Exoplanet Demographics across Stellar Mass and Time

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Outline

Motivation – Why carry out demographic studies across stellar mass and time

Key Insights So Far – What we learned

Looking Ahead – What we could learn

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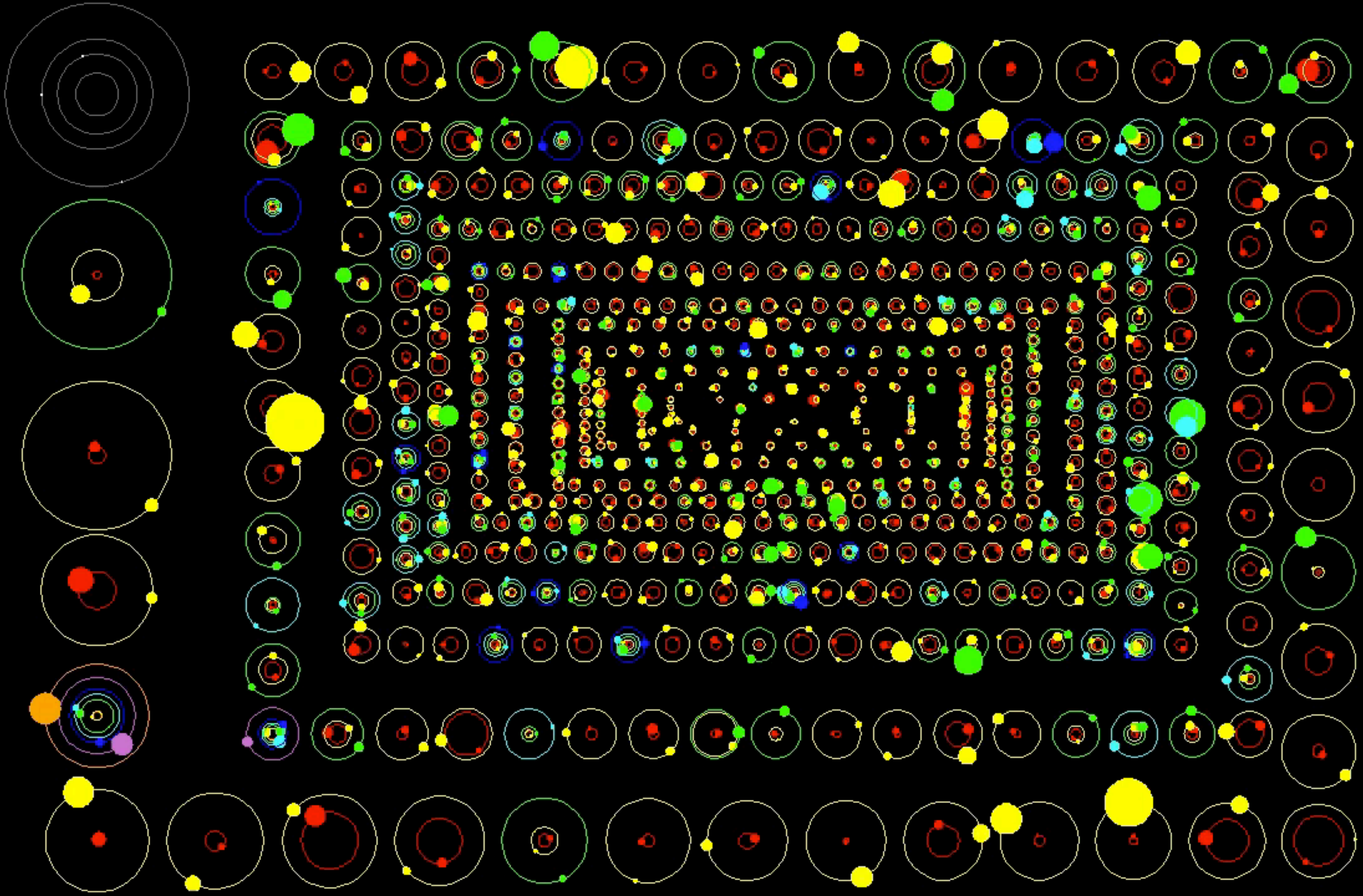
The Kepler Orrery III

t[BJD] = 2455215



Credit: D. Fabrycky

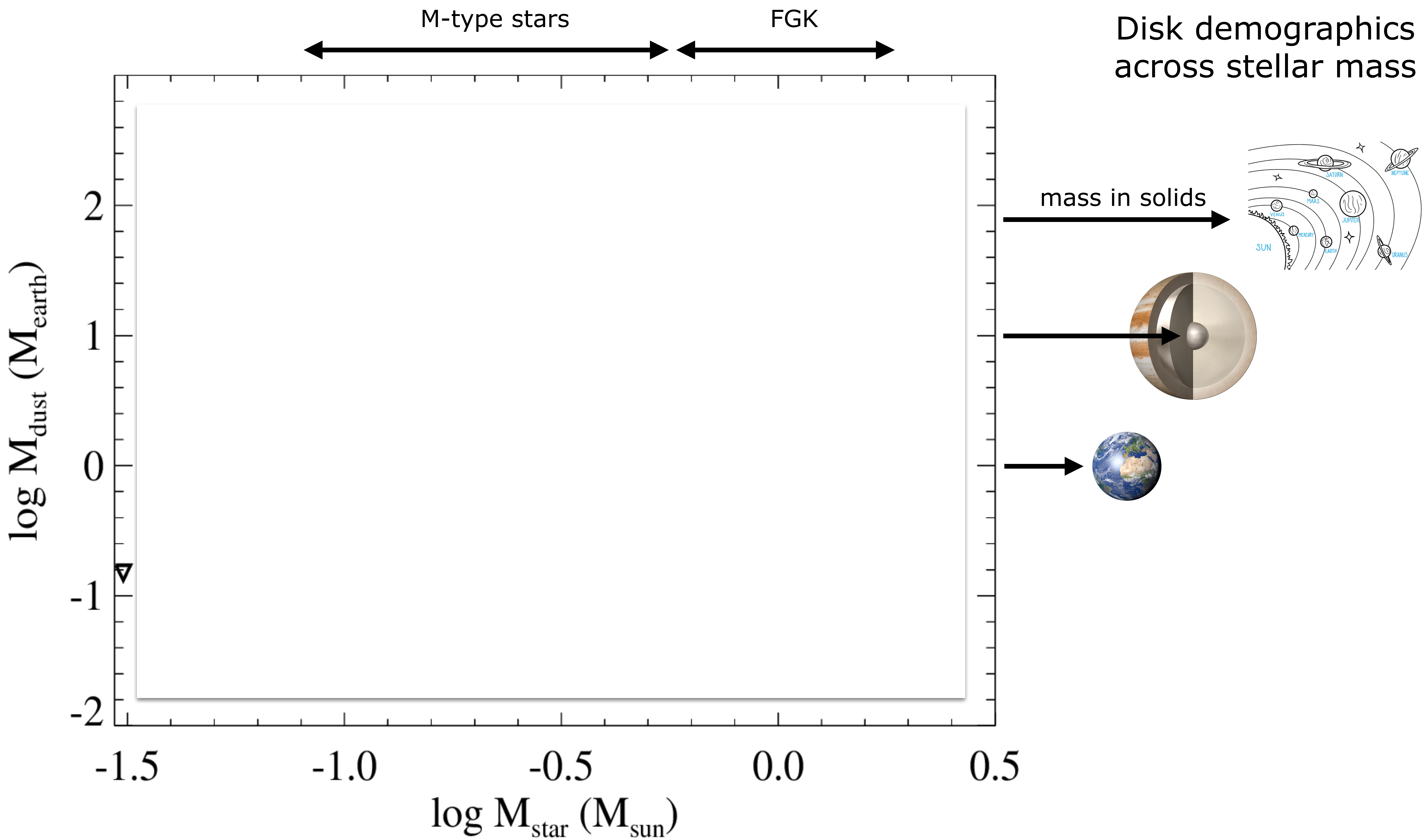
Which are the key physical processes that shape this diversity?

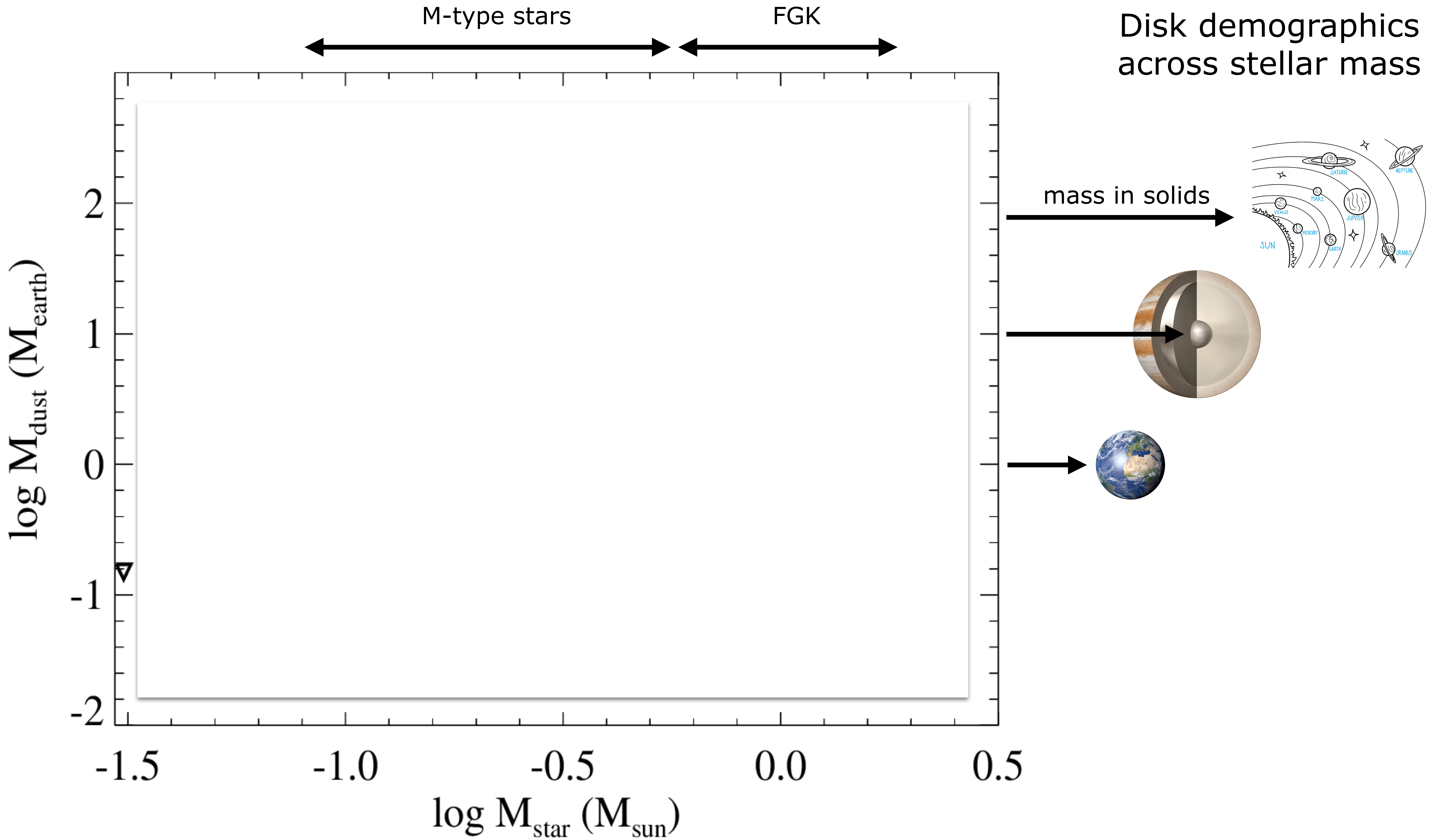
Planet Formation

- Disk properties: i) mass in solids and gas vs time; ii) edges and structures; iii) icelines
- Core formation via planetesimals and/or pebble accretion
- Orbital migration
- …..

Evolution (post-formation)

- Giant planet cooling and contraction
- Atmospheric loss
- Tidal interaction with the star
- Planet-planet scattering and instabilities
- …..


Disk demographics across stellar mass
M-type stars
FGK
mass in solids
SUN
2
1
0
-1
-2
log M_{dust} (M_{earth})
-1.5
-1.0
-0.5
0.0
0.5
log M_{star} (M_{sun})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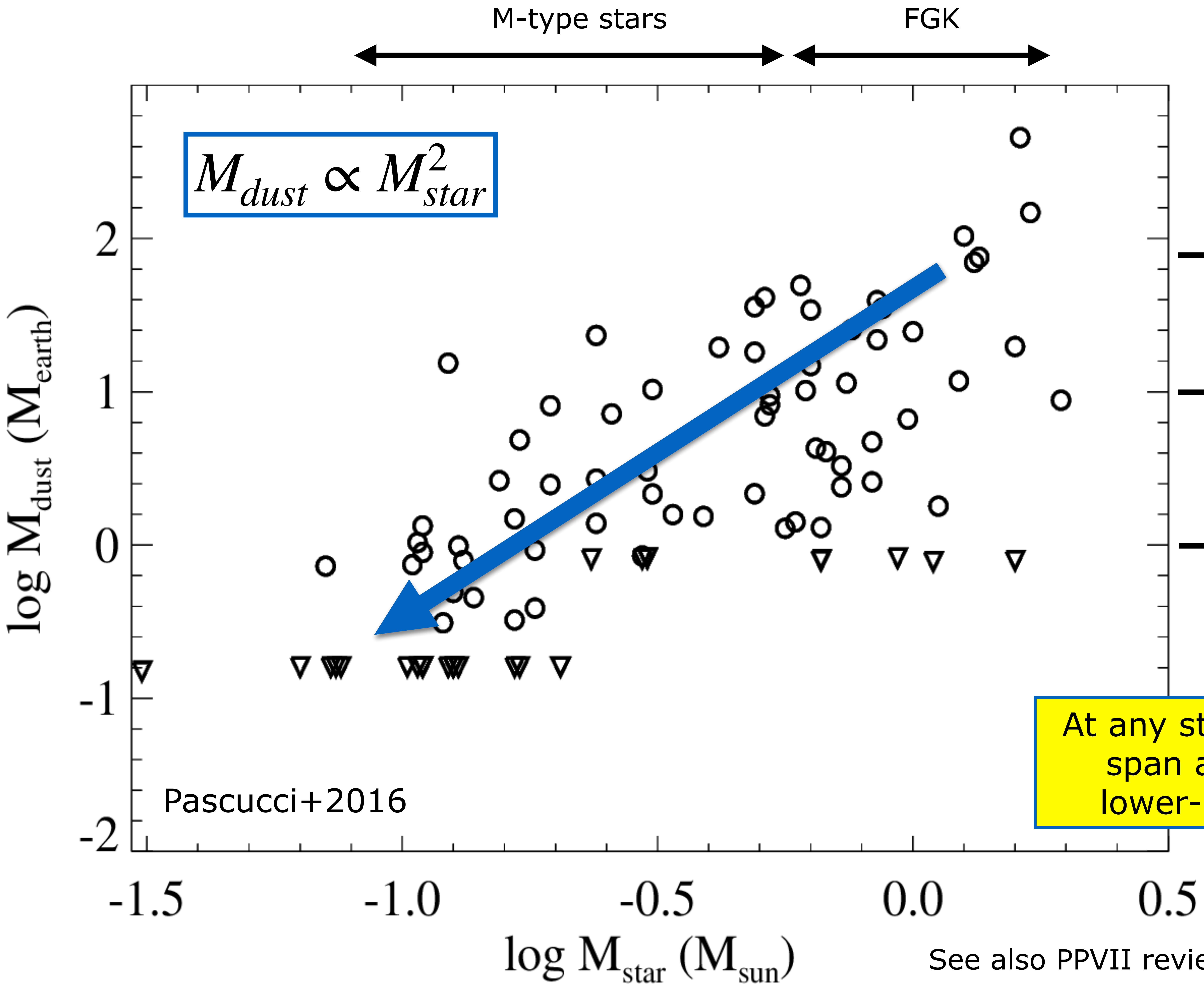
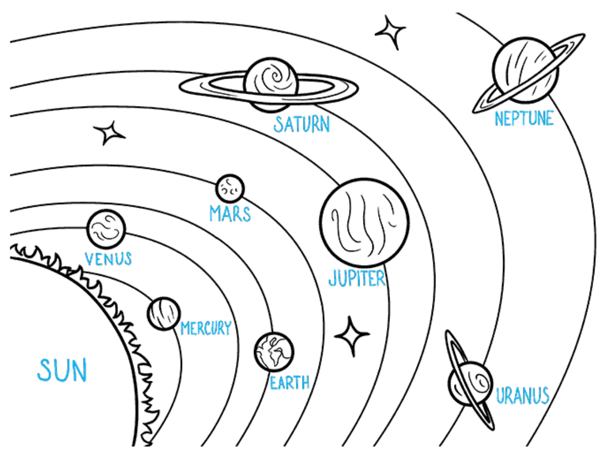
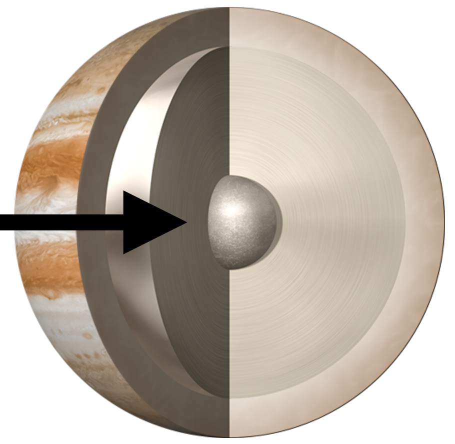
Disk demographics across stellar mass



mass in solids

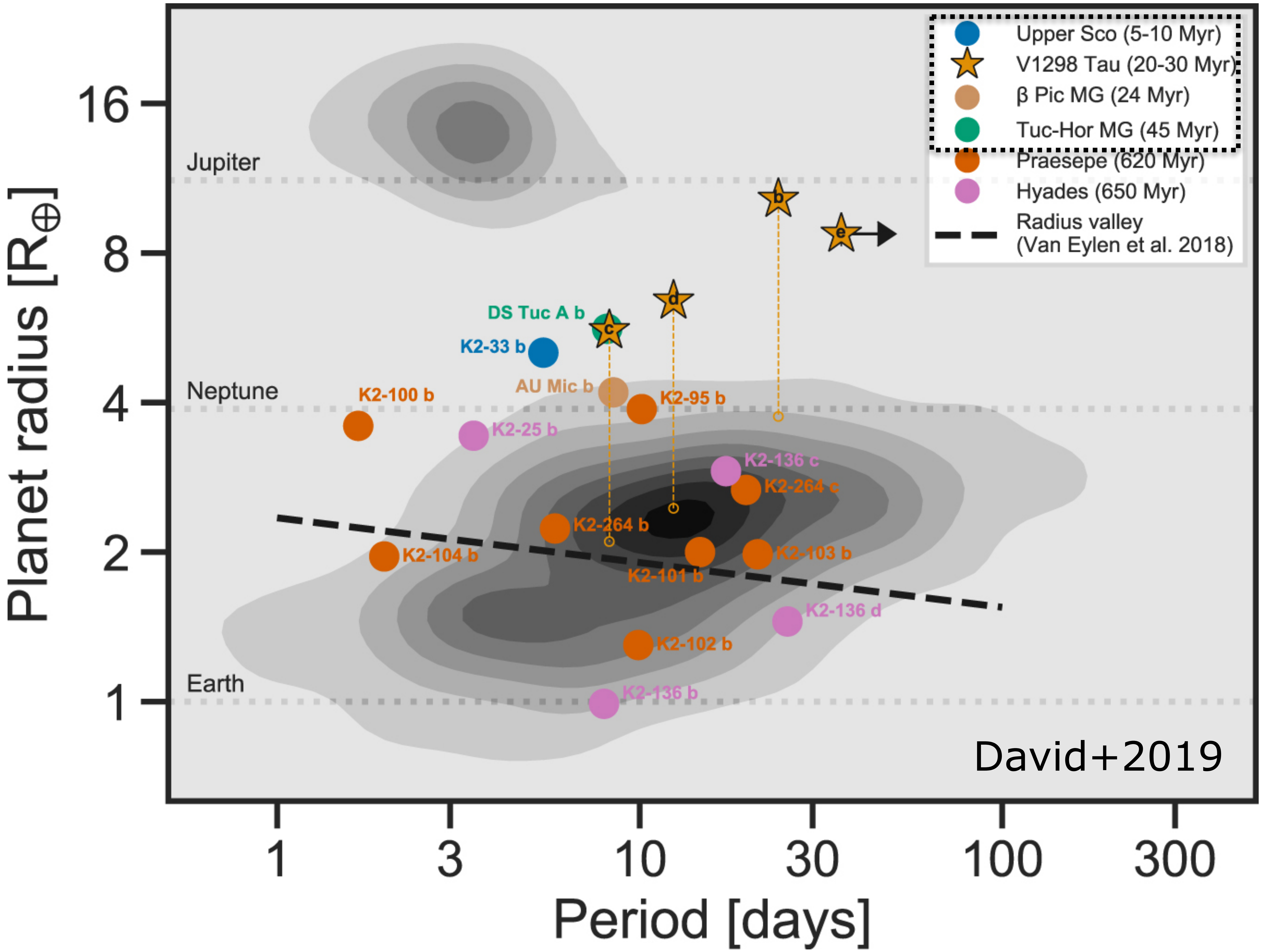




At any stellar mass, disk solid masses span a wide range; disks around lower-mass stars have less solids

