

From tidal migration to exomoon survival:

can giant planets still host detectable satellites?

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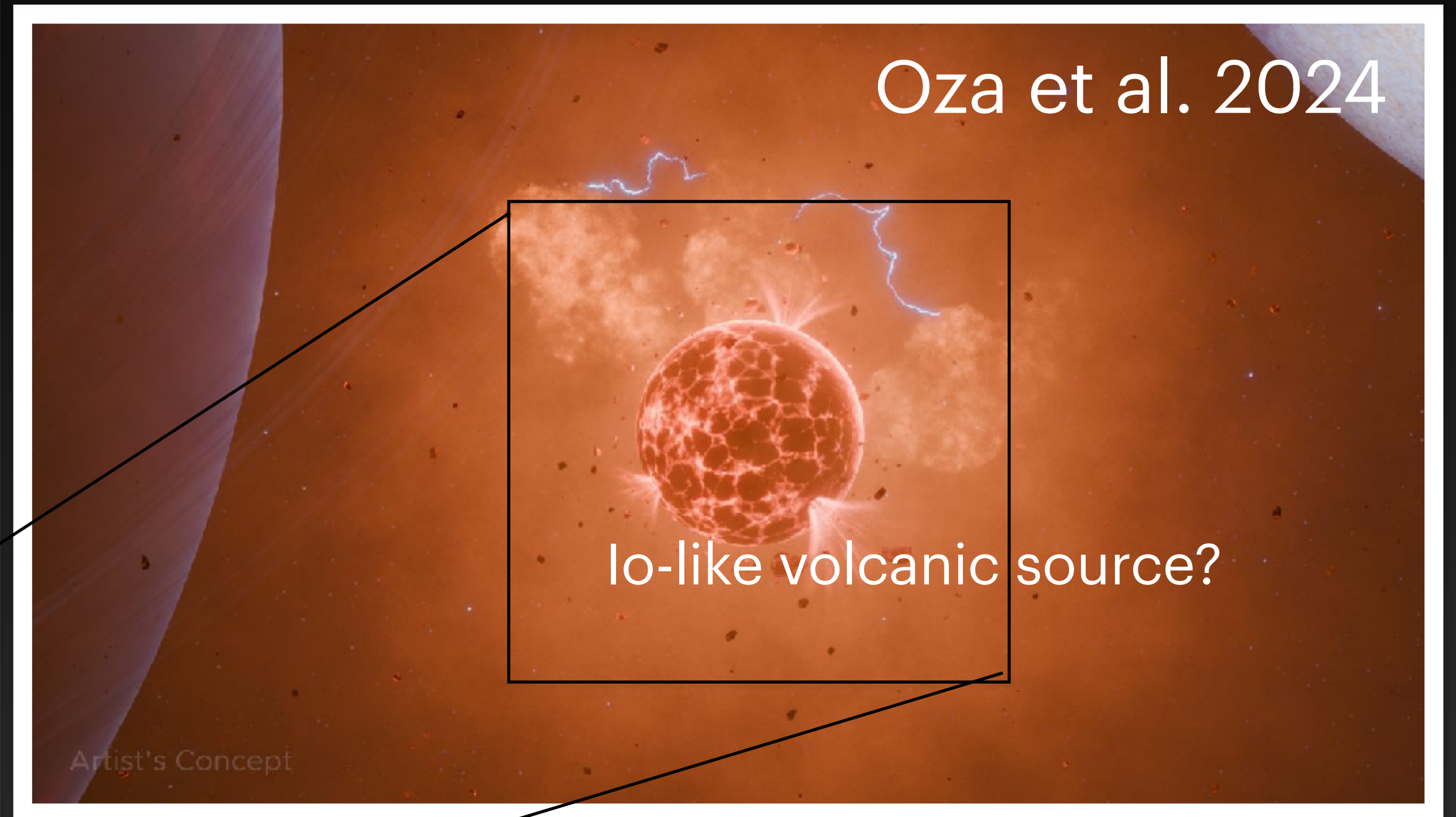
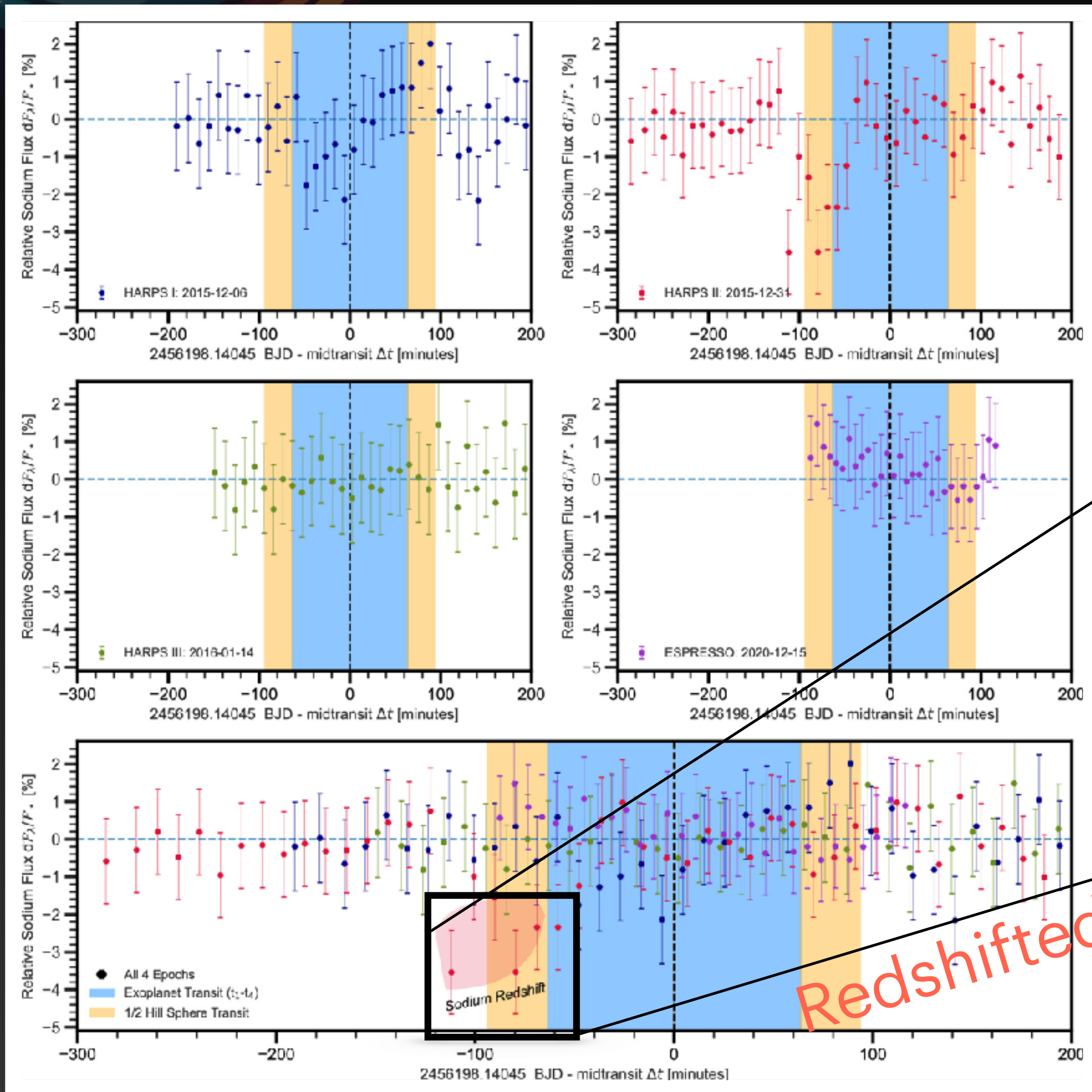
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European Research Council
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The puzzle: a possible volcanic moon?

WASP-49Ab sodium transient



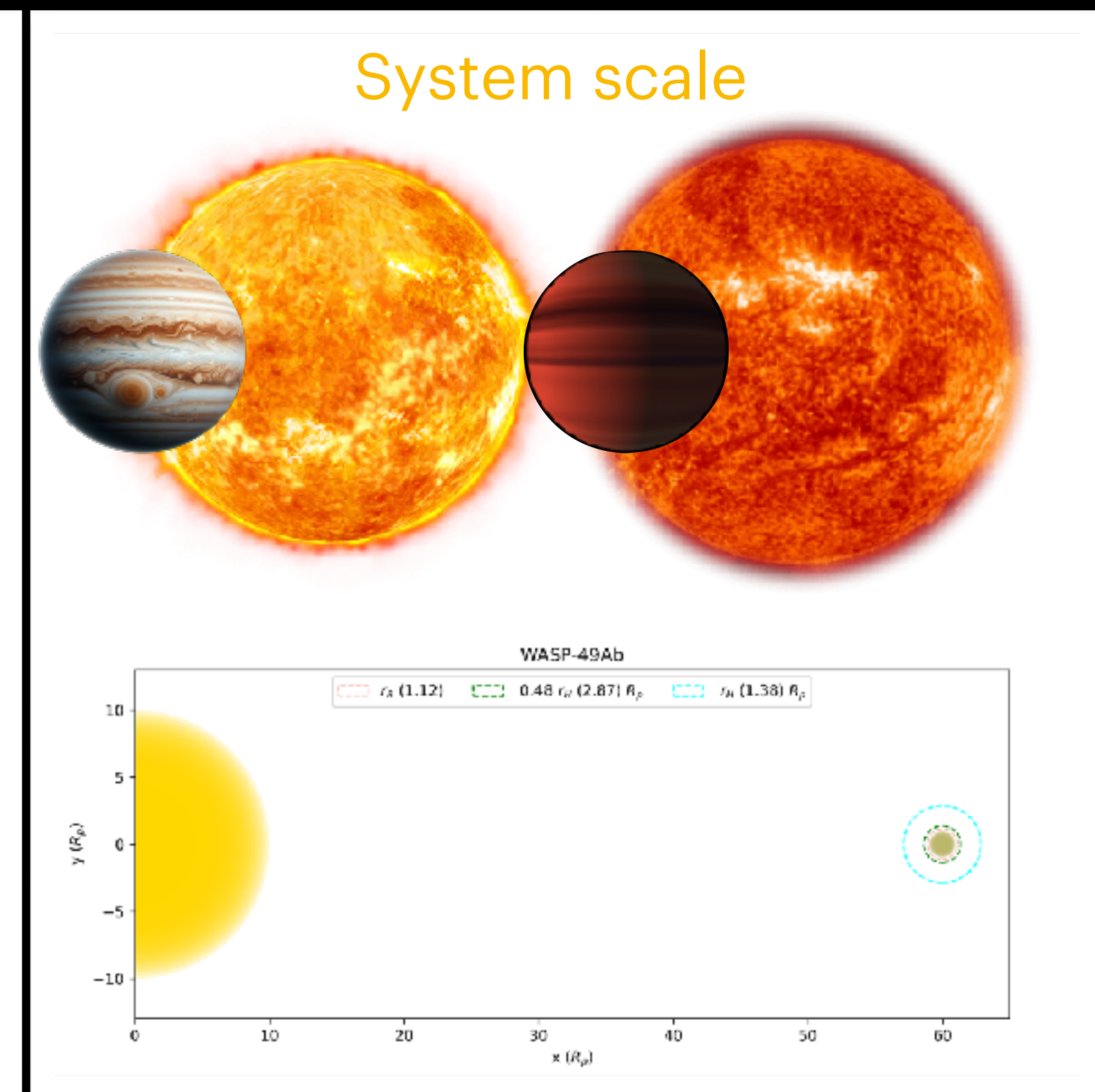
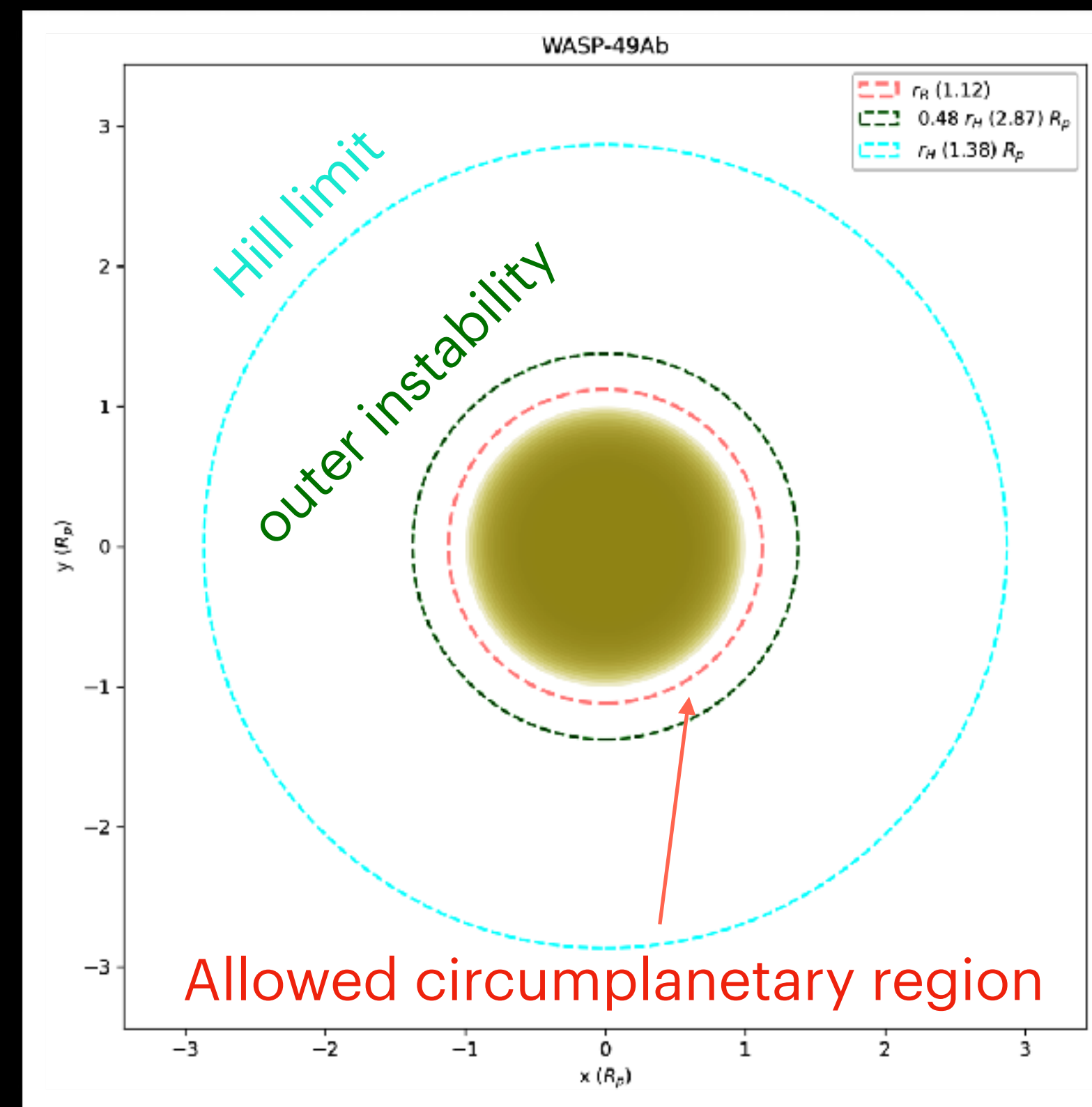
Redshifted sodium transient

