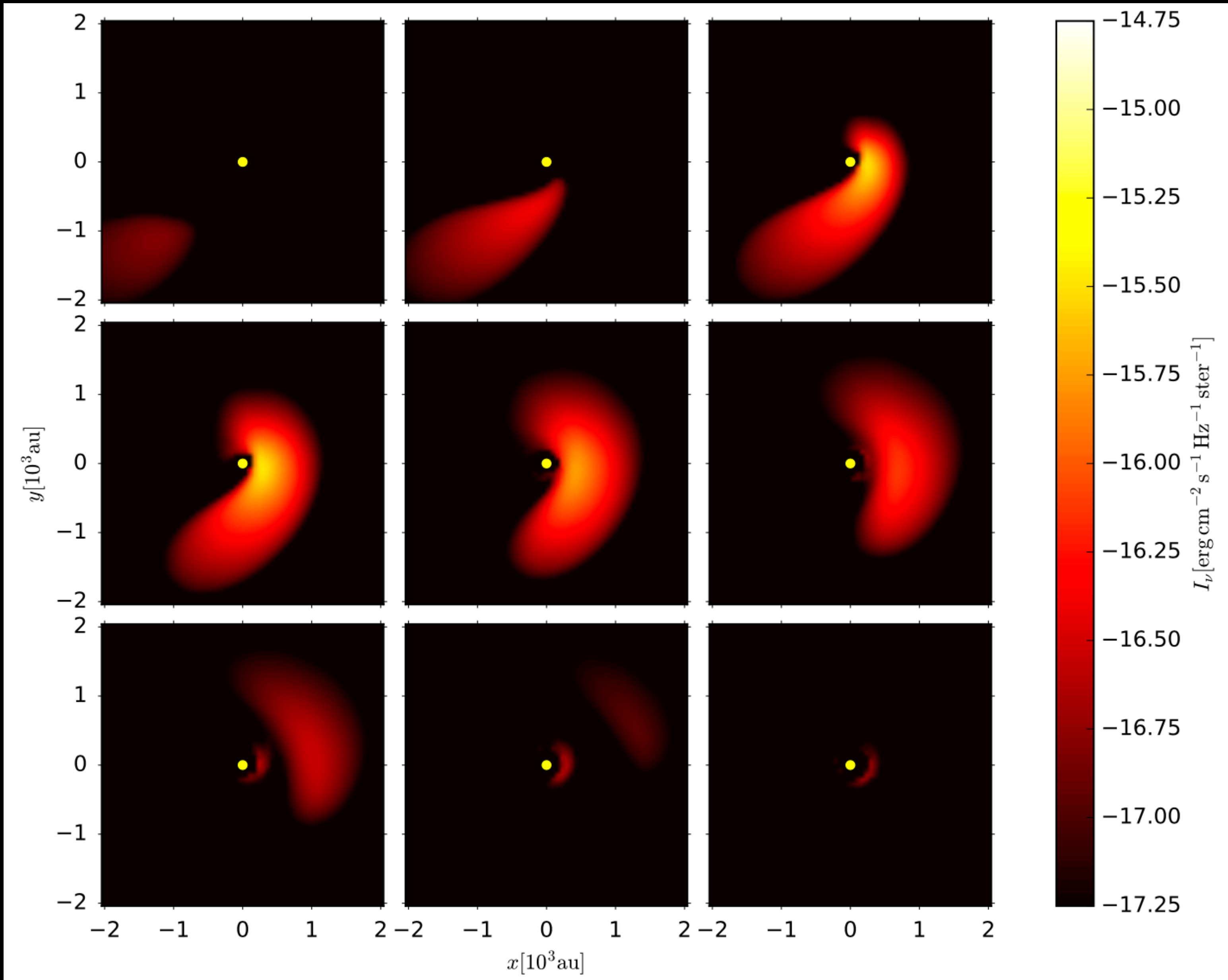
Uni Hawaii 2.2 m Telescope, λ = 0.647 μm
Grady et al. 1999, ApJ, 523, 151

