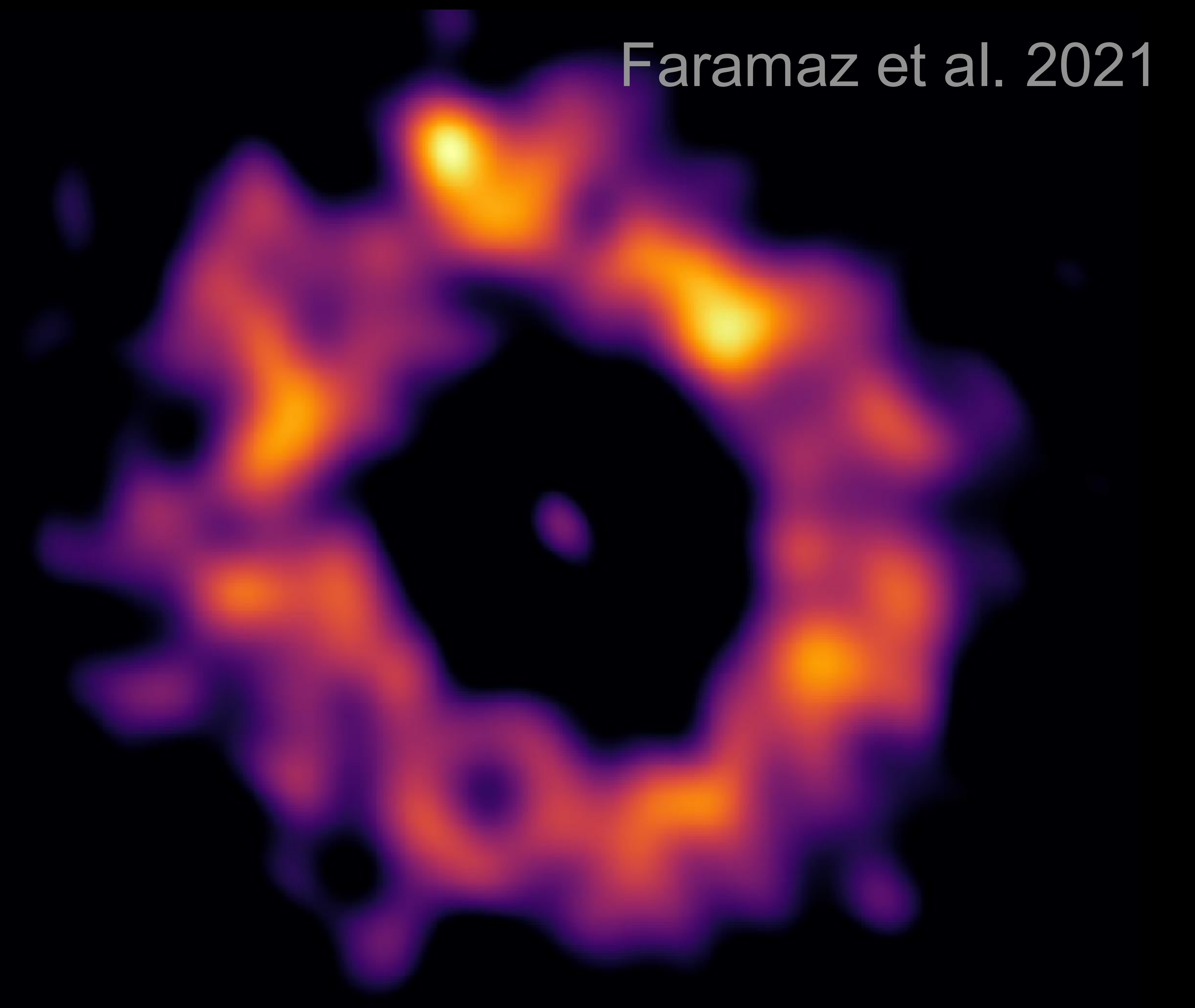


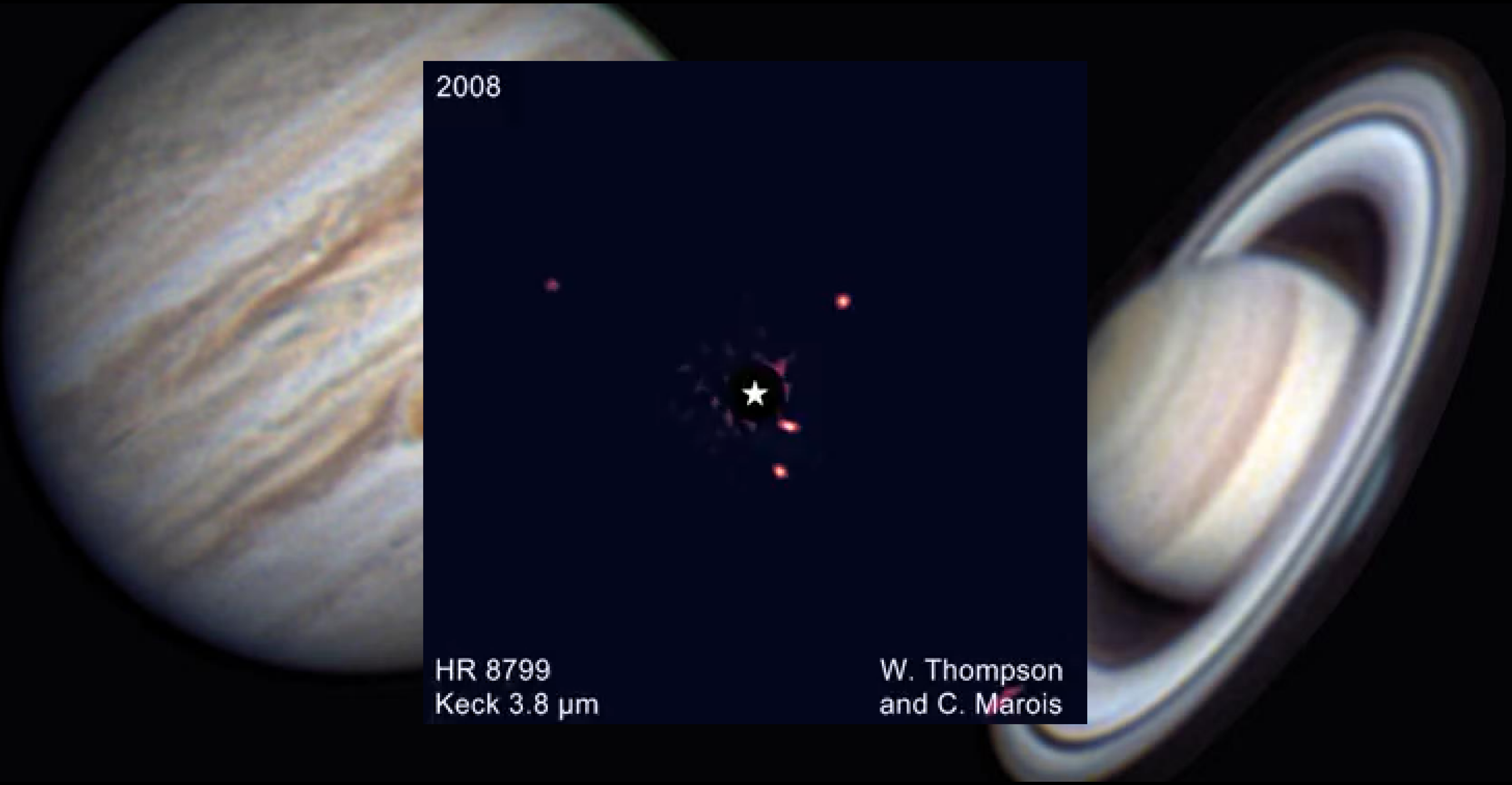
Ring-Driven Planets and Debris Disk Formation in HR 8799 and Other Directly-Imaged Planetary Systems

October 9st 2025 @ 51 Peg b 30th anniversary, OHP

Haochang Jiang
PSF Postdoc Fellow, MPIA

Max-Planck-Institut für Astronomie Heidelberg
Max Planck Institute for Astronomy Heidelberg

Gas giants, by definition, form inside disks full of gas



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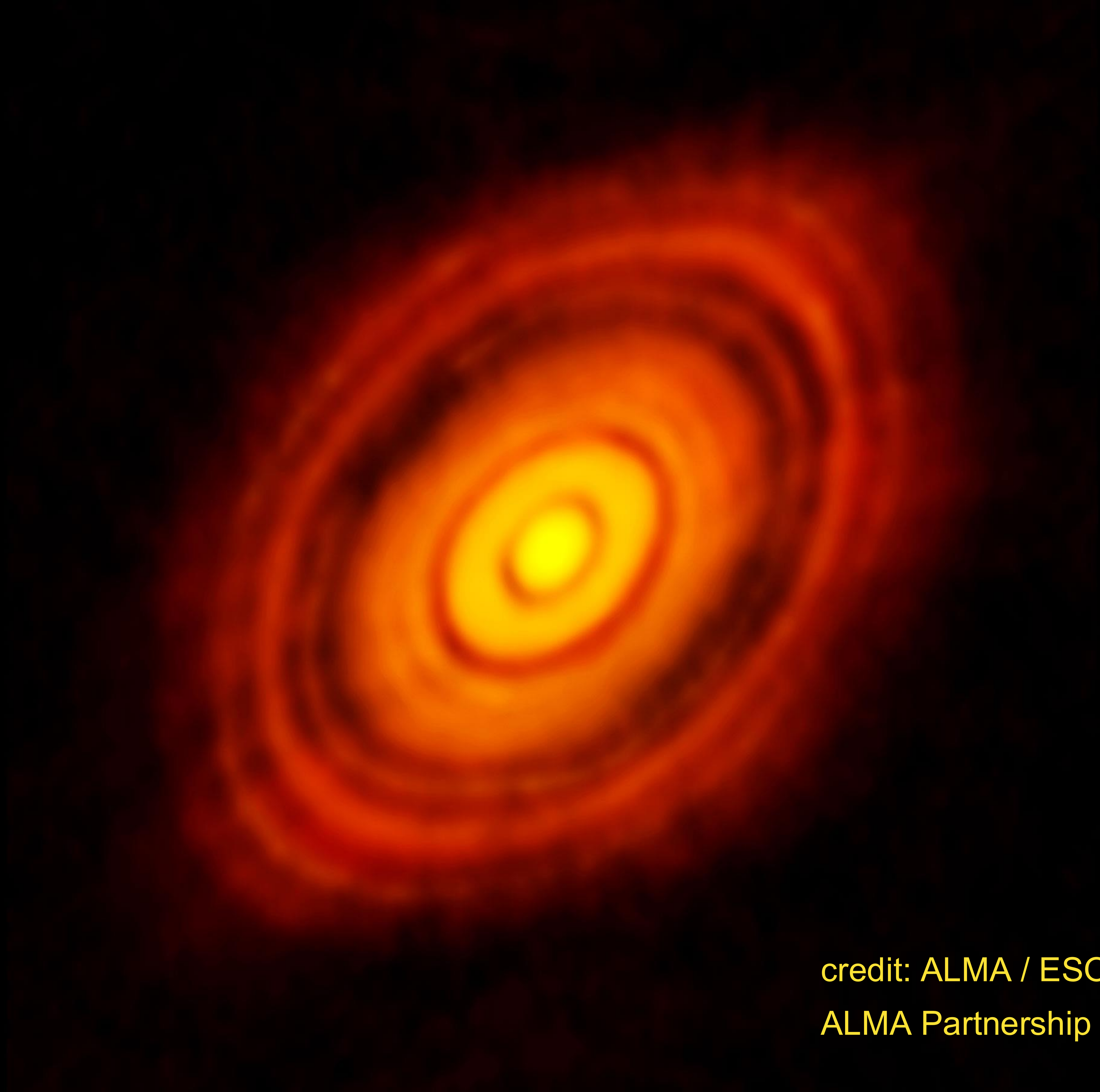
HL Tau



credit: ALMA / ESO / NAOJ / NRAO

ALMA Partnership et al. 2015

HL Tau

Pebble size particle
- (sub)mm

credit: ALMA / ESO / NAOJ / NRAO

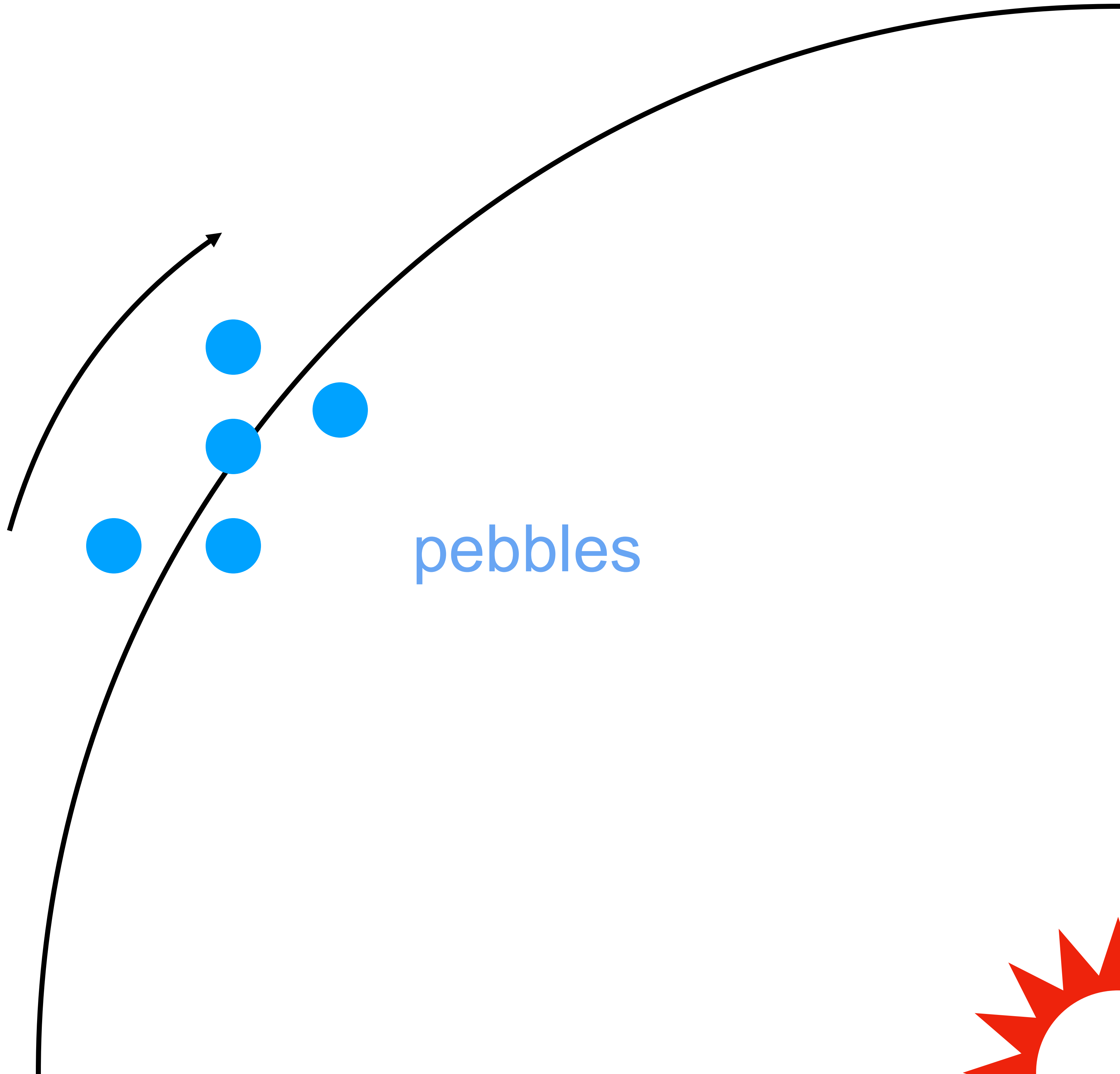
ALMA Partnership et al. 2015

How to get these rings? - dynamics of pebble

$$v_{\rm dr} = \frac{\rm St}{(1+Z)^2+{\rm St}^2}\frac{c_s^2}{\Omega_K r}\frac{\partial \log P}{\partial \log r}$$

Nakagawa, Sekiya & Hayashi 1986

- Pebbles' radial velocity - NSH solution



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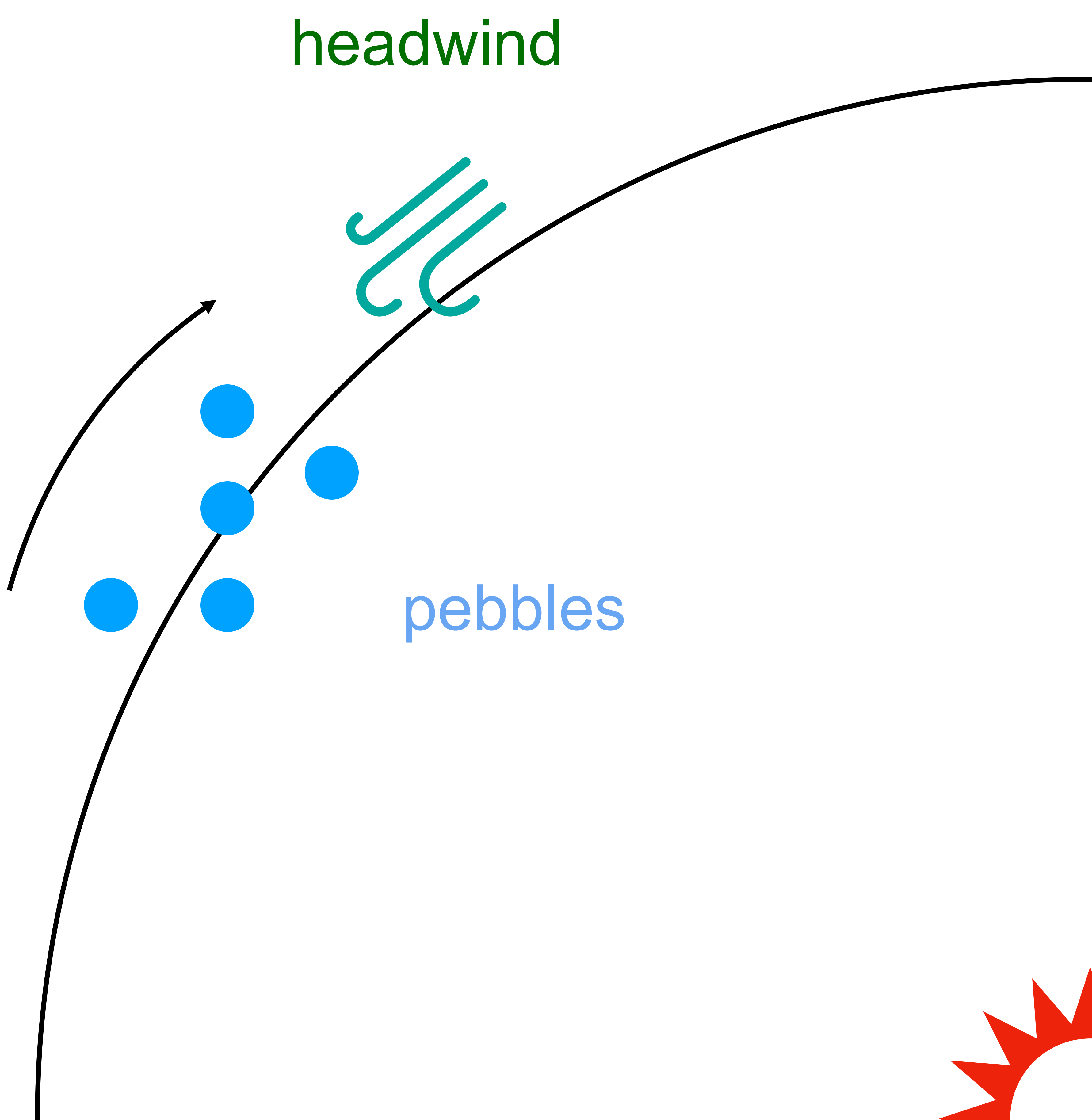

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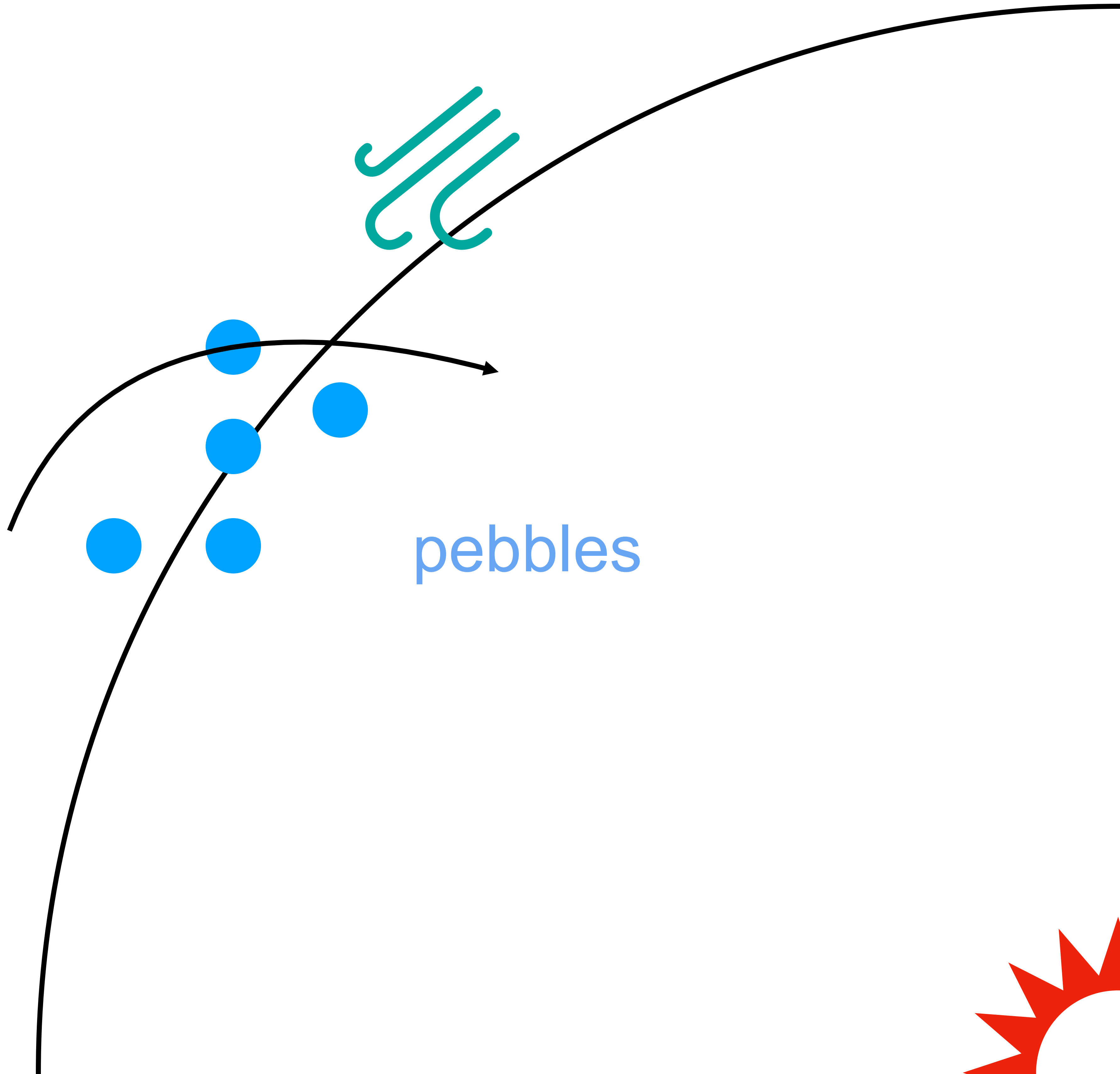

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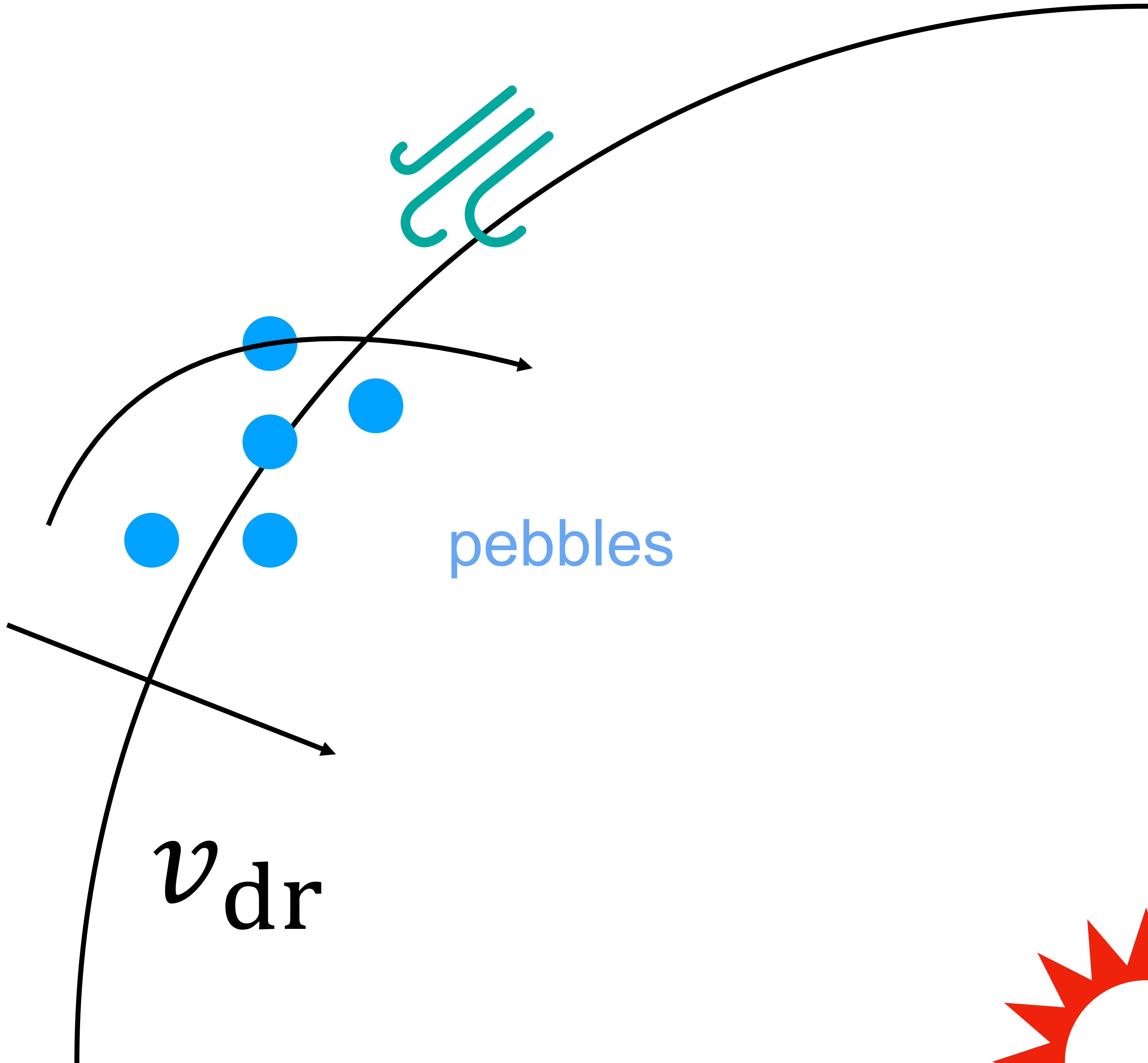
Nakagawa, Sekiya & Hayashi 1986

- Stokes number
- local concentration
- Pressure gradient



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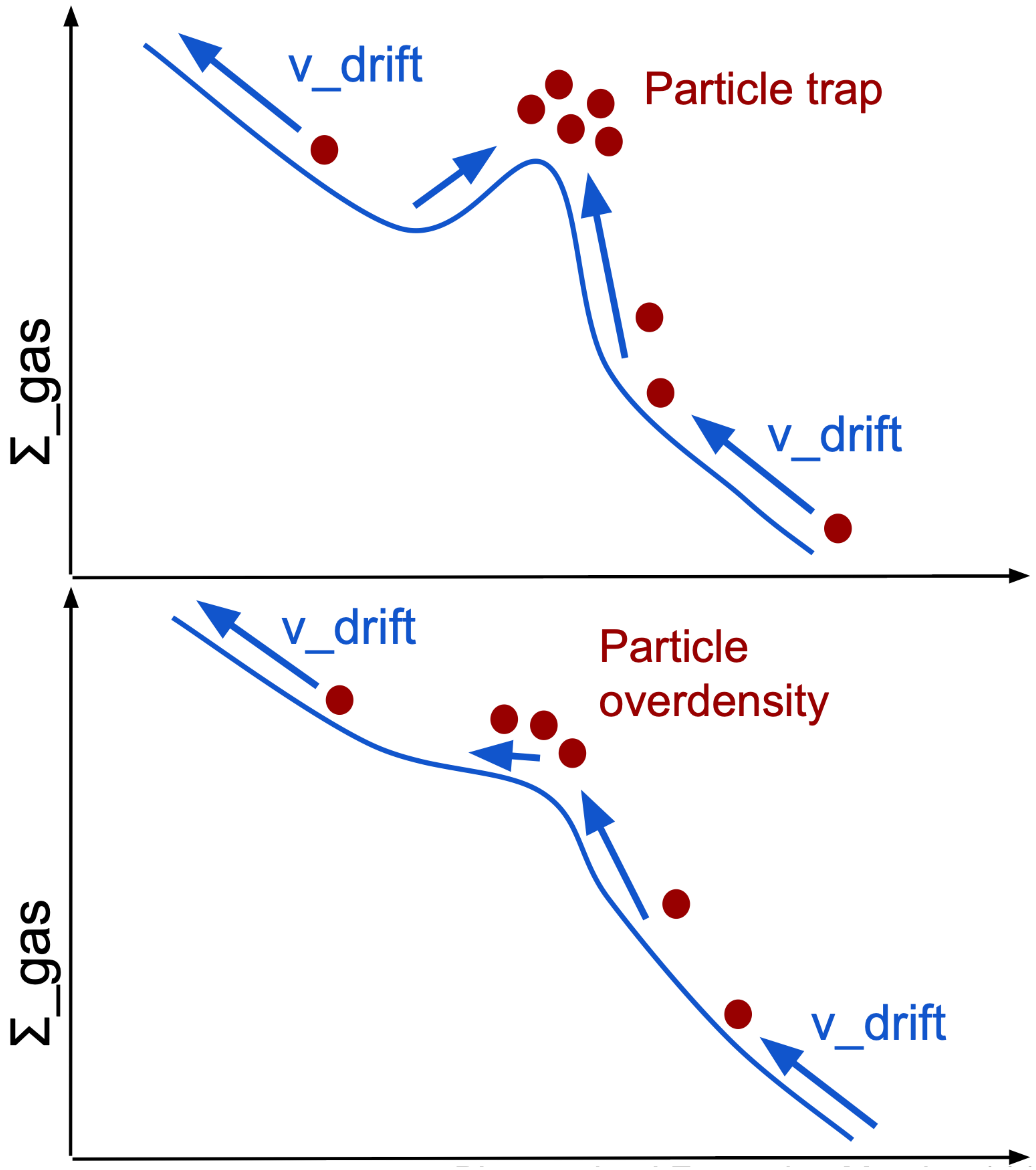
Nakagawa, Sekiya & Hayashi 1986

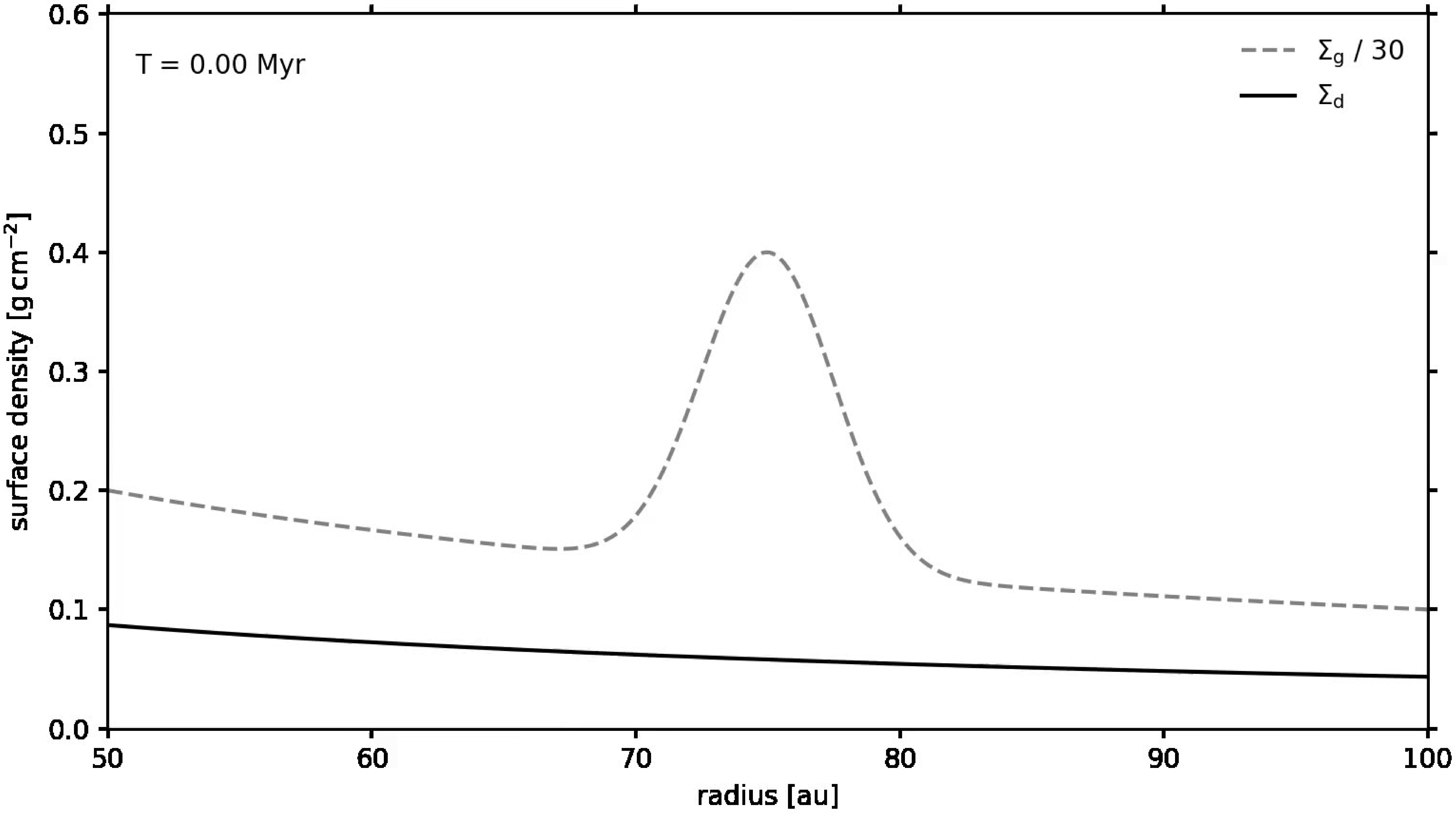
- Pebbles' radial velocity - NSH solution

Dust particles drift along the **pressure gradient**



Daniel Carrera, Planetesimal Formation Meeting 2020

How to get these rings?



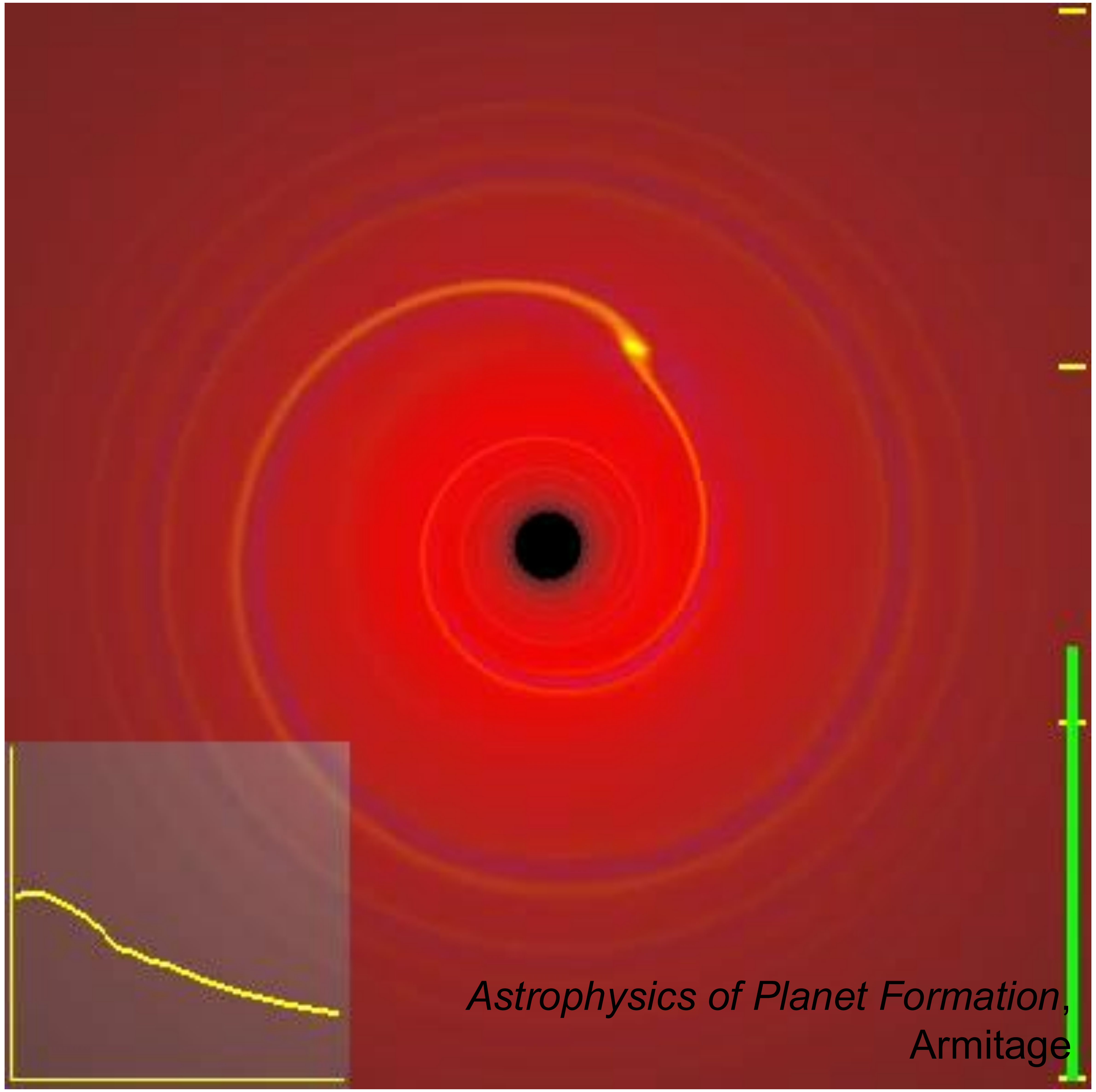
How to get the pressure bump?