But can such a moon survive so close to the star?

If the moon exists, it lives in a tiny dynamical niche

A possible moon must satisfy three constraints:

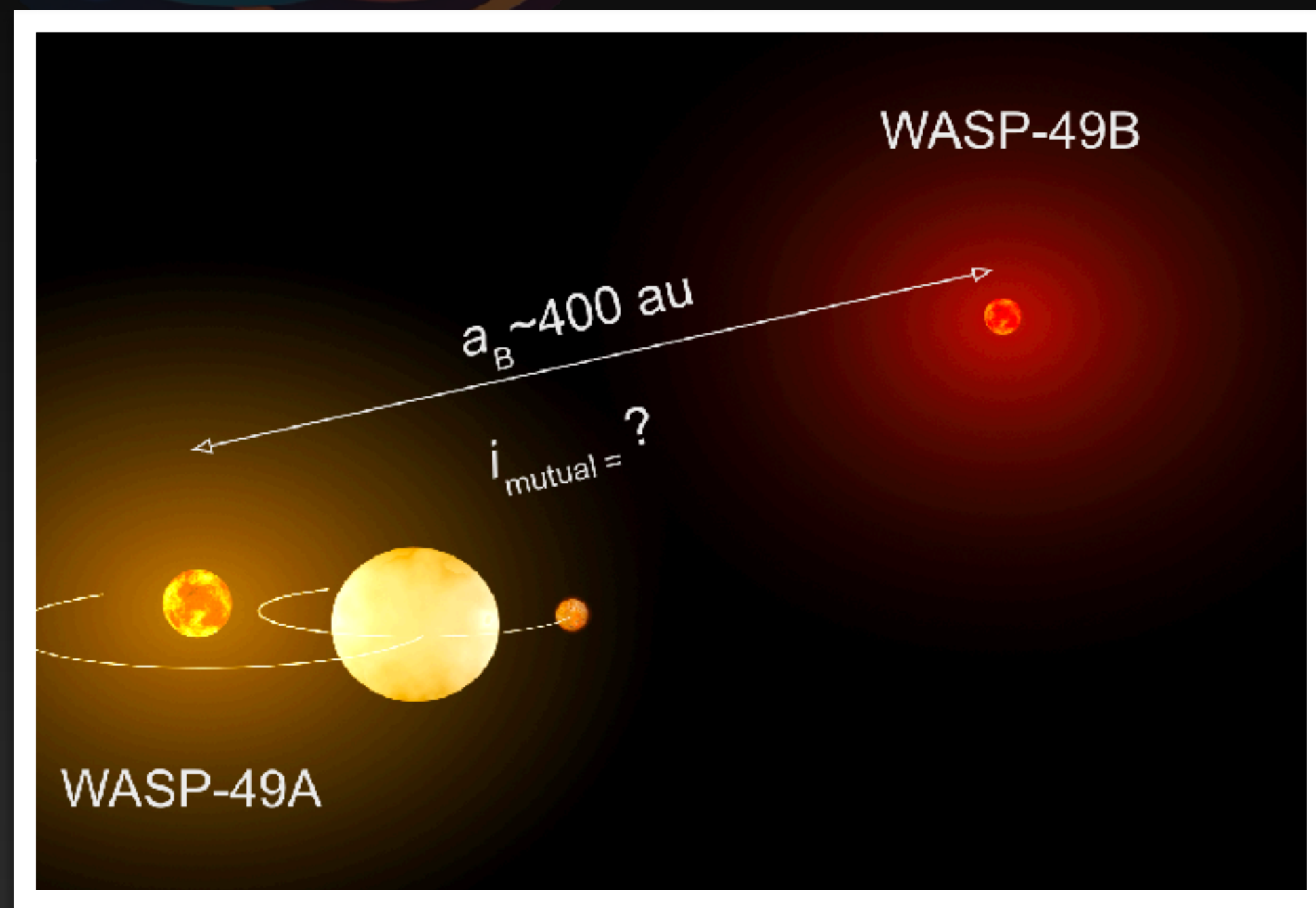
- * avoid collision/disruption
- * remain inside the stable circumplanetary region
- * survive tidal and secular perturbations



Can real moons survive in this environment?

