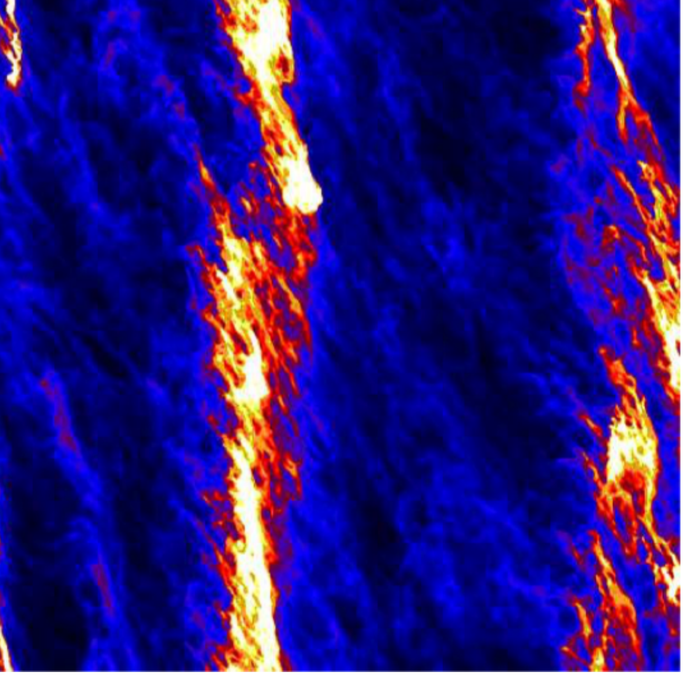
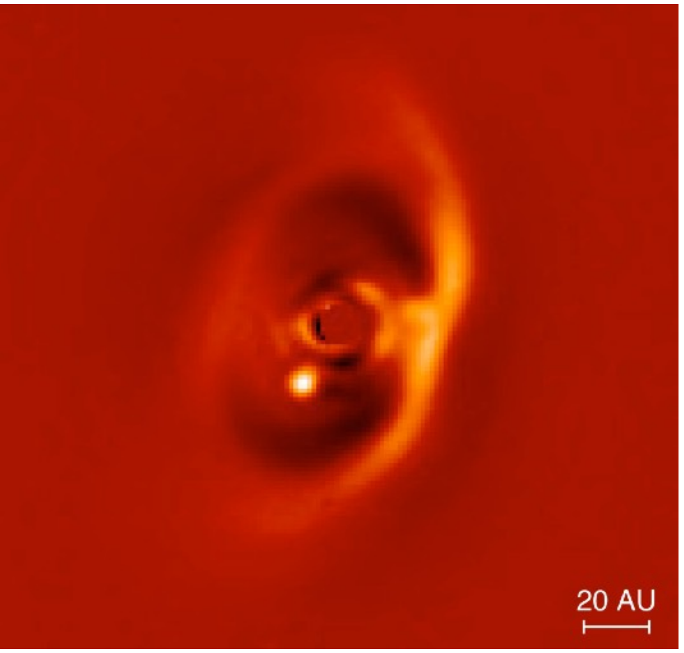
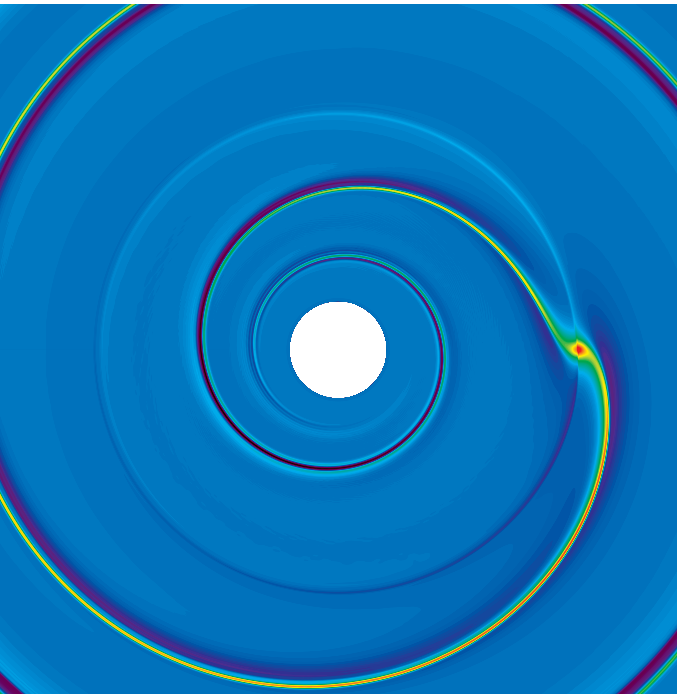






Formation and orbital evolution of (young) planetary systems

Clément Baruteau (CNRS/IRAP)

Evry Schatzman school, 7 October 2021

Menu of the day

- **Observational constraints** (exoplanets)

~

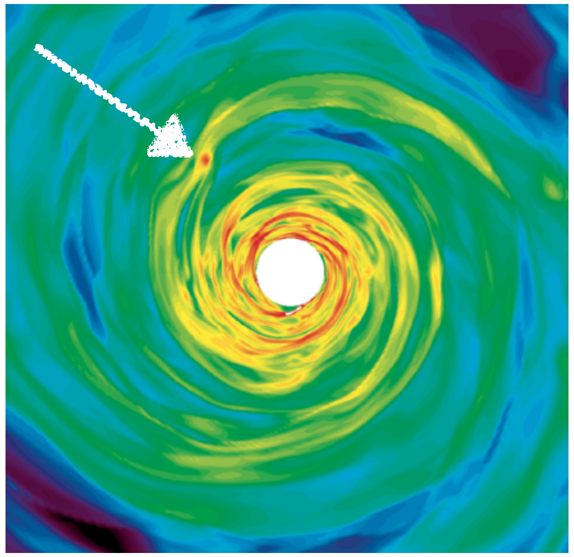
- **Theory**: selection of open **questions** and recent **progress**

Planet formation and orbital evolution

planet formation

core accretion?

gravitational instability?



Planet formation and orbital evolution

planet-disc interactions

change planets semi-major axes (planetary *migration*)

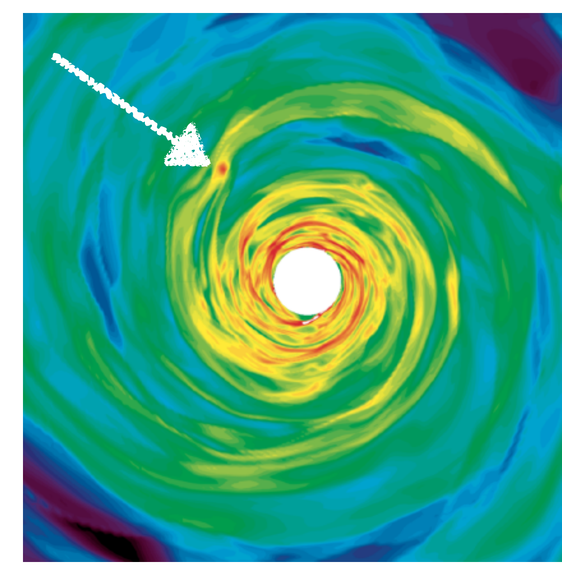
damp eccentricities and inclinations

?

planet formation

core accretion?

gravitational instability?



protoplanetary disc

Planet formation and orbital evolution

planet-disc interactions

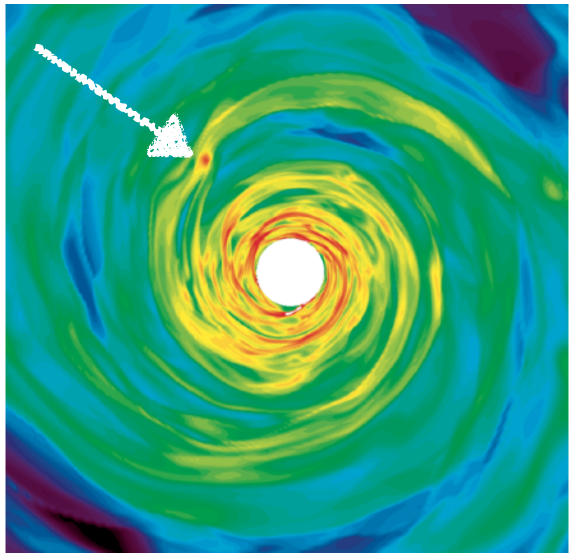
change planets semi-major axes
(planetary *migration*)

damp eccentricities and inclinations

planet formation

core accretion?

gravitational
instability?



planet-planet interactions

also change semi-major axes!

pump eccentricities and inclinations

protoplanetary disc

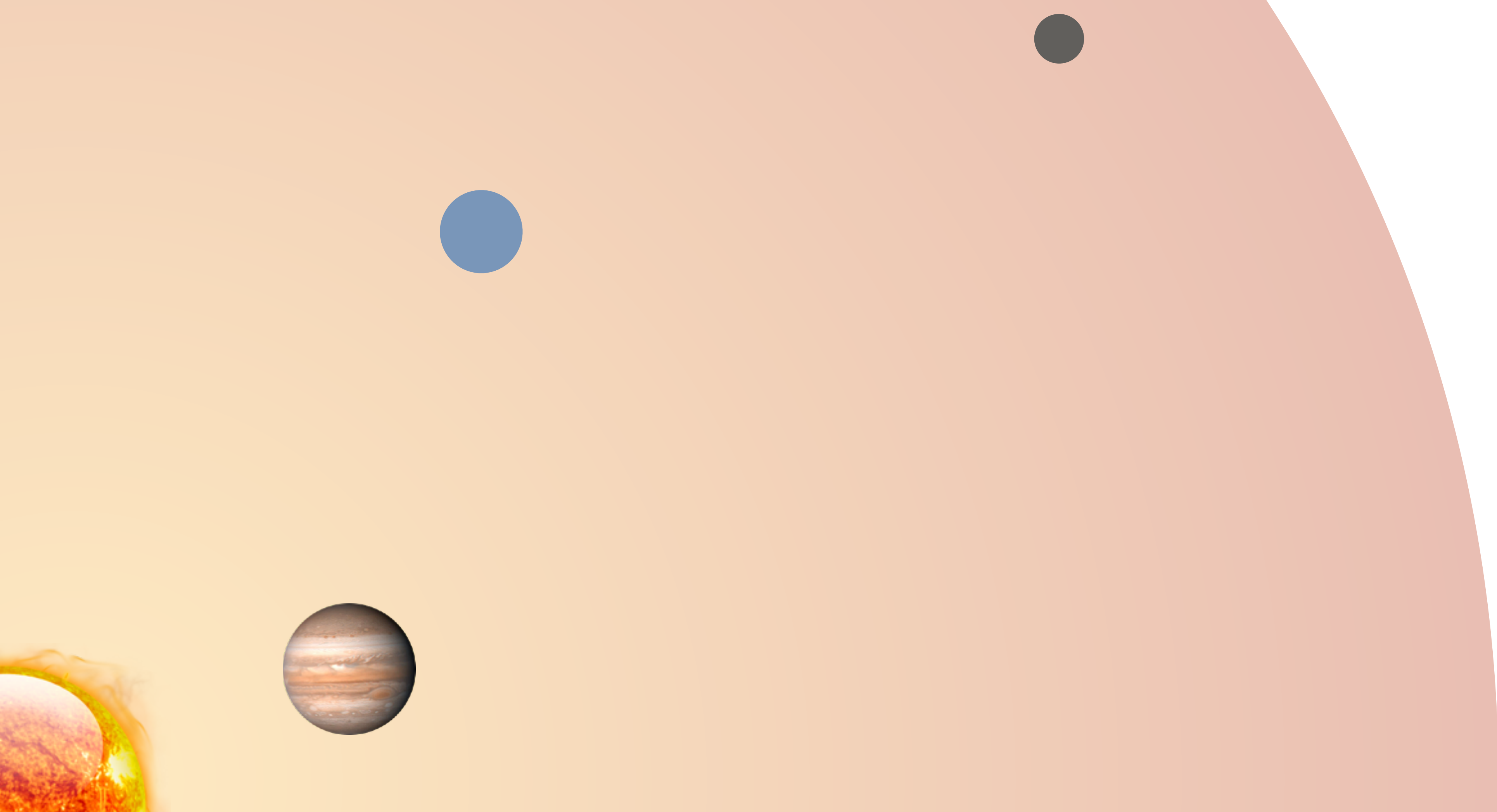
Planet formation and orbital evolution

disc dispersal
(after 1-10 Myr)

. **interactions with the central star** (tides, stellar evolution) **or with nearby stars**

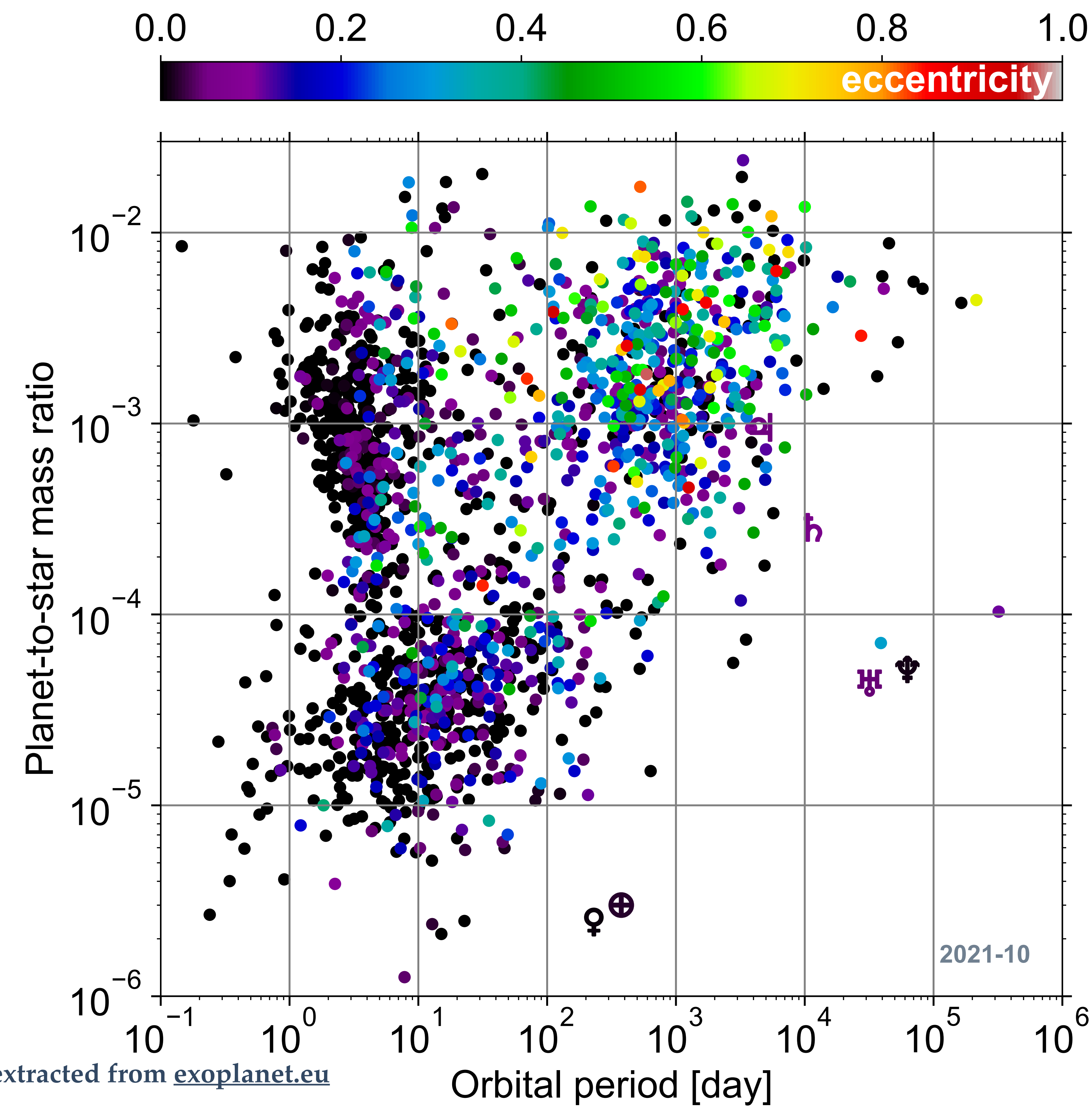
. **planet-planet interactions**

. **planets-debris disc interactions** (further formation of terrestrial planets and migration, like in the "Nice model")



~4800 exoplanets confirmed in 25 years

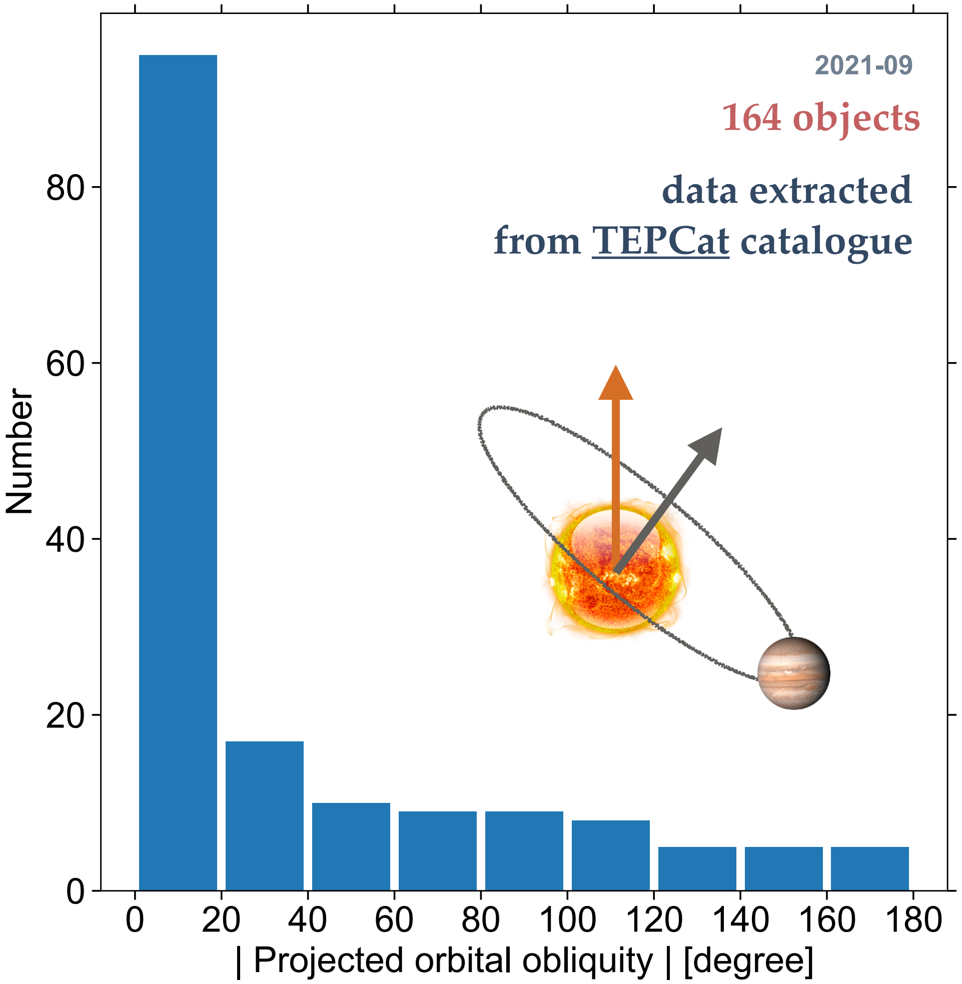
~1 in 3 are in multiple-planet systems



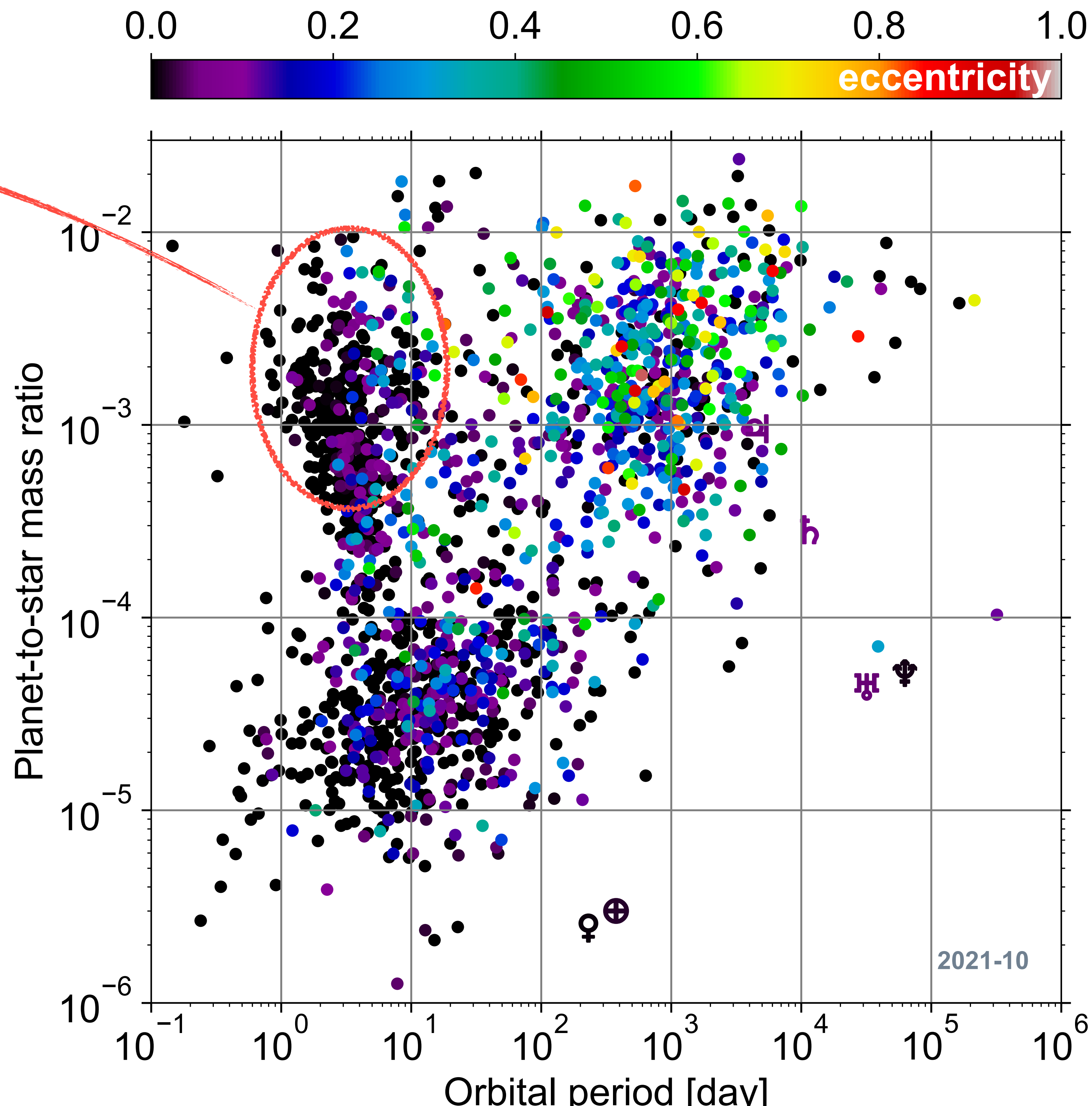
data extracted from exoplanet.eu

~4800 exoplanets confirmed in 25 years
~1 in 3 are in multiple-planet systems

- hot Jupiters
  - found around ~1% of Sun-like stars
    Mayor+ 2011, Wright+ 2012
  - low eccentricity: disc-planet interactions or star-planet tidal interactions?
  - ~1 in 3 has large projected obliquity: a dynamical origin?



