Dust Evolution in Protoplanetary Disks: Models, Observations and Laboratory Experiments

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Max-Planck-Institut für Astronomie Heidelberg

Max Planck Institute for Astronomy Heidelberg

Paola Pinilla

MPIA

New Mexico State University, Astronomy.

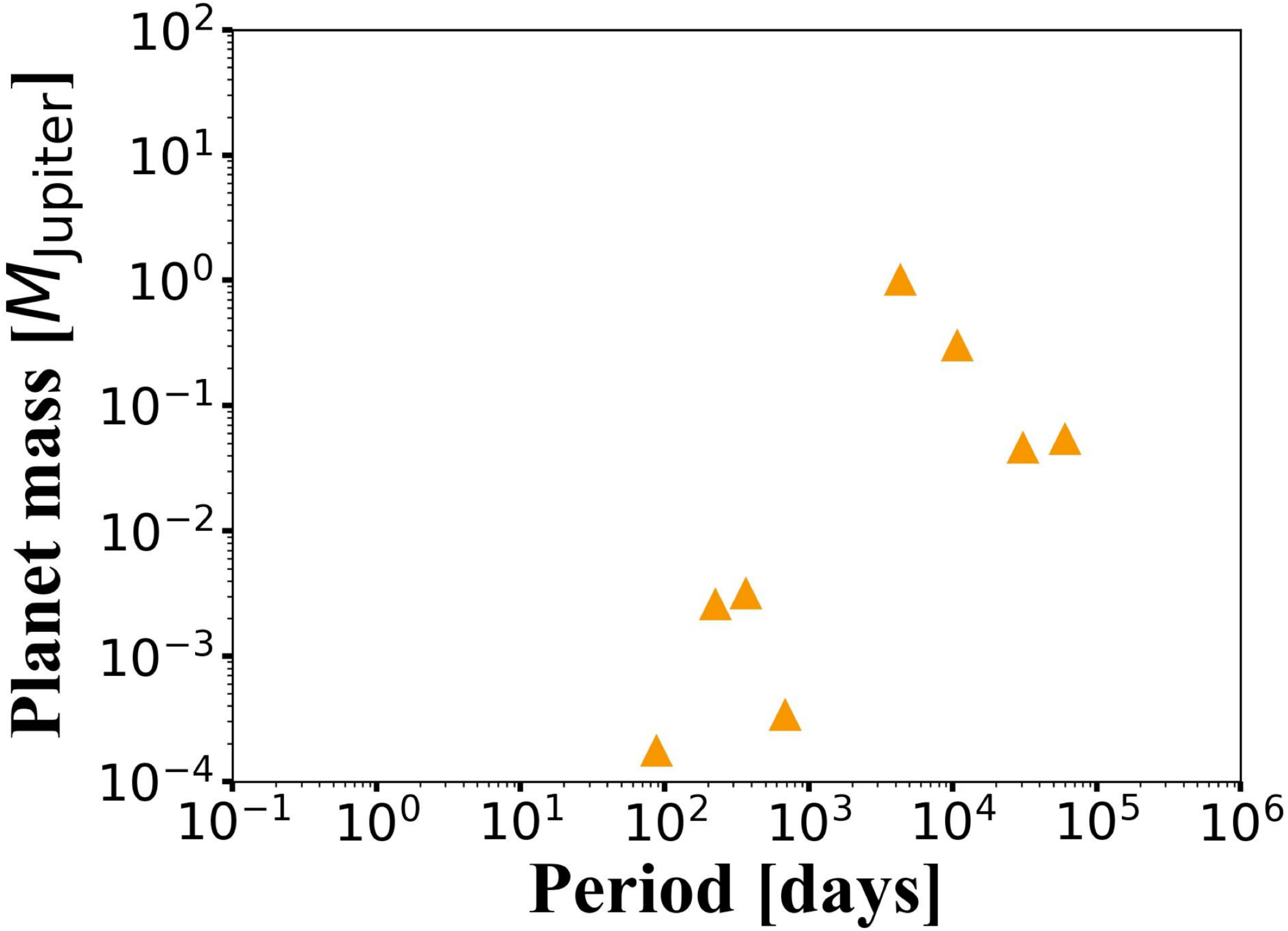
October 23th/2020. Zoom Space

Discovery and Diversity of Exoplanets

Two decades ago
We only knew the planets in our Solar System

1995
First confirmation of an exoplanet orbiting a Sun-like star

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



Today
~ 4300 confirmed exoplanets

Data from: https://exoplanetarchive.ipac.caltech.edu

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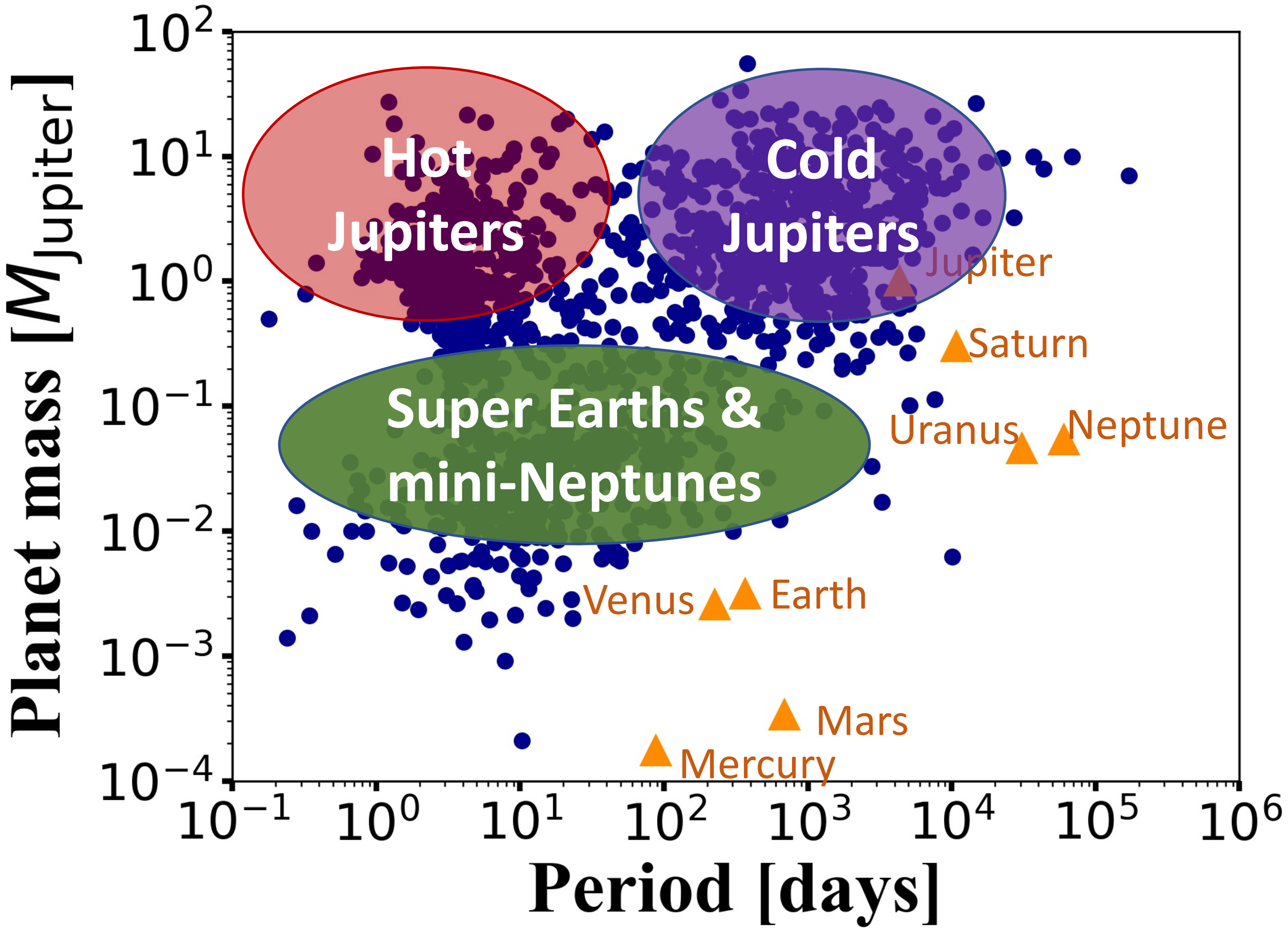

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Today ~ 4200 confirmed exoplanets

Open Questions in Planet Formation

How **and** ***when do*** **planets form?**

What is the origin of the diversity of exoplanets and their architectures?

- What is influence of the hosting star(s)?
- What is the influence of the initial conditions?
- What is the influence of the environment/interactions?

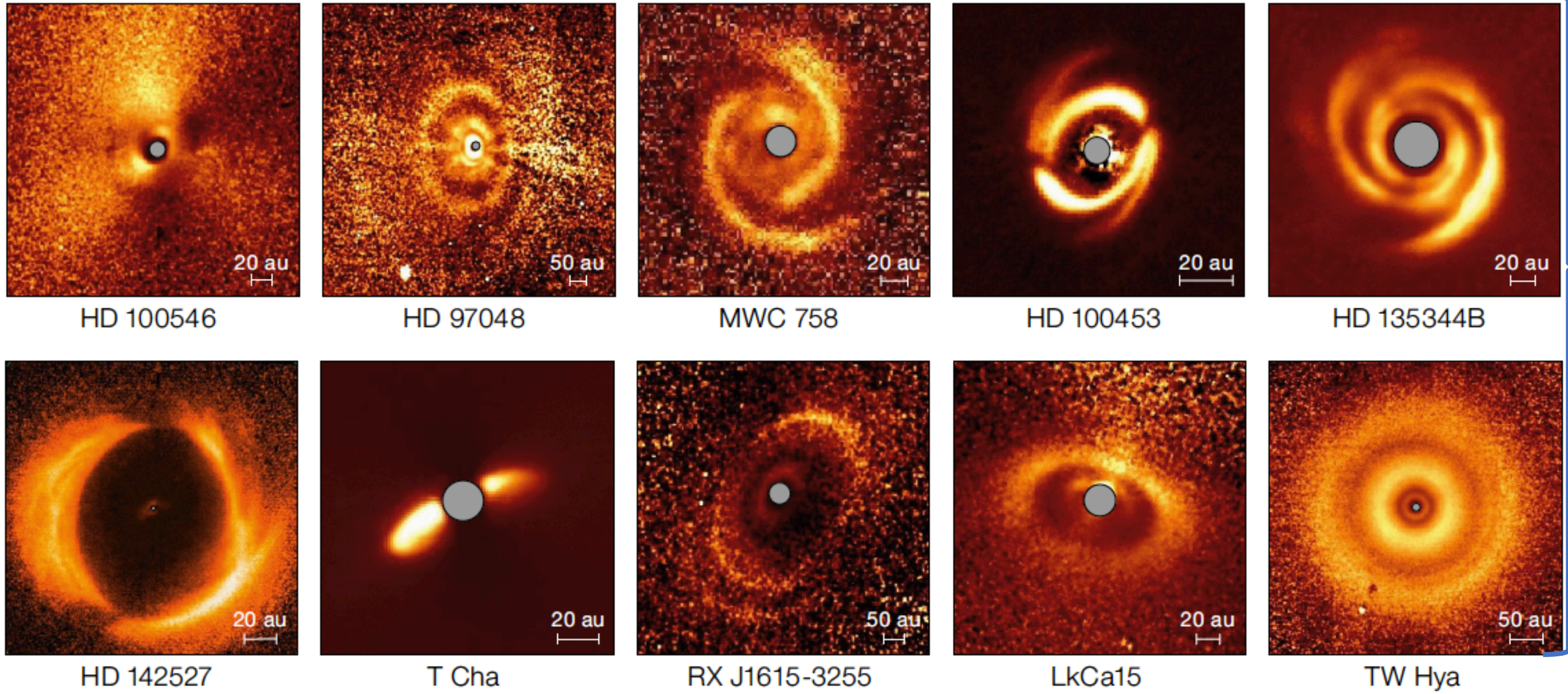
Initial conditions and dynamical evolution protoplanetary disks must leave an imprint on the properties and diversity of exoplanets

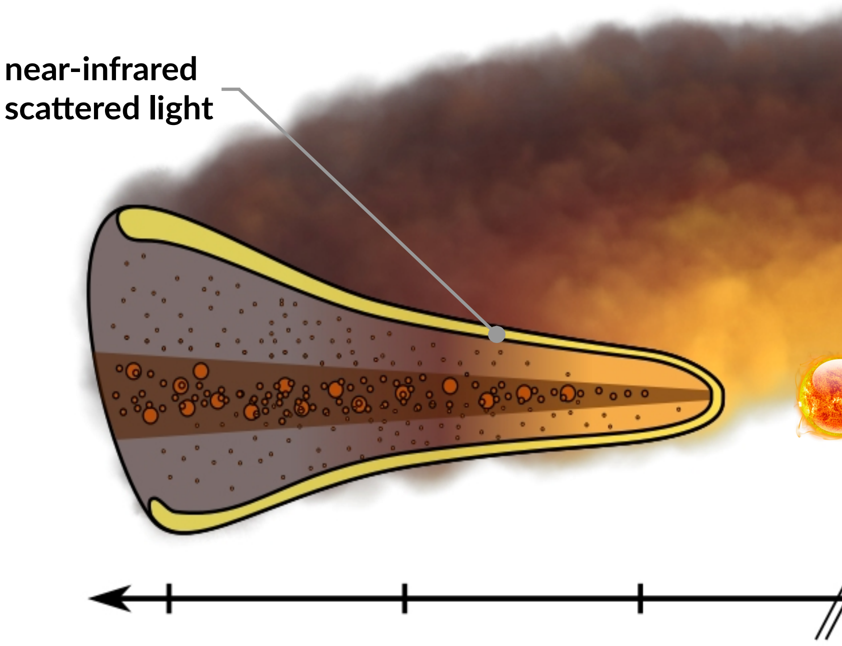
Look back in time …

Most of the information that we have about planets forming in disks comes from the *dust* that dominates the disk opacity

Observing the Evolution of Solids in Protoplanetary Disks

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

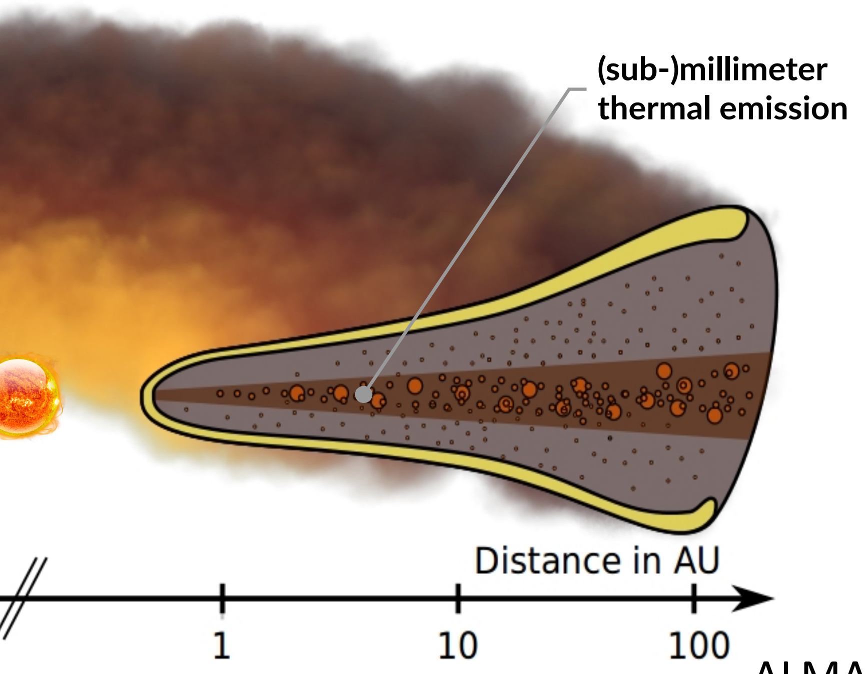


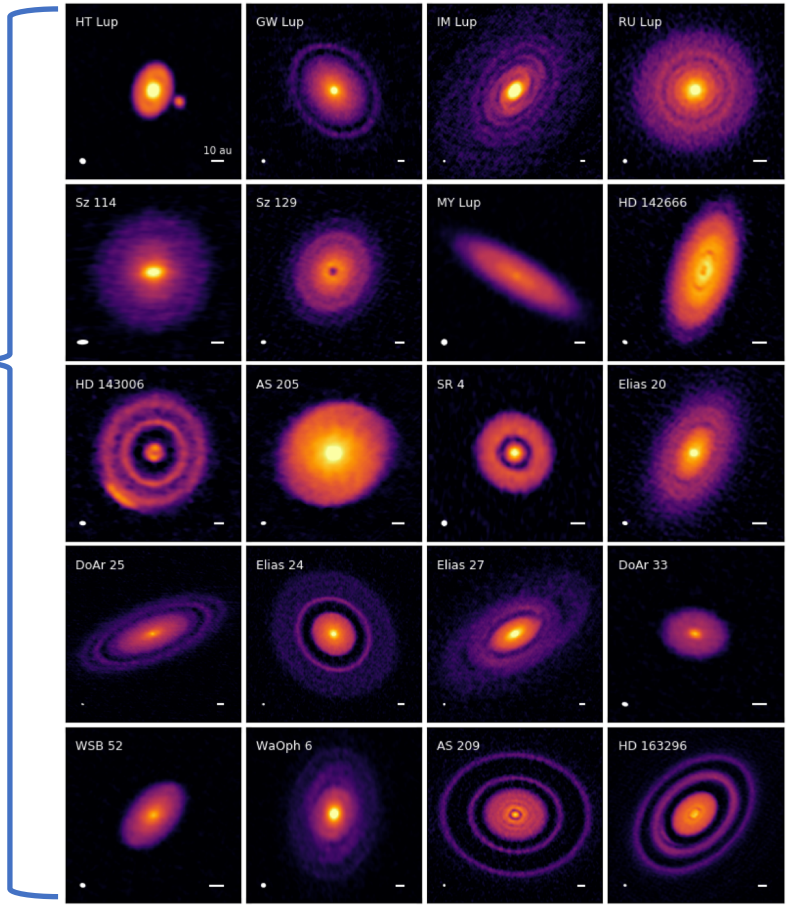


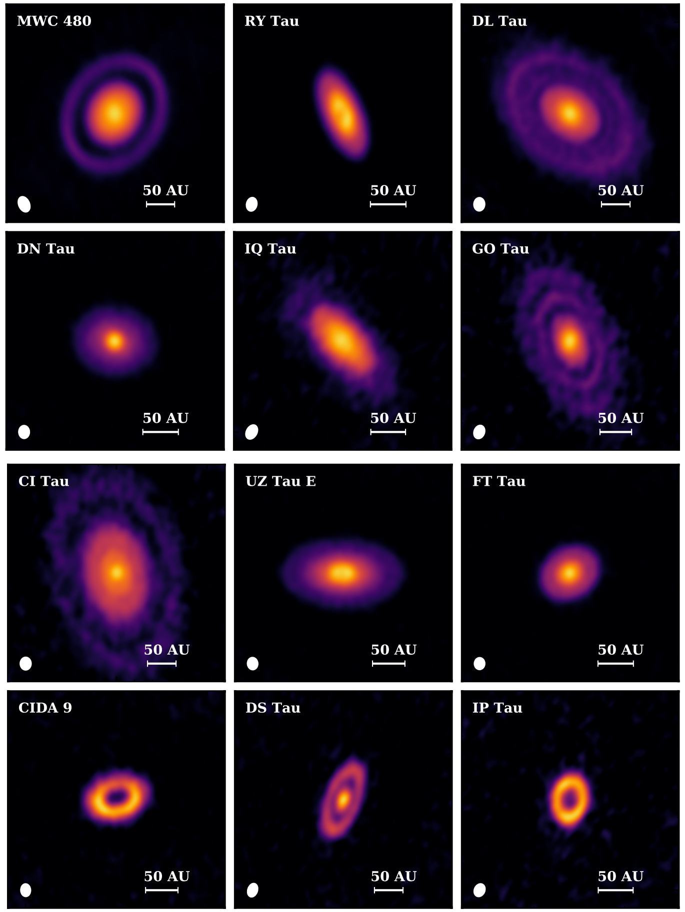
SPHERE (VLT) Observations of protoplanetary disks, Garufi et al. (2017)

Observing the Evolution of Solids in Protoplanetary Disks

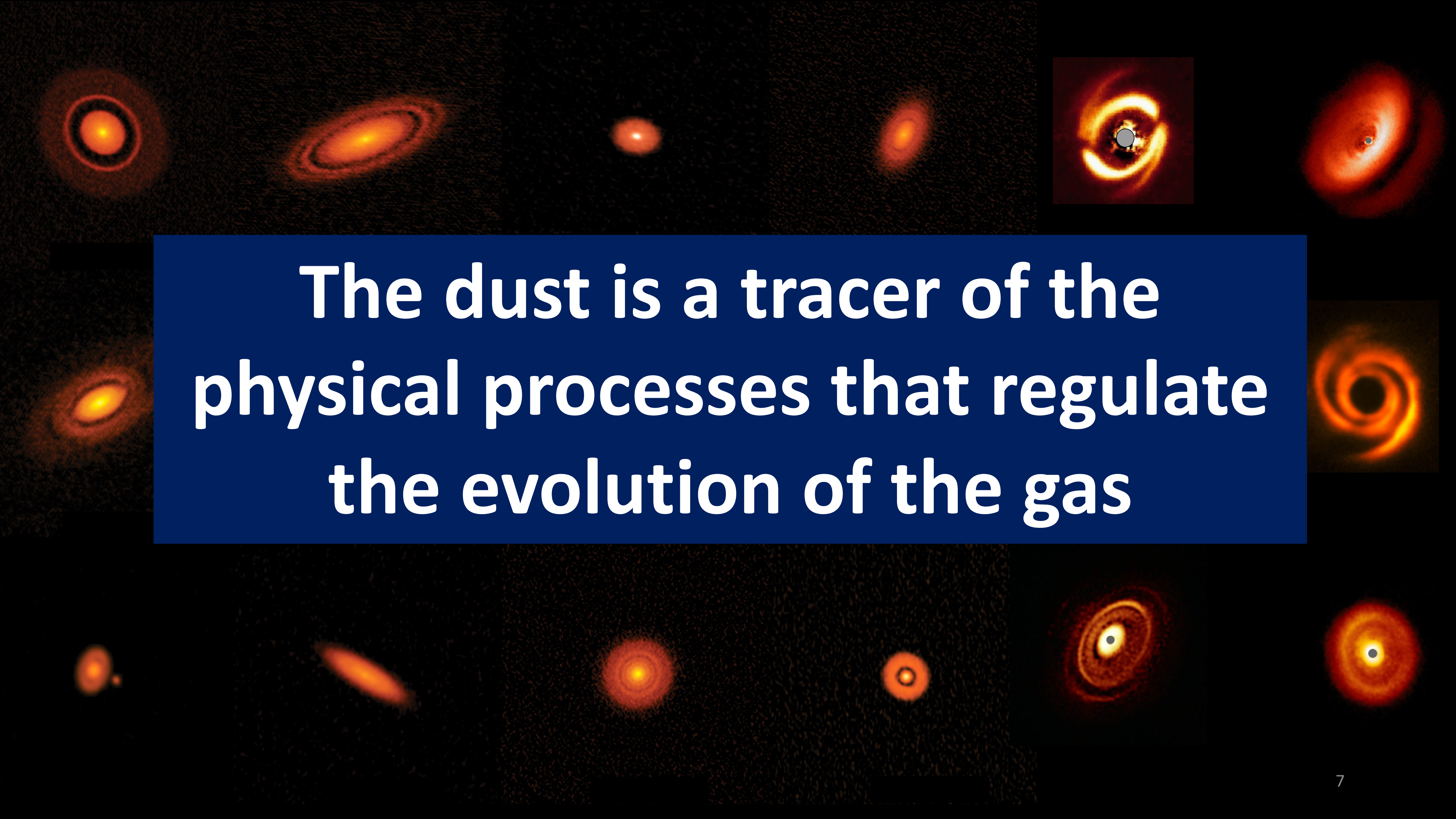
(sub-) millimeter thermal emission → Pebbles in the disk midplane



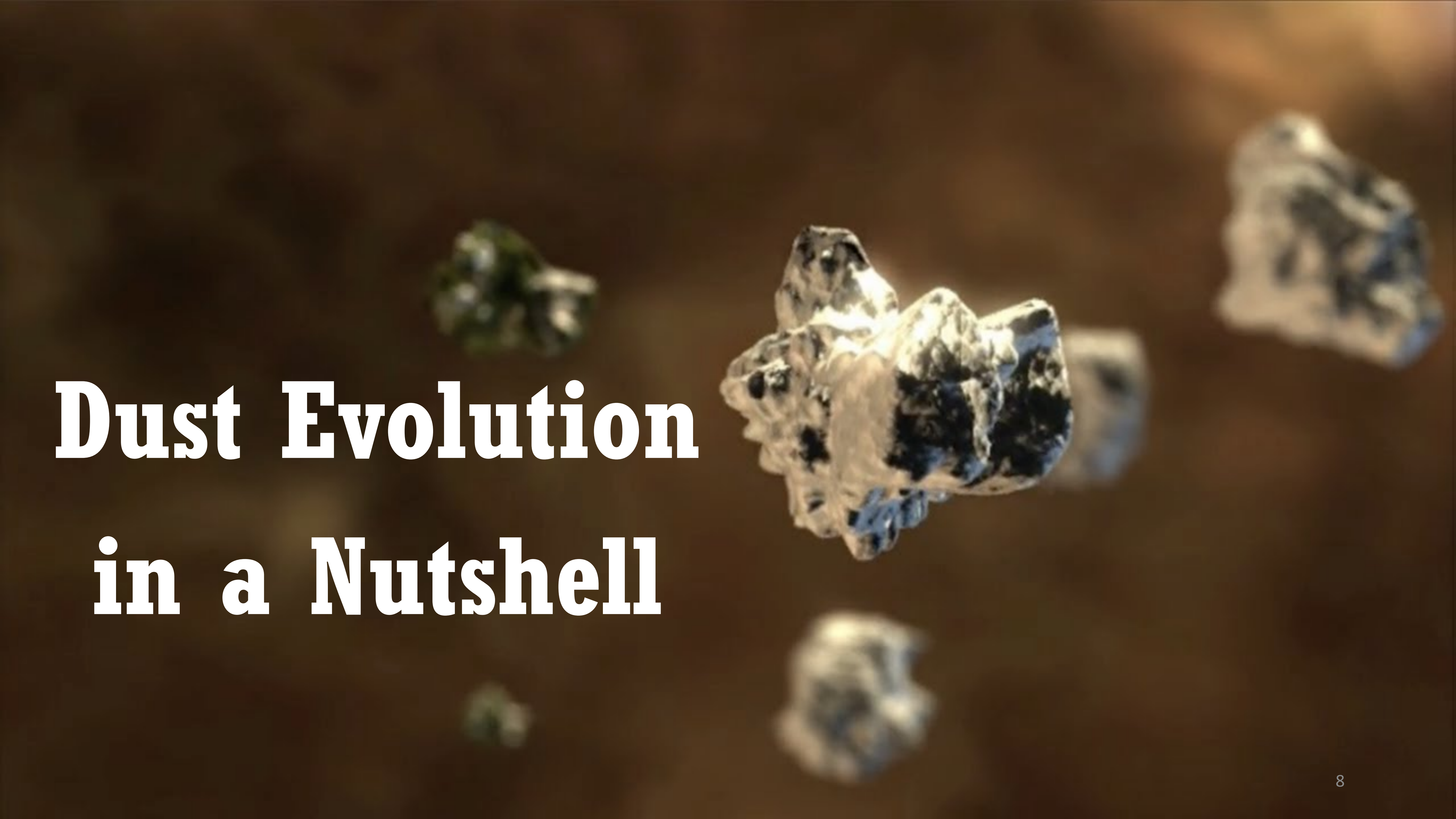




ALMA Observations of protoplanetary disks, Andrews et al. (2018); Long, Pinilla et al. (2018)



