Hopes and challenges in modern planet formation

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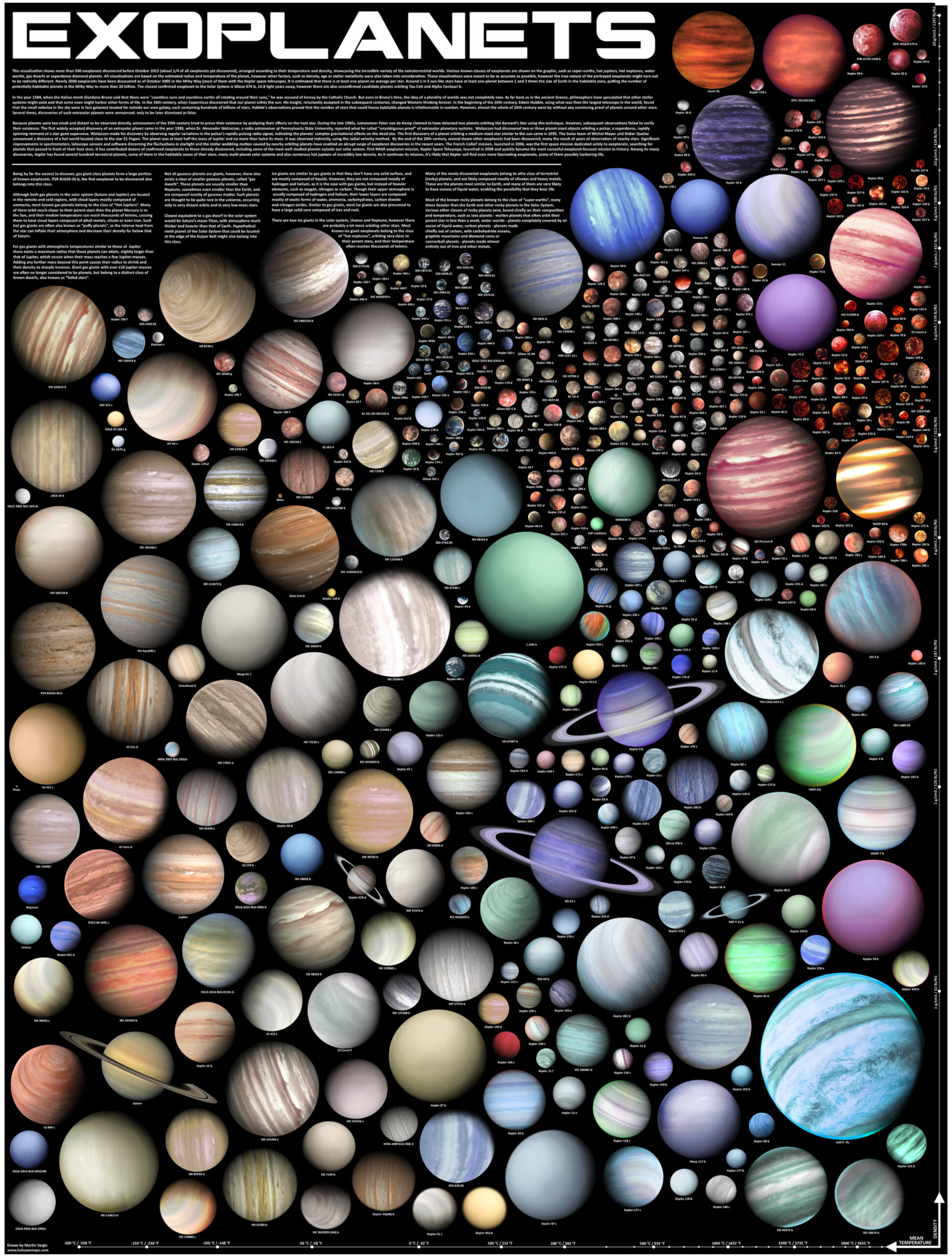
中央研究院 ASIAA
NCTS National Center for Theoretical Sciences, Physics Divisions
NSTC 國家科學及技術委員會 National Science and Technology Council
NCHC NARLabs 財團法人國家實驗研究院 國家高速網路與計算中心 National Center for High-performance Computing

We are not alone

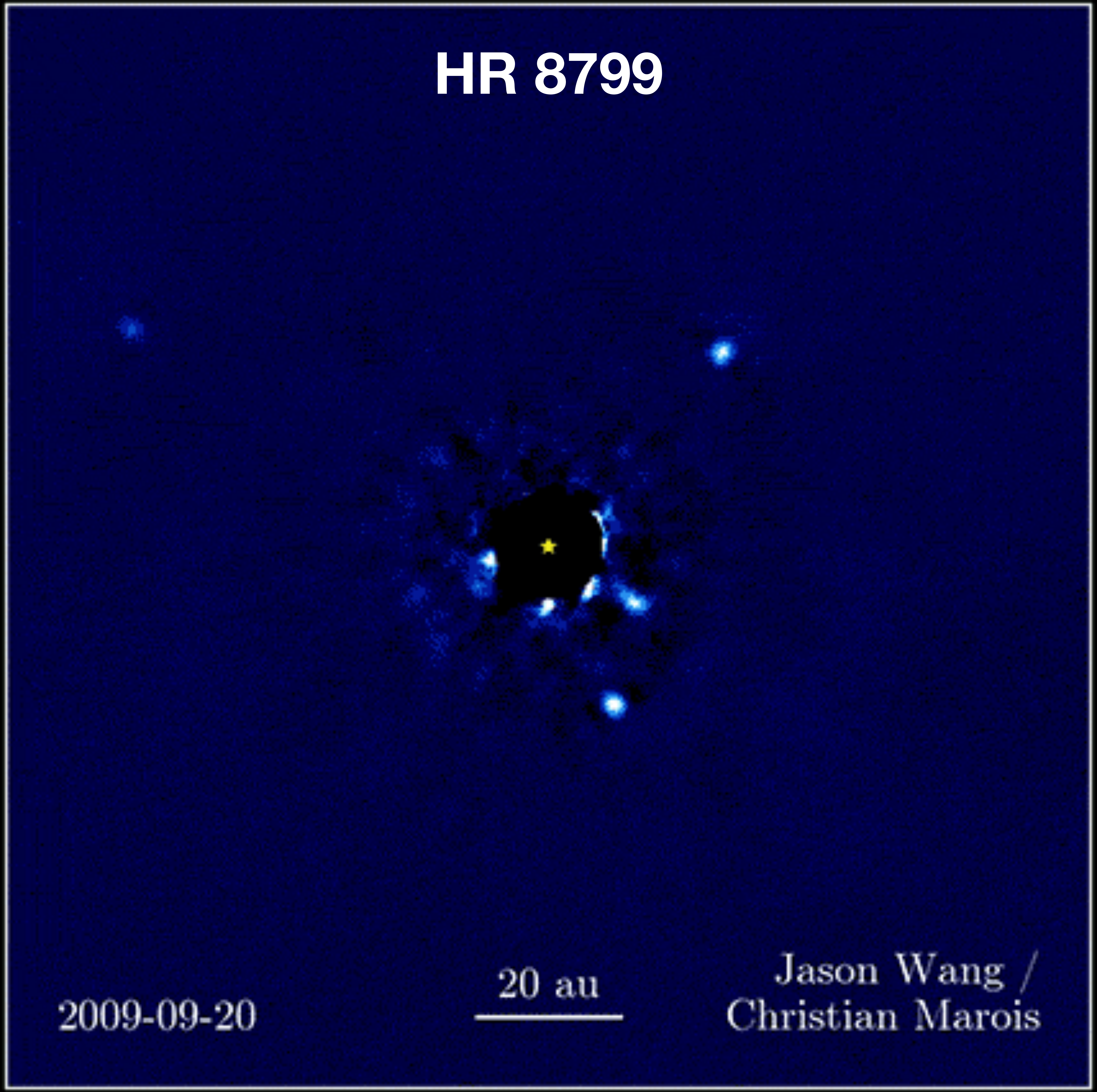
Credit: NASA/ESO/Wikipedia

We are not alone



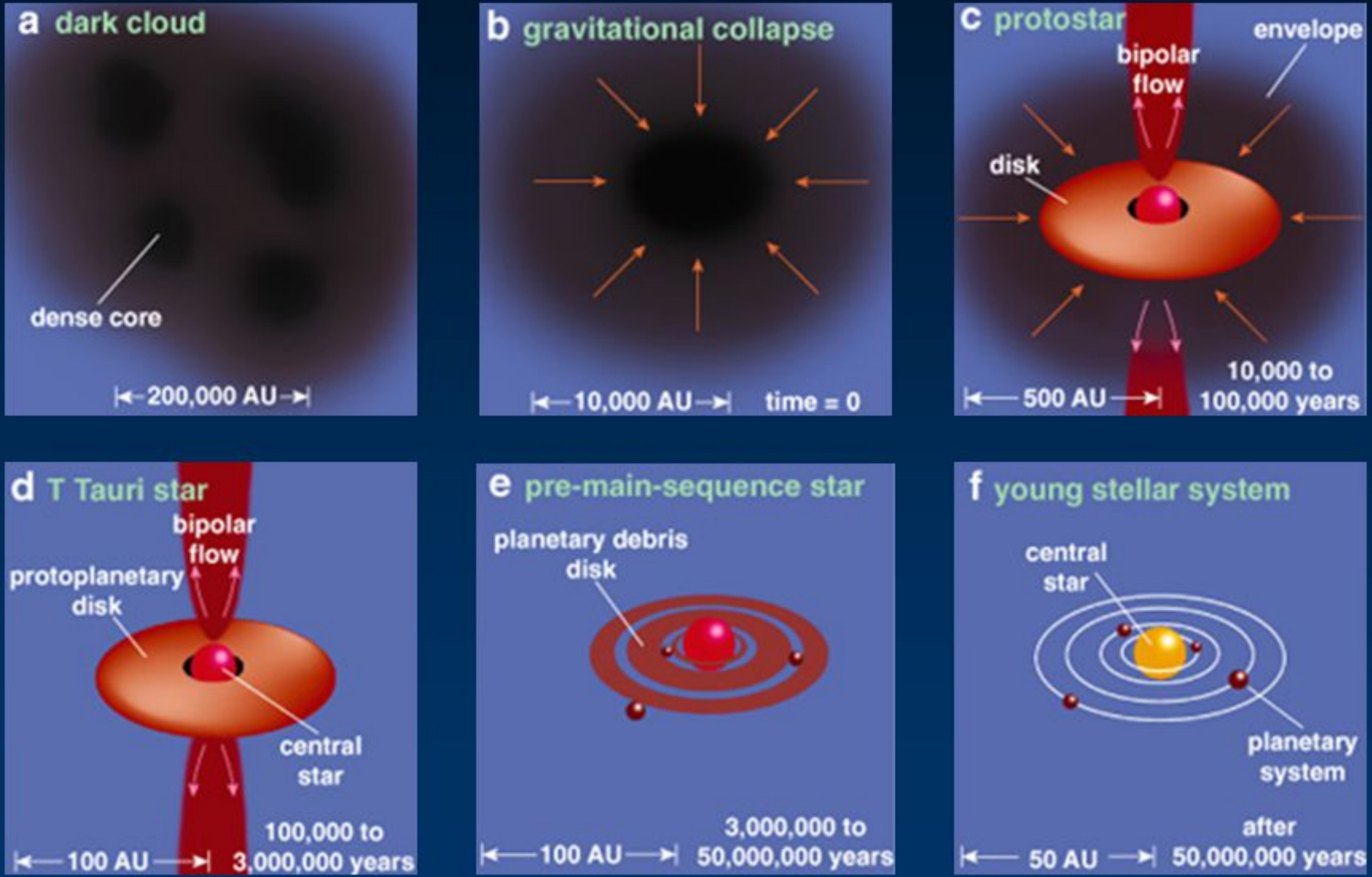
Credit: Martin Vargic

HR 8799



Credit: NASA

Star & planet formation



M. Liu (IfA/Hawaii)

Protoplanetary disks (artist's impression)

Credit: ESO/L. Calçada

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

Real protoplanetary disks

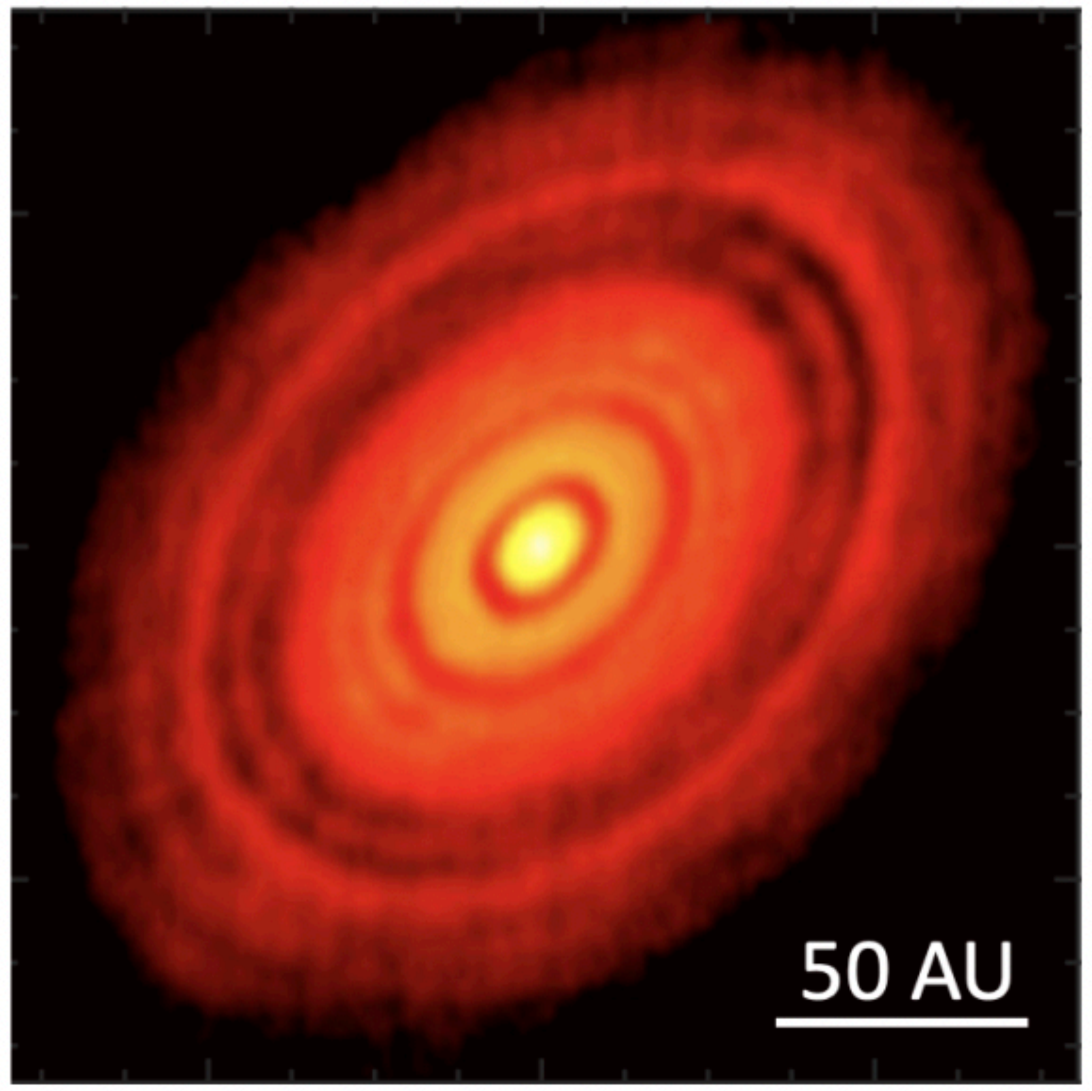
(Andrews et al, 2018; Long et al 2018)

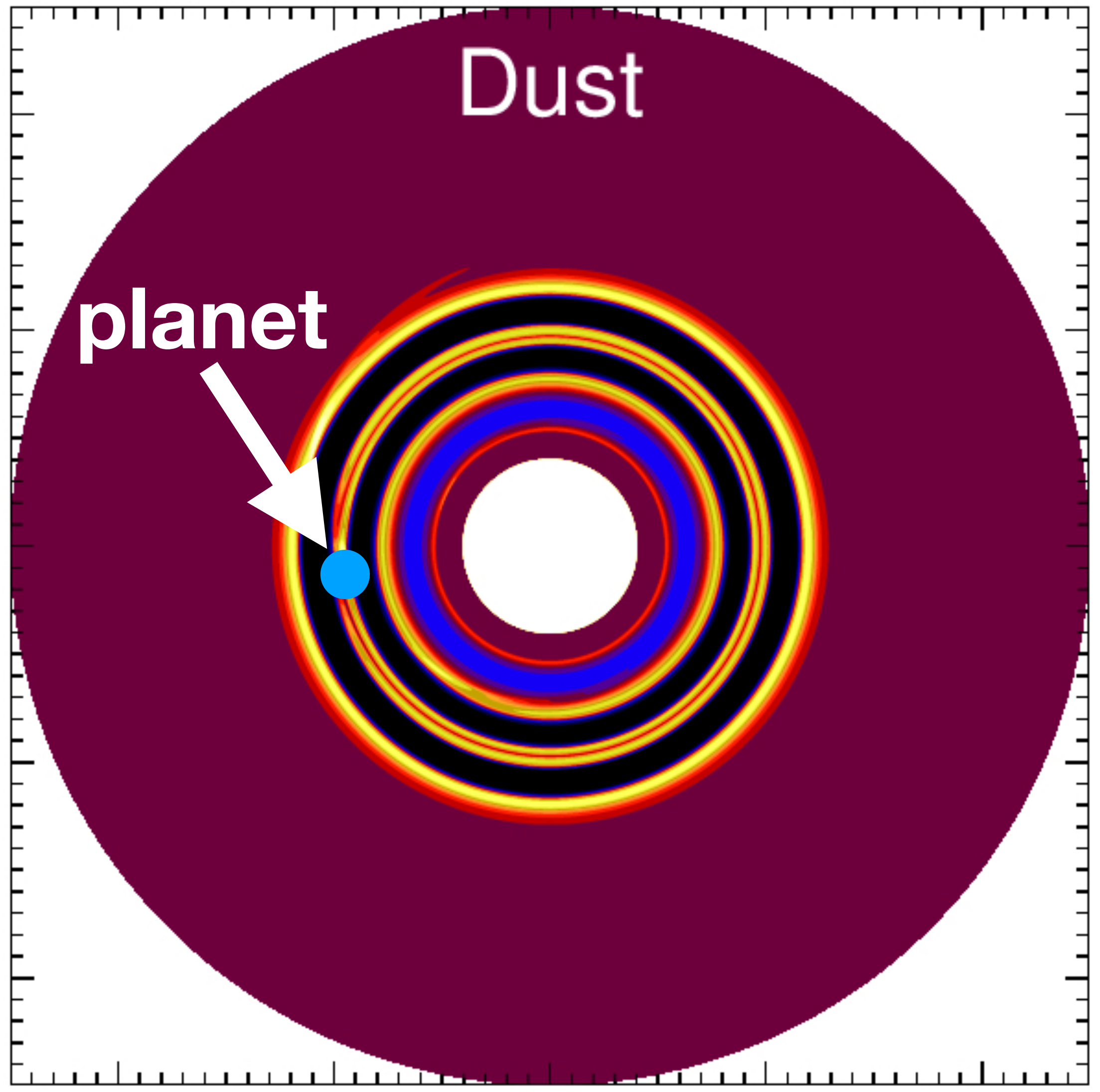
Rings and gaps: signposts of planet formation?

