Dust-free modeling of dusty protoplanetary disks

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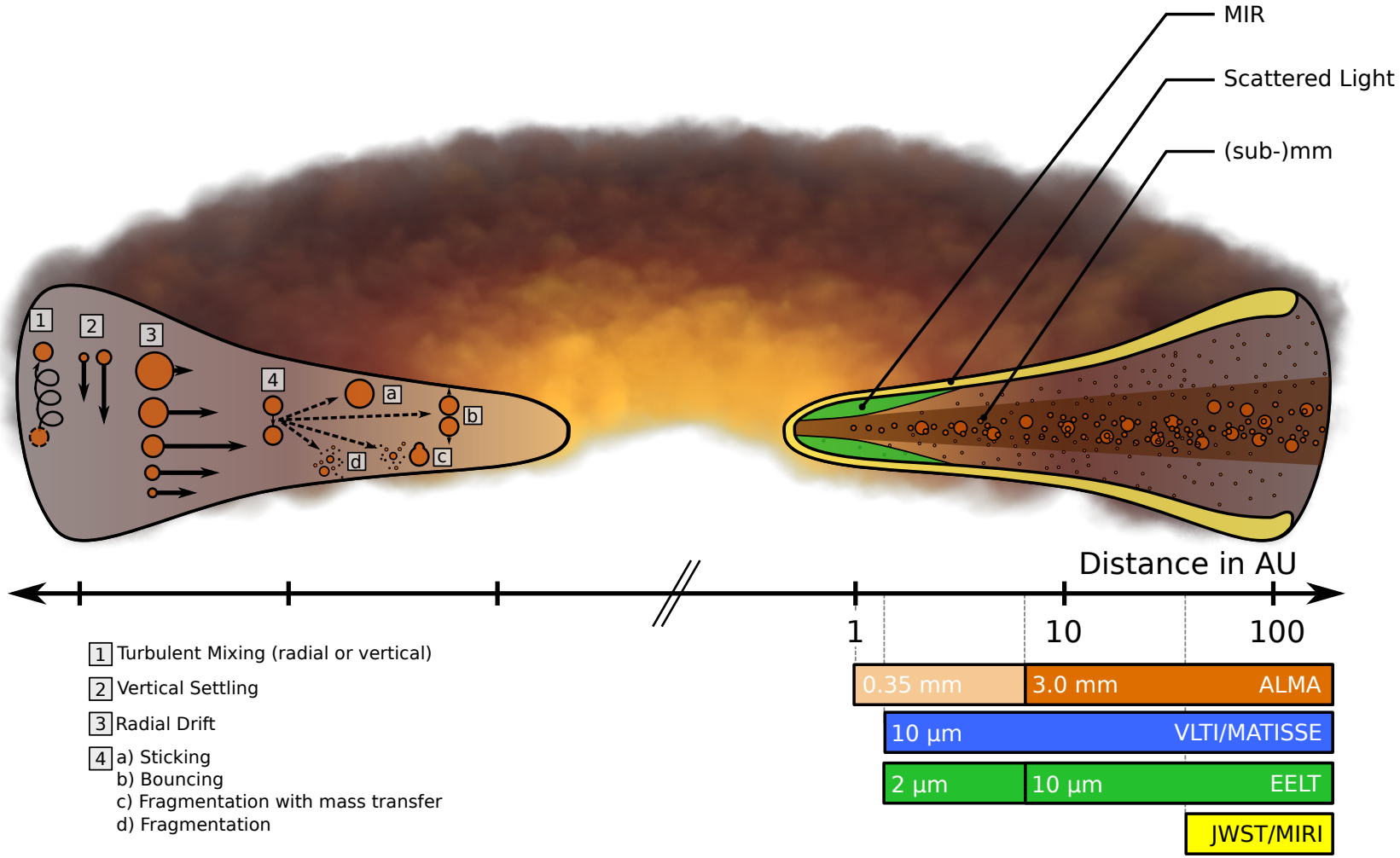
Dusty-gas dynamics in protoplanetary disks



(Testi et al., 2014)

Modeling dust-gas interaction is complicated

A simple framework for dusty-gas dynamics

A simple framework for dusty-gas dynamics

isothermal dusty gas disk ⟷ equivalent for small particles ⟷ textbook hydrodynamics

$$\left.\begin{aligned}
&\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0, \\
&\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v} \cdot \nabla \boldsymbol{v} = -\frac{1}{\rho} \nabla P - \nabla \Phi, \\
&\frac{\partial P}{\partial t} + \boldsymbol{v} \cdot \nabla P = -\Gamma P \nabla \cdot \boldsymbol{v} + \frac{\Gamma P}{\rho_{\rm gas}} \nabla \cdot (f_{\rm dust} t_{\rm stop} \nabla P).
\end{aligned}\right\}$$

Looks like gas dynamics

Lin & Youdin (2017), built upon Laibe & Price (2014)

- Dust-gas friction

+ve particle flux ⟷ -ve heat flux

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- Recent extensions:

Dust diffusion

$$\partial_t \rho_{\rm dust} = \nabla \cdot \left[D P \nabla \left(\frac{\rho}{P} \right) \right]$$

Generalized drag laws

$$t_{\rm stop} \propto |\boldsymbol{v}_{\rm dust} - \boldsymbol{v}_{\rm gas}|^{-\beta}$$

(K. Chen & Lin, in prep.; ASIAA Summer Student Program 2017)

