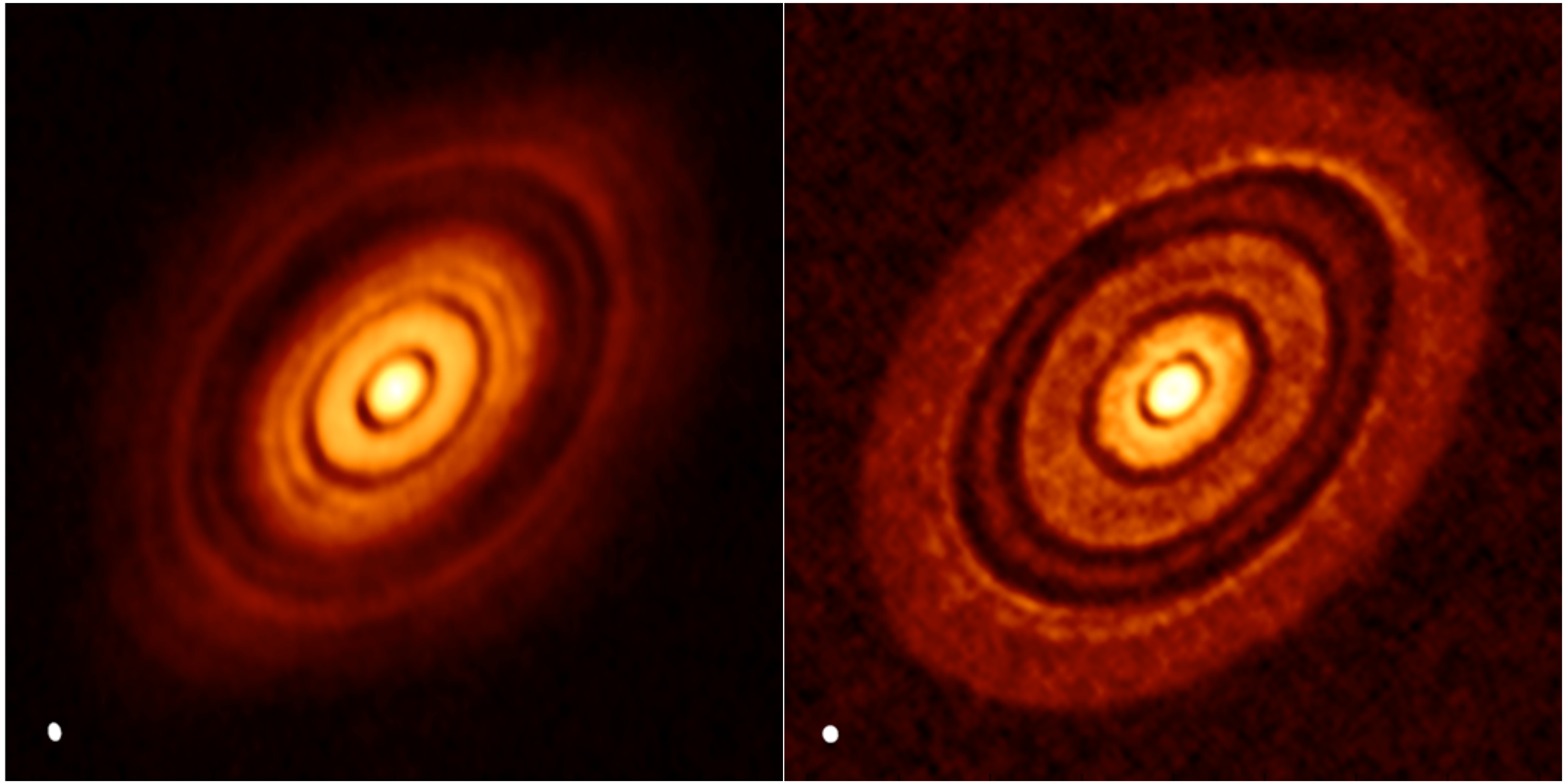
Planet-disc interactions

(a short, biased review)



Richard Alexander

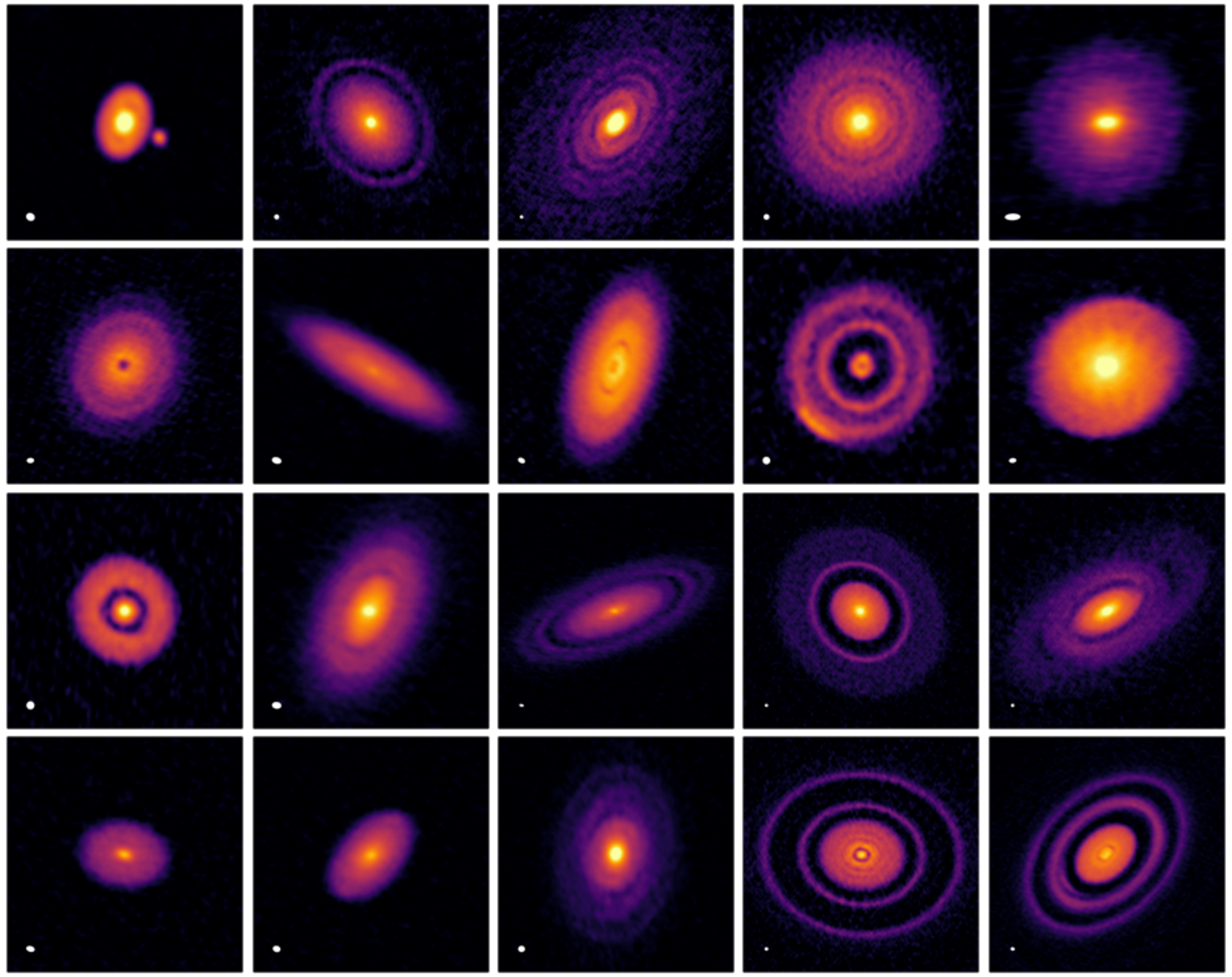
UNIVERSITY OF LEICESTER

UKI Discs Meeting
Cambridge, 20-22 July 2026

Outline

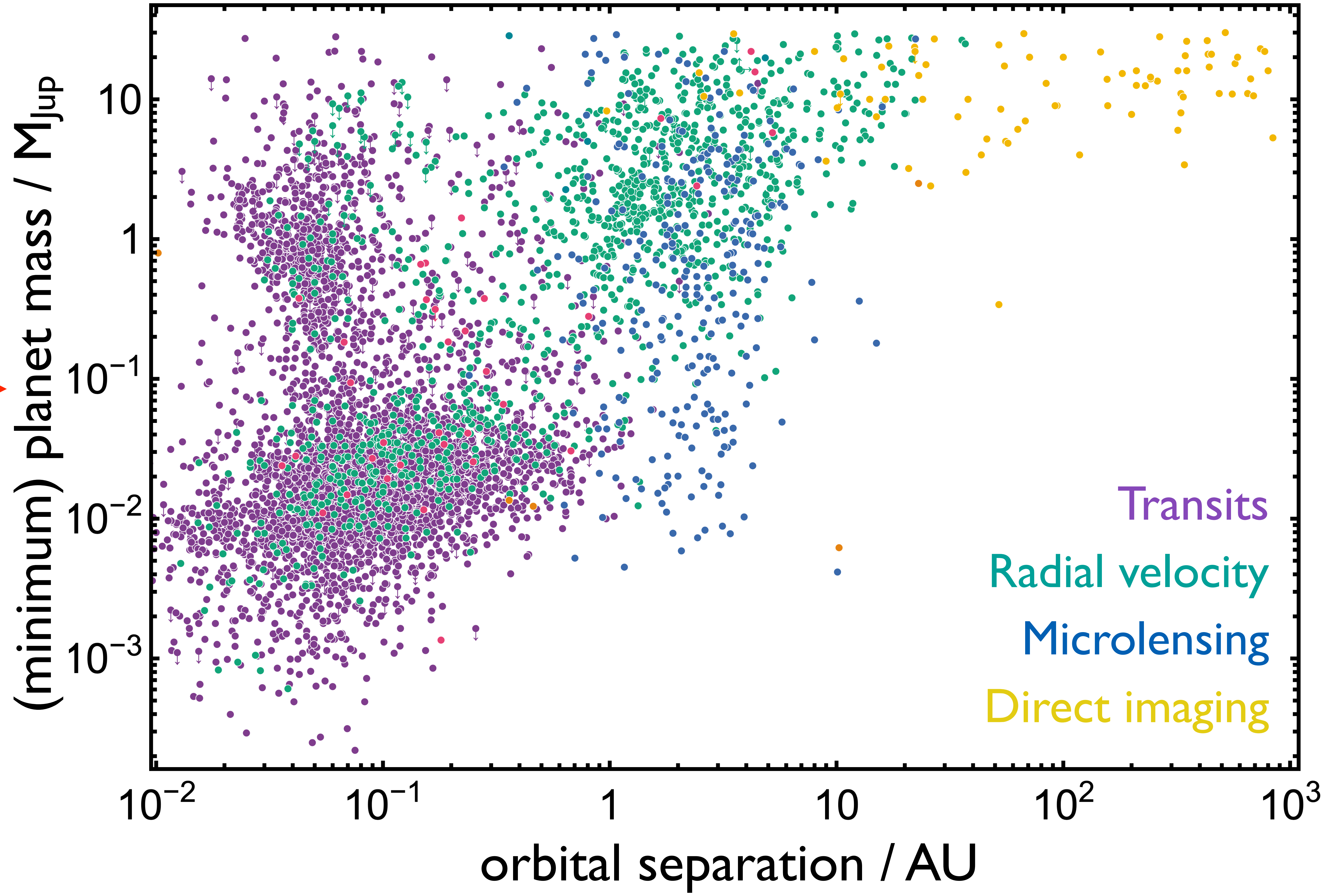
- Introduction to (recap of) planet-disc interaction basics.
- Why does planet migration matter?
- Observational evidence for disc-driven migration.
- Open questions…

Planets form in discs



DSHARP: Andrews+ (2018)

Known exoplanets



(NASA Exoplanet Archive)

What is planet migration?

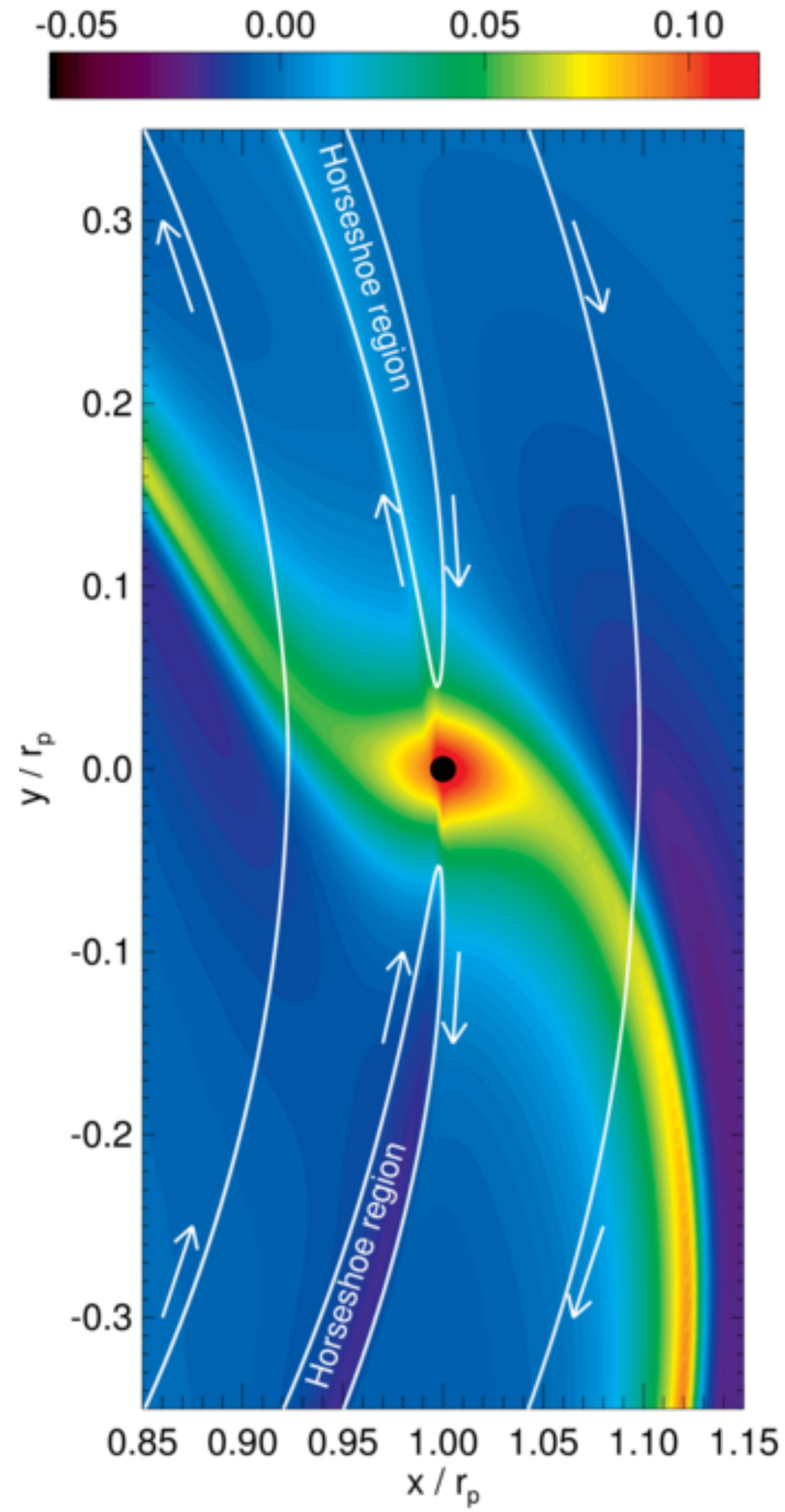
- Planets migrate when they exchange angular momentum (and energy) with another "body" in the system.
- Outcome is a change in the planet's orbit: semi-major axis, eccentricity and inclination can all change.
- There are several different mechanisms for planet migration:
  - planet-planet interactions.
  - interactions with a companion star (binary or external)
  - tides
  - interactions with a planetesimal disc
  - interactions with a gaseous (protoplanetary) disc

What is planet migration?

- Planets migrate when they exchange angular momentum (and energy) with another "body" in the system.
- Outcome is a change in the planet's orbit: semi-major axis, eccentricity and inclination can all change.
- There are several different mechanisms for planet migration:
  - planet-planet interactions.
  - interactions with a companion star (binary or external)
  - tides
  - interactions with a planetesimal disc
  - interactions with a gaseous (protoplanetary) disc

Planet-disc interactions: basics

- Gravitational interaction between planet and gas disc (Goldreich & Tremaine 1979; 1980).
- Spiral density waves launches from Lindblad and corotation resonances.
- This results in **torques**: angular momentum exchange drives migration.
- Outcome depends both qualitatively and quantitatively on both planet mass and (local) disc properties.
- See Paardekooper+ (2023, PP7) for a detailed review.



