

Hopes and challenges in modern planet formation and evolution

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February 2023



The era of exoplanet sciences

30%
GAS GIANT

The size of Saturn or Jupiter (the largest planet in our solar system), or many times bigger. They can be hotter than some stars!

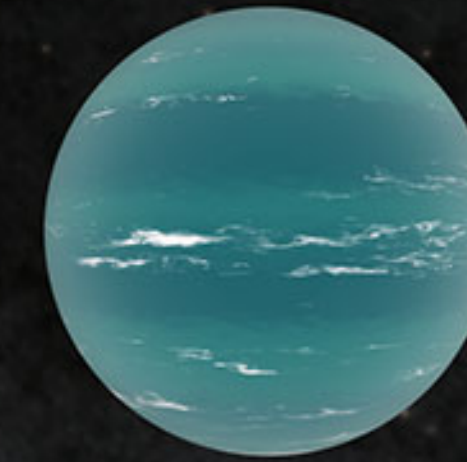
31%
SUPER-EARTH

Planets in this size range between Earth and Neptune don't exist in our solar system. Super-Earths, a reference to larger size, might be rocky worlds like Earth, while mini-Neptunes are likely shrouded in puffy atmospheres.



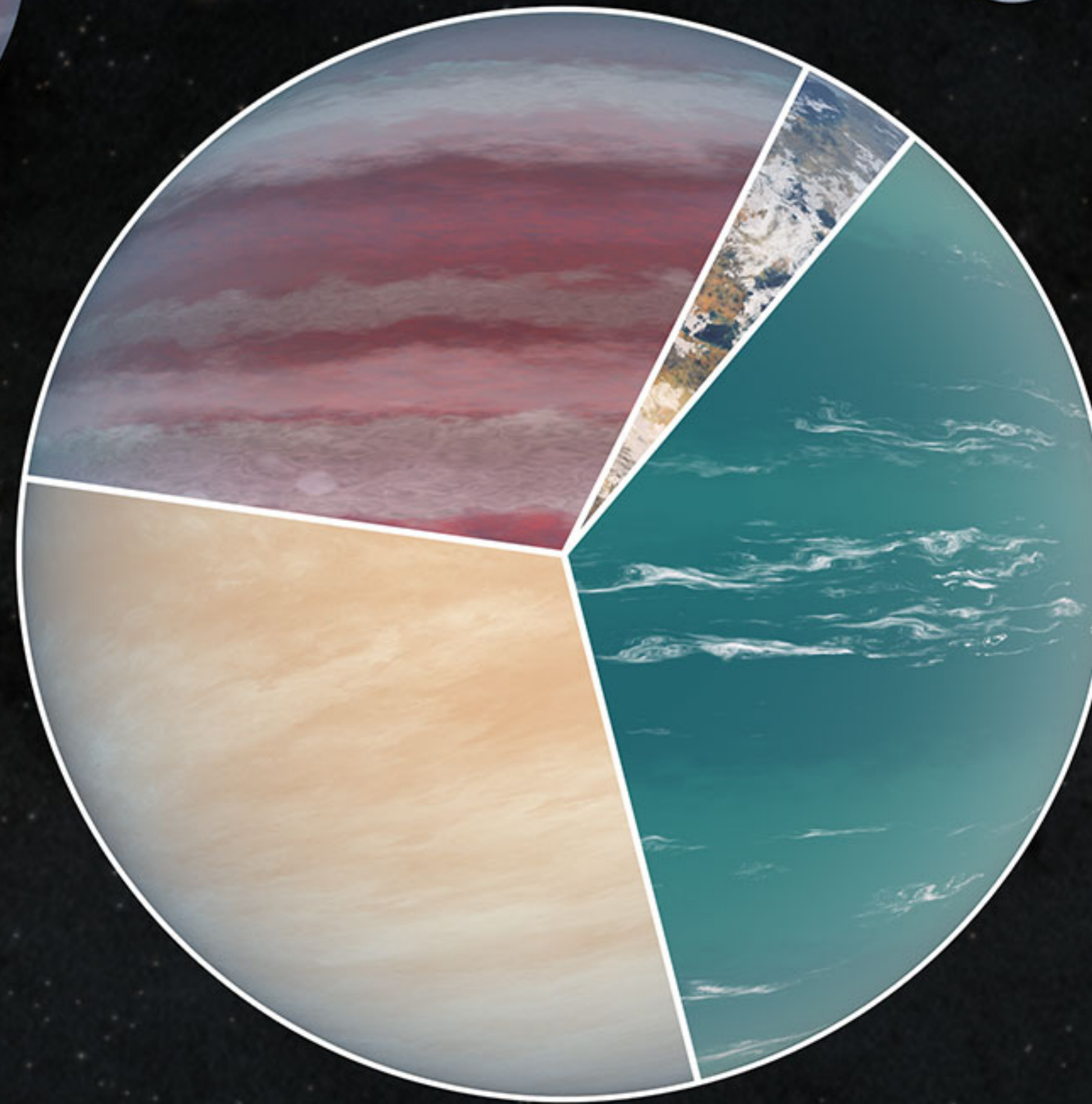
4%
TERRESTRIAL

Small, rocky planets. Around the size of our home planet, or a little smaller.



35%
NEPTUNE-LIKE

Similar in size to Neptune and Uranus. They can be ice giants, or much warmer. "Warm" Neptunes are more rare.

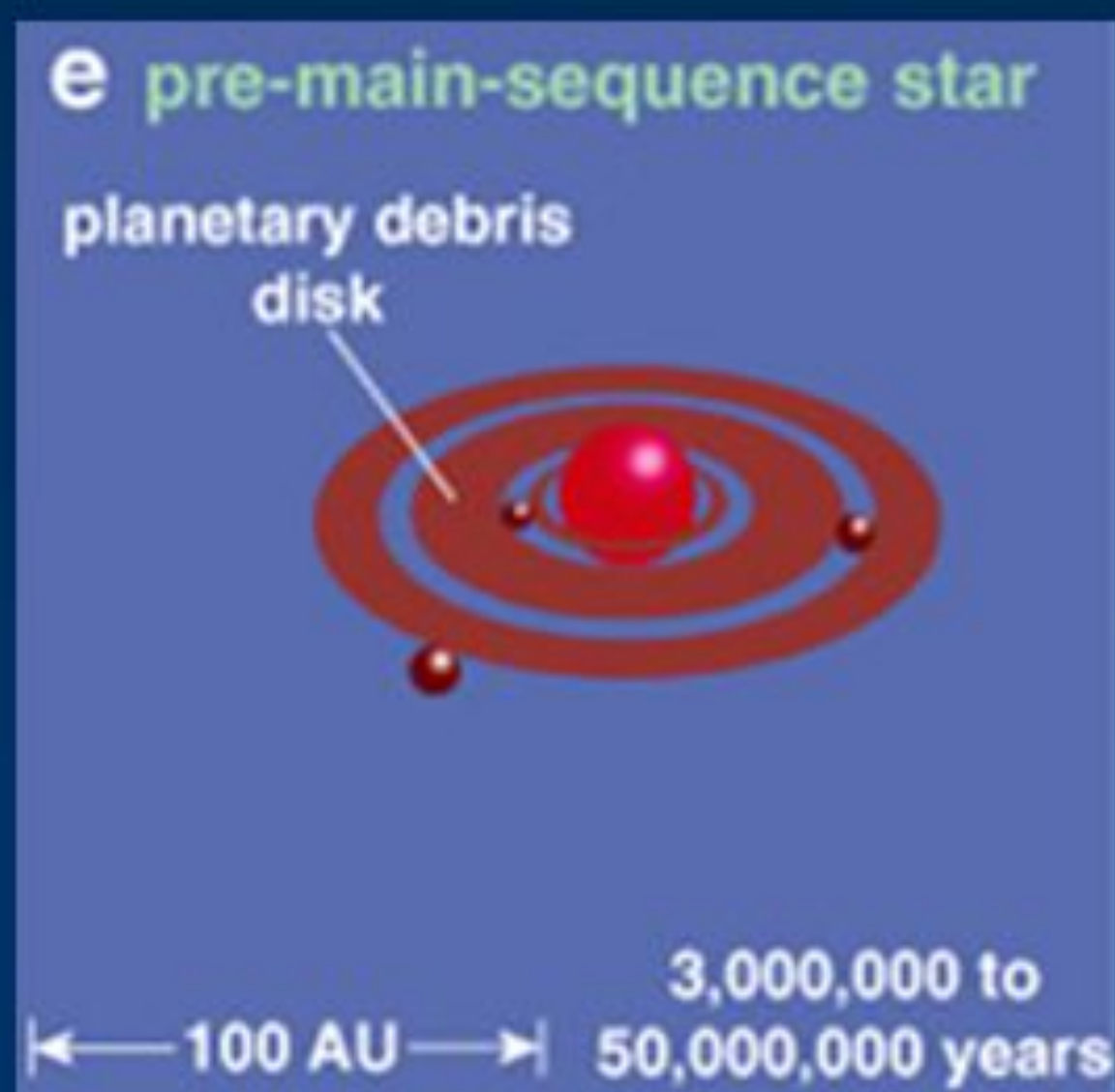
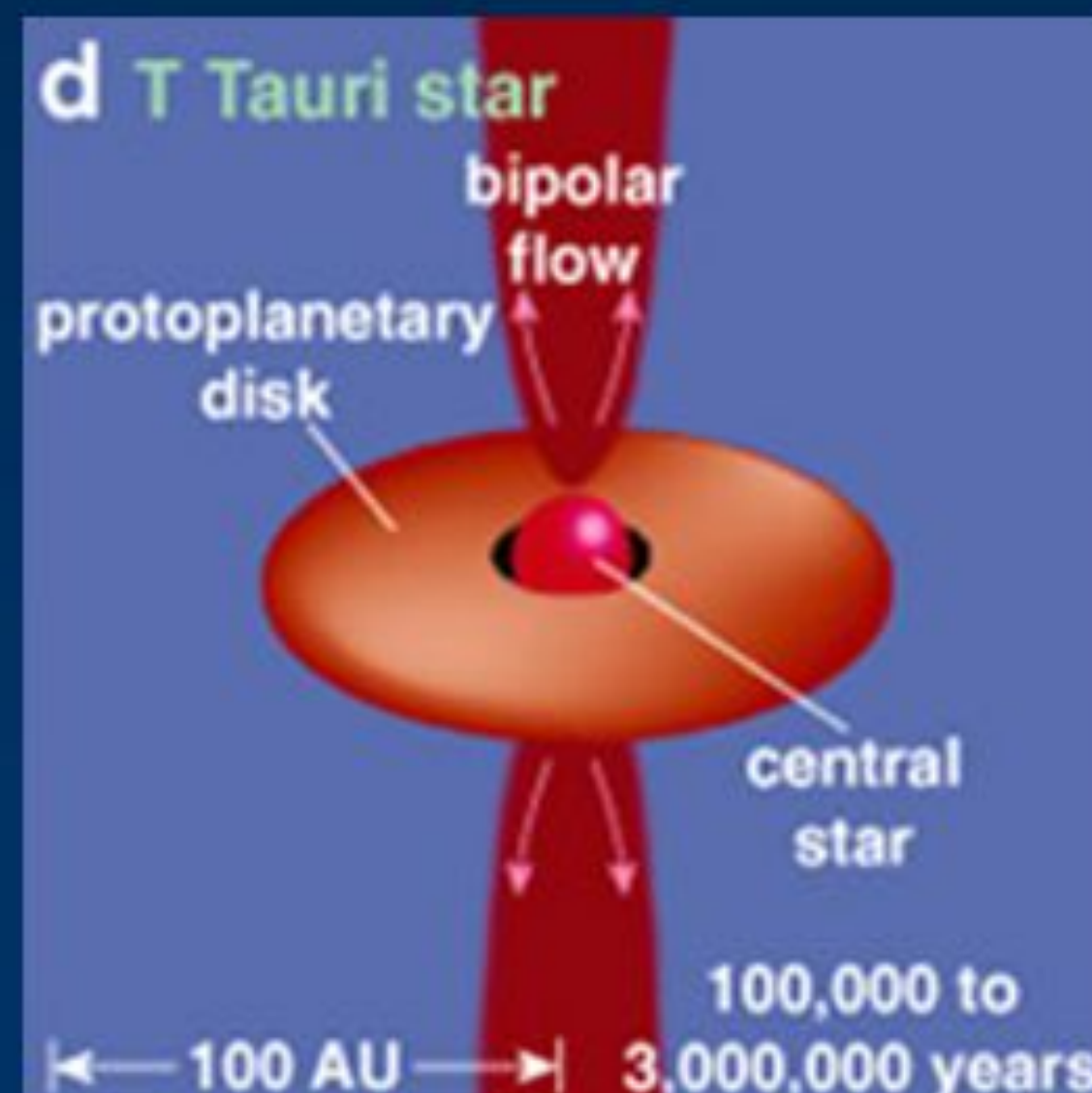
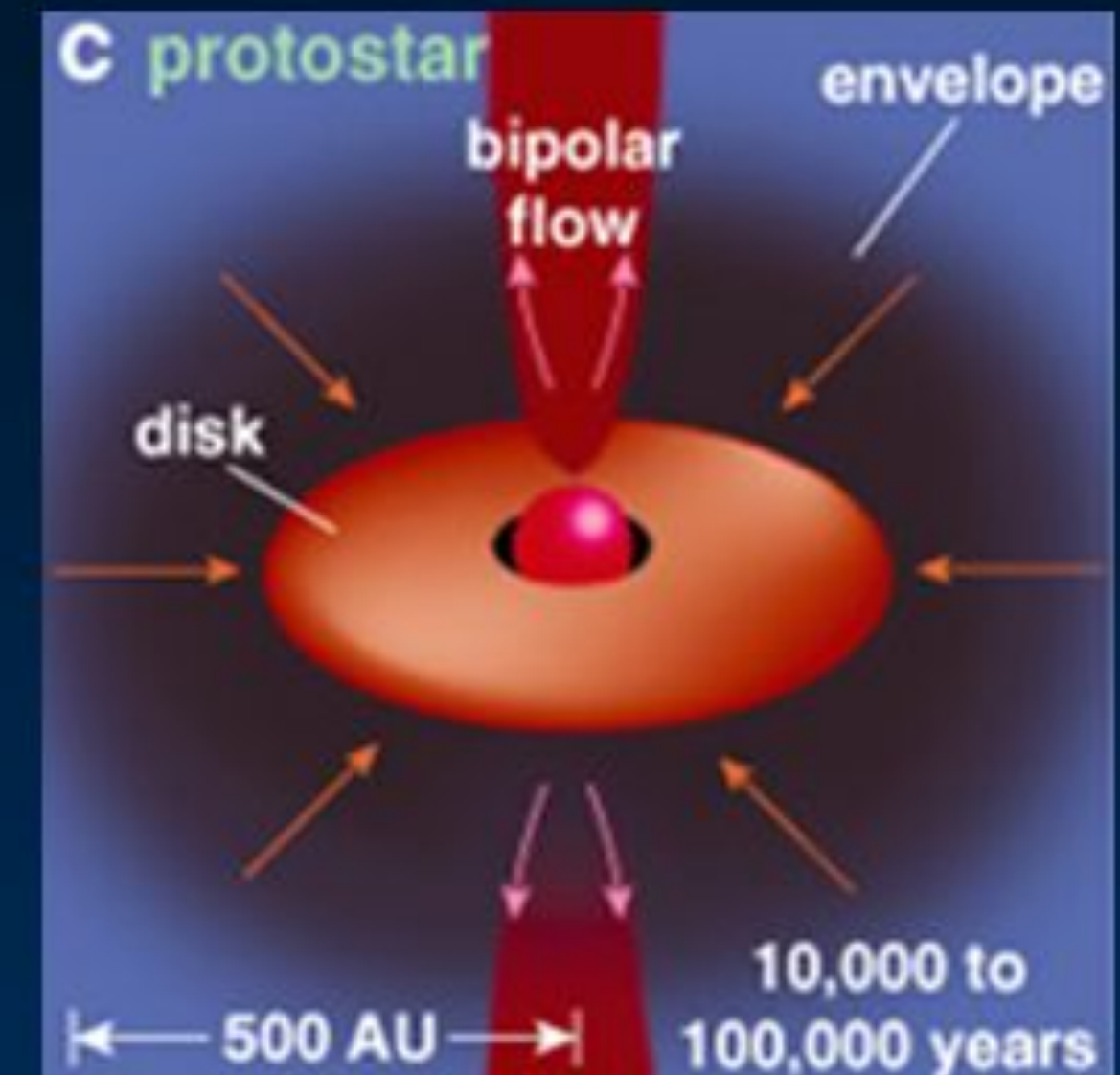
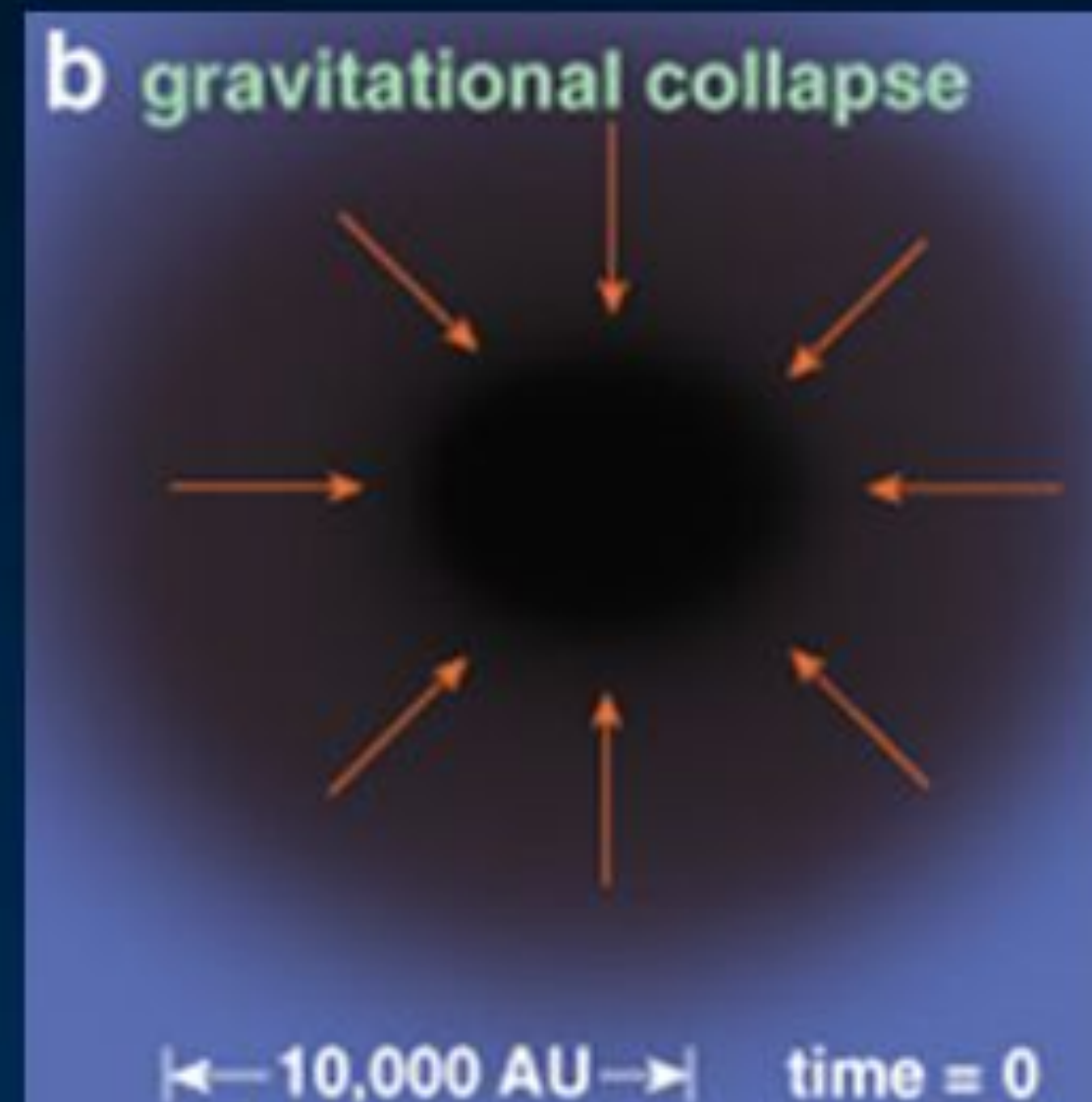
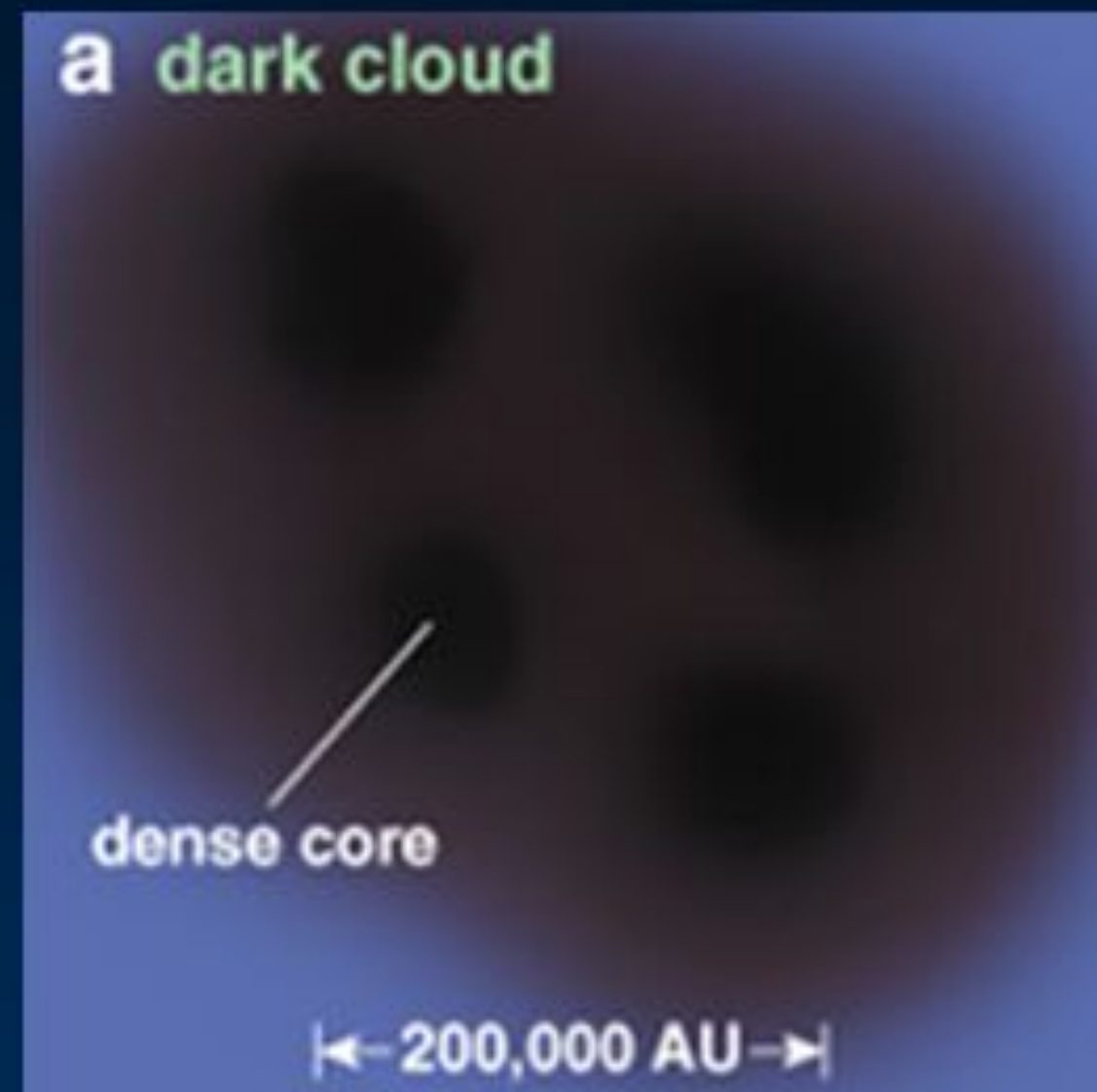