See also PPVII reviews by Manara+ and Miotello+2023

Selected cases pointing to evolution



These few young (~5-50Myr) transiting planets occupy a radius–period space where older planets are scarce

see e.g. also Bouma+2020, Plavchan+2020

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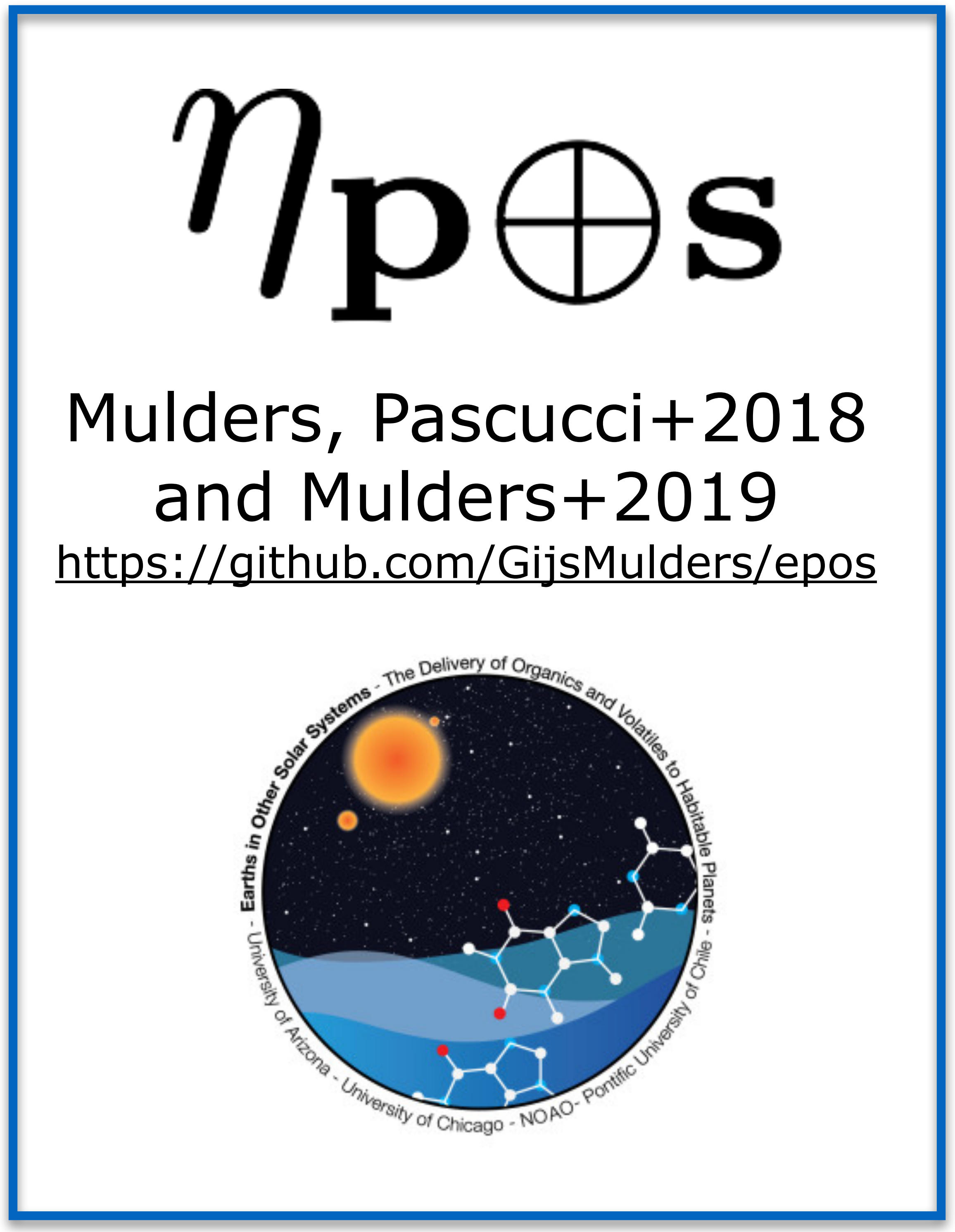
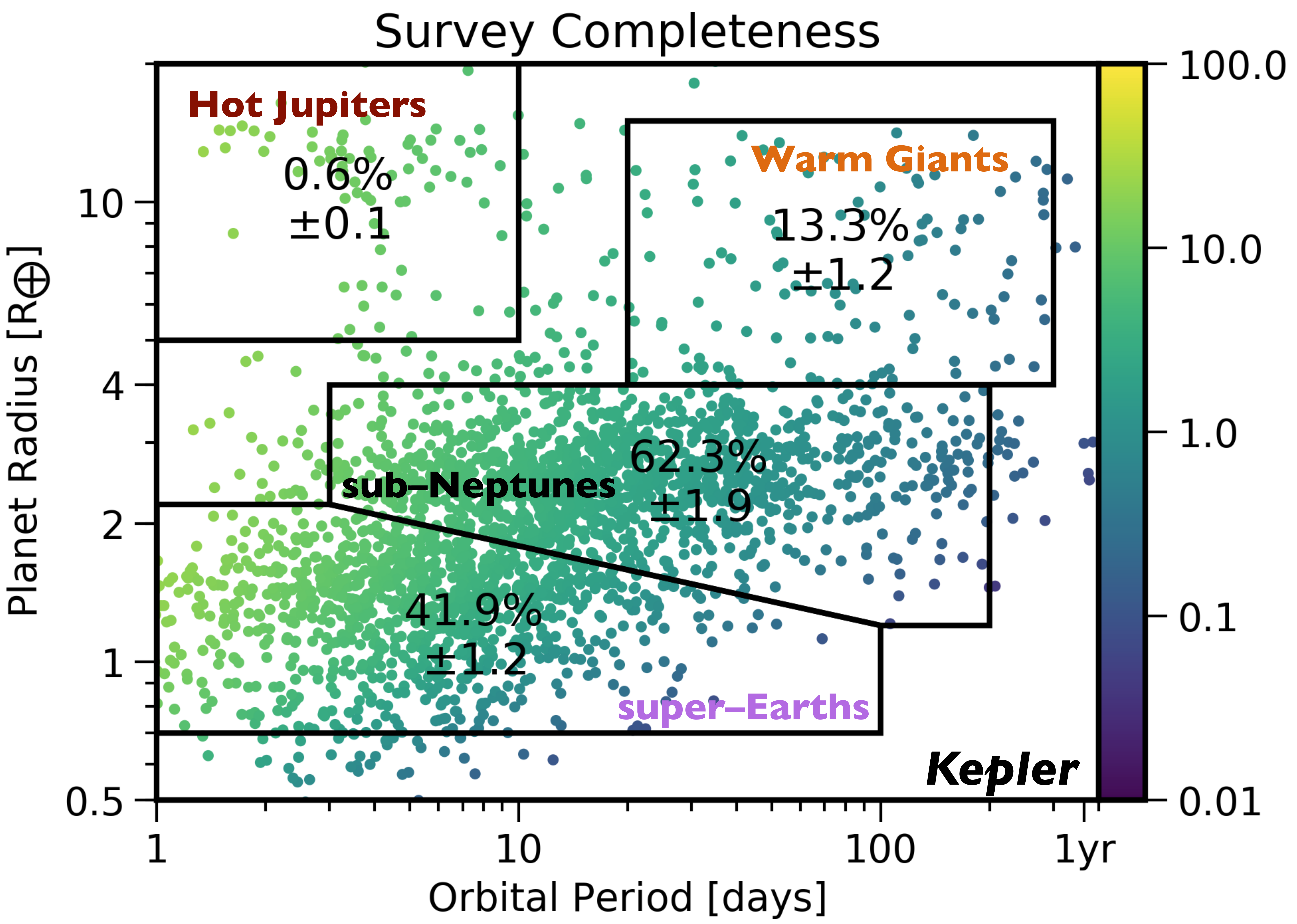
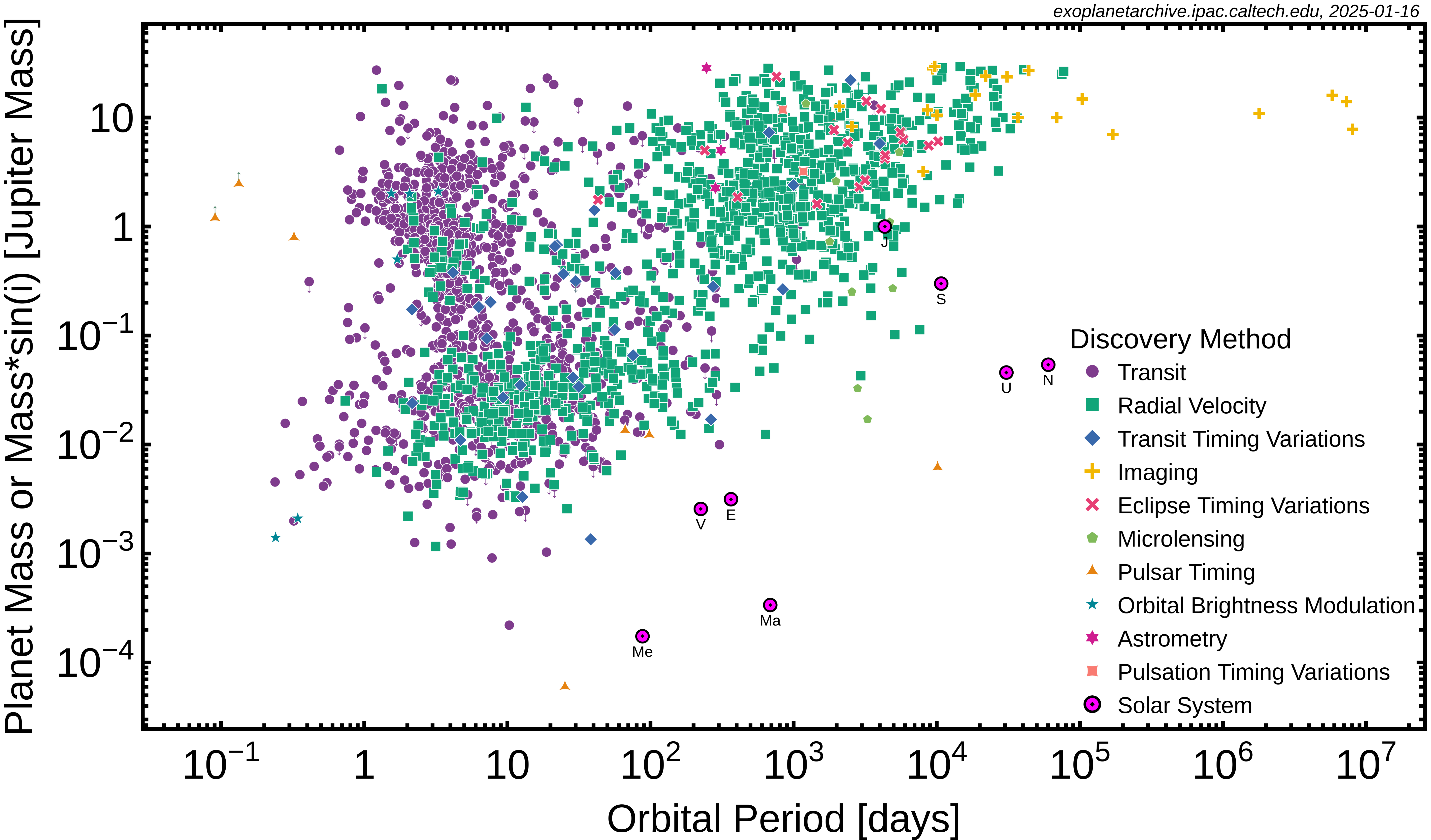




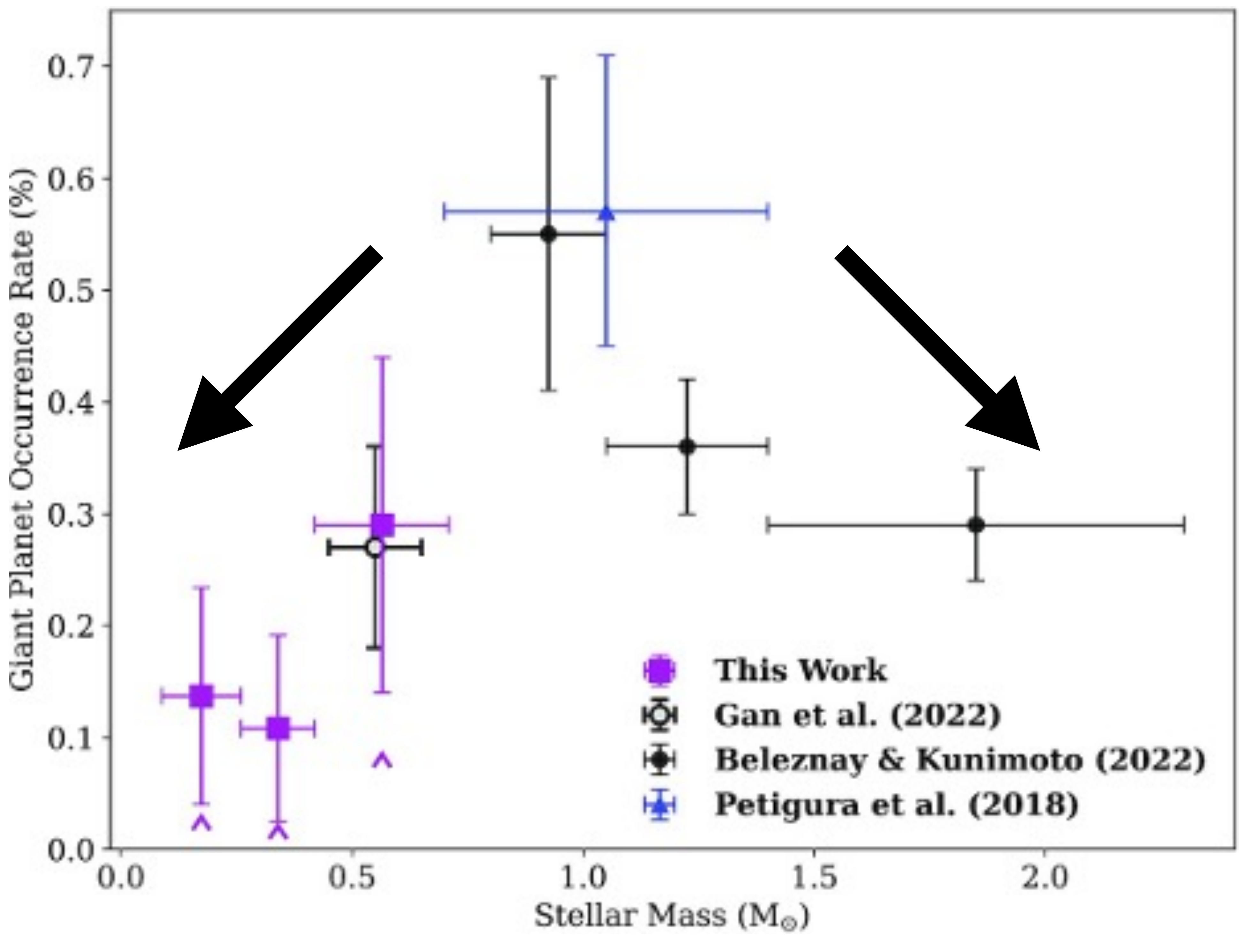
For a review on exoplanet science with ***Kepler*** see Lissauer, Batalha, Borucki 2023 (PPVII)

-> Integrated exoplanet demographics: Hands-on session, BARDIC (Bergsten+)



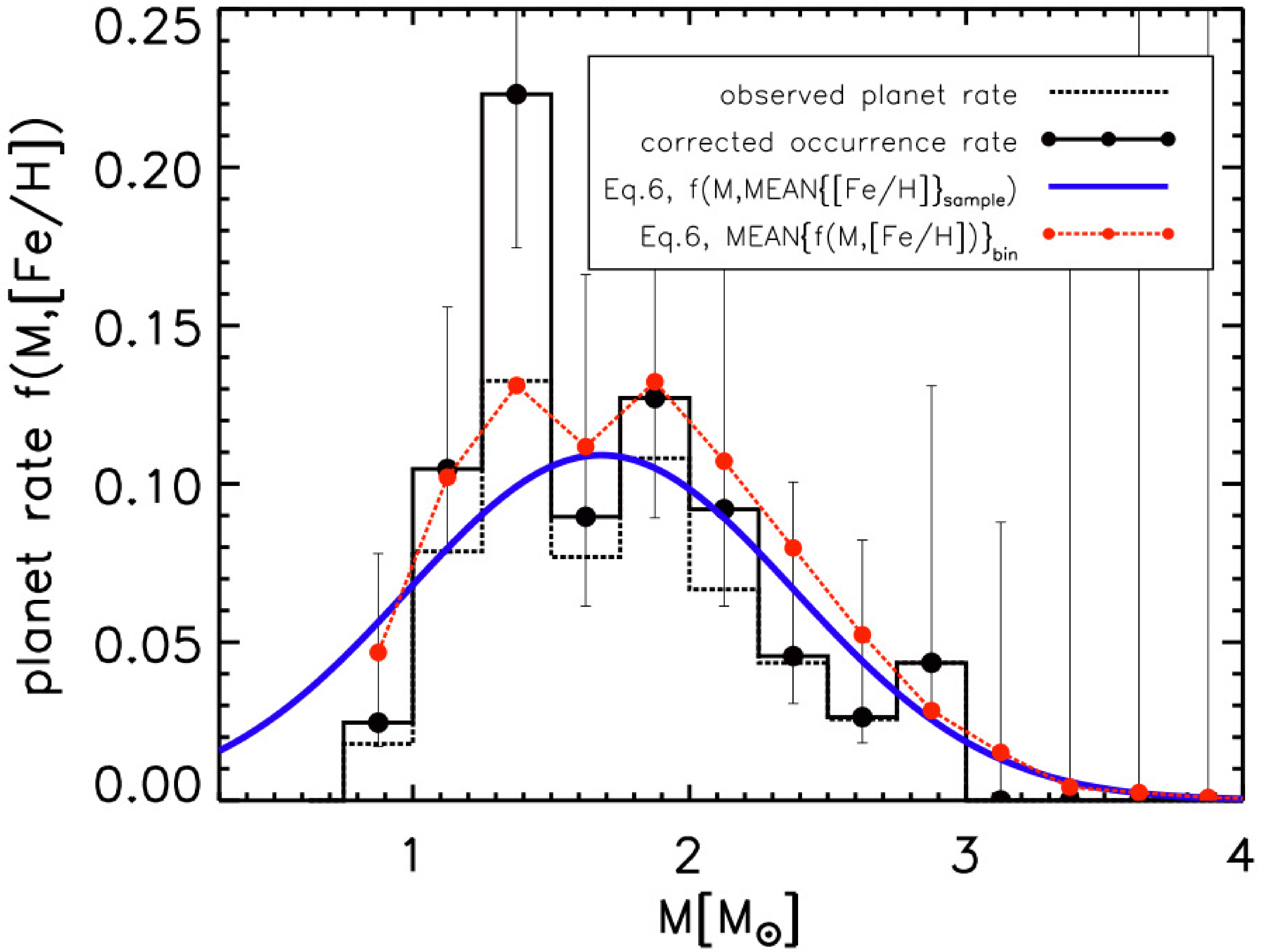
Giants across stellar mass

Bryant+2025 (transit, P< 10 days)