  - handful of detections around few Myr stars
    eg, Donati+ 2016, Yu+ 2017, Plavchan+ 2020



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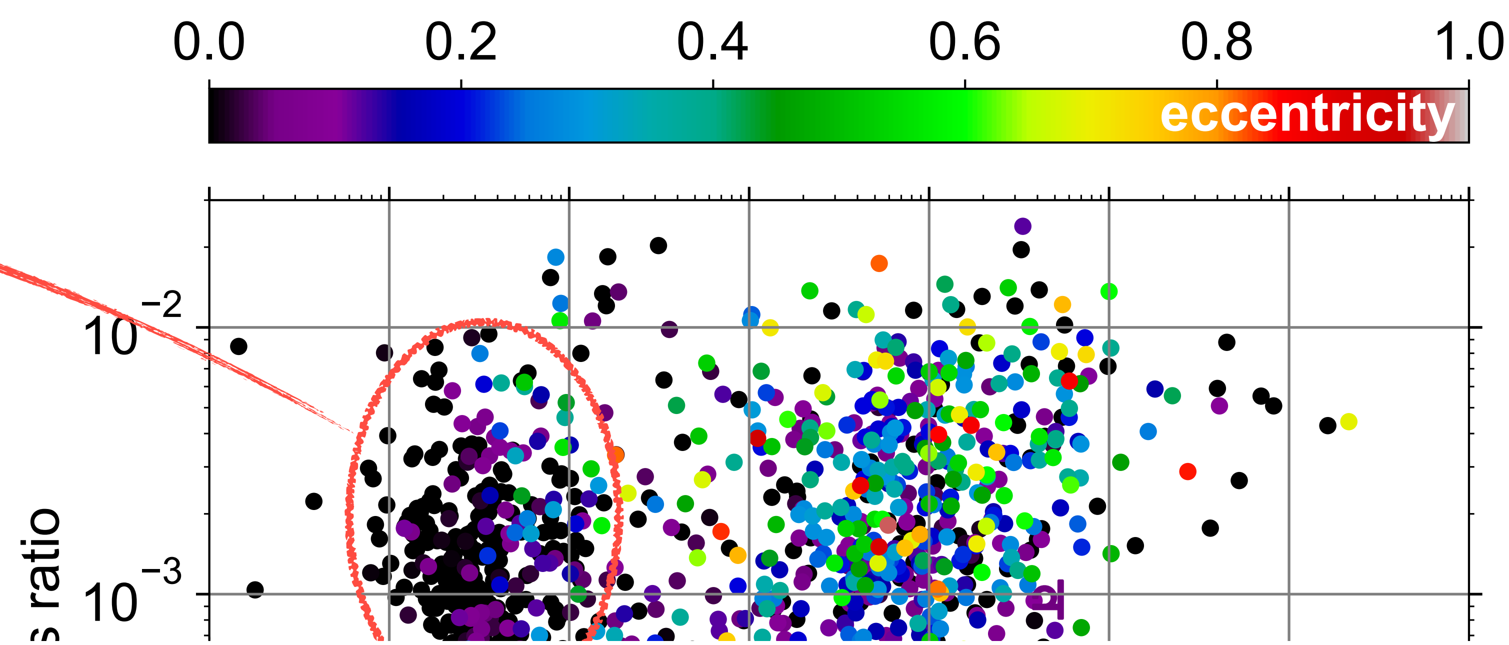

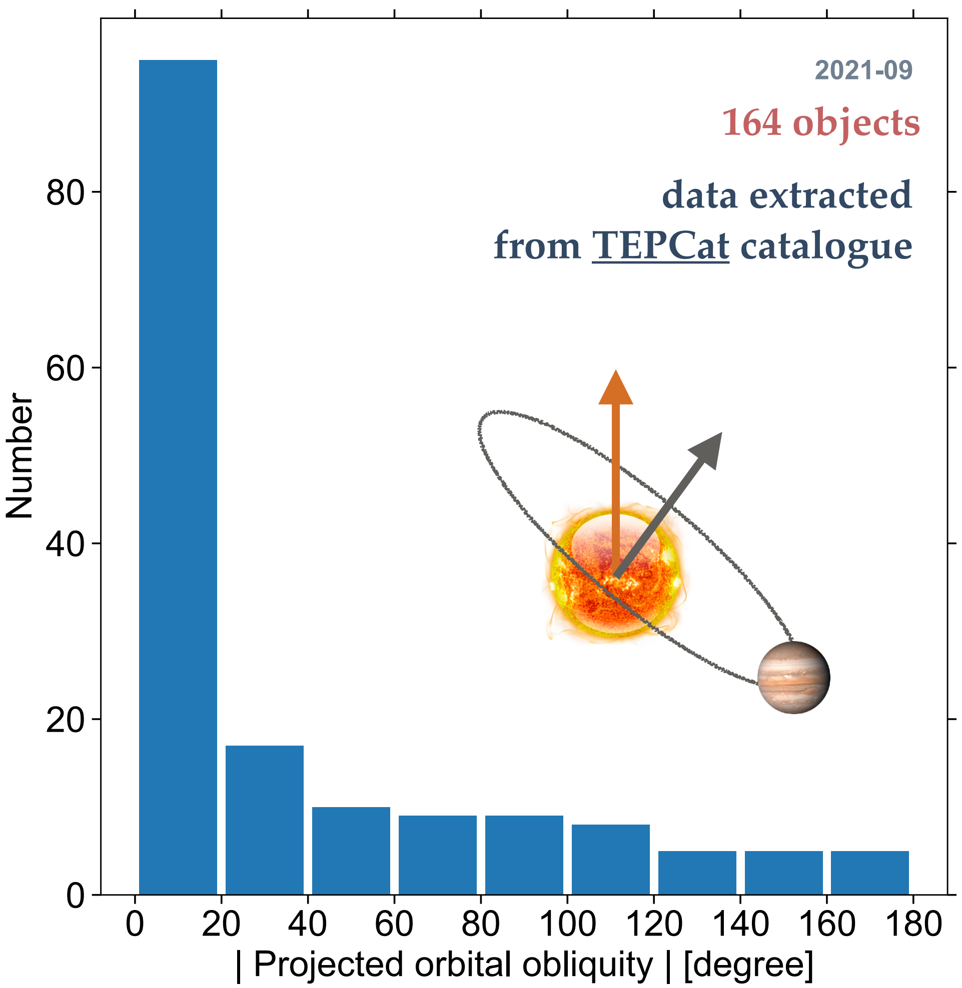

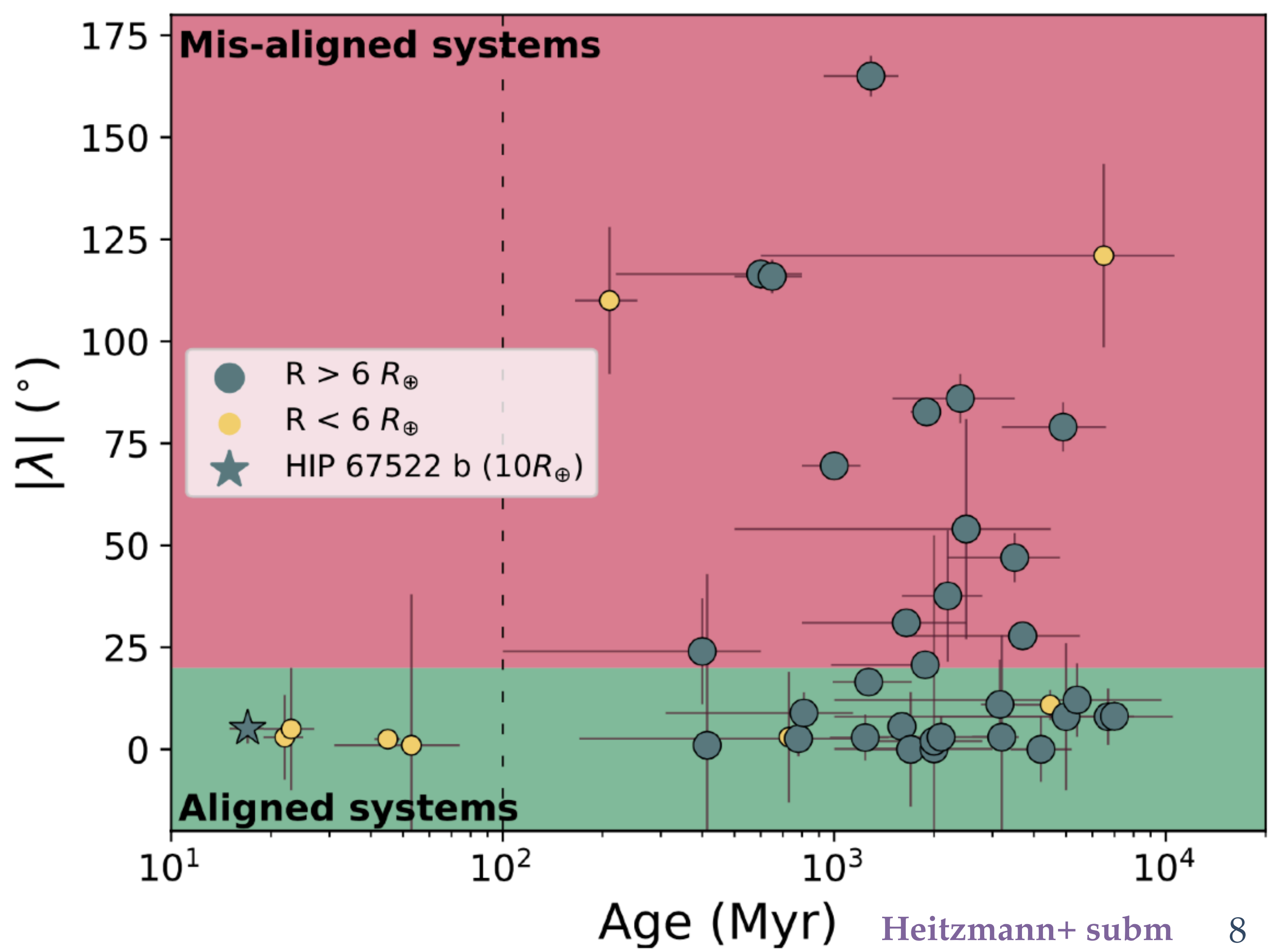

Heitzmann+ subm

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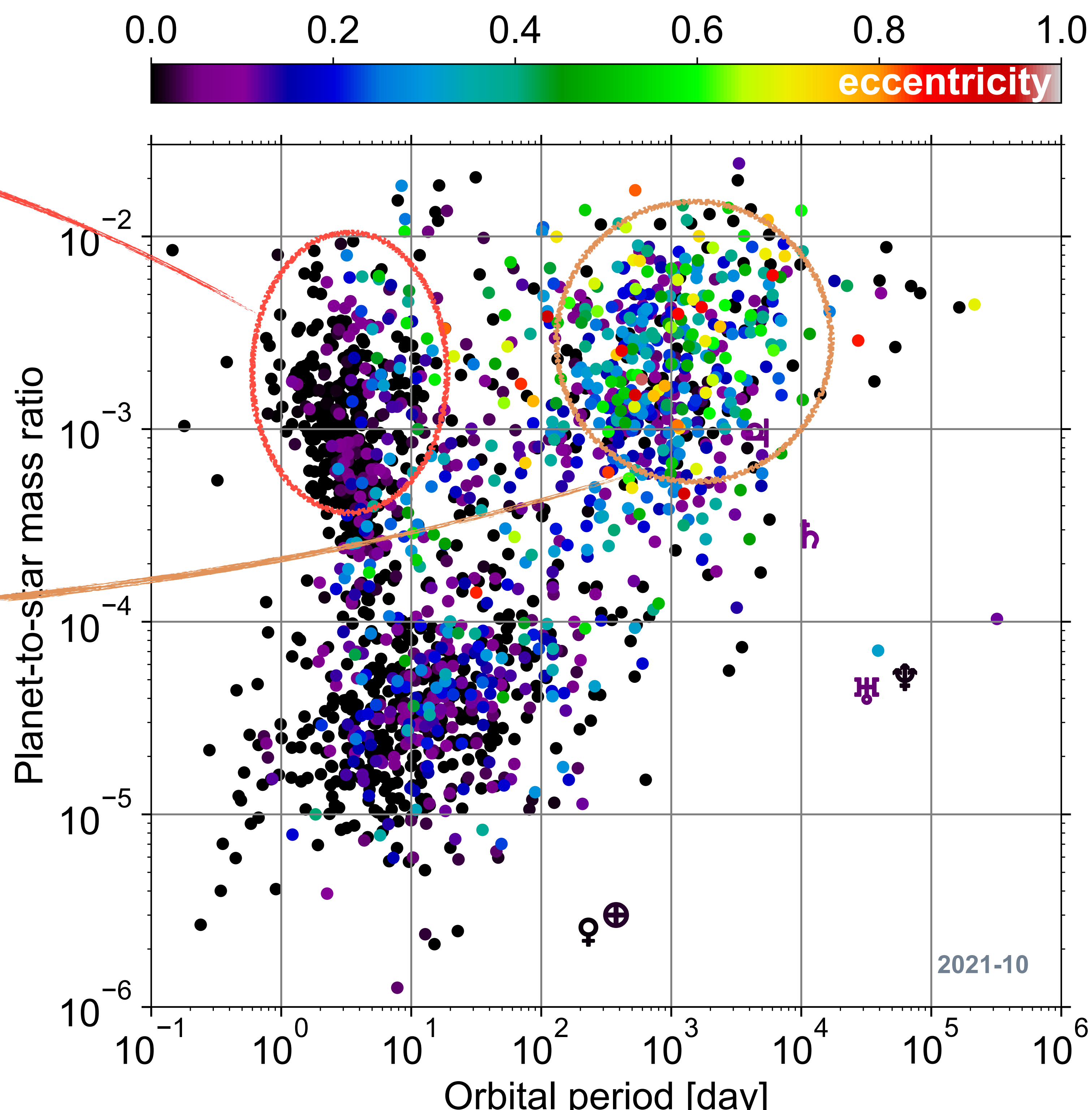
    eg, Donati+ 2016, Yu+ 2017, Plavchan+ 2020

- warm Jupiters
  - found around ~10% of Sun-like stars
    Cumming+ 2008, Mayor+ 2011
  - median eccentricity ~0.25: dynamical interactions? disc-planet interactions?
    eg, Debras+ 2021



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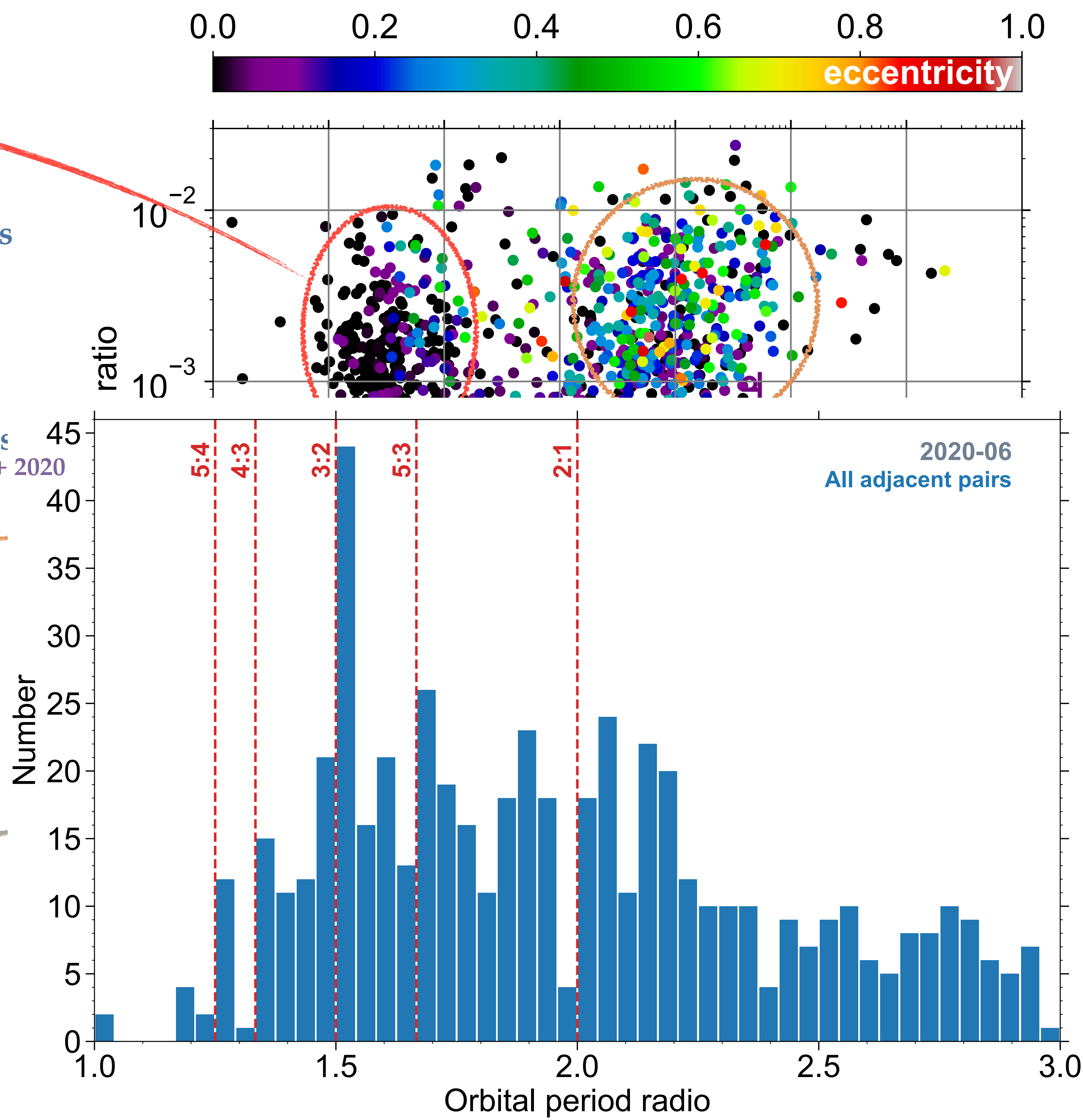
  - found around ~10% of Sun-like stars
    Cumming+ 2008, Mayor+ 2011
  - median eccentricity ~0.25: dynamical interactions? disc-planet interactions?
    eg, Debras+ 2021
- **super Earths**
  - found around ~50% of Sun-like stars
    eg, Fulton+ 2017
  - ~50% in multiple systems, typically have low eccentricities
  - orbital period ratio of planet pairs



Selected open questions

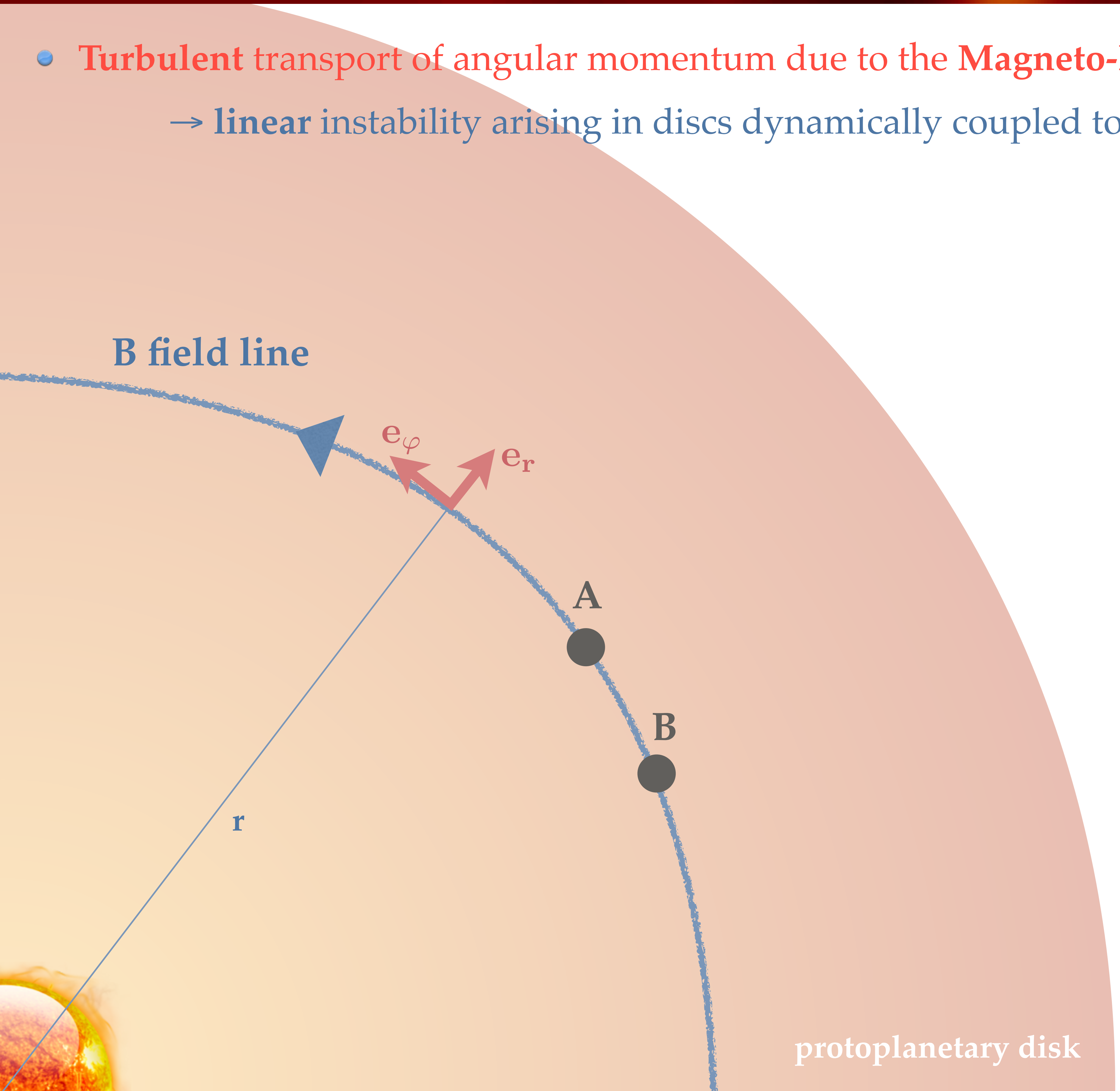
- about protoplanetary discs:
  - what drives the dynamical **evolution** of the disc **gas**? turbulence? winds?…
  - How do they **grow** dust to **planetesimal** (~km) sizes?
  - what is responsible for the many **structures** we see in the discs emission? planets?
- about planetary formation:
  - what primarily drives the **growth** of planetary **cores**? pebbles? planetesimals?
  - how relevant is **disc fragmentation** in forming giant planets?
- about planets orbital evolution:
  - how relevant are **disc-planets** interactions in shaping planetary systems?
- about the central star:
  - how is planet formation and orbital evolution changed with an **M dwarf star**?

