Hopes and challenges in modern planet formation

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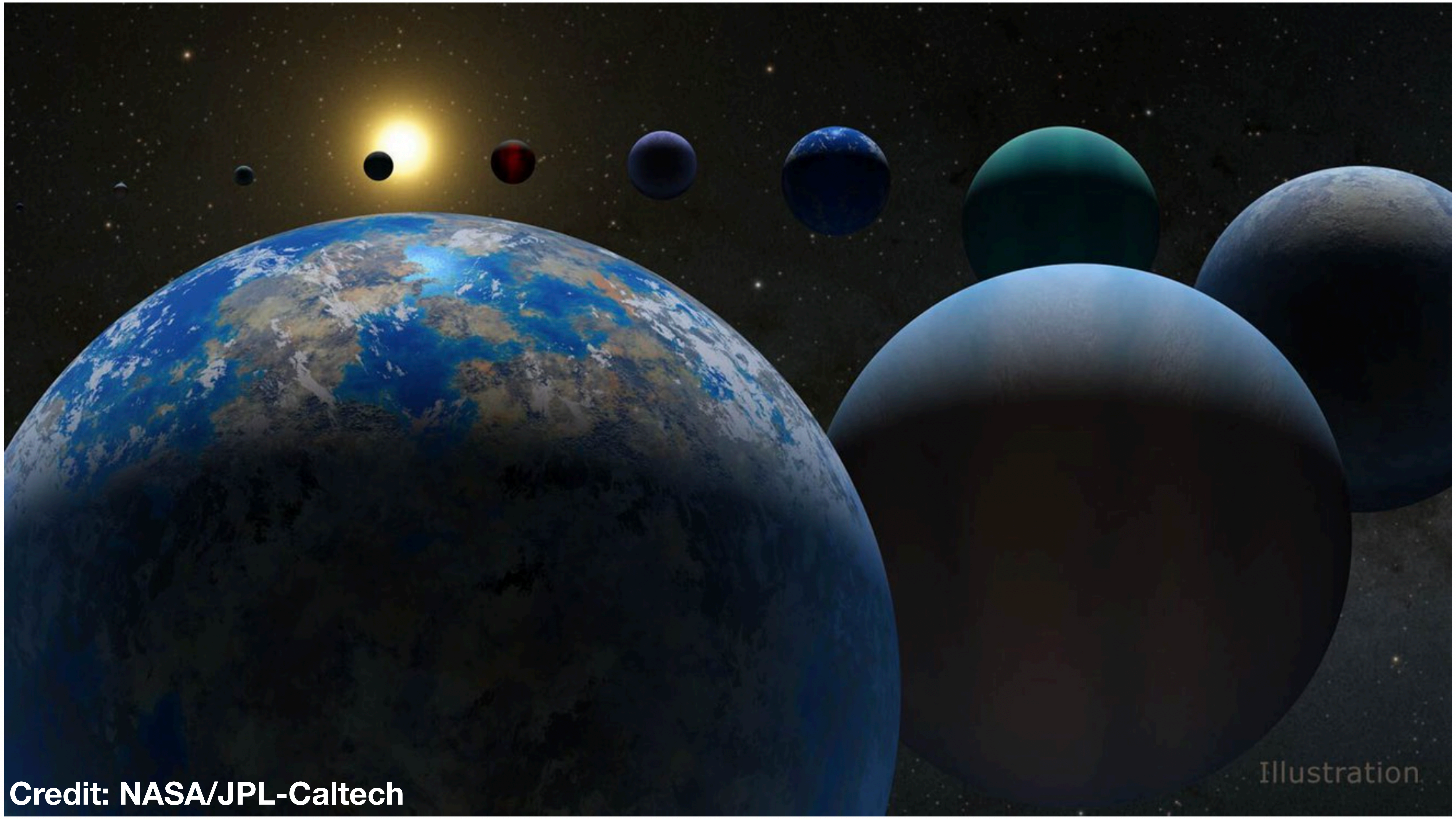
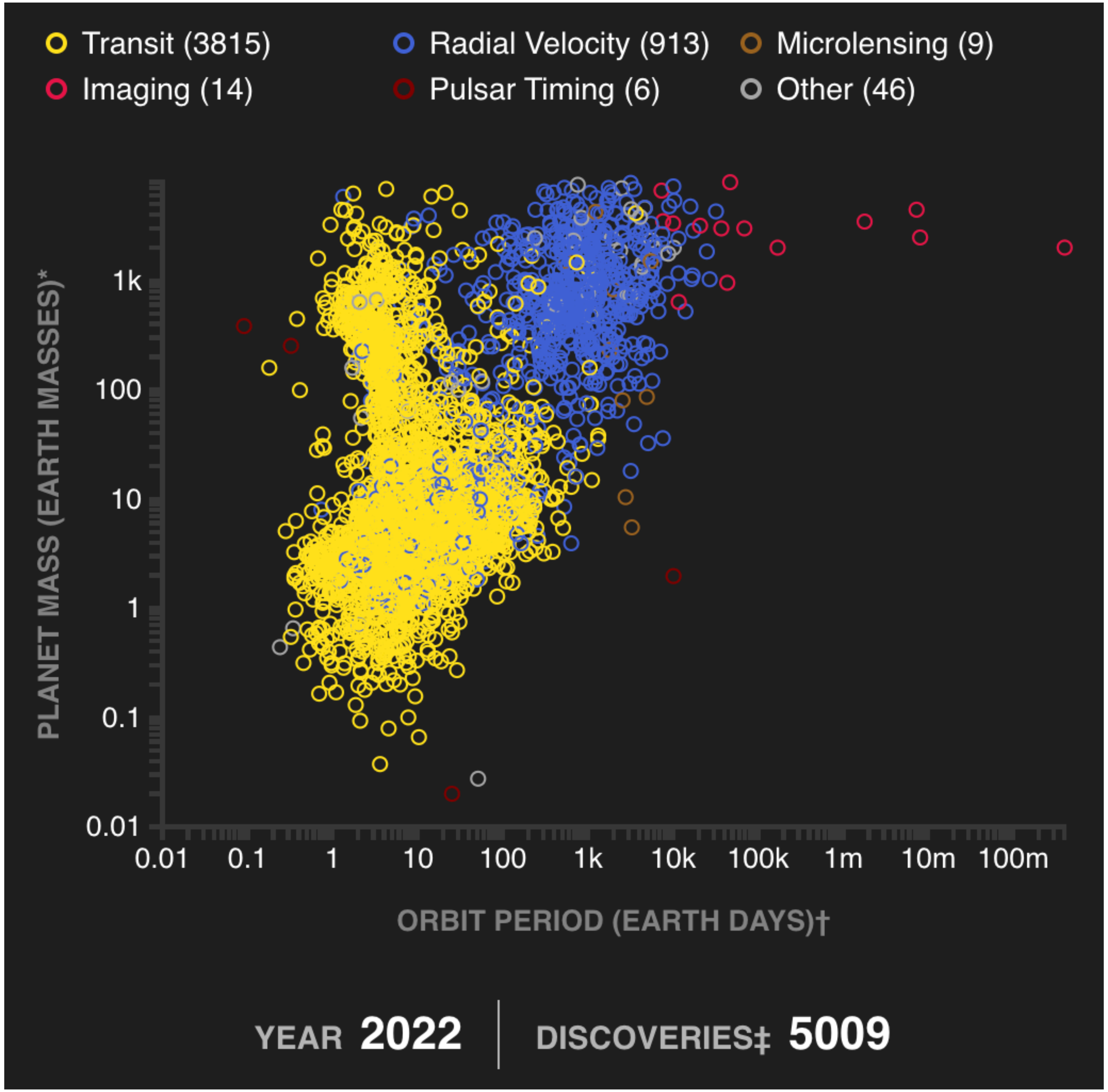
NARLabs 財團法人國家實驗研究院
NCHC 國家高速網路與計算中心
National Center for High-performance Computing

Cosmic Milestone: NASA Confirms 5,000 Exoplanets

March 21, 2022

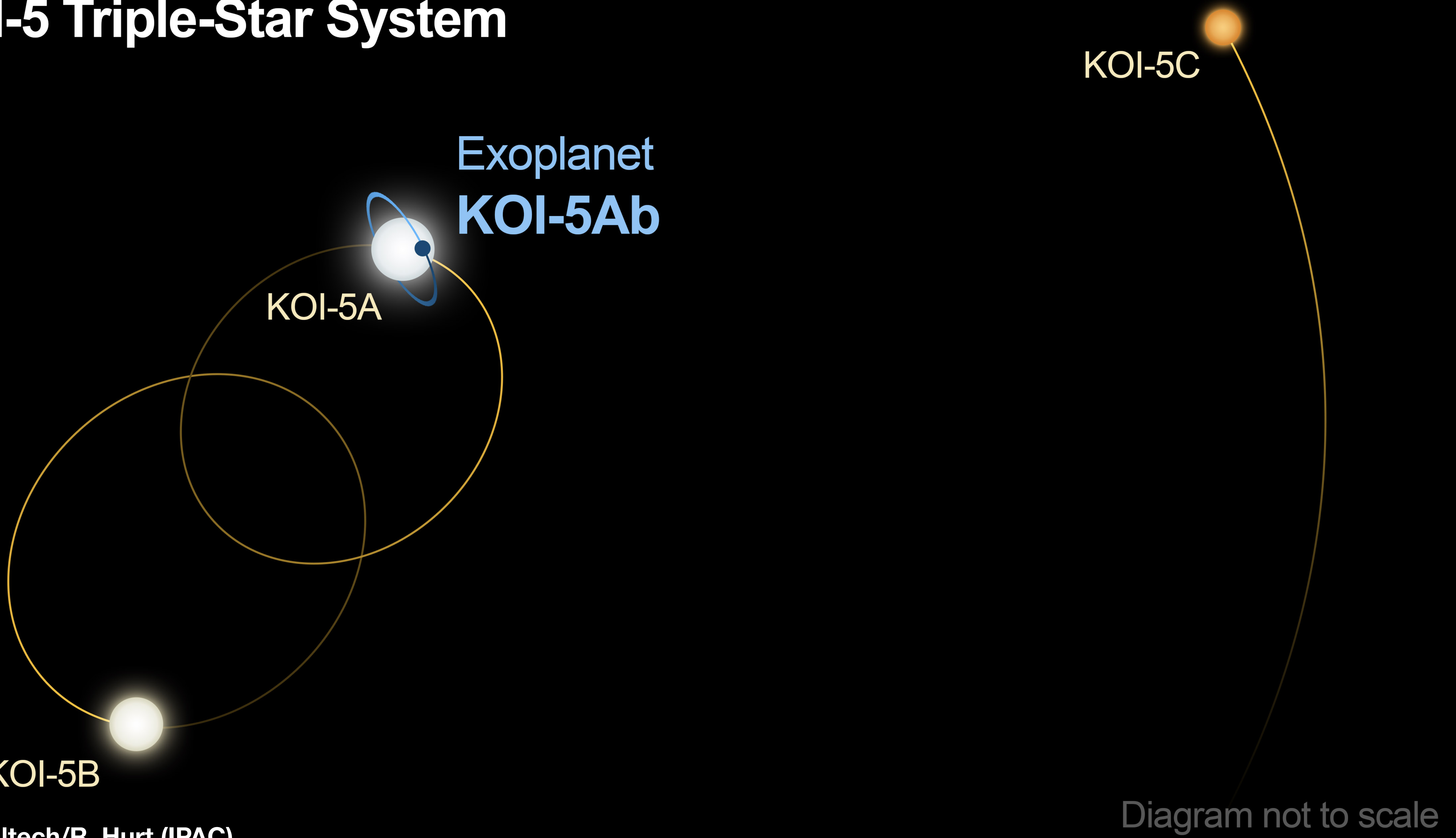


The era of exoplanet sciences



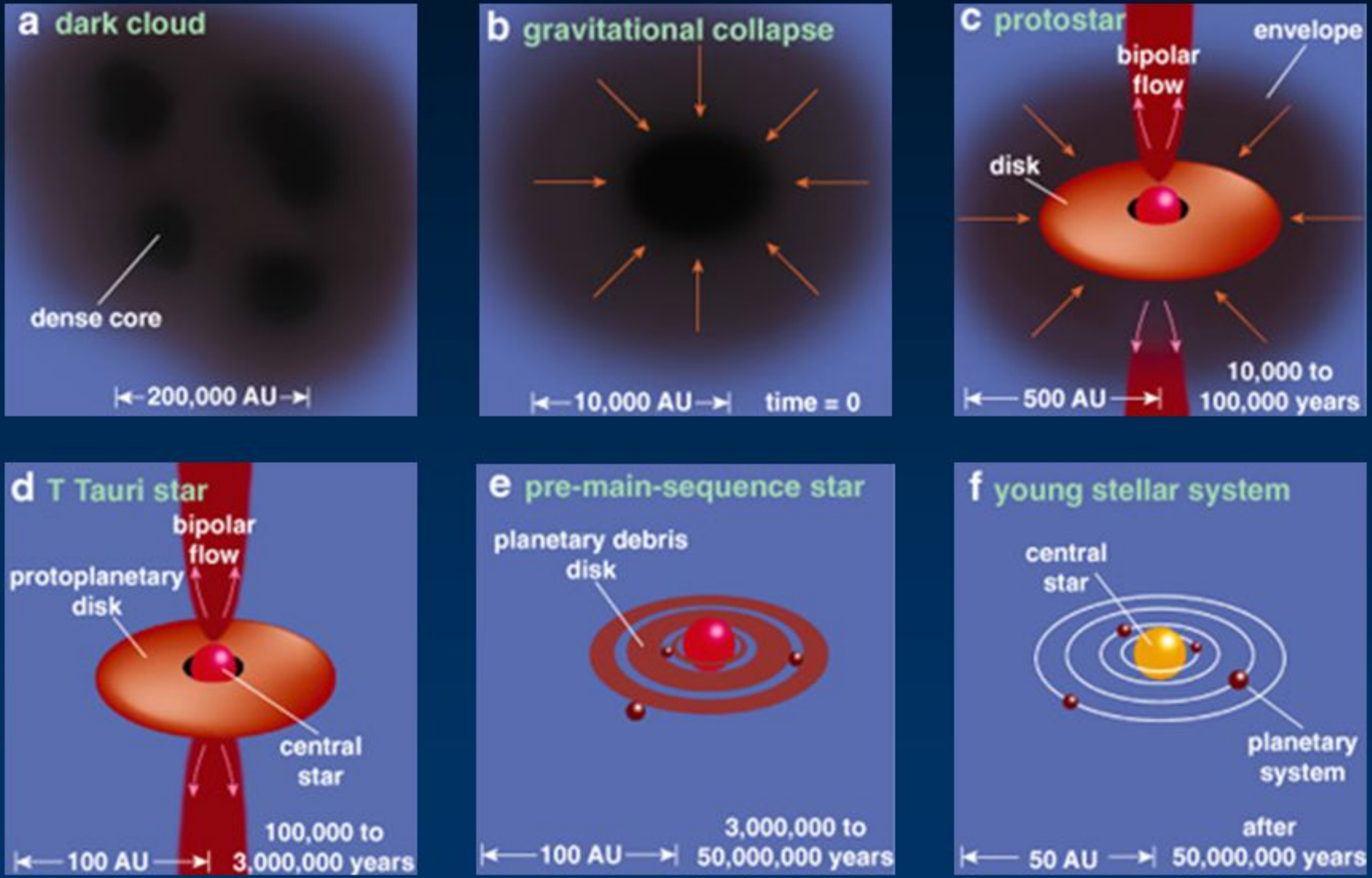
(Image credit: https://exoplanets.nasa.gov/)

KOI-5 Triple-Star System



Credits: Caltech/R. Hurt (IPAC)

