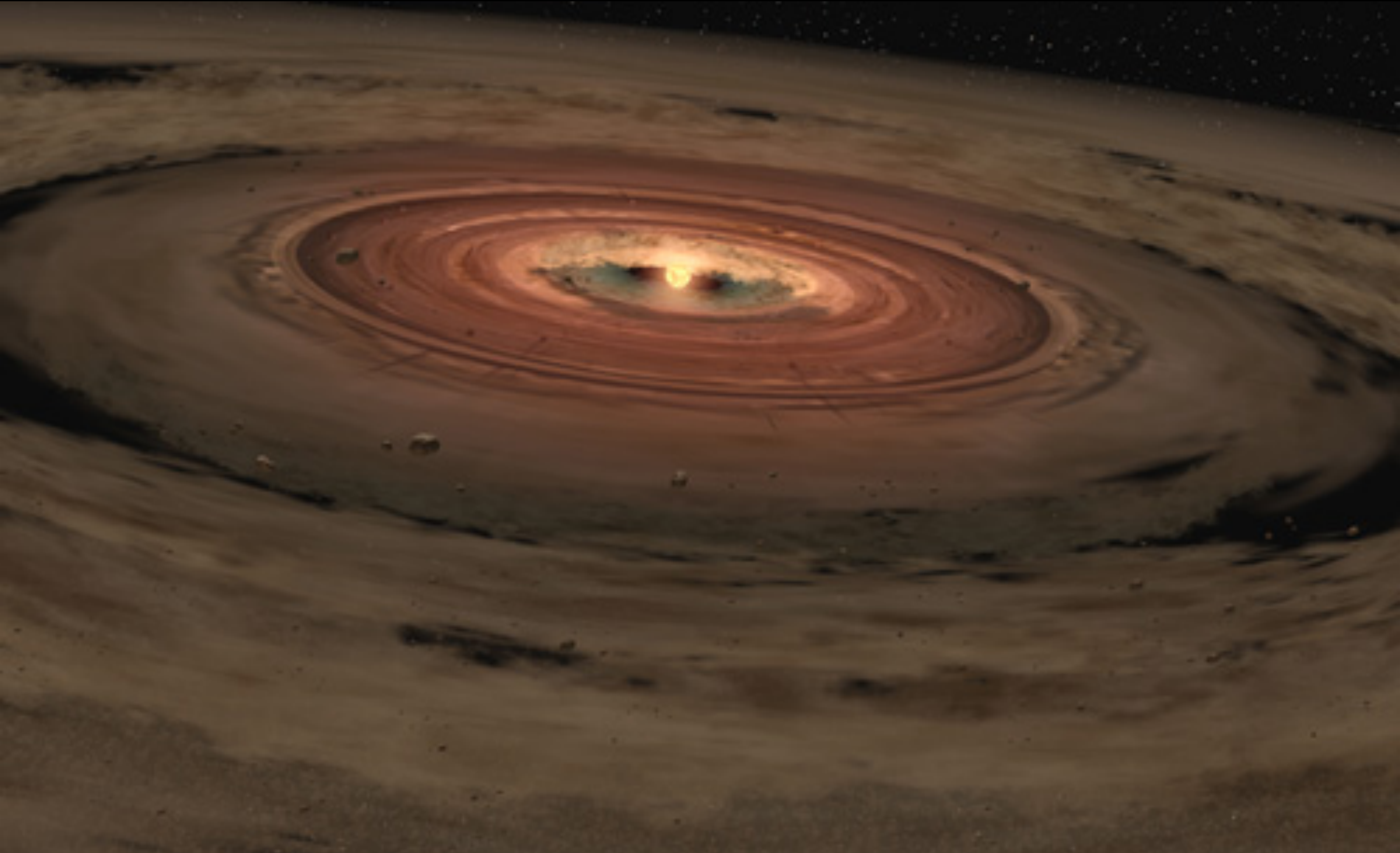
Formation of Planetary Systems

Lecture 3 - Dust dynamics & planetesimal formation



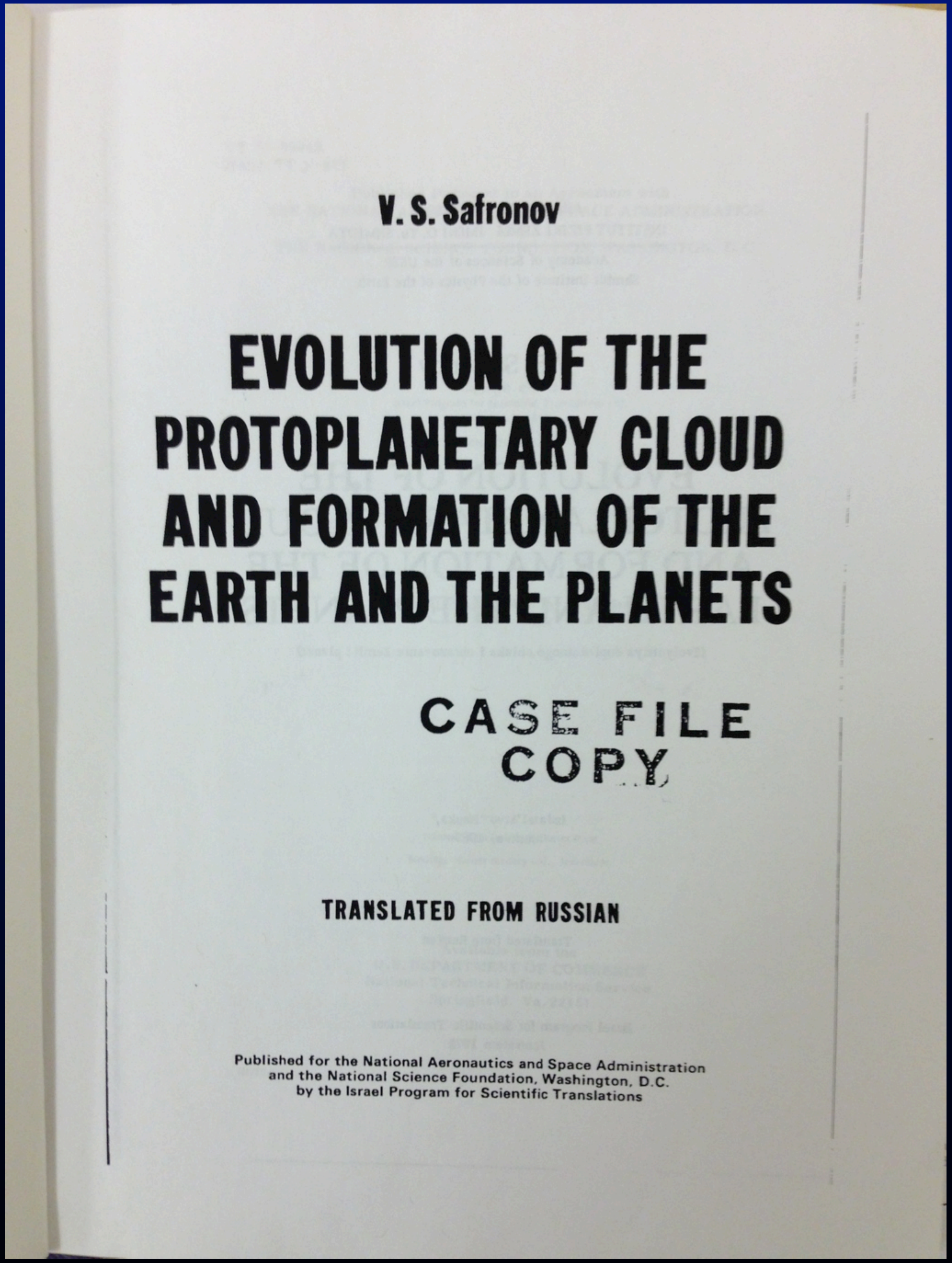
Course Outline

- 5 Lectures, 2 hours each (with a break in the middle!).
    1) Observations of planetary systems
    2) Protoplanetary discs
    3) Dust dynamics & planetesimal formation
    4) Planet formation
    5) Planetary dynamics
- Notes for each lecture will be placed on the course home page *in advance* - you may find it useful to annotate these as we go.
- These slides will also be posted online.
- Textbooks: Armitage - *Astrophysics of planet formation* (CUP).
  Protostars & Planets series (*VI* - 2014; *VII* - 2023)

Course home-page: `rdalexander.github.io/planets_2023.html`

Planetesimal hypothesis

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



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.

