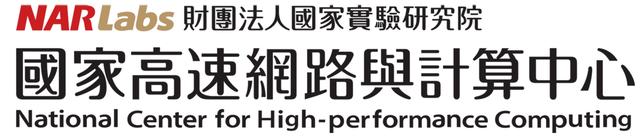
Streaming instabilities in modern protoplanetary disks

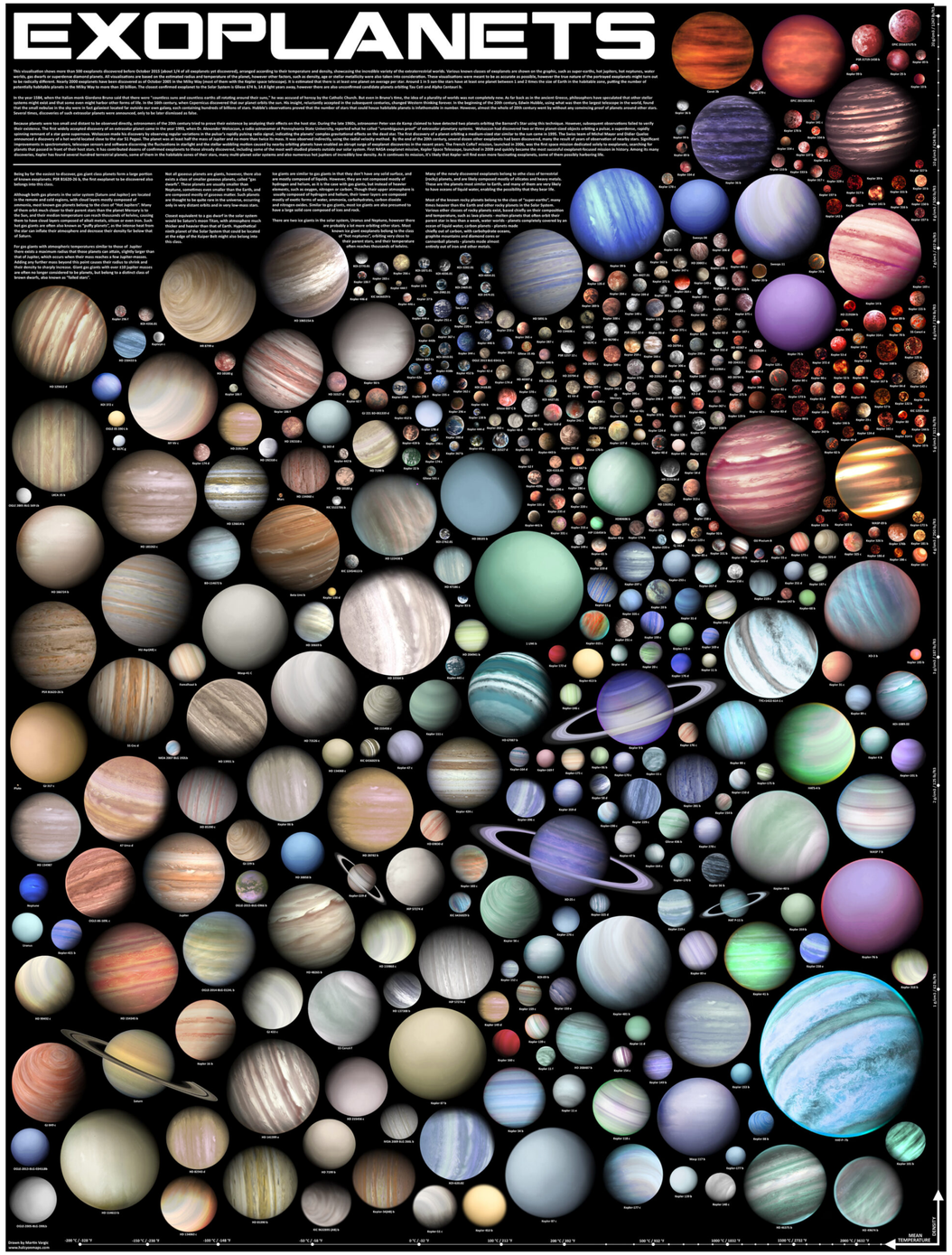
Min-Kai Lin

September 2023



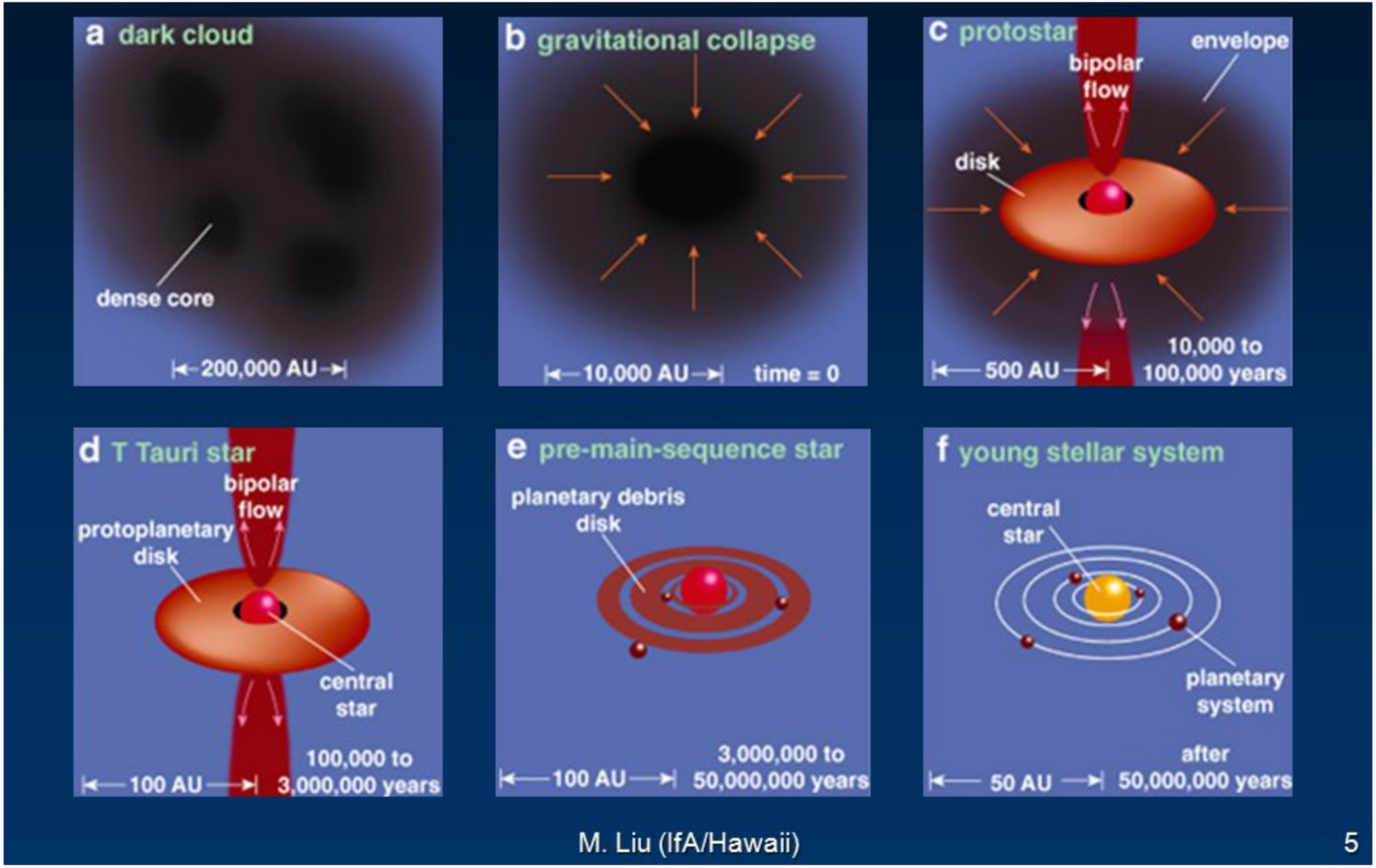
The era of exoplanet sciences

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

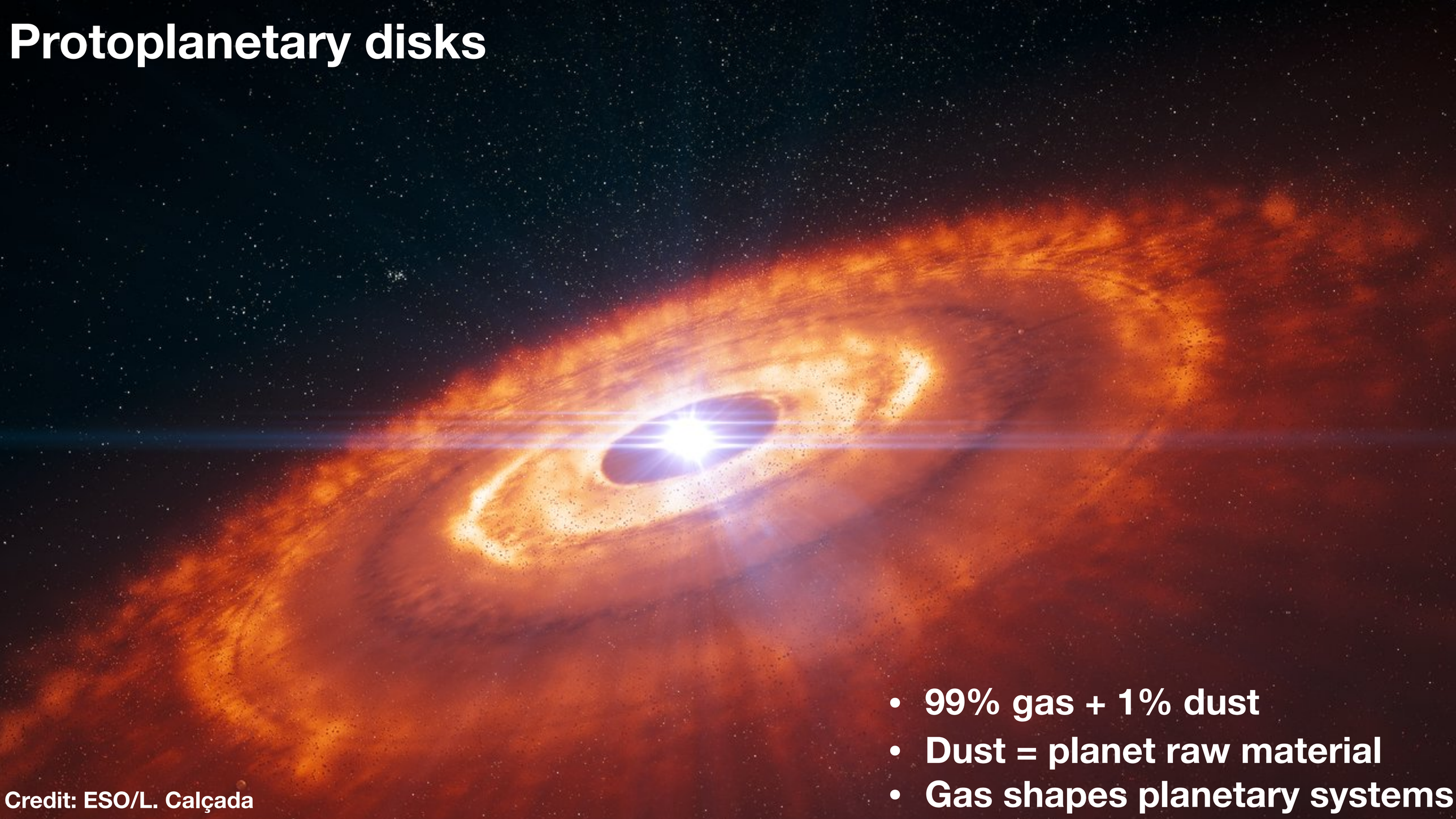


Credit: Martin Vargic

Star & planet formation



Protoplanetary disks

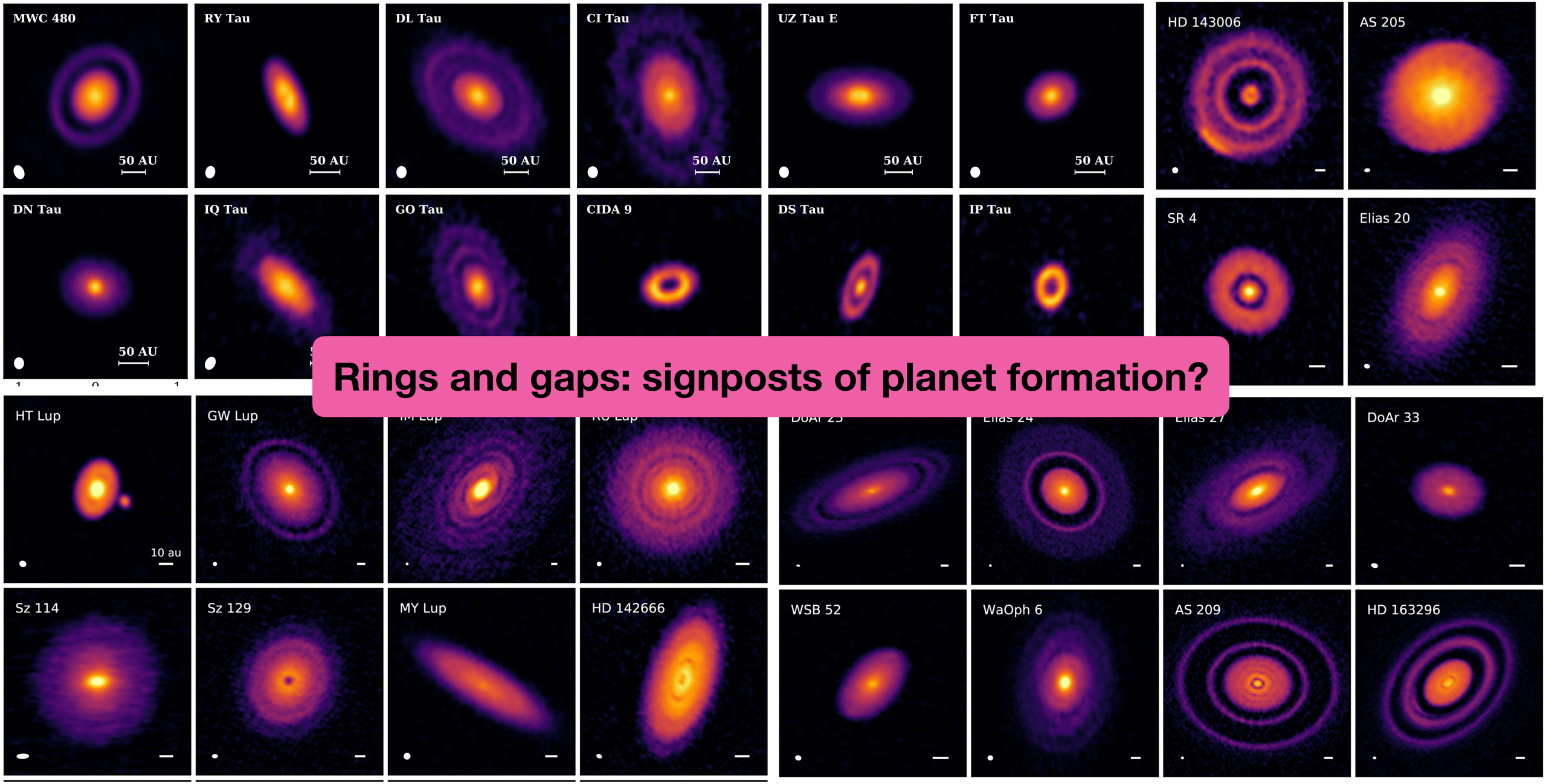


- 99% gas + 1% dust