Baruteau+ (2014, PP6)

Planet-disc interactions: basics

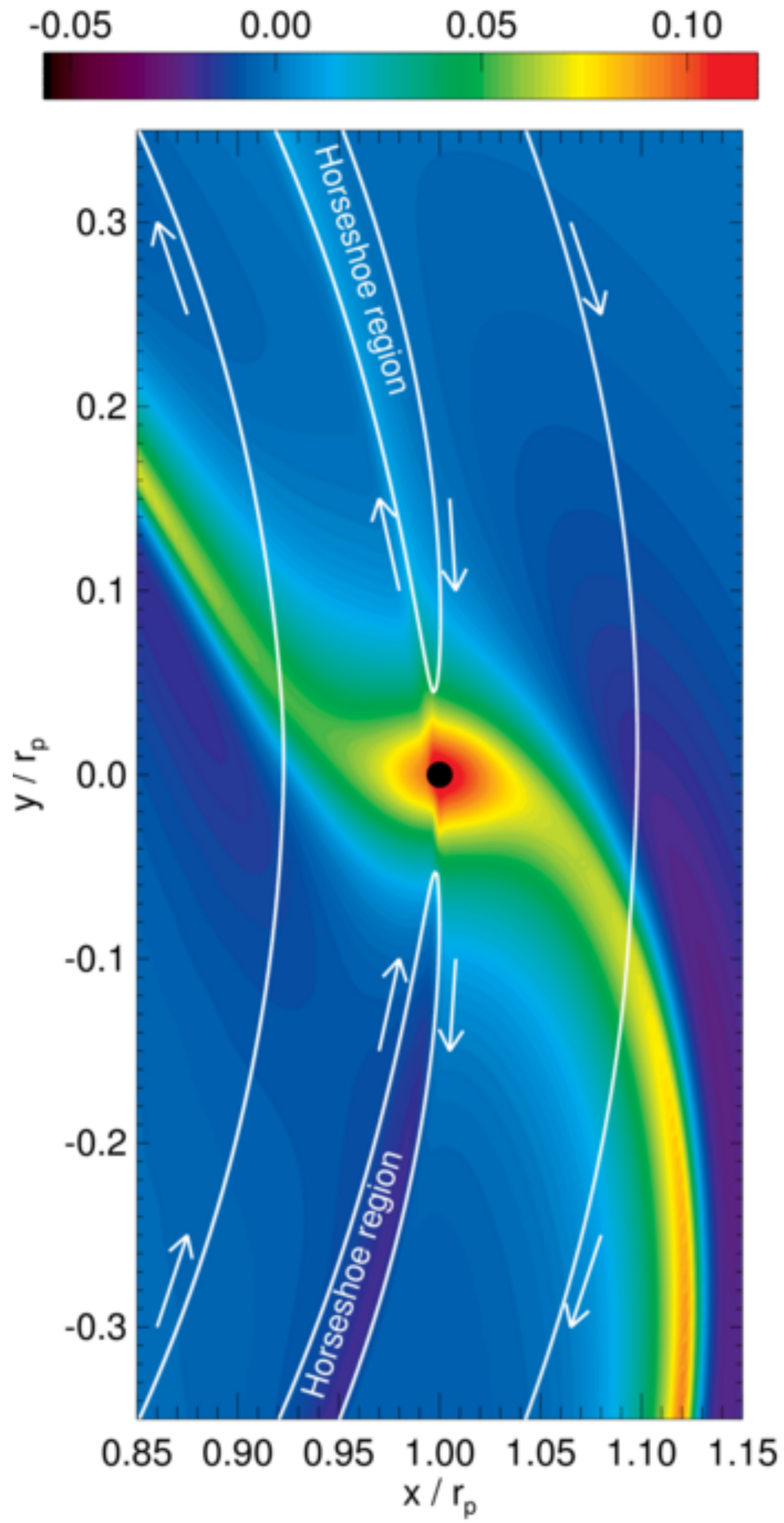
- Net torque on planet:

$$\Gamma = \sum \Gamma_{\rm ILR} + \sum \Gamma_{\rm OLR} + \sum \Gamma_{\rm CR}$$

$$\Gamma_0 = \left(\frac{M_{\rm p}}{M_*}\right)^2 \left(\frac{H}{R}\right)^{-2} \Sigma a_{\rm p}^4 \Omega_{\rm p}$$

- For canonical viscous discs, direction of migration is usually inwards.
- Massive planet opens a gap in the disc (e.g., Duffell & MacFadyen 2013):

$$\frac{M_{\rm p}}{M_*} \gtrsim 5 \left(\frac{H}{R}\right)^{5/2} \alpha^{1/2}$$



Baruteau+ (2014, PP6)

Massive planets open gaps

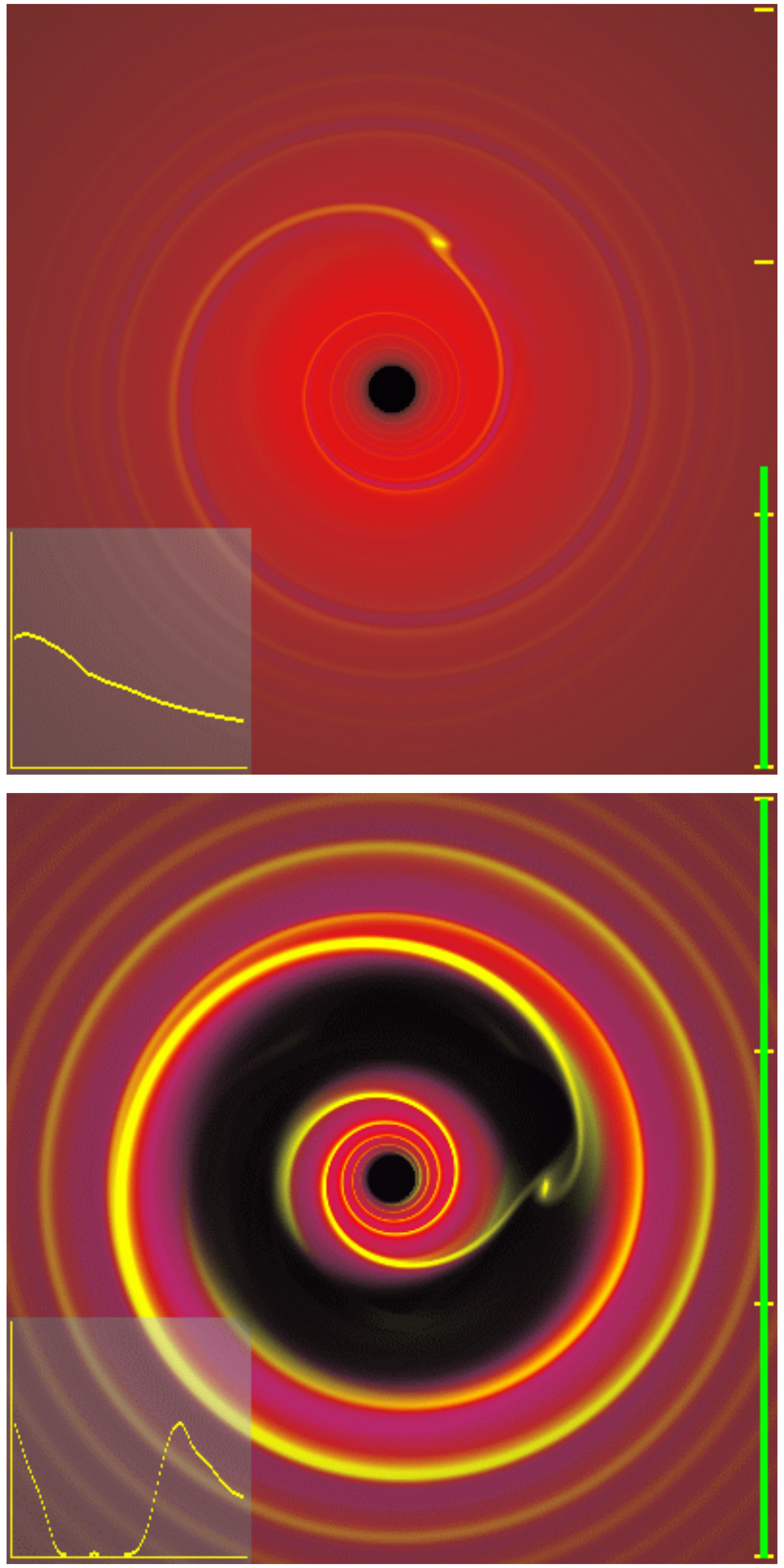
- Traditional migration theory (in viscous discs) has two limiting cases:

$$M_{\rm p} \ll M_{\rm gap}$$ **Type I**

$$M_{\rm p} \gg M_{\rm gap}$$ **Type II**

- For ~solar mass star and a canonical viscous disc parameters:

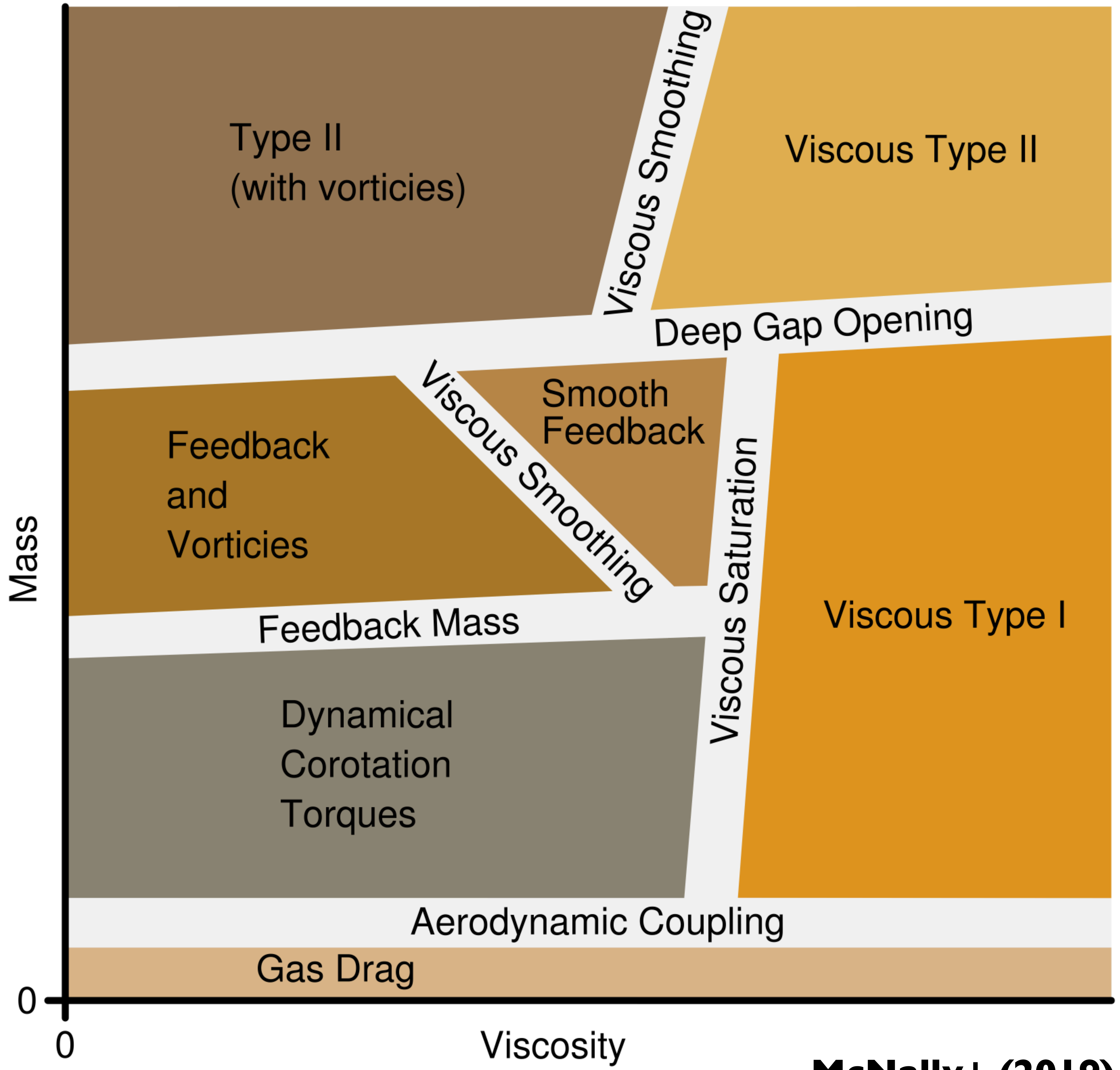
$$M_{\rm gap} \sim 0.1 {\rm M_{Jup}}$$



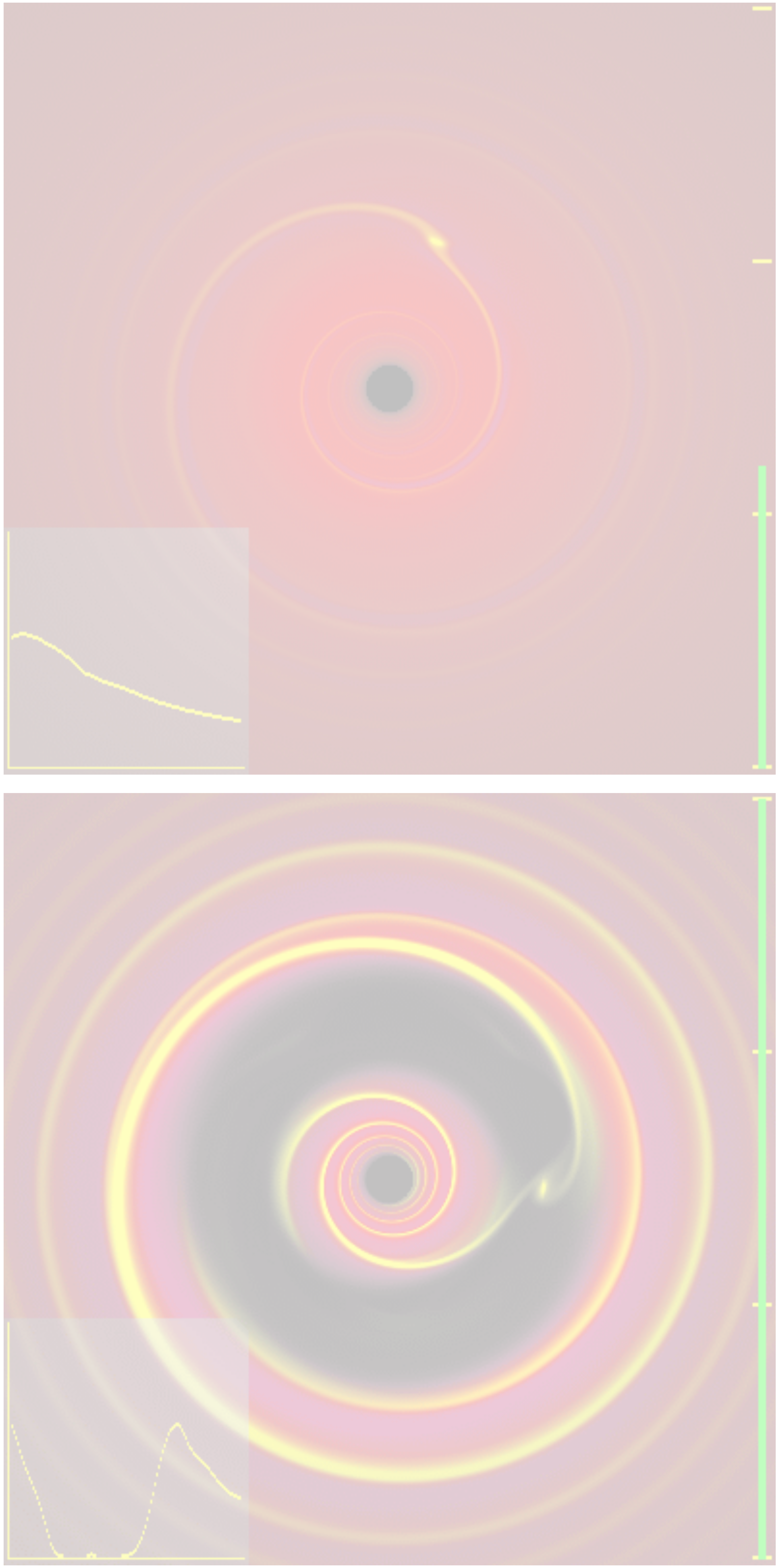
Armitage (2005)

Gap-opening → different migration regimes

- The modern picture is…more complex.