HD 100546



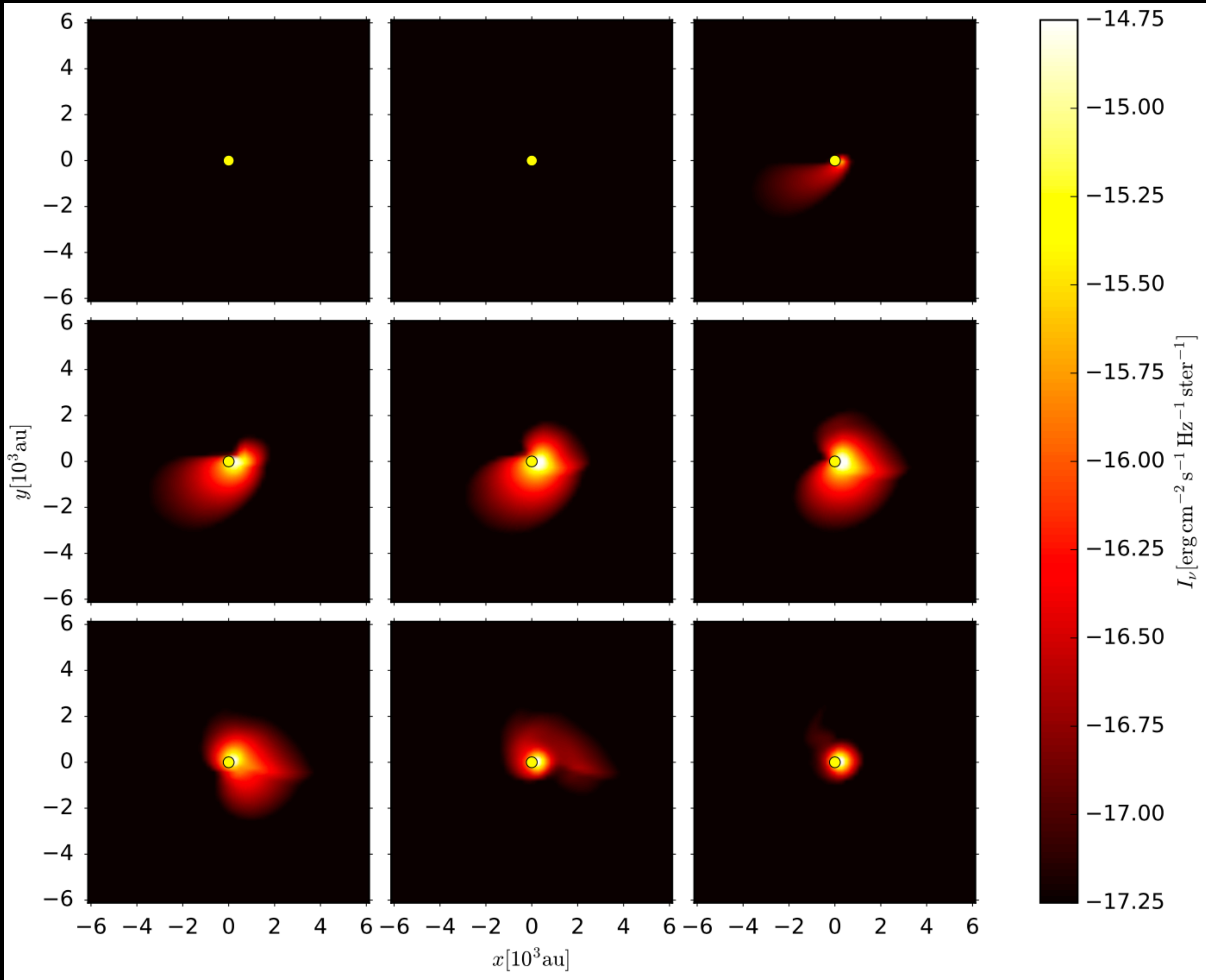
6" = 654 AU
N
E
9
8
7
6
5
4
3
2
1
6"
Hubble Space Telescope, B, V, I bands
Ardila et al. 2007, ApJ, 665, 512

Simple model of cloud flyby/capture



Dullemond, Fukagawa, Oehl & Kramer (submitted)

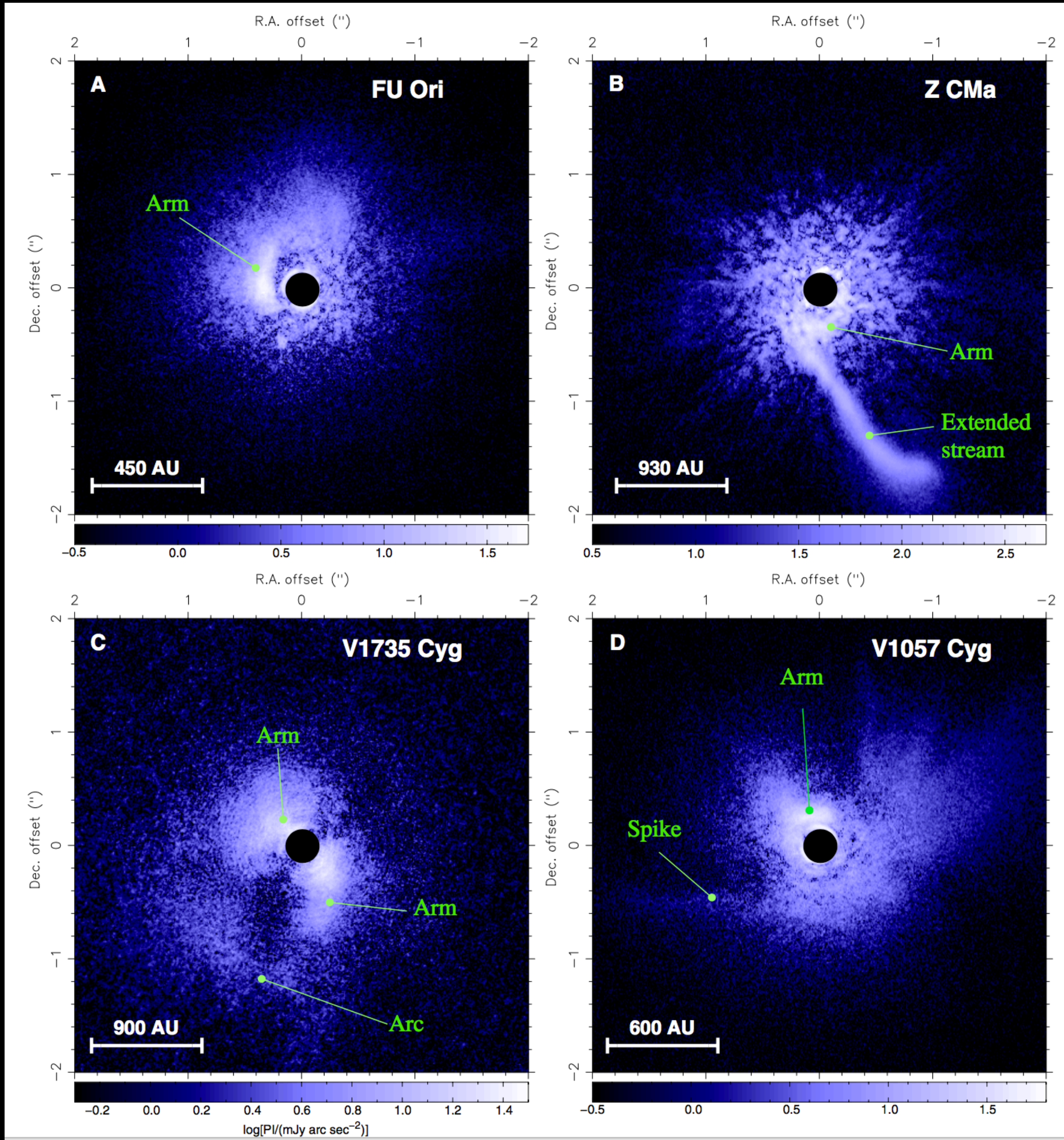
Simple model of cloud flyby/capture



Dullemond, Fukagawa, Oehl & Kramer (submitted)

Other cases of strange nebulosity

FU Orionis stars



Speculation: Could these be cloud capture related?

