Vertical shear instability in dusty protoplanetary disks

Min-Kai Lin

November 2022

中央研究院 ASIAA

NCTS National Center for Theoretical Sciences, Physics Divisions

NSTC 國家科學及技術委員會 National Science and Technology Council

NCHC NARLabs 財團法人國家實驗研究院 國家高速網路與計算中心 National Center for High-performance Computing

Why consider dust & VSI?

Thermal role:

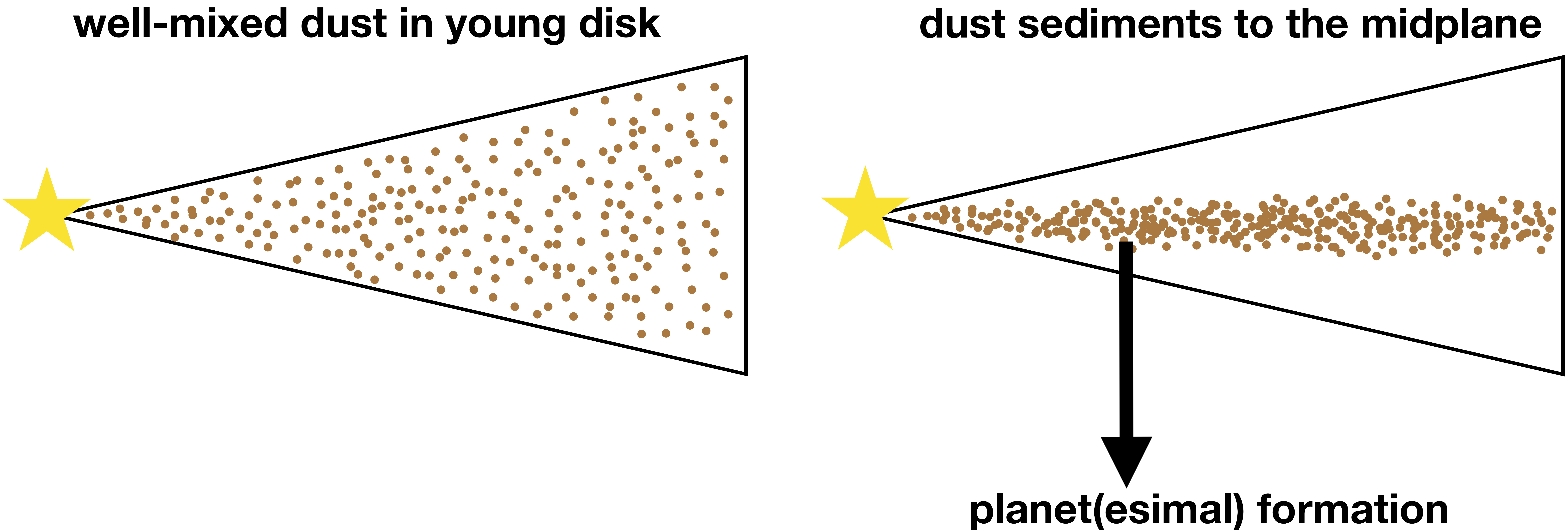
- Rapid cooling & radial temperature gradient ← dust distribution

Yuya and Thomas' talks

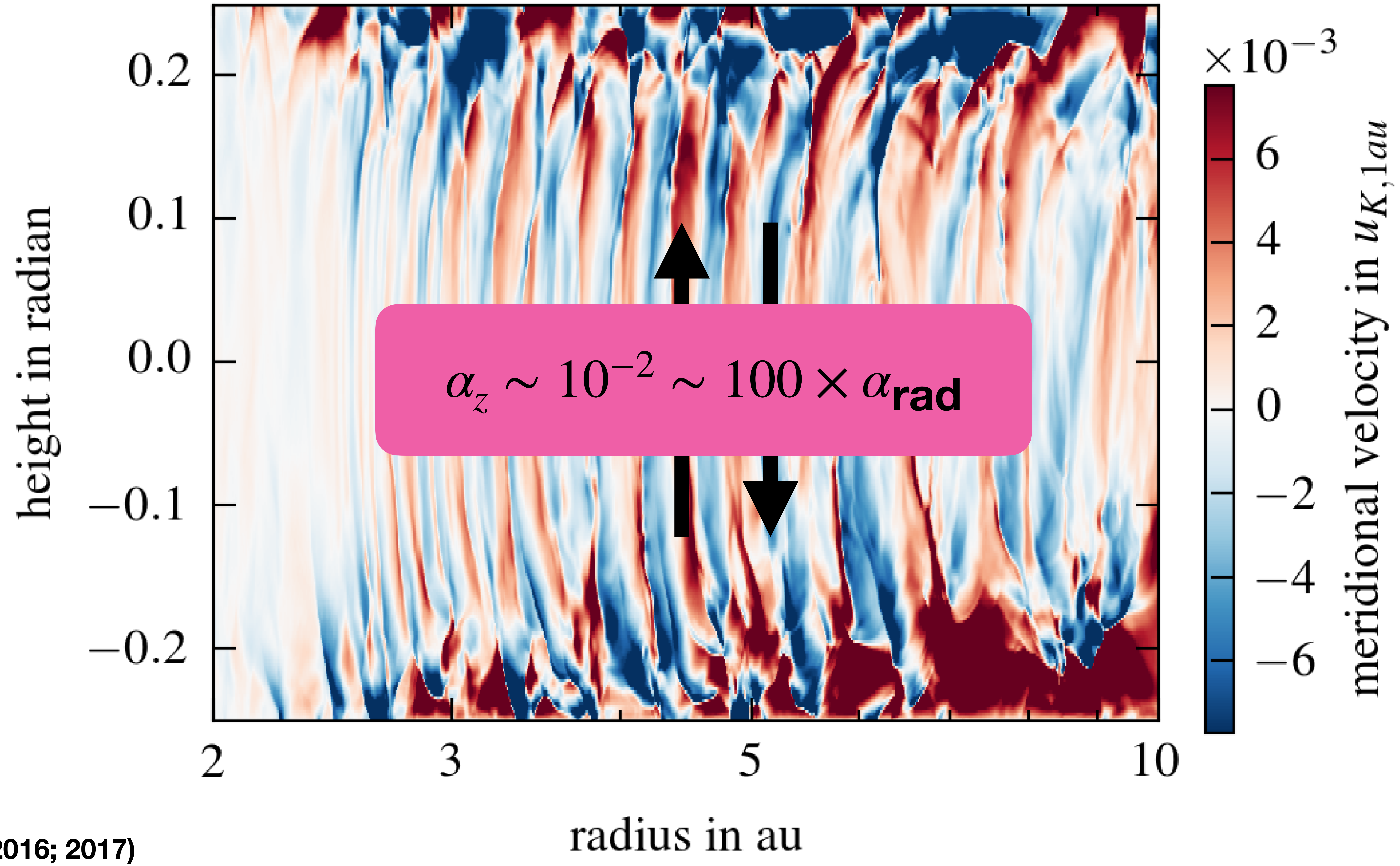
Dynamical role:

- Large vertical gas motions → dust layer dispersal
- Zonal flows/vortices → dust concentrations →
  - observations
  - planetesimals

Dust settling

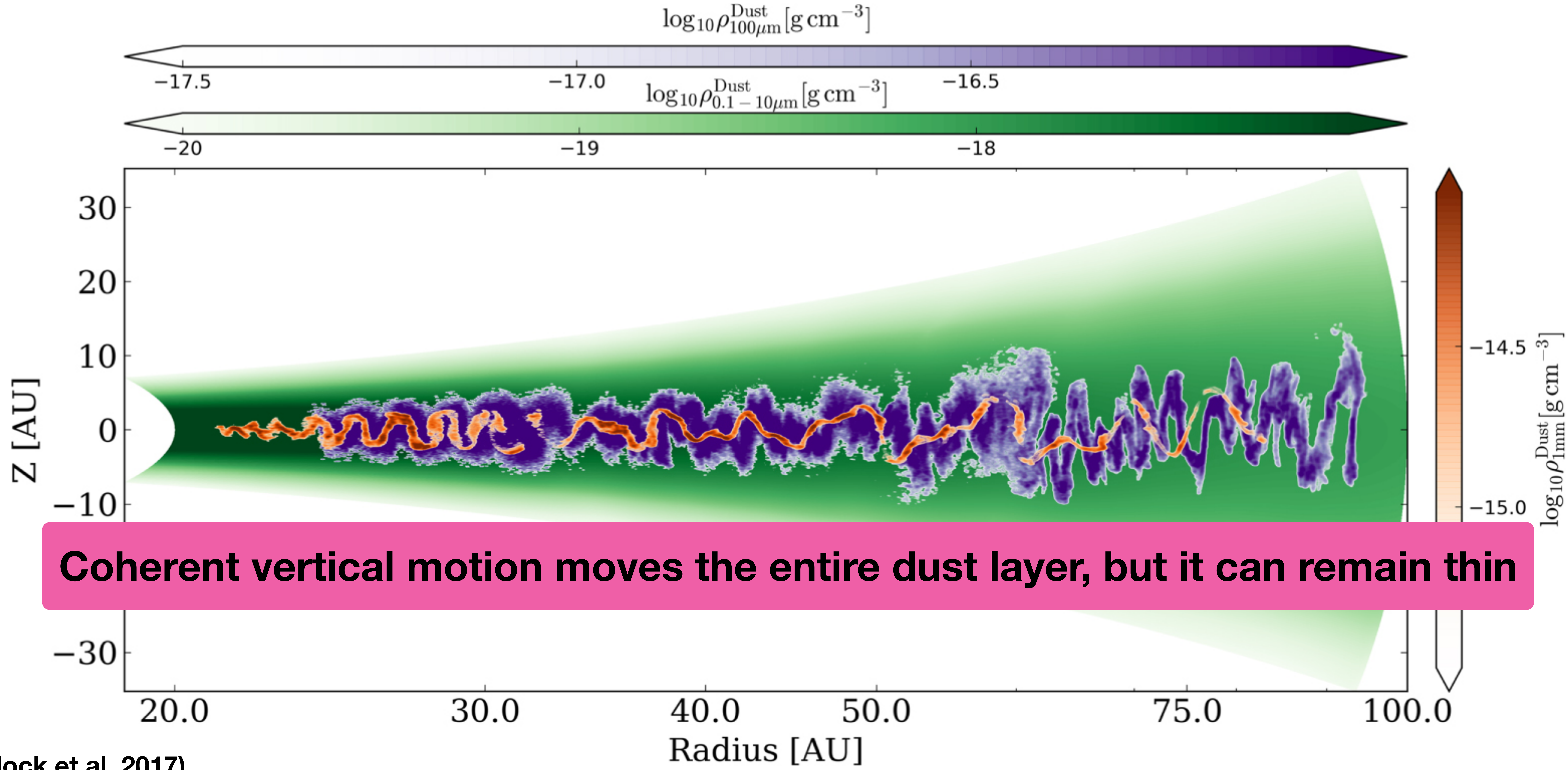


But the VSI involves strong vertical flows



(Stoll & Kley, 2016; 2017)