- **Planet** Gap Opening

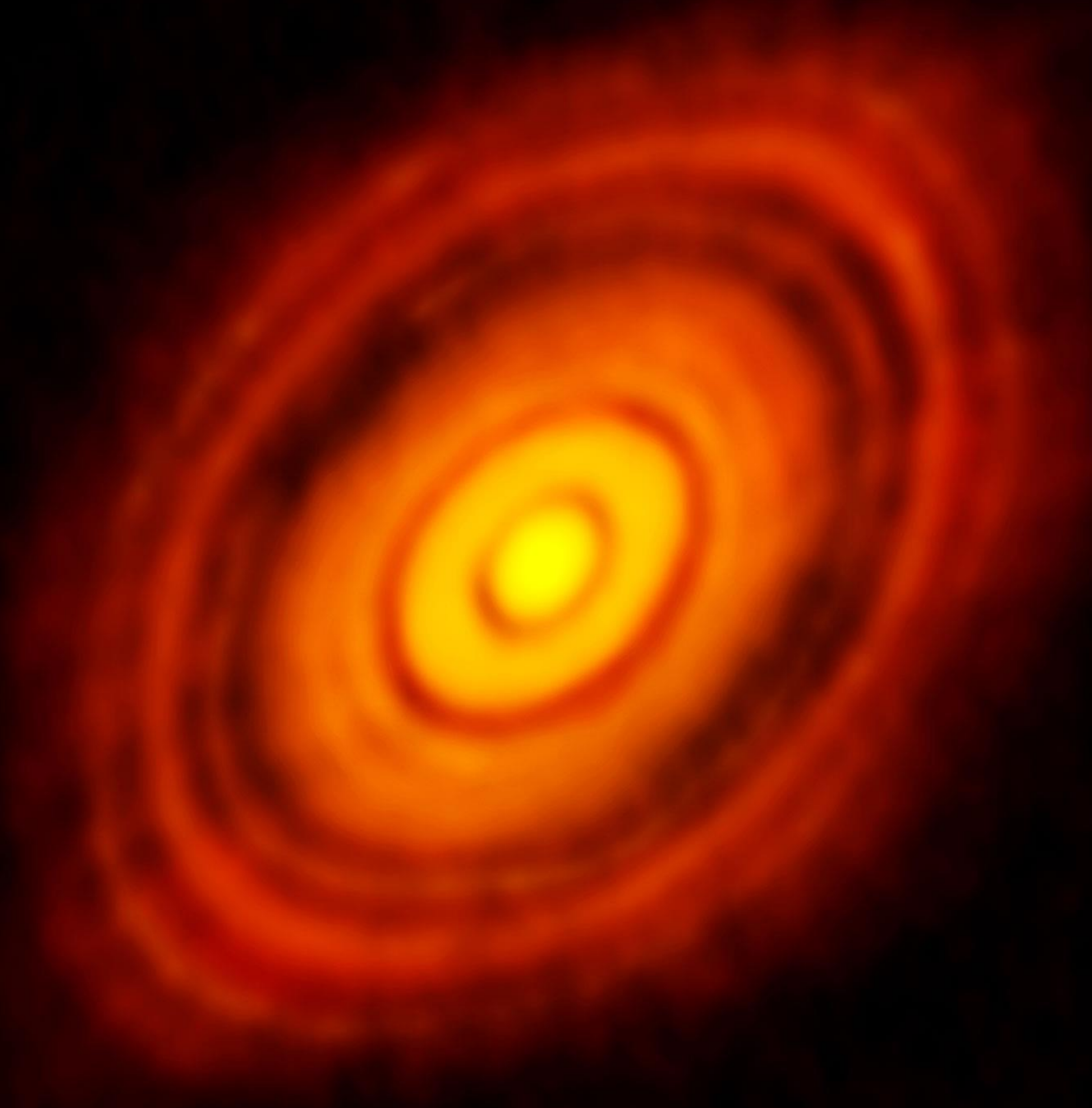
Lin & Papaloizou 1979

⇒ Pressure bumps at the outer edge of the gap

- Goldreich & Tremaine 1980;
- Rice+ 2006; Pinilla+ 2012, 2015;
- Dodson-Robinson & Salyk 2011, Zhu+ 2011
- Zhang+ 2018, Kanagawa+ 2018;
- Dullemond+ 2018



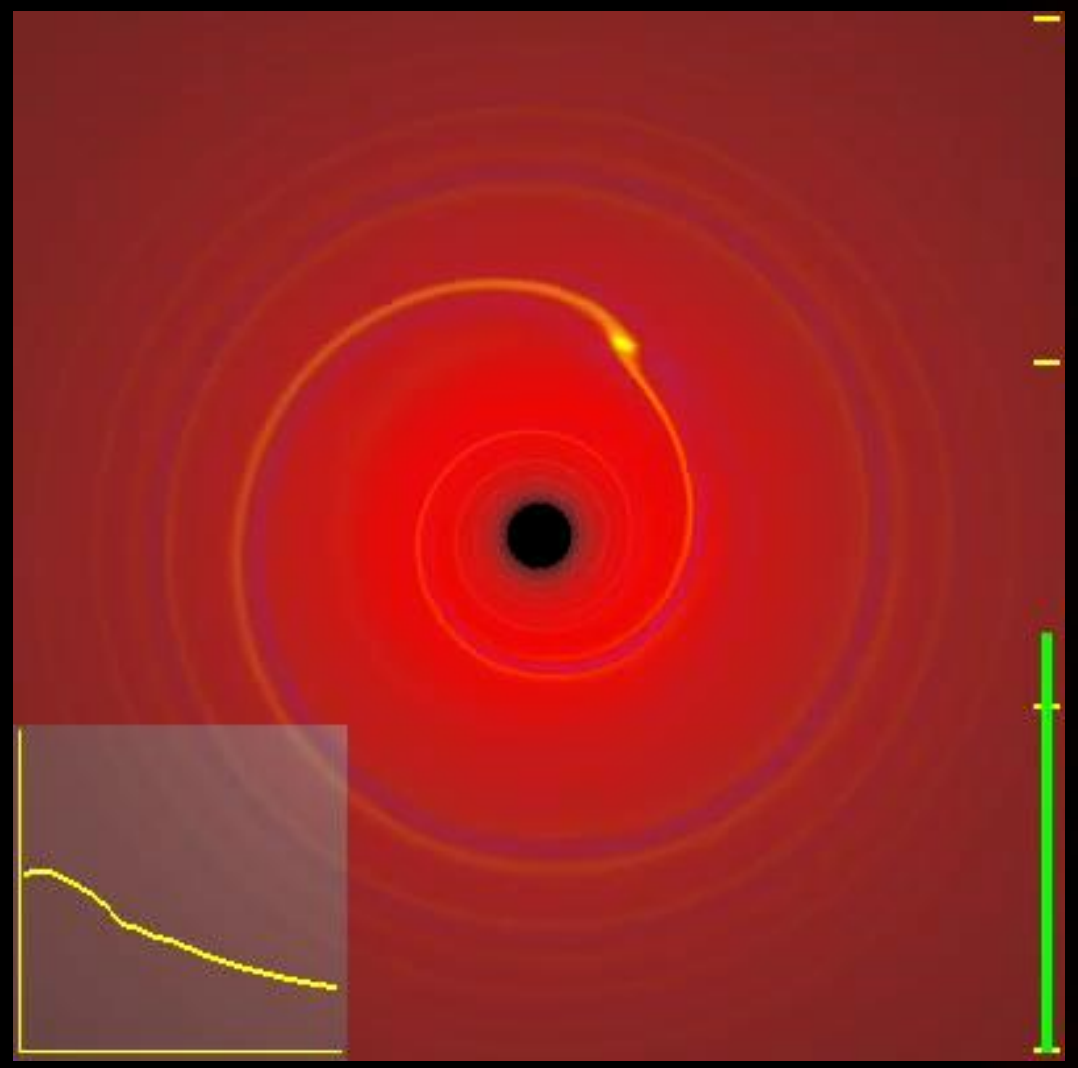
HL Tau

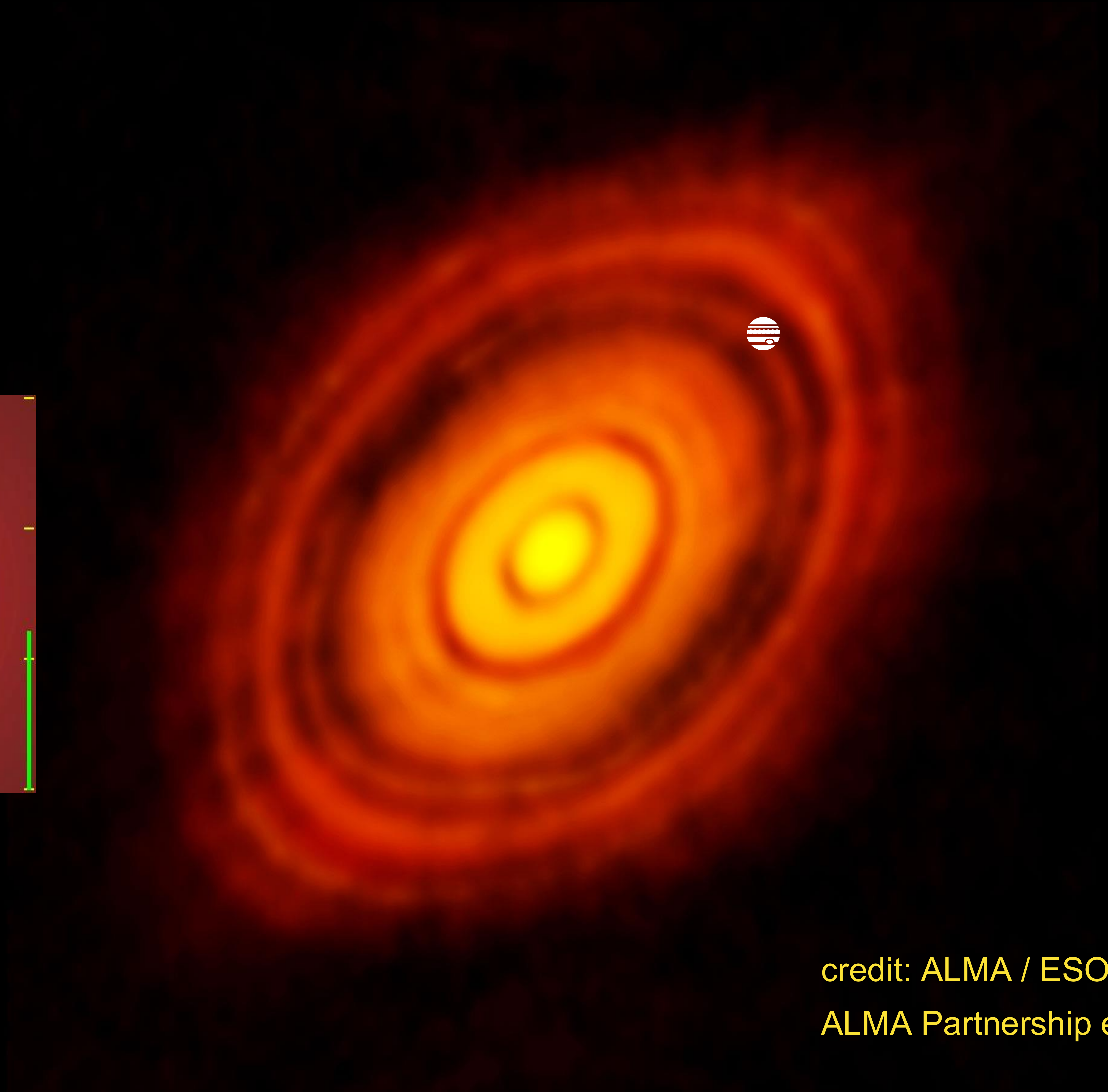


credit: ALMA / ESO / NAOJ / NRAO

ALMA Partnership et al. 2015

HL Tau





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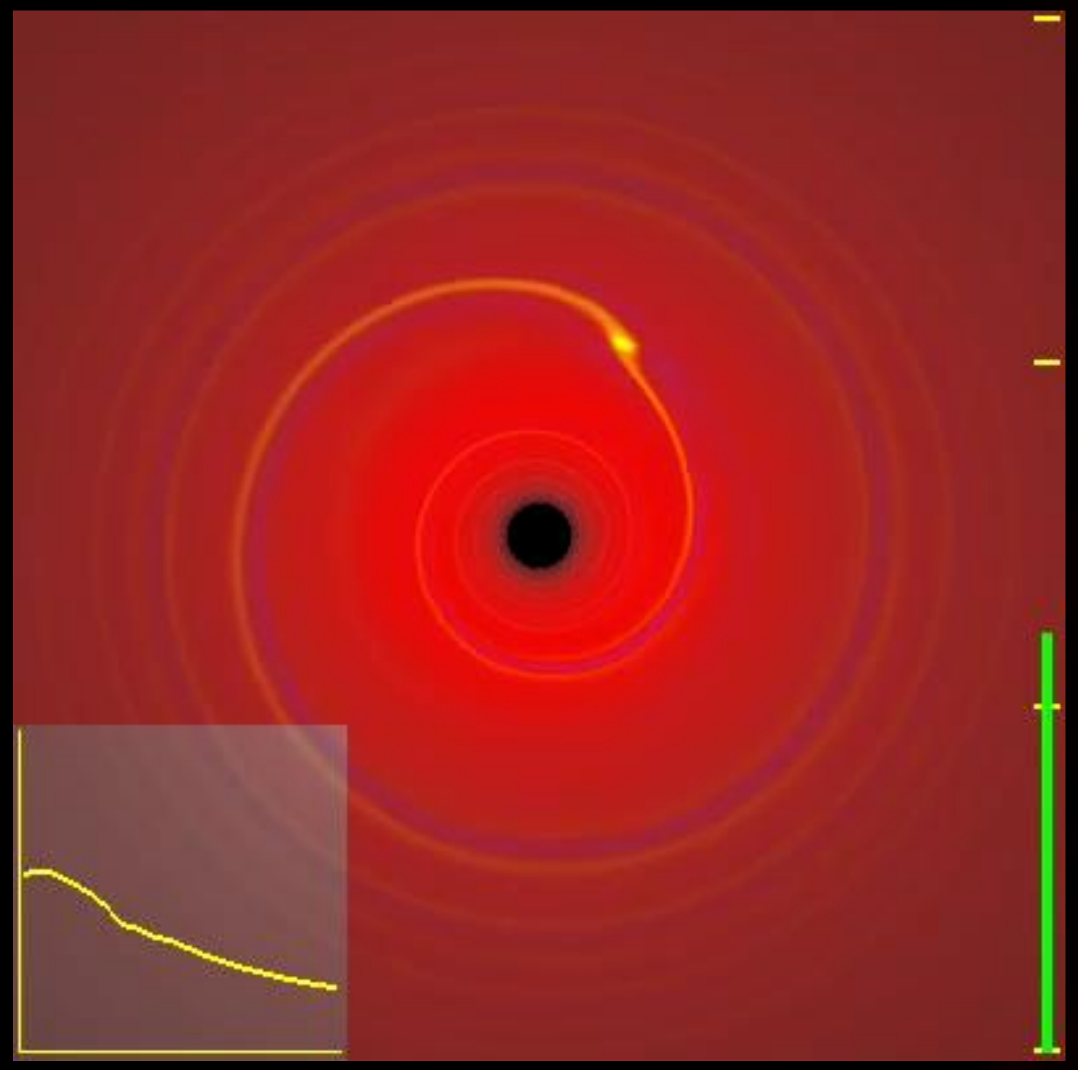
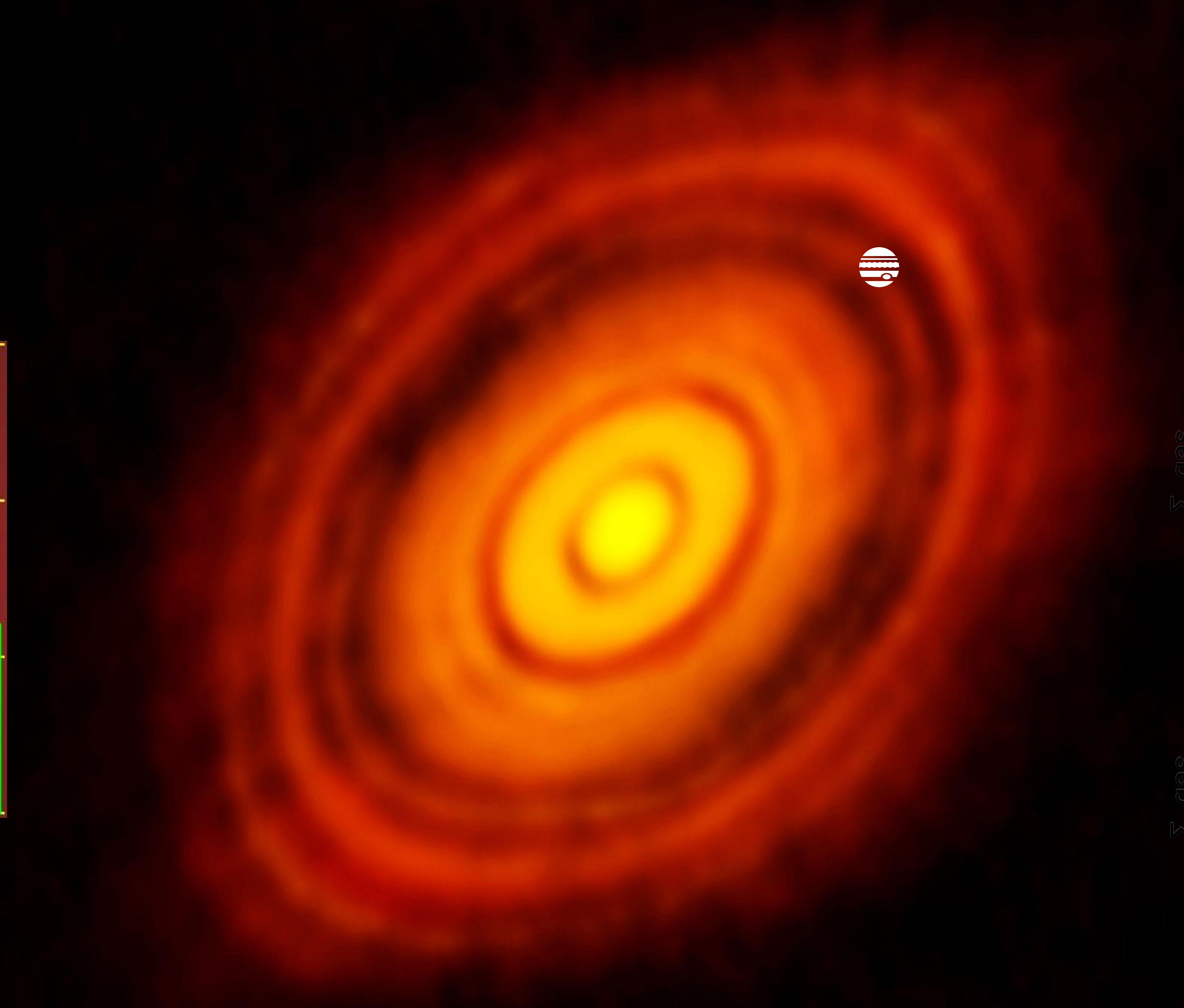
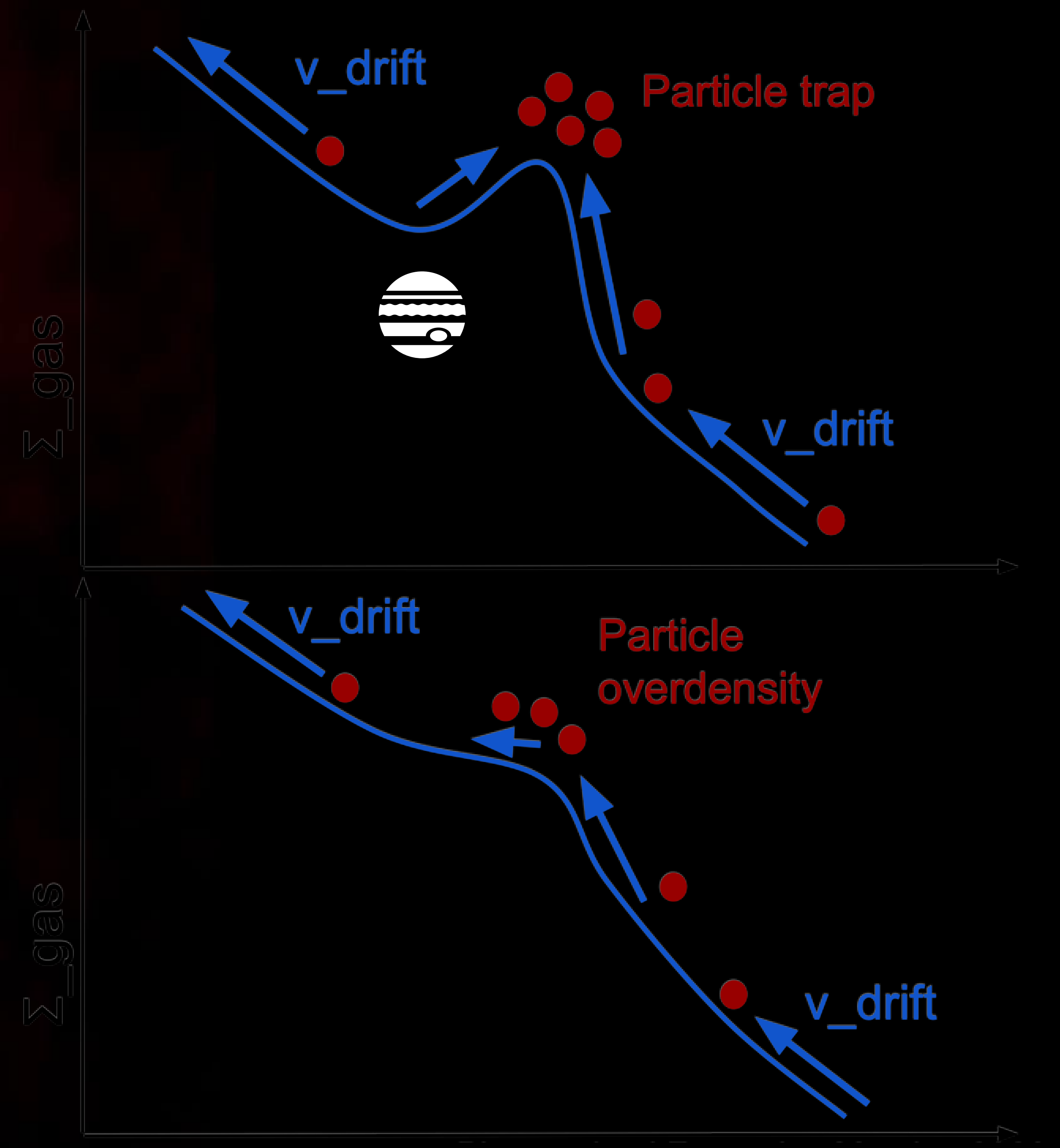


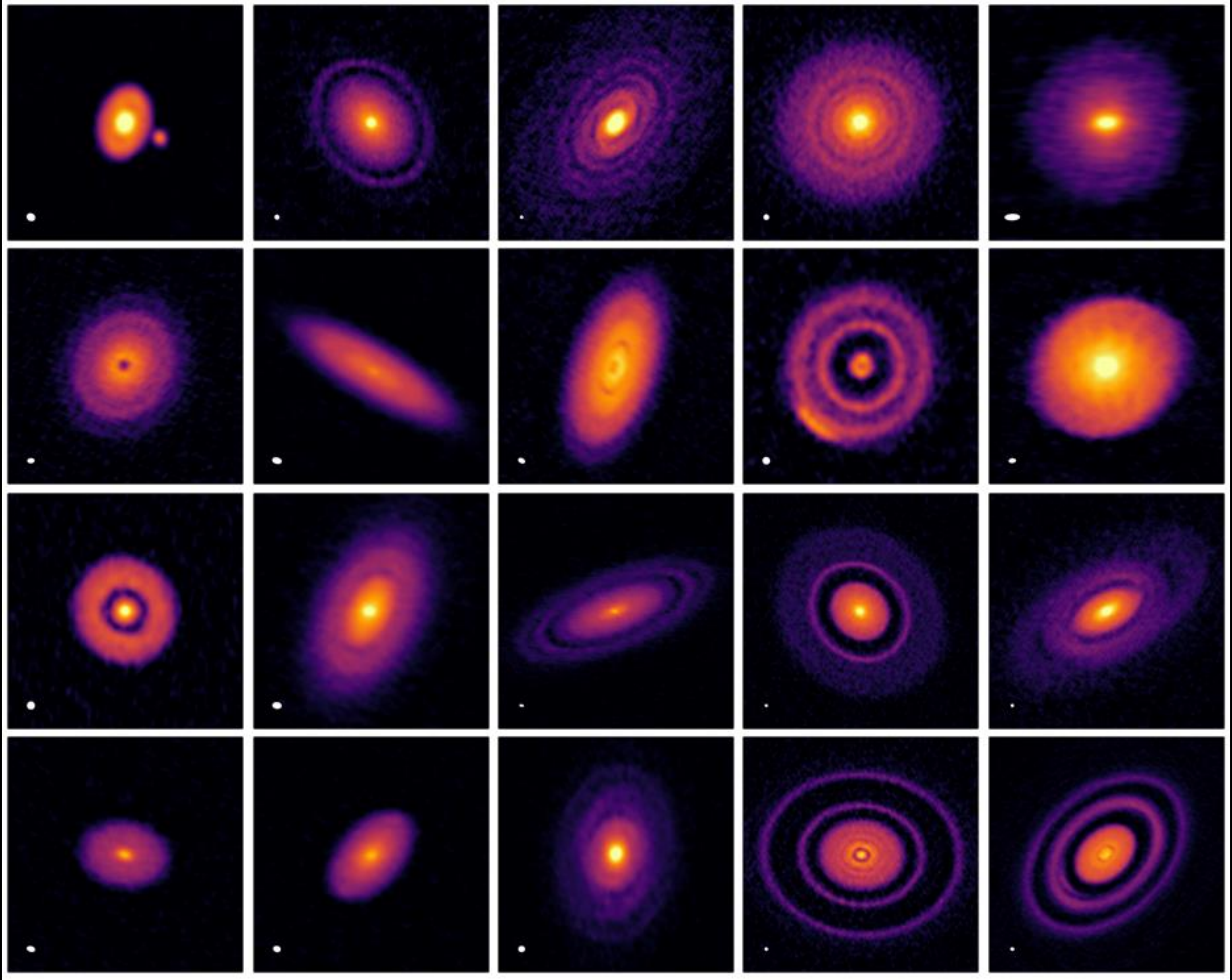




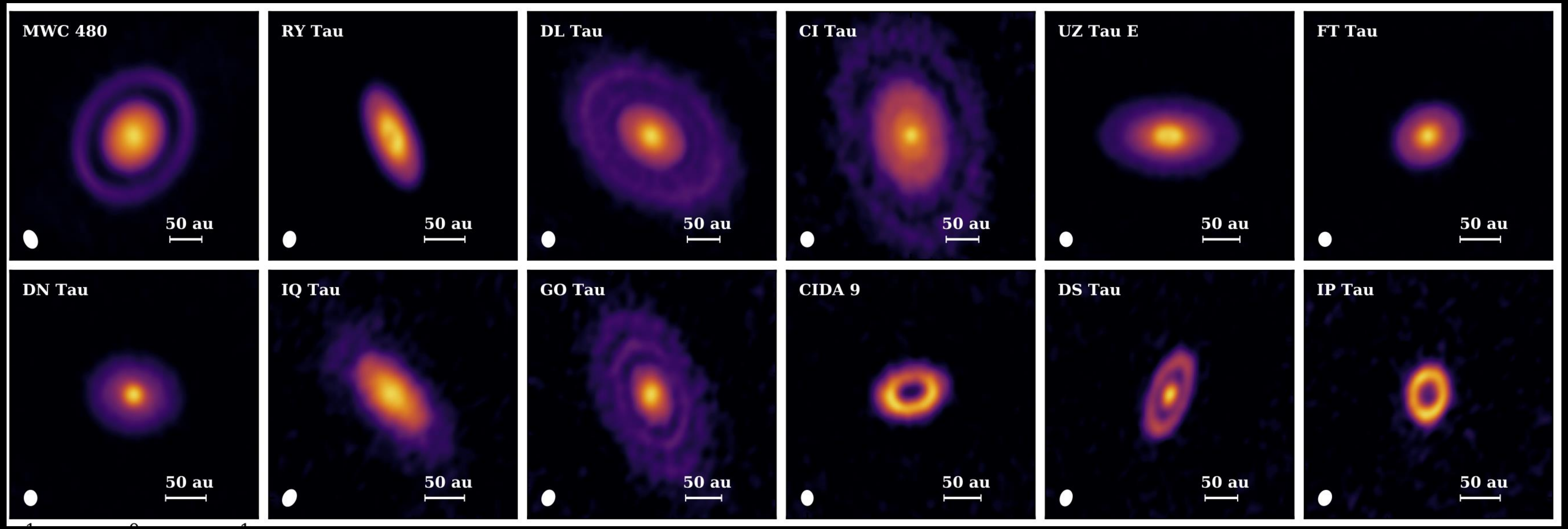
credit: ALMA / ESO / NAOJ / NRAO

ALMA Partnership et al. 2015

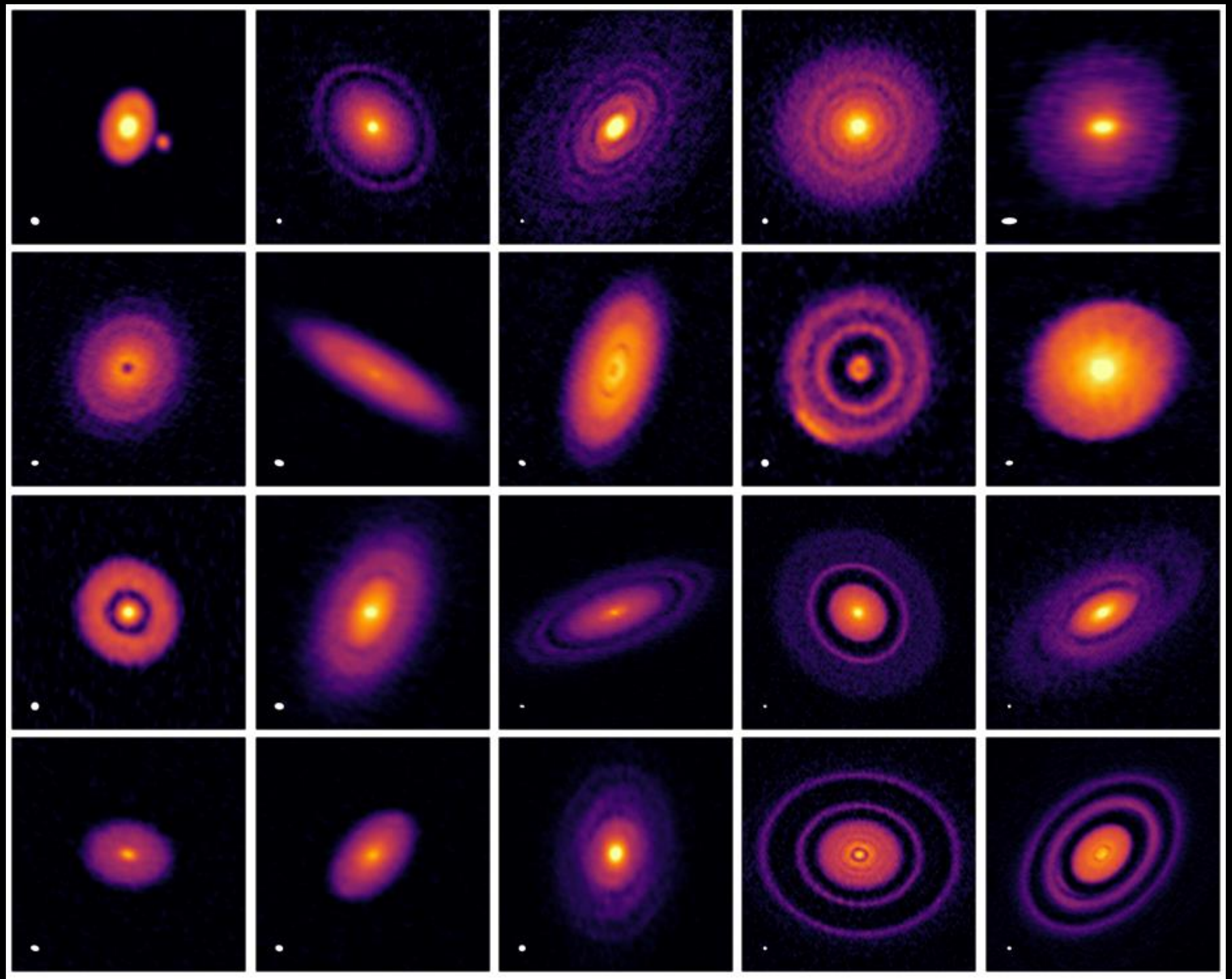
Gaps in Disks

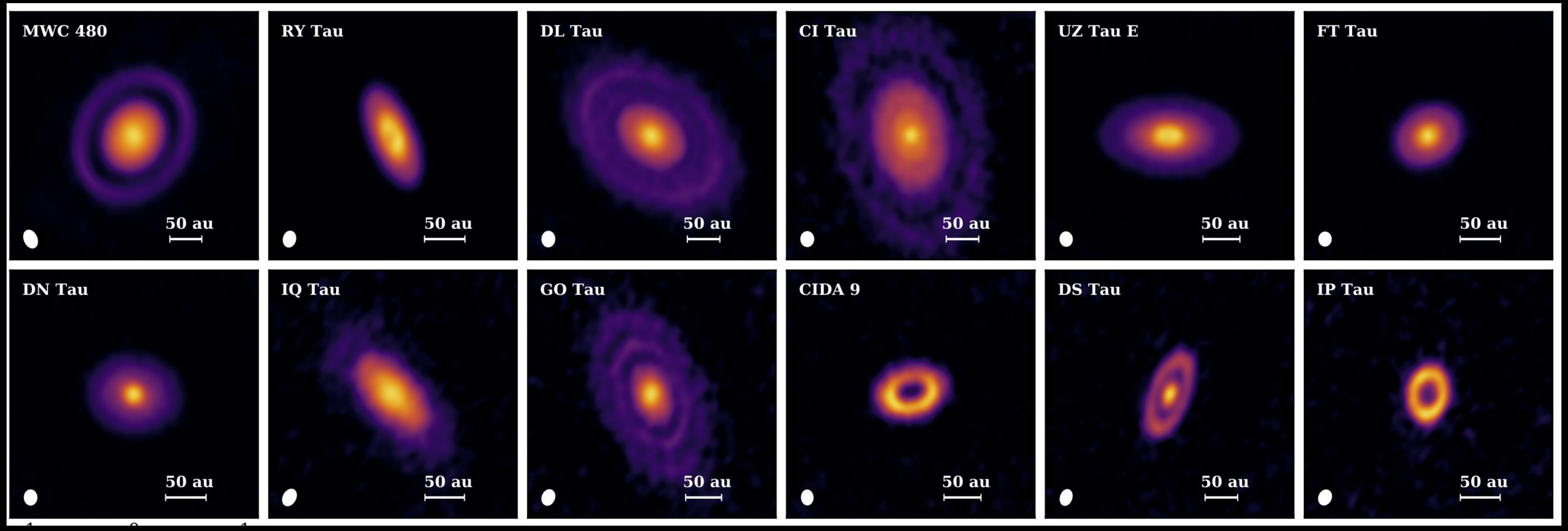


Andrews et al. 2018
Long et al. 2018
Francis et al. 2020
...



Lots of protoplanets!?





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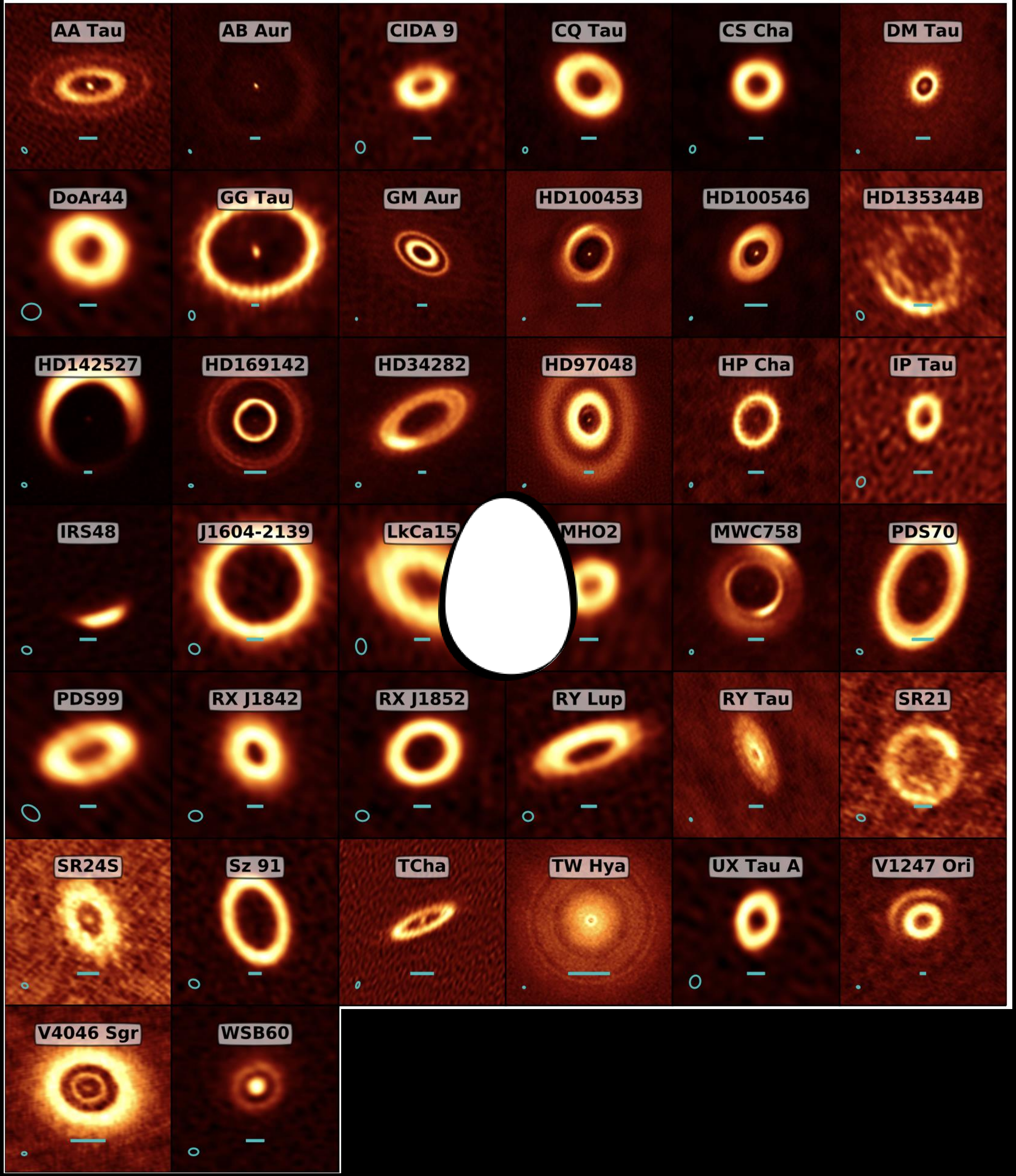

