# A rocky road from dust to planets

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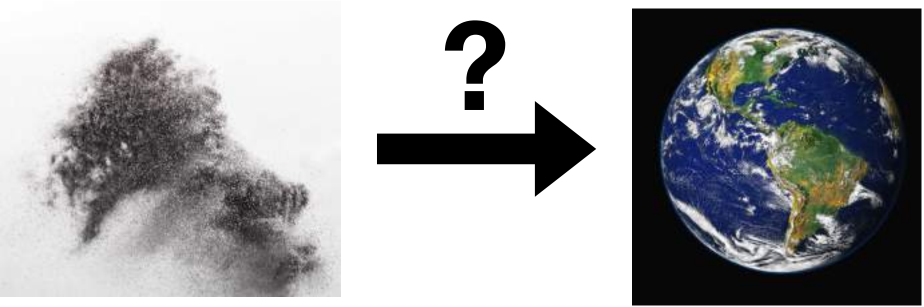
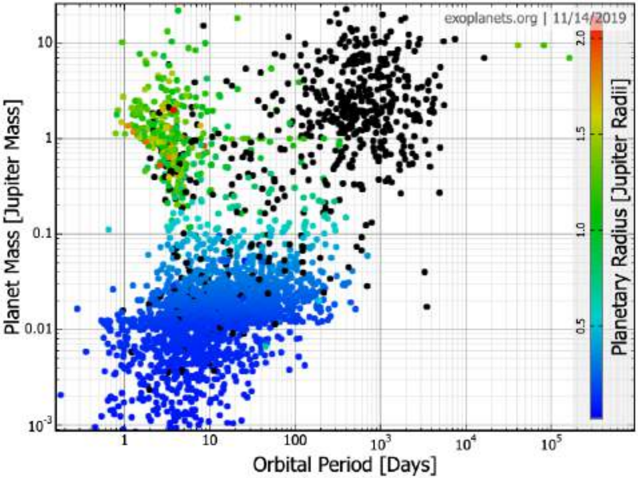
# Research interests




$\sim 10^{-6}\mathbf{m}$ $\quad\quad$ $\sim 10^{7}\mathbf{m}$

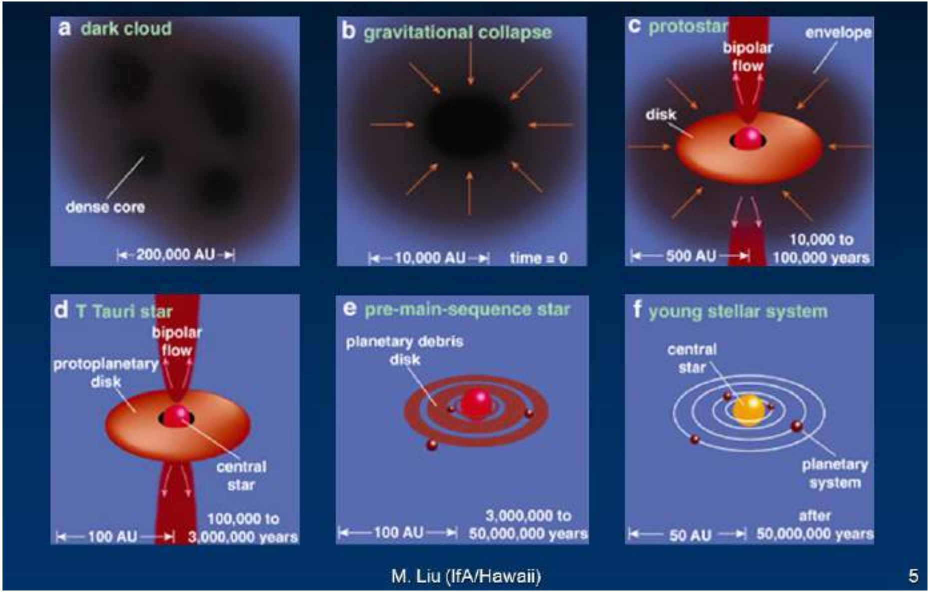
- Astrophysical fluid dynamics
- Accretion disks
- Fluid instabilities
- Structure formation and evolution
- Disk-planet interaction
- Stability analyses
- Numerical simulations

# Diversity of planetary systems



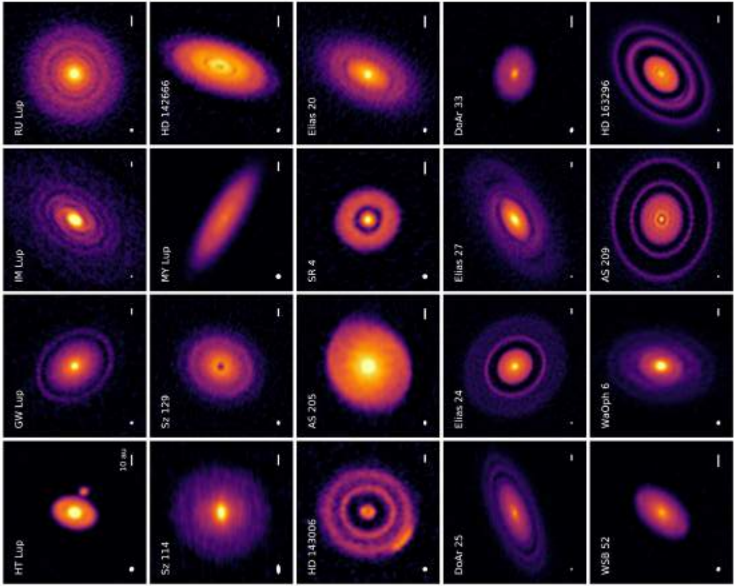

- $>$ 4000 extra-solar planets detected
- $>$ 3000 planetary systems
- Wide range of orbital configurations

# Planets form in accretion disks around young stars



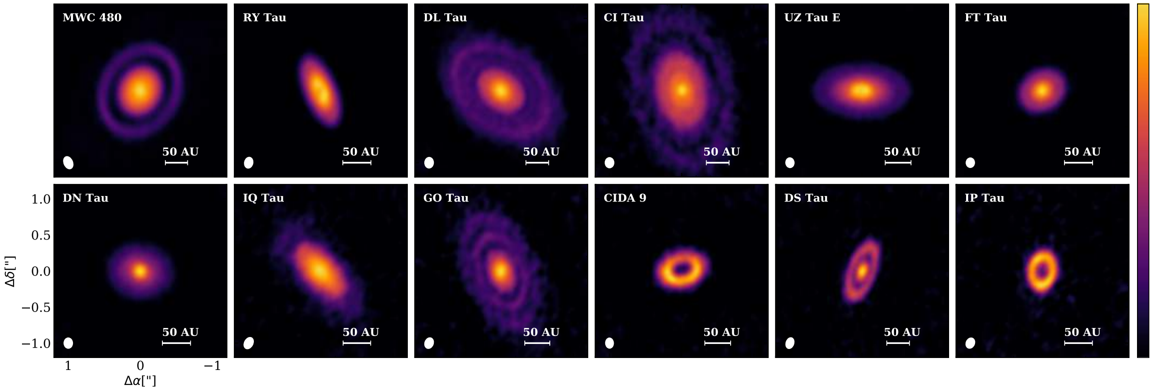

The result is readily obesrved, what about earlier stages, e.g. ‘e’ or even ‘d’?

# Protoplanetary disks



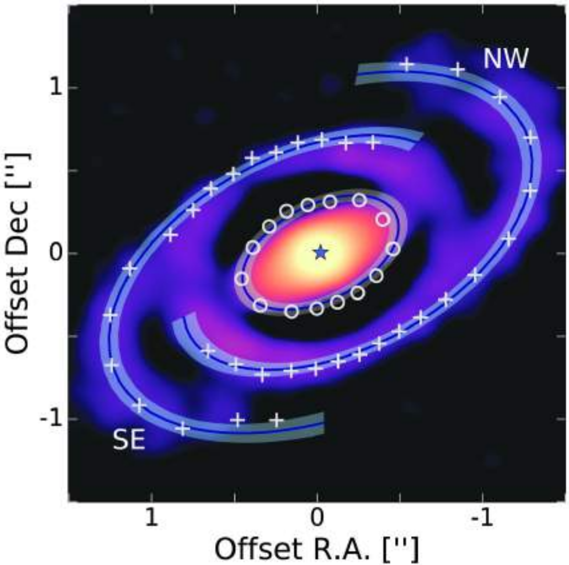

(Andrews et al 2018; DSHARP program)

