Hopes and challenges in modern planet formation and evolution

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May 2023

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National Center for Theoretical Sciences, Physics Divisions
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National Science and Technology Council
NCHC
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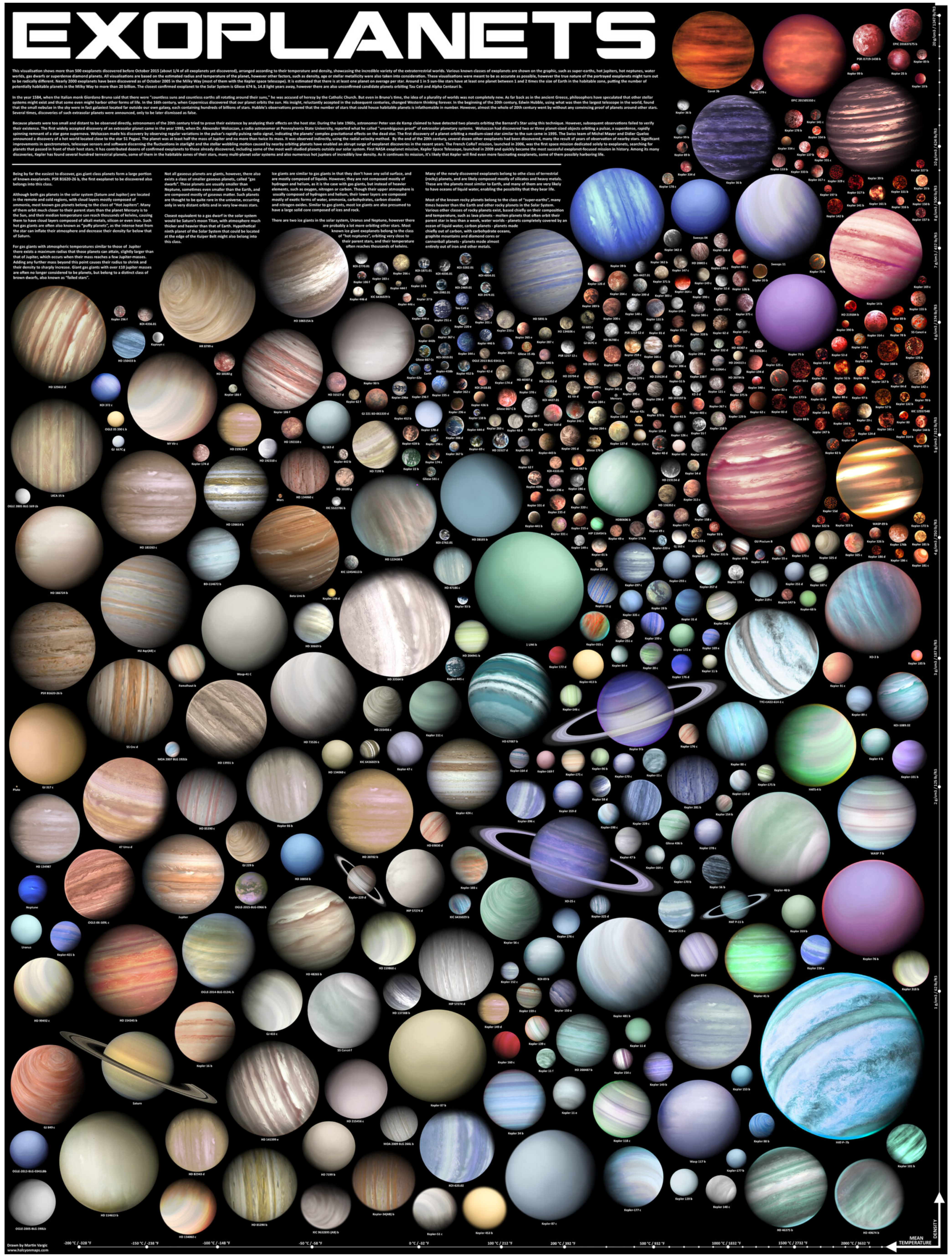
國家高速網路與計算中心
National Center for High-performance Computing

The era of exoplanet sciences

Credit: NASA/ESO/Wikipedia

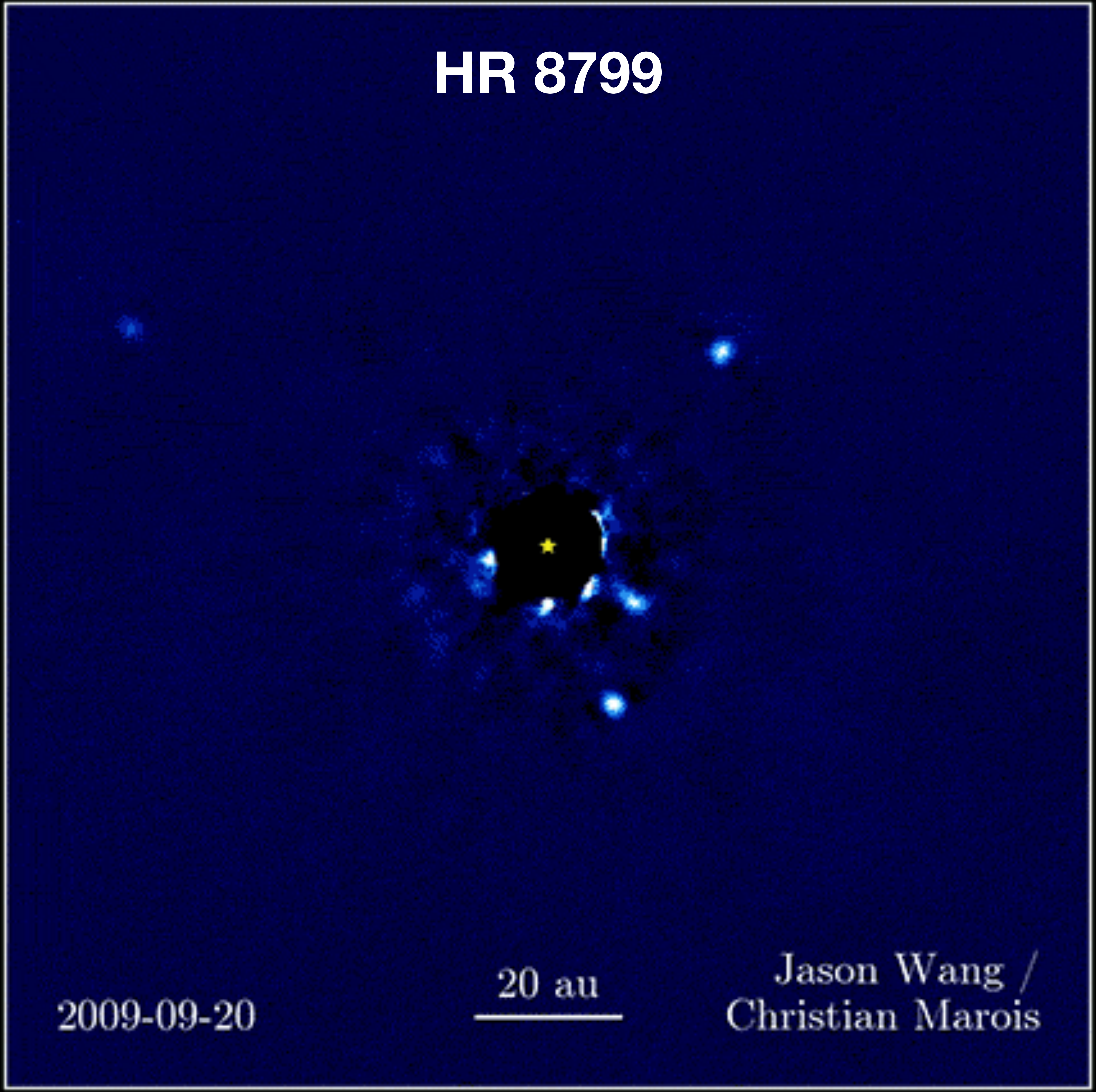
Diversity

- Hot Jupiters
- Cold Jupiters
- Eccentric planets
- Inclined planets
- Multi-planet systems
- Multi-stellar systems
- …etc



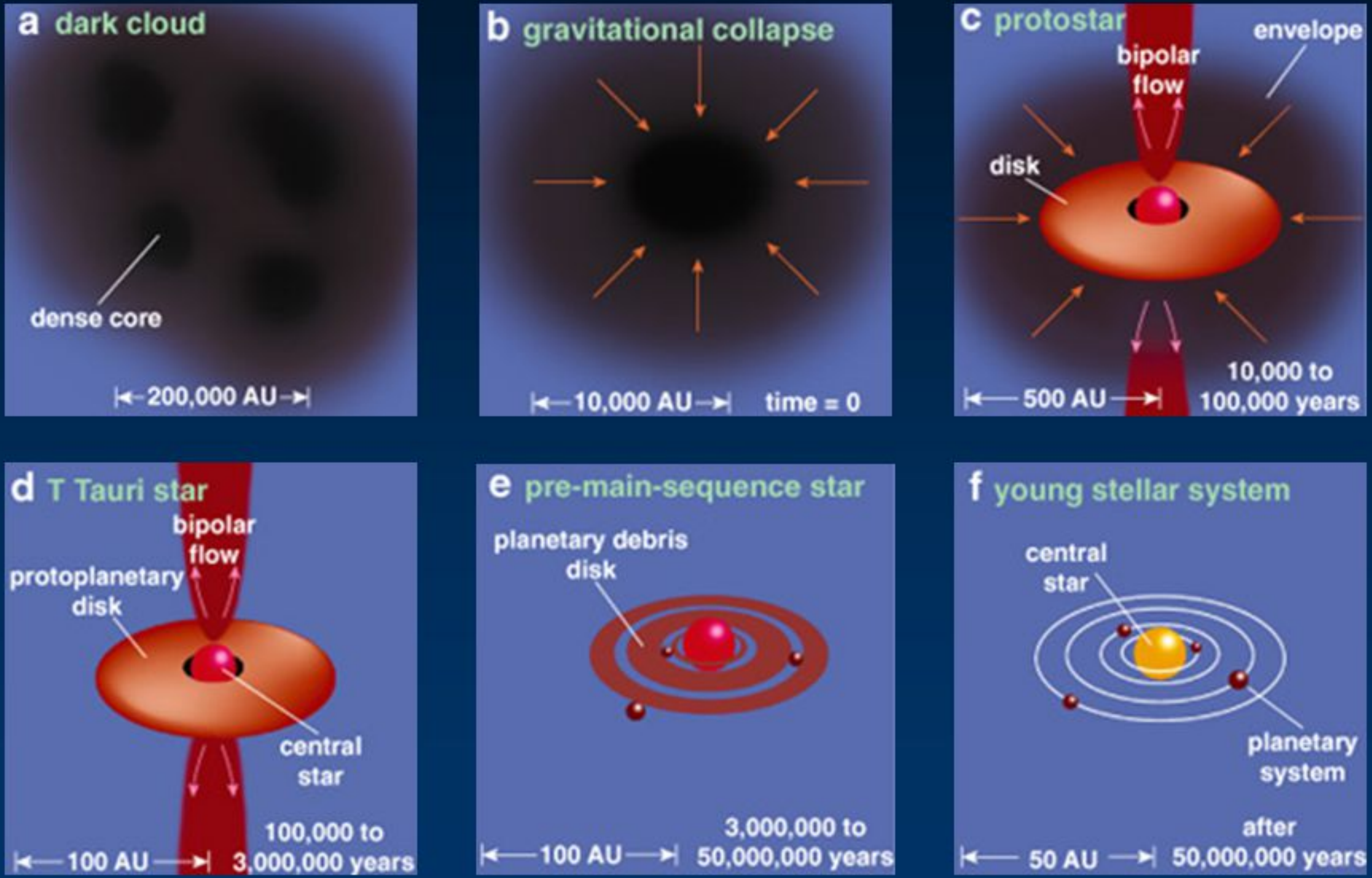
Credit: Martin Vargic

HR 8799



Credit: NASA

Star & planet formation



M. Liu (IfA/Hawaii)

Protoplanetary disks (artist's impression)

- 99% gas + 1% dust
- Dust = planet raw material
- Gas shapes planetary systems

Credit: ESO/L. Calçada

Real protoplanetary disks

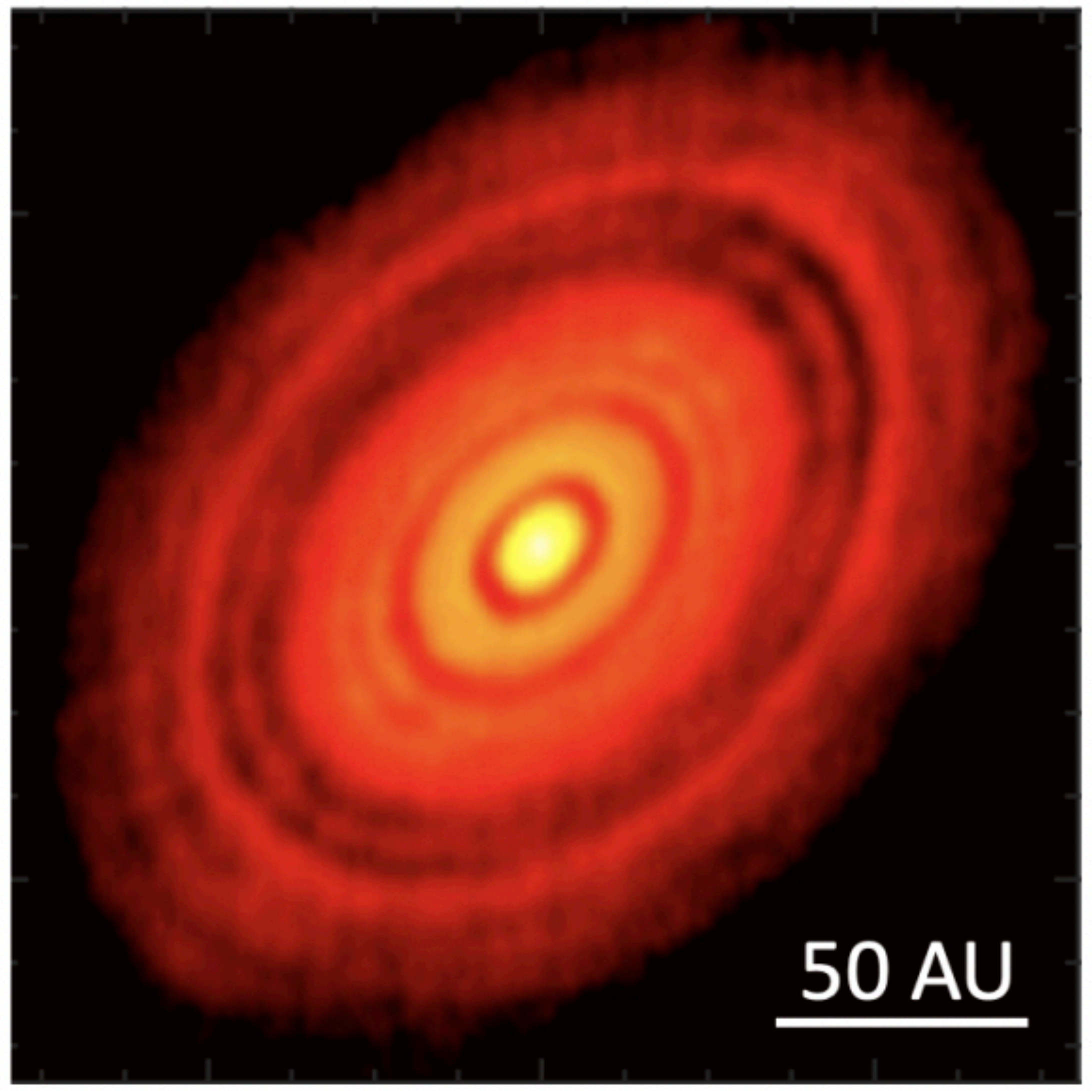
(Andrews et al, 2018; Long et al 2018)

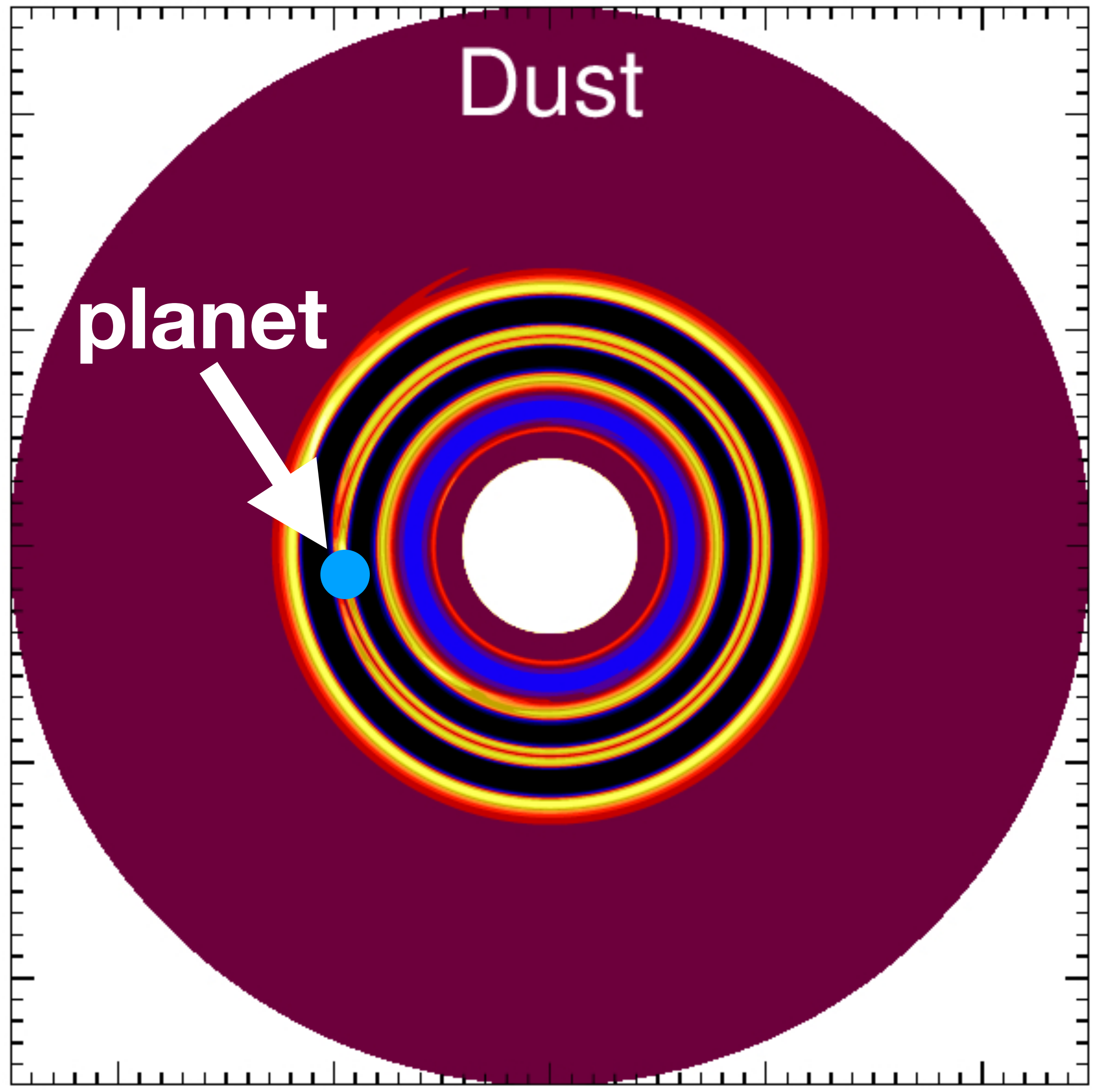
Rings and gaps: signposts of planet formation?