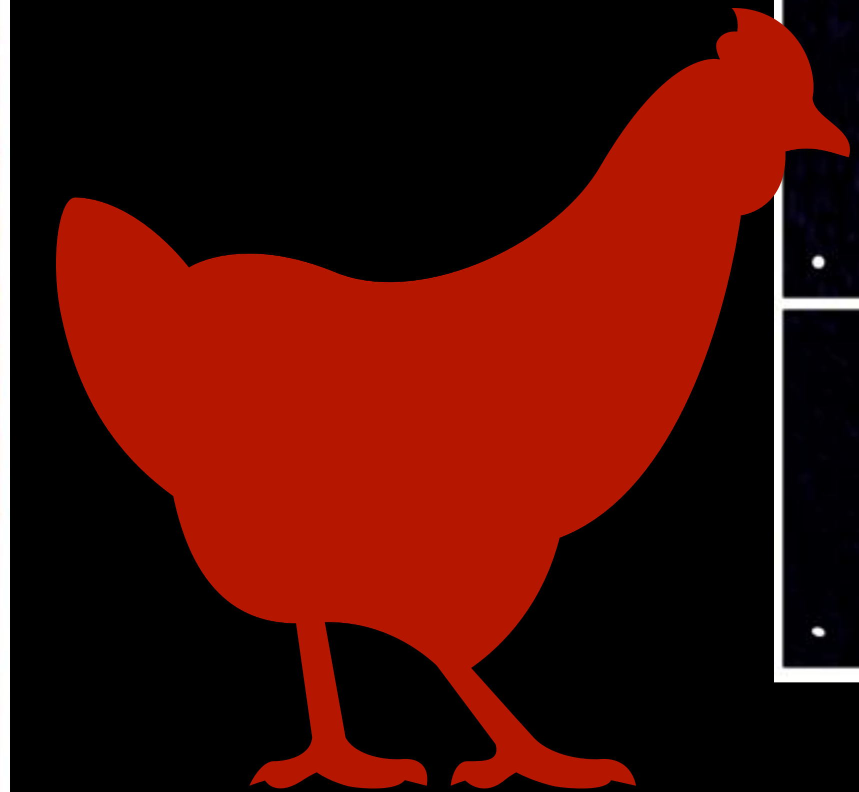

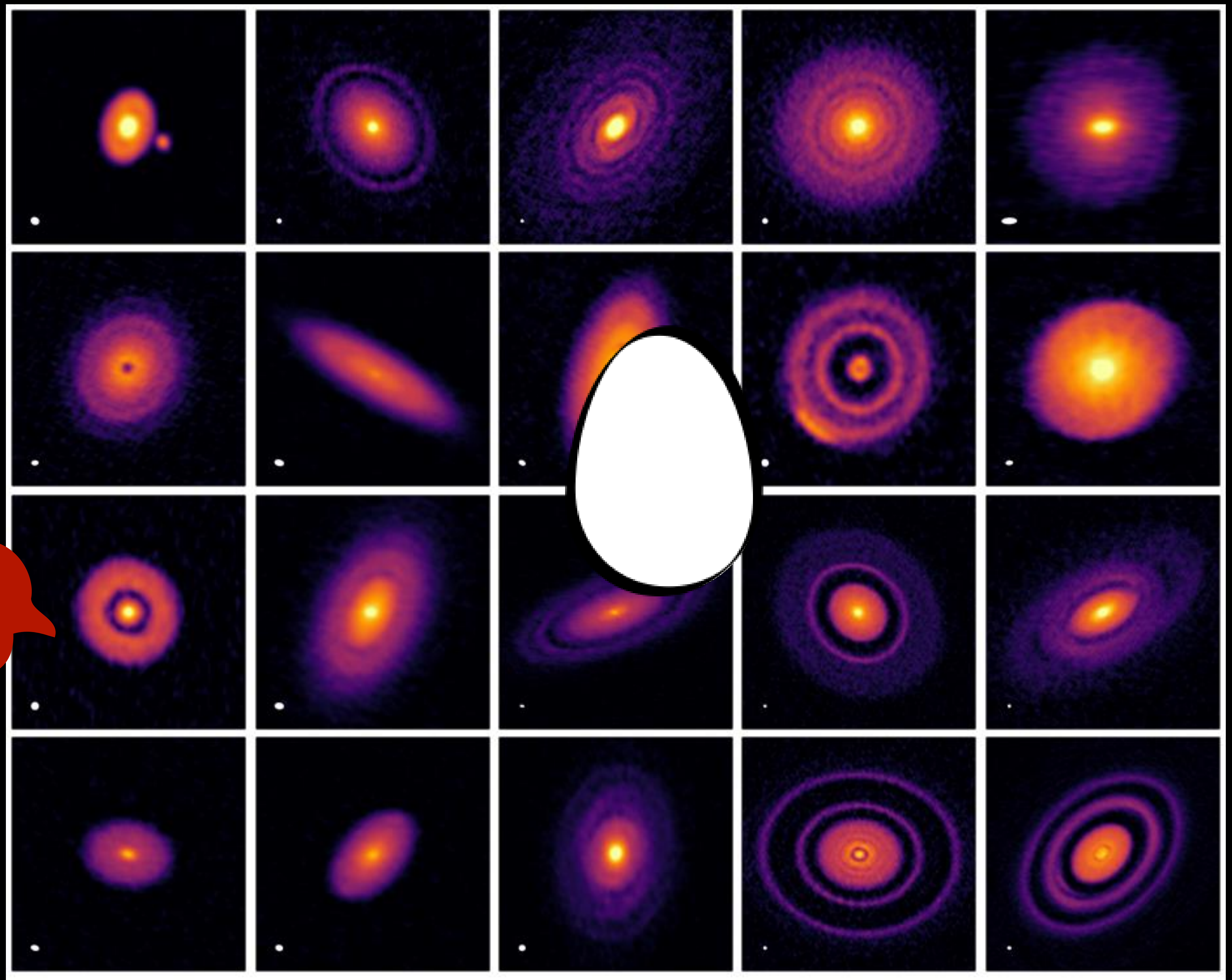

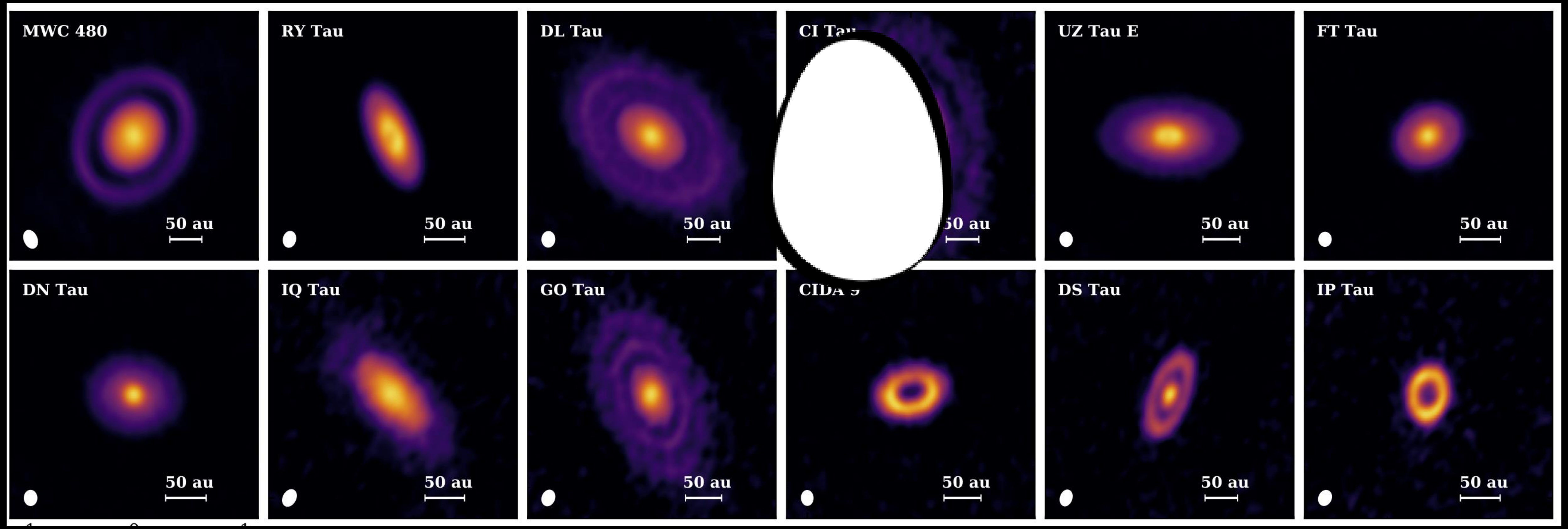

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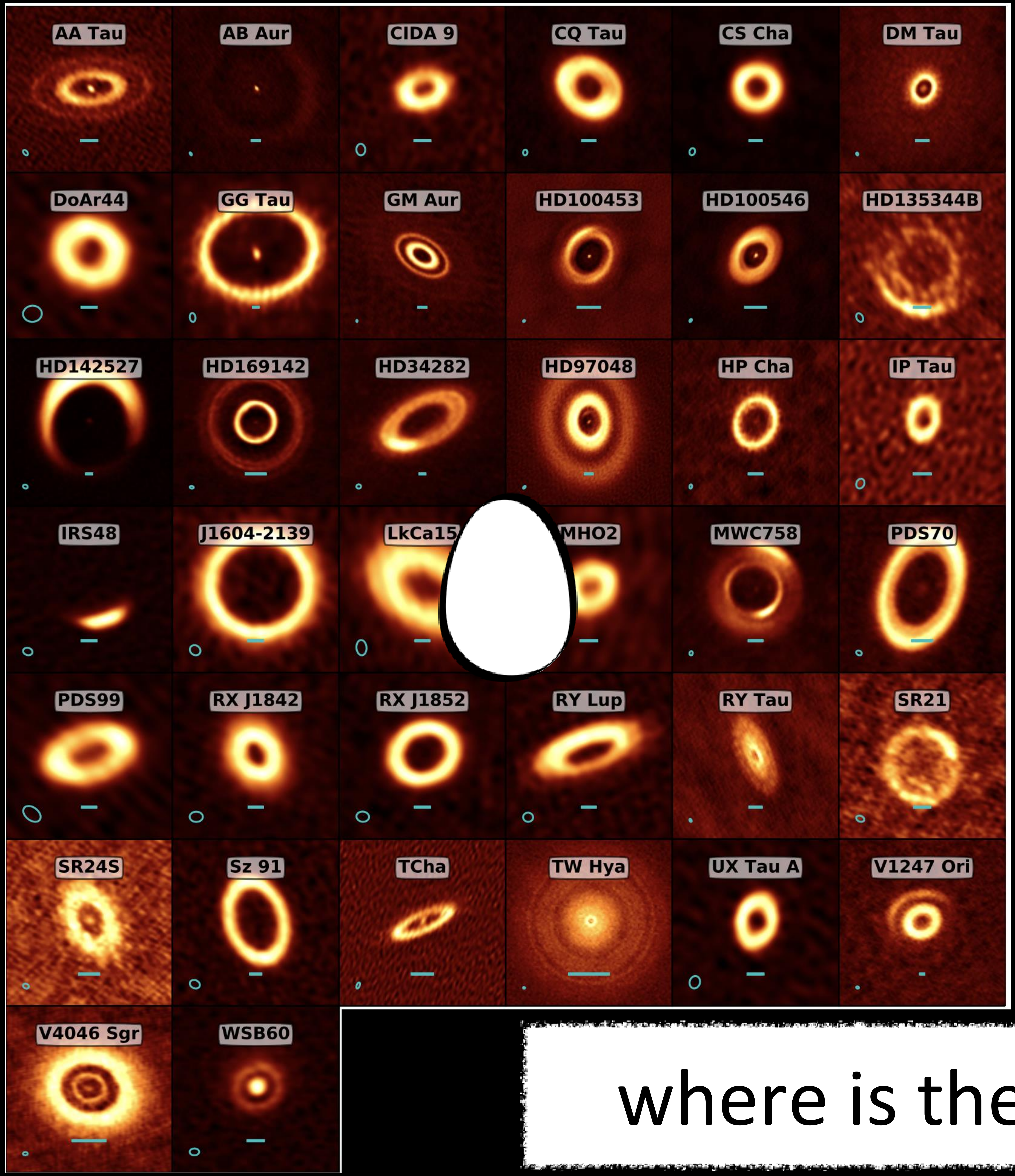

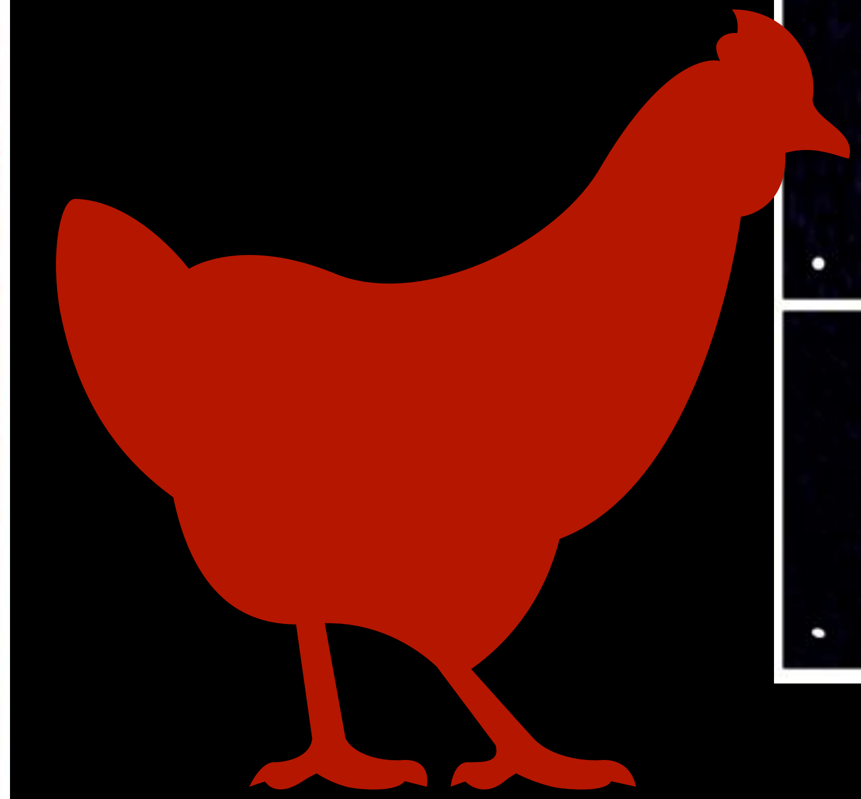

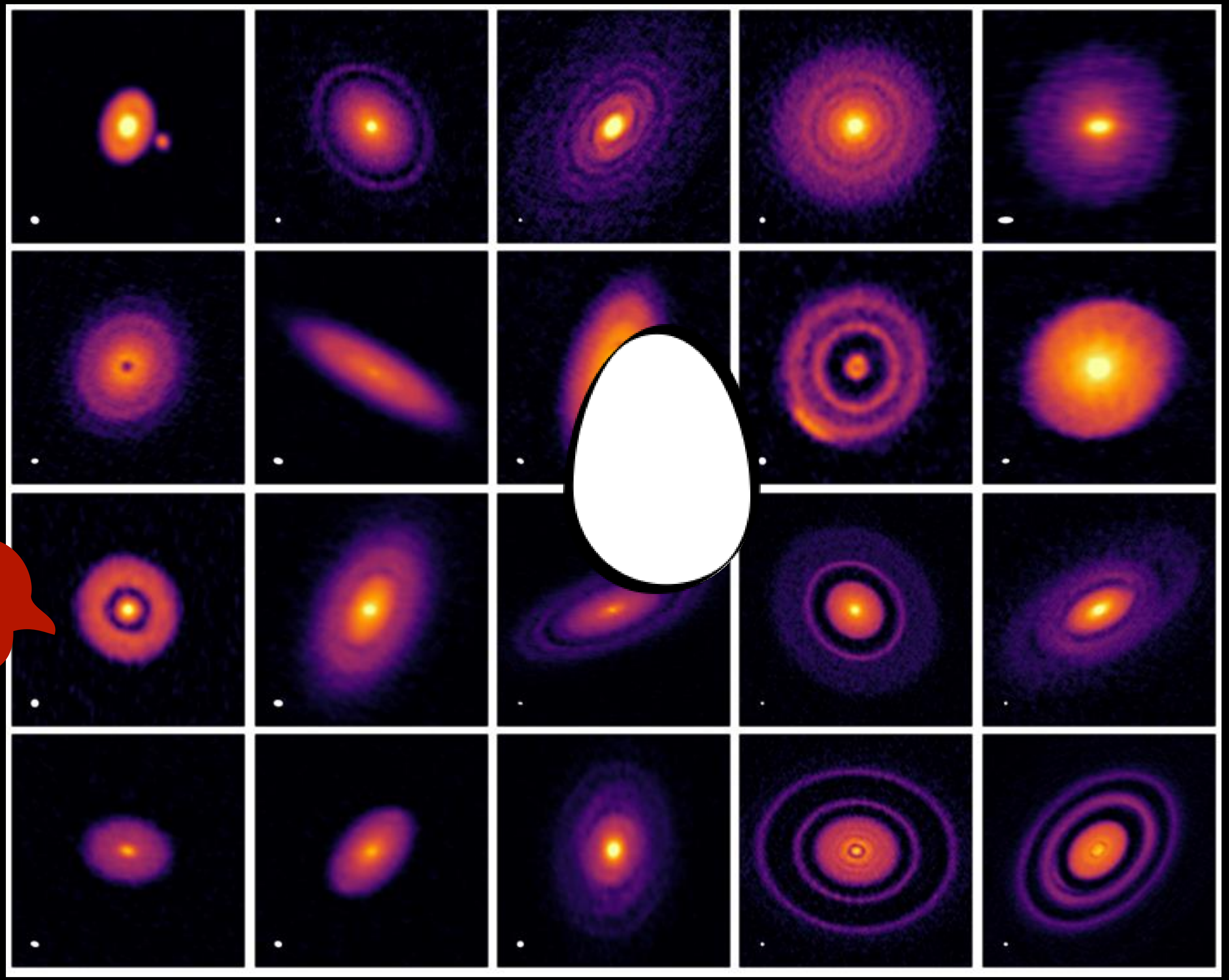

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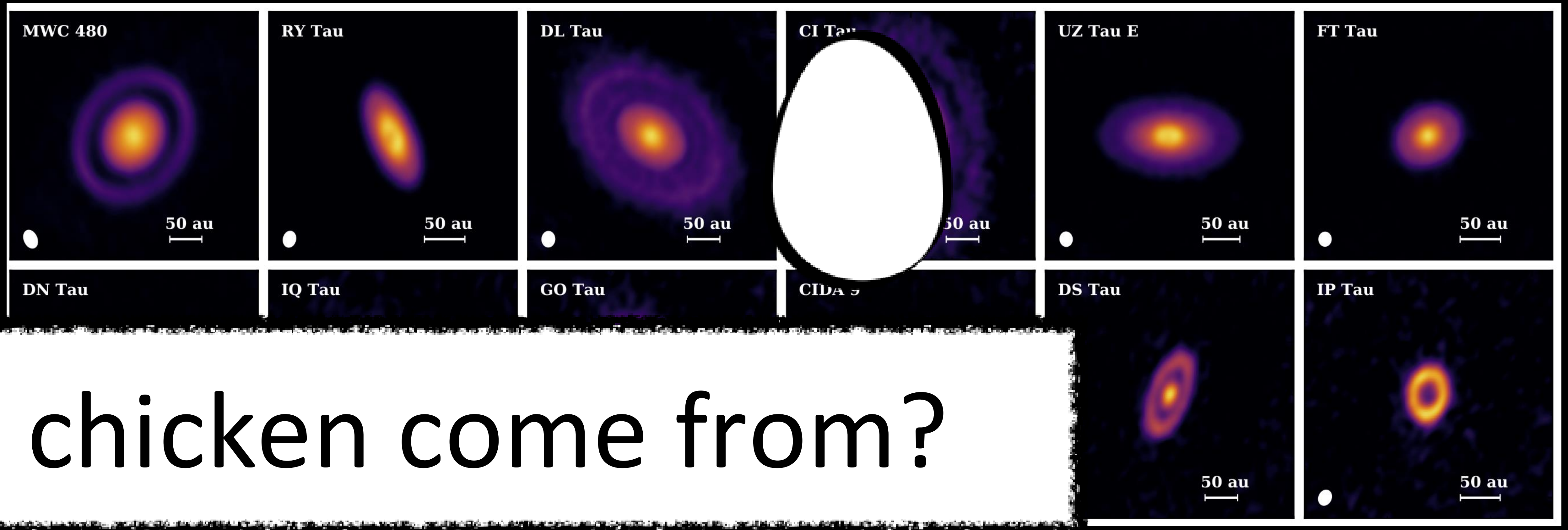
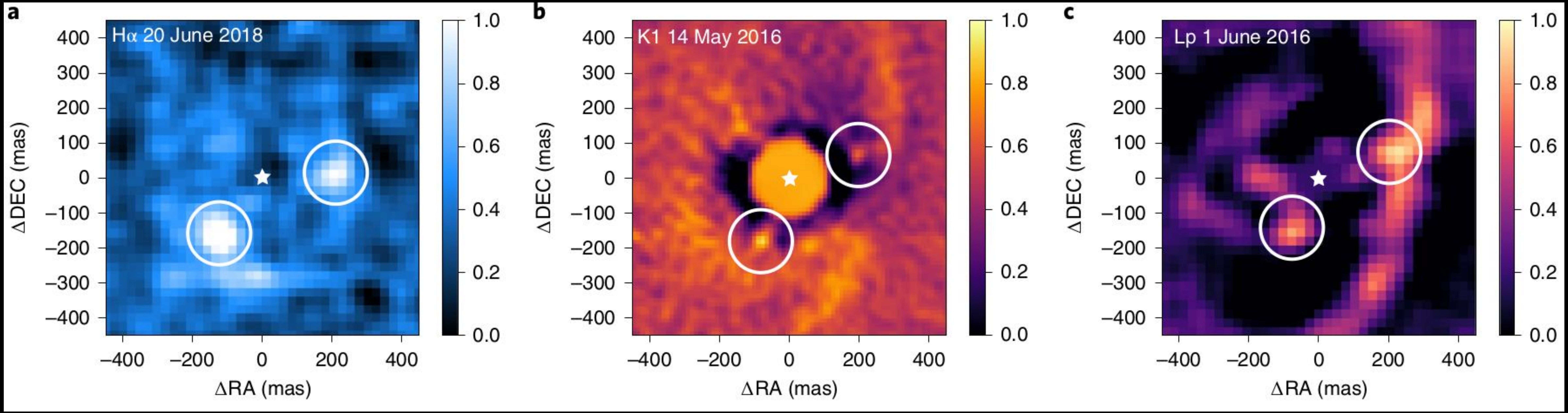


where is the chicken come from?

Confirming planets at such a young phase is *extremely challenging*

Direct imaging searches usually result in non-detections (e.g. Xie et al. 2020; Asensio-Torres et al. 2021; Cugno et al. 2023; Follette et al. 2023; Wallack et al. 2024) with **PDS 70** the famous exception

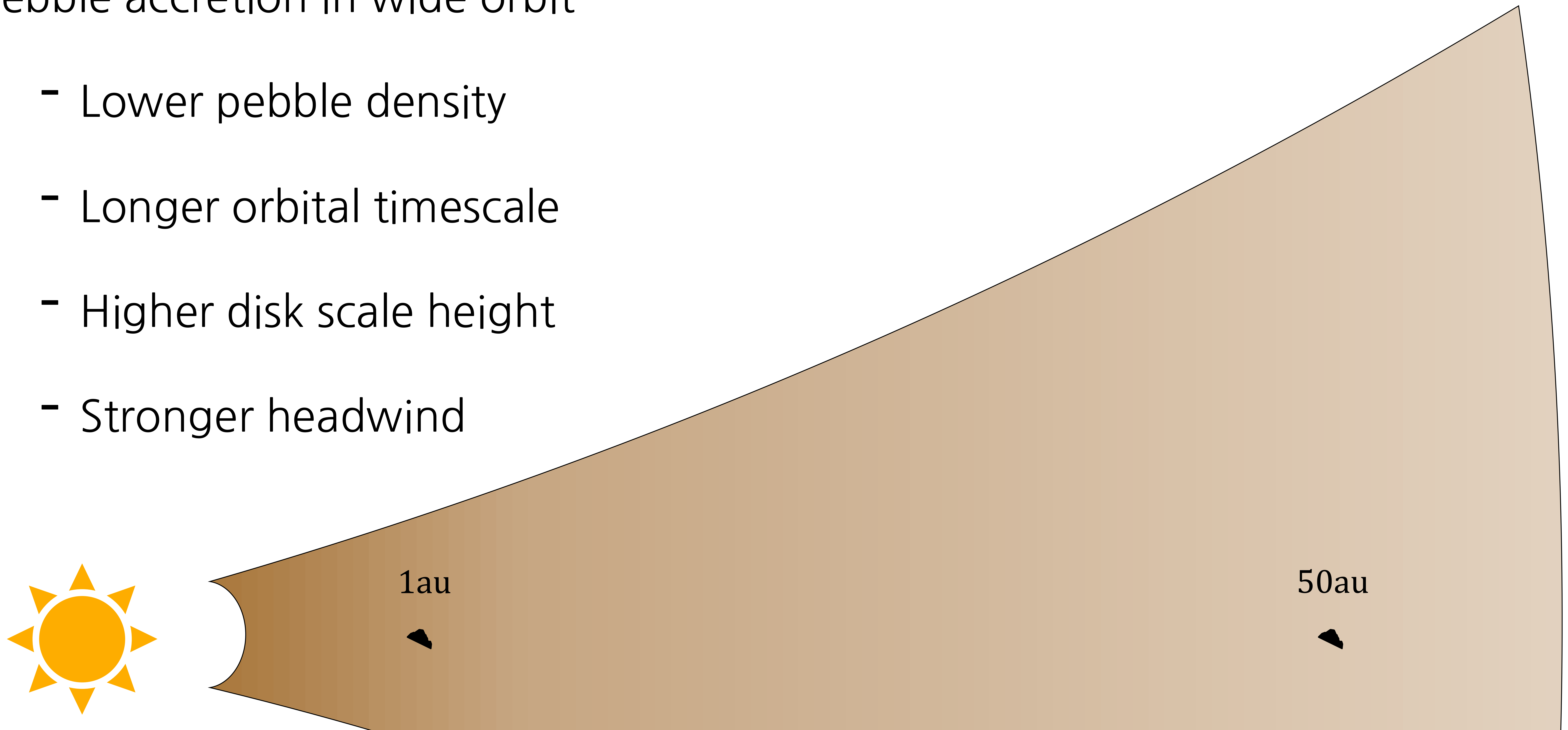


Imaging of PDS 70 has revealed two protoplanets.
The discovery of these planets with multiple VLT instruments (a - Hα/MUSE Haffert et al. (2019); b - K1/SPHERE, Keppler et al. (2018); c - L'/NACO, Keppler et al. (2018)) conclusively hint at a planetary nature.

Formation of planets at wide orbit is hard

Pebble accretion in wide orbit

- Lower pebble density
- Longer orbital timescale
- Higher disk scale height
- Stronger headwind



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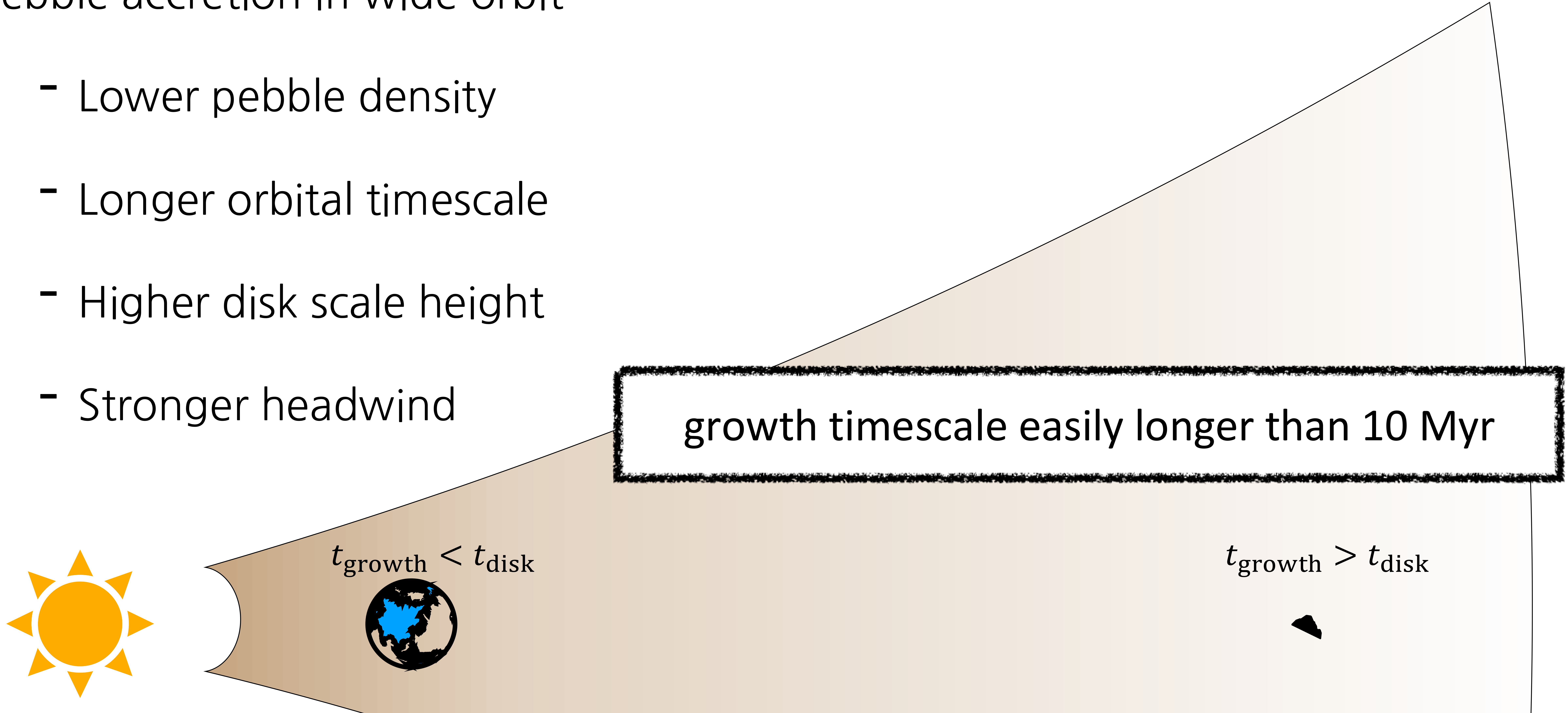
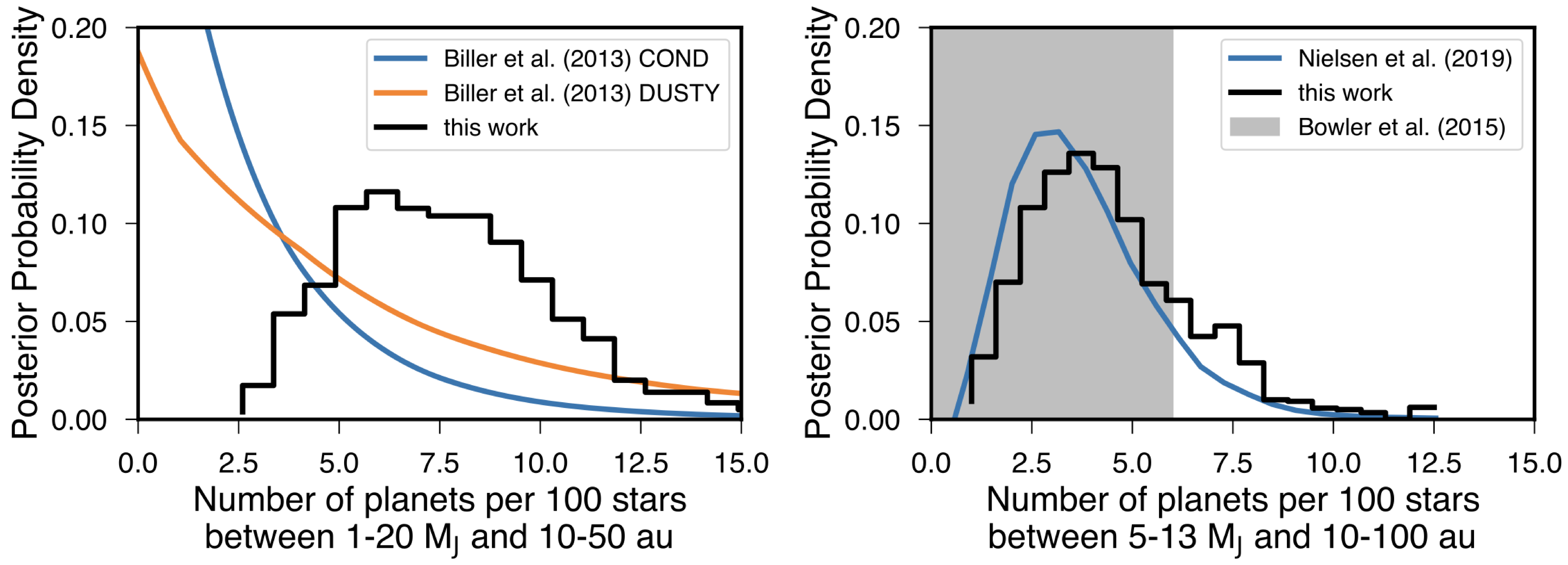


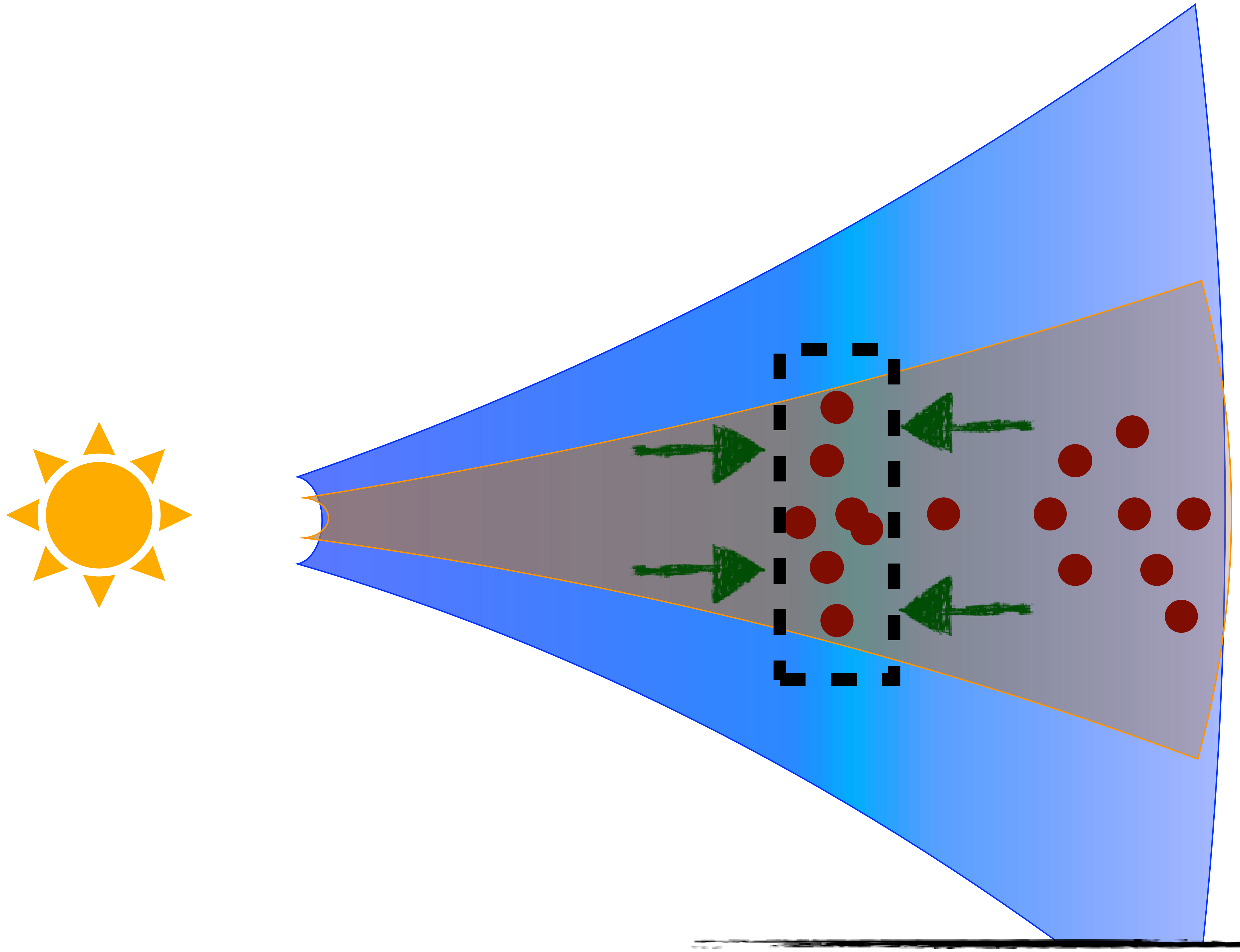
Wide-orbit Giant Planets are Rare



Fulton et al. 2021

1) Can these pebble rings maintain w/o planets? or more generally, w/o a pressure bump?

Clumpy ring model



$$v_{\rm dr} = \frac{\rm St}{(1+Z)^2+{\rm St}^2} \frac{c_s^2}{\Omega_K r} \frac{\partial \log P}{\partial \log r}$$

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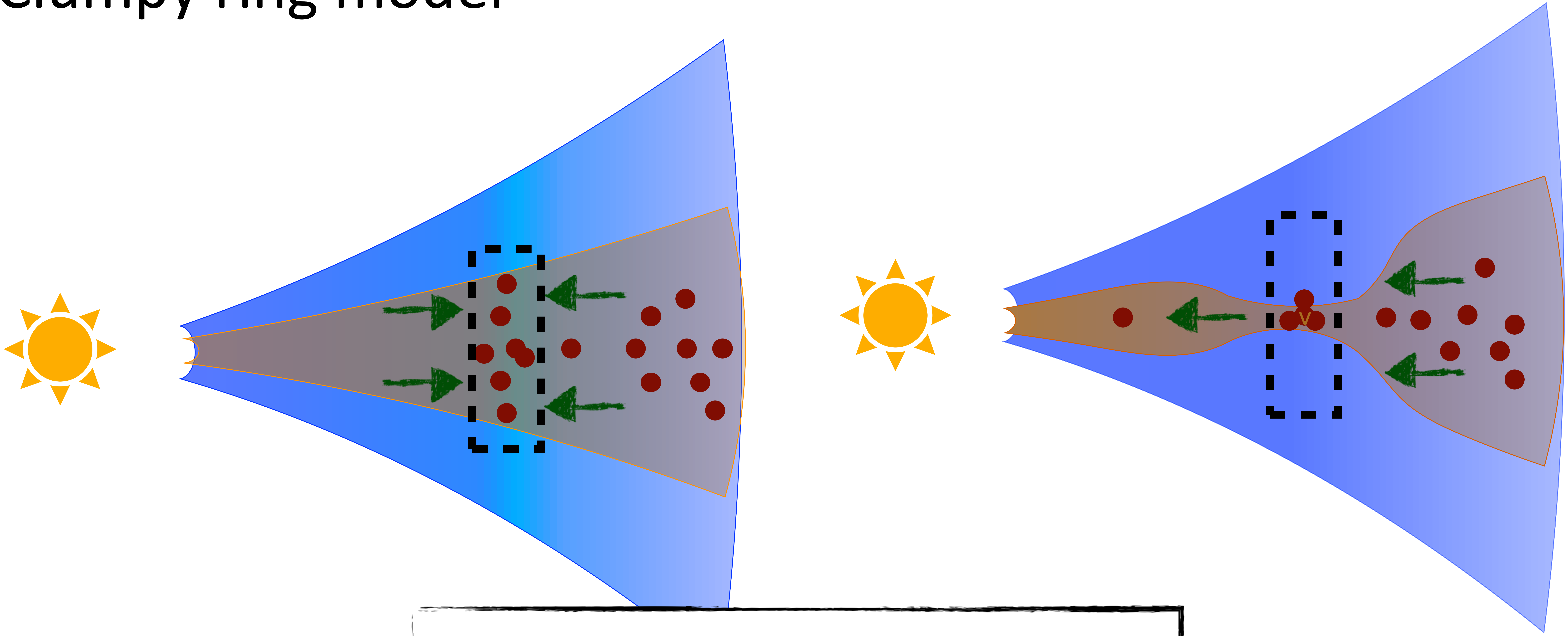

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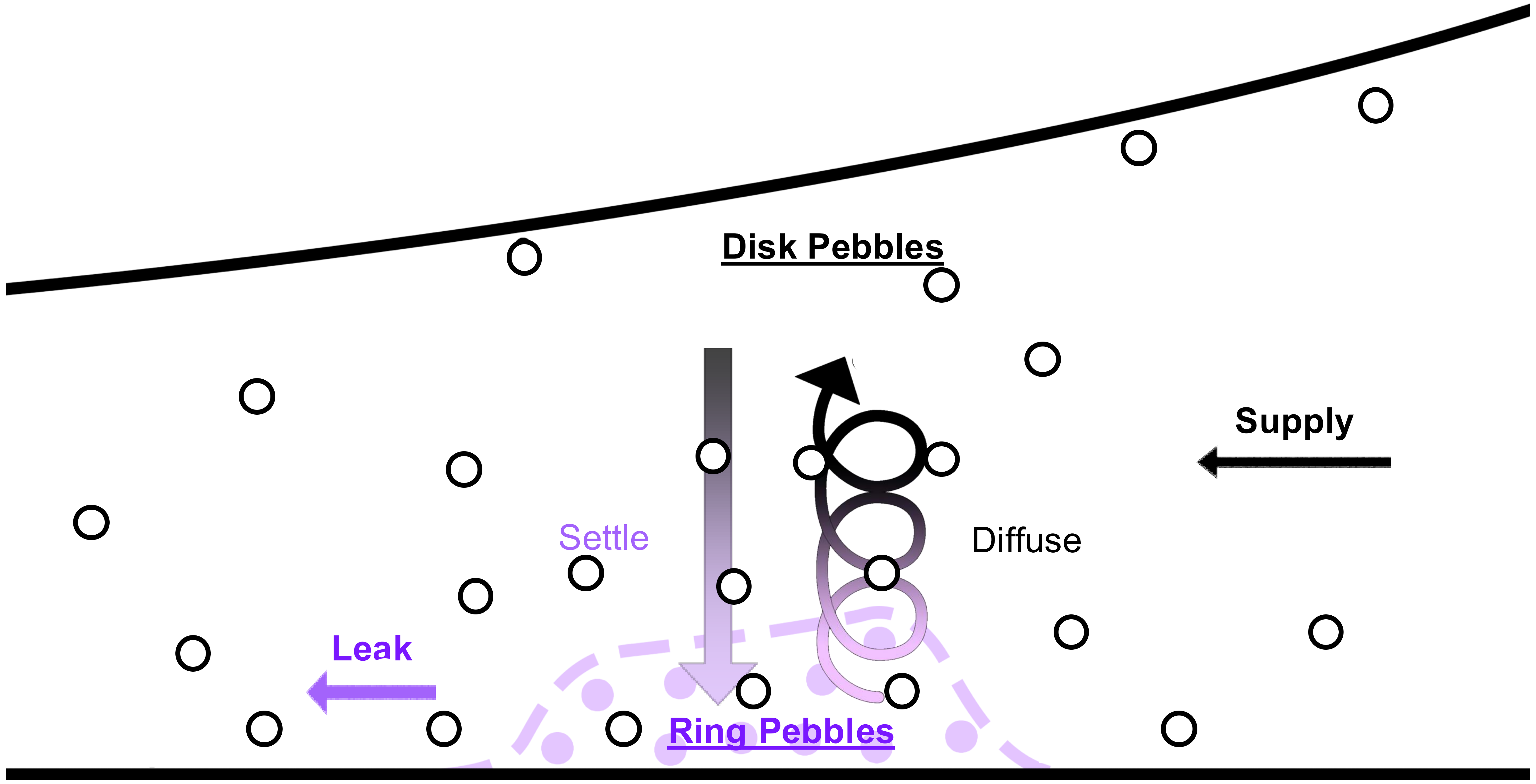
Jiang & Ormel 2021

Clumpy ring model

Particles can be lost from the ring:

- leak away from the front
  no pressure containment
- diffuse in *z* direction
  suppressed by collisions ([Krijt et al. 2017](#))
- converted into planetesimals
  assumed to operate at a rate ε that is a fraction of the settling rate.