# Protoplanetary disks



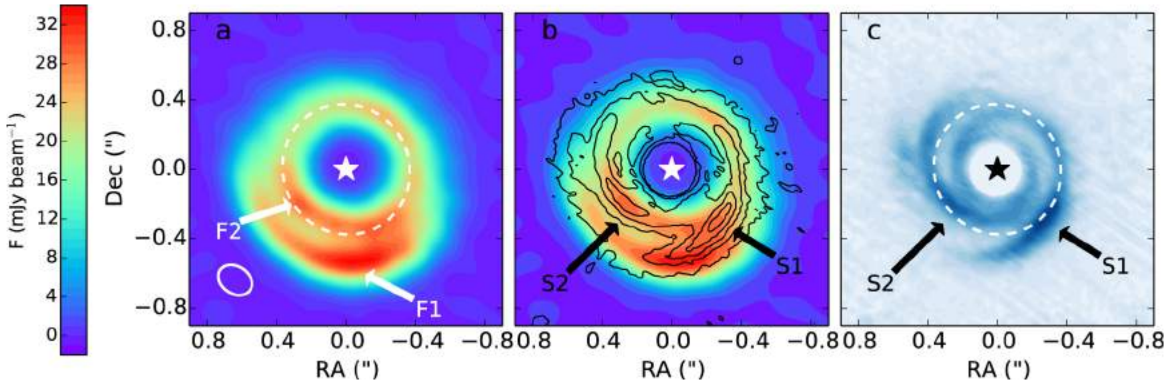

(Long et al 2018)

# Asymmetric protoplanetary disks (rare)




(Elias 2-27, Pérez et al., 2016)

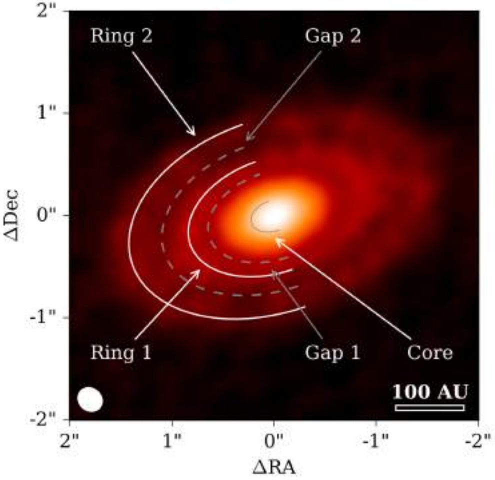
# Asymmetric protoplanetary disks (rare)




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

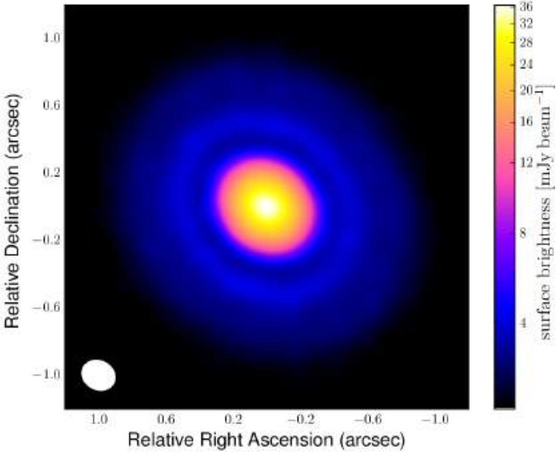
# Observing planet formation?

V1094 Sco




(van Terwisga et al. 2018)

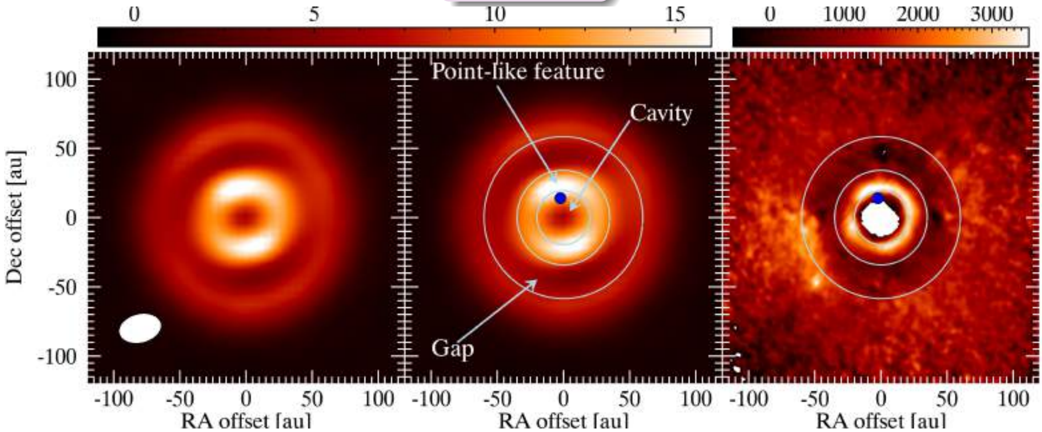
Elias 24




(Dipierro et al. 2018)

# Observing planet formation?

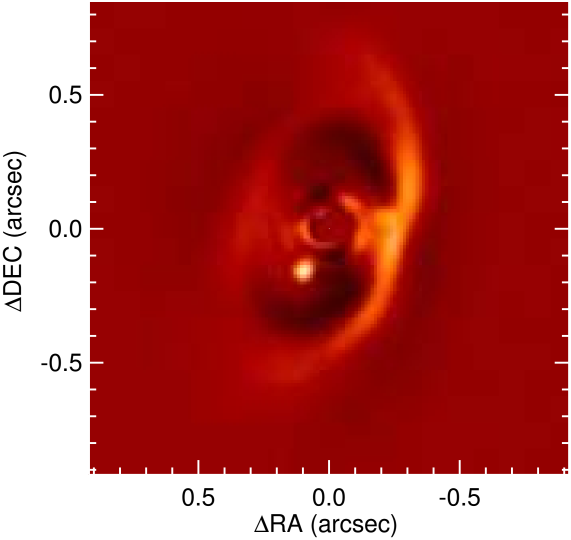
HD 169142




Fedele et al., 2017

# Structures from disk-planet interaction?

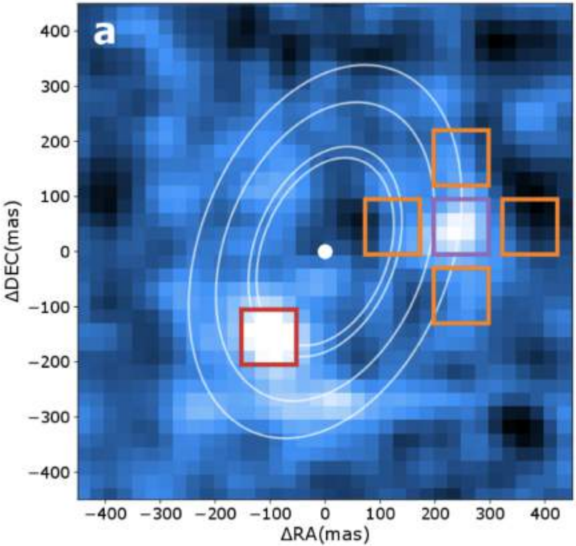
First planet detected inside protoplanetary disk gap




(PDS 70, Müller et al. 2018)

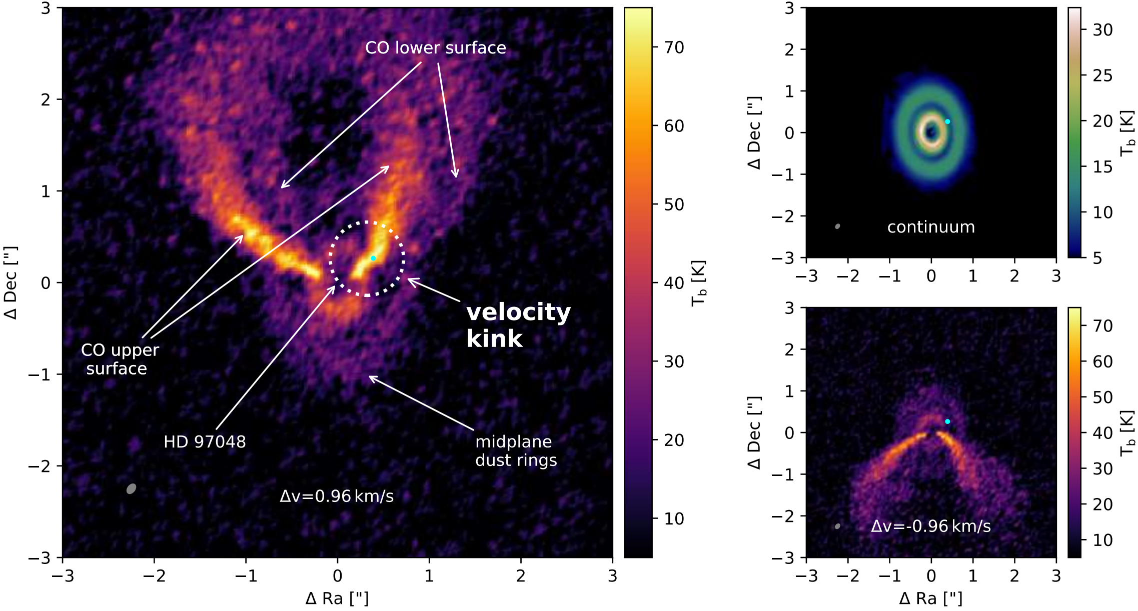
# Structures from disk-planet interaction?

Actually, there are two planets!



