Dust settling in turbulent protoplanetary disks

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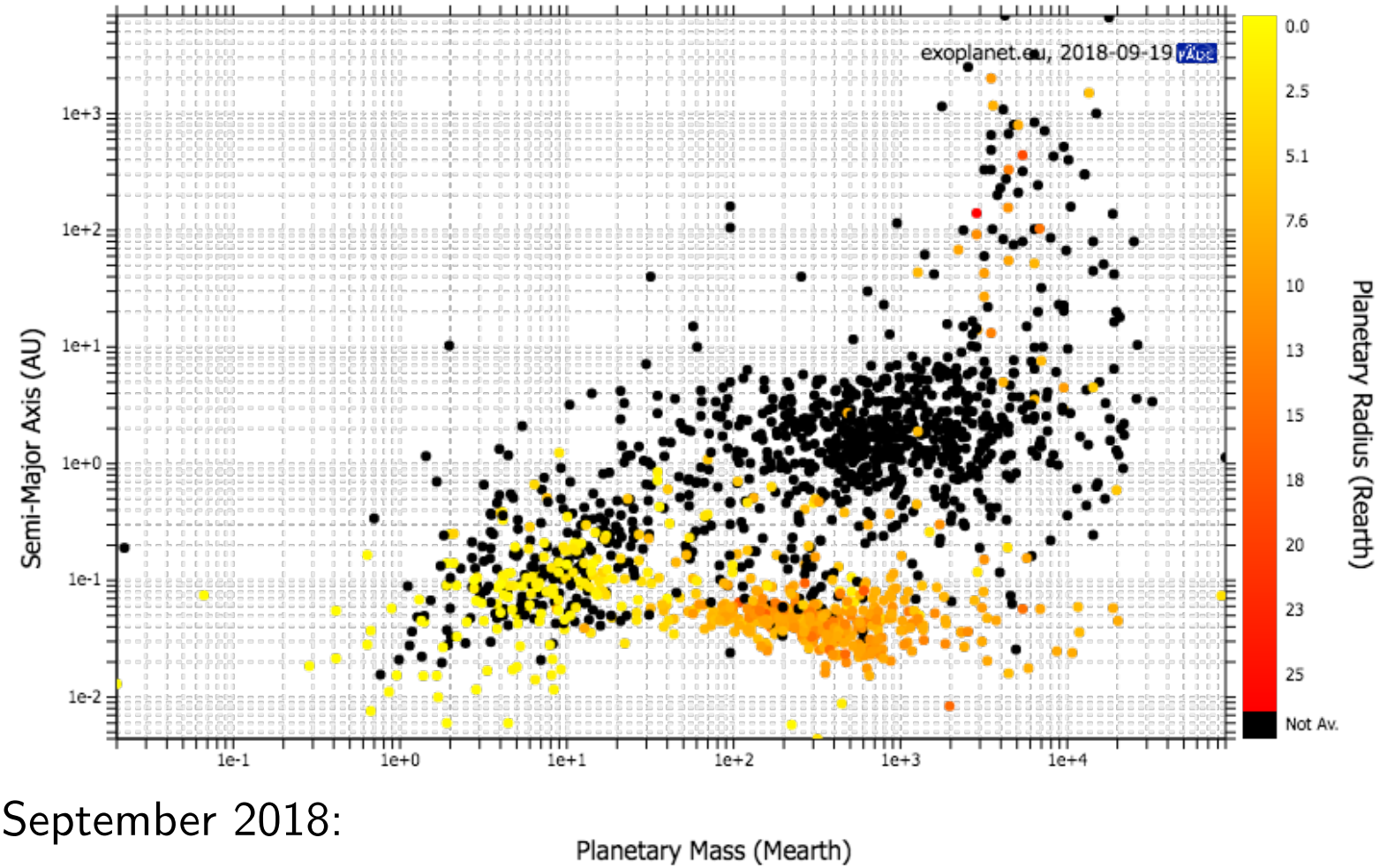
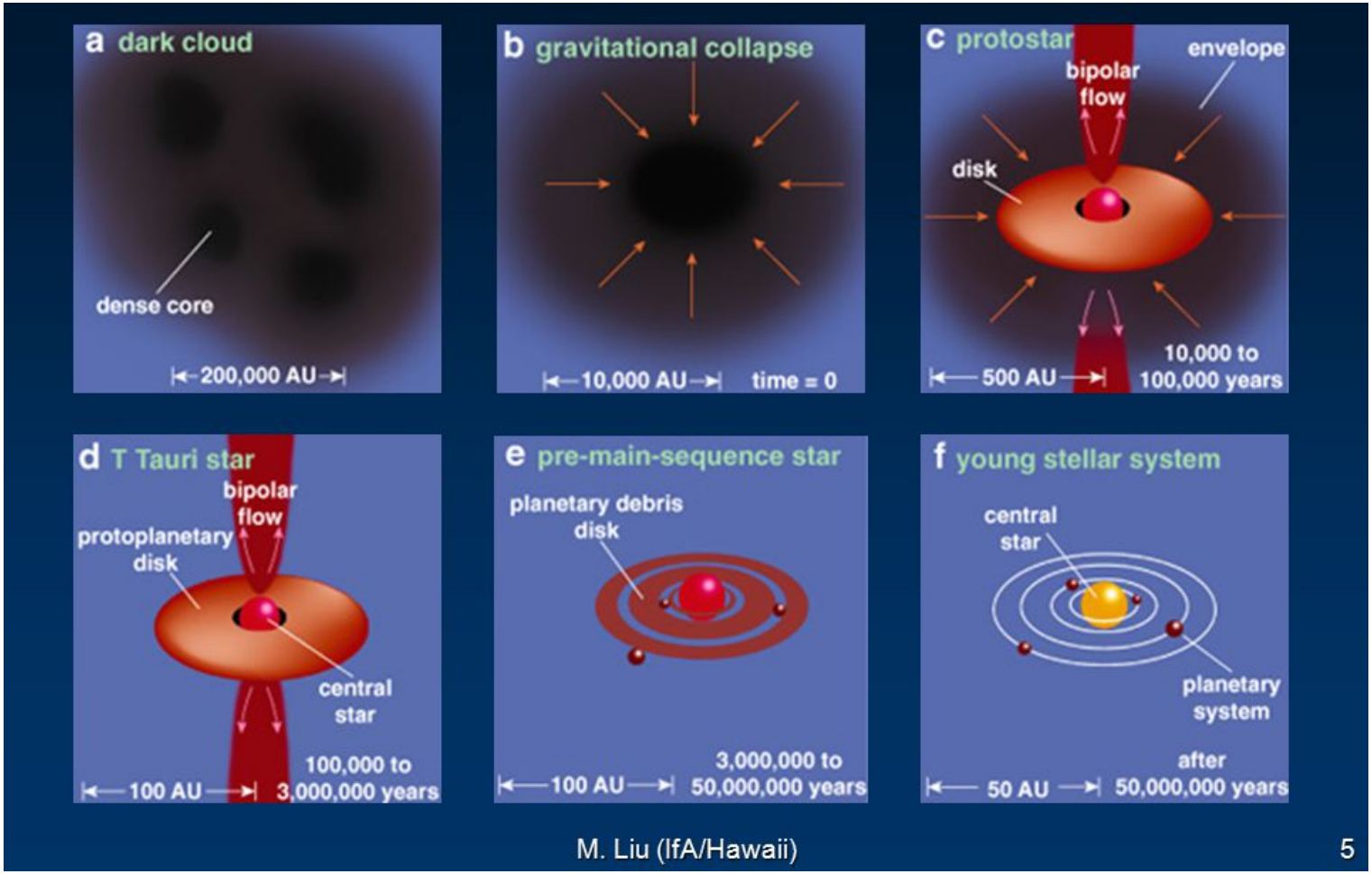
Diversity of planetary systems



As of September 2018:

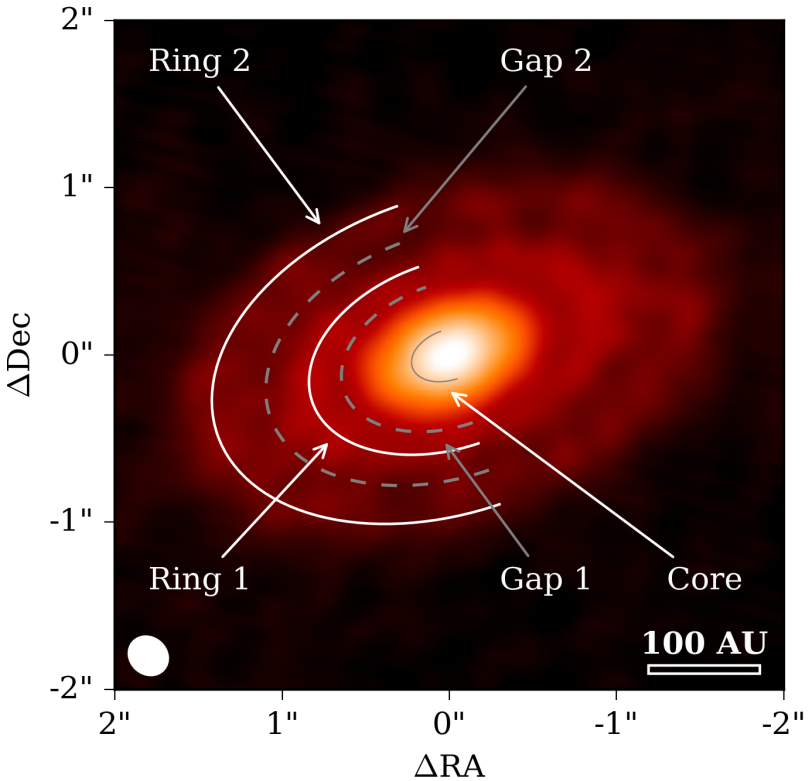
- Over 3700 extra-solar planets detected
- Over 2800 planetary systems
- Wide range of orbital configurations, sizes