Decrease of giants towards higher-mass stars -> shorter disk lifetimes (e.g., Ribas+2015)

Wolthoff+2022 (RV, P~90-3000 days)

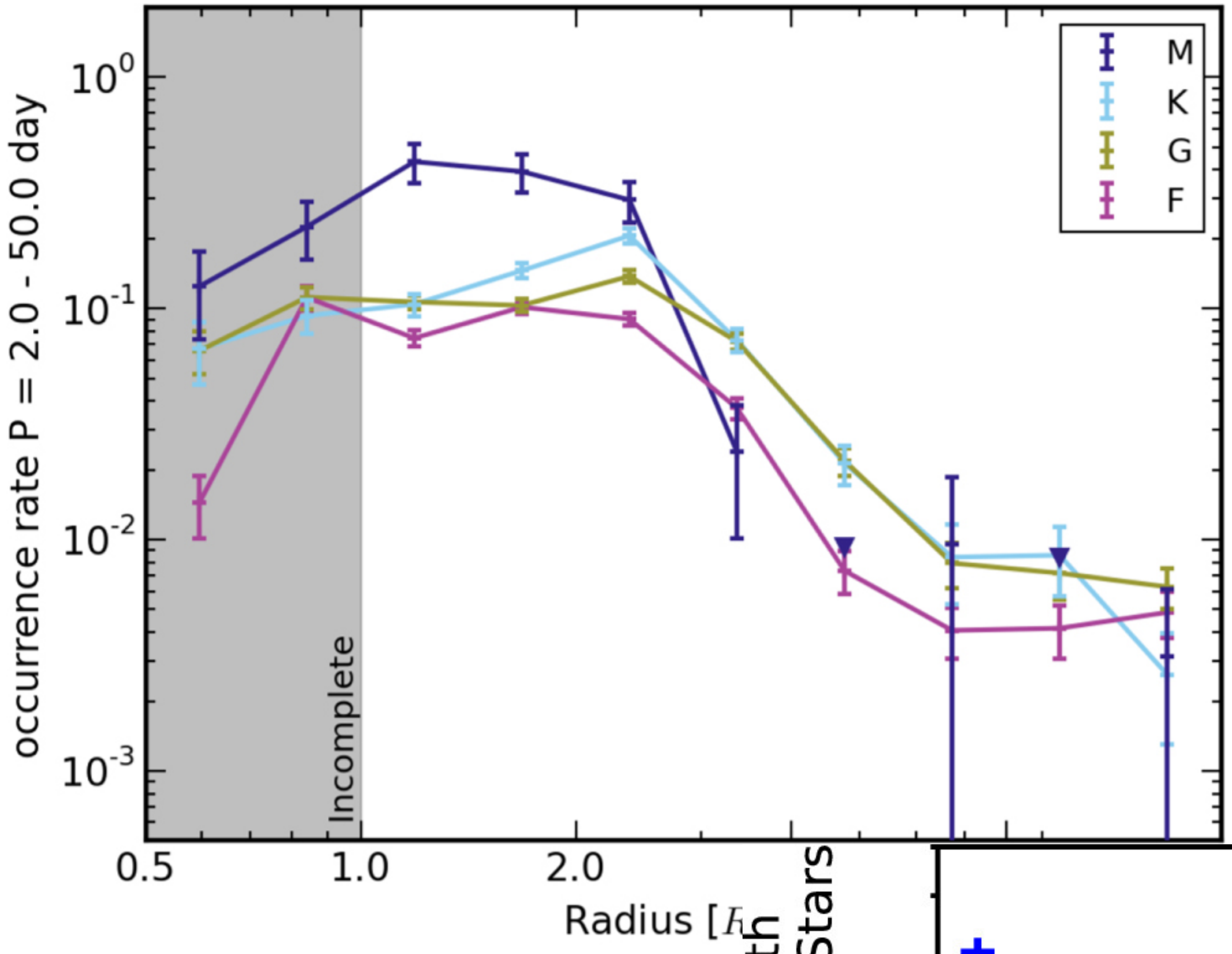


Decrease of giants toward lower-mass stars -> less solids in disks to form their cores (e.g., Pascucci+2016)

Smaller planets across stellar mass

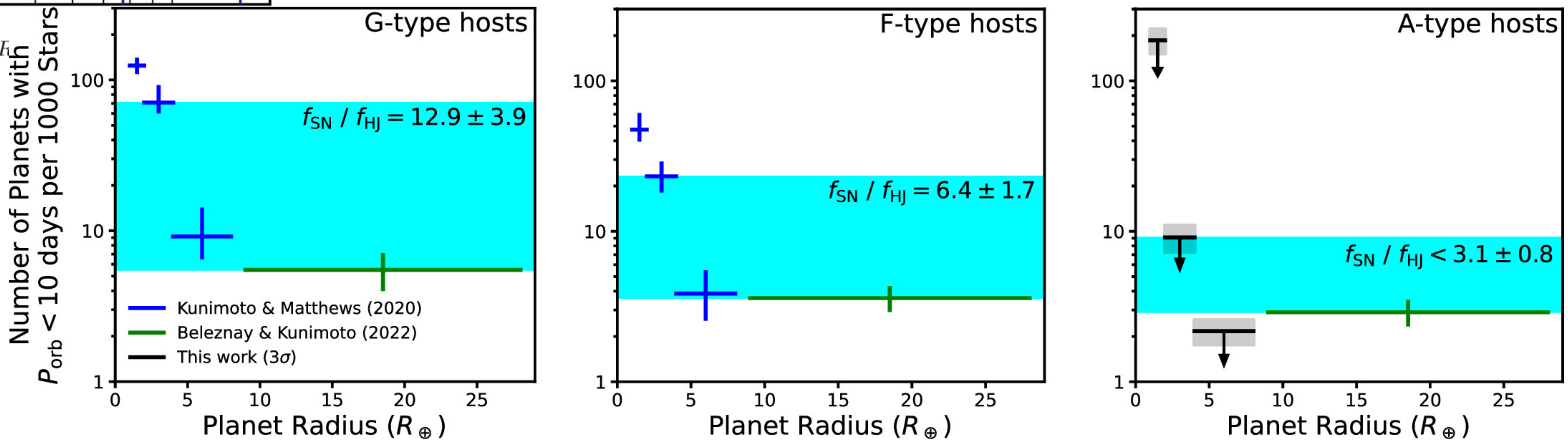
Talk by D. Charbonneau on Thursday

Mulders, Pascucci, Apai 2015 (*Kepler*)



M dwarfs have more small (< 2.5R⊕) but less larger transiting planets (see also e.g., Hardegree-Ullman+2019, Cloutier & Menou 2020, Ment & Charbonneau 2023)

Giacalone & Dressing 2025 (TESS)



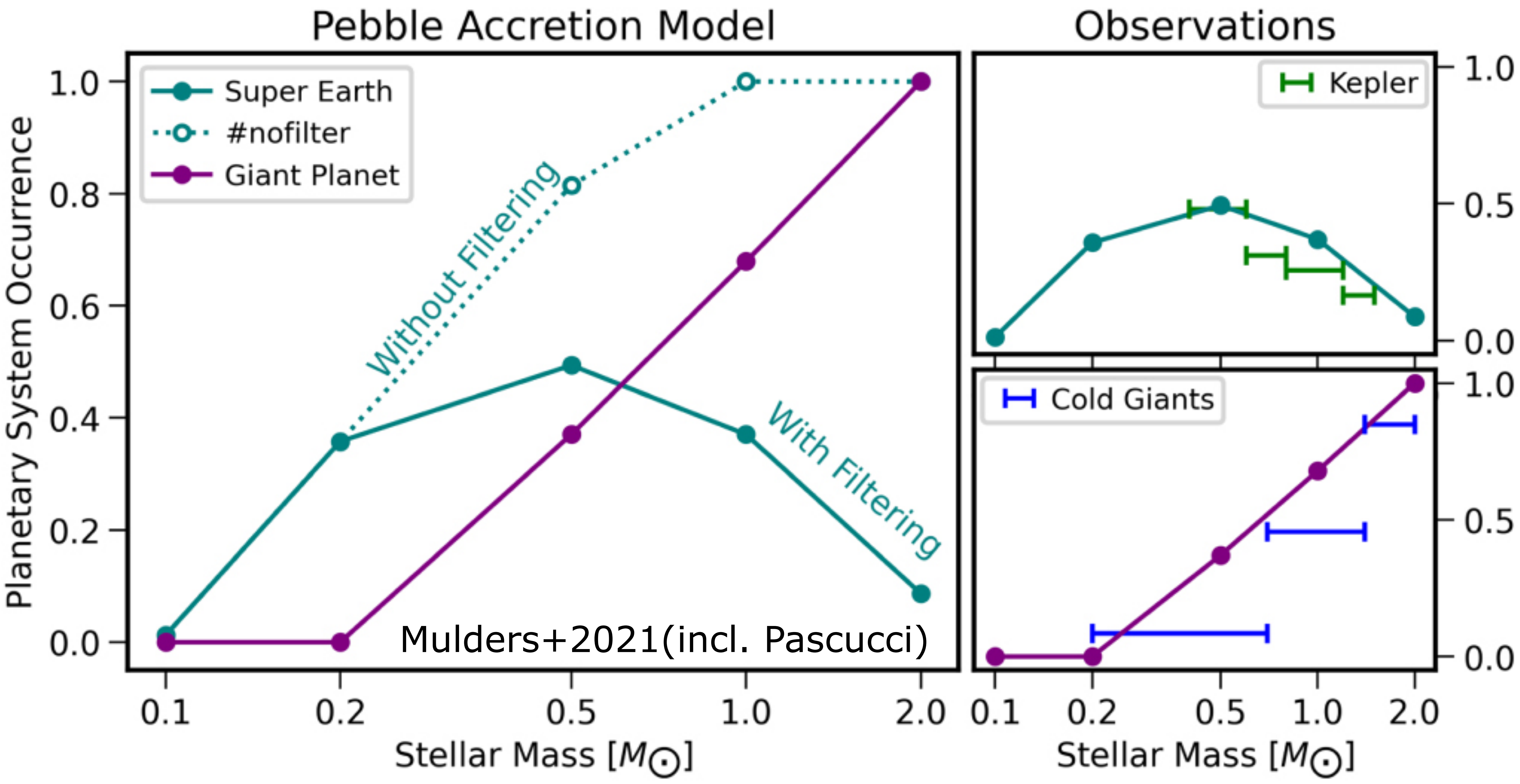
Why do M dwarfs have more small transiting planets?

Talks by C. Mordasini and E. Lee

Forming close-in sub-Neptunes ($< 10M_{Earth}$) requires icy pebbles from the outer disk. A giant planet would reduce the pebble influx (e.g., Lambrechts+2019).

Sketch from Burkhardt+2018

Why do M dwarfs have more small transiting planets?

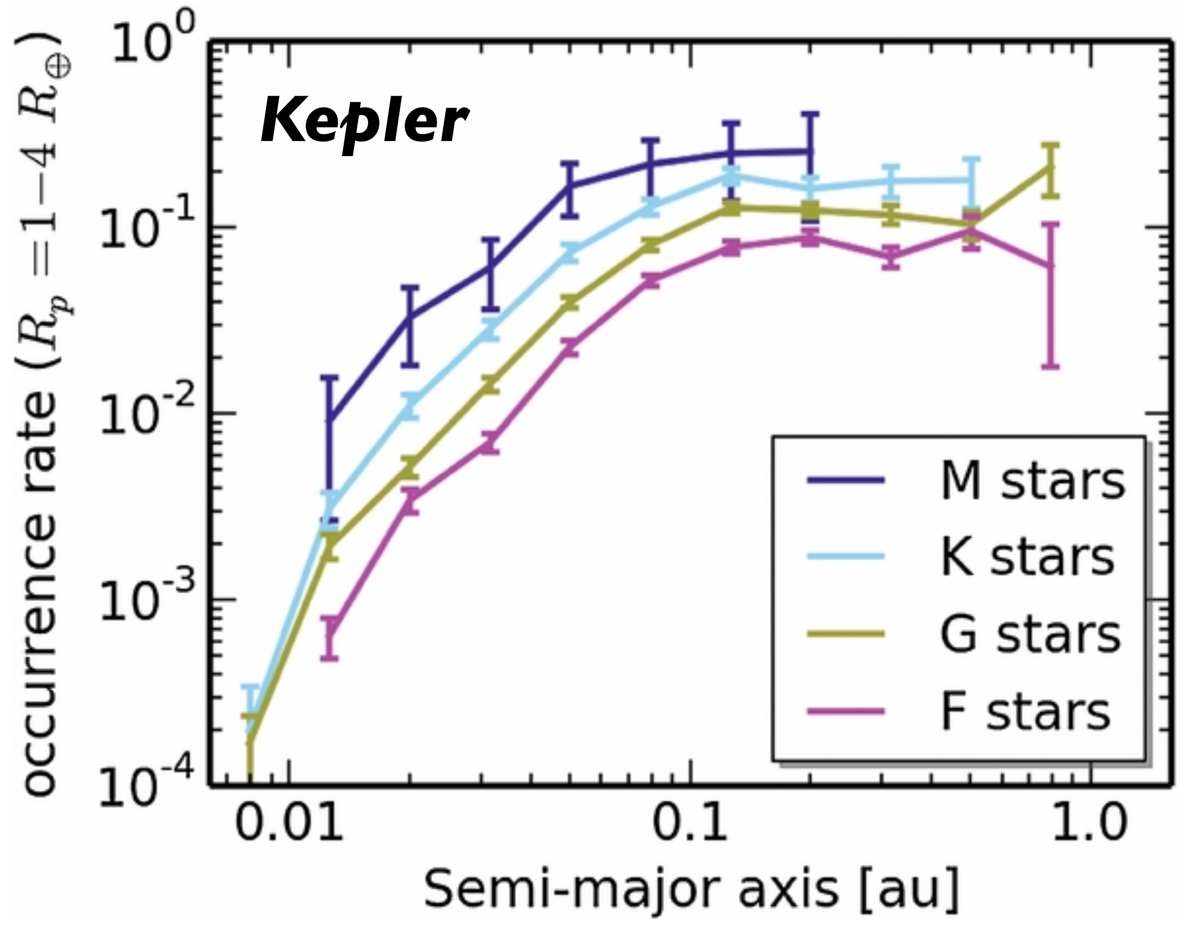


Predictions:

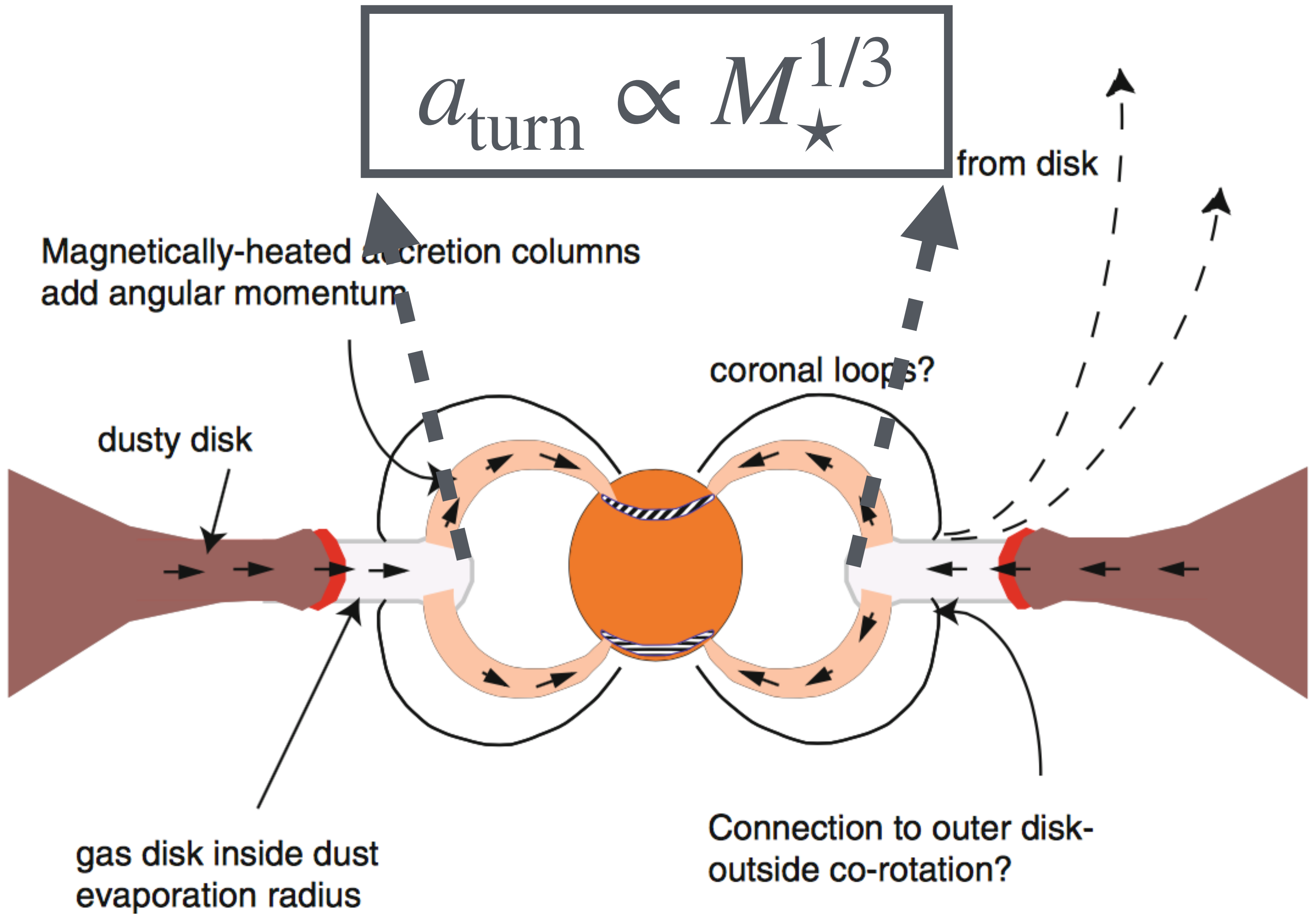
- ~0.1-0.2$M_\odot$ stars have less super-Earths than ~0.5$M_\odot$
- The occurrence of outer giants is anti-correlated with that of super-Earths (e.g., Bonomo+2025 and refs therein)

Pebble accretion is also supported by the linear scaling of the typical planet mass with stellar mass (Pascucci+2018 and Wu 2019)

