The Cradle of Planets: from Cosmic Dust to Planetesimals

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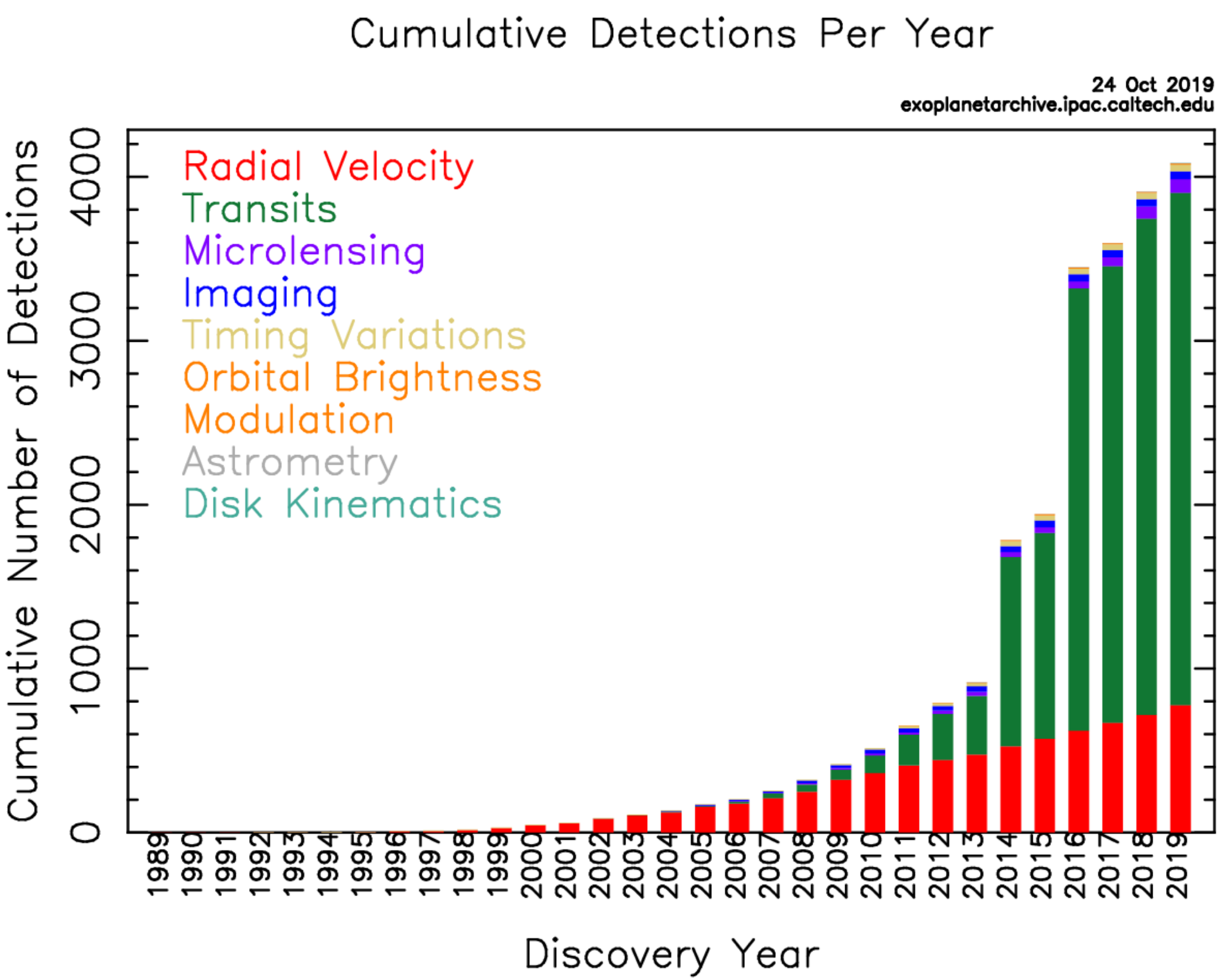
Discovery of Exoplanets



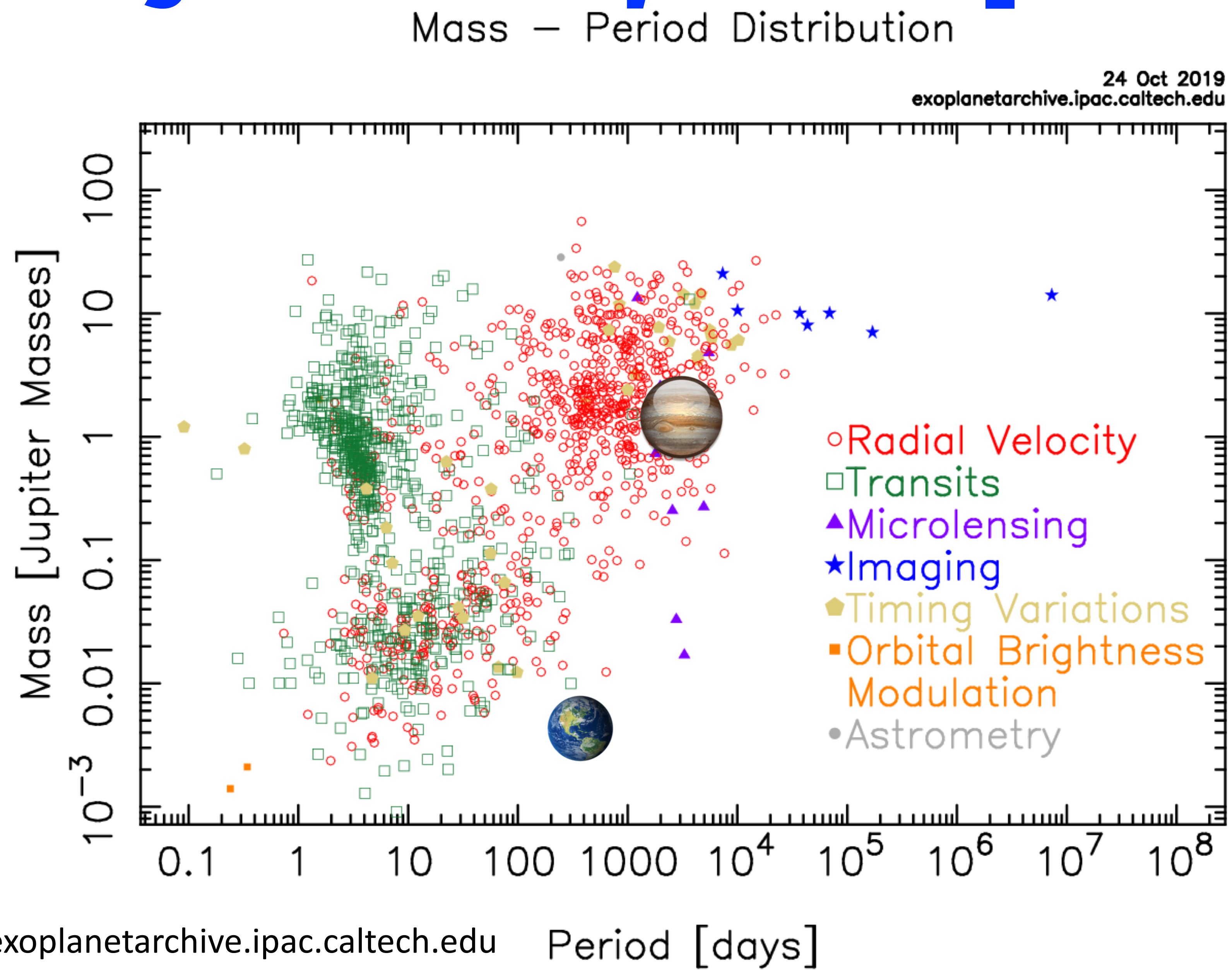
Today
~ 4100 confirmed exoplanets

1995
First confirmation of an exoplanet orbiting a main-sequence star

(Mayor & Queloz, 1995)
Nobel Prize in Physics 2019

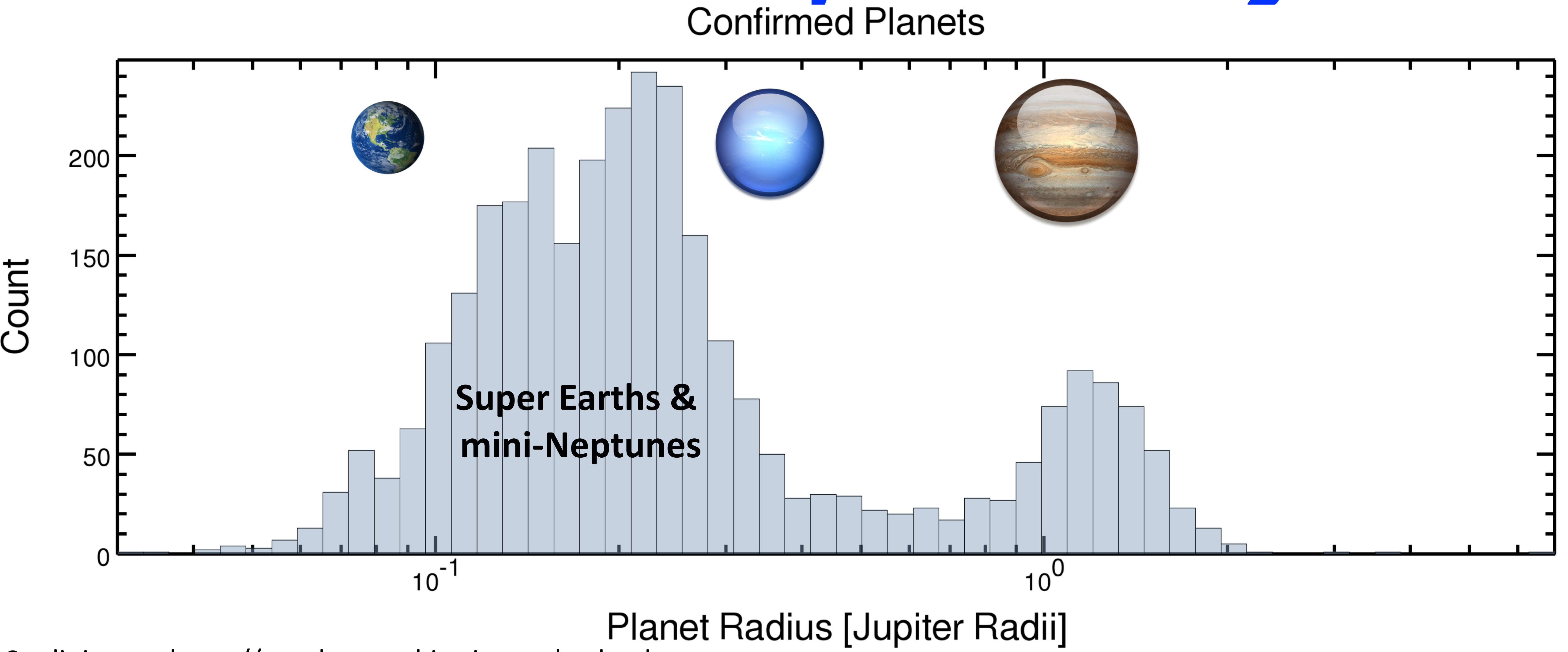
Credit image: https://exoplanetarchive.ipac.caltech.edu

Large Diversity of Exoplanets



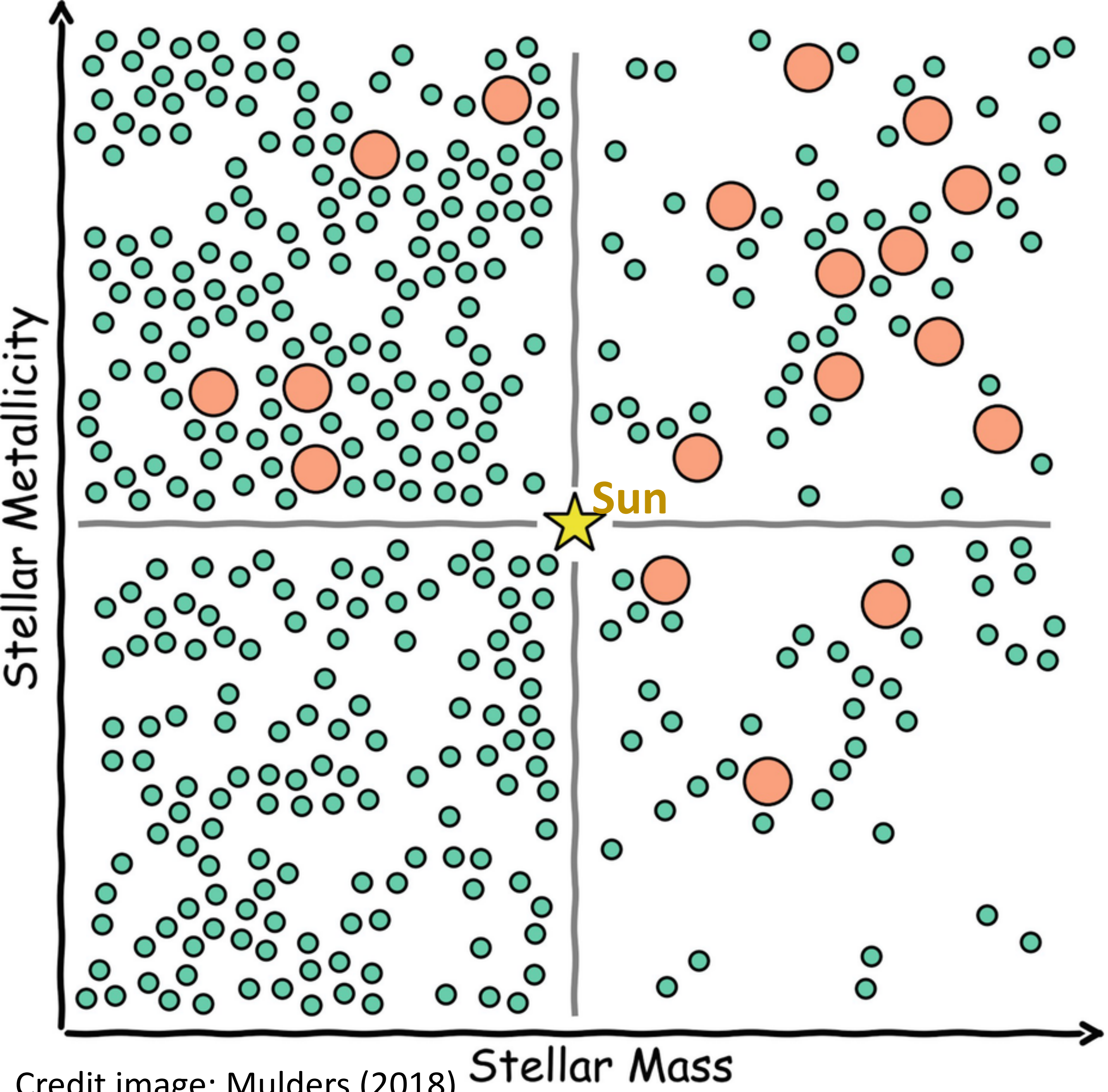
Credit image: https://exoplanetarchive.ipac.caltech.edu

The most common type of exoplanets does not have Solar System analogs



Credit image: https://exoplanetarchive.ipac.caltech.edu

Some trends with the stellar mass have merged



Credit image: Mulders (2018)

1. Giant planets occur more frequently around more massive and more metal-rich stars

2. Sub-Neptunes occur around stars with a wide range of metallicities, but occur more frequently around lower-mass stars

Initial conditions and dynamical evolution protoplanetary disks must leave an imprint on the properties and diversity of exoplanets

Look back in time …

Protoplanetary Disks

Composition: 99% gas, 1% is dust

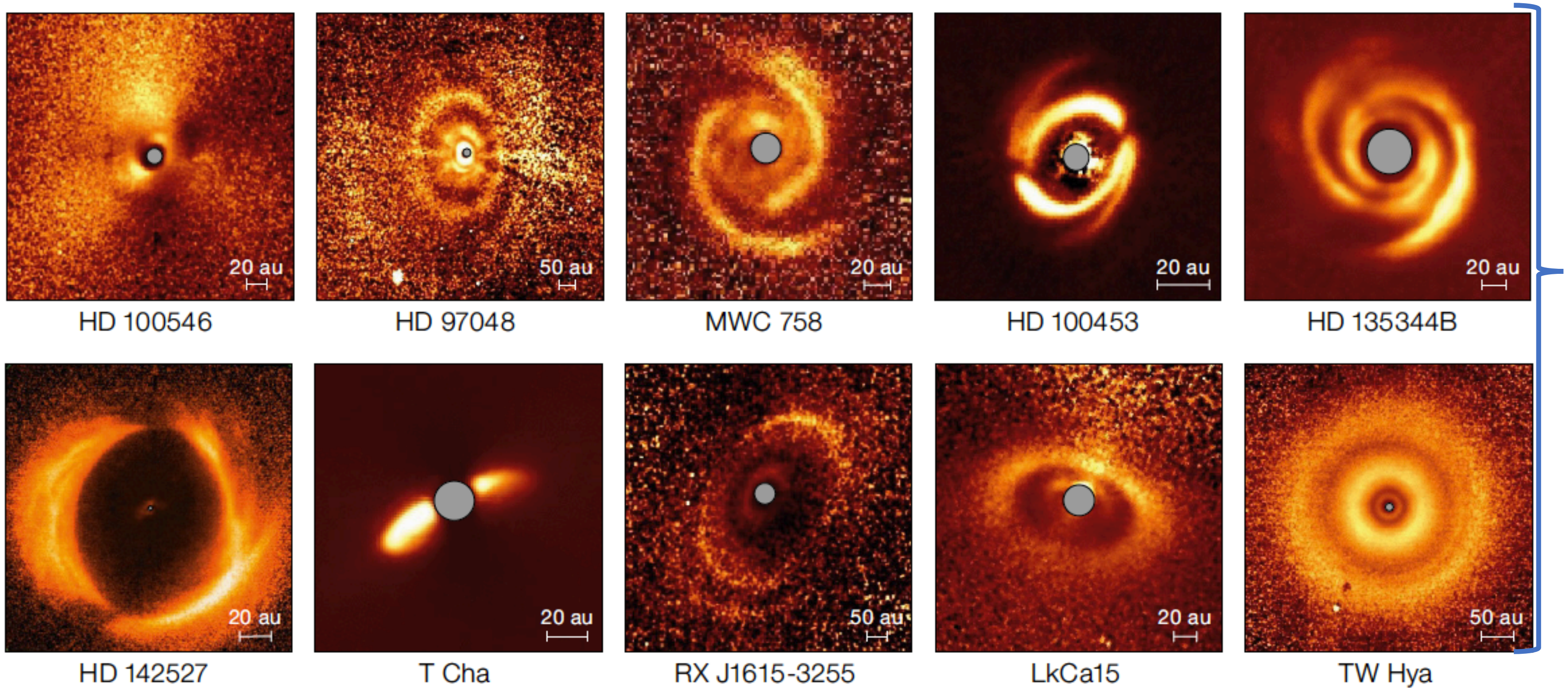
Initial dust size: as ISM (micron-sized)

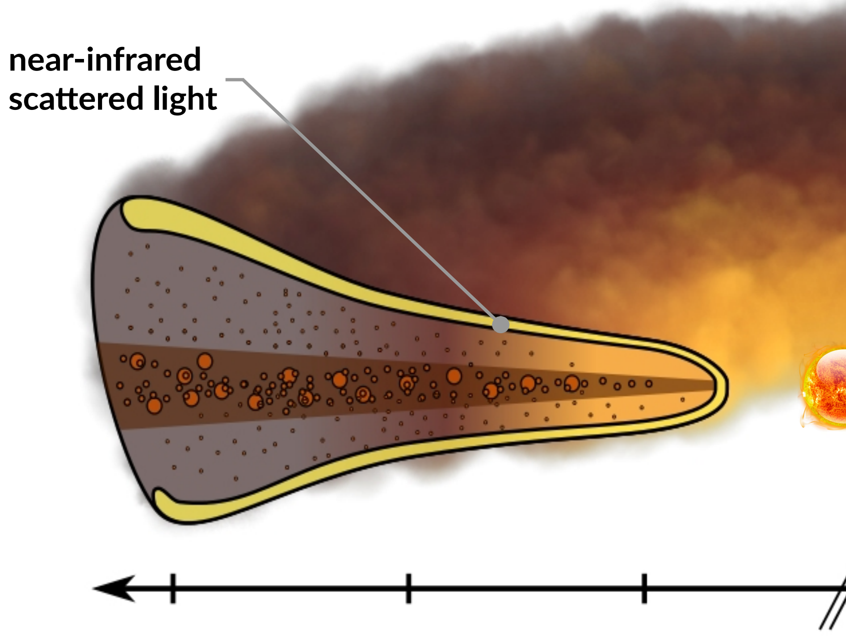
Lifetime: ~3-10 Myr

Radii up to 1000 au
(large range of temperatures 10-1500K)

Observing the Evolution of Solids in Protoplanetary Disks

Optical to near infrared scattered light → Small particles at the disk surface

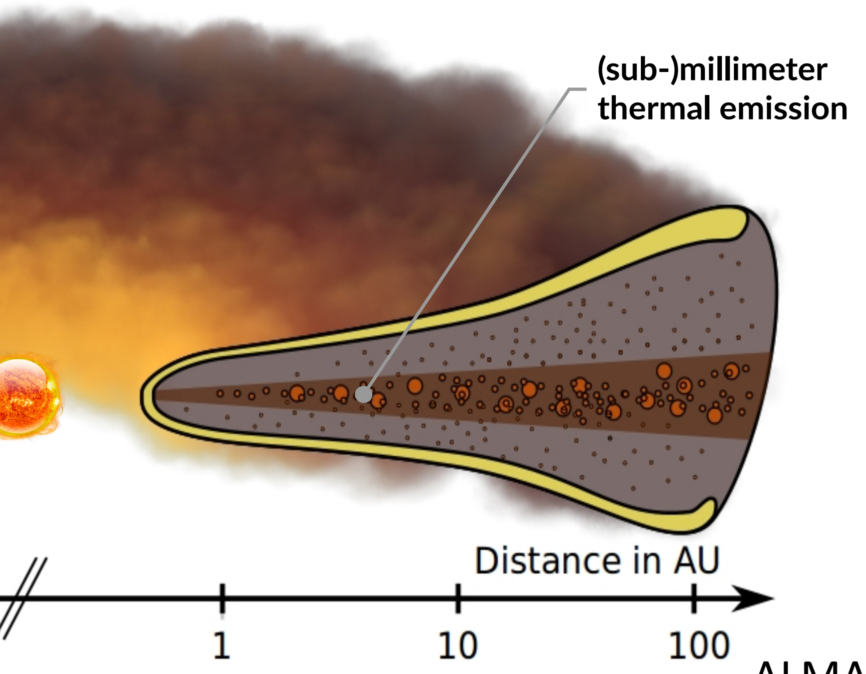


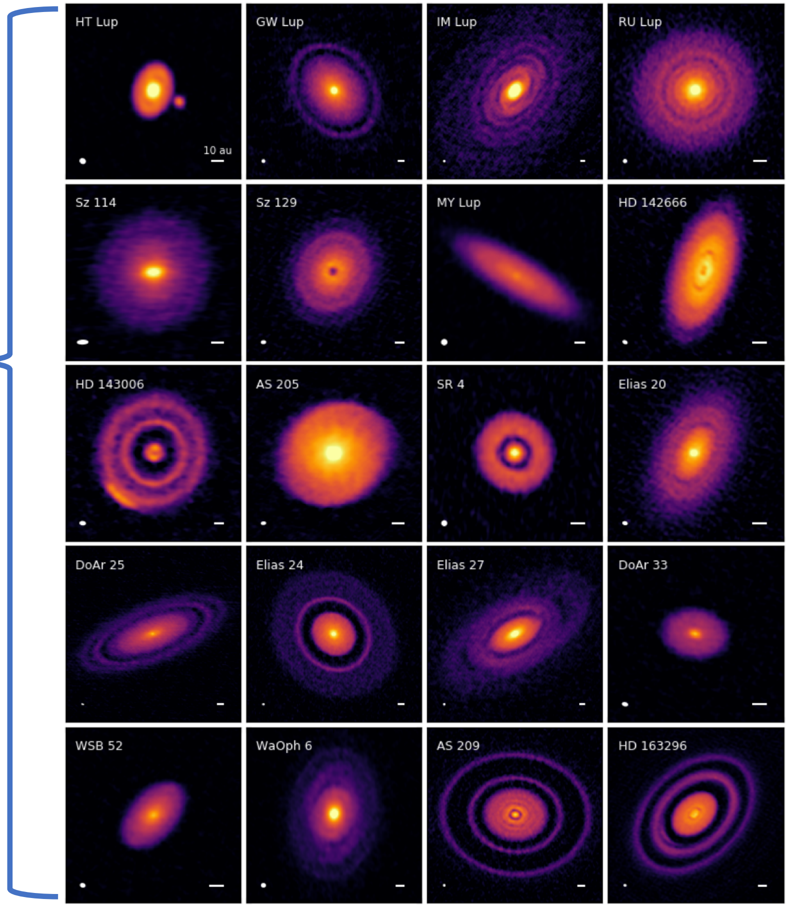


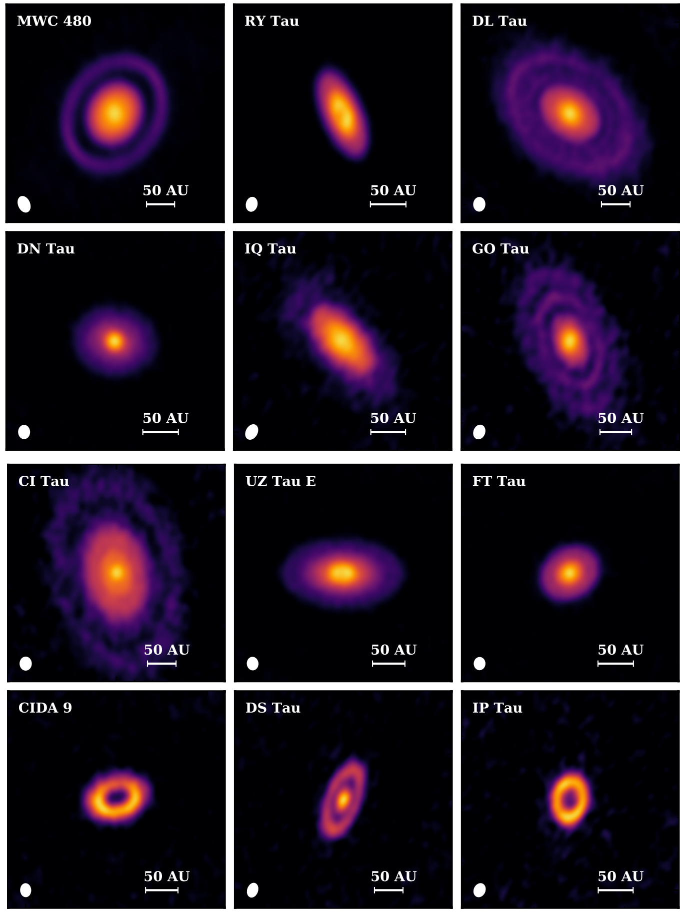
SPHERE (VLT) Observations of protoplanetary disks, Garufi et al. (2017)

