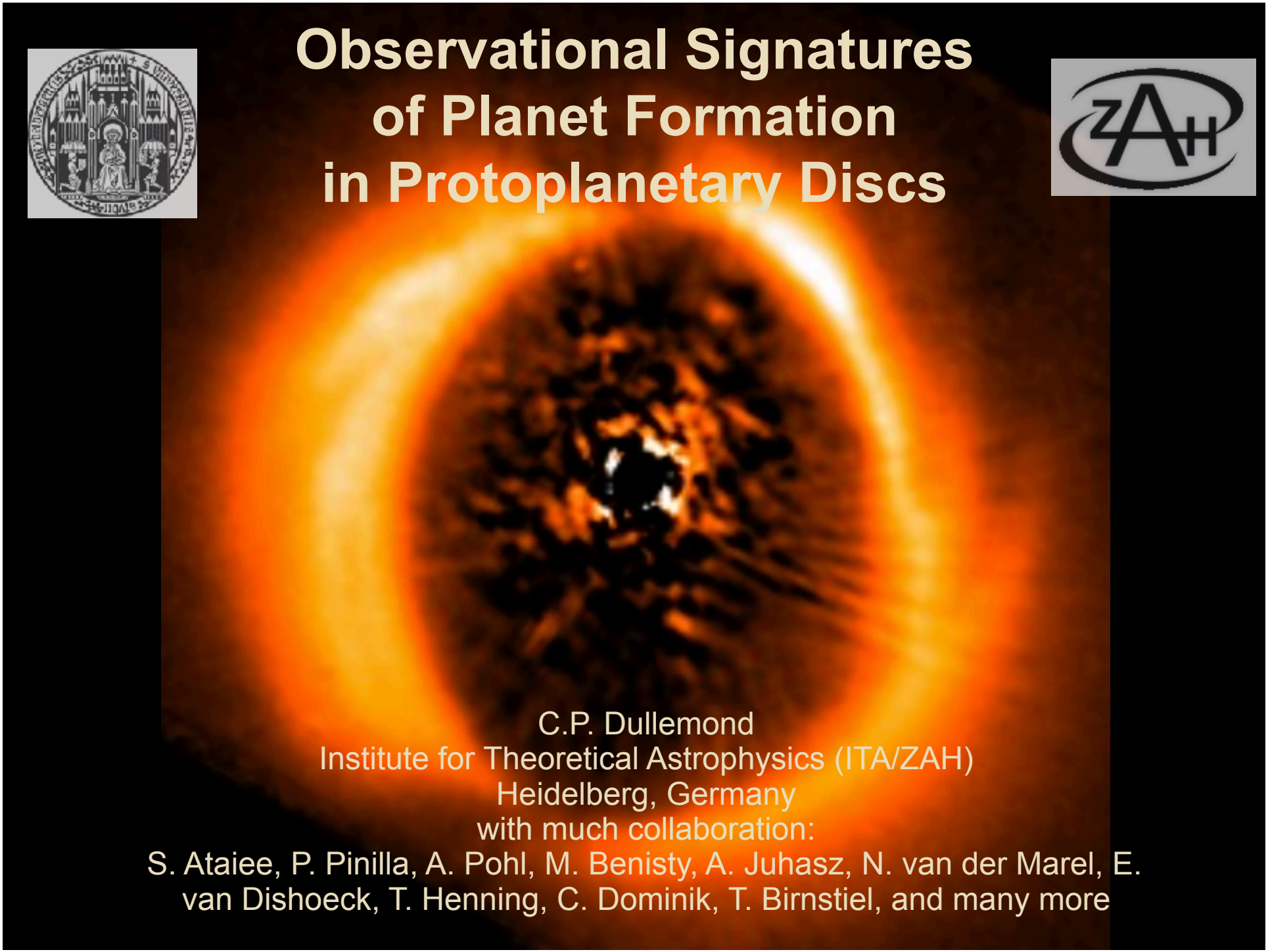
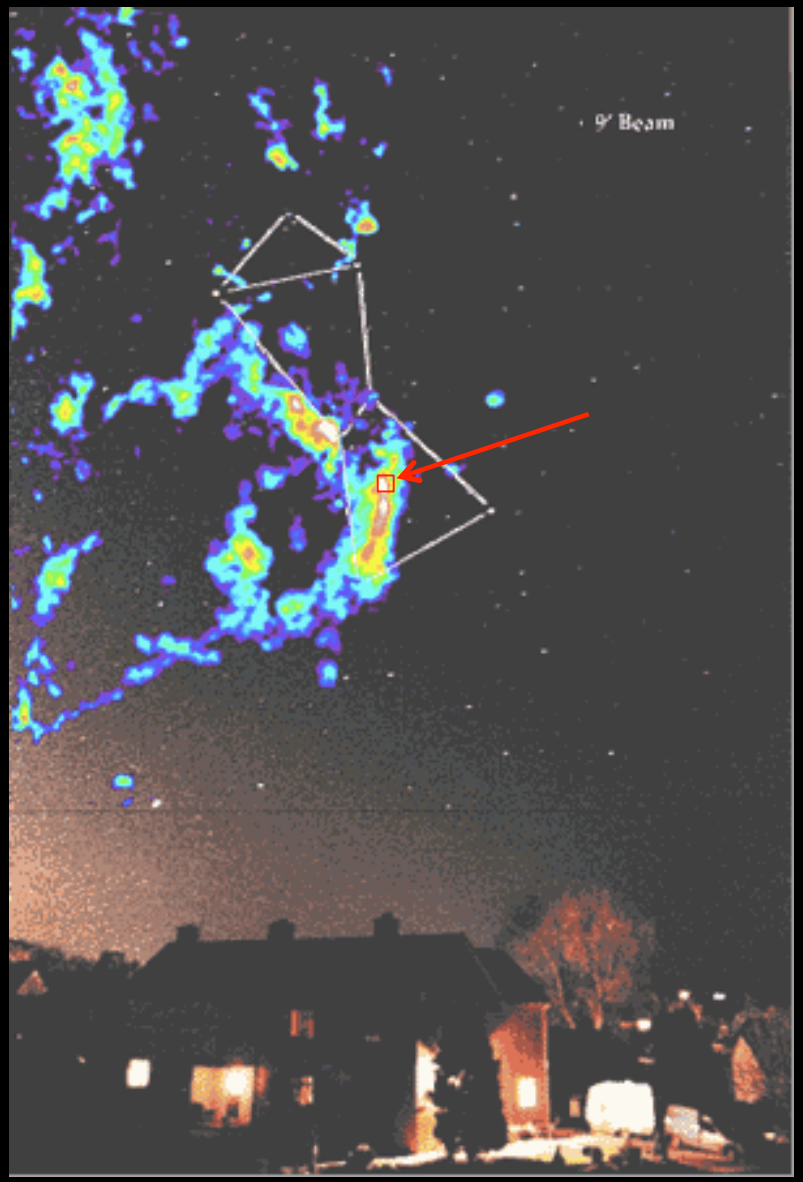


# Observational Signatures of Planet Formation in Protoplanetary Discs

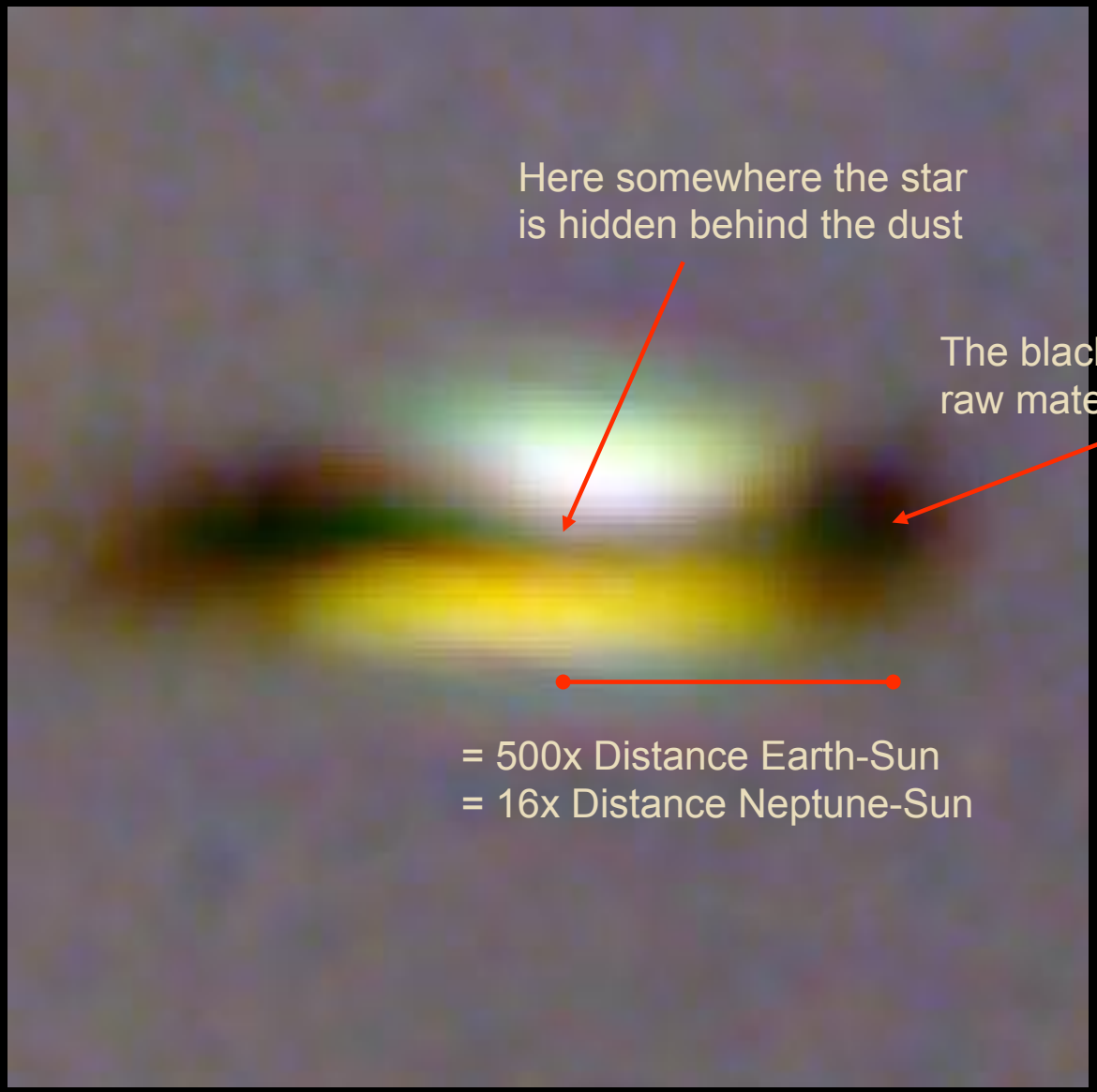
C.P. Dullemond
Institute for Theoretical Astrophysics (ITA/ZAH)
Heidelberg, Germany
with much collaboration:
S. Ataiee, P. Pinilla, A. Pohl, M. Benisty, A. Juhasz, N. van der Marel, E. van Dishoeck, T. Henning, C. Dominik, T. Birnstiel, and many more

# Brief Introduction to protoplanetary discs and planet formation

# A birthplace of planets



# A birthplace of planets



# From Dust to Planets...

**Observational constraints:**

Modeling effort

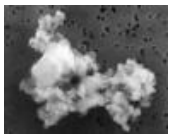
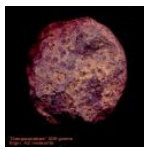
Directly observable through IR and mm observations

?

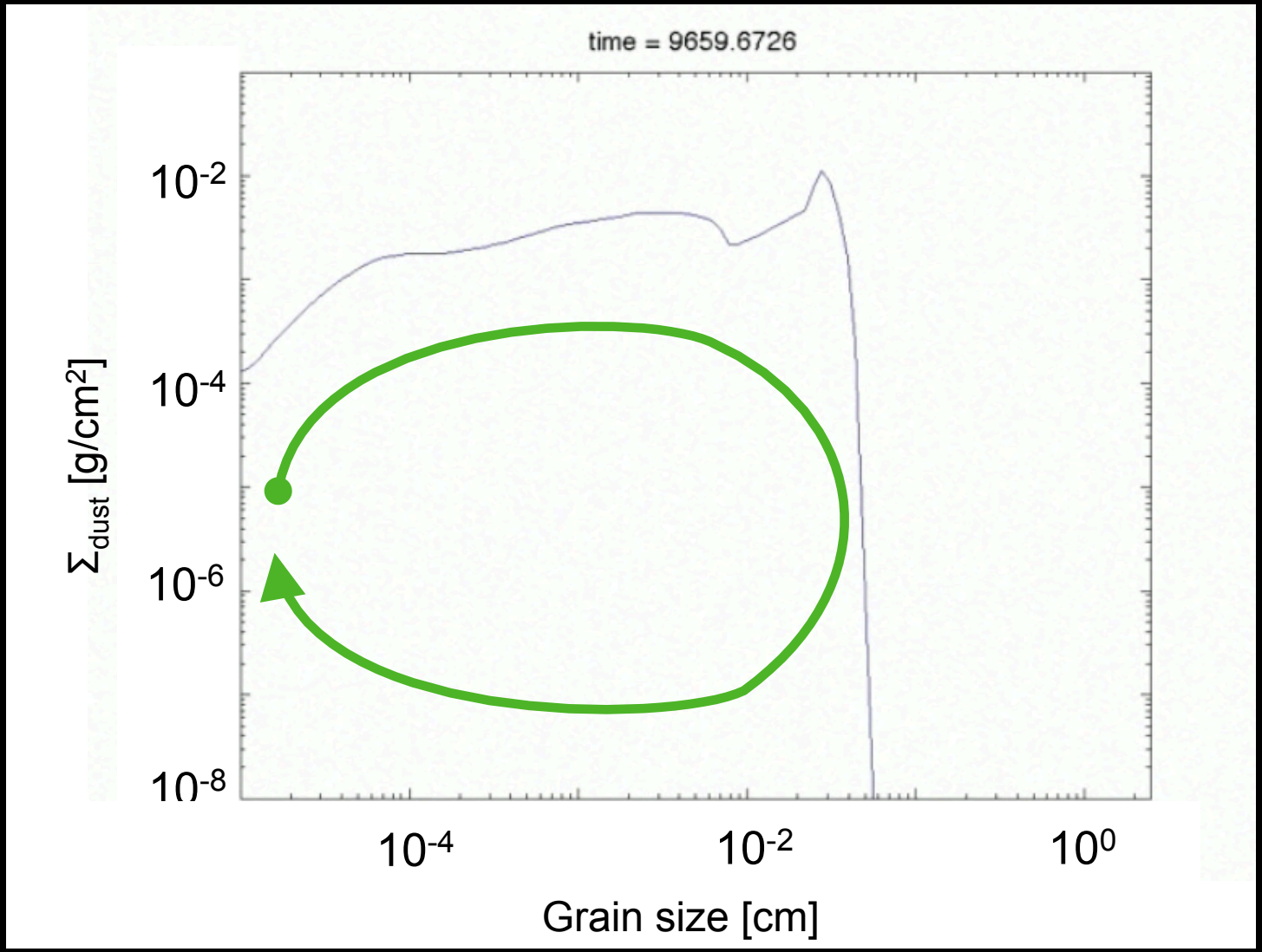
Exo-planets

Solar system constraints (but only 1 object! And 4.5 billion years ago!)

