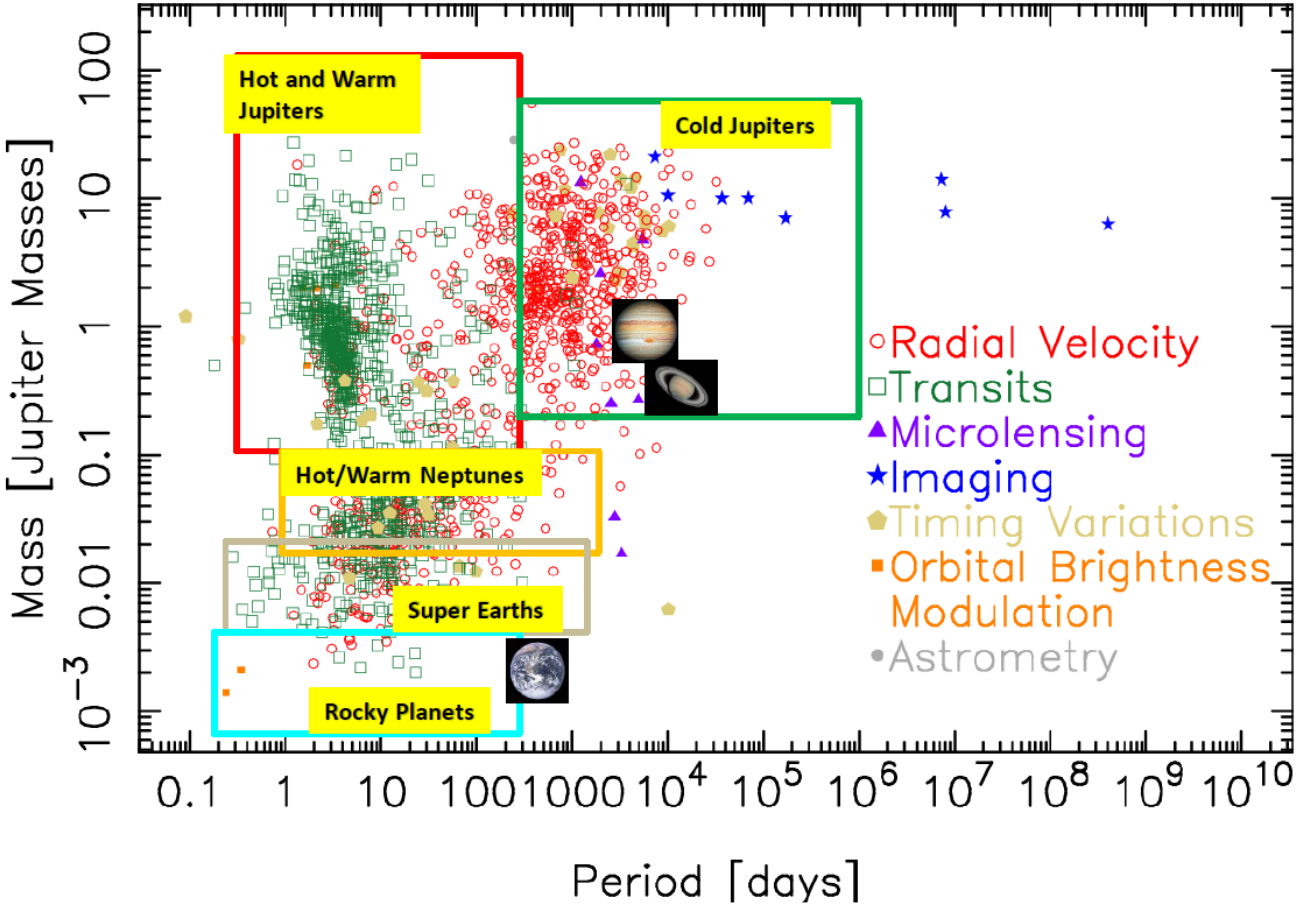
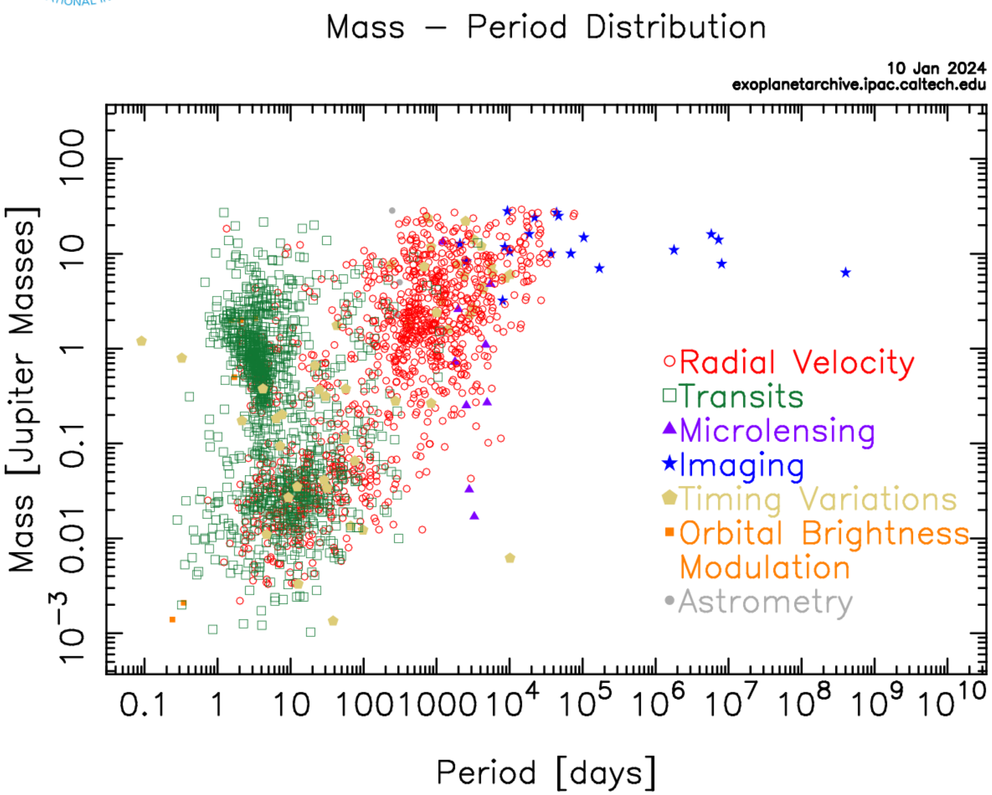
Key Questions in Exoplanet Demographics: The Power of Ultra-high Precision Astrometry