Occurrence vs period across stellar mass



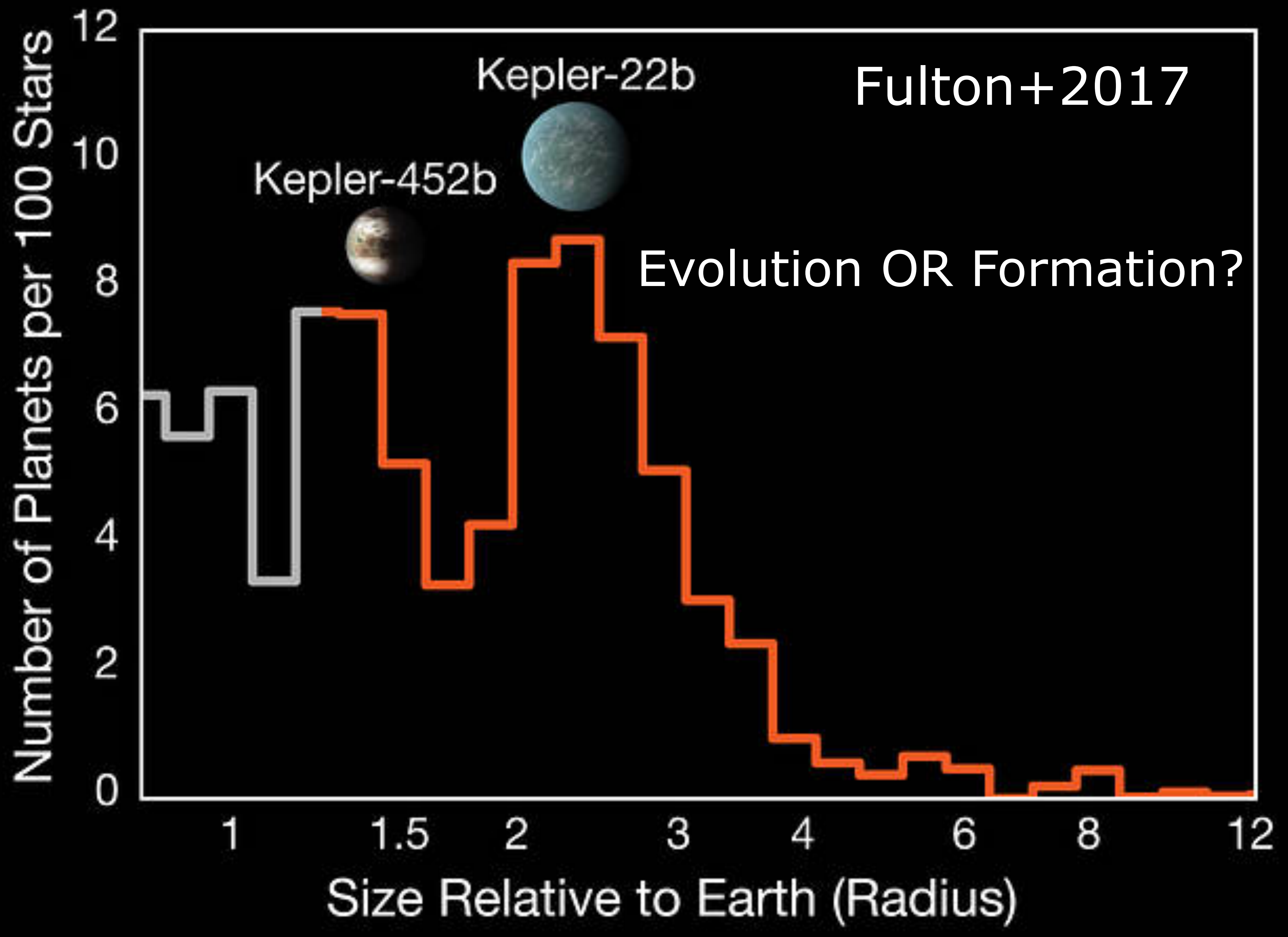
Mulders, Pascucci, Apai (2015)



Disk inner edges shape planetary architectures
by concentrating solids and affecting planets' migration

see also M.-F. Sun+2025, who use *Kepler*+LAMOST+Gaia, correct for metallicity, and find a steeper relation for the innermost planet in multis

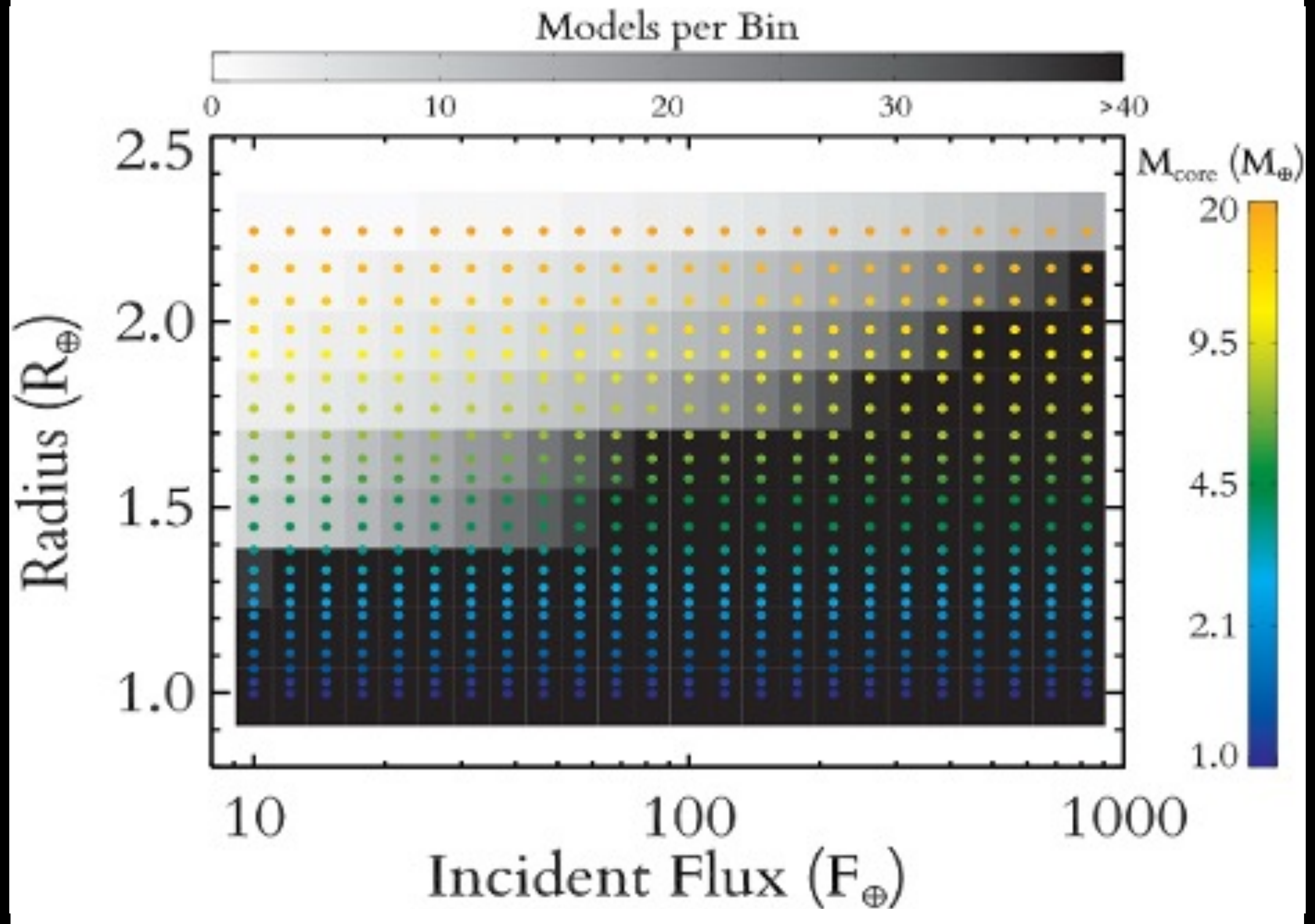
Small Planets Come in Two Sizes



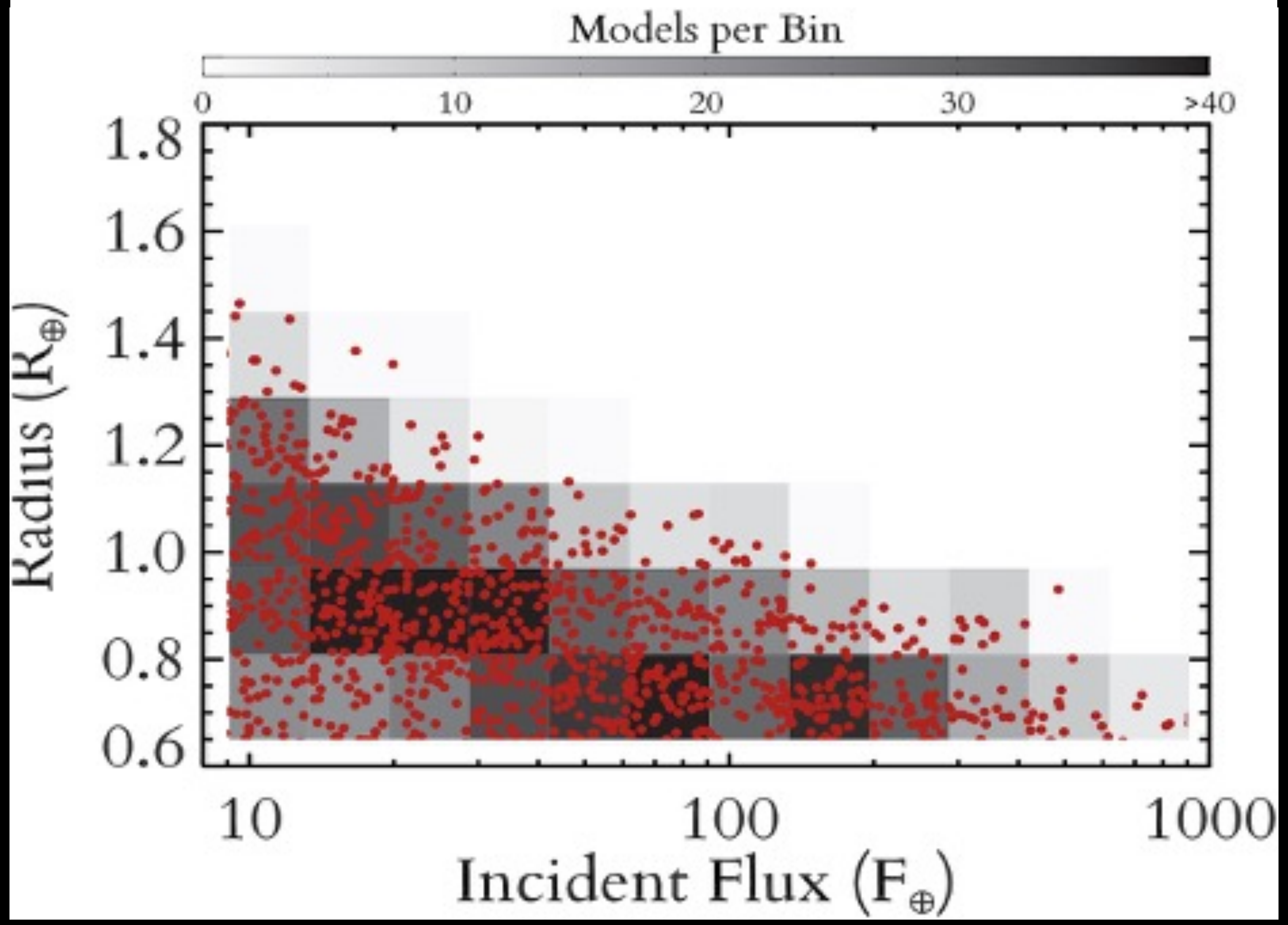
A decreasing transition radius with orbital period implies atmospheric loss, whereas an increasing one points to formation

Lopez & Rice 2018

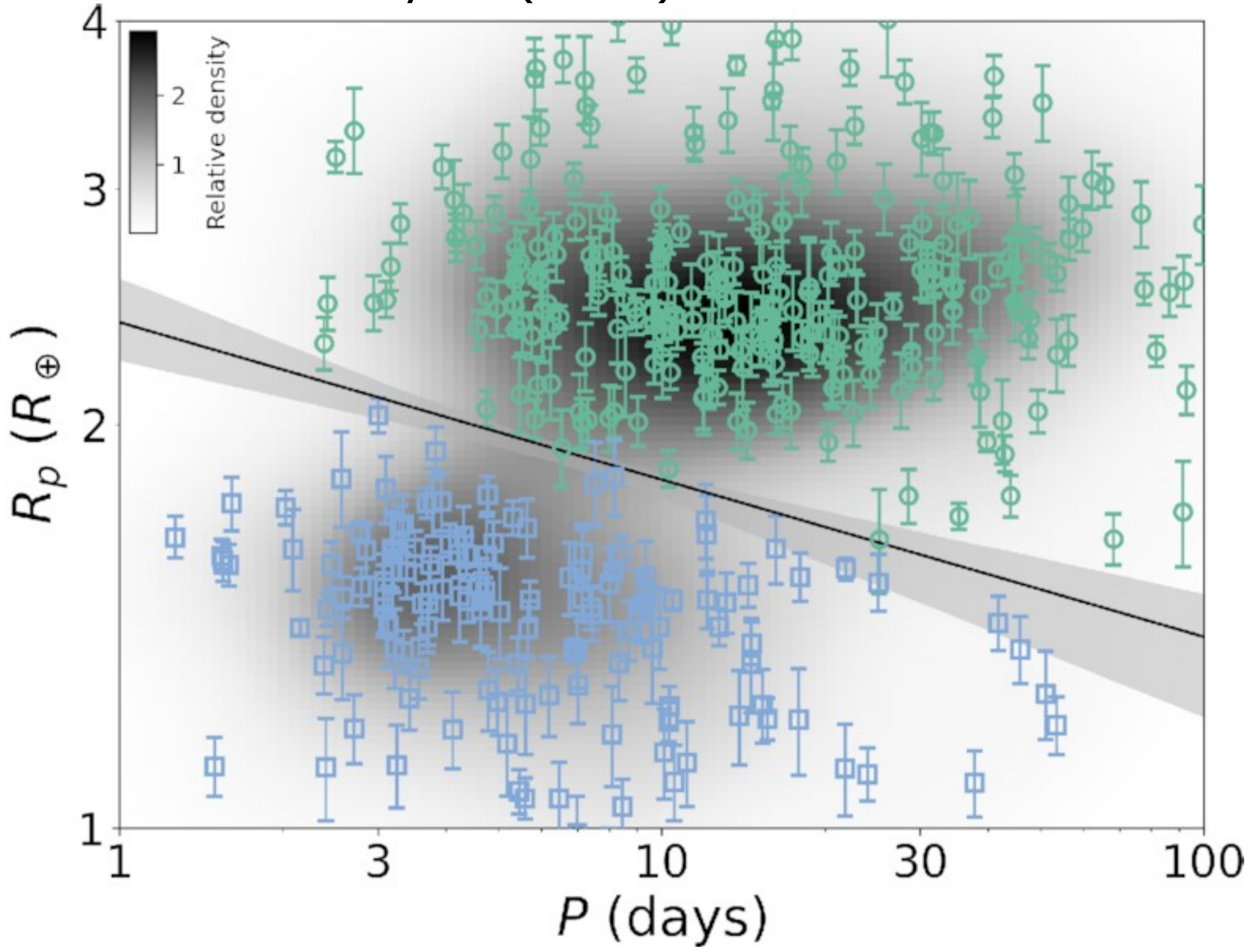
Scenario 1: rocky planets as stripped cores of hot Neptunes



Scenario 2: primordial rocky planets formed after disk dispersal



Ho & van Eylen (2023)

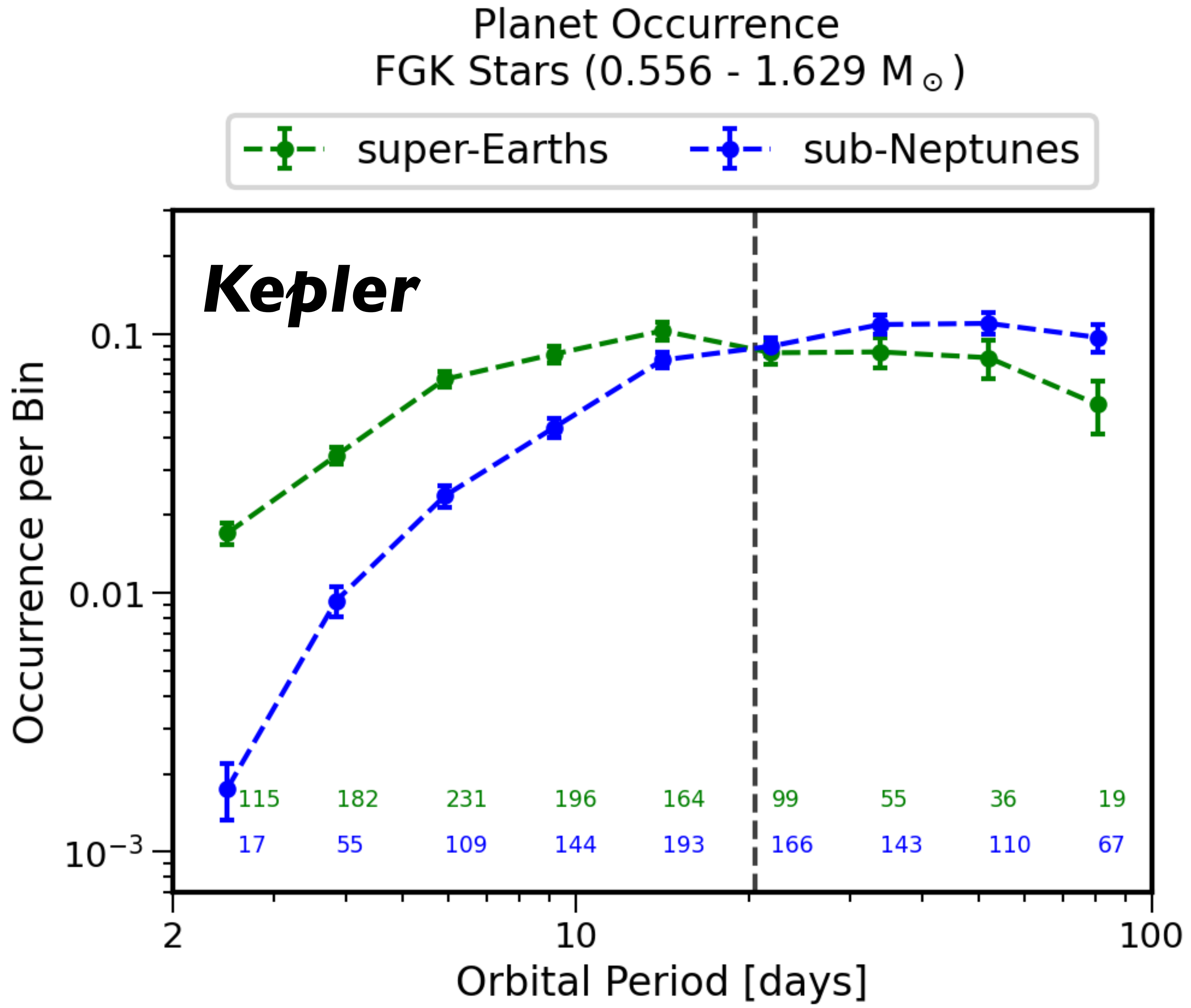


Post-formation atmospheric mass loss shapes the transition between transiting super-Earths and sub-Neptunes

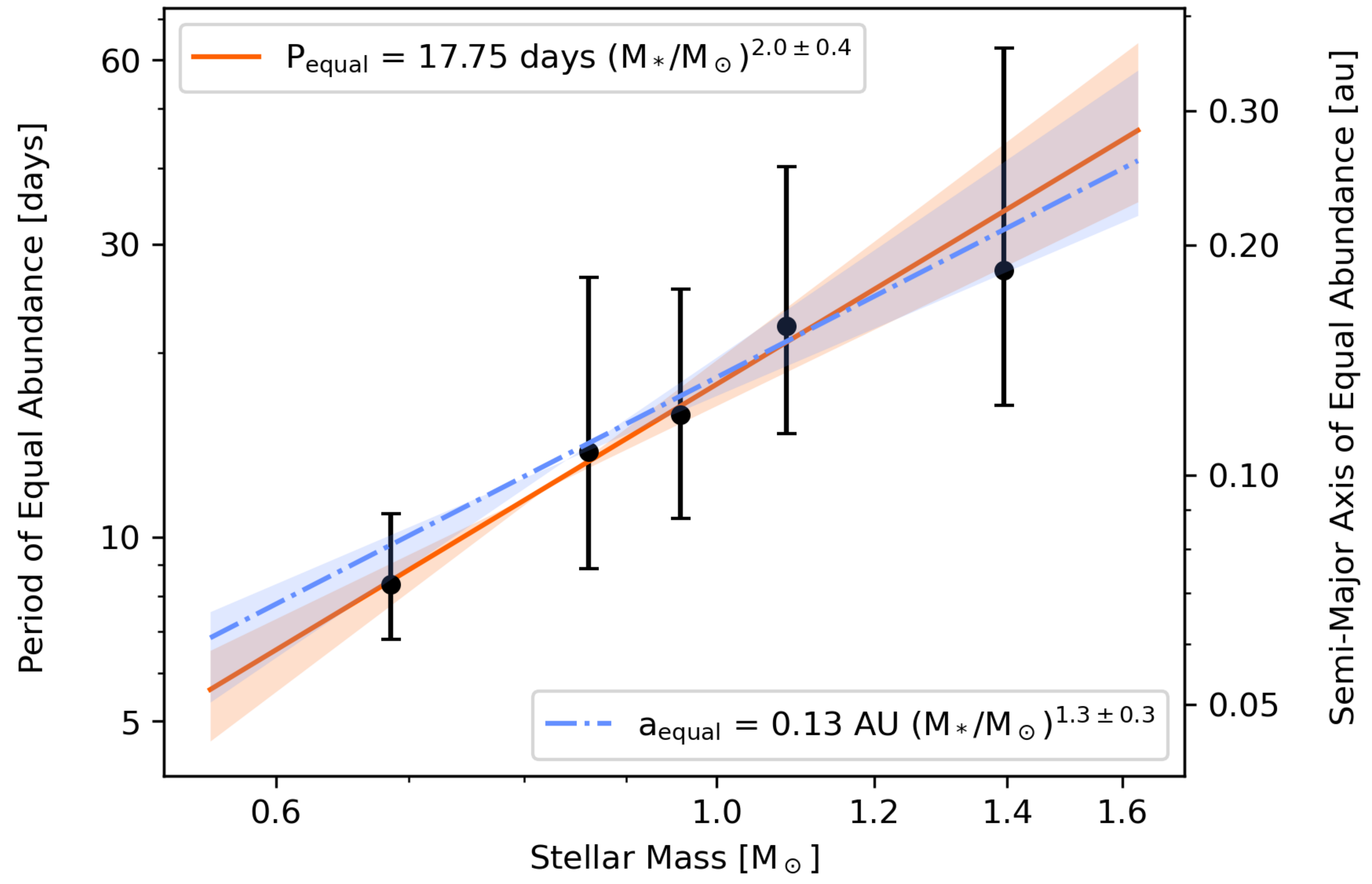
The transition radius decreases at larger orbital periods

Table 6. Slope of the radius valley on the radius–period plane from various sources.