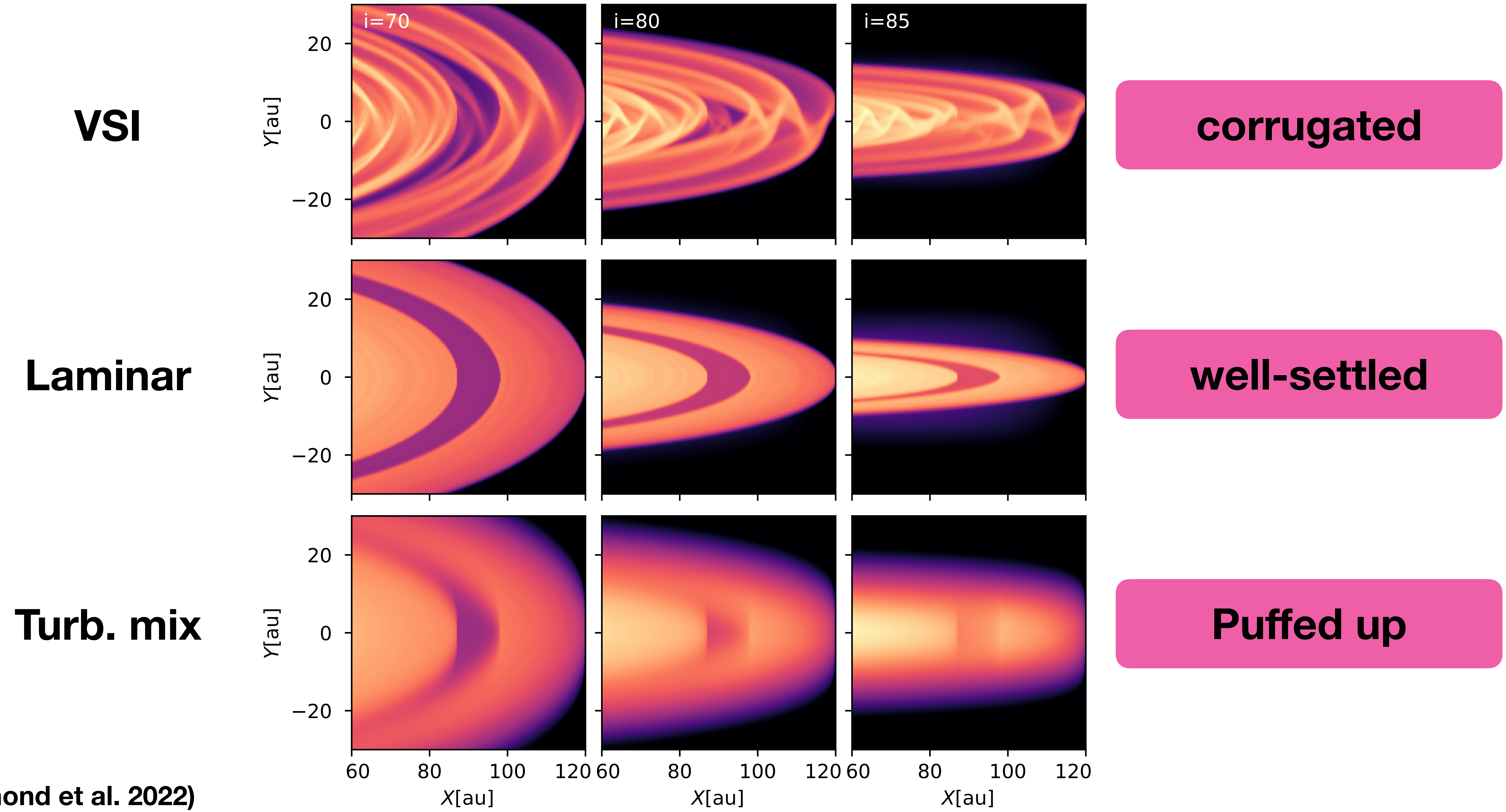
Vertical mixing and corrugated dust layers



Coherent vertical motion moves the entire dust layer, but it can remain thin

(Flock et al. 2017)

Observing VSI through dust layers

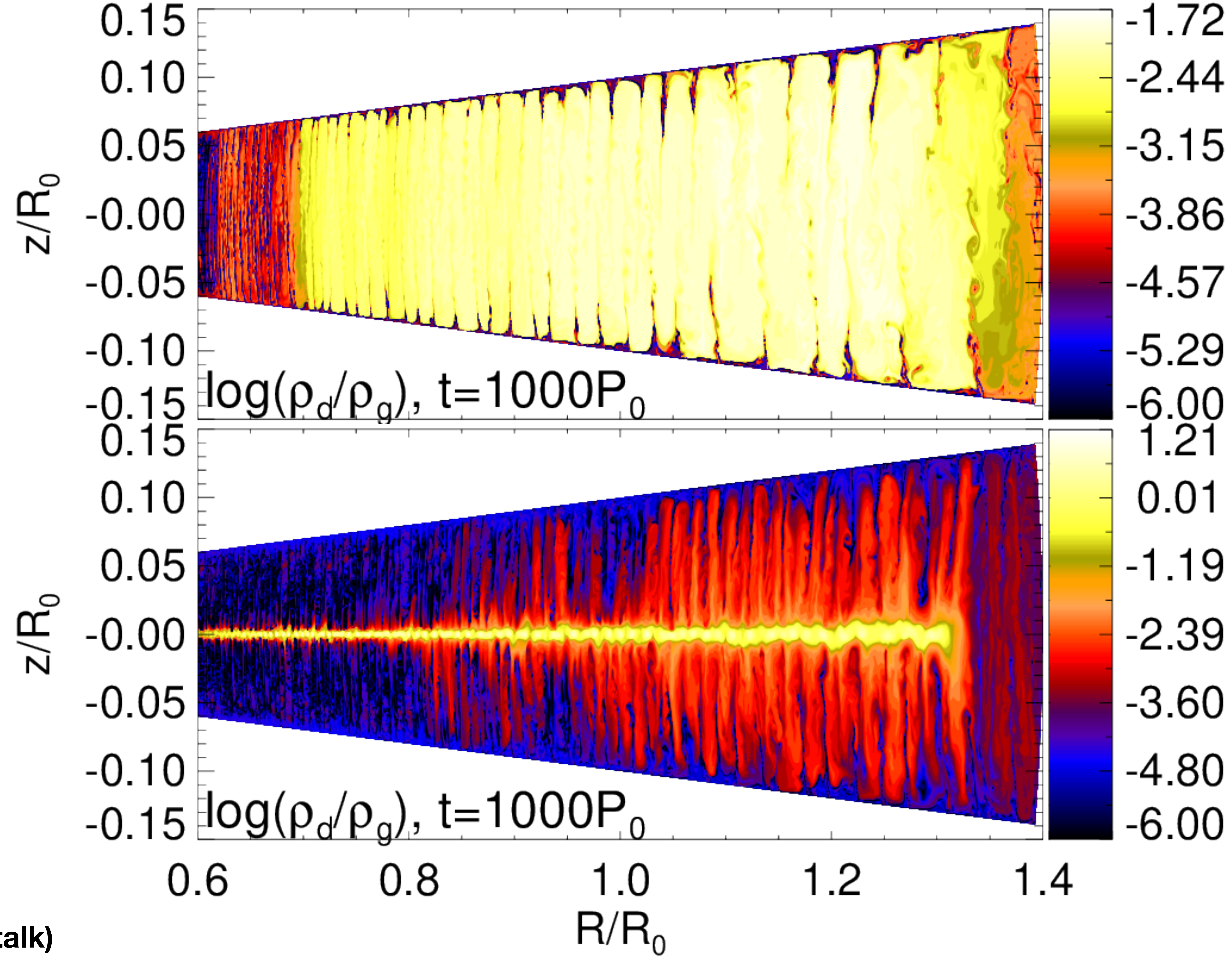


(Dullemond et al. 2022)

Overcoming VSI stirring by dust feedback

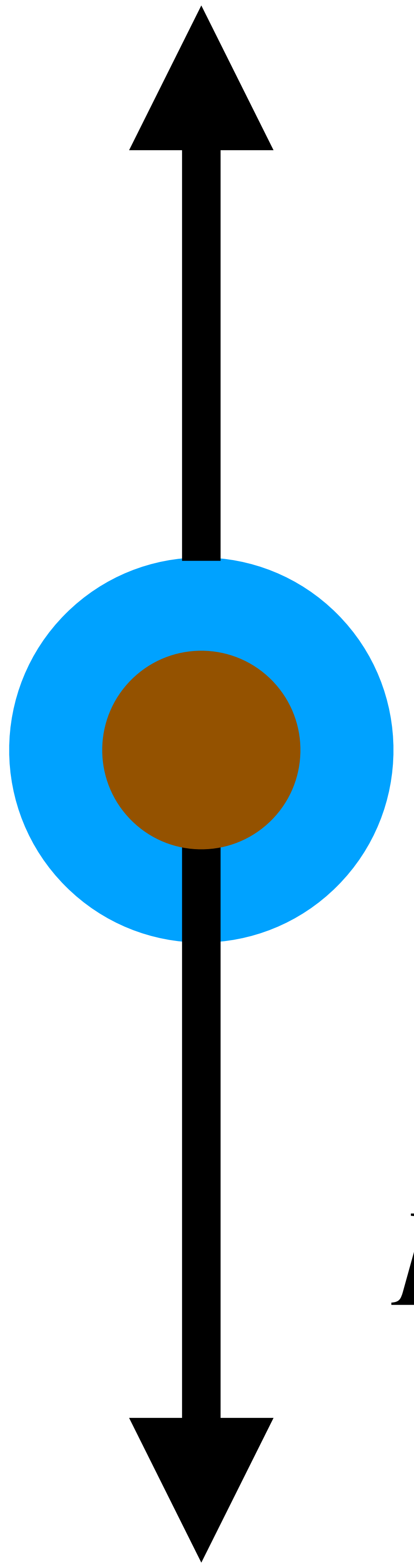
$M_{\textbf{dust}} = 0.01 M_{\textbf{gas}}$

