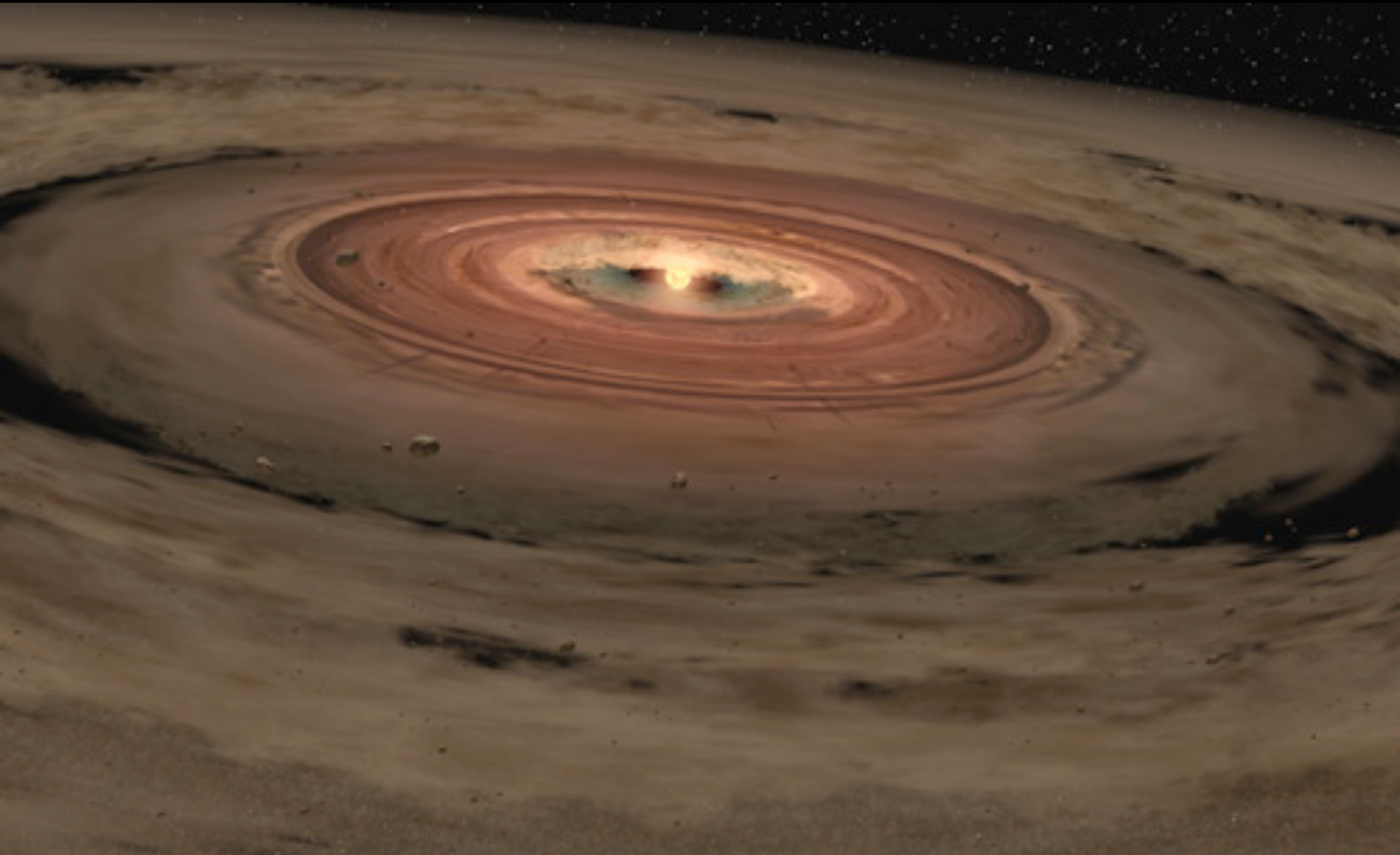
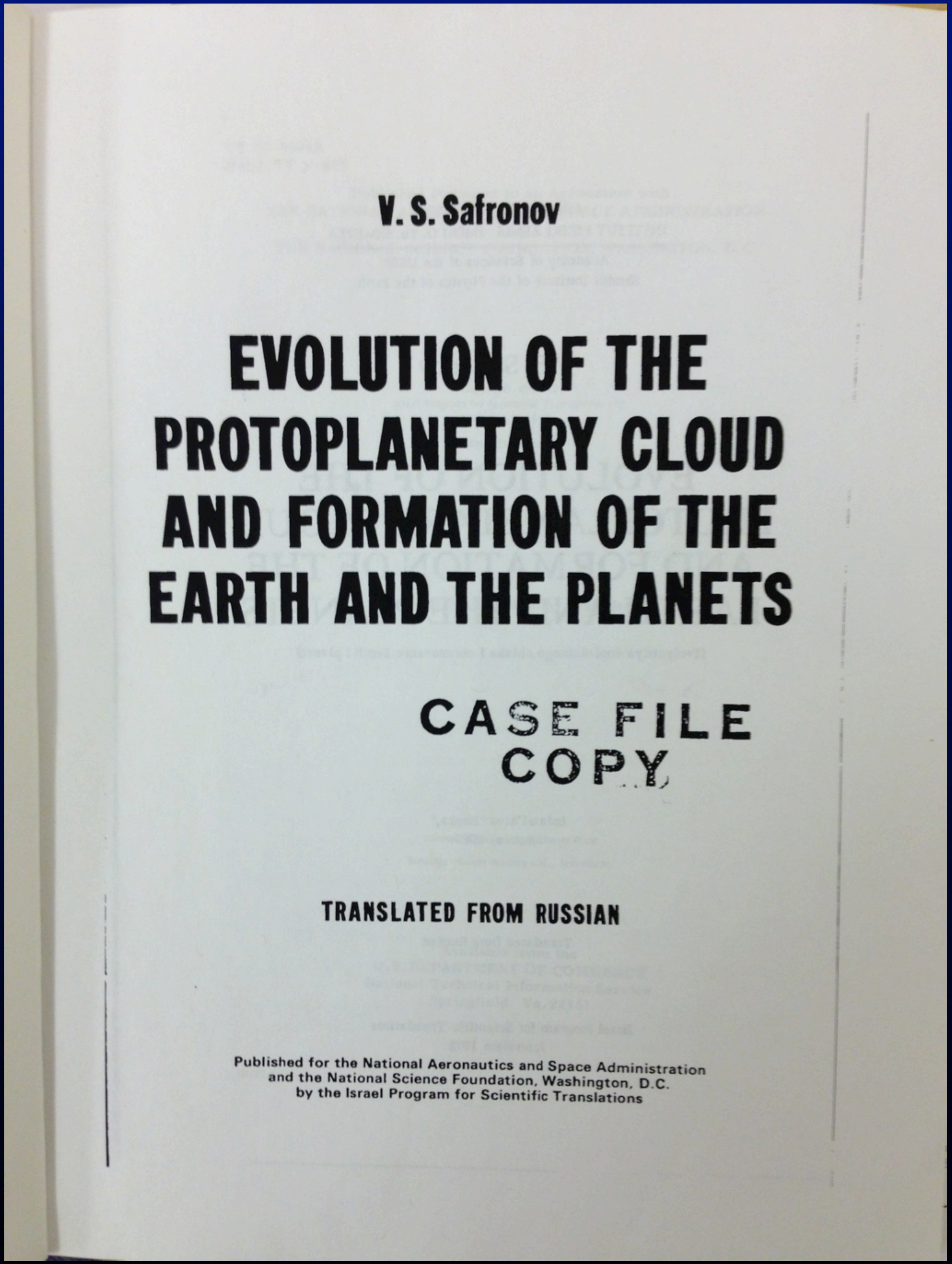
Formation of Planetary Systems

Lecture 3 - Dust dynamics & planetesimal formation



Planetesimal hypothesis

Safronov (1969):
planets form from dust and ice grains that stick together to form ever larger bodies.



V. S. Safronov

EVOLUTION OF THE PROTOPLANETARY CLOUD AND FORMATION OF THE EARTH AND THE PLANETS

CASE FILE
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Planetesimal hypothesis

Safronov (1969): *planets form from dust and ice grains that stick together to form ever larger bodies.*

- We now think of a “three-stage” model for planet formation:

1) dust (~um) → planetesimals (~km)

   sticking due to contact forces during collisions.

3) planetesimals (~km) → proto-planets / cores (~1000km)

   gravity (between solids).

5) proto-planets / cores → planets

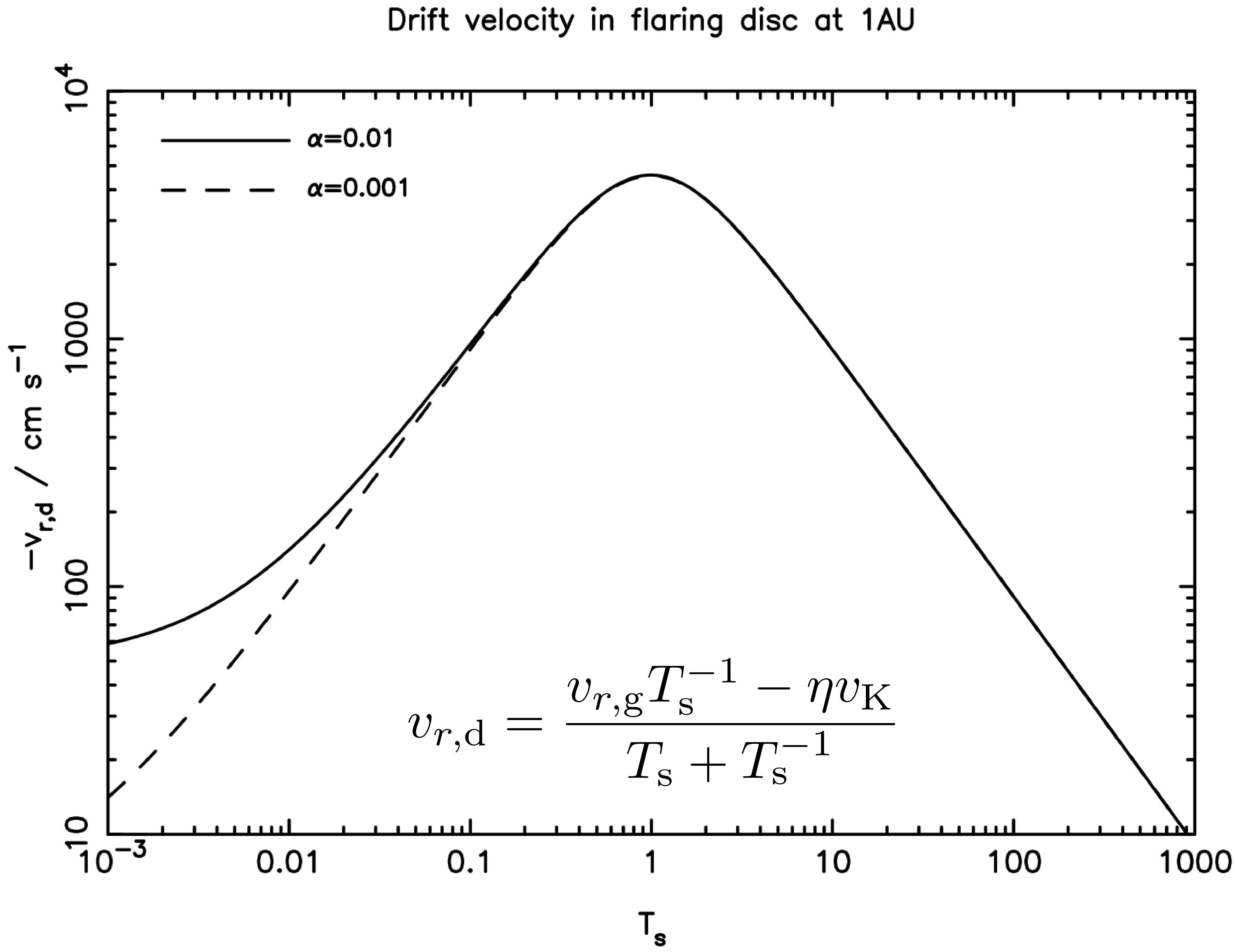
   gravity (gas accretion) and giant impacts.