Observing the Evolution of Solids in Protoplanetary Disks

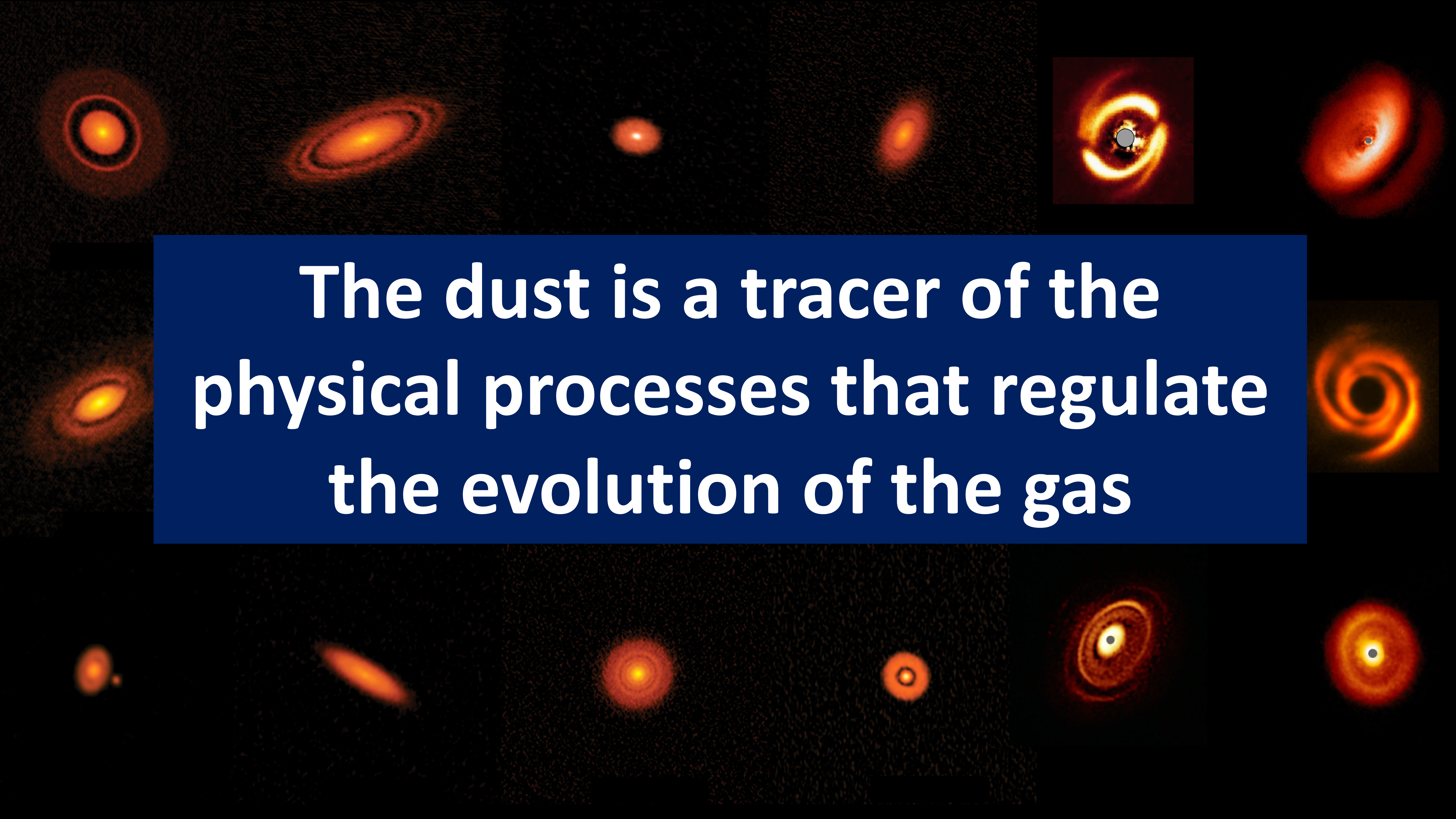
(sub-) millimeter thermal emission → Pebbles in the disk midplane







ALMA Observations of protoplanetary disks, Andrews et al. (2018); Long, Pinilla et al. (2018)


The dust is a tracer of the physical processes that regulate the evolution of the gas

Outline

1. Dust Evolution in a Nutshell:
   Models: Growth and Dynamics.

2. What do we know from observations of PPDs?
   Models vs. Observations.

3. Current Investigation and Future Perspectives.

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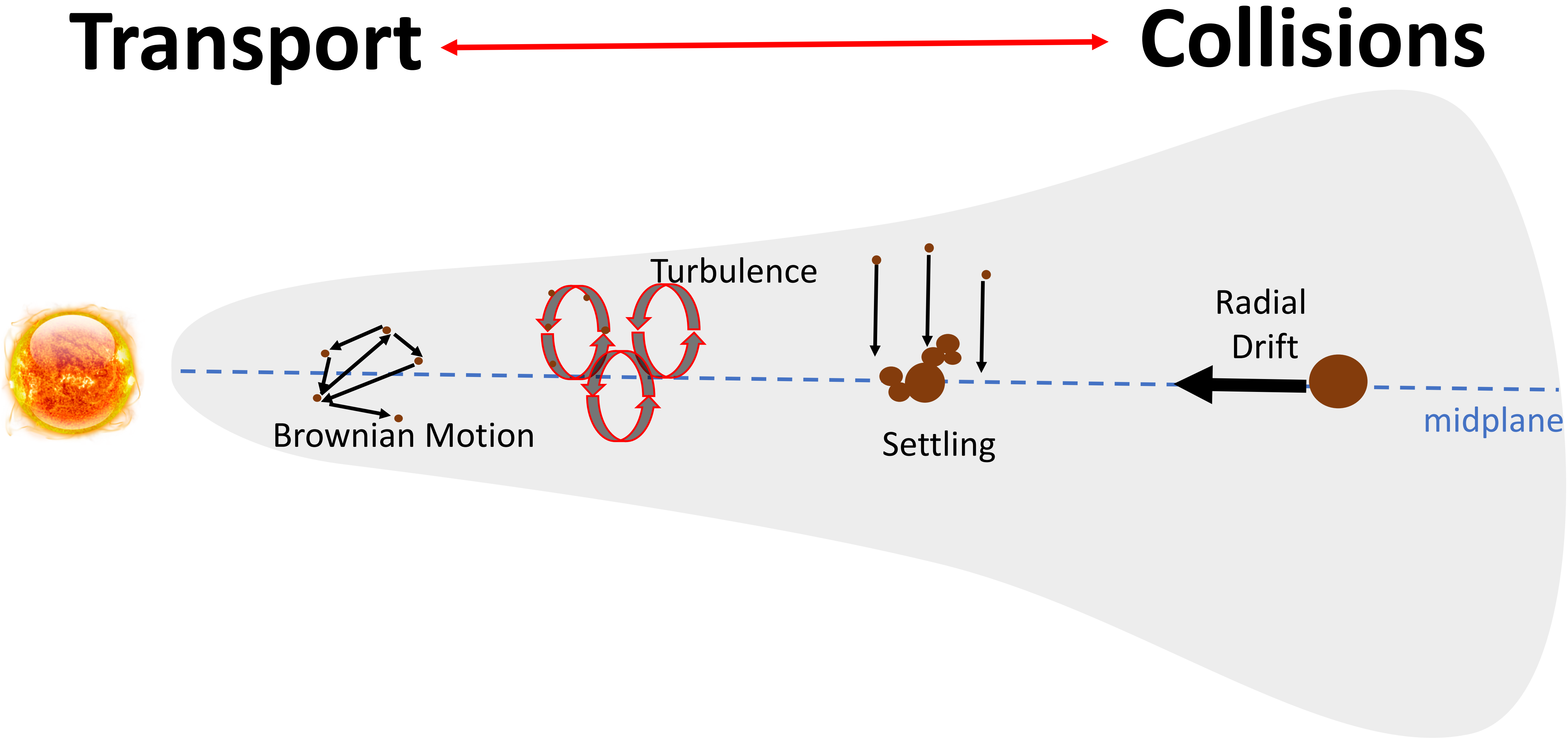
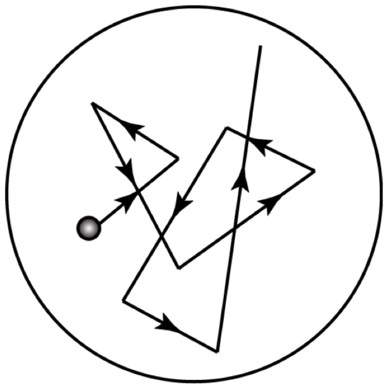
Dust Evolution



Dust Transport

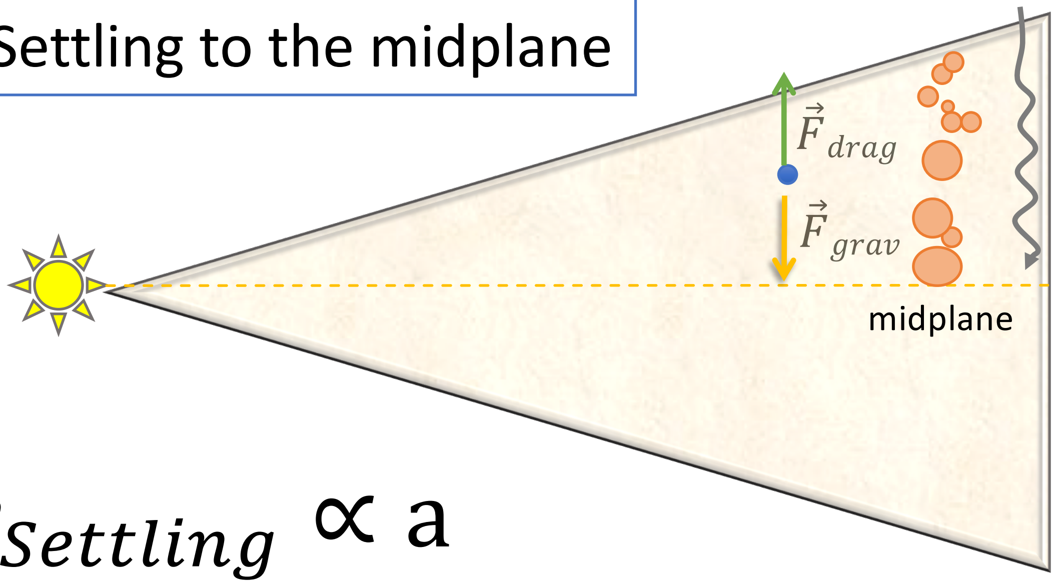
Brownian motion



Brownian Movement

Only relevant for (sub-)micron sized particles

Settling to the midplane



$$v_{Settling} \propto a$$

Turbulent mixing

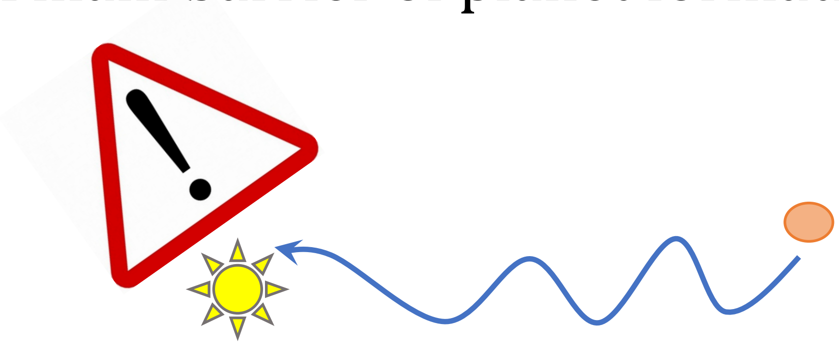
$$\tau_{mix} \propto 1/D$$

$$D \propto \frac{1}{a}$$

Coupling and decoupling to turbulent eddies (Youdin & Lithwick 2007, Ormel & Cuzzi 2007)

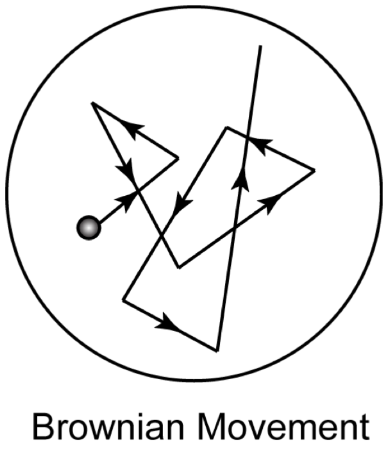
Radial Drift→ strongly depends on particle size

A main barrier of planet formation



Dust Transport

Brownian motion



Only relevant for

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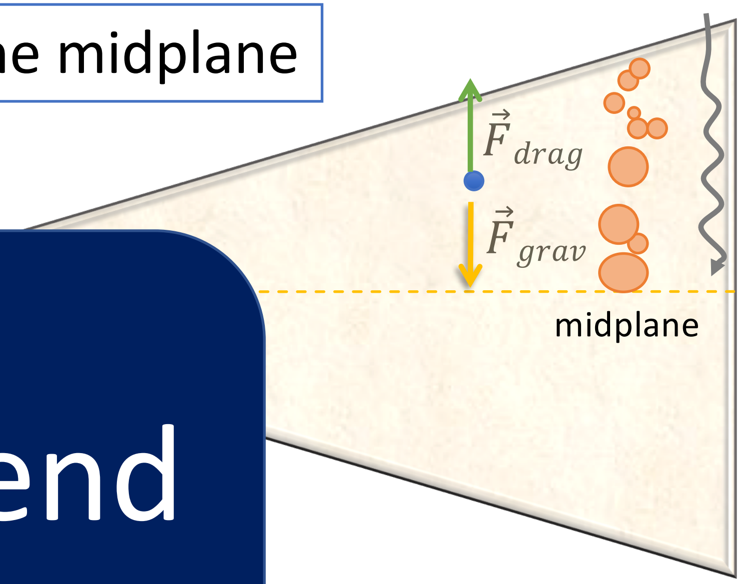
Settling to the midplane



All of them depend on the grain size

Turbulent mixing

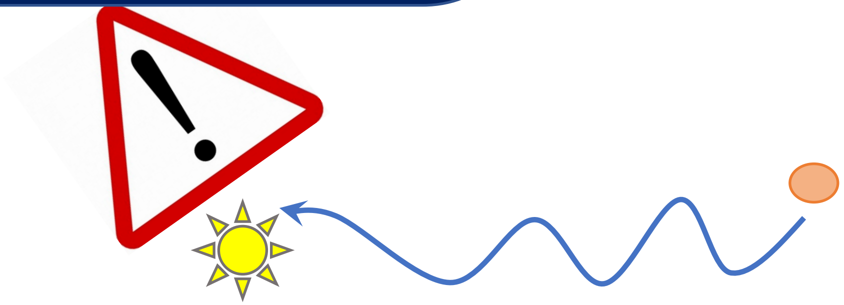
$$\tau_{mix} \propto 1/D$$

$$D \propto \frac{1}{a}$$

Coupling and decoupling to turbulent eddies (Youdin & Lithwick 2007, Ormel & Cuzzi 2007)

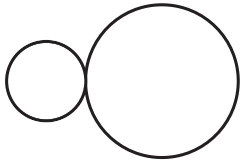
epends on particle size

anet formation



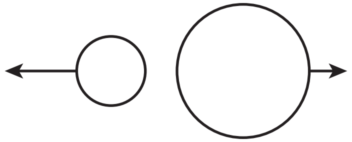
Collision Outcome

Sticking (S)



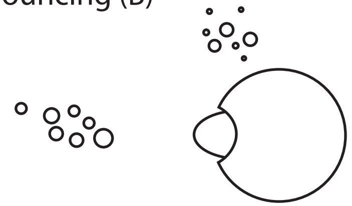
Sticking (S)

Bouncing (B)



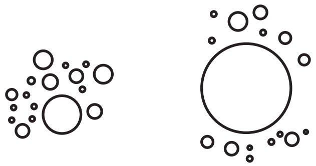
Bouncing (B)

Mass Transfer (MT)



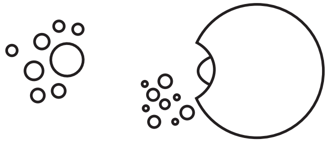
Mass Transfer (MT)

Fragmentation (F)

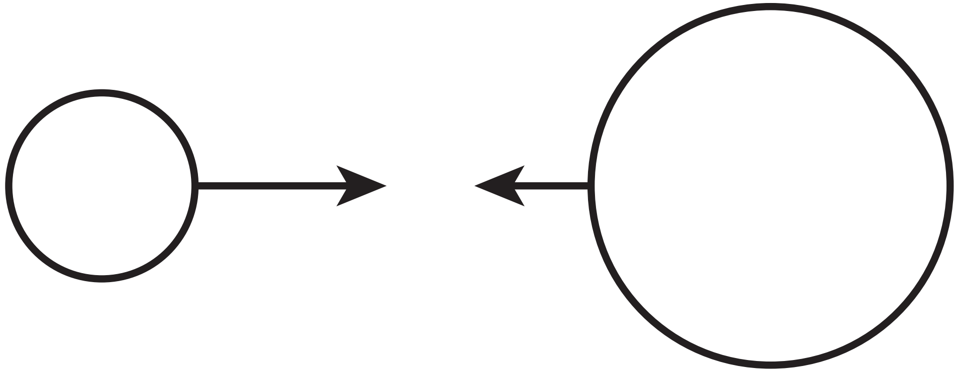


Fragmentation (F)

Erosion (E)



Erosion (E)



Before collision

Collision Outcome

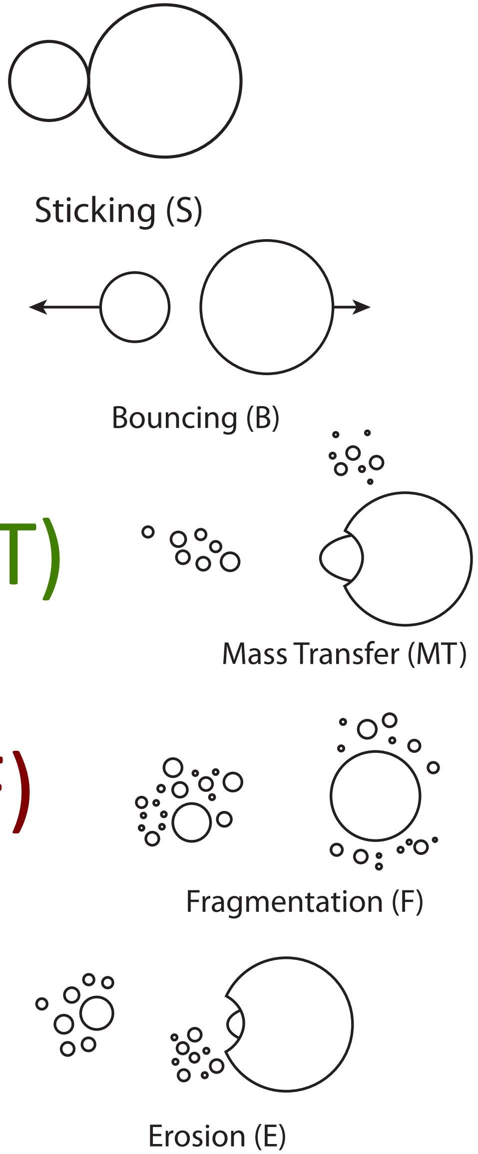
Sticking (S)

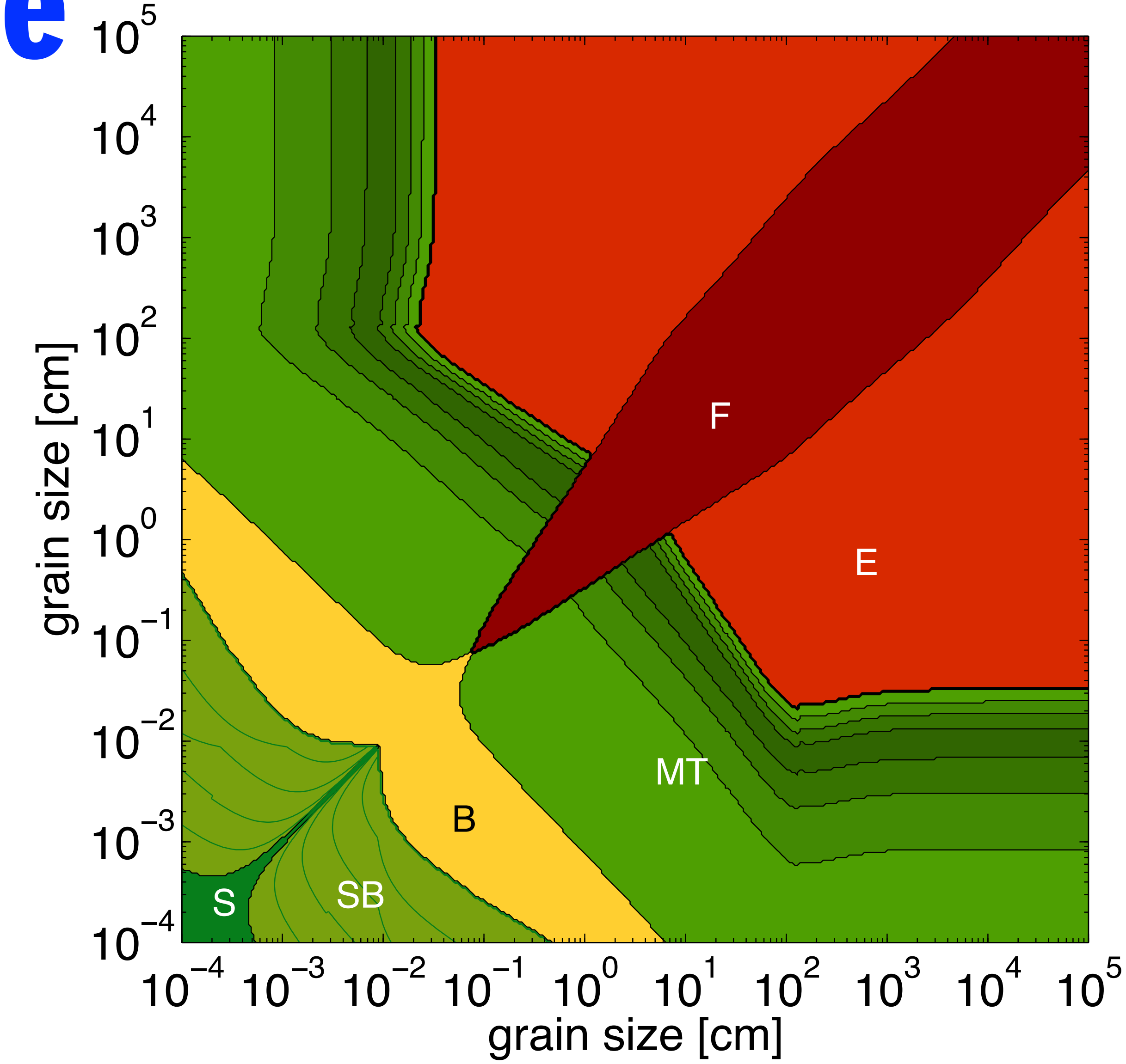
Bouncing (B)

Mass Transfer (MT)

Fragmentation (F)

Erosion (E)



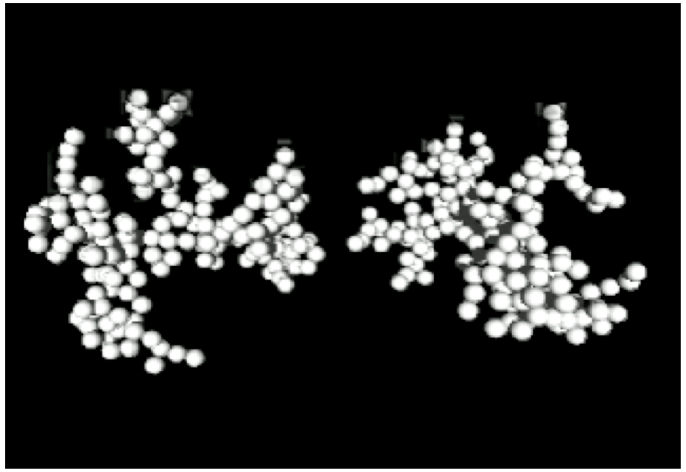


Outcome for collisions at ~3 au distance

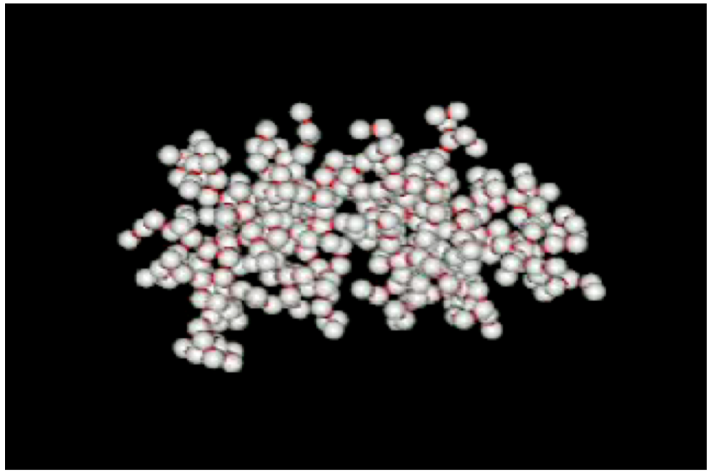
Windmark et al. (2012)

Fragmentation Velocities

Collisions with ice monomers at 8m/s



Collisions with silicate monomers at 2m/s



ice → 10-50 m/s

silicates → 1-5 m/s

From Paszun & Dominik 2009
See also: e.g. by Blum & Wurm 2008, Wada et al. 2007,2011

The lack of water ice mantles in dust particles decreases the van der Waals forces and hence the sticking efficiency between grains