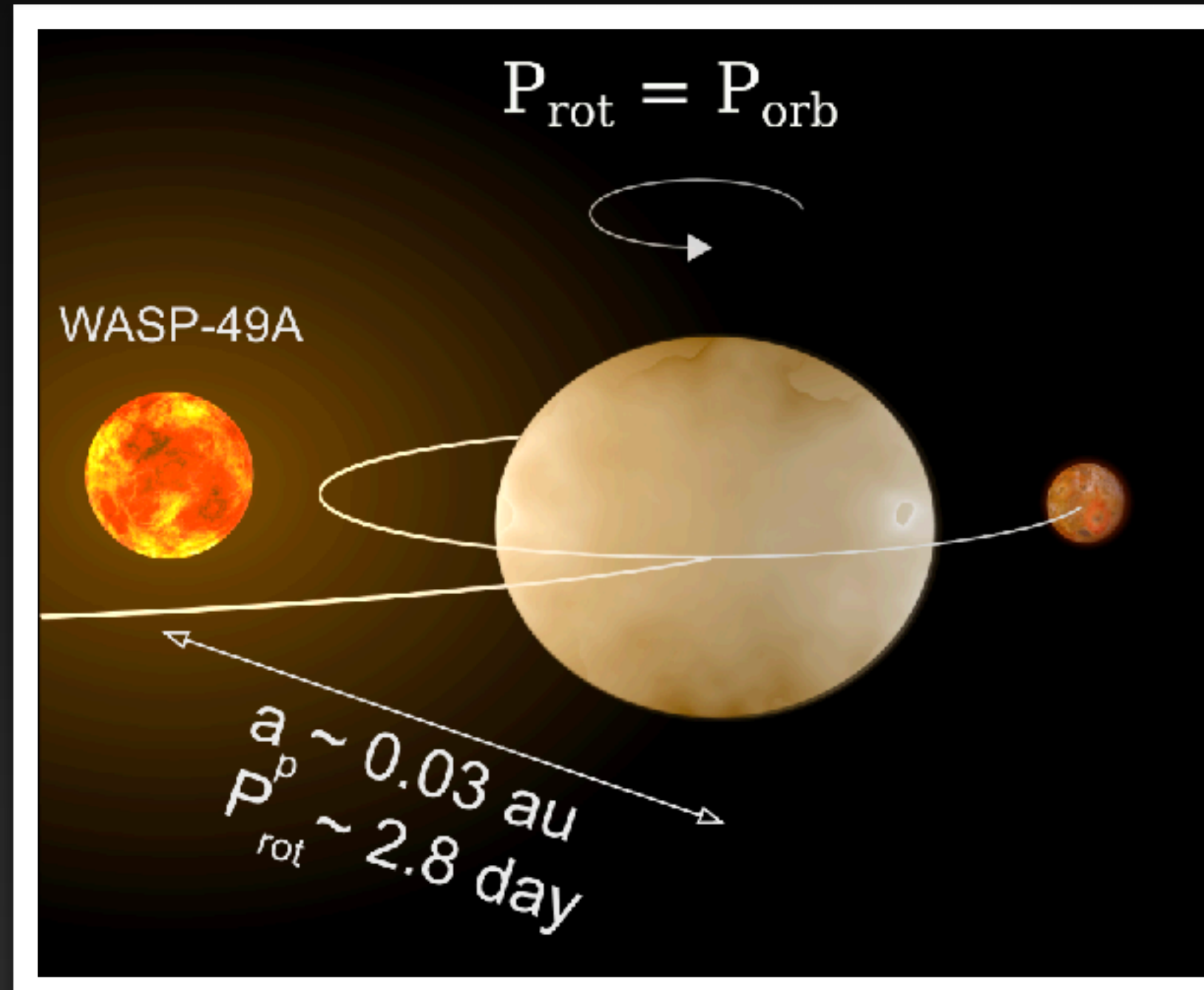


Why WASP-49Ab is hostile to moons



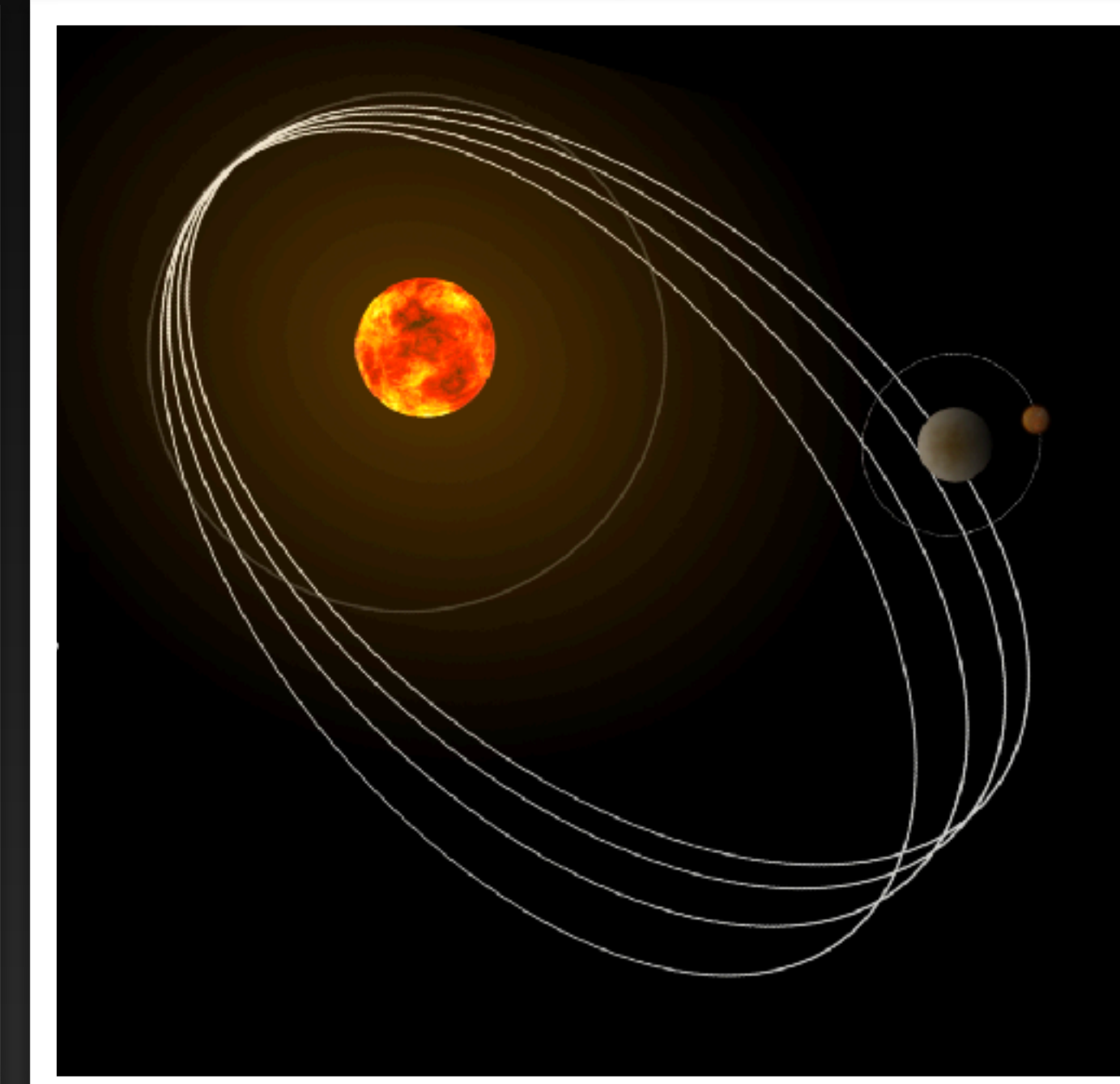
Binary companion

Secular perturbations



Strong planetary tides

moon migration and loss

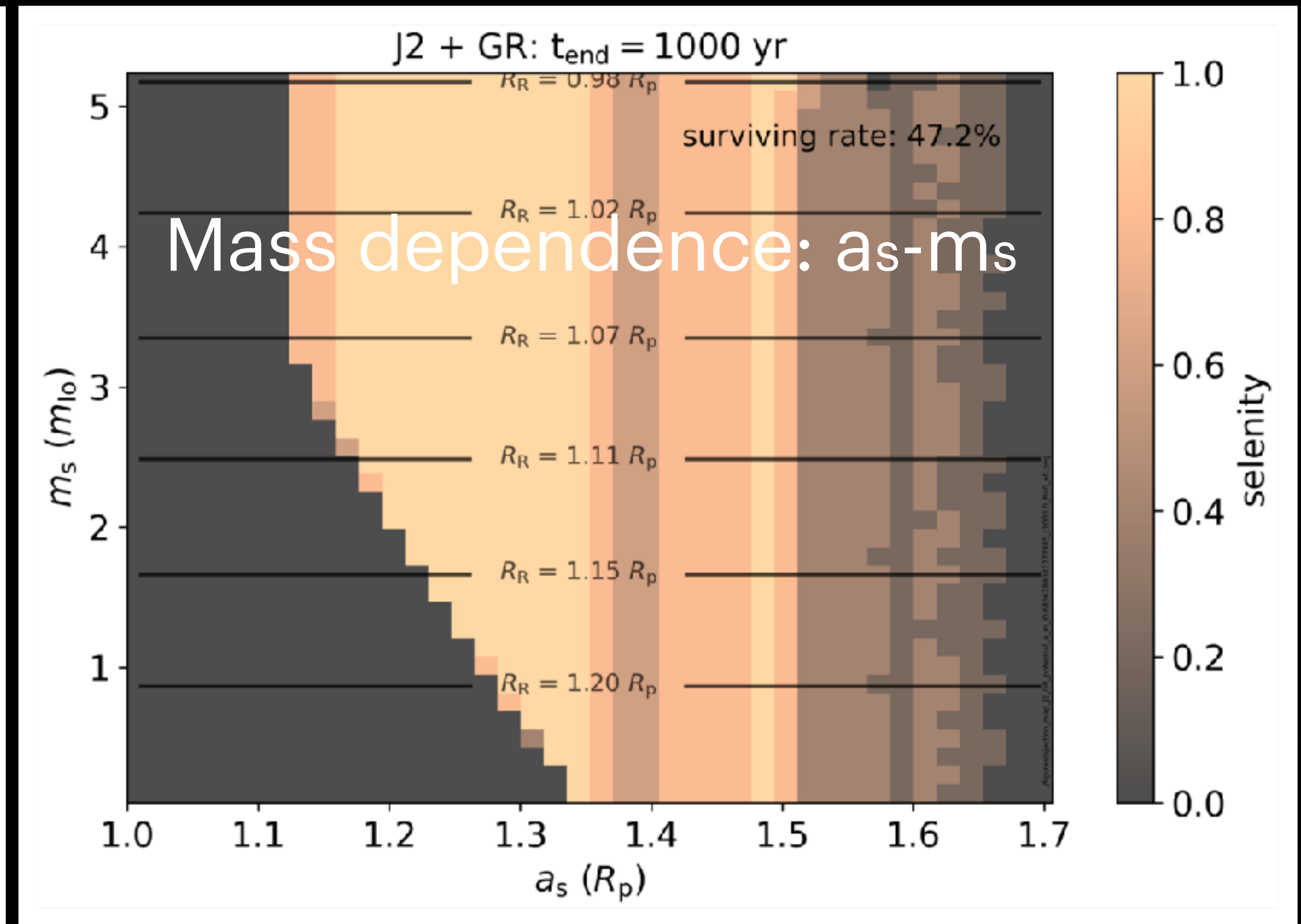
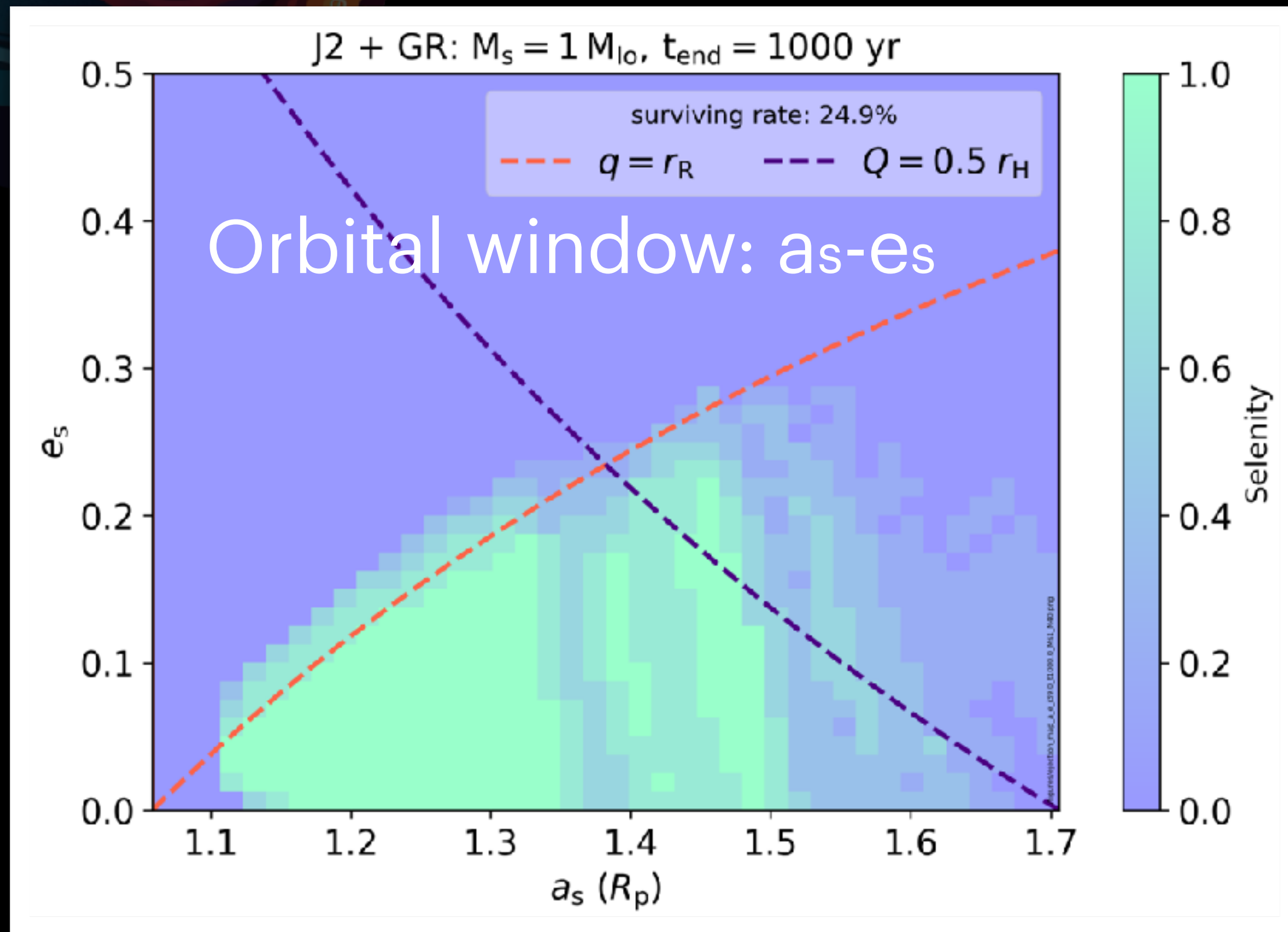


Relativistic precession

may open resonant channels

A moon can survive only inside a narrow region of semi-major axes and eccentricities.

Only a narrow dynamical niche remains



- Model includes: binary companion + J₂, J₄ + GR
- Stable orbits are confined to a narrow $a_s - e_s$ window.
- These maps define a viability window, not the full evolutionary lifetime.

Stability gives us the allowed room. Formation tells us why moons should be there in the first place.

The formation expectation: giant planets should form moons

nature

Vol 441|15 June 2006|doi:10.1038/nature04860

ARTICLES

A common mass scaling for satellite systems of gaseous planets

Robin M. Canup¹ & William R. Ward¹

The Solar System's outer planets that contain hydrogen gas all host systems of multiple moons, which notably each contain a similar fraction of their respective planet's mass ($\sim 10^{-4}$). This mass fraction is two to three orders of magnitude smaller than that of the largest satellites of the solid planets (such as the Earth's Moon), and its common value for gas planets has been puzzling. Here we model satellite growth and loss as a forming giant planet accumulates gas and rock-ice solids from solar orbit. We find that the mass fraction of its satellite system is regulated to $\sim 10^{-4}$ by a balance of two competing processes: the supply of inflowing material to the satellites, and satellite loss through orbital decay driven by the gas. We show that the overall properties of the satellite systems of Jupiter, Saturn and Uranus arise naturally, and suggest that similar processes could limit the largest moons of extrasolar Jupiter-mass planets to Moon-to-Mars size.

$$\frac{M_{\text{sat, tot}}}{M_p} \sim 10^{-4}$$

Formation provides moons; evolution decides which ones survive.

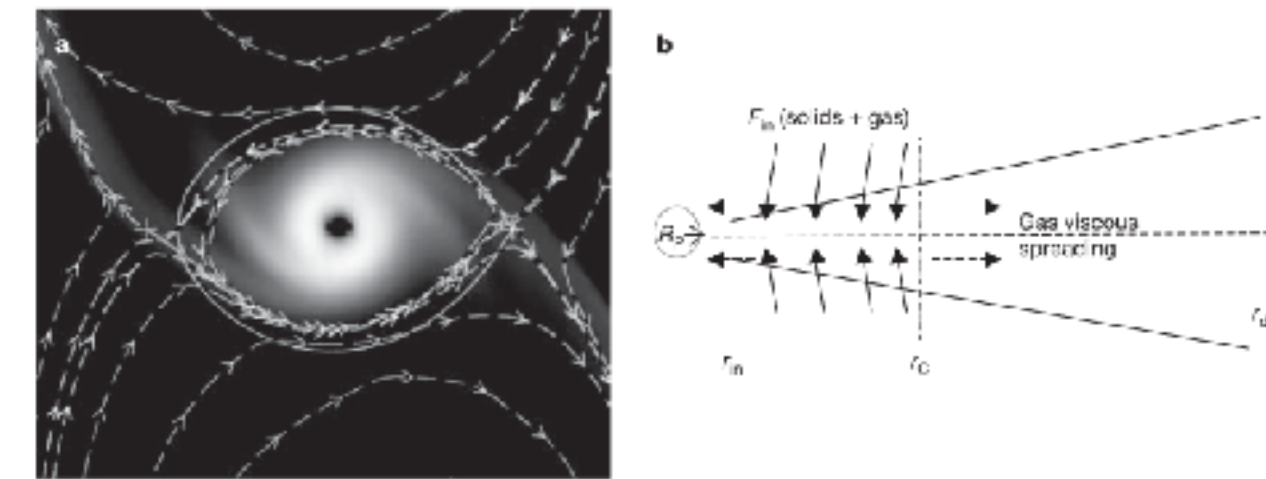


Figure 1 | An inflow-supplied circumplanetary disk. a, Hydrodynamical simulation of a forming giant planet with a circumplanetary disk. b, Schematic diagram of the disk with inflow and outflow rates. $(r_{\text{in}}/r_p) = 0.5$ and $(r_{\text{out}}/r_p) = 0.3$ (ref. 9), where r_p is the disk outer edge and Ω is the orbital frequency.