McNally+ (2019)



Armitage (2005)

Planets migrate quickly

- Canonical Type I (5AU, H/R = 0.05):

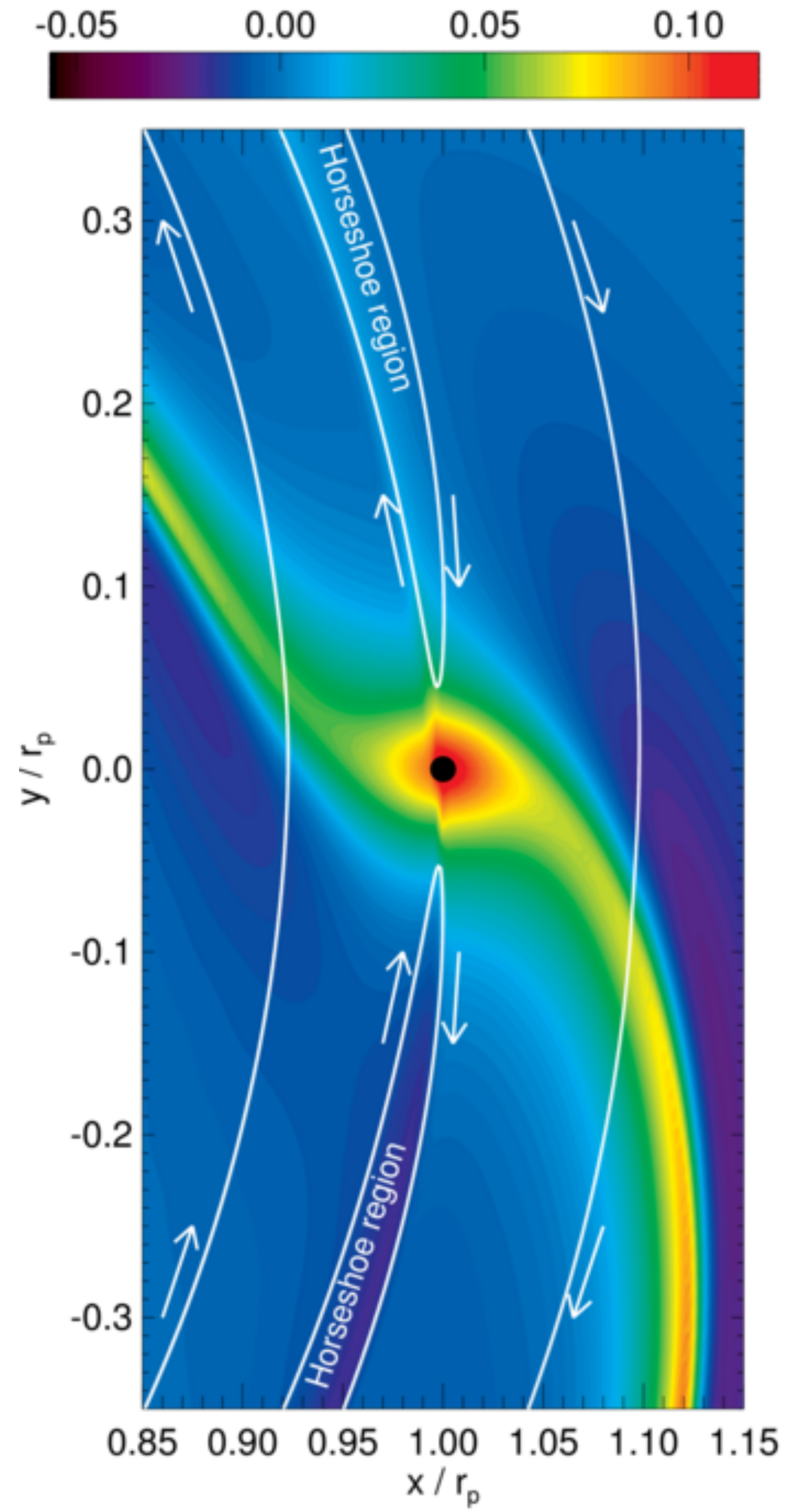
$$\tau_{\mathrm{I}} \simeq 3 \times 10^5 \left(\frac{M_{\mathrm{p}}}{10\mathrm{M}_\oplus}\right)^{-1} \left(\frac{\Sigma}{100\,\mathrm{g\,cm^{-2}}}\right)^{-1} \mathrm{yr}$$

- Typical disc lifetimes are ~1-10Myr, so:

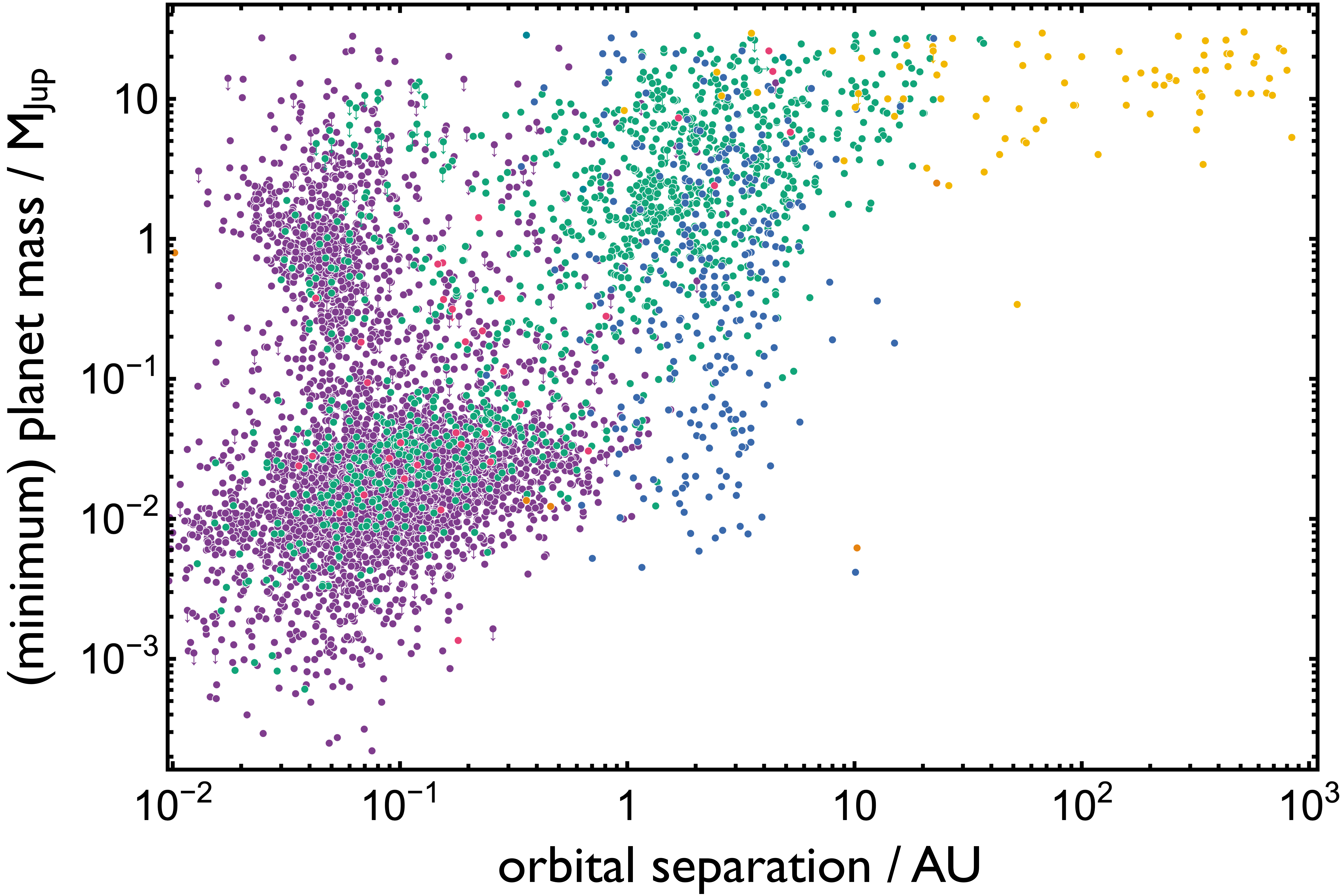
$$t_{\mathrm{migration}} < t_{\mathrm{disc}}$$

- Migration changes (exo)planet orbits *dramatically* over the lifetime of typical protoplanetary discs.

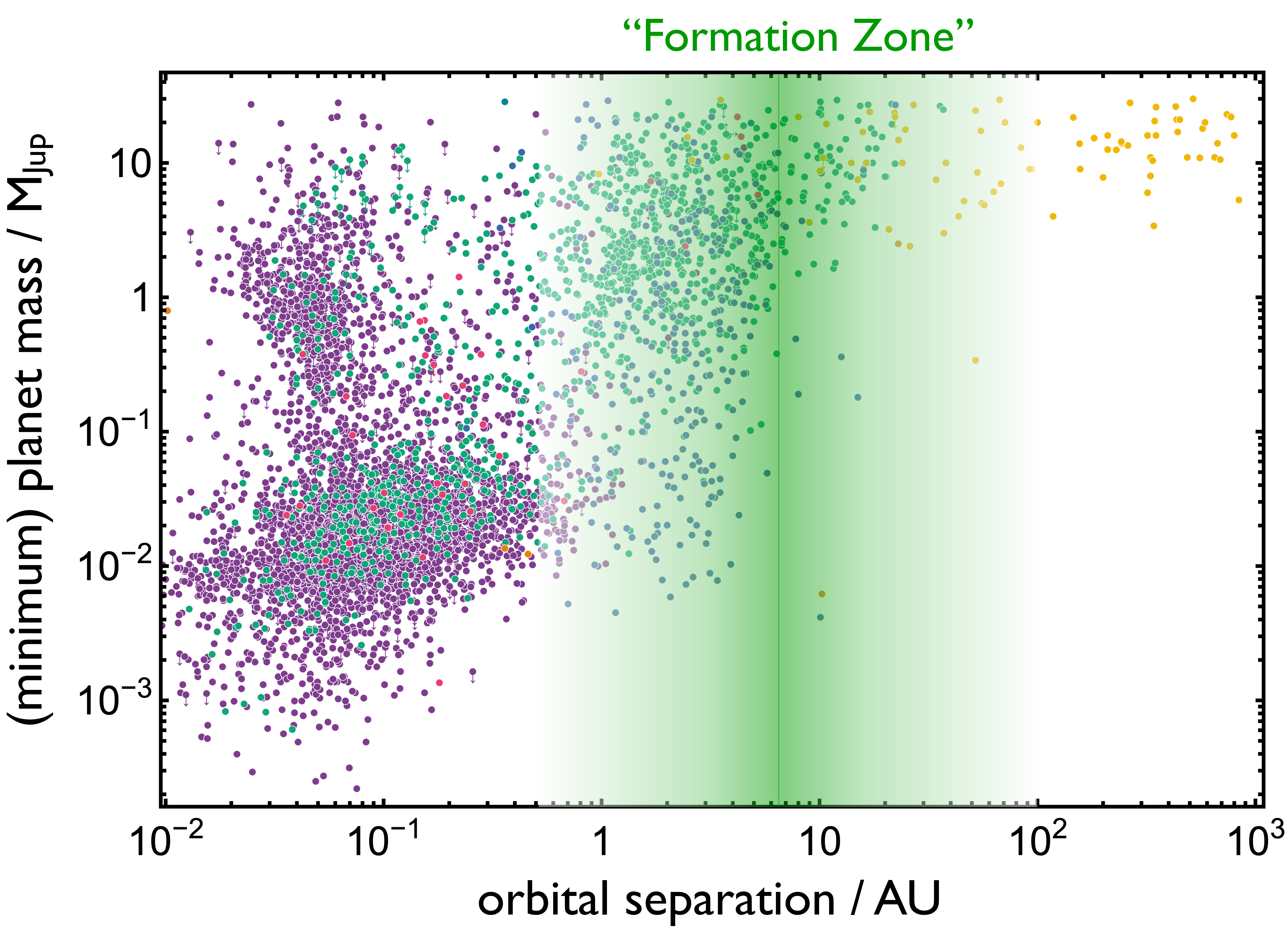
- **Observed (exo)planets are the outcomes of planet migration.**



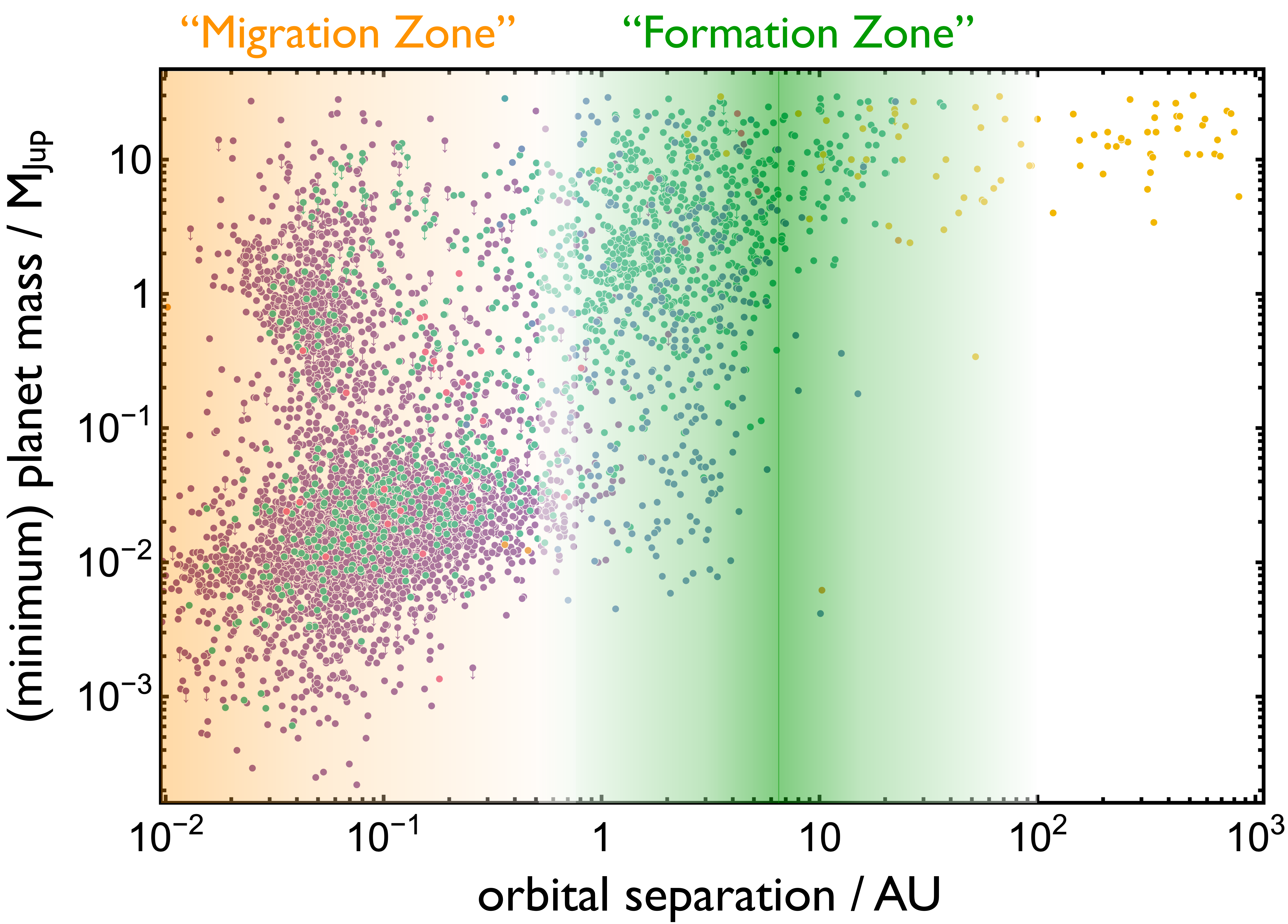
Baruteau+ (2014, PP6)



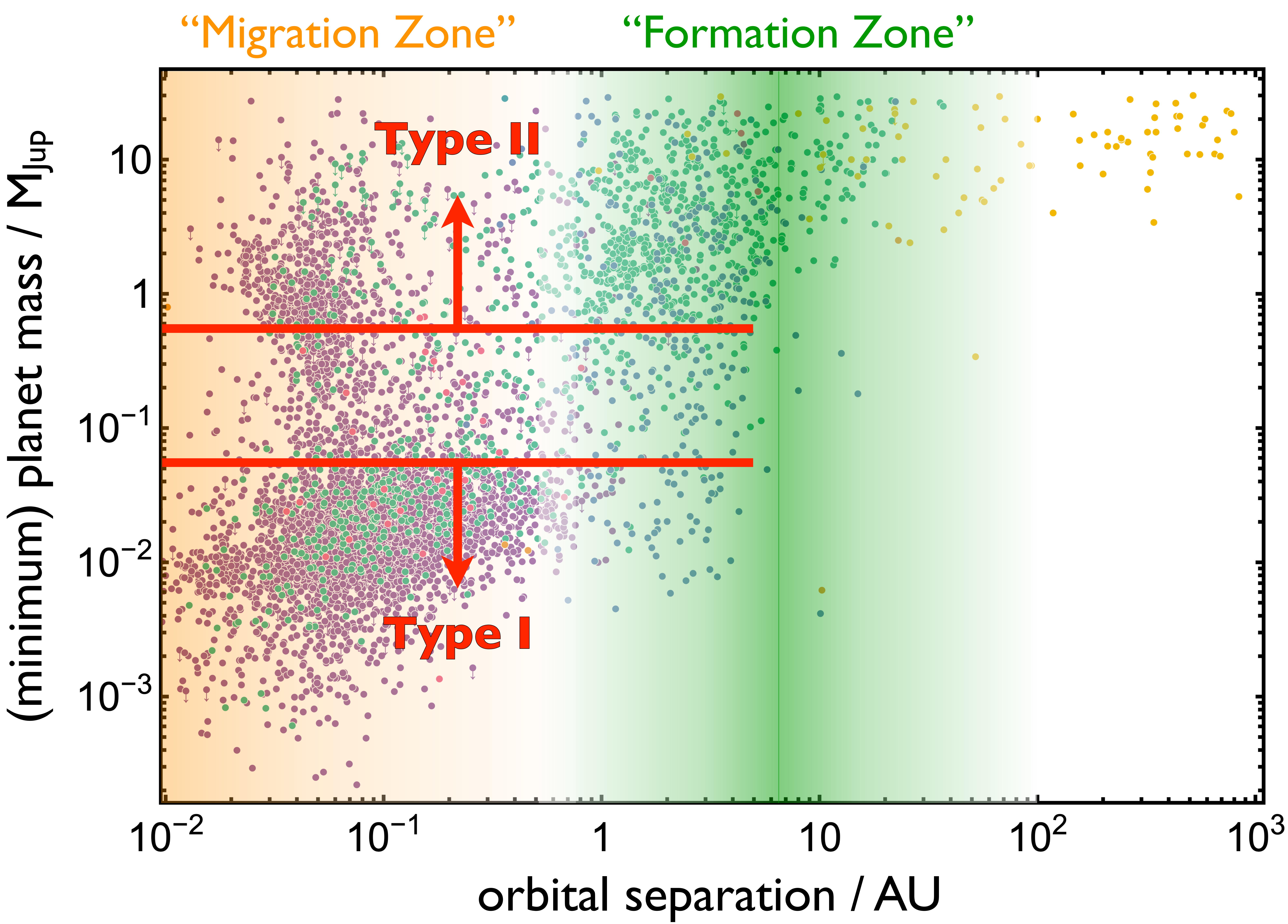
(minimum) planet mass / M_{Jup}
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
orbital separation / AU