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Looks like gas dynamics

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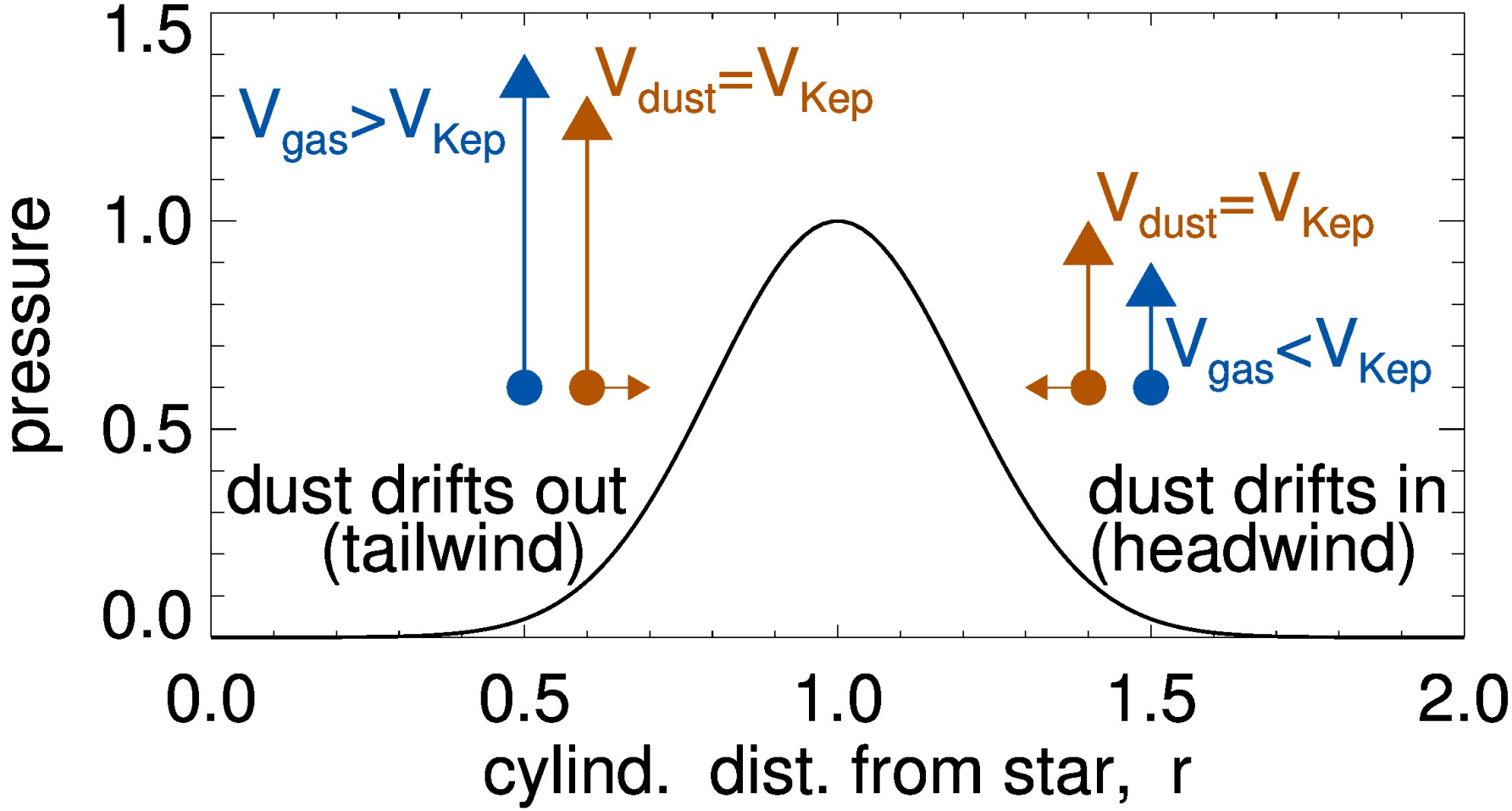
Purpose

- Understand dusty-gas phenomena
- Discover new dusty analogs of hydrodynamic results
- Fast numerical simulations of protoplanetary disks

Dust-trapping by pressure bumps

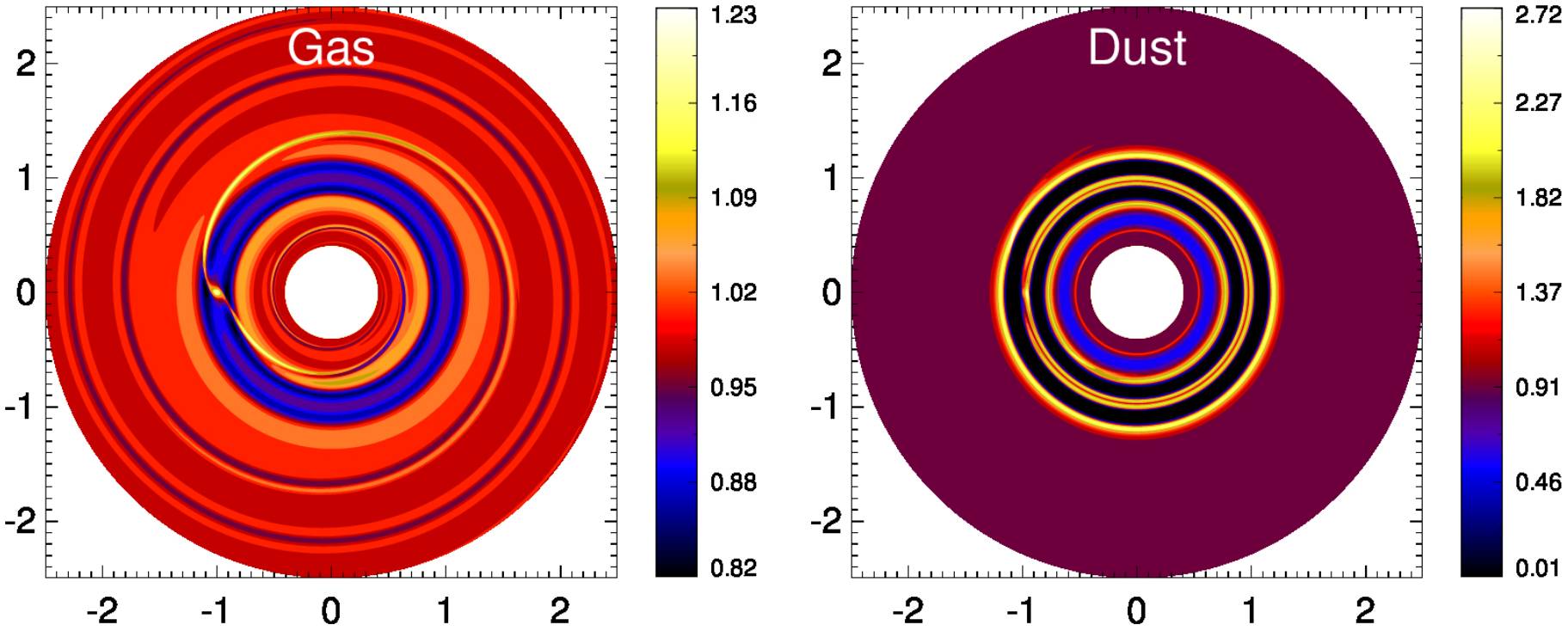


- Drag forces cause dust to accumulate at pressure bumps
- Built into simplified dust-gas framework