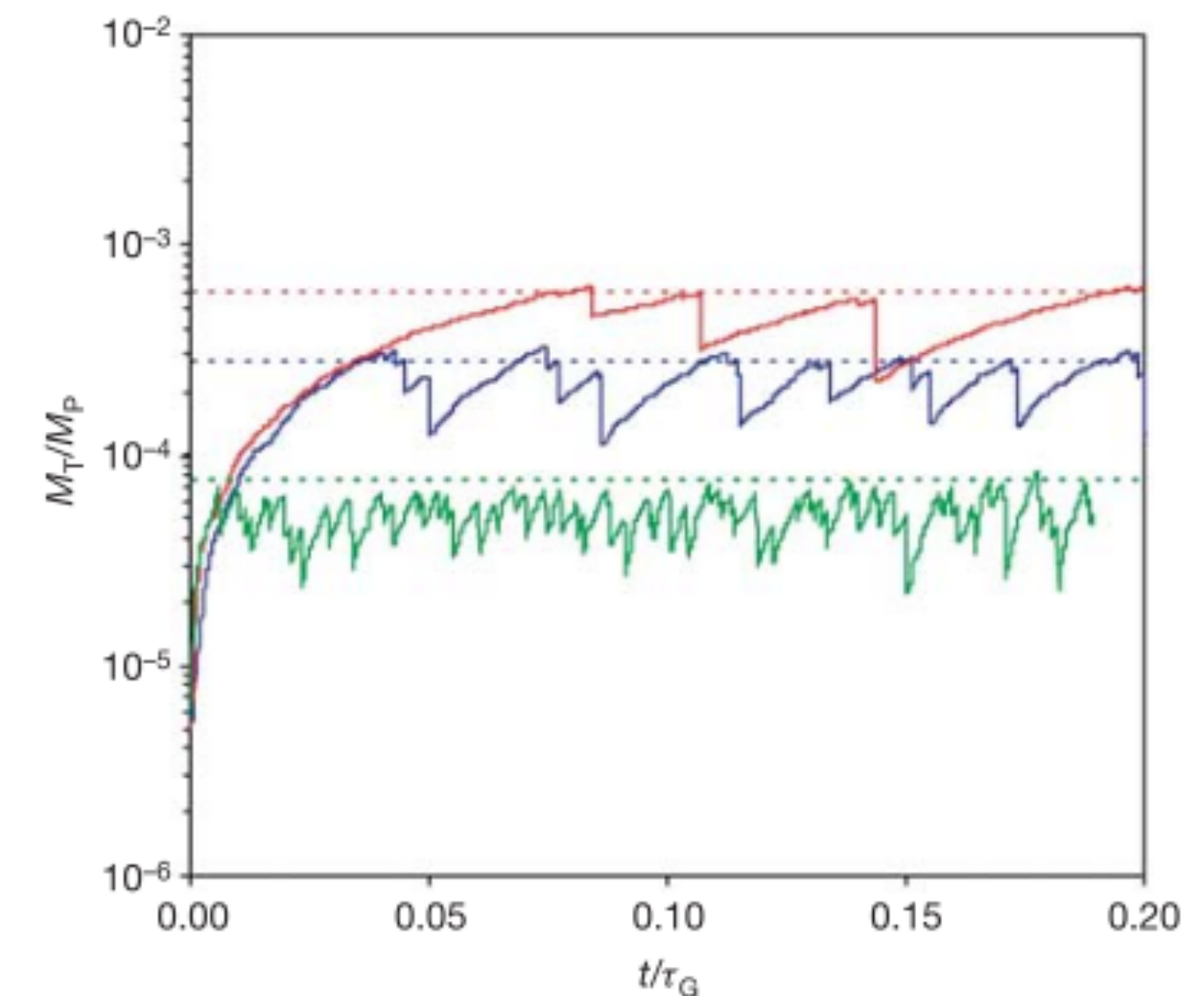
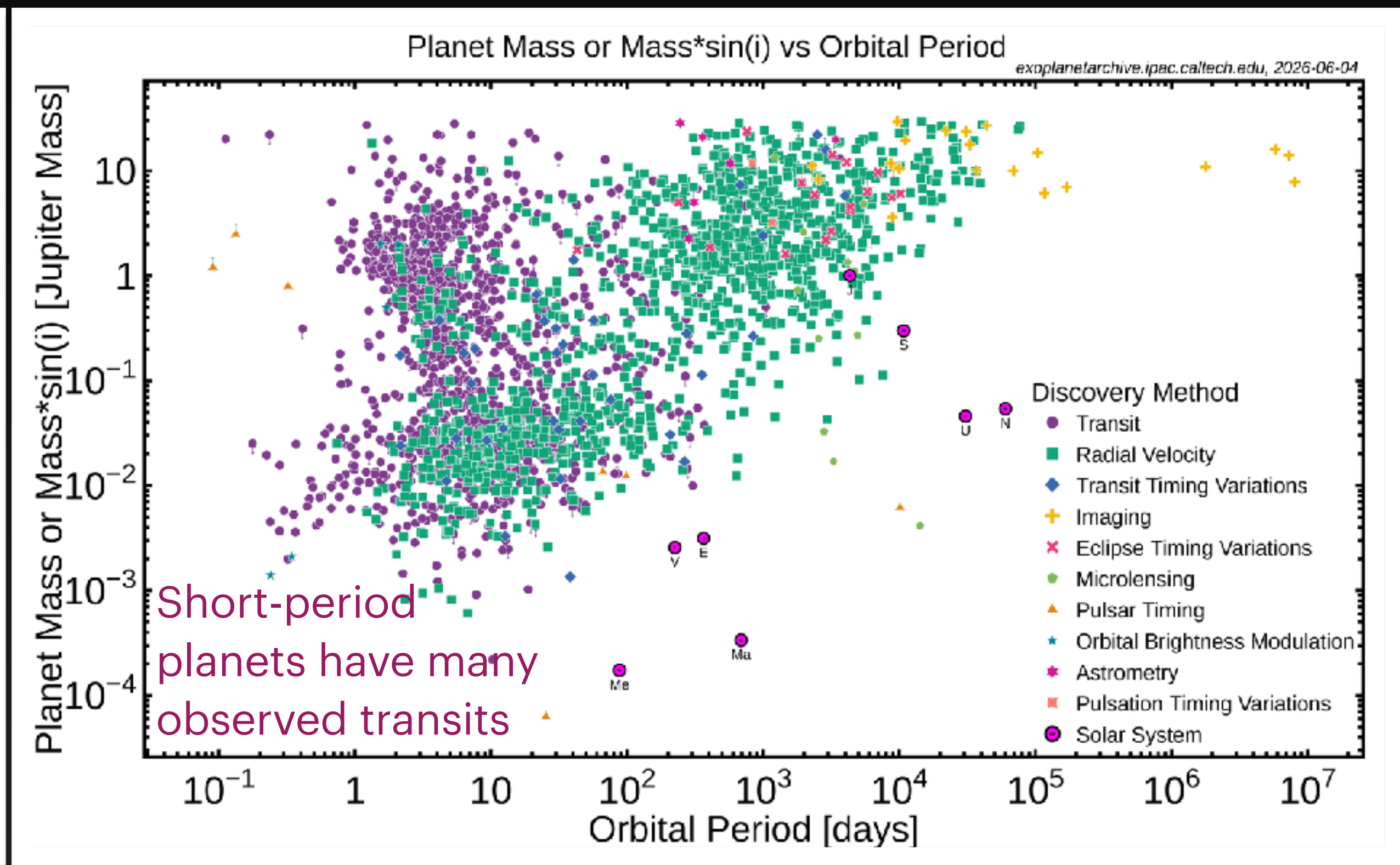
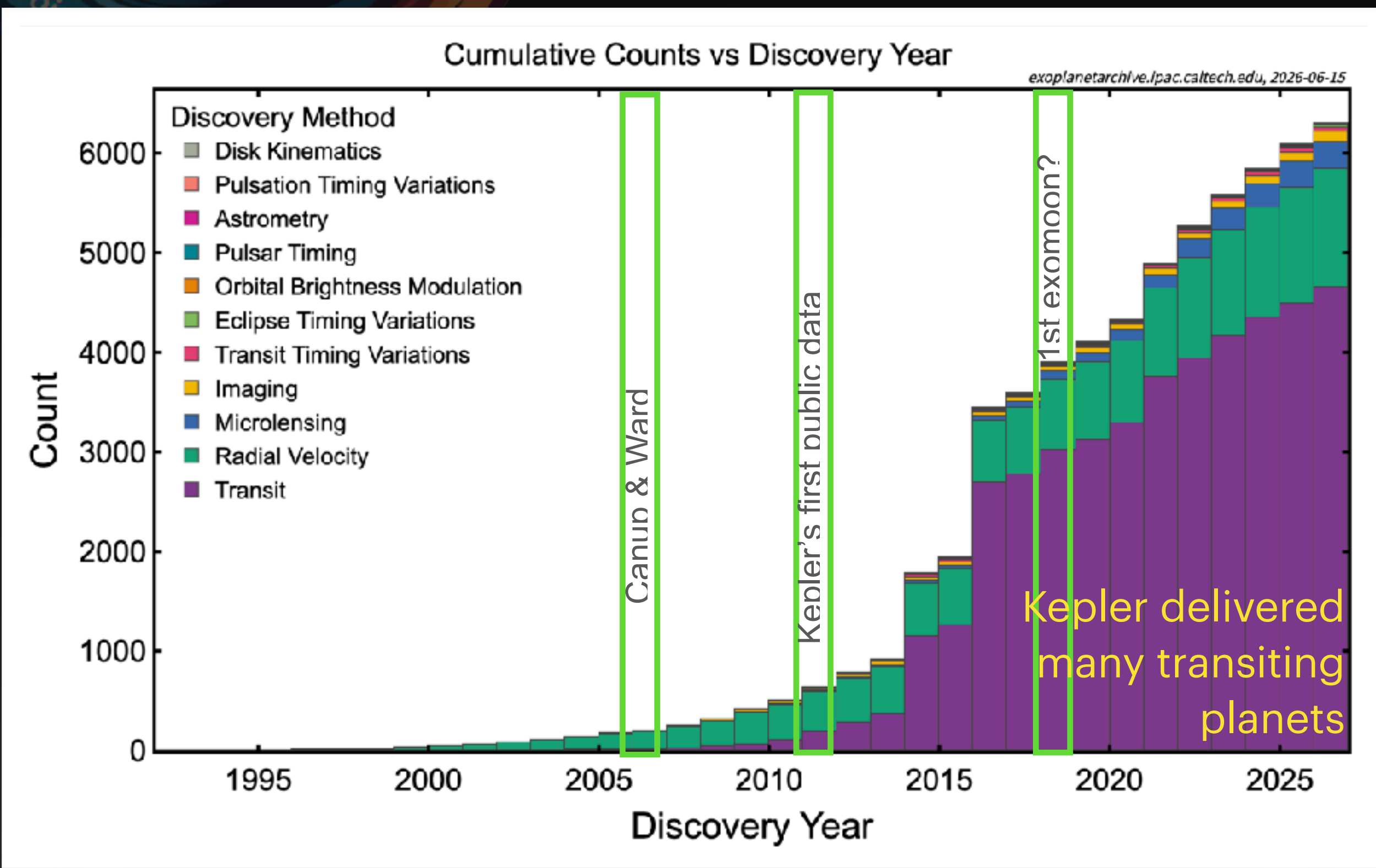


Figure 2 | Results of satellite accretion simulations with time-constant inflows. The total mass in satellites, M_T , scaled to the planet's mass, M_p , is

