Planetesimal Formation in Zonal Flows

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- The First 10 Million Years of the Solar System -
SPP 1385
DFG
a Planetary Materials Approach

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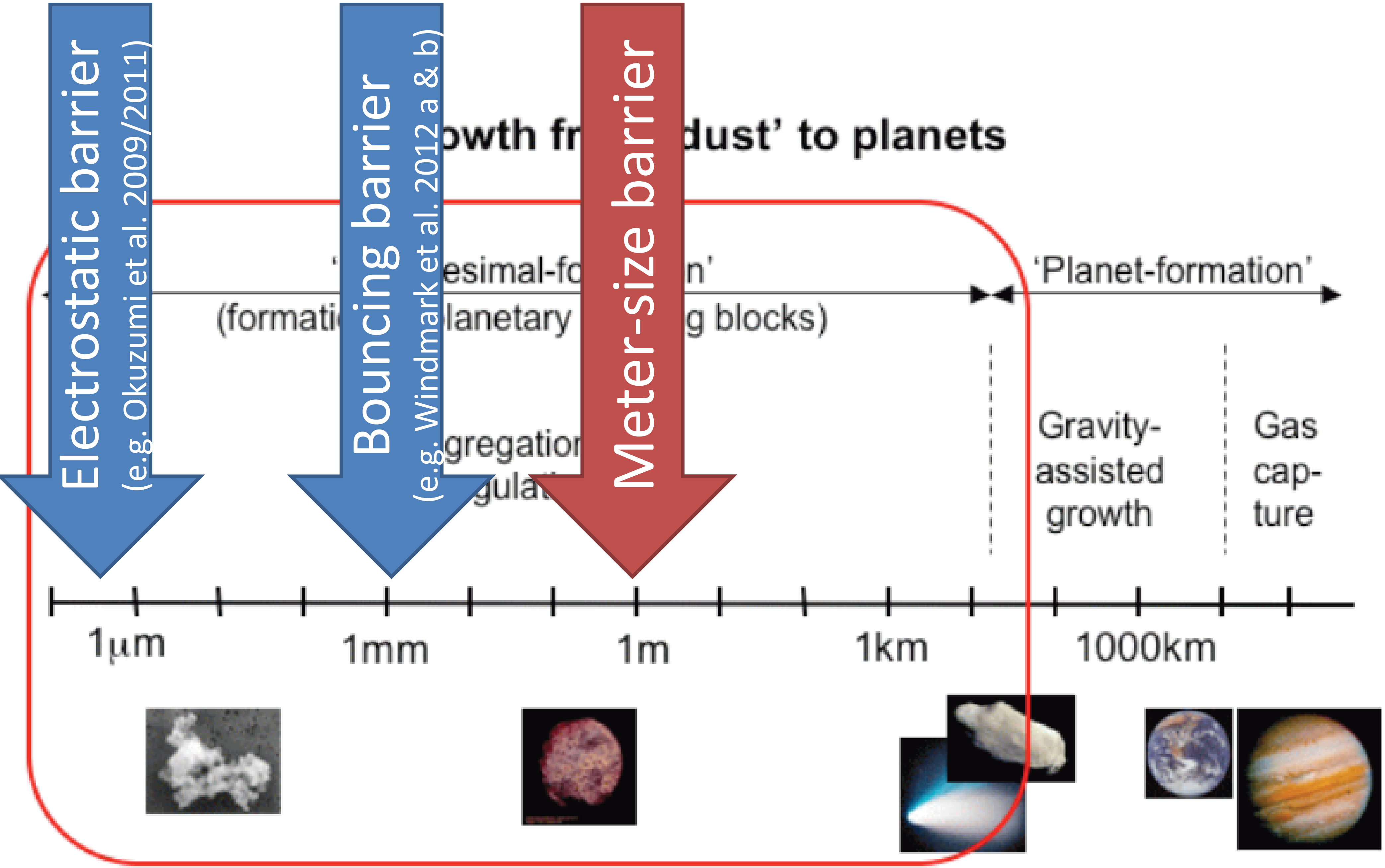
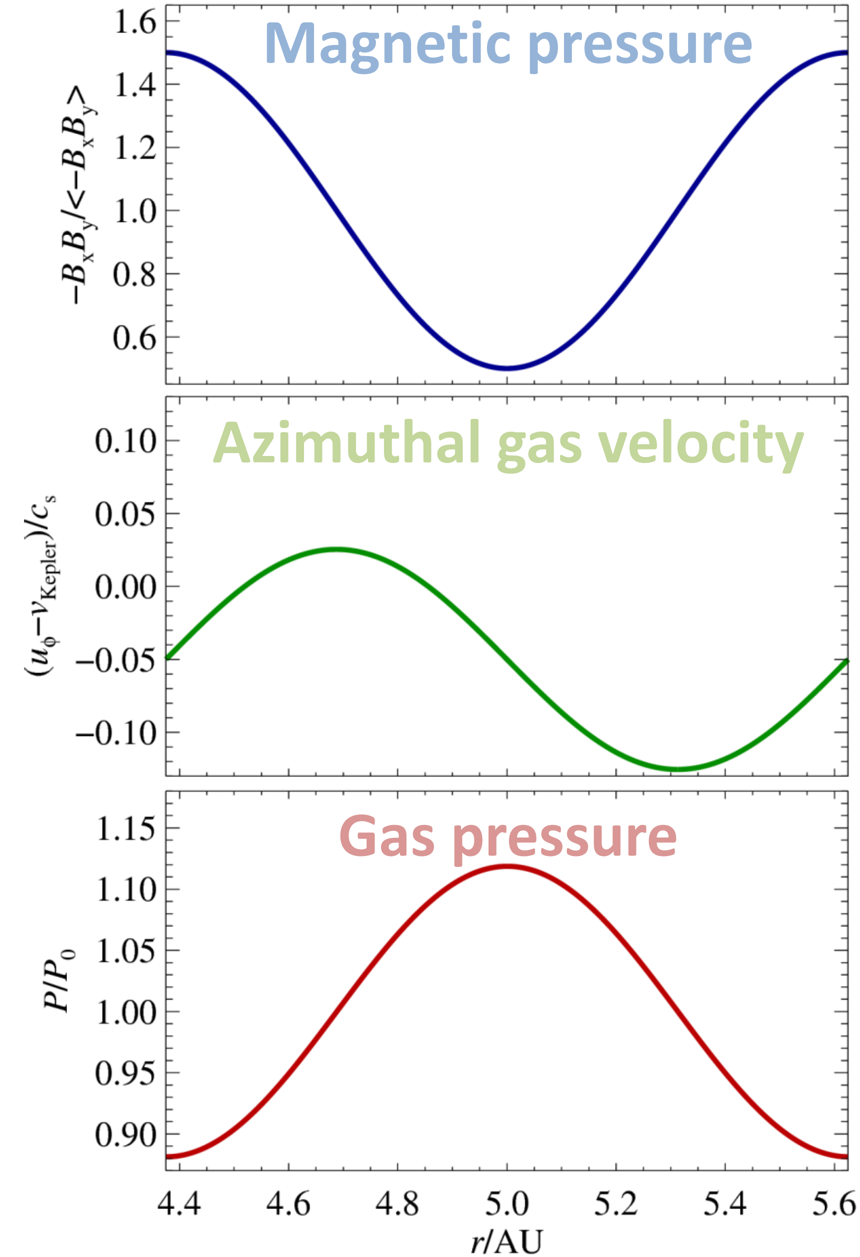
Scales of Planet Formation