Planets form in protoplanetary disks



M. Liu (IfA/Hawaii)

Real protoplanetary disks

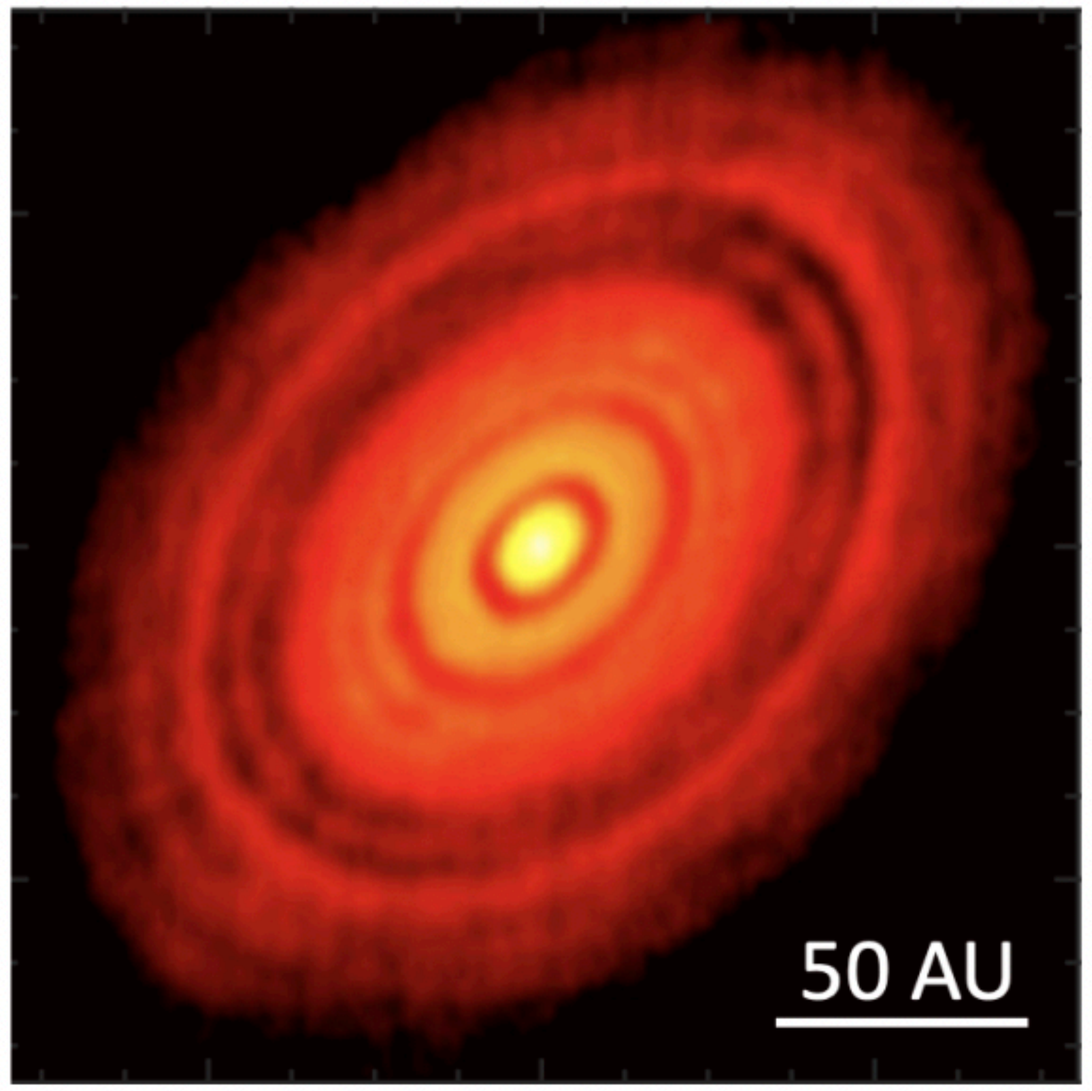
(Andrews et al, 2018; Long et al 2018)

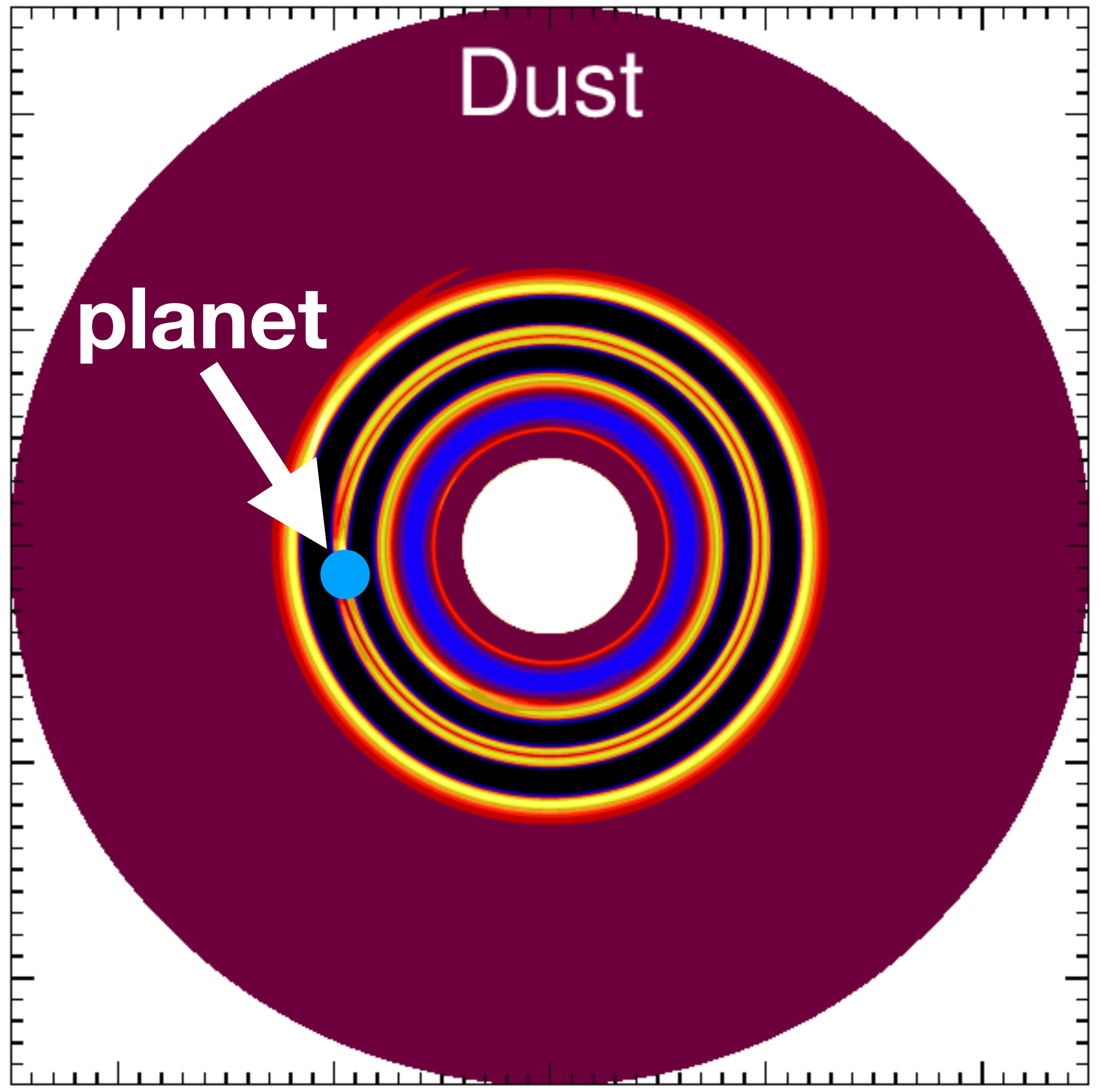
Rings and gaps: signposts of planet formation?

Disk-planet interpretation

HL Tau (ALMA Partnership et al. 2015)

Observations

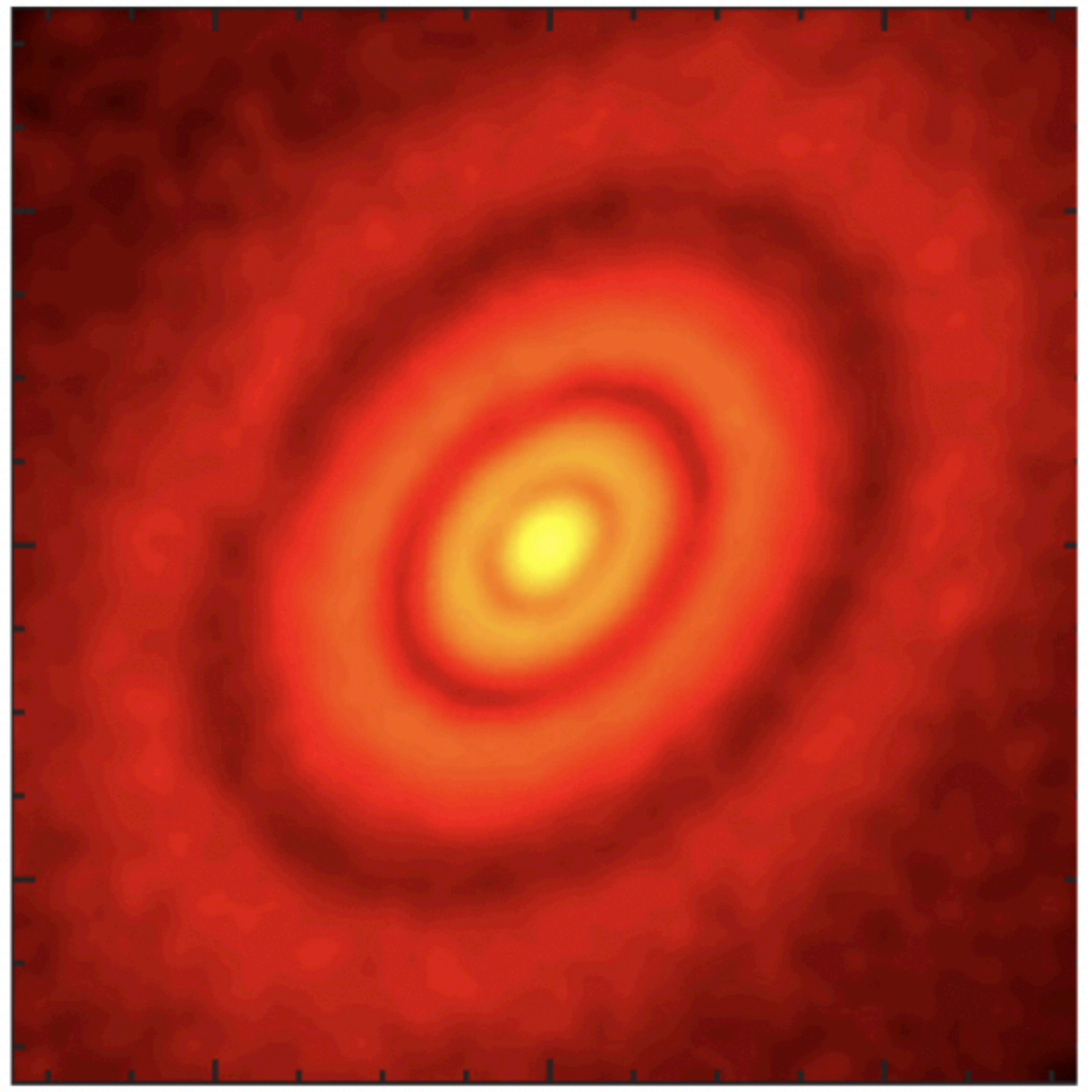




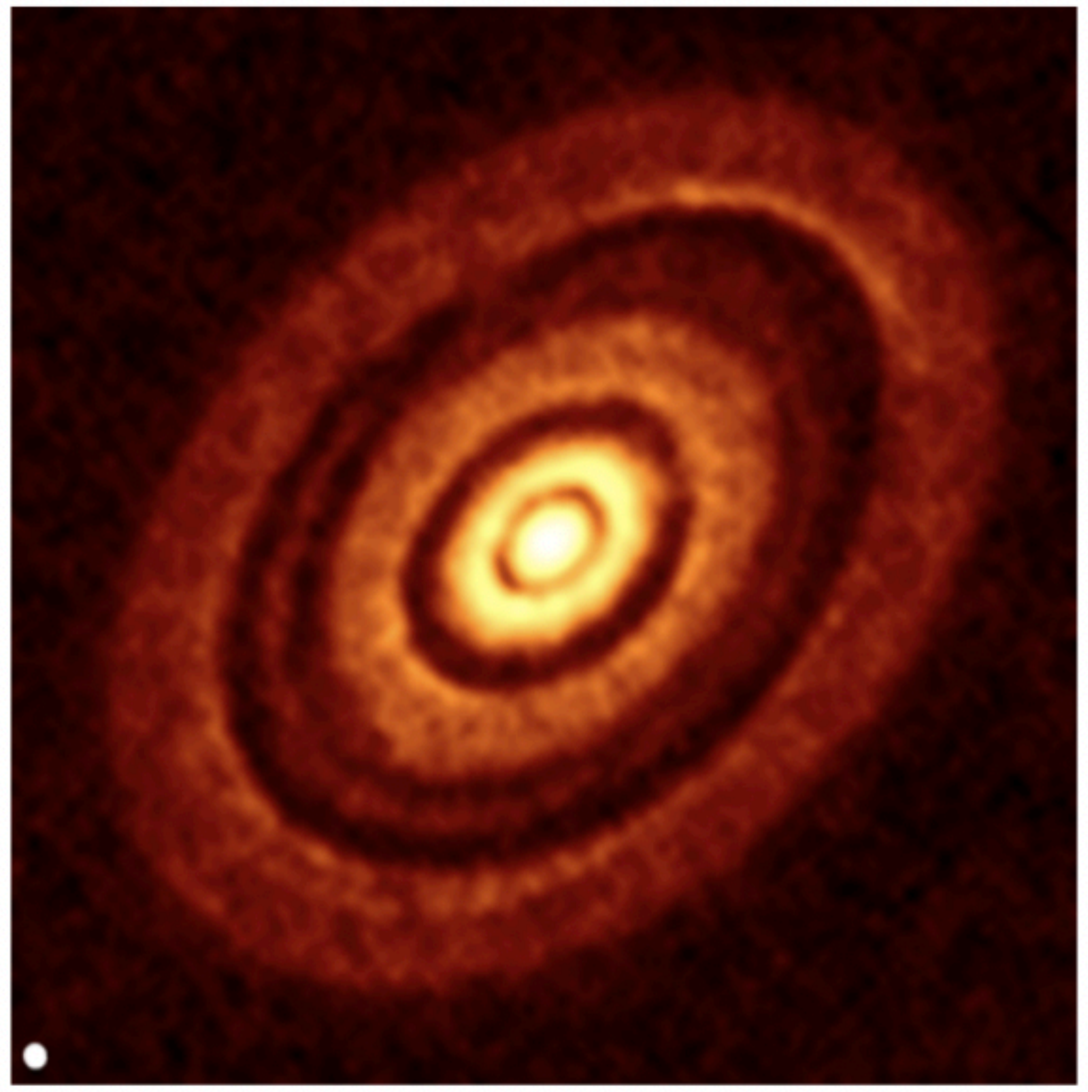
Computer simulation

(Chen & Lin, 2018)