$M_{\textbf{dust}} = 0.1 M_{\textbf{gas}}$



(Lin 2019: single-fluid approx. — See Marius' talk)

Dust-induced buoyancy

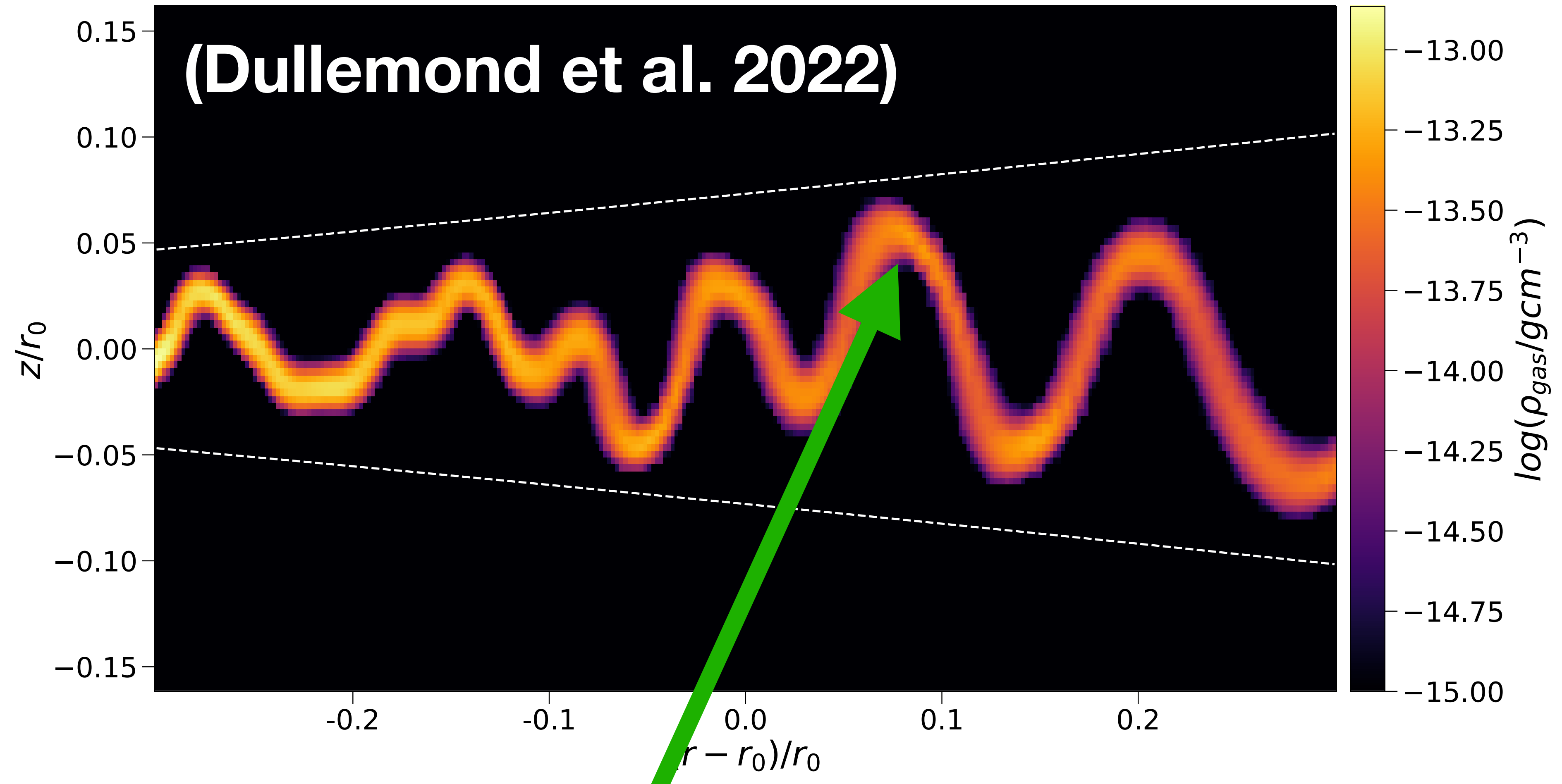


$F_{\mathbf{VSI}}$

$F_{\mathbf{B}} \propto N_z^2$

dust "weighs down" gas

$$N^2_{z,\mathbf{dust}} \sim -\frac{\partial}{\partial z}\left(\frac{\rho_{\mathbf{d}}}{\rho_{\mathbf{g}}}\right) \times \Omega^2$$

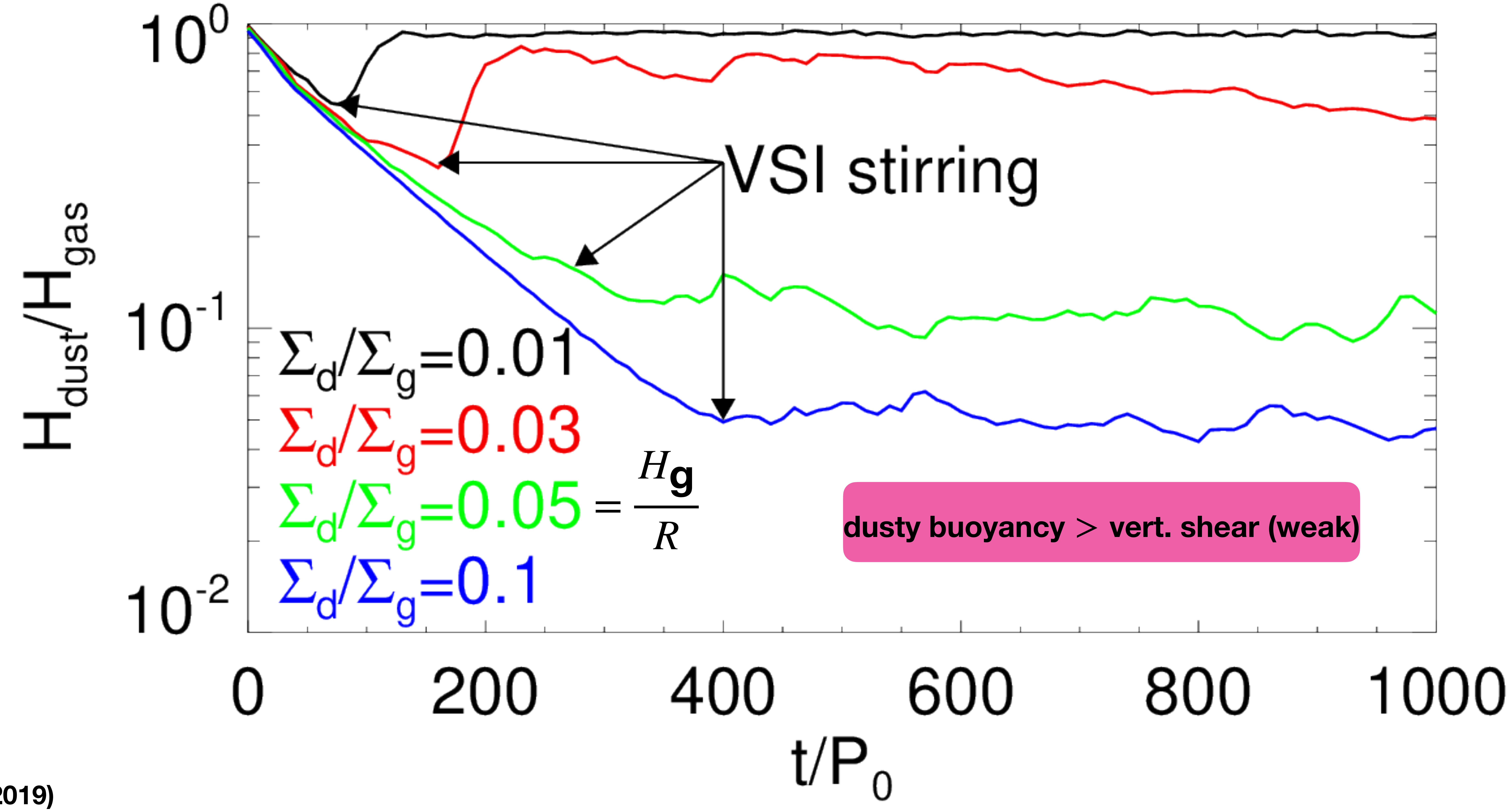


$N^2_{z,\mathbf{dust}} < 0$ **(top-heavy: unstable!)**

dust gradients $\longrightarrow$ **entropy gradients**

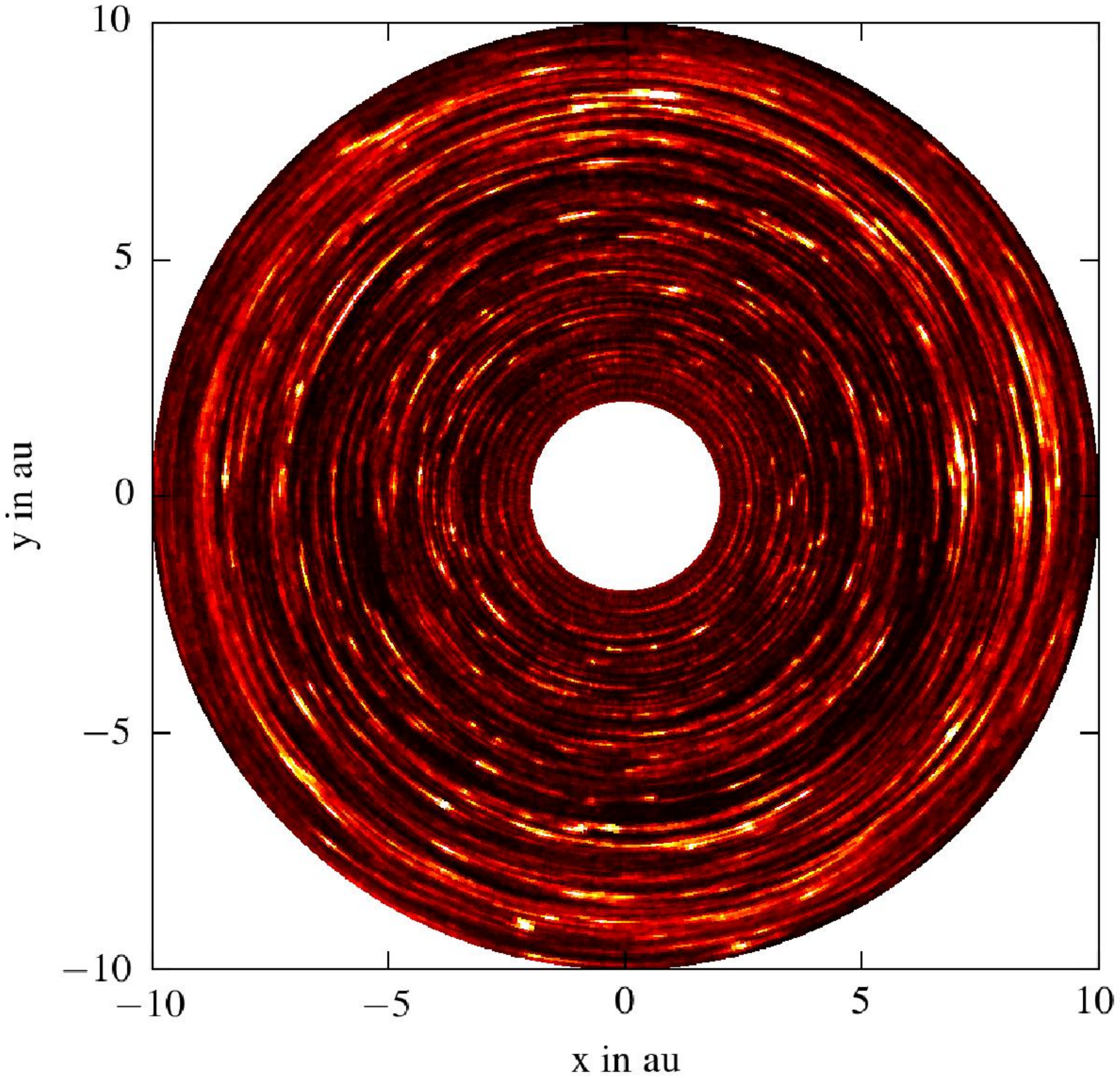
(Lin & Youdin, 2017; Lin 2019)