- Dust = planet raw material
- Gas shapes planetary systems

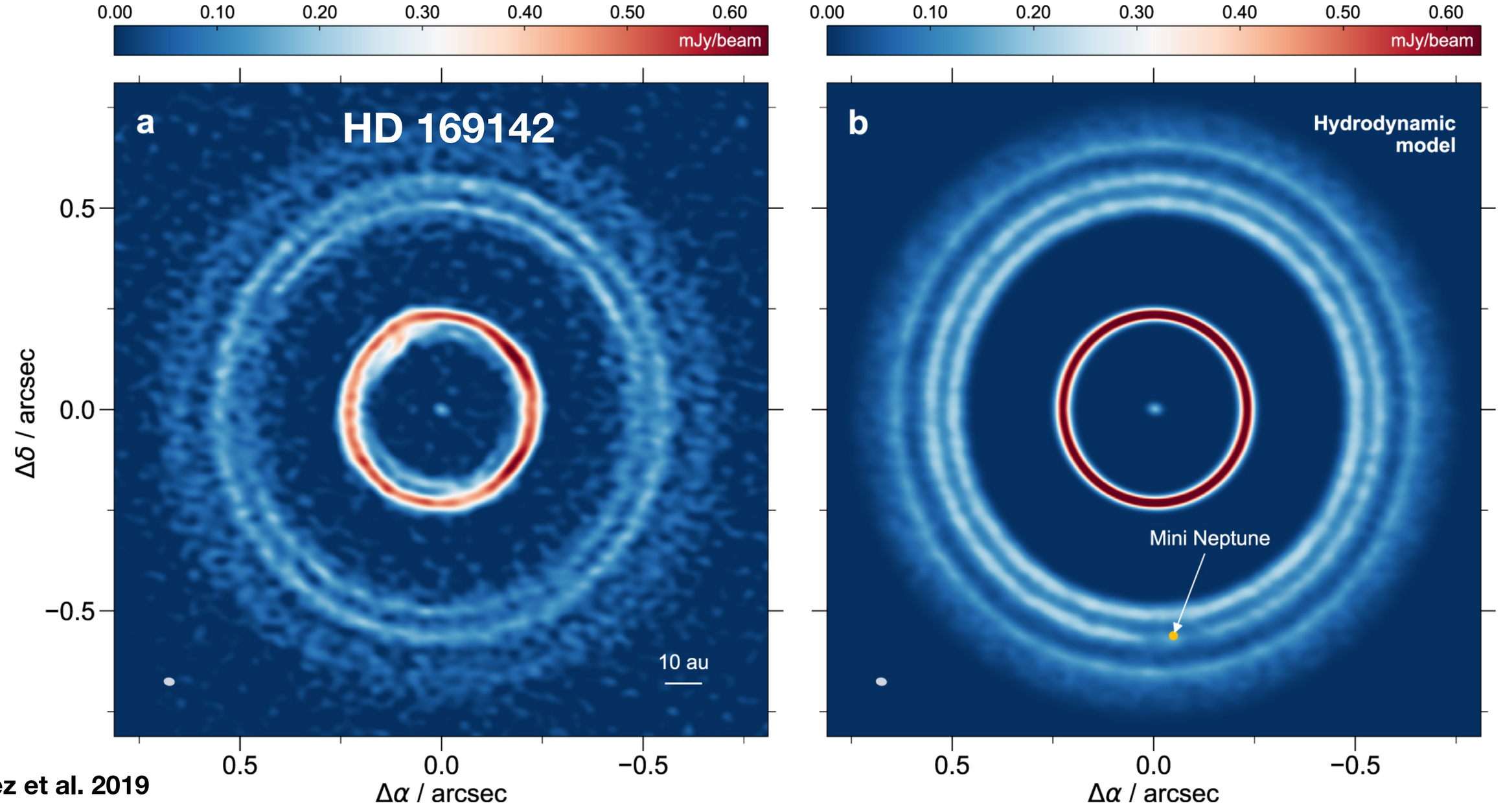
Credit: ESO/L. Calçada

Real protoplanetary disks

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

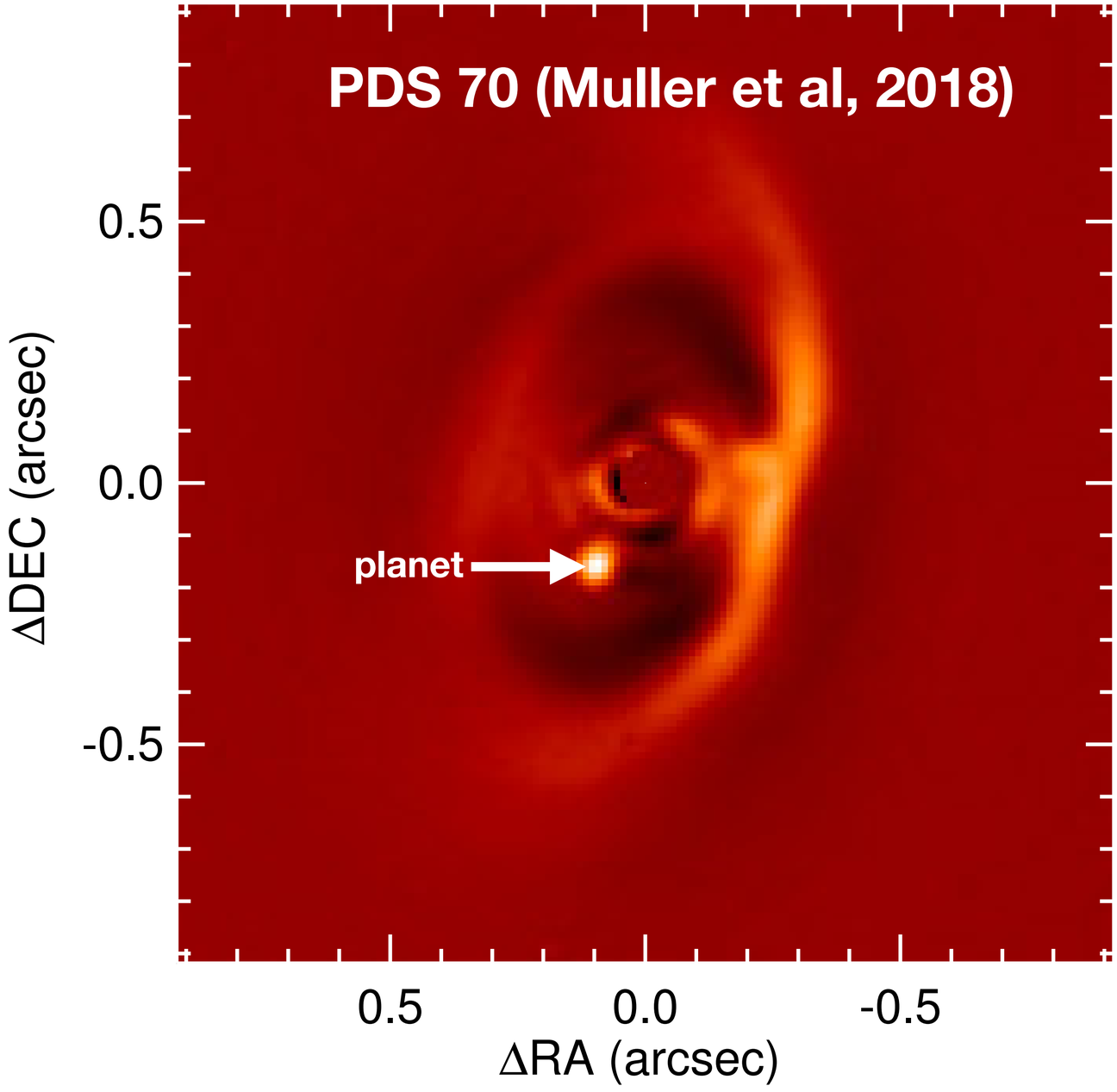


A disk-planet explanation

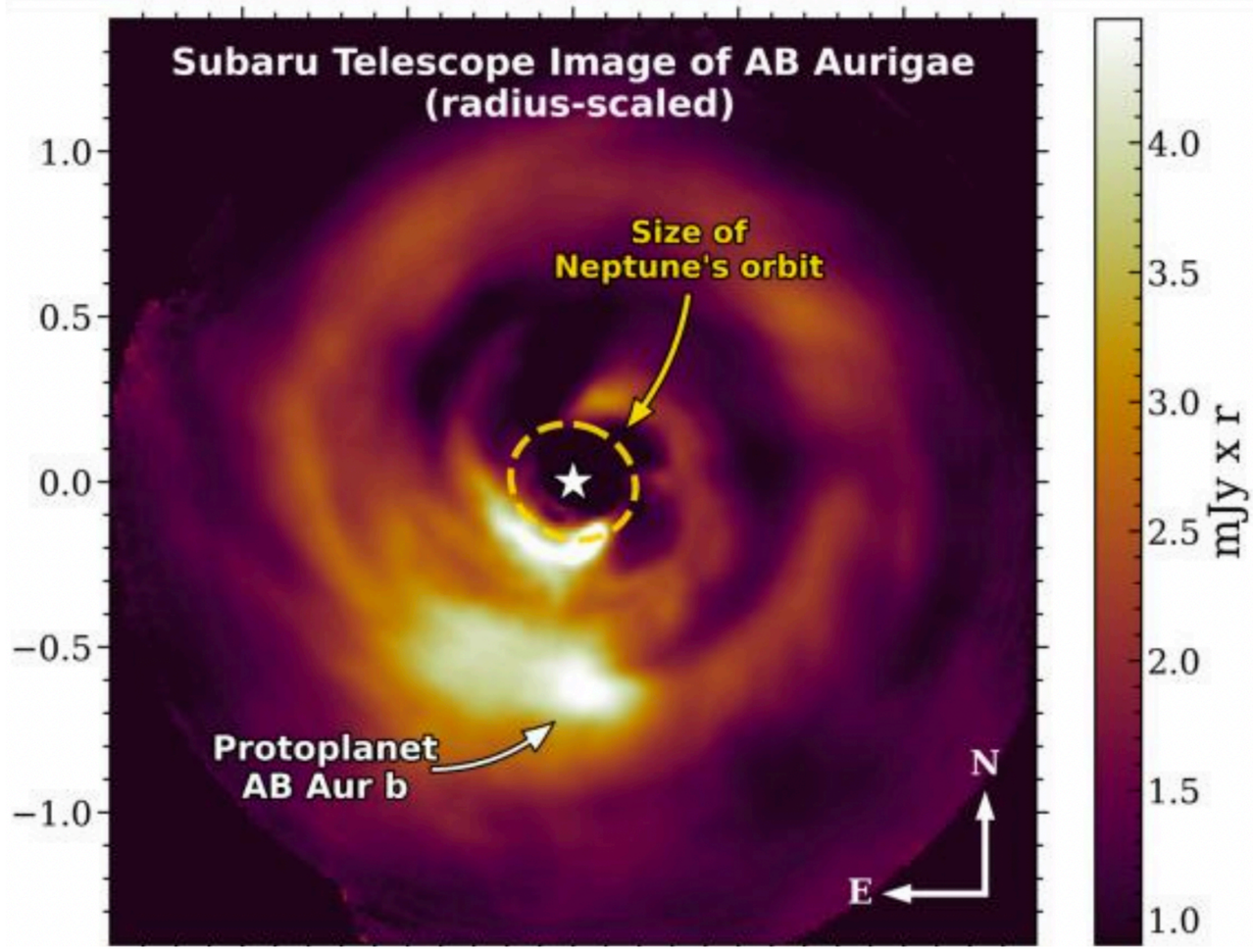


Pérez et al. 2019

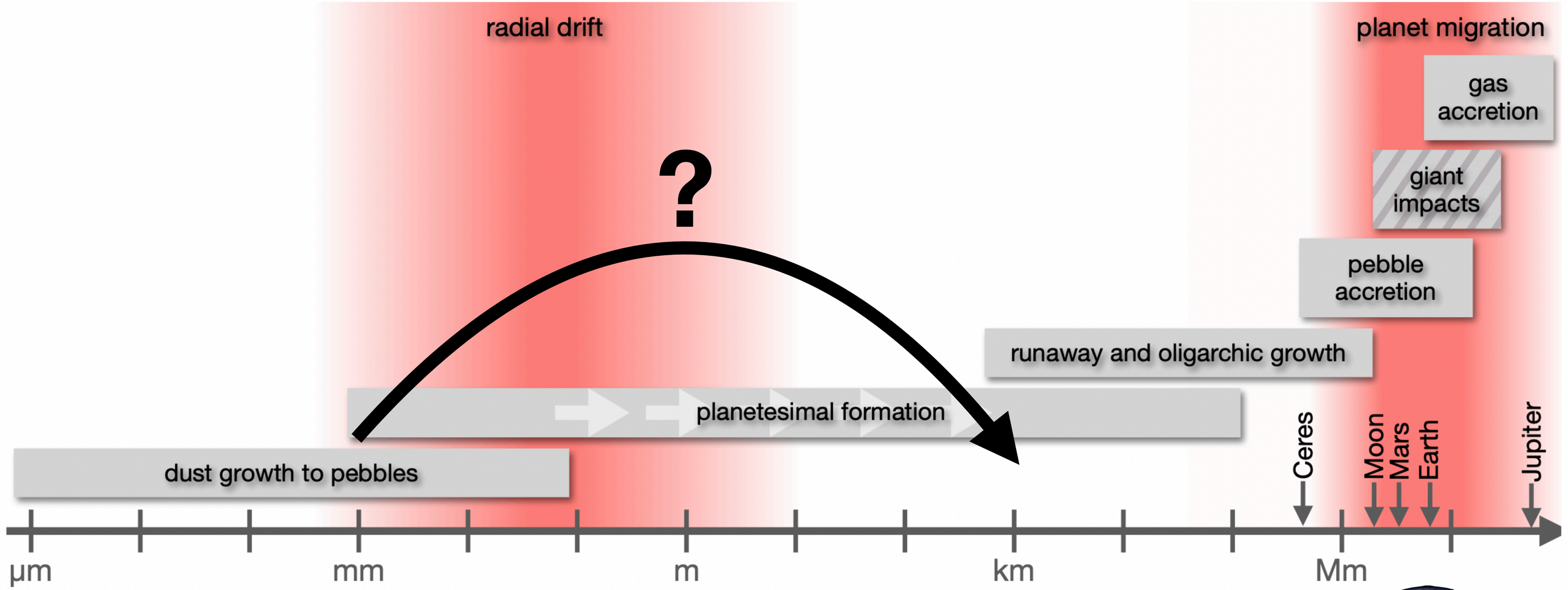
Observations of planets in a disk

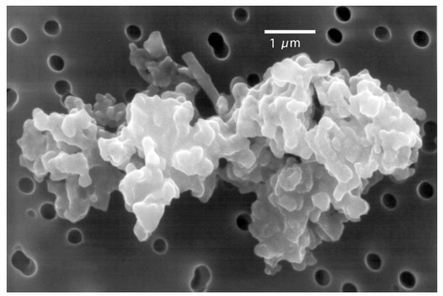


AB Aur (Currie et al, 2022)