Credit: Cornelis Dullemond

Zonal flows and axisymmetric pressure bumps - Theory

- Magnetic pressure forms large-scale structures
- Orbital shear converts magnetic to kinetic energy
  - Zonal flows! $$\frac{\partial \boldsymbol{u}}{\partial t} = \frac{1}{\rho} \boldsymbol{J} \times \boldsymbol{B}$$
- Geostrophic balance excites axisymmetric pressure bumps $$2\Omega u_y = \frac{1}{\rho} \nabla \mathrm{P}$$



Gas

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\boldsymbol{u} + u_y{}^{(0)}\frac{\partial \boldsymbol{u}}{\partial y} = 2\Omega u_y \hat{\boldsymbol{x}} - \frac{1}{2}\Omega u_x \hat{\boldsymbol{y}} + \Omega^2 z \hat{\boldsymbol{z}} + \frac{1}{\rho}\boldsymbol{J}\times\boldsymbol{B} - \frac{1}{\rho}\boldsymbol{\nabla}P + \boldsymbol{f}_\nu(\boldsymbol{u},\rho)$$

$$\frac{\partial \rho}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\rho + u_y^{(0)}\frac{\partial \rho}{\partial y} = -\rho\boldsymbol{\nabla}\cdot\boldsymbol{u} + f_D(\rho)$$

$$P = \rho c_s^2$$

$$\frac{\partial \boldsymbol{A}}{\partial t} + u_y^{(0)}\frac{\partial \boldsymbol{A}}{\partial t} = \frac{3}{2}\Omega A_y \hat{\boldsymbol{x}} + \boldsymbol{u}\times\boldsymbol{B} + \boldsymbol{f}_\eta(\boldsymbol{A})$$