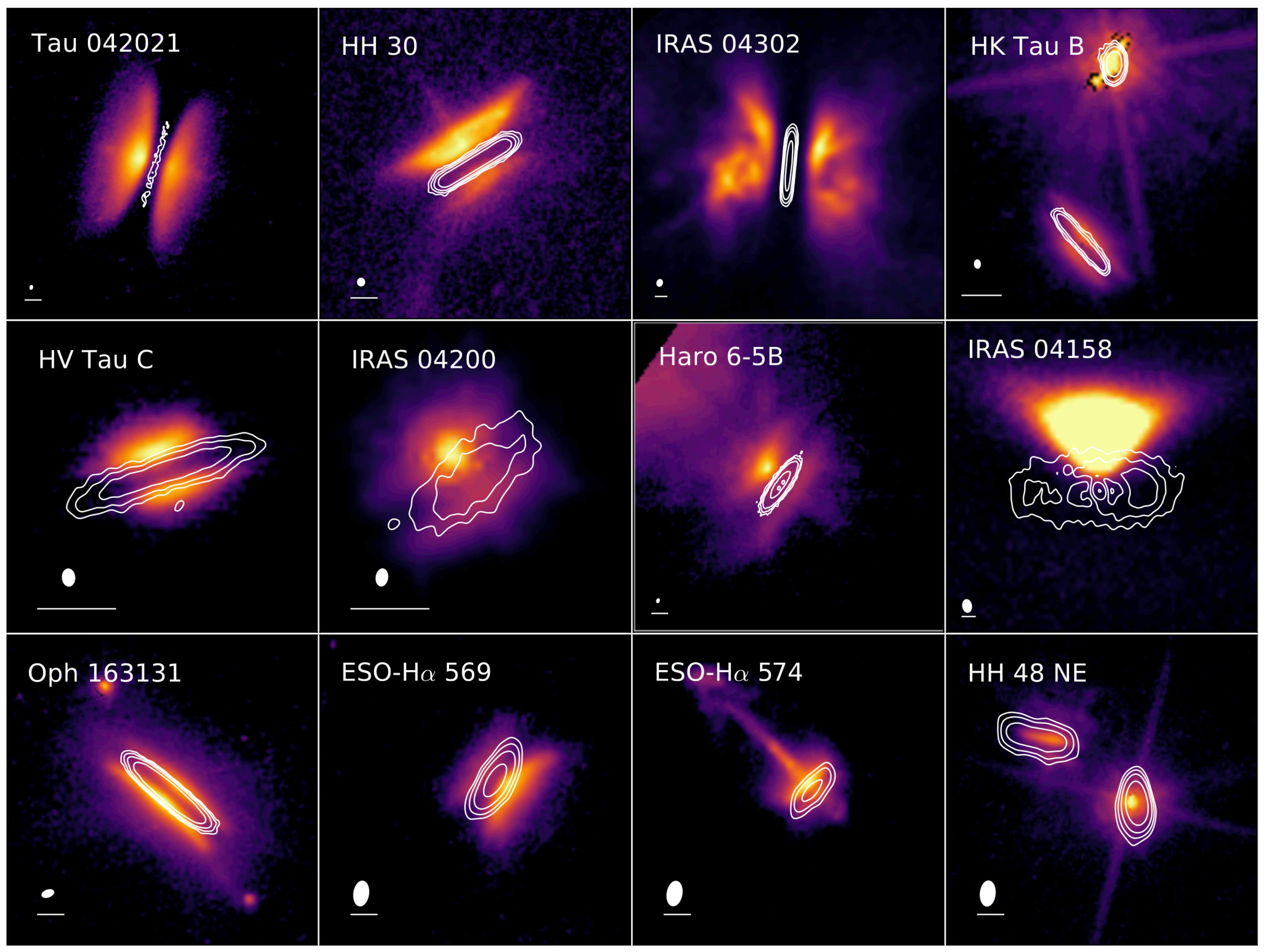
Solid Particles

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

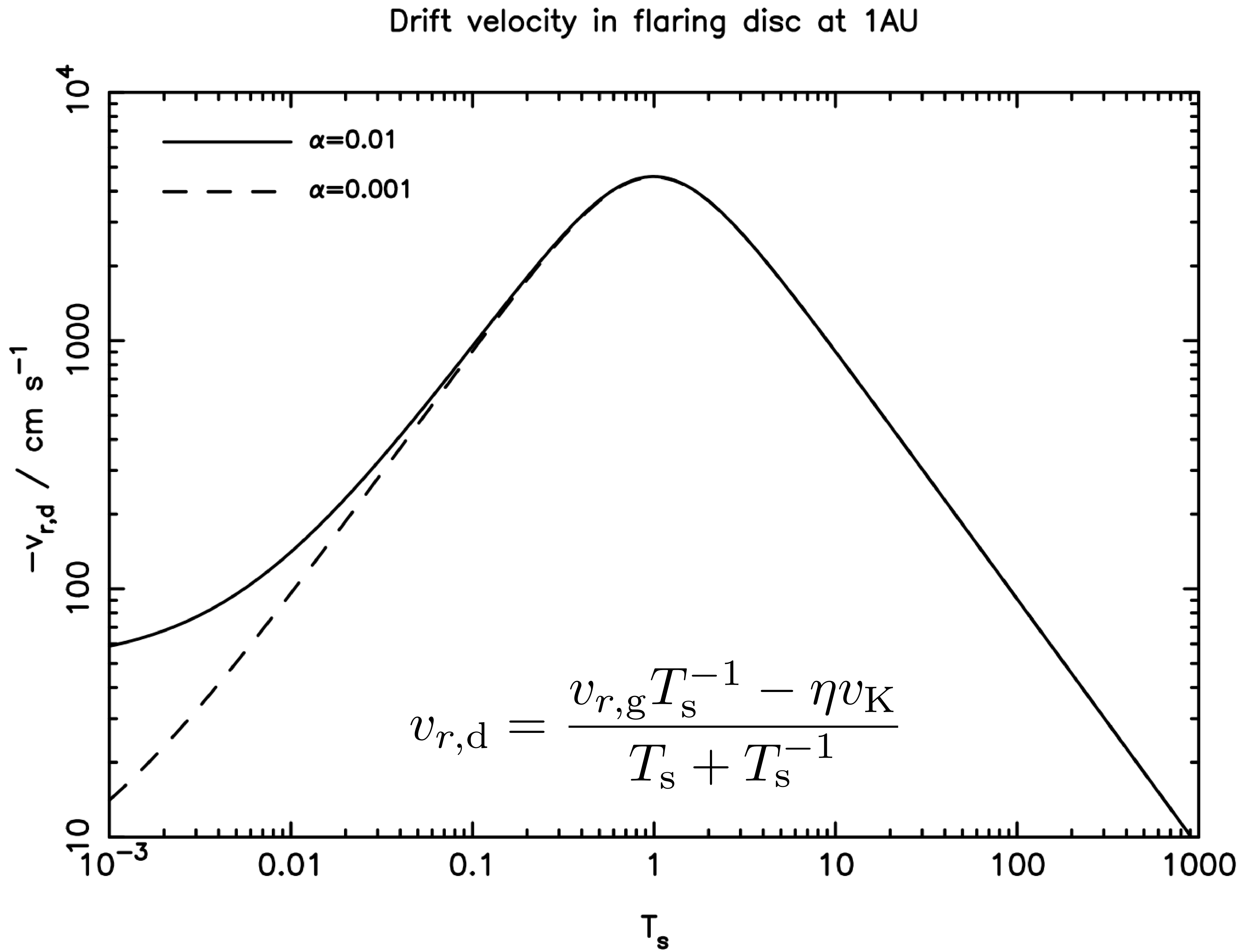
Planetesimals: ~10-1000km bodies. Interact with one another gravitationally – ***N-body dynamics***. (Lecture 4)

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

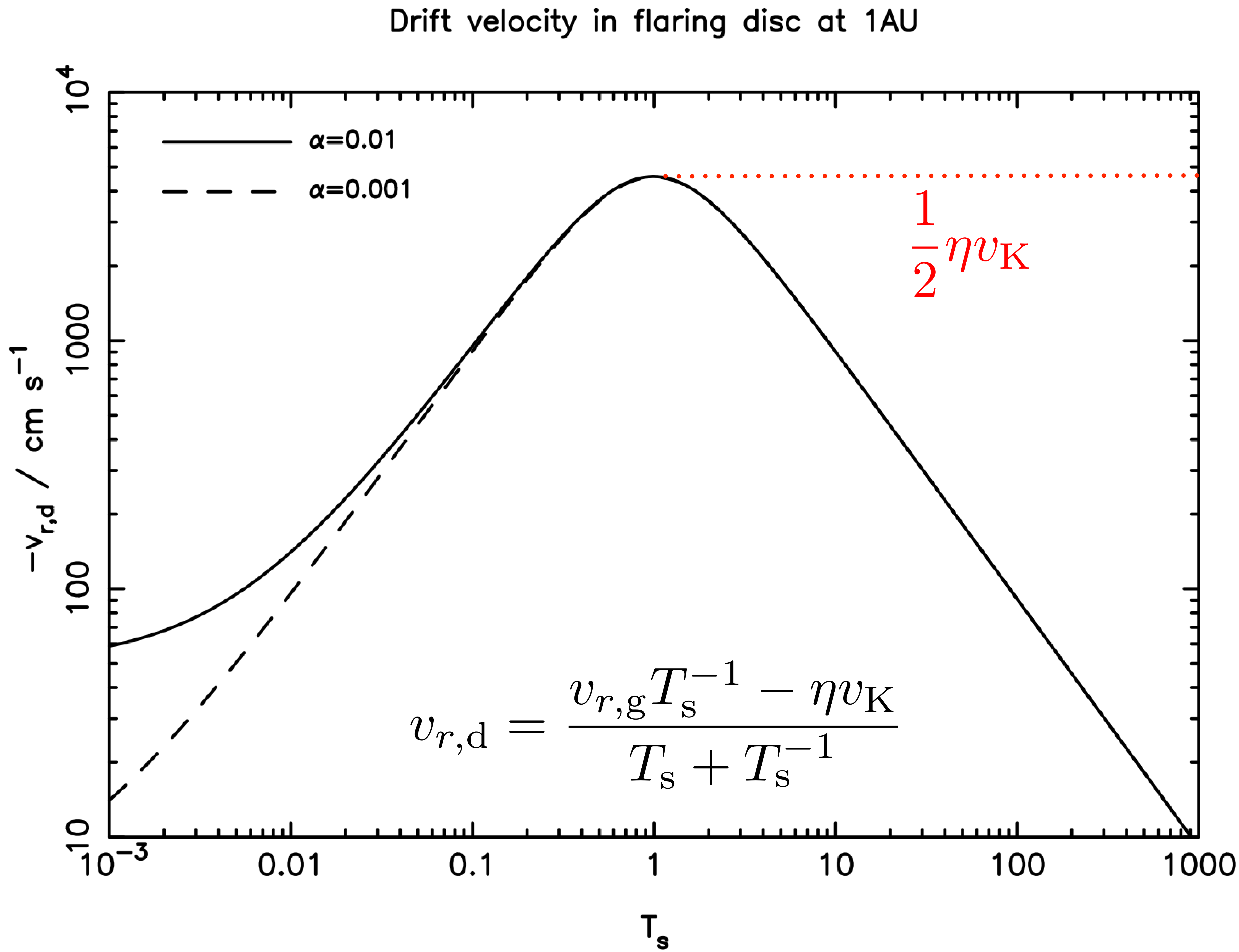
Dust settling is now directly observed



Colours are scattered light; contours are ALMA 850μm (Villenave et al. 2020)

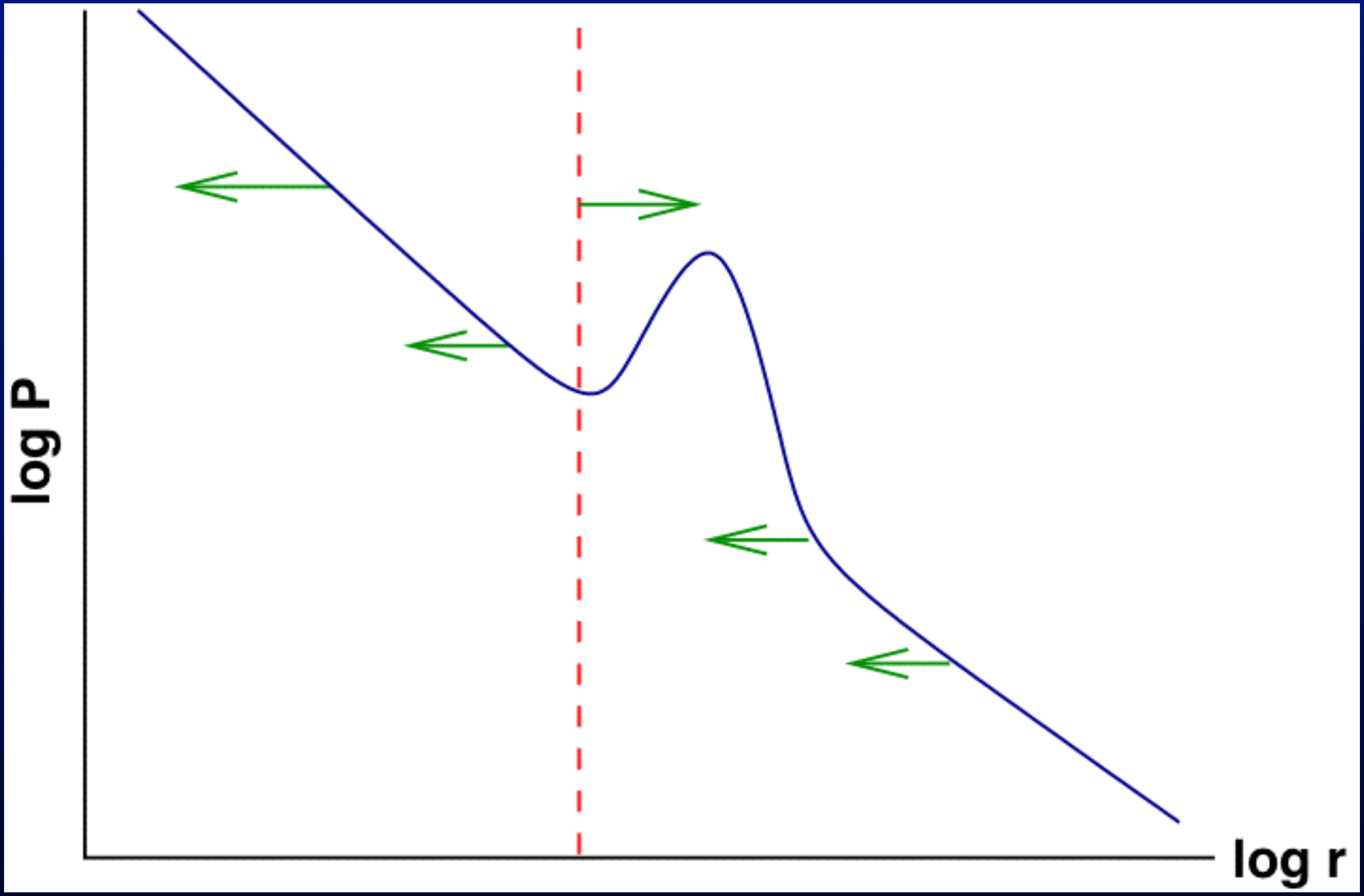


Drift velocity in flaring disc at 1AU
α=0.01
α=0.001
$-v_{r,d}$ / cm s^{-1}
T_s
10
100
1000
10^4
10^{-3}
0.01
0.1
1
10
100
1000
$$v_{r,\mathrm{d}} = \frac{v_{r,\mathrm{g}} T_\mathrm{s}^{-1} - \eta v_\mathrm{K}}{T_\mathrm{s} + T_\mathrm{s}^{-1}}$$