5000+
PLANETS FOUND

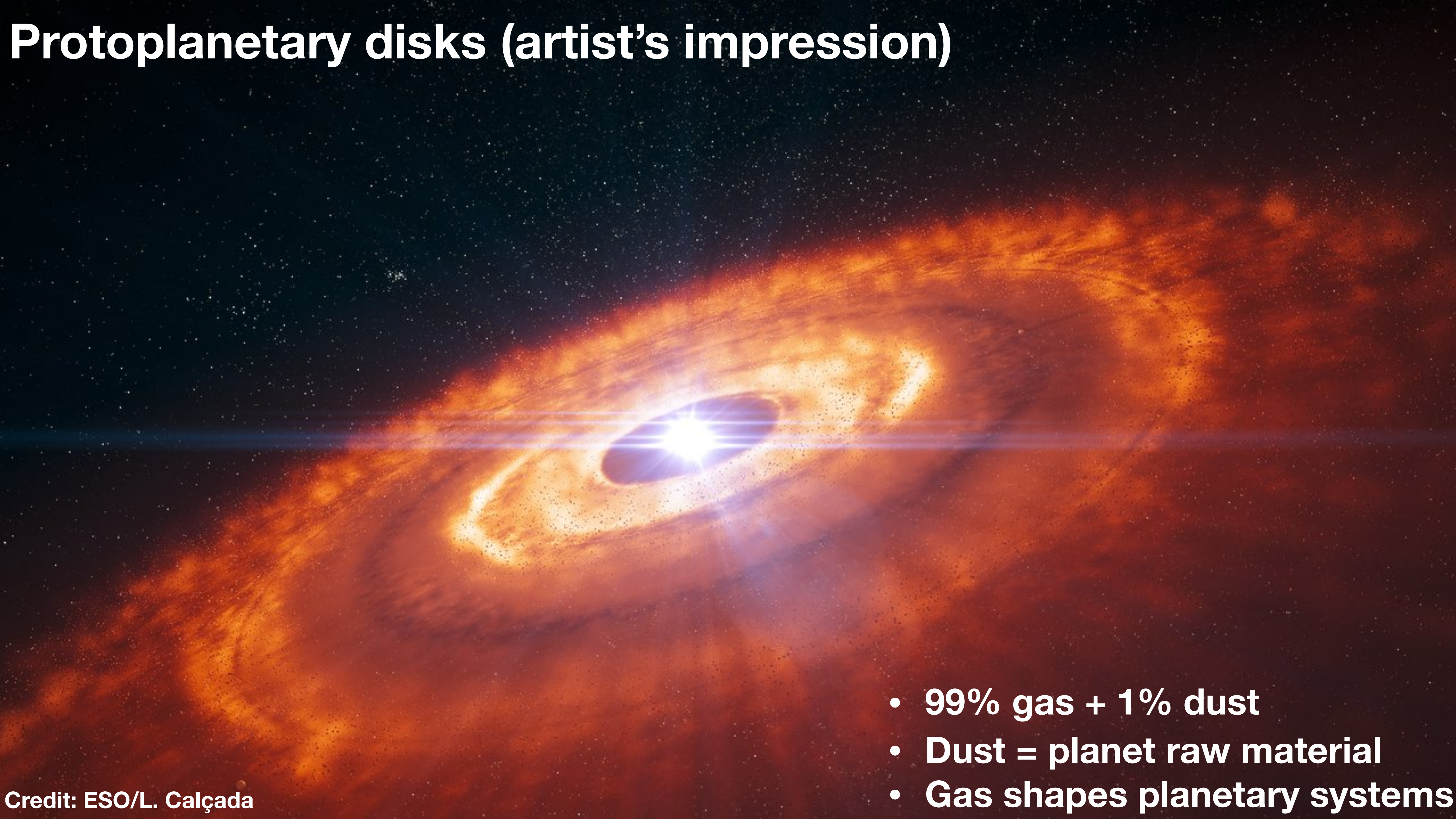
Credit: Martin Vargic

- [illegible]

Star & planet formation



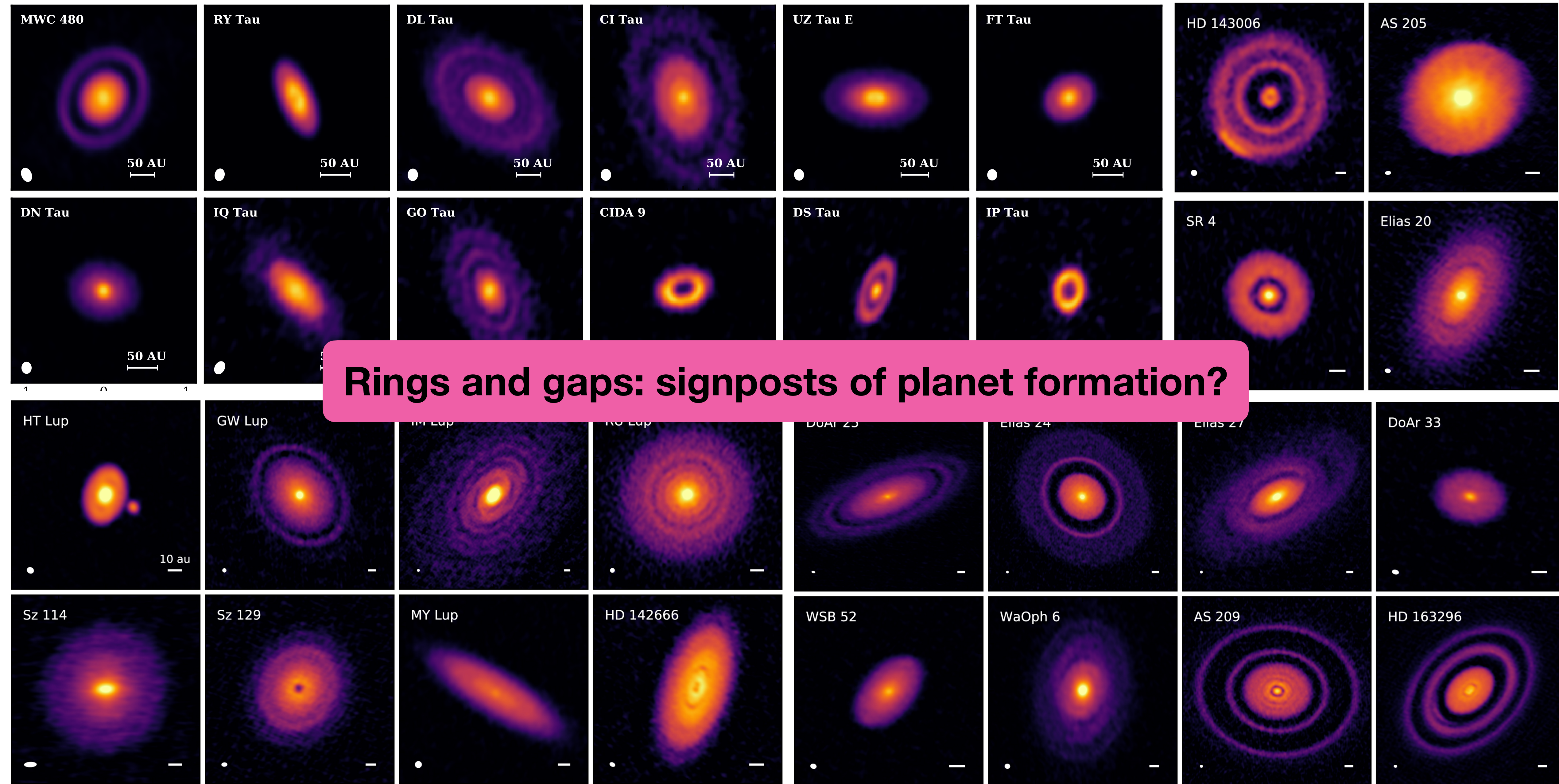
Protoplanetary disks (artist's impression)



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

Real protoplanetary disks

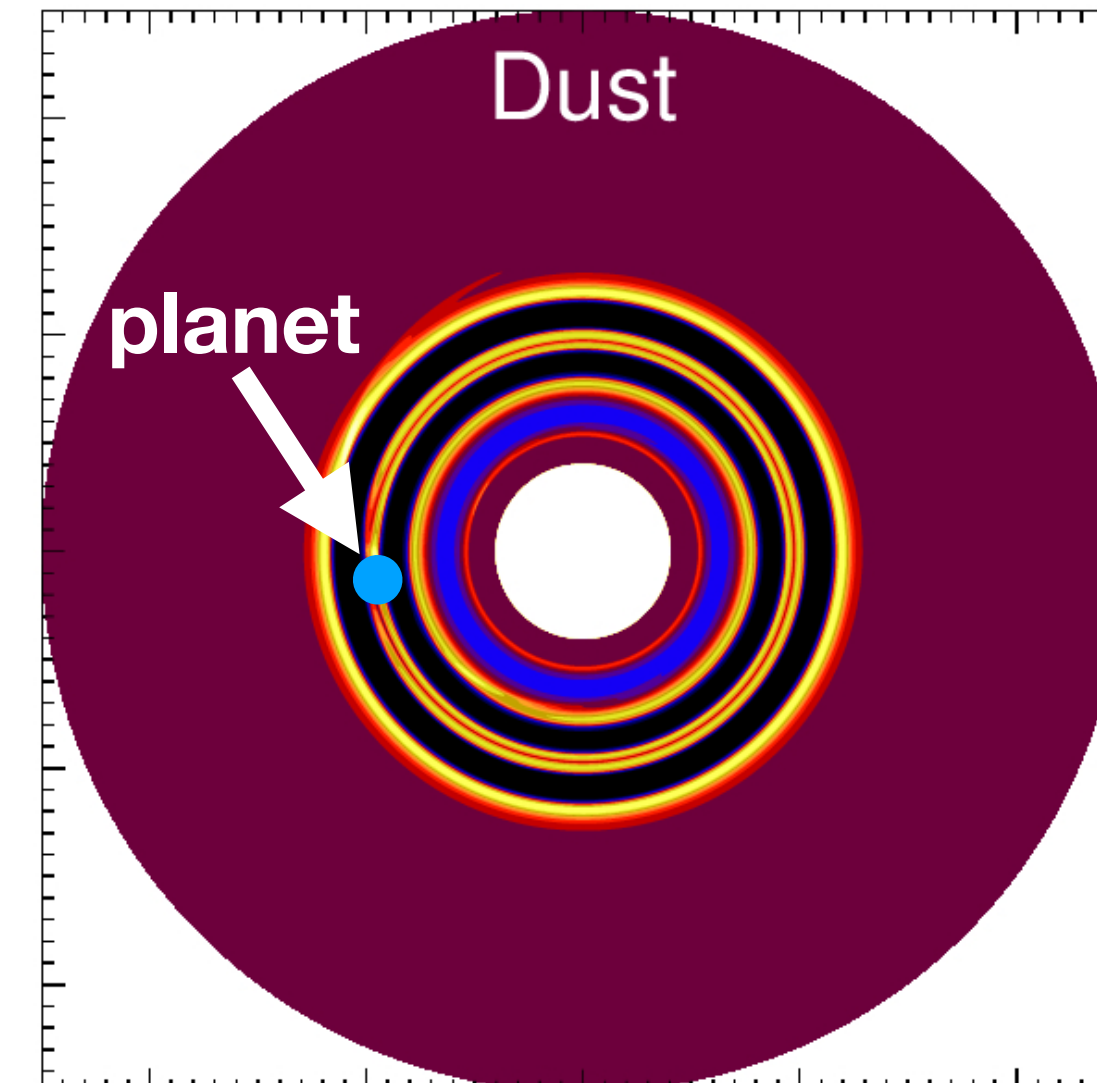
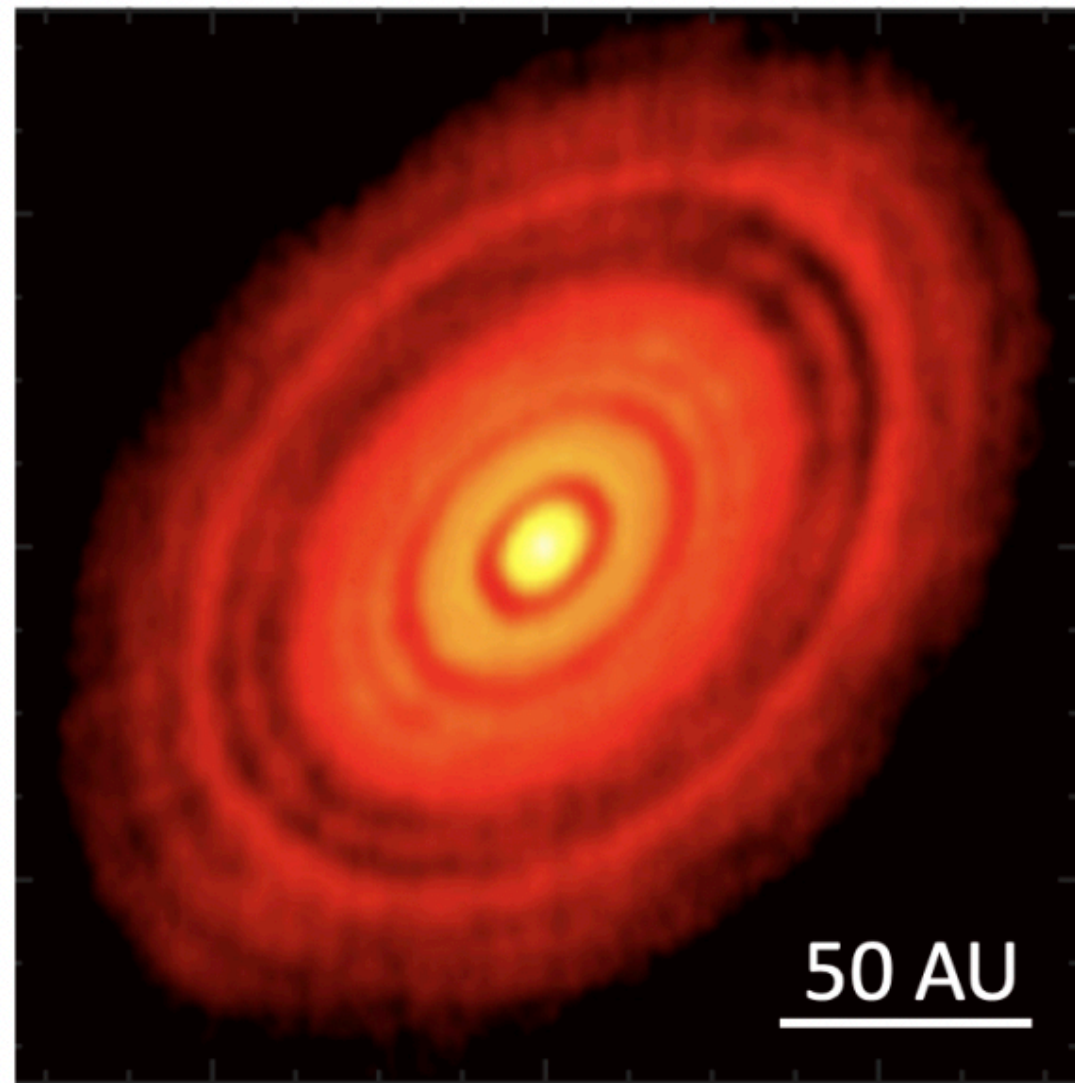
(Andrews et al, 2018; Long et al 2018)



Disk-planet interpretation

HL Tau (ALMA Partnership et al. 2015)