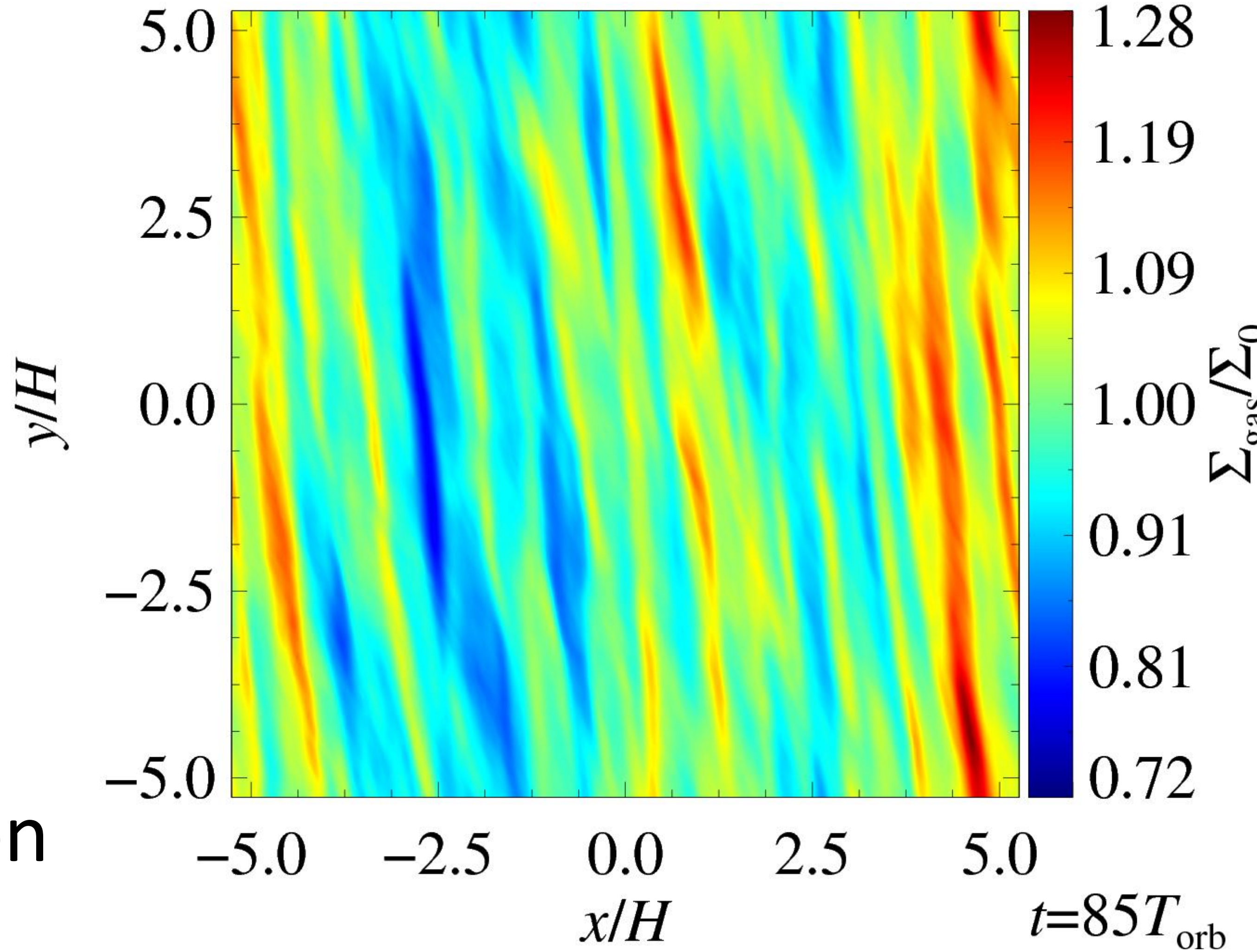
Dust

$$\frac{\partial \boldsymbol{v}^{(i)}}{\partial t} = 2\Omega v_y^{(i)}\hat{\boldsymbol{x}} - \frac{1}{2}\Omega v_x^{(i)}\hat{\boldsymbol{y}} + \Omega^2 z\hat{\boldsymbol{z}} - \frac{1}{\tau_f}\left[\boldsymbol{v}^{(i)} - \boldsymbol{u}\left(\boldsymbol{x}^{(i)}\right)\right]$$

$$\frac{\partial \boldsymbol{x}^{(i)}}{\partial t} = \boldsymbol{v}^{(i)} + u_y^{(0)}\hat{\boldsymbol{y}}$$