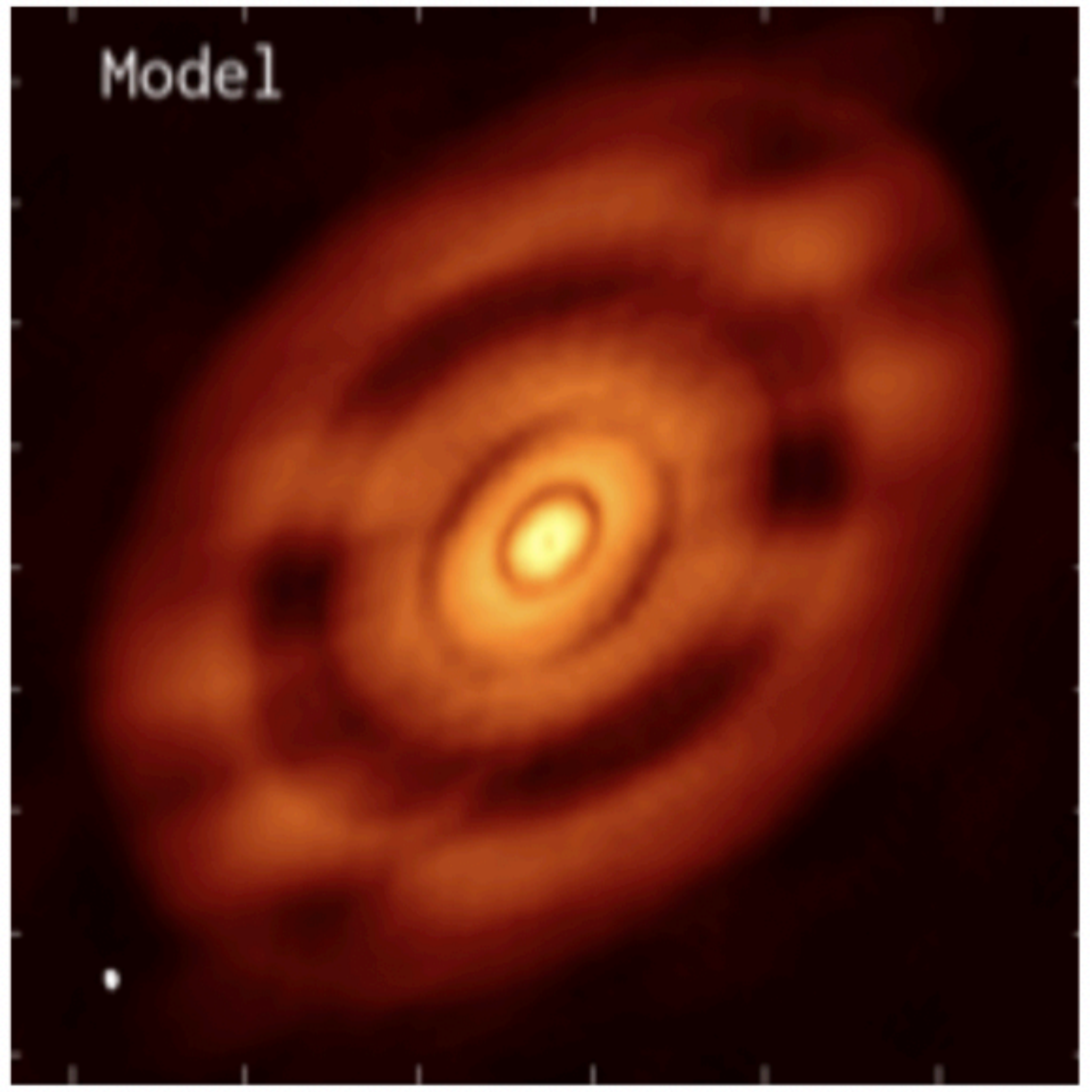
Simulation + synthetic obs.



Dong et al. 2015



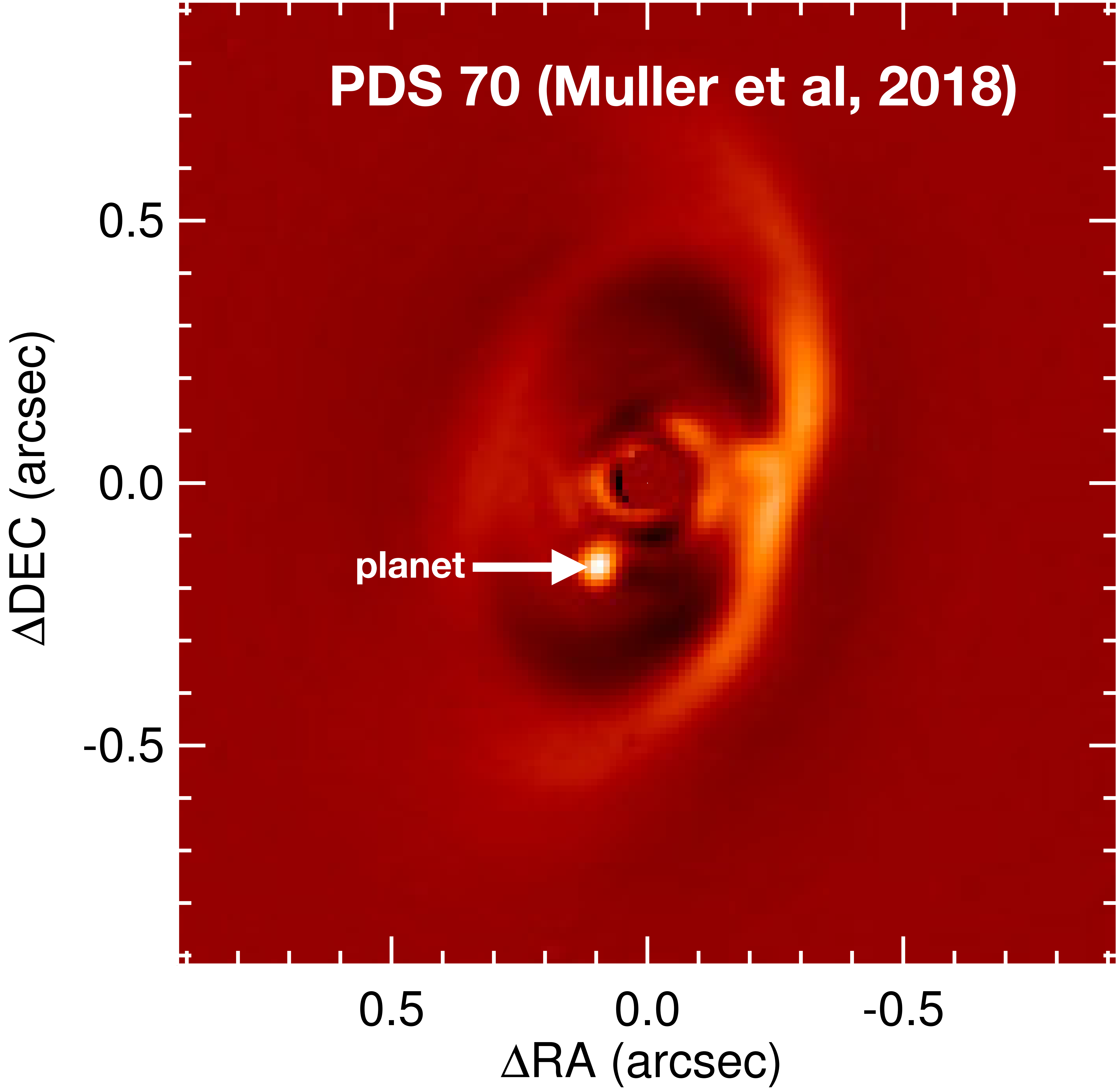
Dipierro et al. 2015



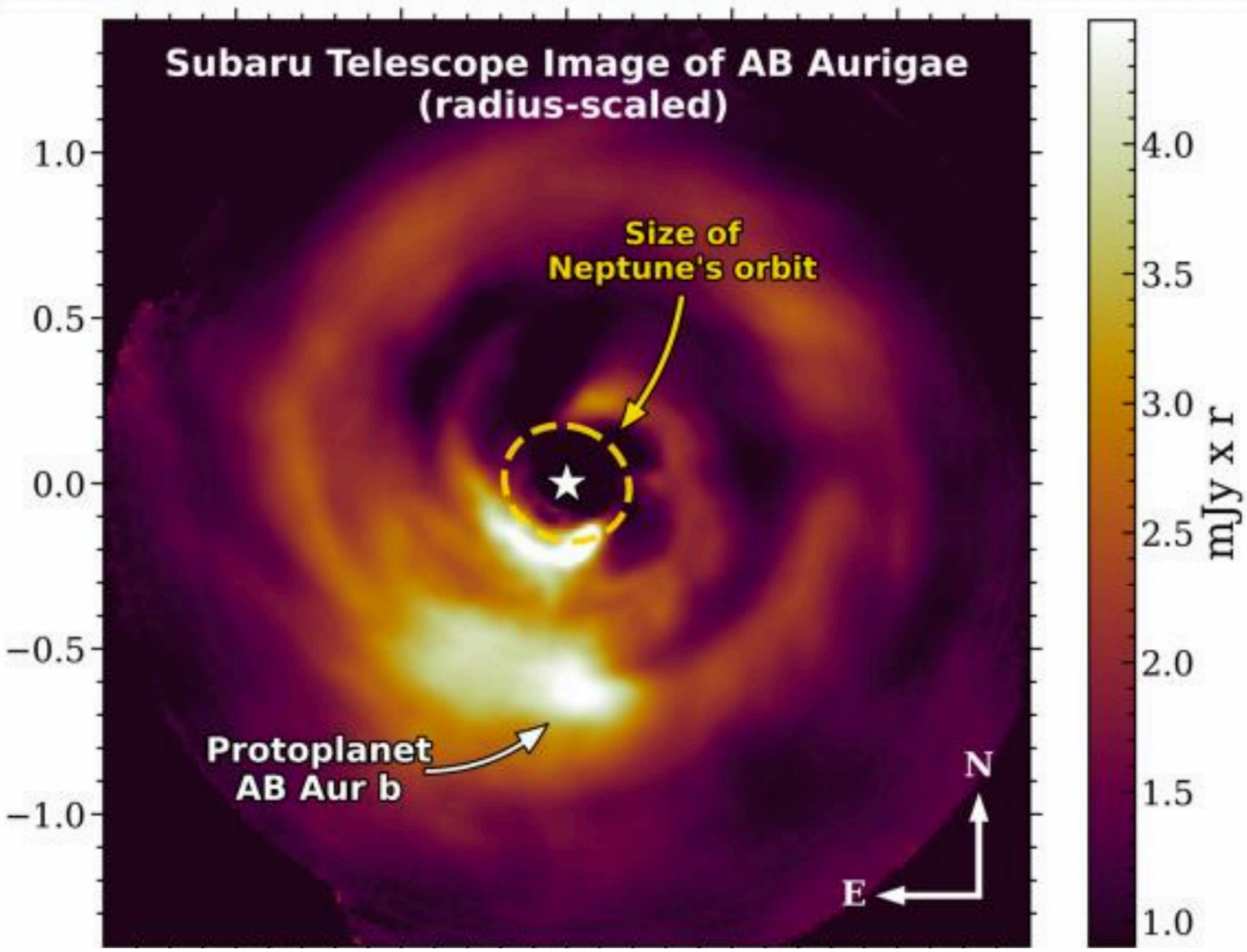
Jin et al. 2016

(Paardekooper et al., 2022, PPVII)

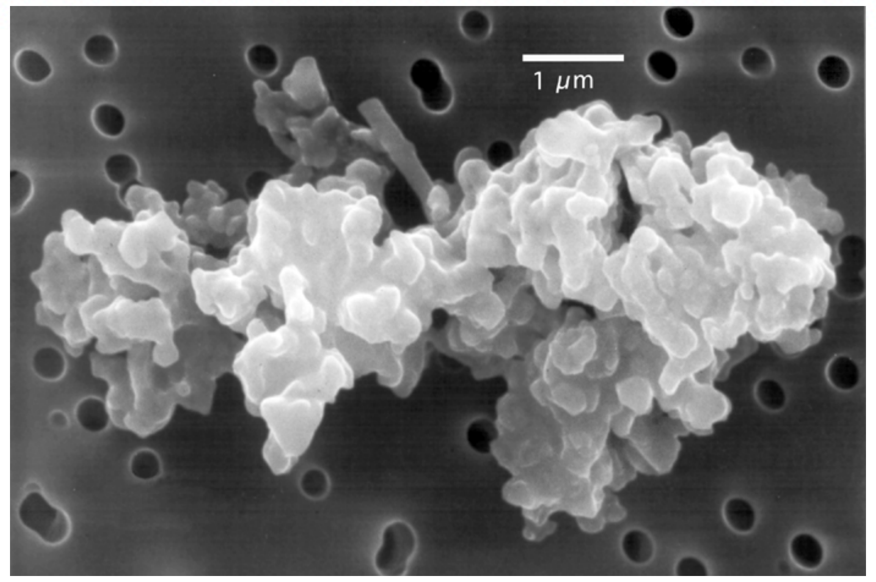
Observations of planets in a disk!



AB Aur (Currie et al, 2022)

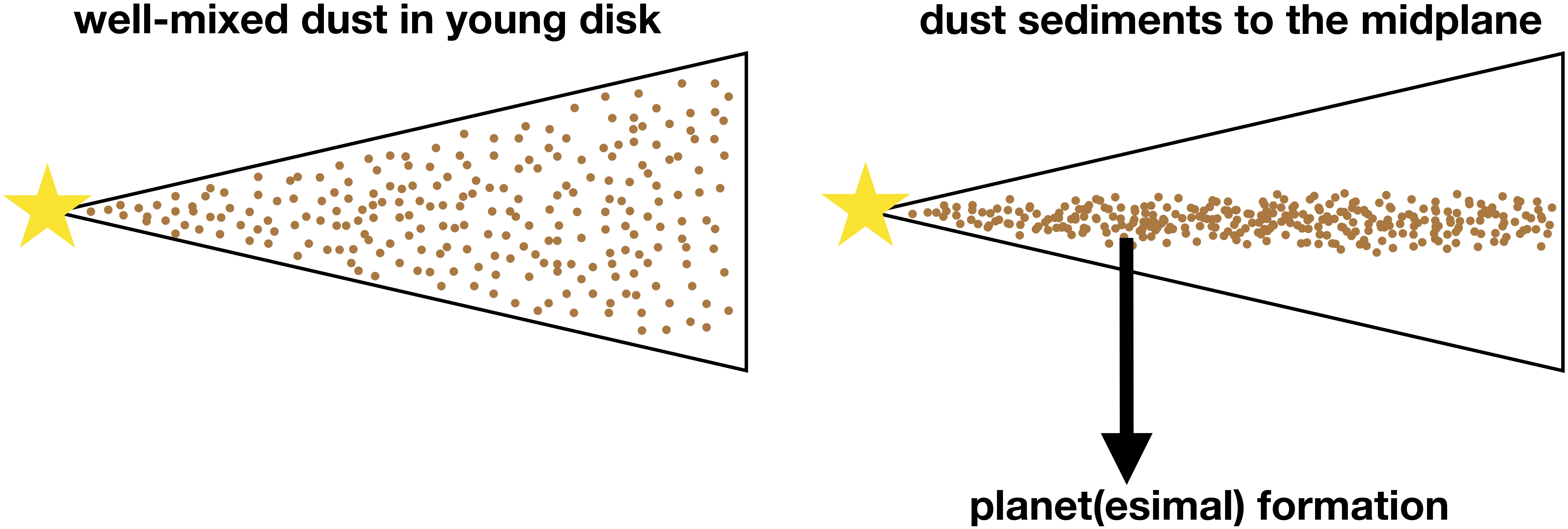


One planet, multiple scales



(Drazkowska et al., 2022, PPVII)