Dust traps at planet gaps

- Enable dusty-gas in PLUTO by hacking its thermal conduction module
- No dust equations explicitly solved

$10M_{\mathrm{Earth}}$ planet

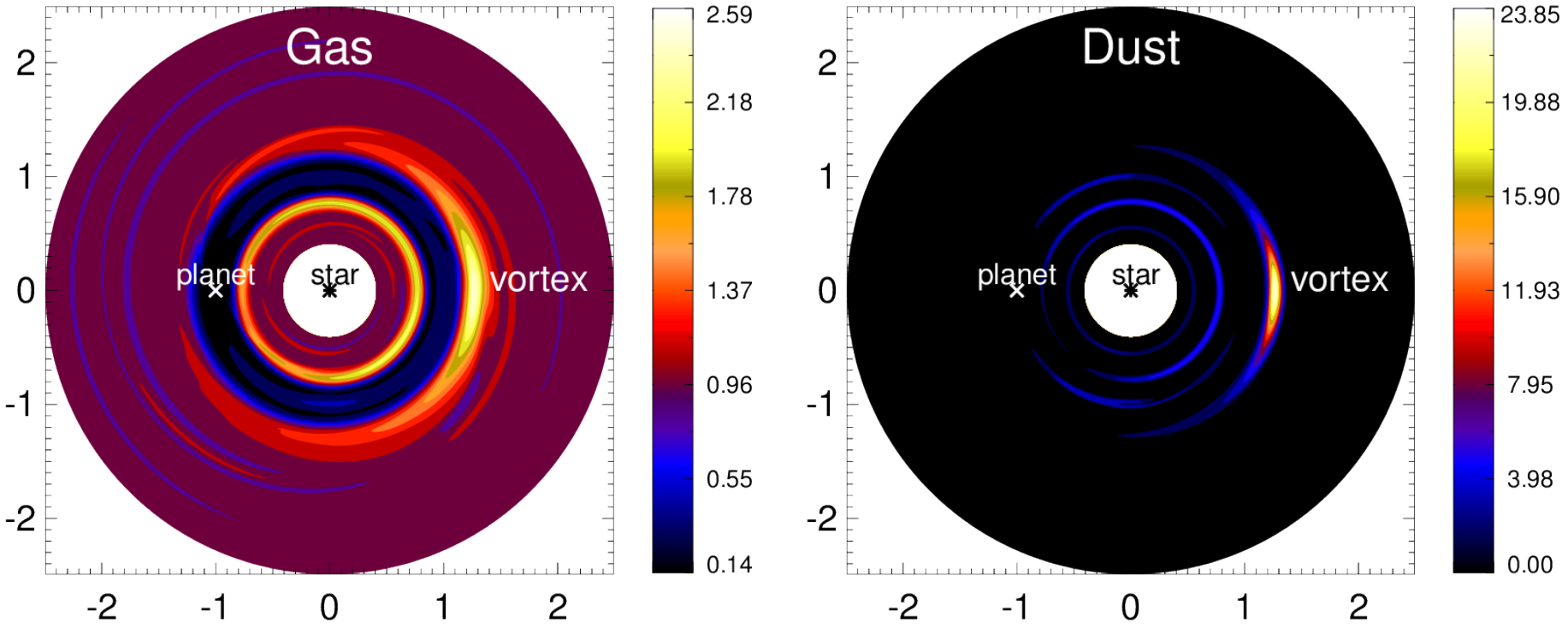


- Pressure bump at gap edges → radial dust trap

Dust traps at planet gaps

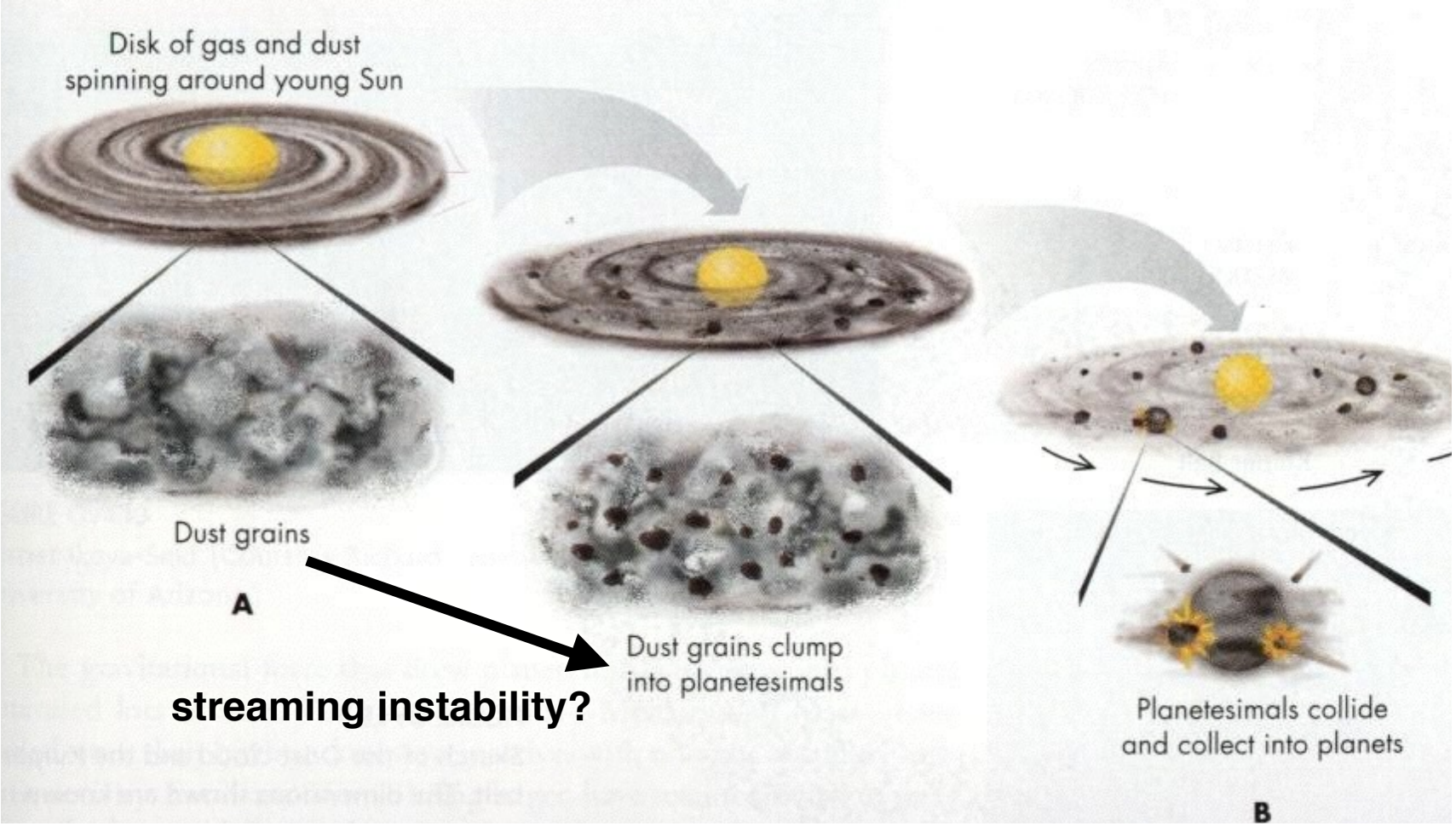
- Enable dusty-gas in PLUTO by hacking its thermal conduction module
- No dust equations explicitly solved