Disk-planet interpretation

HL Tau (ALMA Partnership et al. 2015)

Observations

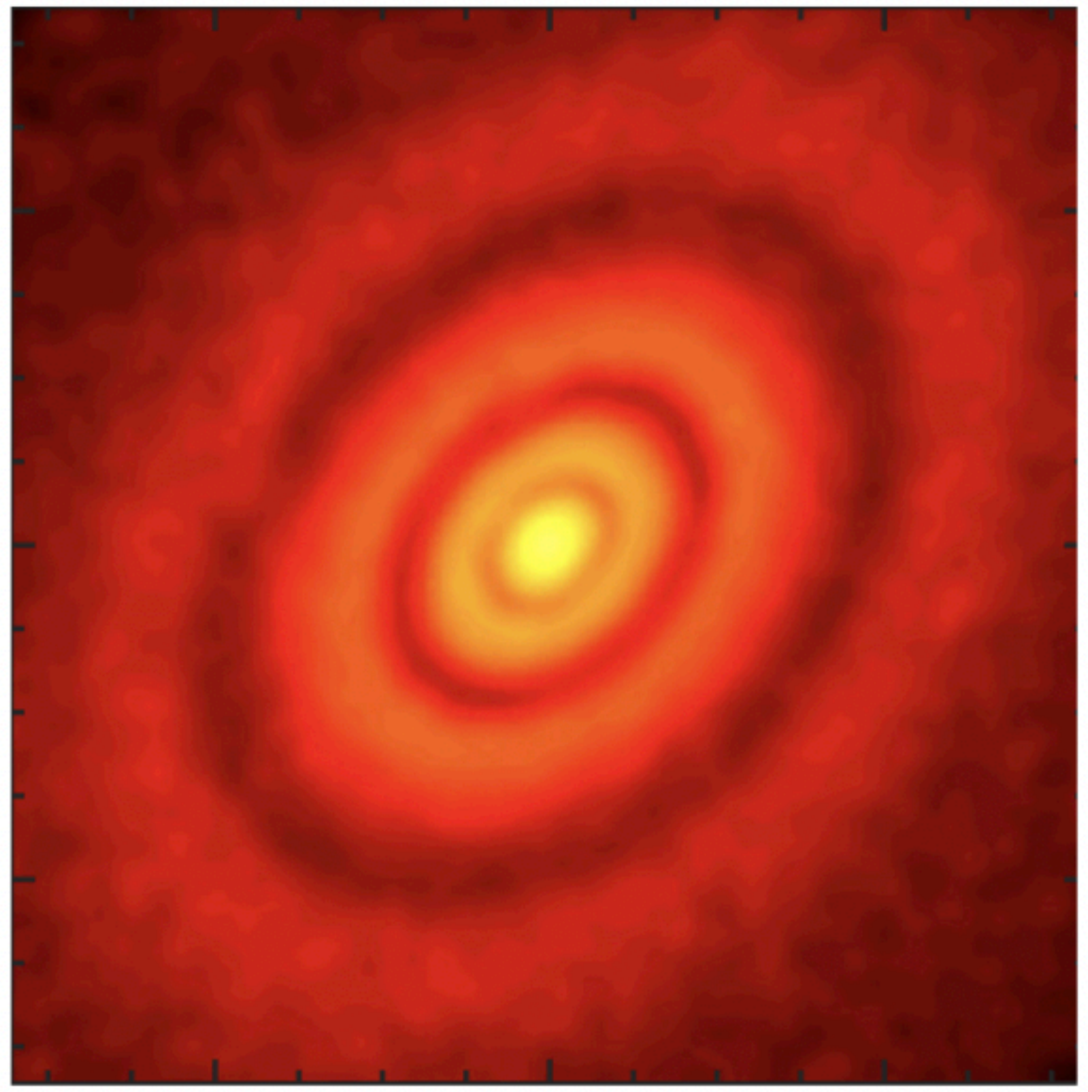




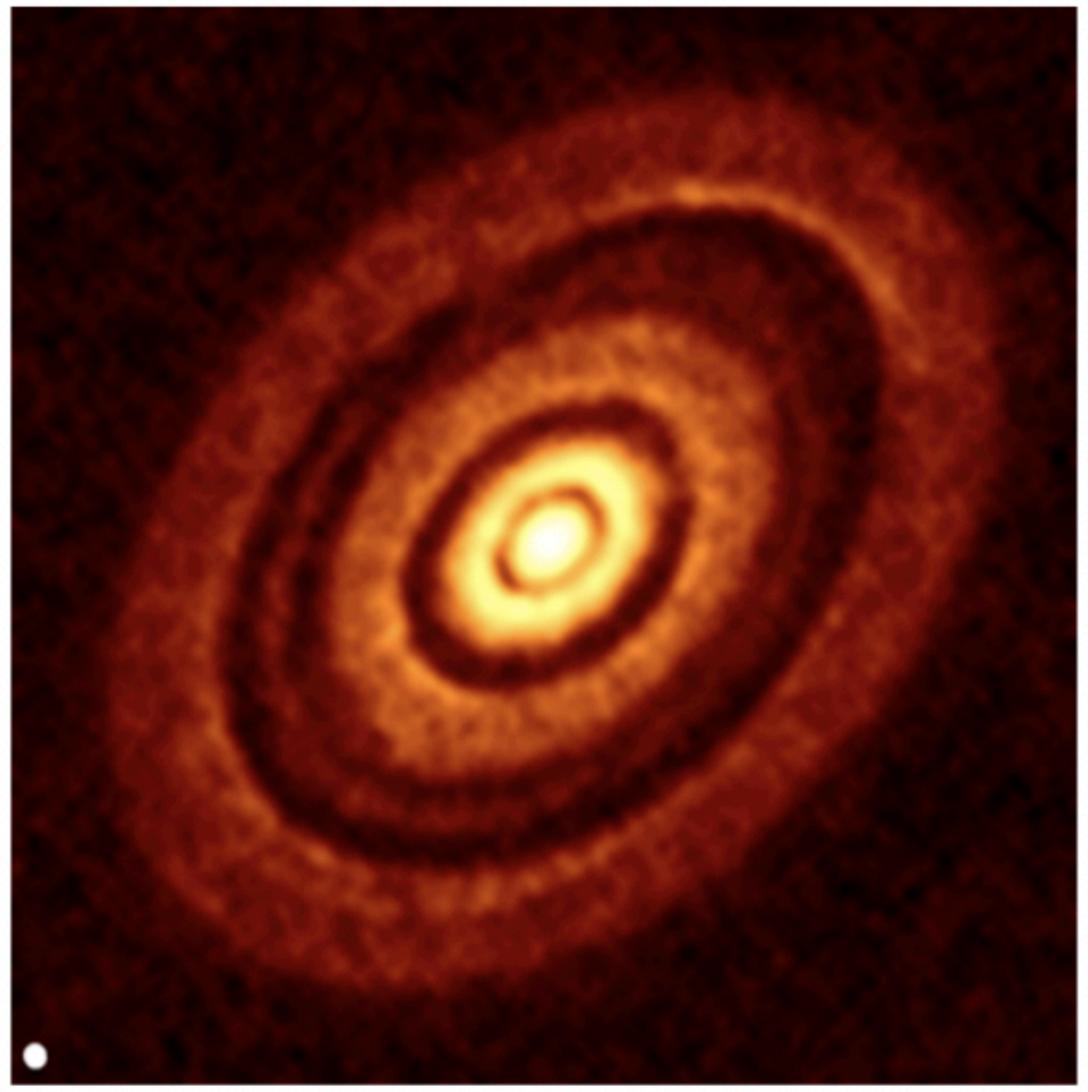
Computer simulation

(Chen & Lin, 2018)

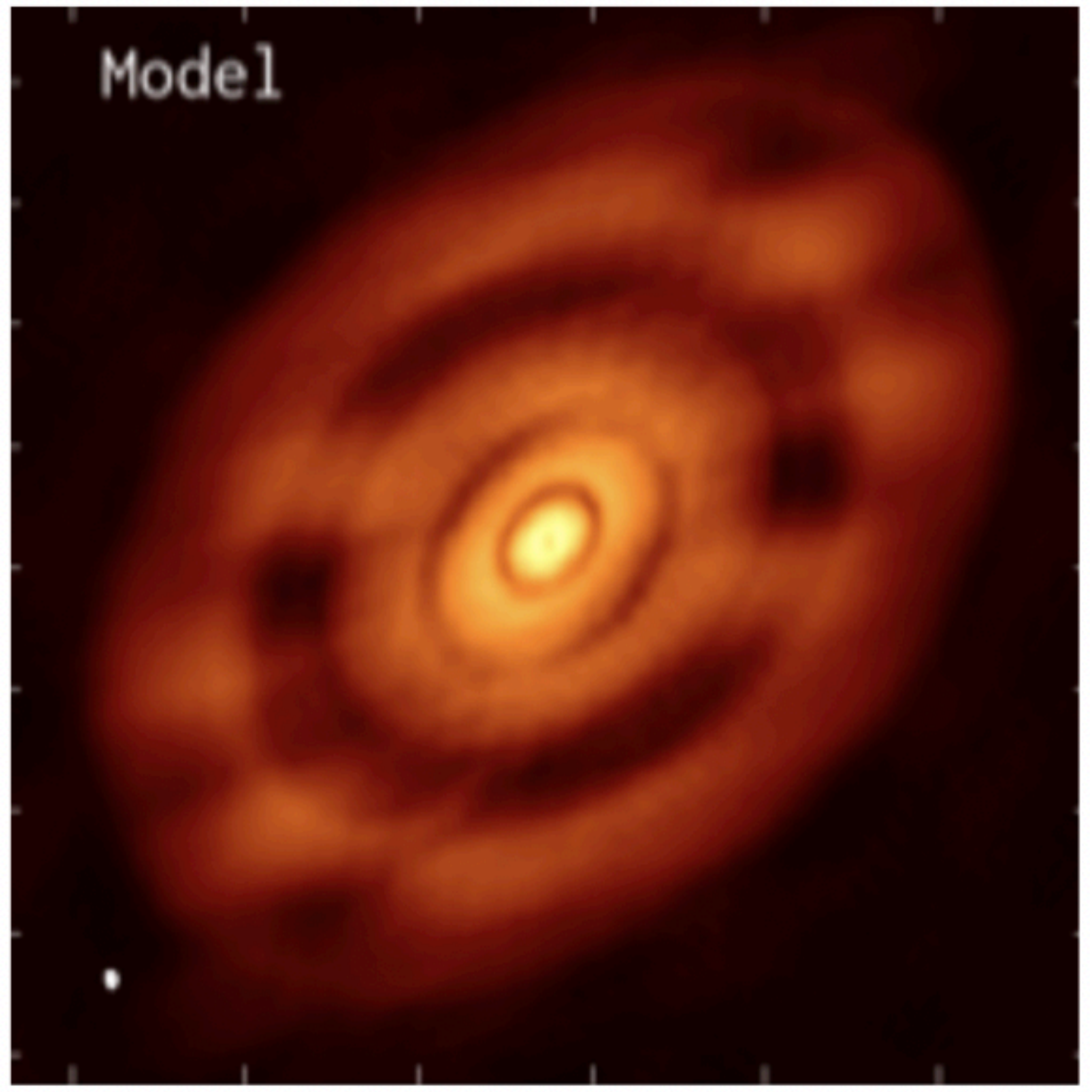
Simulation + synthetic obs.



