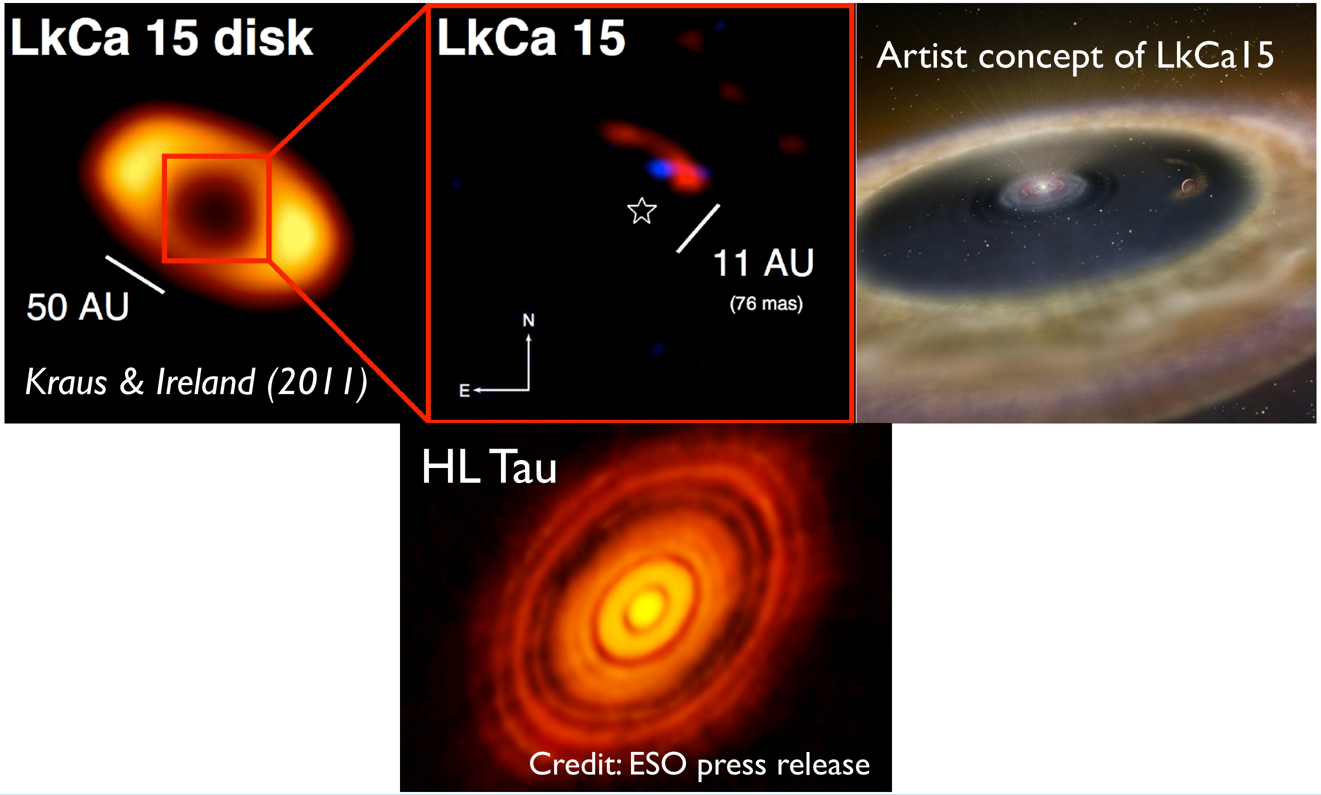


Grain growth and dust trapping in circumstellar disks

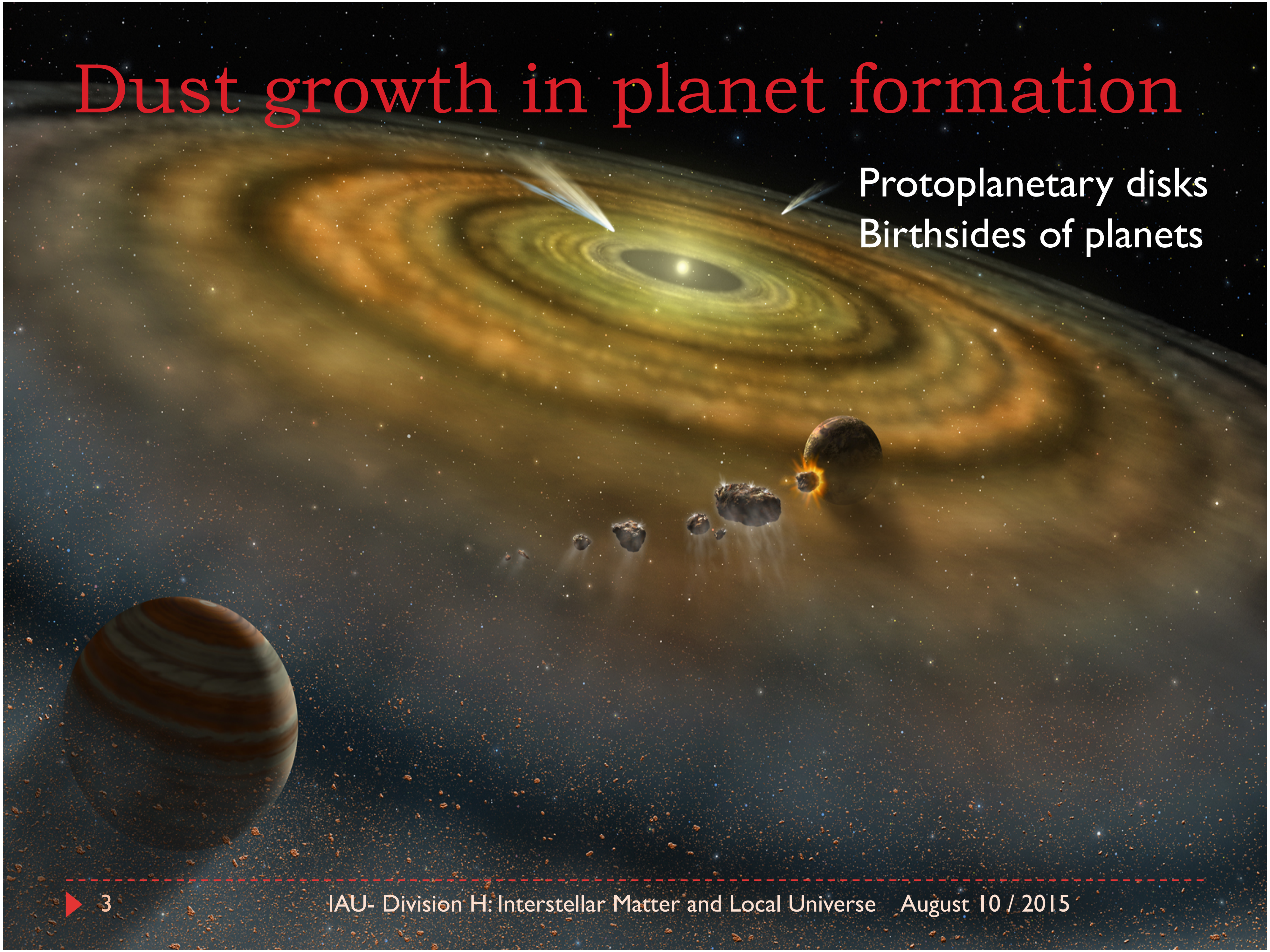
Paola Pinilla
Leiden Observatory

IAU- Division H: Interstellar Matter and Local Universe August 10 / 2015

Outline

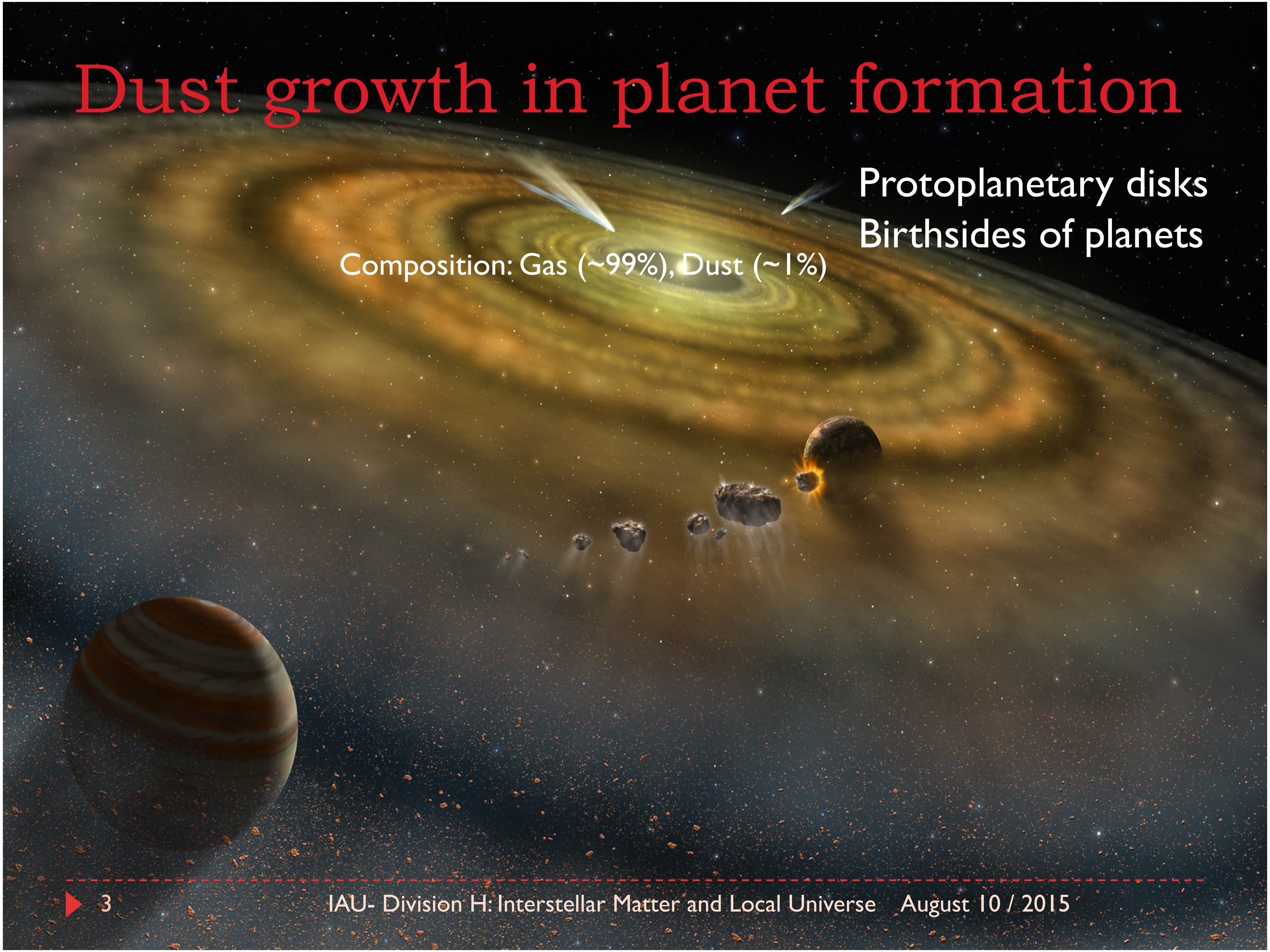
- The role of dust growth in planet formation.
- Dust collisions: laboratory & numerical experiments.
- Dust evolution models: **the radial drift barrier**.
- Pressure traps as a solution of the radial drift problem.
- Example of pressure traps:
  - Multiple rings (HLTau)
  - Rings and asymmetries in transition disks
- Take-away messages