$30 M_{\mathrm{Earth}}$ planet



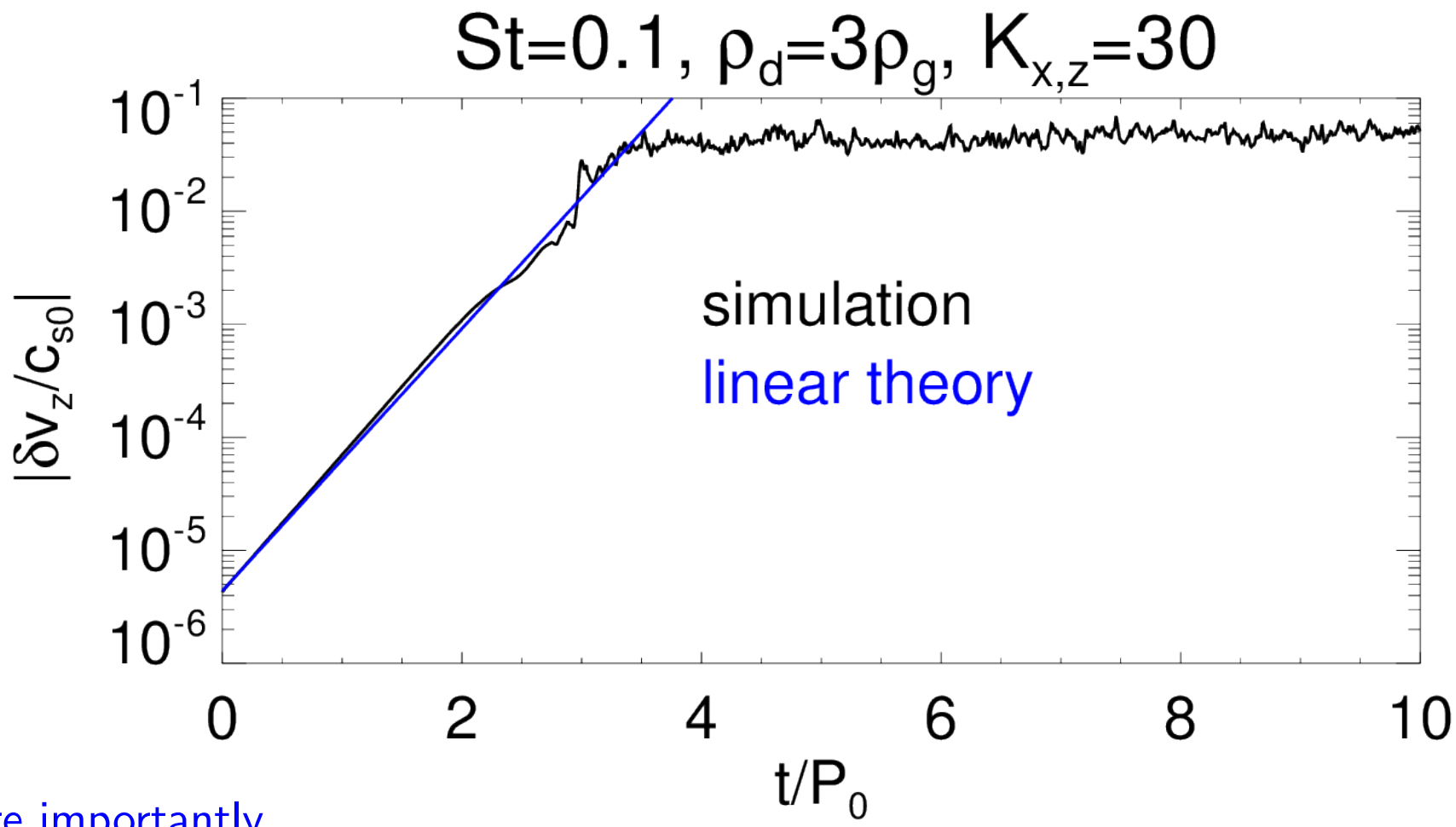
- Gap edge unstable to vortex formation $\rightarrow$ azimuthal dust trap

Planetesimal formation via the streaming instability



- Streaming instability $\rightarrow$ dust clumping mediated by mutual dust-gas drag