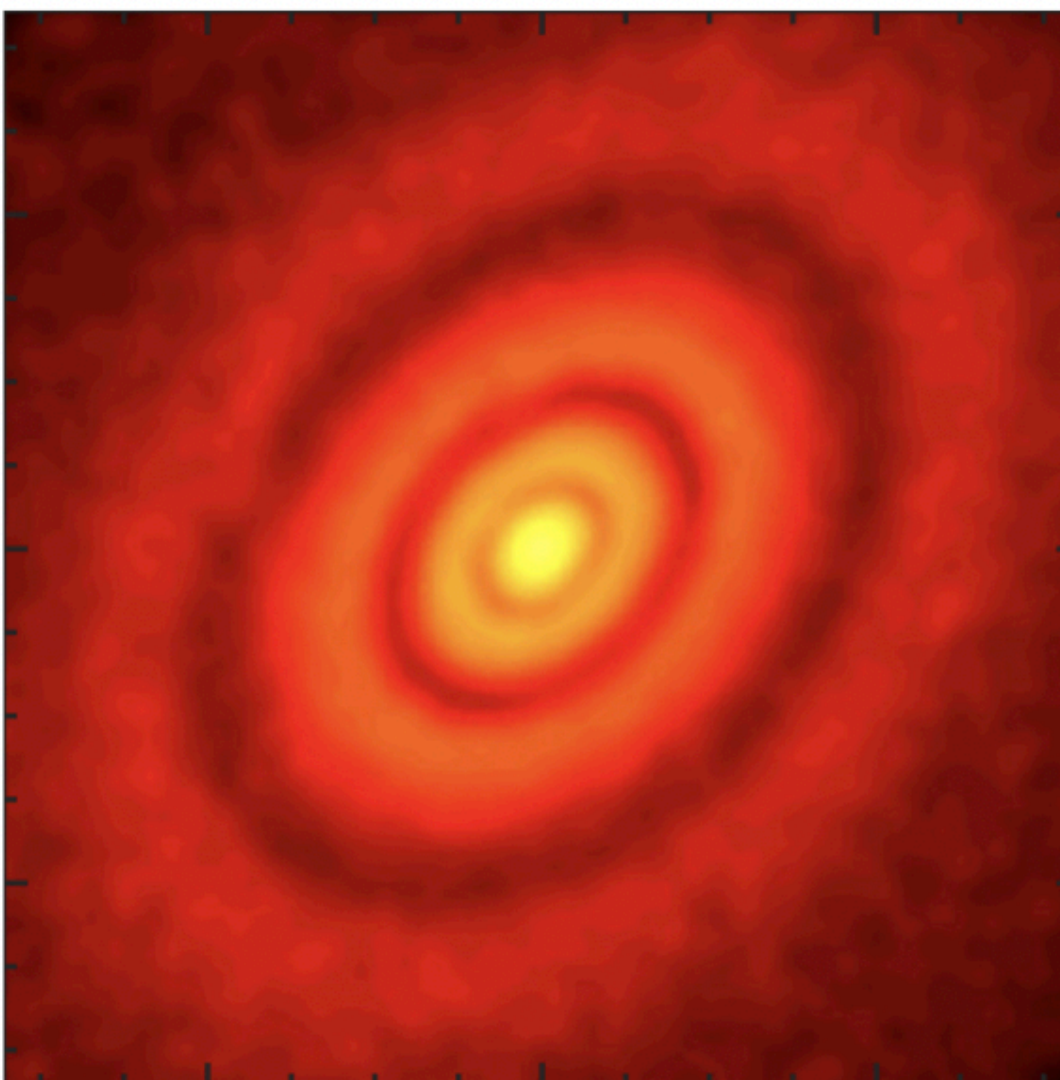
Observations



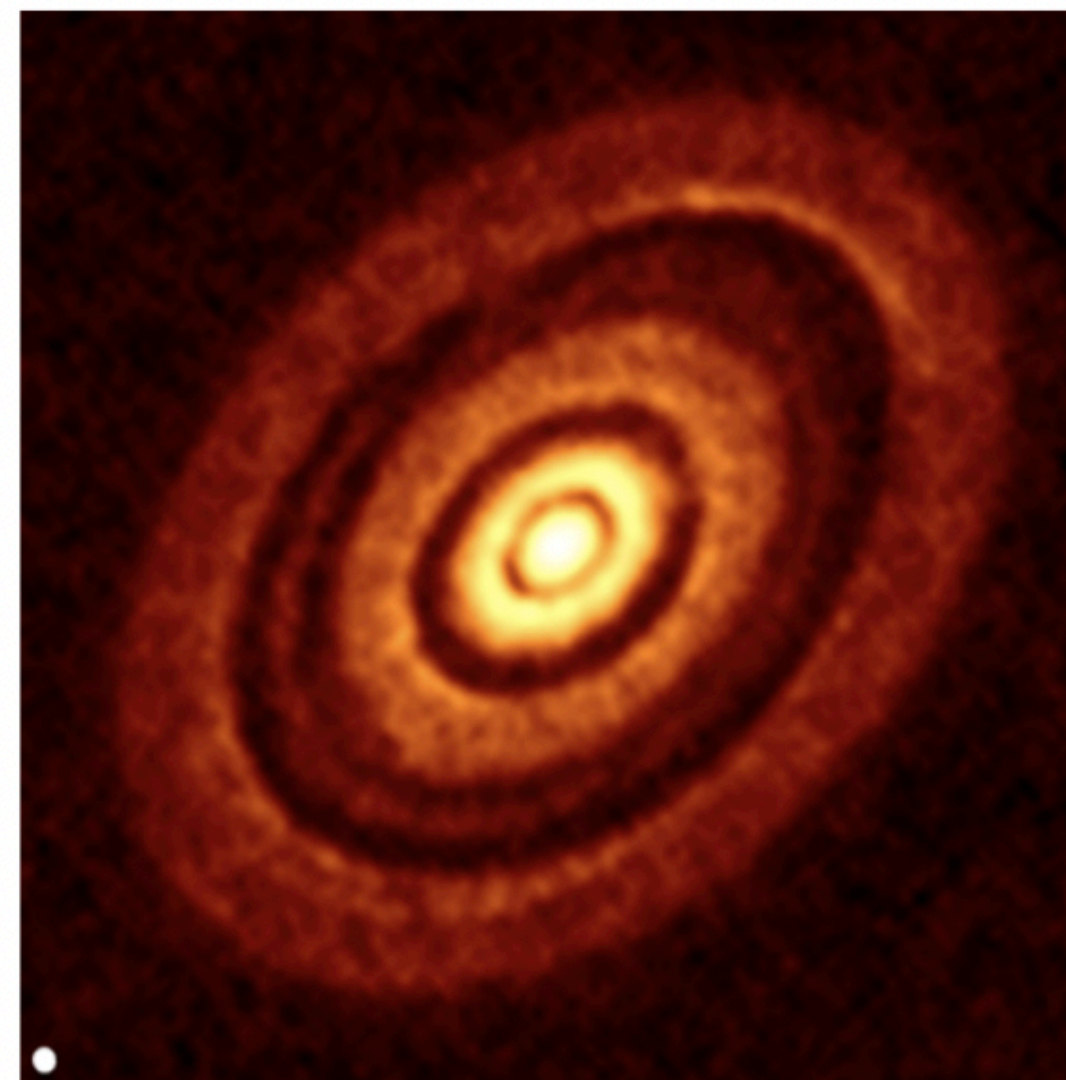
**Computer
simulation**

(Chen & Lin, 2018)

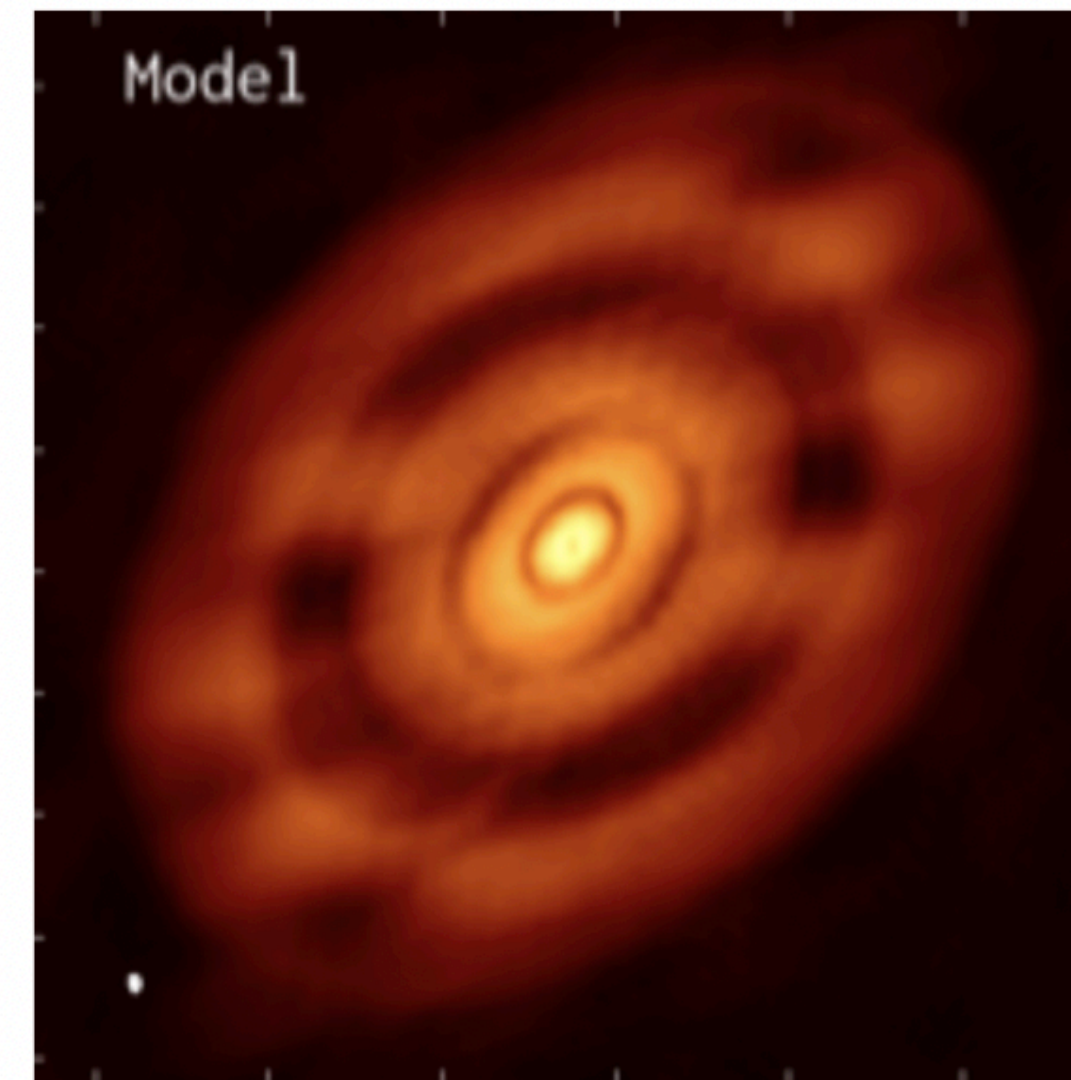
**Simulation
+
synthetic obs.**



Dong et al. 2015



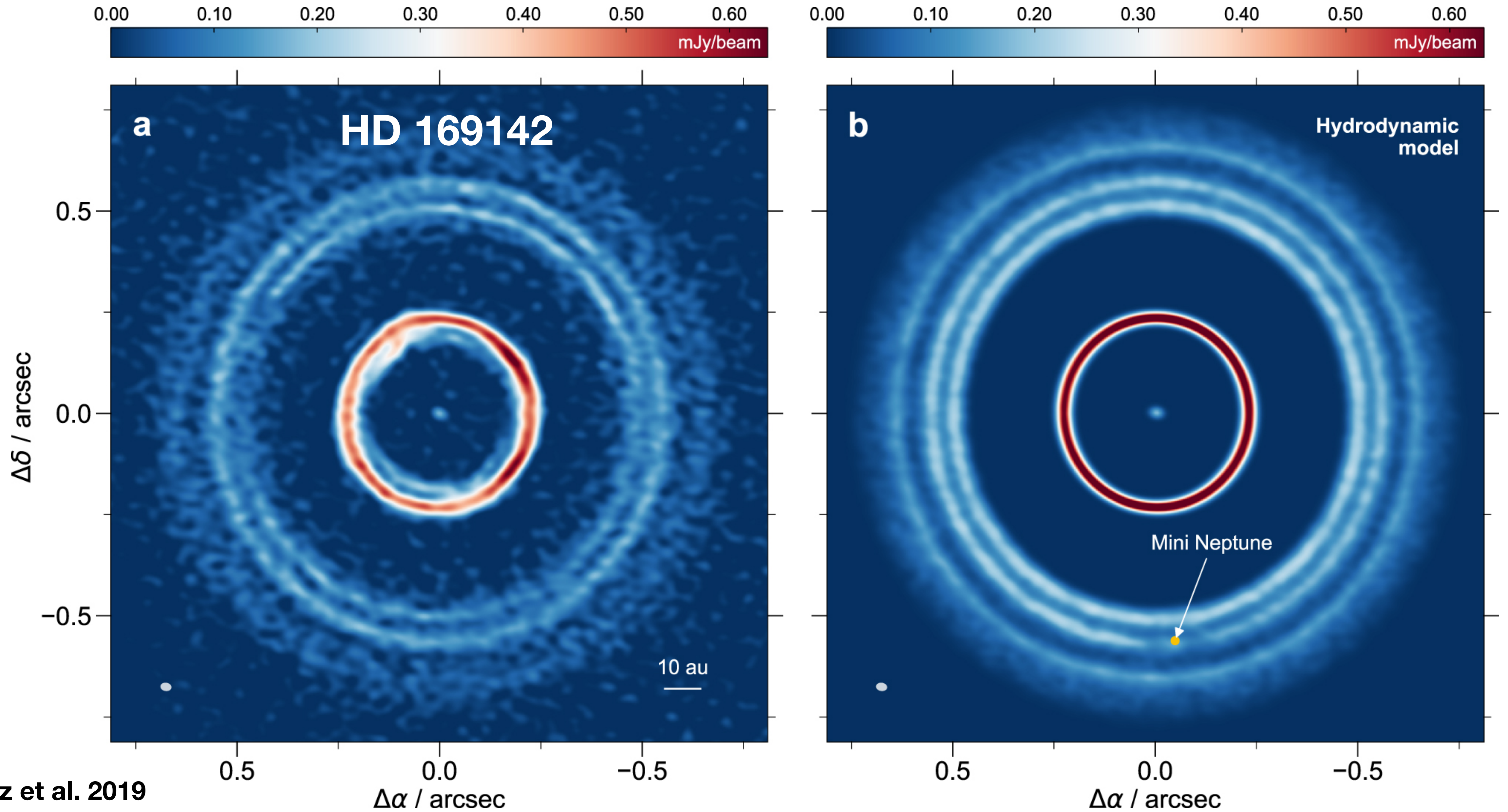
Dipierro et al. 2015



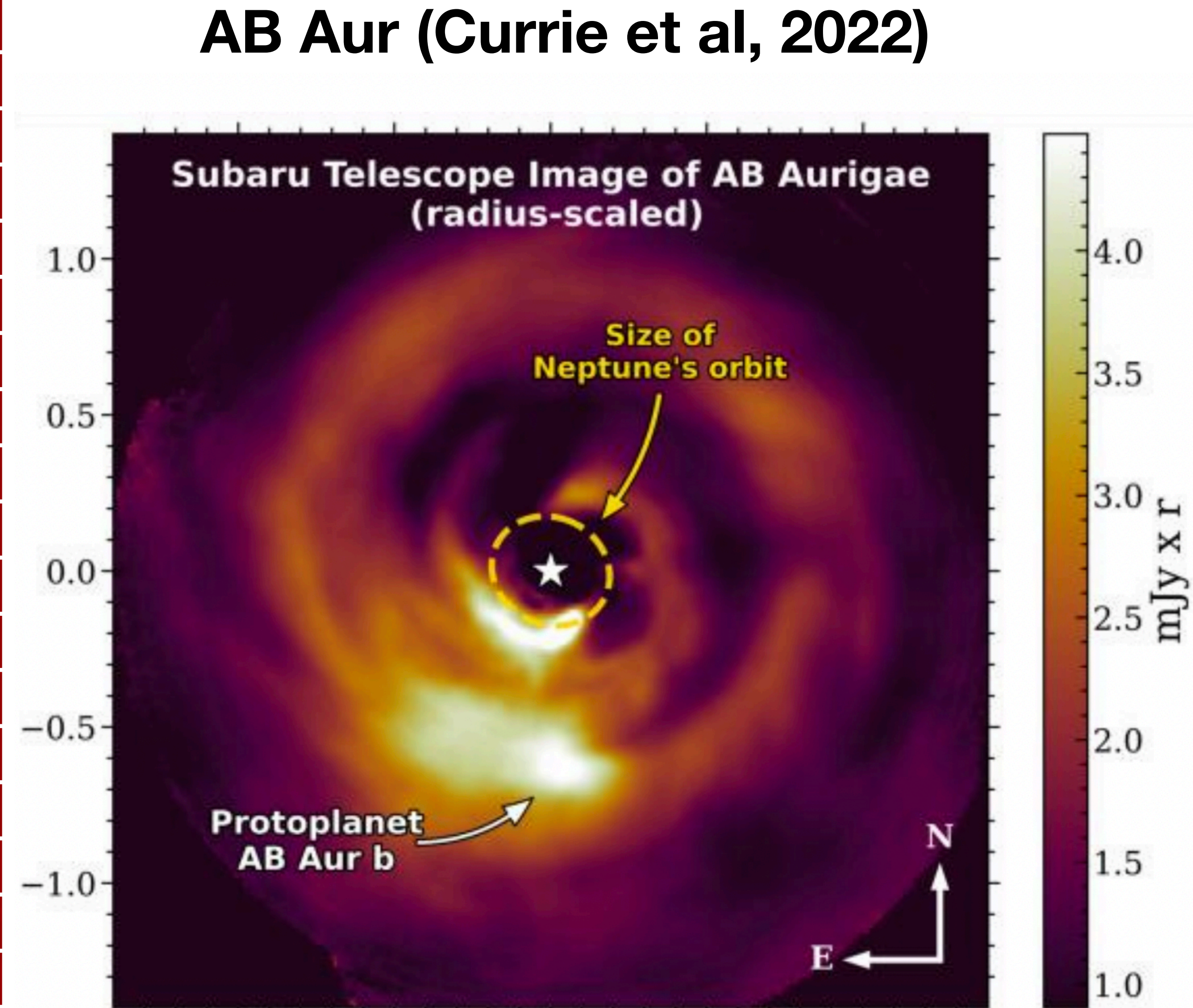
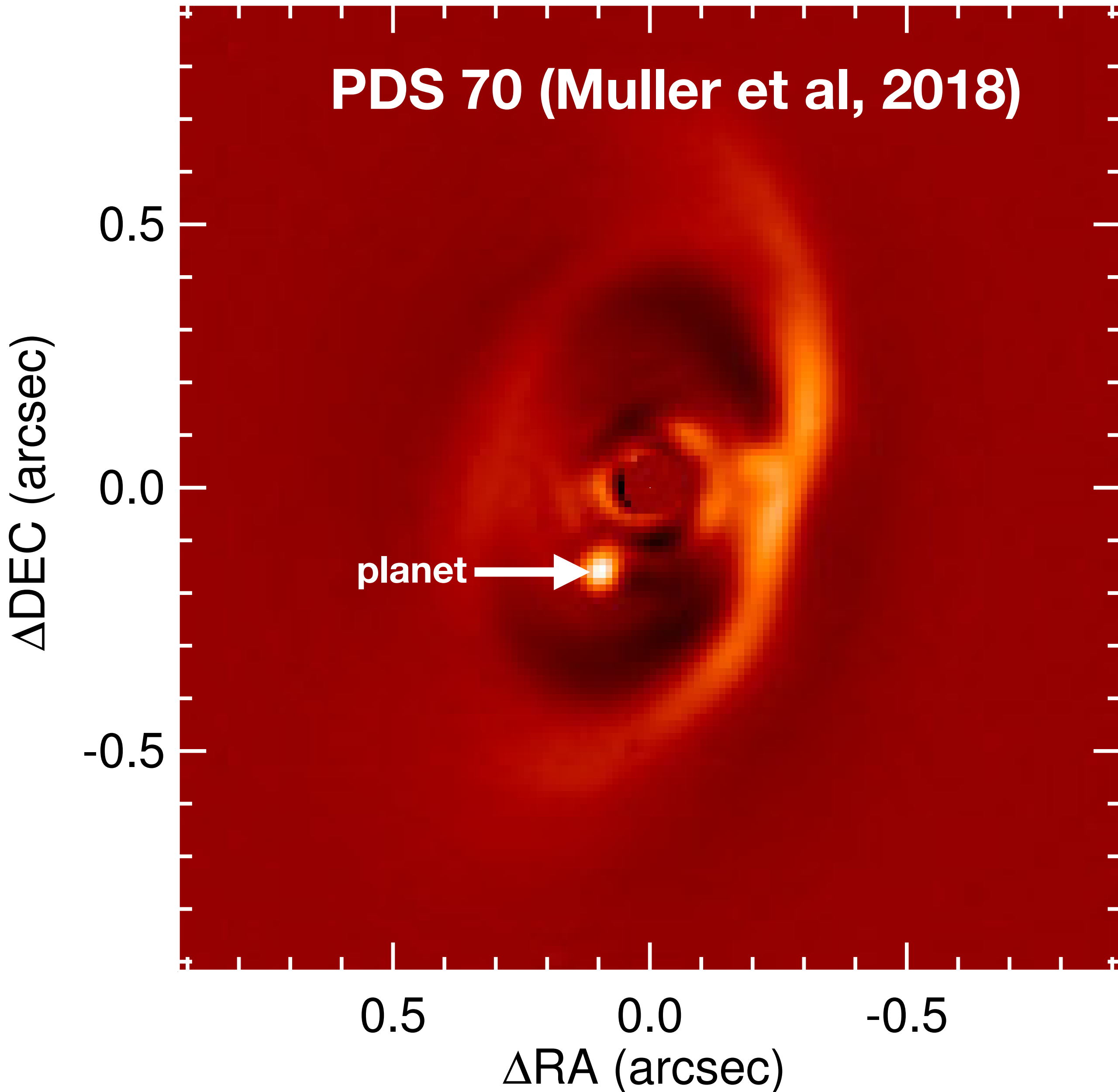
Jin et al. 2016

(Paardekooper et al., 2022, PPVII)