Planets form in accretion disks around young stars



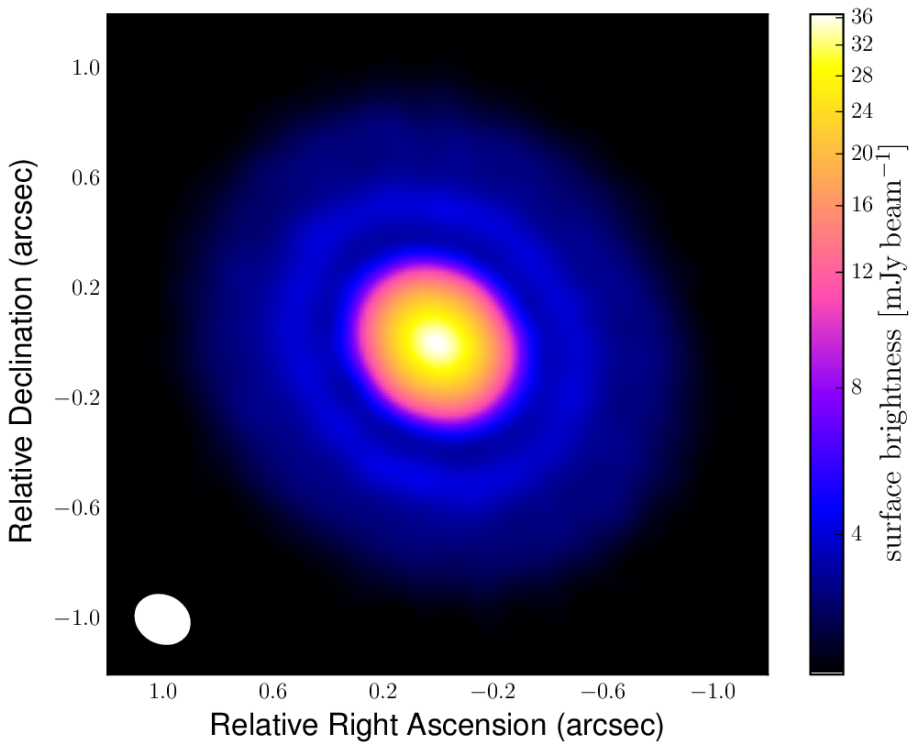
A new era for planet formation

V1094 Sco



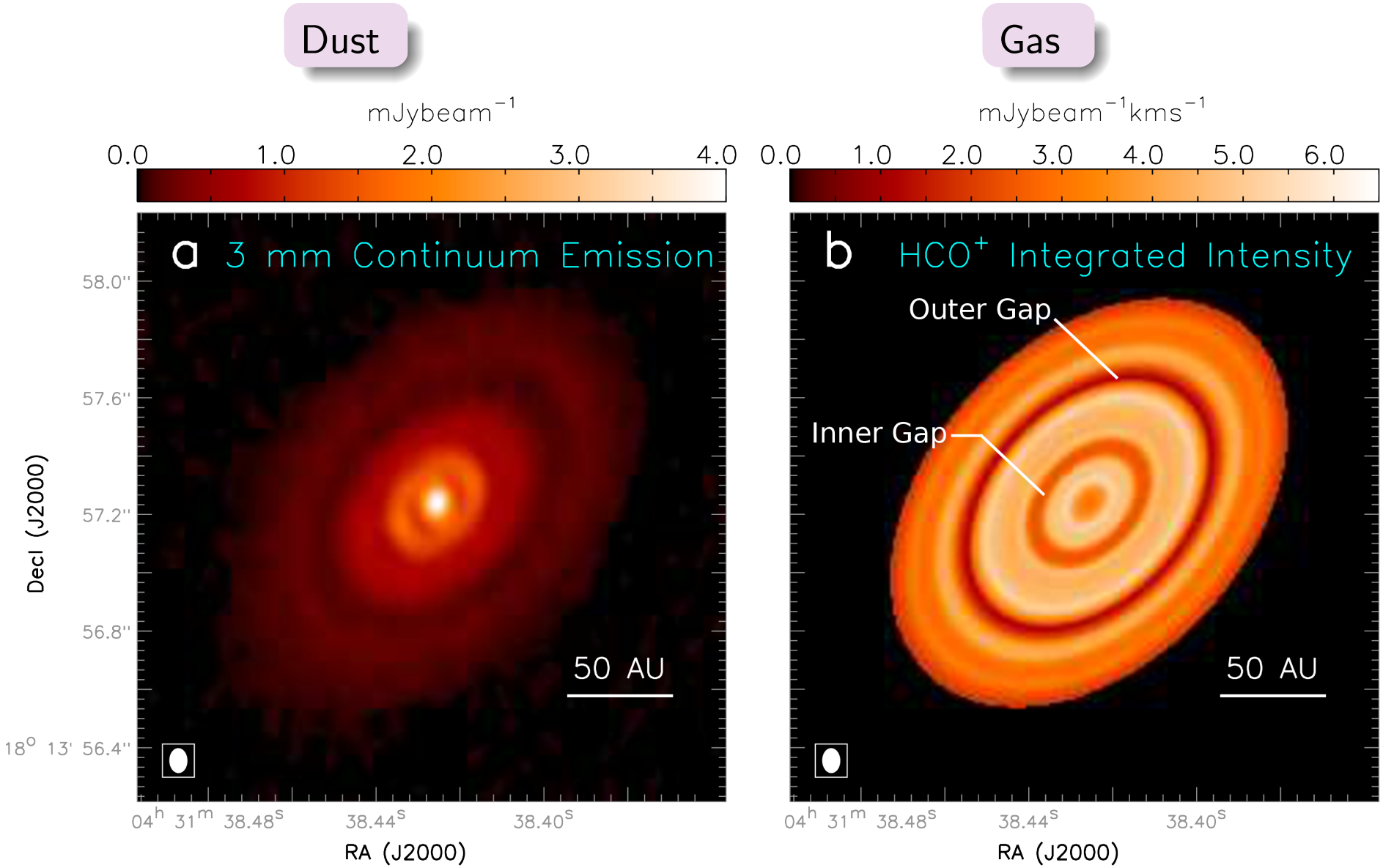
(van Terwisga et al. 2018)

Elias 24



(Dipierro et al. 2018)

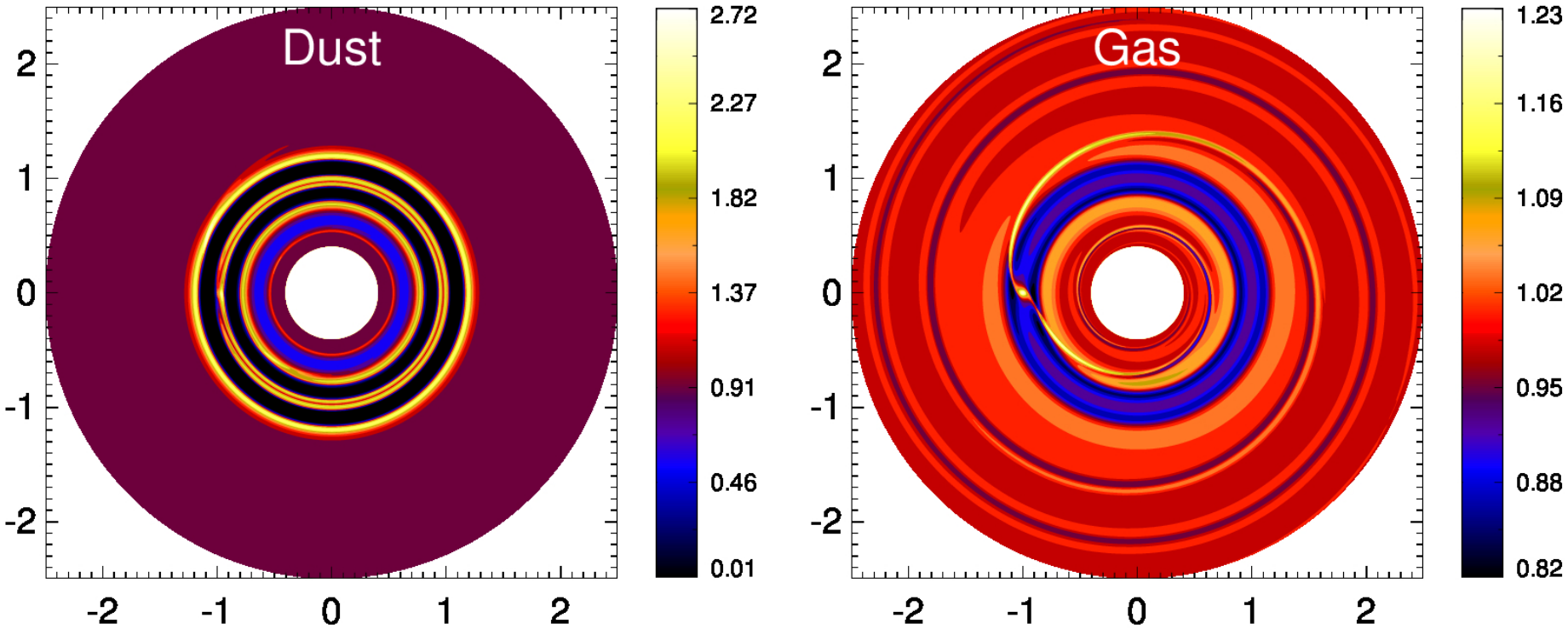
Dusty gas in protoplanetary disks



HL Tau (Yen et al., 2016)

Dusty gas in protoplanetary disks

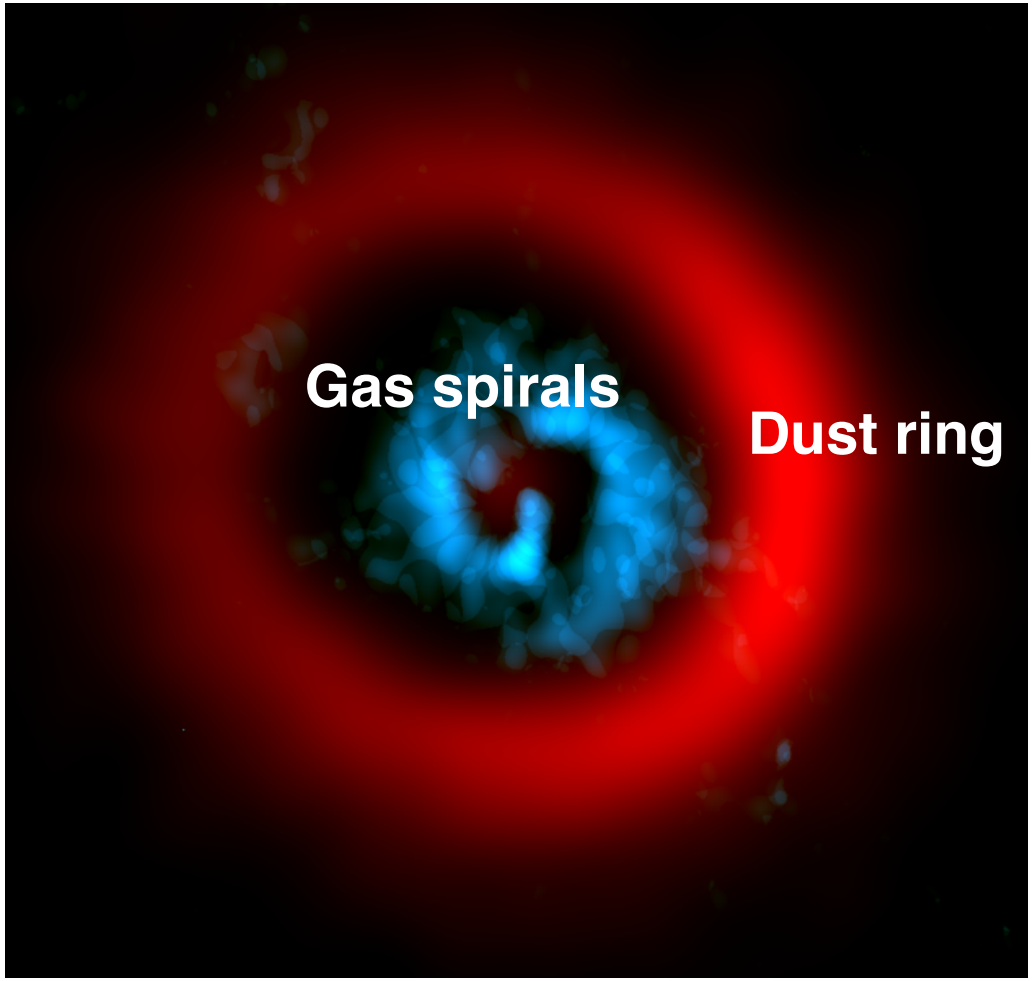
Disk-planet interaction?



(Chen & Lin, 2018)

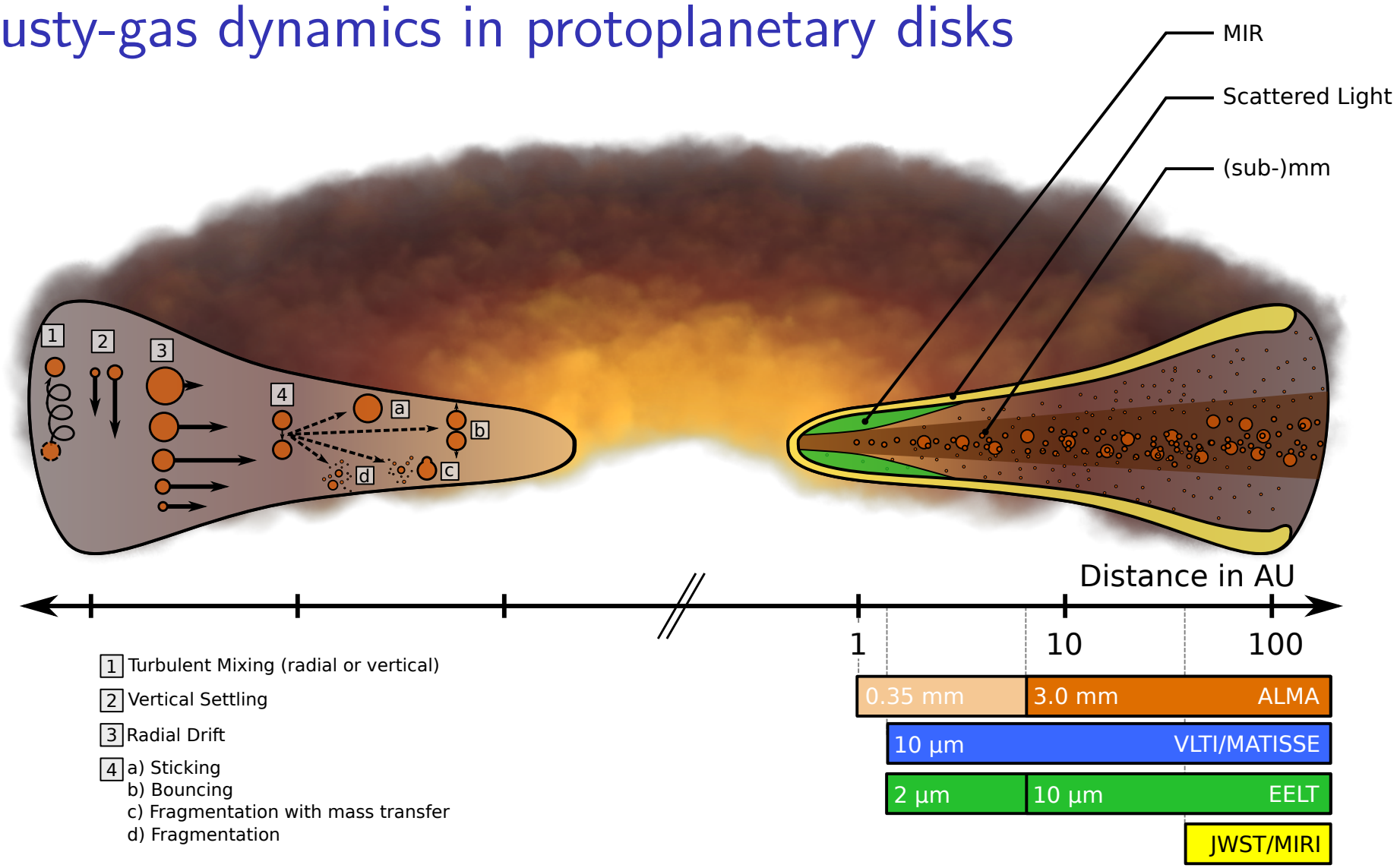
Dusty gas in protoplanetary disks

Gas and dust don't always correleate



AB Aurigae, (Tang et al. 2017)