	Source	$m = \mathrm{d}\log R_p/\mathrm{d}\log P$	Stellar type
Observations	This work	$-0.11^{+0.02}_{-0.02}$	FGK
	V18	$-0.09^{+0.02}_{-0.04}$	FGK
	Martinez et al. (2019)	$-0.11^{+0.02}_{-0.02}$	FGK
	MacDonald (2019)	$-0.319^{+0.088}_{-0.116}$	FGK
	Cloutier & Menou (2020)	$0.058^{+0.022}_{-0.022}$	M
	Van Eylen et al. (2021)	$-0.11^{+0.05}_{-0.04}$	M
	Petigura et al. (2022)	$-0.11^{+0.02}_{-0.02}$	FGKM
	Luque & Pallé (2022)	$-0.02^{+0.05}_{-0.05}$	M
	Source	**$m = \mathrm{d}\log R_p/\mathrm{d}\log P$**	**Model**
Theory	Owen & Wu (2017)	$-0.25 \leq m \leq -0.16$	Photoevaporation
	Lopez & Rice (2018)	-0.09	Photoevaporation
		0.11	Gas-poor formation
	Gupta & Schlichting (2019)	-0.11	Core-powered mass-loss
	Rogers et al. (2021)	-0.16	Photoevaporation
		-0.11	Core-powered mass-loss



Bergsten, Pascucci+2022

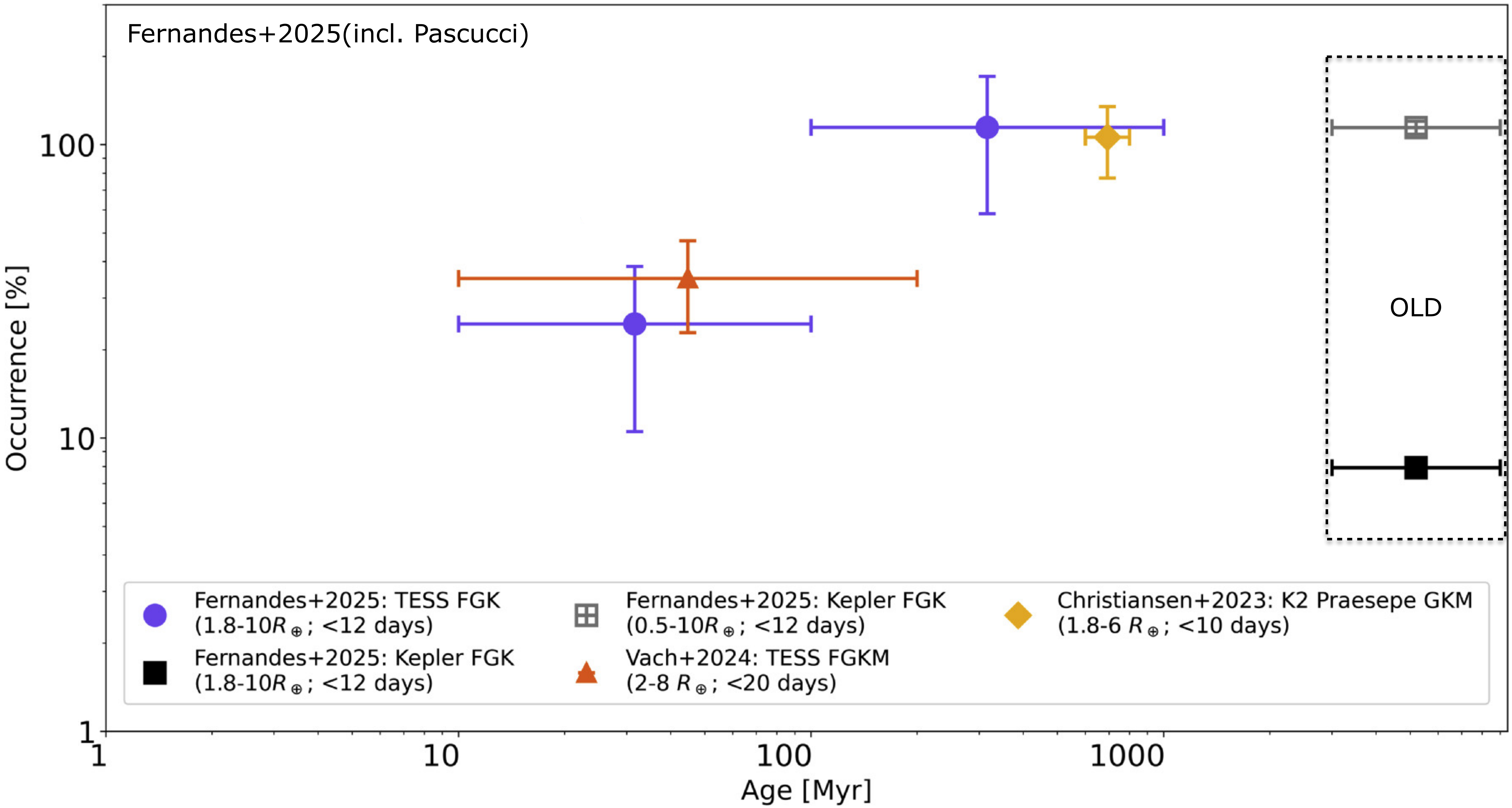


These results support the atmospheric loss scenario

Implications: **1.** Occurrence rates of Earth-size planets in the habitable zone are overestimated if this effect is ignored (e.g., Pascucci+2019 and Bergsten+2022) and

2. Young sub-Neptunes should be more abundant than their older counterparts (e.g., Christiansen+2023, Vach+2024, Fernandes+2025)

Young Neptunes and sub-Neptunes at short periods



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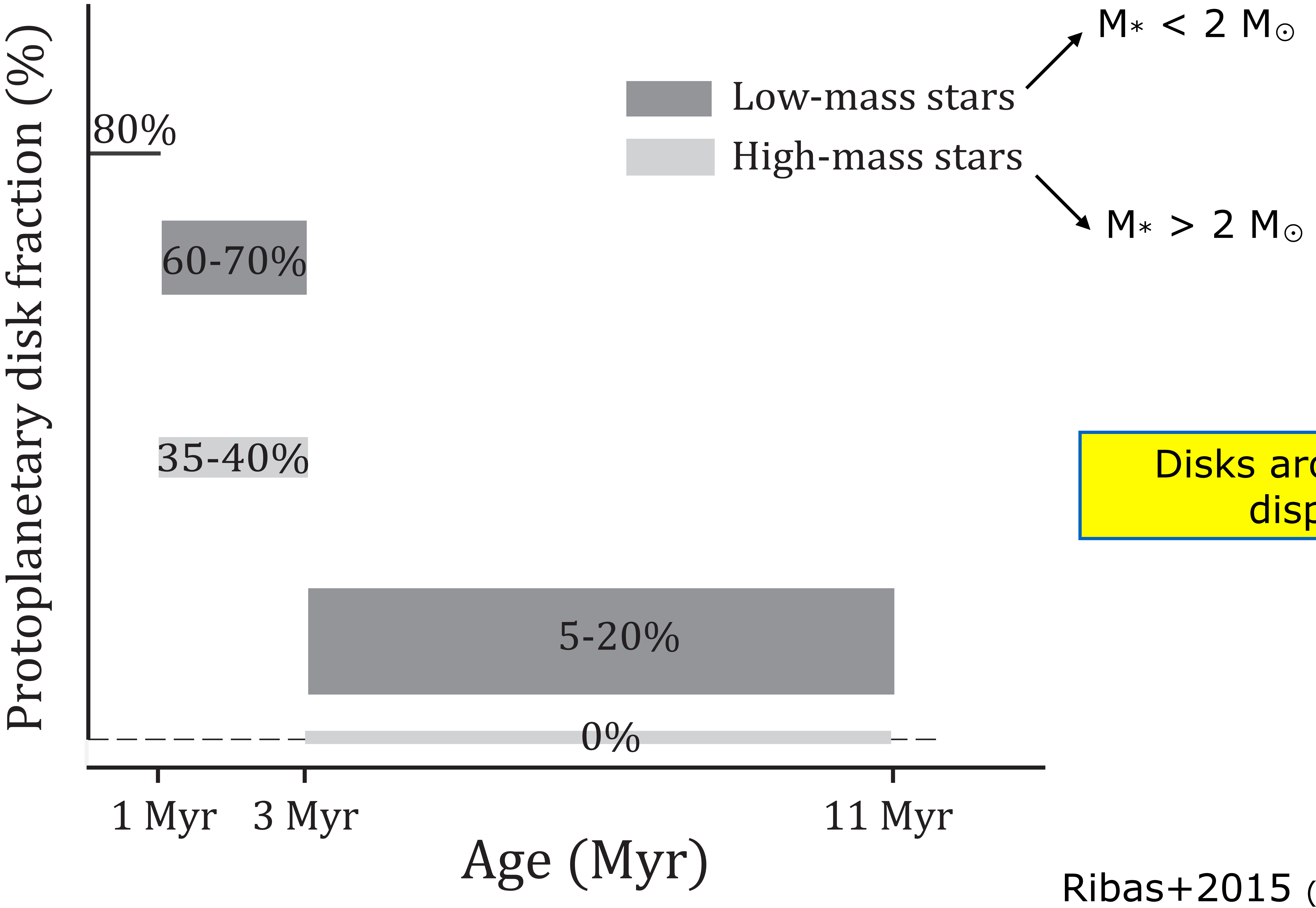
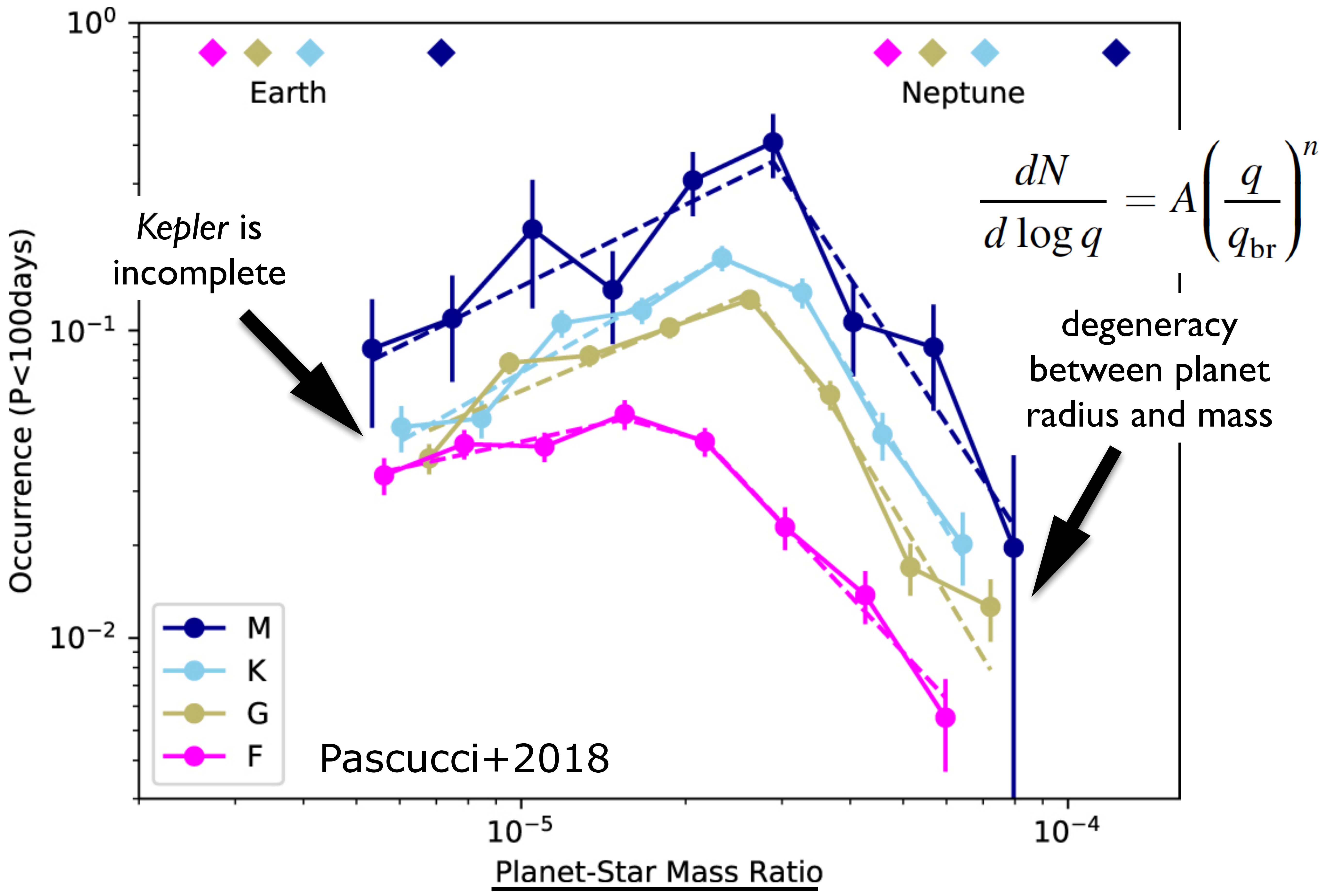
2025
2027
2030
TESS: M dwarfs
Declination (in degrees)
Right Ascension (in hours)
IC2602
THA
PiEri
Uma
UCL
esa
plato
Down to Earths in the HZ of Sun-like stars
Ground-based RVs covering a range of M*
Gaia DR4: outer GPs
(a) all exoplanets
Astrometric signature, α (μas)
Period (yr)
Earth 20 pc
Earth 100 pc
1 μas
Rubin: hot Jupiters + Neptunes
esa
ariel
Atmospheres across stellar mass
Roman: down to Earths near the HZ + imaging of giants
Planet mass (Earth = 1)
Orbital distance from star in AU (Earth = 1)
Kepler discoveries
Other known exoplanets
Roman discoveries (expected)
Shaded curves show the expected Roman detections assuming there's 1 planet per star

Additional slides



Disks around higher-mass stars disperse more quickly

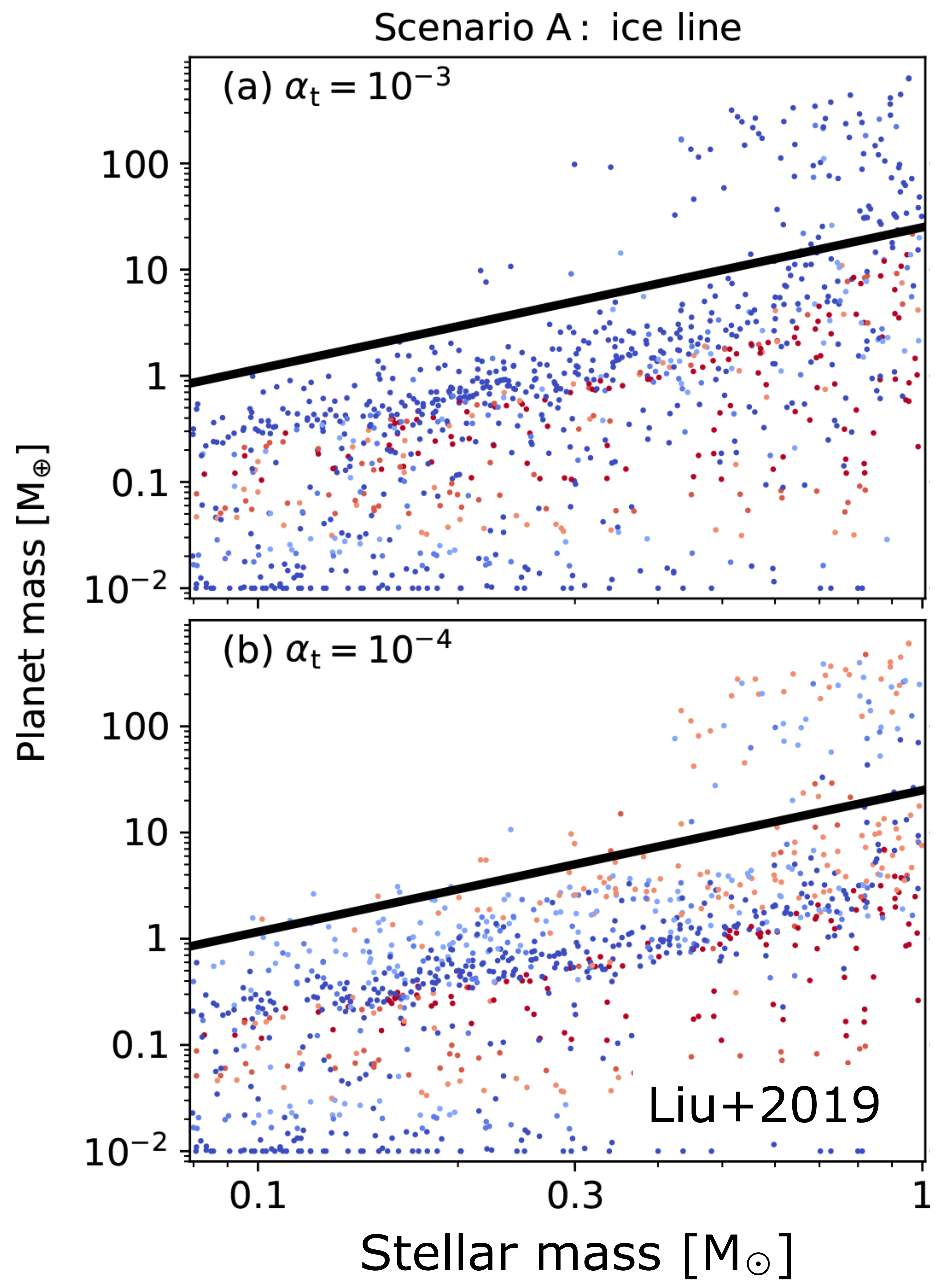
Ribas+2015 (based on IR photometry with Spitzer)