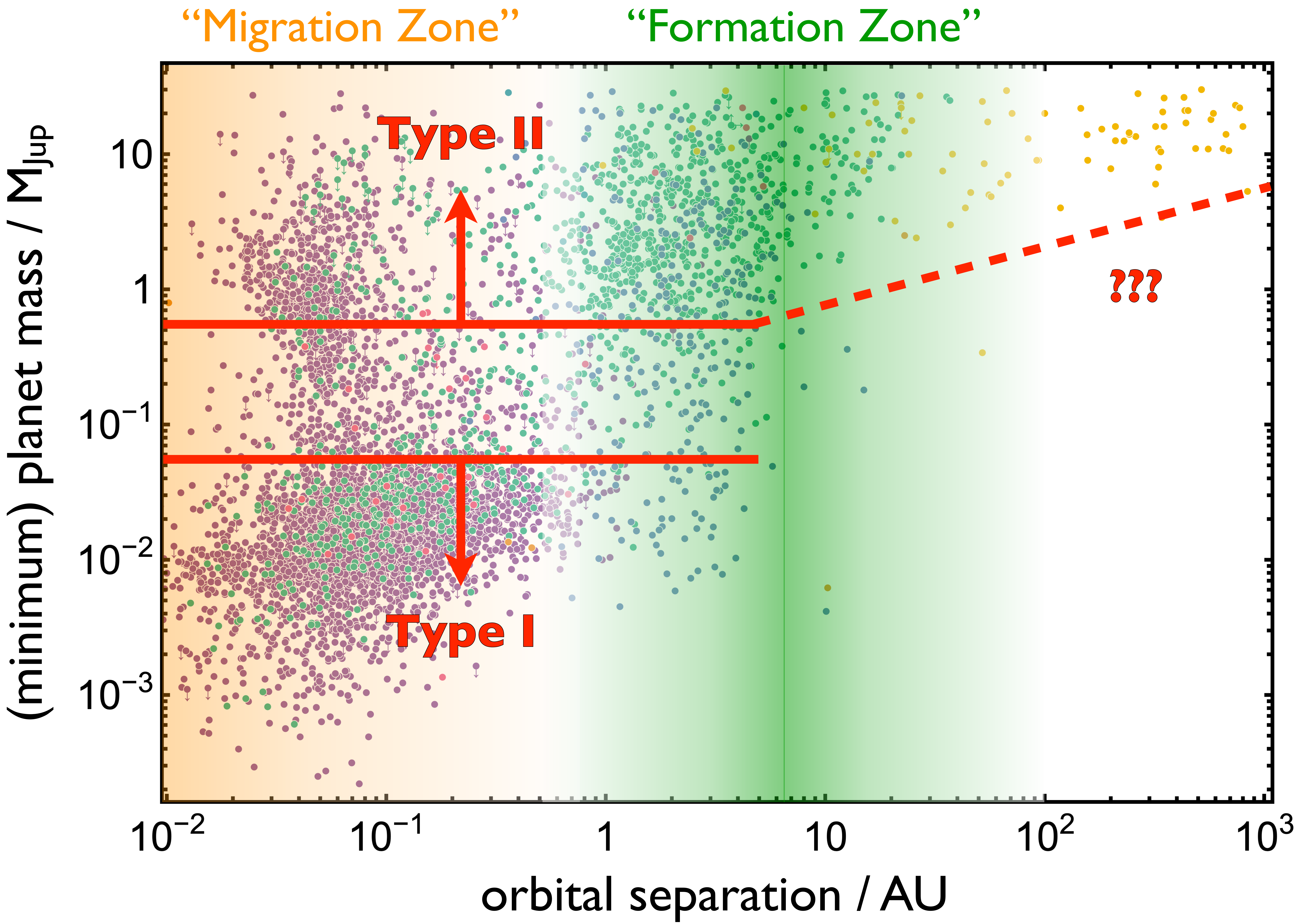
"Formation Zone"
(minimum) planet mass / M_{Jup}
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
orbital separation / AU



“Migration Zone”
“Formation Zone”
(minimum) planet mass / M_{Jup}
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
orbital separation / AU



“Migration Zone”
“Formation Zone”
Type II
Type I
(minimum) planet mass / M_{Jup}
orbital separation / AU
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}



"Migration Zone"
"Formation Zone"
Type II
Type I
???
(minimum) planet mass / M_{Jup}
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
orbital separation / AU

What is the observational evidence for disc-driven migration?

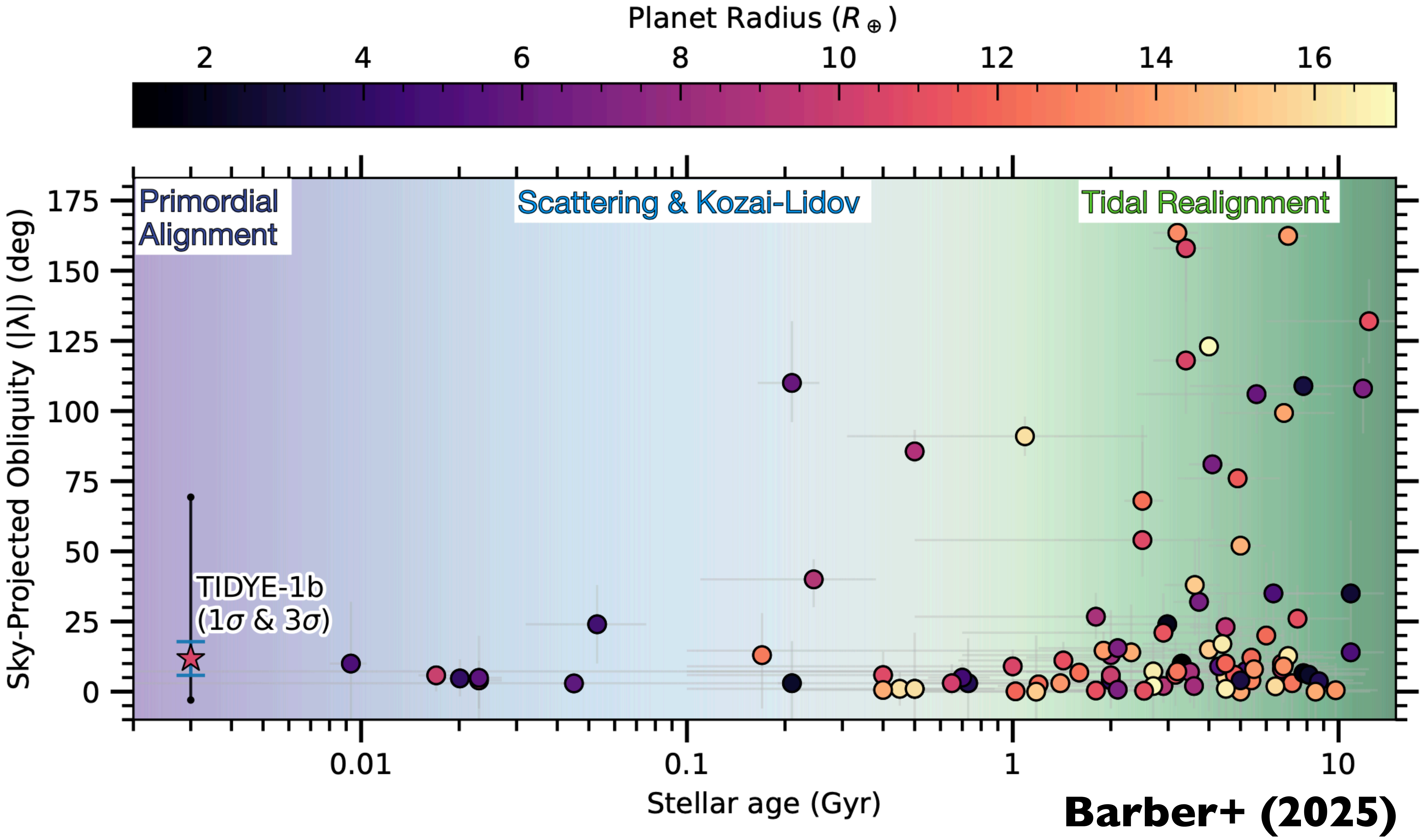
Hot Jupiters 🤔

- Discovery of short-period planets revived interest in migration theory in the 1990s.
- However, the incidence of HJs is difficult to explain purely through disc-driven migration (e.g., Rice+ 2008).
- Obliquity measurements now suggest that high-ecc / tidal migration (Rasio+ 1996) is the origin of many observed HJs.
- Tidal time-scales are ~Gyr, so very young HJs must(?) have a disc-driven origin.
- ~10 short-period planets now discovered orbiting ~Myr-old T Tauri stars…

Mon. Not. R. Astron. Soc. **384,** 1242–1248 (2008)

Why are there so few hot Jupiters?

W. K. M. Rice,[1★] Philip J. Armitage[2,3] and D. F. Hogg[4]
[1]*SUPA,† Institute for Astronomy, University of Edinburgh, Blackford Hill, Edinburgh EH9 3HJ*
[2]*JILA, Campus Box 440, University of Colorado, Boulder, CO 80309, USA*
[3]*Department of Astrophysical and Planetary Sciences, University of Colorado, Boulder, CO 80309, USA*
[4]*School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL*

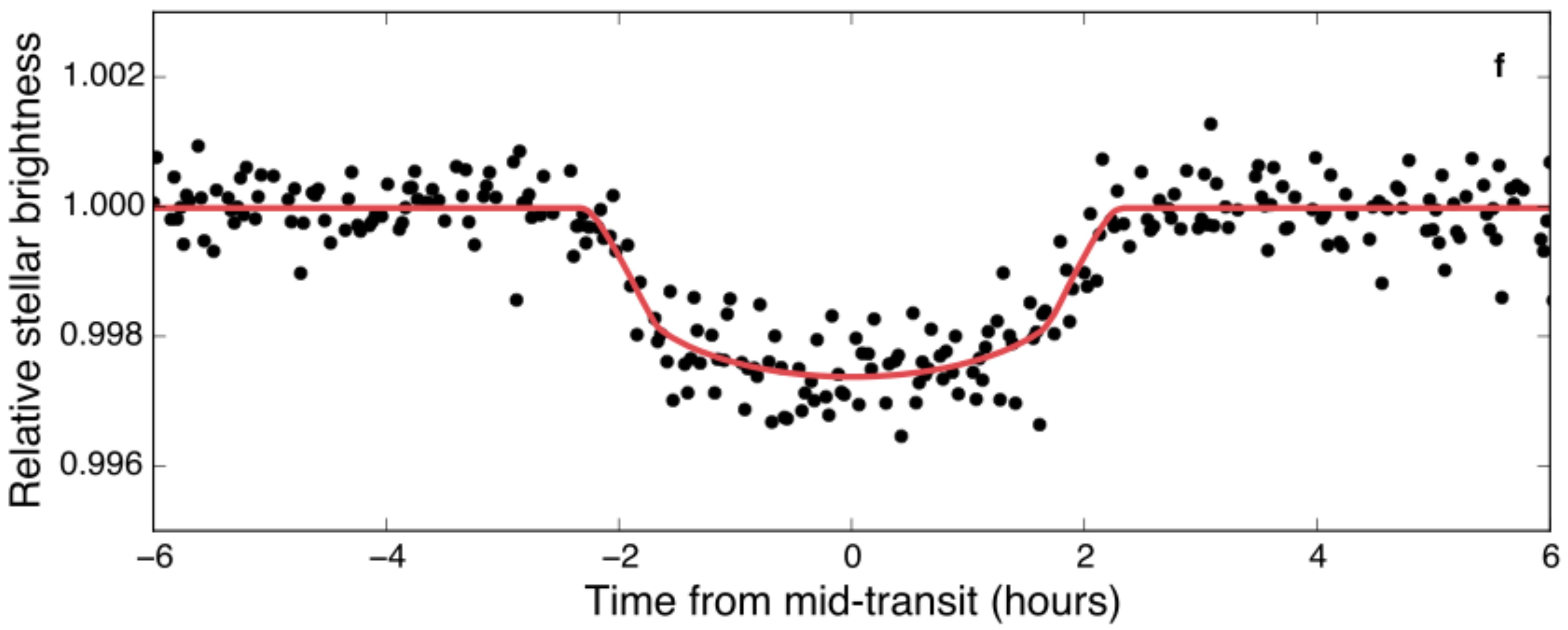


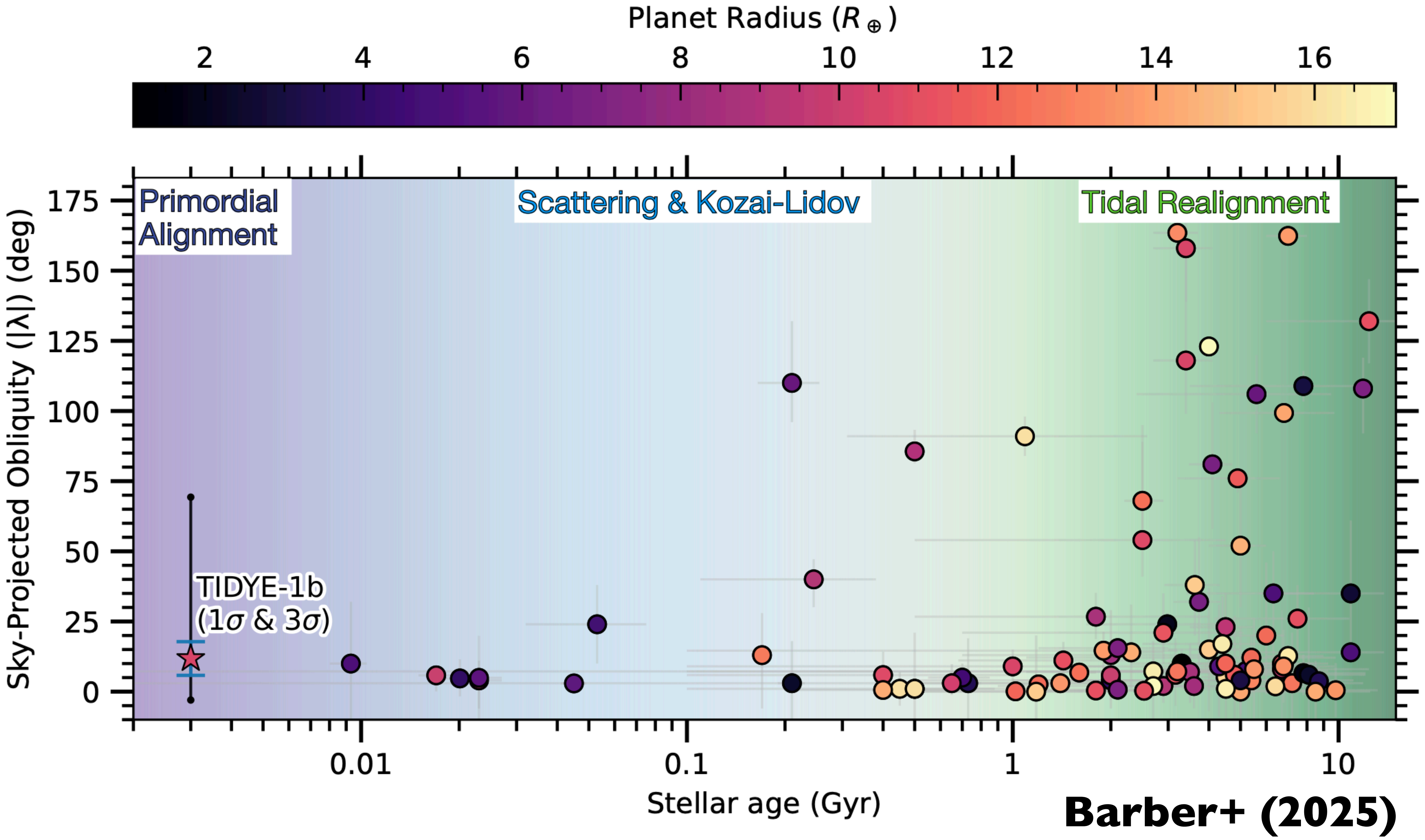
Barber+ (2025)

Young Hot Jupiters

- Several very young (≲10Myr) hot/warm giant planets now known, e.g.:
  - V830 Tau (Donati+ 2016, 2017)
  - K2-33b (David+ 2016)
  - TAP-26b (Yu+ 2017)
  - IRAS 04125 (Barber+ 2024, 2025)
  - TIC 88785435 (Vach+ 2025)
- All are giant planets with P ~ days. Some are even in accreting gaseous discs. (Where measured, low-ecc and aligned.)
- More data still needed to understand properties and incidence…

K2-33b: David+ (2016)