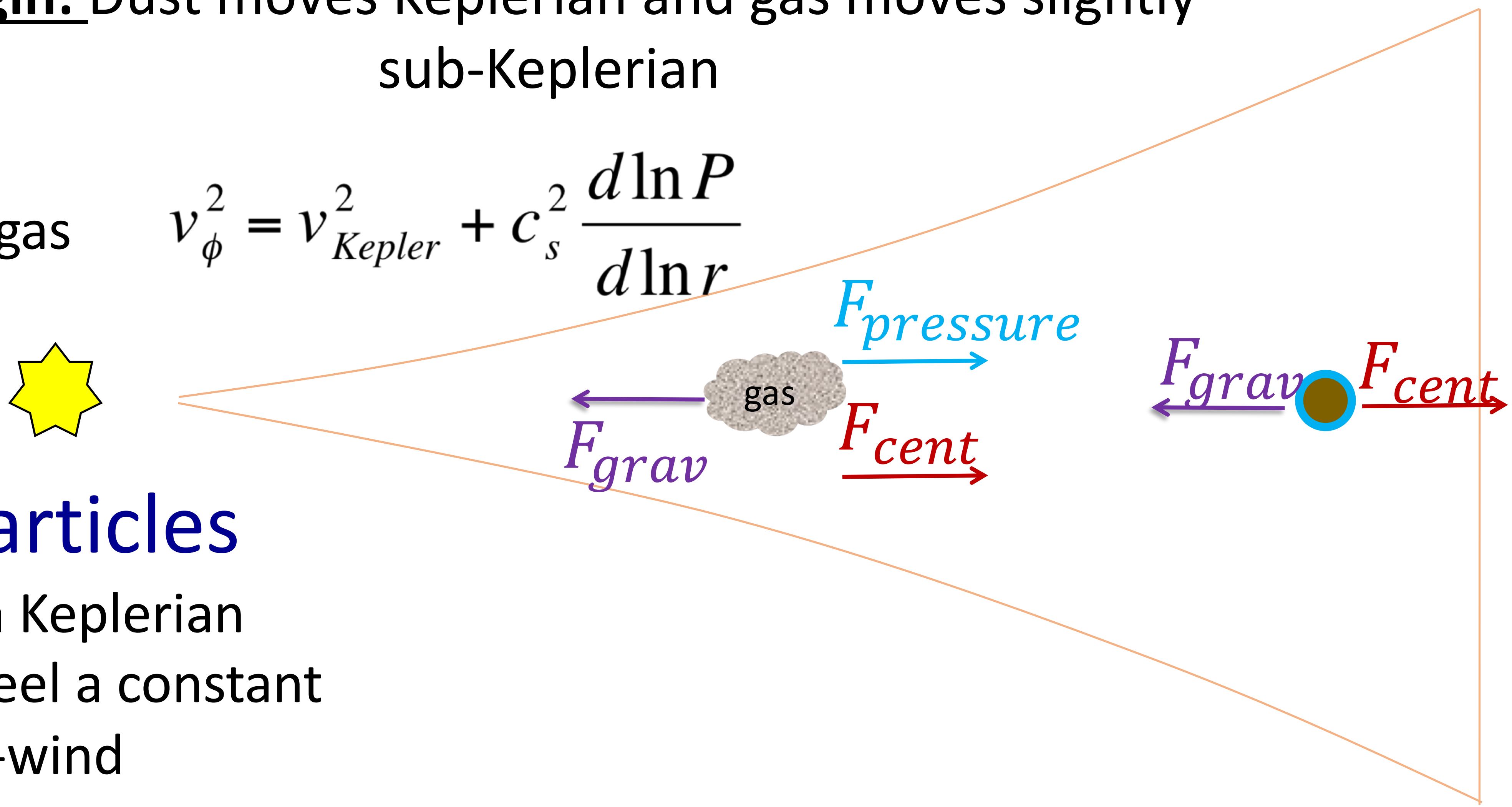
Radial Drift of Particles

Origin: Dust moves Keplerian and gas moves slightly sub-Keplerian

GAS

Supported by gas pressure

$$v_\phi^2 = v_{Kepler}^2 + c_s^2 \frac{d\ln P}{d\ln r}$$

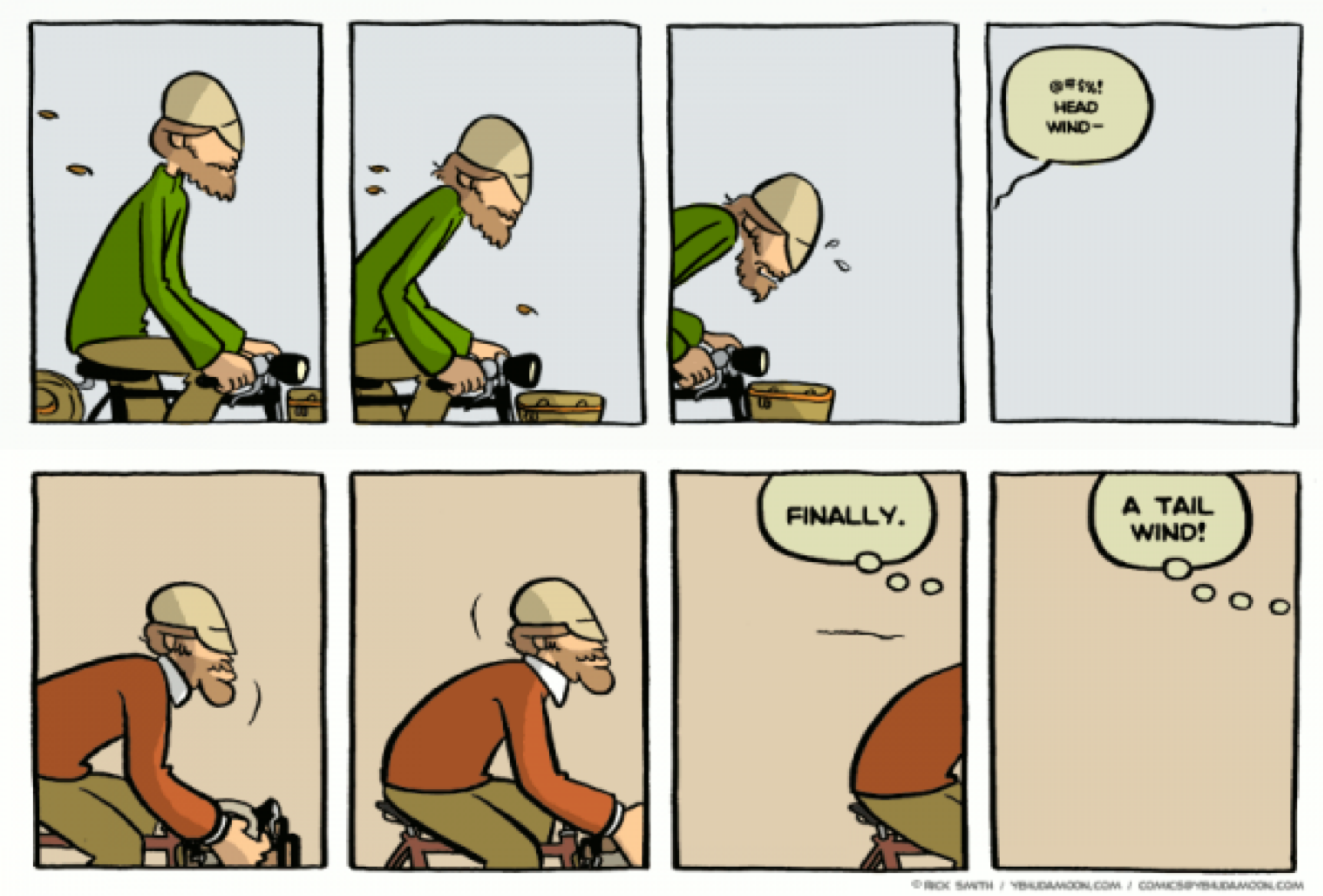


Dust Particles

Move with Keplerian velocity and feel a constant head-wind

Radial Drift of Particles

Origin: Dust moves Keplerian and gas moves slightly sub-Keplerian



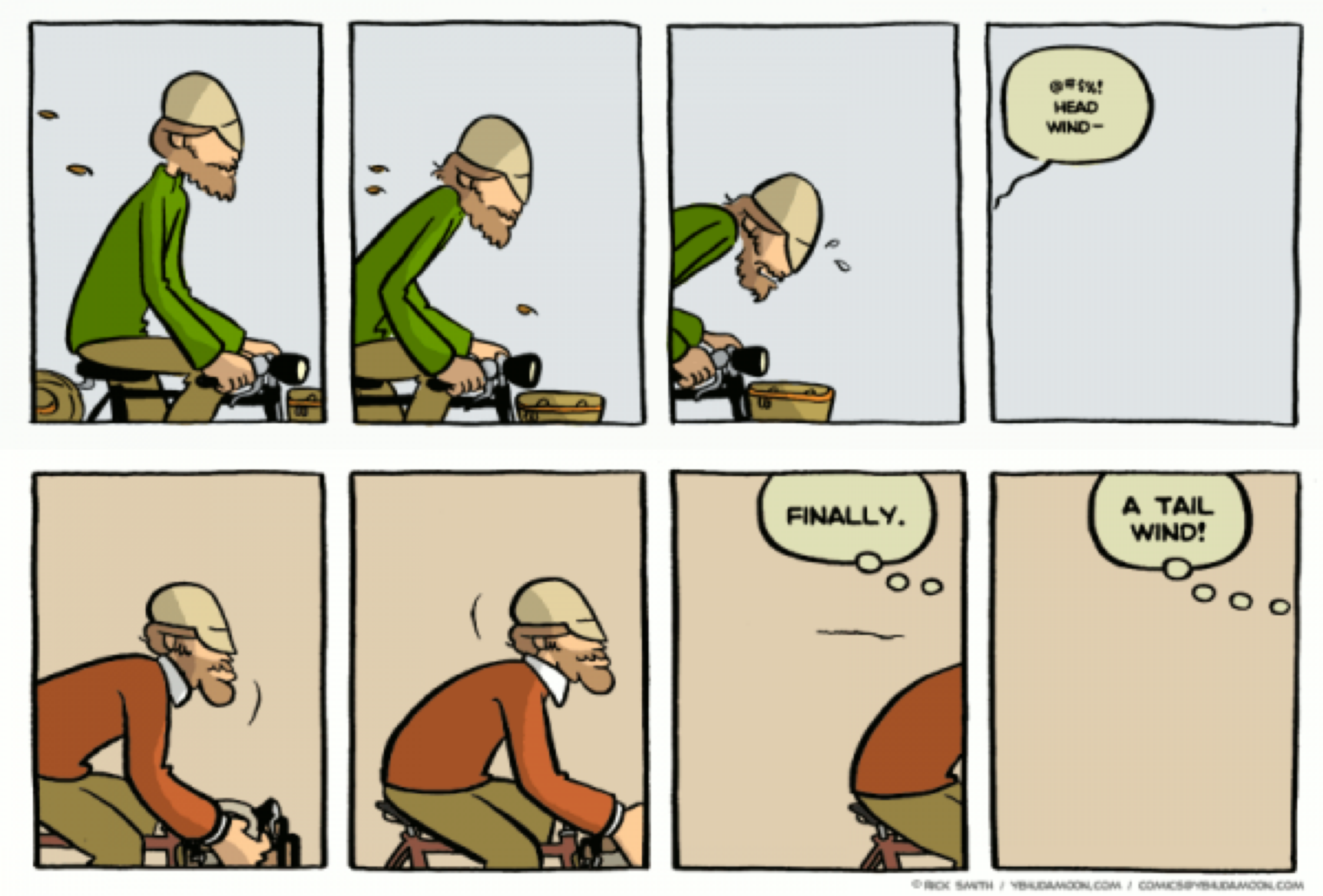
Solutions for particles to reduce their drift:

The head wind disappears or is reduced

$$v_\phi^2 = v_{Kepler}^2 + c_s^2 \frac{d\ln P}{d\ln r}$$

Radial Drift of Particles

<u>Origin:</u> Dust moves Keplerian and gas moves slightly sub-Keplerian

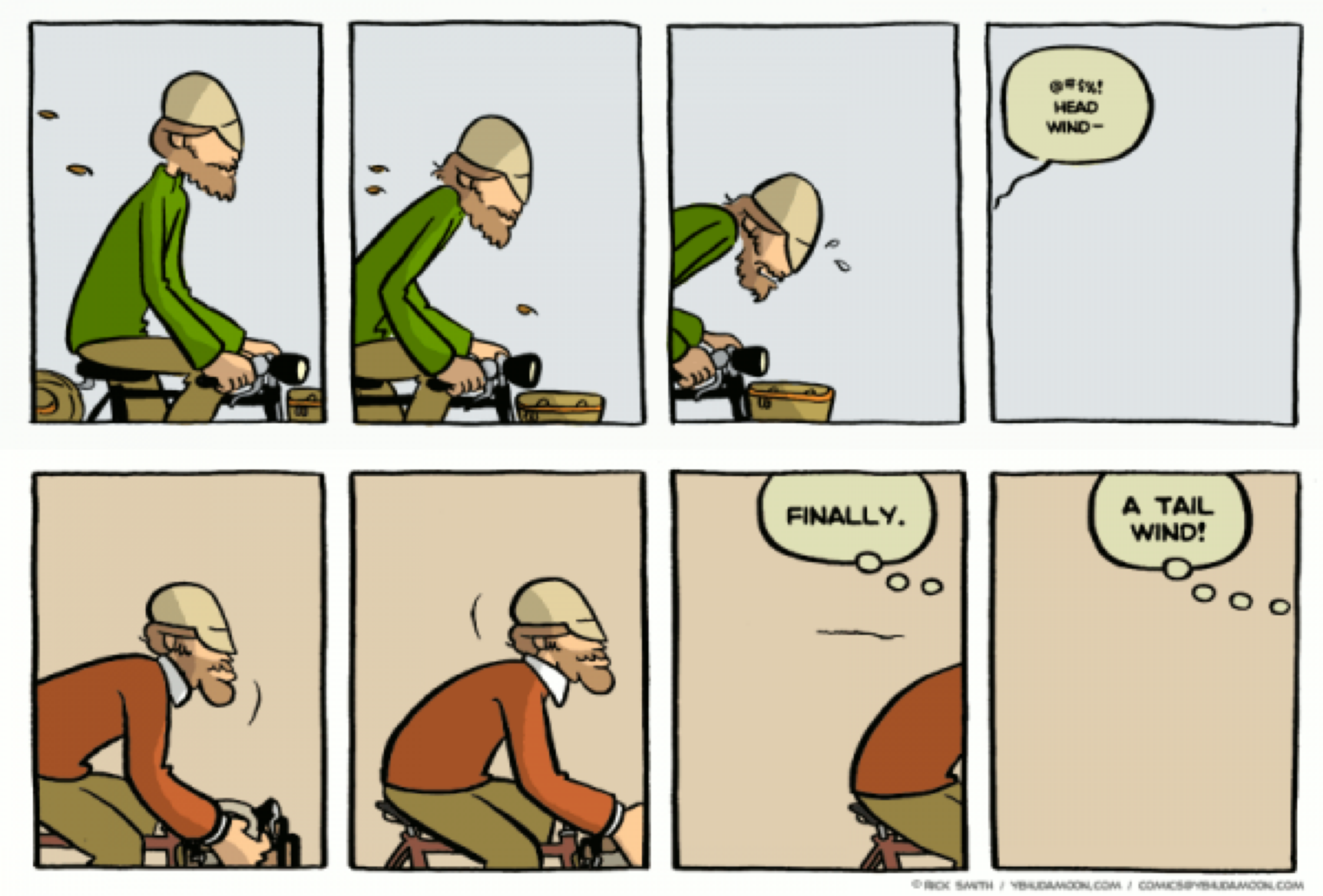


Solutions for particles to reduce their drift:

The dust particles are grouped

Radial Drift of Particles

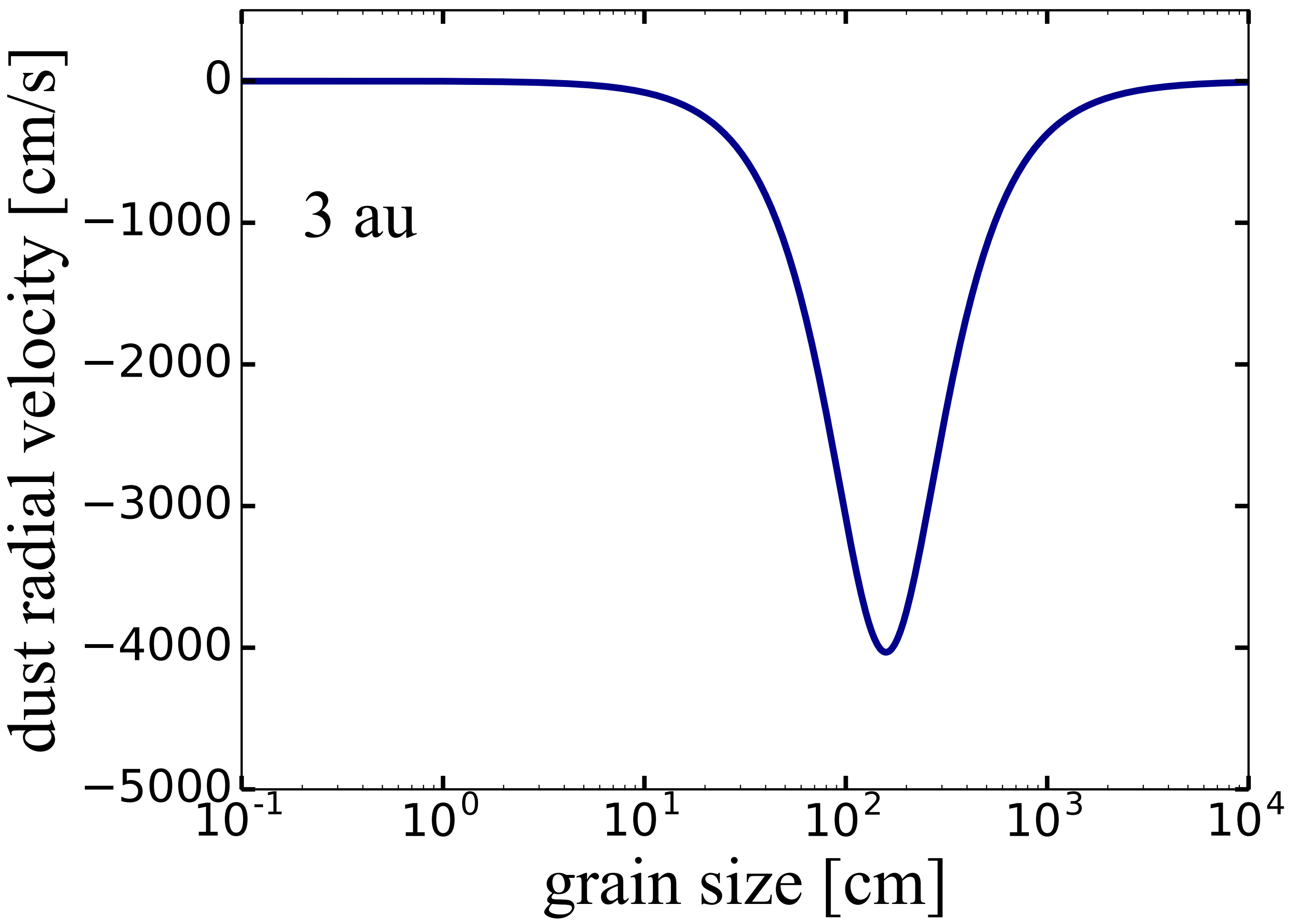
Origin: Dust moves Keplerian and gas moves slightly sub-Keplerian



Solutions for particles to reduce their drift:

The cross section of the particles increased

Radial Drift Velocities

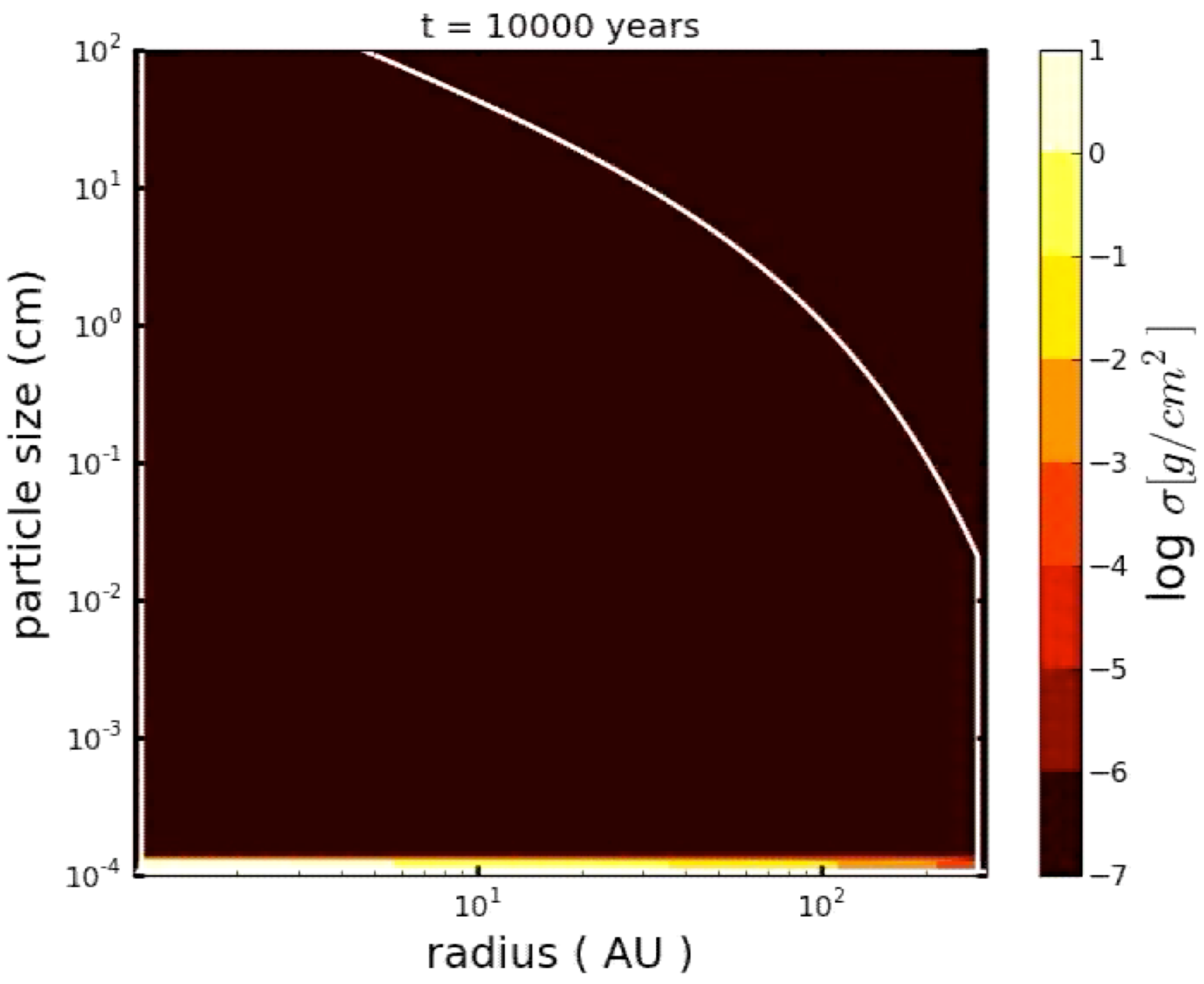


Dust particles acquire inward drift velocities of 4000 cm/s once they reach sufficient sizes.

Collisions at such velocities lead to destruction and the drift leads to the loss of all grains into the star over short timescales ($\lesssim$1000 yrs).

See e.g. Brauer et al. (2008)

Radial Drift Barrier



Pinilla et al. (2012a)

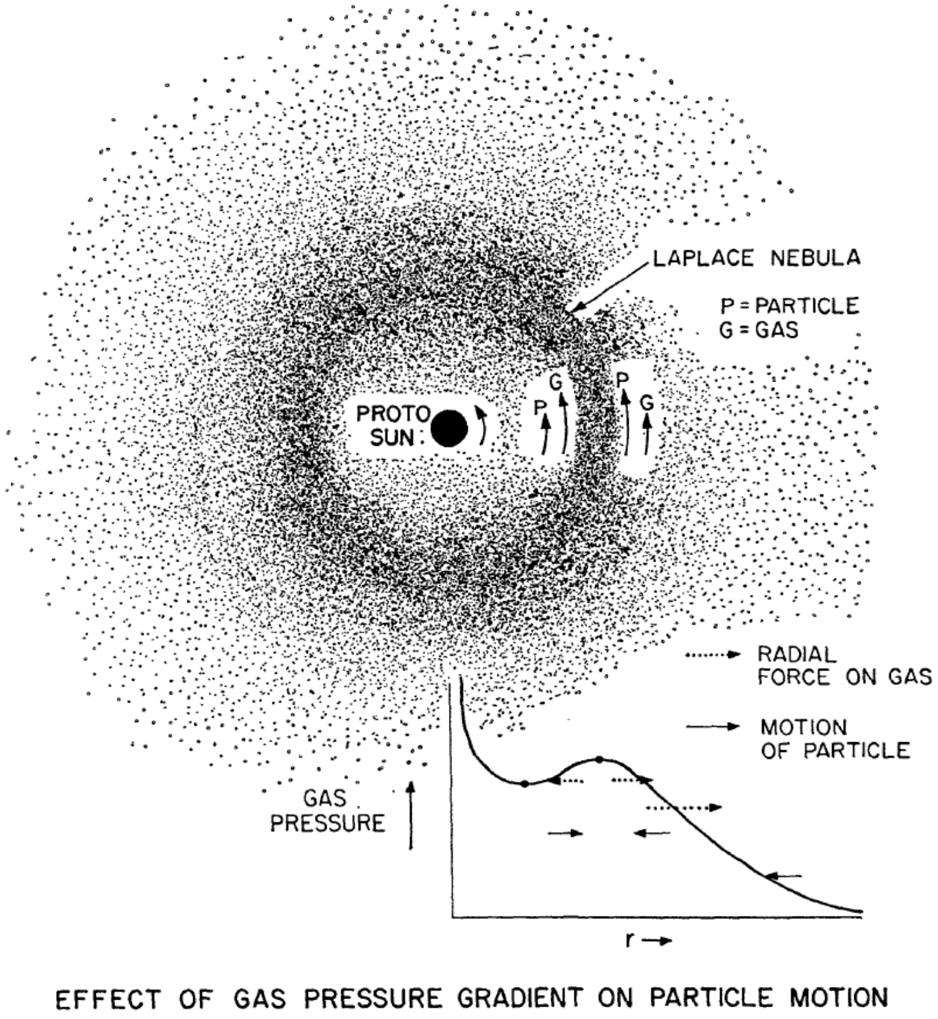
Dust particles acquire inward drift velocities of 4000 cm/s once they reach sufficient sizes.

Collisions at such velocities lead to destruction and the drift leads to the loss of all grains into the star over short timescales (≲1000 yrs).

See e.g. Brauer et al. (2008)

Overcoming the Radial Drift Barrier

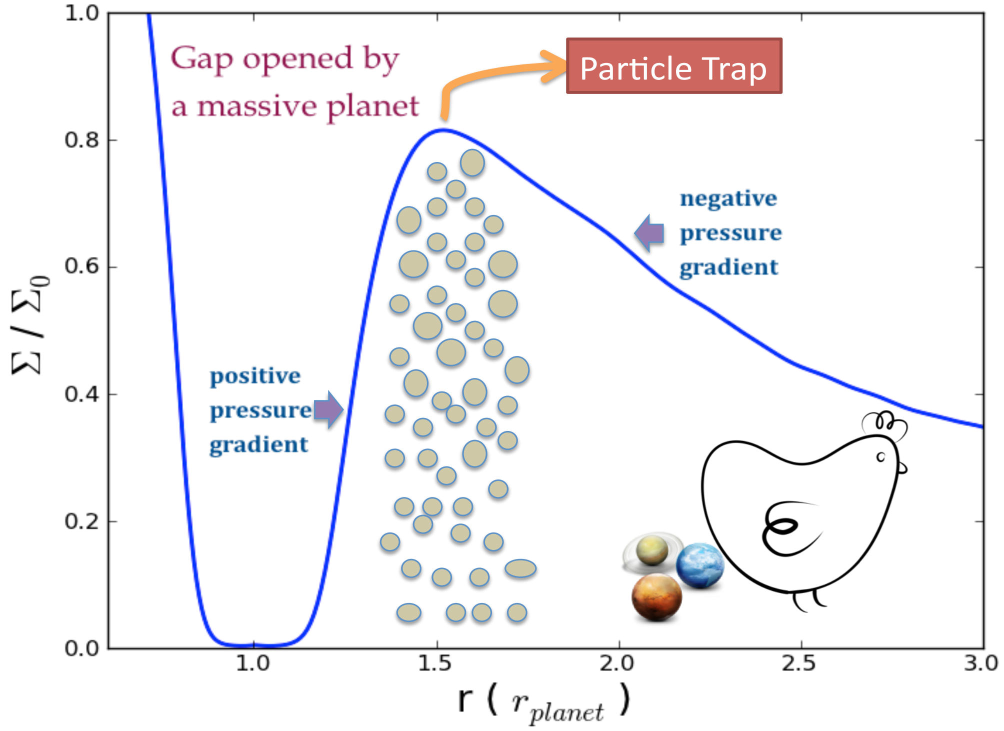
Figure 1 from Whipple (1972)



$$v_\phi^2 = v_{Kepler}^2 + c_s^2 \frac{d \ln P}{d \ln r}$$

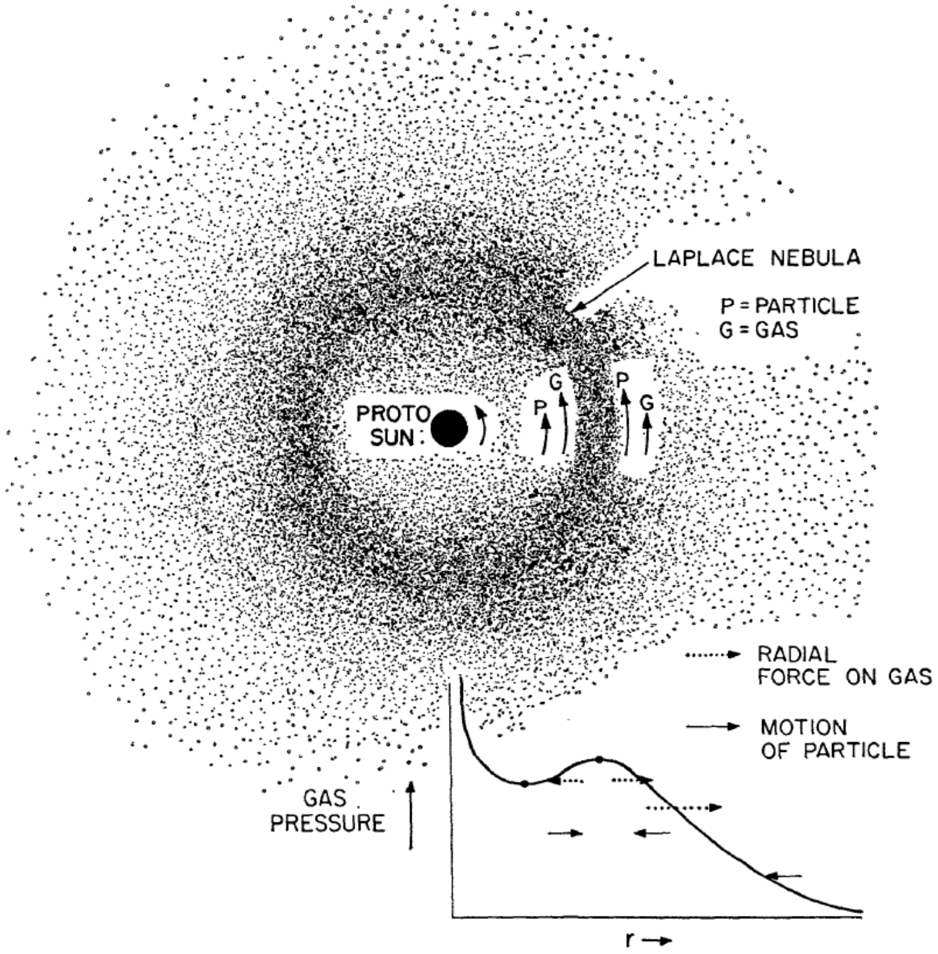
What is the origin of such structures?