Dong et al. 2015



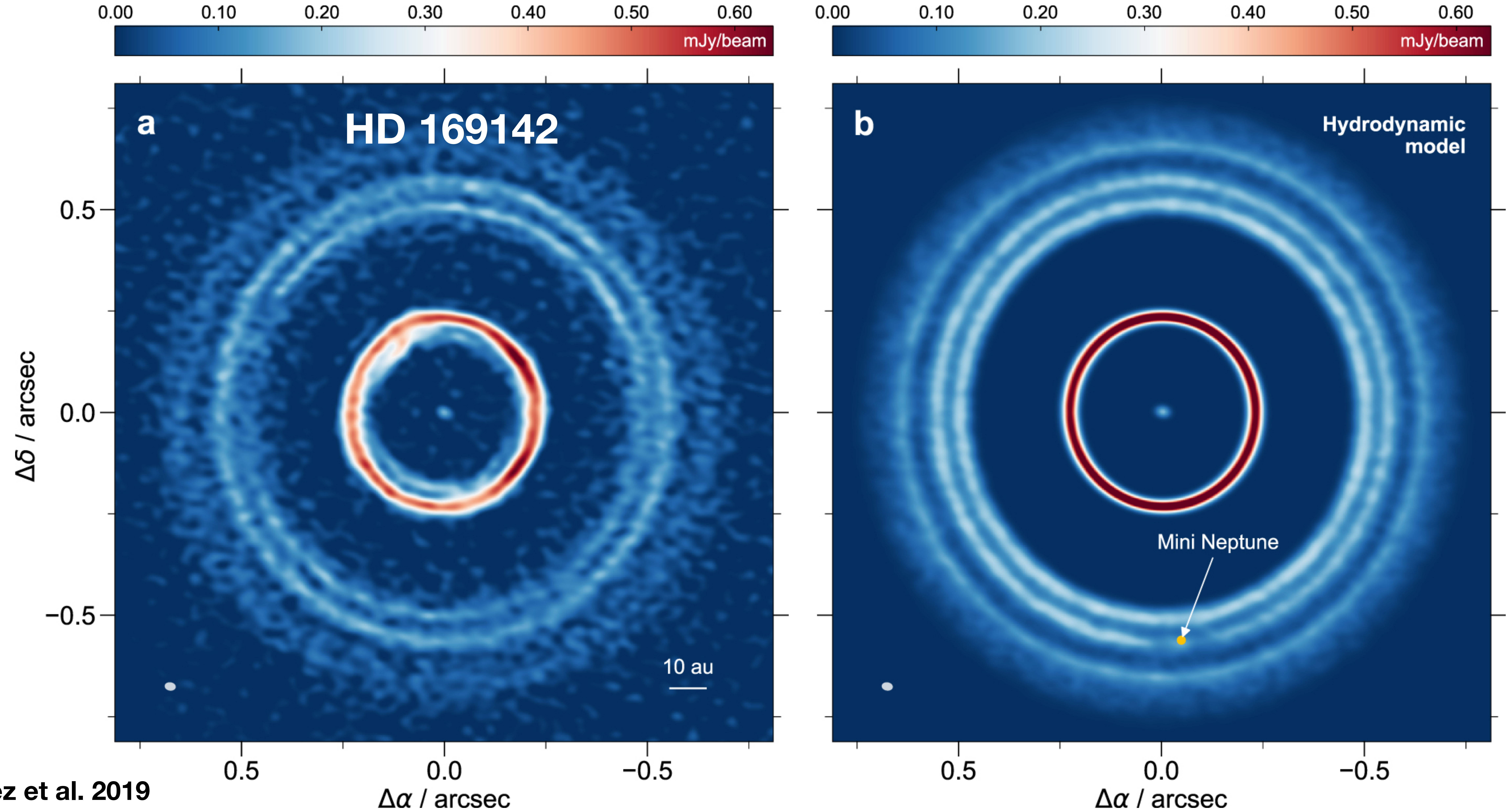
Dipierro et al. 2015



Jin et al. 2016

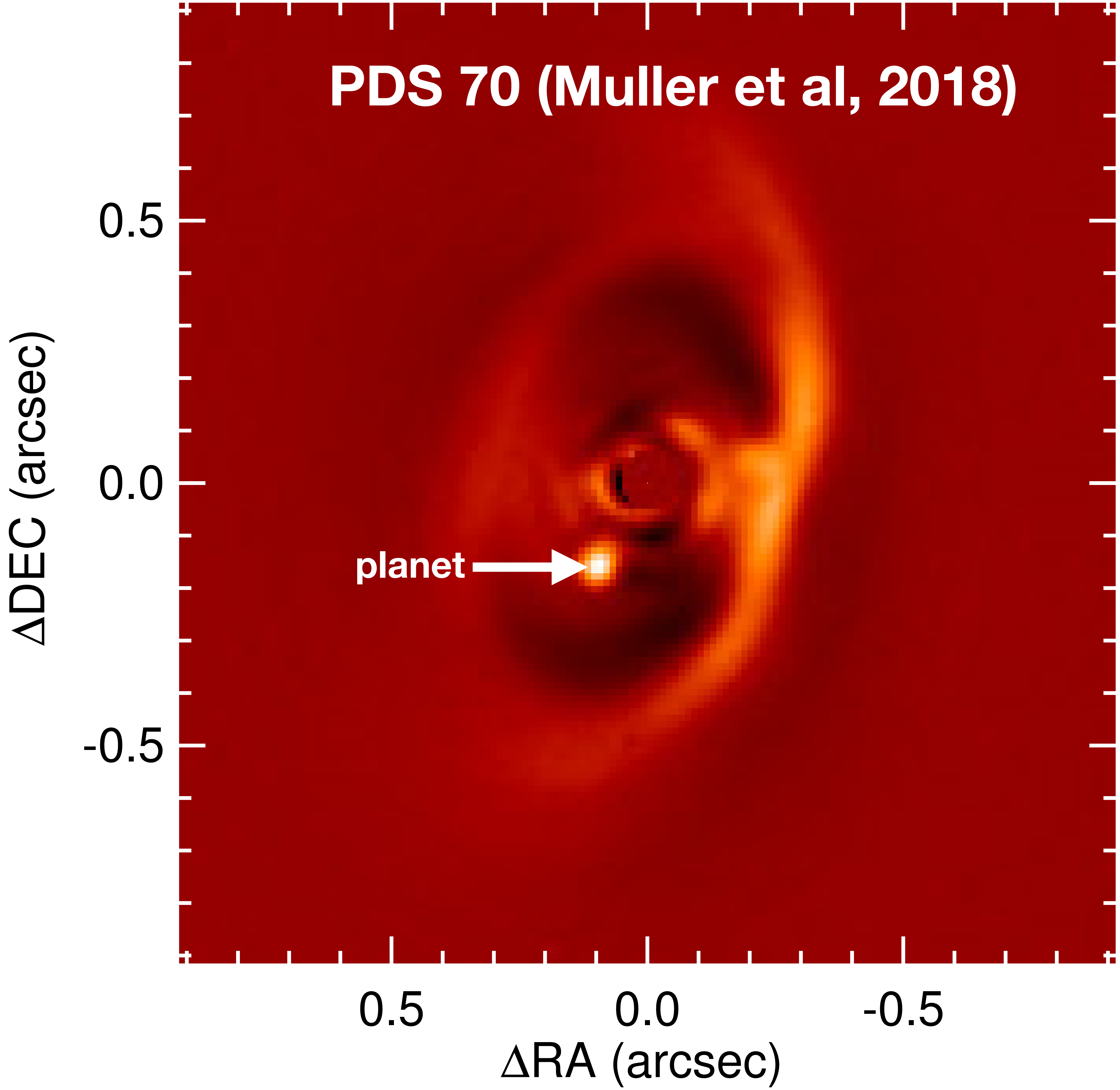
(Paardekooper et al., 2022, PPVII)

Detecting planets via sub-structures

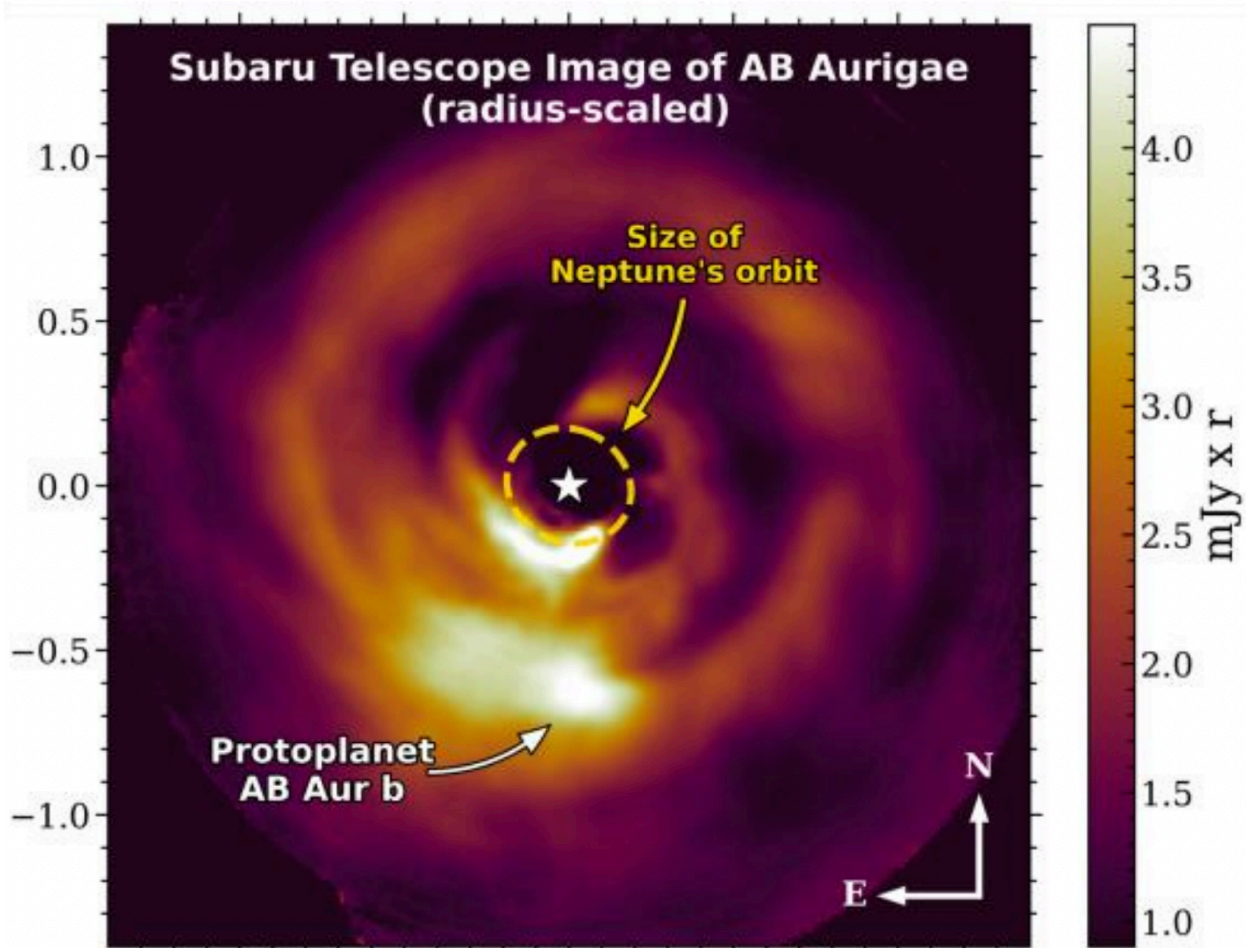


Pérez et al. 2019

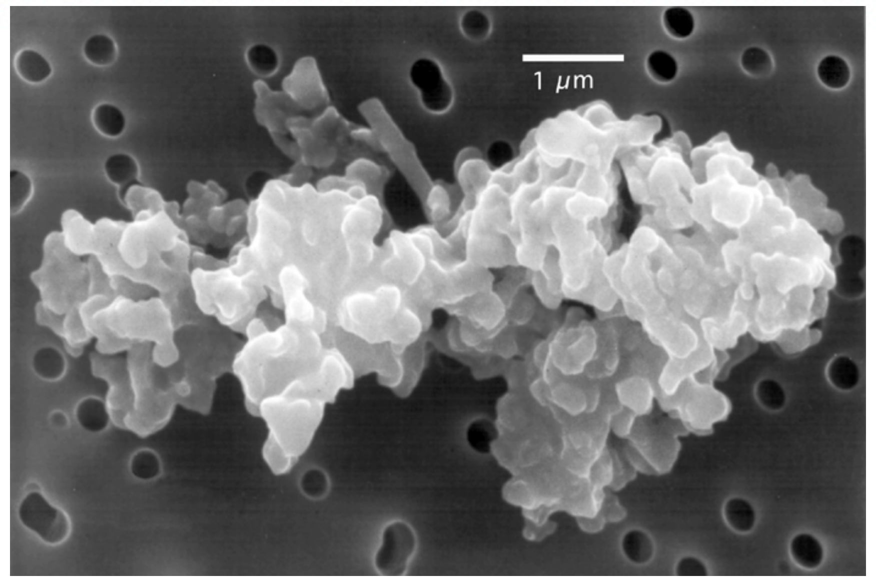
Observations of planets in a disk



AB Aur (Currie et al, 2022)

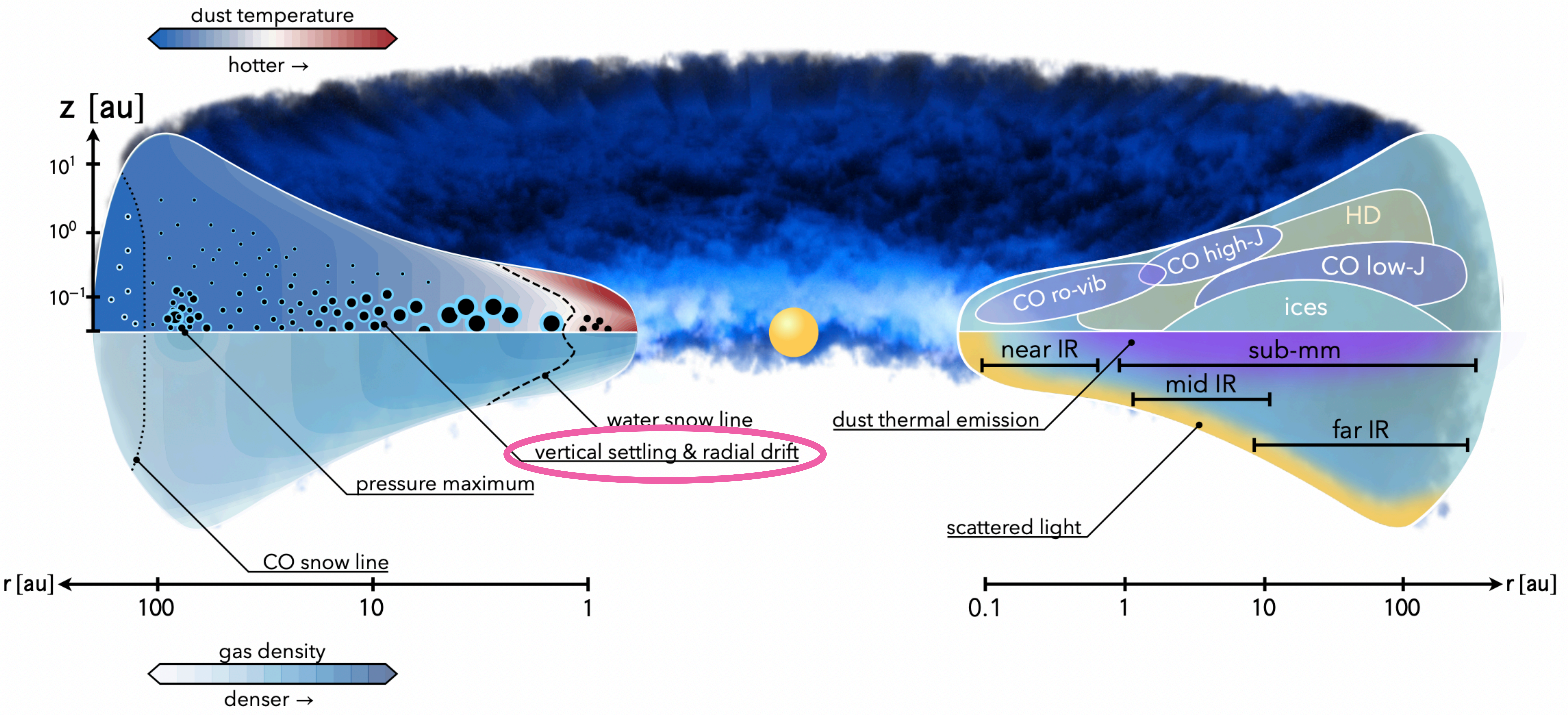


One planet, multiple scales



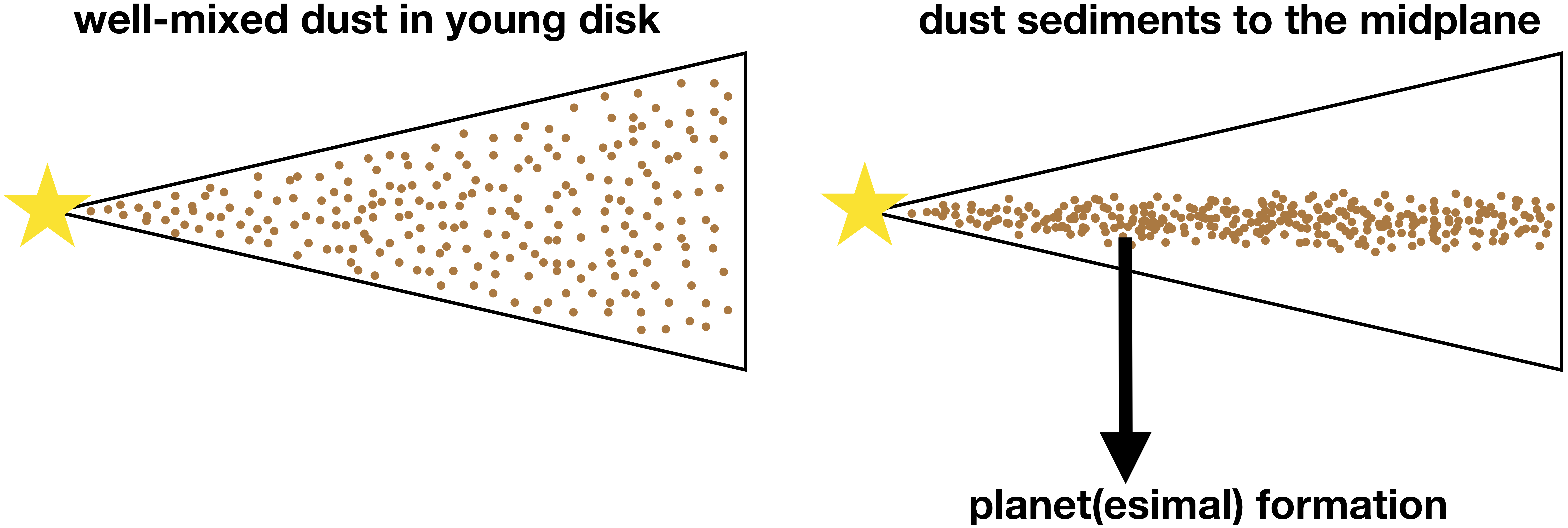
(Drazkowska et al., 2022, PPVII)

Dust in protoplanetary disks



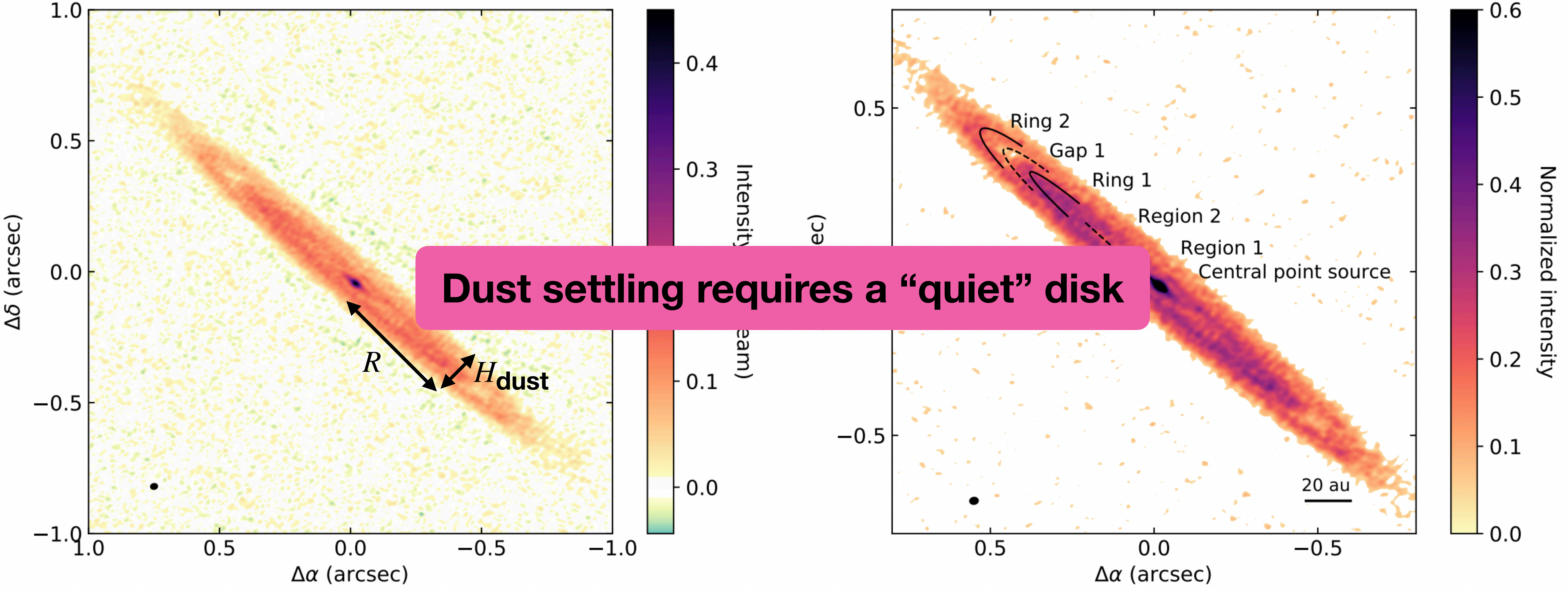
(Miotello et al., 2022, PPVII)