First: Dust settling



First: Dust settling

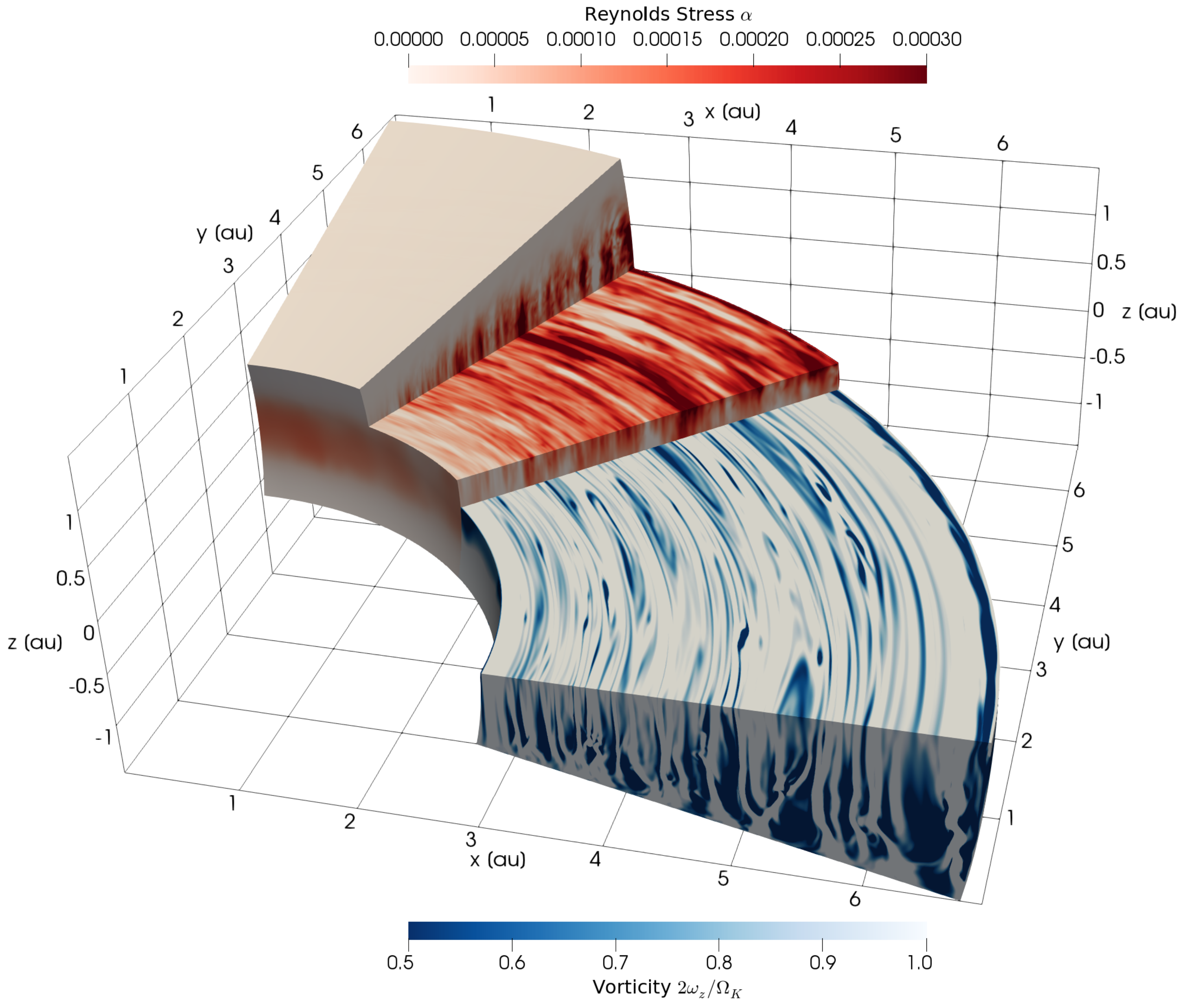
Oph 163131 (Villenave et al. 2022)

Dust settling requires a "quiet" disk

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

But PPDs are likely turbulent

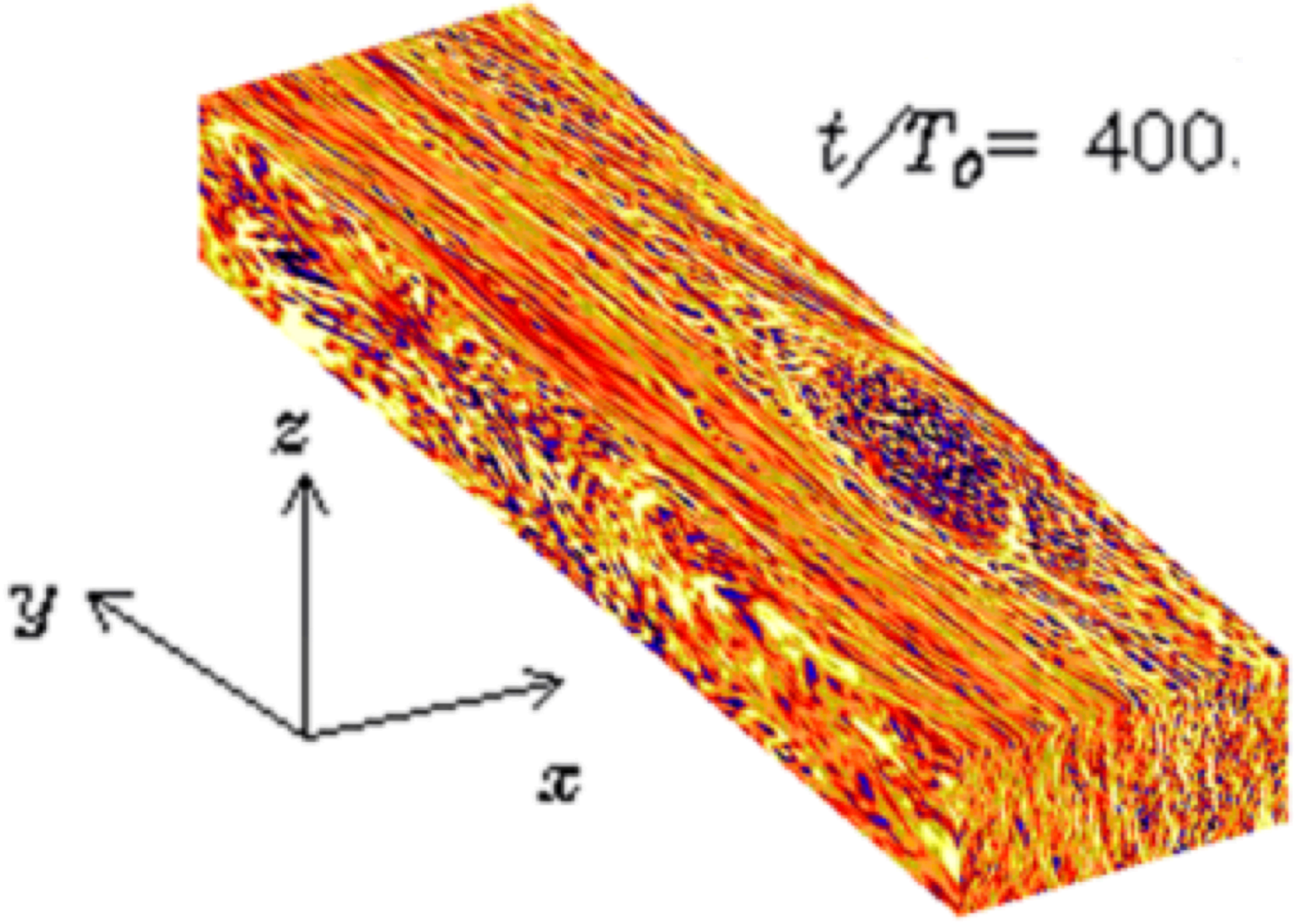
Vertical shear instability



Pfeil & Klahr (2020)

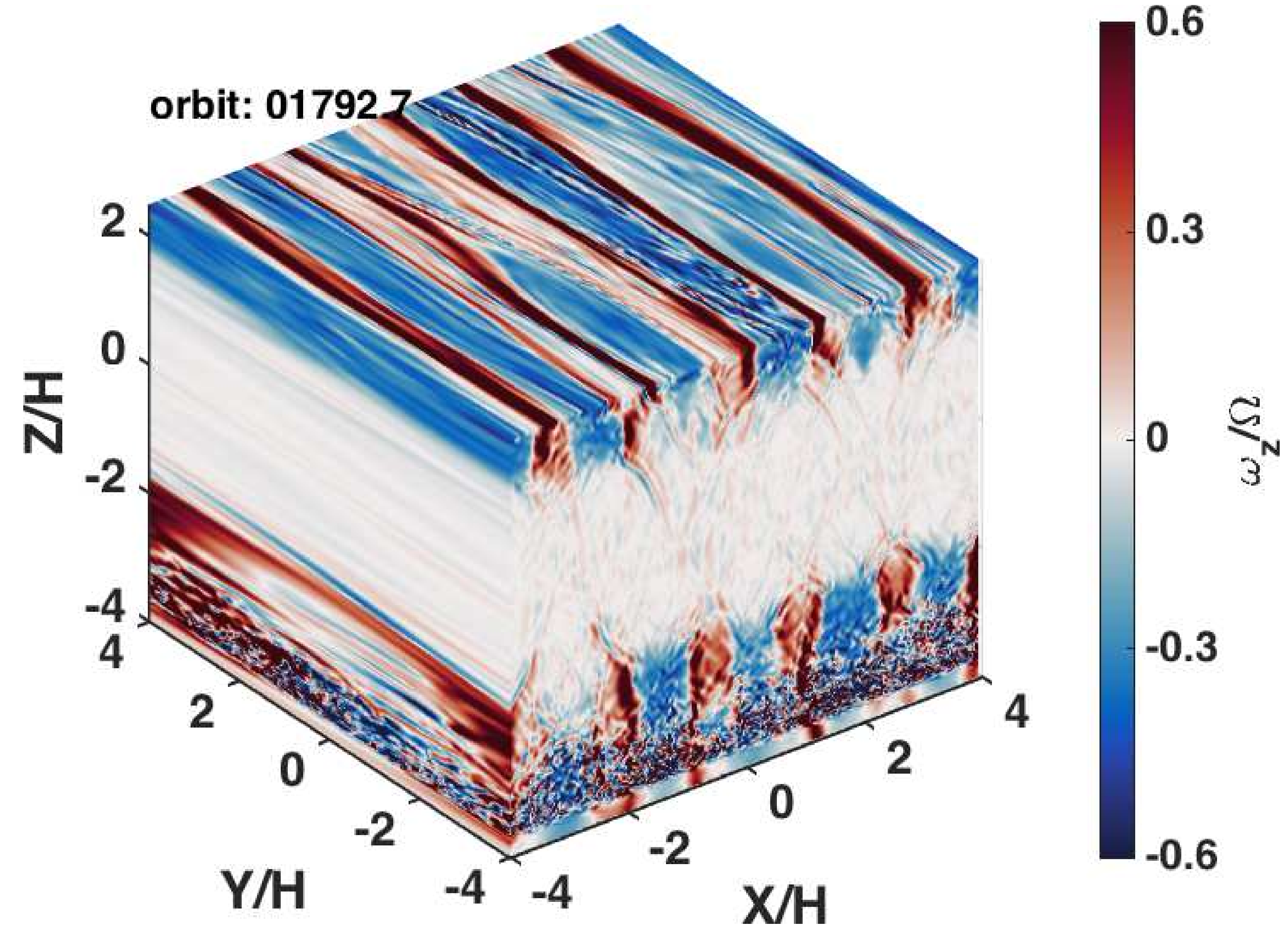
Lin & Youdin (2015)
Cui & Lin (2021)

Convective overstability



Lyra (2014)

Zombie vortex instability



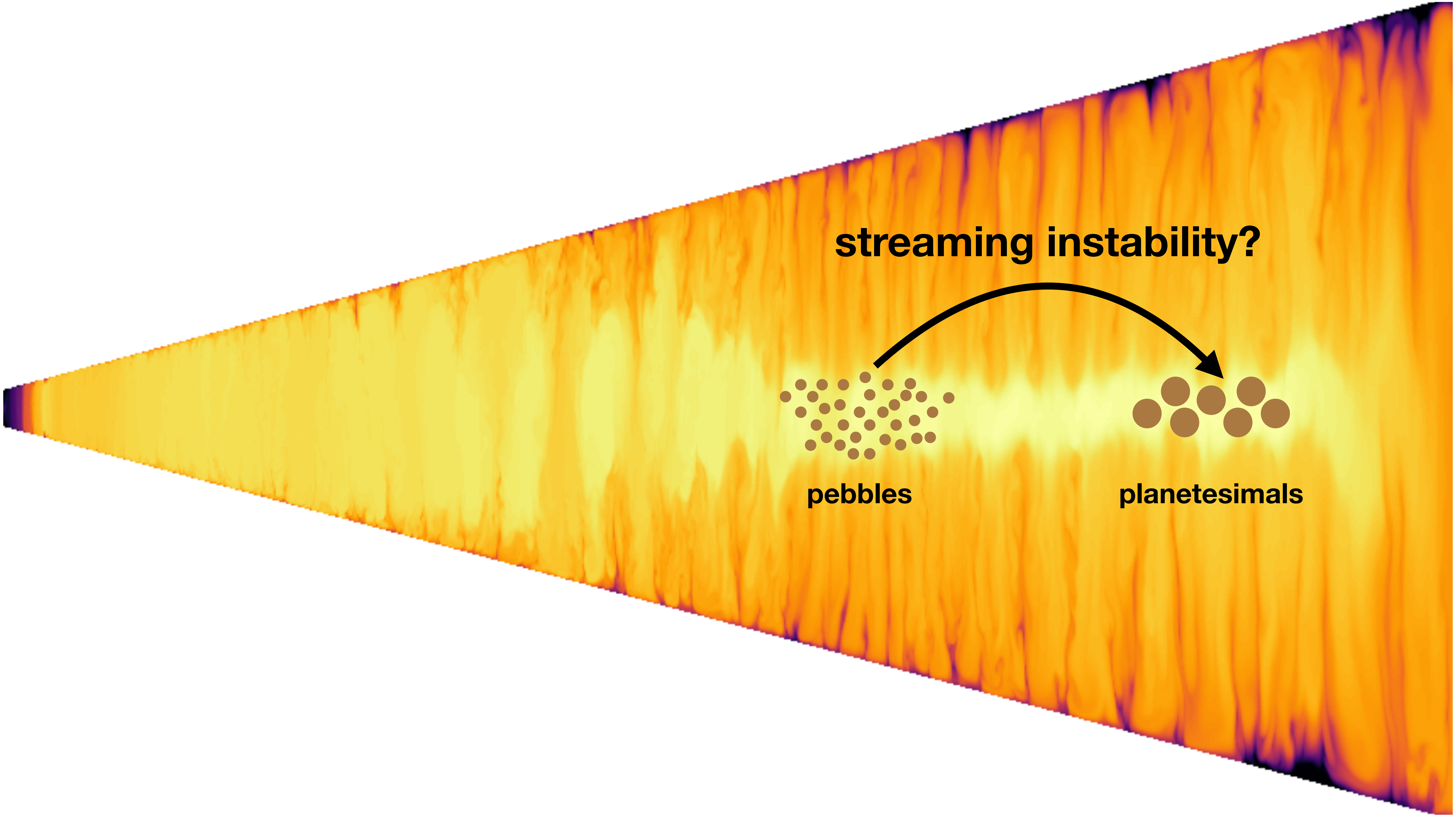
Barranco et al. (2018)

