On the Feeding Zone of Planetesimal Formation by the Streaming Instability

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In collaboration with
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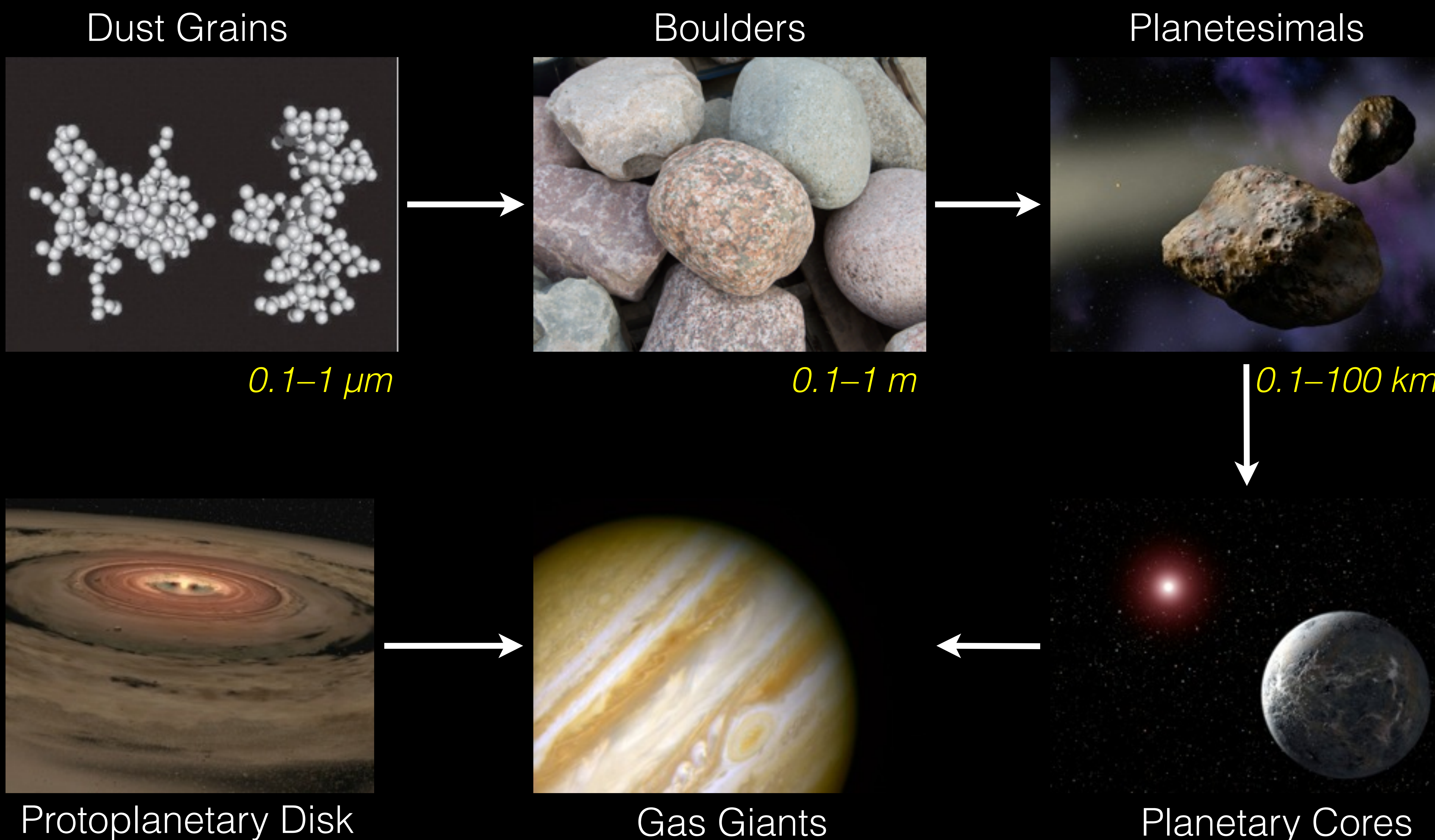
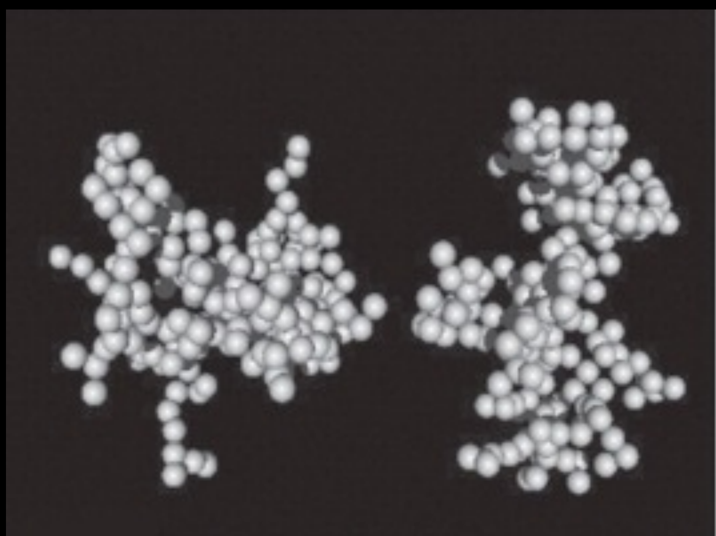
Planet Formation