Vertical dust settling



Edge on disk observations

Oph 163131 (Villenave et al. 2022)

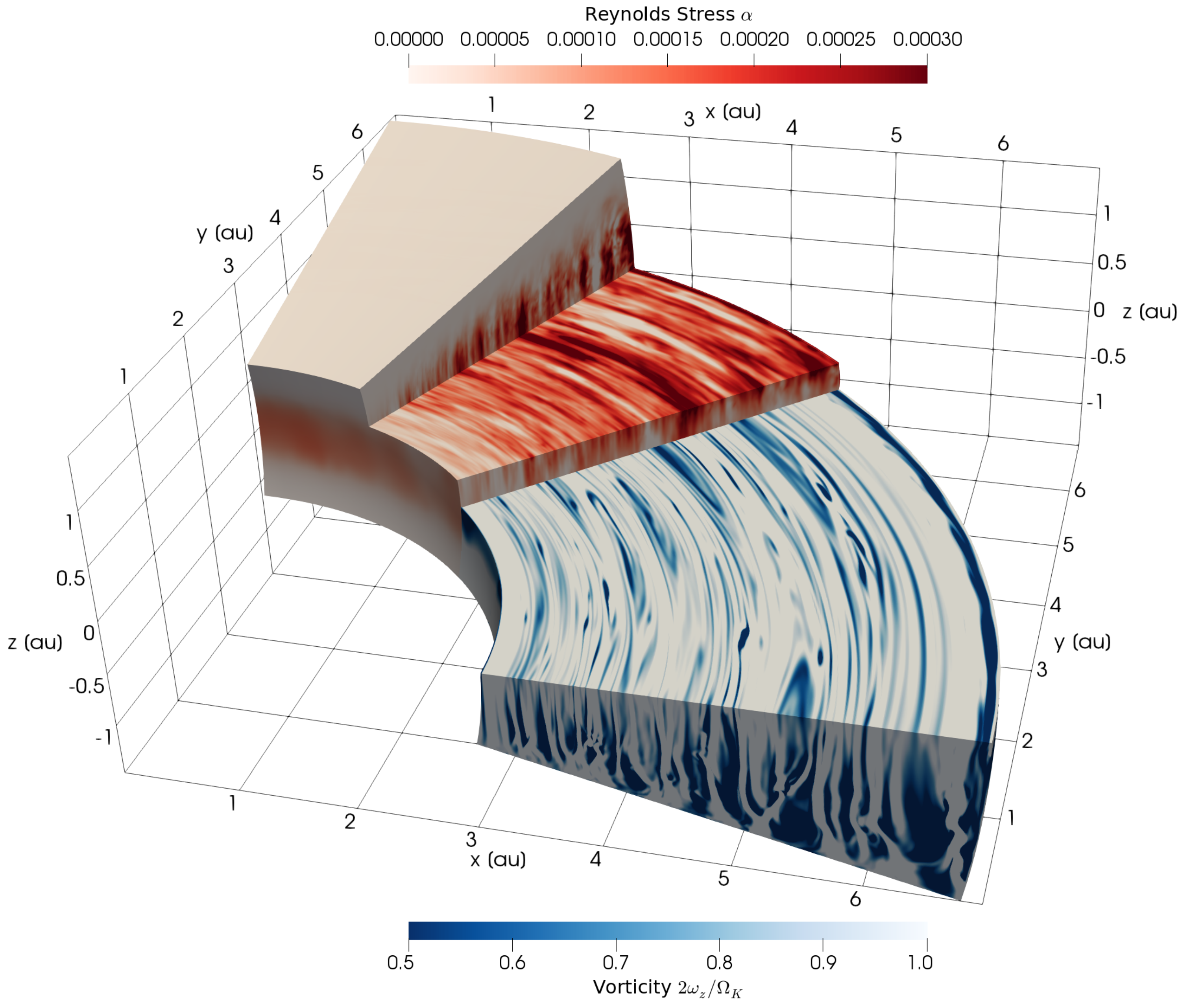


Dust settling requires a "quiet" disk

$$H_{\mathbf{dust}} \sim 0.005R$$

PPDs are (weakly) turbulent

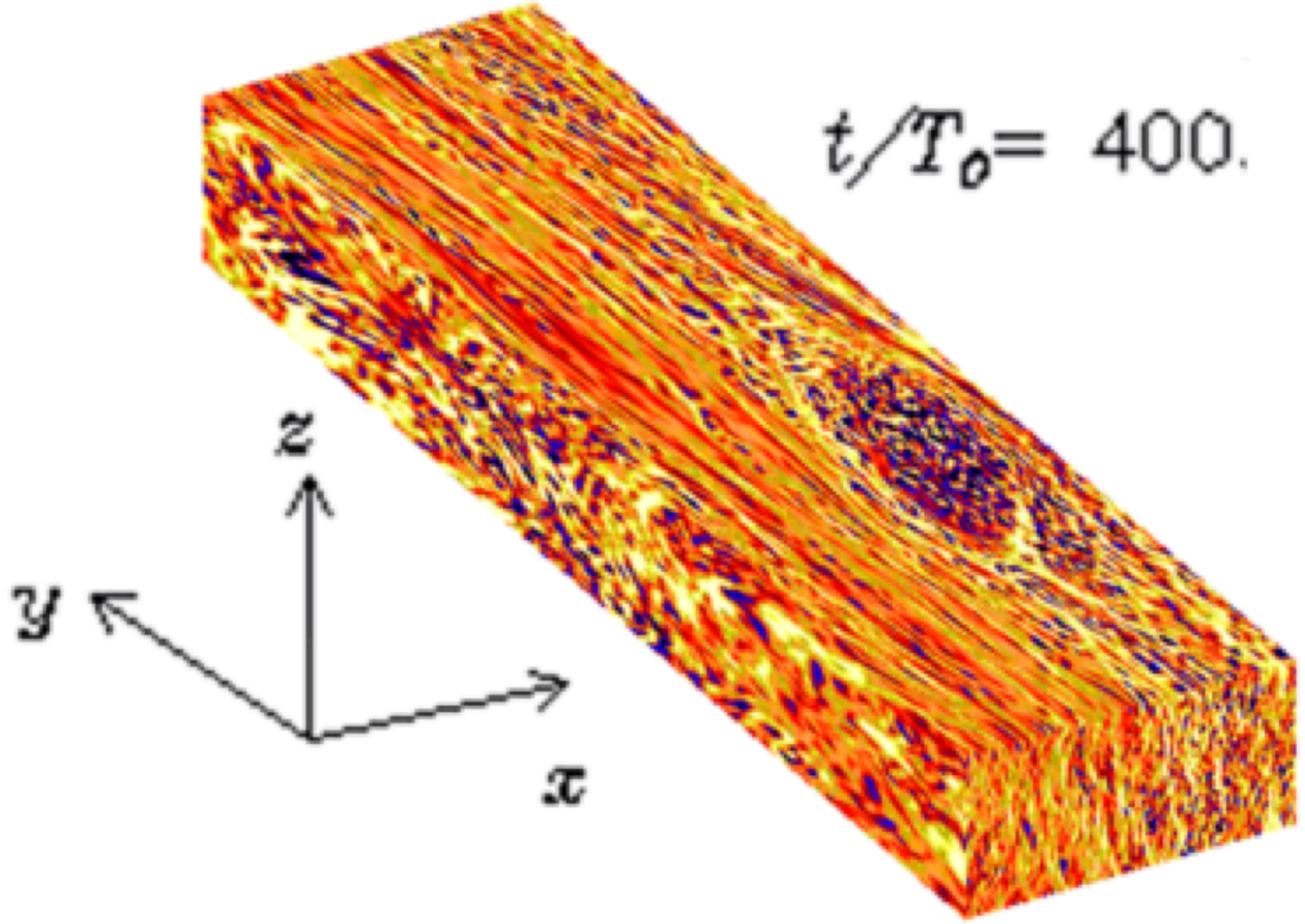
Vertical shear instability



Pfeil & Klahr (2020)

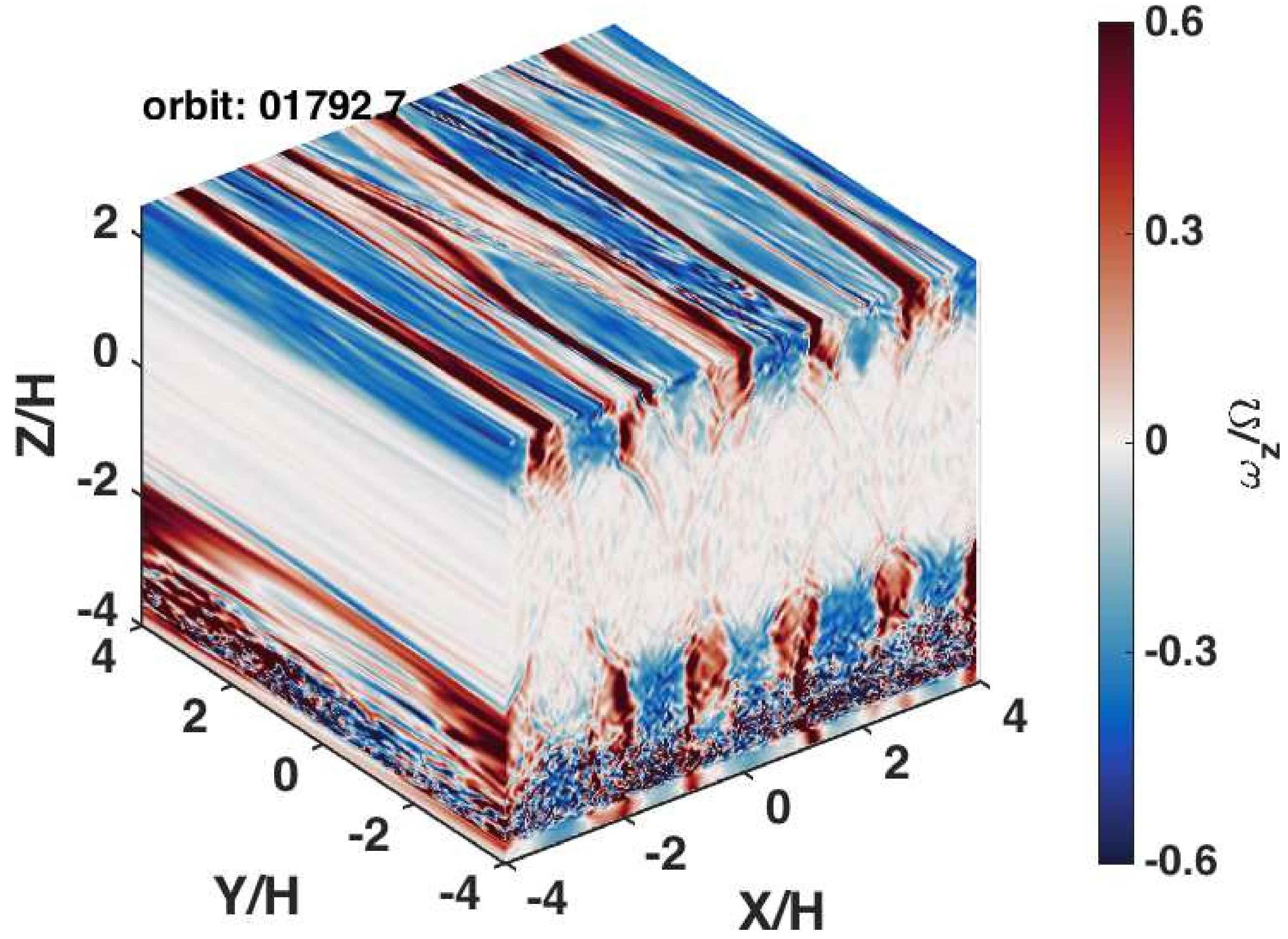
Lin & Youdin (2015)
Cui & Lin (2021)

Convective overstability



Lyra (2014)

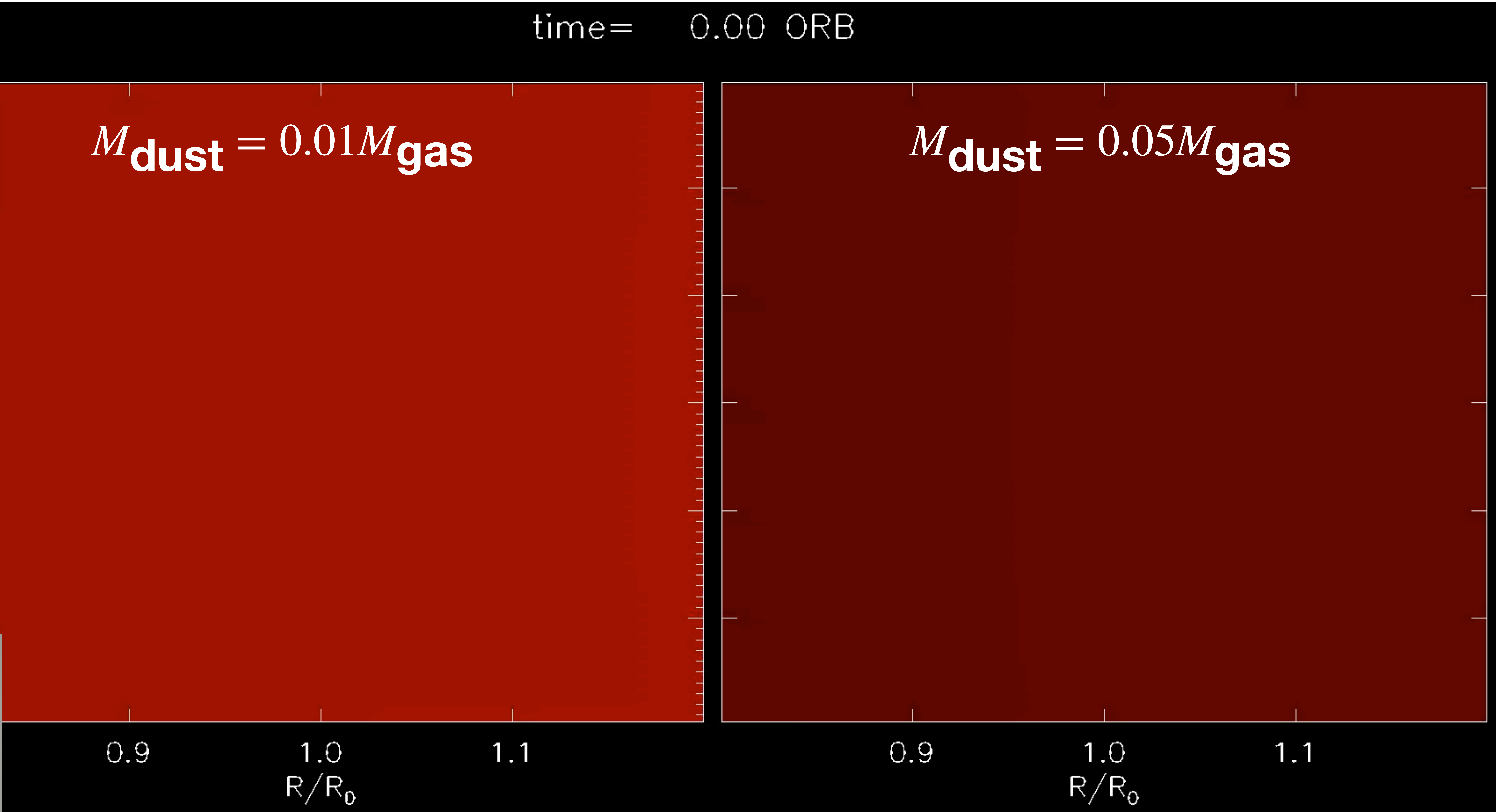
Zombie vortex instability



Barranco et al. (2018)