Zonal flows in numerical simulations

- View from the top of the disk; integrated over vertical direction



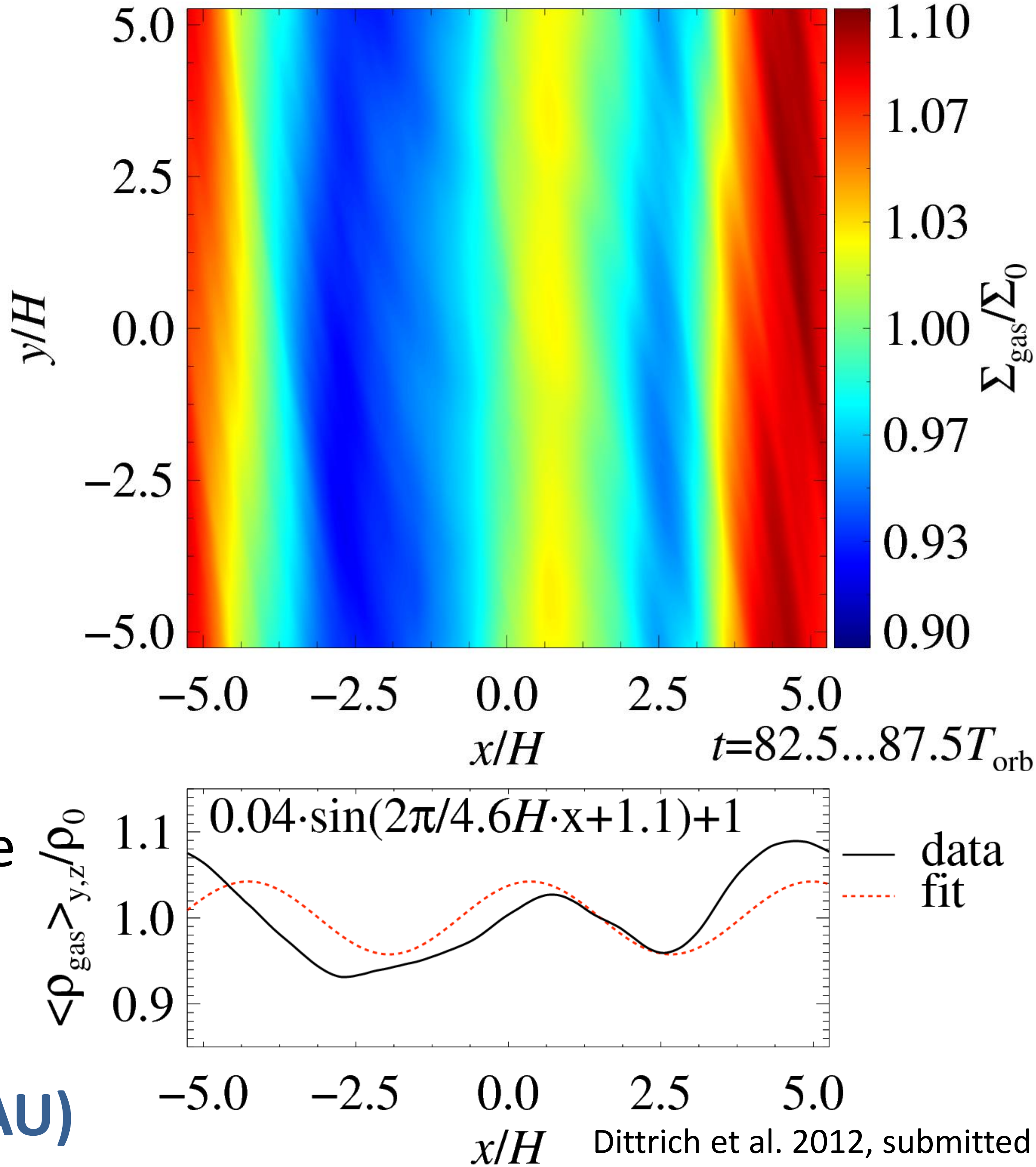
Dittrich et al. 2012, submitted

- Snapshot of the gas surface density shows many short-lived high frequency oscillations

Zonal flows in numerical simulations

- Time-average over 5 orbits reveals radial structure
  - Sinusodial radial structure
  - About 5 scale heights *H*

