Planet Formation Theory

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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 solar system

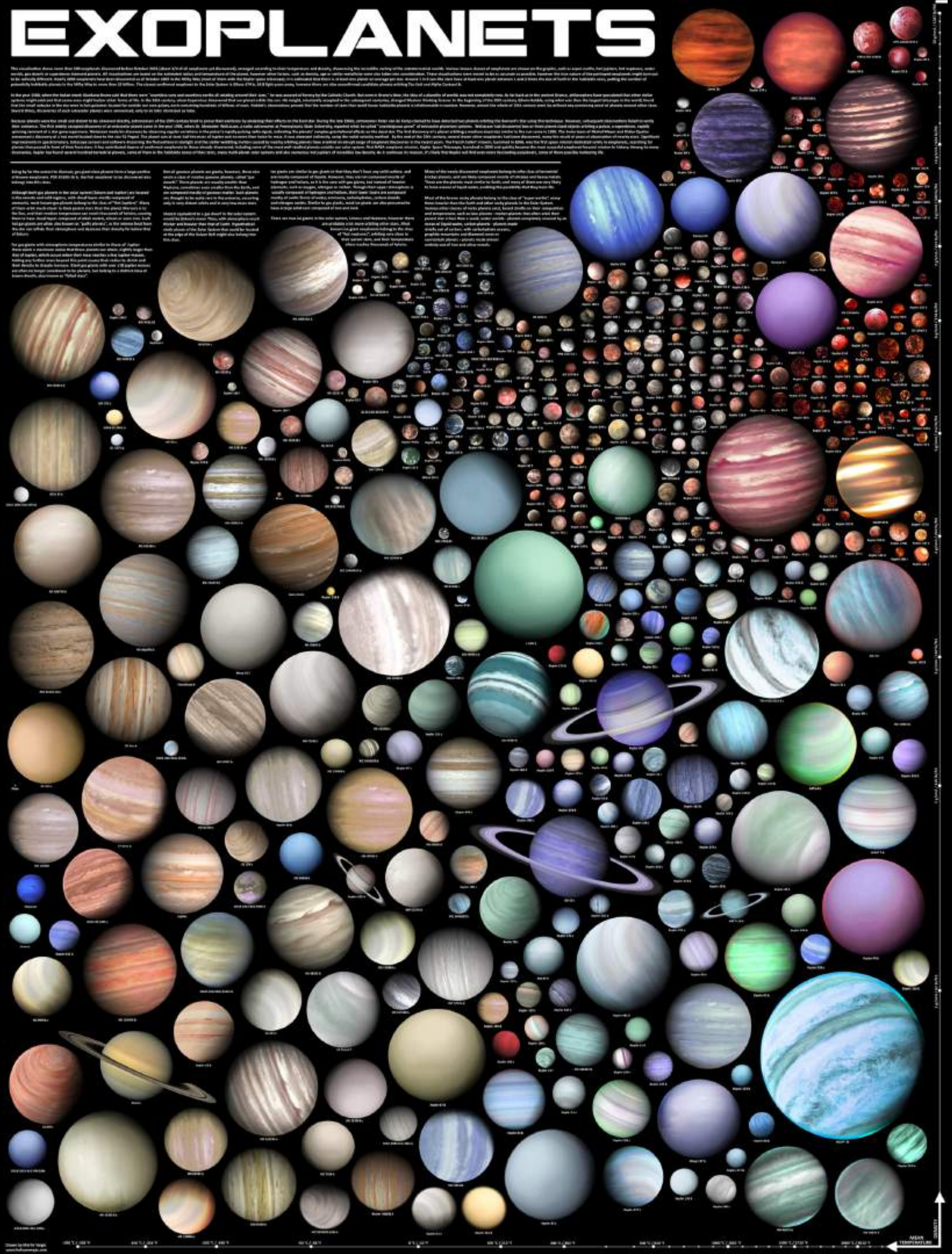
Credit: NASA/ESO/Wikipedia

1995: a Hot Jupiter outside the solar system

Credit: NASA

2024: thousands of planets

- >5000 exoplanets
- Eccentric
- Inclined
- Multi-stellar
- Hot/cold Jupiters
- Free-floating