Drift velocity in flaring disc at 1AU
α=0.01
α=0.001
$\frac{1}{2}\eta v_{\mathrm{K}}$
$v_{r,\mathrm{d}} = \frac{v_{r,\mathrm{g}} T_{\mathrm{s}}^{-1} - \eta v_{\mathrm{K}}}{T_{\mathrm{s}} + T_{\mathrm{s}}^{-1}}$
$-v_{r,d}$ / cm s^{-1}
10^4
1000
100
10
10^{-3}
0.01
0.1
1
10
100
1000
T_s

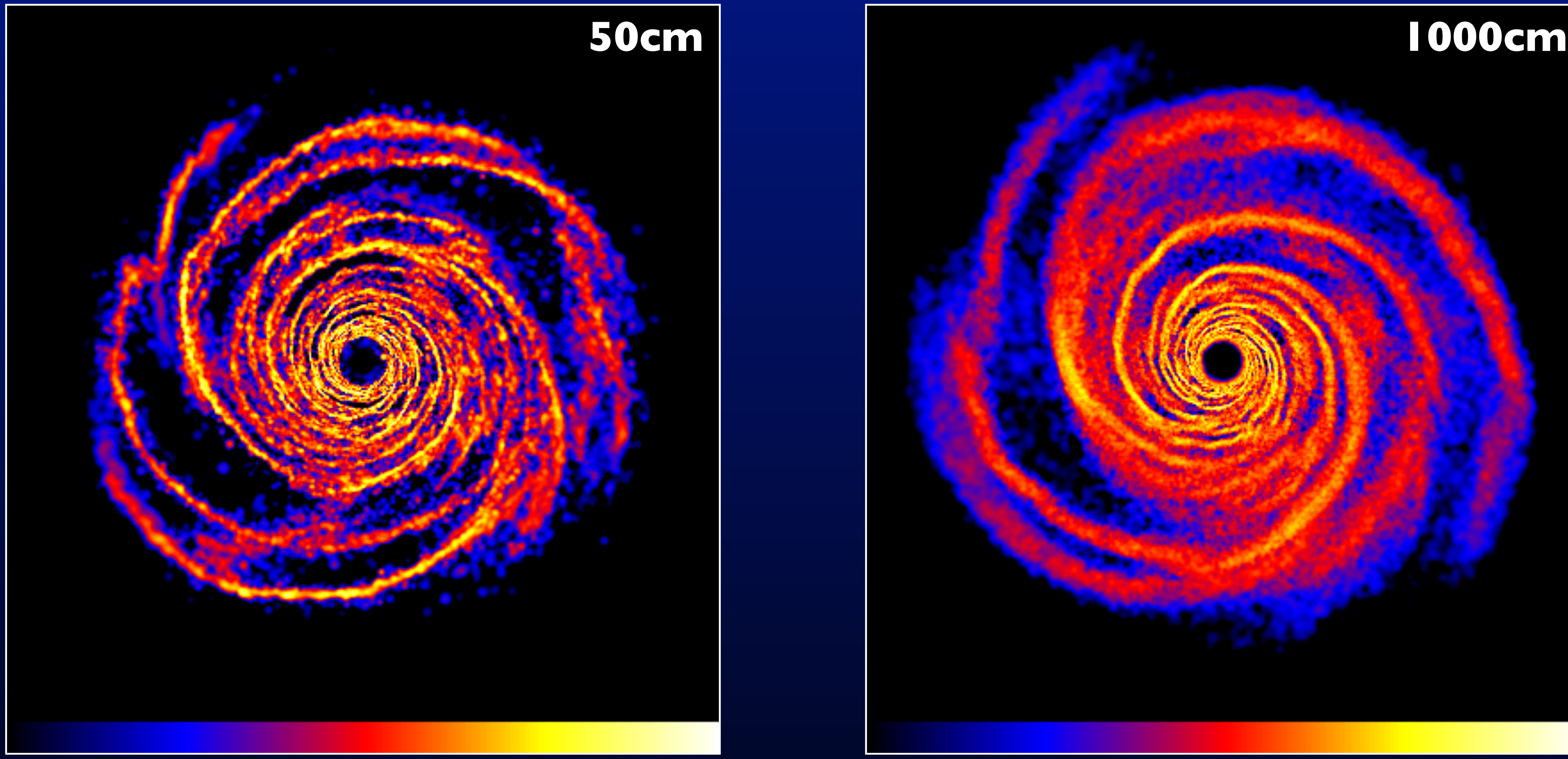
Radial drift can create "dust traps"



Armitage (2007)

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

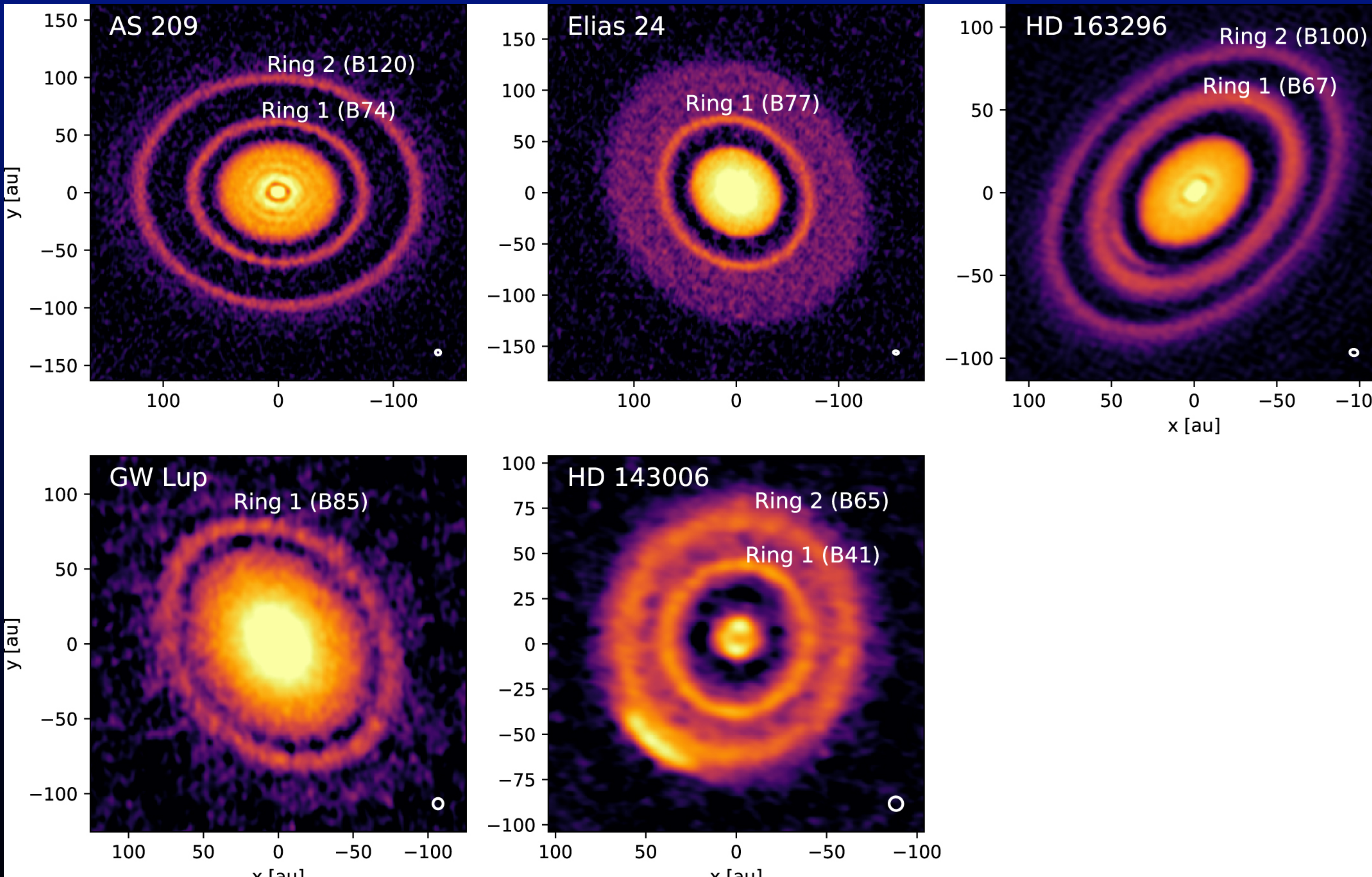
Radial drift can create "dust traps"



Rice et al. (2004, 2006)

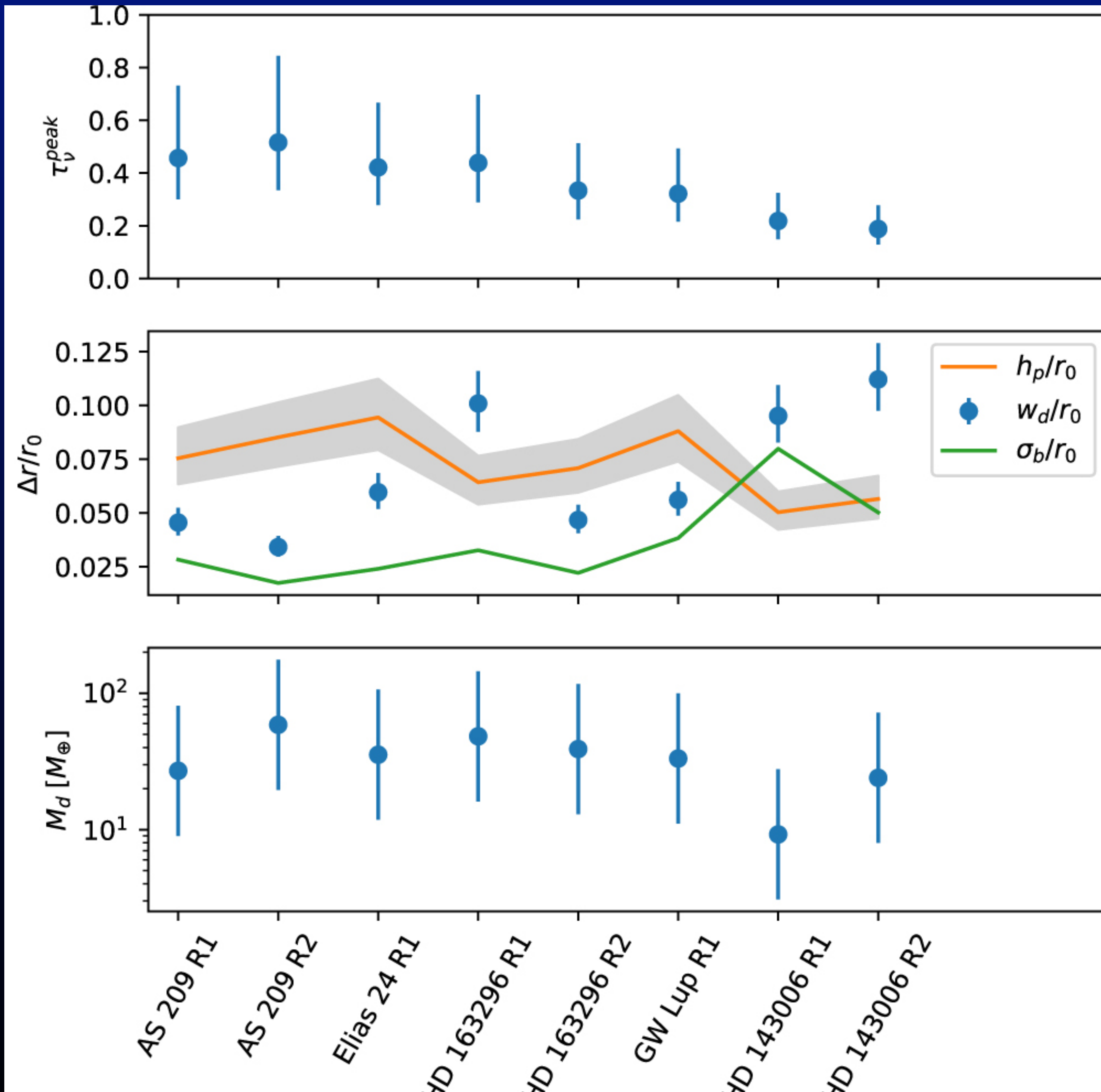
- In general, radial drift moves particles towards pressure *maxima*.
- Can "trap" particles in local disc structures.

