Hopes and challenges in modern planet formation

Min-Kai Lin

May 2023

National Center for Theoretical Sciences, Physics Divisions

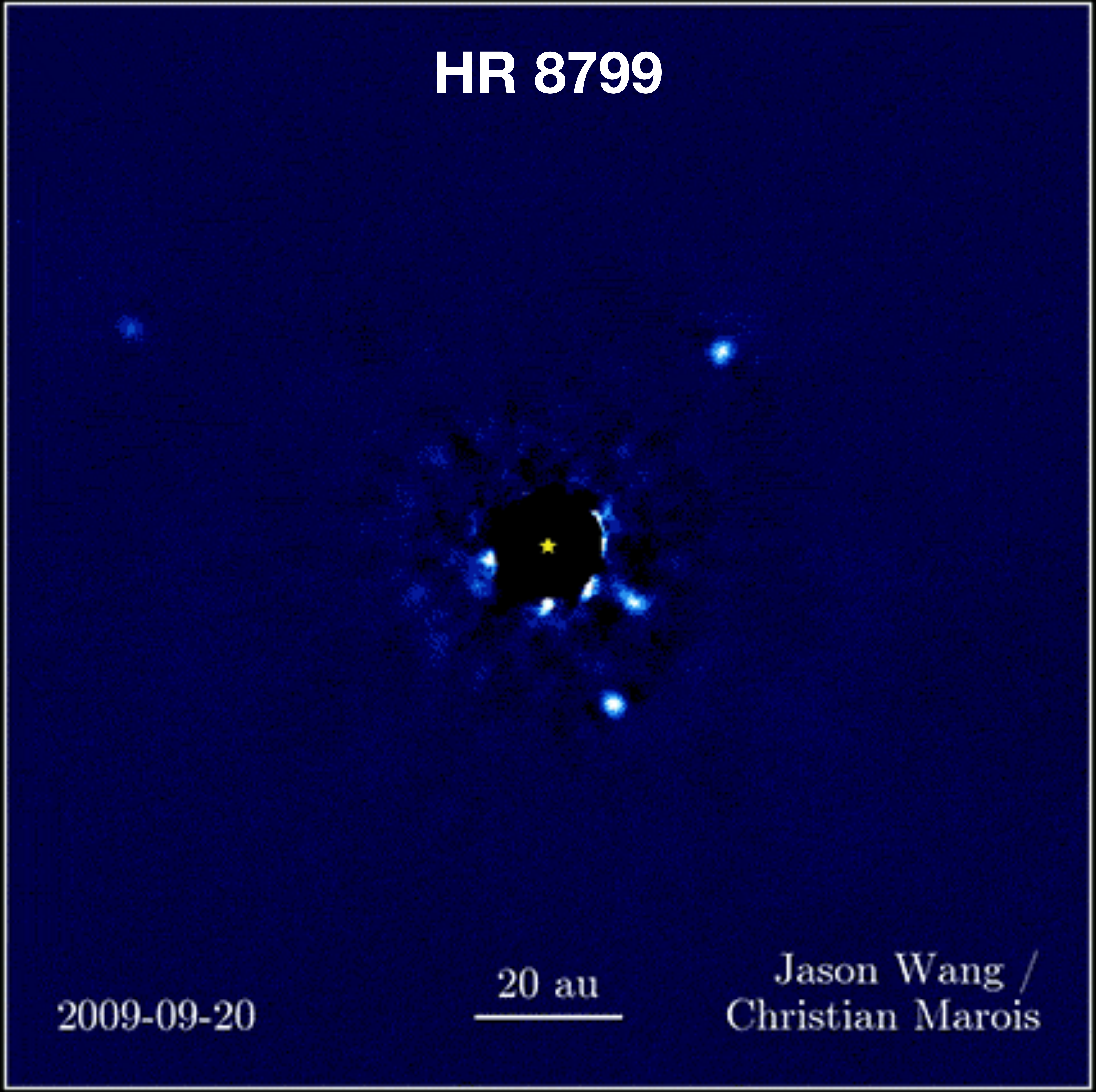
NSTC 國家科學及技術委員會
National Science and Technology Council