Streaming instability with one-fluid

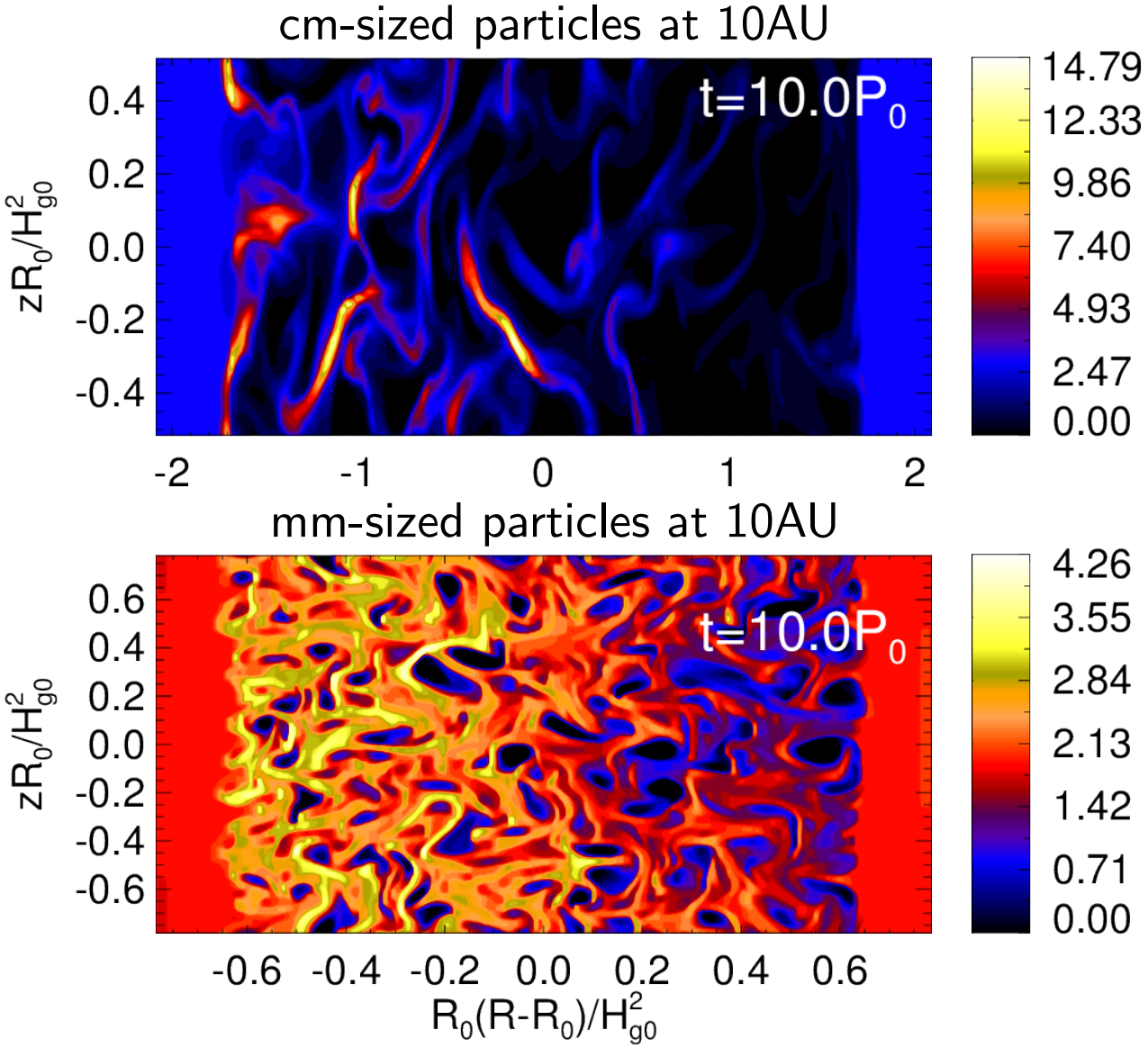


More importantly...

- Thermodynamic interpretation:
  unstable because of pressure-density lag (cf. Carnot cycles)