1μm 1mm 1m 1km 1000km

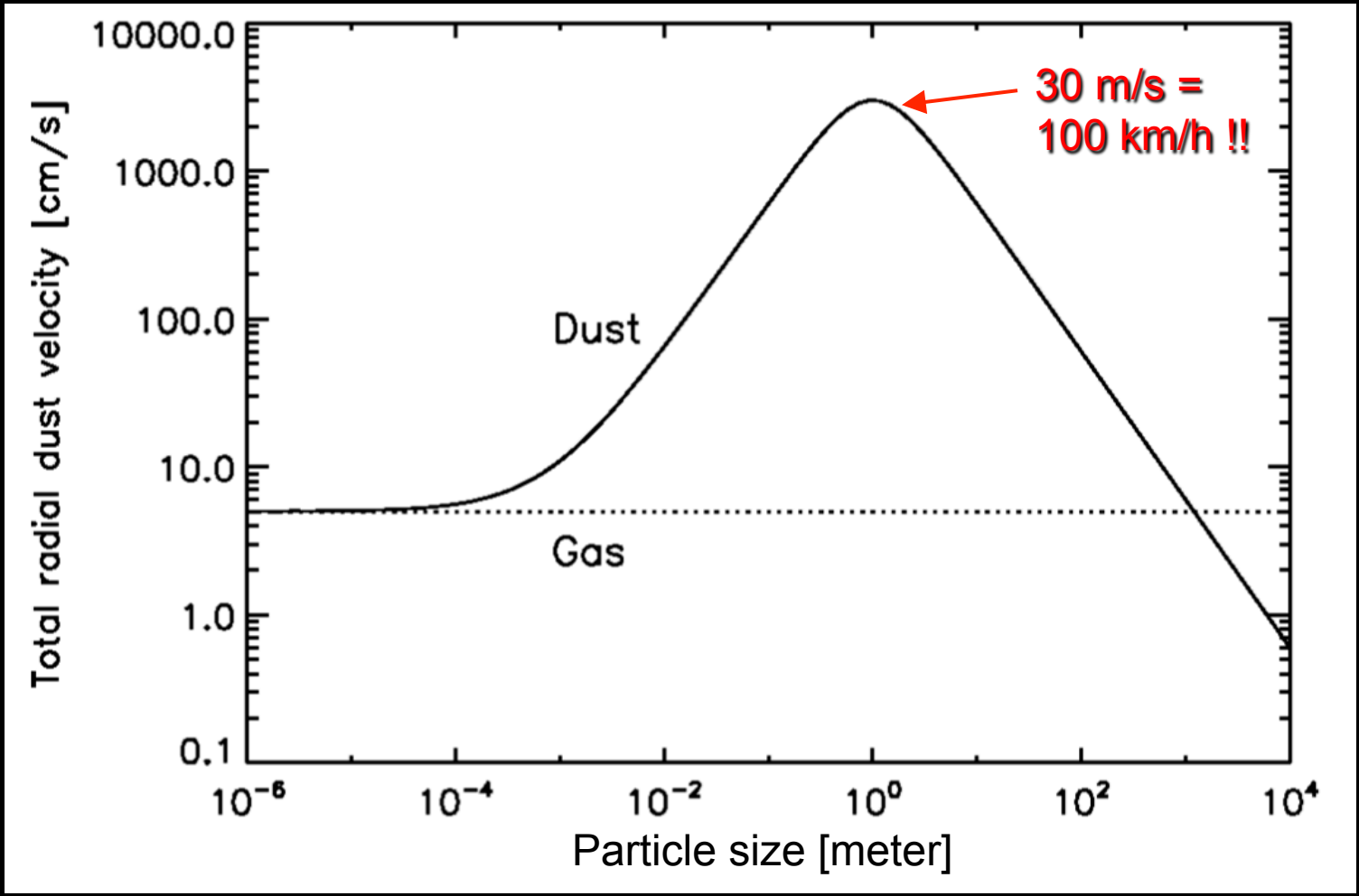



# Dust coagulation+fragmentation model




Birnstiel, Dullemond & Ormel 2010

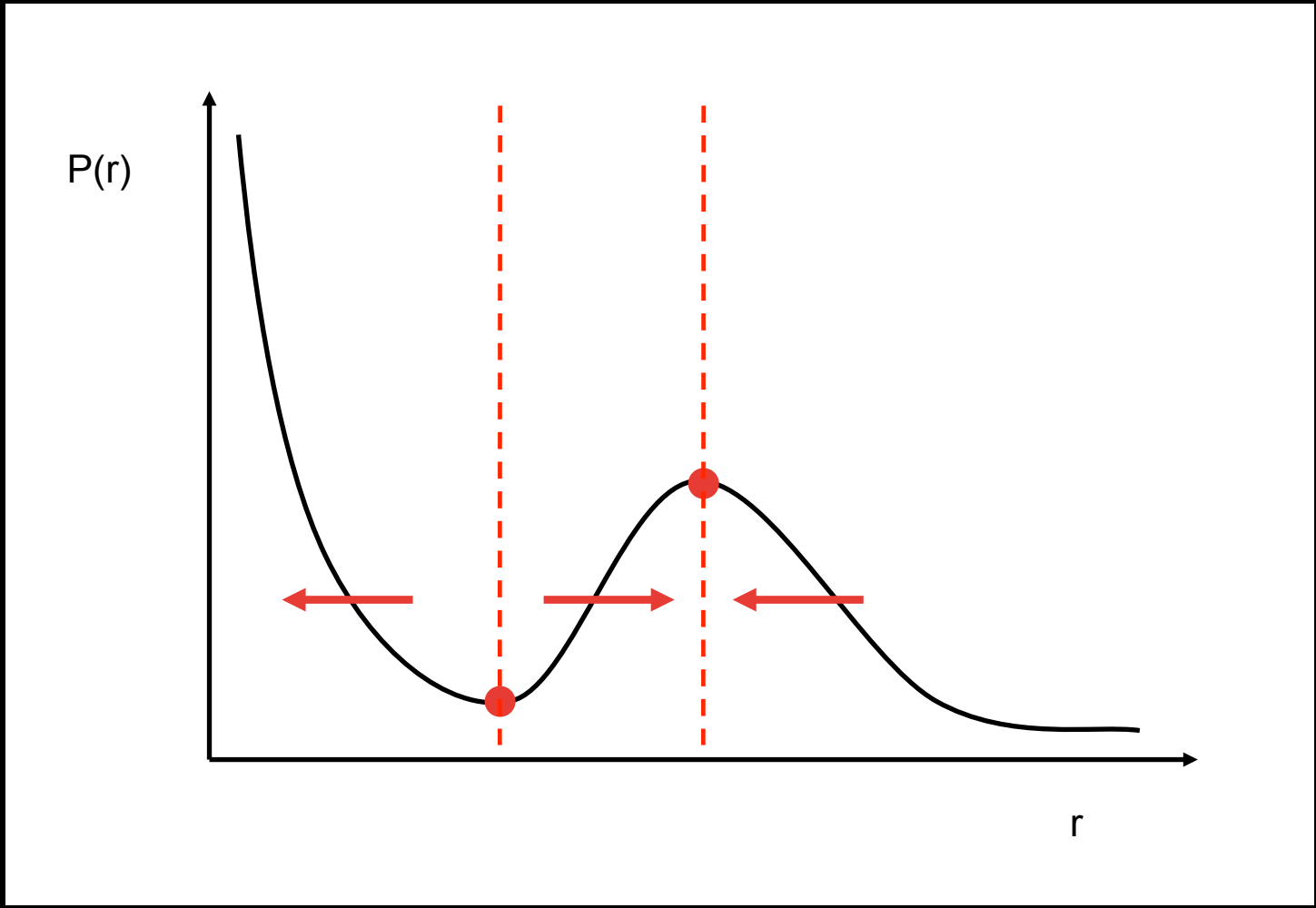
# Main problem: high velocities




In addition: this large radial inward velocity (inward drift) leads to loss of particles into the star before they can grow to planets!

How does Nature keep particles from (too) rapidly drifting inward?

# Particles move toward pressure peak

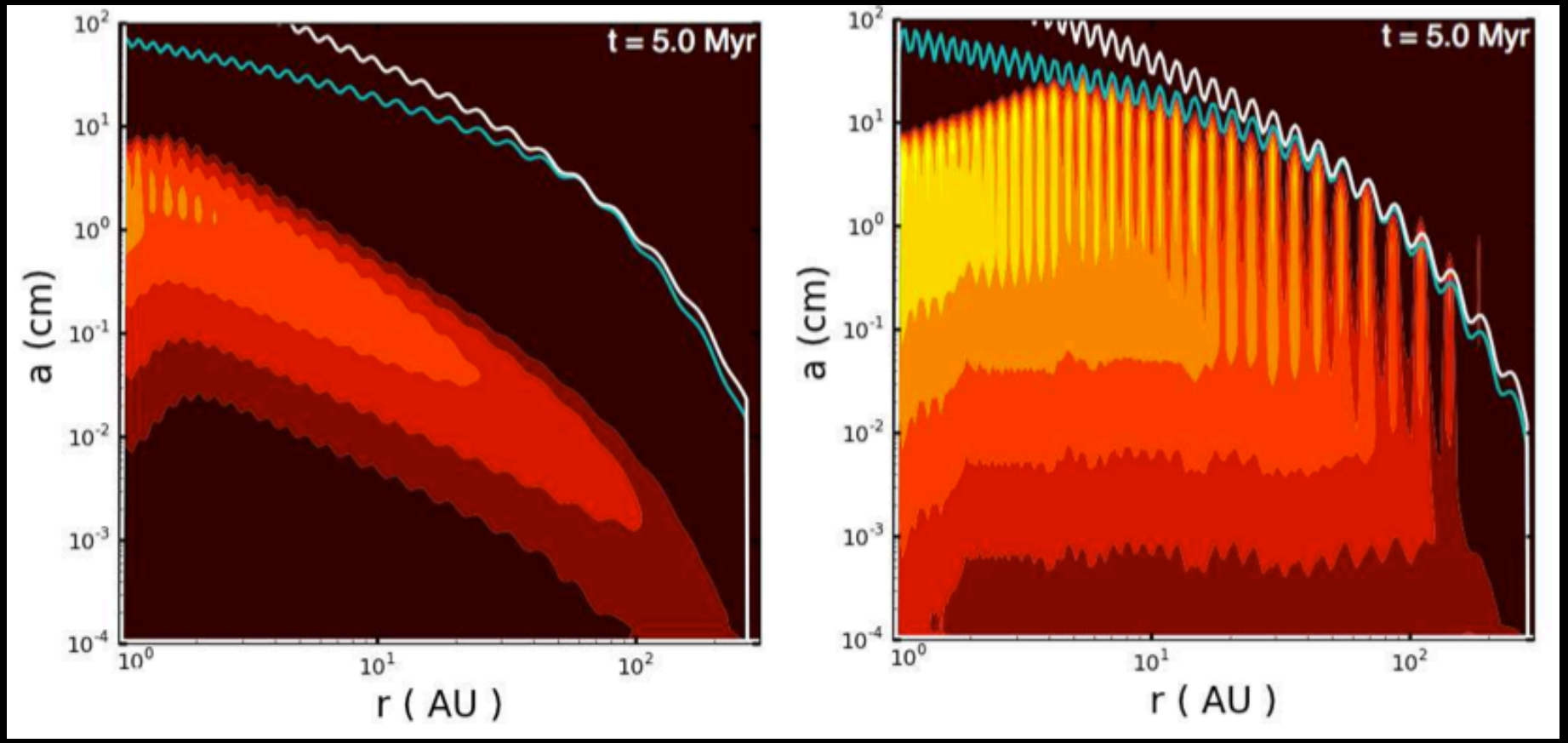



Whipple 1972; Barge & Sommeria 1995; Klahr & Henning 1997; Kretke & Lin 2008; Dzyurkevich et al. 2010; Kato et al. 2010; Johansen et al. 2009; Garaud 2007

