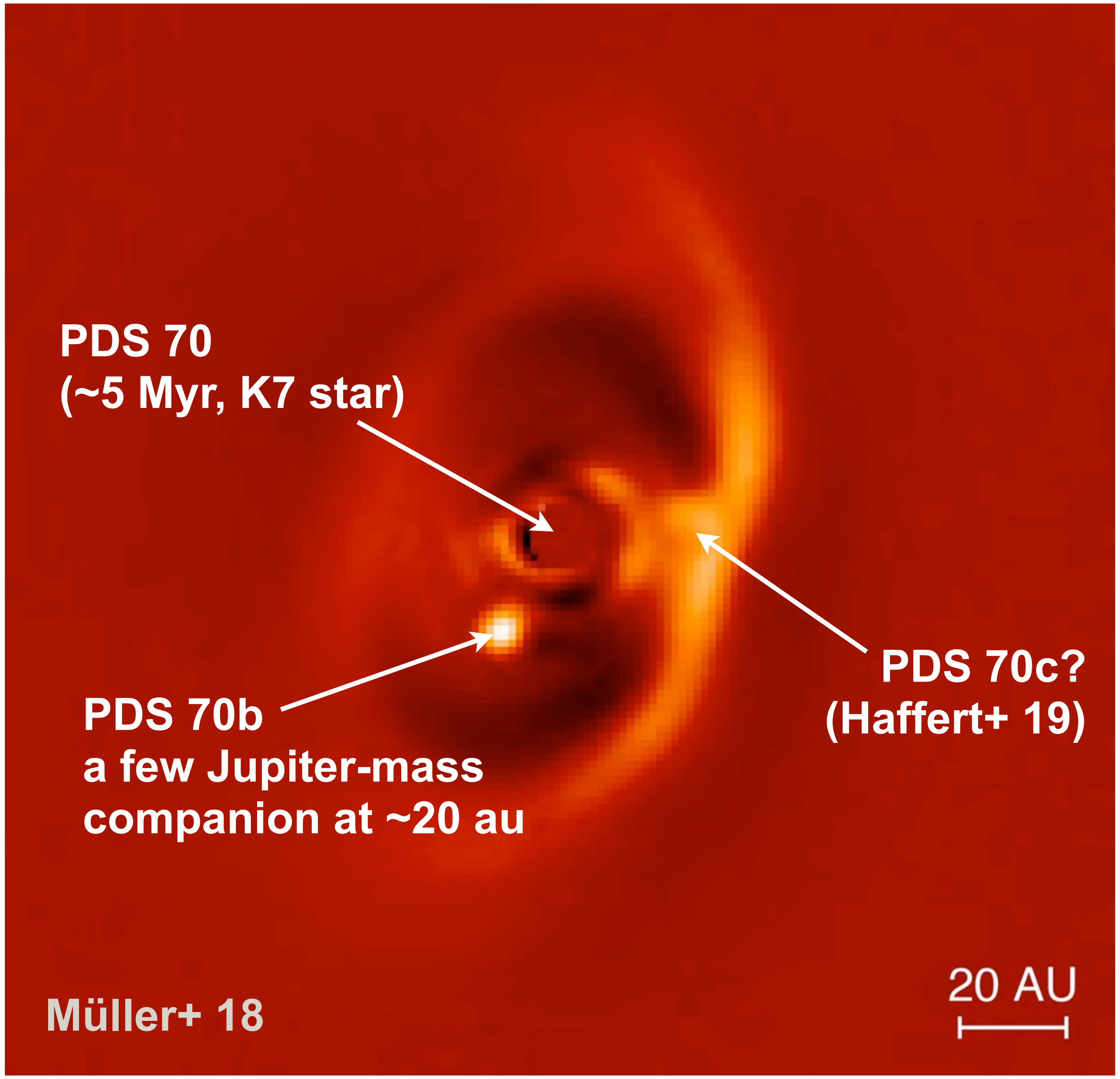
Formation and Orbital Evolution of Young Planetary Systems

Clément Baruteau (CNRS/IRAP, Toulouse)



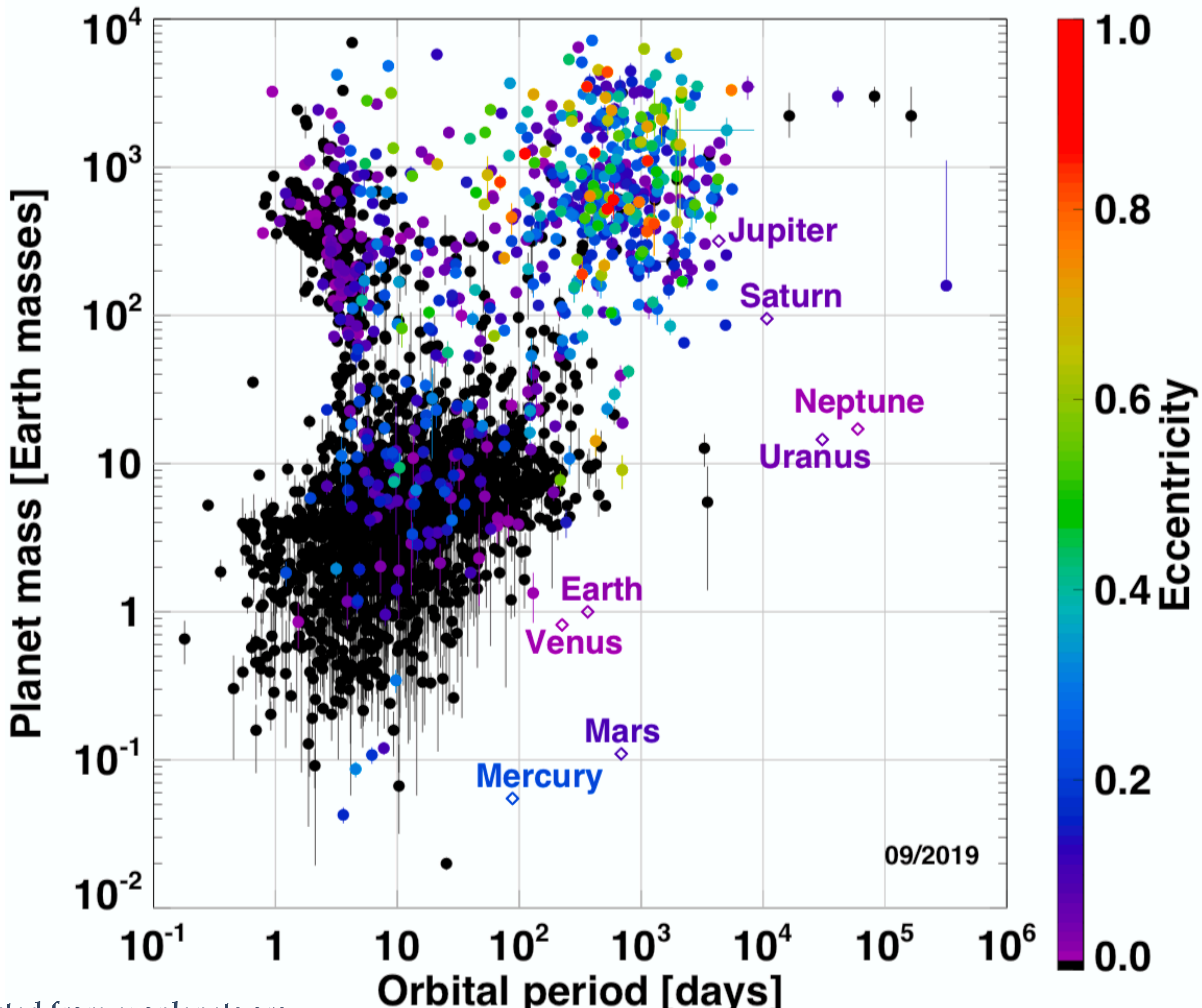
protoplanetary disc around PDS 70 viewed by SPHERE (@~2.1μm)

Outline

- **Observational constraints** (exoplanets, protoplanetary discs)
- Selection of recent **progress** on **theoretical models**
- Why does the **Solar System** look like no other planetary system?