Planet Formation

Dust Grains



0.1–1 μm

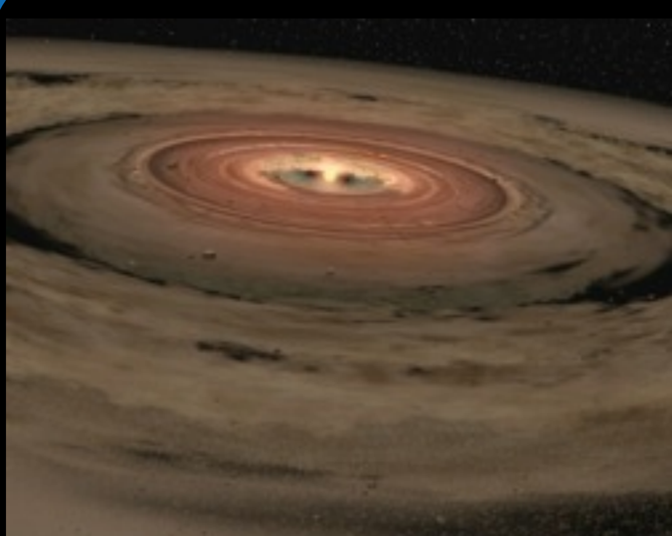
Boulders

0.1–1 m

Planetesimals

0.1–100 km

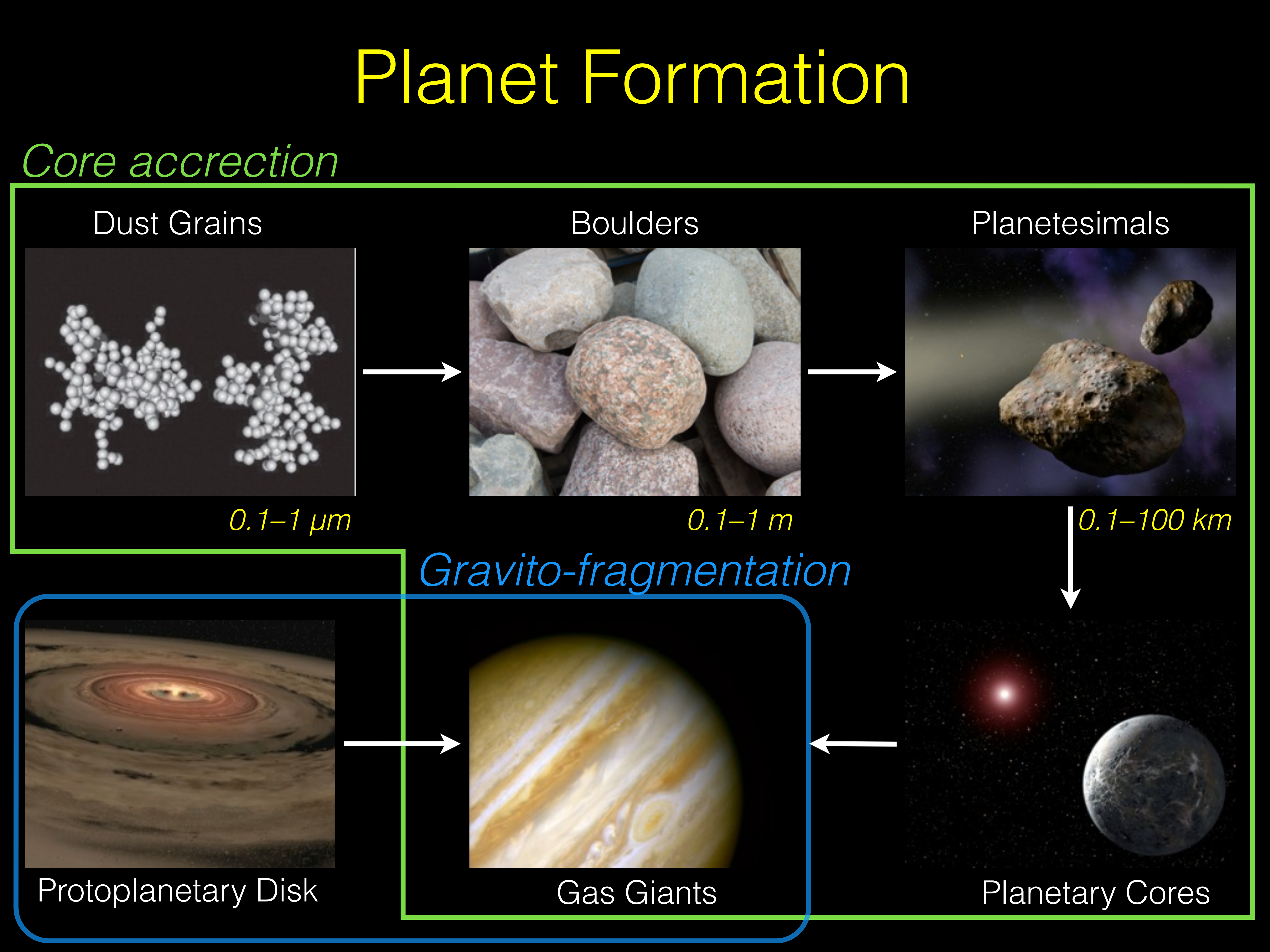
Gravito-fragmentation



Protoplanetary Disk

Gas Giants

Planetary Cores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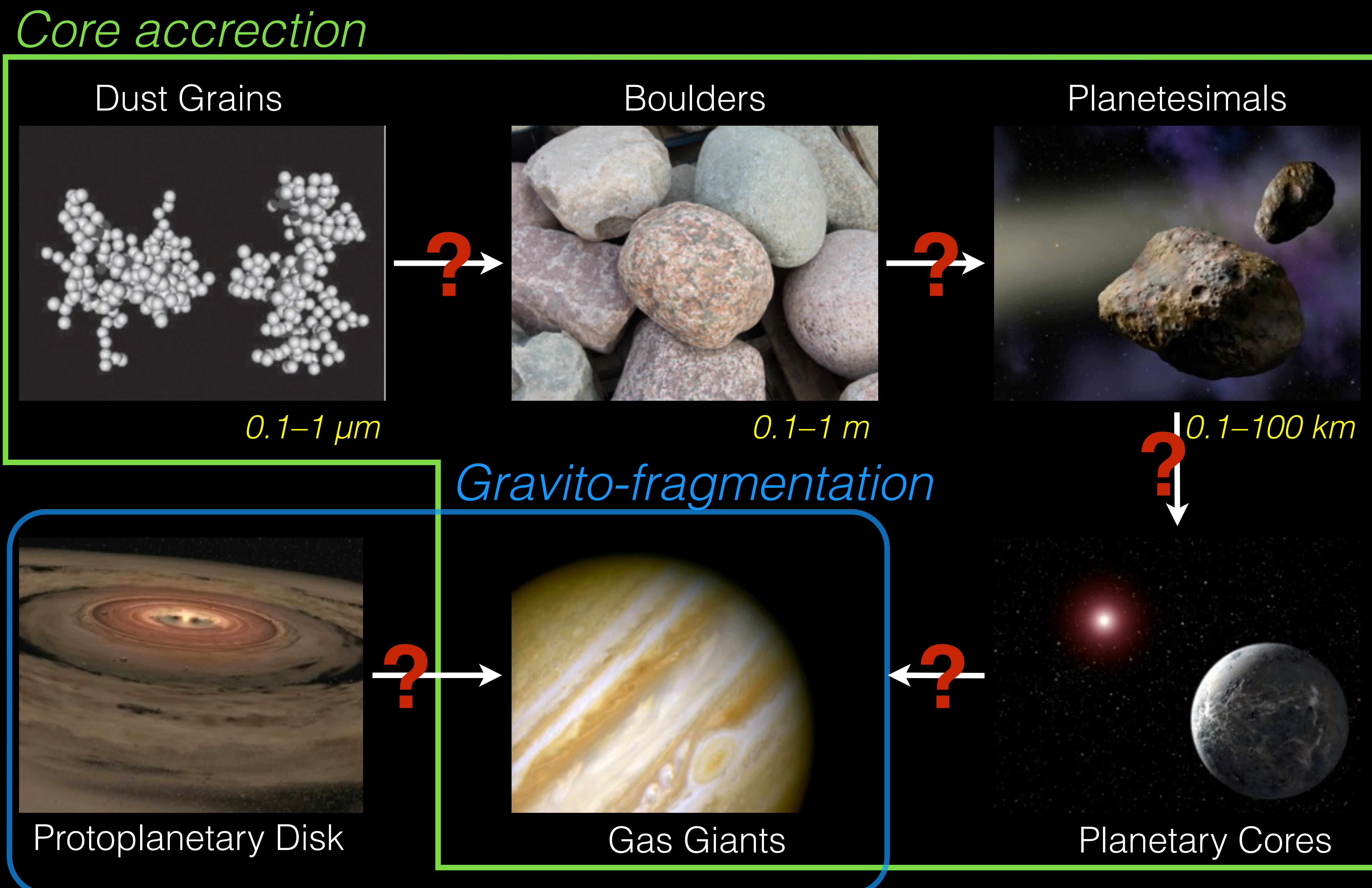
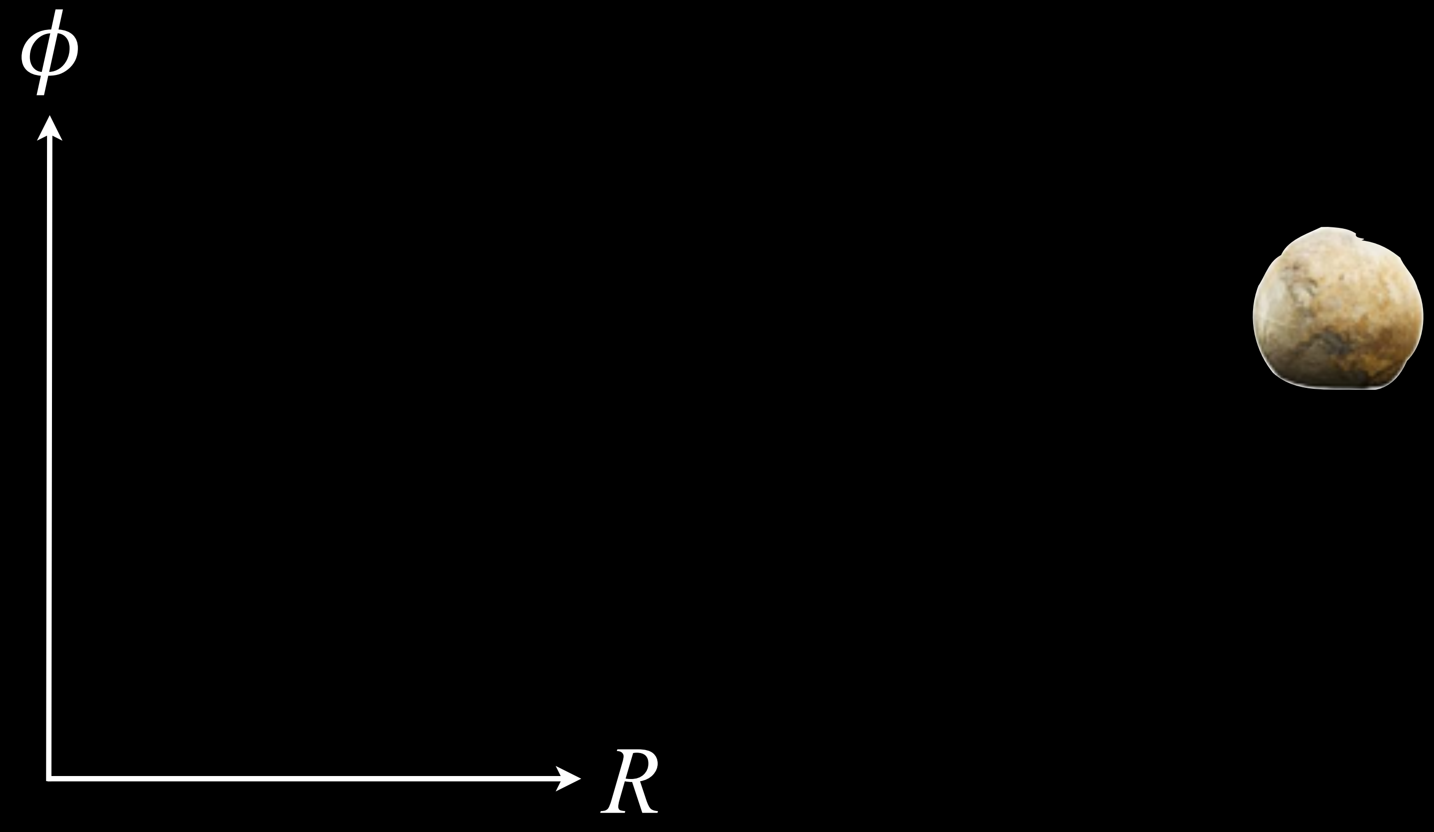
Planet Formation



Meter-size Barrier

(Adachi, Hayashi, & Nakazawa 1976; Weidenschilling 1977)



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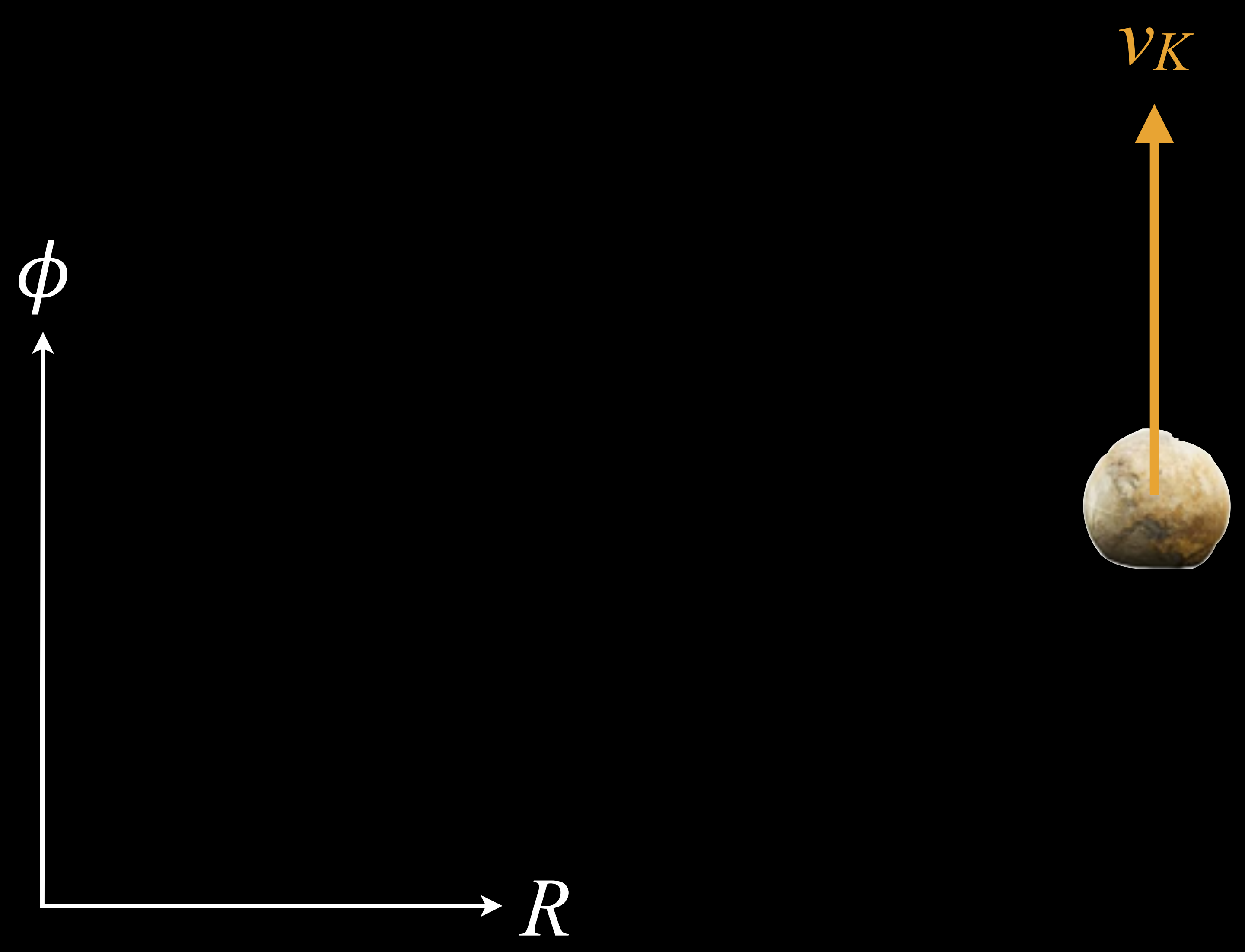