Disk-planet interpretation

HL Tau (ALMA Partnership et al. 2015)

Observations

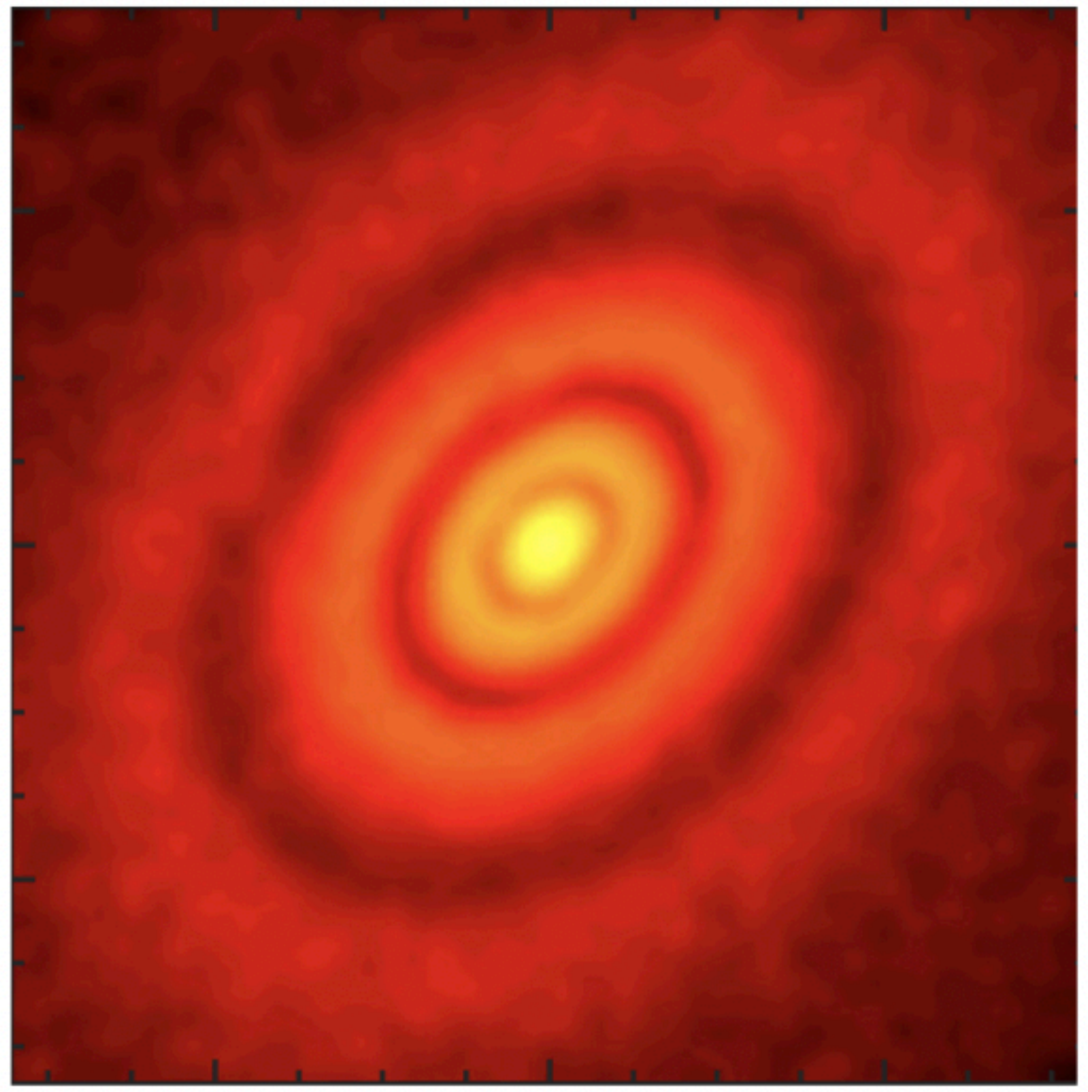




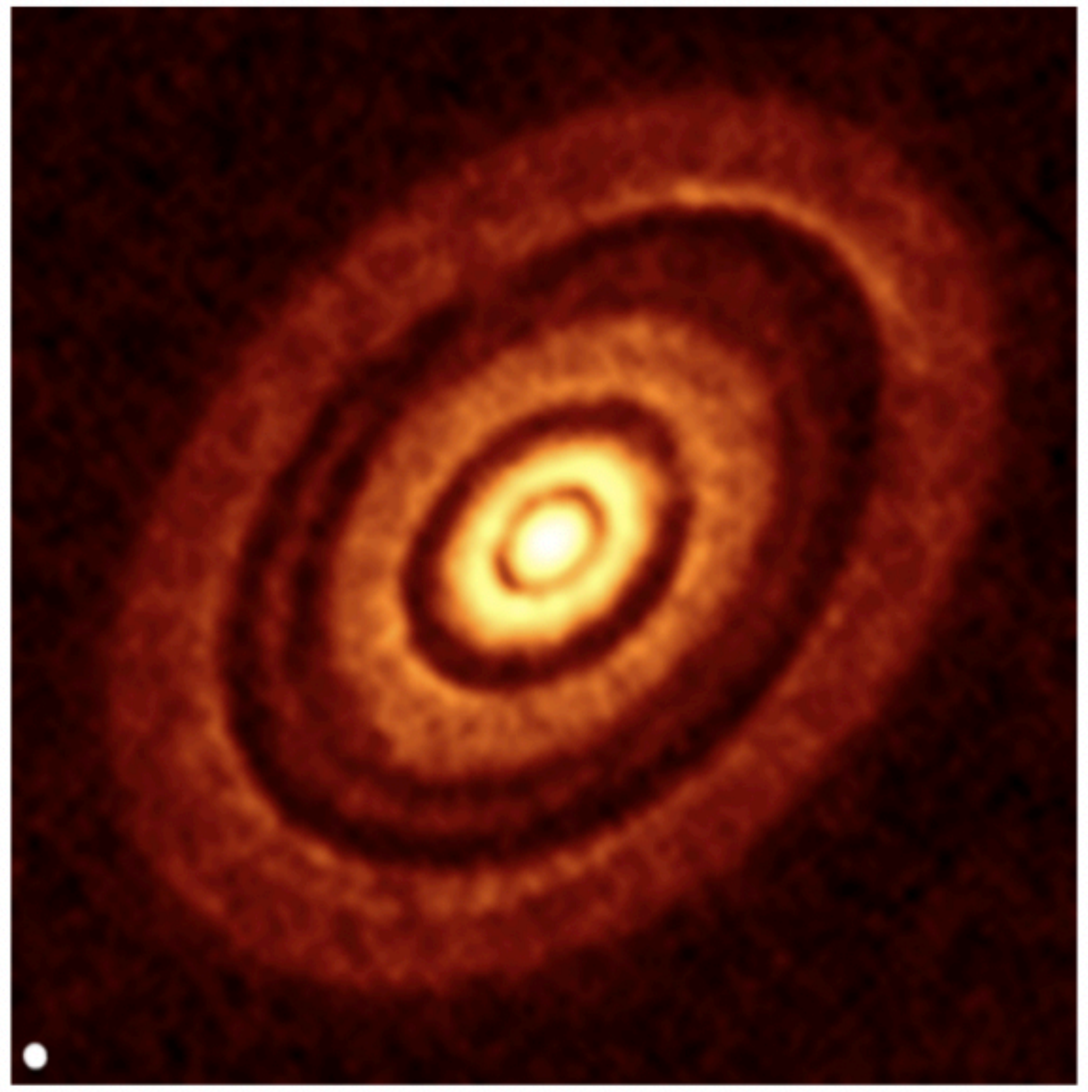
Computer simulation

(Chen & Lin, 2018)

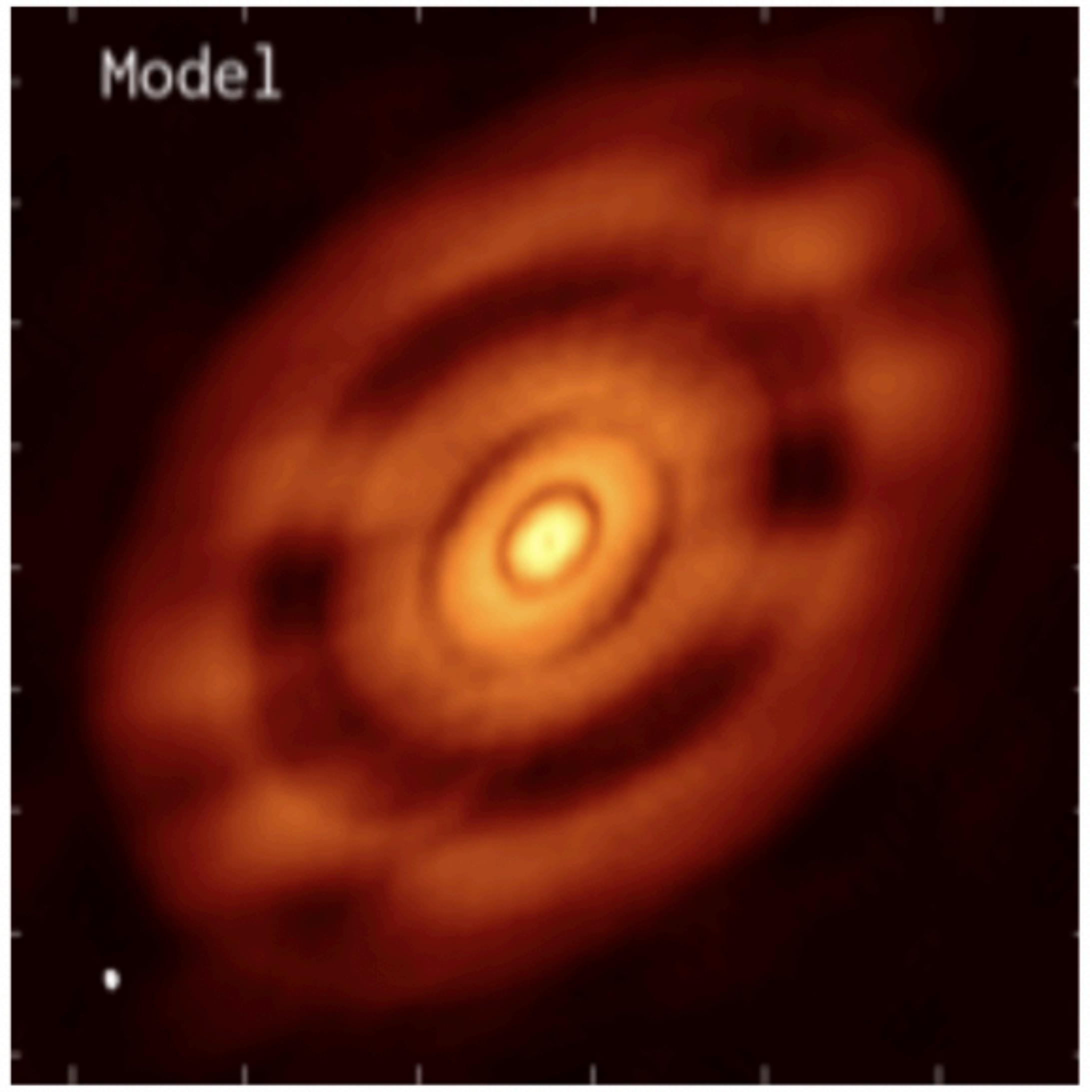
Simulation
+
synthetic obs.



Dong et al. 2015



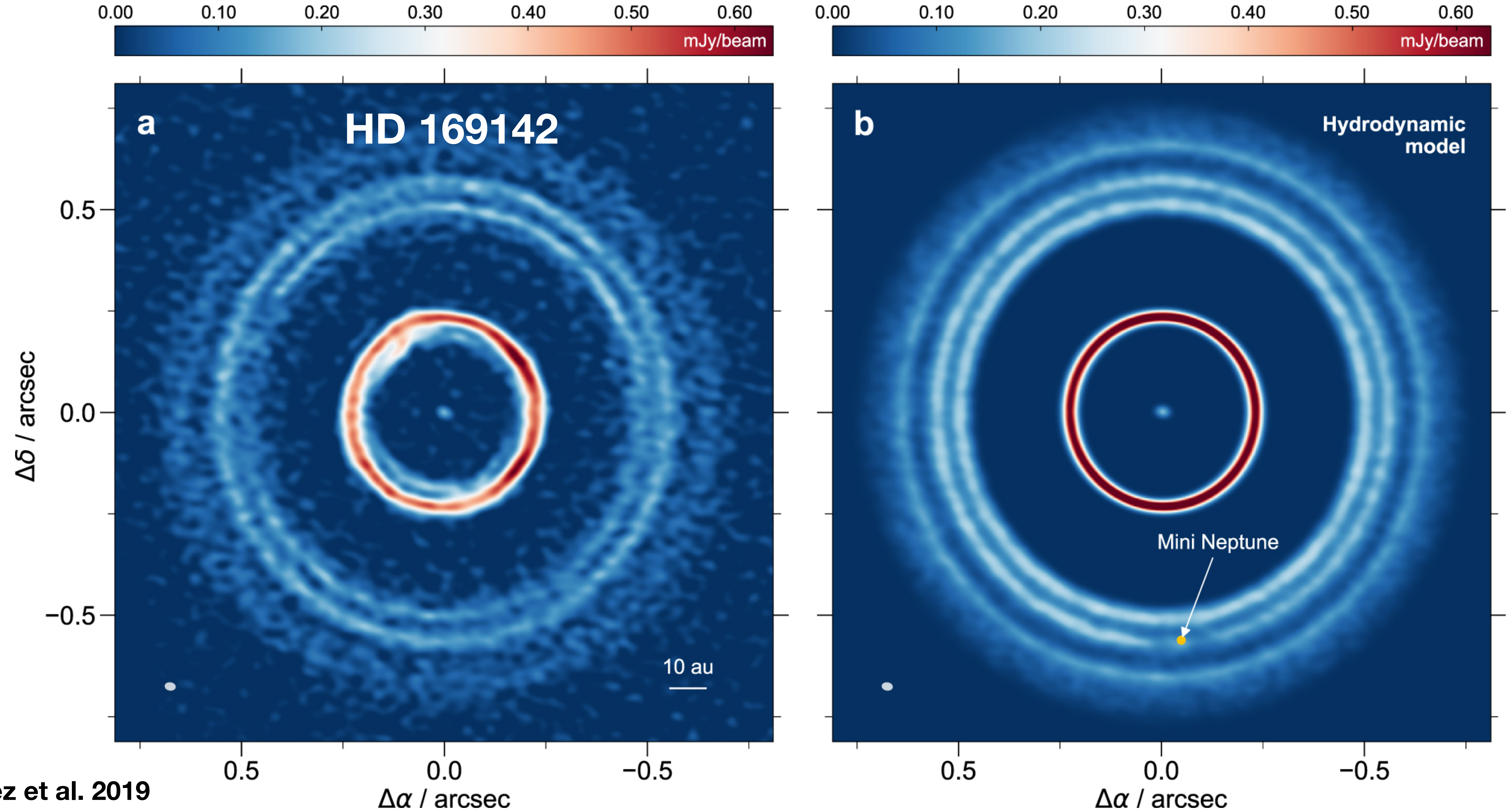
Dipierro et al. 2015



Jin et al. 2016

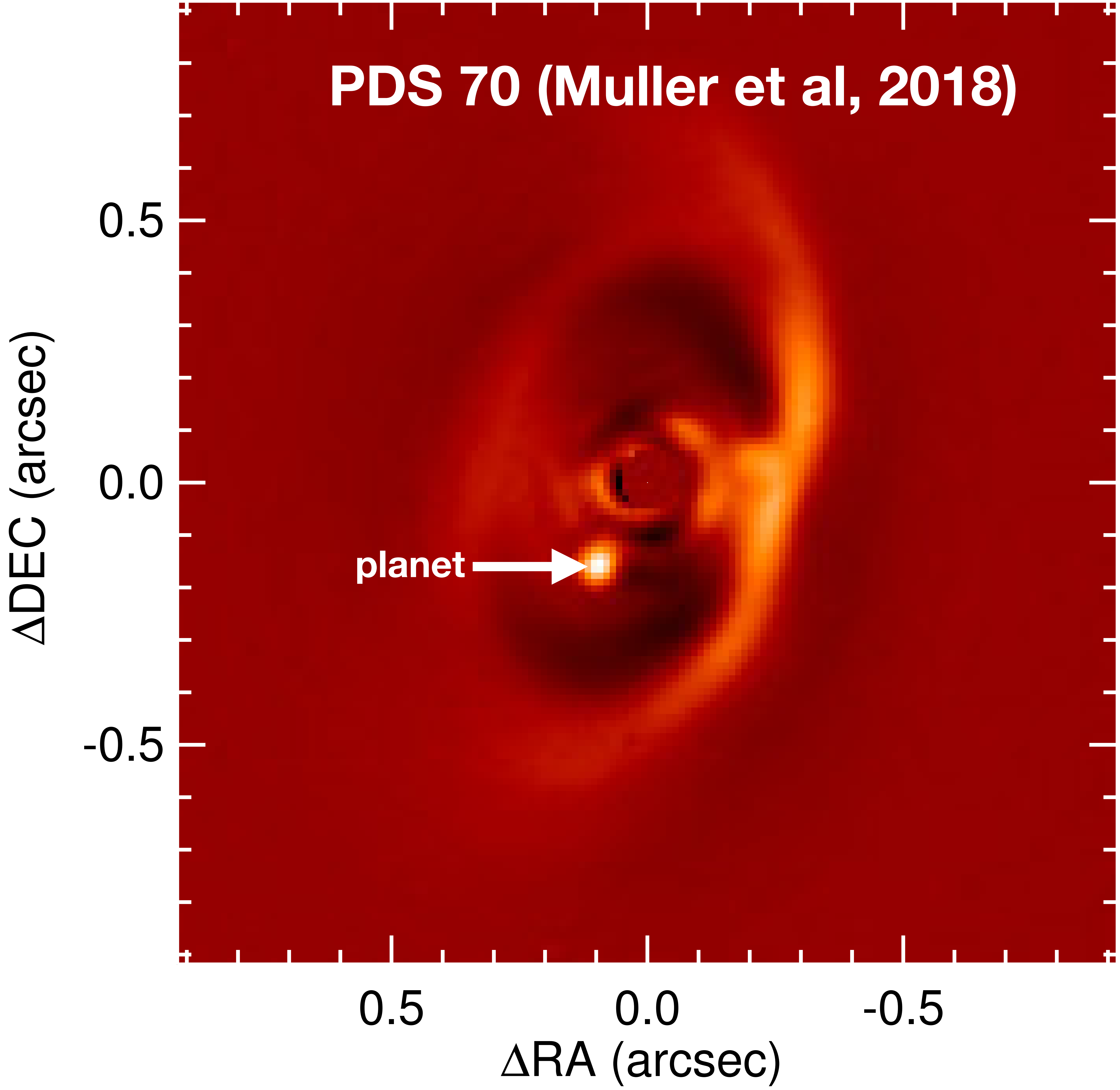
(Paardekooper et al., 2022, PPVII)