Dust growth in planet formation



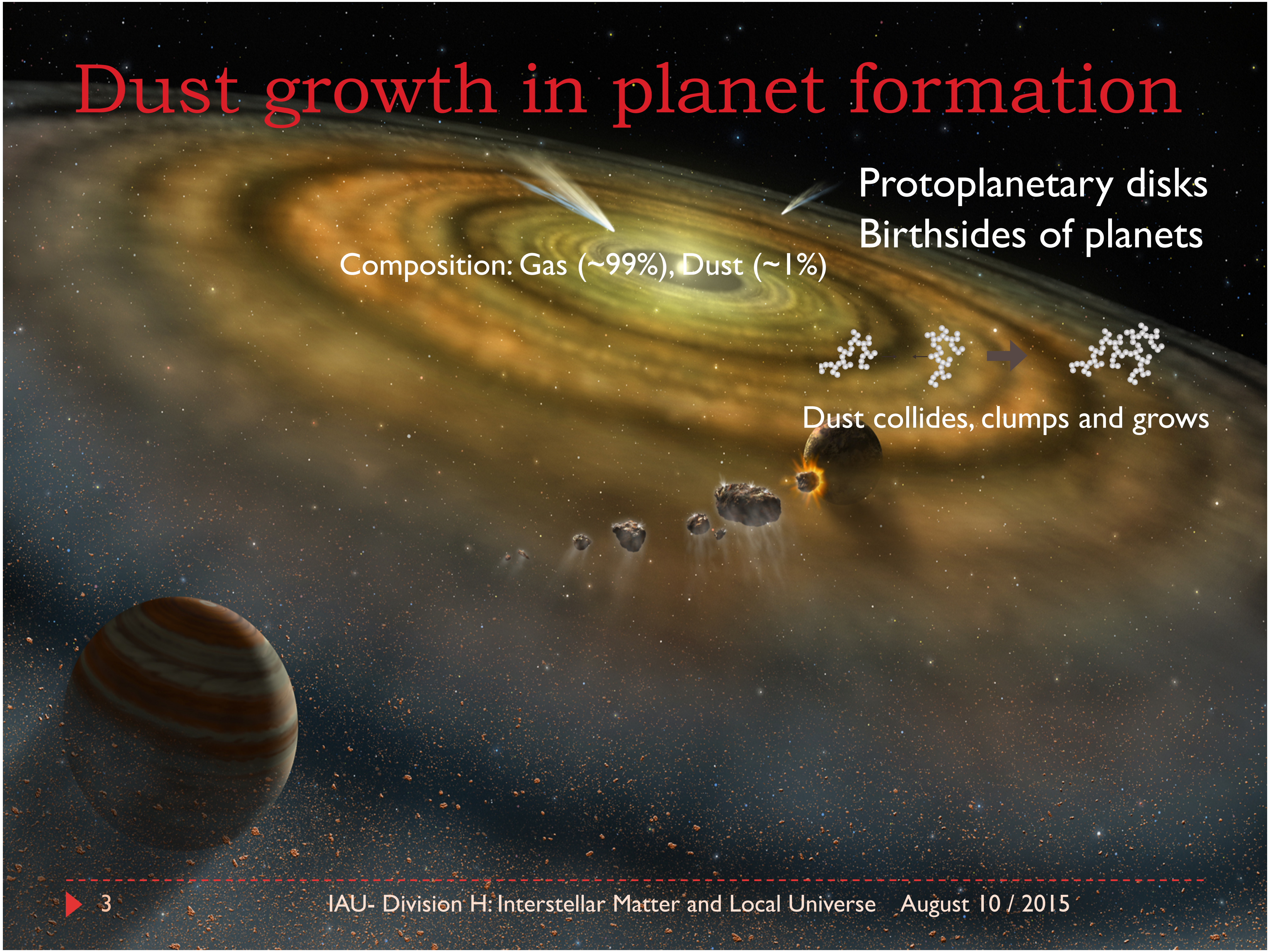
Protoplanetary disks
Birthsides of planets