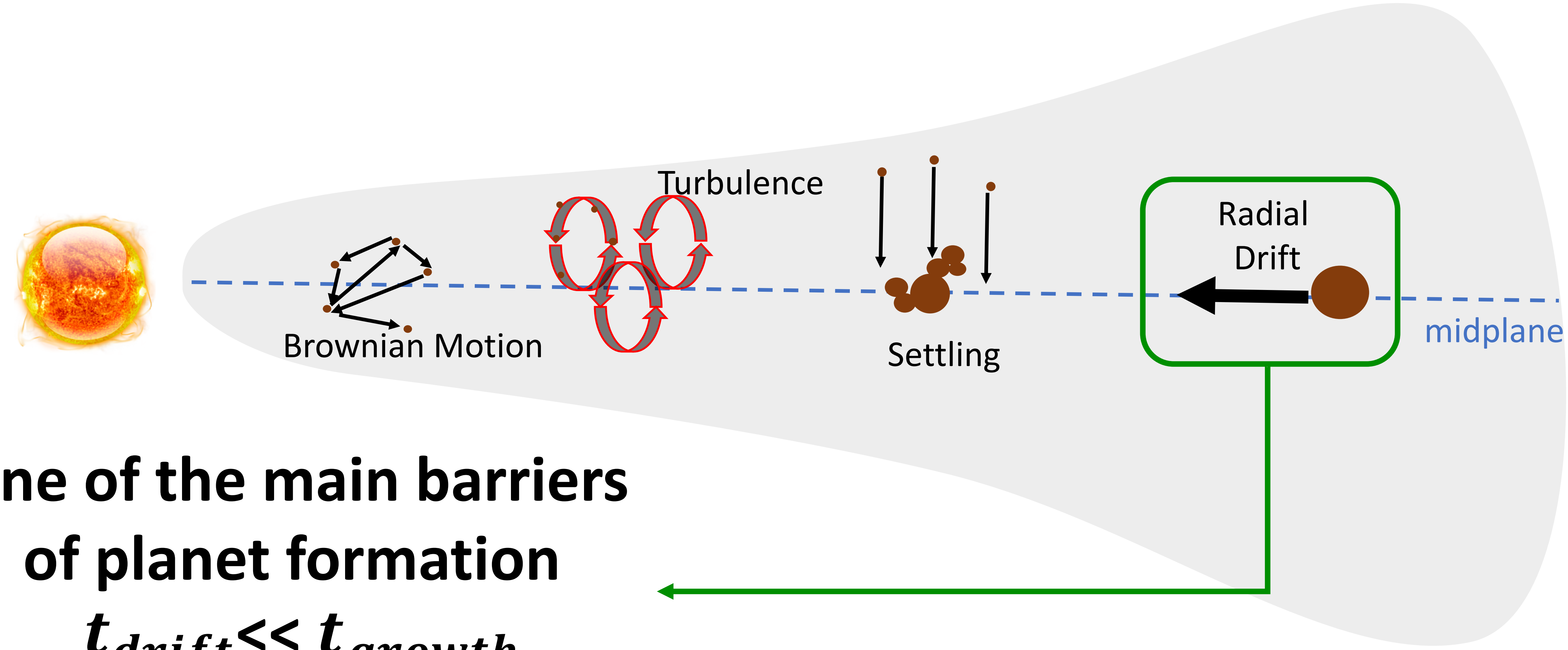
The dust is a tracer of the physical processes that regulate the evolution of the gas



Dust Evolution in a Nutshell

Dust Evolution

Transport ⟷ **Collisions**



One of the main barriers of planet formation

$$t_{drift} << t_{growth}$$

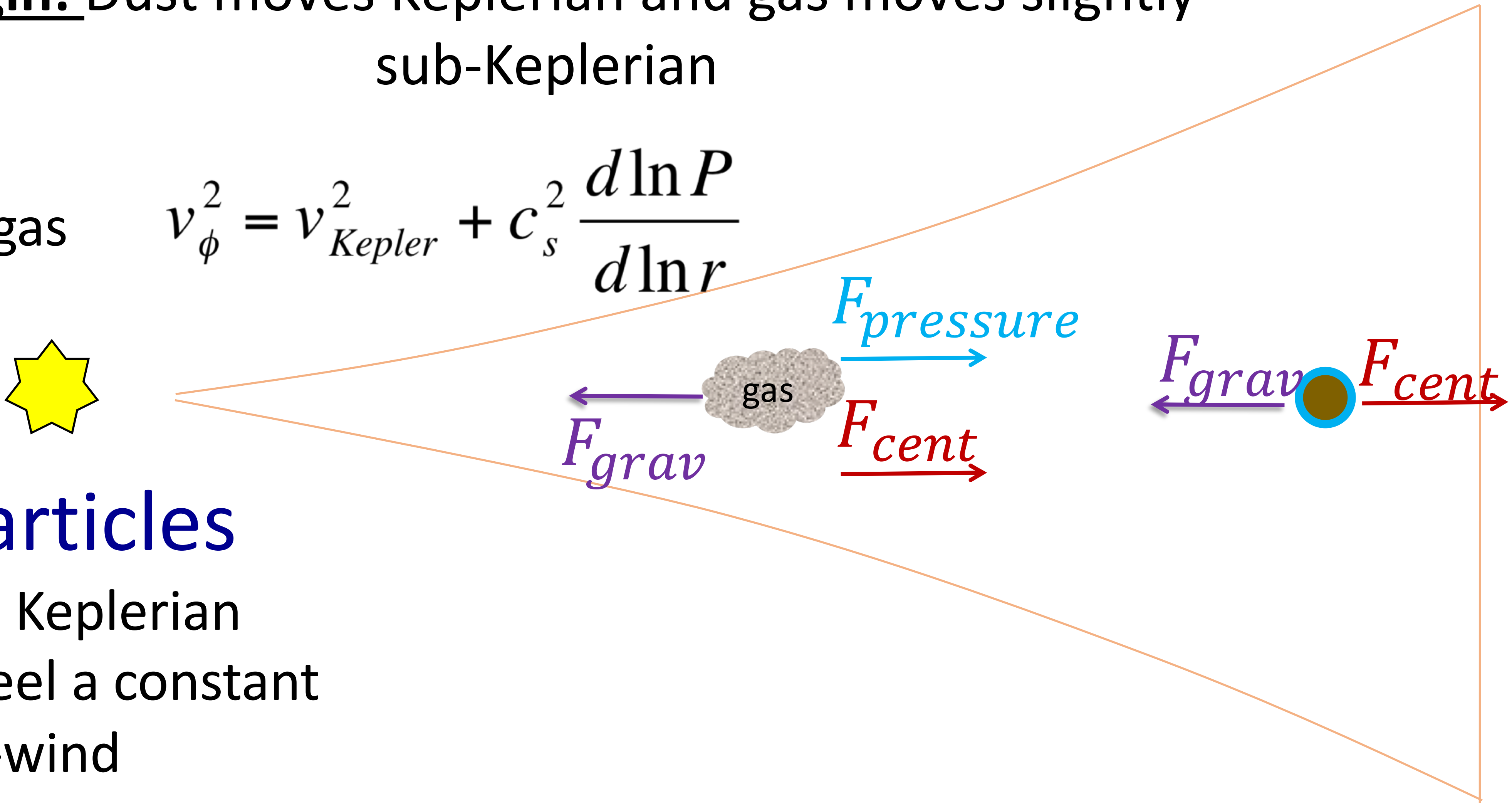
Radial Drift of Particles

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

GAS

Supported by gas pressure

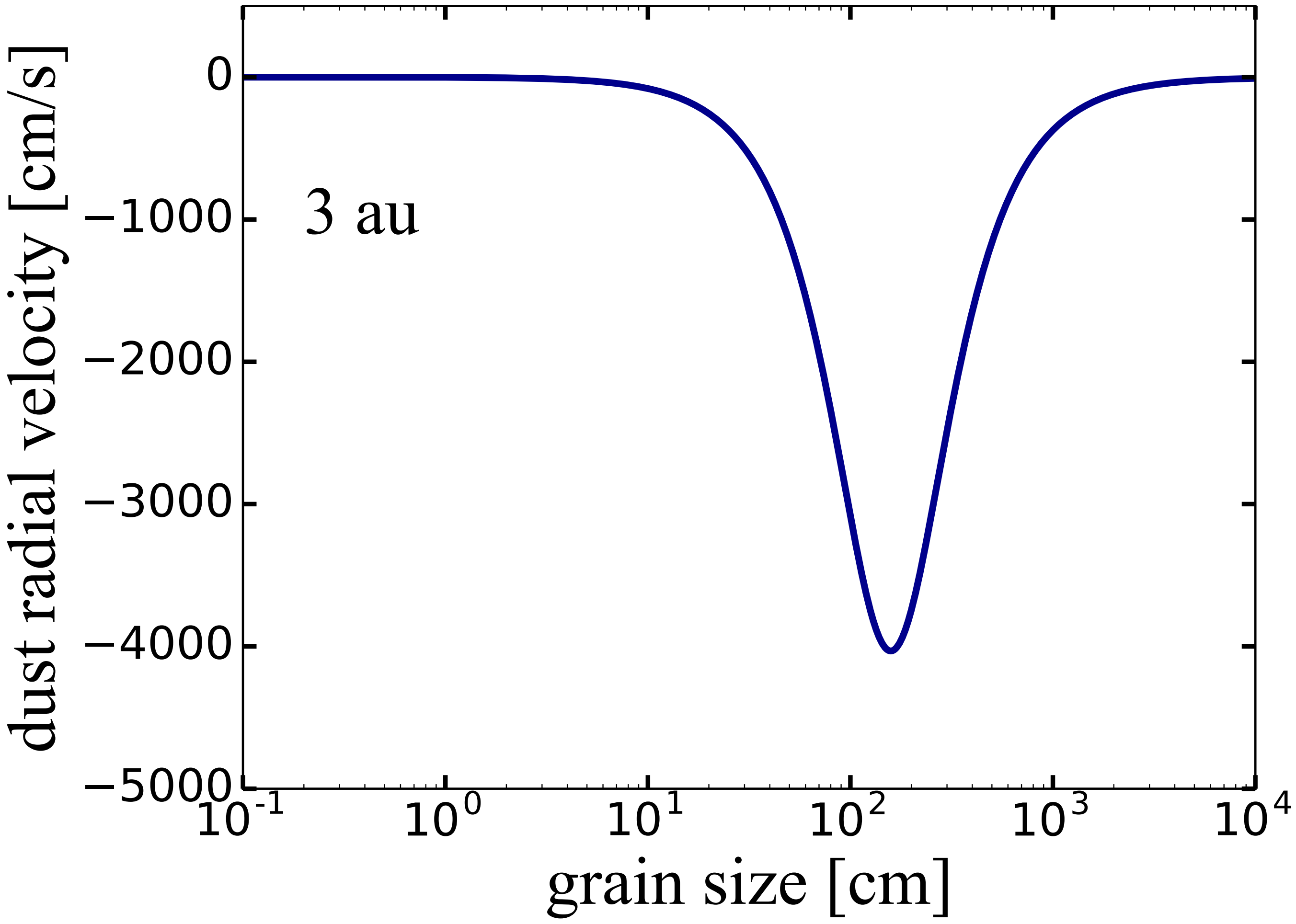
$$v_\phi^2 = v_{Kepler}^2 + c_s^2 \frac{d\ln P}{d\ln r}$$



Dust Particles

Move with Keplerian velocity and feel a constant head-wind

Radial Drift Velocities

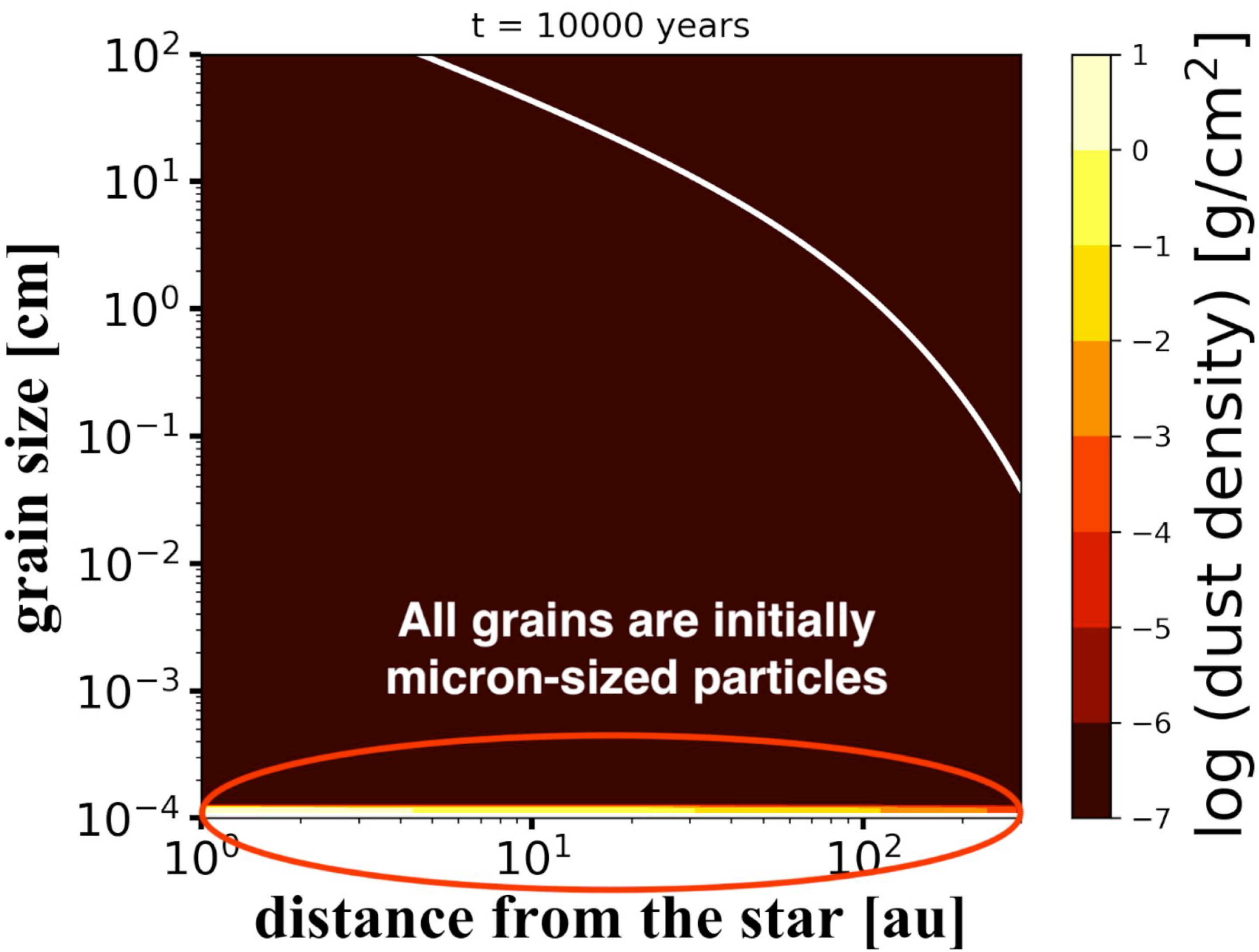


Dust particles acquire inward drift velocities of 4000 cm/s once they reach sufficient sizes.

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), Pinilla & Youdin (2017)

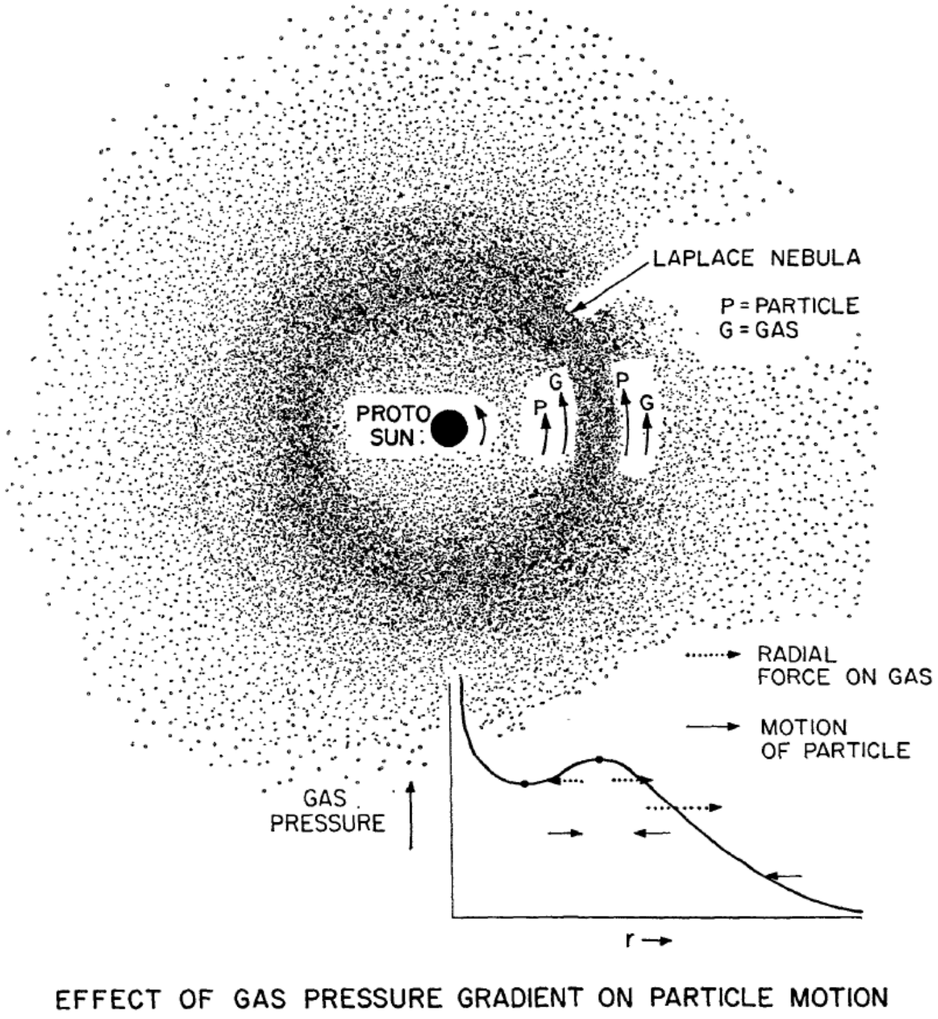
Dust Evolution Models & Radial Drift Barrier



Pinilla et al. (2012a)

Overcoming the Radial Drift Barrier

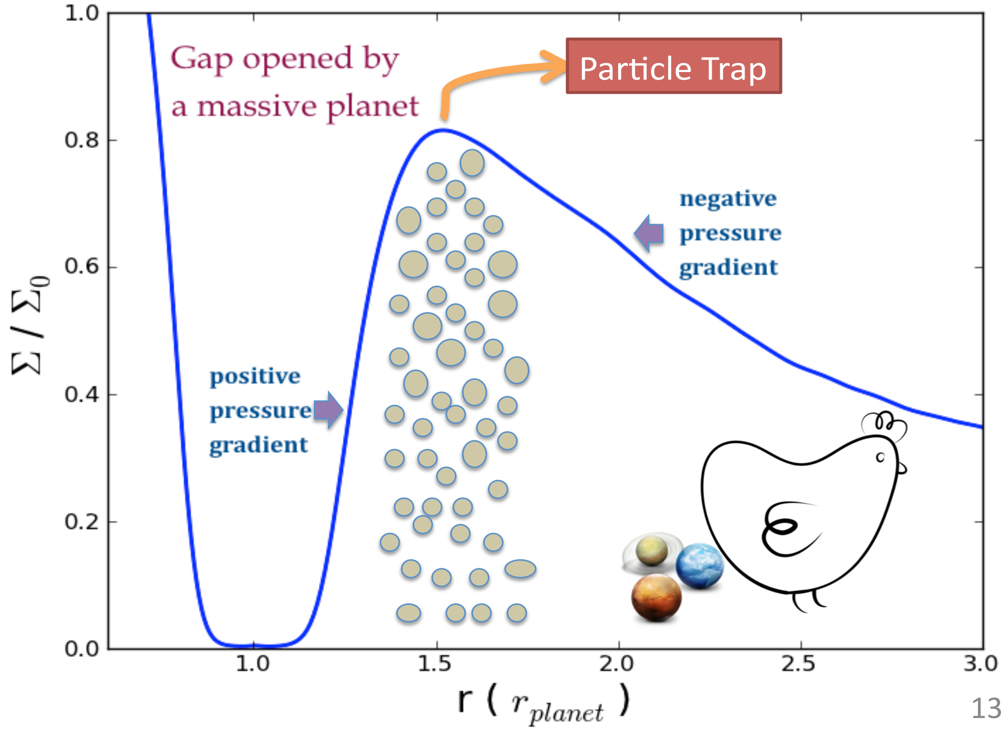
Figure 1 from Whipple (1972)



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

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)



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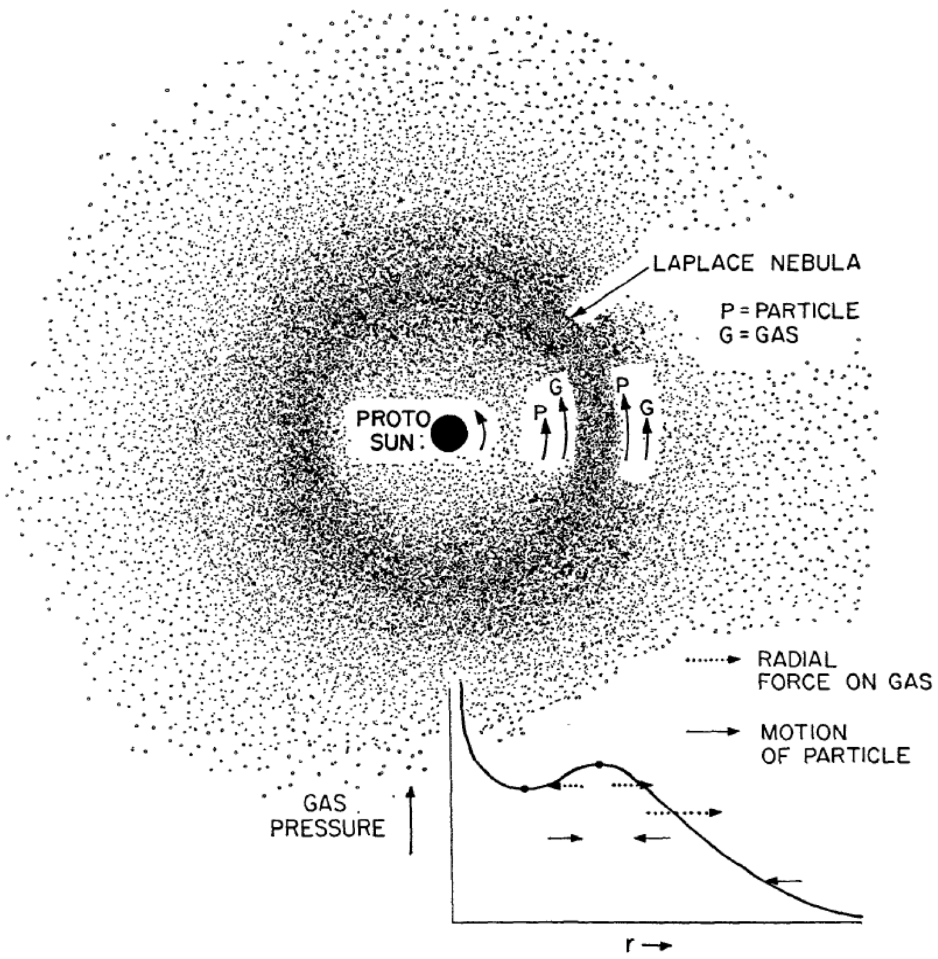


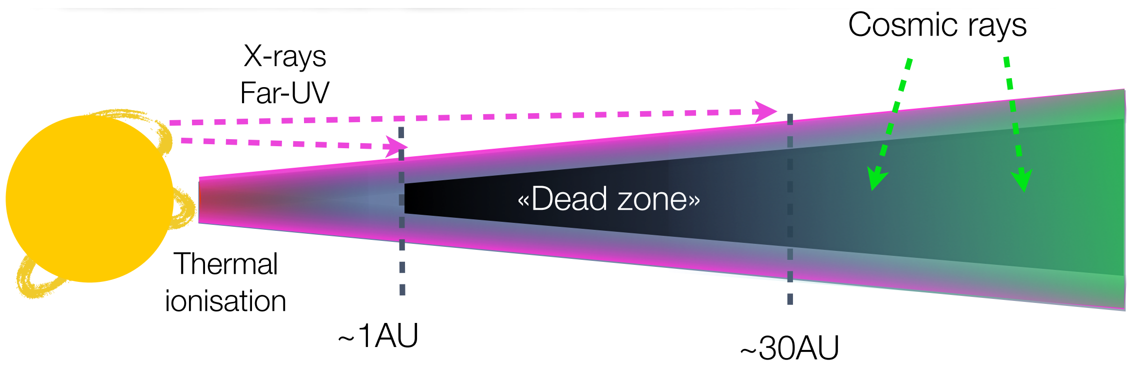
EFFECT OF GAS PRESSURE GRADIENT ON PARTICLE MOTION

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?

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



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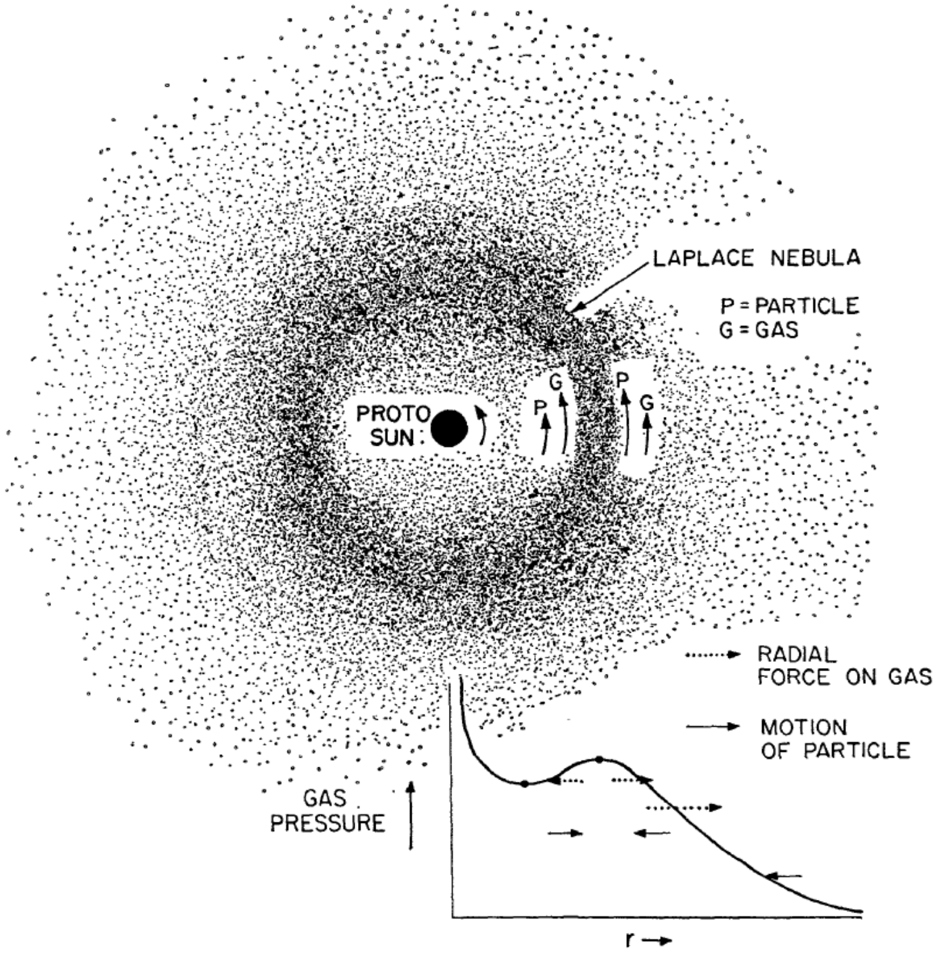
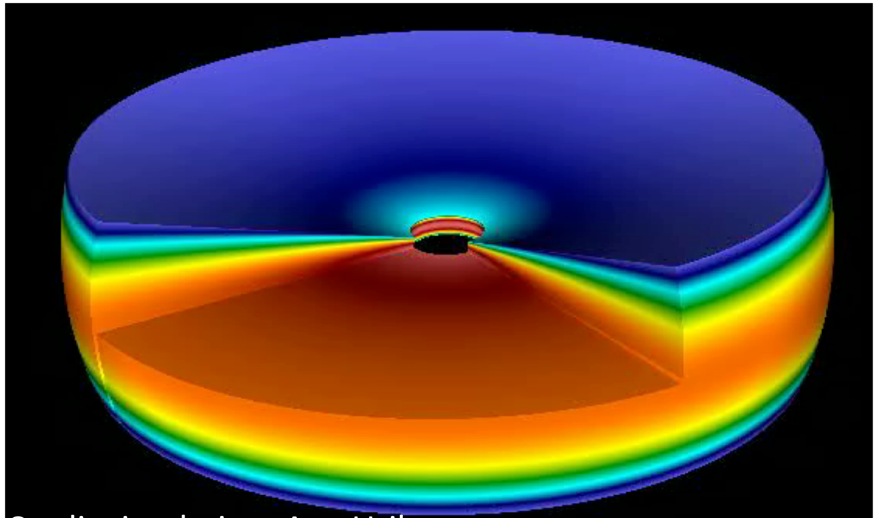


EFFECT OF GAS PRESSURE GRADIENT ON PARTICLE MOTION

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

What is the origin of such structures?