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

The era of exoplanet sciences

Credit: NASA/ESO/Wikipedia

Directly imaged “cold” Jupiters



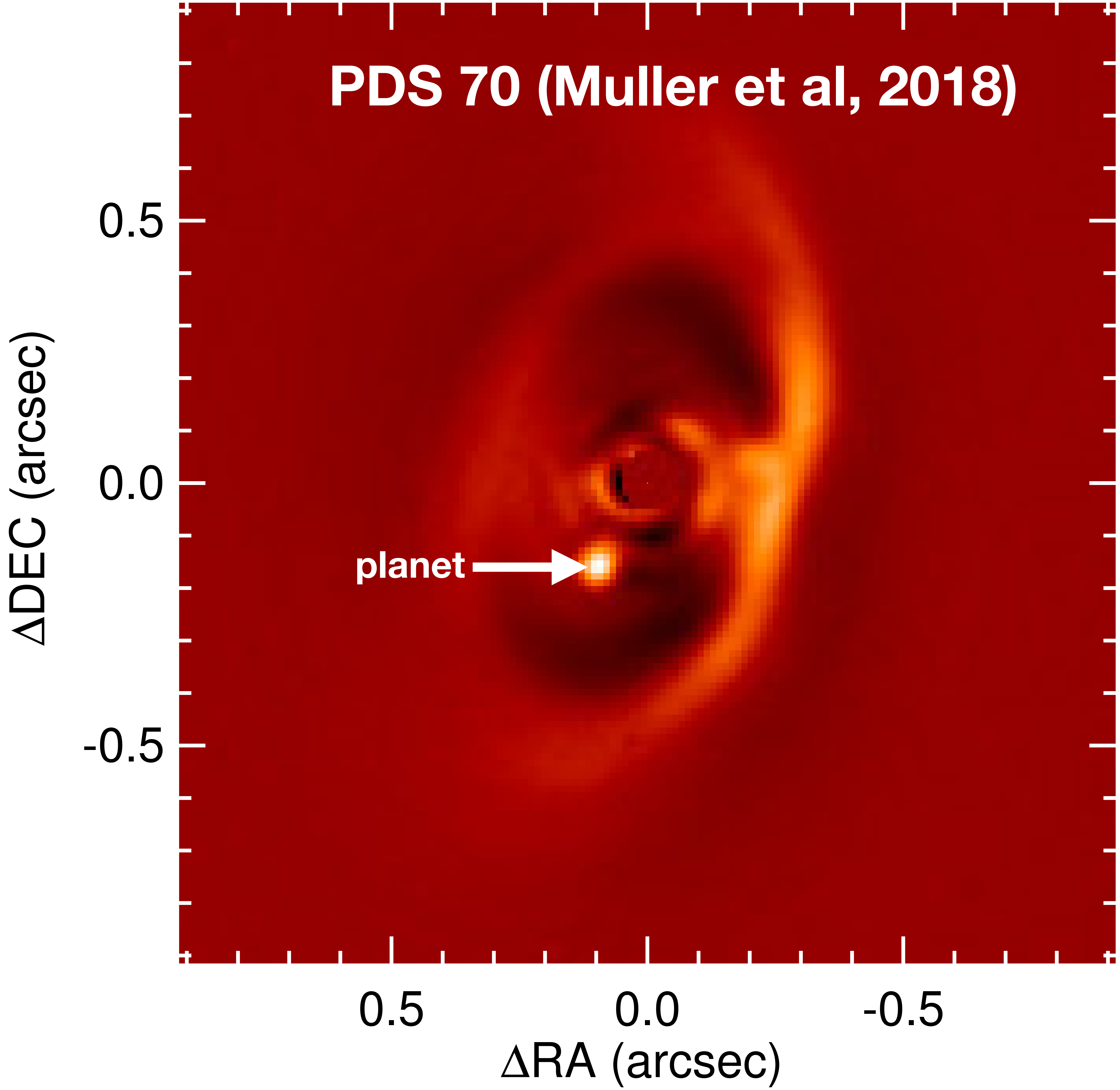
Credit: NASA

Planets form in protoplanetary disks around young stars

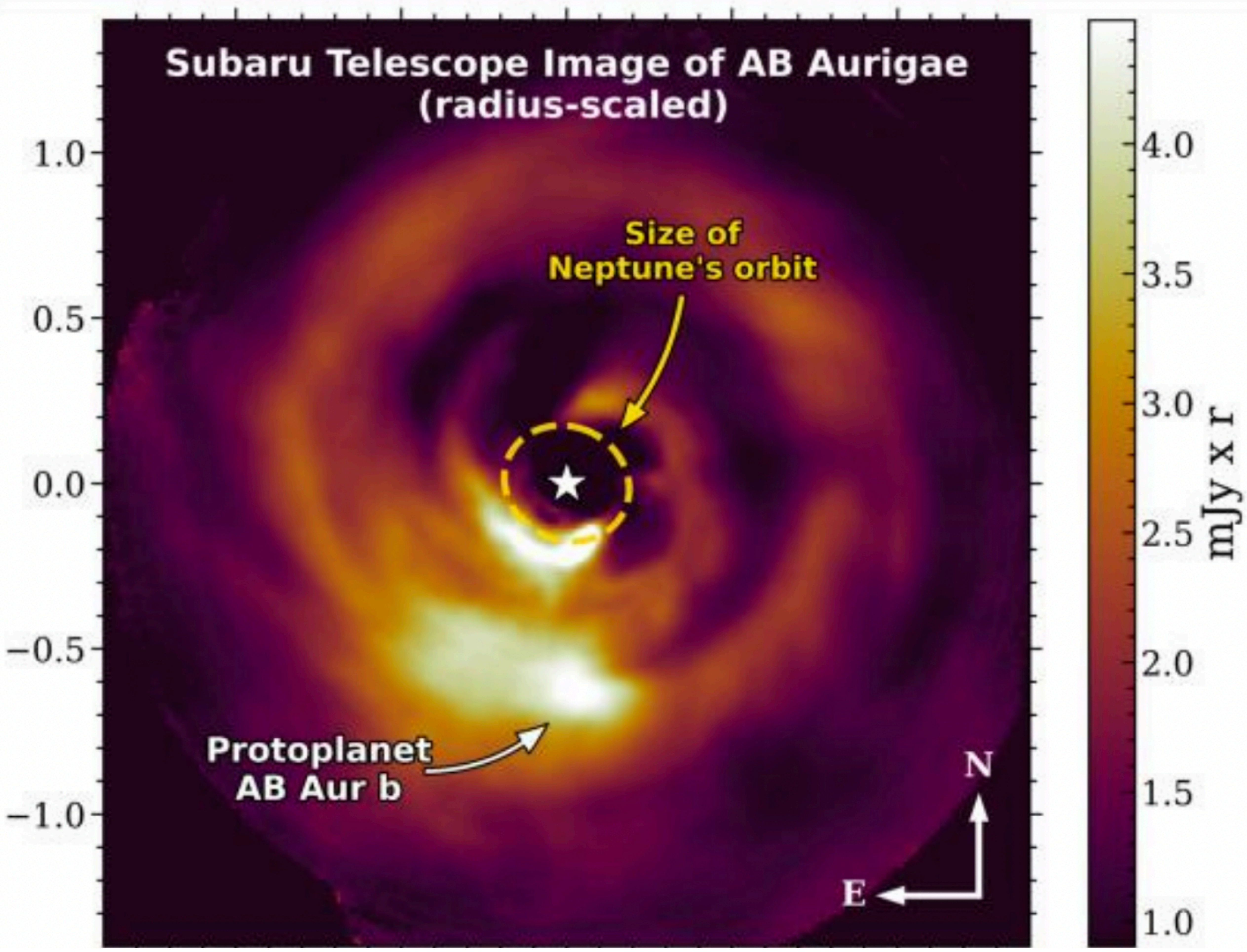
Rings and gaps: signposts of planet formation?

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

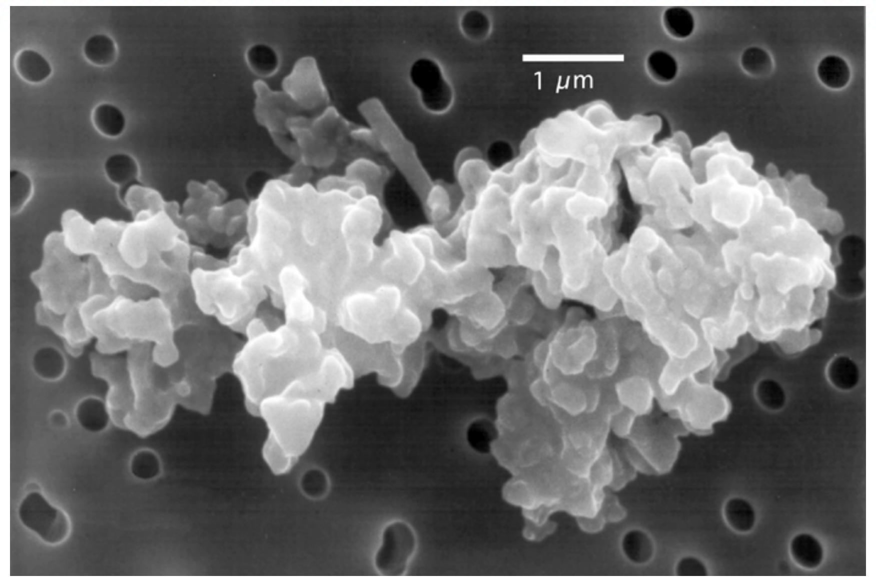
Observations of planets in a disk



AB Aur (Currie et al, 2022)