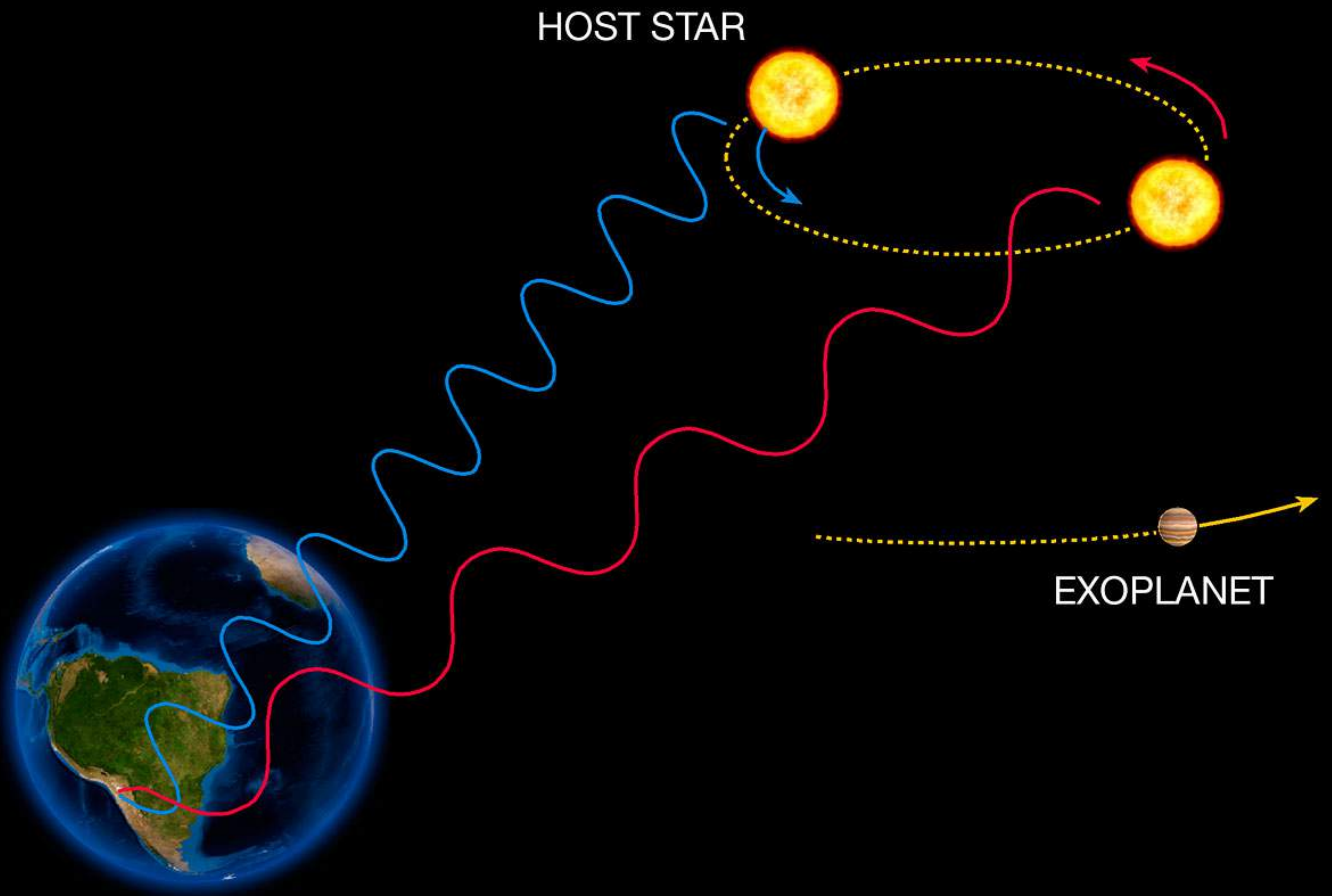


Credit: Martin Vargic

Exoplanet demography

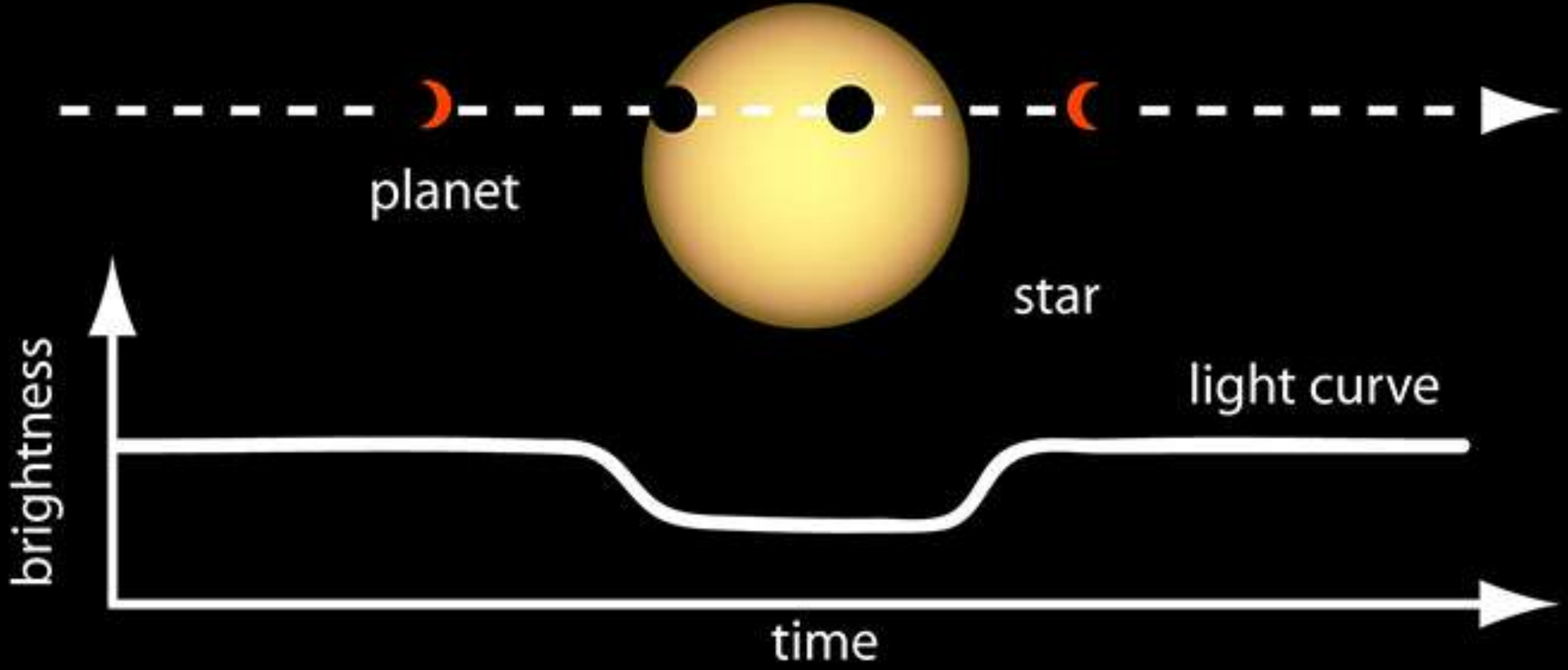
Credit: NASA/ESO/Wikipedia

Finding exoplanets: Doppler effect



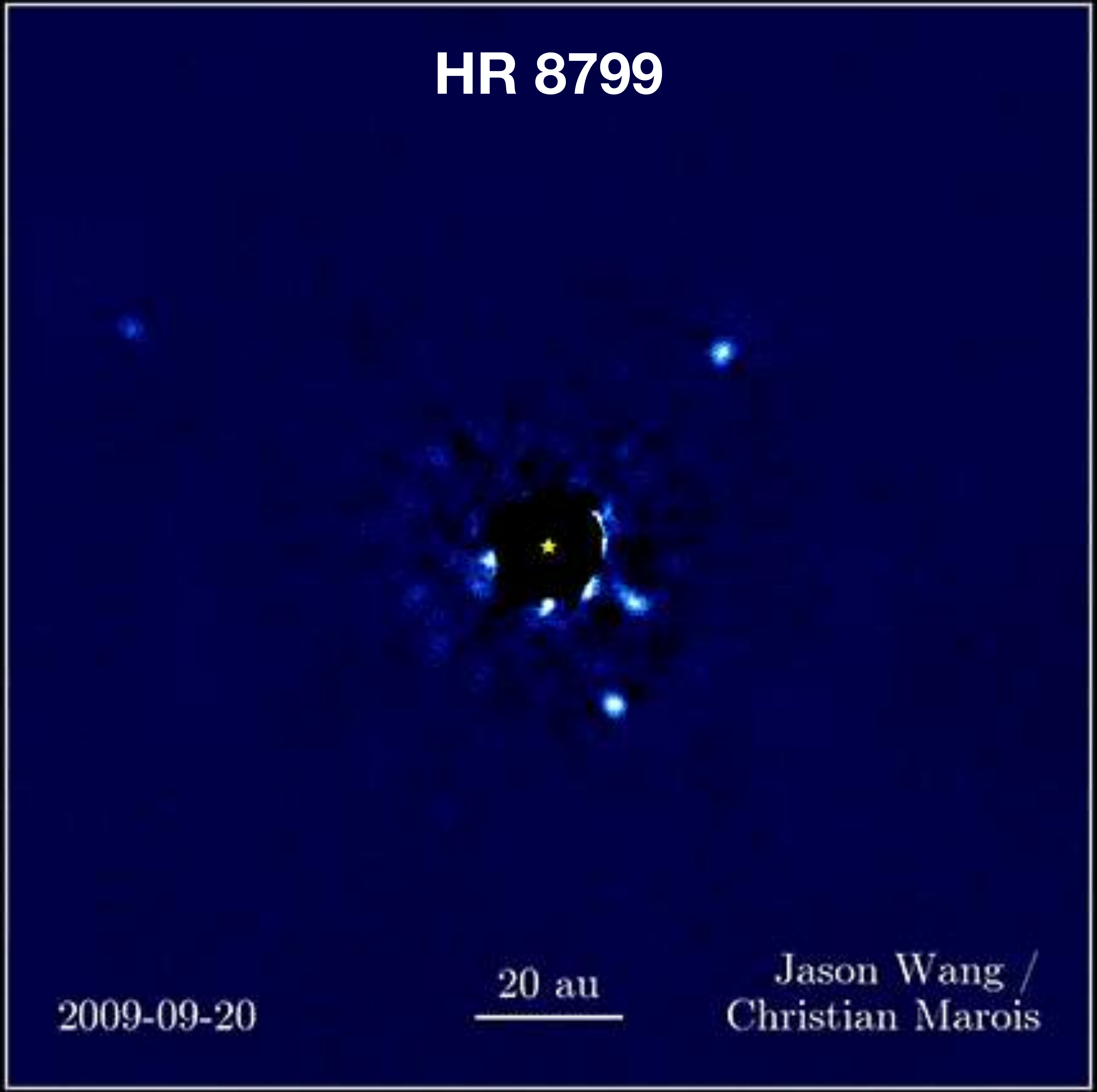
Credit: ESO

Finding explanets: transits



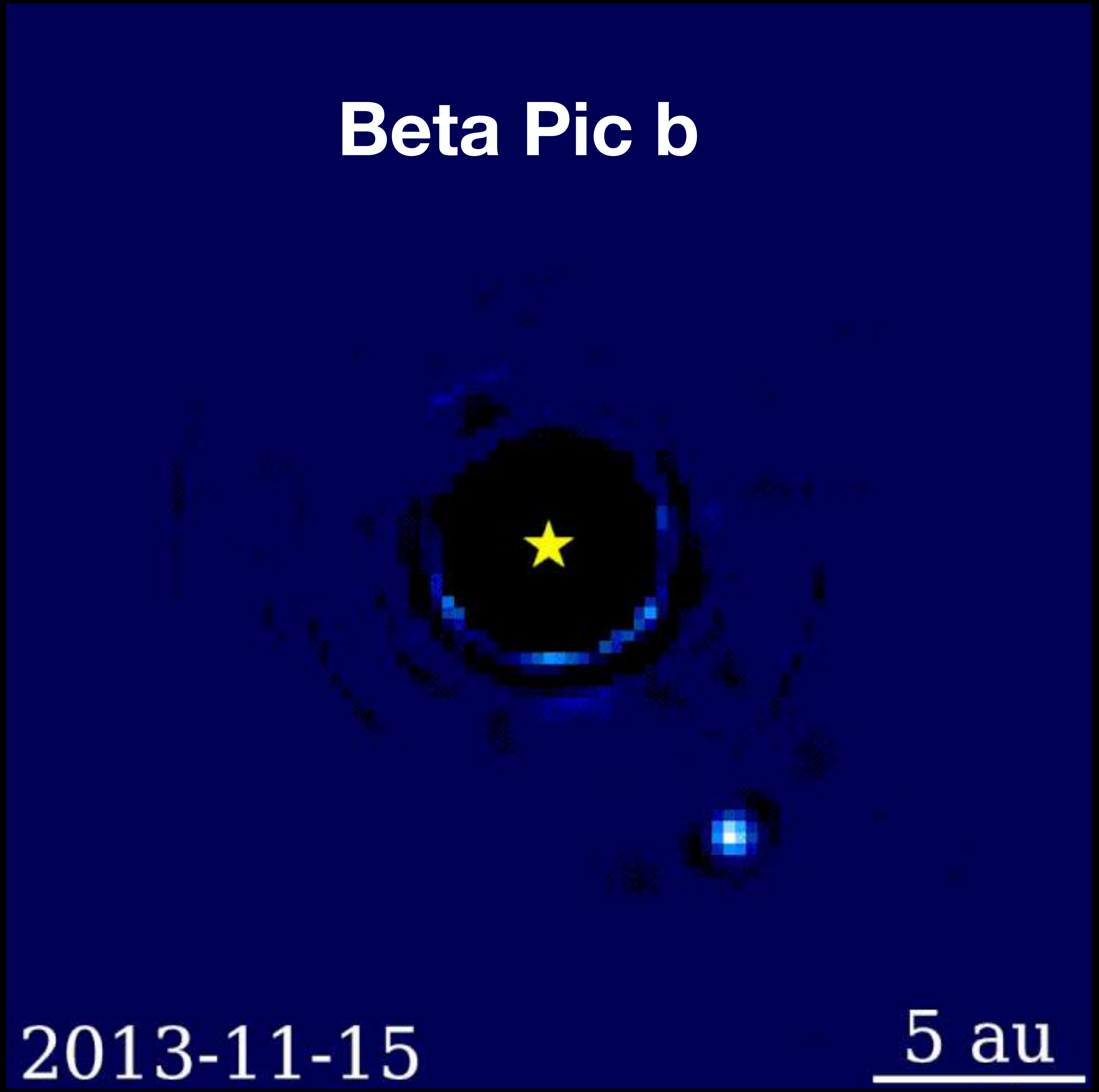
Credit: NASA

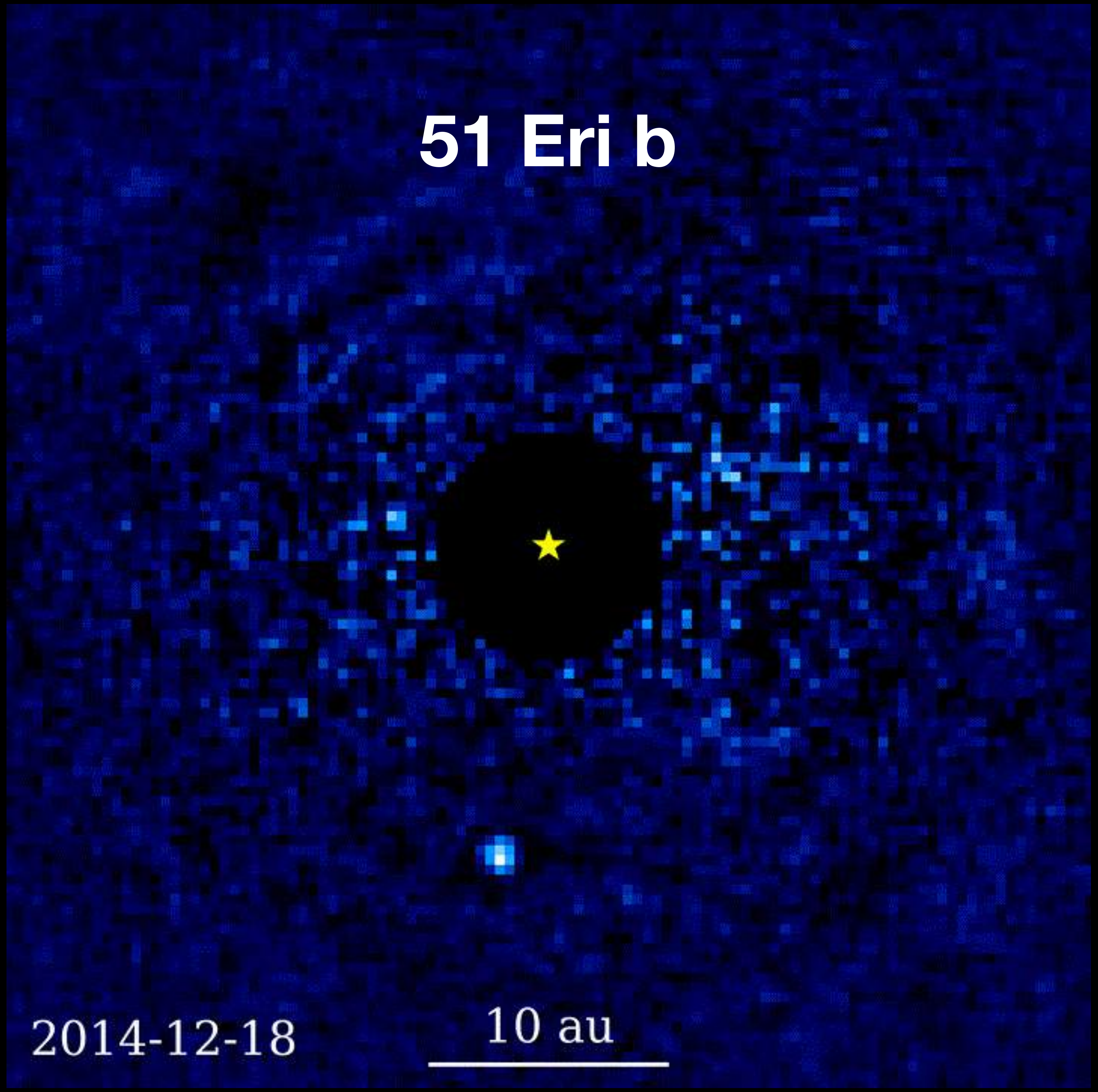
Finding exoplanets directly



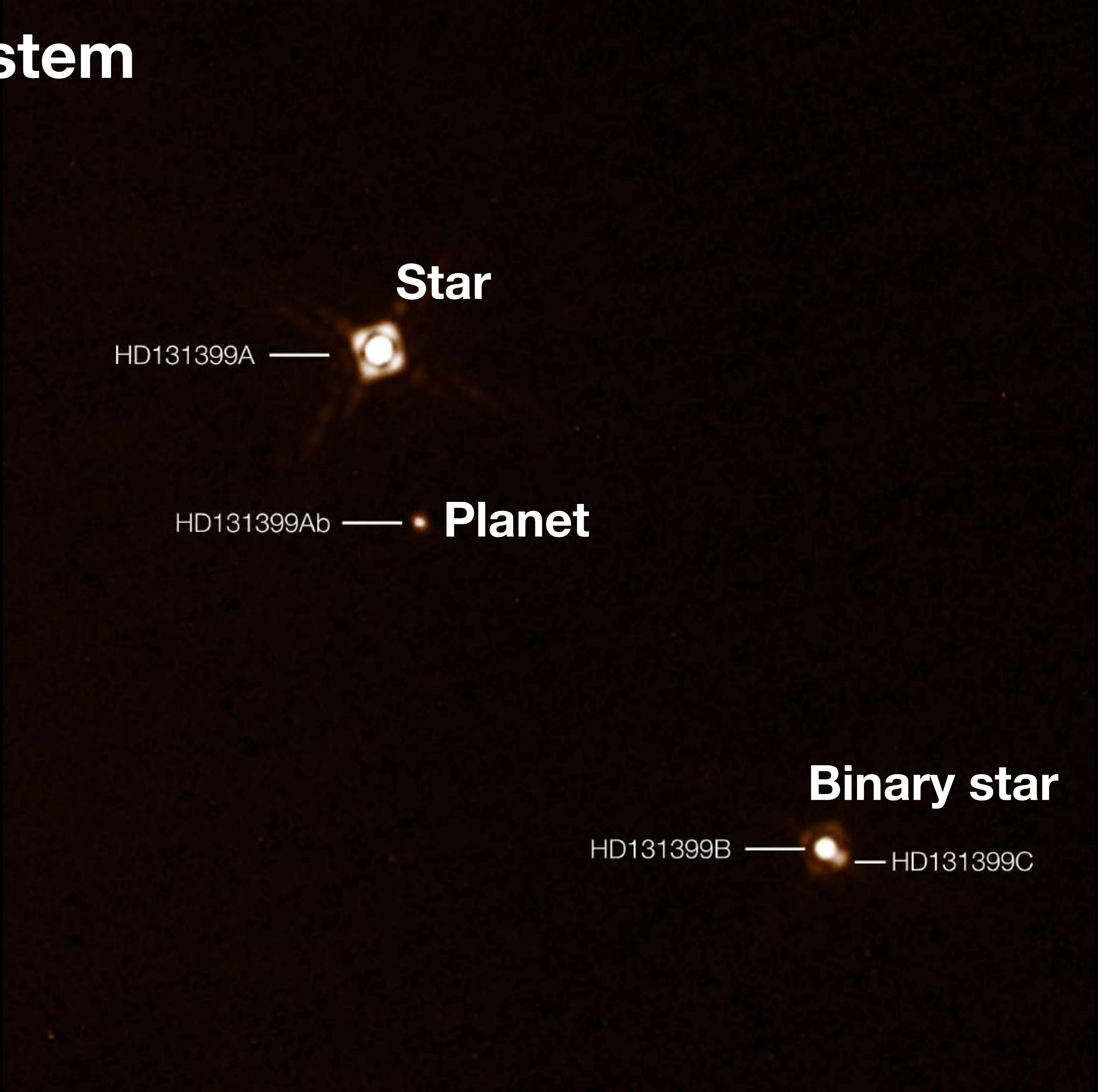
Credit: NASA

Other directly-imaged planets



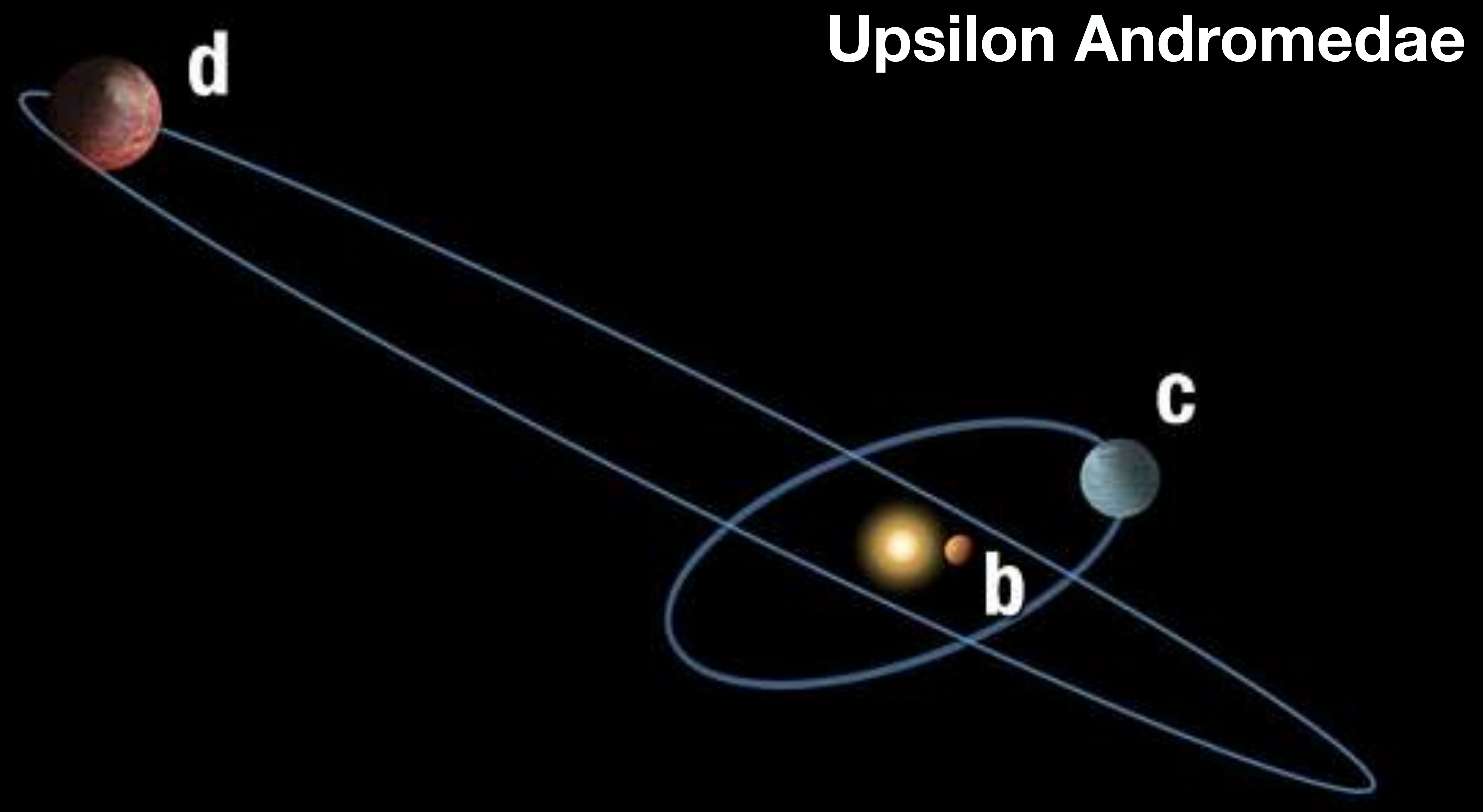


Triple star system



Credit: ESO

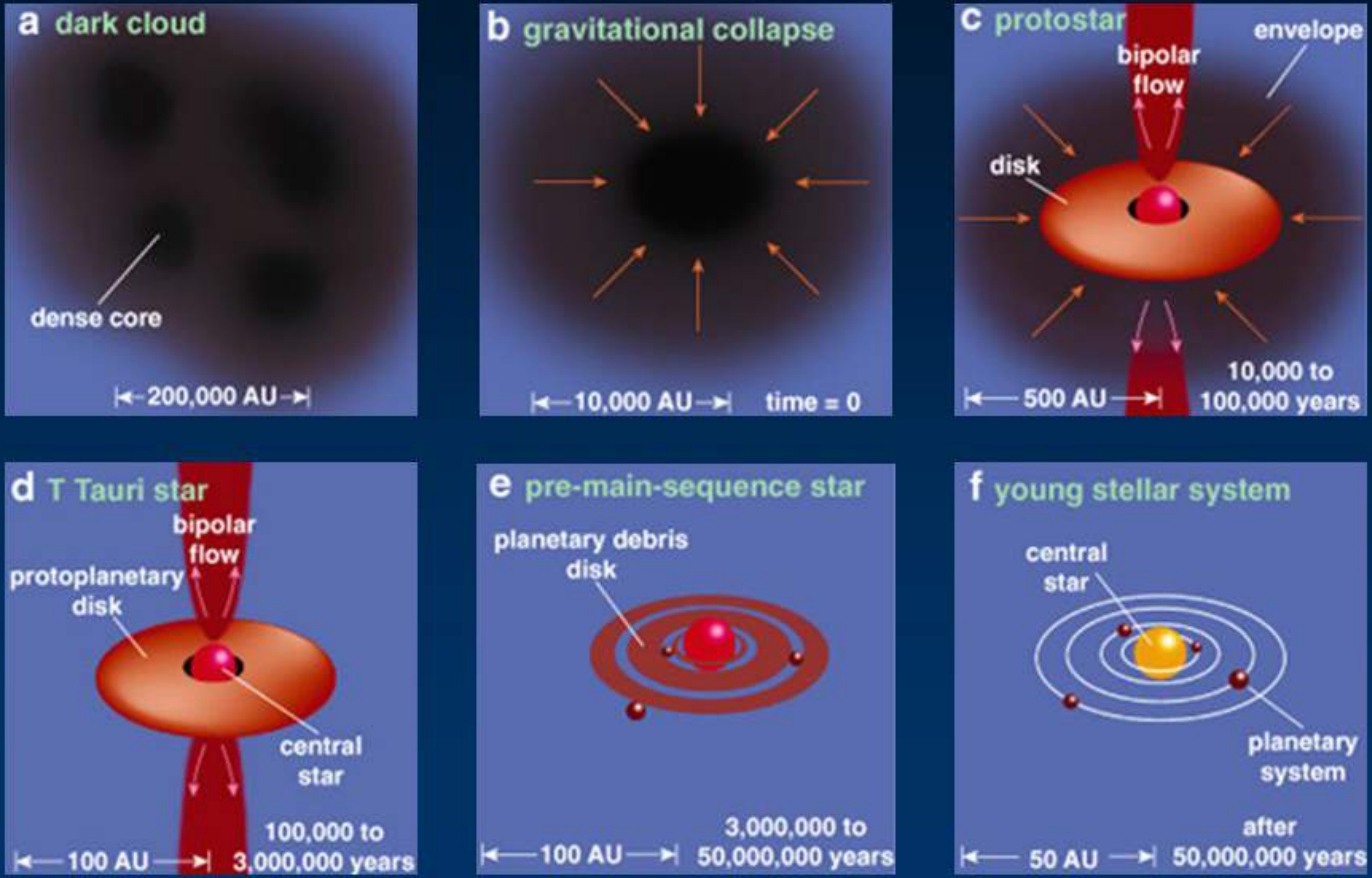
Inclined systems



Credit: NASA, ESA, A. Field (STScI)

How do planets form and evolve to such a diversity?

Star & planet formation is one story



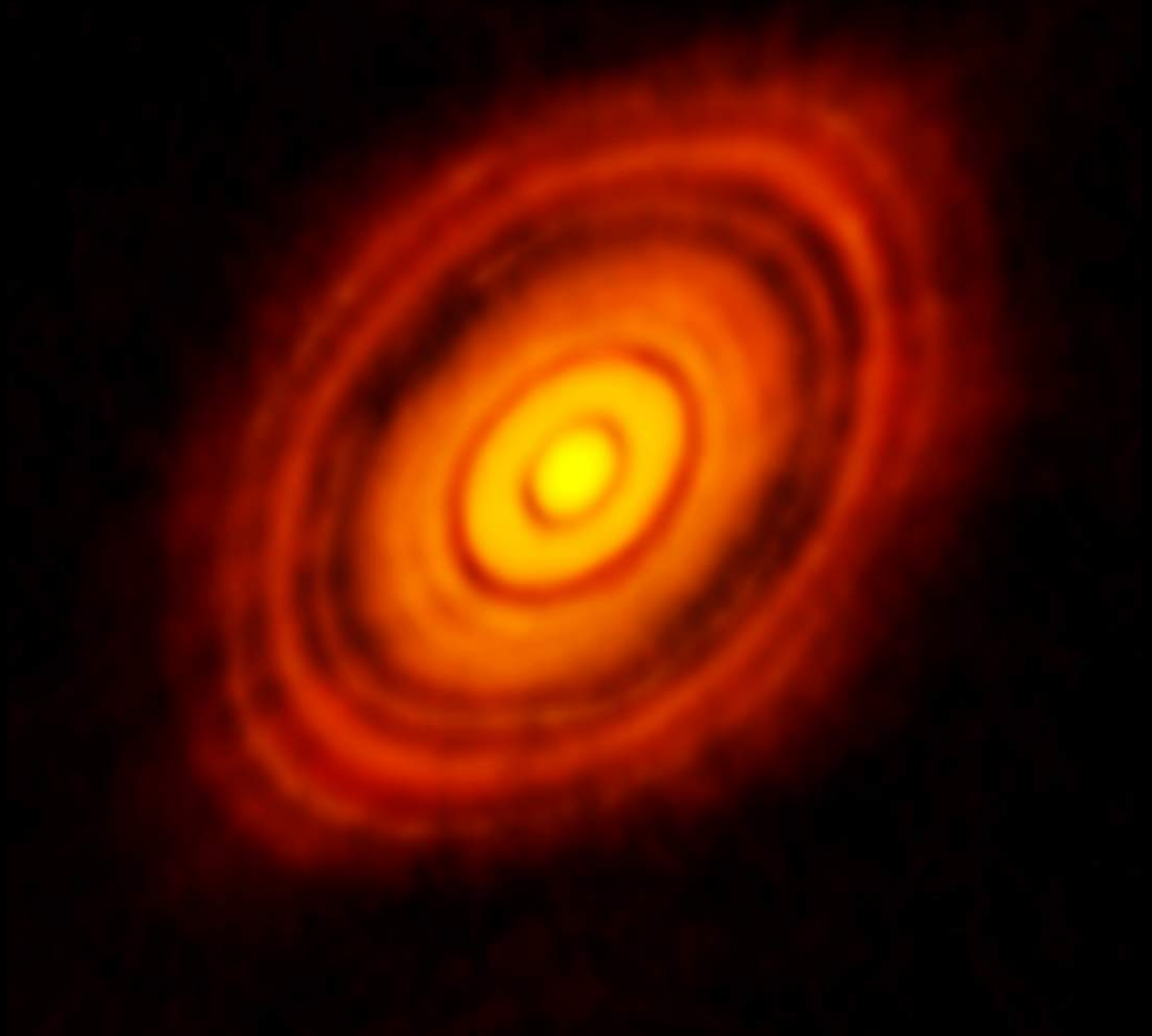
M. Liu (IfA/Hawaii)

Protoplanetary disks

- 99% gas
- 1% dust (solids) — raw material for planets
- Lifetime of a few Myrs

Credit: ESO/L. Calçada

A real PPD around HL Tau



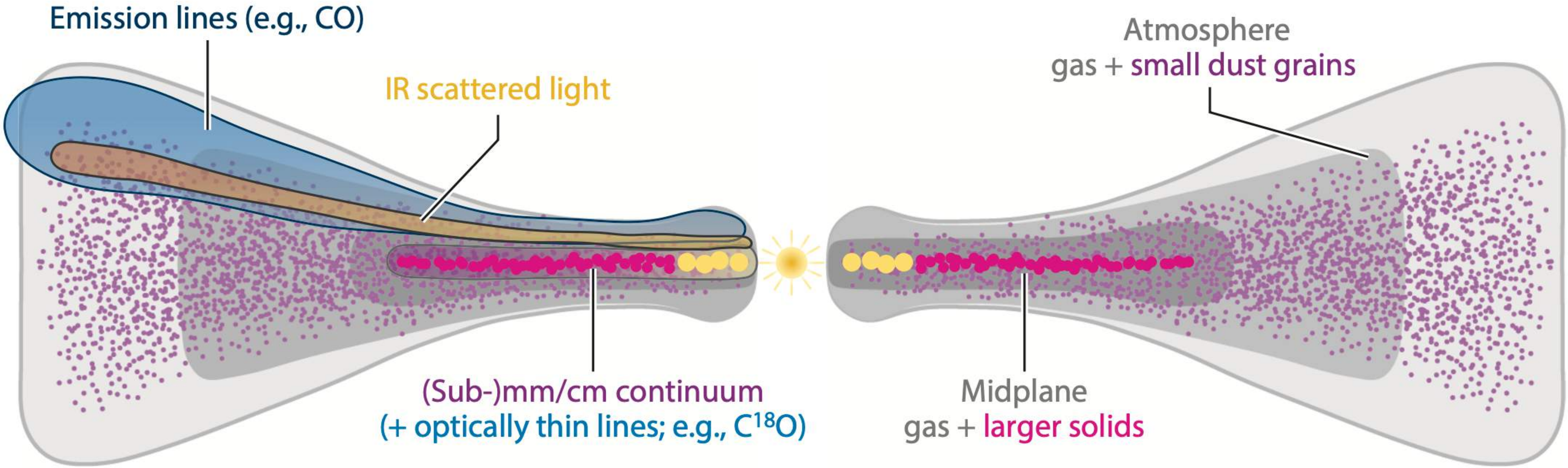
Credit: ALMA

The era of observational planet formation

- **Rings, gaps are common**
- **Some spirals, crescents**
- **Causes: Instabilities, chemistry, planets, etc.**

Andrews et al (2018)

Dust & gas in protoplanetary disks

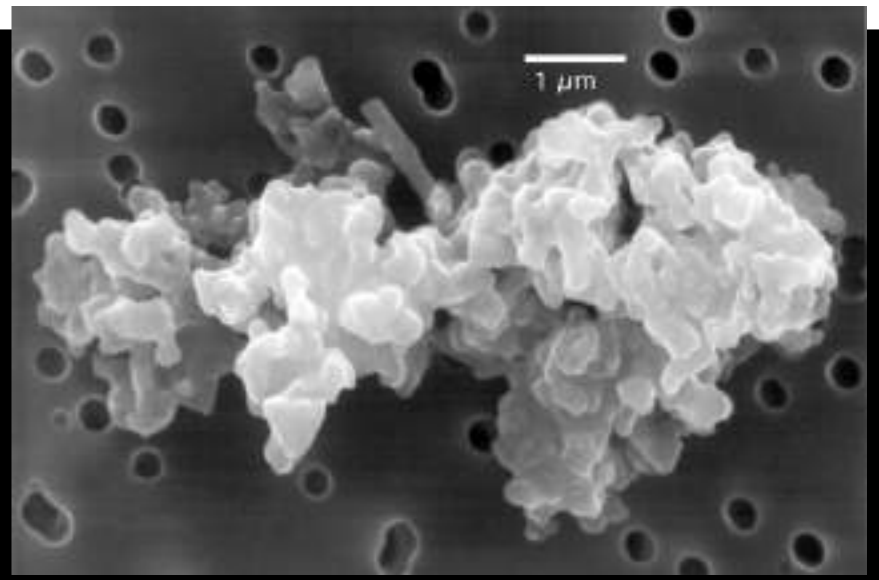


Andrews (2022)