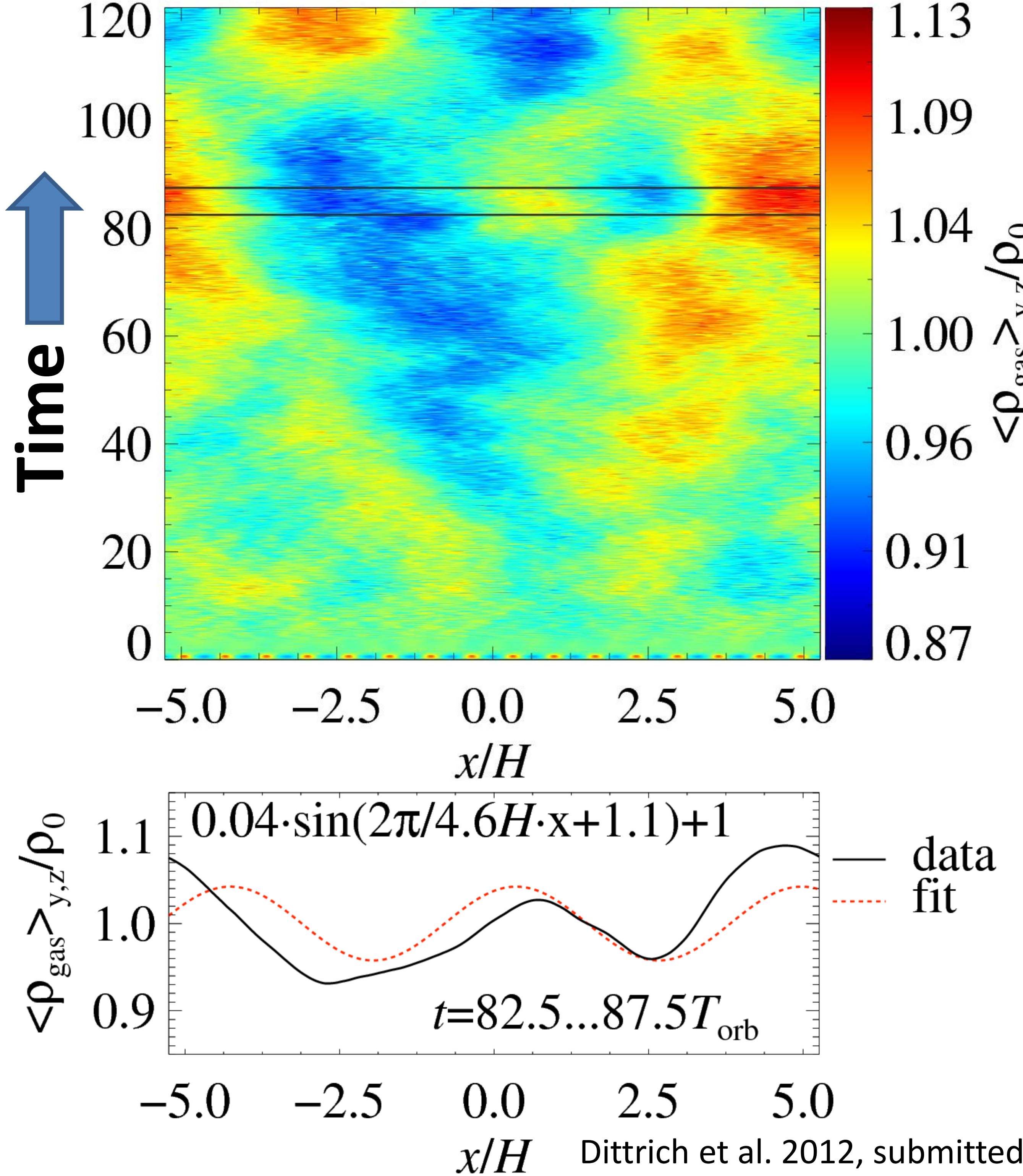
5*H* ≈1.25AU (at 5AU)



Dittrich et al. 2012, submitted

Zonal flows in numerical simulations

- Sinusoidal structure has constant width
- Stable for several tens of local orbits