Solid Particles

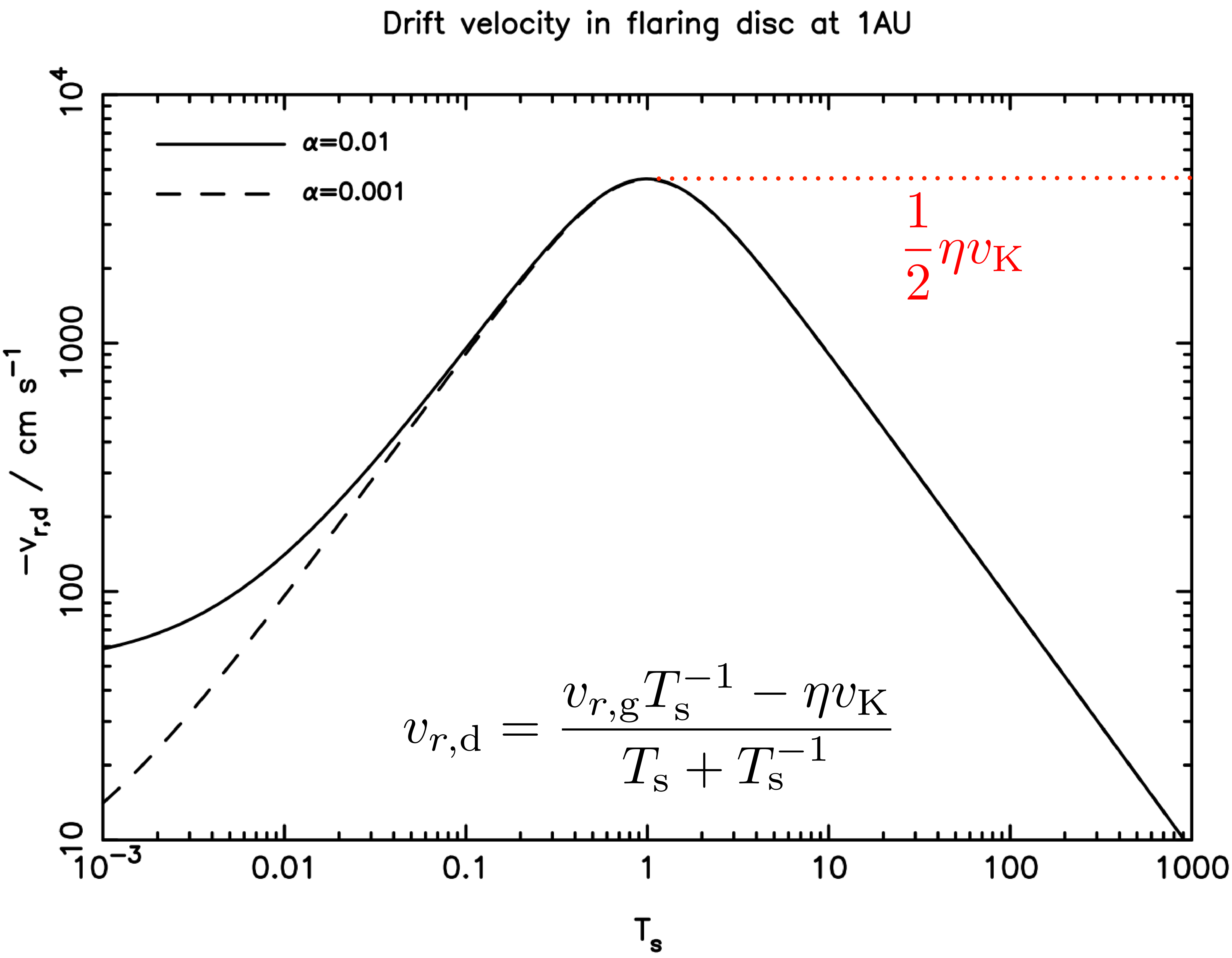
Dust/rocks: small bodies, from sub-μm up to ~km size. Motion dominated by ***aerodynamic drag***.

Planetesimals: ~10-1000km bodies. Interact with one another gravitationally – ***N-body dynamics***. (Lecture 4)

Planetary cores: >1000km in size, approaching Earth mass. Interact gravitationally with the gas, leading to radial ***migration*** and ***gas accretion***. (Lectures 4 & 5)

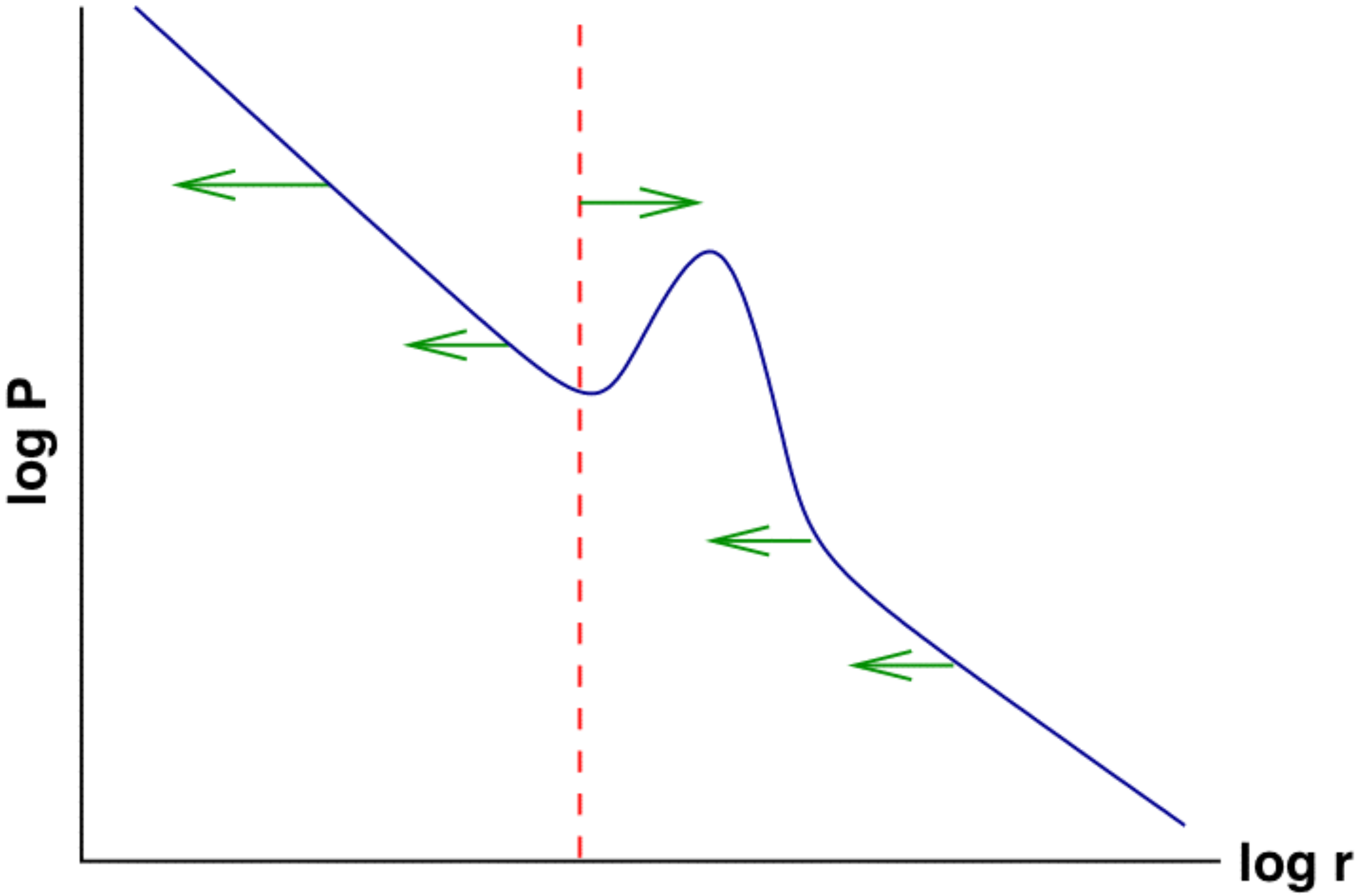


$$v_{r,\mathrm{d}} = \frac{v_{r,\mathrm{g}} T_\mathrm{s}^{-1} - \eta v_\mathrm{K}}{T_\mathrm{s} + T_\mathrm{s}^{-1}}$$



$$v_{r,\rm d} = \frac{v_{r,\rm g} T_{\rm s}^{-1} - \eta v_{\rm K}}{T_{\rm s} + T_{\rm s}^{-1}}$$

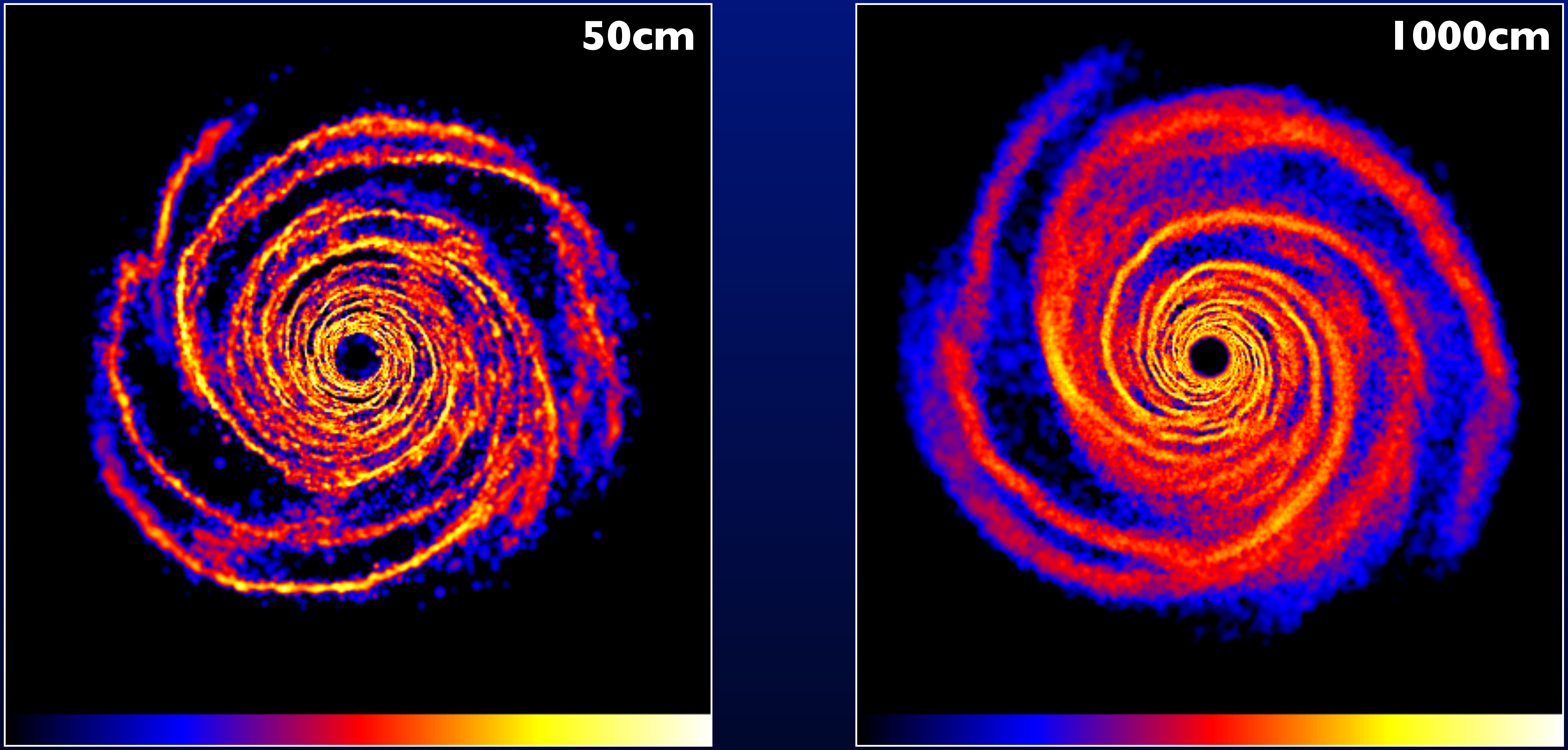
Radial drift can create "dust traps"



Armitage (2007)

- In general, radial drift moves particles towards pressure *maxima*.
- Can "trap" particles in local disc structures.