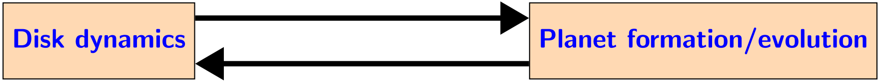

(Haffert et al., 2019)

# Kinematic detection of planets



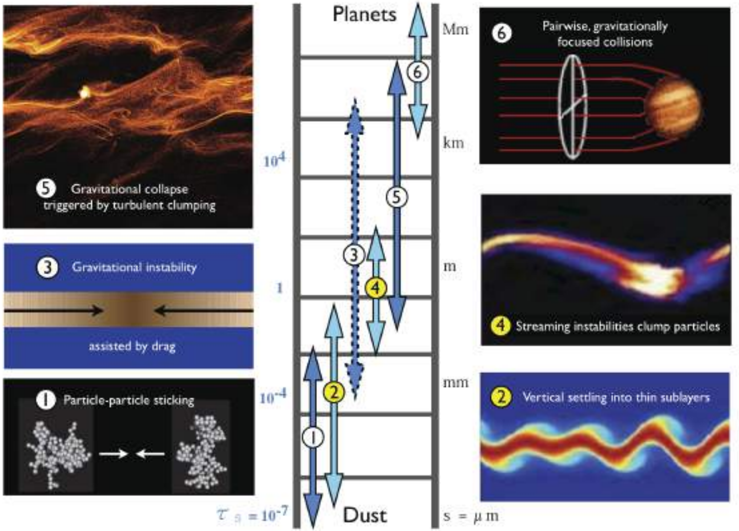

(Pinte et al., 2019)

# The disk-planet connection



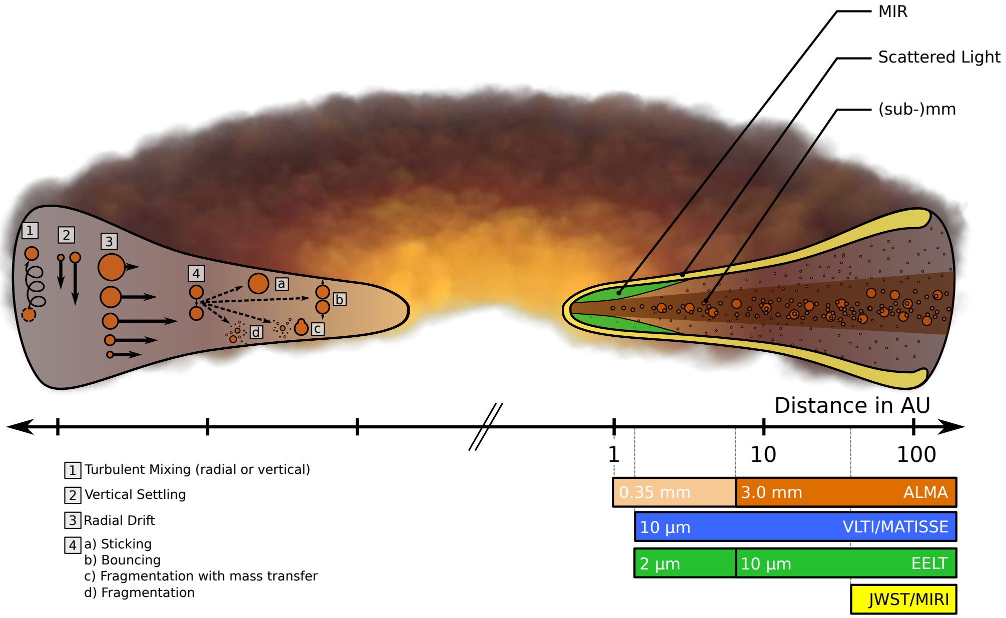

- How do protoplanetary disks accrete onto their stars?
- What are the sources of turbulence in protoplanetary disks?
- Origin of rings, gaps, asymmetries?
- Dust dynamics
  - How do planetesimals form from tiny dust grains?
  - Dust-gas interaction
  - Interpreting observations of PPDs, inferring disk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

# Importance of dust




- Planets form from the solids (at least in core accretion)
- Need to understand how dust grains evolve in the gaseous disk

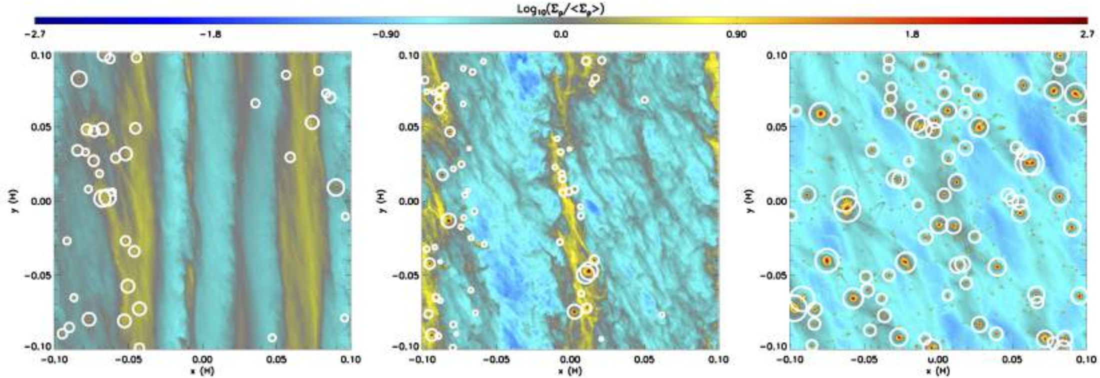
# Dusty-gas dynamics in protoplanetary disks




(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

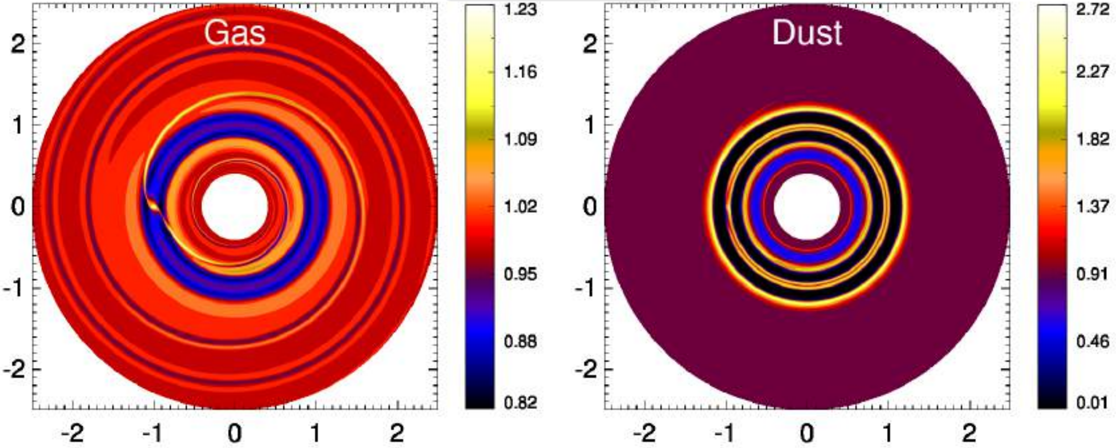
Lin & Youdin (2017)

