# Lifting dust particles by the vertical shear instability

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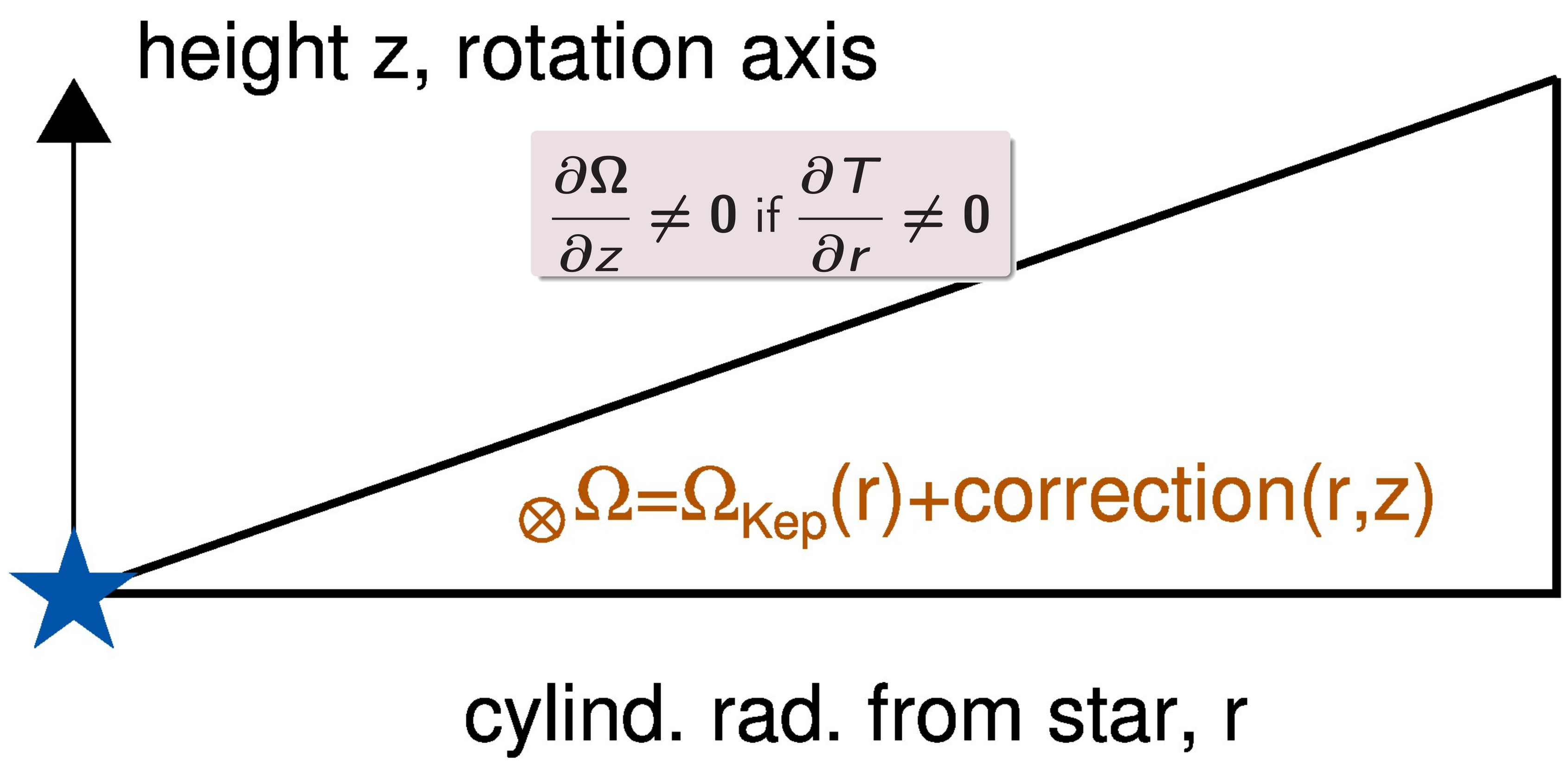
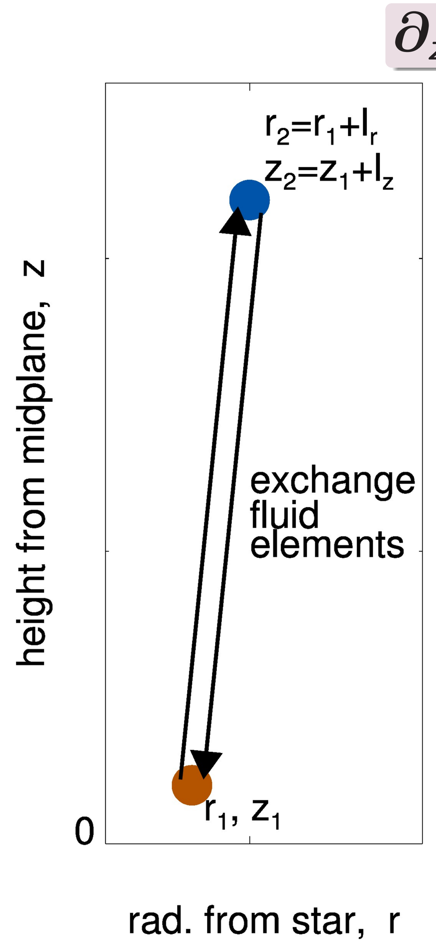
## Introduction