Dust growth in planet formation

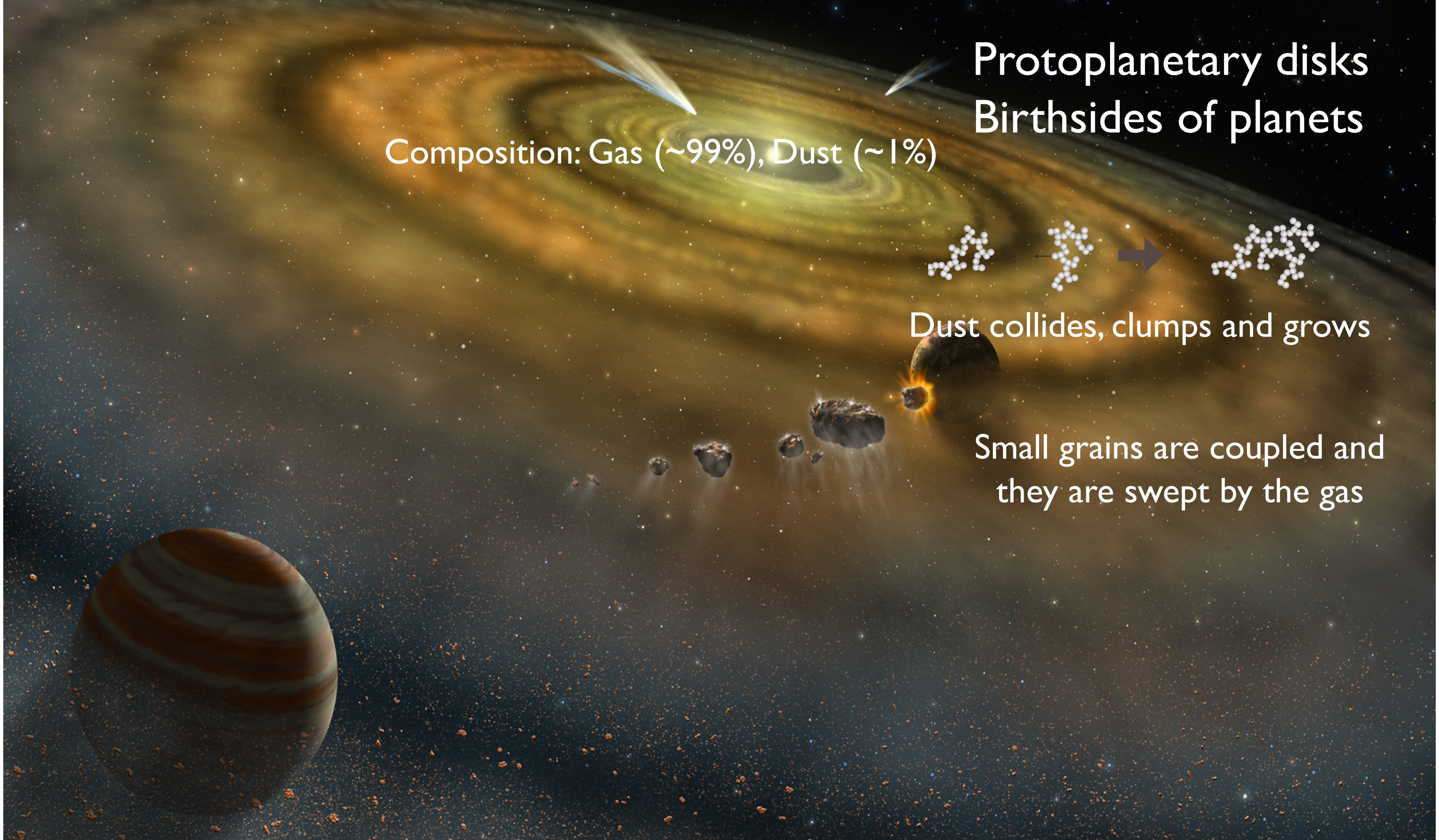


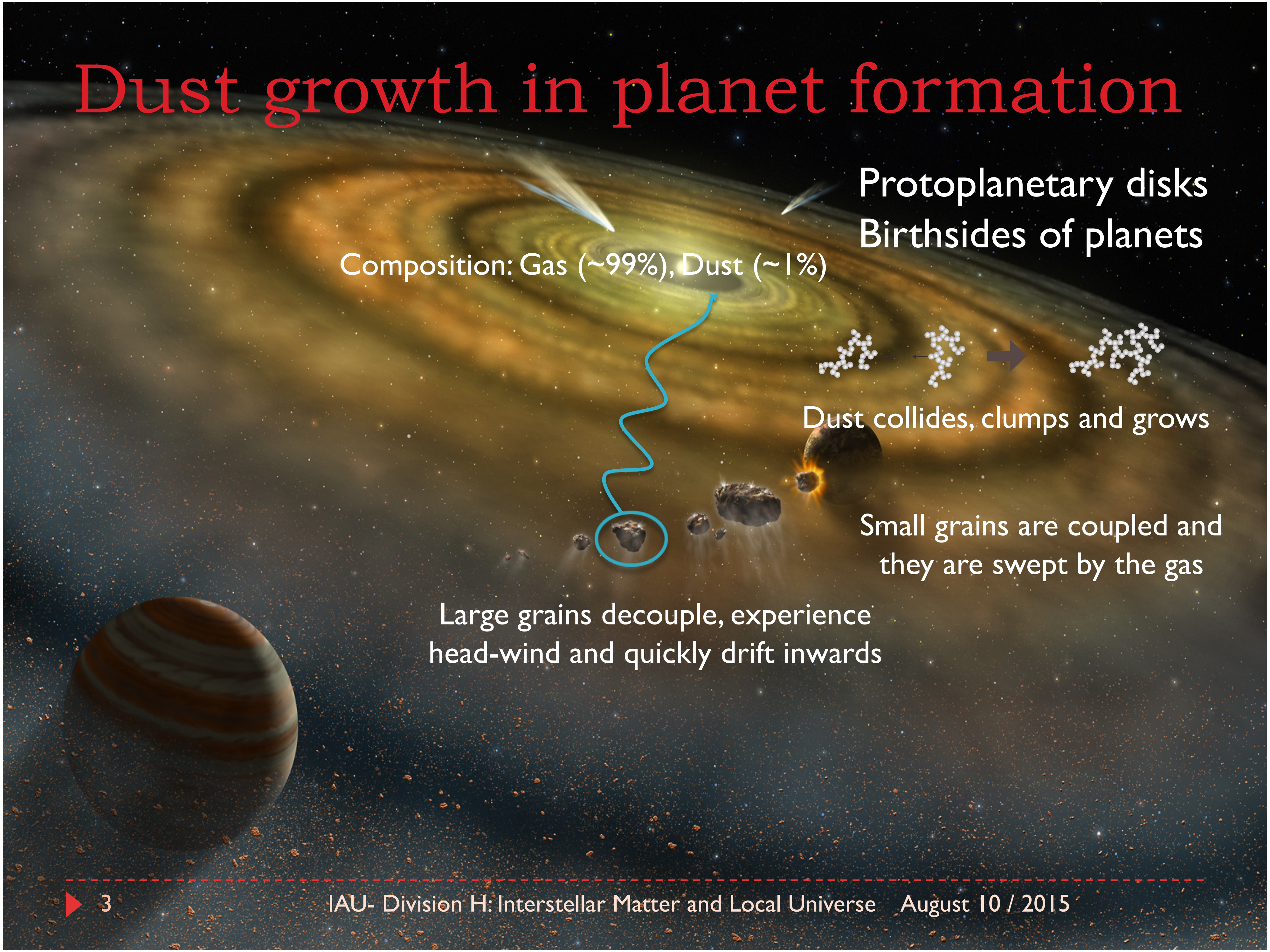
Protoplanetary disks
Birthsides of planets

Composition: Gas (~99%), Dust (~1%)


Dust growth in planet formation
Protoplanetary disks
Birthsides of planets
Composition: Gas (~99%), Dust (~1%)
Dust collides, clumps and grows

Dust growth in planet formation



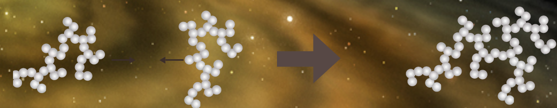

Dust growth in planet formation
Protoplanetary disks
Birthsides of planets
Composition: Gas (~99%), Dust (~1%)
Dust collides, clumps and grows
Small grains are coupled and
they are swept by the gas
Large grains decouple, experience
head-wind and quickly drift inwards
3
IAU- Division H: Interstellar Matter and Local Universe August 10 / 2015

Dust growth in planet formation

Protoplanetary disks
Birthsides of planets

Composition: Gas (~99%), Dust (~1%)

Preferential regions where dust can continue growing to planetesimals



Dust collides, clumps and grows

Small grains are coupled and they are swept by the gas

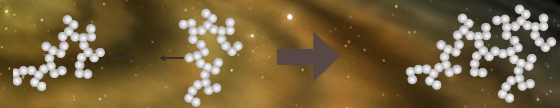
Large grains decouple, experience head-wind and quickly drift inwards

Dust growth in planet formation

Protoplanetary disks
Birthsides of planets

Composition: Gas (~99%), Dust (~1%)

Preferential regions where dust can continue growing to planetesimals



Dust collides, clumps and grows

Small grains are coupled and they are swept by the gas

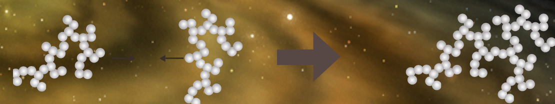
Large grains decouple, experience head-wind and quickly drift inwards

Planets grow through the accretion of planetesimals

Dust growth in planet formation

Protoplanetary disks
Birthsides of planets

Composition: Gas (~99%), Dust (~1%)



Dust collides, clumps and grows

Preferential regions where dust can continue growing to planetesimals

Small grains are coupled and they are swept by the gas

Large grains decouple, experience head-wind and quickly drift inwards

Planets grow through the accretion of planetesimals

Massive planets open gaps and eventually form more traps

DUST EVOLUTION IN CIRCUMSTELLAR DISKS

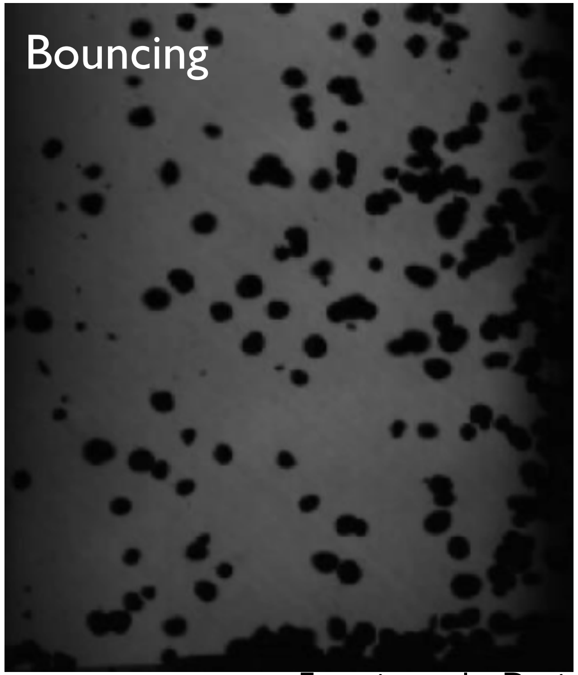
Laboratory and Numerical Experiments
Dust Evolution Models

What we know about dust collisions?

Laboratory Experiments

Stick   Fragment   Bounce   Transfer mass

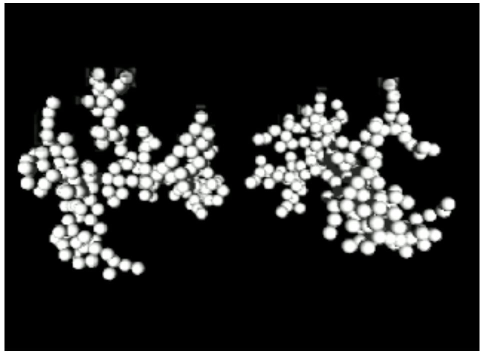
erode, crater



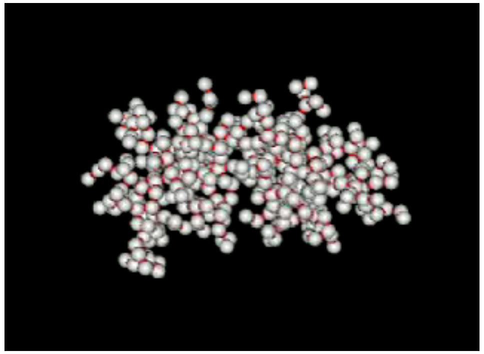
Experiment by Daniel Heißelmann
(IGEP, Germany)

Numerical Simulations

e.g. Paszun & Dominik (2009)



Collisions with ice monomers at 8m/s



Collisions with silicate monomers at 2m/s

The lack of ice mantles in dust particles decreases the sticking efficiency between grains

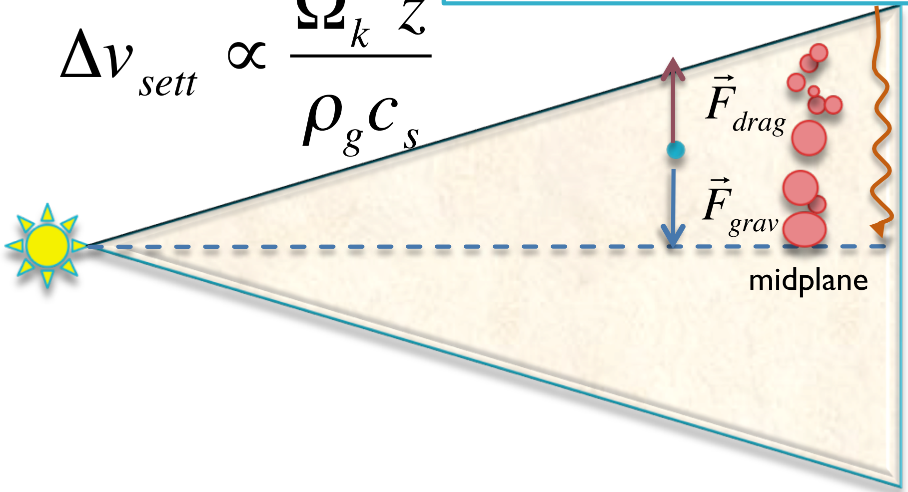
ice $\rightarrow v_{frag} = 10 - 50 m/s$

silicates $\rightarrow v_{frag} = 1 - 5 m/s$

What we know about dust transport?