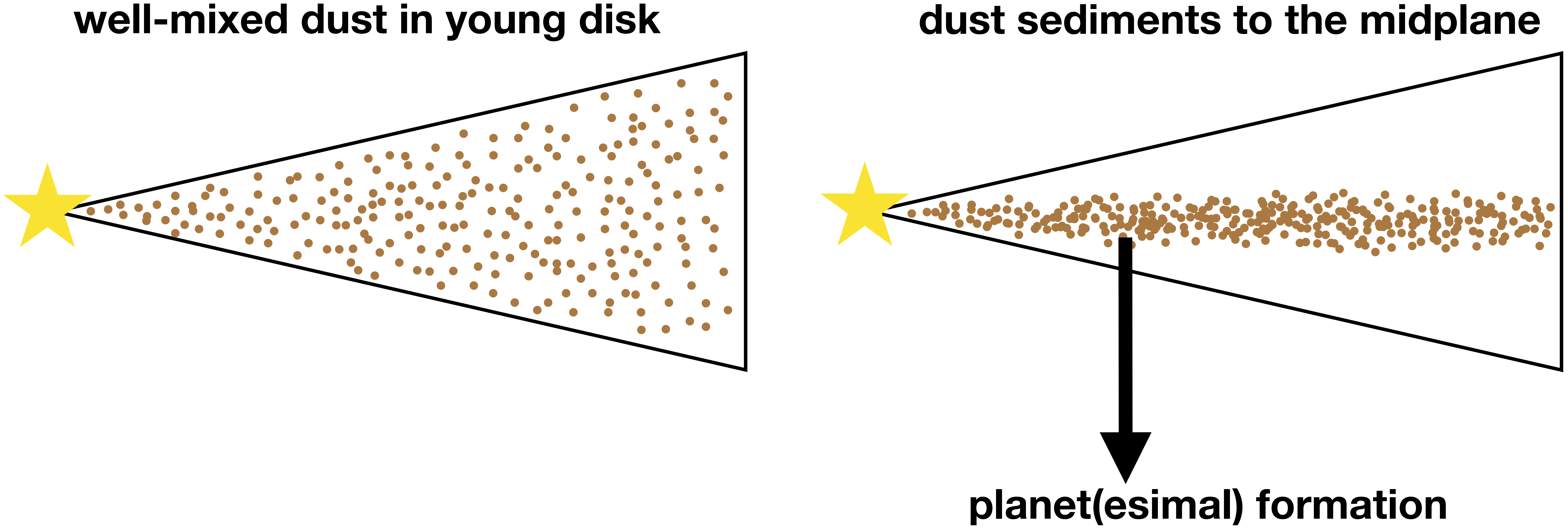


One planet, multiple scales

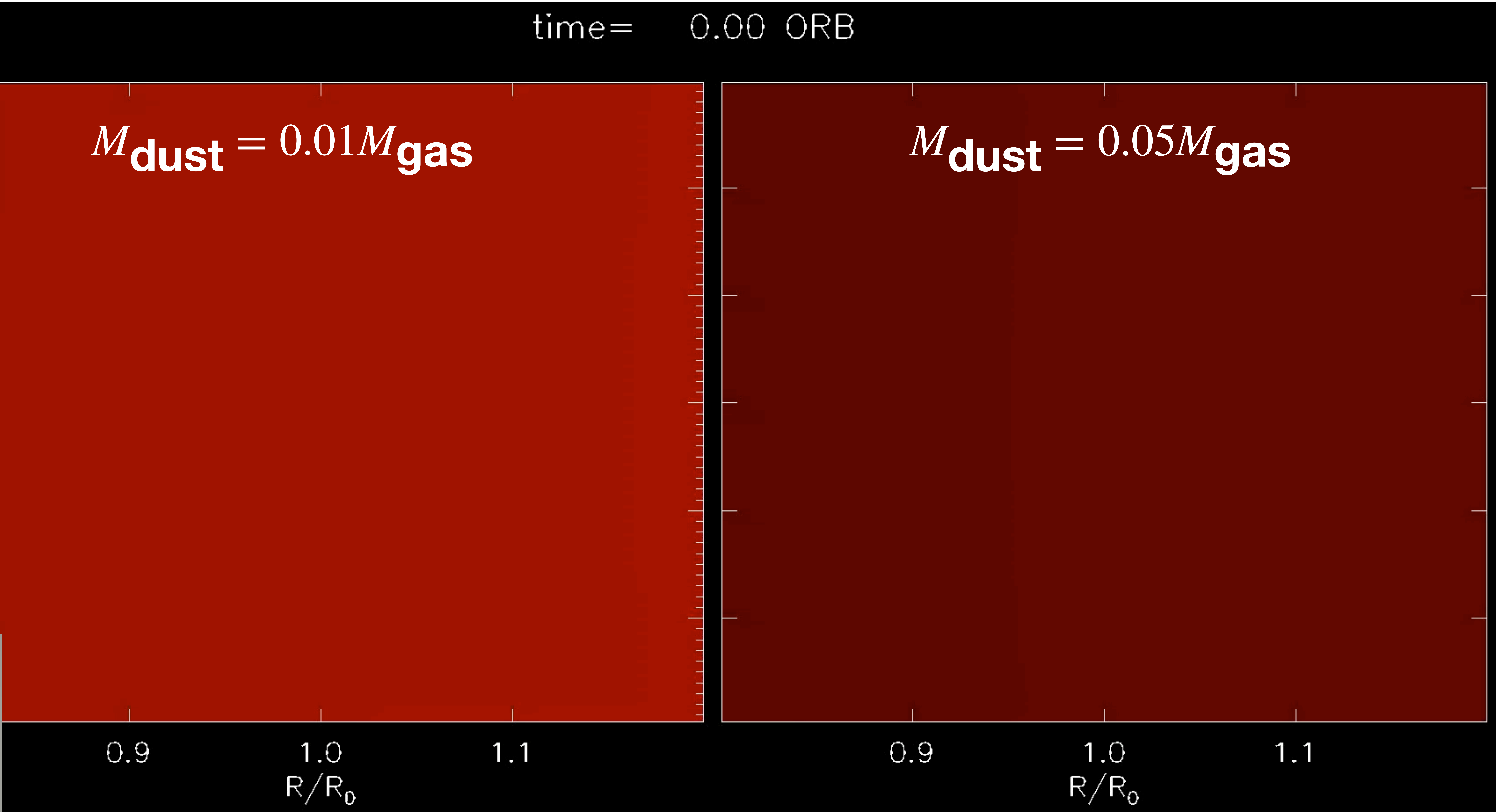


(Drazkowska et al., 2022, PPVII)