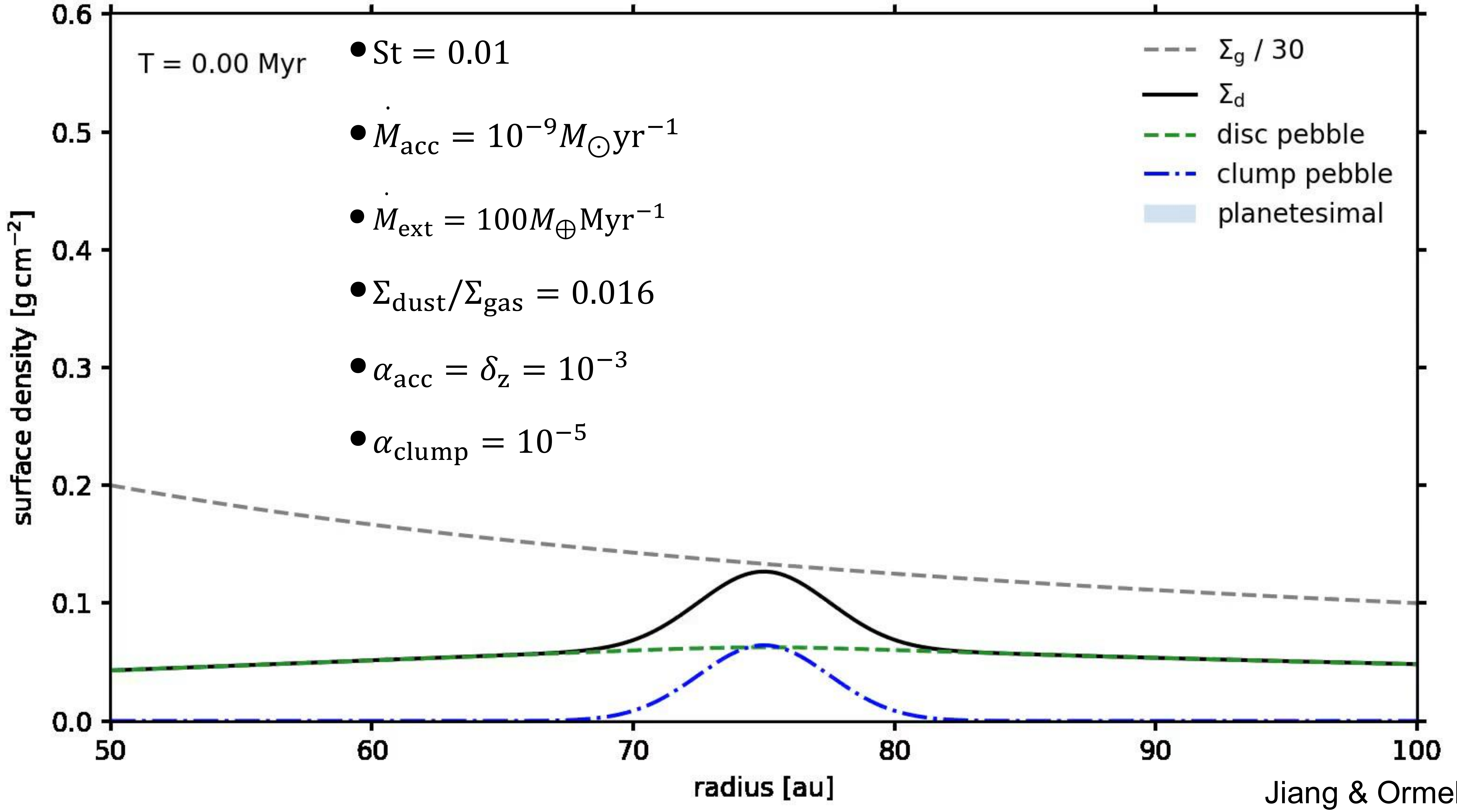
If the mass gain is insufficient, the ring dissolves



$$v_{\rm dr} = \frac{\rm St}{(1+Z)^2+{\rm St}^2}\frac{c_s^2}{\Omega_K r}\frac{\partial \log P}{\partial \log r}$$

Jiang & Ormel 2021

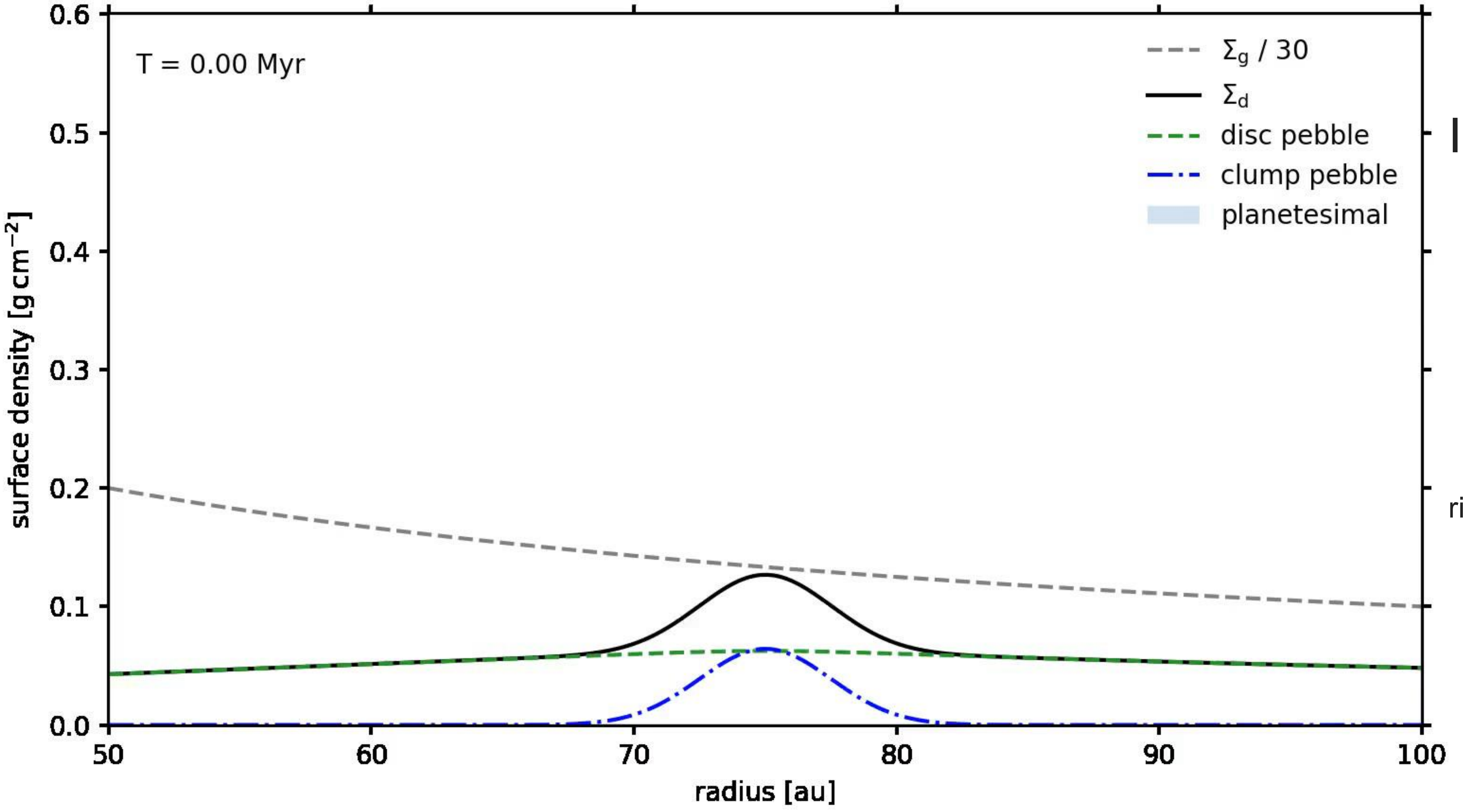
Ring evolution



- $\mathrm{St} = 0.01$
- $\dot{M}_{\mathrm{acc}} = 10^{-9} M_{\odot} \mathrm{yr}^{-1}$
- $\dot{M}_{\mathrm{ext}} = 100 M_{\oplus} \mathrm{Myr}^{-1}$
- $\Sigma_{\mathrm{dust}}/\Sigma_{\mathrm{gas}} = 0.016$
- $\alpha_{\mathrm{acc}} = \delta_{\mathrm{z}} = 10^{-3}$
- $\alpha_{\mathrm{clump}} = 10^{-5}$

Jiang & Ormel 2021

Ring evolution



Jiang & Ormel 2021

In this animation we see the following:

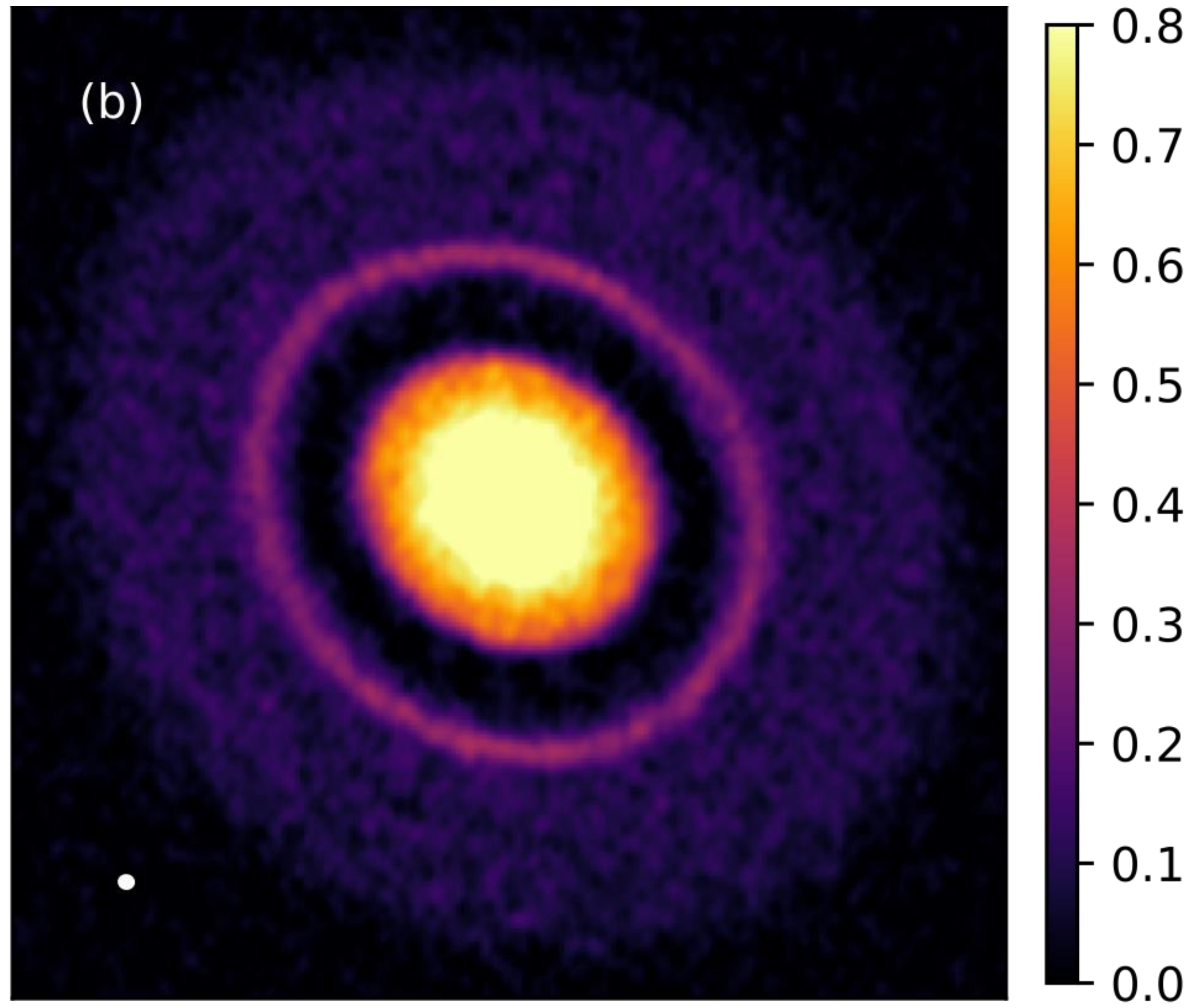
- initially, there is a small bump in dust Σ
- a ring (quickly) reaches a quasi steady-state

balancing influx from disk pebbles upstream and loss from ring pebbles downstream

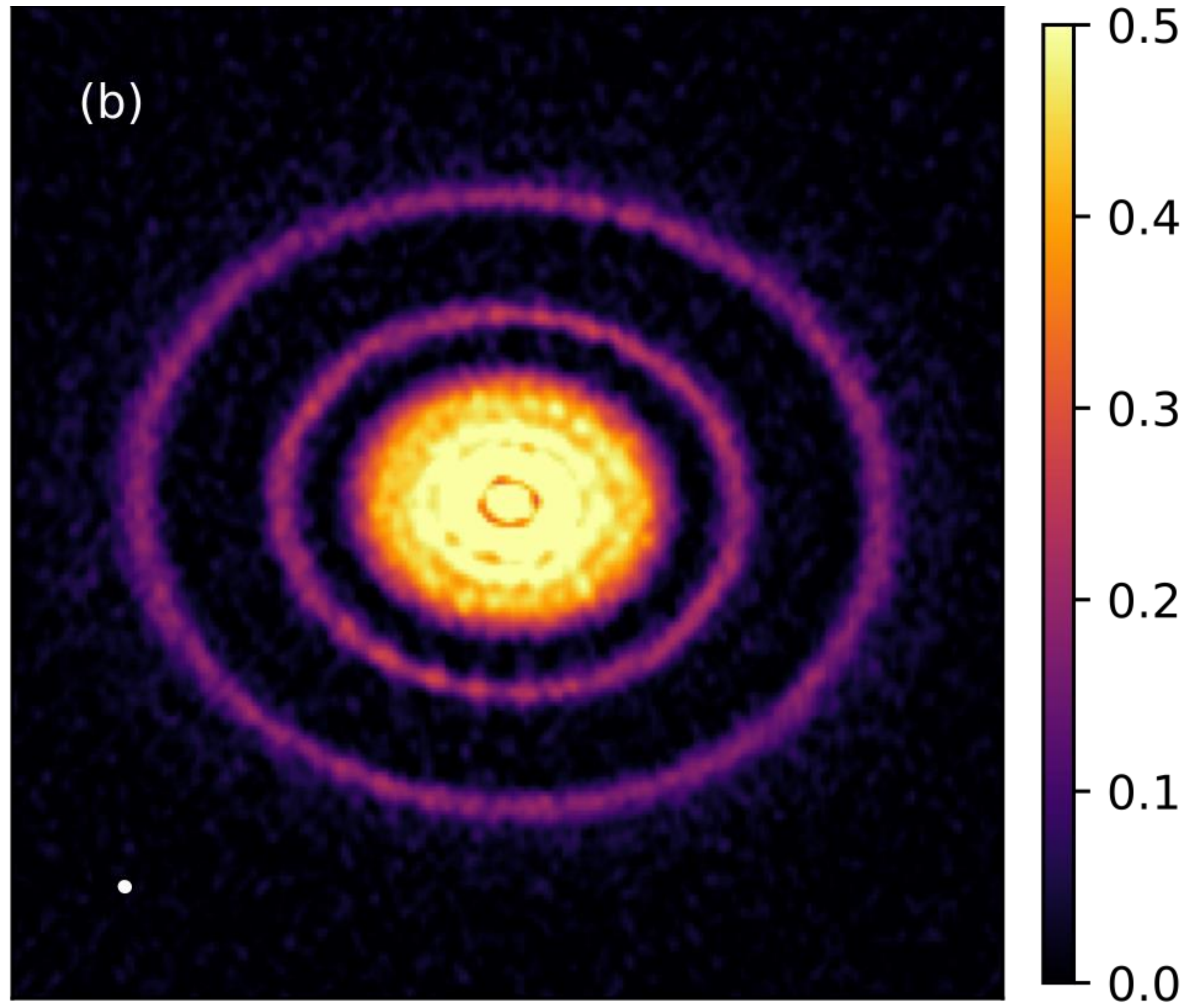
- it migrates (imperceptibly) outwards
- it converts a fraction of the incoming mass into planetesimals

Simobservation

Elias 24



AS 209



- Constant size setup
- ALMA band 6, 239GHz

Simobservation

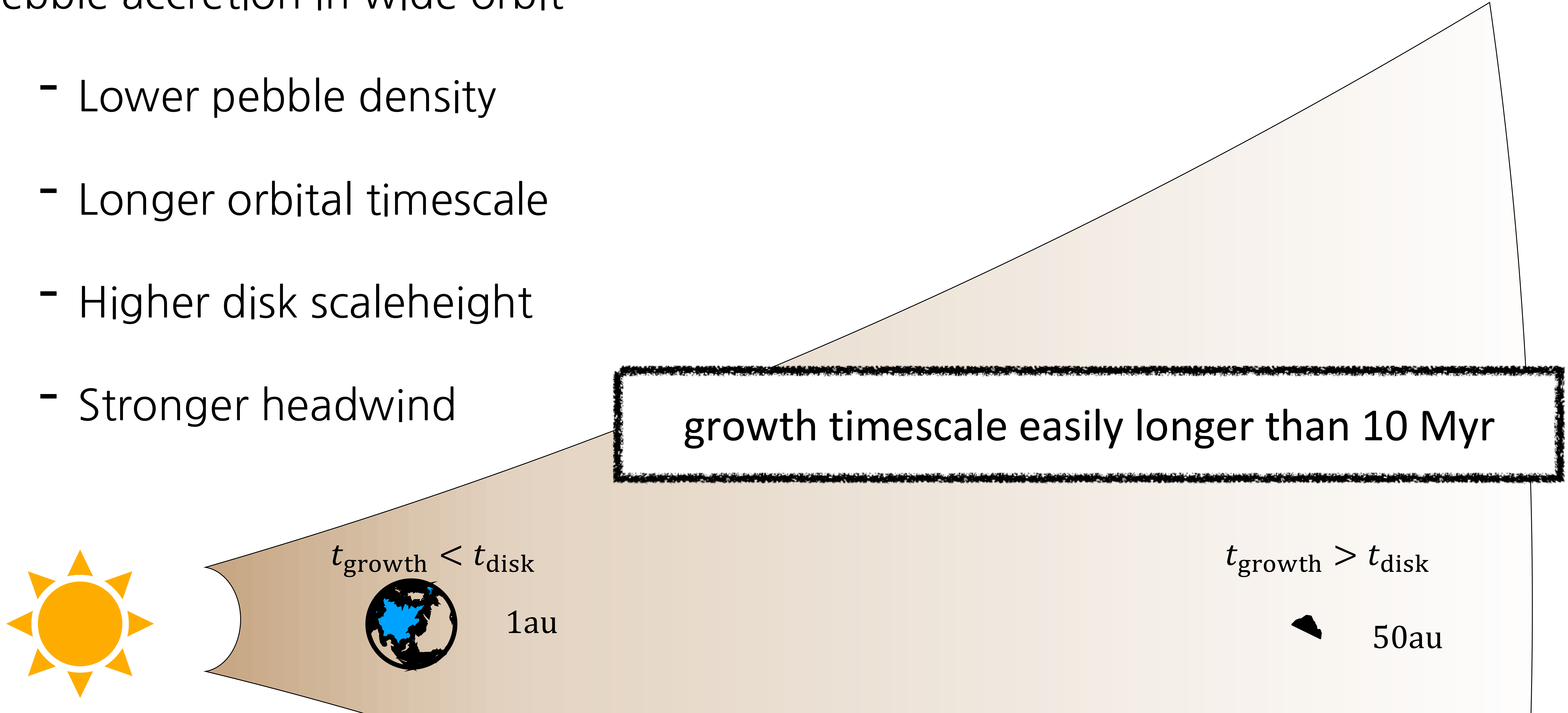
- Constant size setup
- ALMA band 6, 239GHz

Formation of planets at wide orbit is hard

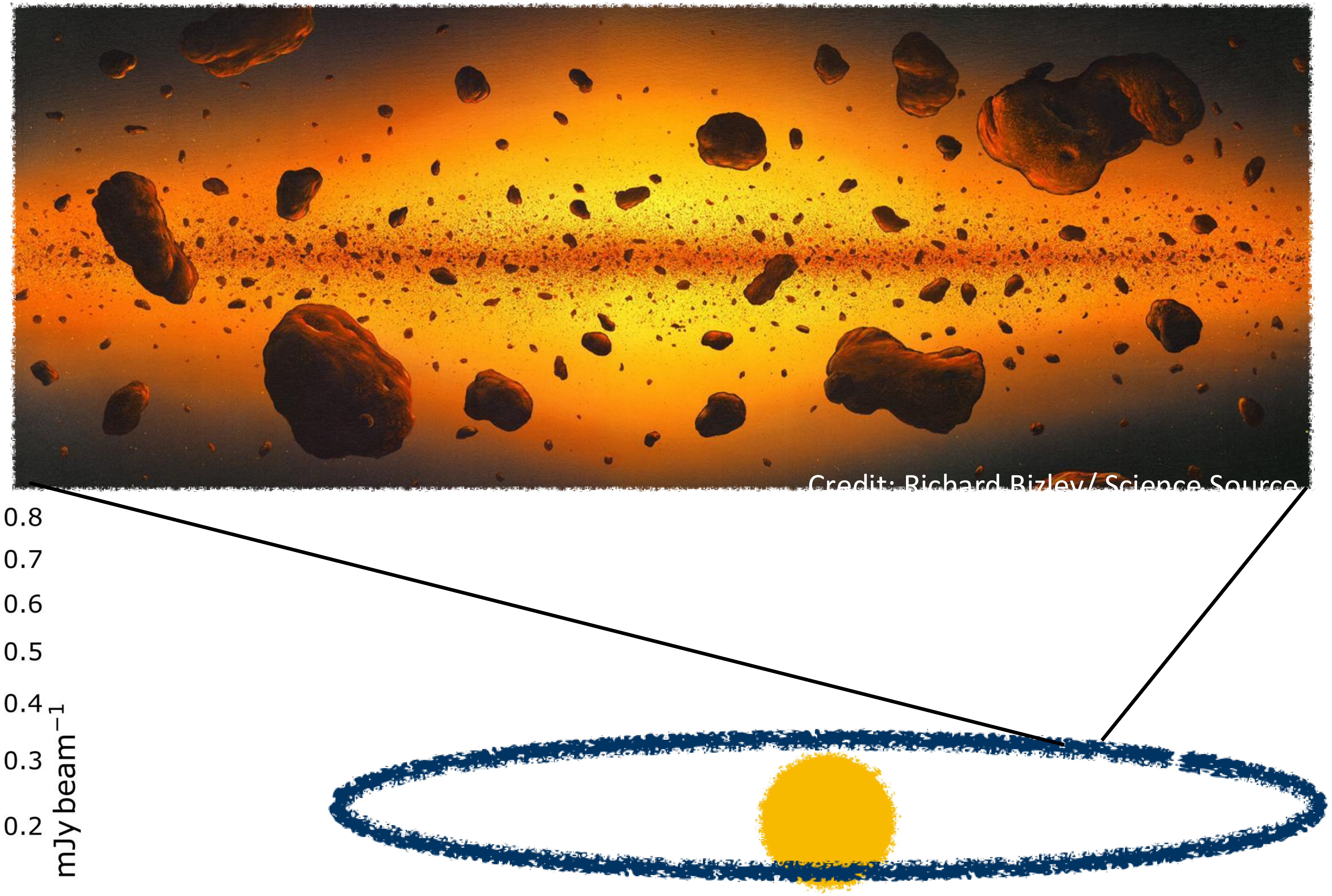
Pebble accretion in wide orbit

- Lower pebble density
- Longer orbital timescale
- Higher disk scaleheight
- Stronger headwind

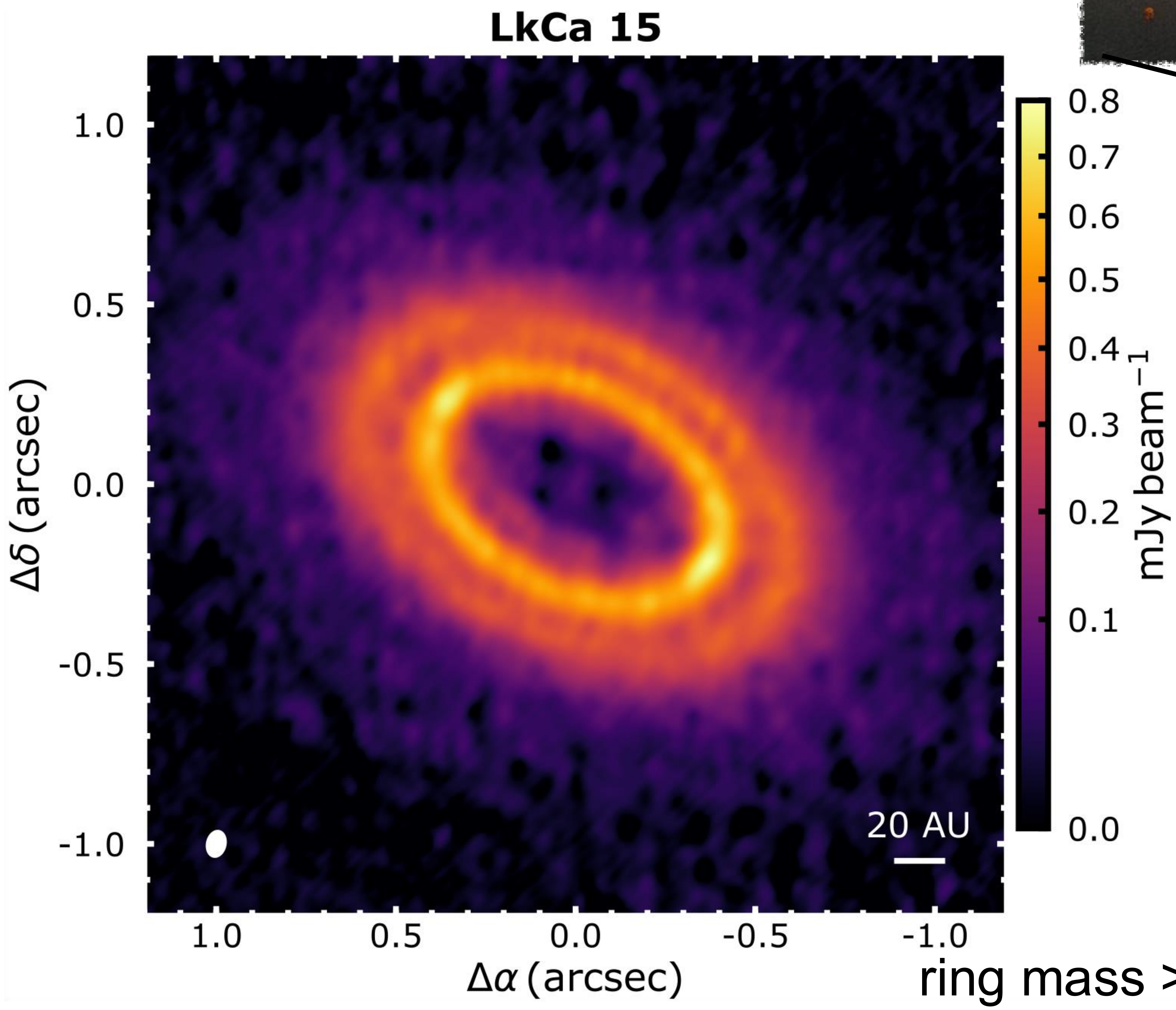
growth timescale easily longer than 10 Myr



Chicken or Egg?



Pebble ring are massive

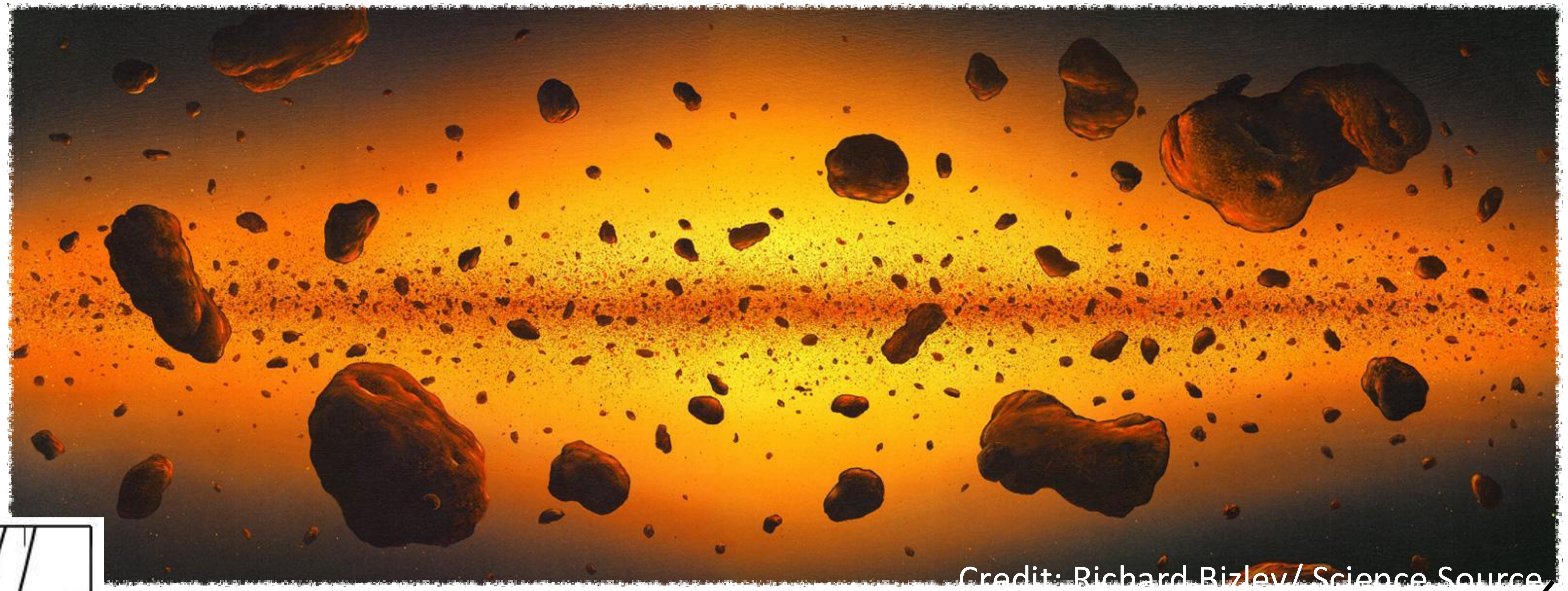


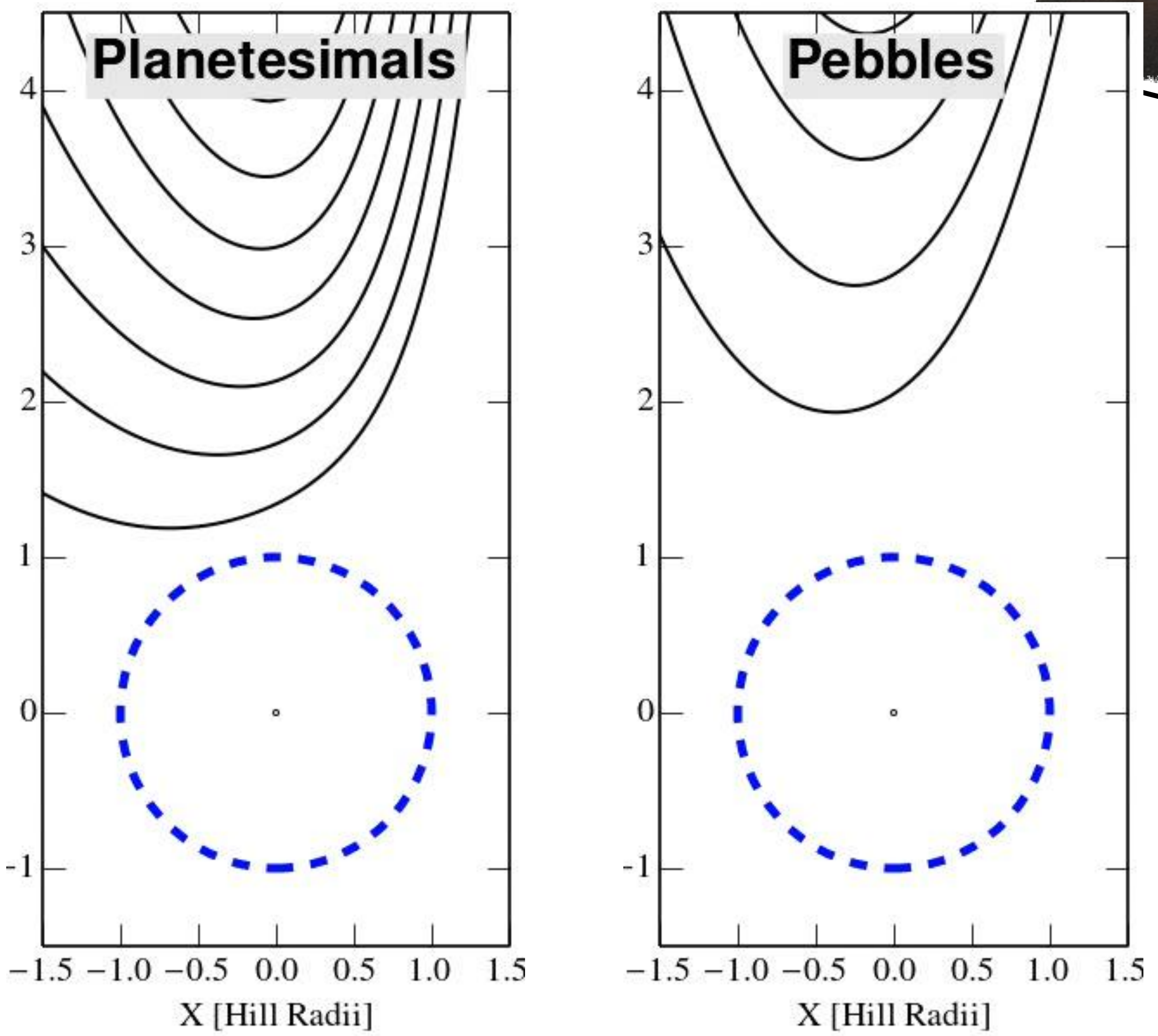
ring mass > $150 M_{\oplus}$, Facchini et al. 2020

Chicken or Egg?

Pebble accretion

cross sections are huge

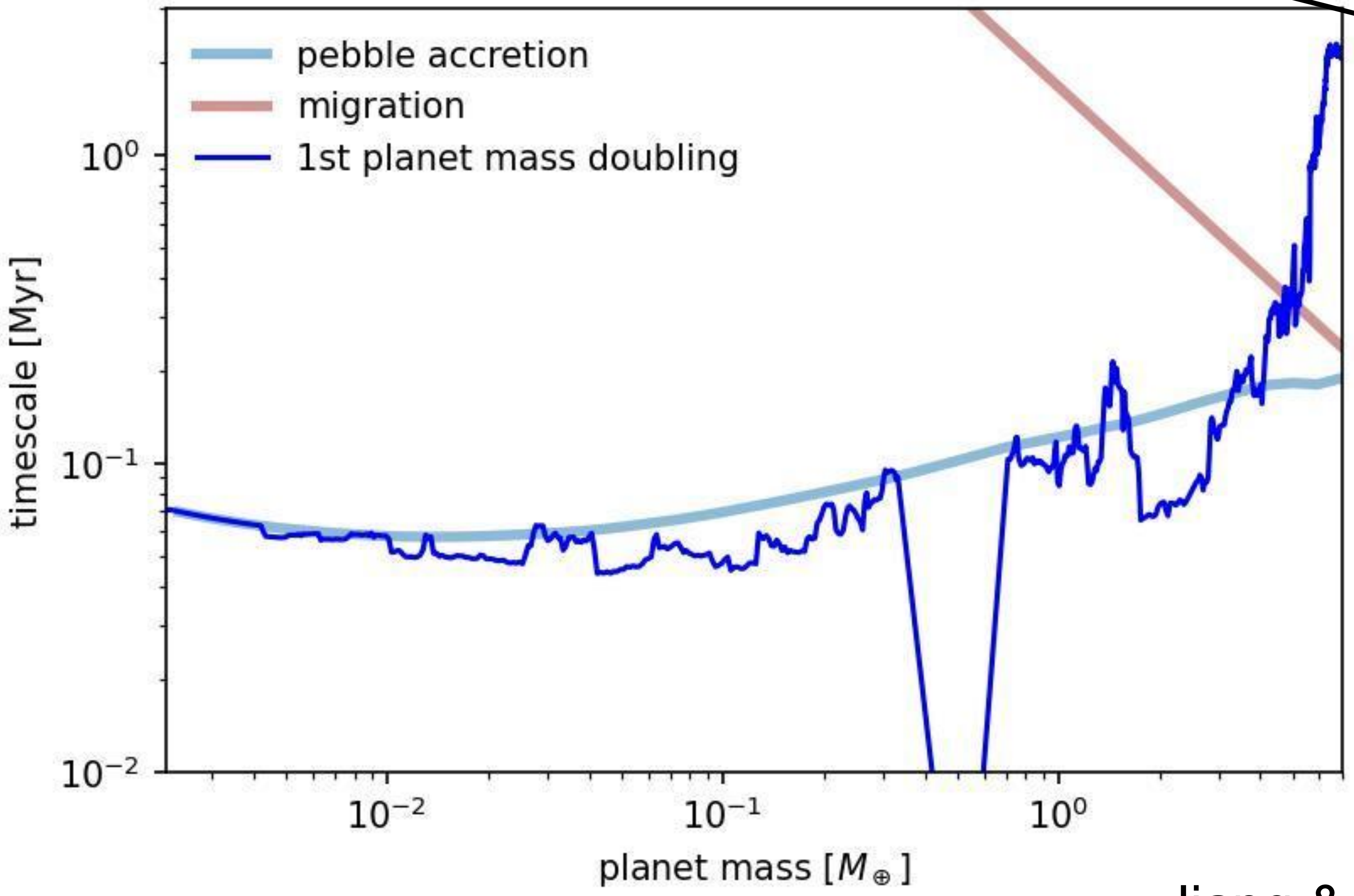




Chicken or Egg?

planet-pebble

(relative) velocities are small



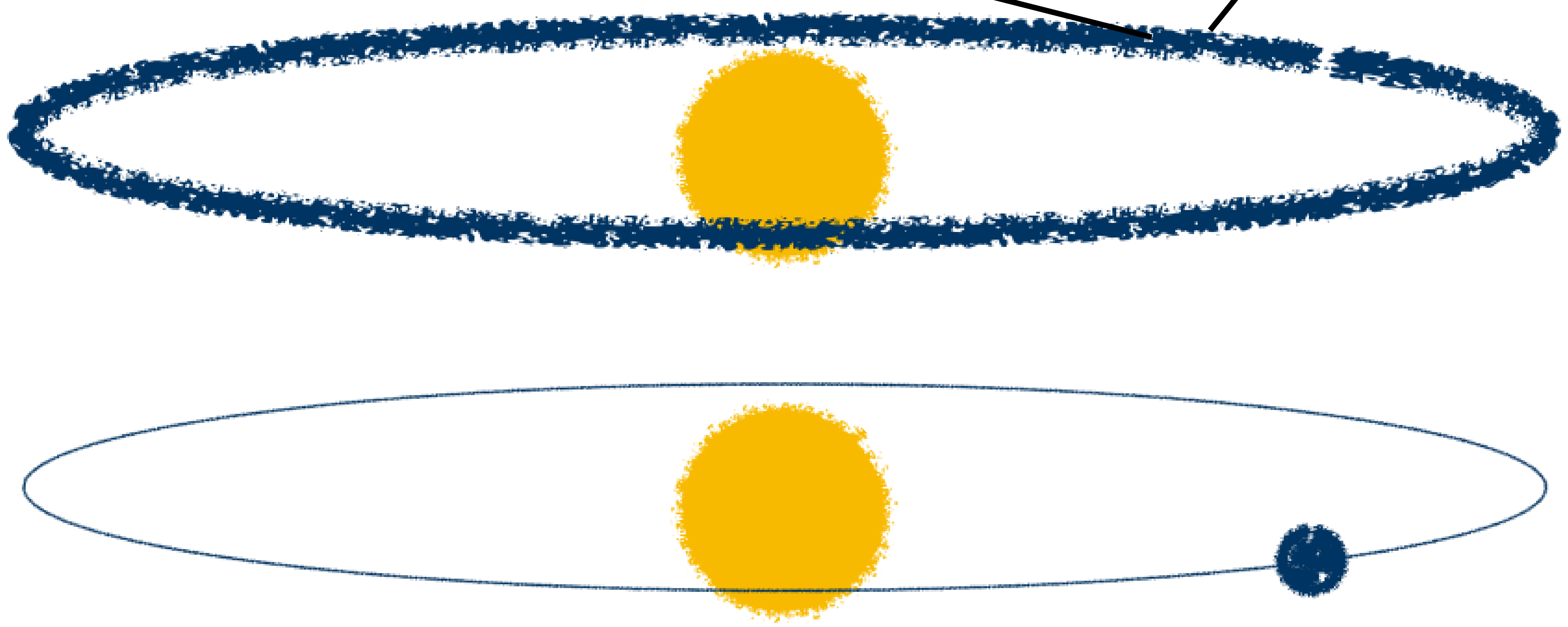
enables P.A. even for small planetesimals (Visser & Ormel 2016)

Jiang & Ormel 2023

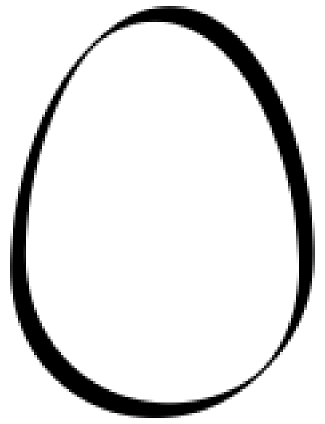
Chicken or Egg?

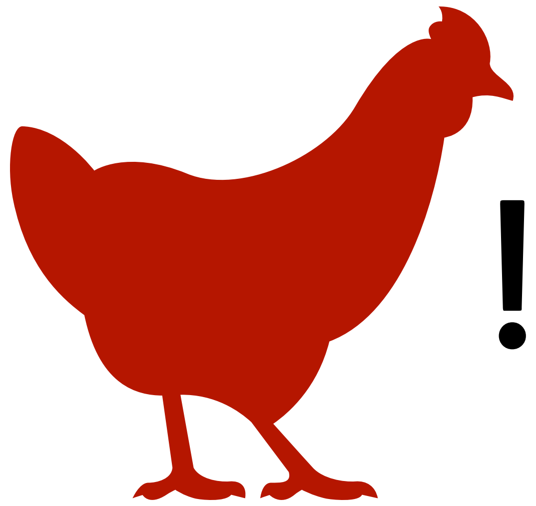
Dust/Pebble inside the ring

- High density, mass budget
- Large cross section
- low relative velocity



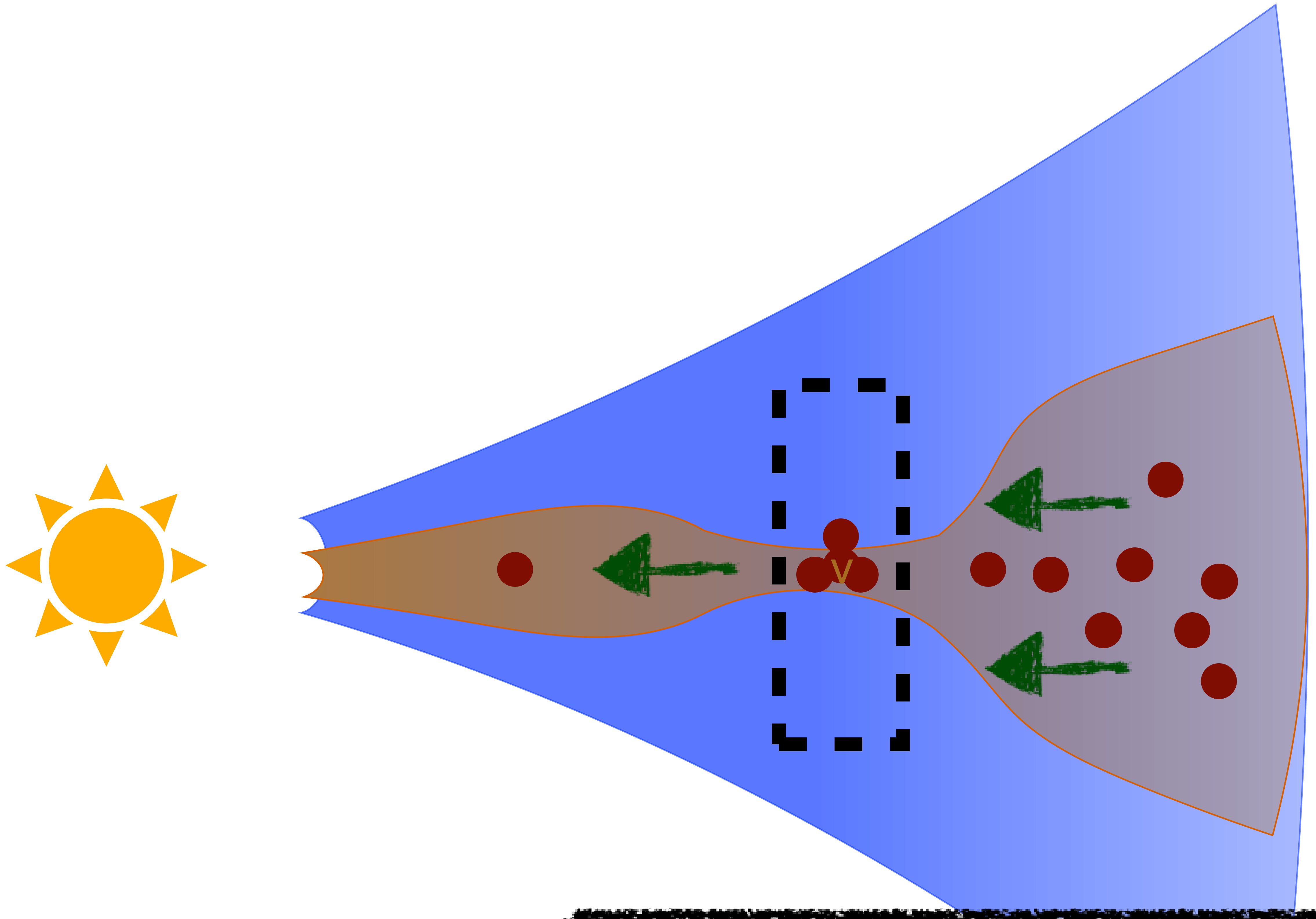
Rings could be the birthplace of planets!

