清華大學天文系
Department of Astronomy, Tsinghua University

Universiteit Leiden

The dynamics of planets across their formation and evolution

—— ET Science seminar

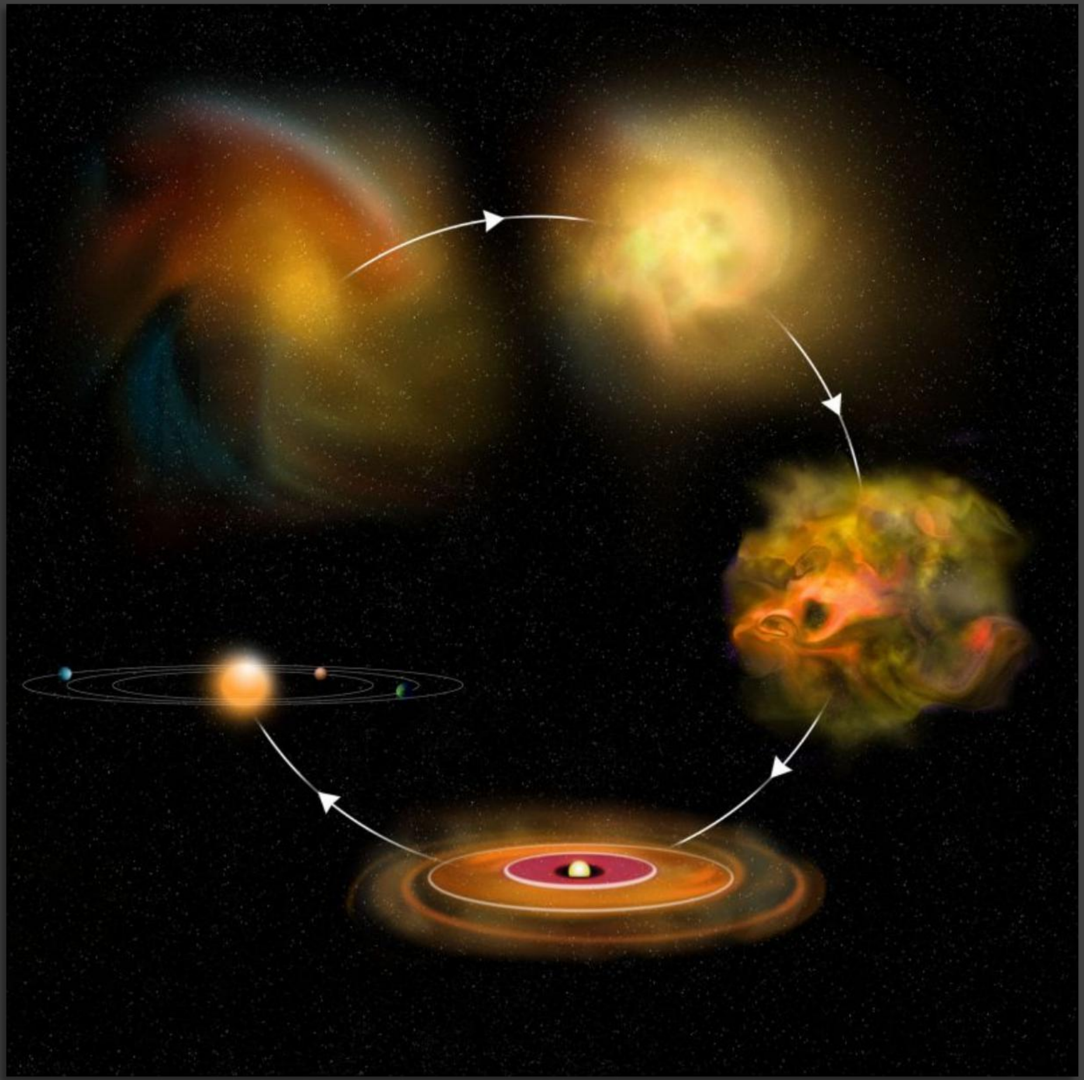
https://shuohuanggit.github.io

Presenter: Shuo Huang

In cooperation with: Chris Ormel, Simon Portegies Zwart, Nienke van der Marel, Maite Wilhelm

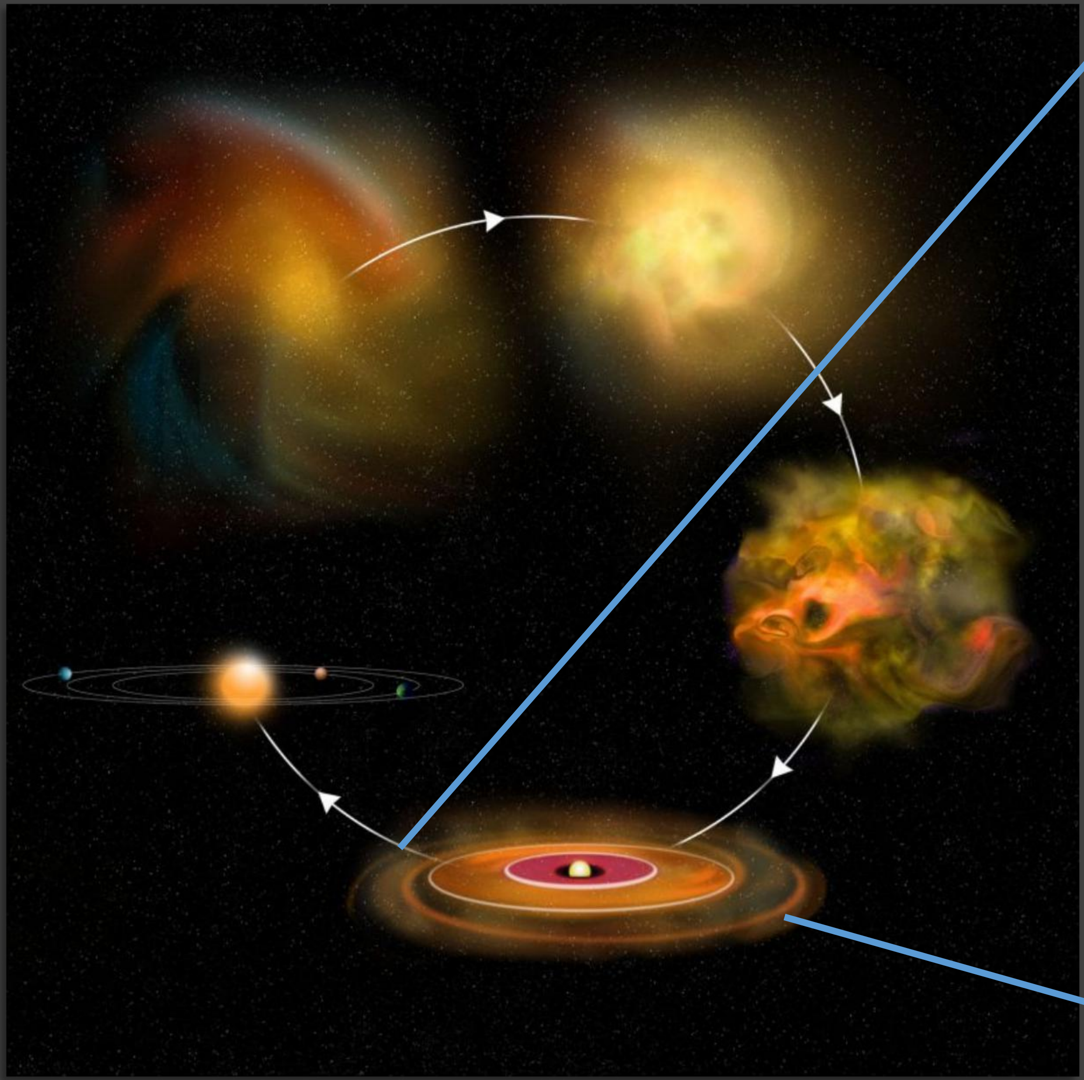
Time: 2024.10

The naturalistic story about planet formation

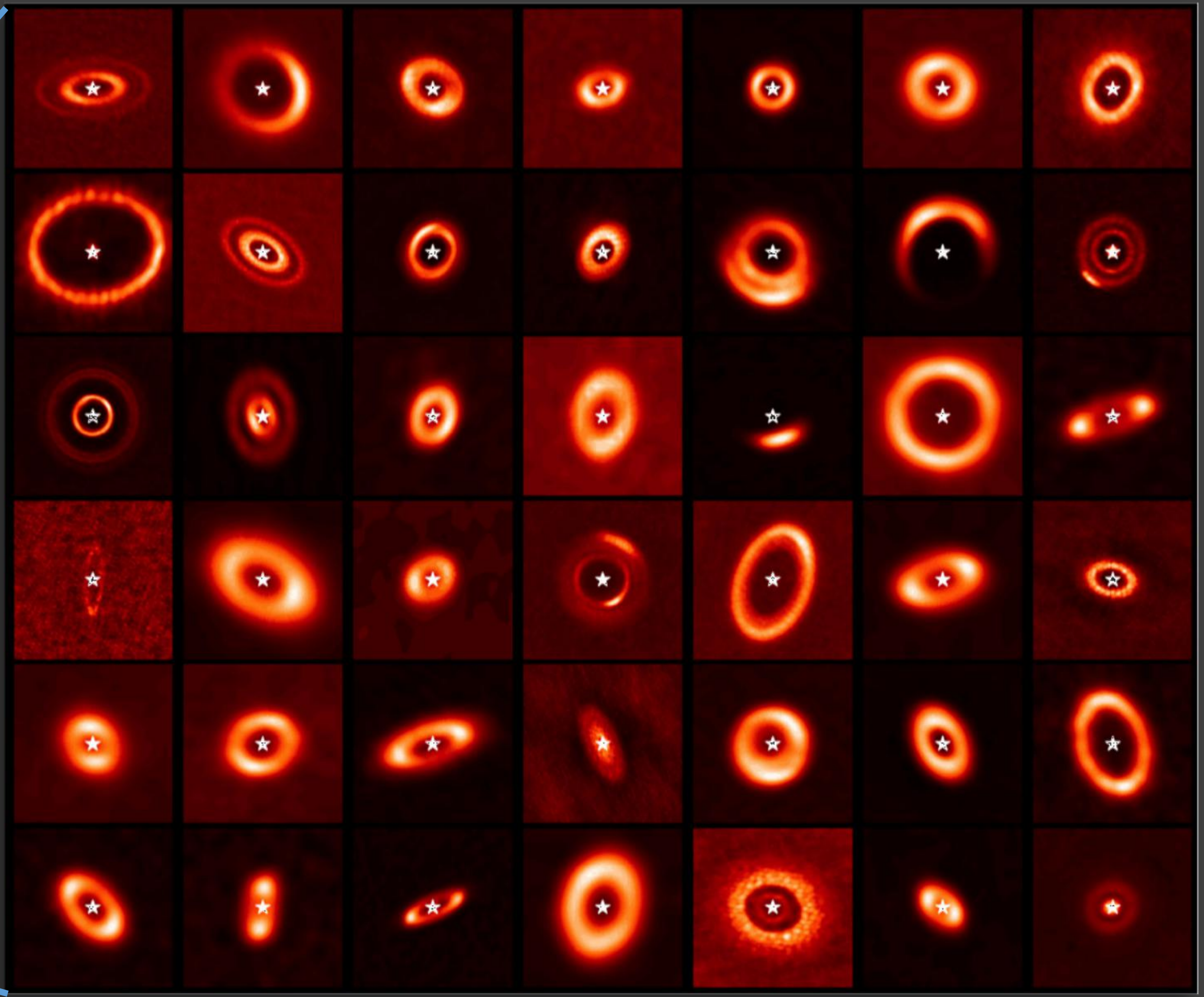


(c) Bill Saxton, NRAO/AUI/NSF

Planet dynamics start to matter in protoplanet disks

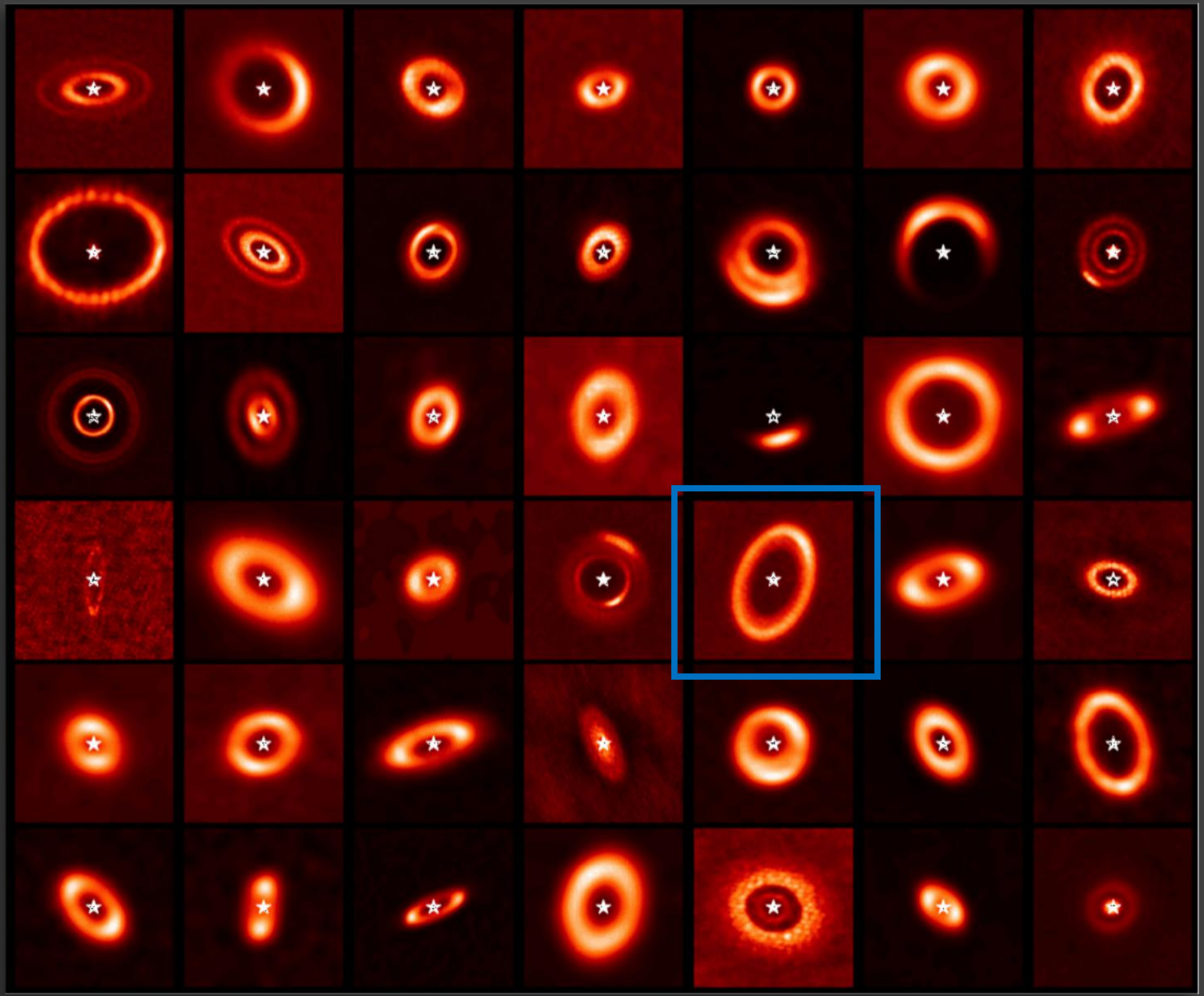


(c) Bill Saxton, NRAO/AUI/NSF



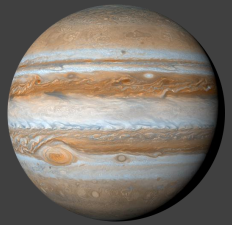
Transition disks are those with central cavities.
There maybe planets.

Where are other planets?

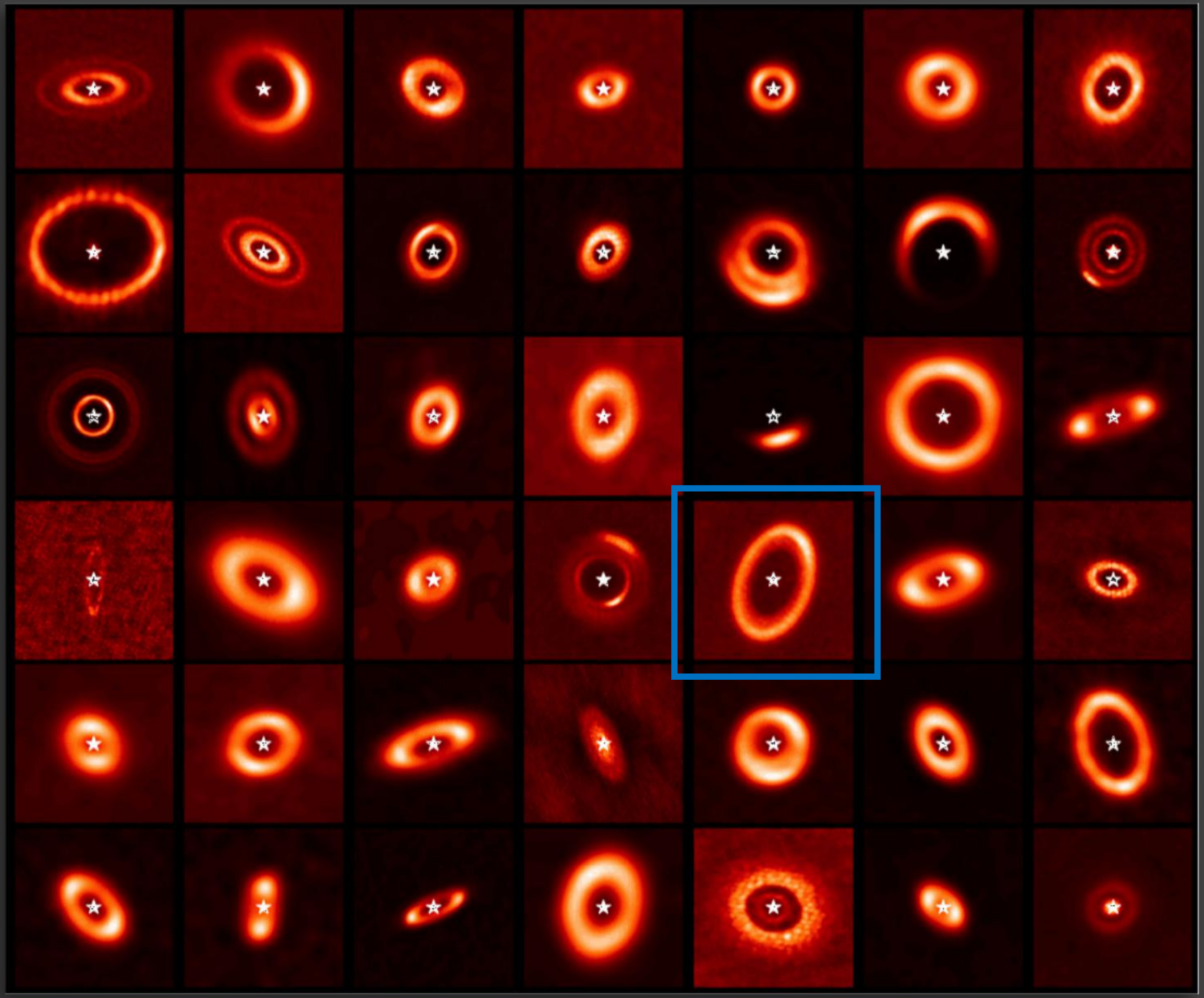


PDS 70:

5×



Where are other planets?



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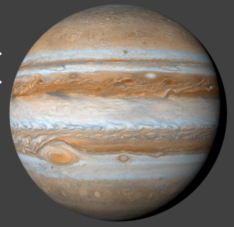
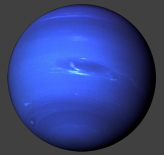


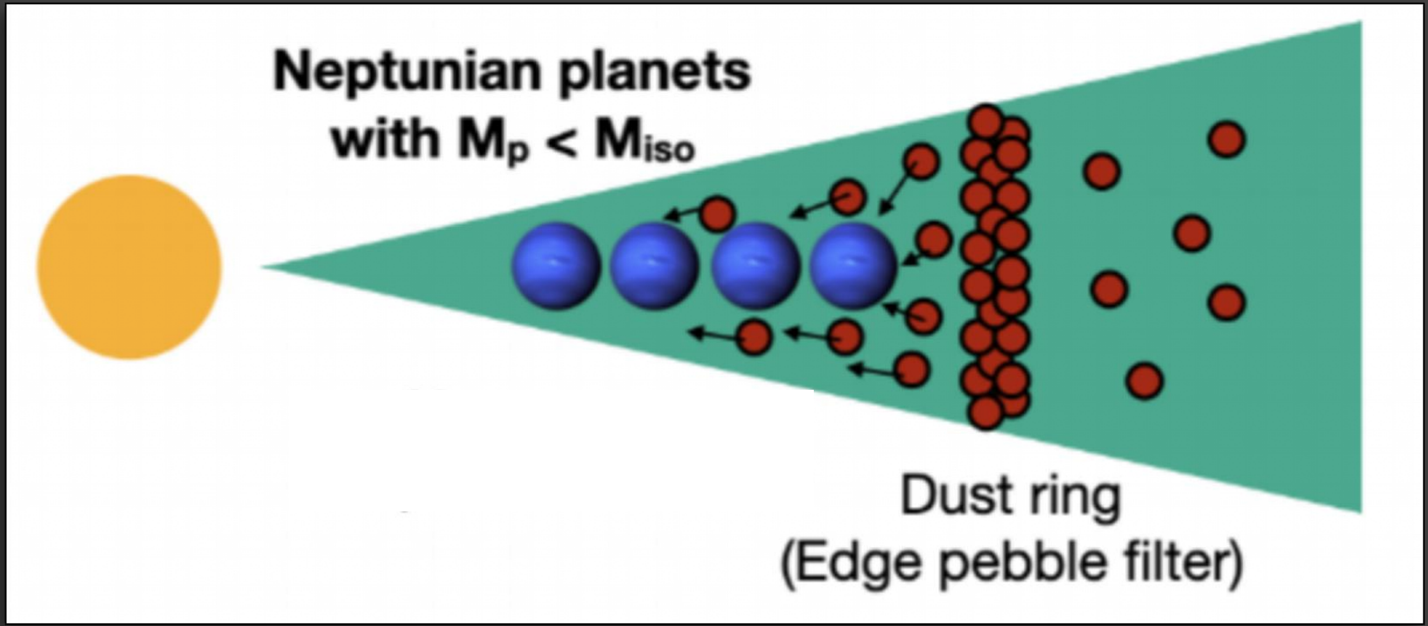
Others: 1×



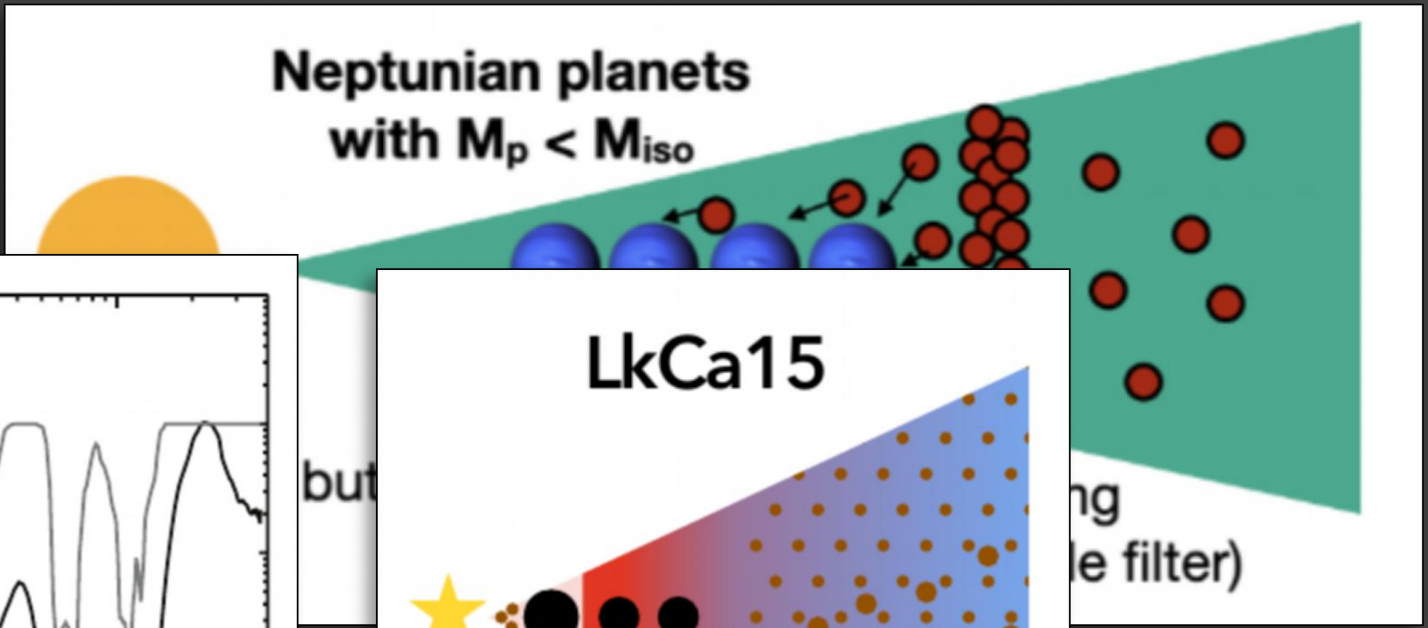
?