Streaming instability with one-fluid

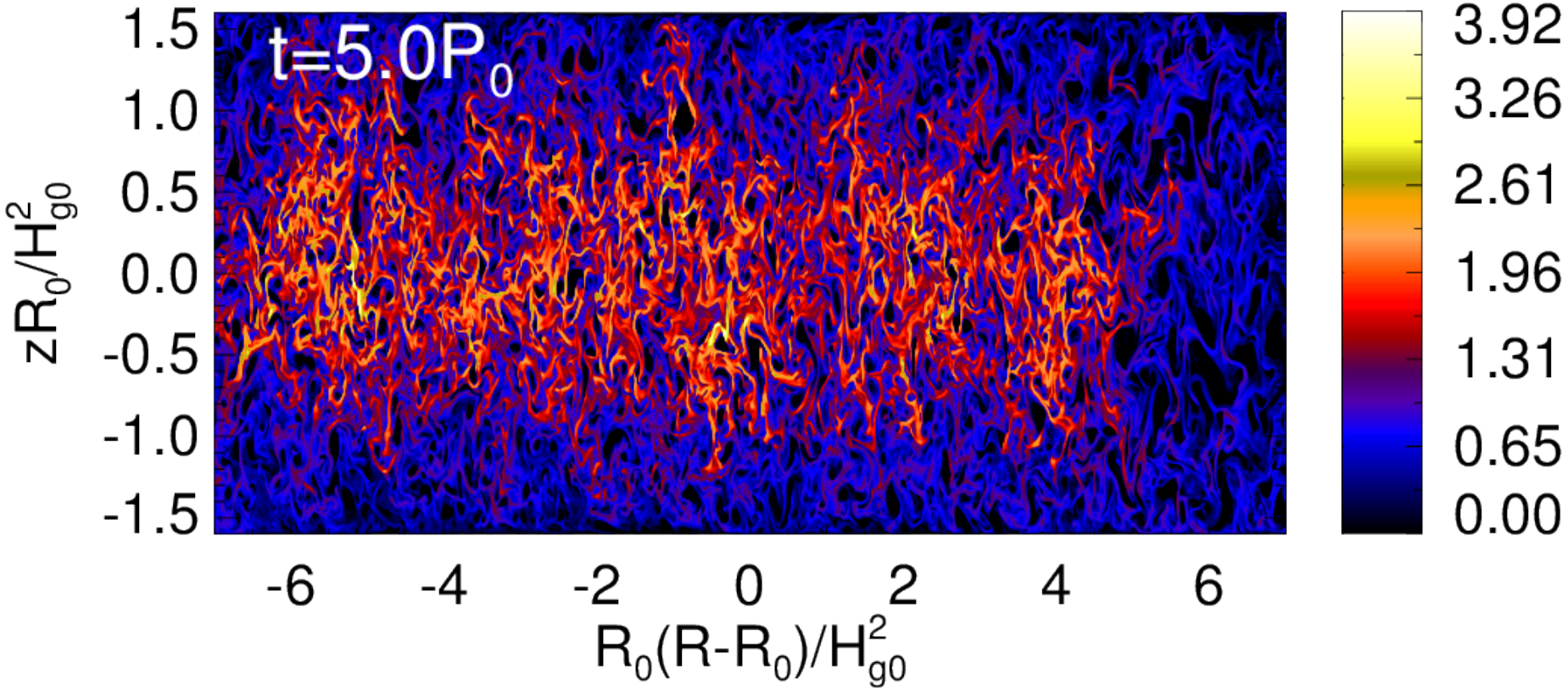
Numerical simulations



- $\rho_{\rm dust}/\rho_{\rm gas}$ shown
- No dust module used

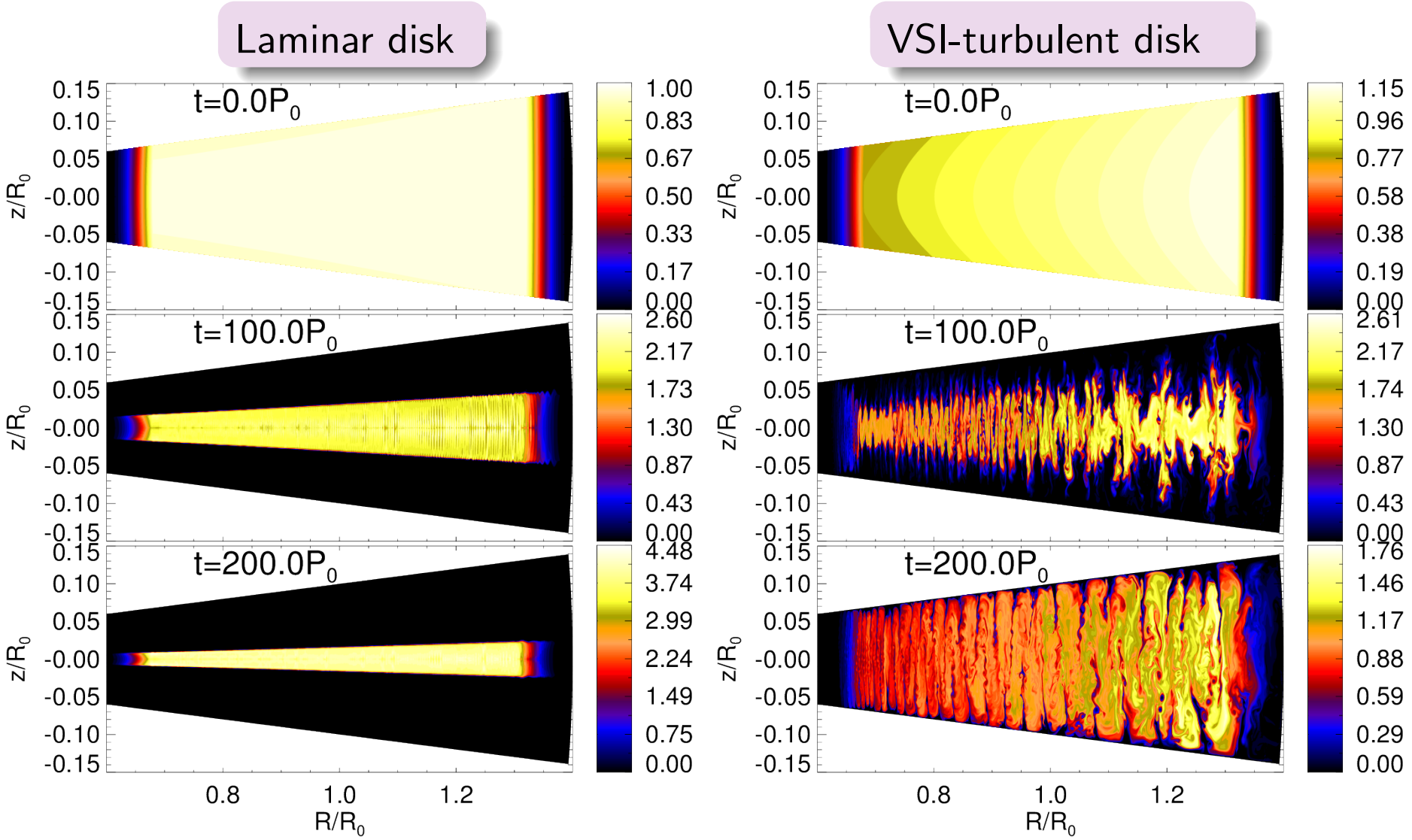
Streaming instability with one-fluid

Stratified disk



- Global cylindrical geometry
- SI needs $\rho_{\rm dust} > \rho_{\rm gas}$. Do particles settle to the midplane to begin with?

Dust settling against hydrodynamic turbulence



- $100 \times \rho_{\rm dust}/\rho_{\rm gas}$ shown; $t_{\rm stop}\Omega = 0.001\,(\ll H/R)$
- Protoplanets born into dust-rich environments?