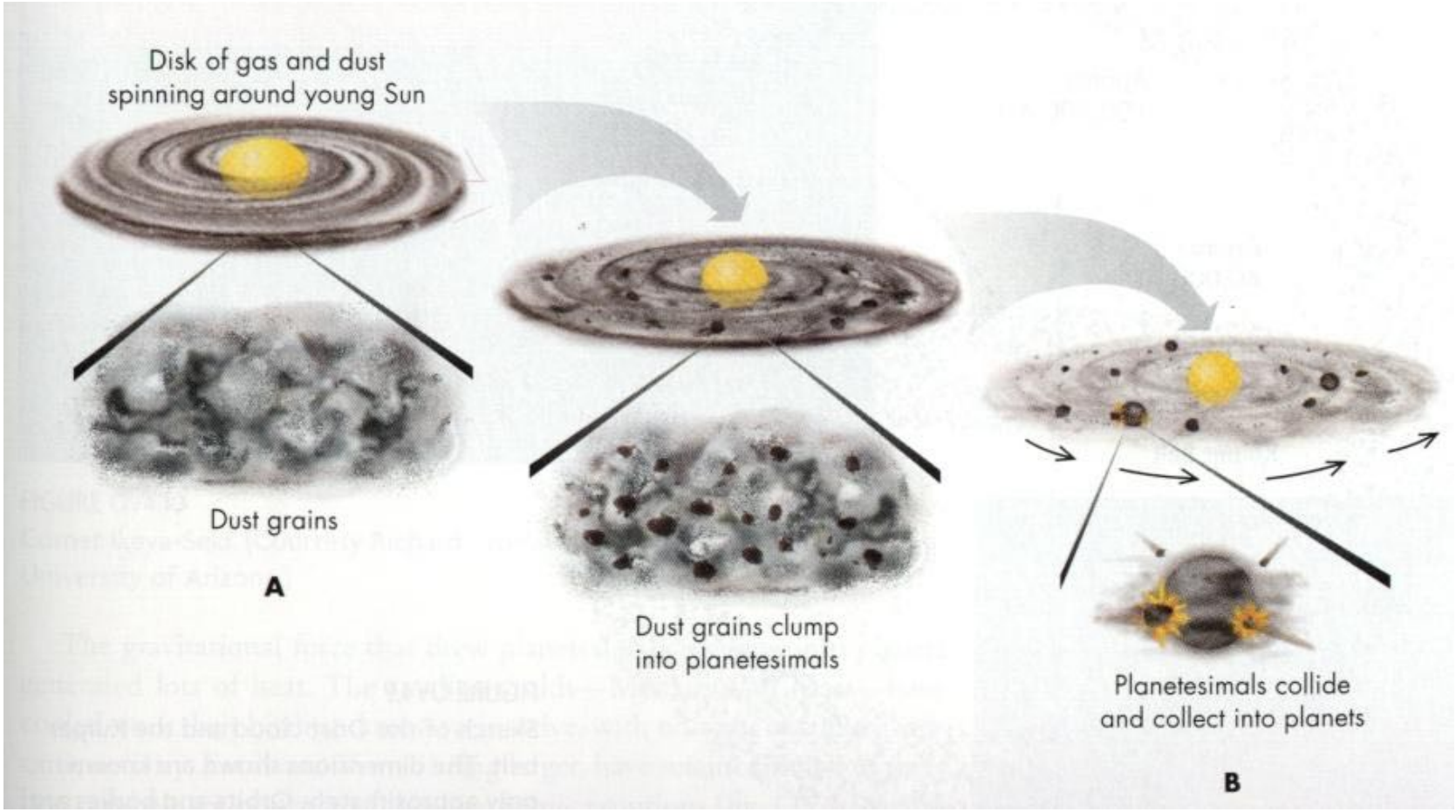
Dusty-gas dynamics in protoplanetary disks



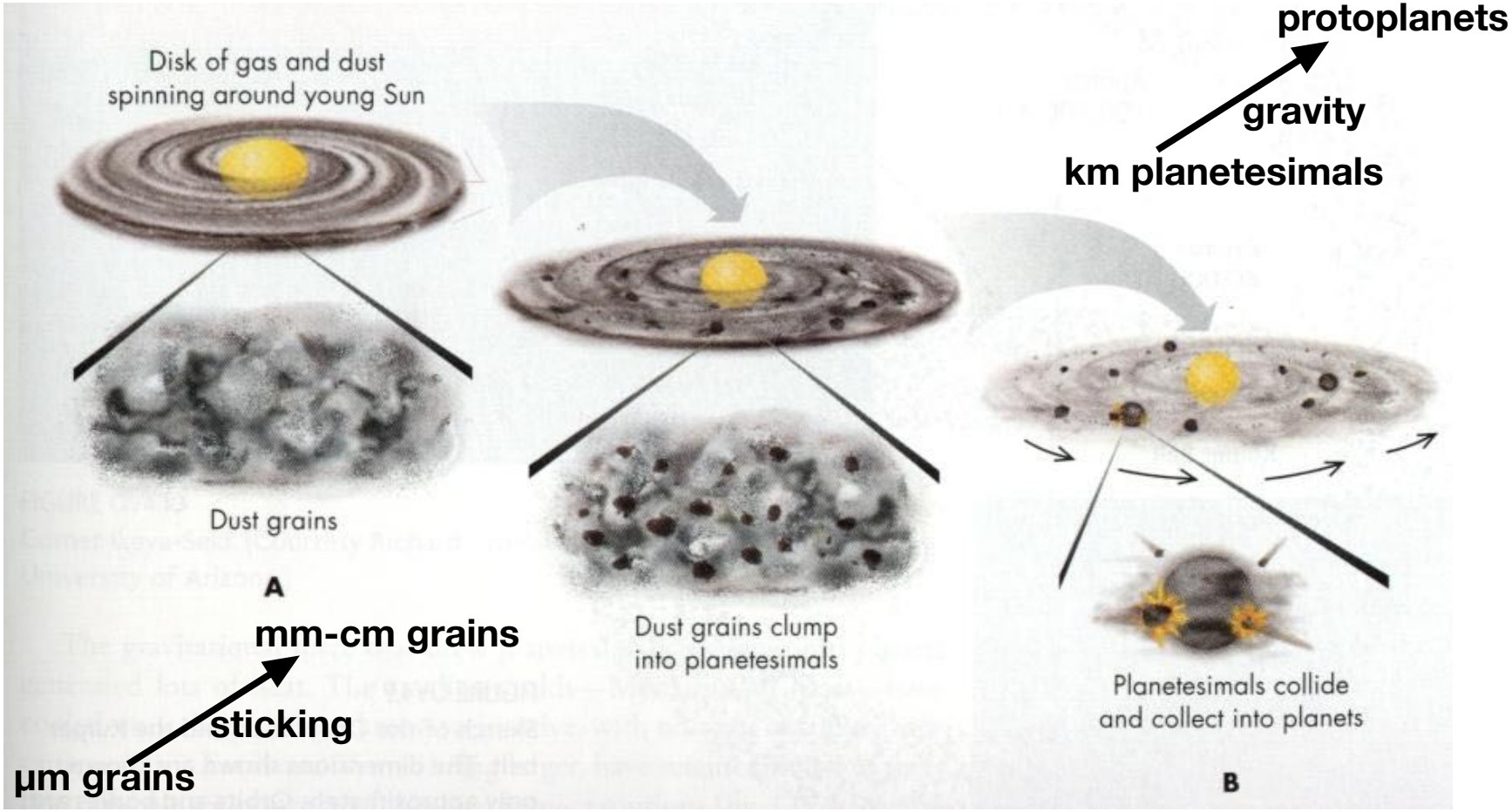
(Testi et al., 2014)

- Protoplanetary discs are $\sim 99\%$ gas, $\sim 1\%$ dust
- Planets form from the solids (at least in core accretion)