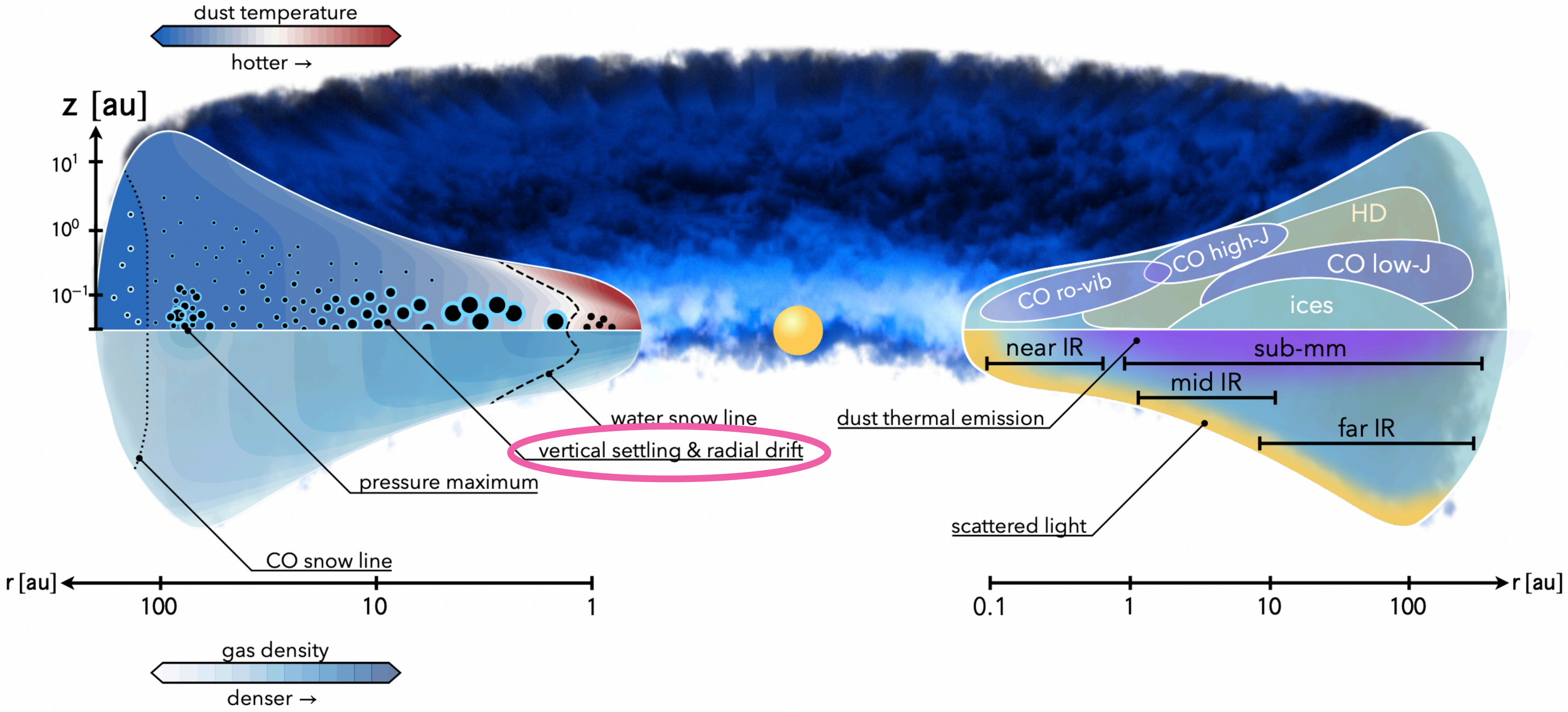
One planet, multiple scales





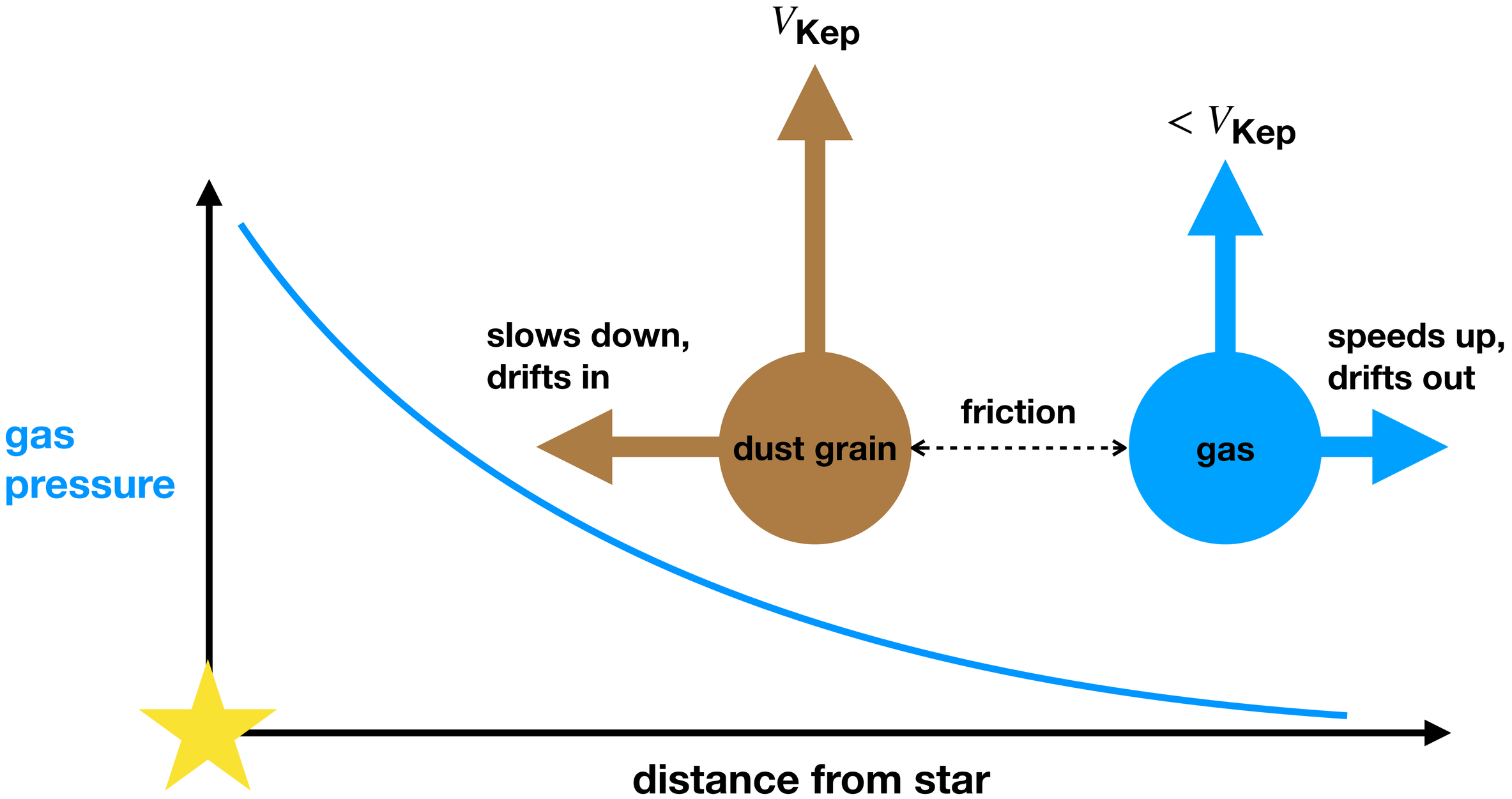
(Drazkowska et al., 2022, PPVII)

Dust in protoplanetary disks



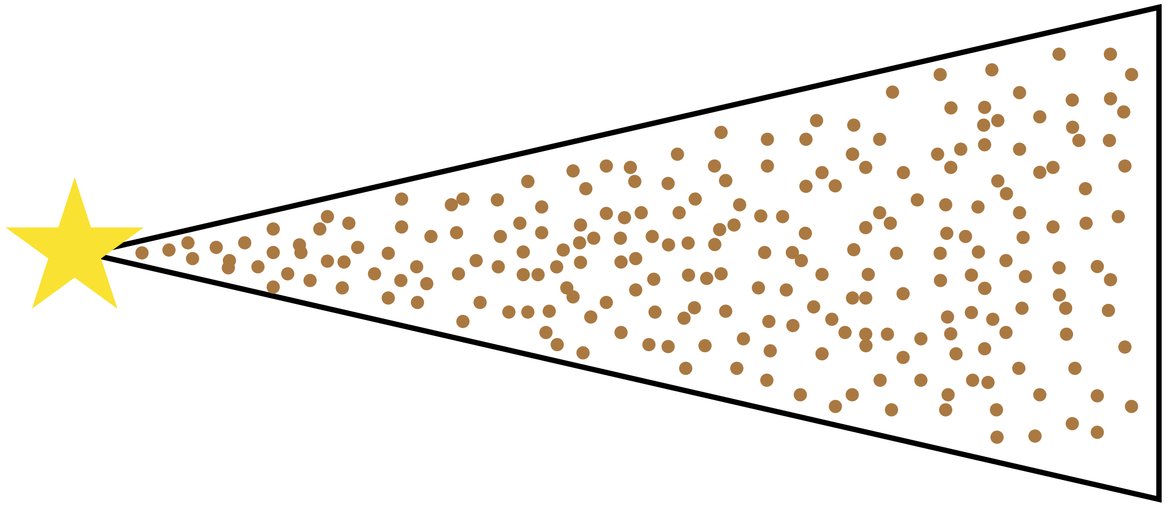
(Miotello et al., 2022, PPVII)