~3200 exoplanets confirmed in 25 years

~1 in 3 are in multiple-planet systems



data extracted from exoplanets.org

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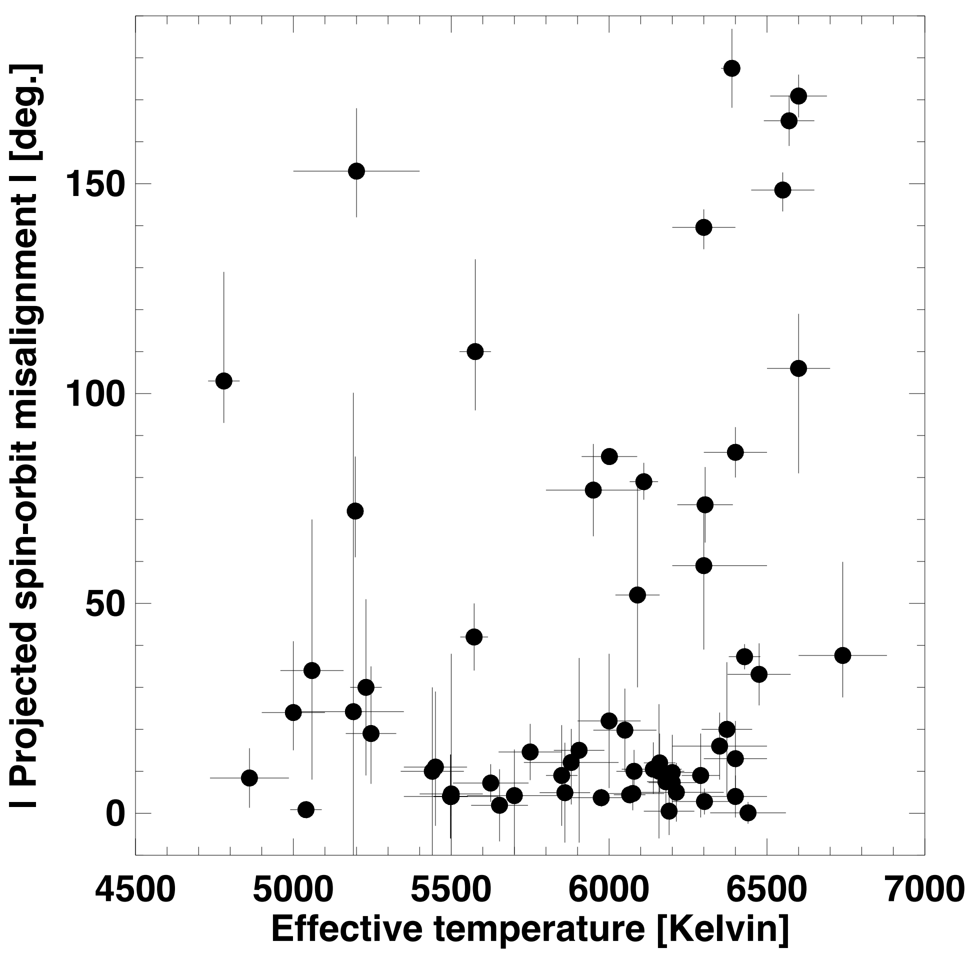
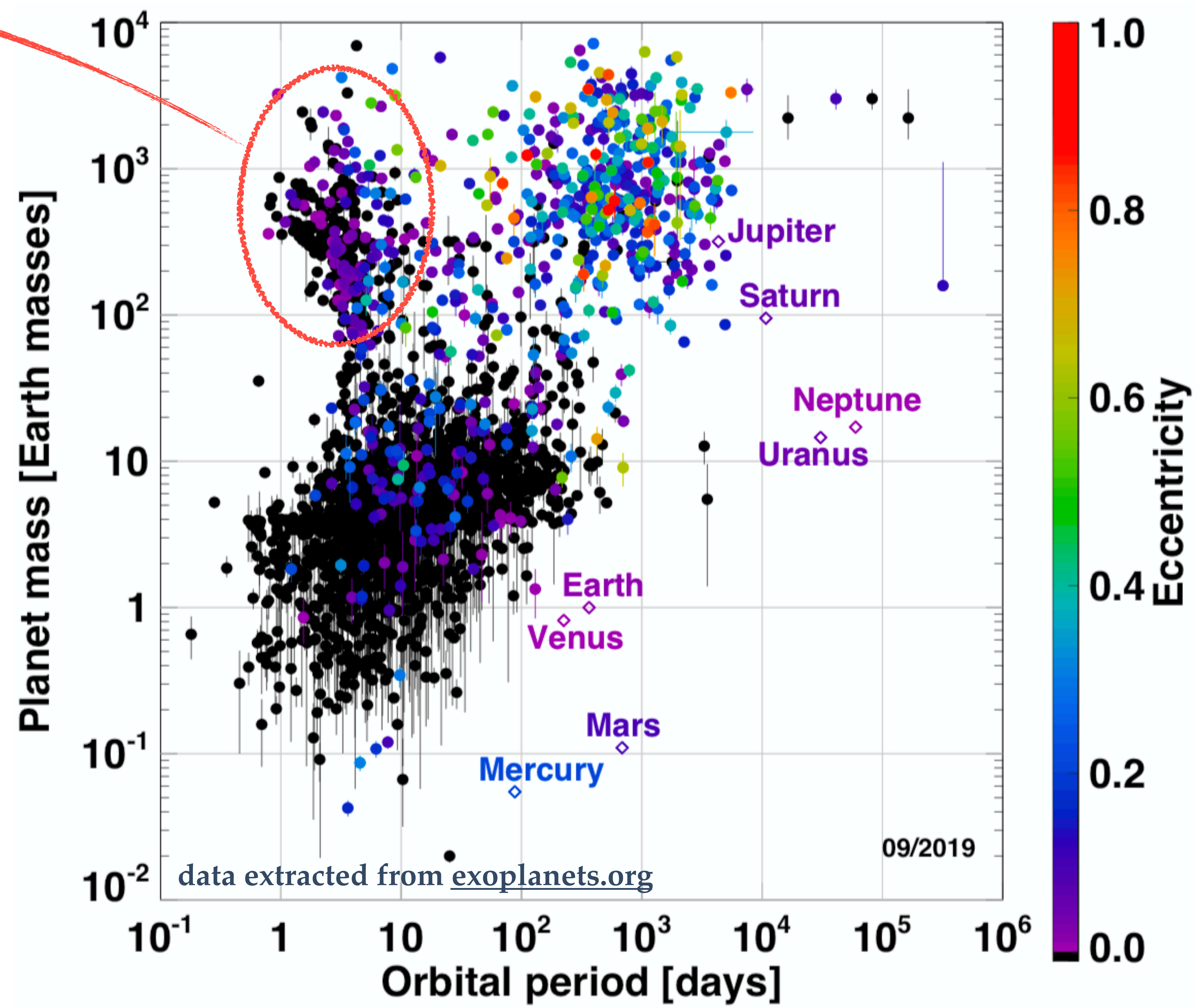
- hot Jupiters
  - found around ~1% of Sun-like stars
    Mayor+ 11, Wright+ 12
  - 2 detections around few Myr stars
    Donati+ 16, Yu+ 17
  - low eccentricity: tidal interactions?
  - ~1 in 3 has large projected obliquity



Baruteau+ 16 (data extracted from TEPCat catalogue)



  - formation channel: in-situ formation? disc migration? dynamical "high-eccentricity" migration?

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- warm Jupiters
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    Cumming+ 08, Mayor+ 11
  - median eccentricity ~0.25: dynamical interactions?

- super Earths
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    eg, Fulton+ 17
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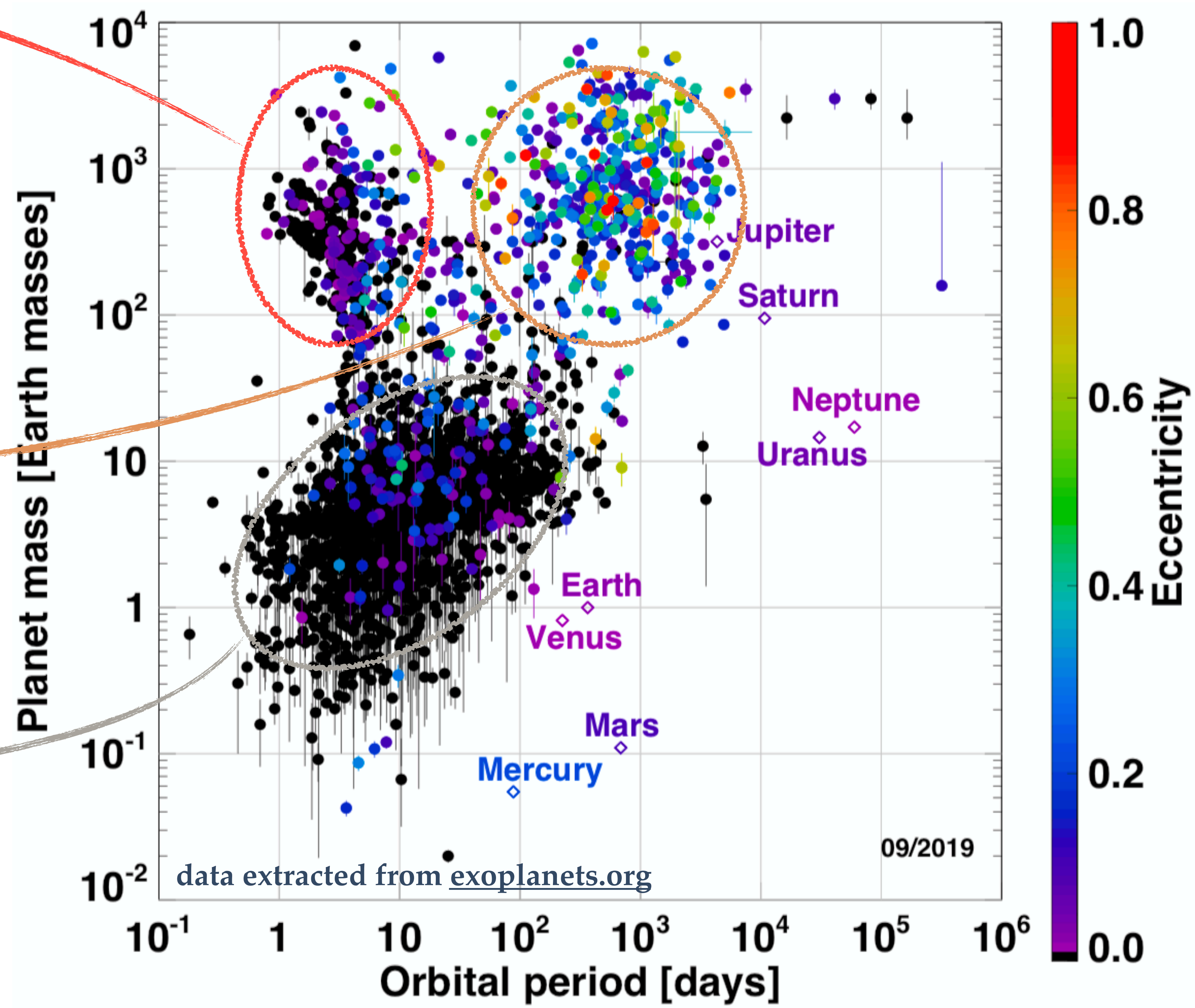