- ✓ 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)



Credit simulation: Ana Uribe

Overcoming the Radial Drift Barrier

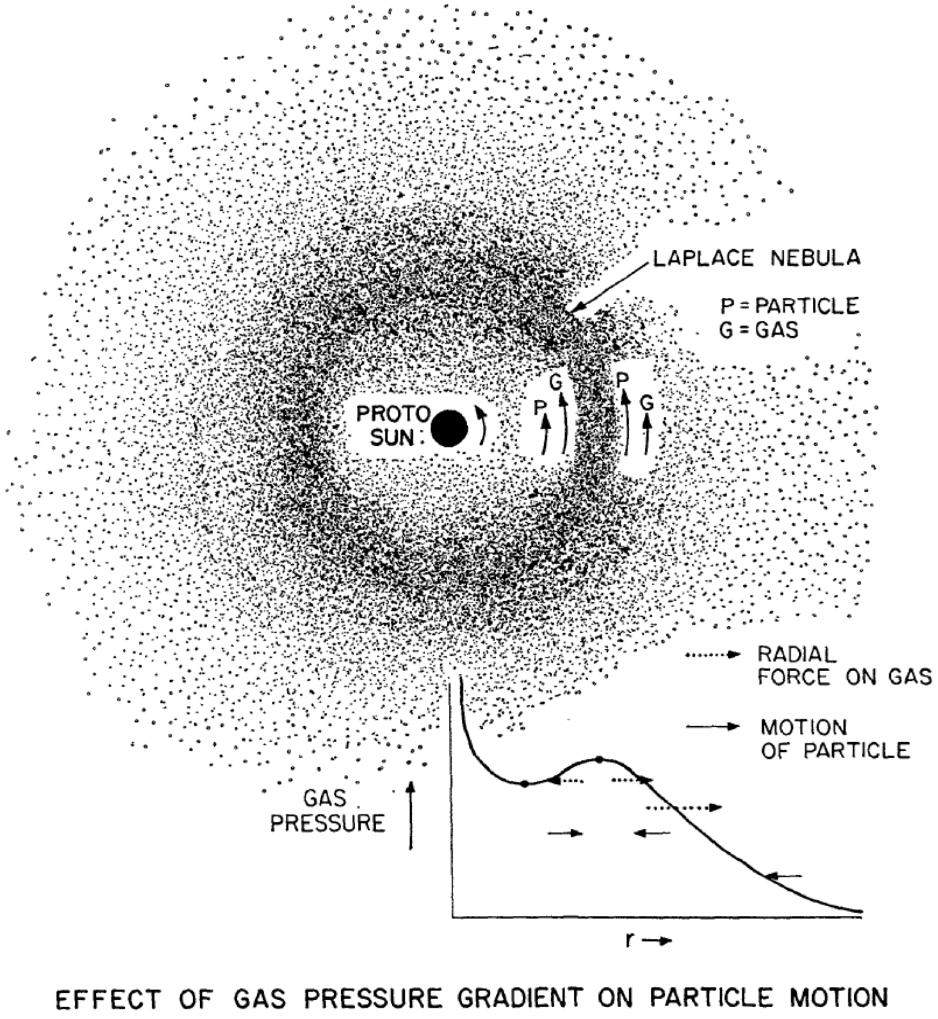
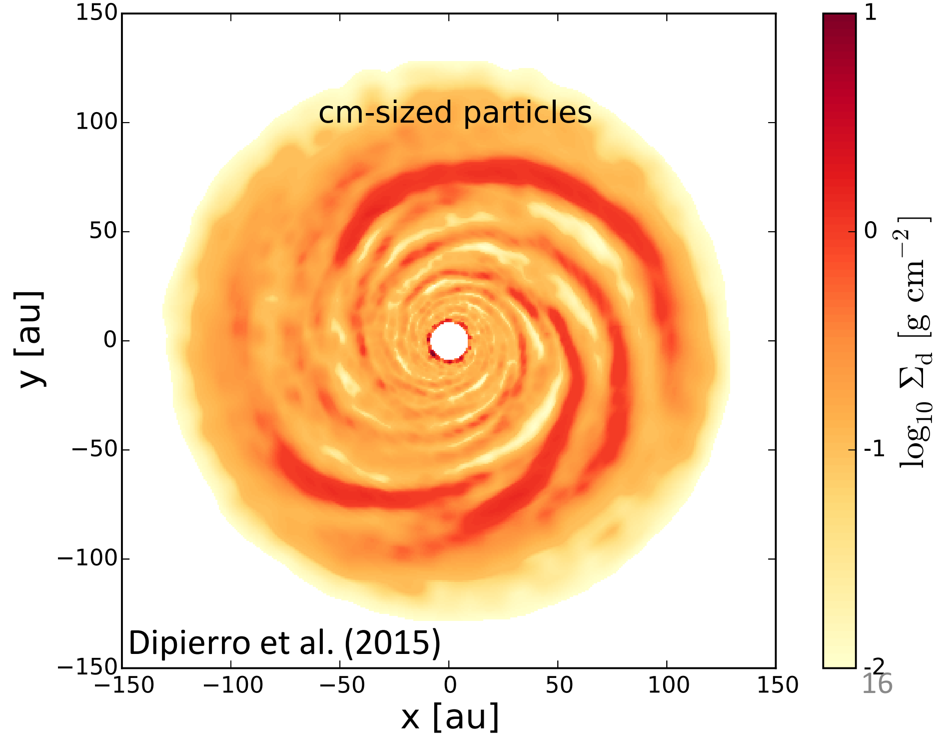


Figure 1 from Whipple (1972)

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

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

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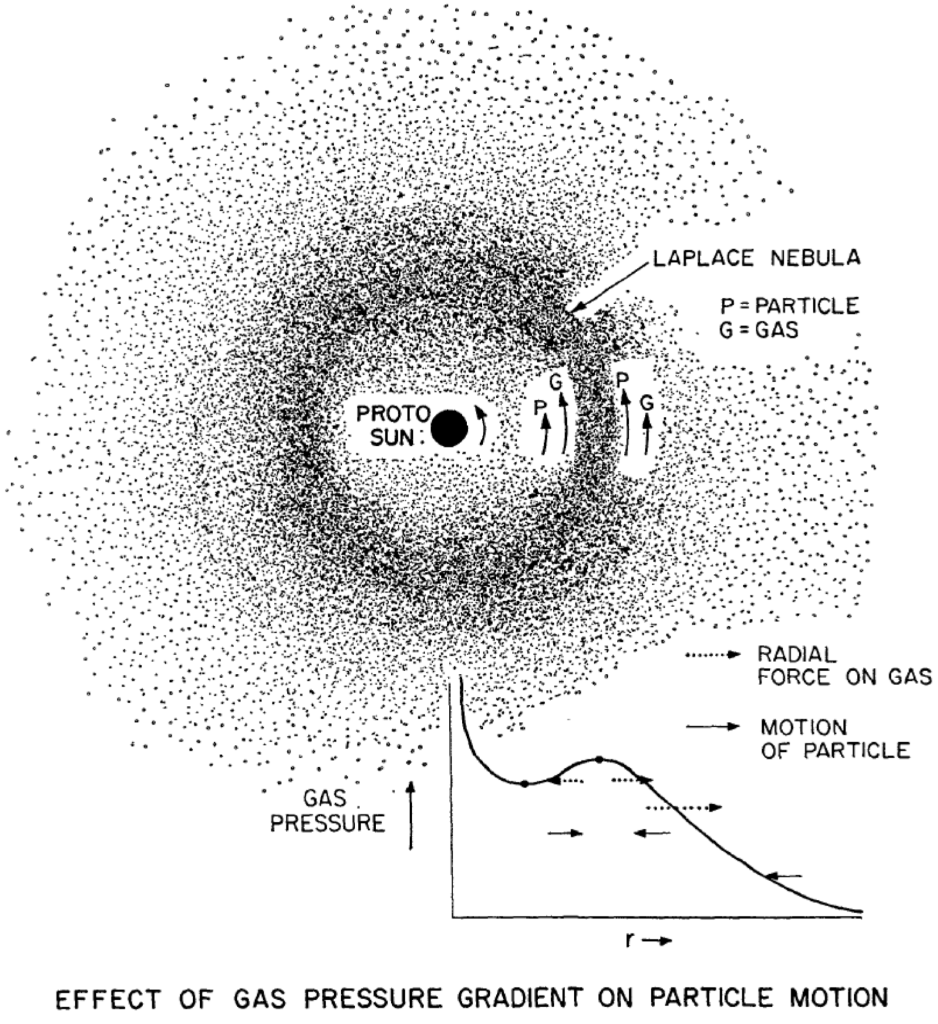
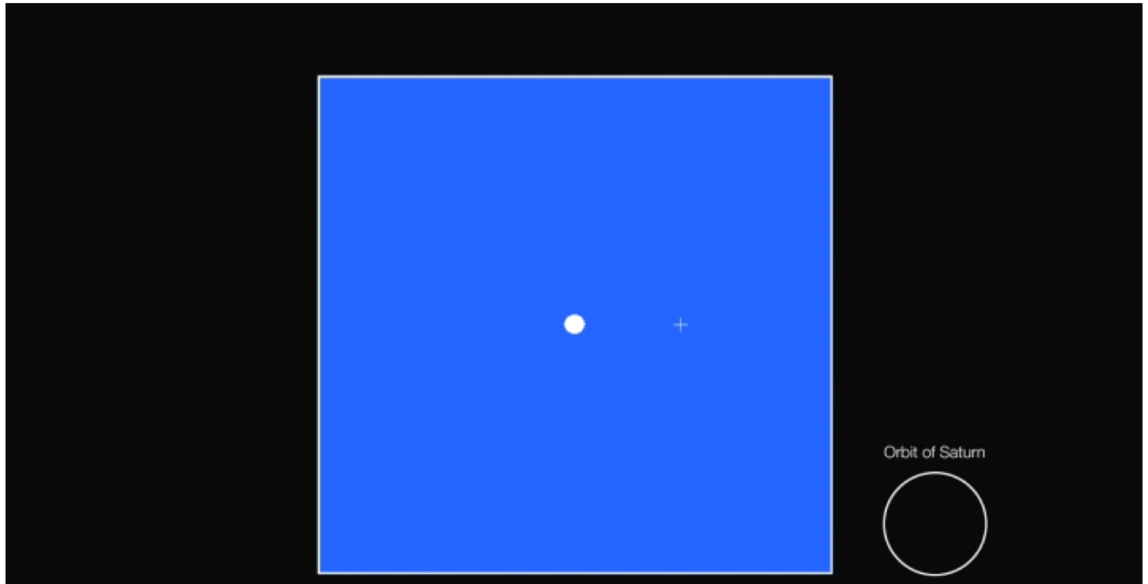


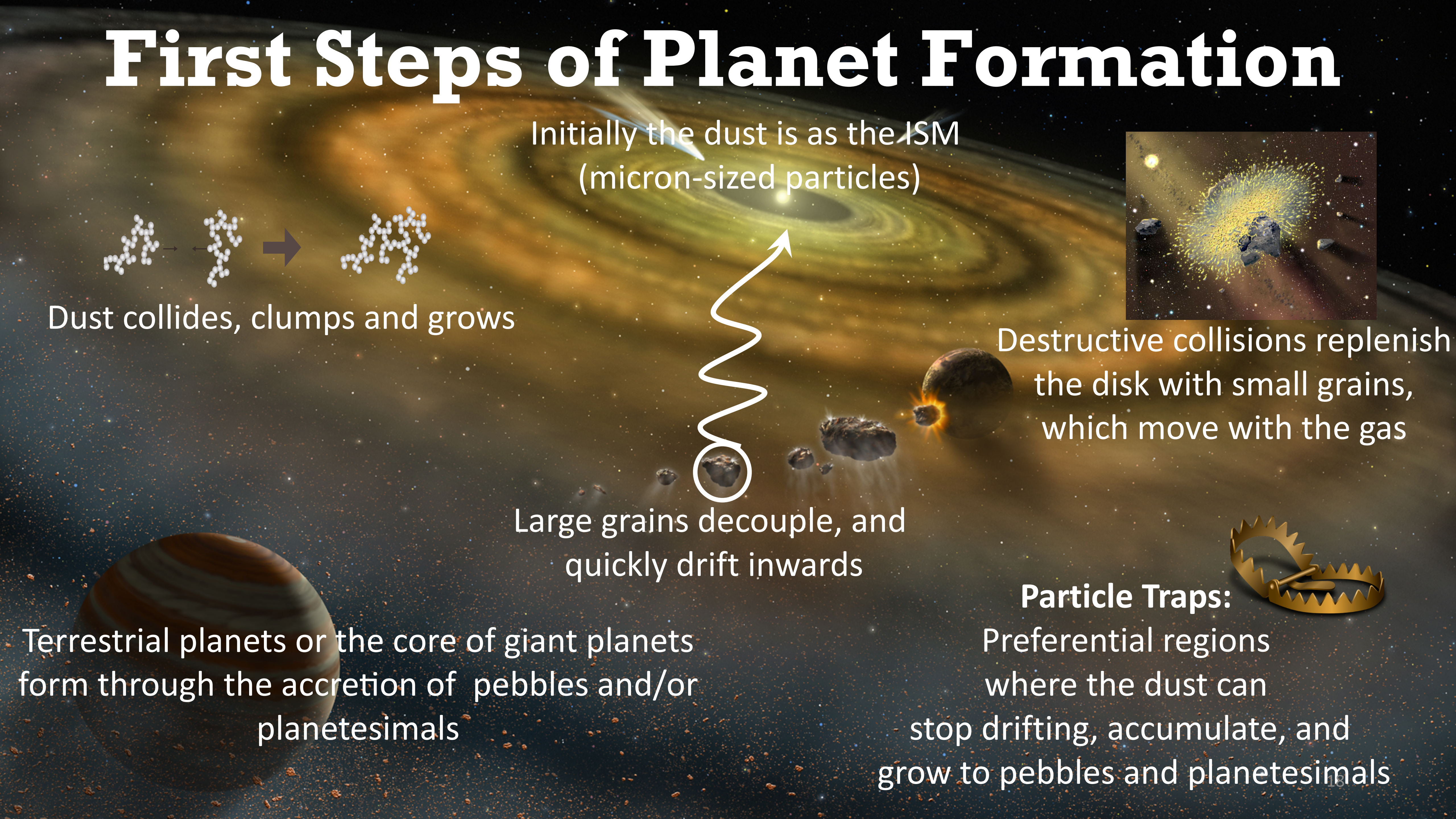
$$v_\phi^2 = v_{Kepler}^2 + c_s^2 \frac{d\ln P}{d\ln r}$$

What is the origin of such structures?

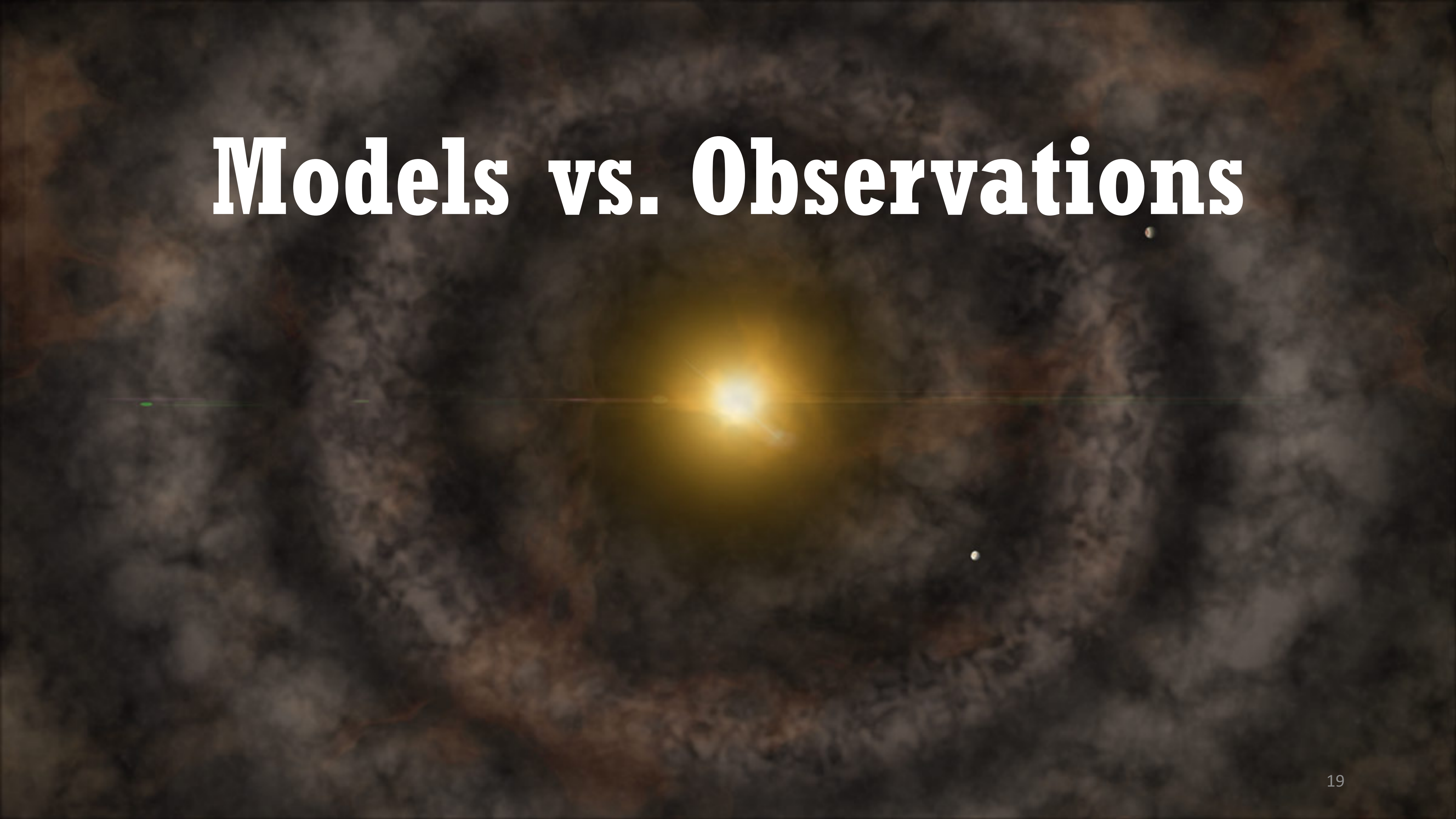
- ✓ Vortices (e.g. De Val-Borro et al. 2007; Lin & Papaloizou 2011, Ataiee, Pinilla, et al., 2013, Hammer, Pinilla, et al., 2019)



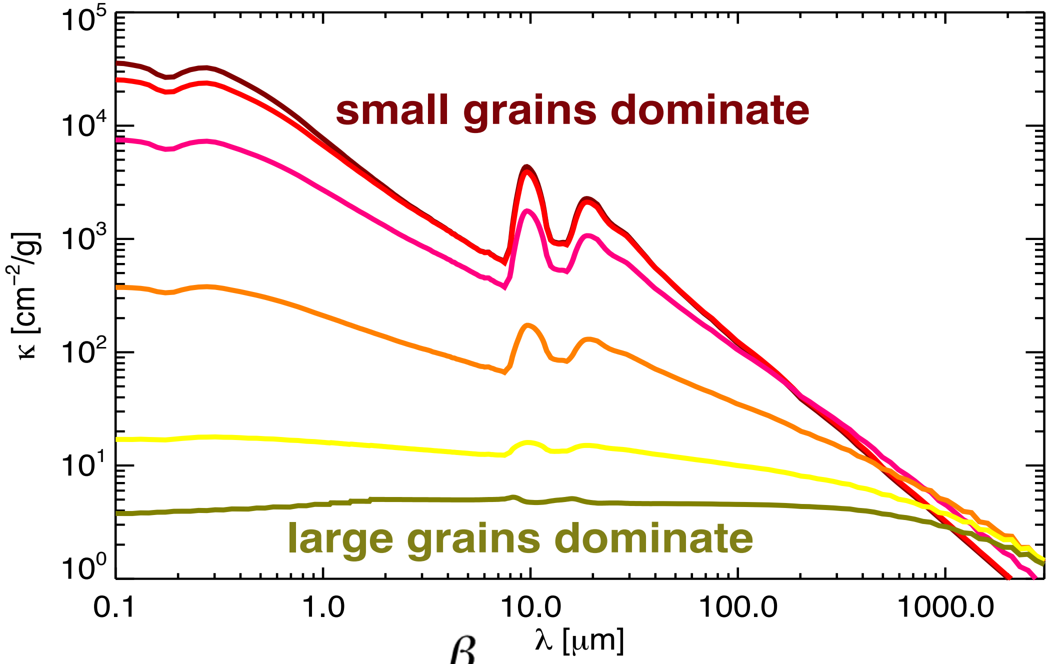
Credit simulation: P. Pinilla (ESO press realease)


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
18

Models vs. Observations



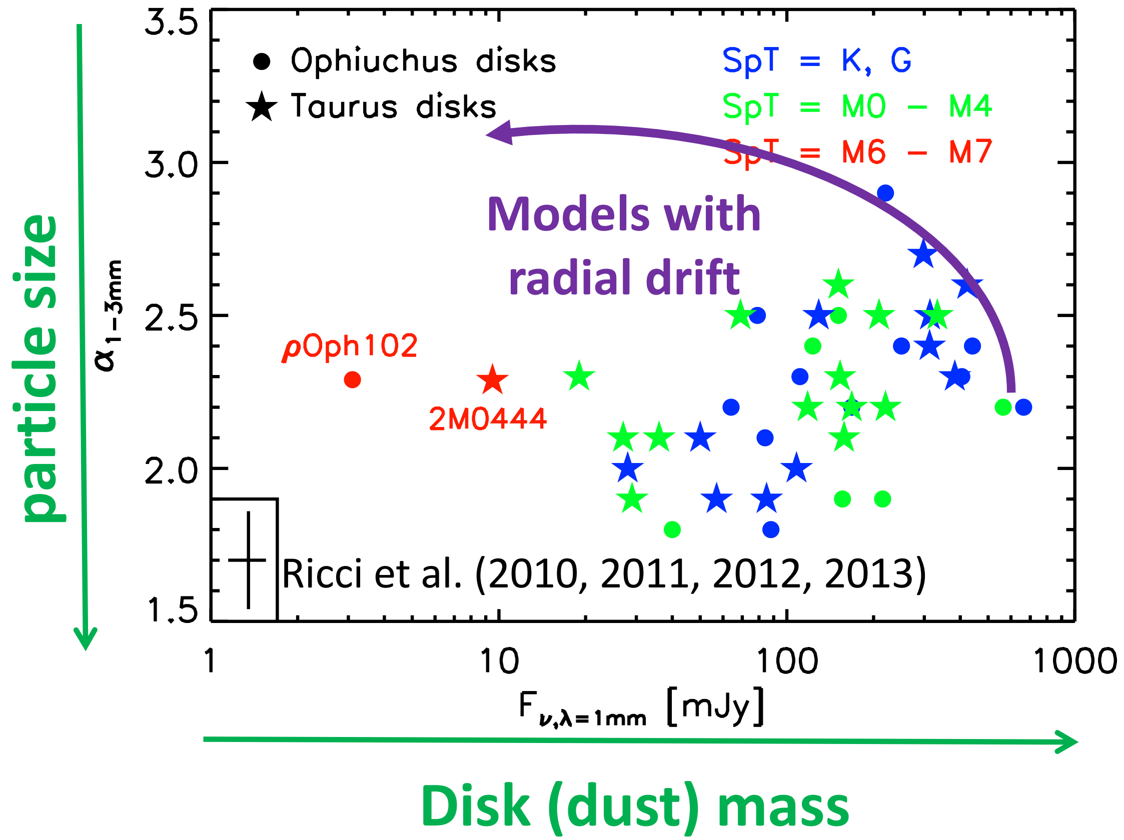
Evidence of mm-grains in PPDs



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

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

If $\beta \leq 1$ ($\alpha_{mm}<3$), 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?

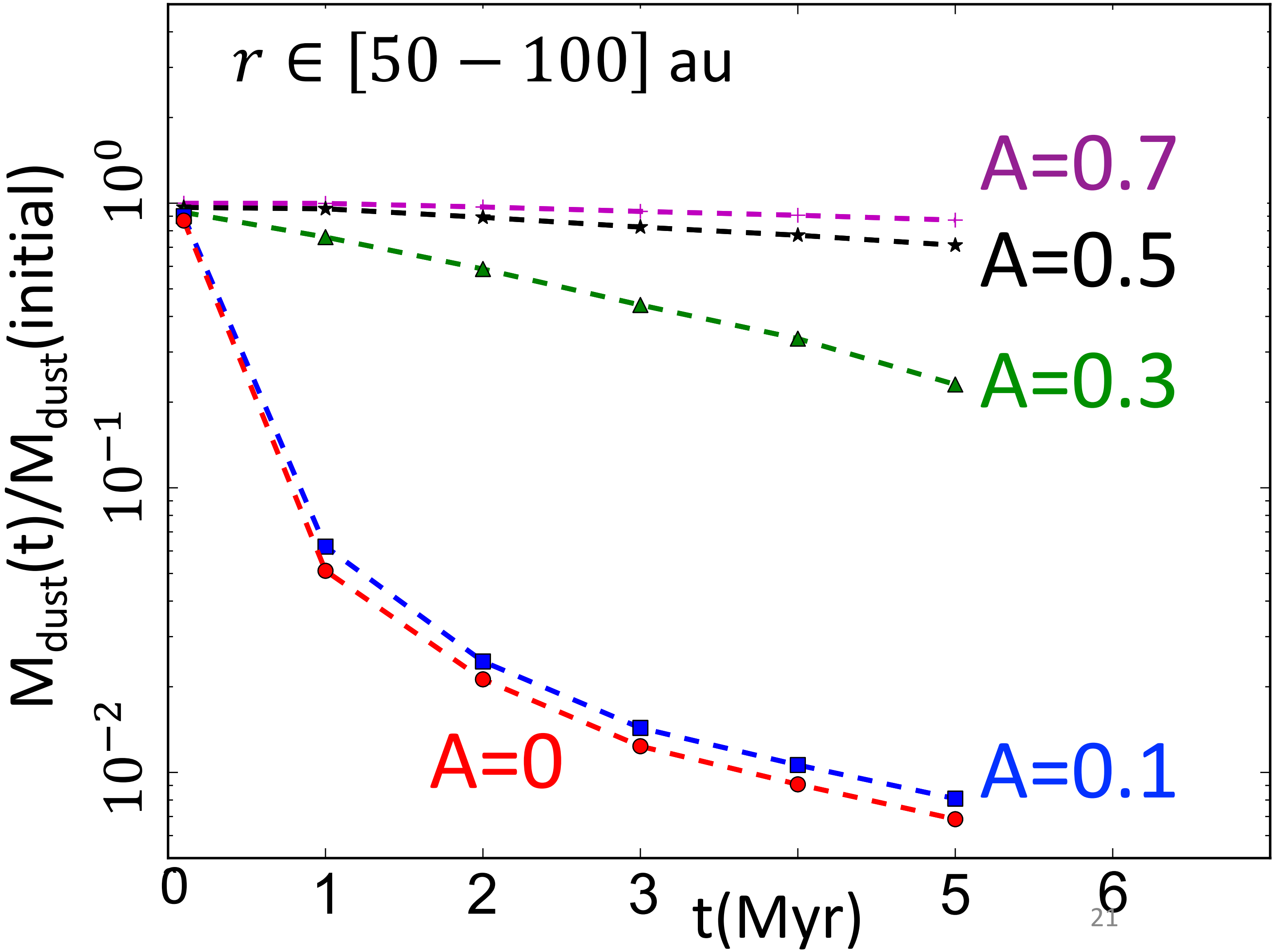
Assumption: a vertically isothermal disk, with gas surface density inhomogeneities