Dust and gas move relative to each other

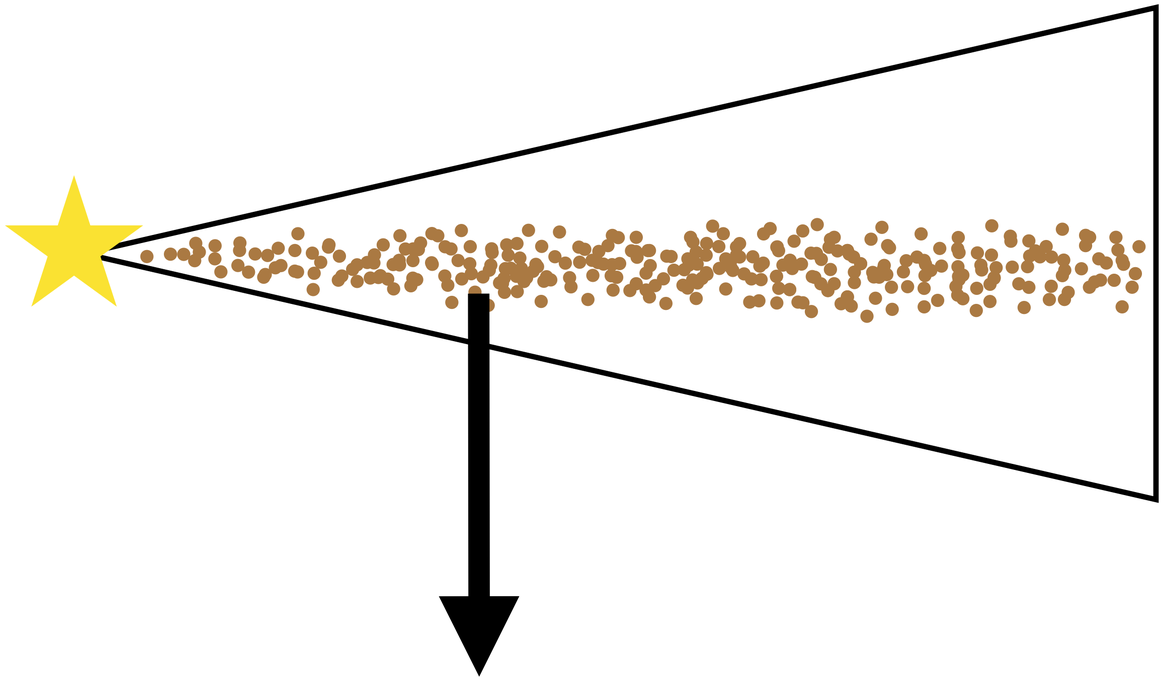


Vertical dust settling

well-mixed dust in young disk



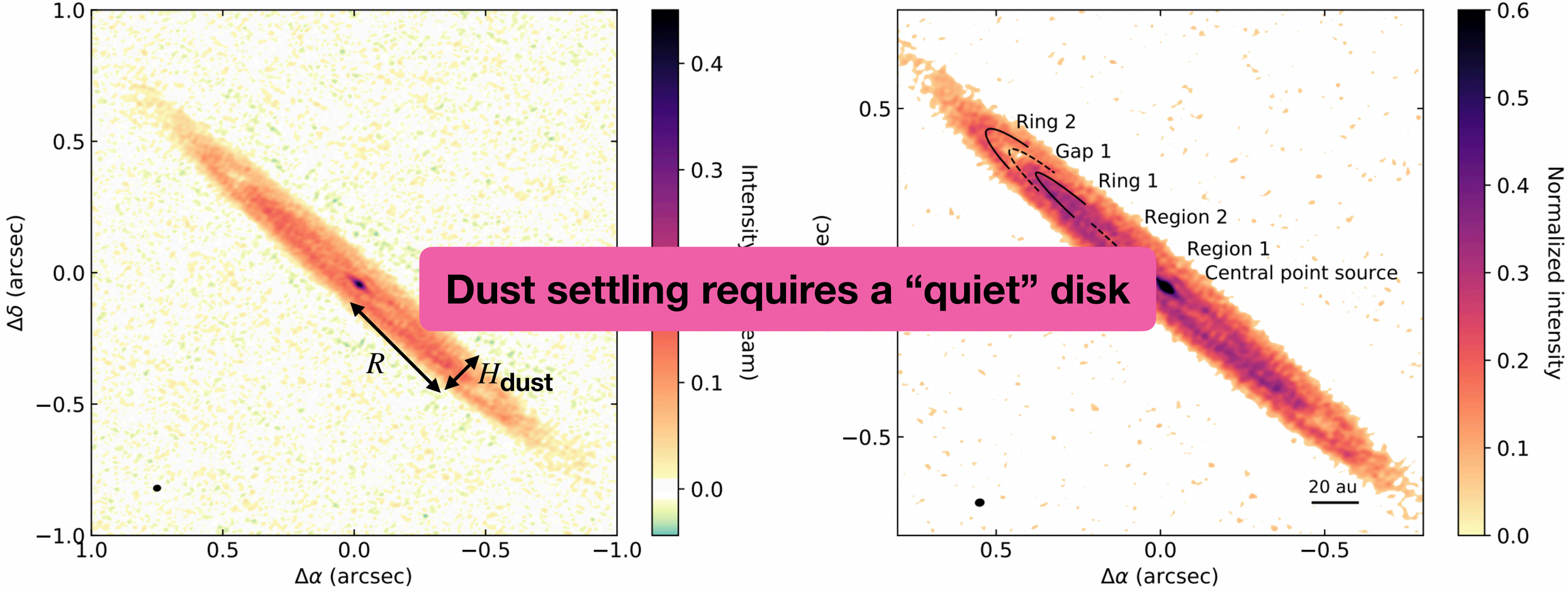
dust sediments to the midplane



planet(esimal) formation

Edge on disk observations

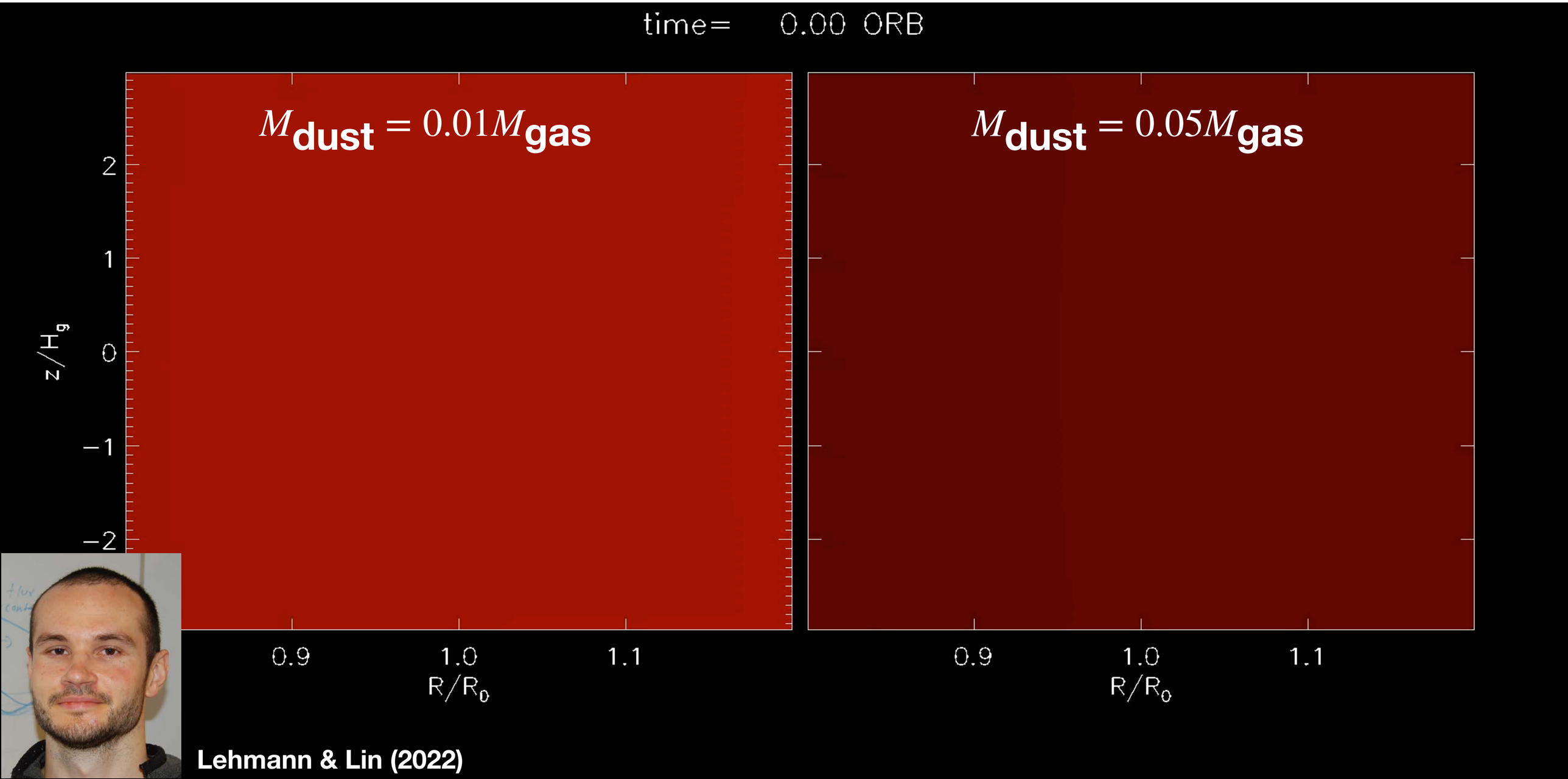
Oph 163131 (Villenave et al. 2022)



Dust settling requires a “quiet” disk

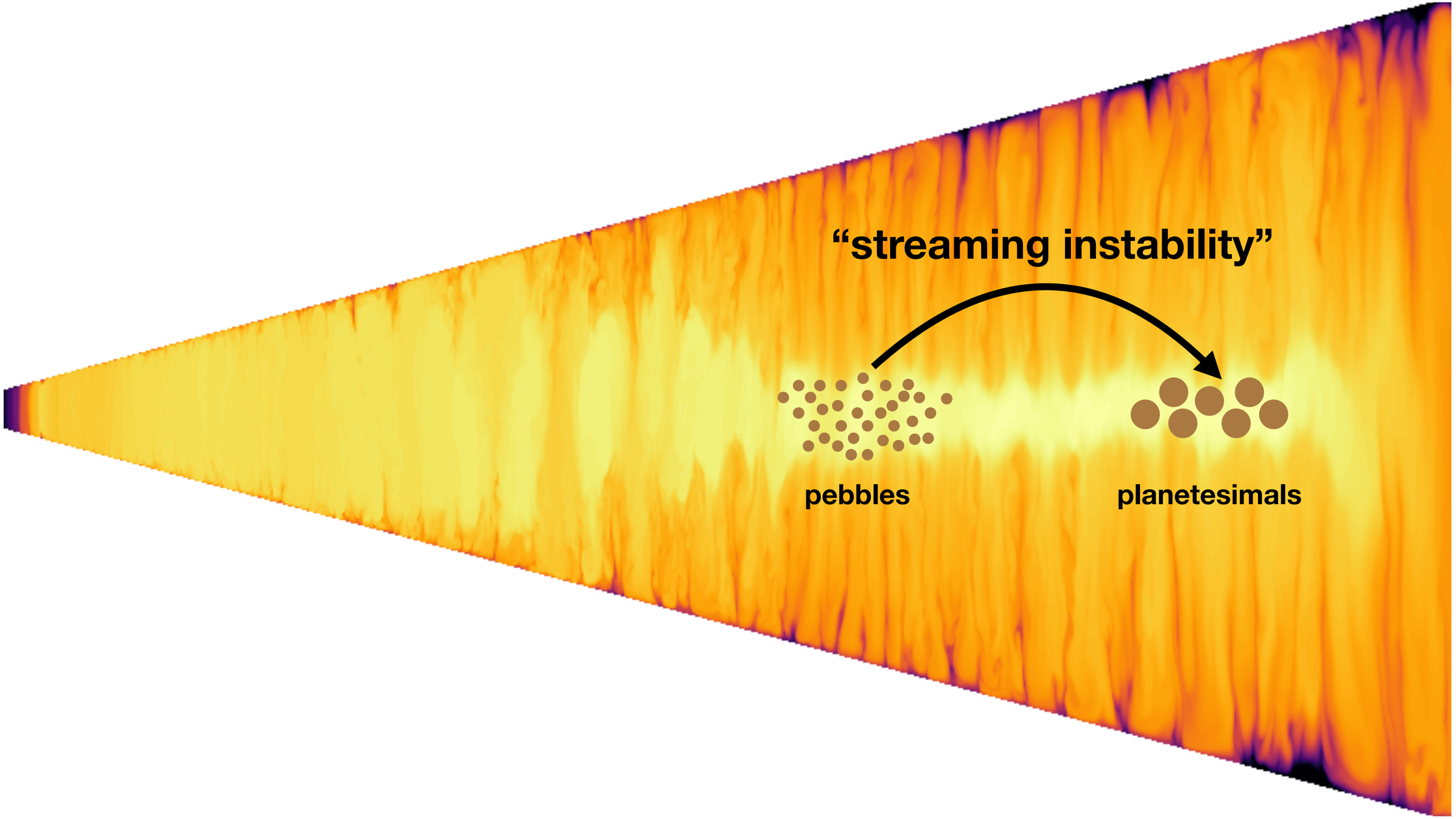
$$H_{\text{dust}} \sim 0.005R$$

Dust settling vs. turbulence

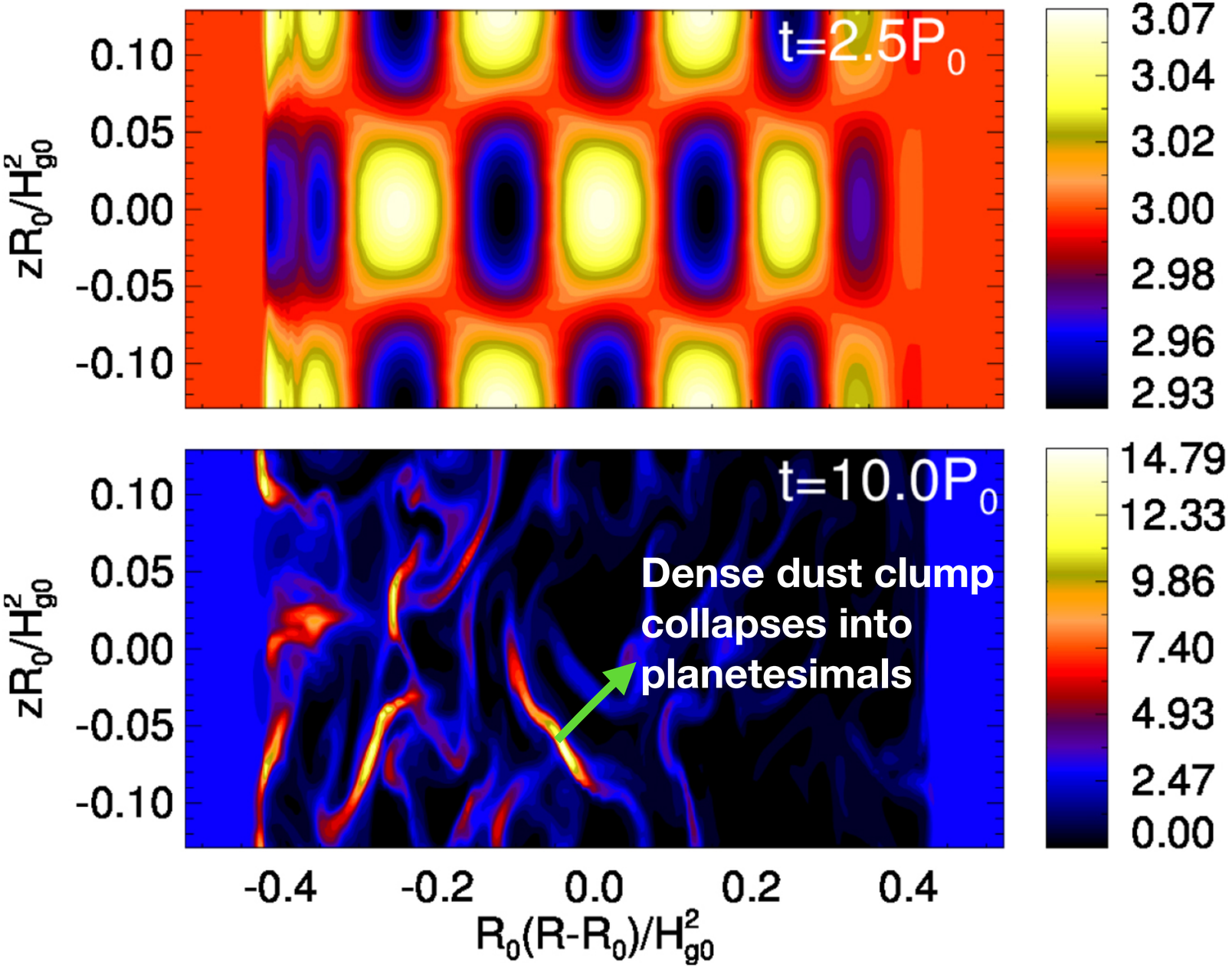


Lehmann & Lin (2022)

Planetesimal formation in the disk midplane

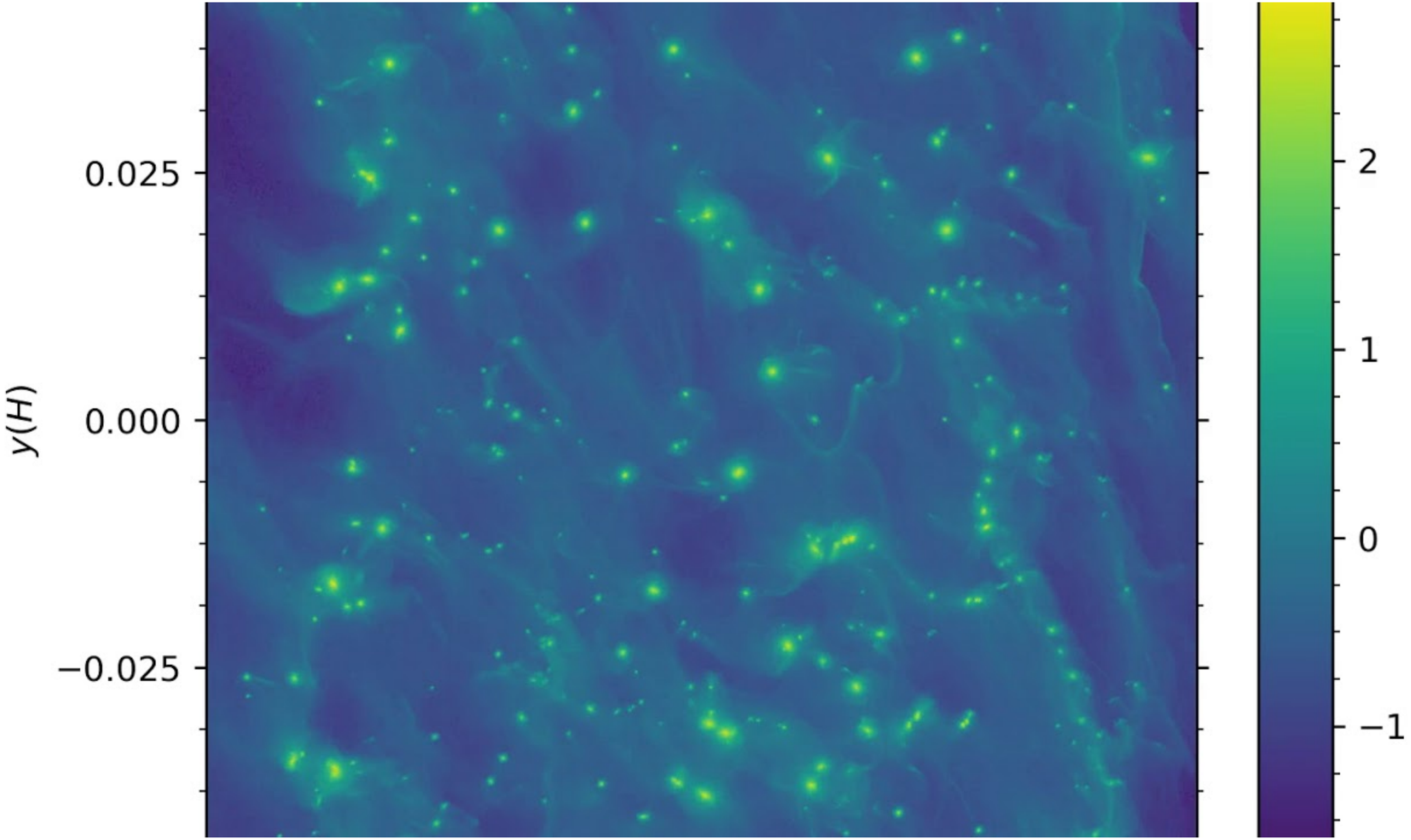


Streaming instability of dusty gas



Chen & Lin (2018)