 ?

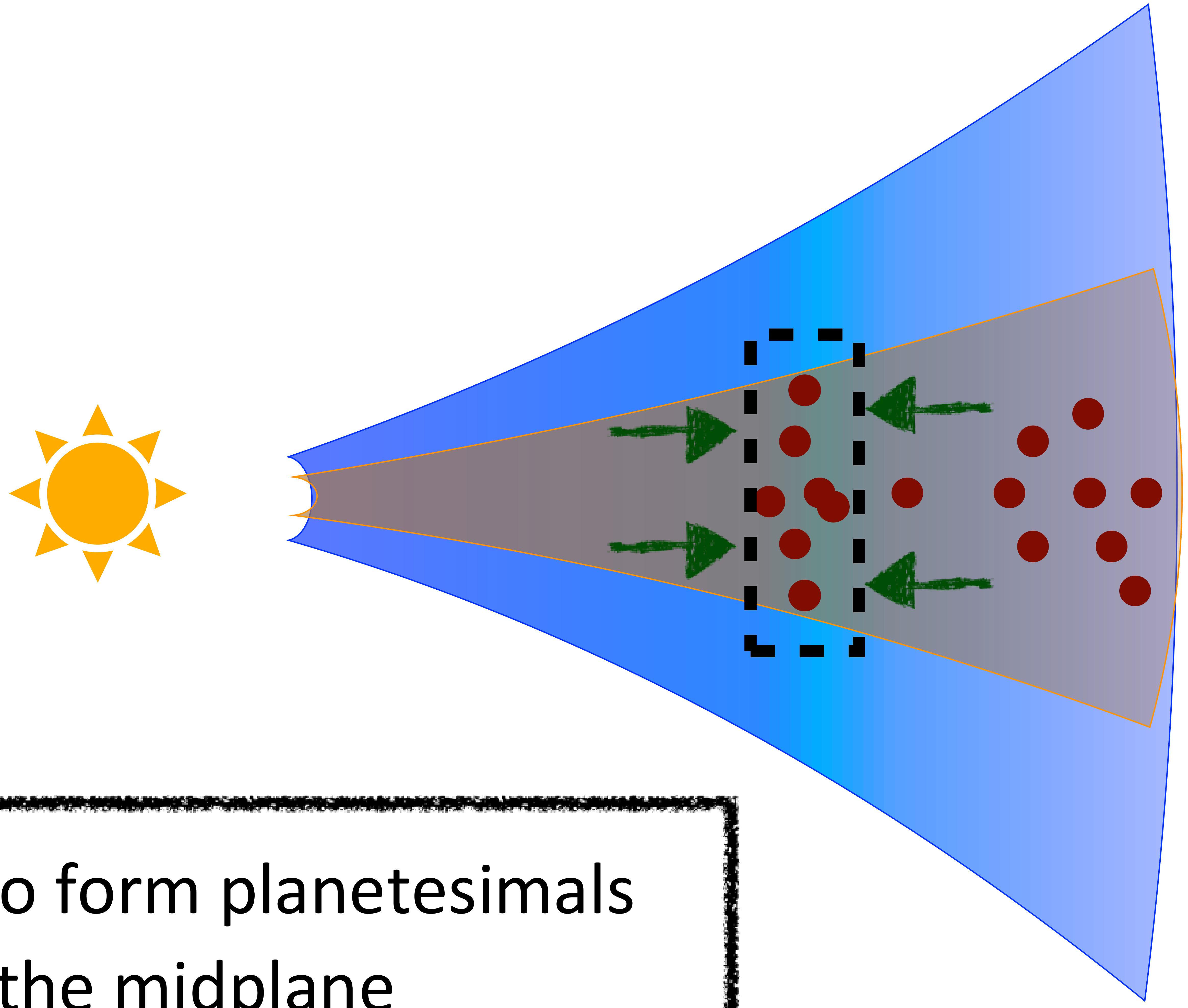
 !

2) Can planets form inside these pebble rings?

Clumpy ring



Pressure-Bump ring

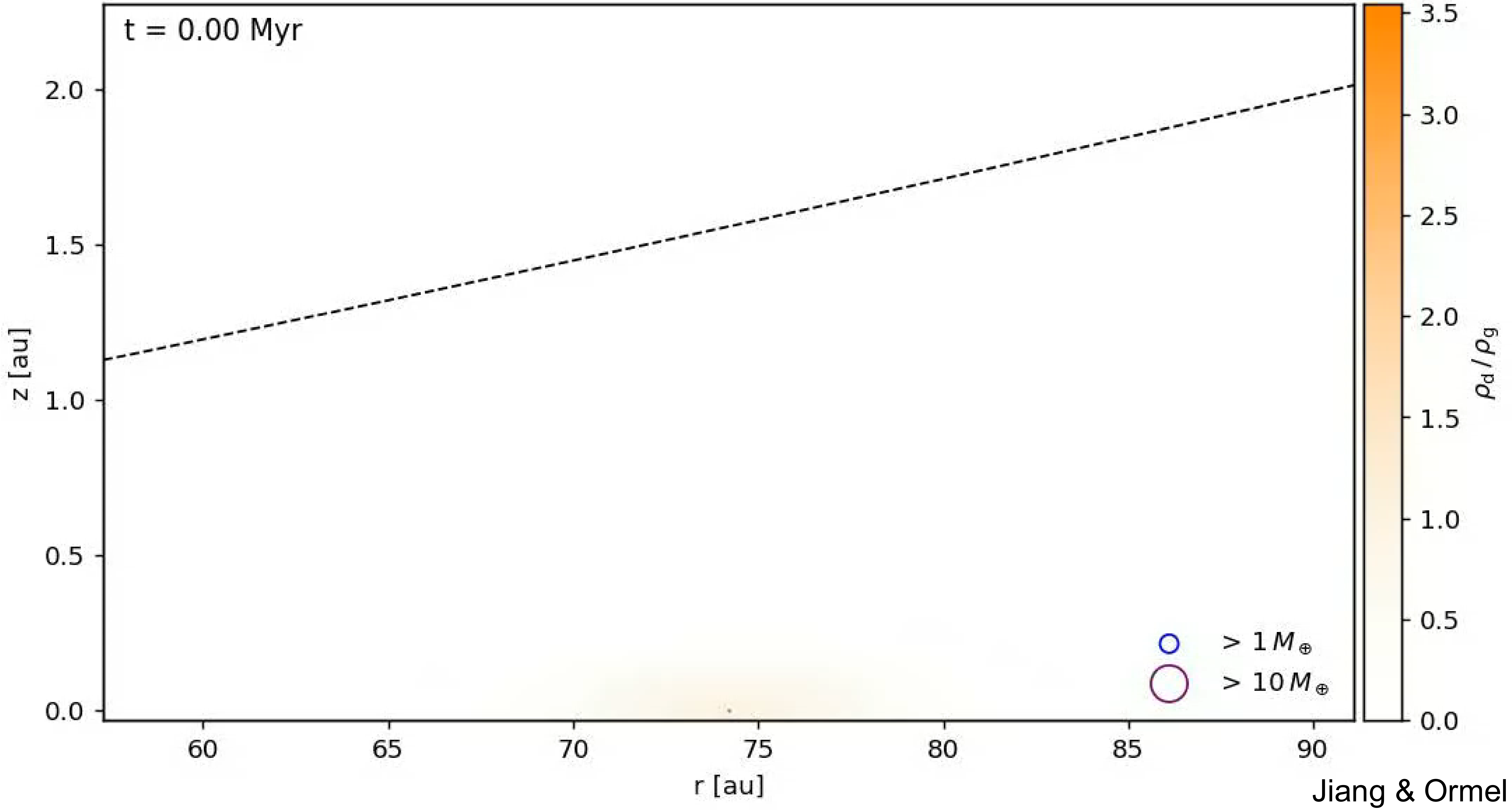


rings massive enough to form planetesimals

$\rho_{\mathrm{d}}/\rho_{\mathrm{g}} = 1$ at the midplane

Xu & Bai 2022

N-body simulation with pebble accretion
Planets formation inside the ring

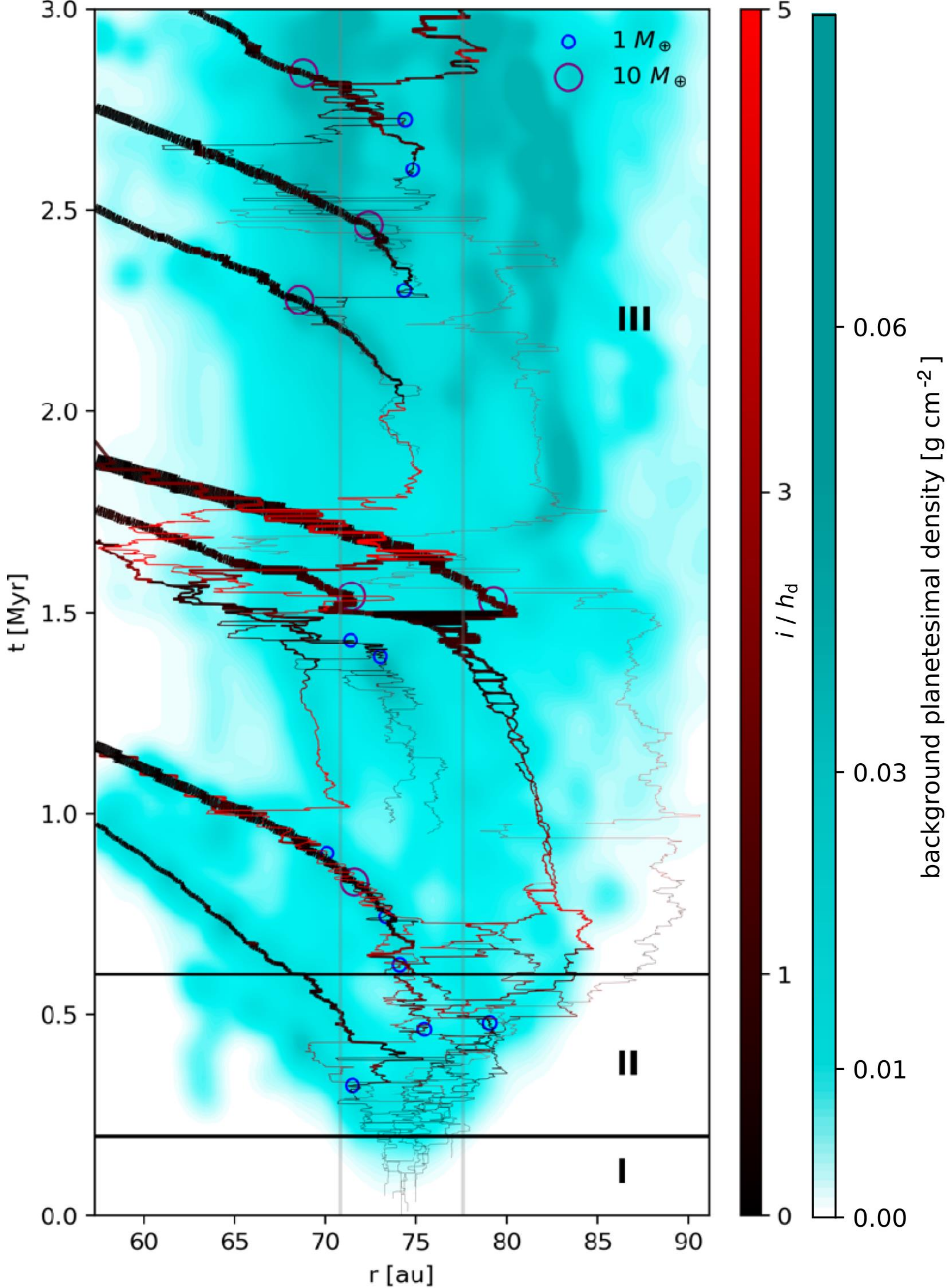


Jiang & Ormel 2023

Planets formation inside the ring

Condition of planetesimal formation

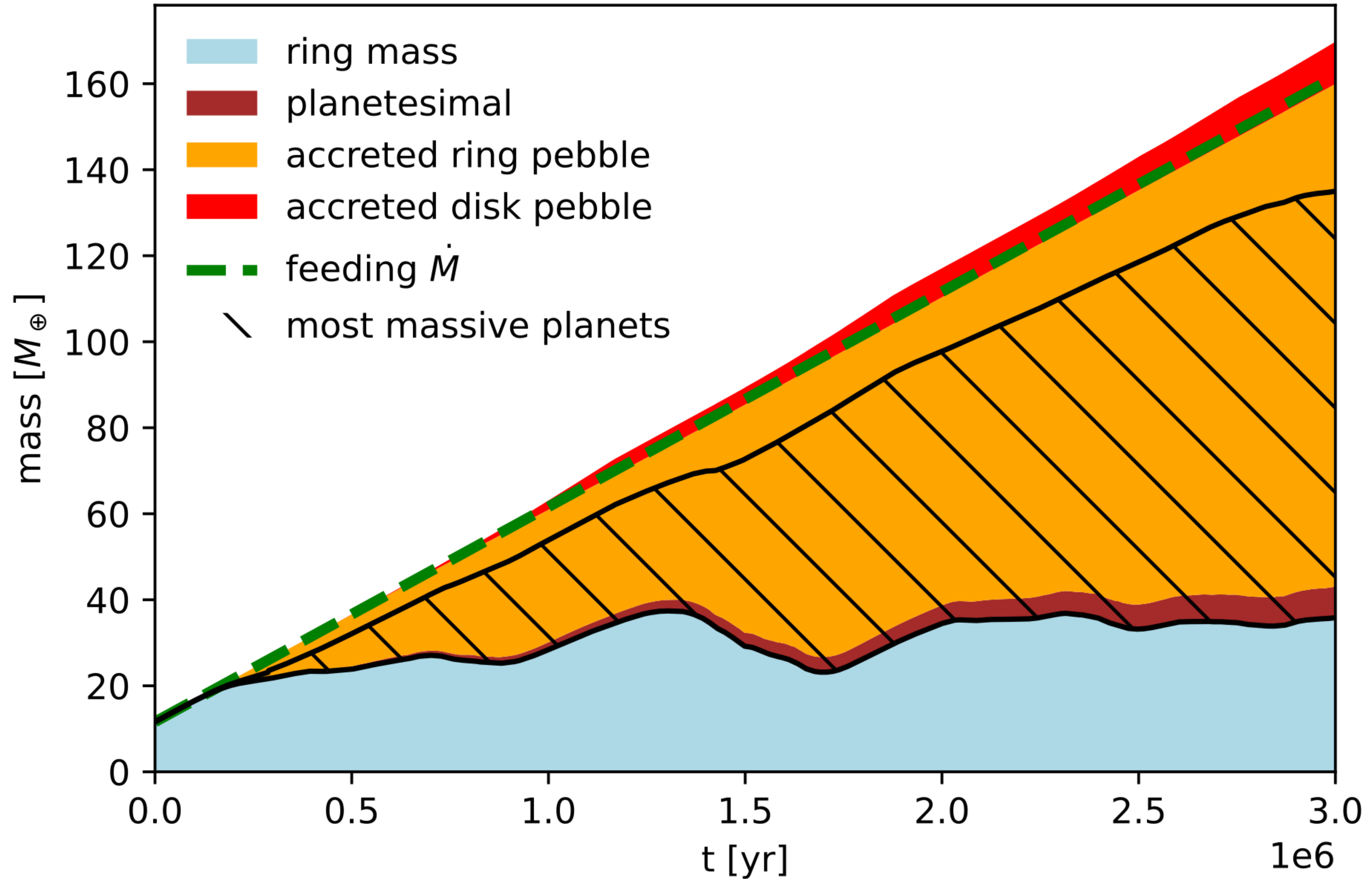
- High pebble density
- Low headwind

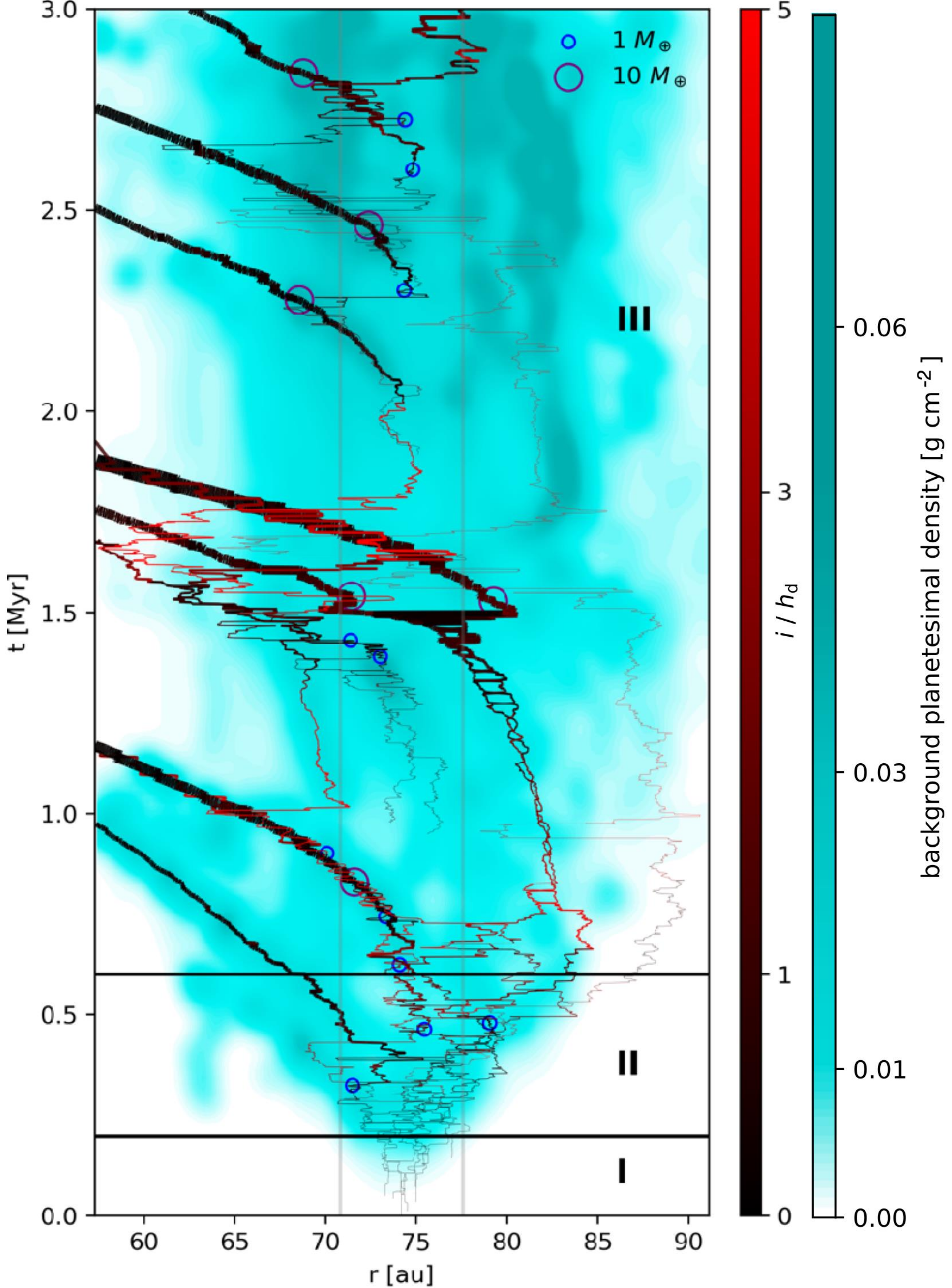


Planets formation inside the ring

Condition favored by pebble accretion

- High pebble density
- Low headwind



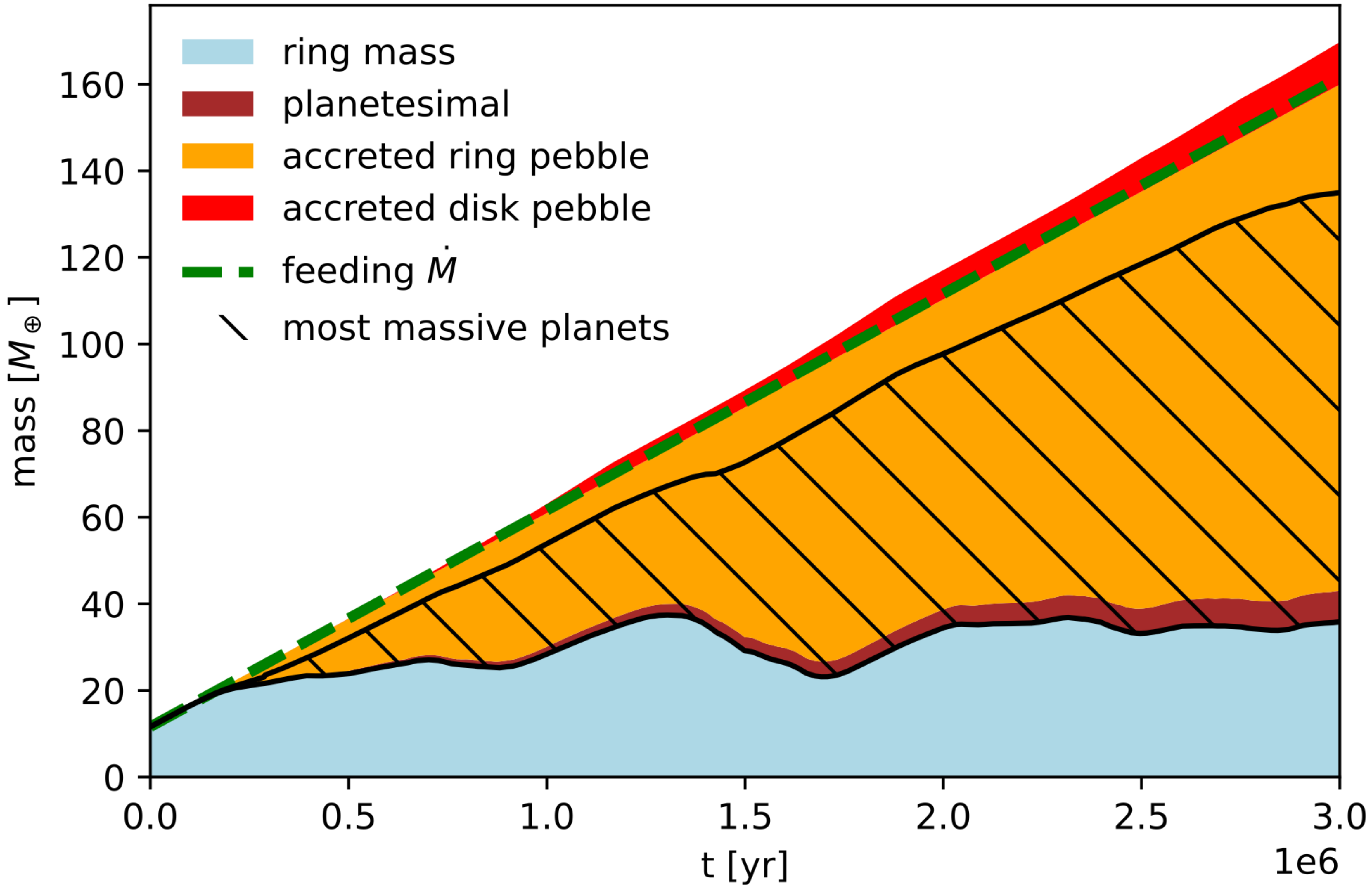


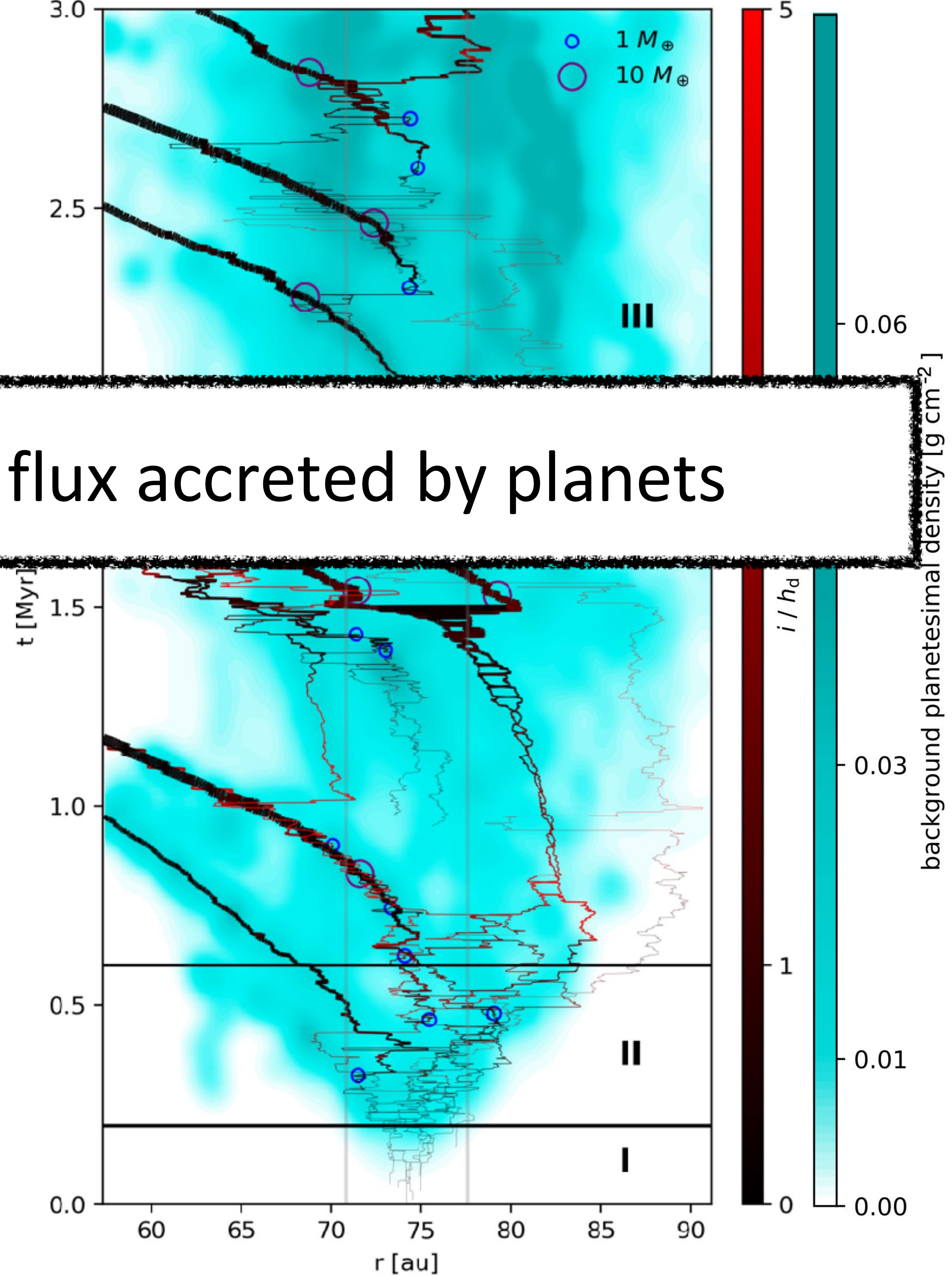
Planets formation inside the ring

Condition favored by pebble accretion

mass flux fed to the ring ≃ mass flux accreted by planets

- Low headwind

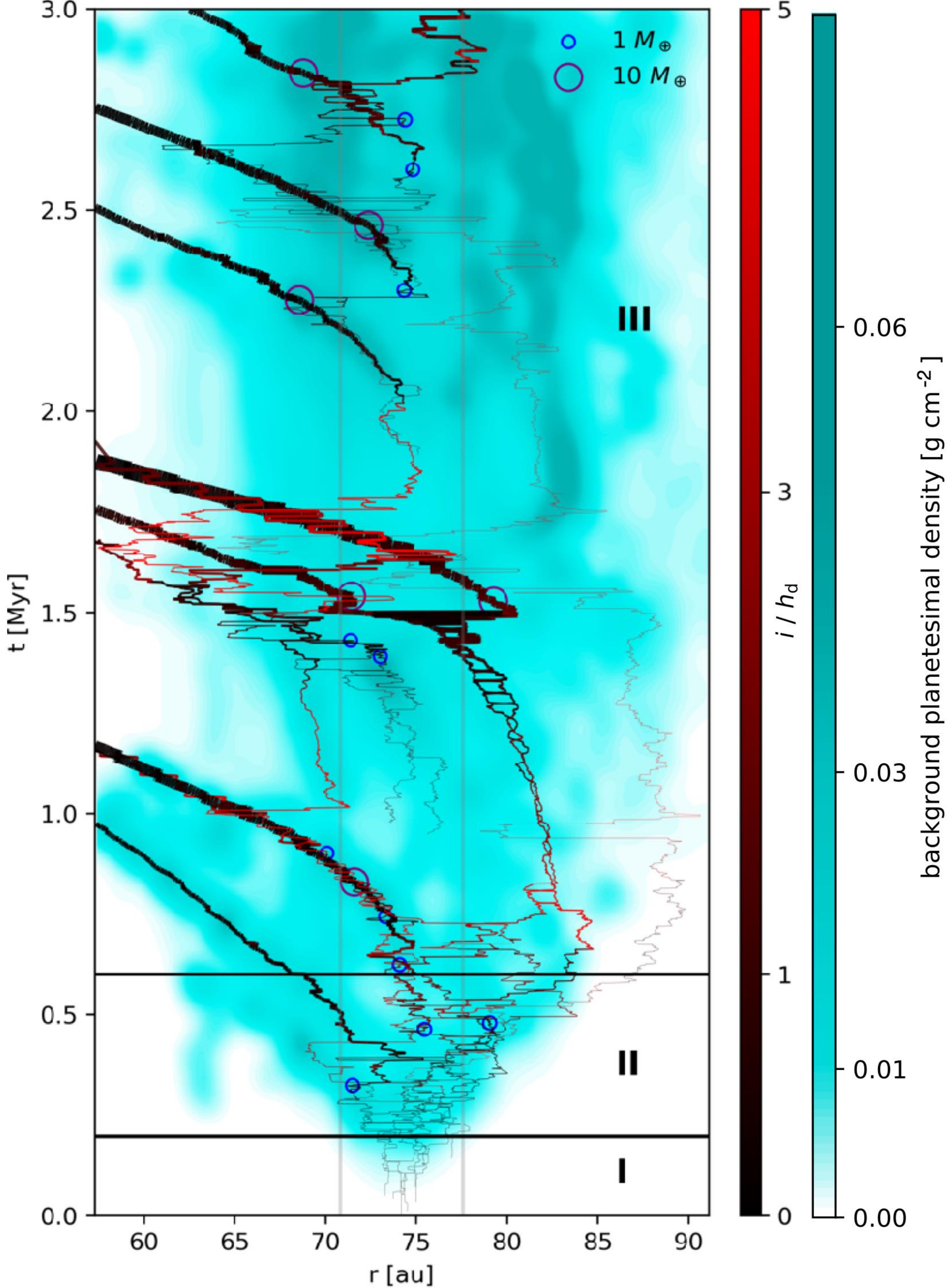




Planetesimals belt - radial profile

Cyan background

“left-over” planetesimal belt

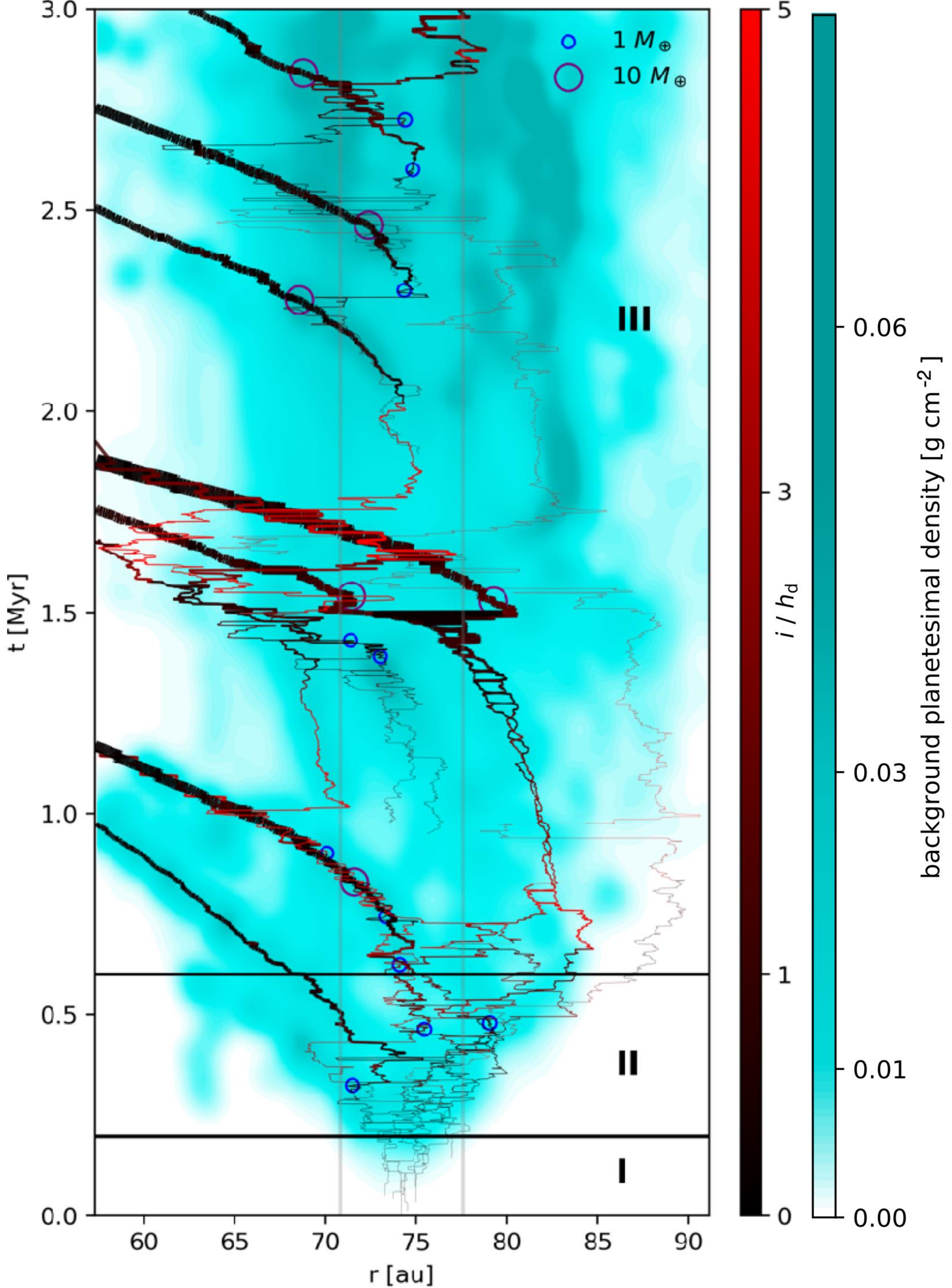


Planetesimals belt - radial profile

Cyan background

“left-over” planetesimal belt

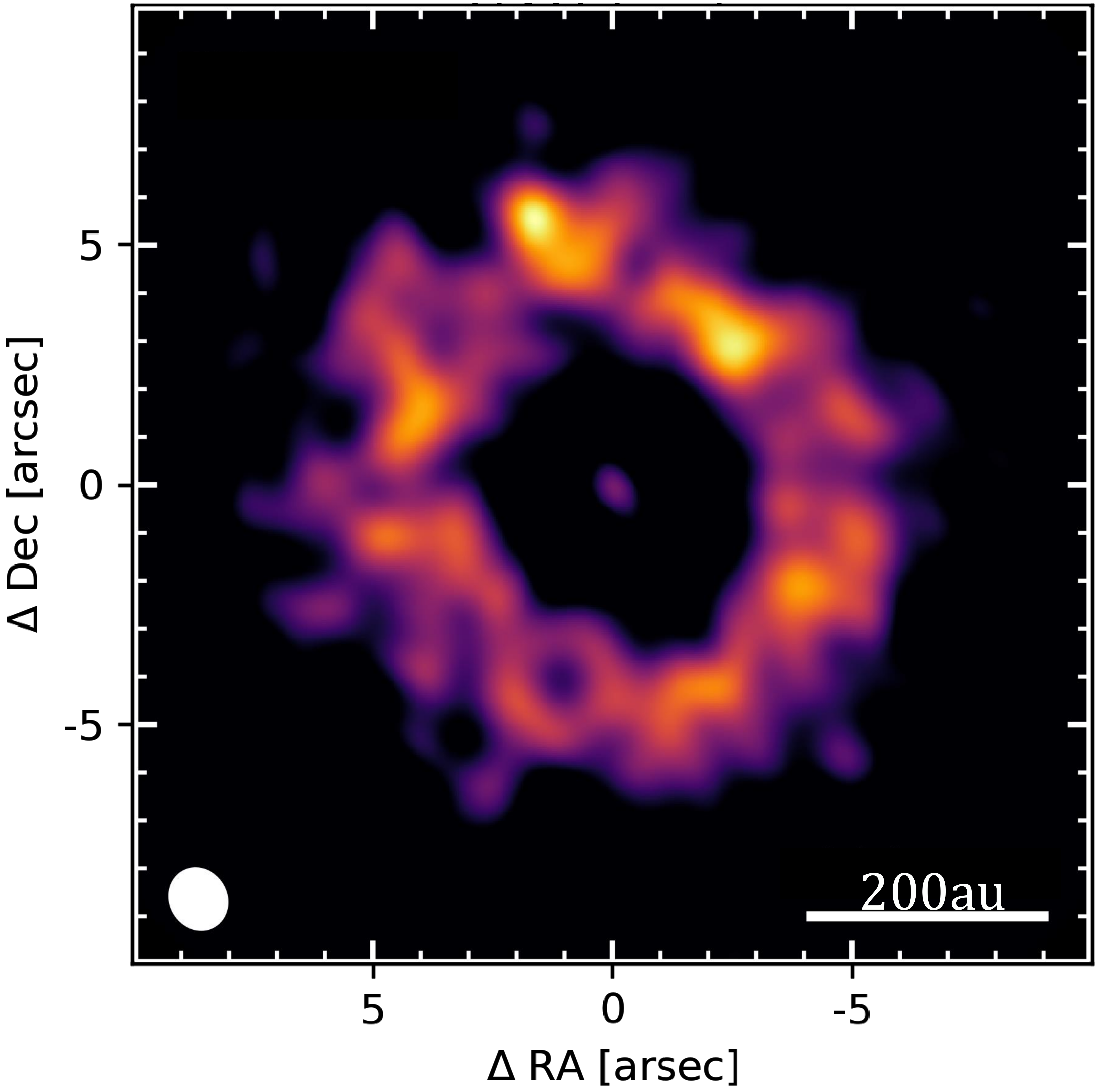
divide the planetesimal mass into bins at each radius