Dust-rich disk-planet interactions

with J.-W. Chen (NTU)

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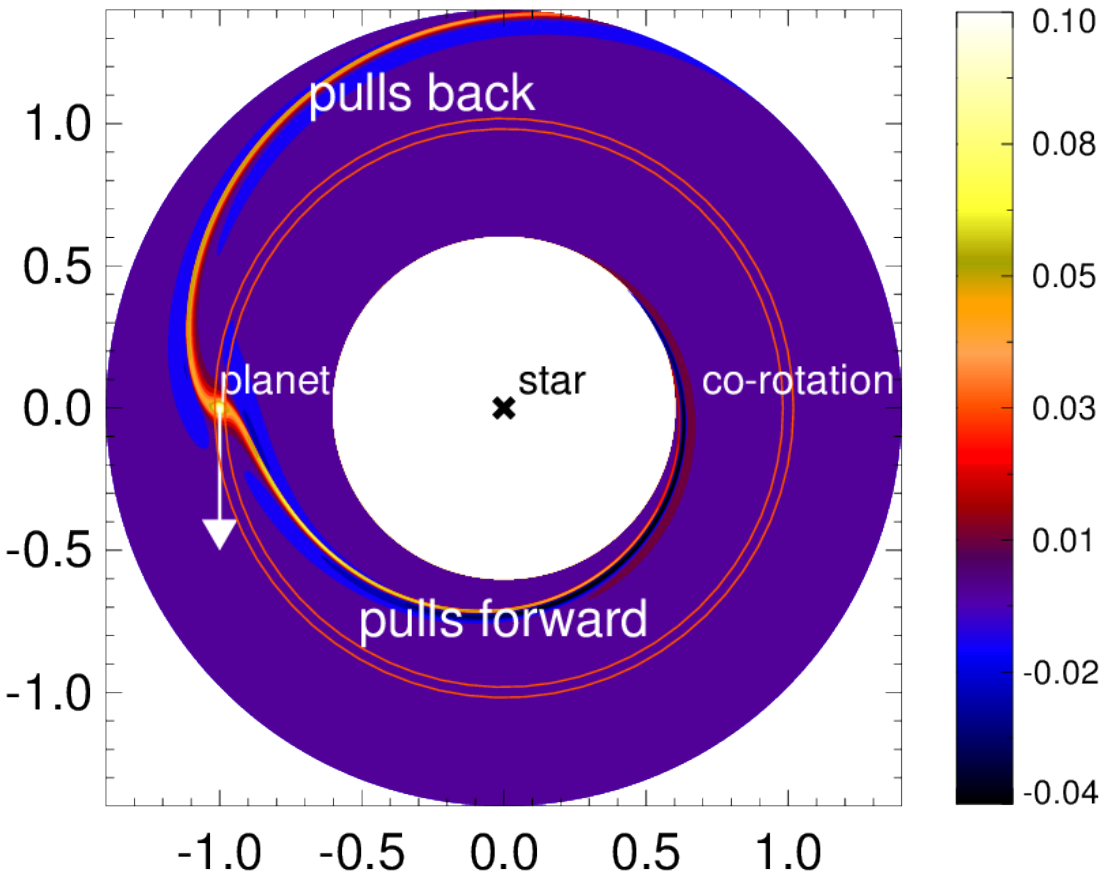
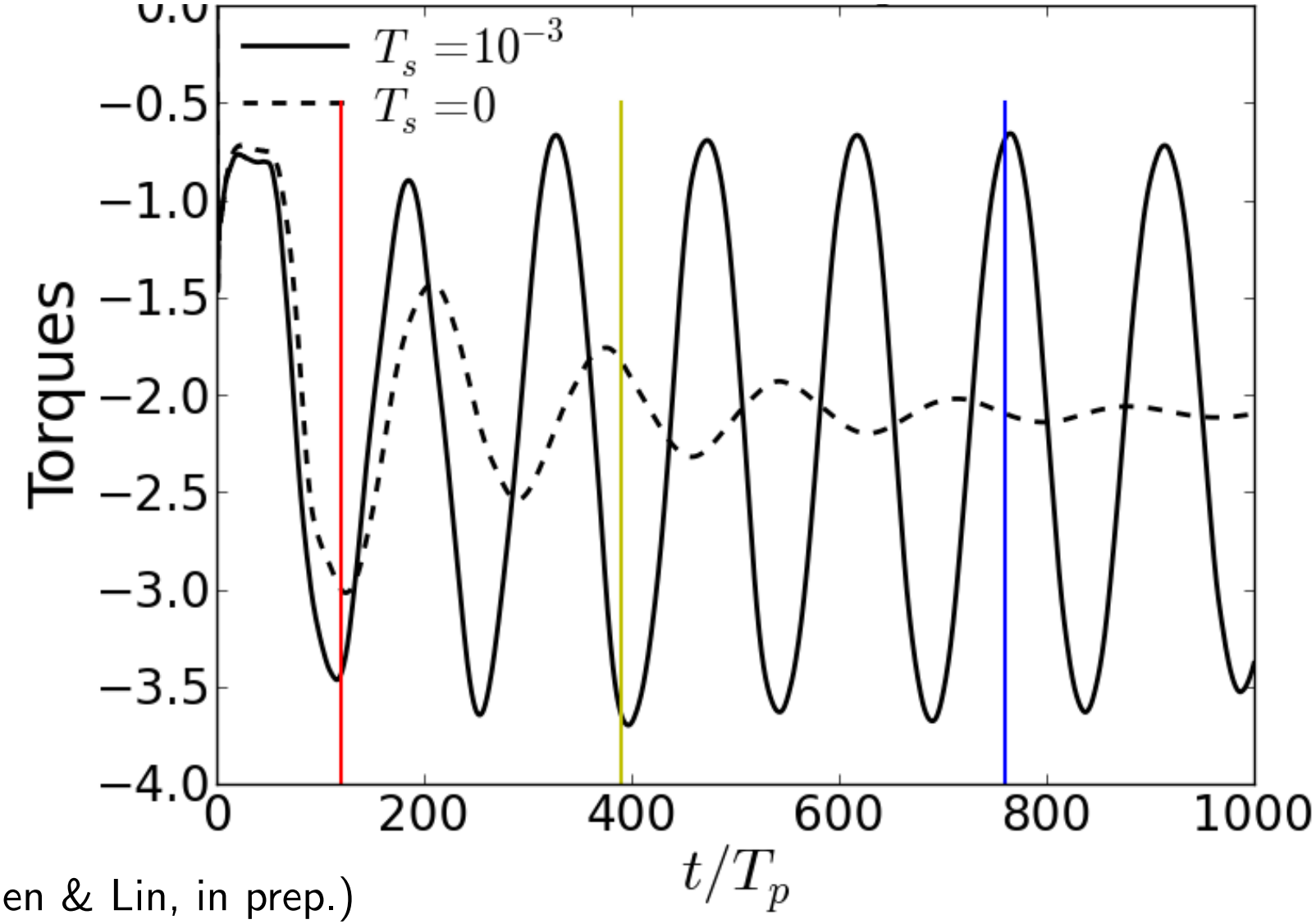
Academia Sinica Institute of Astronomy and Astrophysics
2017 ASIAA Summer Student Program

- What happens to planet migration in dusty gas disks?