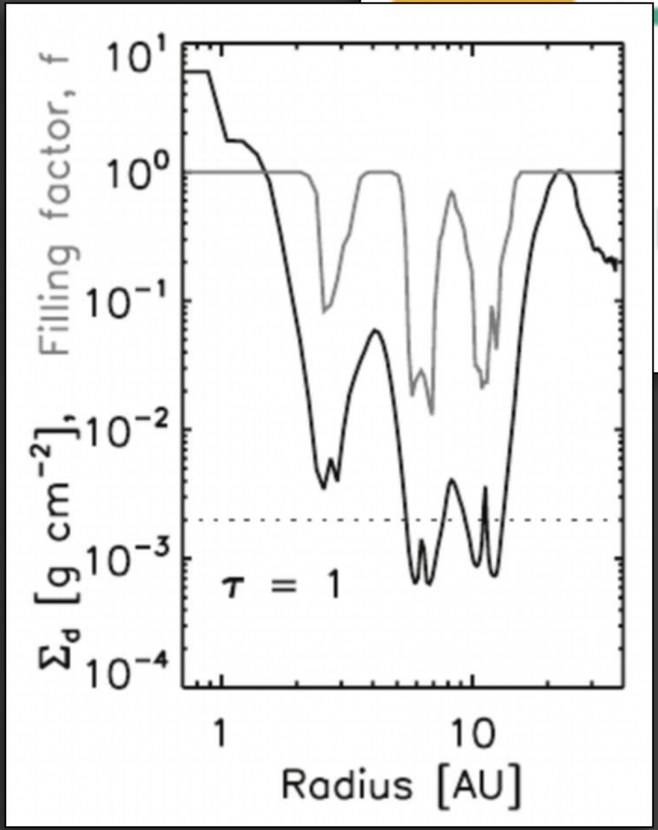
We propose that the dust cavity in some other disks can be explained by a sequence of low-mass planets

A sequence of low mass planets

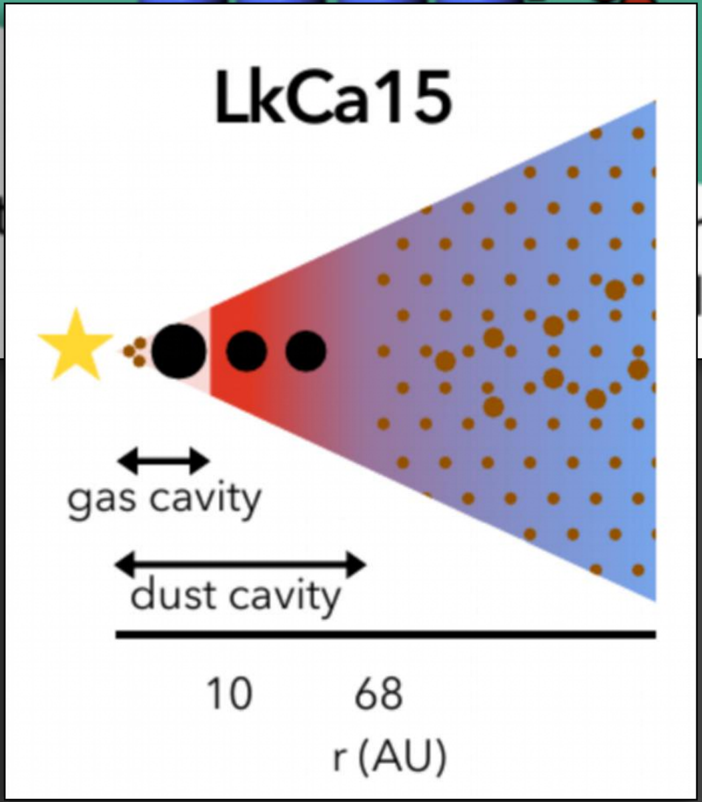


The idea is not new ...





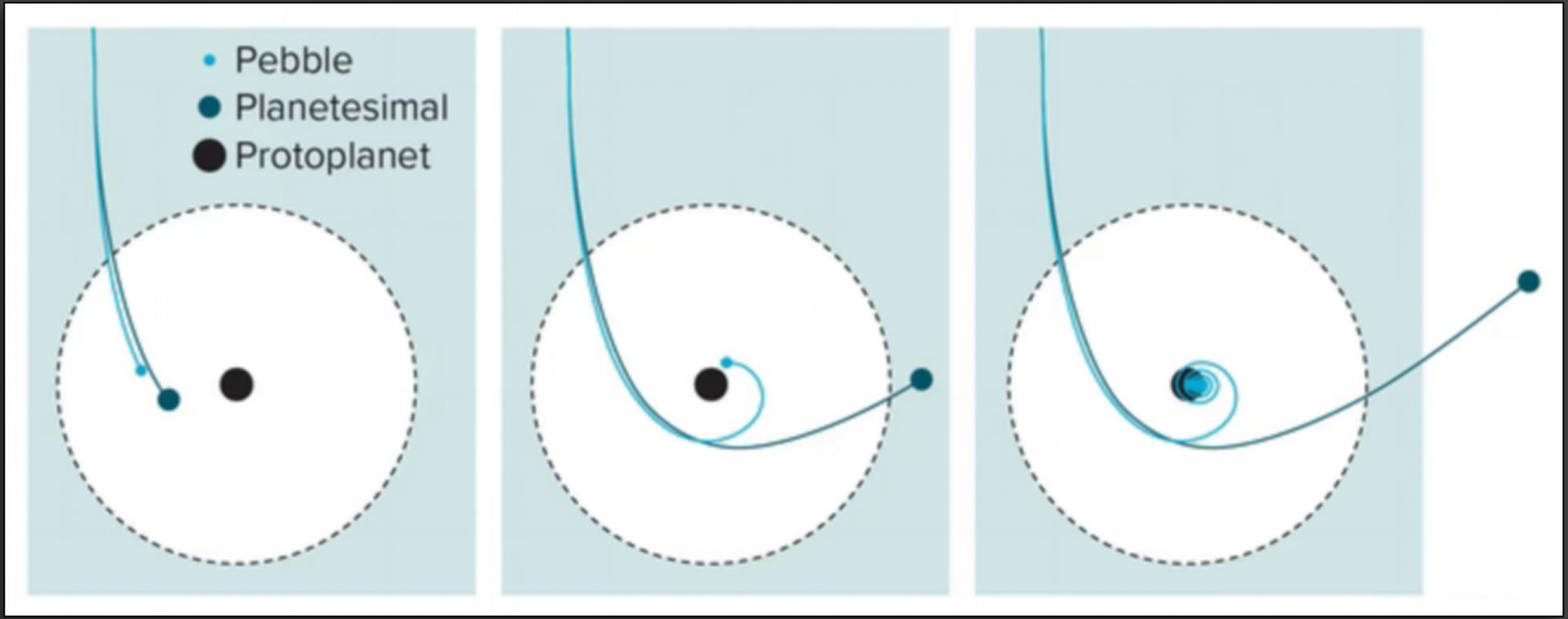
Dodson-Robinson & Salyk (**2011**)



Leemker et al. (2022)

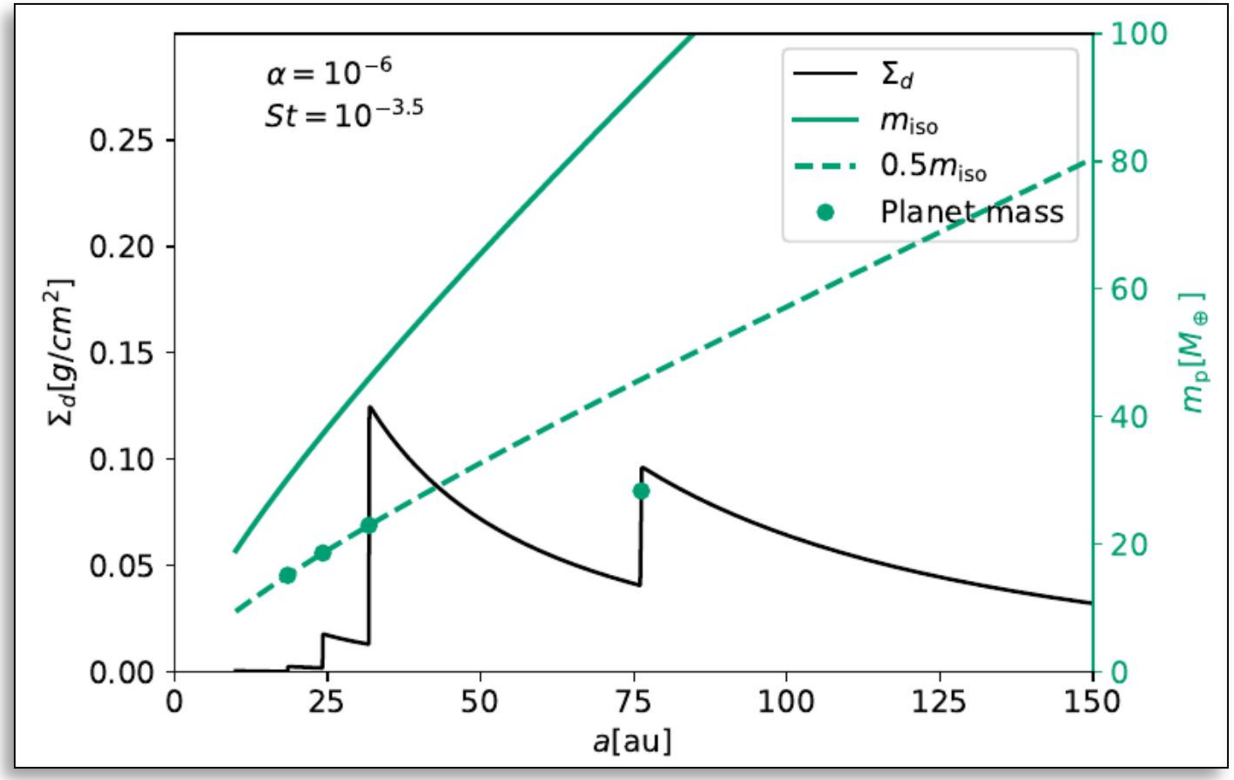
Classically, low mass planets create shallow pressure bumps in the gas disk, trapping dust.

But pebble accretion is newer



Pebbles can efficiently be accreted onto planets (Ormel & Klahr **2010**; Lambrechts & Johansen **2012**).

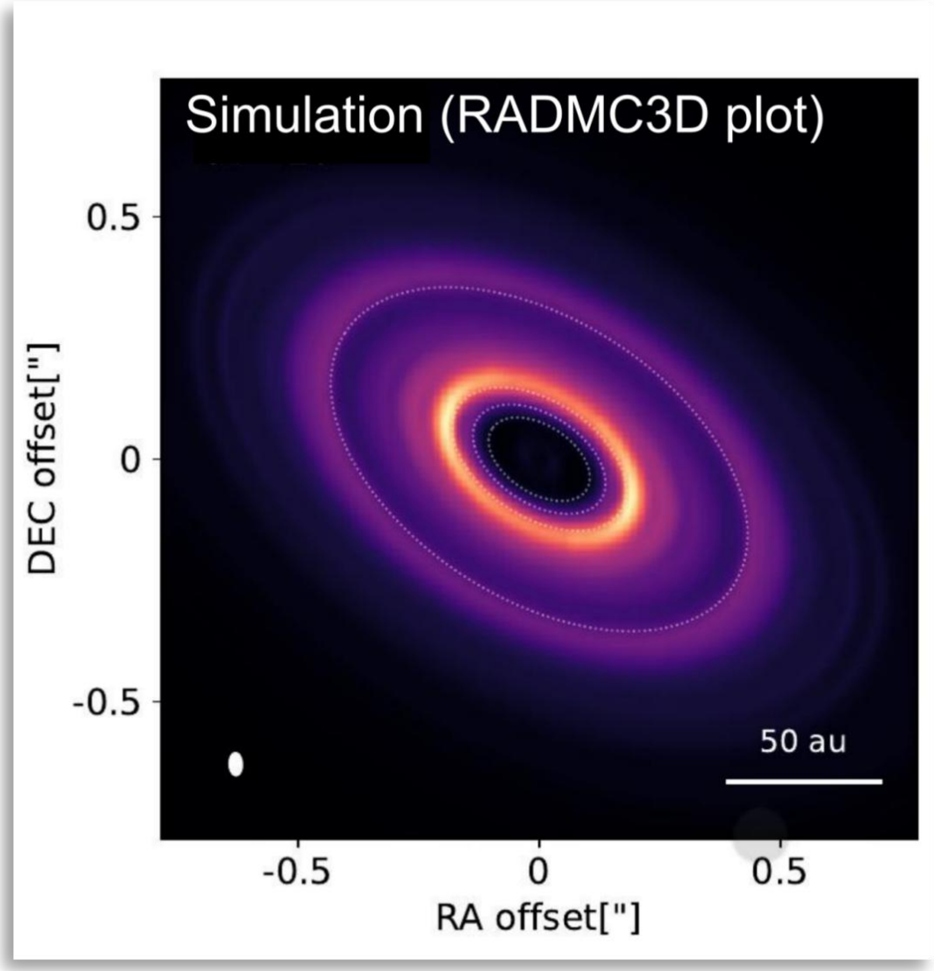
1-D dust transport result

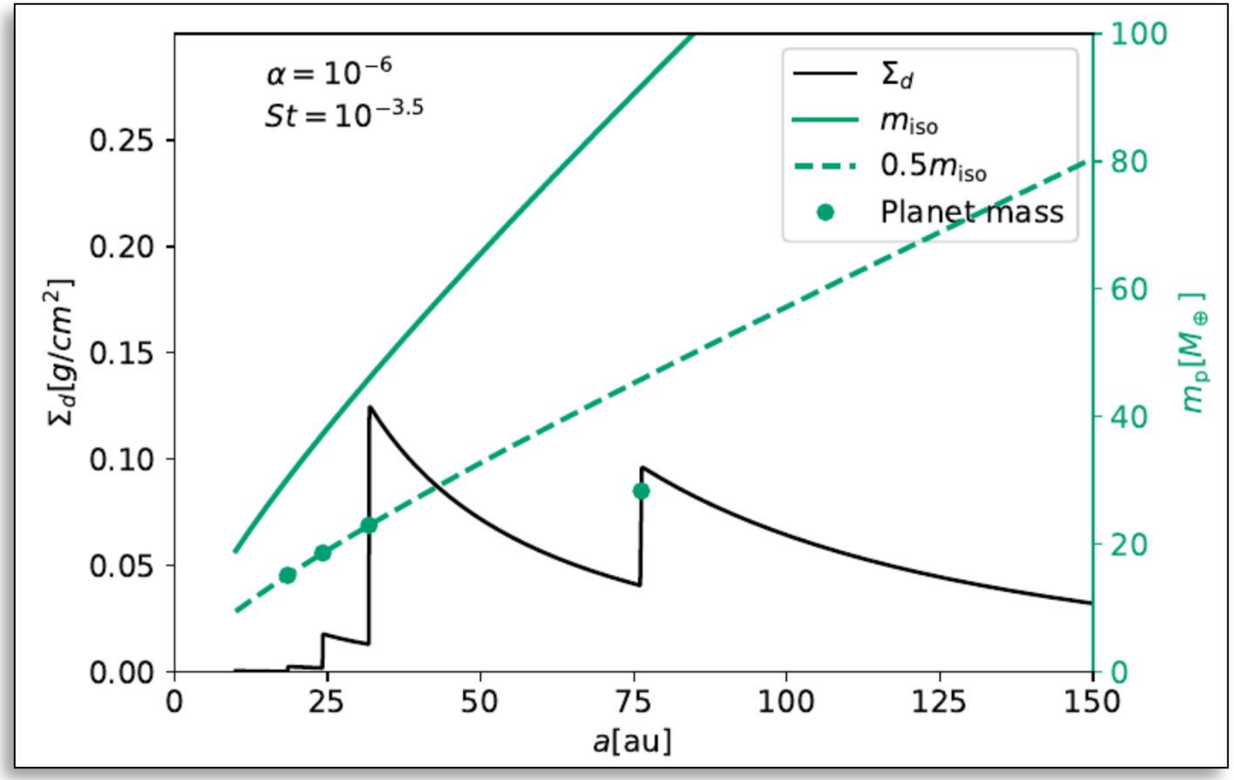


Huang S., van der Marel N., Portegies Zwart, S. A&A, arXiv:2410.02856

Planets are not big enough to open gas gaps. We consider the pebble accretion by the planet.

1-D dust transport result





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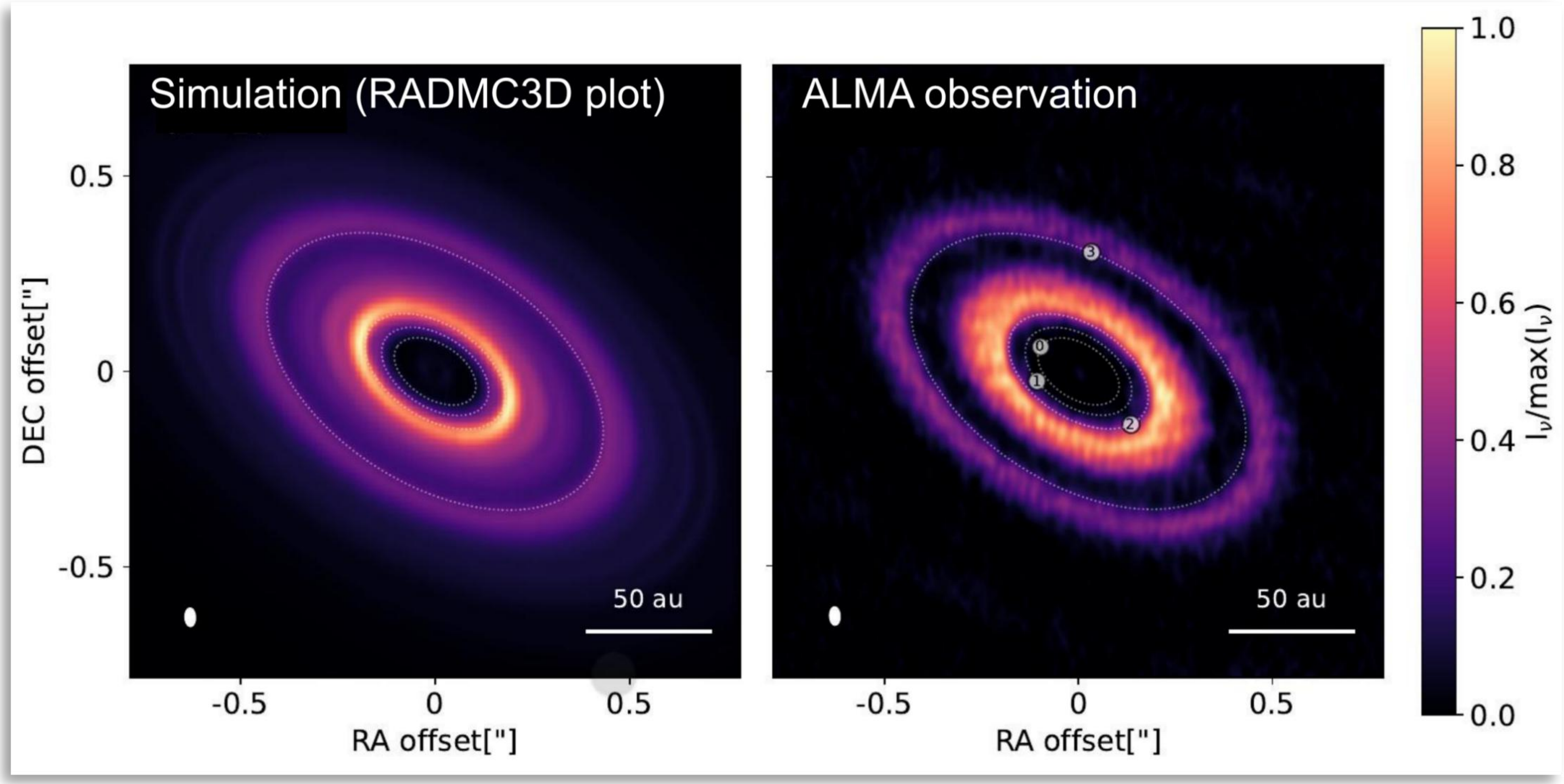
GM Aur ring features extended outer edge



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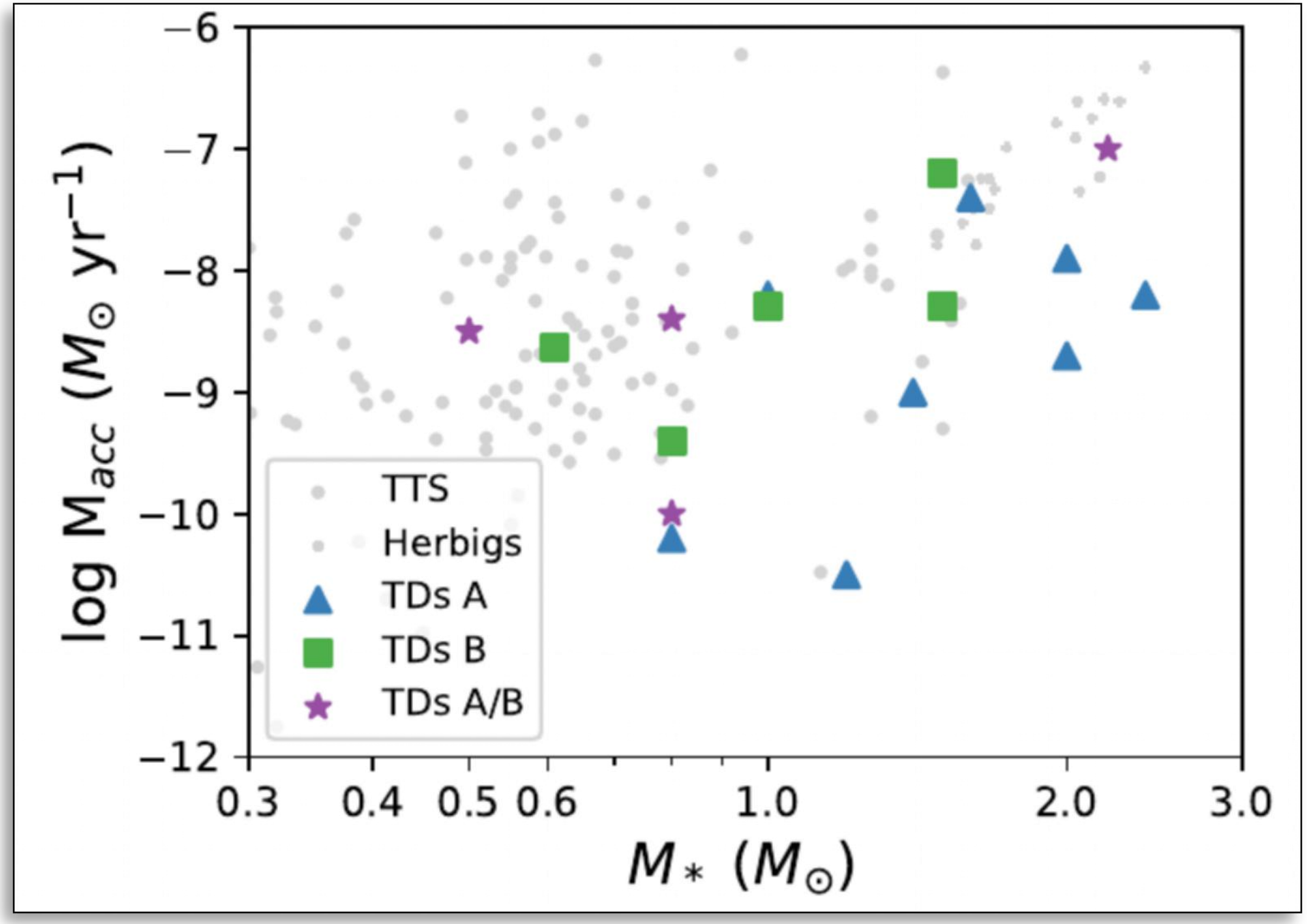
Planets are not big enough to open gas gaps. We consider the pebble accretion by the planet. We can reproduce the cavity and rings in GM Aur.