**The outer parts of protoplanetary disks are irradiated by their central stars. The resulting radial temperature gradient, $\partial_r T \neq 0$, causes the disk angular velocity to vary with height from the midplane, $\partial_z \Omega \neq 0$. This can lead to hydrodynamic turbulence due to the Vertical Shear Instability (VSI). We study how the VSI affects dust settling via a suite of axisymmetric numerical simulations of dusty disks. We find that particles can be lifted by VSI-turbulence. In fact, small particles do not settle against the VSI and remain well-mixed with the gas. Our results indicate the VSI constrains particle sizes and disk conditions under which planetesimal formation can be self-consistently modeled.**

## Vertical shear instability

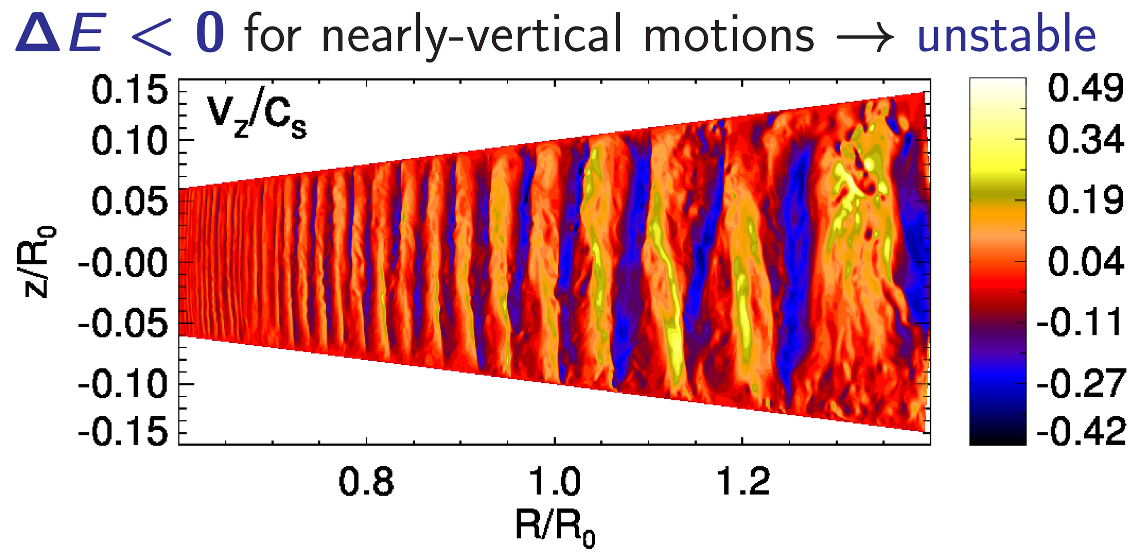
$\partial_z \Omega \neq 0 \Rightarrow$ free energy $\rightarrow$ instability?




- Change in kinetic energy:

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

- $\Delta E < 0$ for nearly-vertical motions $\longrightarrow$ unstable




- But VSI can be stabilized by buoyancy

## Single-fluid description of dusty gas

- For small dust particles mixed with isothermal gas ($P = c_s^2 \rho_{\mathrm{gas}}$), Lin & Youdin (2017) showed that:

isothermal gas+dust $\longleftrightarrow$ ideal gas + cooling (equivalent for small particles)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0,$$

$$\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} = -\frac{1}{\rho} \nabla P - \nabla \Phi_*,$$

$$\frac{\partial P}{\partial t} + \nabla \cdot (P \vec{v}) = P \vec{v} \cdot \nabla \ln c_s^2 + c_s^2 \nabla \cdot (t_{\mathrm{stop}} f_{\mathrm{d}} \nabla P)$$