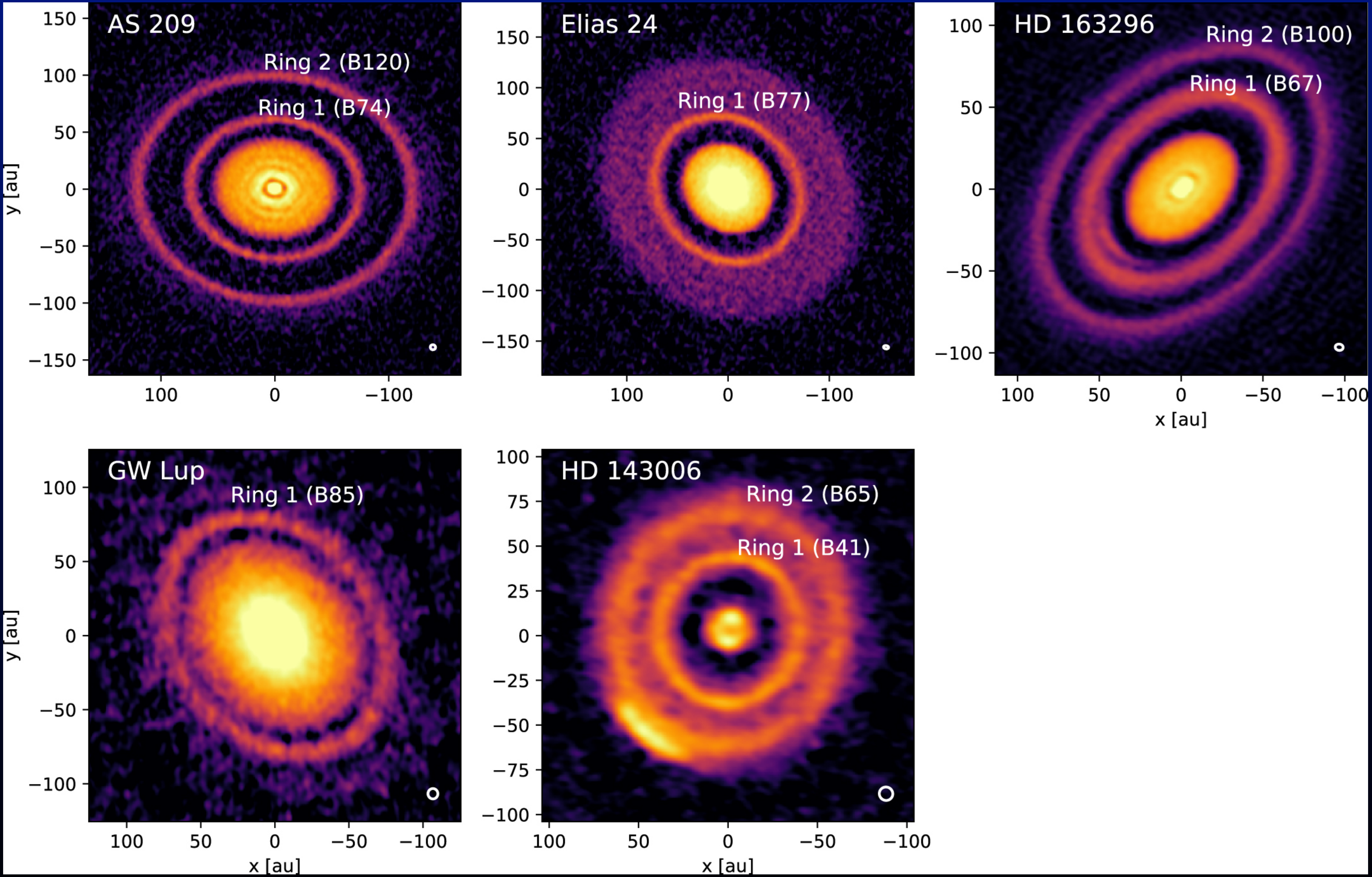
Radial drift can create "dust traps"



Rice et al. (2004, 2006)

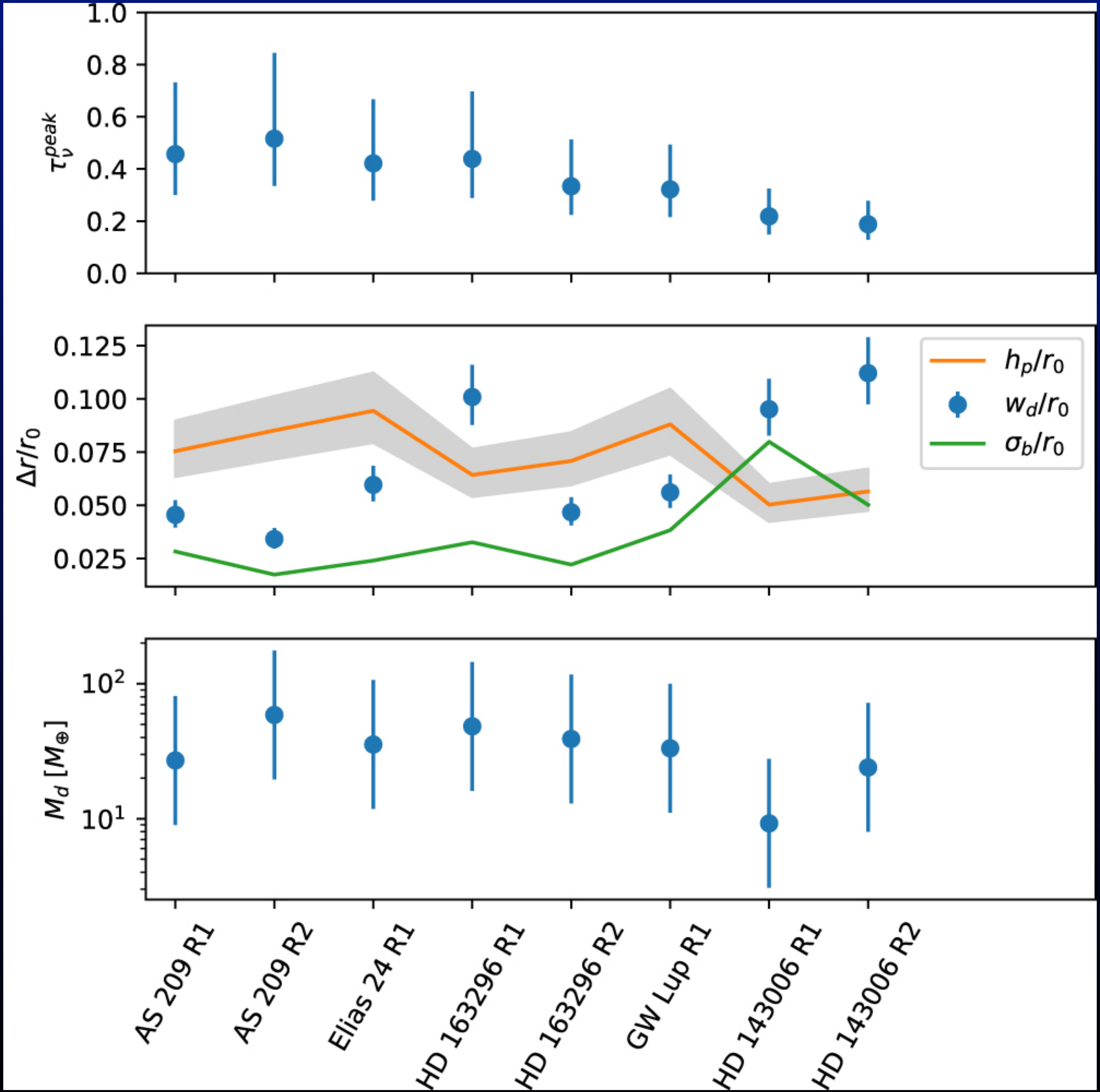
- In general, radial drift moves particles towards pressure *maxima*.
- Can "trap" particles in local disc structures.

Dust trapping measured with ALMA



Dullemond et al. (2018)