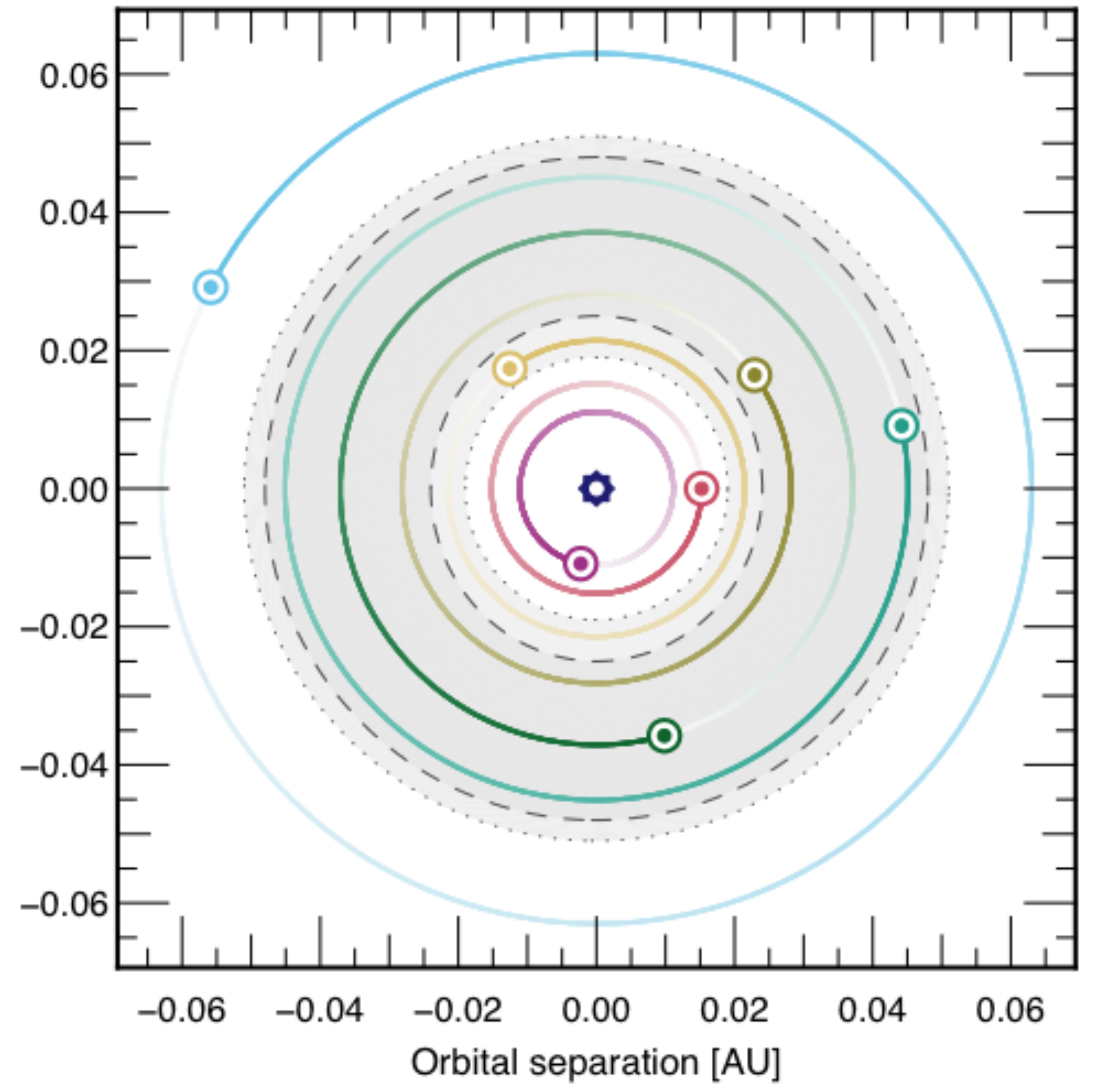




Barber+ (2025)

Mean-motion resonances

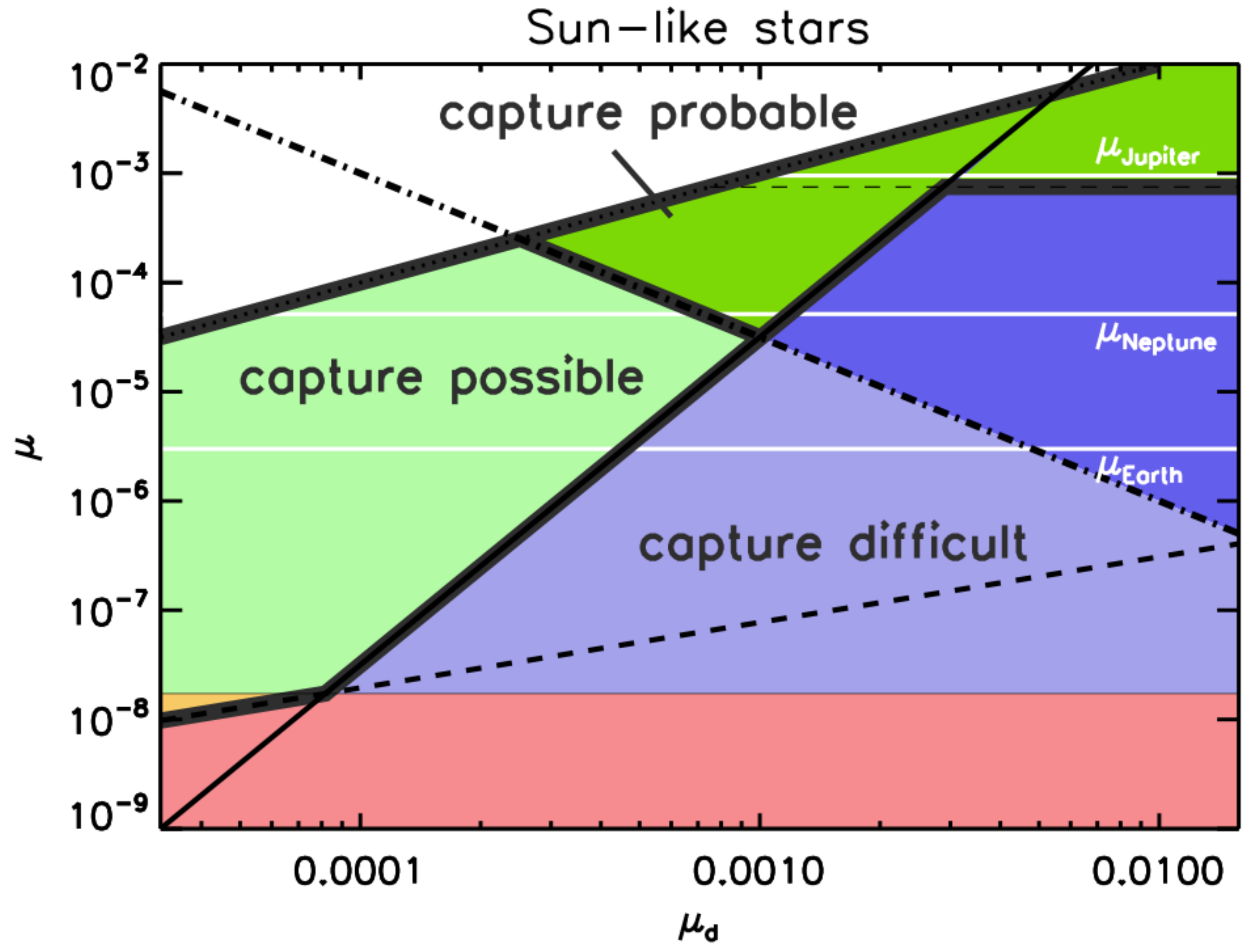
TRAPPIST-1: Gillon+ (2017)



- Many known exoplanet systems are in mean-motion resonances:
  - GJ876: three gas giants in 1:2:4.
  - Kepler-36: super-Earths in 7:6.
  - TRAPPIST-1: seven ~Earth-mass planets in two resonant chains.

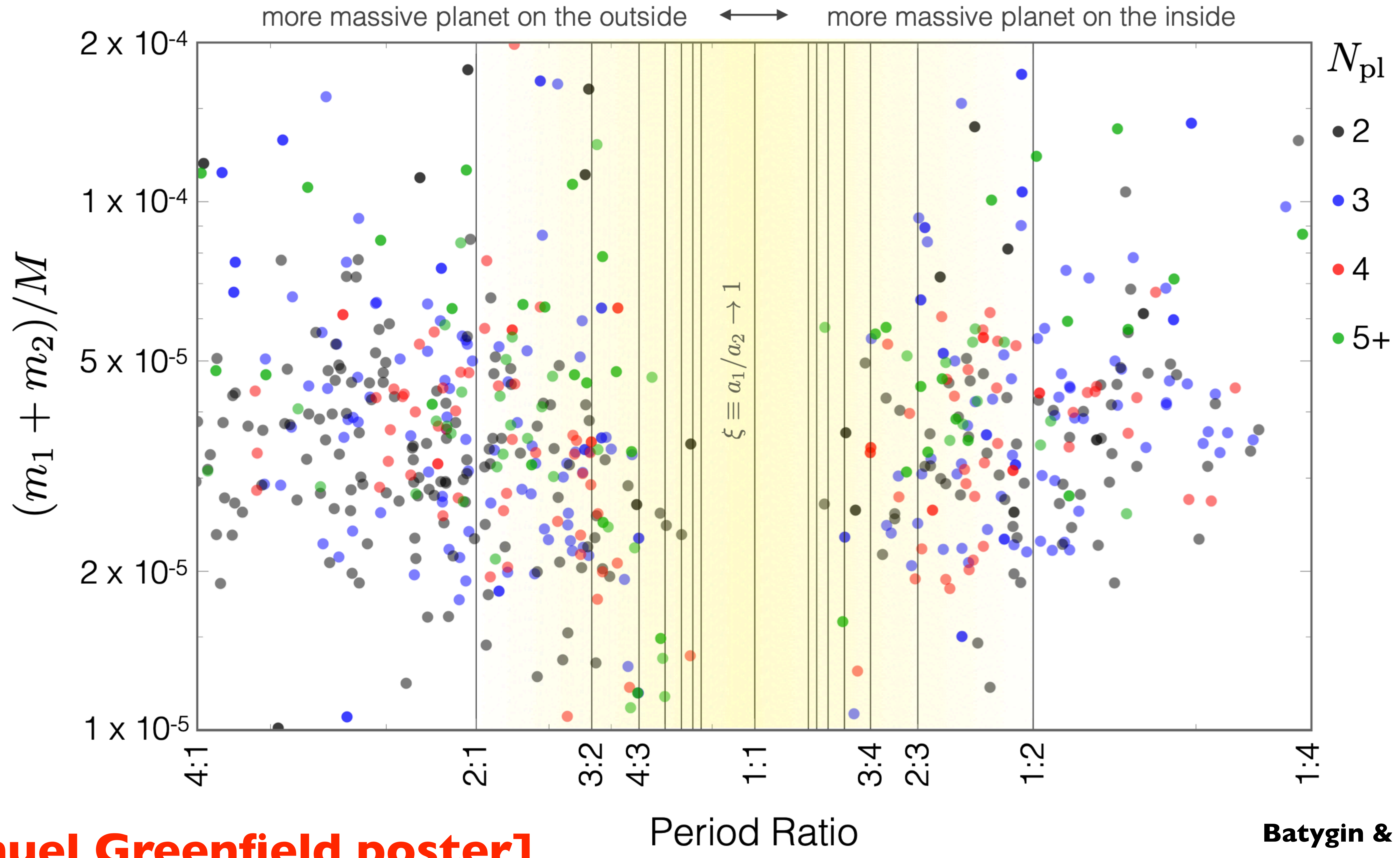
- Resonant capture requires *slow* differential migration in aligned, *low-eccentricity* orbits.

- **The existence of numerous resonant systems points strongly towards disc-driven migration.**



Pan & Schlichting (2017)

BUT…most multiple systems are not resonant



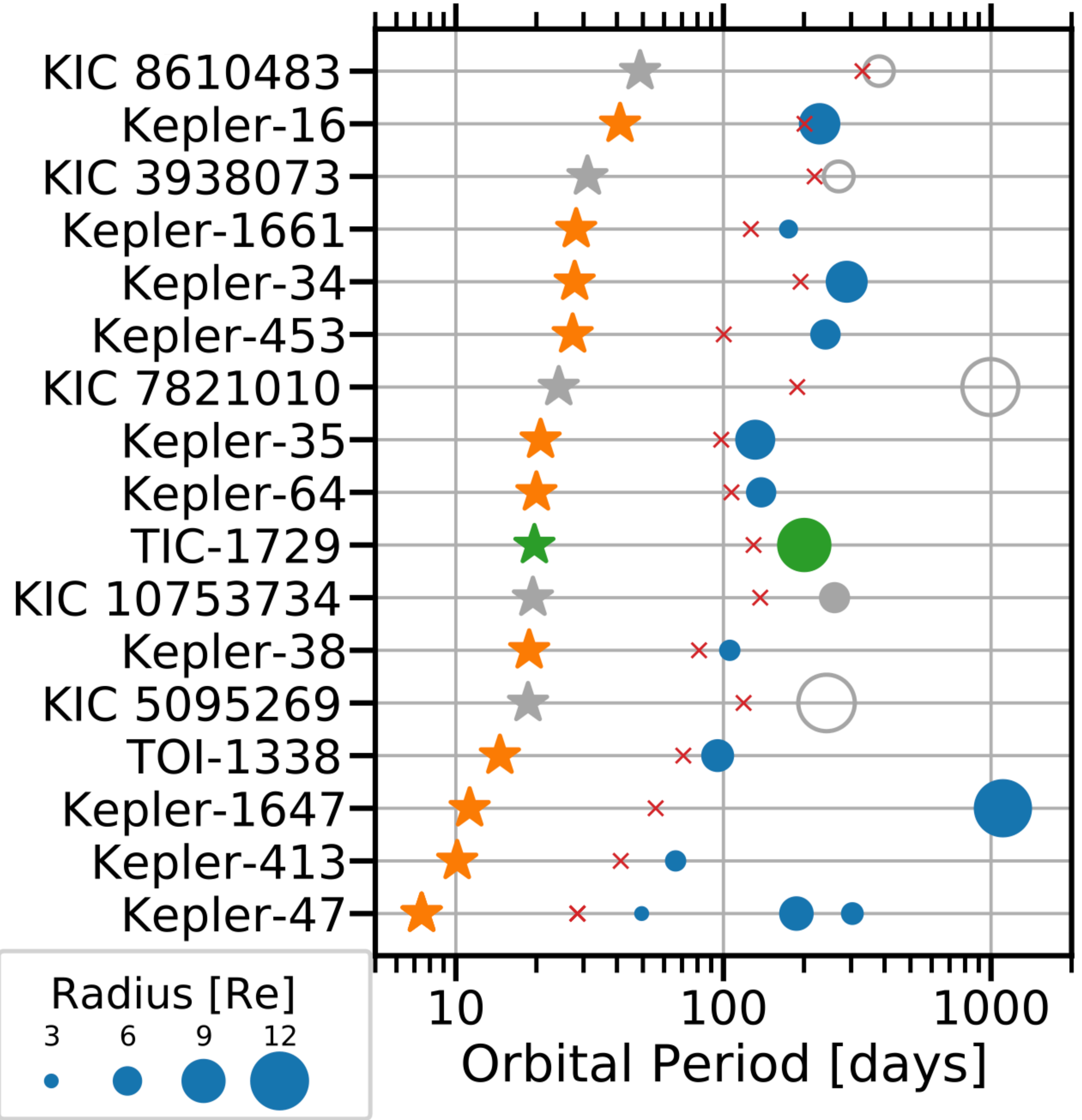
[Emmanuel Greenfield poster]

Batygin & Adams (2017)

Circumbinary planets

- Majority of the known CB planets are co-planar, and lie very close to the inner orbital stability limit (i.e., where gas disc was truncated).
- In-situ formation very unlikely; tides negligible at ~AU separations.
- Known system consistent with predictions of migration models (e.g., Pierens & Nelson 2008; 2009)
- **Circumbinary planets close to the stability limit are arguably(!) the strongest direct evidence for disc-driven migration.**

Kostov+ (2021)



[Talks by Penzlin & Chen; poster by Munnelly]