For Sun-like and lower-mass stars, same broken power law with: $q_{br} \sim 3 \times 10^{-5}$

i. e. the mass of the most common planet scales linearly with stellar mass (Pascucci+2018, see also Wu 2019)

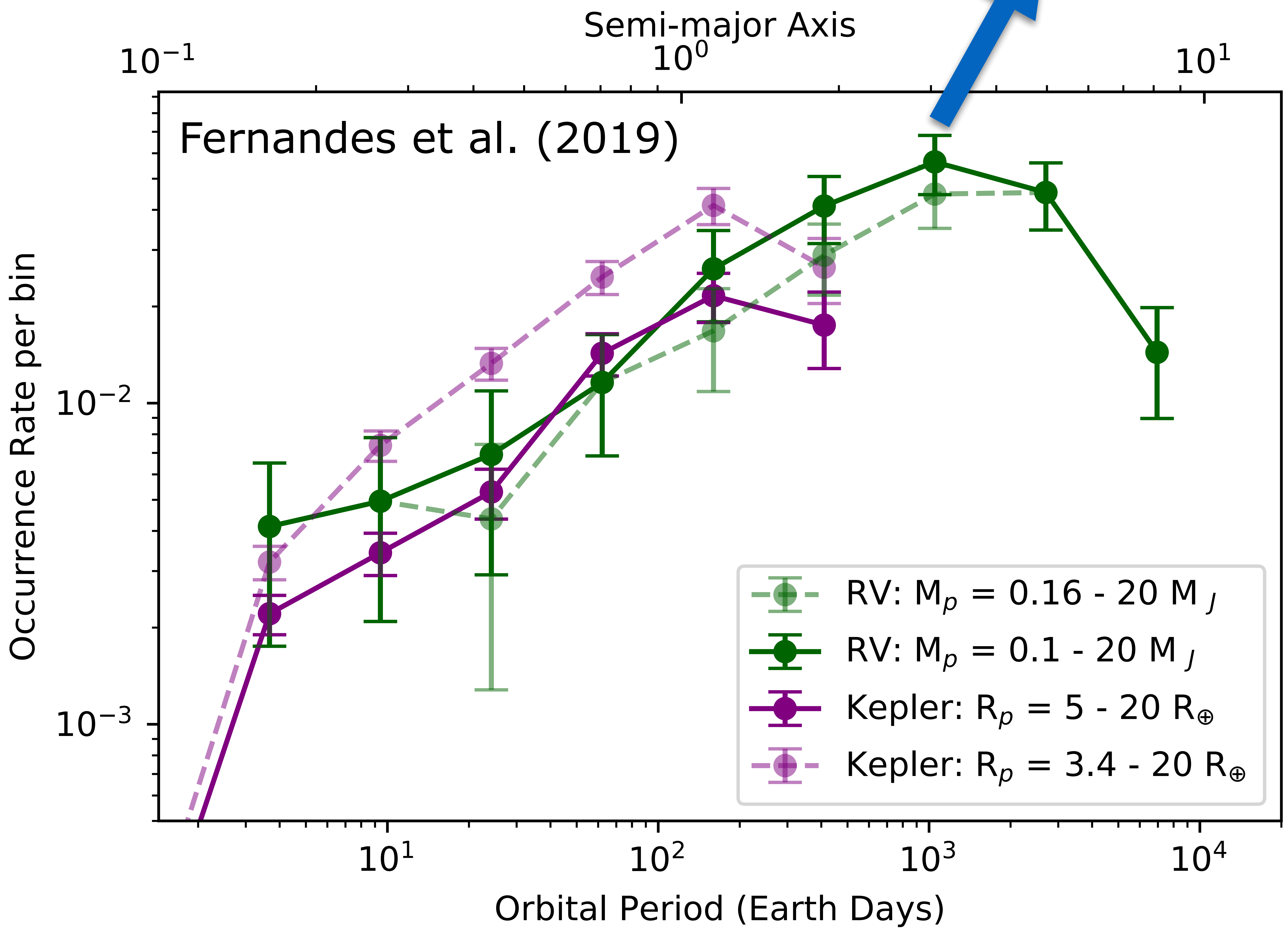
In pebble accretion models, the most common planet mass is set by the pebble isolation mass and scales with stellar mass



Is the occurrence of wide-orbit giant planets an extension of the close-in one?

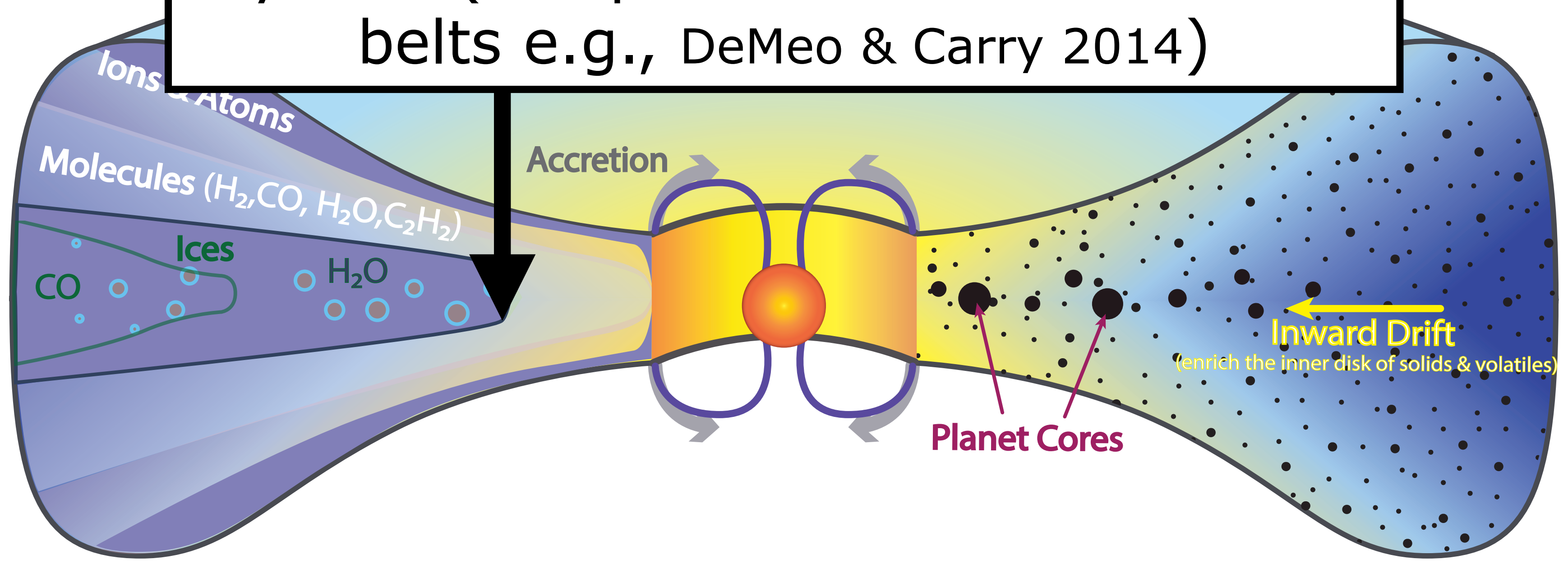
Kepler and RV comparison…

Discovery of a turnover in the giant planet occurrence rate near 2–3au

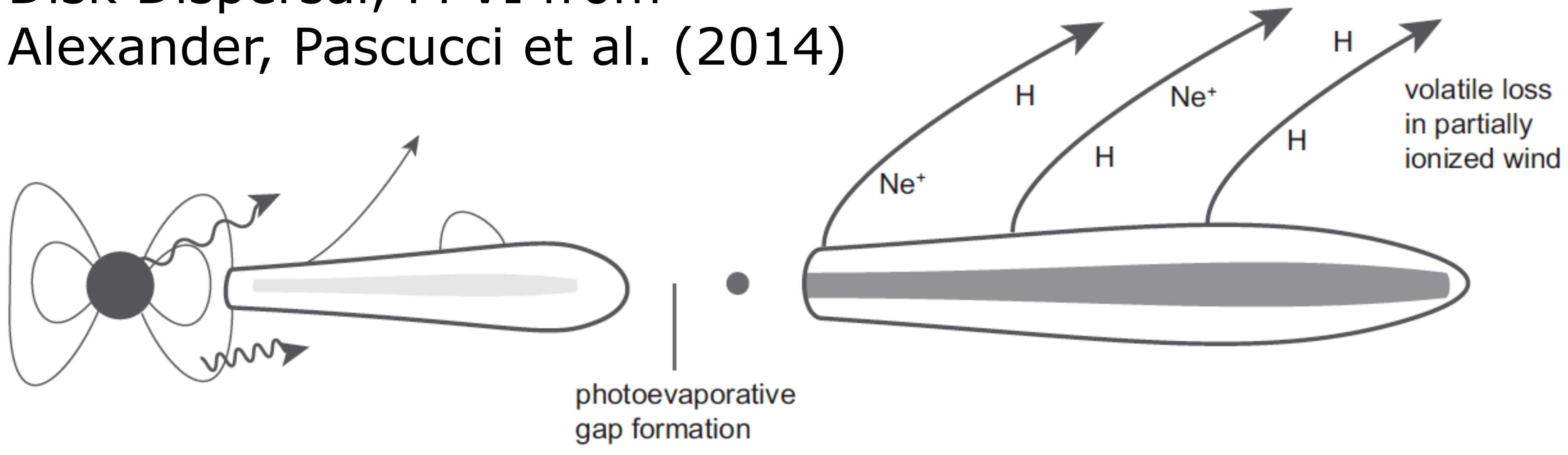


Turnover confirmed by Fulton et al. (2021) using California Legacy Survey RV data

Snowline: at ~2.5au in the Solar System (composition of main asteroid belts e.g., DeMeo & Carry 2014)

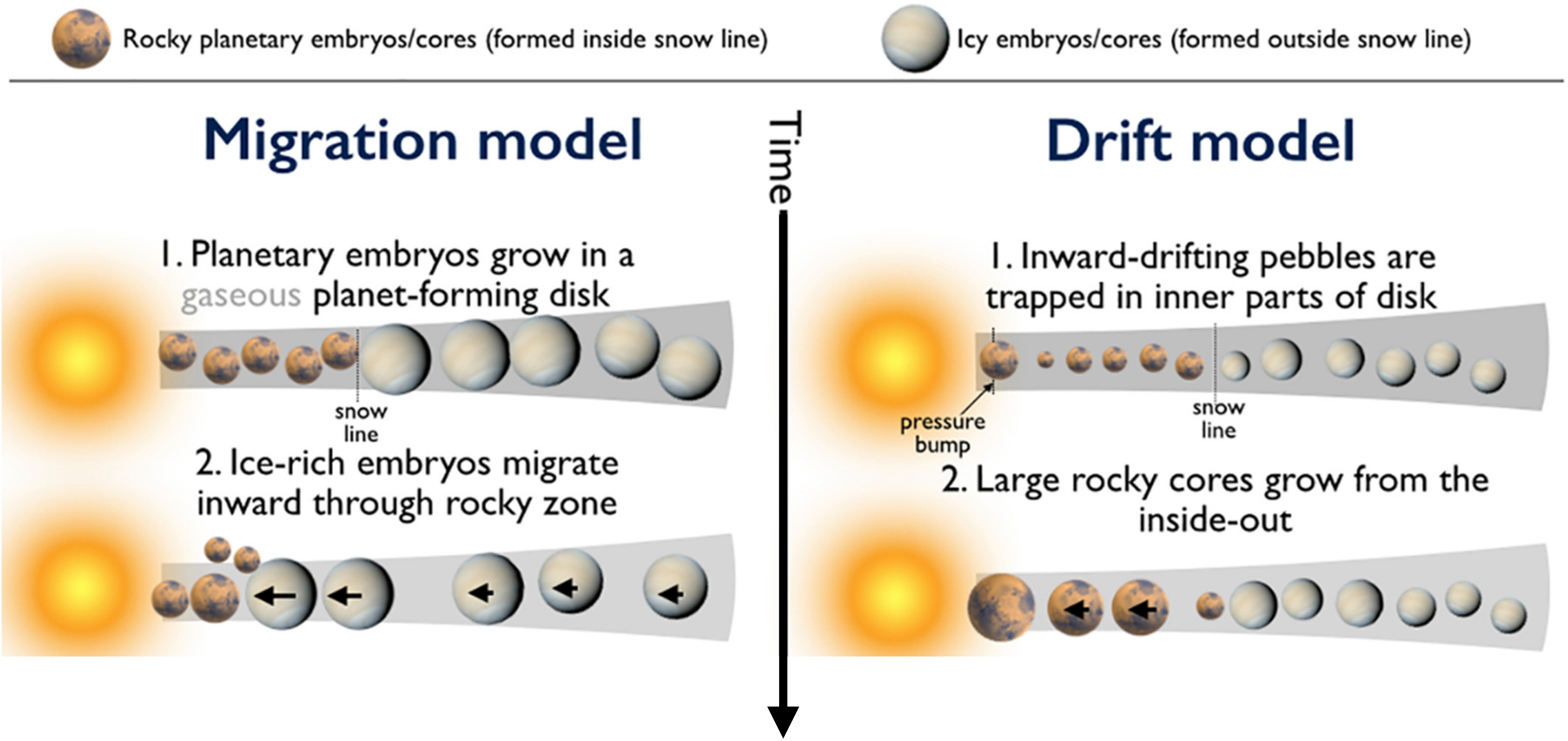


Disk Dispersal, PPVI from Alexander, Pascucci et al. (2014)



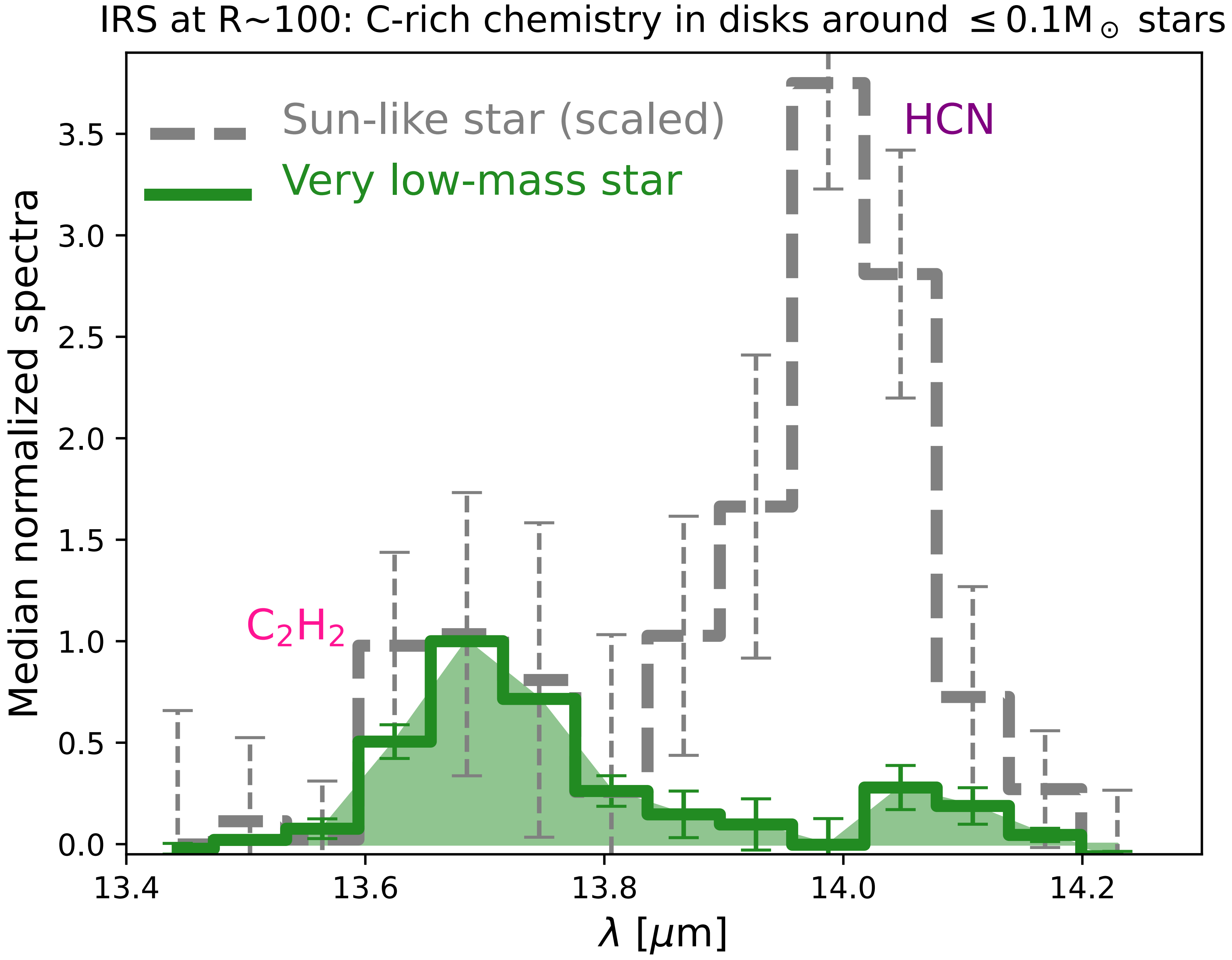
Alexander & Pascucci (2012): giant planets pile up at the gap opened by photoevaporative winds

Formation scenarios for sub-Neptunes require migration



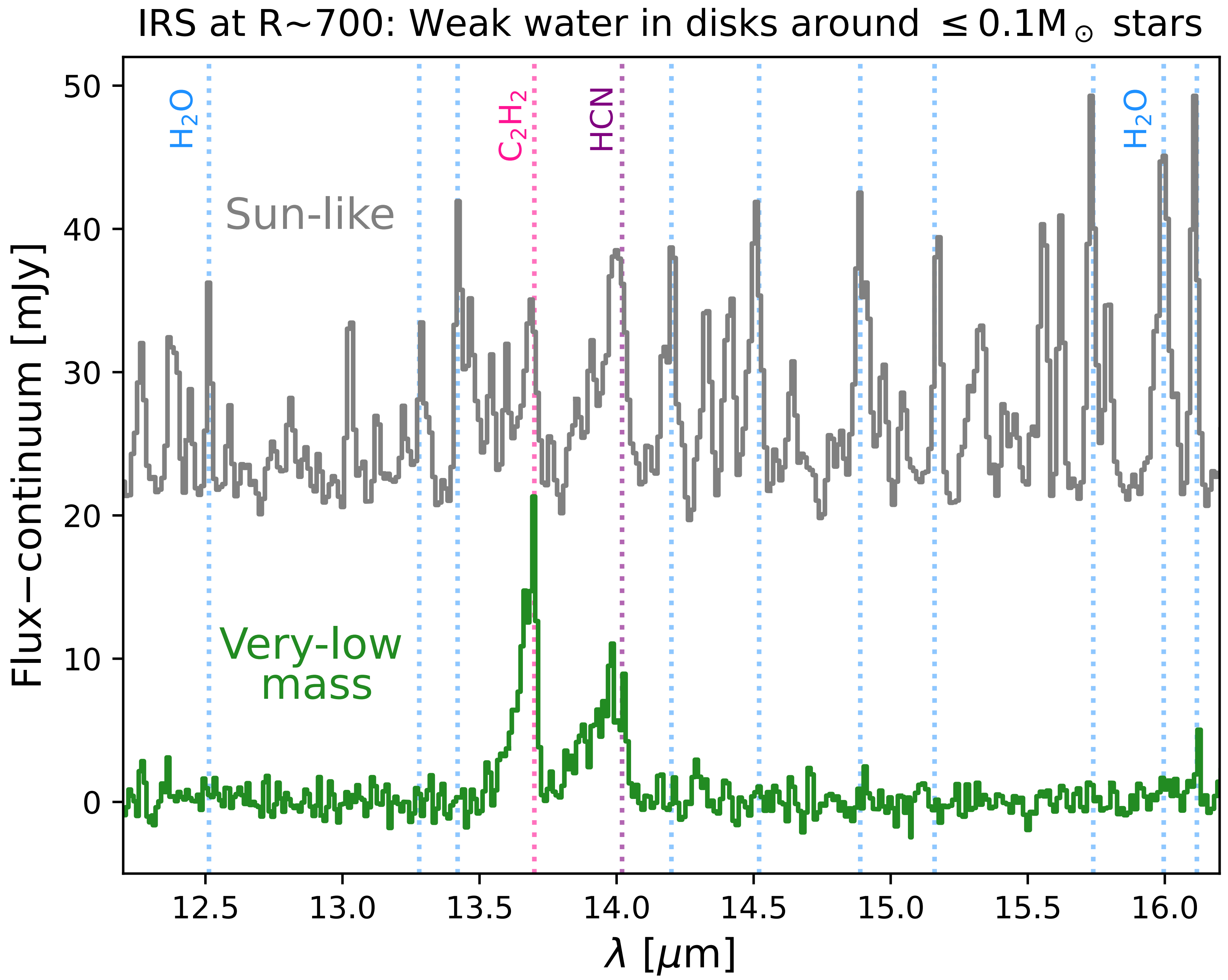
from Bean, Raymond and Owen (2020)