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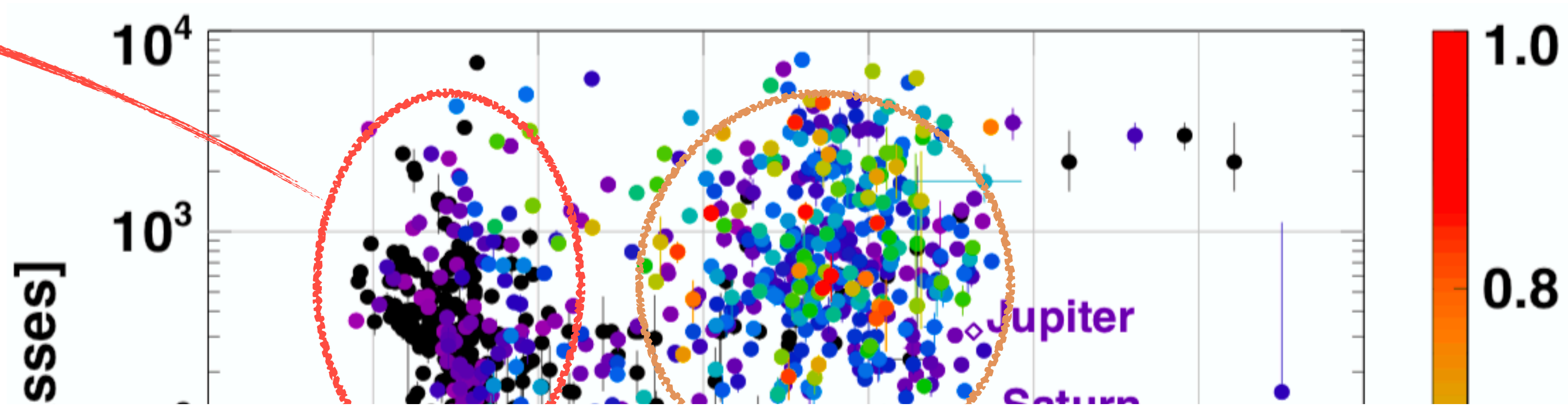
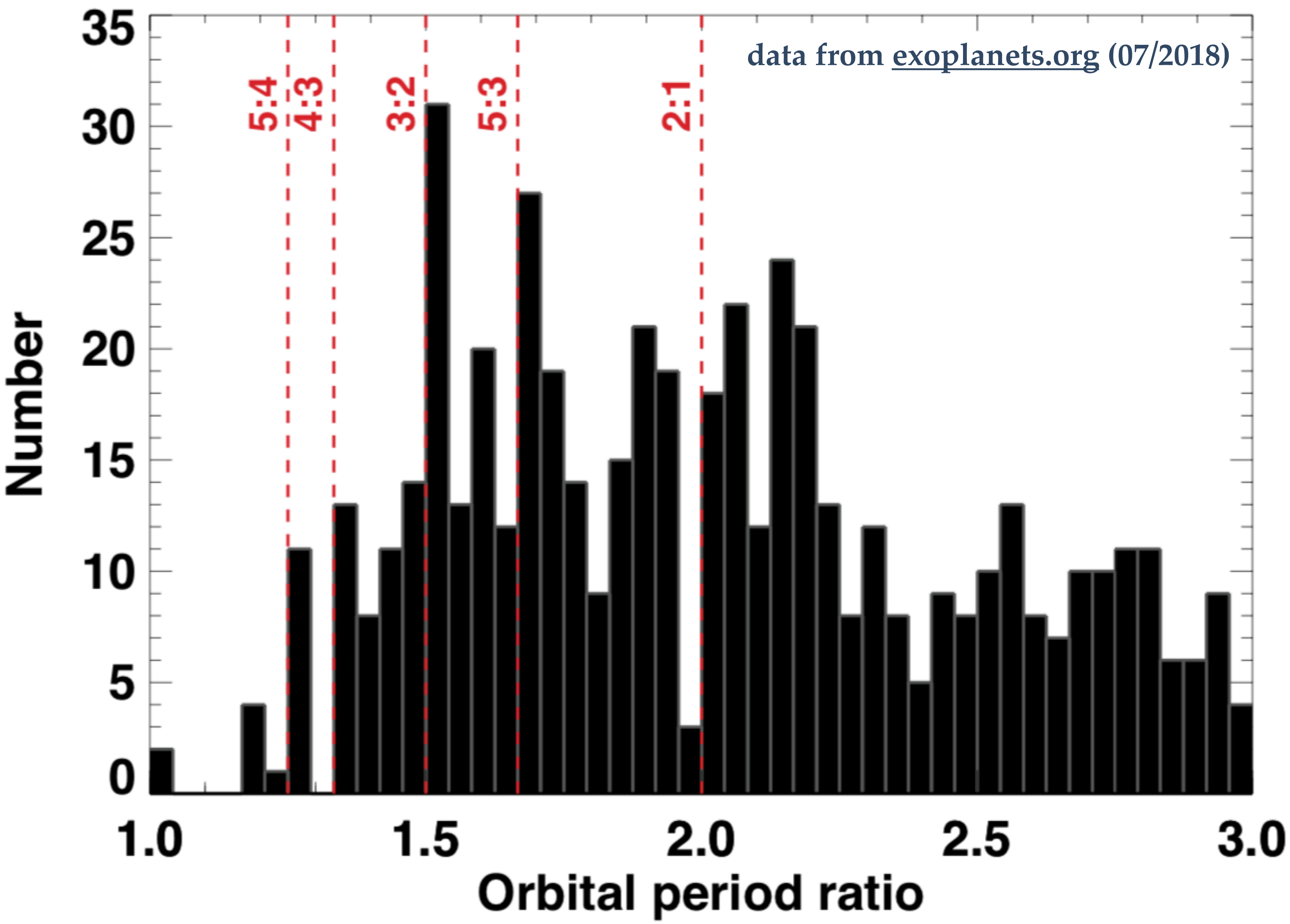
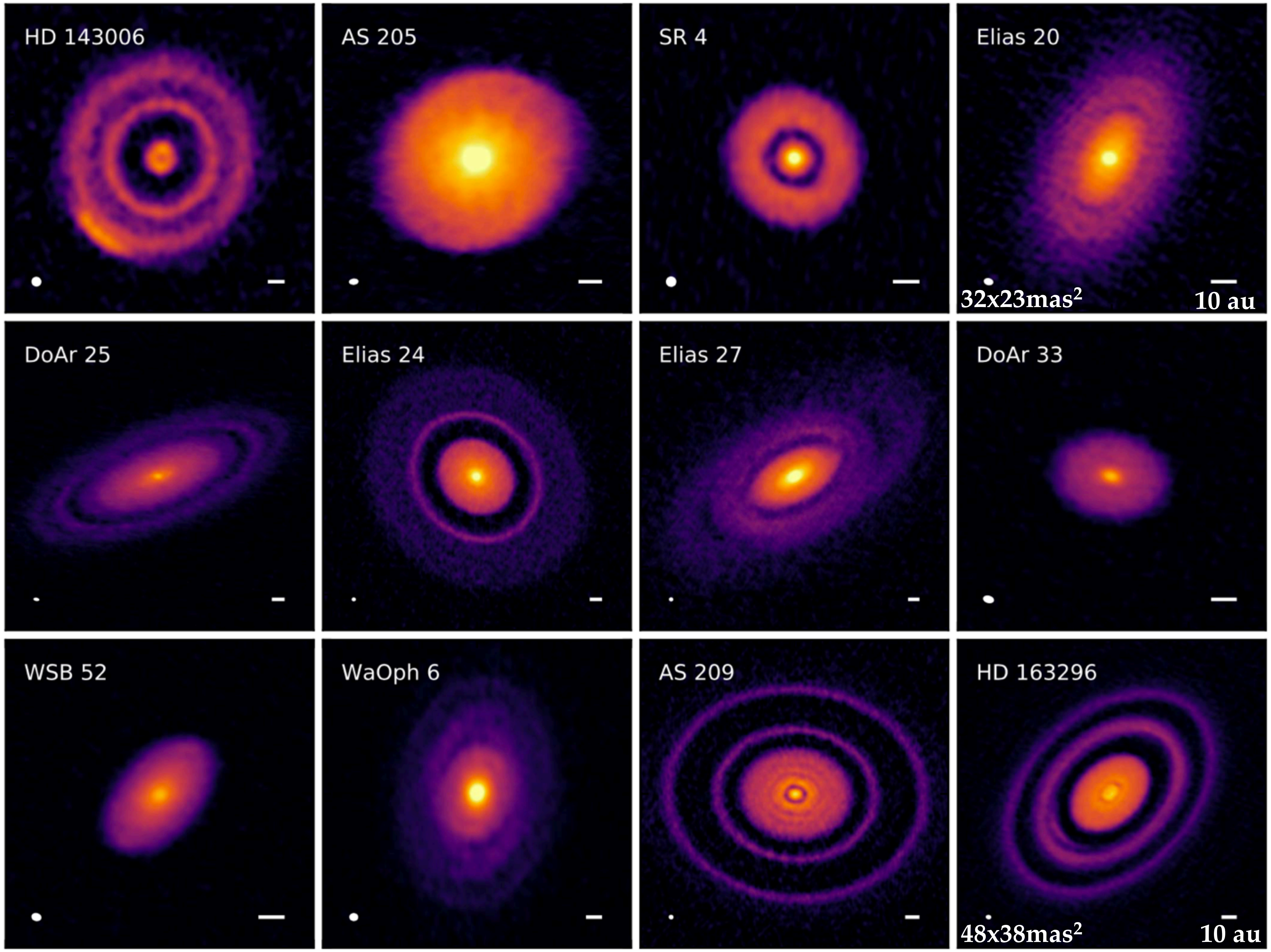
  - orbital period ratio of planet pairs: disc migration vs. in-situ formation