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



The SI is both simple and complex

Simple ingredients:

- **Mutually interacting dust and gas in rotation**

But protoplanetary disks are much more

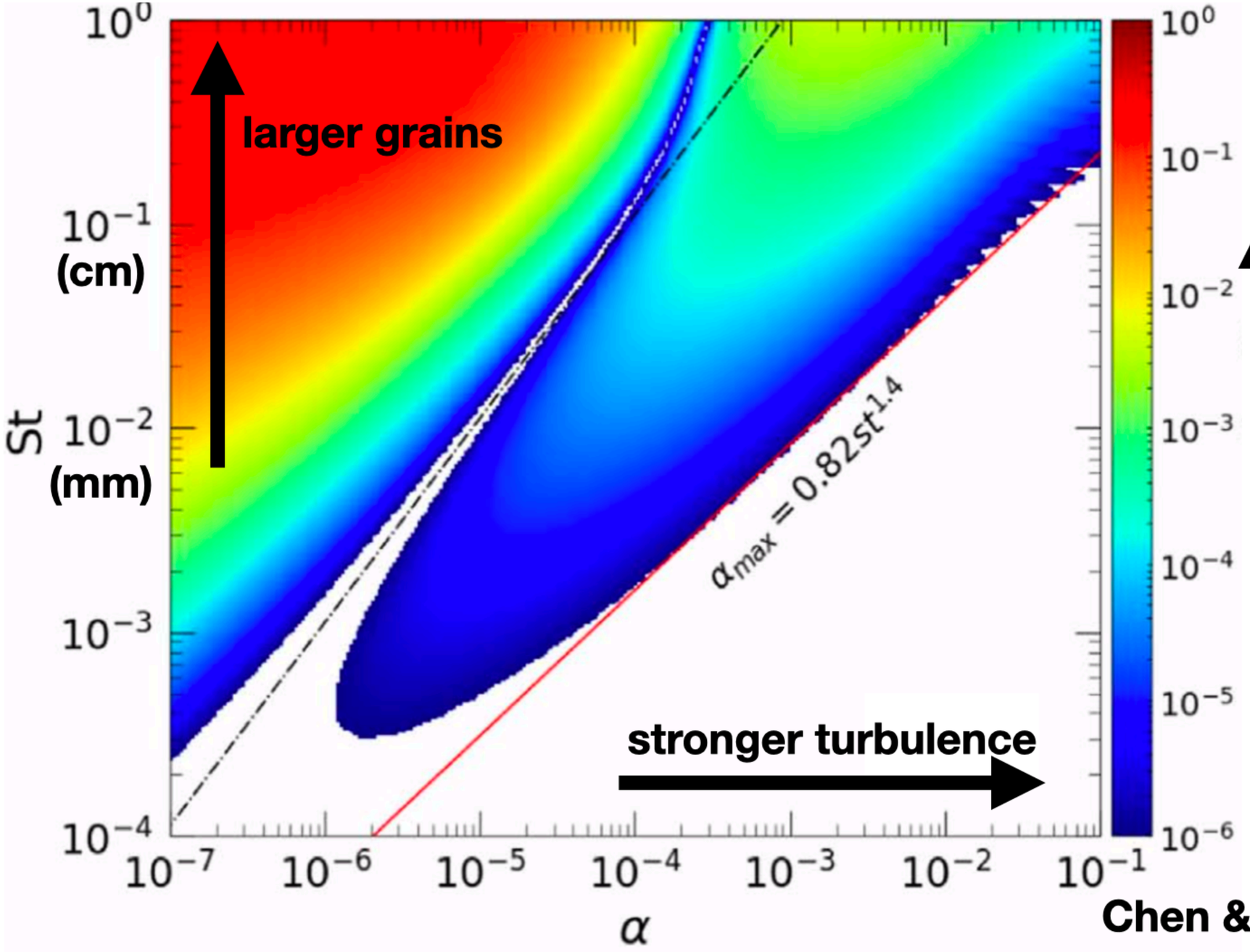
- **Self-enhancing dust-traps by pressure max. (Jacquet et al. 2011)**
- **Work done by pressure-density lag in a dusty gas (Lin & Youdin 2017)**
- **Resonance between dust-gas drift and inertial waves (Squire & Hopkins 2018)**

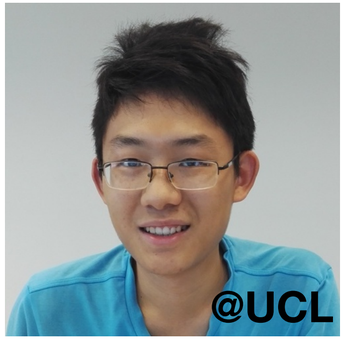
Powered by dust-gas drift

Extensions to the SI and dust dynamics

- turbulence → Chen & Lin (2020)
- vertical structure → Lin (2021)
- magnetic fields → Lin & Hsu (2022), Hsu & Lin (2022), Wu, Lin et al. (in prep.)
- thermodynamics → Lehmann & Lin (2023)

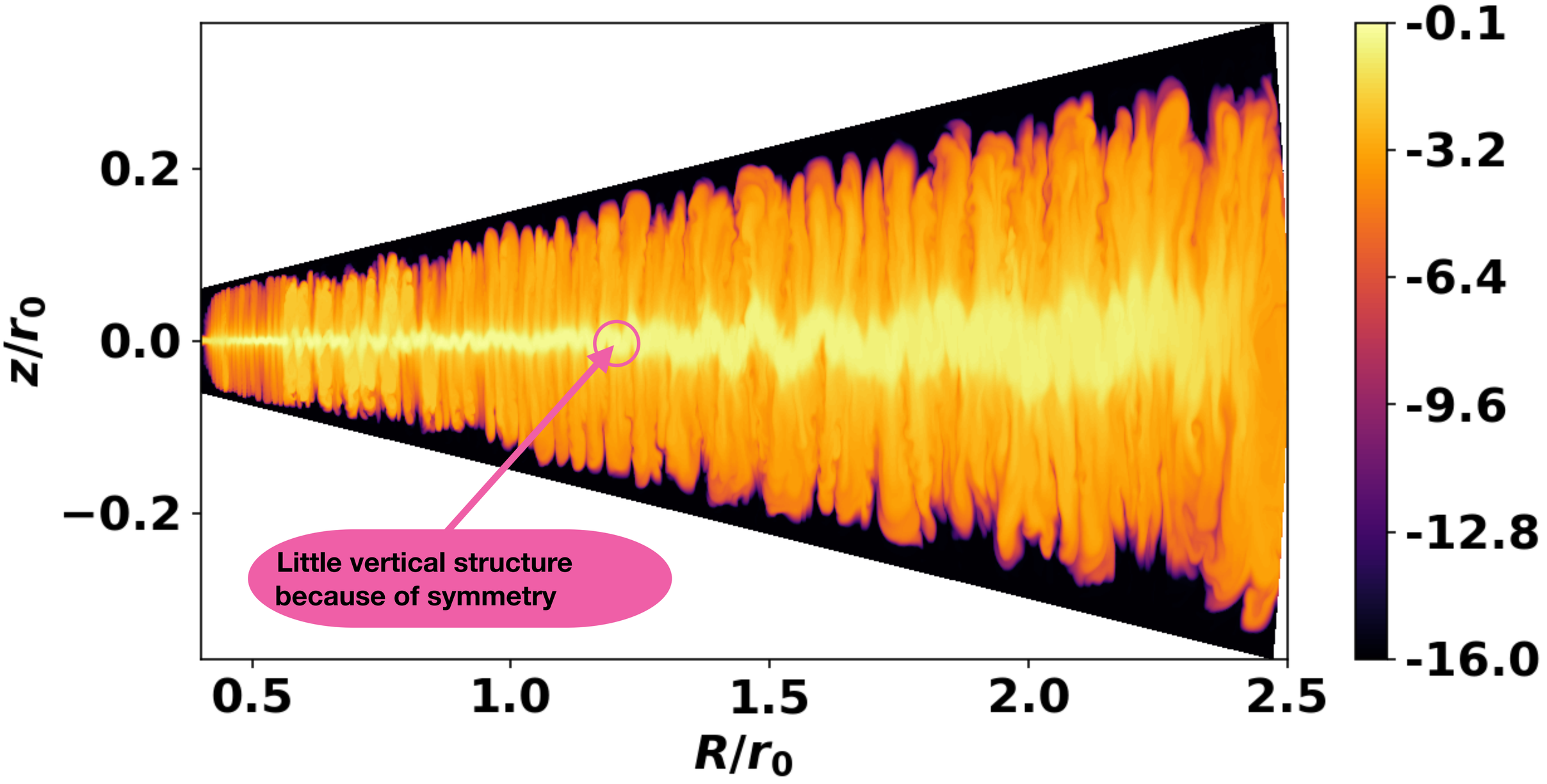
Streaming instability is easily killed by turbulent viscosity



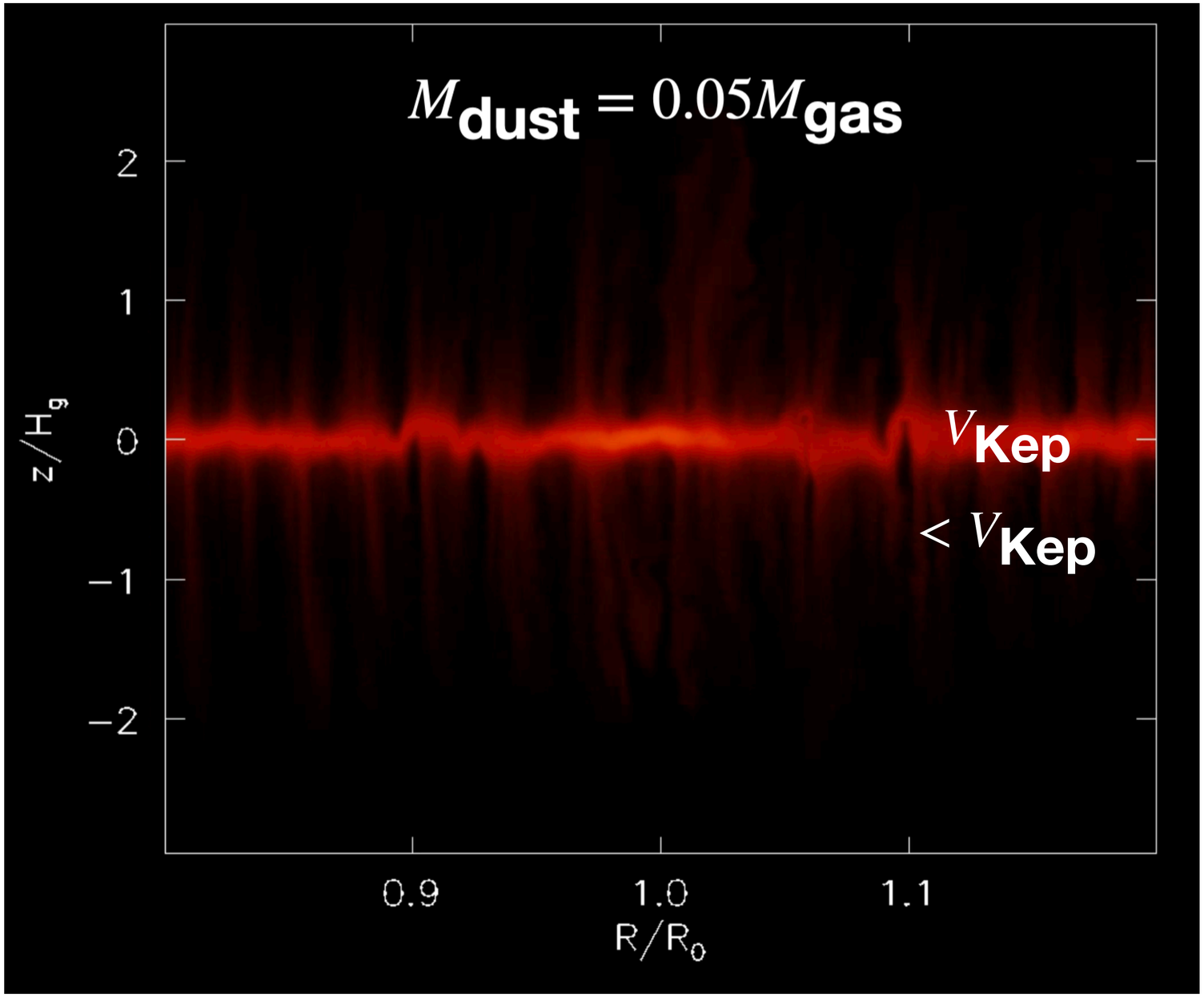


Chen & Lin (2020)