Detecting planets via sub-structures

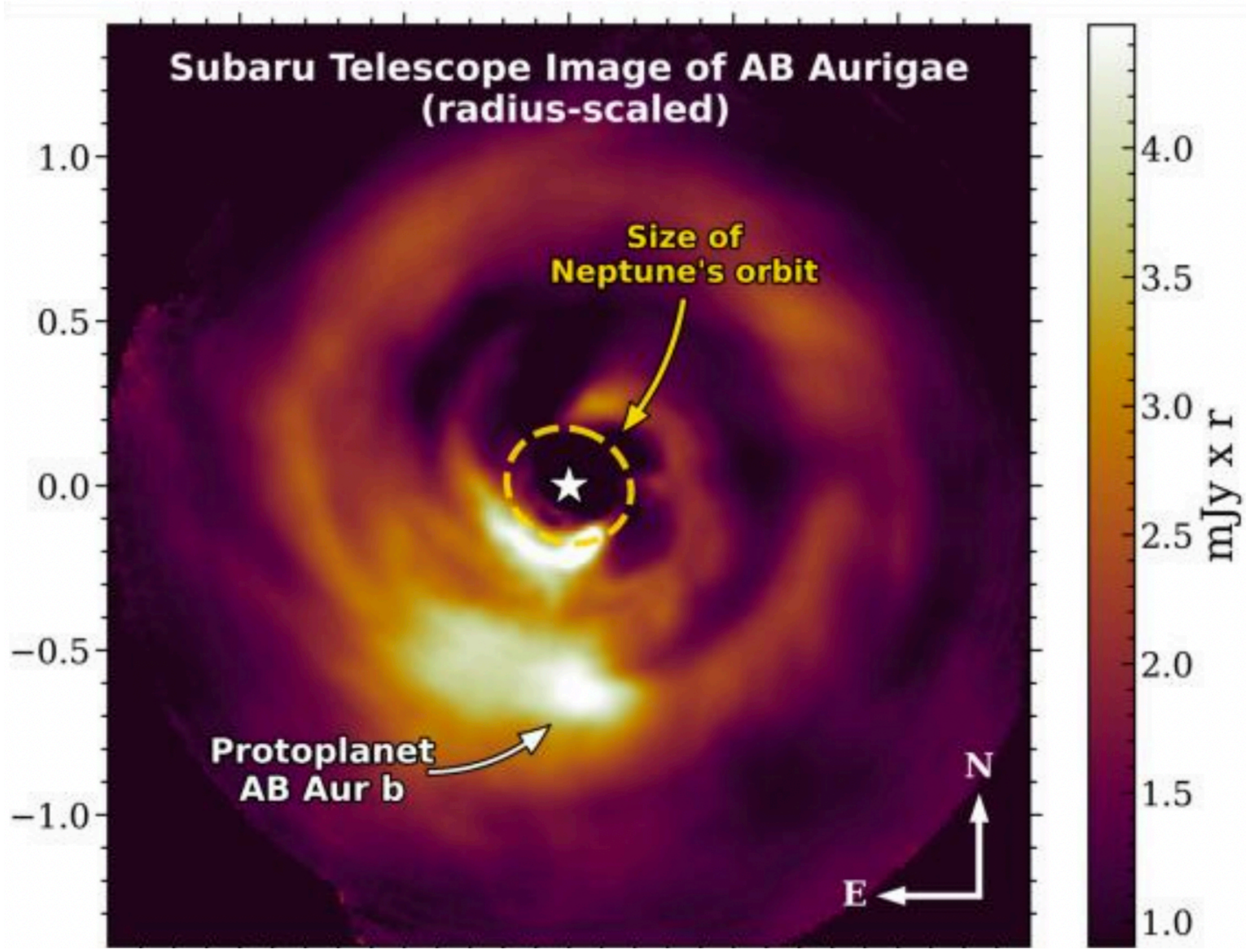


Pérez et al. 2019

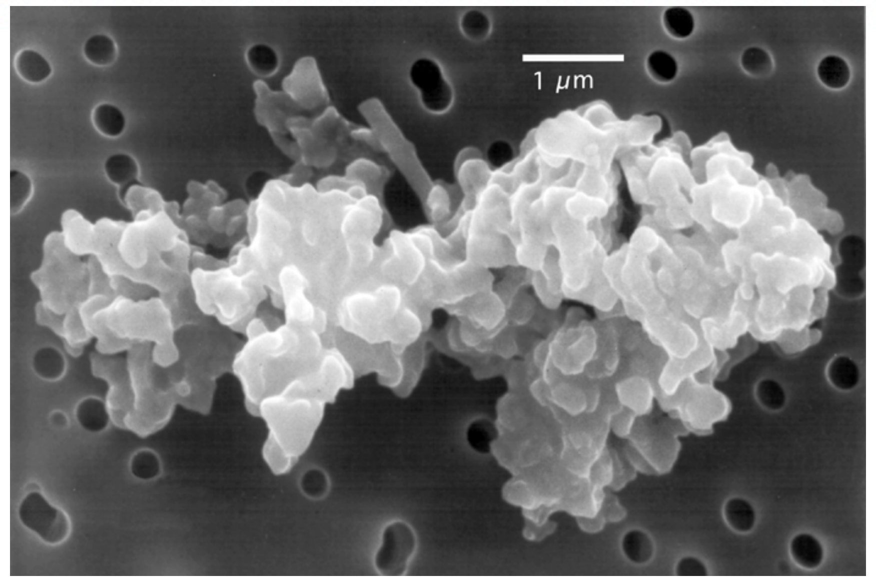
Observations of planets in a disk



AB Aur (Currie et al, 2022)

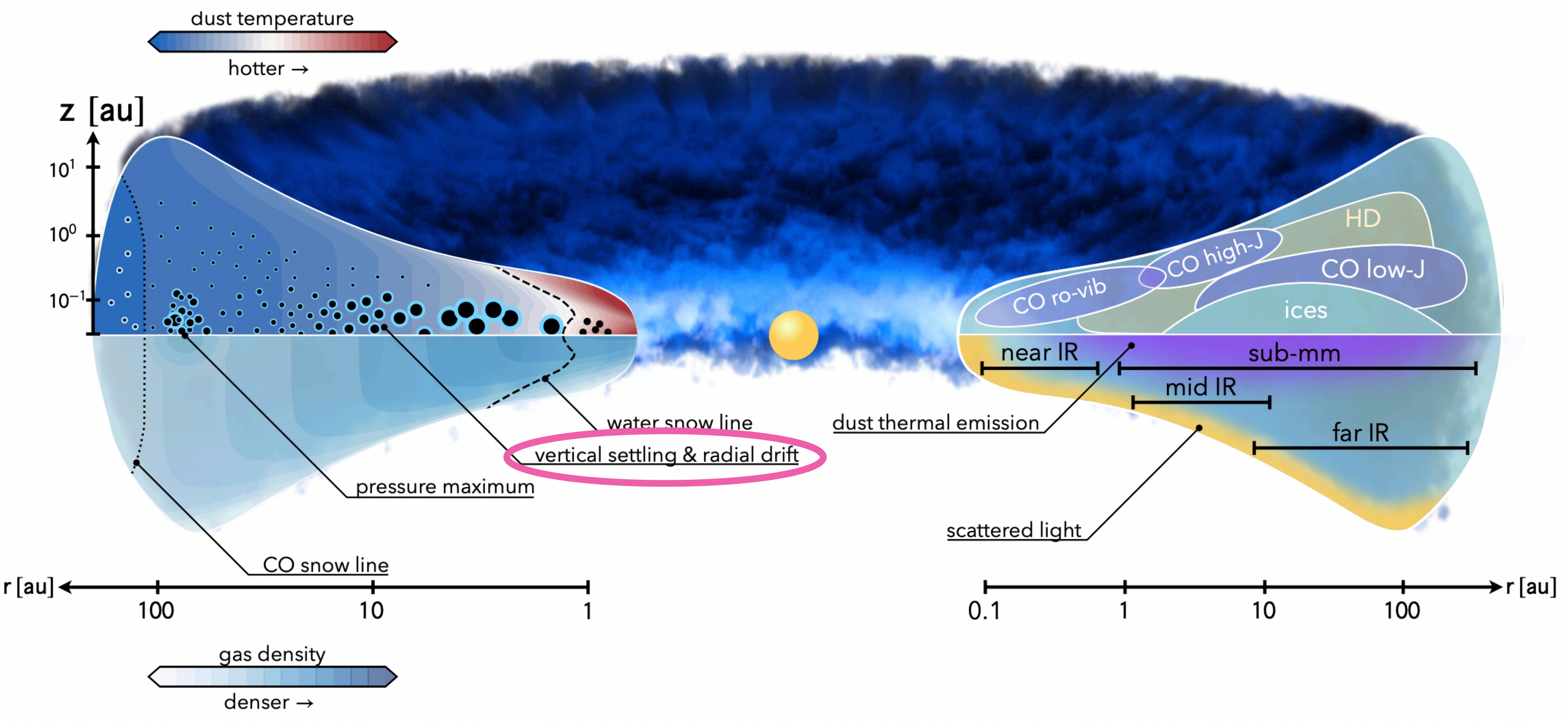


One planet, multiple scales



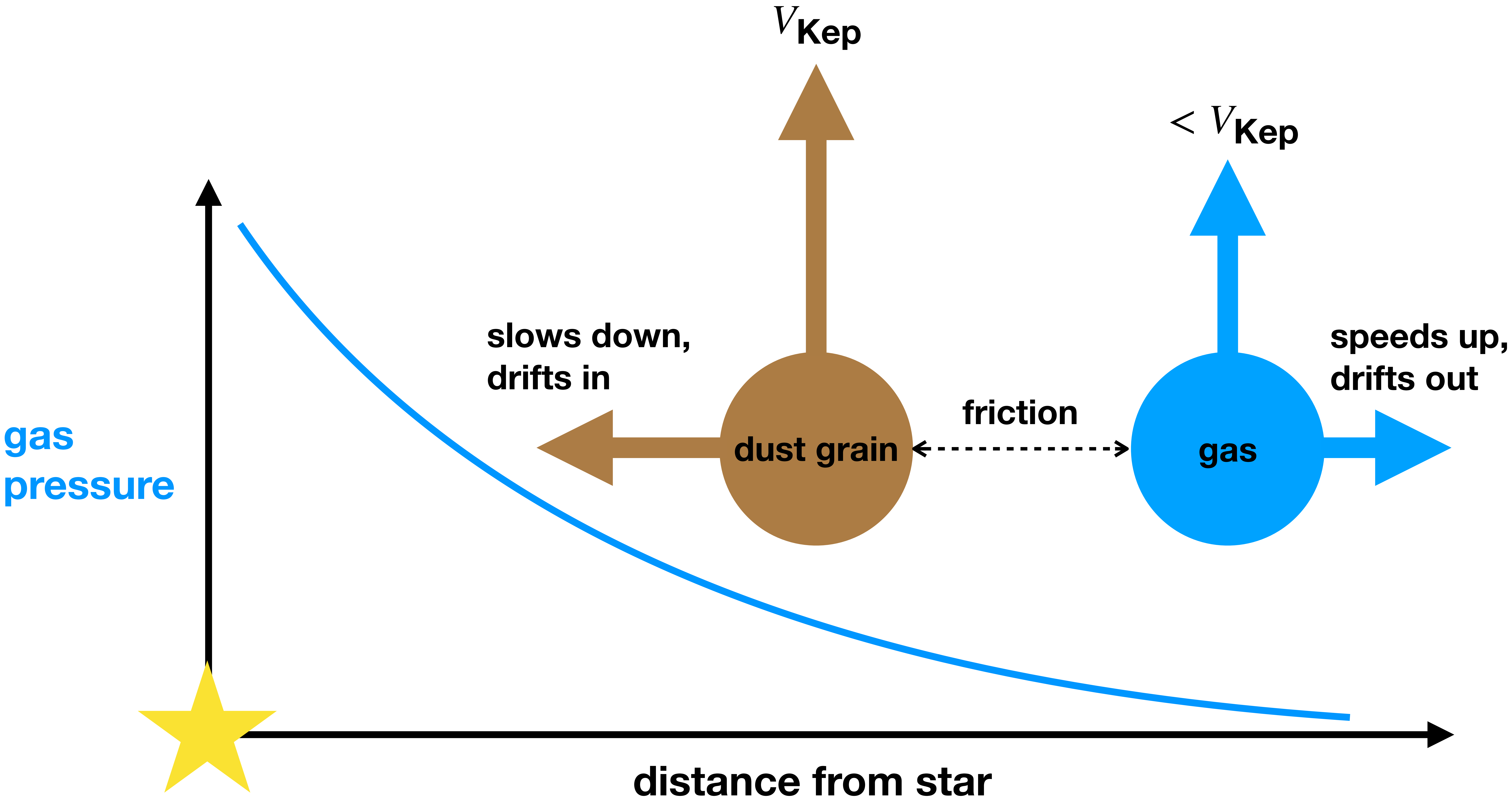
(Drazkowska et al., 2022, PPVII)

Dust in protoplanetary disks

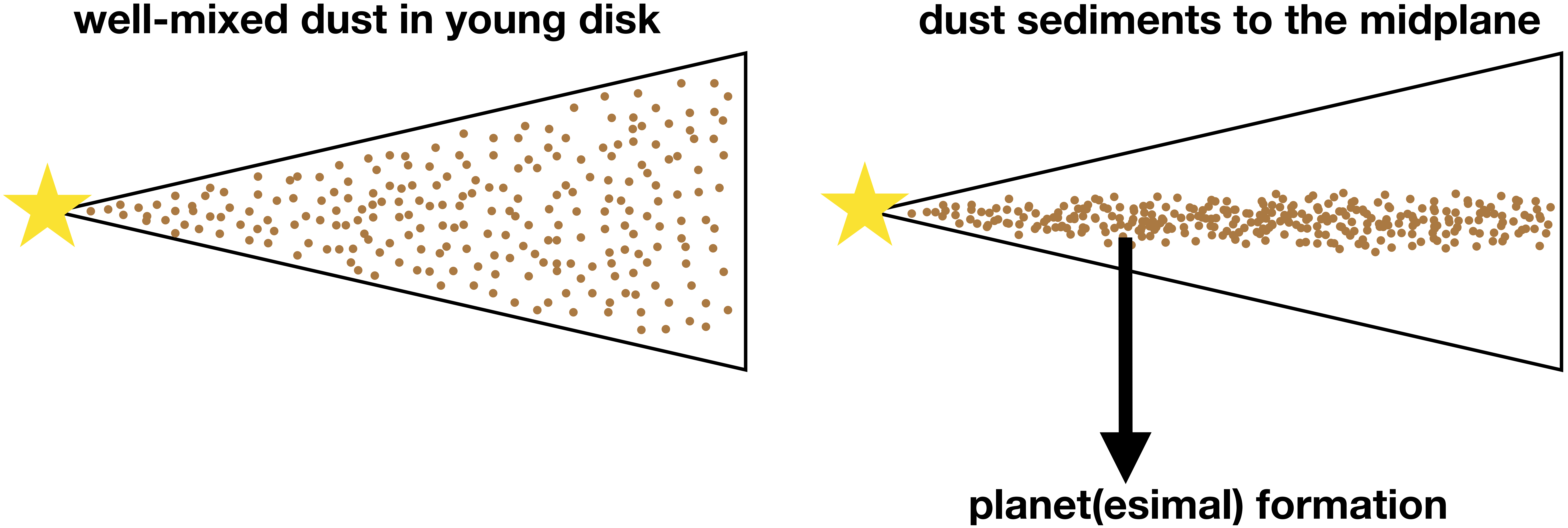


(Miotello et al., 2022, PPVII)