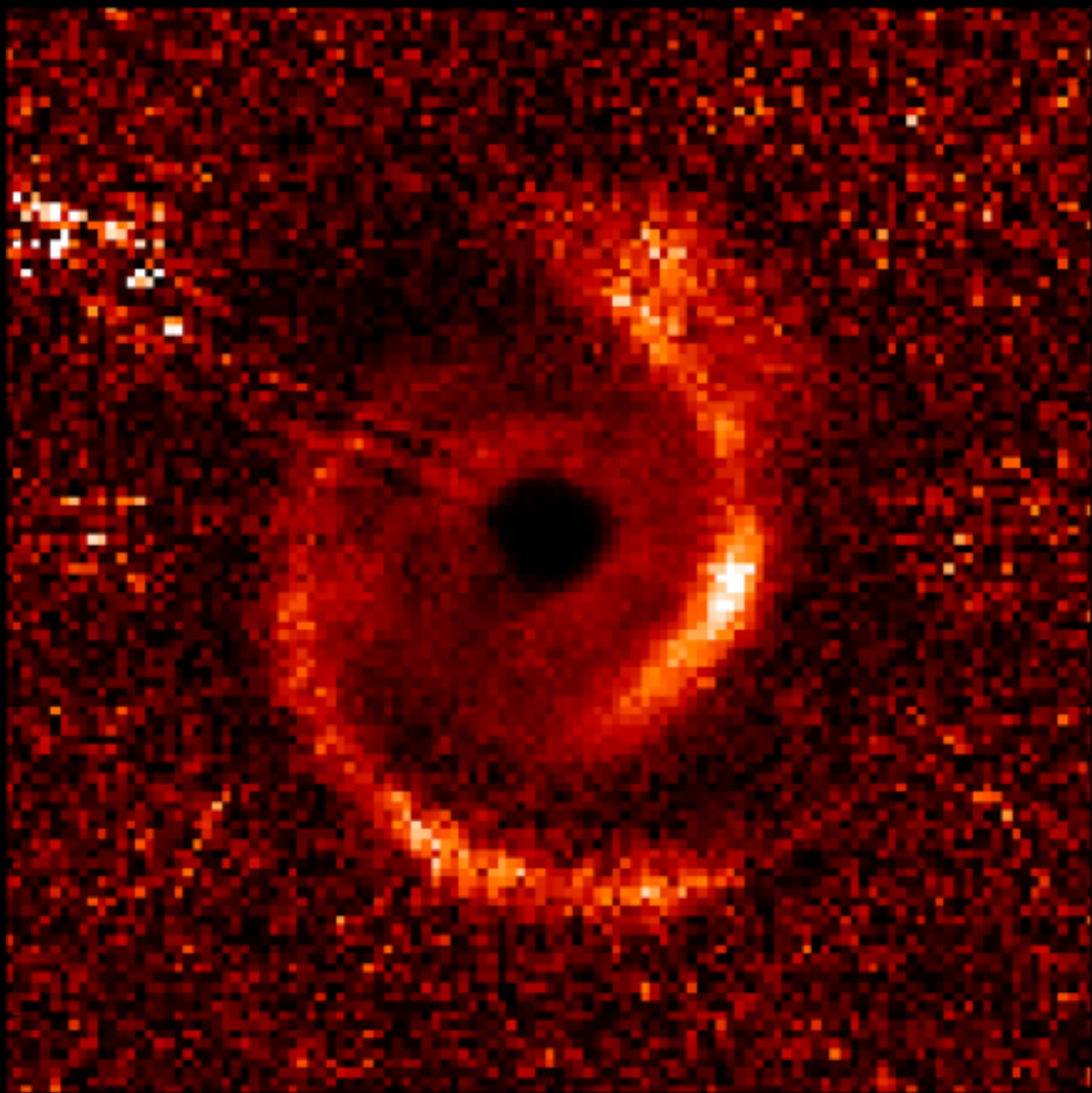
Hauyu Baobab Liu et al. 2016

Topic 3

Spiral waves in protoplanetary disks

Spirals in protoplanetary disks

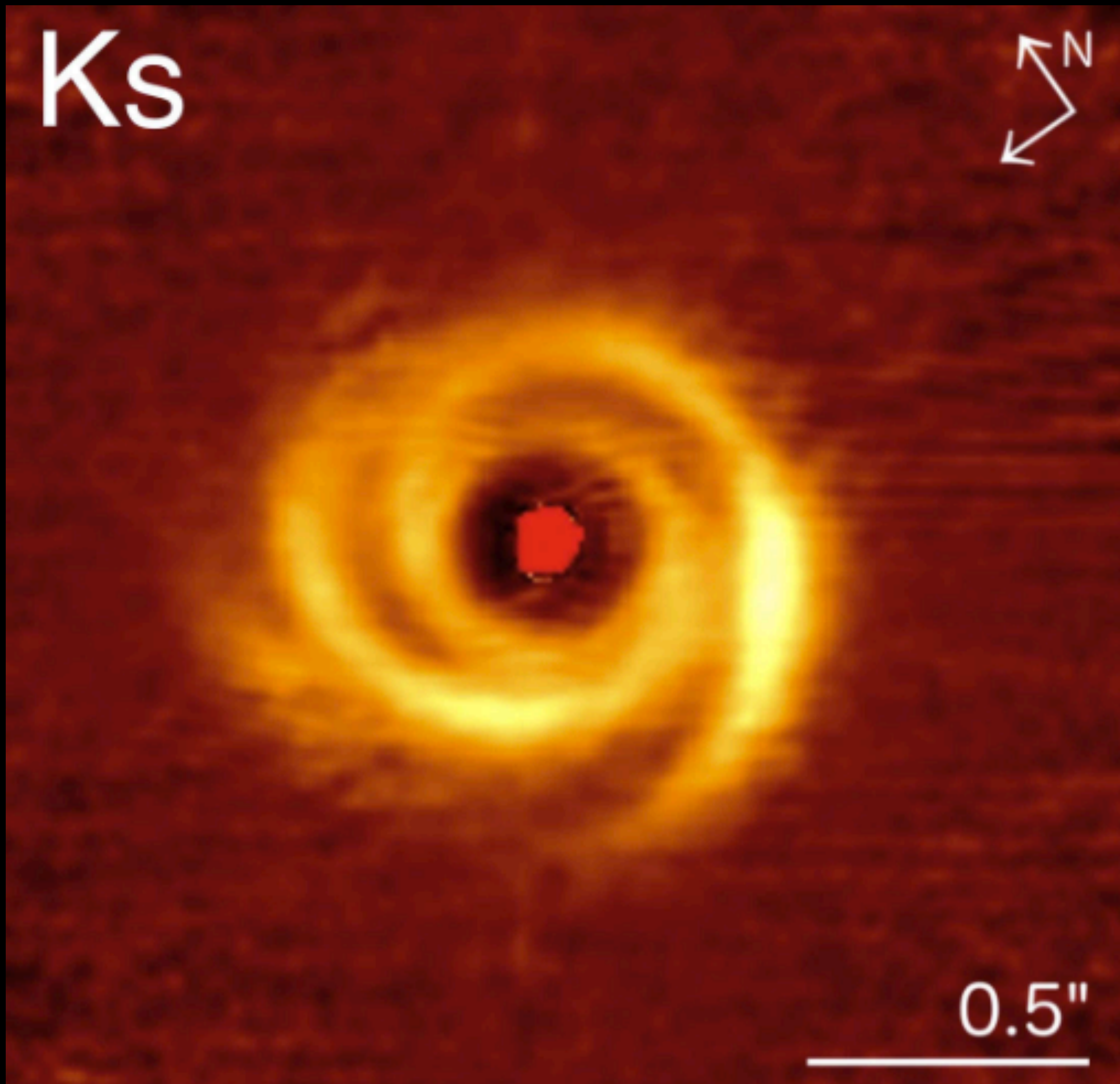
MWC 758



