A rocky road from dust to planets

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Research interests

$\sim 10^{-6}\mathbf{m}$

?

$\sim 10^{7}\mathbf{m}$

- Astrophysical fluid dynamics
- Accretion disks
- Fluid instabilities
- Structure formation and evolution
- Disk-planet interaction
- Stability analyses
- Numerical simulations

Promotion

Lin & Youdin (2017, ApJ)

- Simplified model of dust-gas dynamics in protoplanetary disks

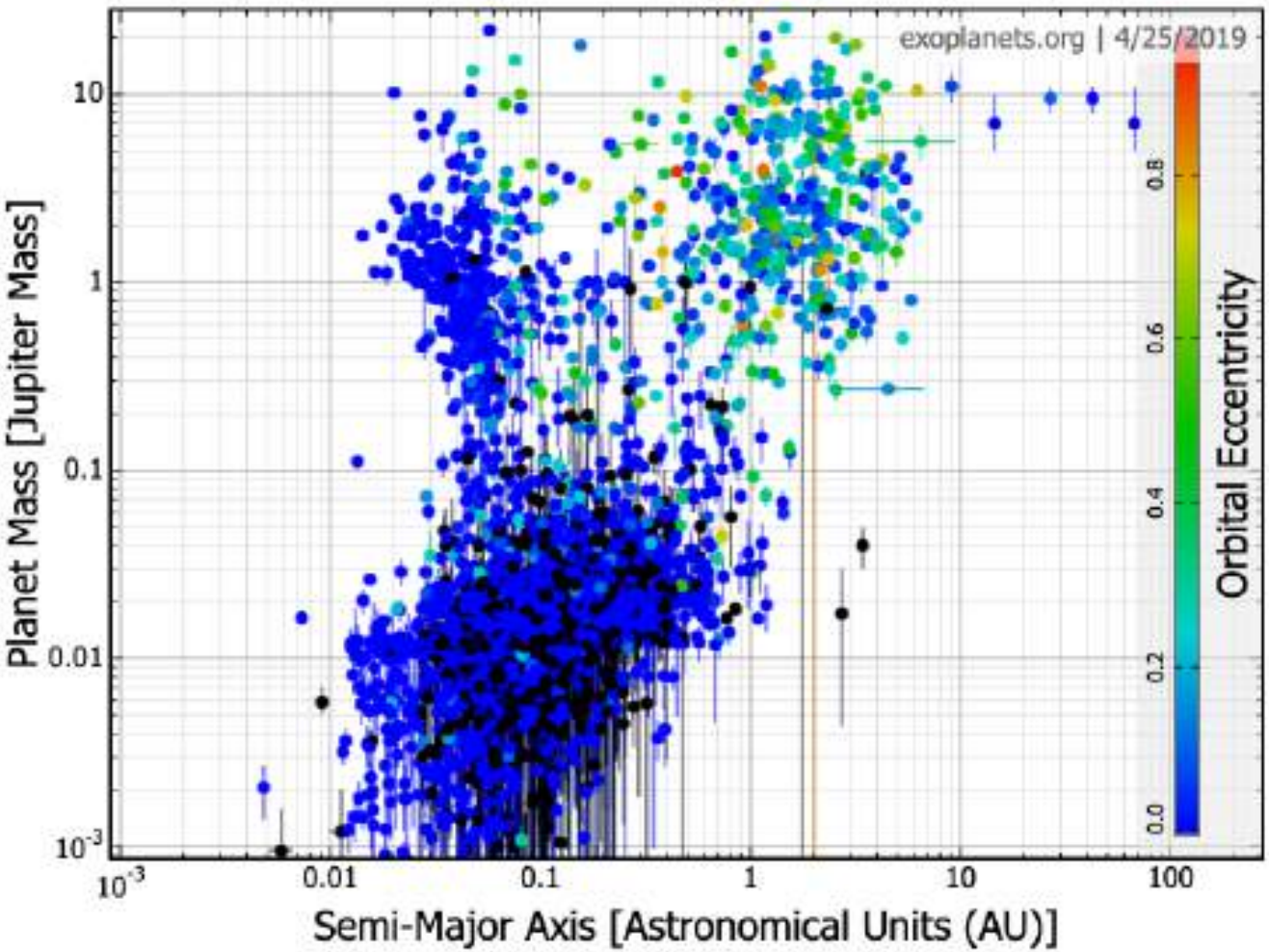
Chen & Lin (2018, MNRAS)

- Application to disk-planet interaction

Lin (2019, MNRAS)

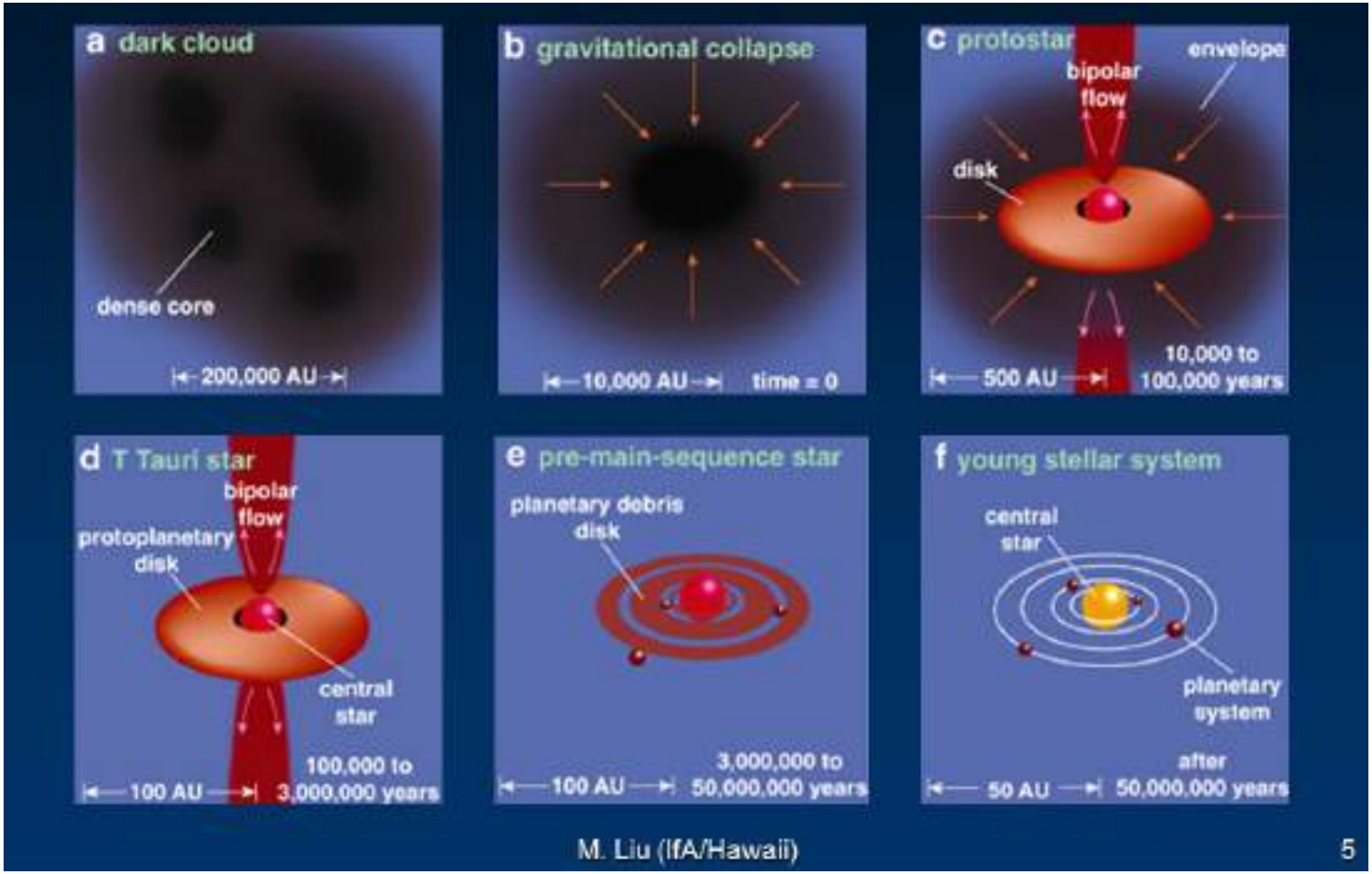
- Application to dust settling in turbulent disks

Diversity of planetary systems



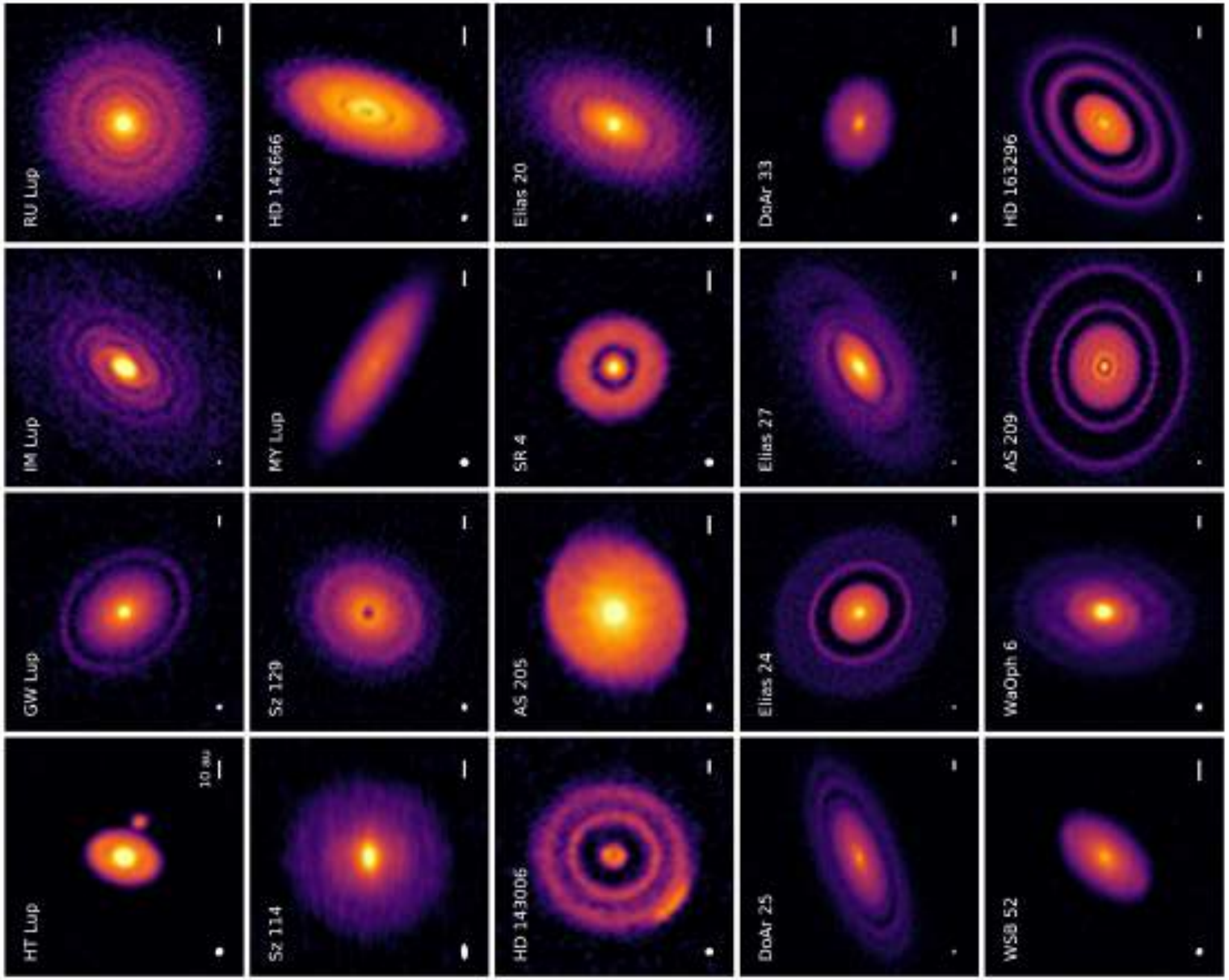
- $O\left(10^3\right)$ extra-solar planets detected
- $O\left(10^3\right)$ planetary systems, $O\left(10^2\right)$ multi-planet
- Wide range of orbital configurations

Planets form in accretion disks around young stars



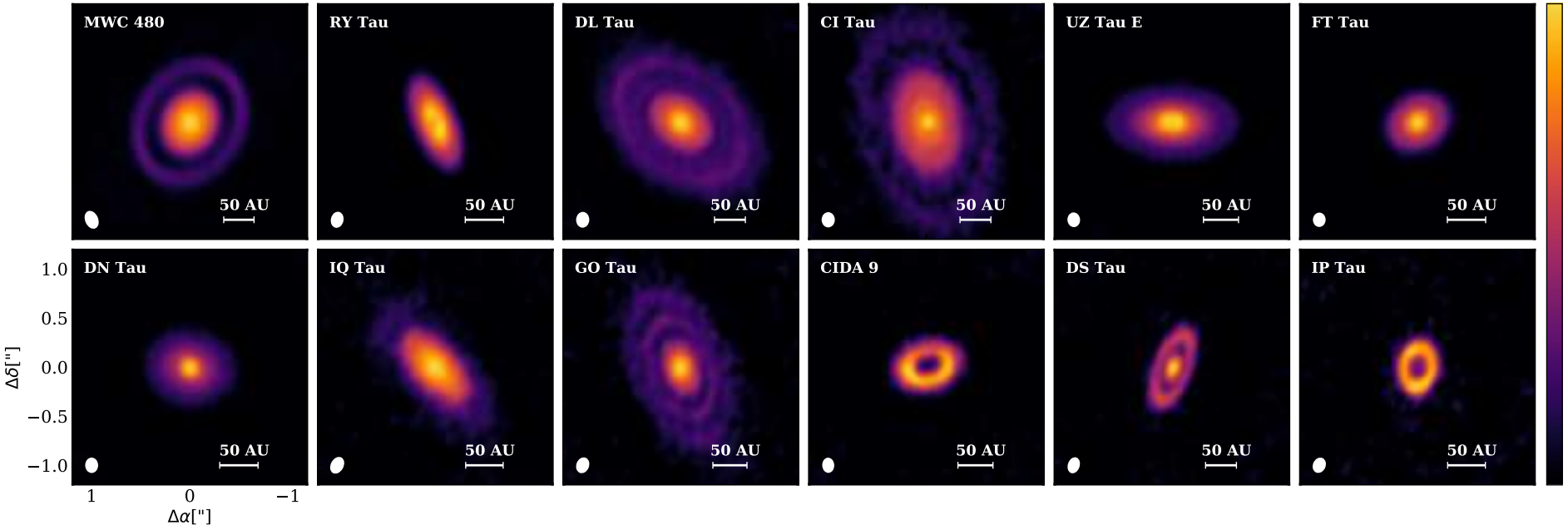
The result is readily obesrved, what about earlier stages, e.g. ‘e’ or even ‘d’?

HL Tau is *so* 2015



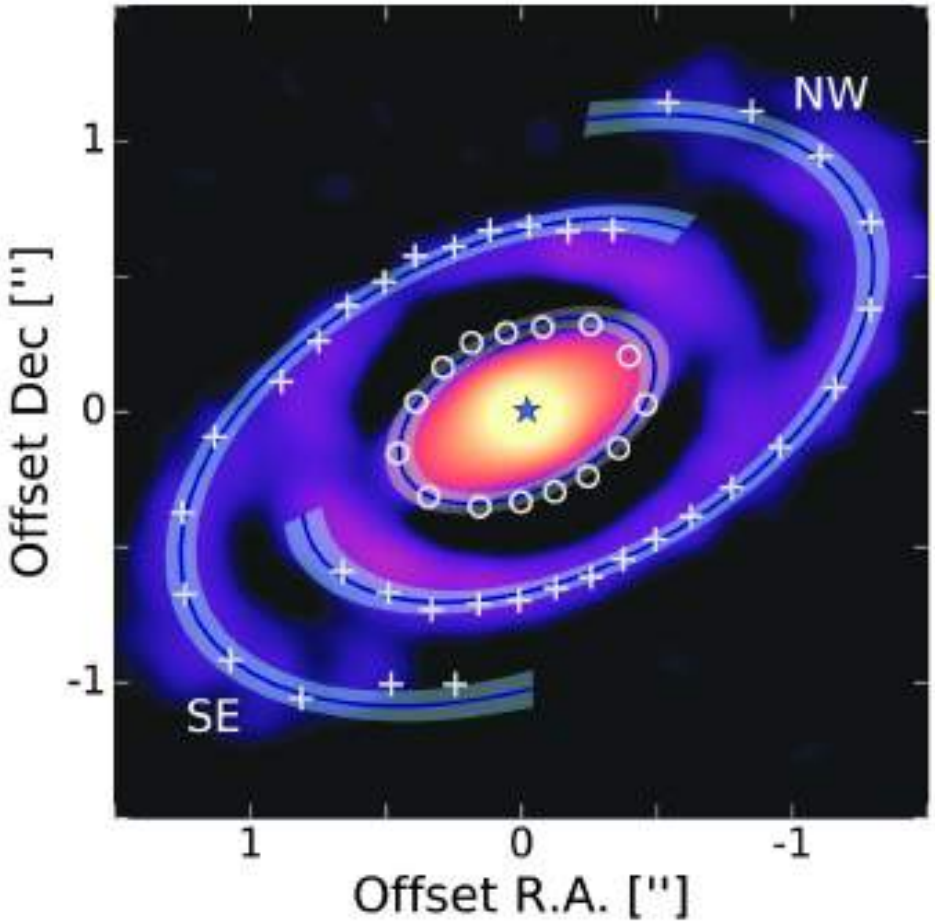
(Andrews et al 2018; DSHARP program)

HL Tau is *so* 2015



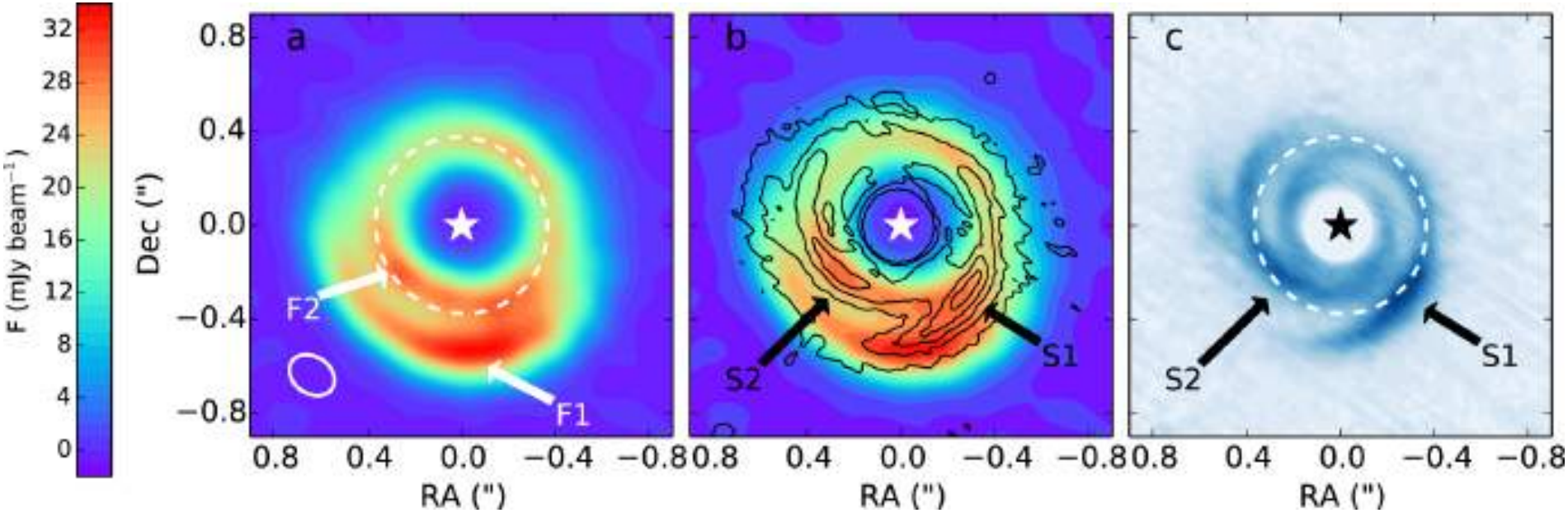
(Long et al 2018)