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

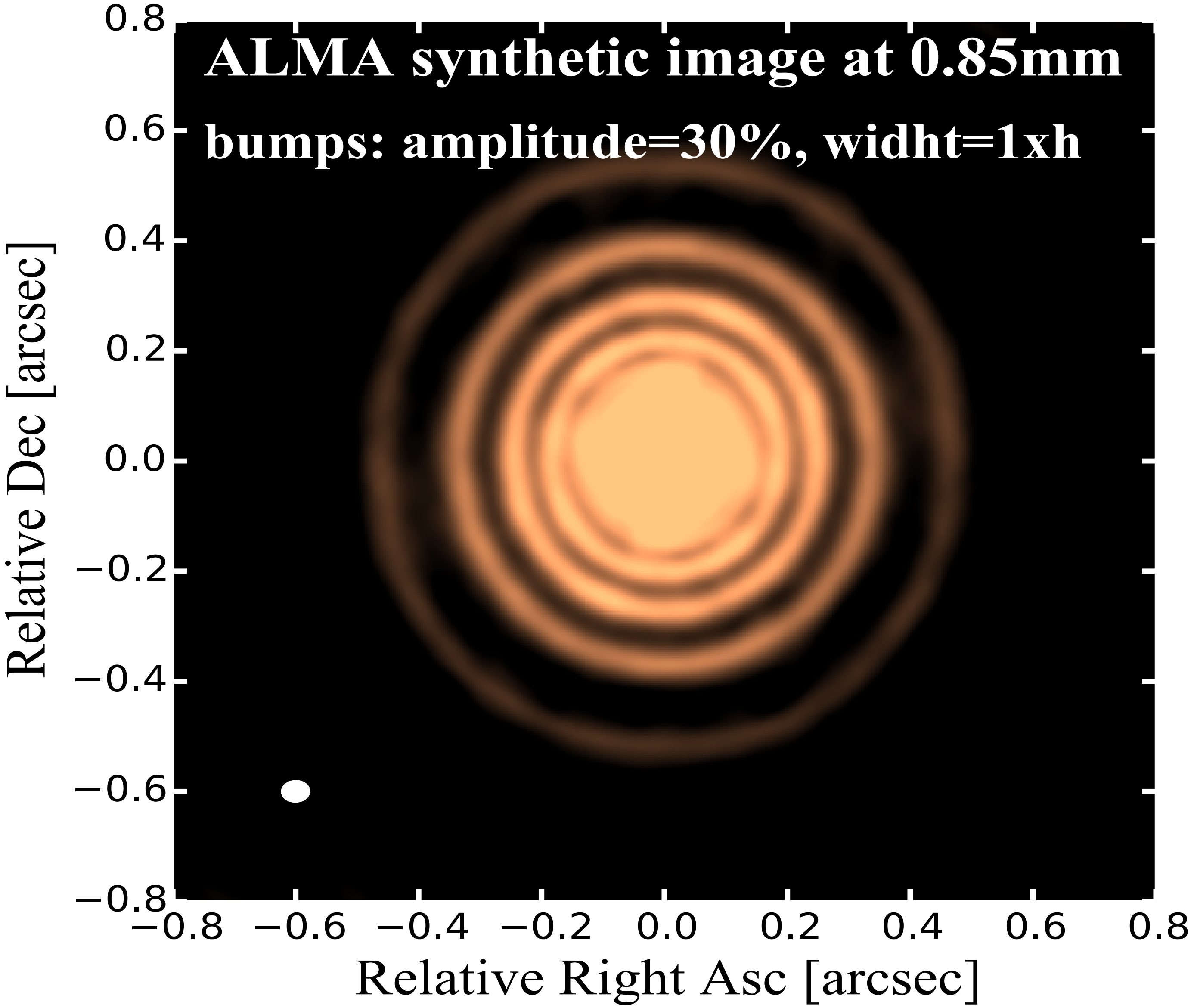
Condition to have $\frac{dP}{dr} > 0$

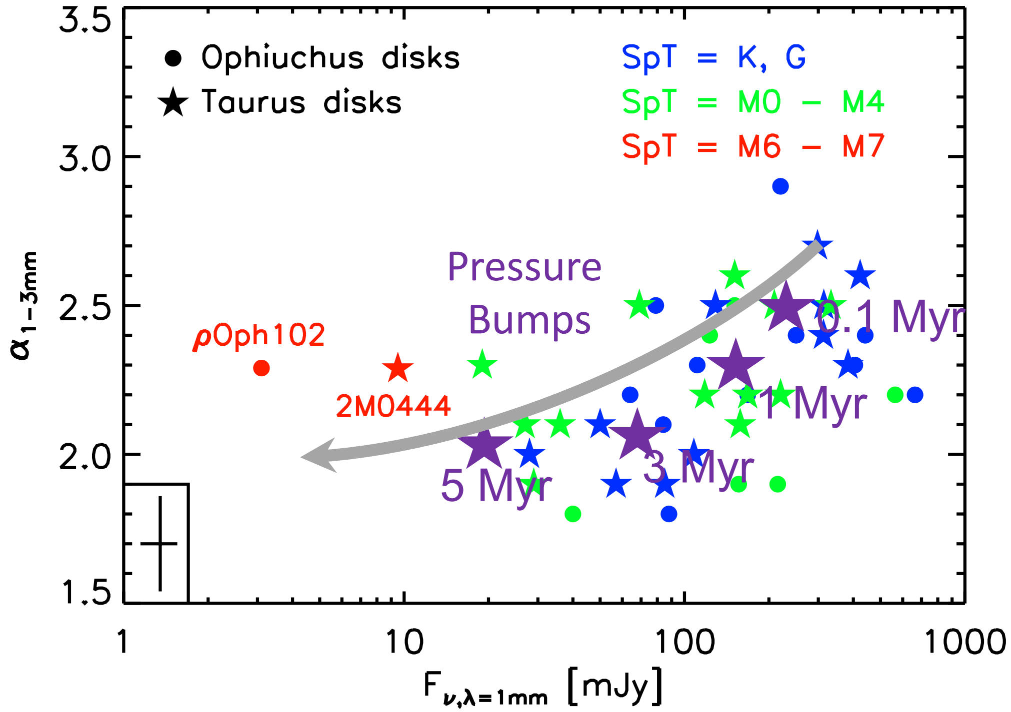
$$\boxed{A_{min} = 0.1}$$

Pinilla et al. (2012a)



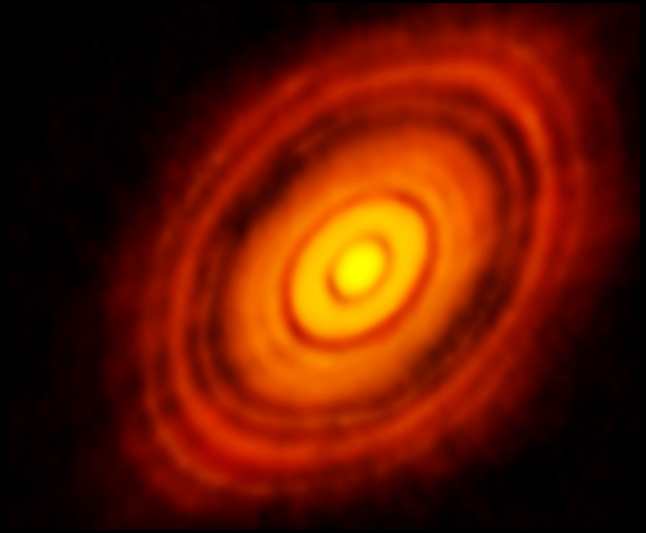
Trapping by Global Pressure Bumps



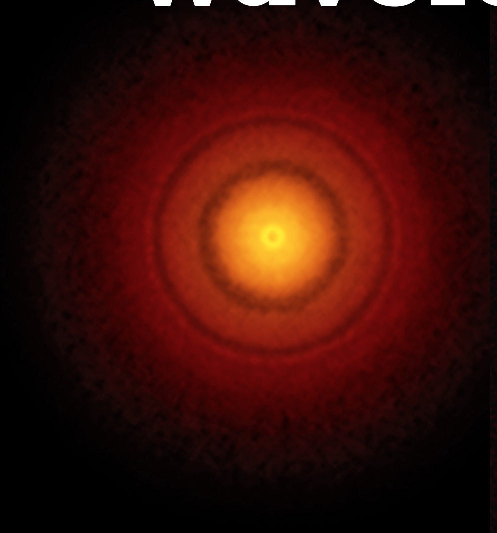


Pressure bumps of 25-30% of amplitude allow to reduce radial drift and keep millimeter particles in the outer regions of disks

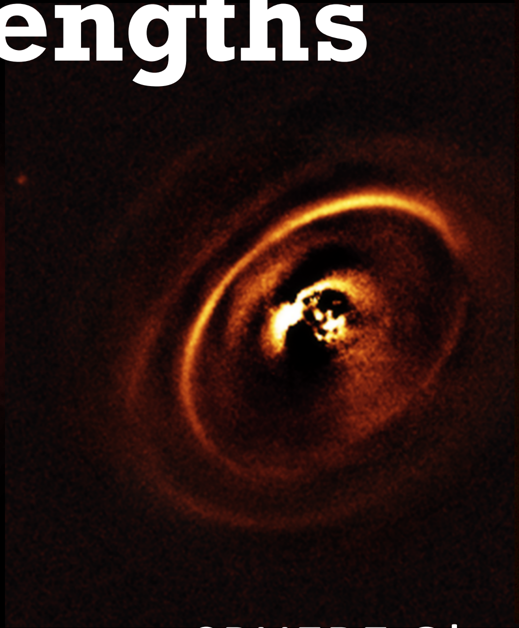
Multiple Rings Observed at Different Wavelengths



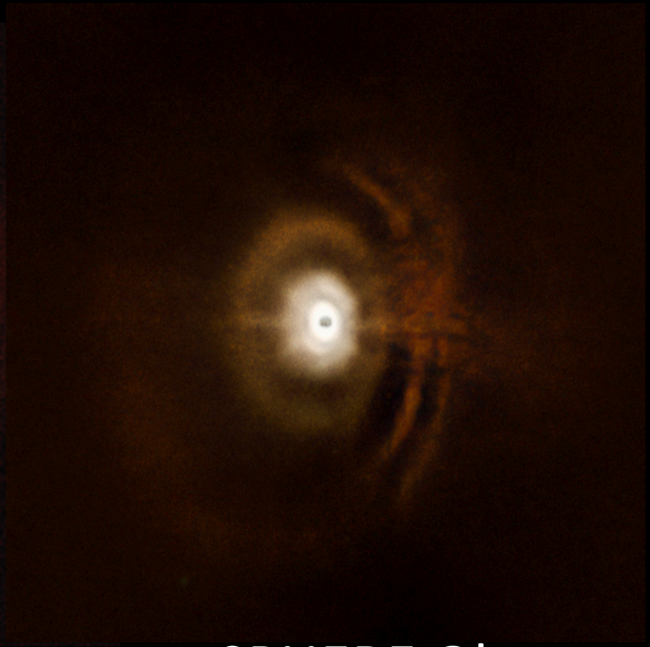
ALMA Obs
HL Tau
ALMA Partnership et al. (2015)



ALMA Obs
TWHya
Andrews et al. (2016)

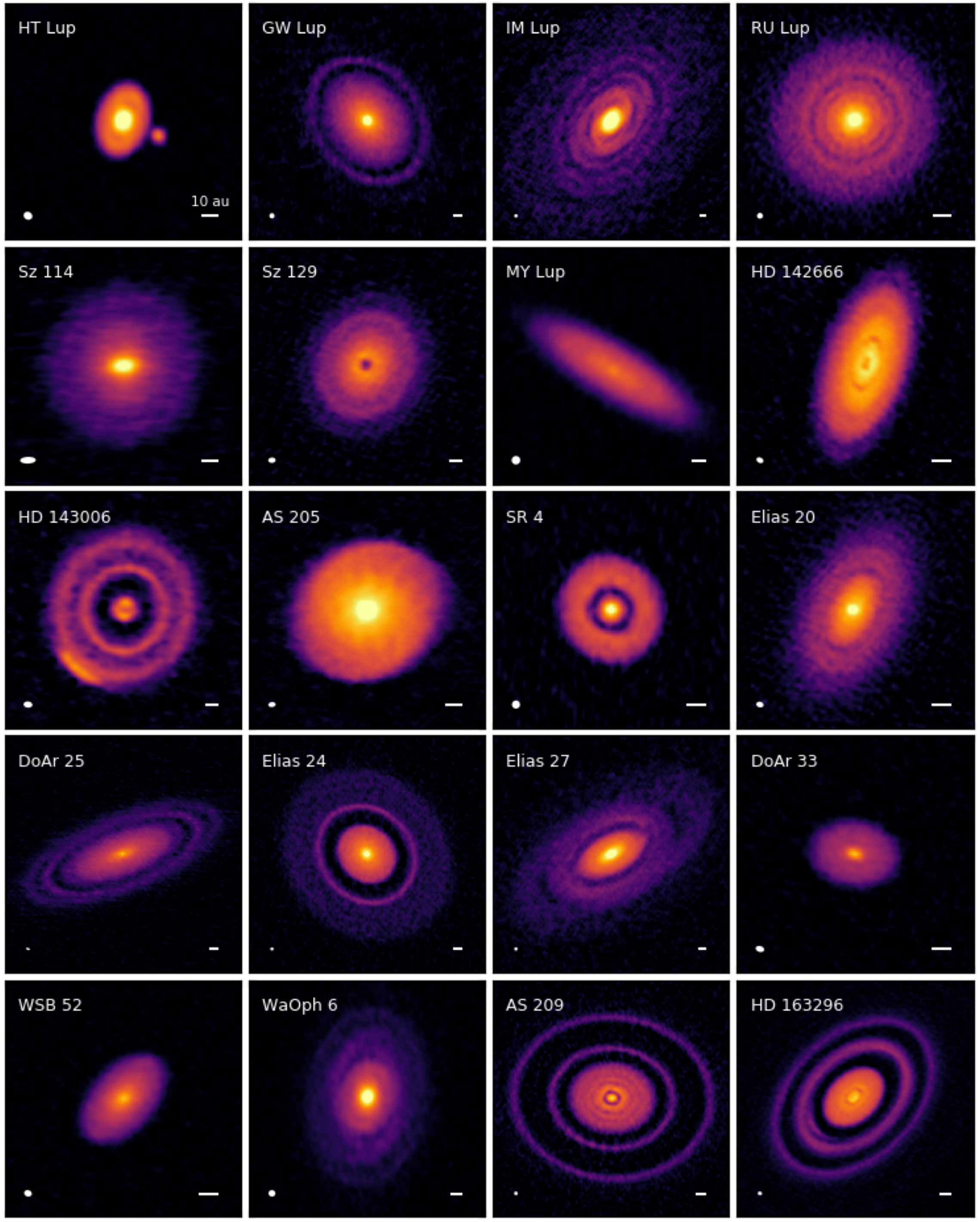


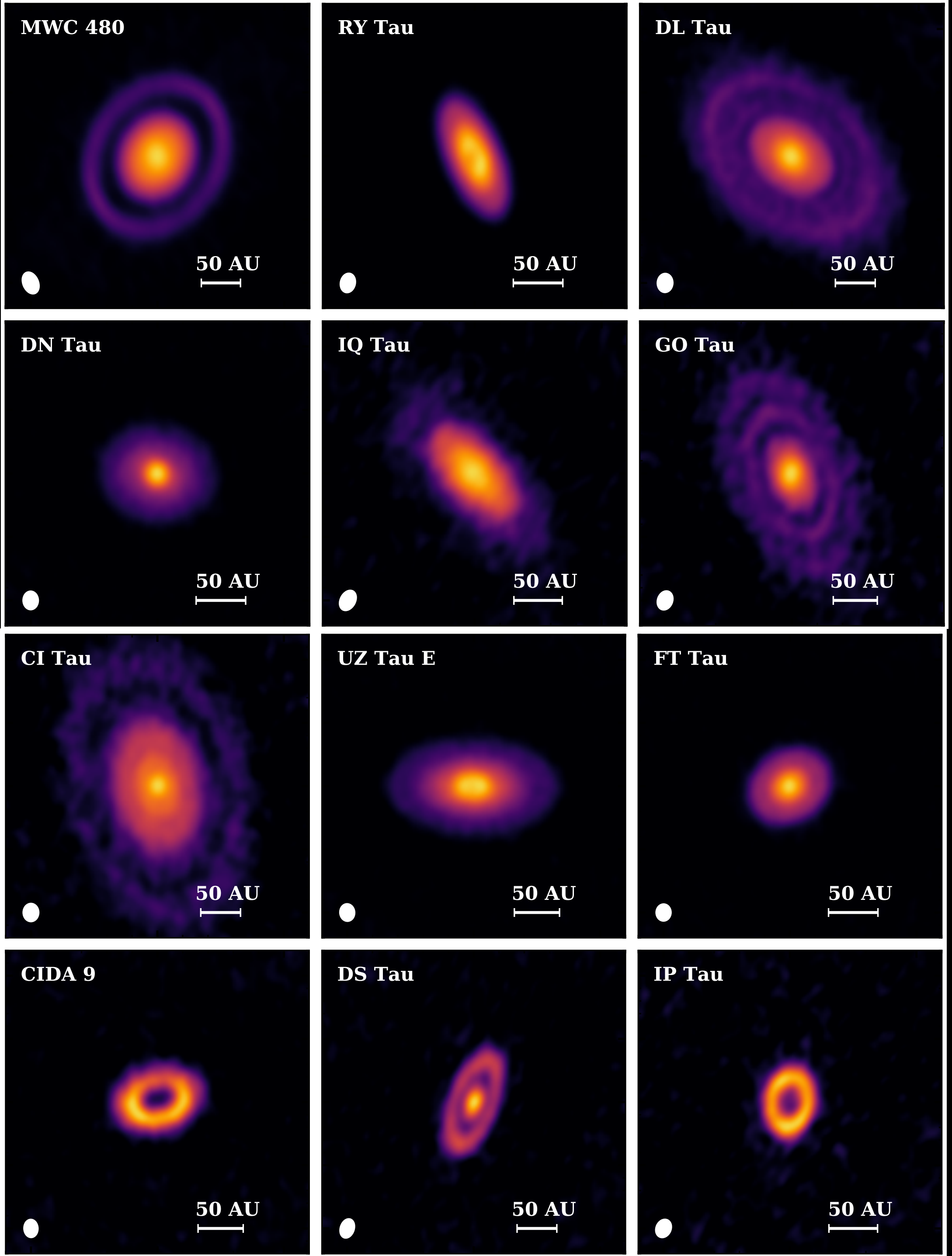
SPHERE Obs
RX J1615
de Boer et al. (2016)



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.



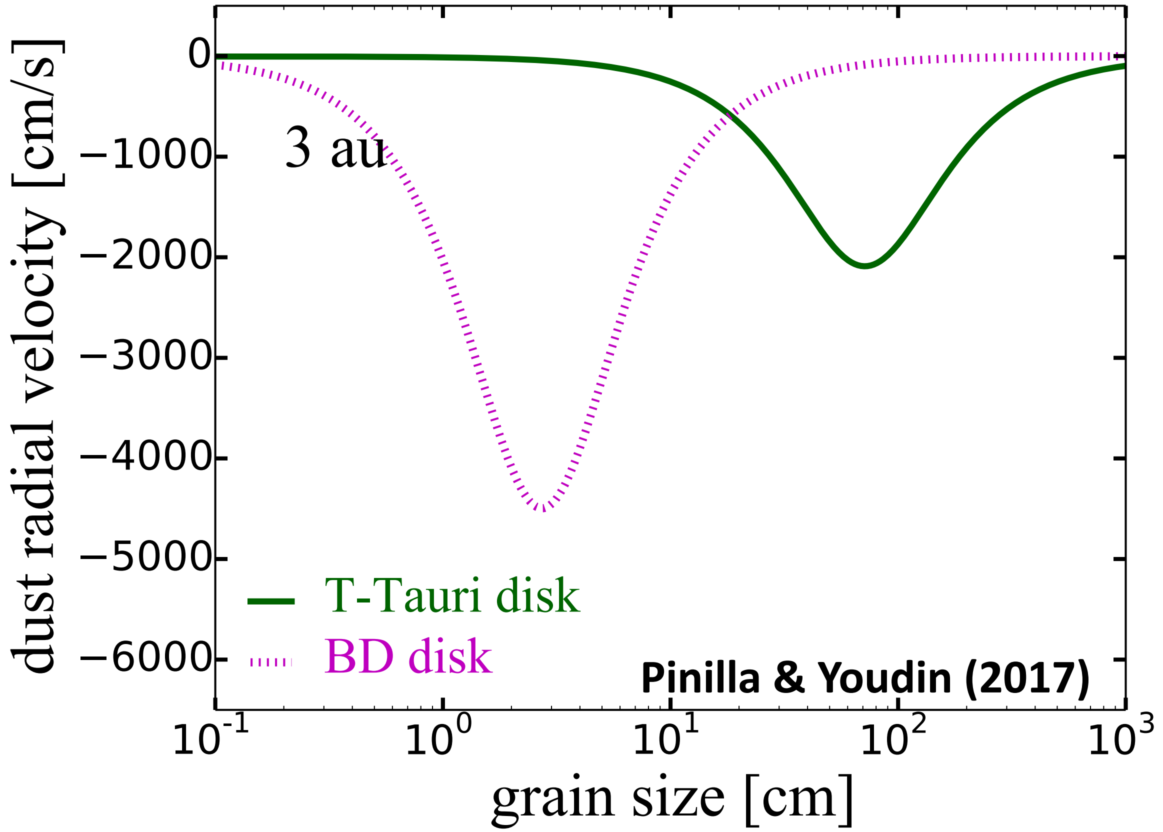


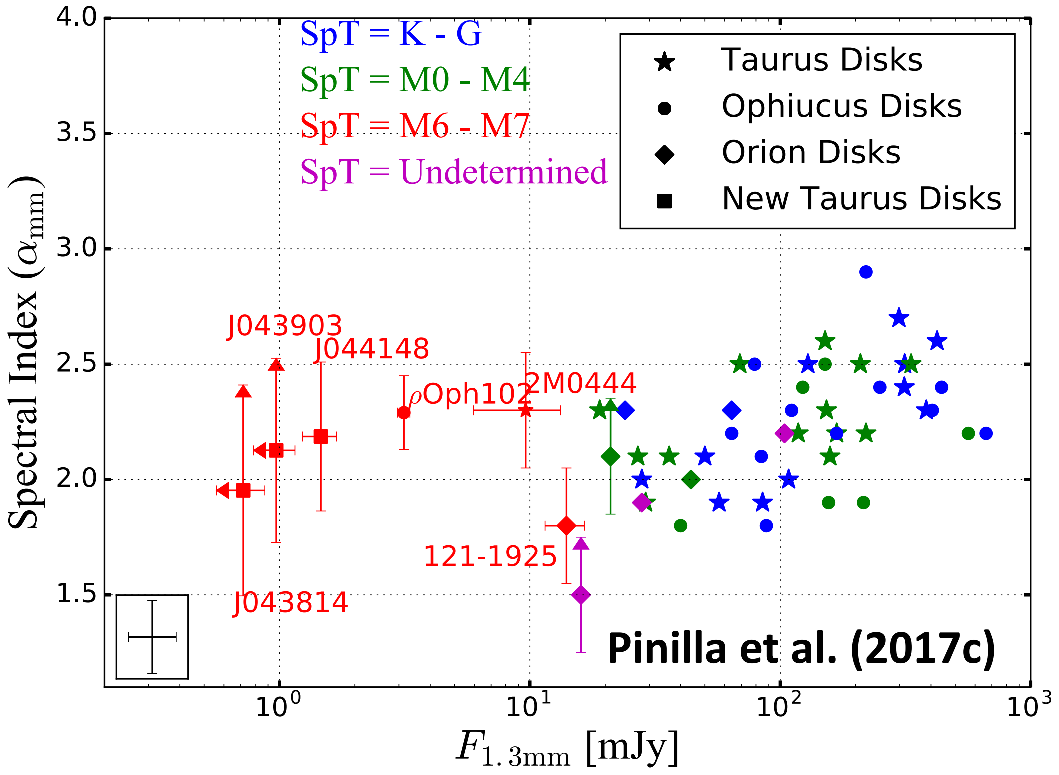
New view with ALMA

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

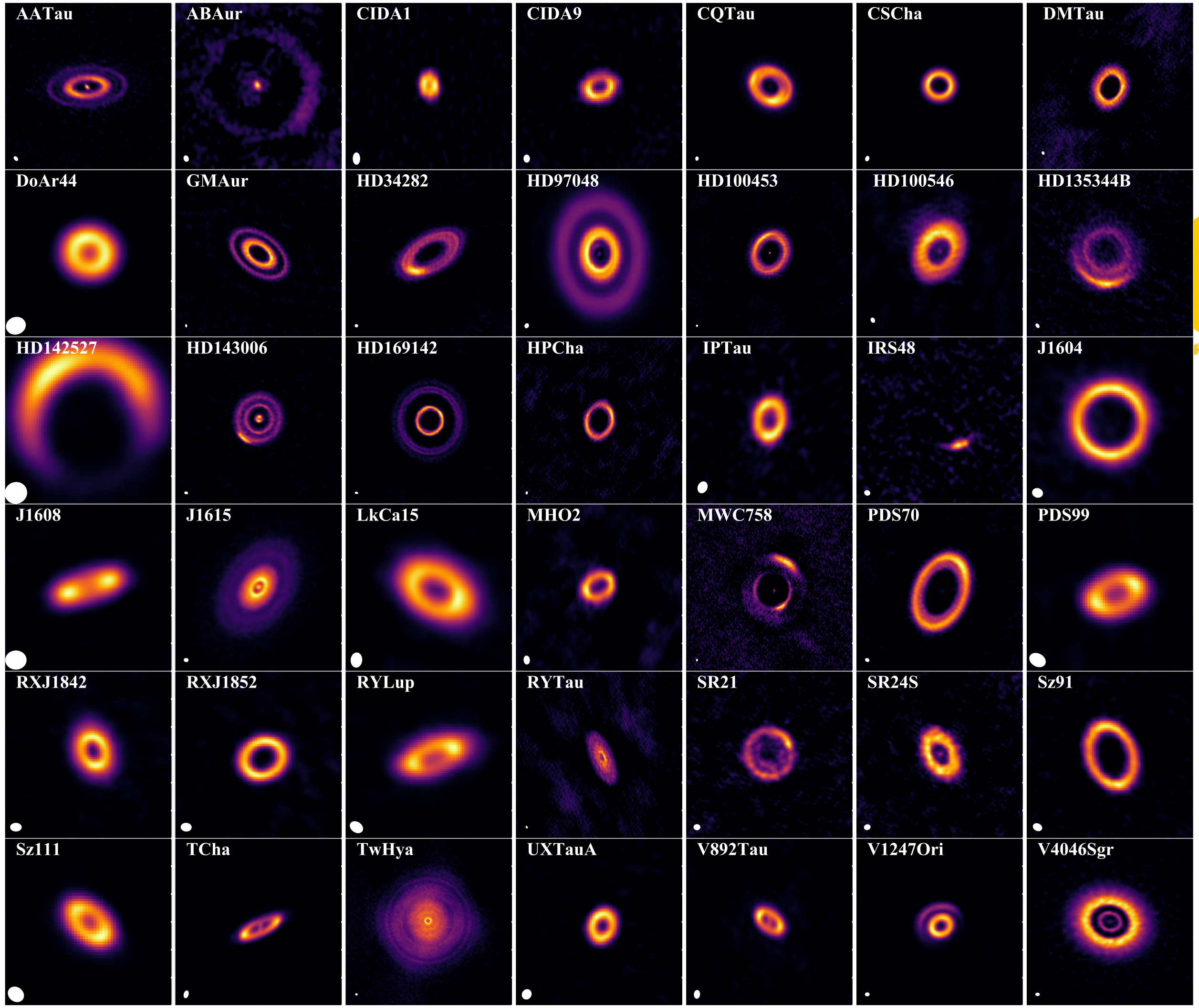




The radial-drift barrier is more difficult to overcome for the dust around Brown Dwarfs disks than around typical T-Tauri disks

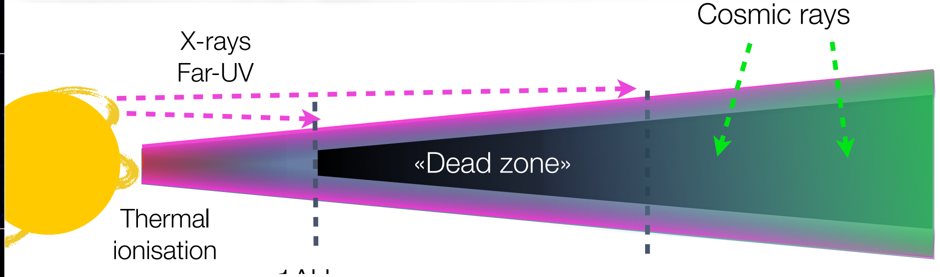
Current Research

Transition Disks: Dust Depleted Inner Cavities

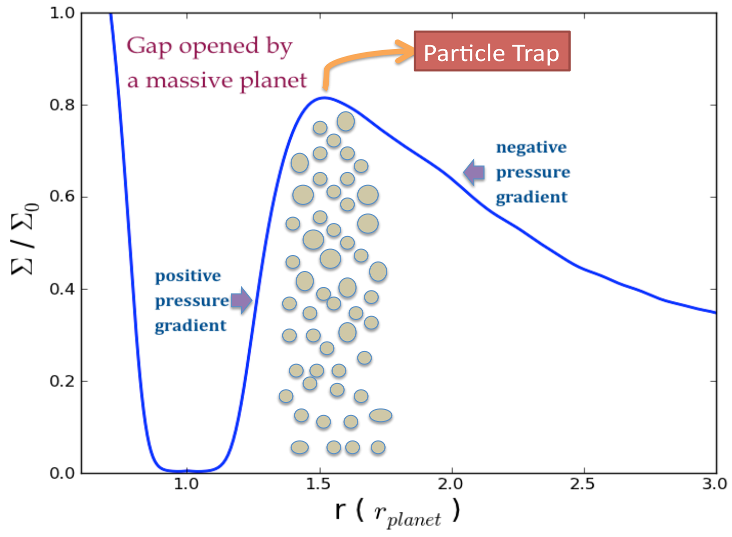


Collection of TDs
observed with ALMA

What is the origin of the structures?