Benisty et al. 2015

Spirals in protoplanetary disks

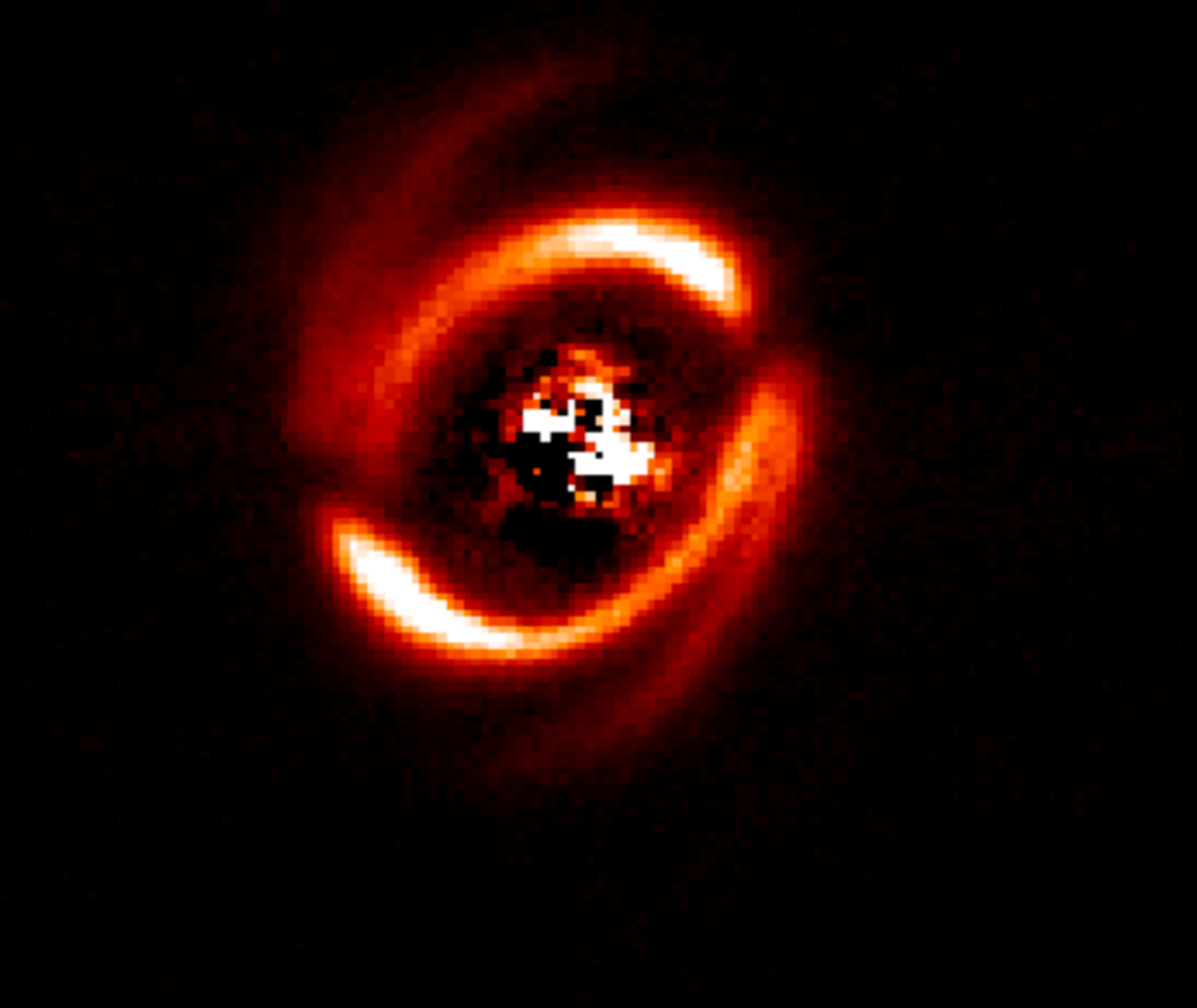
HD 135344b



Garufi et al. 2013

Spirals in protoplanetary disks

HD 100453



Benisty et al. (2017)