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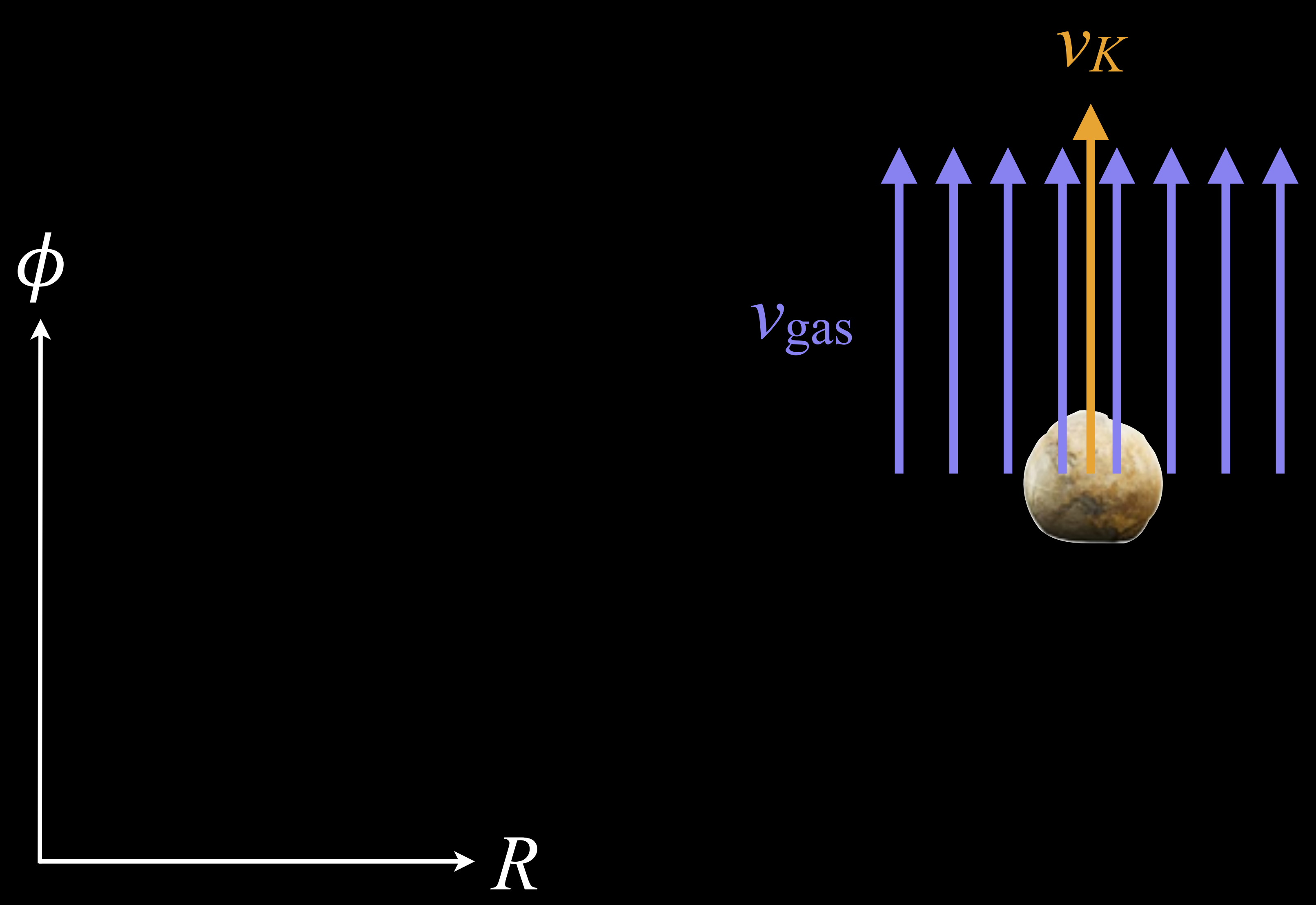

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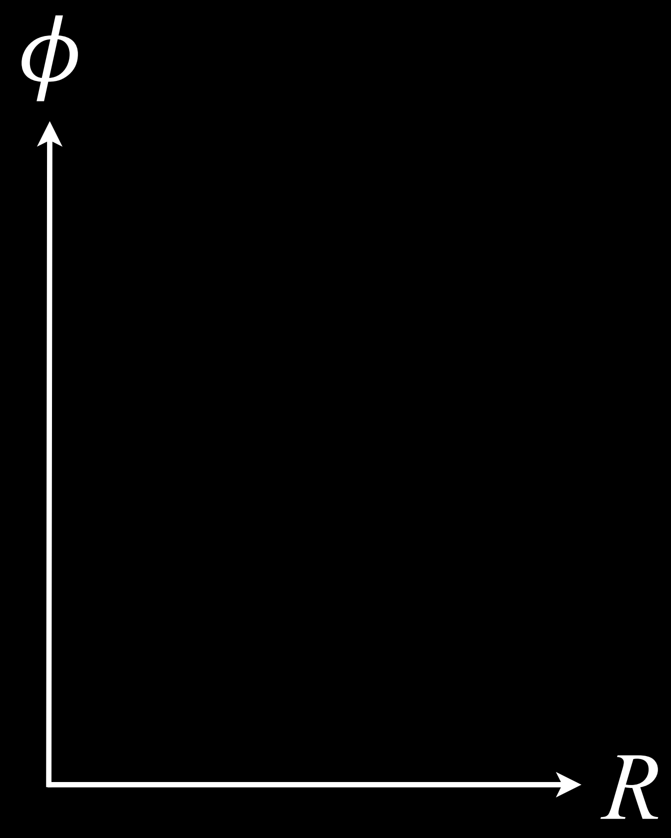

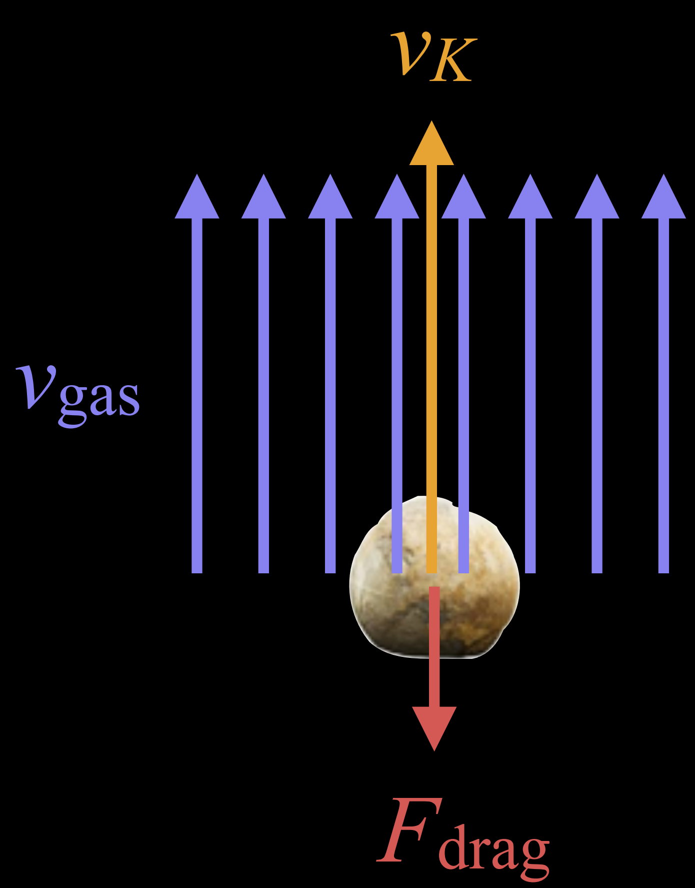

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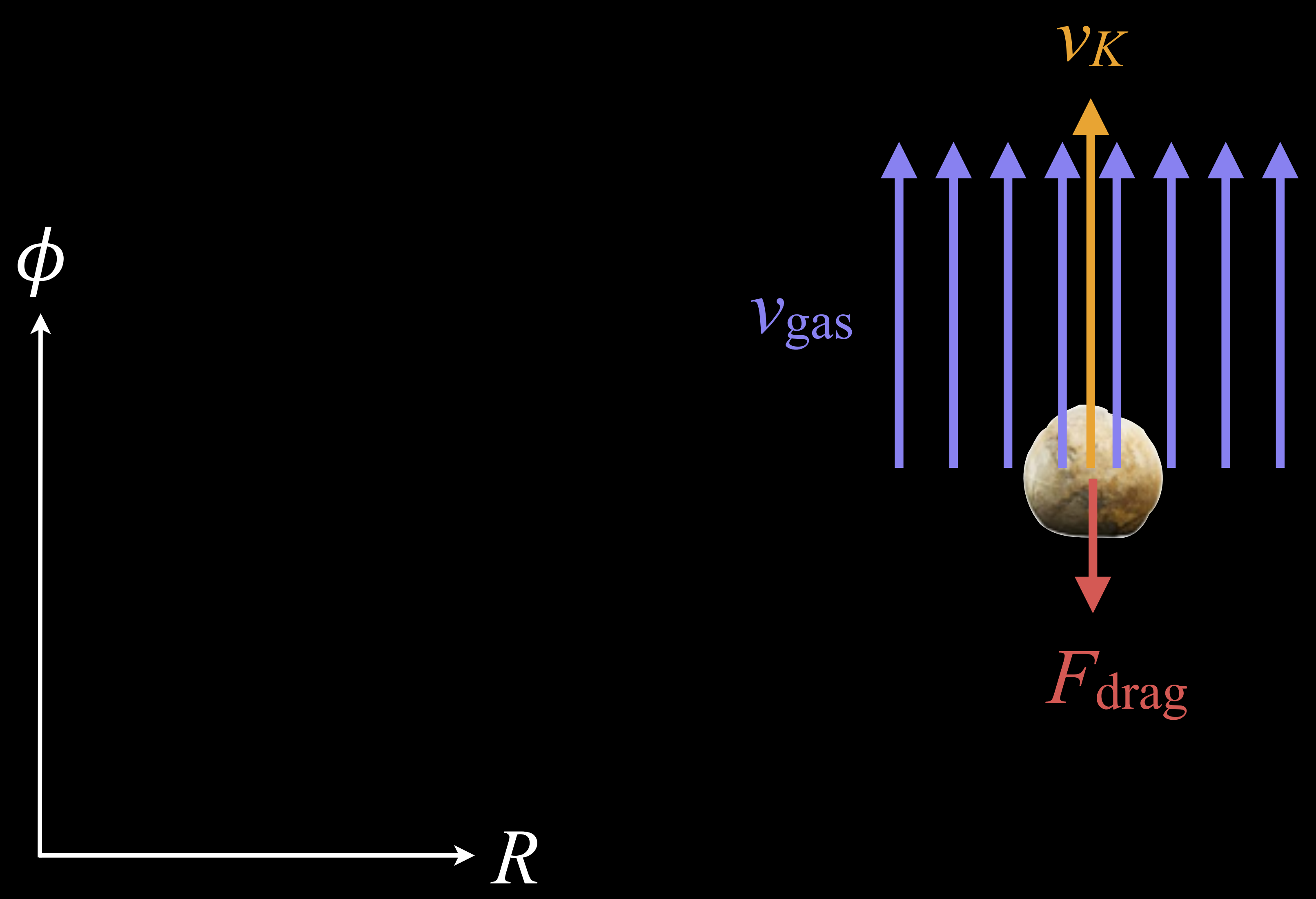