✓ Outer edge of a planet-carved gap (e.g. Rice et al. 2006, Pinilla et al. 2012b, 2015a, b, 2016b, 2017)



Overcoming the Radial Drift Barrier

Figure 1 from Whipple (1972)

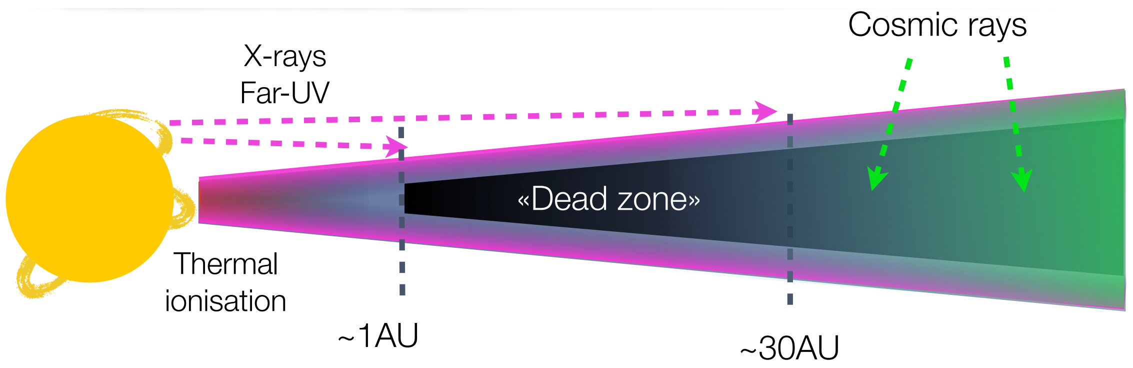


EFFECT OF GAS PRESSURE GRADIENT ON PARTICLE MOTION

$$v_{\phi}^2 = v_{Kepler}^2 + c_s^2 \frac{d\ln P}{d\ln r}$$

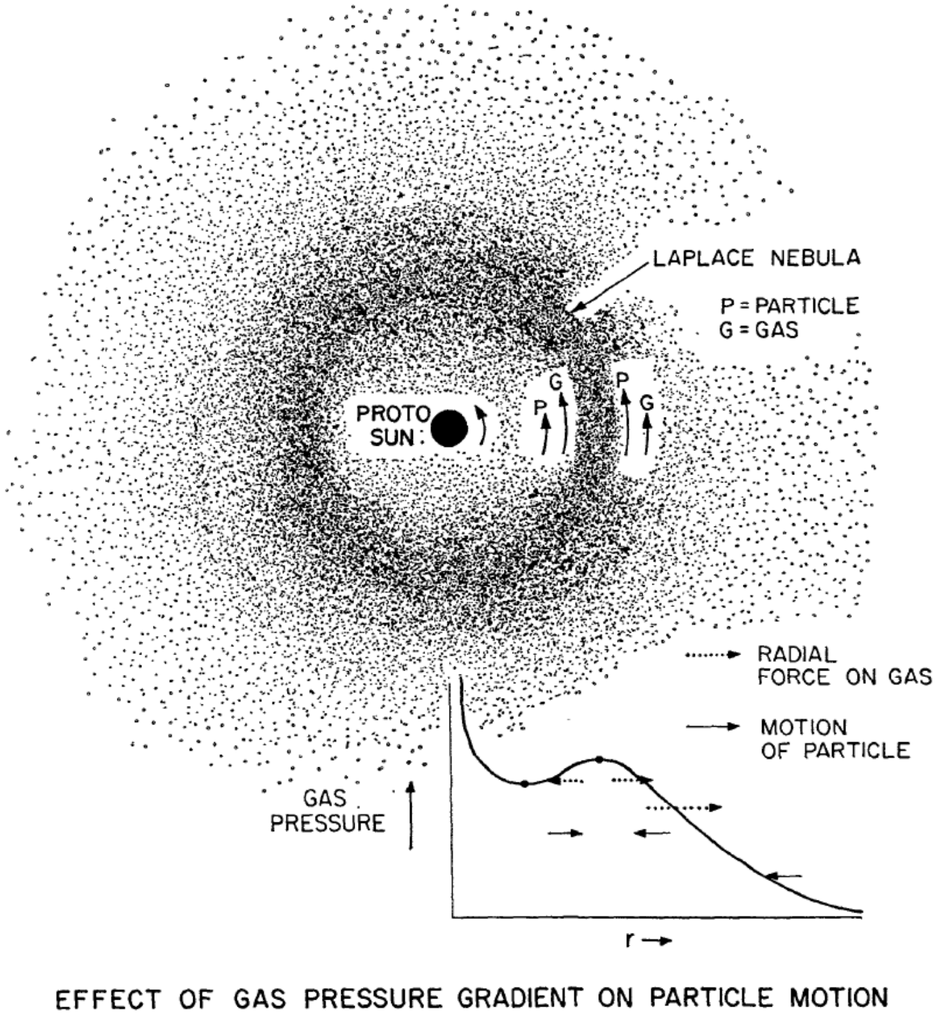
What is the origin of such structures?

✓ Edge of a dead zone (regions of low ionization rate, e.g. Varnière & Tagger 2006, Dzyurkevich et al. 2010, Pinilla et al., 2016)



Overcoming the Radial Drift Barrier

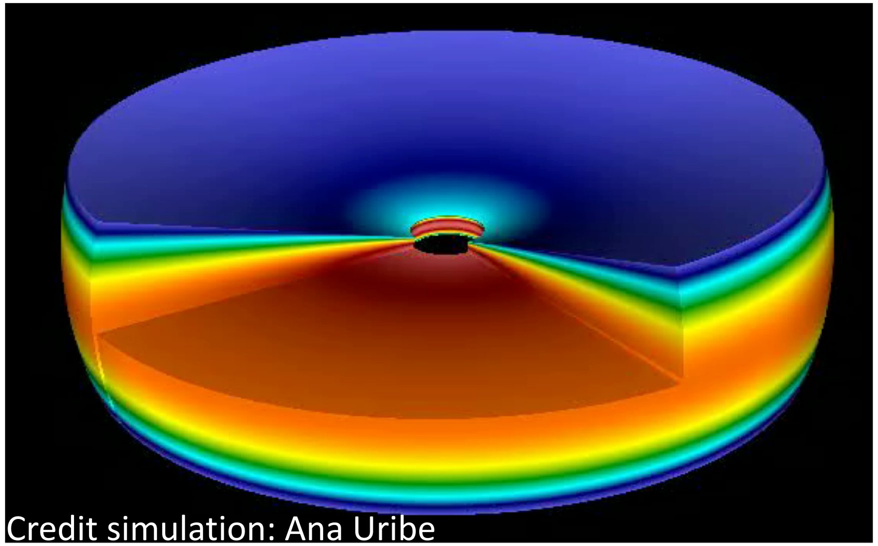
Figure 1 from Whipple (1972)



$$v_\phi^2 = v_{Kepler}^2 + c_s^2 \frac{d\ln P}{d\ln r}$$

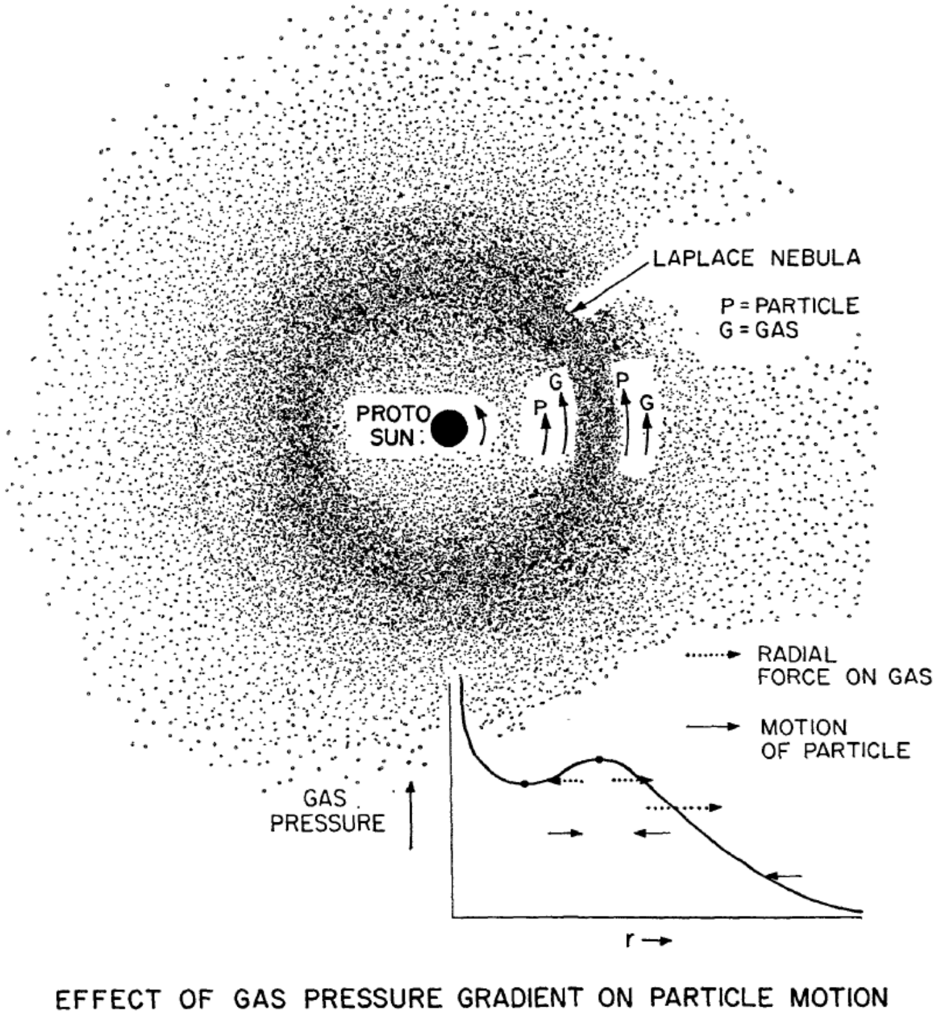
What is the origin of such structures?

✓ Bumps from magnetic fields (e.g. global pressure bumps call zonal flows, Johansen et al. 2009, Uribe et al. 2011, Pinilla et al. 2012a, 2013, Simon et al. 2014)



Overcoming the Radial Drift Barrier

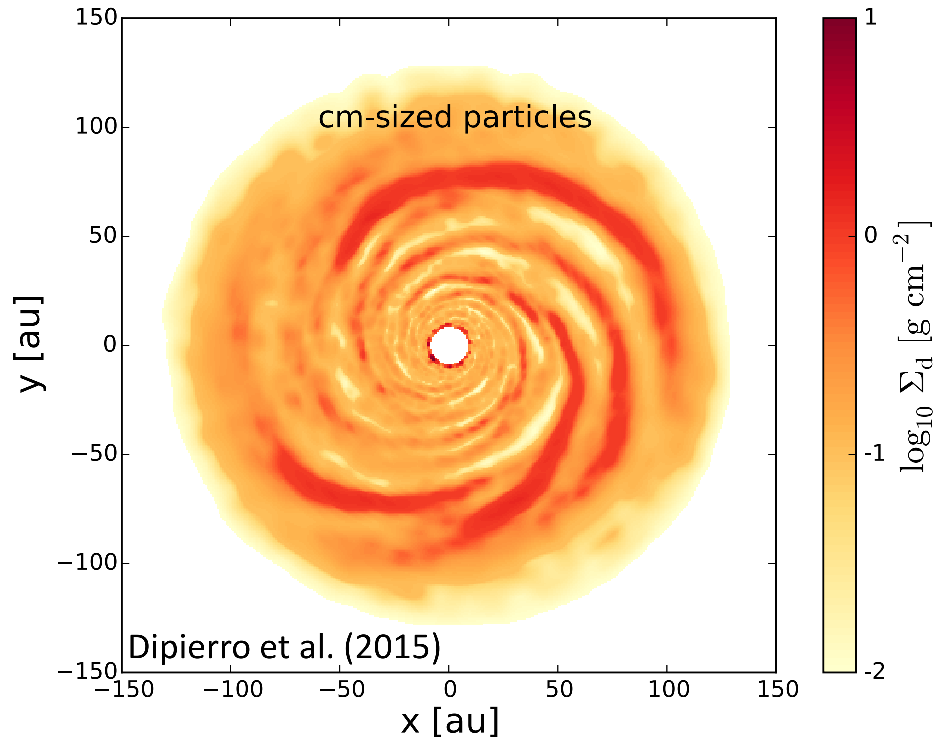
Figure 1 from Whipple (1972)



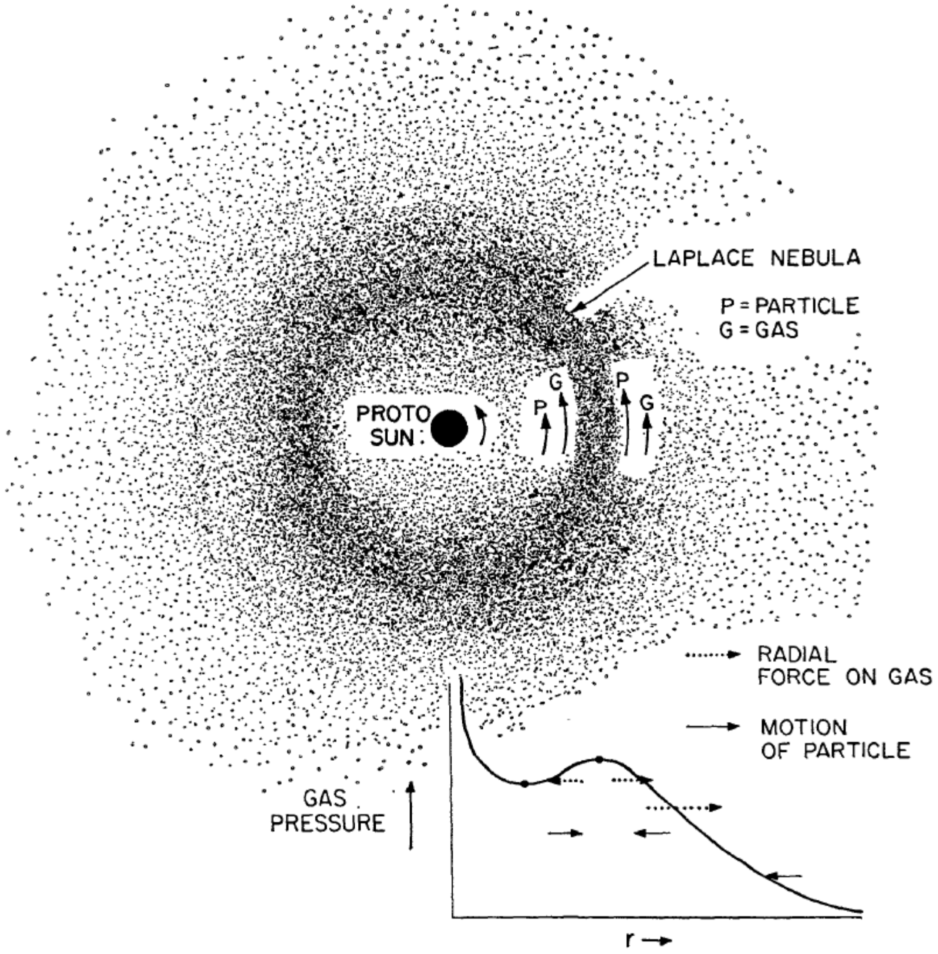
$$v_\phi^2 = v_{Kepler}^2 + c_s^2 \frac{d\ln P}{d\ln r}$$

What is the origin of such structures?

- ✓ Spiral arms in self-gravitating disks (e.g. Lodato & Rice 2004; Dipierro, Pinilla et al. 2015)



Overcoming the Radial Drift Barrier



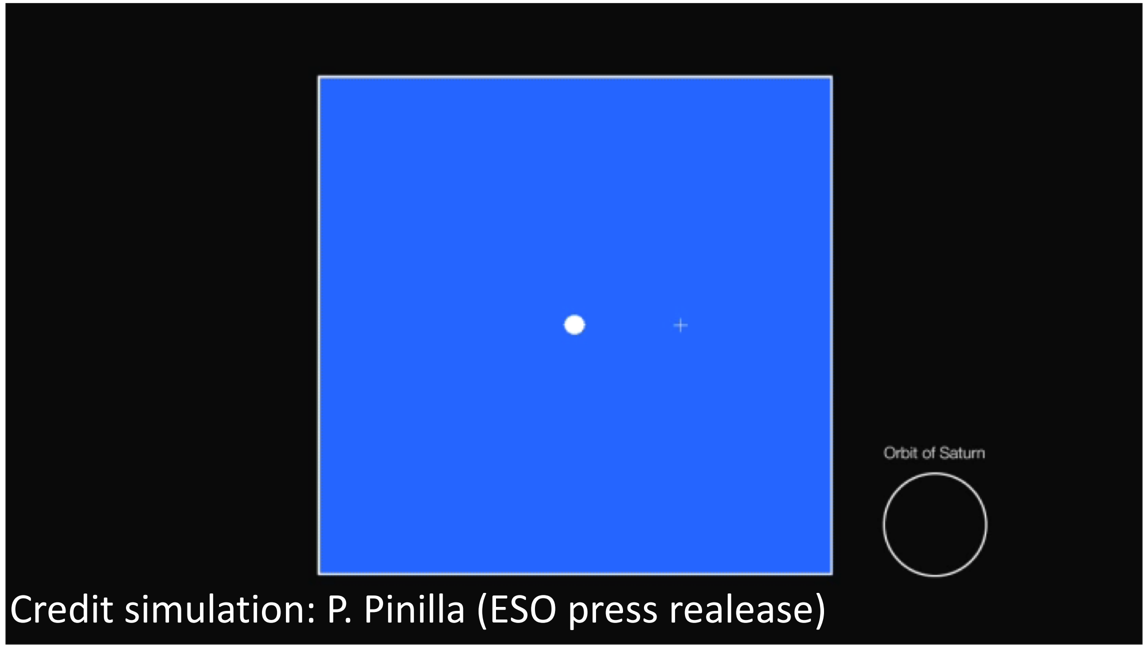
EFFECT OF GAS PRESSURE GRADIENT ON PARTICLE MOTION

Figure 1 from Whipple (1972)

$$v_{\phi}^{2} = v_{Kepler}^{2} + c_{s}^{2}\frac{d\ln P}{d\ln r}$$

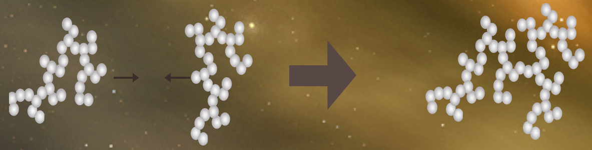
What is the origin of such structures?

✓ Vortices (e.g. De Val-Borro et al. 2007; Lin & Papaloizou 2011, Ataiee, Pinilla, et al., 2013, Hammer, Pinilla, et al., 2019)



First Steps of Planet Formation

Initially the dust is as the ISM
(micron-sized particles)



Dust collides, clumps and grows

Destructive collisions replenish the disk with small grains, which move with the gas

Large grains decouple, and quickly drift inwards

Particle Traps:
Preferential regions where the dust can stop drifting, accumulate, and grow to pebbles and planetesimals

Terrestrial planets or the core of giant planets form through the accretion of pebbles and/or planetesimals

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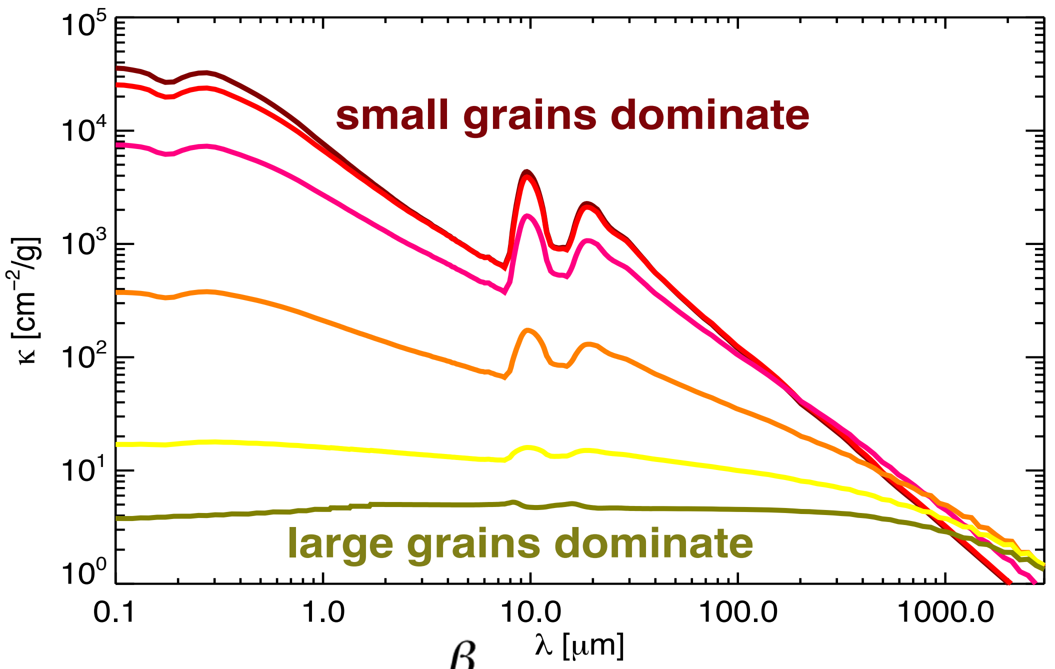
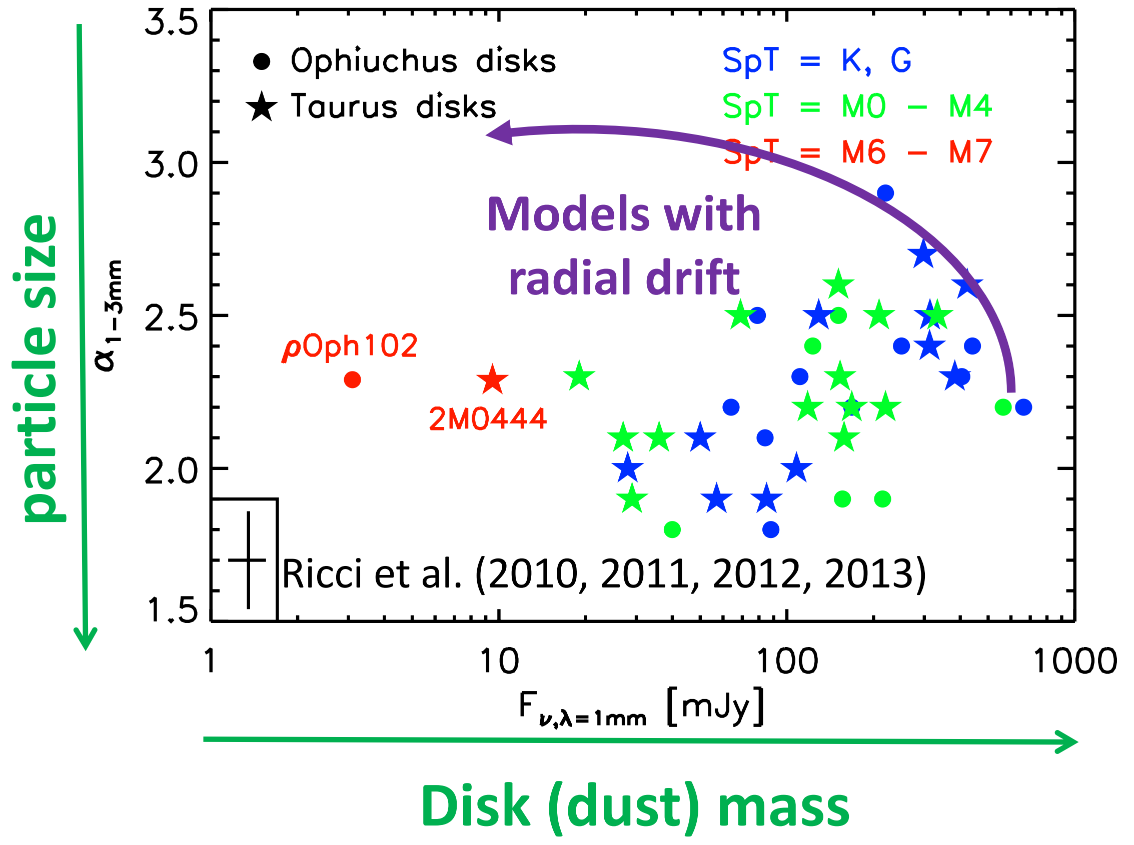
Evidence of mm-grains in PPDs



$$\kappa \propto \nu^{\beta}$$

$$F_\nu \propto \nu^{\beta+2} \propto \nu^{\alpha_{mm}}$$

If β≤ 1 (α_{mm}<3), dust grains have grown to millimeter sizes



mm-sized pebbles survive despite the fast inward drift and possible fragmentation

Global Pressure Bumps

How strong must they be to explain mm-observations?

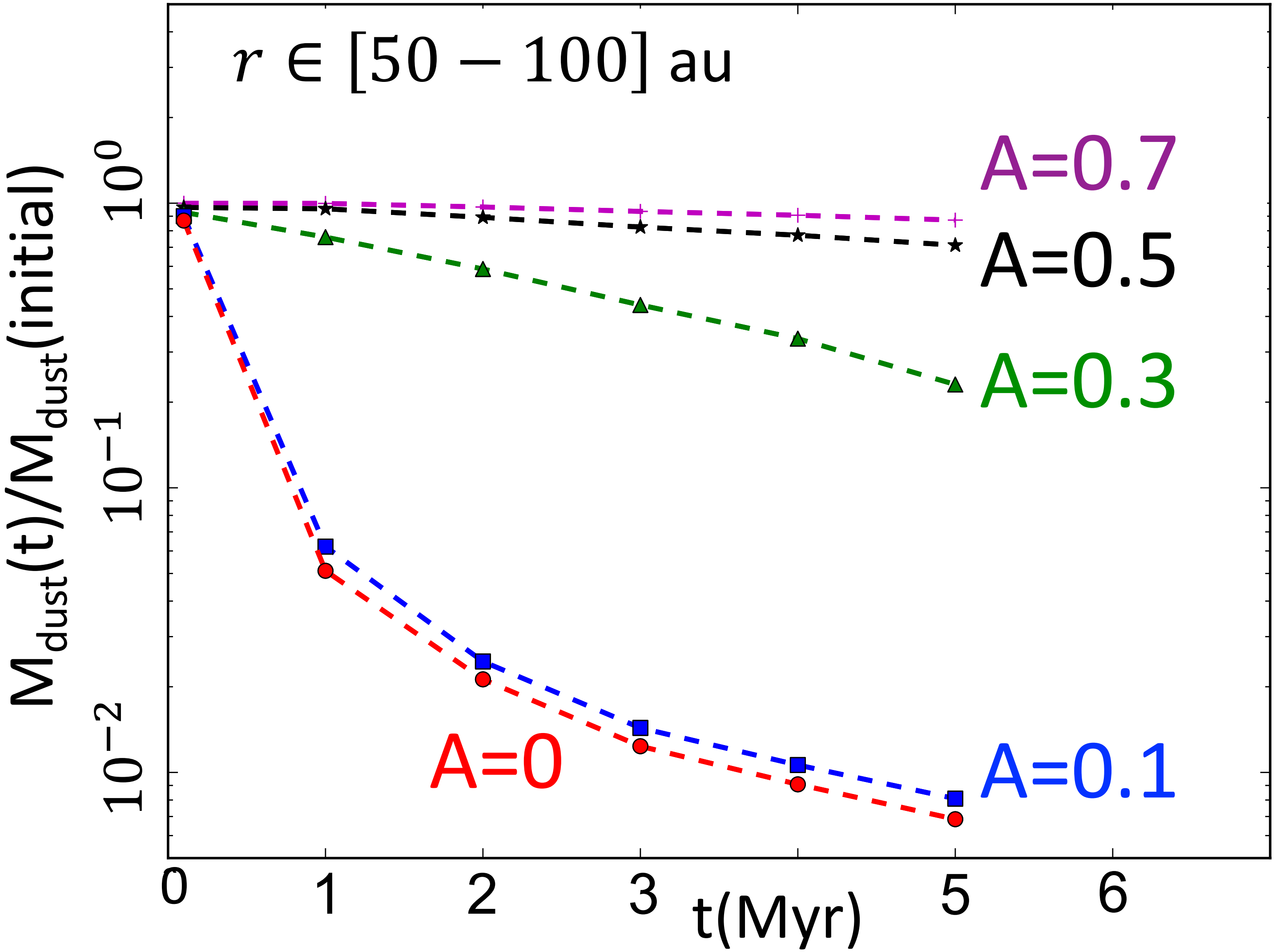
Assumption: a vertically isothermal disk, with gas surface density inhomogeneities