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

**(for small particles)**

# Dust rings and traps at planet gaps

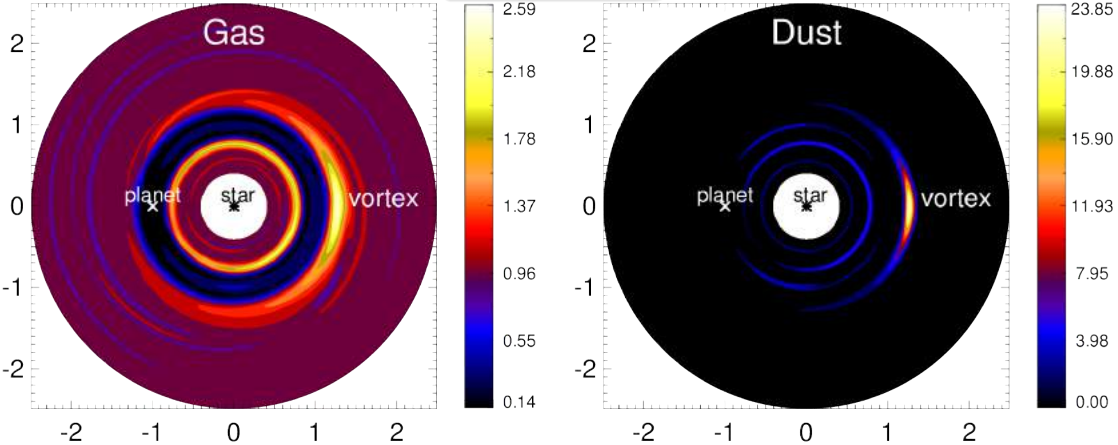
$10M_{\mathrm{Earth}}$ planet




- Pressure gradient at gap edges $\rightarrow$ radial dust ring

# Dust rings and traps at planet gaps

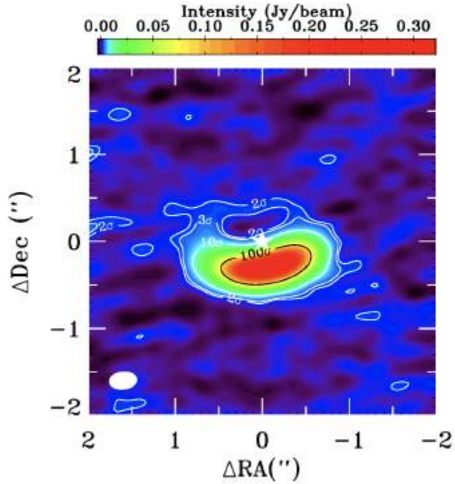
$30M_{\mathrm{Earth}}$ planet




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

# Dust rings and traps at planet gaps

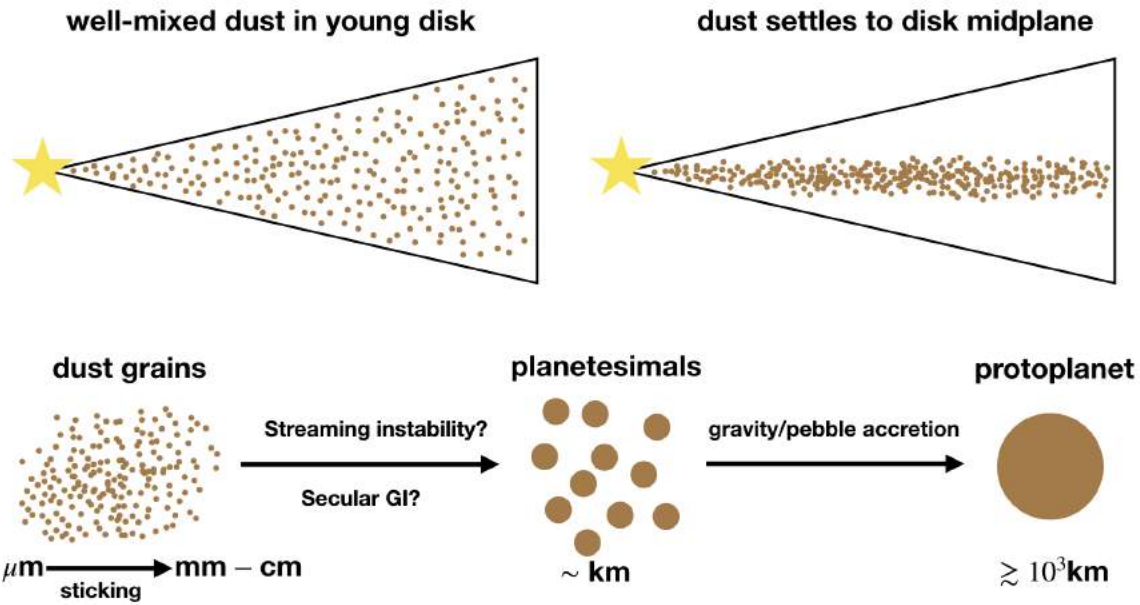
Observed dust trap




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

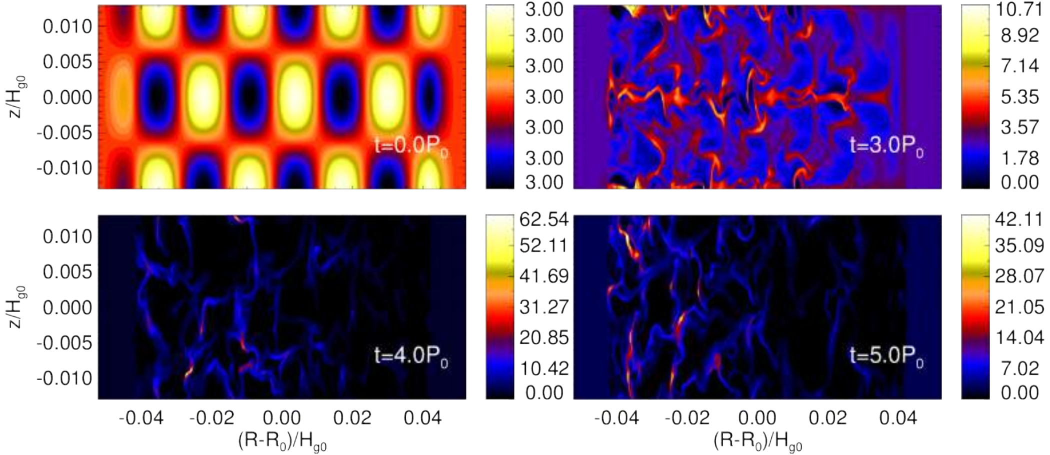
How to make the planet?

# From dust to planets



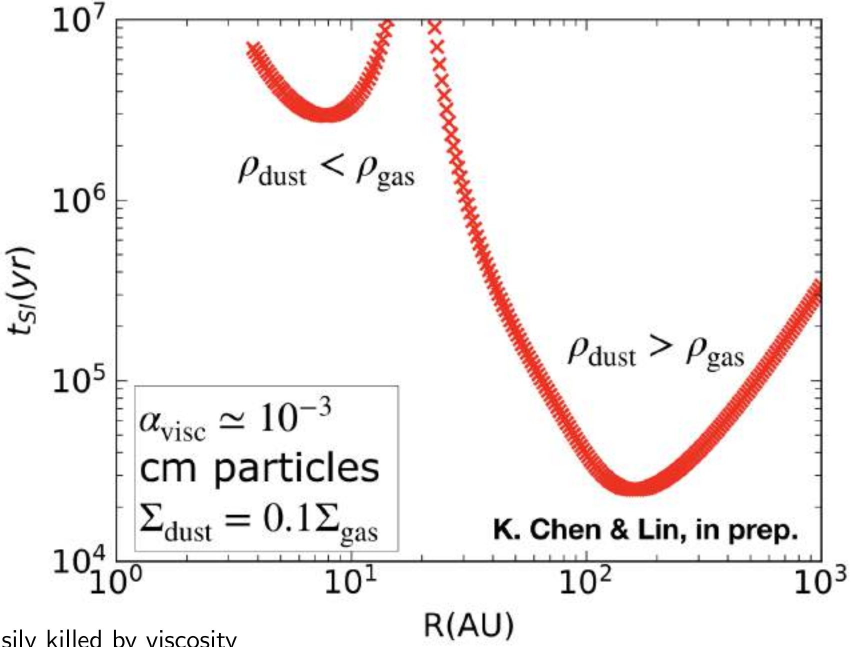
# Streaming instability

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




- One-fluid model using PLUTO; cf. Youdin & Johansen (2007)
- Idealized setup

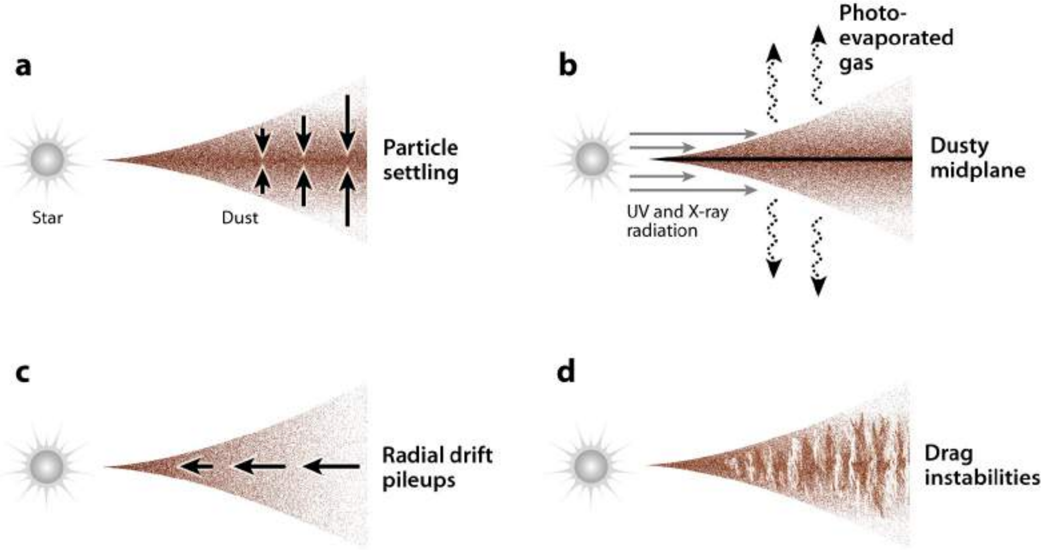
# Streaming instability in a physical disk model