Structures in the emission of protoplanetary discs



Andrews+ 18 (ALMA@1.3mm)

- what structures are **indirect** signatures of planets?
- if planets, except in the PDS 70 disc, why don't we see them **directly**? Would these structures **constrain** planet **formation** or **migration**?

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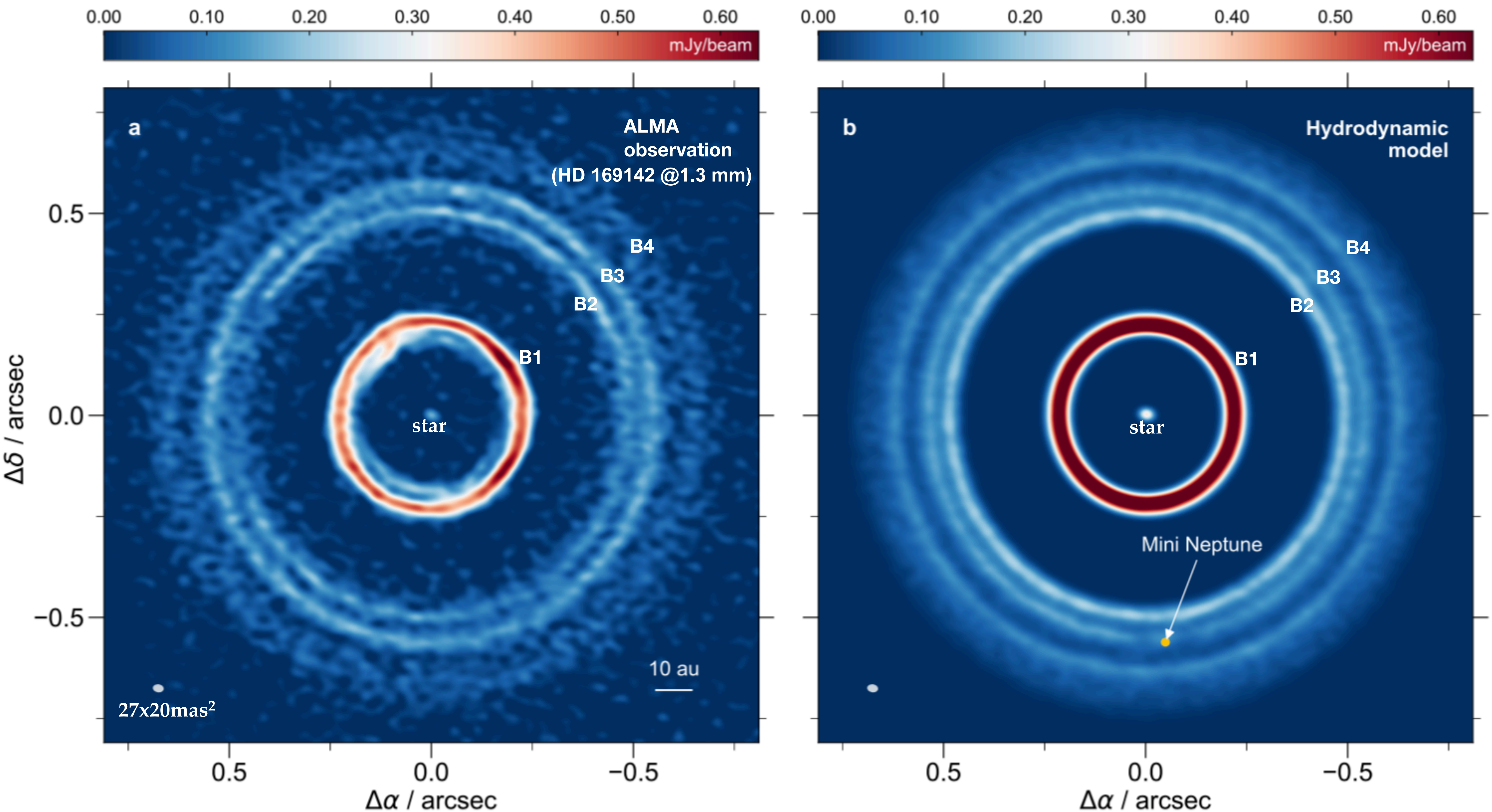
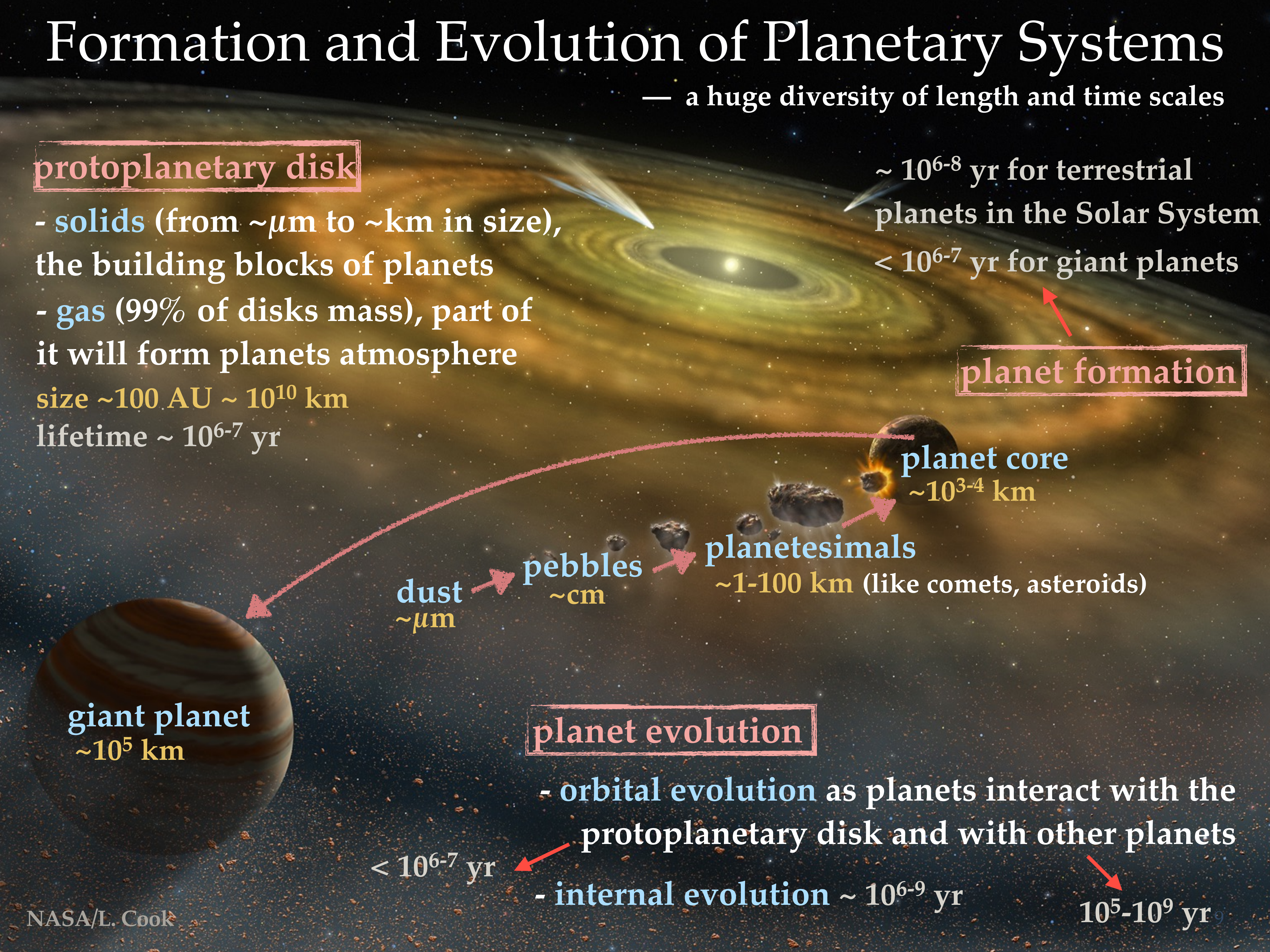