- $\rho = \rho_{\mathrm{gas}} + \rho_{\mathrm{dust}}$, $\vec{v} =$ dust-gas center of mass velocity
- Stellar irradiation
- Dust-gas drag ( $f_{\mathrm{d}} = \rho_{\mathrm{dust}} / \rho$, $t_{\mathrm{stop}} \propto$ particle size)
- Model implemented in the PLUTO hydrodynamics code

## Physical interpretation

- Dust particles 'cool' the mixture:

$$T \rightarrow \frac{T}{\sqrt{1 + \rho_{\mathrm{dust}} / \rho_{\mathrm{gas}}}}$$

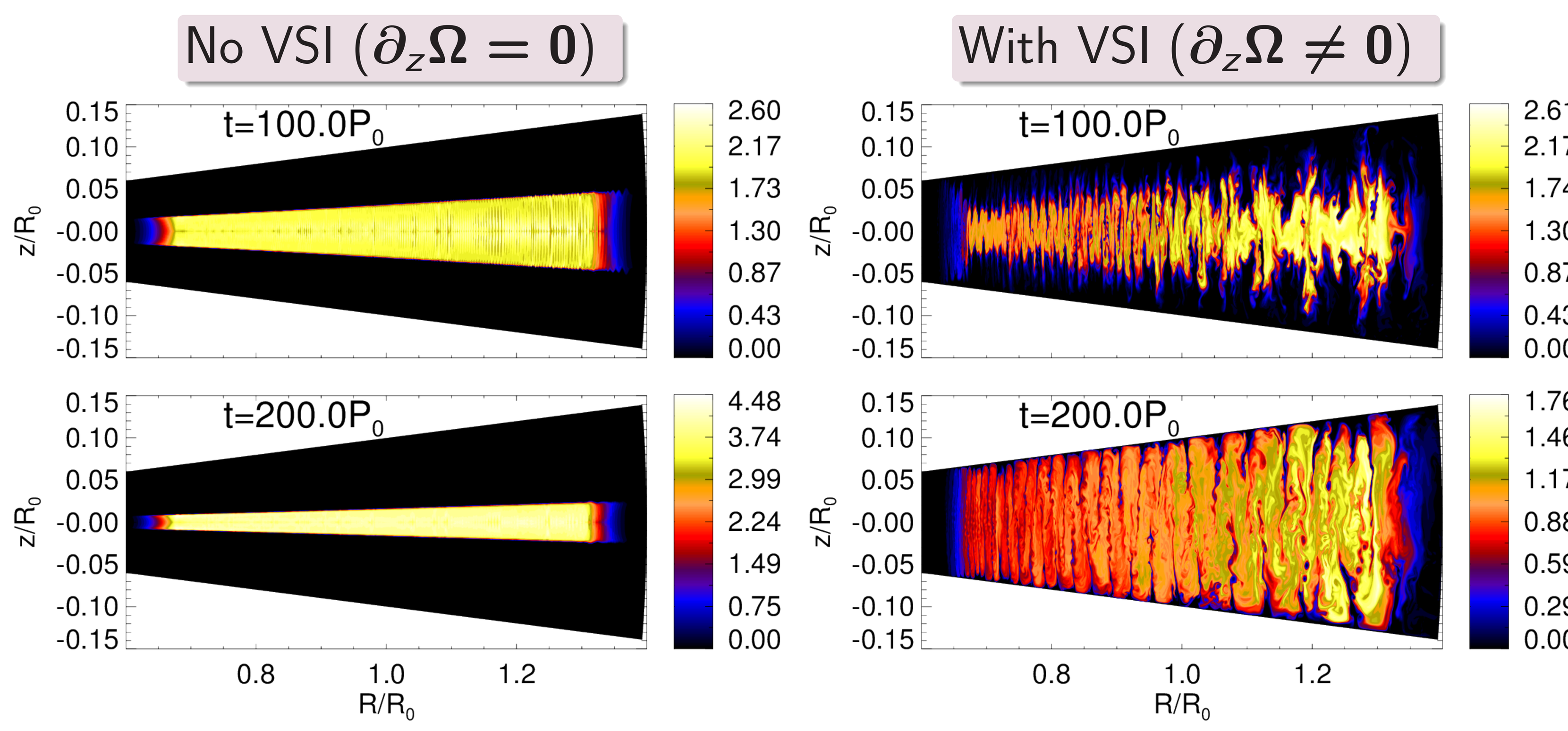
- Dust particles induce buoyancy forces:

$$N_z^2 = \frac{c_s^2}{\left(1 + \rho_{\mathrm{dust}}/\rho_{\mathrm{gas}}\right)^2} \frac{\partial \ln \rho_{\mathrm{gas}}}{\partial z} \frac{\partial}{\partial z} \left( \frac{\rho_{\mathrm{dust}}}{\rho_{\mathrm{gas}}} \right)$$