Dust dynamics

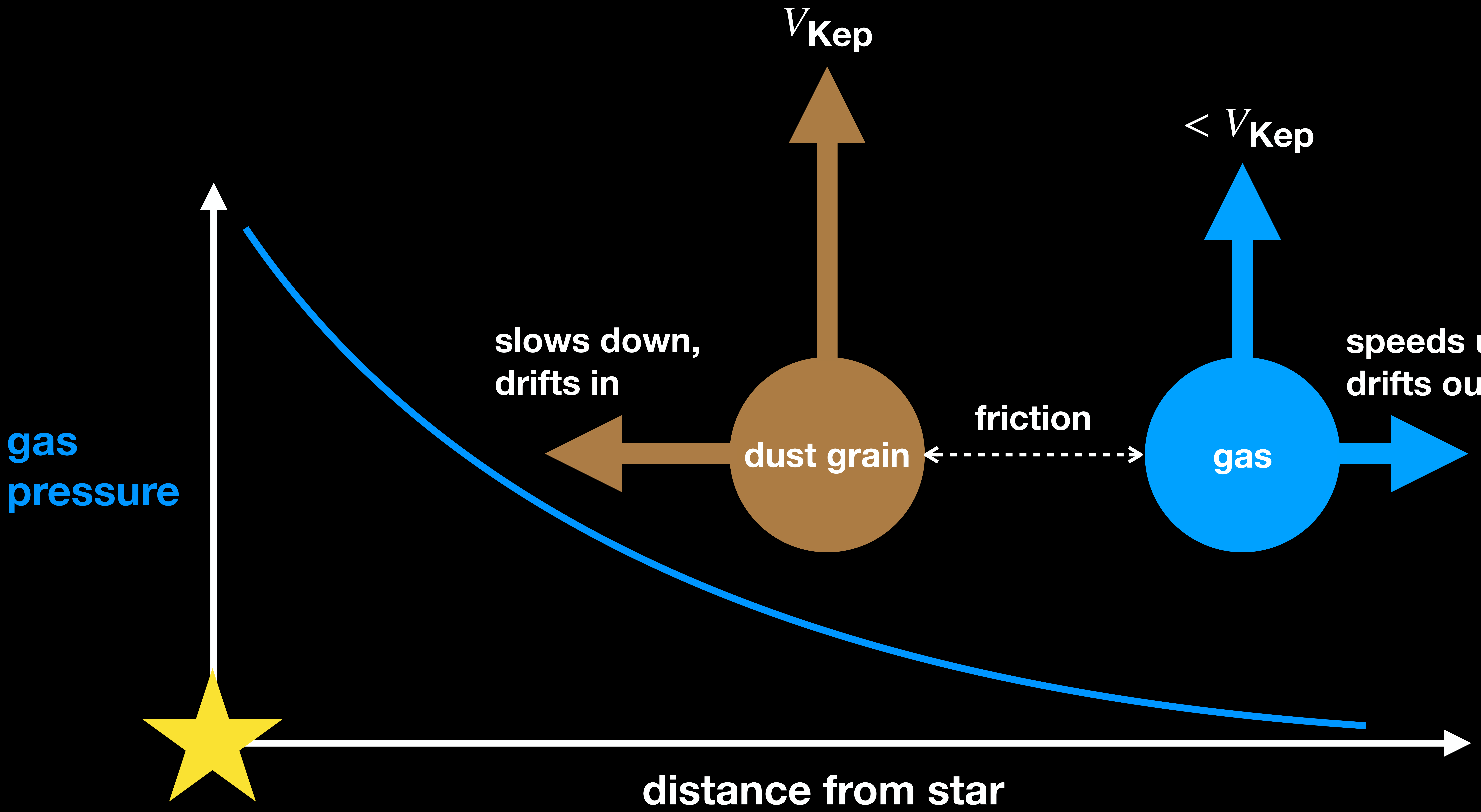
Miotello et al (2023)

Planet formation in a nutshell



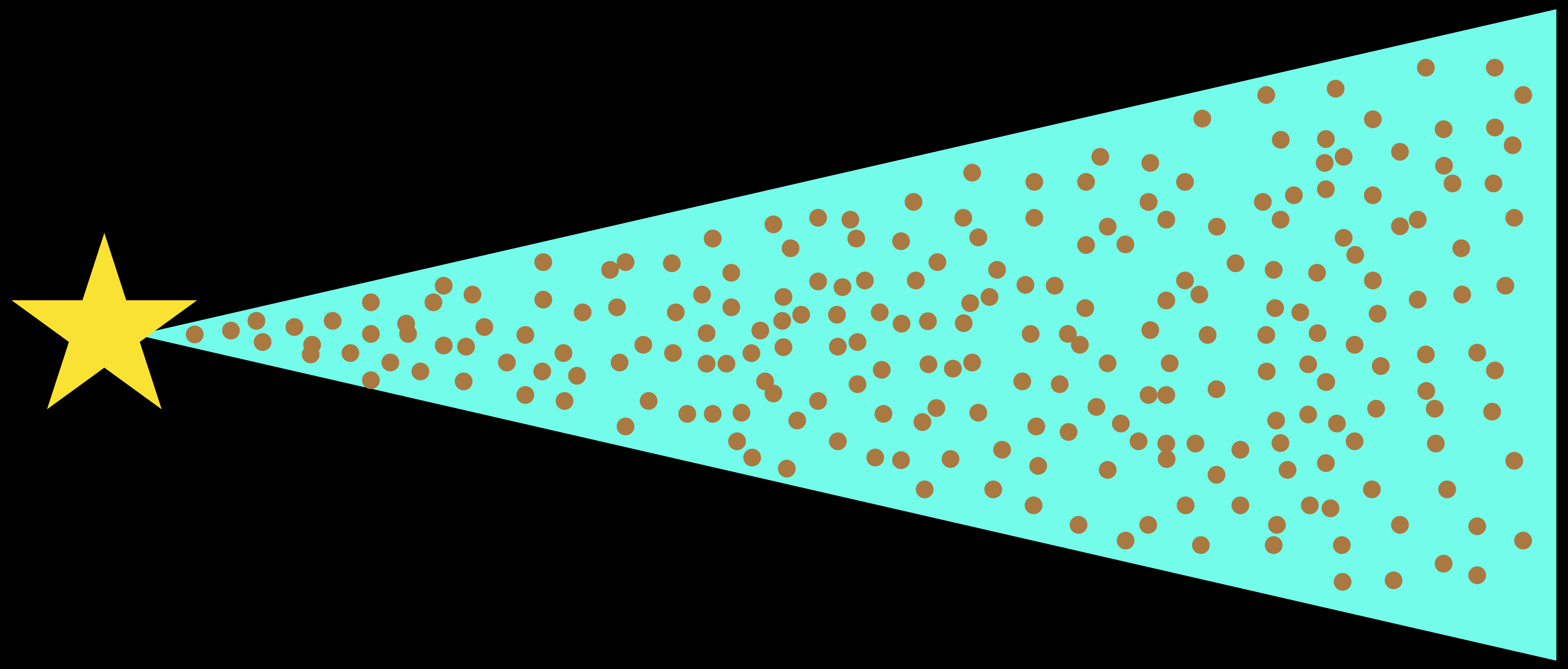
(Drazkowska et al., 2023, PPVII)

Radial drift of dust grains

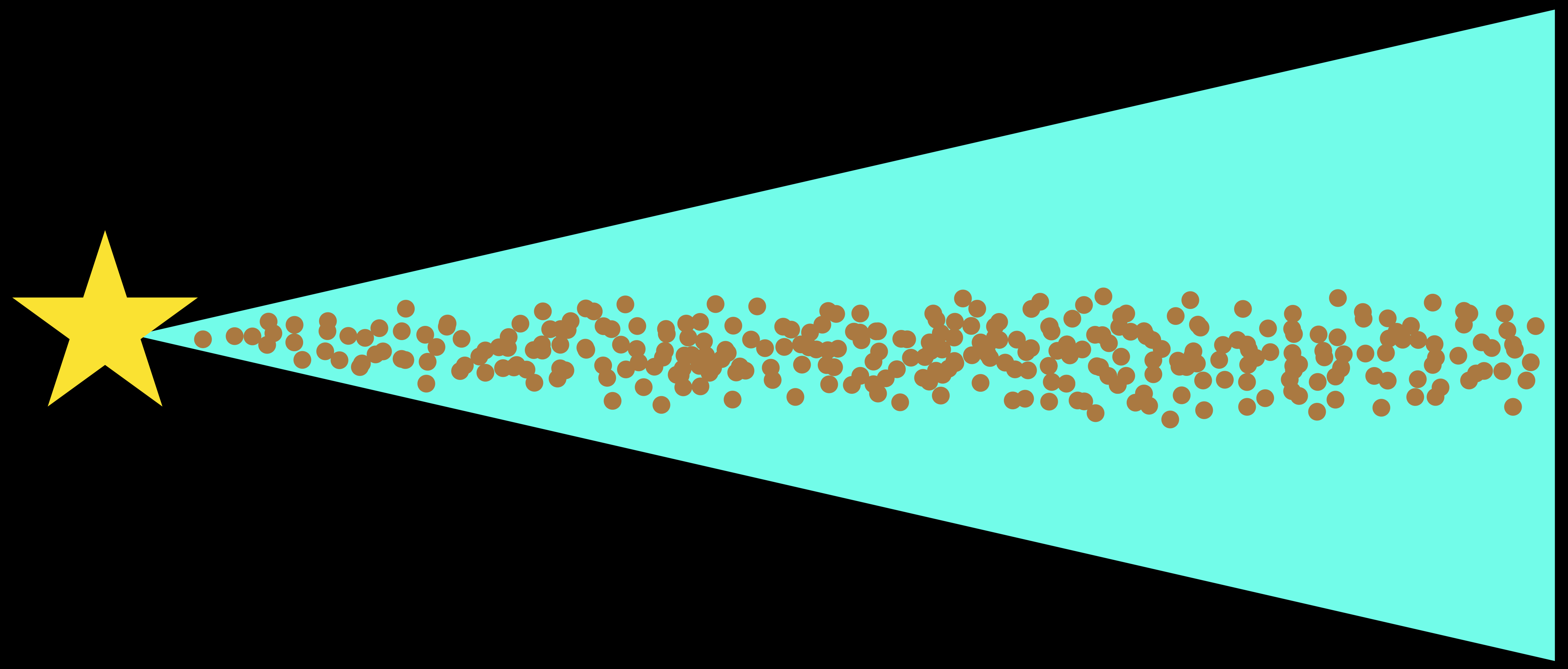


Vertical dust settling

well-mixed dust in young disk



dust sediments to the midplane



Observational evidence of settling

Oph 163131 (Villenave et al. 2022)

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

Theoretical modeling

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

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

Gas

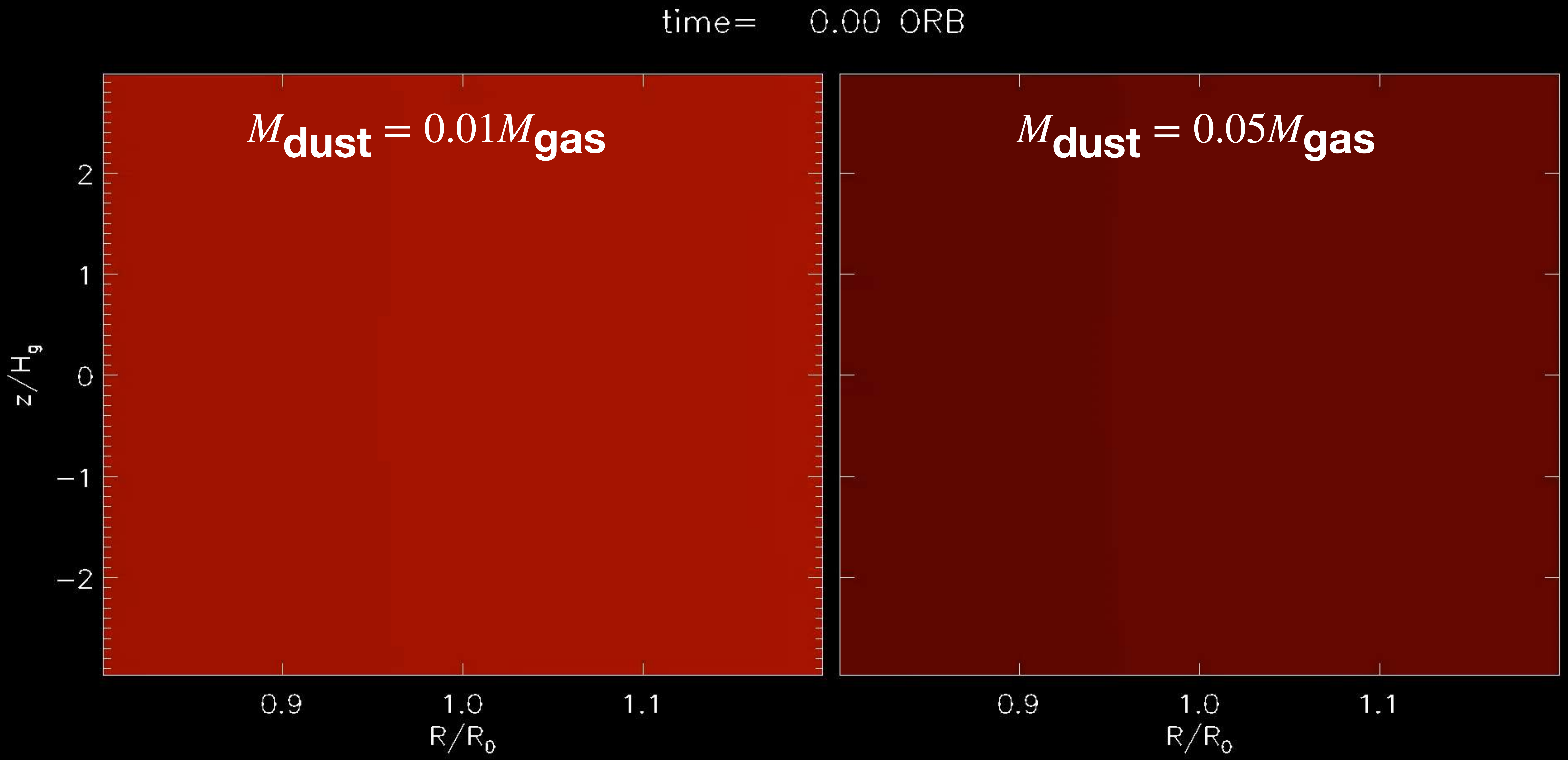
$$\left(\frac{\partial}{\partial t} + \boldsymbol{v}_{\rm d} \cdot \boldsymbol{\nabla}\right) \rho_{\rm d} = -\rho_{\rm d} \left(\boldsymbol{\nabla} \cdot \boldsymbol{v}_{\mathbf{d}}\right) + \boldsymbol{\nabla} \cdot \left(\nu \rho \boldsymbol{\nabla} f_{\rm d}\right),$$

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

Dust (as a fluid)

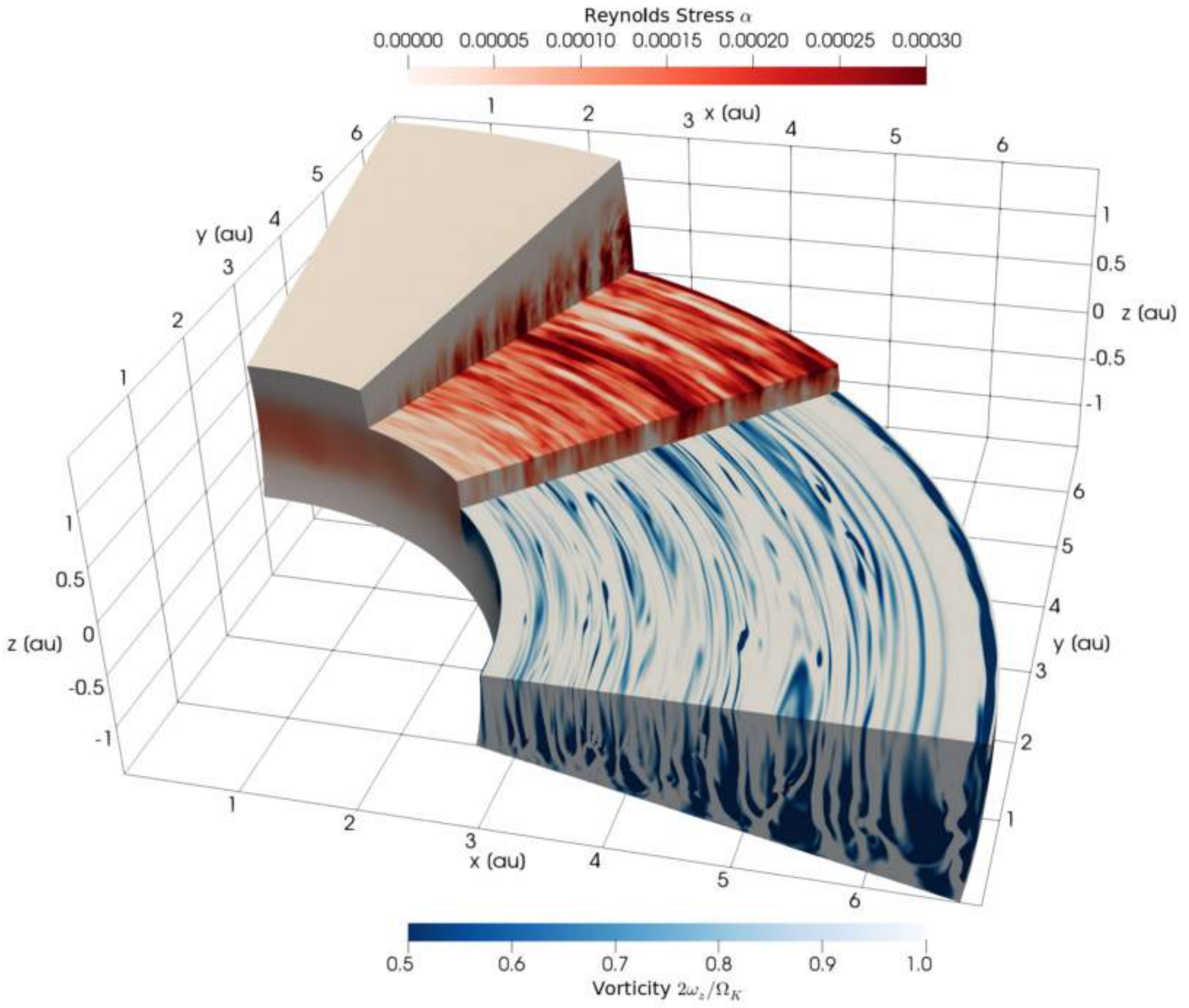
friction between dust and gas

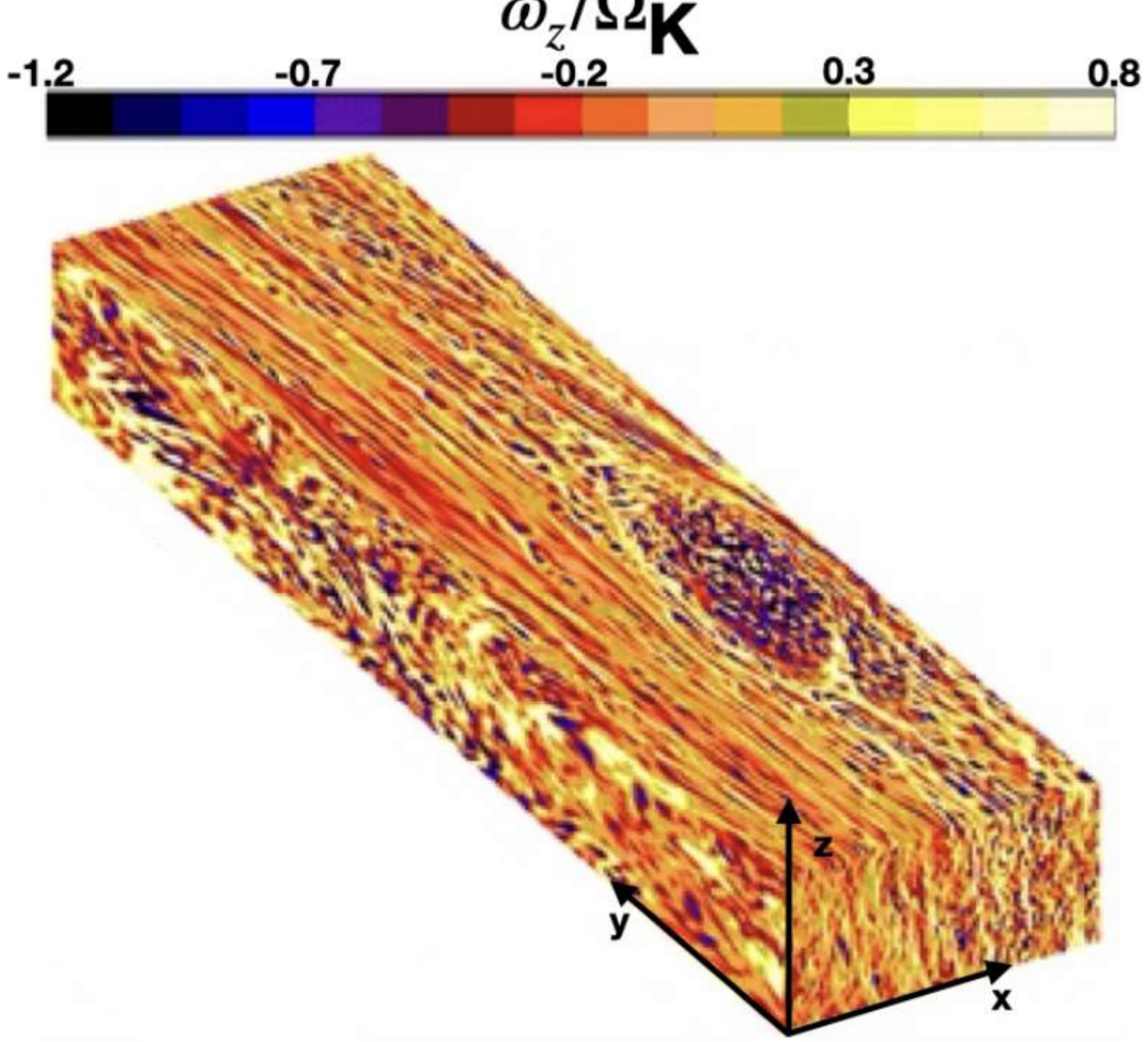
Numerical simulations of dust settling

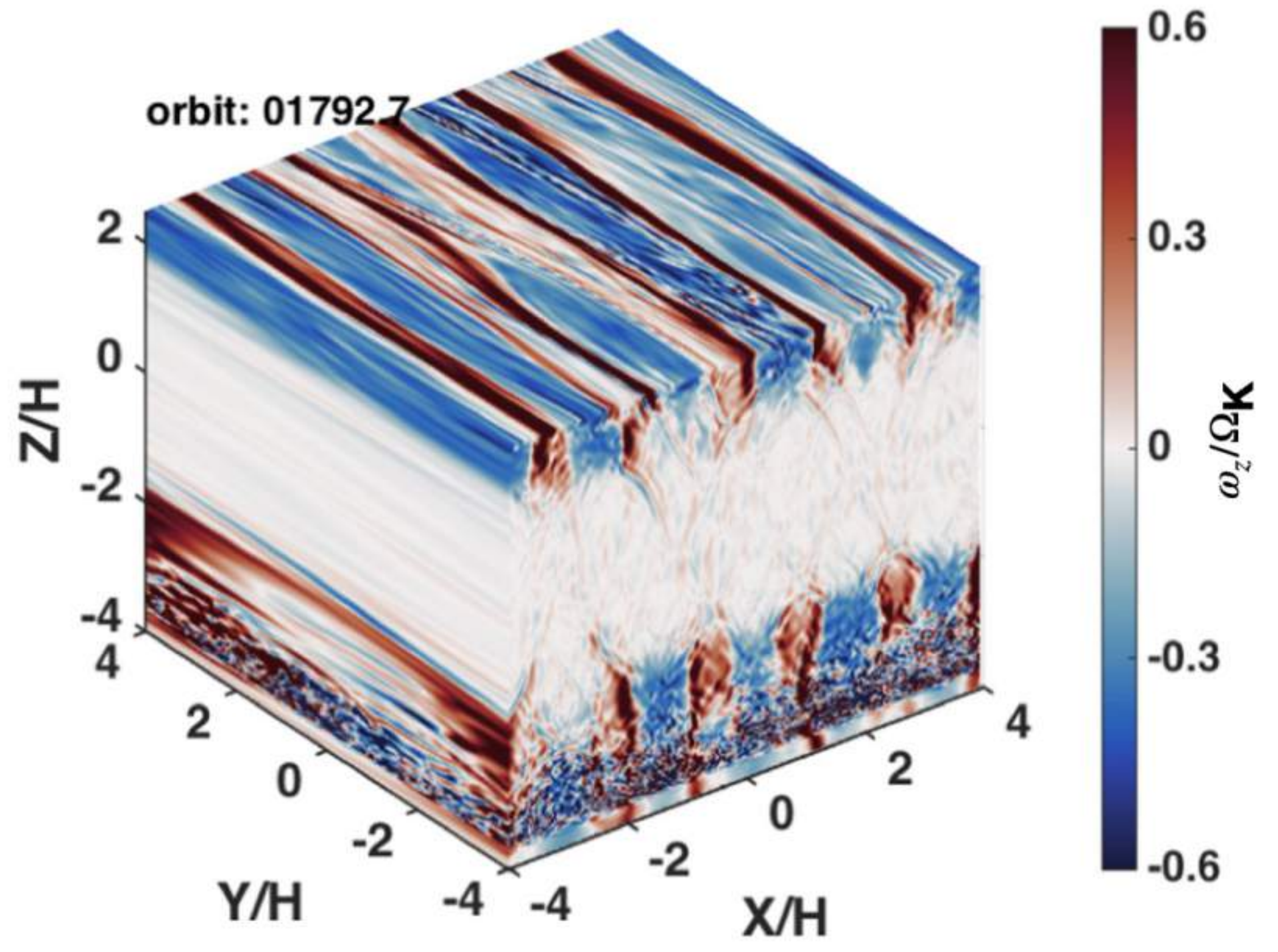


Lin (2019); Lehmann & Lin (2022)