Standard SI analyses neglect vertical structure



Stratified dust layers

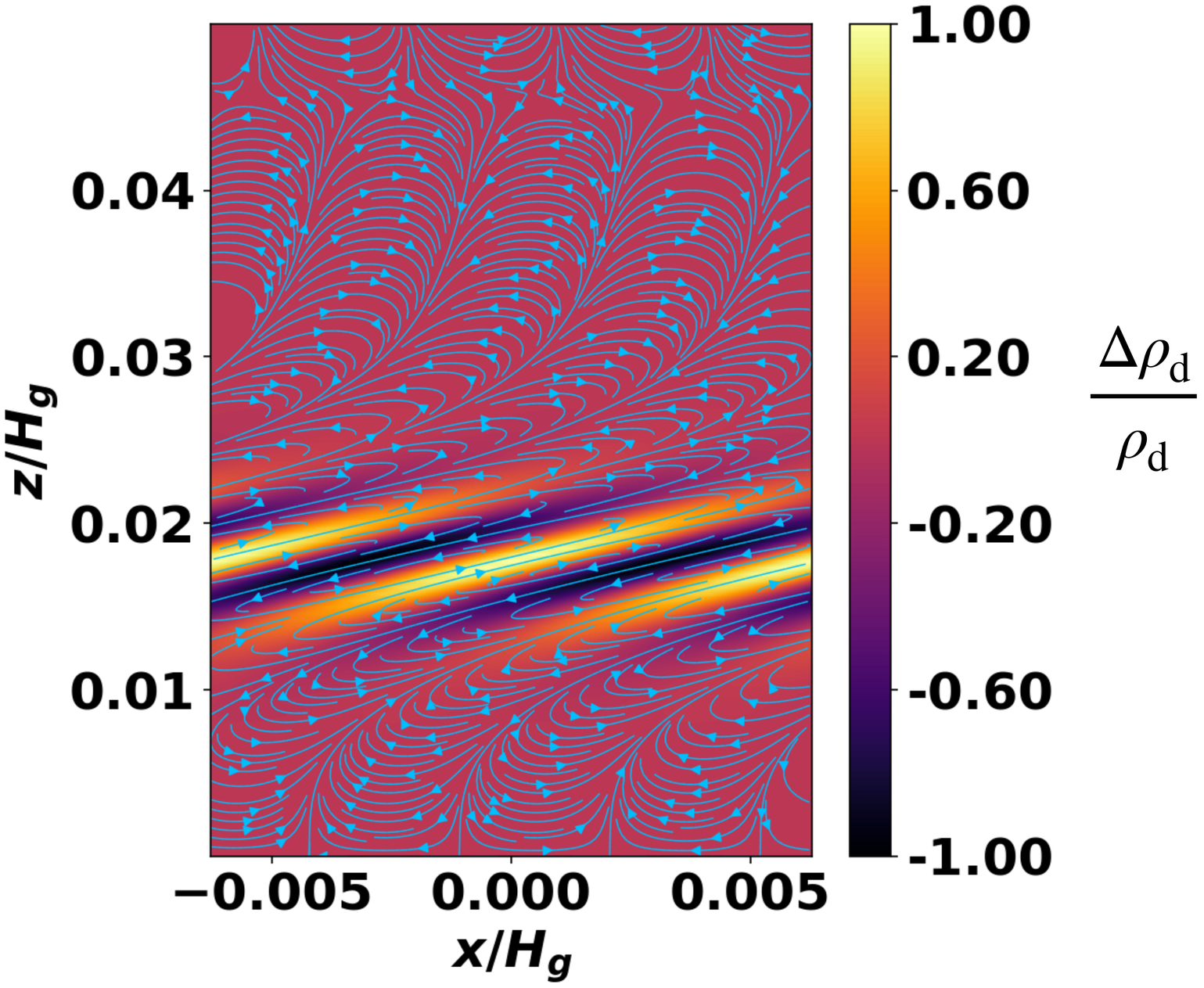


$$\frac{\partial \Omega}{\partial z} \neq 0$$

Lehmann & Lin (2022)

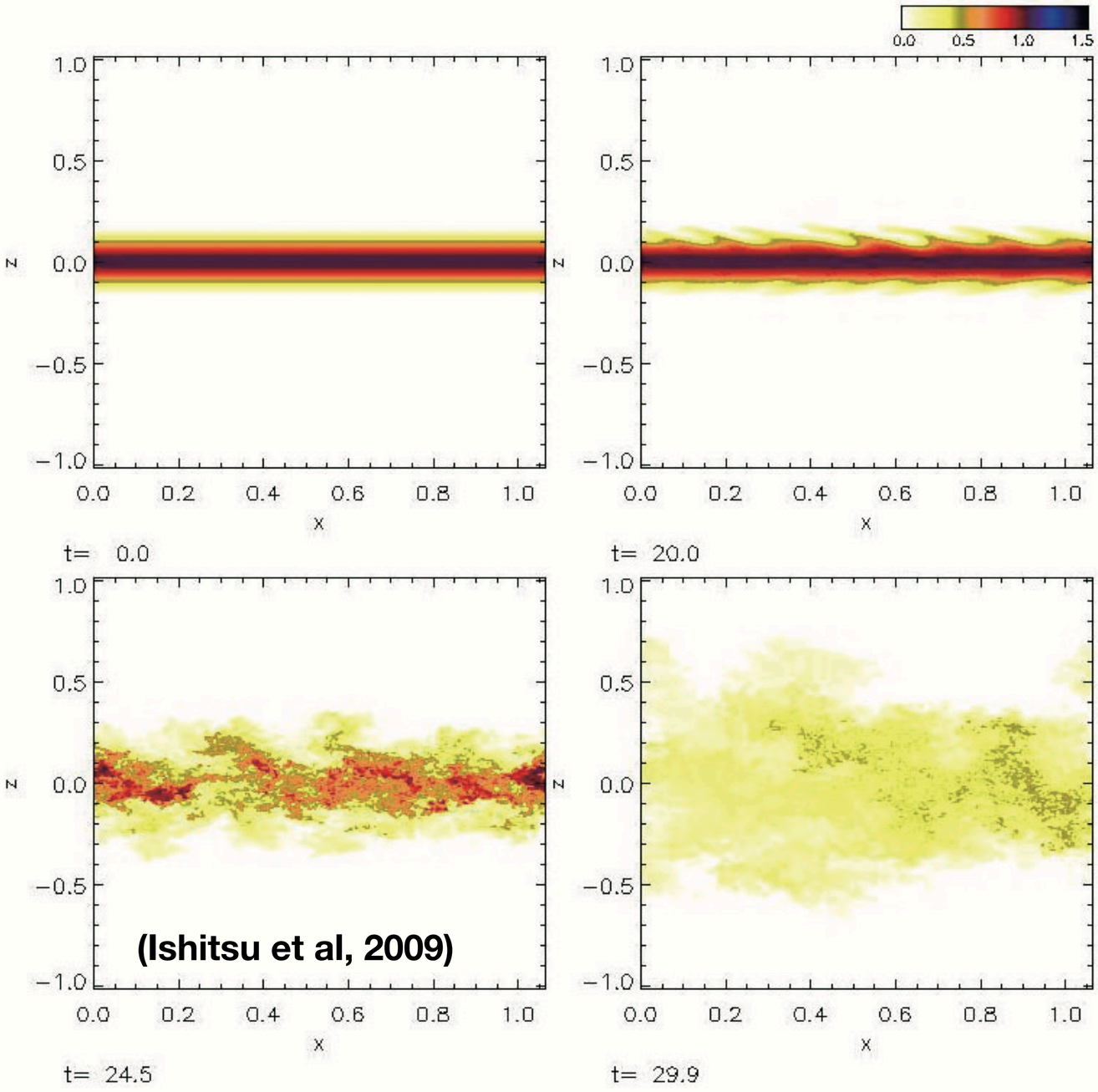
“Vertically shearing SI” in stratified disks

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



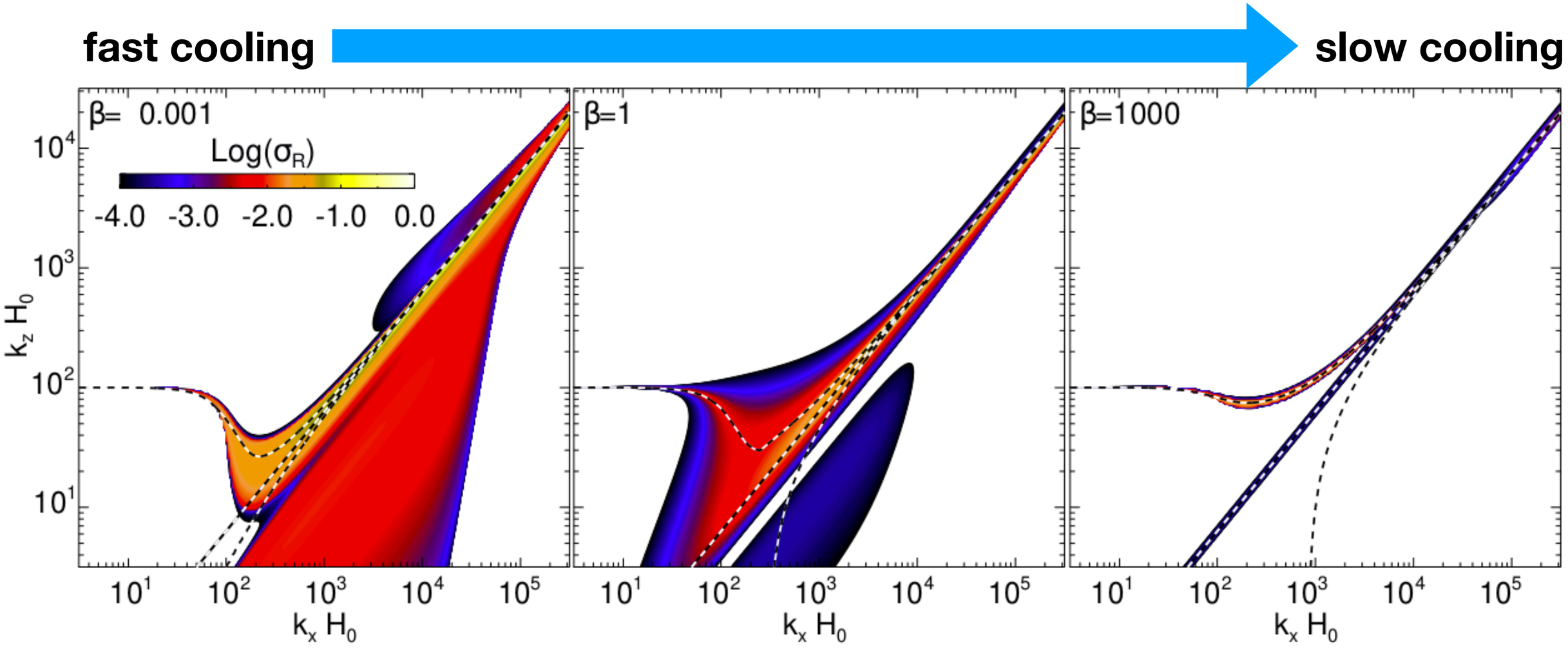
Lin (2021)

Vertically shearing SIs grow fast but…



dust layer dispersed

SI in non-isothermal disks



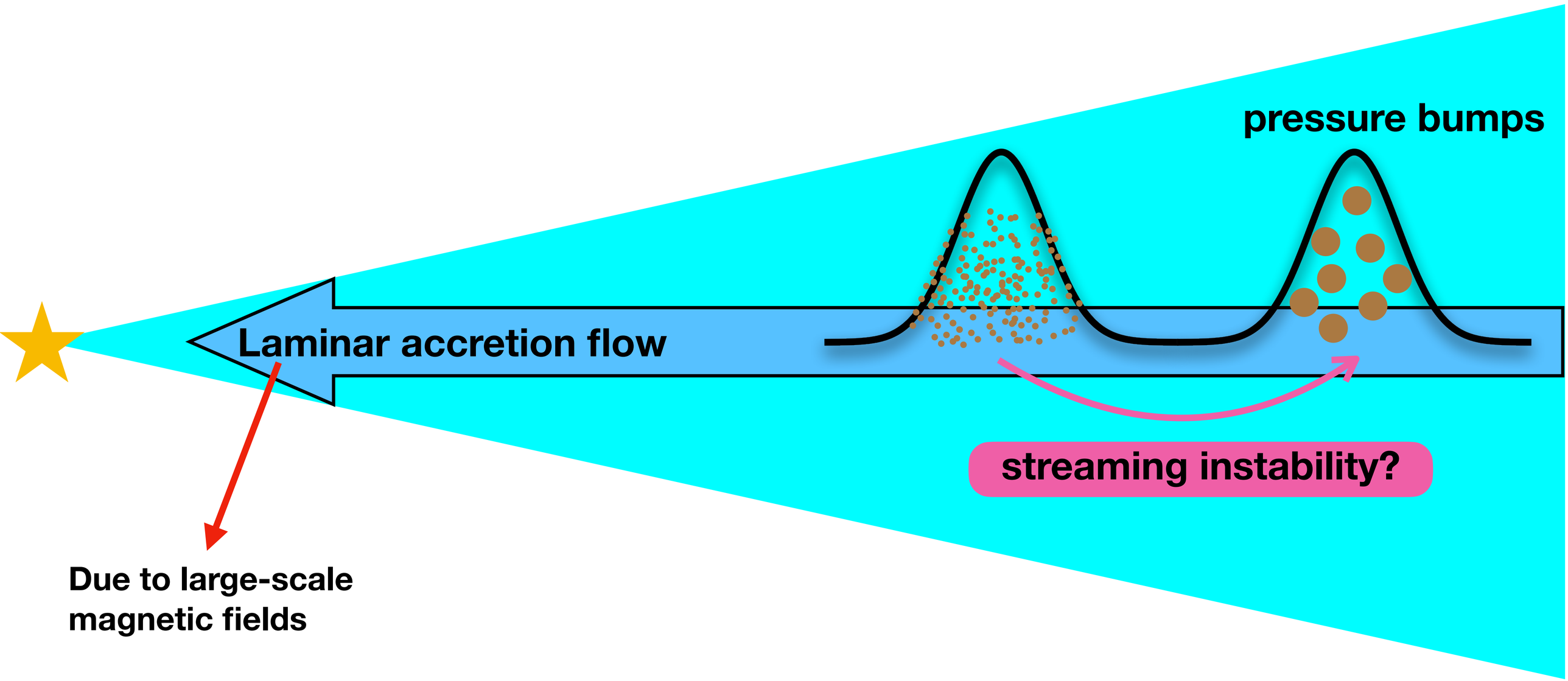
Lehmann & Lin (2023)