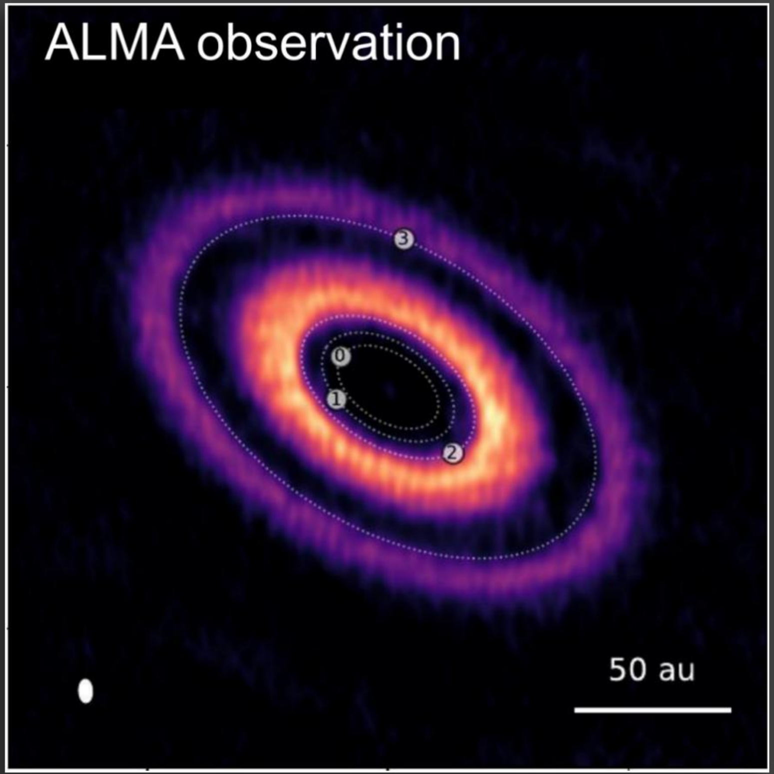
Disk with small planets has high $\dot{M}$

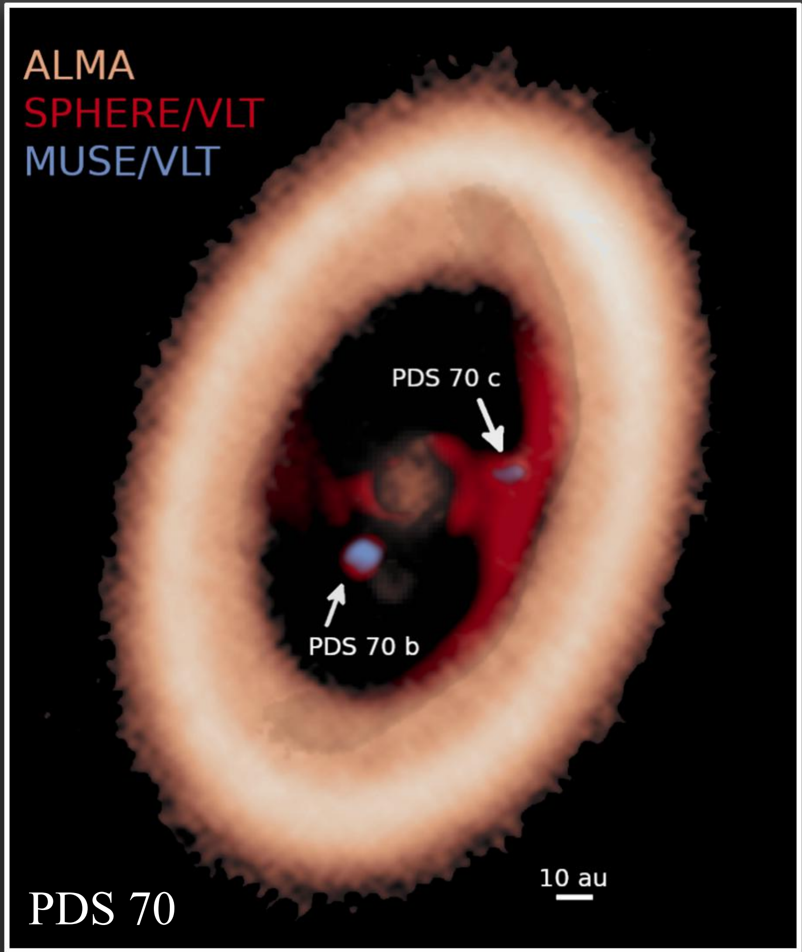


Huang S., van der Marel N., Portegies Zwart, S. A&A, arXiv:2410.02856

Sharp rings are associated with high disk accretion rates and CO gas in the dust cavity.

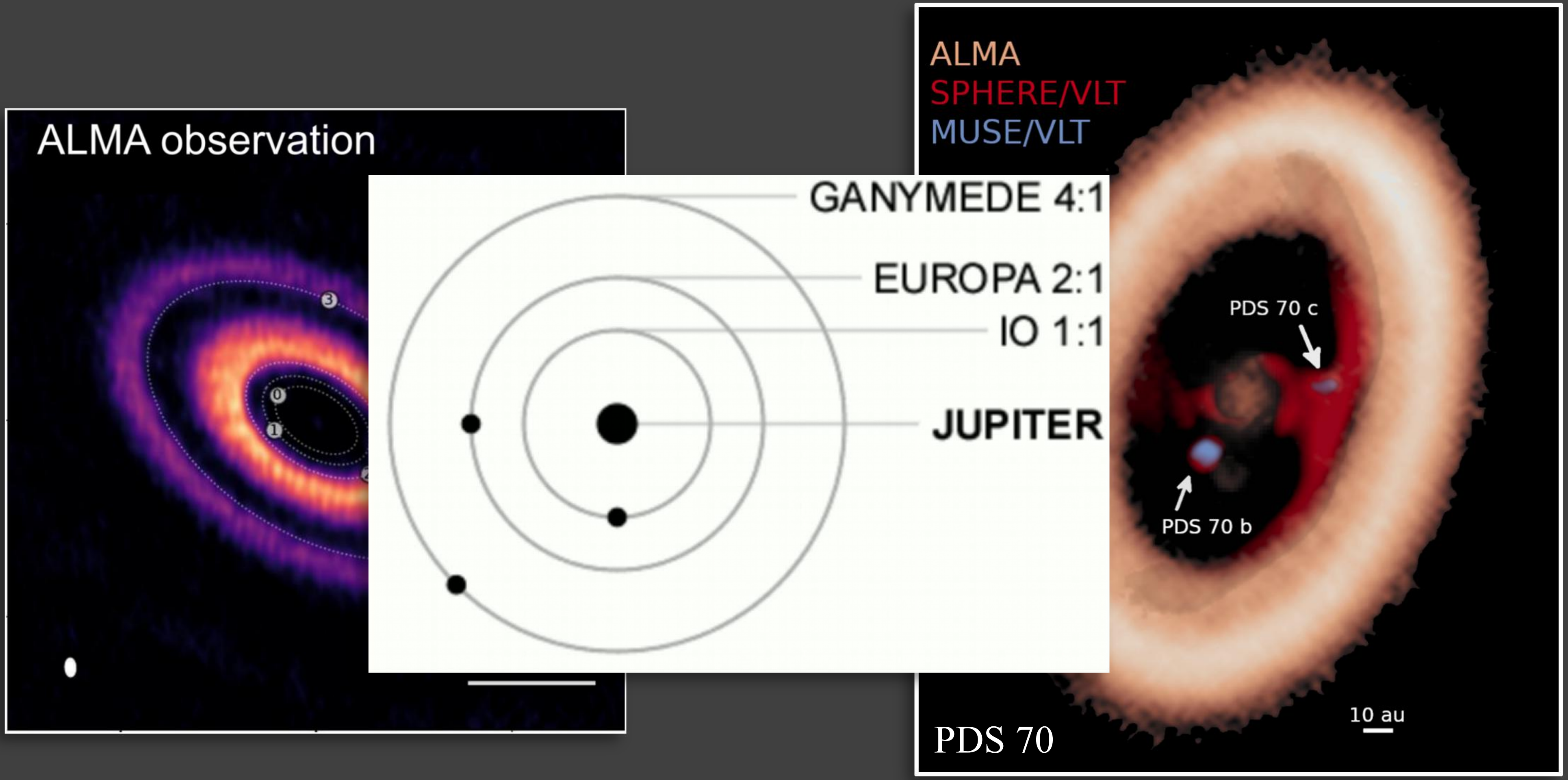
Mean motion resonance





The hypothetical planets are in resonance. The two directly imaged planets in PDS 70 are also in resonance. They have integer period ratios.

Mean motion resonance



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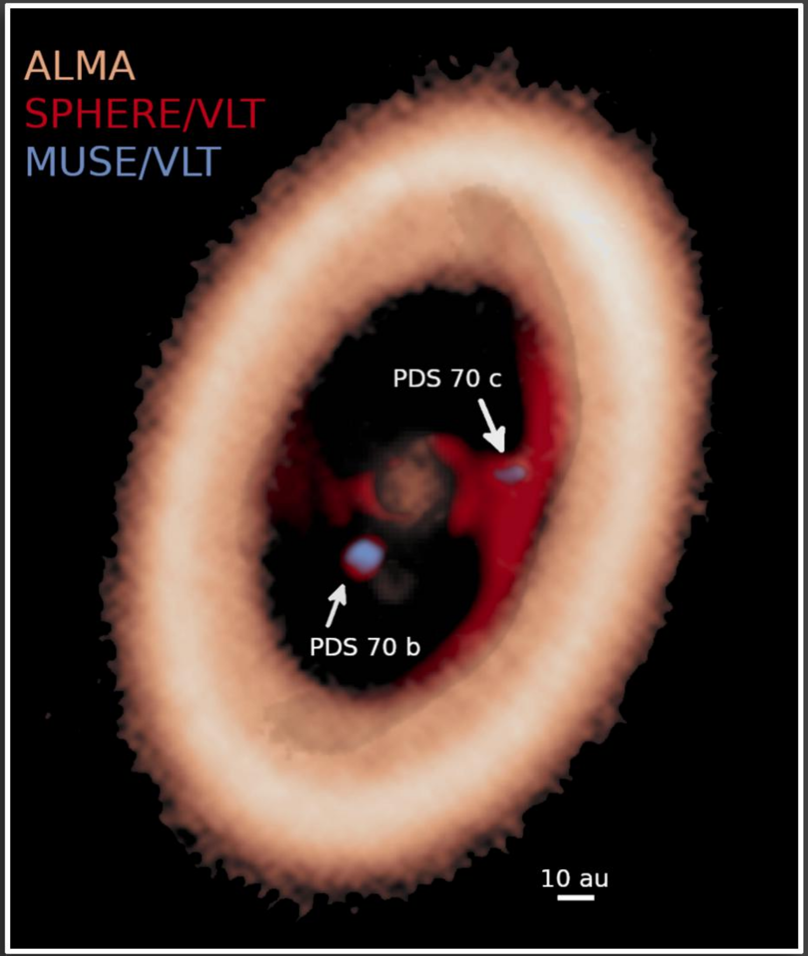
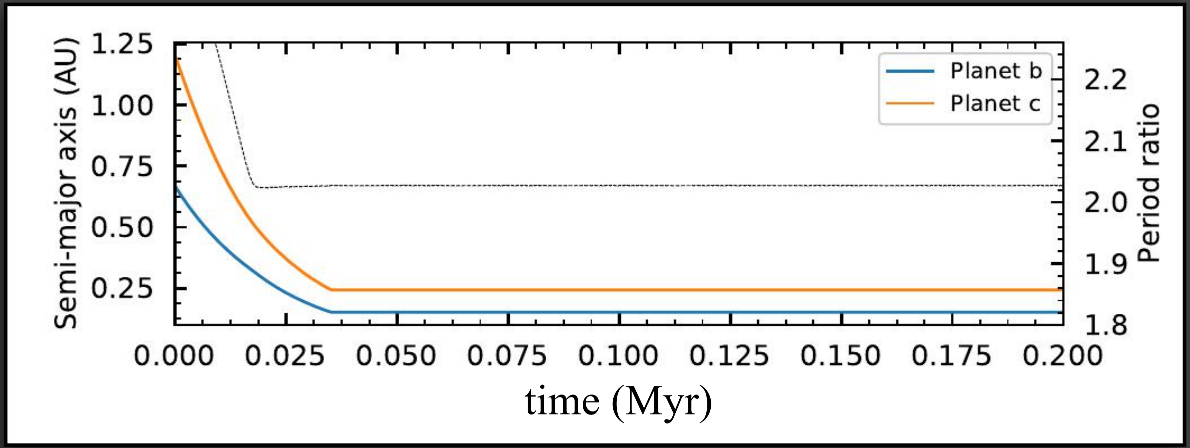


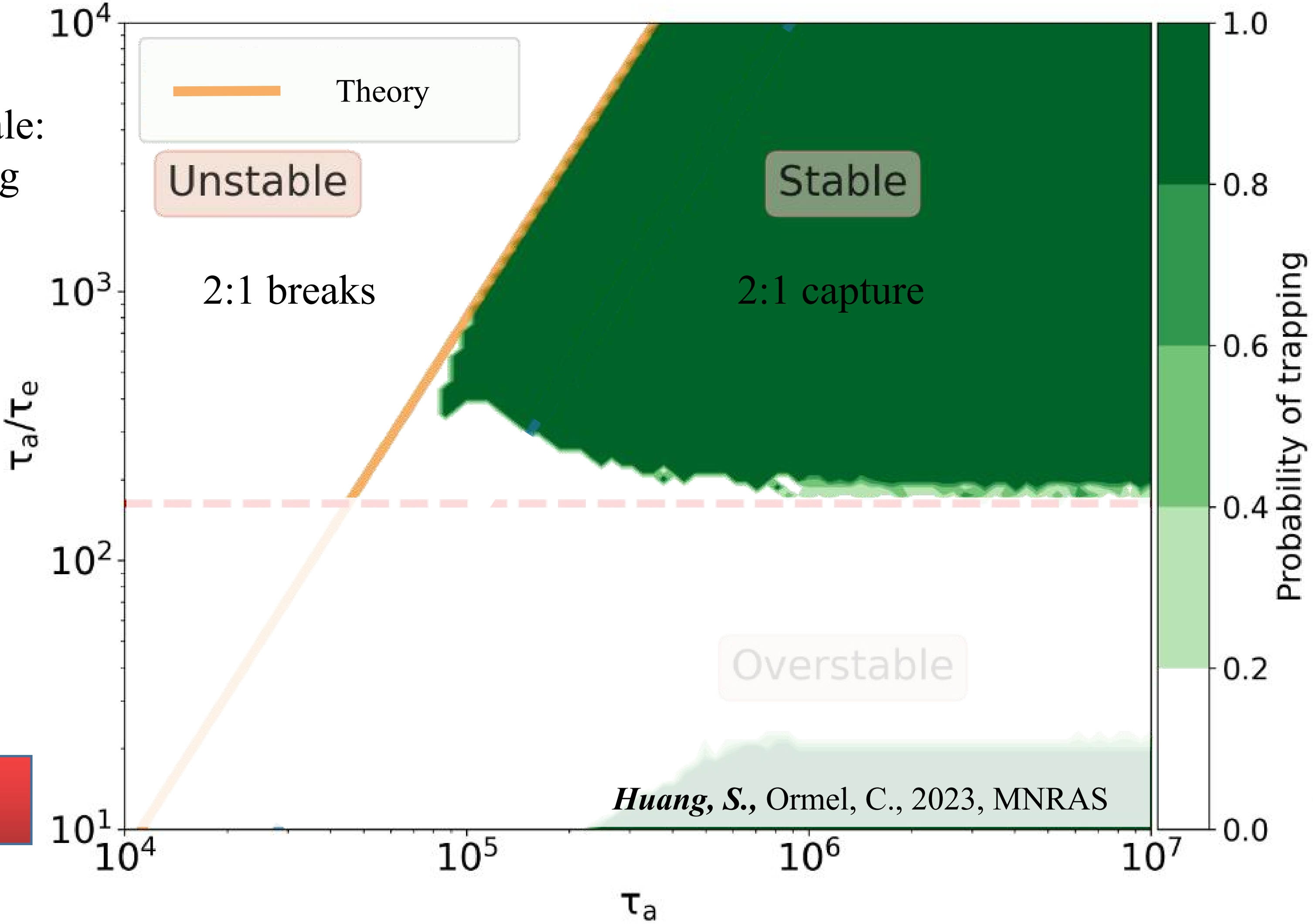


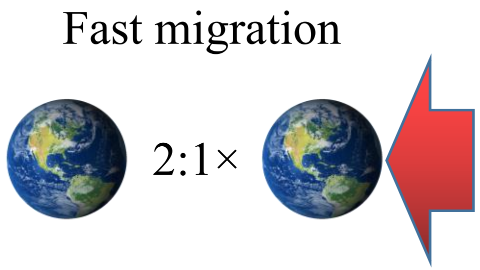
Nbody simulation. Teyssandier et al. 2021

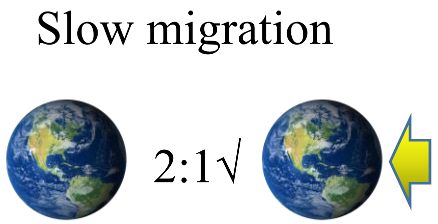
Planet migration (and eccentricity damping) naturally leads to resonances. **How Fast?**

Resonance trapping criterion

Planet migration timescale: τ_a, Eccentricity damping timescale: τ_e

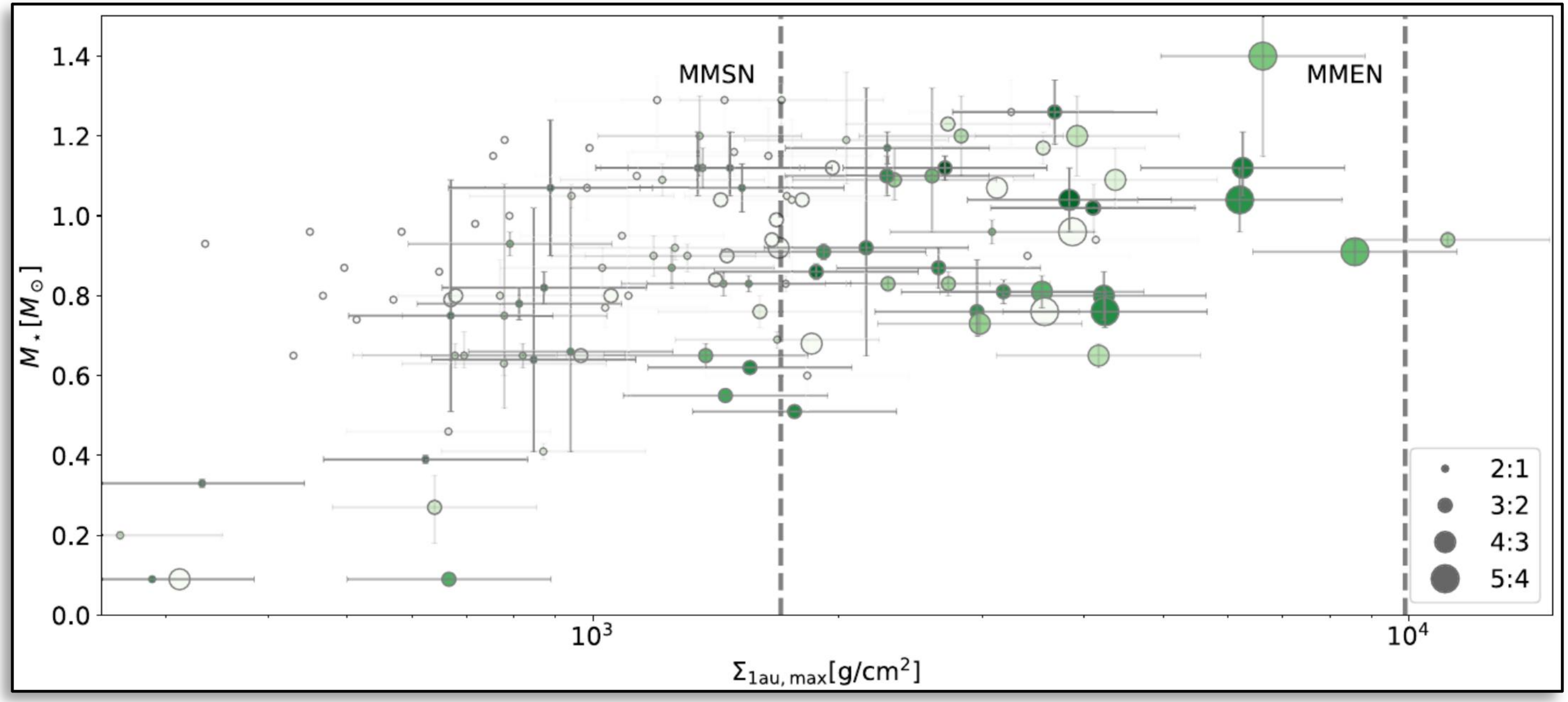






Taking an example of 2:1 resonance, our theory of resonance trapping criteria matches N-body simulations well. Too fast migration (small τ_a) results in resonance crossing.

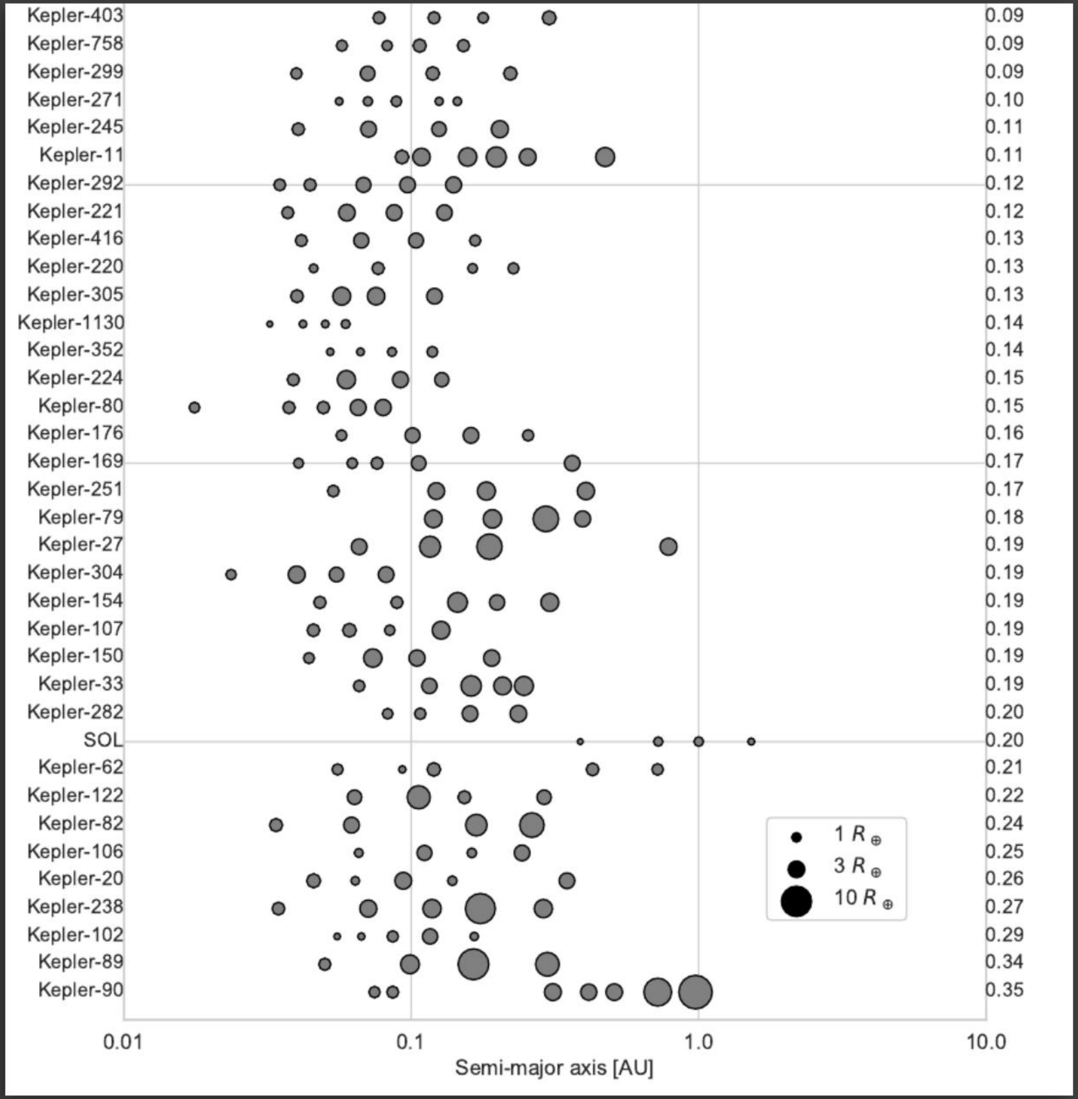
Application: constraint on planet-forming disk mass



Huang, S., Ormel, C., 2023, MNRAS

The migration timescale can not be too short = the disk can not be too dense. The disk density upper limits are close to MMSN, but below MMEN.

Multi-planet systems provide more infos

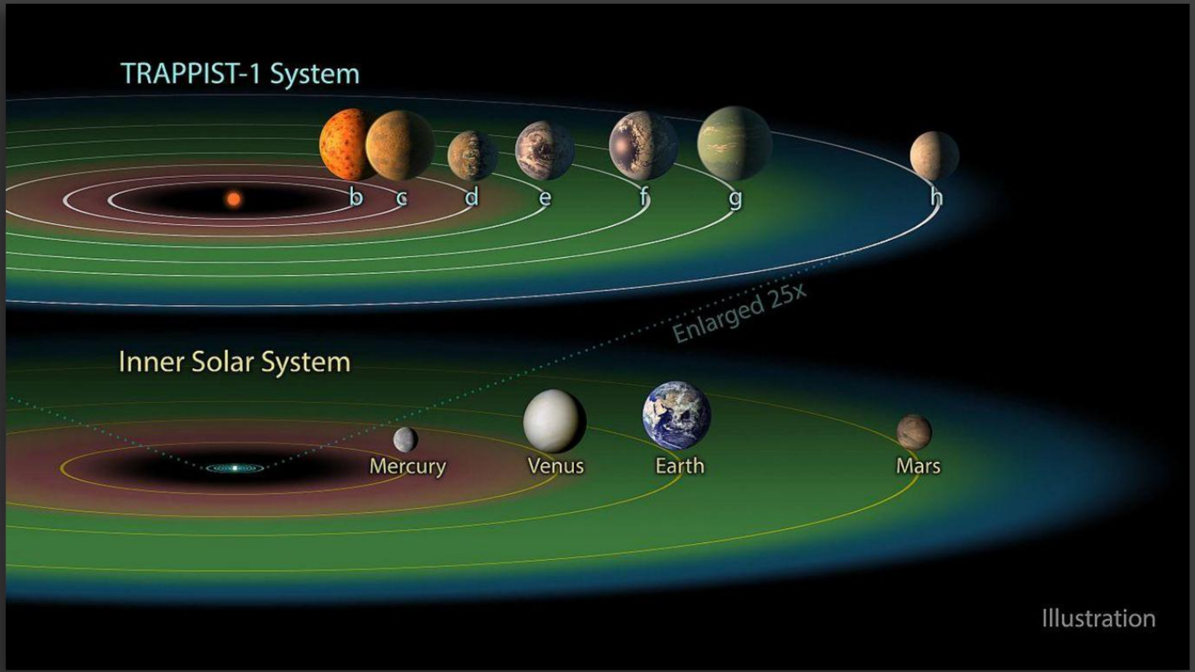


(c) PPVII Chapter, by Weiss et al.