Radial drift of dust grains

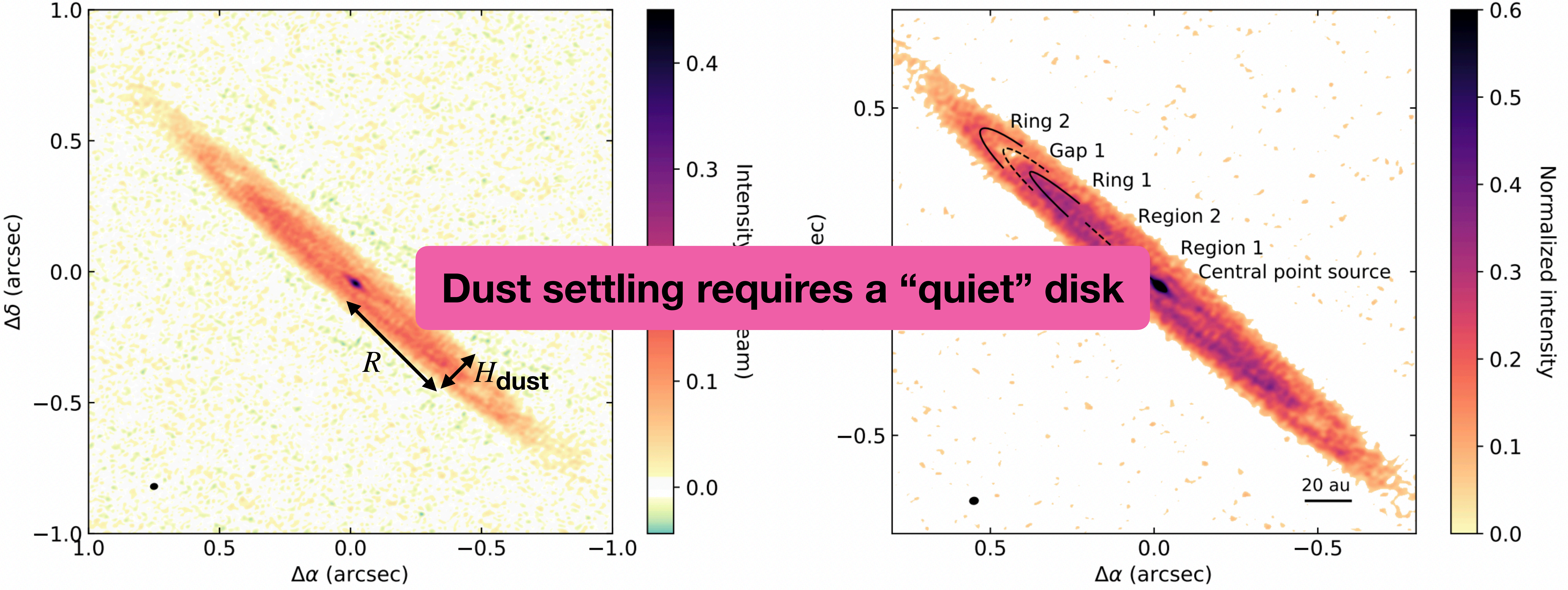


Dust settling



Edge on disk observations

Oph 163131 (Villenave et al. 2022)

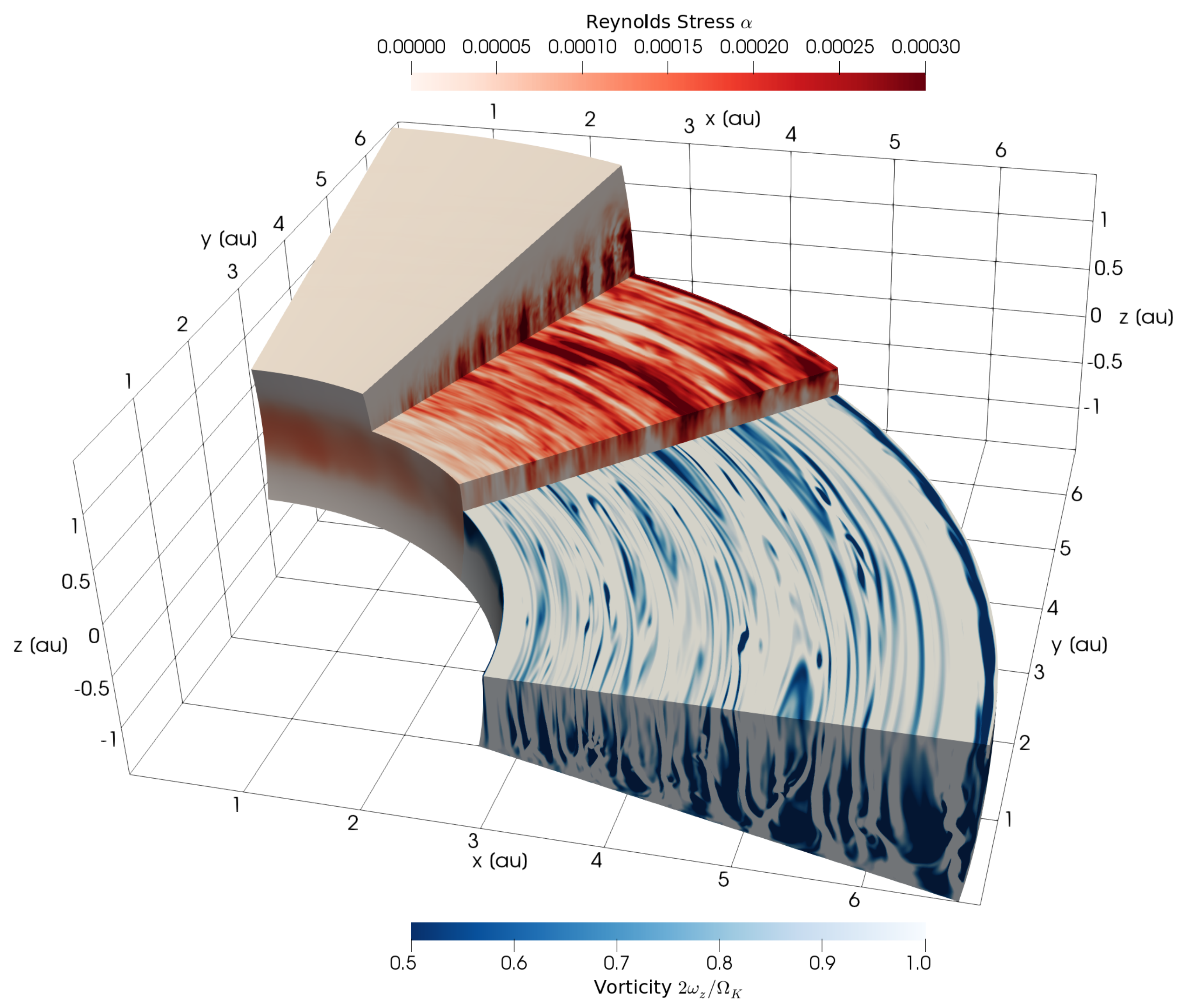


Dust settling requires a "quiet" disk

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

But PPDs are likely turbulent

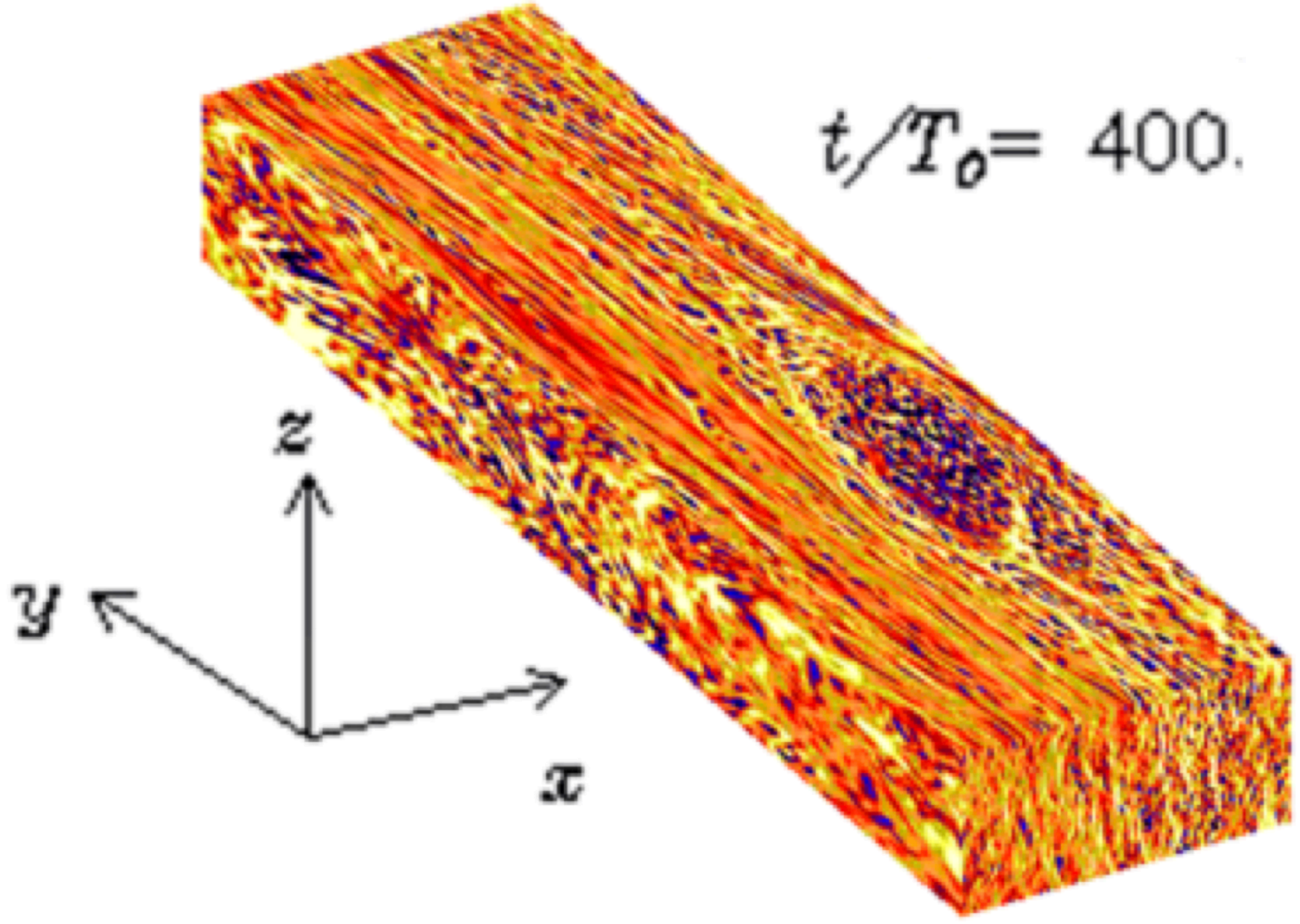
Vertical shear instability



Pfeil & Klahr (2020)

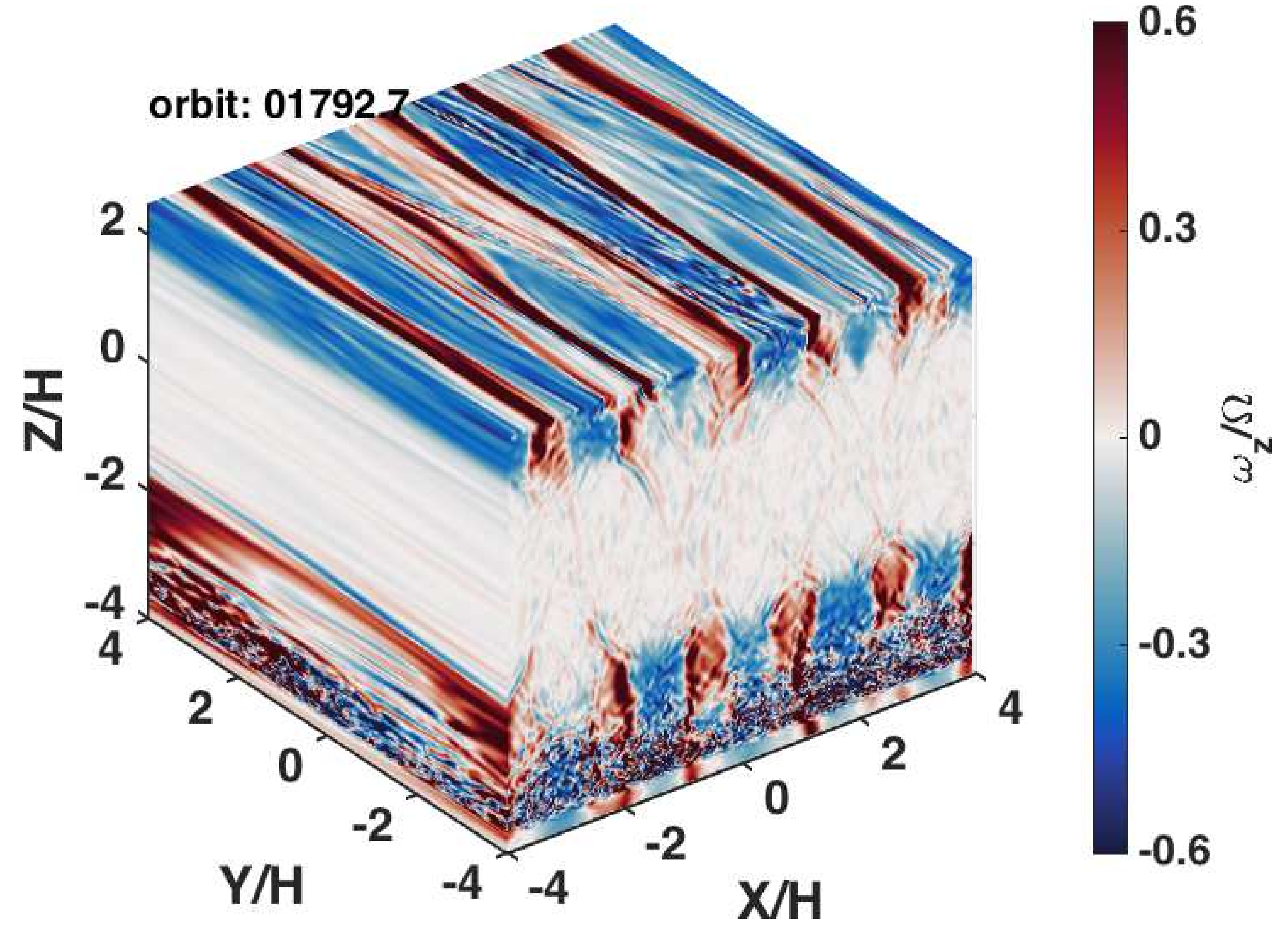
Lin & Youdin (2015)
Cui & Lin (2021)

Convective overstability



Lyra (2014)

Zombie vortex instability



Barranco et al. (2018)

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

Modeling protoplanetary disks

$$\left(\frac{\partial}{\partial t} + \boldsymbol{v}_\mathrm{g} \cdot \boldsymbol{\nabla}\right) \rho_\mathrm{g} = -\rho_\mathrm{g} \left(\boldsymbol{\nabla} \cdot \boldsymbol{v}_\mathrm{g}\right),$$

$$\left(\frac{\partial}{\partial t} + \boldsymbol{v}_\mathrm{g} \cdot \boldsymbol{\nabla}\right) \boldsymbol{v}_\mathrm{g} = -\frac{1}{\rho_\mathrm{g}} \boldsymbol{\nabla} P + \frac{1}{\rho_\mathrm{g}} \boldsymbol{\nabla} \cdot \hat{T} - \boldsymbol{\nabla} \Phi_* - \frac{\epsilon}{t_\mathrm{s}} \left(\boldsymbol{v}_\mathrm{g} - \boldsymbol{v}_\mathrm{d}\right),$$