Asymmetric protoplanetary disks (rare)



(Elias 2-27, Pérez et al., 2016)

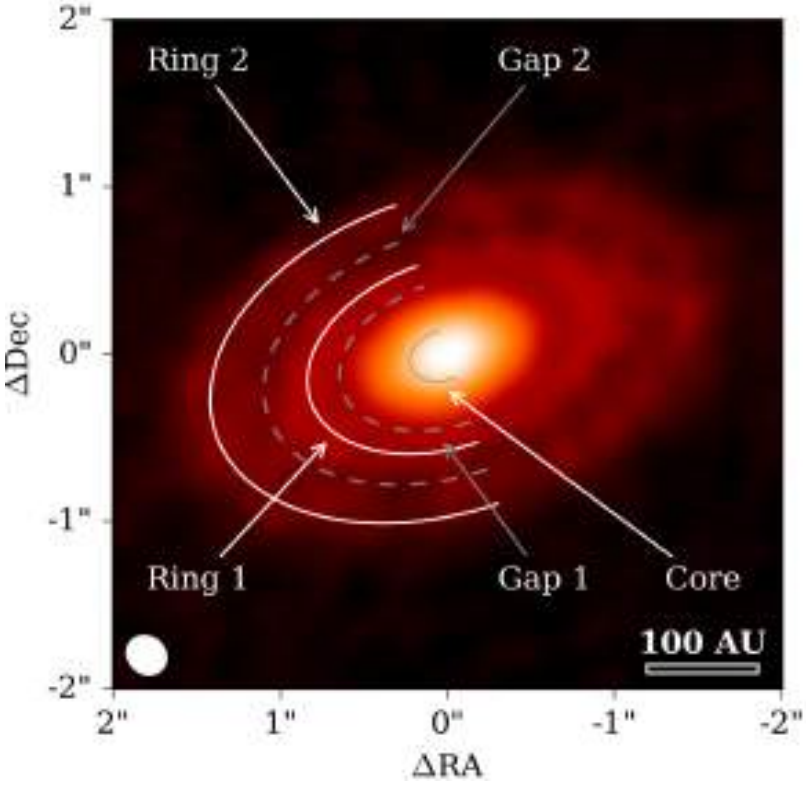
Asymmetric protoplanetary disks (rare)



(HD 135344B, van der Marel et al., 2016)

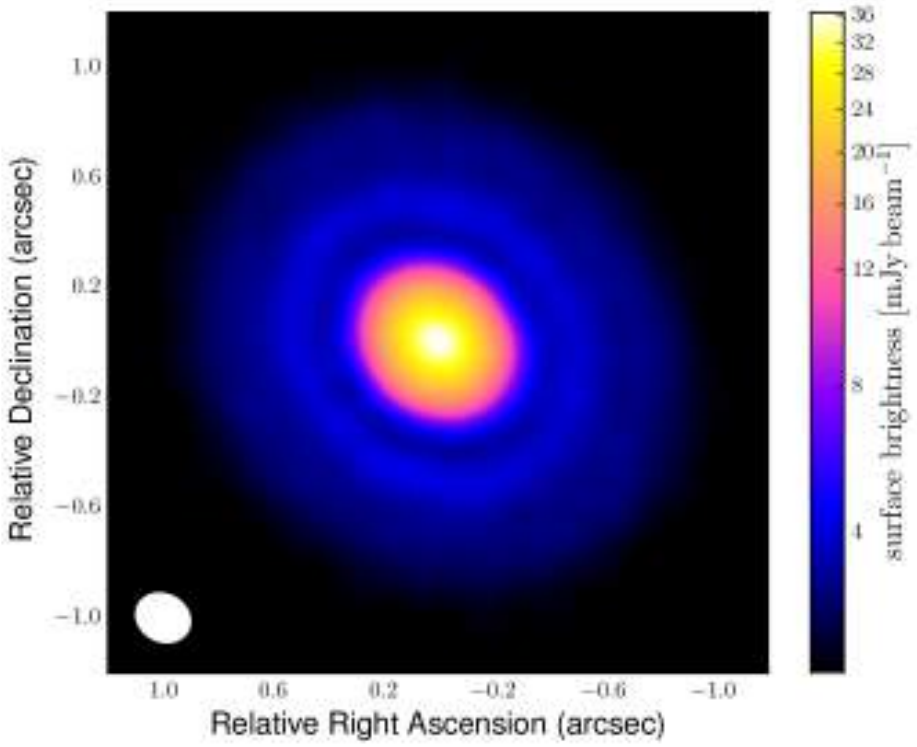
Observing planet formation?

V1094 Sco



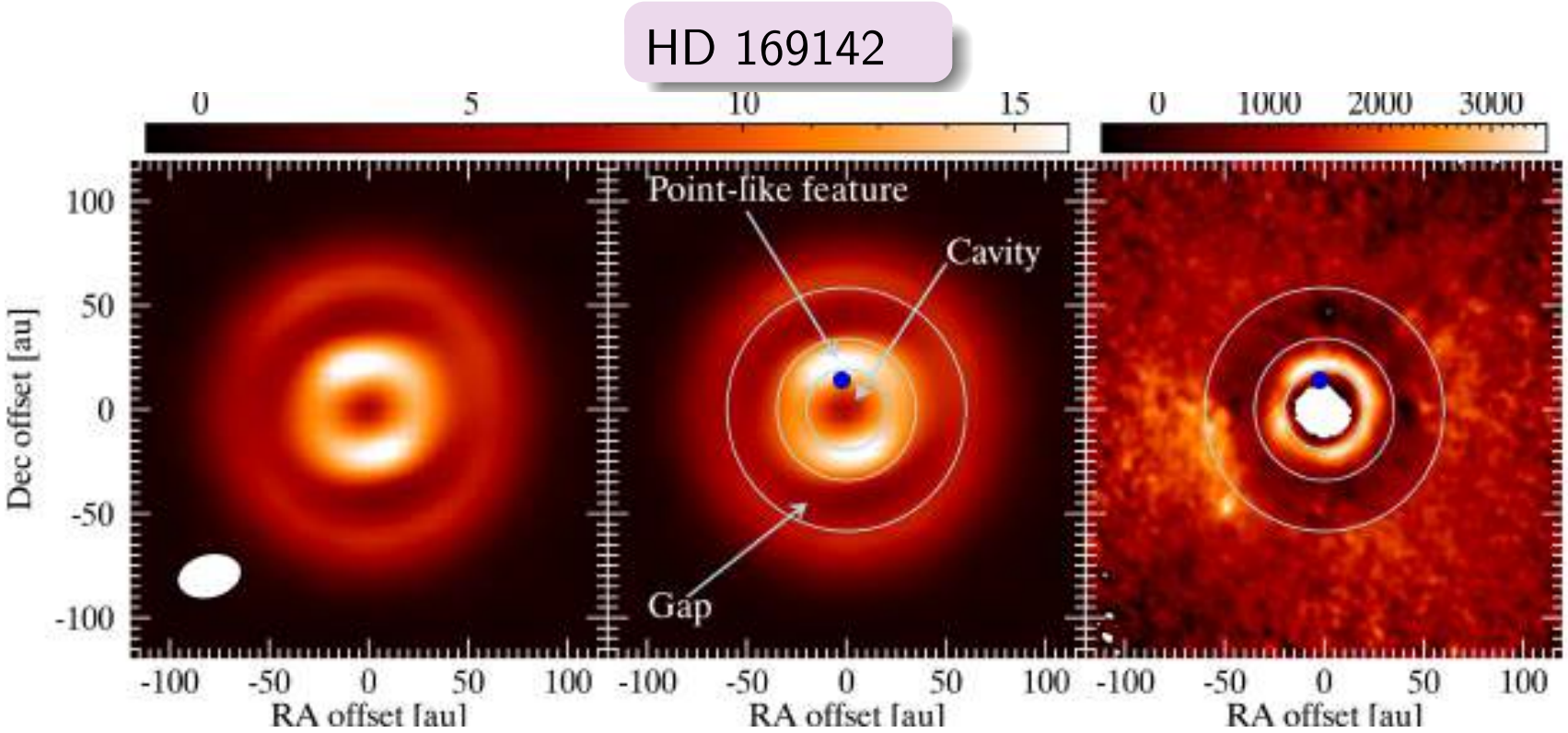
(van Terwisga et al. 2018)

Elias 24



(Dipierro et al. 2018)

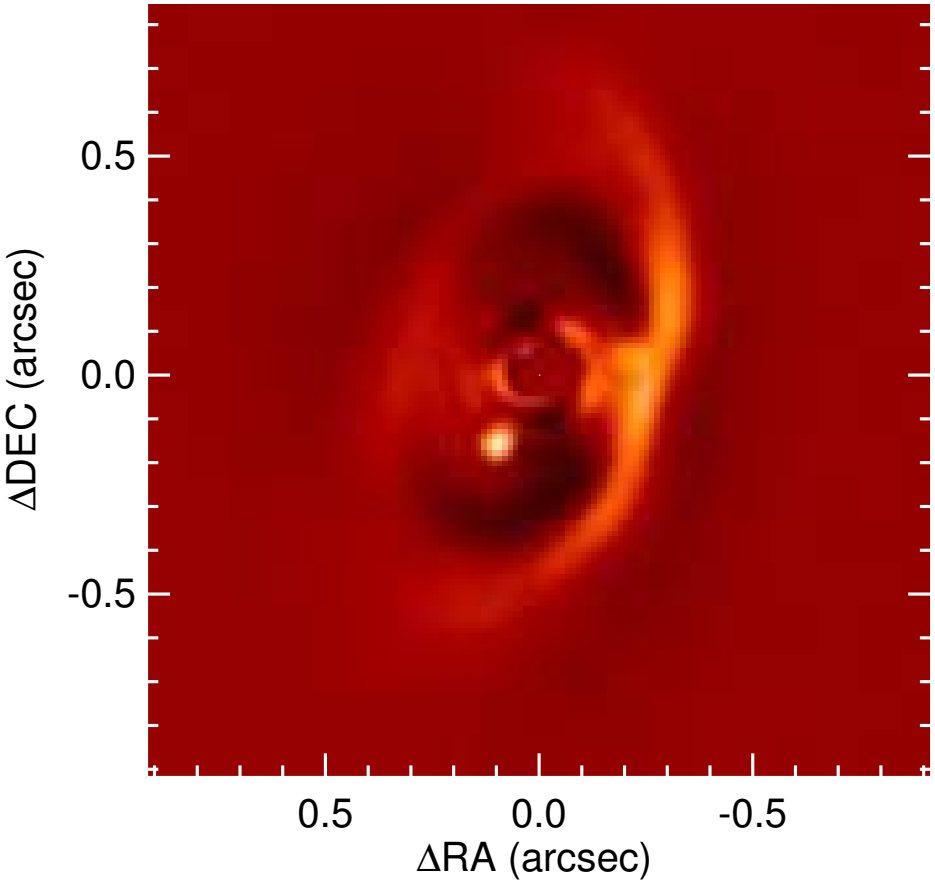
Observing planet formation?



Fedele et al., 2017

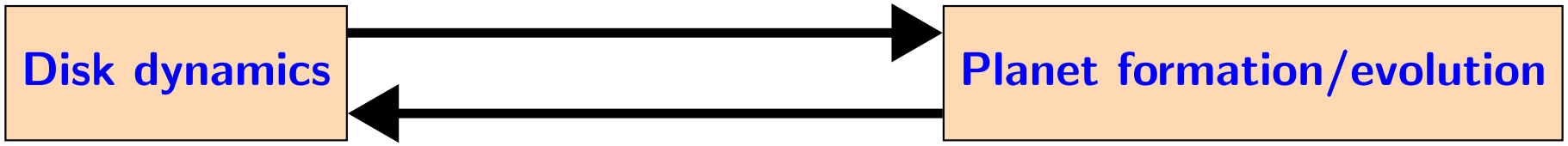
Structures from disk-planet interaction?

First planet detected inside protoplanetary disk gap?



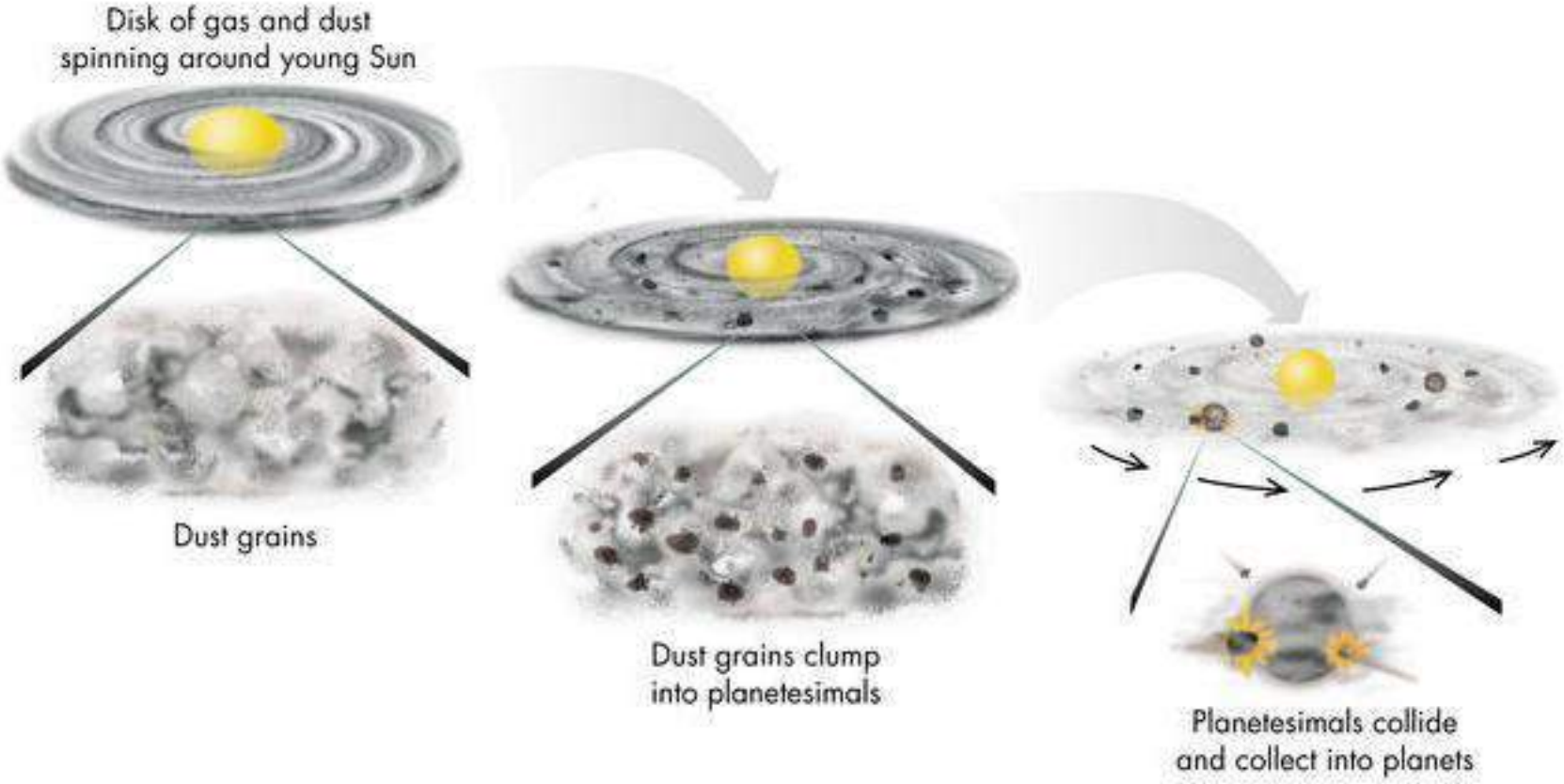
(PDS 70, Müller et al. 2018)

The disk-planet connection



- How do protoplanetary disks accrete onto their stars?
- What are the sources of turbulence in protoplanetary disks?
- Origin of rings, gaps, asymmetries?
- Dust dynamics
  - How do planetesimals form from tiny dust grains?
  - Dust-gas interaction
  - Interpreting observations of PPDs, inferring disk structure/conditions

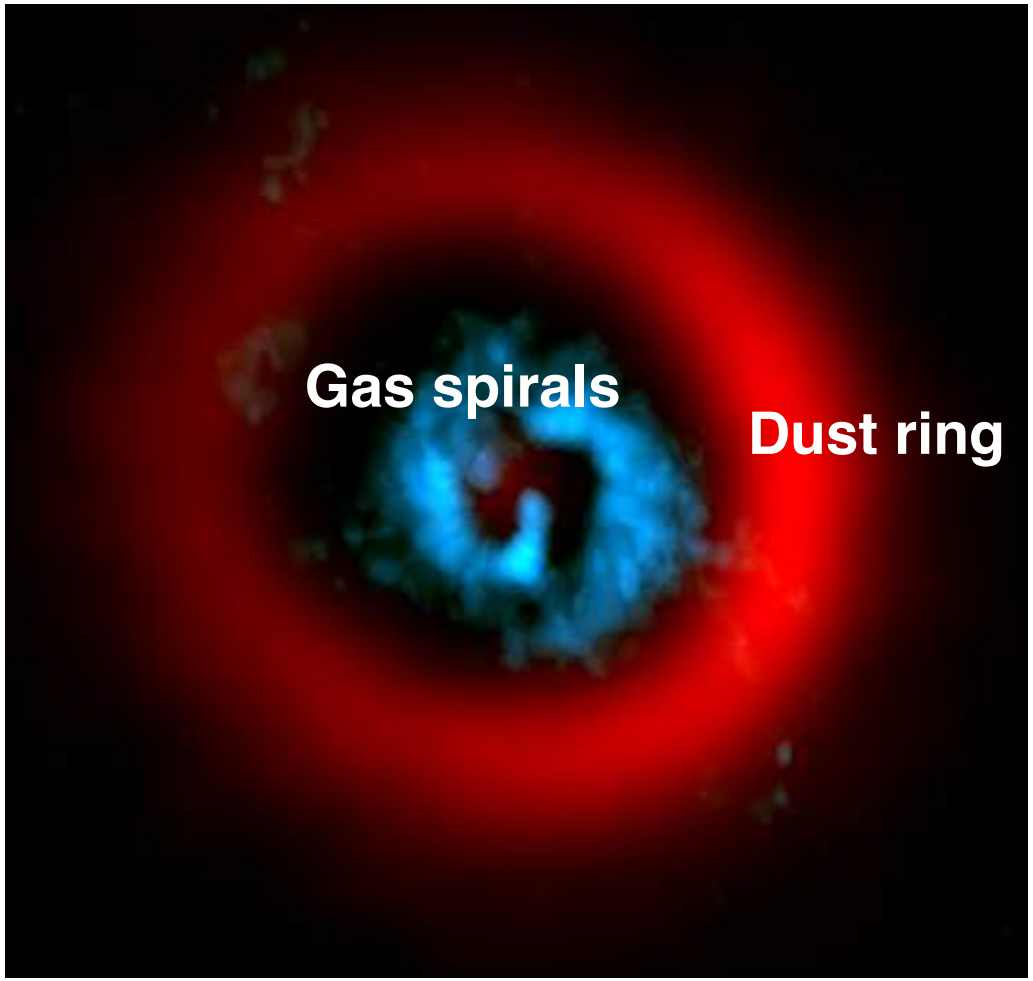
Importance of dust



- Protoplanetary disks are $\sim 99\%$ gas, $\sim 1\%$ dust
- Planets form from the solids (at least in core accretion)
- Need to understand how dust grains evolve in the gaseous disk