# Simple experiment: Lots of small bumps

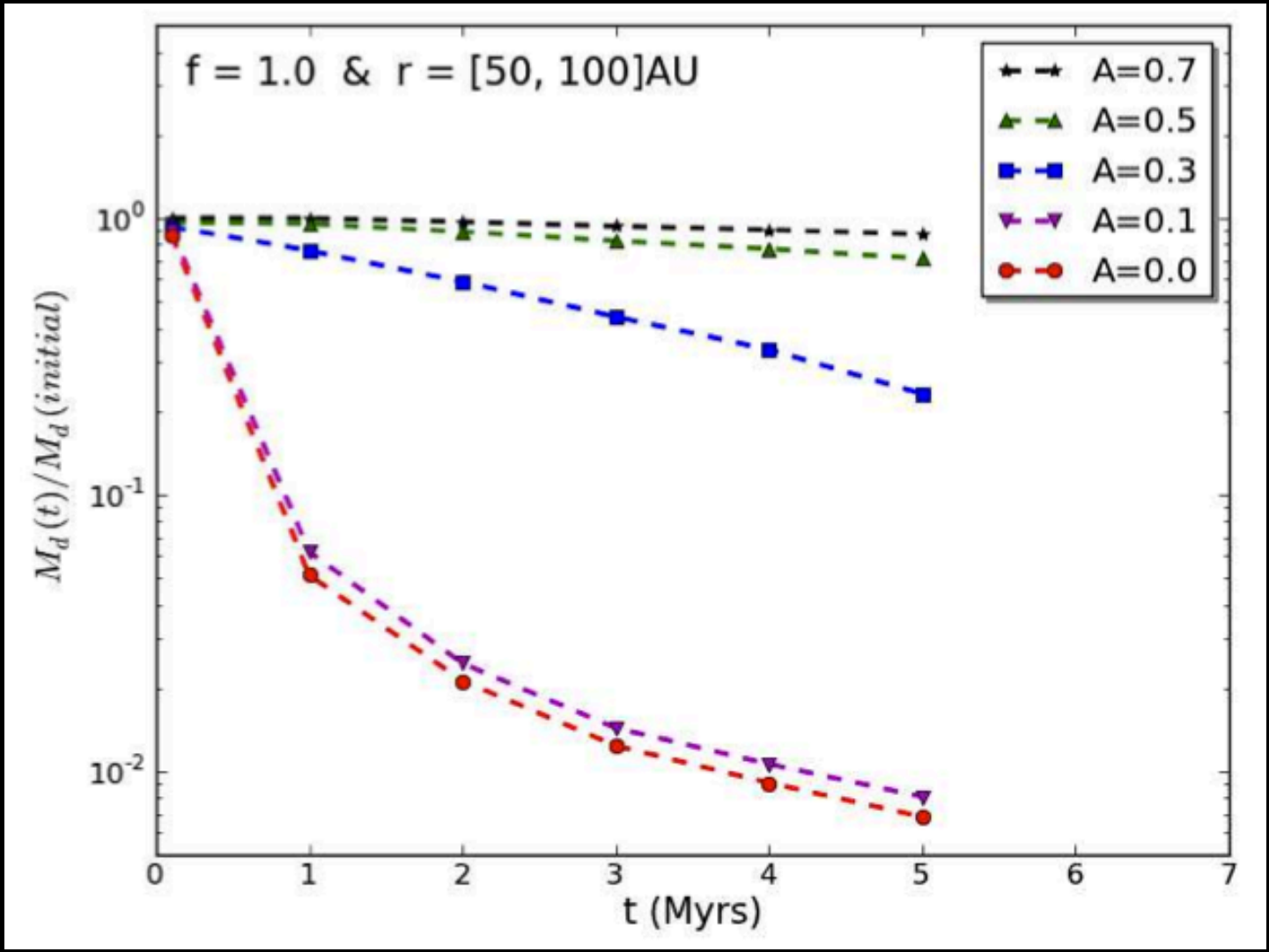
Weak bumps

Strong bumps




Pinilla, Birnstiel, Ricci, Dullemond et al. 2012

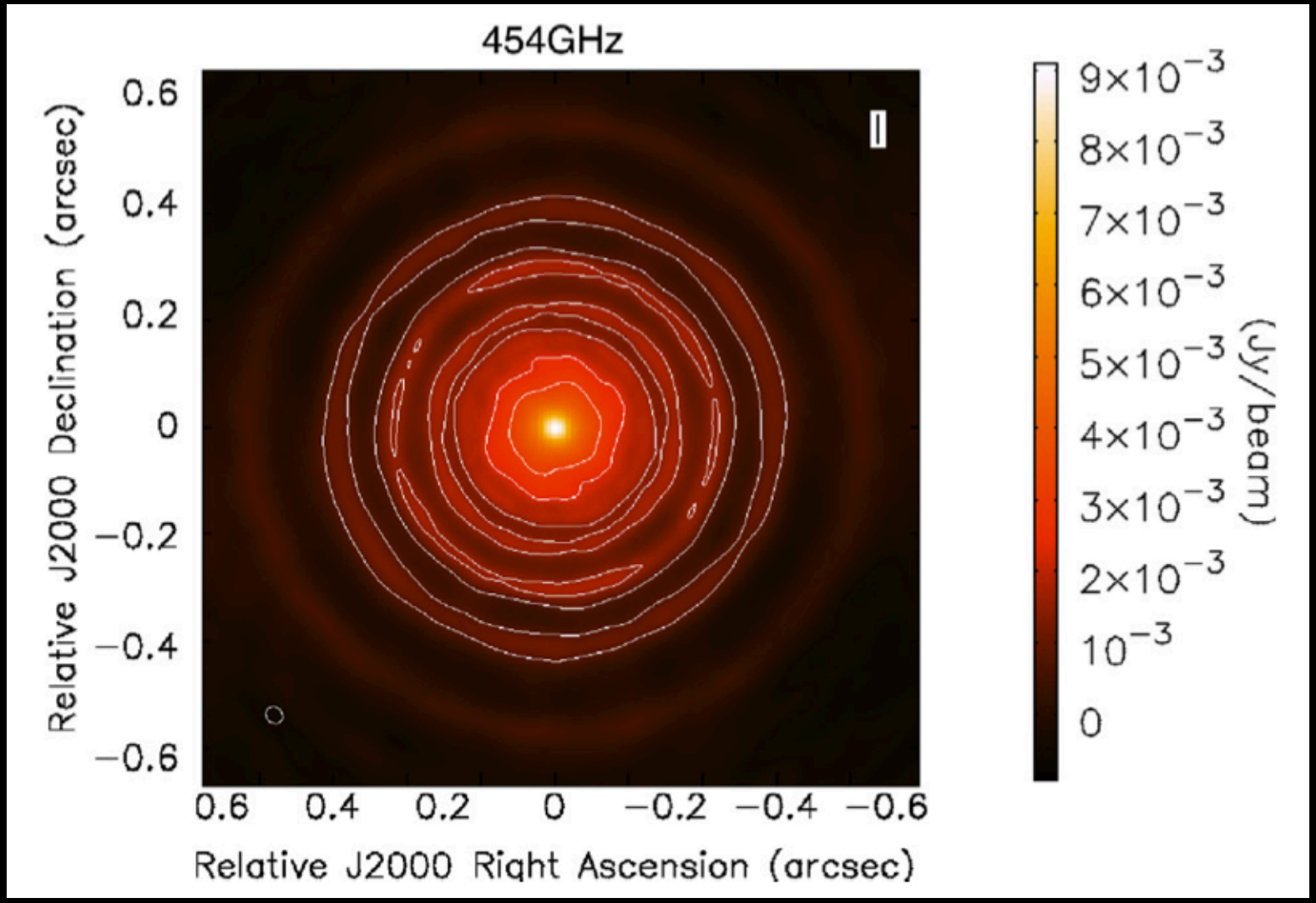
# Simple experiment: Lots of small bumps




Pinilla, Birnstiel, Ricci, Dullemond et al. 2012

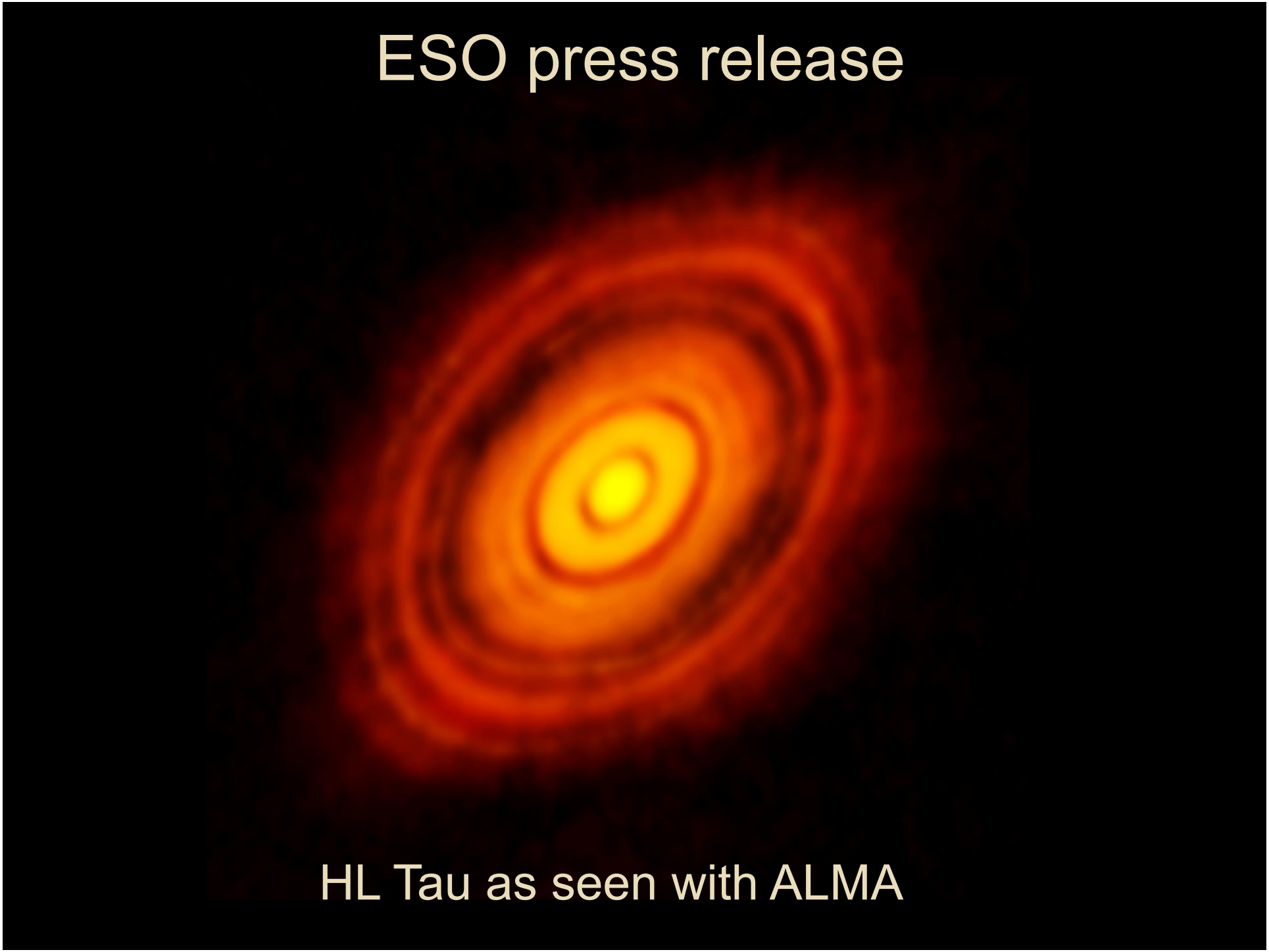
# Simple experiment: Lots of small bumps

ALMA prediction




Pinilla, Birnstiel, Ricci, Dullemond et al. 2012

# ESO press release

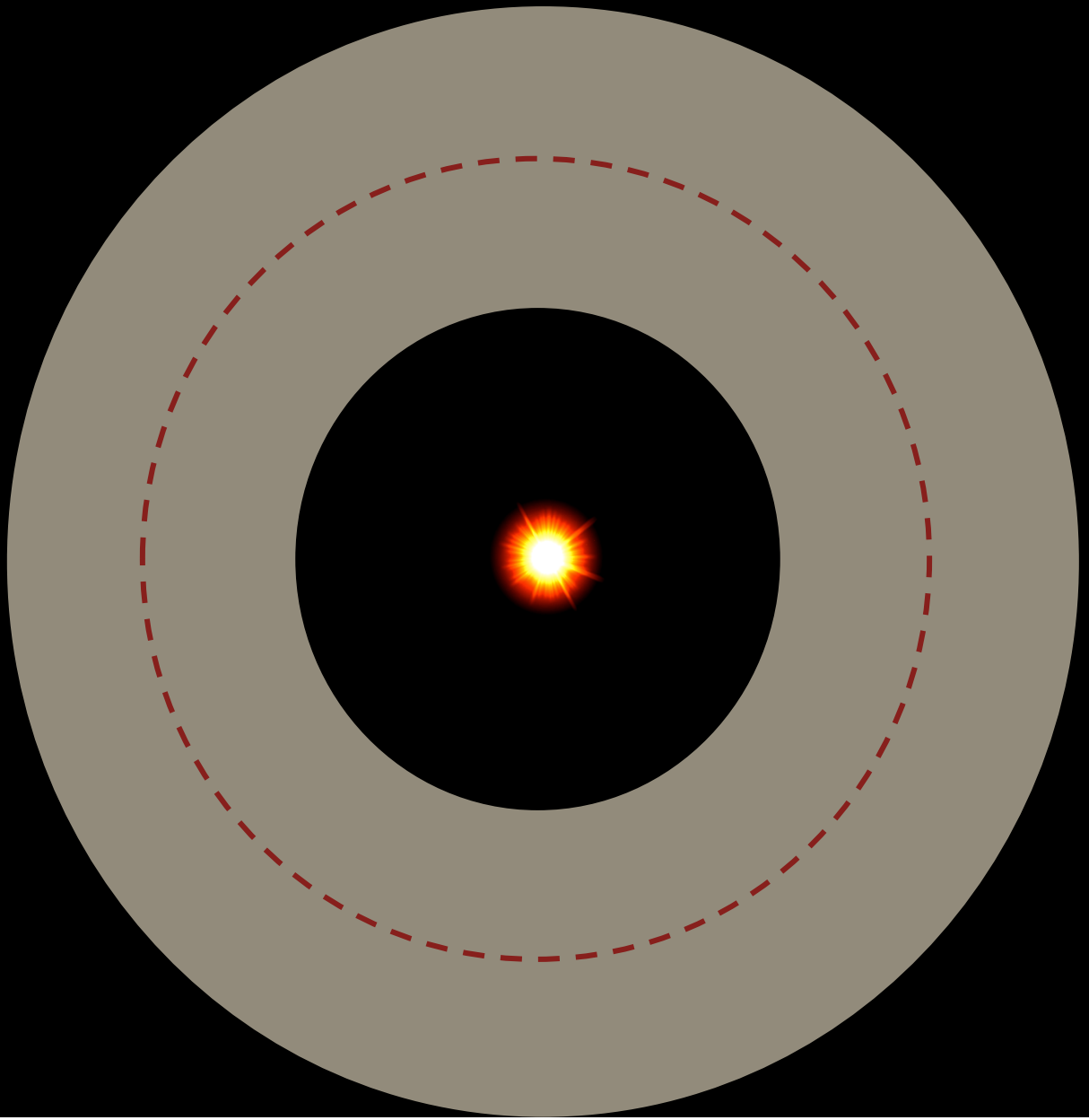


HL Tau as seen with ALMA

Or what about a single big dust trap?

# Particle trapping in large pressure bump

Barge & Sommeria; Klahr & Henning; Johansen et al.; Kretke & Lin; Kato et al.; Dzyurkevich et al.



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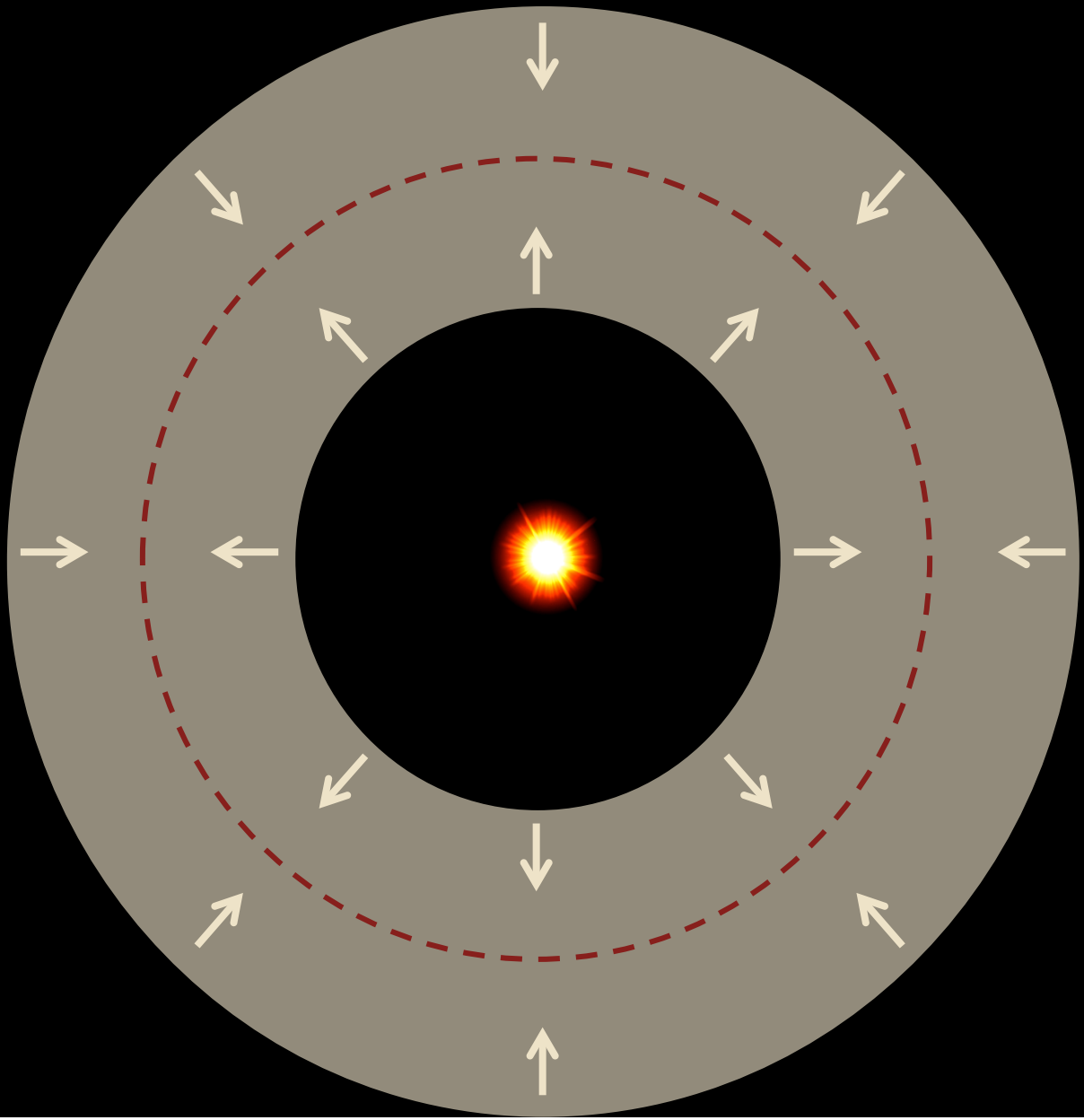