Dust trapping measured with ALMA



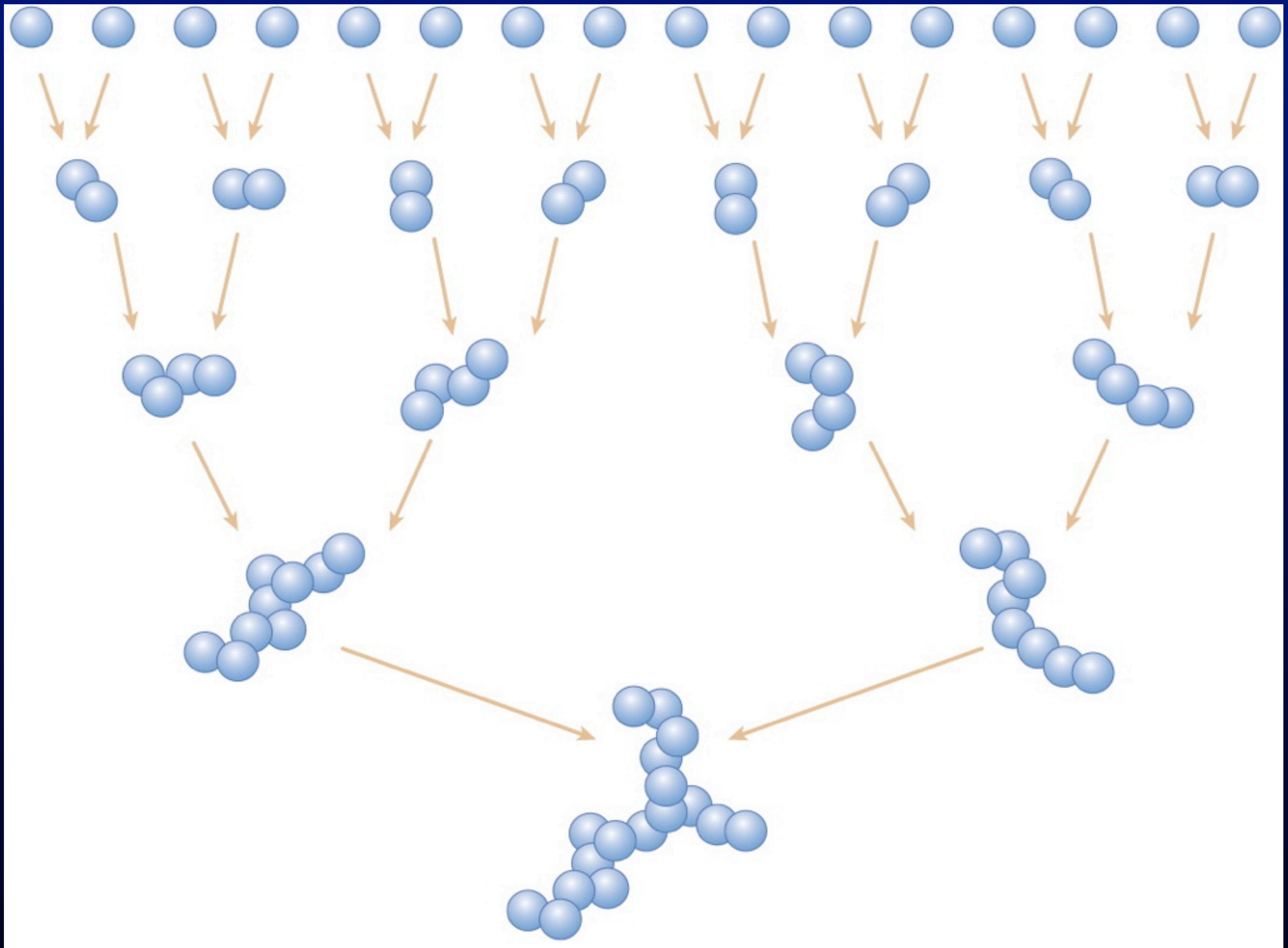
- In several cases the observed dust rings have:

$$\Delta R_\mathrm{d} < H_\mathrm{g}$$

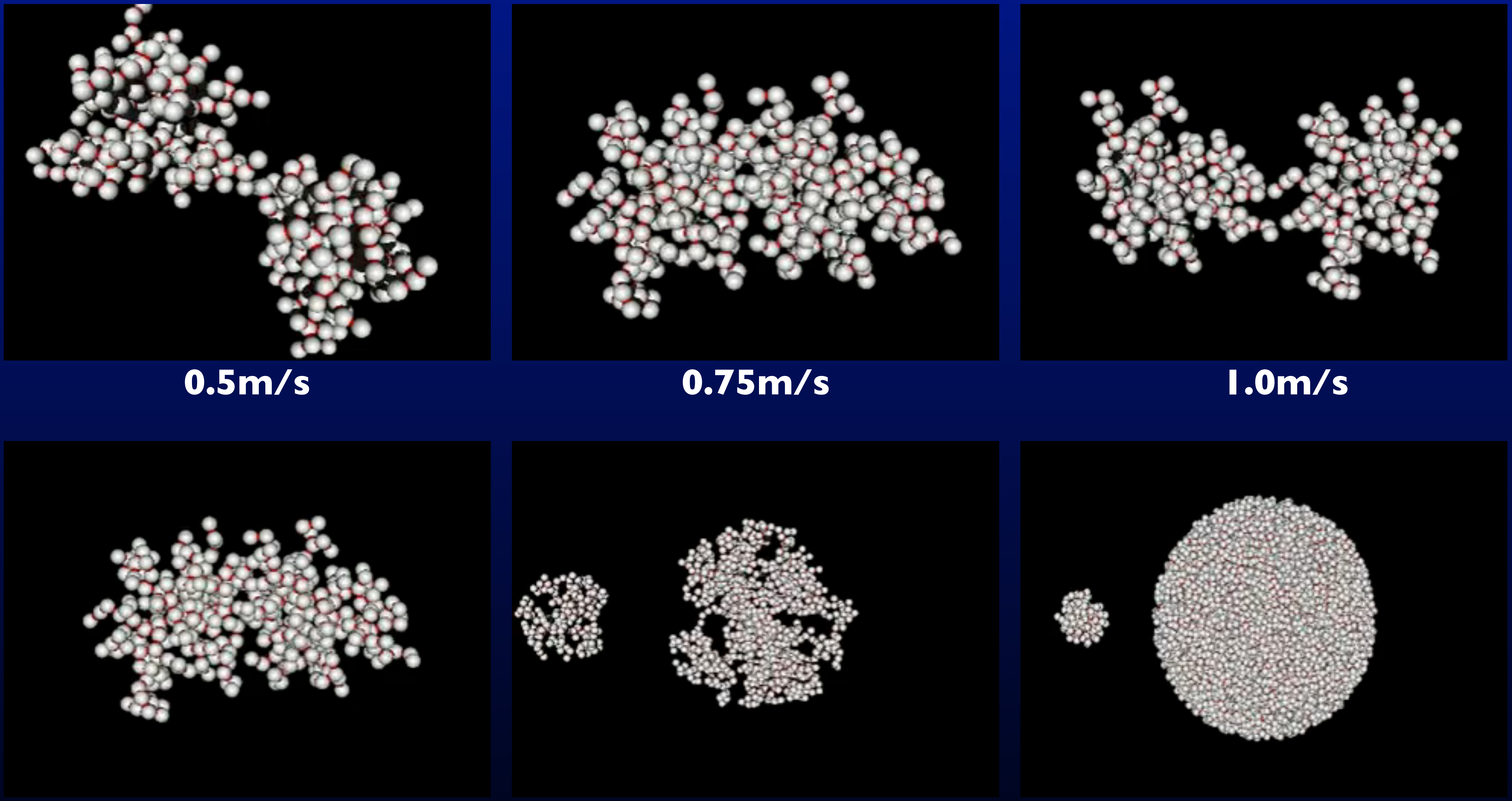
- Dust structures narrower than gas structures – this requires **trapping**.

Dullemond et al. (2018)

Collisions - fractal growth



Blum J, Wurm G. 2008.
Annu. Rev. Astron. Astrophys. 46:21–56



0.5m/s

0.75m/s

1.0m/s

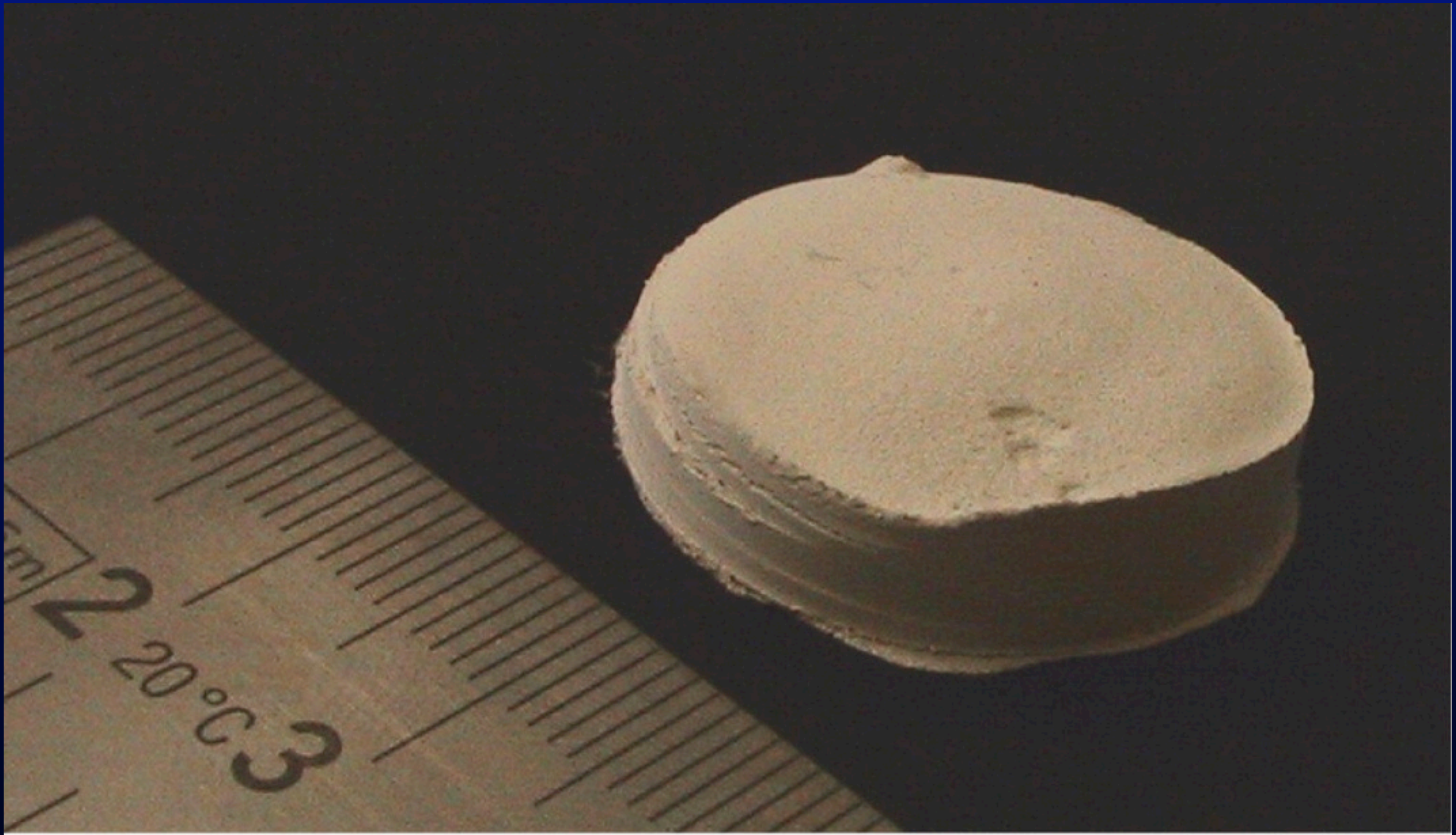
2.0m/s

2.0m/s

25m/s

Animations of numerical simulations by Paszun & Dominik (2008).
Individual “particles” are spherical SiO_2 monomers of radius 0.6μm.