Step 1: Vertical dust settling

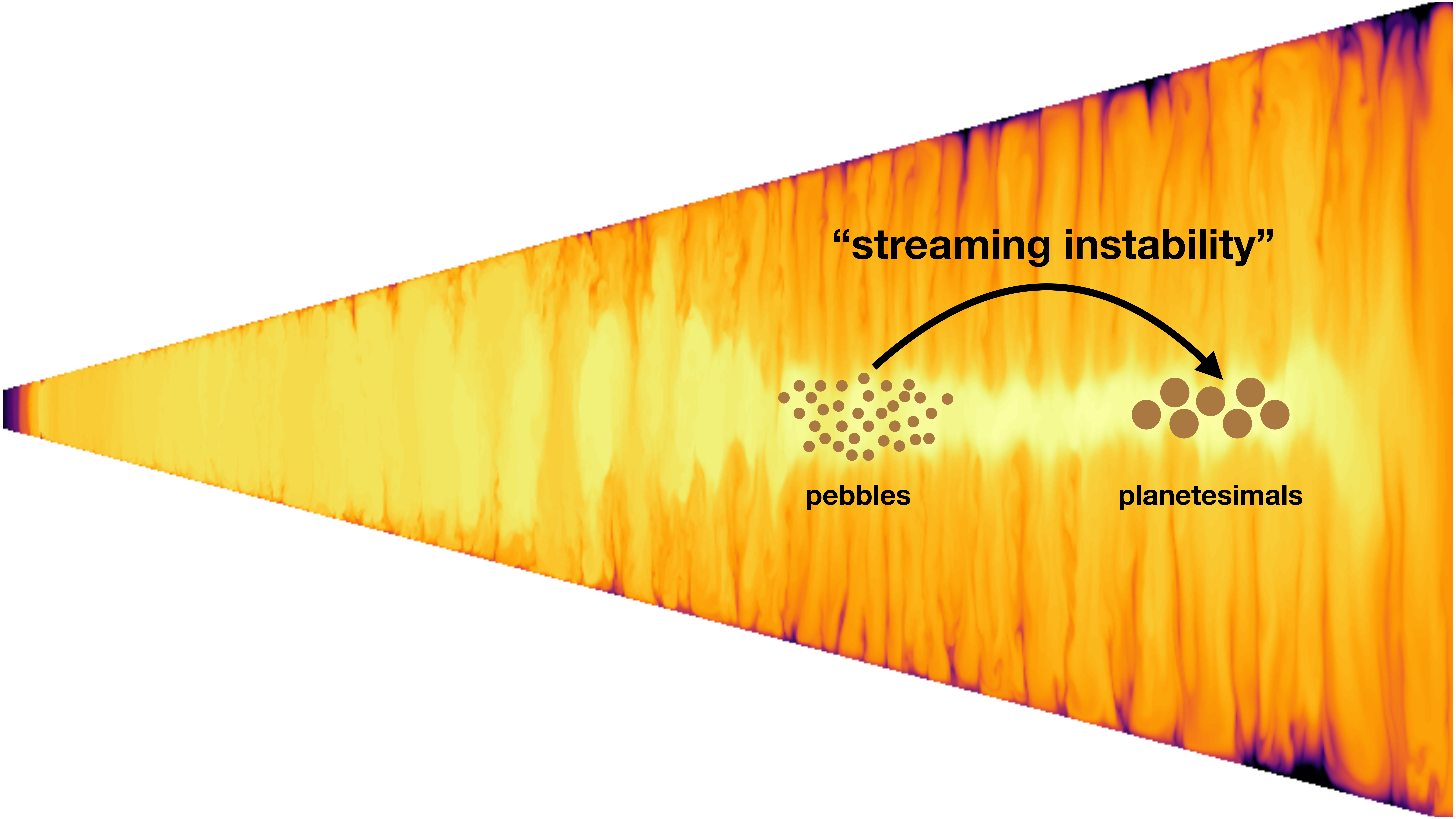


Dust settling vs. turbulence

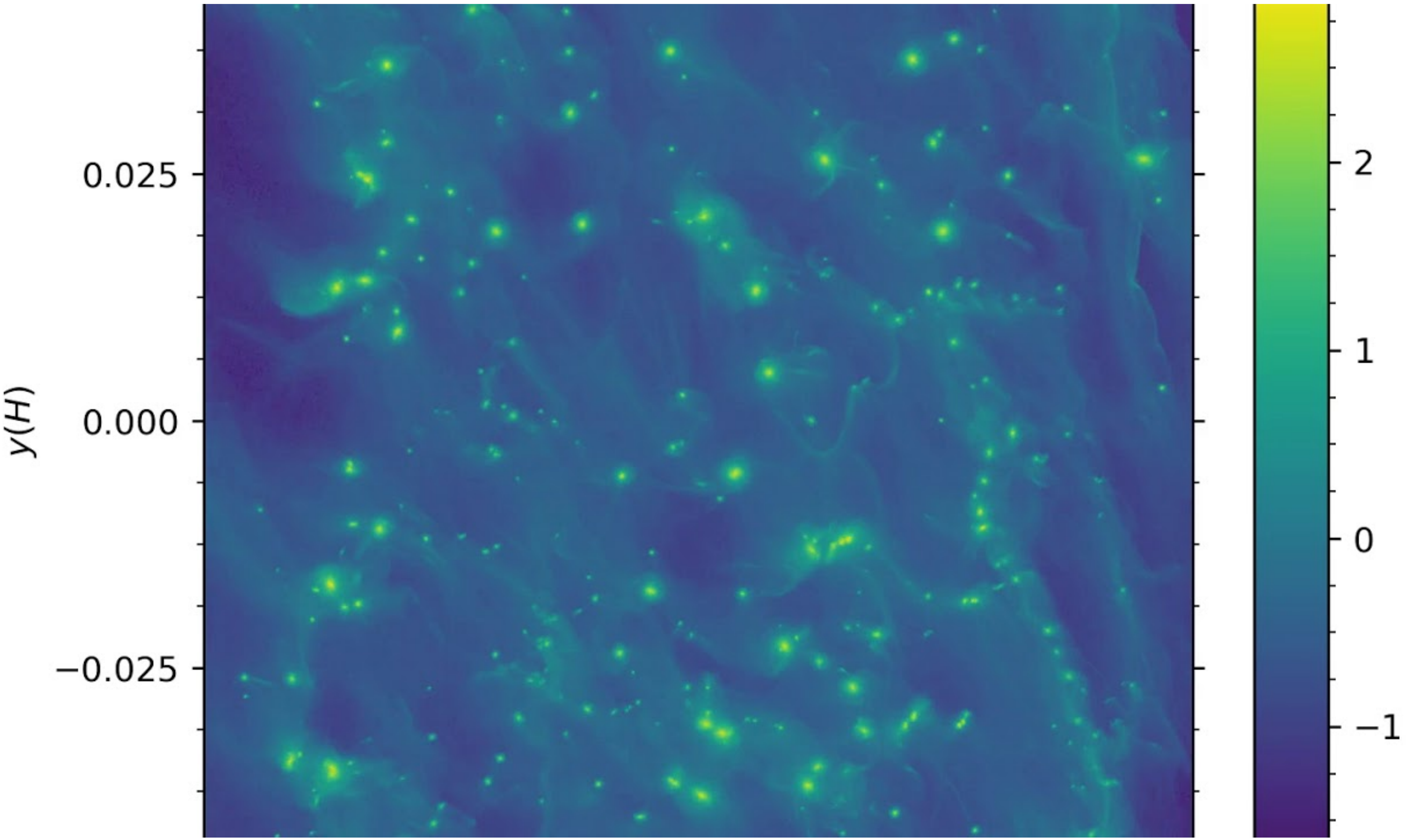