What drives the gas evolution in discs?

- **Turbulent** transport of angular momentum due to the **Magneto-Rotational Instability (MRI)?**

  → **linear** instability arising in discs dynamically coupled to a weak **magnetic** field

  Balbus & Hawley 1991



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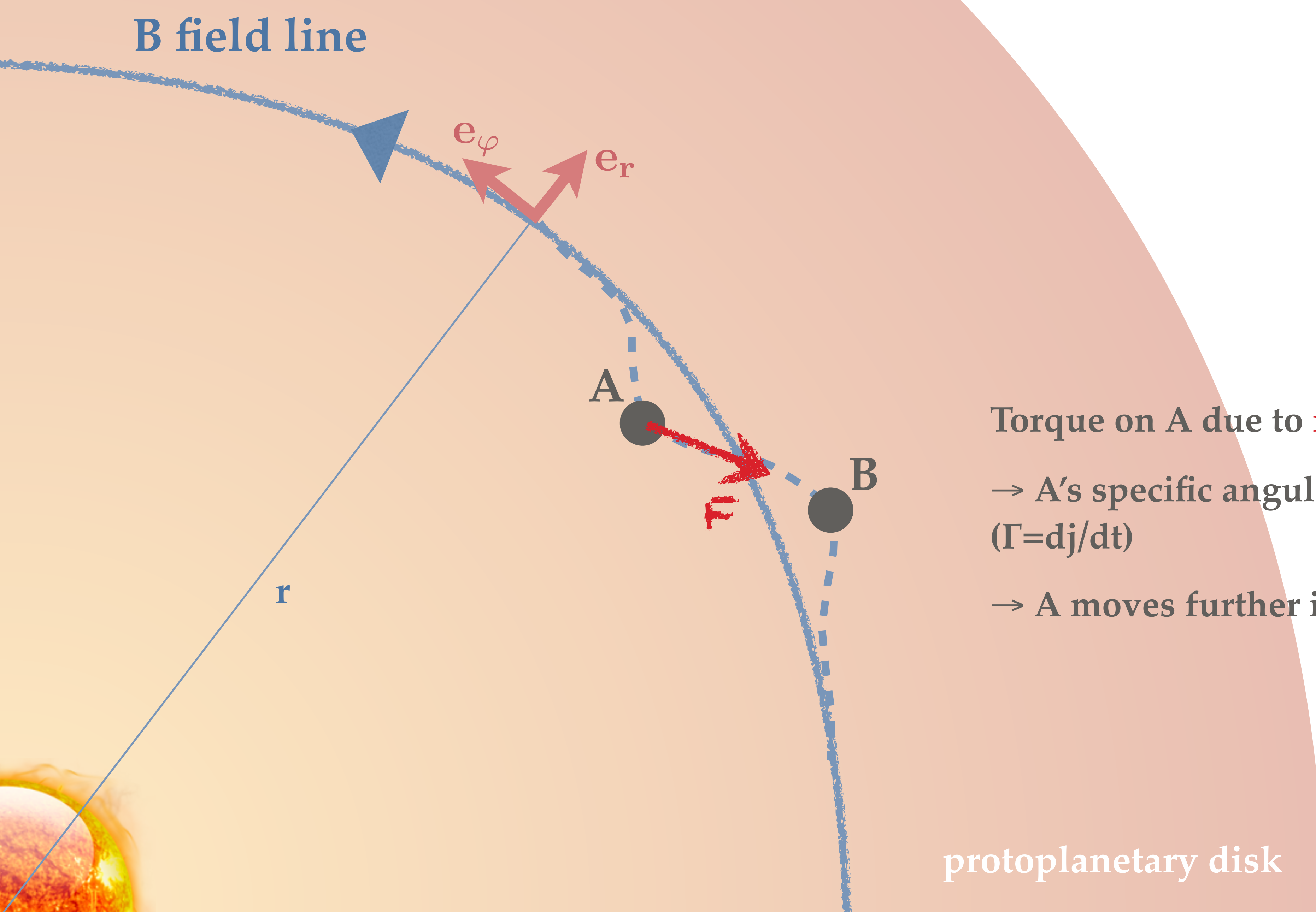


Torque on A due to magnetic tension $\Gamma \sim r_A \times F_\phi < 0$

→ A's specific angular momentum (j) decreases ($\Gamma = dj/dt$)

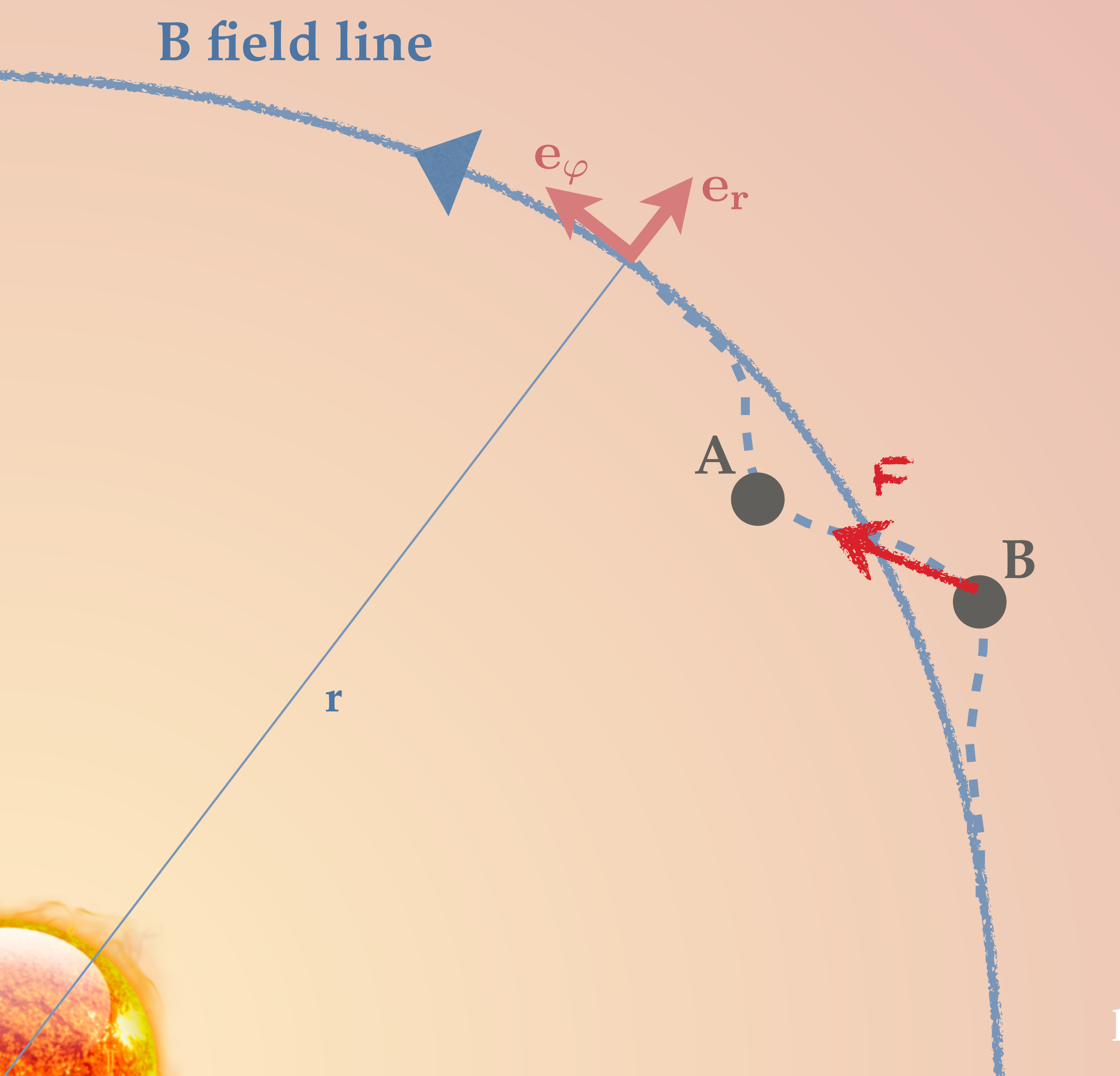
→ A moves further in! ($j = r v_\varphi = \sqrt{GM_\star r}$)

What drives the gas evolution in discs?

- **Turbulent** transport of angular momentum due to the **Magneto-Rotational Instability (MRI)?**

  → **linear** instability arising in discs dynamically coupled to a weak **magnetic** field

  Balbus & Hawley 1991



Torque on B due to **magnetic tension** $\Gamma \sim r_B \times F_\phi > 0$

→ B's specific angular momentum (j) increases ($\Gamma = dj/dt$)

→ B moves further out! ($j = r v_\varphi = \sqrt{G M_\star r}$)

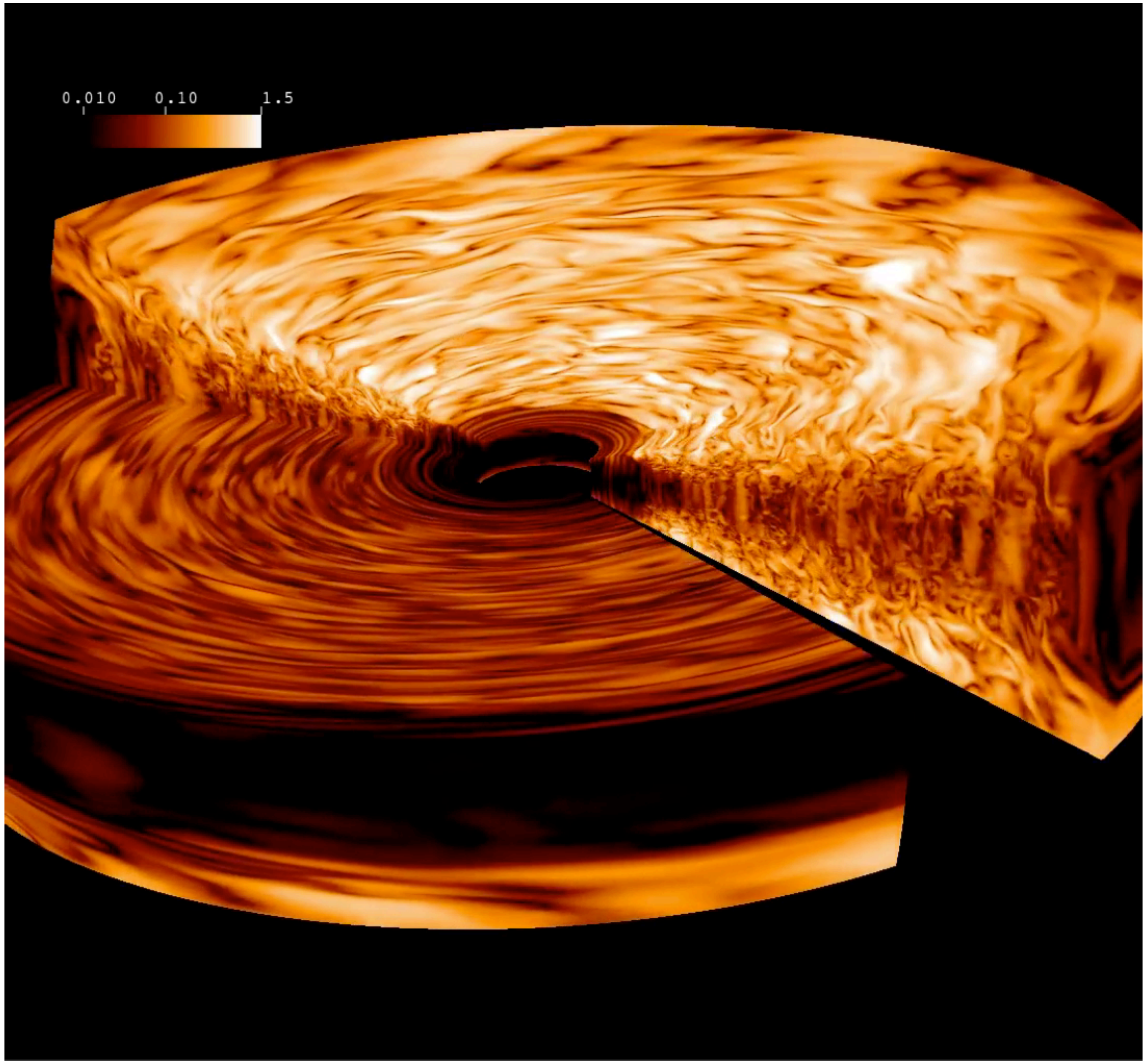
What drives the gas evolution in discs?

- **Turbulent** transport of angular momentum due to the **Magneto-Rotational Instability (MRI)?**

→ linear instability arising in discs dynamically coupled to a **weak** magnetic field

Balbus & Hawley 1991

$$|B|^2/2\mu_0 \lesssim \rho c_s^2$$



Gas Mach number (r.m.s. turbulent velocity in units of the local sound speed). Disc extends from R=0.5 to 1.5 au, and the r.m.s. turbulent velocity goes from ~1 to ~1000 m/s

Flock+ 2013

→ the disk reaches a quasi steady-state with **turbulent** mass **accretion rates** in fair agreement with **observed stellar accretion rates** ($\dot{M} \sim 10^{-8}\ M_\odot\ yr^{-1}$)

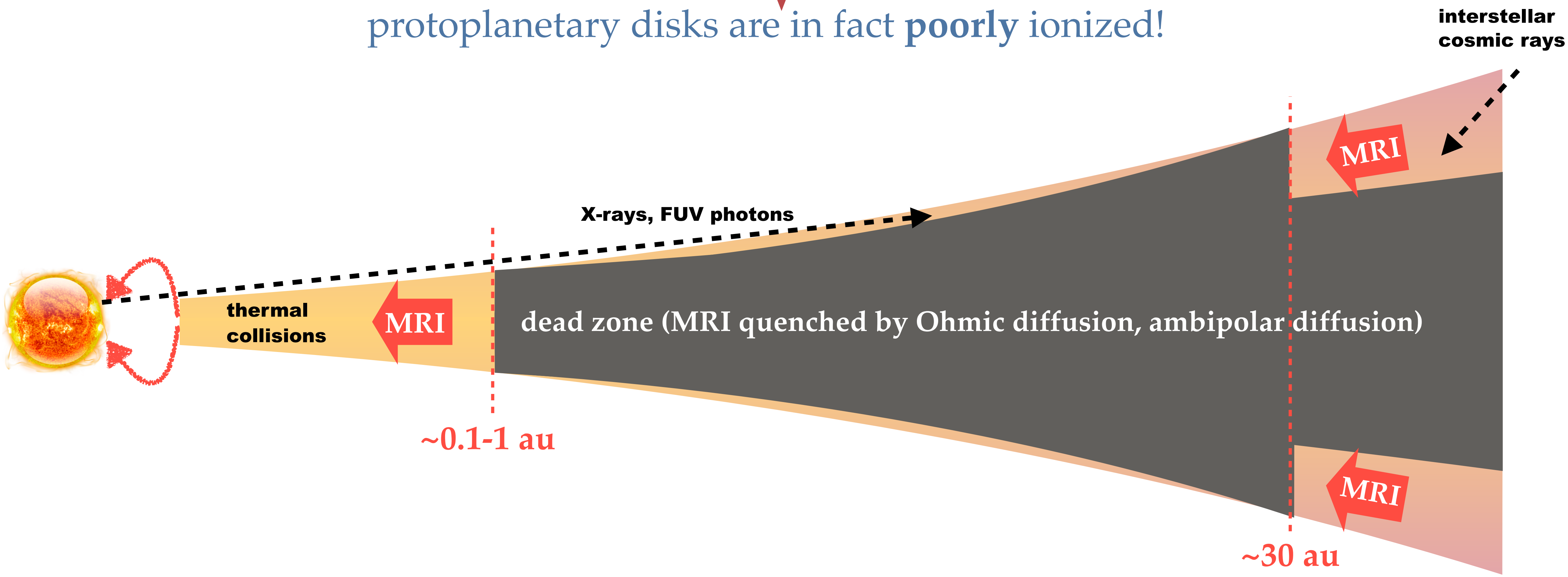
What drives the gas evolution in discs?

- **Turbulent** transport of angular momentum due to the **Magneto-Rotational Instability (MRI)?**

→ linear instability arising in discs **dynamically** coupled to a weak magnetic field

Balbus & Hawley 1991

protoplanetary disks are in fact **poorly** ionized!



→ Ohmic diffusion (electrons-neutrals collisions) and ambipolar diffusion (ions-neutrals collisions) **quench MRI** in a large fraction of the bulk disc

Gammie 1996, Bai 2013, Simon+ 2013, Lesur+ 2014…

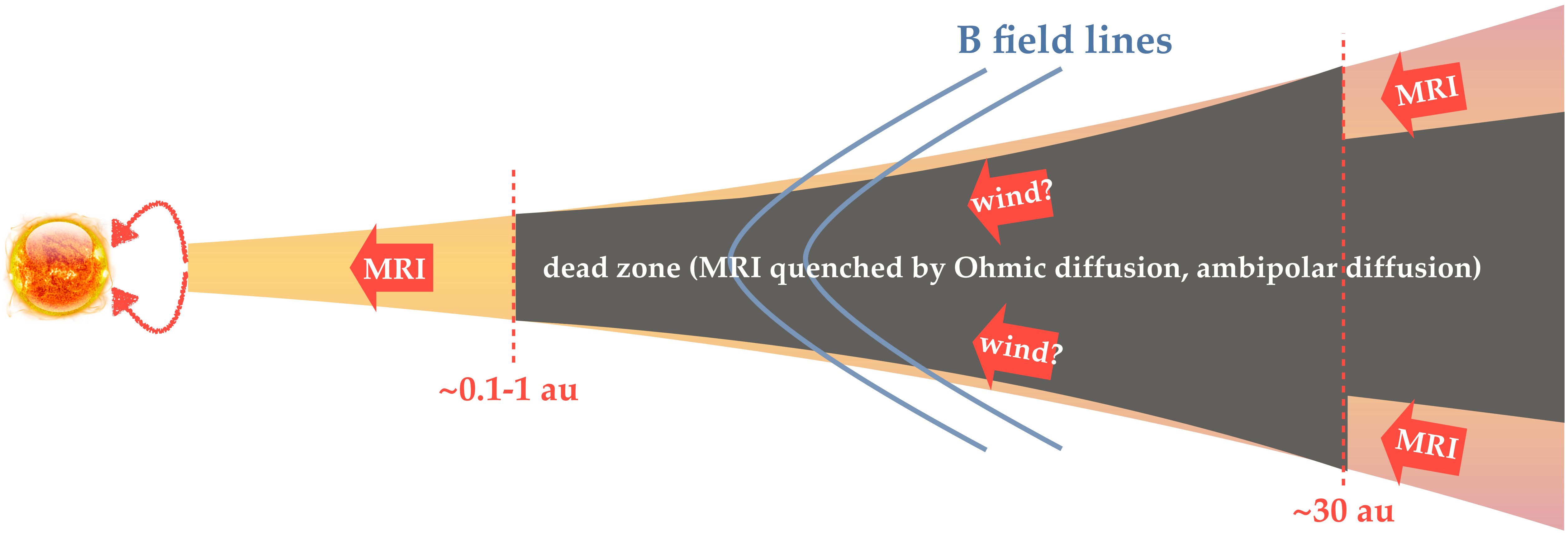
→ overall consistent with **observations** of the (small!) **non-thermal broadening** of molecular gas lines in discs

eg, Flaherty+ 2015

What drives the gas evolution in discs?