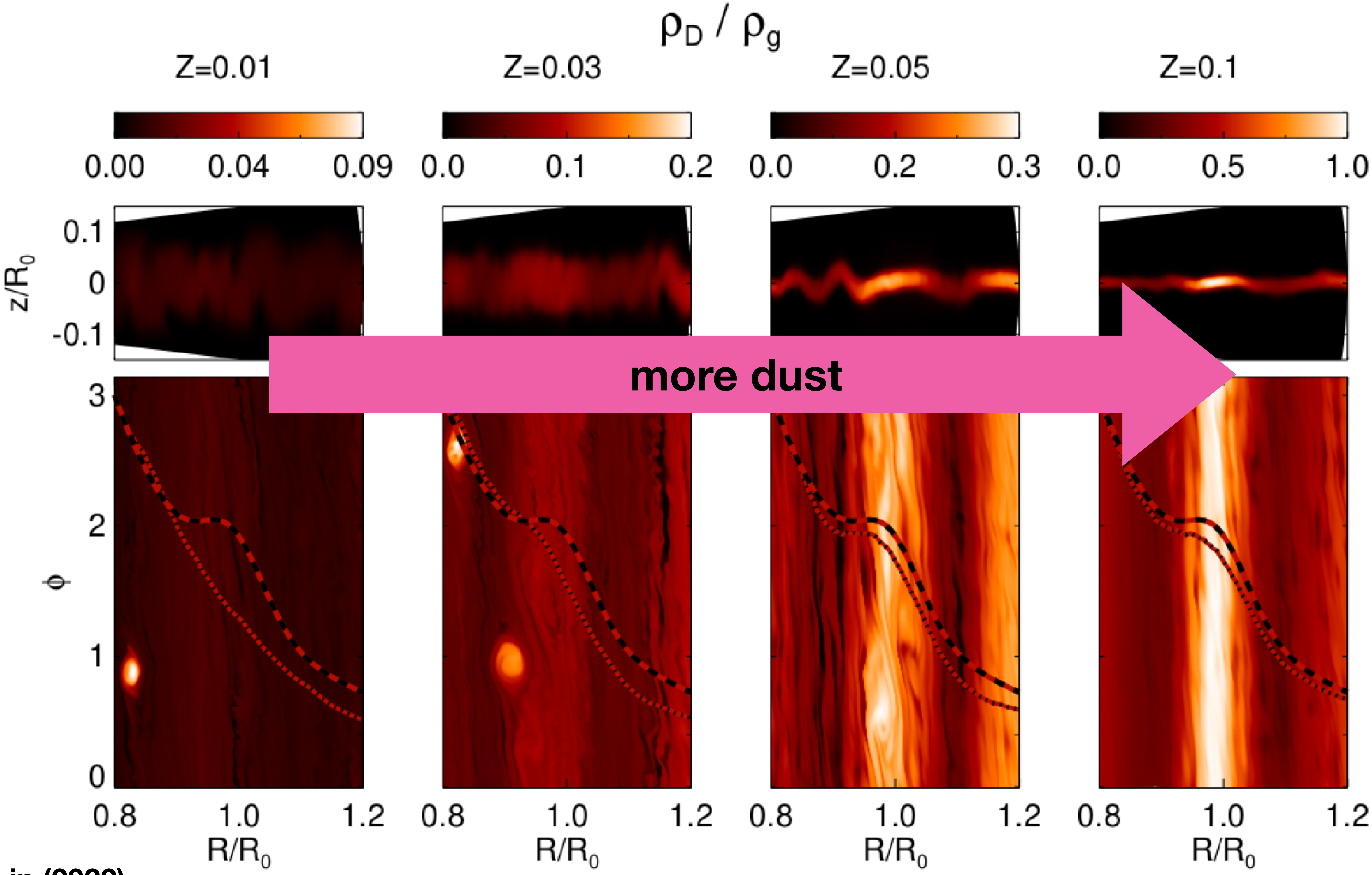
See Lesur,..., Lin, et al. (2022) PPVII review

Dust settling vs. turbulence



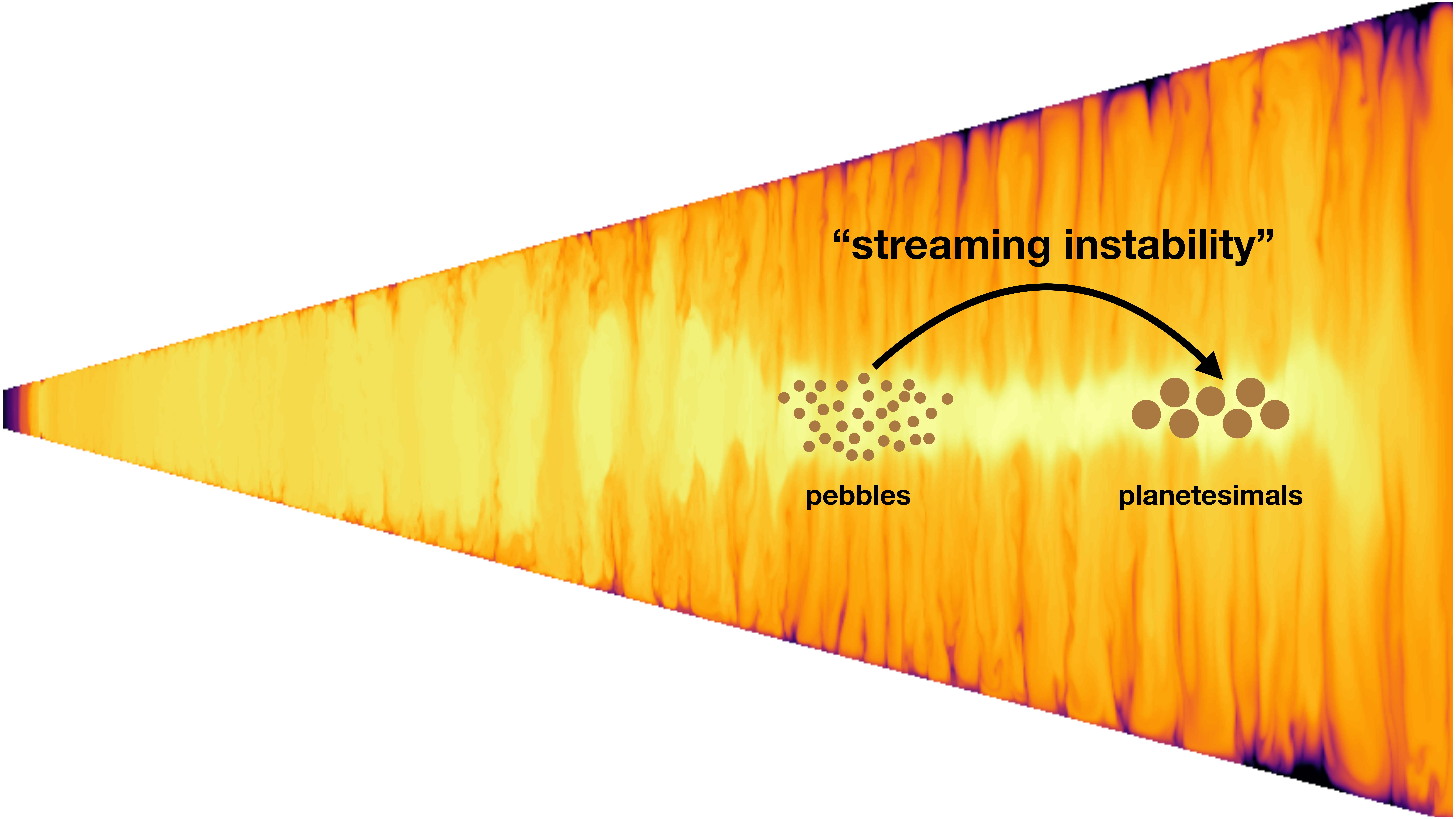
Lehmann & Lin (2022)

Dust rings or vortices?

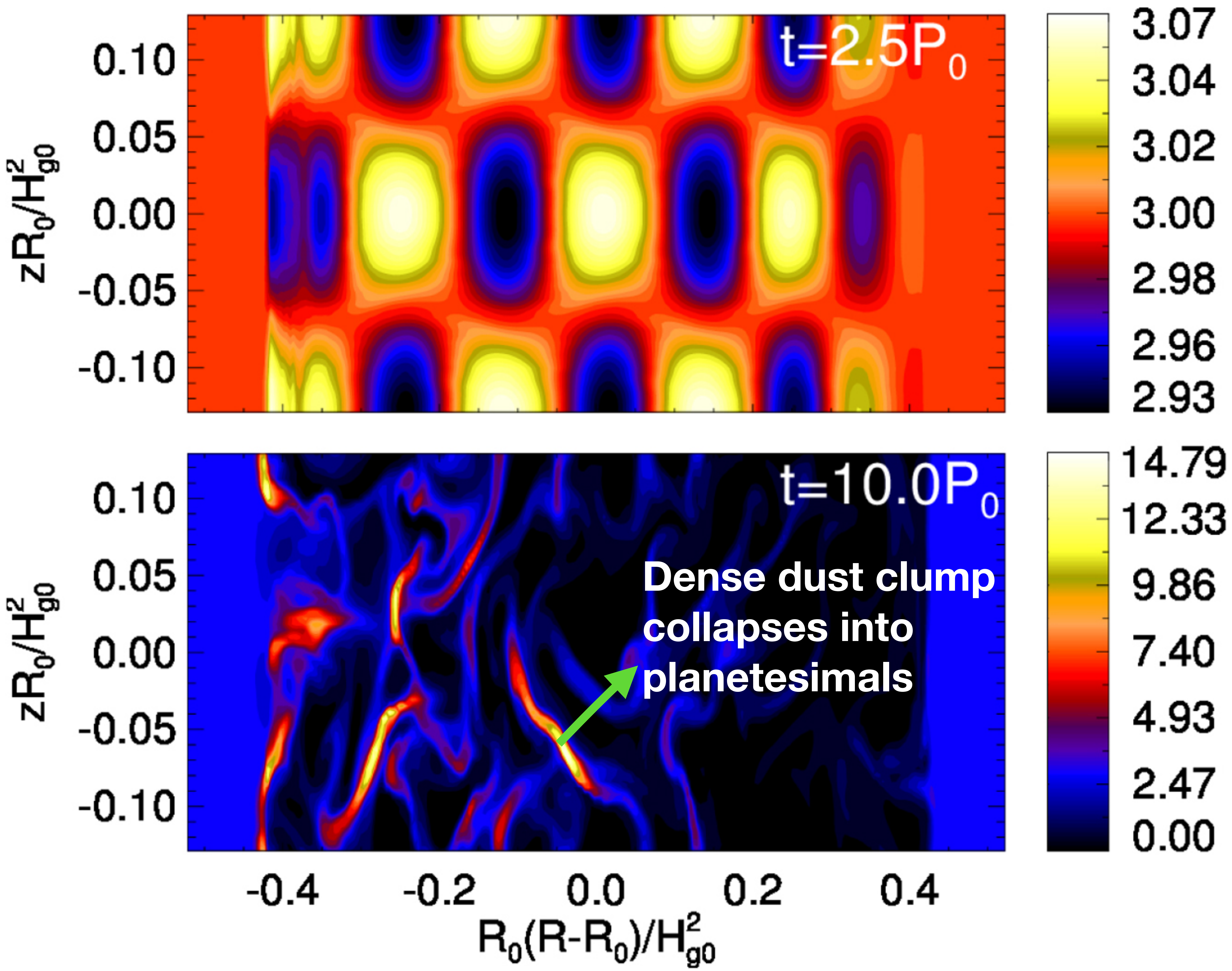


Lehmann & Lin (2022)

Planetesimal formation in the mid-plane

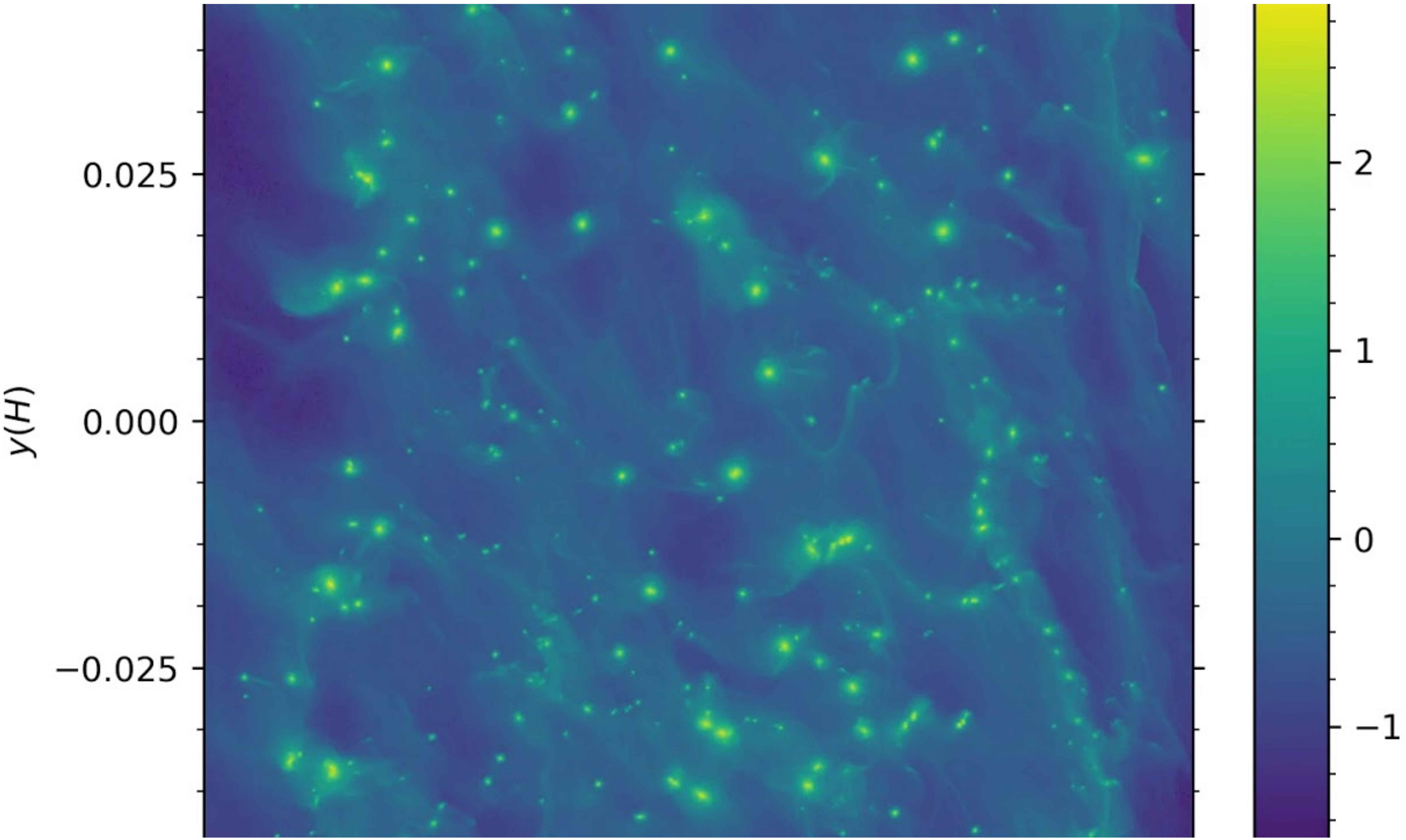


Streaming instability of dusty gas



Chen & Lin (2018)

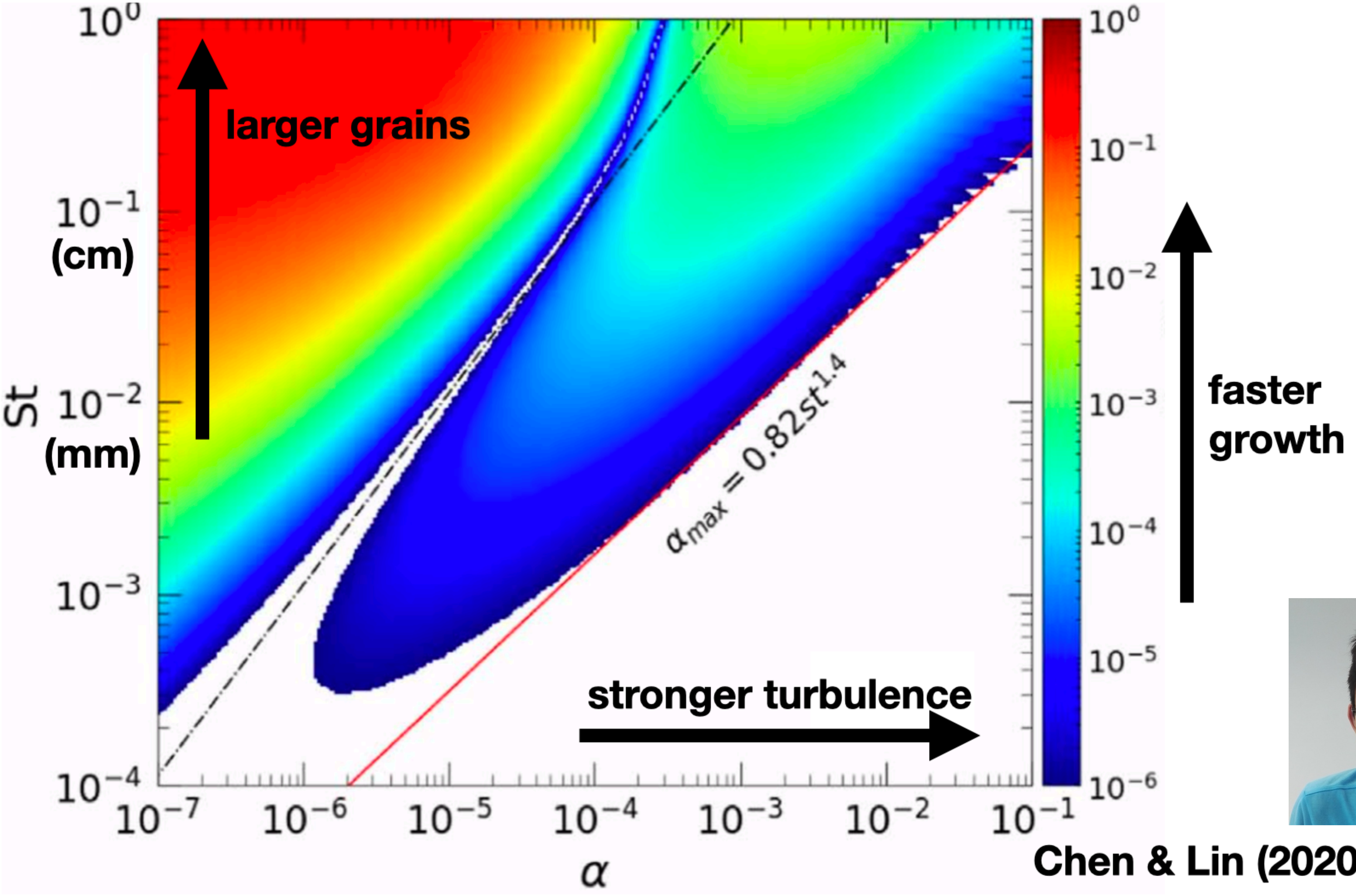
State-of-the-art simulations (Nesvorný et al., 2020)