Gas

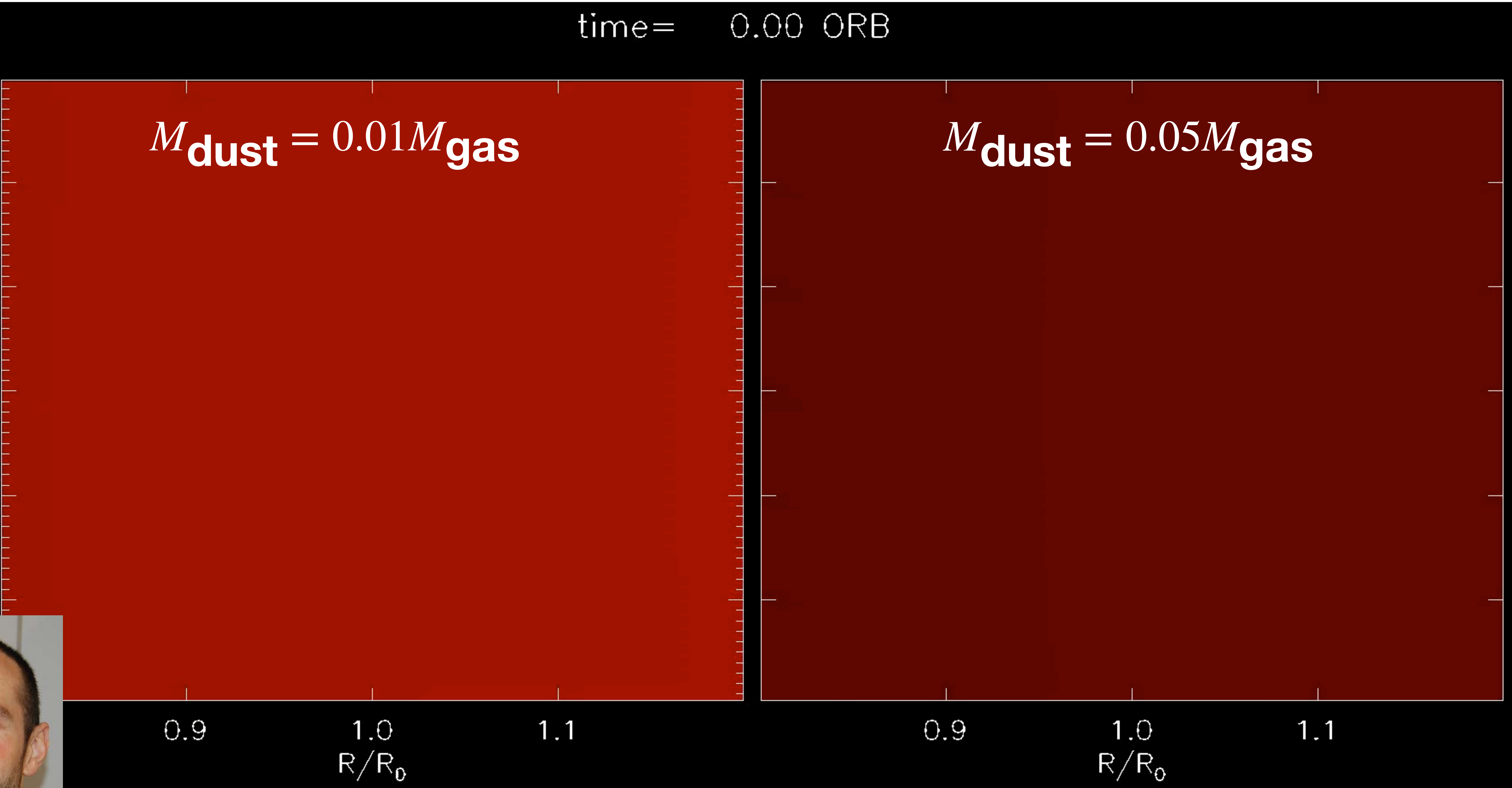
$$\left(\frac{\partial}{\partial t} + \boldsymbol{v}_\mathrm{d} \cdot \boldsymbol{\nabla}\right) \rho_\mathrm{d} = -\rho_\mathrm{d} \left(\boldsymbol{\nabla} \cdot \boldsymbol{v}_\mathbf{d}\right) + \boldsymbol{\nabla} \cdot \left(\nu \rho \boldsymbol{\nabla} f_\mathrm{d}\right),$$

$$\left(\frac{\partial}{\partial t} + \boldsymbol{v}_\mathrm{d} \cdot \boldsymbol{\nabla}\right) \boldsymbol{v}_\mathrm{d} = -\boldsymbol{\nabla} \Phi_* - \frac{1}{t_\mathrm{s}} \left(\boldsymbol{v}_\mathrm{d} - \boldsymbol{v}_\mathrm{g}\right),$$

Dust (as a fluid)

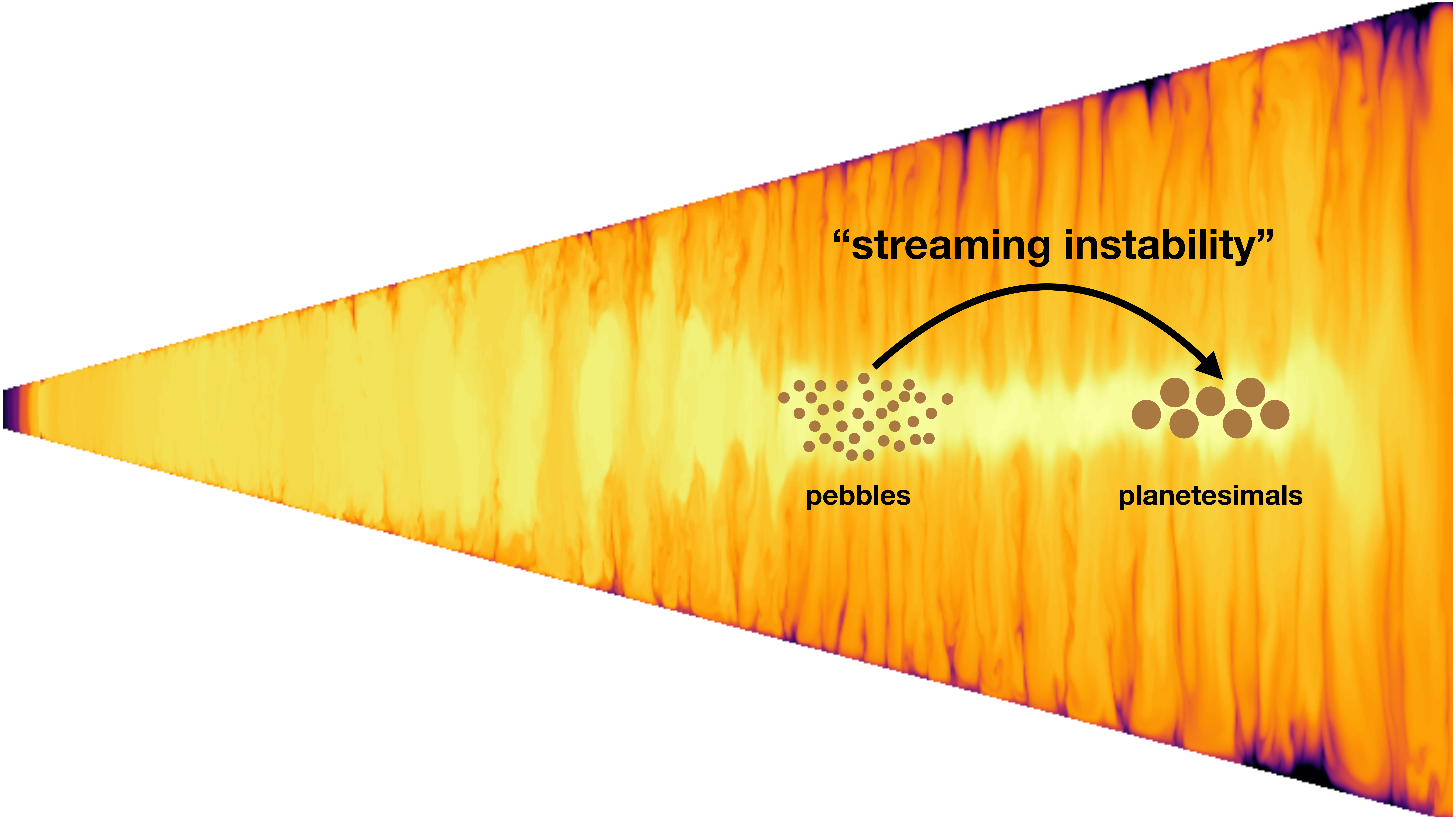
friction between dust and gas

Dust settling vs. turbulence

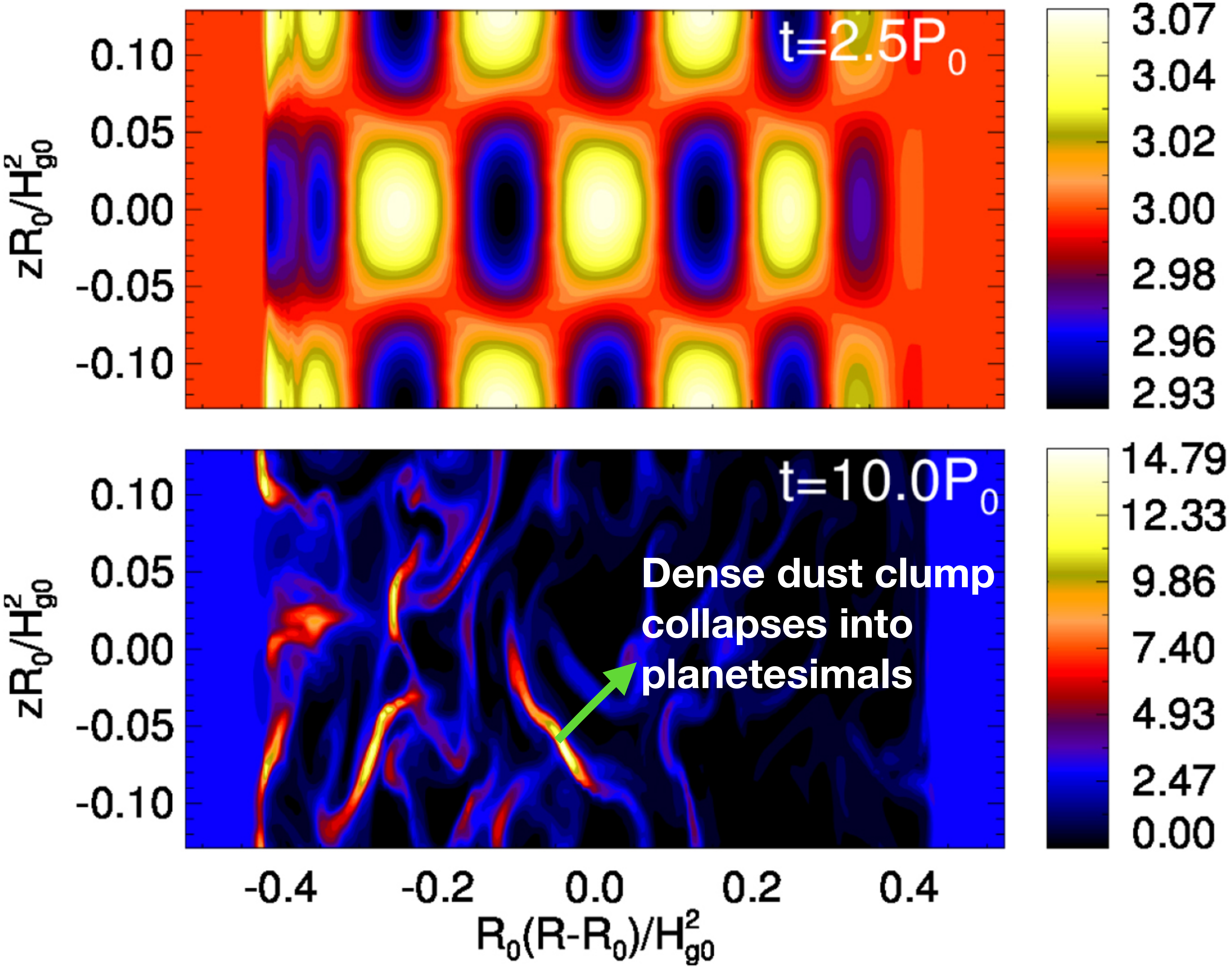


Lehmann & Lin (2022)

Planetesimal formation in the mid-plane

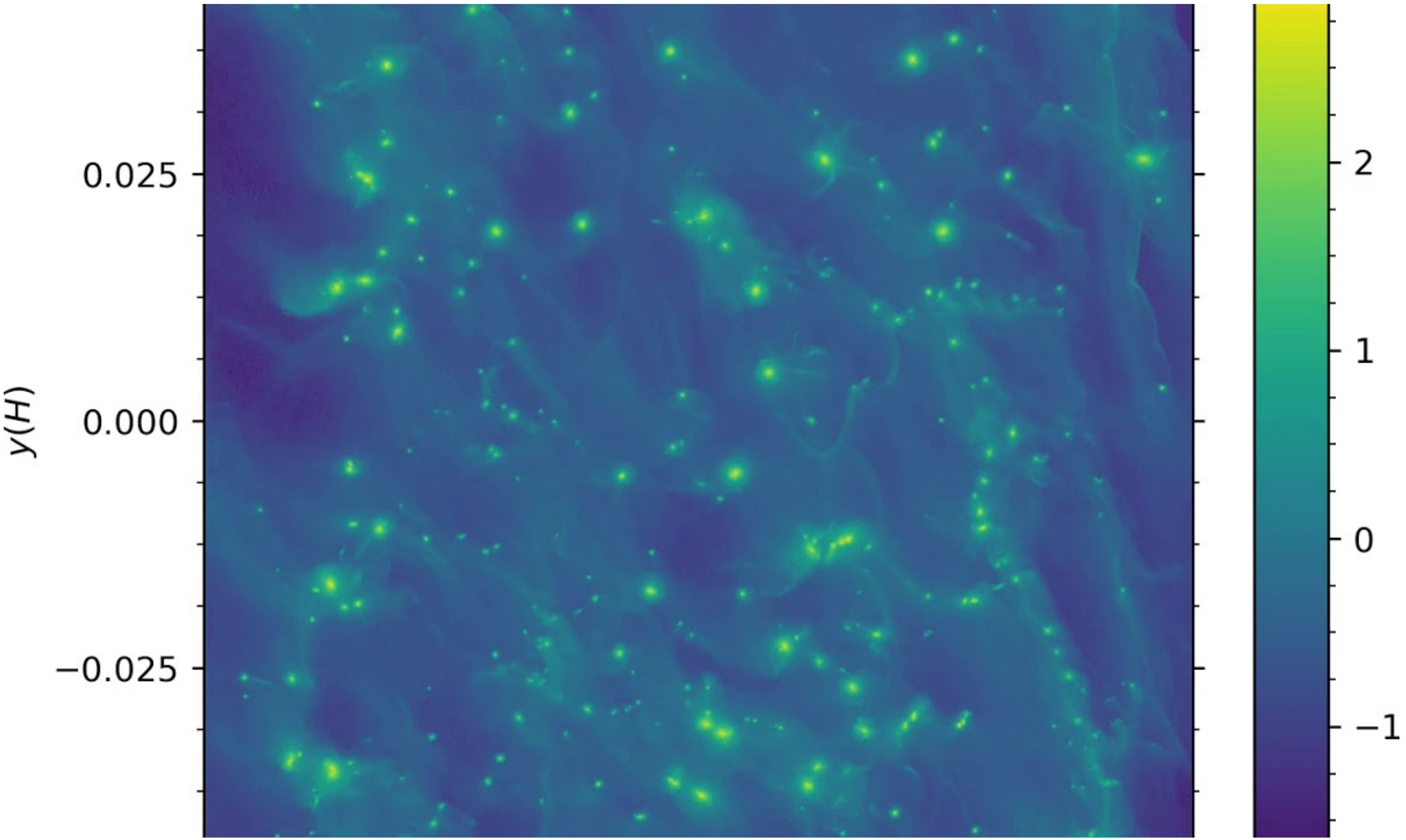


Streaming instability of dusty gas



Chen & Lin (2018)

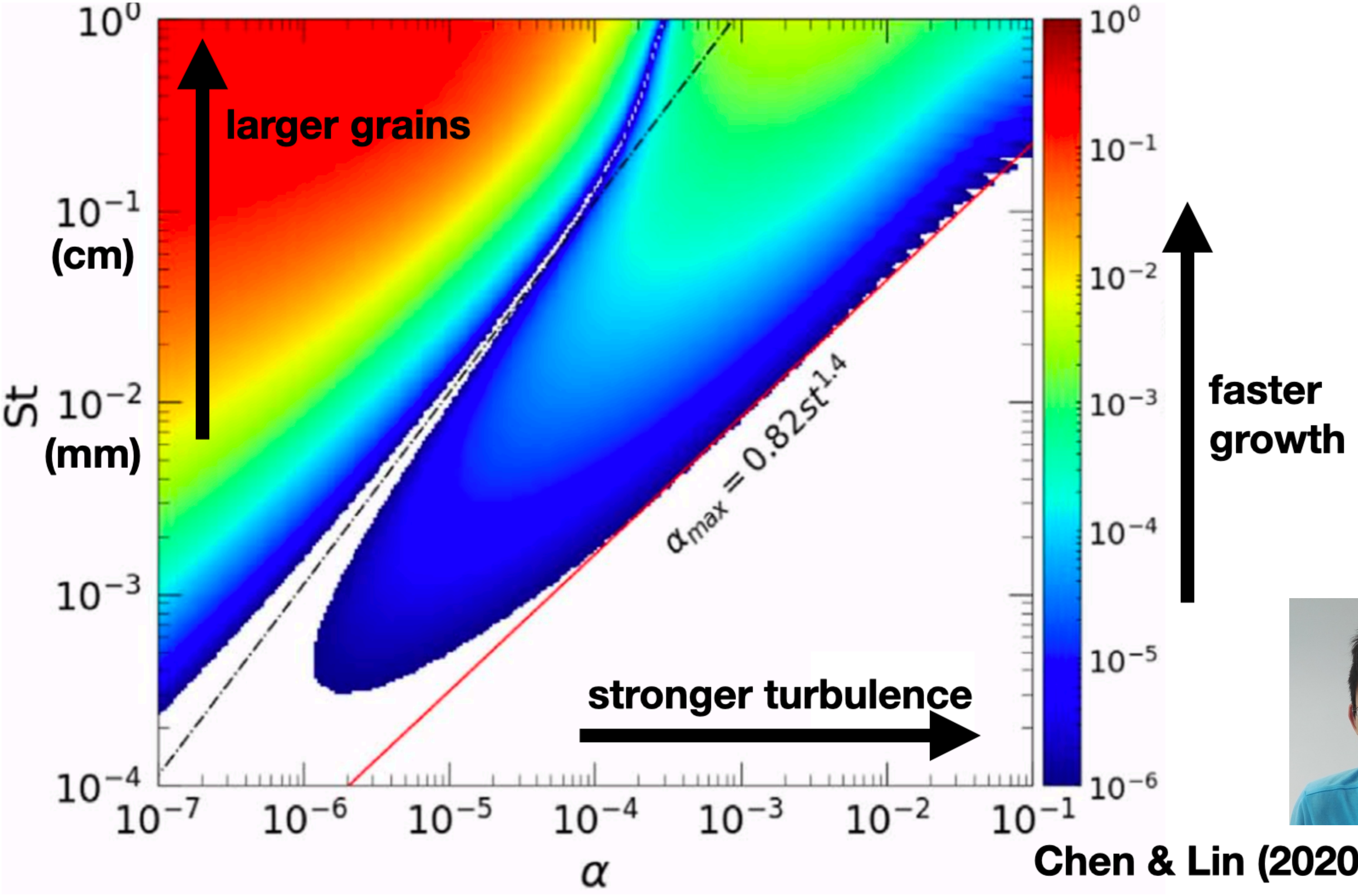
State-of-the-art simulations (Nesvorný et al., 2020)