$$\Sigma'(r) = \Sigma(r)(1 + A\cos[2\pi \frac{r}{L(r)}])$$

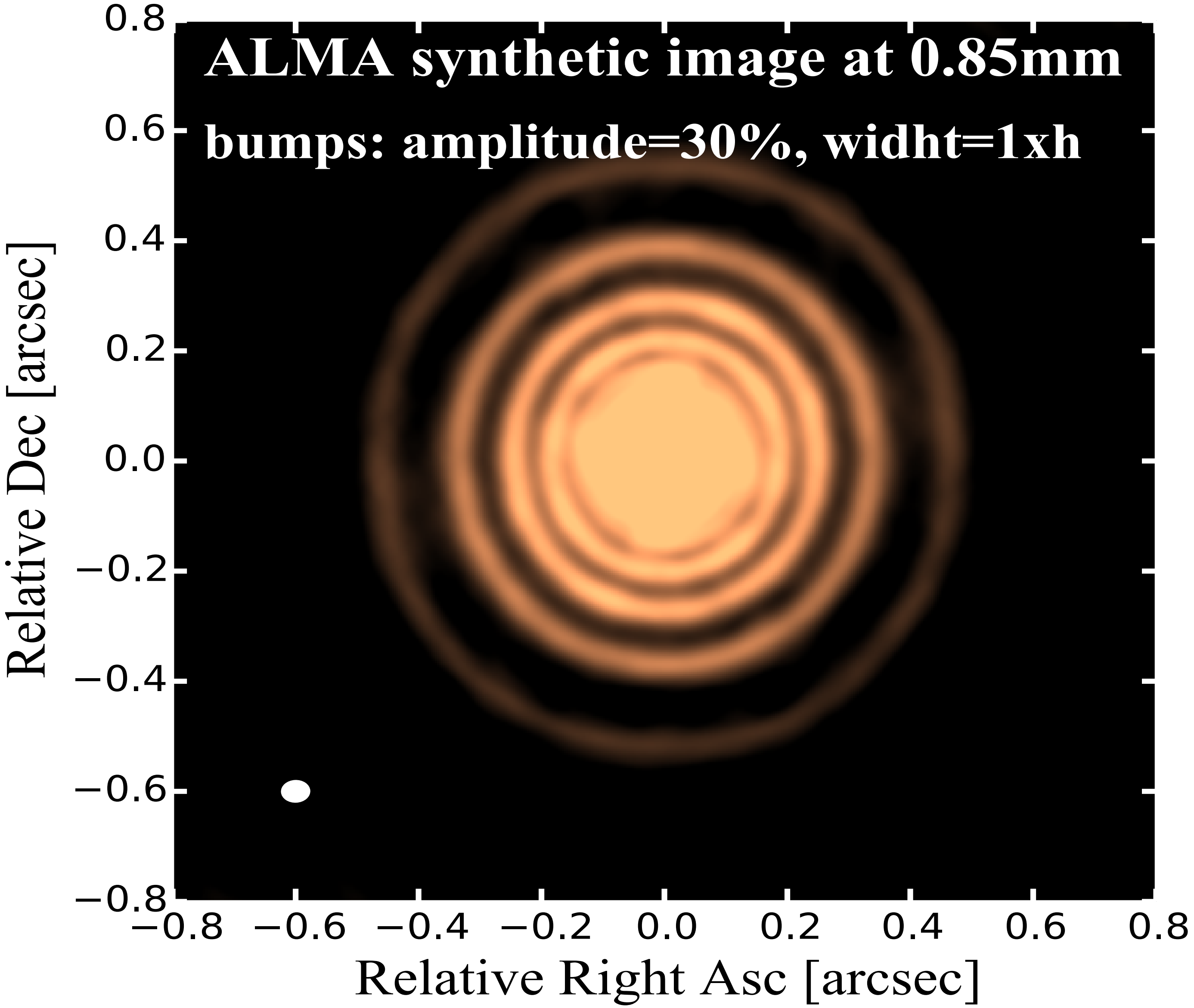
Condition to have $\frac{dP}{dr} > 0$

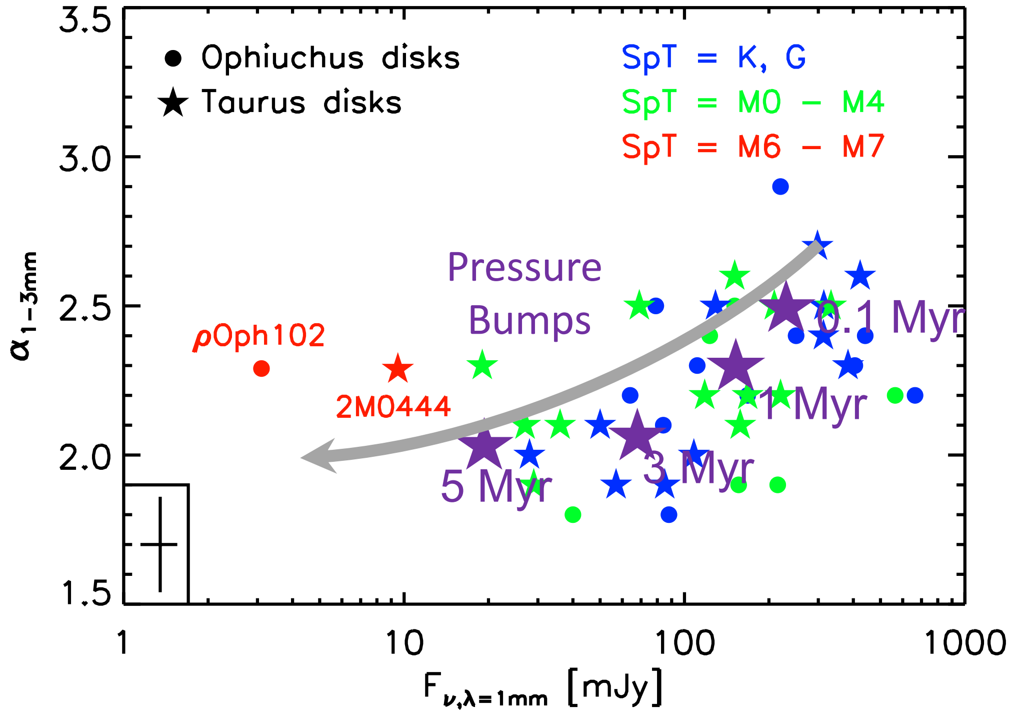
$$\boxed{A_{min} = 0.1}$$

Pinilla et al. (2012a)



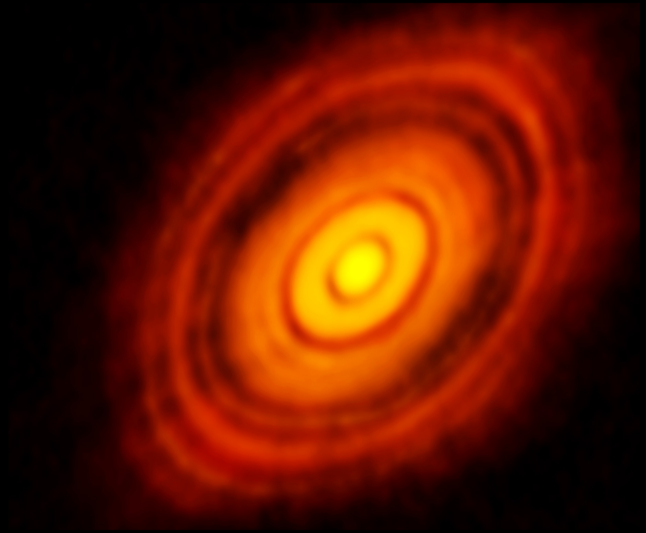
Trapping by Global Pressure Bumps



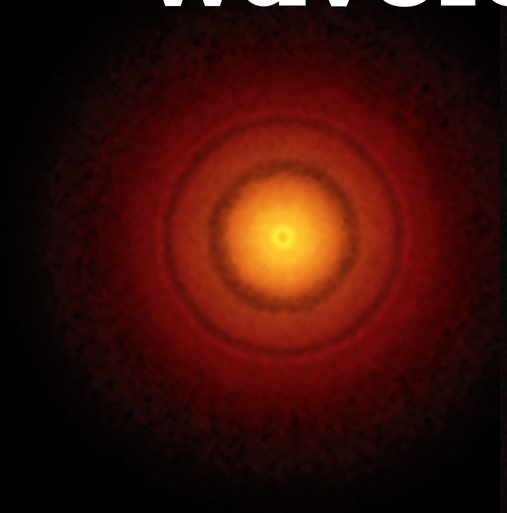


Pressure bumps of 25-30% of amplitude allow to reduce radial drift and keep millimeter particles in the outer regions of disks

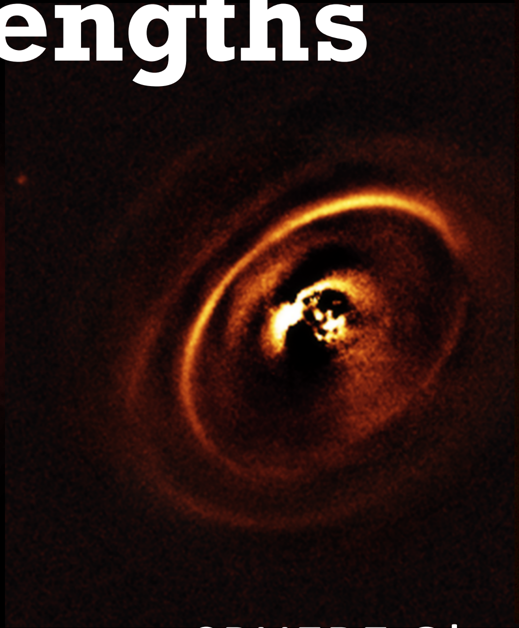
Multiple Rings Observed at Different Wavelengths



ALMA Obs
HL Tau
ALMA Partnership et al. (2015)



ALMA Obs
TWHya
Andrews et al. (2016)

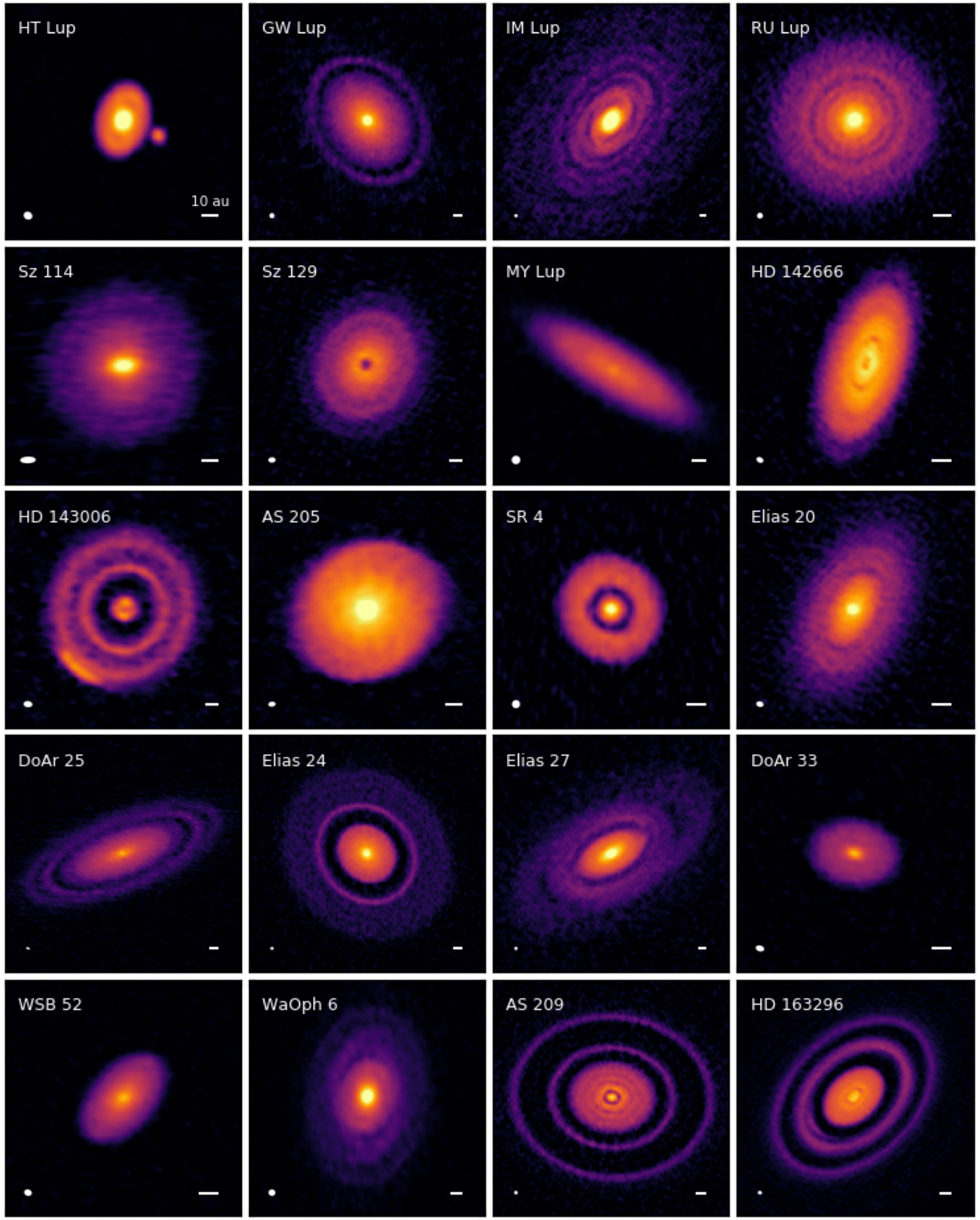


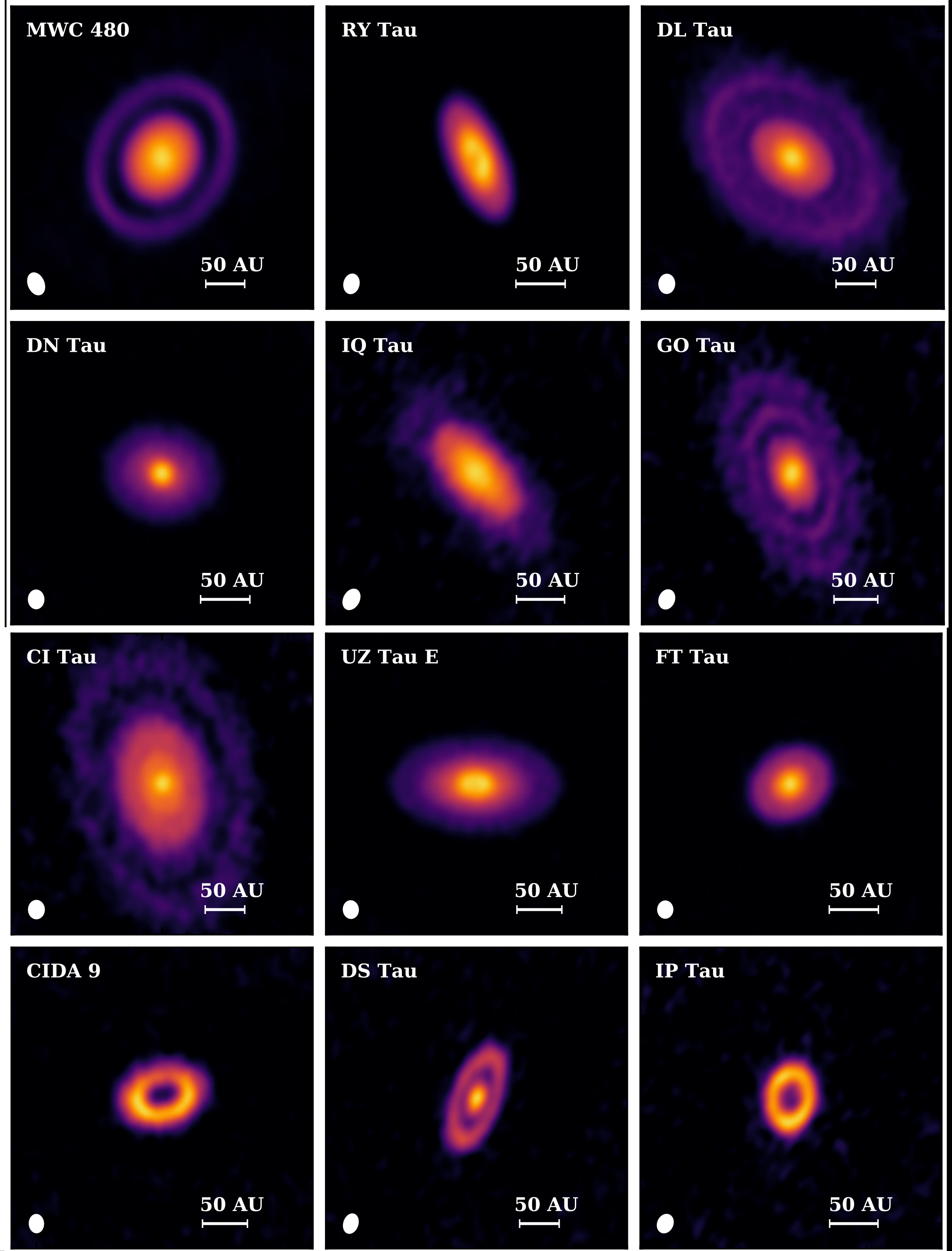
SPHERE Obs
RX J1615
de Boer et al. (2016)

SPHERE Obs
HD 97048
Ginski et al. (2016)

Planet-disk interaction is a popular explanation for the origin of these structures, but there are several theoretical alternatives and currently the real origin remains unknown.

New view with ALMA

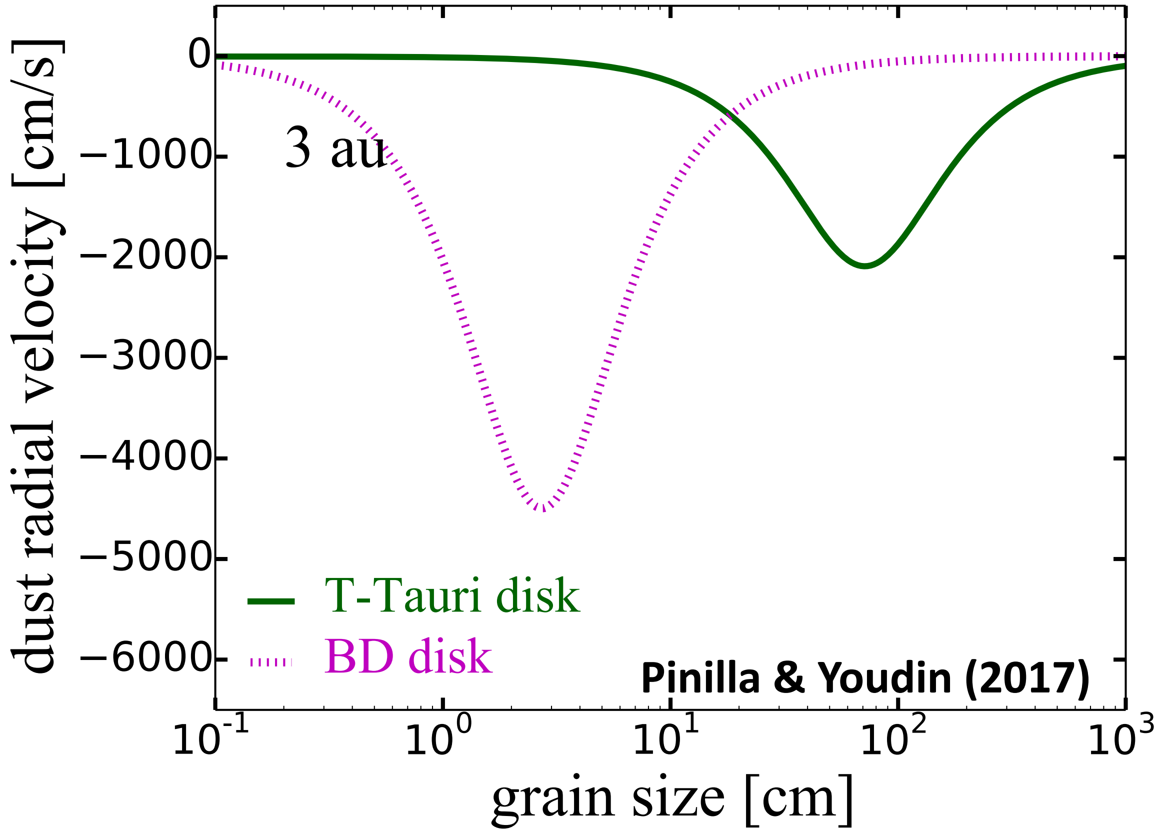


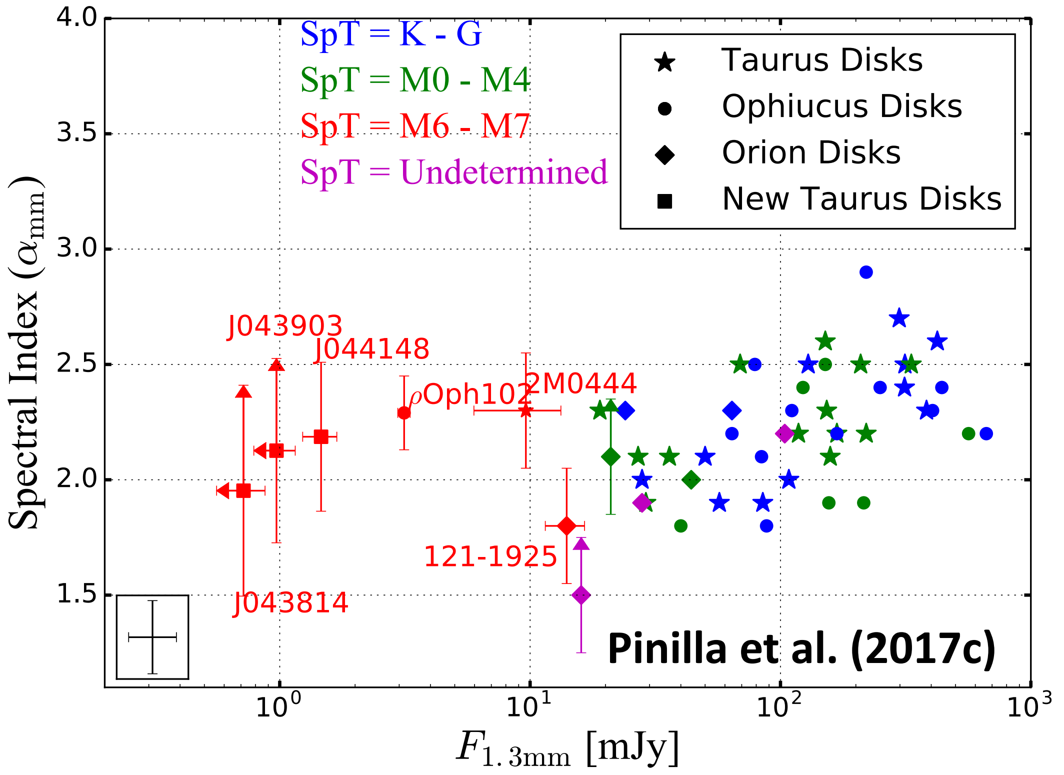


DSHARP
Andrews at al. (2018)

Taurus
Long, Pinilla at al. (2018)

Because Radial Drift is More Effective around Low Mass Stars, Rings and Gaps are Expected to be More Predominant





The radial-drift barrier is more difficult to overcome for the dust around Brown Dwarfs disks than around typical T-Tauri disks

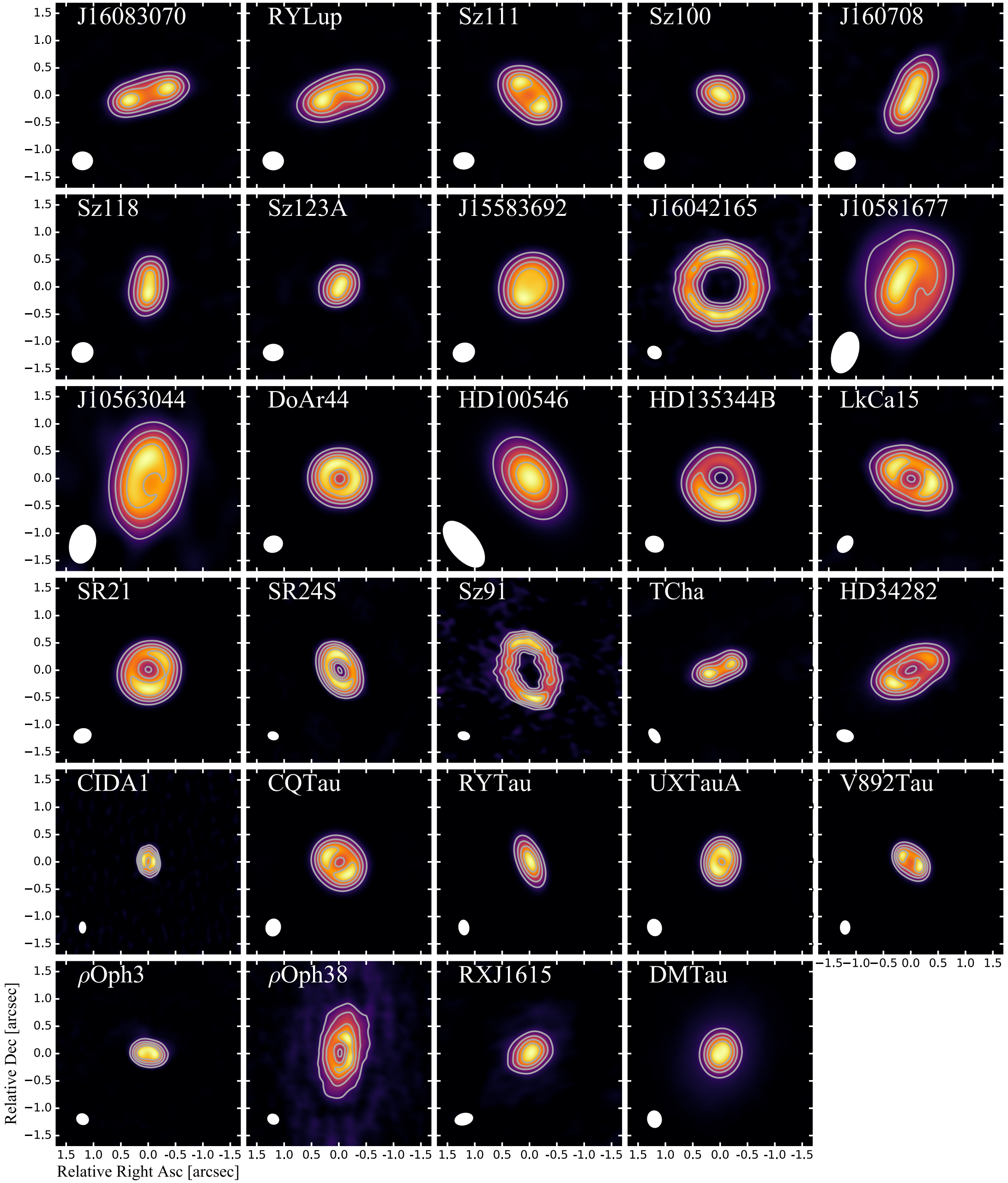
Outline

1. Dust Evolution in a Nutshell:
Models: Growth and Dynamics.

2. What do we know from observations of PPDs?
Models vs. Observations.

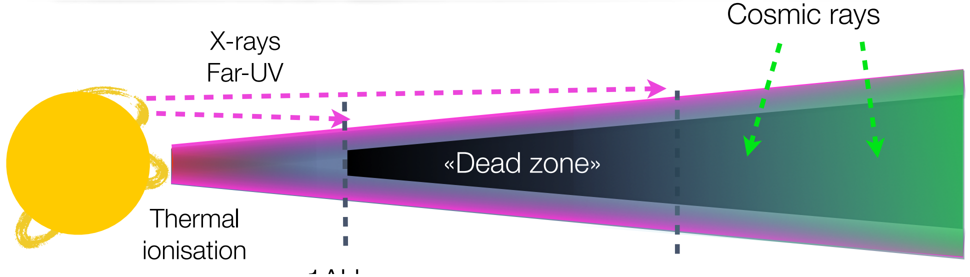
3. Current Investigation and Future Perspectives.

Transition Disks: Dust Depleted Inner Cavities

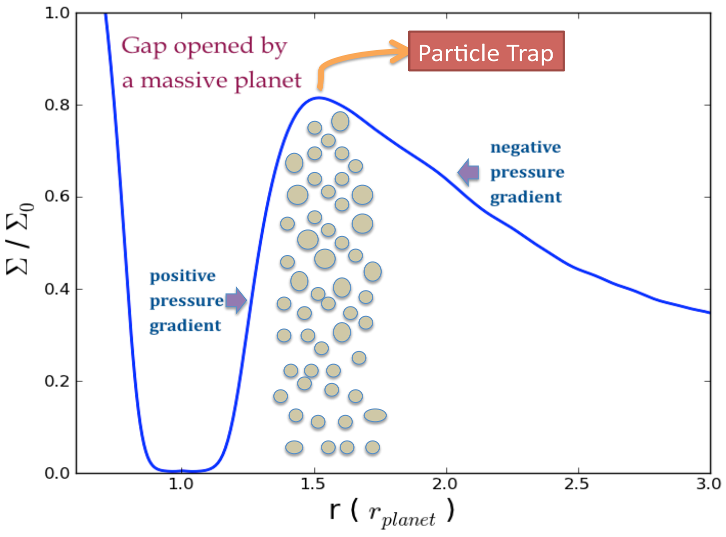


ALMA Observations of Transition Disks.
Figure from Pinilla et al (2018a)

What is the origin of the structures?