- SI is easily killed by viscosity

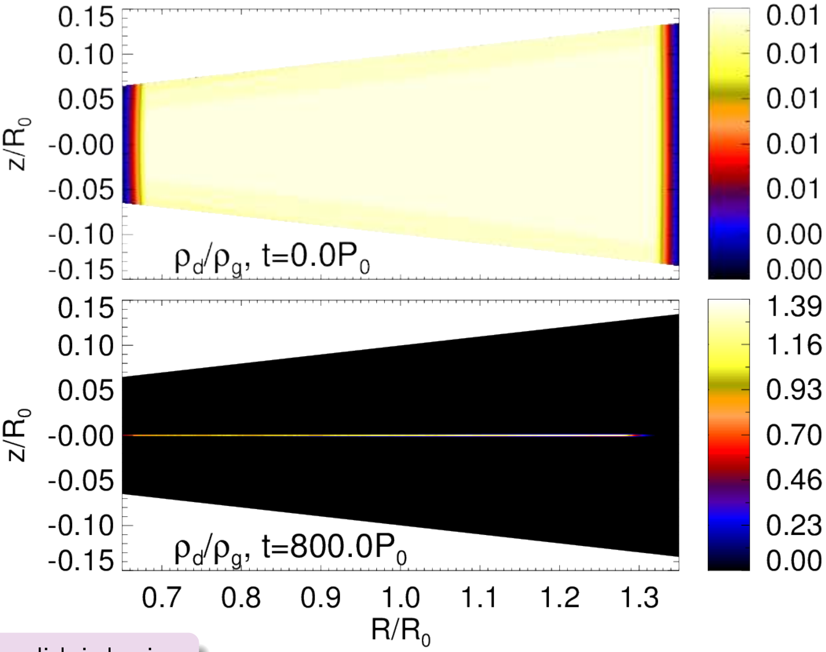
# Rapid planetesimal formation requires high dust-to-gas ratios

# Enhancing the dust-to-gas ratio in protoplanetary disks




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

# Dust settling?

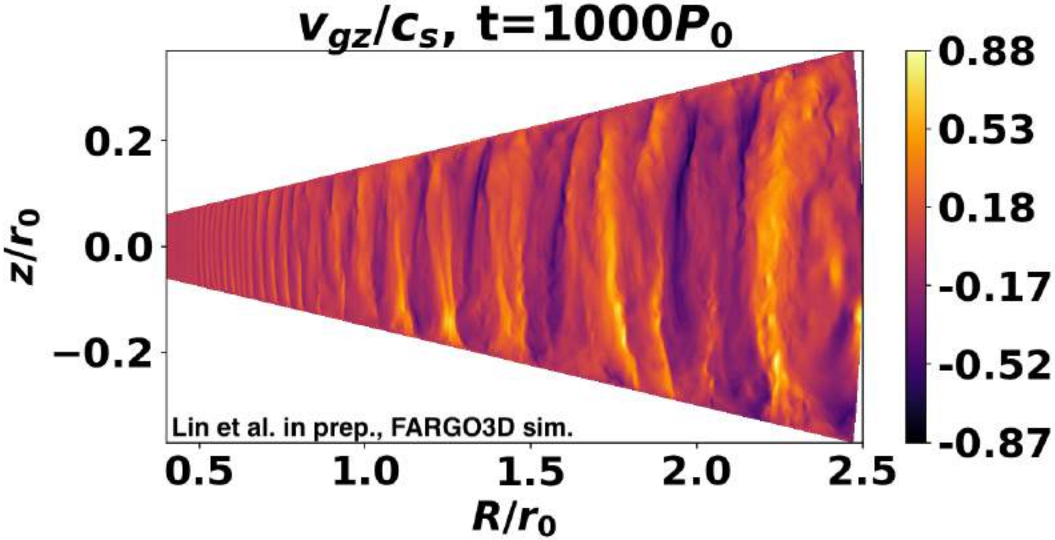



- Yes... if the disk is laminar

# Vertical shear instability

(Nelson et al., 2013; Lin & Youdin, 2015; Barker & Latter, 2015; Latter & Papaloizou, 2018)

- A centrifugal instability that feeds off **vertical shear:** $\partial_z \Omega \neq 0$
- Requires **rapid cooling**; applicable to 10s to 100 AU in protoplanetary disks



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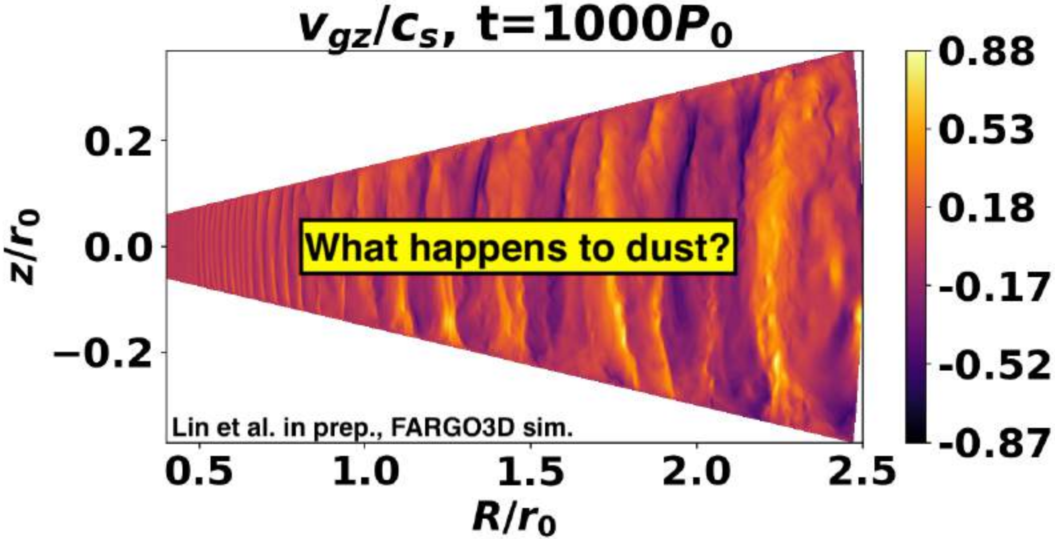
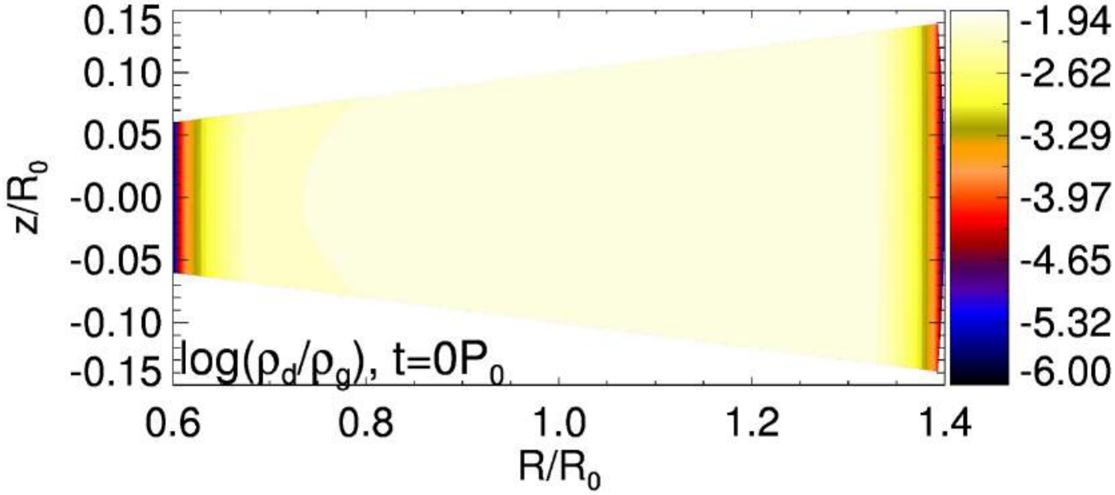