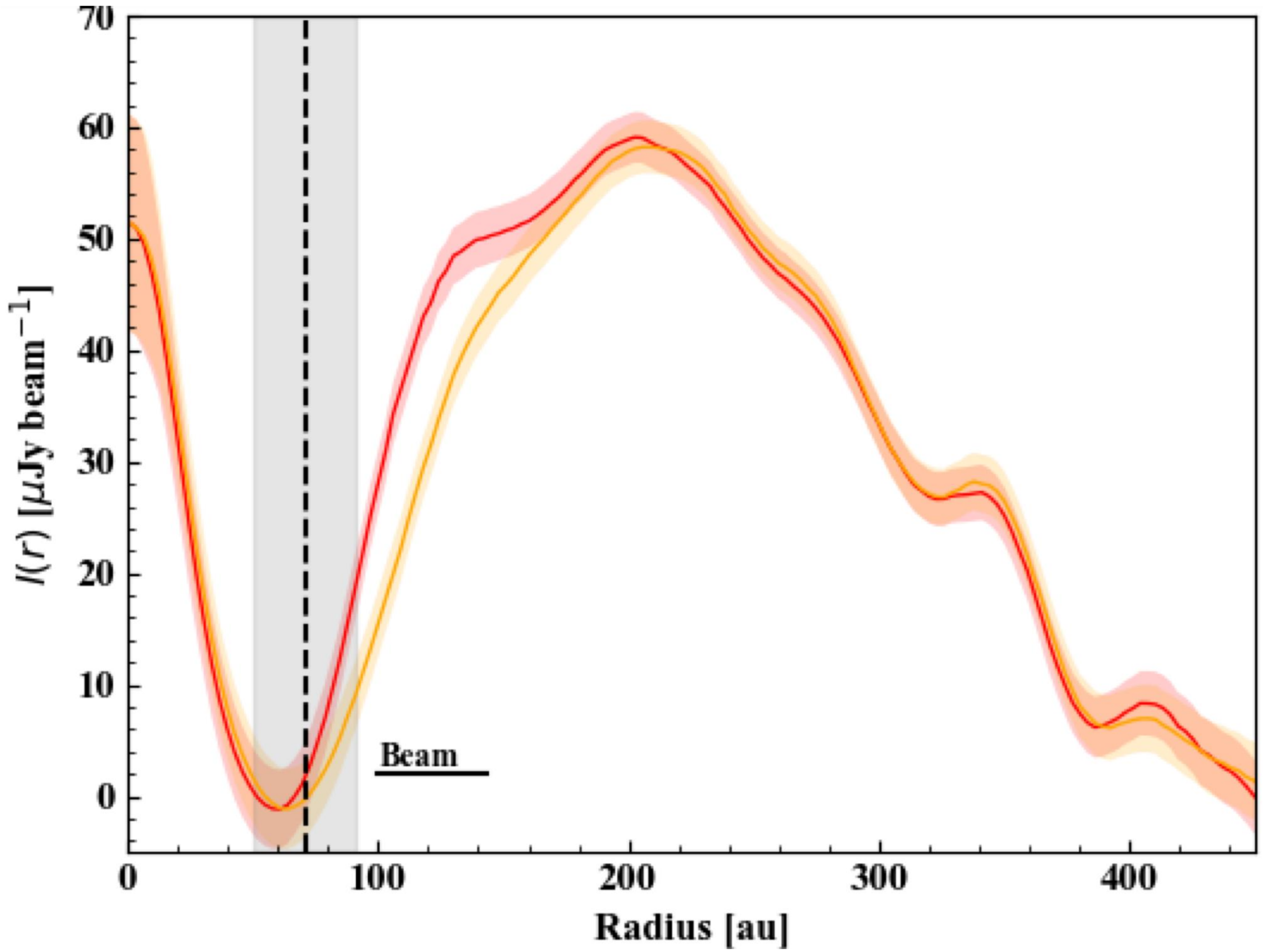


Planetesimals belt - radial profile

Planetesimals belt - radial profile

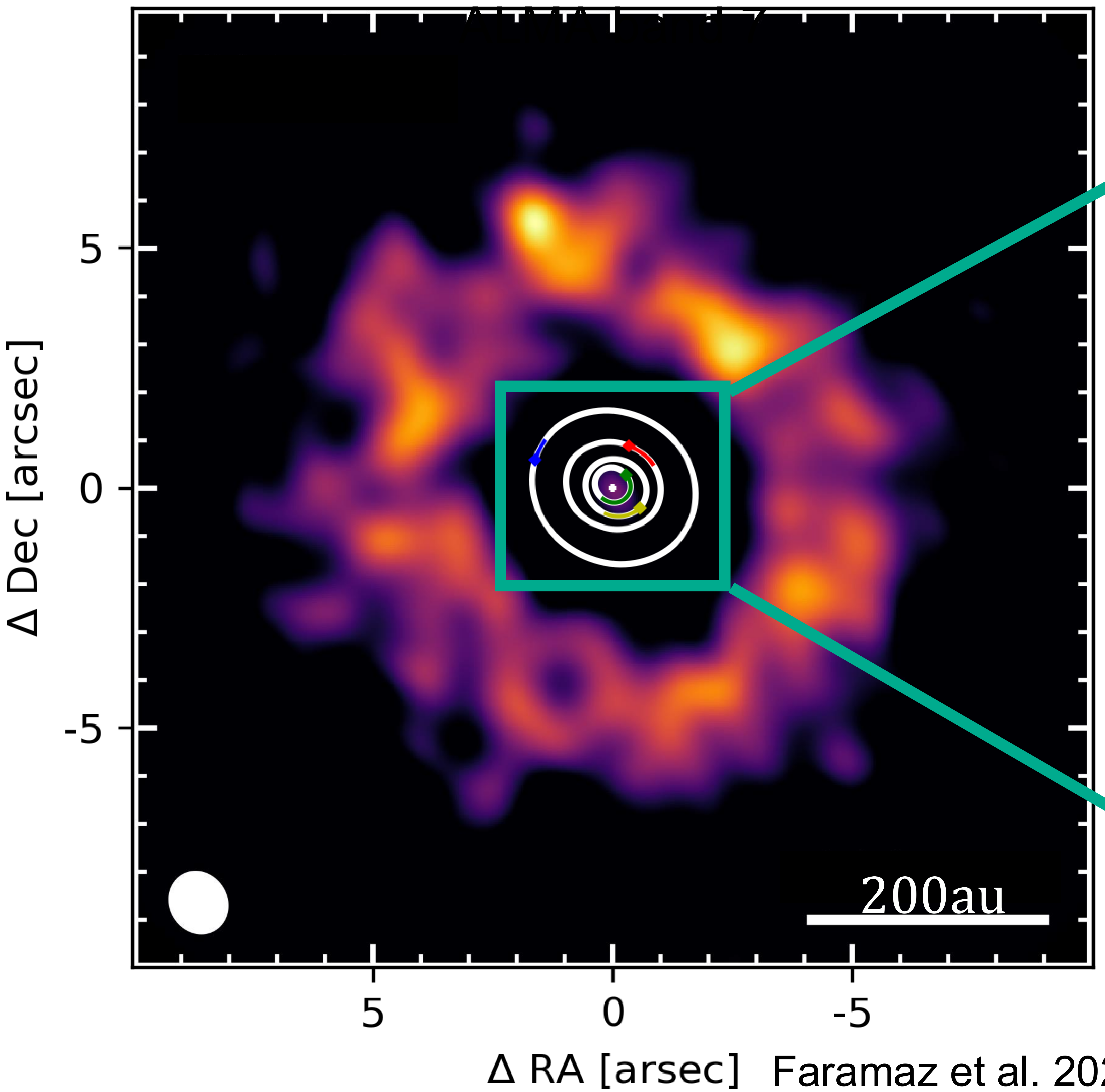
A Debris disk



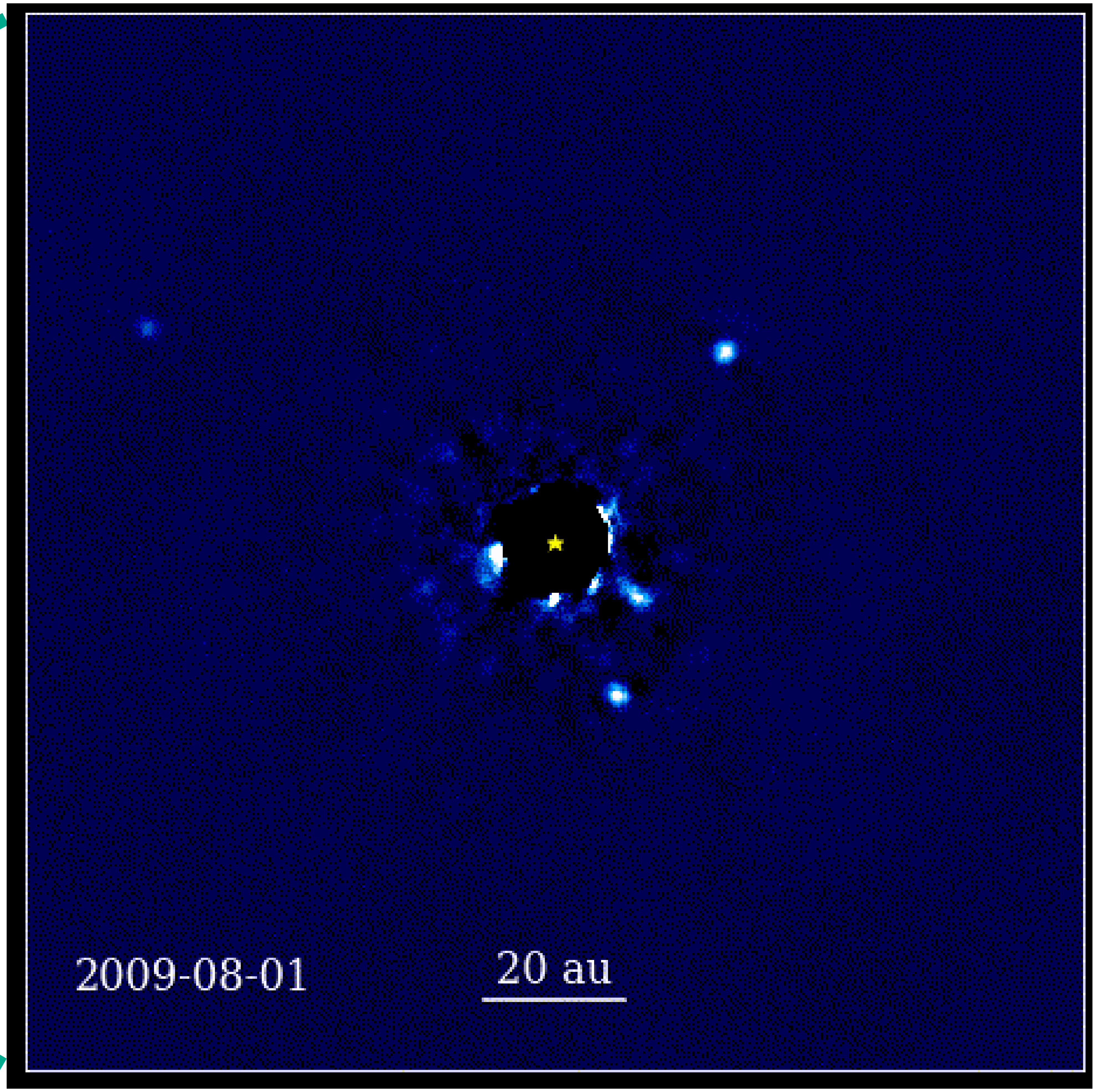


Faramaz et al. 2021

The Cold Debris disk around HR 8799

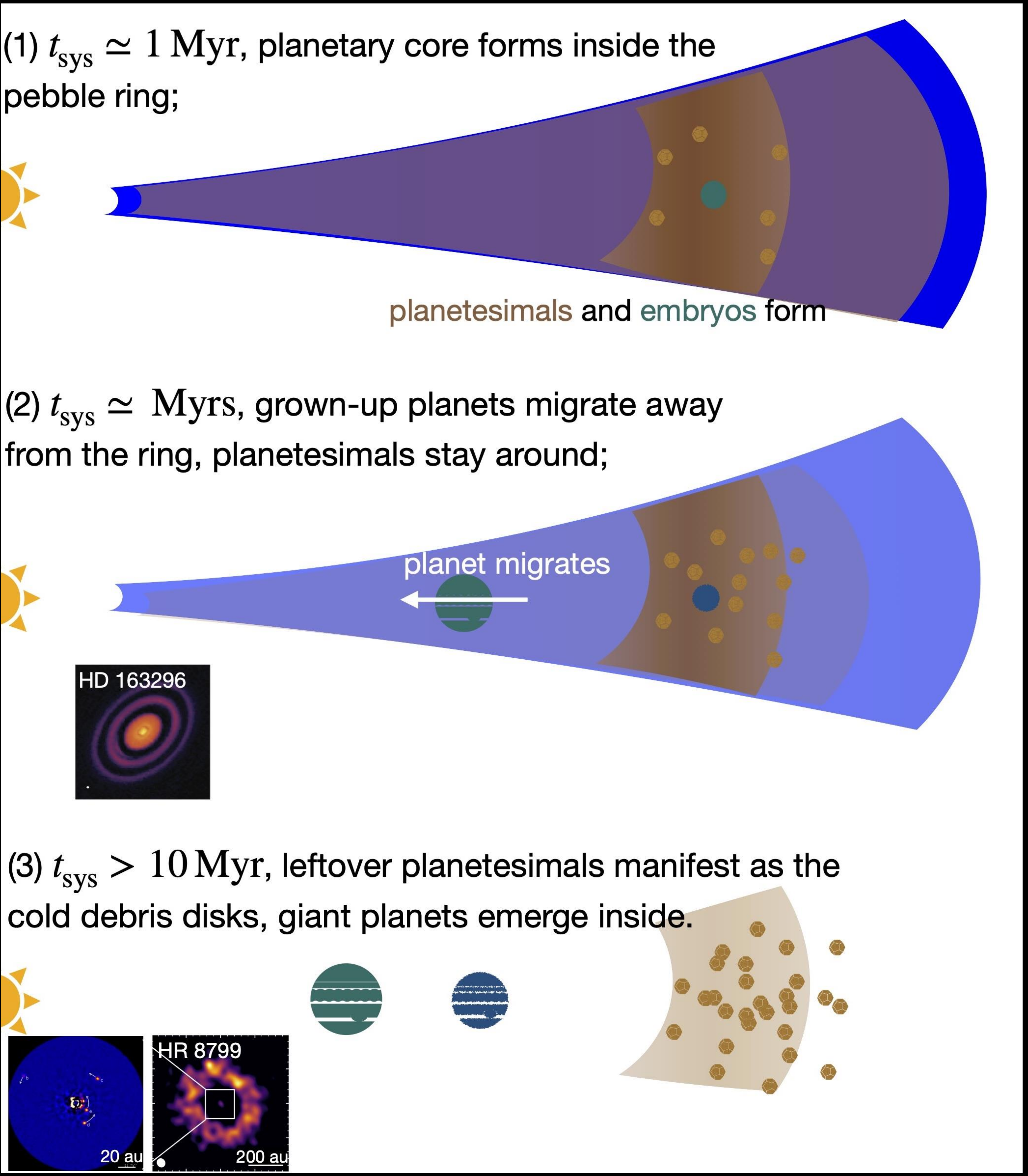


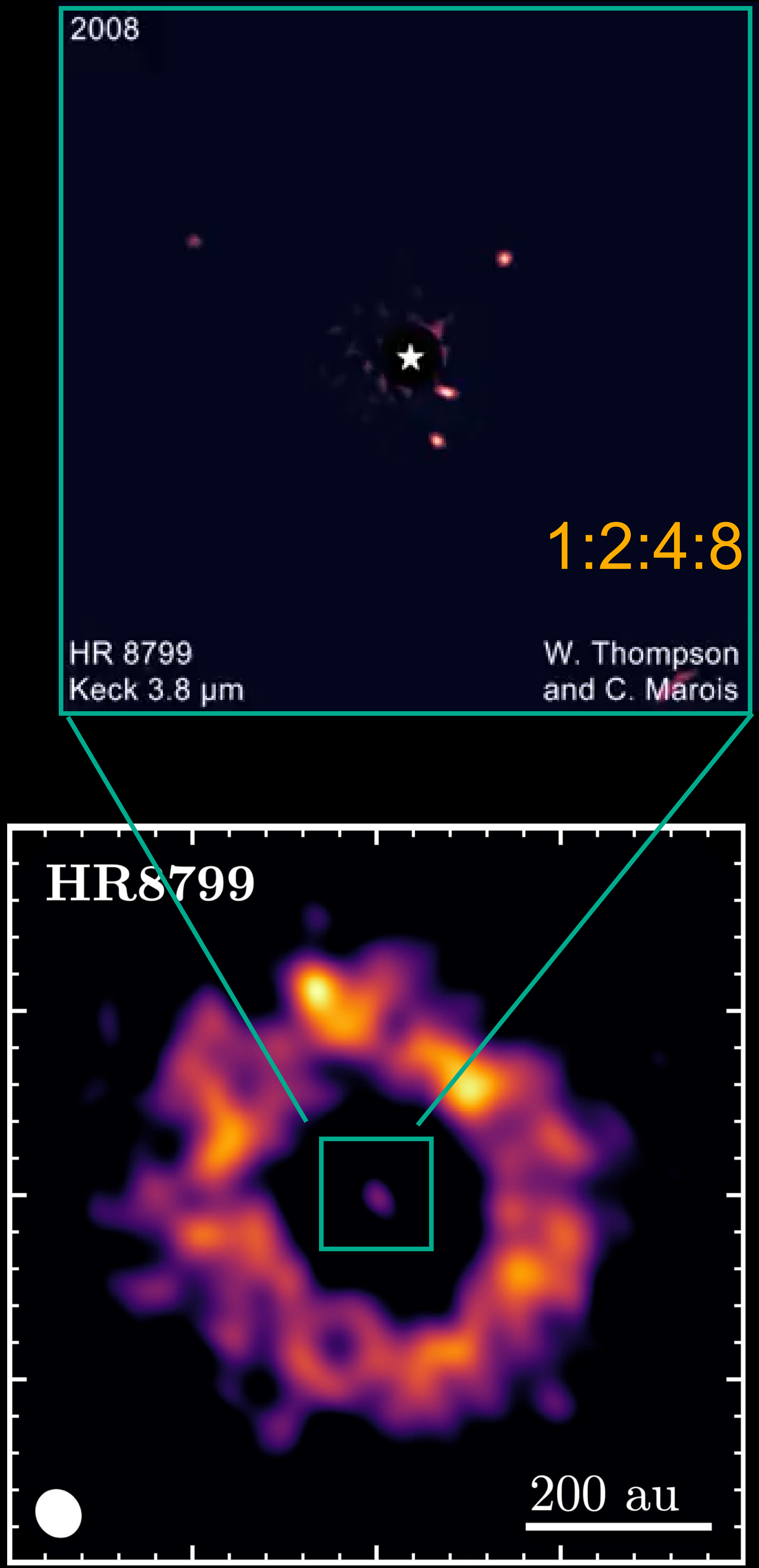
Faramaz et al. 2021



Credit: Jason Wang (Northwestern)/William Thompson (UVic)/Christian Marois (NRC Herzberg)/Quinn Konopacky (UCSD)

Formation of HR 8799





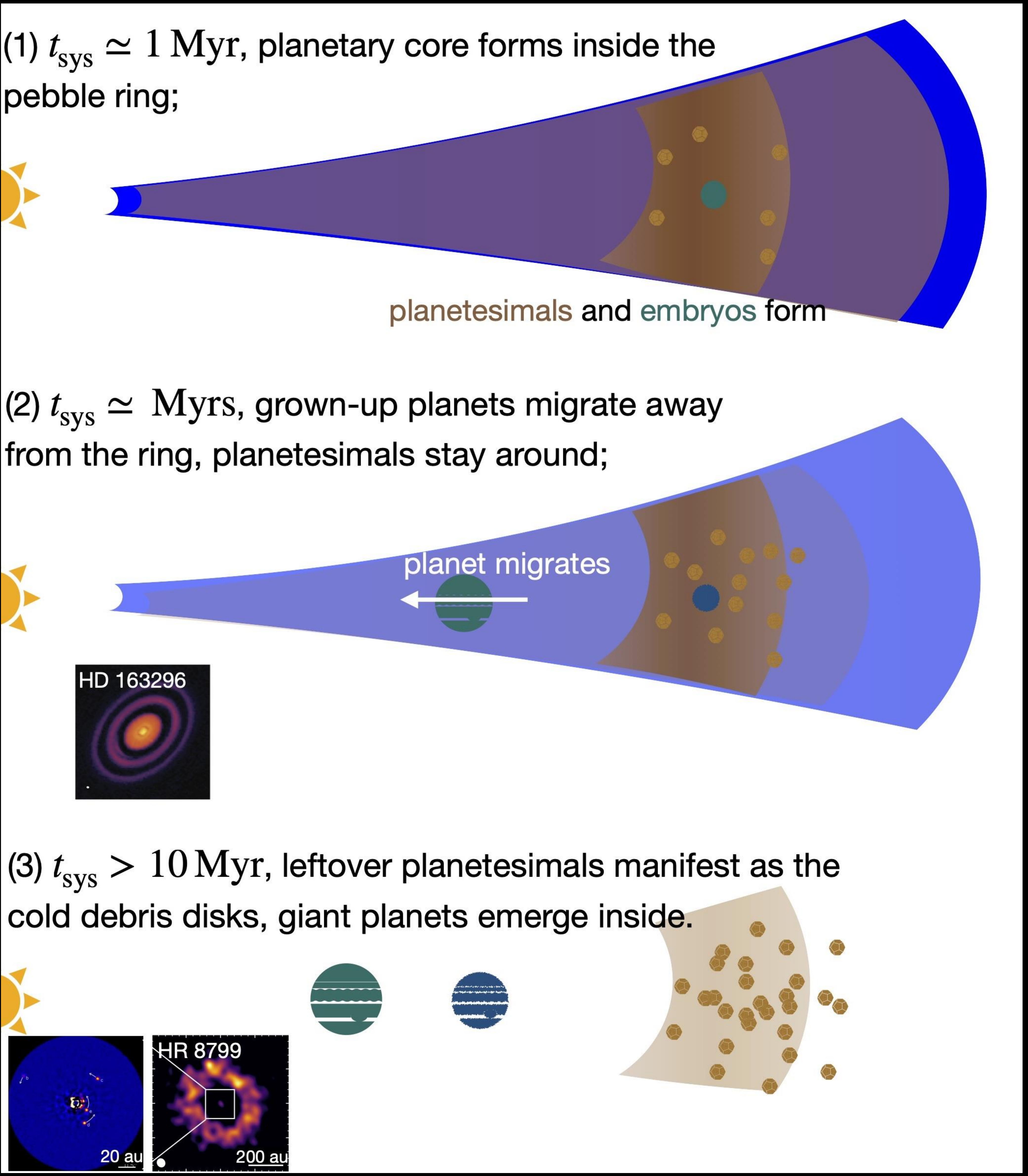
1:2:4:8 resonance

Wang et al. 2018

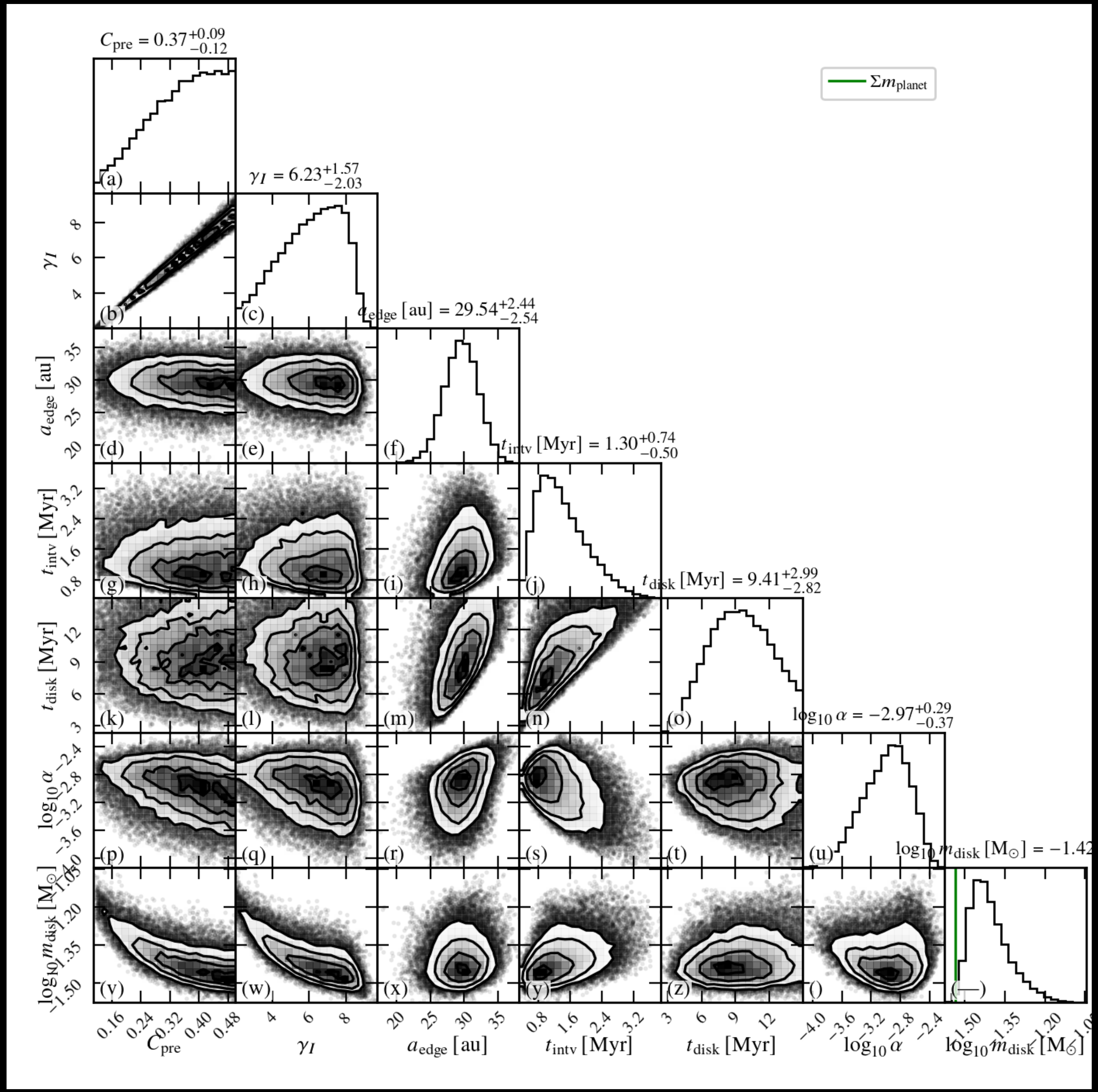
Zurlo et al. 2022

Faramaz et al. 2021

Formation of HR 8799

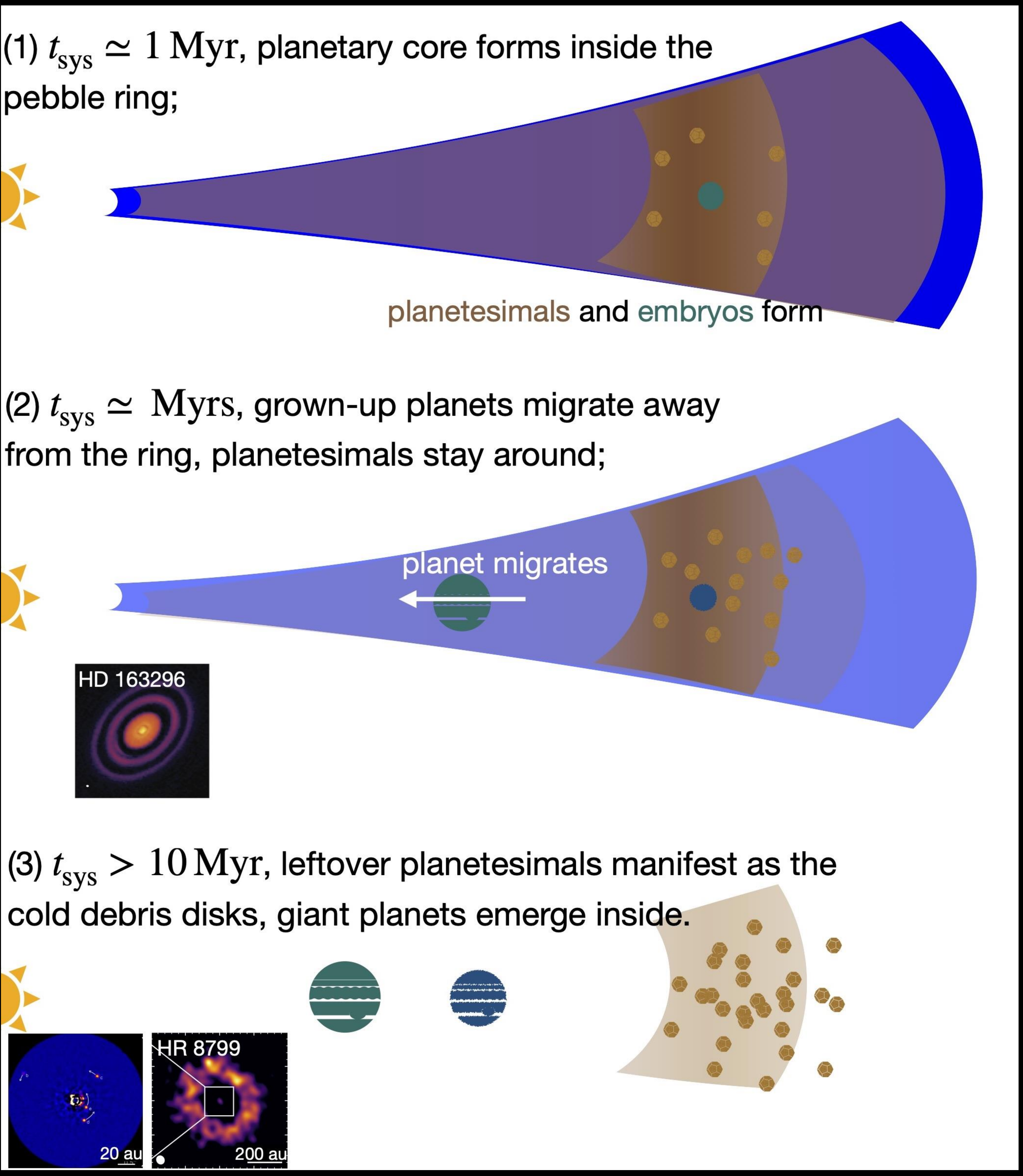


- use MCMC to "tune" parameters

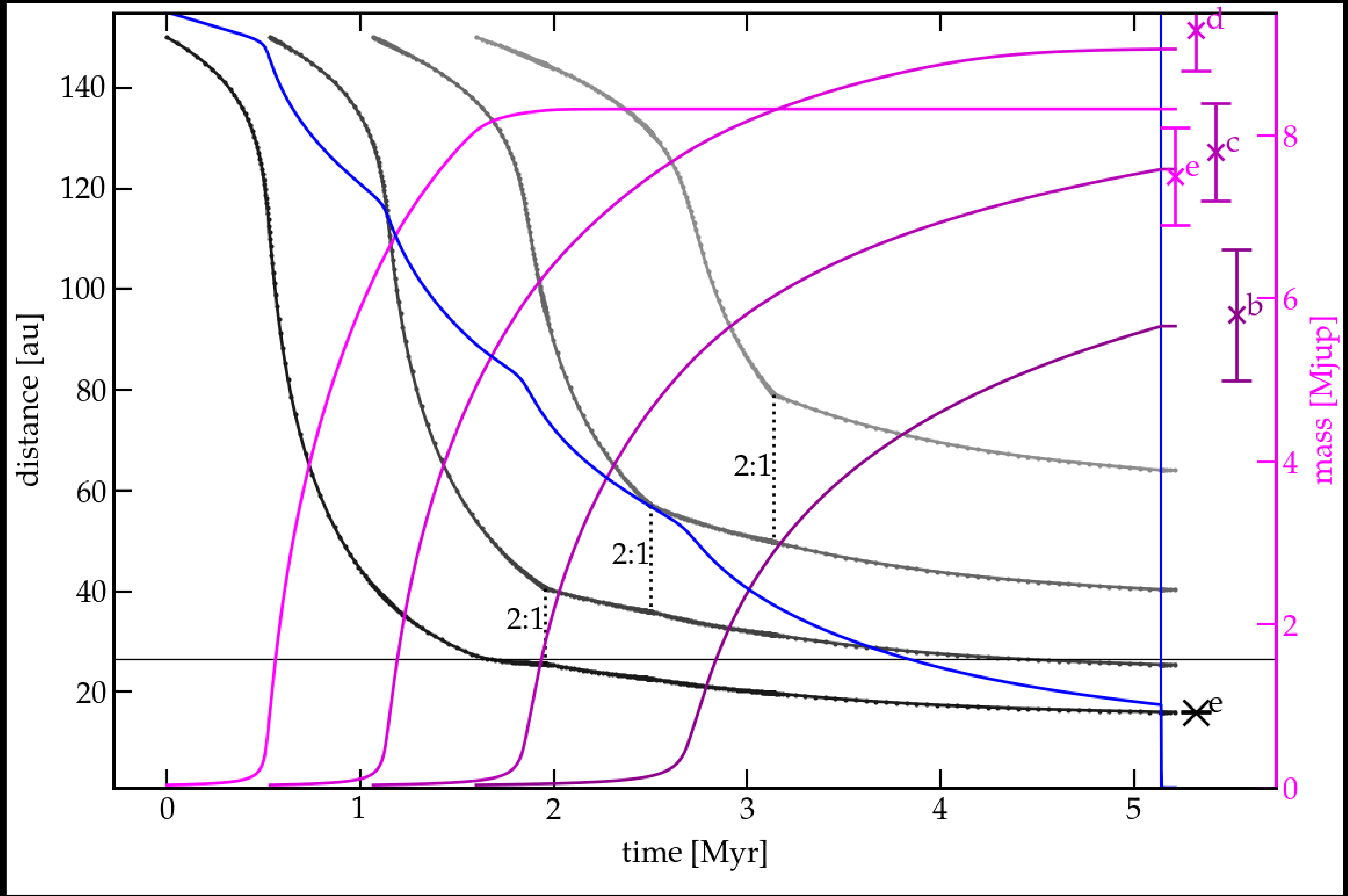


- disk mass
- migration speed
- turbulence
- interval

Formation of HR 8799



- a sample semi-analytical solution:



- disk mass
- migration speed
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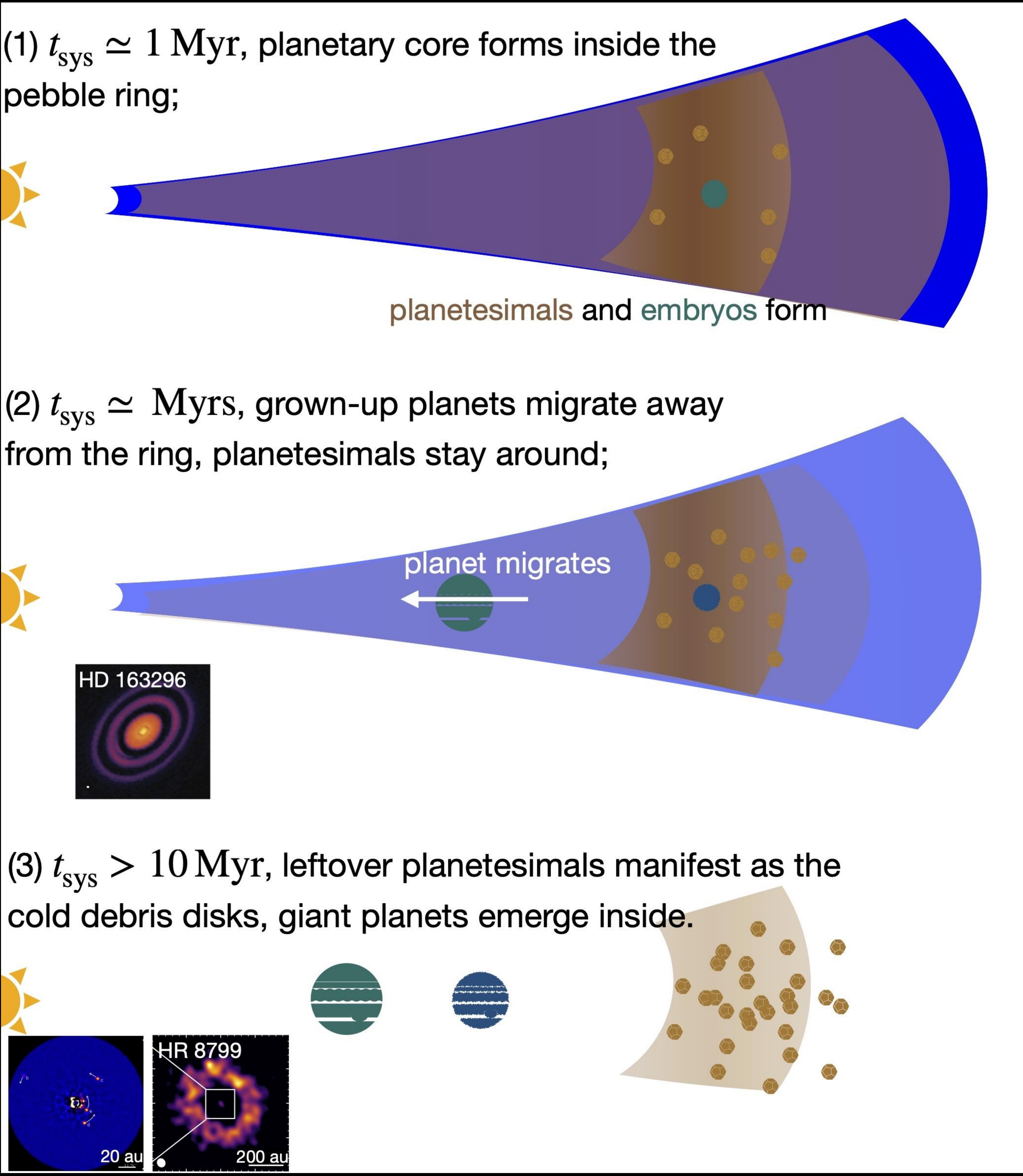
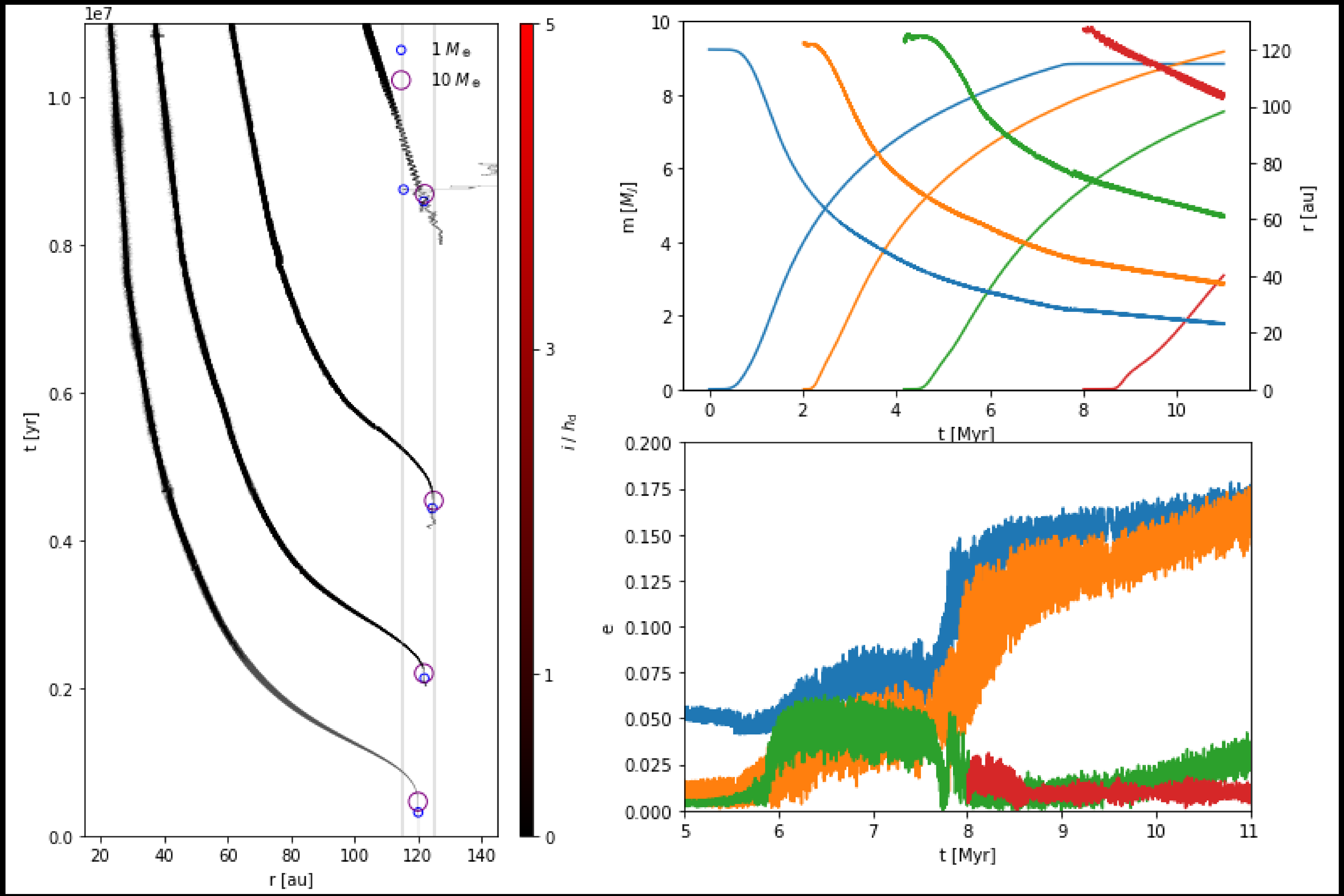
Formation of HR 8799