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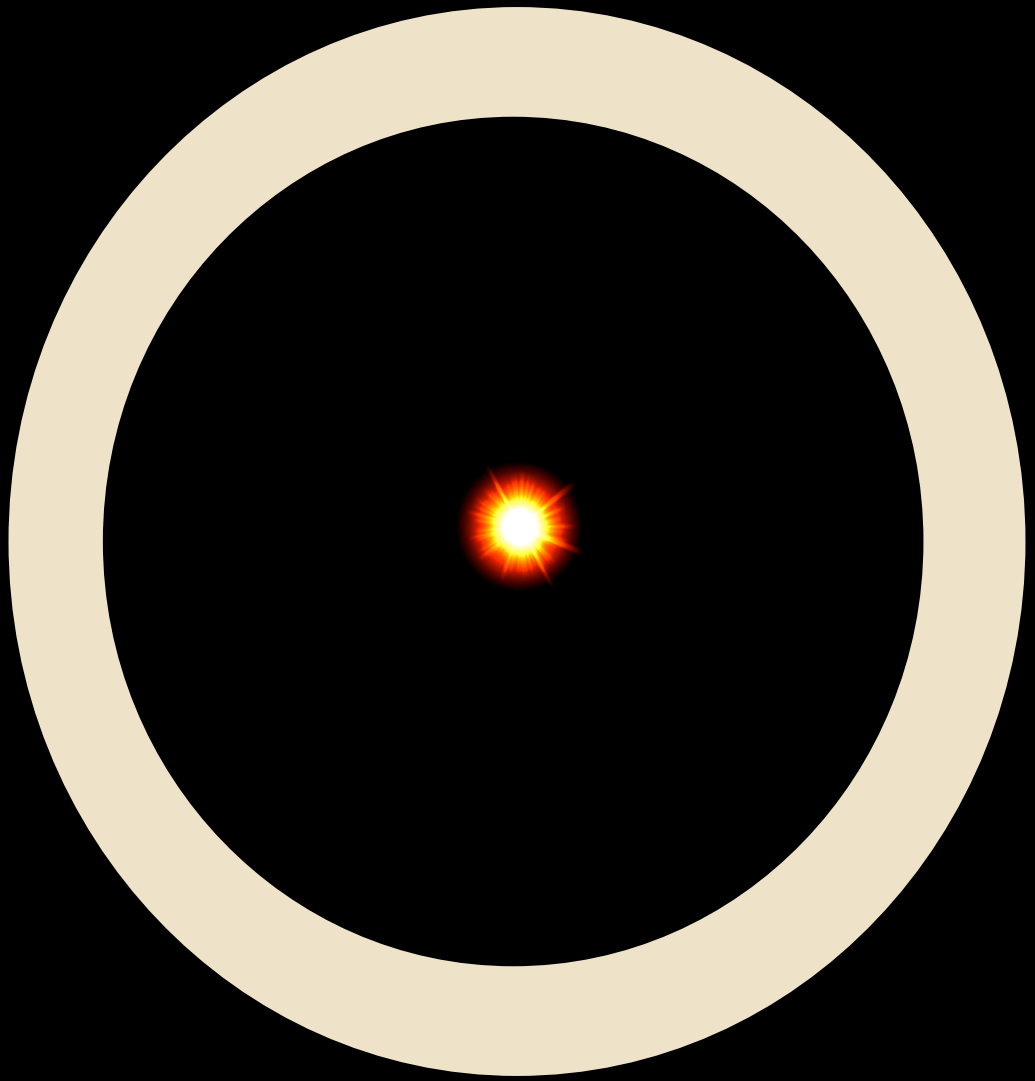
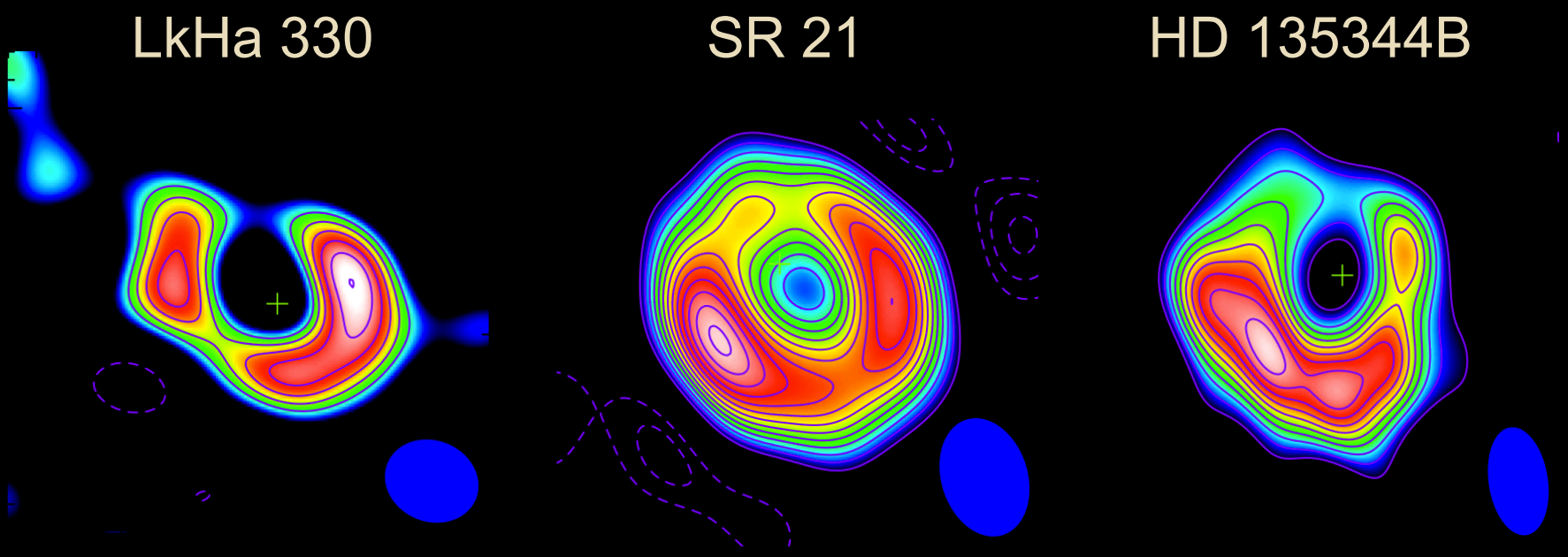


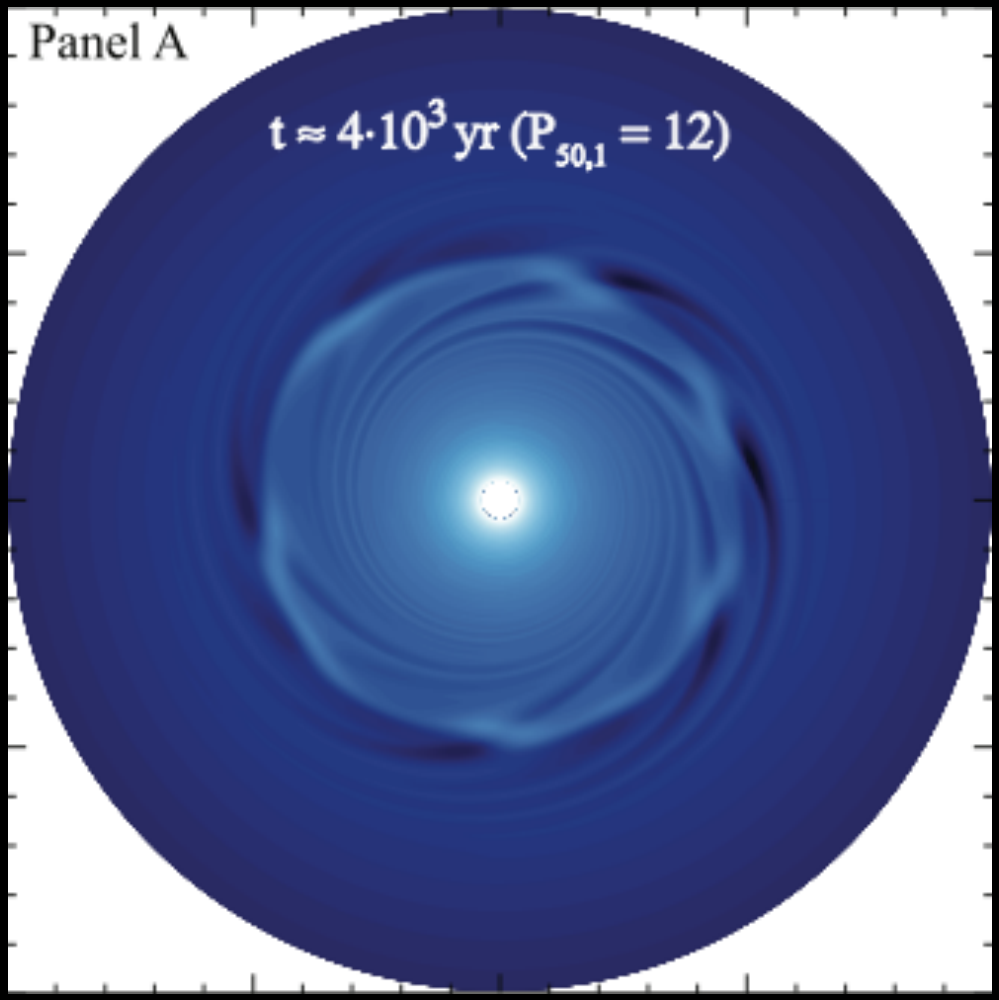
# Presumably we already observe them...




Brown et al. 2009

# Hydrodynamics of a pressure bump

If the bump is too strong, hydrodynamic instabilities will occur:
e.g. Rossby wave instability
Vortices will form!




Regaly, Juhasz
et al. 2011

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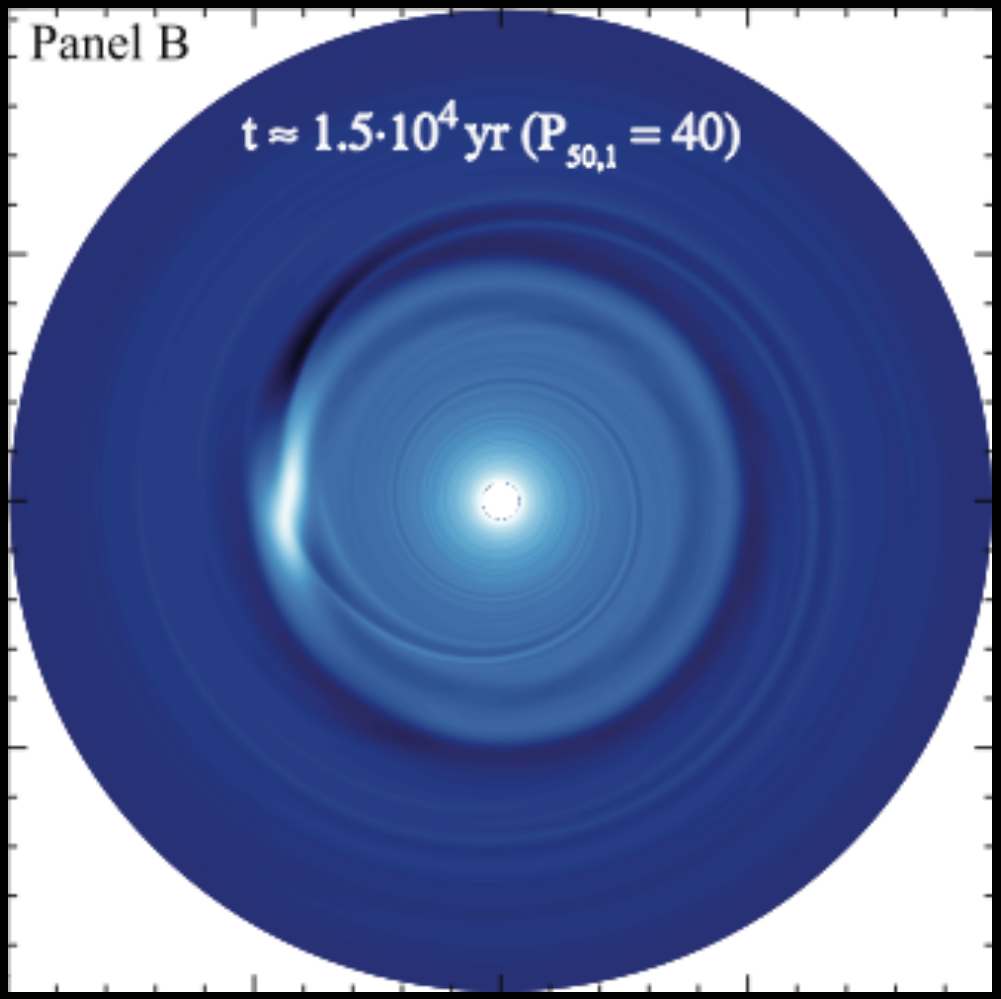


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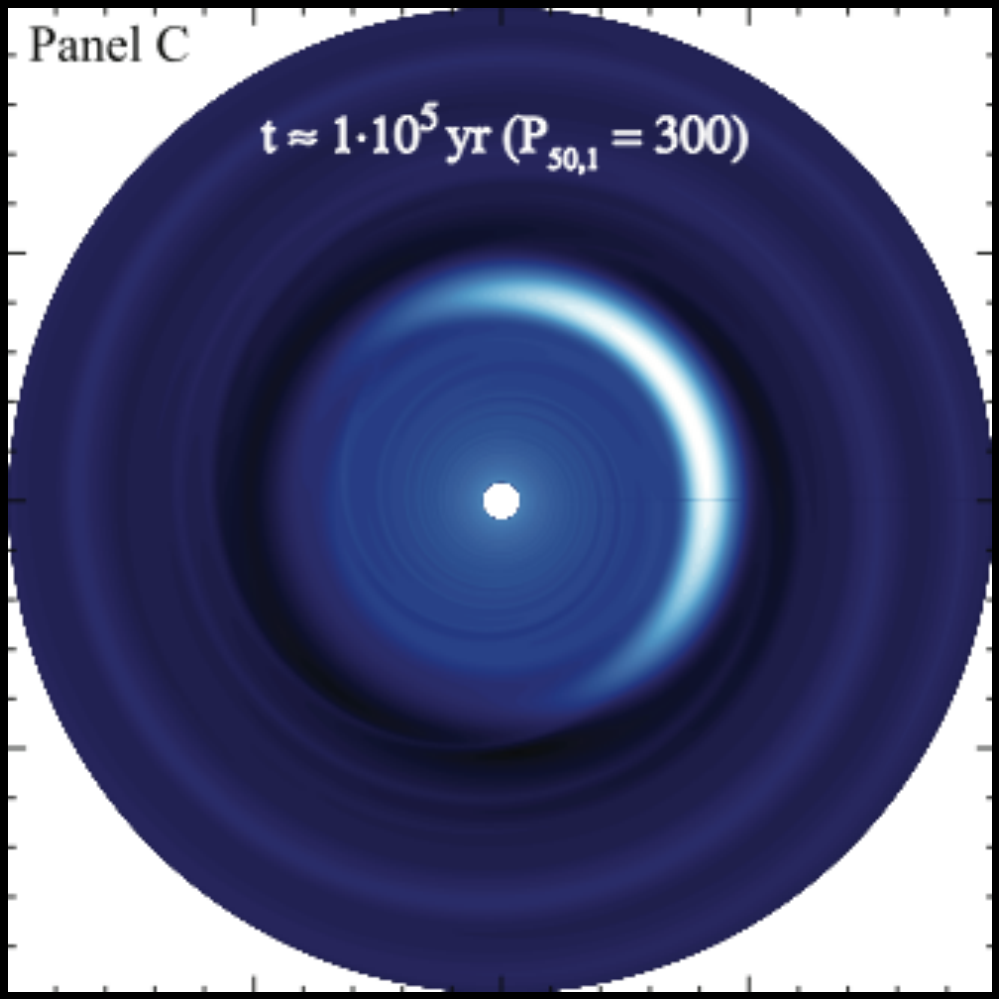