Dust trapping measured with ALMA



Dullemond et al. (2018)

Dust trapping measured with ALMA



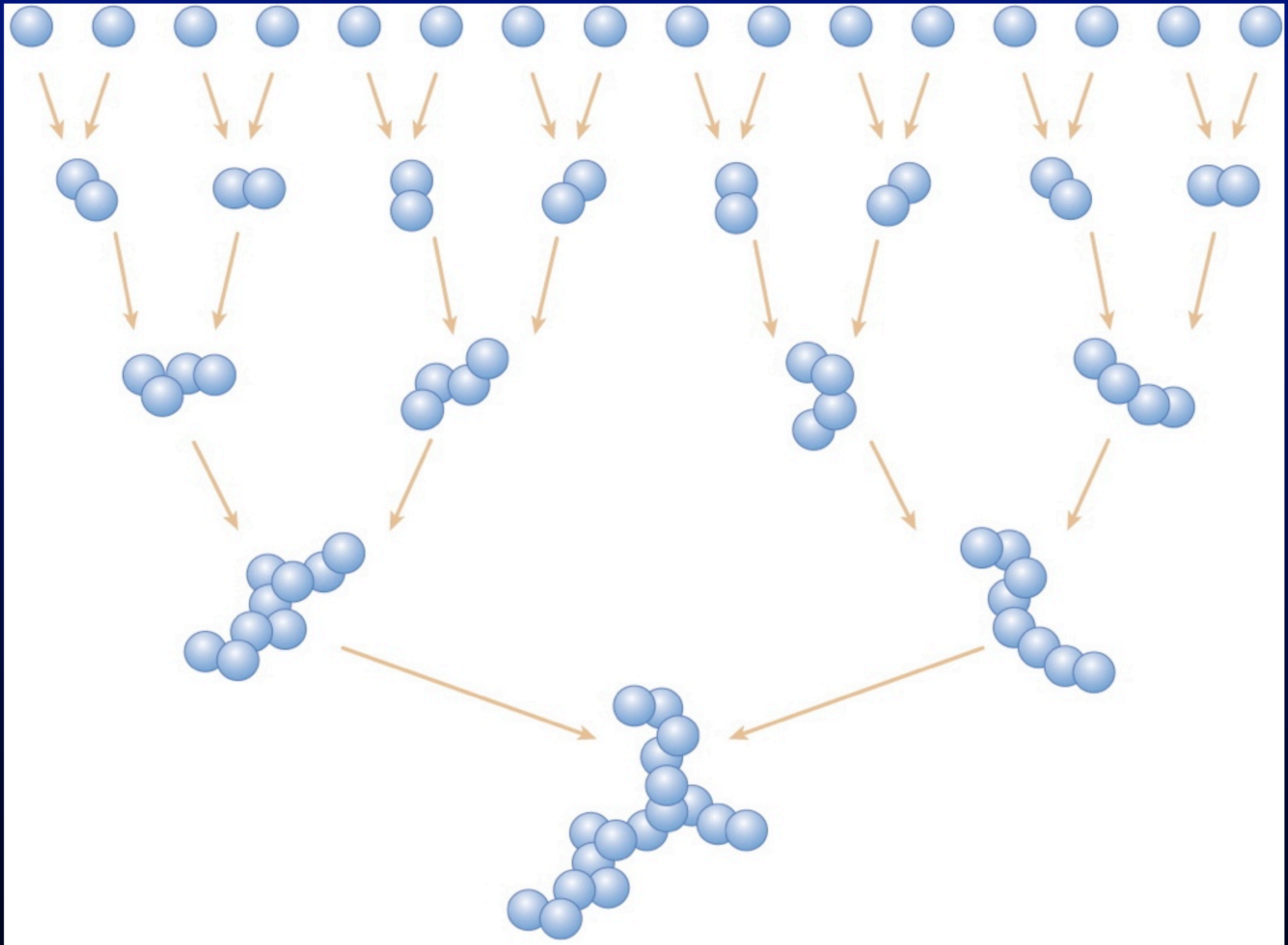
- In several cases the observed dust rings have:

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

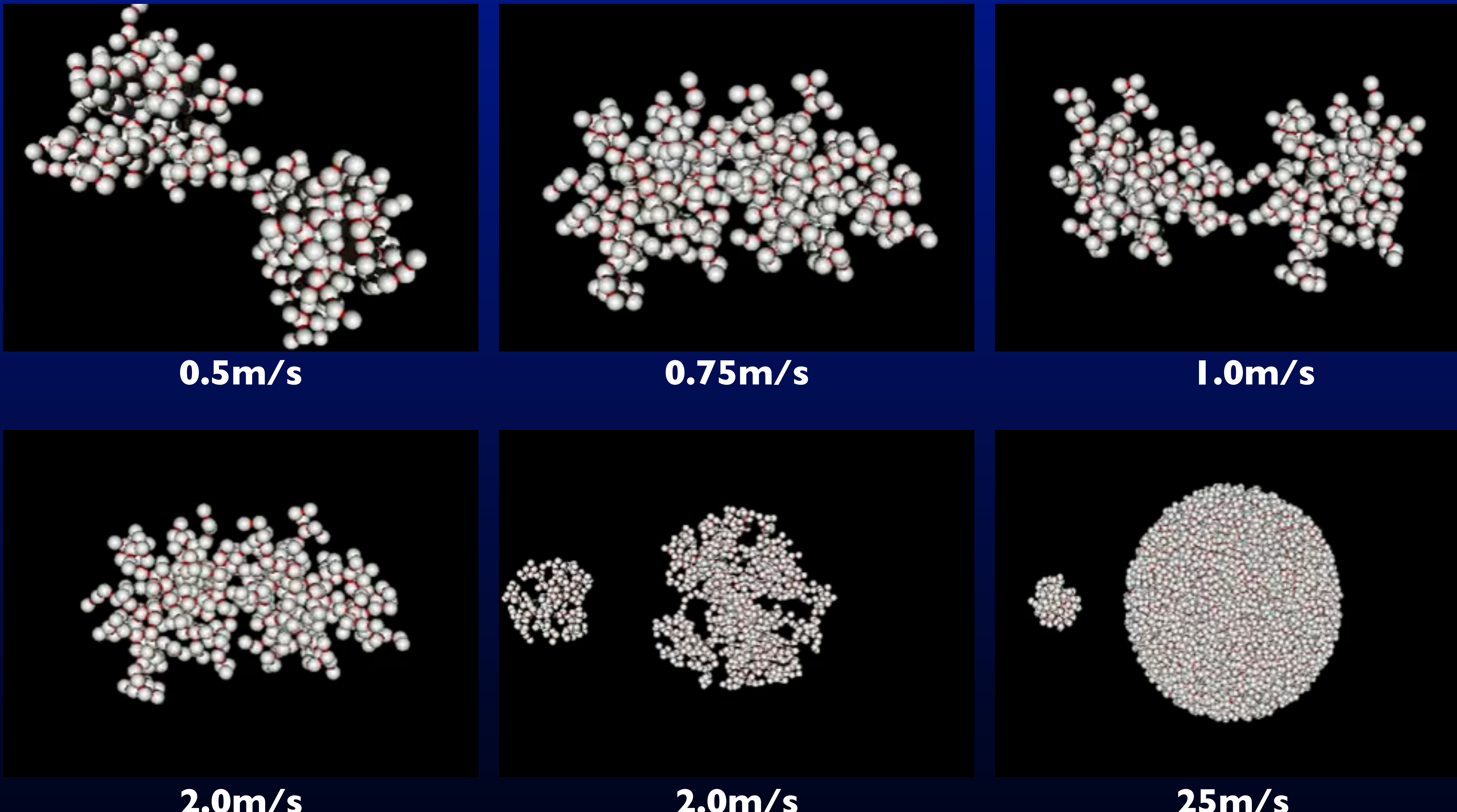
- Dust structures narrower than gas structures – this requires **trapping**.

Dullemond et al. (2018)