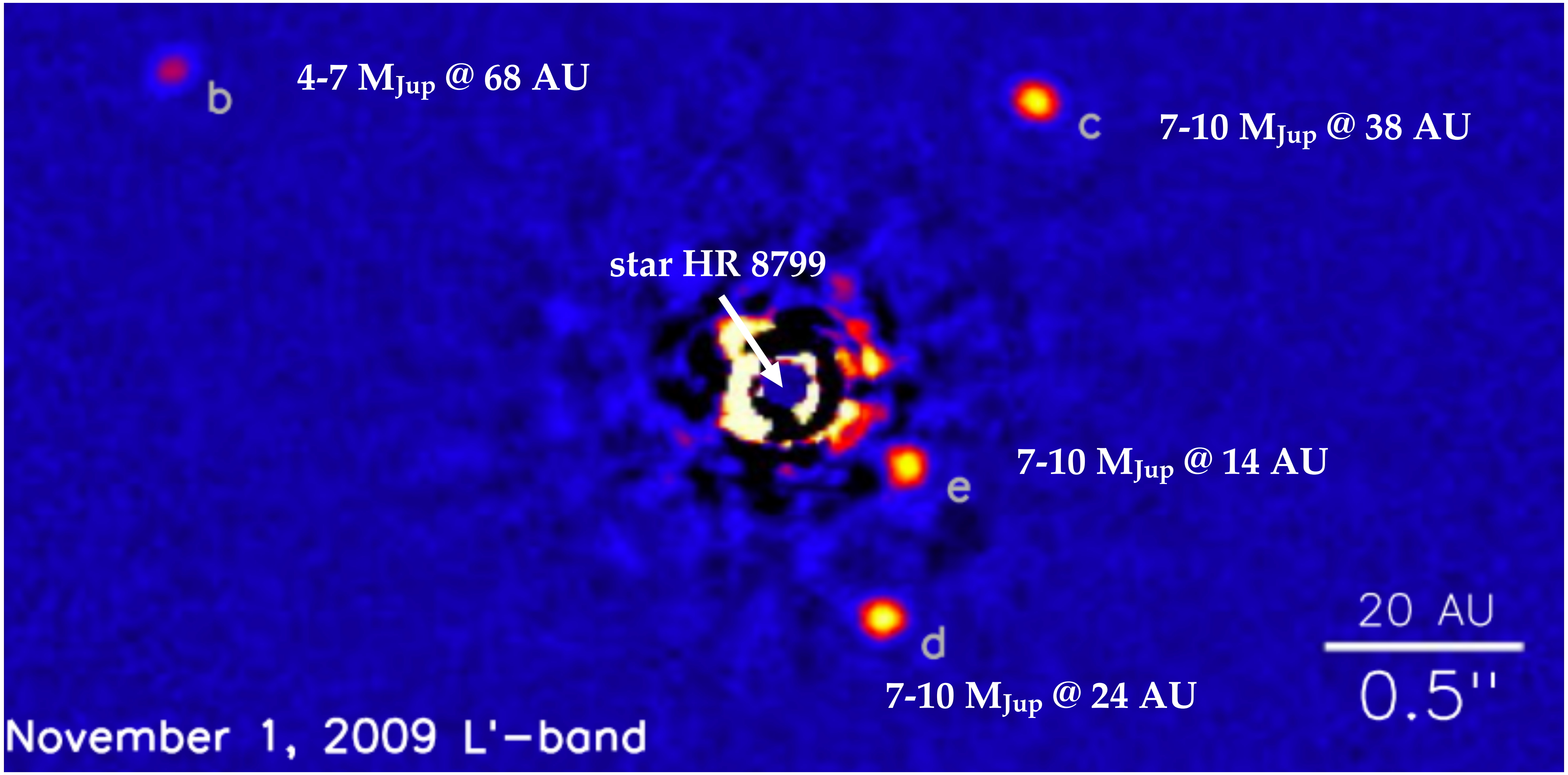
Pérez+ 19

→ **radial asymmetry** of the fine **rings** B2, B3, B4 could spot an **inward-migrating mini Neptune**


Formation and Evolution of Planetary Systems
— a huge diversity of length and time scales
protoplanetary disk
- solids (from ~μm to ~km in size), the building blocks of planets
- gas (99% of disks mass), part of it will form planets atmosphere
size ~100 AU ~ 10^10 km
lifetime ~ 10^6-7 yr
~ 10^6-8 yr for terrestrial planets in the Solar System
< 10^6-7 yr for giant planets
planet formation
planet core
~10^3-4 km
dust
~μm
pebbles
~cm
planetesimals
~1-100 km (like comets, asteroids)
giant planet
~10^5 km
planet evolution
- orbital evolution as planets interact with the protoplanetary disk and with other planets
< 10^6-7 yr
- internal evolution ~ 10^6-9 yr
10^5-10^9 yr
NASA/L. Cook

Recent progress in theoretical models (selection)

- Planetary **formation**: **planetesimal** vs. **pebble** accretion
  - the conventional mechanism of planetesimal growth by accretion of other planetesimals cannot form **giant** planets at **large orbital separations** (≳ 10 AU: growth is **too slow!**)



Marois+ 10

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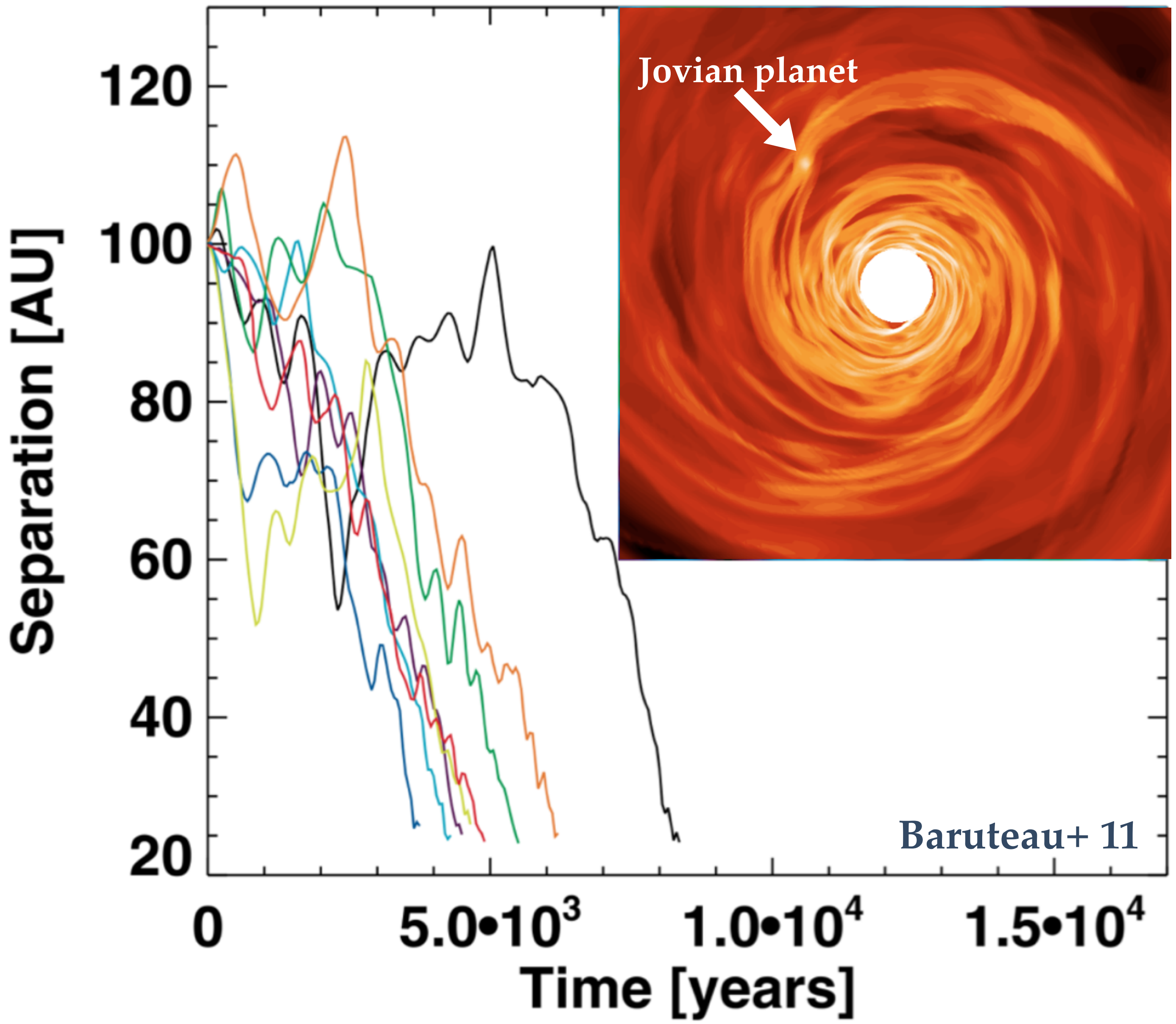