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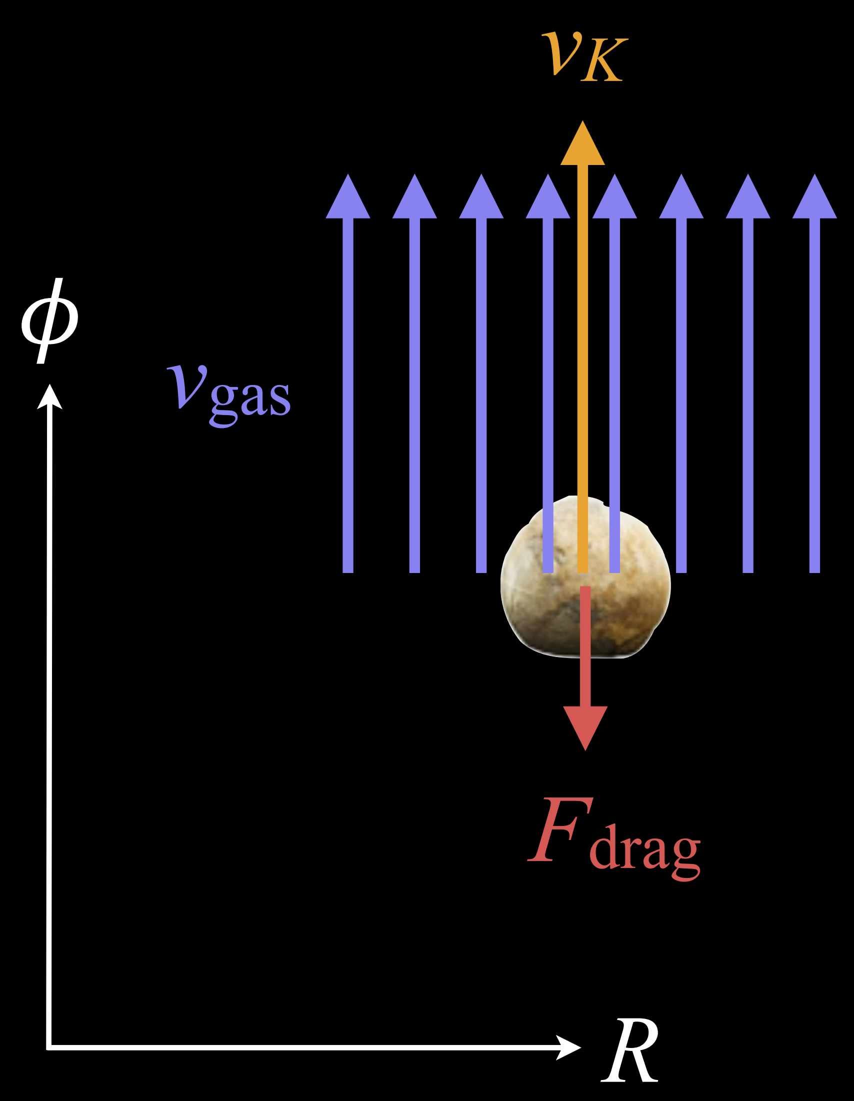

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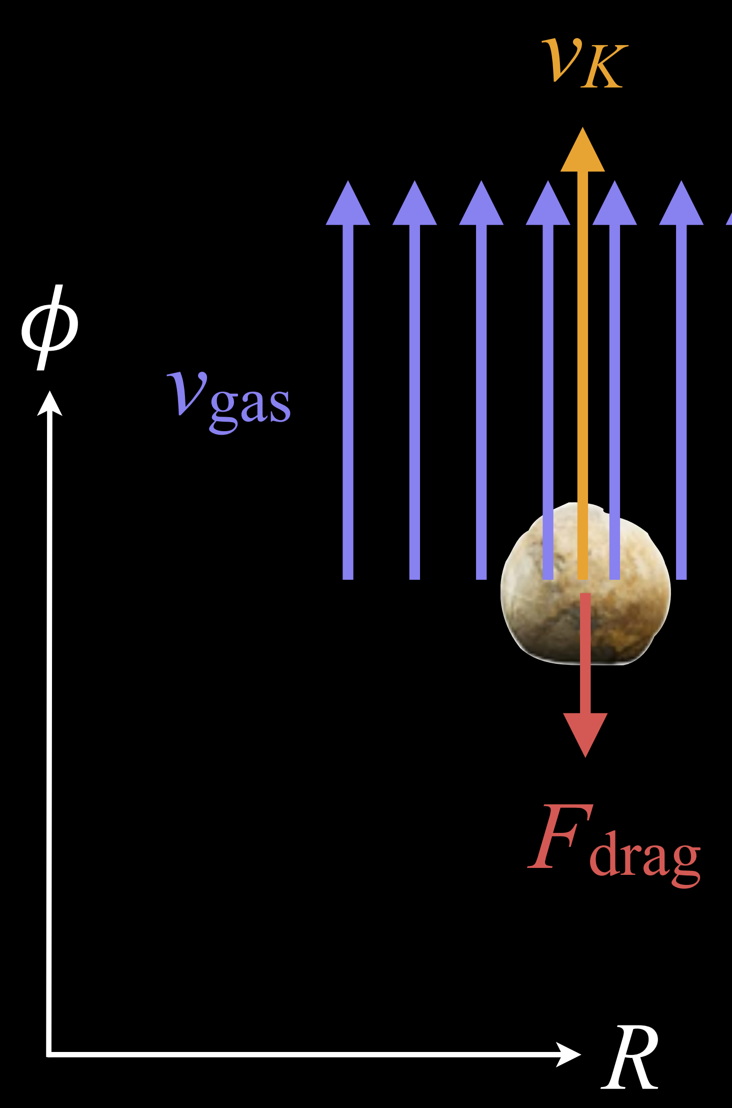
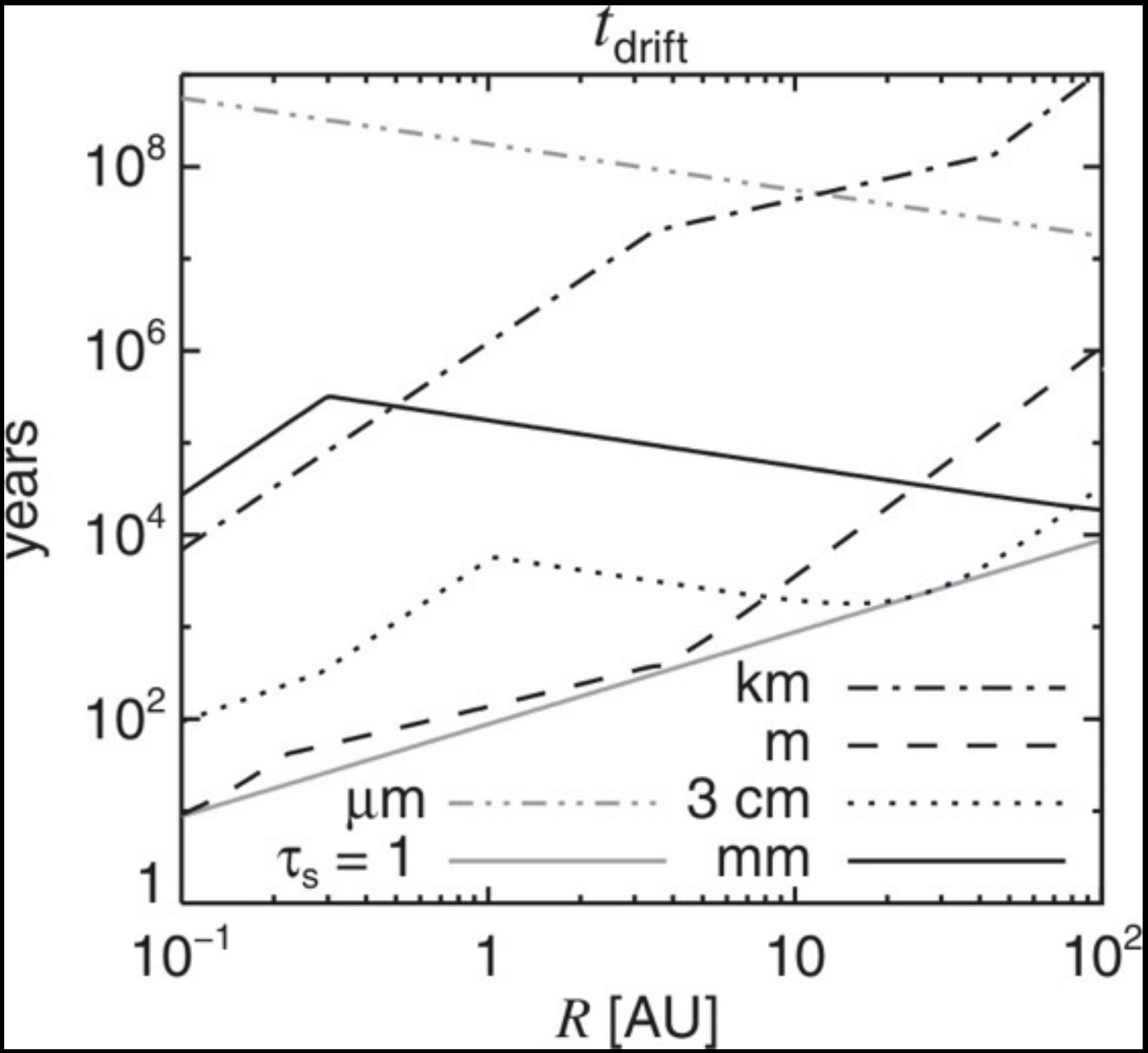