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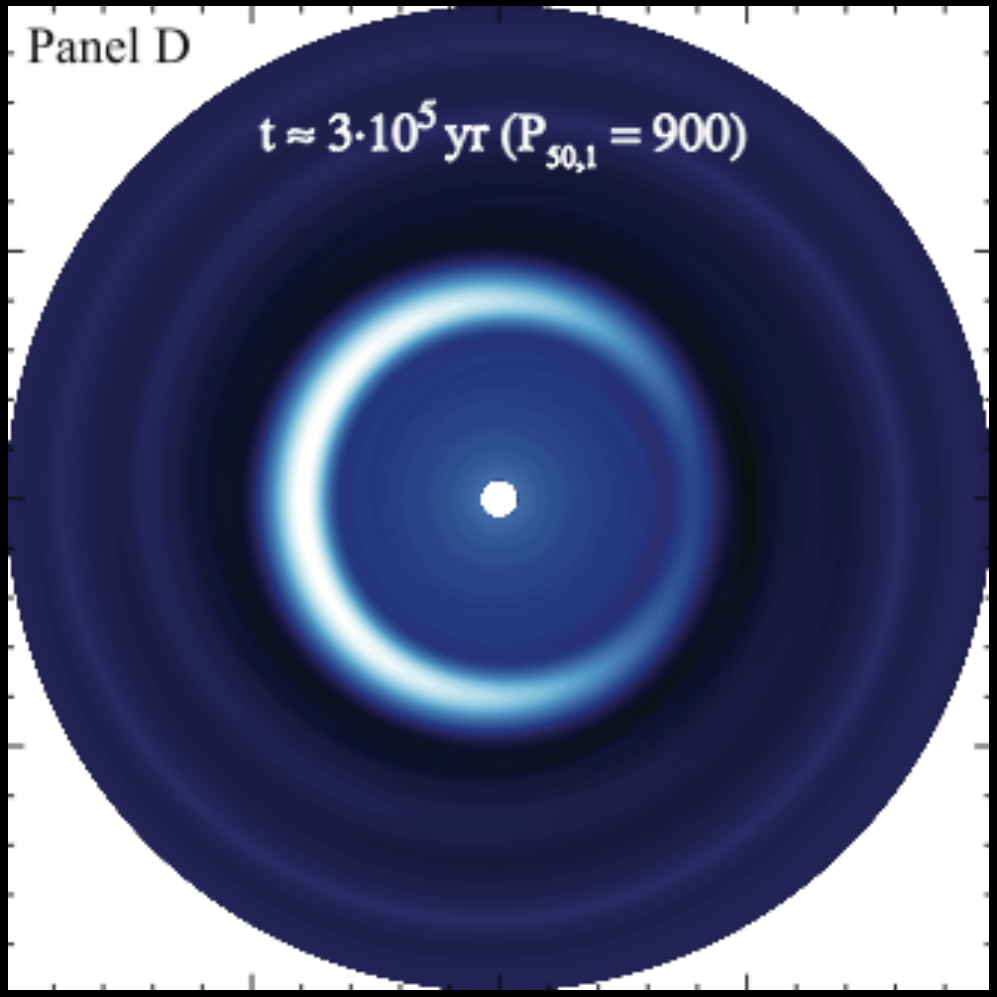


Regaly, Juhasz
et al. 2011

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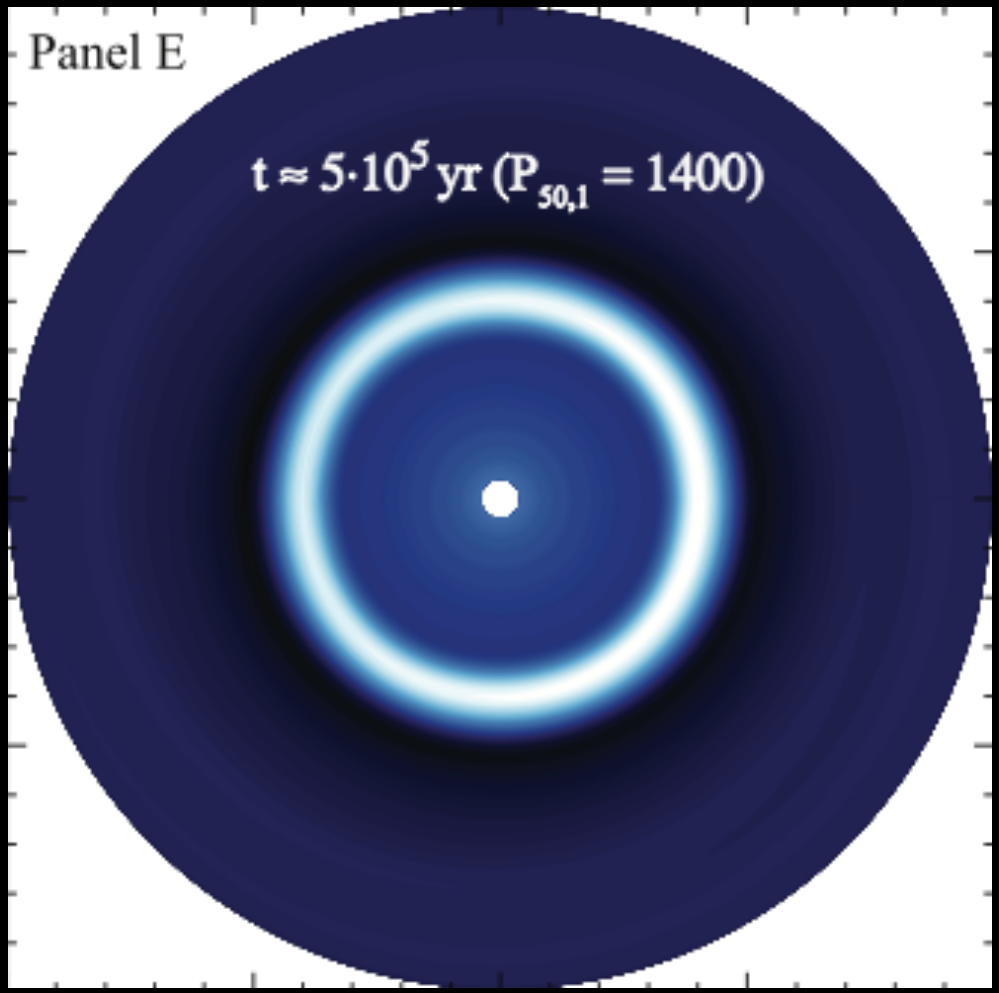


Regaly, Juhasz
et al. 2011

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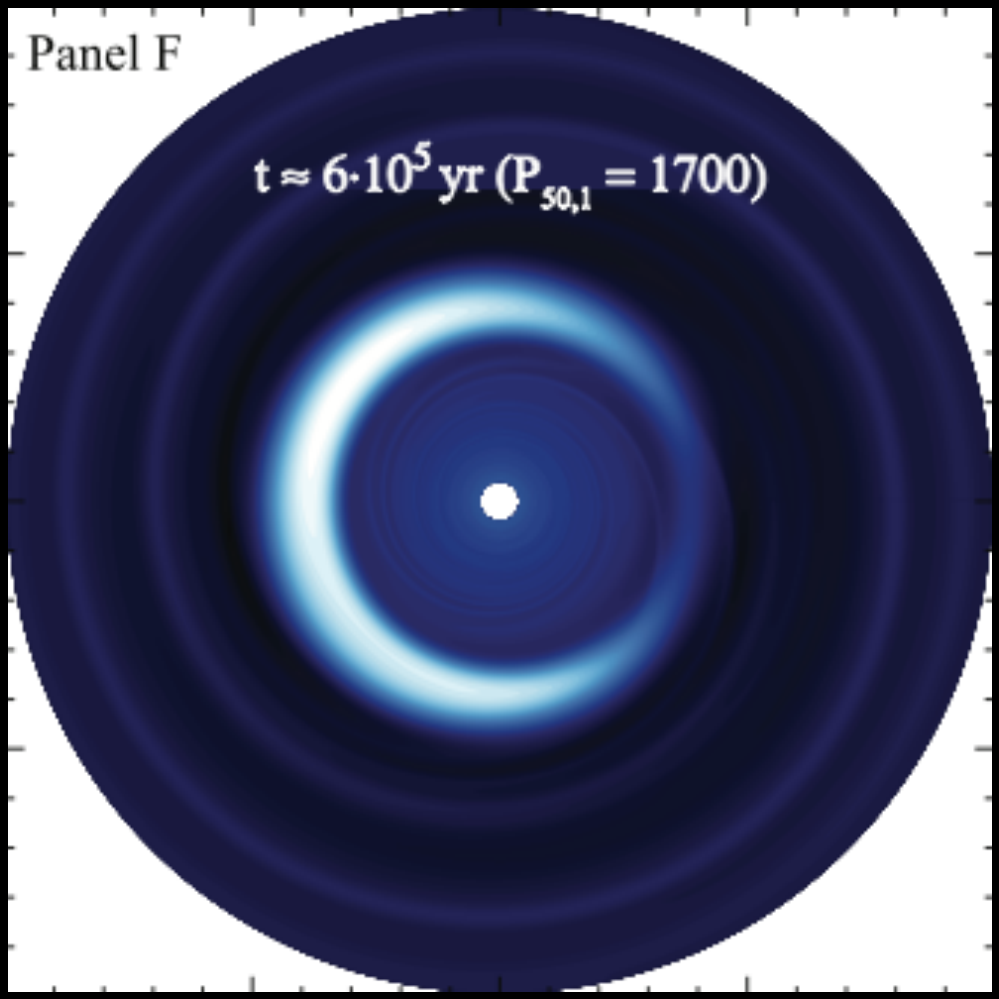



Regaly, Juhasz
et al. 2011

# Vortices by Rossby-wave instability

Just FYI: Banana-shaped vortices by RWI = not a new idea:

- Lovelace et al. 1999
- Li et al. 2000, 2001
- Meheut et al. 2012a/b
- Varniere & Tagger 2006

We just applied it to observed disks

# First comparison to observations...

Observations:

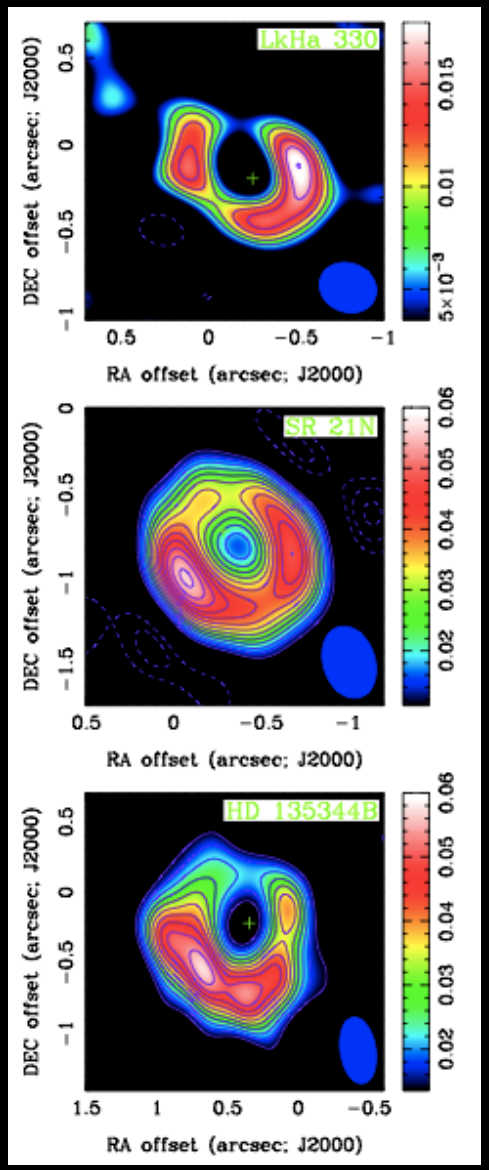
Brown et al. 2009

Model:

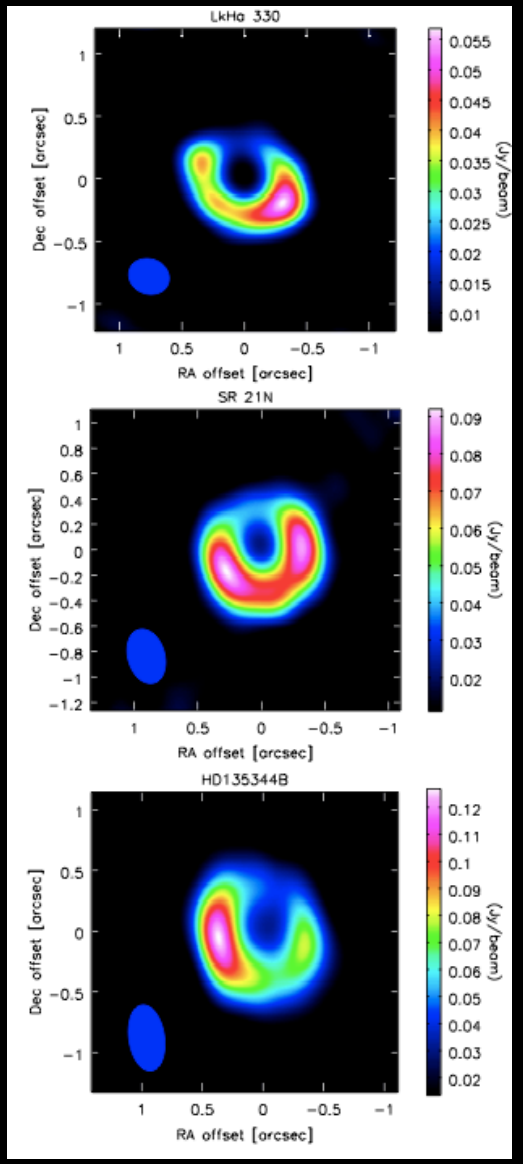
Regaly, Juhasz, Sandor et al. 2012

See also Wolf & Klahr 2002

Observations:



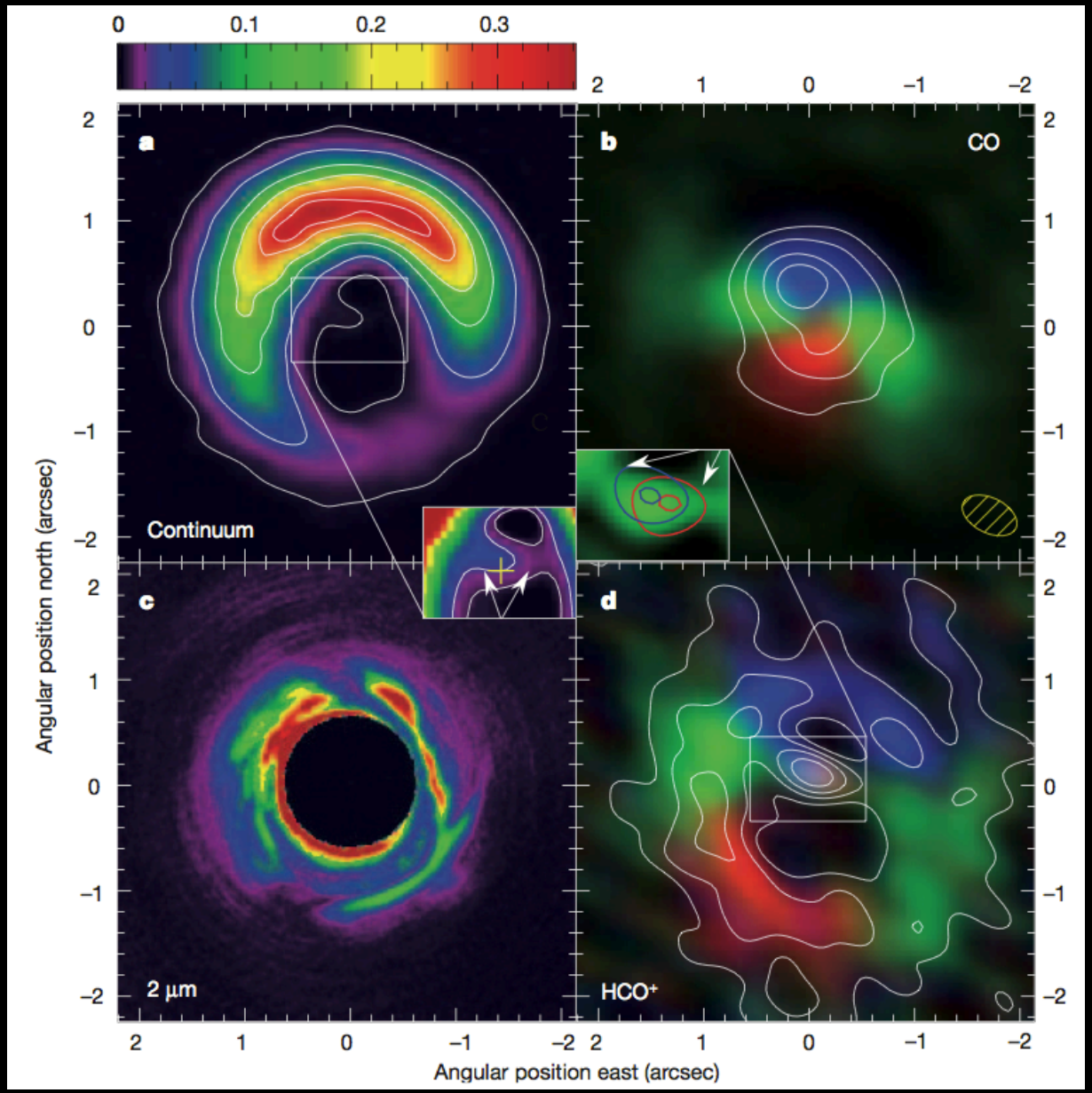

Model:



# Problem: SMA images are not high-enough S/N to be sure!

## Need ALMA

# First dust arc with ALMA



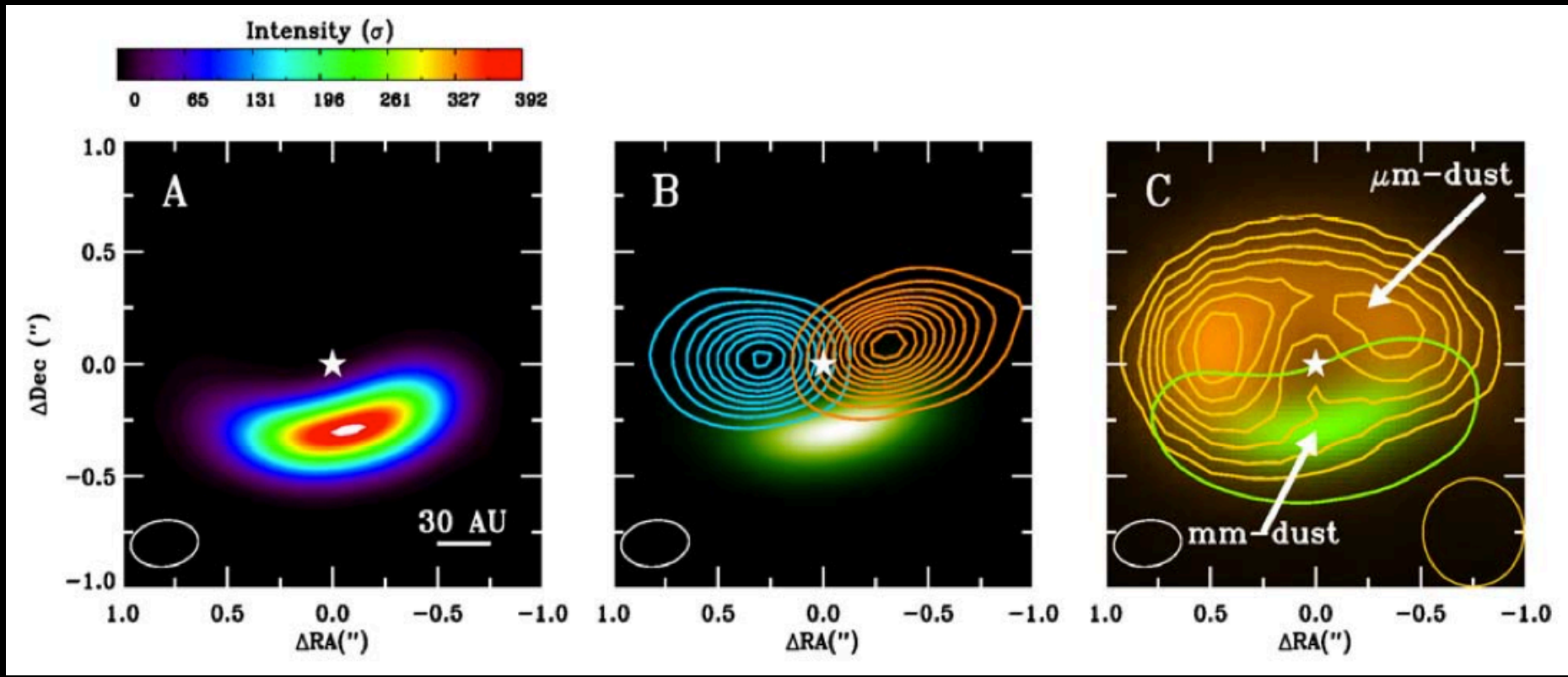

HD 142527
(Herbig Ae star)

Ring radius =
140 AU

Casassus et al.
Nature (2013)

# Dust trapping observed?

## Oph IRS 48

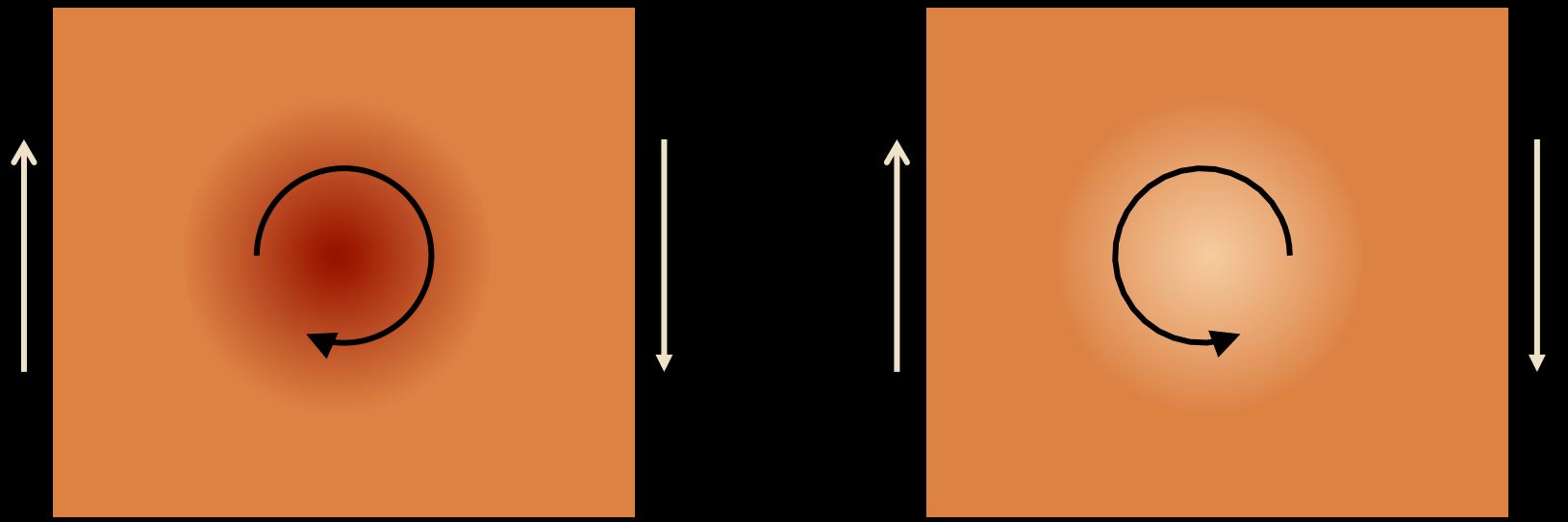



Van der Marel et al. Sience (2013)

# Vortex as a pressure trap

Anti-cyclonic vortex:
Dust gets trapped

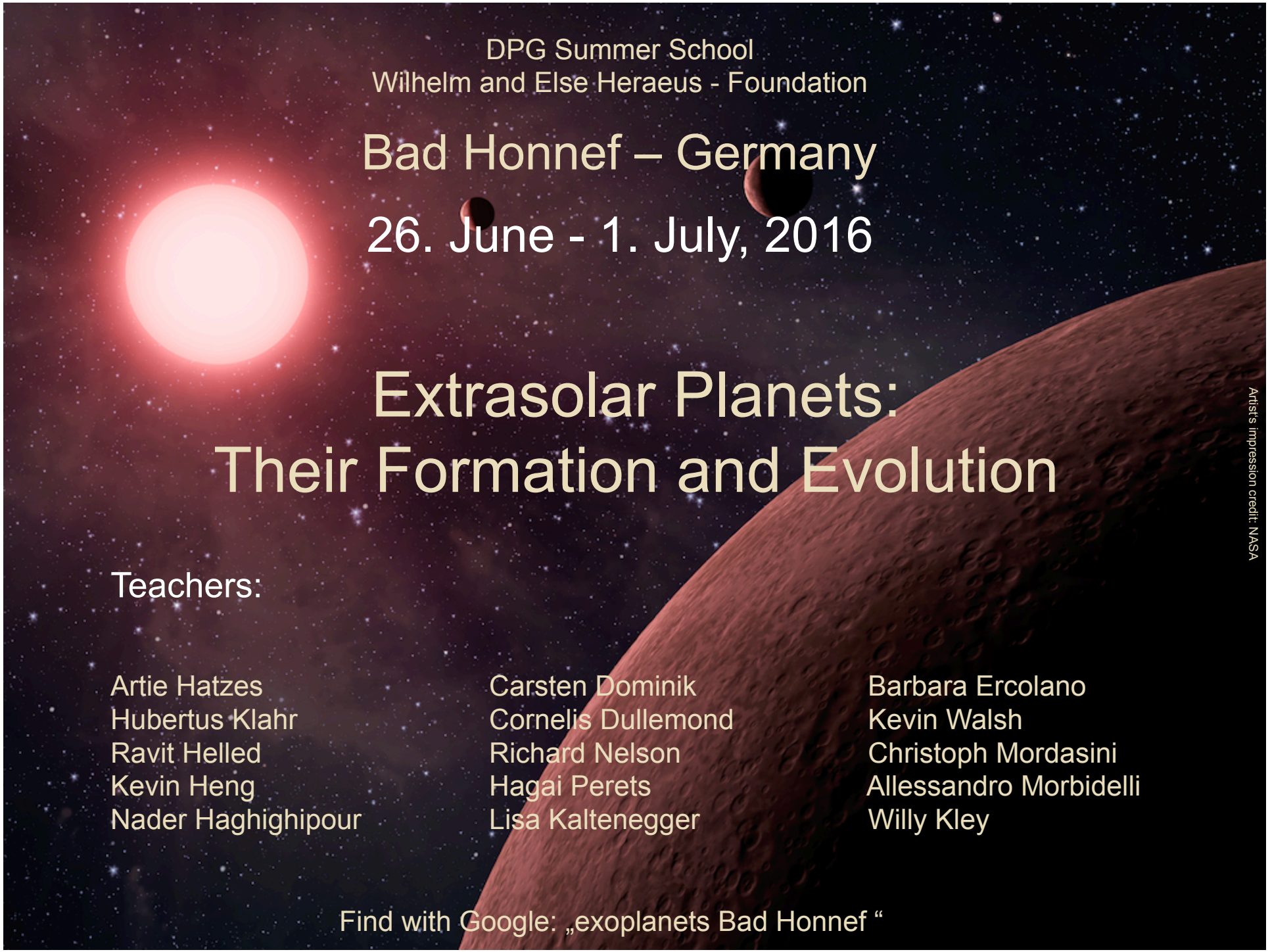
Cyclonic vortex:
Dust gets expelled



Star

Barge & Sommeria (1995), Klahr & Henning (1997)

Commercial Break...



DPG Summer School
Wilhelm and Else Heraeus - Foundation

Bad Honnef – Germany

26. June - 1. July, 2016

# Extrasolar Planets: Their Formation and Evolution

Artist's impression credit: NASA

Teachers:

Artie Hatzes
Hubertus Klahr
Ravit Helled
Kevin Heng
Nader Haghighipour

Carsten Dominik
Cornelis Dullemond
Richard Nelson
Hagai Perets
Lisa Kaltenegger

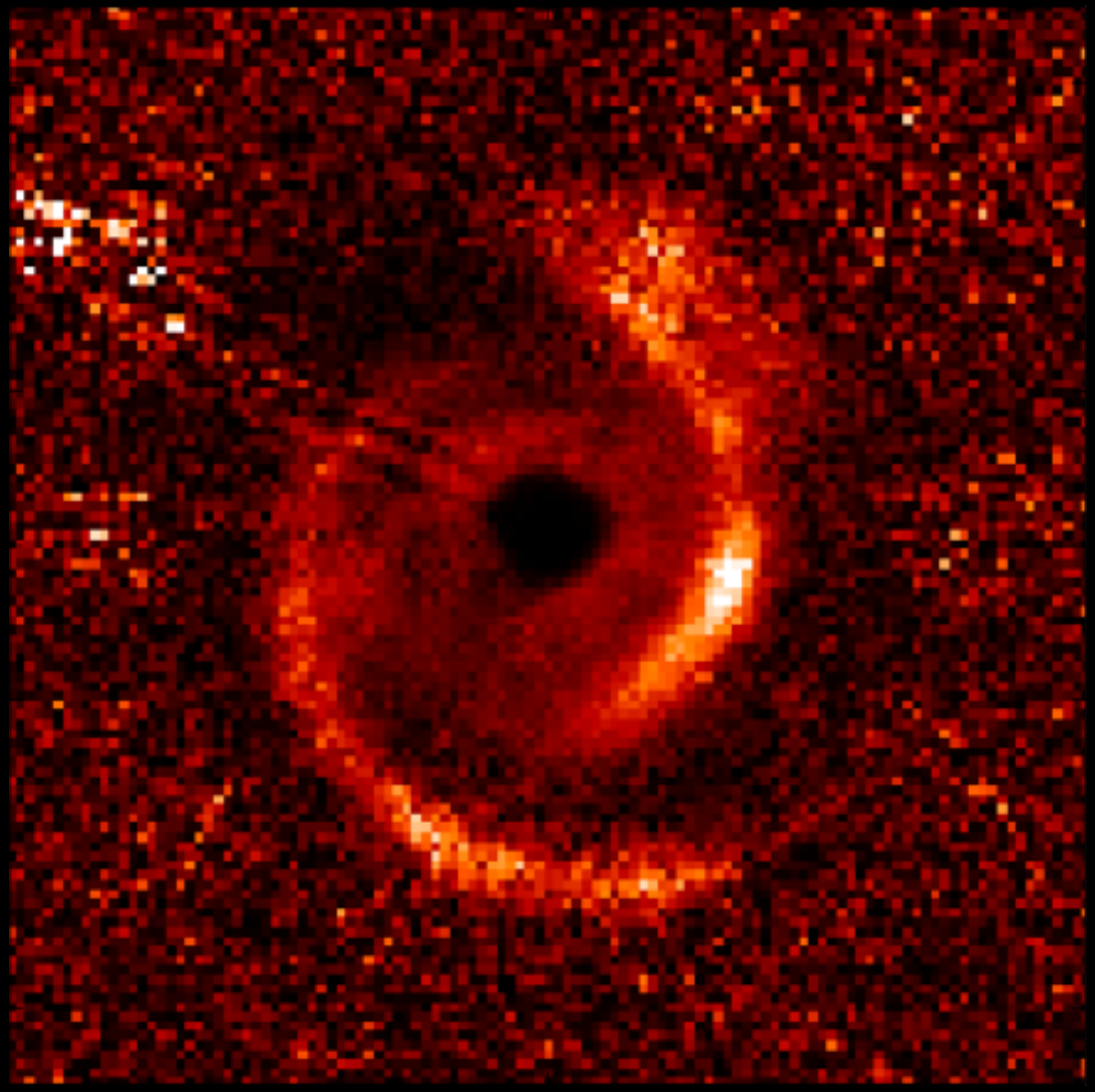
Barbara Ercolano
Kevin Walsh
Christoph Mordasini
Allessandro Morbidelli
Willy Kley