Laboratory experiments



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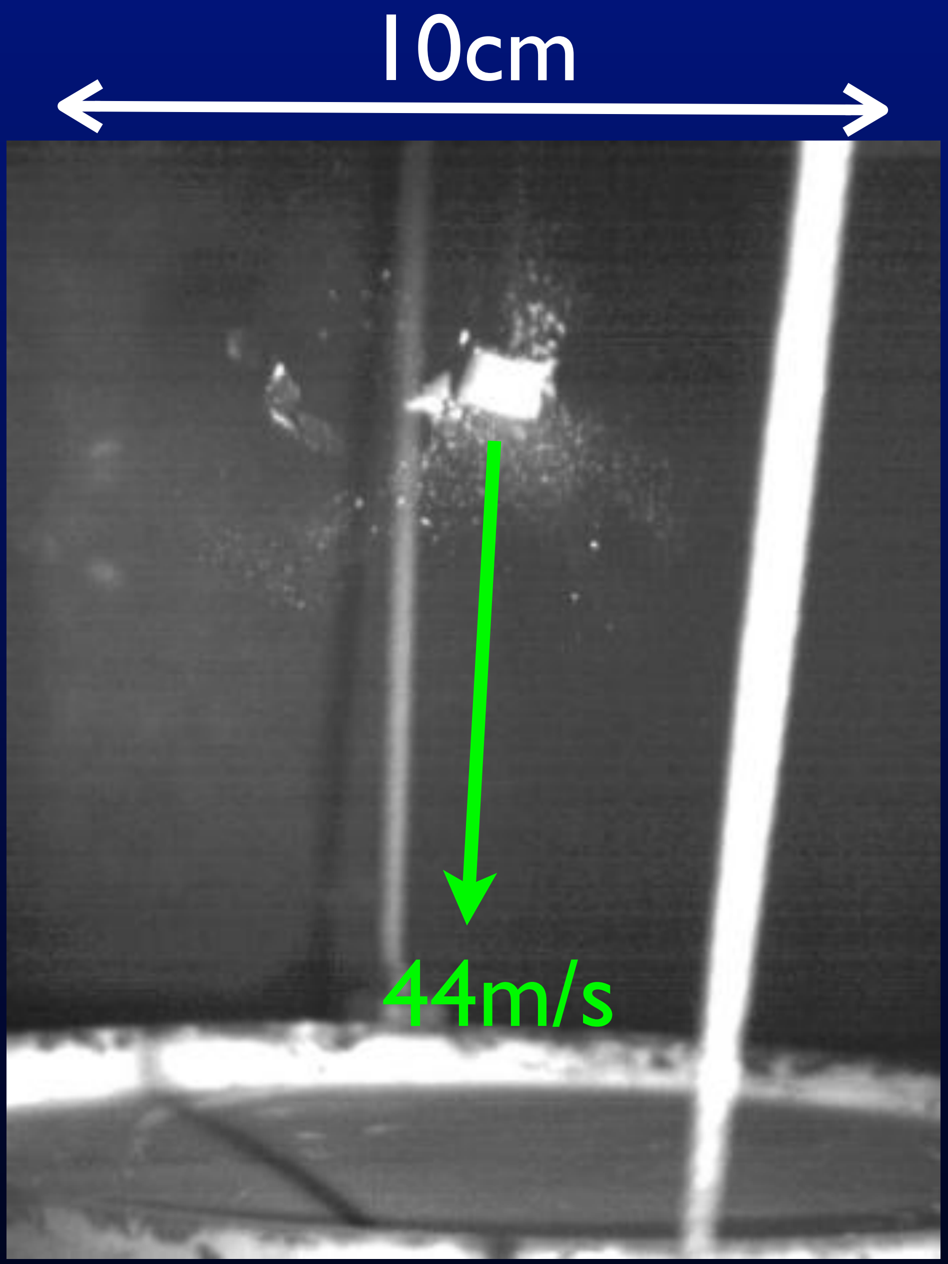
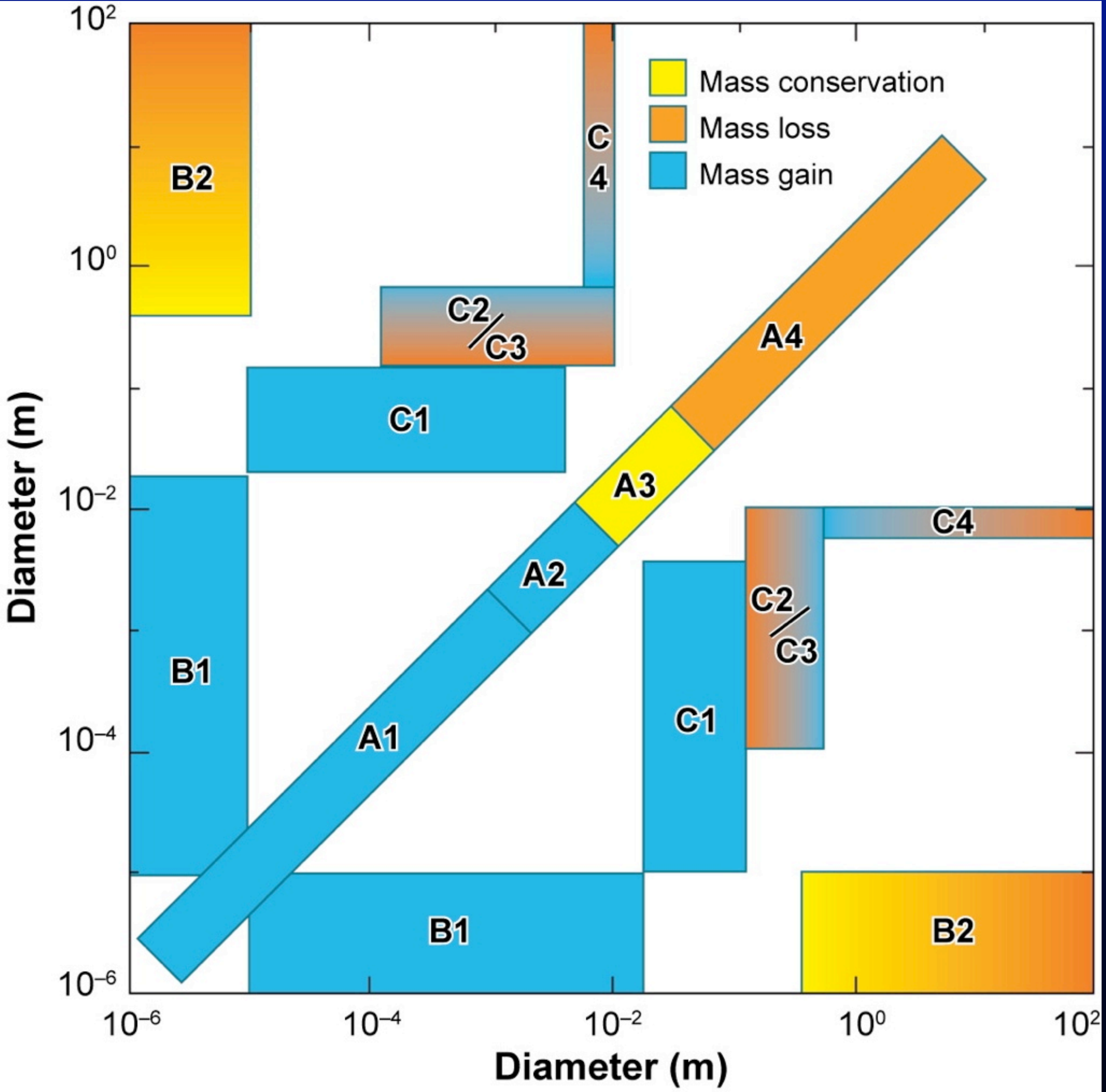


Teiser & Wurm (2009)



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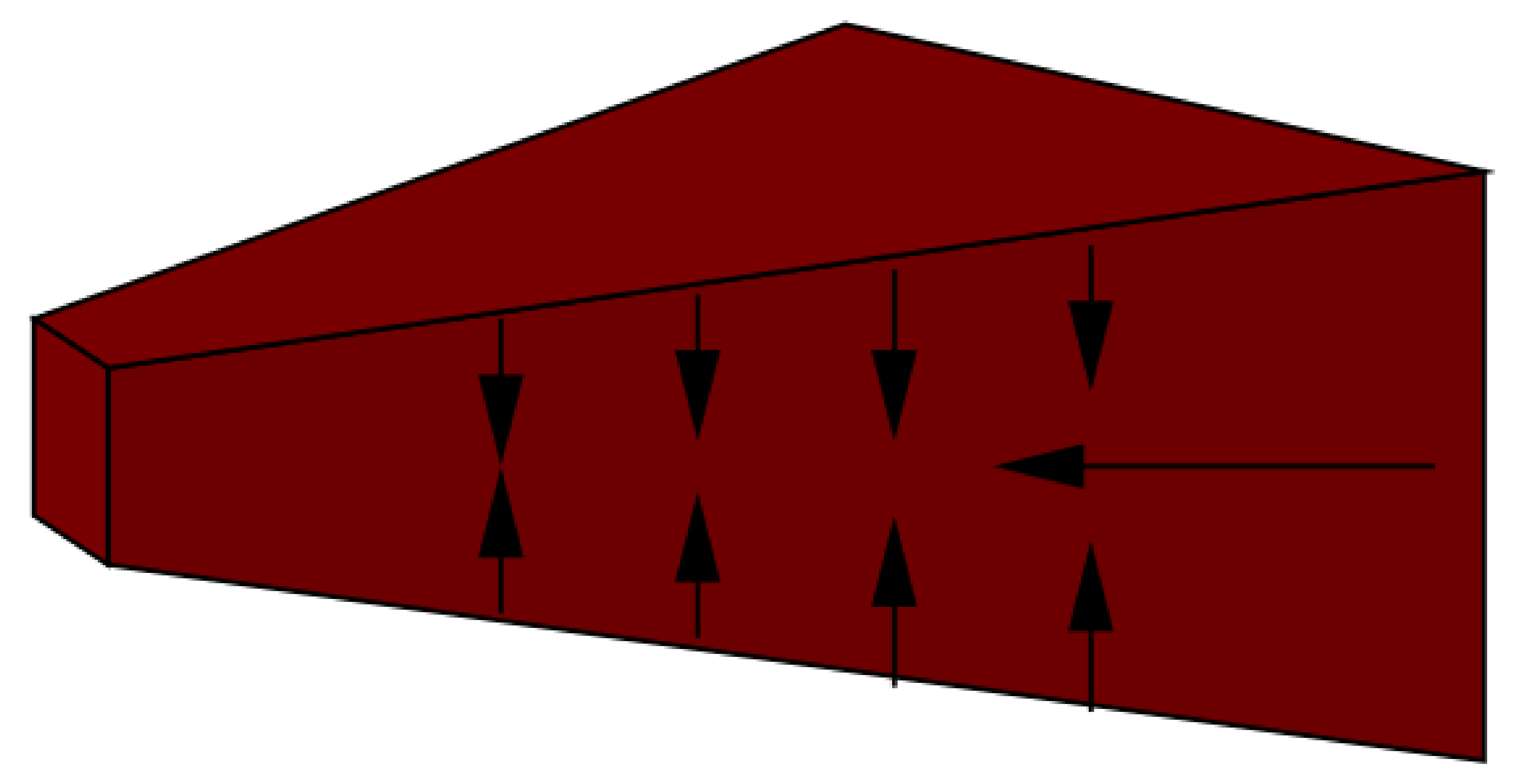
The Goldreich-Ward mechanism