- **Vertical transport (extraction)** of angular momentum by **magneto-centrifugal winds?**

  → **wind**-driven **laminar** accretion if a vertical B field threads the disc
  eg, Blandford & Payne 1982, Béthune+ 2017

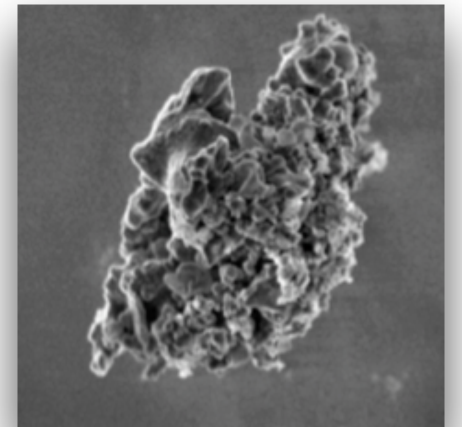


→ **observational support** via [O I] kinematics? **eg, Banzatti+ 2019**

→ **impact** on planet formation and evolution? (global models needed)

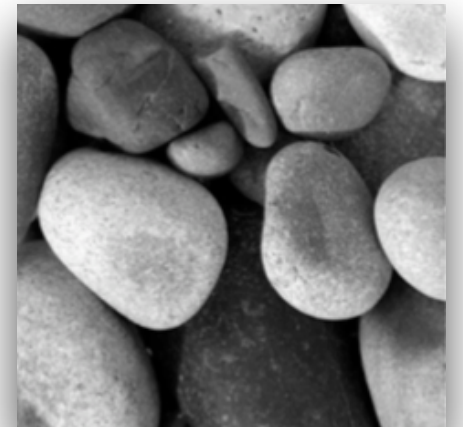
How do planetesimals form?

dust grains



μm

pebbles



cm

planetesimals

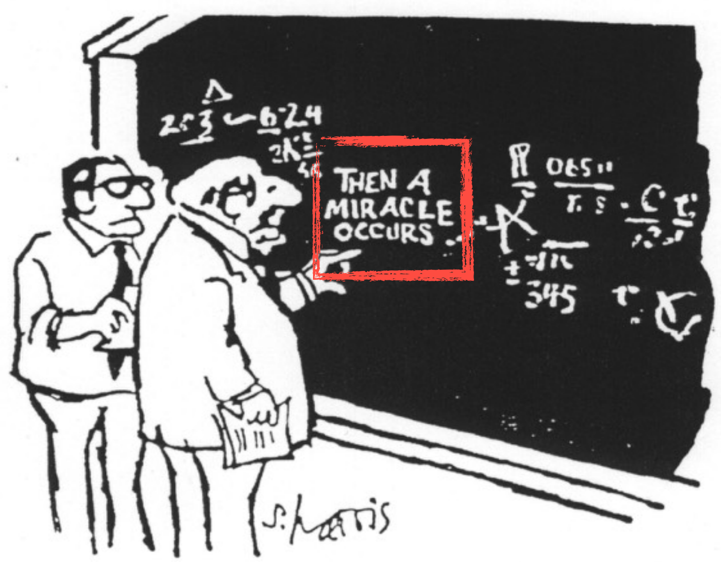
km

planet cores

~10^3 km

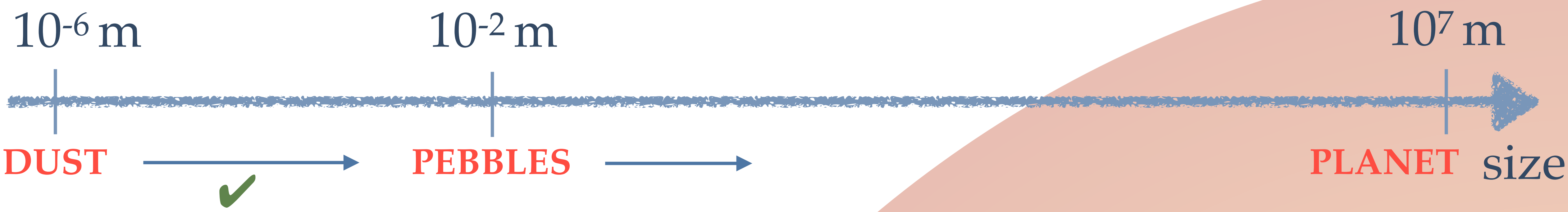
surface forces

gravity



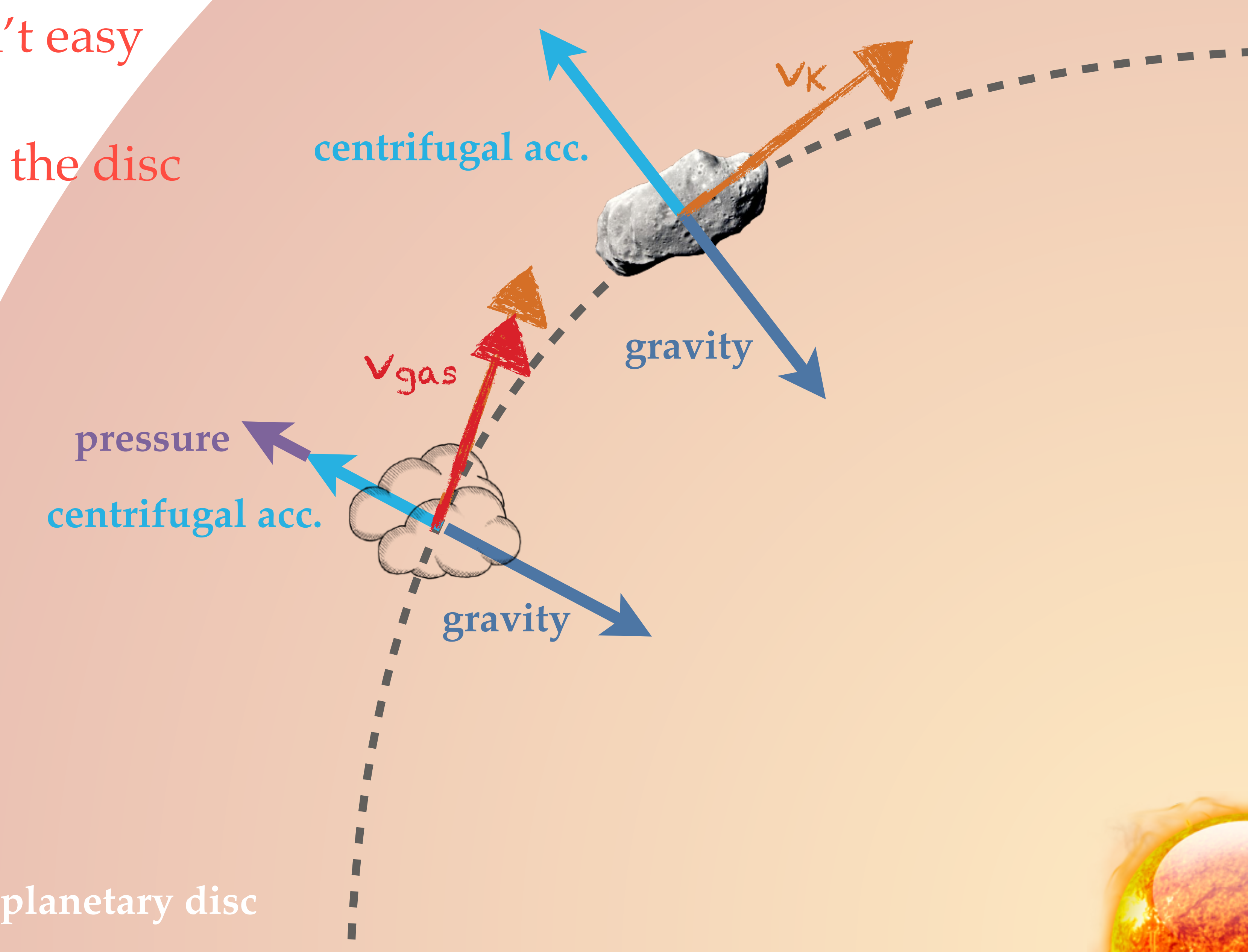
I think you should be a little
more specific, here in Step 2

How do planetesimals form?



growth beyond pebble sizes isn't easy because of:

- rapid **radial drift** of solids in the disc



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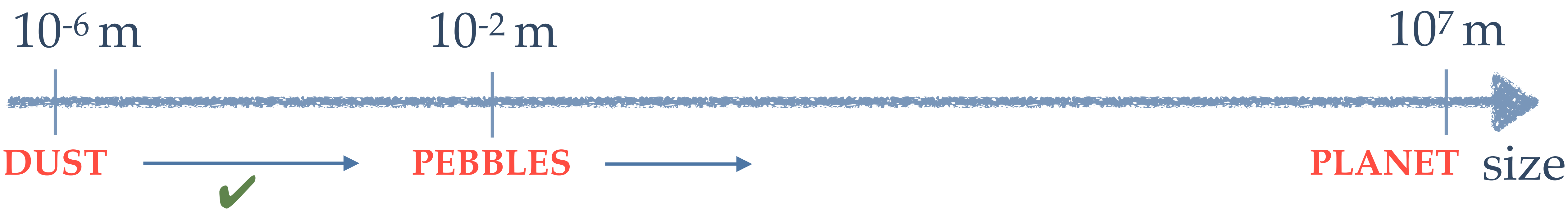
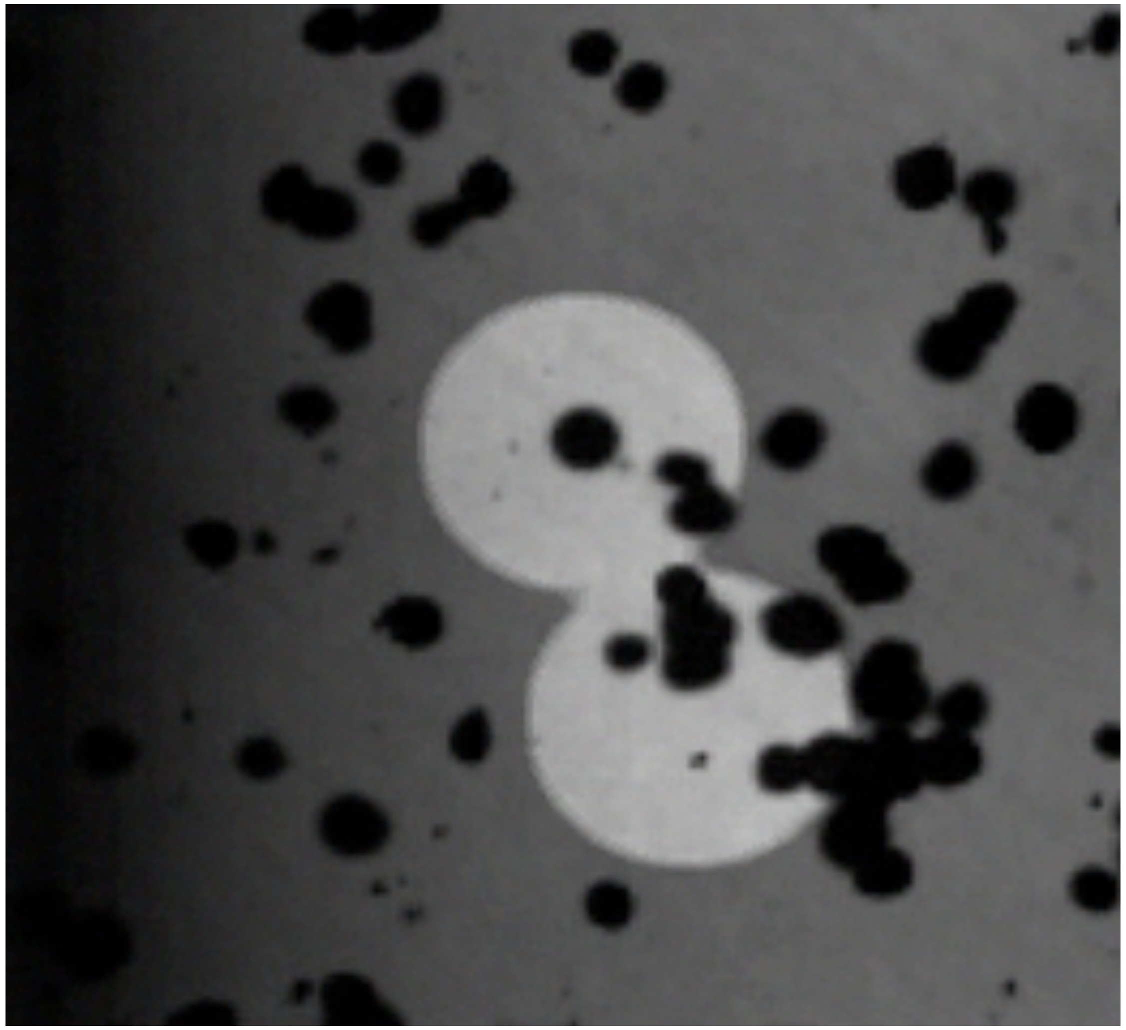


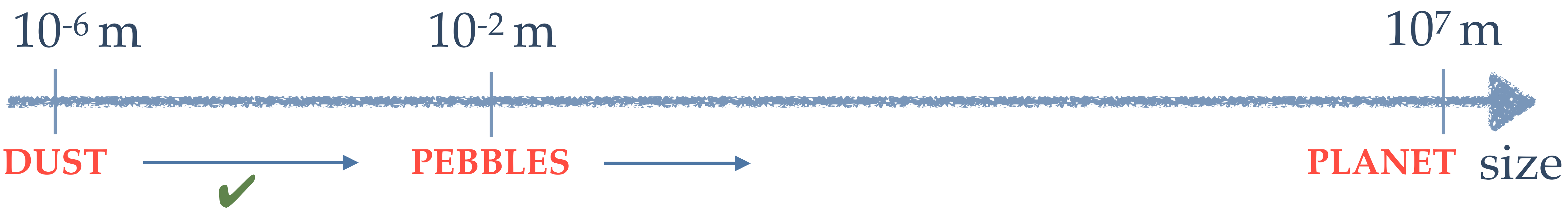
growth beyond pebble sizes isn't easy because of:

- rapid radial drift of solids in the disc
- **bouncing** at **low** relative velocities



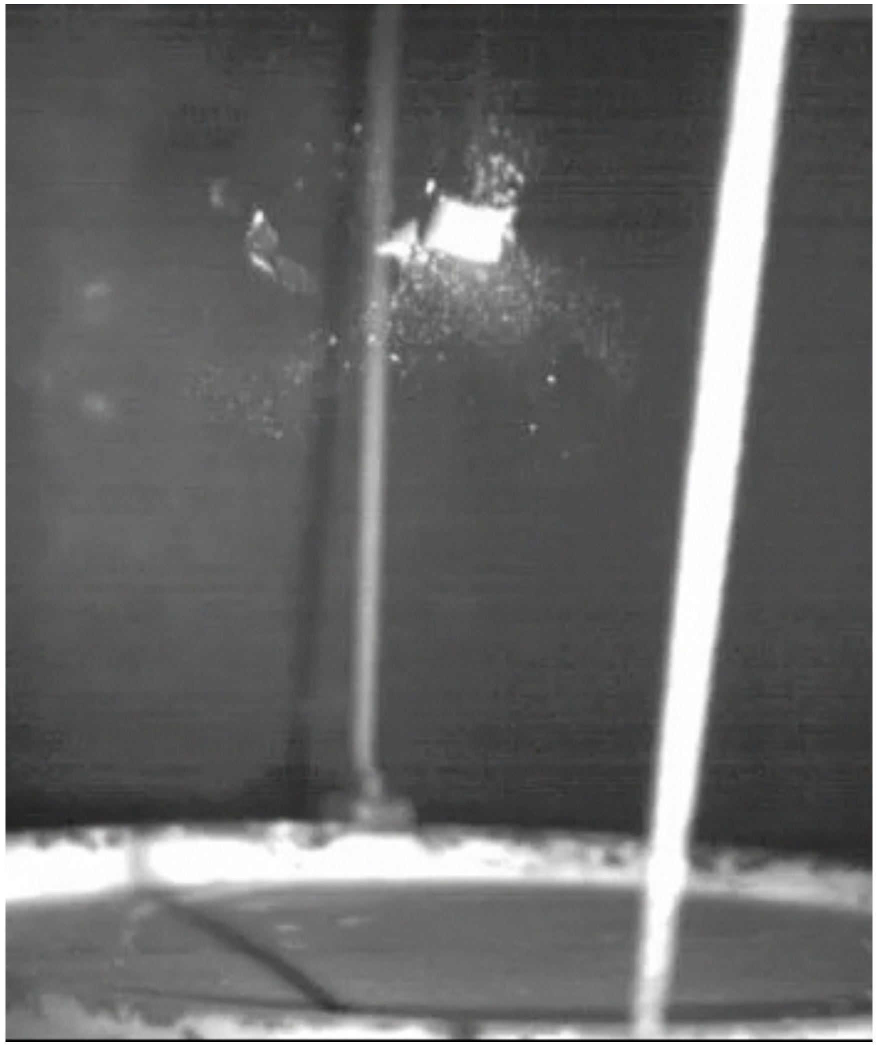
Weidling+ 2012 (mm-sized particles @ ~0.1 m/s)

How do planetesimals form?



growth beyond pebble sizes isn't easy because of:

- rapid radial drift of solids in the disc
- bouncing at low relative velocities
- **fragmentation** at **large** relative velocities



Guettler+ 2010 (mm-sized particles @ ~40 m/s)

How do planetesimals form?

10^{-6} m — 10^{-2} m — 10^{7} m

DUST → ✔ PEBBLES → PLANET size

growth beyond pebble sizes isn't easy because of:

- rapid radial drift of solids in the disc
- bouncing at low relative velocities
- fragmentation at large relative velocities

but may work if a large target experiences repeated collisions with smaller projectiles. This is **mass transfer**

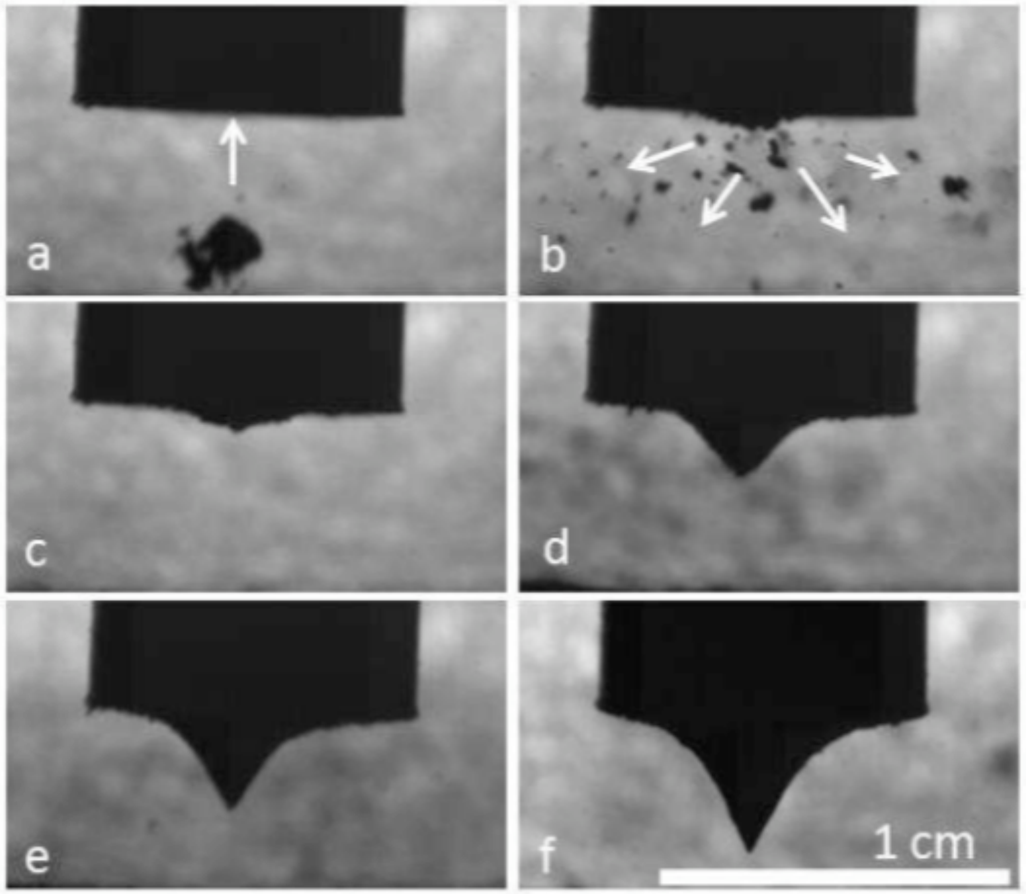


Fig. 10.— Experimental example of mass transfer in fragmenting collisions. All experiments were performed in vacuum. (a) A mm-sized fluffy dust aggregate is ballistically approaching the cm-sized dusty target at a velocity of 4.2 m/s. Projectile and target consist of monodisperse SiO_2 spheres of 1.5 μm diameter. (b) Shortly after impact, most of the projectile's mass flies off the target in form of small fragments (as indicated by the white arrows); part of the projectile sticks to the target. (c) - (e) The same target after 3 (c), 24 (d), 74 (e) and 196 (f) consecutive impacts on the same spot. Image credit: Stefan Kothe, TU Braunschweig.

Johansen+ 2014 (PPVI)

How do planetesimals form?