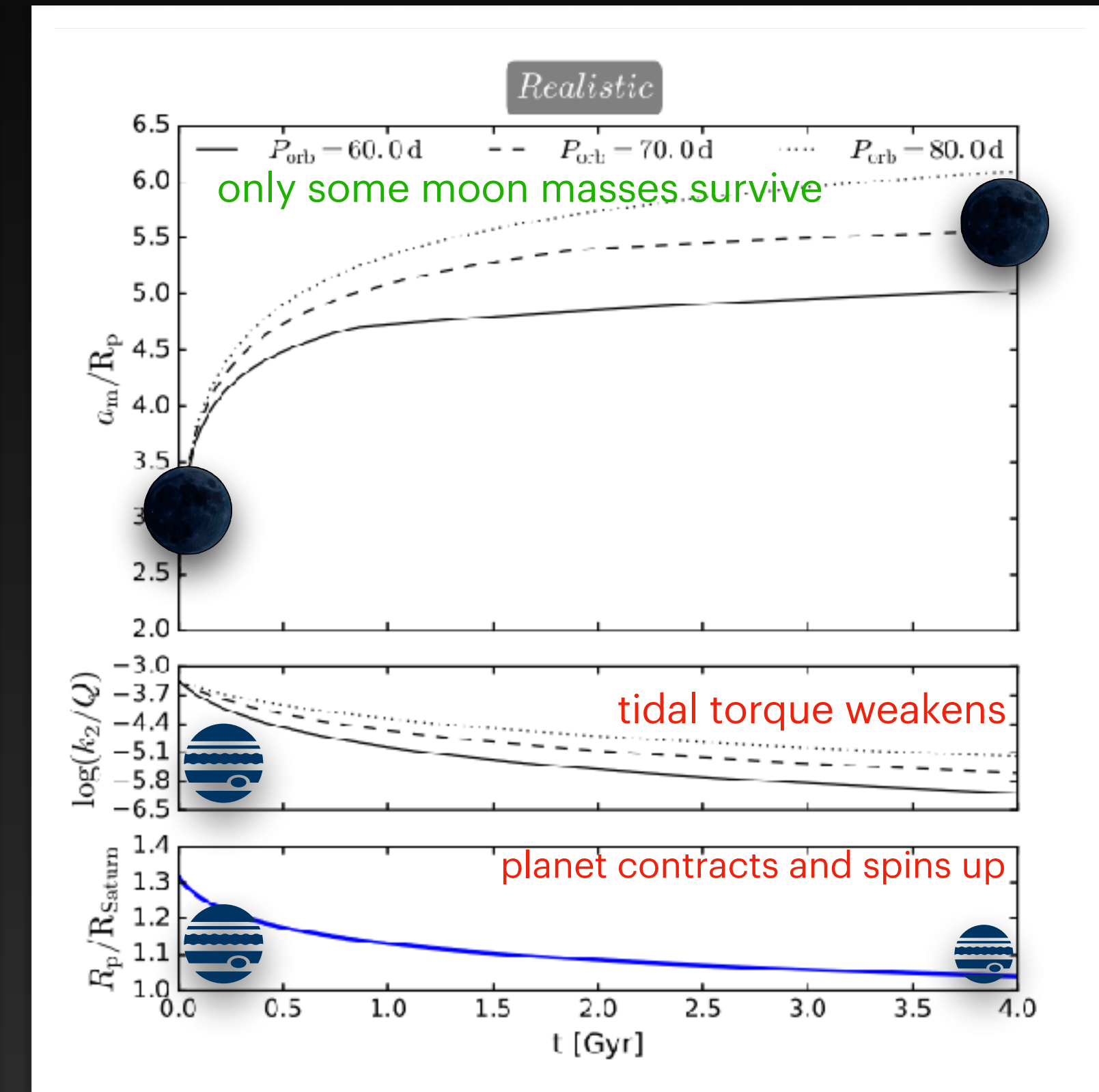
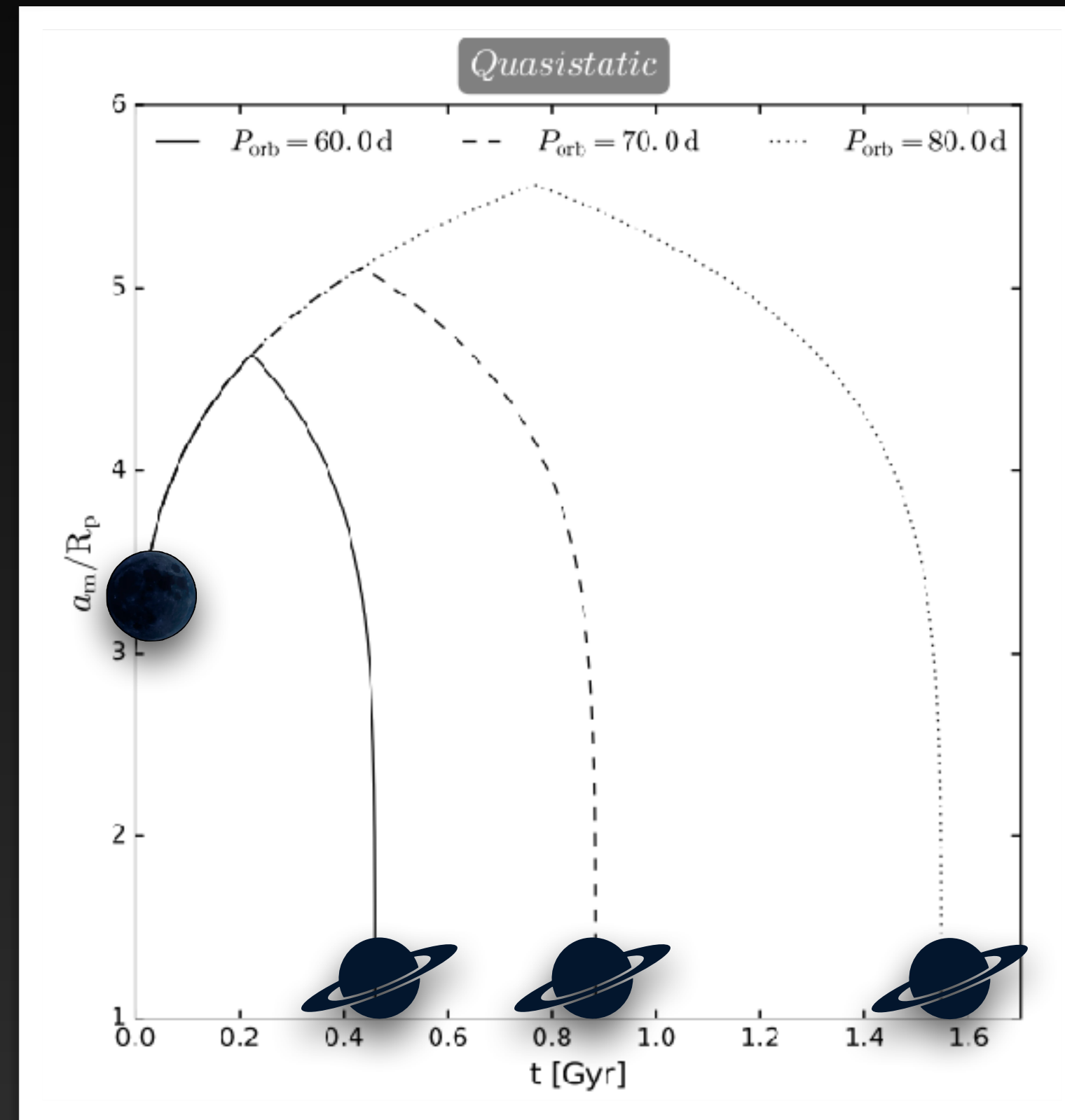
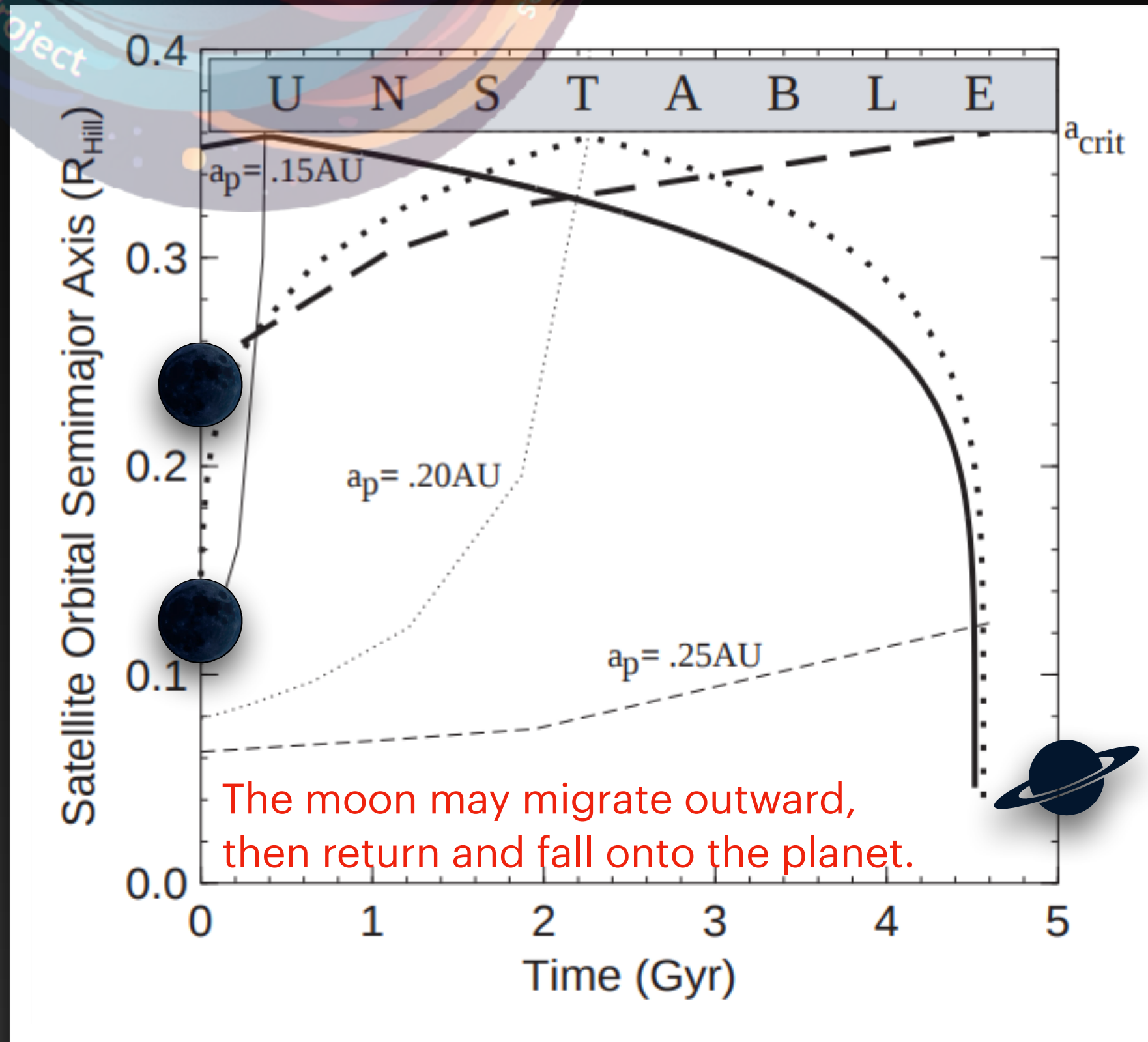
Formation predicts moons — where are they?



- ✱ Giant planets should form moons — but Kepler did not reveal a clear exomoon population.
- ✱ Are they rare, hidden, or lost?

Where are the moons?

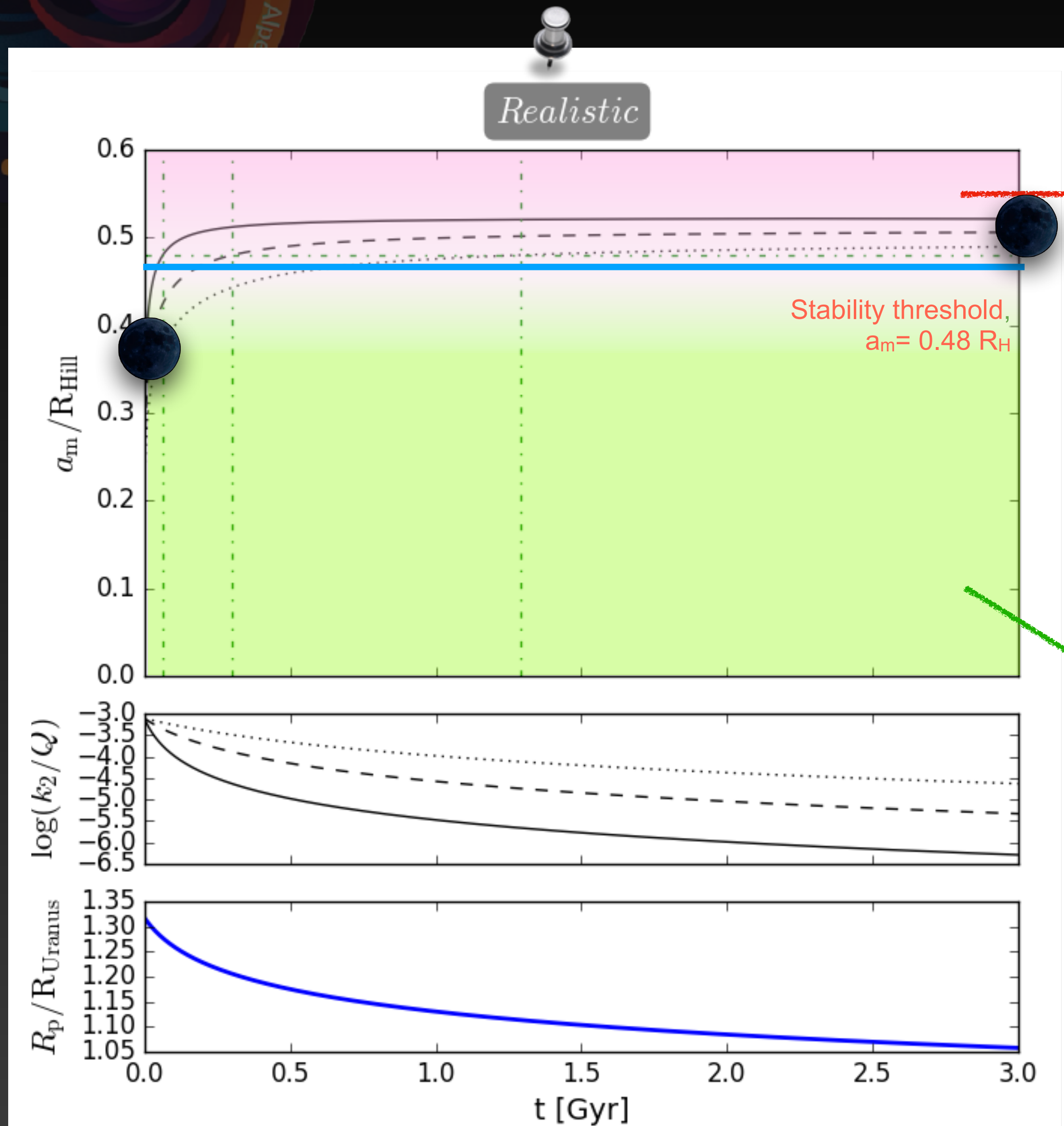
Tidal evolution sets the survival boundary



The moon migrates outward, but the tidal torque weakens with time.