Alessandro Sozzetti
(INAF – Osservatorio Astrofisico di Torino)

What is Exoplanet Demographics?



$$\frac{d^n N_{pl}}{dp_1 \dots p_n} = Af(p_1) \dots f(p_n)$$

WARNING!

Accounting for:

- **Completeness (missing planets)**
- **Reliability (false positives)**
- **Incorrect parameter estimates**

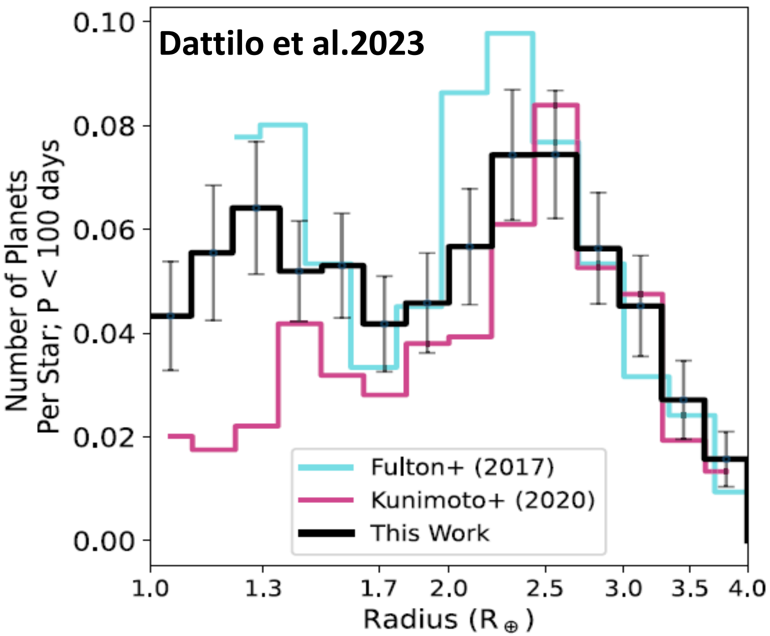
NOT TRIVIAL!