Lehmann & Lin (2022)

Planetesimal formation in the mid-plane



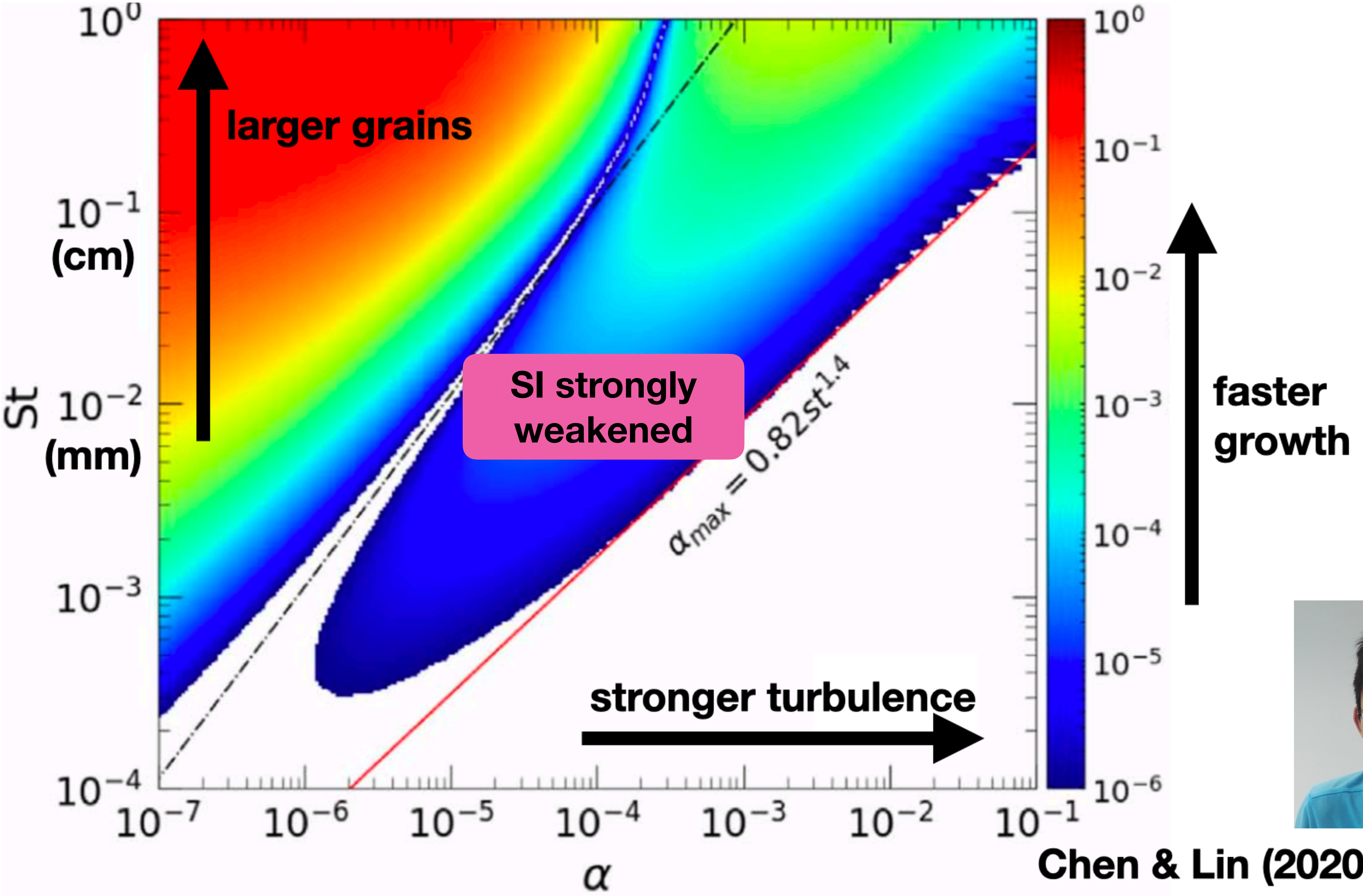
State-of-the-art SI simulations (Nesvorný et al., 2020)