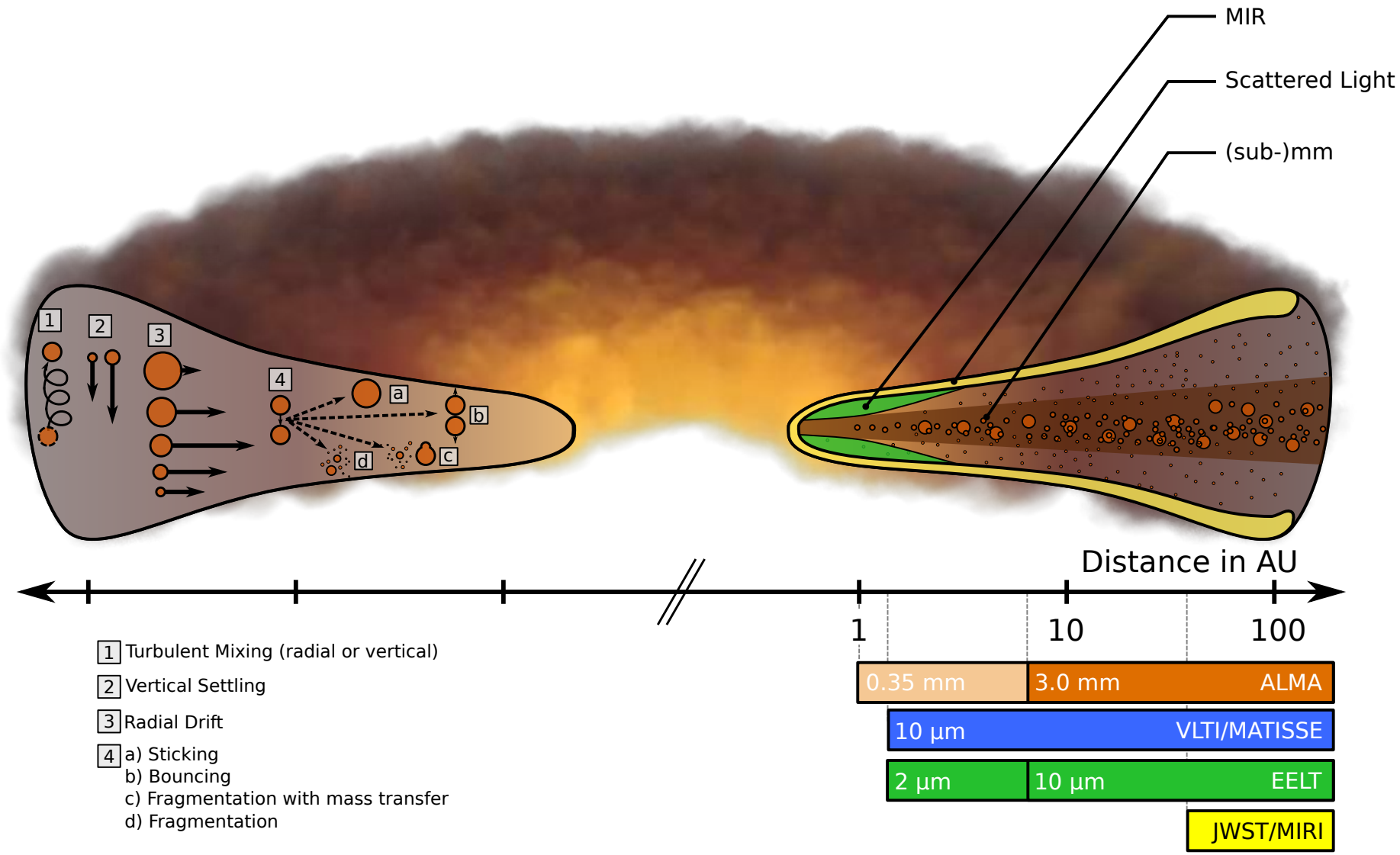
Dusty gas in protoplanetary disks

Gas and dust don't always correleate



AB Aurigae, (Tang et al. 2017)

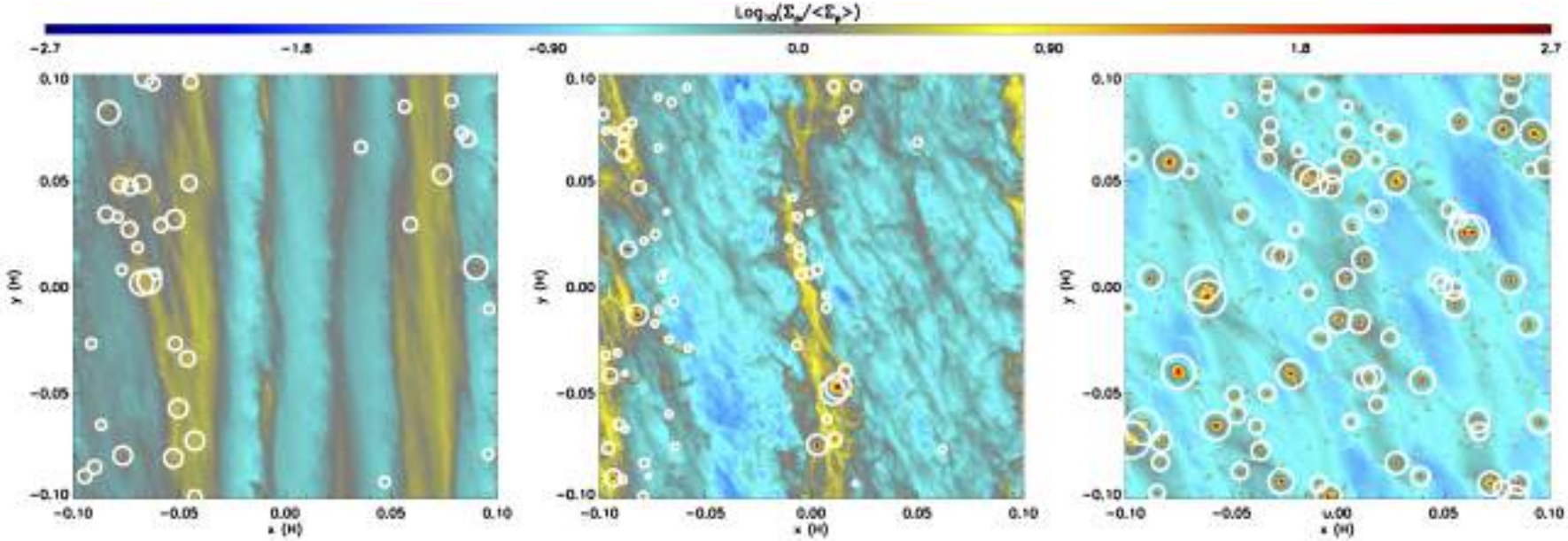
Dusty-gas dynamics in protoplanetary disks



(Testi et al., 2014)

Modeling dust-gas dynamics is complicated

- State-of-the-art: gas+solid dynamics



(Simon et al., 2017)

- Intellectually & computationally demanding

Is there a simpler way?

A dust-free description of dusty gas

Lin & Youdin (2017)

polytropic gas with dust $\approx$ **pure gas with cooling**

(for small particles)

A dust-free description of dusty gas

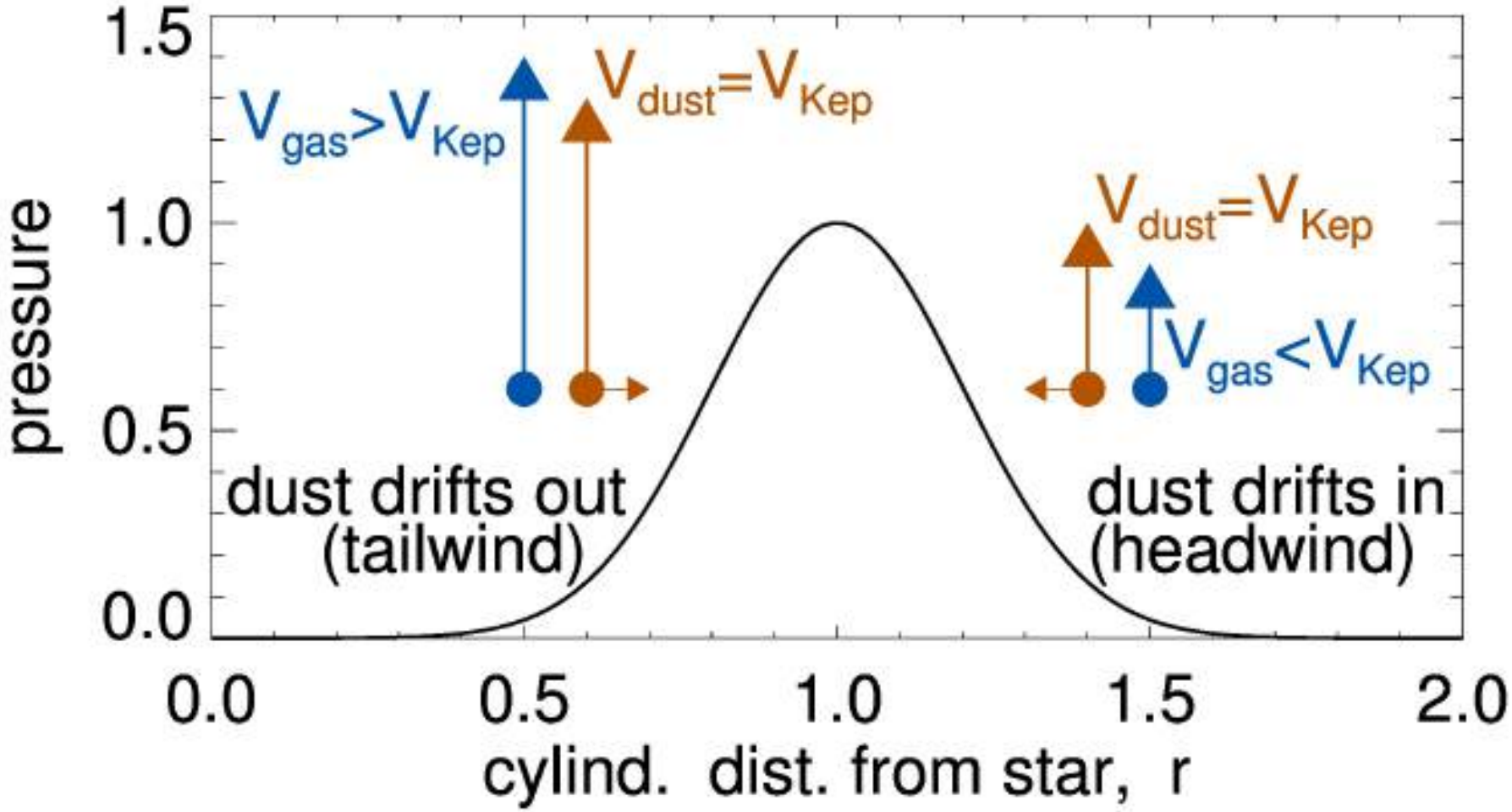
Lin & Youdin (2017)

$$\left.\begin{aligned}
&\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0, \\
&\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v} \cdot \nabla \boldsymbol{v} = -\frac{1}{\rho} \nabla P - \nabla \Phi, \\
&\frac{\partial P}{\partial t} + \boldsymbol{v} \cdot \nabla P = -\Gamma P \nabla \cdot \boldsymbol{v} + P \boldsymbol{v} \cdot \nabla \ln c_s^2 \\
&\qquad\qquad + \frac{\Gamma P}{\rho_{\text{gas}}} \nabla \cdot (f_{\text{dust}} t_{\text{stop}} \nabla P).
\end{aligned}\right\}$$

Looks like gas dynamics

(see also Fromang & Papaloizou, 2006; Laibe & Price 2014)

Particle drift in protoplanetary disks



- Drag forces $\rightarrow$ ang. mom. exchange with gas $\rightarrow$ dust drifts to high pressure

Thermodynamic view of particle drift

- Dust particles $\sim$ cold, pressureless fluid
- $T \propto c_s^2 \sim P_{\text{gas}} / (\rho_{\text{dust}} + \rho_{\text{gas}})$

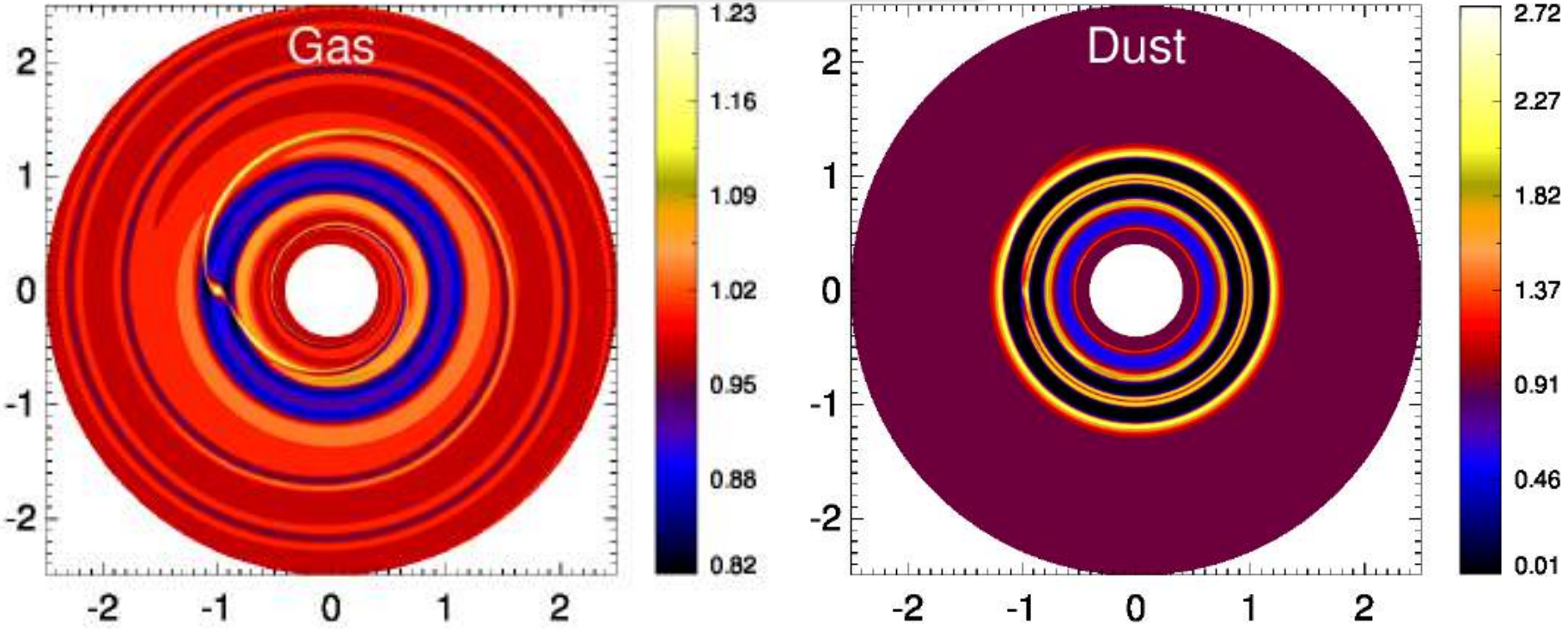
positive particle flux $\approx$ **negative heat flux**

Model applications and predictions

- Thermodynamic interpretation of dusty phenomena
- Dusty analogs of thermodynamic processes
- Example: dusty edges are unstable ($\rightarrow$ entropy edges)

Dust rings and traps at planet gaps

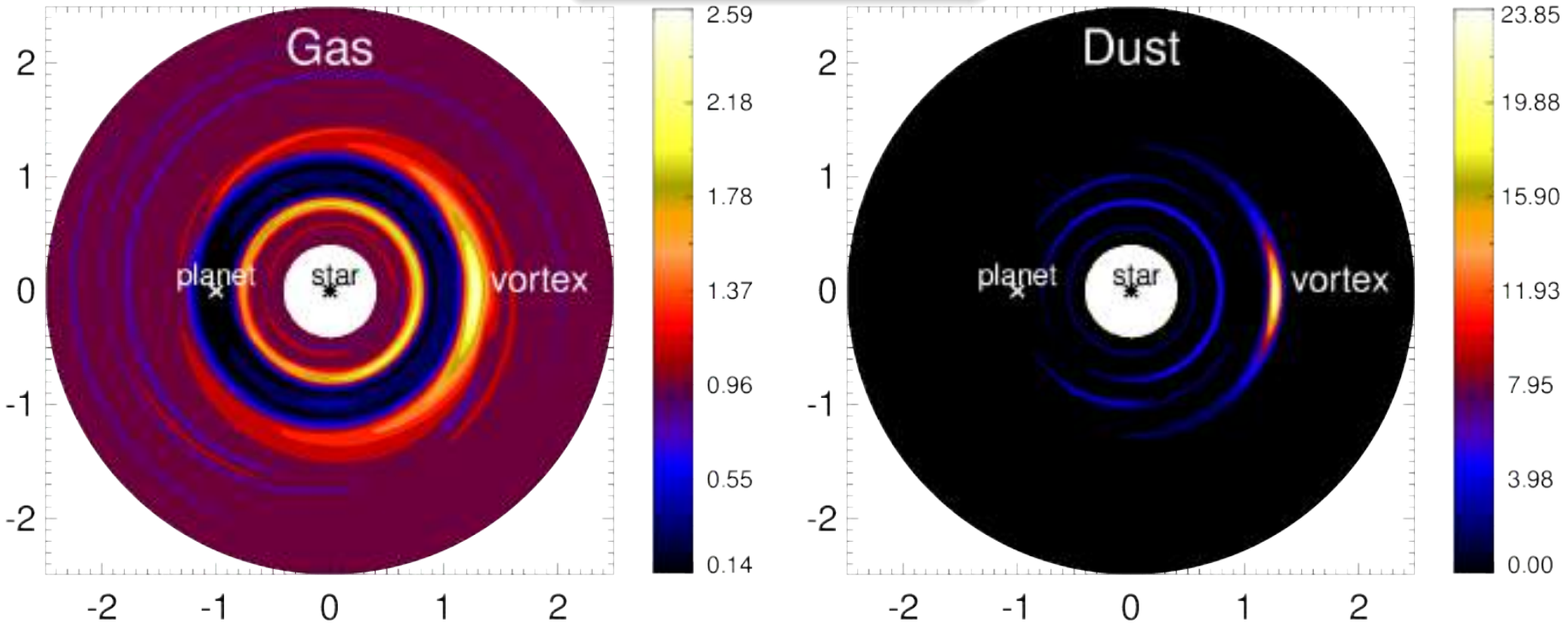
$10 M_{\mathrm{Earth}}$ planet



- Pressure gradient at gap edges $\rightarrow$ radial dust ring
- PLUTO code doesn't know about dust