More dust leads to thinner layers



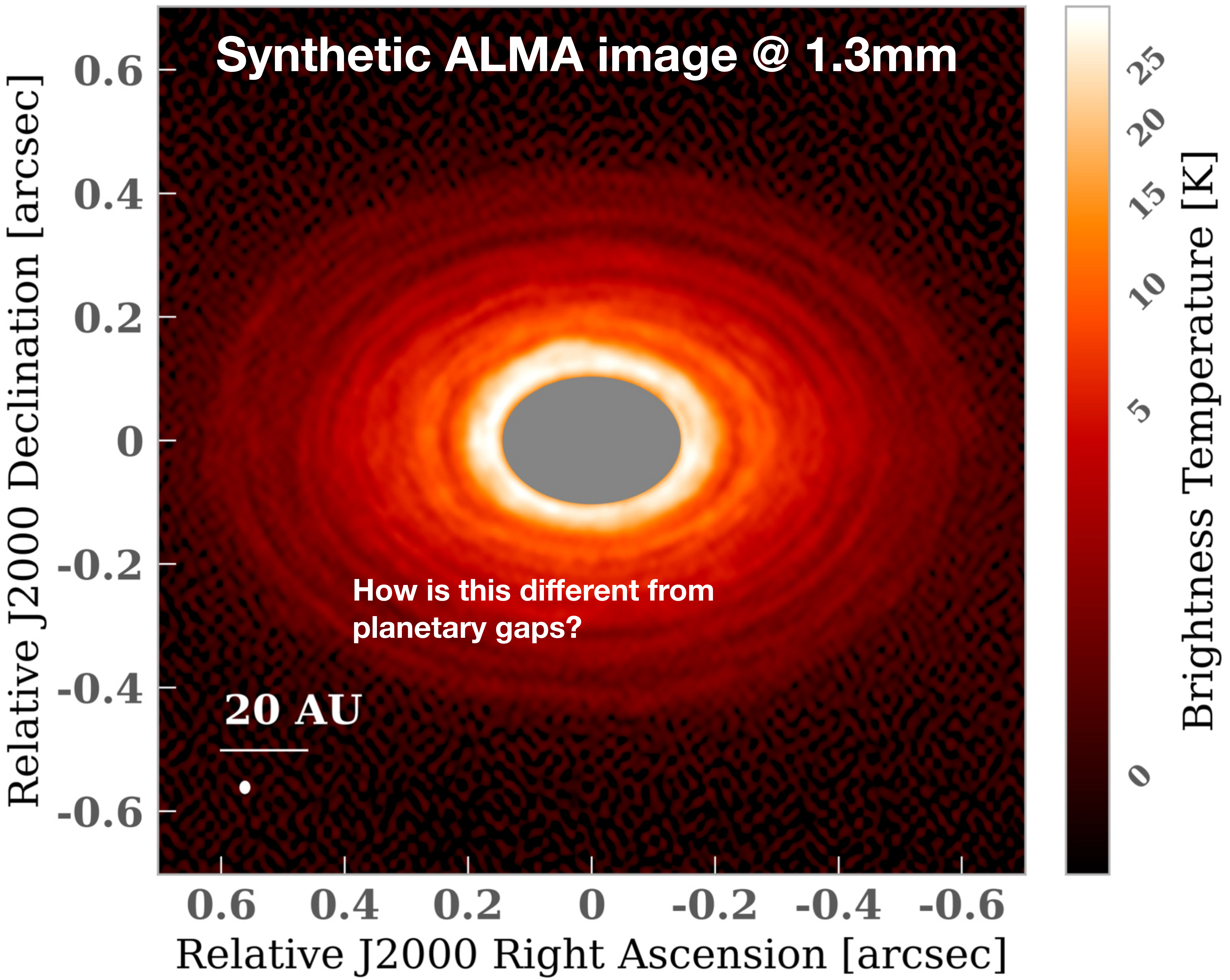
(Lin 2019)

Dust concentrations by the VSI



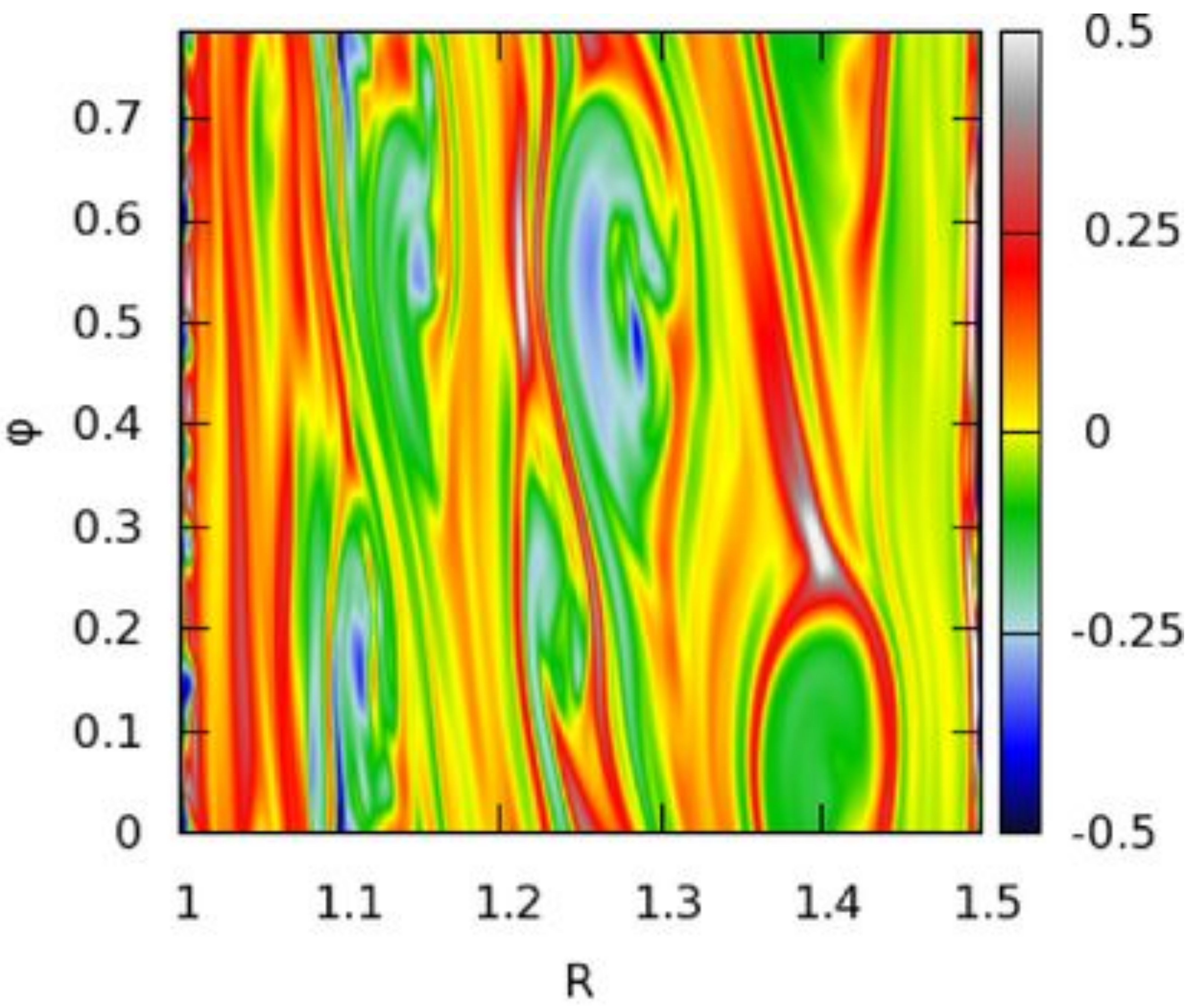
(Stoll & Kley, 2016)