The Hill boundary defines the room; tides decide how long the moon can stay inside.
So tidal migration turns moon survival into a stay-or-go problem.

Tidal migration: should the moon stay or go?



Massive moons
fast outward migration
 $a_m > a_{crit}$
escape / collision / **ploonets**



Low-mass moons
slow outward migration
 $a_m < a_{crit}$
retained, but weak signals

Mass filters survival; size filters detectability.



Distance favours moon retention

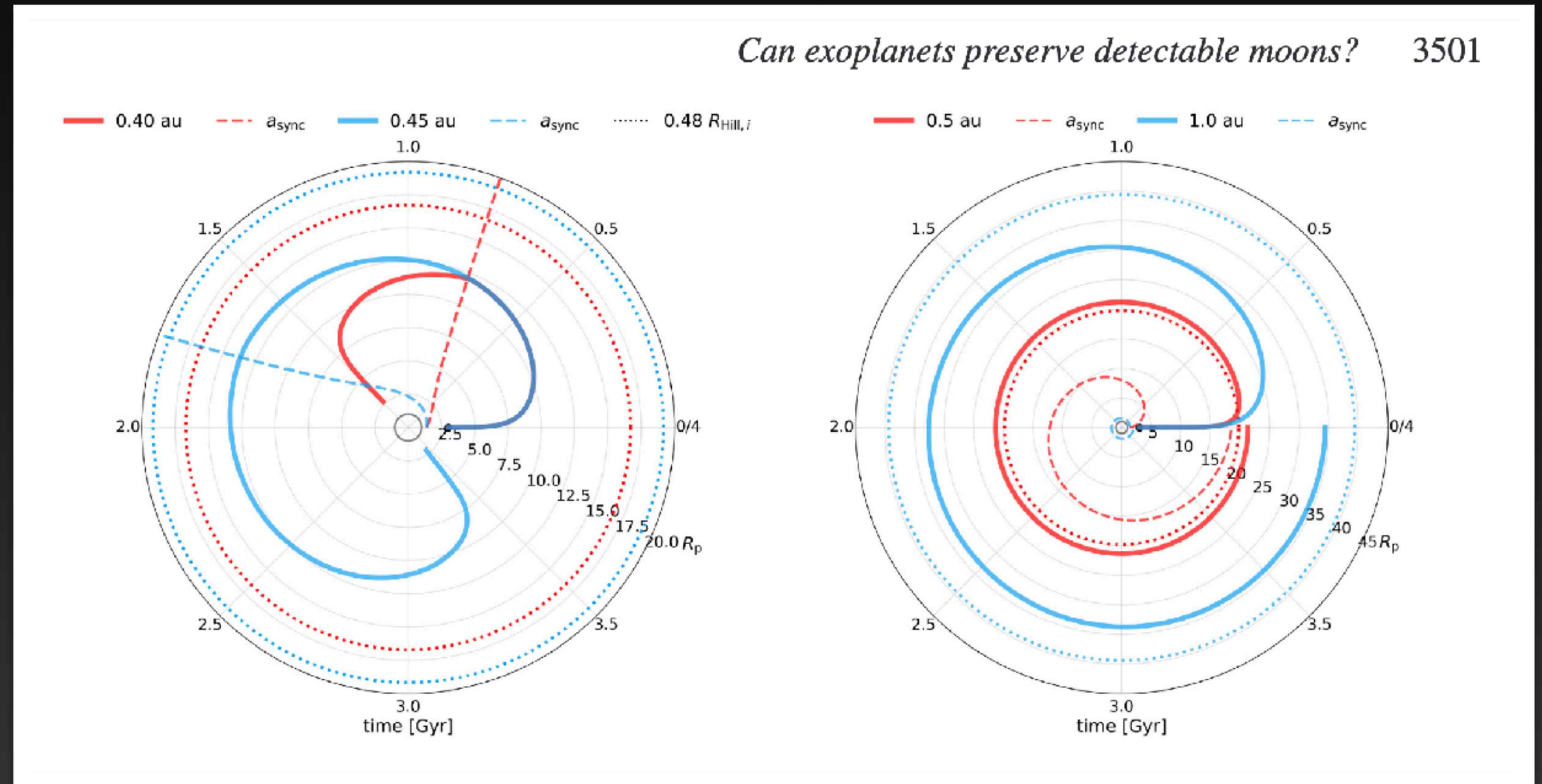
- More distance means:
- Farther from the star:

$$R_H \propto a_p$$

- larger Hill sphere

$$F_{tide} \propto a_p^{-3}$$

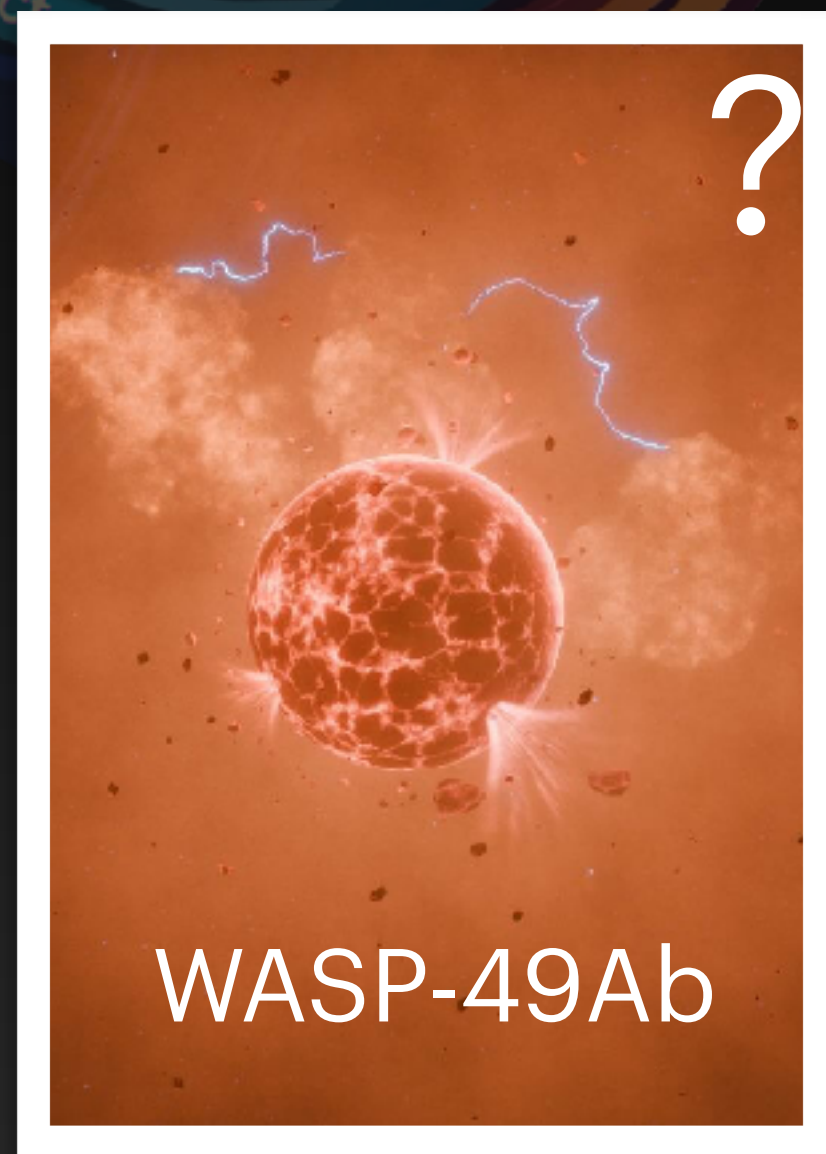
- weaker stellar tides
- More room + weaker forcing → higher chance of retention



Sucerquia et al. 2018, 2019

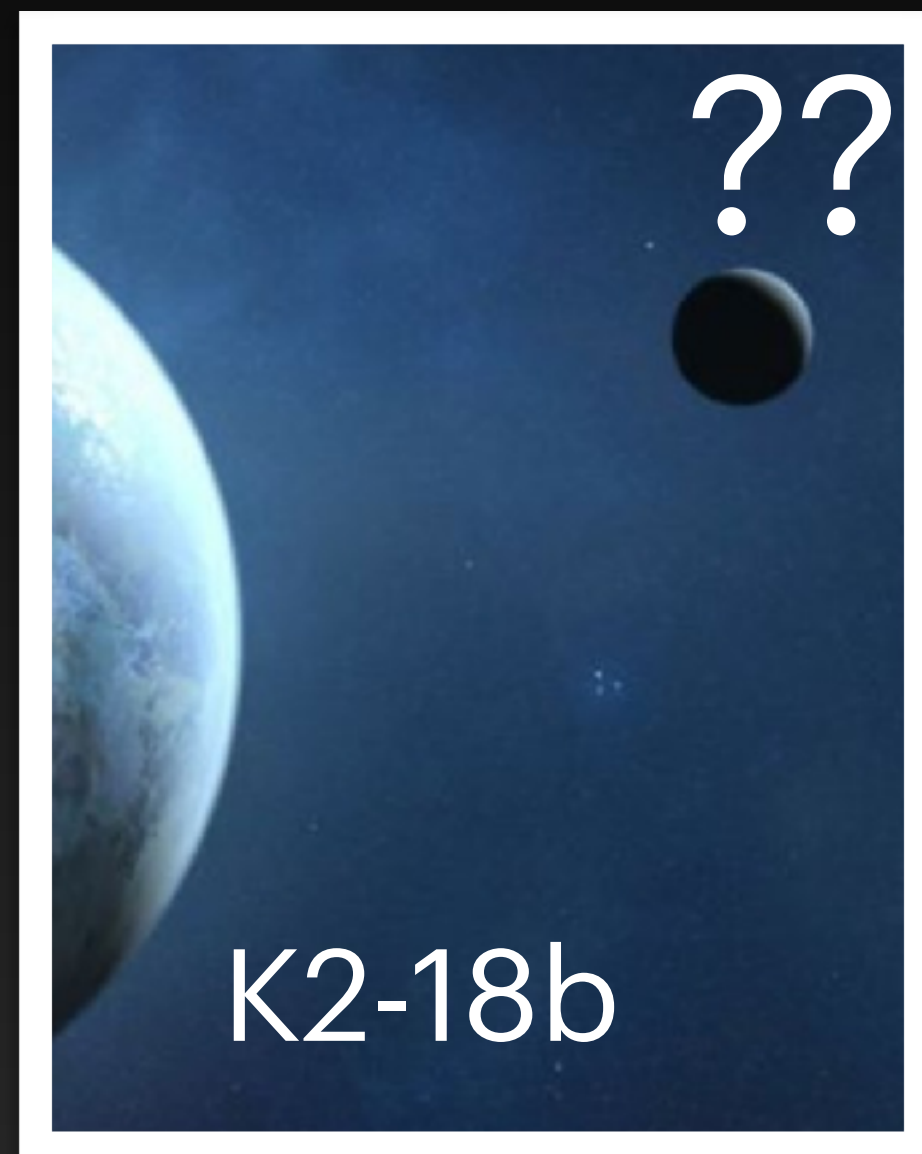
Distance favours survival, but challenges detectability.