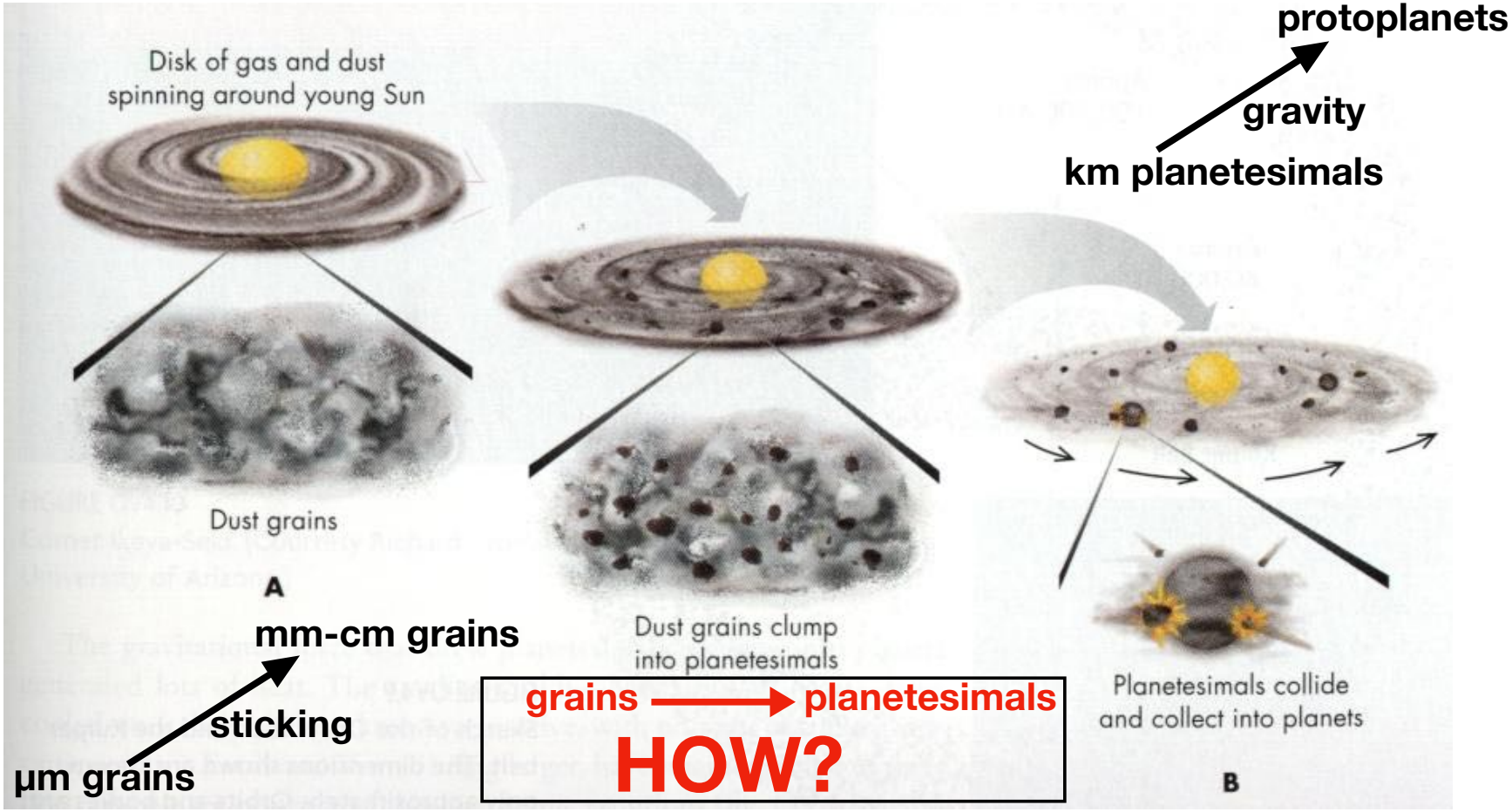
From dust to planets



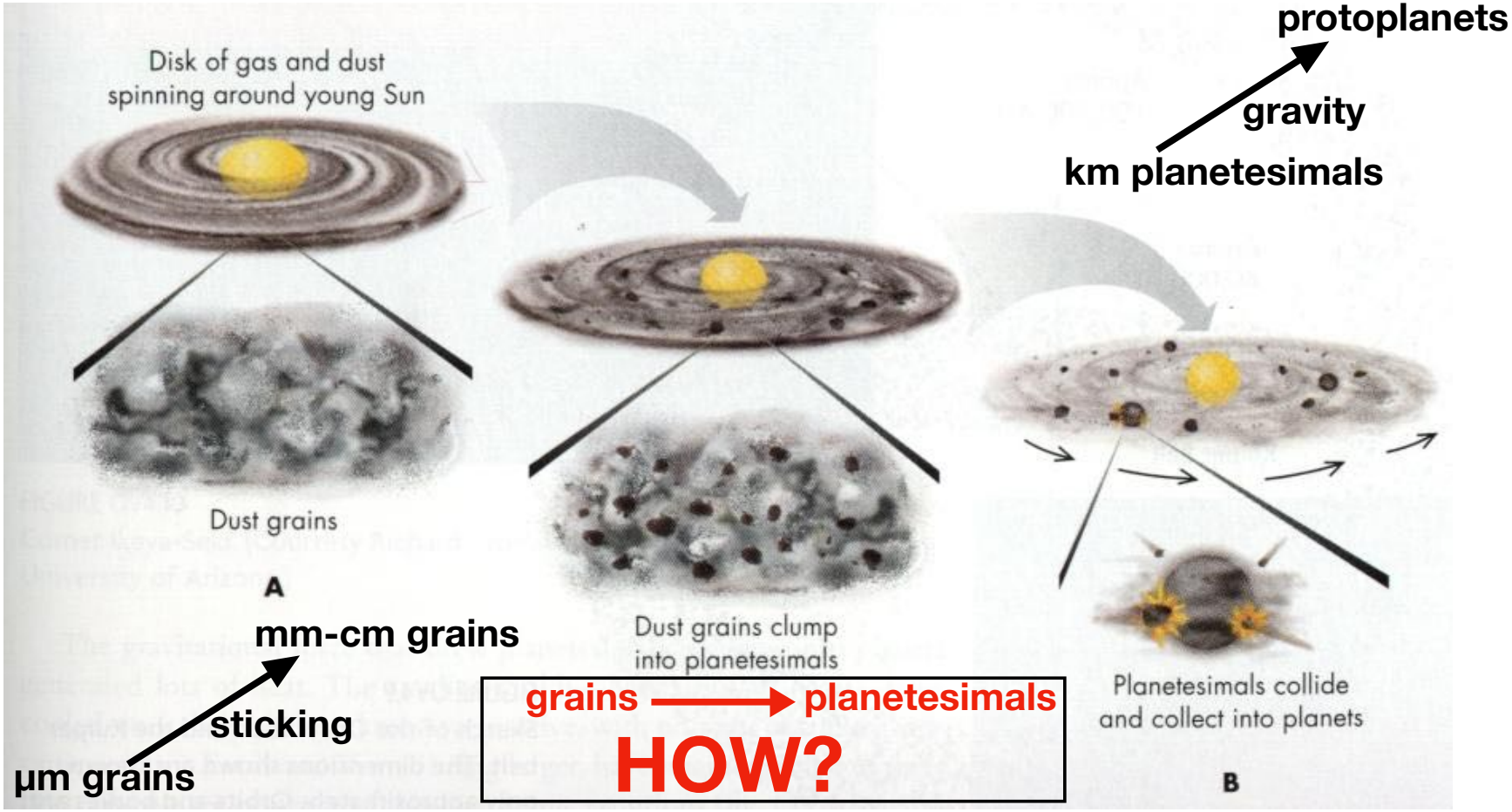
From dust to planets



From dust to planets

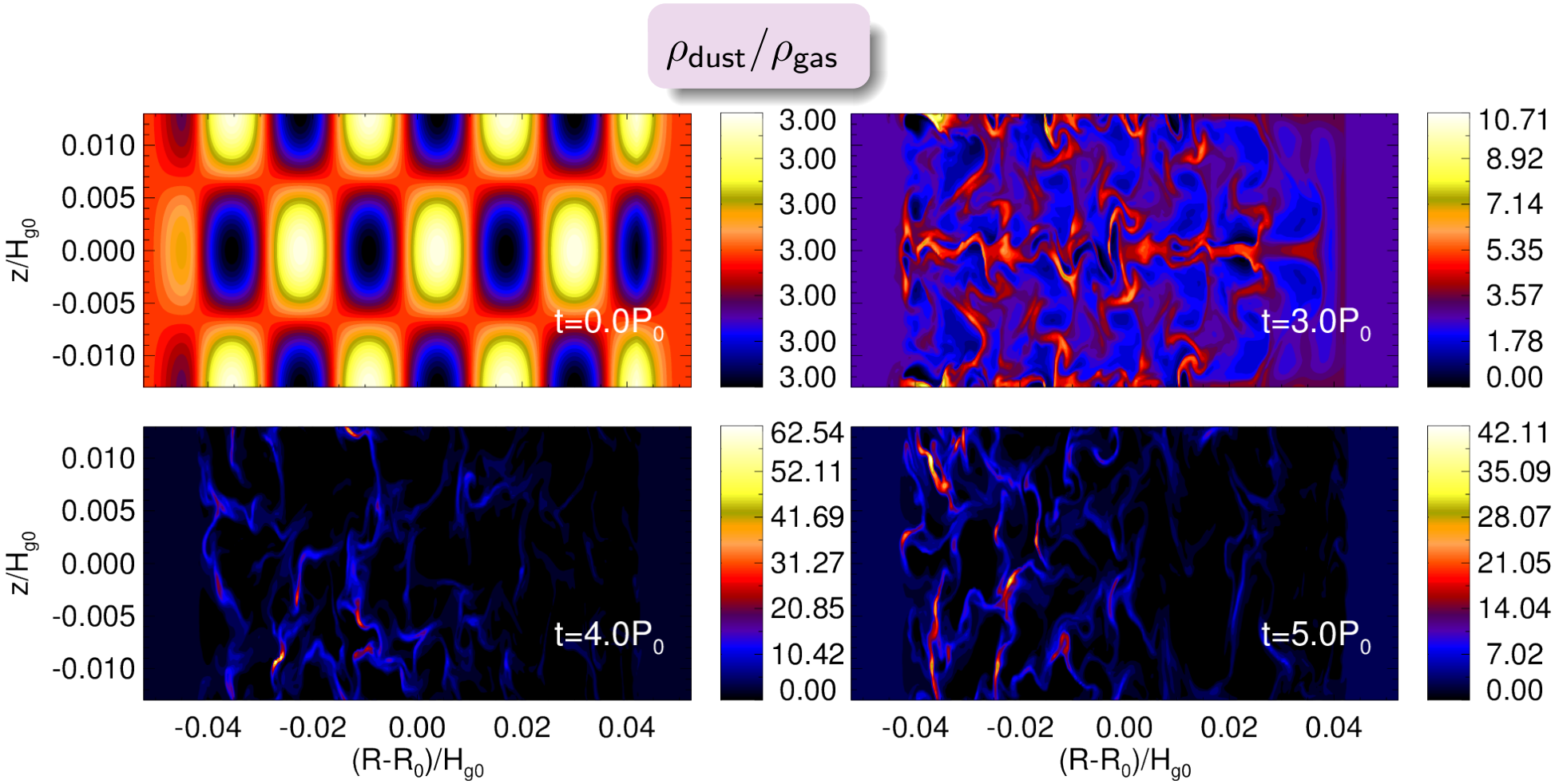


From dust to planets



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

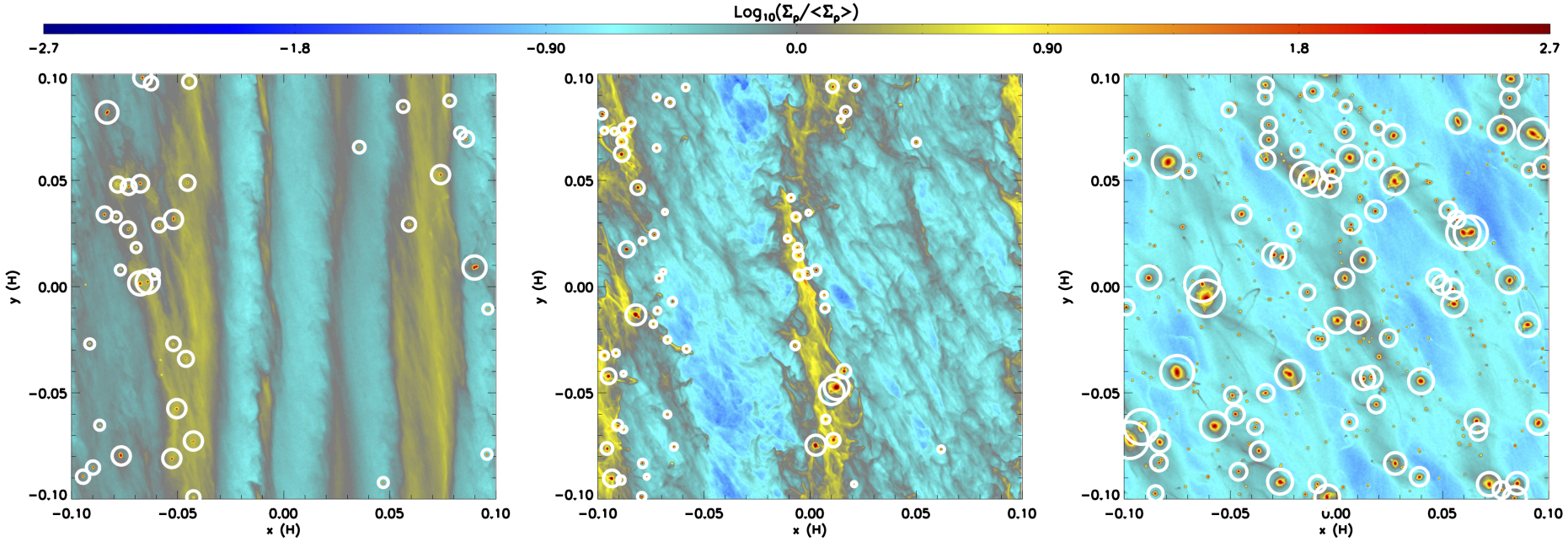
Planetesimal formation by the streaming instability



(Chen & Lin, 2018)

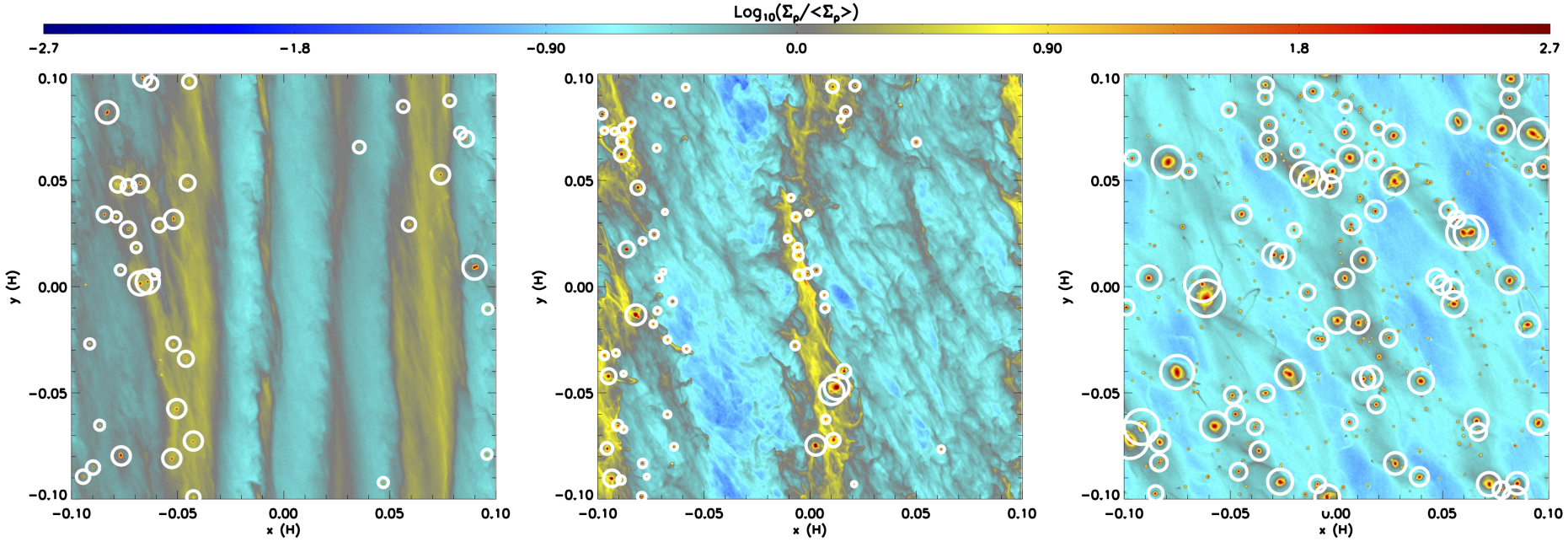
- Two-phase instability driven by dust-gas friction
- Subtle physics → see Lin & Youdin (2017) for a recent interpretation