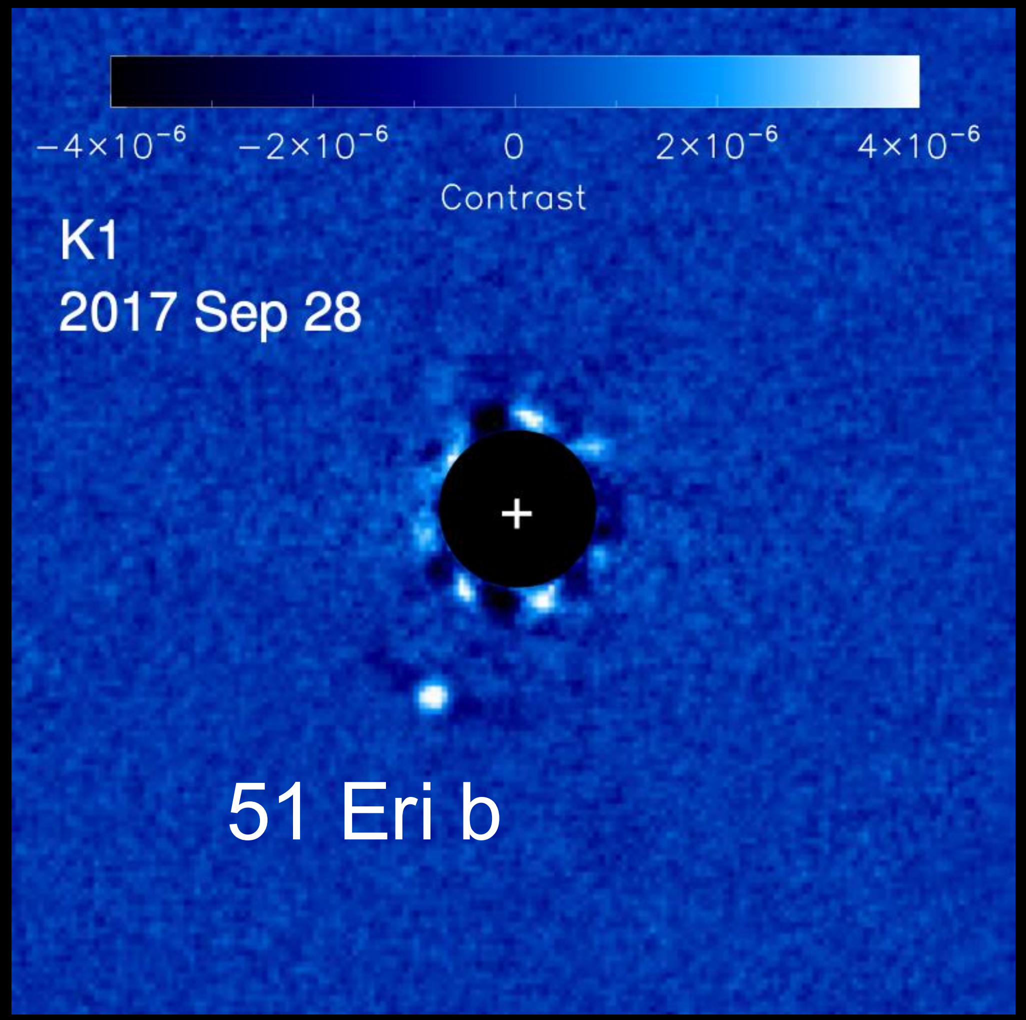




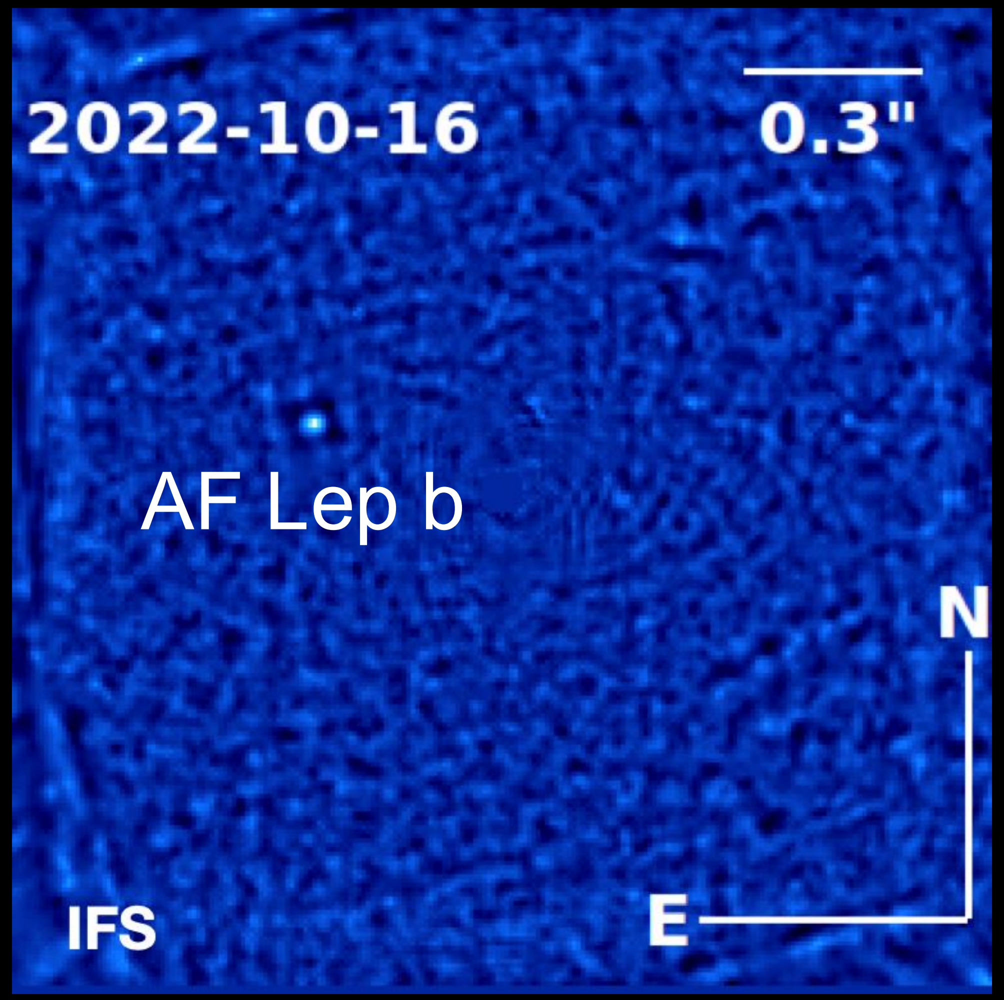
- reproduce the semi-analytical results
- by N-body simulation

Most direct imaged planets

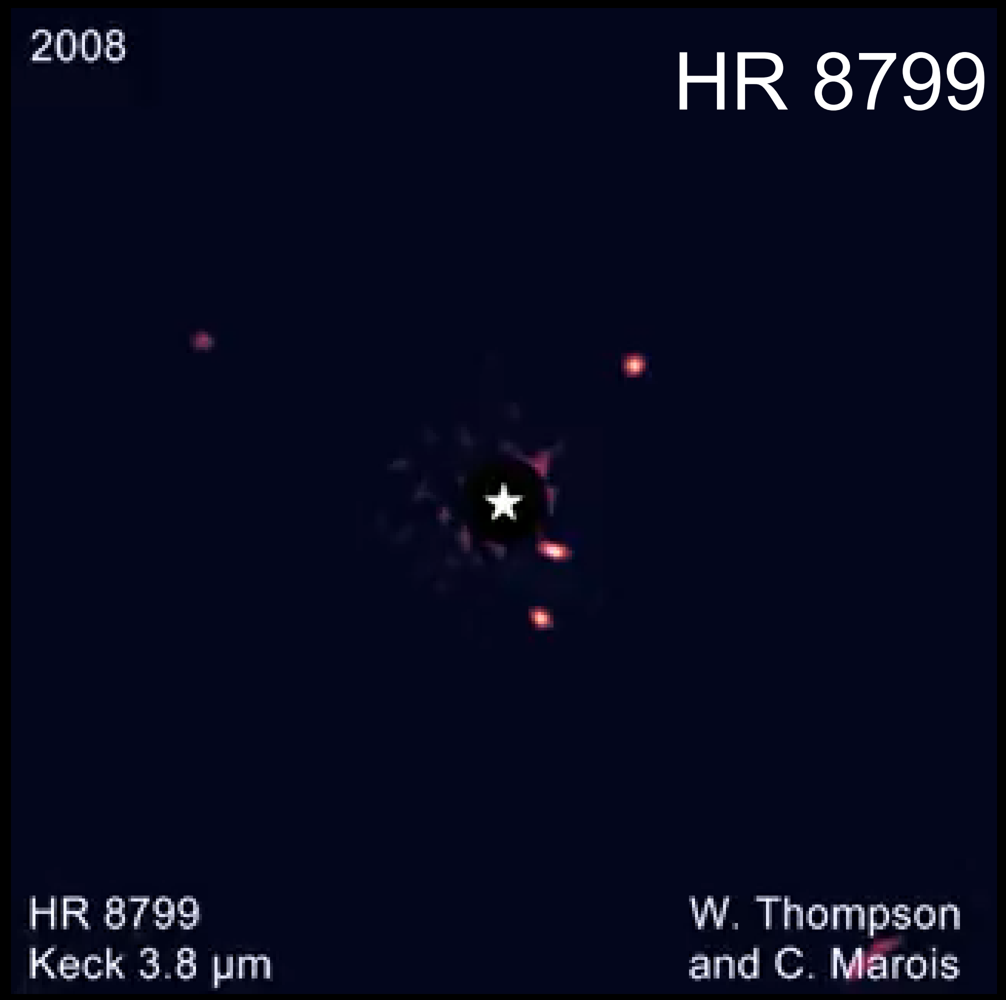
Maire et al. 2019



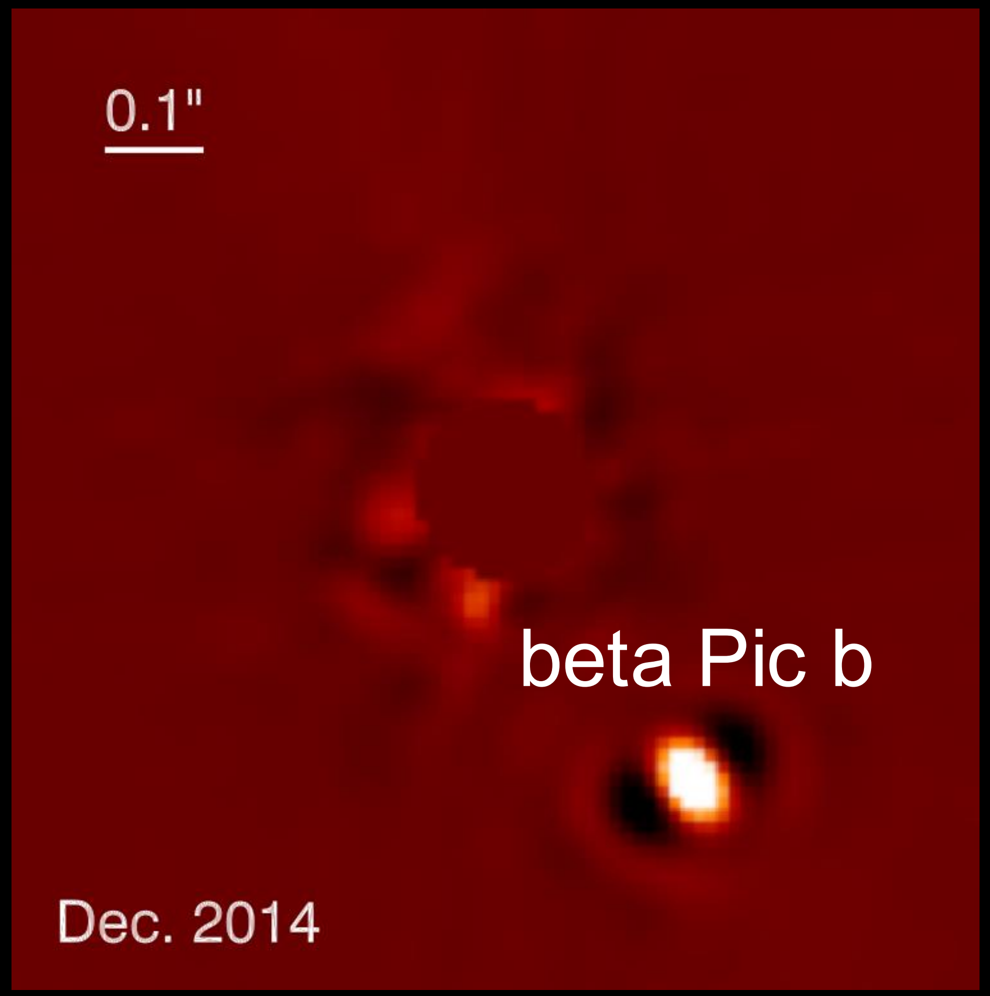
Mesa et al. 2023



Thompson et al. 2023

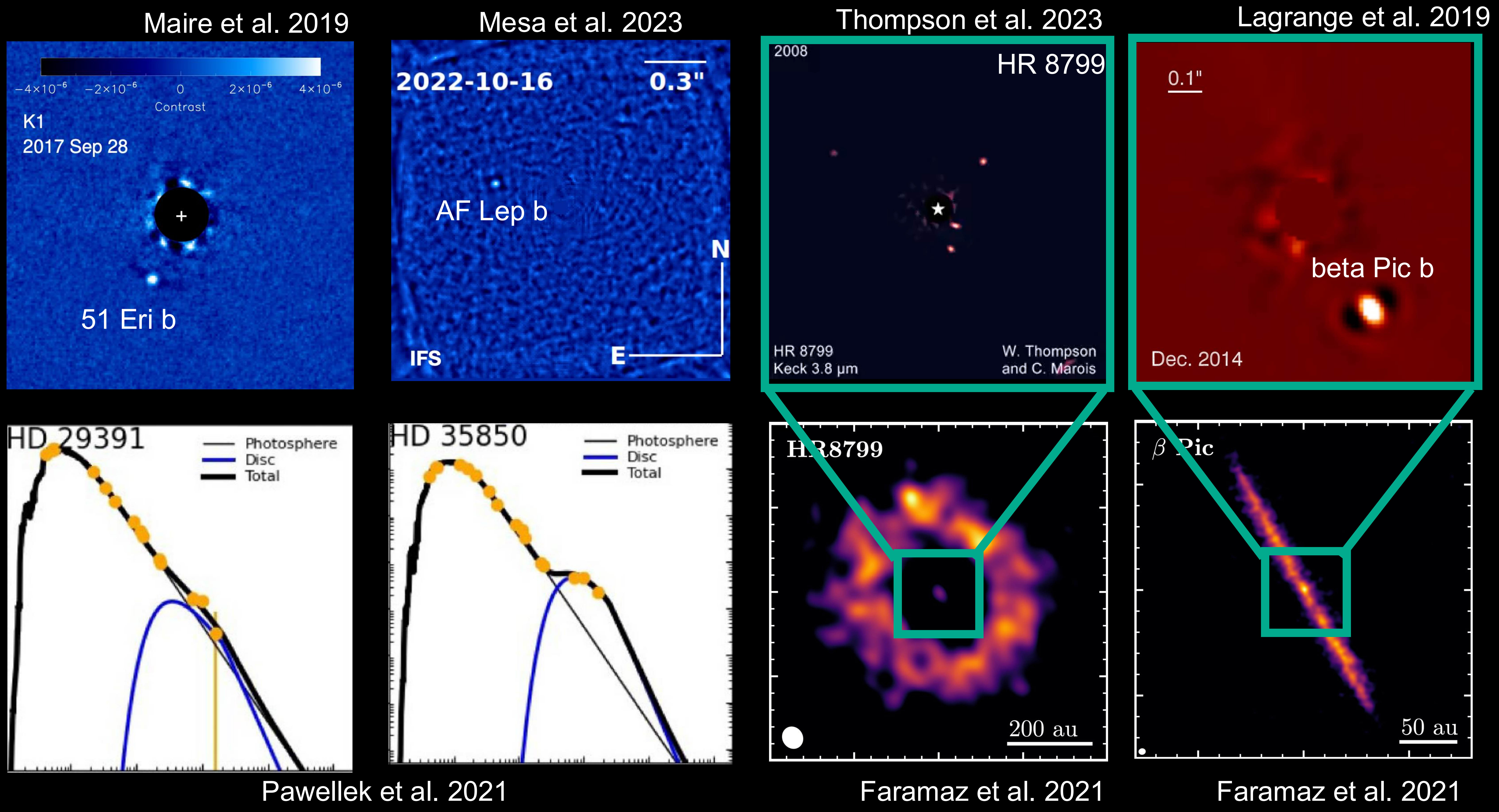


Lagrange et al. 2019



Most direct imaged planets co-exist w/ disk

if not all…



Most direct imaged planets co-exist w/ disk

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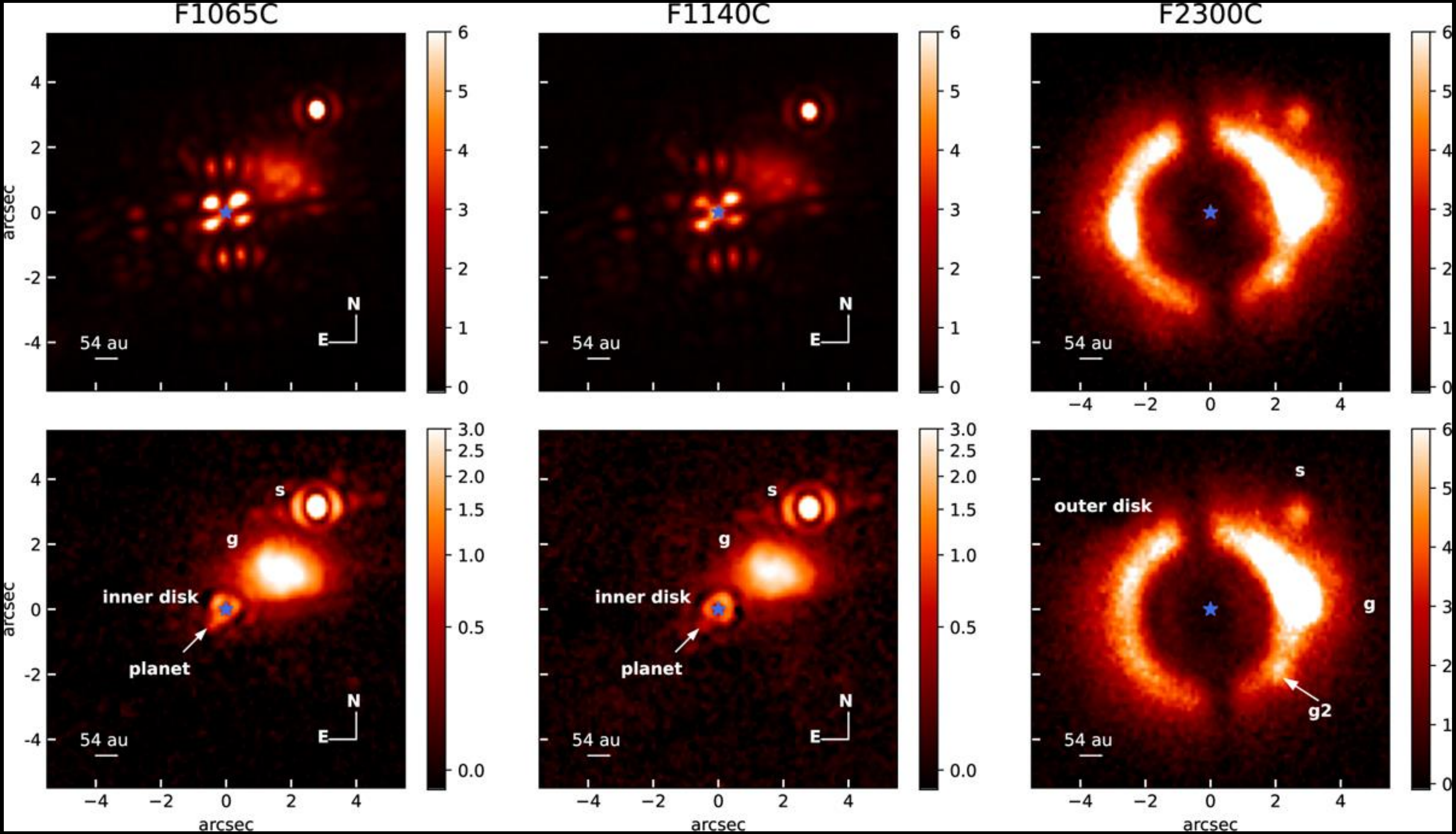
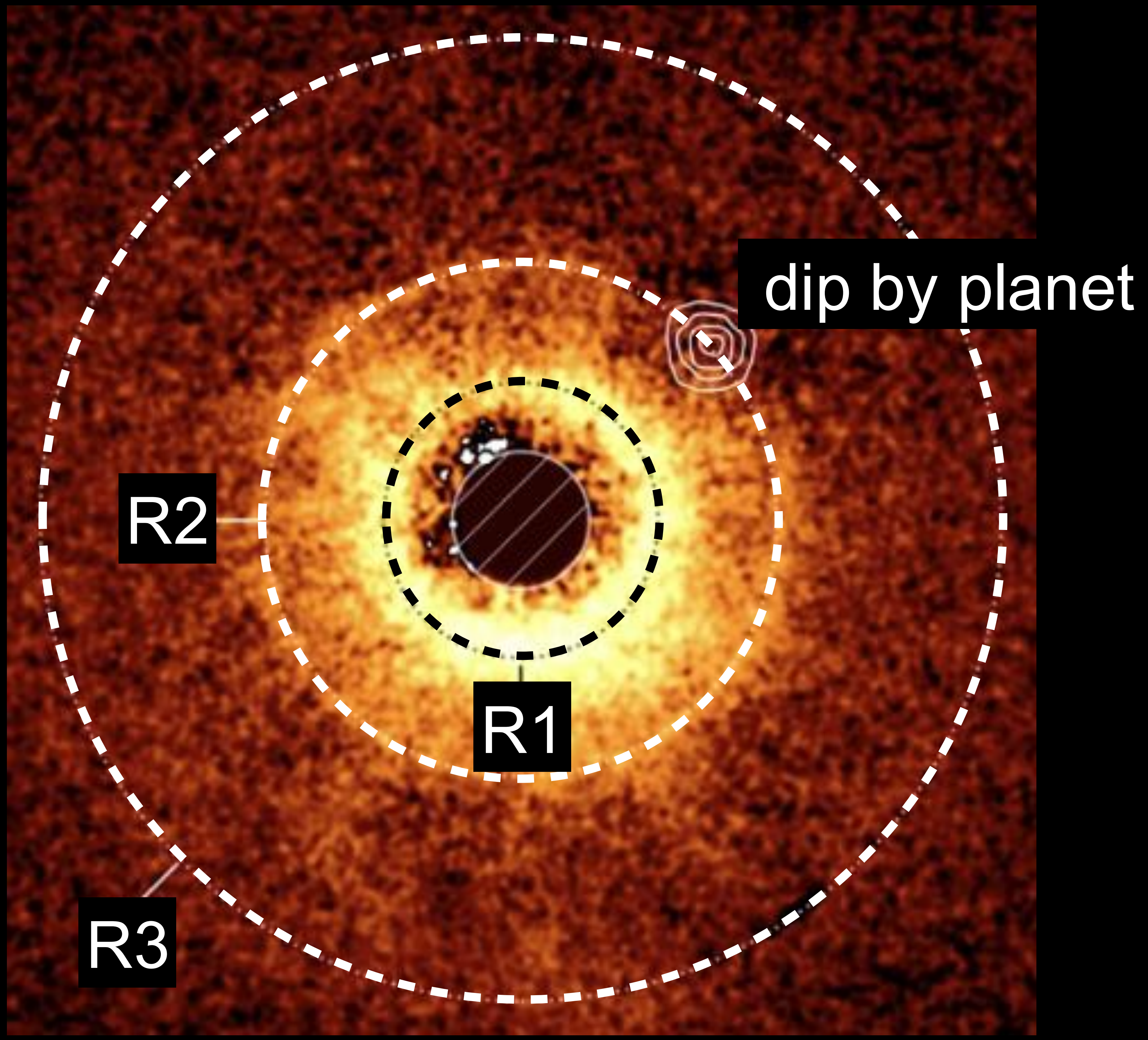


Mâlin et al. 2025

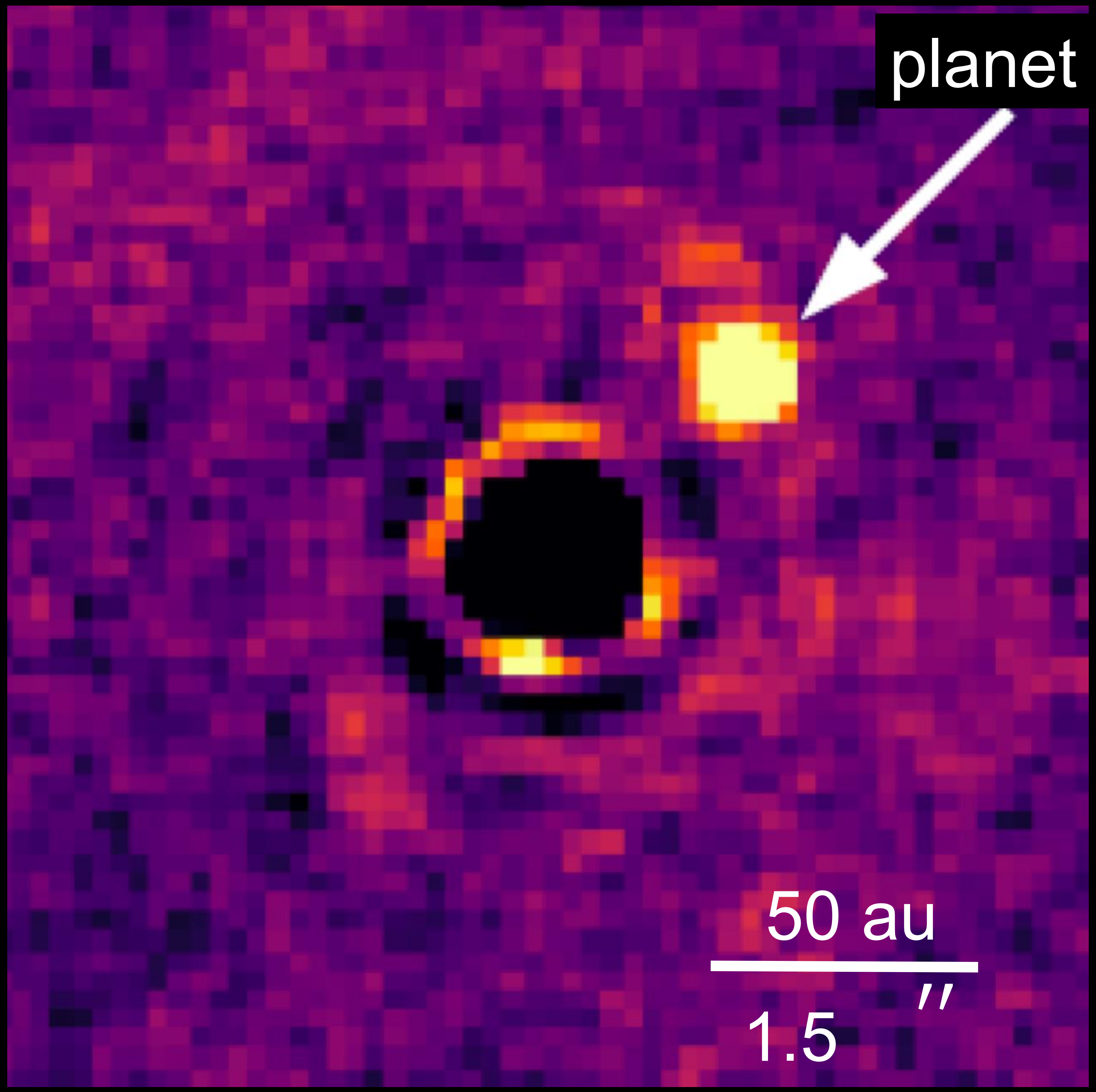
A barely grown baby giant planet?

VLT/SPHERE



Ren et al. 2021

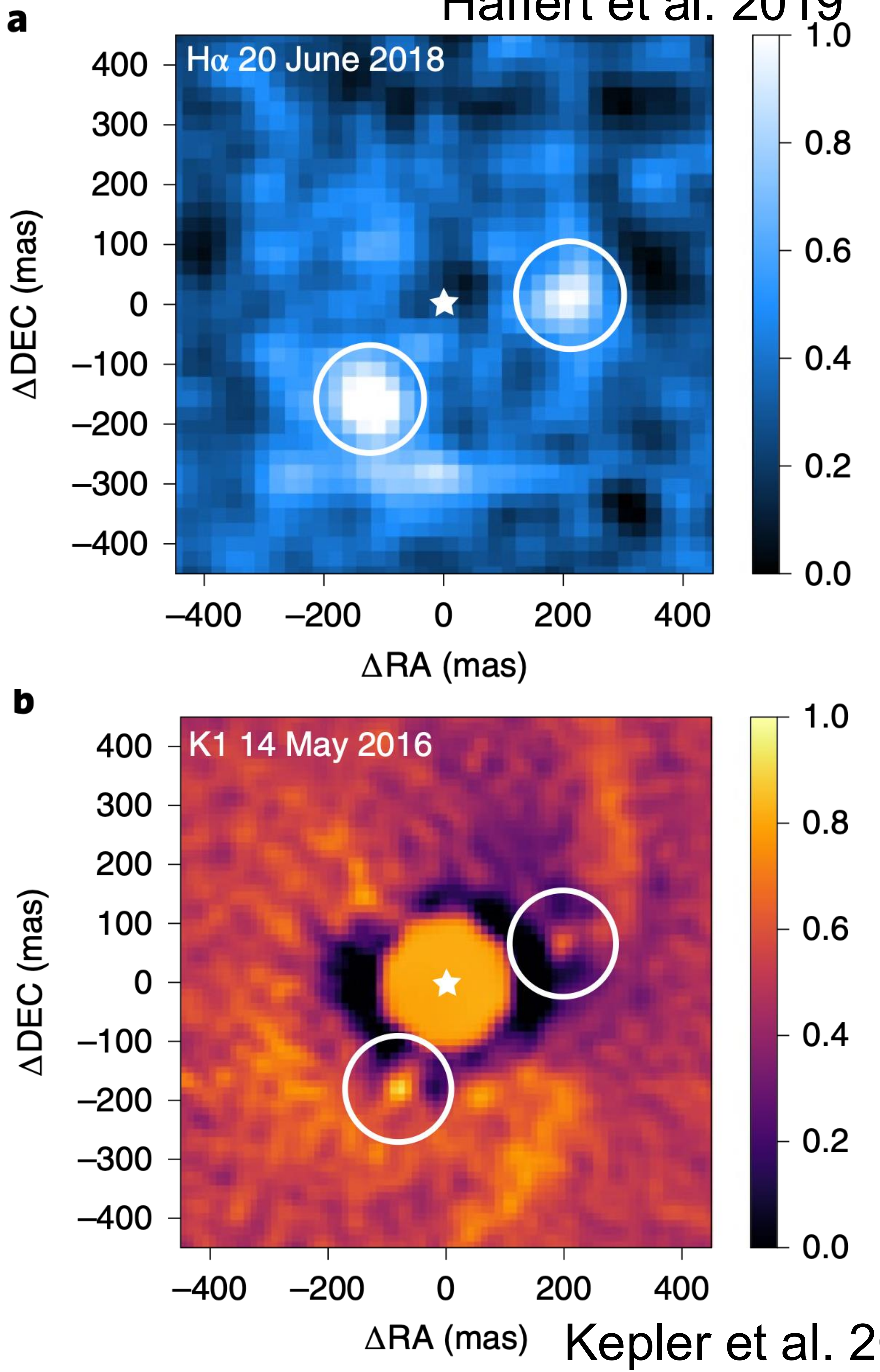
JWST/MIRI



Lagrange et al. 2025

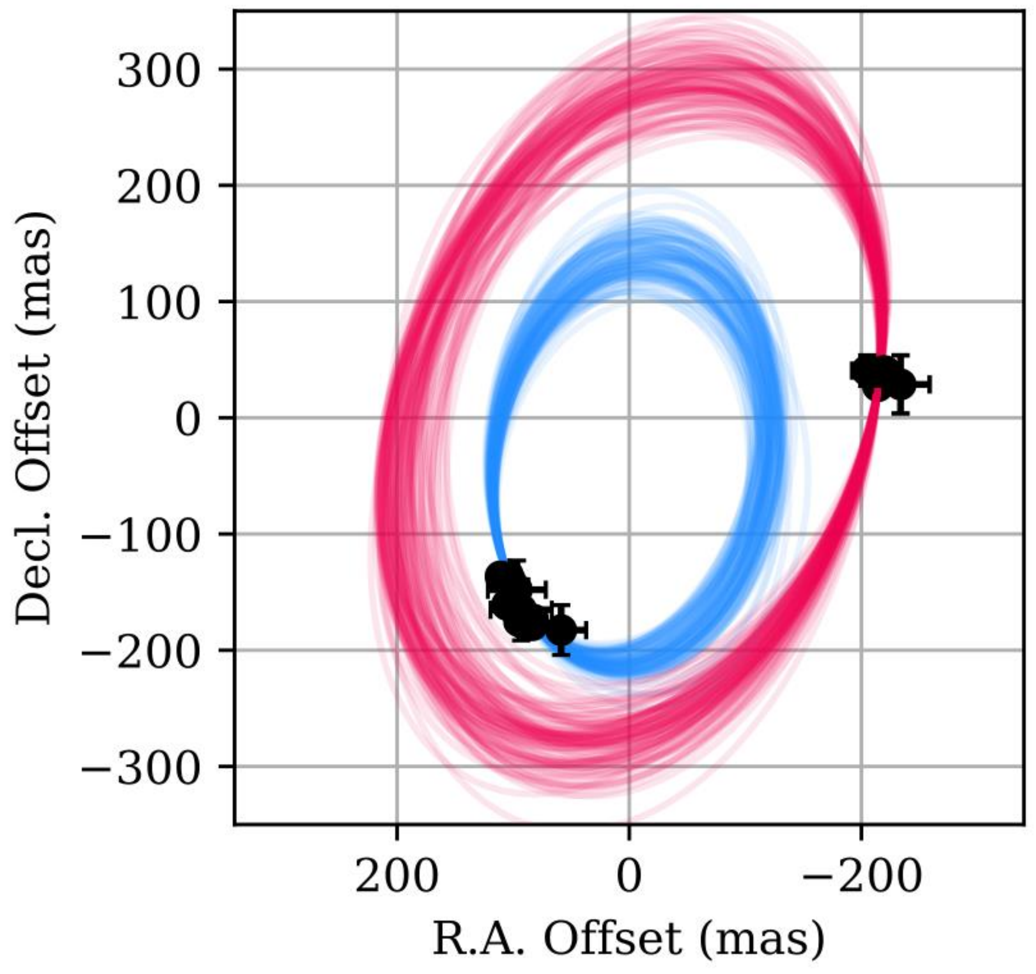
Two giant planets inside the cavity rim - PDS 70

Haffert et al. 2019



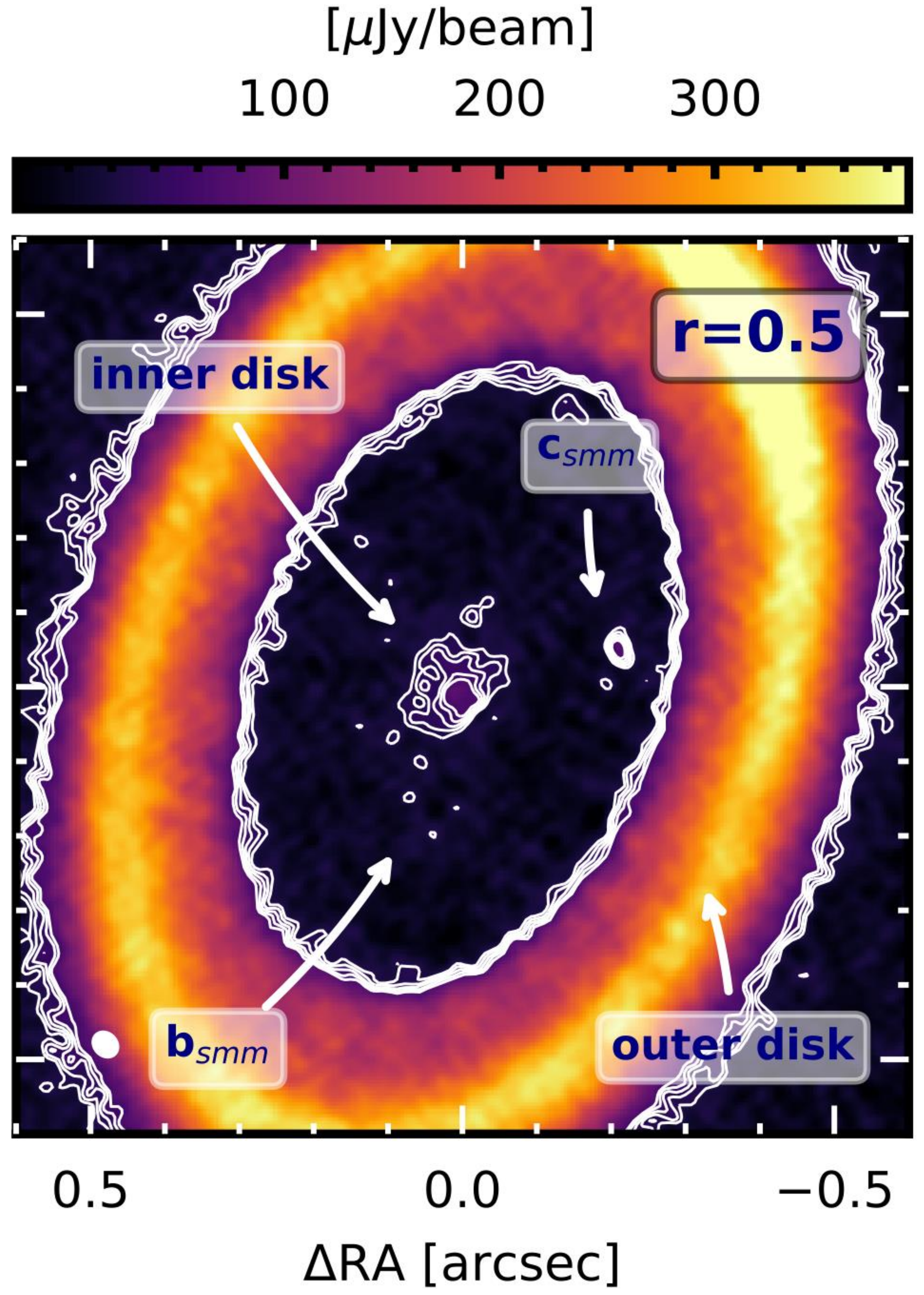
Kepler et al. 2018

2:1 resonance ?