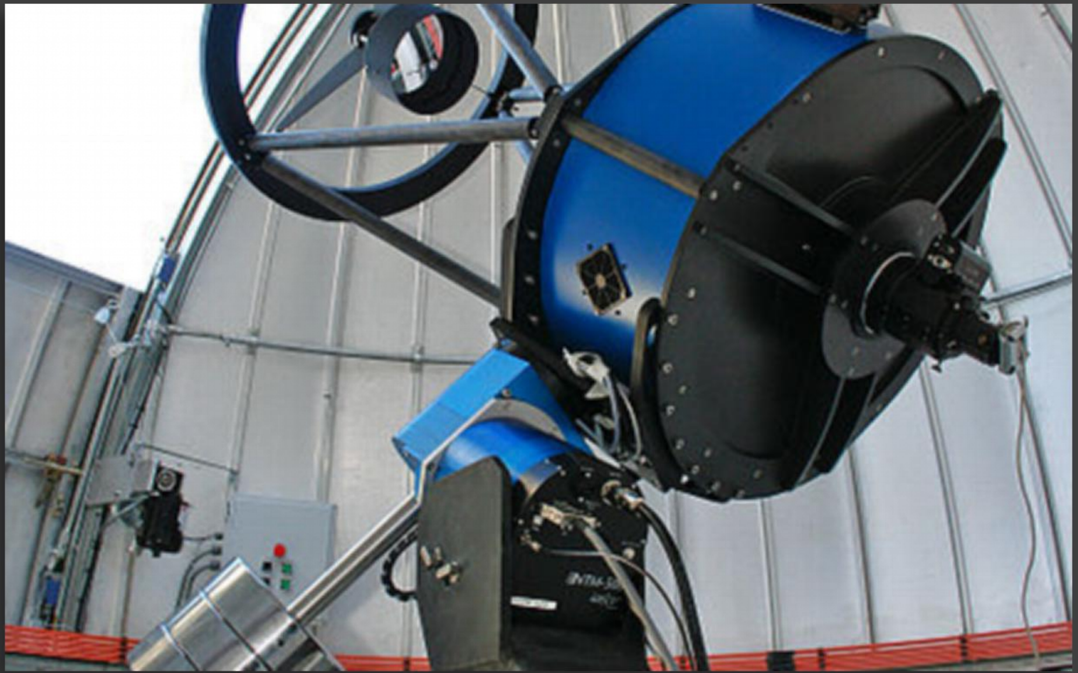
Multi-planet systems are rich in dynamics and very likely contain planet formation imprint.

They are rich in orbital dynamics and commonly show "peas in a pod", hinting their formation origin.

Introduction of TRAPPIST-1 system: Discovery



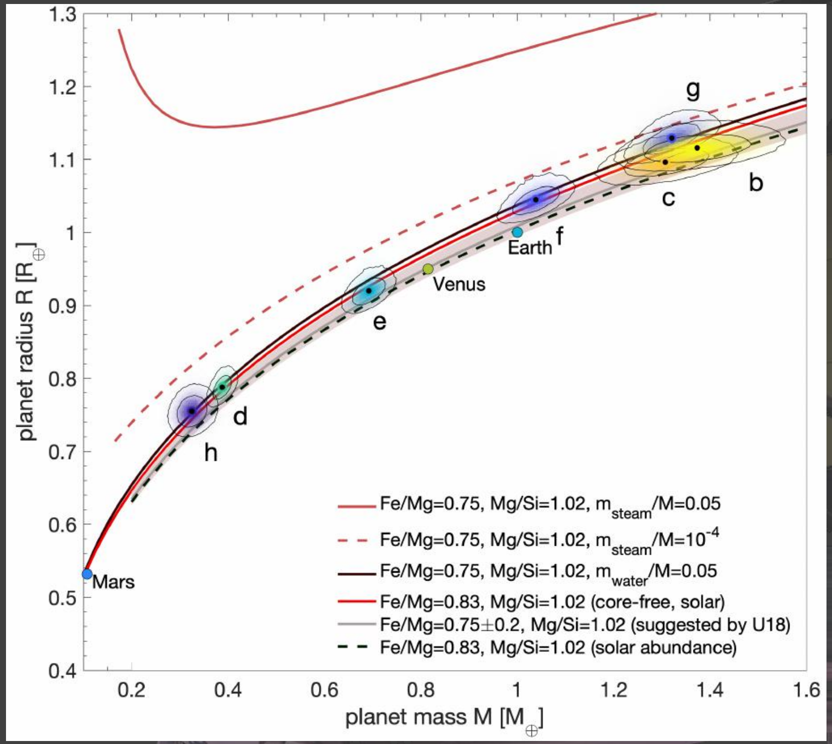
TRAPPIST-1 system and Solar system



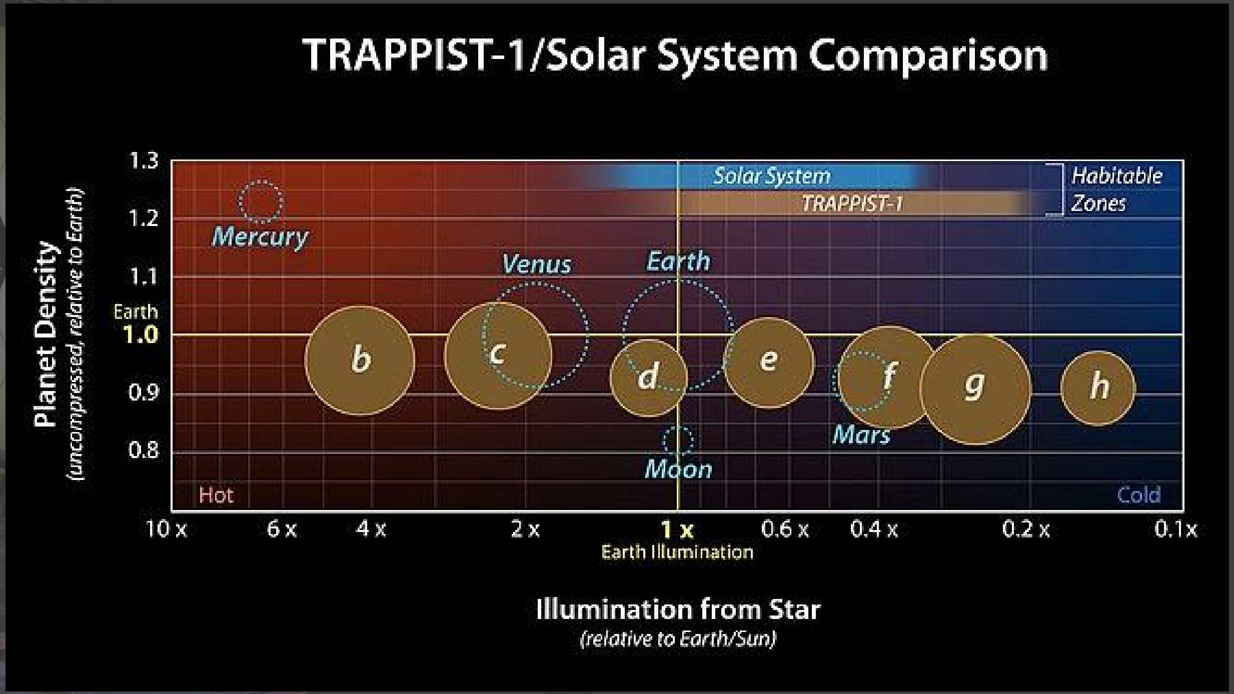
TRAPPIST telescope

There are **SEVEN EARTH** size planets around an M-dwarf. They are first discovered (in 2017) by TRAPPIST, therefore named TRAPPIST-1 system.

Introduction of TRAPPIST-1 system: Similarity



Mass constraint by TTV (Agol et al. 2020)

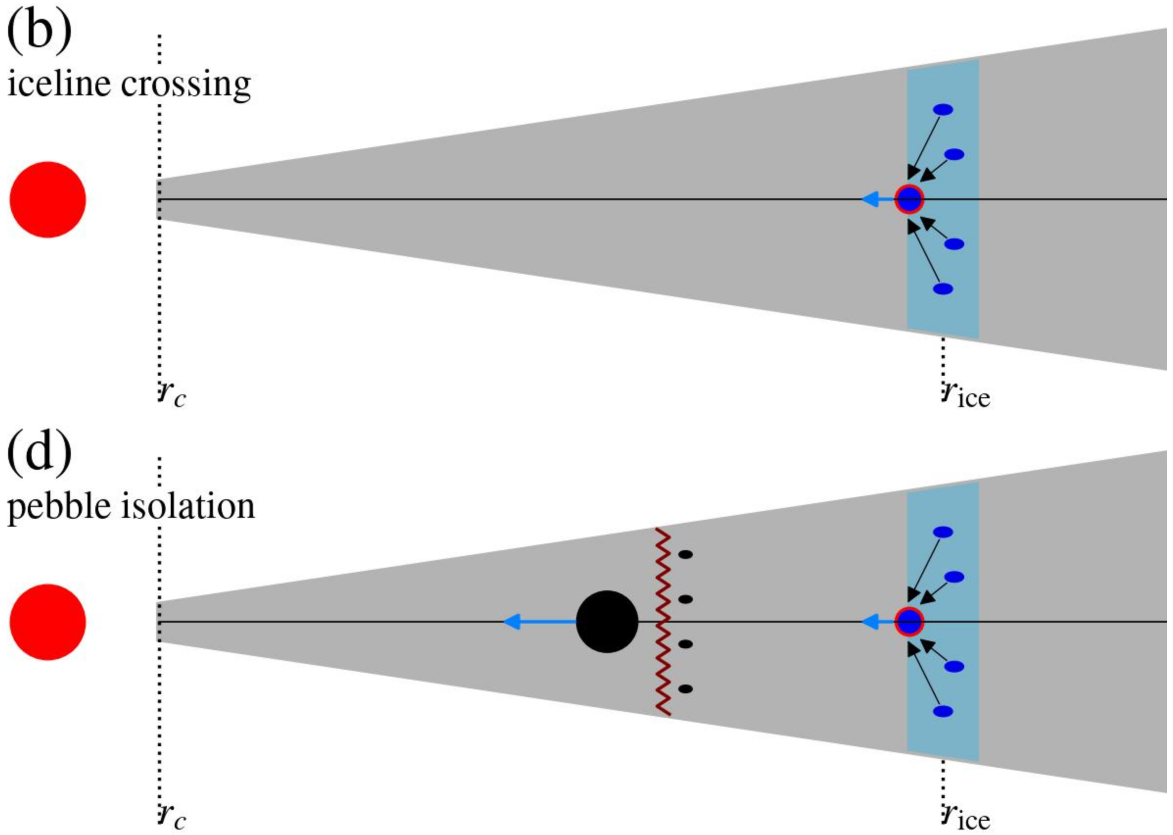


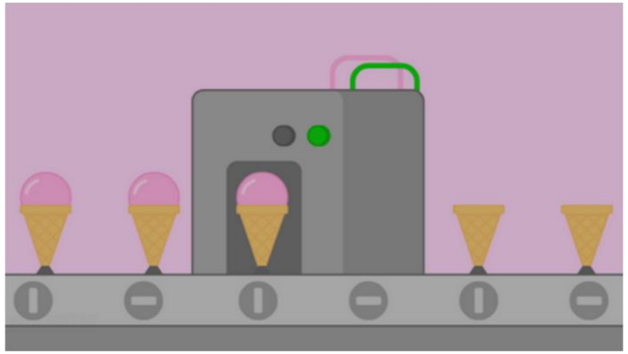
TRAPPIST-1 planets vs solar terrestrial planets

All seven planets have similar mass, densities. They very likely have the same formation origin.

Formation of TRAPPIST-1 planets

Ormel et al. (2017); Schoonenberg et al. (2019)





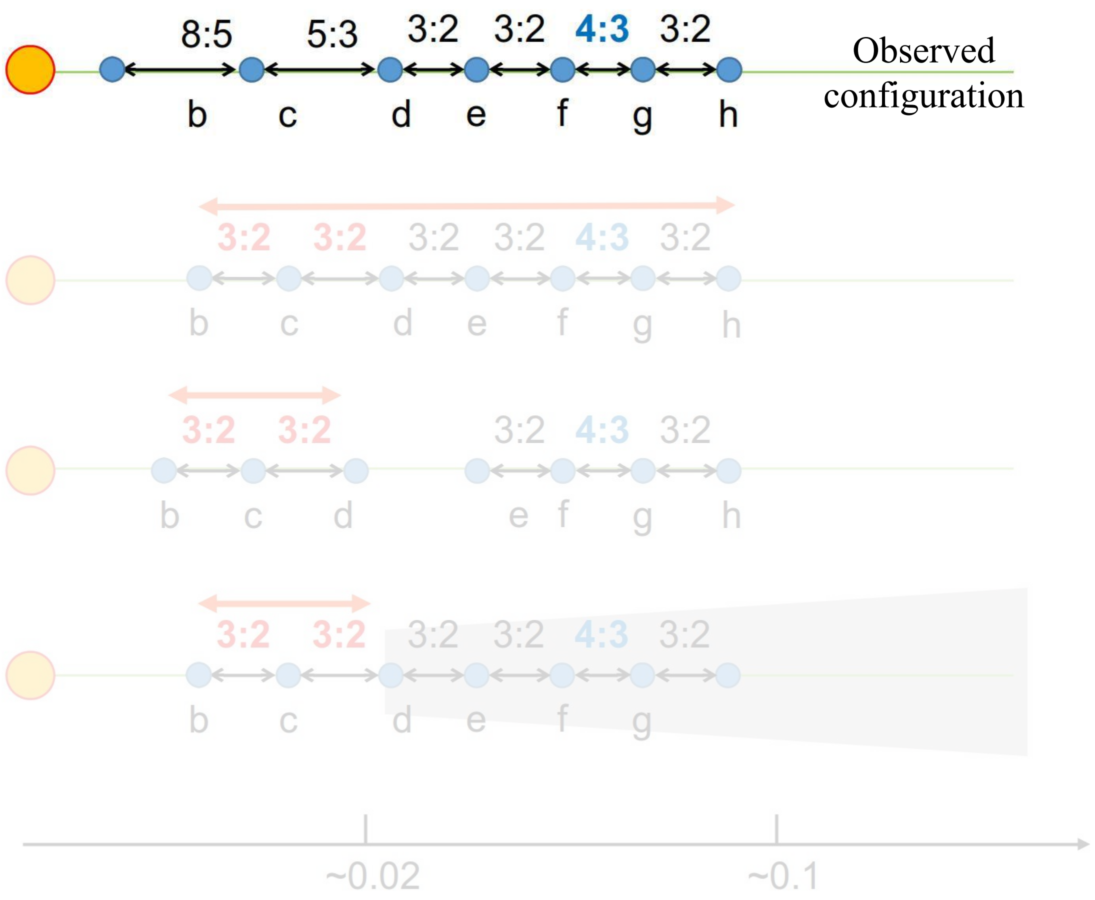
TRAPPIST-1 planets form via pebble accretion outside the water iceline.

- Sequential planet formation
- Planets' similarities are well-explained

Model does not yet explain dynamical properties

Explaining higher order MMRs challenging

Teyssandier et al. (2022)



If two planets are in mean motion resonance (MMR, 2-body res.), the period ratio is near:

$$\frac{P_2}{P_1} = \frac{j+o}{j}$$

where o is the order of resonance.

Higher order resonances are weaker.

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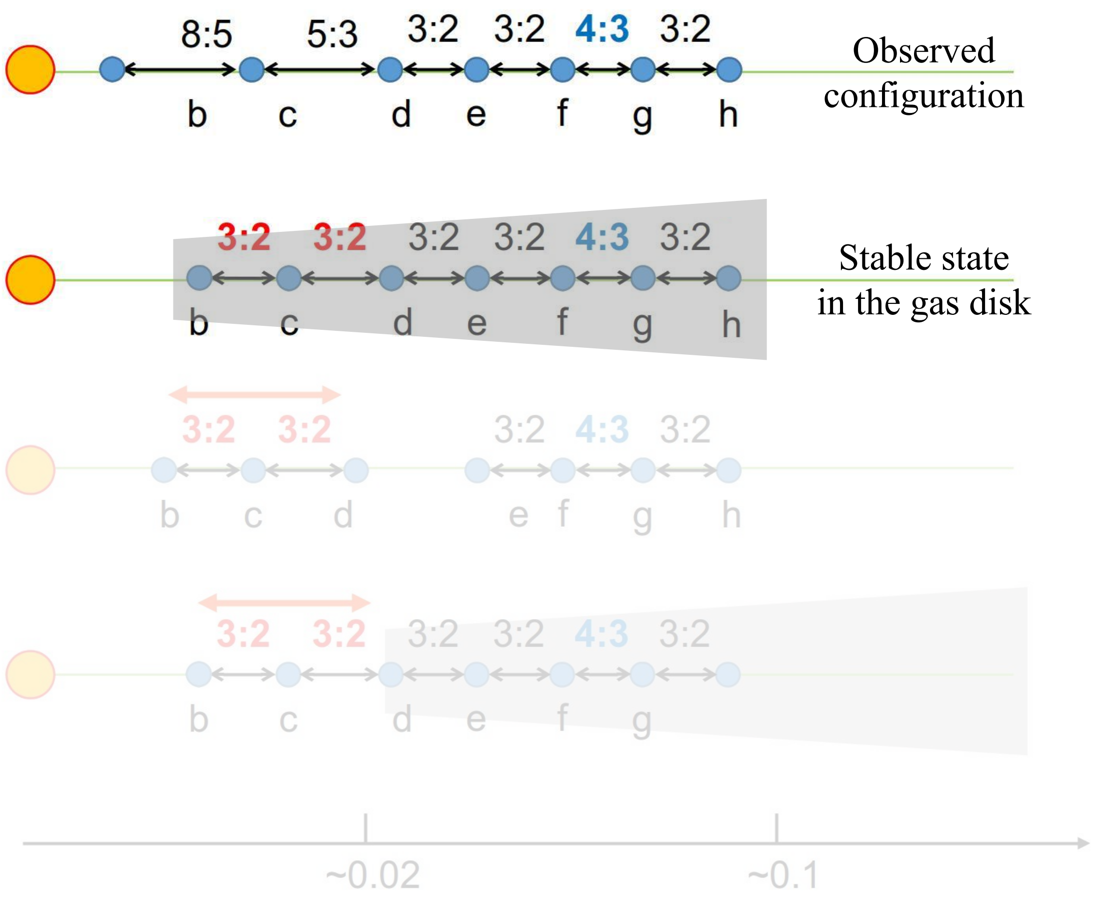

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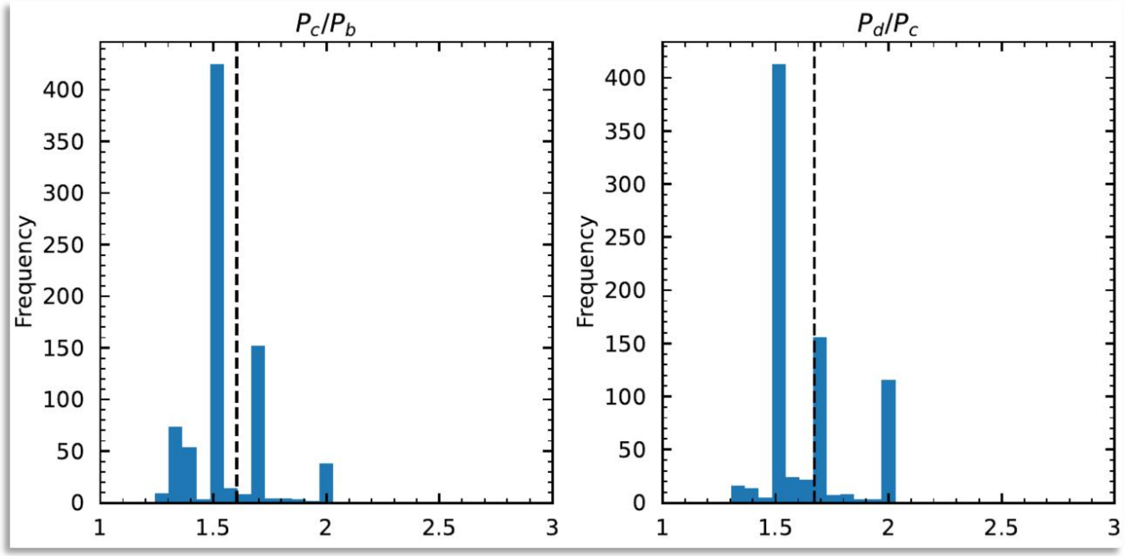
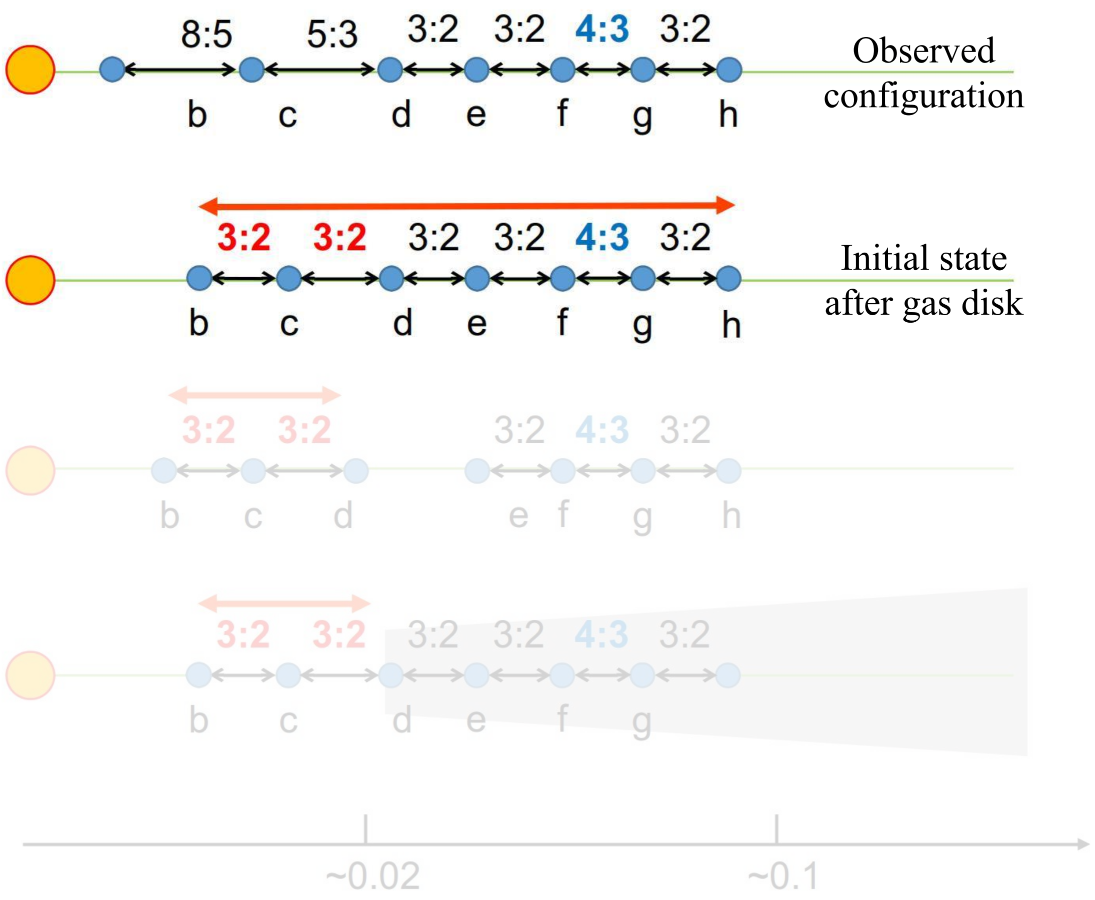


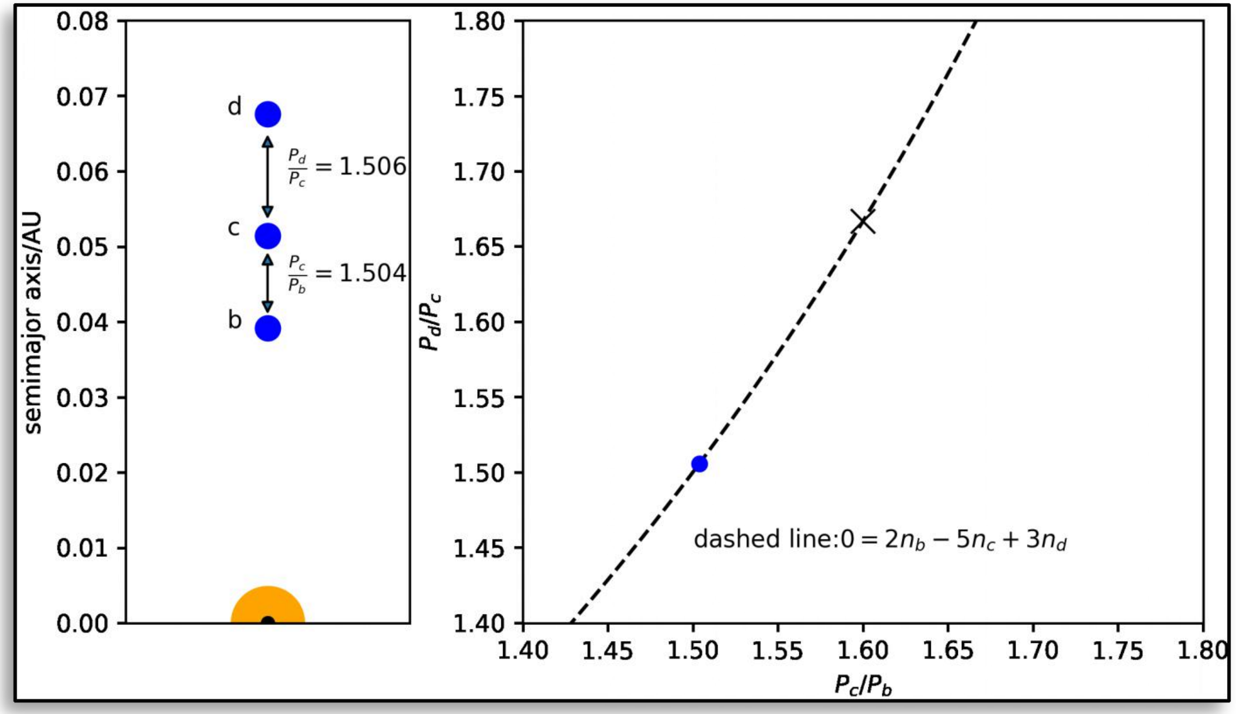
Planets in the gas disk tend to stay at first order resonance.