Appearance of VSI rings

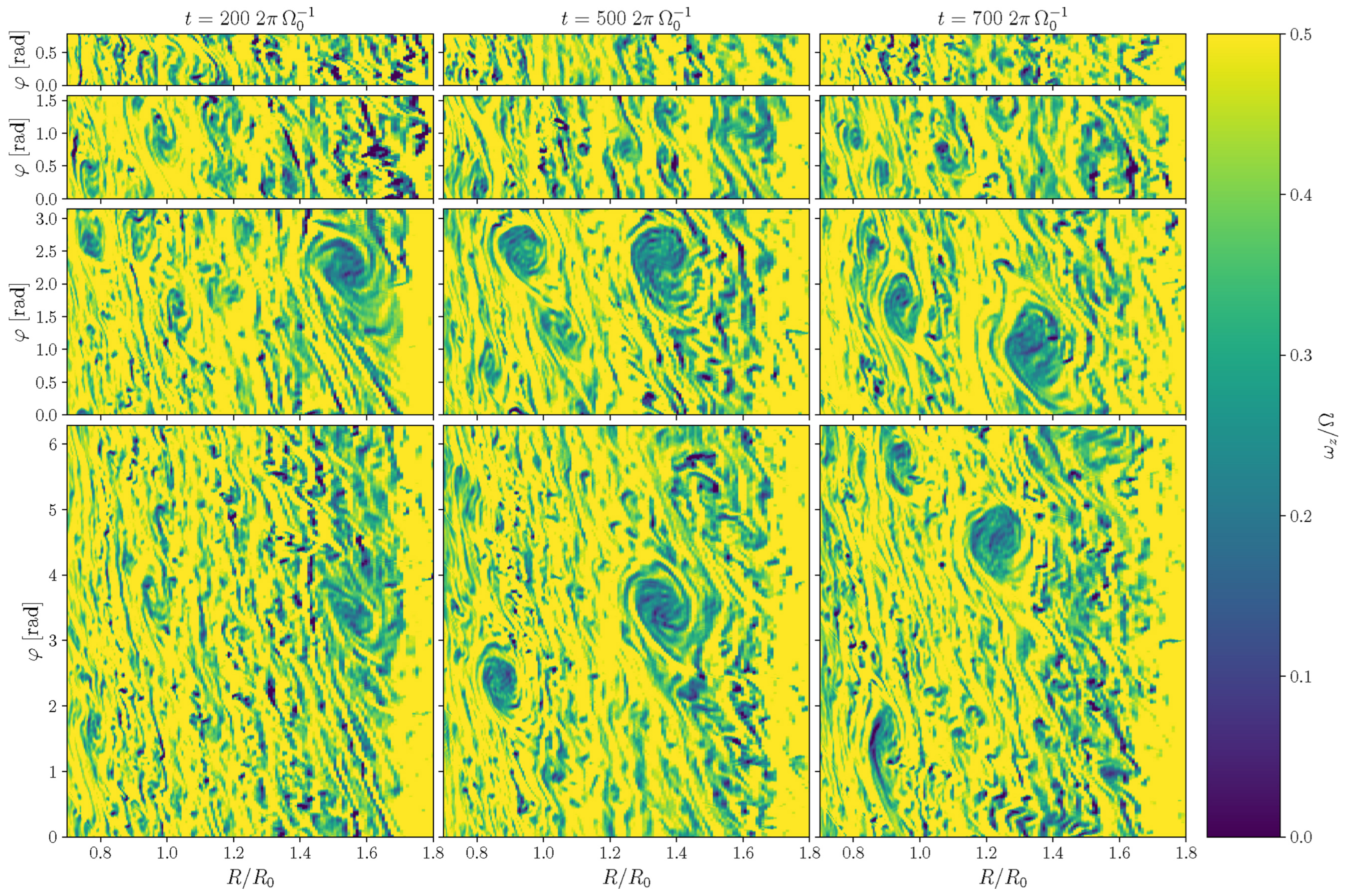


(Blanco et al. 2021)

VSI also produces vortices



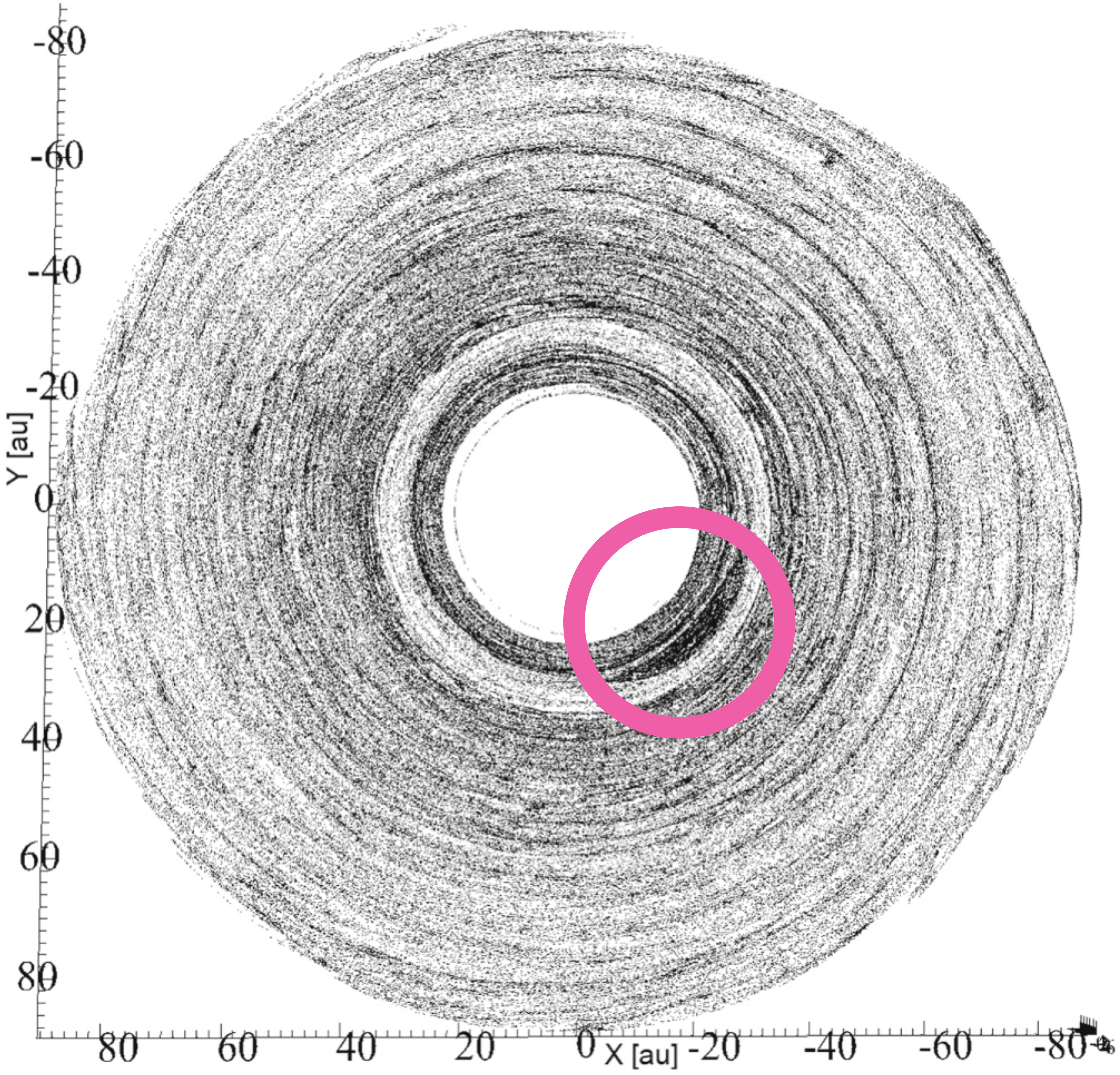
(Richard et al. 2016)



(Manger & Klahr, 2018; 2020)

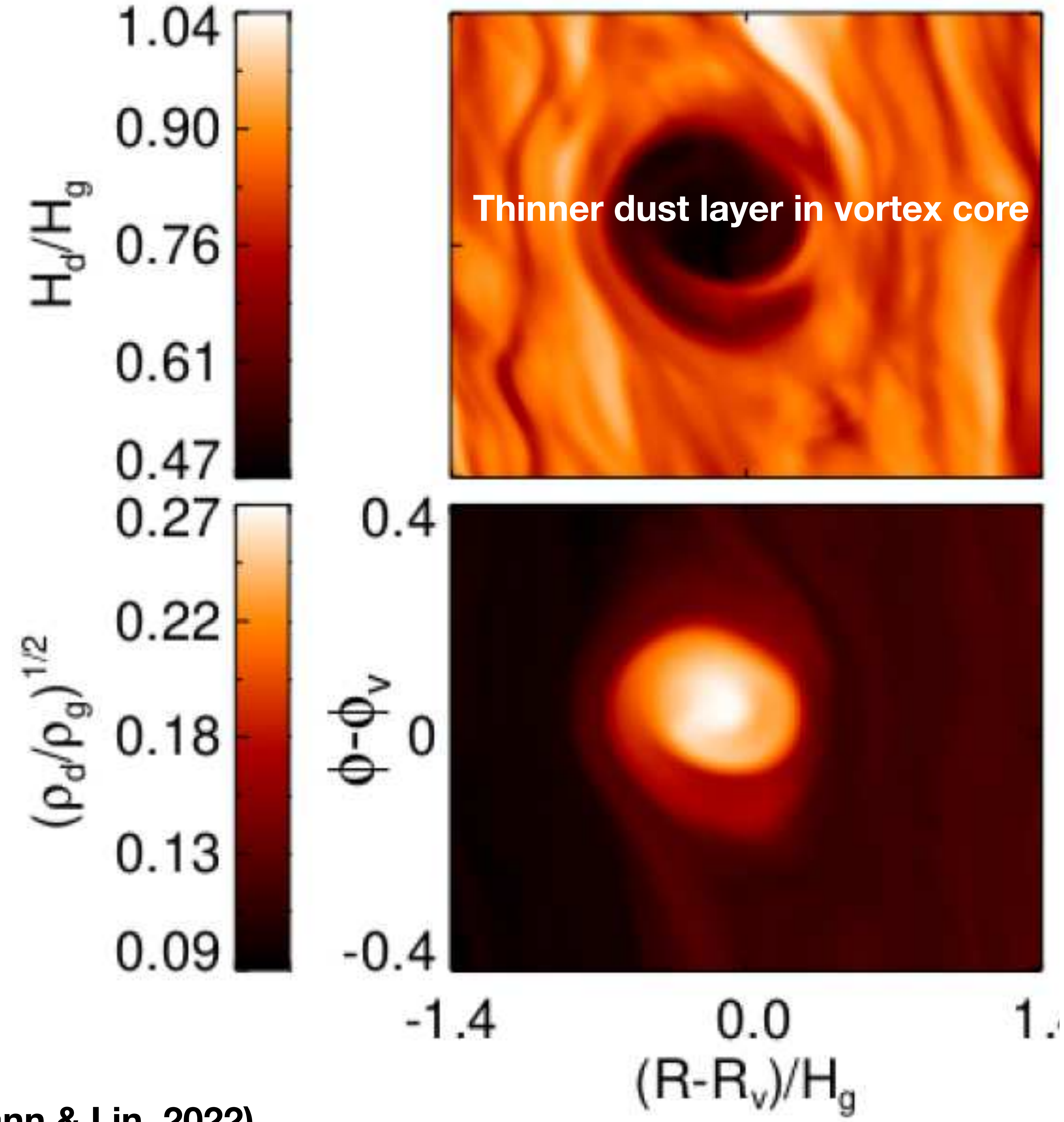
Due to: small-scale, secondary Kelvin-Helmholtz instabilits, large-scale Rossby wave instability of VSI vorticity rings, RWI of density edges from variable accretion