10^{-6} m — 10^{-2} m — 10^{7} m

DUST → ✔ **PEBBLES** → ? **PLANET** size

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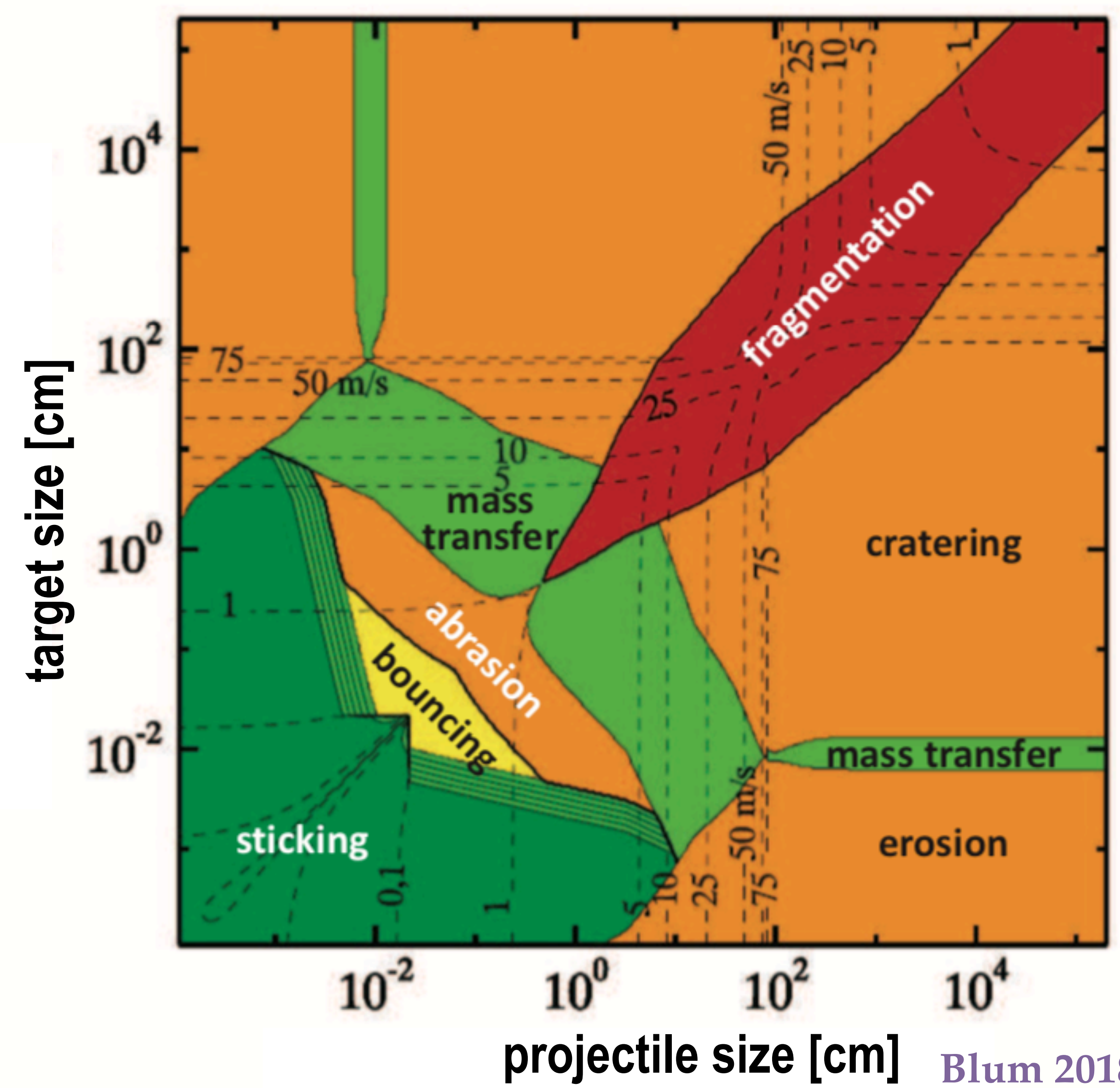
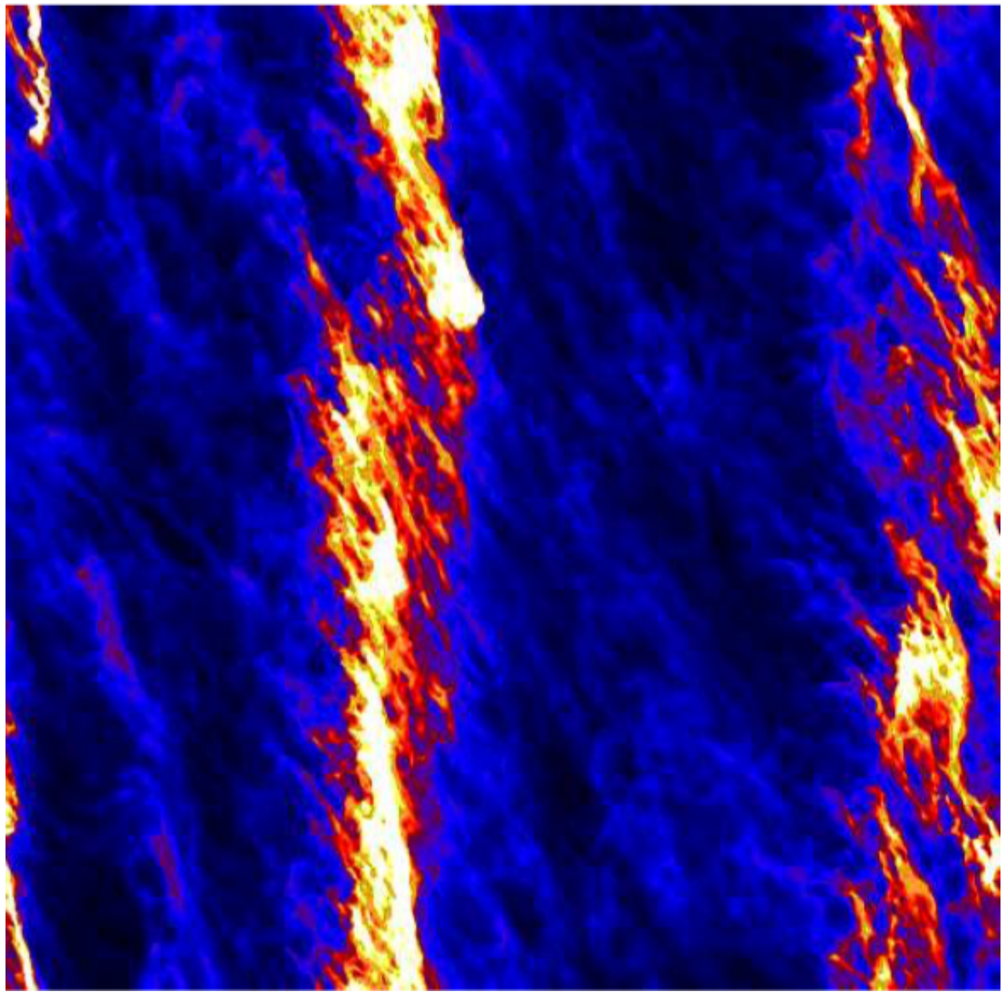


Blum 2018

How do planetesimals form?

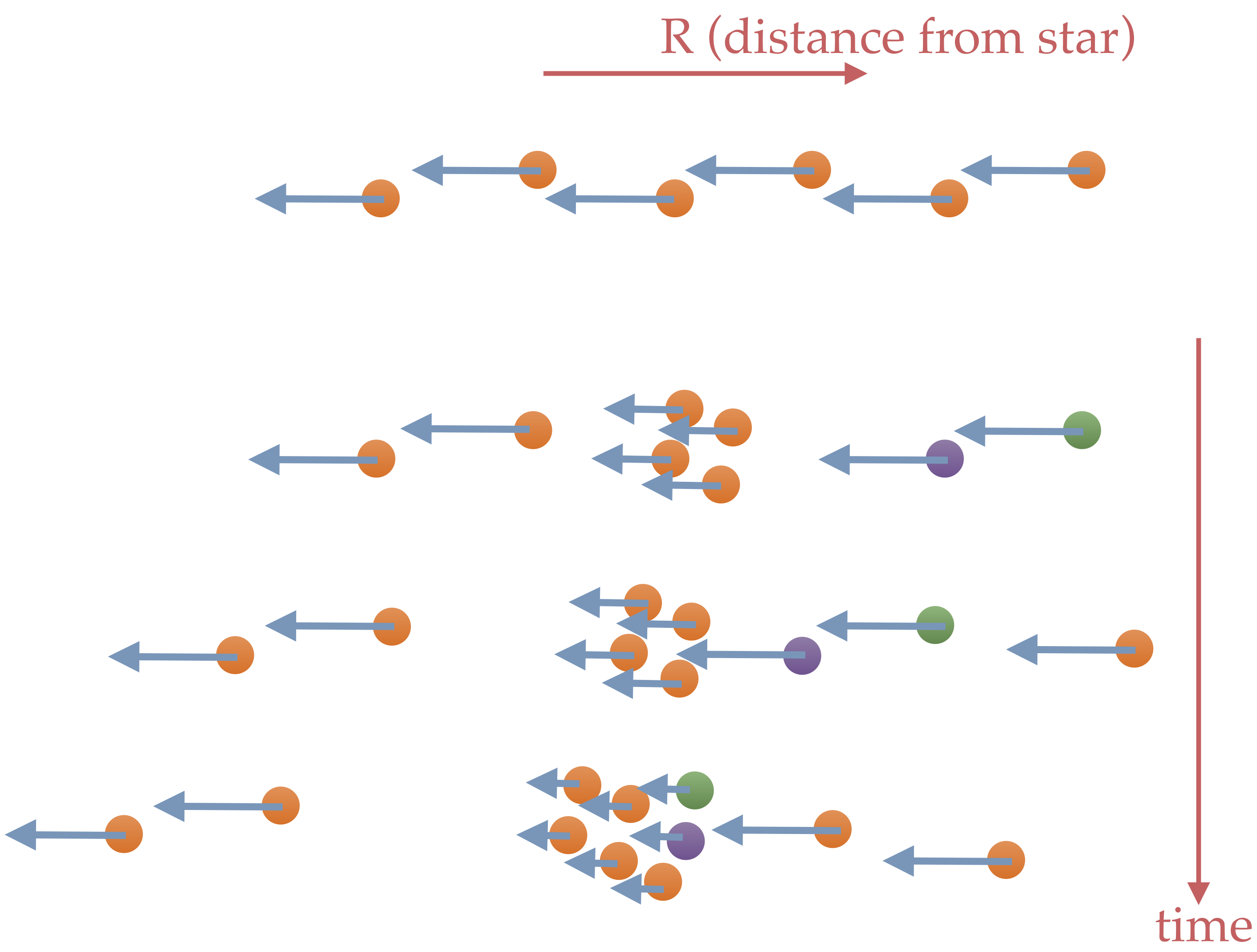
- Dust **drag** on the gas can **slow** down radial **drift** and **help growth** — eg, Gonzalez+ 2017
- It also leads to a **linear instability**: the streaming instability — Youdin & Goodman 2005

  → formation of **dust filaments** with a very large concentration of solids



Formation of dust filaments by the streaming instability
The dust-to-gas density ratio can reach a few x 1000

Johansen+ 2014 (PPVI)



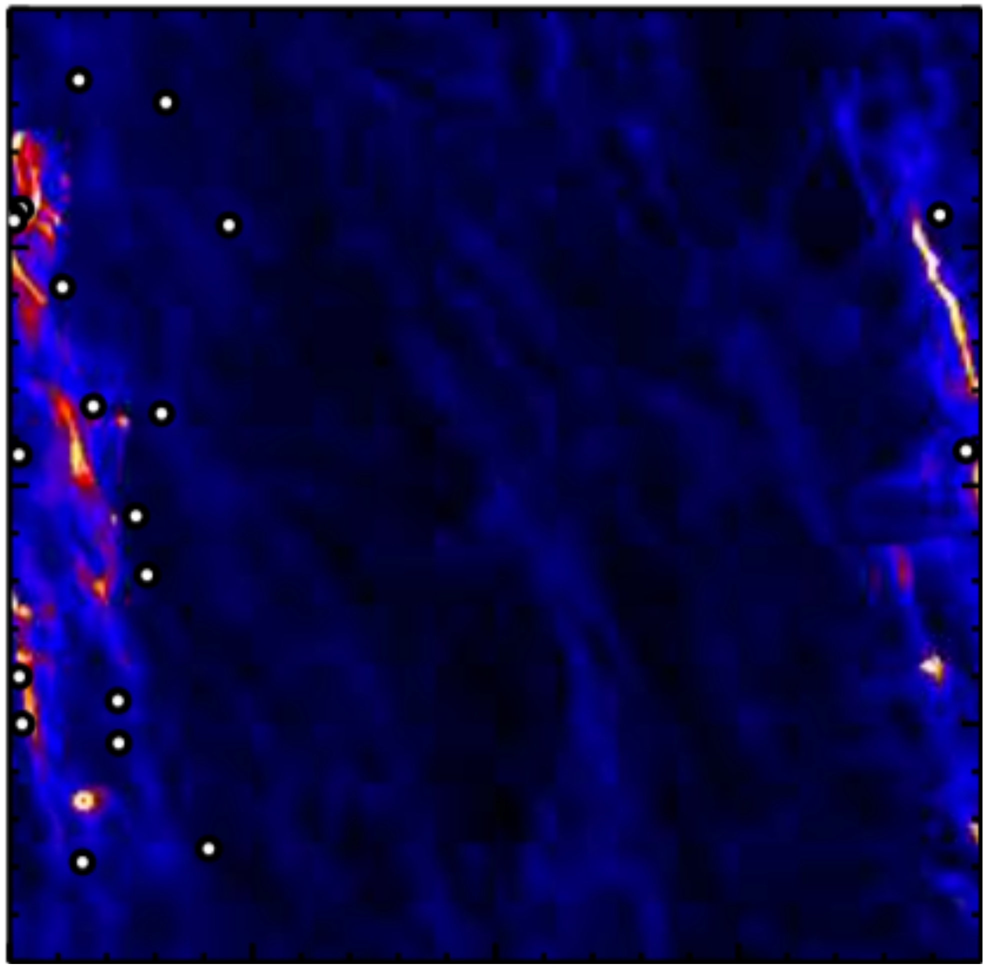
sort of dust traffic jam!

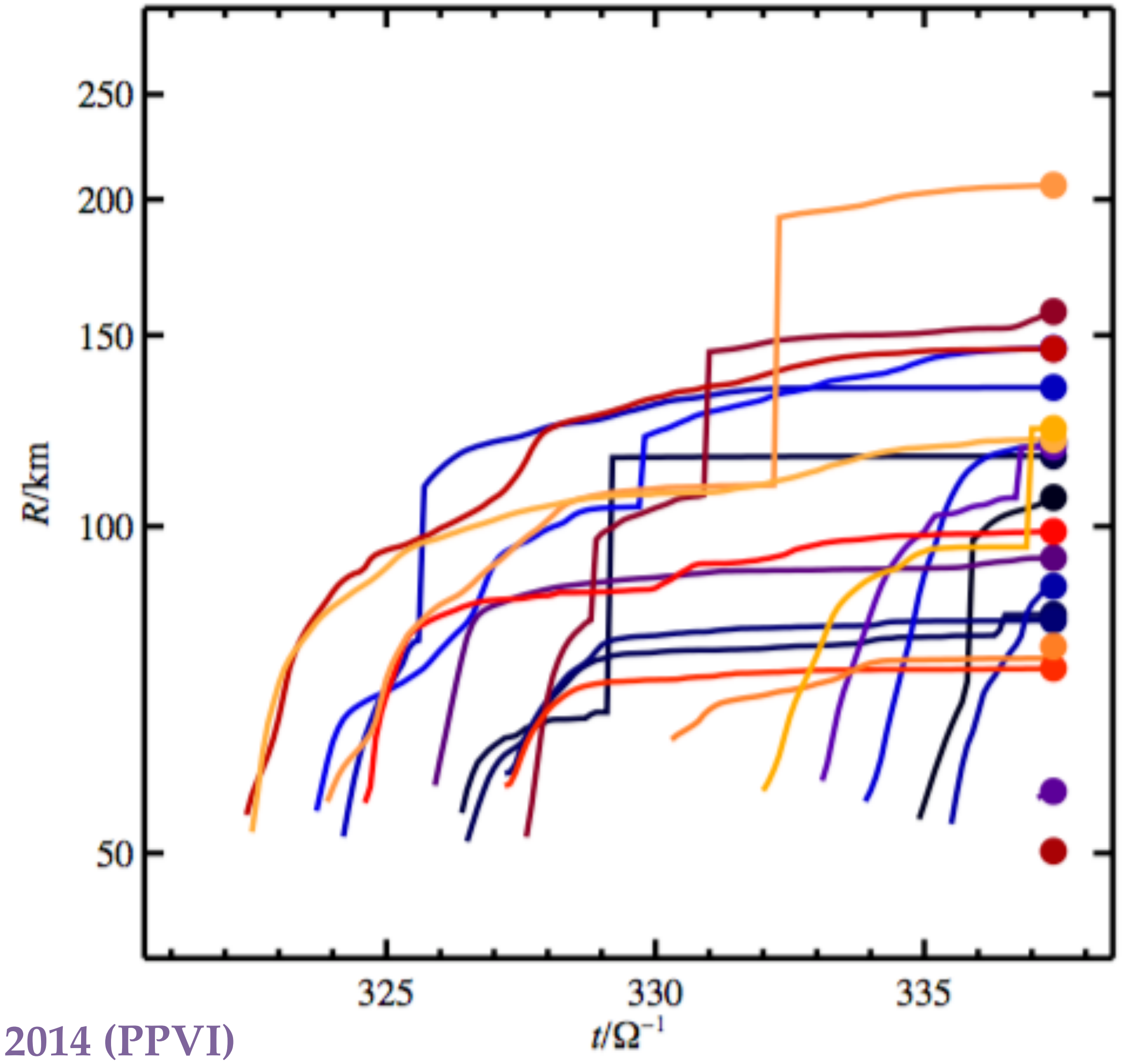
How do planetesimals form?

- Dust **drag** on the gas can **slow** down radial **drift** and **help growth** — eg, Gonzalez+ 2017
- It also leads to a **linear instability**: the streaming instability — Youdin & Goodman 2005

→ formation of **dust filaments** with a very large concentration of solids

→ dust's self-gravity causes the dust filaments to **collapse** which, with the help of collisions, can typically **form** ~100 km-sized **planetesimals**

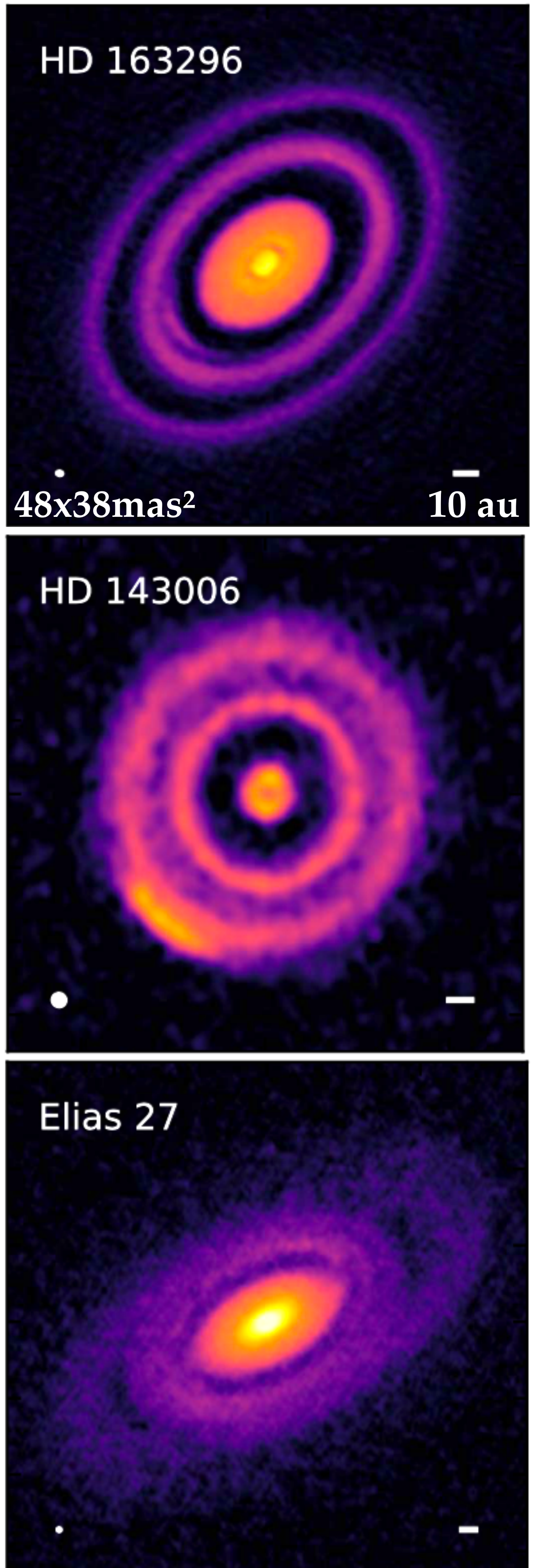




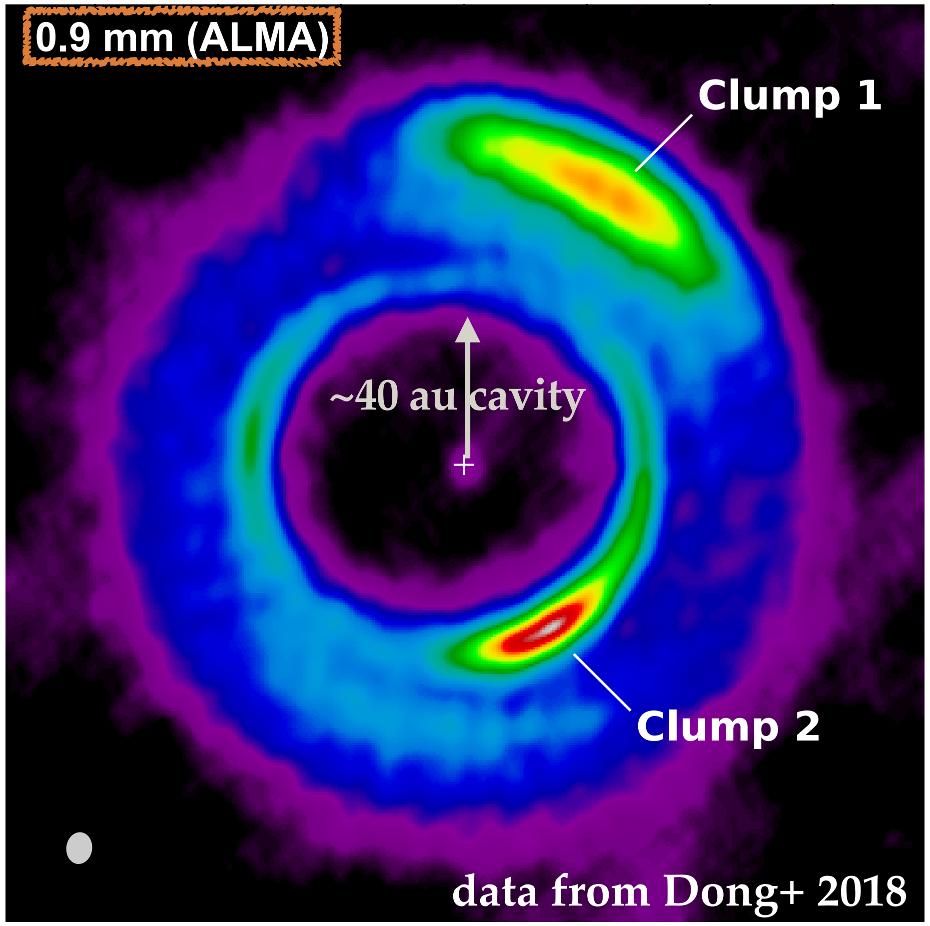
Johansen+ 2014 (PPVI)