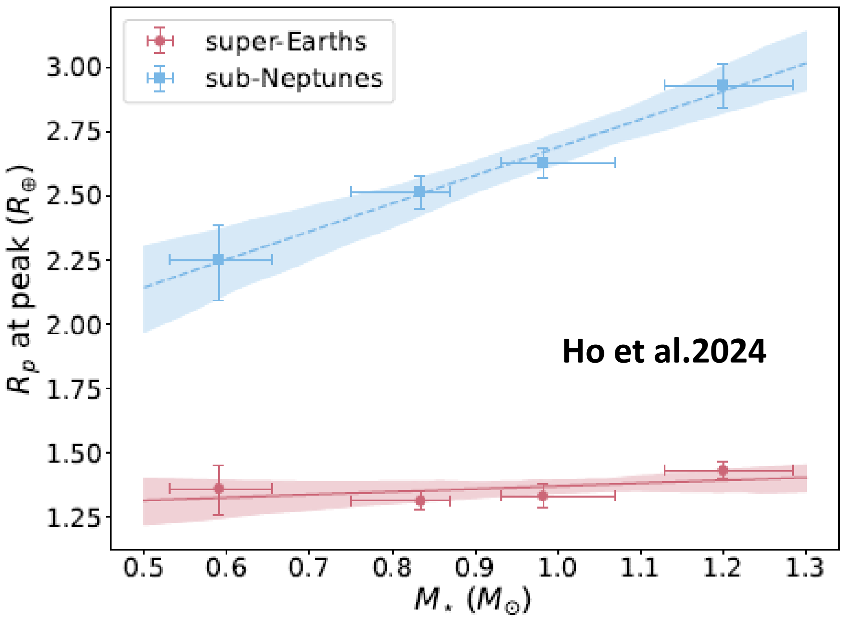
Distribution functions retain imprints of planet formation and evolution processes

They allow to address key questions of Planetary Systems Demographics:

A) What is the diversity of planets and planetary system architectures? **B)** How do they depend on stellar and environmental properties? **C)** How common are true Solar System analogs?

Radius Distribution





Clearly bimodal: Radius 'Valley' or 'Gap'