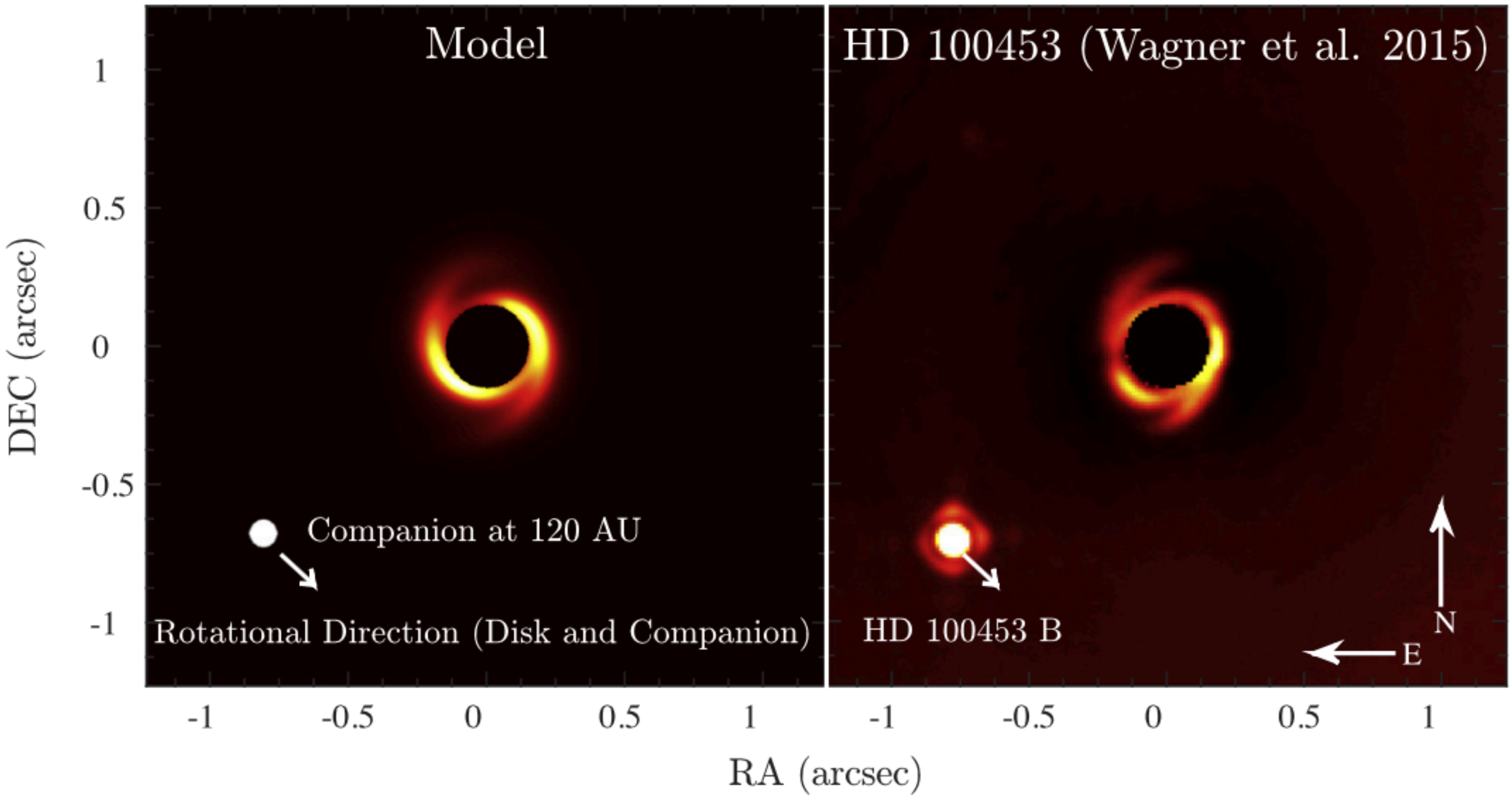
In Heidelberg we have such a thing...

Haus der Astronomie
(on the premises of the MPIA in Heidelberg)