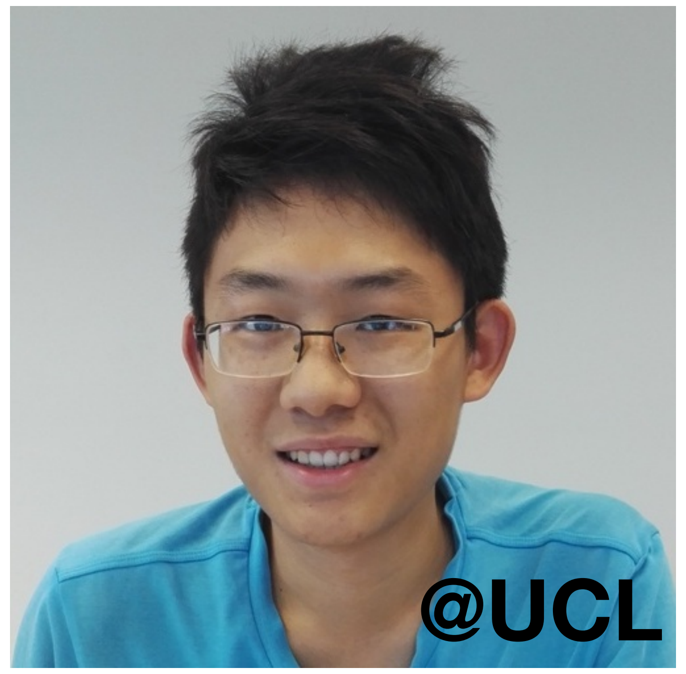


The ideal SI

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

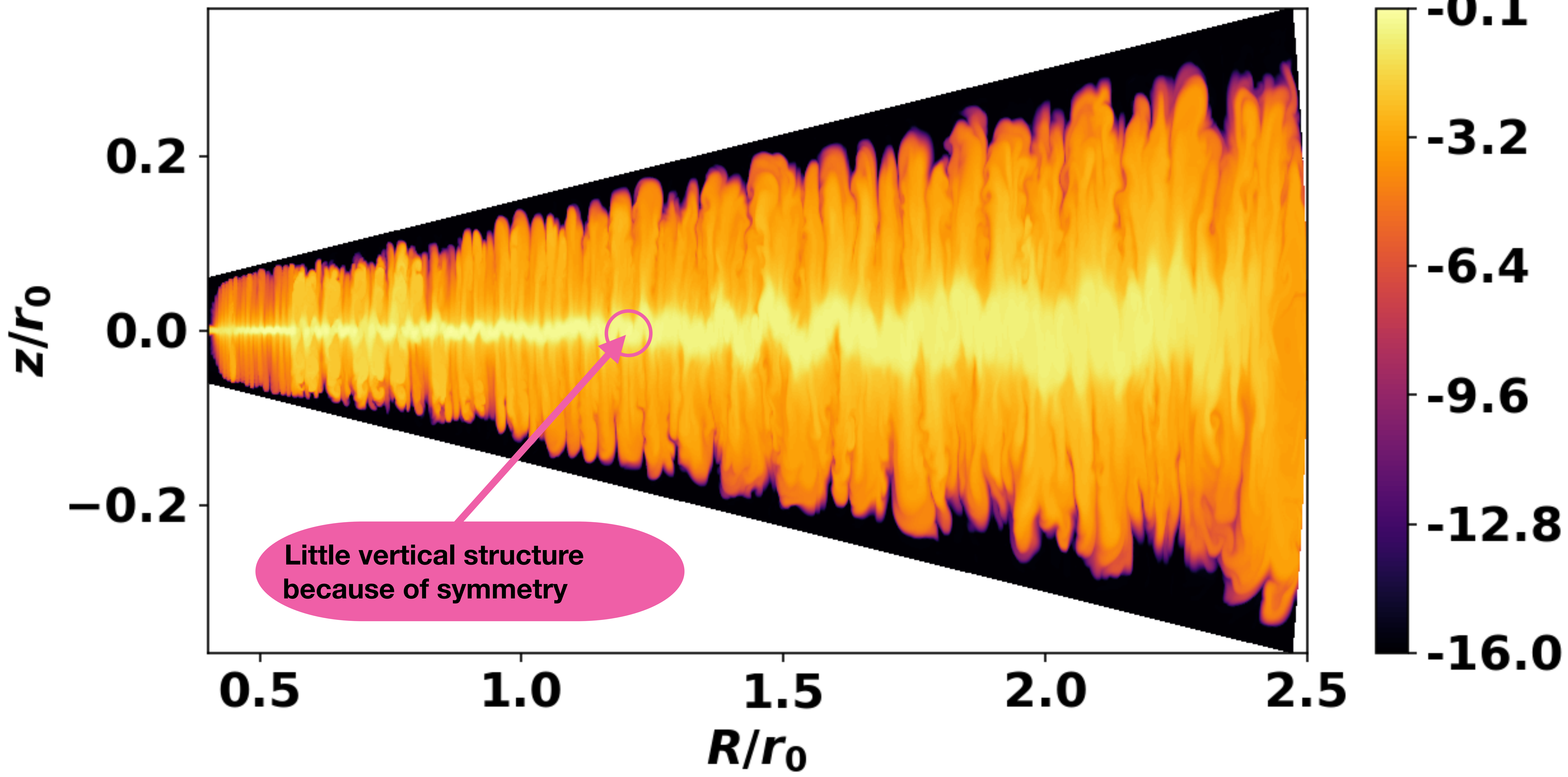
Streaming instability is easily killed by turbulent viscosity



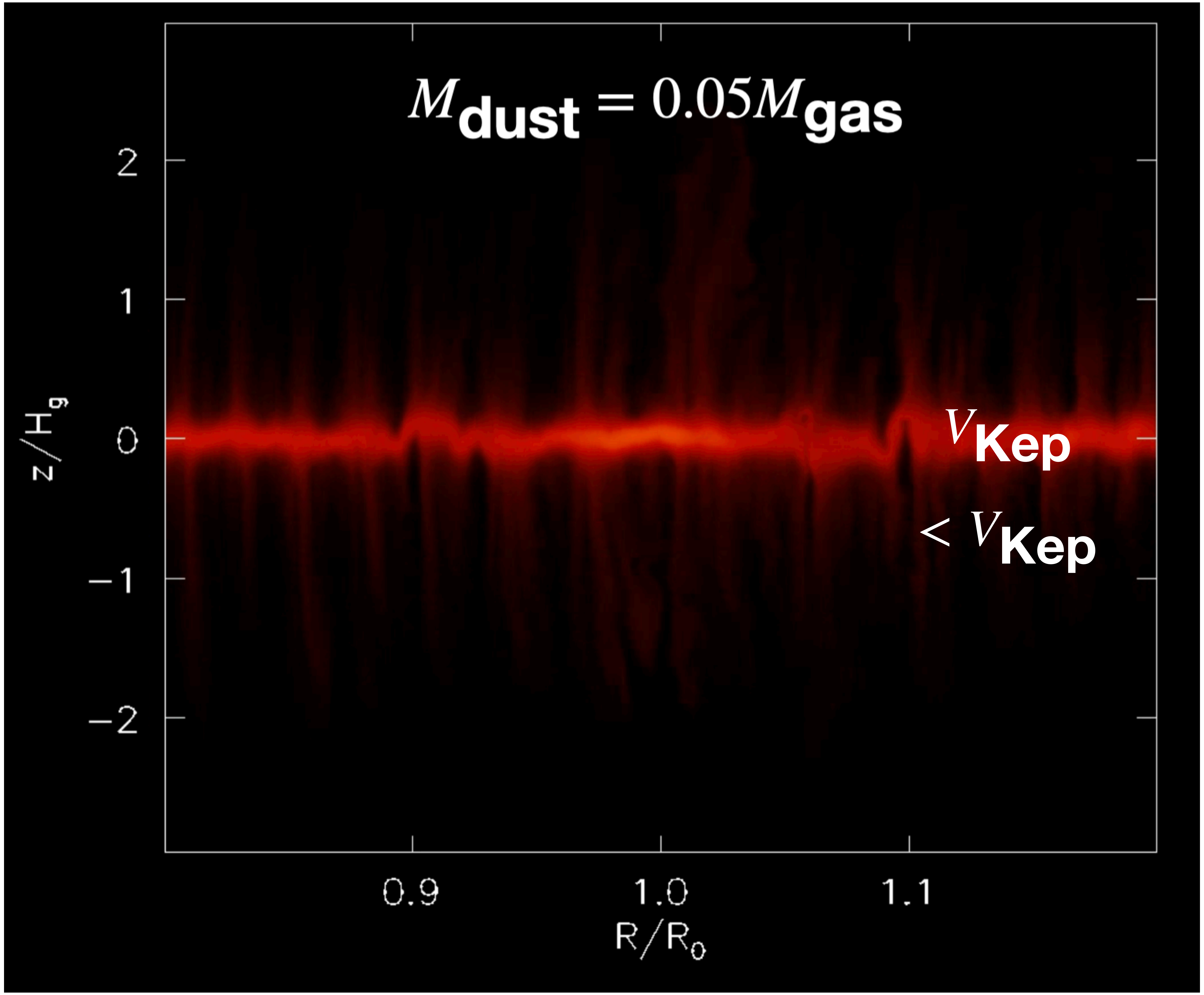


Chen & Lin (2020)

SI analyses use unstratified disk models



Stratified dust layers

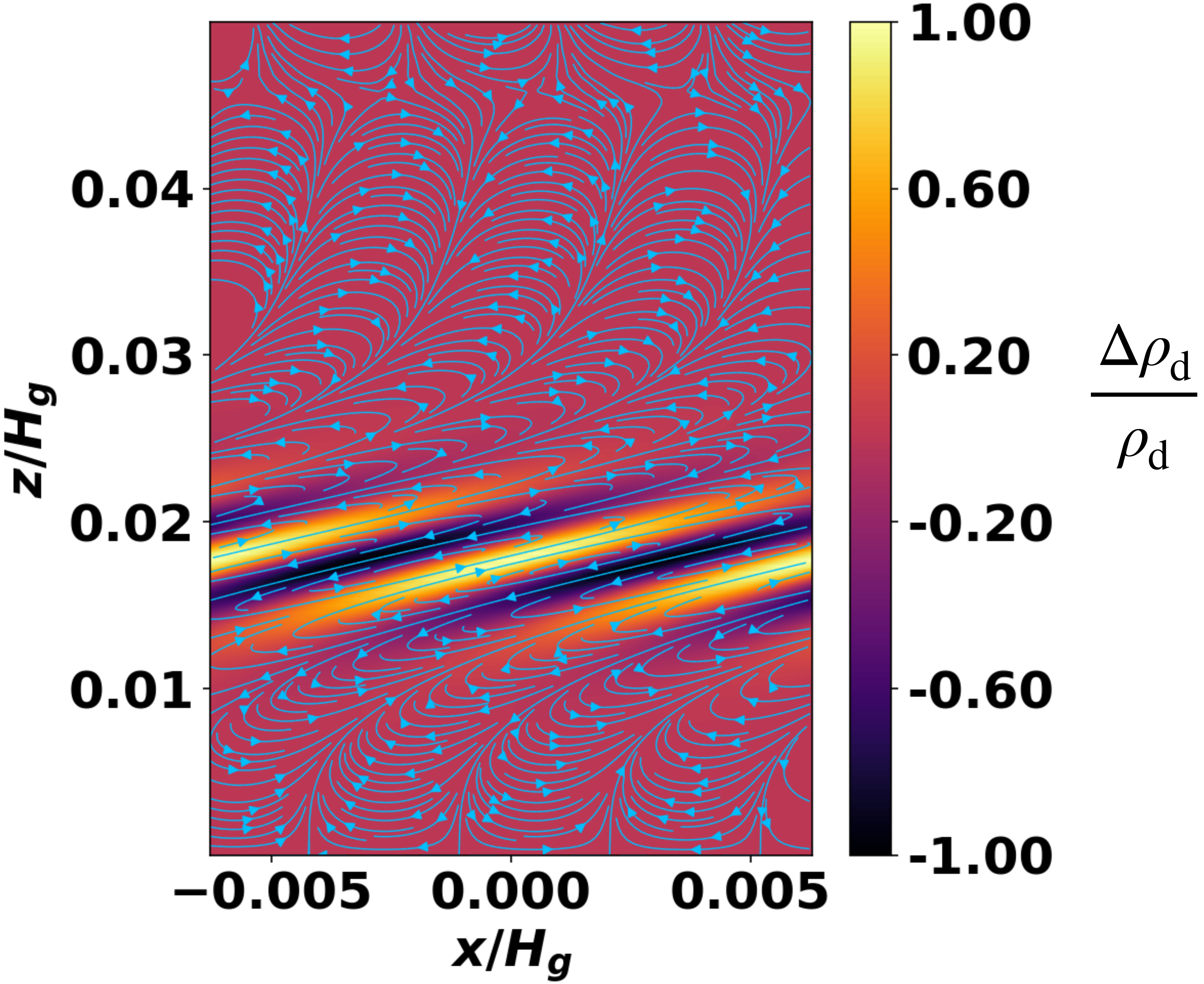


$$\frac{\partial \Omega}{\partial z} \neq 0$$

Lehmann & Lin (2022)

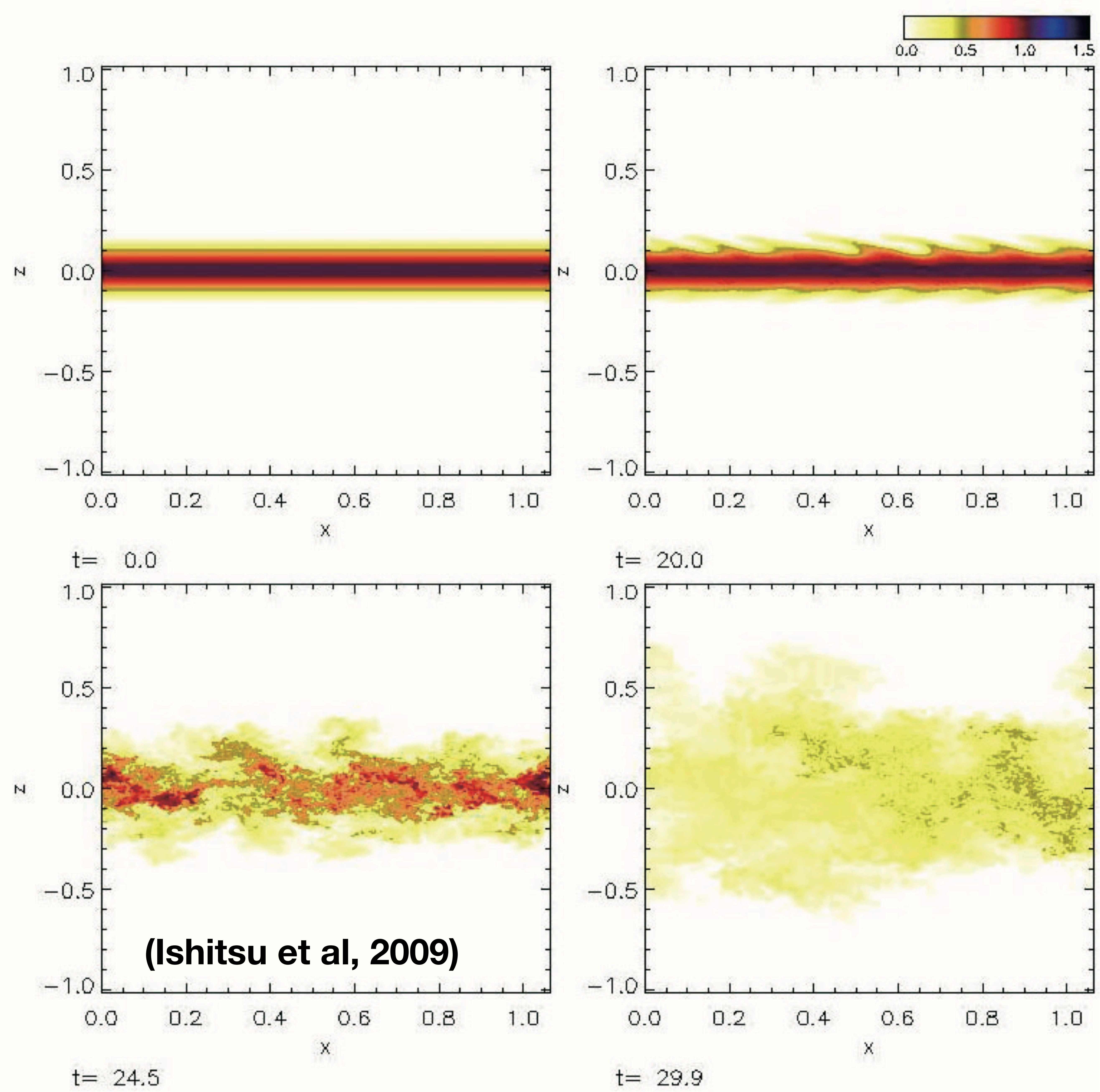
“Vertically shearing SI” in stratified disks

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



Lin (2021)