Outer edge of a dead zone

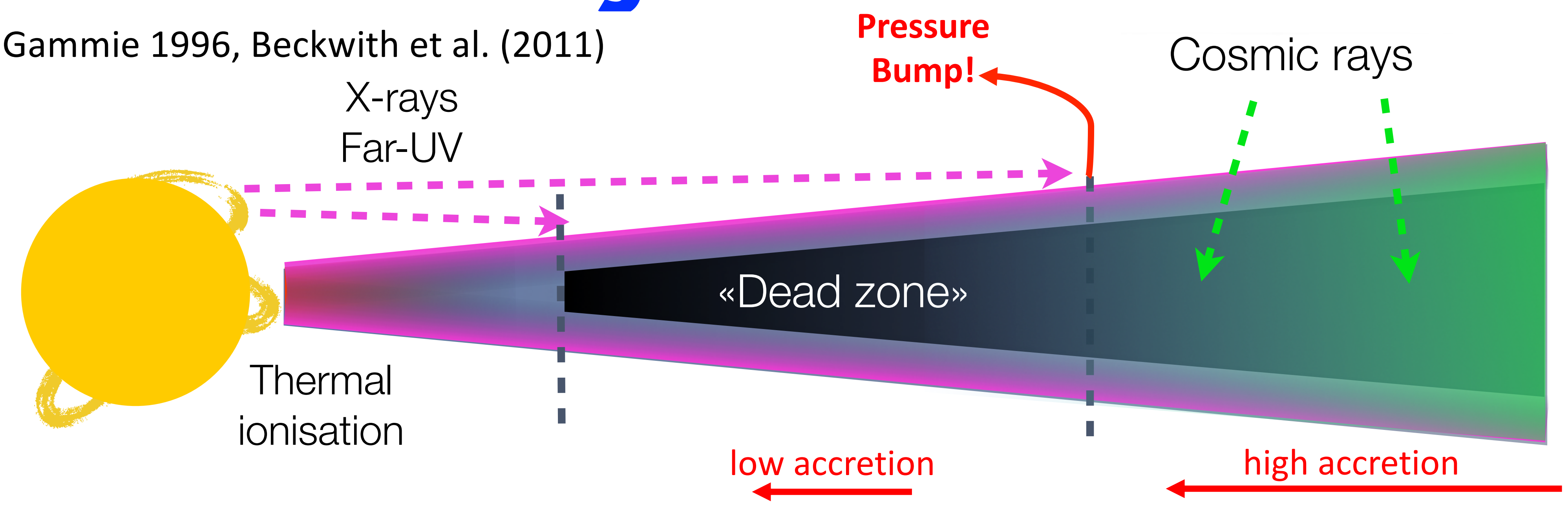


Planet-disk interaction

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

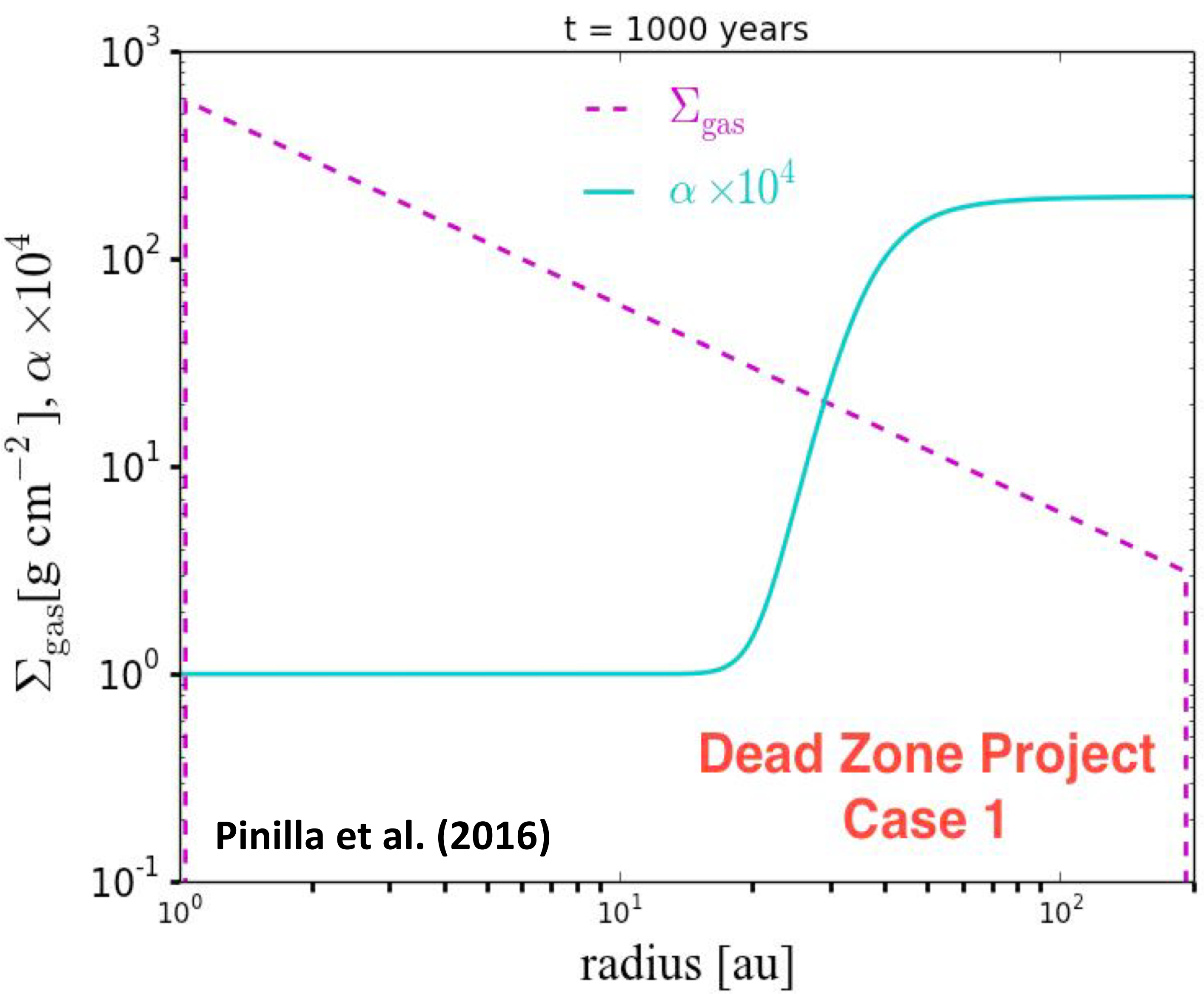
$$\nu_t = \alpha c_s H \begin{cases} \text{In an } \textbf{\textit{active zone}} & 10^{-3} < \alpha < 10^{-2} \\ \text{In a } \textbf{\textit{dead zone}} & \alpha \leq 10^{-4} \end{cases}$$

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

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

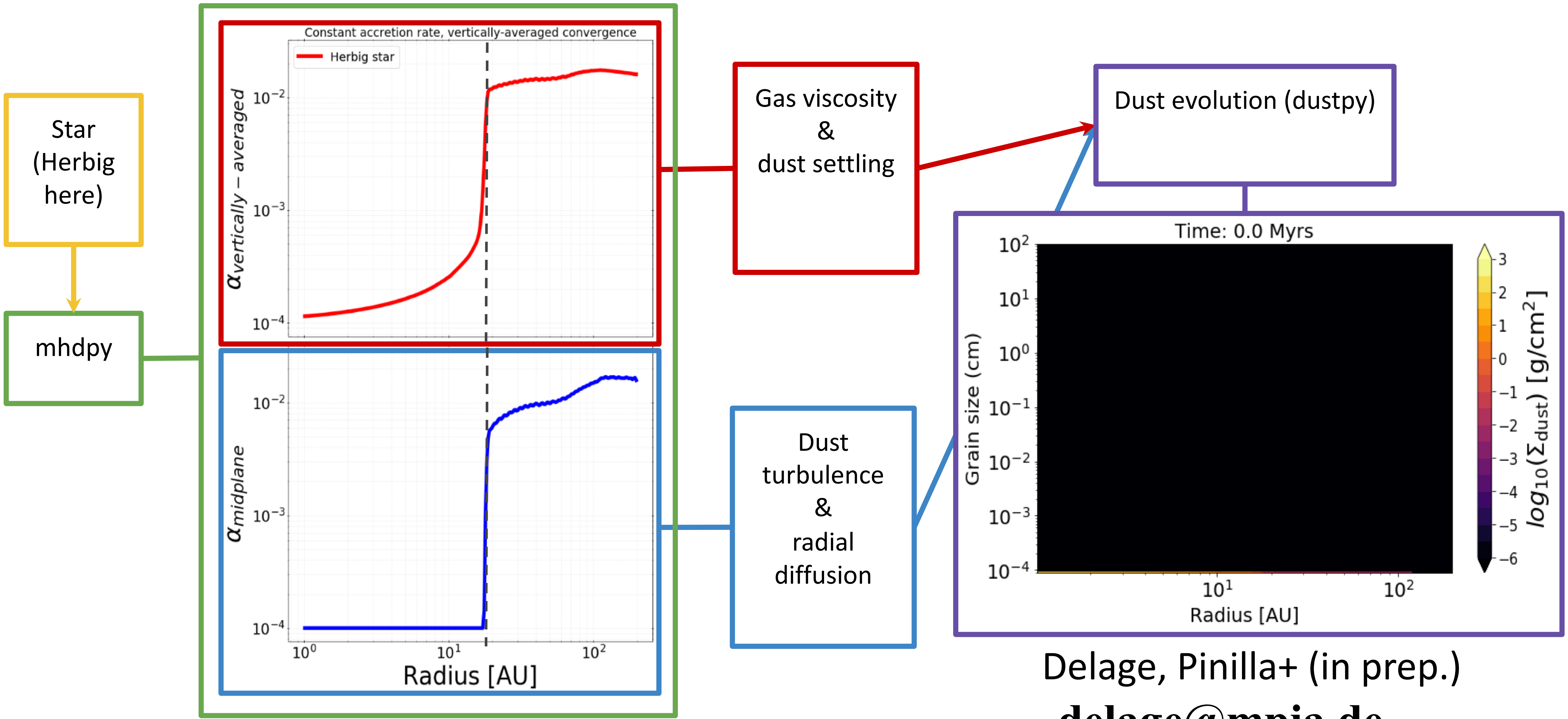


MHD + Gas/Dust Evolution

1. **Obtain a radial profile for the α-parameter**, **<u>self-consistently</u>** derived from the disk properties and ionisation level through **non-ideal MHD calculations**

2. Understand how this **self-consistent radial profile for the α-parameter <u>impacts on the dust transport mechanisms</u>** through a **dust/gas evolution model**

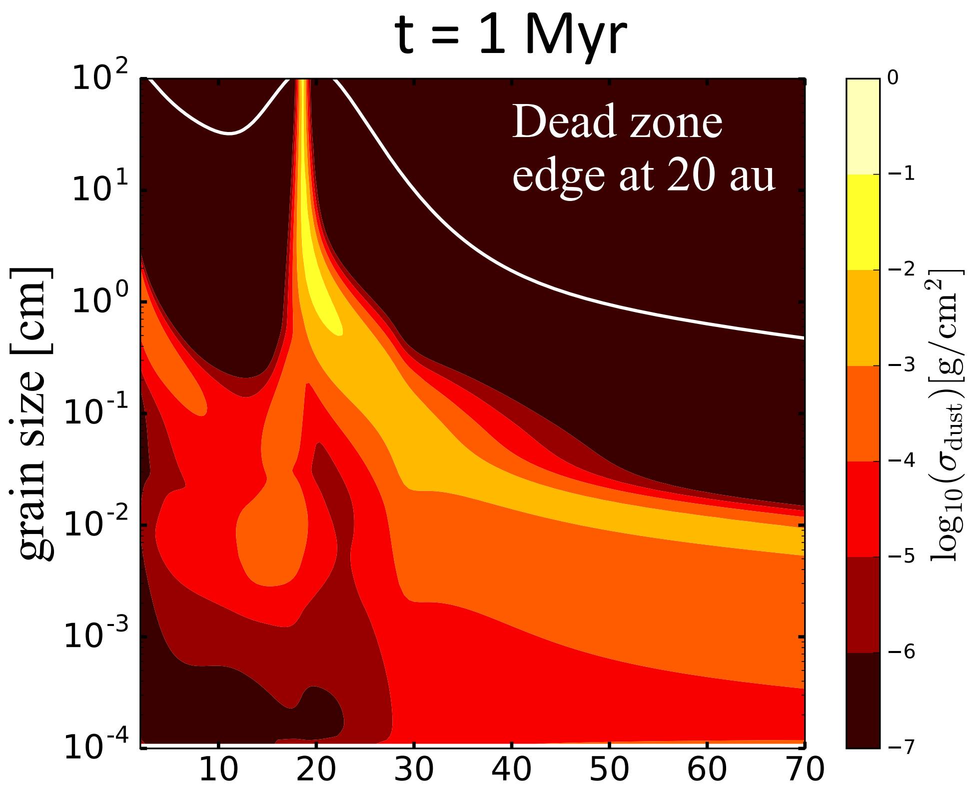
MHD + Gas/Dust Evolution



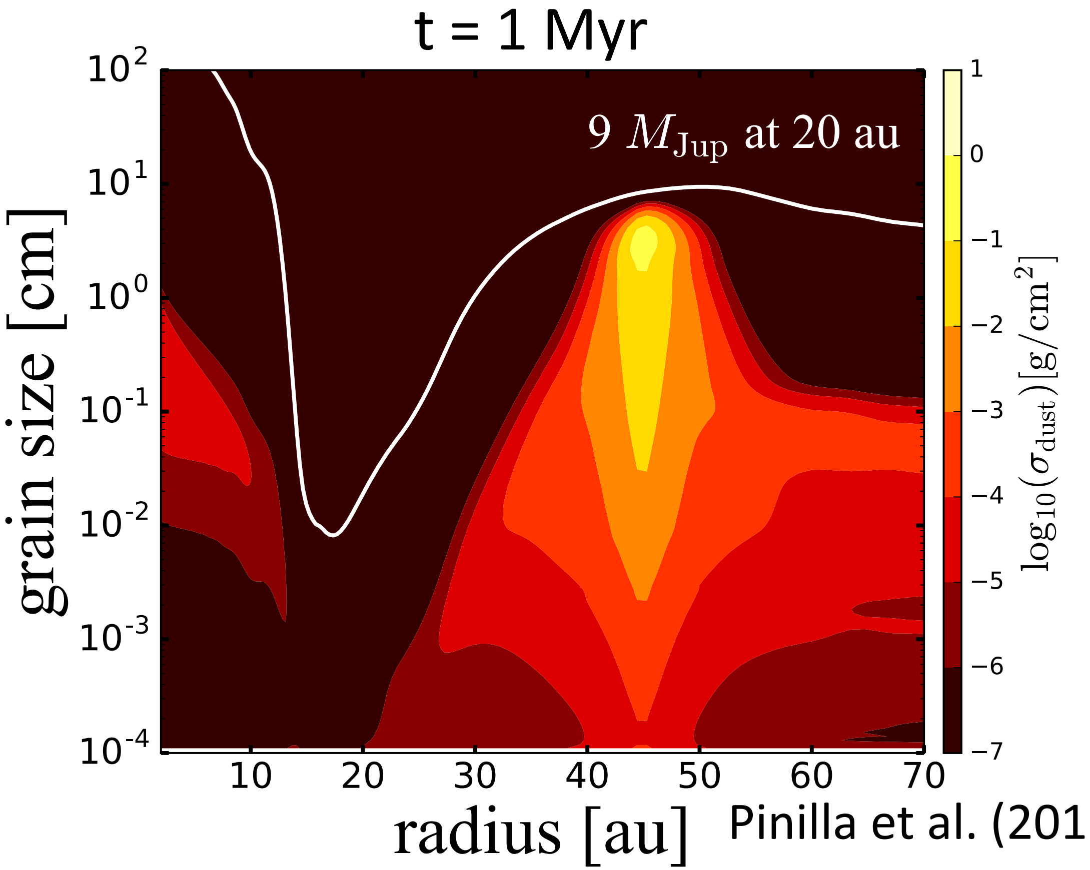
Delage, Pinilla+ (in prep.)

delage@mpia.de

Dead Zones vs. Planets: how do we distinguish?



Pinilla et al. (2016b)



Pinilla et al. (2012b)

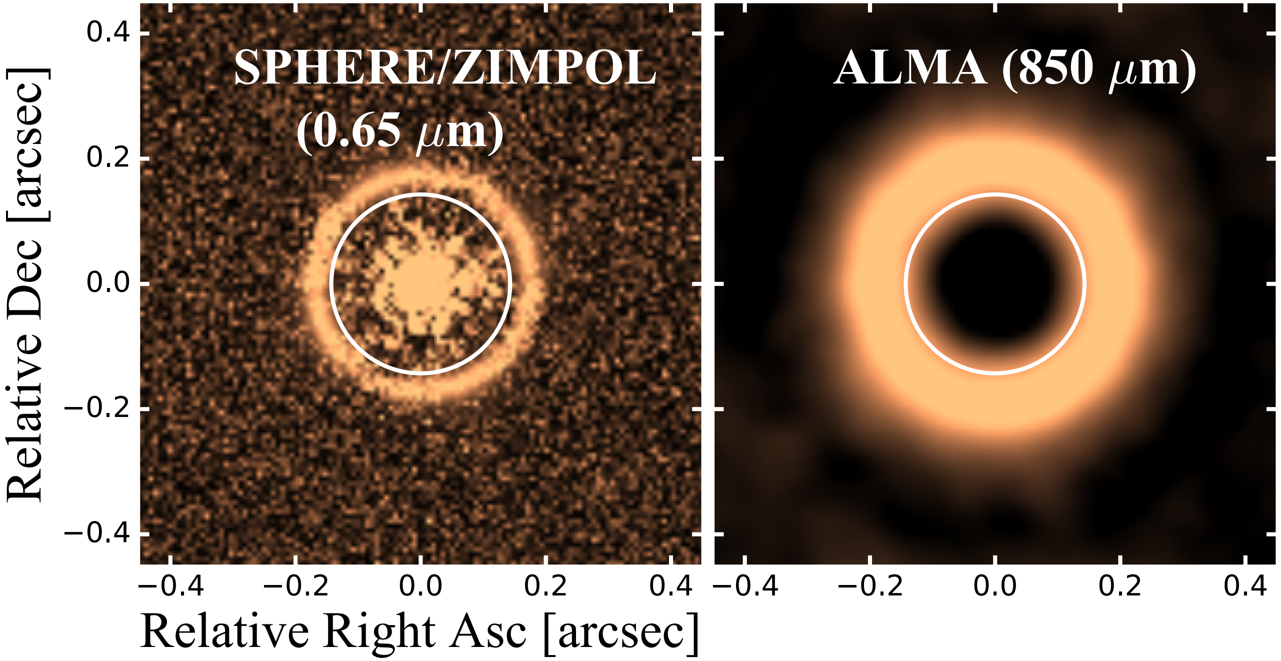
Dead Zones

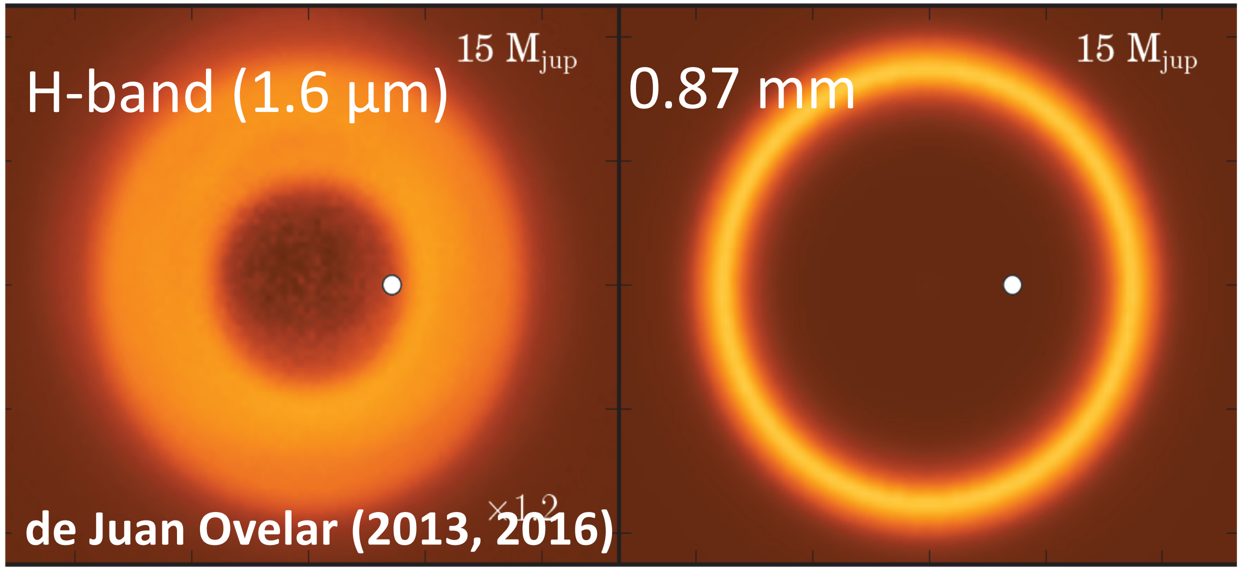
Size of the cavities is similar at short and long wavelengths.

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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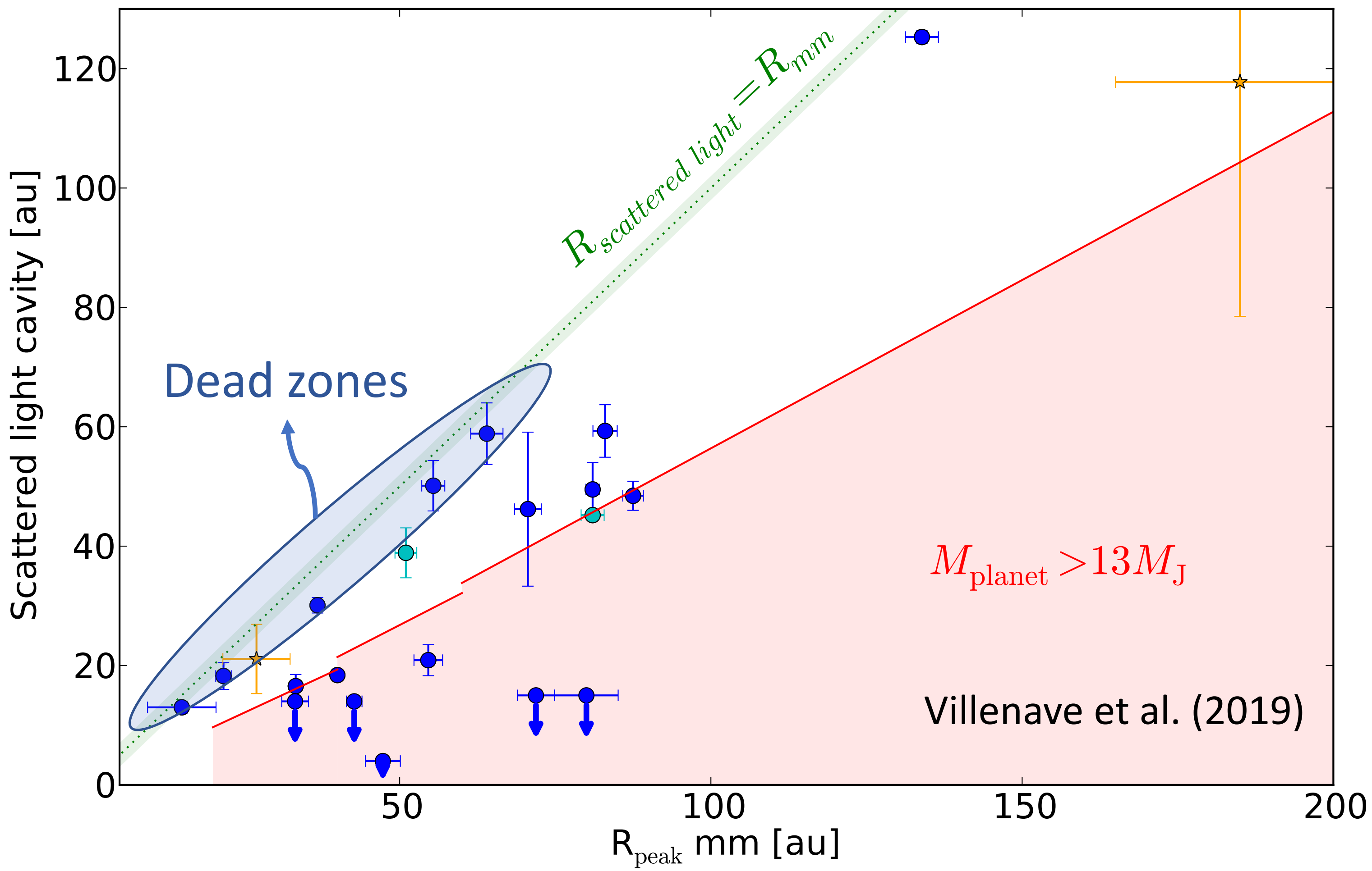
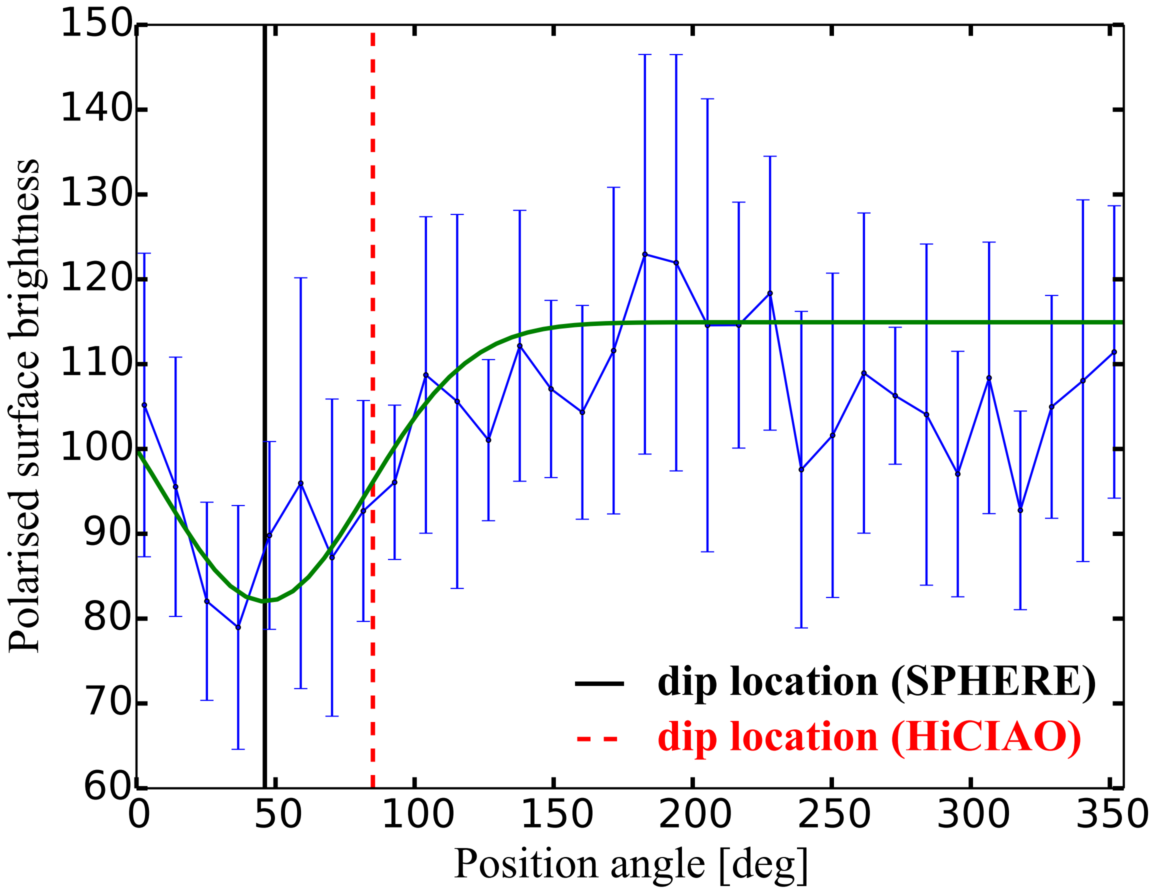
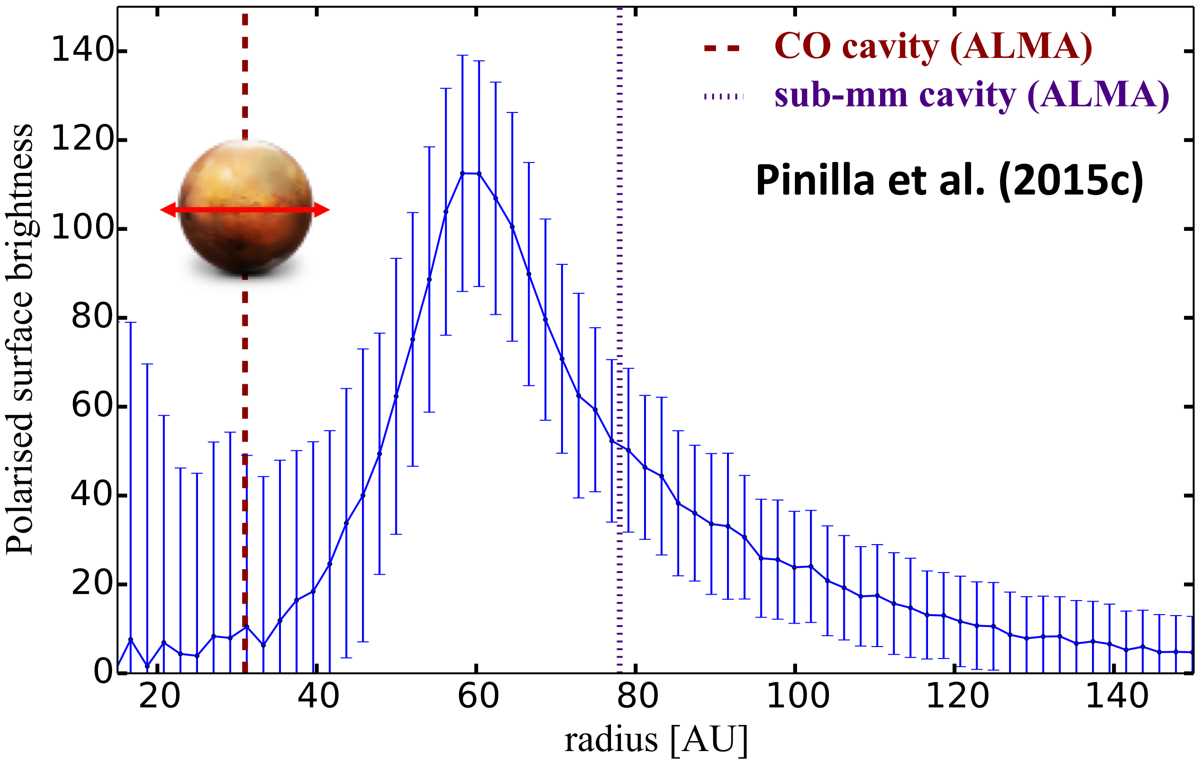
Dead Zones vs. Planets: how do we distinguish?