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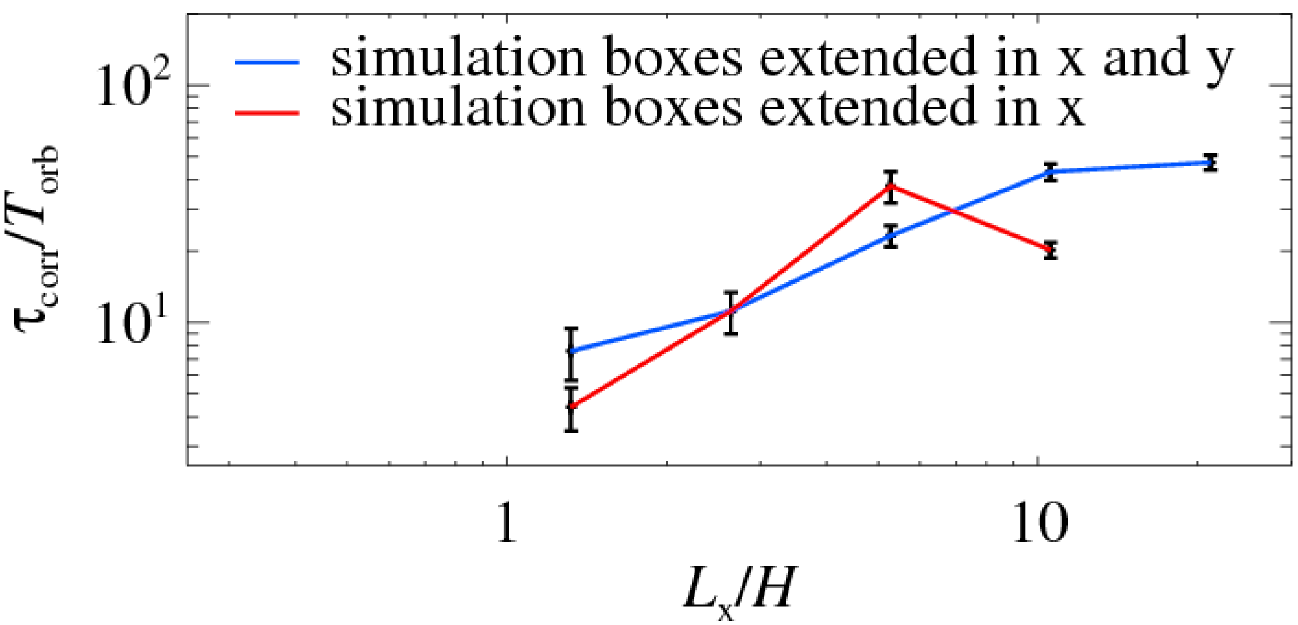
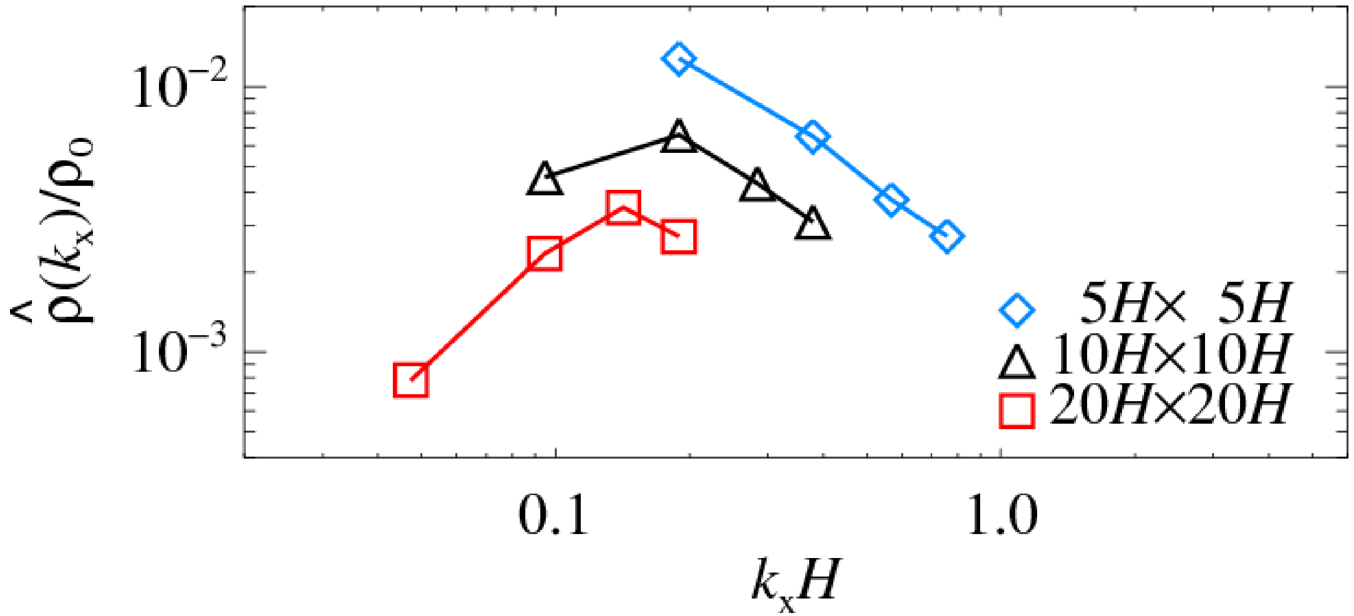
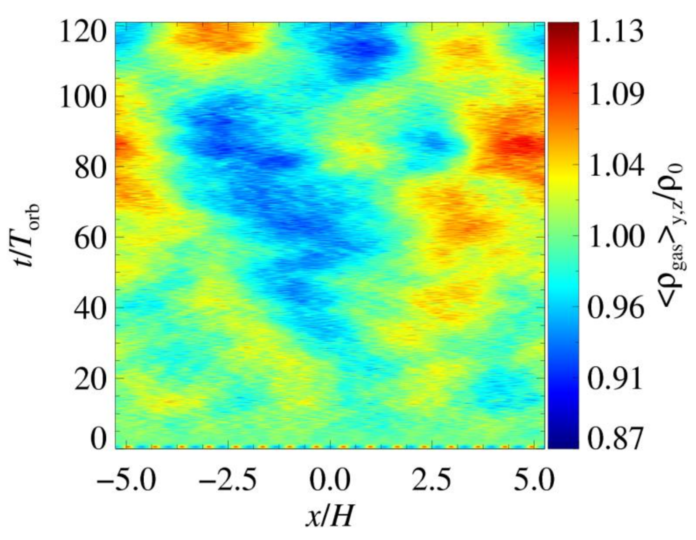
Zonal flows in numerical simulations