Find with Google: „exoplanets Bad Honnef “

Spiral waves in protoplanetary disks

# Spirals in protoplanetary disks

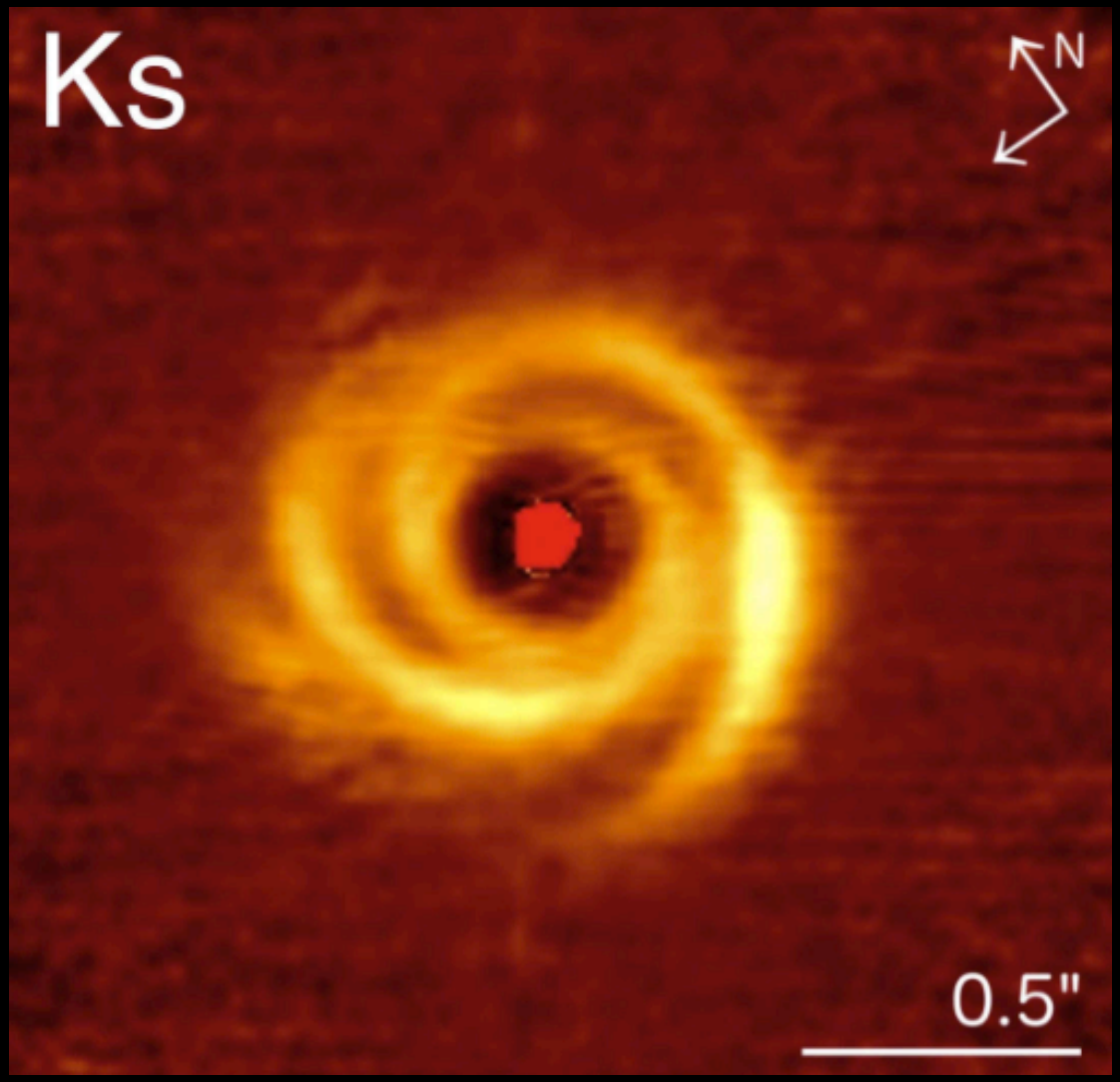
MWC 758



Benisty et al. 2015

# Spirals in protoplanetary disks

HD 135344b



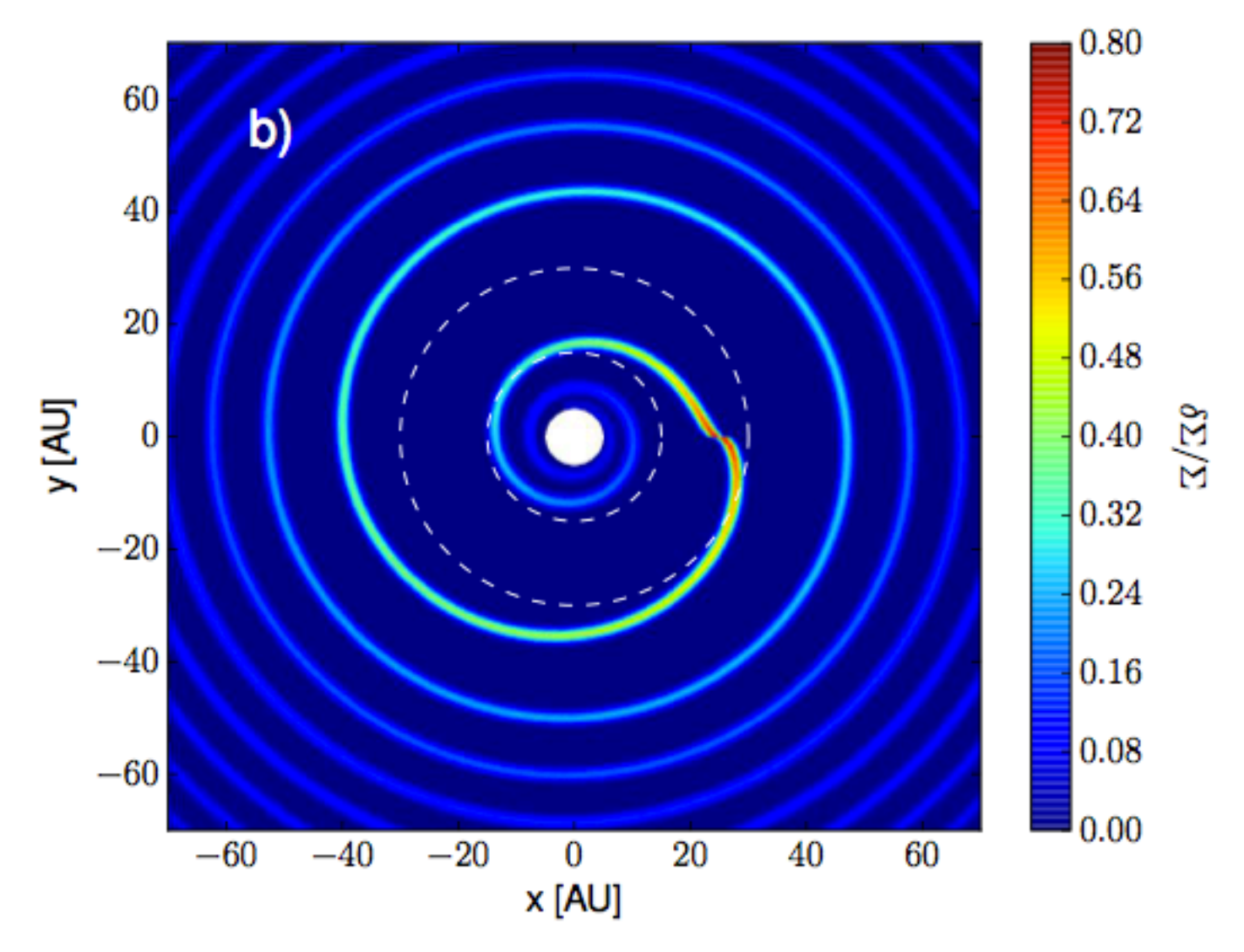

Garufi et al. 2013

# In Heidelberg we have such a thing...

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

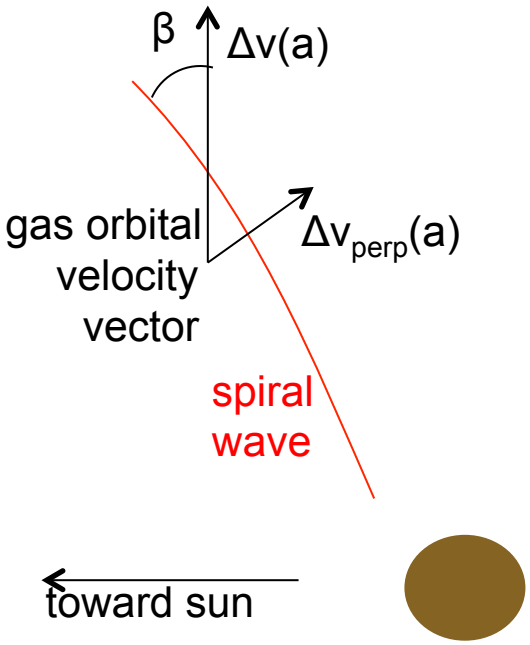
Modeled after M51, but also seems to fit HD135344b

# 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



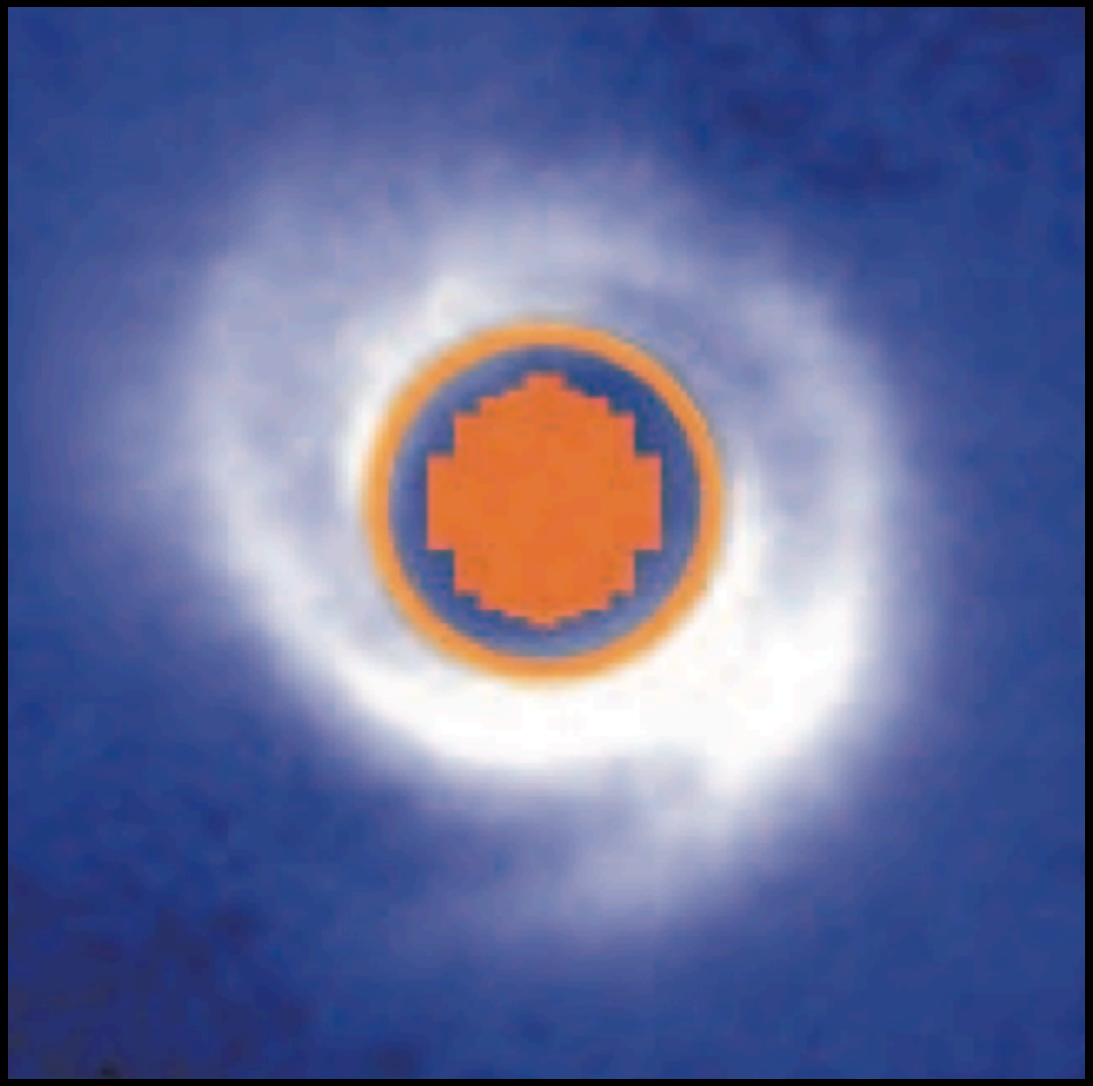

To ensure that the spiral wave is stationary in the reference frame corotating with the planet, the component of the orbital velocity Δv(a) perpendicular to the spiral wave (i.e. $\Delta v_{perp}(a)$) must be precisely equal to the sound speed (assuming the wave is not a shock).

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

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

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

# Are these giant spirals consistent with planet-induced spirals?



Muto et al. 2012

Issues to consider:

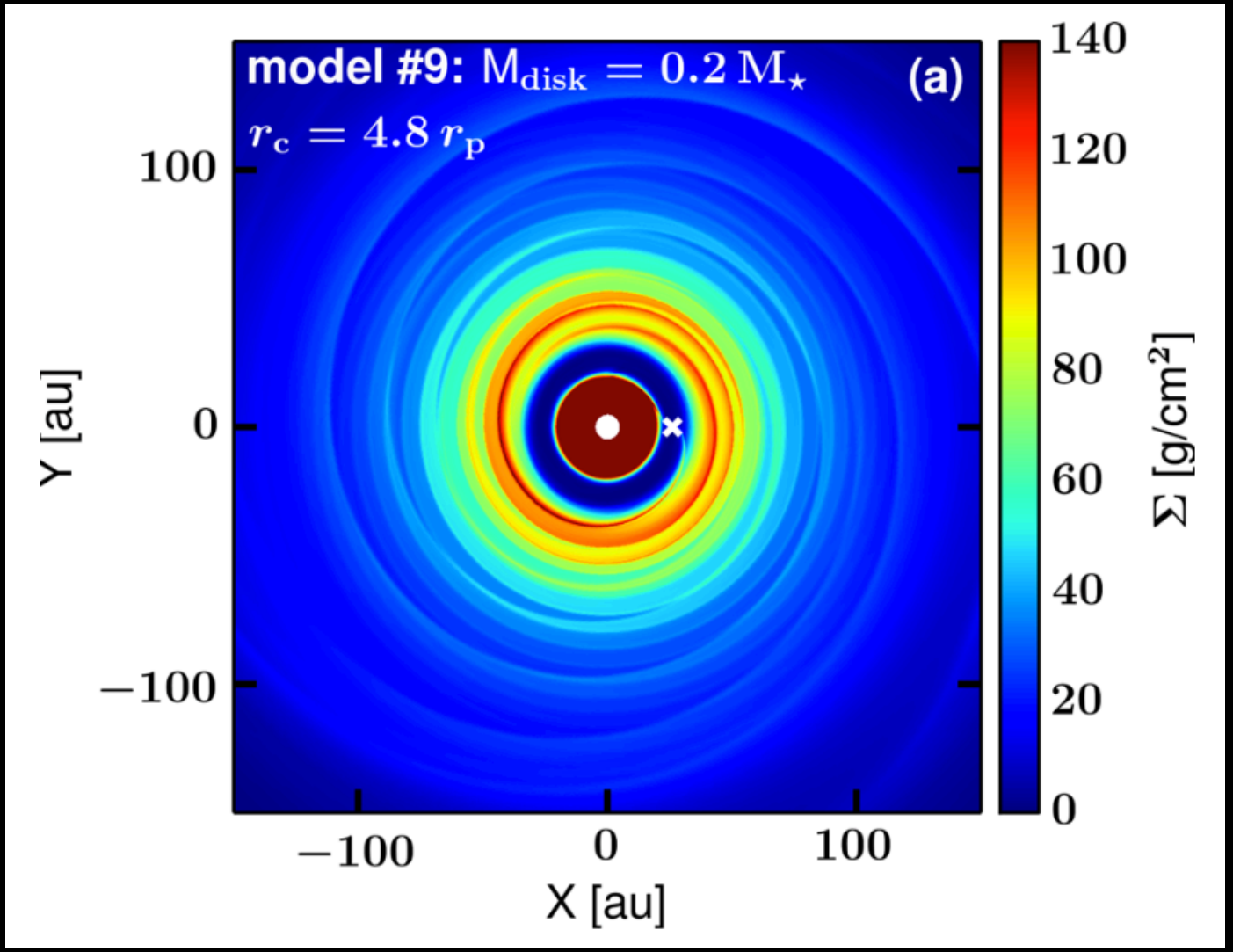
- Are the waves strong enough to make this contrast?
- Is the winding number consistent with the expected H/R of the disk?