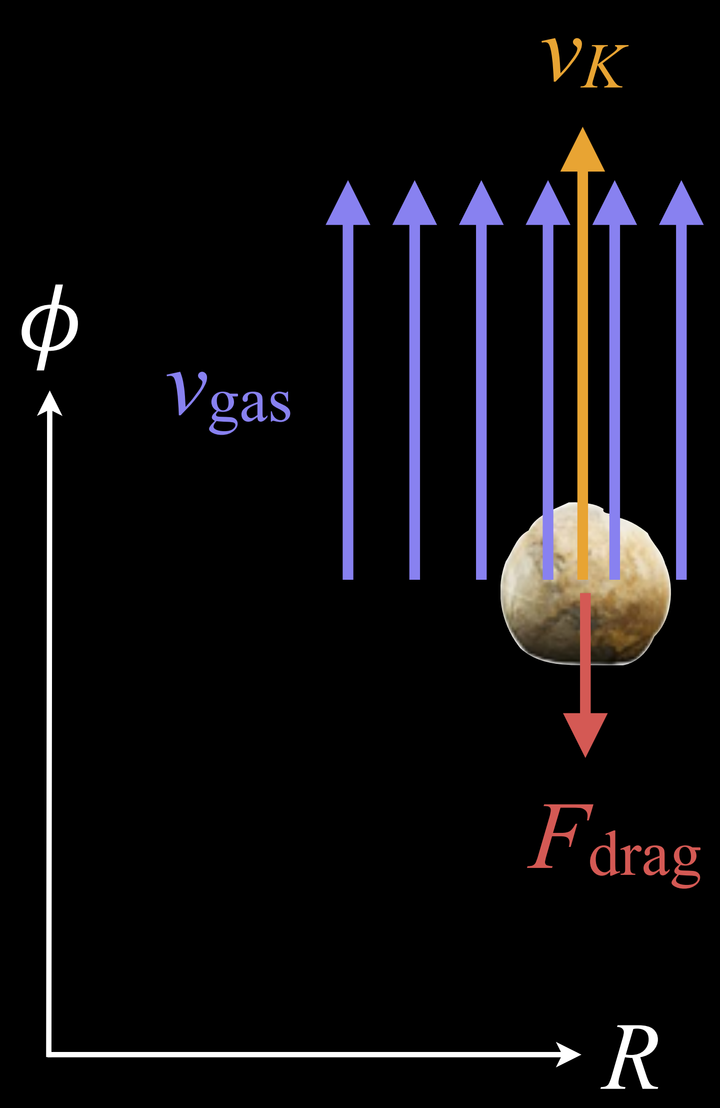


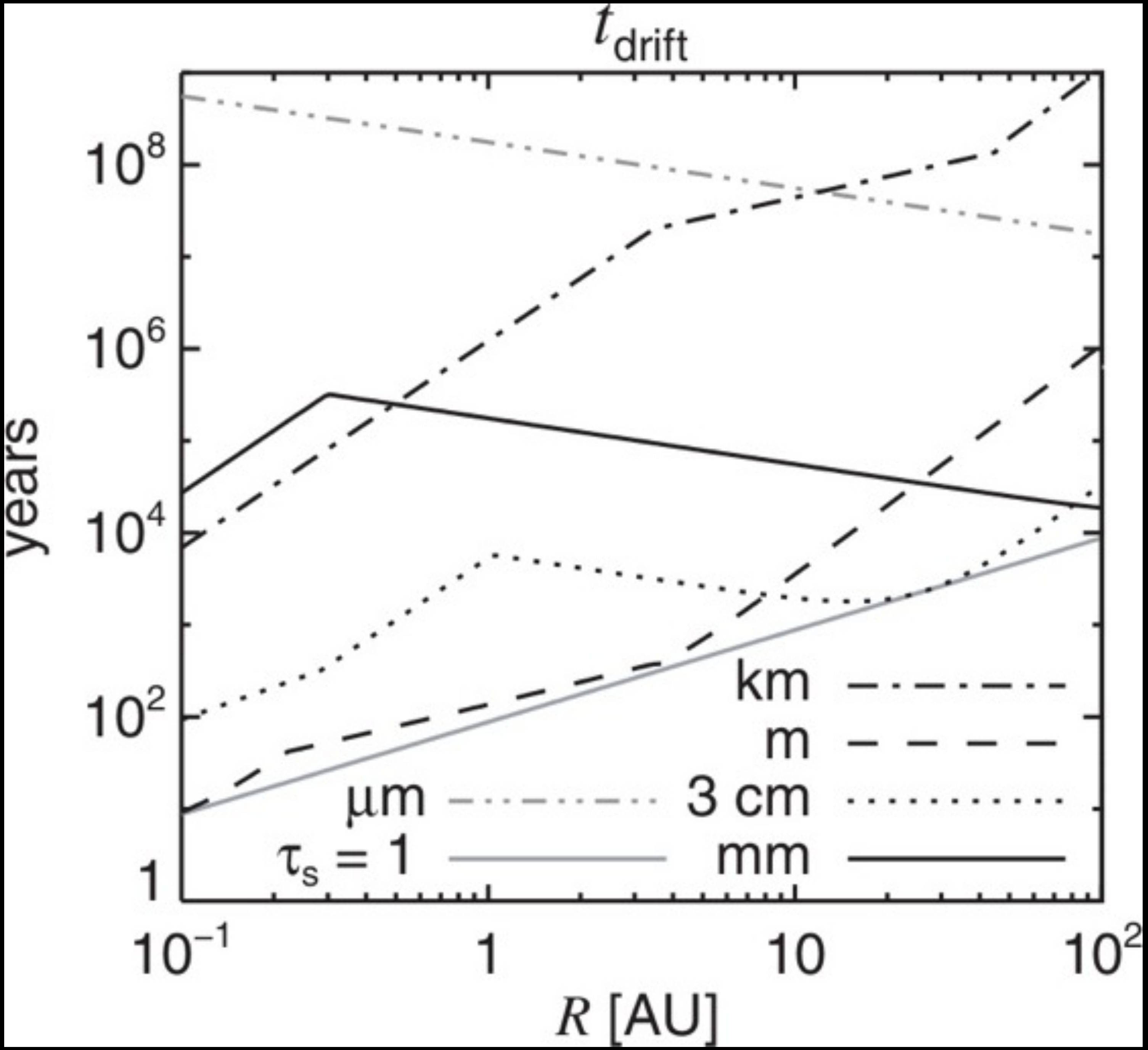
Youdin (2010)

Meter-size Barrier

(Adachi, Hayashi, & Nakazawa 1976; Weidenschilling 1977)

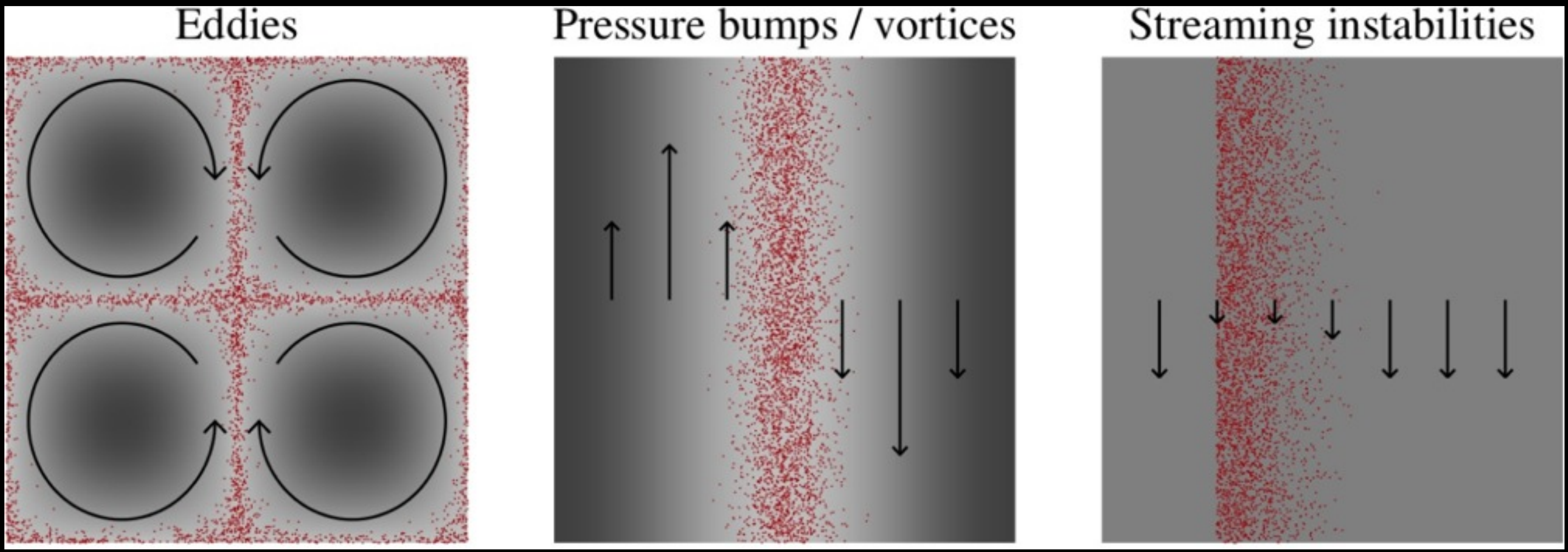
Disk lifetime ~ 2–10 Myr





Youdin (2010)