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

Example of Dust Filtering: Disk Around J160421





If the dip is the same, this suggests an average dip rotation of 12 deg/year

Current observations suggest the presence of a massive companion ($5\text{-}10 M_{Jup}$) embedded at ~20-40 au distance from the star

Accepted C6 ALMA observations to spatially resolve any kinematic signature of a warp

Pinilla et al (2018b)

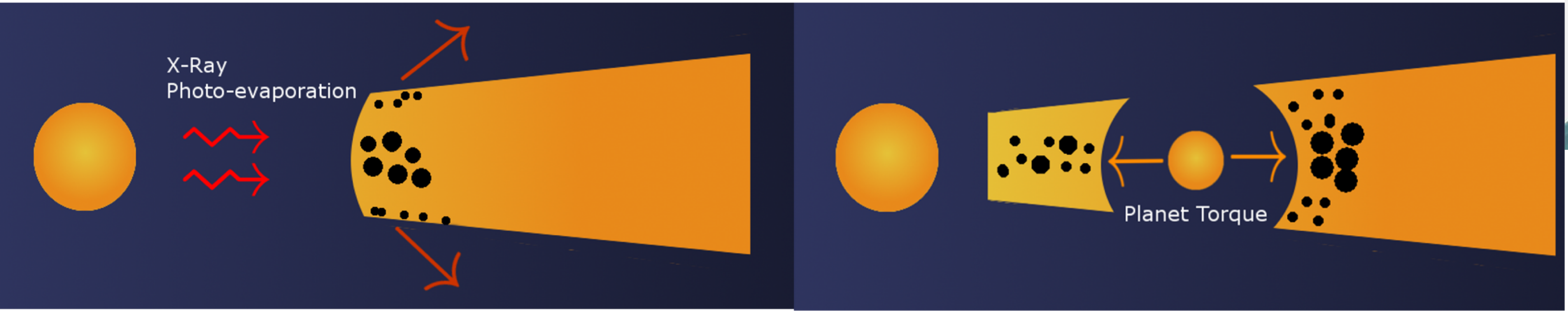
Origin of Transition Disk Structures

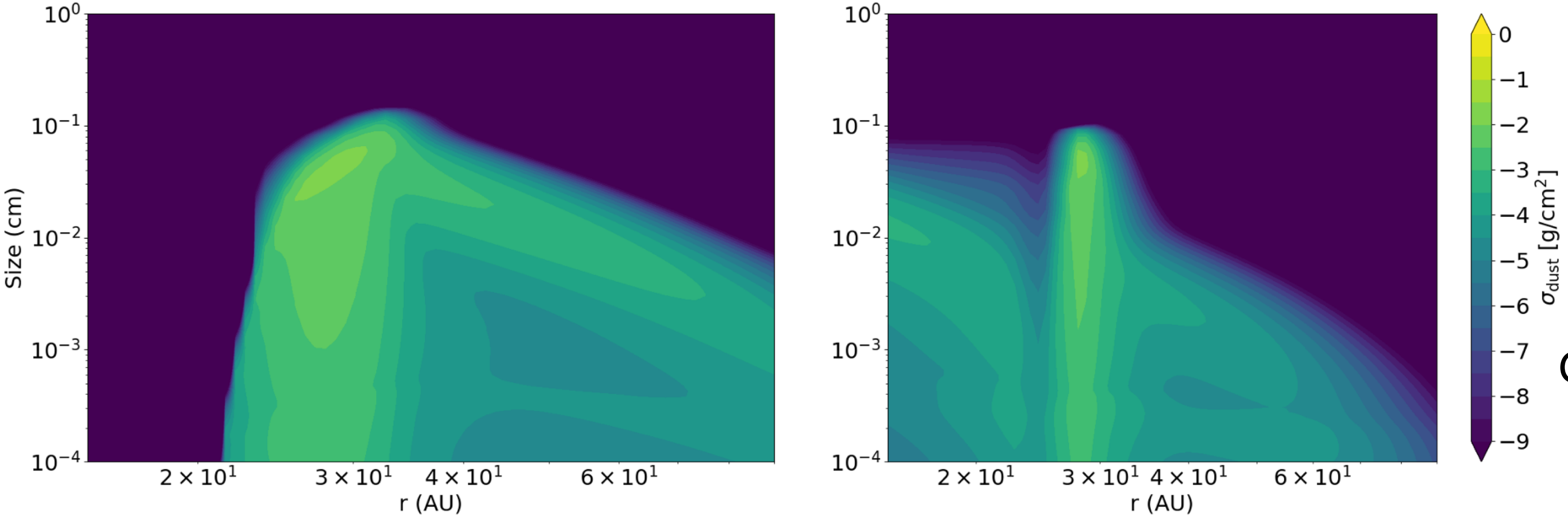
Model	mm-cavity	micron-sized cavity	≠ cavity size of the small and large grains
Embedded planet(s)	yes	for very massive planets (> 1 M_{Jup})	yes
Dead zone	yes	yes	no

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

Overview in Pinilla & Andrew (2017)

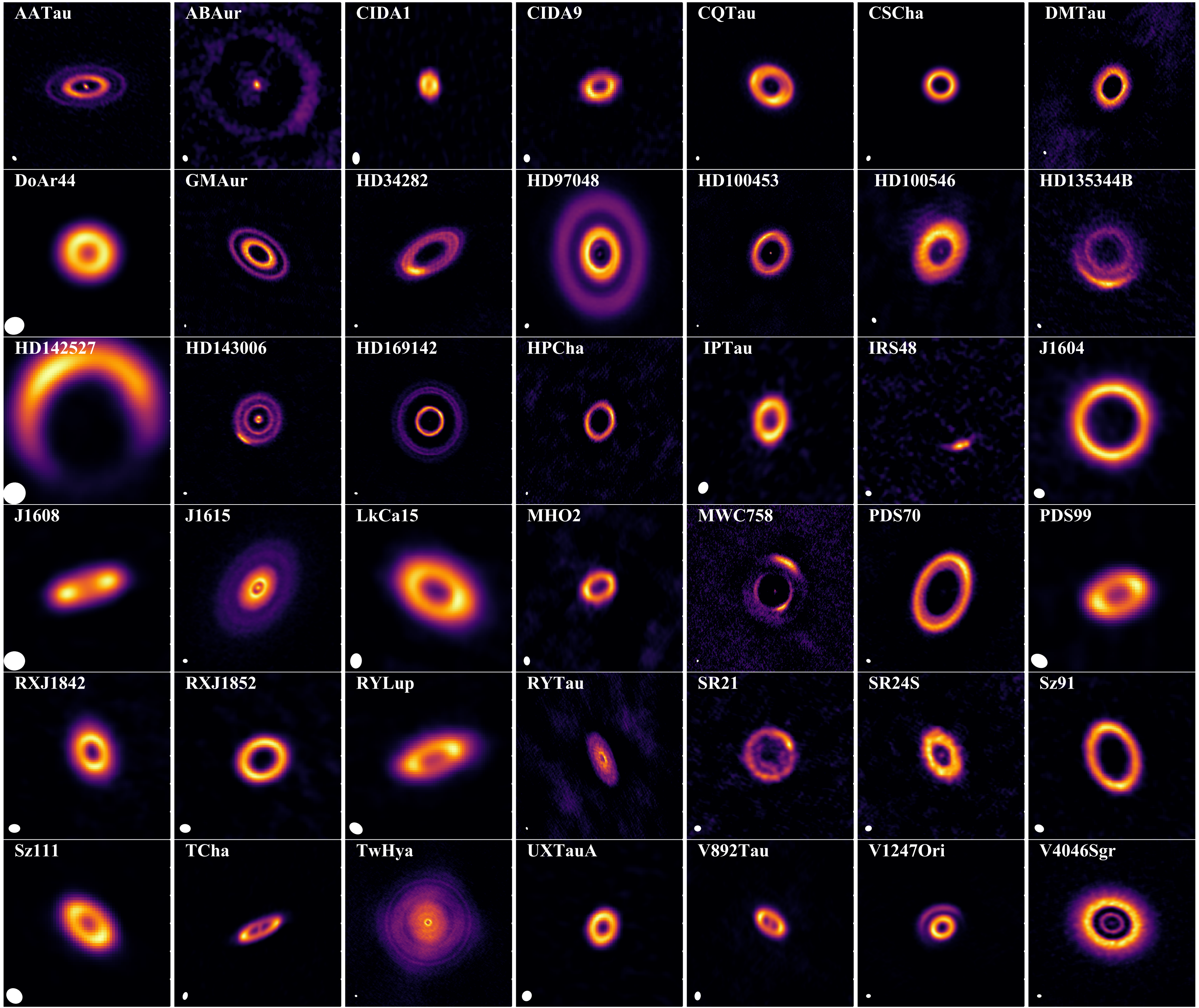
Photoevaporation + Dust Evolution



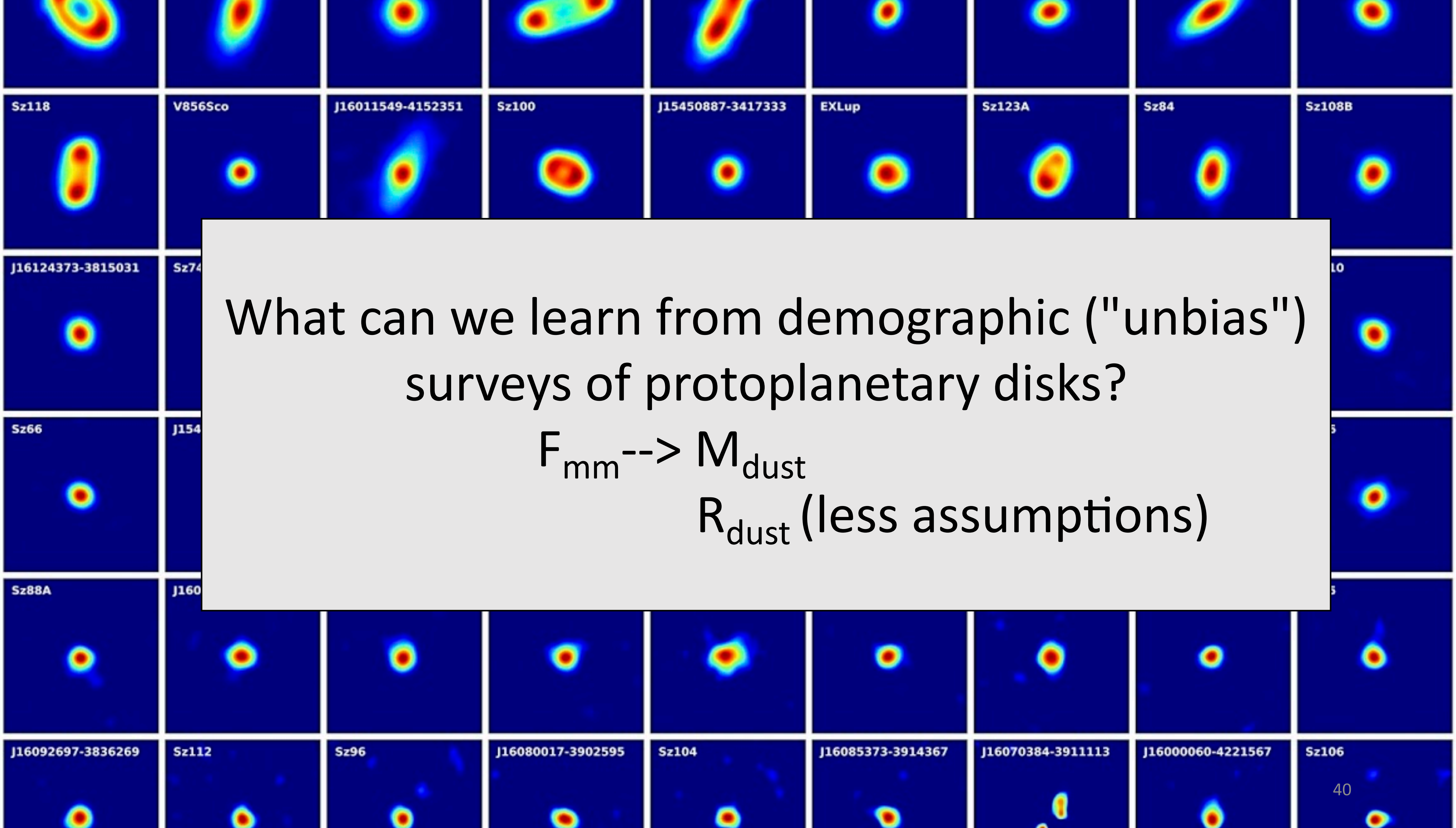


Gárate et al, in prep

garate@mpia.de



Most observations at high angular resolution have prominent bias: *targeting bright disks*

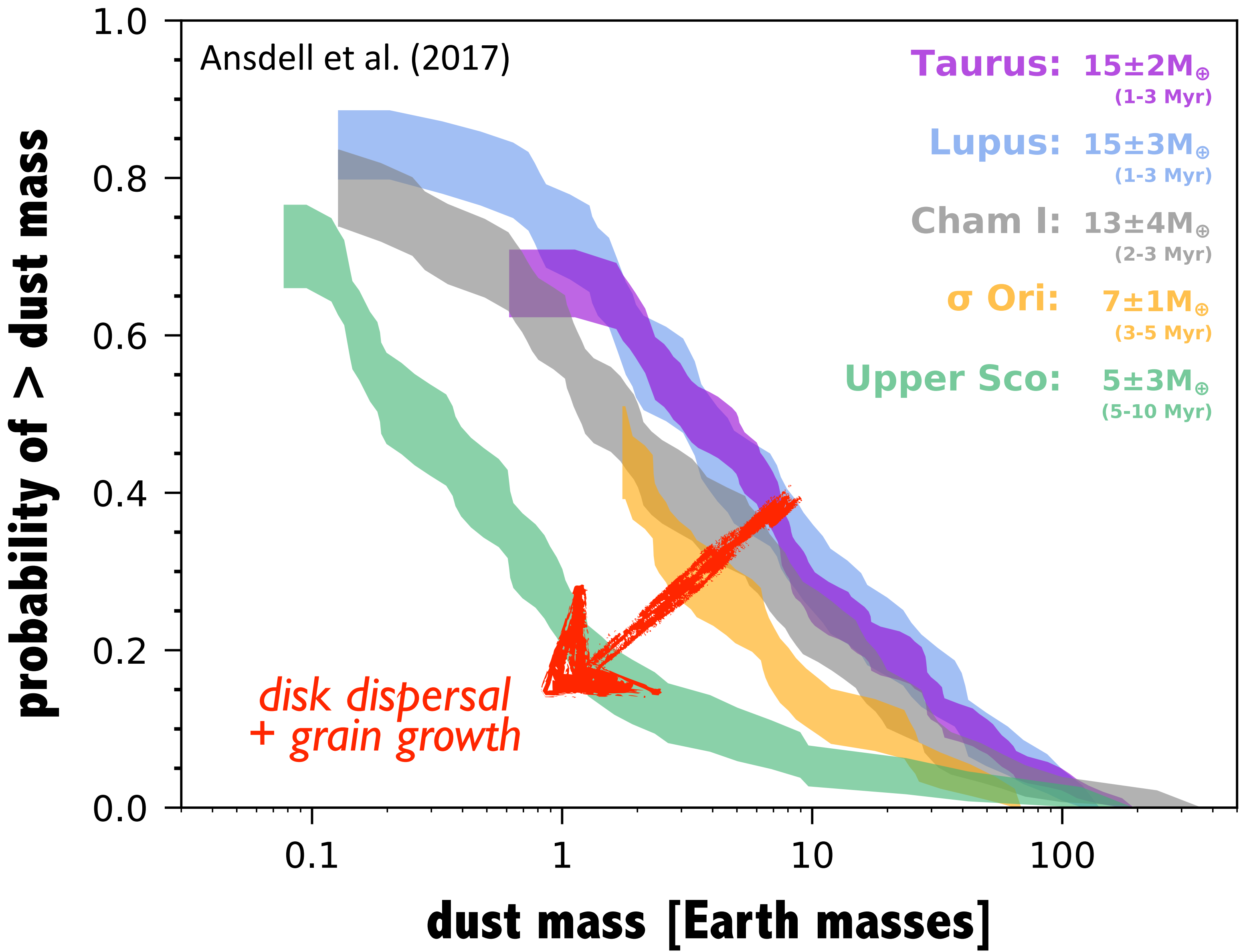


What can we learn from demographic ("unbias") surveys of protoplanetary disks?

F_{mm} --> M_{dust}

R_{dust} (less assumptions)

M_{dust} from ALMA Surveys



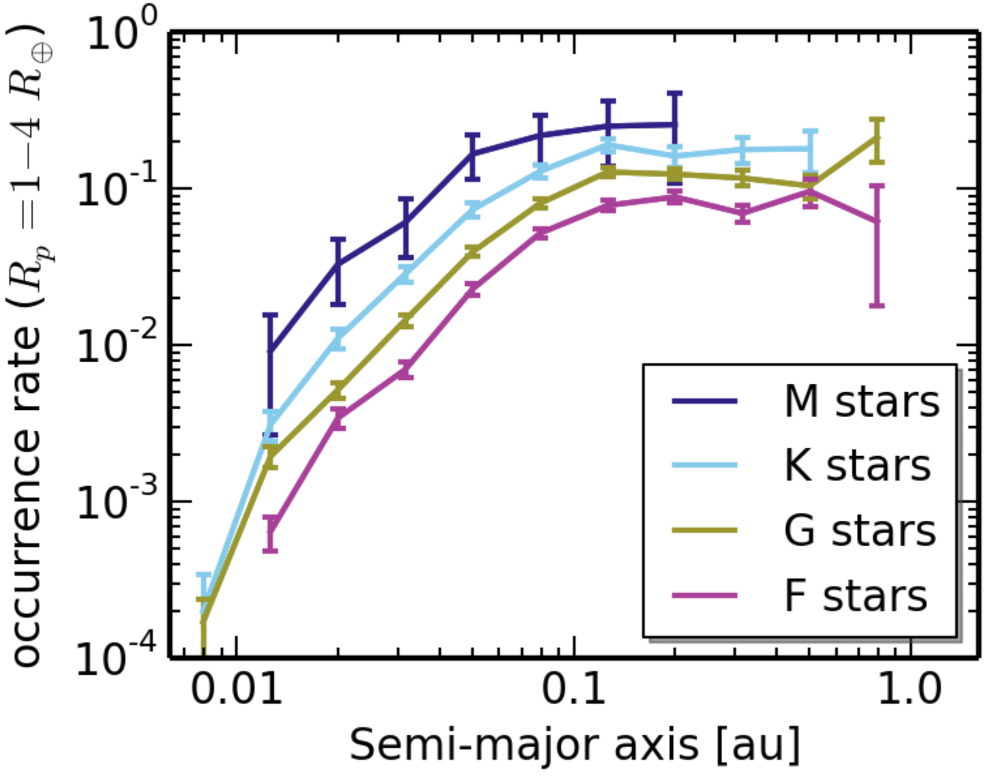
% of disks with
>= 10 Earth masses

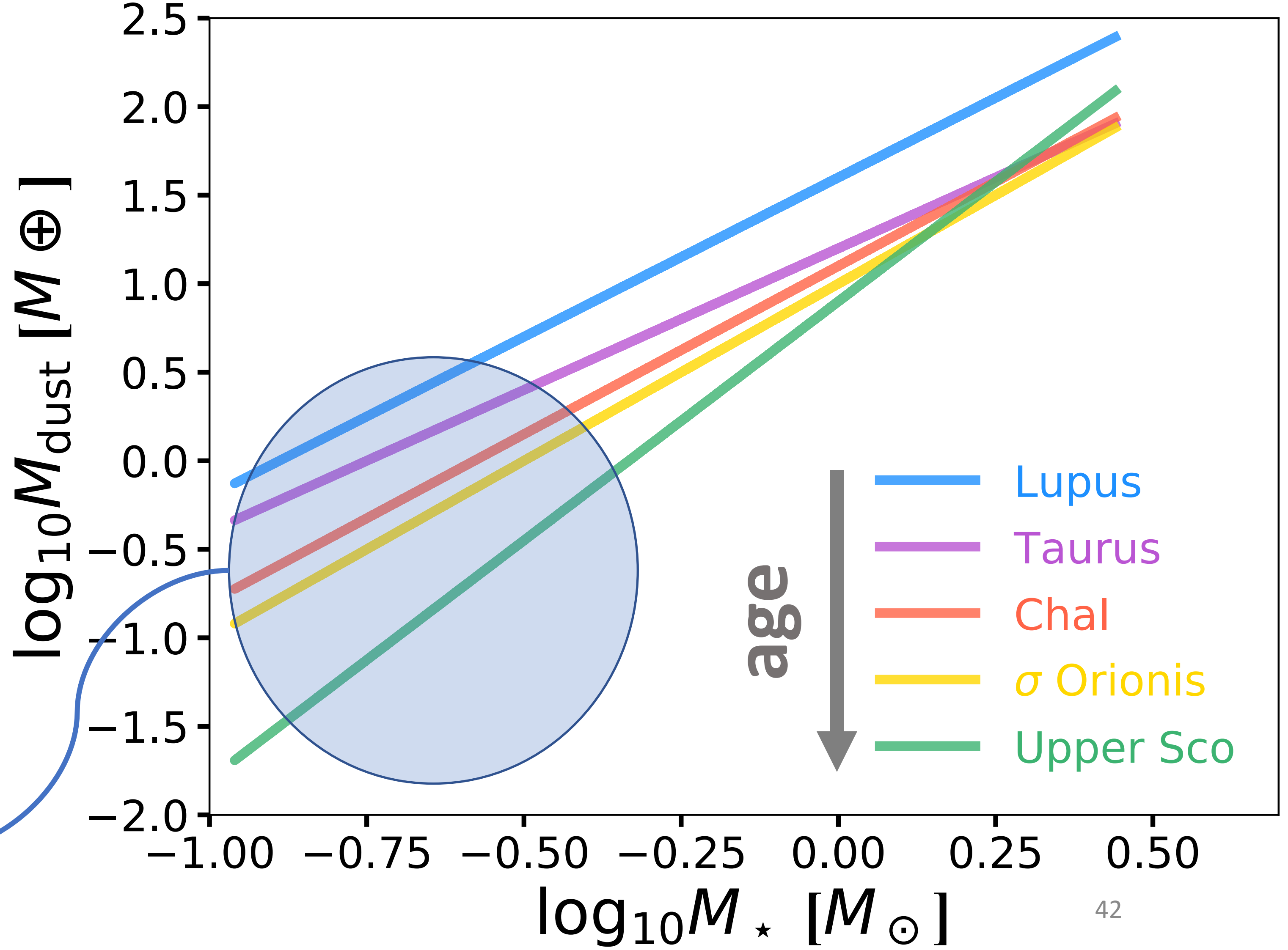
1-3 Myr → 25%

3-5 Myr → 13%

5-10 Myr → 5%

M_{dust} from ALMA Surveys



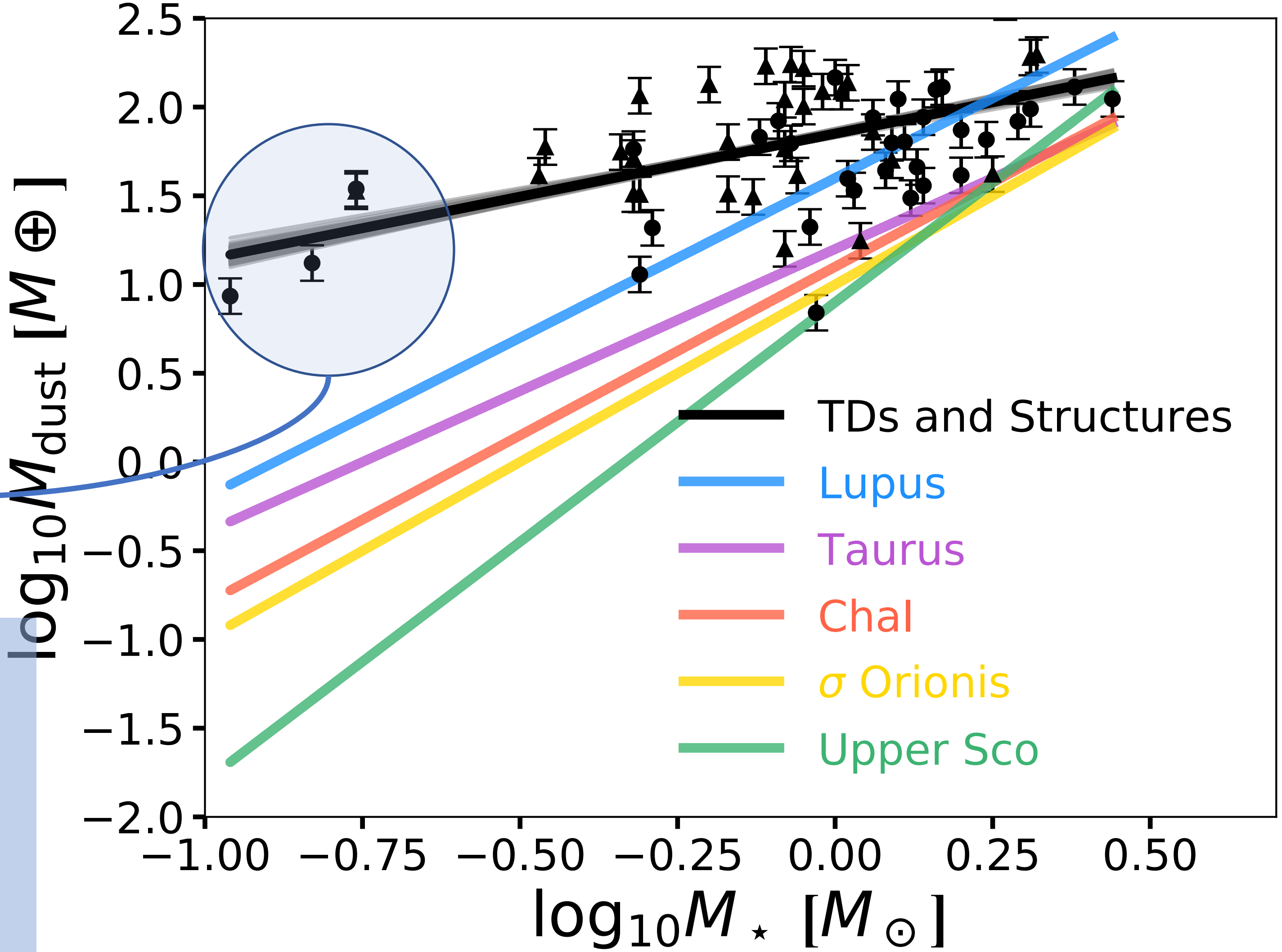


Stellar mass effect
(drift is more efficient
around low mass stars)