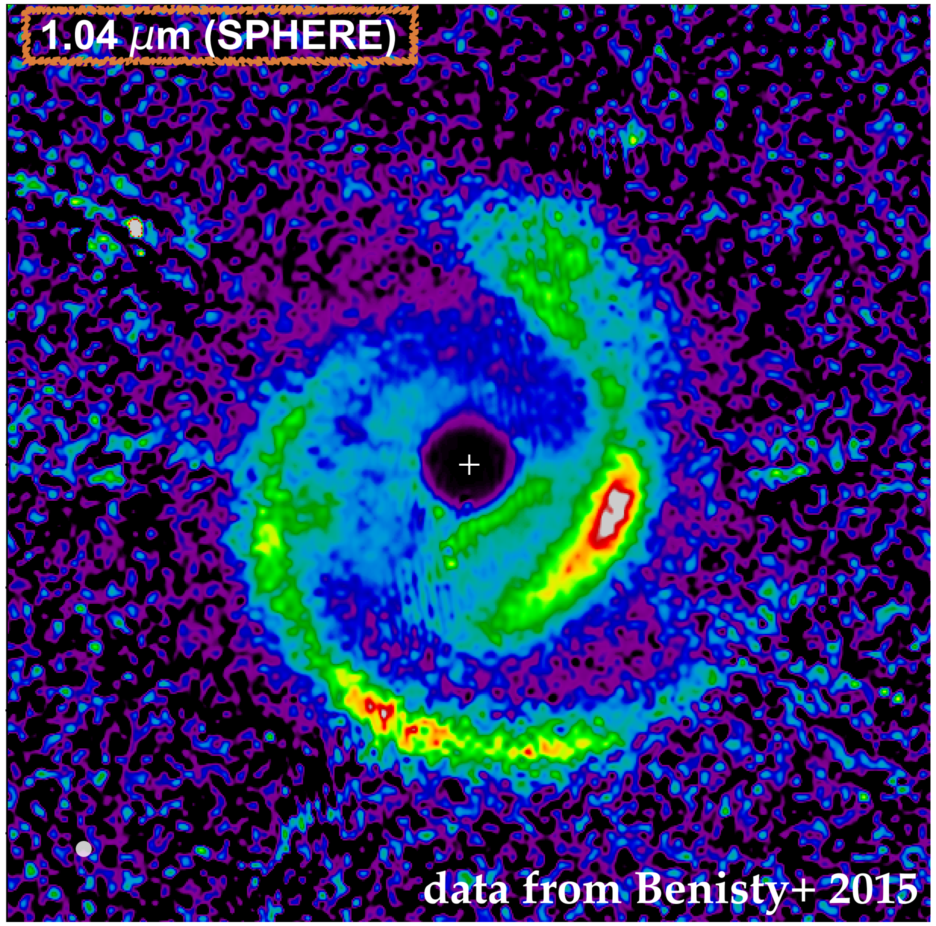
- Most studies assume dust particles are **compact spheres**… what if they are not?

Why so many structures in the discs emission?



Andrews+ 2018 (ALMA@1.3mm)

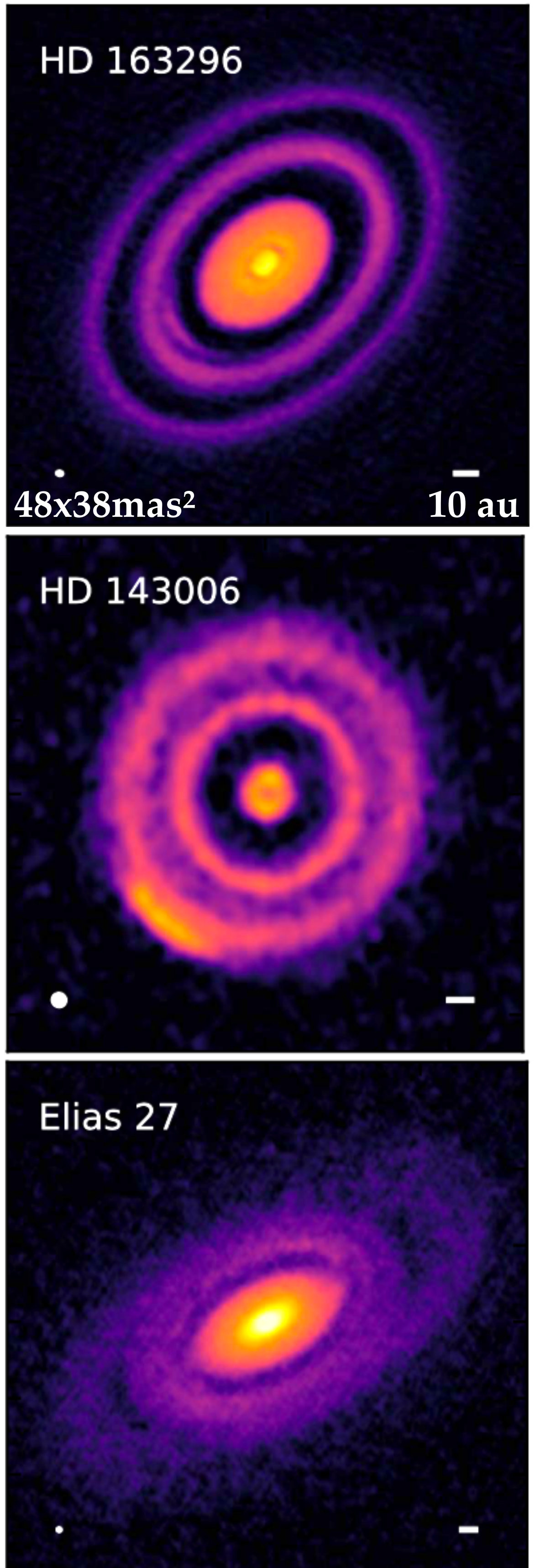




MWC 758 disc seen byALMA and SPHERE
(see Baruteau+ 2019 for a model of this disc with 2 planets)

- what structures are **indirect** signatures of planets?

Why so many structures in the discs emission?



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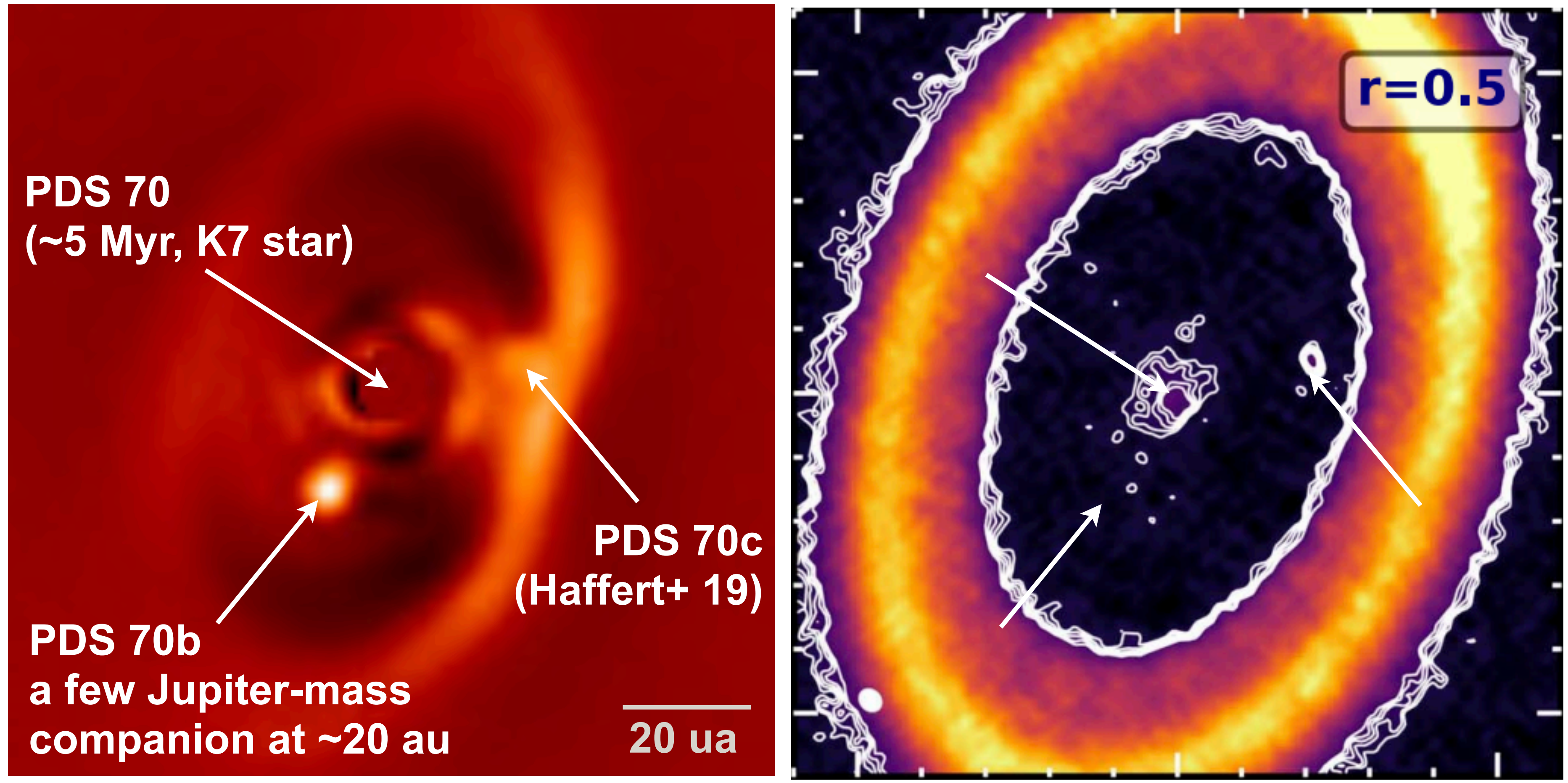
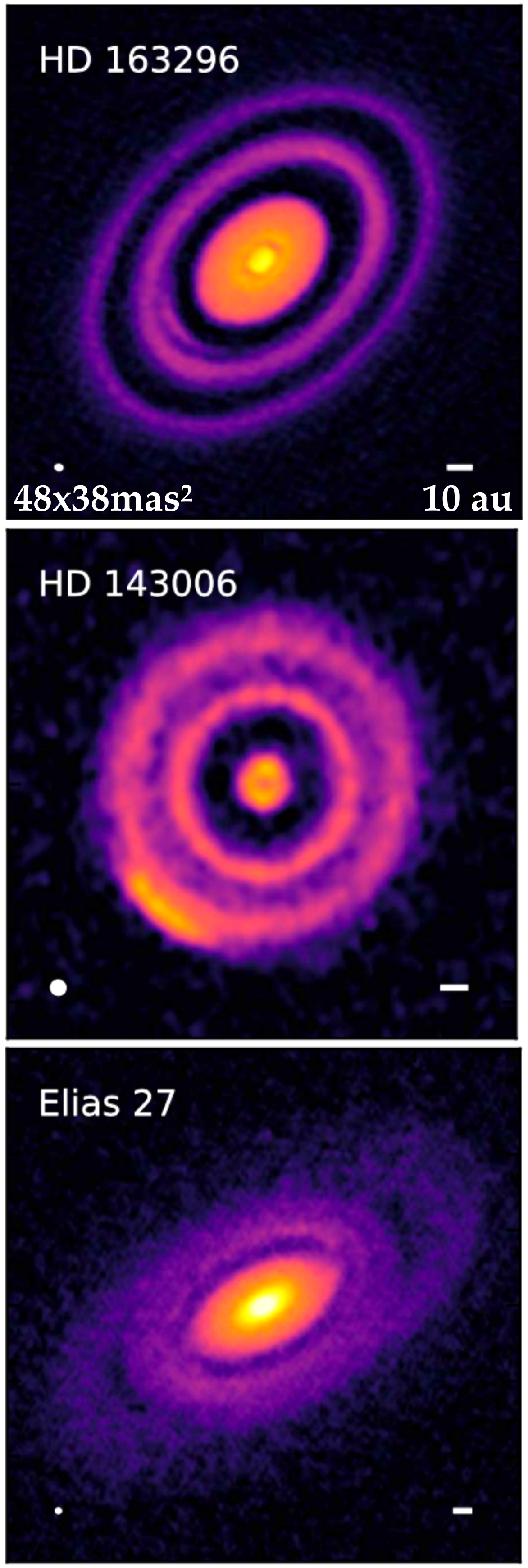


protoplanetary disc around PDS 70 viewed by SPHERE (@~2.1μm, left, Müller+ 2018) and by ALMA (@~0.9mm, right, Benisty+ 2021)

- 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**?

Why so many structures in the discs emission?



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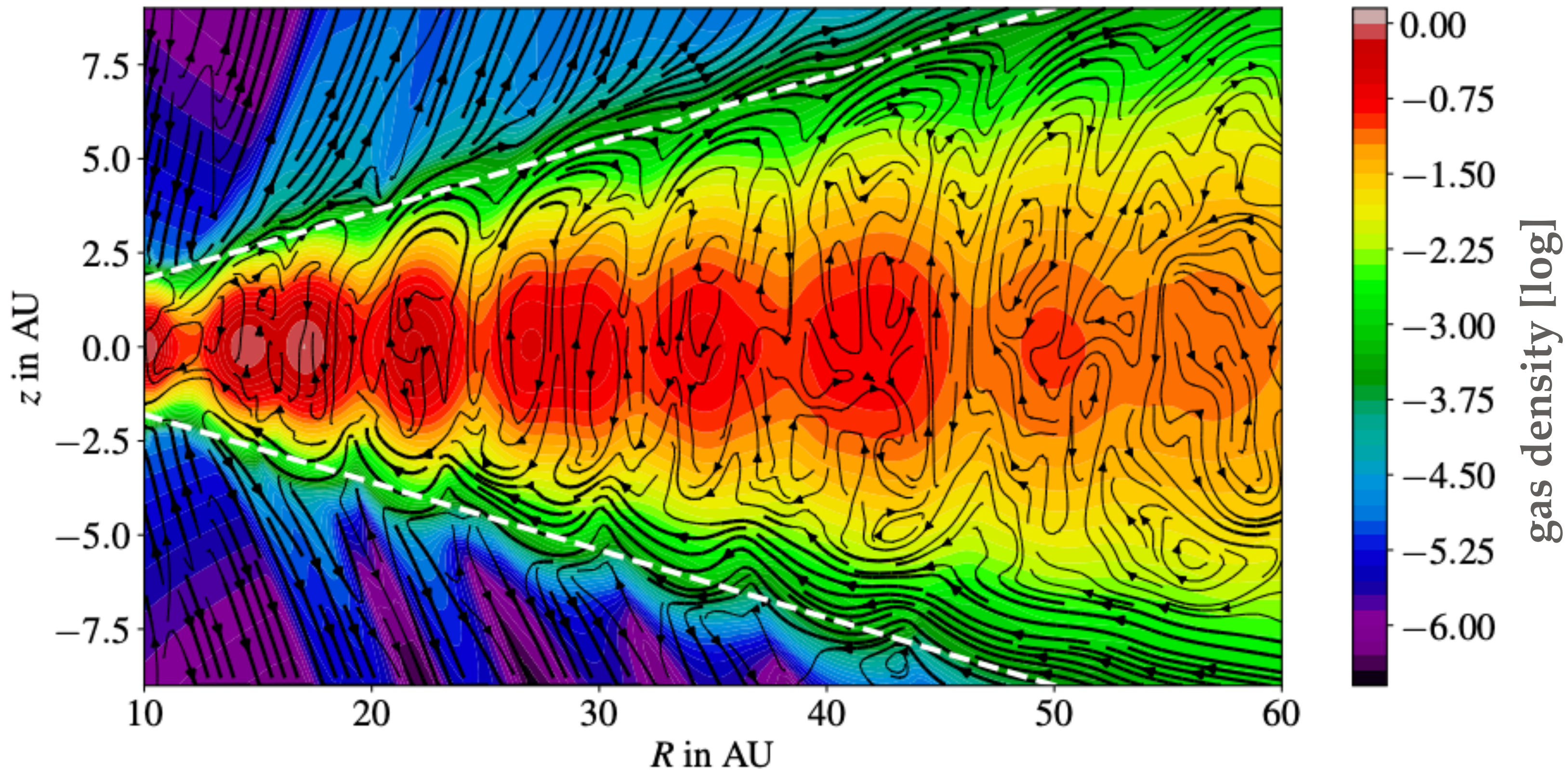
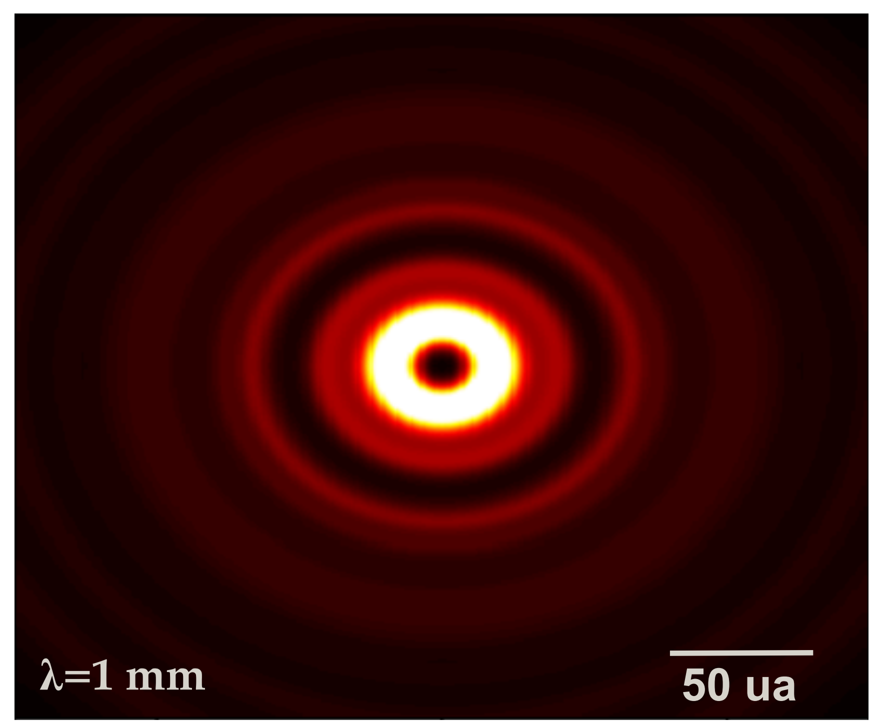


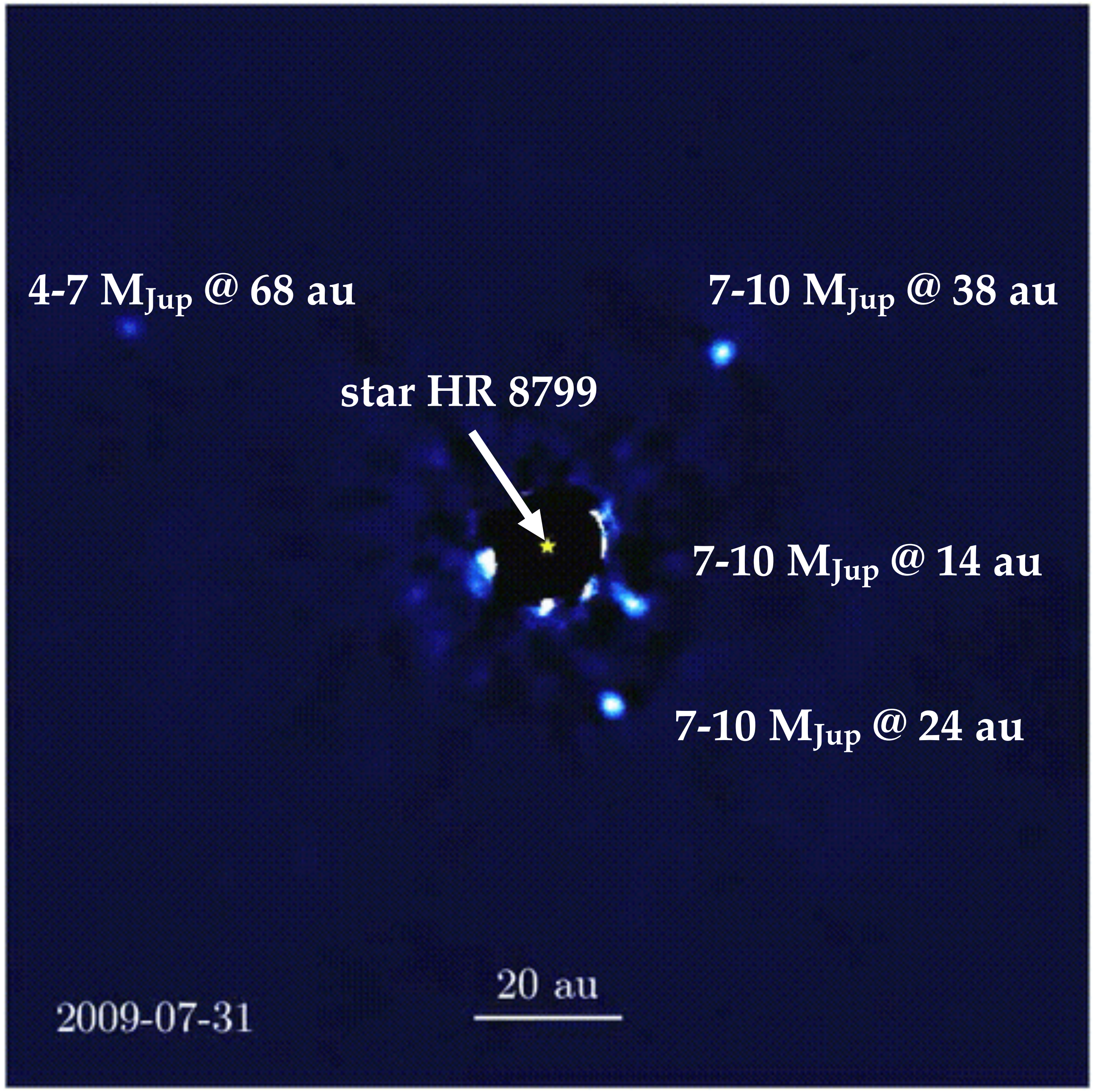


Riols+ 2020

- if not planets, what else? zonal flows in low-turbulent discs?