- Life time up to 50 local orbits
- Radial scale of 5 pressure scale heights







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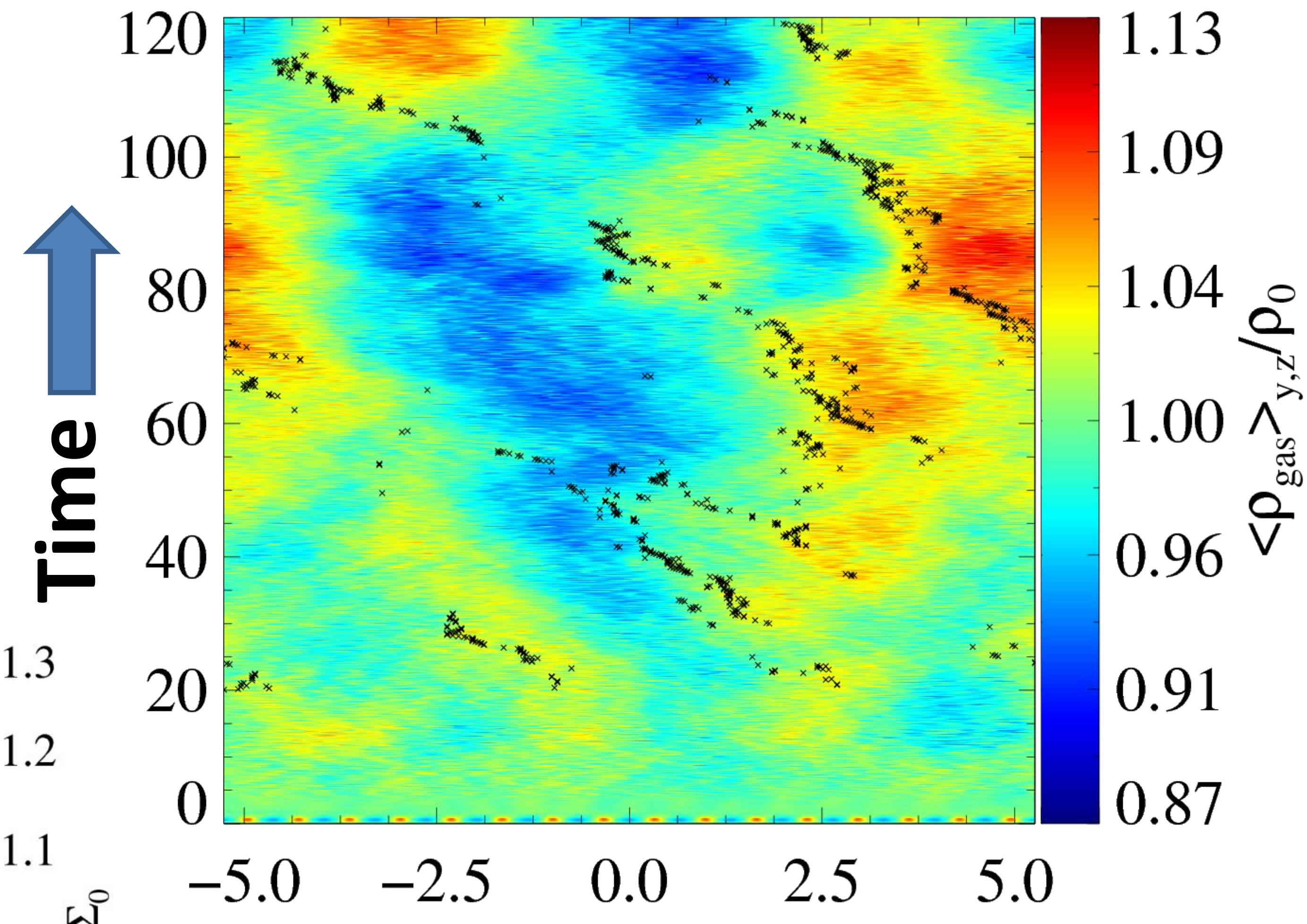
Planetesimal formation in zonal flows