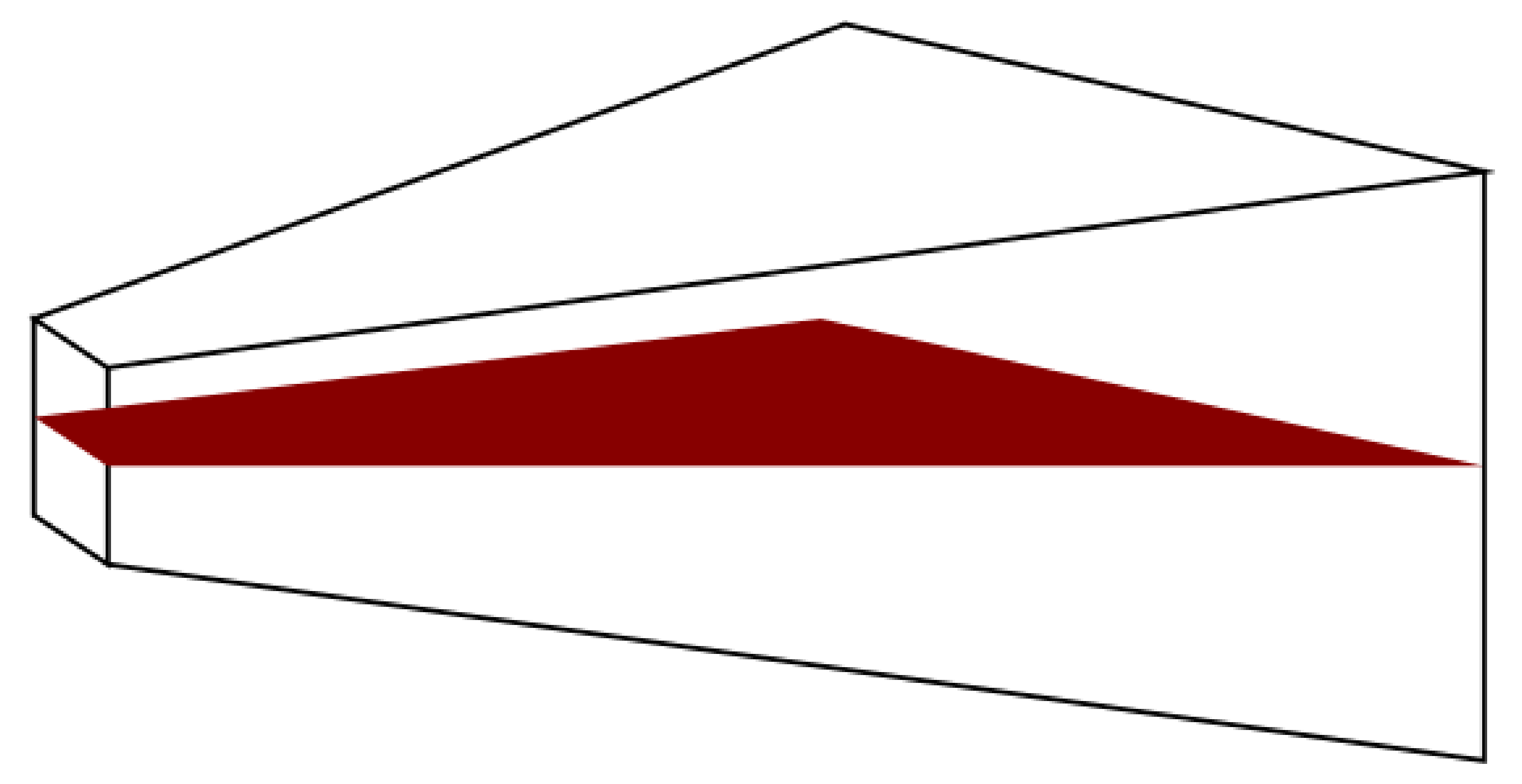
Goldreich & Ward (1973); figures from Armitage (2007)



Vertical settling (& radial drift) leads to...

The Goldreich-Ward mechanism

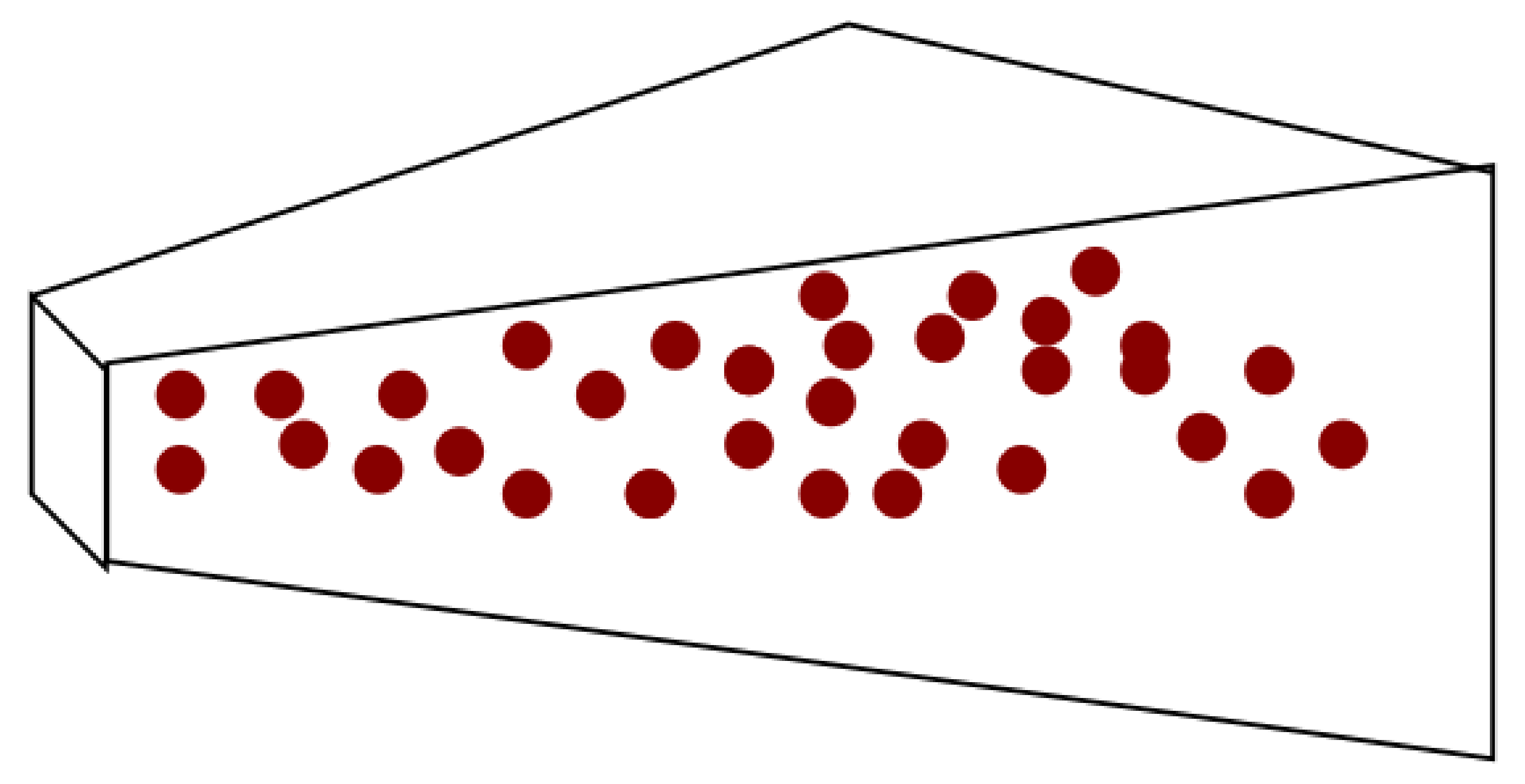
Goldreich & Ward (1973); figures from Armitage (2007)



...enhanced dust-to-gas ratio at disc midplane, causing...

The Goldreich-Ward mechanism

Goldreich & Ward (1973); figures from Armitage (2007)



...gravitational instability in the dust layer.

The Goldreich-Ward mechanism

Goldreich & Ward (1973); figures from Armitage (2007)

- Gravitational instability in the dust layer requires:

$$Q_{\rm dust} = \frac{\sigma\Omega}{\pi G \Sigma_{\rm dust}} = 1$$

- This implies a very thin dust layer, with σ ~ 10cm/s.
- Turbulence in real discs prevents the dust layer from ever becoming this thin. (In fact, the dust layer becomes Kelvin-Helmholz unstable & drives turbulence!)
- However, the idea is attractive because it allows km-size planetesimals to form rapidly from small dust grains, bypassing the problematic m-size regime.

Turbulent planetesimal formation

- Disc ***turbulence*** has both positive and negative effects:
  - **trapping of particles in long-lived pressure maxima, increasing collision rates.**
  - **high particle collision speeds, leading to more shattering/fragmentation during collisions.**

- As in the G-W mechanism, for sufficiently large particle concentrations ***collective effects*** become important.
  - differential dust-gas motion gives rise to a number of different instabilities.

Streaming instability

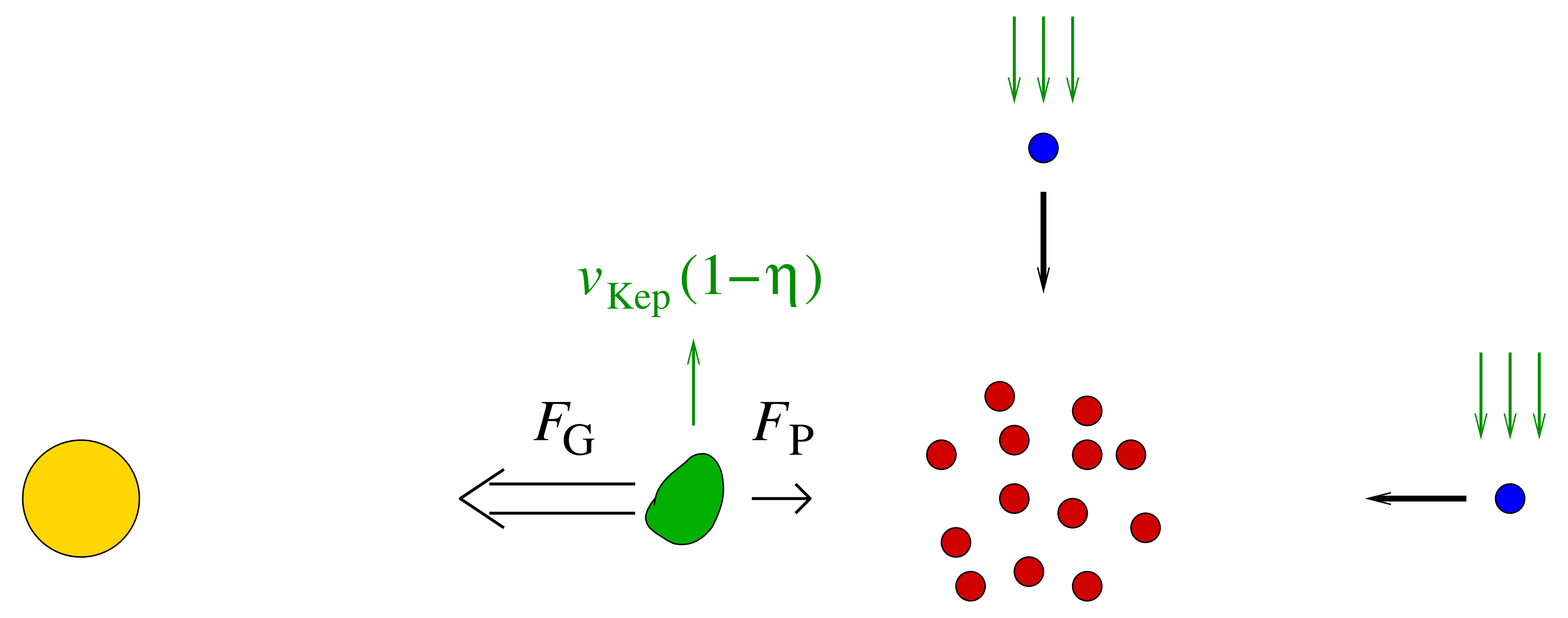


Figure courtesy of Anders Johansen

- Enhancements in the local dust-to-gas ratio can drive a number of different instabilities, which drive both turbulence in the gas and clumping in the solids.
- Most well-known is the ***streaming instability***, discovered by Youdin & Goodman (2005).