Gas instabilities in protoplanetary disks





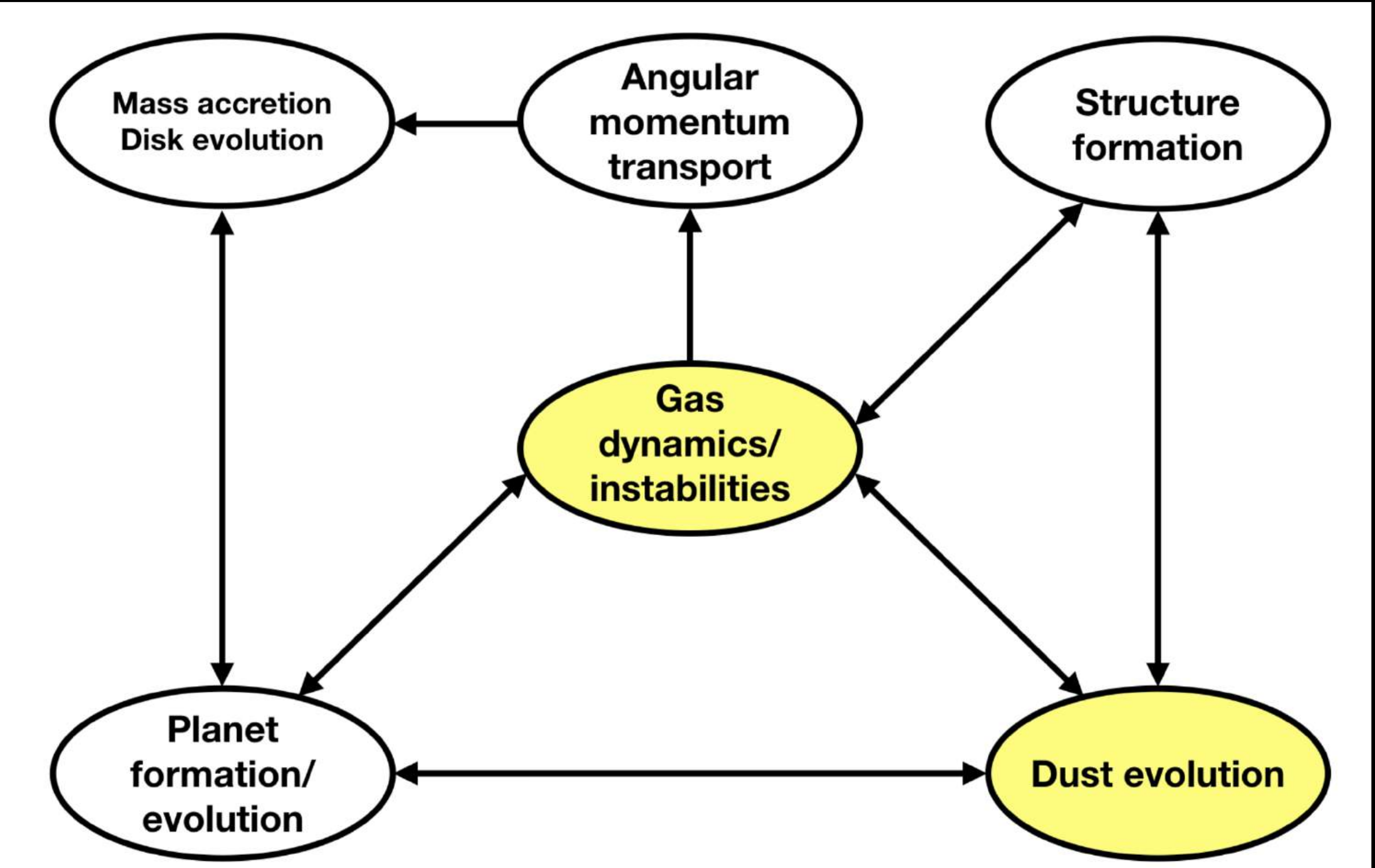


Vertical Shear Instability	Convective Overstability	Zombie Vortex Instability
$\tau_{\rm cool}\Omega_{\rm K} \ll 1$	$\tau_{\rm cool}\Omega_{\rm K} \sim 1$	$\tau_{\rm cool}\Omega_{\rm K} \gg 1$
$q \neq 0$	$-1 < p/q < 1/(\gamma - 1)$	$\lvert z\rvert \gtrsim \sqrt{\gamma/(\gamma-1)}H$
$\alpha_{\rm S} \sim 10^{-4}$	$\alpha_{\rm S} \sim 10^{-3}$	$\alpha_{\rm S} \sim (10^{-5}\text{–}10^{-4})^\dagger$

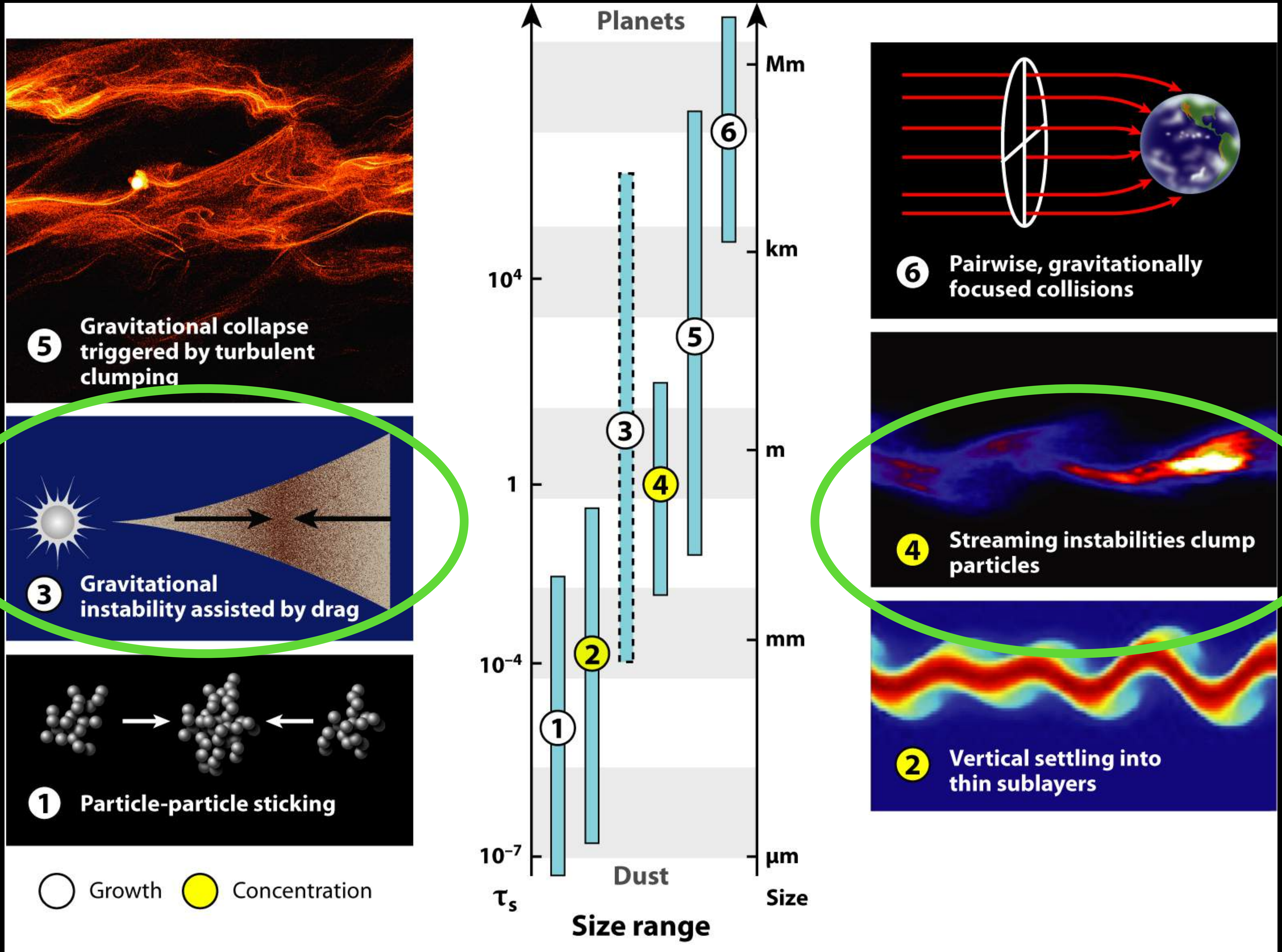
Outcome: turbulence & vortices

Lesur et al (2023), PPVII review on disk instabilities

Gas dynamics of protoplanetary disks



Dust+gas instabilities



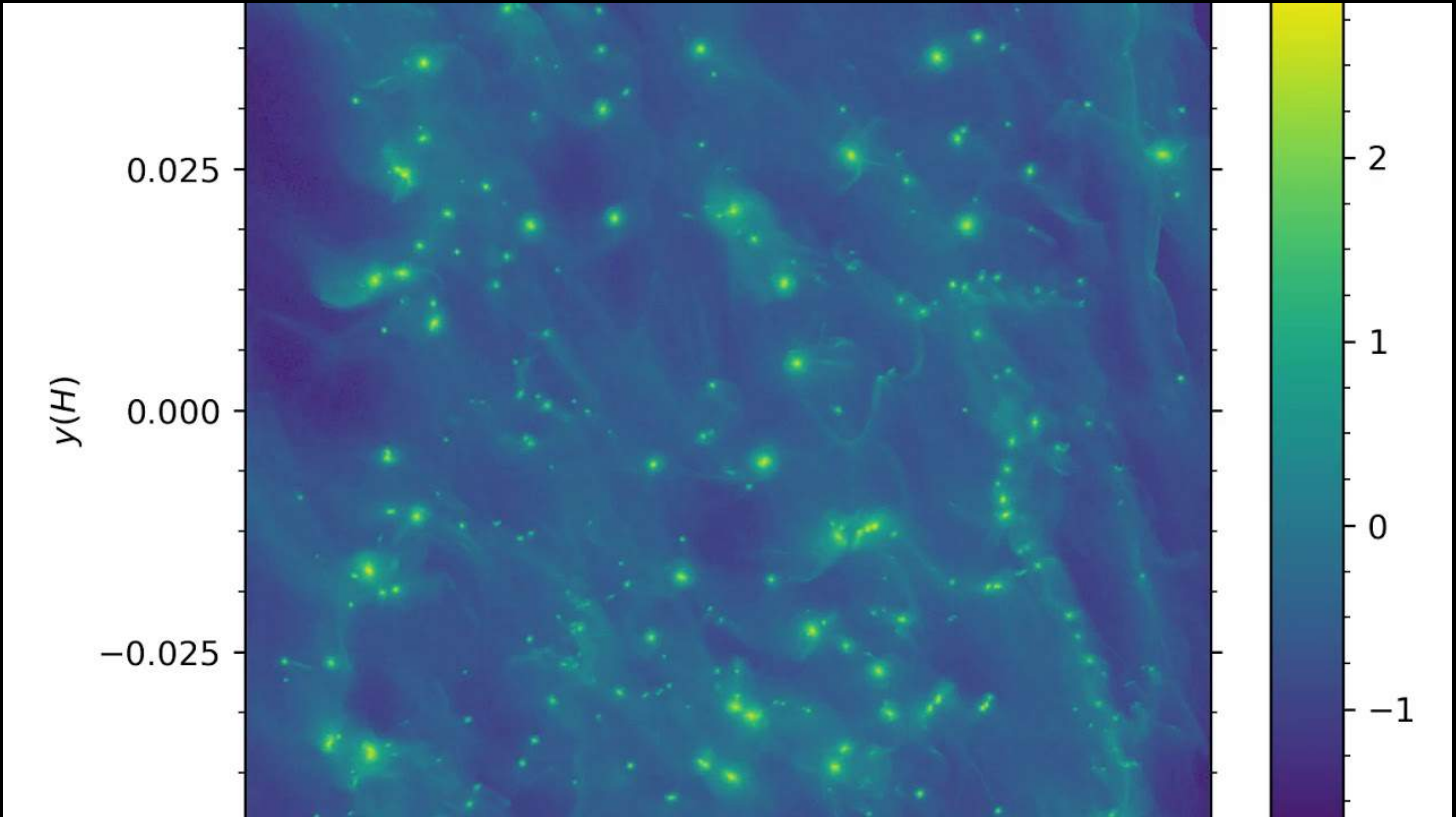
Chiang E, Youdin AN. 2010.
Annu. Rev. Earth Planet. Sci. 38:493–522

Streaming instability: unstable dust-gas interaction

Dust filaments may collapse into planetesimals

Making planetesimals from the SI

(Nesvorný et al., 2020)



Generalized dust-gas interaction

Classical SI

laminar, unmagnetized, unstratified, isothermal

+vertical structure

Lin (2021)

+turbulence

Chen & Lin (2020)

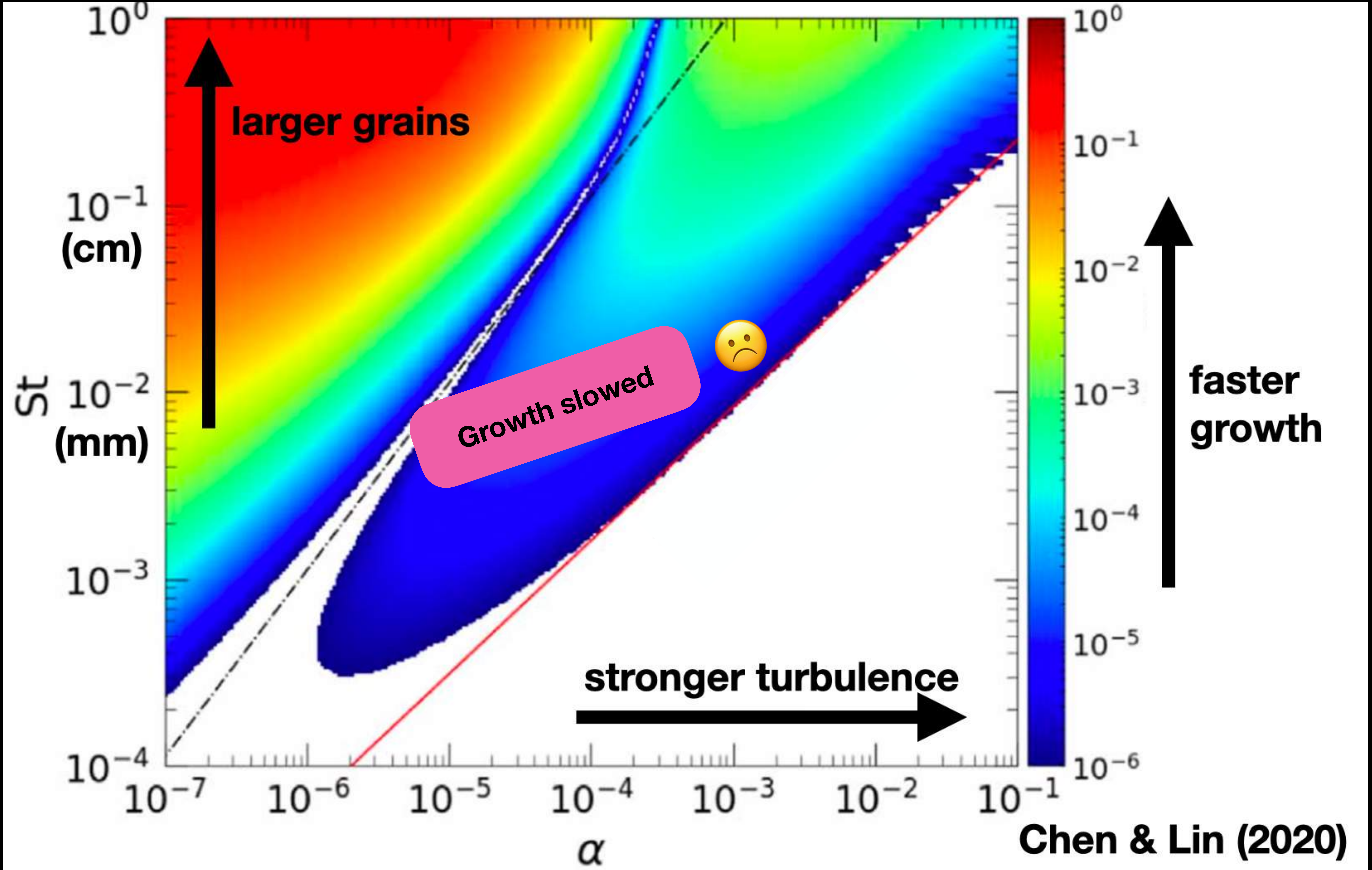
+magnetic fields

Lin & Hsu (2022)
Hsu & Lin (2022)
Wu, Lin, et al. (2024)
Wang & Lin (in prep.)

+non-isothermal gas

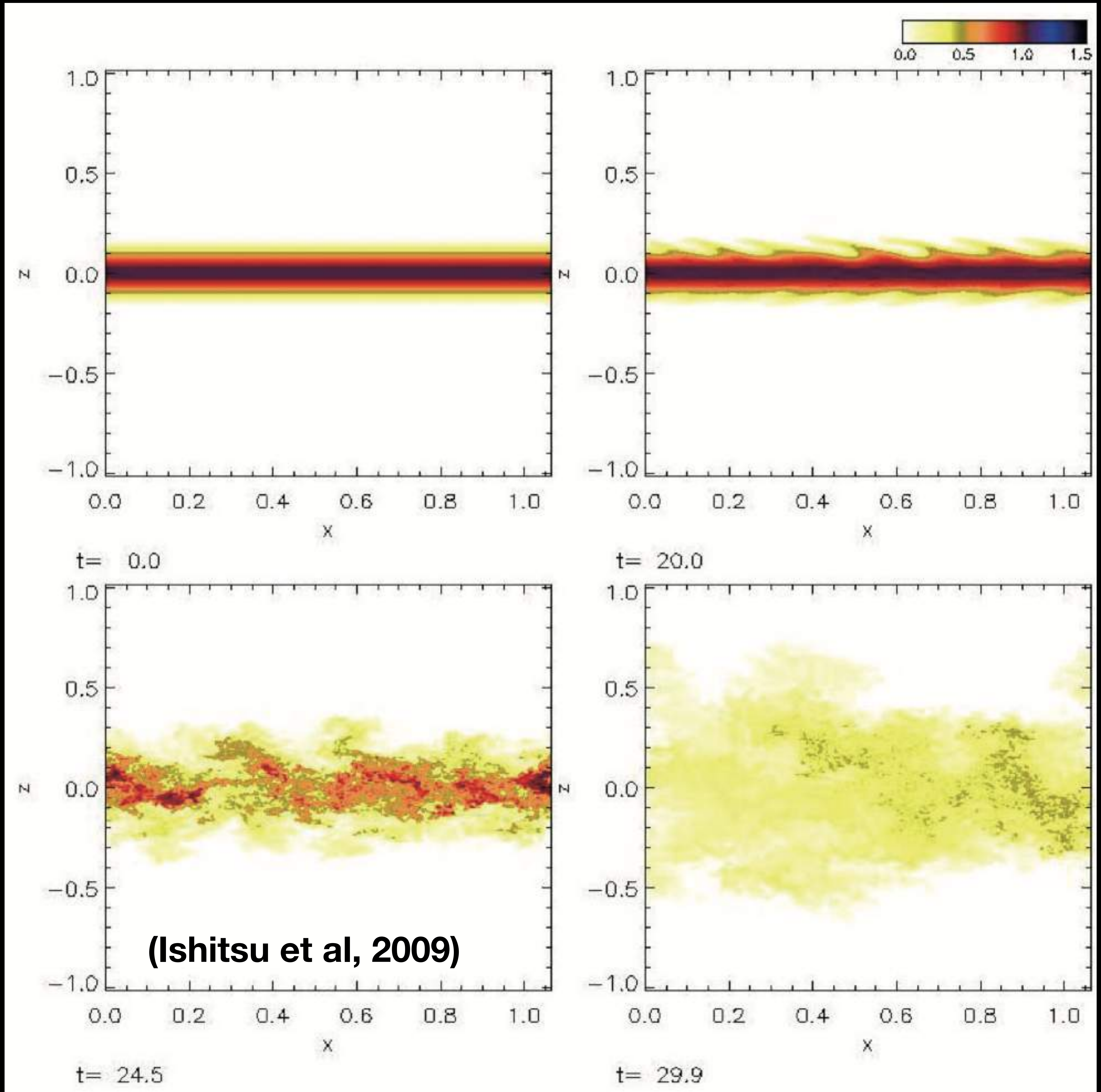
Lehmann & Lin (2023)
Lin & Lehmann (in prep.)