Modeled after M51, but also seems to fit HD135344b

M51 spirals due to companion

HD 100453 also has companion

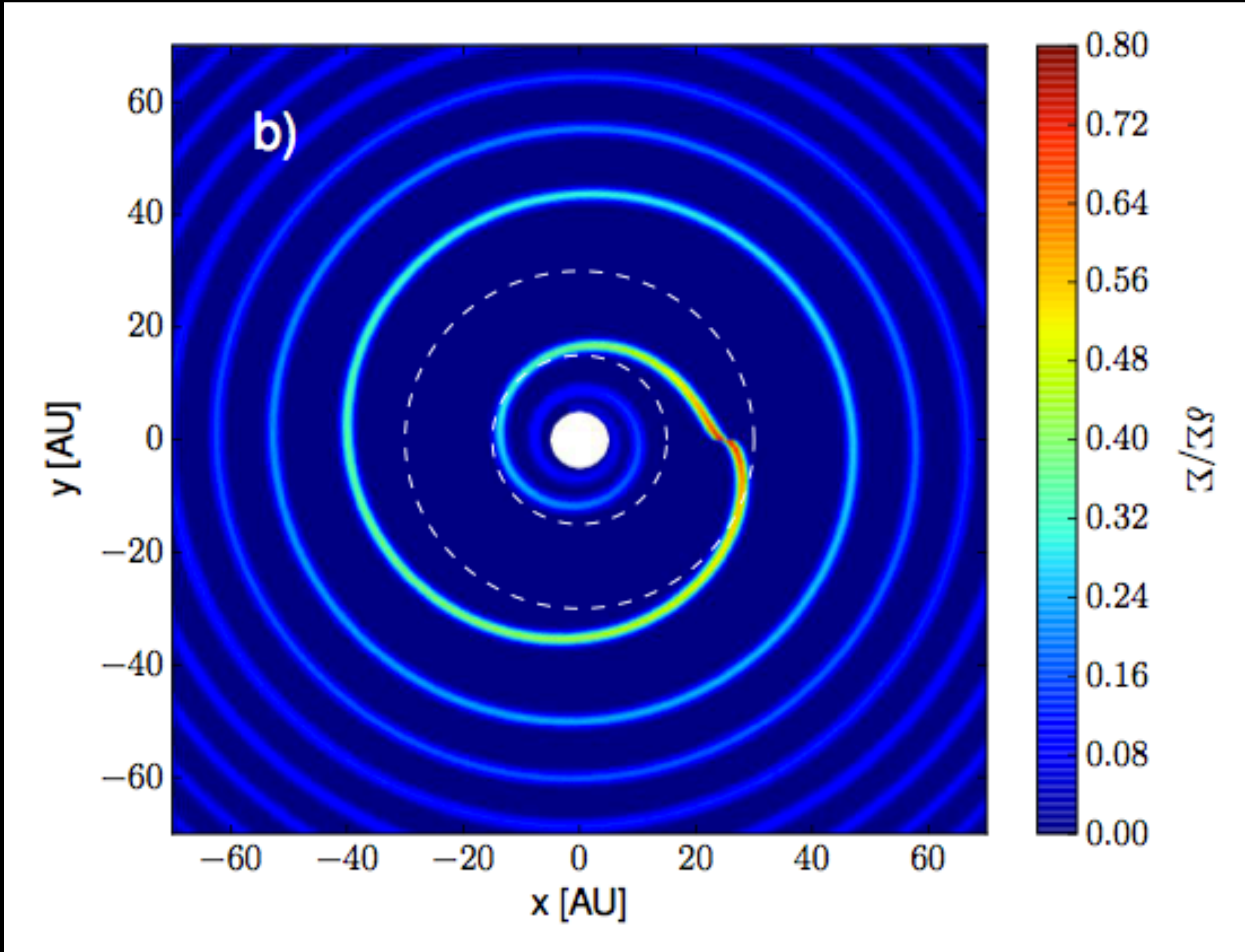


Dong et al. 2016

But we love to believe in planets...

- For HD 100453 the spirals are very likely due to the companion
- But could the other cases be signposts of planets?