Stellar tides driven expansion

Huang & Ormel (2022); Brasser et al. (2022)



- Planets in the gas disk tend to stay at first order resonance.
- **Stellar tides may help:** $\tau_{stellar} \propto a^{6.5}$

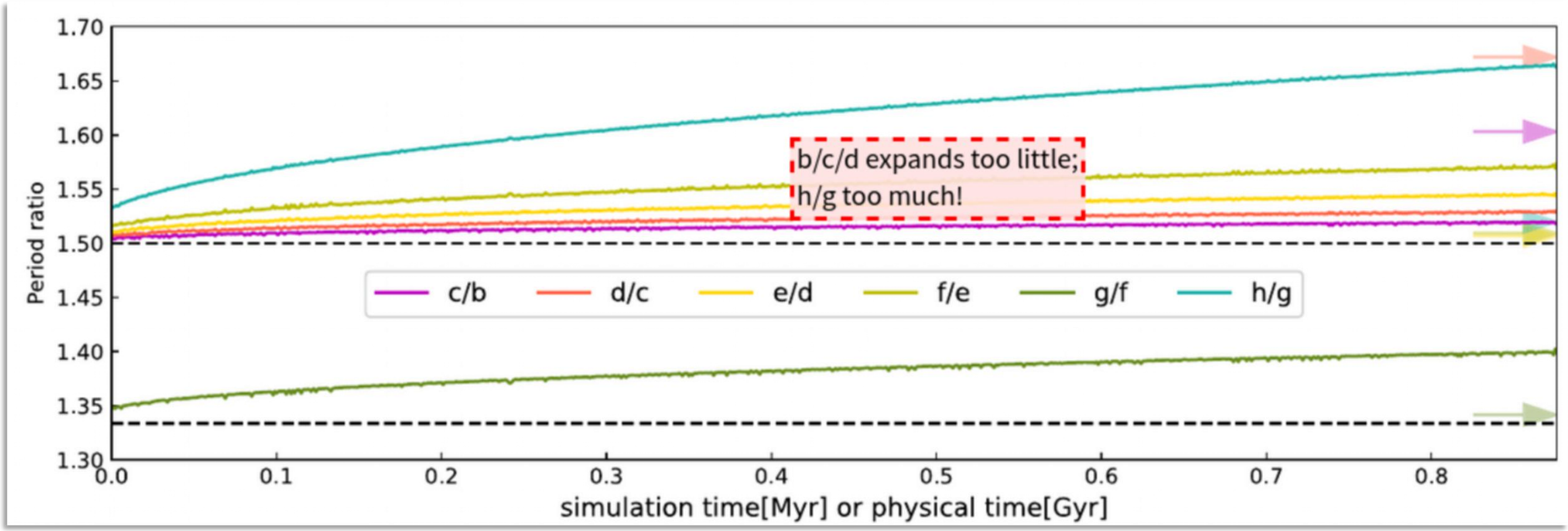


Papaloizou et al.; Charalambous et al. 2018

Stellar tides driven expansion

Huang & Ormel (2022); Brasser et al. (2022)

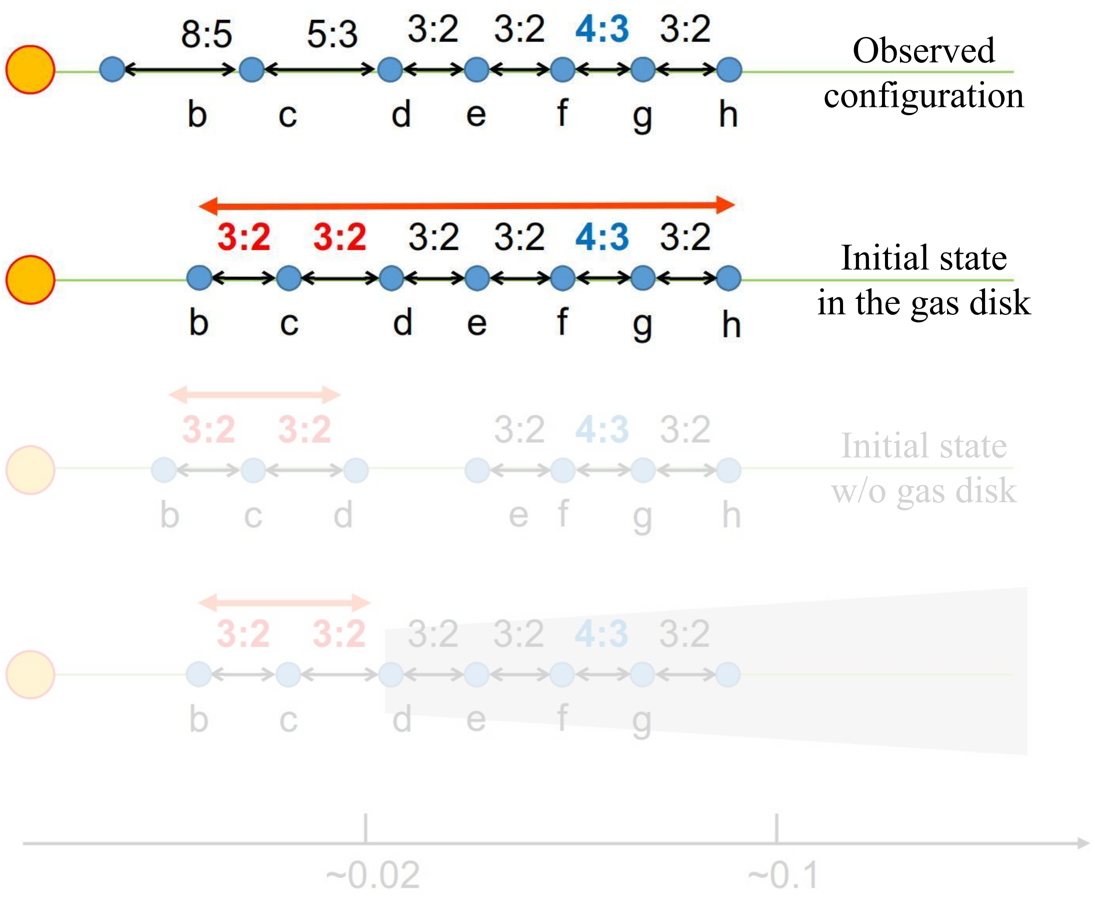
- **Stellar tides X**



If they are in resonance, they are very stable.

One possible solution?

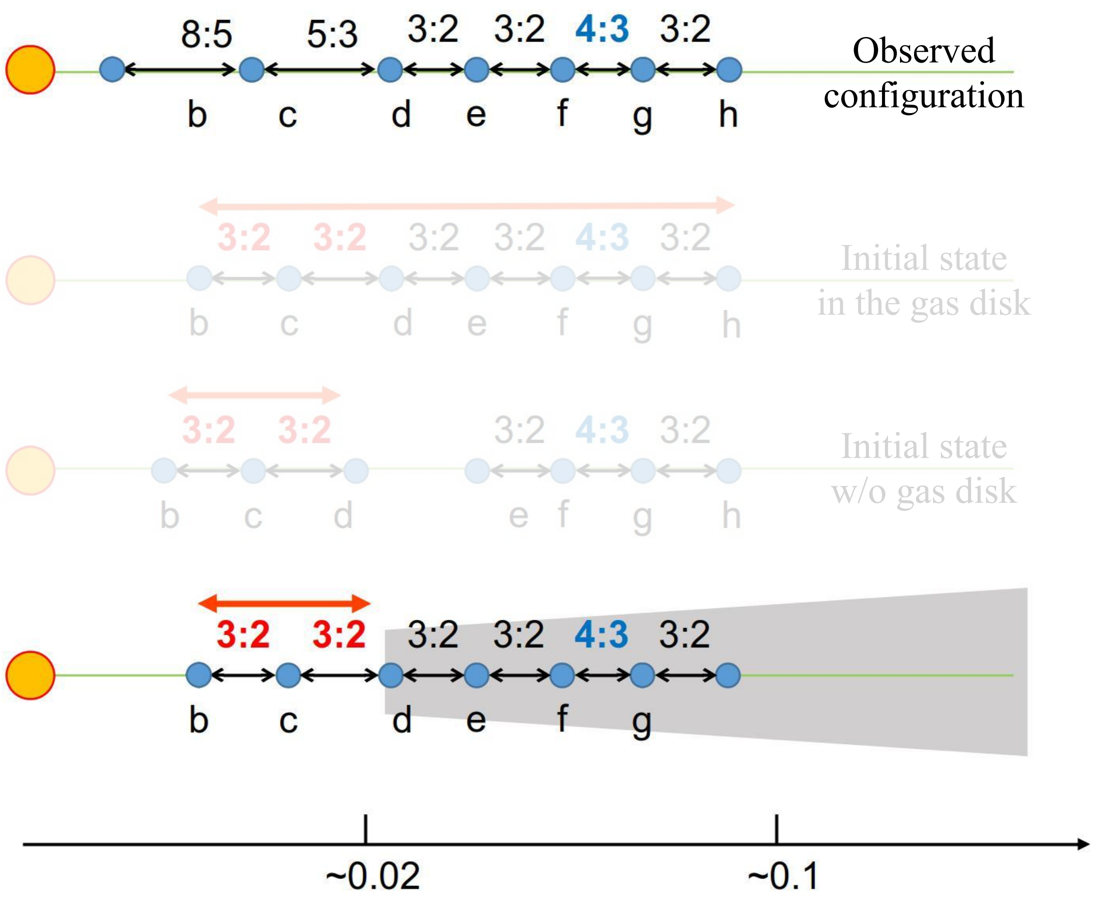
Papaloizou et al. (2018)



- Planets in the gas disk tend to stay at first order resonance.
- Stellar tides **X** ⟹ **We must break the wrong resonance chain early before disk dispersal.**

Early orbital expansion

Huang & Ormel (2022)

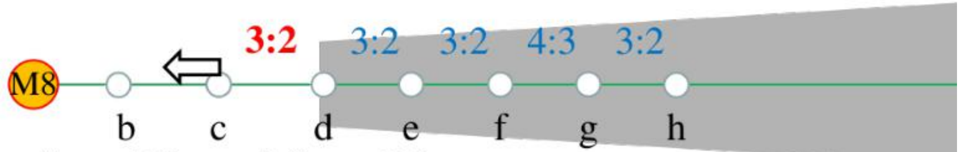


- Planets in the gas disk tend to stay at first order resonance.
- We must break the wrong resonance chain early during planet formation/migration.
- **We consider the inner two planets enter the gas free cavity, while the outer ones stay.**

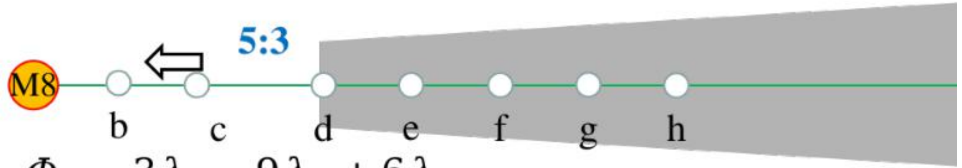
Early orbital expansion

Huang & Ormel (2022)

- **We consider the inner two planets enter the gas free cavity, while the outer ones stay.**



$\Phi_1 = 2\lambda_c - 5\lambda_d + 3\lambda_e$



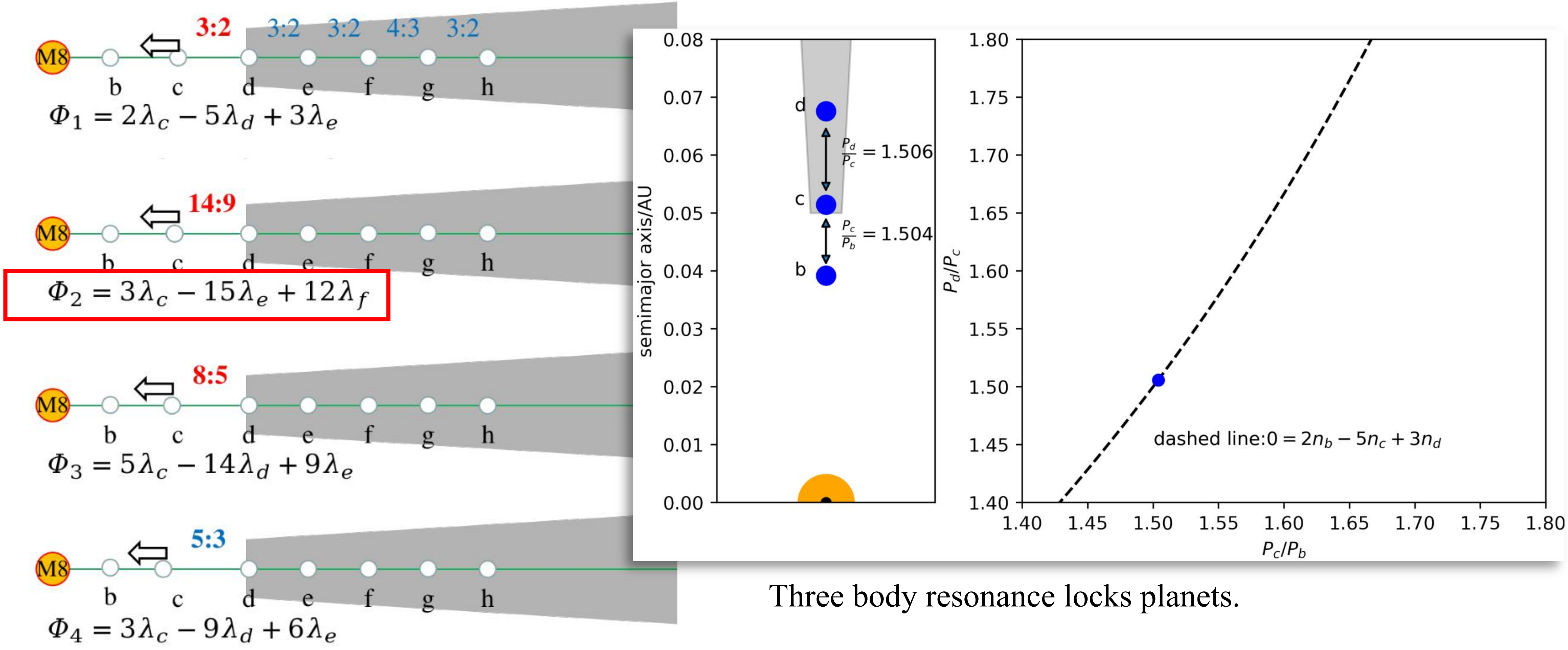
$\Phi_4 = 3\lambda_c - 9\lambda_d + 6\lambda_e$

The theory is promising.

Early orbital expansion

Huang & Ormel (2022)

- **We consider the inner two planets enter the gas free cavity, while the outer ones stay.**



Three body resonance locks planets.

Early orbital expansion

Huang & Ormel (2022)

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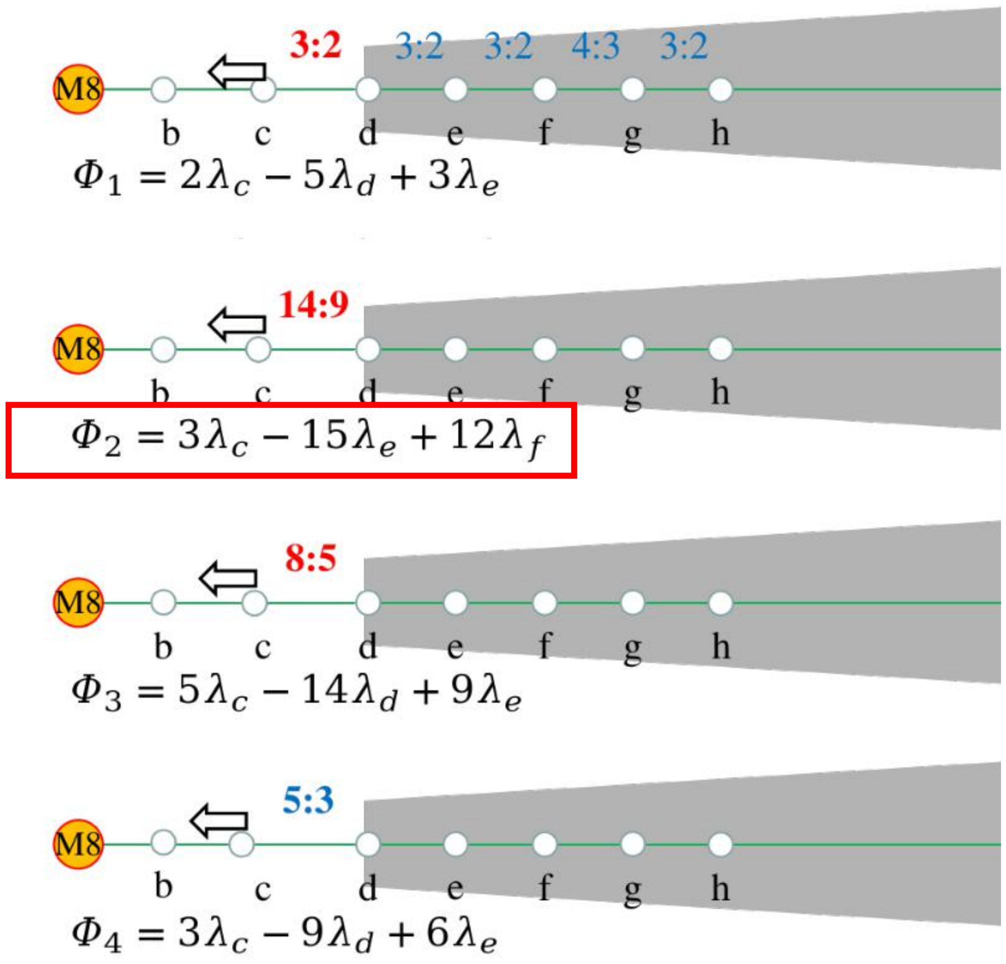
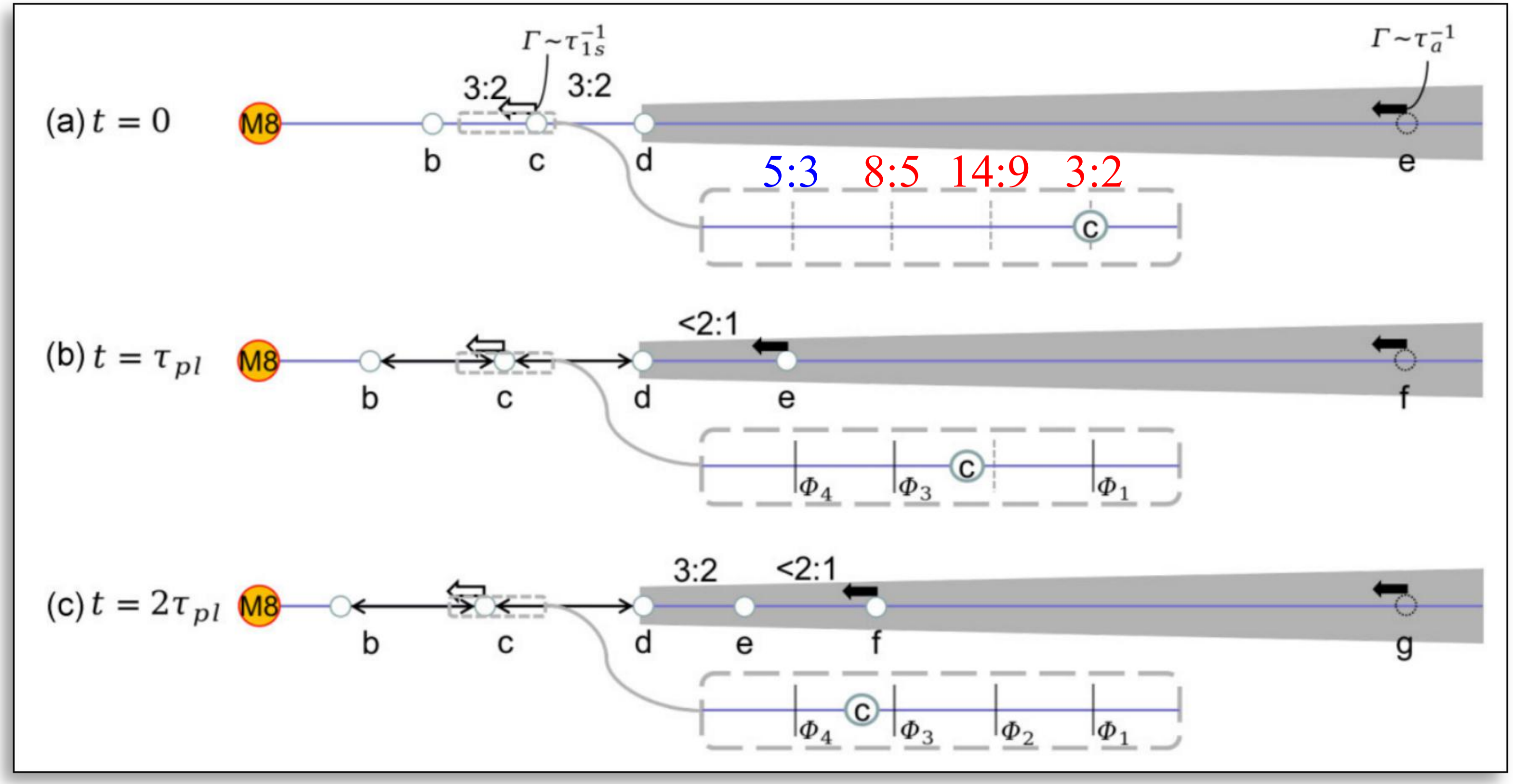


Successful simulations require fine tune because of too many wrong resonances in the halfway ... which is the big problem