Collisions - fractal growth

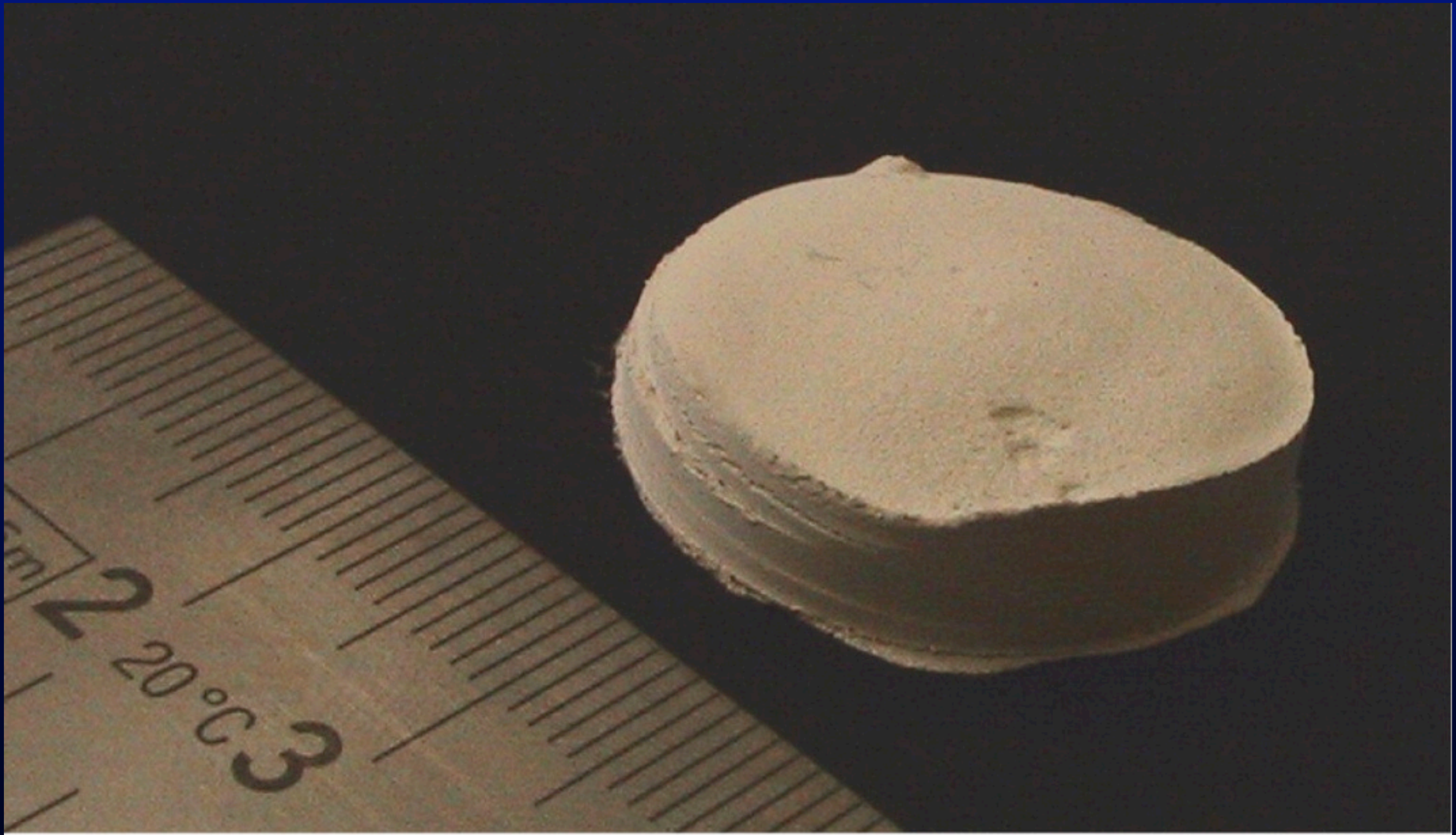


Blum J, Wurm G. 2008.
Annu. Rev. Astron. Astrophys. 46:21–56



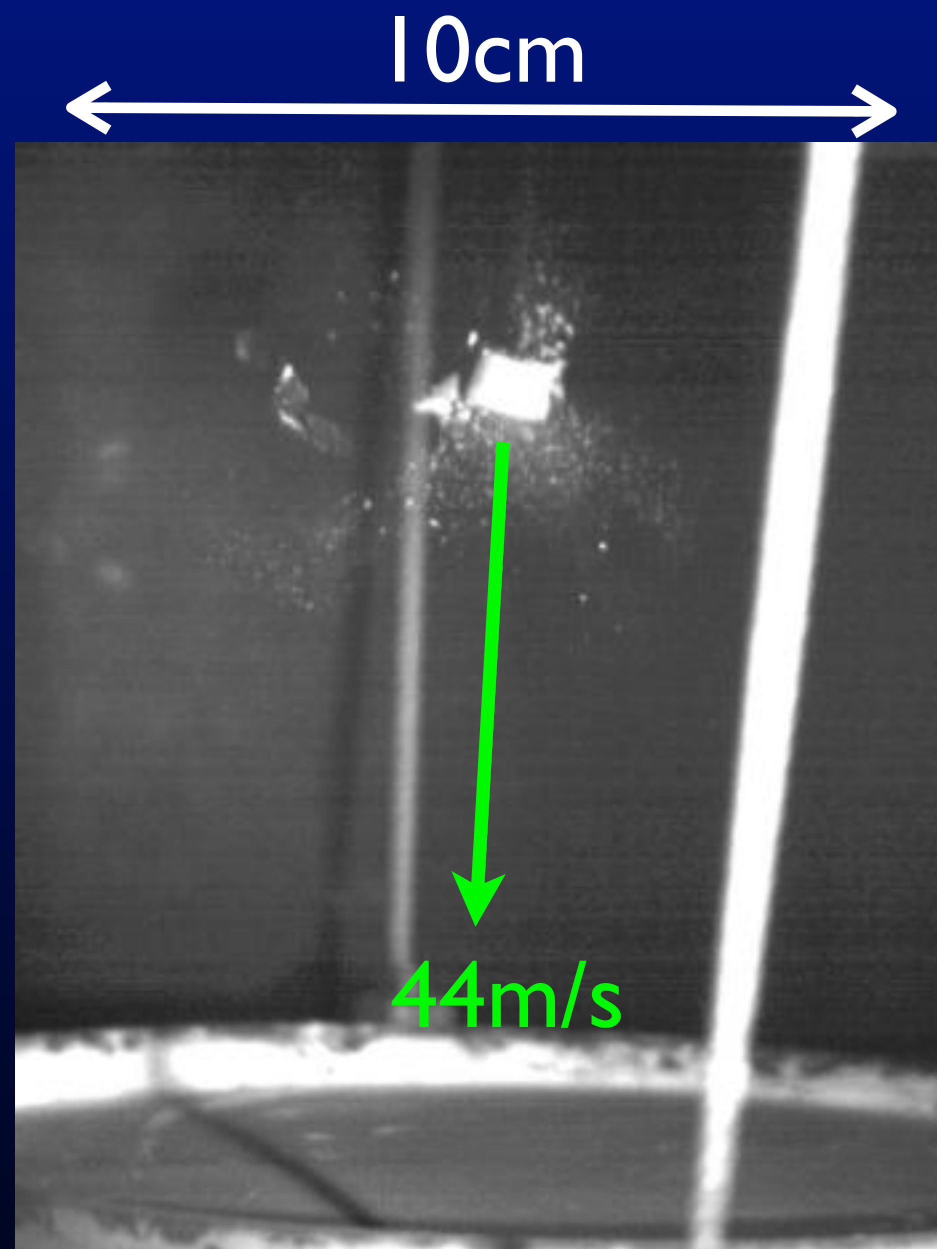
Animations of numerical simulations by Paszun & Dominik (2008). Individual “particles” are spherical SiO_2 monomers of radius 0.6μm.

Laboratory experiments

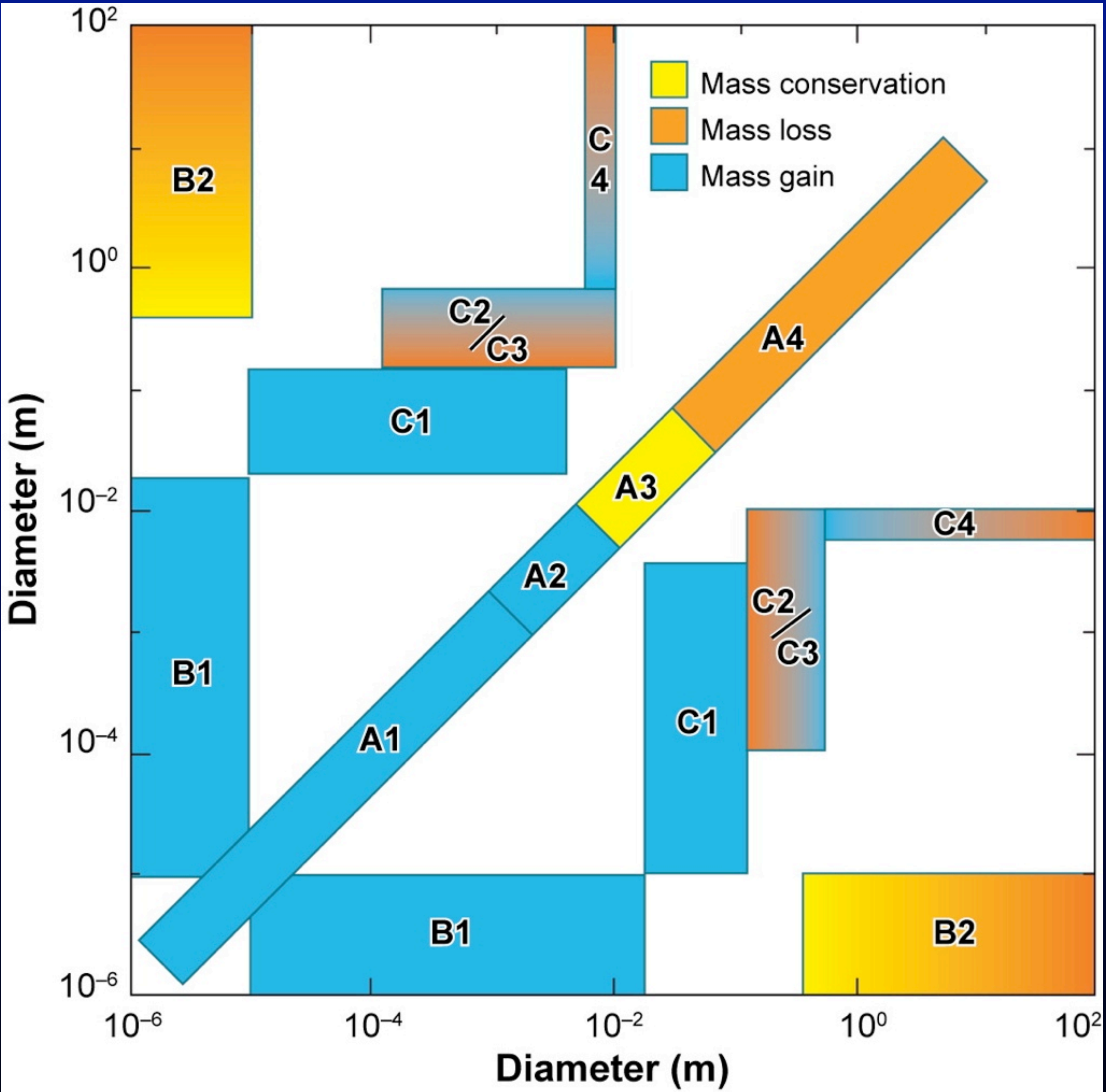


Blum J, Wurm G. 2008.
Annu. Rev. Astron. Astrophys. 46:21–56

Laboratory experiments



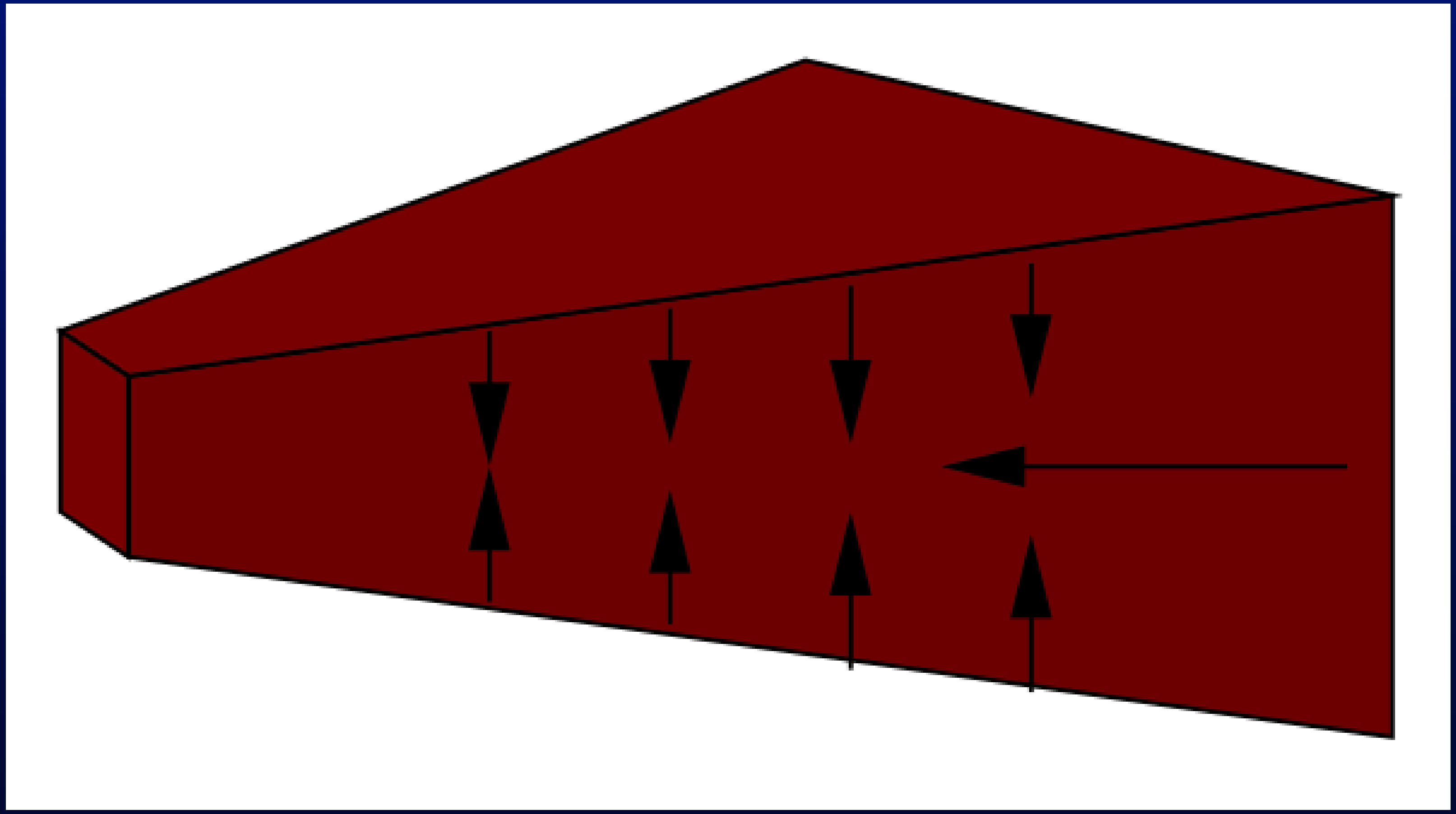
Teiser & Wurm (2009)