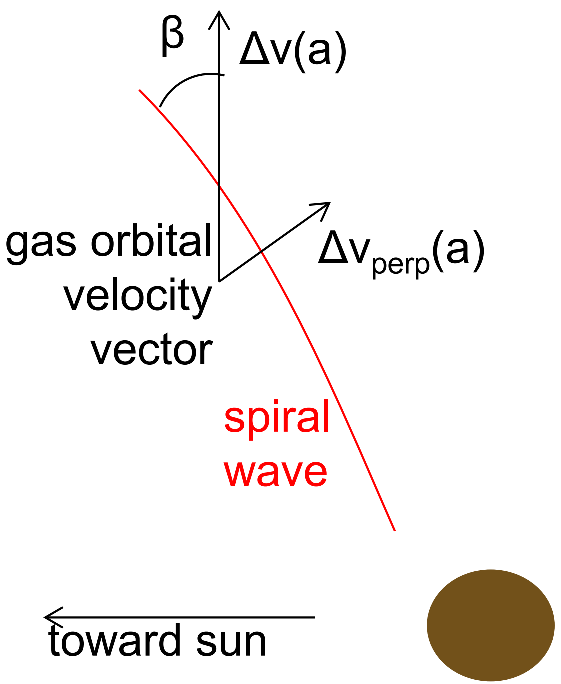
Spiral winding number depends on H/R



from: Juhasz et al. 2014

Analytic spiral wave model by Rafikov 2002, Muto et al. 2011

Simple model of wave pitch angle



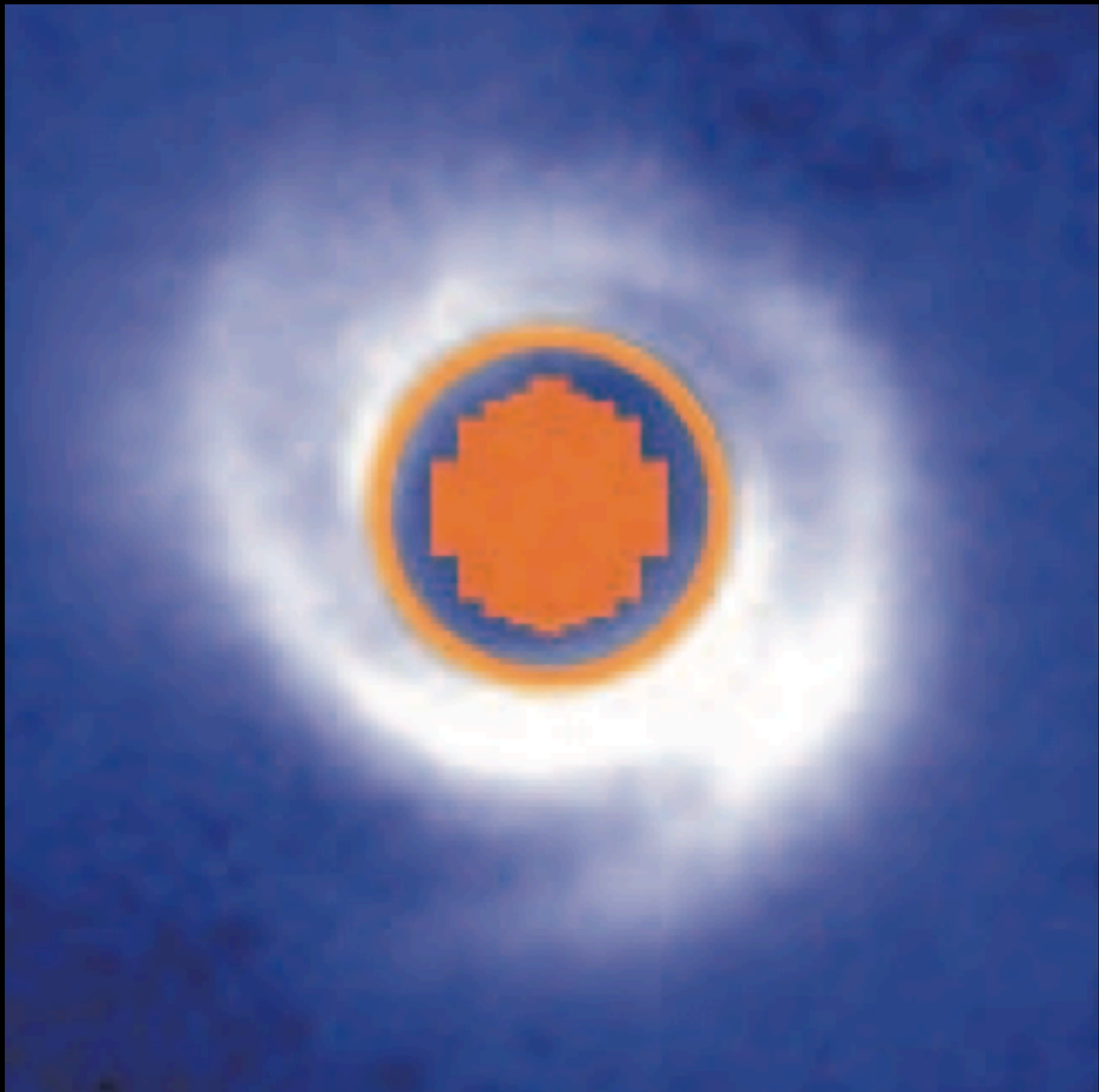
To ensure that the spiral wave is stationary in the reference frame corotating with the planet, the component of the orbital velocity Δv(a) perpendicular to the spiral wave (i.e. $\Delta v_{perp}(a)$) must be precisely equal to the sound speed (assuming the wave is not a shock).

$$\Delta v(a) = (\Omega - \Omega_p)a$$

$$\Delta v_\perp(a) = \Delta v(a)\sin\beta = c_s$$

$$\sin\beta = \frac{c_s}{(\Omega(a) - \Omega_p)a}$$

Are these giant spirals consistent with planet-induced spirals?



Muto et al. 2012

Issues to consider:

- Are the waves strong enough to make this contrast?
- Is the winding number consistent with the expected H/R of the disk?