Early infall model

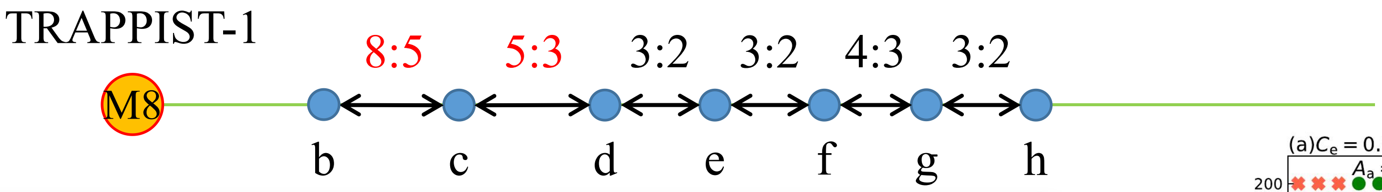


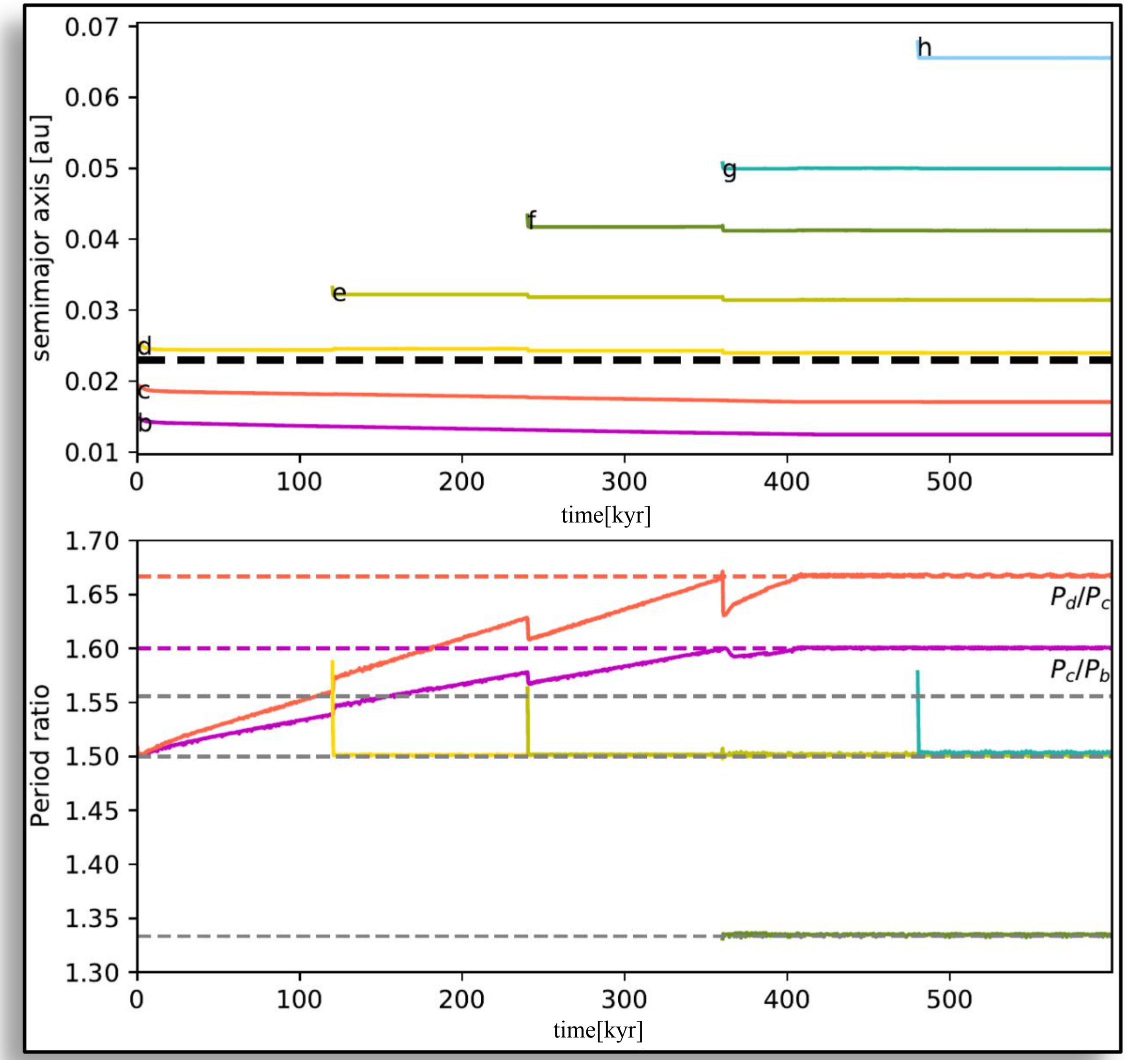
Huang, S., Ormel, C. 2022, MNRAS

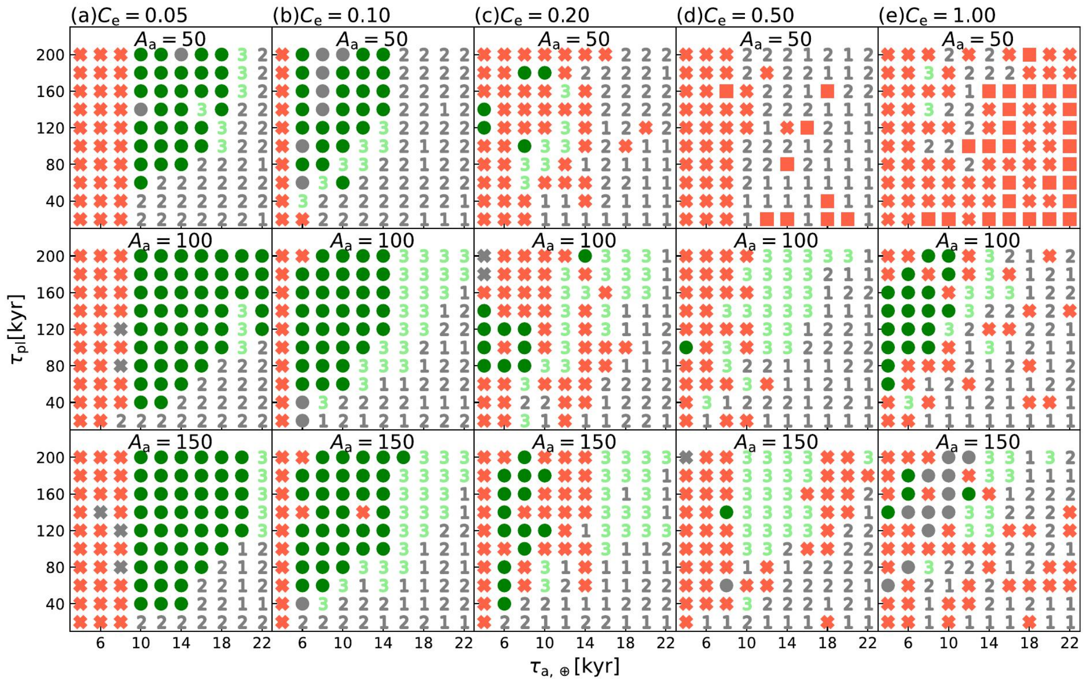
The only way we find is that:

- Planets form (on timescale τ_{pl}) and migrate (on timescale τ_a) sequentially inward.
- Planet b and c enter the gas cavity and expand early before external planets' formation.
- The wrong resonance chain can be avoided.

Systems with widelier separated inner planets



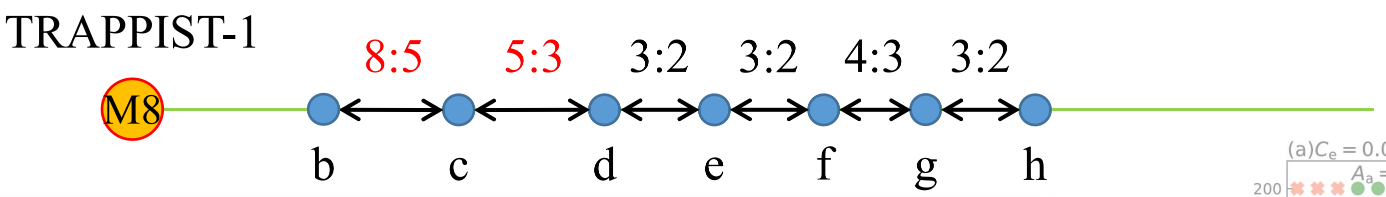


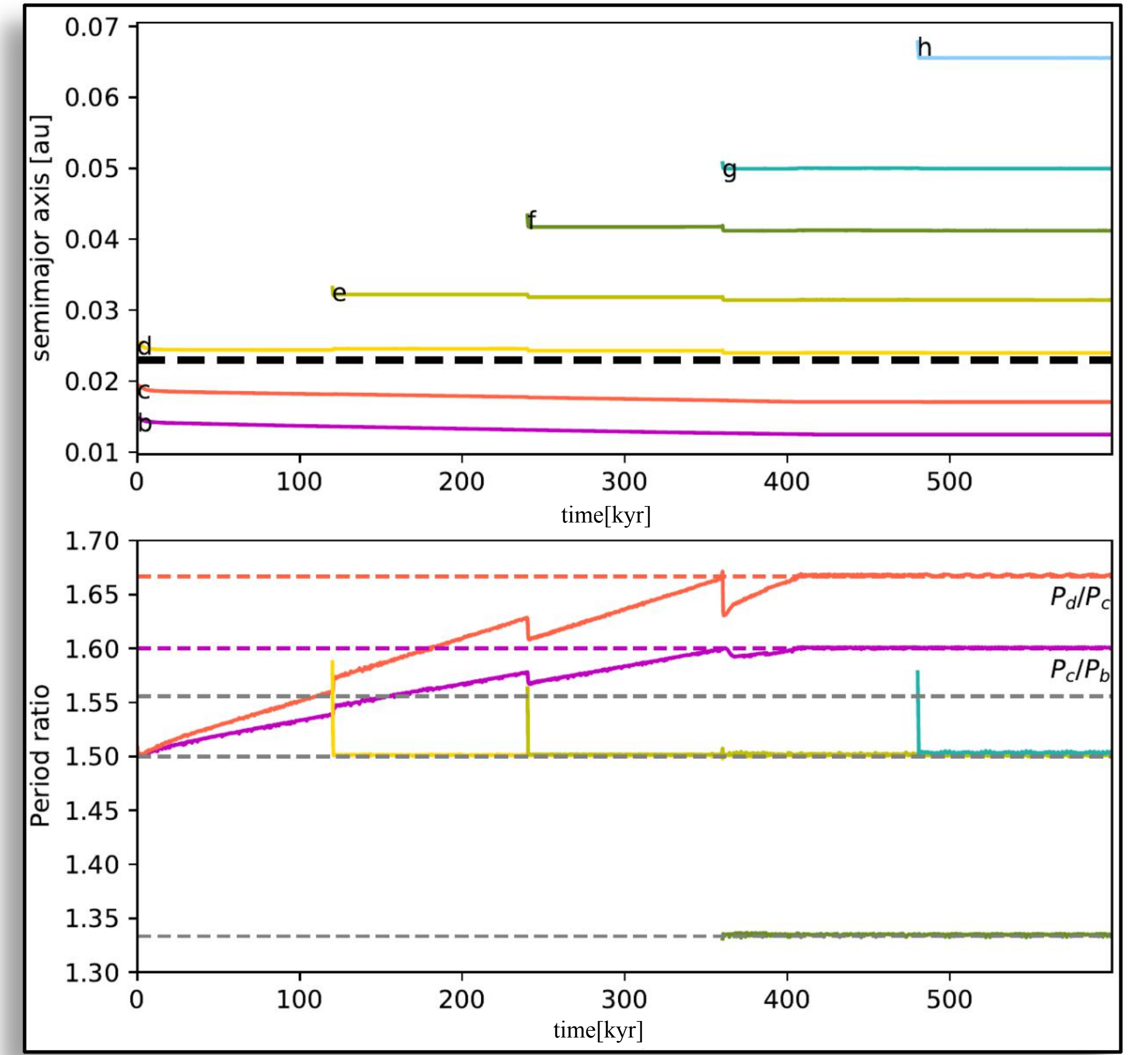


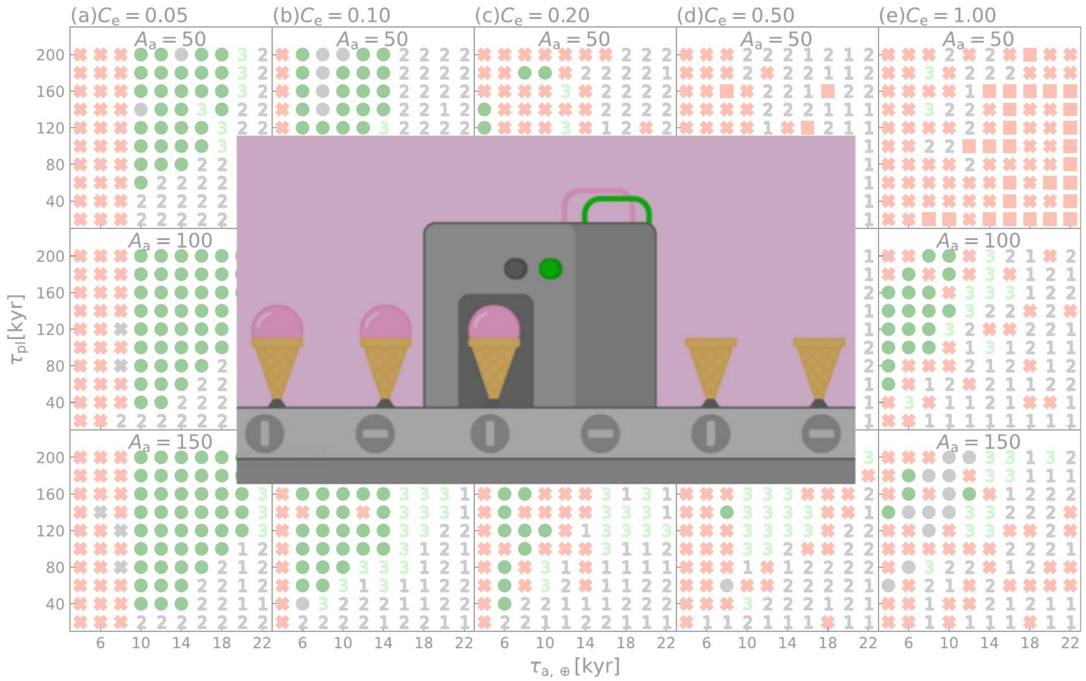
Check ***Huang, S.***, Ormel, C., 2022, MNRAS for details

- Our model constrains that planets formed sequentially on the timescale of ~100 kyr.
- The first model successfully explain the architecture of TRAPPIST-1 system from formation perspective.

Systems with widelier separated inner planets







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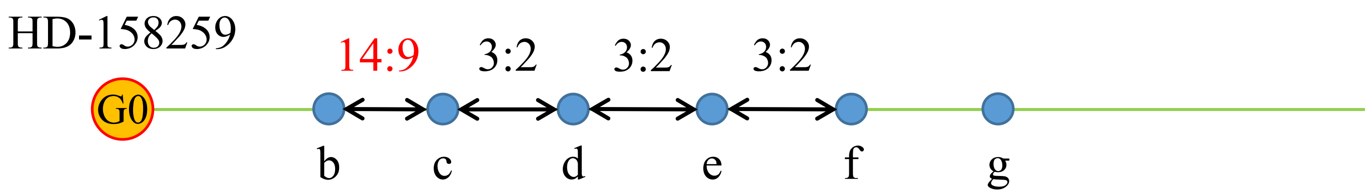

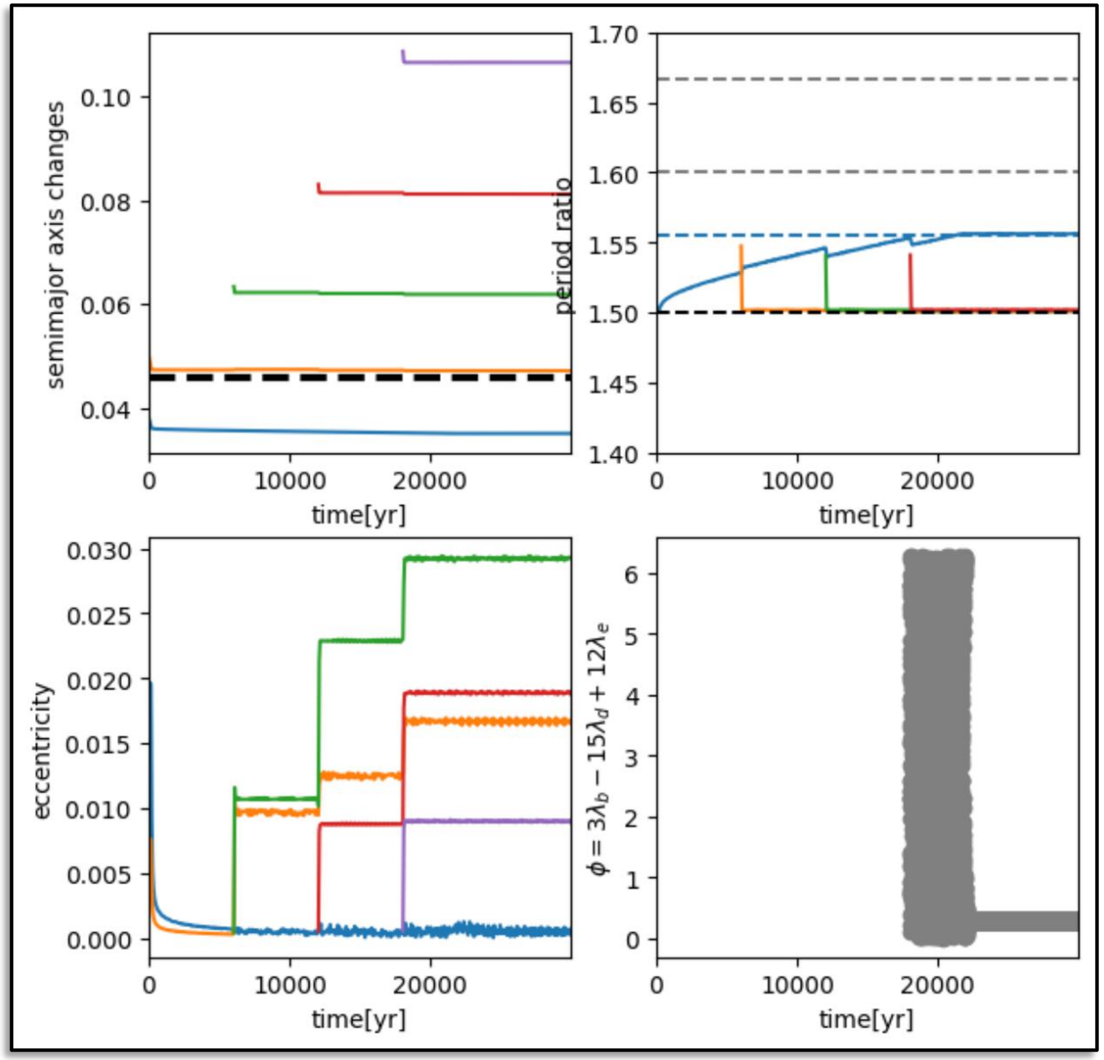

We are also applying our model to more other systems listed here (e.g. HD-158259, TOI-178) and trying to study the potential implification in the statistical level (*Huang et al. in prep*).

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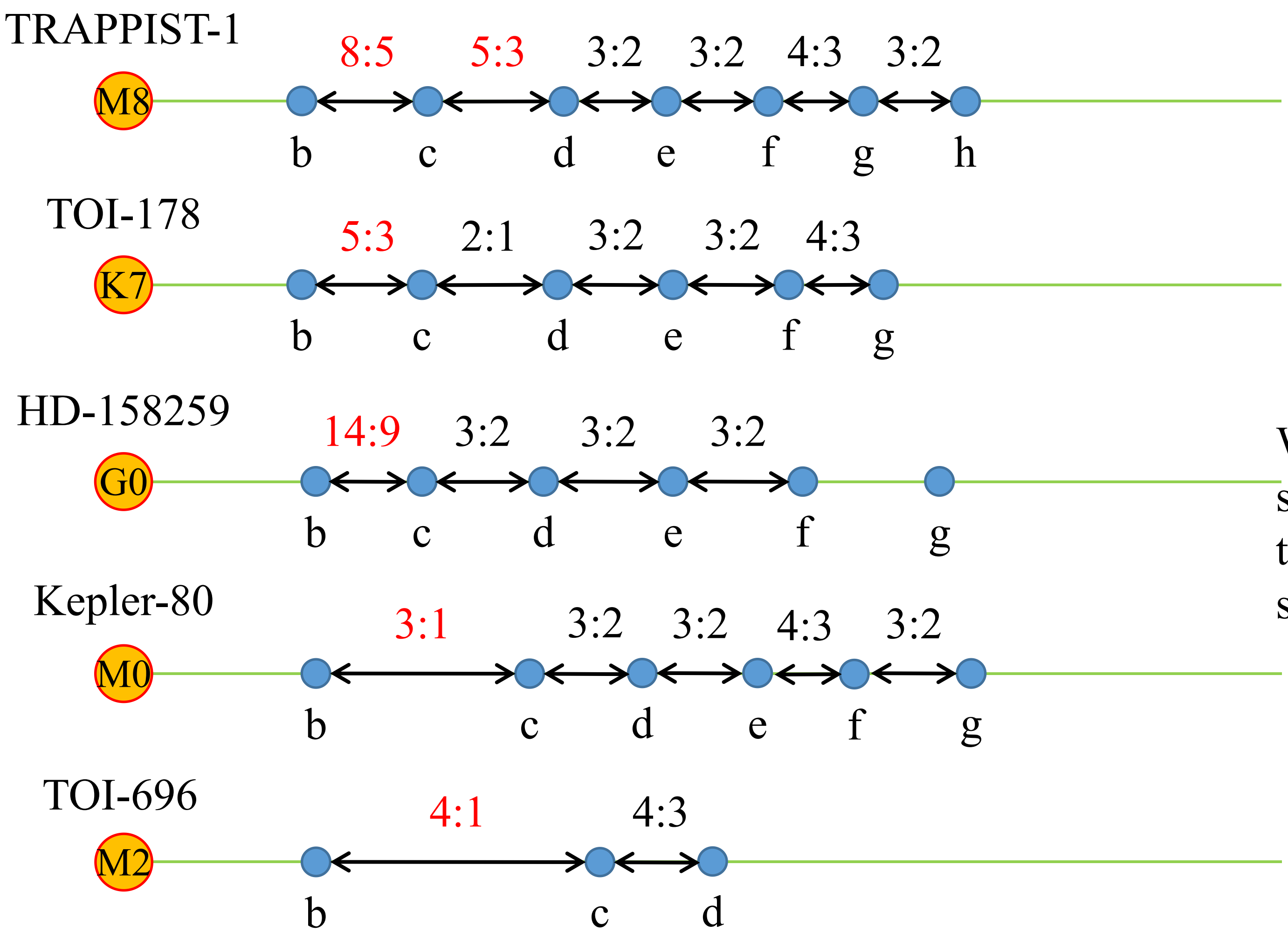

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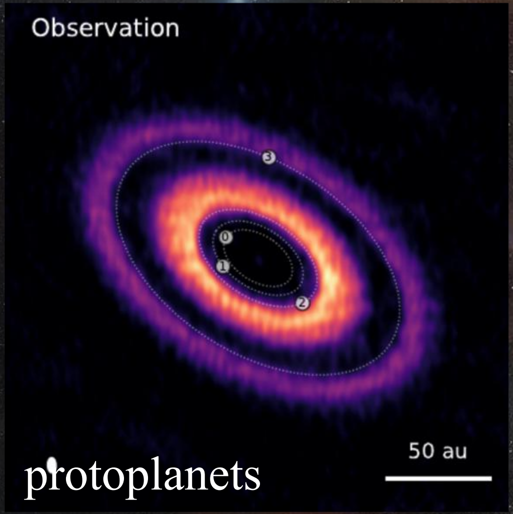
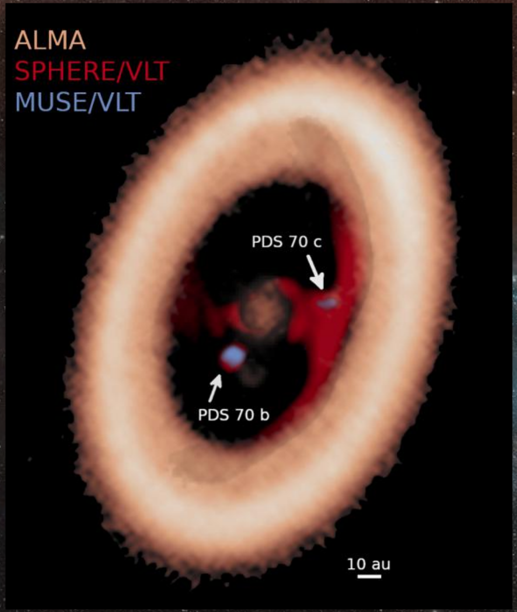
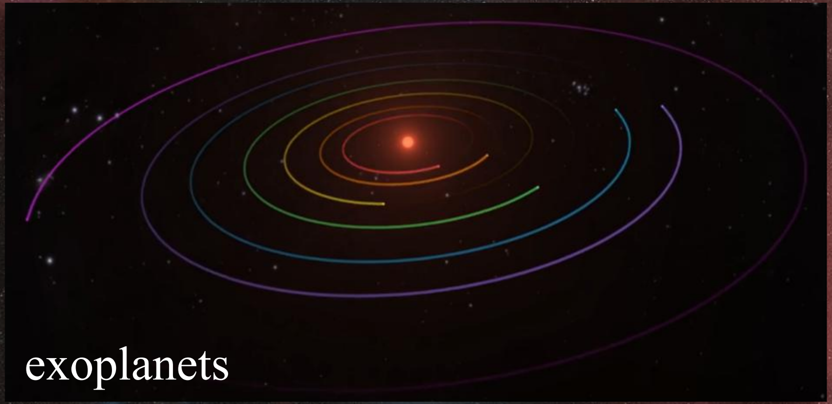
The dynamics of planets across their formation and evolution