So far, not so good

- turbulence
- vertical structure
- thermodynamics

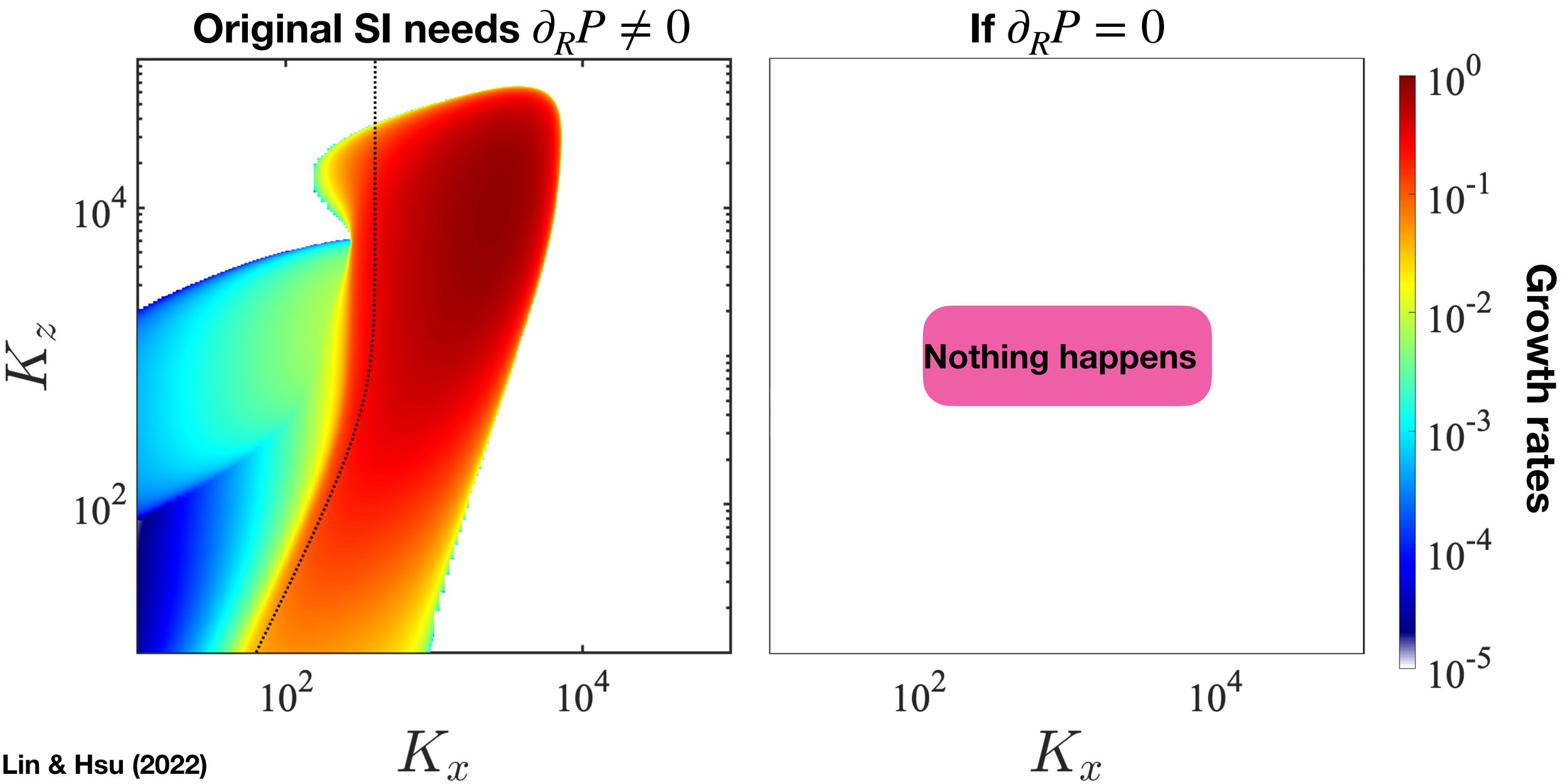
SI weakened

Can modern disk models help?



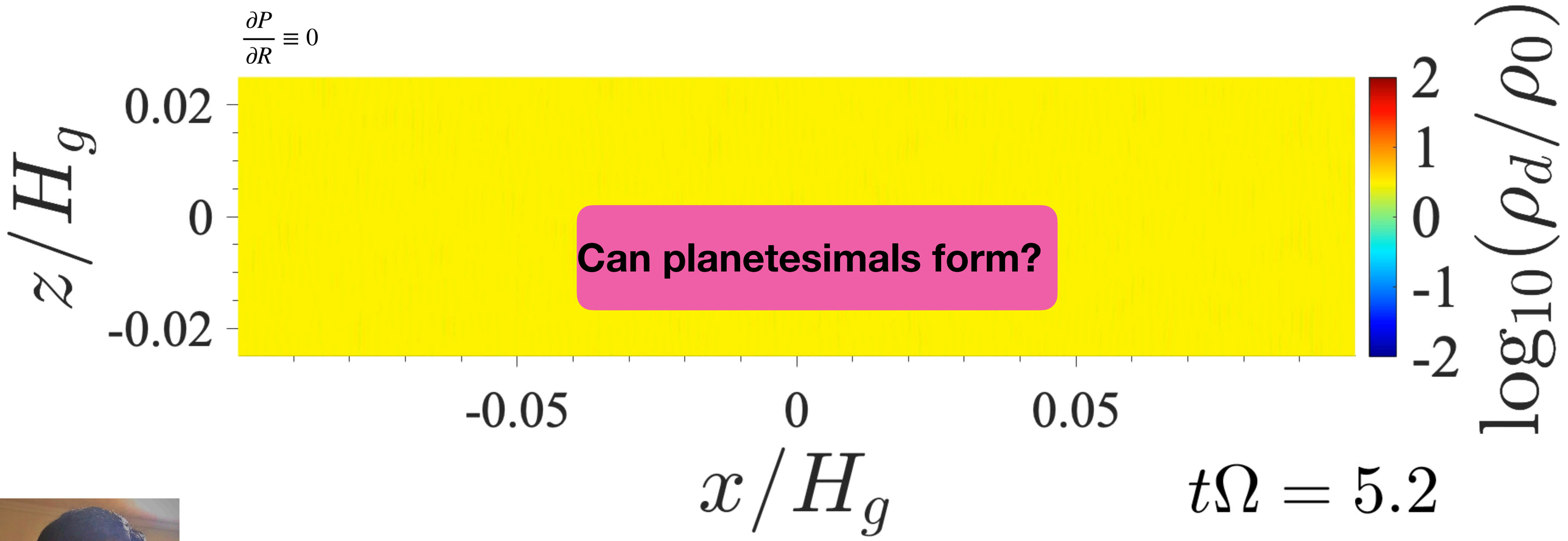
(e.g. Riols et al. 2020, Cui & Bai 2021)

SI in accreting disks



Lin & Hsu (2022)

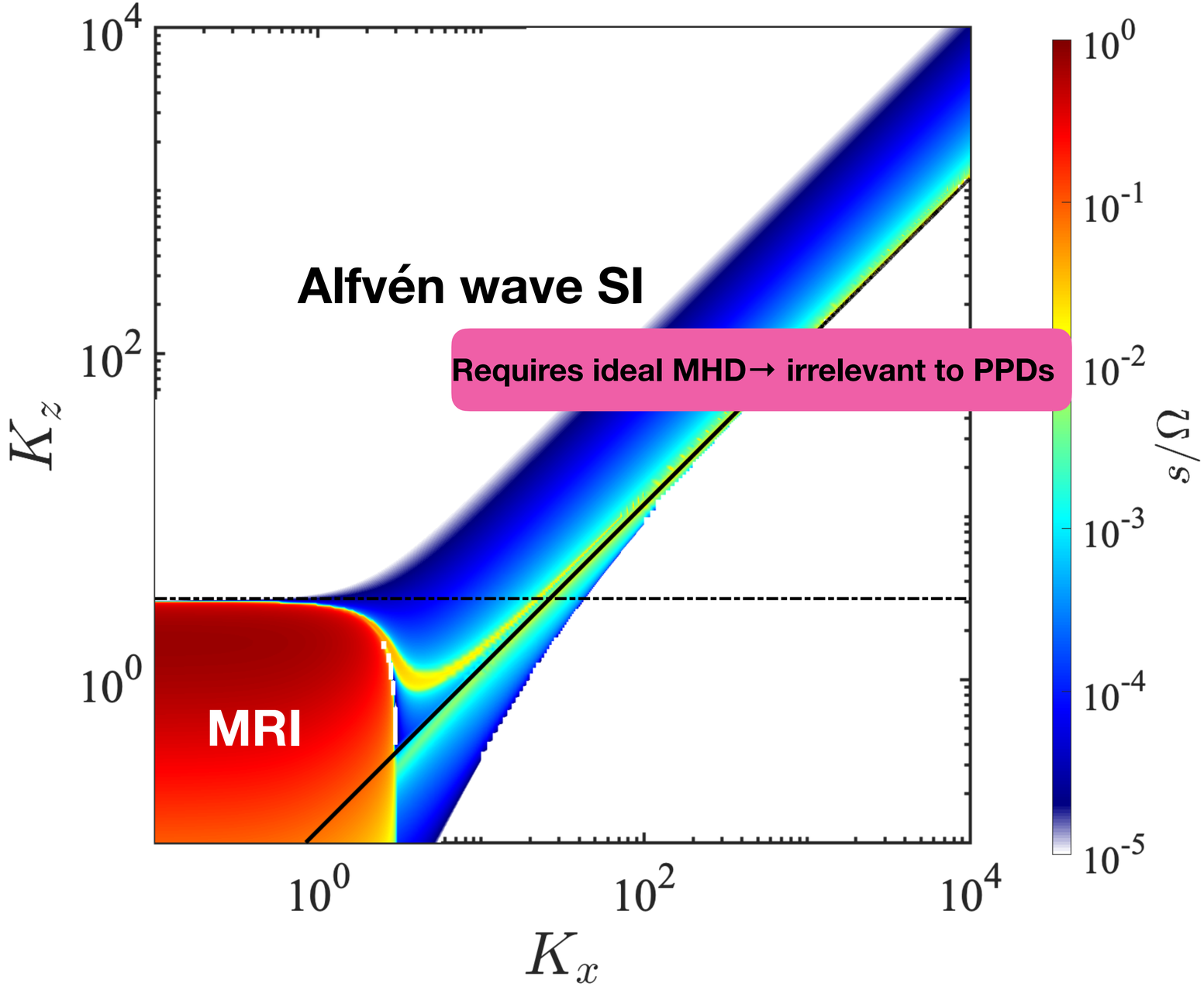
Nonlinear evolution of the SI in accreting disks



Can planetesimals form?