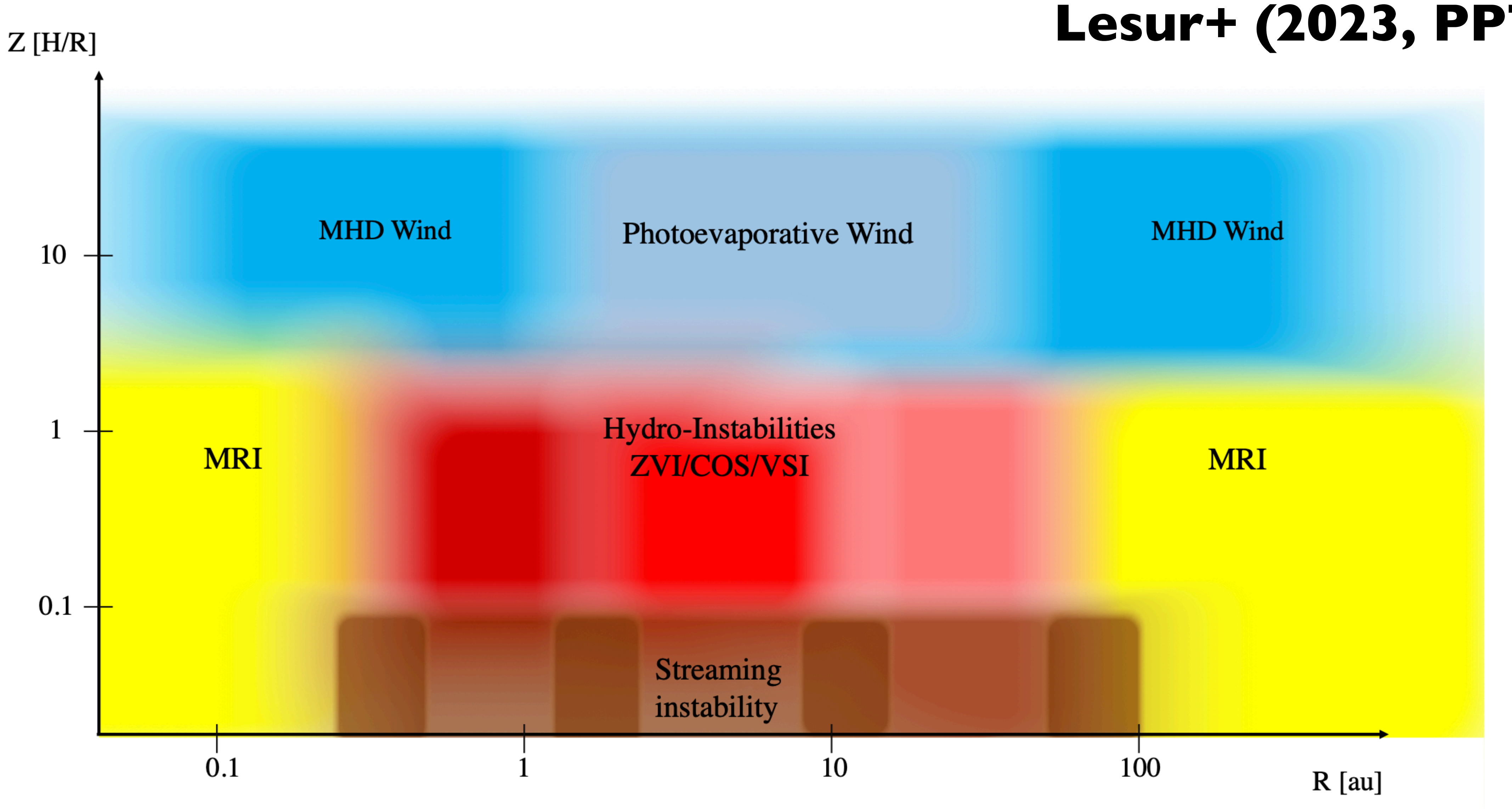
★ = secondary star ✕ = stability limit

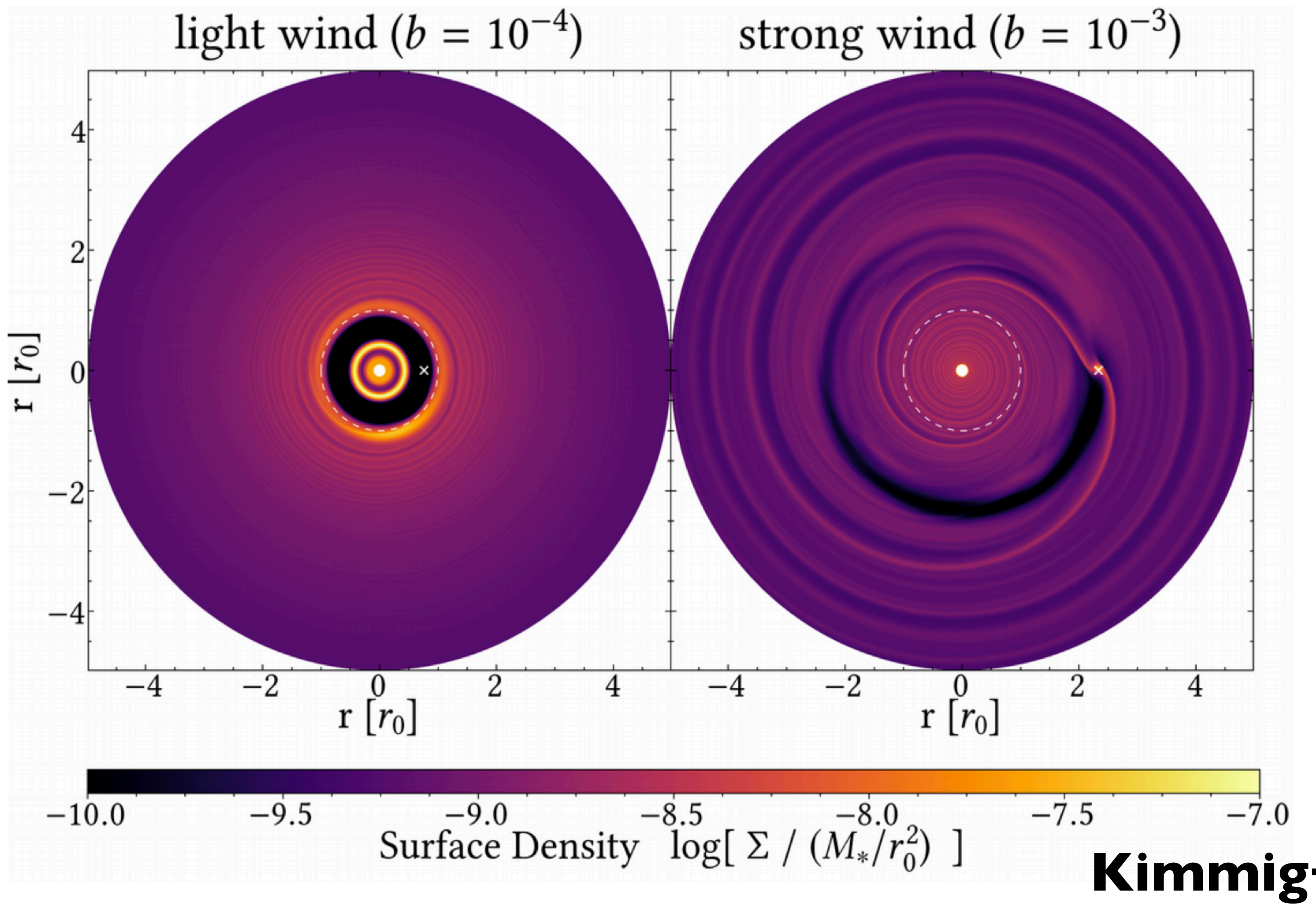
What are the most important / most interesting open questions?

What happens in wind-driven / low-viscosity discs?

- Large regions of discs are not viscous; accretion is due to wind torques (e.g., Bai 2026; **Garcia-Lopez & Latter talks**).
- Major implications for disc evolution and planet formation; fundamentally changes planet-disc interactions:
  - gap-opening is much easier in low-viscosity discs.
  - migration in wind-driven discs not well understood: outward migration in much of the disc. (Wafflard-Fernandez+ 2025)
  - 3-D models are probably(?) needed (**Amelia Cordwell talk**).

Lesur+ (2023, PP7)



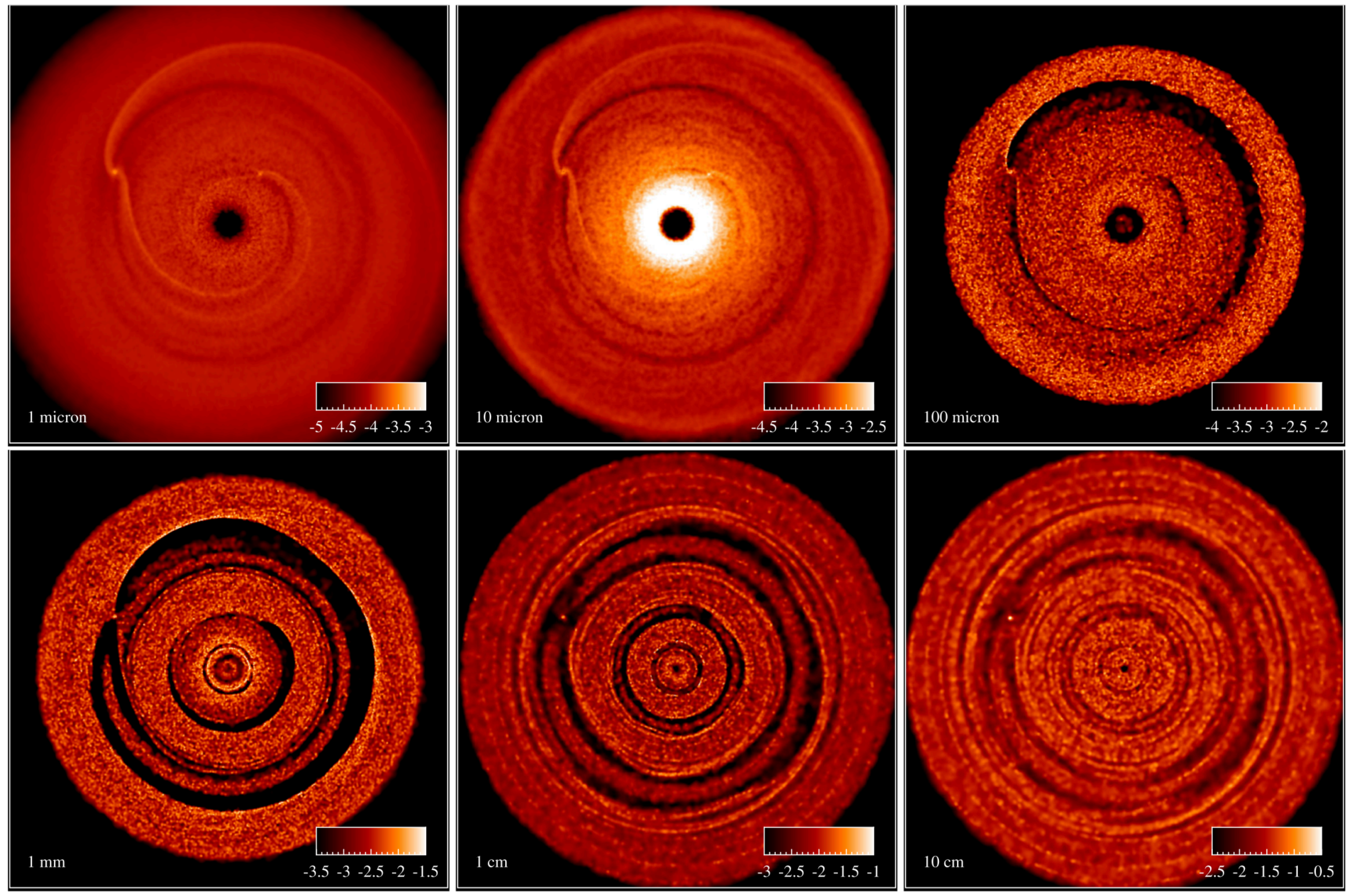


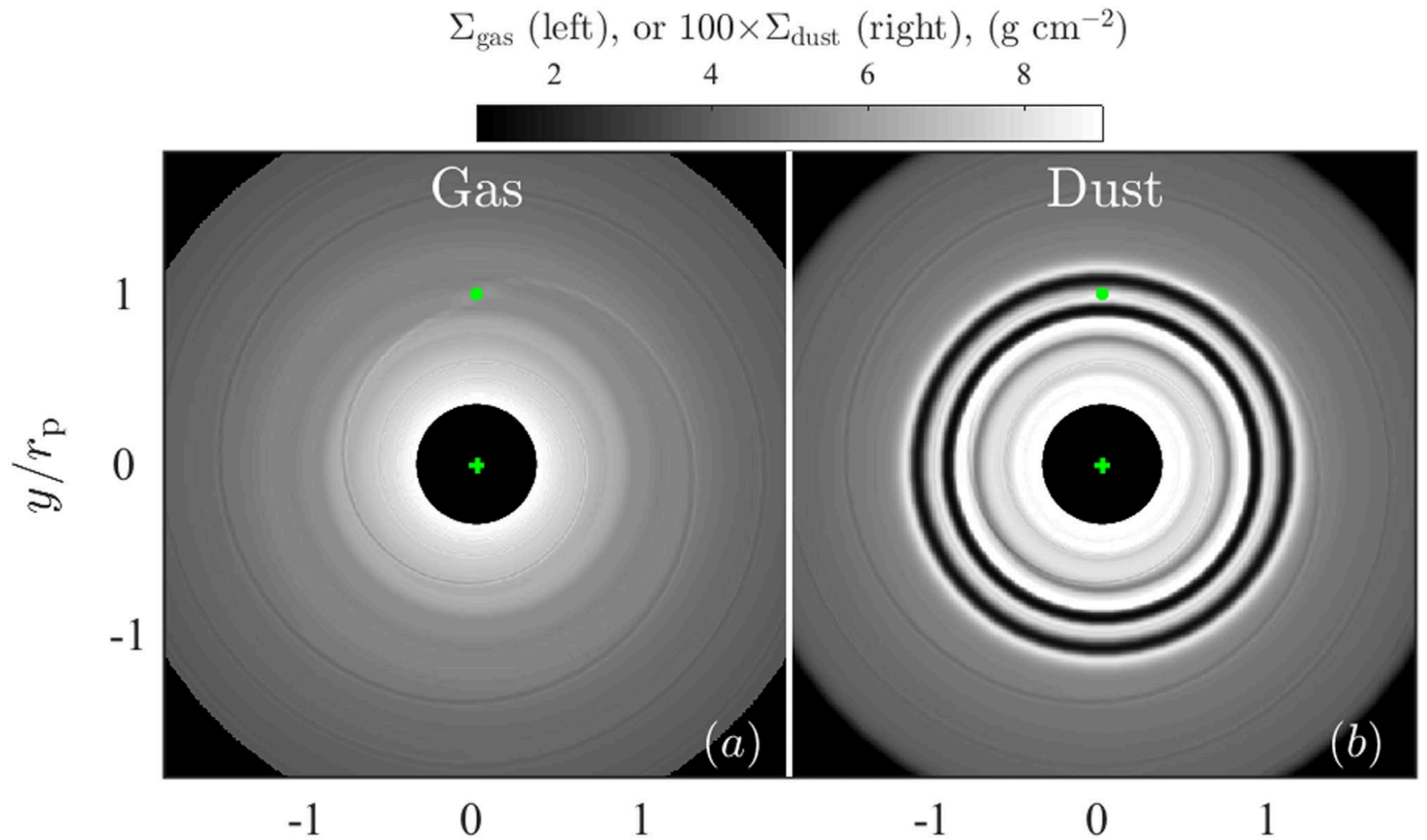
Kimmig+ (2020)

Gap-opening

- ***Gas*** gaps depend on M_p + local disc temperature and "viscosity".
- In wind-driven or low-viscosity discs, ~Earth-mass planets can open gaps.
- Observed gaps in real discs are usually seen in dust rather than gas.
- ***Dust*** gaps depend on M_p, particle size (*St*) and local gas conditions.
- Possible to open one (or more) gaps in dust where no gas gap exists.
- Can use observed gaps to infer unseen planet masses (e.g., Rosotti+ 2016; Kanagawa+ 2016; Dipierro & Laibe 2017).