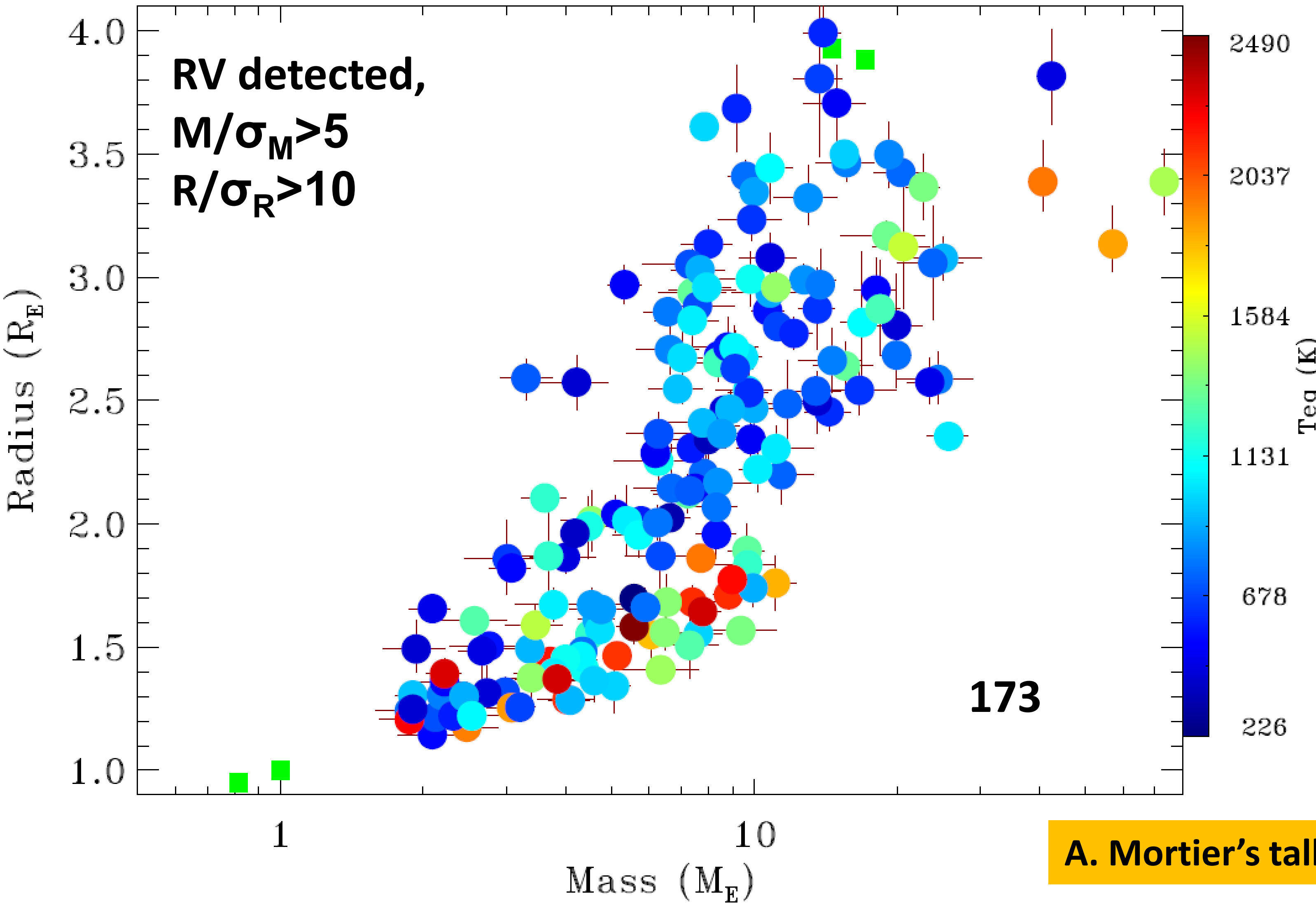
The gap and peaks (both locations function of M_*) in the planet size distribution identify two classes of small planets:

a) **(mostly) rocky super-Earths**

b) **volatile-rich or/ gas-dominated sub-Neptunes**

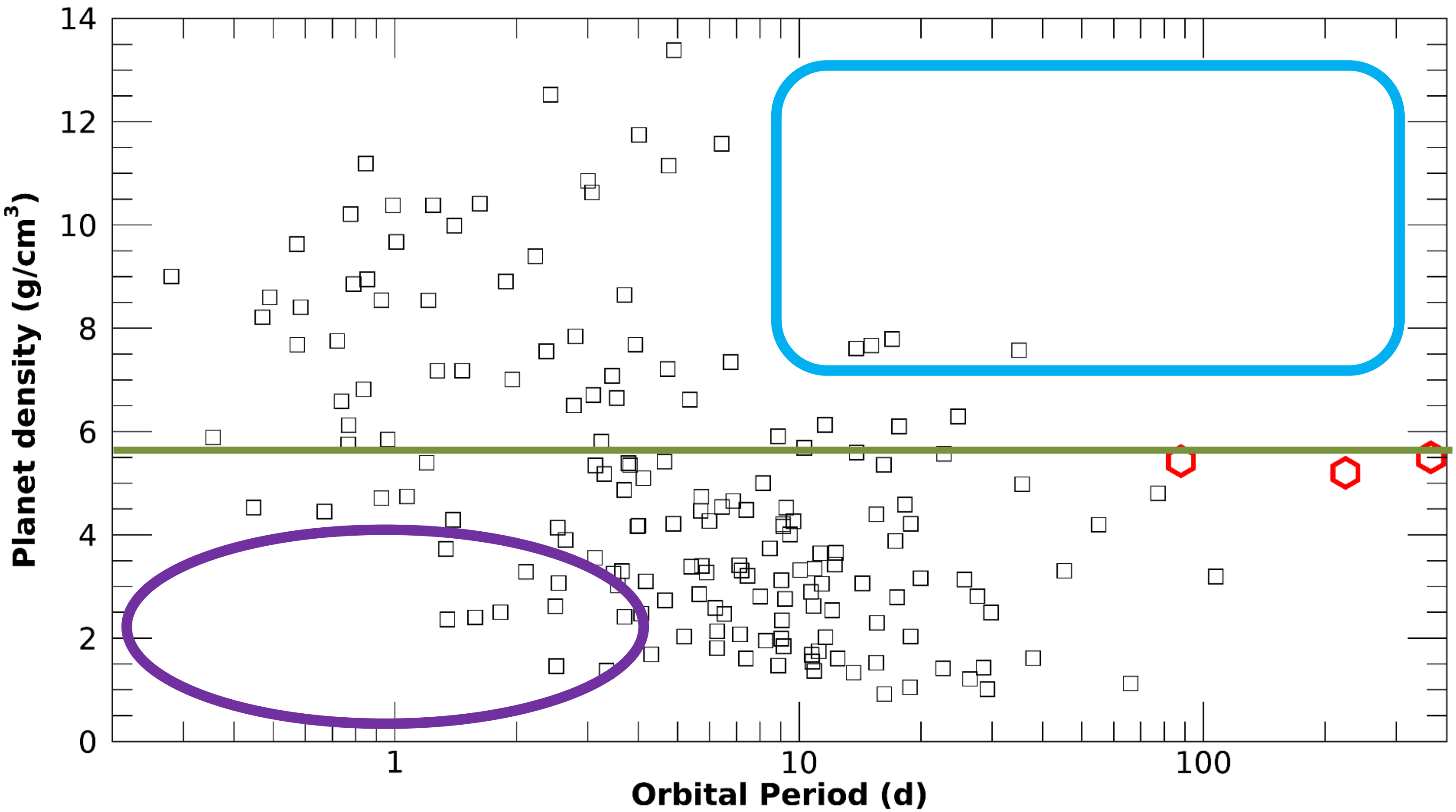
A direct evidence of evolutionary processes (photoevaporation?) of planetary systems