Time

References:
[1] ***Huang, S.***, van der Marel, N. & Portegies Zwart, S., On the origin of transition disk cavities: Pebble-accreting protoplanets vs Super-Jupiters, accepted by A&A
[2] ***Huang, S.*** & Ormel, C., When, where, and how many planets end up in first-order resonances?, 2023, MNRAS
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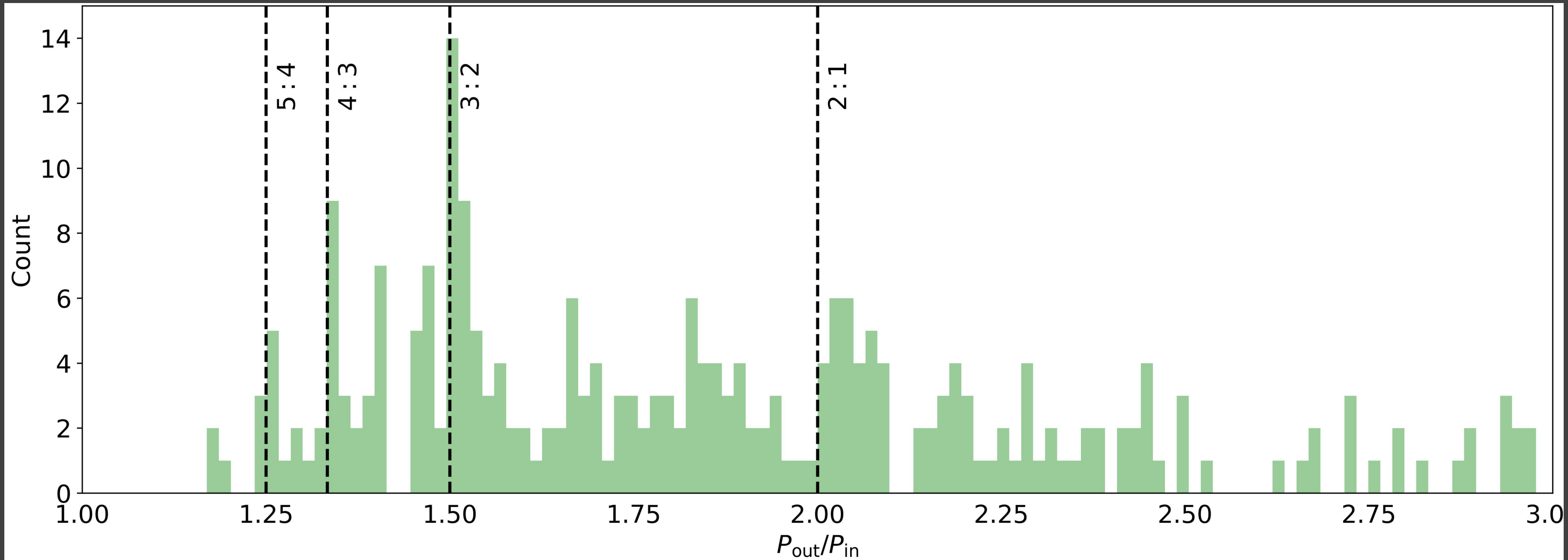
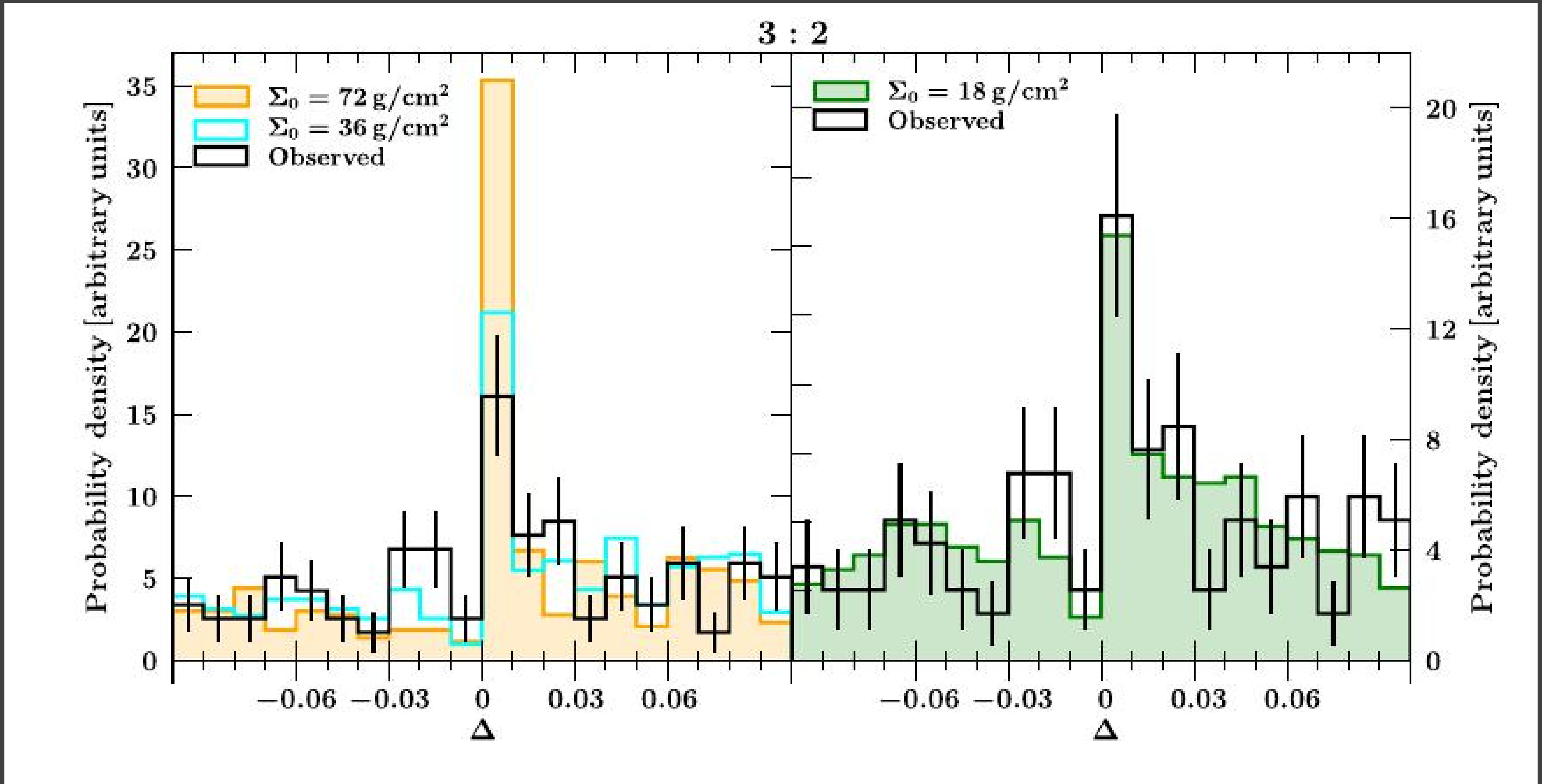
So far so good?

But ... most planets are not in resonance



The period ratio distribution of exoplanets. Only 15% (Huang & Ormel 2023) exoplanets are in resonance.

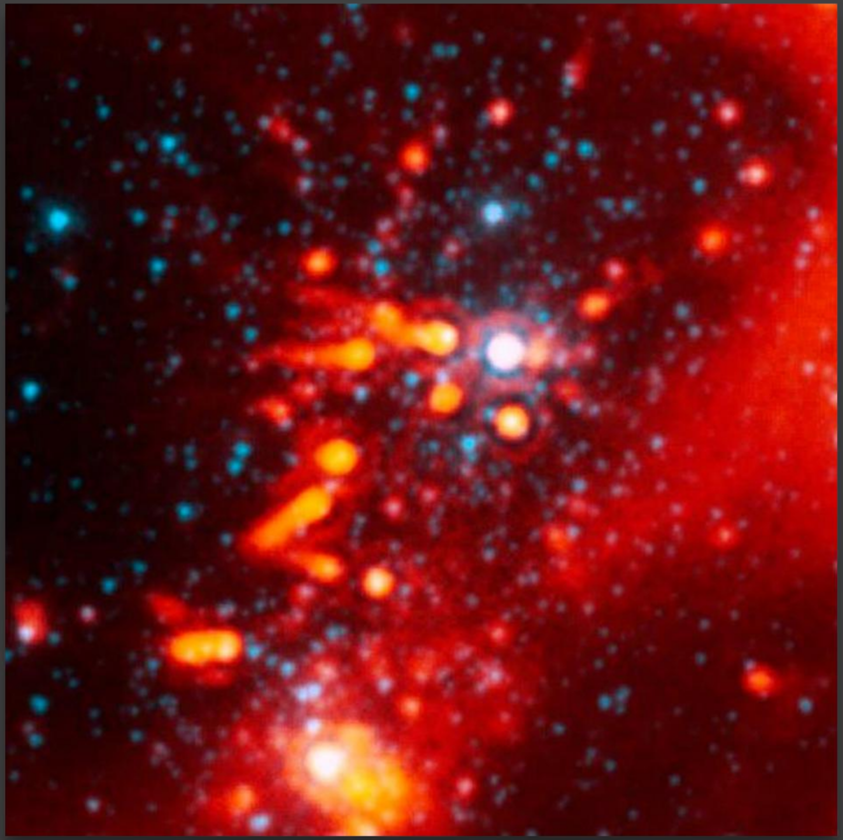
But ... most planets are not in resonance

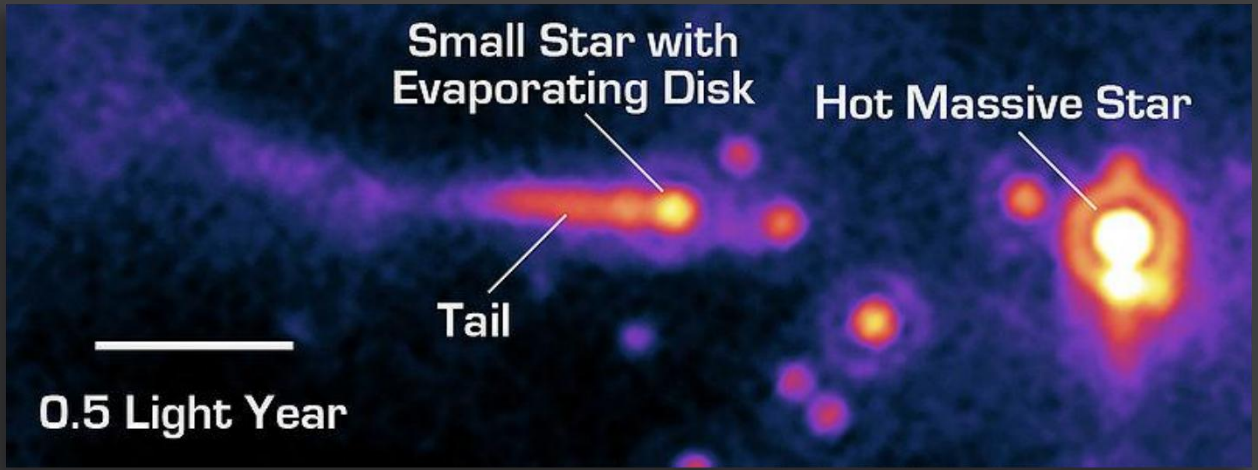


Planets are not in resonance possibly due to:

1. Inefficient migration (e.g., Late planet formation, Choksi&Chiang 2020)
2. Post-disk perturbation

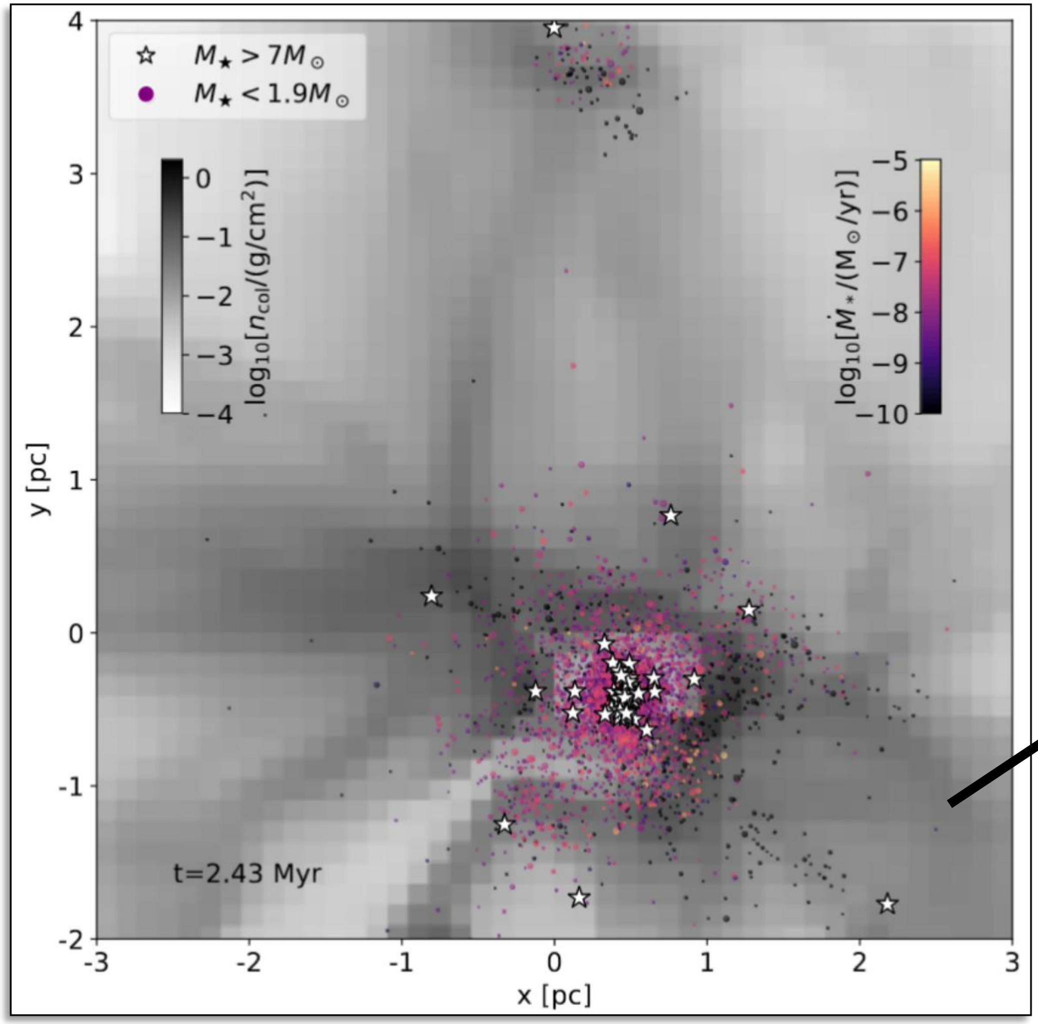
Short disk lifetime

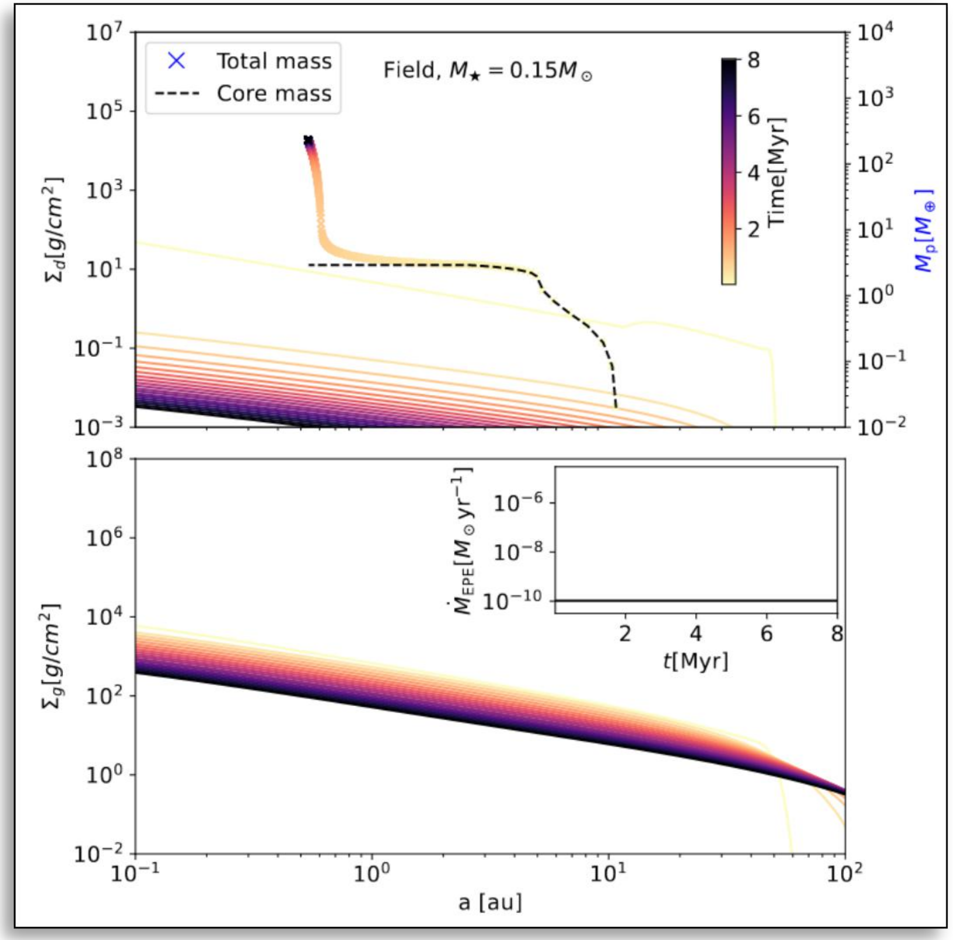




The protoplanetary disks in the star cluster have much shorter disk lifetime than those in isolation.

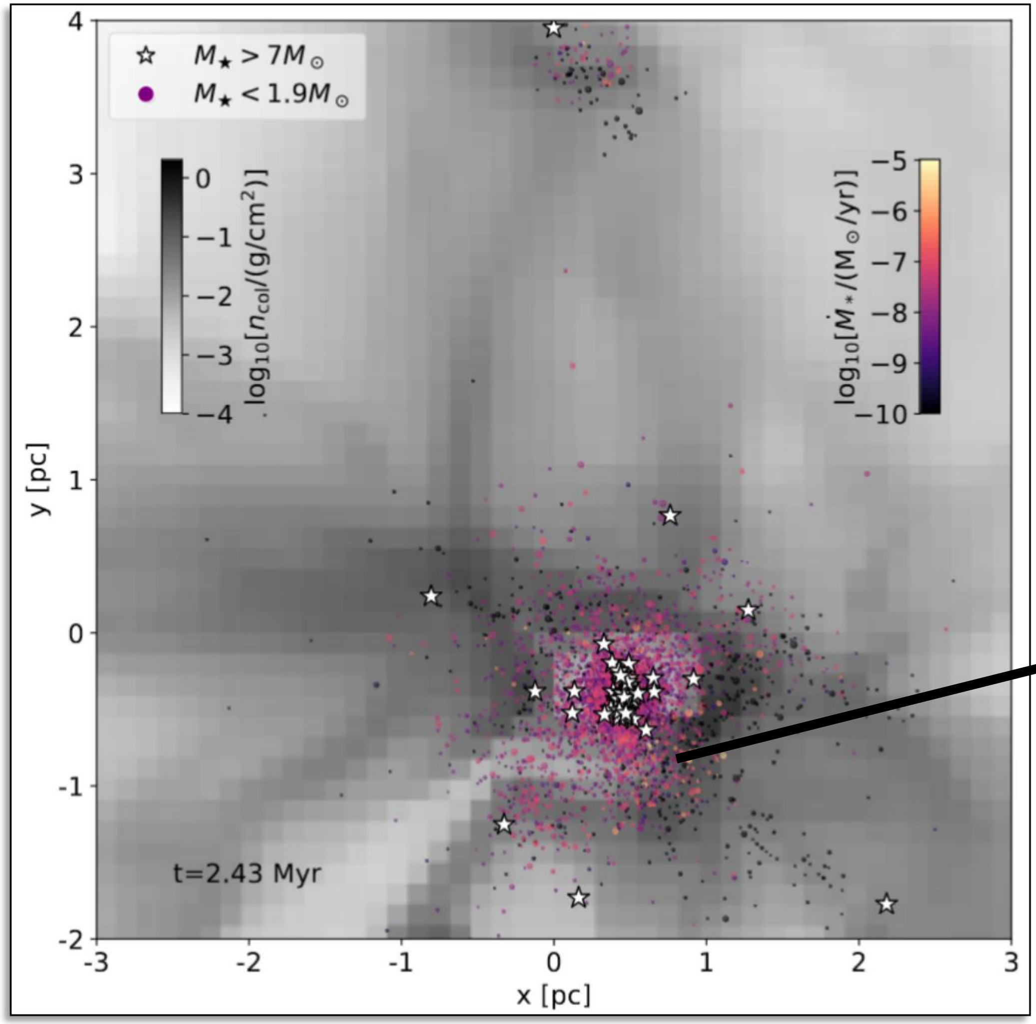
Planet formation in isolation

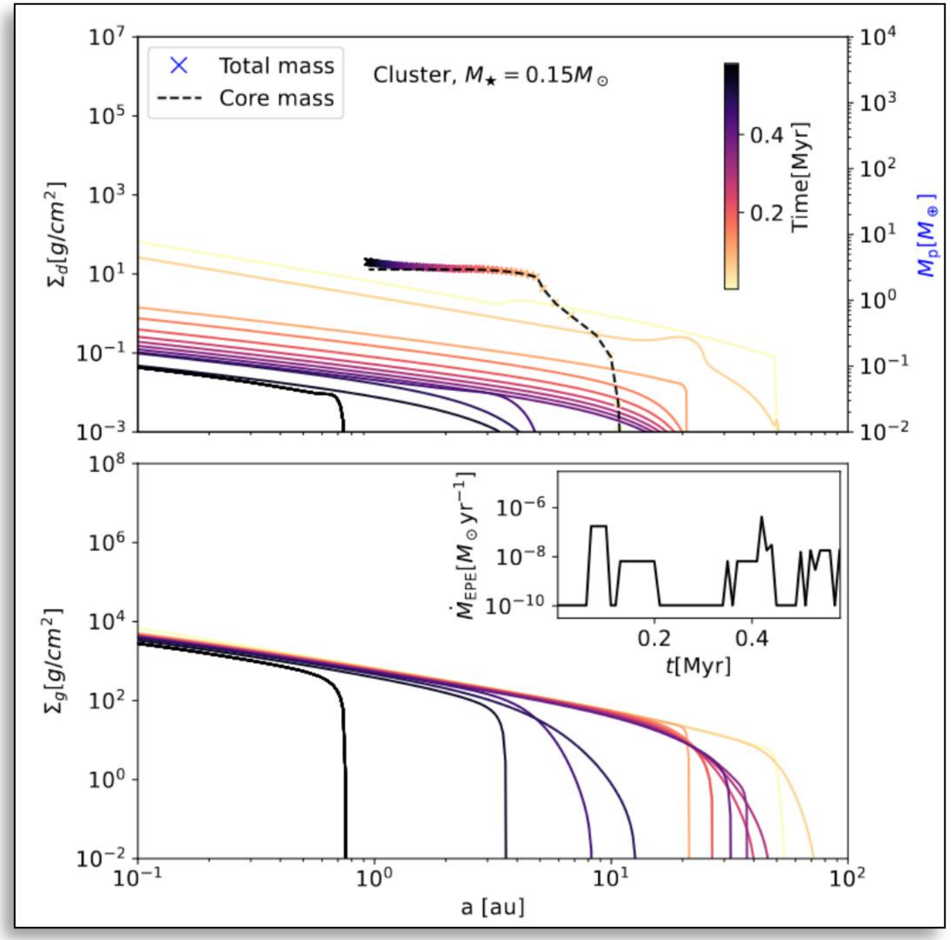




Gas viscous evolution, Dust radial drift, Planet growth (pebble + gas accretion), Planet migration.

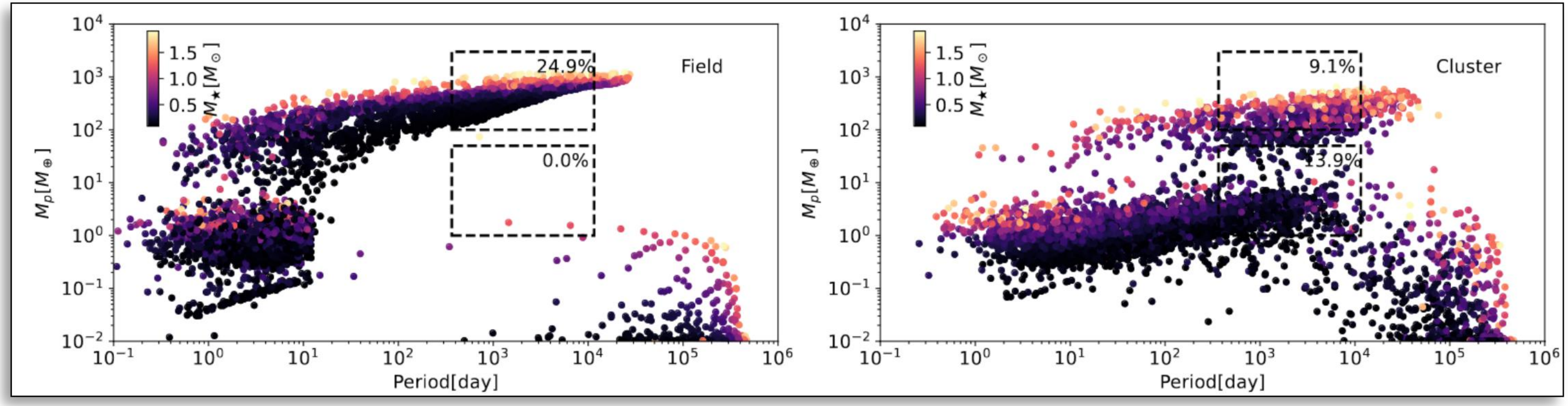
Planet formation in clustered environment





Gas viscous evolution, Dust radial drift, Planet growth (pebble + gas accretion), Planet migration.