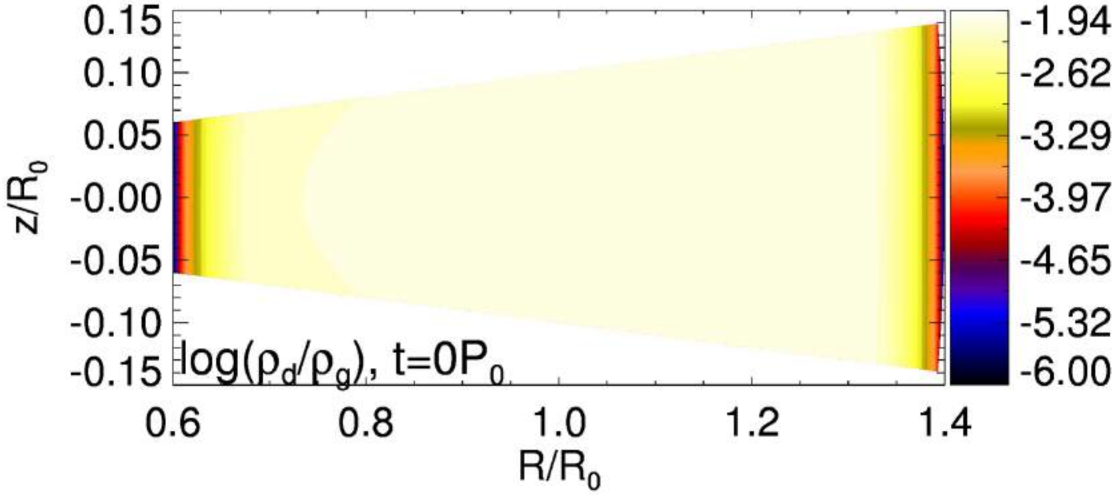
# Lifting dust particles by the VSI

Moderately turbulent disk

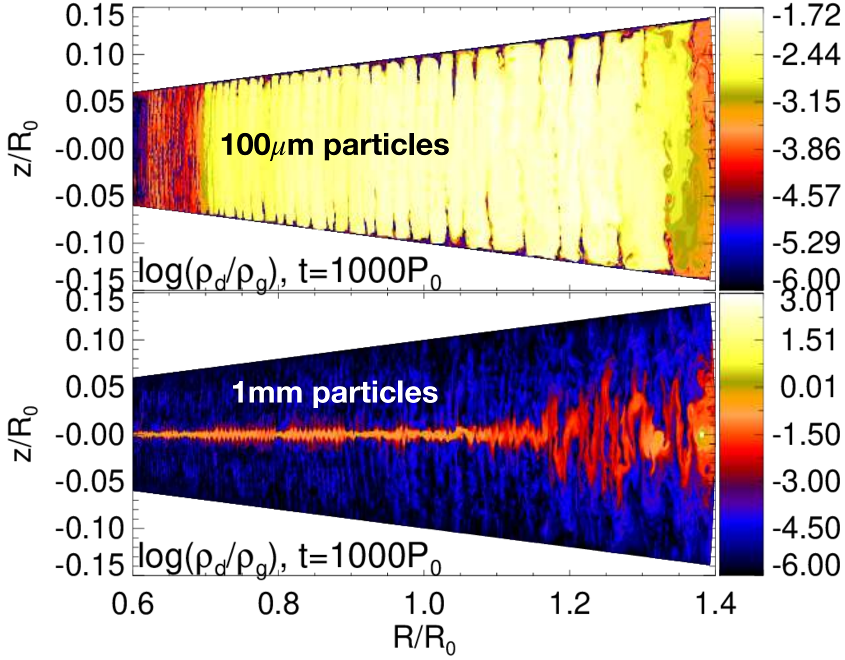


# Lifting dust particles by the VSI

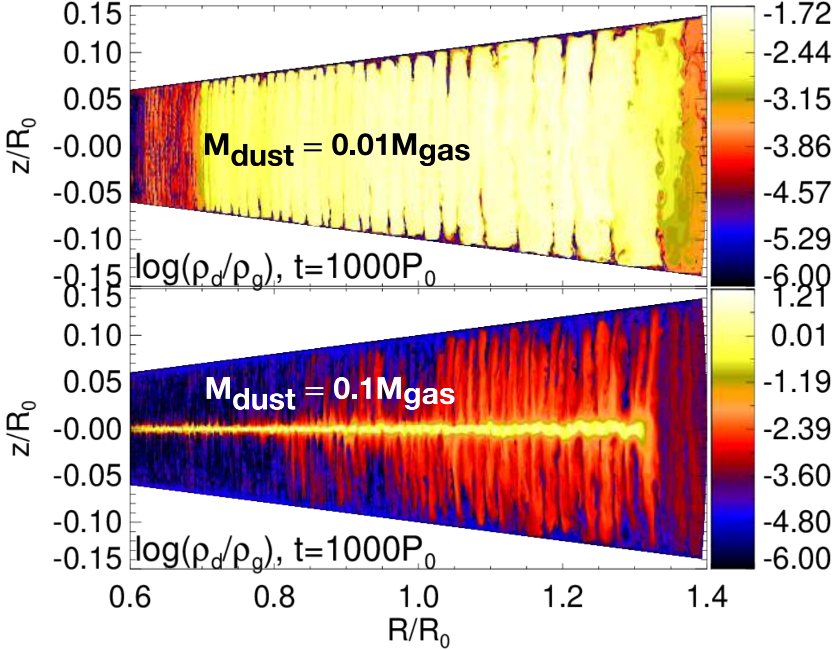
Strongly turbulent disk



# Effect of particle size



# Effect of metallicity (Lin, 2019; one-fluid approx.)




- Dust-loading → buoyancy → stabilizes VSI

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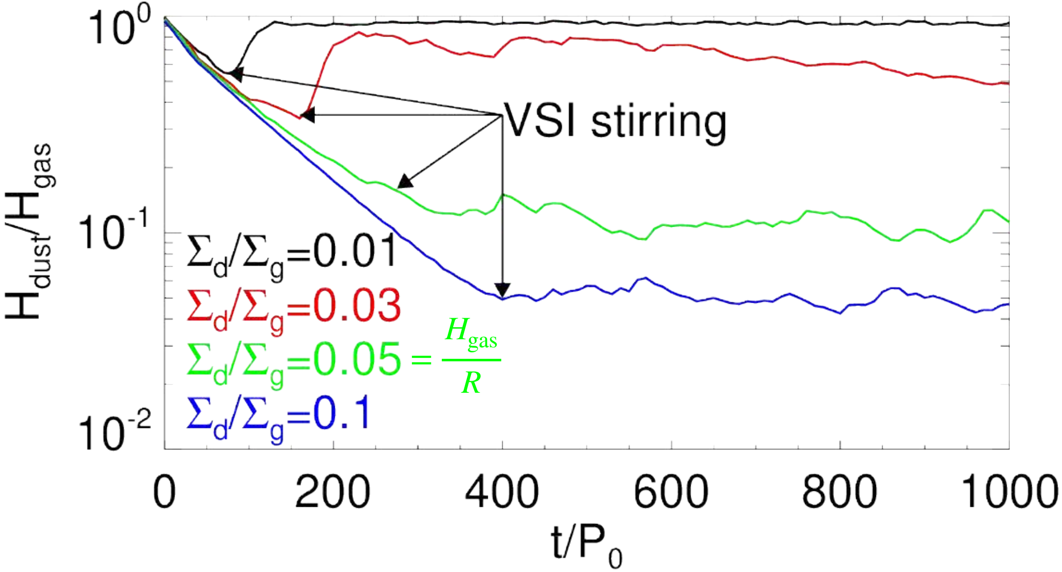


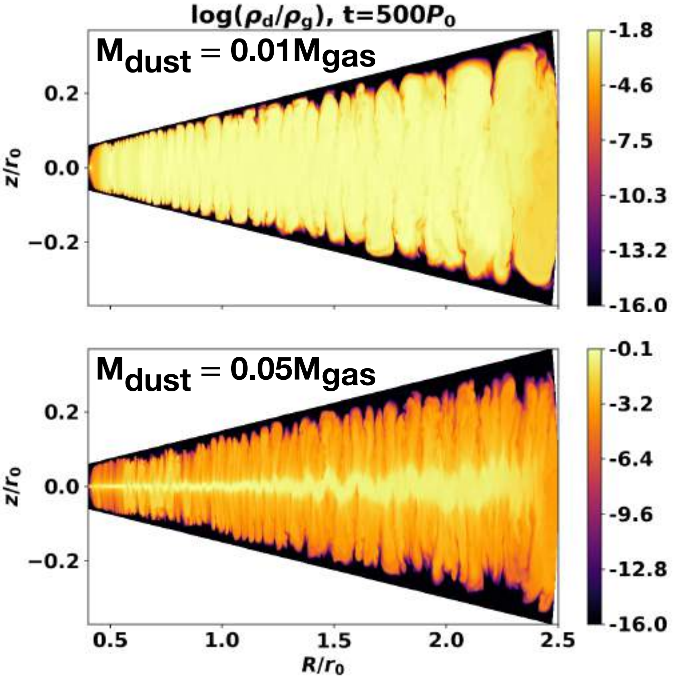

- More dust settles to thinner layers

# How much dust can overcome the VSI?

$$\Sigma_{\mathrm{dust}} \gtrsim \frac{H_{\mathrm{gas}}}{R}\Sigma_{\mathrm{gas}}$$

- Compare destabilizing effect of vertical shear, $\partial_z\Omega \propto H_{\mathrm{gas}}/R$ with
- Stabilizing effect of dust-loading, $\Sigma_{\mathrm{dust}}/\Sigma_{\mathrm{gas}}$