Streaming instability

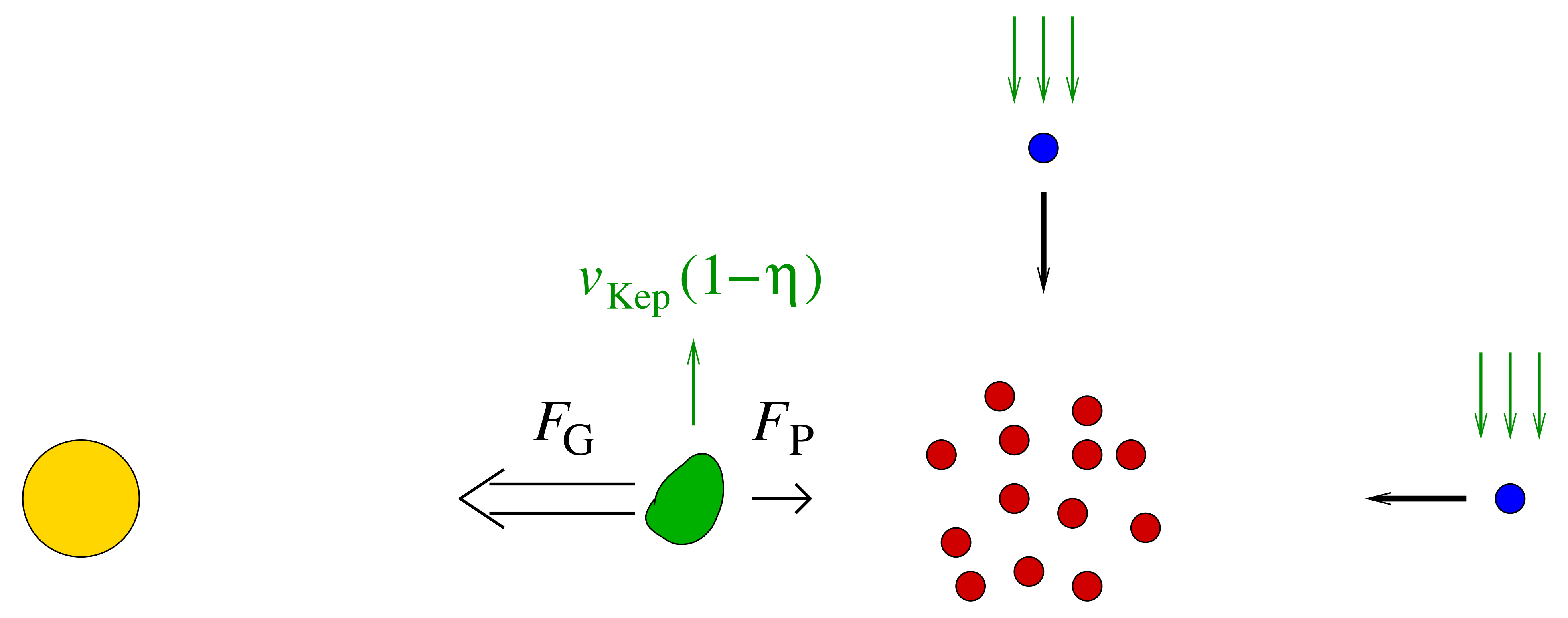
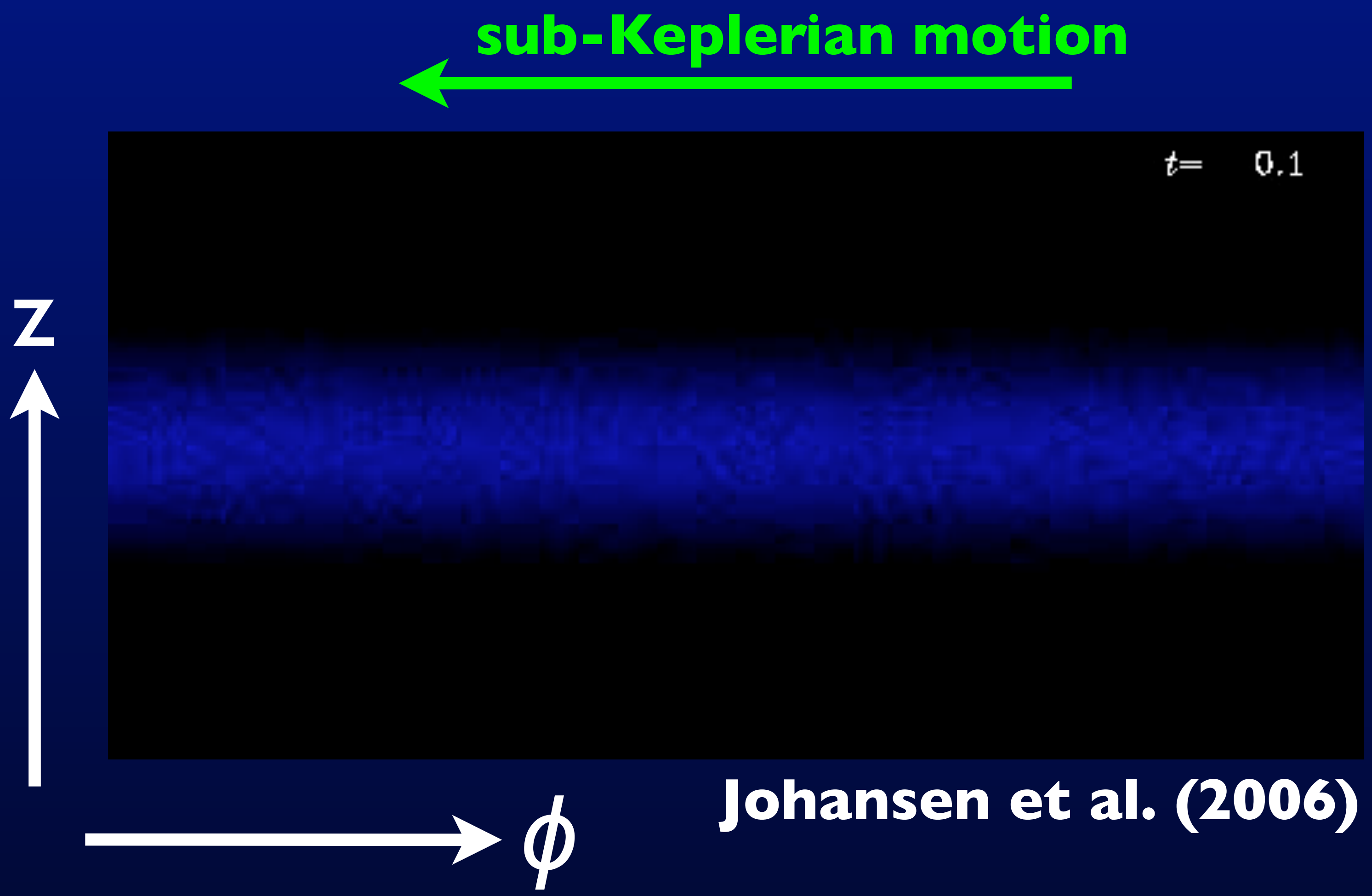


Figure courtesy of Anders Johansen

- Solids lose angular momentum due to headwind, but headwind reduced when particles "clump".
- Leads to further clumping → instability.
- Streaming instability most effective for particles with $T_s = 1$. Still requires rapid growth up to ~cm to ~m sizes.

Streaming instability



Johansen et al. (2006)

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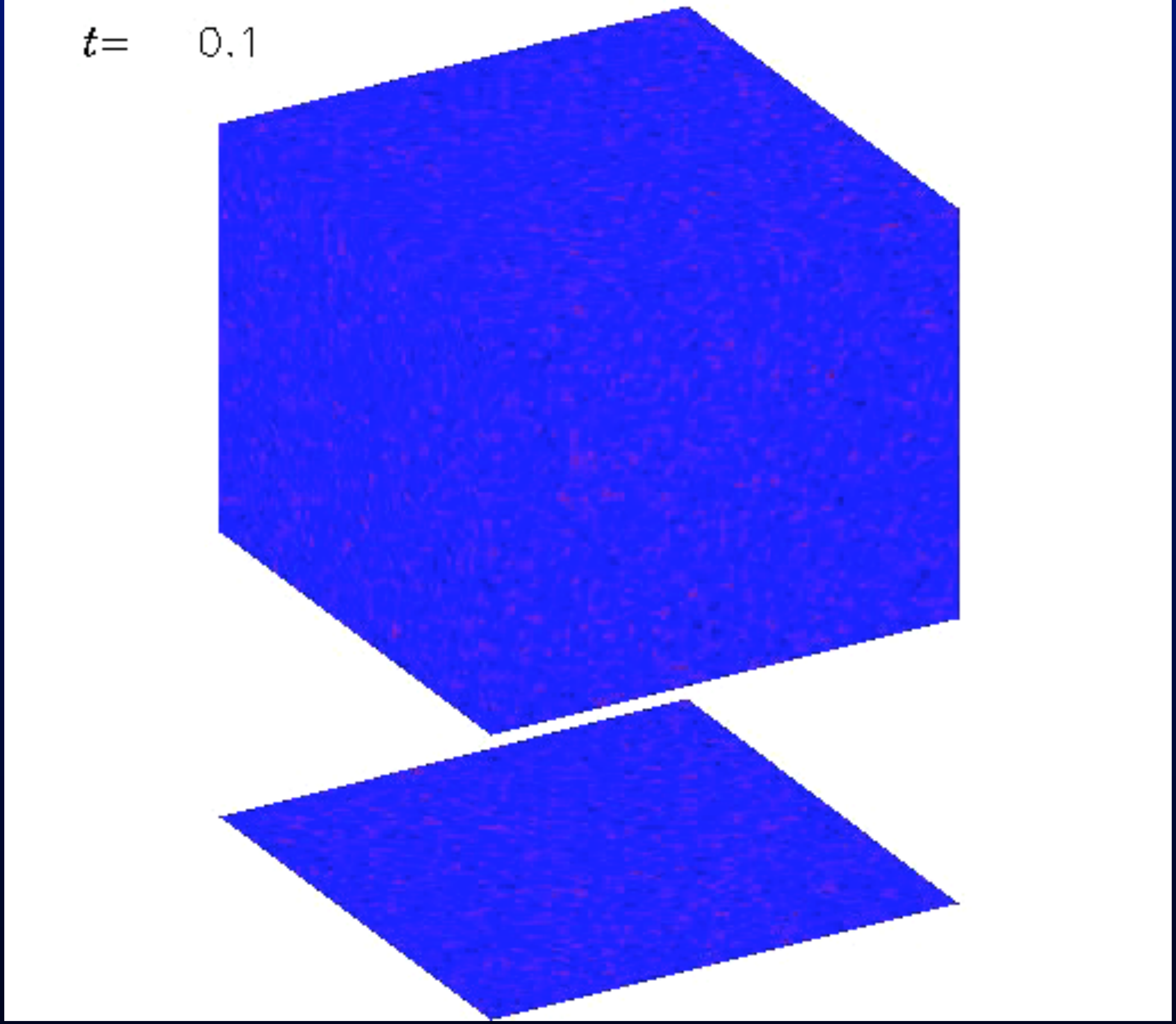
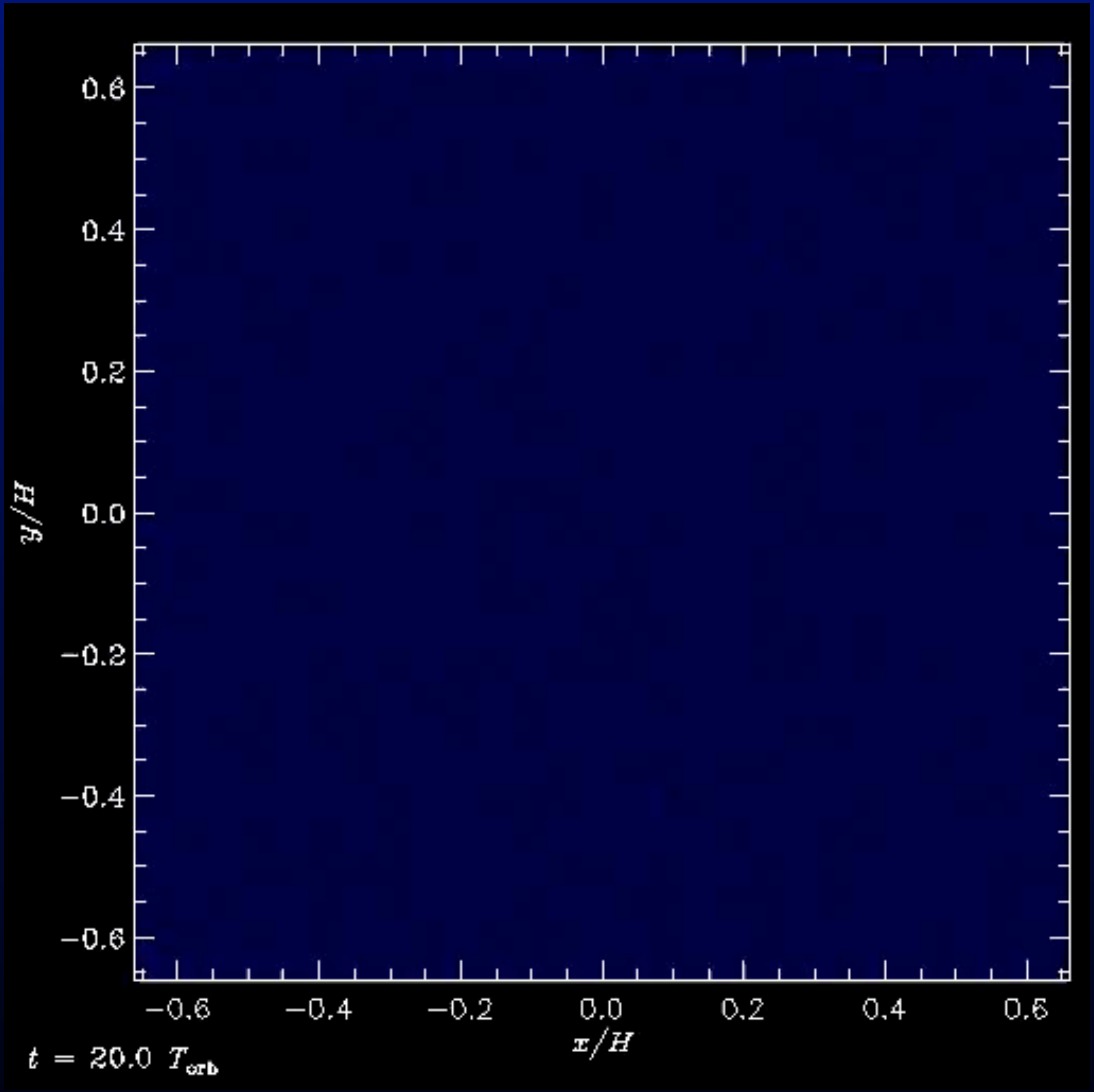
Planetesimal formation in turbulent discs