Planet population: field & clustered stars



Huang, S. et al. 2024, A&A

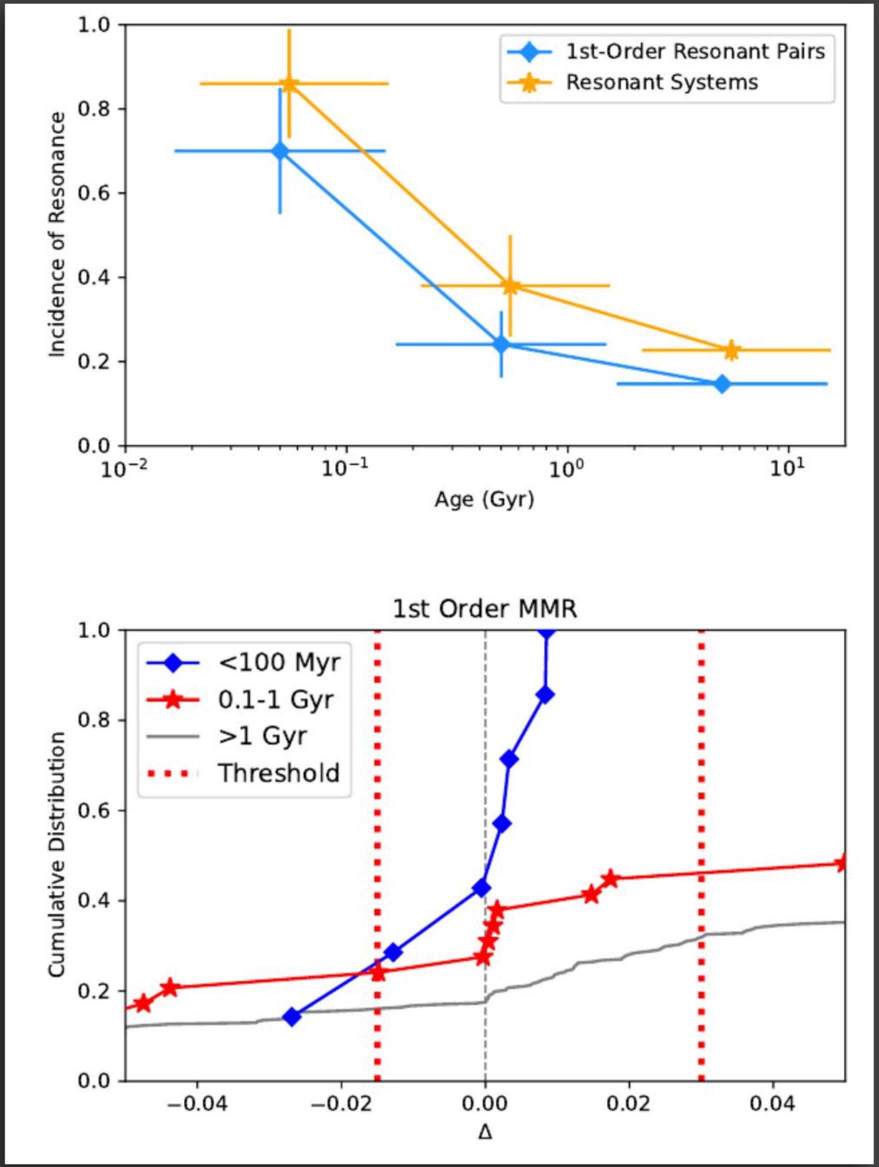
Less cold Jupiters but more cold super-Earths are formed in the star cluster environment (inefficient growth and migration). Planets hardly get trapped into resonance in the clustered environment (still requires more investigation).

But ... most planets are not in resonance

Planets are not in resonance possibly due to:
1. Inefficient migration (e.g., Late planet formation, Choksi&Chiang 2020)
2. Post-disk perturbation

Resonance breaks ~ Gyr (Dai et al. 2024), by e.g., collision with embryos (Li et al. 2024).

Also stellar tides, atmosphere loss can break resonances.



Dai et al. 2024

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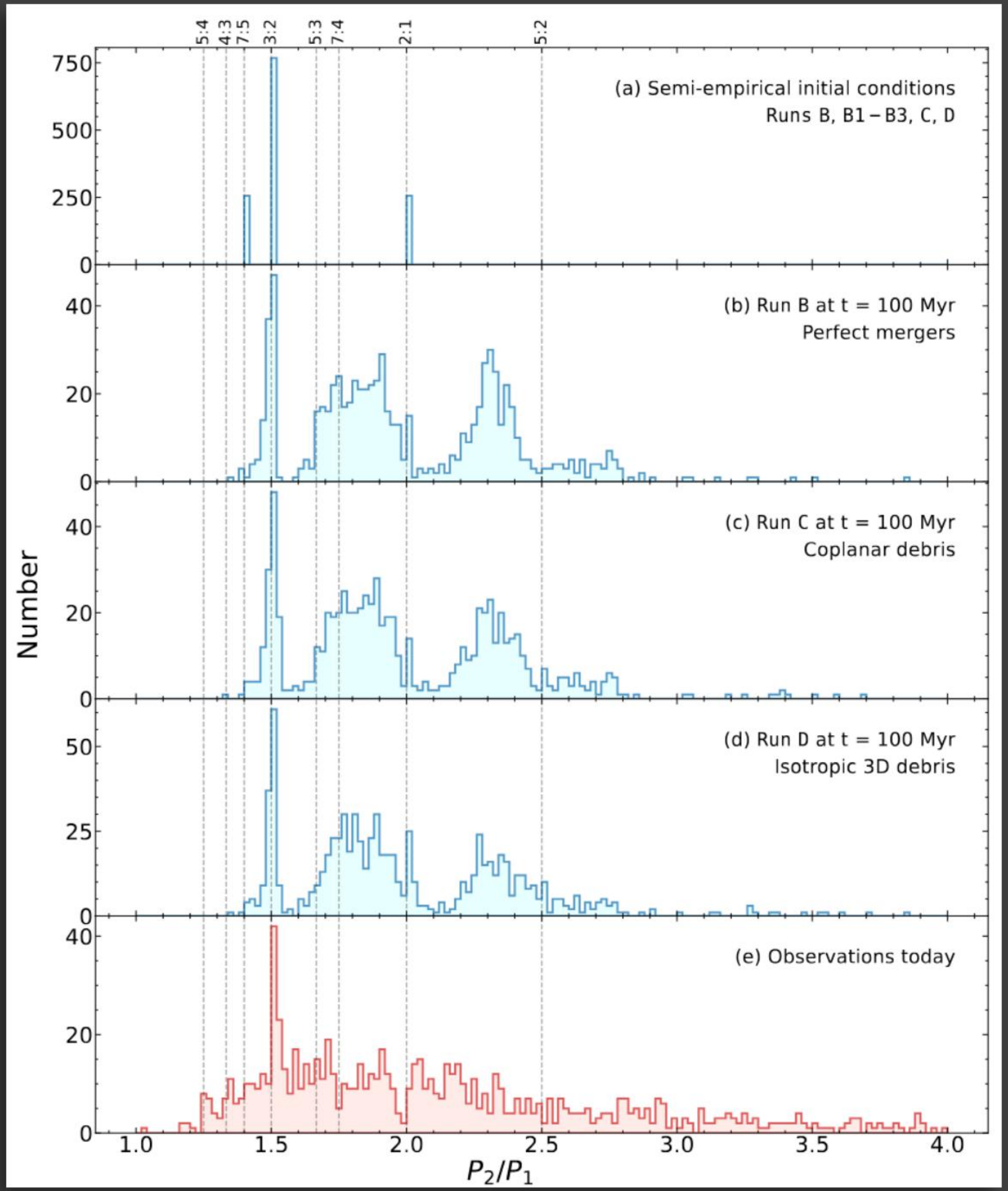
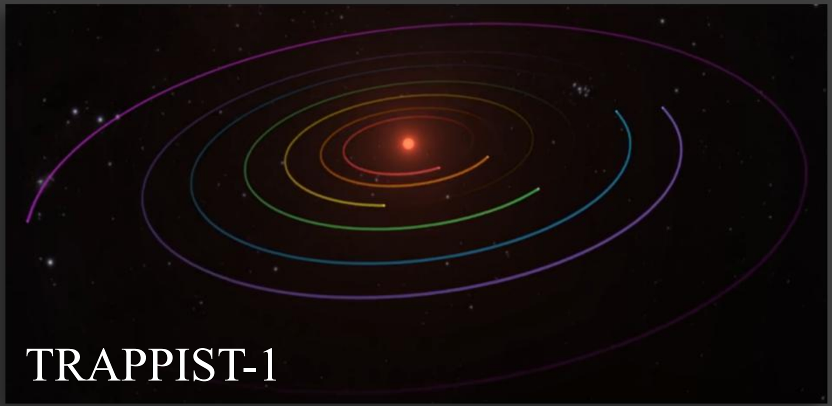
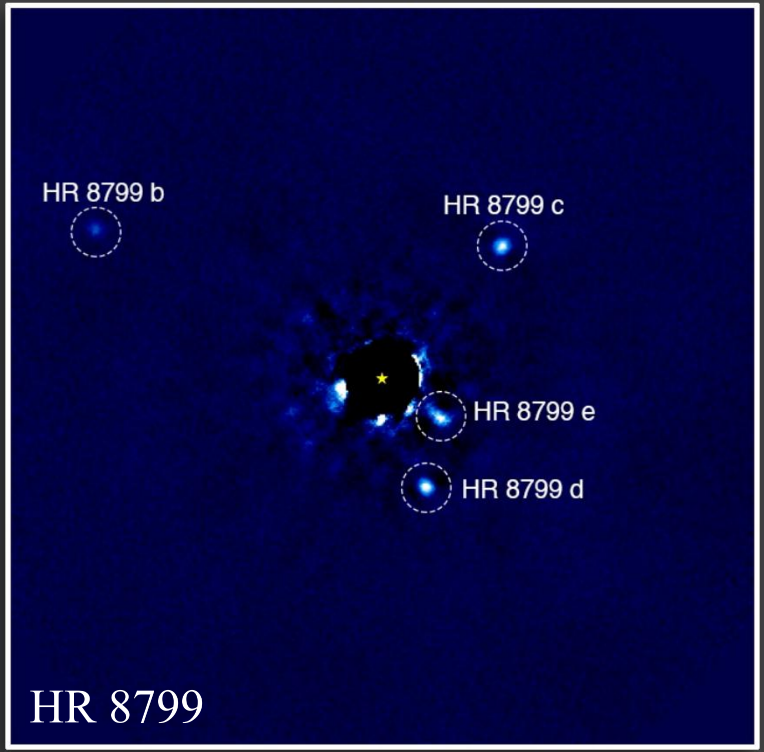


Li et al. 2024 (arxiv e-prints)

Stability of mean-motion resonance chains in the star clusters



<0.1 au, super stable

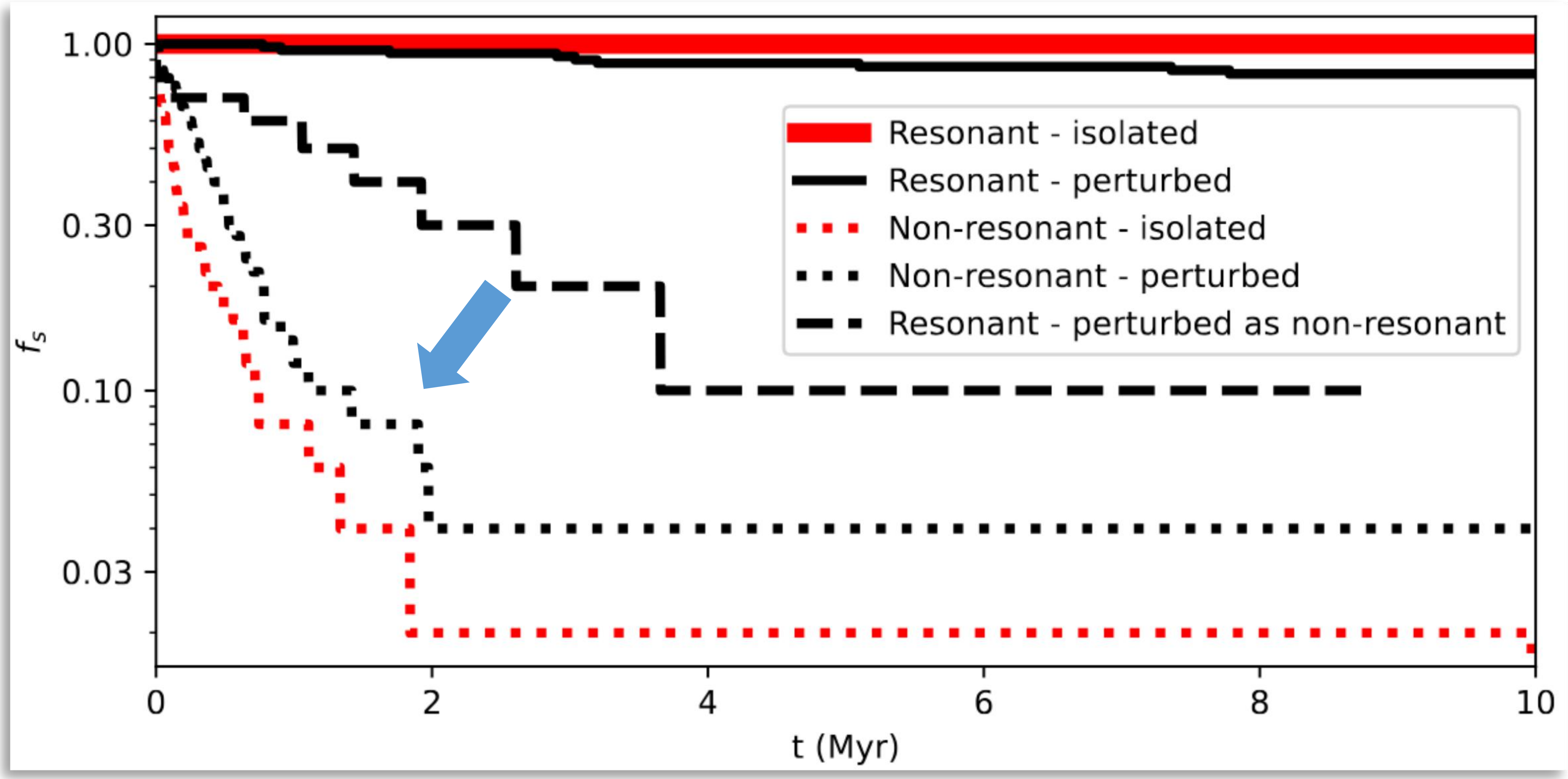


70 au, less stable

Brent Maas, visiting student @Leiden

Maas, B., ***Huang, S.***, Portegies Zwart, S., almost submitted.

Stability of mean-motion resonance chains in the star clusters



Maas, B., ***Huang, S.***, Portegies Zwart, S., almost submitted.

- The four planets in HR8799 must be in resonance, other wise it become unstable after ~ 1Myr
- 20% resonant chain become unstable after 10 Myr, in a cluster of 5000 stars and Plummer radius of 0.7 pc

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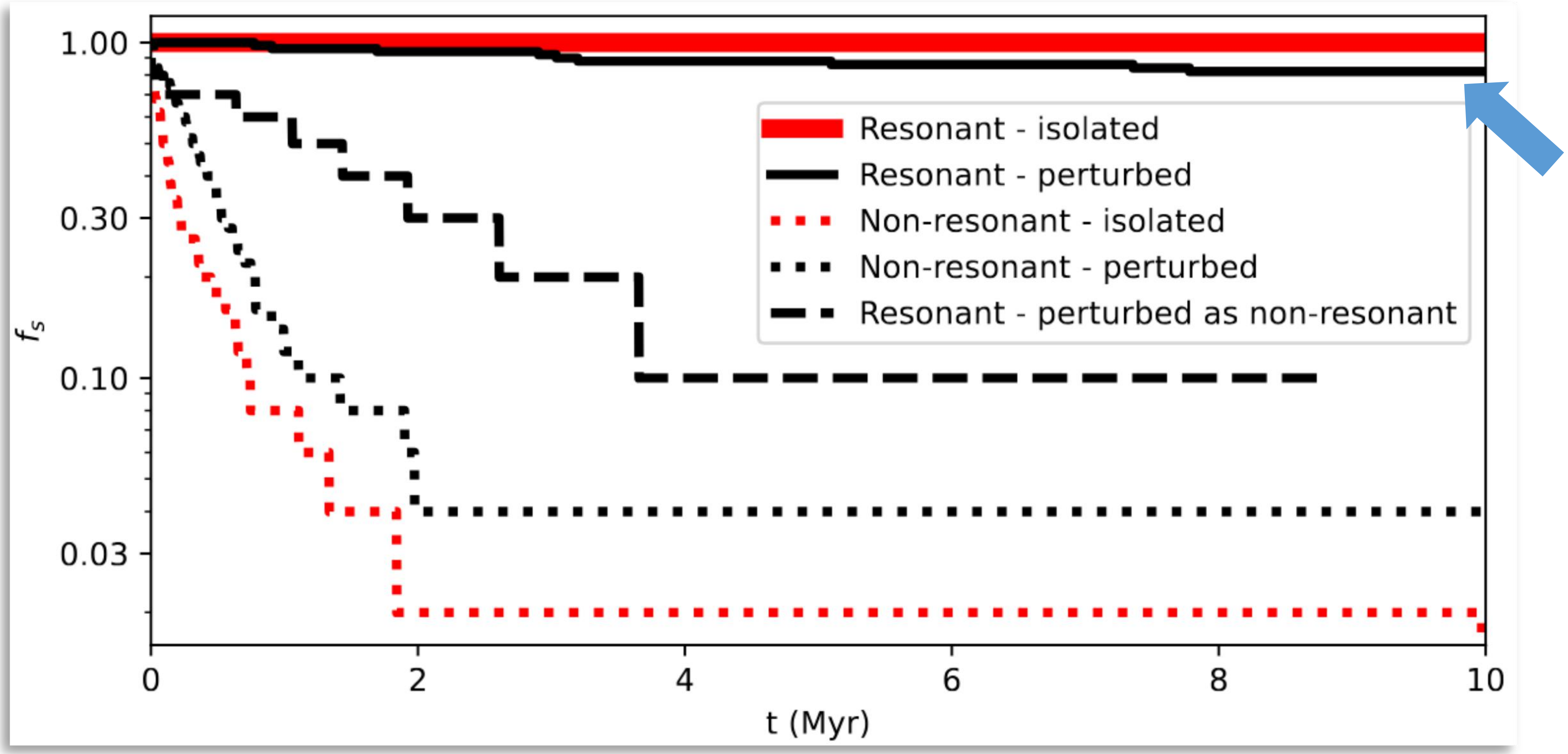

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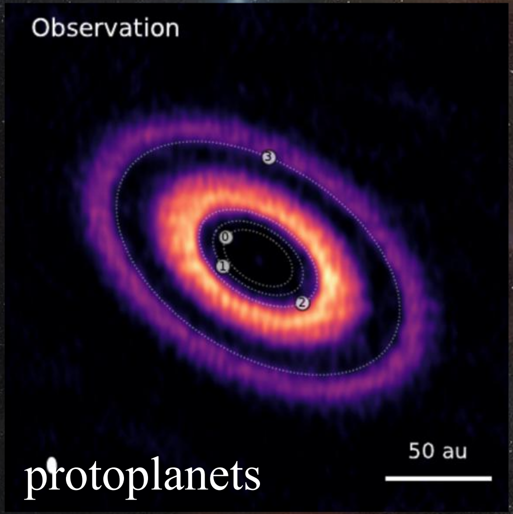
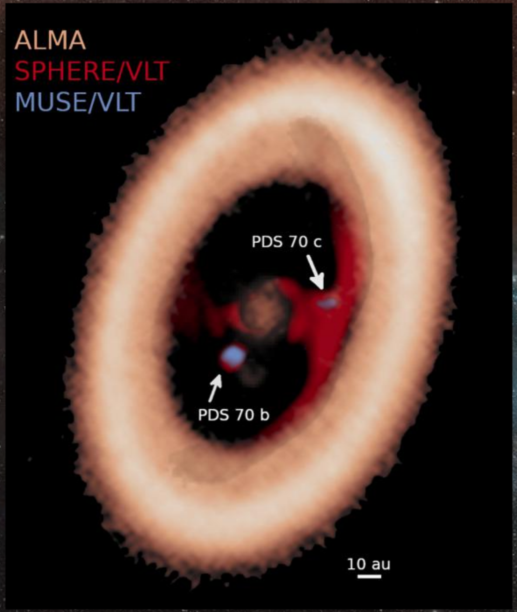
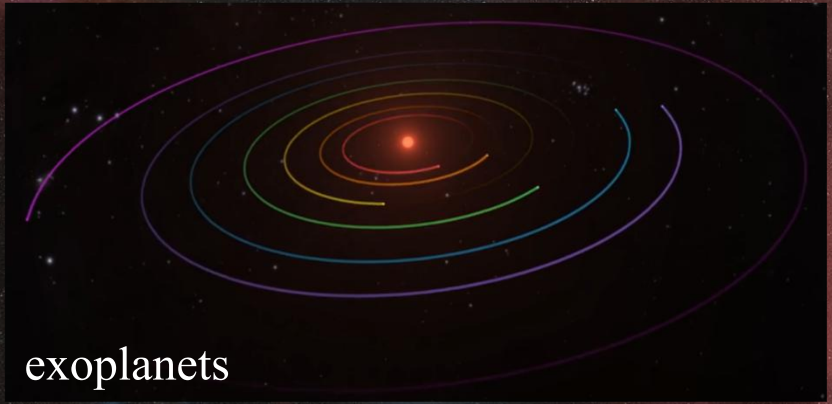
The dynamics of planets across their formation and evolution





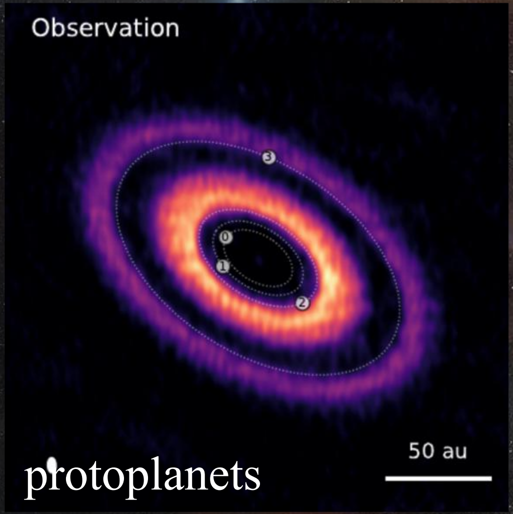


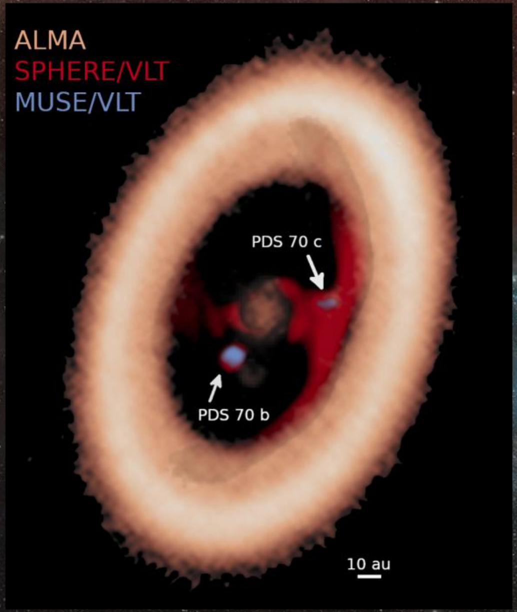
Time

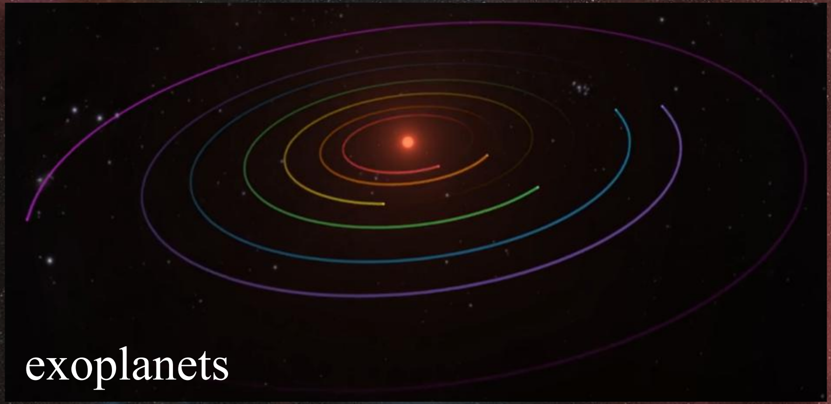
Conclusions:

- The dynamics of planets start to matter in protoplanet disks.
- Resonance capture can be done with moderate planet migration and ecc-damping.
- The formation/migration origin of exoplanet systems can be inferred from dynamical architectures.
- Planet mean motion resonance can break due to inefficient migration, post disk perturbations.

The dynamics of planets across their formation and evolution







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[3] ***Huang, S.***, Ormel, C., The dynamics of the TRAPPIST-1 system in the context of its formation, 2022, MNRAS
[4] ***Huang, S.***, Portegies Zwart, S., Wilhelm, M. Suppression of giant planet formation around low-mass stars in clustered environments, 2024, A&A
[5] Maas, B., ***Huang, S.***, Portegies Zwart, S., Stability of mean-motion resonance chains in wide planetary systems, almost submitted