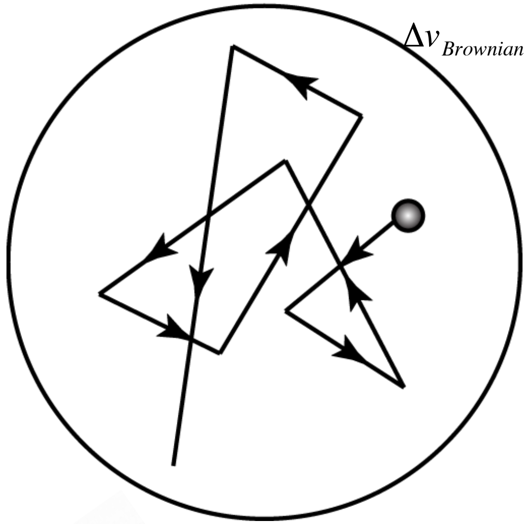
Settling to the midplane

$$\Delta v_{sett} \propto \frac{\Omega_k^{\,2} z}{\rho_g c_s}$$

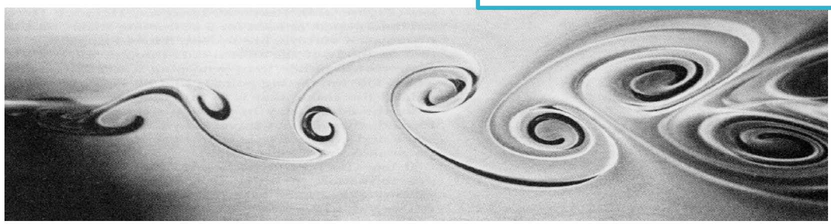


Brownian motion (small grains)

$$\Delta v_{Brownian} = \sqrt{\frac{8k_B T}{\pi} \times \frac{m_1 + m_2}{m_1 m_2}}$$



Turbulent mixing

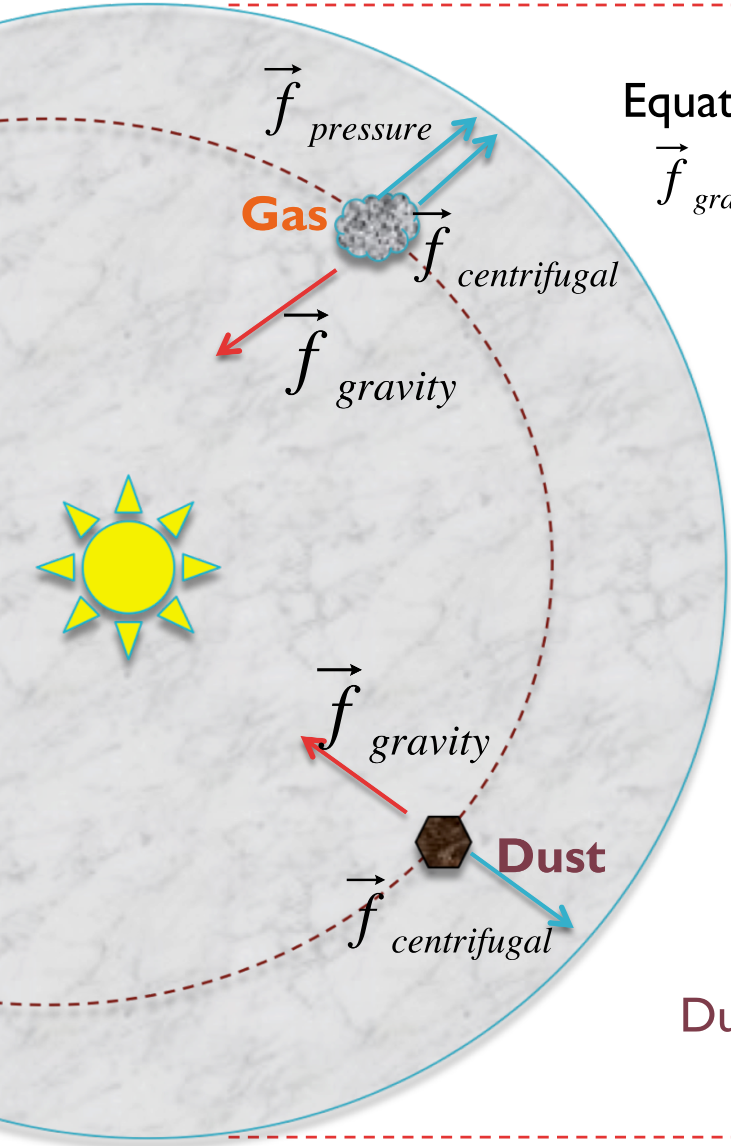


$$\Delta v_{turb} \propto \sqrt{\alpha_{turb}}\, c_s$$

Coupling and decoupling to turbulent eddies *(Ormel & Cuzzi 2007)*

Radial drift

Radial Drift



Equation of motion for the **gas:**

$$\vec{f}_{gravity} + \vec{f}_{centrifugal} + \vec{f}_{pressure} = 0$$

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

Gas moves with sub-Keplerian velocity

Equation of motion for the **dust:**

$$\vec{f}_{gravity} + \vec{f}_{centrifugal} \neq 0$$

$$\vec{f}_{gravity} + \vec{f}_{centrifugal} + \vec{f}_{drag} = 0$$

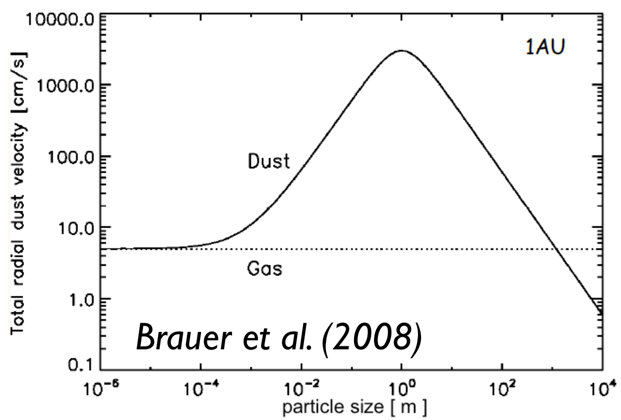
Dust moves towards the higher P_{gas}

e.g. *Weidenschilling (1977)*

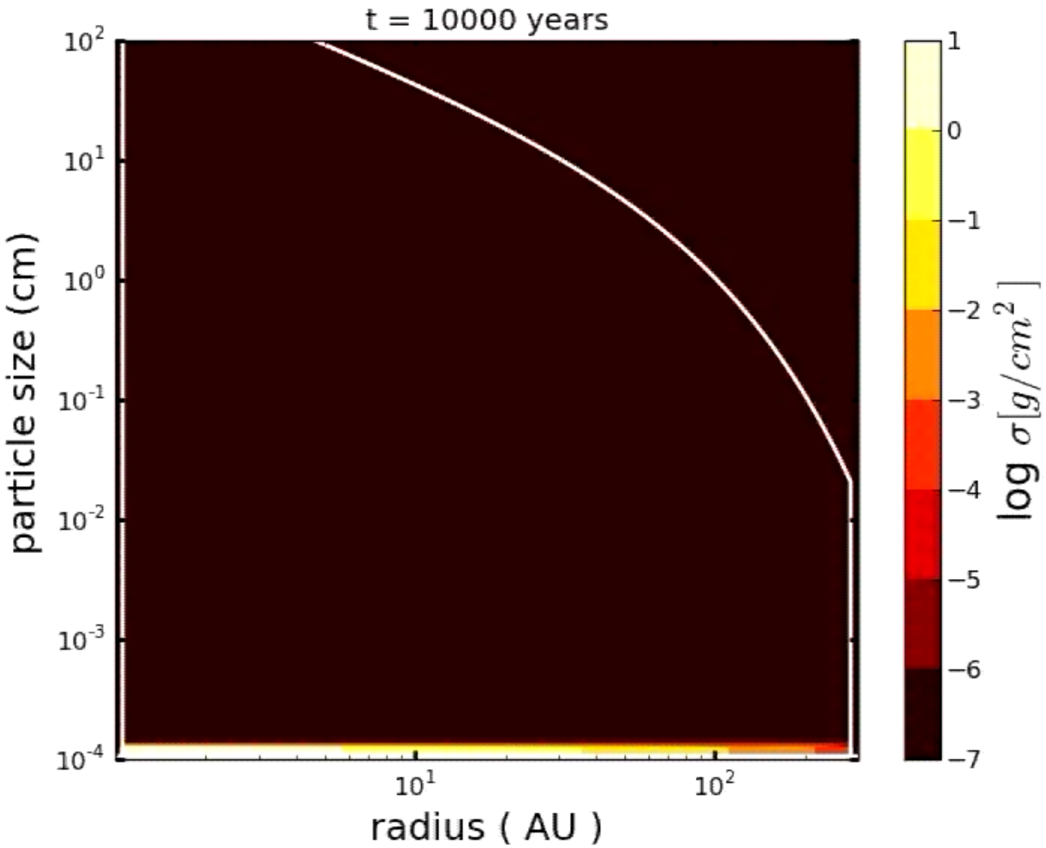
Dust Radial Velocities

$$v_{dust} = \underbrace{\frac{v_{gas}}{1+St^2}}_{drag-term} + \underbrace{\eta\frac{v_{Kepler}}{St+St^{-1}}}_{drift-term}$$

$$\eta = \frac{1}{\rho r \Omega^2}\frac{dP}{dr} \qquad St \propto \frac{a\rho_s}{\Sigma}$$



Dust evolution models: transport and growth



Birnstiel et al. (2010)

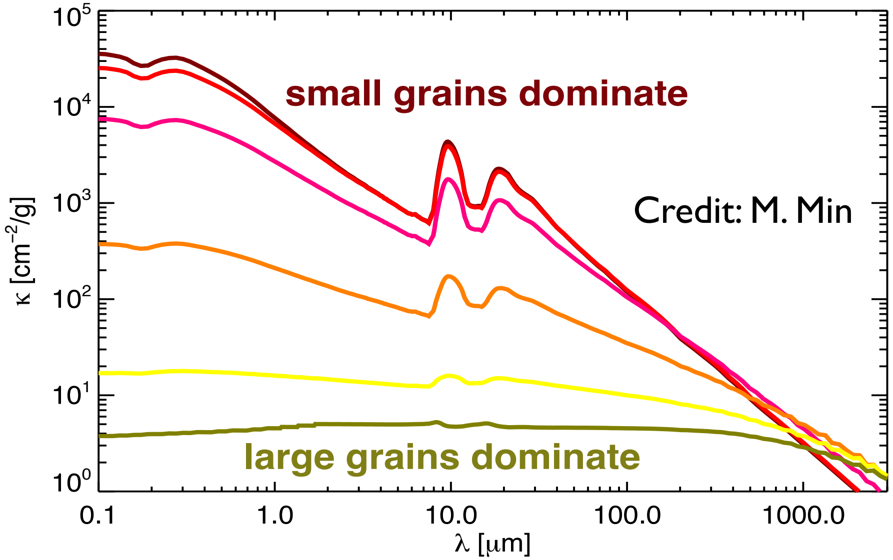
Solid white line $St \propto \frac{a\rho_s}{\Sigma} = 1$