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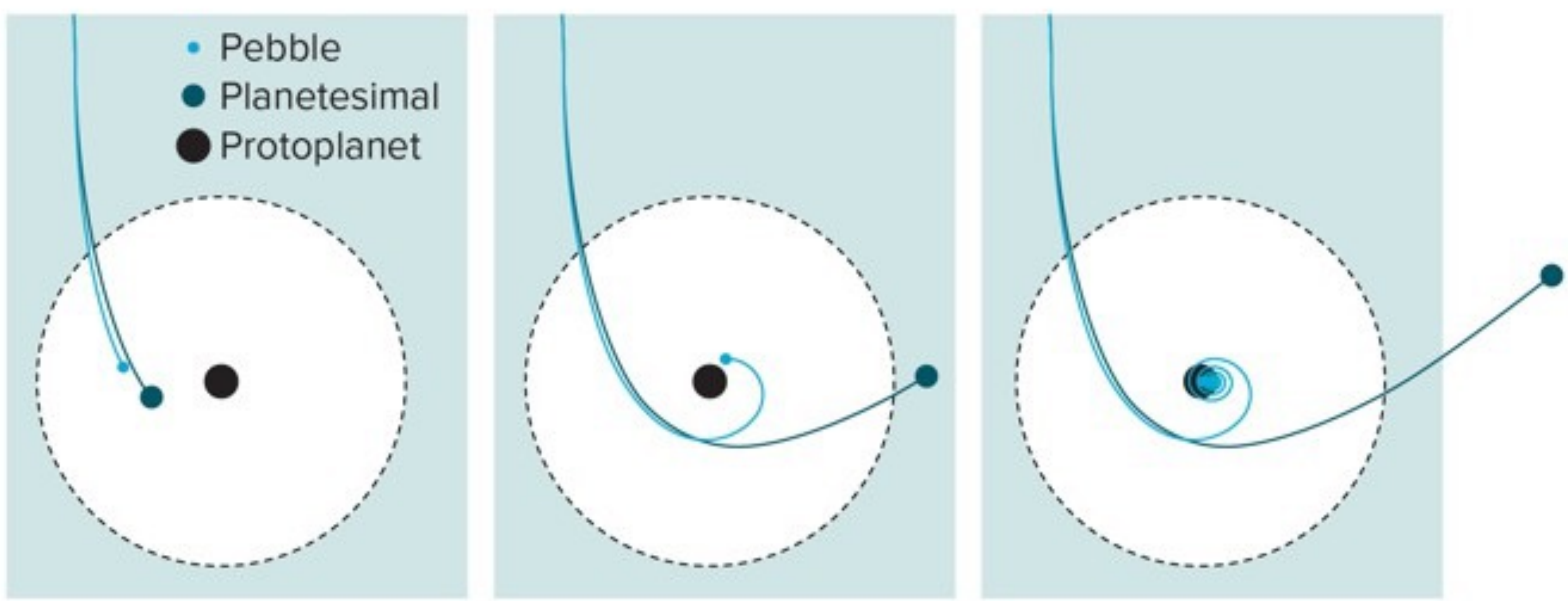

Lambrechts & Johansen / Modica / Knowable

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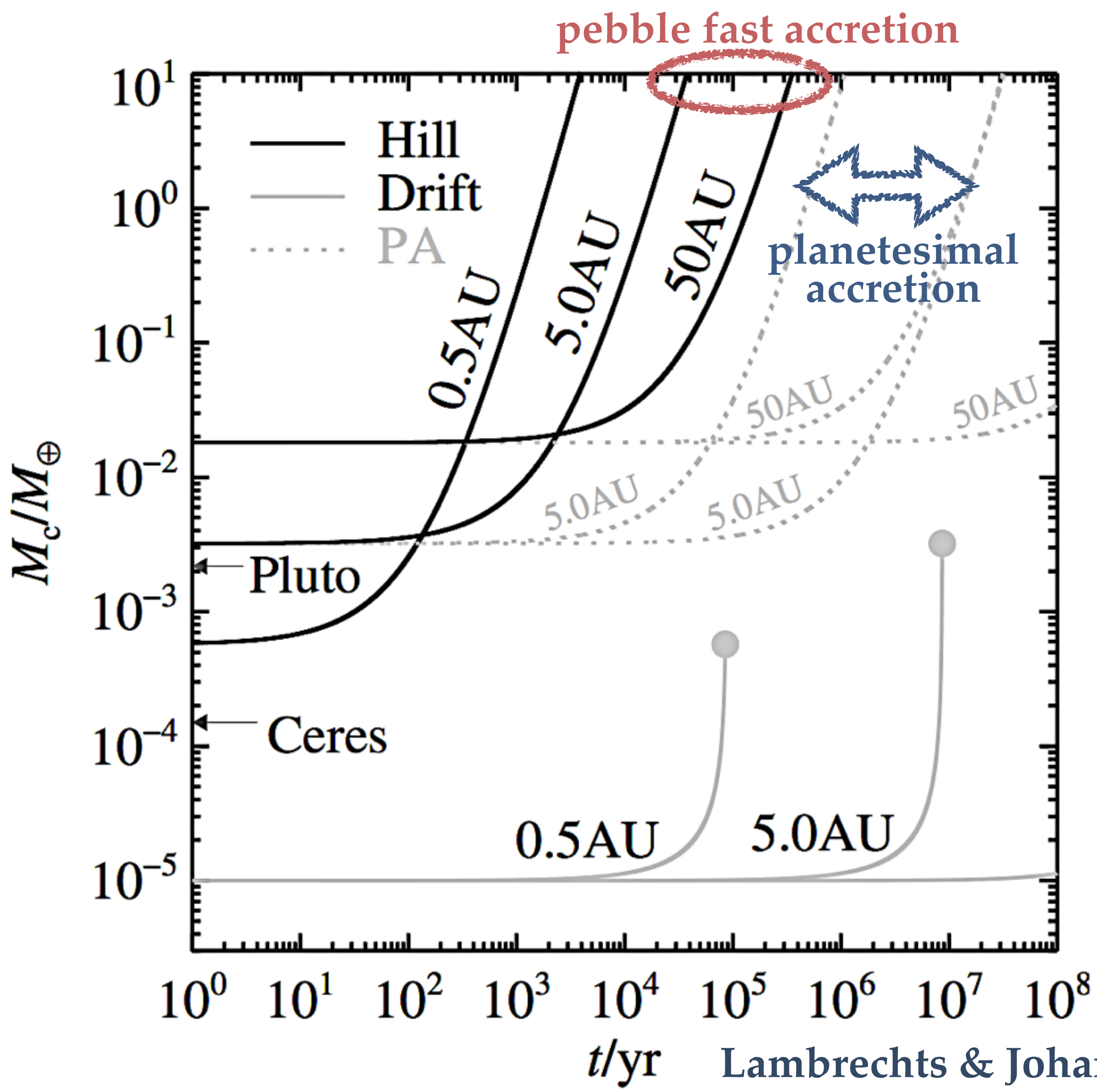
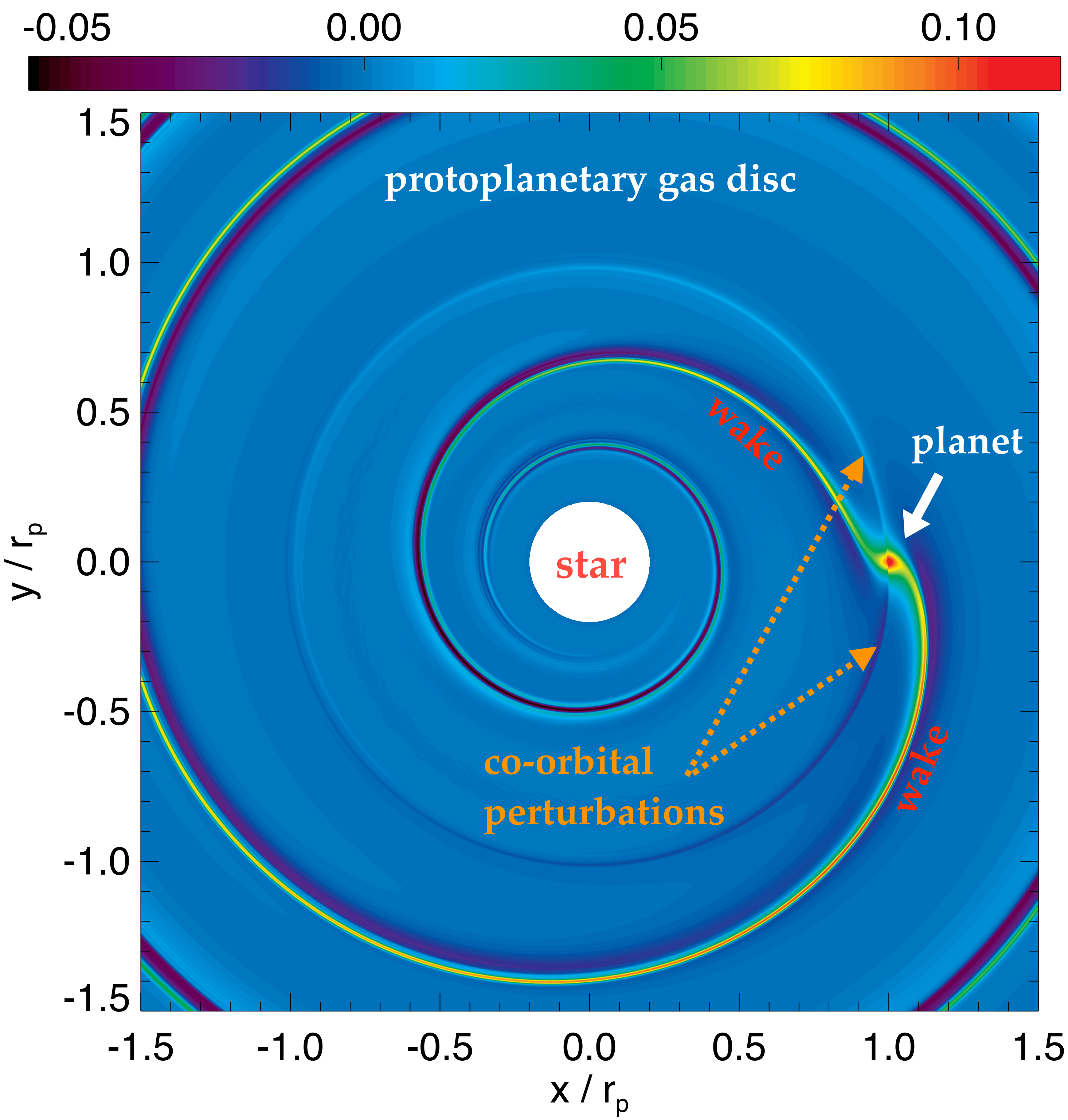