Planetesimal formation by the streaming instability



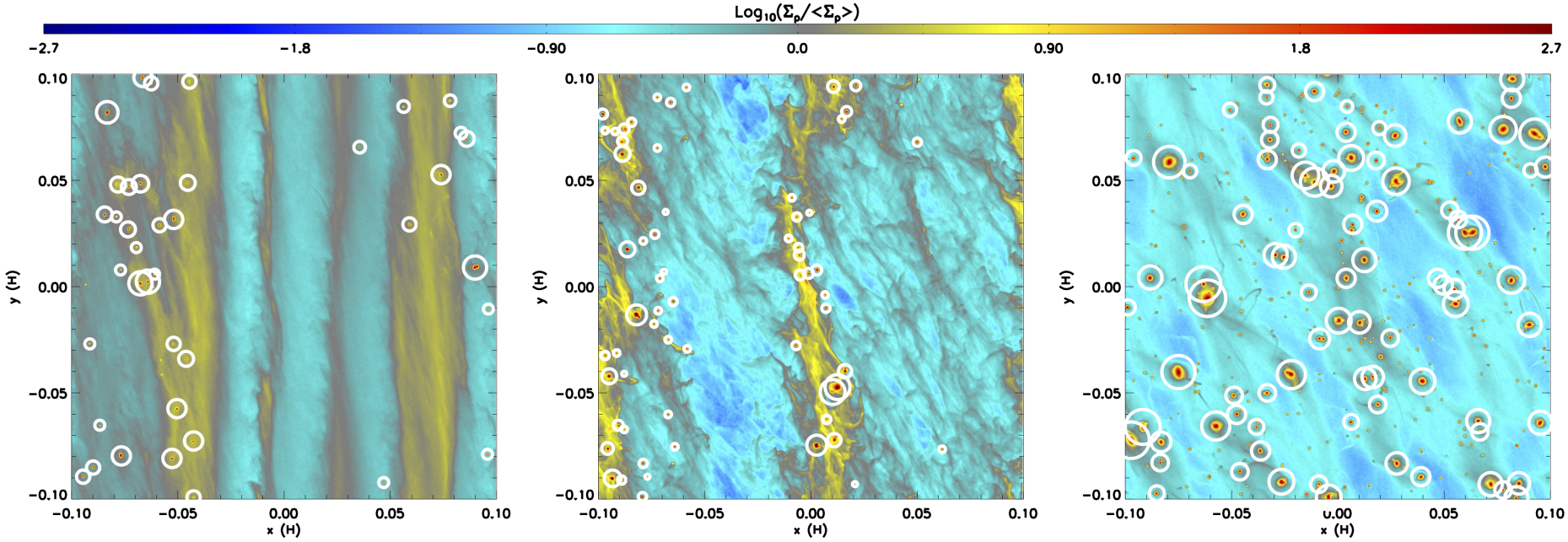
(SI with self-gravity, Simon et al., 2017)

Planetesimal formation by the streaming instability



- Strong clumping by SI requires $\rho_{\text{dust}} \sim \rho_{\text{gas}}$ to begin with

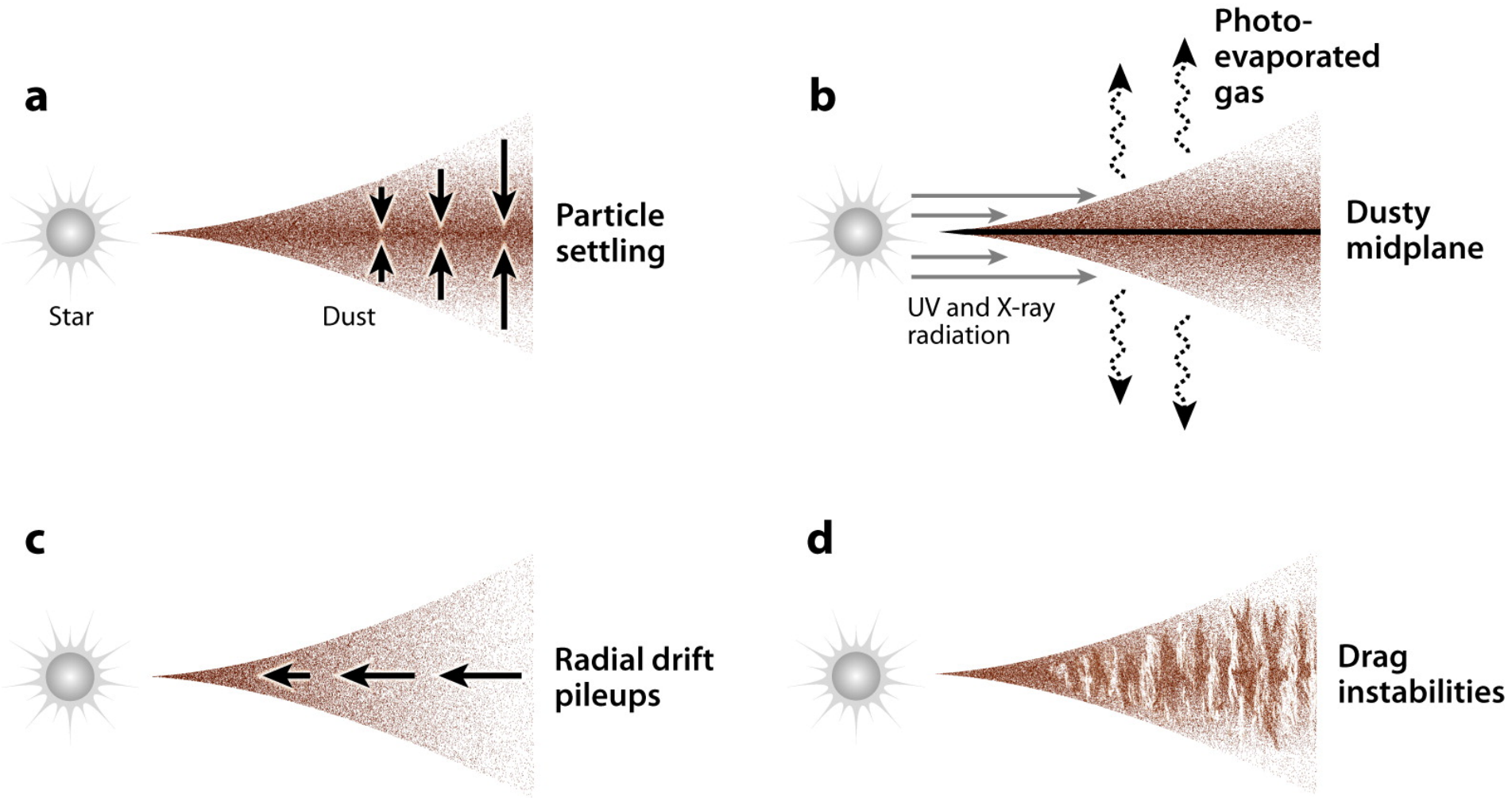
Planetesimal formation by the streaming instability



- Strong clumping by SI requires $\rho_{\text{dust}} \sim \rho_{\text{gas}}$ to begin with

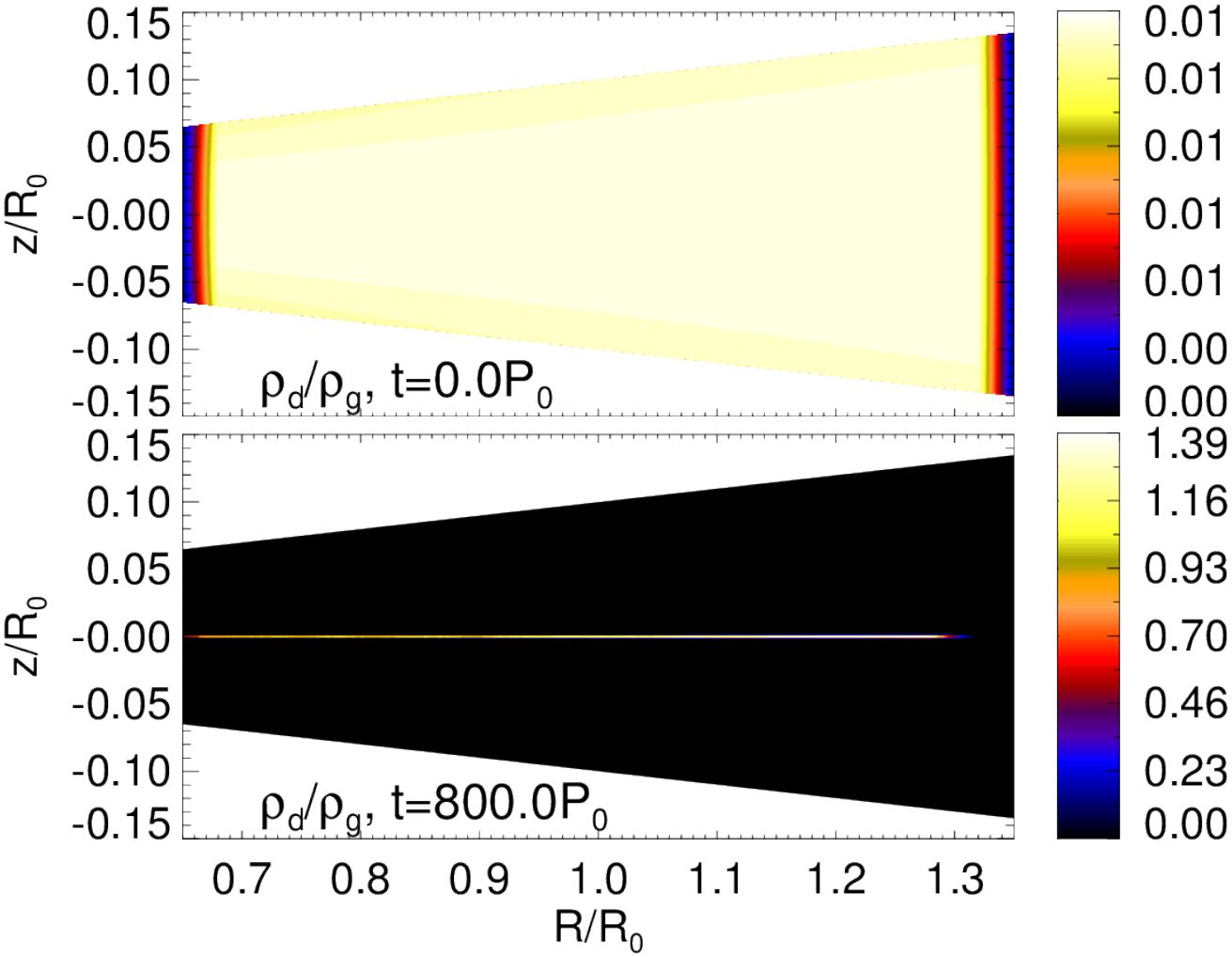
$\frac{\rho_{\text{d}}}{\rho_{\text{g}}} \sim 0.01$ in ISM $\xrightarrow{\text{HOW?}}$ $\frac{\rho_{\text{d}}}{\rho_{\text{g}}} \sim 1$ for SI

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 disc is laminar

Instabilities in protoplanetary disks

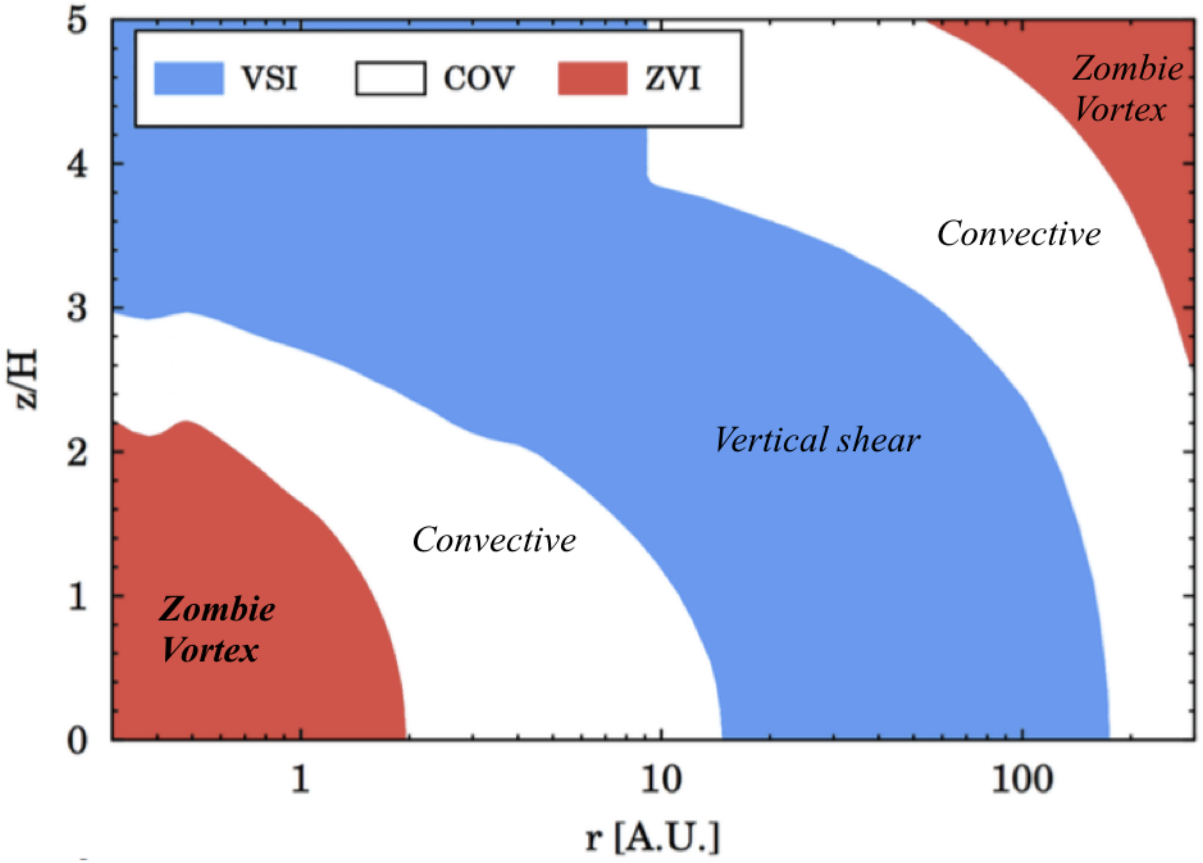
Classic sources of turbulence

- Magneto-rotational instability (Balbus & Hawley 1991)
  - Needs enough ionization
- Gravitational instability (Gammie, 2001)
  - Needs a massive disk