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

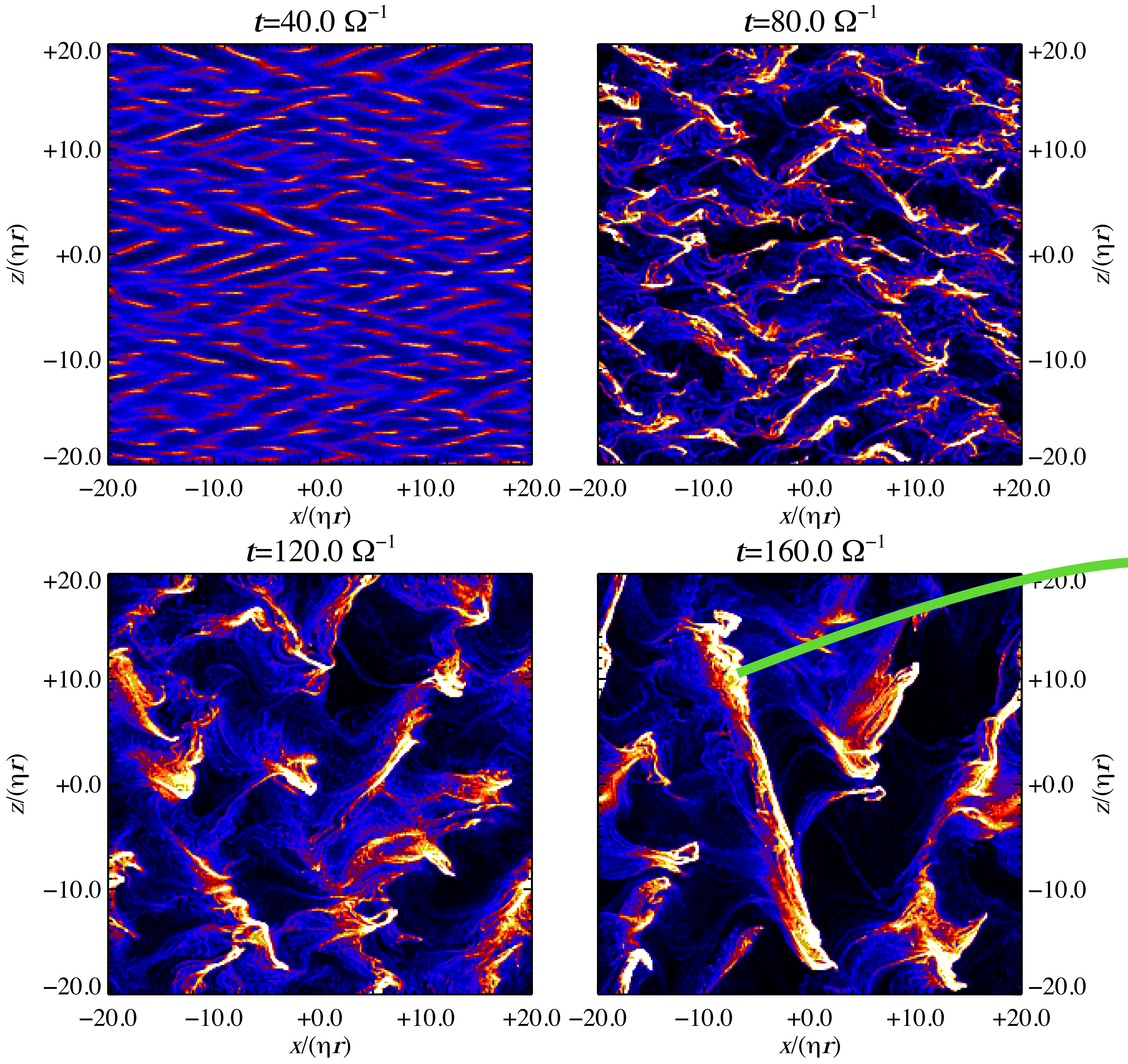
Dust settling vs VSI turbulence

Lin (2019); Lehmann & Lin (2022)

Next: Planetesimal formation



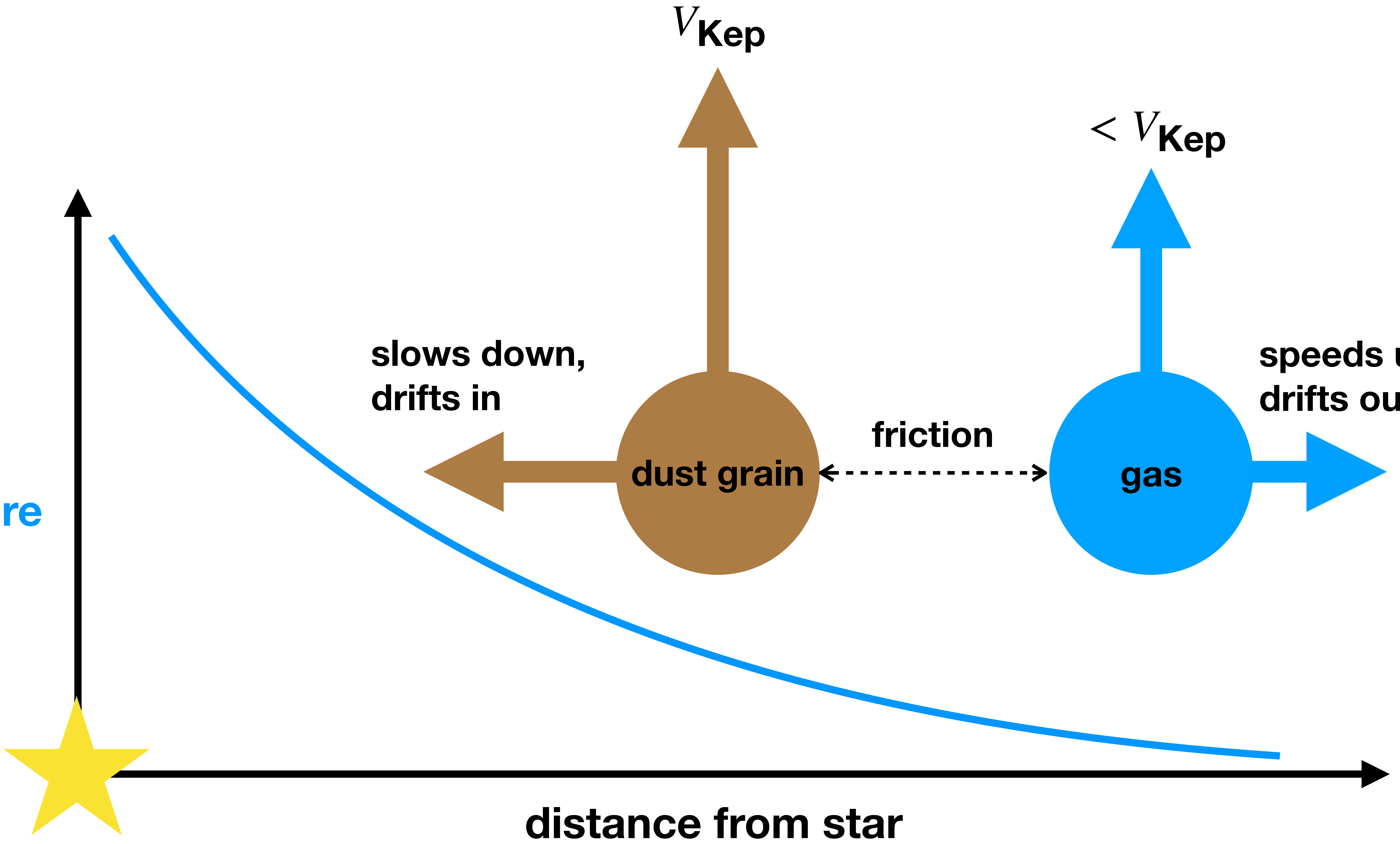
Relative motions between dust and gas drives instability



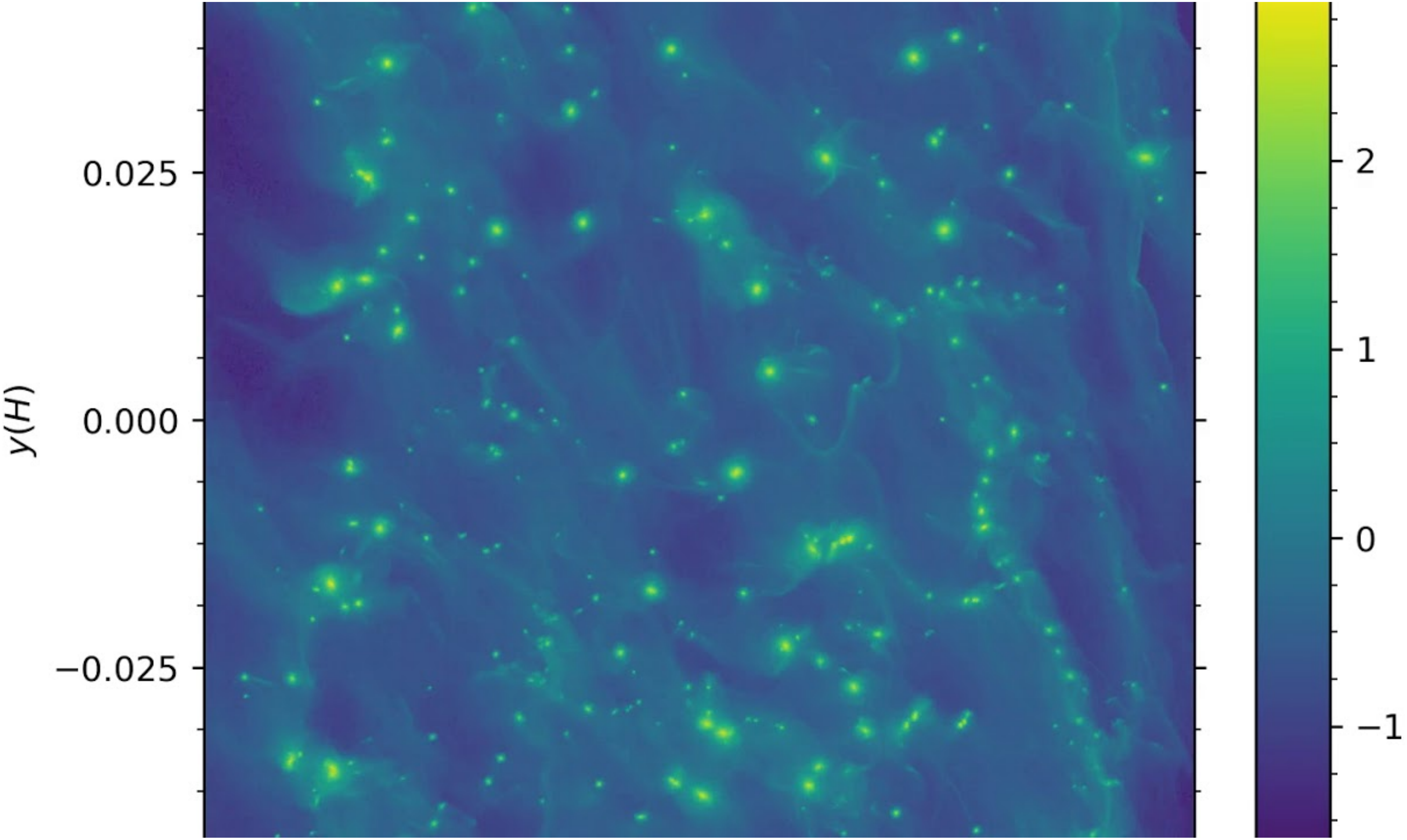
Dense dust clump may collapse into planetesimals

Johansen & Youdin (2007)

Radial drift of dust grains



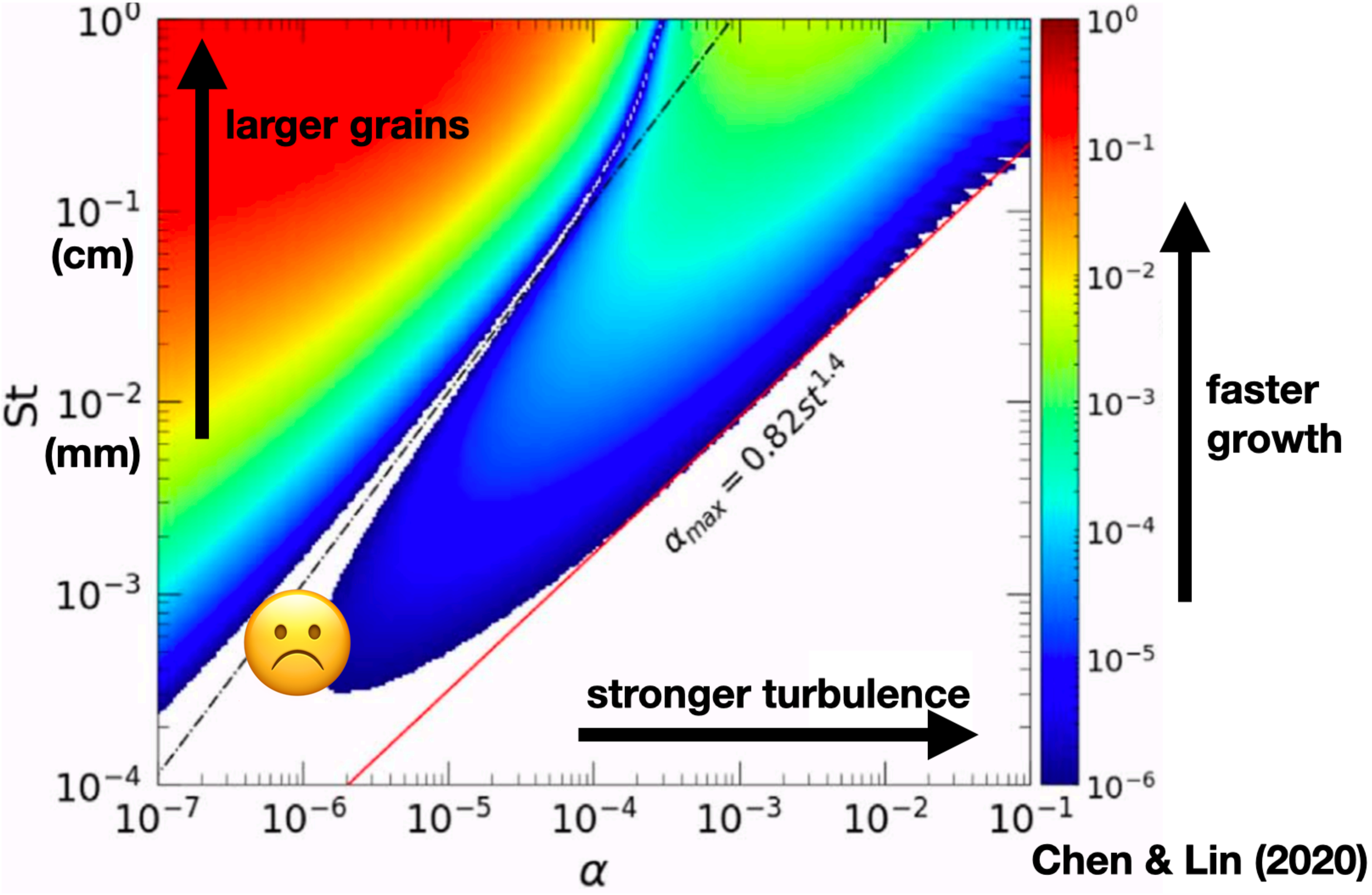
State-of-the-art simulations (Nesvorný et al., 2020)