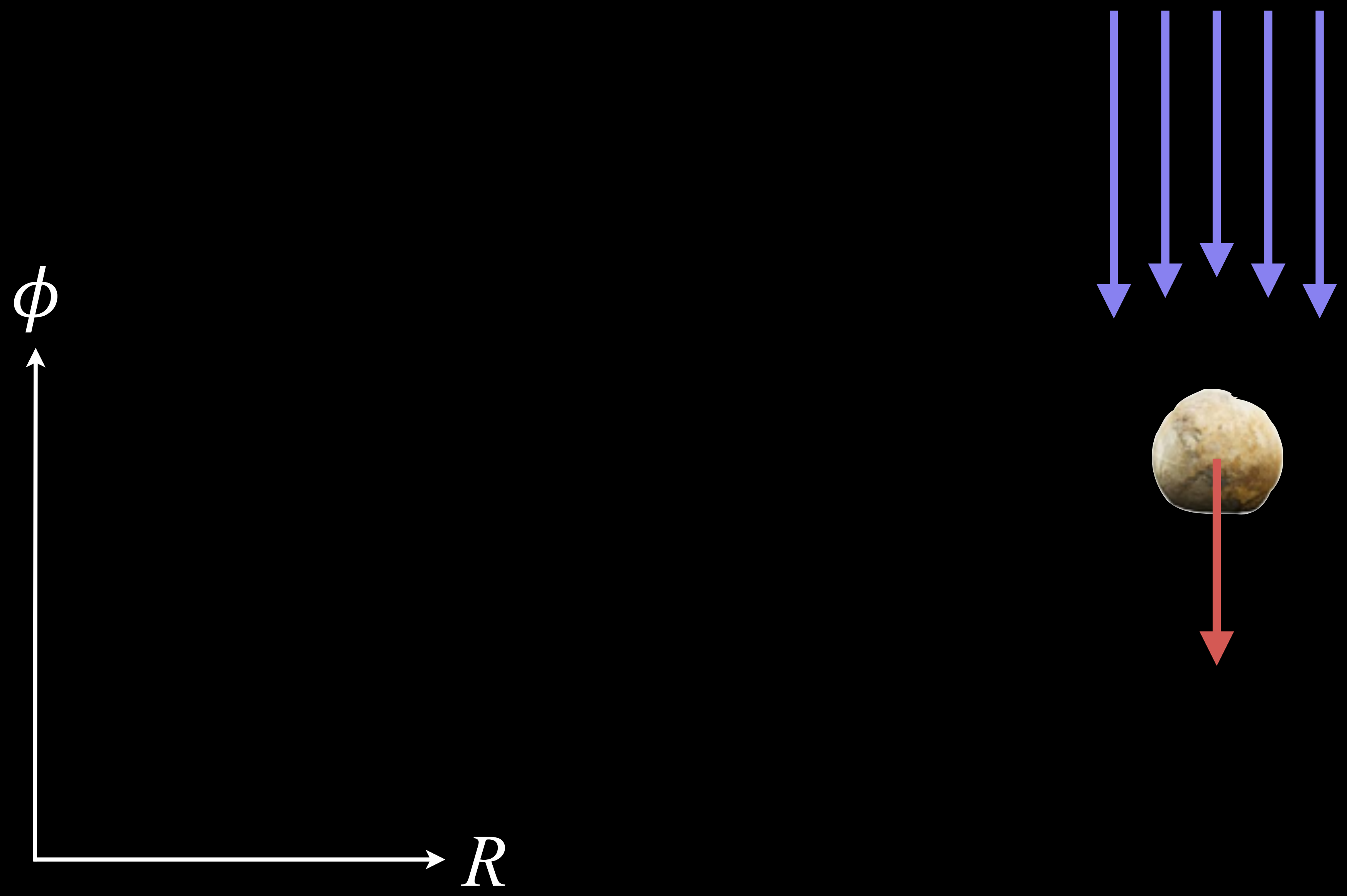
Concentrating the Solids



Johansen et al., Protostars & Planets VI

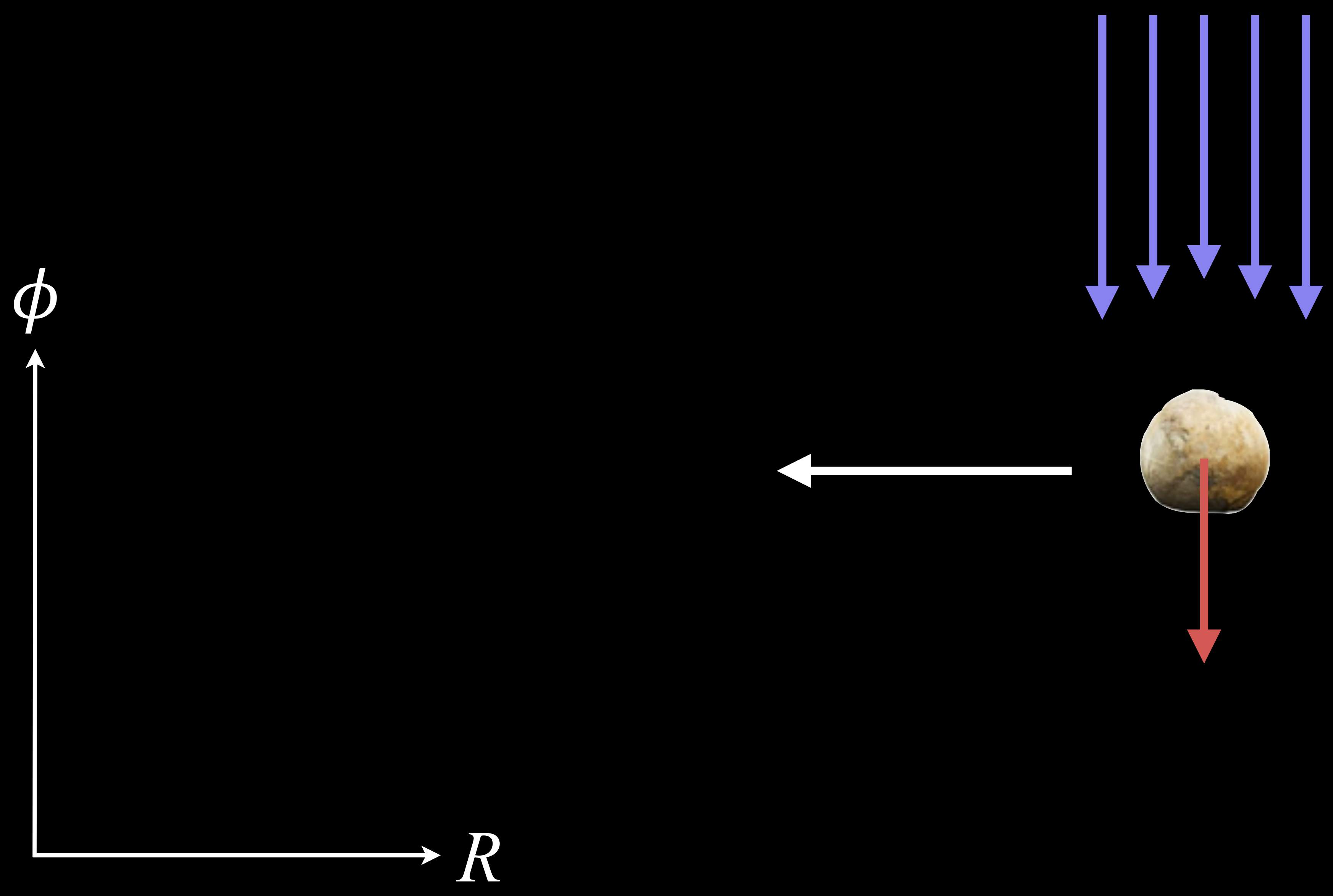
Streaming Instability

(Youdin & Goodman 2005)



Streaming Instability

(Youdin & Goodman 2005)



Streaming Instability

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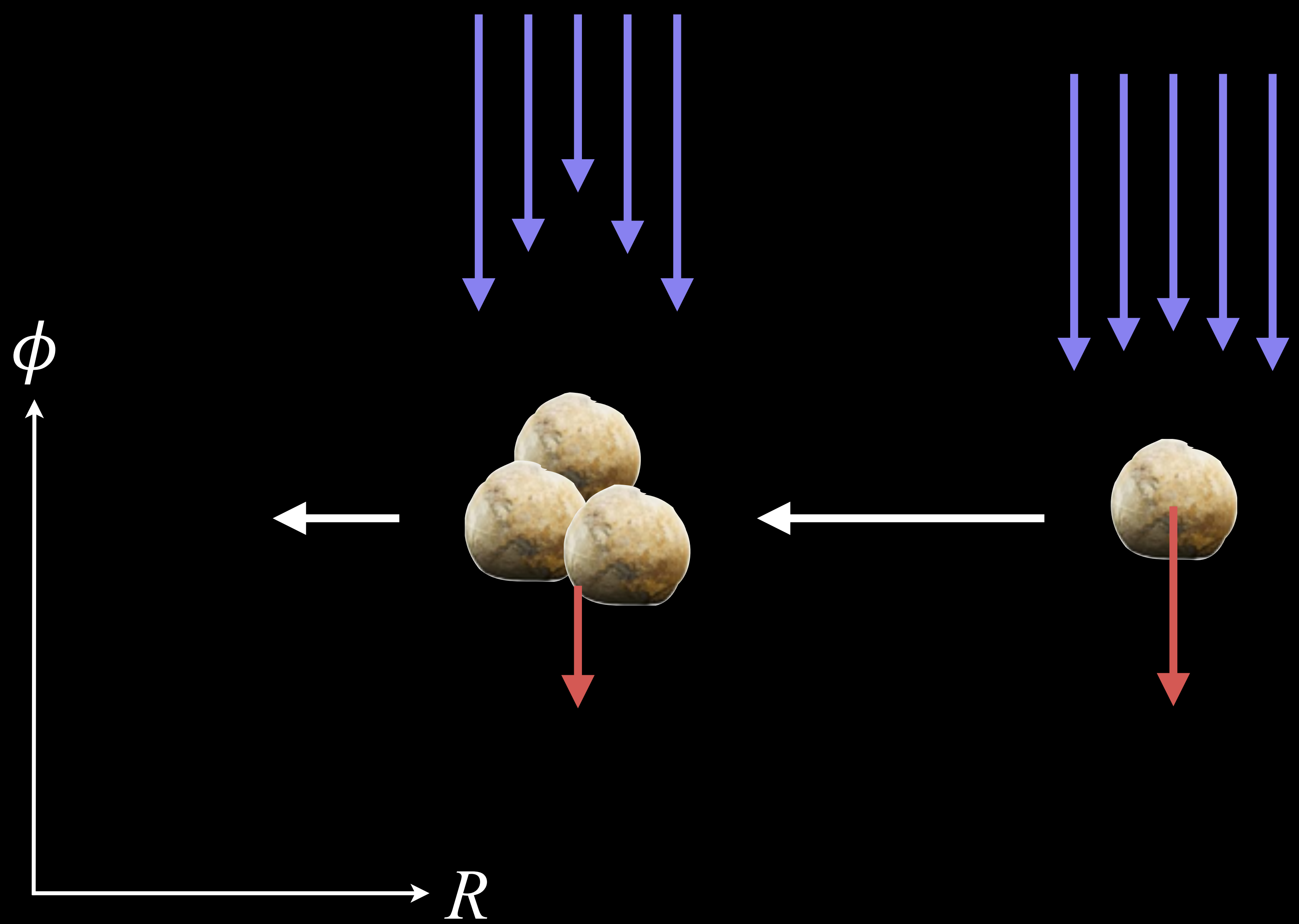
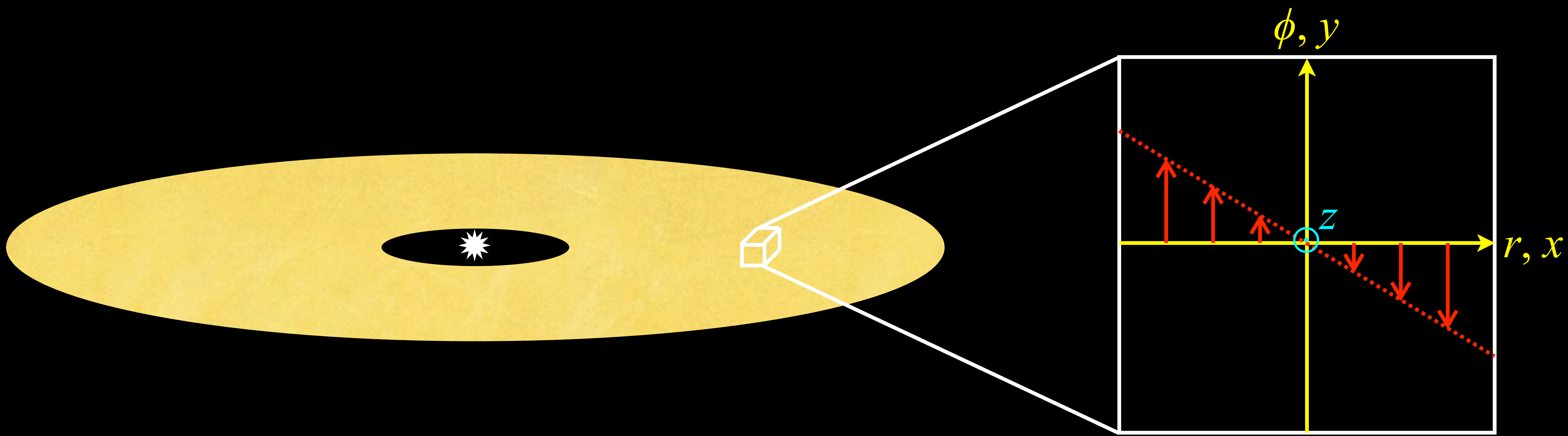


Scales at 1AU

- Mean free path $\lambda \sim 1$ cm
- Disk aspect ratio $H / R \sim 0.03$
- Orbital velocity $v_K \sim 5$ km/s
- Head wind velocity $\Delta v \sim 10^{-3}\, v_K \sim 9$ m/s
- Stopping time $\tau_s \equiv \Omega_K t_s$; we focus on $\tau_s \sim 0.3$
  - $t_s \sim 0.6$ month for $a \sim 15$ cm

Local Shearing Box



$$\frac{\partial \rho_g}{\partial t} - \frac{3}{2}\Omega_K x \frac{\partial \rho_g}{\partial y} + \nabla \cdot (\rho_g \mathbf{u}) = 0$$

Gas:

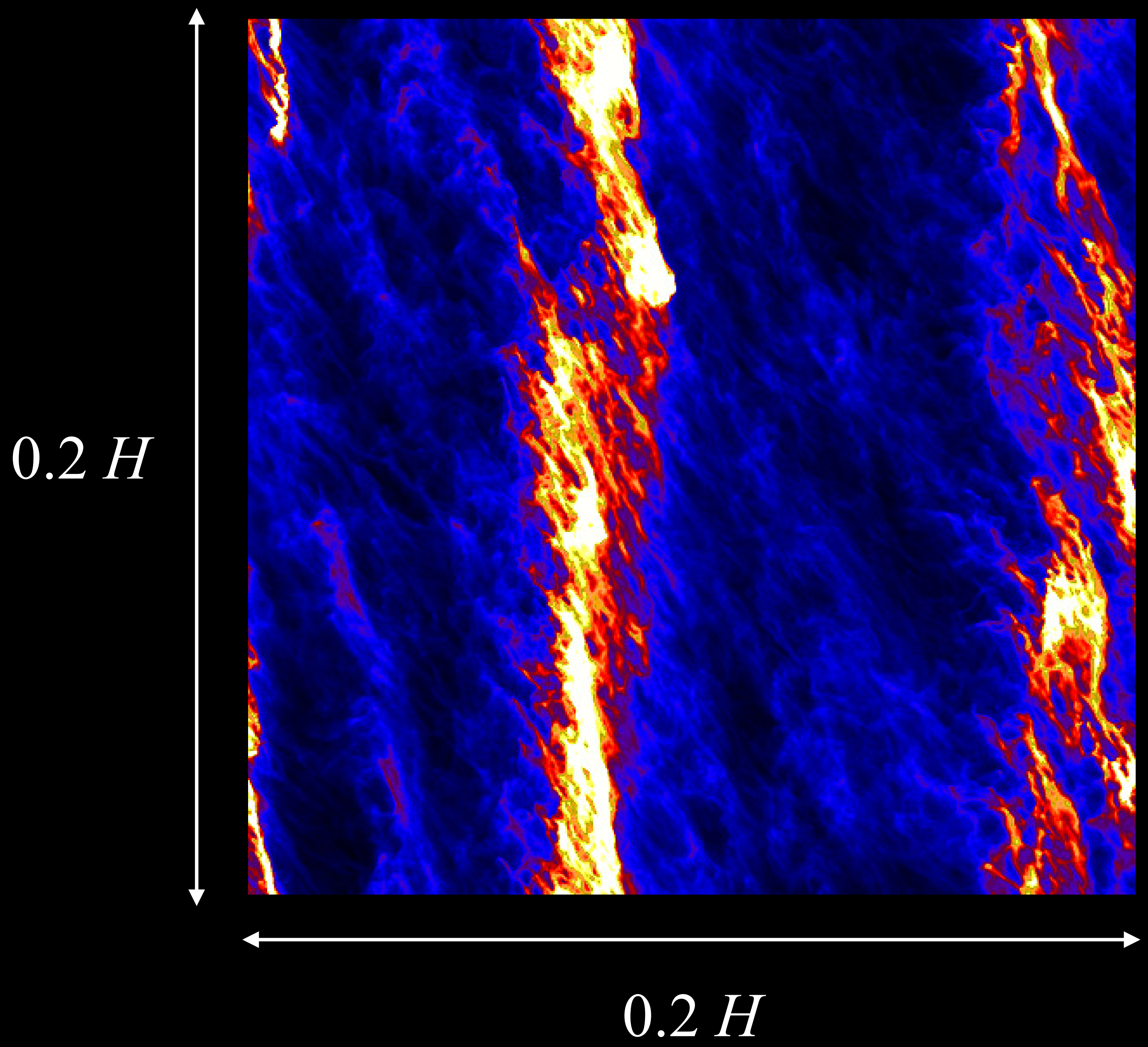
$$\frac{\partial \mathbf{u}}{\partial t} - \frac{3}{2}\Omega_K x \frac{\partial \mathbf{u}}{\partial y} + \mathbf{u} \cdot \nabla \mathbf{u} = -c_s^2 \nabla \ln \rho_g + \left(2\Omega_K u_y \hat{\mathbf{x}} - \frac{1}{2}\Omega_K u_x \hat{\mathbf{y}} - \Omega_K^2 z \hat{\mathbf{z}}\right) + 2\Omega_K \Delta v \hat{\mathbf{x}} + \frac{\rho_p}{\rho_g}\frac{\mathbf{v} - \mathbf{u}}{t_s}$$