The velocity before particles fragment is set in the models to ~10m/s (average for particles with ice mantles)

Growth
Sticking Erosion Fragmentation

Transport
Radial Drift Settling Turbulent mixing

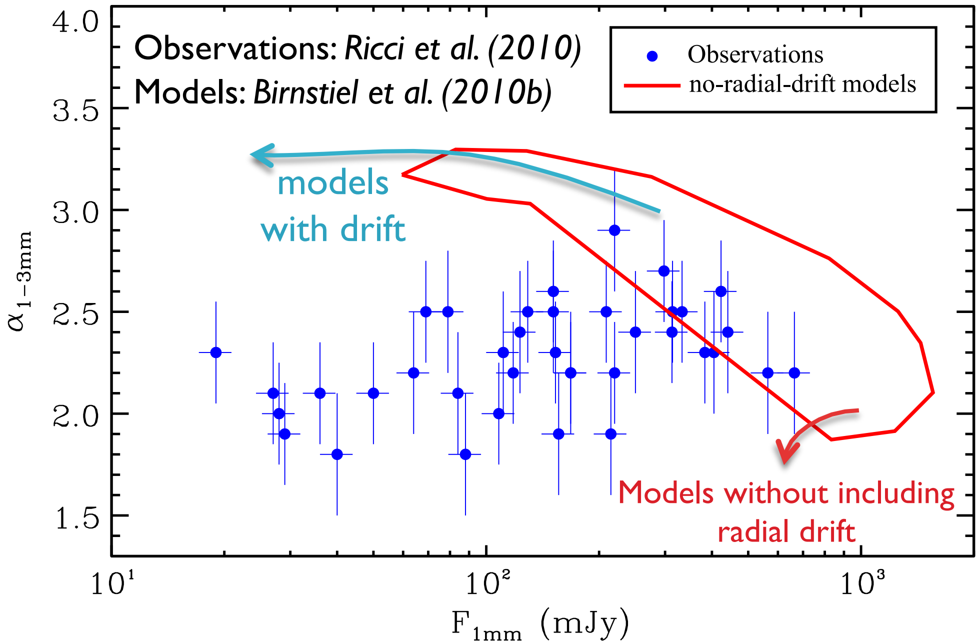
Evidence of mm-grains in PPD



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

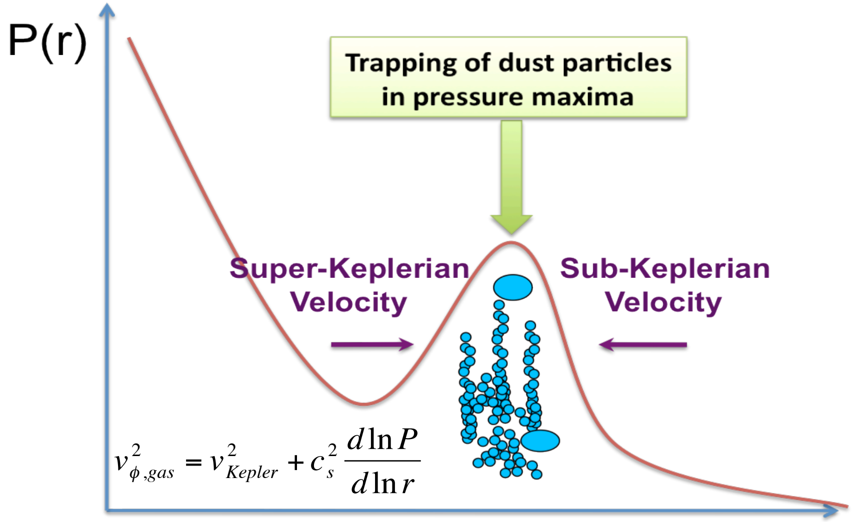
$$F_{\nu} \propto \nu^{\beta+2} \propto \nu^{\alpha_{mm}}$$

If $\beta \le 1$ (α_{mm}<3), dust grain have grown to millimeter sizes

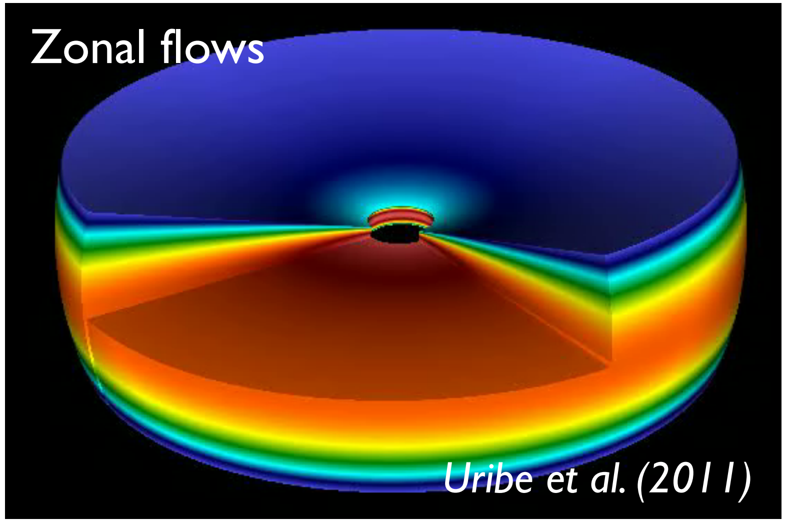


mm-sized pebbles survive despite the fast inward drift and possible fragmentation

Pressure bumps: Possible solution for the drift barrier



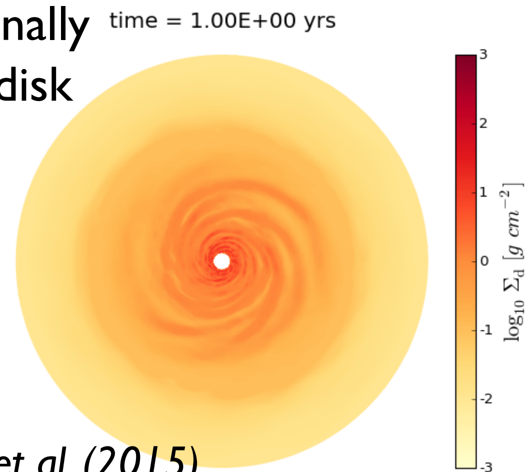
e.g. Klahr & Henning (1997) ; Fromang & Nelson (2005); Johansen et al. (2009); Pinilla et al. (2012a)



Example of pressure bumps in disks:

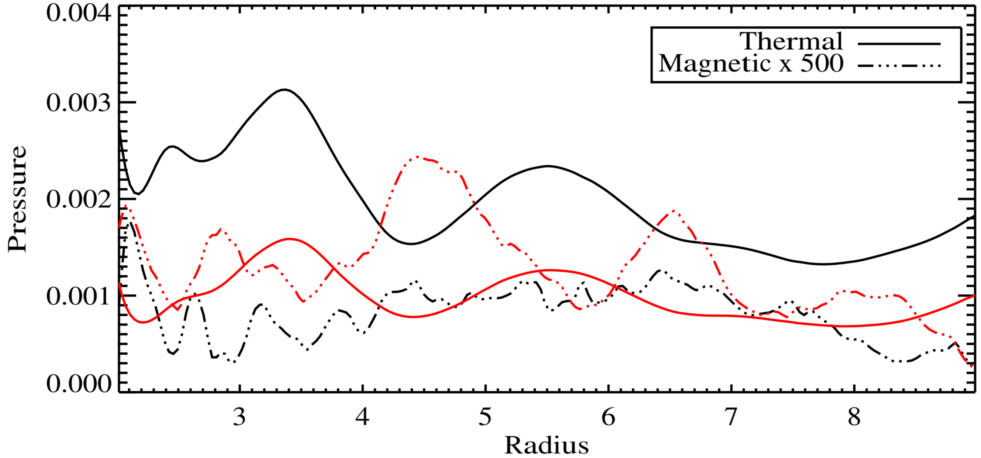
✓ Edge of a dead zone (regions of low ionization rate, e.g. Dzyurkevich et al. 2010)
✓ MRI instabilities (e.g. zonal flows, Uribe et al. 2011)
✓ Spiral arms in self-gravitating disks (e.g. Lodato & Rice 2004, Dipierro et al. 2015)
✓ Outer edge of a planet-carved gap (e.g. Pinilla et al. 2012b, Zhu et al., 2012)

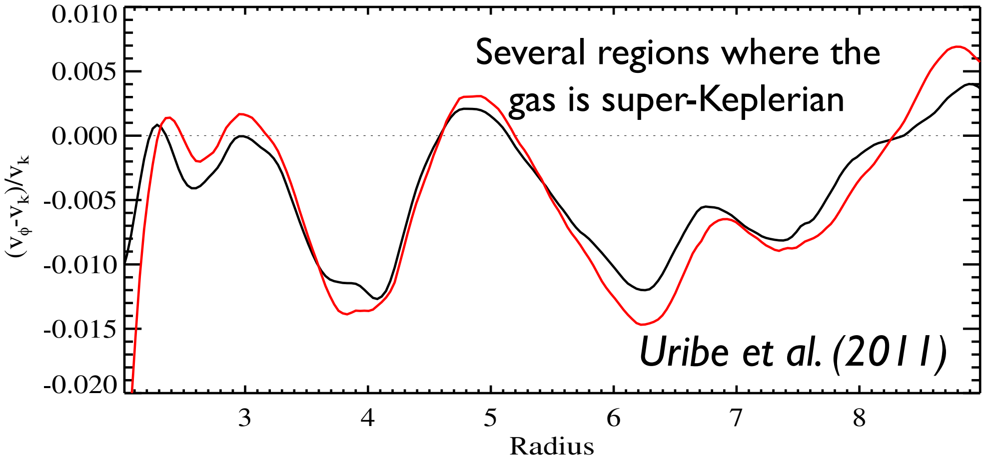
Gravitationally unstable disk



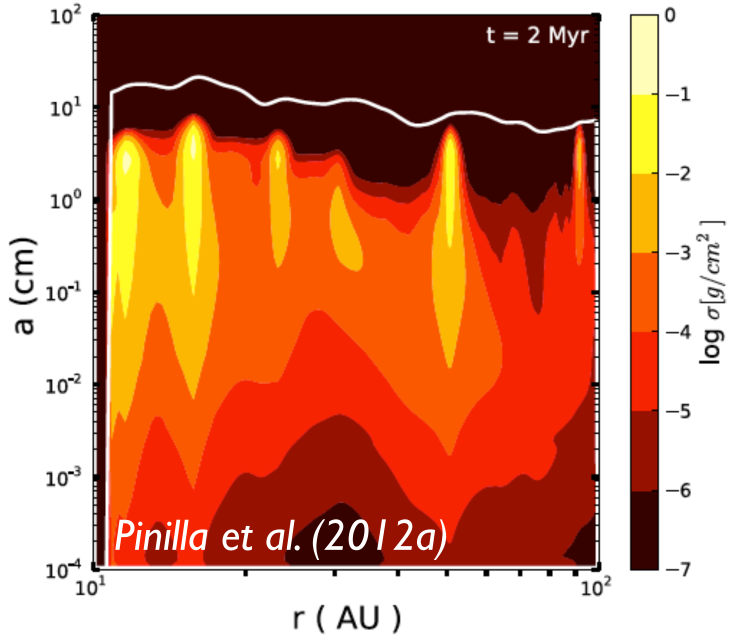
Dipierro et al. (2015)