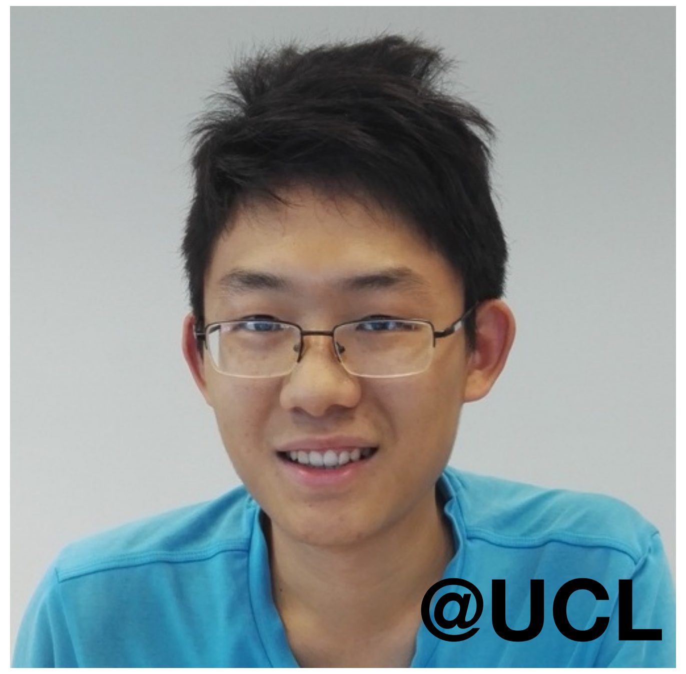


Generalizations of the ideal SI

- disk is non-turbulent → Chen & Lin (2020)
- disk has no vertical structure → Lin (2021)
- disk is unmagnetized → Lin & Hsu (2022), Hsu & Lin (2022)
- disk is isothermal → Lehmann & Lin (2023)

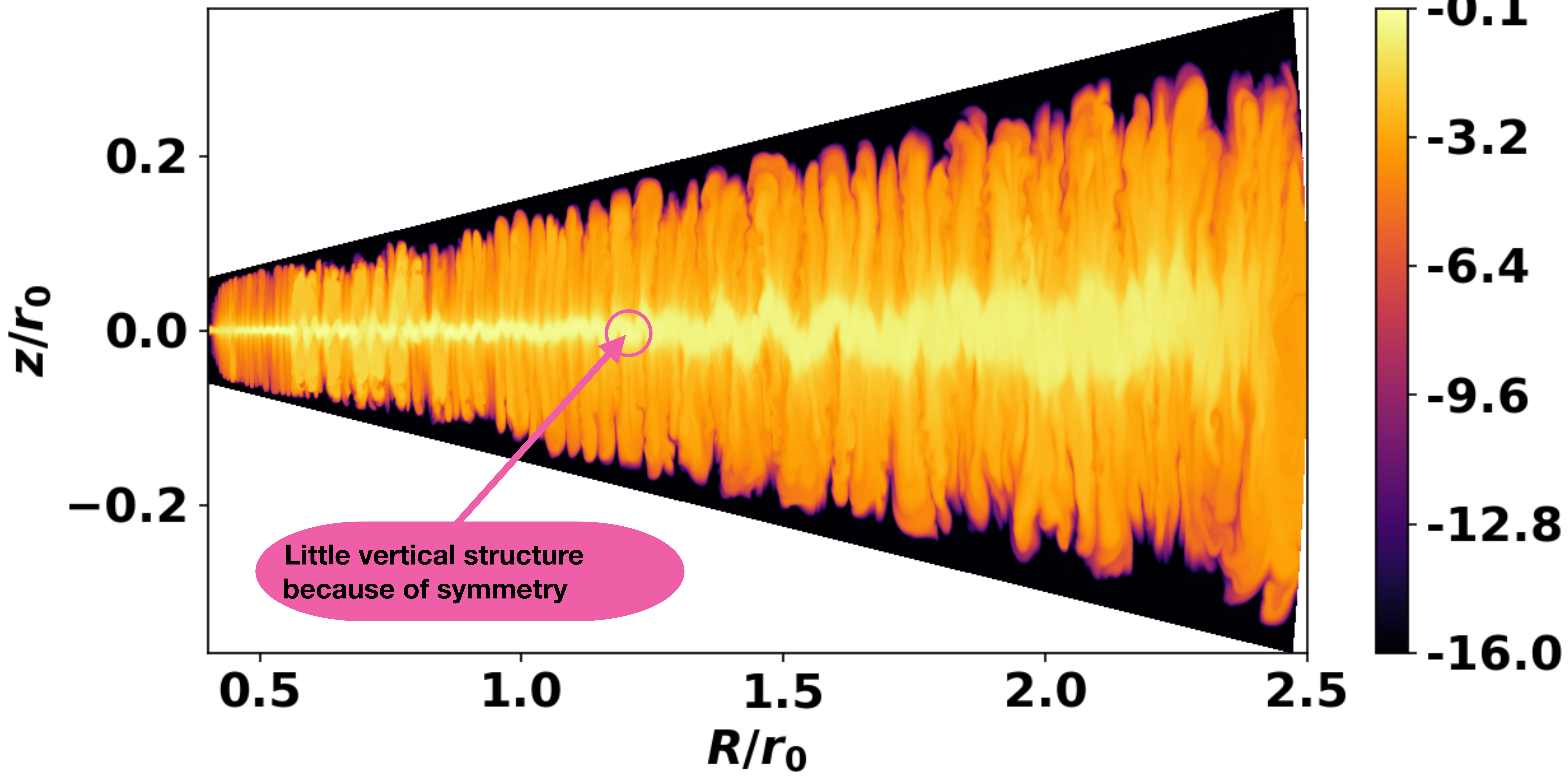
Streaming instability is easily killed by turbulent viscosity



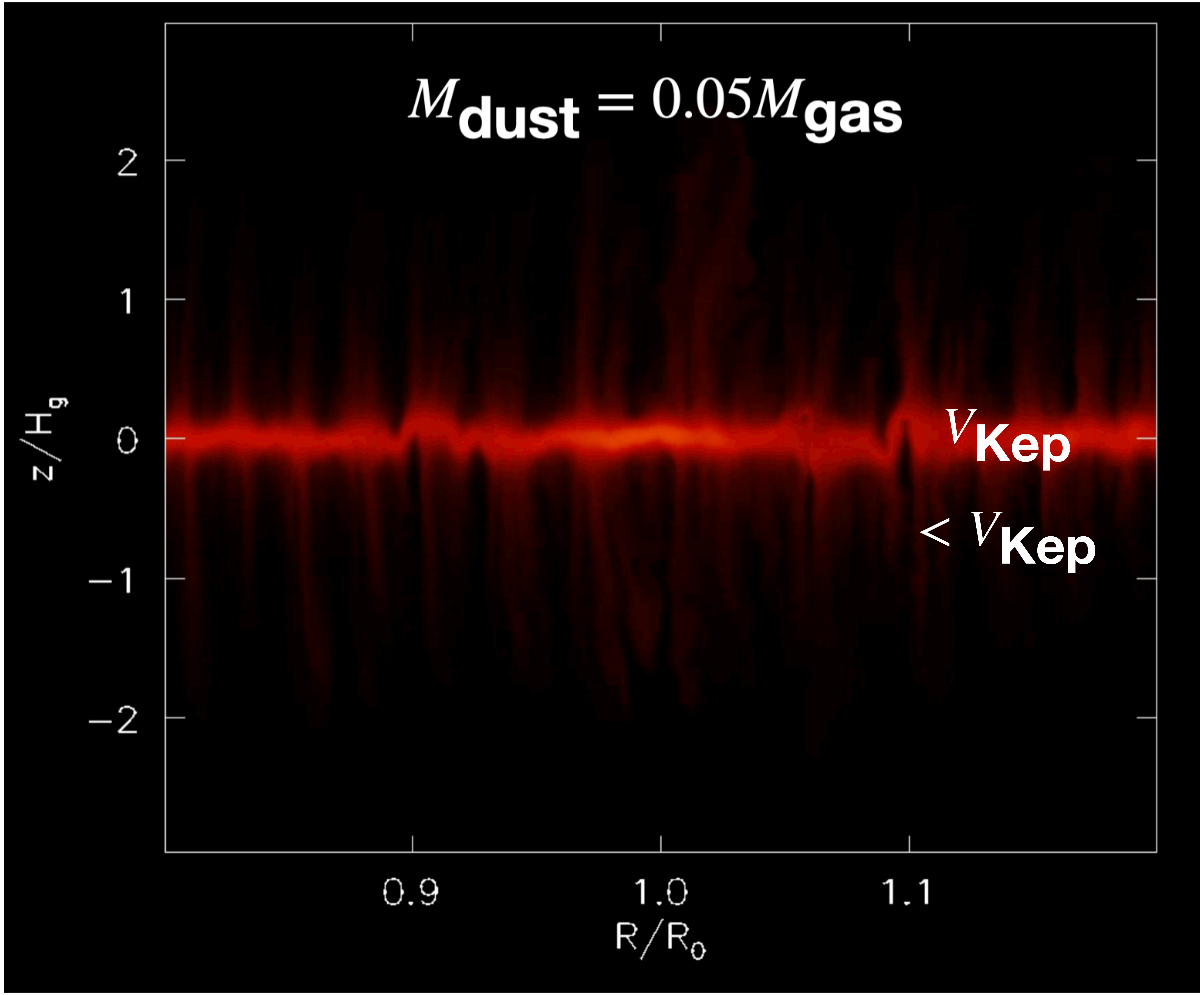


Chen & Lin (2020)

SI analyses use unstratified disk models



Stratified dust layers

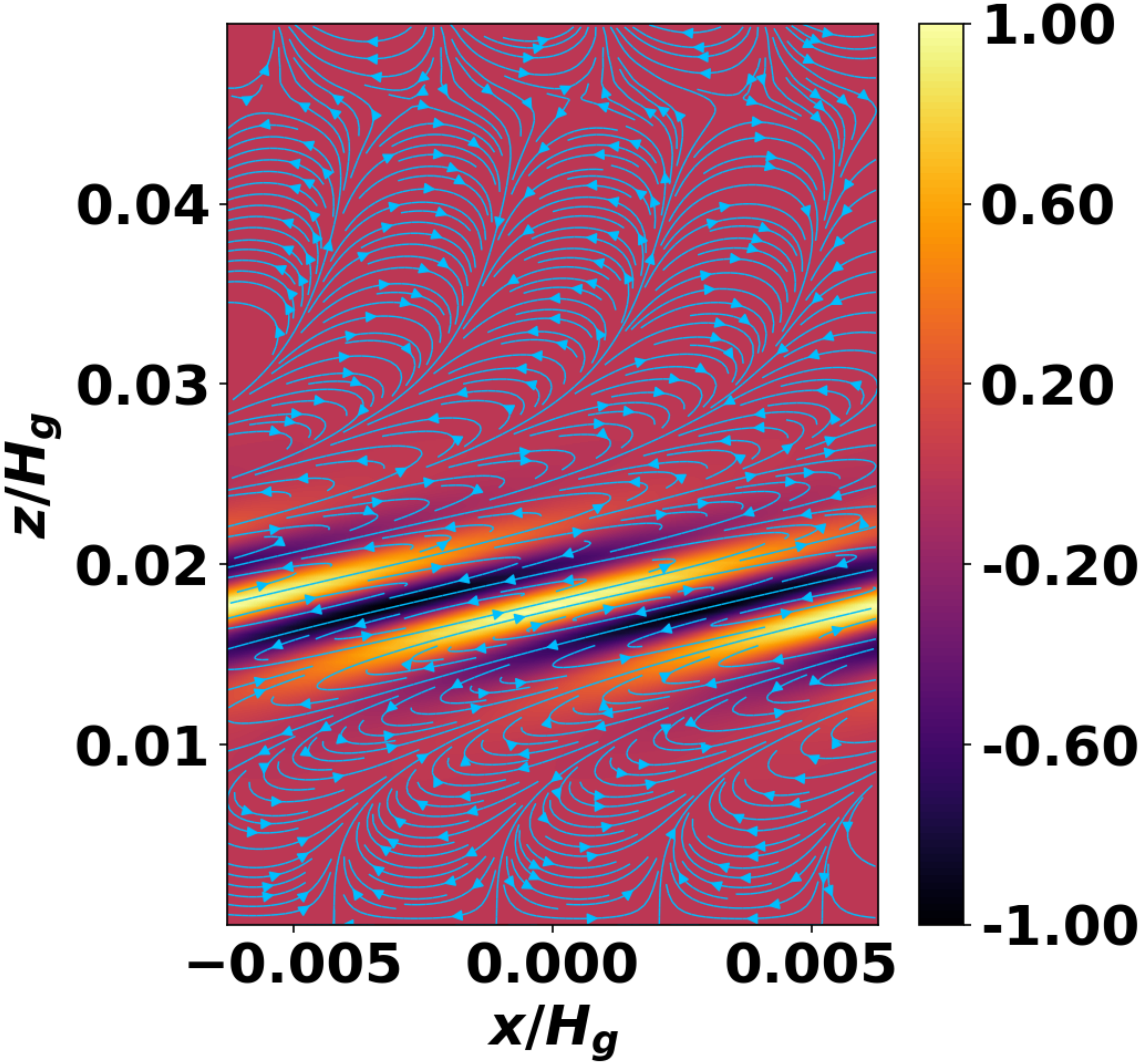


$$\frac{\partial \Omega}{\partial z} \neq 0$$

Lehmann & Lin (2022)