Dipierro+ (2015)





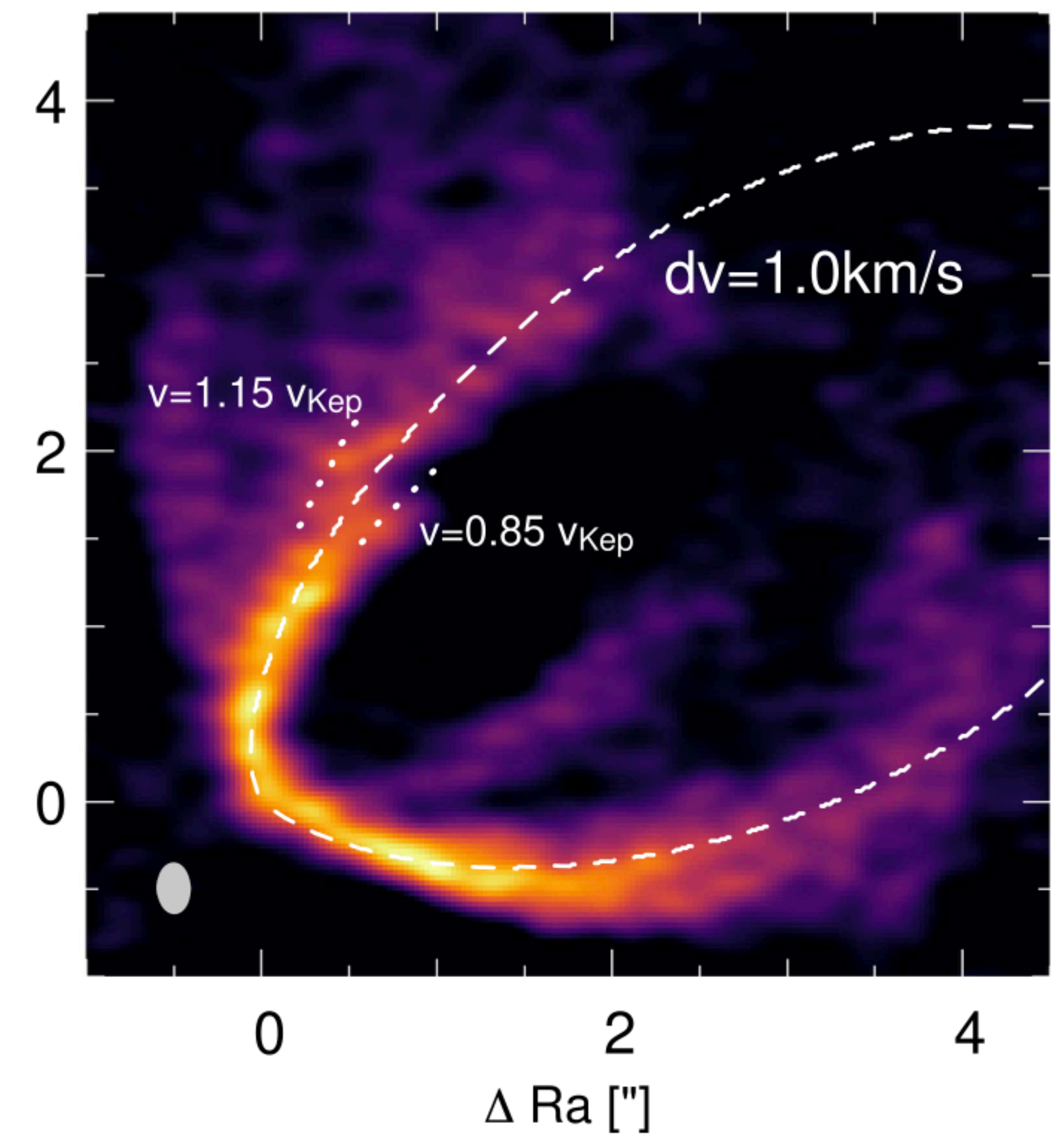
Dong+ (2018)

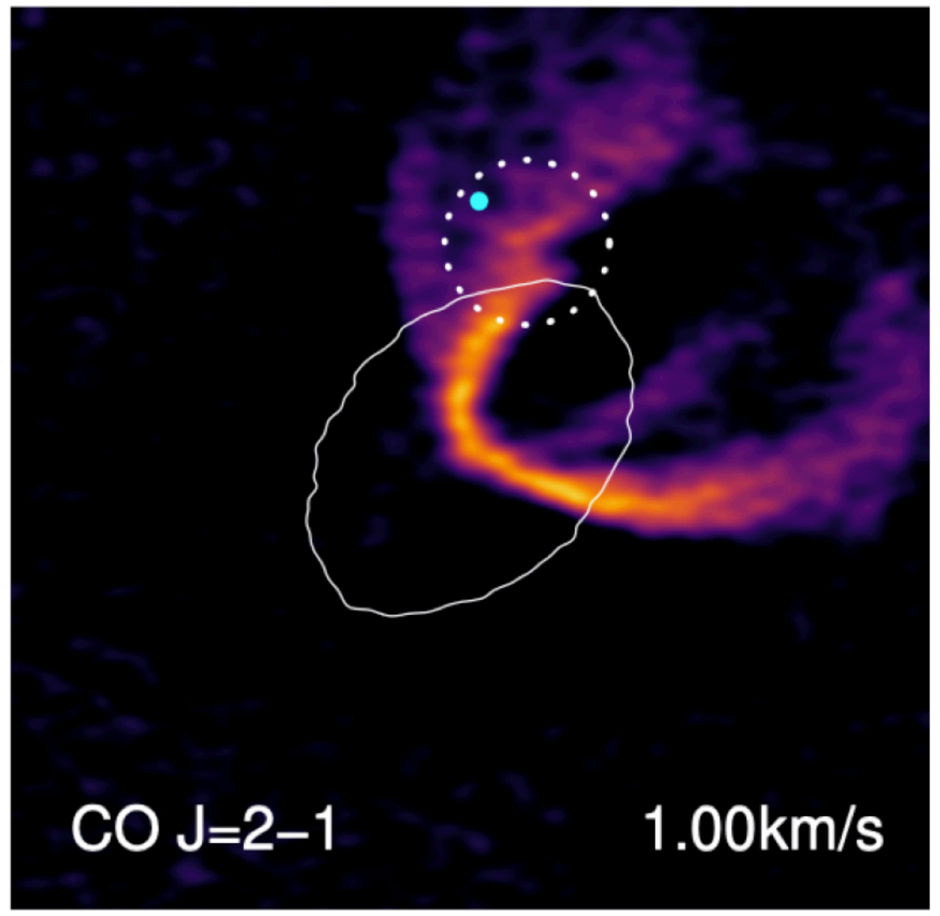
What are the masses of observed young planets?

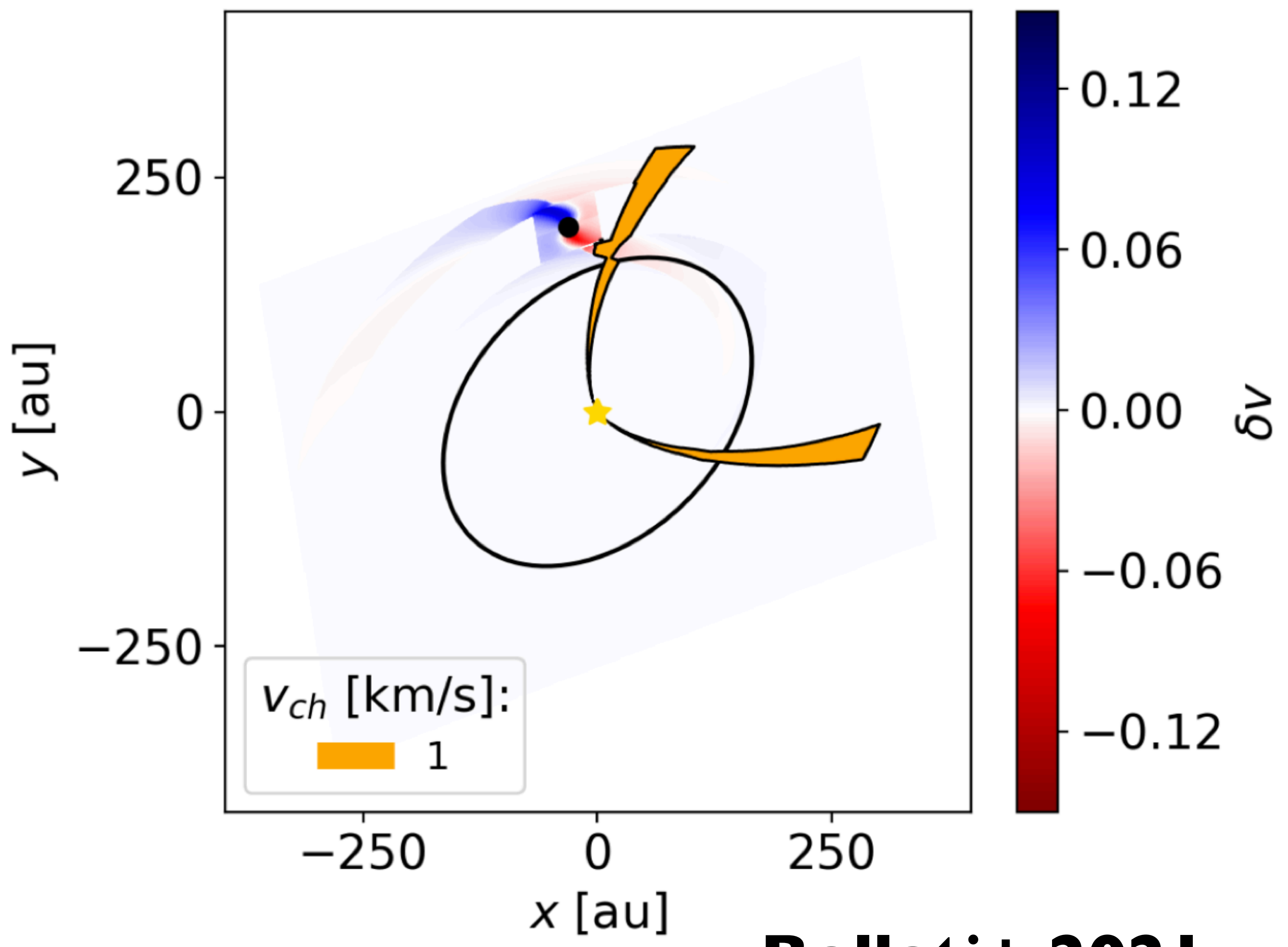
- Disc kinematics now allow us to detect planets and measure their masses.
- *Direct probe of planet-disc interactions!*
- >10 detections now made with ALMA (e.g., Teague+ 2018; Pinte+ 2019; 2023).
- Kinematics show good agreement with both analytic theory and simulations.
- ***BUT***…planet masses derived from kinematics are up to 10x larger than from gap-opening (in the same discs).

[Amelia Cordwell talk]

HD163296 (Pinte+ 2018)





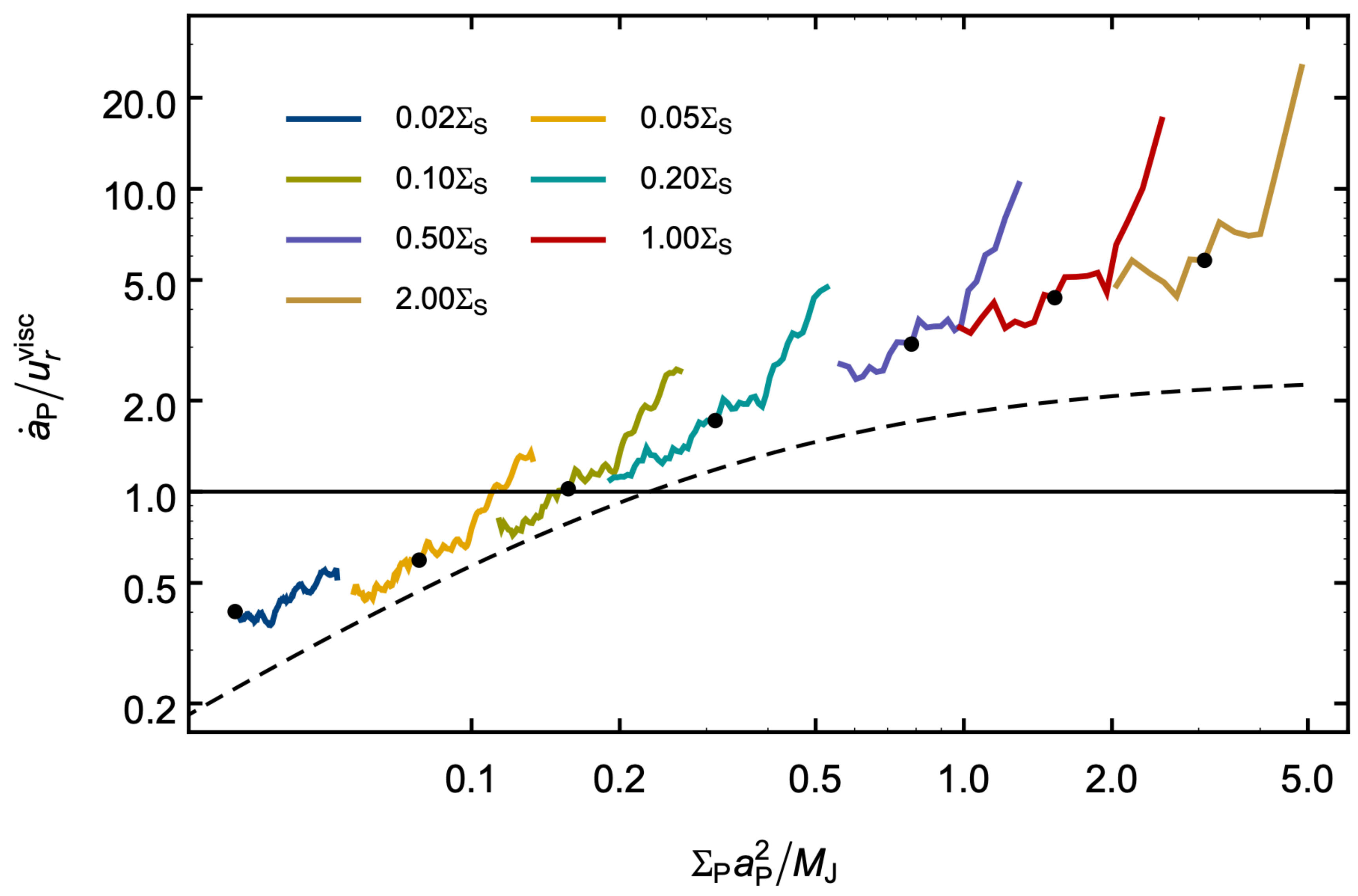


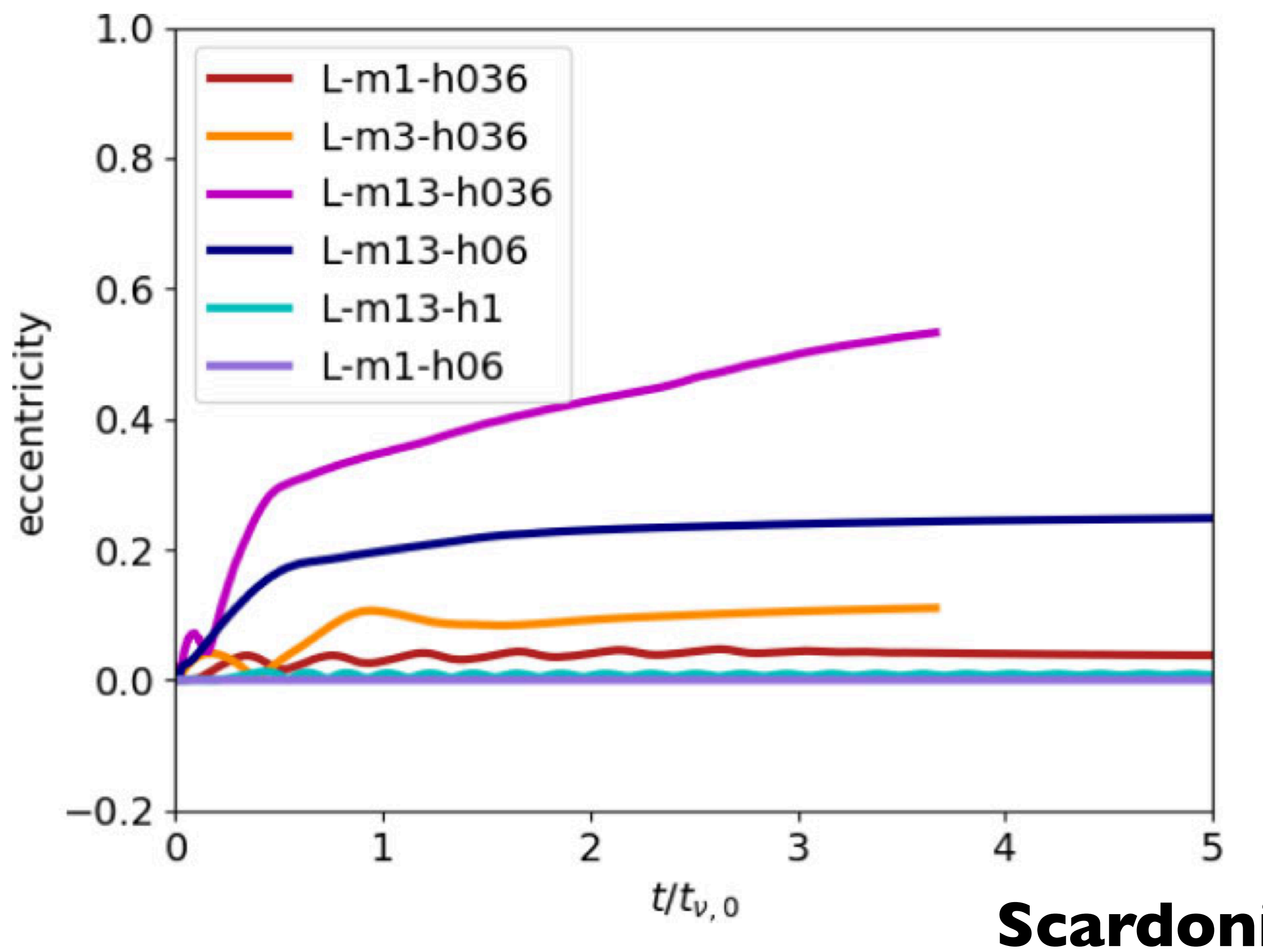
Bollati+ 2021

(How) Does Type II migration happen?

- Traditional Type II migration sees the planet and gap migrate at the viscous rate.
- Some simulations fail to recover this behaviour in viscous discs (Duffell+ 2014; Dürmann & Kley 2015).
- Long-duration simulations show the importance of eccentricity excitation; we see both inward and outward migration (Dempsey+ 2020, 2021; Scardoni+ 2022, 2025; **Chiara Scardoni talk**).
- Still unclear how Type II behaves in the wind-driven regime.