Vertically shearing SIs grow fast but…

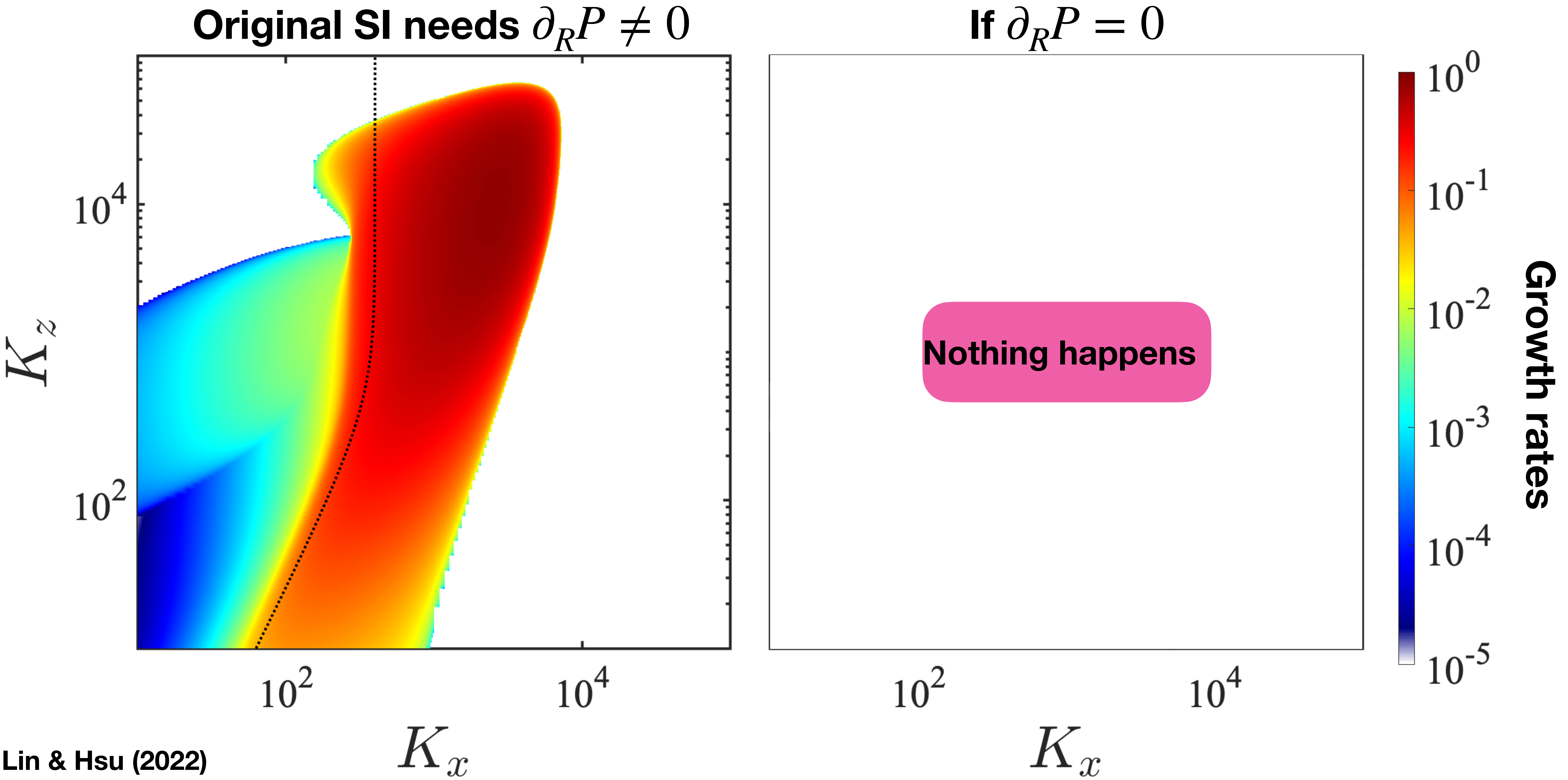


dust layer dispersed

Can modern disk models help?

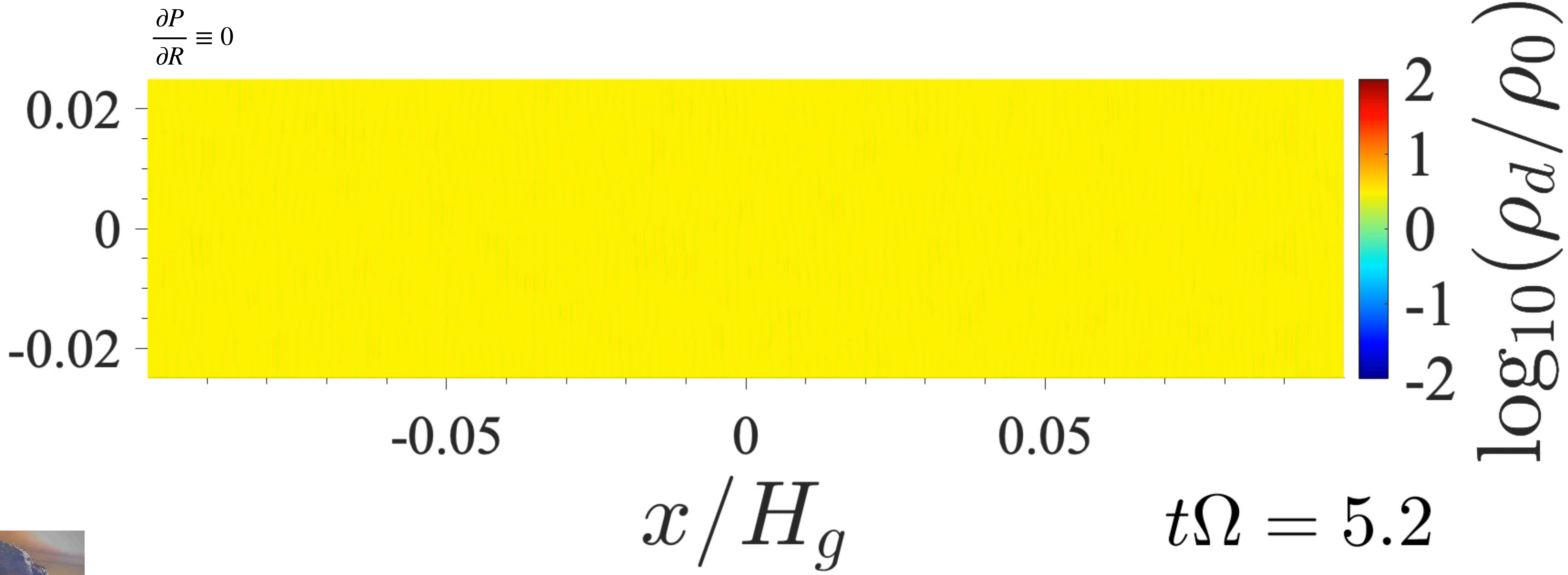
(e.g. Riols et al. 2020, Cui & Bai 2021)

Streaming instability in accreting disks



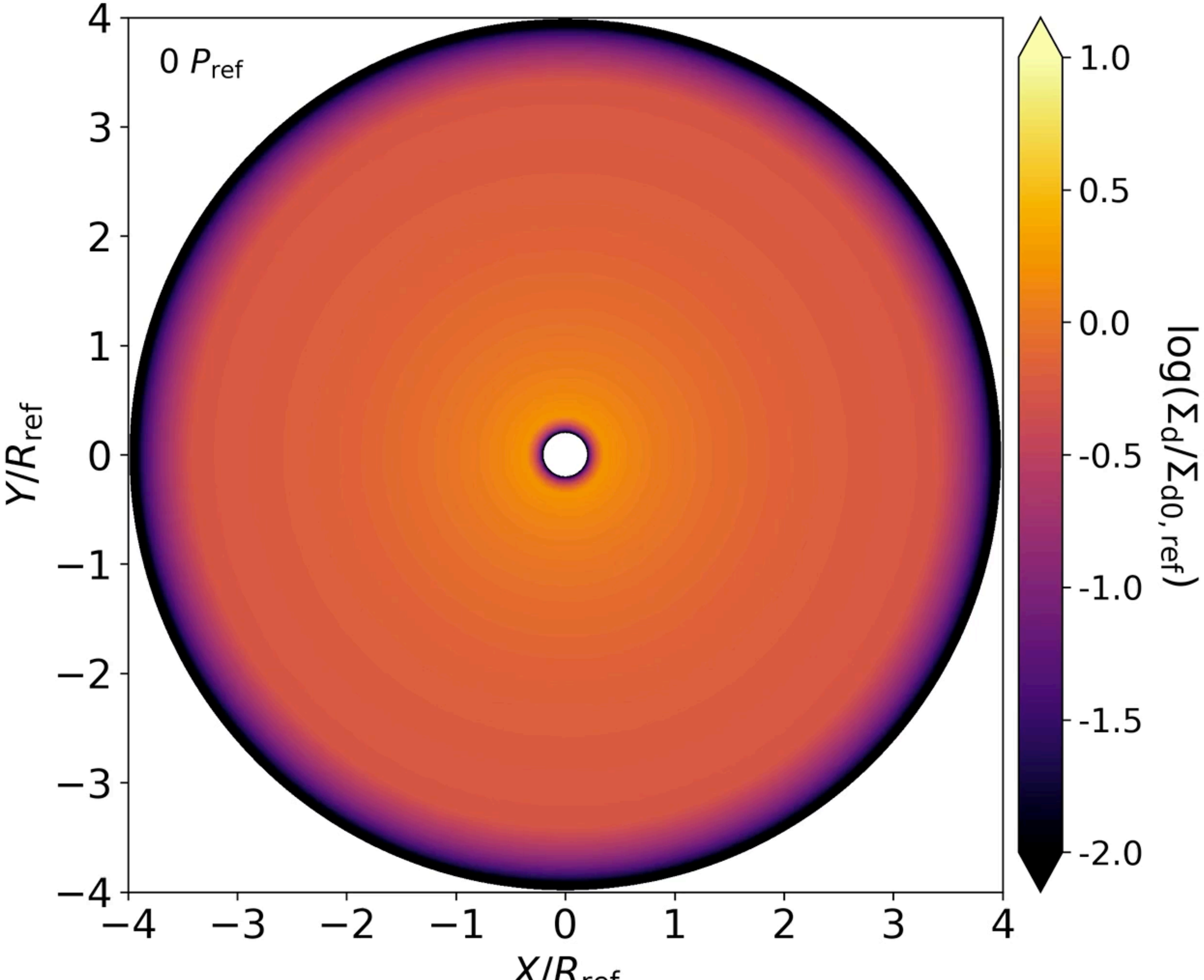
Lin & Hsu (2022)

Azimuthal drift streaming instability



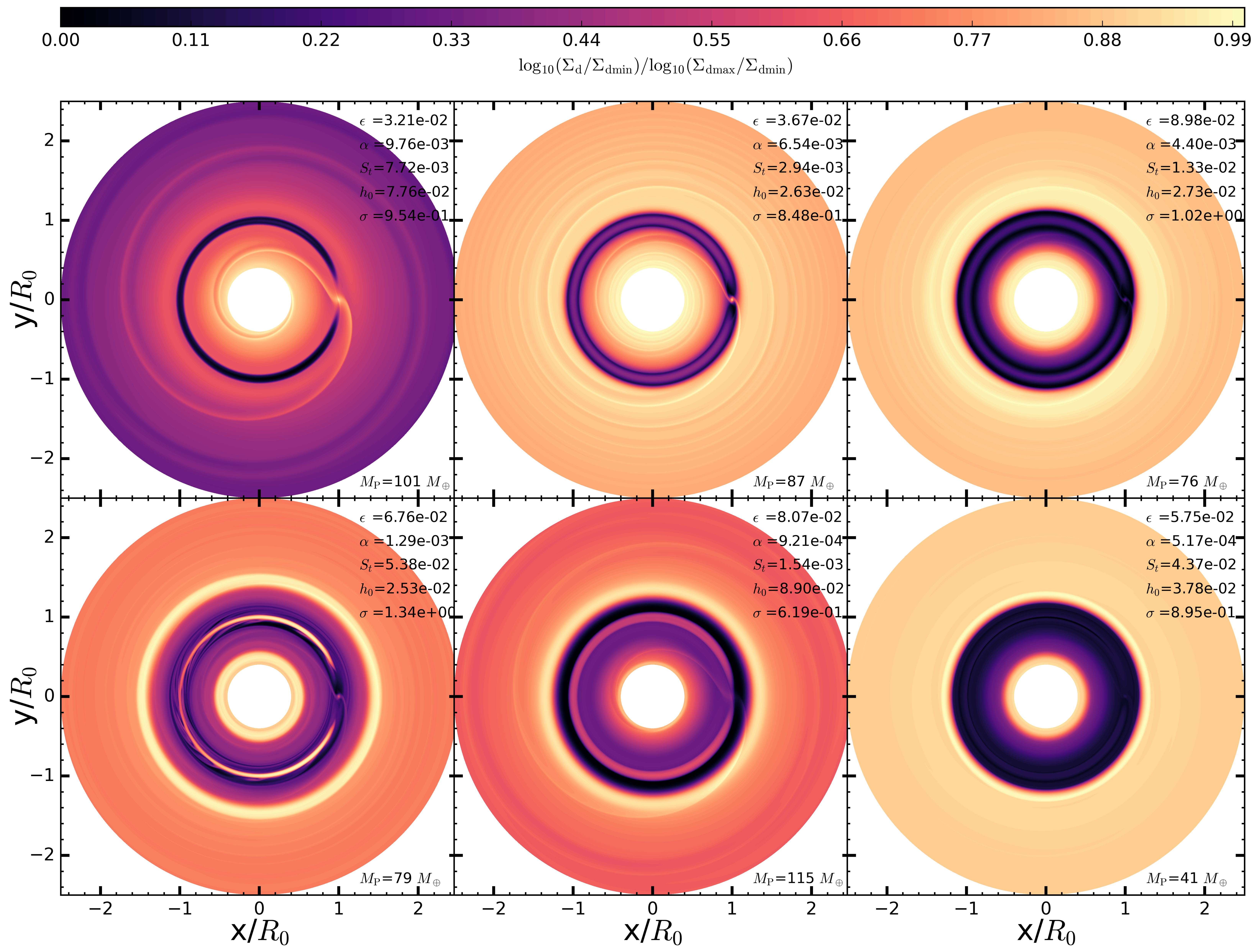
Hsu & Lin (2022)

Planets form somehow, so what's next?



Bi, Lin, Dong (2022)

Disk-planet morphology



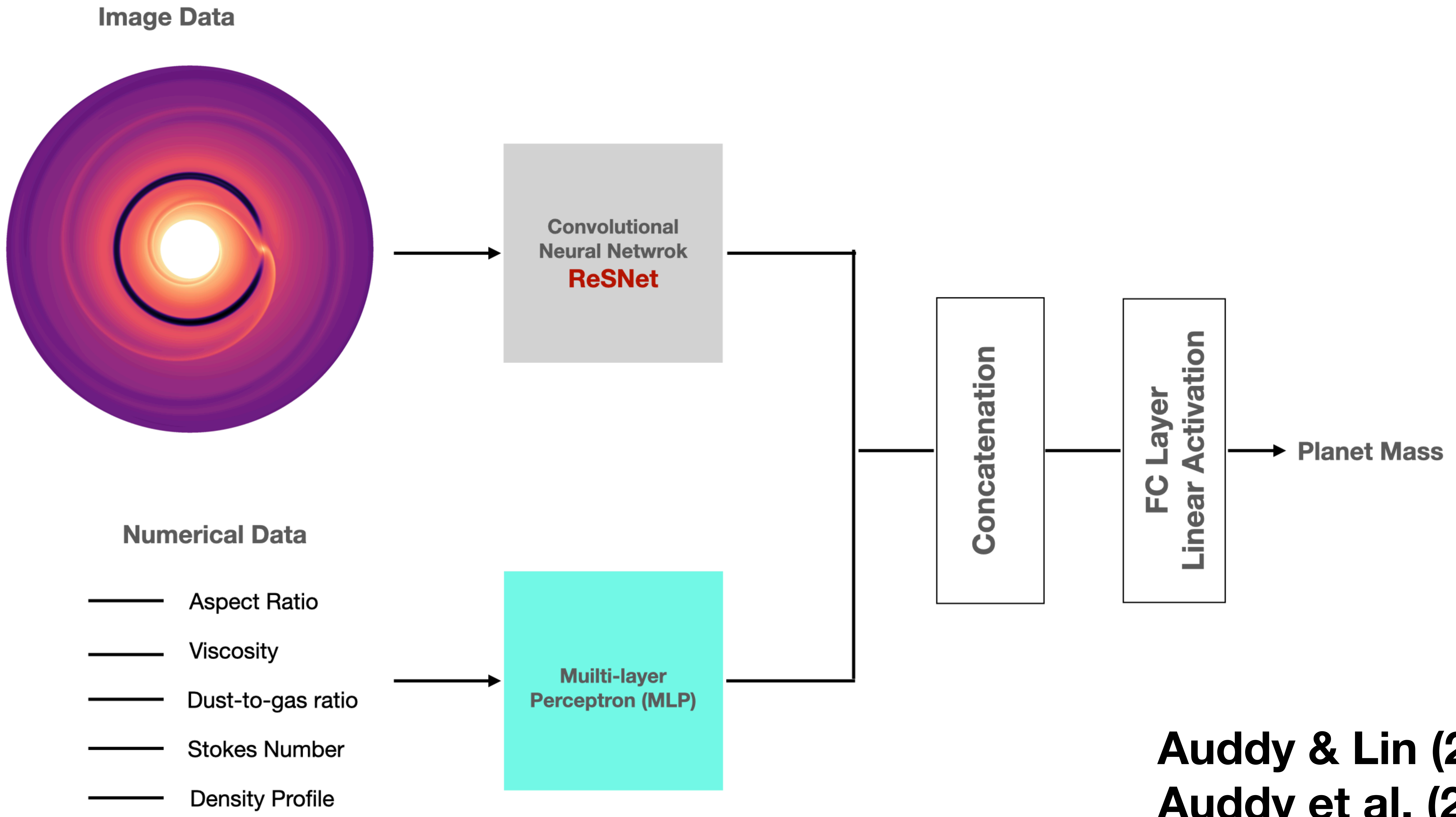
Auddy & Lin (2020)

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)