Adding turbulence



Chen & Lin (2020)

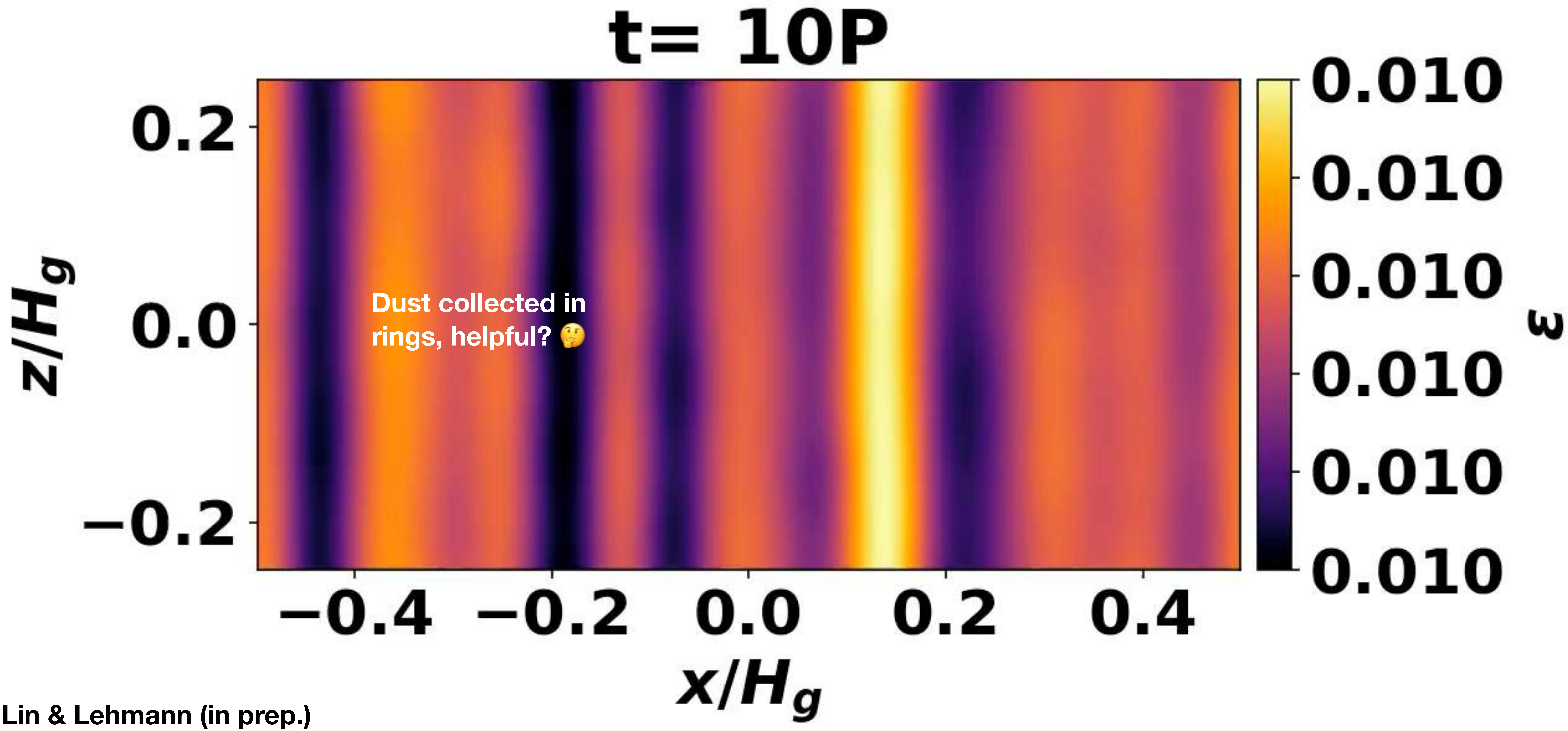
Adding vertical structure



(Ishitsu et al, 2009)

dust layer dispersed

Adding thermodynamics (convection)



Lin & Lehmann (in prep.)

What about magnetic fields?

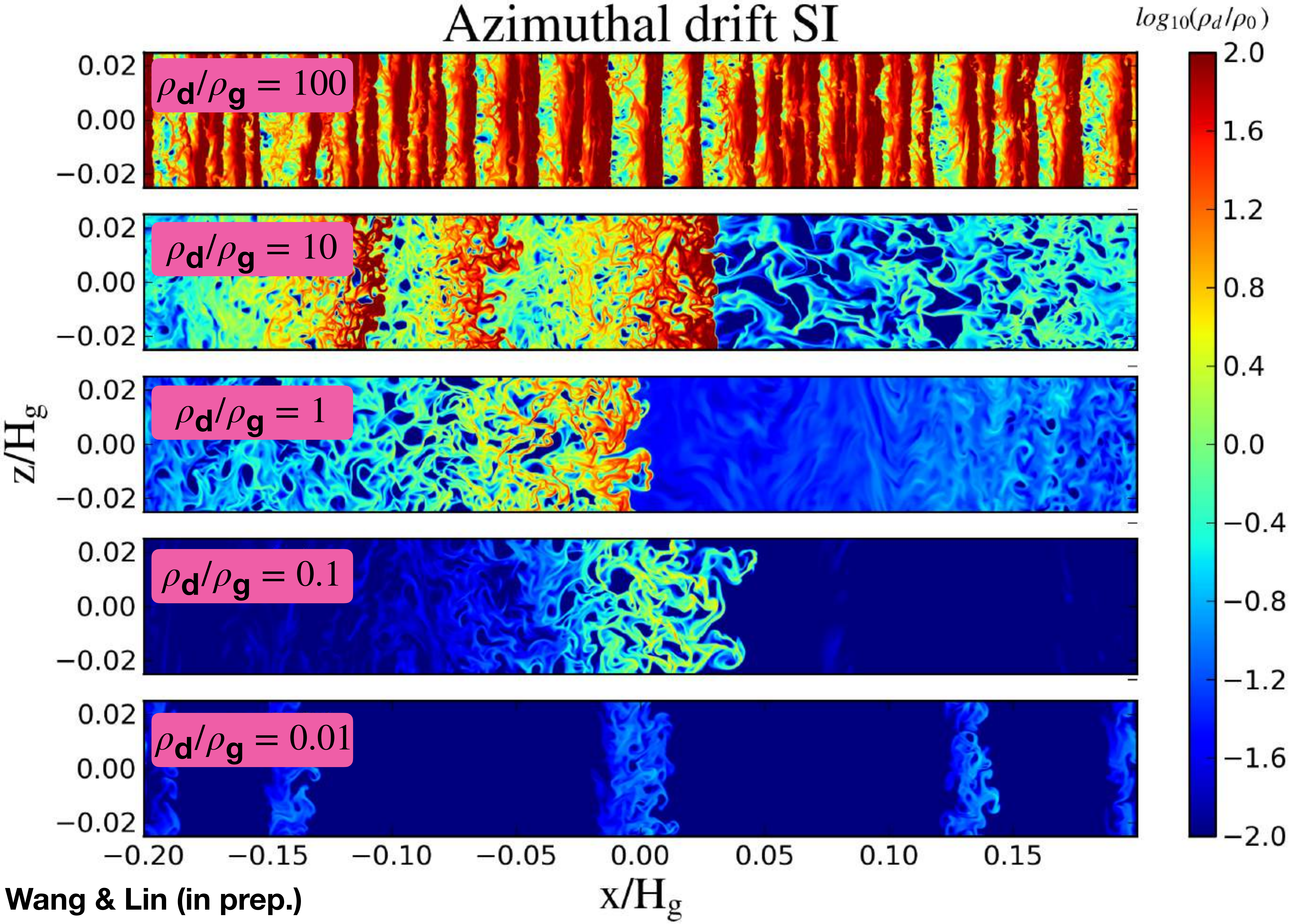
(e.g. Riols et al. 2020, Cui & Bai 2021)

Nonlinear evolution of the SI in accreting disks

$$\frac{\partial P}{\partial R} \equiv 0$$

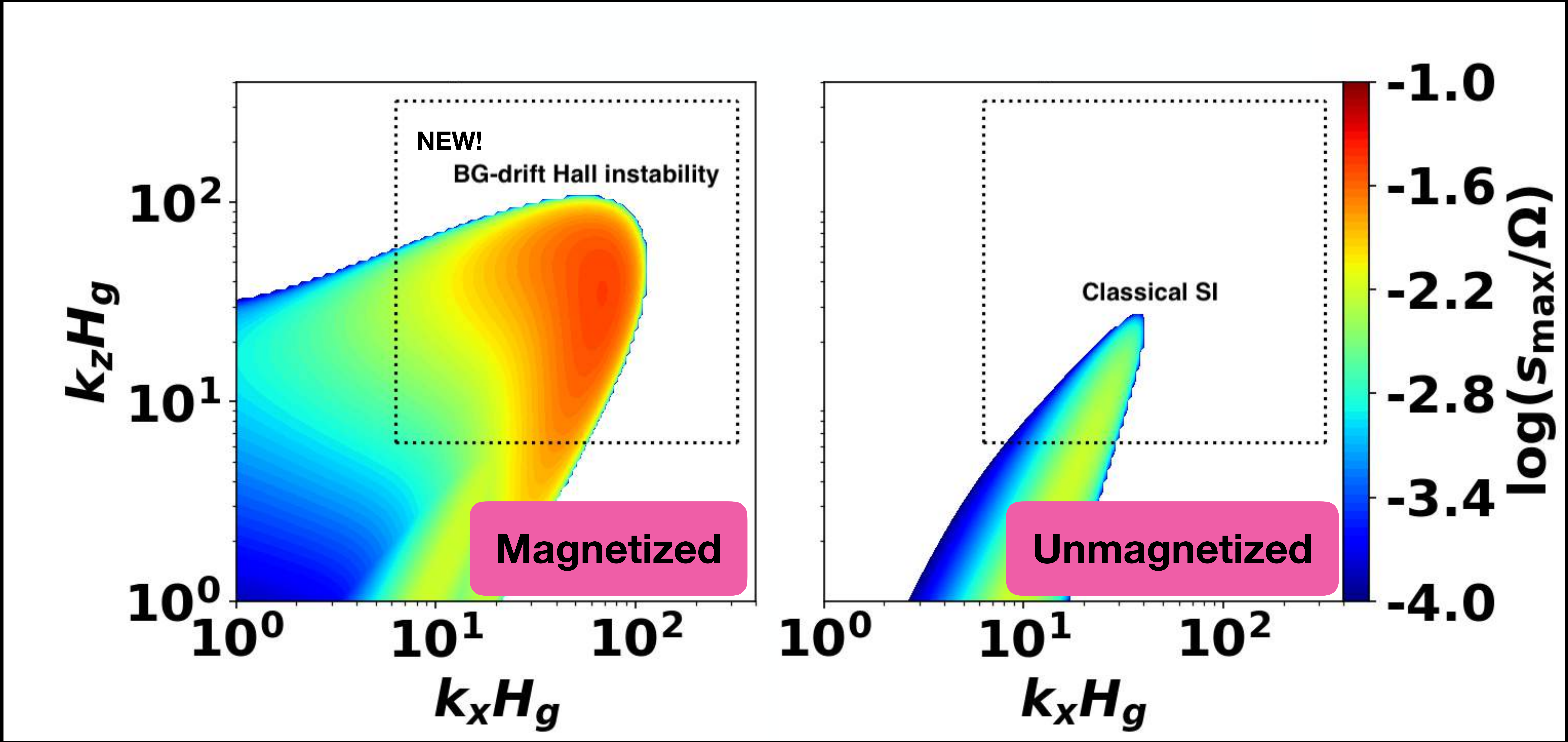
Lin & Hsu (2022), Hsu & Lin (2022)

Parameter study



Wang & Lin (in prep.)

Live magnetic field



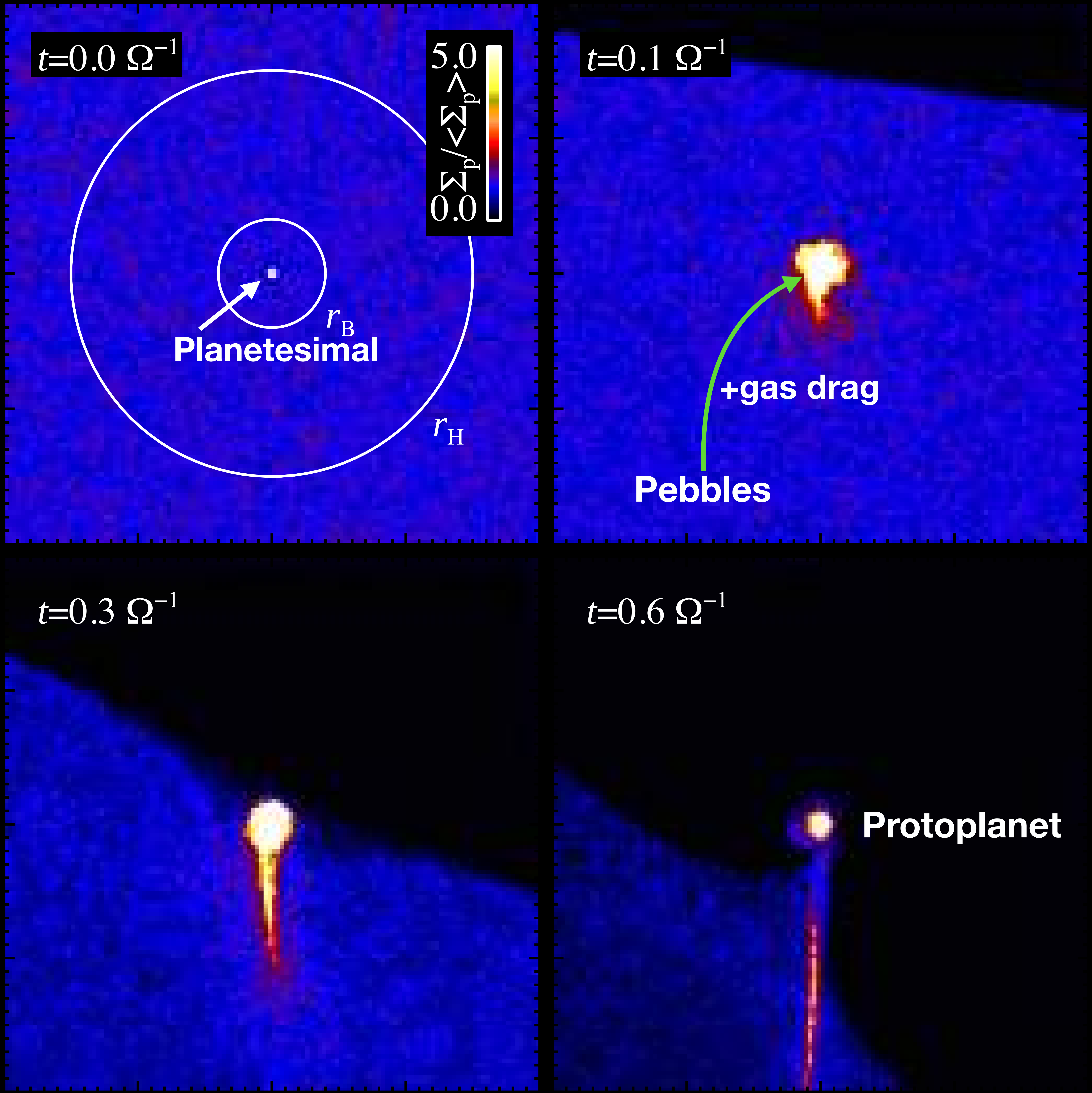
Wu, Lin, et al. (2024)

Dusty-MHD simulations

Wu, Lin, et al. (2024)

- Streaming Instability is the leading hypothesis for planetesimal formation
- Realistic physics/geometries may inhibit or promote the SI
- SI is not the only theory for planetesimal formation
- But planetesimals must form — what’s next?

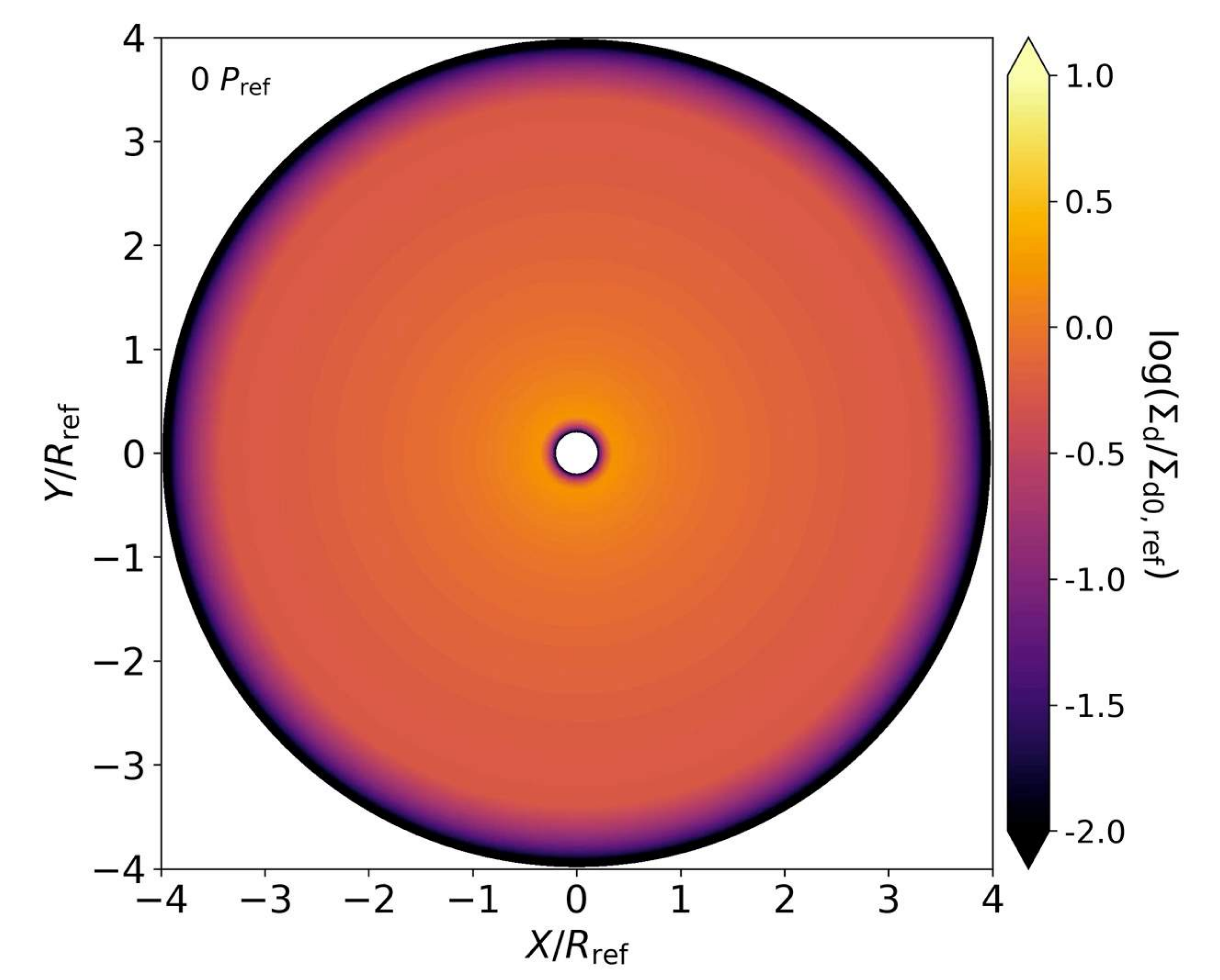
Building towards a planet via pebble accretion



Lambrechts & Johansen (2022)

What happens after planet formation?