Particle trapping by zonal flows





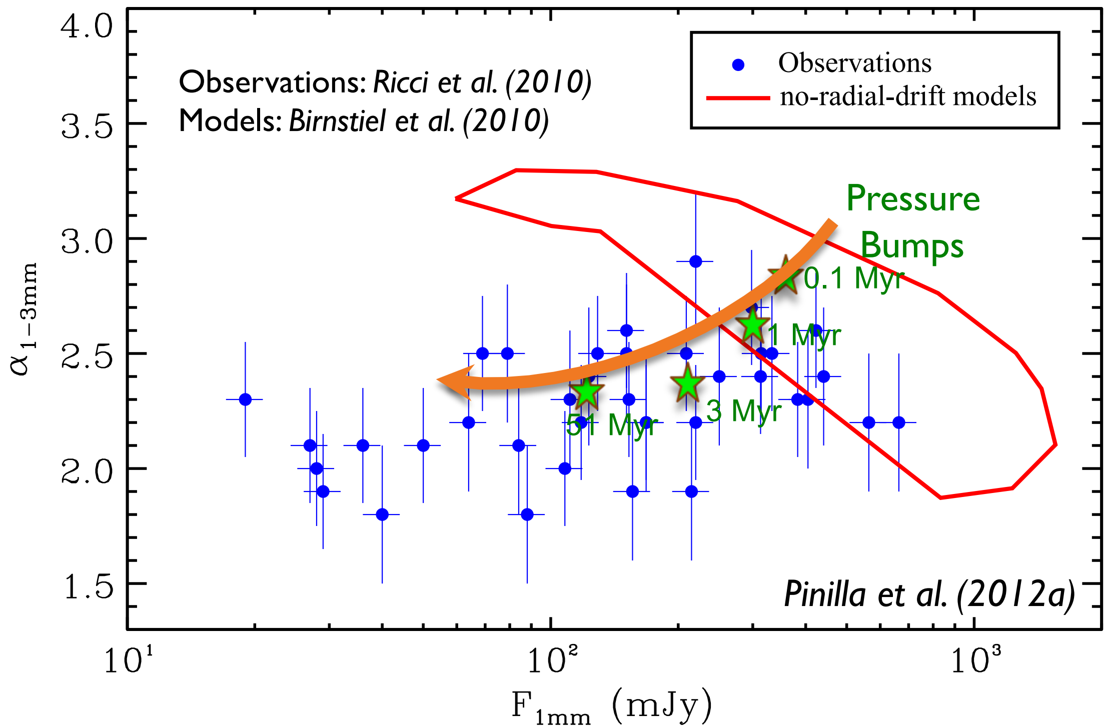
Dust density distribution at 2Myr

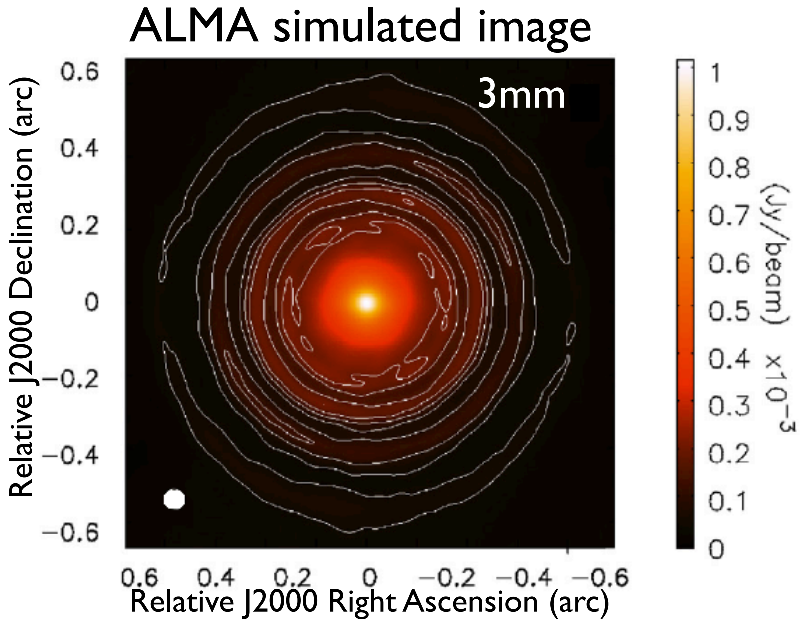


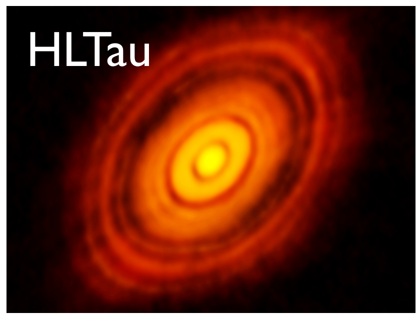
Pressure bumps of 25-30% of amplitude allow to reduce radial drift and keep millimeter particles in the outer regions of disks

See also Dittrich et al. (2013); Simon & Armitage (2014)

Comparison with observations

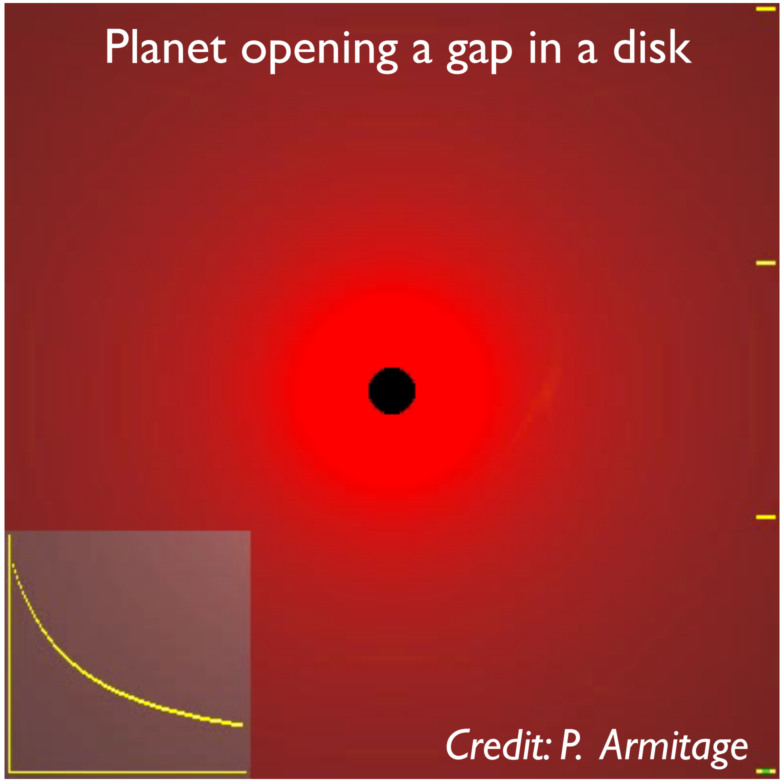


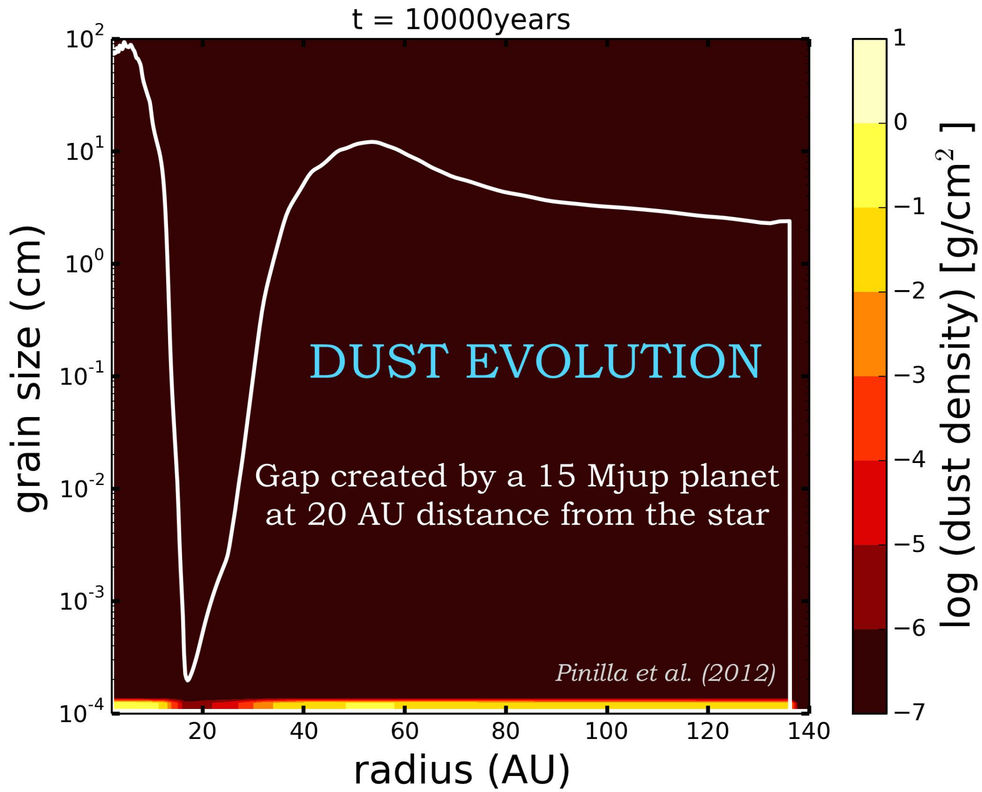




The observed rings in HLTau can originate from particle trapping in pressure bumps. These bumps naturally arise in simulations that include magnetic fields.