Instabilities in protoplanetary disks

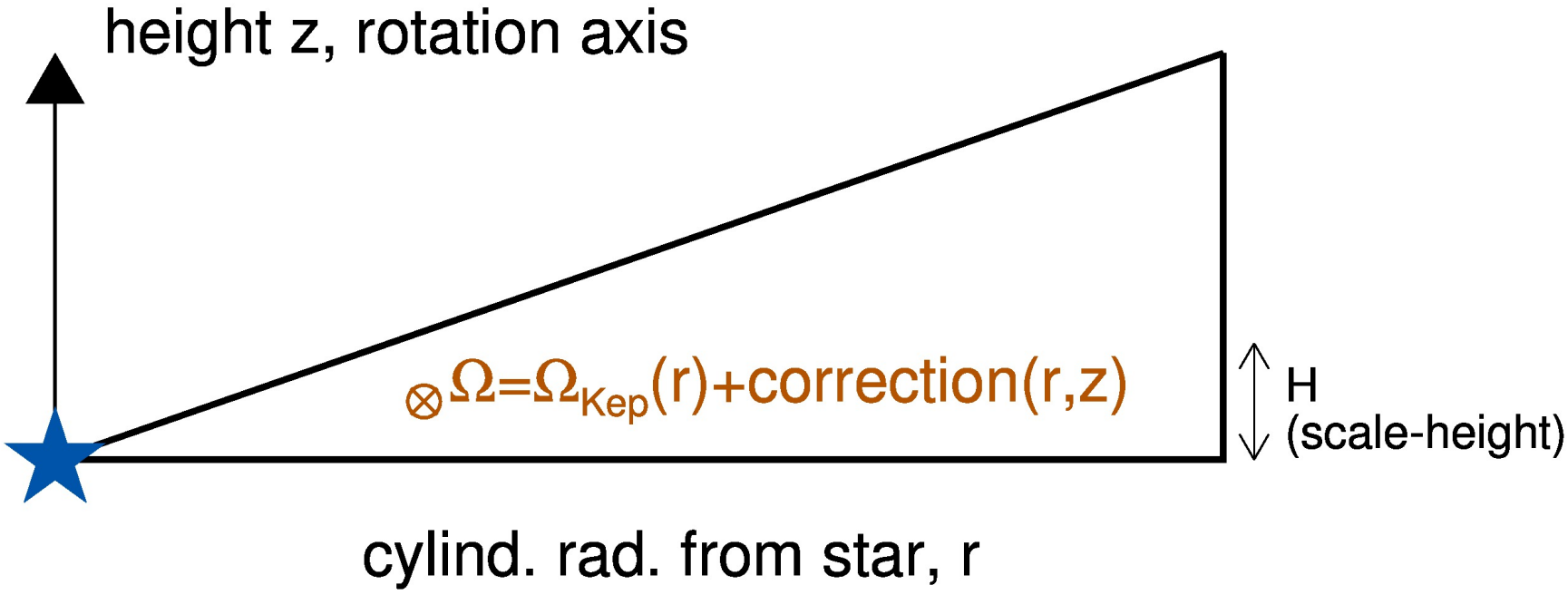
Newly (re)discovered sources of turbulence

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



(Malygin et al., 2017;Lyra & Umurhan, 2018)

Vertical shear instability

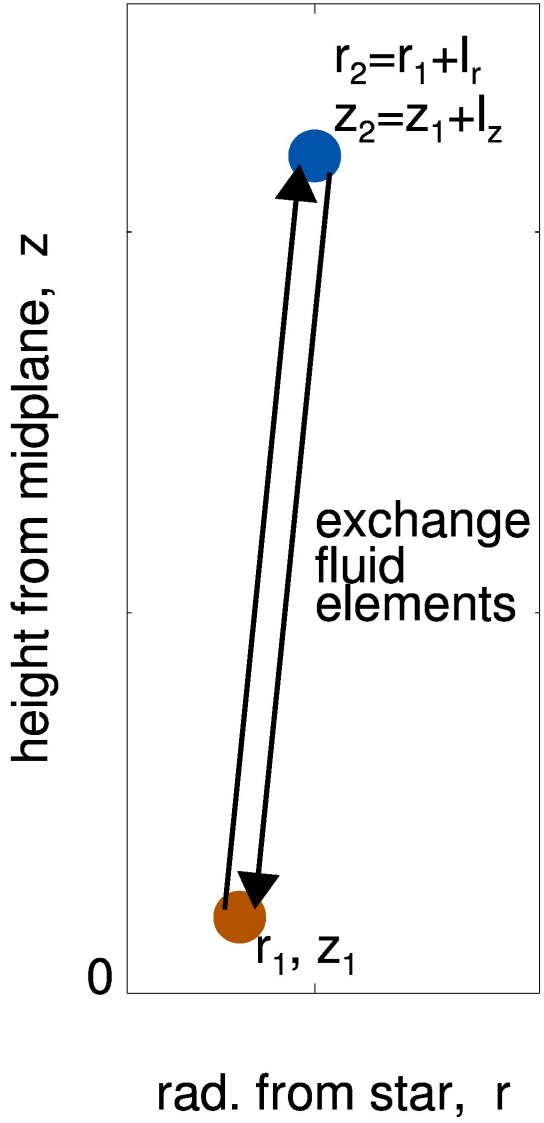


$$\frac{\partial \Omega}{\partial z} \neq 0$$

(Because $\nabla P \times \nabla \rho \neq 0$)

Vertical shear instability

$\partial_z \Omega \neq 0 \Rightarrow$free energy$\rightarrow$instability?



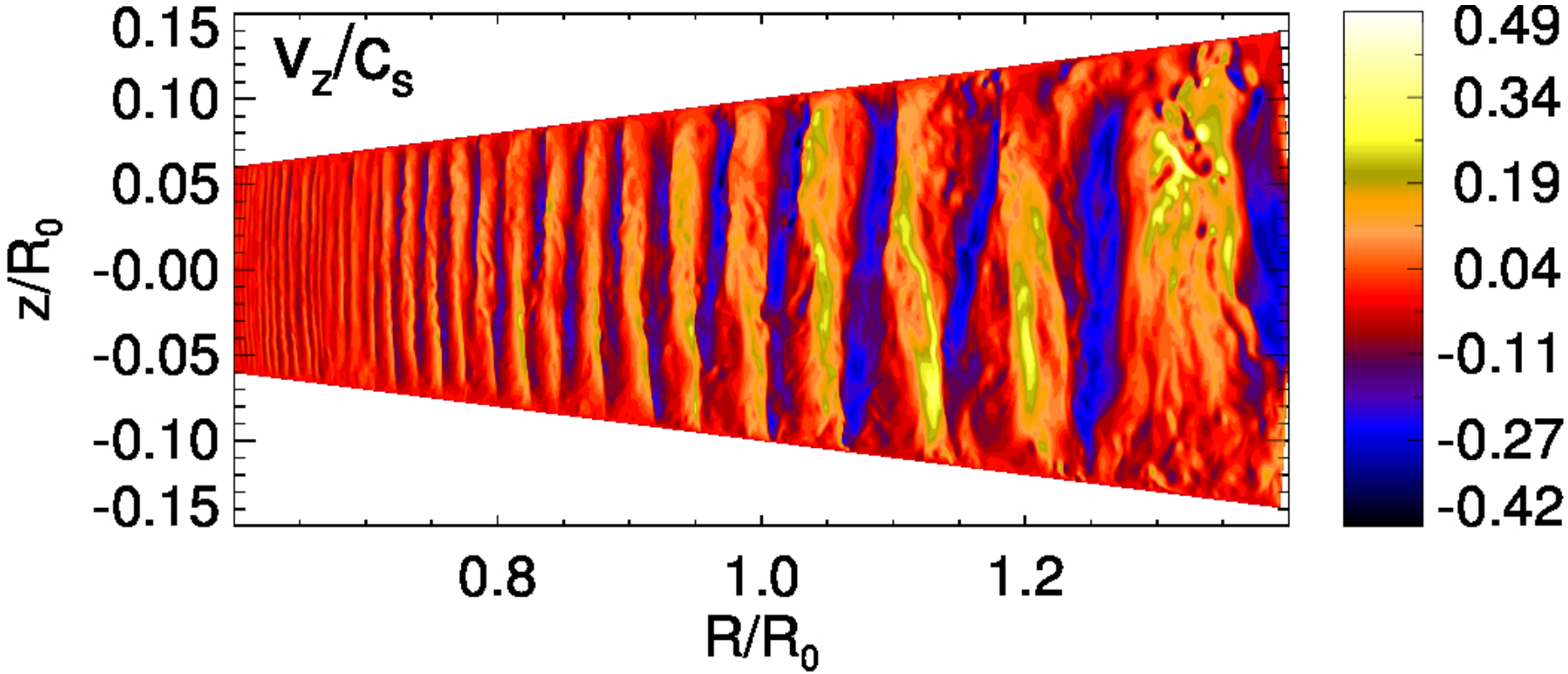
- Change in kinetic energy:

$$\Delta E \sim l_r^2 \left(\Omega^2 + \frac{l_z}{l_r} \cdot r \frac{\partial \Omega^2}{\partial z} \right)$$

- $\Delta E < 0 \Rightarrow$ unstable
  - Possible for vertically elongated disturbances.
- Essentially a Rayleigh-type instability
- Needs rapid cooling to overcome buoyancy forces $\rightarrow$ most unstable for isothermal gas

Vertical shear instability

$\partial_z \Omega \neq 0 \Rightarrow$free energy$\rightarrow$instability?



- VSI $\rightarrow$ large-scale up/down motions

(Lin, in prep.)

Can dust particles still settle?

Modeling dusty-gas without dust

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

dust+polytropic gas+drag ⟷ equivalent for small particles ⟷ hydrodynamics+cooling

- Implicit modelling of dust-gas friction or drag:

$$\rho_{\mathrm{d}} \left.\frac{\partial \boldsymbol{v}_{\mathrm{d}}}{\partial t}\right|_{\mathrm{drag}} = -\rho_{\mathrm{g}} \left.\frac{\partial \boldsymbol{v}_{\mathrm{g}}}{\partial t}\right|_{\mathrm{drag}} = -\frac{\rho_{\mathrm{d}}\rho_{\mathrm{g}}}{\rho_{\mathrm{tot}}} \frac{(\boldsymbol{v}_{\mathrm{d}} - \boldsymbol{v}_{\mathrm{g}})}{t_{\mathrm{stop}}}.$$

- $t_{\mathrm{stop}} \propto$ particle size

Modeling dusty-gas without dust

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

dust+polytropic gas+drag $\xleftrightarrow[\text{small particles}]{\text{equivalent for}}$ hydrodynamics+cooling

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

- ρ =total density; $\boldsymbol{v}$ =center of mass velocity
- Dust-gas friction, f_{dust}: dust-fraction, $t_{\text{stop}} \propto$ particle size