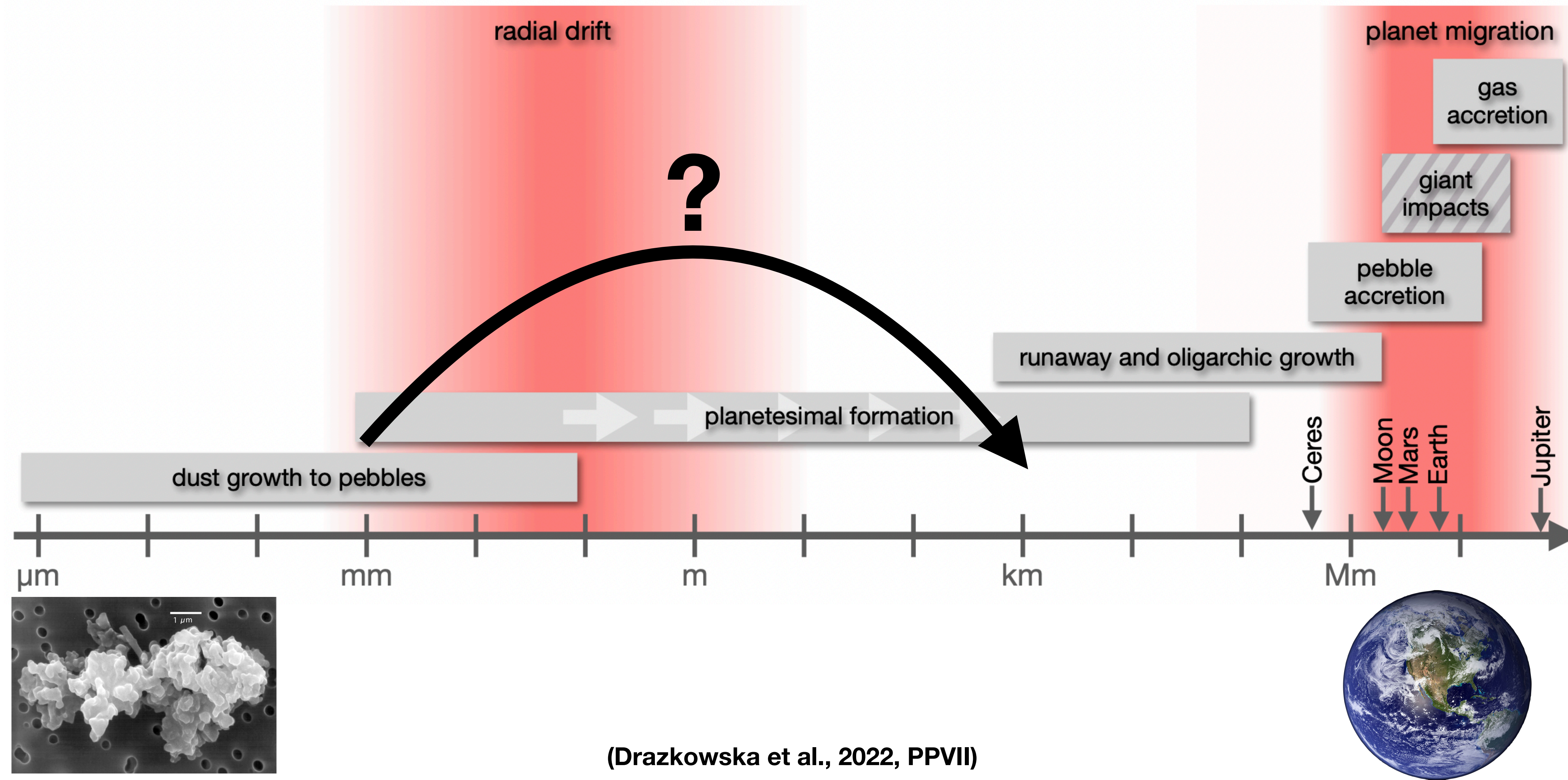
Detecting planets via sub-structures



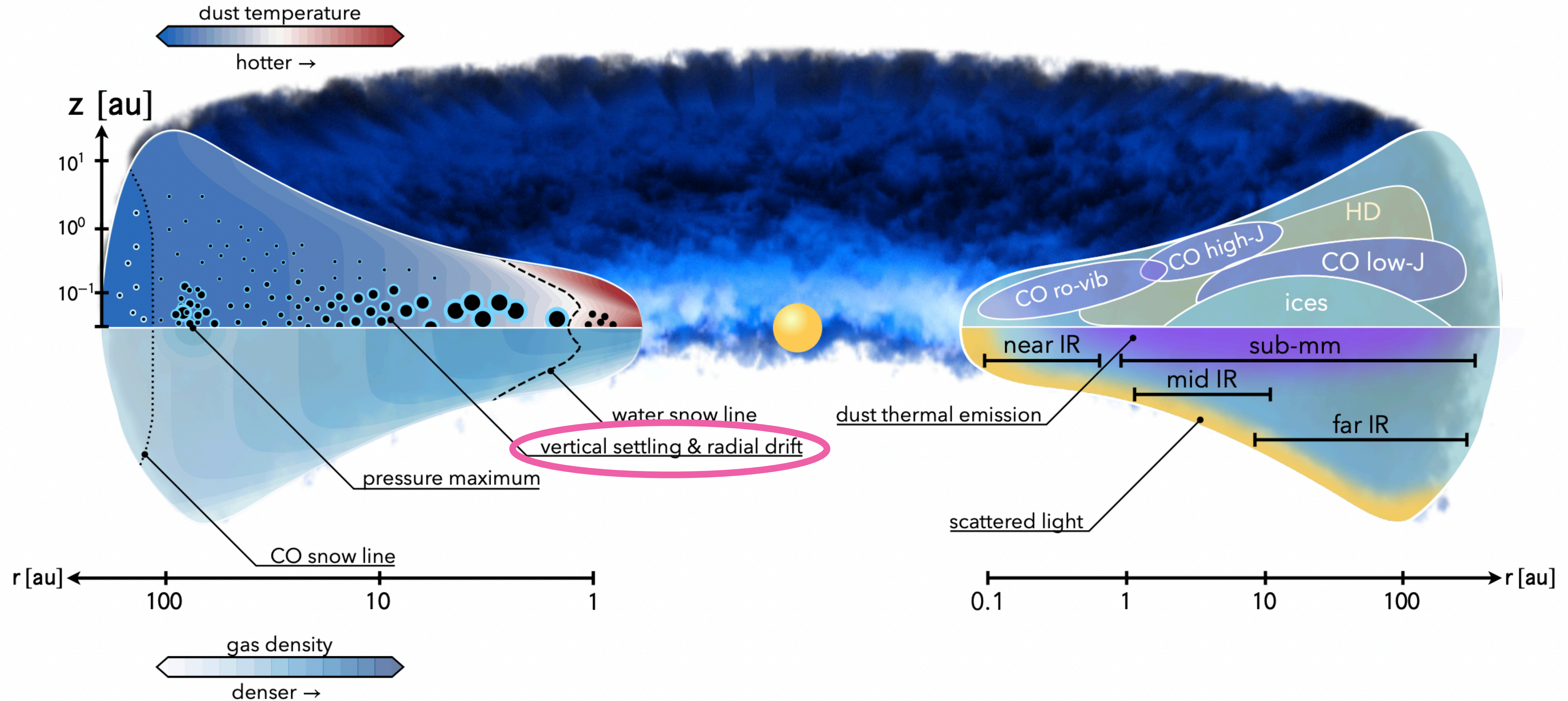
Observations of planets in a disk



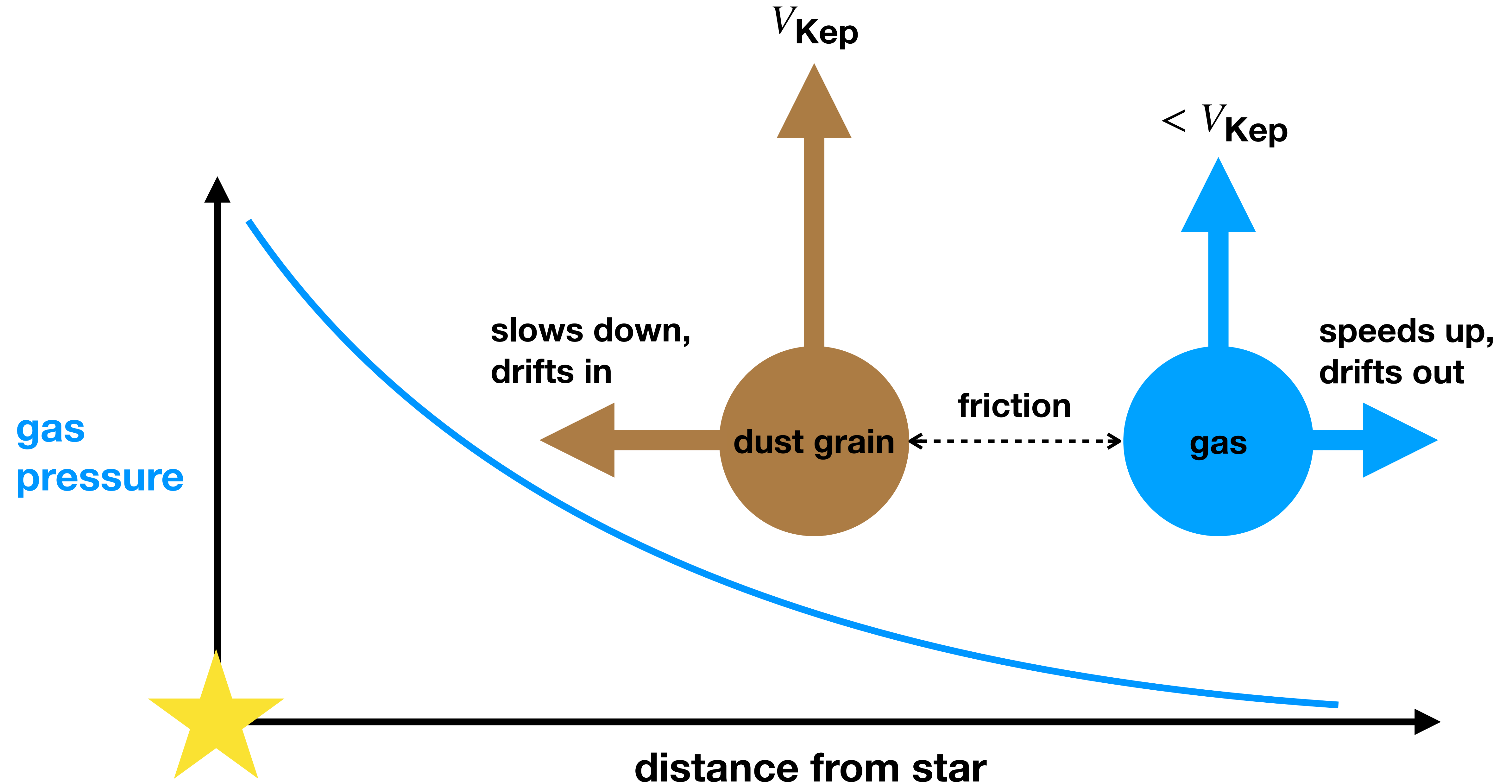
One planet, multiple scales



Dust in protoplanetary disks

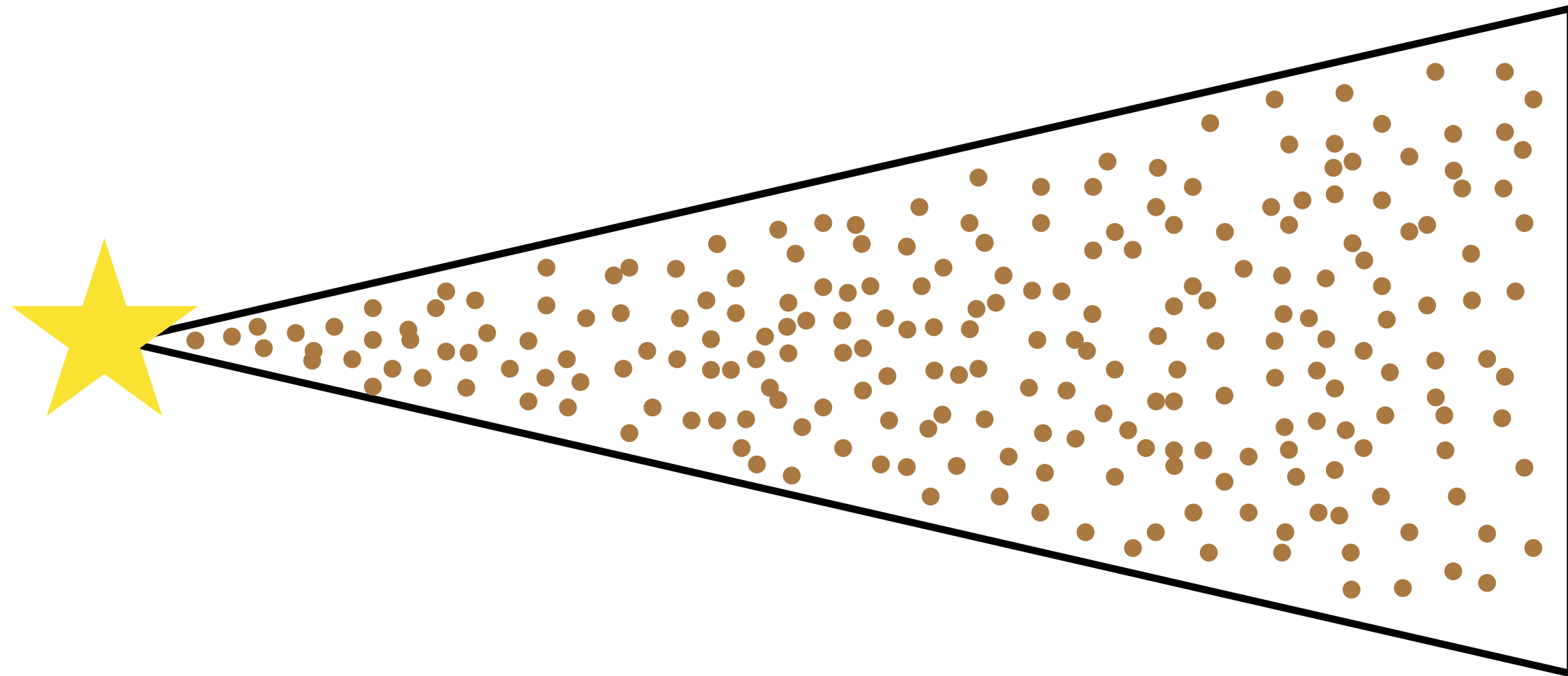


Radial drift of dust grains

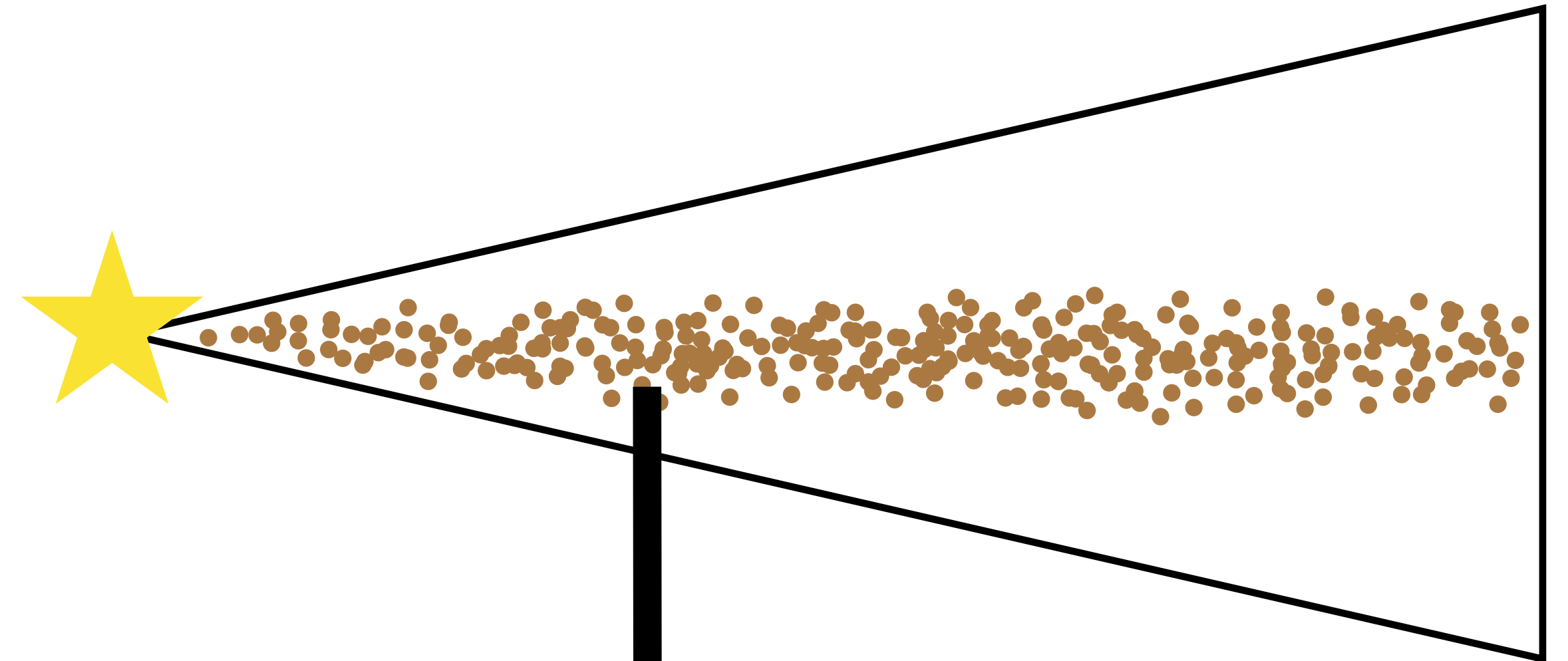


Vertical dust settling

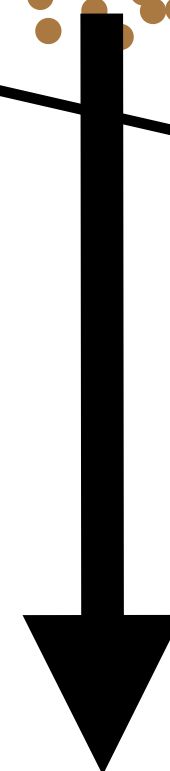
well-mixed dust in young disk



dust sediments to the midplane

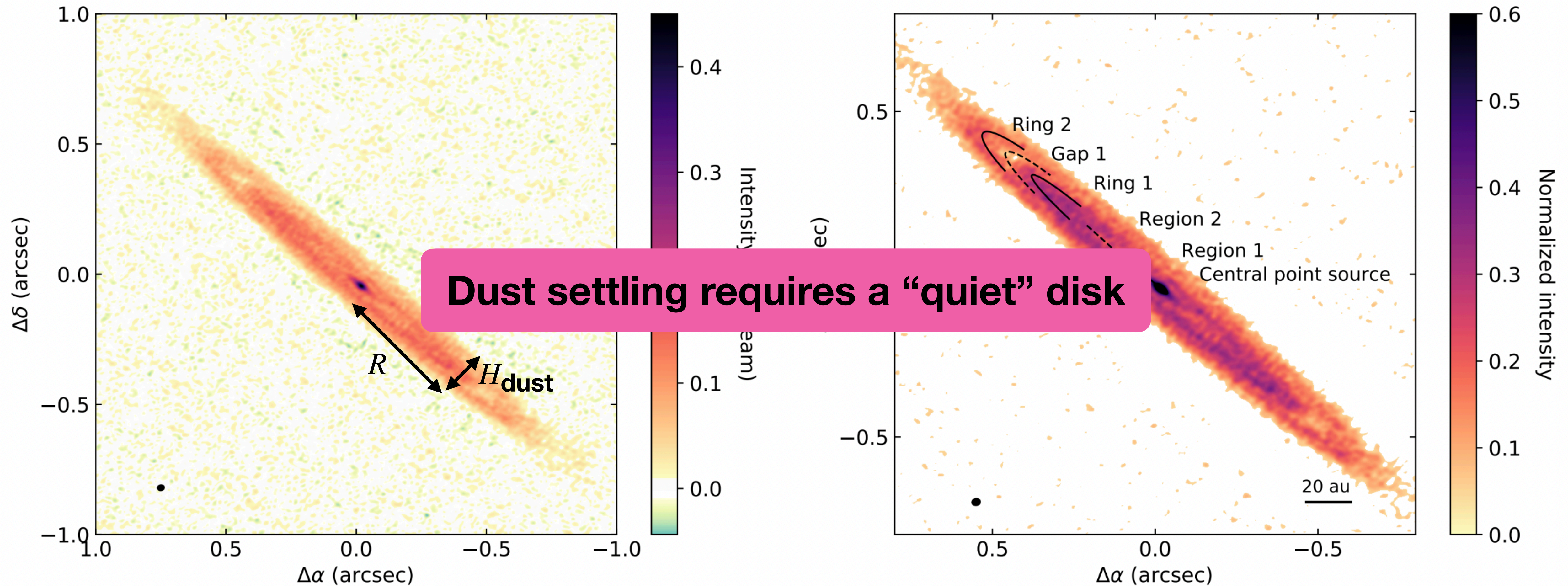


planet(esimal) formation



Edge on disk observations

Oph 163131 (Villenave et al. 2022)