Lambrechts & Johansen 12

Recent progress in theoretical models (selection)

- **Migration** of **low-mass** planets (up to a few tens of Earth masses)

Baruteau+ 14 in Protostars & Planets VI



← gas density perturbation by a 5 Earth-mass planet

- the planet **wakes** (spiral density waves) favor **inward migration**

  Tanaka+ 02

- the **co-orbital perturbations** favor **outward migration**

  Masset & Casoli 10, Paardekooper+ 11, Guilet+ 13…

- diffusion of **heat** released by **planet accretion** favors **outward migration**

  Benitez-Llambay+ 15

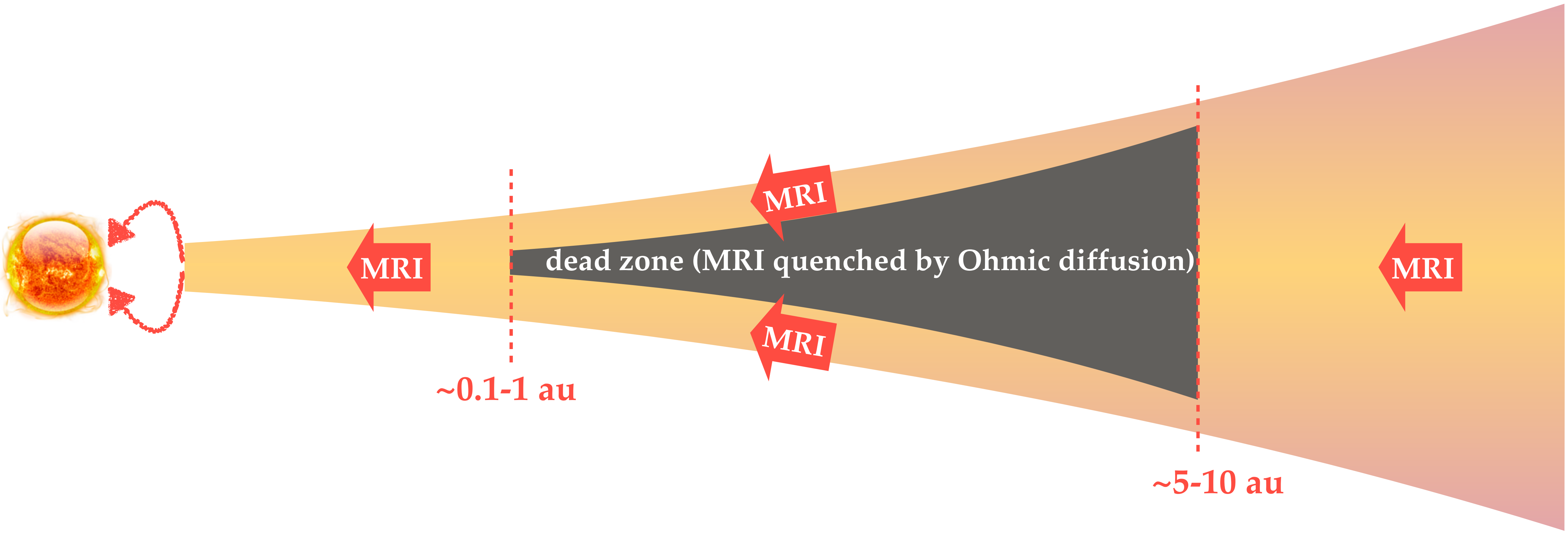
→ **direction** and **speed** of **migration** depend on the planet mass and, **crucially**, on the **disc's physical properties** near the planet location (density, temperature, magnetic field, turbulence…)

→ need to further develop **global** models of planet formation & evolution + disc evolution

Recent progress in theoretical models (selection)

- Dynamical **evolution** of protoplanetary **discs**

✣ **turbulent (radial) transport** of angular momentum due to the **Magneto-Rotational Instability (MRI)?**
Balbus & Hawley 91



→ Ohmic diffusion (electrons-neutrals collisions) makes a large fraction of the bulk disk magnetically inactive (probably **good** for **planet formation**!)

→ layered accretion **Gammie 96**

Recent progress in theoretical models (selection)

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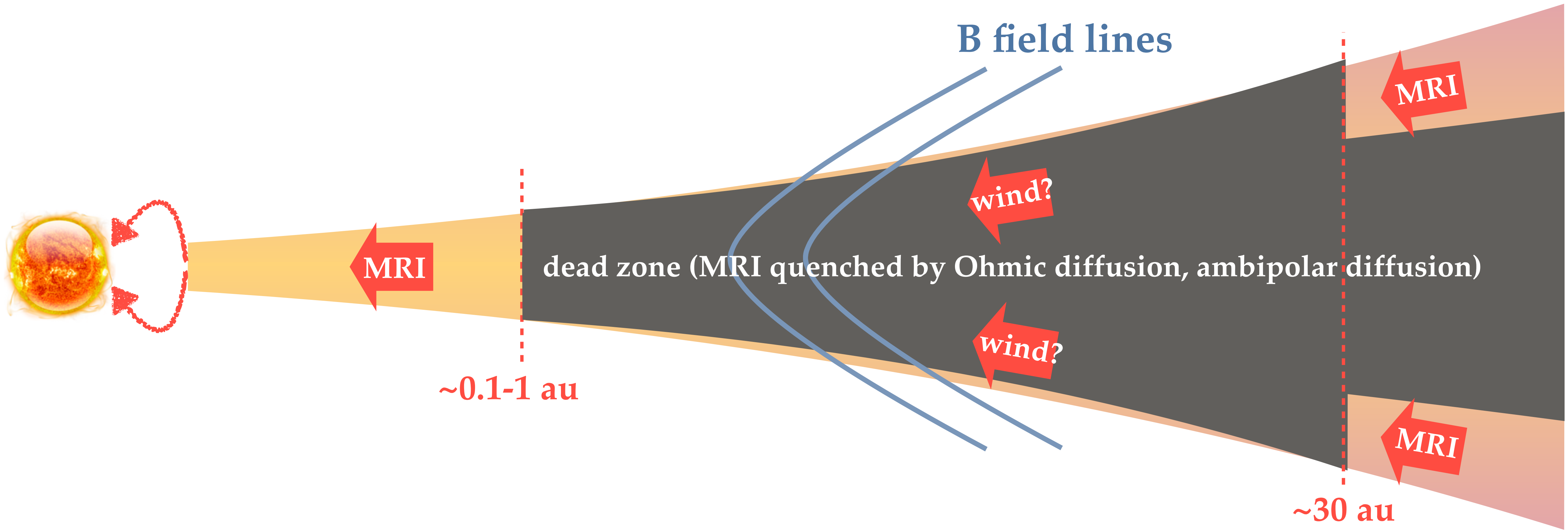
Balbus & Hawley 91

✣ **vertical transport (extraction)** of angular momentum by **magneto-centrifugal winds?**
Bai 13, Simon+ 13, Lesur+ 14…



→ Ambipolar diffusion (ions-neutrals collisions) largely **quenches** MRI in the disk's surface layers, and partly in its outer parts

→ **Wind**-driven **laminar** accretion if a vertical B field threads the disk

→ **Even better for planet formation?** (global models needed)

What's special about the Solar System?