Streaming instability theory: Assumptions

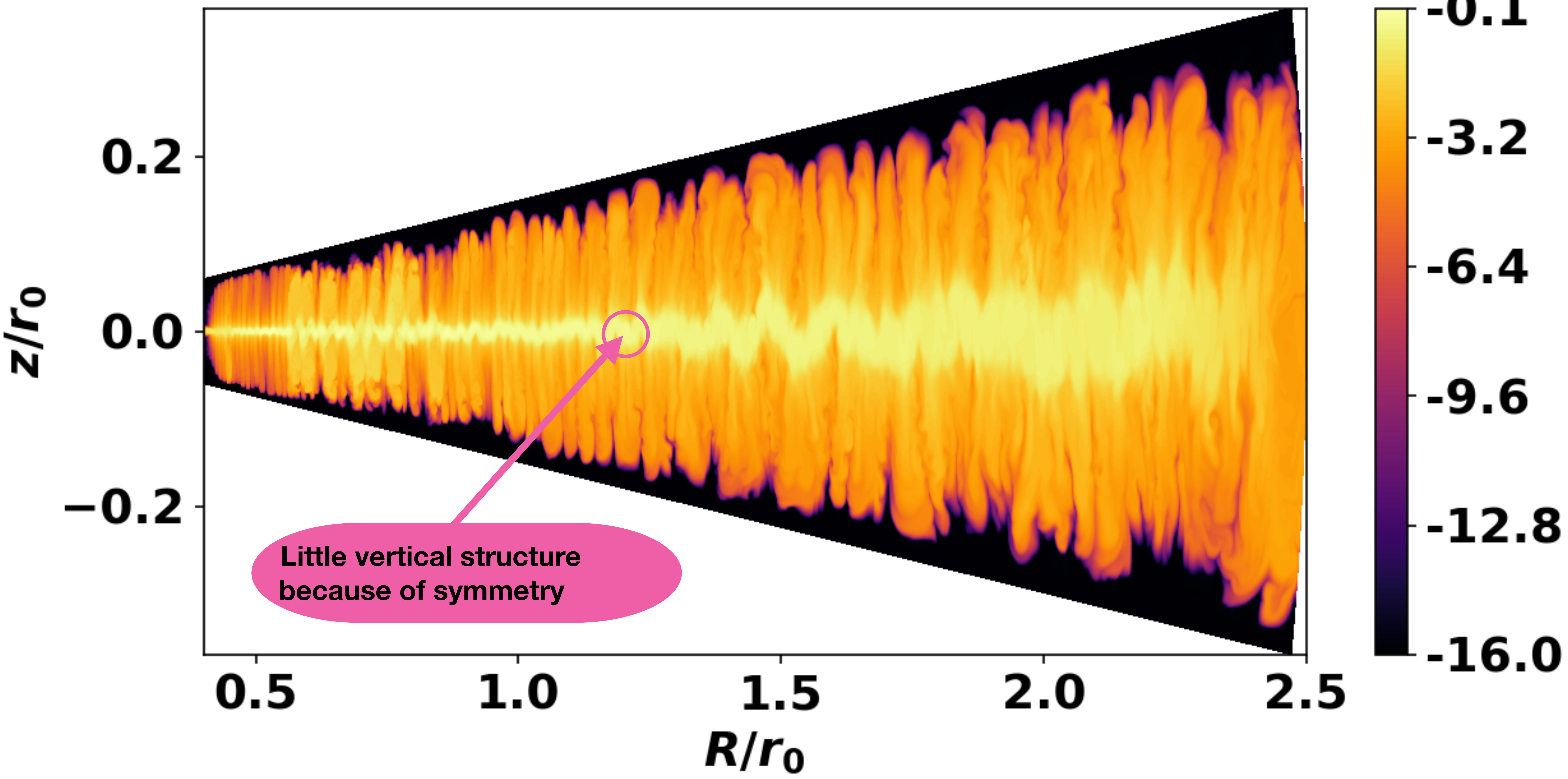
- disk is non-turbulent → Chen & Lin (2020)
- disk has no vertical structure → Lin (2021)
- disk is unmagnetized → Lin & Hsu (2022)

Streaming instability is easily killed by turbulence

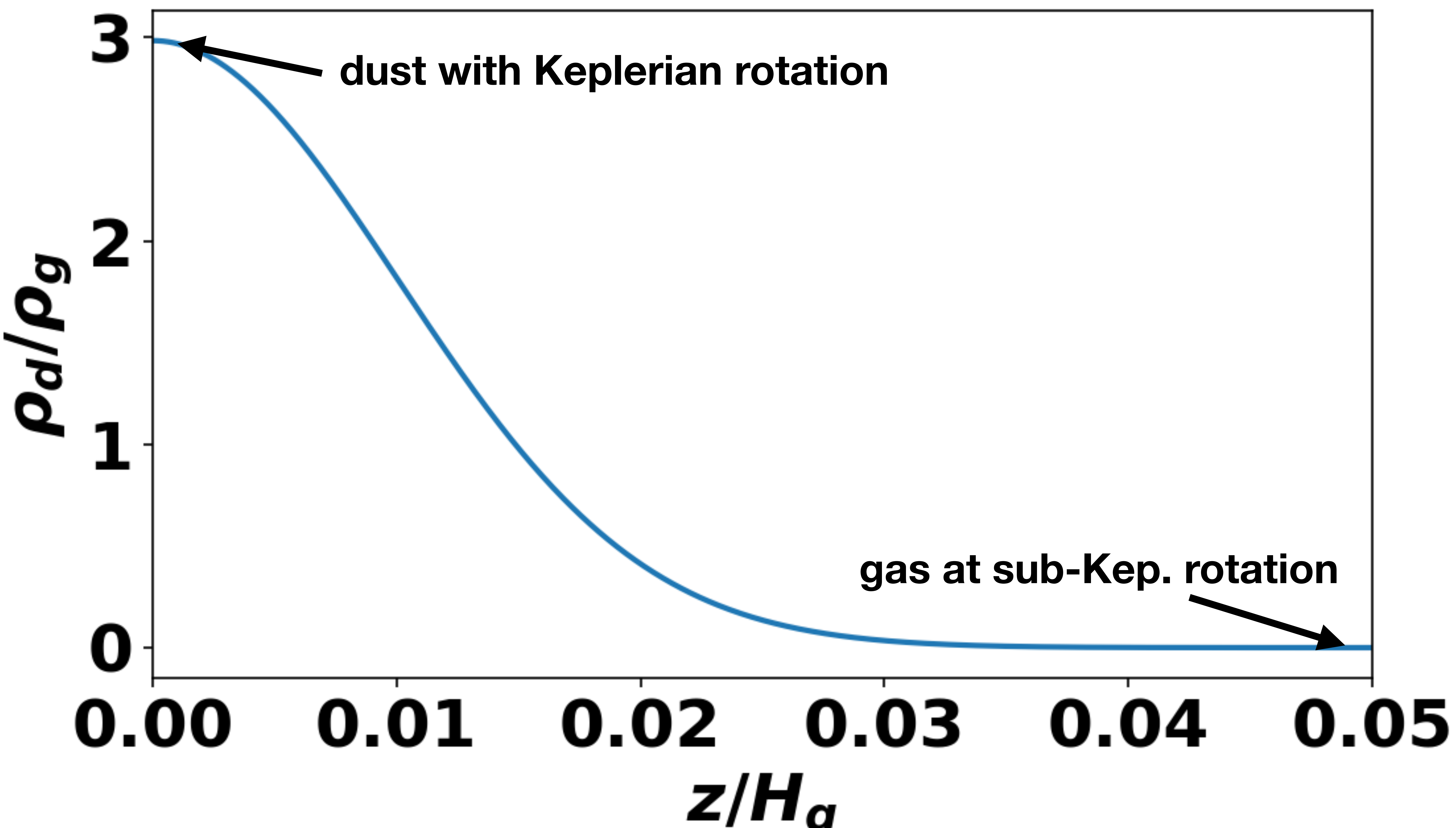


Chen & Lin (2020)

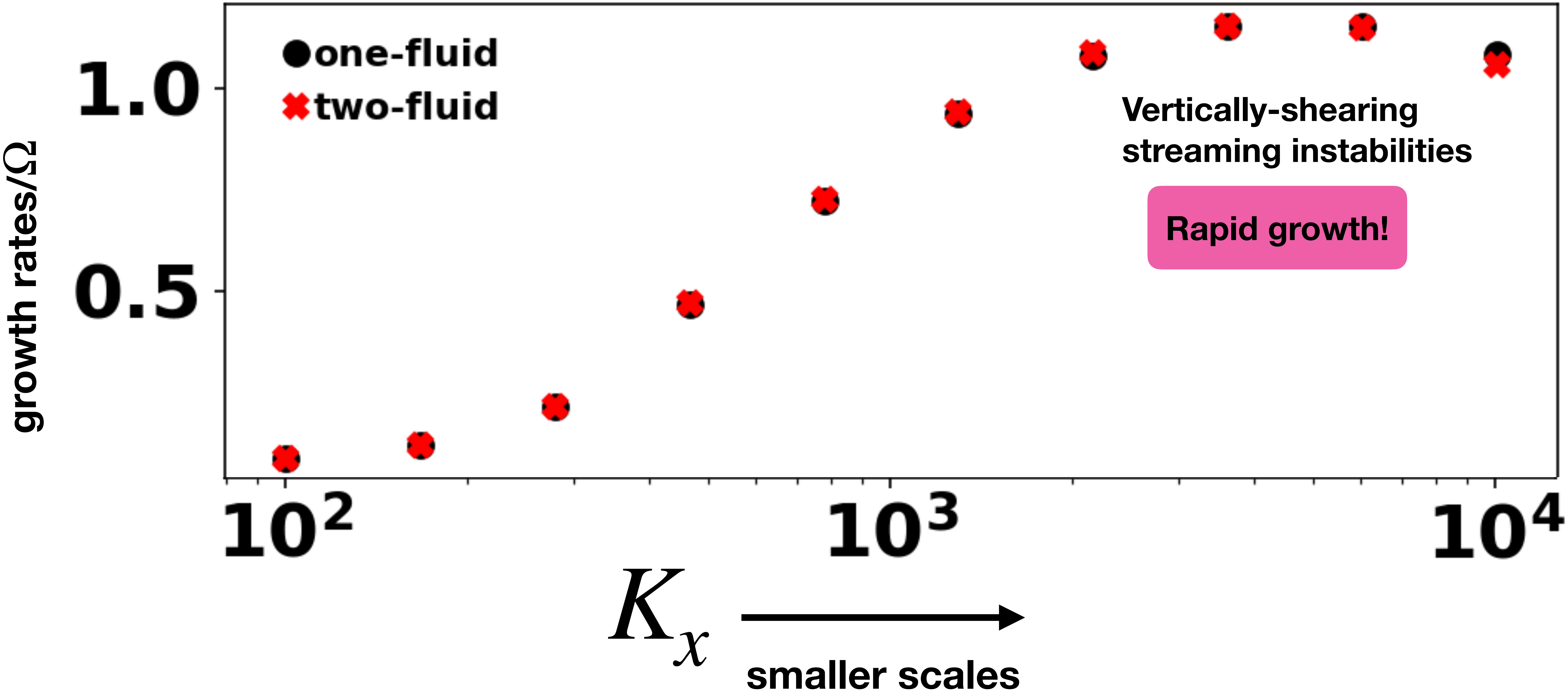
Unstratified models for midplane dynamics



Real dust layers have vertical structure

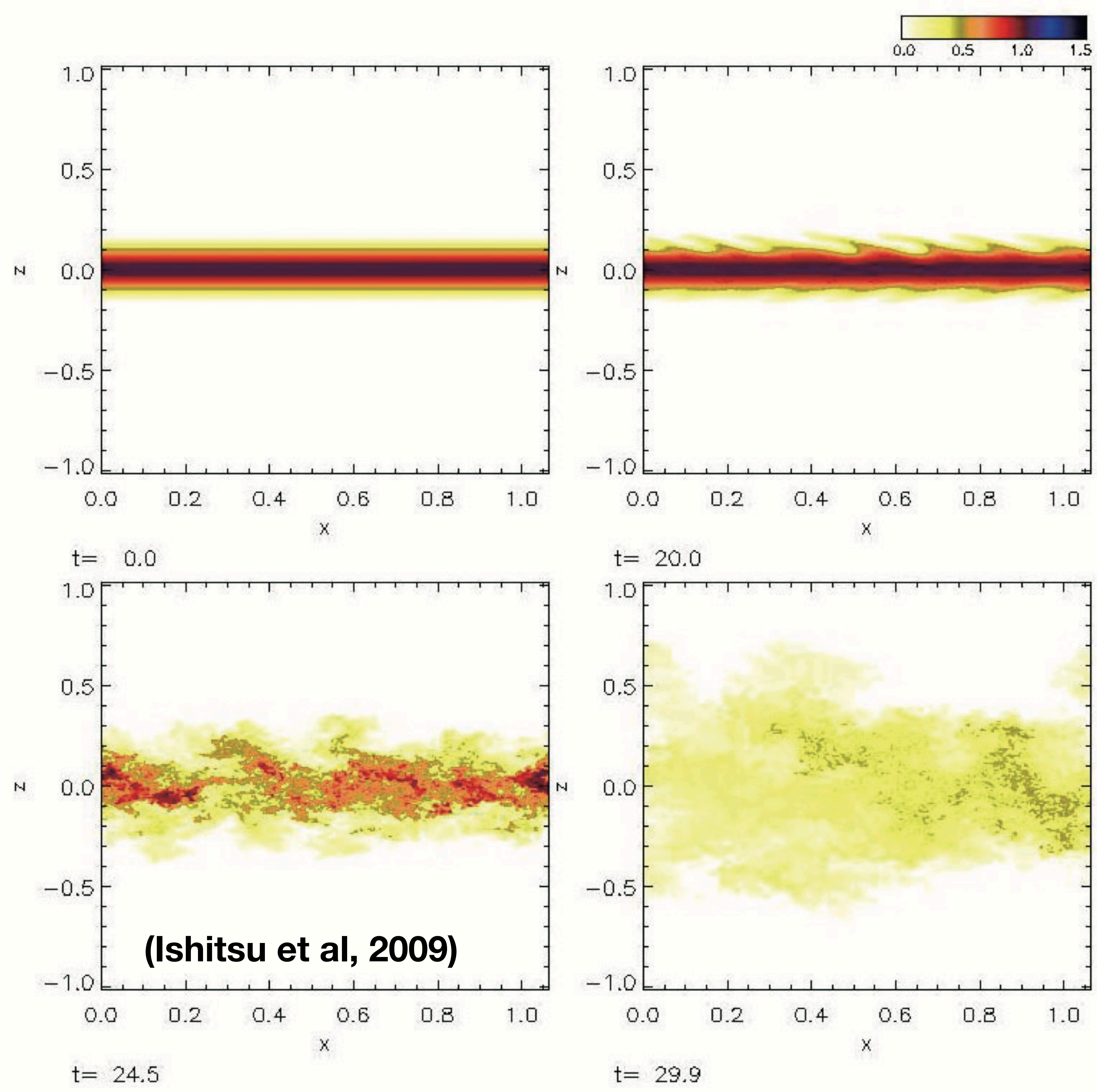


A new instability in stratified dust layers



Lin (2021)

Vertically shearing SIs grow fast but…

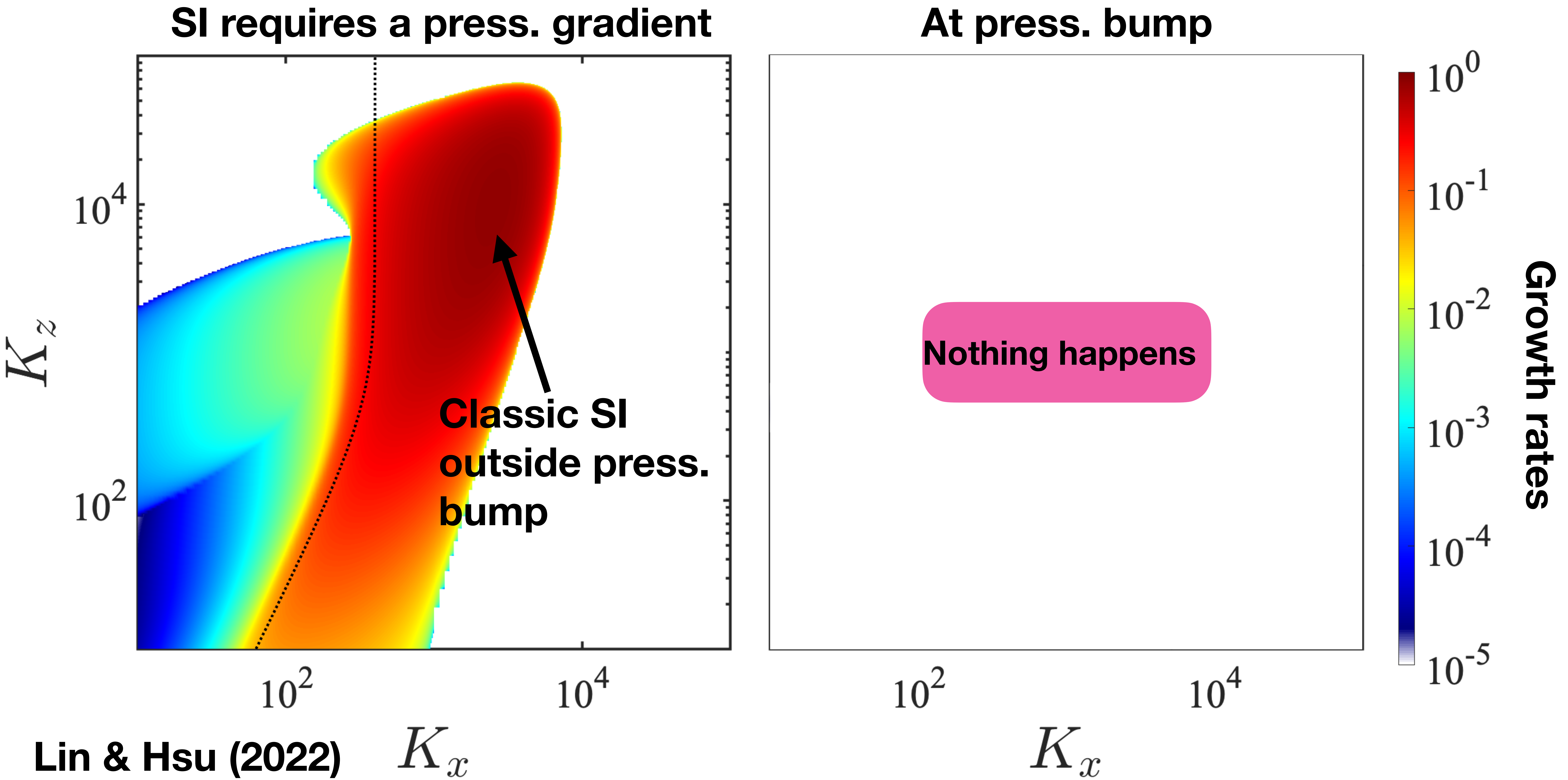


dust layer dispersed

Can modern disk models help?