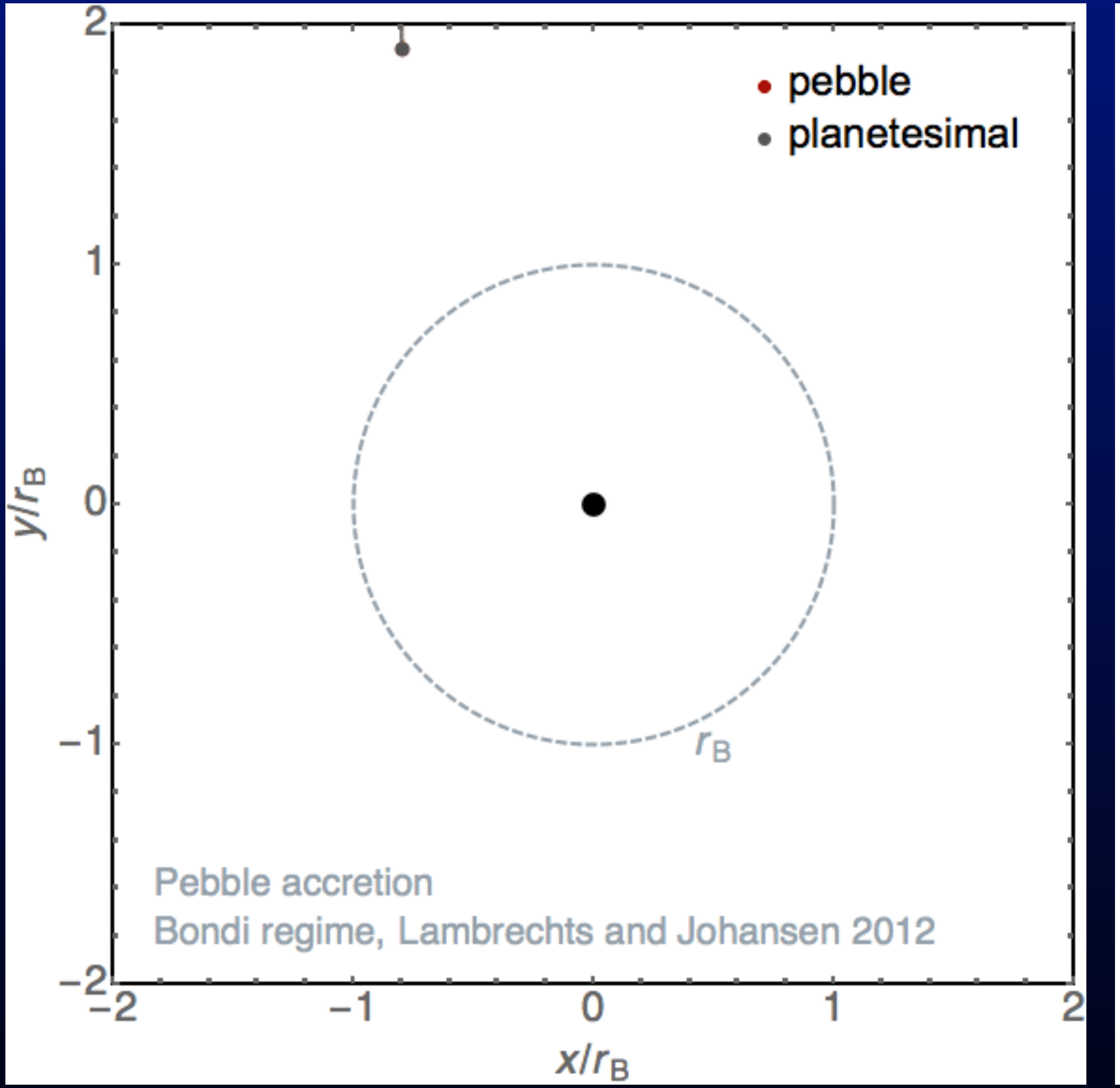
Johansen & Youdin (2007)

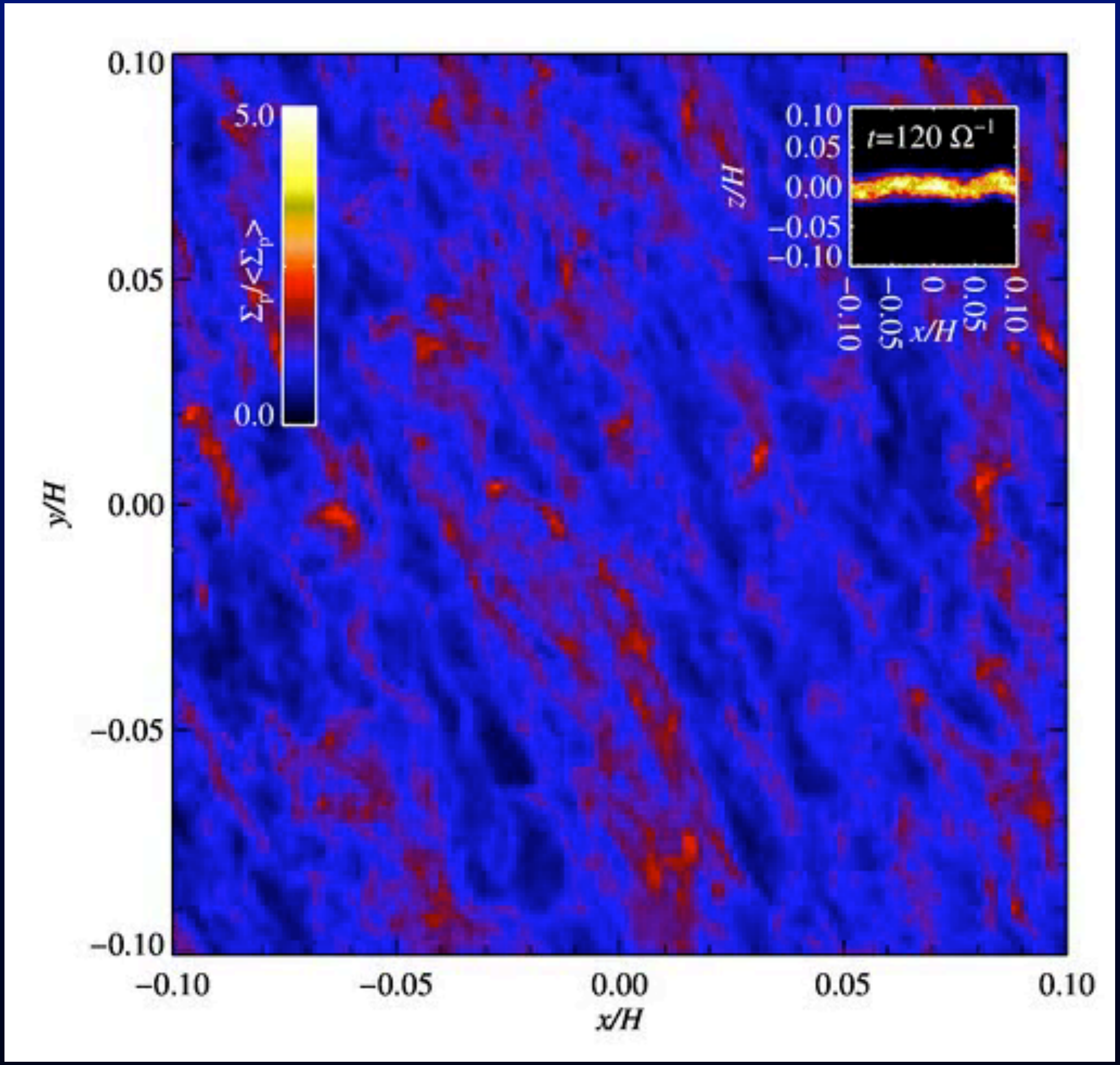
Planetesimal formation in turbulent discs



Johansen et al. (2011)

Pebble accretion





Lambrechts & Johansen (2012)