How do giant planets grow?

- Planetary **formation**: **planetesimals** vs. **pebbles** accretion
  - the conventional mechanism of core growth by planetesimals accretion cannot form **giant** gas planets at **large orbital separations** ($\gtrsim$ 10 au: core growth is **too slow!**)



Marois+ 2010 / movie by Jason Wang

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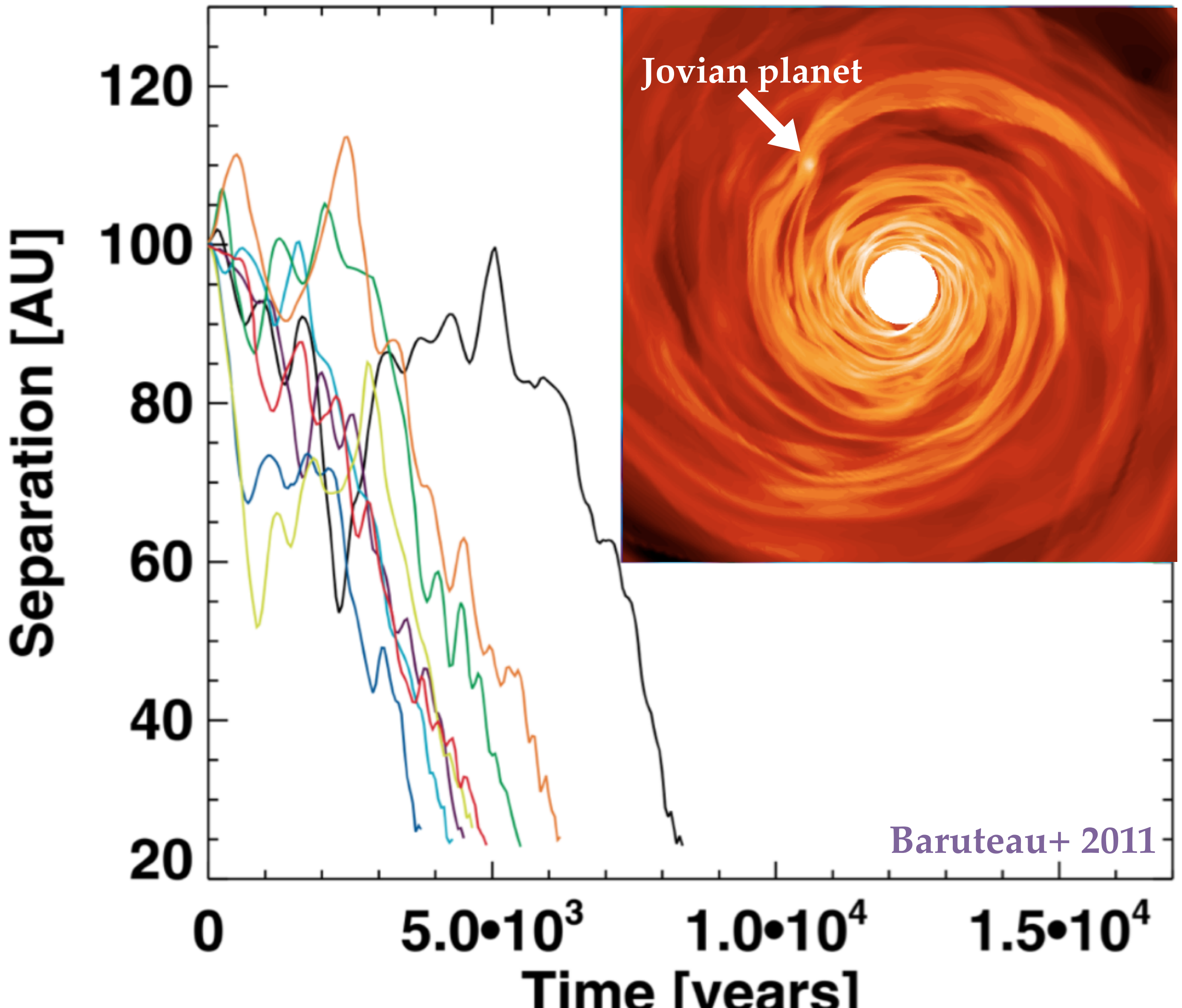
  - the conventional mechanism of core growth by planetesimals accretion cannot form **giant** gas planets at **large orbital separations** ($\gtrsim$ 10 au: core growth is **too slow!**)

    → formation by **disc fragmentation?**

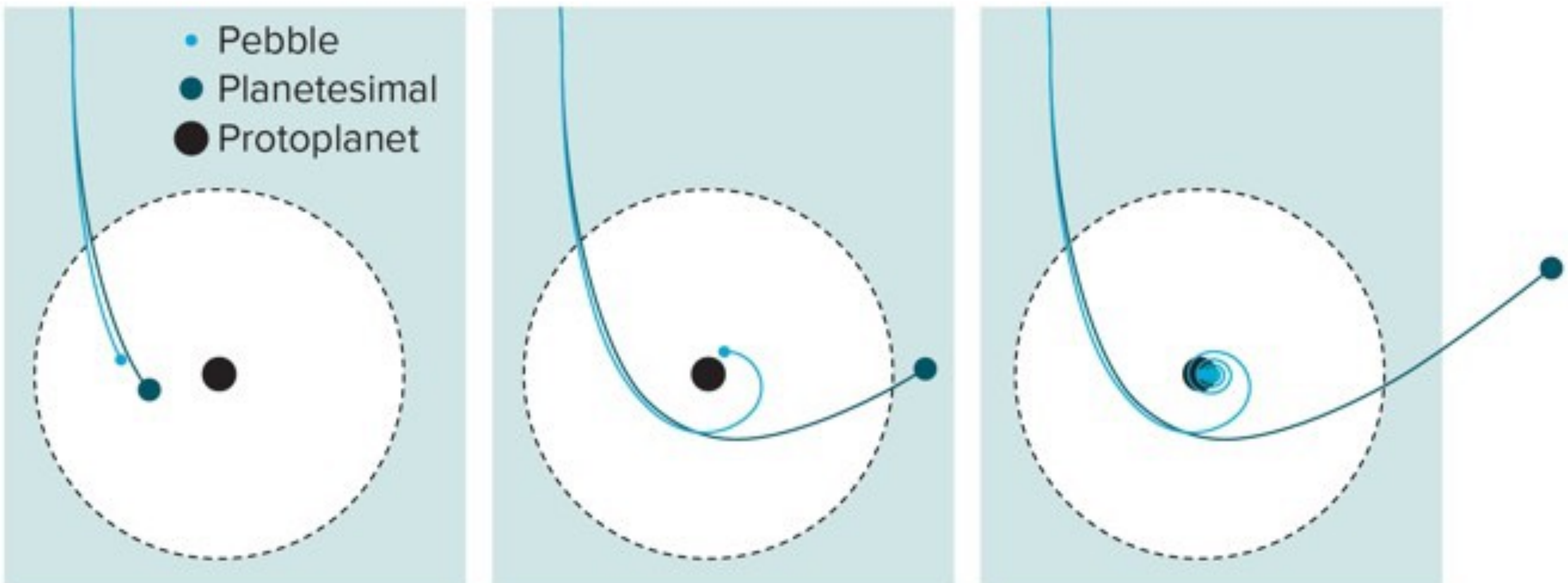


How do giant planets grow?

- Planetary **formation**: **planetesimals** vs. **pebbles** accretion
  - the conventional mechanism of core growth by planetesimals accretion cannot form **giant** gas planets at **large orbital separations** ($\gtrsim$ 10 au: core growth is **too slow!**)

    → formation by **disc fragmentation?**

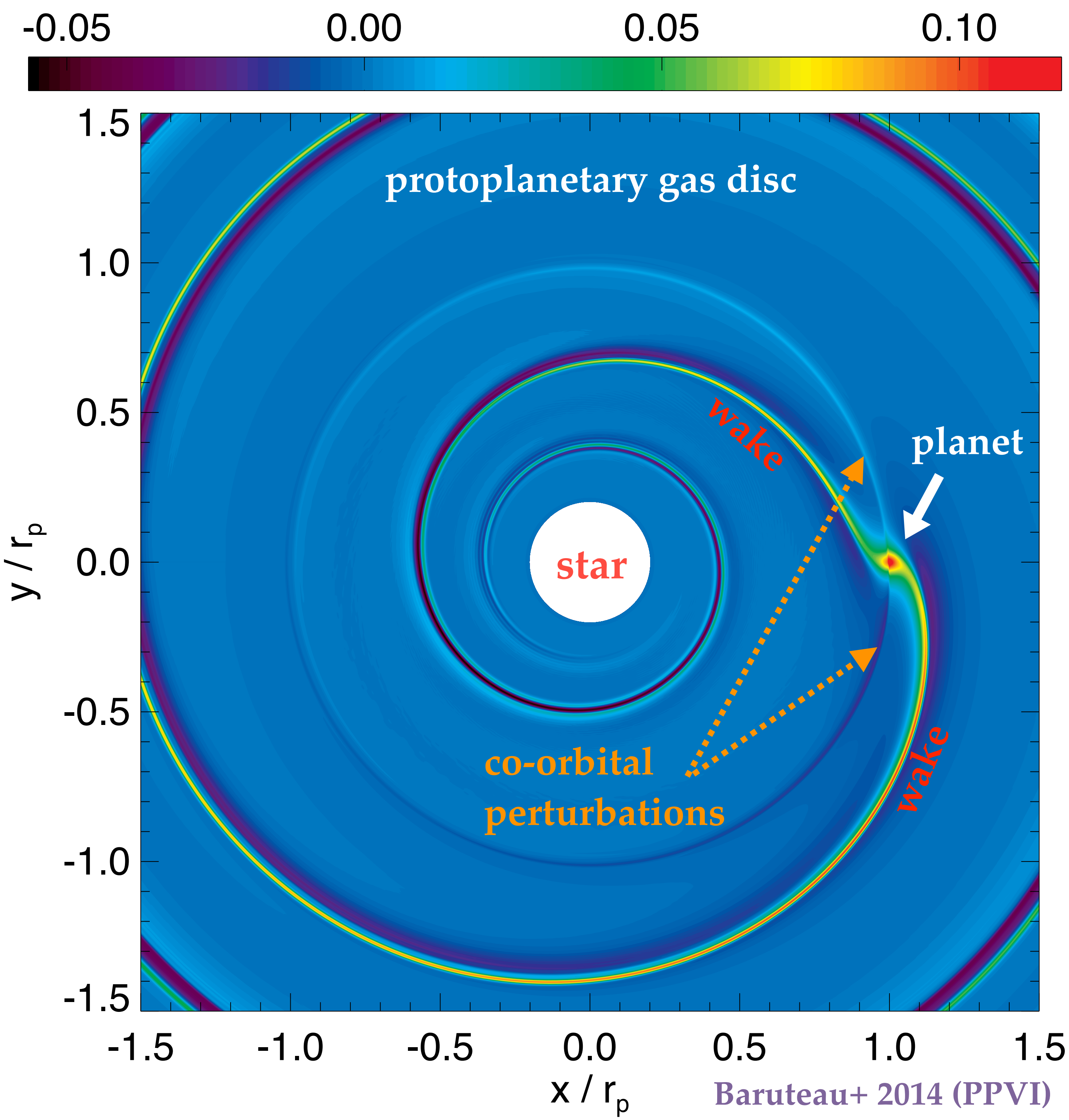
    → growth of planetary **cores** accelerated by **pebble accretion?**



Lambrechts & Johansen / Modica / Knowable

What drives the orbital evolution of planets?

- **disc**-planet interactions?



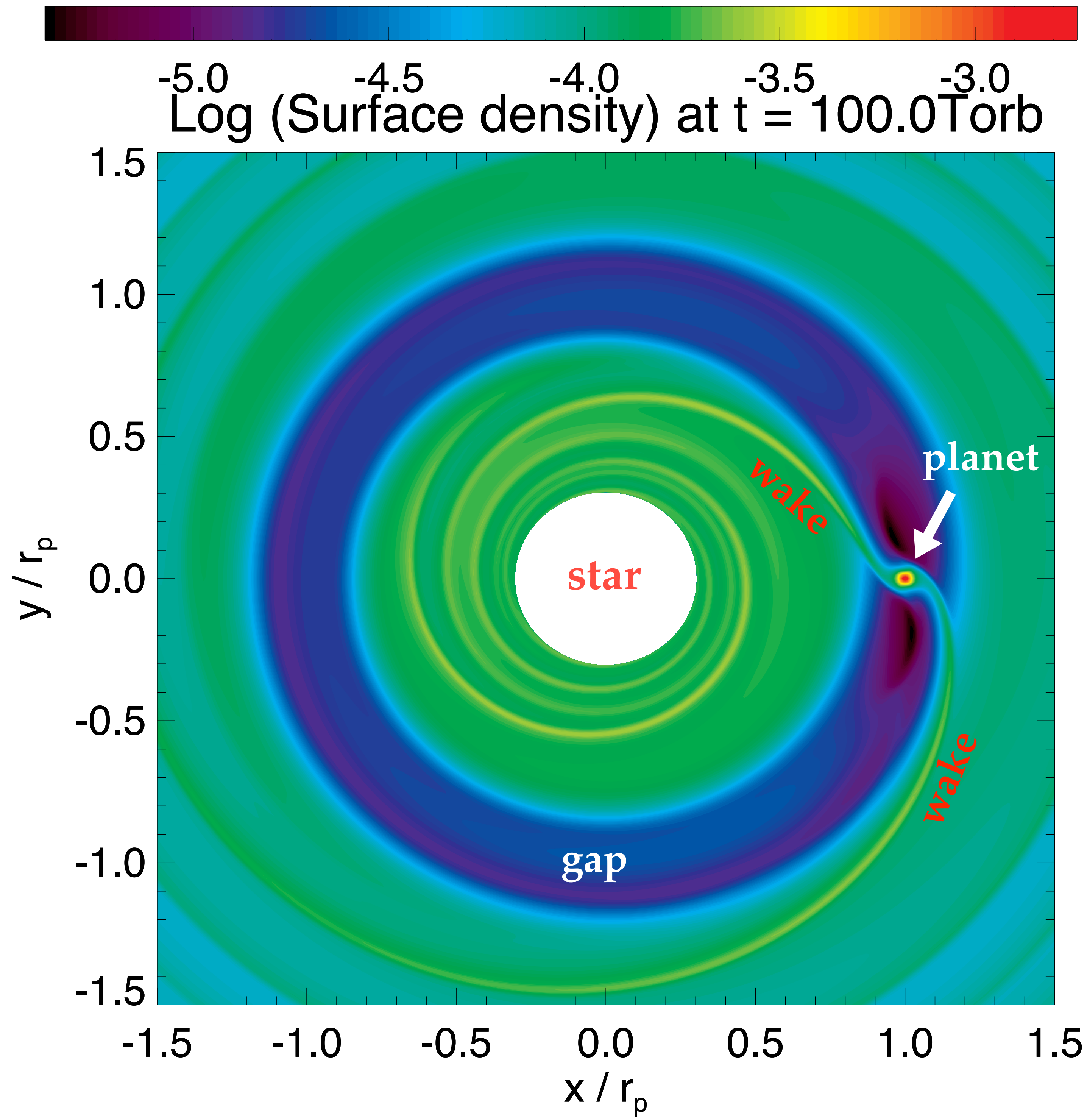
Baruteau+ 2014 (PPVI)

← **gas density perturbation by a 5 Earth-mass planet**

- long-standing, zeroth-order issue of way-too-**rapid inward migration** of **low-mass** planets probably solved…

What drives the orbital evolution of planets?

- **disc**-planet interactions?



← **log of gas surface density (in units of $M_\star/r_p^2$) of a disc perturbed by a 3 Jupiter-mass planet**

- long-standing, zeroth-order issue of way-too-**rapid inward migration** of **low-mass** planets probably solved…

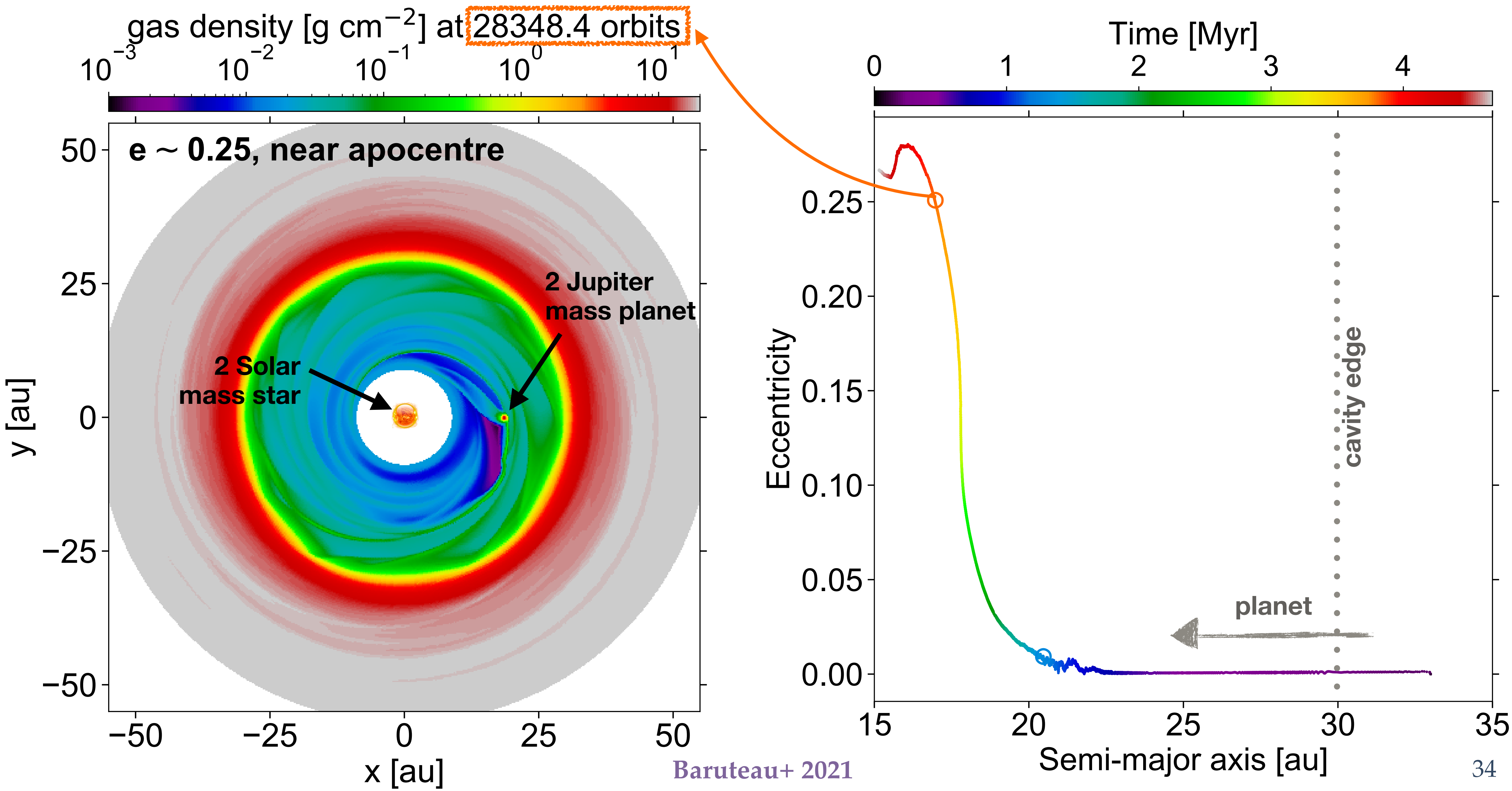
- … next-order issue of **rapid inward migration** of **massive** planets is still standing!