Particles:

$$\frac{d\mathbf{x}_p}{dt} = -\frac{3}{2}\Omega_K x_p \hat{\mathbf{y}} + \mathbf{v}$$

$$\frac{d\mathbf{v}}{dt} = \left(2\Omega_K v_y \hat{\mathbf{x}} - \frac{1}{2}\Omega_K v_x \hat{\mathbf{y}} - \Omega_K^2 z_p \hat{\mathbf{z}}\right) + \frac{\mathbf{u} - \mathbf{v}}{t_s}$$

Top View of the Particle Distribution



Anders Johansen

What We Know

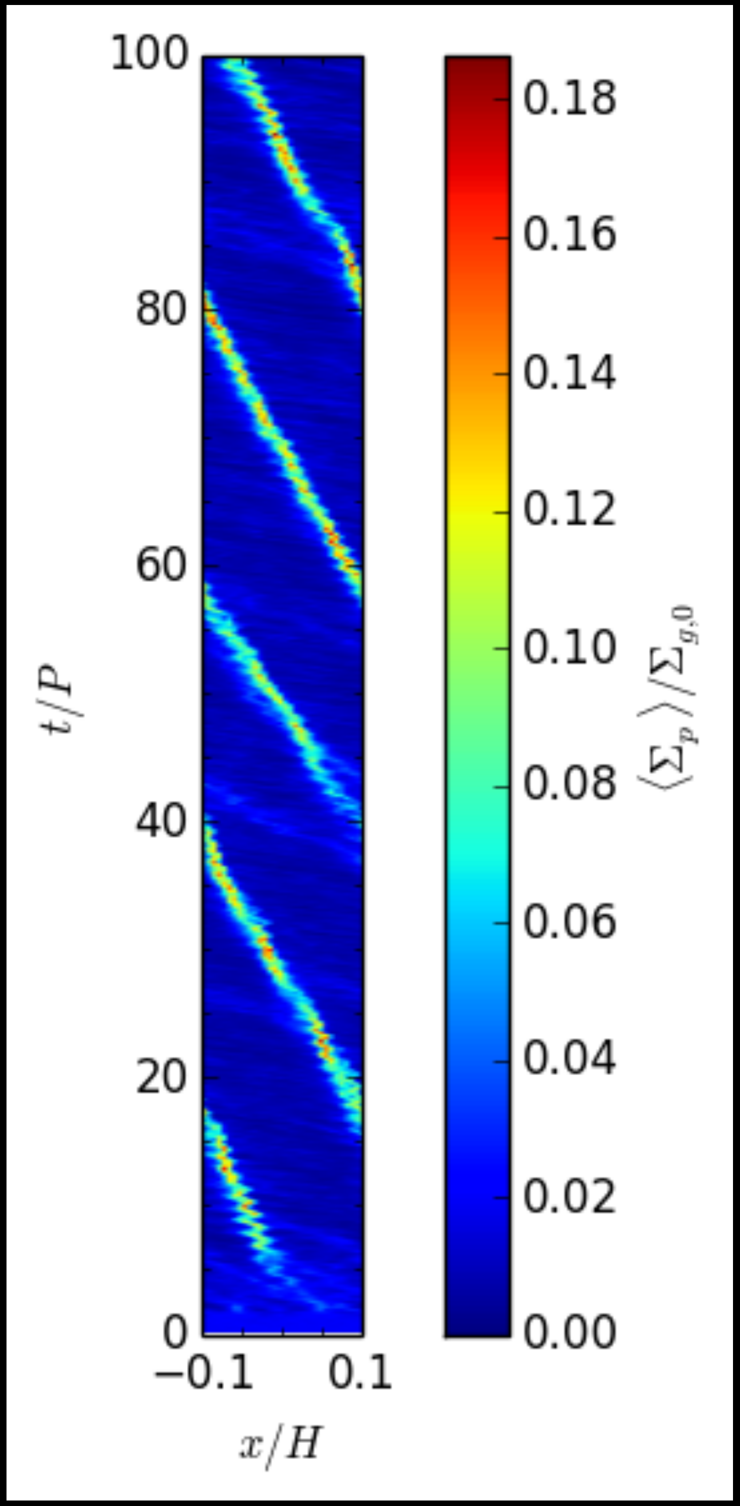
- It works with both laminar *(Johansen et al. 2009; Bai & Stone 2010b)* and turbulent *(Johansen et al. 2007; Balsara et al. 2009; Kato et al. 2012)* disks.
- It can concentrate particles to high density to create Ceres-sized planetesimals by direct gravitational collapse *(Johansen et al. 2007, 2012)*.
- There exists a critical solids-to-gas ratio *(Johansen et al. 2009; Bai & Stone 2010b)*.
- This ratio depends on the radial pressure gradient of the gas *(Bai & Stone 2010a)*.

More Questions

- Can we predict the initial mass function of planetesimals? (*Johansen, Mac Low, & Lacerda, in prep.*)
- Does it work with smaller-sized particles? (*Carrera, Johansen, & Davies, in prep.*)
- What is the characteristic separation between forming planetesimal belts? *(Yang & Johansen, ApJ, submitted)*
- How does it interact with more complicated environment of the gas disk?