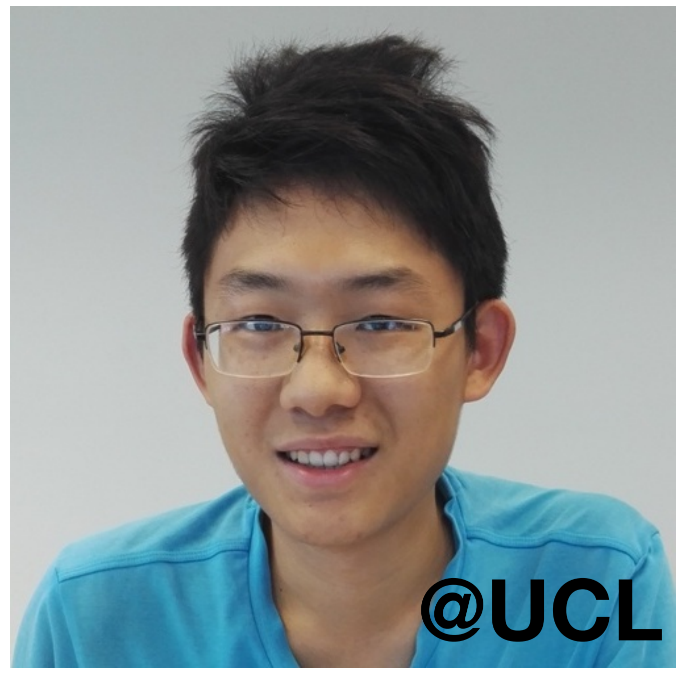


Generalizations of the ideal SI

- add turbulence → Chen & Lin (2020)
- add vertical structure → Lin (2021)
- add magnetic fields → Lin & Hsu (2022)
Hsu & Lin (2022)
- add thermodynamics → Lehmann & Lin (2023)

SI in classical “turbulent” protoplanetary disks





Chen & Lin (2020)

Modern “windy” protoplanetary disks

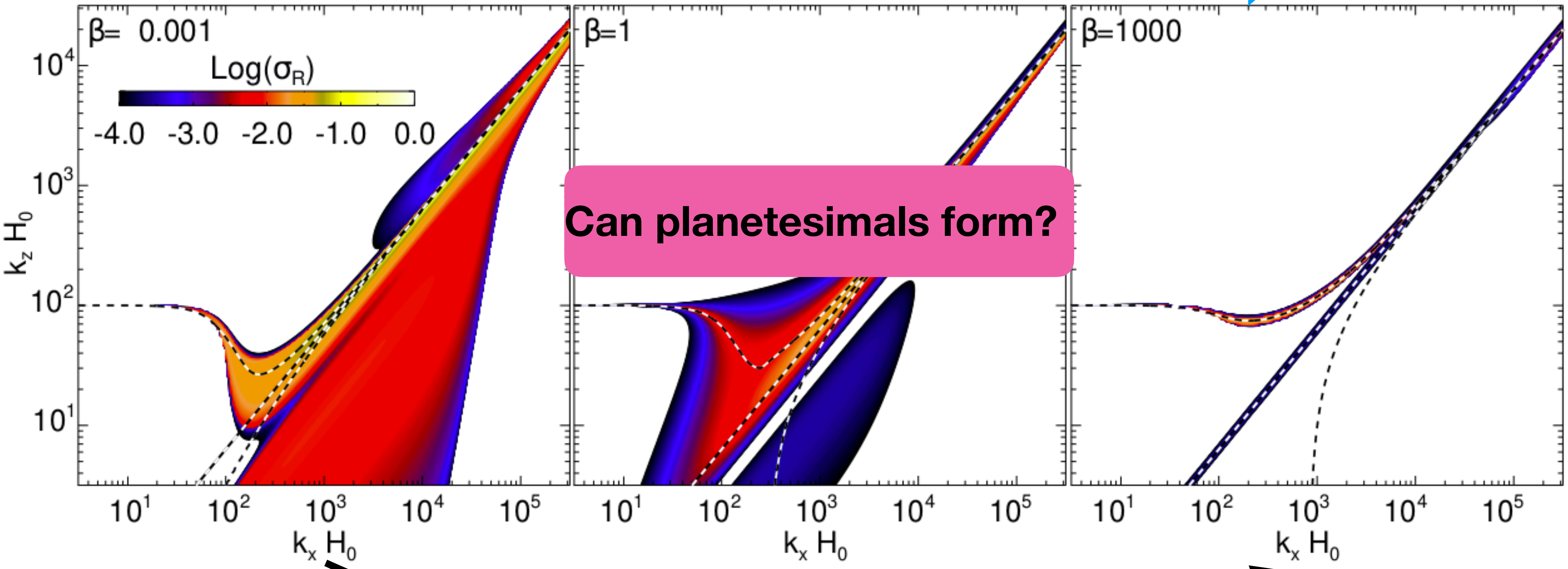
(e.g. Riols et al. 2020, Cui & Bai 2021)