- Radial drift is slowed down by pressure bumps
- Leads to high dust densities



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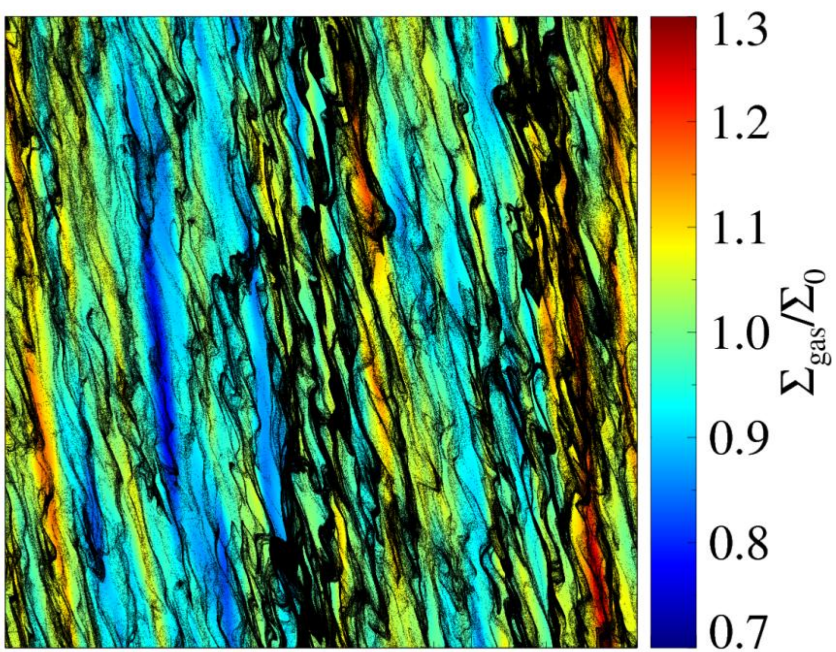
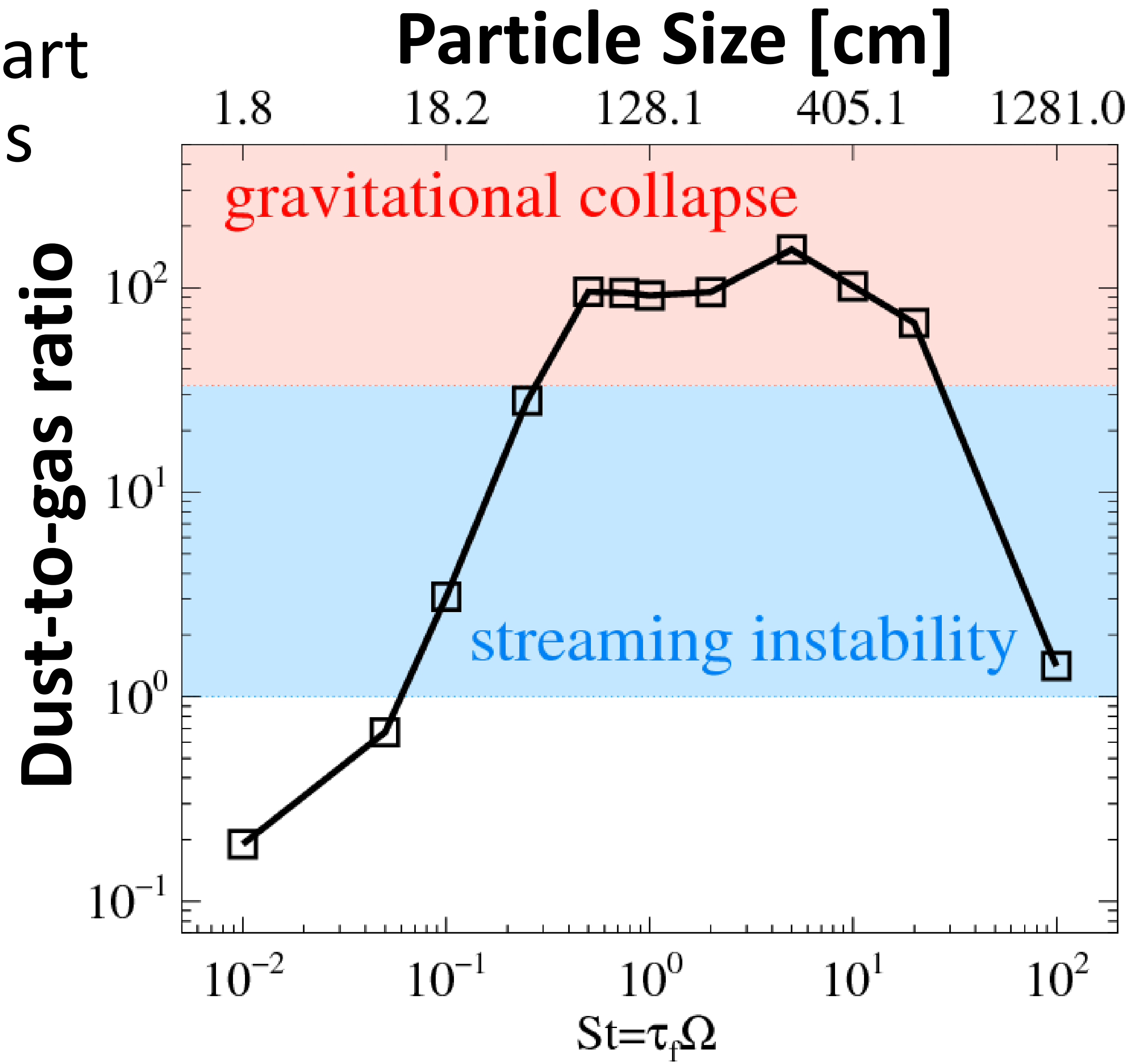


$$\boldsymbol{v}_{dust} = \boldsymbol{v}_{gas} + \frac{\tau_f}{\rho} \nabla P$$

Planetesimal formation in zonal flows

- All simulations start with a dust-to-gas ratio of 10^{-2}
- Maximal concentrations reached during simulation:
  - 10^4 for meter-sized particles
  - Some 100 for decimeter-sized particles



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Summary

- Zonal flows and the resulting pressure bumps are a physical feature of magneto-rotationally-unstable protoplanetary disks
  - Life-time of several tens of local orbits
  - Radial size of 5 scale heights (~1.25AU at a 5AU orbit); in agreement with global simulations (e.g., Uribe et al. 2011)
- Dust gets trapped at pressure bumps and forms over-densities
  - Decimeter-sized pebbles can trigger streaming instability
  - Meter-sized boulders can undergo gravitational collapse to form planetesimals