Dust rings and traps at planet gaps

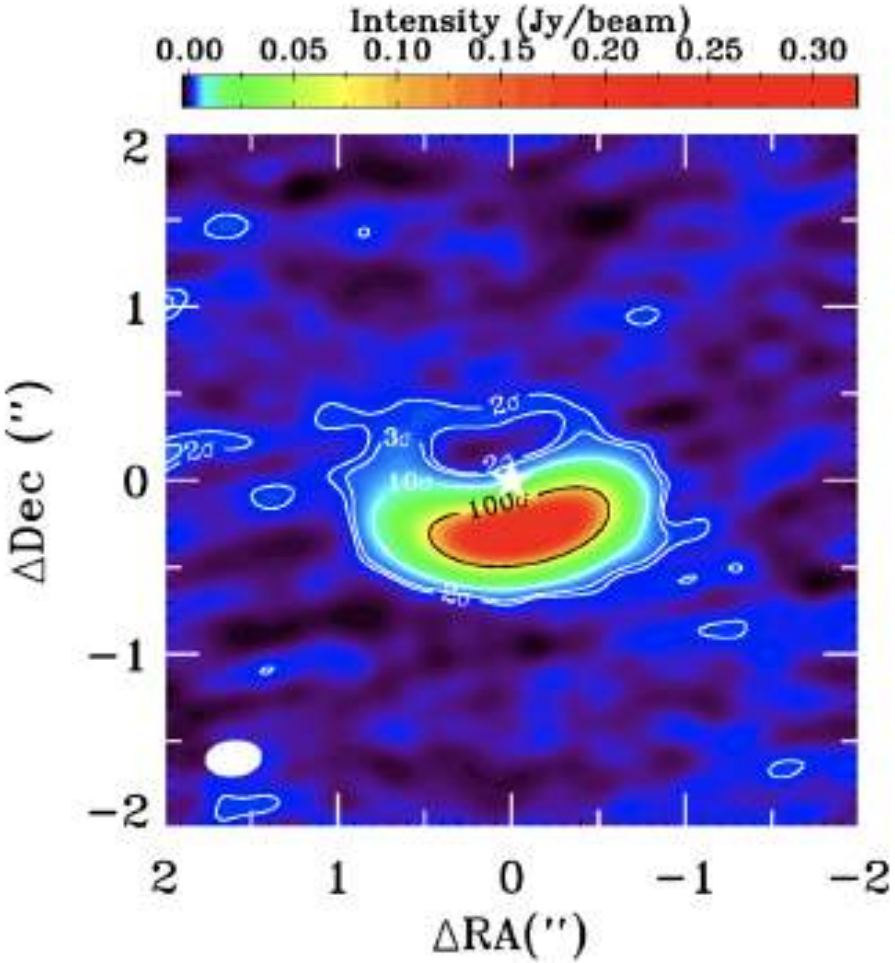
$30 M_{\mathrm{Earth}}$ planet



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

Dust rings and traps at planet gaps

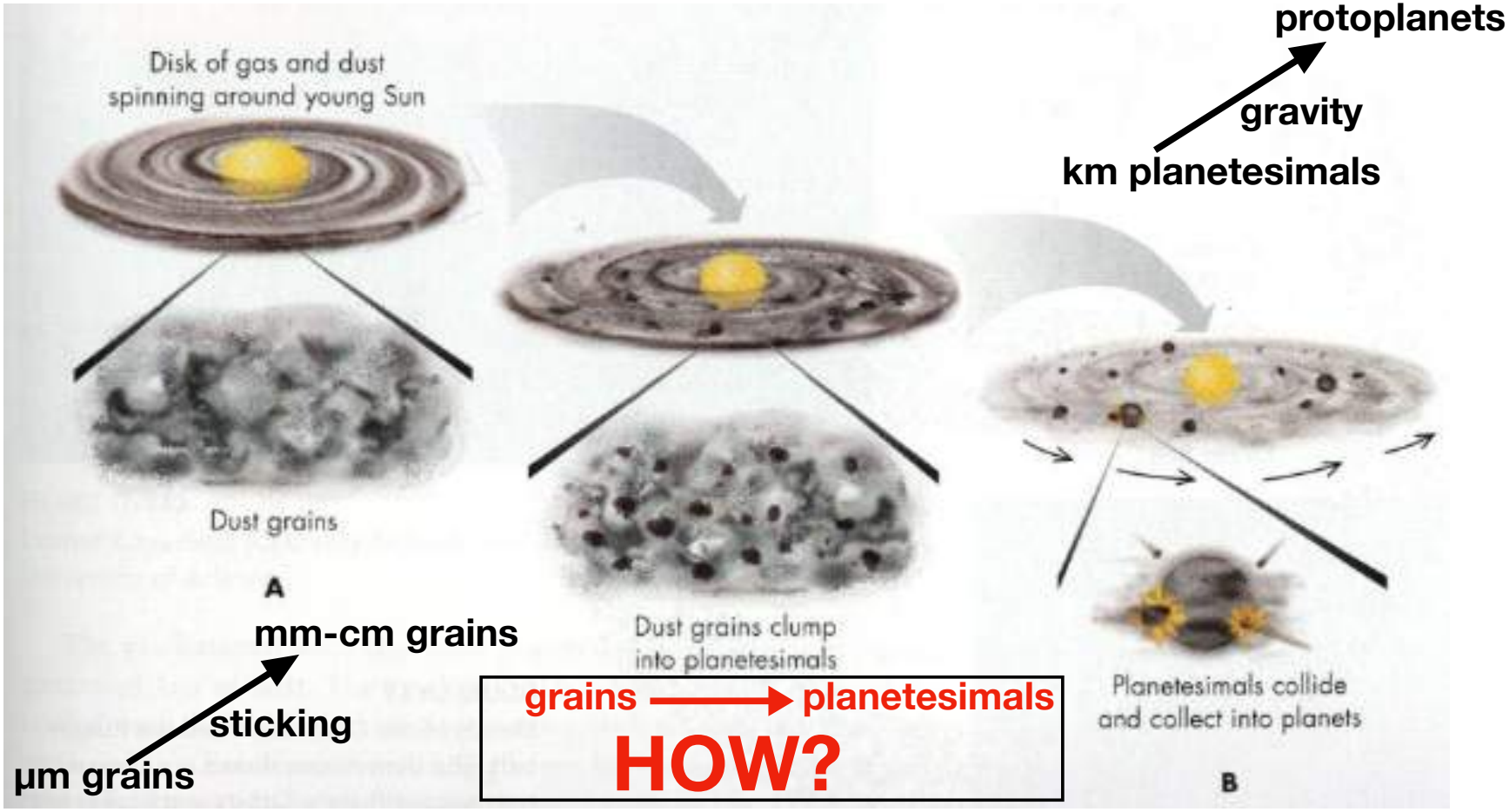
Observed dust trap



- (van der Marel et al 2013) an unseen planet?

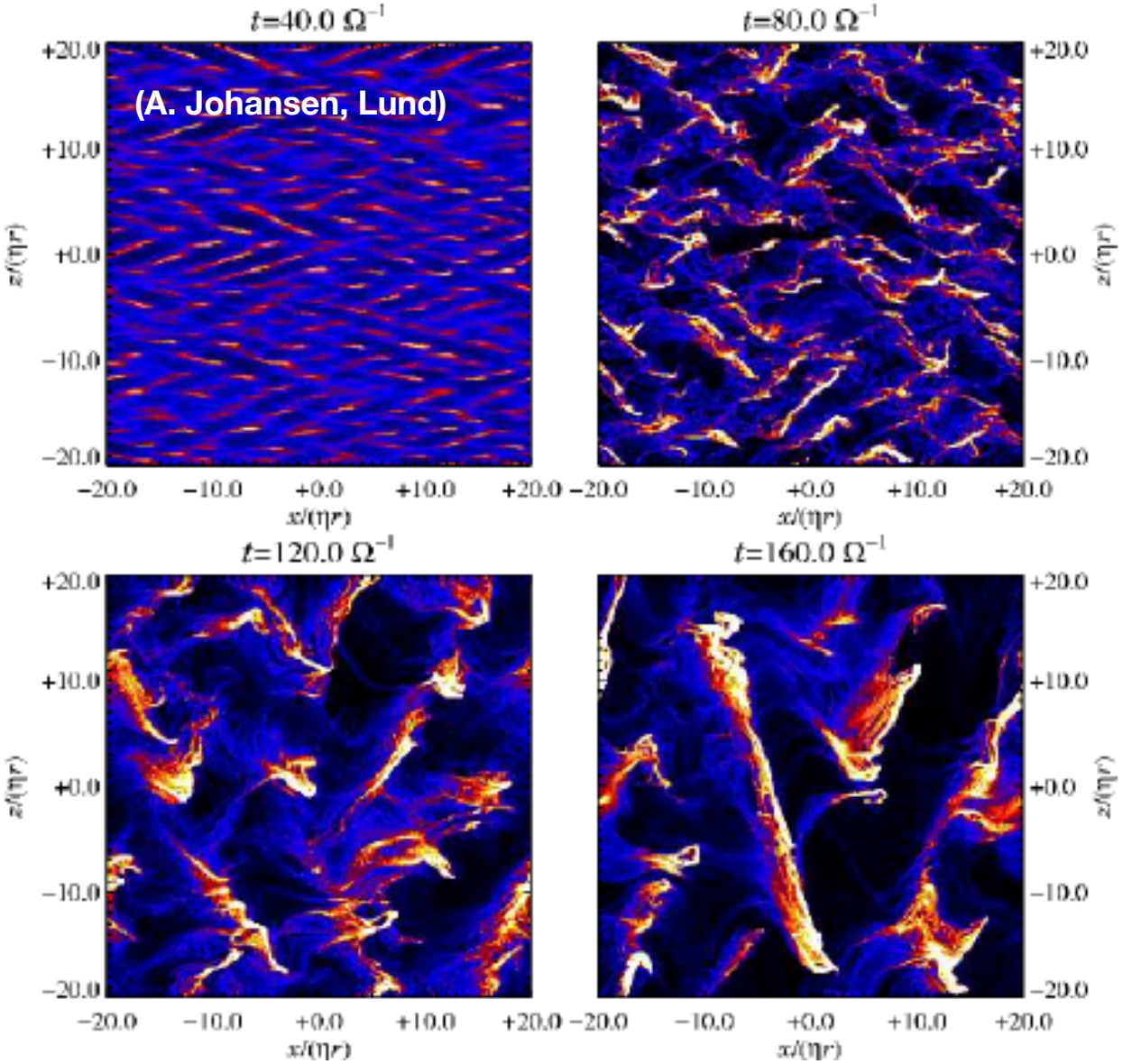
How to make the planet?

From dust to planets



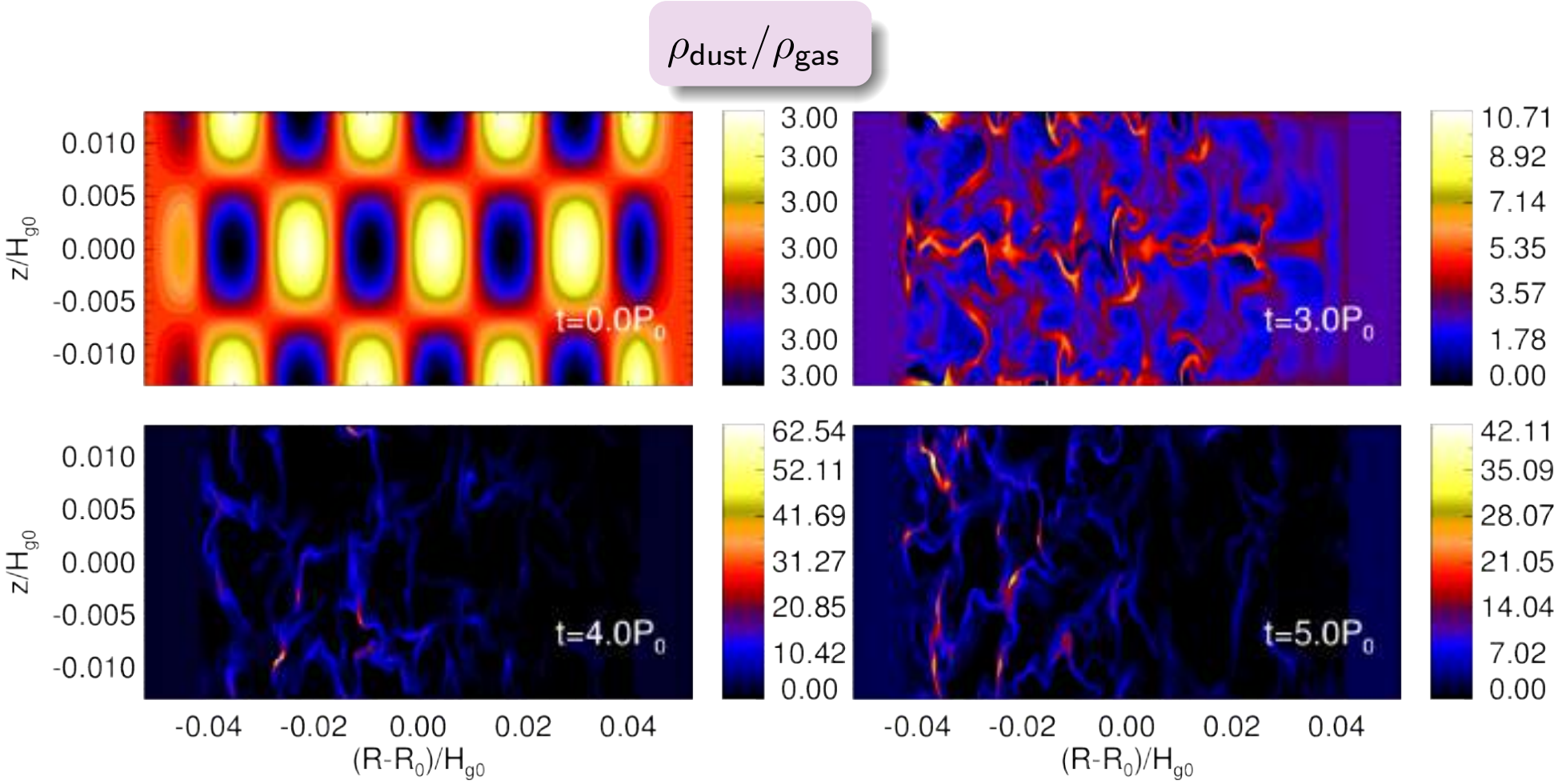
- Dust-trapping by gas vortices (Barge 1995, Lyra & Lin, 2013)
- Secular gravitational instabilities (Youdin 2011; Takahashi & Inutsuka, 2014)
- Streaming instability (Youdin & Goodman, 2005)

Streaming instability: particle+gas simulations

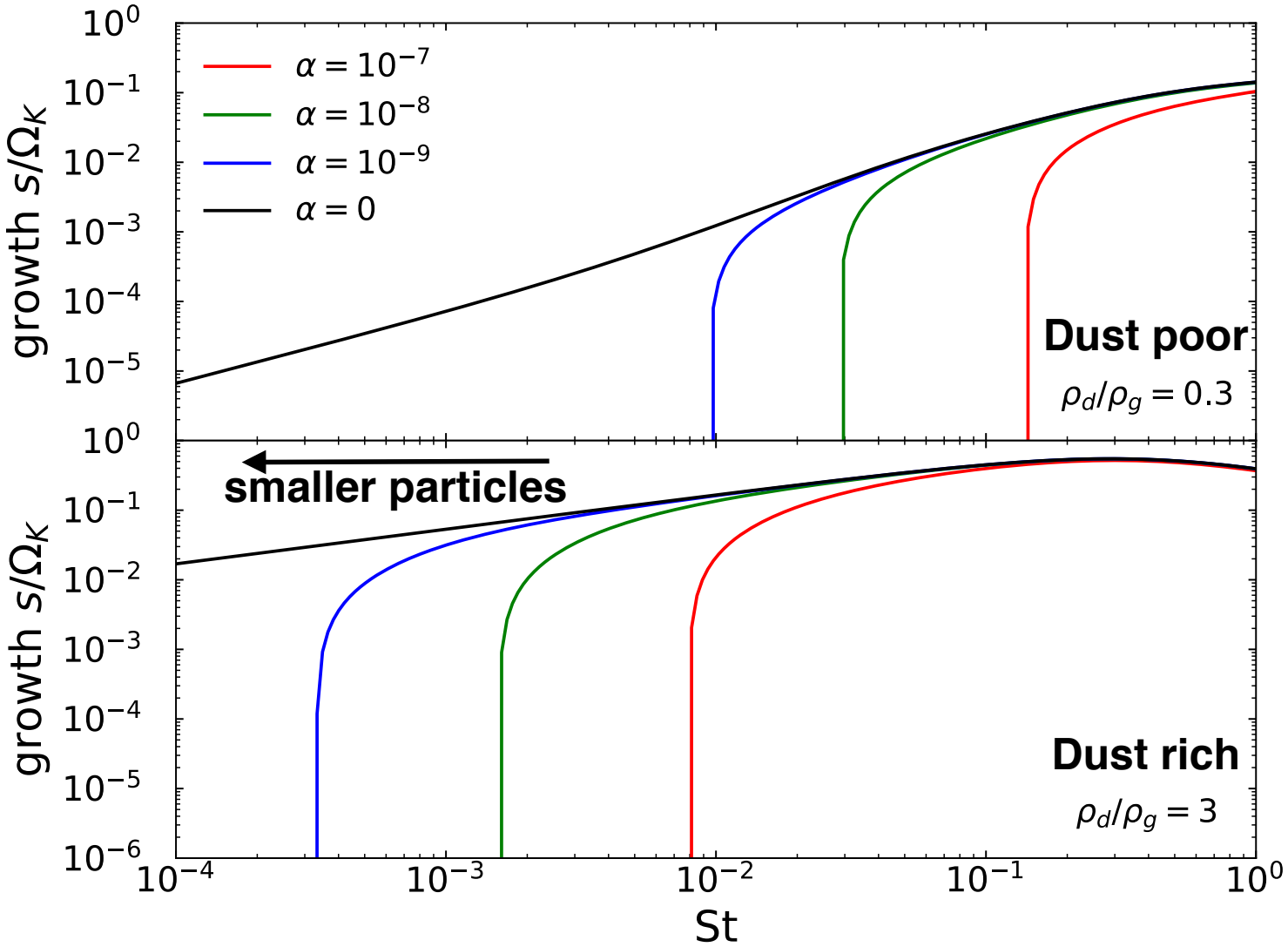


- Streaming instability $\rightarrow$ dust clumping mediated by mutual dust-gas drag