Dust-rich disk-planet interactions

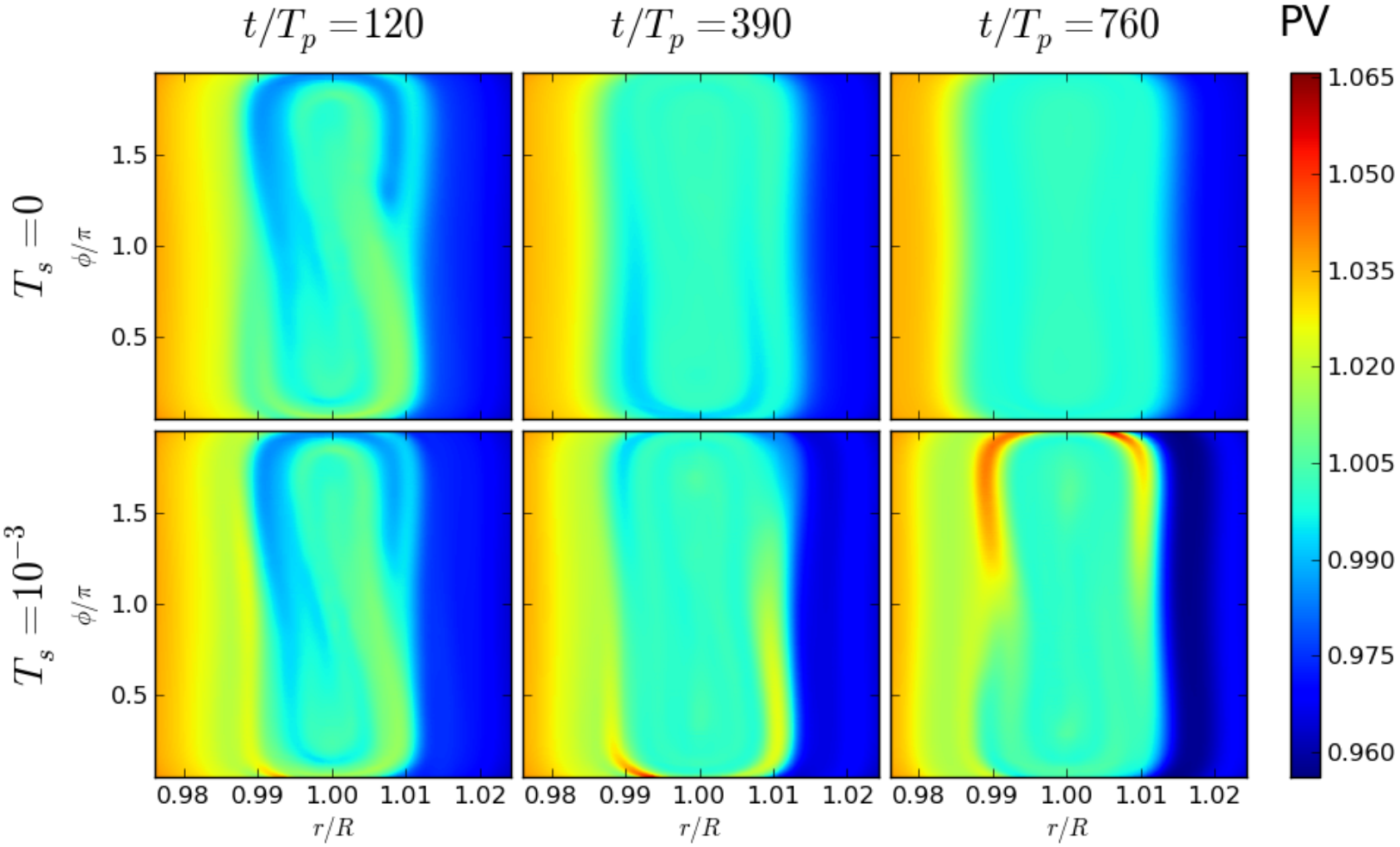
with J.-W. Chen (NTU)



(Chen & Lin, in prep.)

- Oscillitory torques with sufficient $t_{\rm stop}$ and/or $\Sigma_{\rm dust}/\Sigma_{\rm gas}$ (=0.5 here)

Baroclinic dusty torques



(Chen & Lin, in prep.)

- Perfectly coupled particles ⇒ potential vorticity mixing in co-orbital region
- Finite particle size ⇒ PV generation

Baroclinic dusty torques

Pressure-density misalignment translates to gas/dust density misalignment in isothermal disks:

$$\frac{D}{Dt}\left(\frac{\omega_z}{\Sigma}\right) = \frac{1}{\Sigma^3}\nabla\Sigma \times \nabla P$$
$$= \frac{c_s^2}{\Sigma^3}\nabla\Sigma_{\rm dust} \times \nabla\Sigma_{\rm gas}$$

(Laibe & Price 2014)

$$\frac{\partial}{\partial t}\left(\nabla\Sigma \times \nabla P\right)\Big|_{\rm drag} = c_s^2 \nabla\Sigma \times \nabla\left[\nabla \cdot \left(f_{\rm dust}\, t_{\rm stop} \nabla P\right)\right]$$

(Chen & Lin, in prep.)

Summary

isothermal dusty gas disk ⟷ equivalent for small particles ⟷ hydrodynamics+cooling

(Lin & Youdin, 2017, ApJ, 849, 129)

- Dust-drag phenomenon have thermodynamic interpretations
- Dusty analogs of known hydrodynamic effects?
  - Rossby wave/vertical shear/baroclinic instabilities, convective overstability, zombie vortices...etc.
  - Thermodynamic torques in gas disks
- Planet migration and eccentricity evolution in dust-rich disks?

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