SI in magnetically-driven protoplanetary disks

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

SI in non-isothermal disks

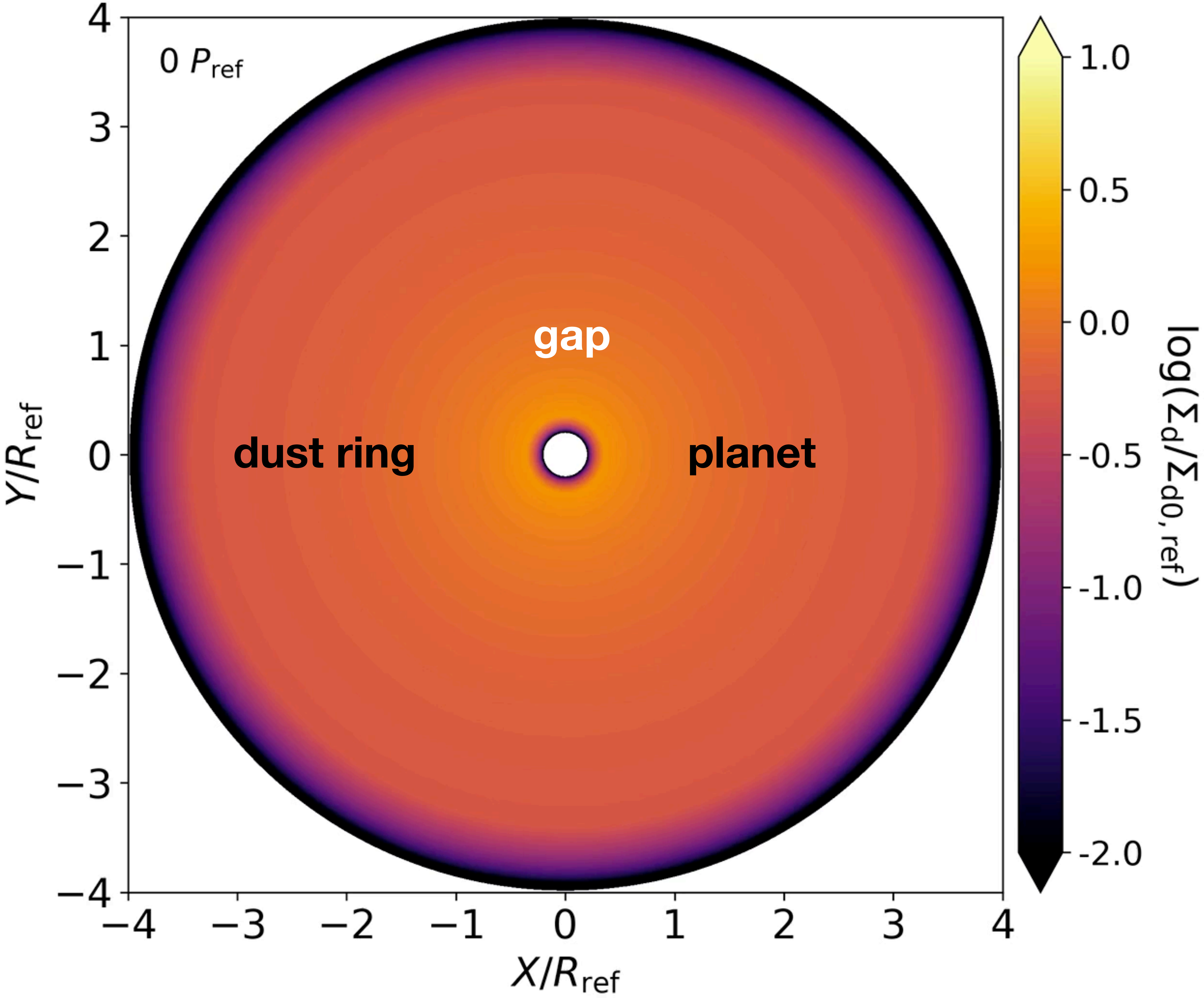
fast cooling → slow cooling



stabilized

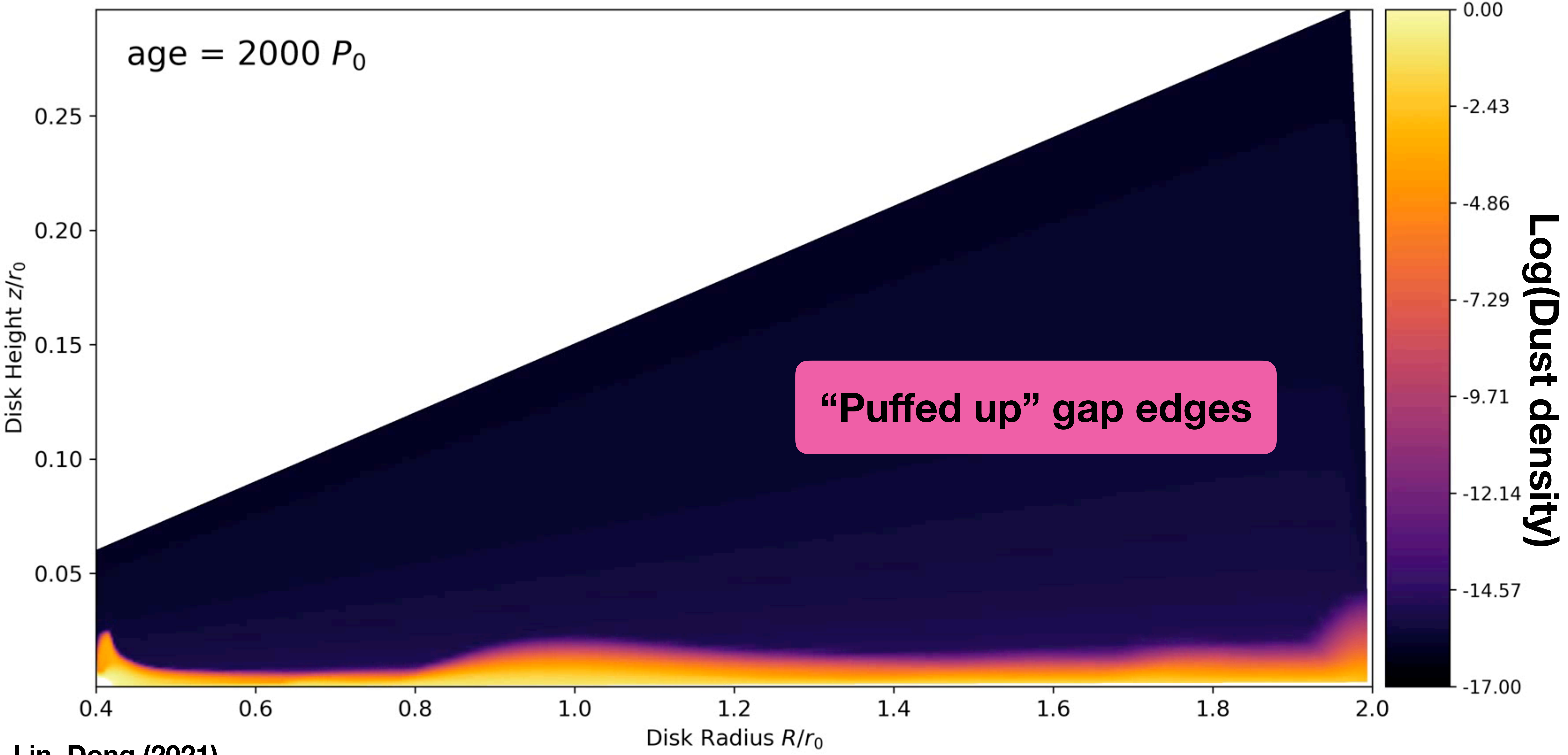
Lehmann & Lin (2023)

Planets form somehow, so what's next?