Dust trapping by large VSI/Rossby vortex



(Flock et al. 2020)

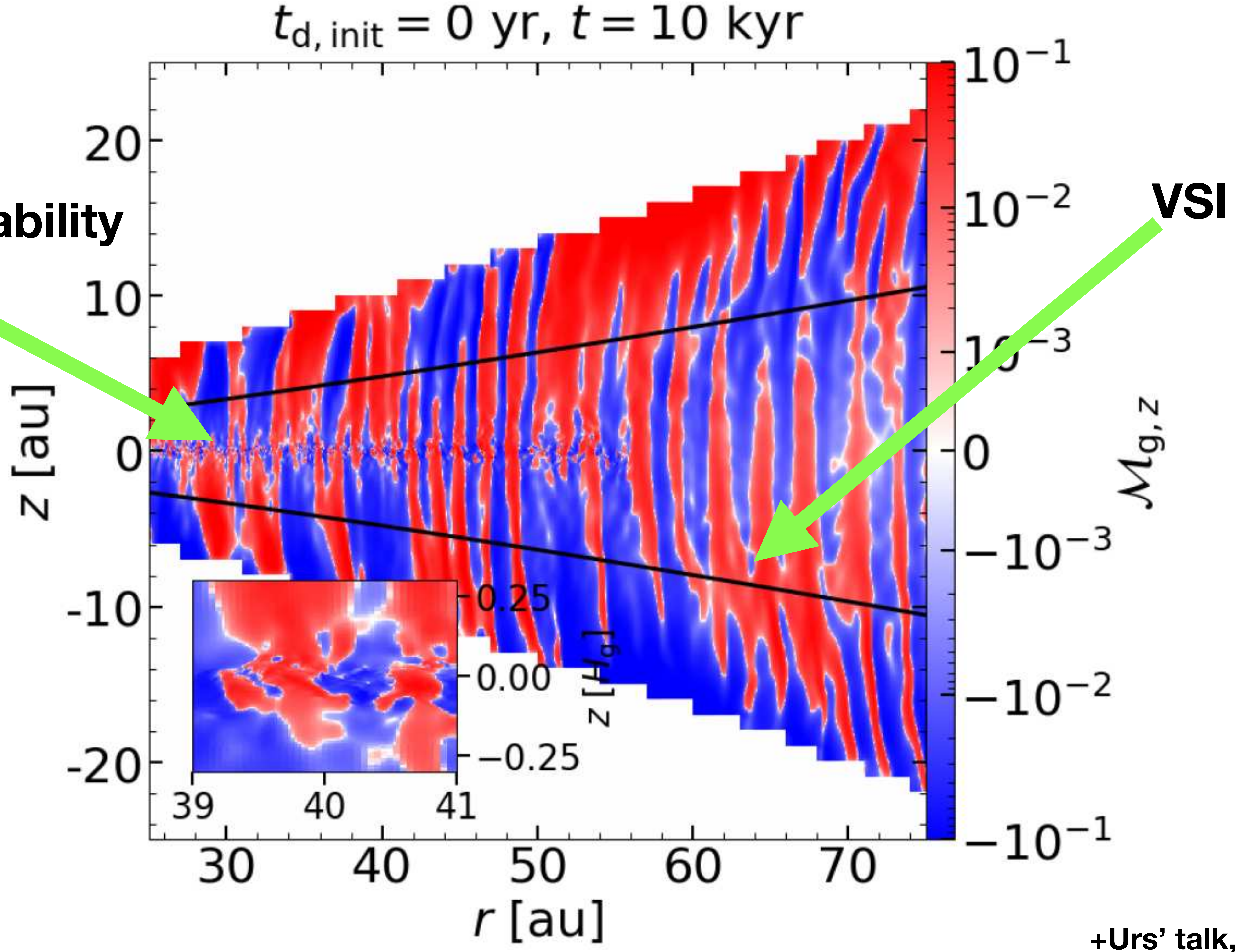
What about dust feedback & vortices?



See next talk by Marius Lehmann

(Lehmann & Lin, 2022)

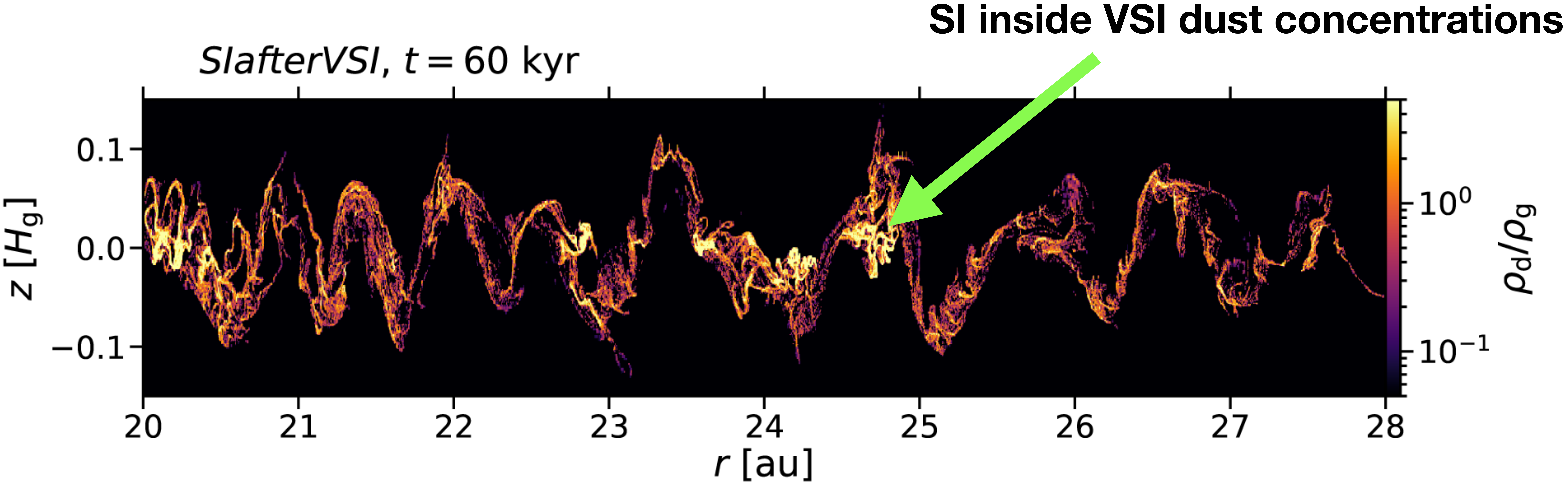
Planetesimal formation: VSI and the streaming instability



(Schafer et al. 2020)

+Urs' talk, Pinghui's poster

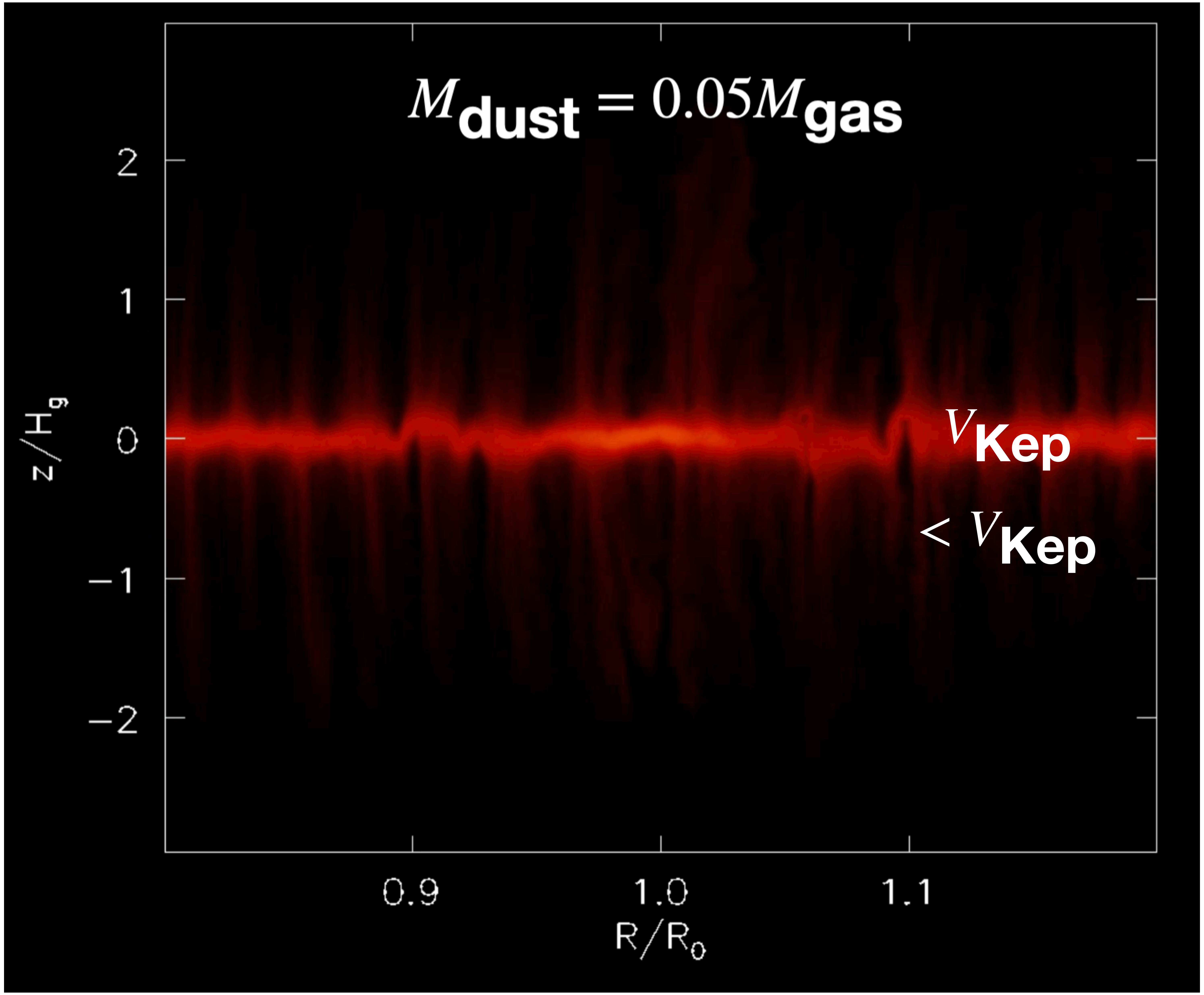
VSI-mediated SI



VSI lowers the metallicity threshold for planetesimal formation via the SI

(Schafer & Johansen 2022)