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

The Goldreich-Ward mechanism

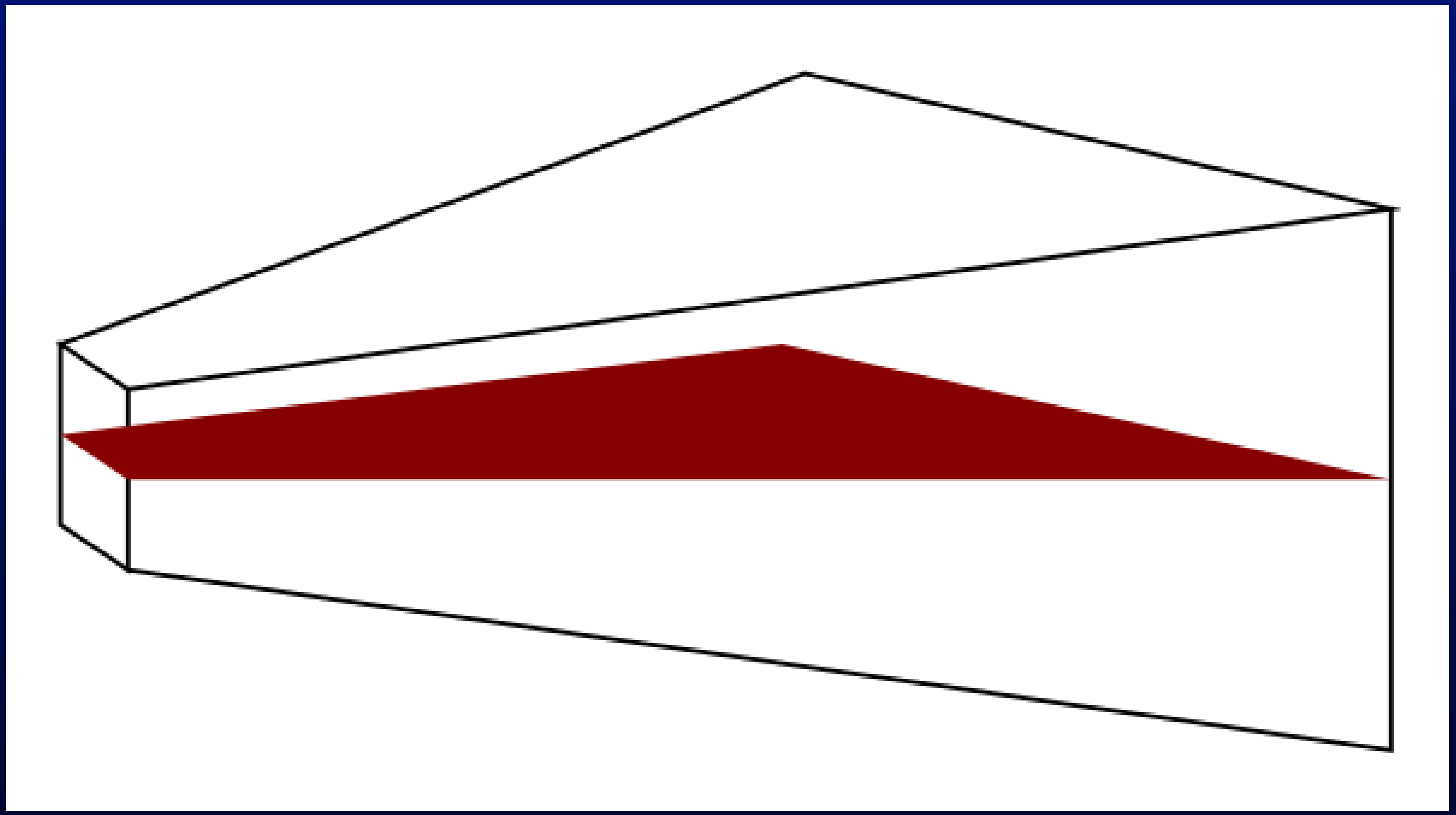
Goldreich & Ward (1973); figures from Armitage (2007)



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

The Goldreich-Ward mechanism

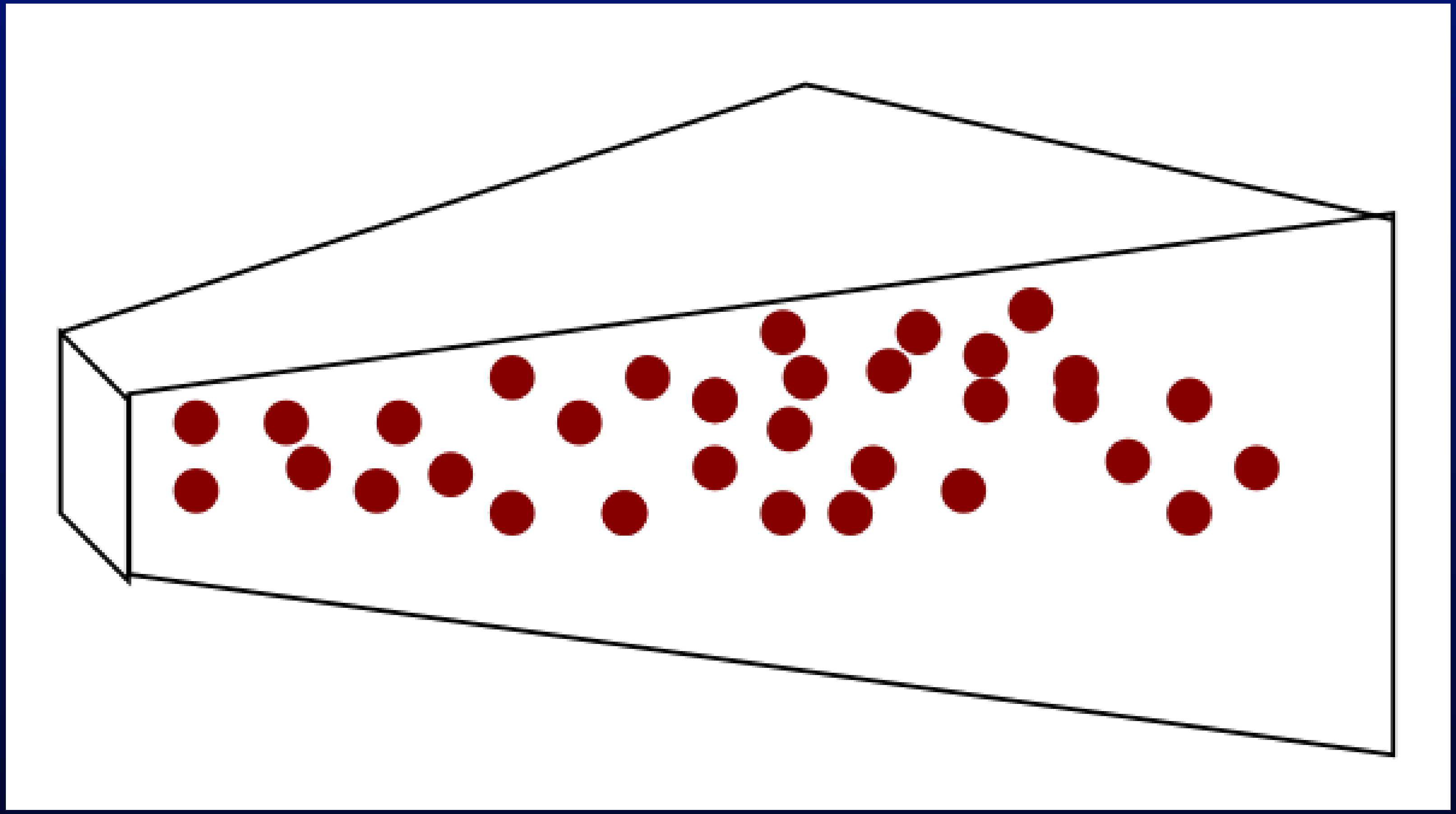
Goldreich & Ward (1973); figures from Armitage (2007)