Streaming instability: one-fluid model



Planetesimal formation requires high dust-to-gas ratios



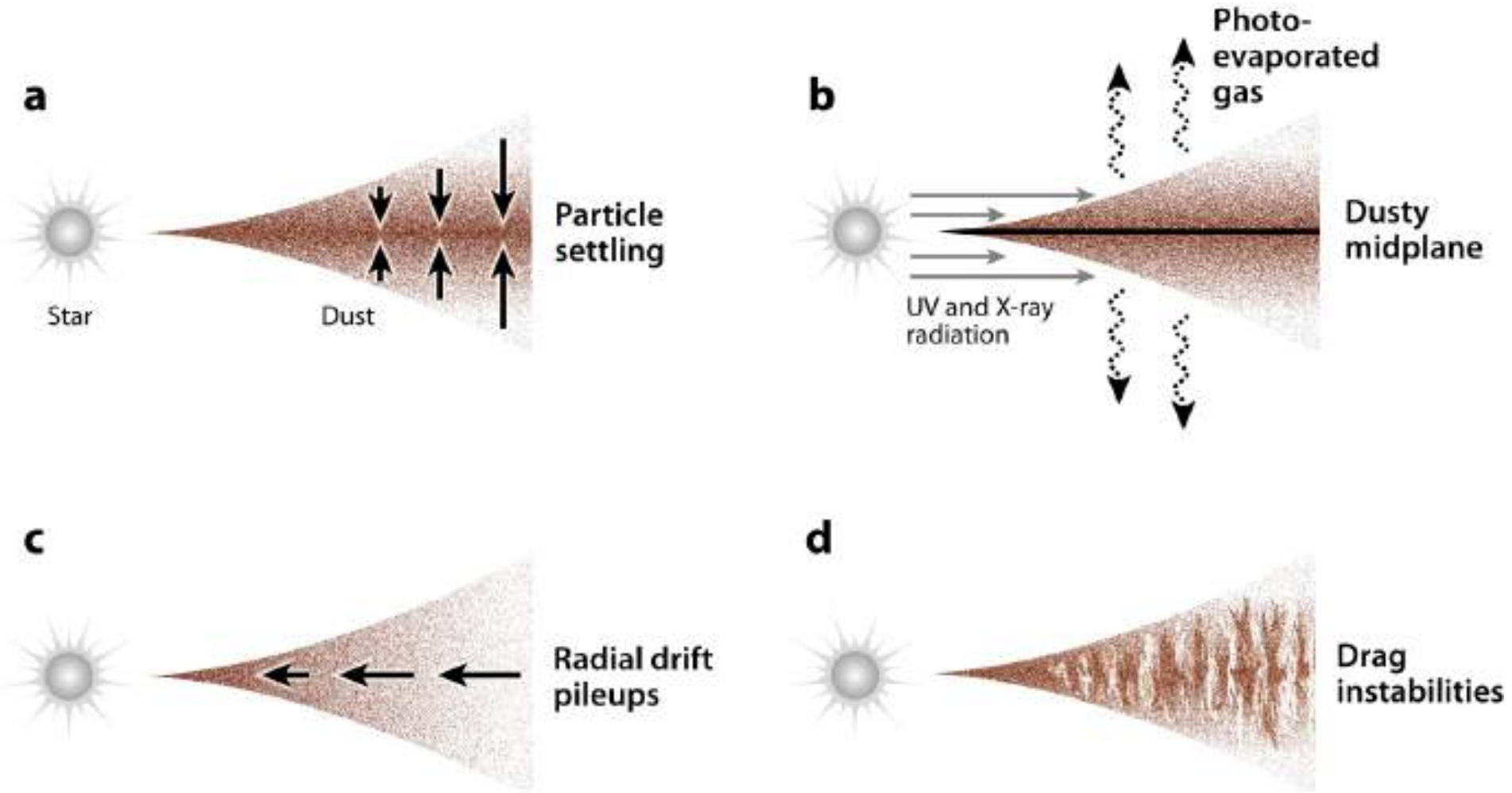
(SI in viscous disks; K. Chen & Lin, in prep.)

- SI needs $\rho_{\rm dust} \gtrsim \rho_{\rm gas}$ for strong clumping ($\rightarrow$ collapse into planetesimals)

Planetesimal formation requires high dust-to-gas ratios

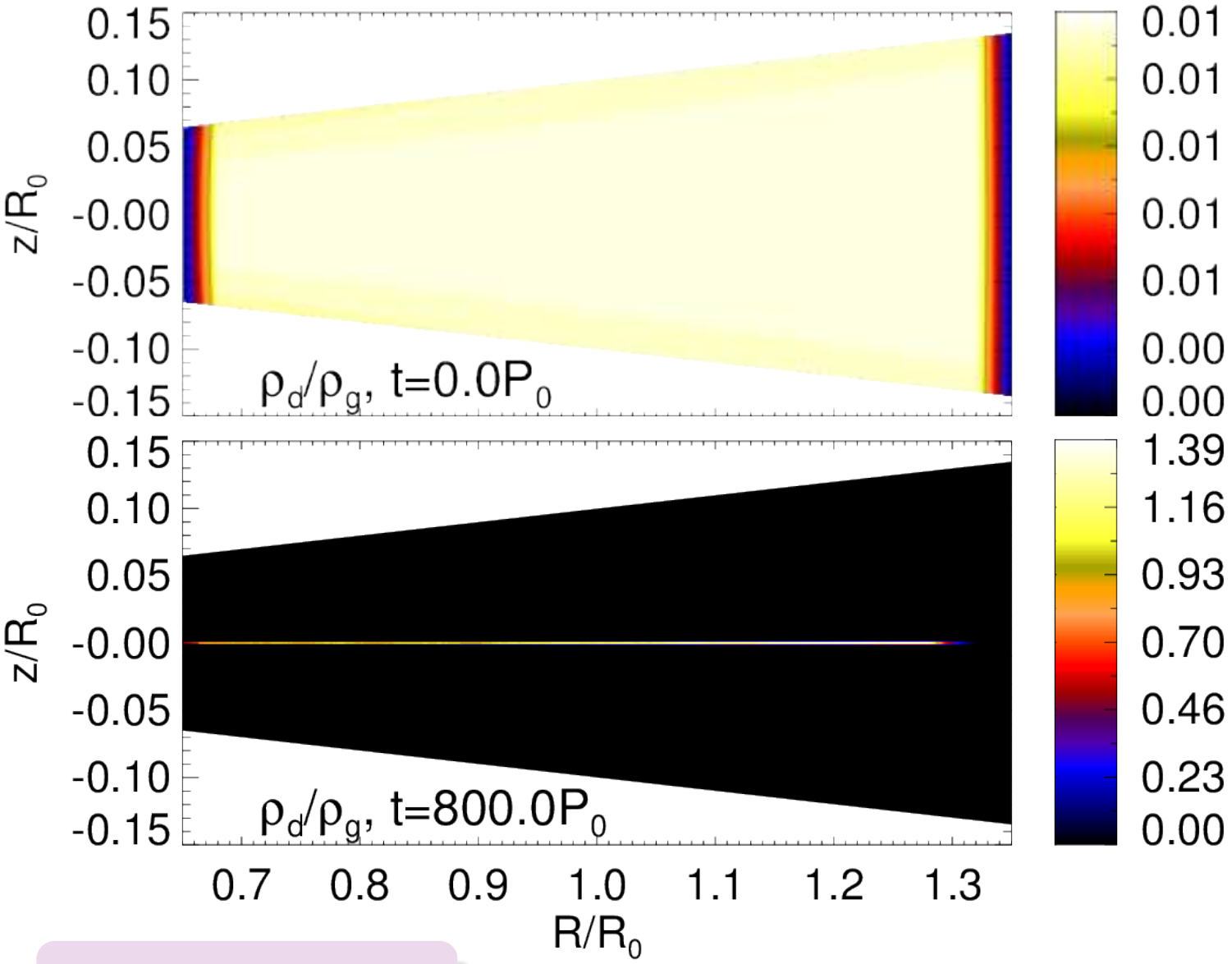
$\rho_d \sim 0.01\rho_g$ in ISM → HOW? → $\rho_d \sim \rho_g$ for SI

Enhancing the dust-to-gas ratio in protoplanetary disks



Chiang E, Youdin AN. 2010.
Annu. Rev. Earth Planet. Sci. 38:493–522

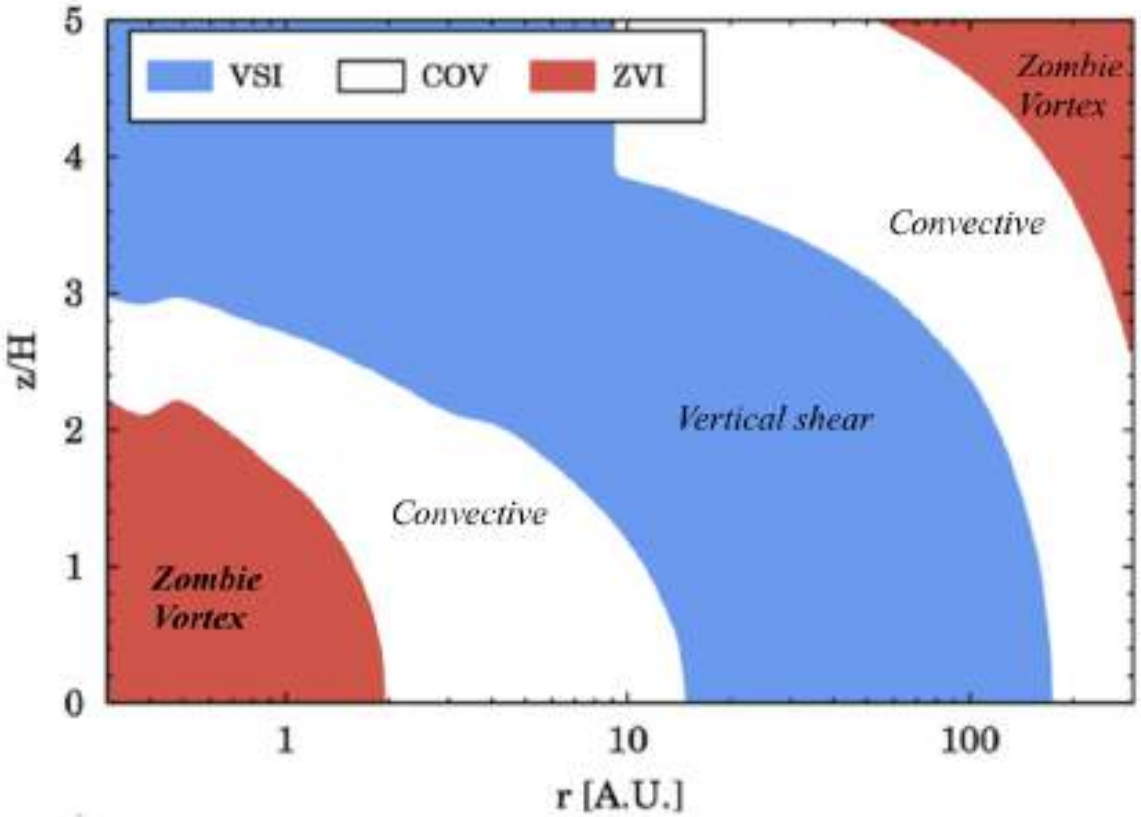
Dust settling?



- Yes... if the disk is laminar

Hydrodynamic turbulence in protoplanetary disks

- Zombie vortex instability (Marcus et al., 2015)
- Convective overstability (Klahr & Hubbard, 2014)
- Vertical shear instability (Nelson et al., 2013, Lin & Youdin, 2015)



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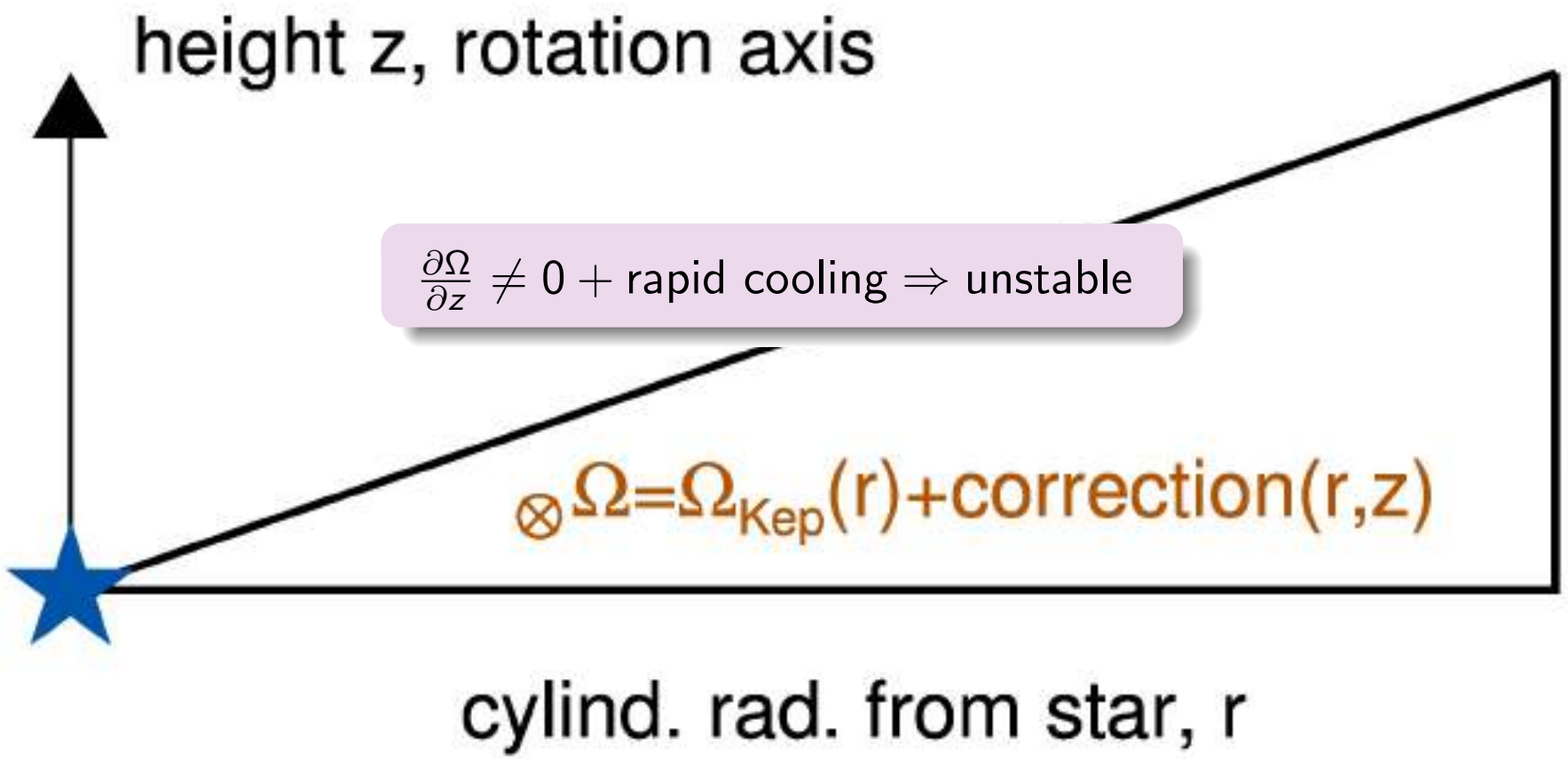
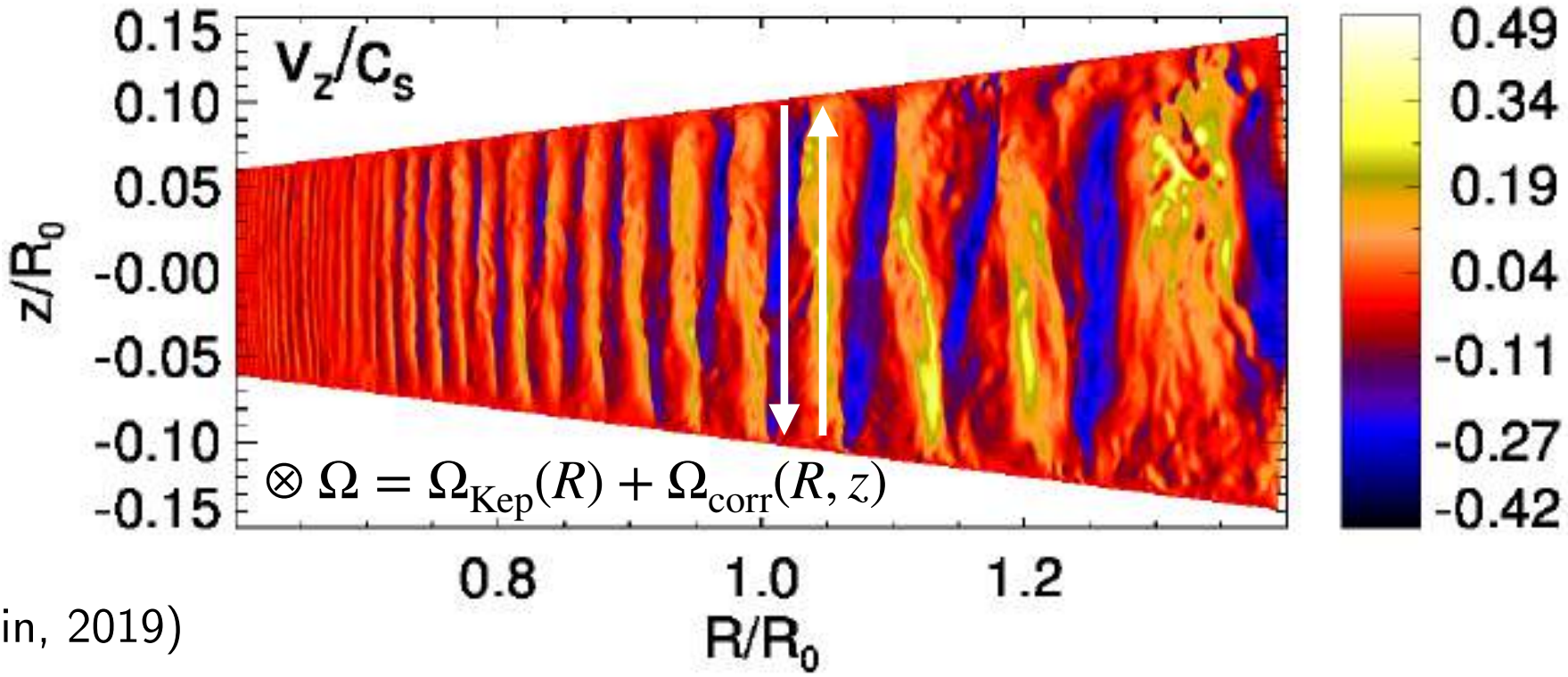


Vertical shear instability



(Lin, 2019)

What happens to dust?