“Vertically shearing SI” in stratified disks

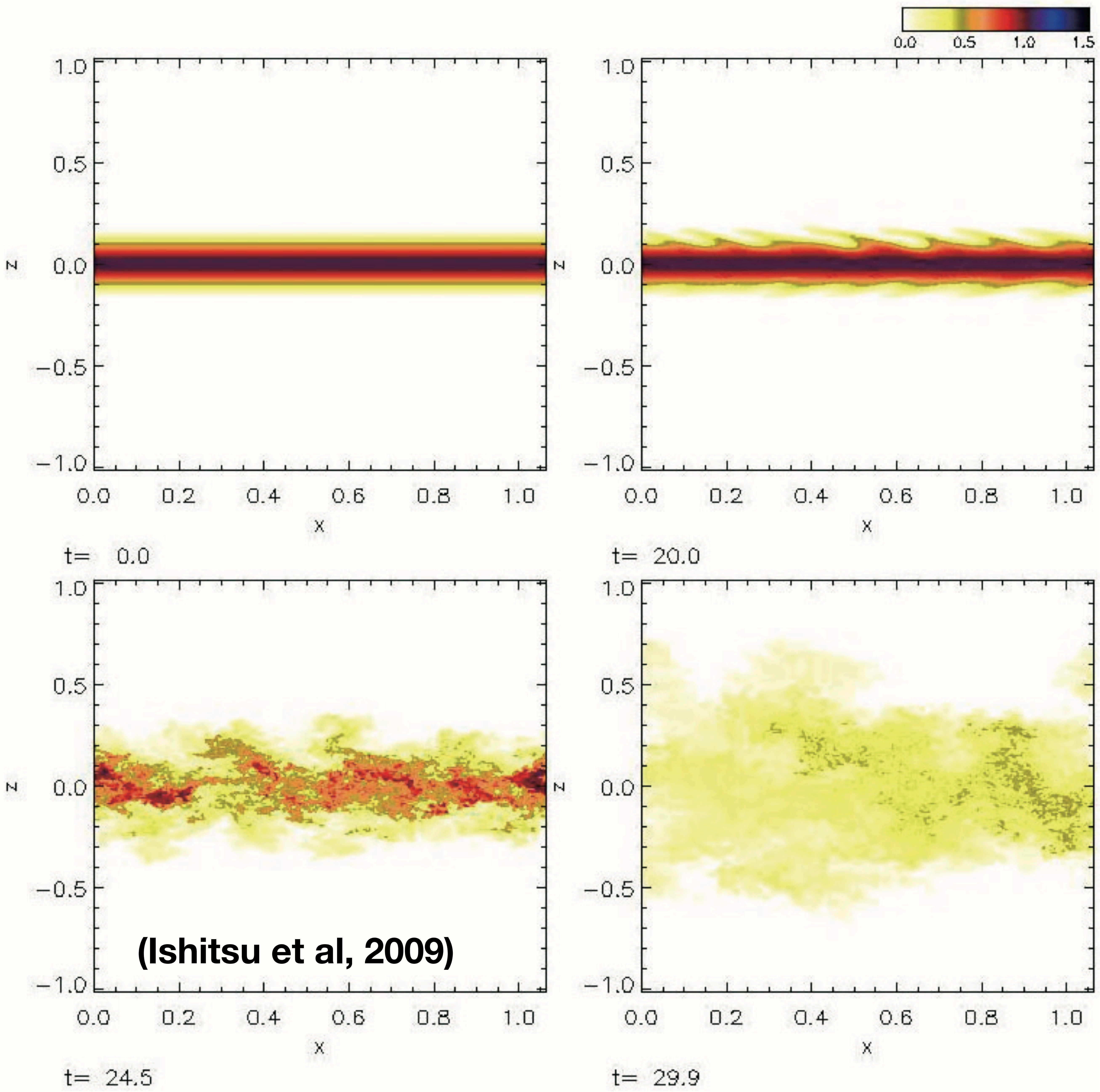
$s_{\mathbf{grow}} \sim \Omega$



$$\frac{\Delta\rho_{\mathrm{d}}}{\rho_{\mathrm{d}}}$$

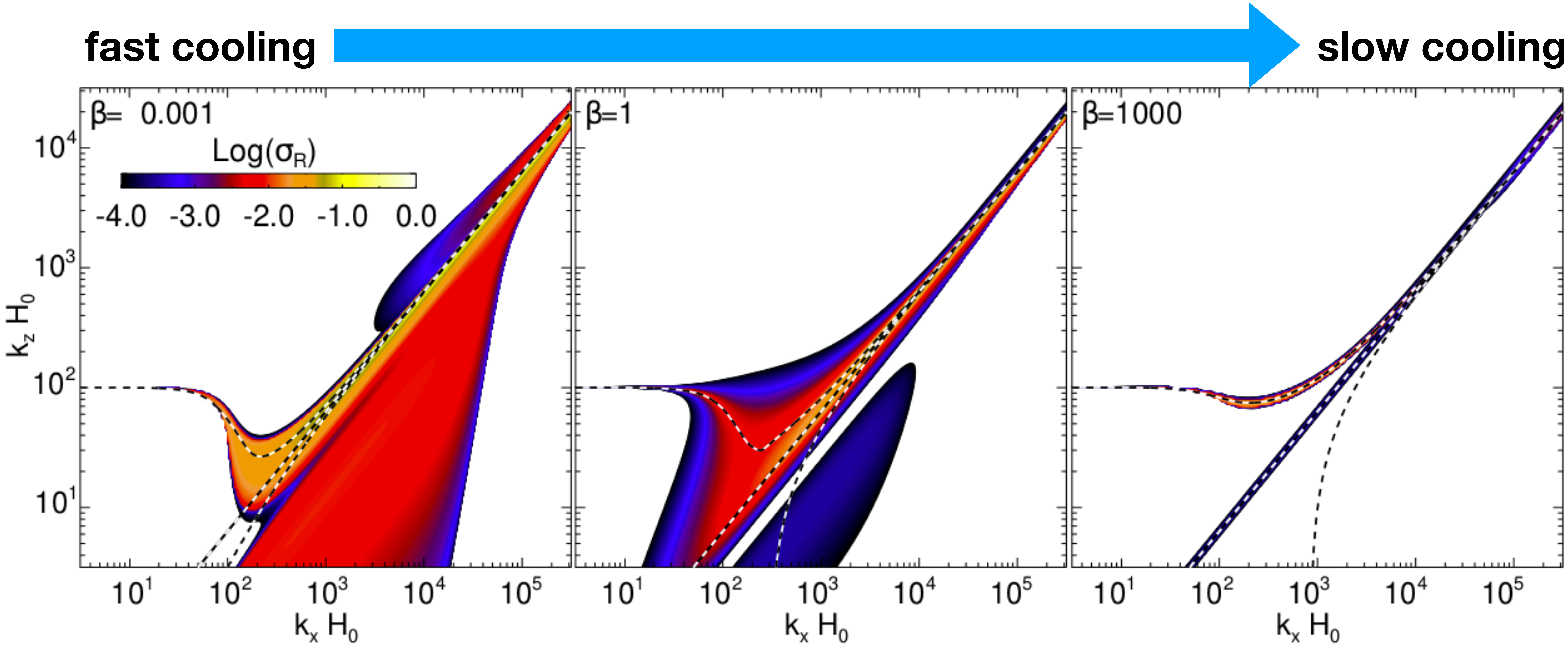
Lin (2021)

Vertically shearing SIs grow fast but…



dust layer dispersed ☹️

SI in non-isothermal disks



Lehmann & Lin (2023)

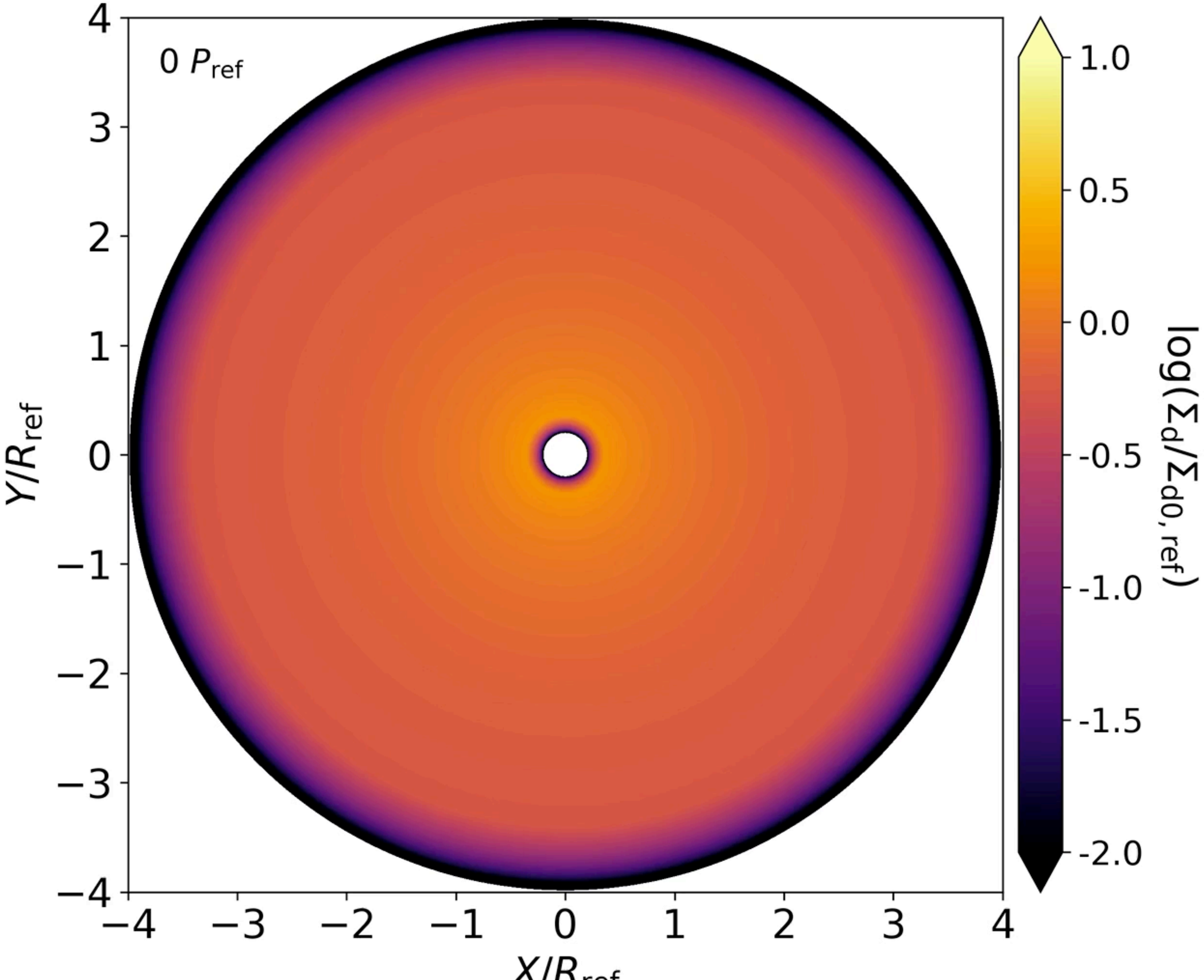
Can modern disk models help?

(e.g. Riols et al. 2020, Cui & Bai 2021)

SI in a pressure bump with a background accretion flow

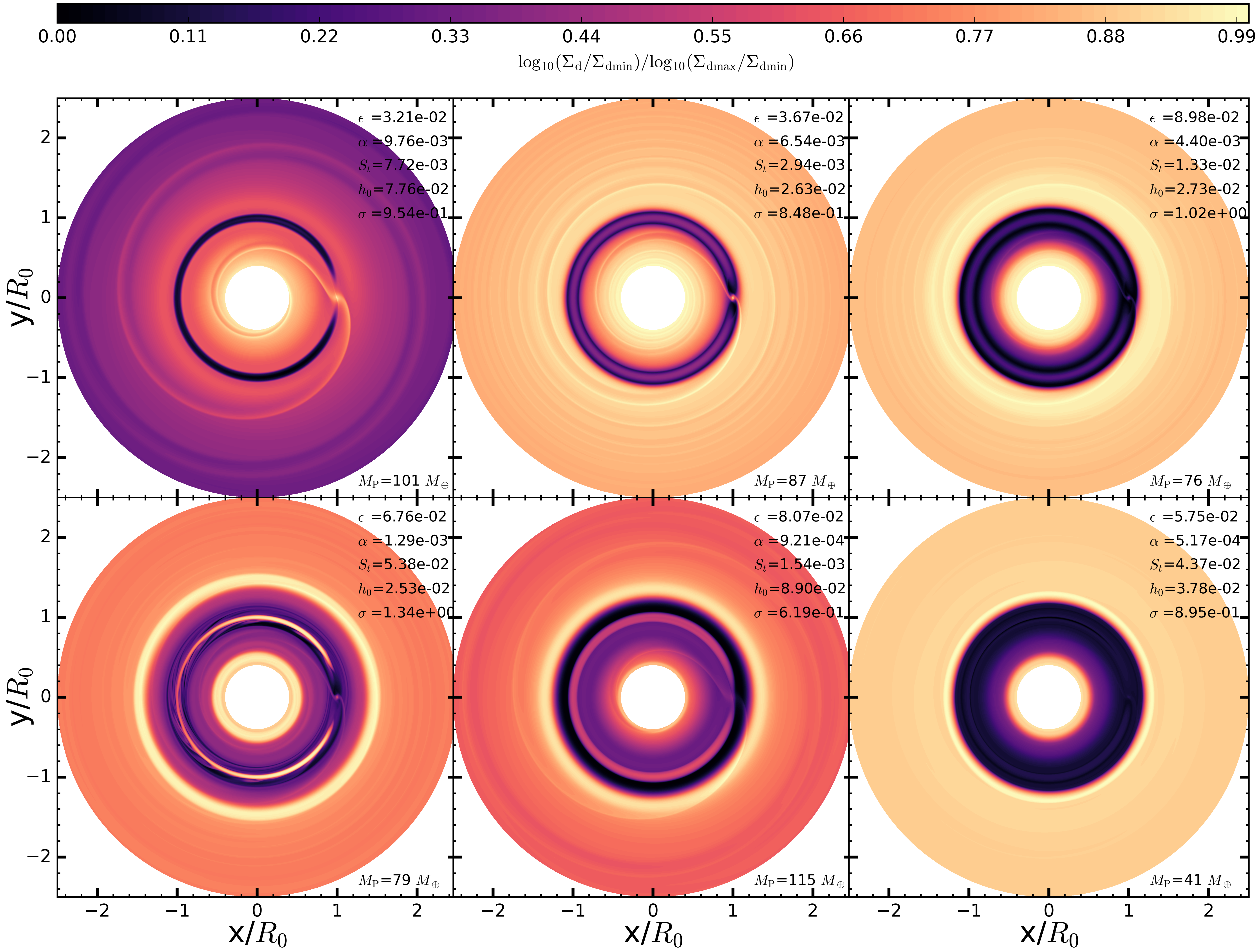
Lin & Hsu (2022), Hsu & Lin (2022)

Planets form somehow, so what's next?



Bi, Lin, Dong (2021)

Disk-planet morphology



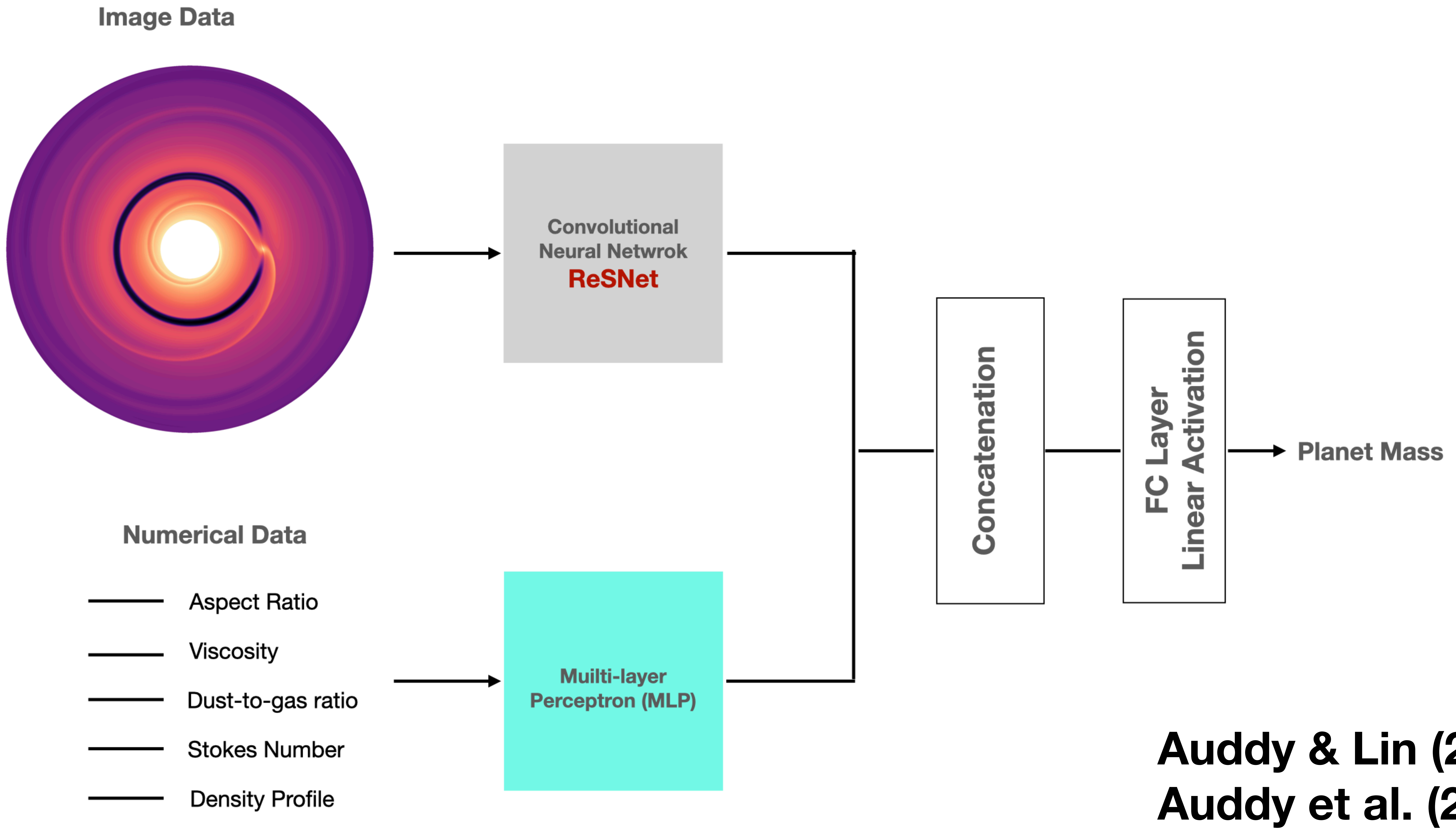
Auddy & Lin (2020)

Detecting unseen planets via disk morphology

AS 209, DSHARP (Zhang et al. 2018)

But each observation requires many simulations

Modeling planet gaps with artificial/convolutional NN



Auddy & Lin (2020)
Auddy et al. (2021)
Auddy et al. (2022)

Estimating planet masses around HL Tau

- **Hydrodynamic simulations**

(Dong et al. 2015, Dipierro et al. 2015, Jin et al. 2016)