Lifting dust particles by the VSI

- $c_s^2 \propto R^{-q}$, $\partial_z \Omega \propto q = 0.5$

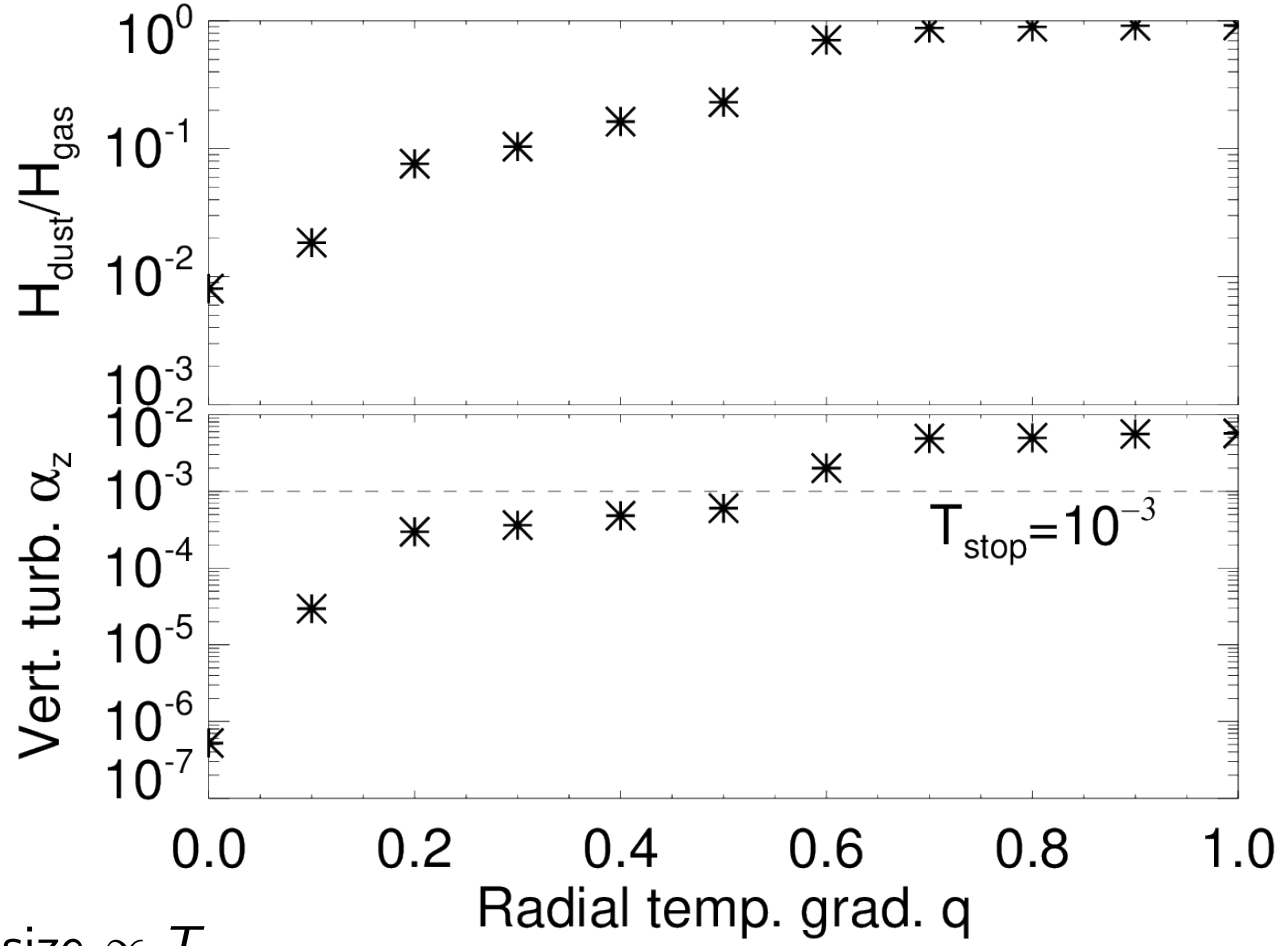
Moderately turbulent disk

Lifting dust particles by the VSI

- $c_s^2 \propto R^{-q}$, $\partial_z \Omega \propto q = 1$

Strongly turbulent disk

Dust settling against VSI turbulence

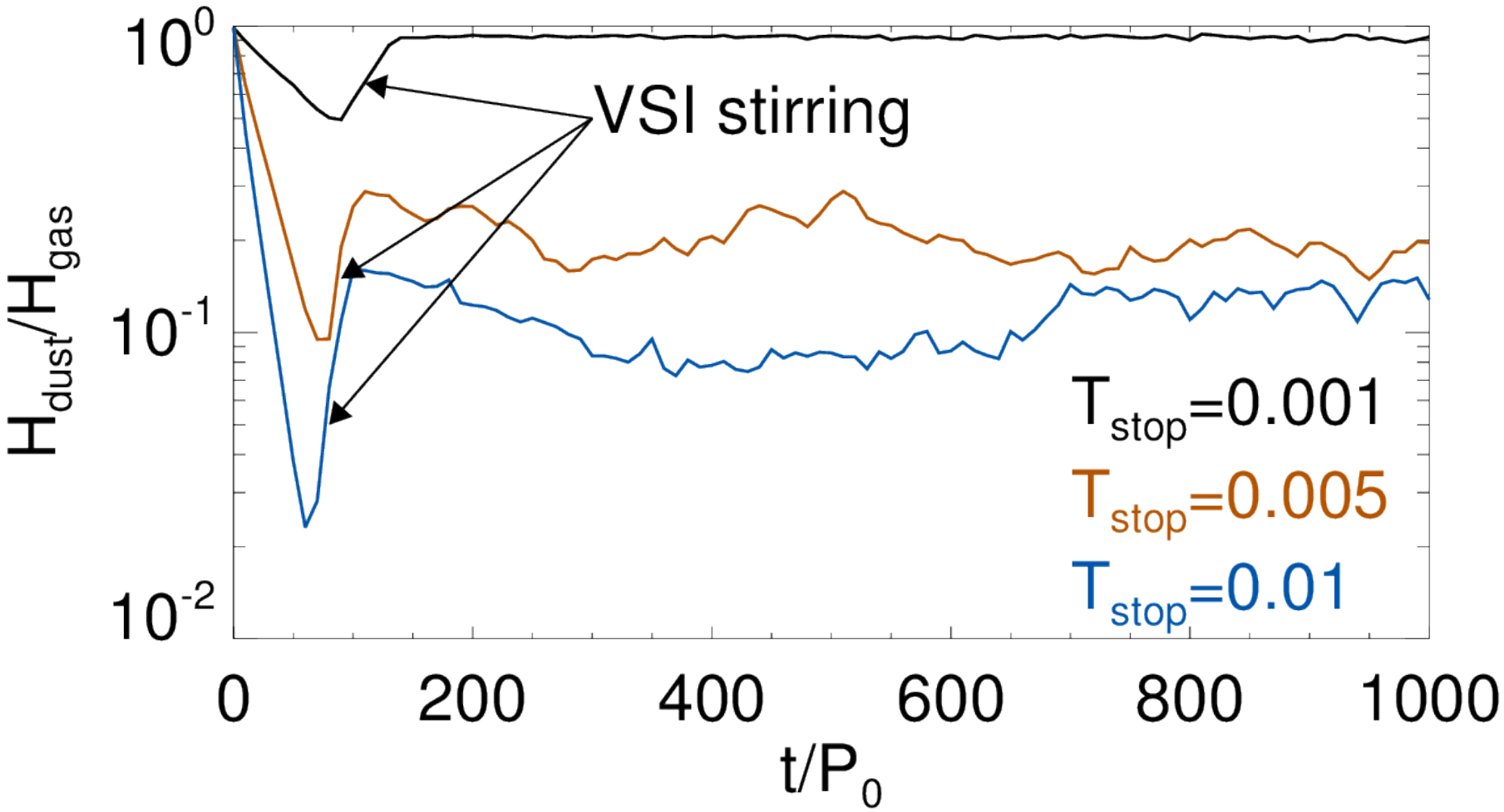


- Particle size $\propto T_{\text{stop}}$
- Settling only occurs for $\alpha_z < T_{\text{stop}}$ or

Particle size > turbulent stirring

Consistent with theory (Dubrulle et al., 1995)

Effect of particle size ($T_{\rm stop}$)



- Large particles settle faster ($t_{\rm settle} \propto 1/T_{\rm stop}$)
- Large particles settles to thin layer and weakens subsequent VSI stirring

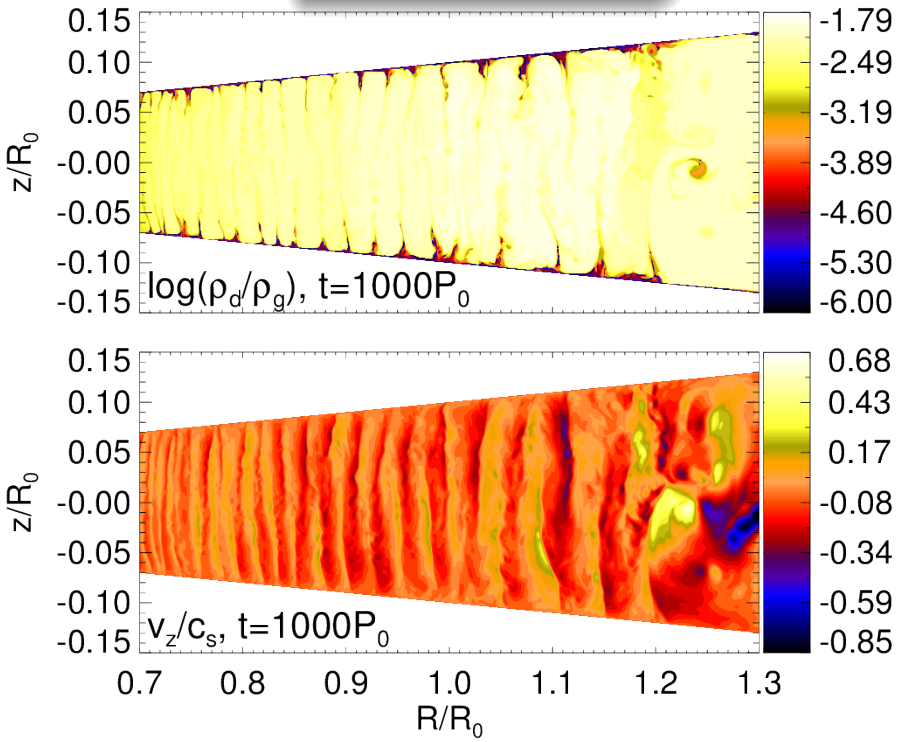
Particle back-reaction on the gas

- Dust-on-gas coupling adds weight (inertia) but not pressure (restoring force)
- Dust-loading induces a vertical buoyancy frequency N_z
- Buoyancy stabilize vertical motions of the VSI $\rightarrow$ reduced turbulence

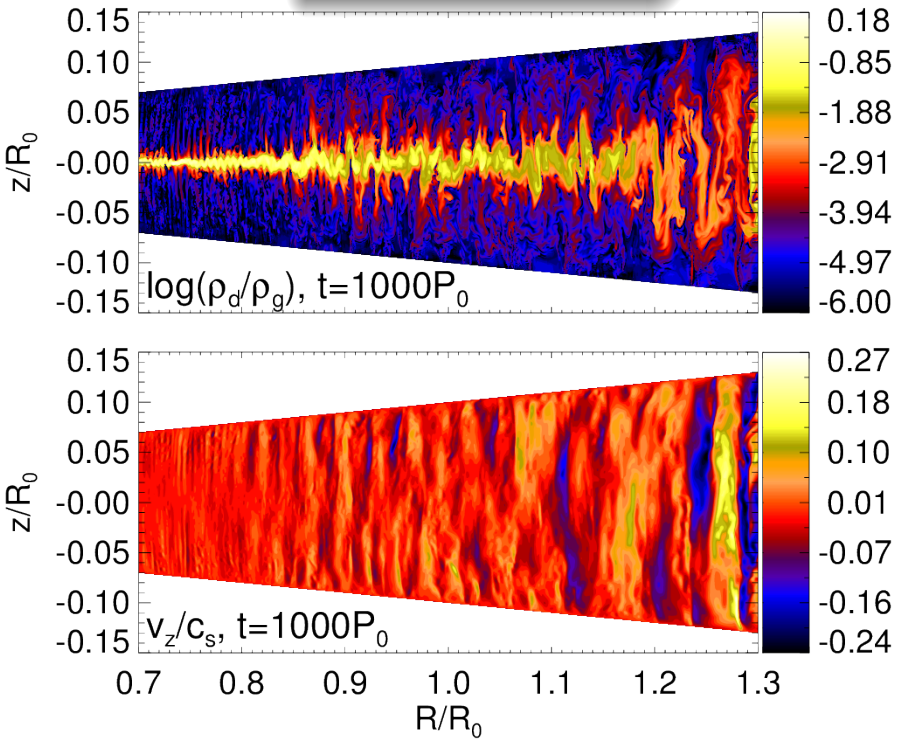
Particle back-reaction on the gas

- Dust-on-gas coupling adds weight (inertia) but not pressure (restoring force)
- Dust-loading induces a vertical buoyancy frequency N_z
- Buoyancy stabilize vertical motions of the VSI $\rightarrow$ reduced turbulence

$T_{\rm stop} = 0.001$

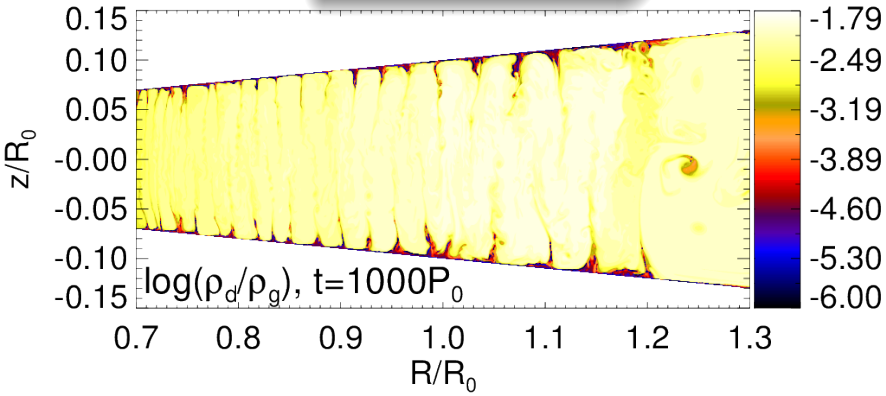


$T_{\rm stop} = 0.01$

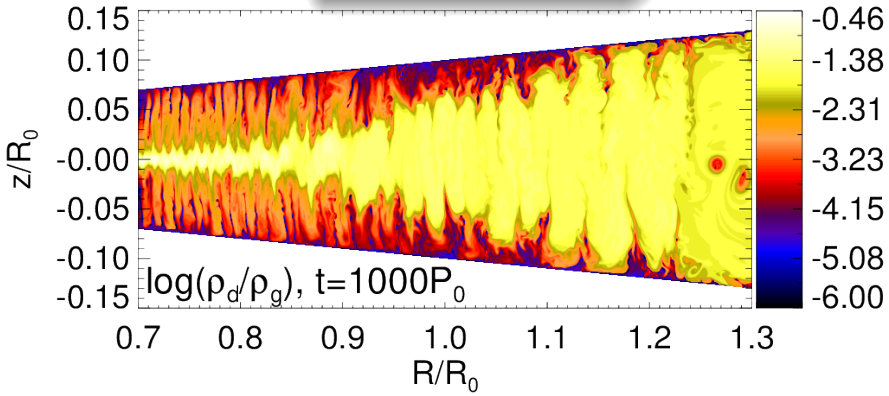


Effect of metallicity ($\Sigma_{\rm dust}/\Sigma_{\rm gas}$)