M-R Relation: Small Planets

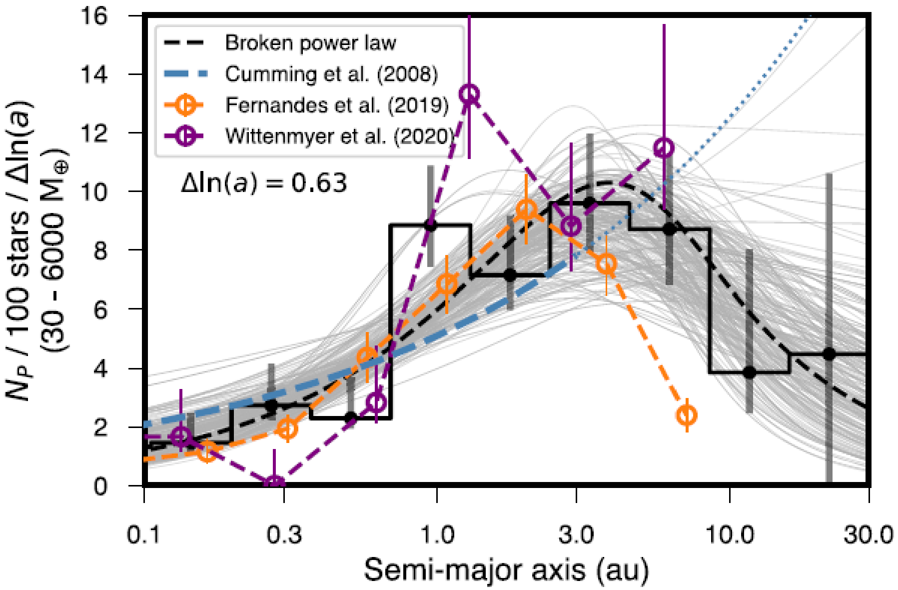


A. Mortier's talk

From Ultra-Short to Long Periods



Separation Distribution

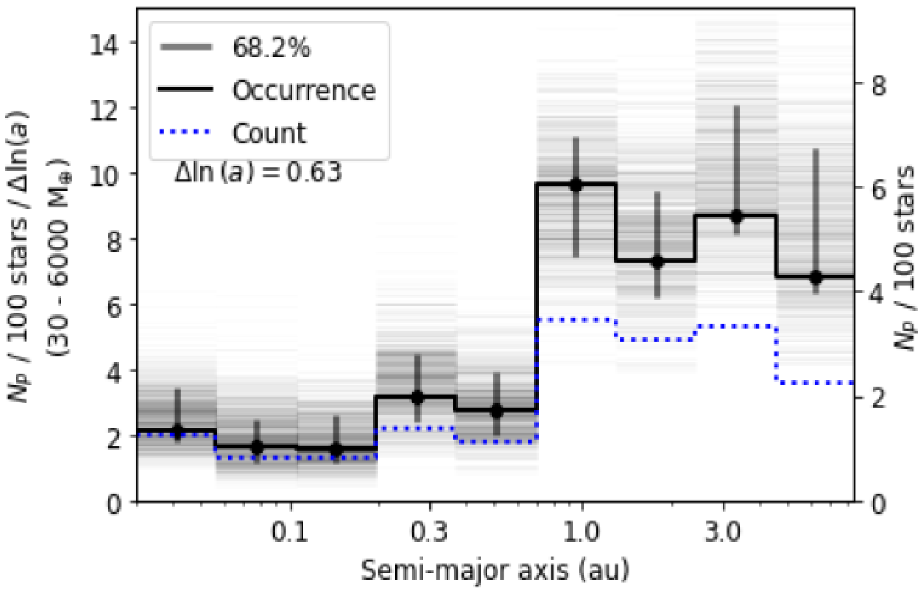


Fulton et al. 2021

Giant planet frequency declines beyond the snowline

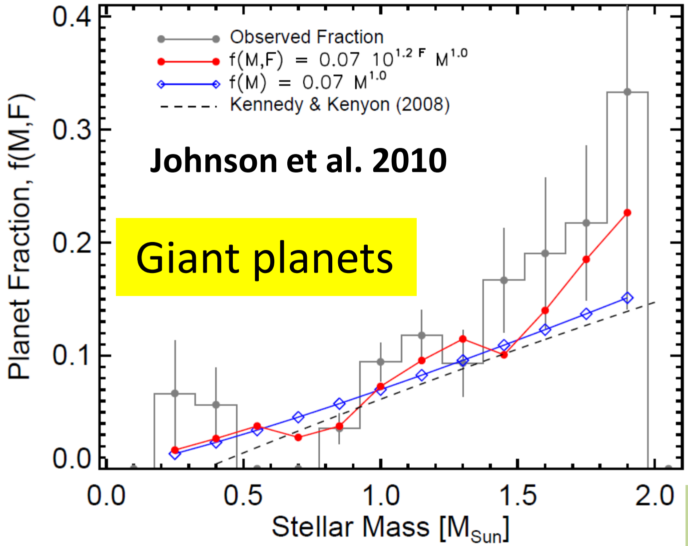
Or does it?