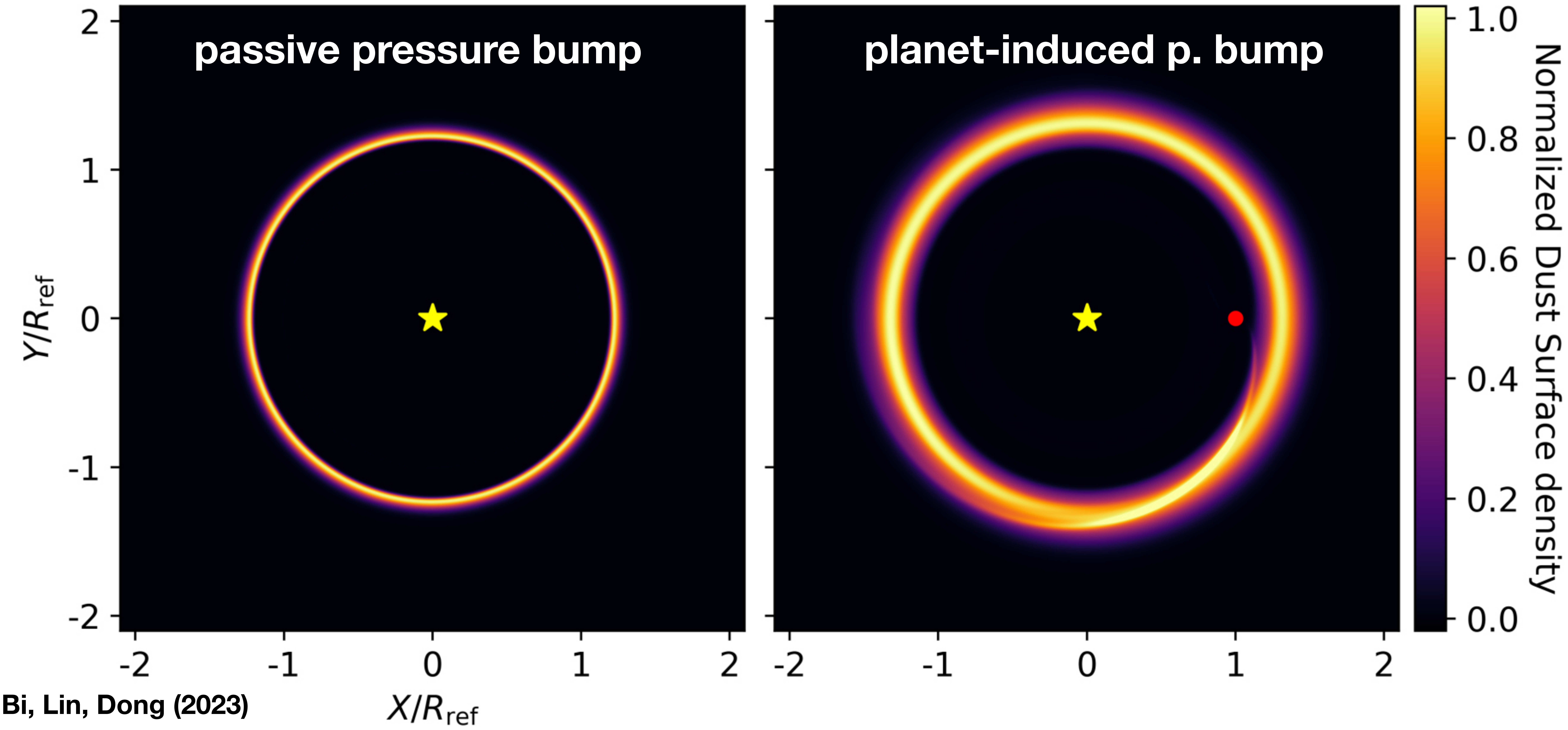
$$M_p = 0.2 - 0.35M_J, 0.17 - 0.27M_J, 0.2 - 0.55M_J$$

- **Disk-Planet Neural Network**

(Auddy & Lin, 2020)

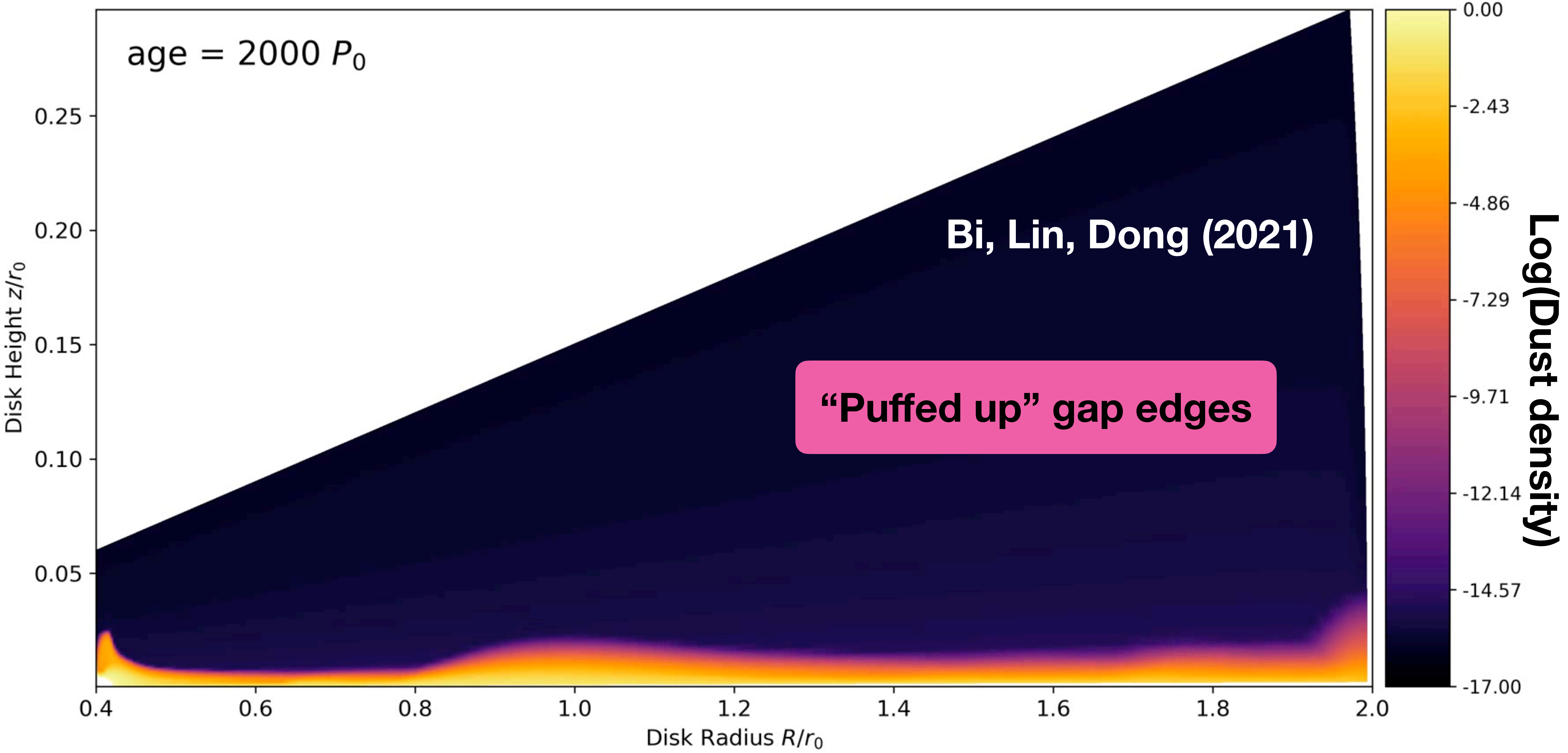
$$M_p = 0.24M_J, 0.21M_J, 0.2M_J$$

Are all observed dust rings caused by planets?



Bi, Lin, Dong (2023)

Three-dimensional models

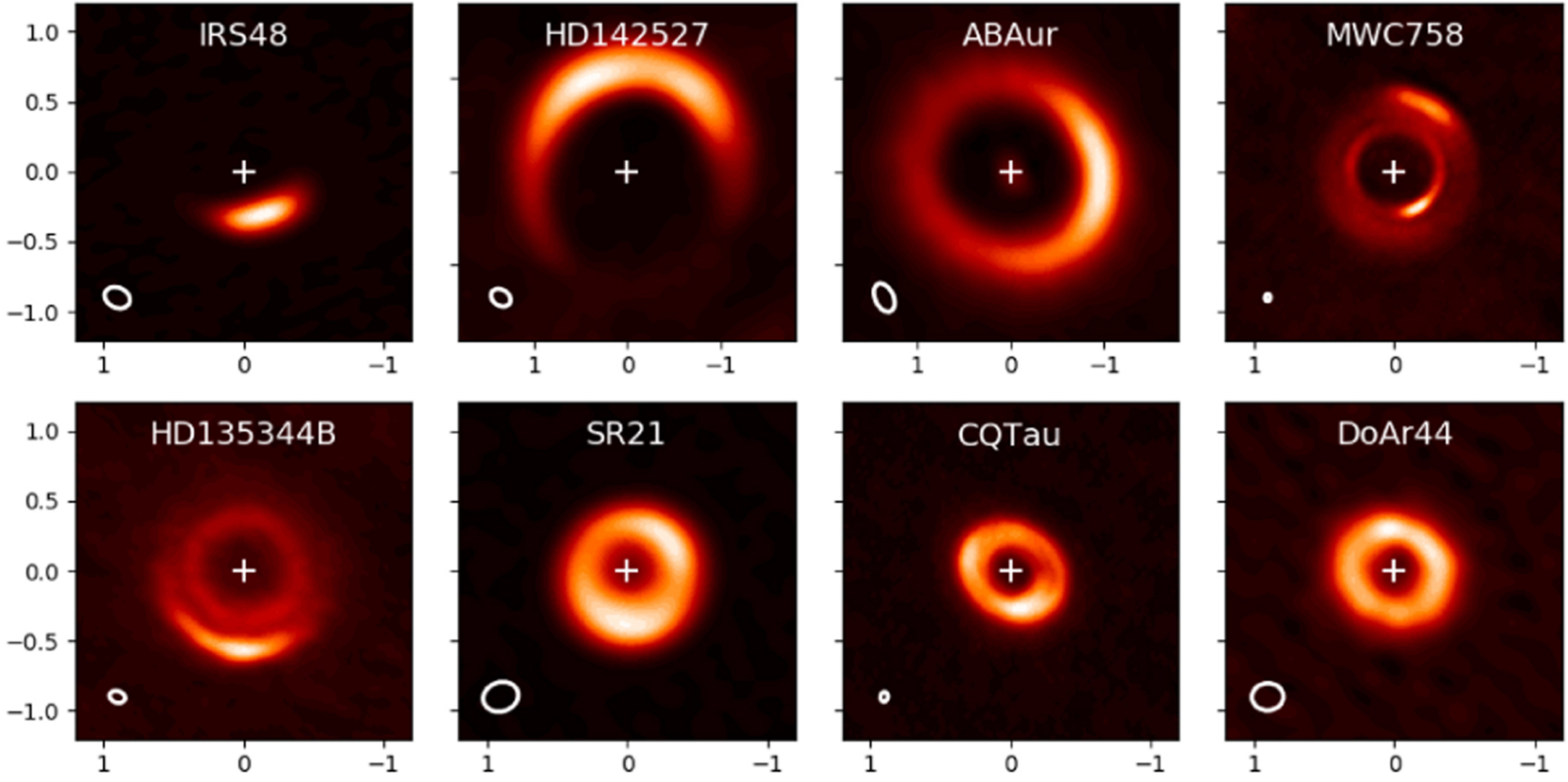


Puffed up rings in observations: Sign of planets?

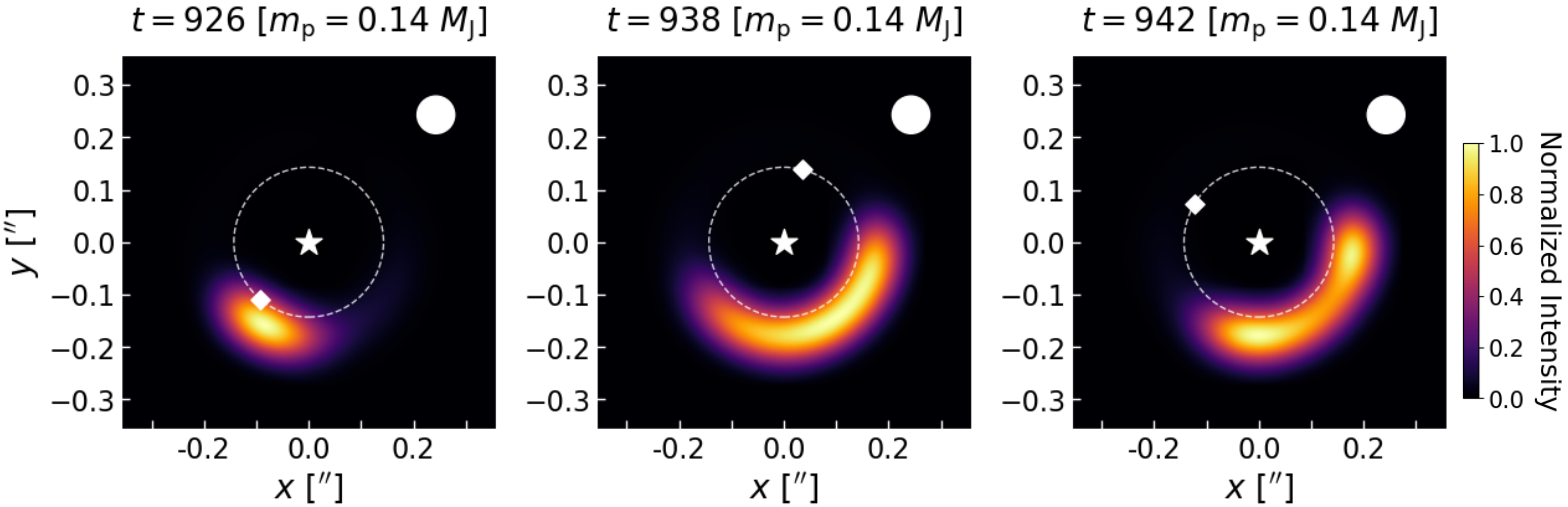
Doi & Kataoka (2021)

Some observed disks are asymmetric

(van de Marel, et al. 2021)



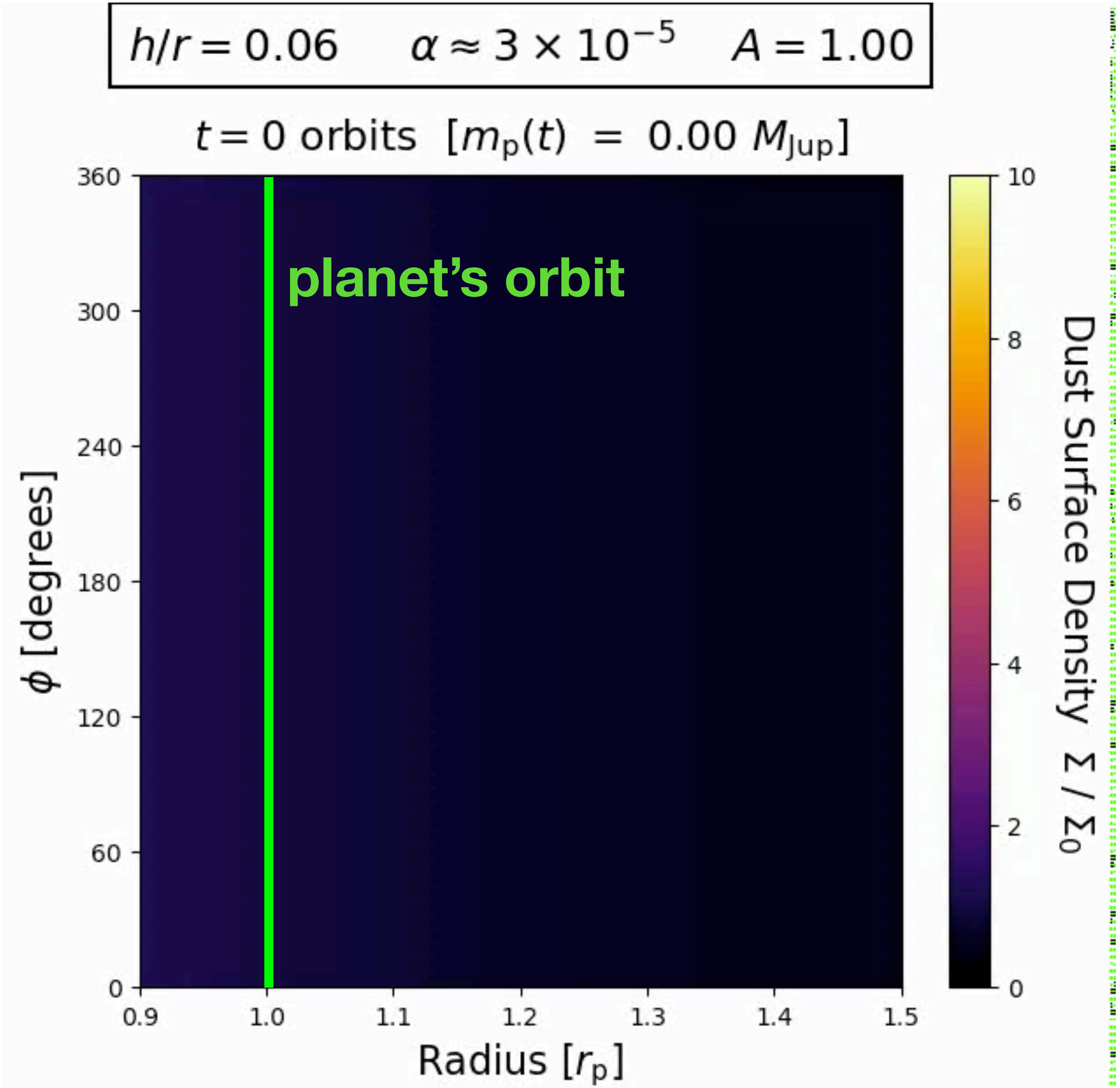
Can planets also explain them?



Vortex formation due to the "Rossby wave" instability

(Hammer, Lin, et al. 2021)

Planet-induced, compact vortices in turbulent disks



Hammer, Lin, Pinilla (in prep)

Summary

- We are in a golden age for planetary sciences
- The streaming instability is the leading theory for planetesimal formation
- Modern disk models may challenge the SI or provide new pathways to planetesimal formation
- Planet-disk interaction can be used to reveal or rule out hidden planets in observations of protoplanetary disks

Thank you

@linminkai