Vertical shear of the dust layer itself

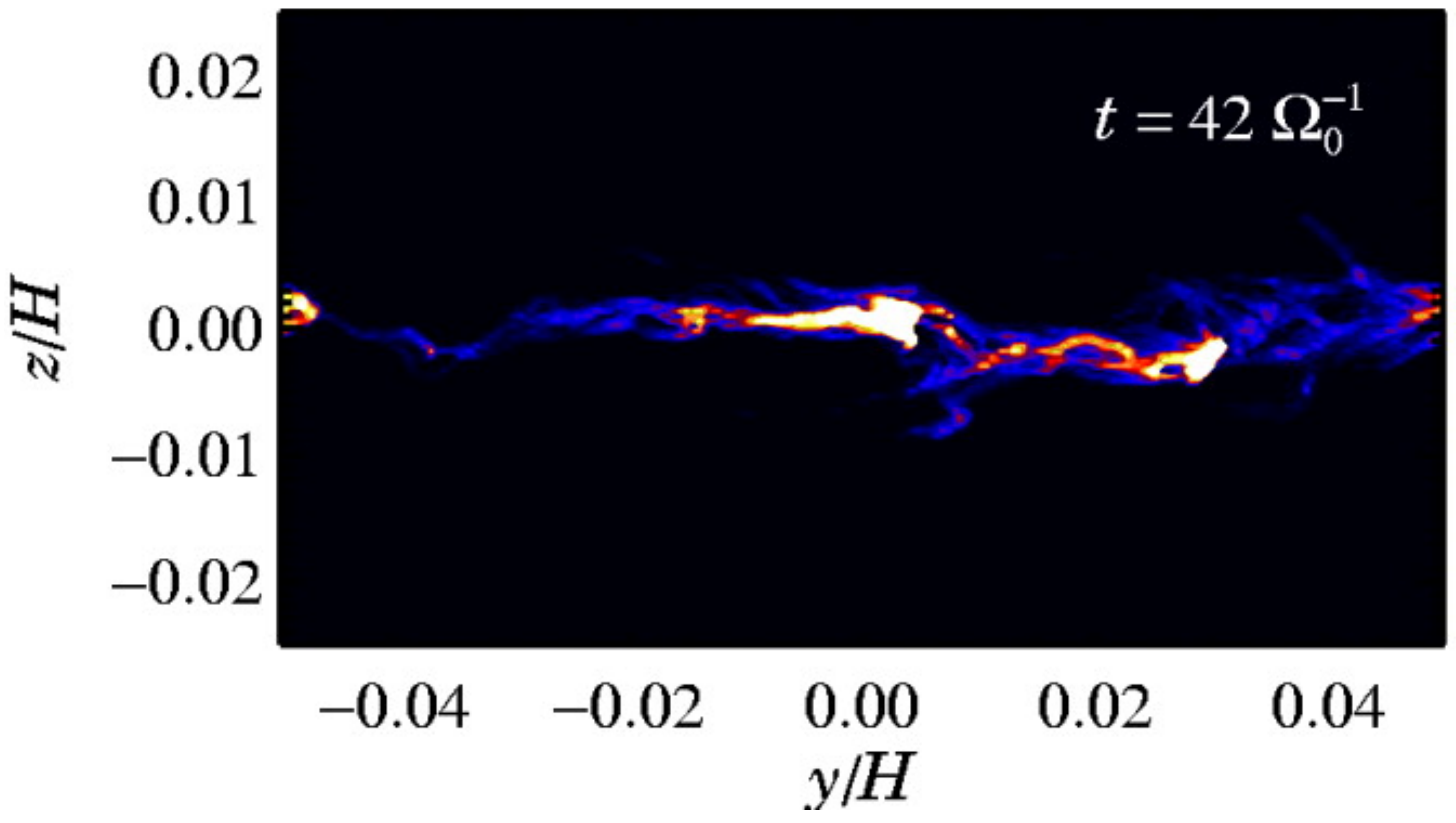


$$\frac{\partial \Omega}{\partial z} \neq 0$$

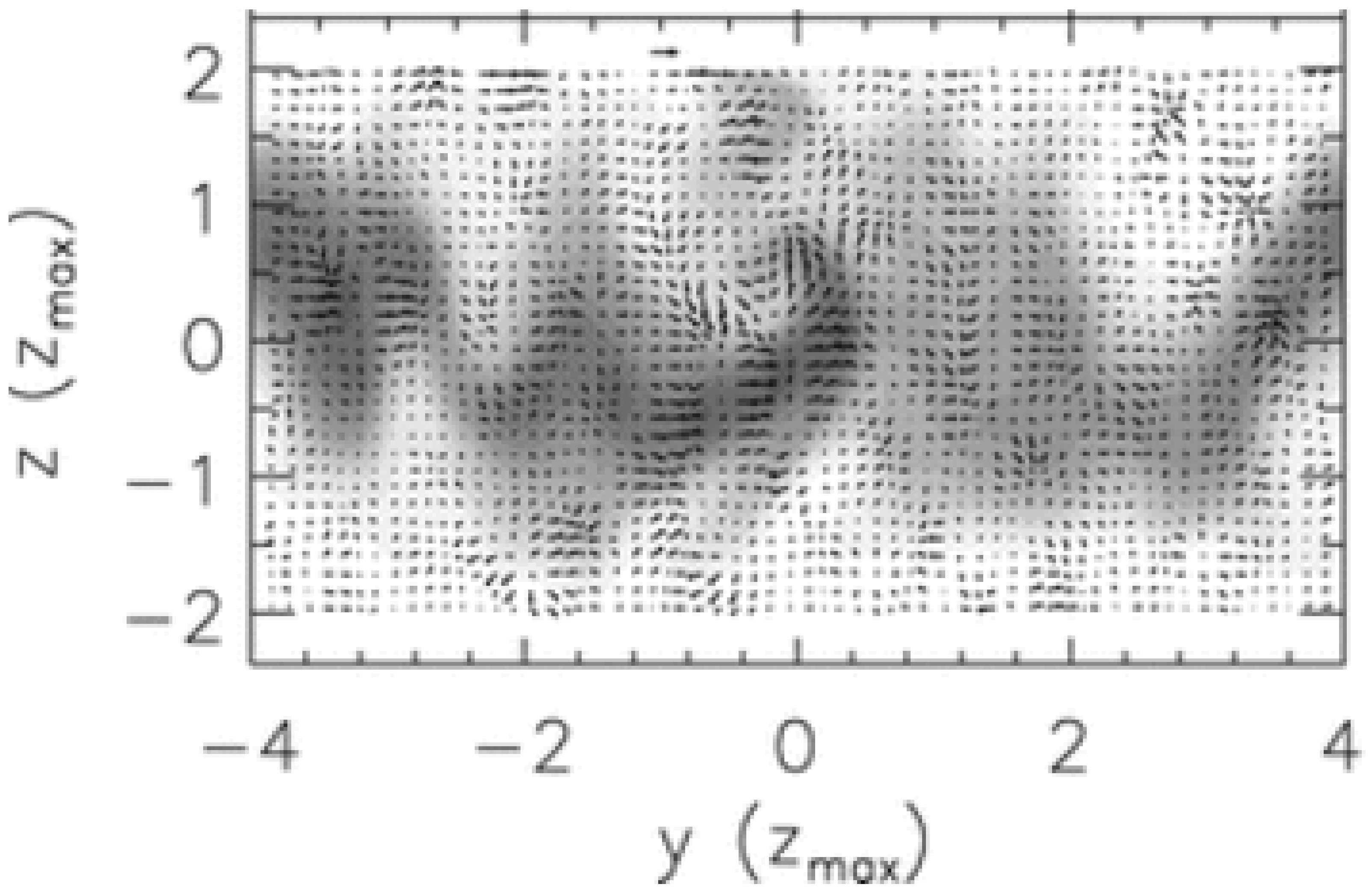
Lehmann & Lin (2022)

Kelvin-Helmholtz instability

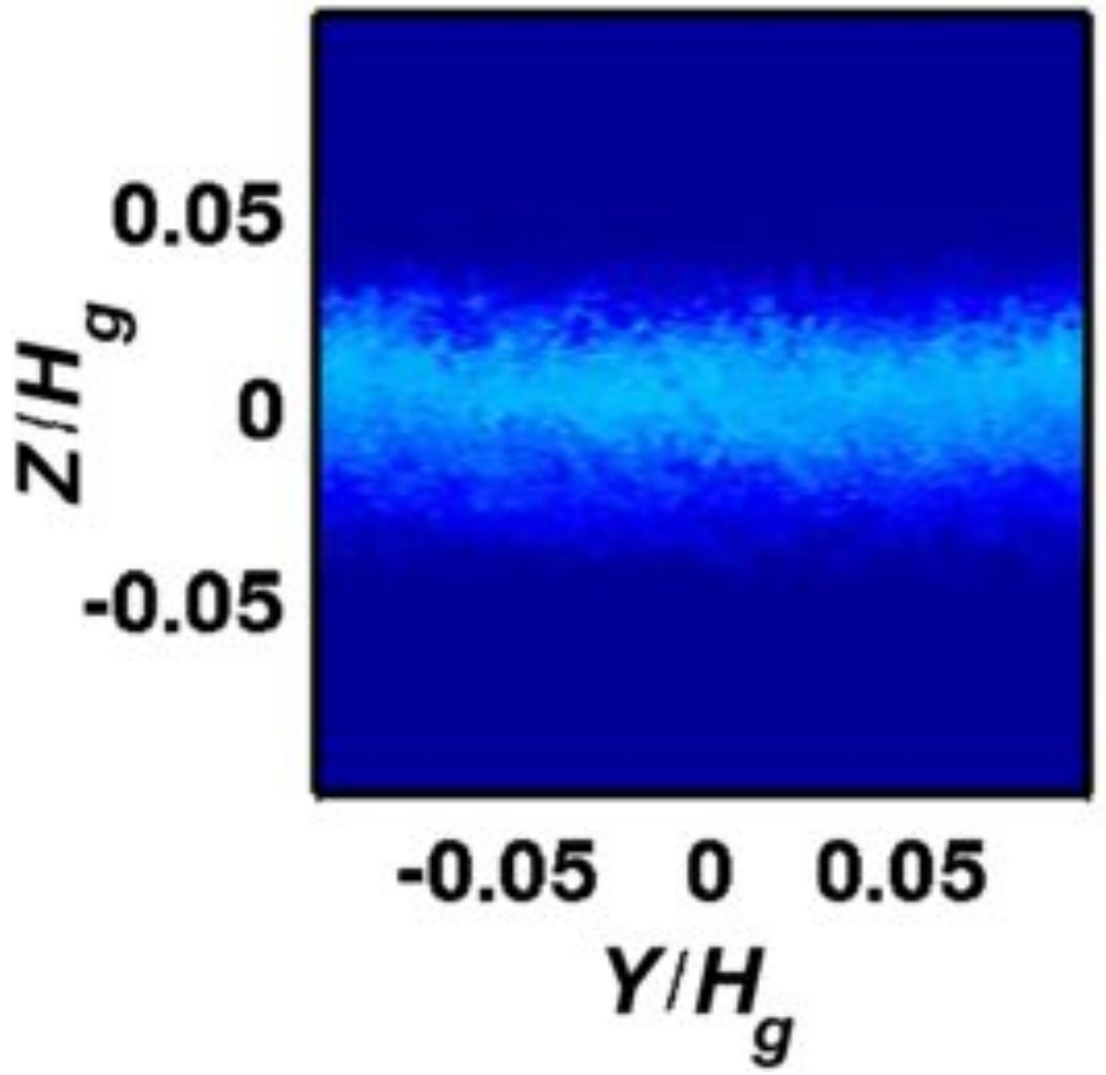
Johansen et al. (2006)