M_{dust} - $M_\star$ relation for disks with structures

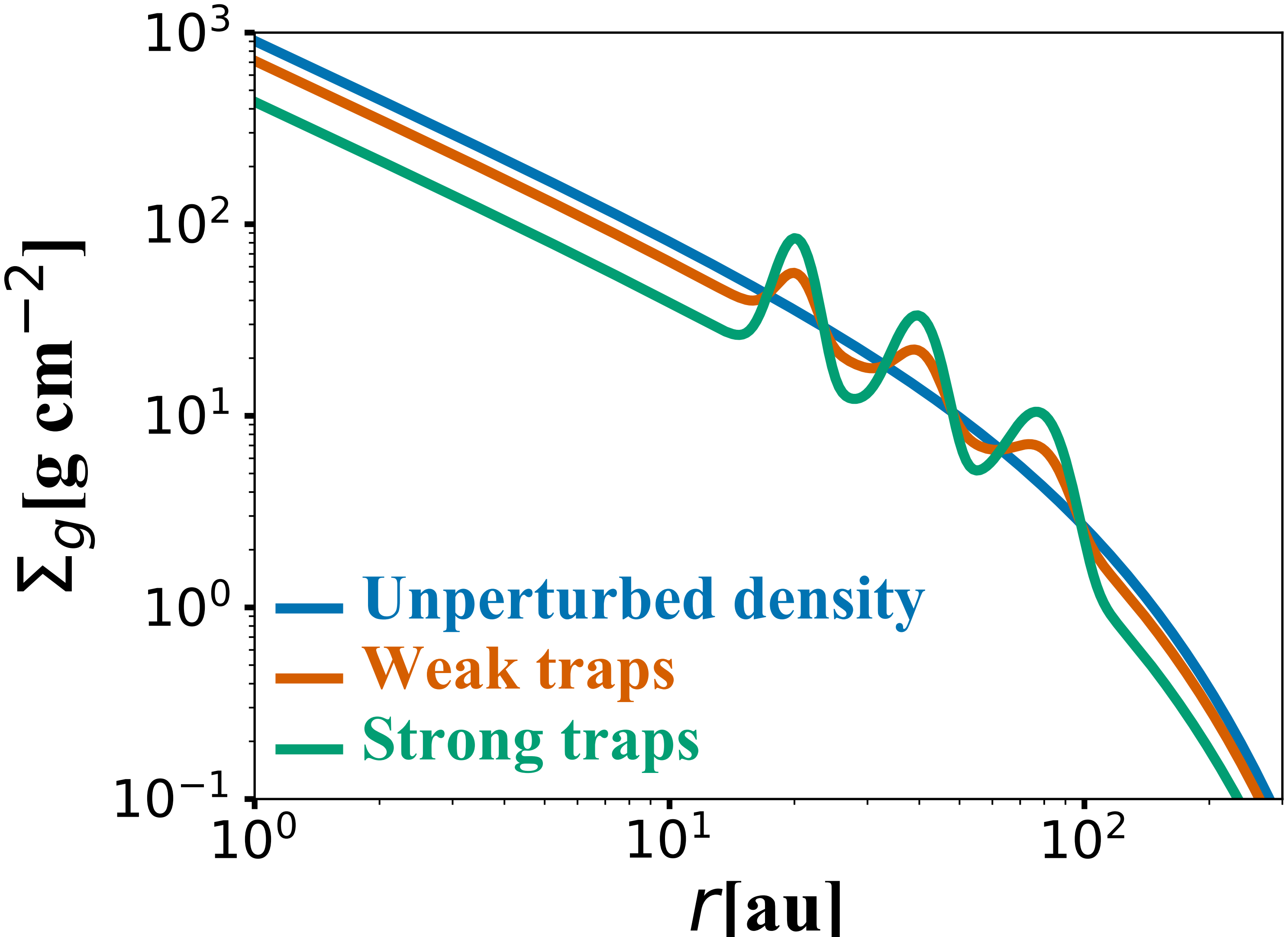
TDs and disks with substructures remain massive independent of the stellar mass

Accepted ALMA (C6 & C7) proposals to search for substructures around low mass stars (Kurtovic, Pinilla, submitted)



Pinilla et al. (2020)

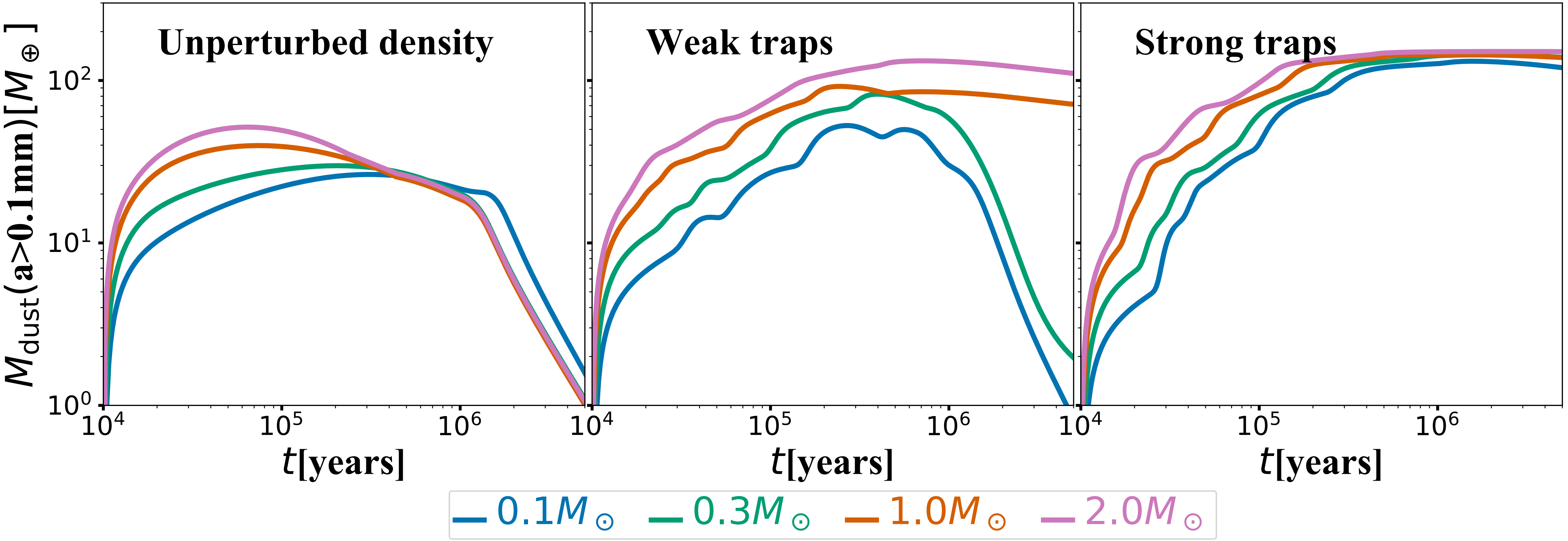
Can we learn from the origins of traps from the M_{dust} - $M_\star$ relation?



We perform dust evolution models:

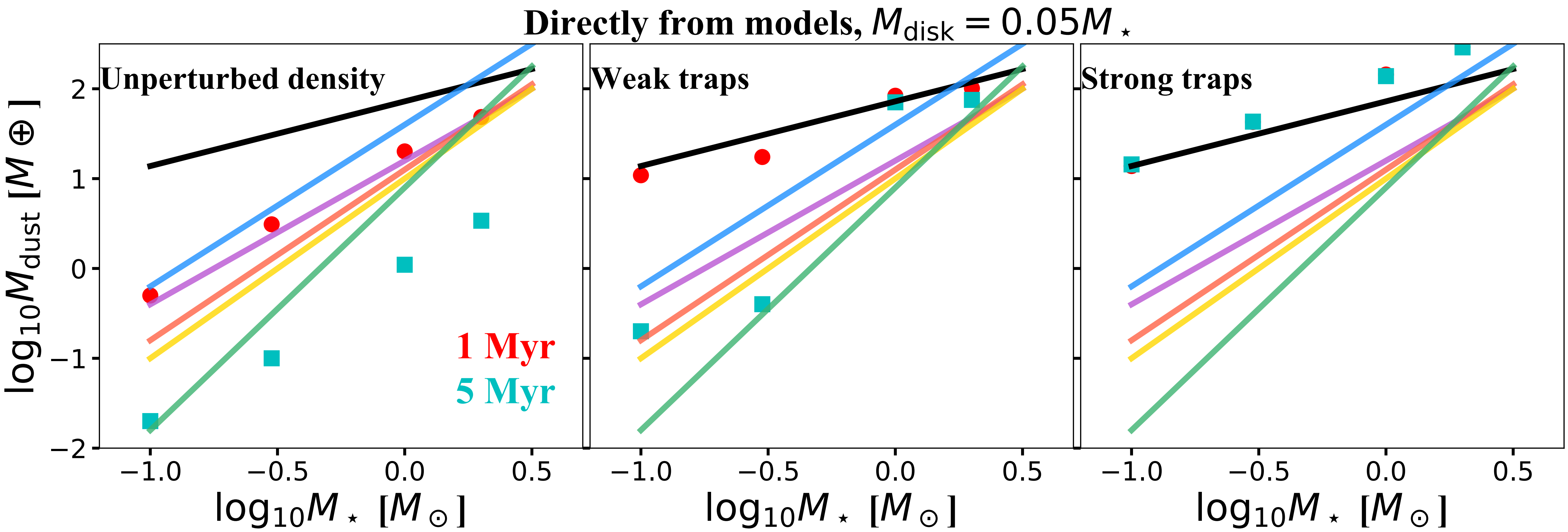
- Different types of pressure bumps (mini Neptune vs. Jupiter)
- Different stellar mass: [0.1, 0.3, 1, 2] M_{sun}

Evolution of the mass in large grains for different pressure bumps and stellar mass

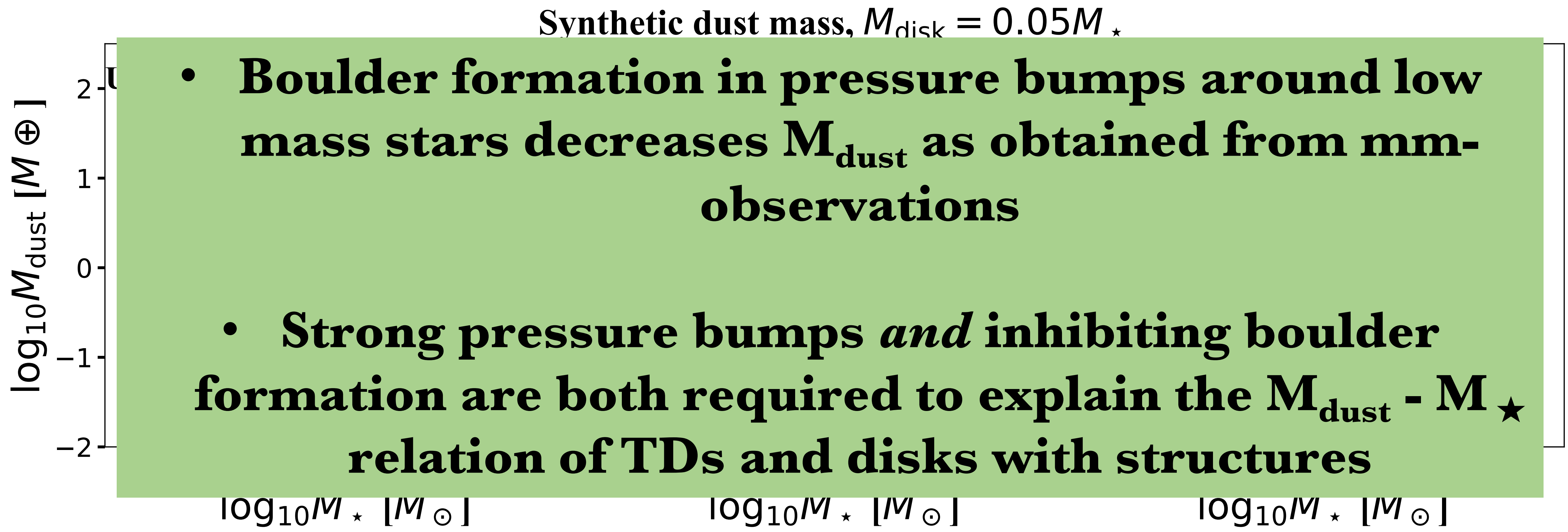


Pinilla et al. (2020)

Comparison between observations and the mass in large grains directly obtained from models



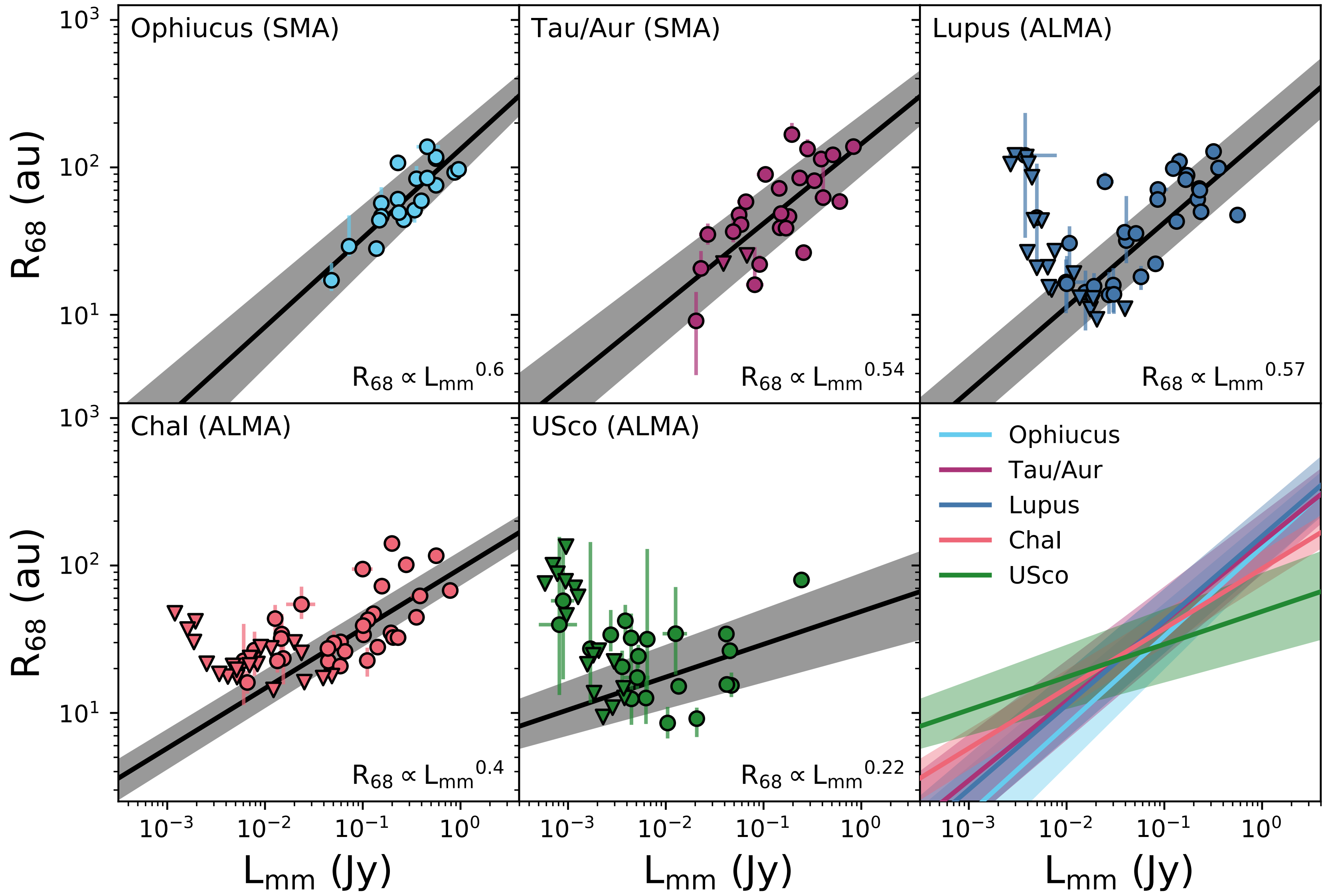
Comparison between observations and the *synthetic mass* as observed with ALMA



- **Boulder formation in pressure bumps around low mass stars decreases M_{dust} as obtained from mm-observations**

- **Strong pressure bumps *and* inhibiting boulder formation are both required to explain the M_{dust} - $M_\star$ relation of TDs and disks with structures**

R_{dust} from ALMA Surveys

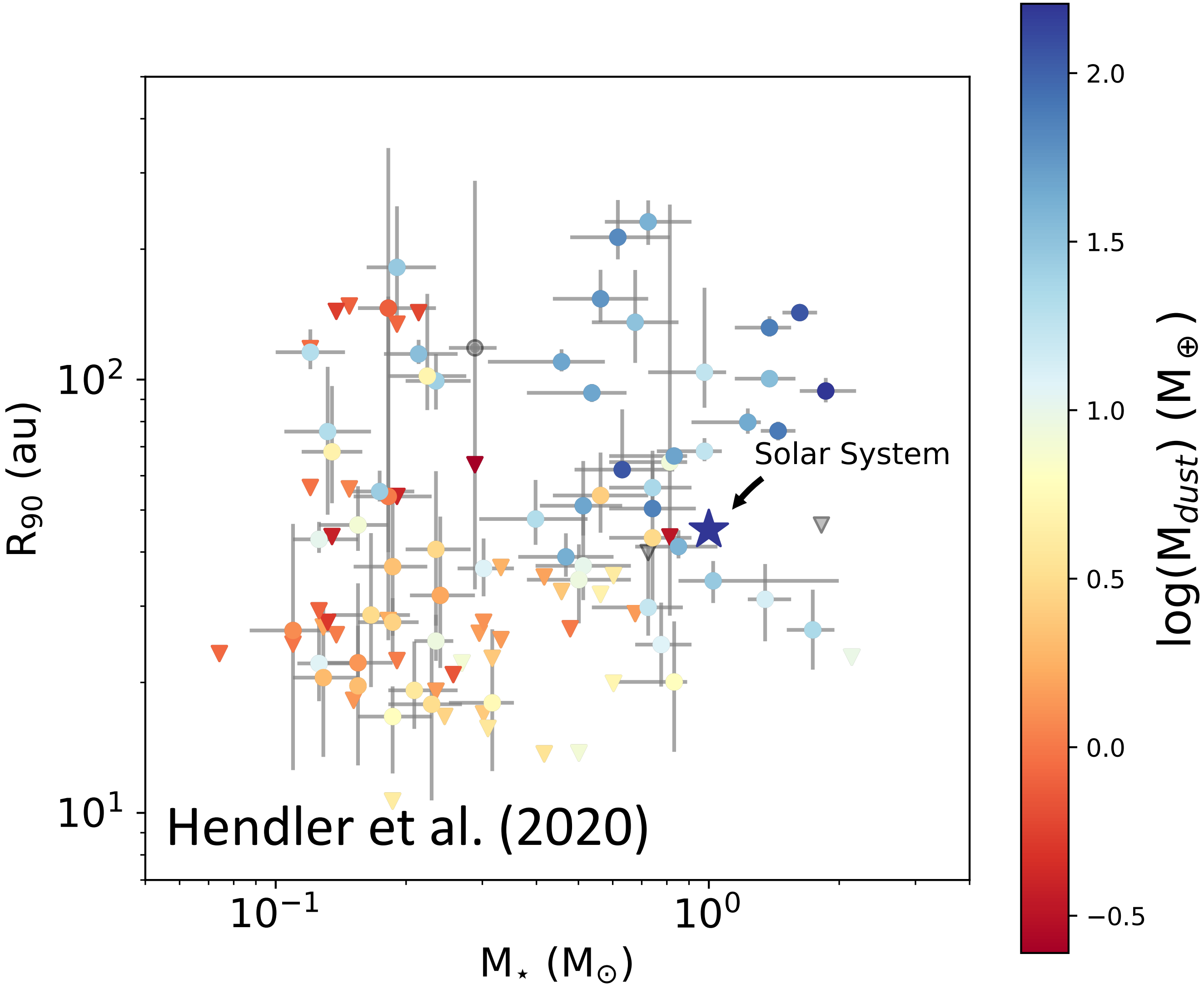


$R_{eff} - L_{mm}$ relation is not the same in all regions, it becomes flatter for older regions:

- Radial Drift
- Planetesimal formation
- Photoevaporation

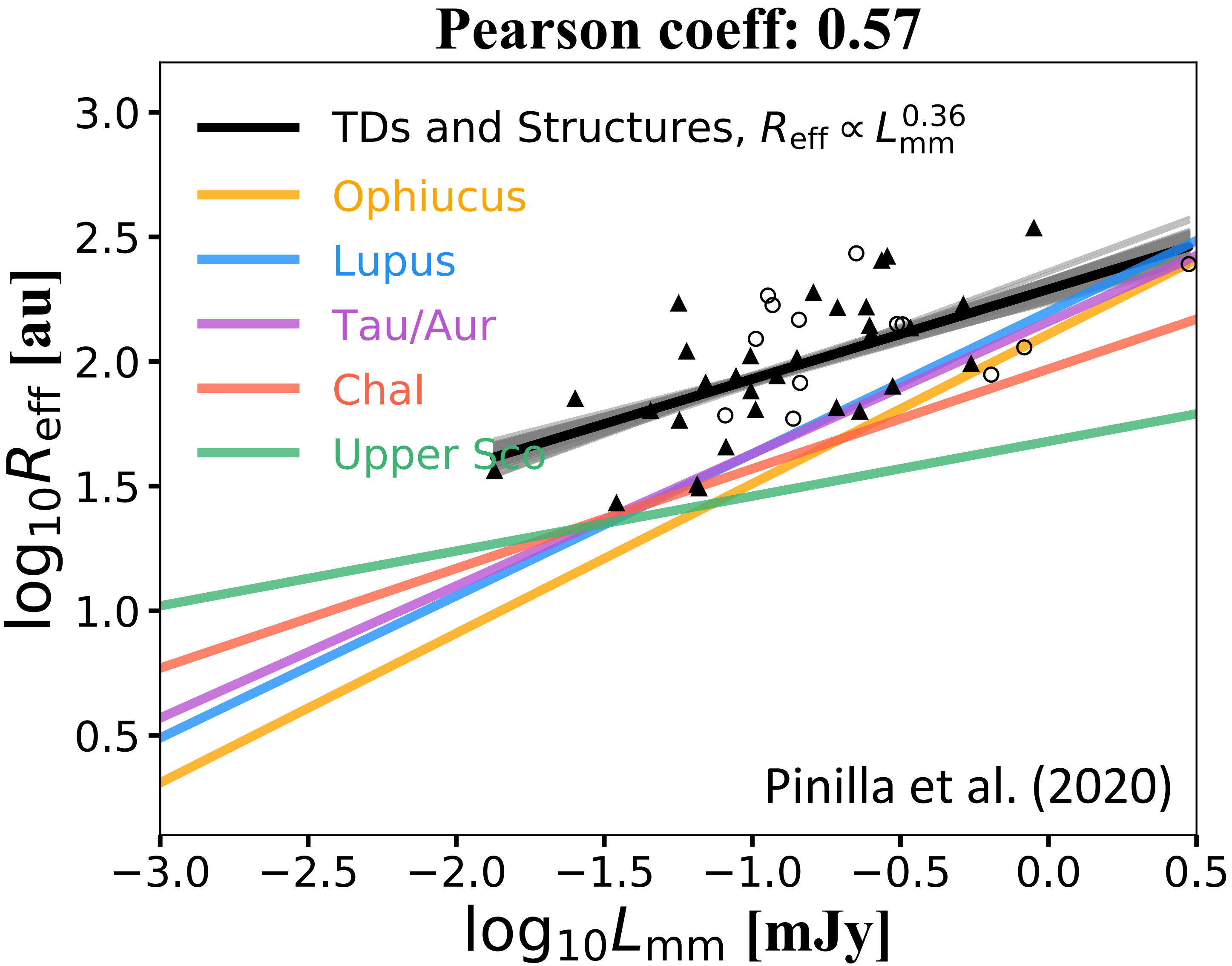
Hendler et al. (2020)

Our Solar System is not an outlier when compared with typical 1-3Myr disks



- A truncating event (e.g. a stellar encounter or external photoevaporation) may not be required to explain the Solar System size.
- The mass of solids in the Solar System falls within the range of estimated dust-disk masses estimated for our sample.