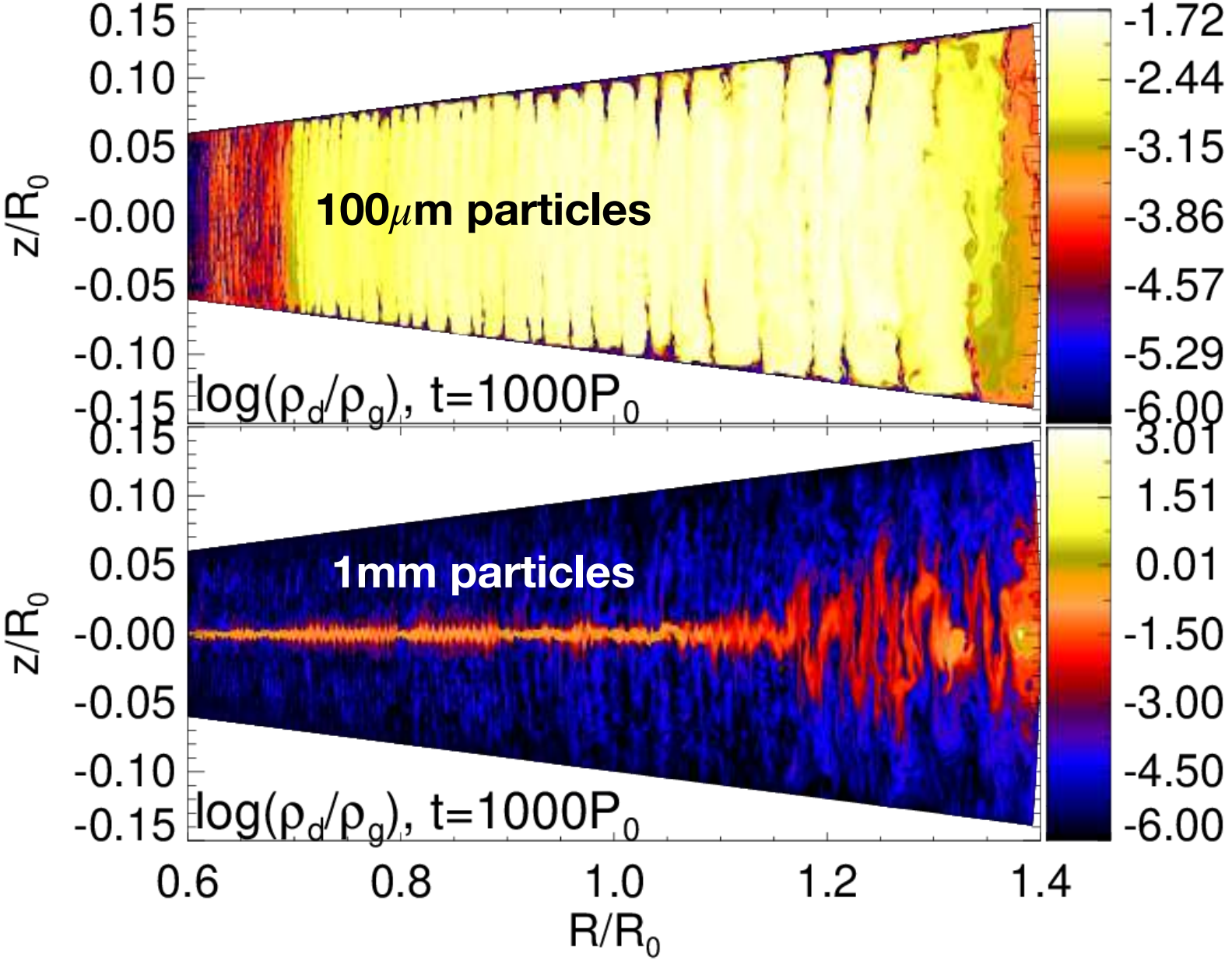
Lifting dust particles by the VSI

Moderately turbulent disk

Lifting dust particles by the VSI

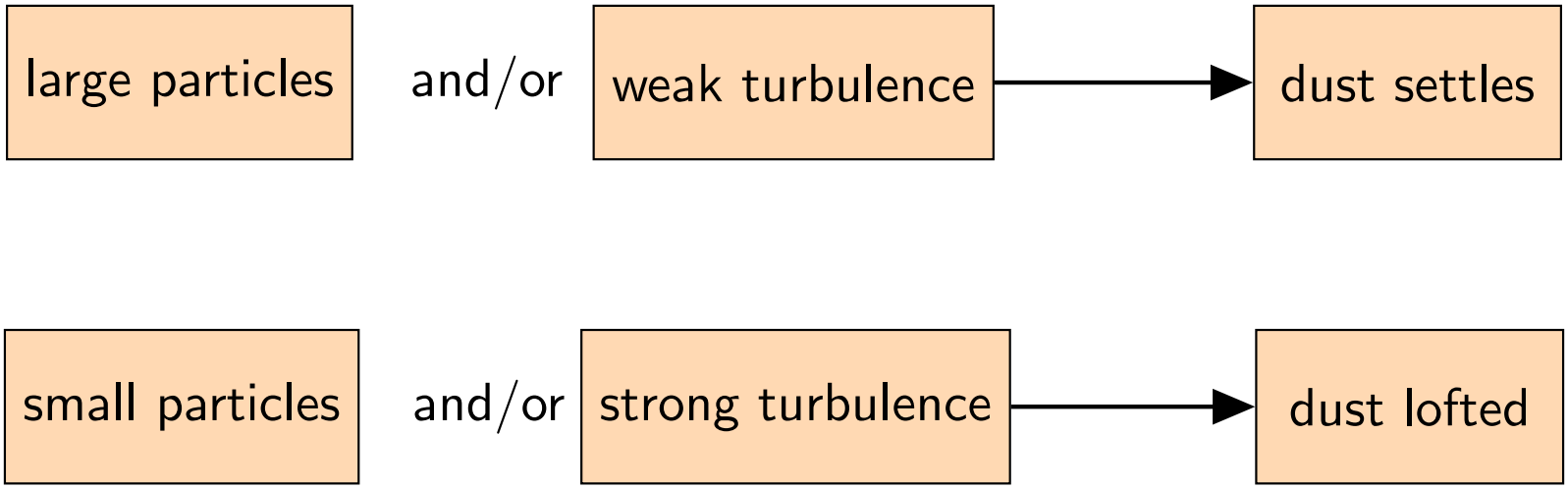
Strongly turbulent disk

Effect of particle size



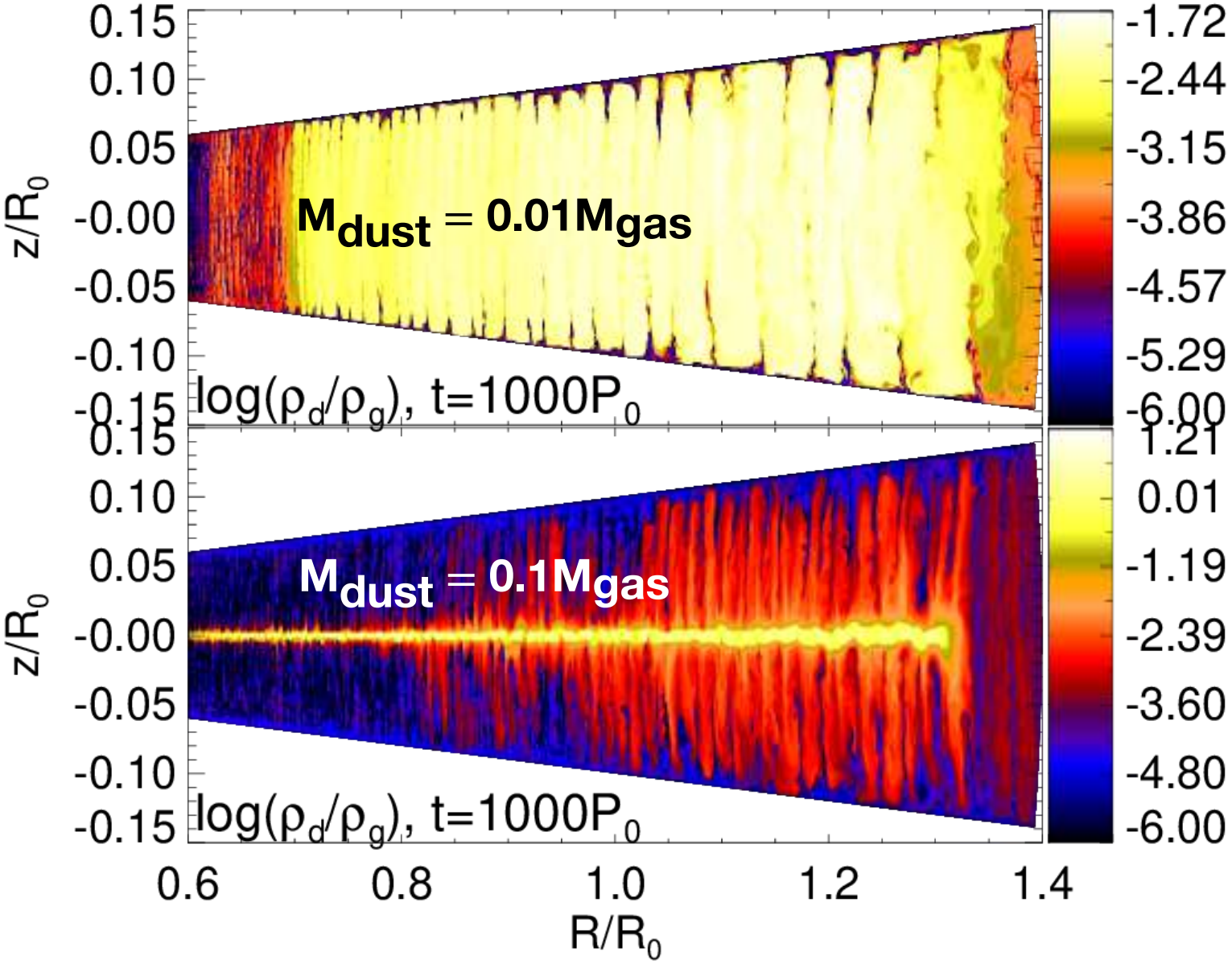
- Small particles remain well-mixed with gas: no settling

Classic picture: passive particles



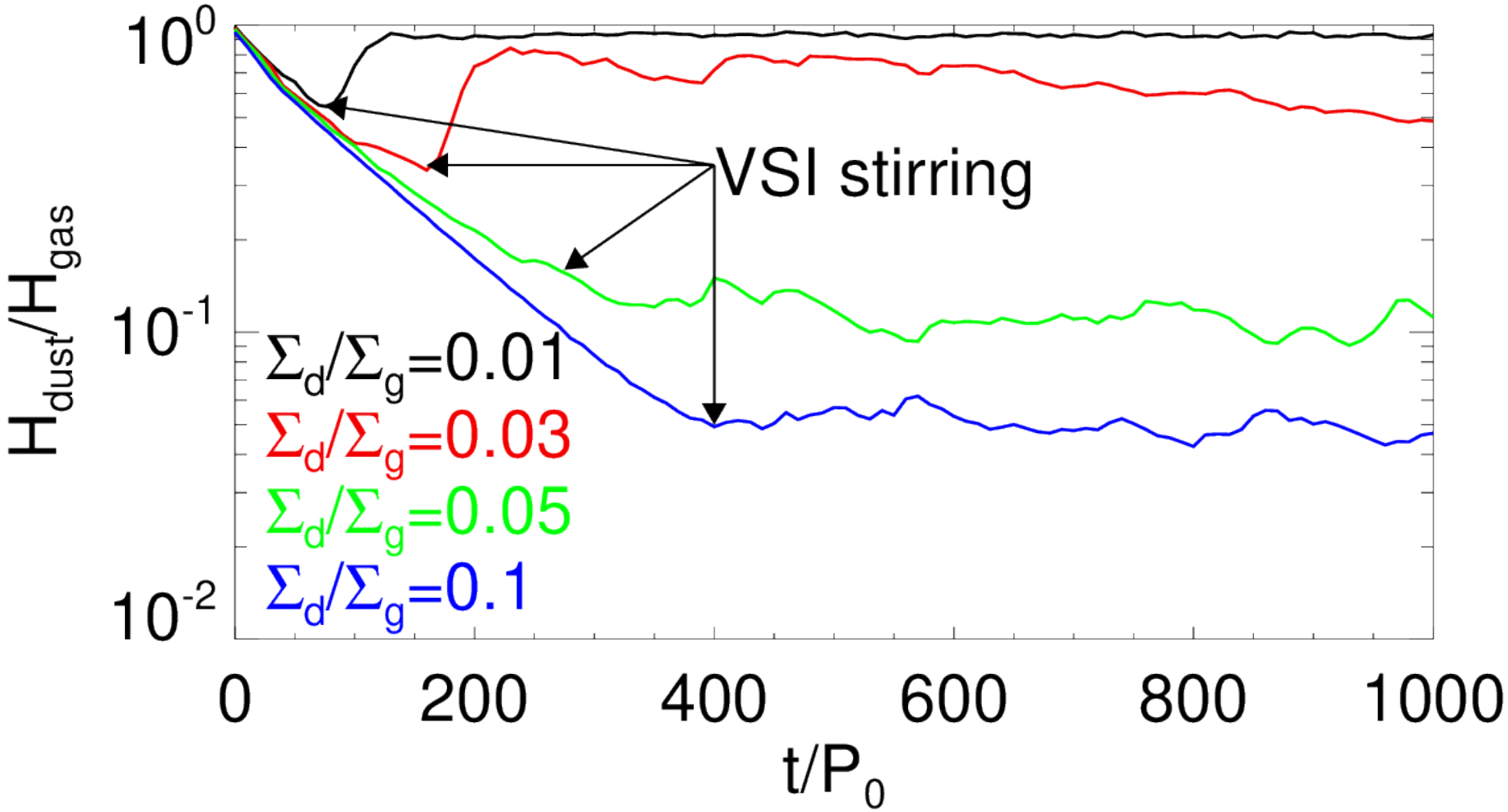
- Dust-on-gas drag neglected
- What about solid abundance?

Effect of metallicity ($\Sigma_{dust}/\Sigma_{gas}$)



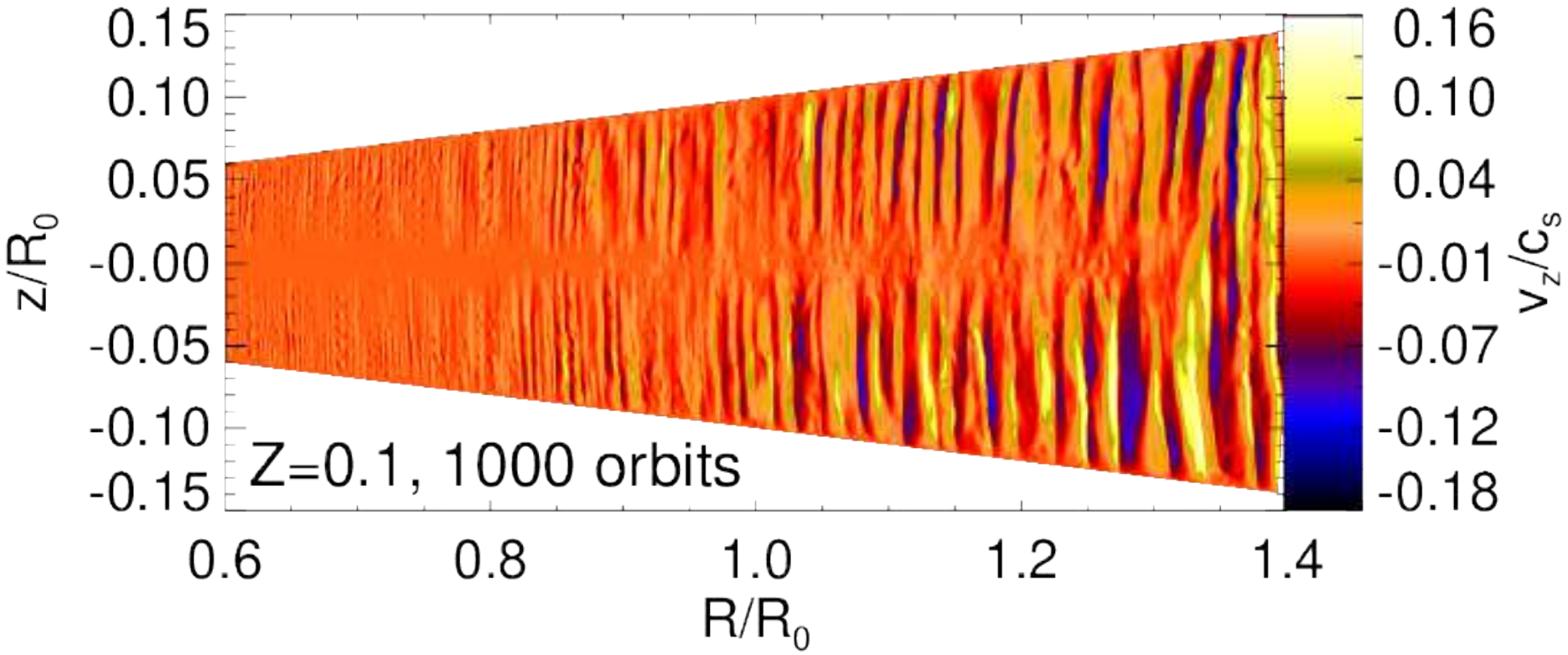
- Dust loading → system becomes 'heavy' → more difficult to stir up

Effect of metallicity ($\Sigma_{dust}/\Sigma_{gas}$)



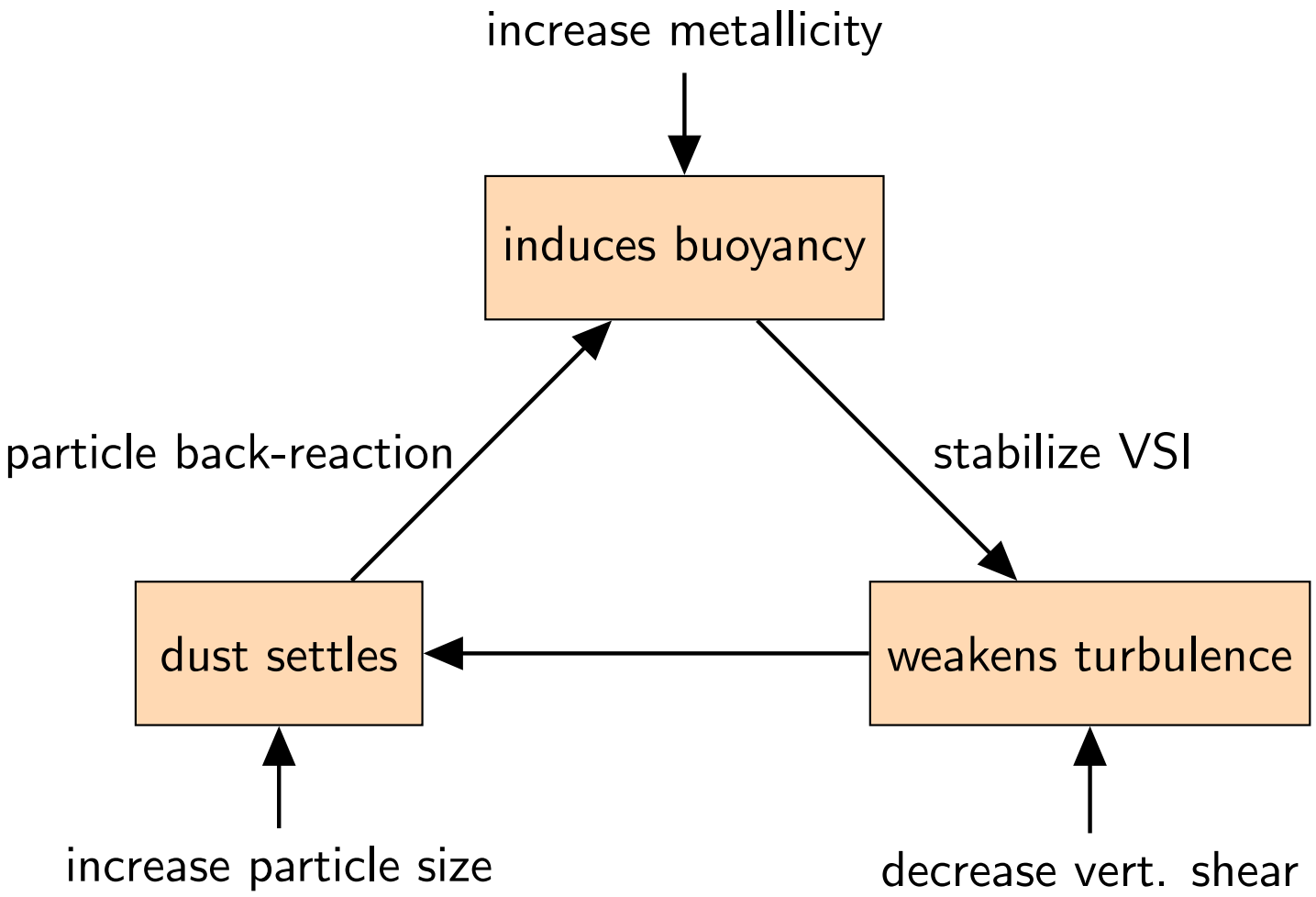
- More dust settles to thinner layers

Effect of metallicity ($\Sigma_{dust}/\Sigma_{gas}$)