Exomoon searches across planetary orbital periods



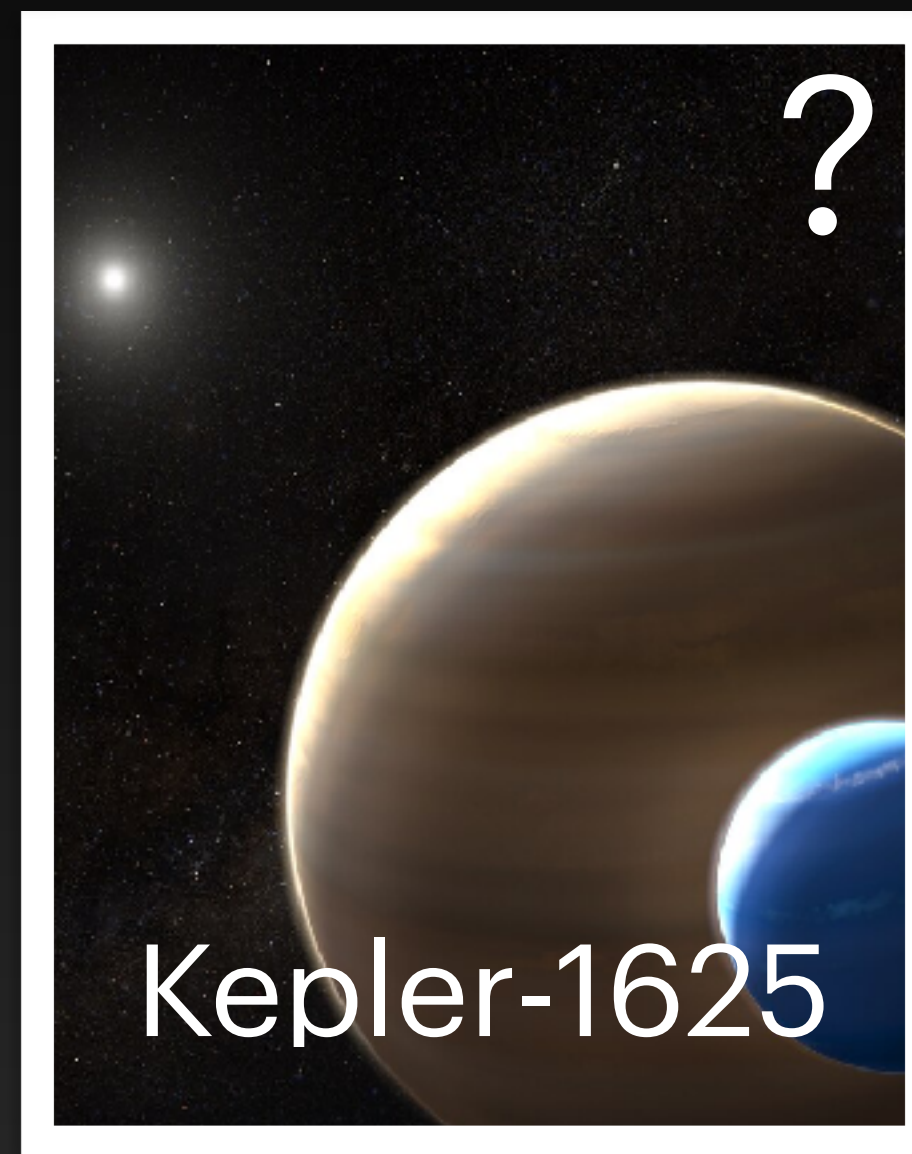
indirect signature

2.8



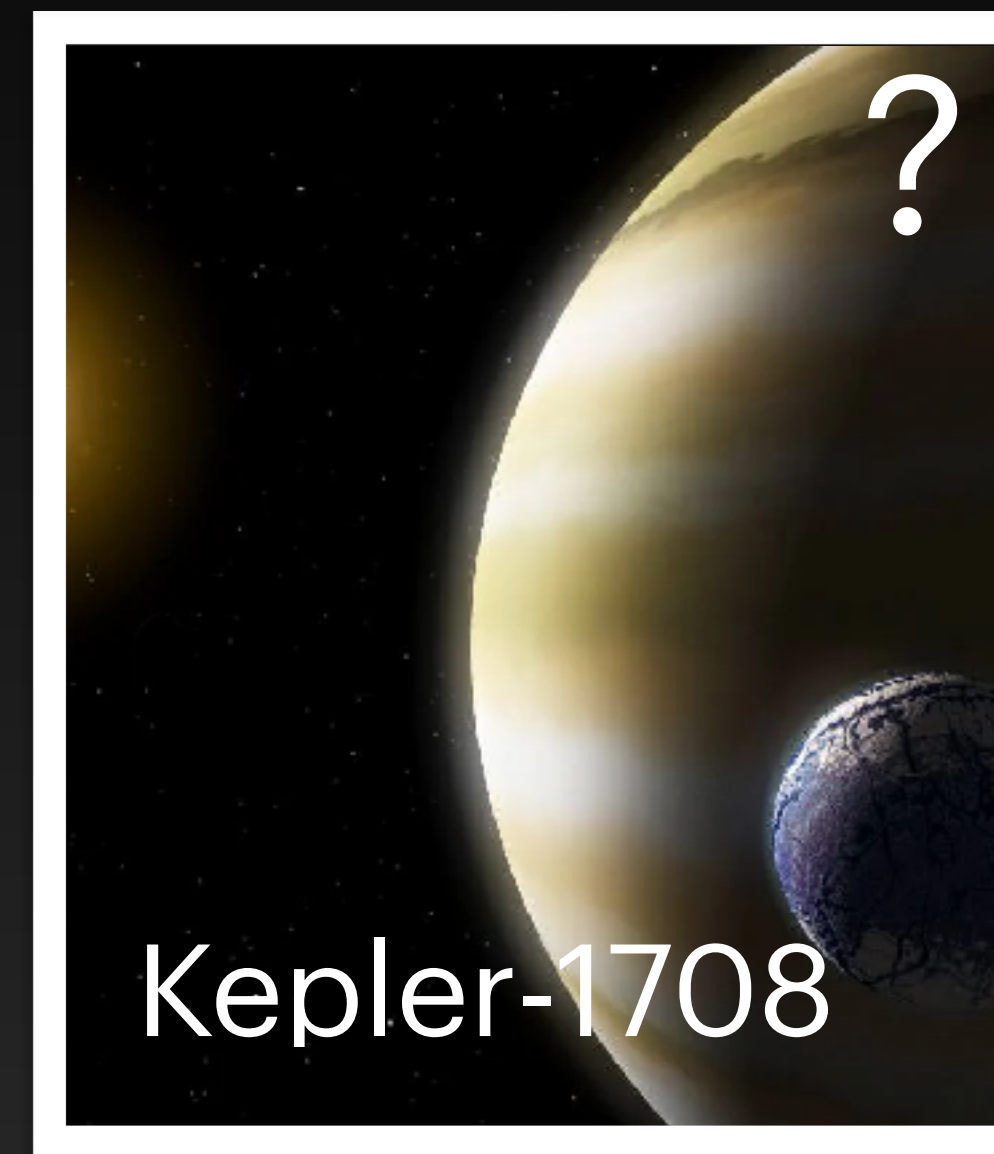
survival test

32.9



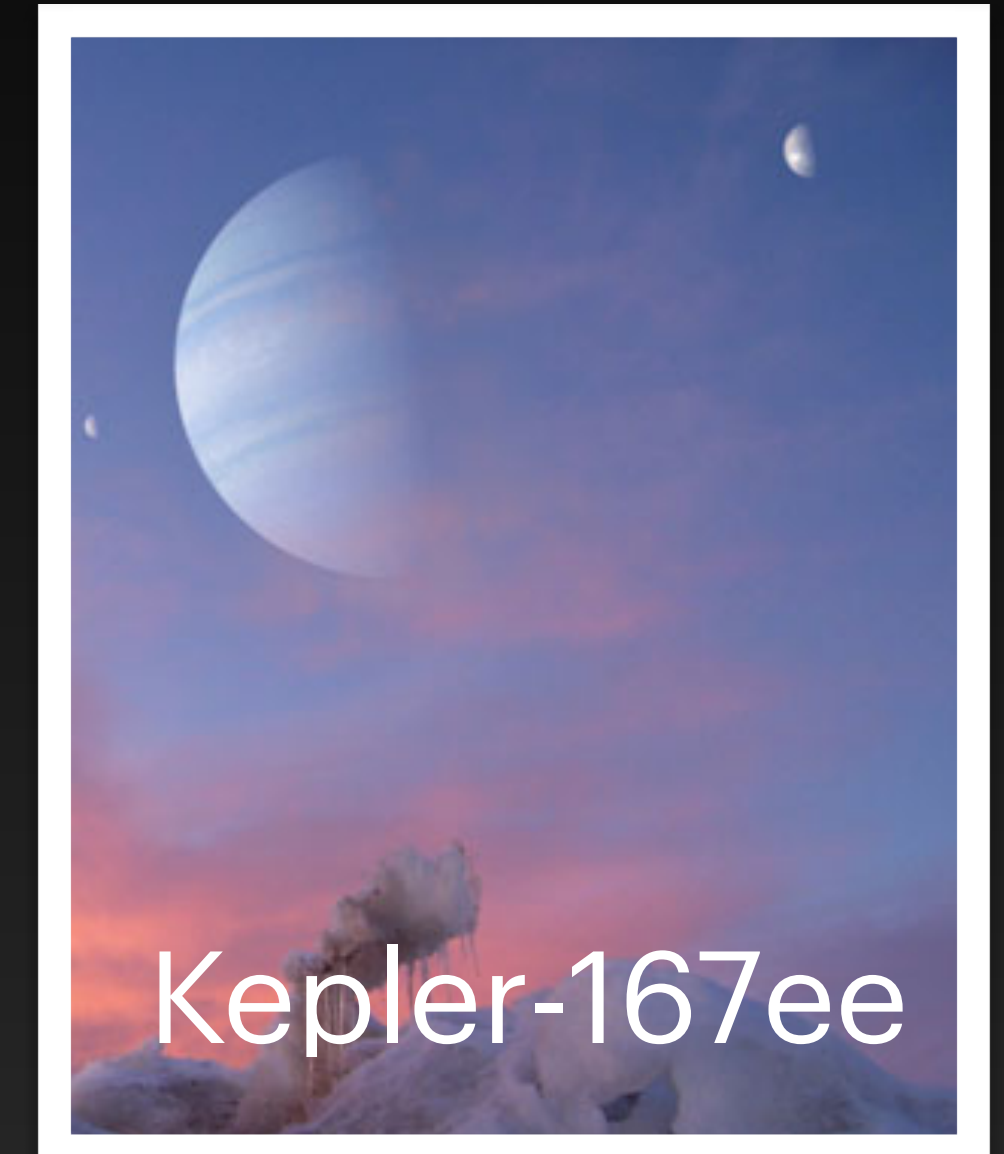
claimed moon

287



claimed moon

737



JWST target

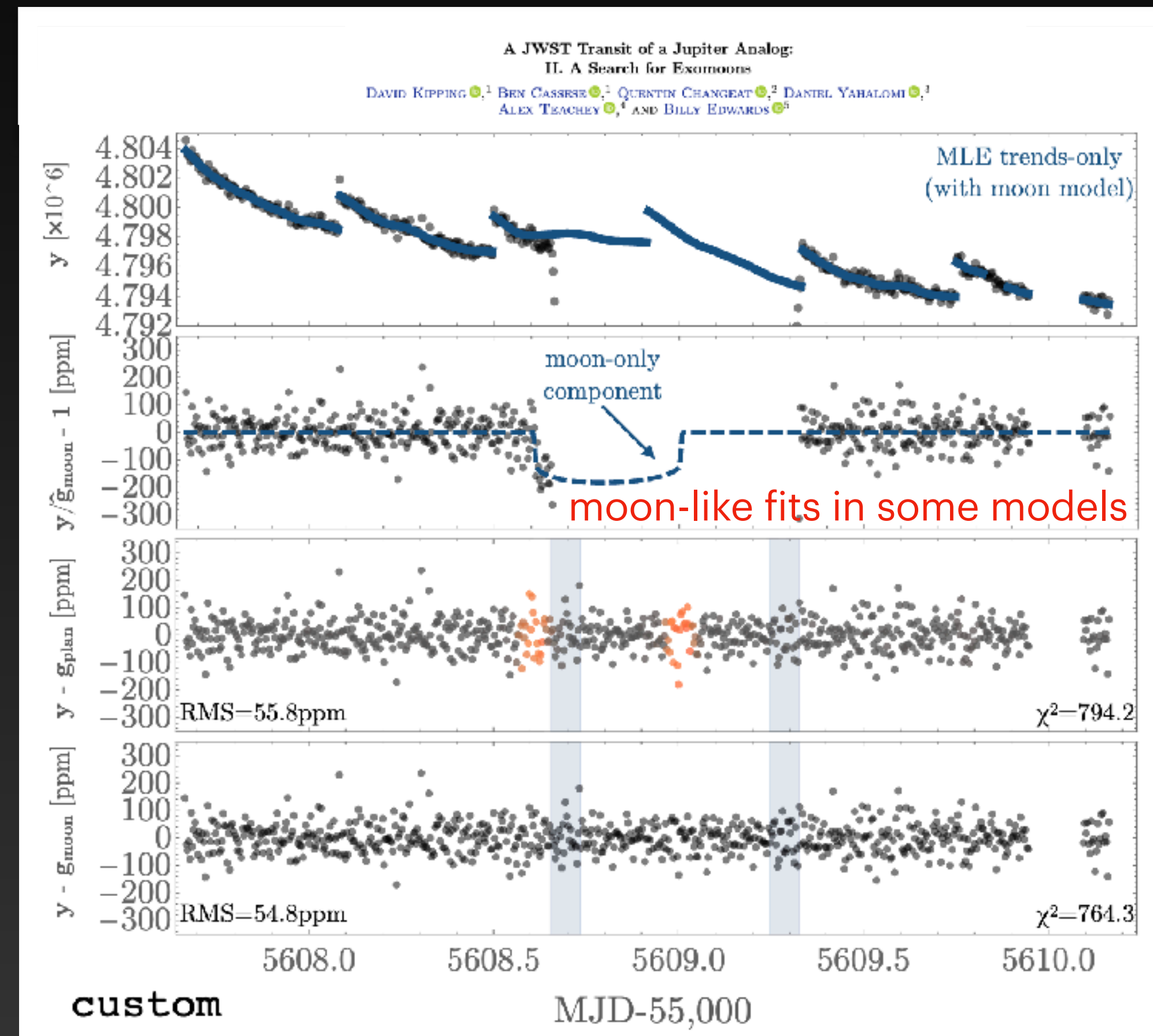
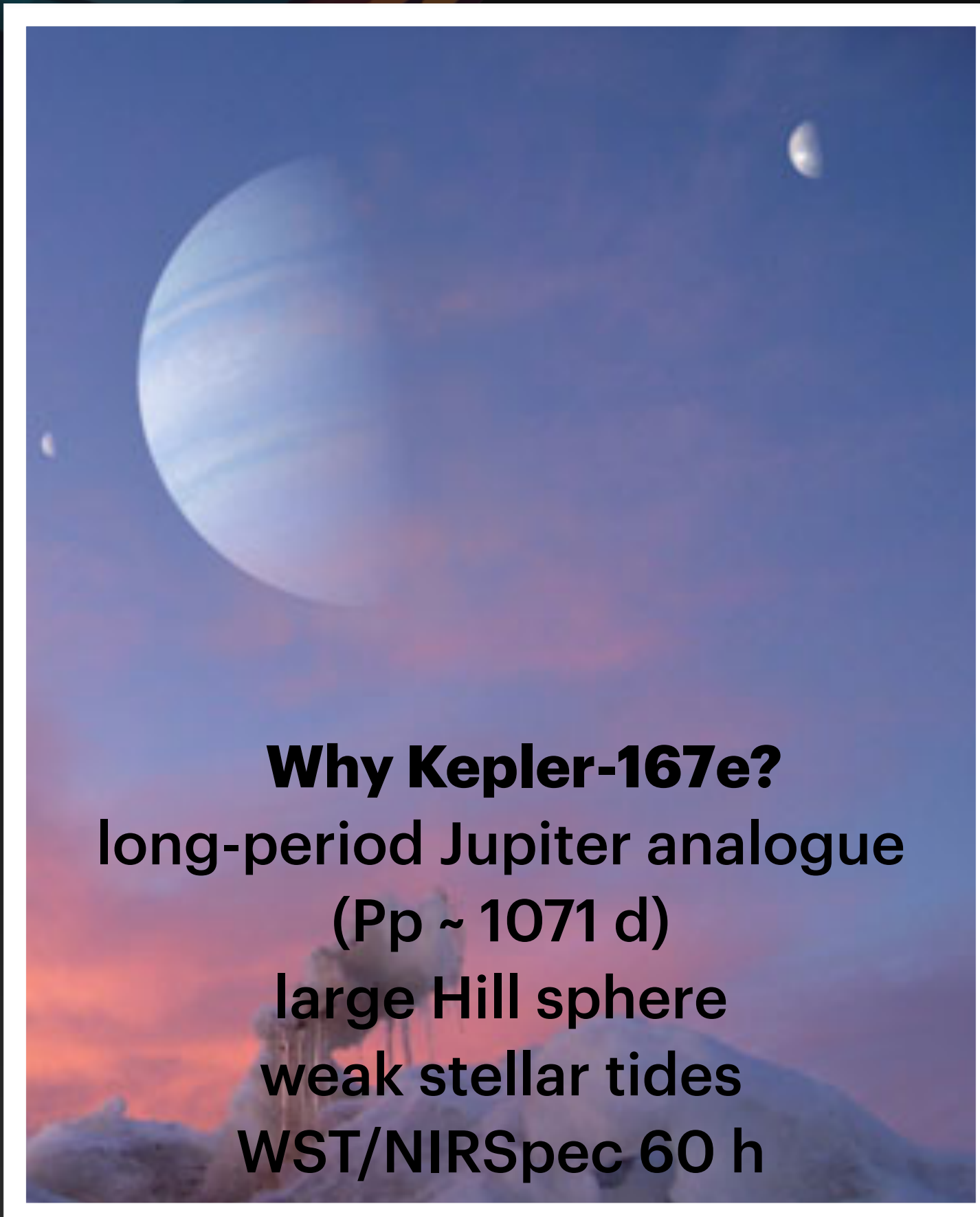
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day

Planet orbital period: from tidal hostility to survival

From WASP-49Ab to Kepler-167e, moon survival becomes dynamically more favourable but observationally more demanding.

Kepler-167e: favourable for moons, difficult to confirm



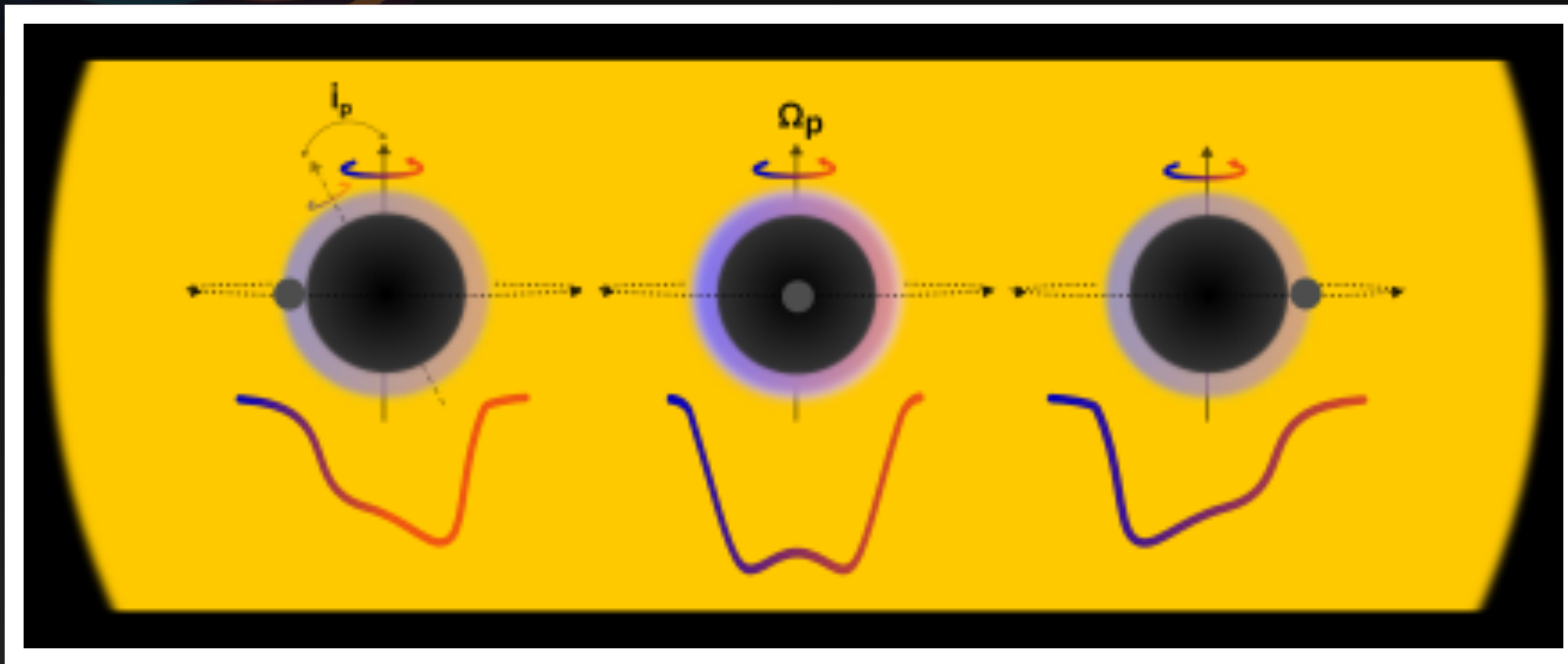
Why photometry remains ambiguous

- * model dependence