Trapping induced by embedded planets in disks

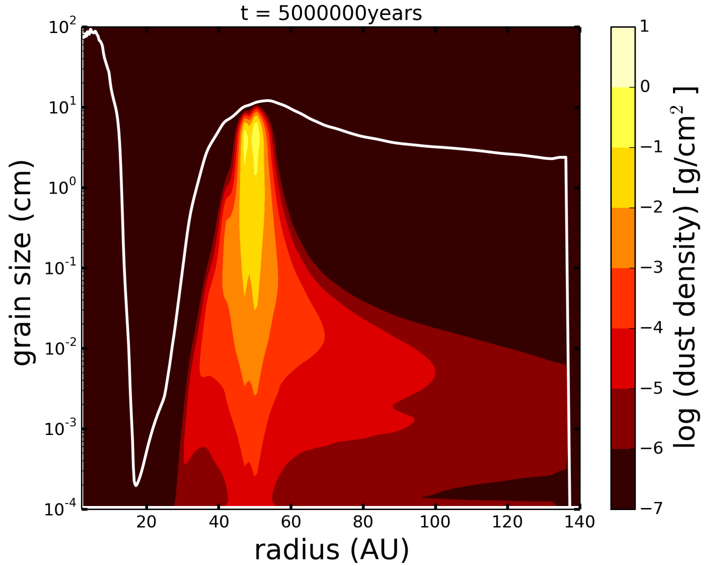




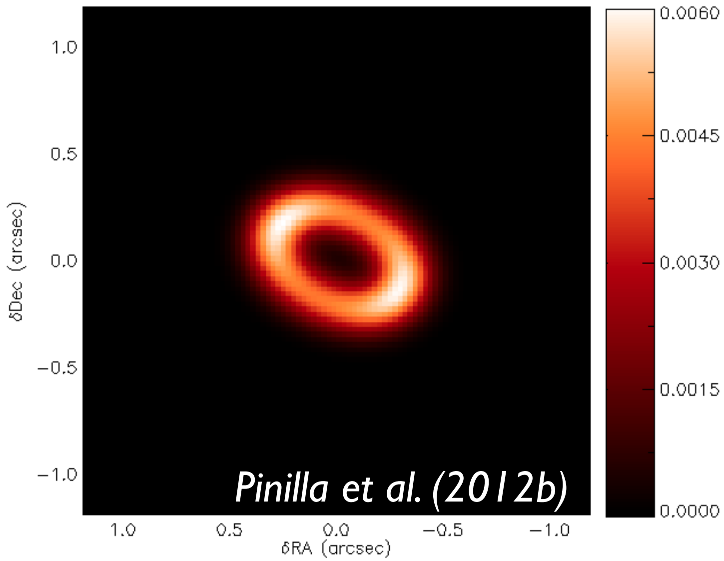
At the outer edge of a planet carved-gap, the pressure gradient is positive and particles can be trapped.

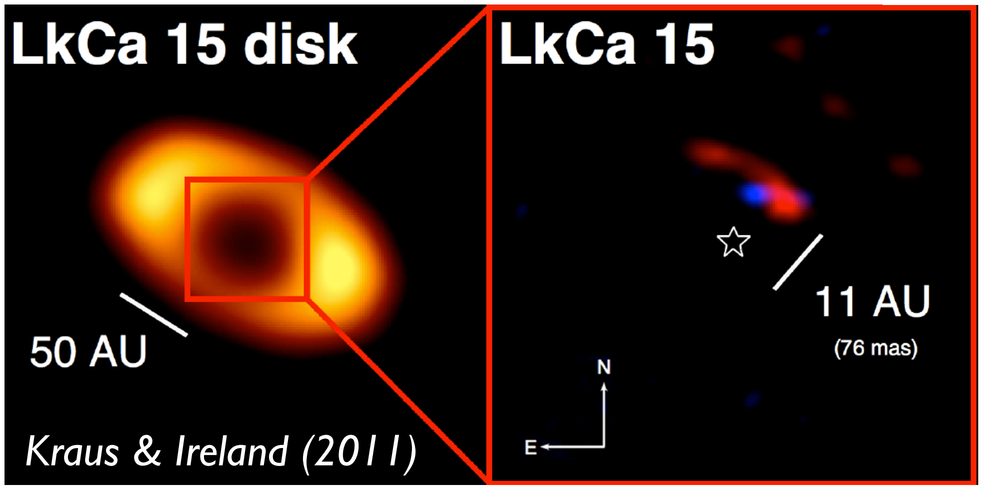
Solid white line $St \propto \frac{a\rho_s}{\Sigma} = 1$

Ring-like structure in transition disks



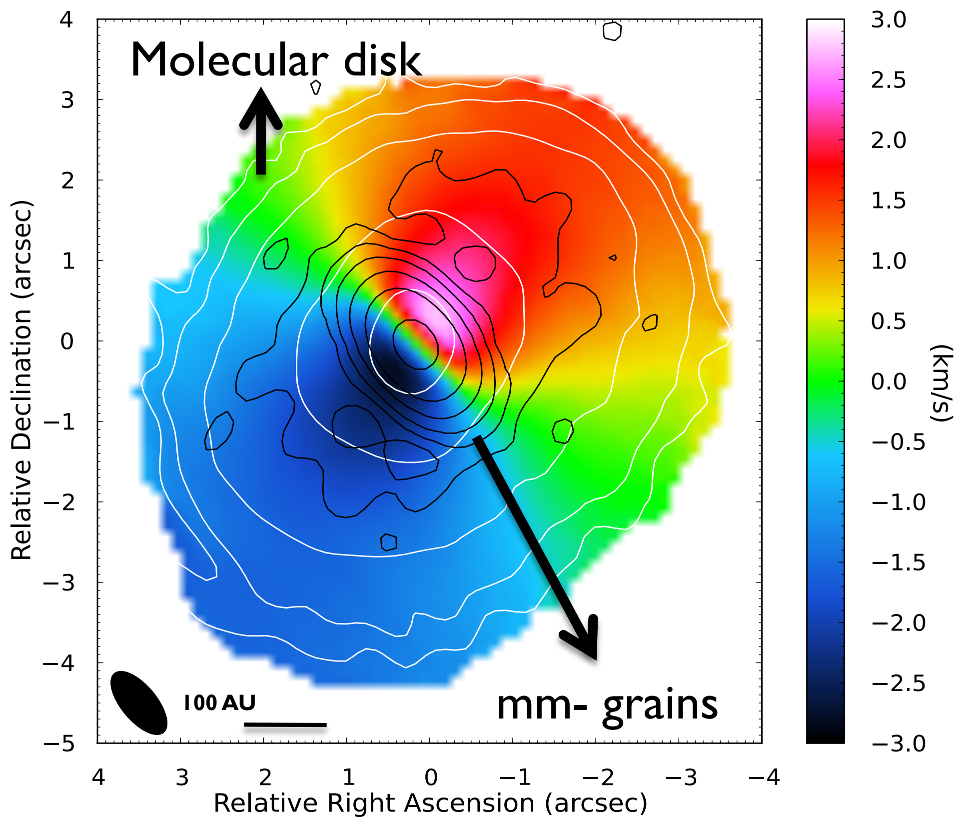
+ Radiative Transfer





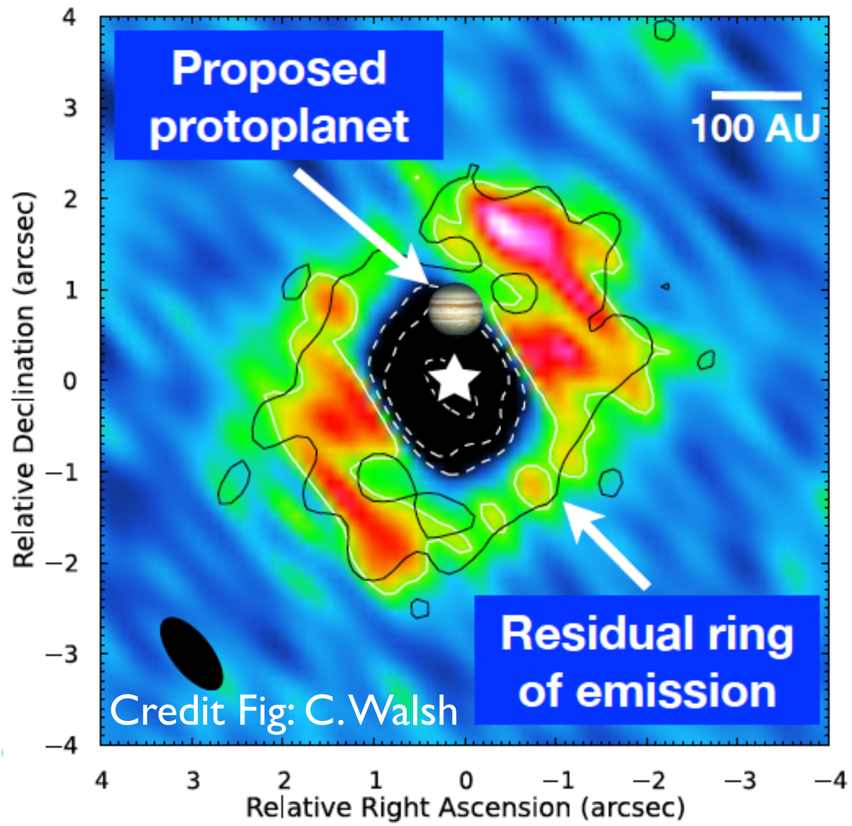
Transition disk structures appear to support the presence of ***unseen planets*** or companions in protoplanetary disks