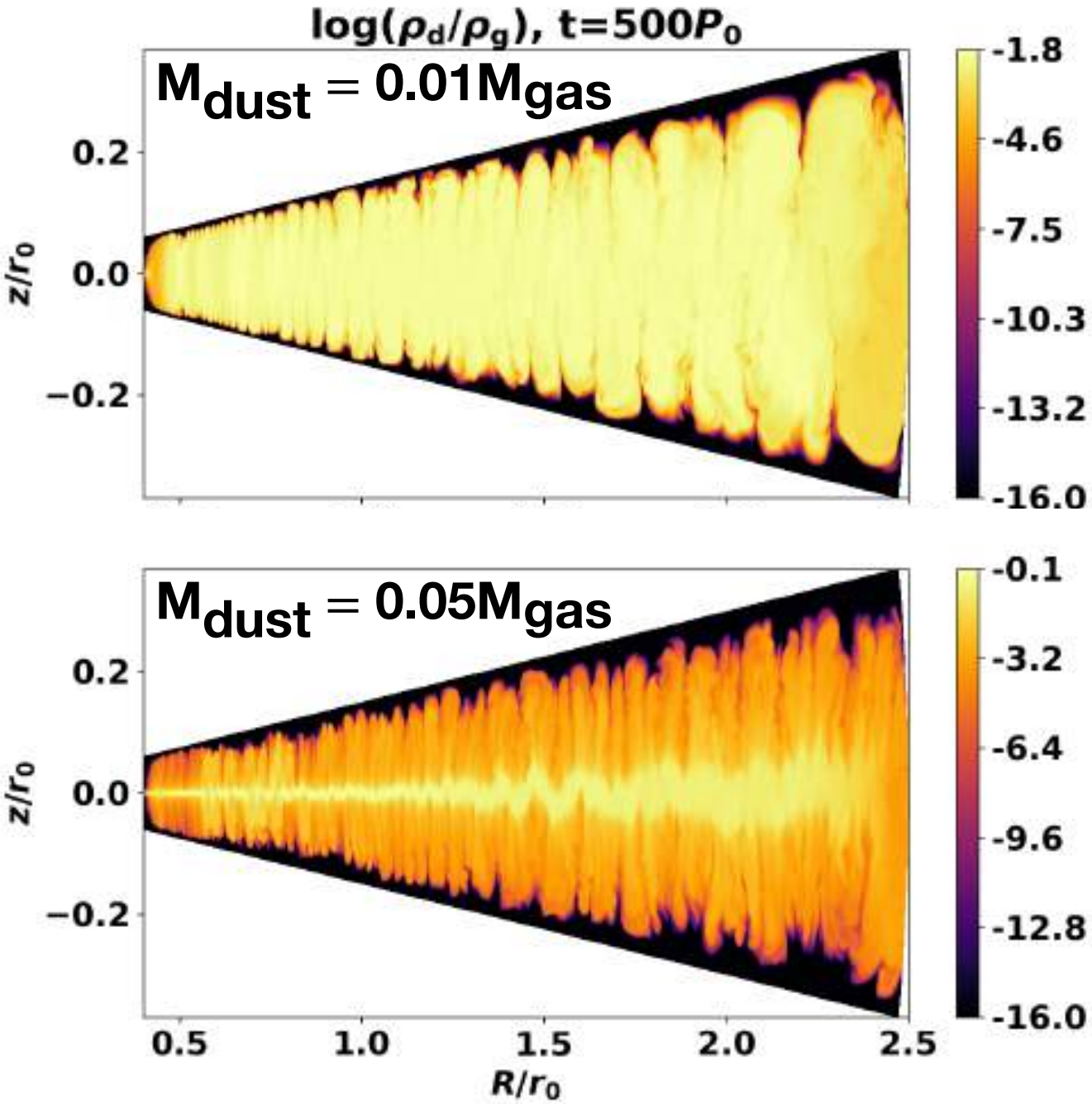
- Self-stabilized dust layer, similar to 'dead zones'

Active dust settling in turbulent disks

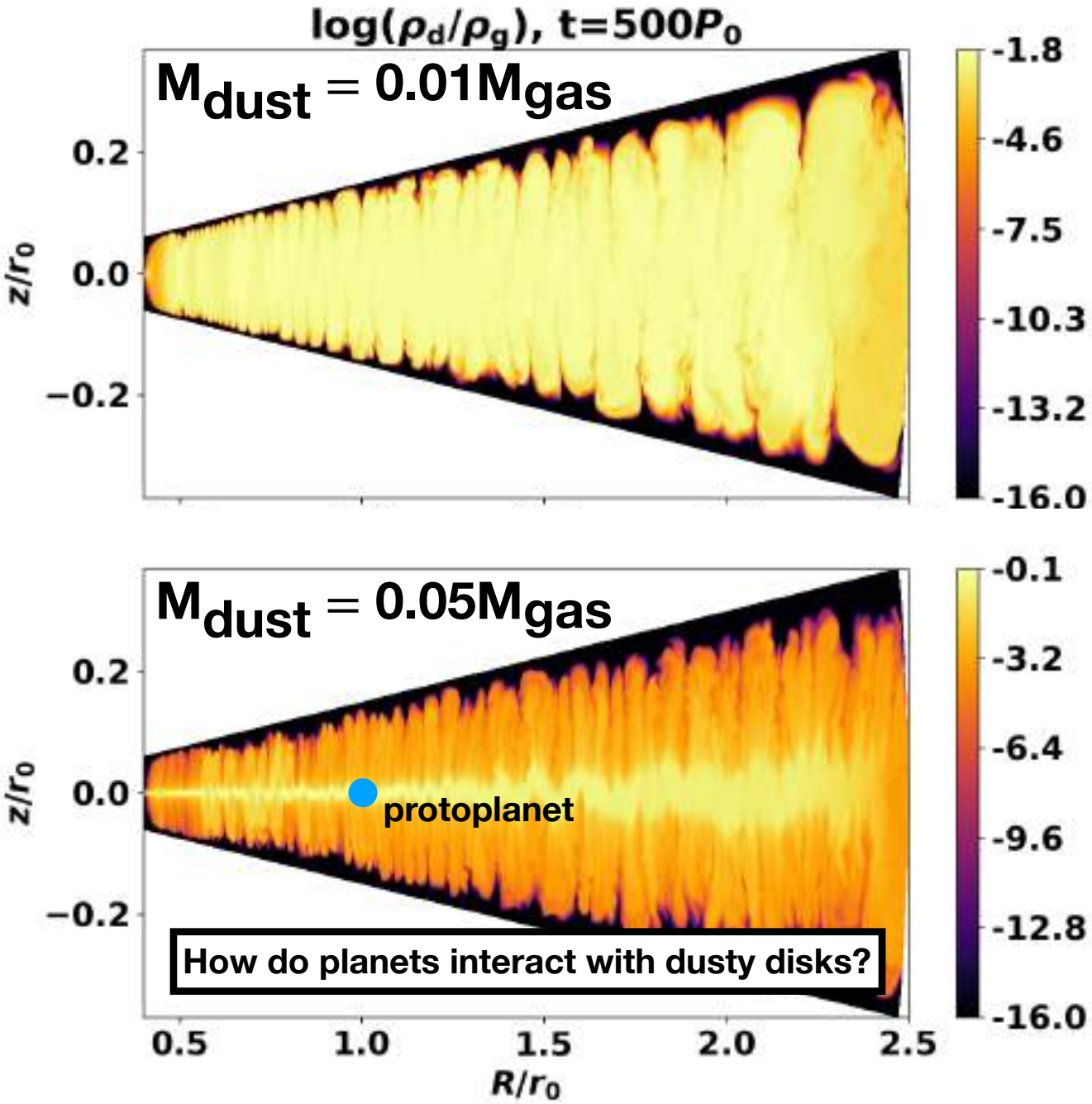


- Settling via dust-loading: $\Sigma_{\rm dust} \gtrsim (H_{\rm gas}/R)\Sigma_{\rm gas}$
- Dust rings should be thinner than dust gaps

Full two-fluid treatment with FARGO3D

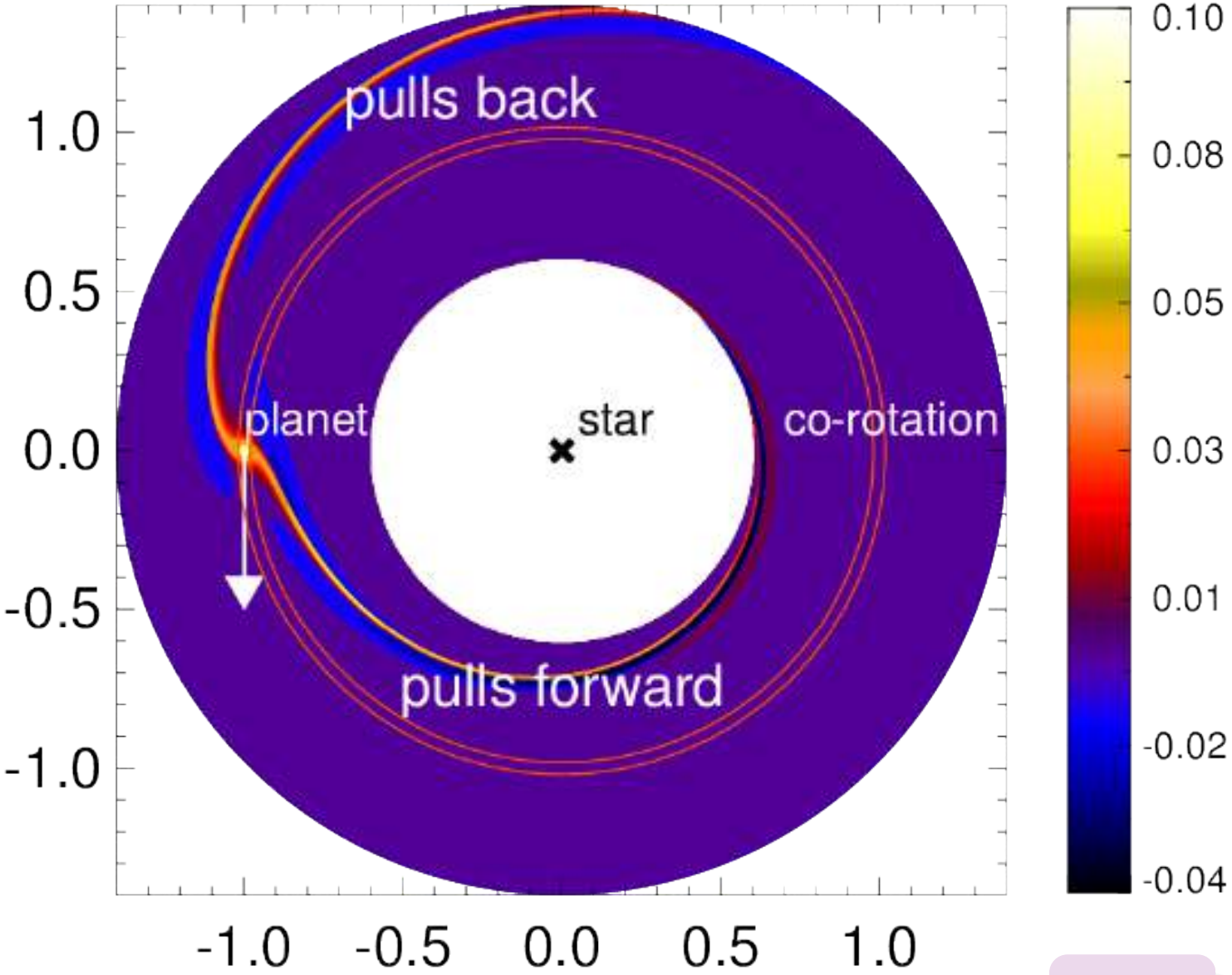


Full two-fluid treatment with FARGO3D



How do planets interact with dusty disks?

Dusty disk-planet interactions



- Disk material exerts a gravitational force on the planet → torques
- What happens in dusty disks?

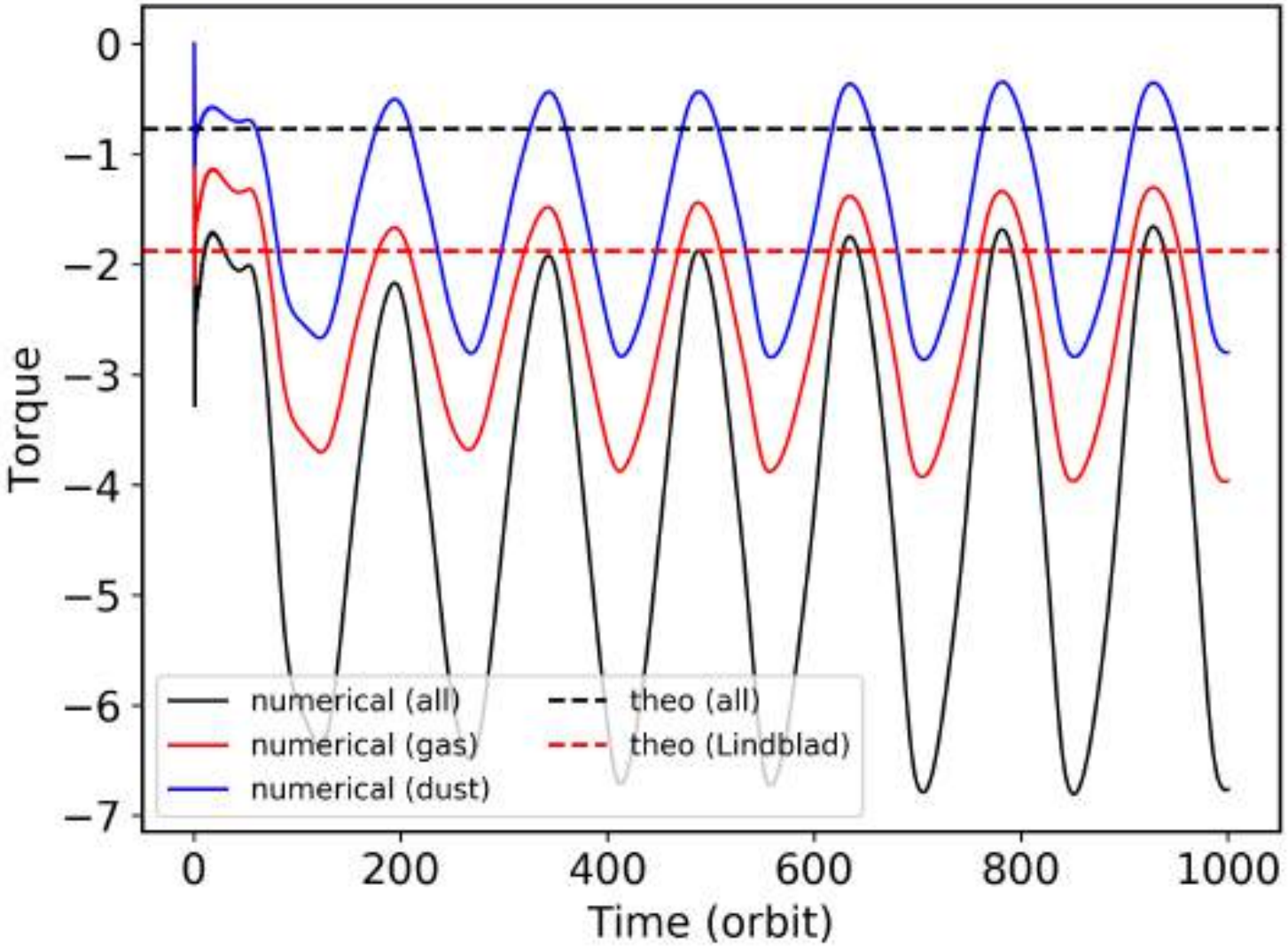
Torque oscillations in dust-rich disks

- $\Sigma_{\text{dust}} = 0.5\Sigma_{\text{gas}}$ (2D disks)
- One-fluid approximation to treat dust using PLUTO code

(J.-W. Chen & Lin, 2018)

- Top: zero particle size (Stokes number $\rightarrow 0$)
- Bottom: finite particle size (Stokes number$\sim 10^{-3}$)