Outer edge of a dead zone

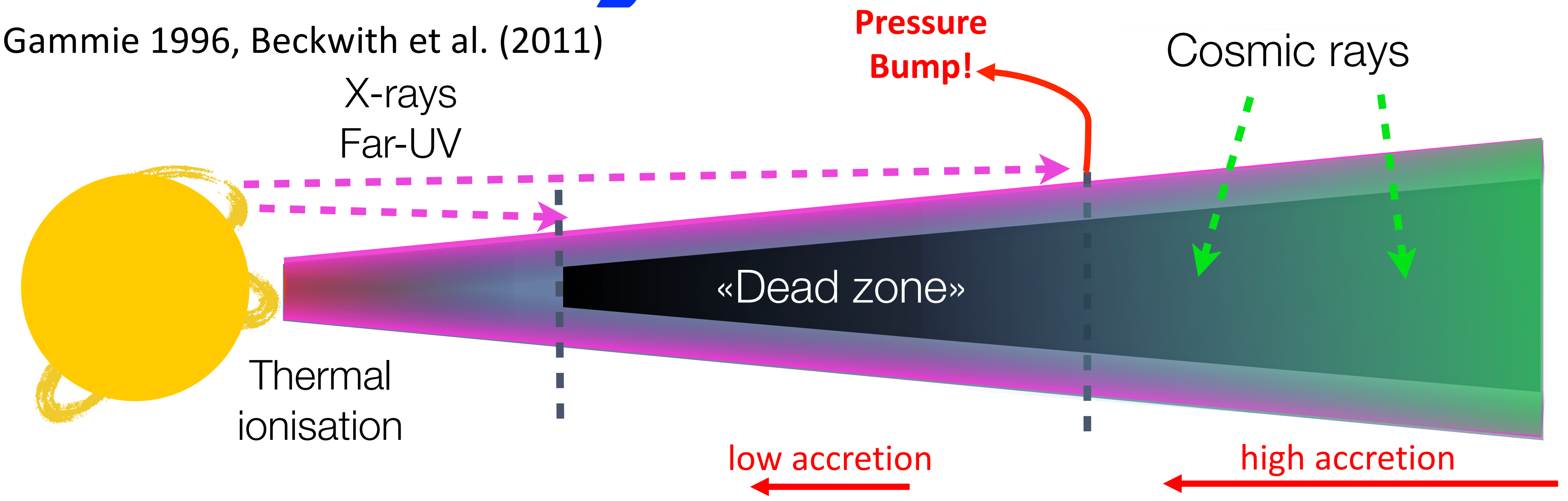


Planet-disk interaction

How can we distinguish from observations?

Potential Origin of TDs: Dead Zones

See e.g.: Gammie 1996, Beckwith et al. (2011)



MRI leads to self-sustaining turbulence within sufficiently well-ionized accretion disks

If MRI is suppressed the effective turbulence is low

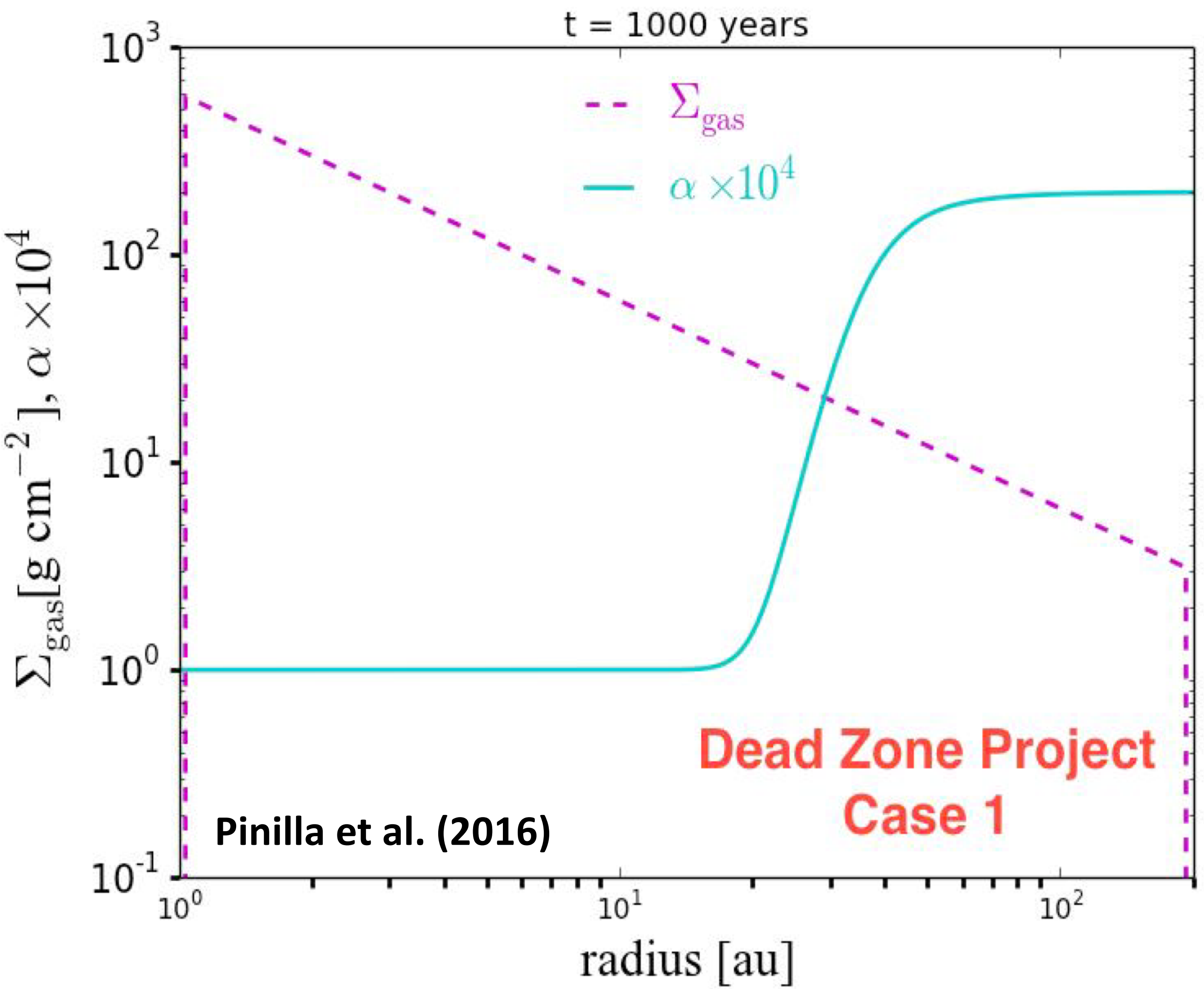
$$\nu_t = \alpha c_s H \begin{cases} \text{In an } \textbf{\textit{active zone}} & 10^{-3} < \alpha < 10^{-2} \\ \text{In a } \textbf{\textit{dead zone}} & \alpha \leq 10^{-4} \end{cases}$$

$$\boxed{\dot{M} \propto \nu_t}$$

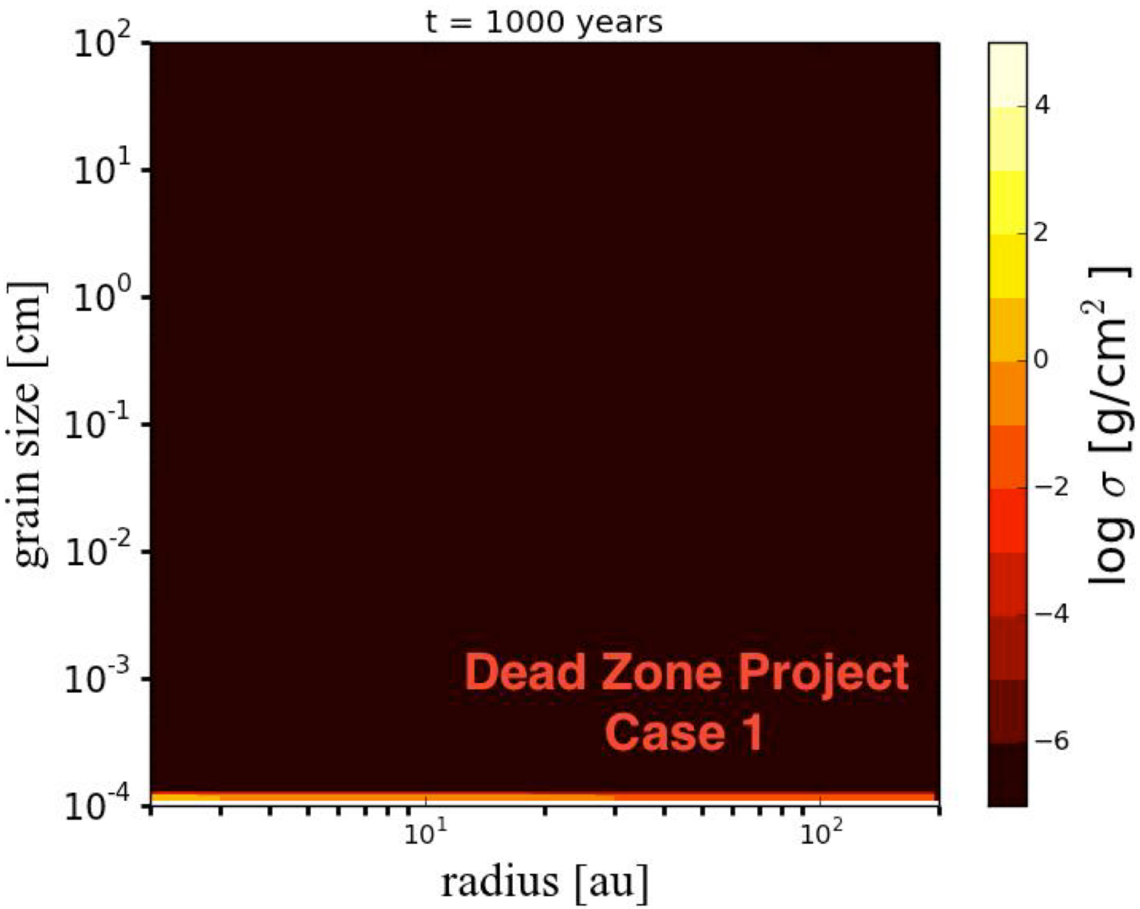
Analytical Approximation of a DZ

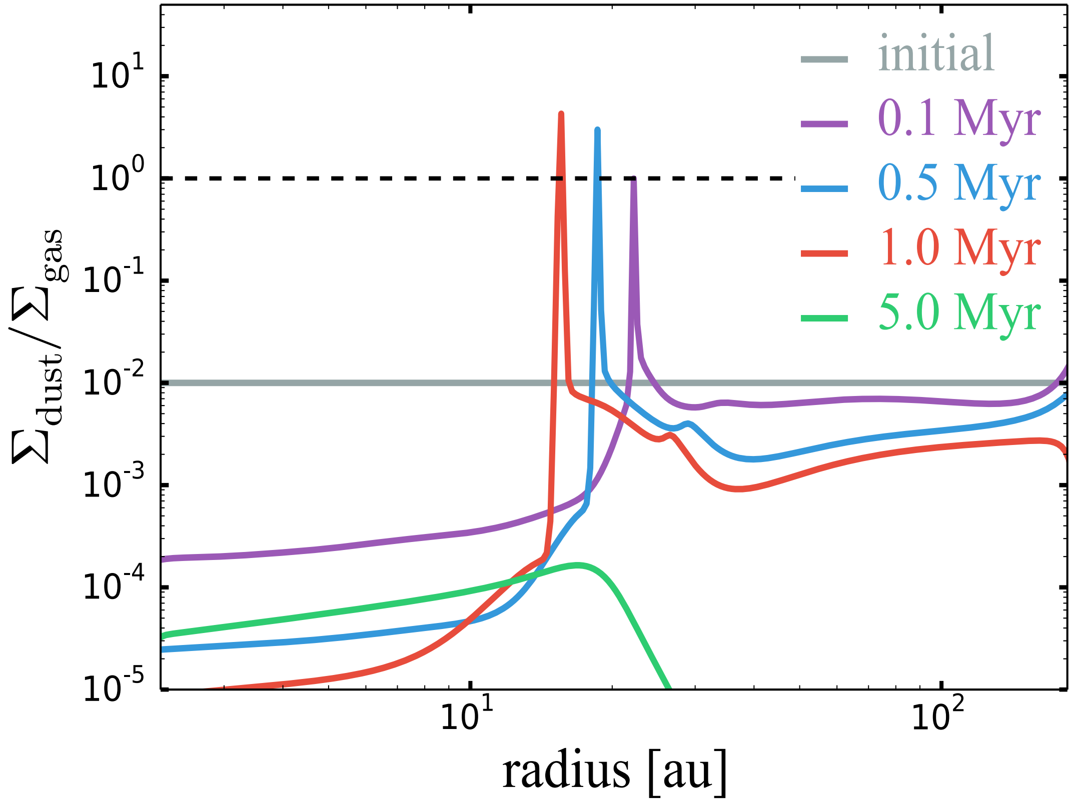
We implement
a dependence on surface
density, so that a change
in surface density can switch
the disk from active to dead
and back.

See also: Varnière & Tagger 2006; Kretke & Lin 2007; Brauer et al. 2008; Dzyurkevich et al. 2010; Drażkowska et al. 2013; Ruge et al. 2016



Formation of the First Core at the Edge of a Dead Zone

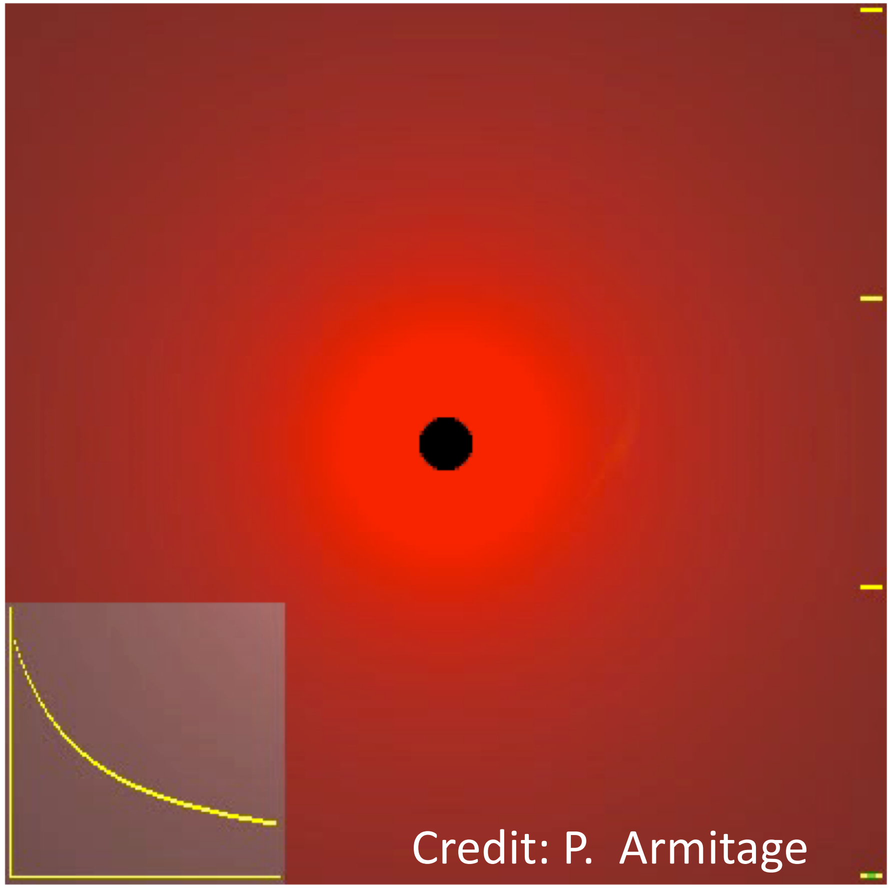


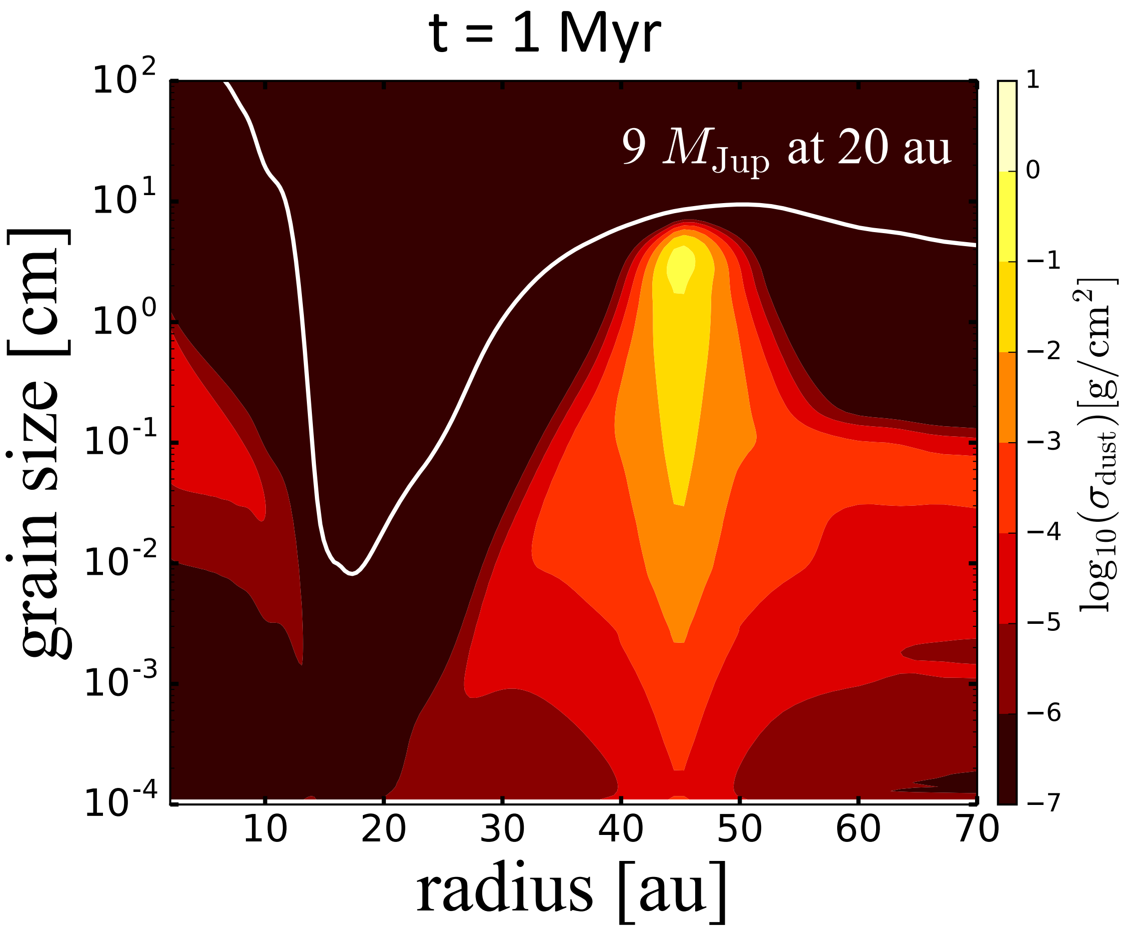


The mass of the accumulated dust in the region where a dust trap exists and moves during the simulation (~ 10- 30 au) can reach values over 100 M_{earth} If this mass can be assembled into a core (by e.g. streaming instabilities), it is sufficient to start gas accretion and form giant planets

Pinilla et al. (2016)

Potential Origin of TDs: Embedded Planets

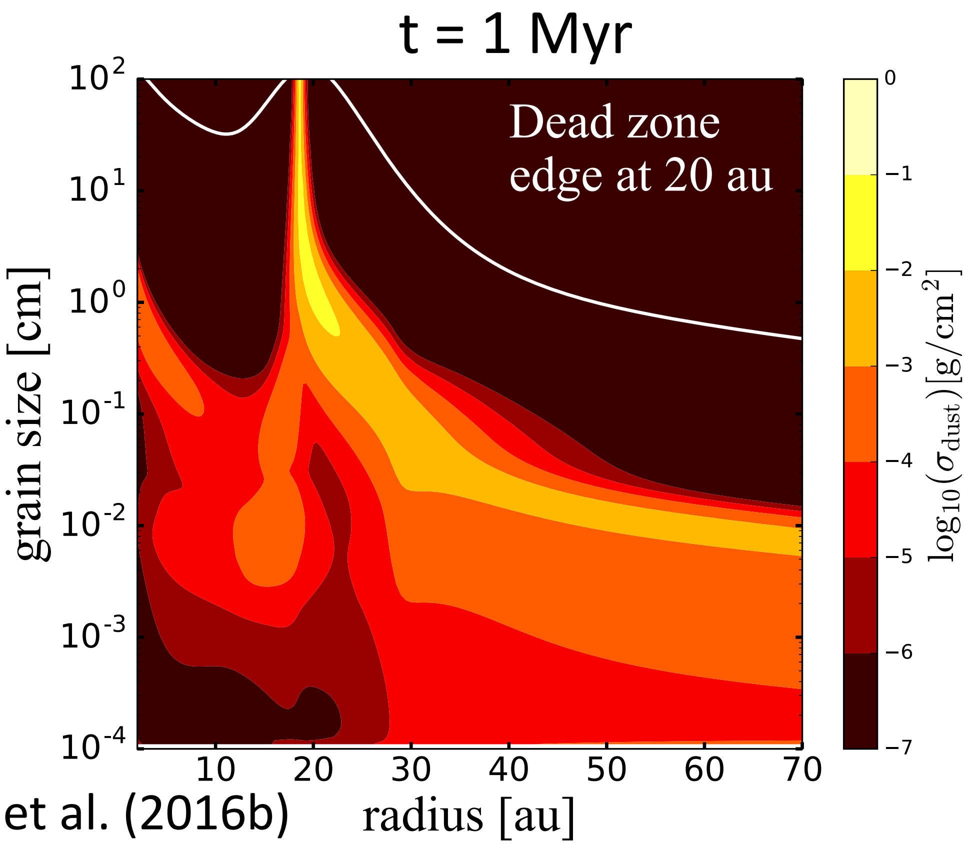




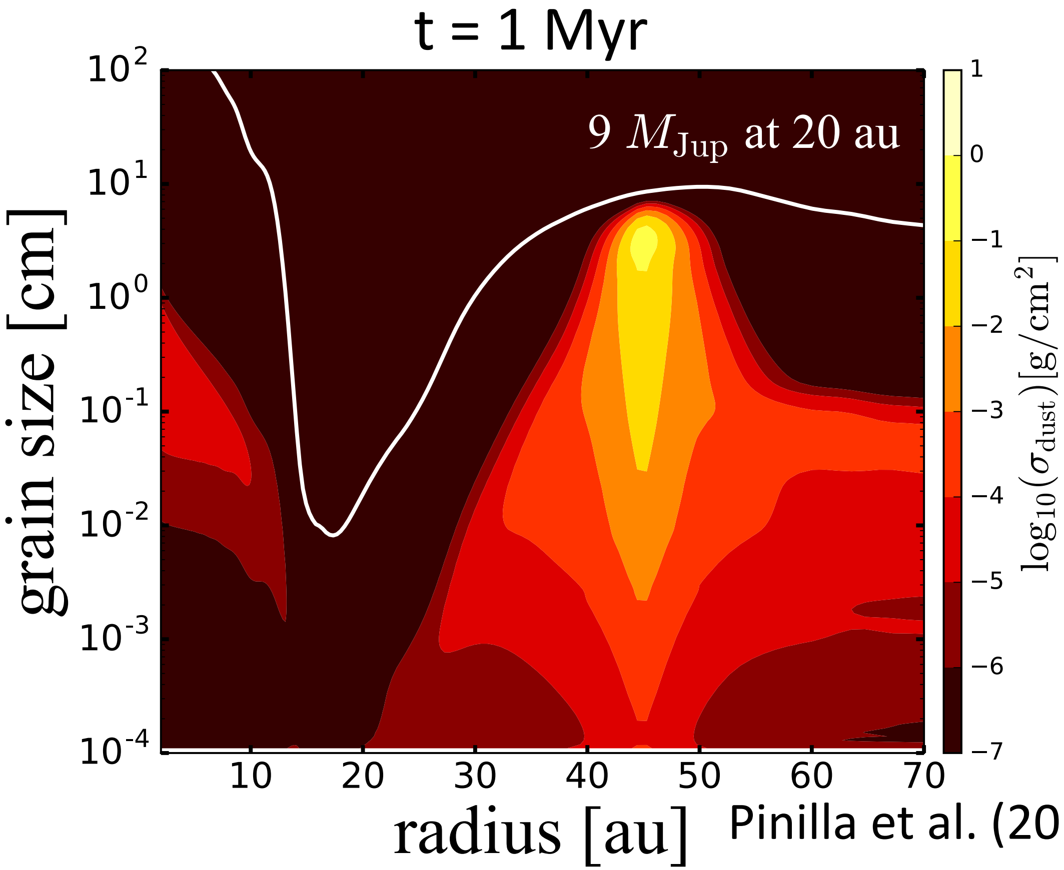
At the outer edge of a planet carved-gap, the pressure gradient is positive and particles can be trapped.

See also e.g.: Zhu et al. (2012, 2014), Dong et al. (2014, 2015), Rosotti et al. (2016), Bae et al. (2017)

Dead Zones vs. Planets: how do we distinguish?



Pinilla et al. (2016b)



Pinilla et al. (2012b)

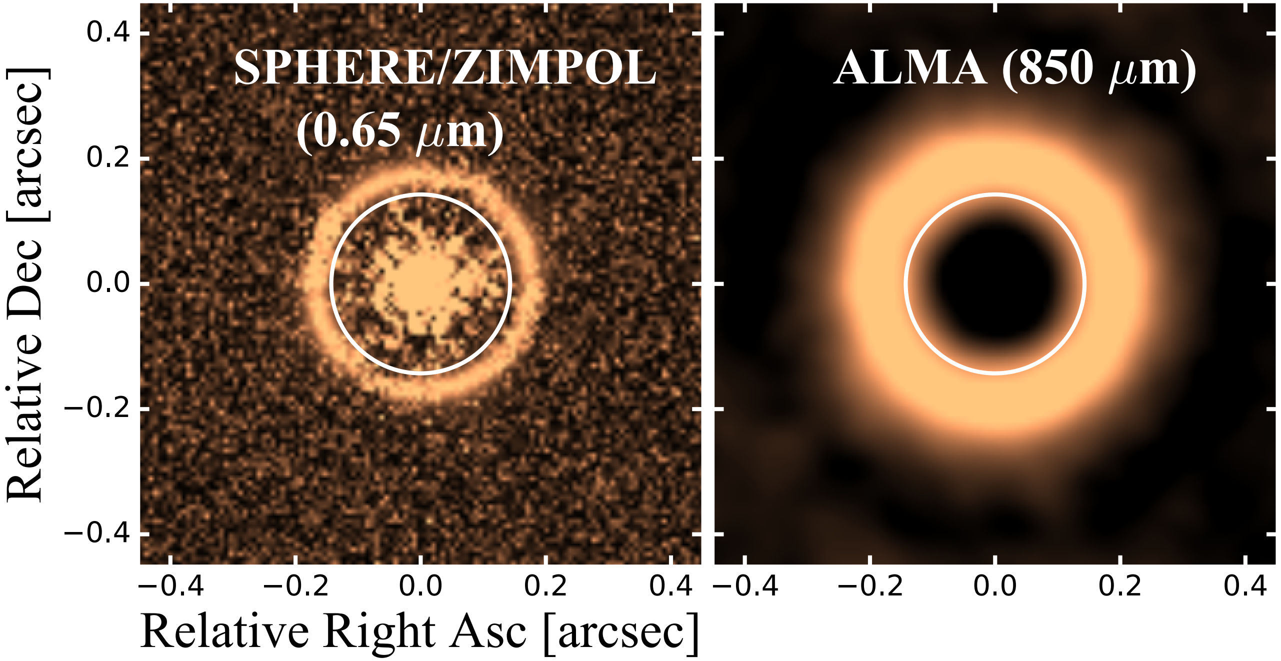
Dead Zones

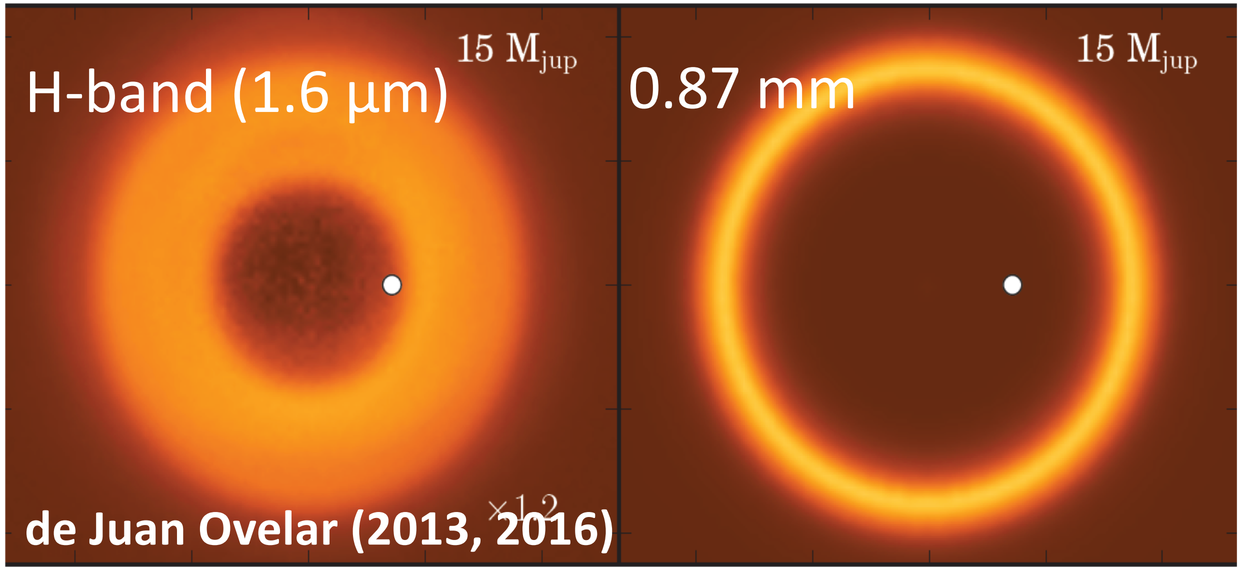
Size of the cavities is similar at short and long wavelengths.