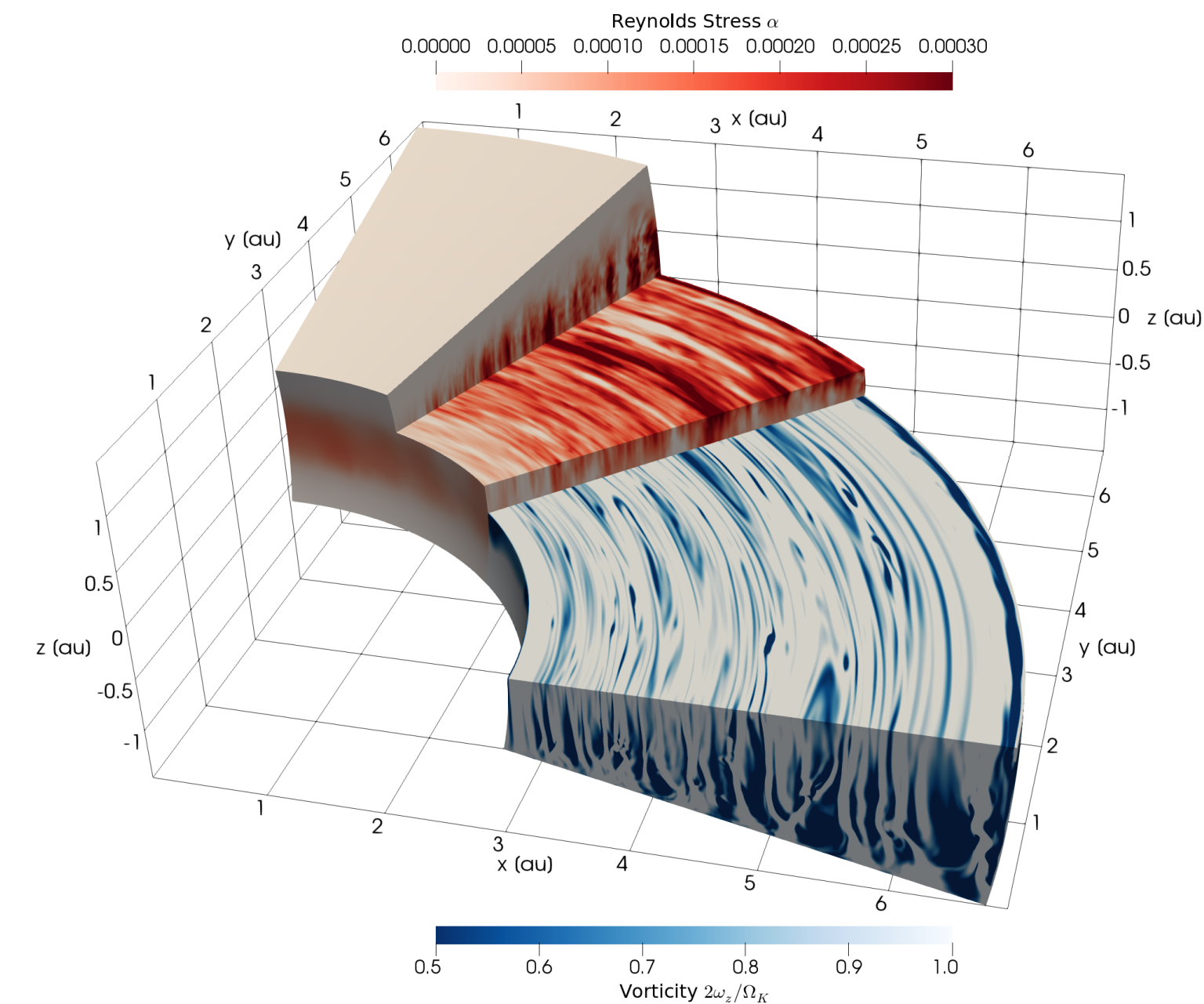


Dust settling requires a “quiet” disk

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

PPDs are (weakly) turbulent

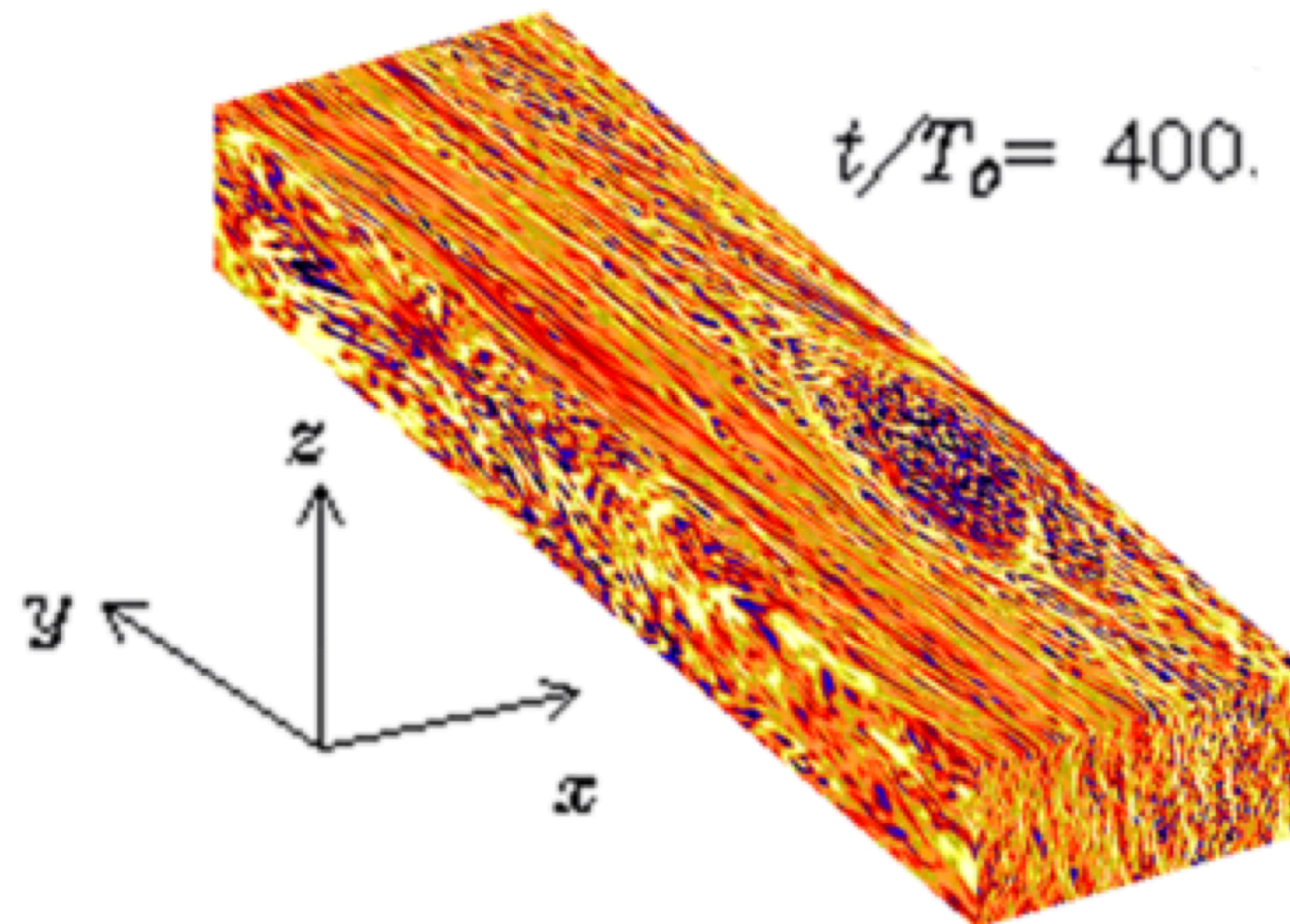
Vertical shear instability



Pfeil & Klahr (2020)

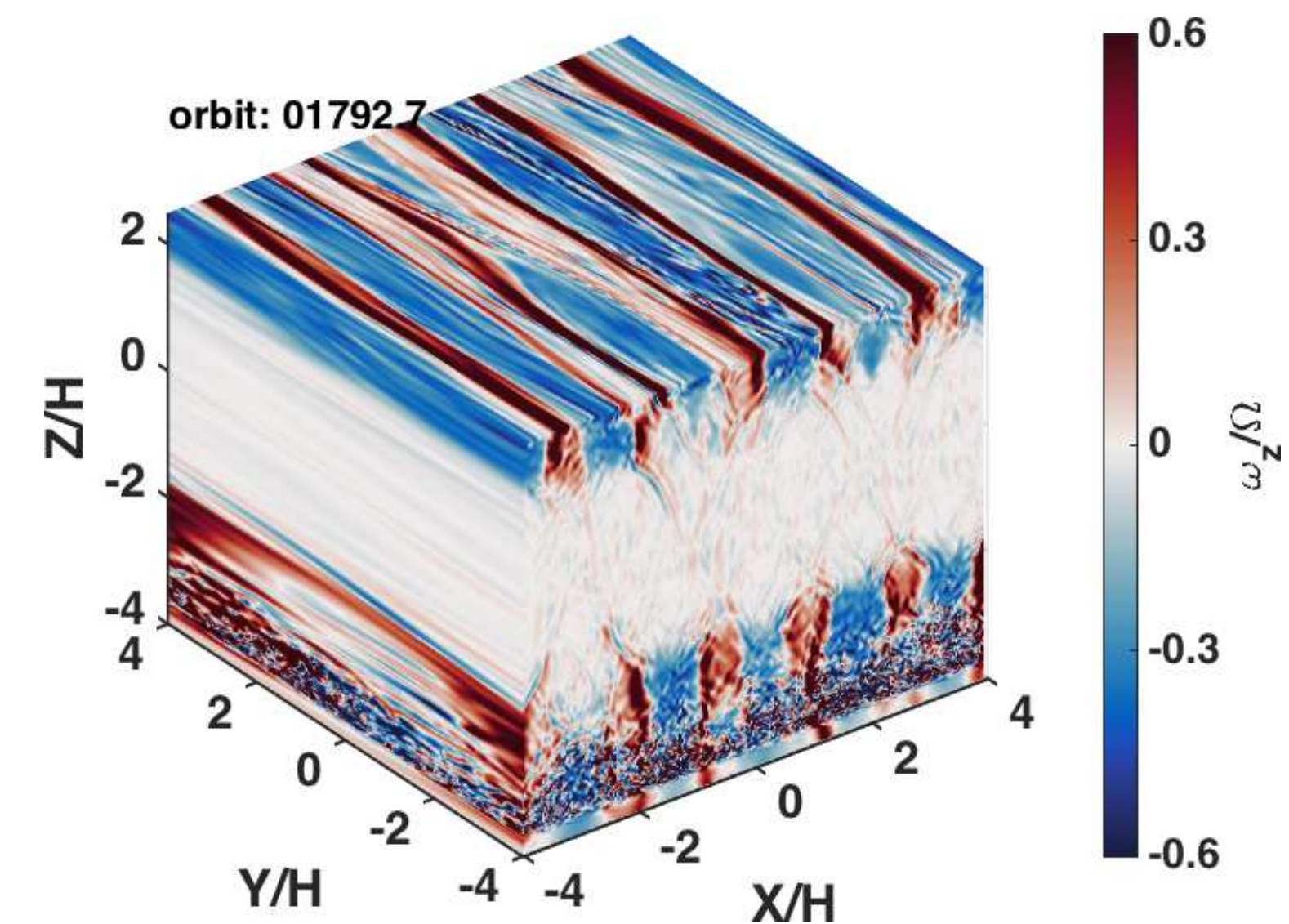
Lin & Youdin (2015)
Cui & Lin (2021)

Convective overstability



Lyra (2014)

Zombie vortex instability



Barranco et al. (2018)

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

Dust settling vs. turbulence

time= 0.00 ORB

$$M_{\text{dust}} = 0.01 M_{\text{gas}}$$

$$M_{\text{dust}} = 0.05 M_{\text{gas}}$$

z/H_g

2
1
0
-1
-2

0.9

1.0
 R/R_0

1.1

0.9

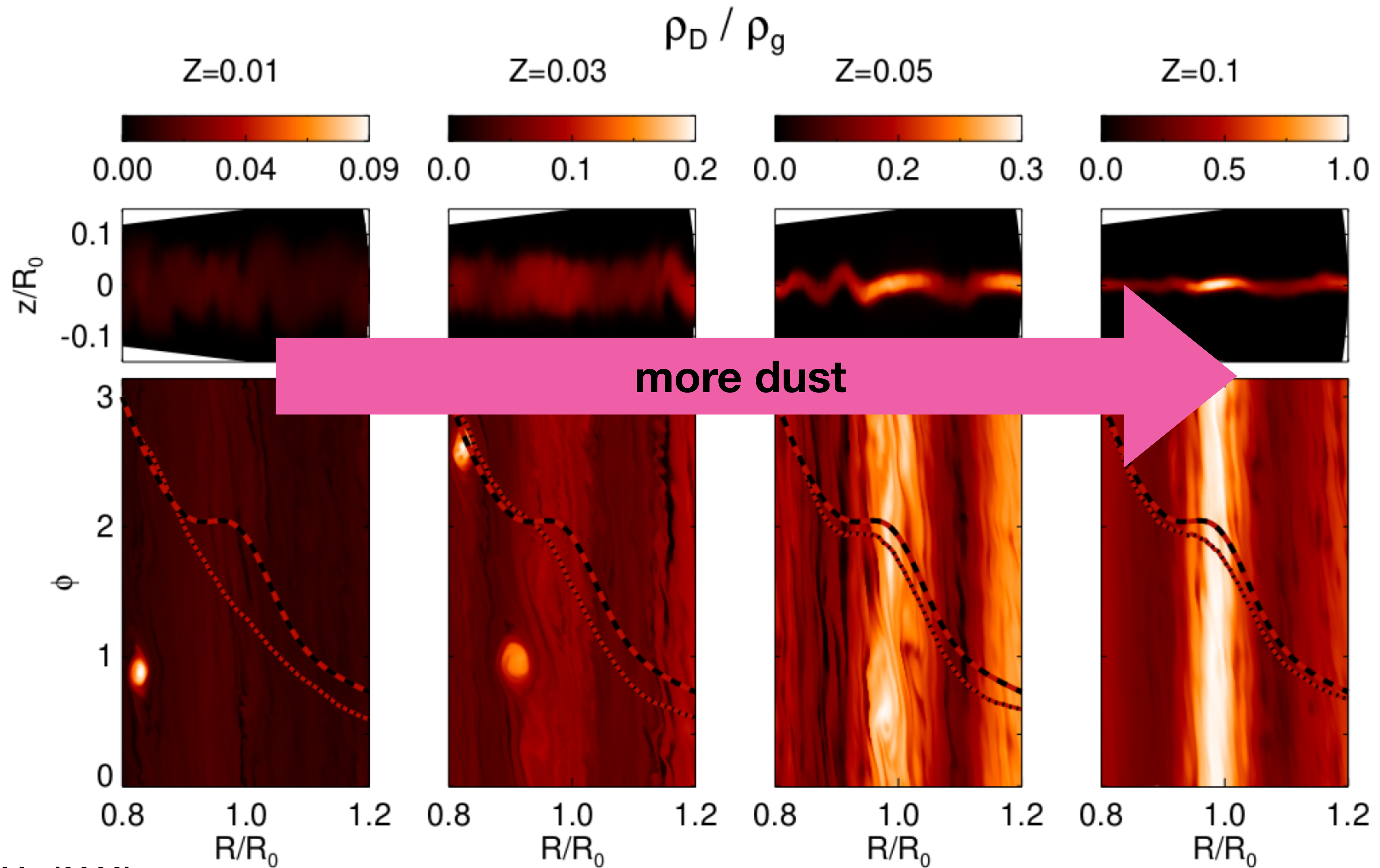
1.0
 R/R_0

1.1

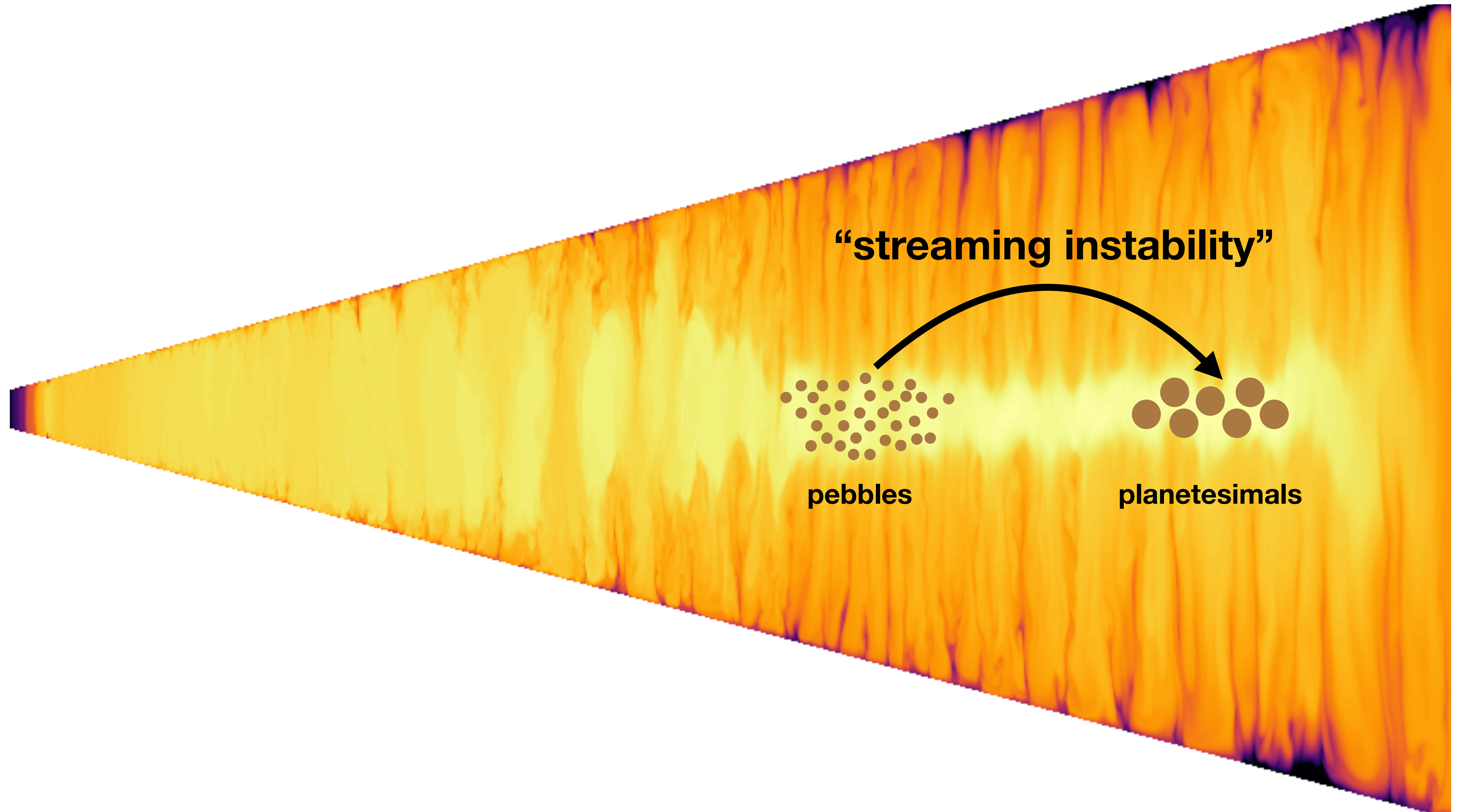


Lehmann & Lin (2022)

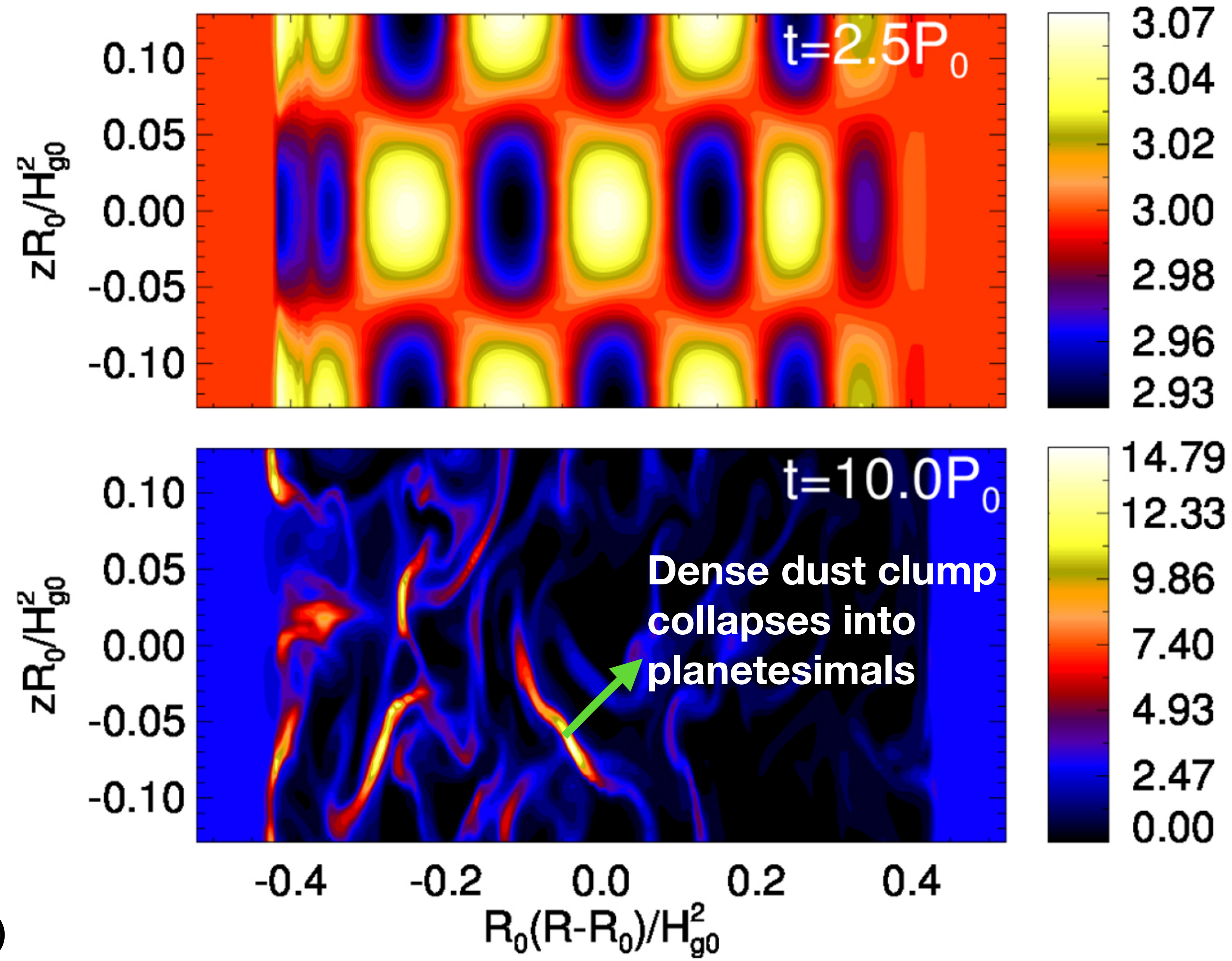
Dust rings or vortices?