Disk-planet interaction



Bi, Lin, Dong (2023)

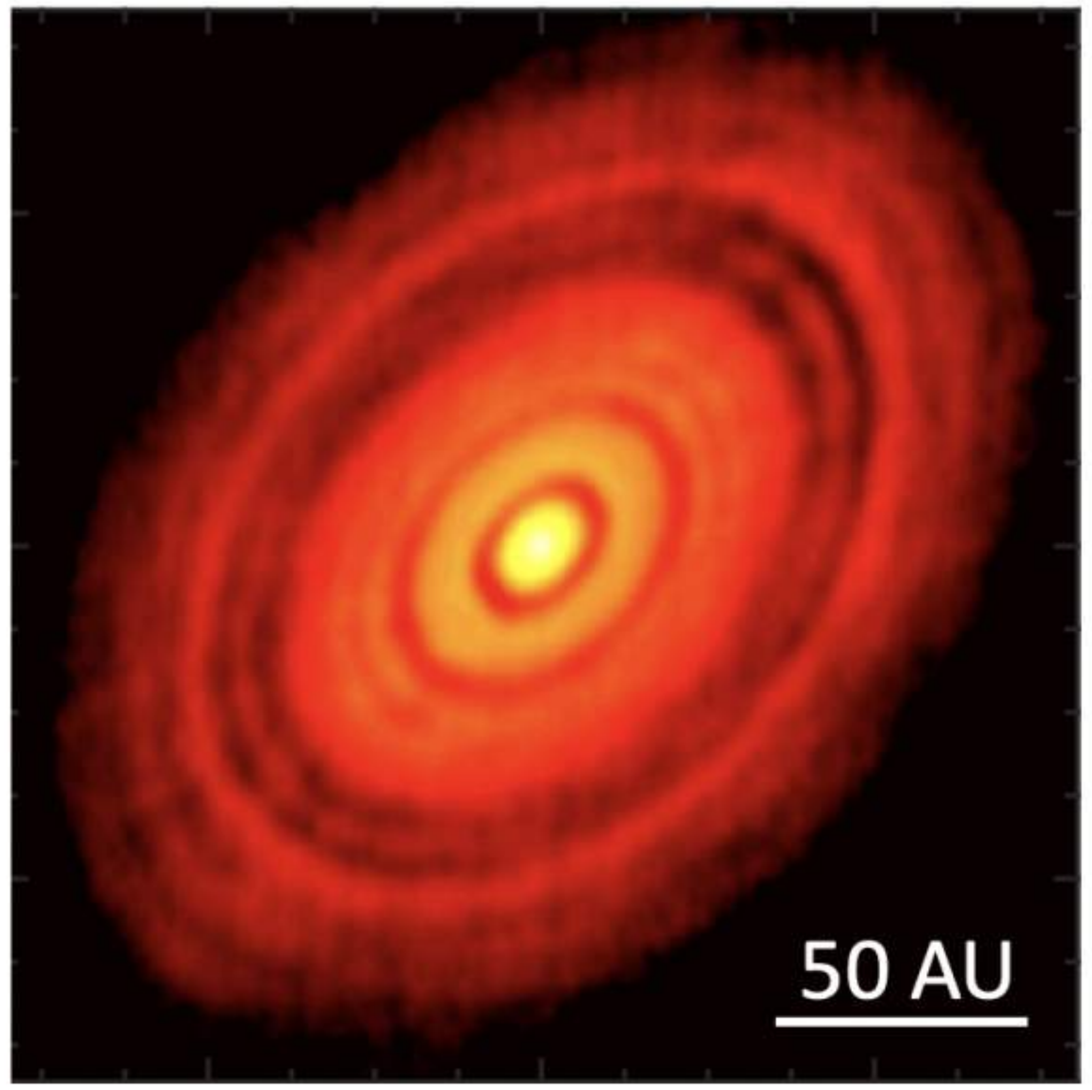
Rings and gaps: planet signatures?

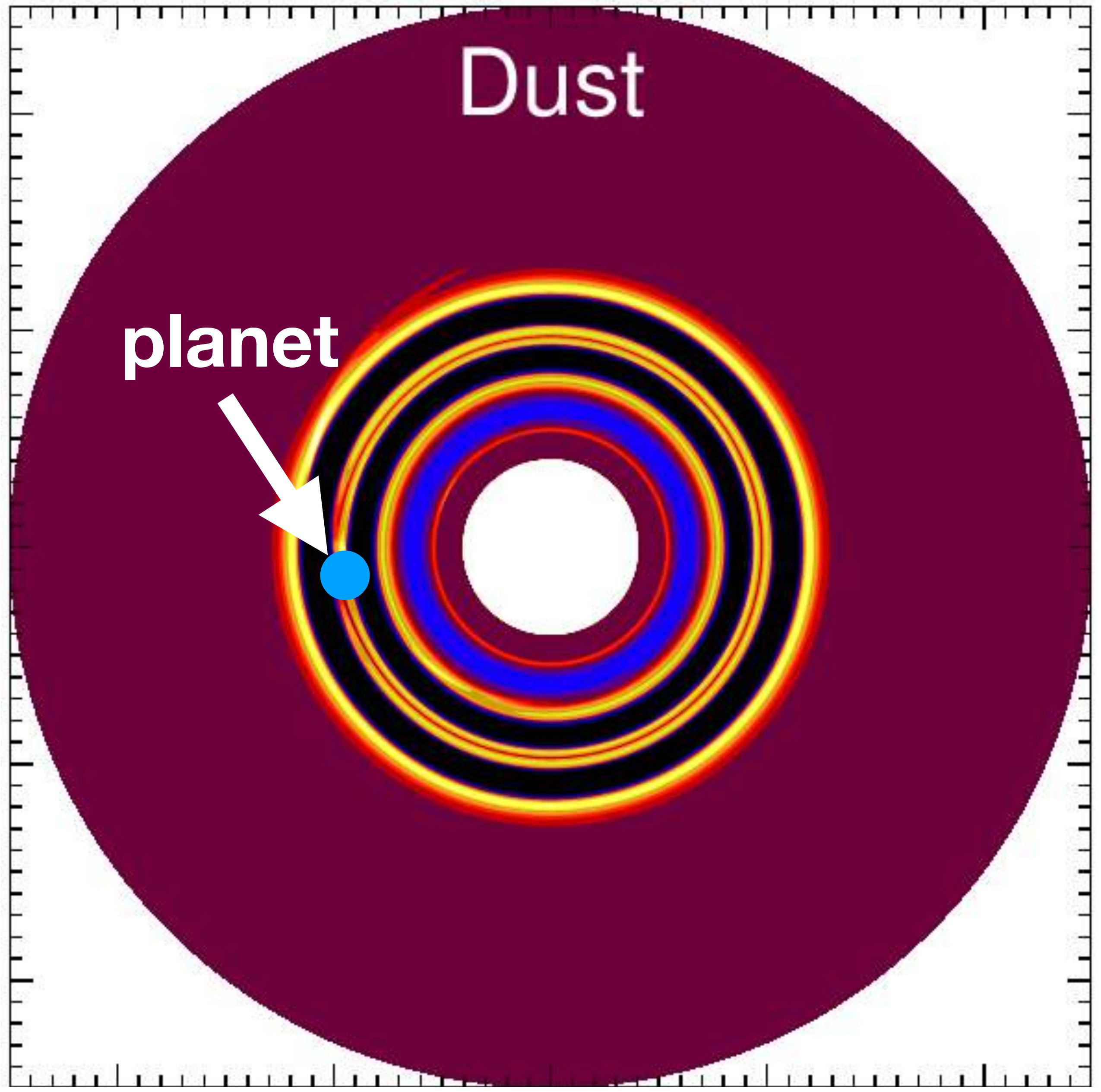
(Andrews et al, 2018; Long et al 2018)

Going beyond simulations

Observation

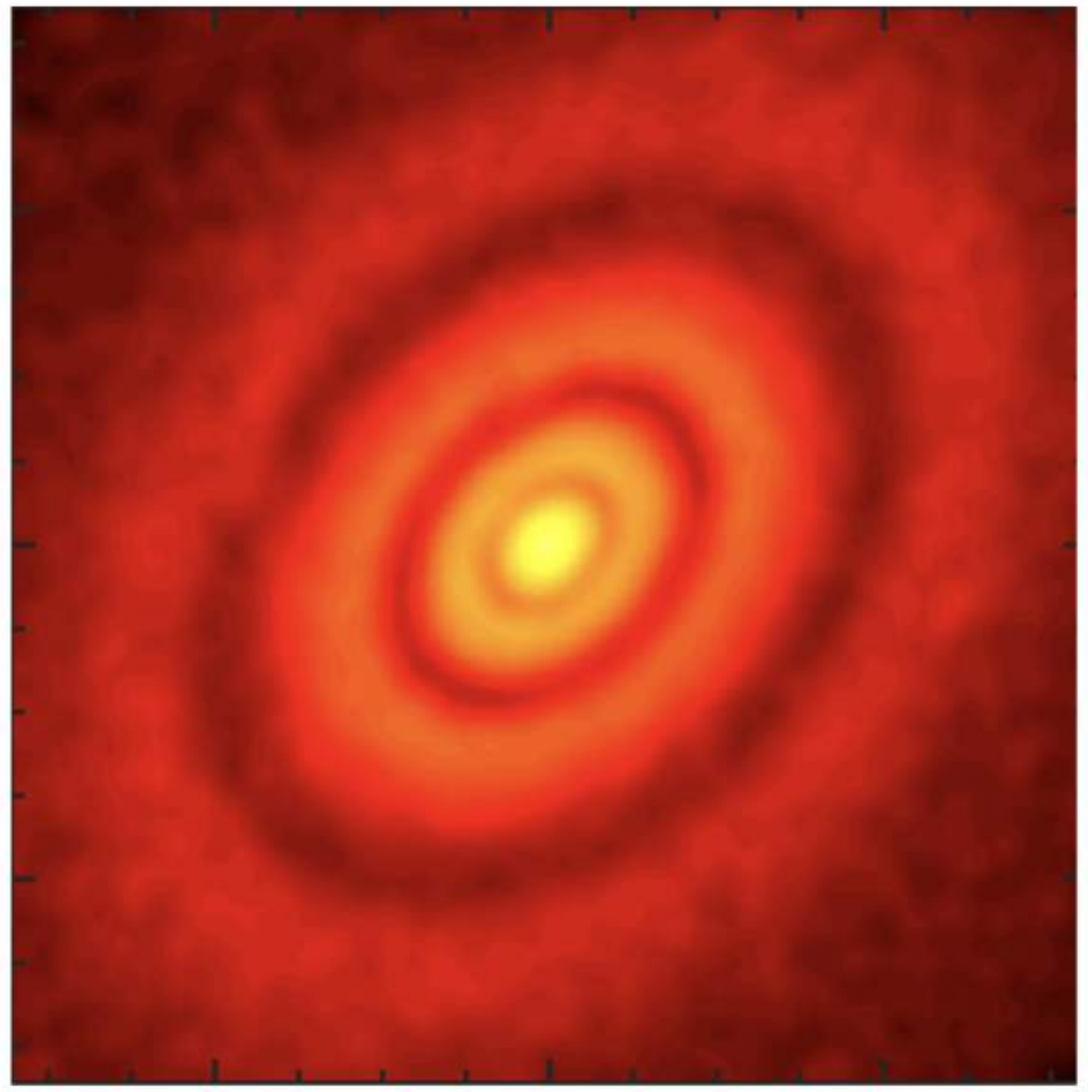
HL Tau (ALMA Partnership et al. 2015)



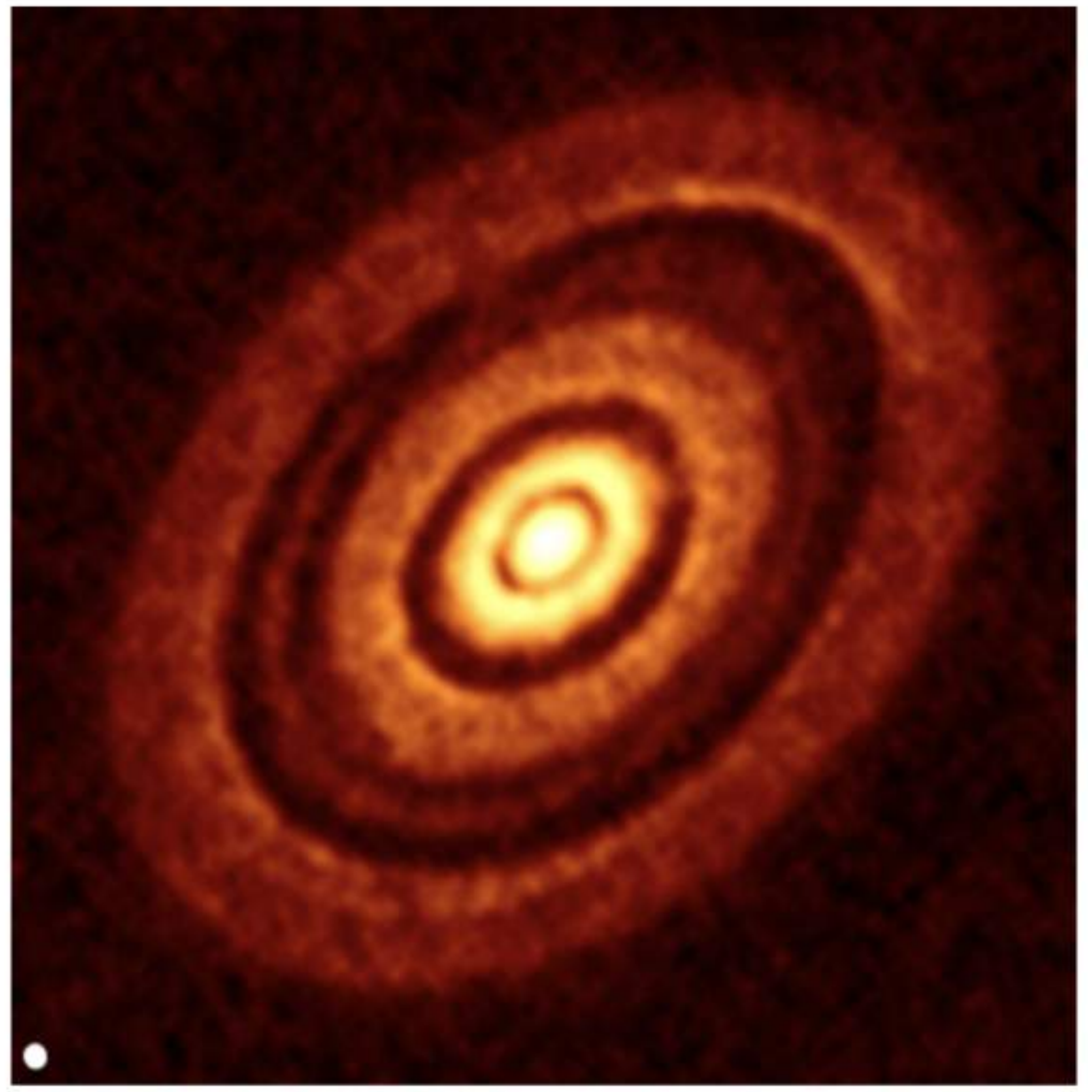


Computer simulation
(Chen & Lin, 2018)

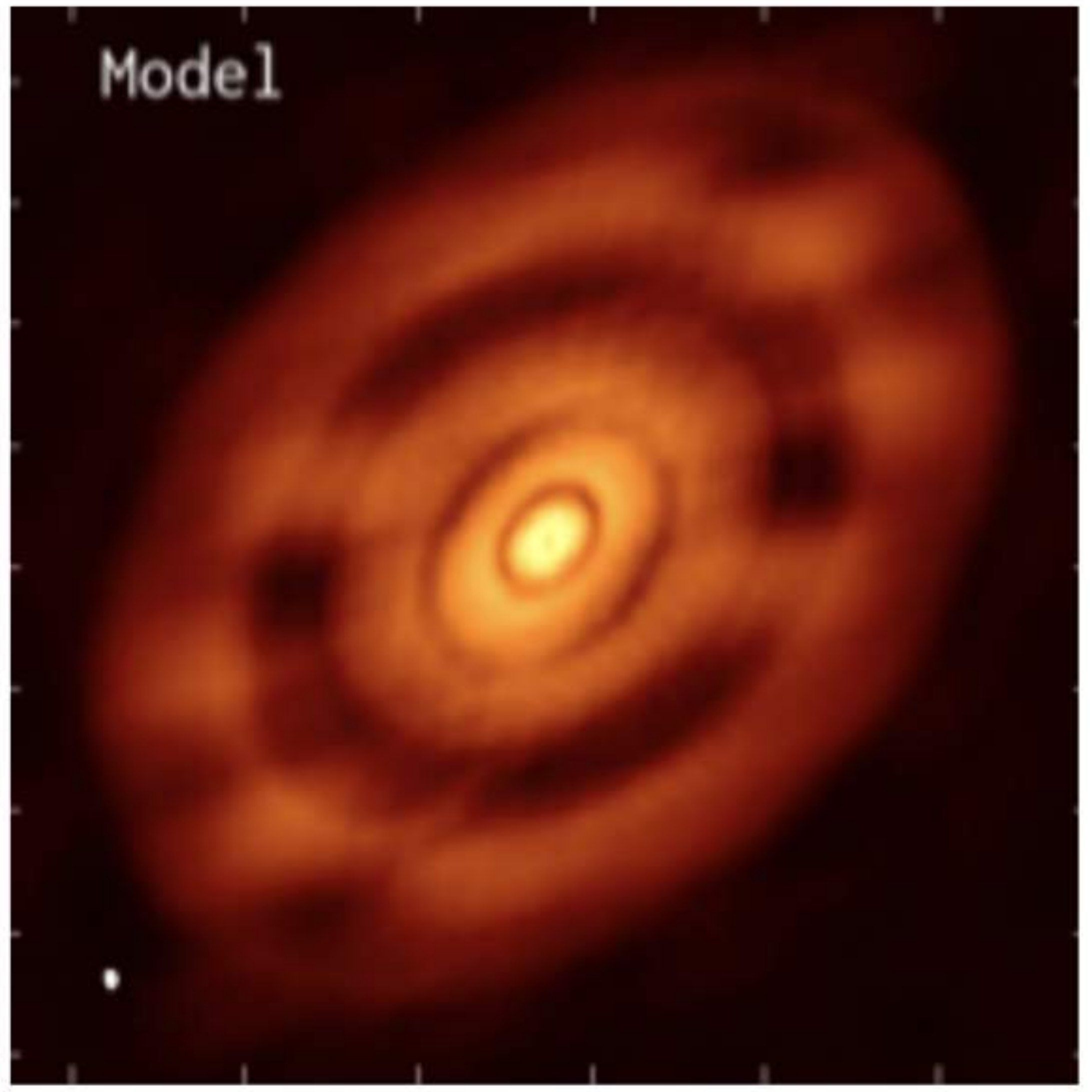
Simulation
+
synthetic obs.