Planets

Size of the cavities is smaller at short than at long wavelengths.

Dead Zones vs. Planets: how do we distinguish?





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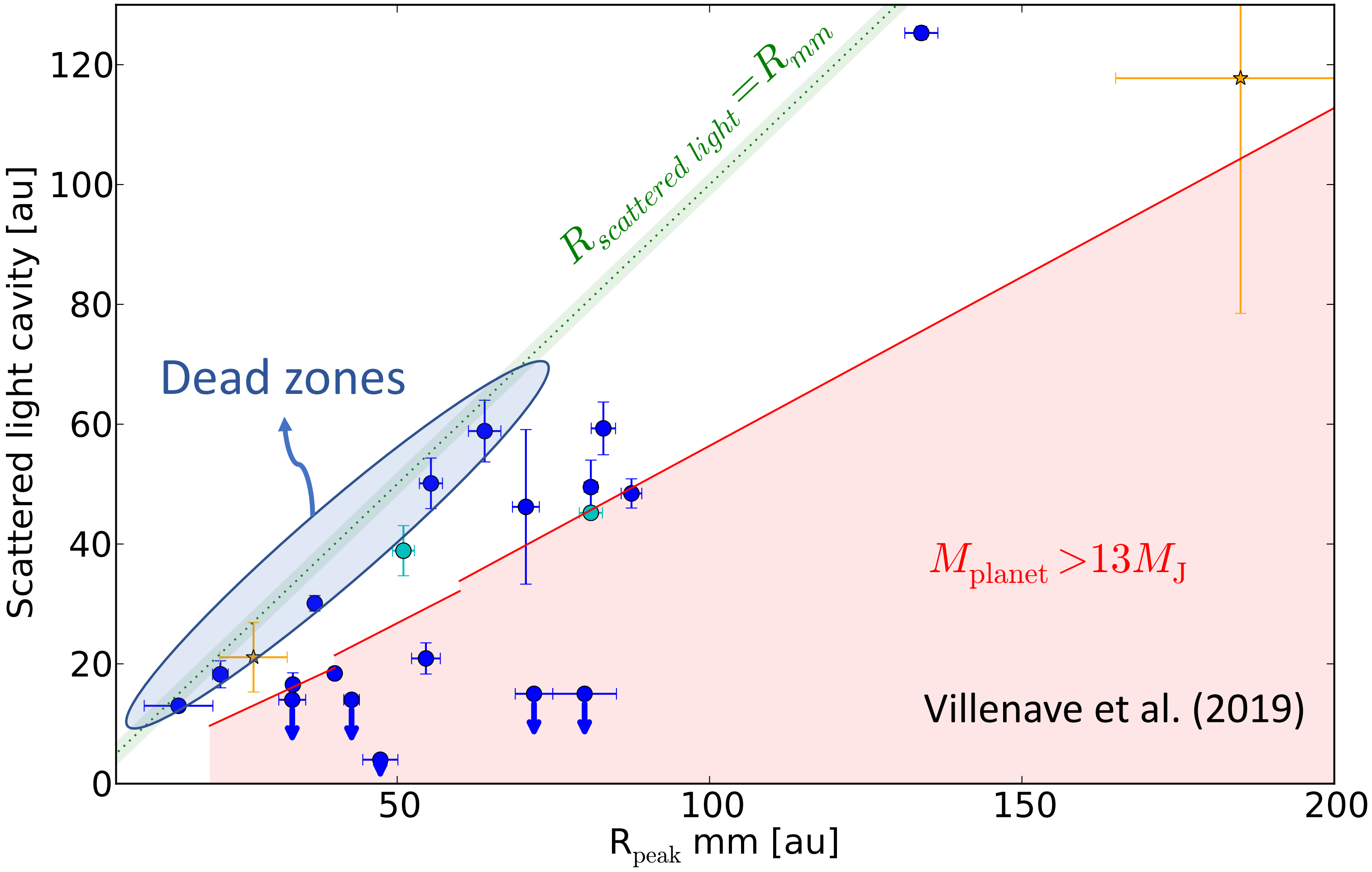
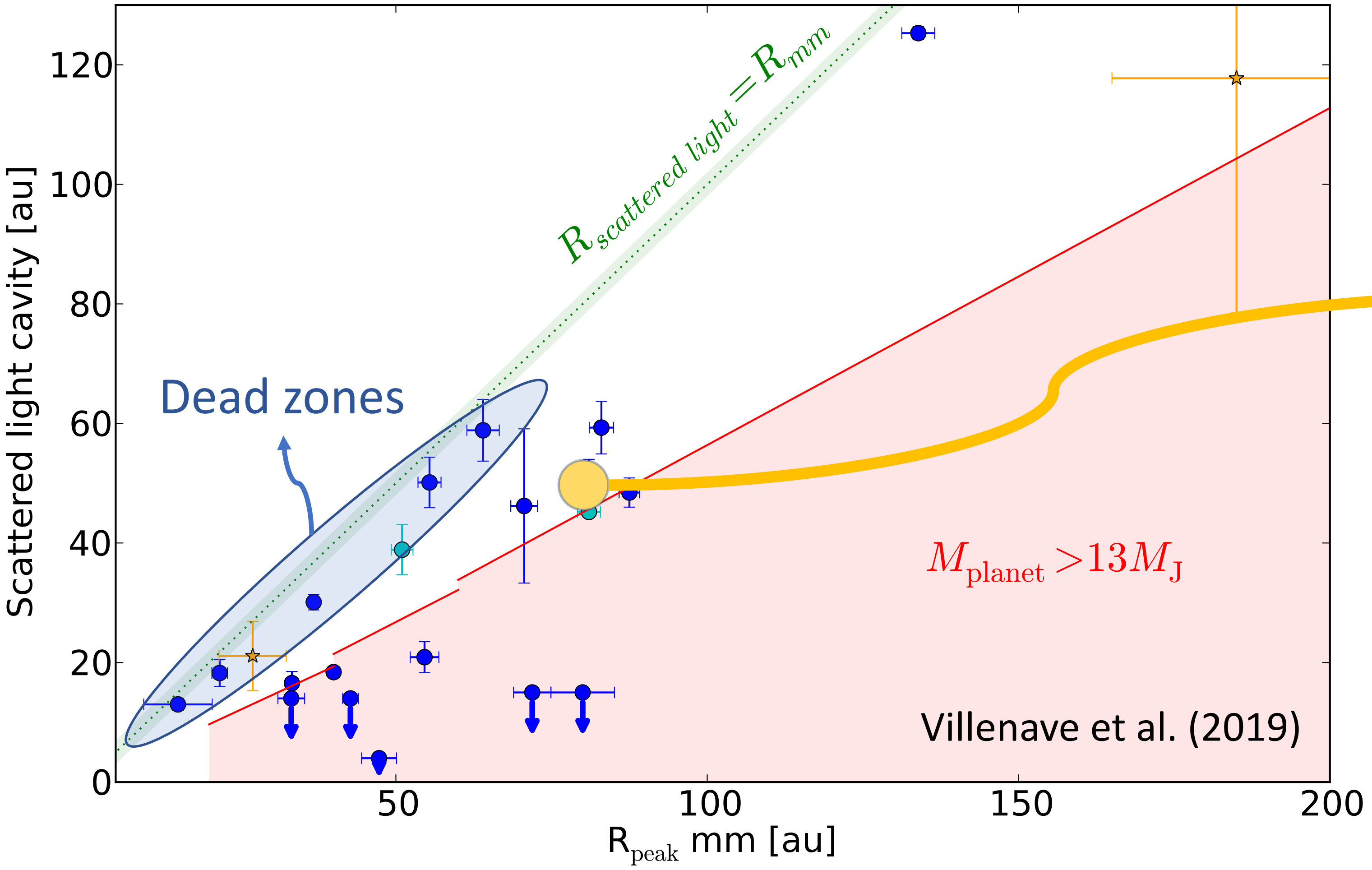
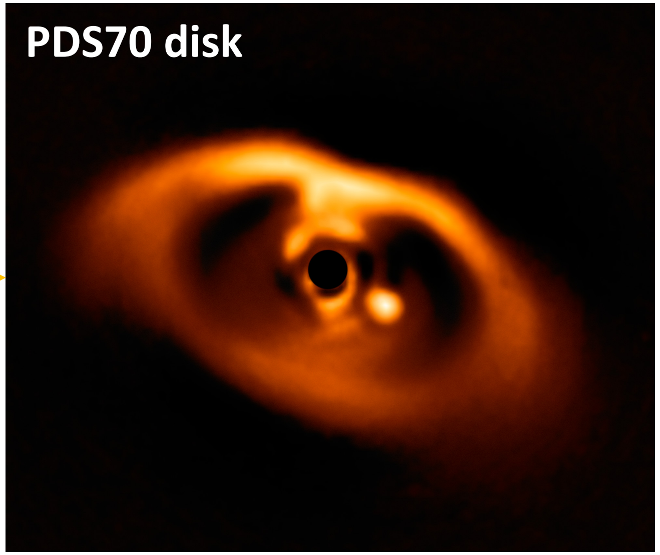


In a sample of 22 transition disks imaged with both ALMA and SPHERE

Dead Zones vs. Planets: how do we distinguish?

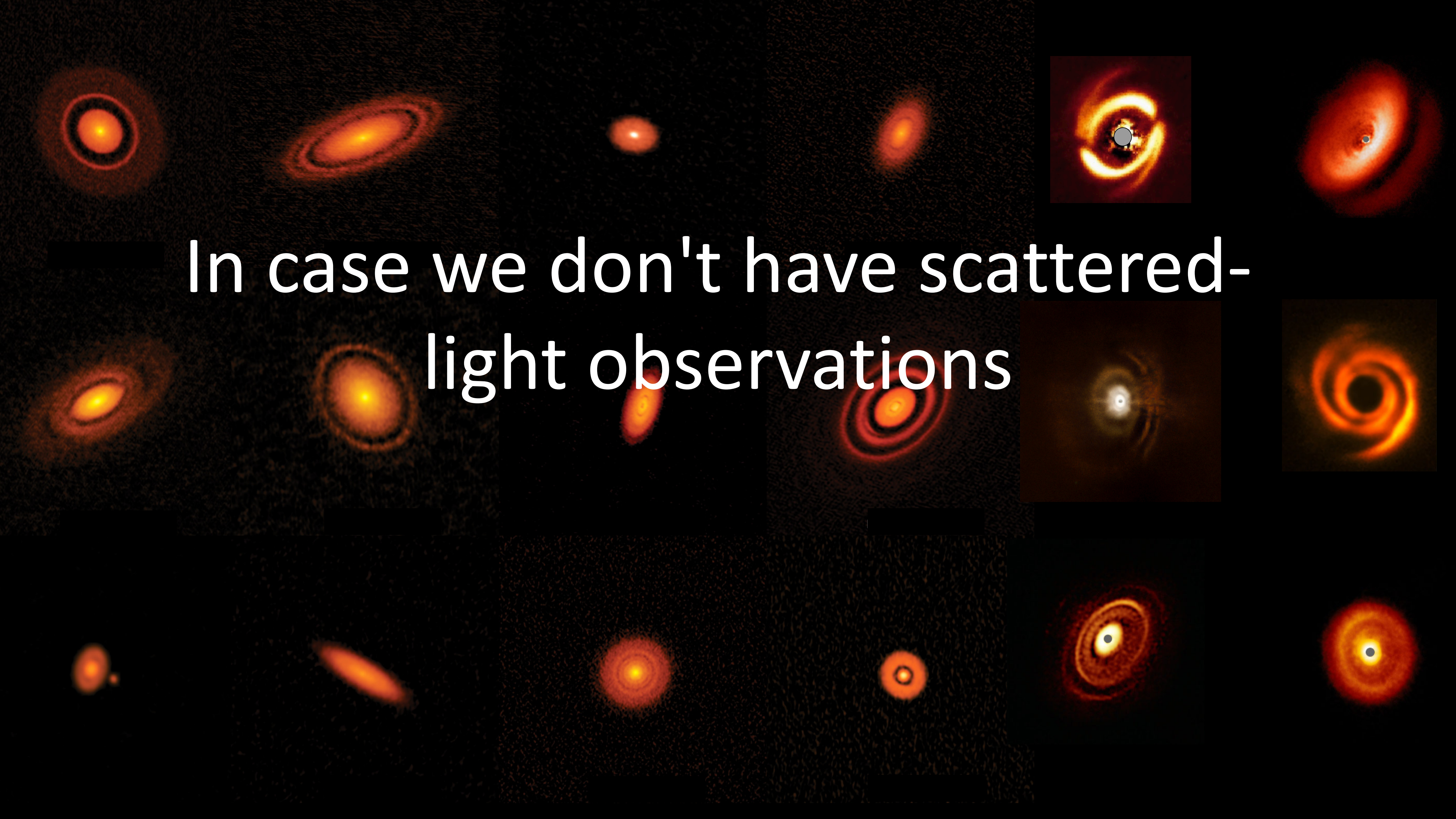


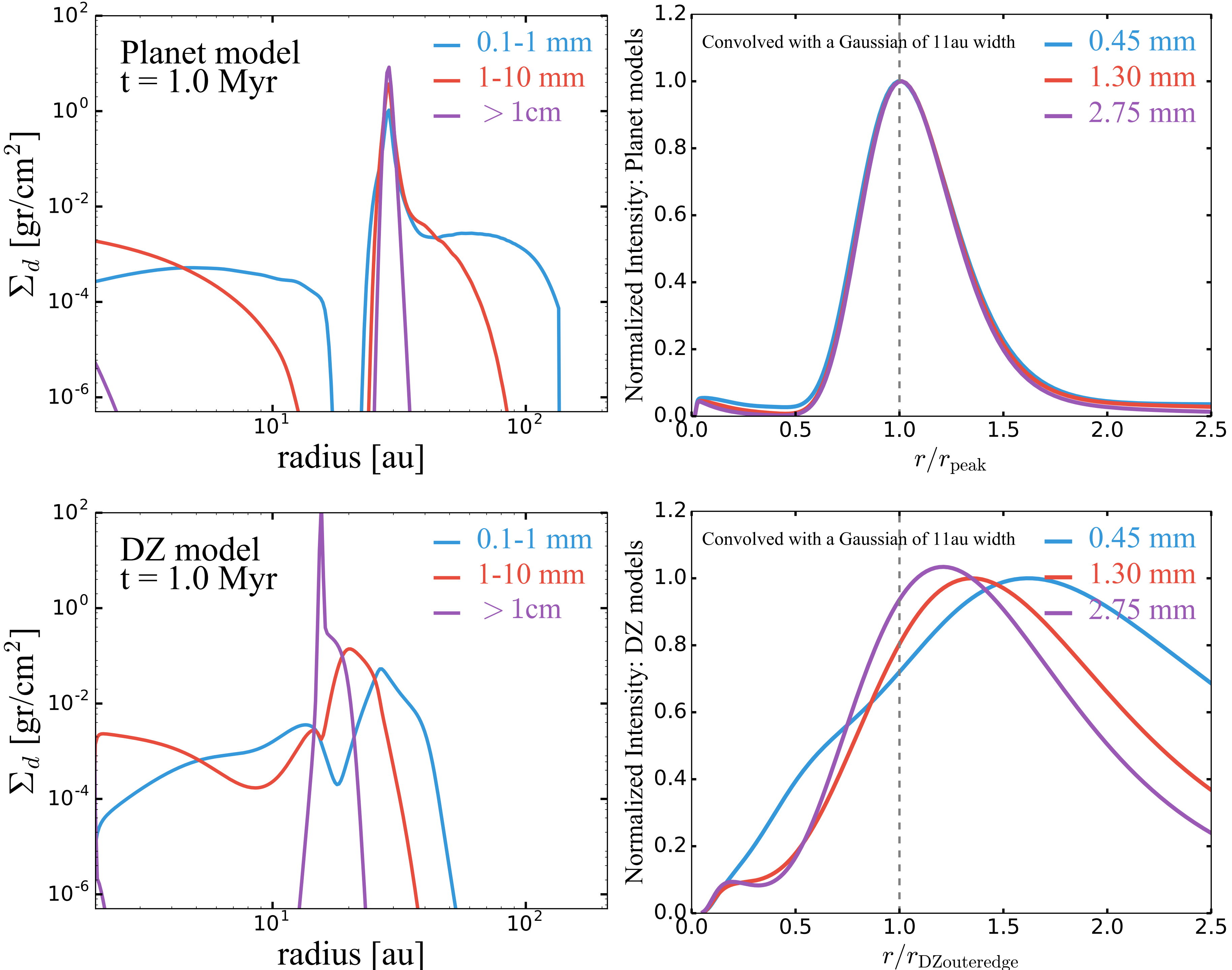


The first robust and still the only detection of a planet inside a disk (Keppler et al., 2018)

In a sample of 22 transition disks imaged with both ALMA and SPHERE

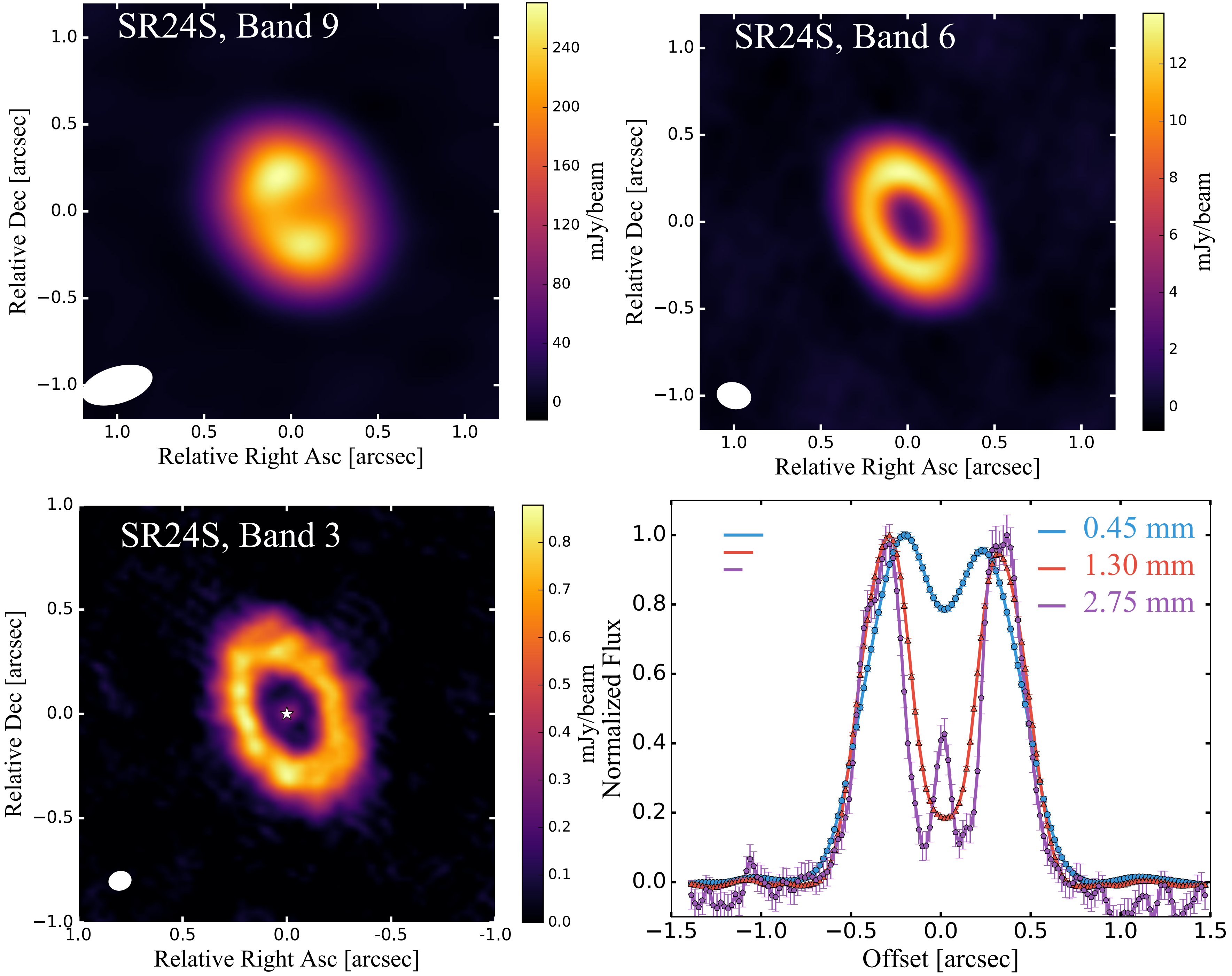
In case we don't have scattered-light observations





Dead Zones vs. Planet(s) By Looking at Longer Wavelengths

Pinilla et al. (2019)



SR24S

Current observations of this TD favor the planet scenario

Pinilla et al. (2019)

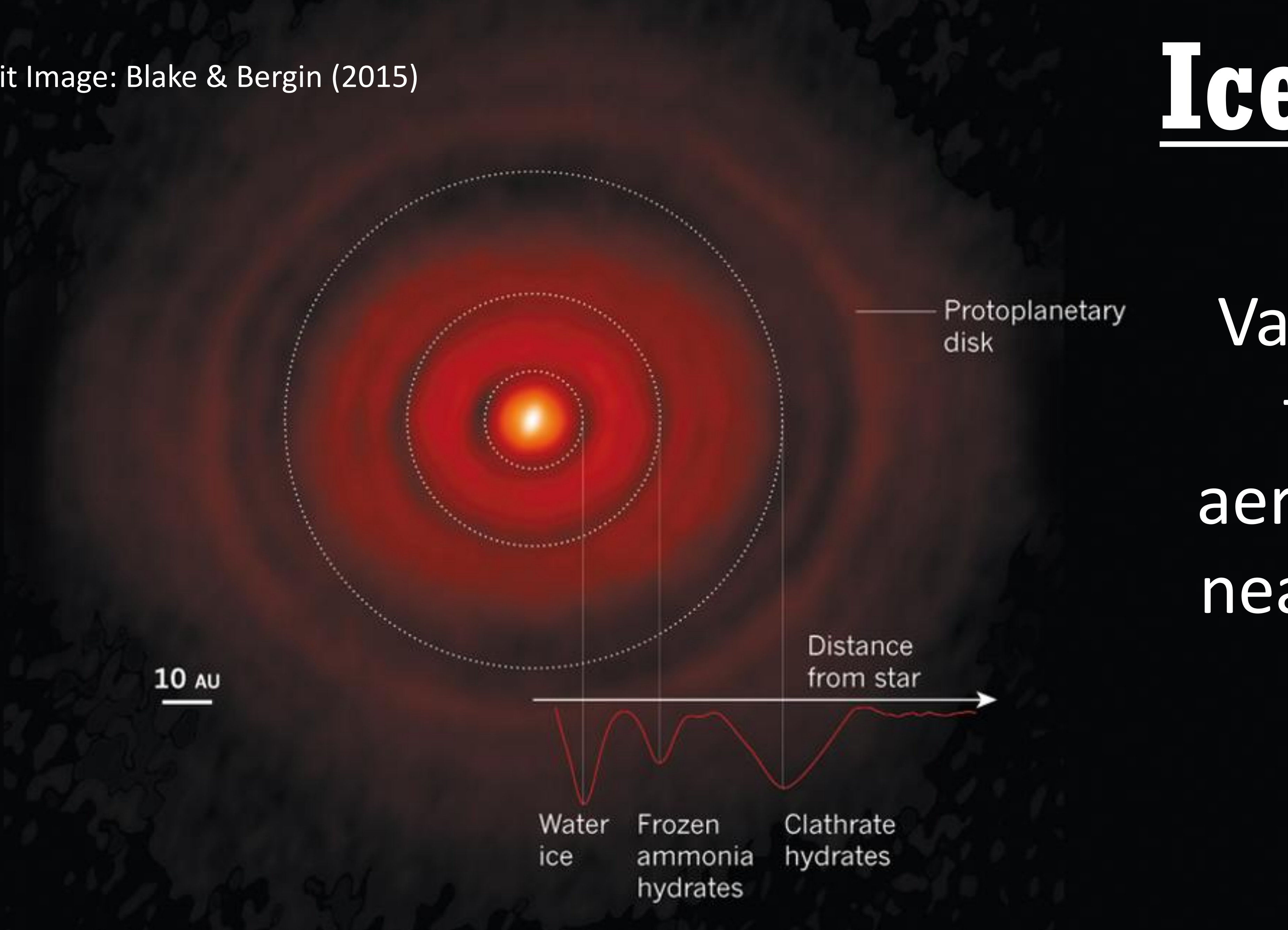
Origin of Transition Disk Structures

Model	mm-cavity	micron-sized cavity	≠ cavity size of the small and large grains
Embedded planet(s)	yes	for massive planets (> 1 $M_{Neptune}$)	yes
Dead zone	yes	yes	no

See also e.g.: Alexander et al. (2006, 2014), Pascucci et al. (2009), Owen et al. (2011, 2012) for internal photoevaporation as a possible origin

Credit Image: Blake & Bergin (2015)

Ice Lines



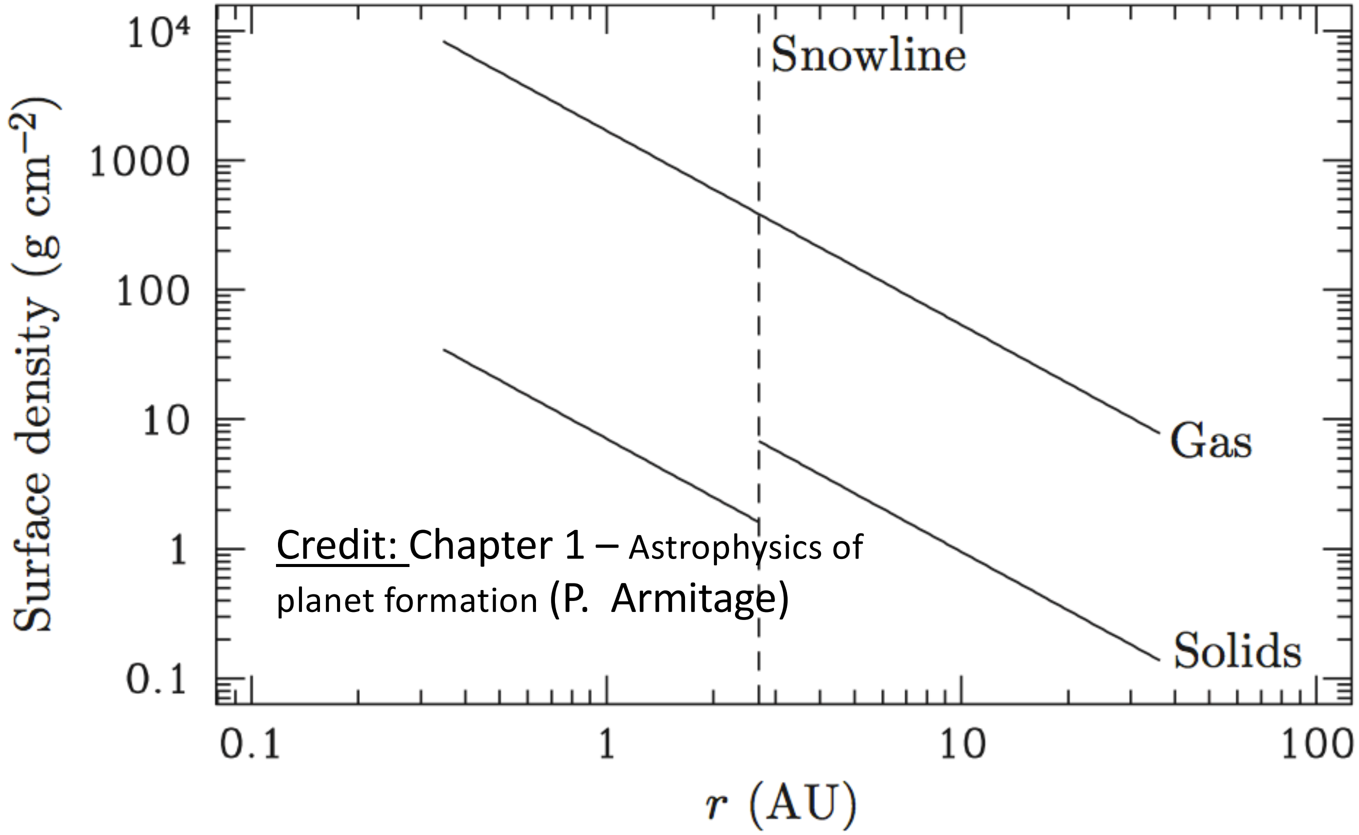
Variations of the dust aerodynamics near different ice lines