## Dust settling vs. VSI-turbulence

- Simulate dusty, stratified disks with $T \propto r^{-q}$, so $\partial_z \Omega \propto q$

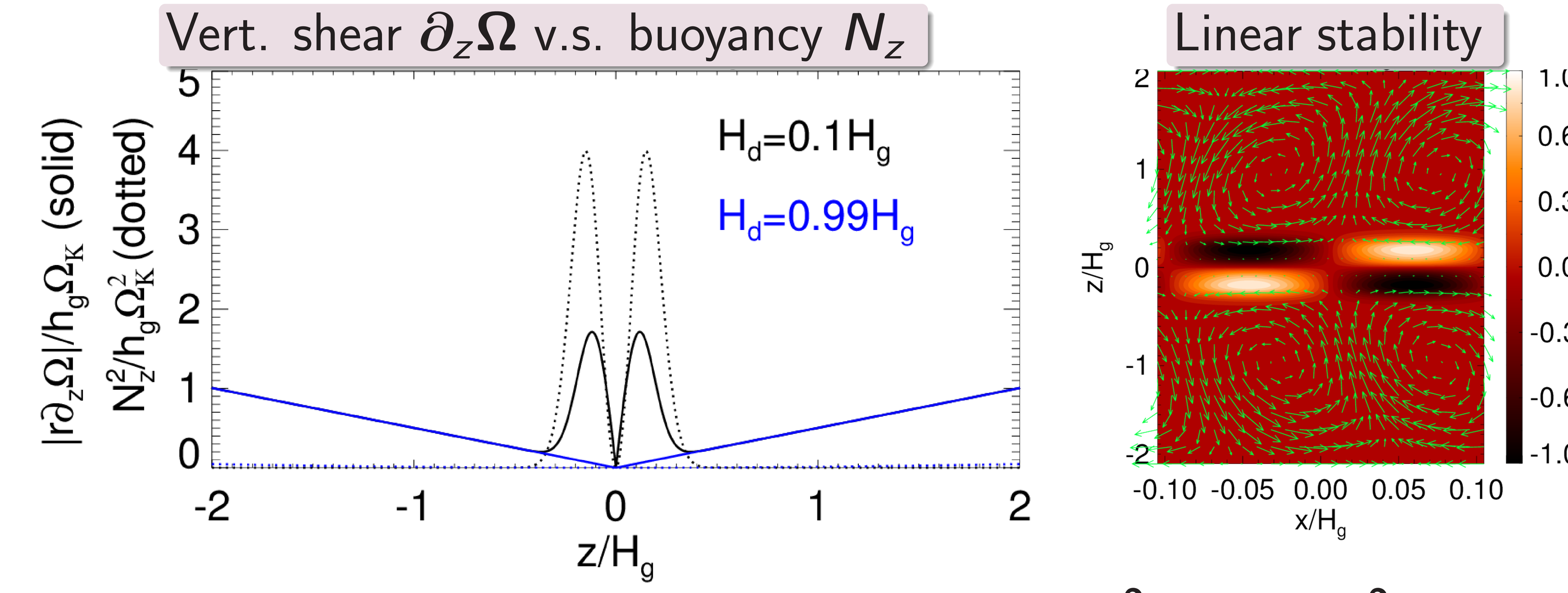
$\rho_{\mathrm{dust}} / \rho_{\mathrm{gas}} \times 100$




- Particles with Stokes number $t_{\mathrm{stop}} \Omega = 10^{-3}$
- Vertically integrated metalicity, $\Sigma_{\mathrm{dust}} / \Sigma_{\mathrm{gas}} = 0.01$
- Particles get lifted by VSI turbulence before it can settle