Dong et al. 2015

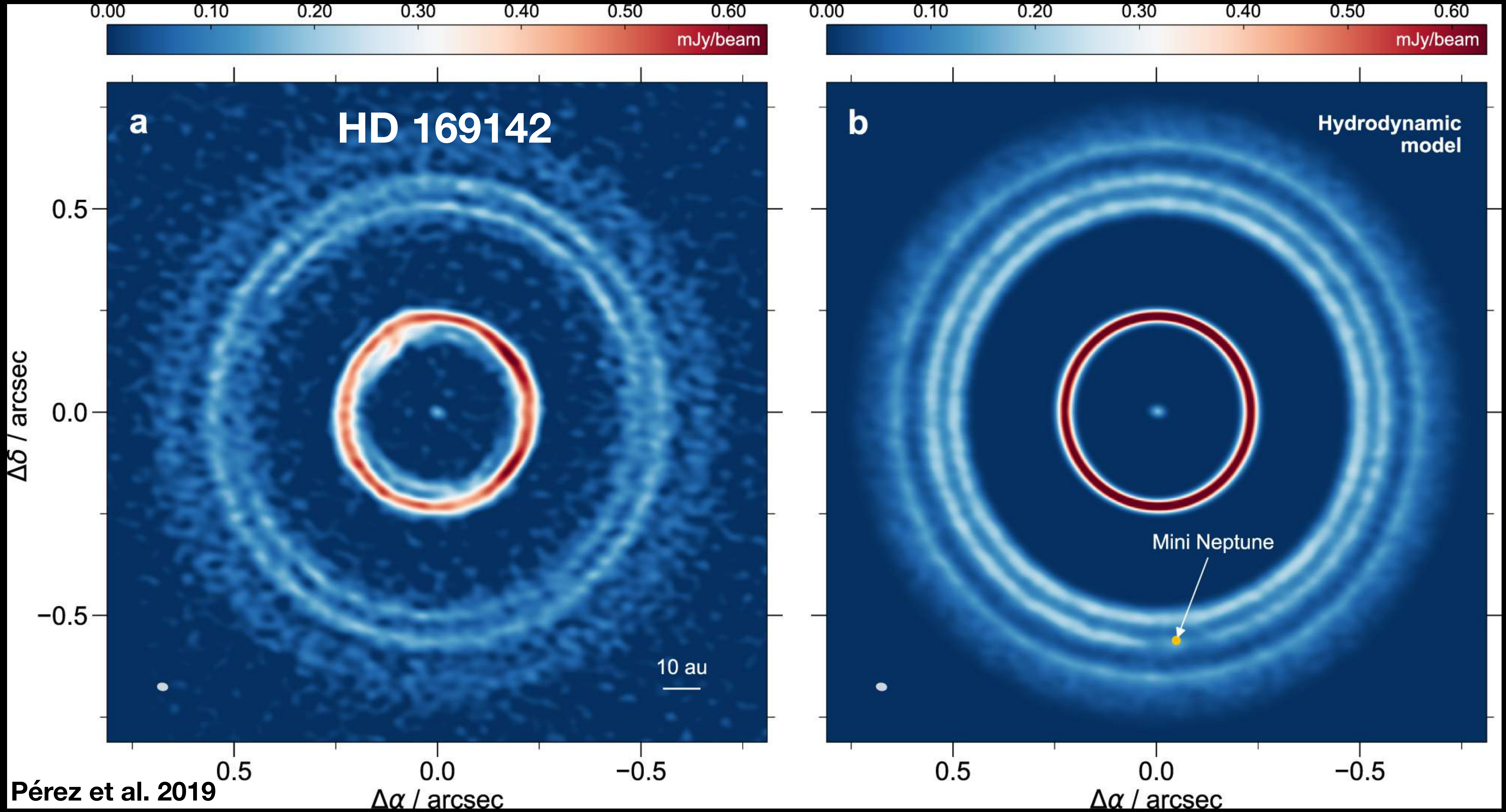


Dipierro et al. 2015



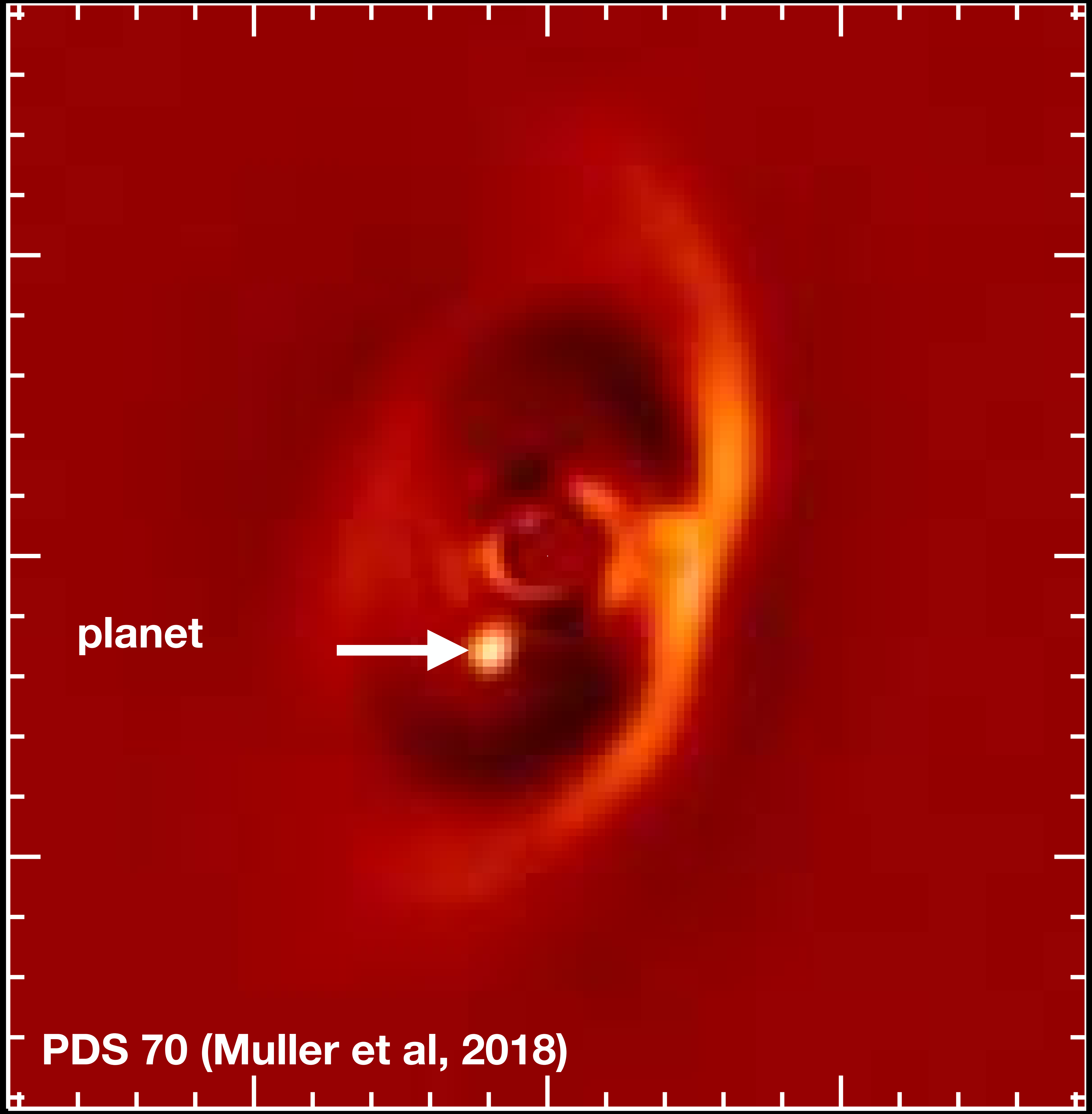
Jin et al. 2016

Detecting planets via sub-structures

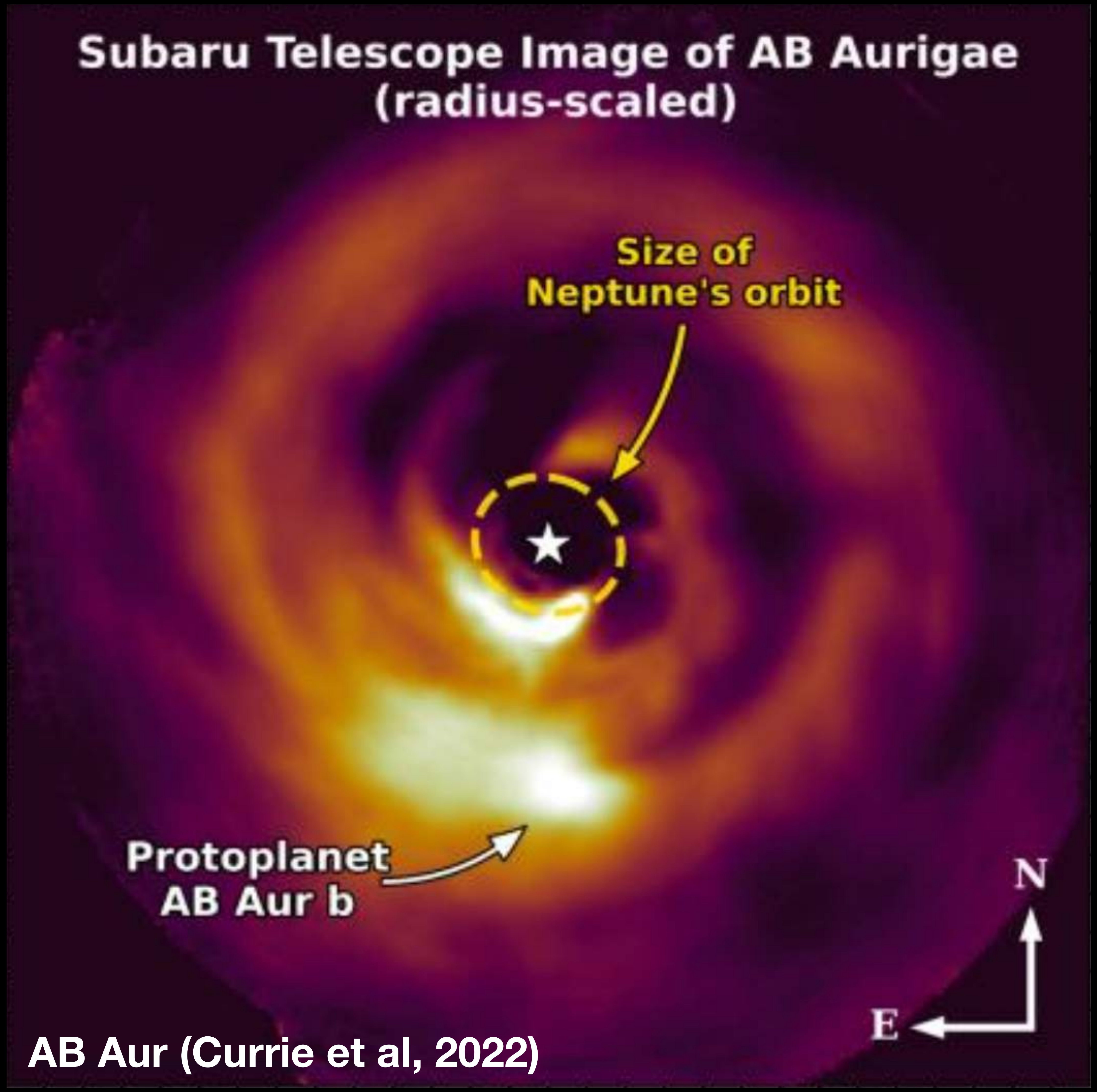


Pérez et al. 2019

Observations of planets in a disk

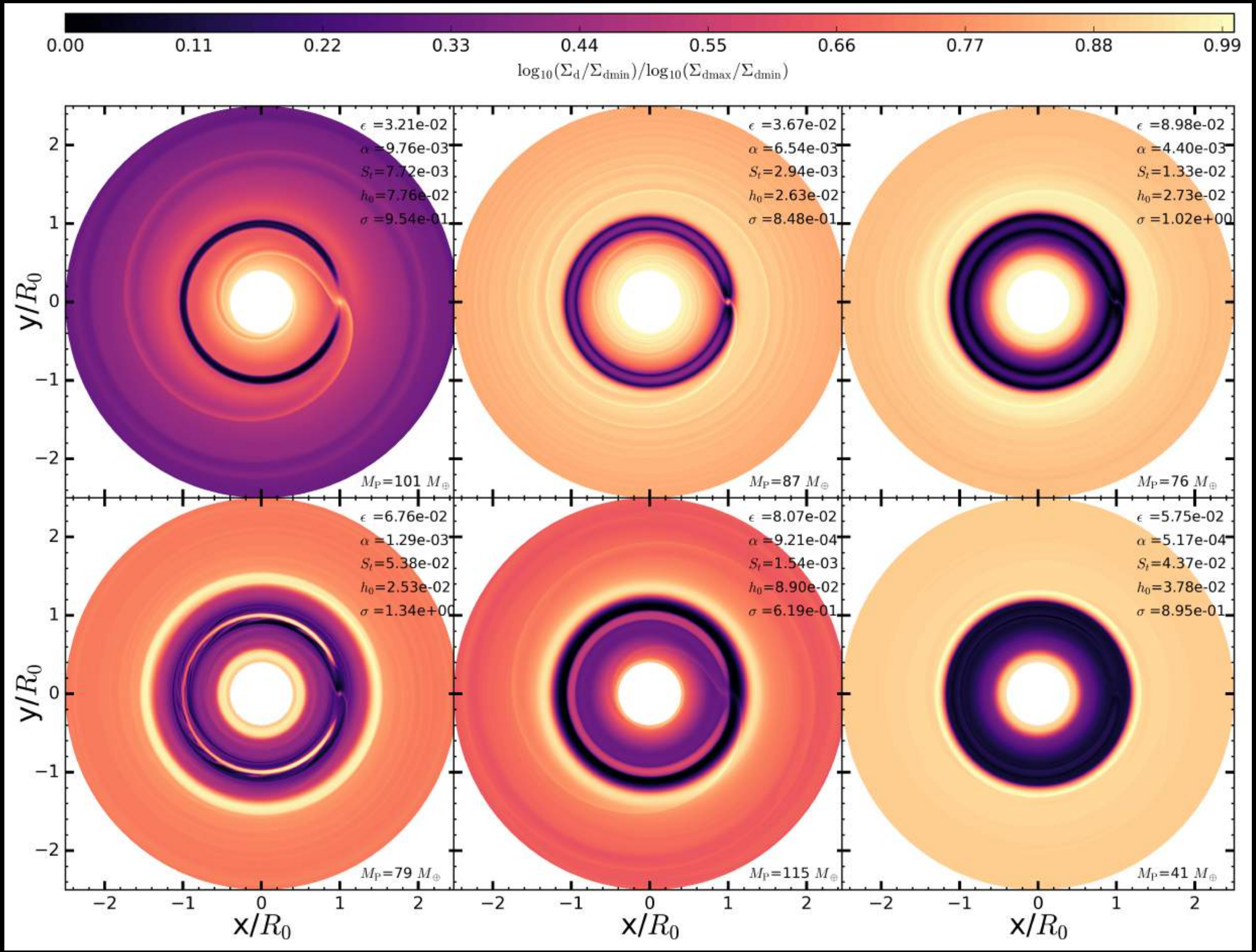


PDS 70 (Muller et al, 2018)



AB Aur (Currie et al, 2022)

Many parameters, many outcomes



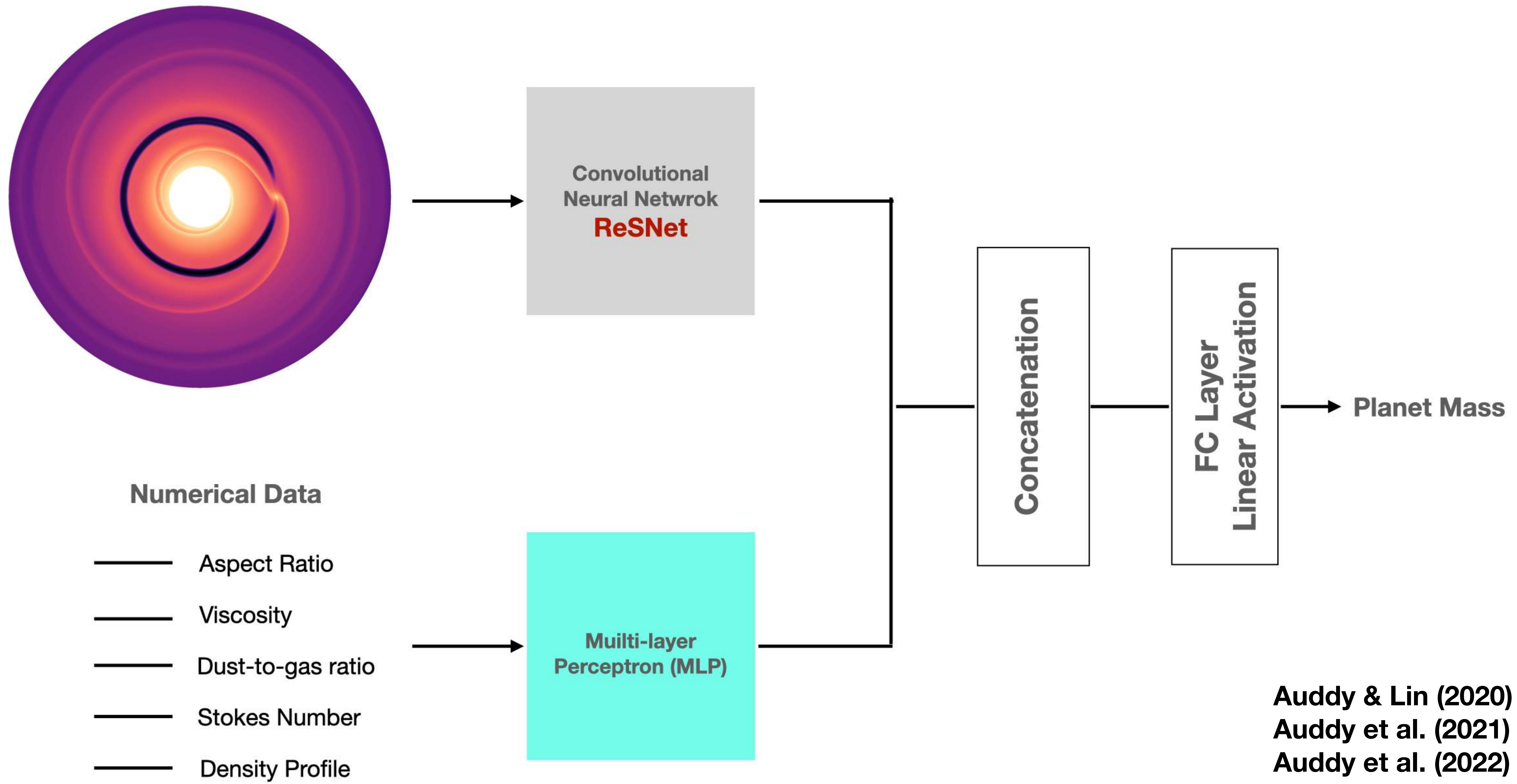
Auddy & Lin (2020)

Detecting unseen planets via disk morphology

AS 209, DSHARP (Zhang et al. 2018)

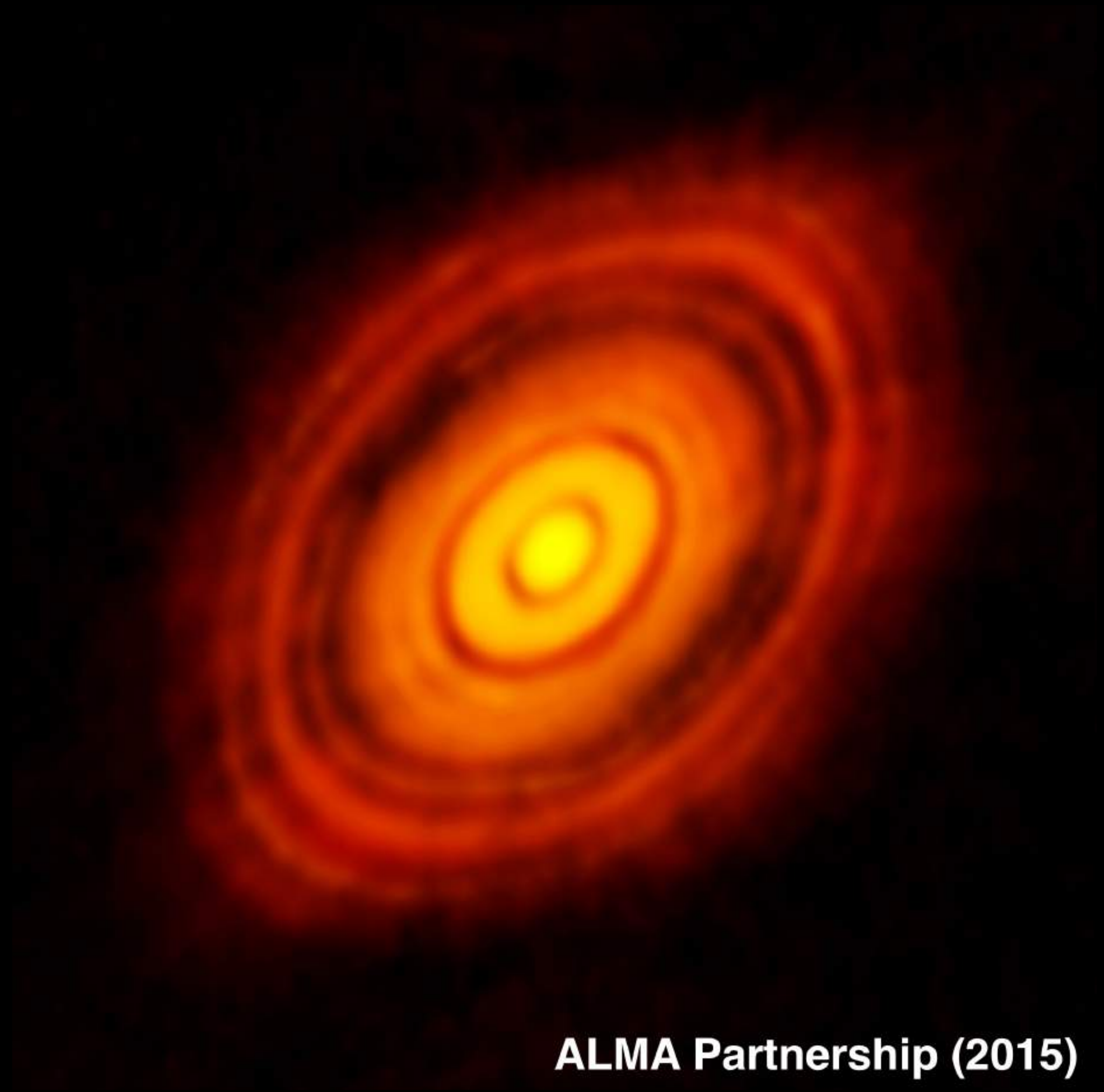
But each observation requires many simulations

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)

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

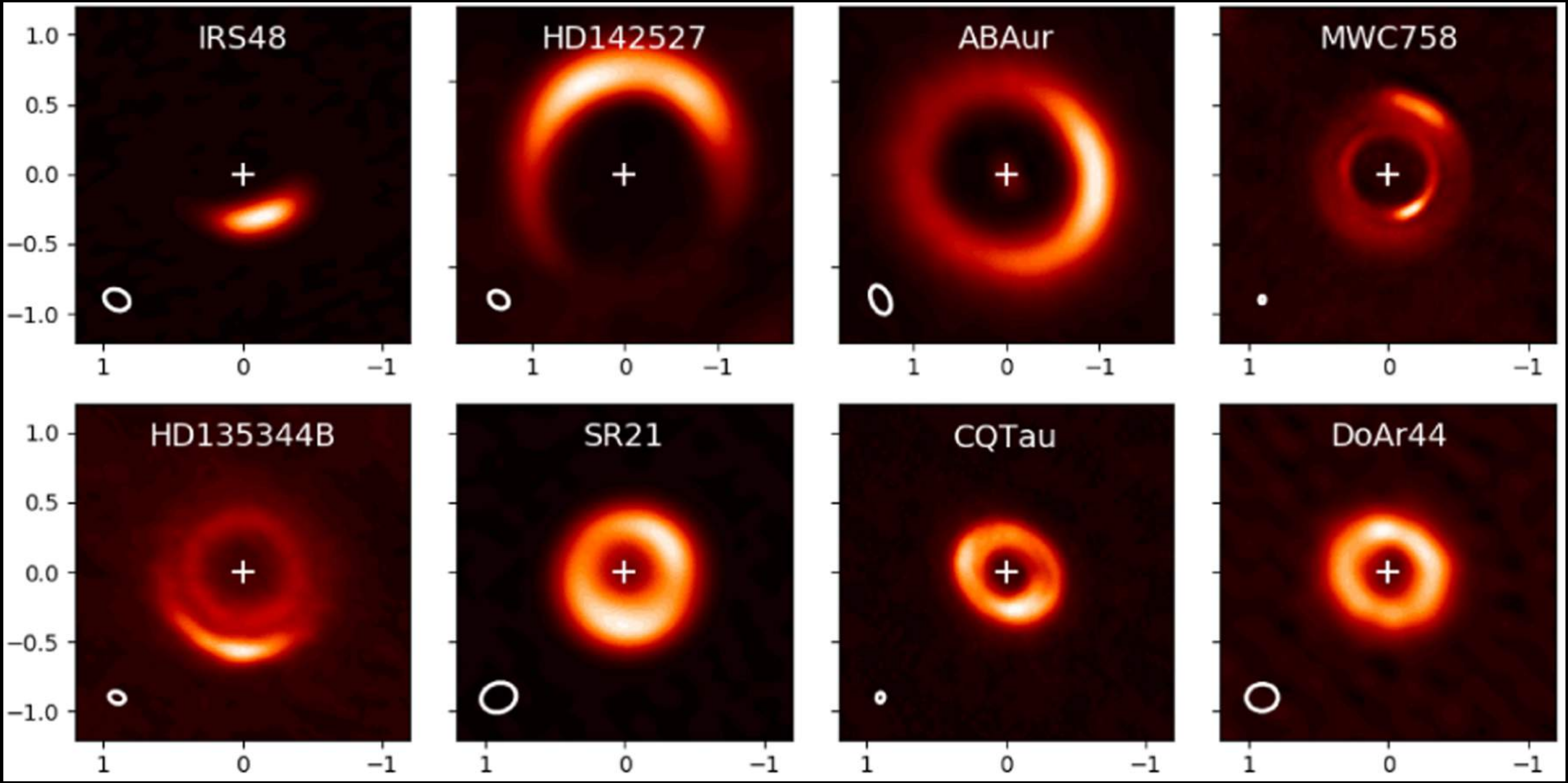
- **Disk-Planet Neural Network**

(Auddy & Lin, 2020)