...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

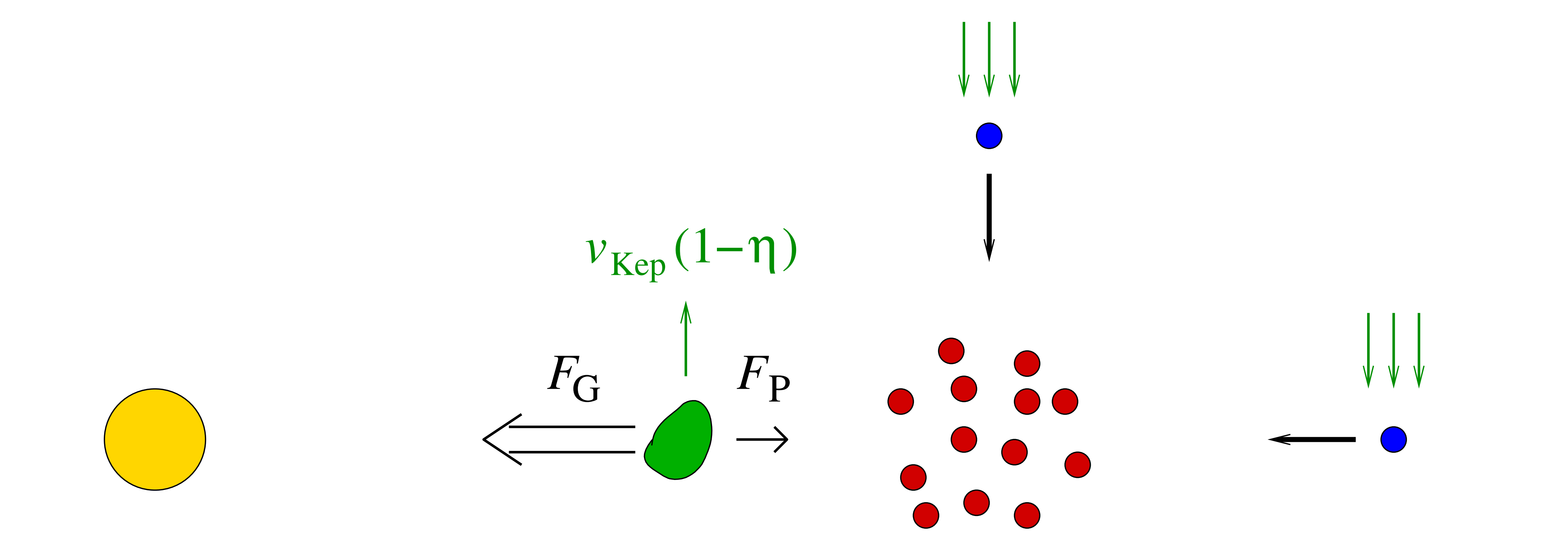


Figure courtesy of Anders Johansen

- 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

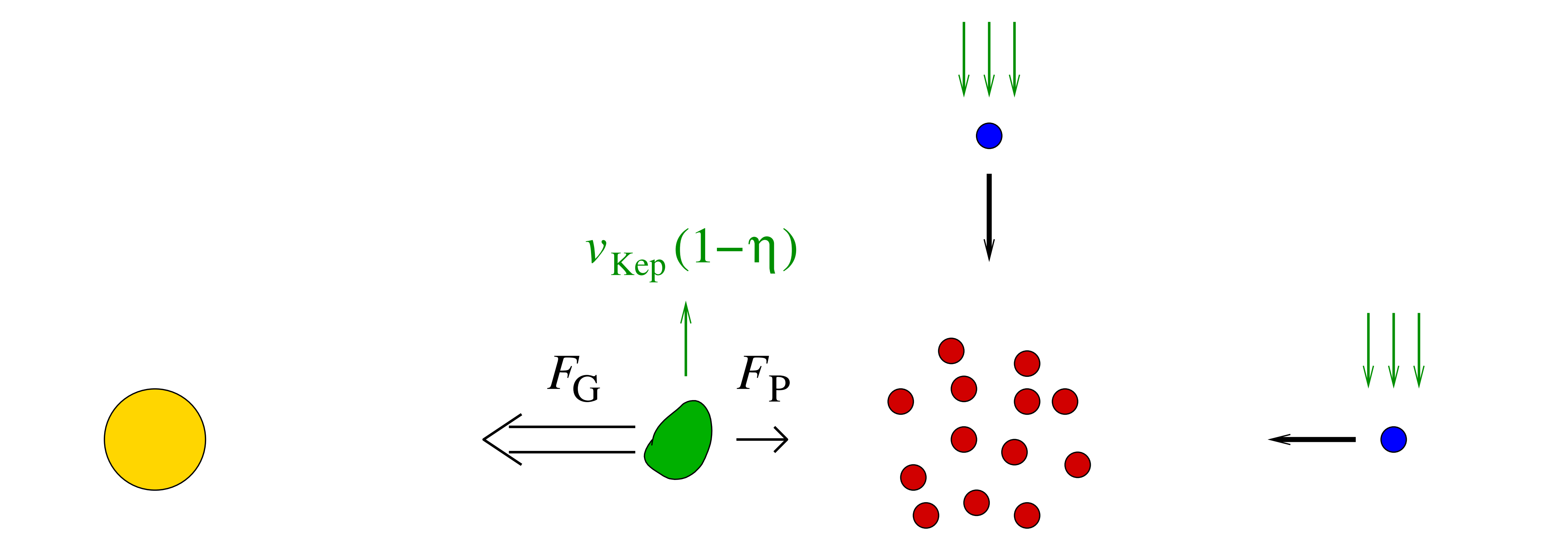
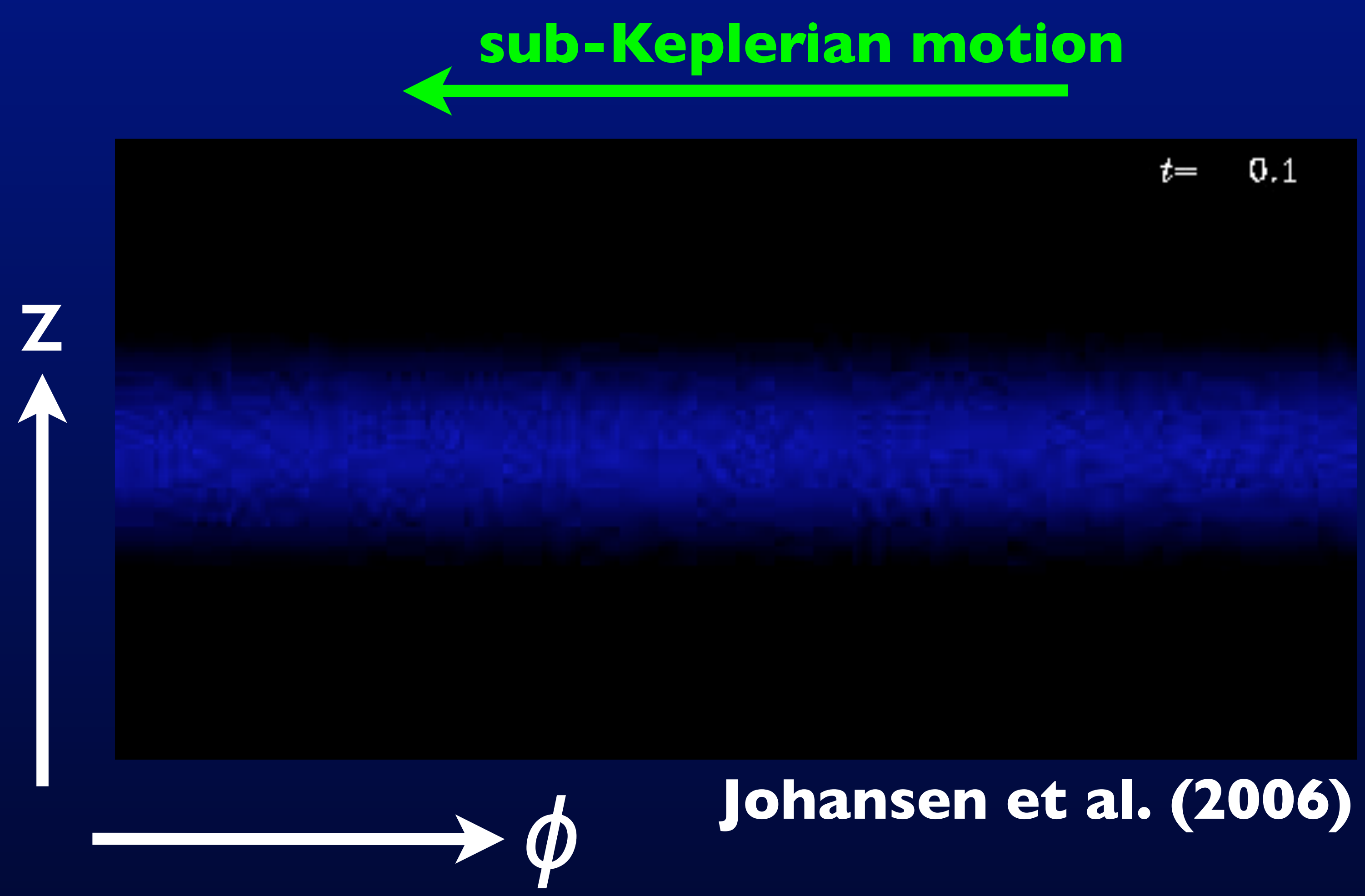


Figure courtesy of Anders Johansen

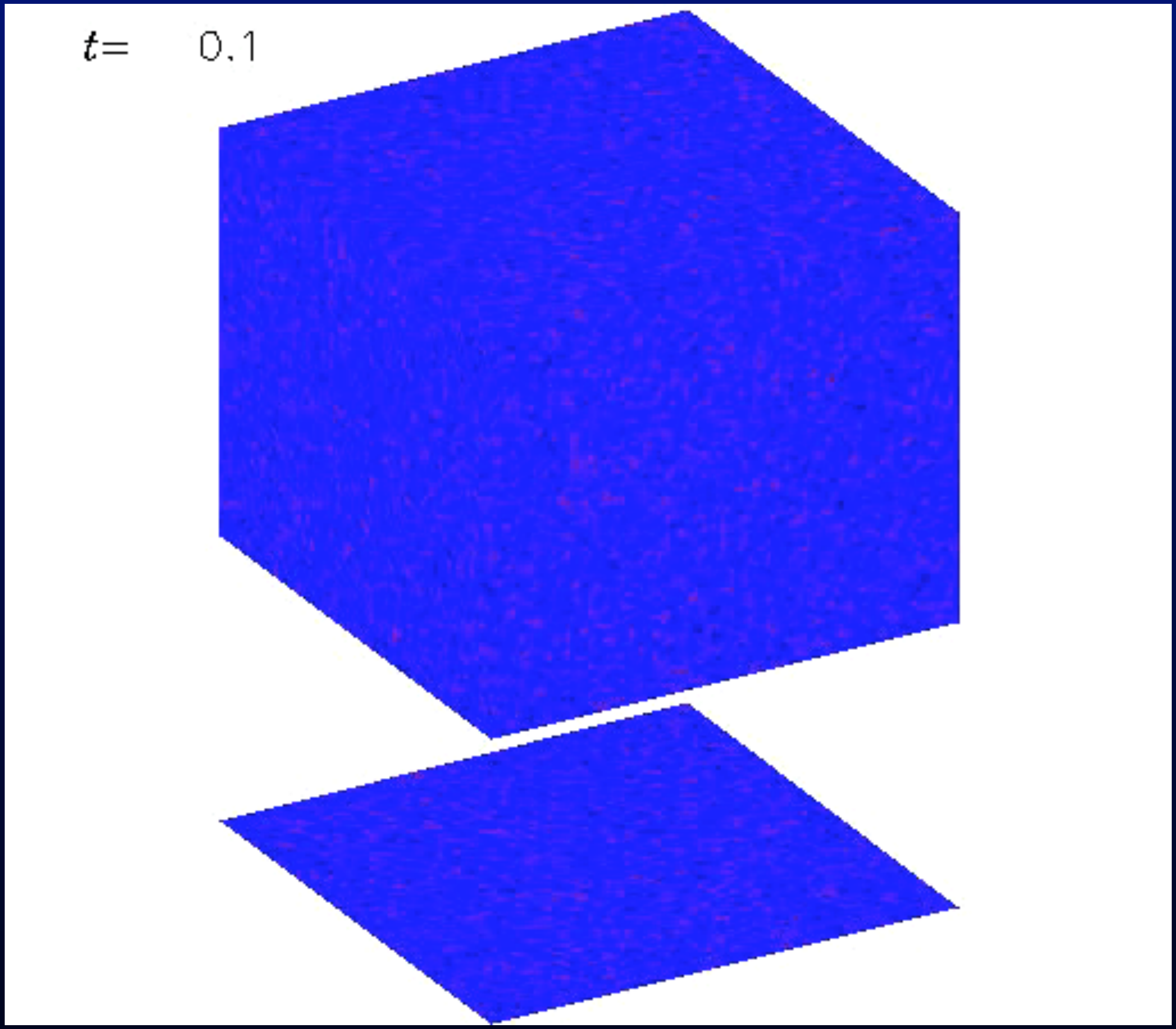
- Solids lose angular momentum due to headwind, but headwind reduced when particles "clump".
- Leads to further clumping → instability.
- Streaming instability most effective for particles with $T_s = 1$. Still requires rapid growth up to ~cm to ~m