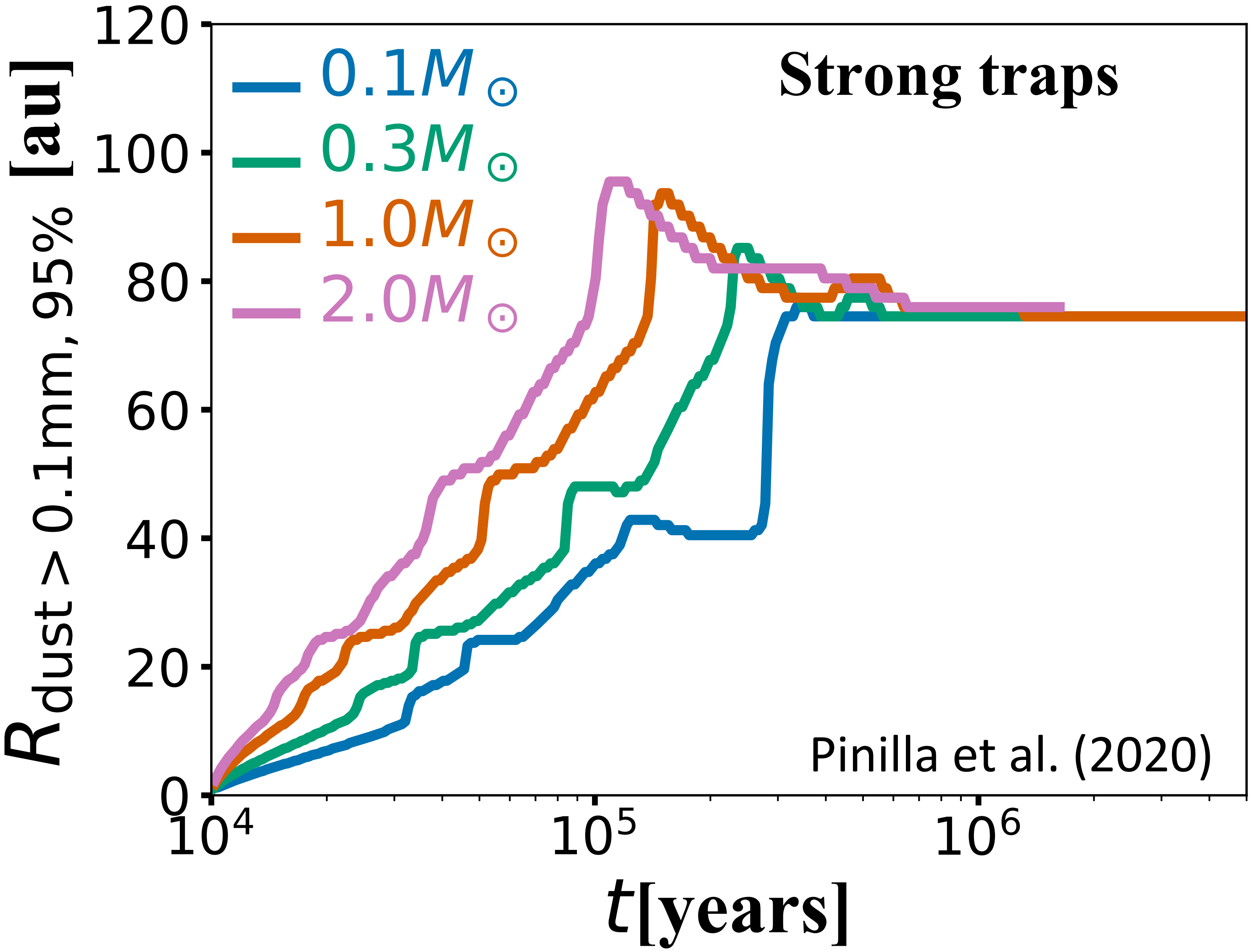
R_{eff} for TDs and disks with substructures



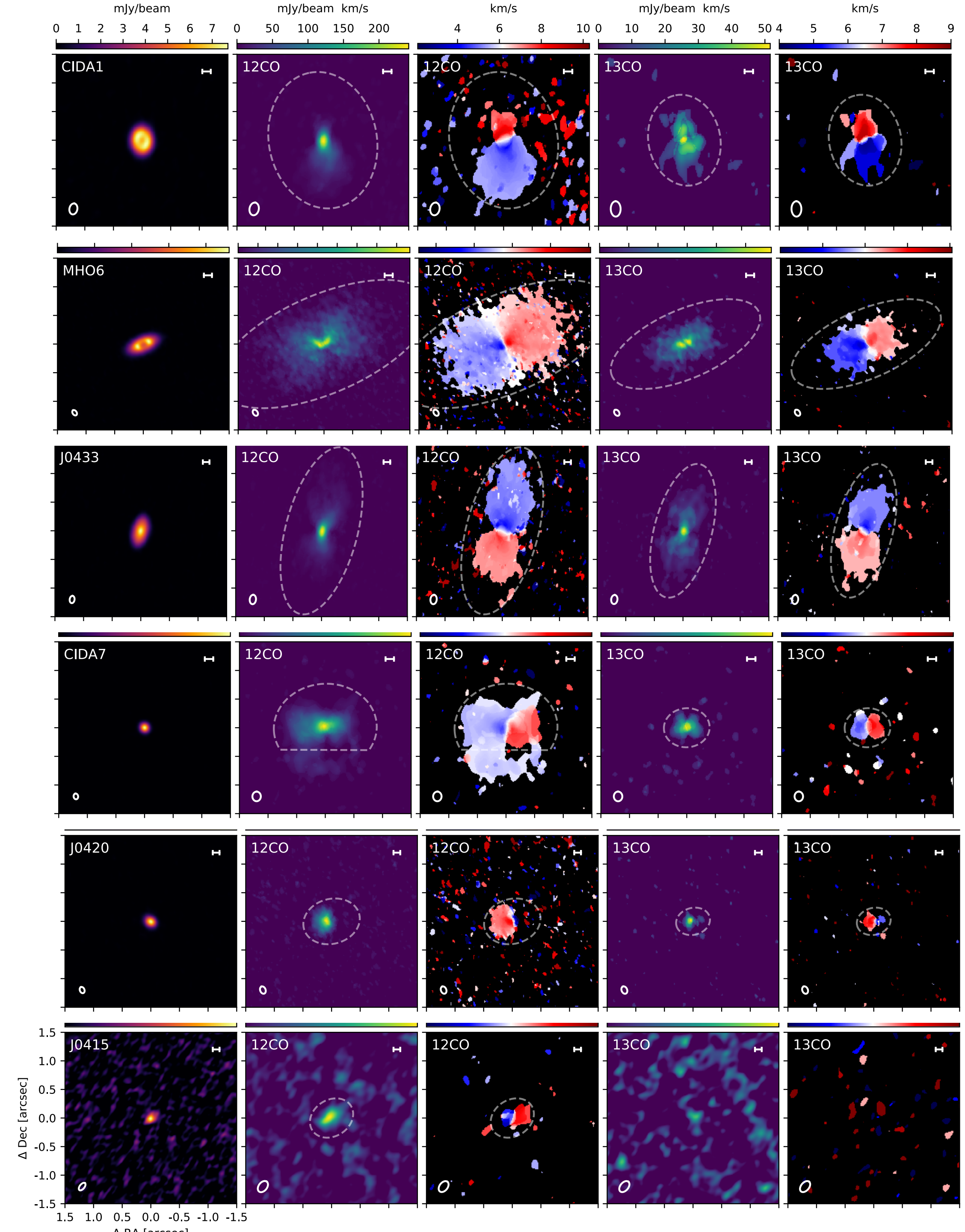
- $R_{eff} - L_{mm}$ relation is flatter than observed in Oph, Lupus, and Taurus/Auriga star-forming regions

- The slope value of our sample lies in the range found for older regions, that is, Cha I and Upper-Sco

R_{eff} for TDs and disks with substructures



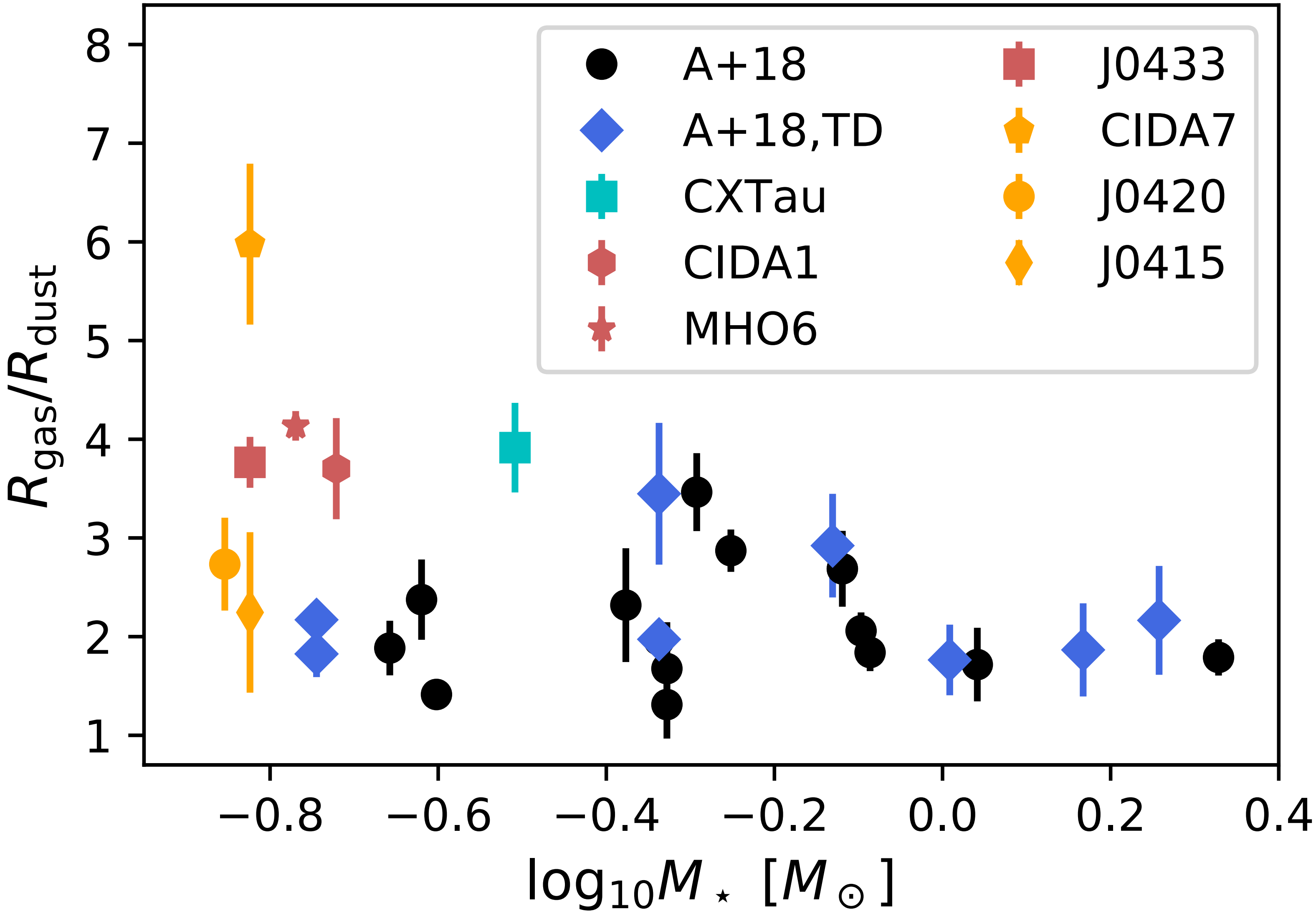
The $R_{eff} - L_{mm}$ relation may flatten due to inefficient radial drift, in which case R_{eff} traces the location of the farther pressure bump at any time of evolution.



Size and structures in disks around very low mass stars

6 disks in Taurus observed at high angular resolution (continuum, 12CO and 13CO)

Structures in 50% of the sample

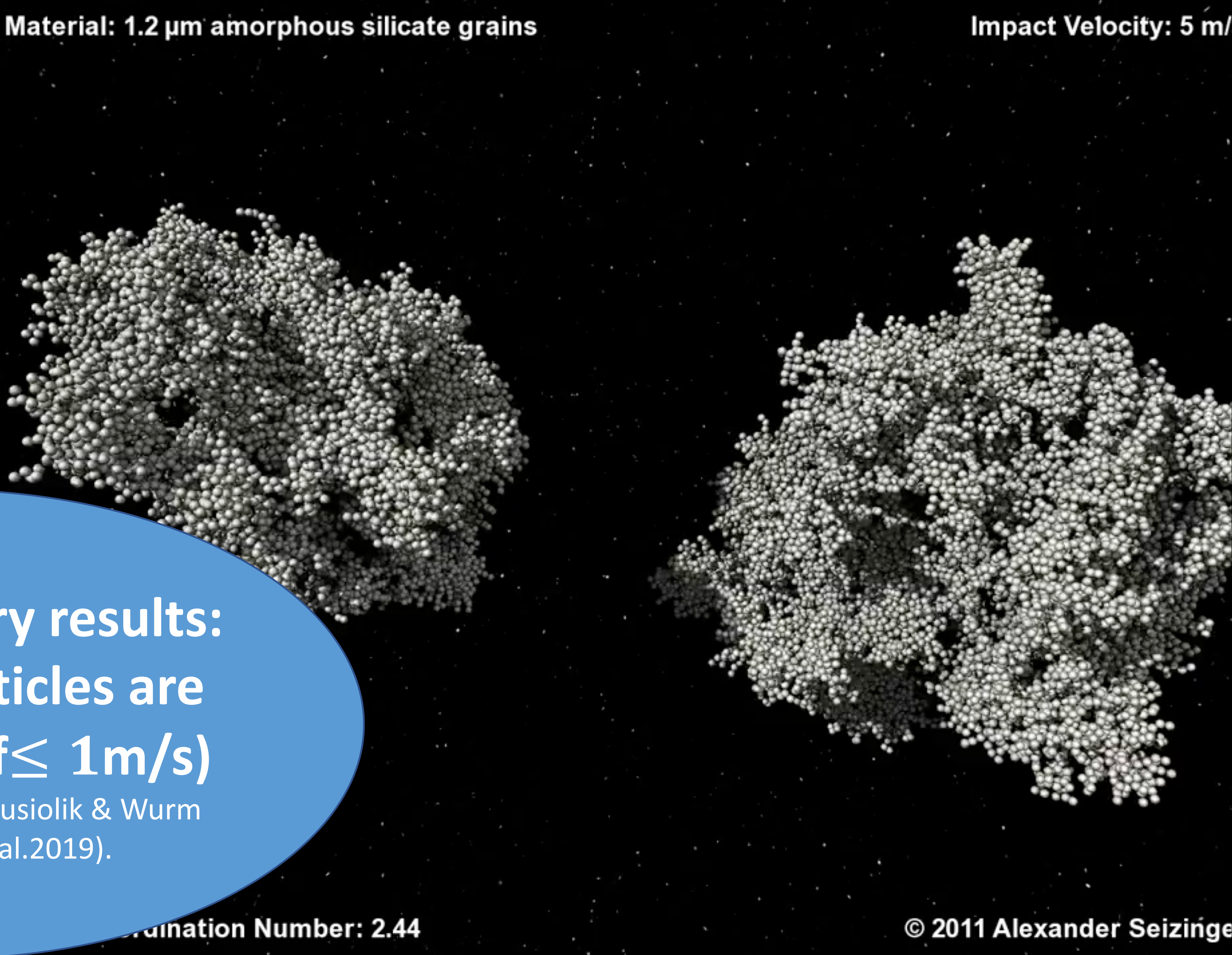


High R_{gas}/R_{dust} evidences very efficient radial drift

Kurtovic, Pinilla et al. (submitted)

kurtovic@mpia.de

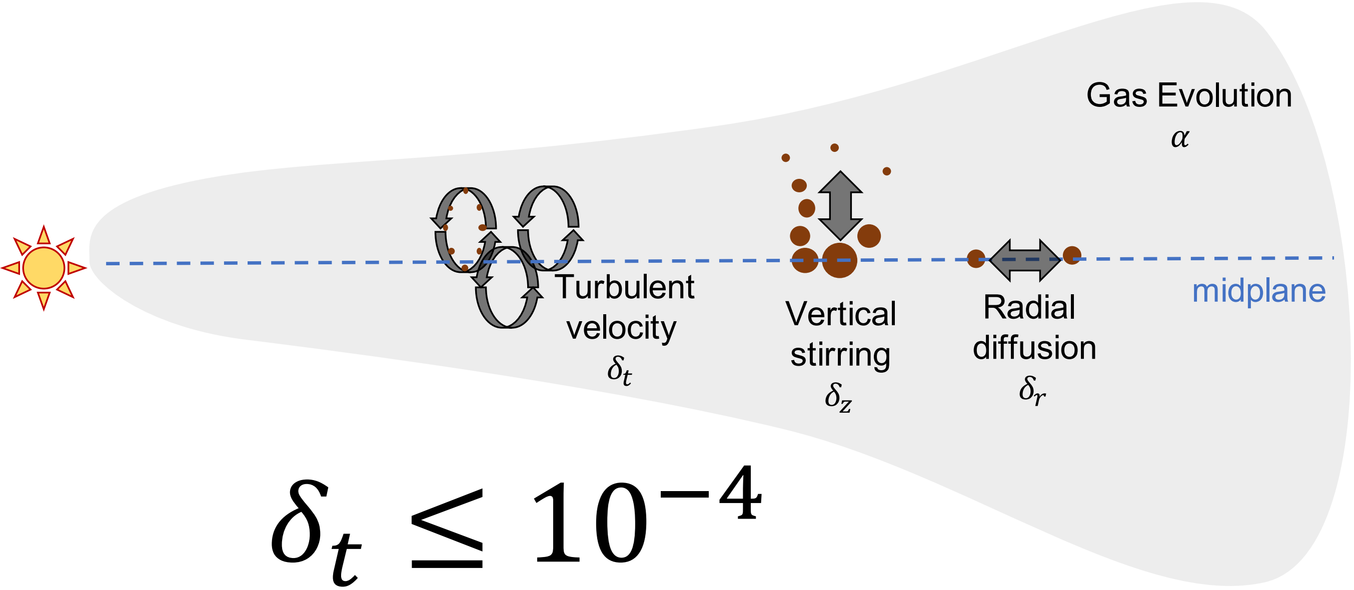
Fragmentation Velocities



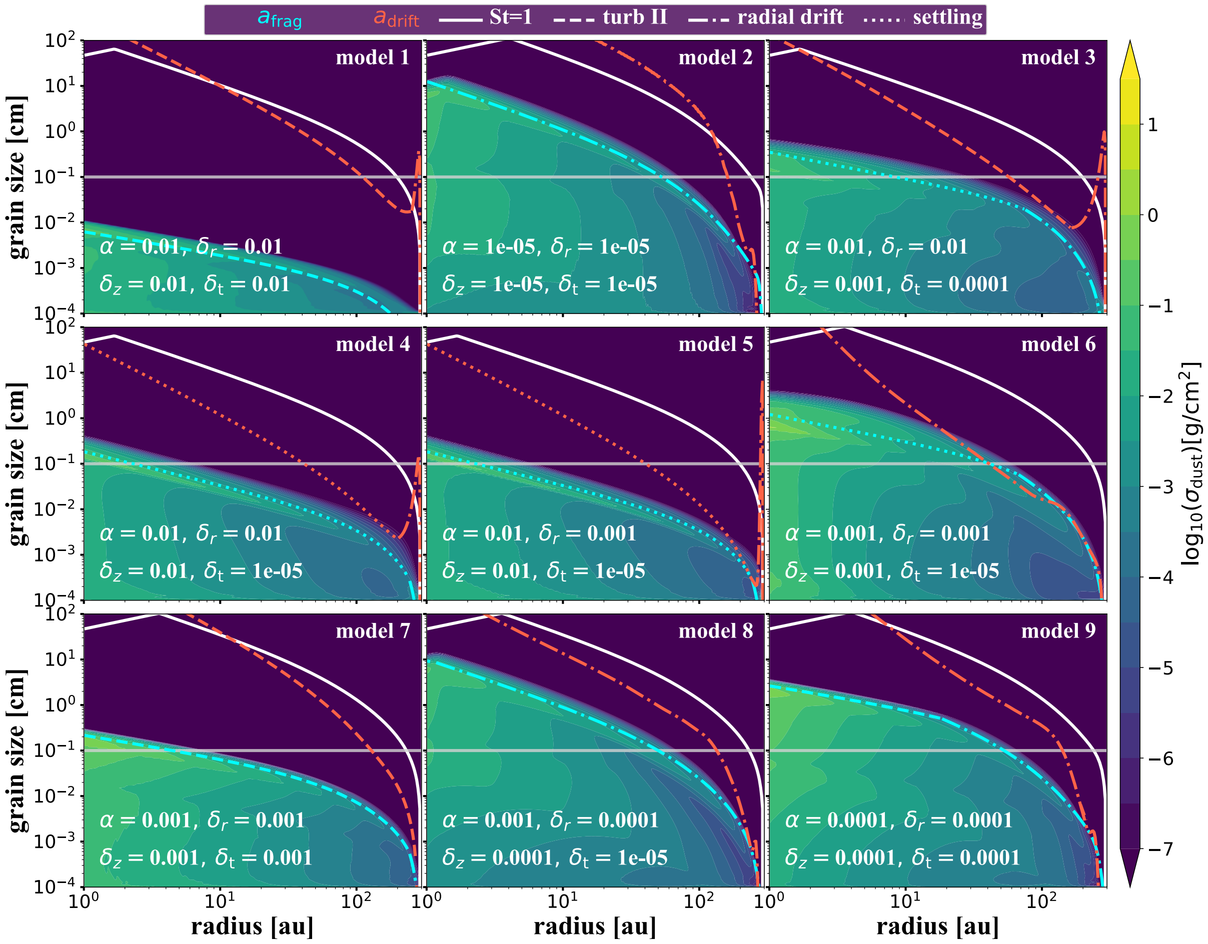
New Laboratory results: Water ice particles are very fragile ($v_f \leq$ 1m/s)

(Gundlach et al. 2018; Musiolik & Wurm 2019; Steinpilz et al.2019).

How we can grow to pebbles and trap them with low v_f



$$\delta_t \leq 10^{-4}$$
$$\delta_z \leq 10^{-3}$$
$$\delta_r \geq 10^{-3}$$
$$\alpha \sim 10^{-3} - 10^{-2}$$



Pinilla & Lenz (submitted)

Future Perspectives

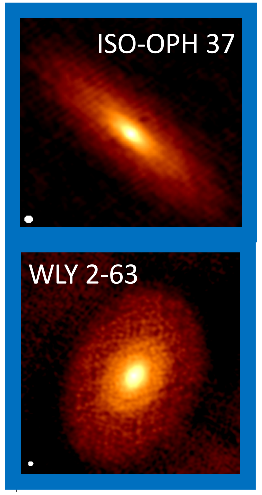
Discs form with no clear gaps or only shallow gaps.

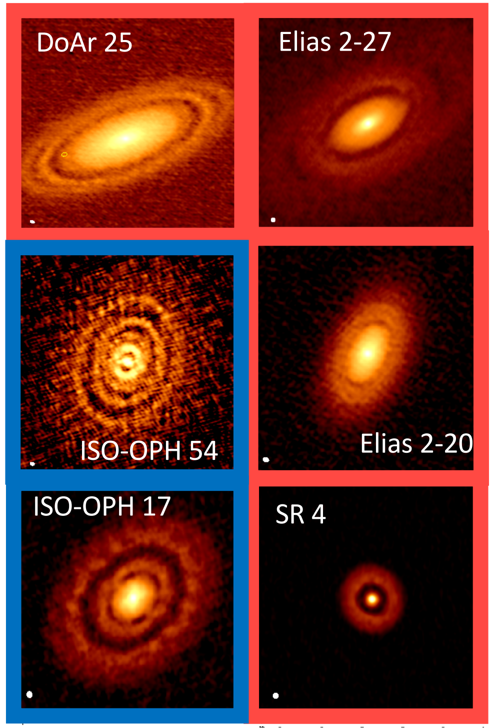
Planets start to growth, resulting in clear rings and/or deep gaps.

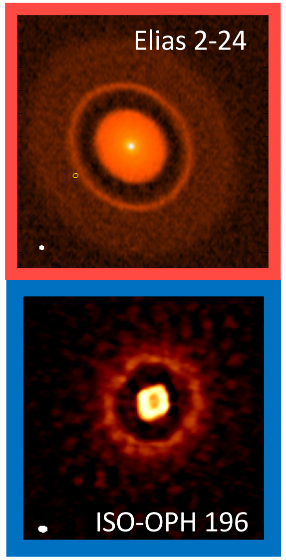
Some planets become gas giants through runway gas accretion and gaps widen. Dust starts to accumulate at the inner edges of the rings.

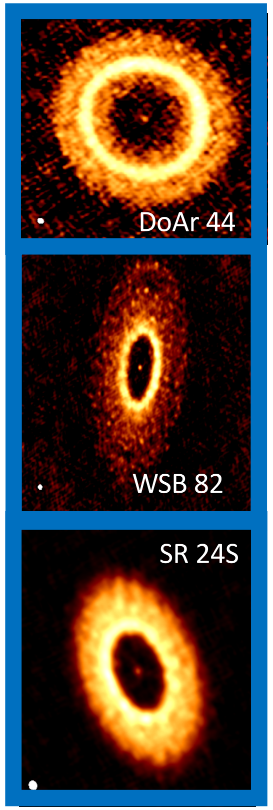
Dust filtration at cavity edges deplete dusty inner discs. Dust from outer discs continue to accumulate in rings.

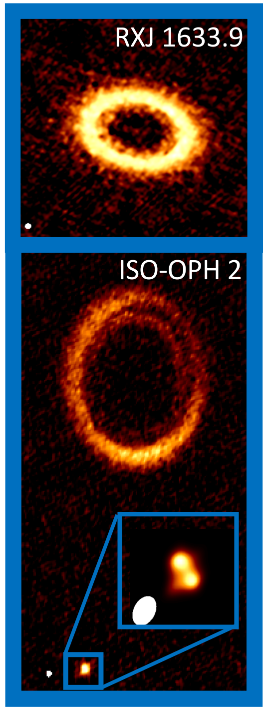
Inner dust discs dissipate. Most of the dust from the outer discs accumulates in the rings.











ODISEA

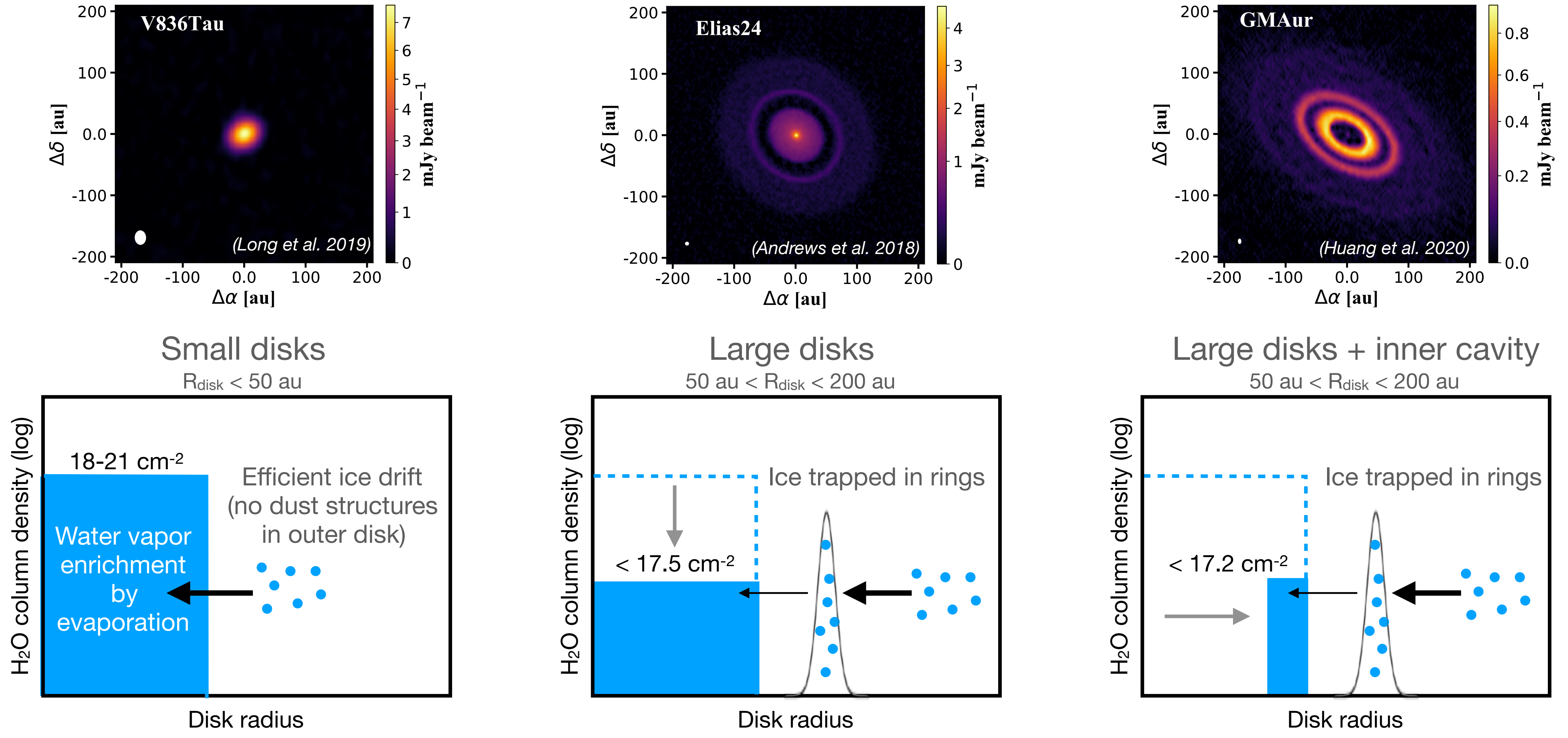
DSHARP

The brightest disks in ODISEA: only program with ALMA observing disks in one single star-forming region at 0.02-0.05''

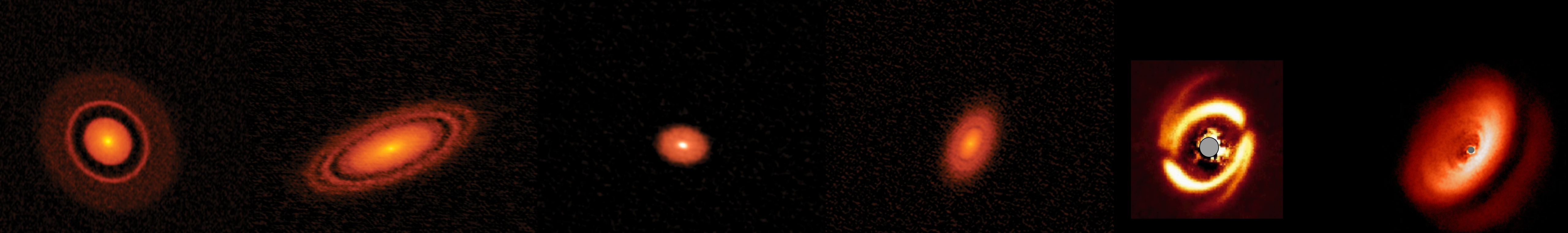
Cieza+ (submitted)

Effect of Structures on the Inner Disk Composition

Banzatti, et al. (2020)



Dust delivers water to the inner disk (<1au). It has an important effect on planet composition



Thank you for your attention