$\Sigma_{\rm d} = 0.01\Sigma_{\rm g}$



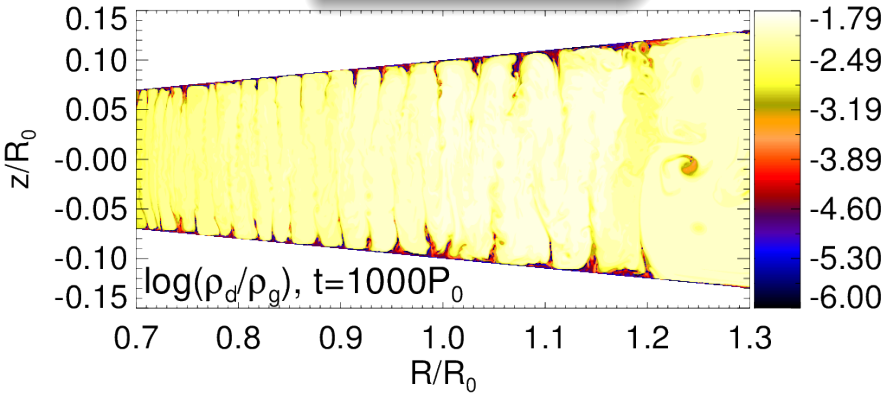
$\Sigma_{\rm d} = 0.03\Sigma_{\rm g}$



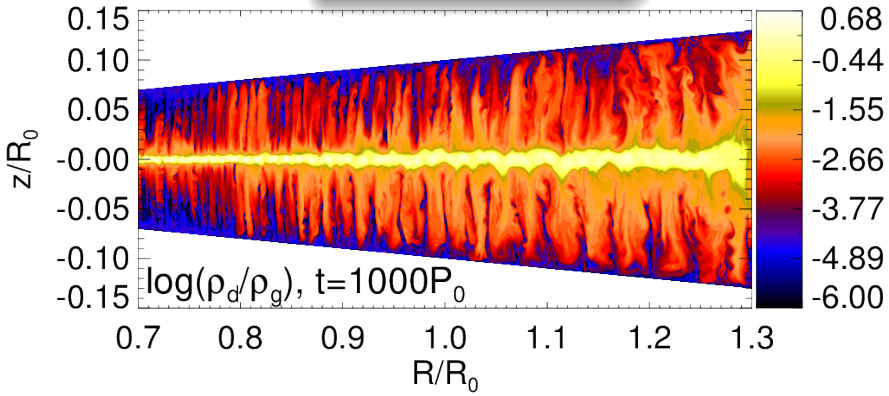
- Increasing the overall dust content makes the system 'heavy' $\rightarrow$ more difficult for VSI to stir up

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

$\Sigma_{\rm d} = 0.01\Sigma_{\rm g}$



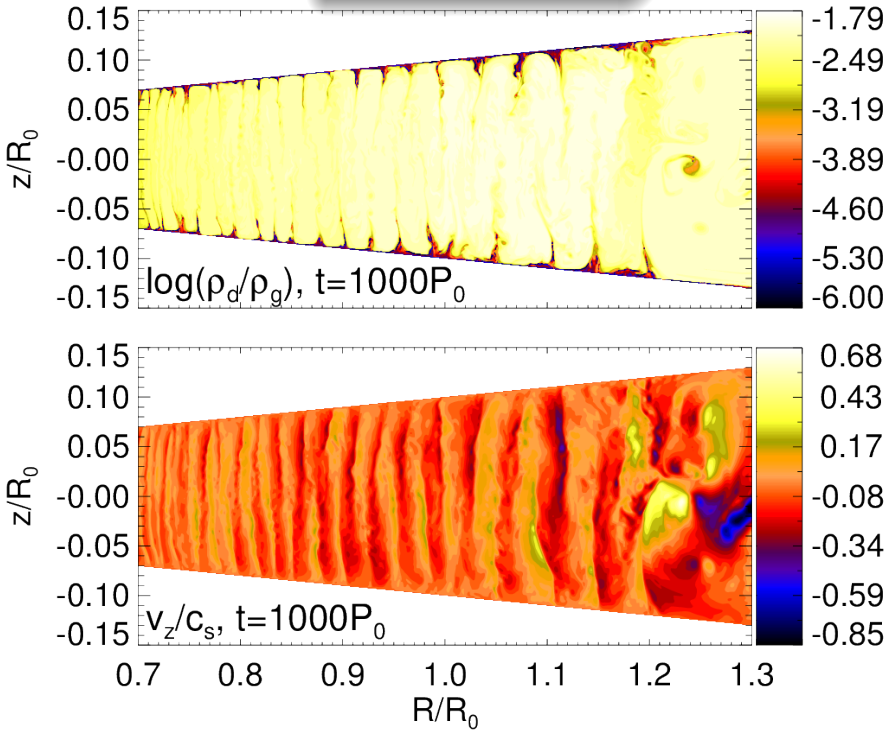
$\Sigma_{\rm d} = 0.1\Sigma_{\rm g}$



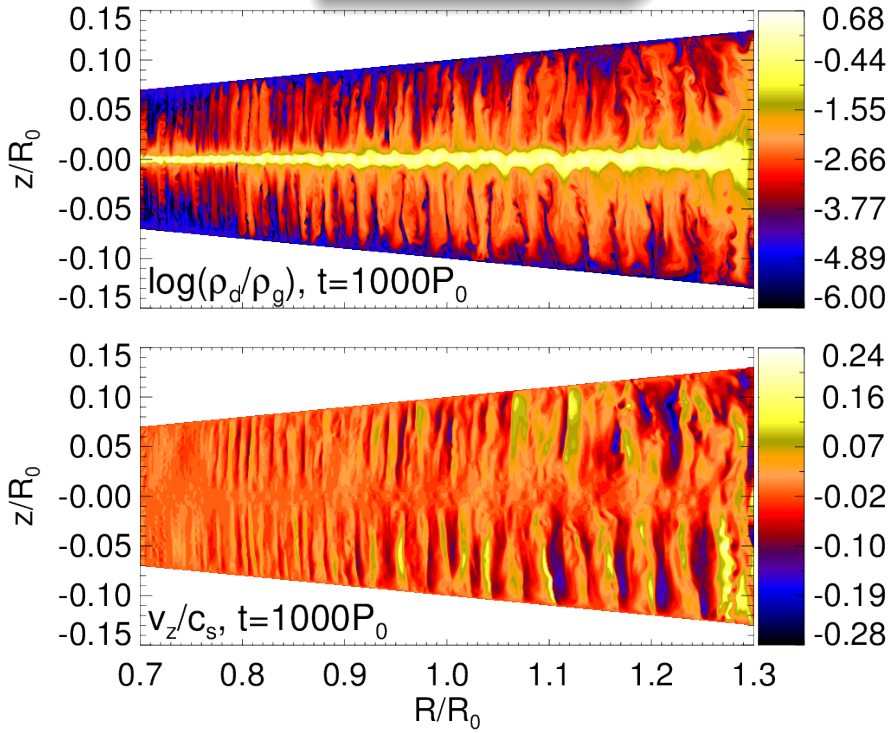
- Increasing the overall dust content makes the system 'heavy' $\rightarrow$ more difficult for VSI to stir up

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

$\Sigma_{\rm d} = 0.01\Sigma_{\rm g}$

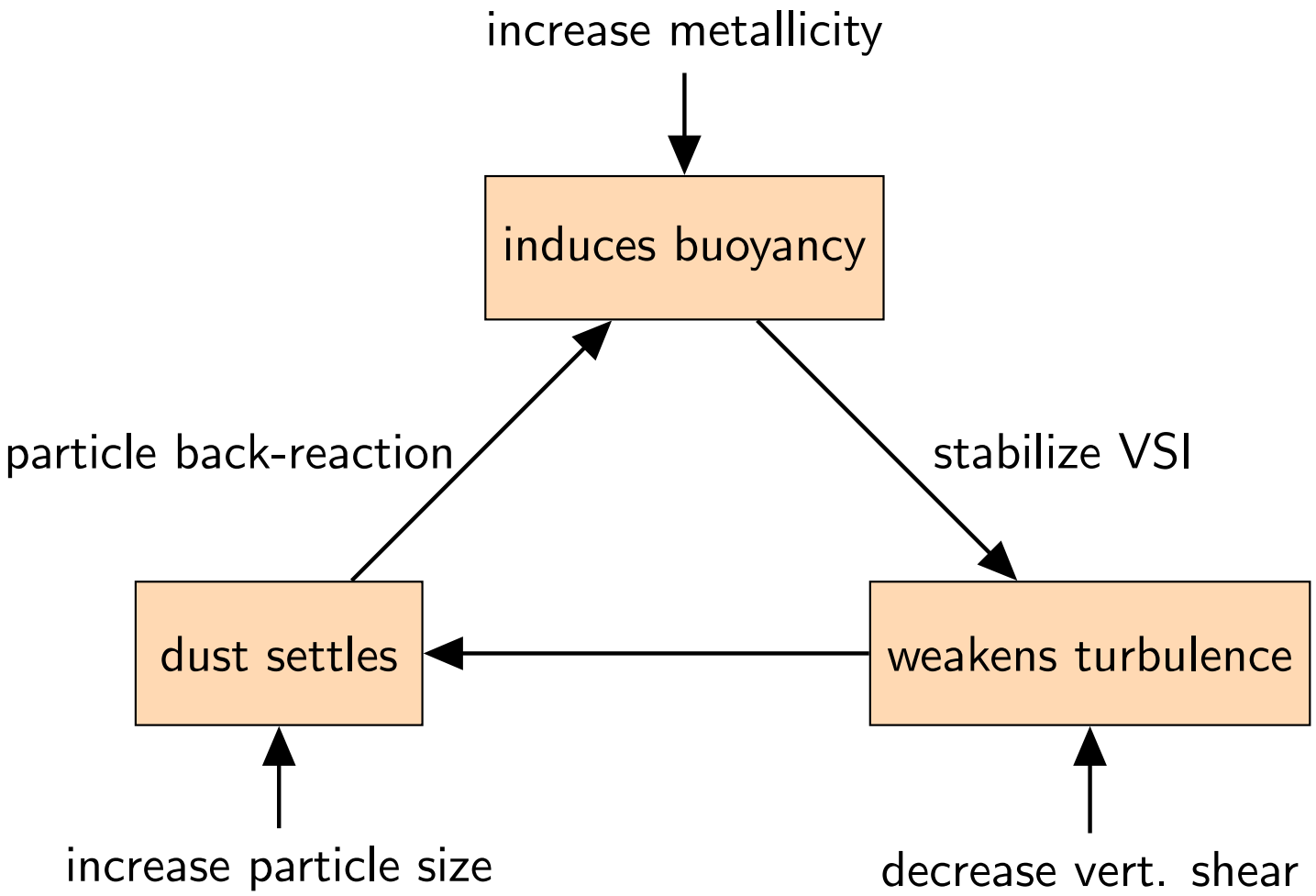


$\Sigma_{\rm d} = 0.1\Sigma_{\rm g}$



- Increasing the overall dust content makes the system 'heavy' $\rightarrow$ more difficult for VSI to stir up
- Dense particle layer is self-stabilized against VSI

Self-sustained settling



Summary

- Rapid planetesimal formation require dust-to-gas ratios to be first enhanced by ~ 100 from the ISM value
- Dust-settling is one way to enhance $\rho_{\rm d}/\rho_{\rm g}$
- Dust-settling is opposed by turbulence, e.g. from the vertical shear instability
- VSI turbulence can be circumvented by
  - Increased particle size
  - Increased metallicity
- Particle back-reaction allows a feedback loop for self-sustained settling

Near-future work

- Full 3D simulations to account for non-axisymmetric structures
- Mutual interaction with protoplanets
- VSI (or other hydro.) turbulence and self-gravity
- Influence of infall from external envelope
- Non-circular flows (eccentric disks, vortices)

Thank you

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