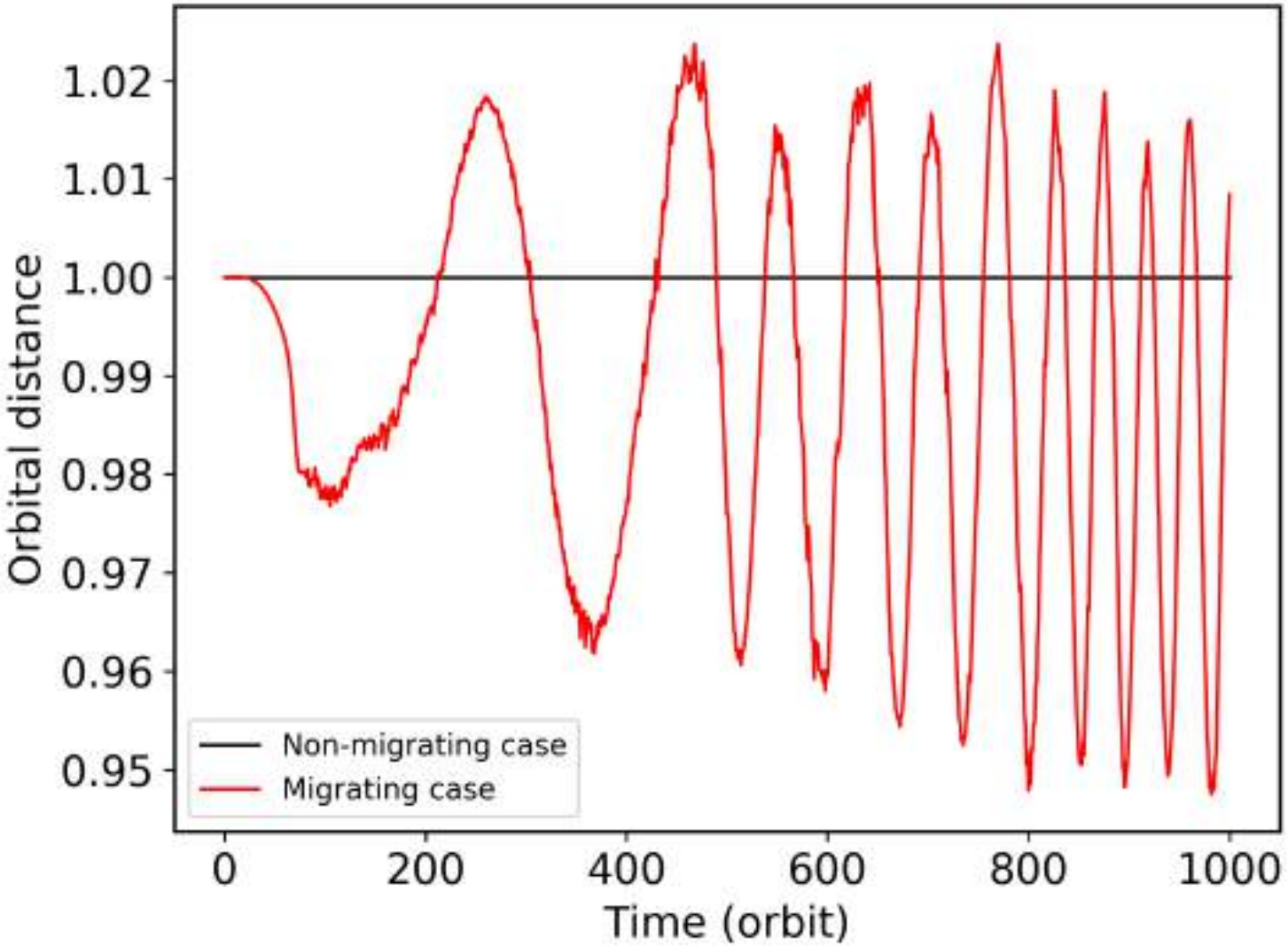
Full two-fluid treament with FARGO3D



Credit: He-Feng Hsieh (NTHU)

- Planet fixed on a circular orbit; just measure torques

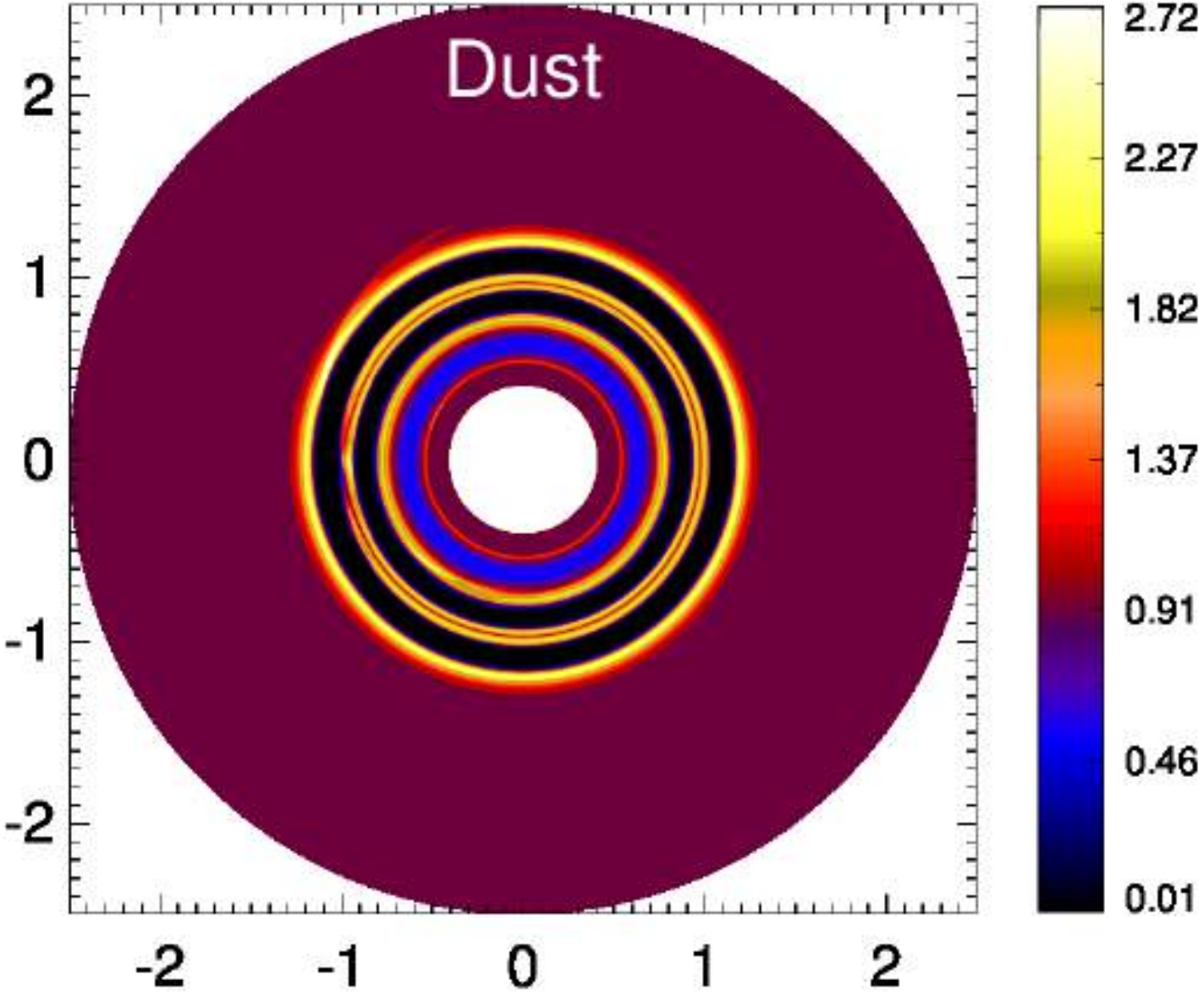
(Non-)migrating planets in dust-rich disks



Credit: He-Feng Hsieh (NTHU)

- Planet allowed to move, using FARGO3D

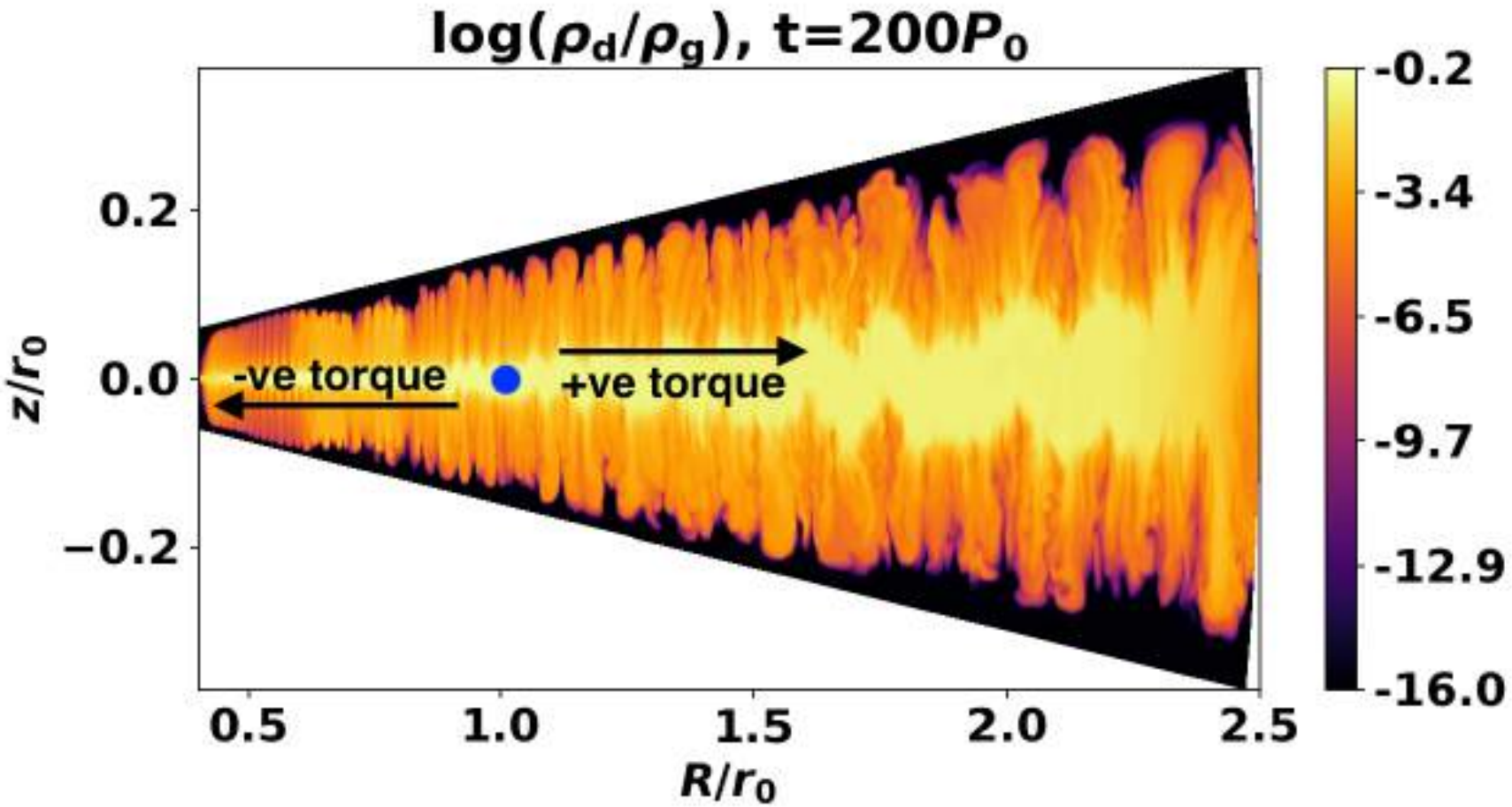
Planet-induced rings



What happens in 3D?

2019 ASIAA Summer Student Program

- Full 3D disk-planet simulations (Jiaqing Bi & Robin Dong, UVic)
- Axisymmetric disk-planet simulations (Simin Tong, Jilin University)



Is dust settling compatible with gap opening?

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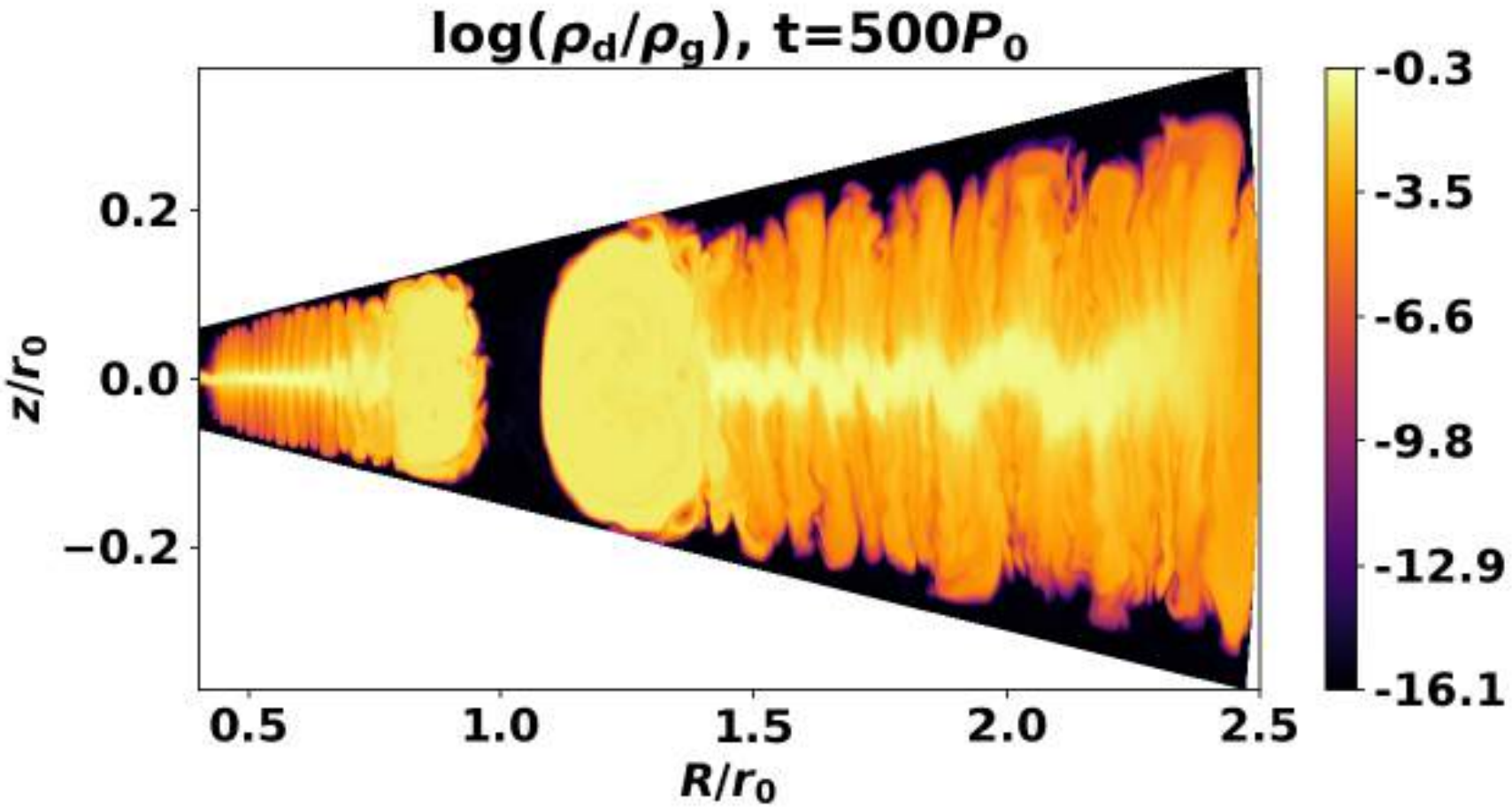


No settling at gap edges??

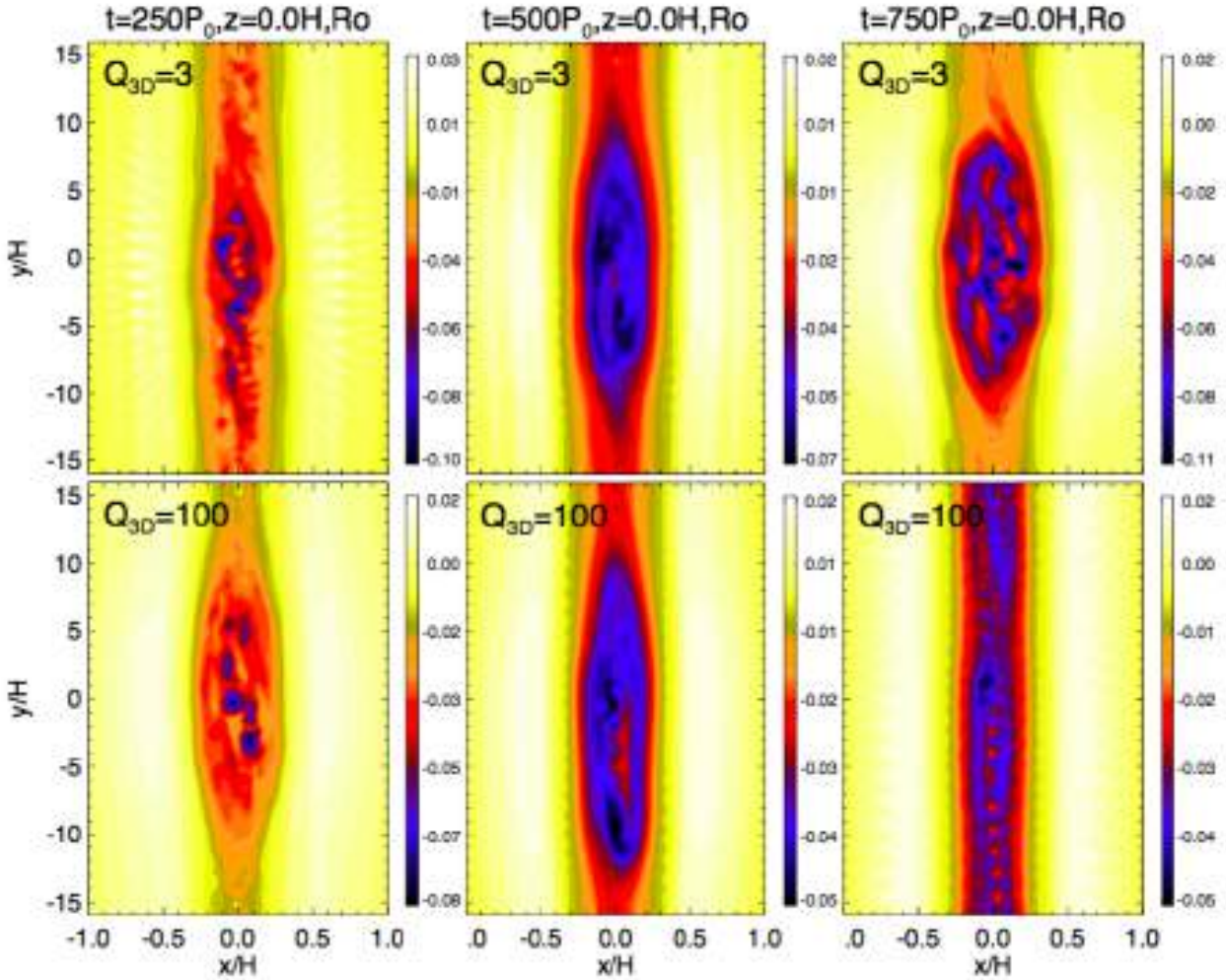
Summary

- Dust is fundamental to planet formation and evolution
- A simple model for dust-gas dynamics (Lin & Youdin, 2017)
- Dust settling depends on solid abundance (Lin, 2019)
- Oscillitory torques affect planet migration in dusty disks (Chen & Lin, 2018)

Other topics

Vortices in protoplanetary disks

- Vortices in 3D self-gravitating disks (Lin & Pierens, 2018)
- Vortices in massive, non-isothermal disks (Pierens & Lin, 2018)
- Observational implications (Hammer, Pinilla, Kratter & Lin, 2019)



Other topics

Ongoing

- 'Streaming instability' in global 2D disks,
  with Sayantan Auddy (ASIAA)
- Streaming instability with particle diffusion and non-linear drag laws,
  with Kan Chen (Nanjing University)
- Stability of stratified, dusty disks,
  with Jack Ng (NTU) and Pin-Gao Gu (ASIAA)
- VSI turbulence and self-gravity,
  with Wei-Ting Liao (UIUC) and Hsi-Yu Schive (NTU)
- Planet-induced dusty vortex instabilities,
  with Arnaud Pierens (Bordeaux)

Opportunities at ASIAA

- Undergraduate research, summer student program
- Graduate research, visiting students
- Postdoctoral research

Ask me!

Thank you

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