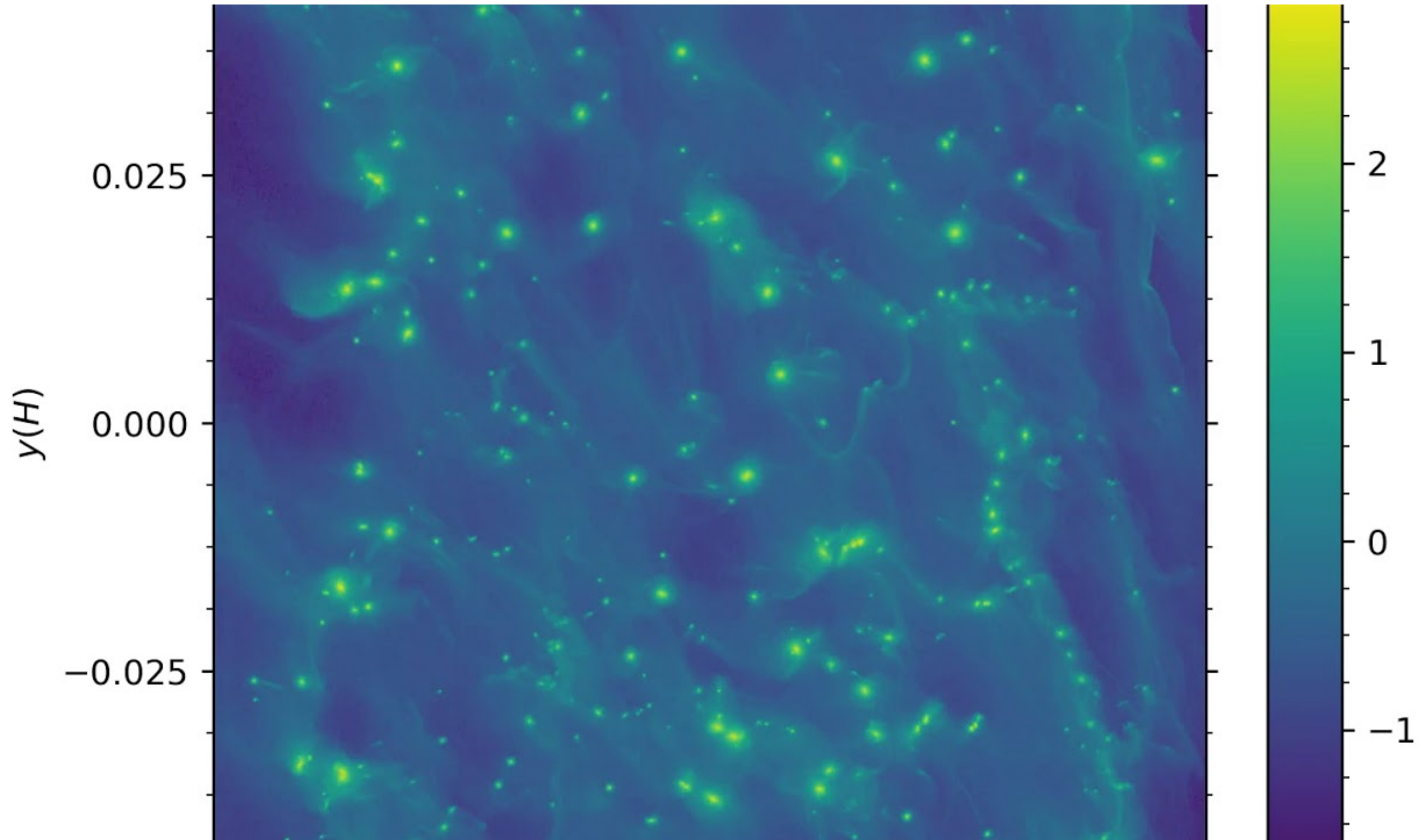
Planetesimal formation in the mid-plane



Streaming instability of dusty gas



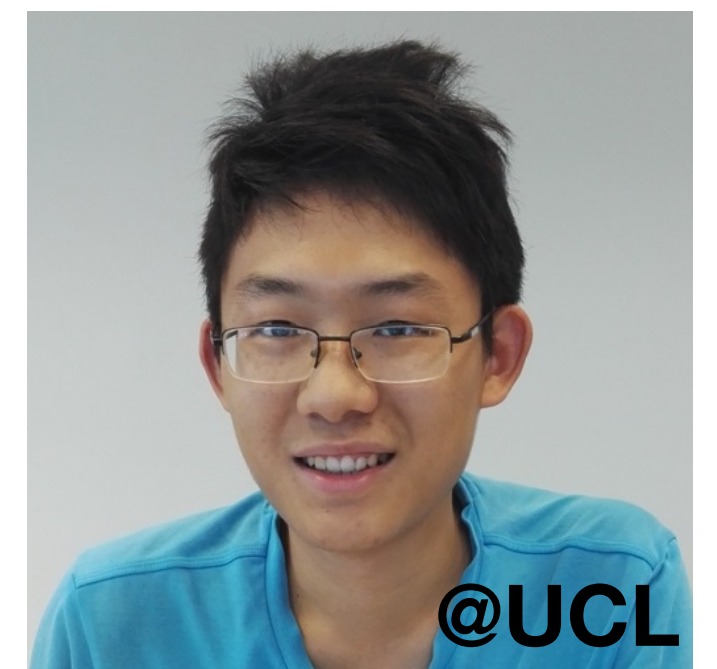
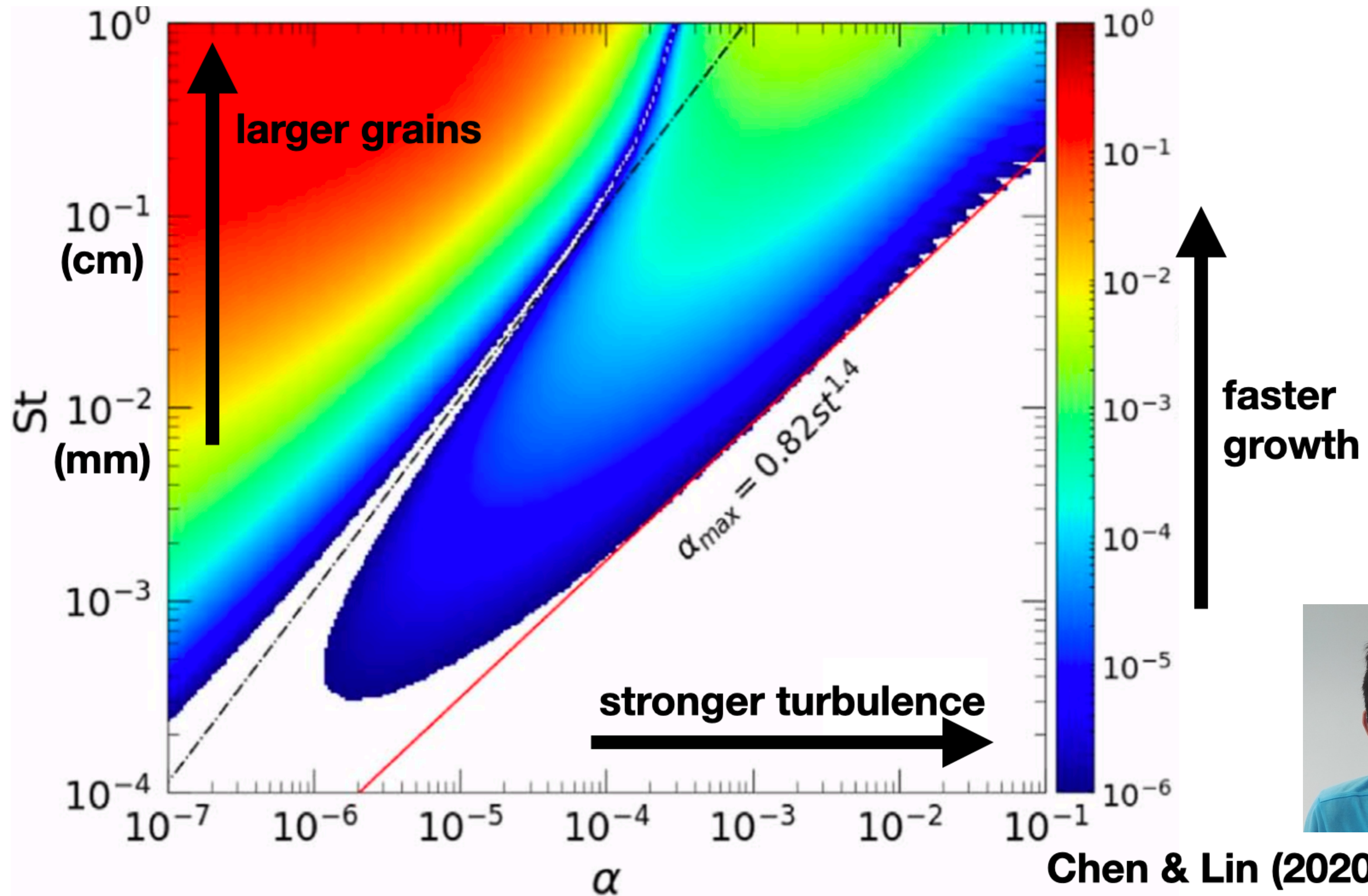
State-of-the-art simulations (Nesvorný et al., 2020)



The ideal SI

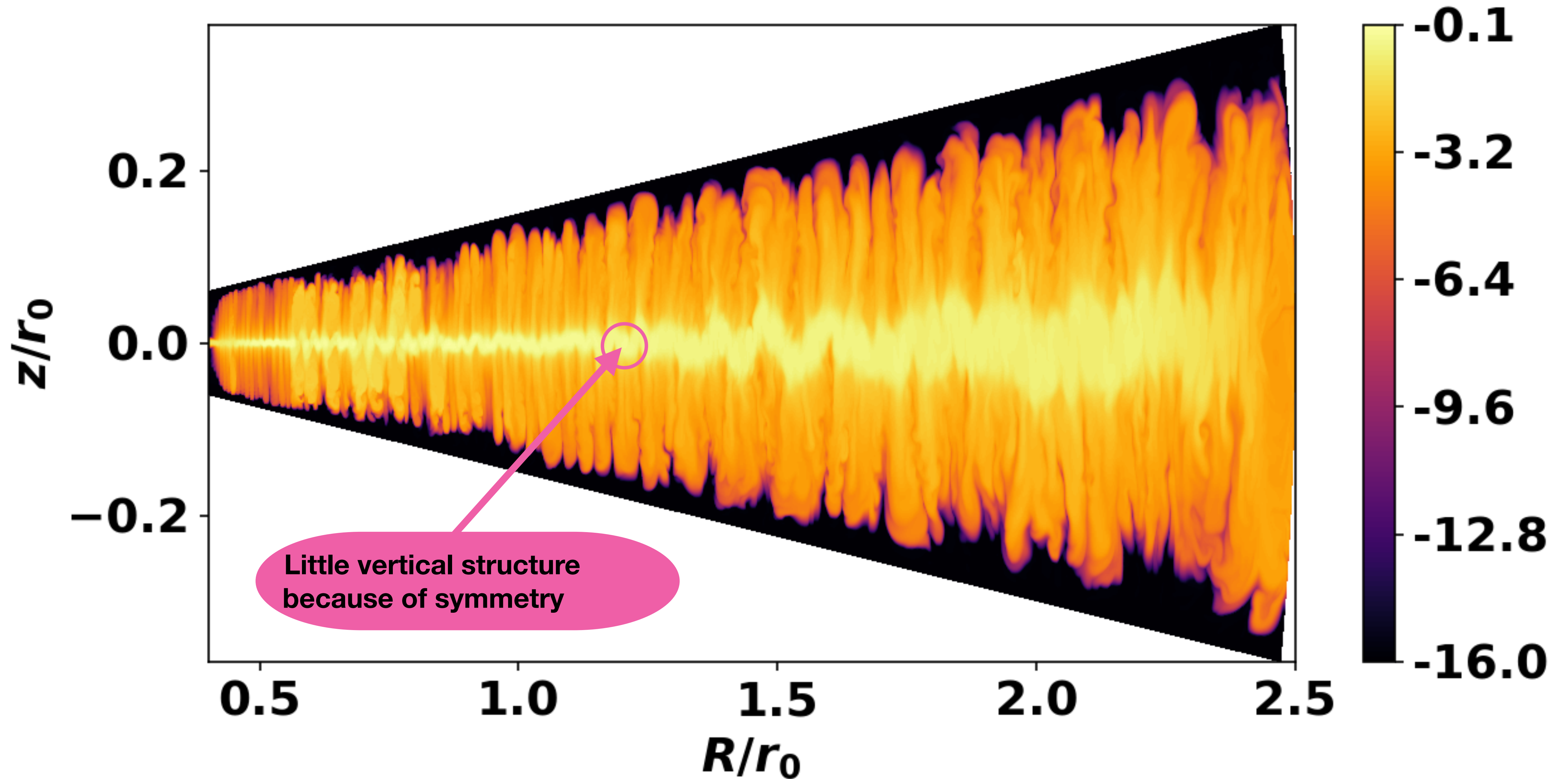
- **disk is non-turbulent** → **Chen & Lin (2020)**
- **disk has no vertical structure** → **Lin (2021)**
- **disk is unmagnetized** → **Lin & Hsu (2022)**
Hsu & Lin (2022)

Streaming instability is easily killed by turbulent viscosity

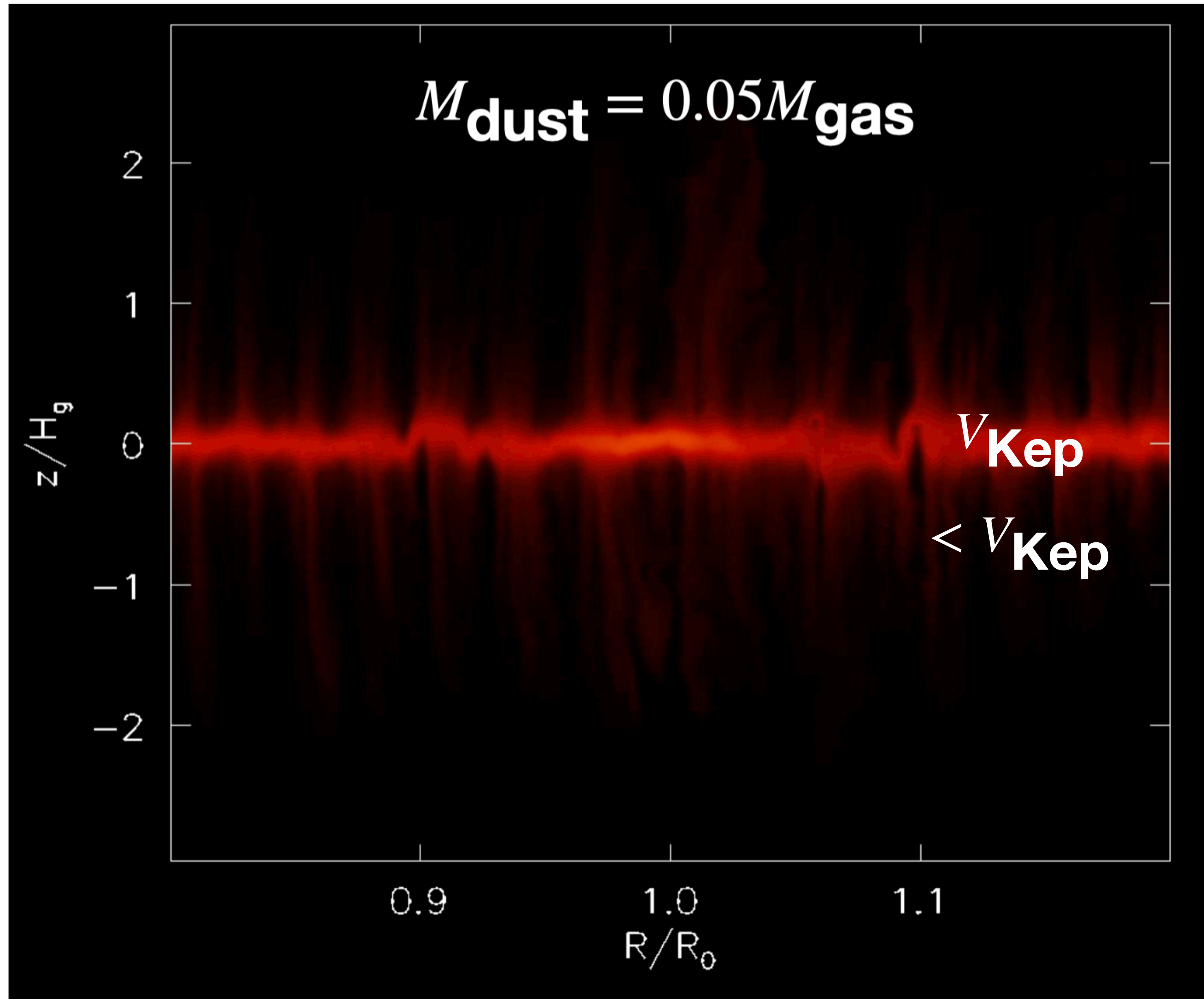


Chen & Lin (2020)

SI analyses use unstratified disk models



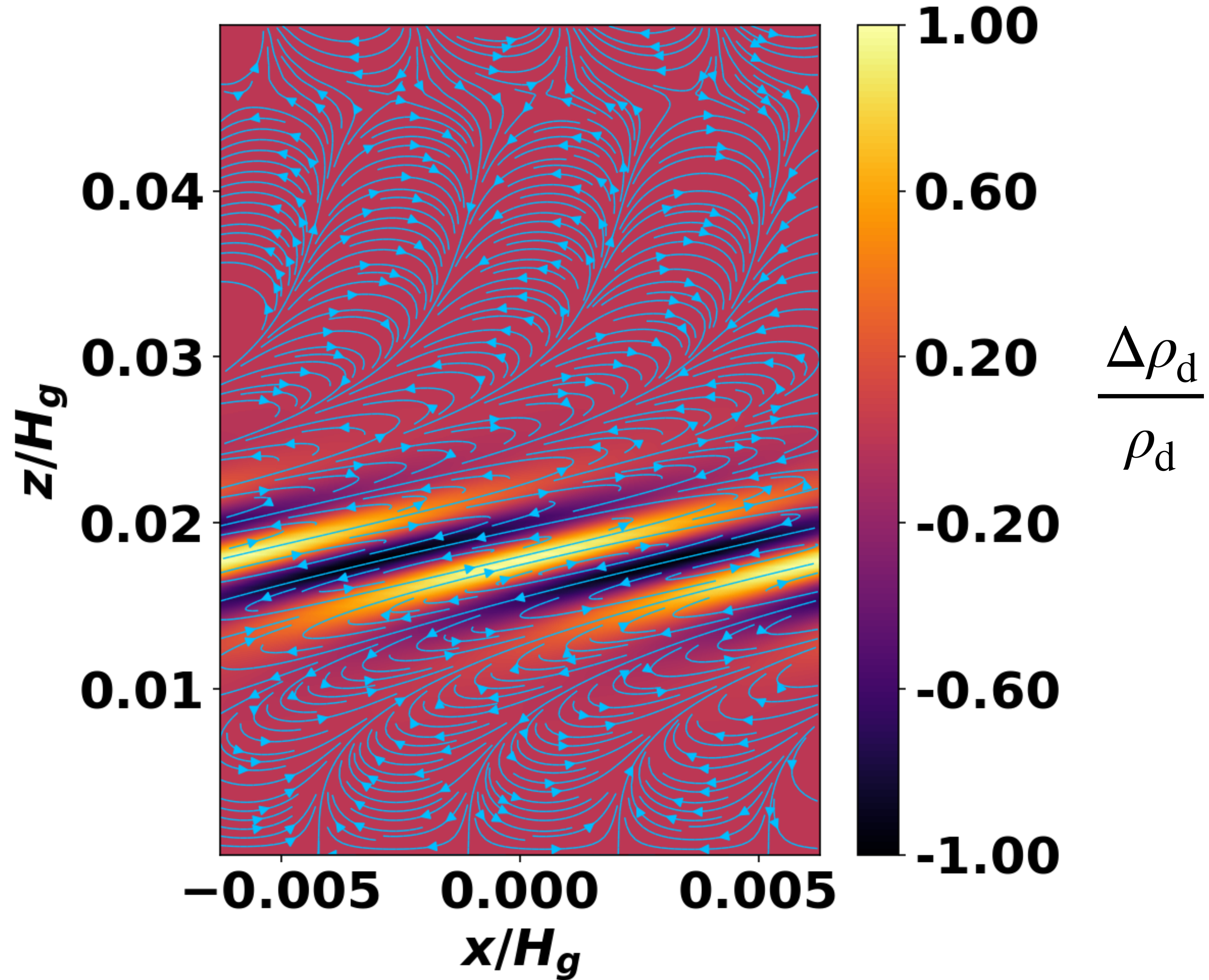
Stratified dust layers



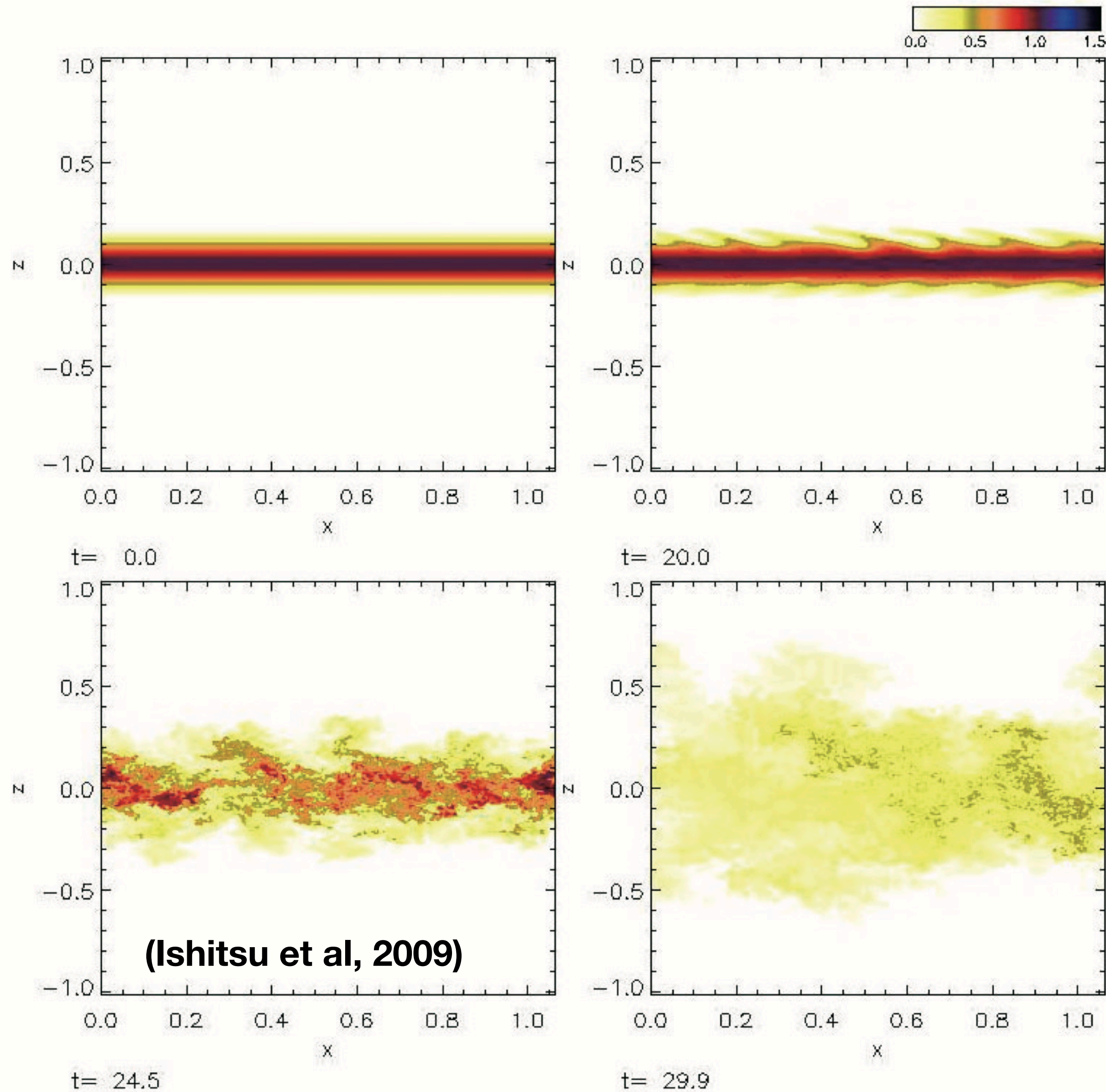
$$\frac{\partial \Omega}{\partial z} \neq 0$$