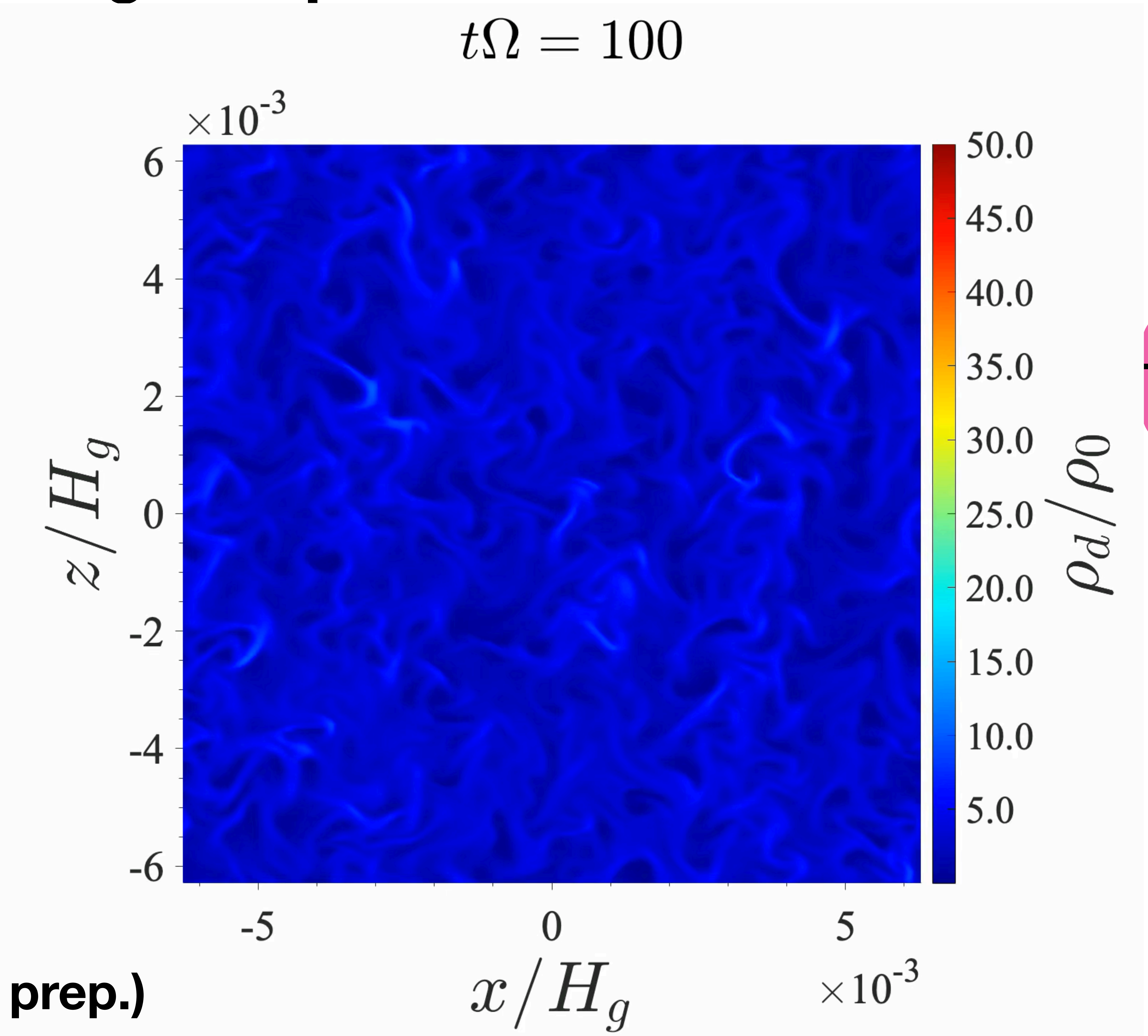
(e.g. Riols et al. 2020, Cui & Bai 2021)

SI in accreting bumps: Linear theory



Lin & Hsu (2022)

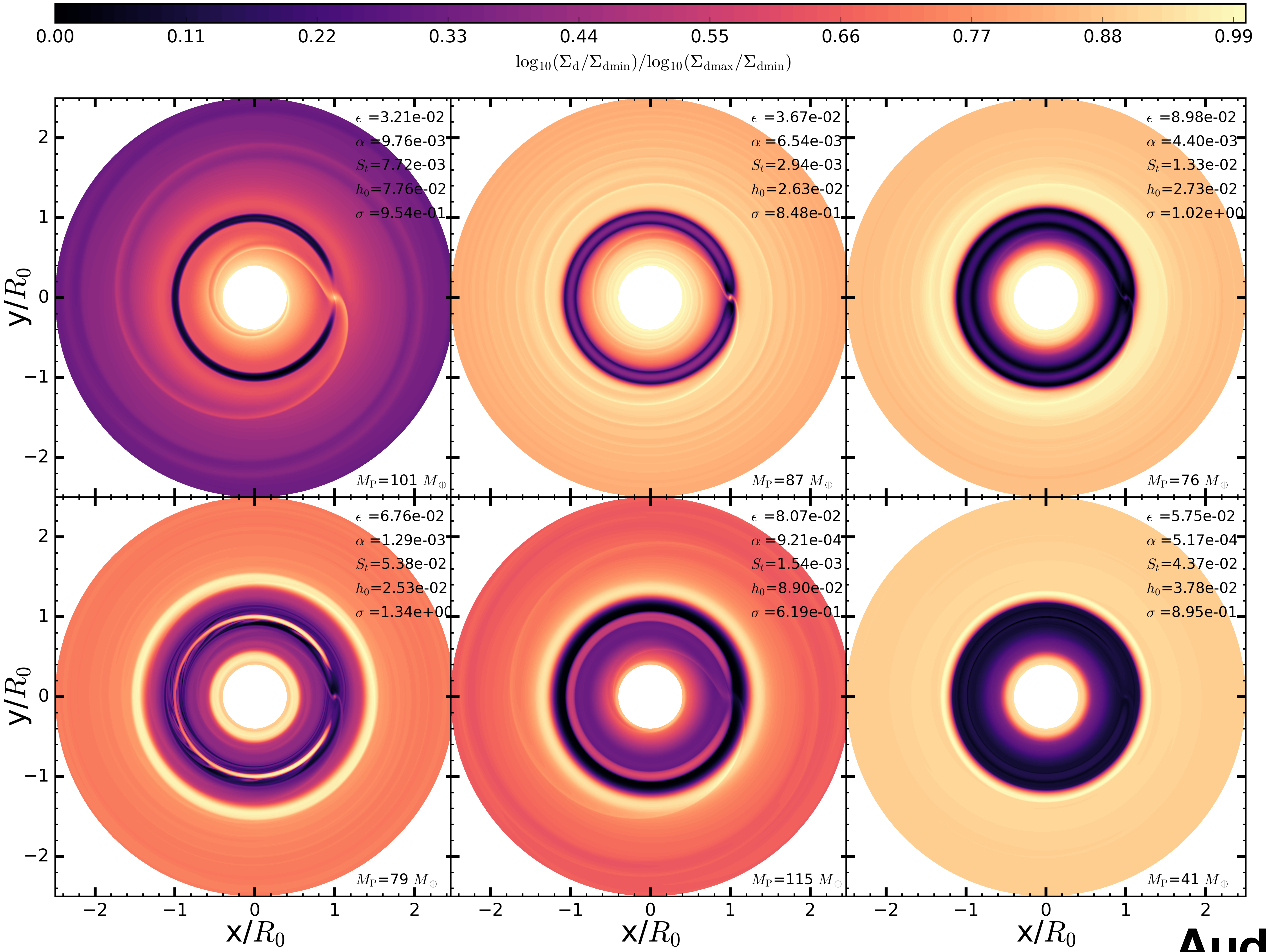
SI in accreting bumps: Nonlinear evolution



Turbulence or clumping? 🤔

Hsu & Lin (in prep.)

Planets form somehow, so what's next?

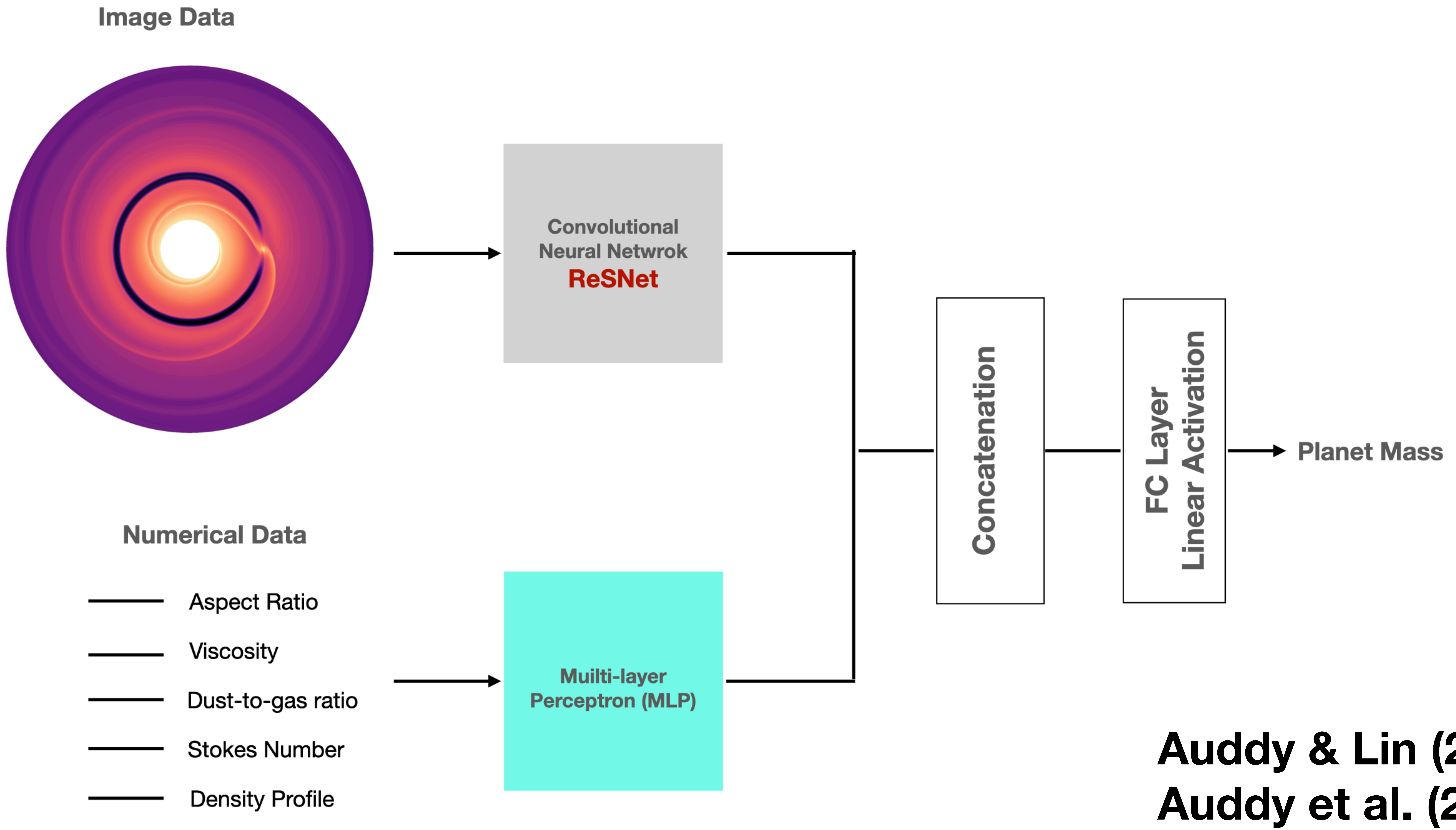


Auddy & Lin (2020)

But each observation require many simulations

Can we automate this process?

Modeling planet gaps with artificial/convolutional NN



Auddy & Lin (2020)
Auddy et al. (2021)
Auddy et al., submm.