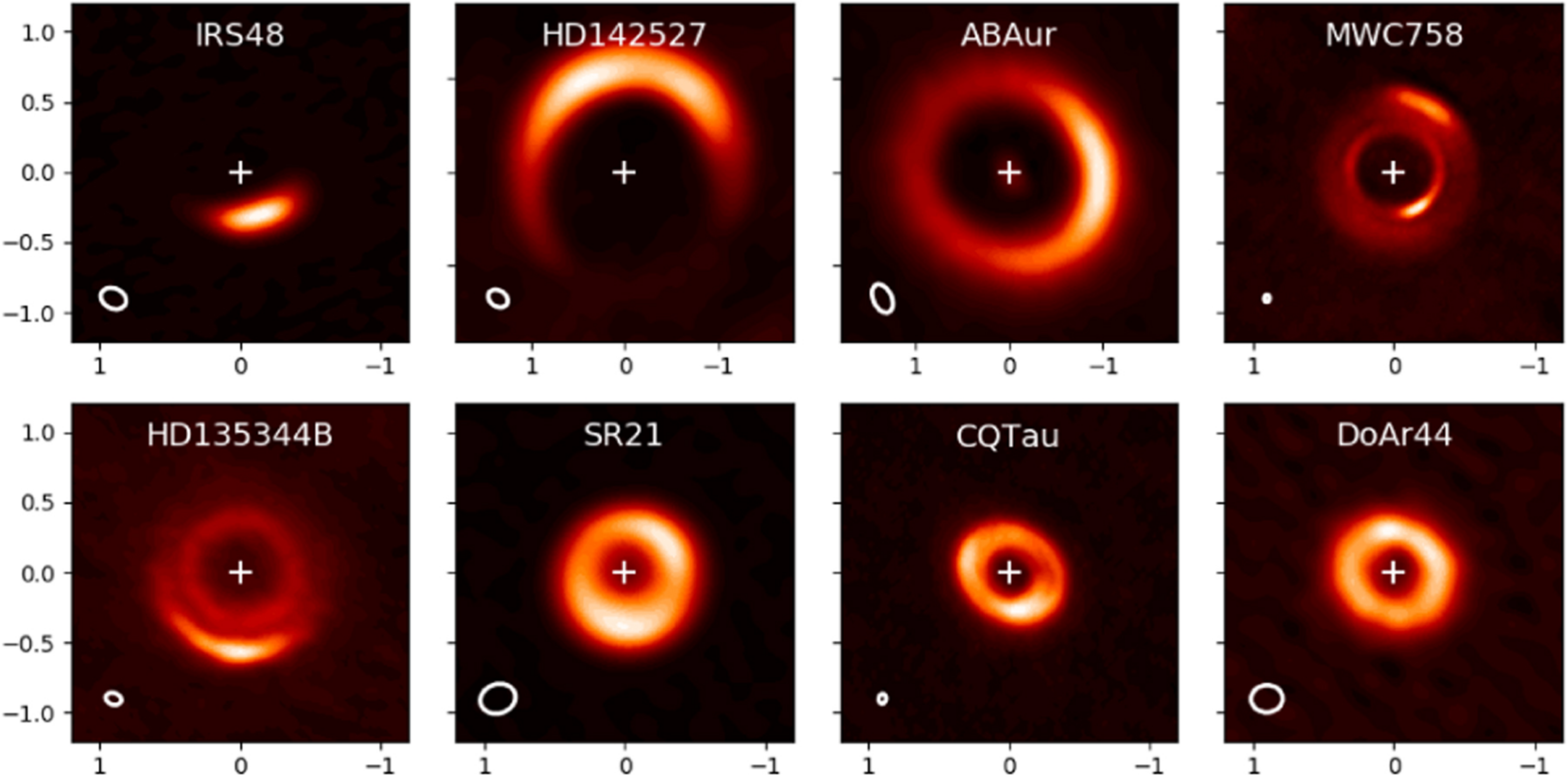
$$M_p = 0.24M_J, 0.21M_J, 0.2M_J$$

Simulation caveats

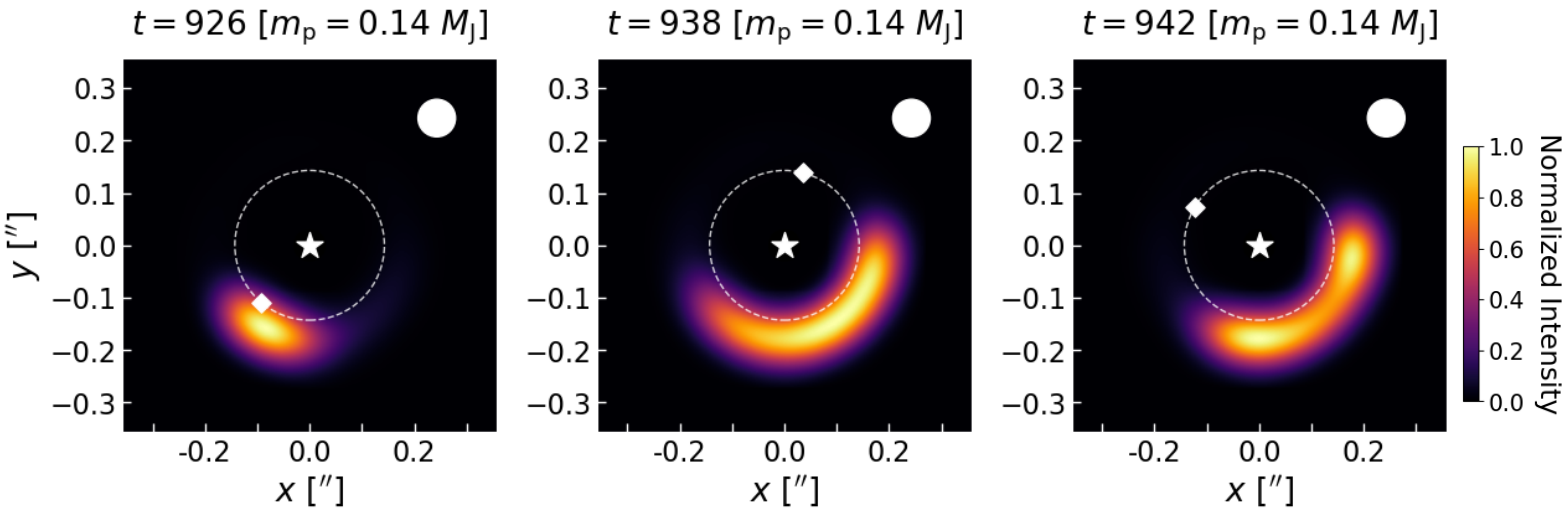
- Focus on axisymmetric structures
- Planet on fixed orbits
- 2D disk

Some observed disks are asymmetric

(van de Marel, et al. 2021)



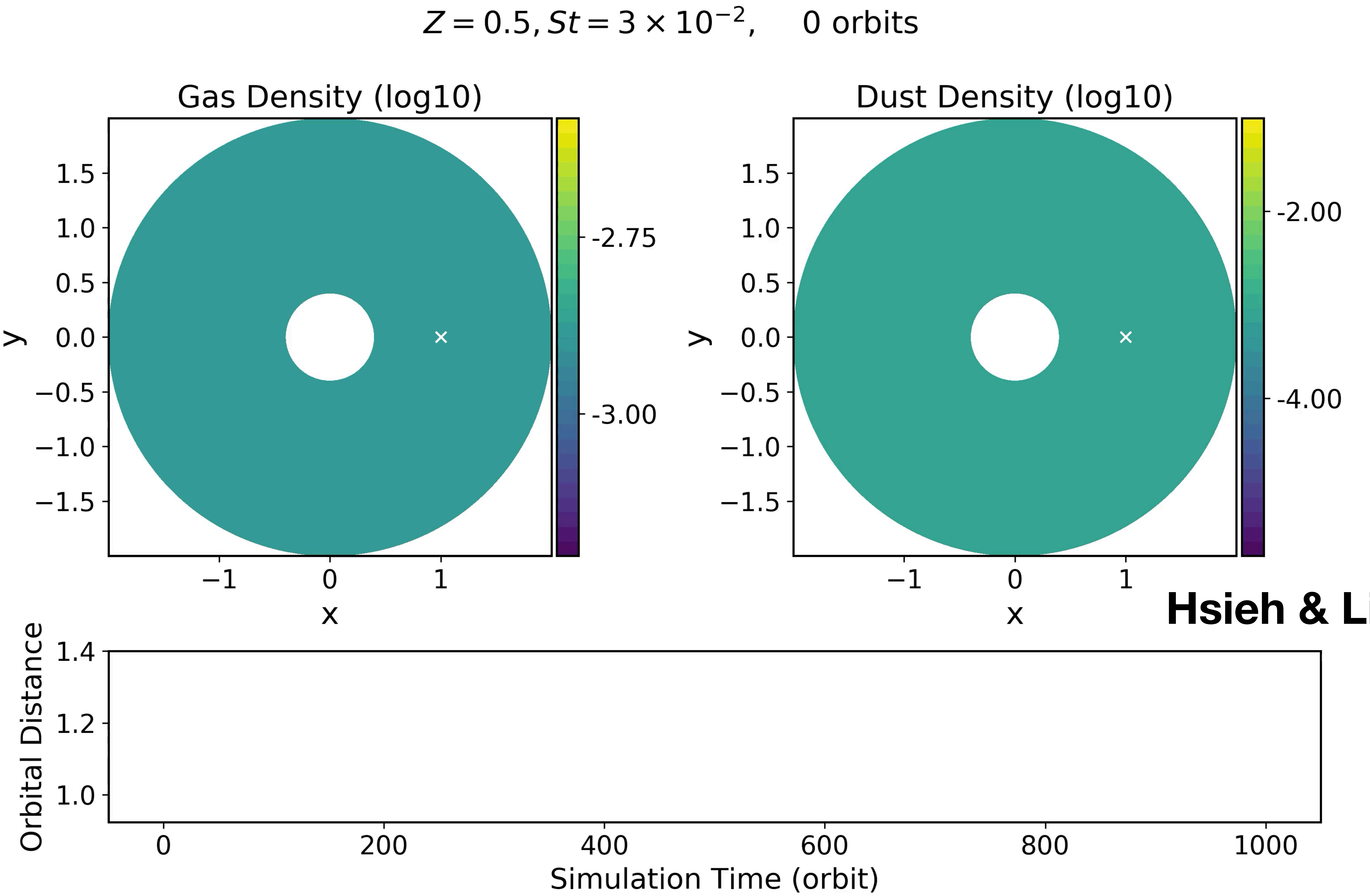
Can planets also explain them?



Vortex formation due to the "Rossby wave" instability

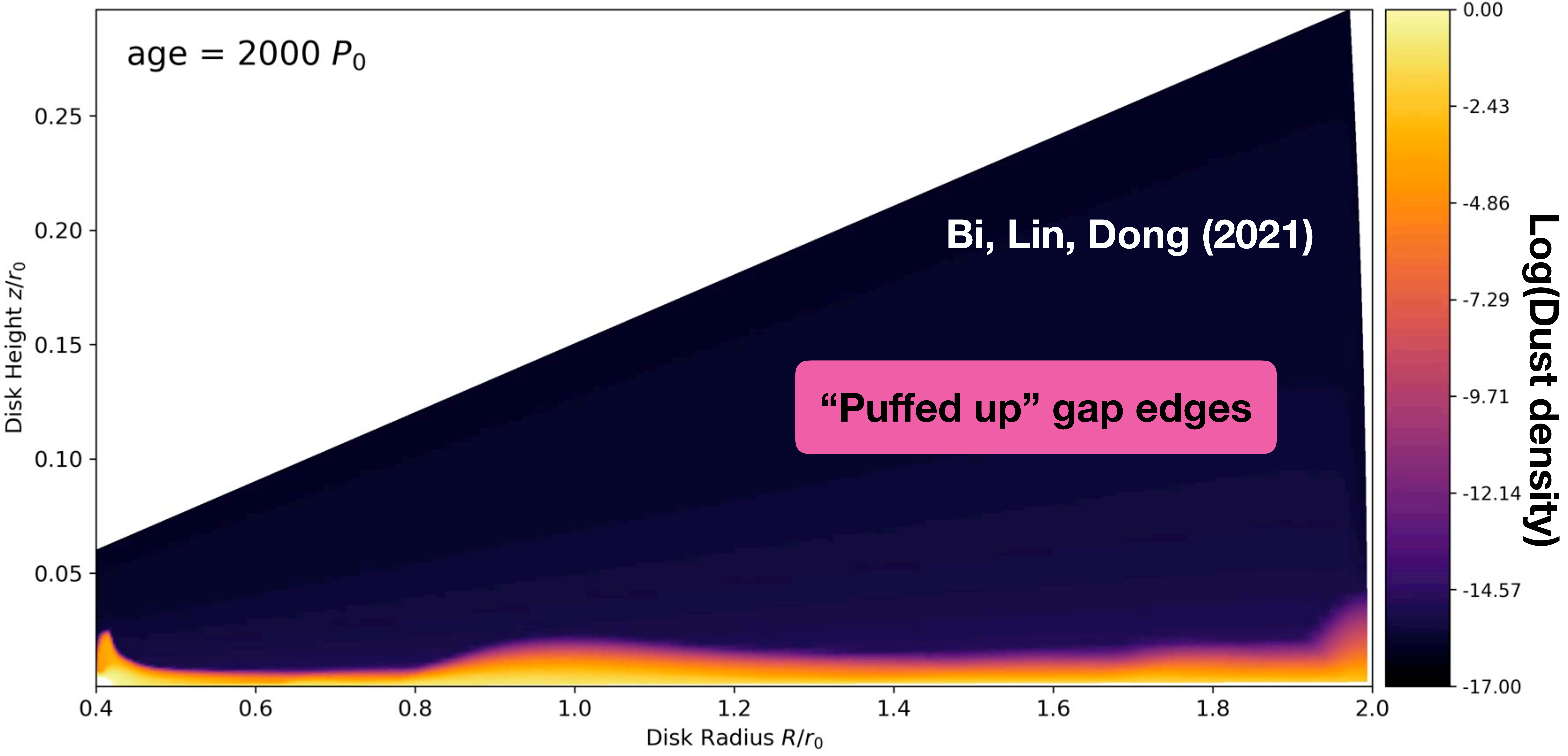
(Hammer, Lin, et al. 2021)

Moving planets in dusty disks

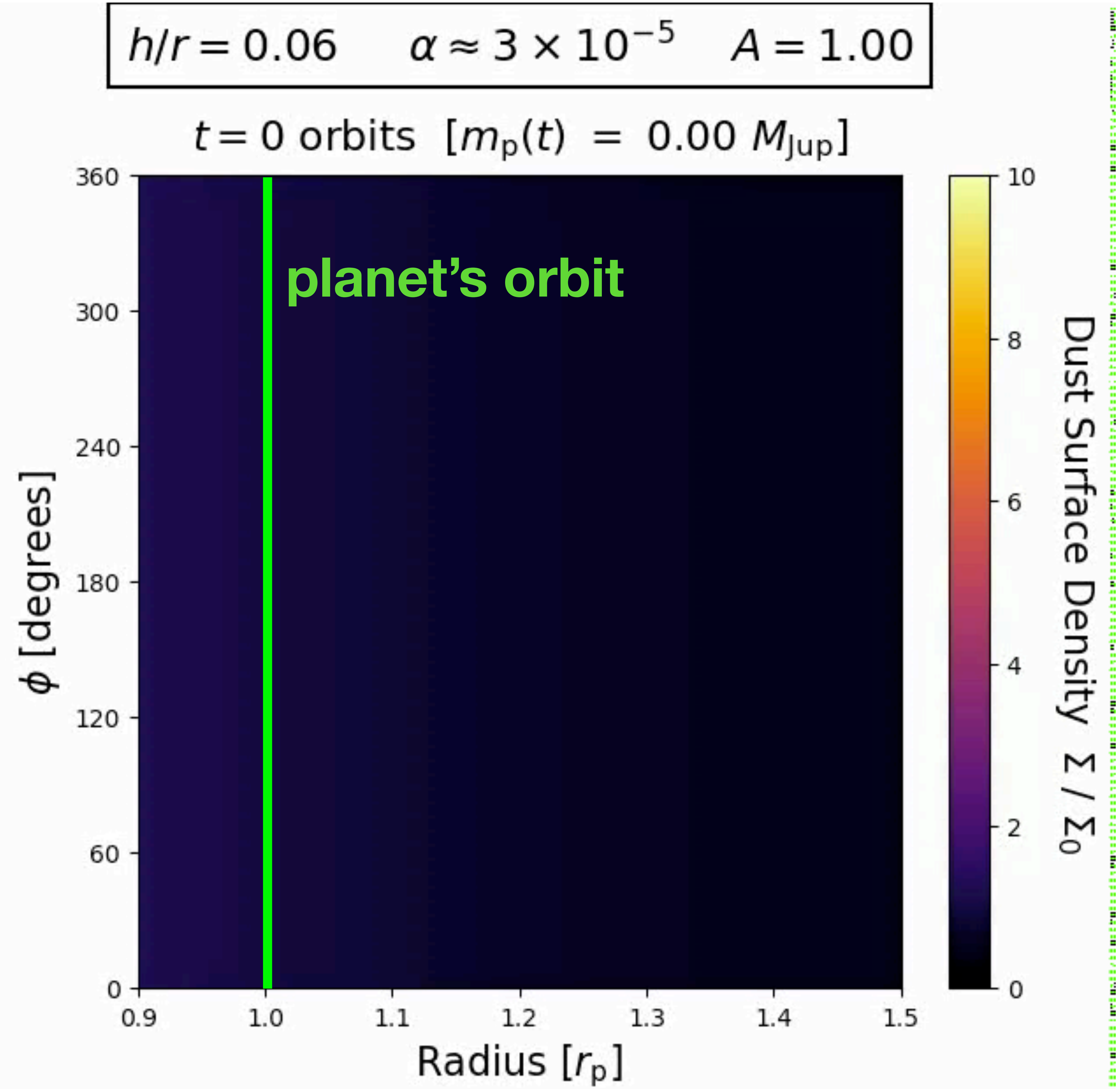


Hsieh & Lin (2020)

Three-dimensional models



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 clumping
- Planet-disk interaction can be used to reveal or rule out hidden planets in observations of protoplanetary disks

Thank you

@linminkai

2022 NCTS ANNUAL THEORY MEETING: PARTICLE PHYSICS, STRING THEORY, COSMOLOGY, AND ASTROPHYSICS

https://www.phys.ncts.ntu.edu.tw/act/actnews/2022-62215217/home

Dec. 14-16
[astro: 15-16]