# New: full two-fluid treatment with FARGO3D



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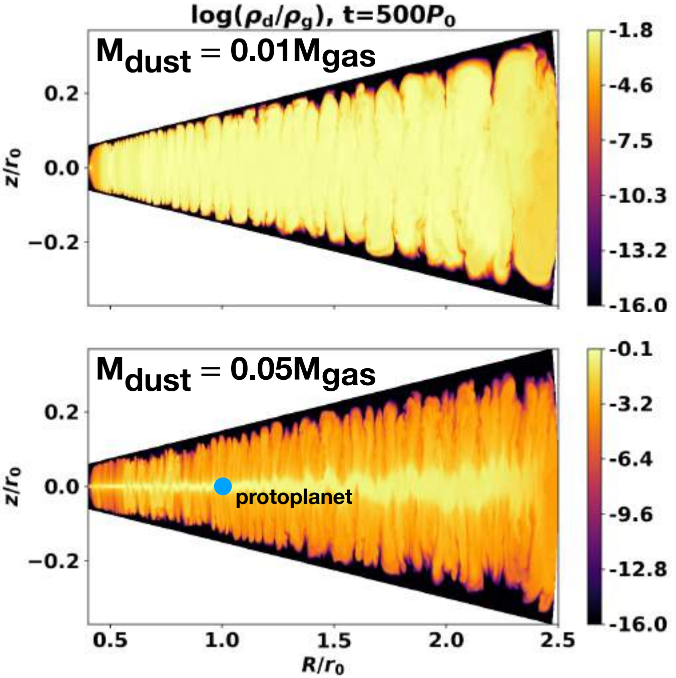
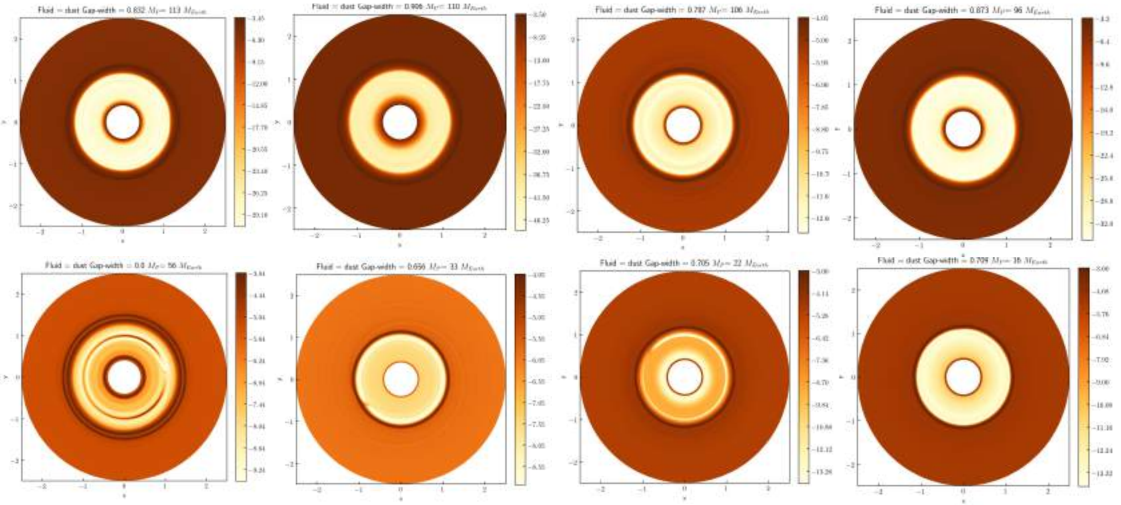
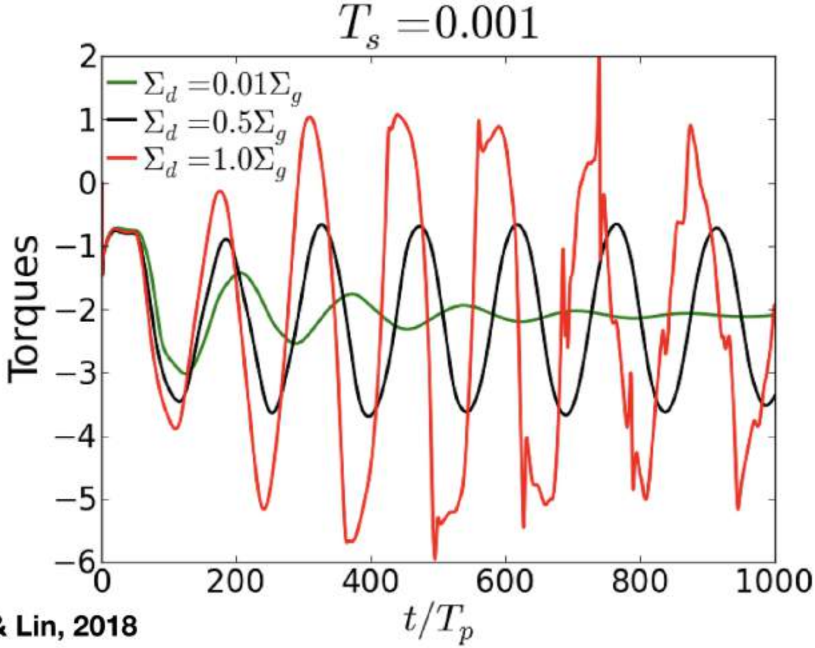


# Planet gaps and dust rings



Auddy & Lin, in prep.: application of machine learning to many-parameter surveys

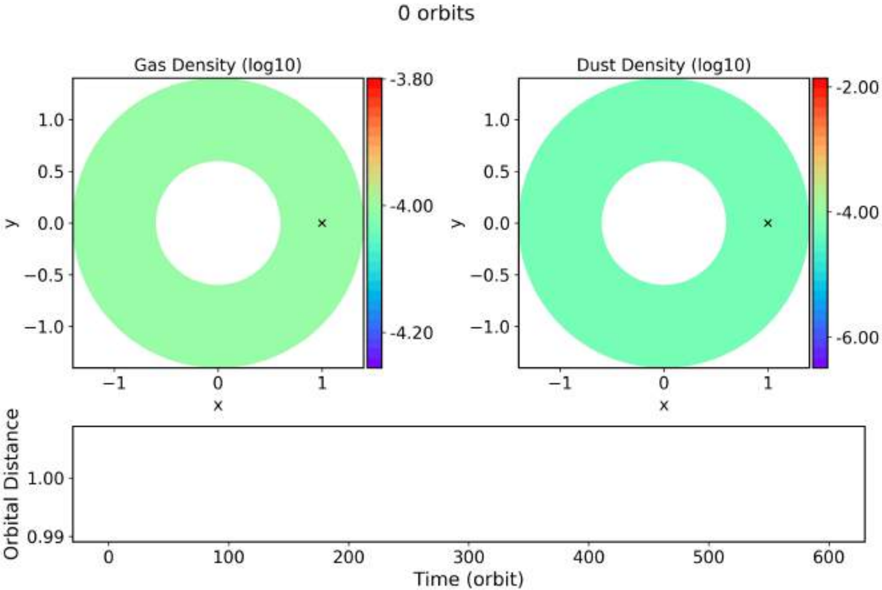
# Oscillatory torques in dusty disks



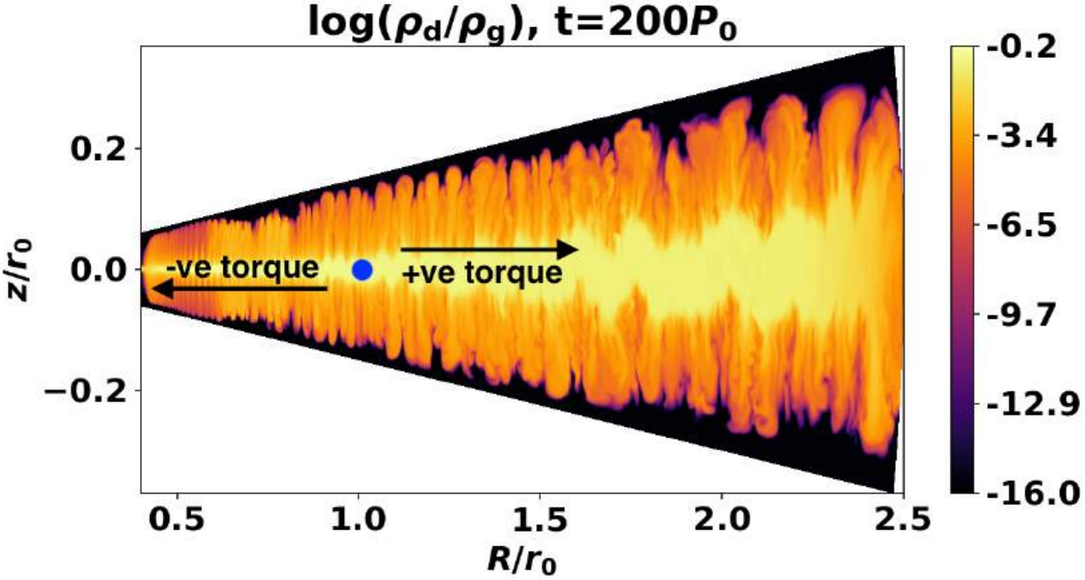

**Chen & Lin, 2018**

# Planet migration in dust-rich disks

Hsieh & Lin, in prep.