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

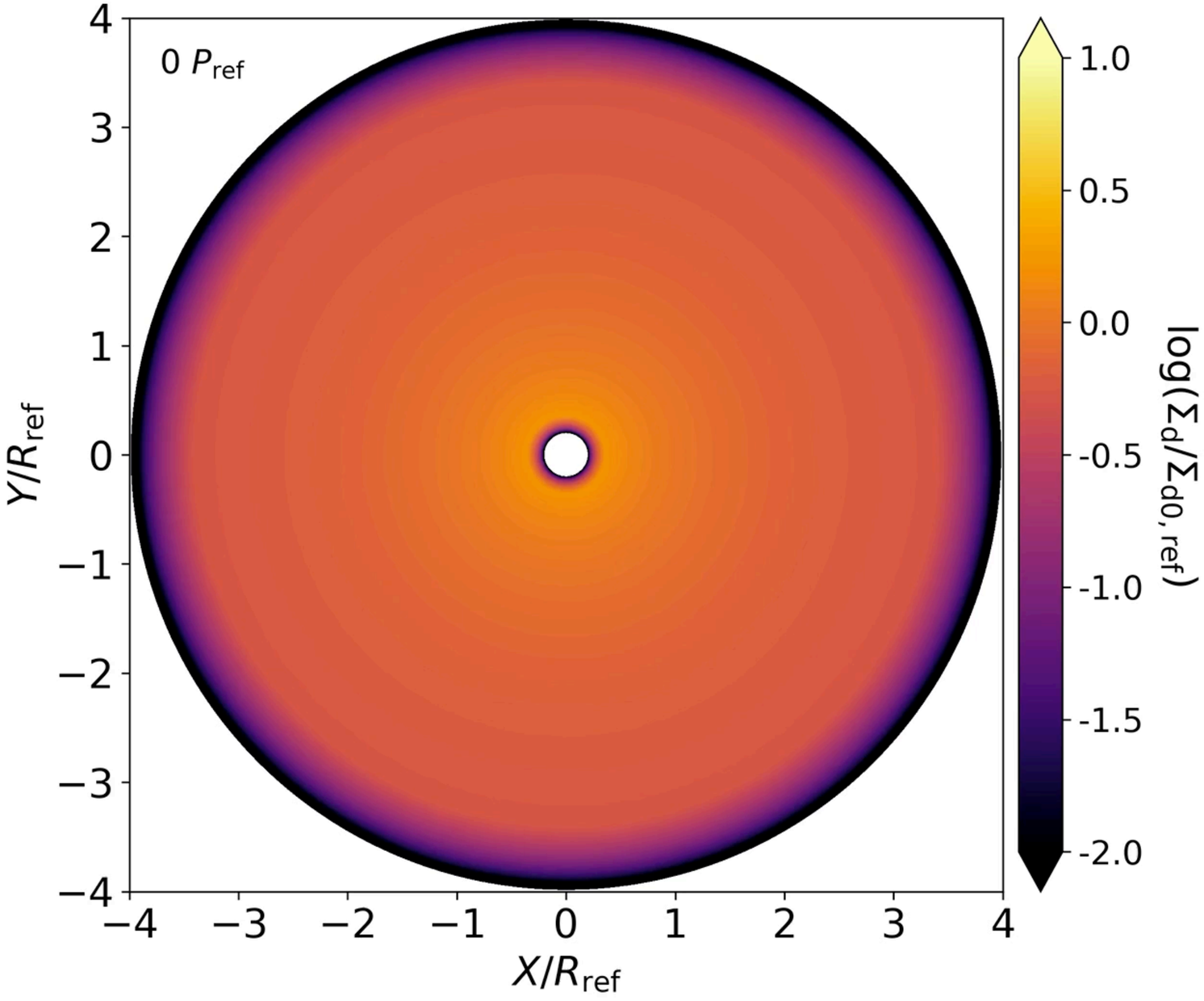
Role of an active magnetic field



Requires ideal MHD→ irrelevant to PPDs

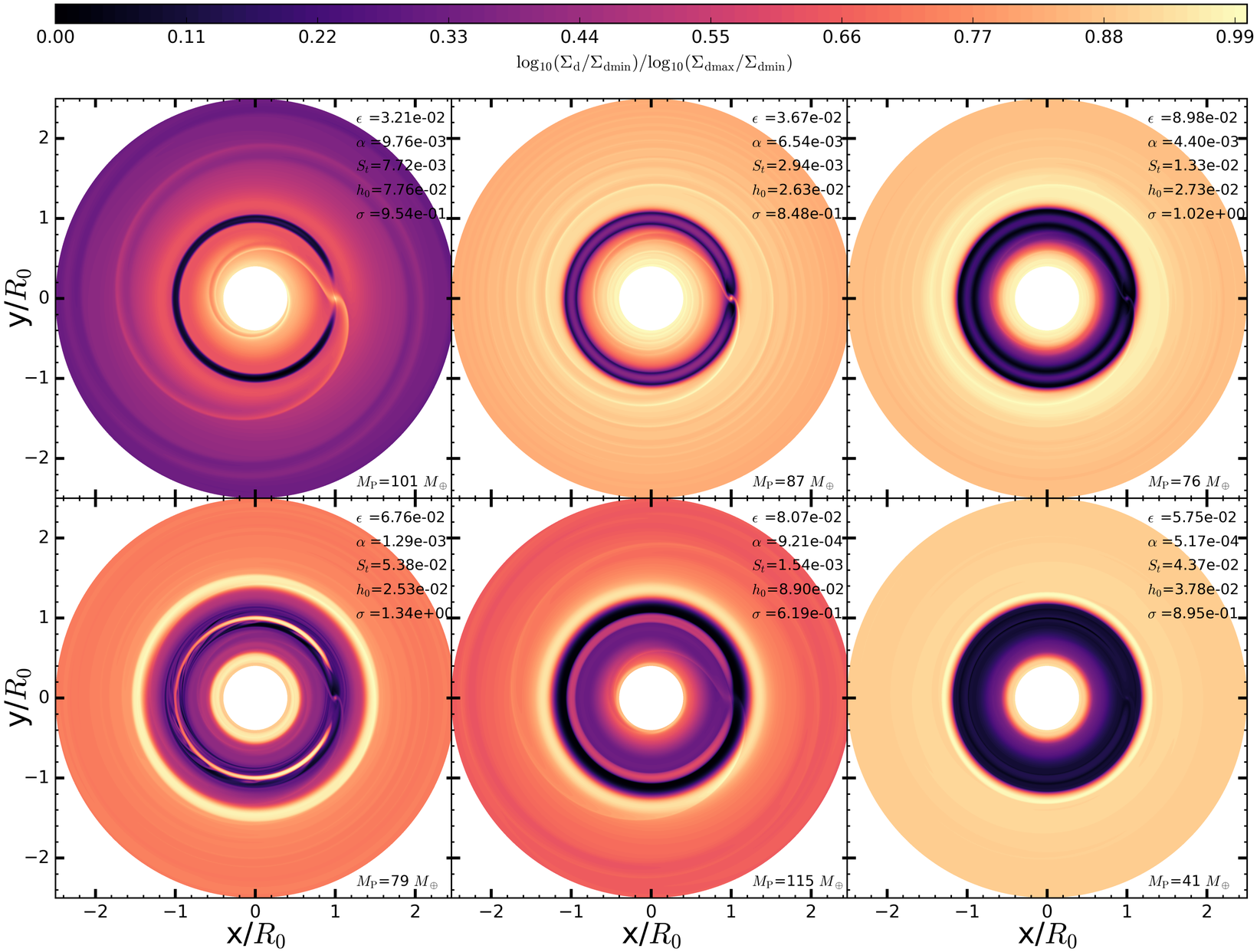
Lin & Hsu (2022)

Planets form somehow, so what's next?



Bi, Lin, Dong (2021)

Disk-planet morphology



Auddy & Lin (2020)

Modeling planet gaps with artificial/convolutional NN

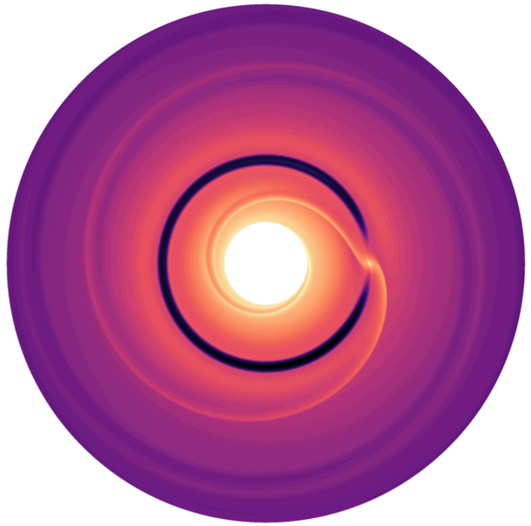


Image Data

Convolutional Neural Netwrok **ReSNet**

Numerical Data

- Aspect Ratio
- Viscosity
- Dust-to-gas ratio
- Stokes Number
- Density Profile

Muilti-layer Perceptron (MLP)

Concatenation

FC Layer Linear Activation

Planet Mass

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)

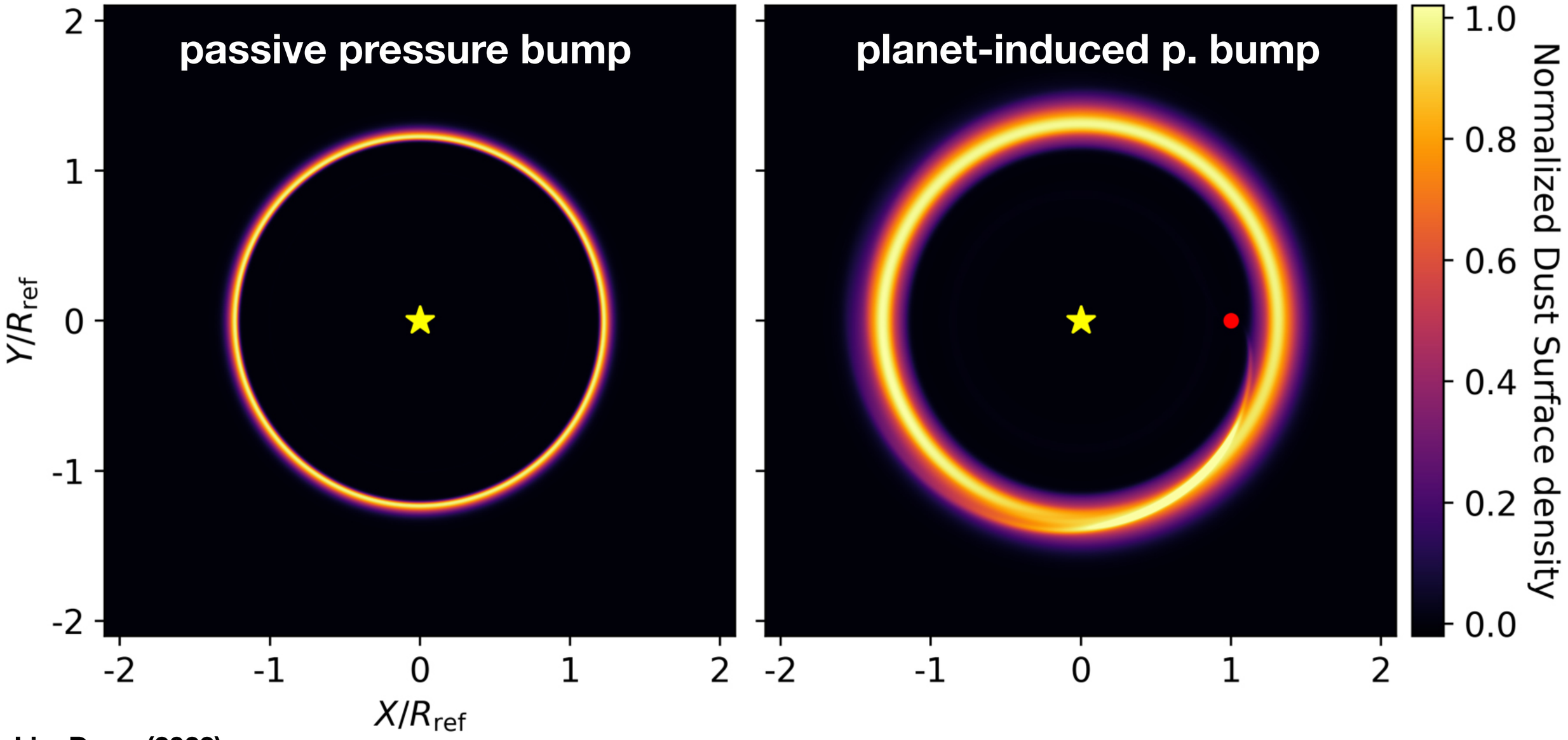
$$M_p = 0.2 - 0.35 M_J, 0.17 - 0.27 M_J, 0.2 - 0.55 M_J$$

- **Disk-Planet Neural Network**

(Auddy & Lin, 2020)

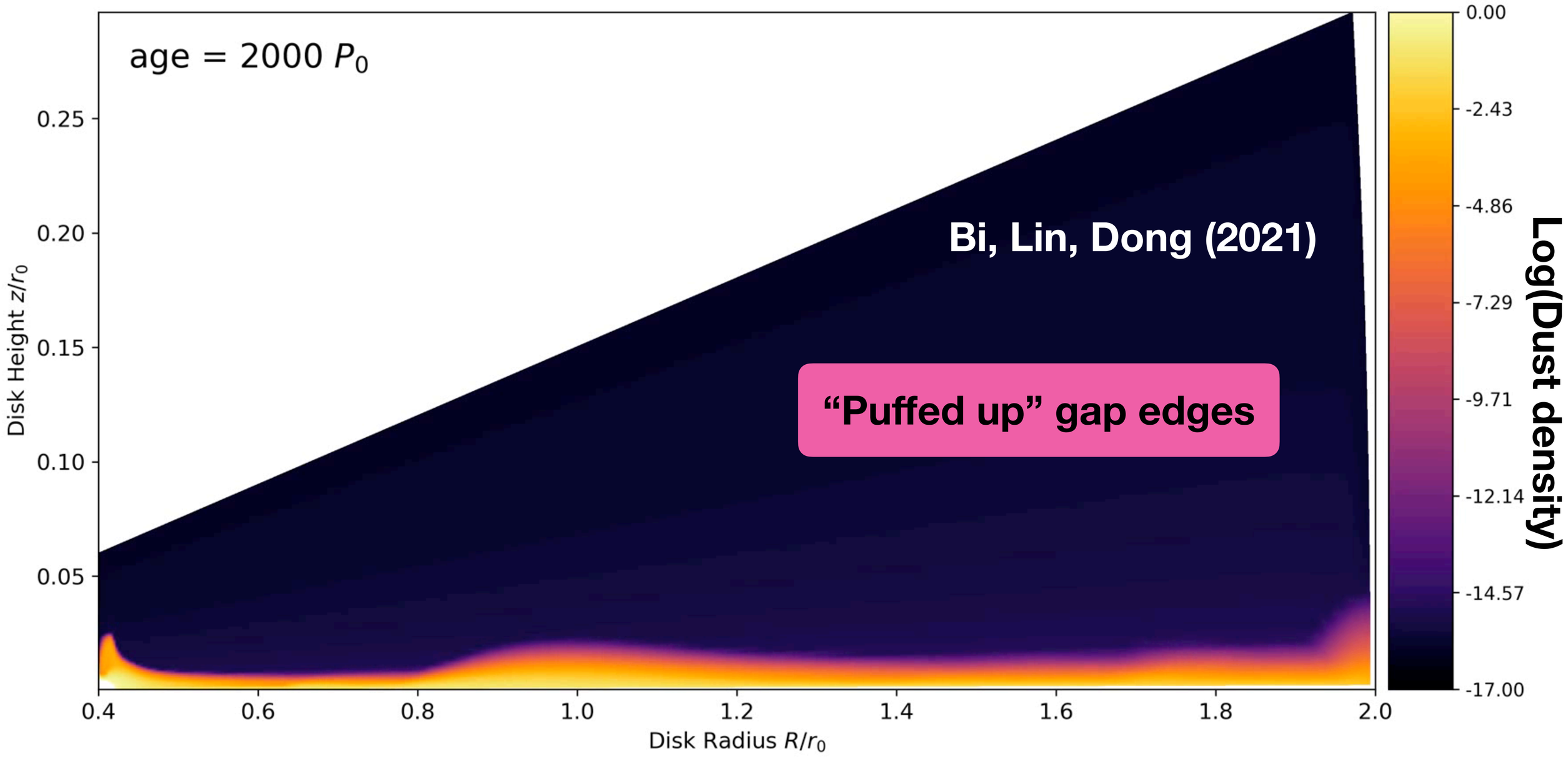
$$M_p = 0.24 M_J, 0.21 M_J, 0.2 M_J$$

But are all observed dust rings caused by planets?

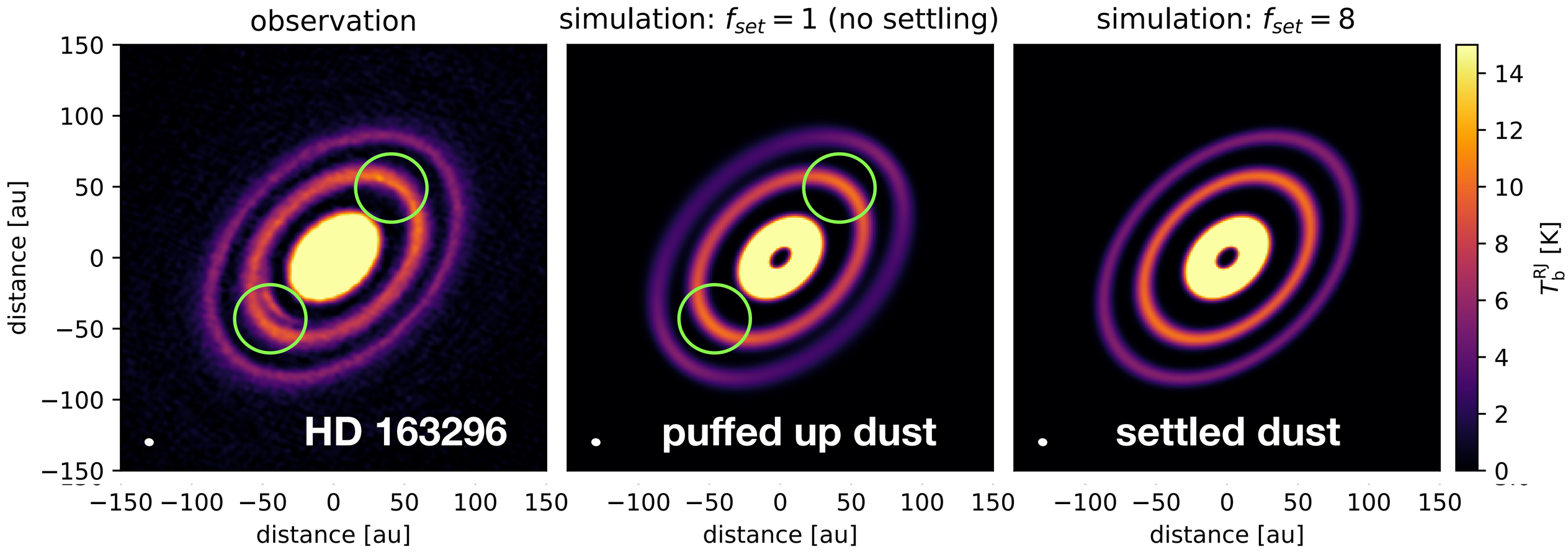


Bi, Lin, Dong (2023)

Three-dimensional models



Puffed up rings in observations: Sign of planets?



Doi & Kataoka (2021)

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 clumping
- Planet-disk interaction can be used to reveal or rule out hidden planets in observations of protoplanetary disks
- Not all dust rings are produced by planets

Thank you

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