“Vertically shearing SI” in stratified disks

$$S_{\text{grow}} \sim \Omega$$



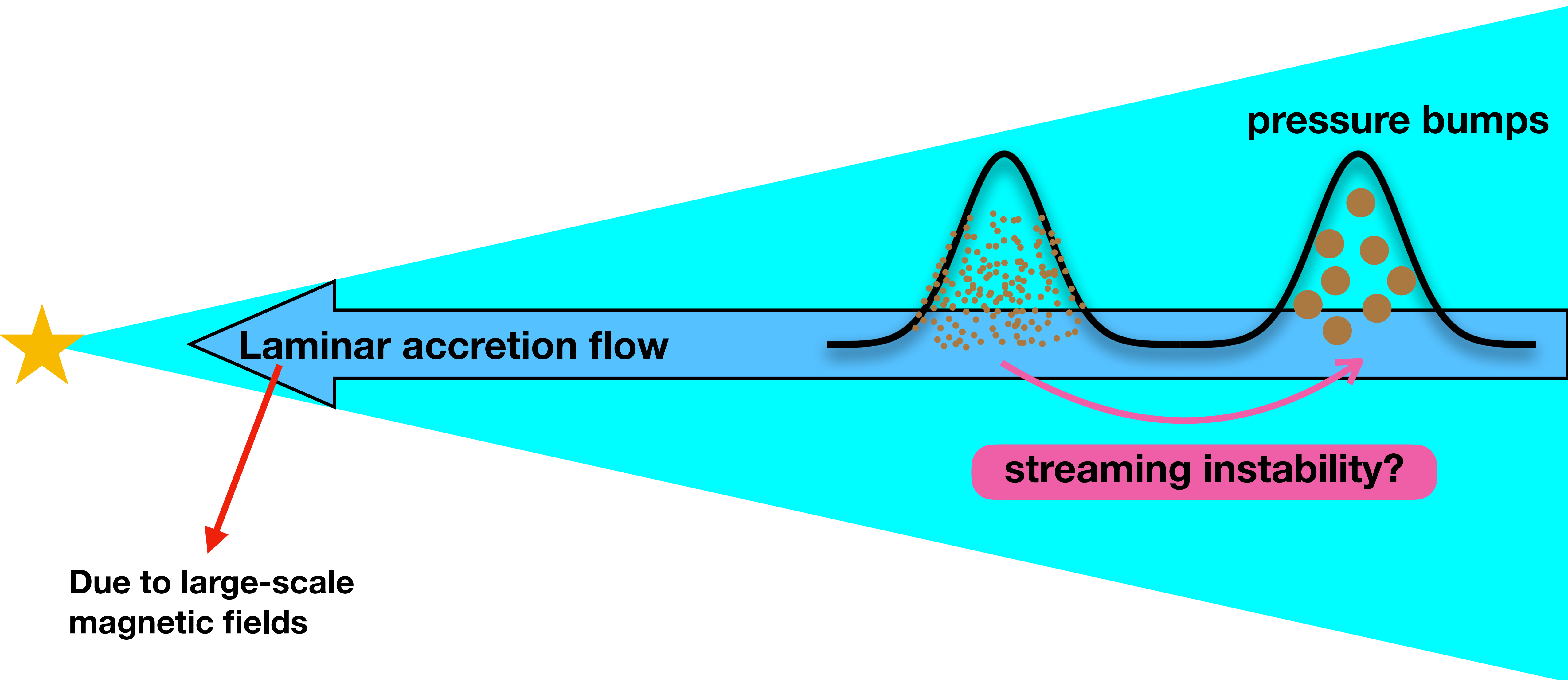
Vertically shearing SIs grow fast but...



dust layer
dispersed

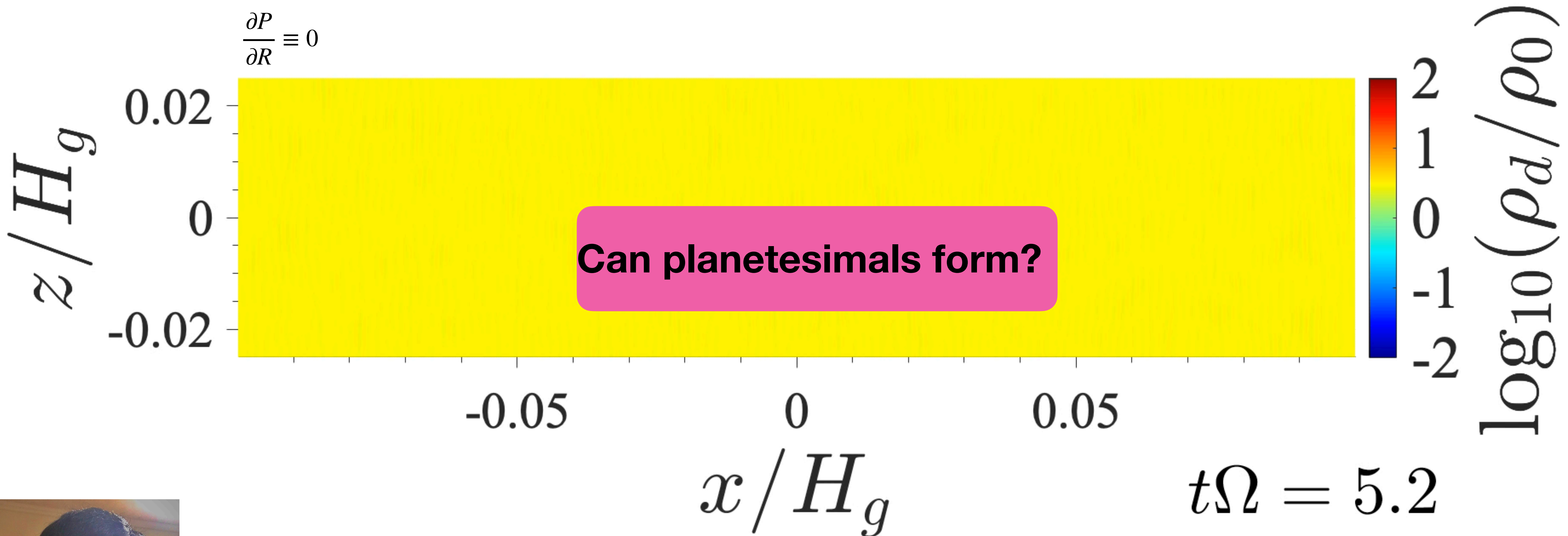


Can modern disk models help?

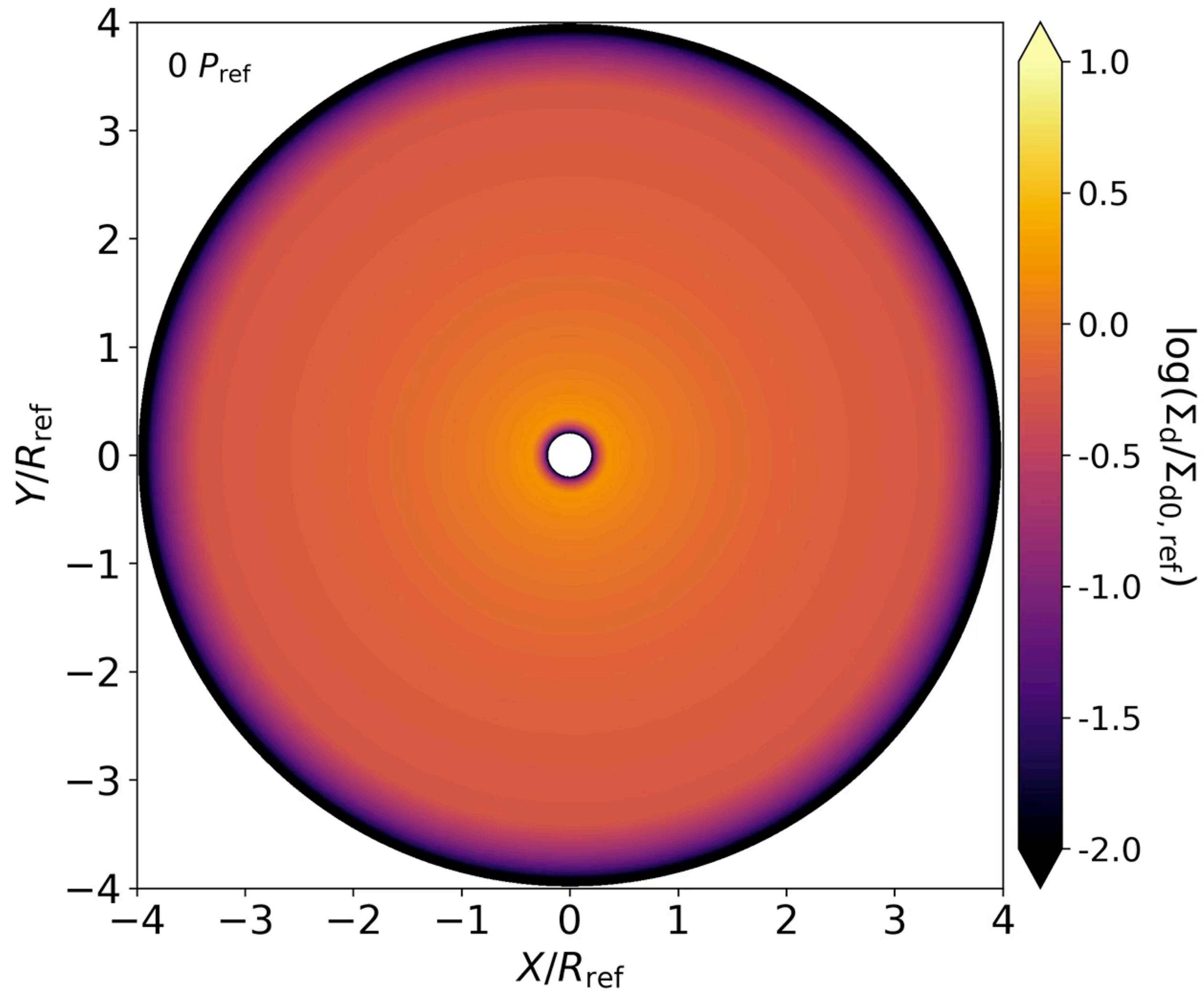


(e.g. Riols et al. 2020, Cui & Bai 2021)

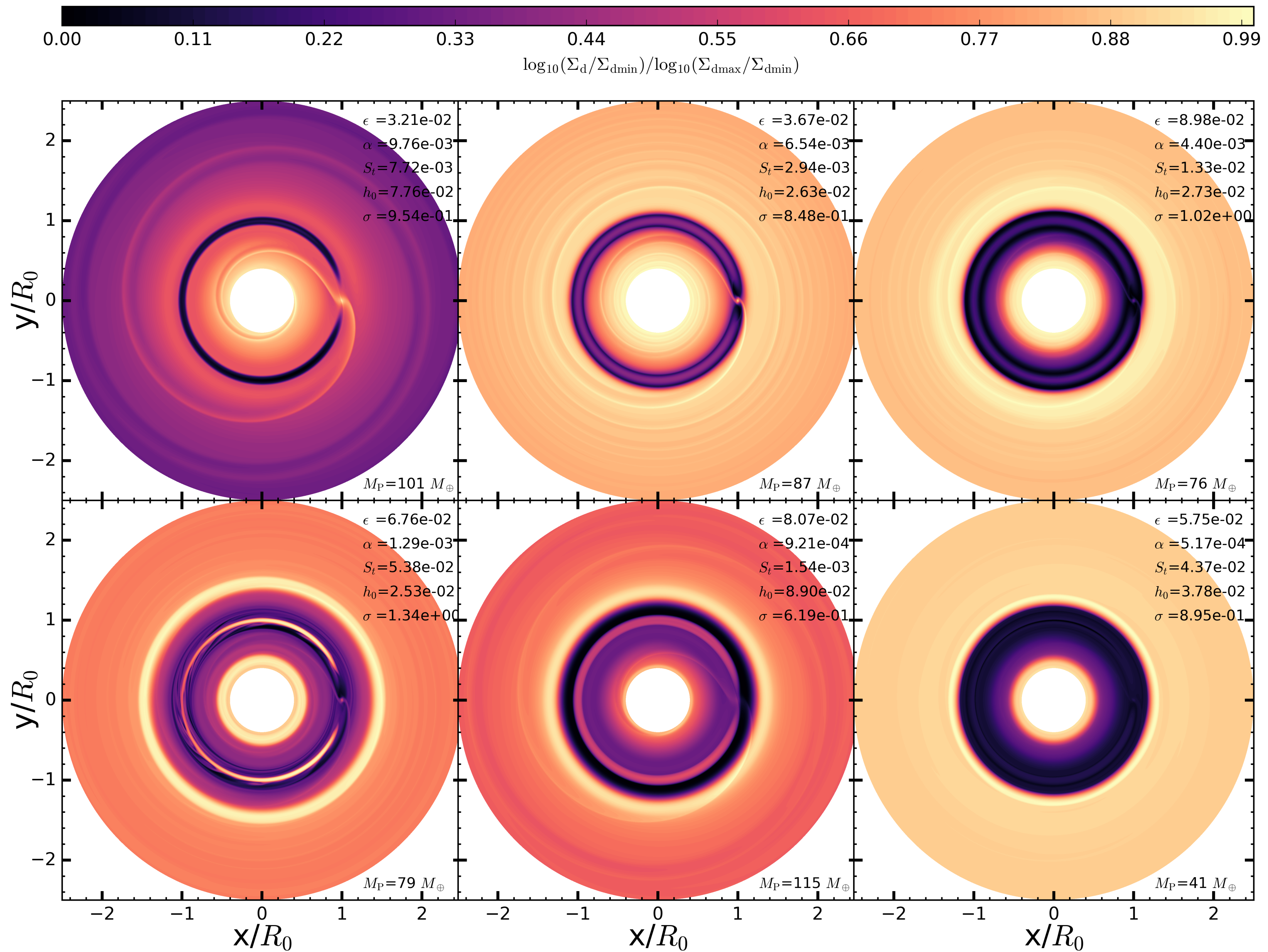
SI in a pressure bump with a background accretion flow



Planets form somehow, so what's next?

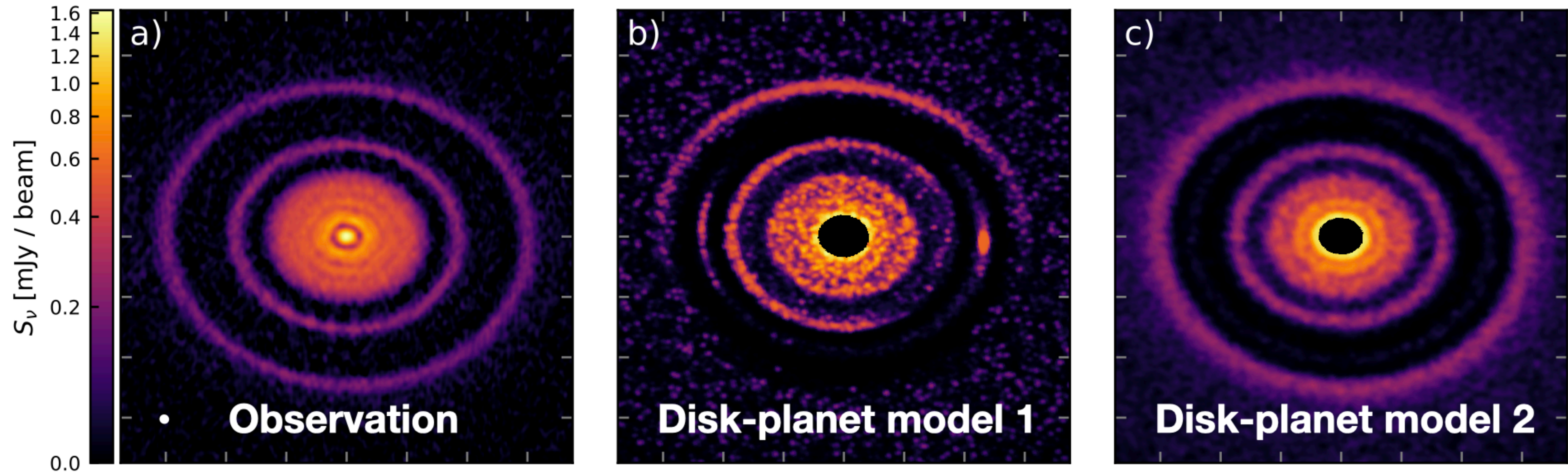


Disk-planet morphology



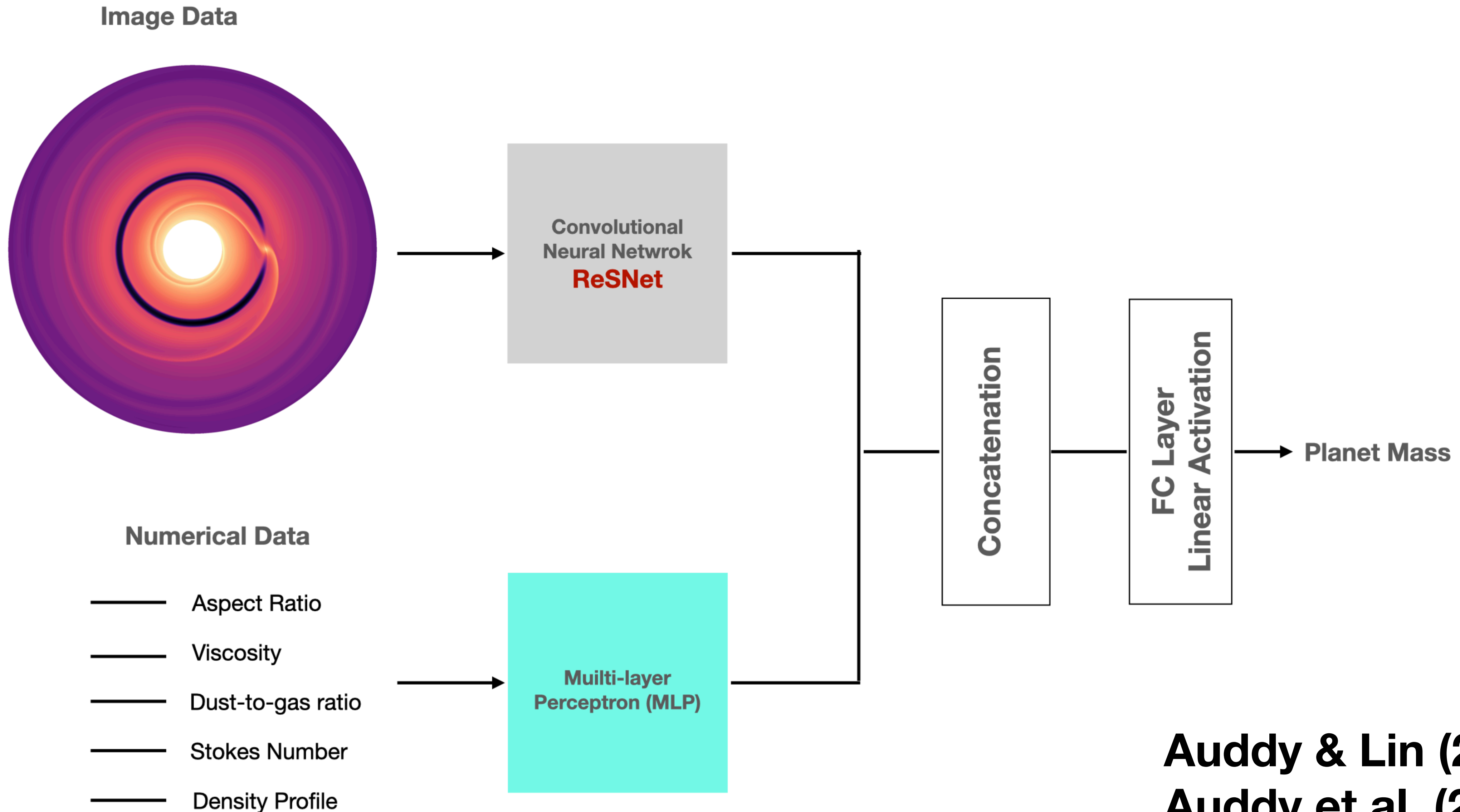
Detecting unseen planets via disk morphology