# Disk modeling to understand spirals

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

An m=2 spiral appears.

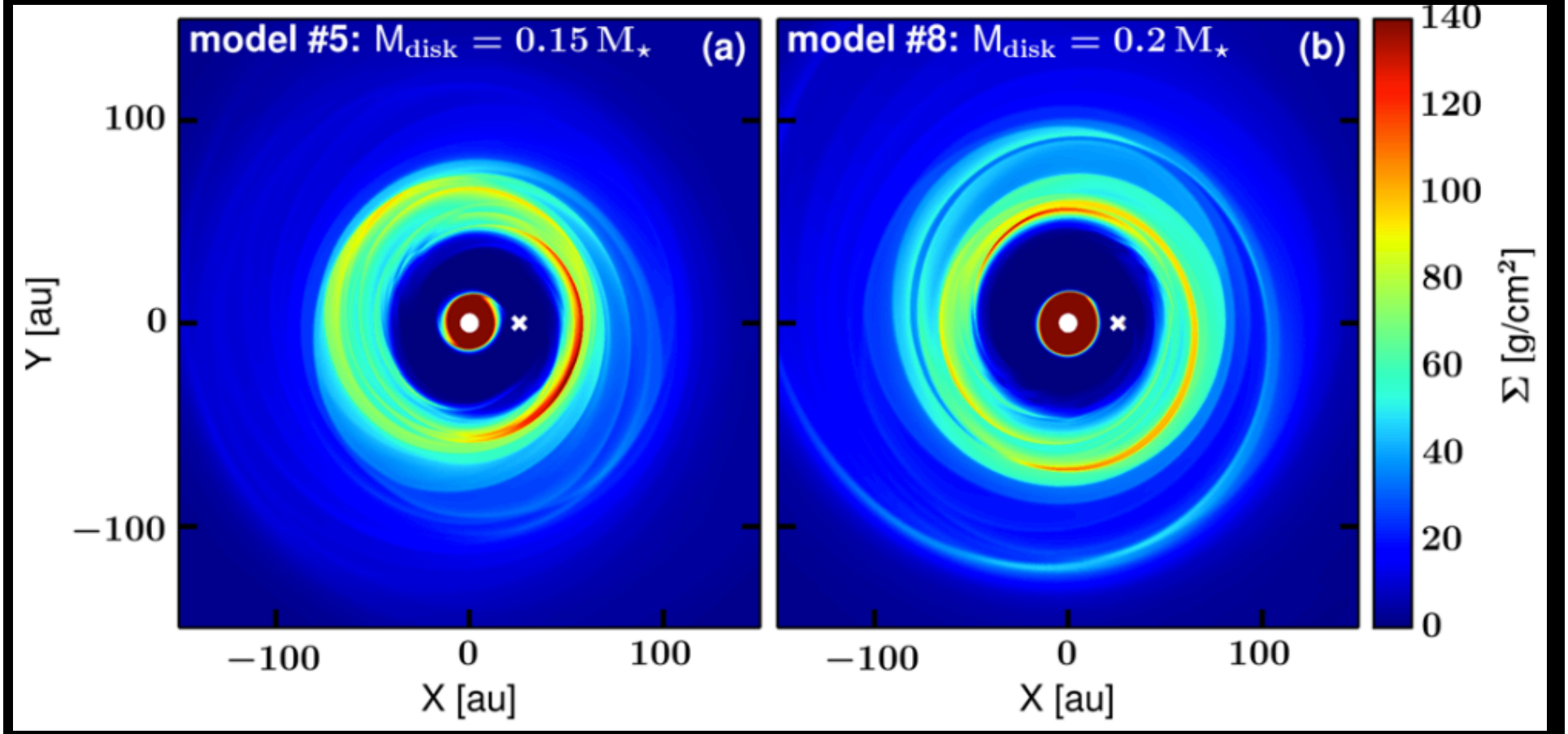
Larger pitch angle, but not enough.




Pohl et al. 2015

# Disk modeling to understand spirals

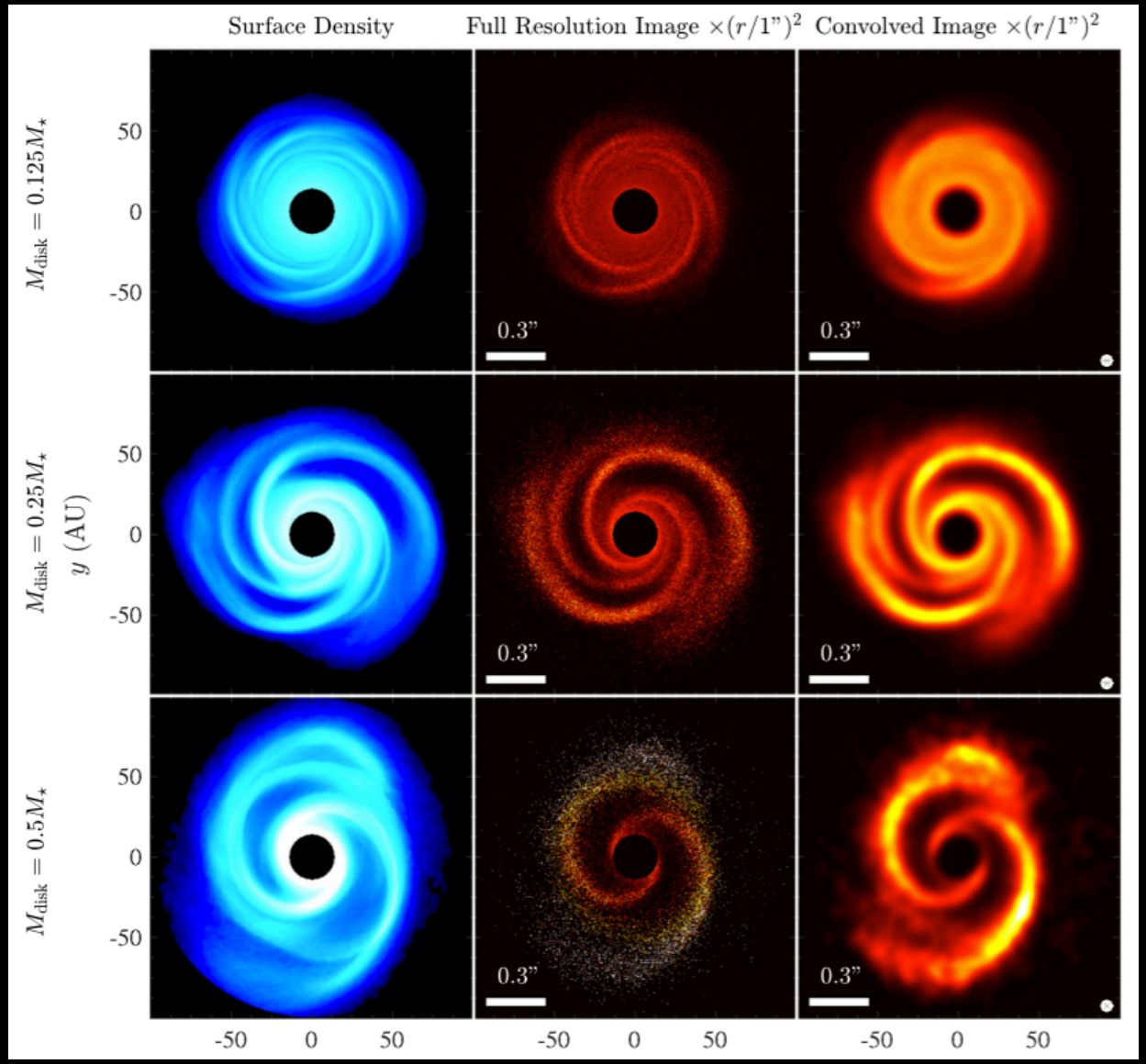
Larger planet mass and self-gravity:
large pitch angle, but one-armed




Pohl et al. 2015

# Very massive disk, no companion

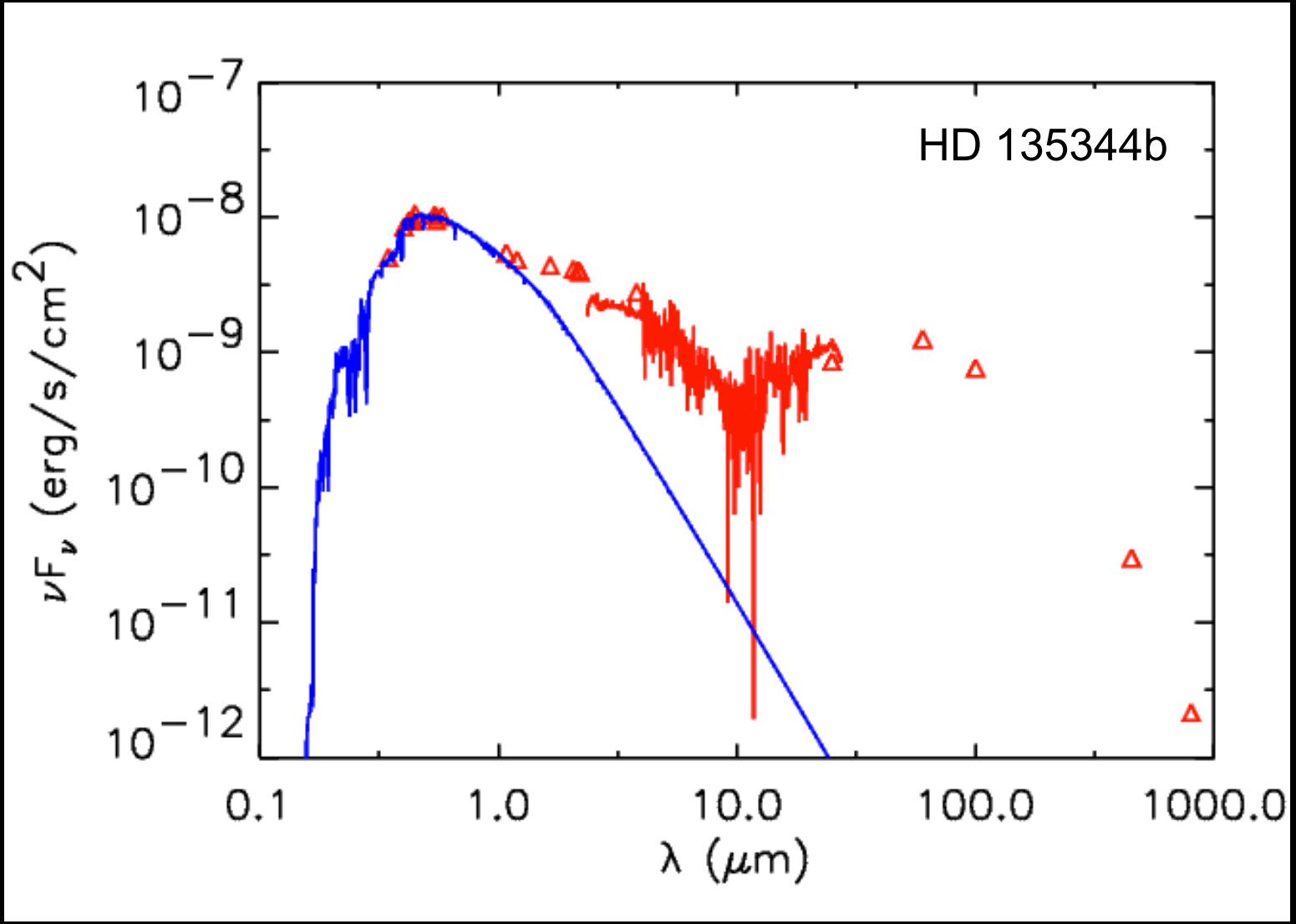
$M_{disk}=0.5M_*$




Dong, Hall, Rice & Chiang 2015

The tiny inner dust disk
a „puff of smoke“

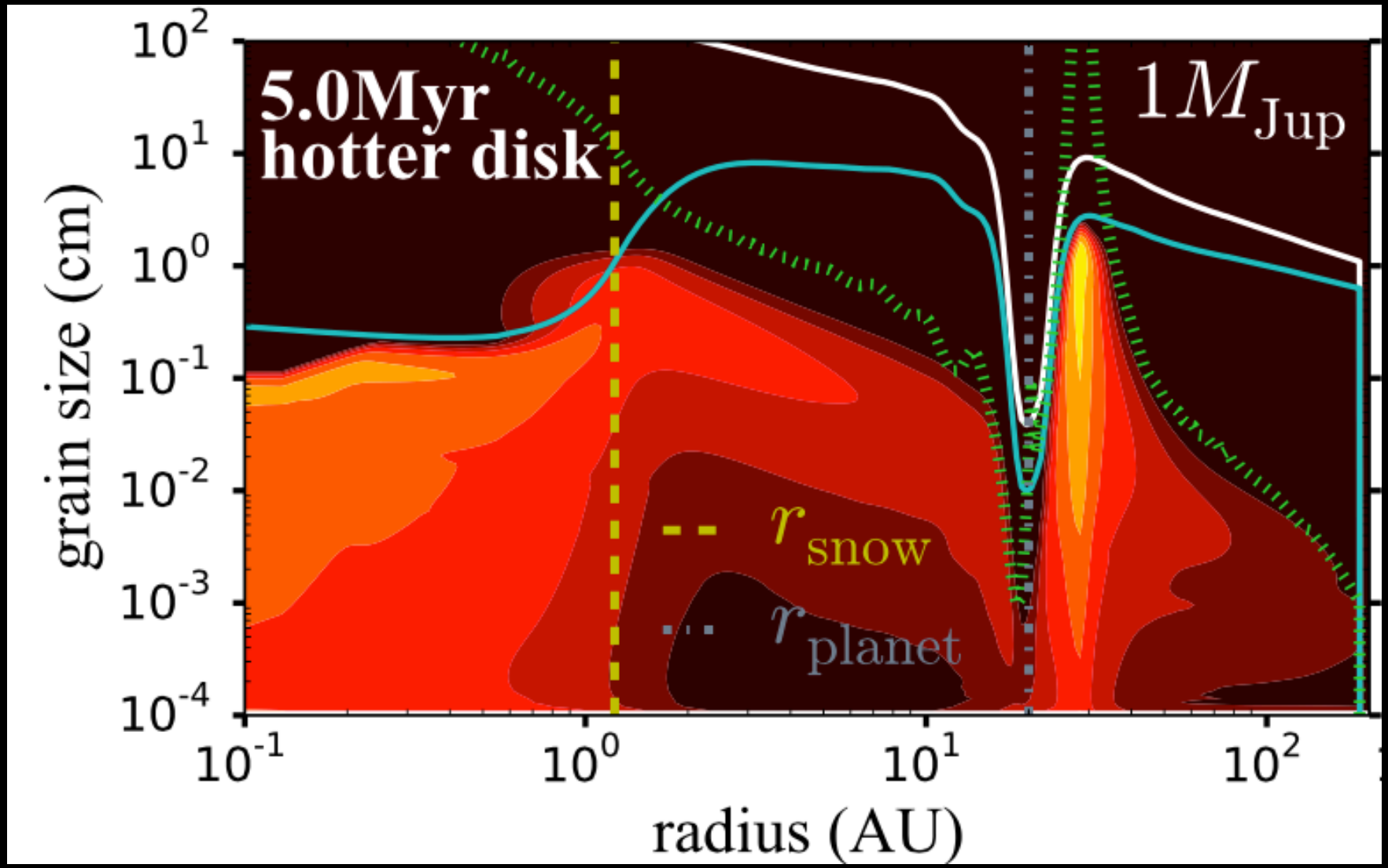
# Many Transition Disks have NIR flux




Therefore: Inner hole cannot be totally empty
Very close to the star there remains a „puff of smoke“

Why?

# Idea: Pebble Drift through the snow line




Pinilla et al. 2016