HD100546: two ring-like emission



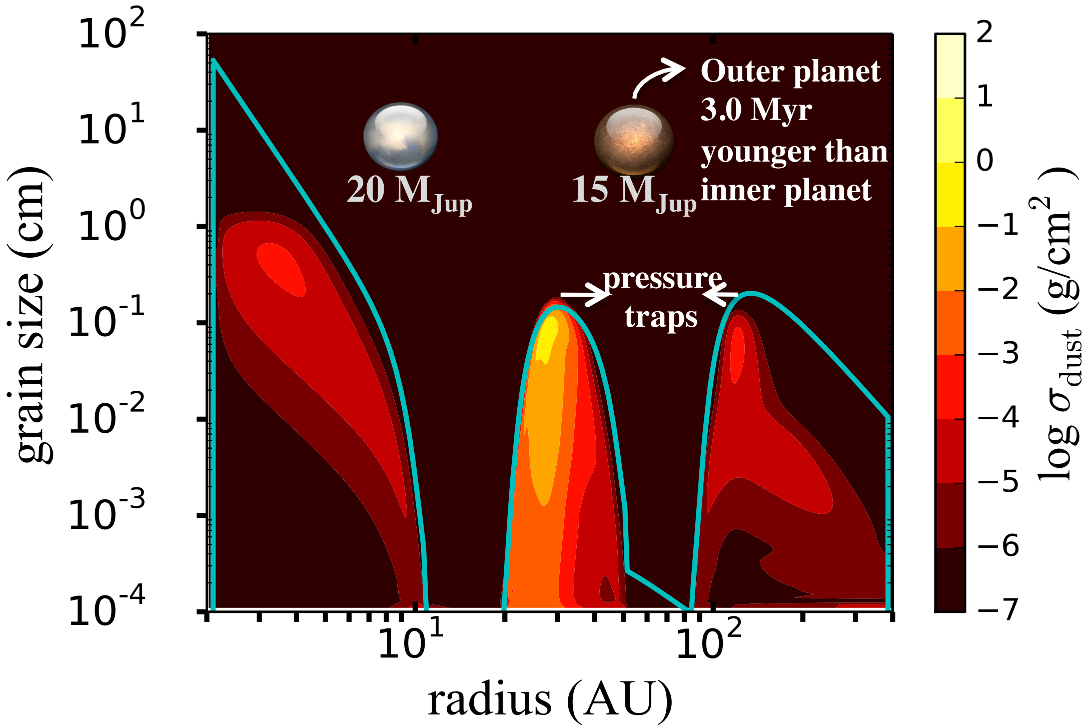
ALMA-Cycle 0, *Walsh et al. (2014)*

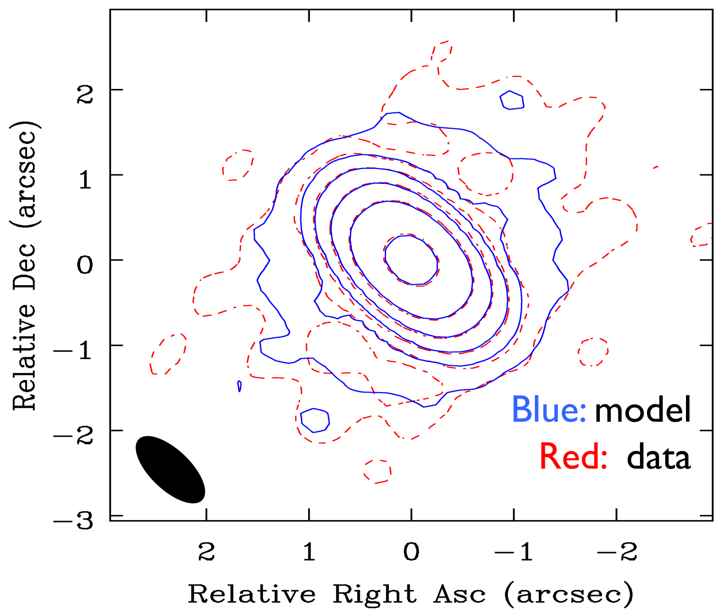
Large dust grains are significantly more centrally concentrated than molecular gas



Ring of dust external to the proposed protoplanet at 70 AU *(Quanz et al. 2013, 2015, Currie et al. 2015)*

Sequential planet formation in HD 100546





Pinilla et al. (in press)

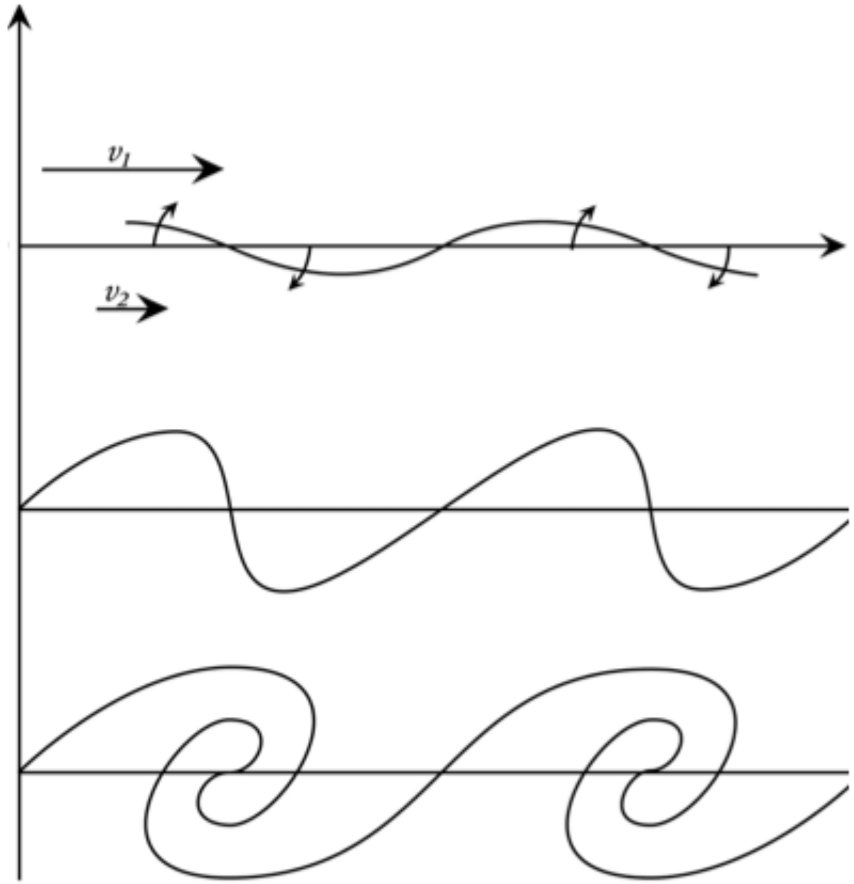
The two-ring like emission is consistent with tapping by two companions. If the outer companion is massive, it ***must be younger (2.5-3Myr)*** than the inner companion, to trap the right amount of dust.

Talk in FM 1(Wed 12 August)

No only radial trapping can happen
Azimuthal trapping too → Vortices

Velocity difference across the interface between two fluids

Rossby wave instability or Kelvin–Helmholtz instability in rotating disks



Example: coffee and cream

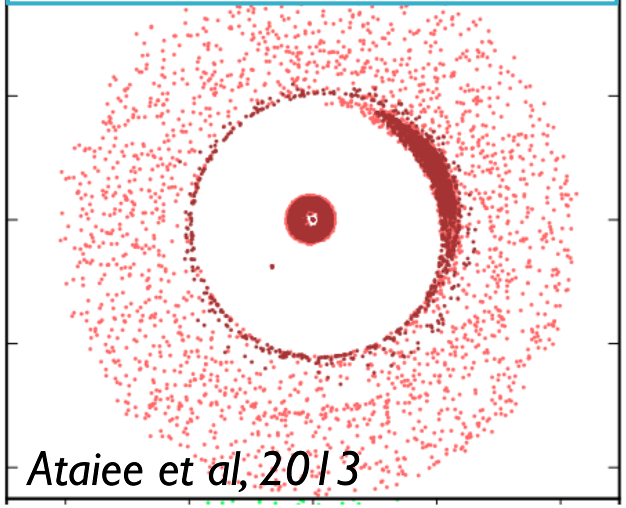
In a disk, they can form:

- Active/Dead boundary zone *(e.g. Lyra & Mac Low, 2012, Regaly et al., 2012, Flock et al, 2014)*
- At the edge of planet gap *(e.g. Ataiee et al, 2013, Zhu & Stone 2014)*

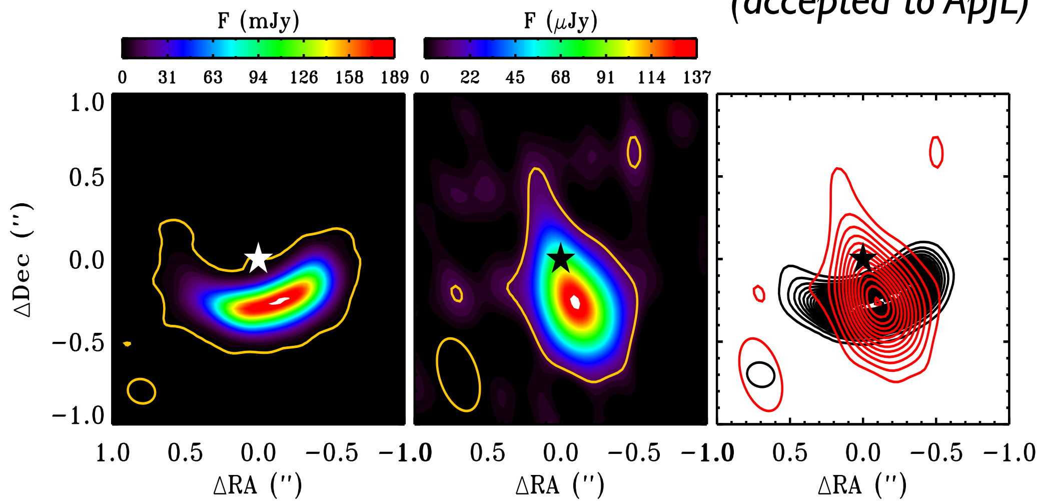
Vortices efficiently trap particles

IRS 48

Vortex at the outer edge of gap



ALMA Cycle 2 (Band 9 -450 μ m) | VLA (9 mm) | *van der Marel et al. (accepted to ApJL)*



Vortices can create high-contrast asymmetries. Larger grains are expected to be more azimuthally concentrated than smaller particles.

But not all the observed asymmetries are vortices.
Stay tuned for SR21 and HD 135344B cases *(Pinilla et al., in rev)*

Take-away messages

1. Rapid radial drift is a problem that affects all disks. Pressure traps should be a common phenomena in circumstellar disks.

Thank you!

2. Particle trapping can create single or multiple ring structures. Example: HLTau (magnetic pressure bumps), LkCa15, HD 100546 (embedded planets)

3. Vortices efficiently trap particles in the azimuthal direction, creating high-contrast asymmetries. Example: IRS 48