- It is definitely **atypical** in light of current exoplanet statistics
    - ~10% of all stars are **Sun-like** stars,
    - ~10% of Sun-like stars have a **warm Jupiter**,
    - ~10% of warm Jupiters have an **orbit comparable** to that of **our** Jupiter,
    - ~50% of stars hosting exoplanets have **no super Earths**,

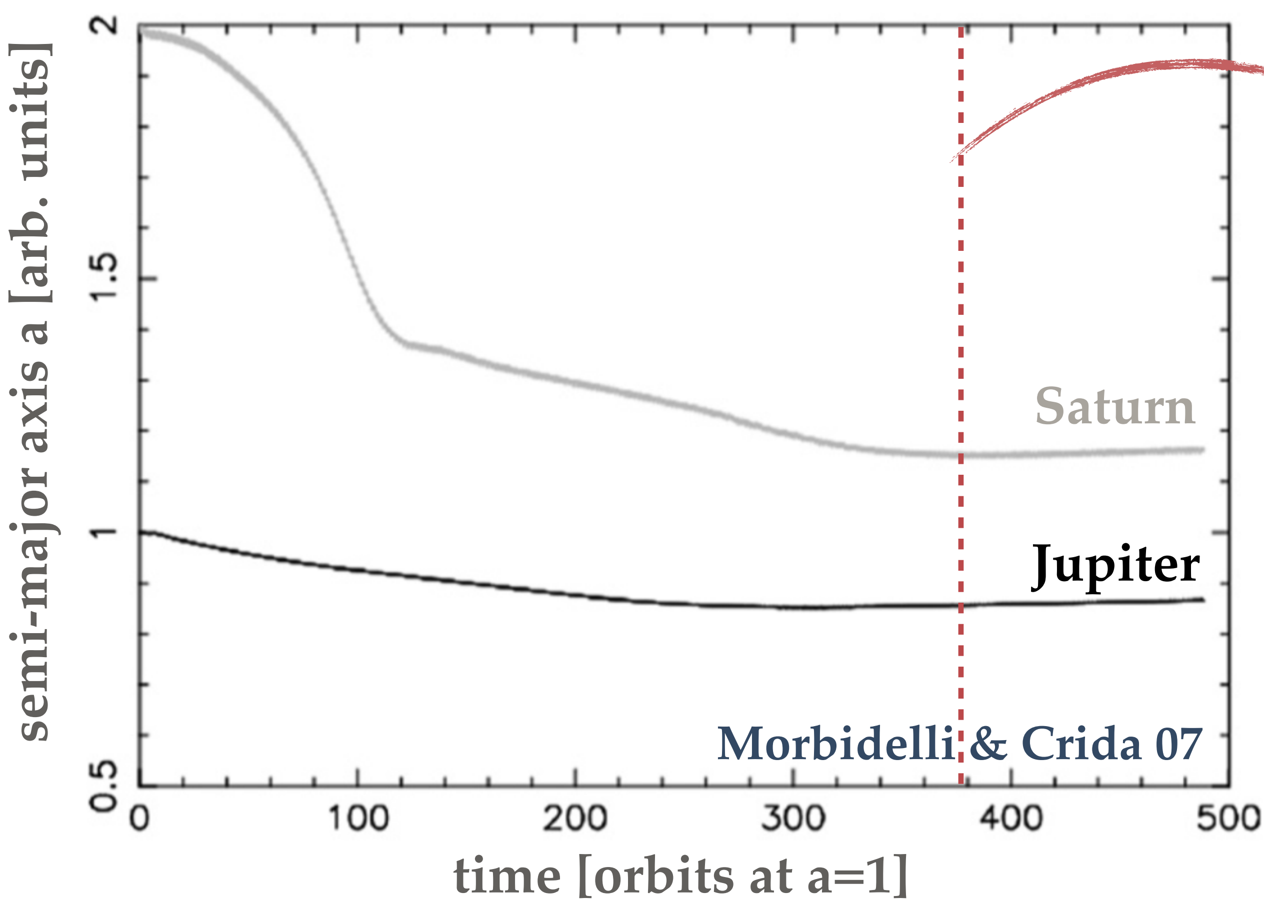
  → **rate** of **occurrence** of planetary systems similar to our own is $\lesssim$ **0.05%**!

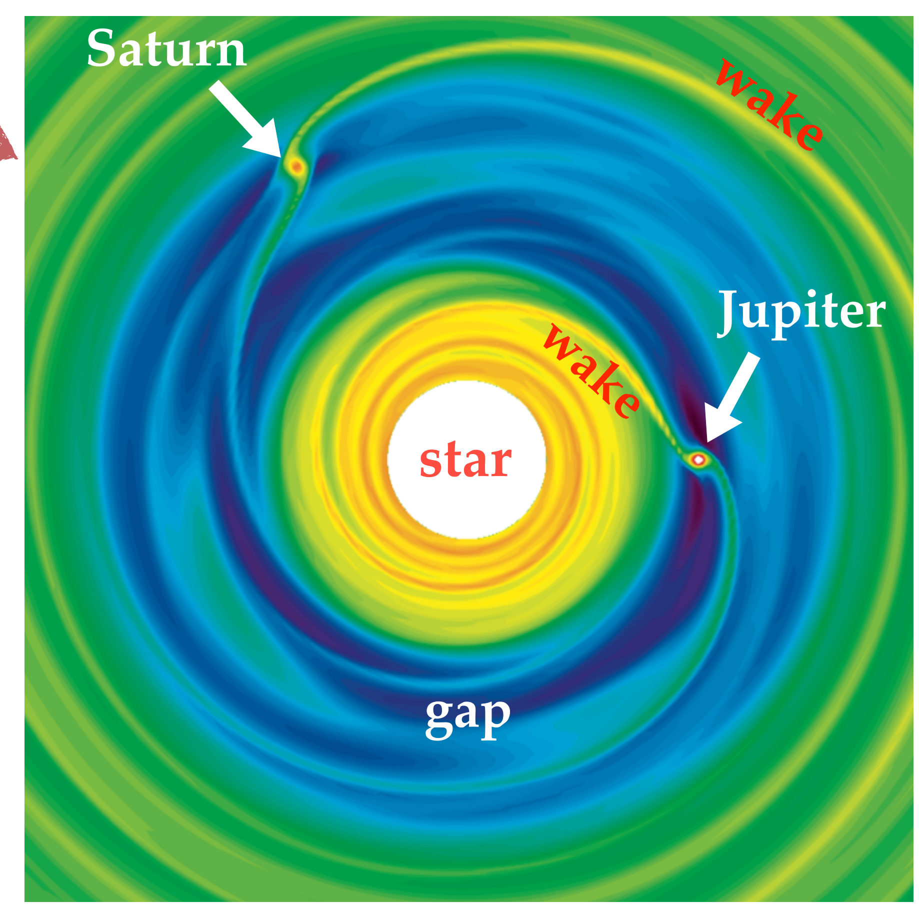
What's special about the Solar System?

- It is definitely **atypical** in light of current exoplanet statistics (rate of occurrence ≲ 0.05%)
- A **lucky** set of circumstances?
  - **early** formation of **Jupiter** near the **ice line** in the protoplanetary disc **deprived** the **inner** Solar System of **solids**

    → **low mass of terrestrial planets + slow disc-migration = no super Earths in our Solar System**

  - formed later, **Saturn** first migrated inward **faster** than Jupiter in the disc due to its lower mass, then the two planets experienced **joined outward migration** near their 3:2 orbital **resonance**





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    → **Grand Tack** **(Walsh+ 11)**: a viable scenario, but rather **unlikely** **(eg, D’Angelo & Marzari 12)**

    → **our Jupiter didn’t become a *hot or warm Jupiter*!**

  - after **dissipation** of the protoplanetary **disc,** no **close encounters** occurred between Jupiter and Saturn, which **preserved** near **circular** orbits

    → **Nice model** **(eg, Nesvorny & Morbidelli 12)**

    → **our Jupiter didn’t become a *warm eccentric Jupiter*!**

What's special about the Solar System?

- It is definitely **atypical** in light of current exoplanet statistics (rate of occurrence $\lesssim 0.05\%$)
- A **lucky** set of circumstances?
- A **few open questions** that could be discussed during this workshop:
  - **how does the optical and physical properties (porosity, composition) of the dust collected by Rosetta can help in the modeling of disk observations?**
  - **what do the chondrules that form chondritic meteorites tell us about the early evolution of the Solar System?**
  - **if Planet Nine was observed some day (by 2061?), what implication would this have on the early/late evolution of the Solar System?**

Thanks for your attention!