Wang et al. 2021

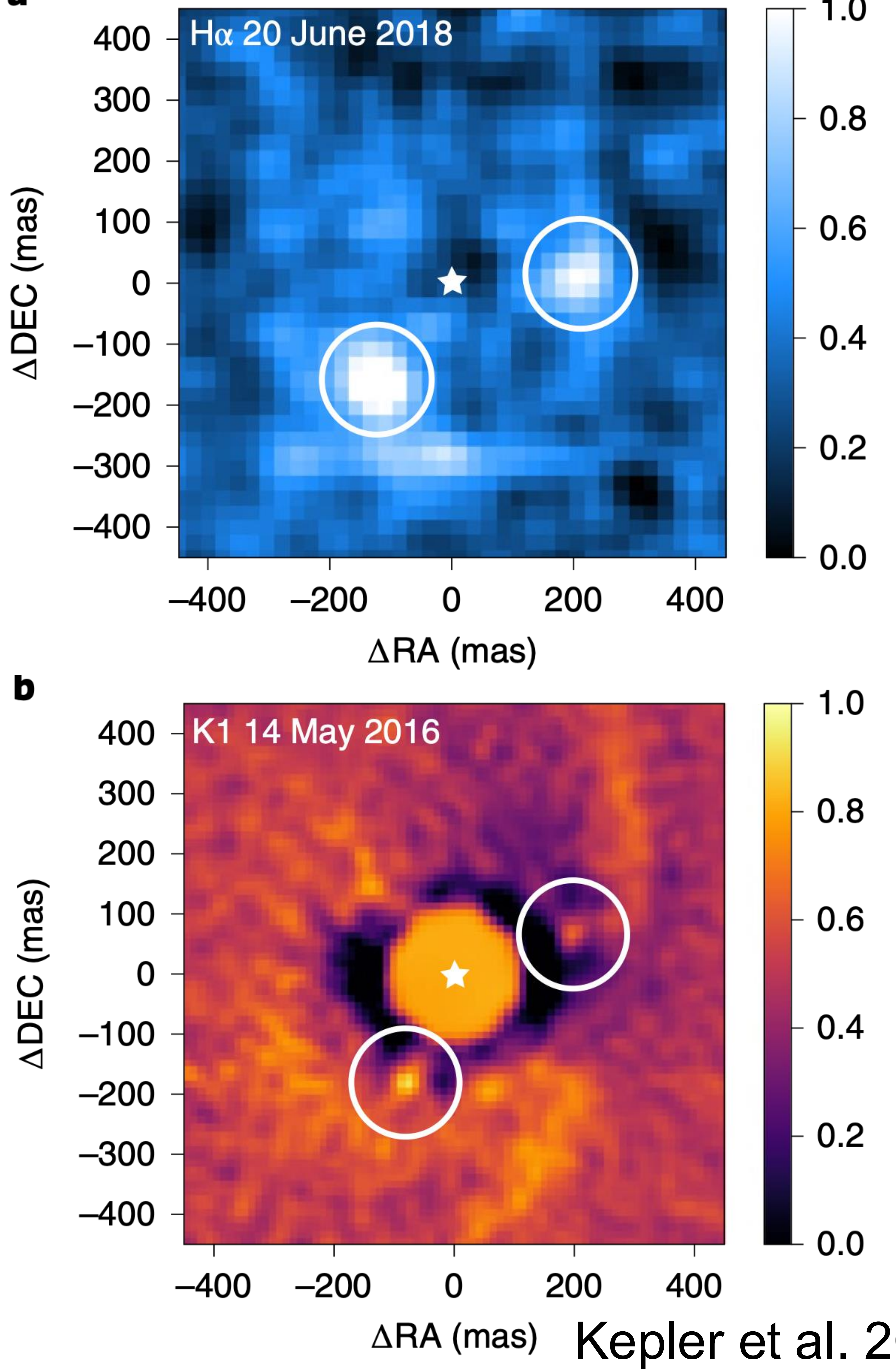
+



Benisty et al. 2021

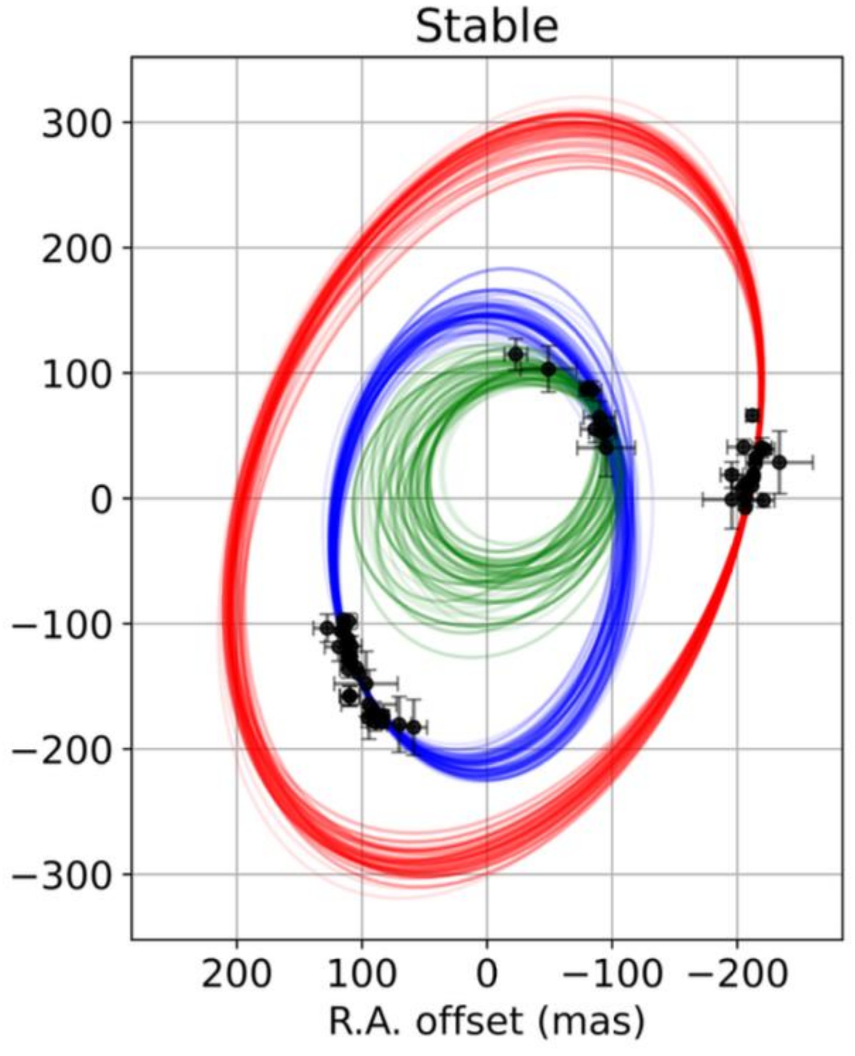
Three? giant planets inside the cavity rim - PDS 70

Haffert et al. 2019



Kepler et al. 2018

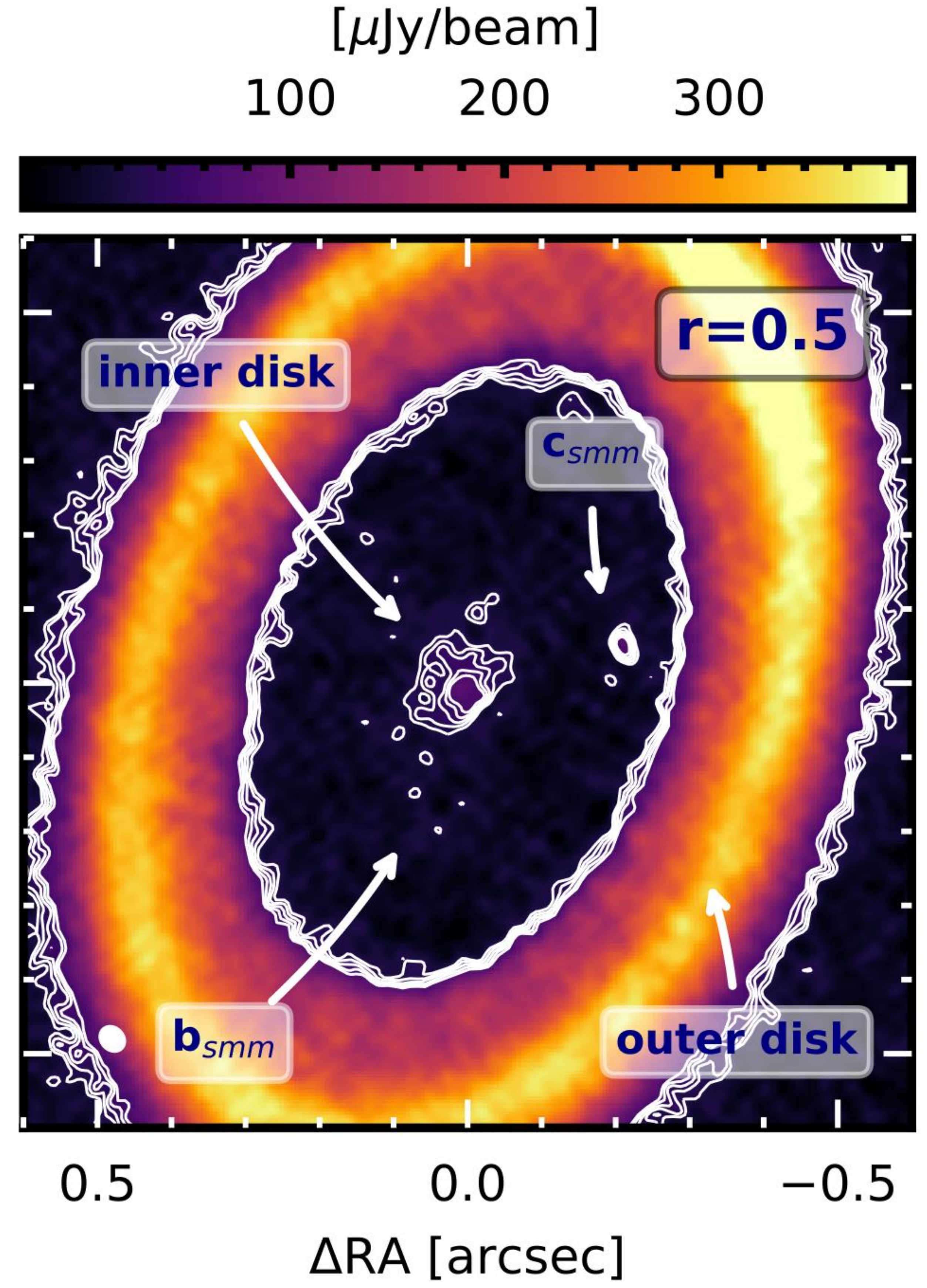
4:2:1 resonance ?



Trevascus et al. 2025

see also Hammond et al. 2025

+



Benisty et al. 2021

Giant planets around M stars?

Well, look at the disks around them…

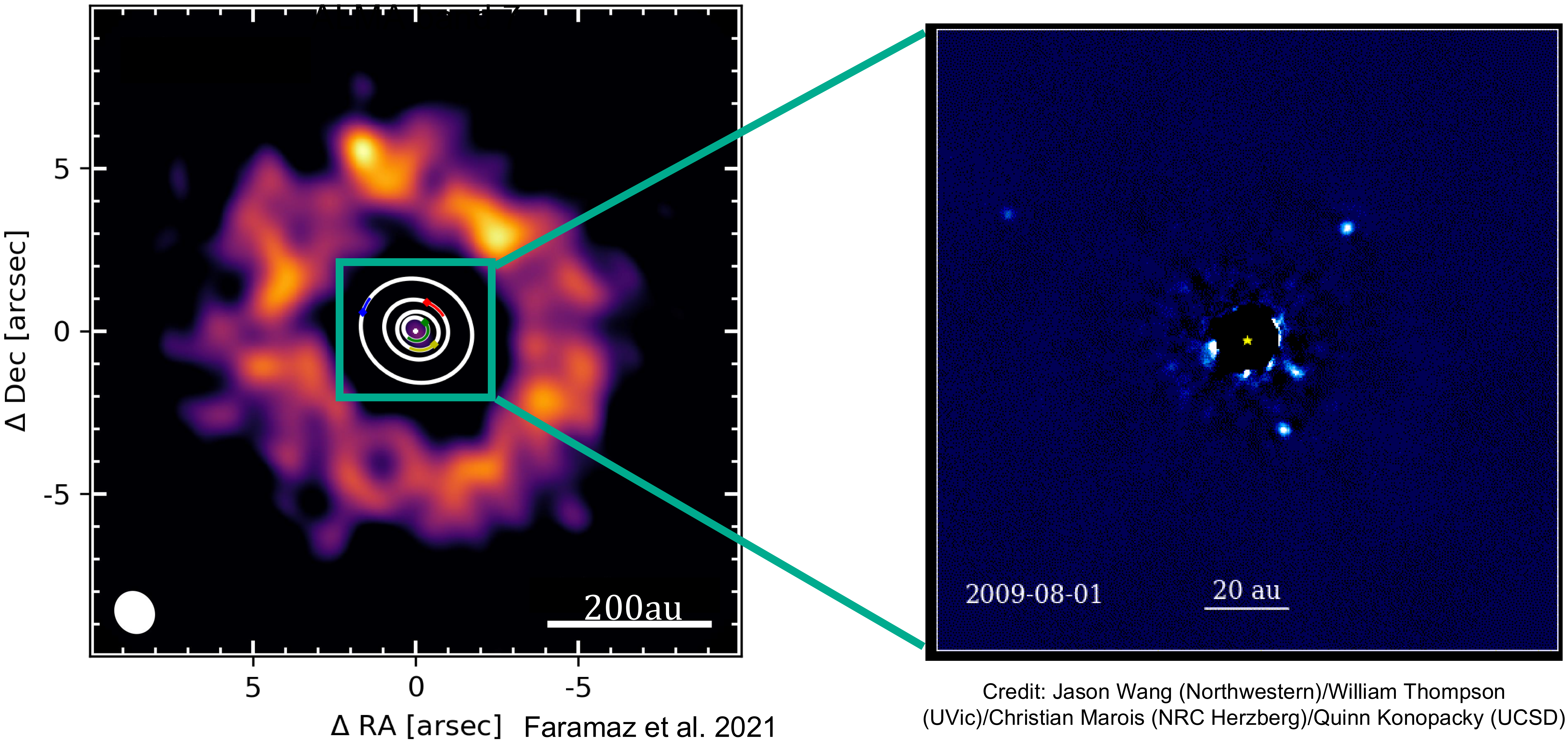
All known disks around VLMSs (<0.2 M_sol) resolved by ALMA and has a disk radii > 0.2” (~30 au)

Collection from Pinilla 2022, Kurtovic et al. 2022, Shi et al. 2024 and private communication with the DMOST team

Take home messages

- Pebble rings can stay stable without pressure bumps, creating wide belts of planetesimals. Jiang & Ormel 2021
- These rings can form planets even far from the star (>50 au). Jiang & Ormel 2023
- This idea can explain systems like HR 8799, where giant planets sit inside a cold outer belt. Jiang & Ormel in prep.

Take home messages



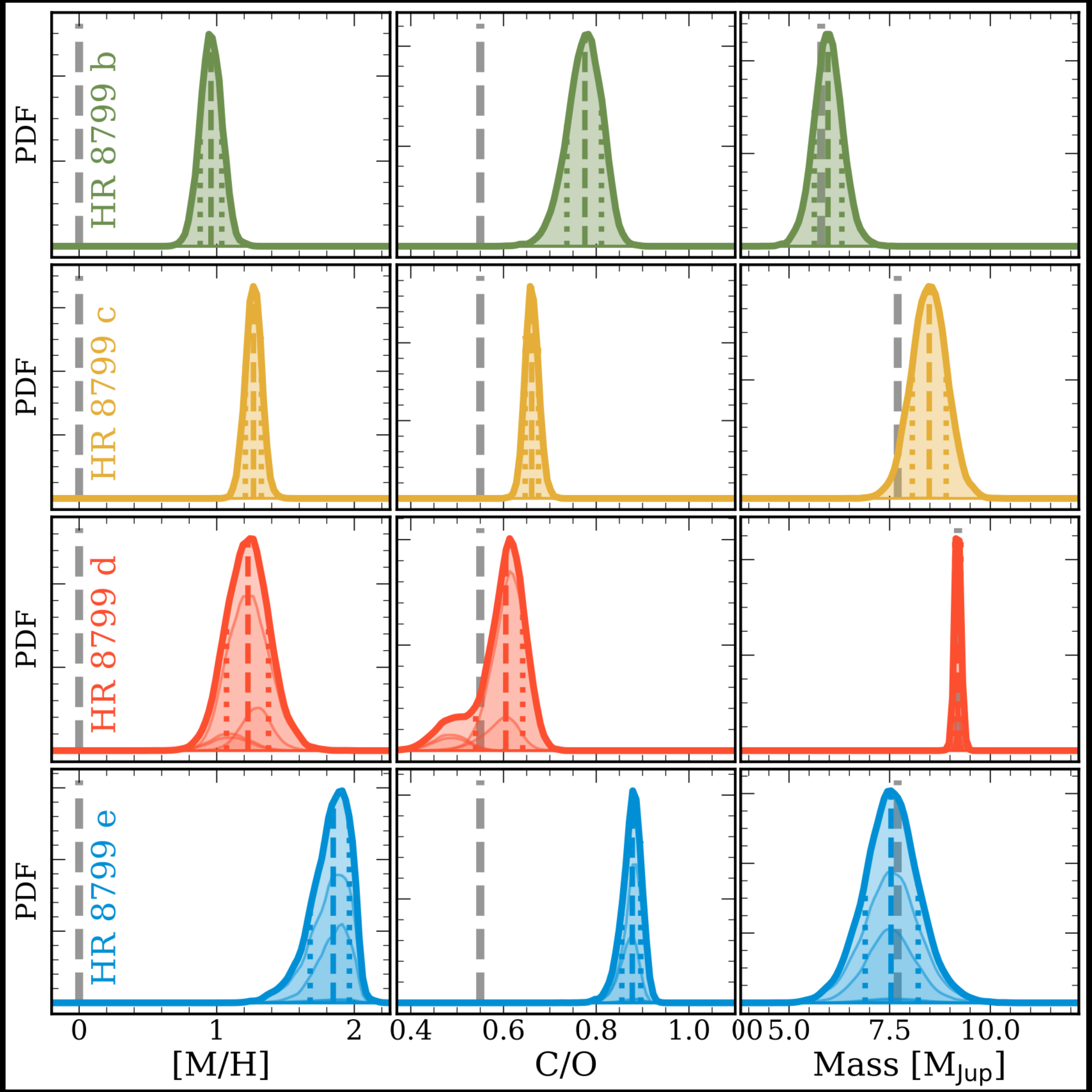
Faramaz et al. 2021

Credit: Jason Wang (Northwestern)/William Thompson (UVic)/Christian Marois (NRC Herzberg)/Quinn Konopacky (UCSD)

Disk substructure statistics

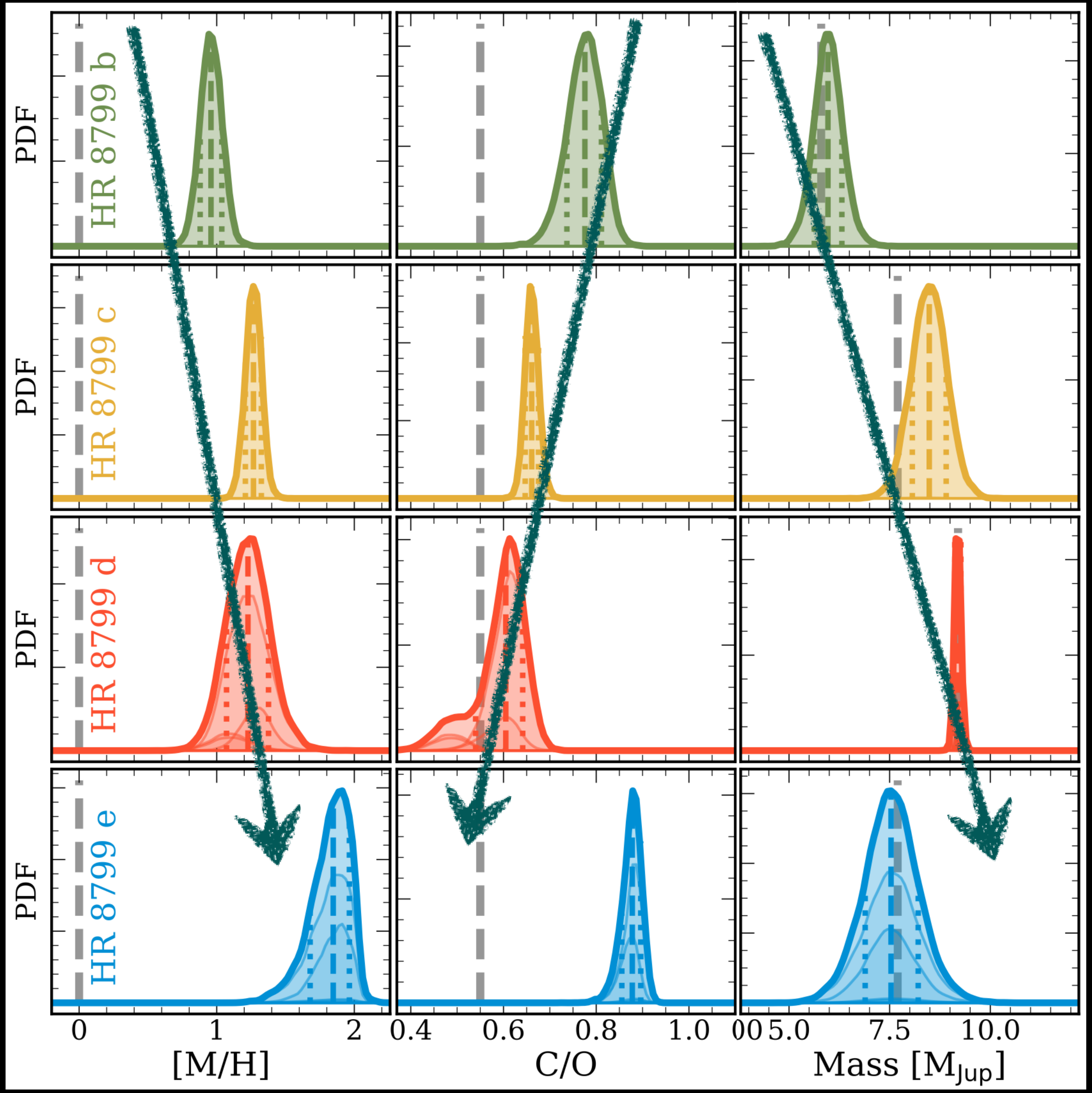
van der Marel & Mulders 2021

Composition of HR 8799 planets

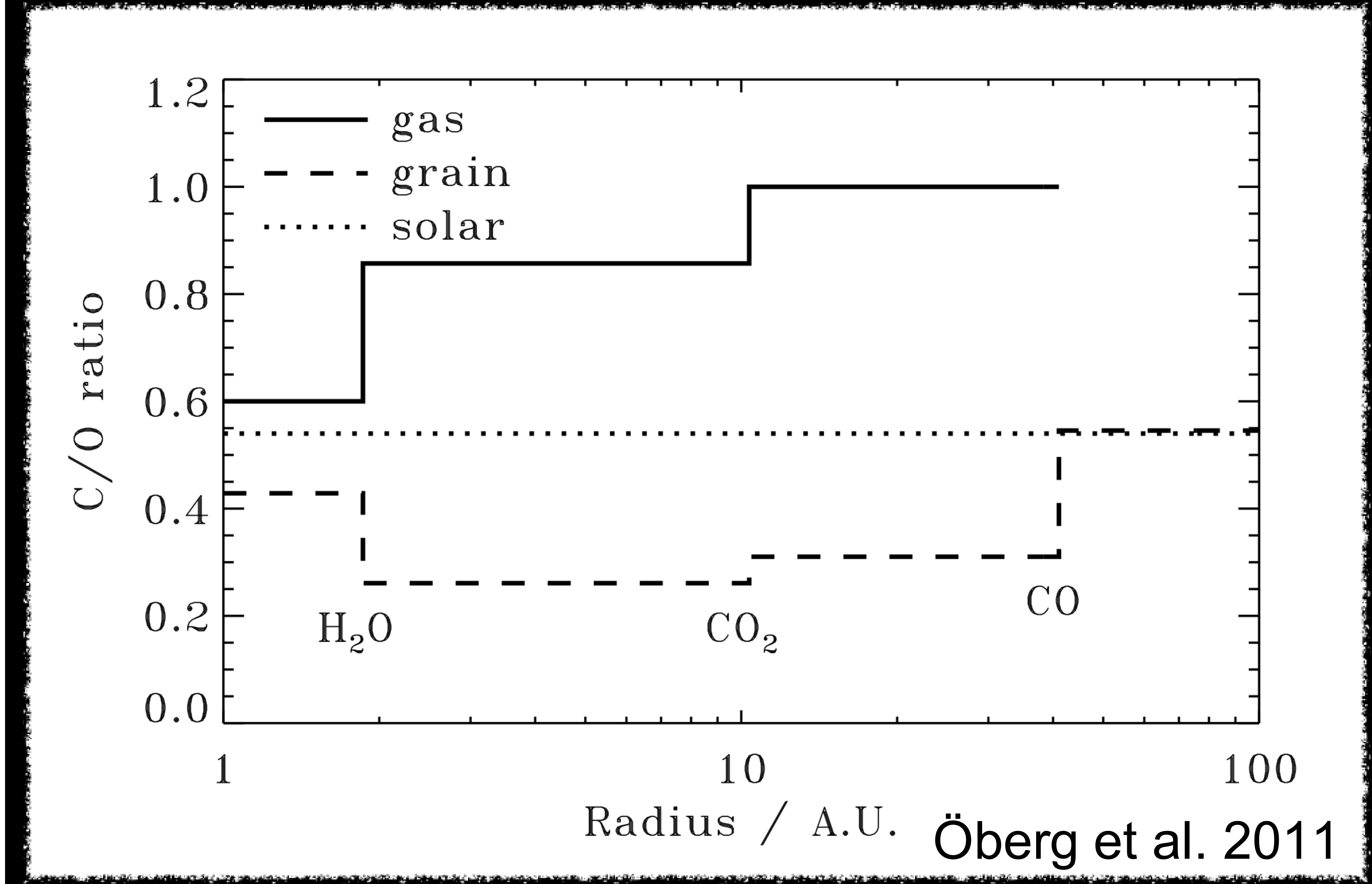


Nasedkin et al. 2024

Composition of HR 8799 planets

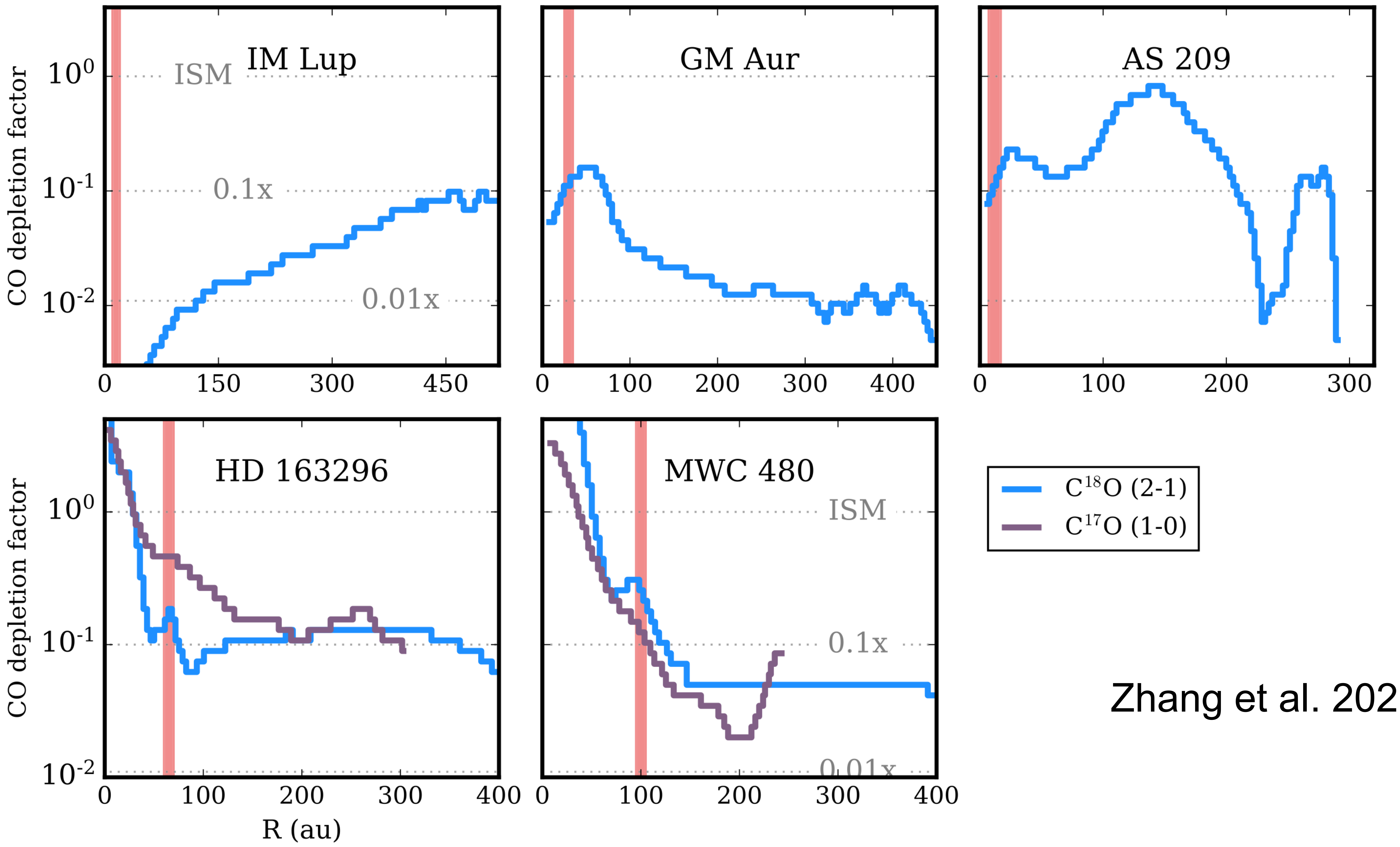


Nasedkin et al. 2024



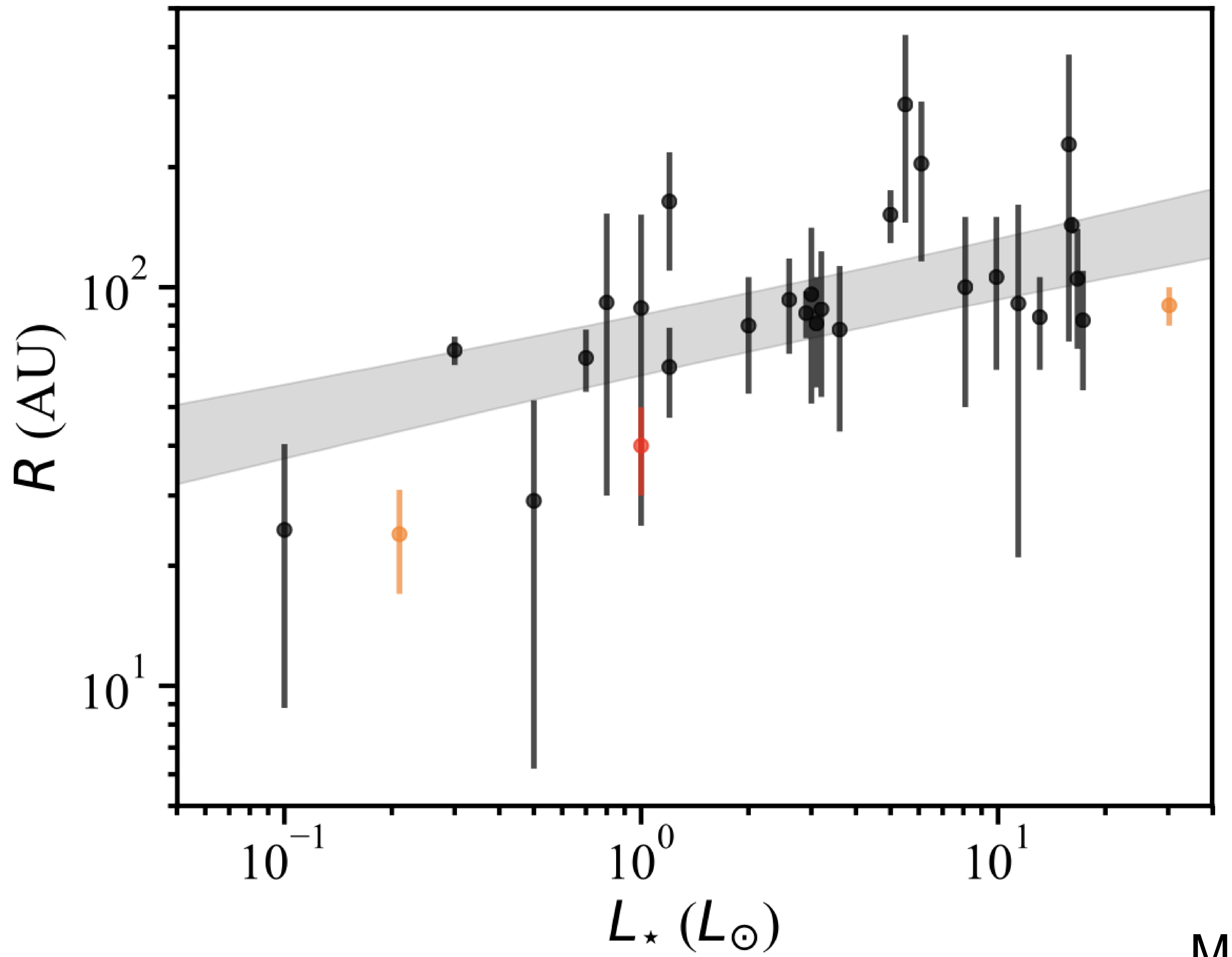
Öberg et al. 2011

CO snowlines as 1st-gen ring?



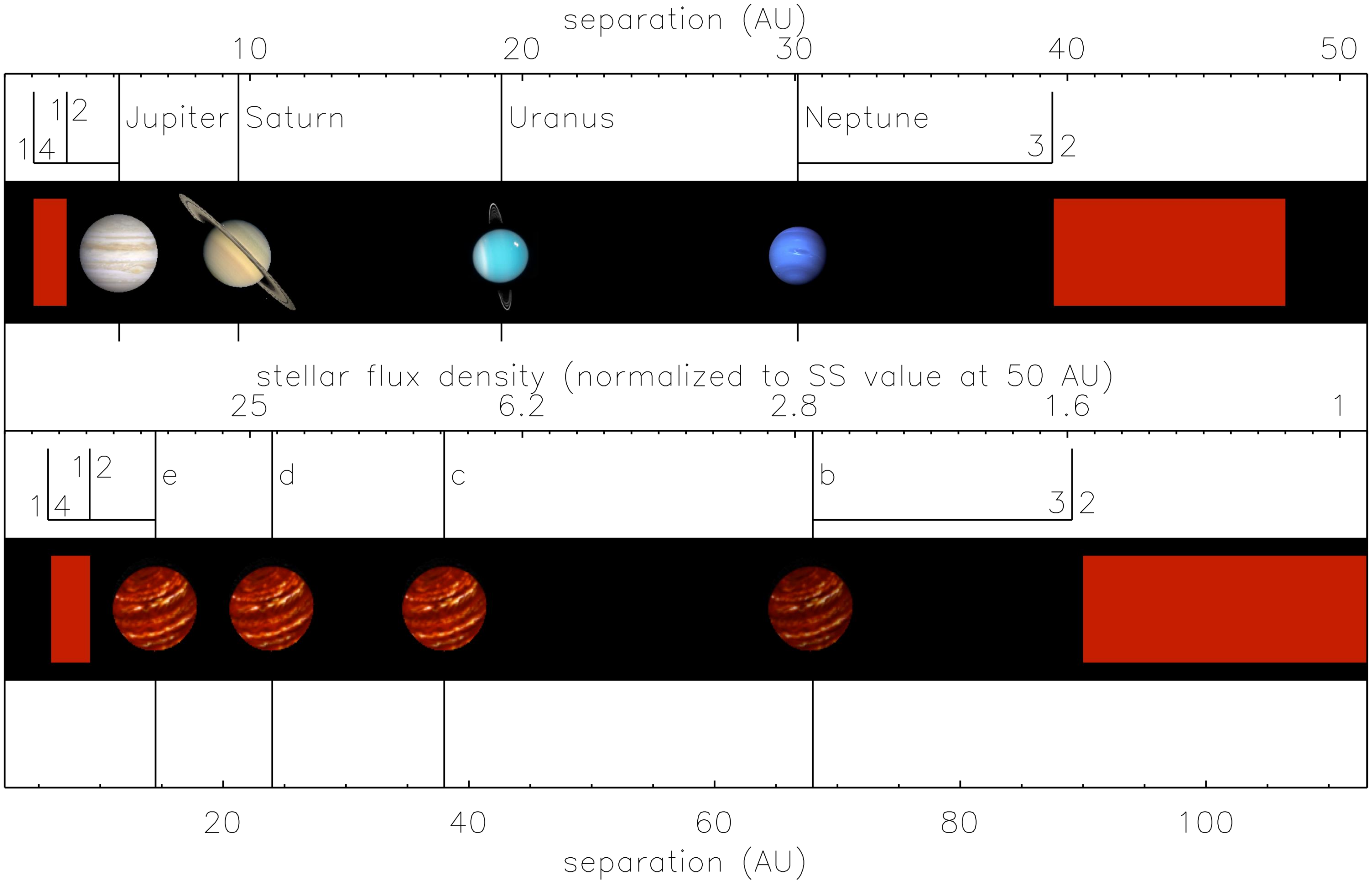
Zhang et al. 2021

CO snowlines as 1st-gen ring?

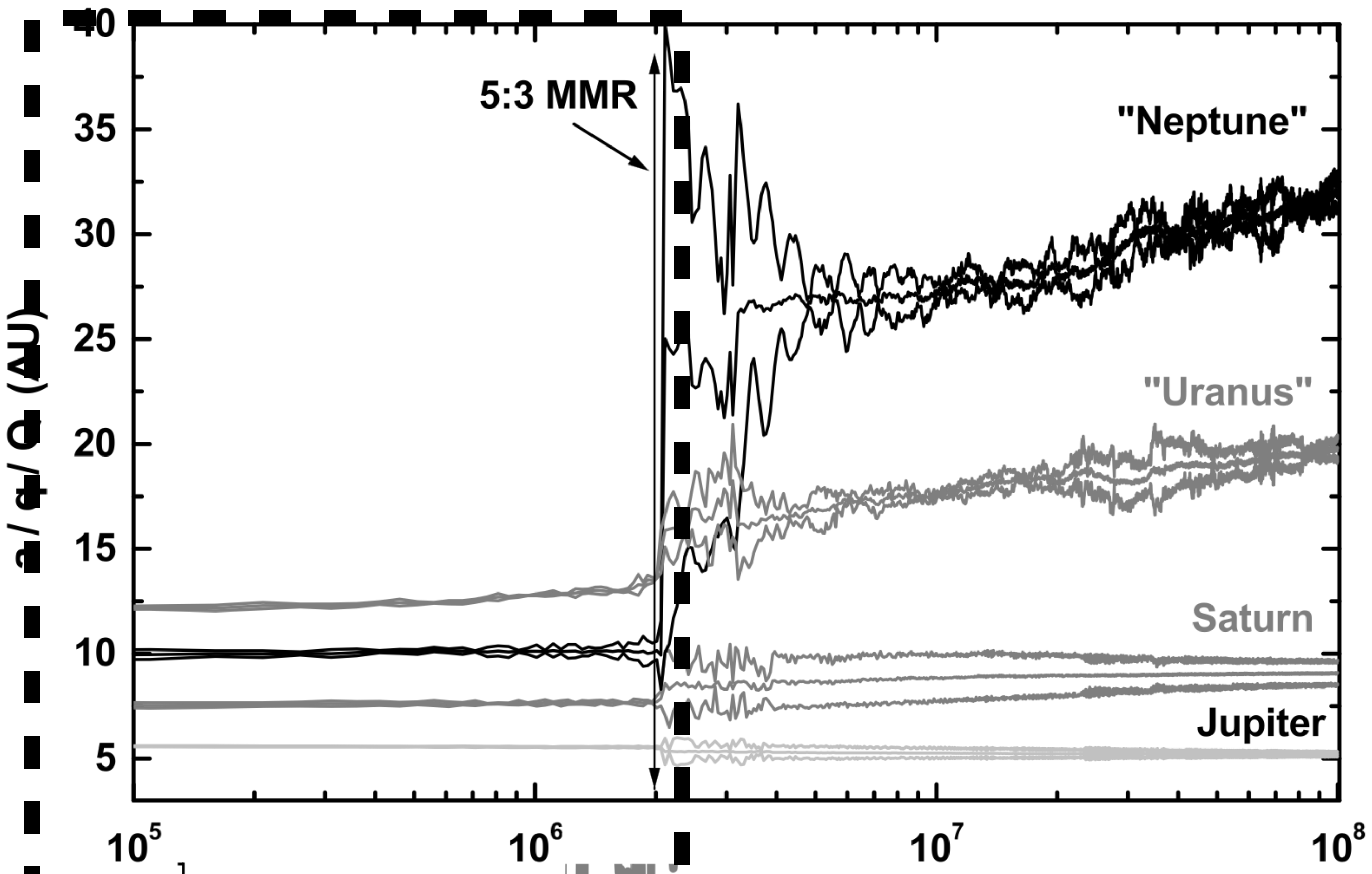


Matra et al. 2018

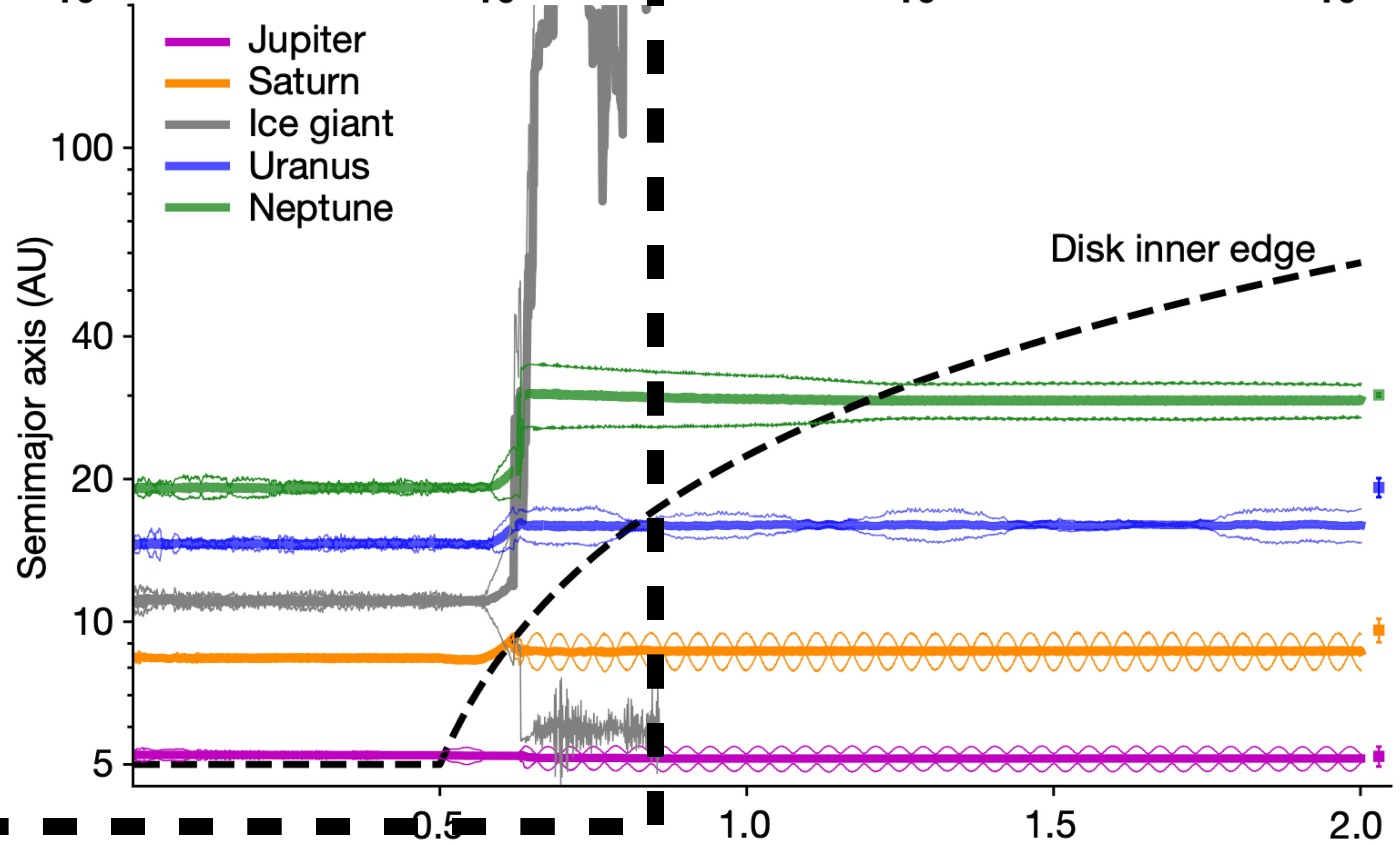
Solar System?



Solar System?



Morbidelli et al. 2007



Liu et al. 2022

Kuiper Belt - inner Oort cloud