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)

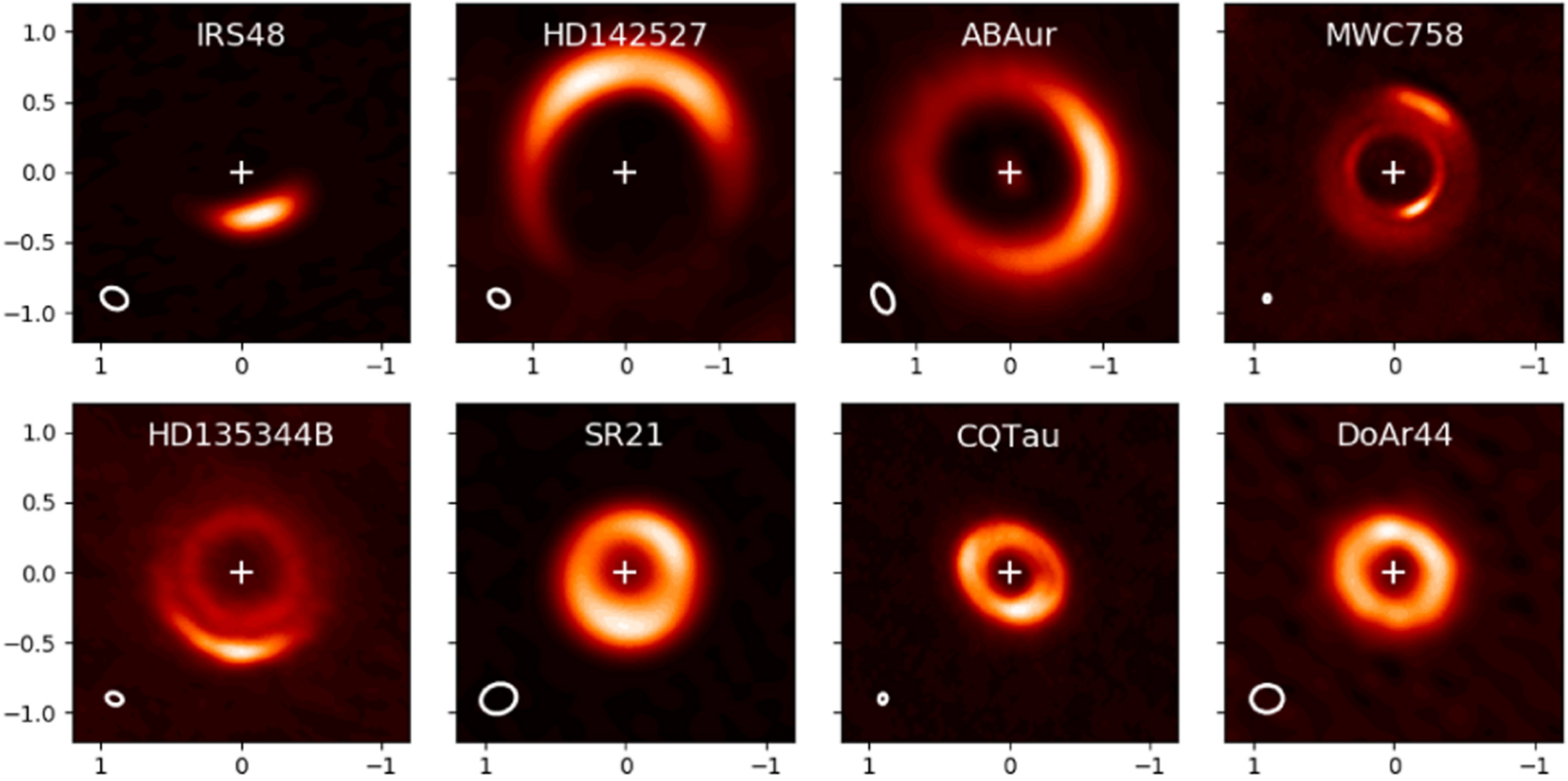
$$M_p = 0.24 M_J, 0.21 M_J, 0.2 M_J$$

Simulation caveats

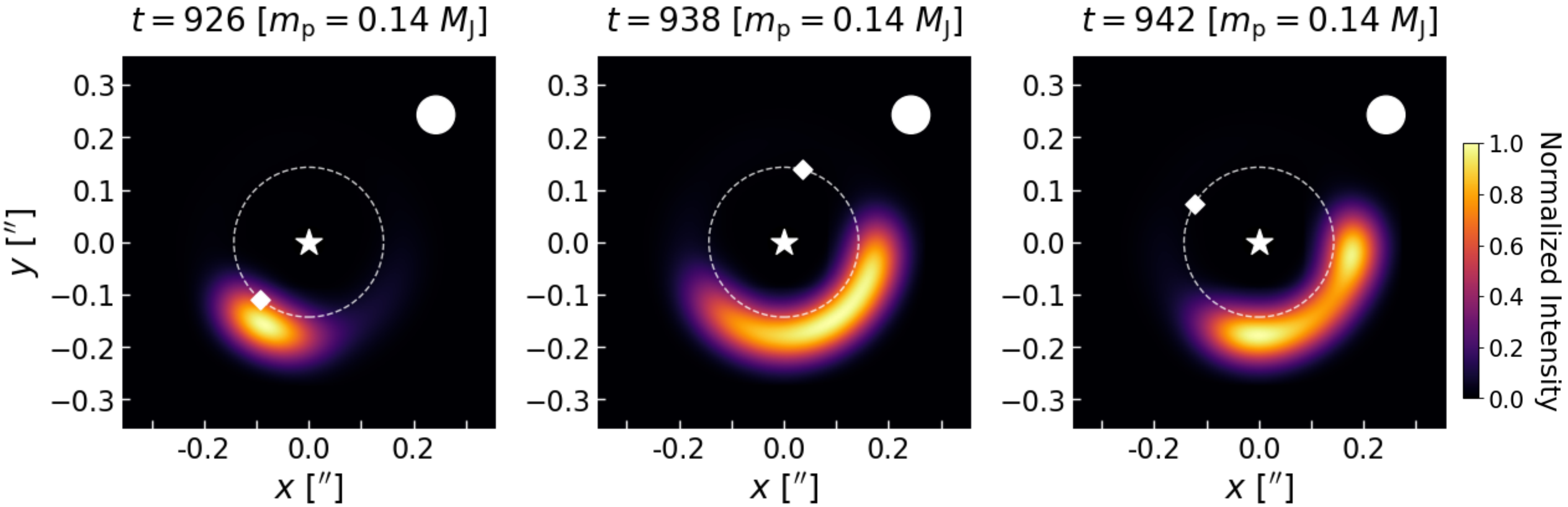
- Focus on axisymmetric structures
- Planet on fixed orbits
- 2D disk

Some observed disks are asymmetric

(van de Marel, et al. 2021)



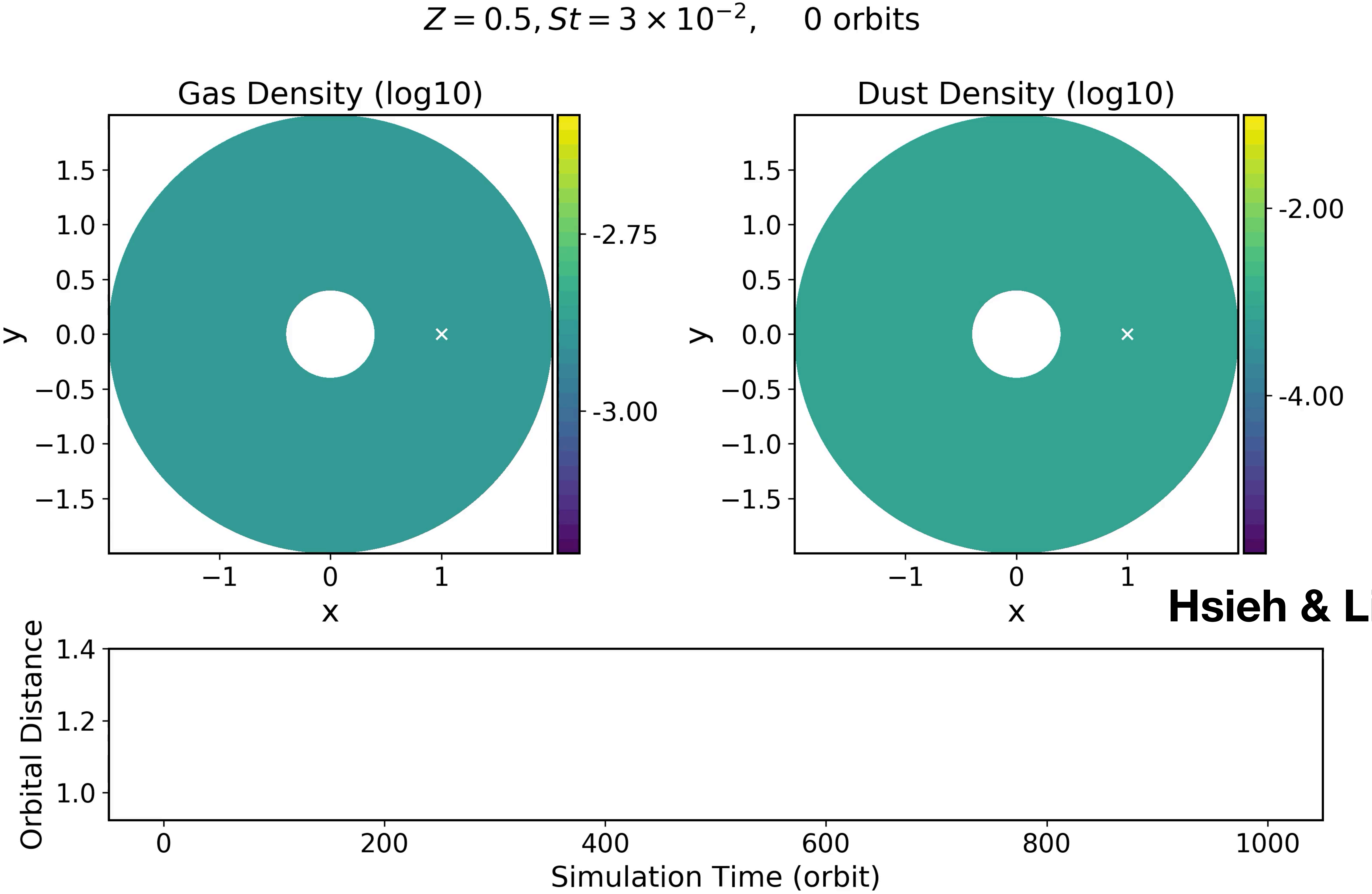
Can planets also explain them?



Vortex formation due to the "Rossby wave" instability

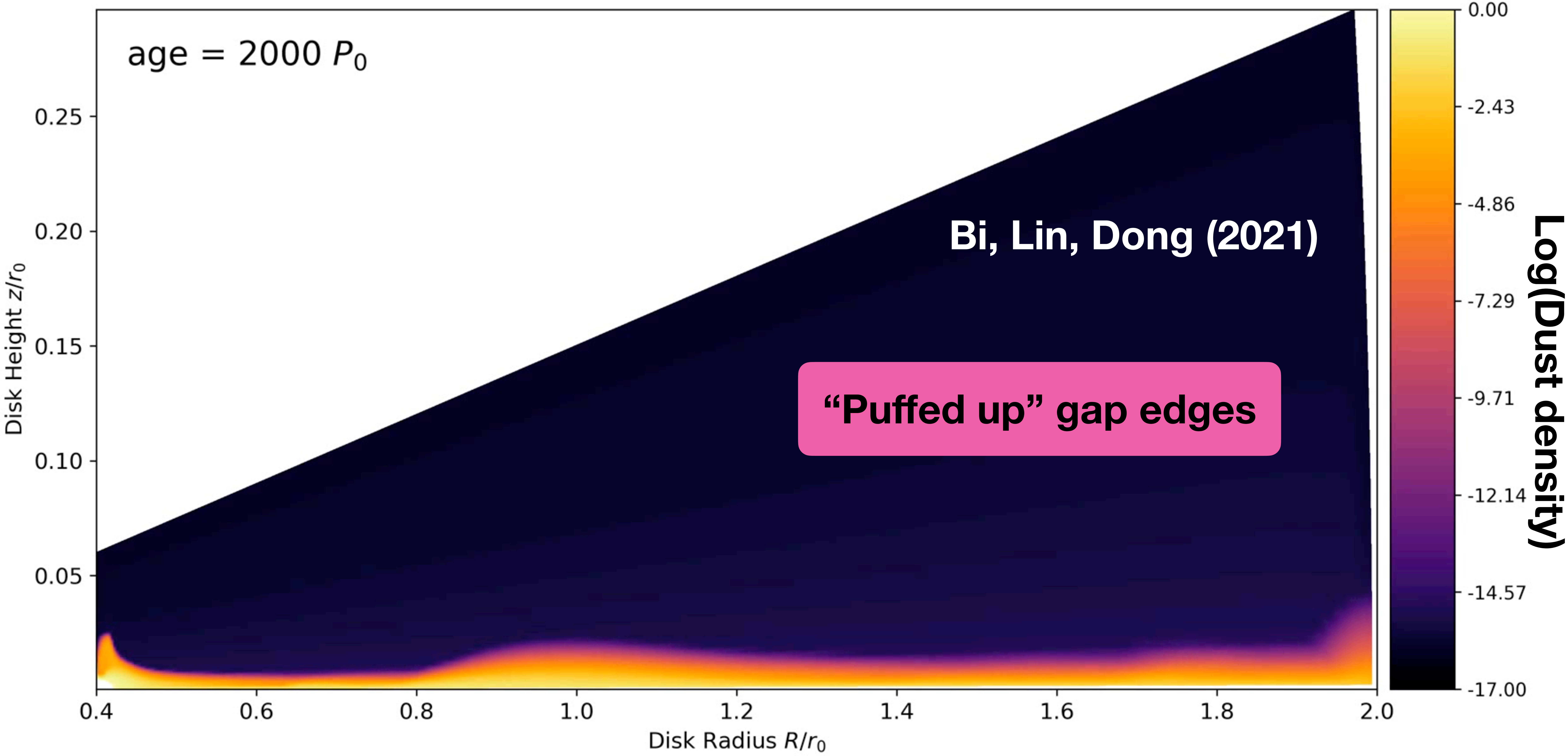
(Hammer, Lin, et al. 2021)

Migrating planets in dusty disks



Hsieh & Lin (2020)

Three-dimensional models



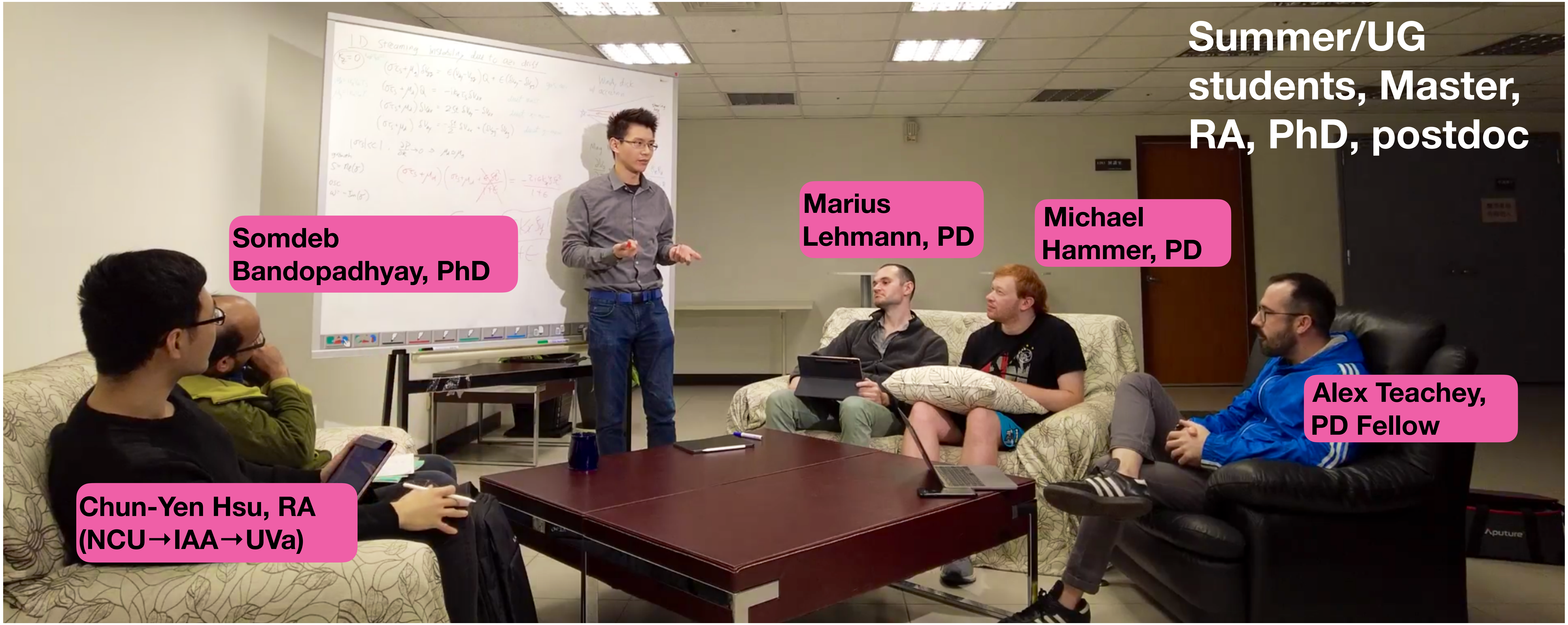
Puffed up rings in observations: Sign of planets?

Doi & Kataoka (2021)

Summary

- We are in the era of observing planet formation
- The streaming instability is the leading theory for planetesimal formation, but realistic disk conditions may challenge it or provide new pathways to clumping
- Planets continue to interact with their nascent disks to produce observable structures, which can in turn be used to reveal or rule out hidden planets

Opportunities at ASIAA and NCTS



Thank you

@linminkai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