Radial Concentration of Particles

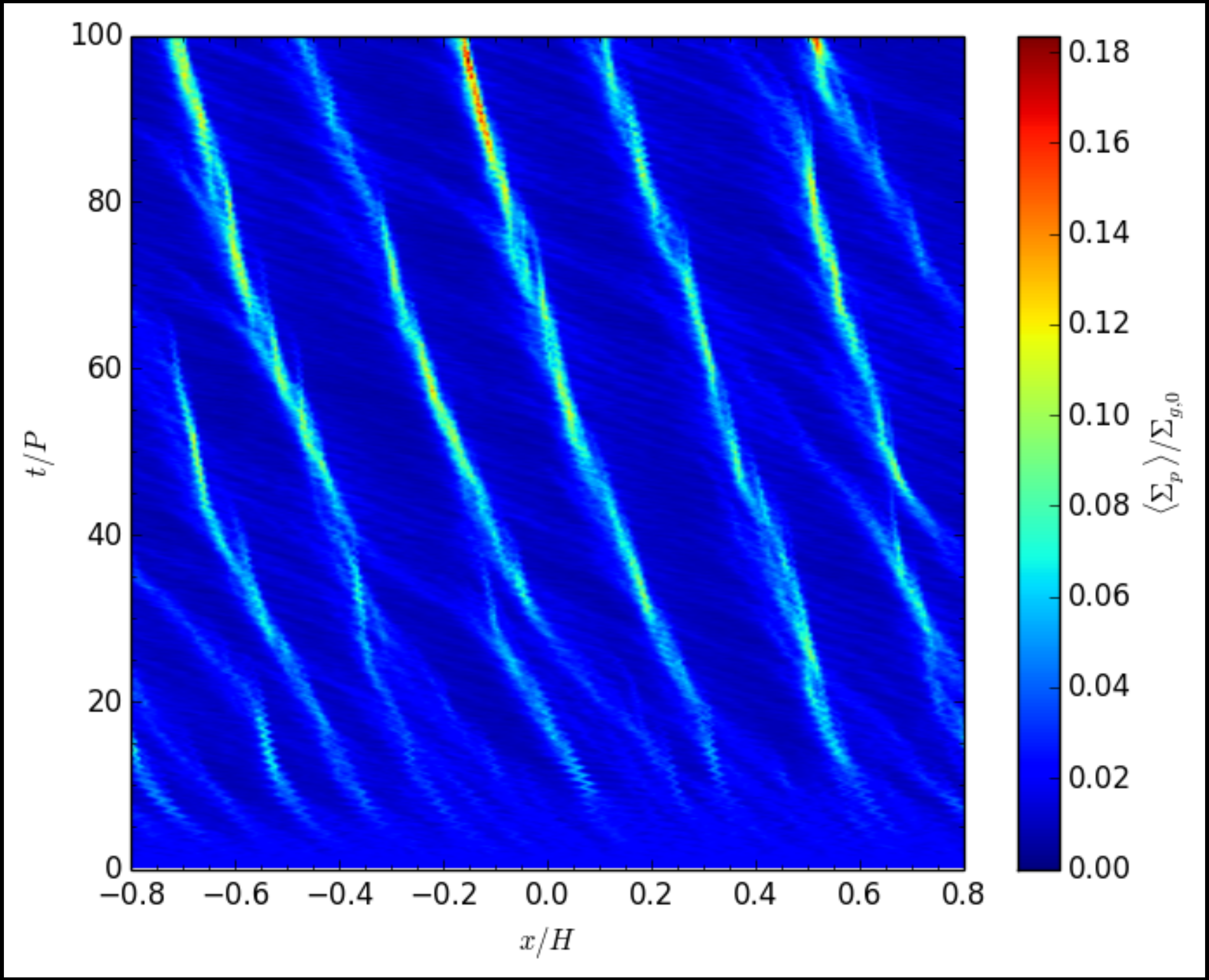
$0.2H \times 0.2H \times 0.2H$ box



Yang & Johansen, ApJ, submitted

Radial Concentration of Particles

$1.6H \times 1.6H \times 0.2H$ box



Yang & Johansen, ApJ, submitted

Radial Concentration of Particles

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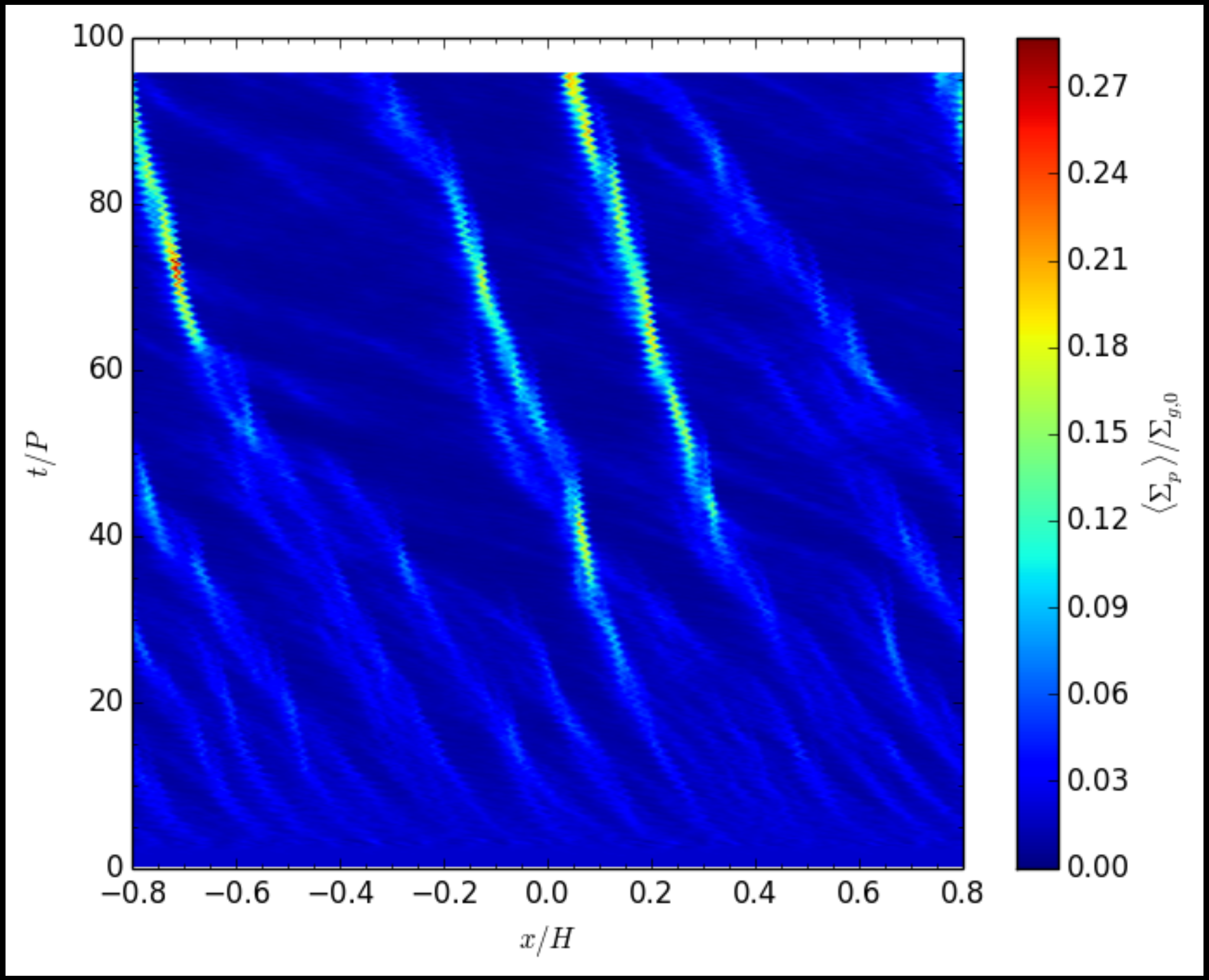

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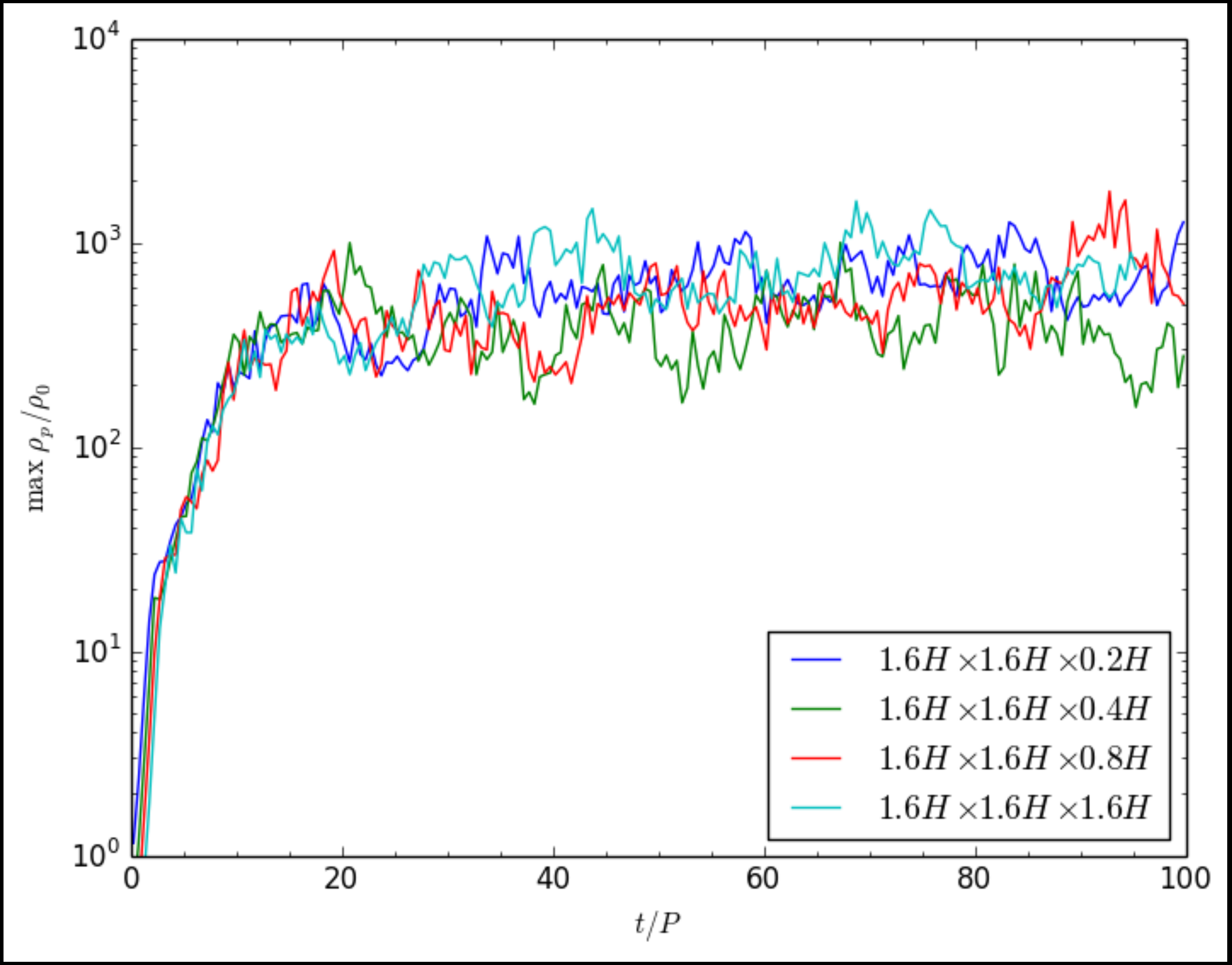
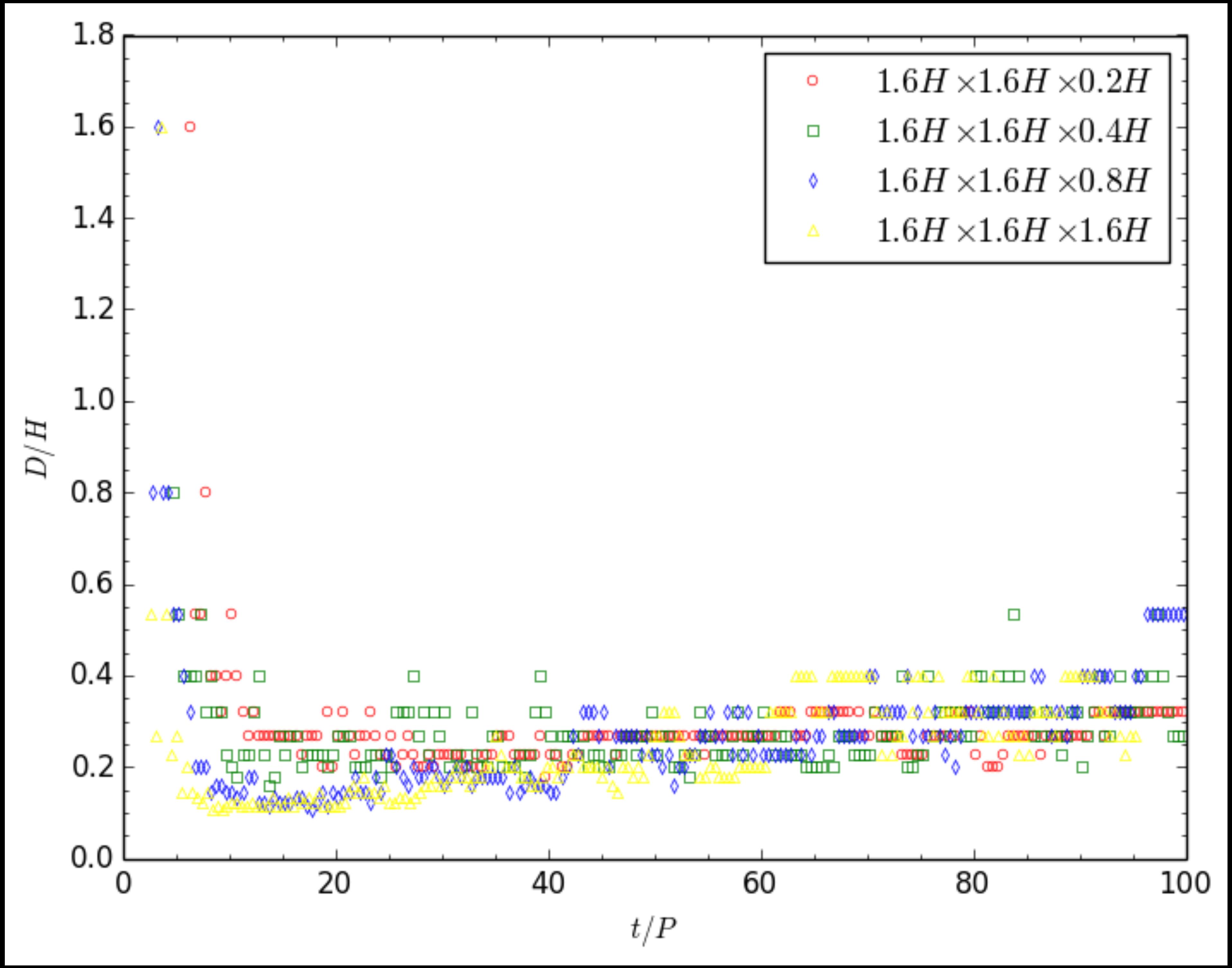
Maximum Local Concentration



Yang & Johansen, ApJ, submitted

Radial Separation of Particle Filaments



Yang & Johansen, ApJ, submitted

Concluding Remarks

- The streaming instability interacts with the gas over at least one gas scale height.
- The new-born planetesimals may have an initial feeding zone of size $\sim 0.2\,H$.
    - Probing the chemical inhomogeneity of the natal nebula down to this scale, especially near the ice line.
- It is conceivable that the streaming instability may not be independent of complicated gas flow on large scale in a magnetized disk.