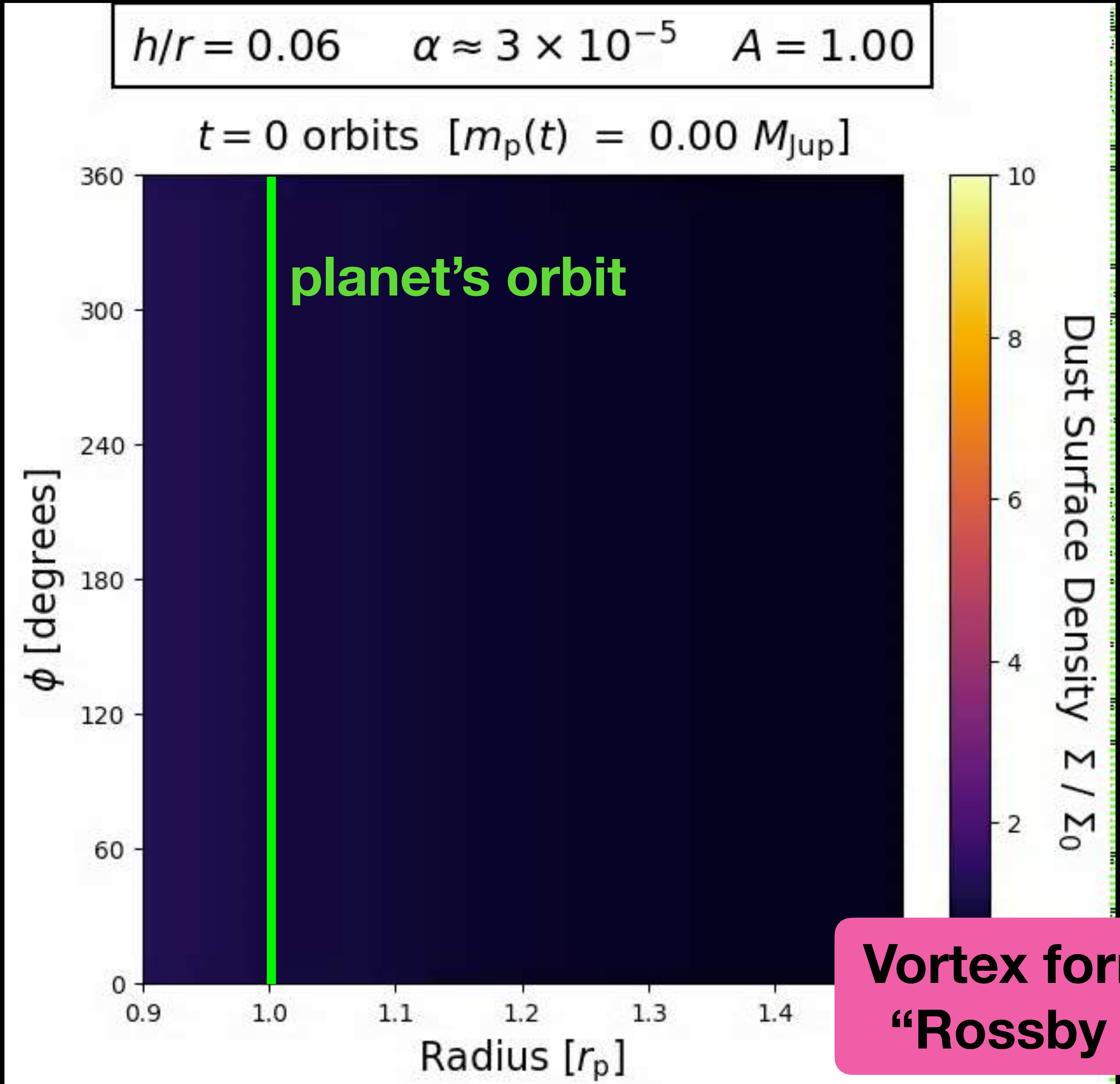
$$M_p = 0.24M_J, 0.21M_J, 0.2M_J$$

Some disks are asymmetric

(van de Marel, et al. 2021)



Can planets explain asymmetries?



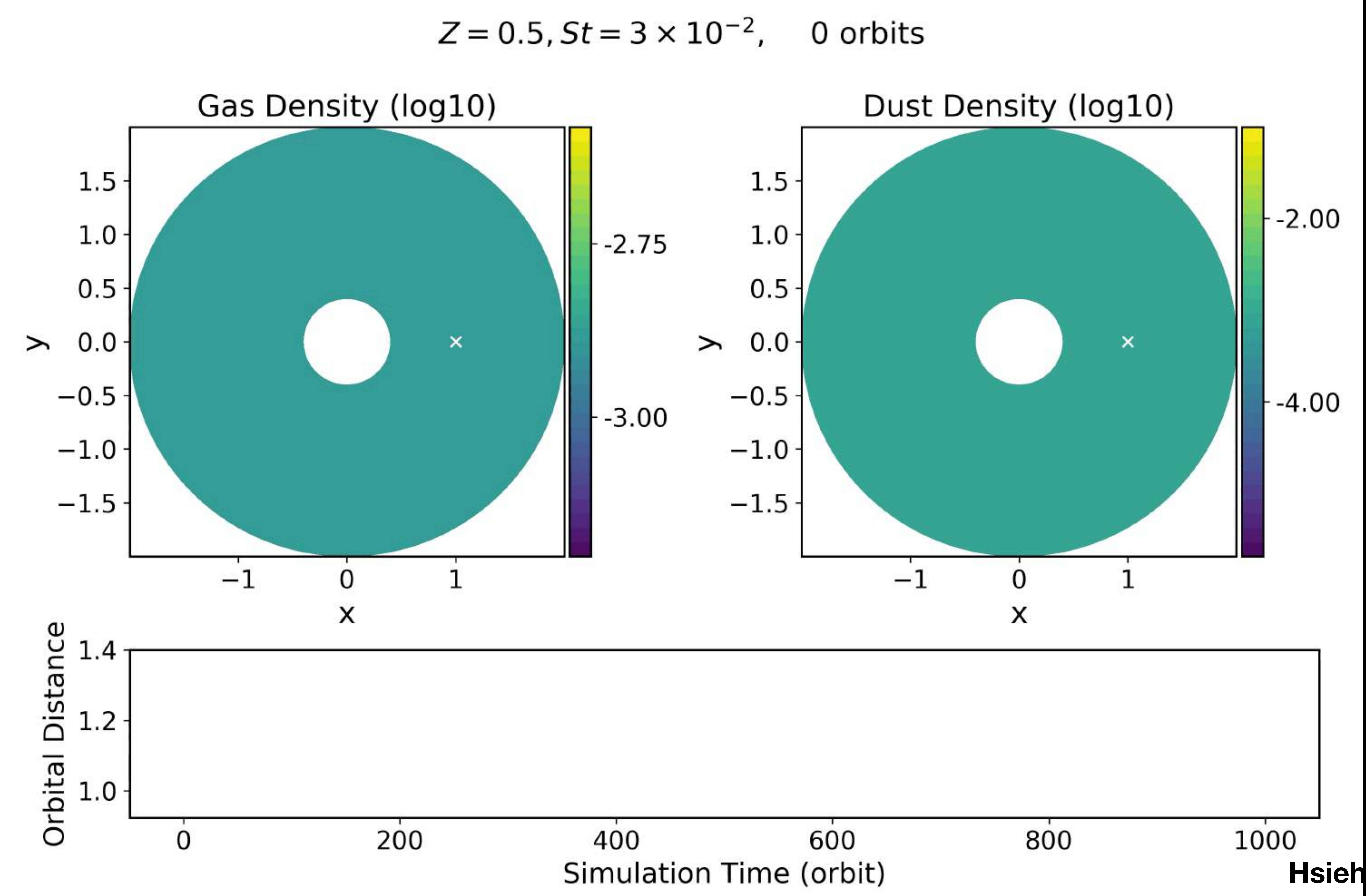
Vortex formation due to the "Rossby wave" instability

Hammer & Lin (2023)

Synthetic observations

(Hammer, Lin, et al. 2021)

Moving planets in dusty disks



Hsieh

Three-dimensional models

Bi, Lin, Dong (2021)

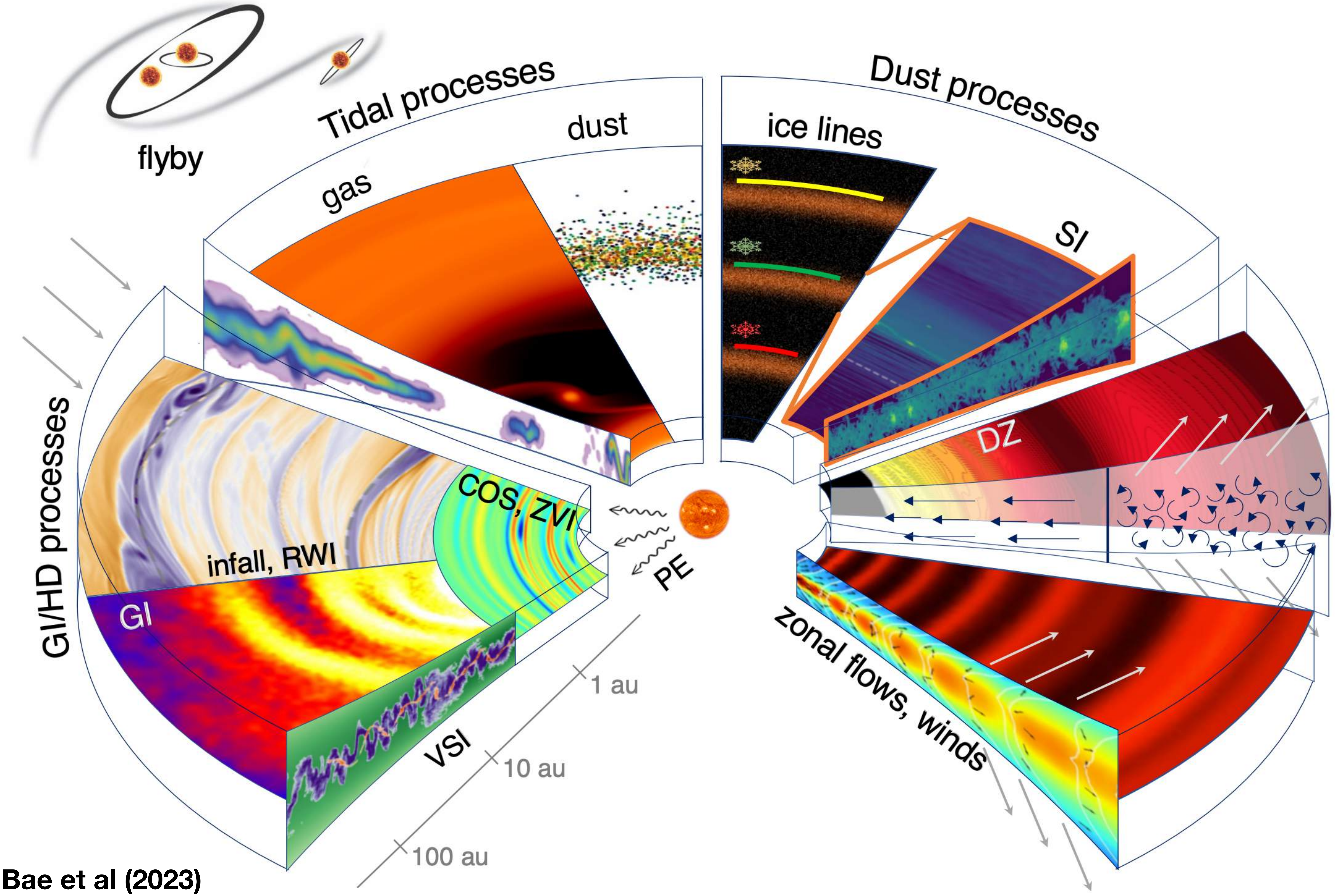
Planet mass & grain sizes

Bi, Lin, Dong (2021)

Puffed up rings in observations: Sign of planets?

Doi & Kataoka (2021)

Are all sub-structures due to unseen planets?

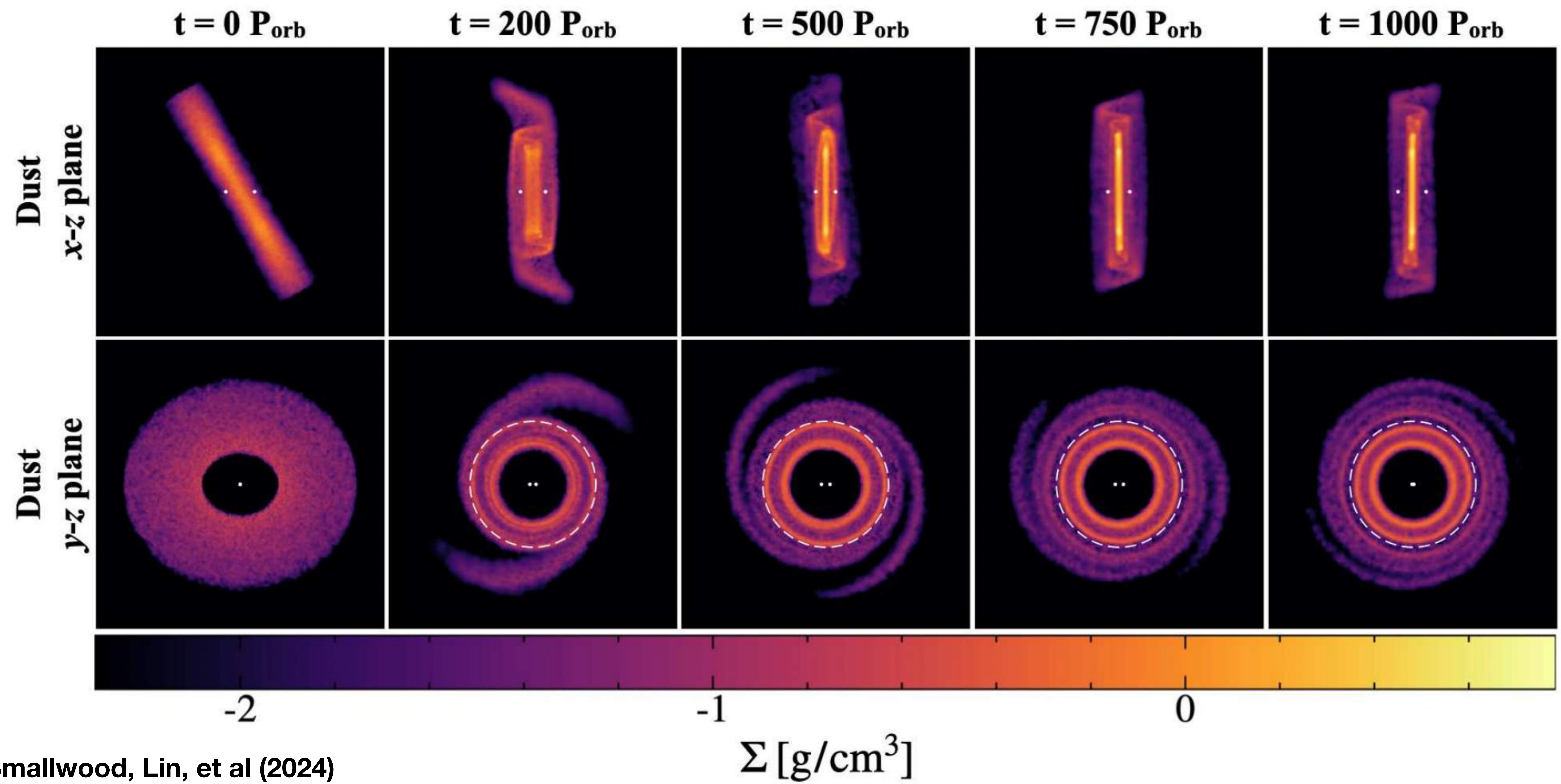


Bae et al (2023)

Planet vs. non-planet dust rings

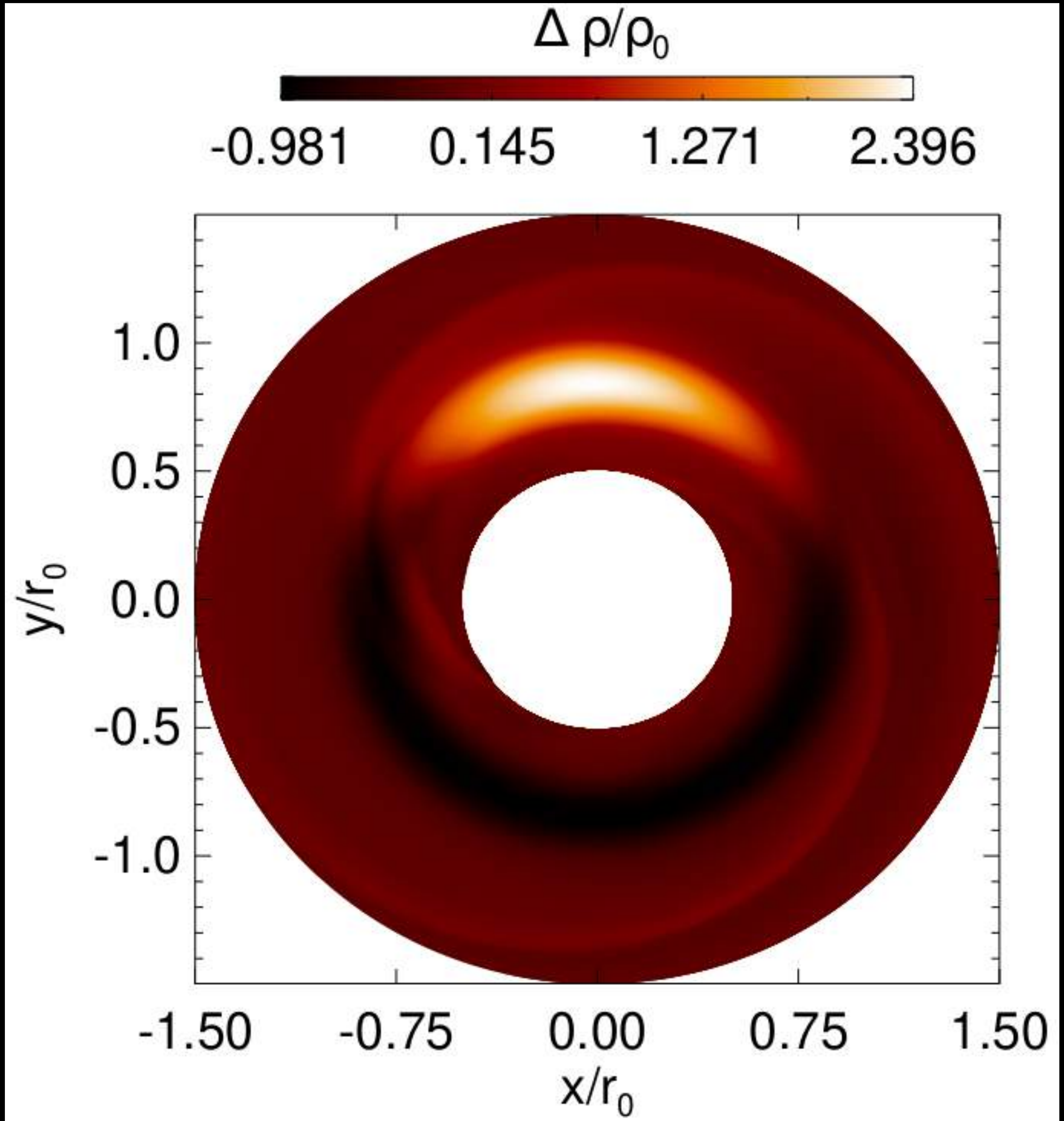
Bi, Lin, Dong (2023)

Dust rings in misaligned circumbinary disks



Smallwood, Lin, et al (2024)

Vortex formation from convection



Lehmann & Lin (2024)

Missed topics

- Fundamentals of PPD gas dynamics: magnetic fields, winds, accretion
- From protoplanets to a fully grown planet
- Planet formation via disk instability
- Disks around planets, satellite formation
- Planet migration: gas and plantesimal-driven
- Planet-planet interactions, N-body problems

See “Protostars & Planets VII” book

Summary

- Planetary systems are ubiquitous, formation should be easy
- Mainstream idea is to build planets from small grains across many orders of magnitude
- Gas and dust dynamics are critical, turbulence, SI
- Planets shape protoplanetary disks
- Disk substructures are not exclusive to disk-planet interaction

𝕏 @linminkai