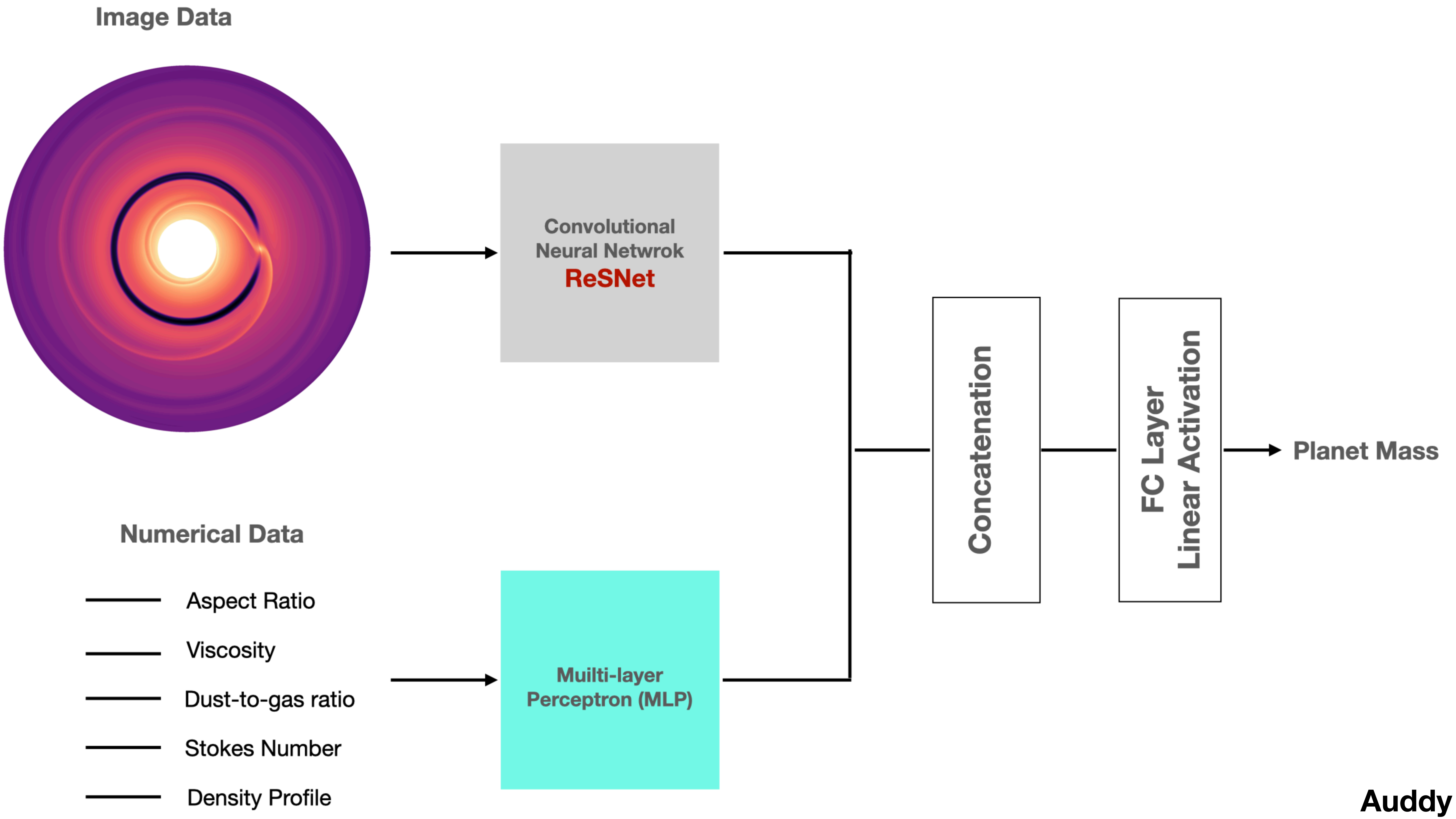
Bi, Lin, Dong (2021)

Three-dimensional models



Bi, Lin, Dong (2021)

Modeling planet gaps with artificial/convolutional NN



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

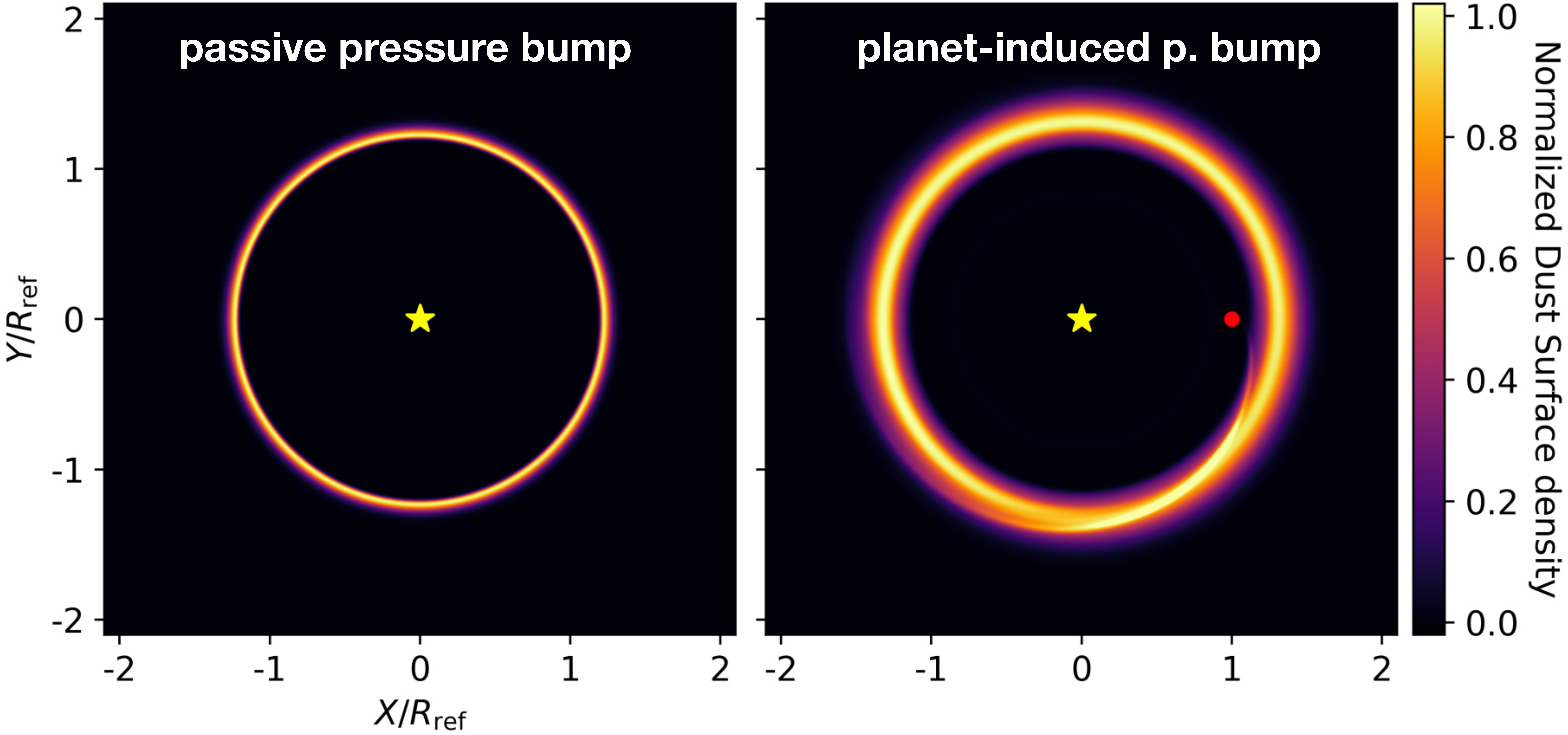
Estimating planet masses around HL Tau

Disk-Planet Neural Network

(Auddy & Lin, 2020)

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

Caution: Not all dust rings are made by planets



Bi, Lin, Dong (2023)

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