Spitzer spectroscopy of TRAPPIST-1 disk analogs



adapted from Pascucci et al. 2009

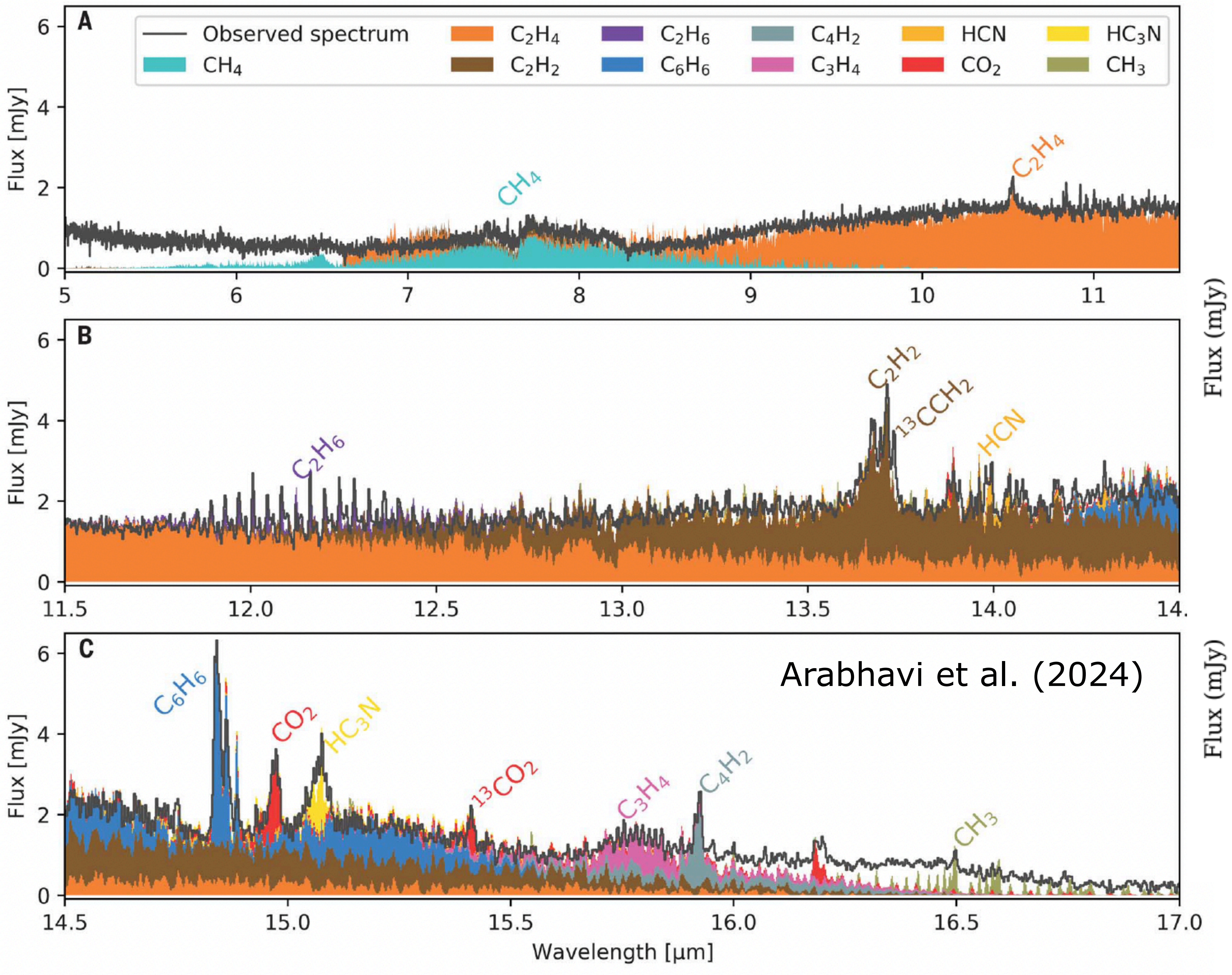
Gas inside the snowline of TRAPPIST-1 disk analogs is water poor and C-rich —> ***Hints*** for high C/O (>0.8)!



adapted from Pascucci et al. 2013

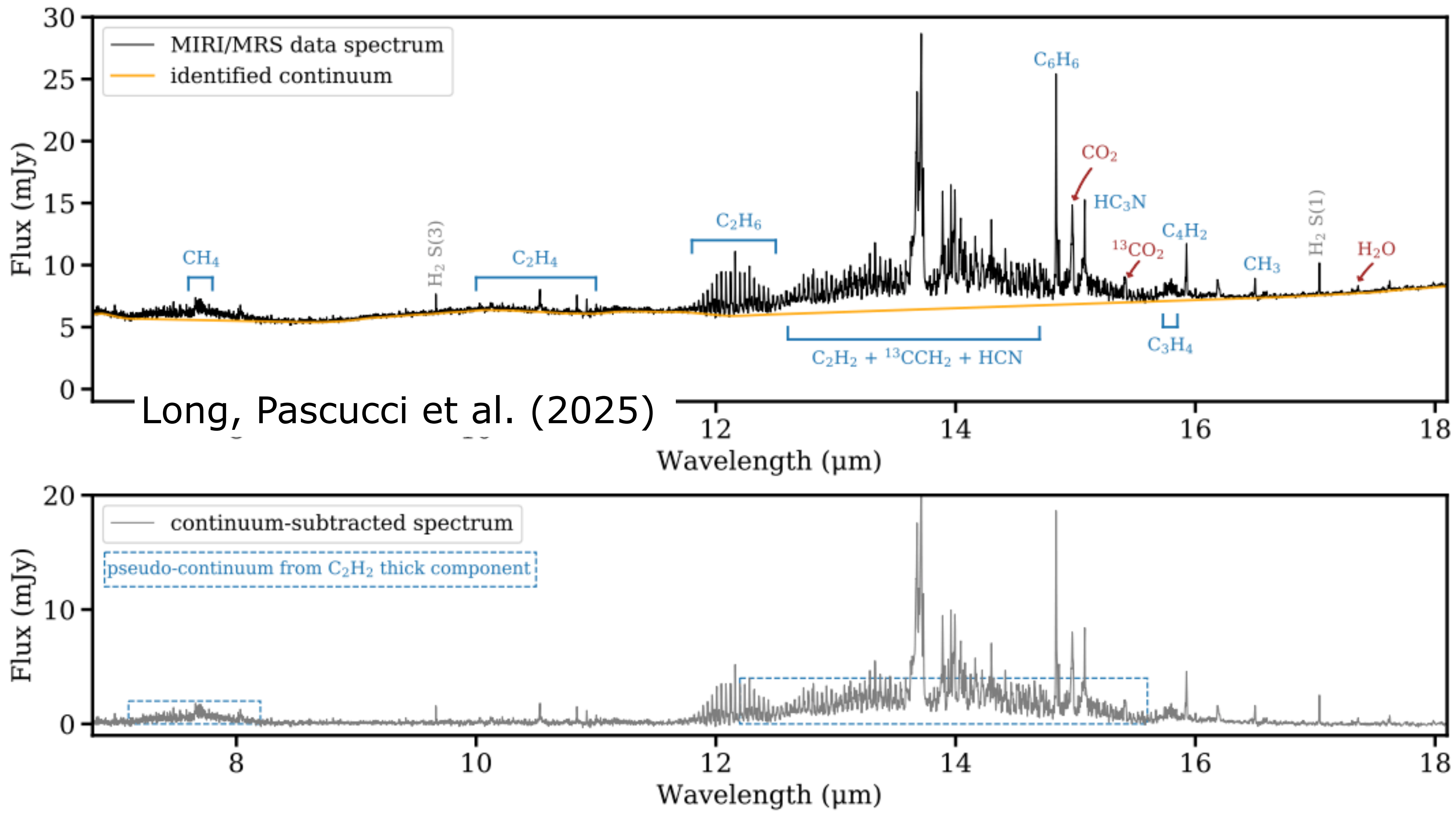
JWST spectroscopy of TRAPPIST-1 disk analogs confirms high C/O!

ISO-ChaI 147: ~1-2Myr old disk around a ~0.1M_{star}



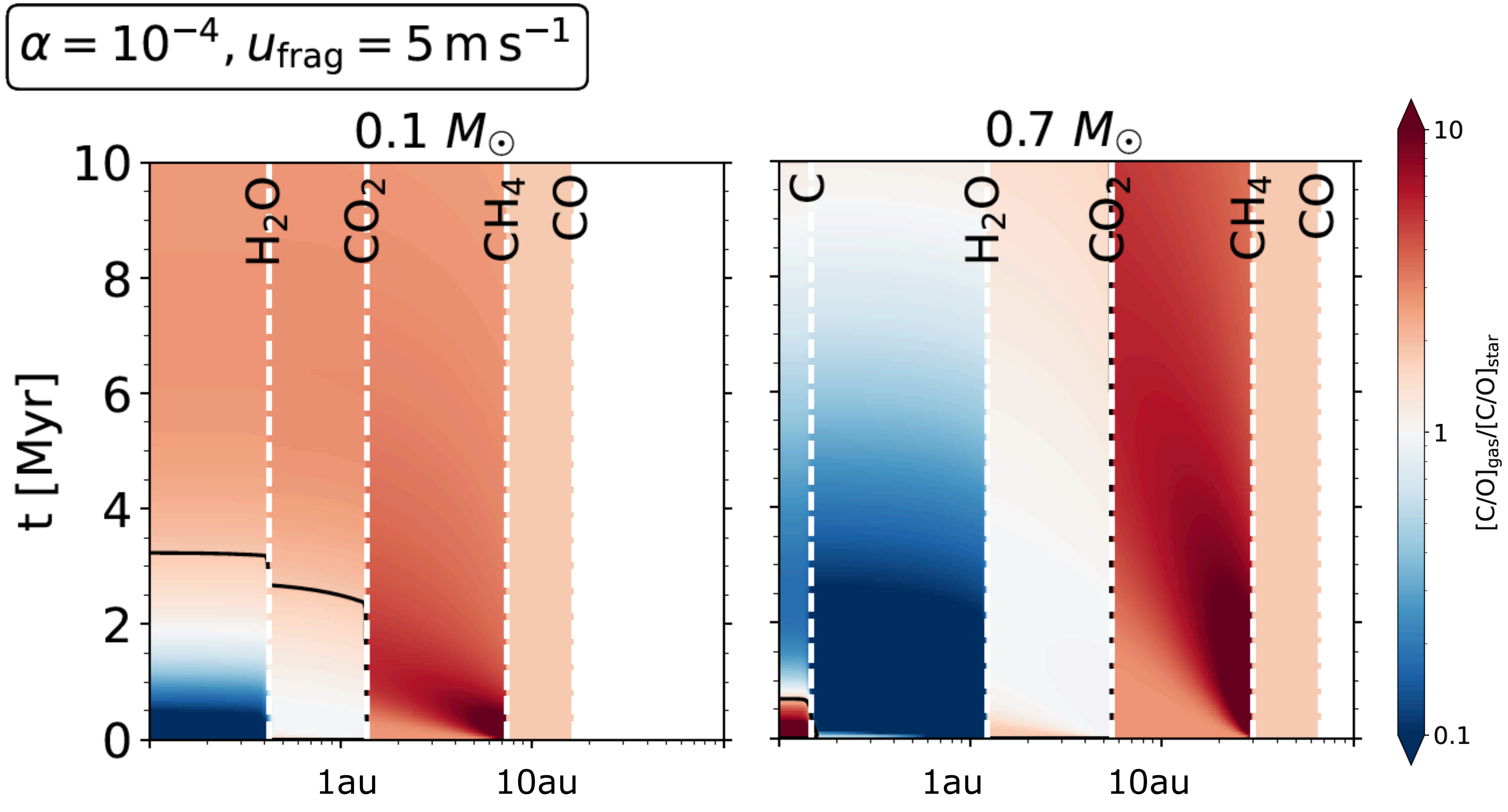
Arabhavi et al. (2024)

J0446B: ~30Myr old disk around a ~0.2 M_{star}



Long, Pascucci et al. (2025)

Why a high C/O ratio in the inner disks of very low-mass stars?

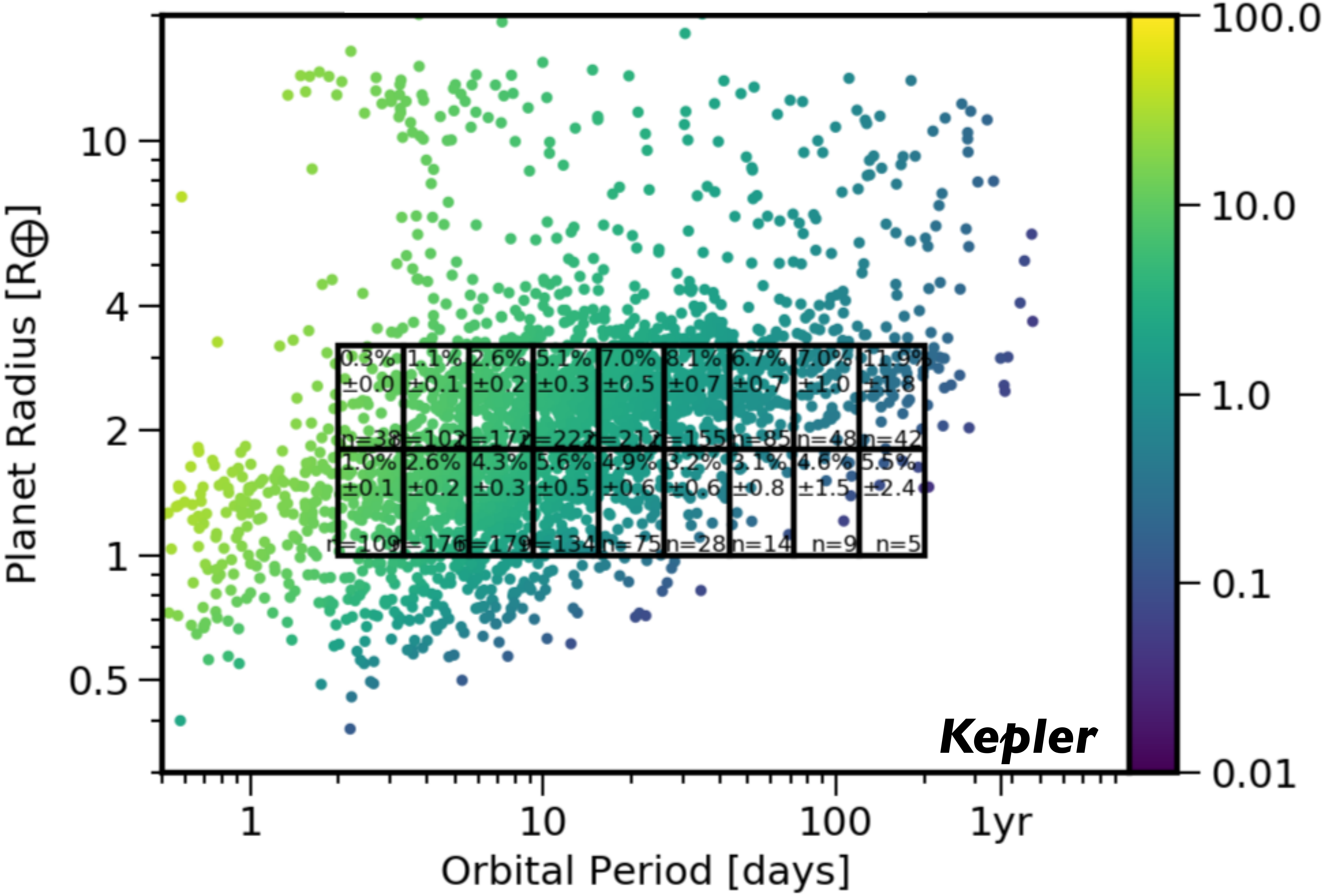


Mah, Bitsch, Pascucci, Henning (2023)

Icy pebbles migrate faster in disks around very low-mass stars, releasing water vapor that accretes faster onto the star, while C-rich outer gas moves inward. This accelerates the rise of a high C/O ratio inside the snowline.

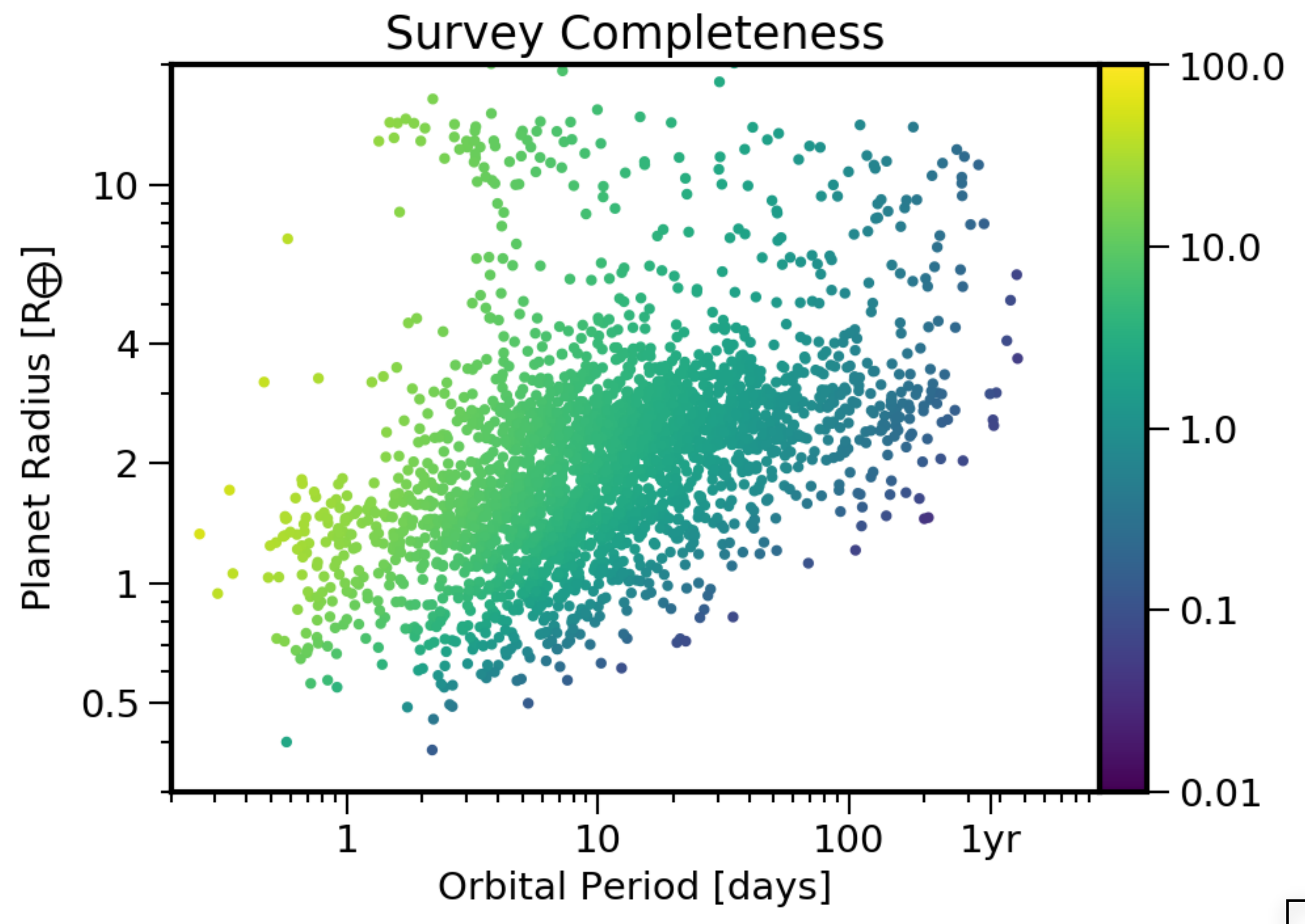
What are the consequences for the formation and evolution of rocky planets?