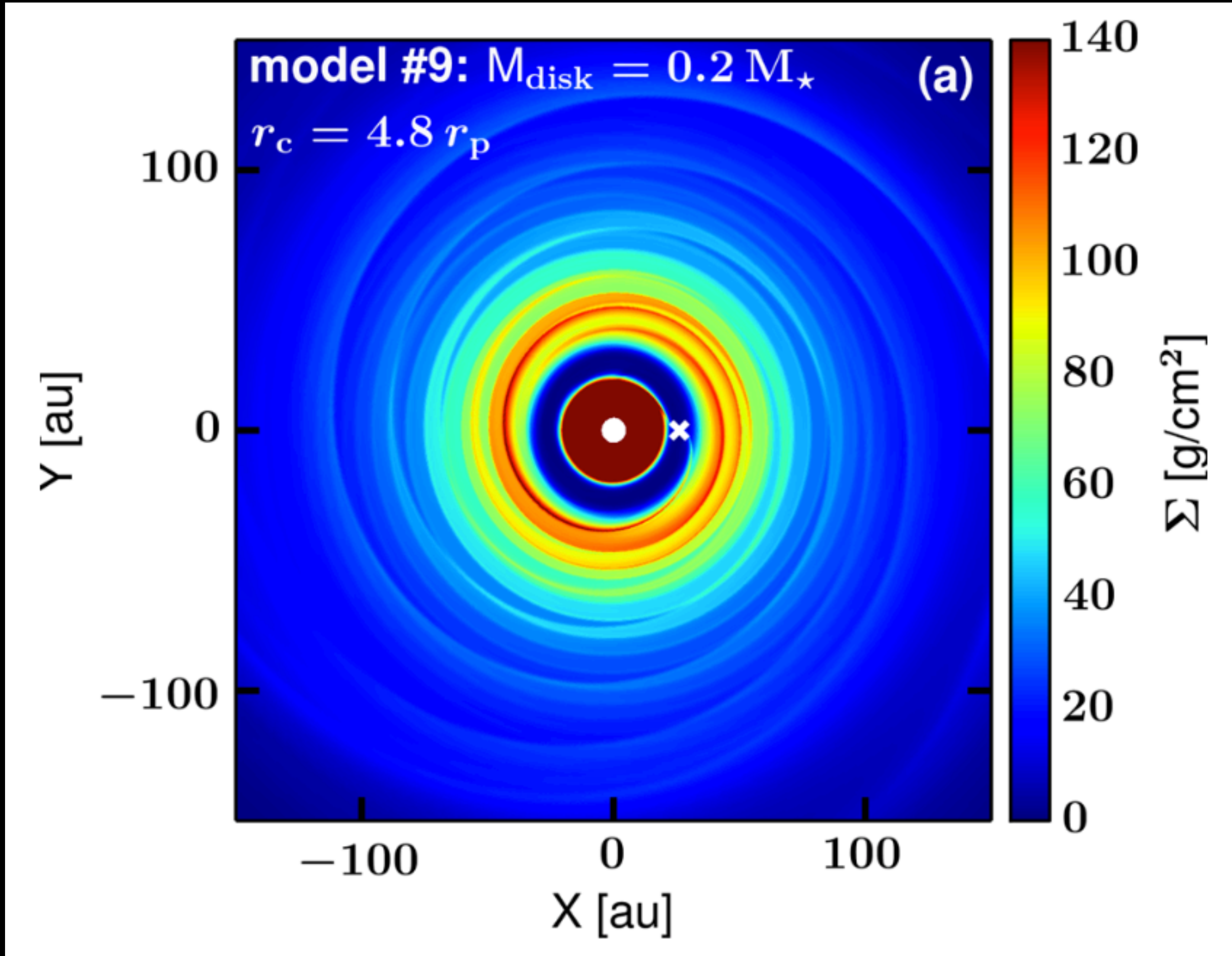
Disk modeling to understand spirals

Normally:
planet → m=1

Now add self-gravity, keeping the disk very close to Q=1

An m=2 spiral appears.

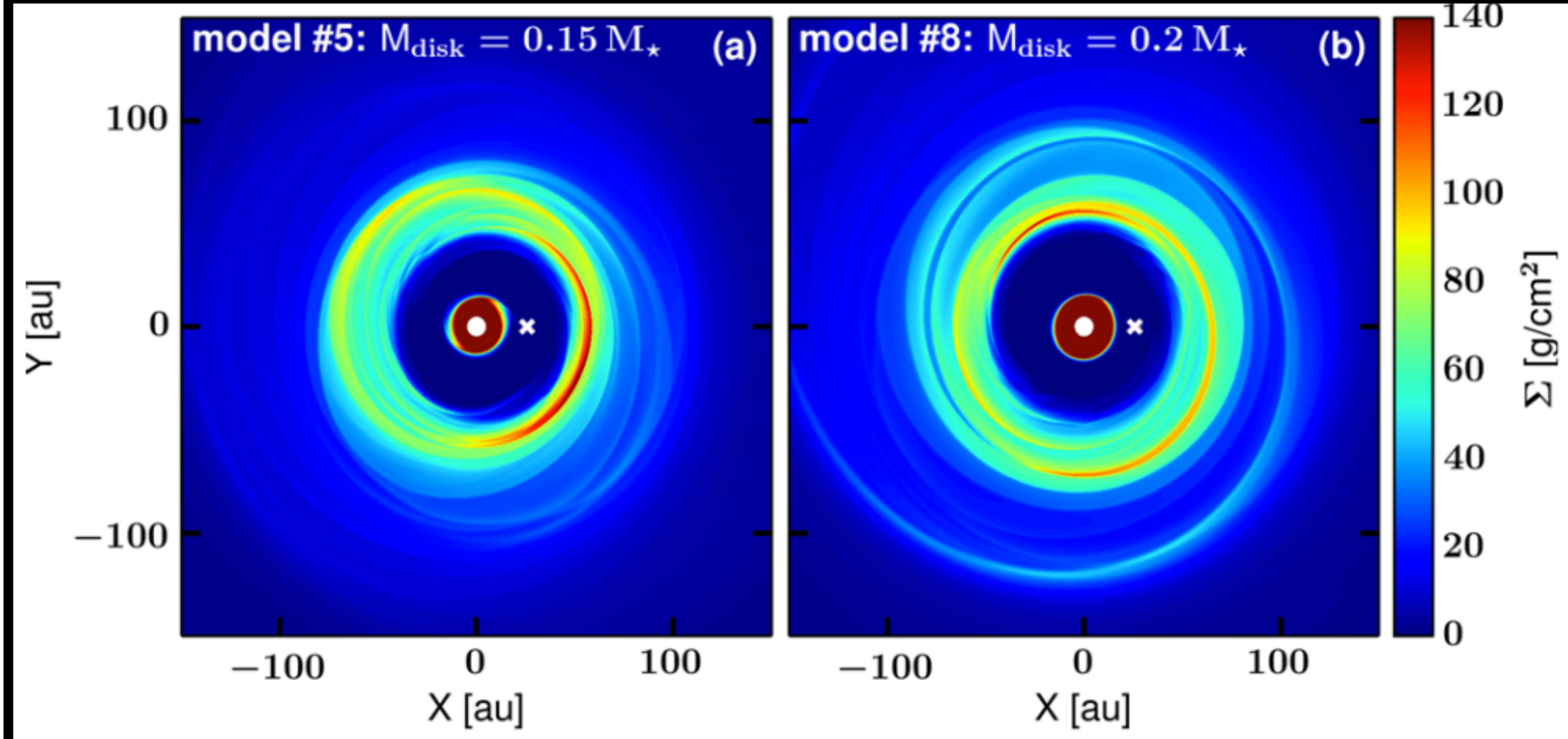
Larger pitch angle, but not enough.



Pohl et al. 2015

Disk modeling to understand spirals

Larger planet mass and self-gravity:
large pitch angle, but one-armed



Pohl et al. 2015

Conclusions

- Protoplanetary disk observations show:
  – Disks are structured!
  – But the structures are well-defined (not messy)
  – Great playground for theorists!
- ALMA and high-contrast imaging:
  – Protoplanetary disks are exciting!

About codes:

- (My case: RADMC-3D "swiss-army" radiative transfer package)

- To the code users:
  - Always test on the simplified version of your problem first (i.e. if possible come up with a toy model)
  - Please provide feedback to the author (or on the code forum) if you find a problem.

- To code developers:
  - Please write documentation (even if only a tutorial)
  - Please open source your code