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)

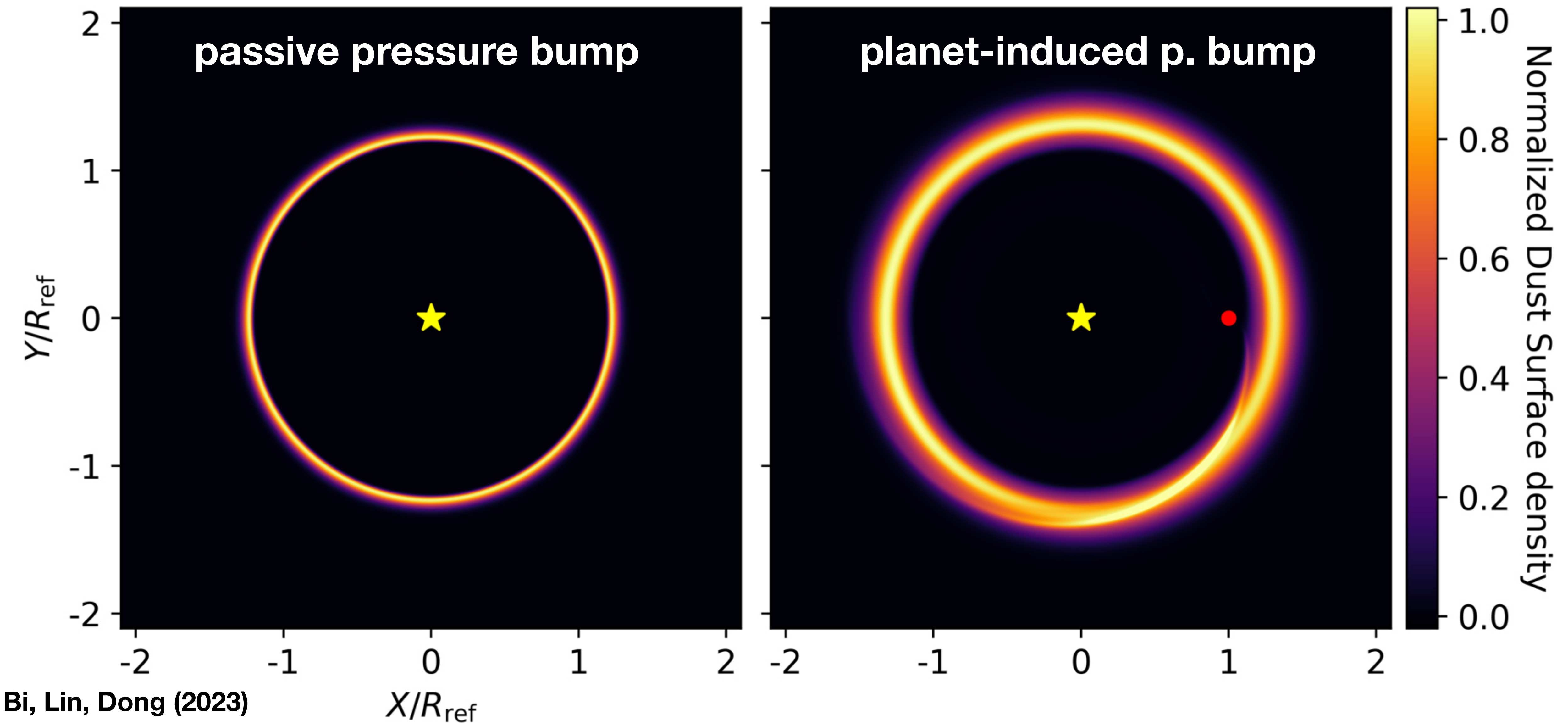
$$M_p = 0.2 - 0.35M_J, 0.17 - 0.27M_J, 0.2 - 0.55M_J$$

- **Disk-Planet Neural Network**

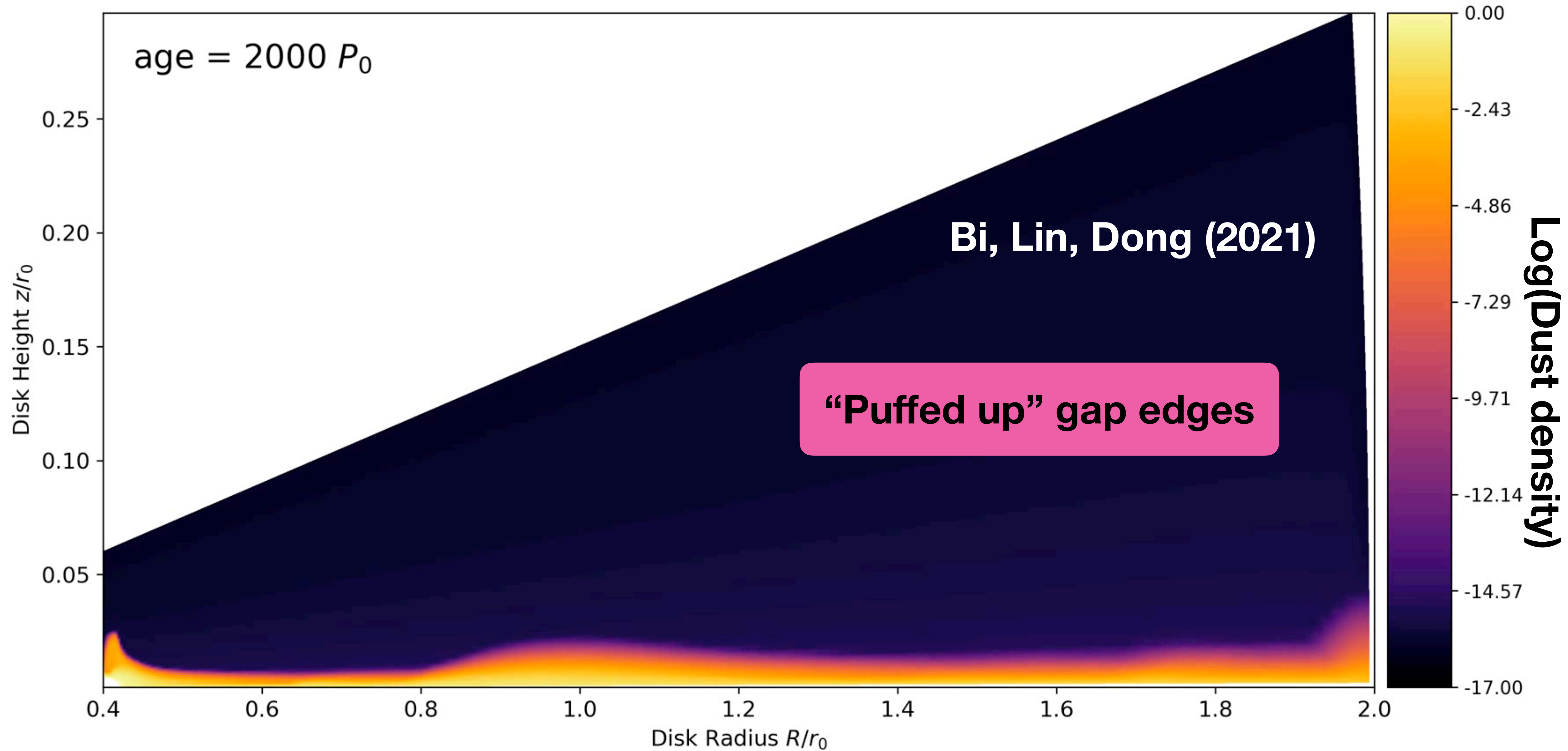
(Auddy & Lin, 2020)

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

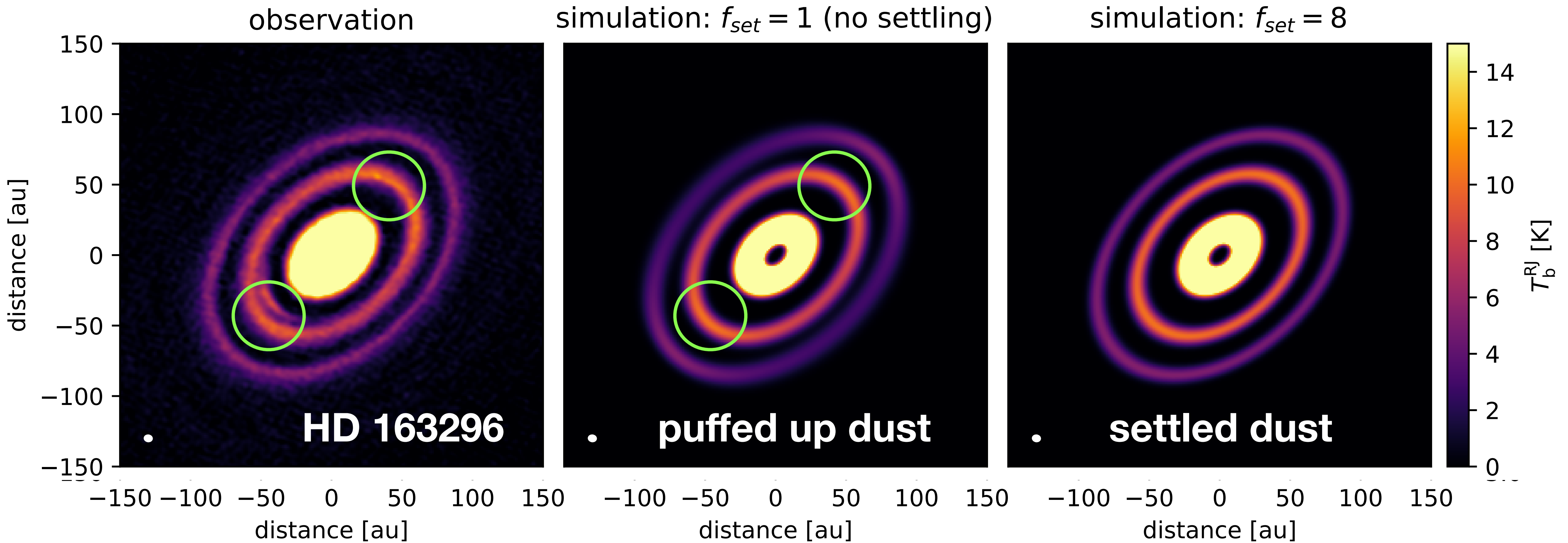
But are all observed dust rings caused by planets?



Three-dimensional models

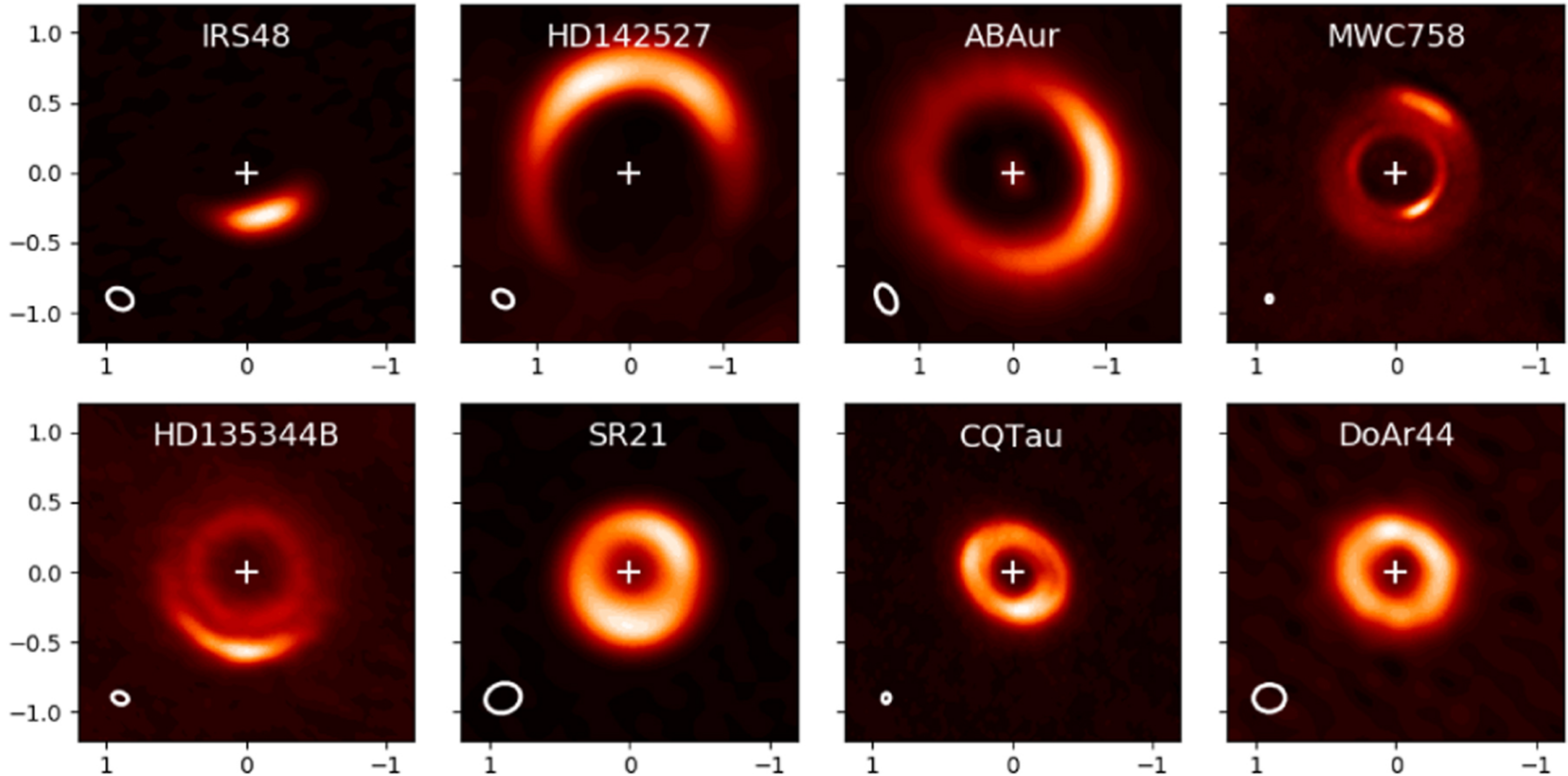


Puffed up rings in observations: Sign of planets?

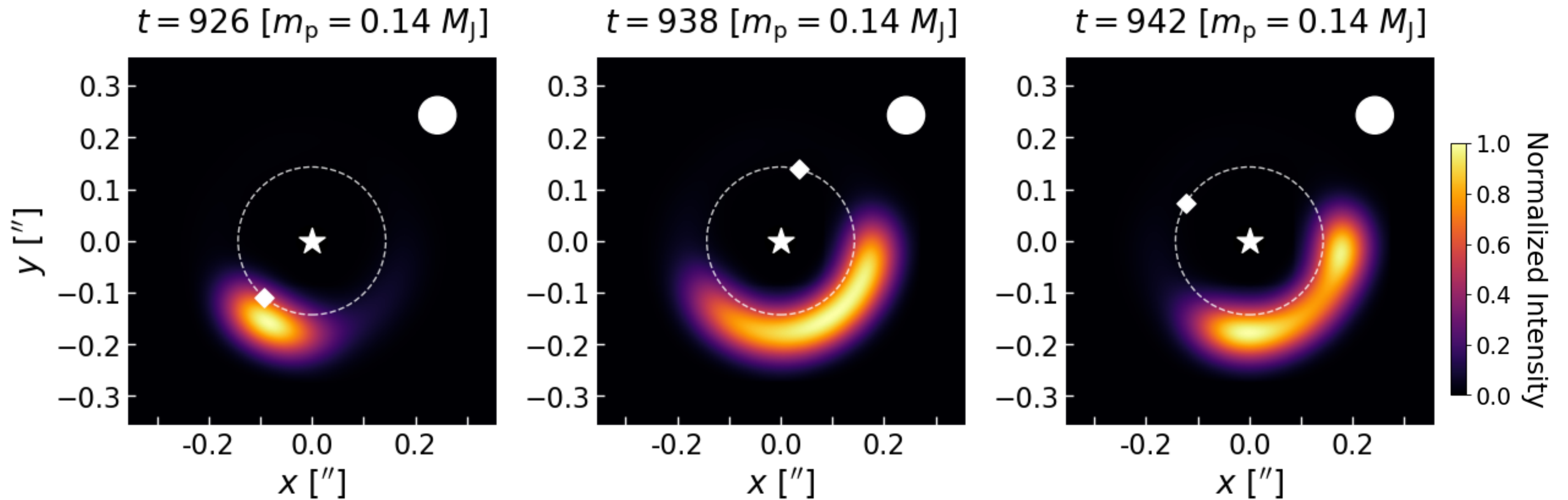


Some observed disks are asymmetric

(van de Marel, et al. 2021)



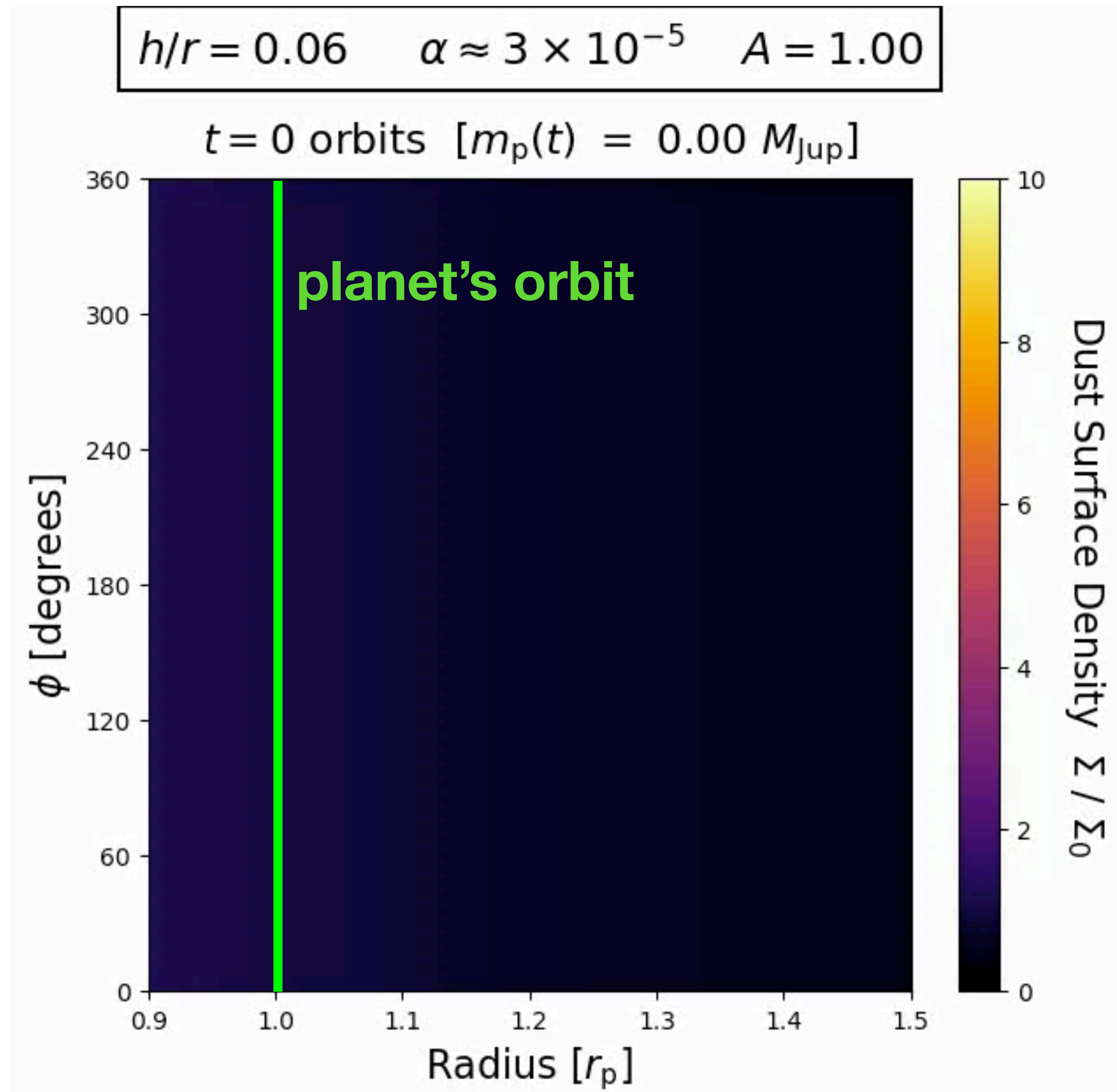
Can planets also explain them?



Vortex formation due to the “Rossby wave” instability

(Hammer, Lin, et al. 2021)

Planet-induced, compact vortices in turbulent disks



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
 **@linminkai**