When extrapolations exclude short-period planets, the frequency of Earth-size planets in the HZ drops by a factor of ~3-5



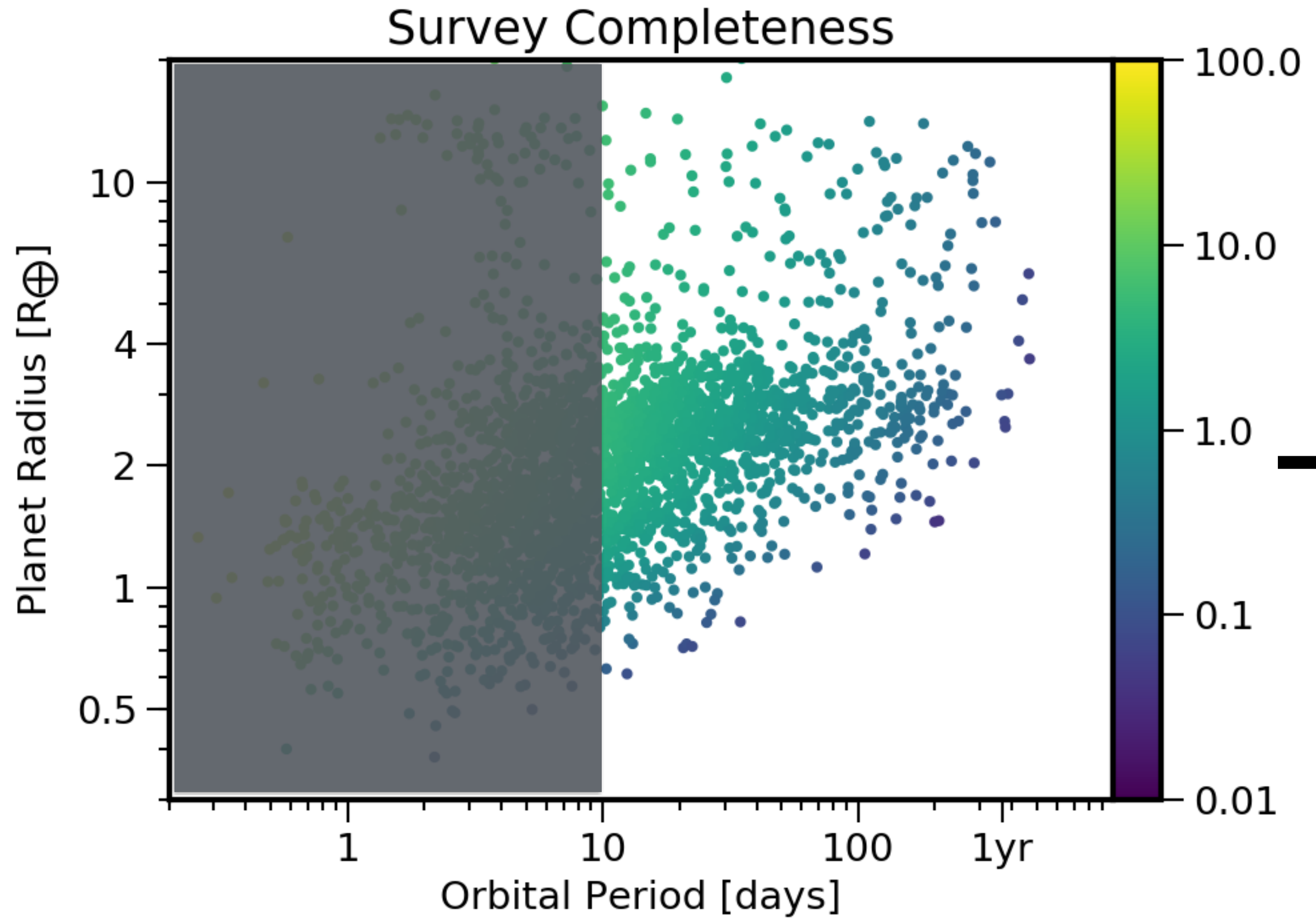
Pascucci et al. (2019)

Removing the population of close-in planets (many of which could be stripped cores) reduces the occurrence of Earth analogues!

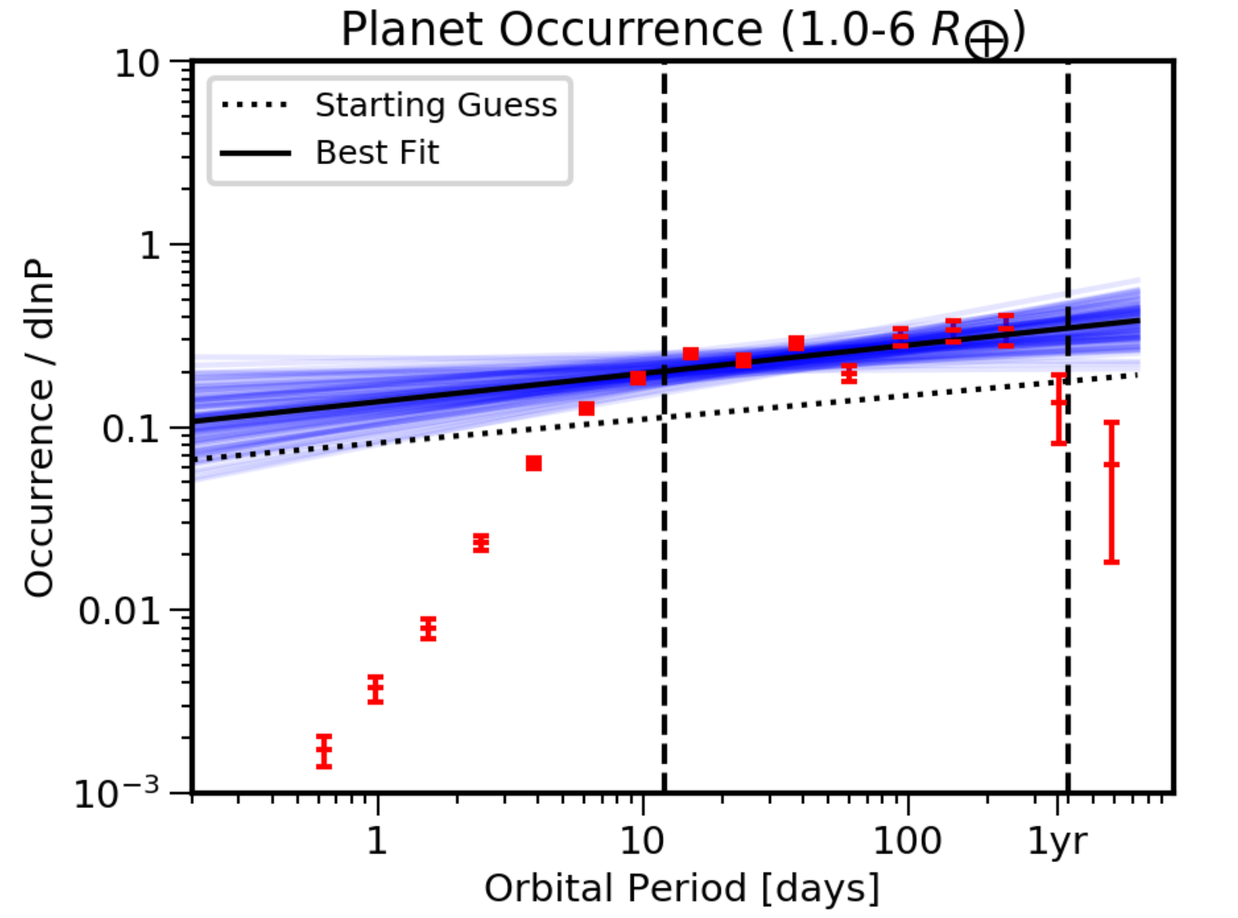


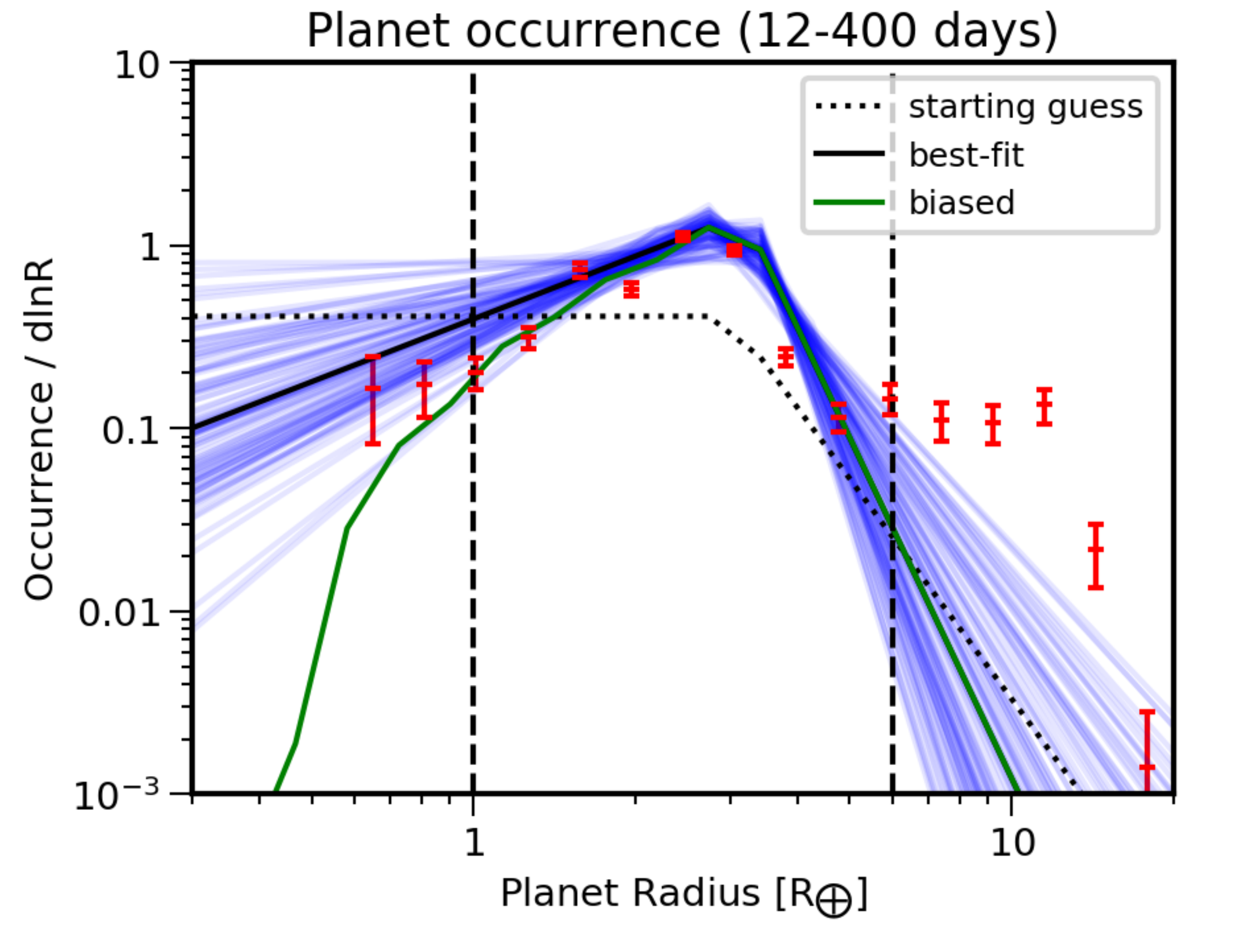
η⊕ ~ 40%

Pascucci, Mulders, Lopez (2019)

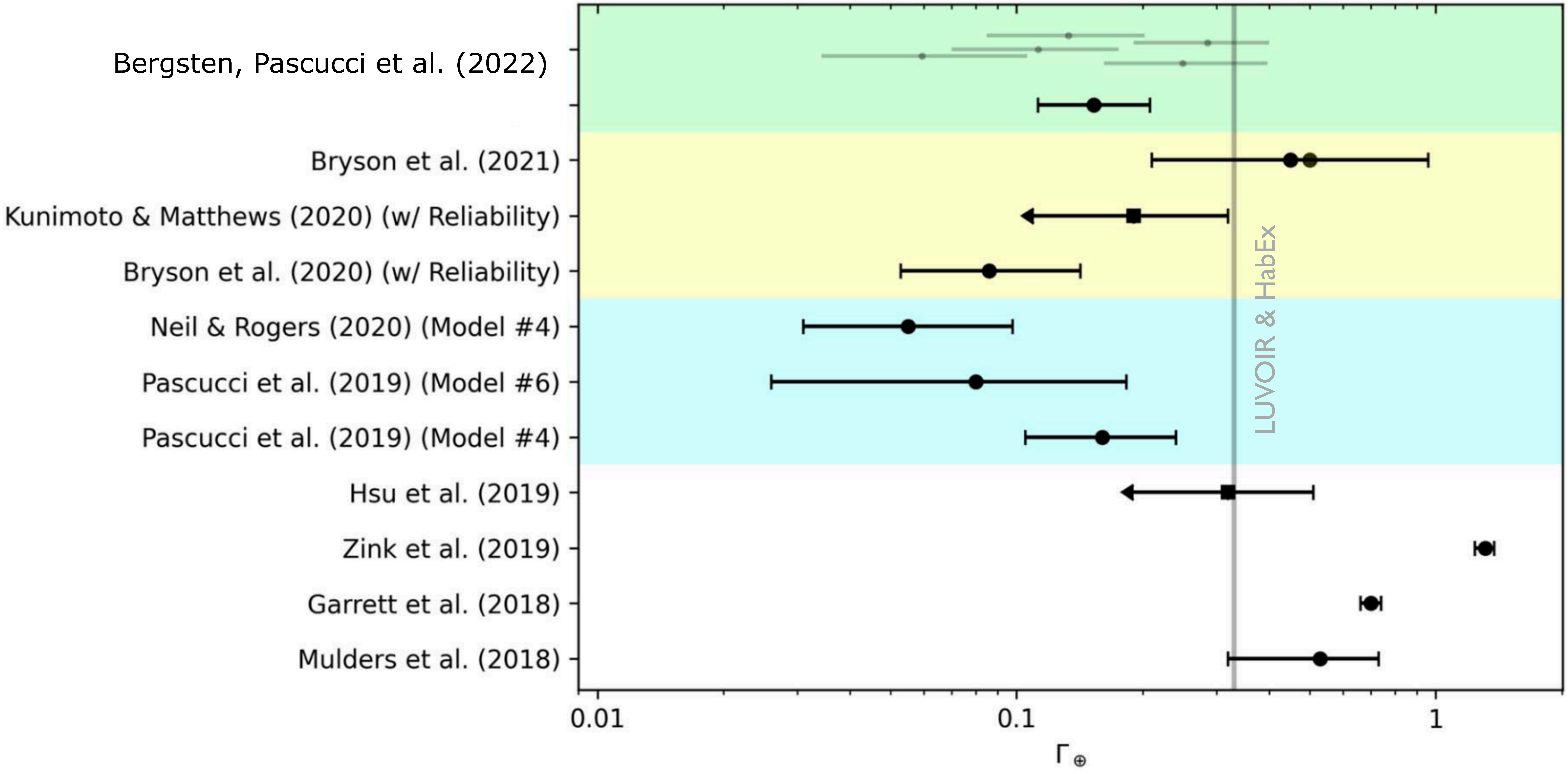


η⊕ ~ 10%



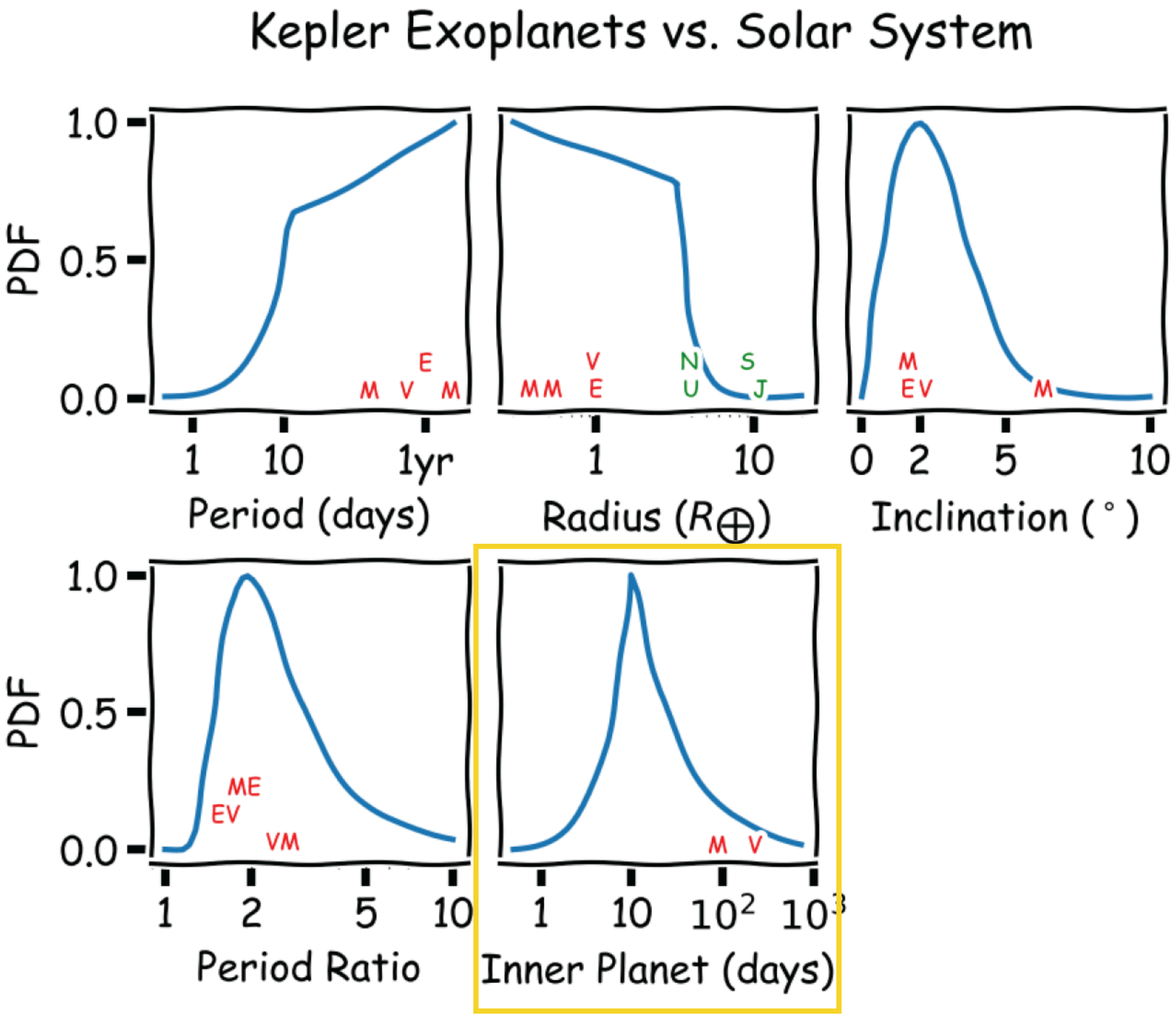


Habitable Zone occurrence rates normalized by period and radius range



How common are systems like our Solar System?

Only 3% of multi-planet systems have no planets interior to Venus



EPOS

Mulders, Pascucci et al. (2018)