→ need more studies for low-turbulent discs with magnetized winds

→ need to further develop **global** models of planet formation & evolution + disc evolution **in 2D**

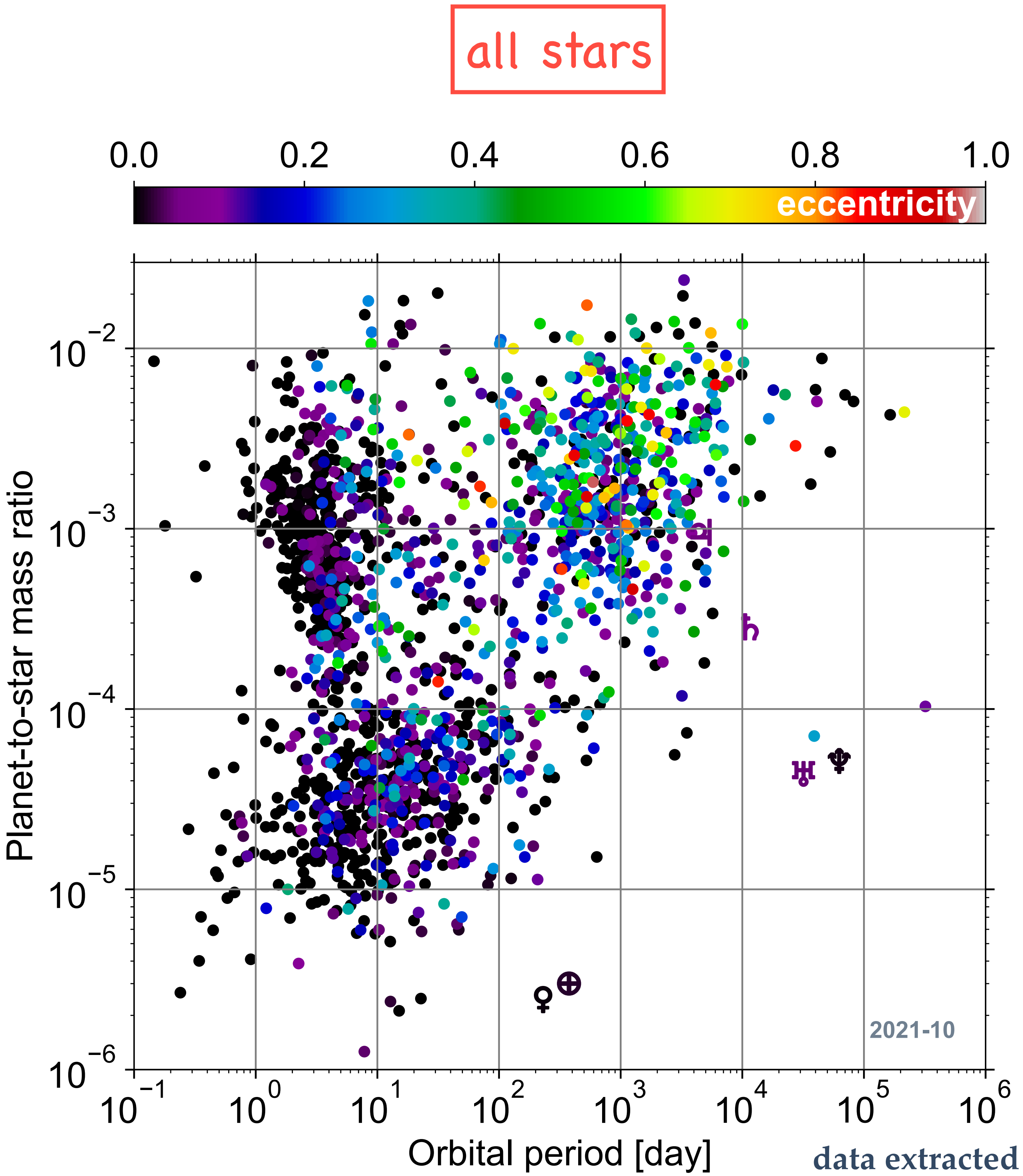
What drives the orbital evolution of planets?

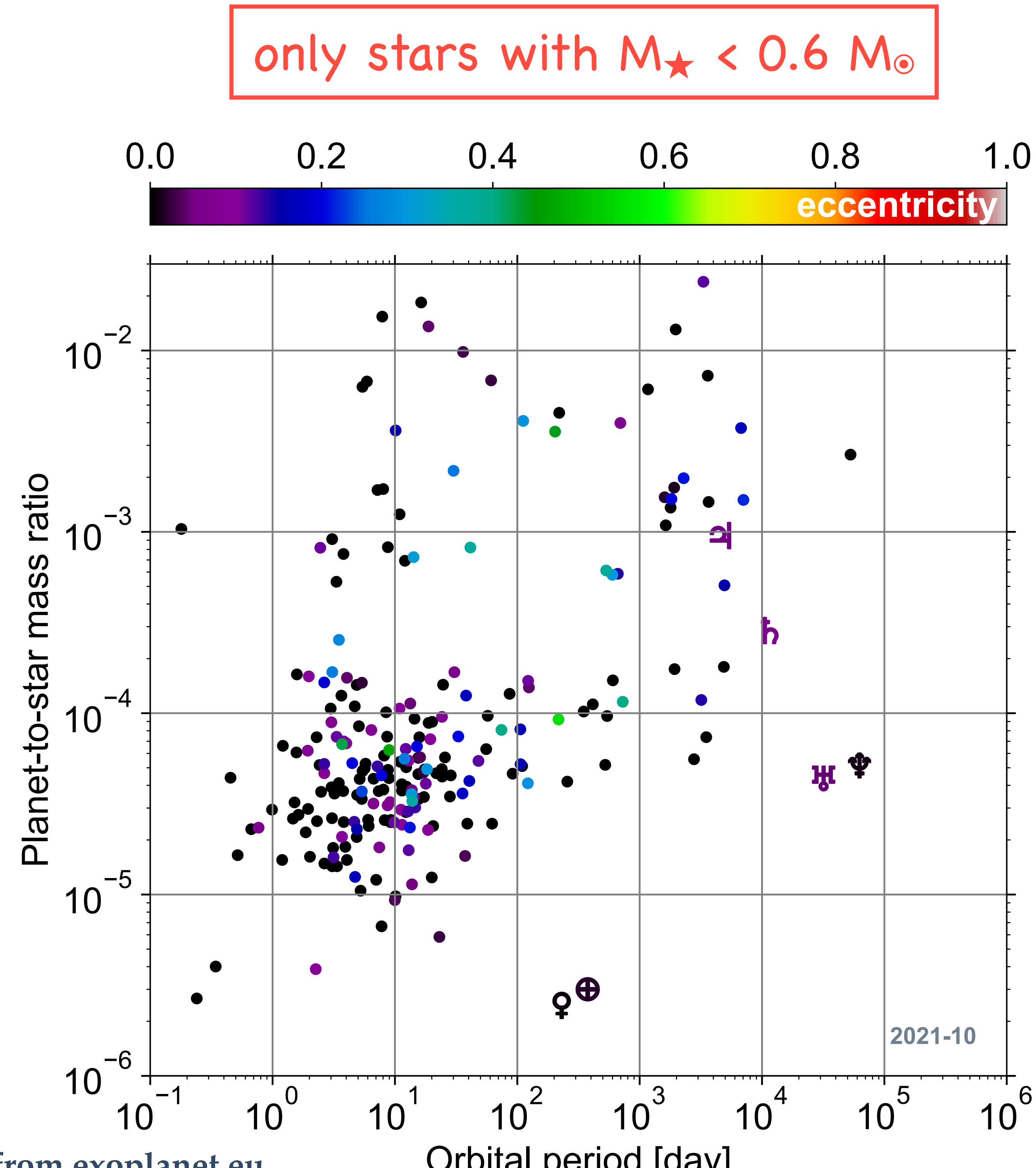
- how about **planet**-planet interactions and **star**-planet interactions?
  - likely origin for **hot Jupiters** with **large** orbital **obliquities**, and for **eccentric warm Jupiters**
    - → an **alternative** scenario for eccentric warm Jupiters: disc migration inside a **cavity** Debras+ 2021



Baruteau+ 2021

And what if the star is an M dwarf?



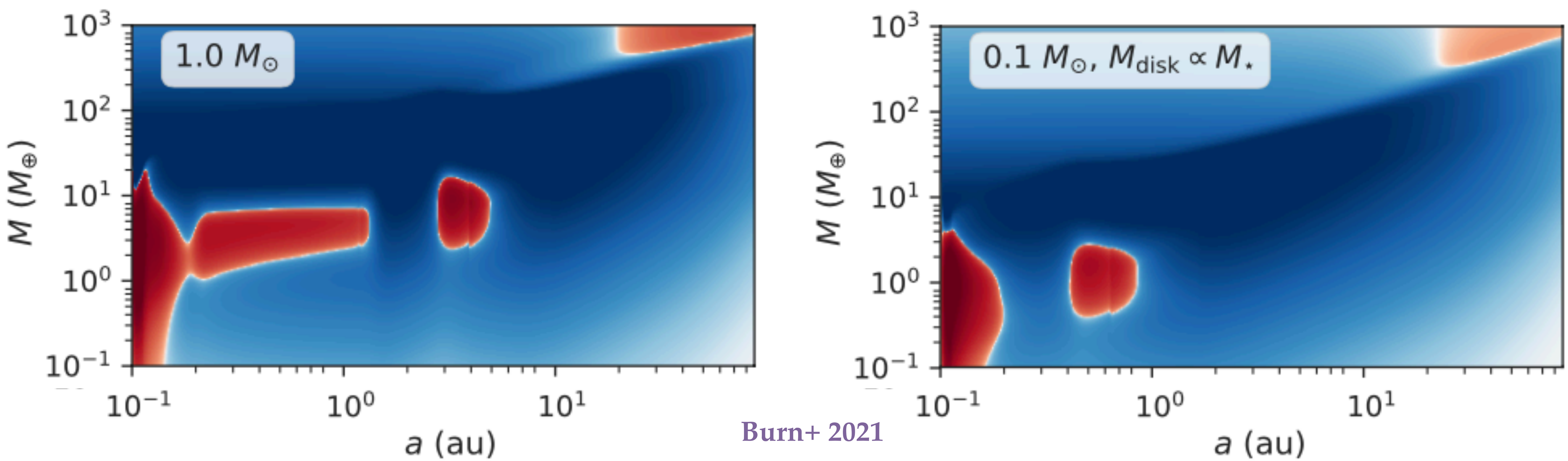


data extracted from exoplanet.eu
(only planets < 15 M_{jup} are shown)

- M dwarfs host **~10%** of the confirmed exoplanets so far (biased)
- **few giant** planets around M dwarfs, but a large **diversity** in planet-to-star mass ratio

And what if the star is an M dwarf?

- the **lower** the **mass** of the star… **R. Burn+ 2021**
    - the **lower** the **mass** of the **disc**, its **size**, but also its surface **density**
    - the **lower** the **mass accretion rate** (lifetime weakly dependent on stellar mass?)
    - the **longer** the **orbital period**
        - → the **slower** to **grow** planet cores by **planetesimals** accretion (less massive cores thus form)
        - → **same** for planet cores growing by **pebbles** accretion! **Coleman+ 2019, Liu+ 2019**
    - the **cooler** the disc at a same radial distance, which affects the **migration** timescale of planetary cores

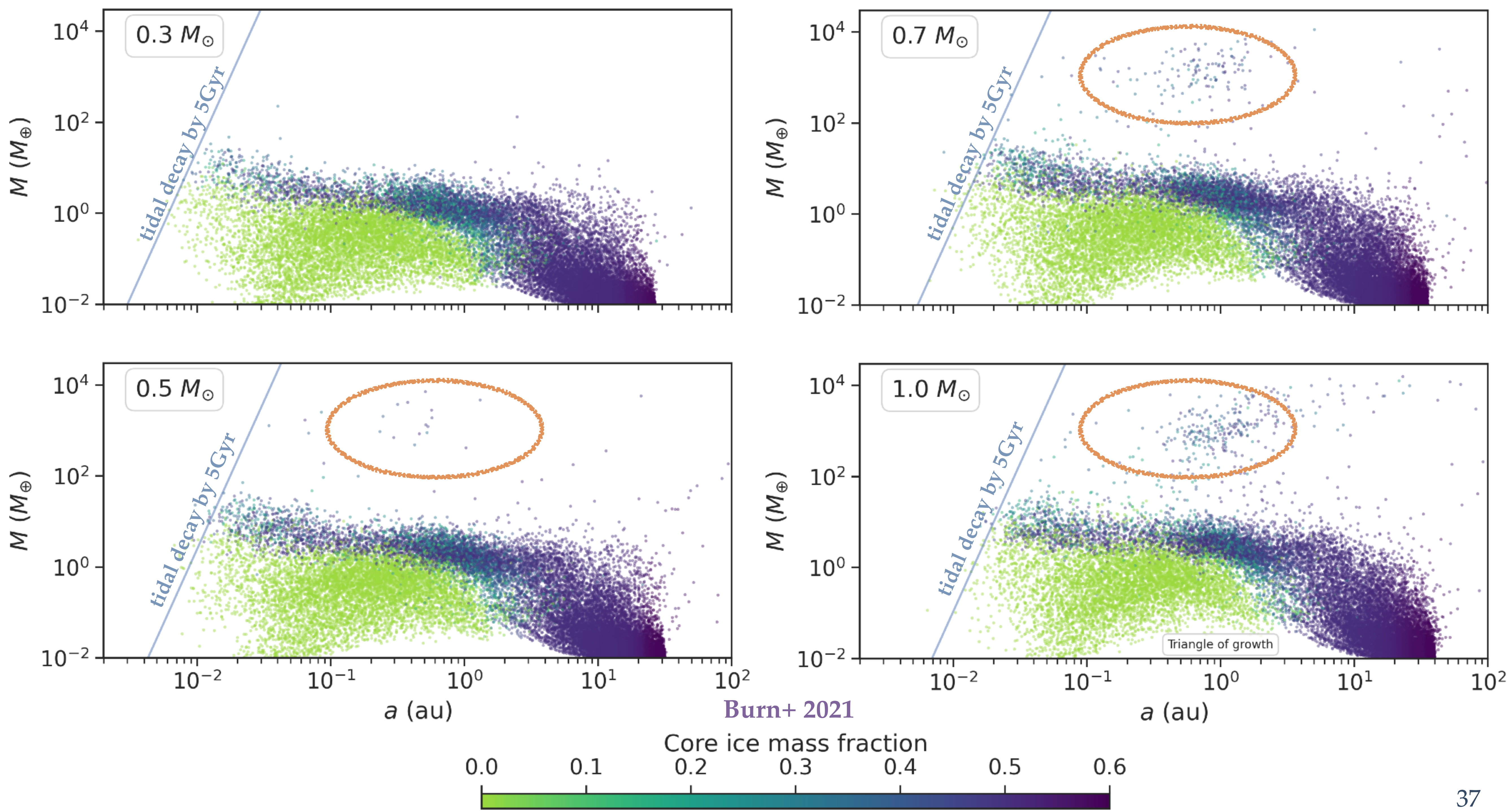


Burn+ 2021

blue: inward migration — red: outward migration

And what if the star is an M dwarf?

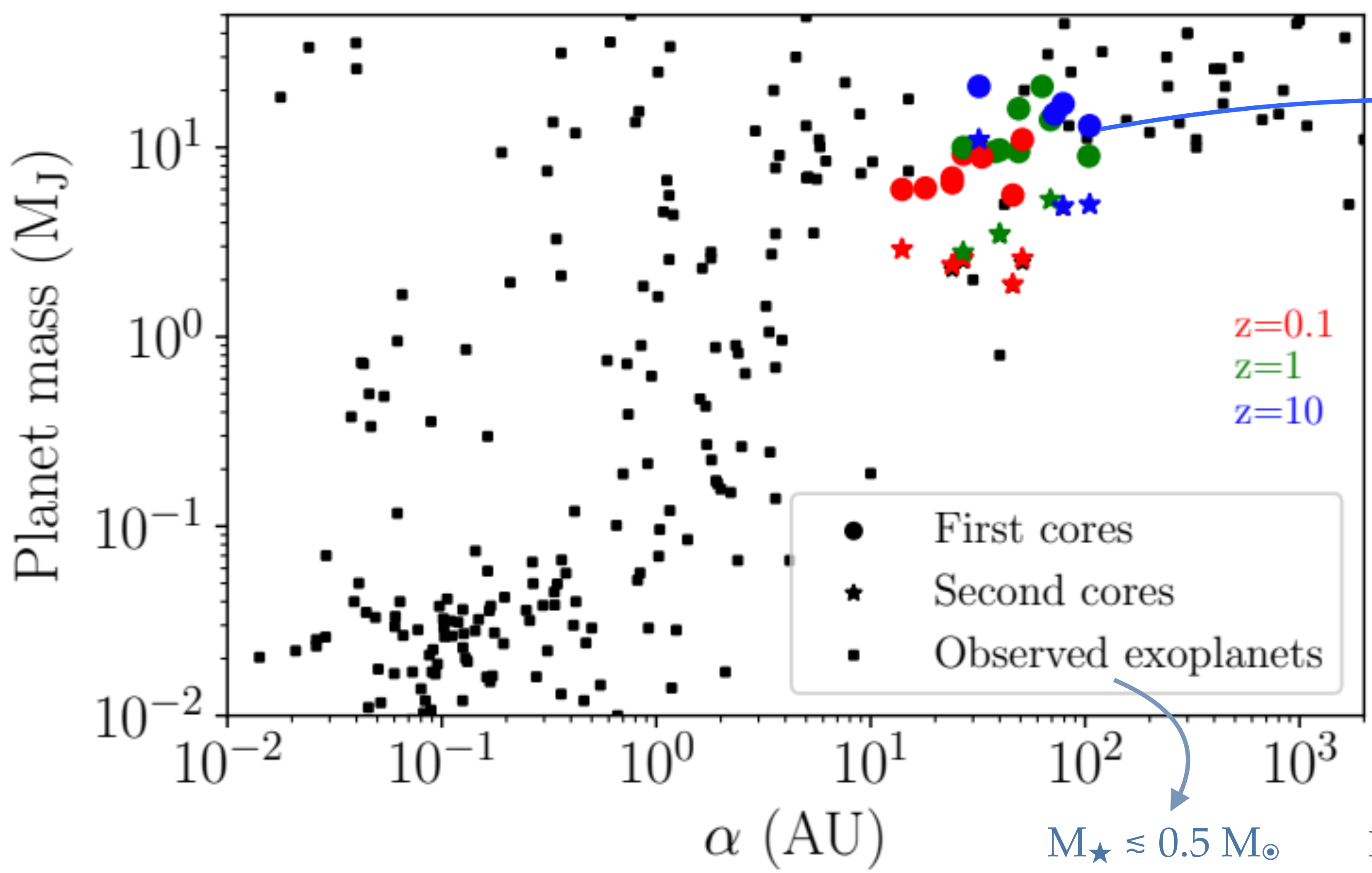
- the **lower** the **mass** of the star… **Burn+ 2021**
  - the **fewer giant planets form** (by planetesimals accretion), but their **typical** mass tends to be **similar**
  - **no** giant planets predicted for $M_\star \lesssim 0.5\ M_\odot$

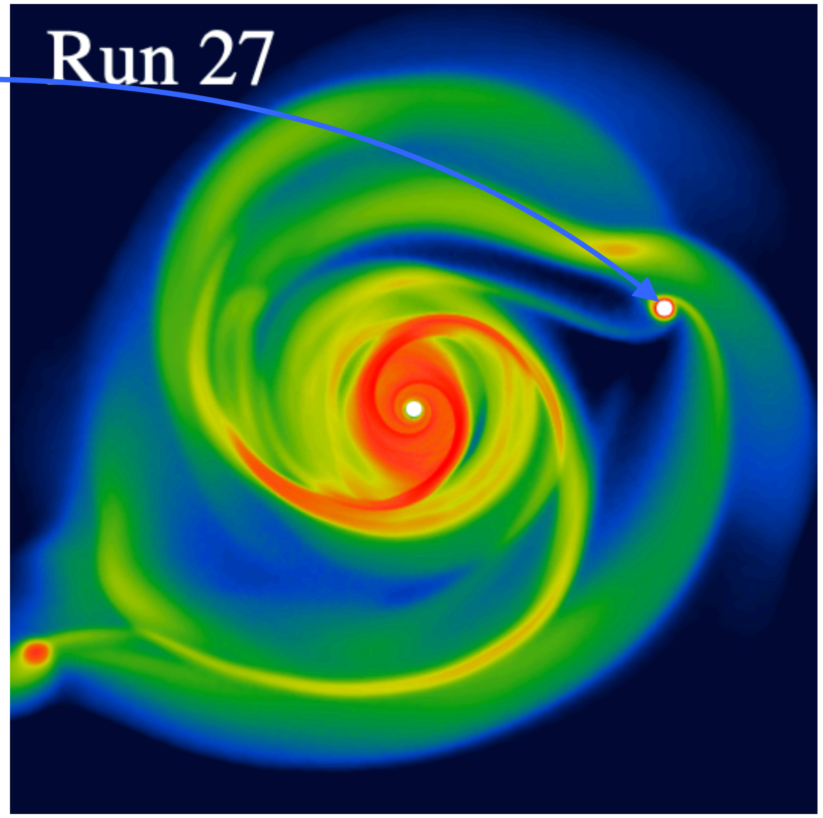


Burn+ 2021

And what if the star is an M dwarf?

- the **lower** the **mass** of the star… **Burn+ 2021**
  - the **fewer giant planets form** (by planetesimals accretion), but their **typical** mass tends to be **similar**
  - **no** giant planets predicted for $M_\star \lesssim 0.5\ M_\odot$
  - **similar** predictions with only **pebble** accretion! **Liu+ 2019**
  - do **giant** planets around M dwarfs have to form via **disc fragmentation**?





$M_\star \lesssim 0.5\ M_\odot$ **Mercer & Stamatellos 2020**

radial distance where cores form

https://exosystemes2.sciencesconf.org

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CONTEXTE

La série d'ateliers ExoSystèmes, que nous poursuivons cette année, a pour but de structurer la communauté française autour de la formation des systèmes étoiles-planètes, leur évolution, leur fin de vie, la diversité des planètes et de leur architecture orbitale, ou encore leur habitabilité autour de différents types d'étoiles. Son but est de favoriser et renforcer les multiples synergies instrumentales, observationnelles et théoriques de nos communautés en France.

Ce deuxième atelier, ExoSystèmes II, est ouvert à toute la communauté stellaire et (exo)planétaire, et aura pour thème général 'Structure', couvrant par là-même une gamme étendue des propriétés des systèmes planétaires depuis l'étoile jusqu'aux planètes. Quatre sessions sont anticipées: (i) structure interne et atmosphères (exo-)planétaires, (ii) multiplicité stellaire et planétaire: architecture orbitale des exosystèmes, (iii) structures dans les disques protoplanétaires: exosystèmes en formation? et (iv) structure et activité stellaires: effets sur la détection et l'évolution planétaires.

Nous encourageons tout particulièrement les jeunes chercheuses et chercheurs à soumettre des contributions orales pour cet atelier.

... thanks!