Ros & Johansen (2013), Zhang et al. (2015), Okuzumi et al. (2016), Stammler et al. (2017)

Water Snow Line

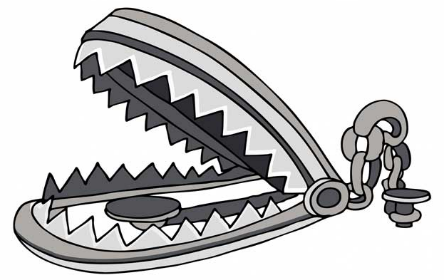
Beyond the snow line there is an amplification of the solid surface density, which can lead to <u>higher core mass and faster core formation.</u>

But it does not change the gas surface density significantly, <u>no pressure bump</u>



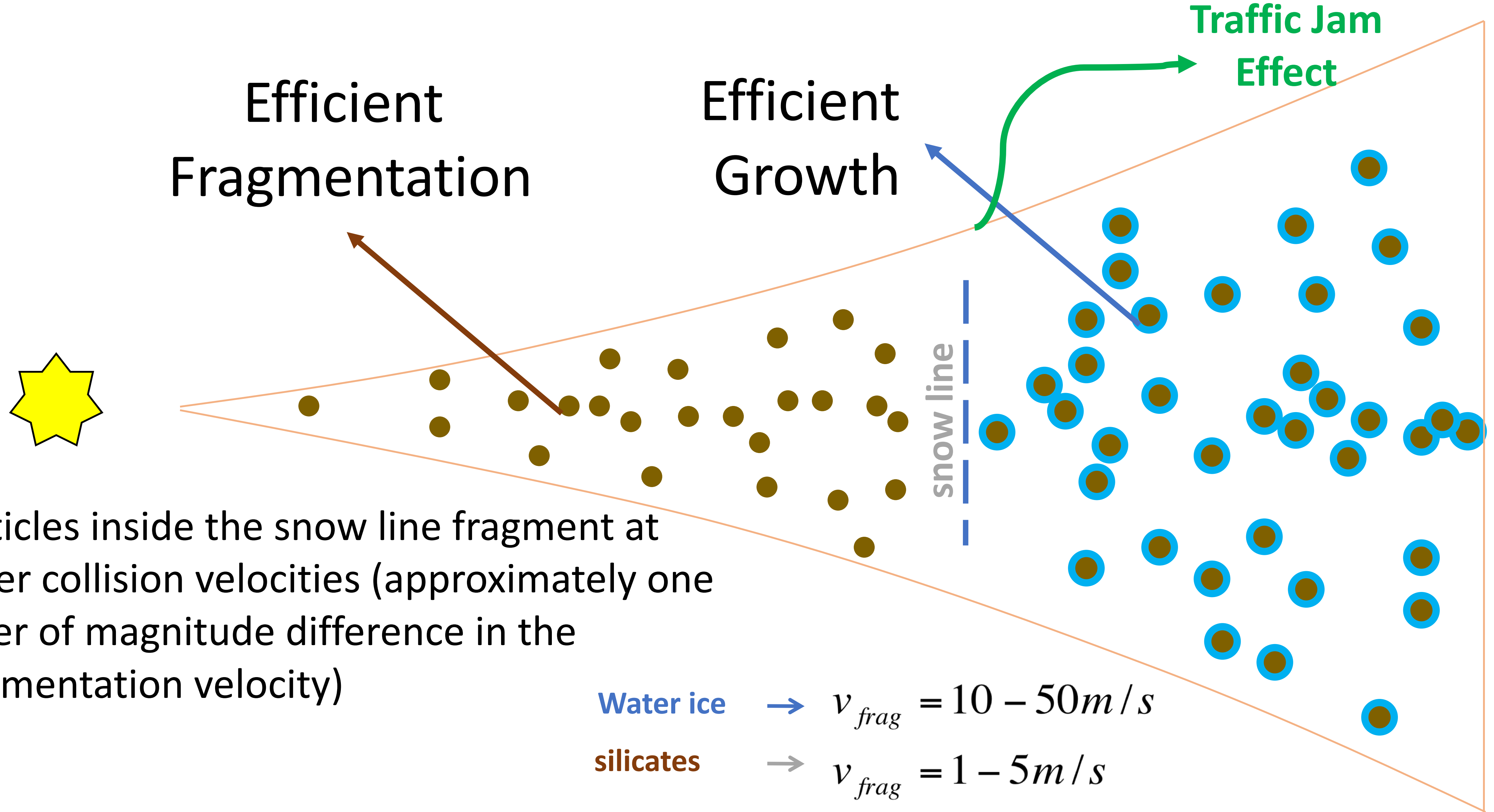
<u>Credit:</u> Chapter 1 – Astrophysics of planet formation (P. Armitage)

≠



Snow lines are not particle traps

Water snow line has an effect on dust aerodynamics



Particles inside the snow line fragment at lower collision velocities (approximately one order of magnitude difference in the fragmentation velocity)

Water ice → $v_{frag} = 10 - 50 m/s$

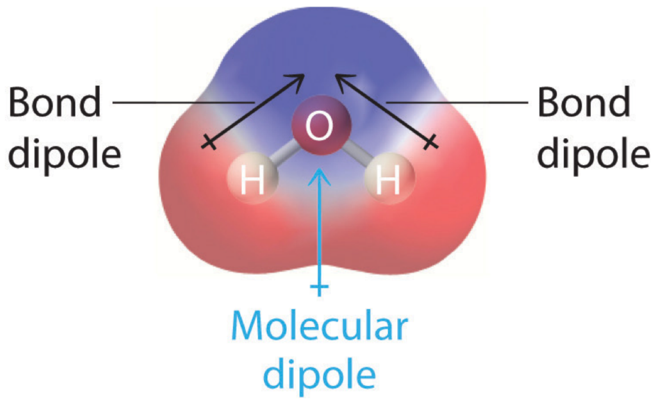
silicates → $v_{frag} = 1 - 5 m/s$

See e.g. Ciesla & Cuzzi (2006), Birnstiel et al. (2010), Wada et al. (2009, 2011), Banzatti et al. (2015)

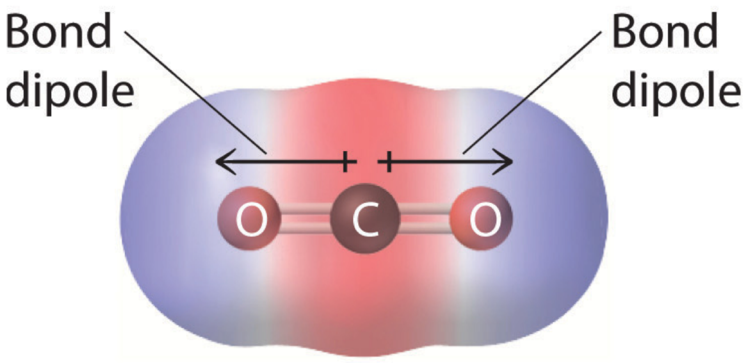
Other Ice Lines Effect

Van der Waals Forces:

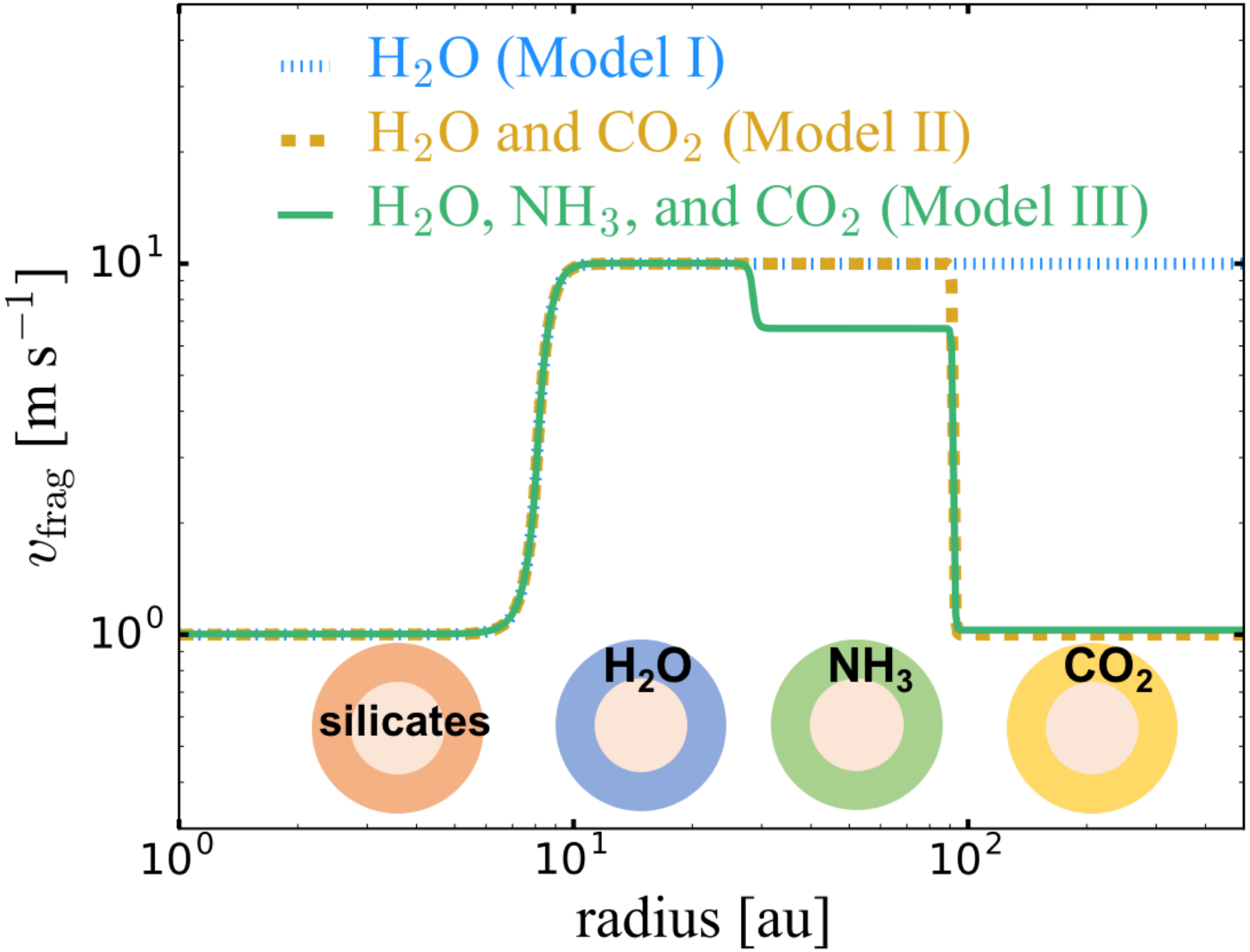
Depend on the dipole moment



Net dipole moment



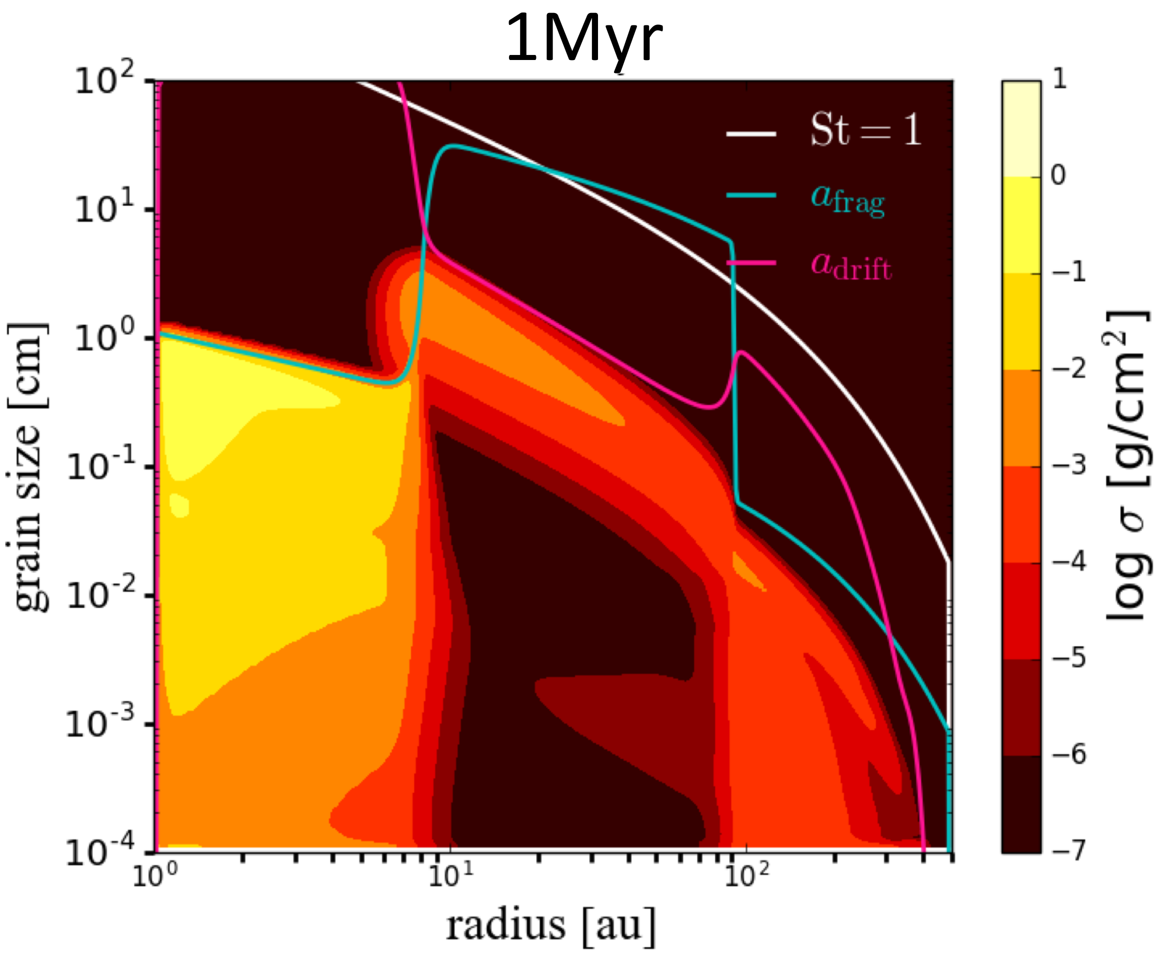
No net dipole moment

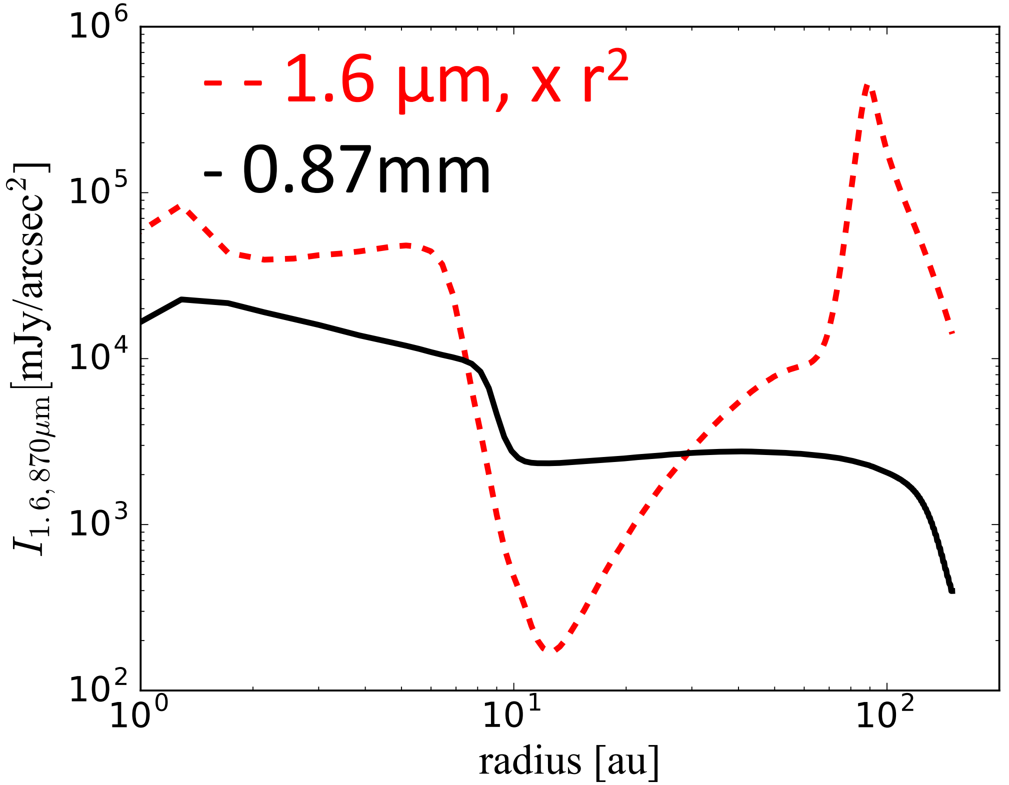


Pinilla et al. (2017),
see also: Musiolik et al. (2016a, b)

Dust Density Distribution

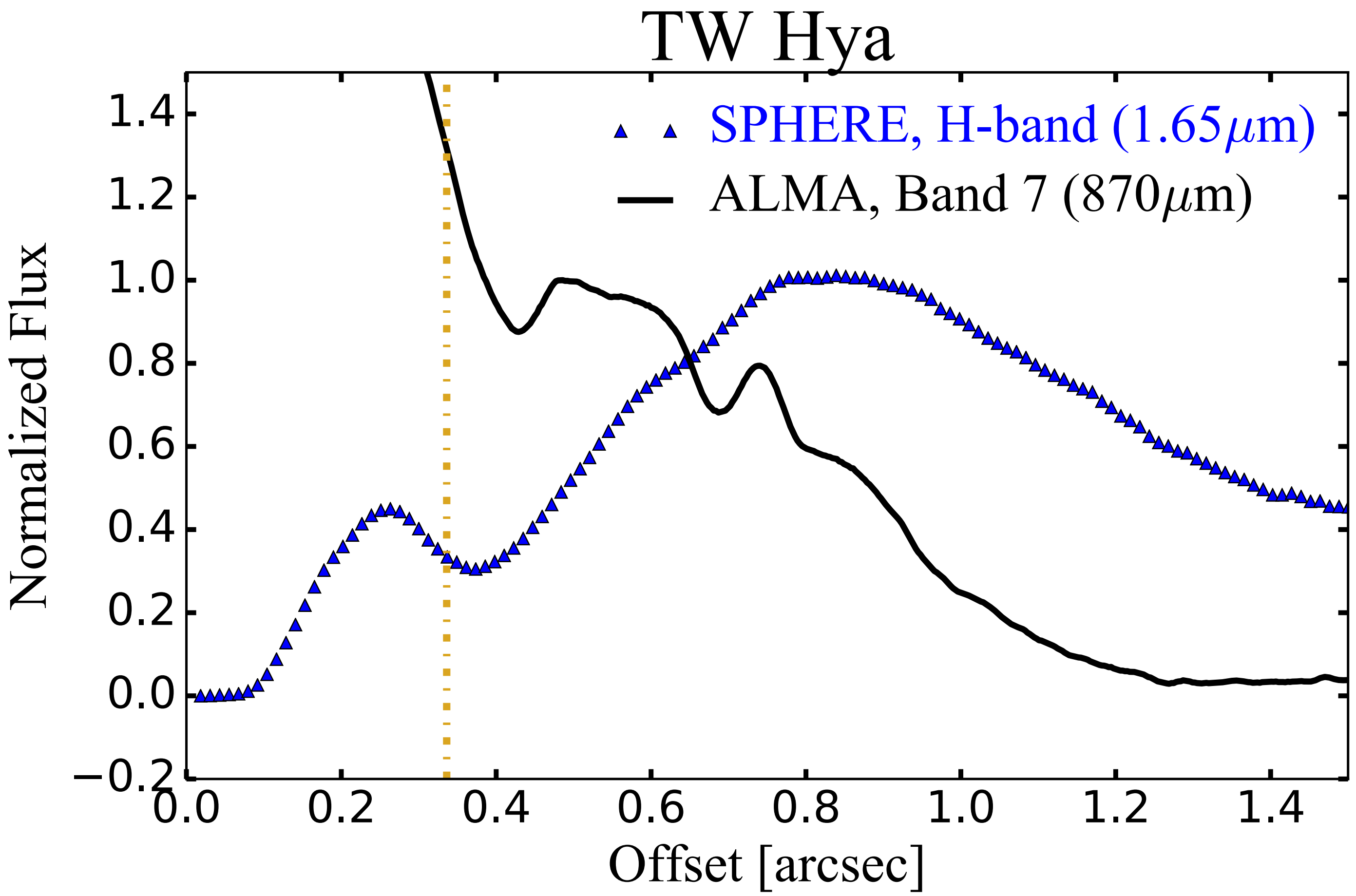
Model II: H_2O & CO_2 ice lines





The gap at mm-emission is much shallower than at NIR scattered-light

Comparison with Observations



The gaps near the CO ice line of TWHya are in agreement with our findings.

Opposite to the results expected by models of embedded planets or particle traps.

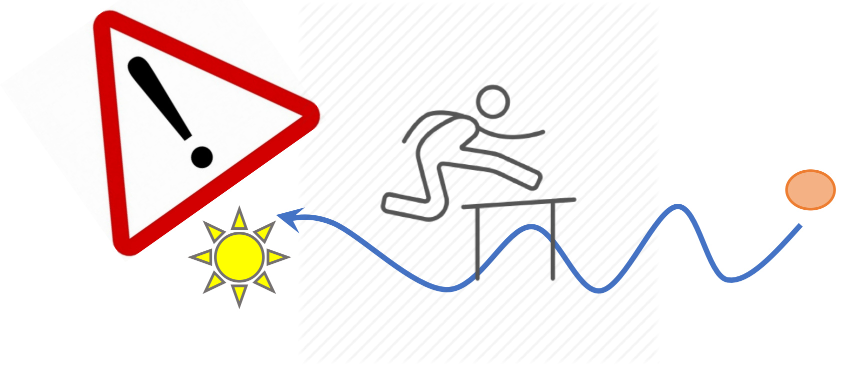
Pinilla et al. (2017)

Origin of Gaps and Rings

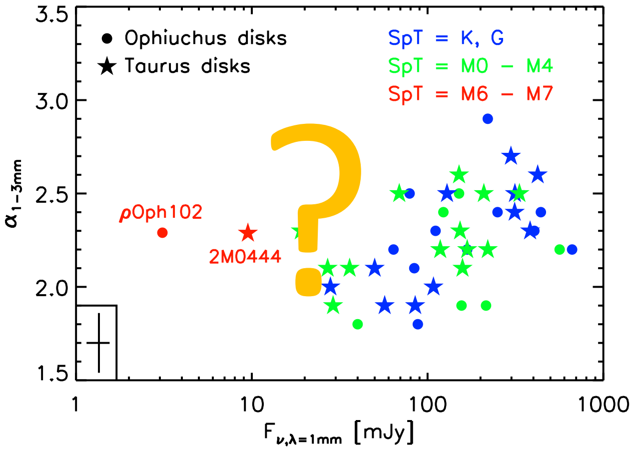
Model	mm-gap	scattered-light gap	Gap shape
Embedded planet(s)	yes	It could be	Depends on planet mass, scale height, and viscosity (smaller and shallower at NIR than mm)
Viscosity variations	yes	yes	multiple variations of the disk viscosity - to be investigated
Ice lines	yes	yes!	smaller and shallower at mm than NIR

Summary

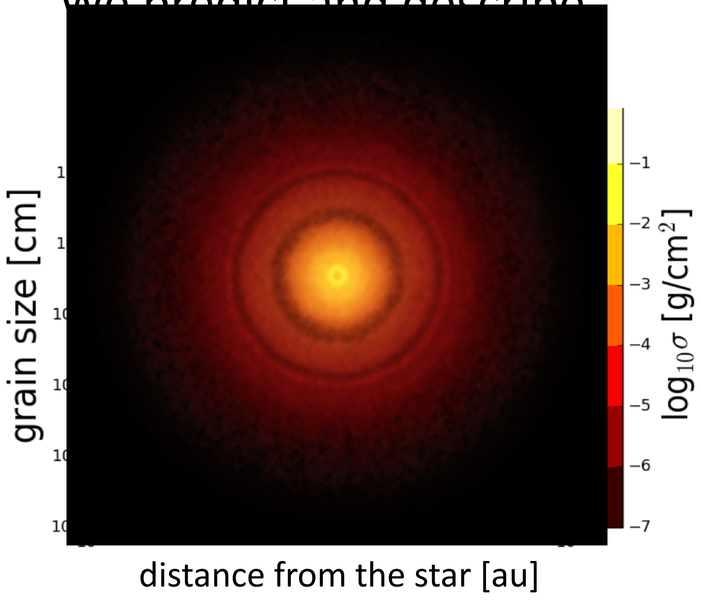
Radial drift barrier



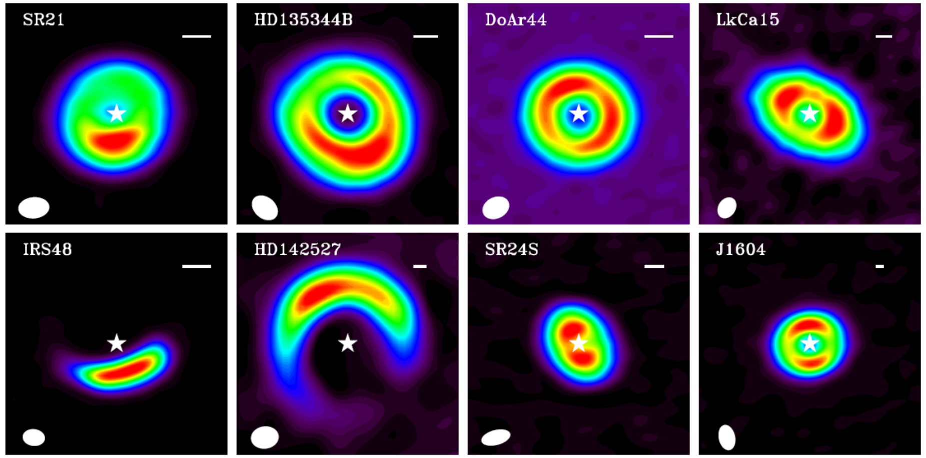
Models with radial drift in contradiction with observations



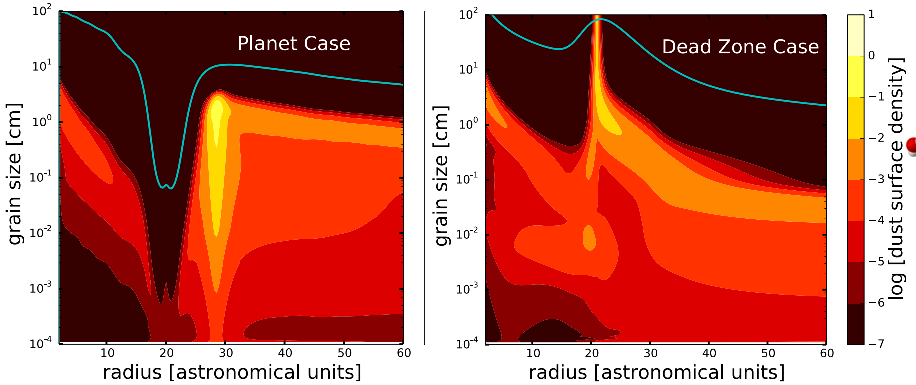
We predict and describe

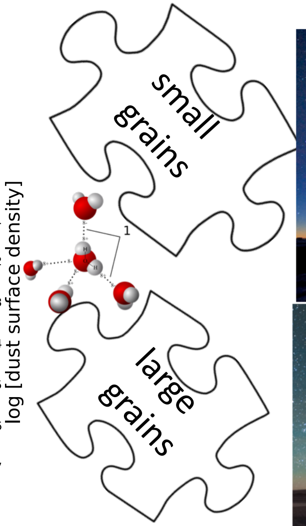


TDs: Excellent laboratories



Different potential origins





But we can (and we will) distinguish

Thank you for your attention