- * systematics
- * starspots
- * single-transit degeneracy

Survival-friendly systems are not automatically detection-friendly.

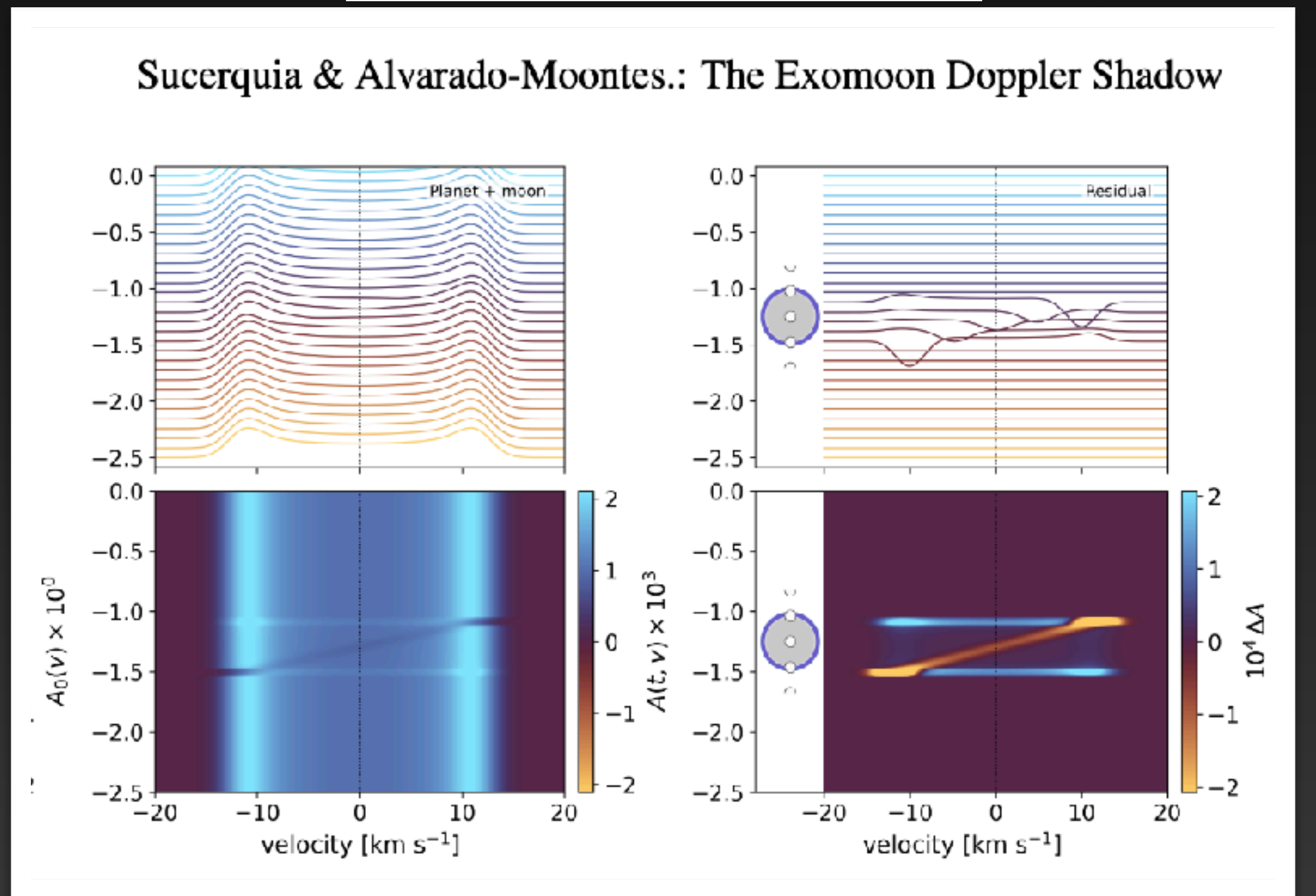
This motivates complementary signatures beyond photometry.

Beyond photometry: the Exomoon Doppler Shadow XDS



A transiting moon removes light from a specific Doppler velocity.

time-velocity residual map



Photometry asks:
is there an extra dip?

XDS asks:

where is the missing light in velocity space?



Take-home message

Formation is natural: giant planets may form moons.

Survival is selective: close-in giants can lose, eject, or transform them.

long-period giants are better for survival, but harder to observe.

New approaches are needed to detect and confirm exomoons.