Streaming instability



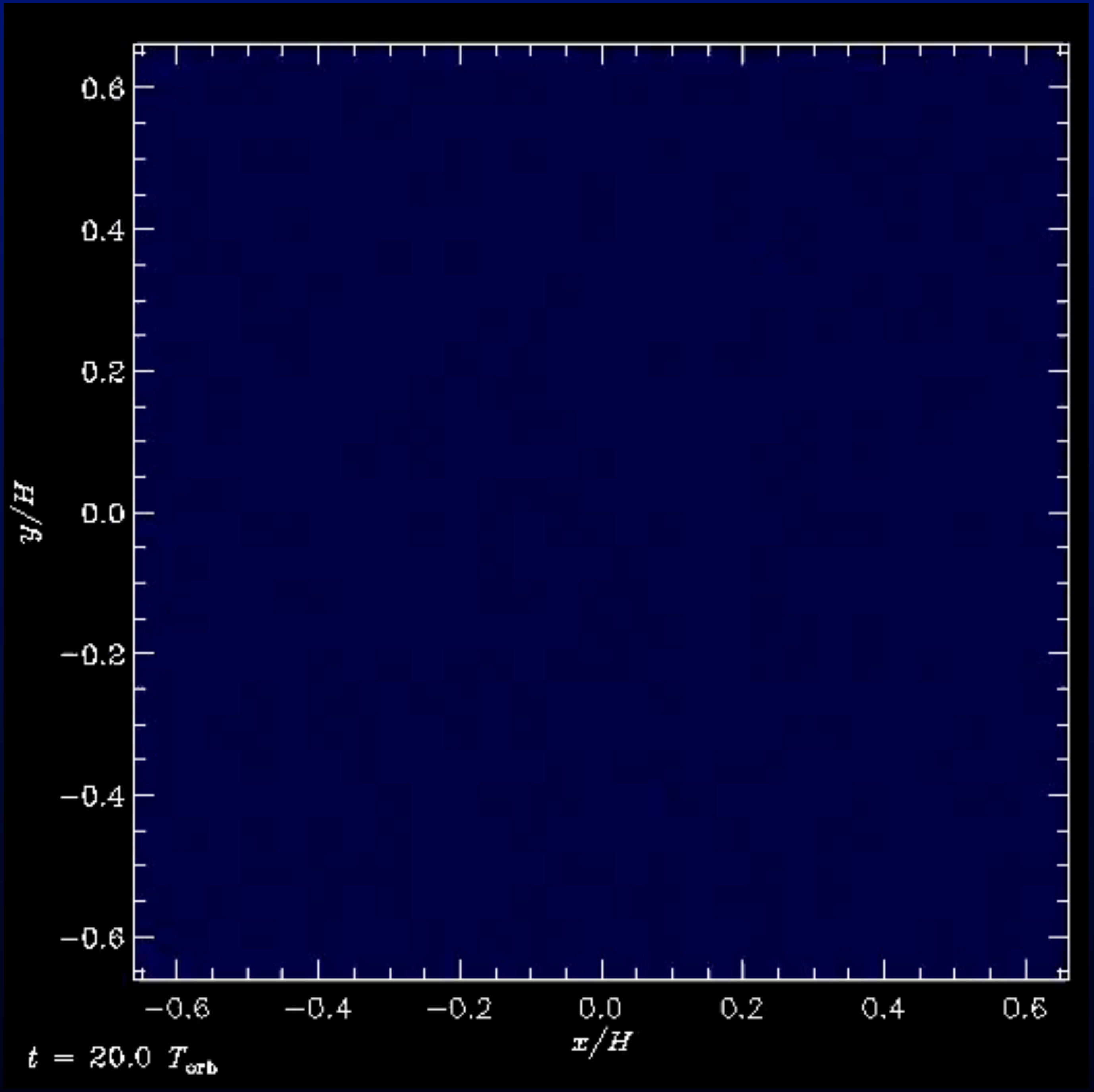
- Solids lose angular momentum due to headwind, but headwind reduced when particles "clump".
- Leads to further clumping → instability.
- Streaming instability most effective for particles with $T_s = 1$. Still requires rapid growth up to ~cm to ~m

Planetesimal formation in turbulent discs



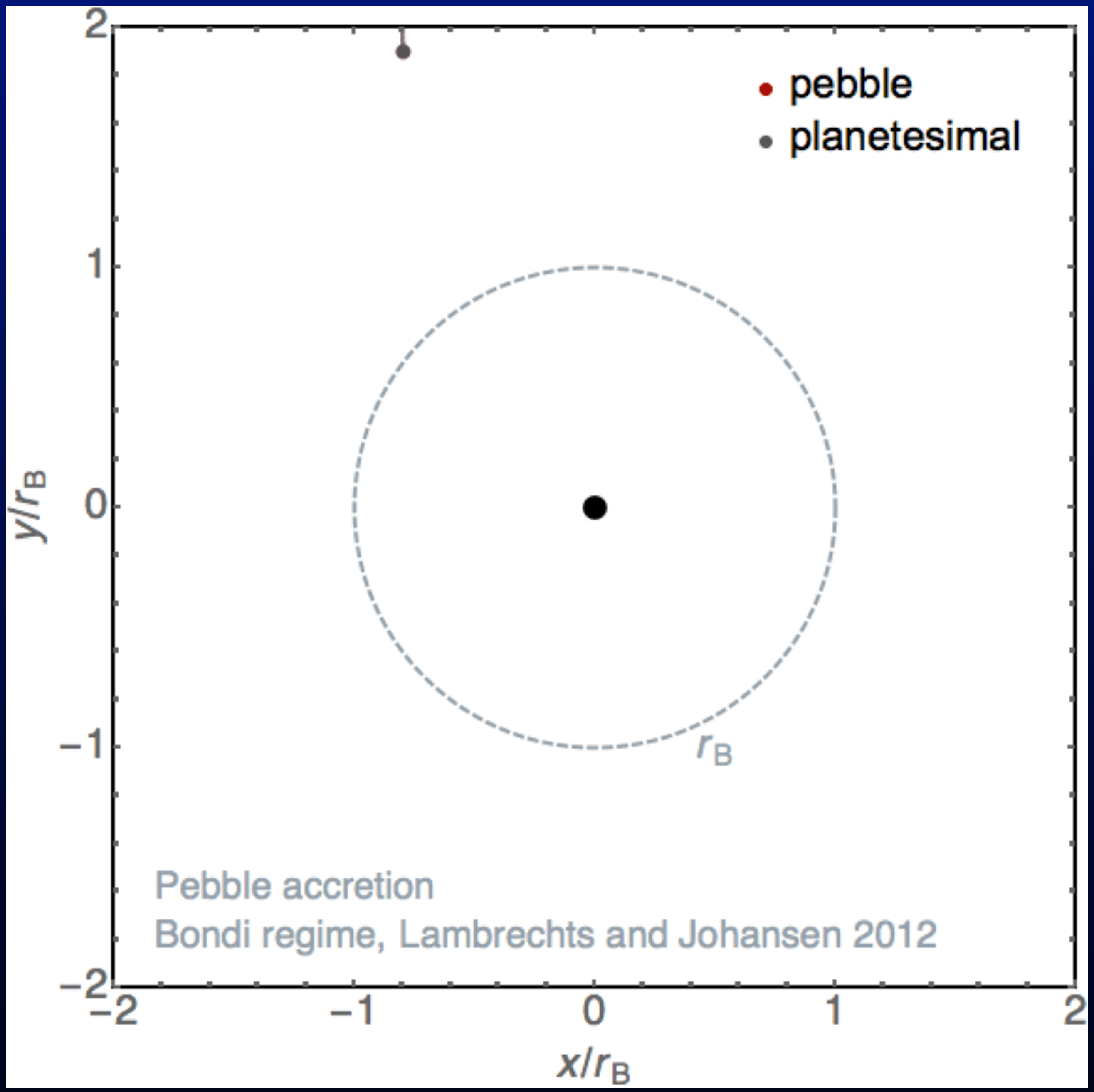
Johansen & Youdin (2007)

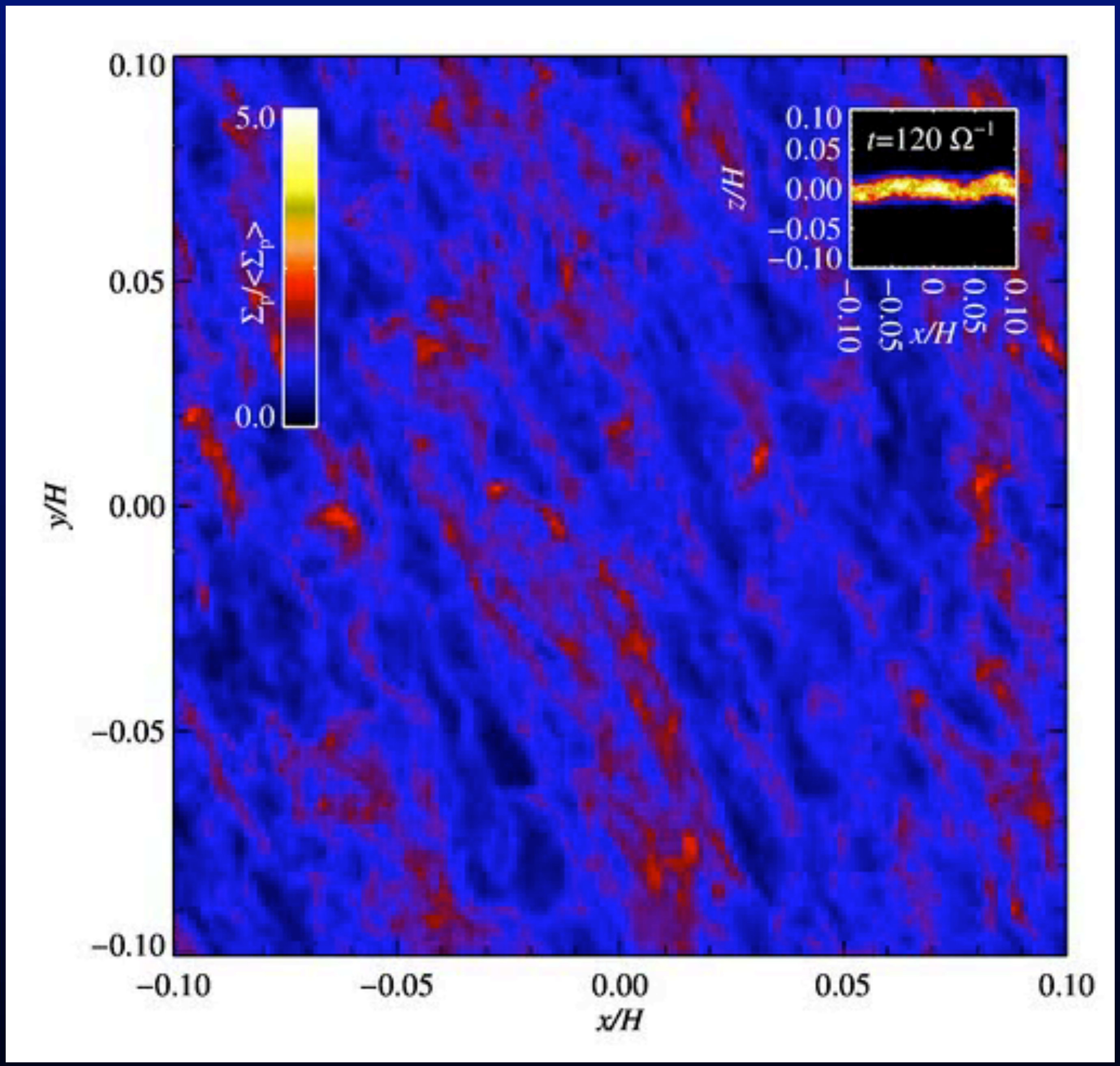
Planetesimal formation in turbulent discs



Johansen et al. (2011)

Pebble accretion





Lambrechts & Johansen (2012)