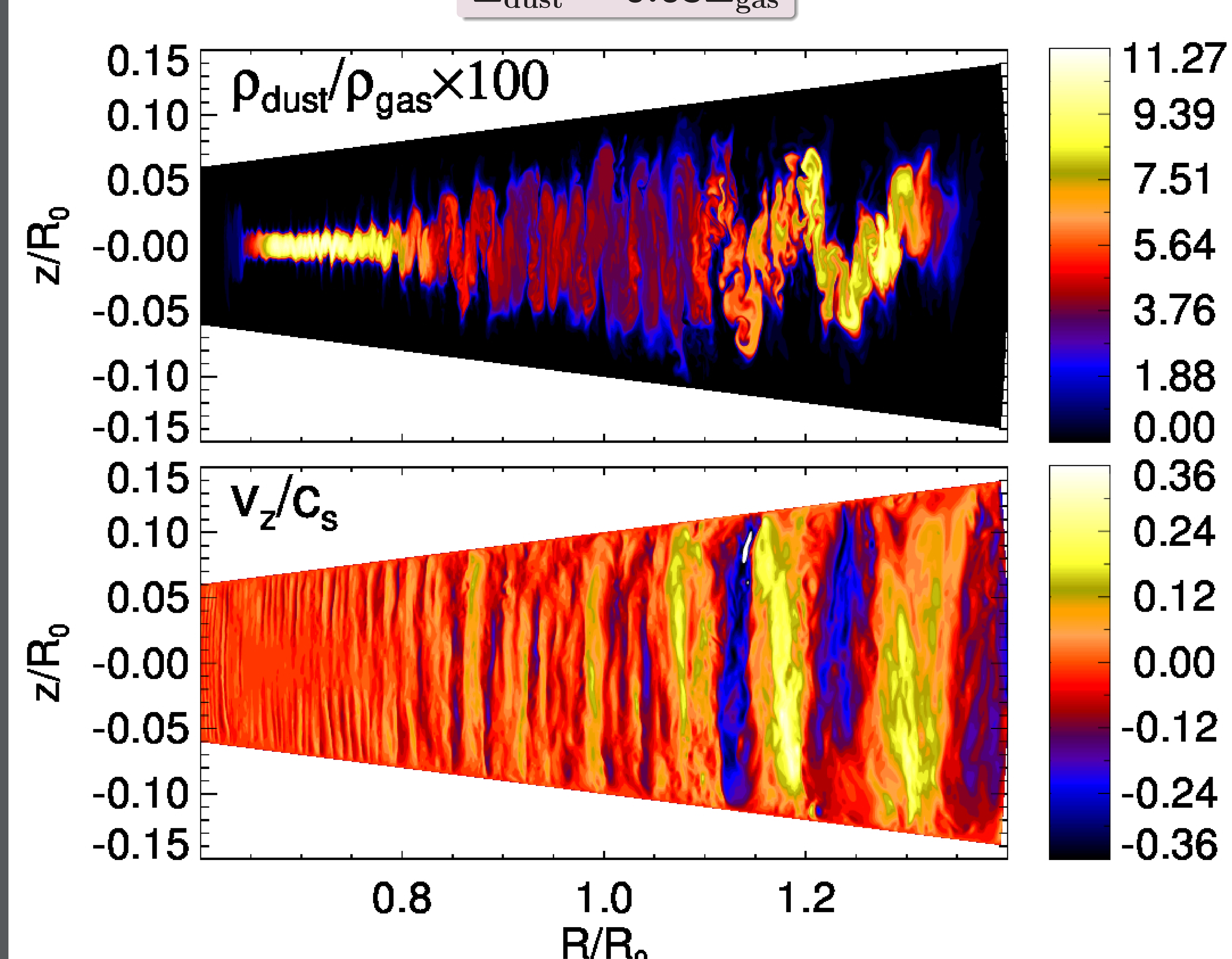
## Dust feedback and buoyancy

- If dust settles faster than VSI growth, a thin dust layer can form, which induces an effective buoyancy to stabilize the VSI




- Midplane motion suppressed by dusty buoyancy ($N_z^2 \gtrsim |r \partial_z \Omega^2|$)
- Particle settling favored for
  - Increased metalicity $\Sigma_{\mathrm{dust}} / \Sigma_{\mathrm{gas}}$
  - Increased particle size or $t_{\mathrm{stop}}$
  - Decreased vertical shear $|\partial_z \Omega|$

$\Sigma_{\mathrm{dust}} = 0.03 \Sigma_{\mathrm{gas}}$




- Dust settling in the inner disk stabilized the VSI

## Summary

**We simulate dusty protoplanetary disks with hydrodynamic turbulence due to the Vertical Shear Instability, using a newly developed framework to study small solids mixed with isothermal gas. We find VSI turbulence may present an obstacle to standard planetesimal formation mechanisms by preventing dust particles from settling towards the midplane.**

- **Related work: Lin & Youdin, 2017, ApJ, 849, 129**