Chiang (2008)



Barranco (2009)

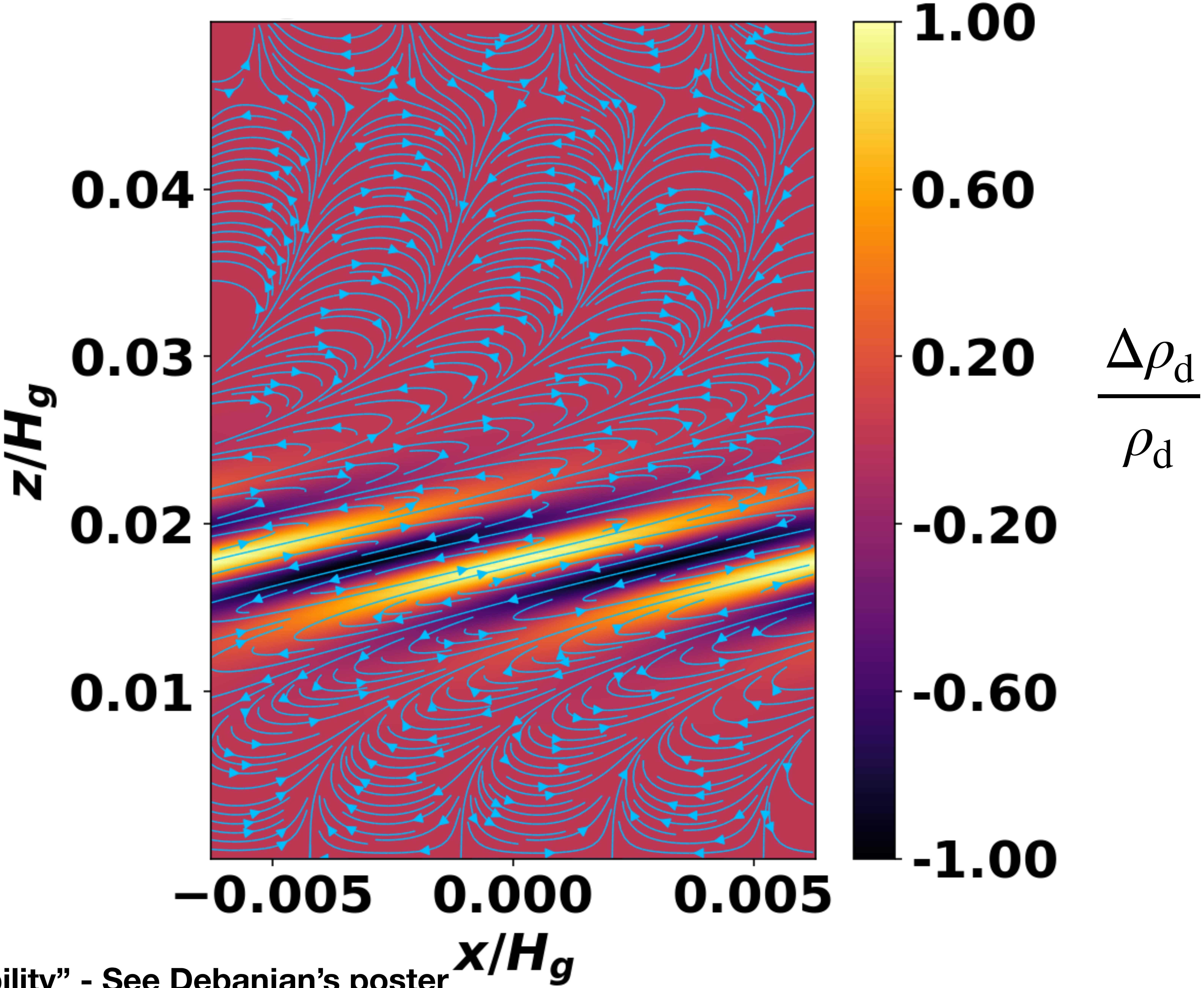


azimuth, ϕ

Conventional KHI works for perfectly coupled grains but is non-axisymmetric (no linear stability criteria available)

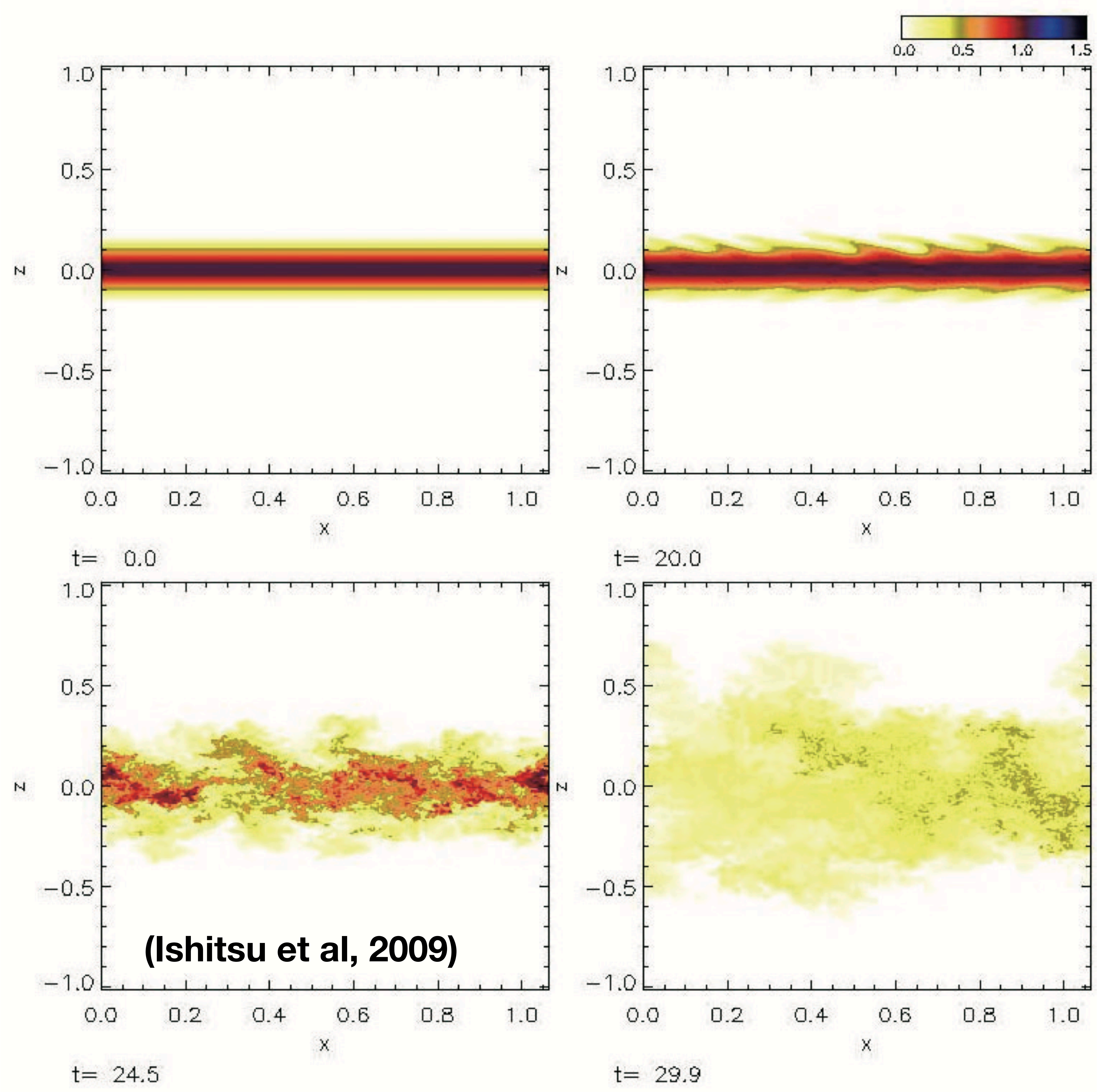
“Vertically shearing SI” in stratified disks

- **Axisymmetric**
- **Partial dust coupling**
- $S_{\text{grow}} \sim \Omega$
- **Scale** $\sim 10^{-3} H_{\text{g}}$



Lin (2021)
Sengupta & Umurhan (2022): “symmetric instability” - See Debanjan’s poster

Vertically shearing SIs grow fast but…



dust layer dispersed

☹️

But planets do form: interaction with dusty VSI

Similar dust morphology and pebble accretion rates, but no feedback

+ Michael Hammer's poster

Summary

- **VSI is sensitive to dust feedback**
- **VSI motions can produce corrugated dust layers**
- **VSI rings and vortices can trap dust**
- **Dusty flavors of the VSI: KHI and VSSIs**

Open questions

- **Effect of a particle size distribution with feedback?**
- **Effect of finite dust-gas coupling?**

cf. perfectly coupled, dusty buoyancy

- **Interaction with other dusty instabilities**

e.g. “dust settling instability” (Squire & Hopkins, 2018; Krapp et al. 2020)

- **Vertical shear by dust: Role of KHI and VSSI**

needs > 1000 cells/Hg

- **Self-consistent thermal and dynamical inclusion of dust**

Thank you

@linminkai

Obligatory plug

ASIAA Postdoctoral Positions in Observation, Theory, or Instrumentation

EACOA Research Fellowship Program 2023

The 2023 East Asian Core Observatories Association (EACOA)
Research Fellowship Program

Deadline: Nov. 15, 2022

@ASIAA: Michael Hammer, Marius Lehmann, Jeremy Smallwood