Dürmann & Kley (2015)





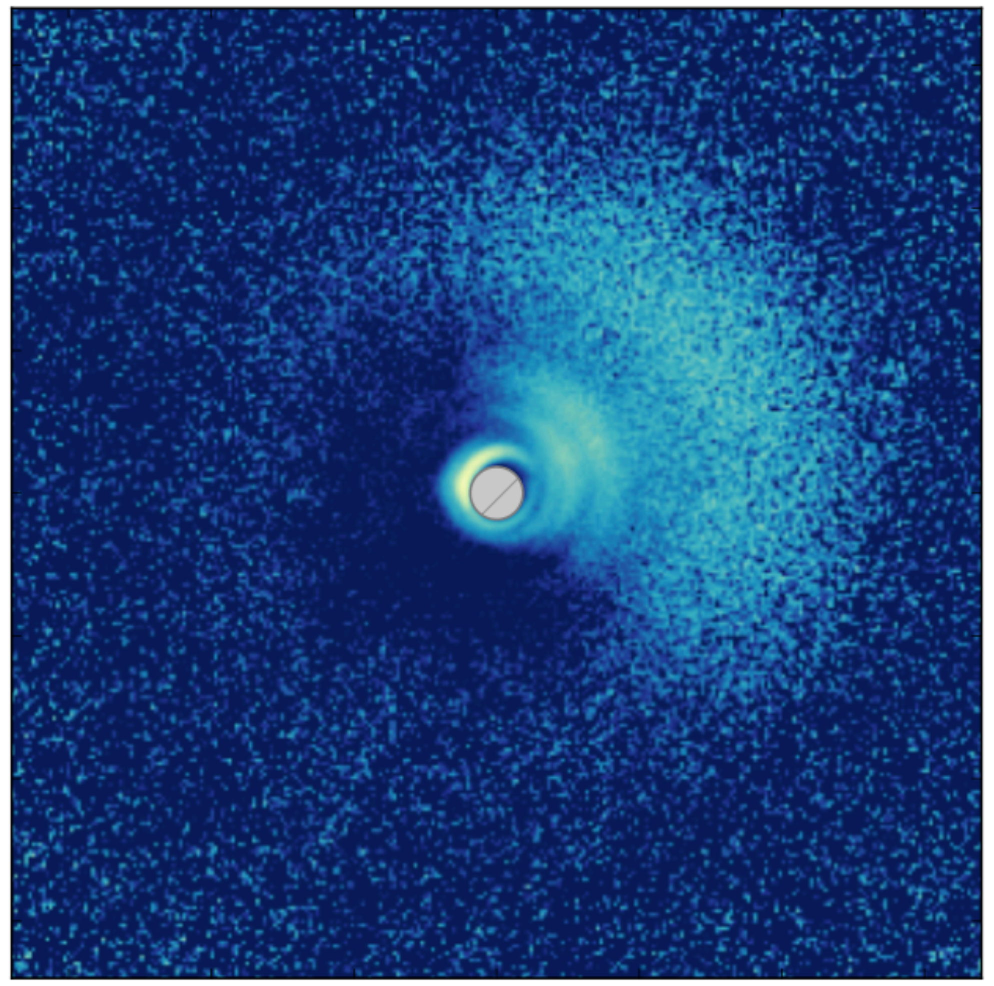
Scardoni+ (2022)

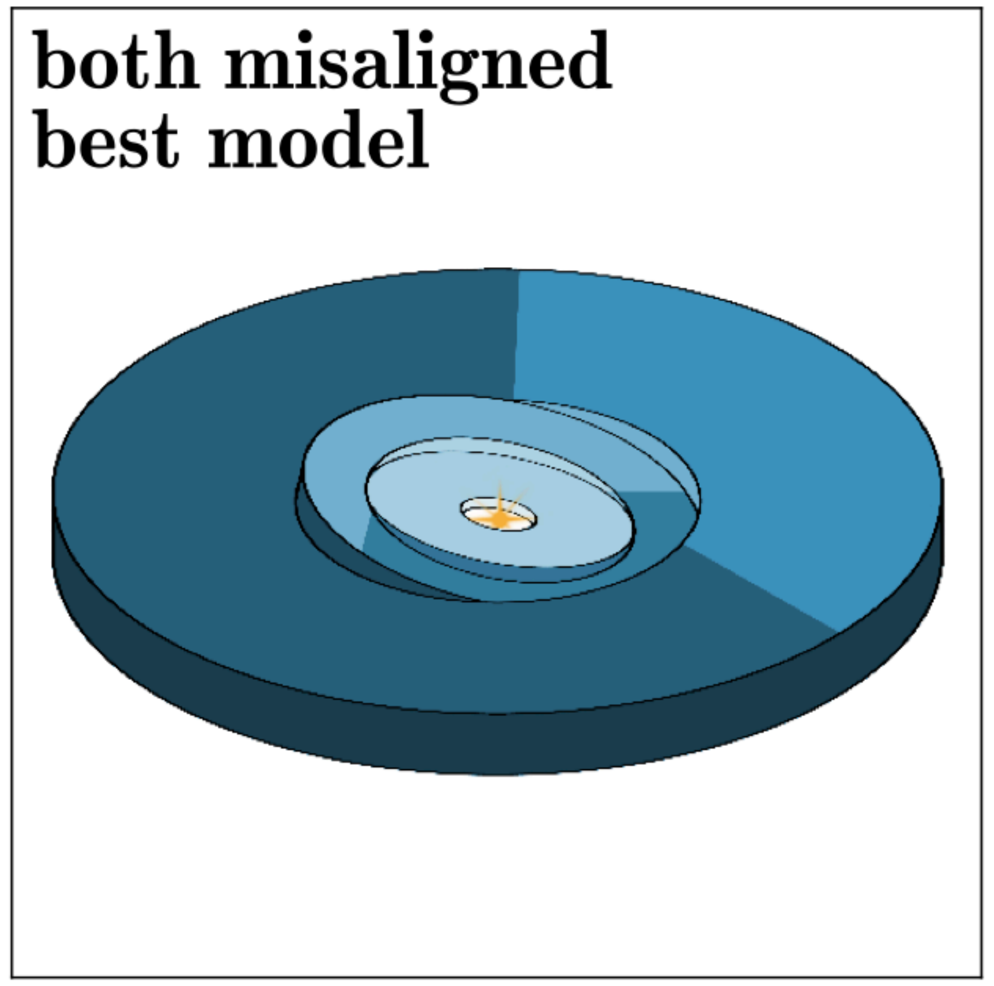
Other open questions

- Are observed shadows due to inclined / misaligned planets (e.g., Nealon+ 2018)?
  - often need to invoke multiple planets.
  - shadows appear long-lived, but inclination damping should(?) be rapid.

[Alison Young talk, Deniz Akansoy poster]

IR scattered light: HD139614





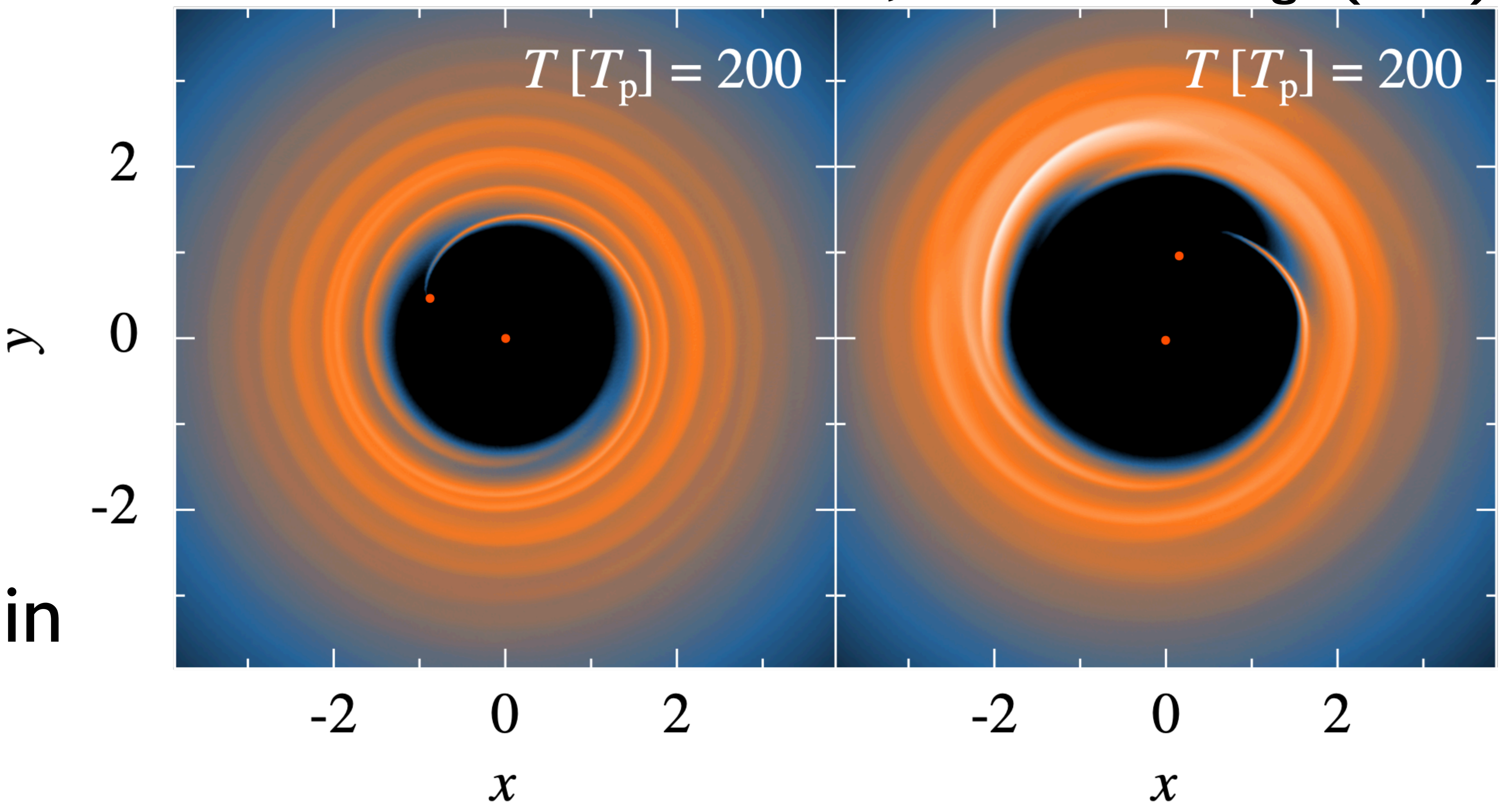
Muro-Arena+ (2020)

Other open questions

- Are observed shadows due to inclined / misaligned planets (e.g., Nealon+ 2018)?
  - often need to invoke multiple planets.
  - shadows appear long-lived, but inclination damping should be rapid.
- What role do planet-disc interactions play in exciting orbital eccentricities?
  - exoplanet eccentricity distribution is very broad; can't all be scattering(?).

[Corey Padgett poster]

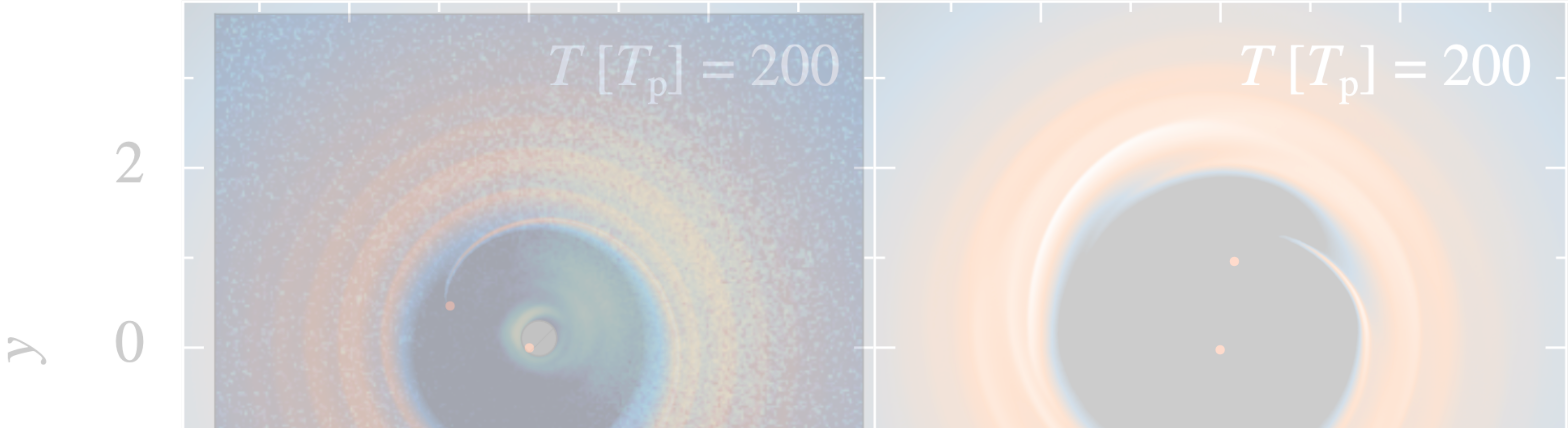
Dunhill, RDA & Armitage (2013)

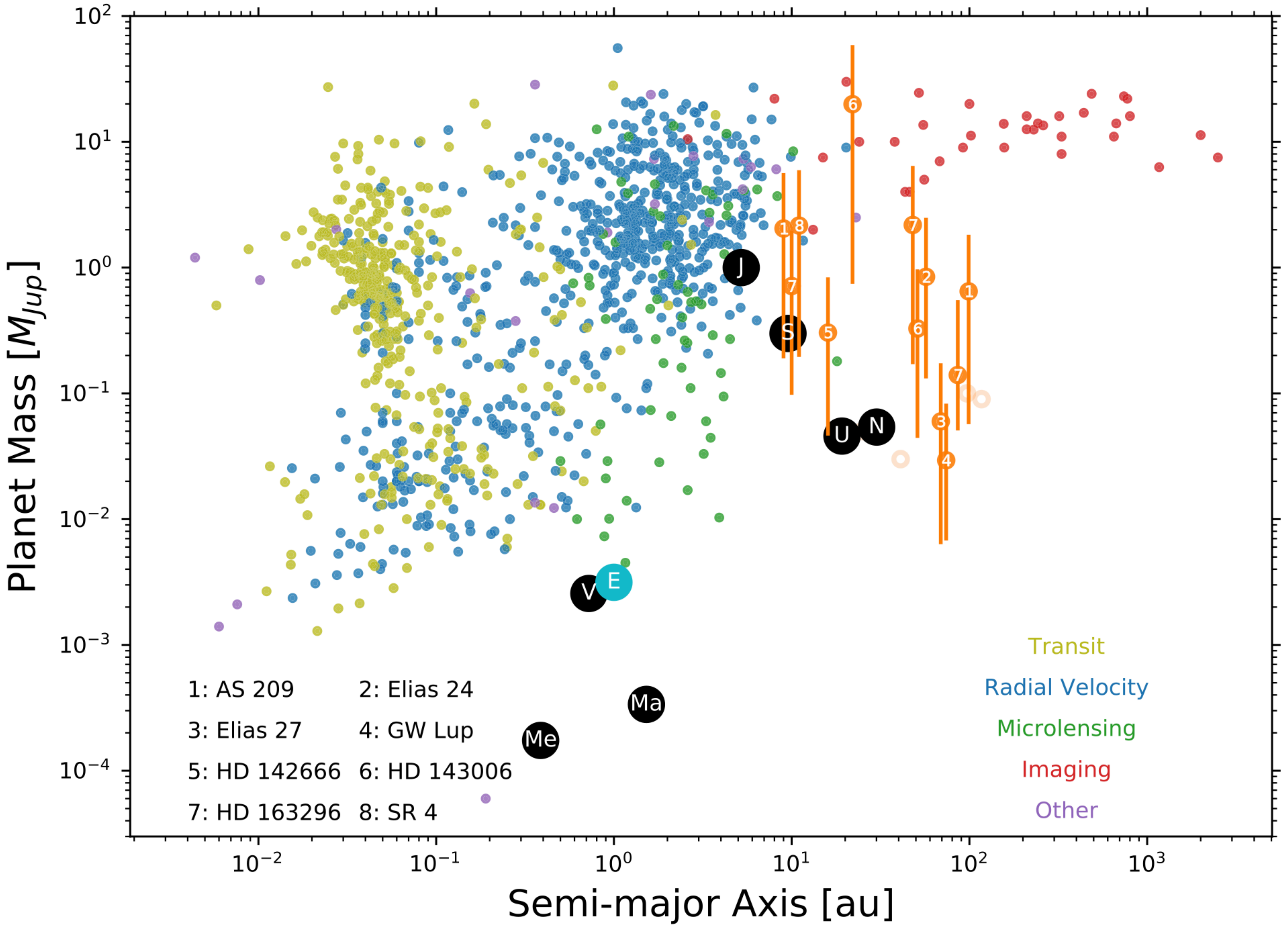


Muro-Arena+ (2020)

Other open questions

- Are observed shadows due to inclined / misaligned planets (e.g., Nealon+ 2018)?
  - often need to invoke multiple planets.
  - shadows appear long-lived, but inclination damping should be rapid.
- What role do planet-disc interactions play in exciting orbital eccentricities?
  - exoplanet eccentricity distribution is very broad; can't all be scattering(?).
- How does migration work in the outer disc?
  - ALMA gaps/rings/spirals suggest many planets at large separations (~50–100AU), but these are not seen in direct imaging surveys.





Zhang+ (2018; DSHARP VII)

[Lee, Longarini, Zhang posters]

Concluding thoughts

- Major theoretical uncertainty is now the "input" disc physics. Are we actually modelling realistic planet-disc interactions?

- To what extent are formation and migration intertwined?

- Can we understand migration well enough to inform our understanding of formation (time, location, etc.)?

- What are the most important observational tests?