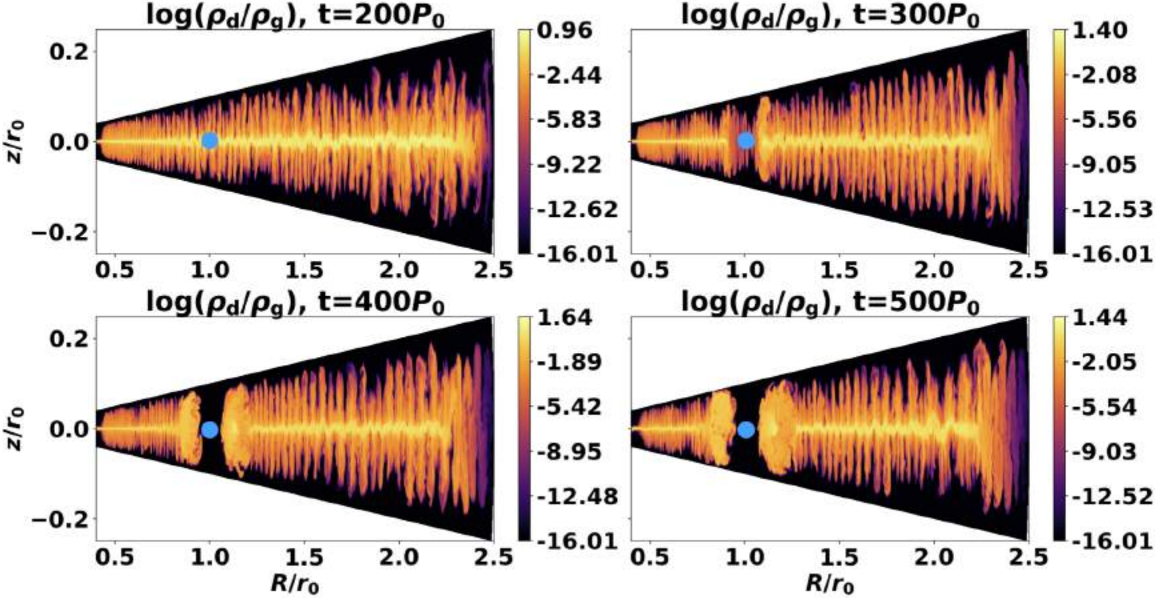


# What happens in 3D?



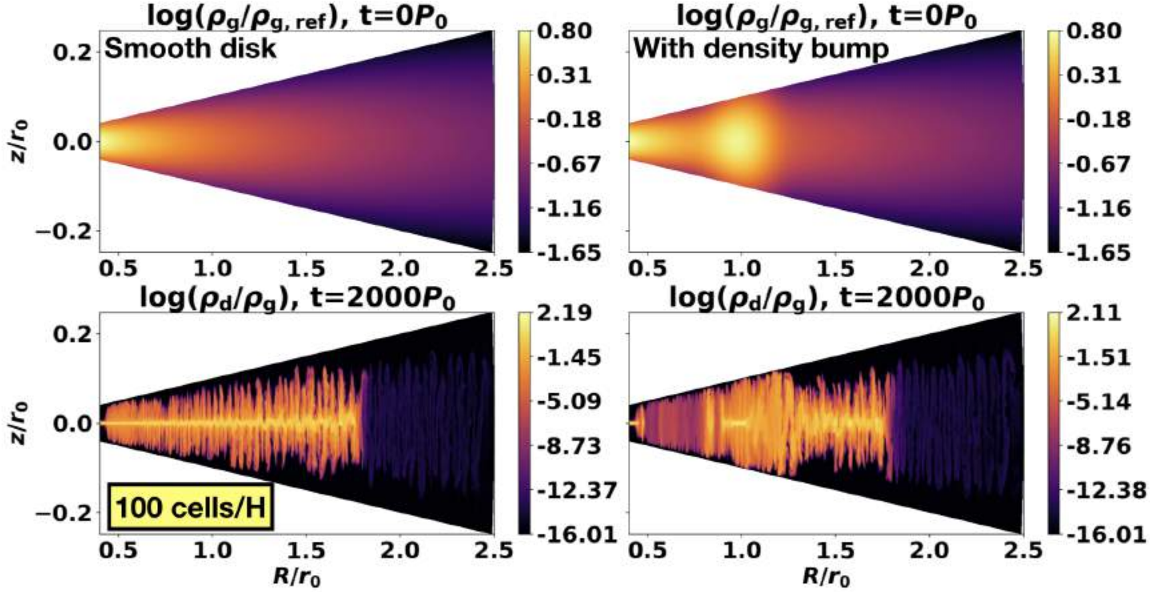
# Fake planet-disk simulations

(Lin & Tong, in prep.)



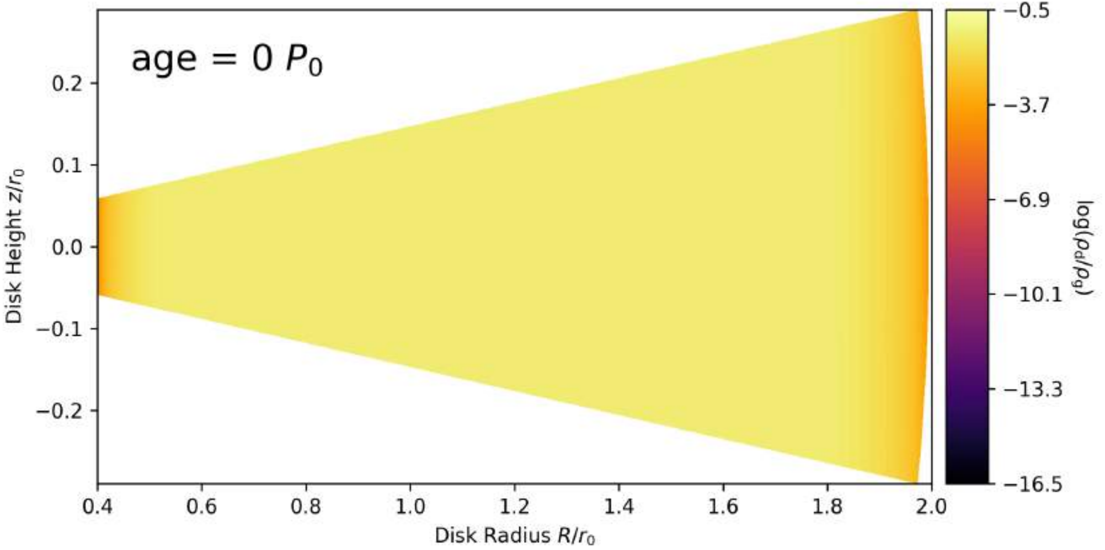
# Simplified setup with pressure bumps

(Lin & Tong, in prep.)



# Full 3D simulations

(Bi, Lin, & Dong, in prep.)



# Advertisement


- Seeking collaborations (zero wait times right now)

# Summary

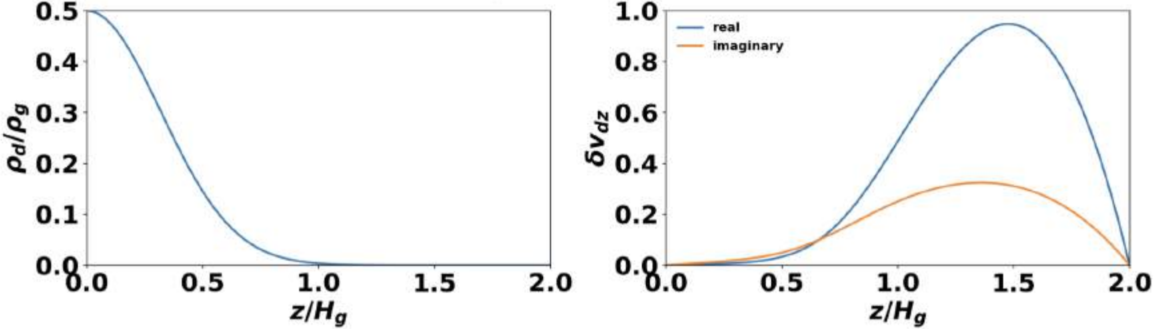
- Dust is fundamental to planet formation and evolution
- A simple model for dust-gas dynamics (Lin & Youdin, 2017)
- Dust settling depends on solid abundance (Lin, 2019)
- Dust-rich disk-planet interaction (Chen & Lin, 2018)
- How does dust settling proceed in structured disks, e.g. near planet gaps? Observational implications?

# Waves in stratified dusty disks

Stokes number = 0.01

Diffusion = $0.001 c_s H_{\text{gas}}$

Decay rate = $-0.01\Omega$



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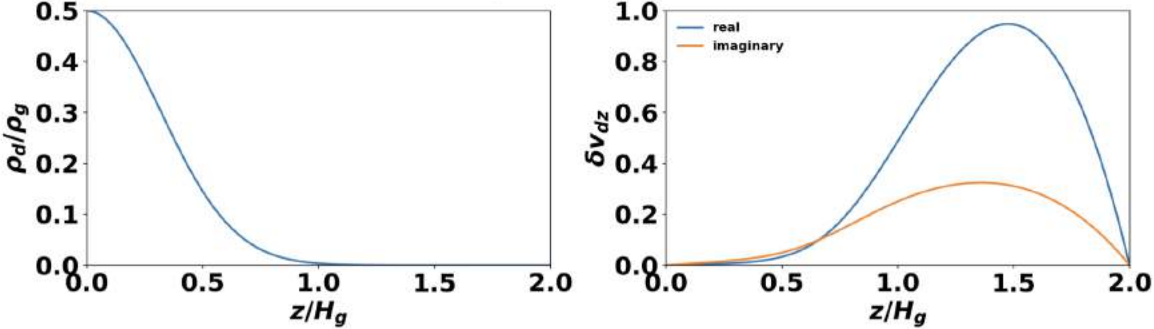


**Thank you**


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