Lagrange et al. 2023



Same technique, different surveys: Different answers!

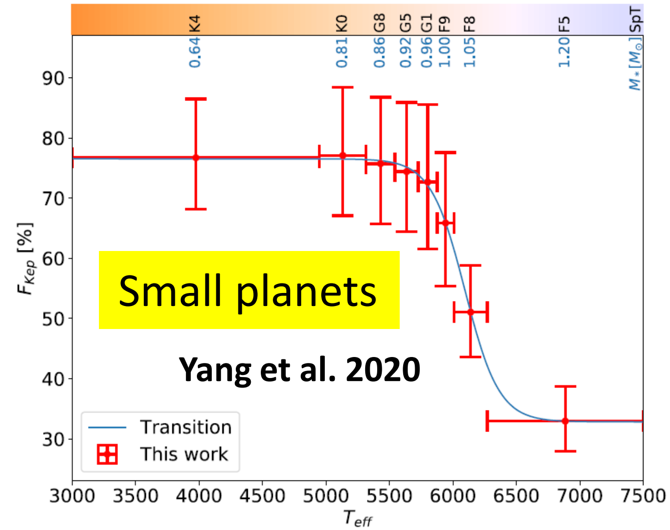
The Planet-Star Connection

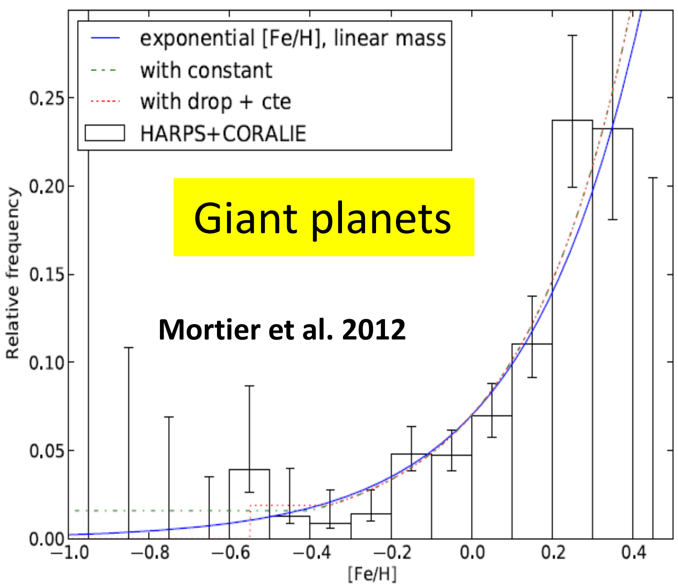


F_p vs M_*

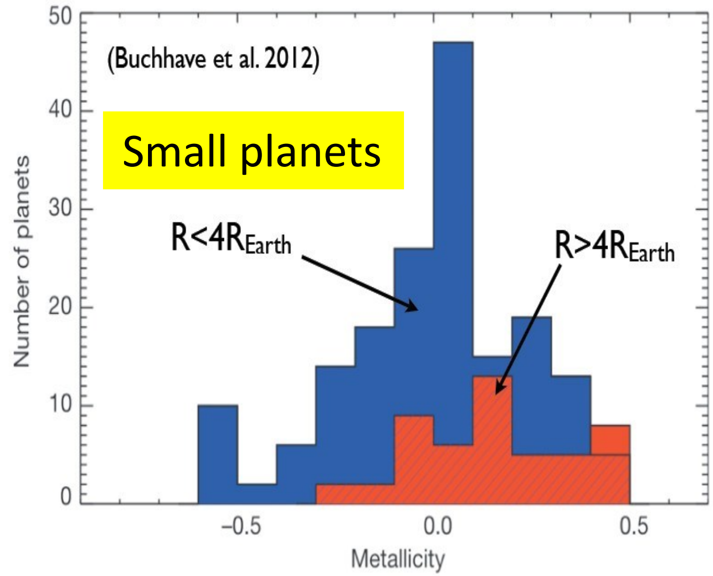
a < 3-4 au

P < 100 d

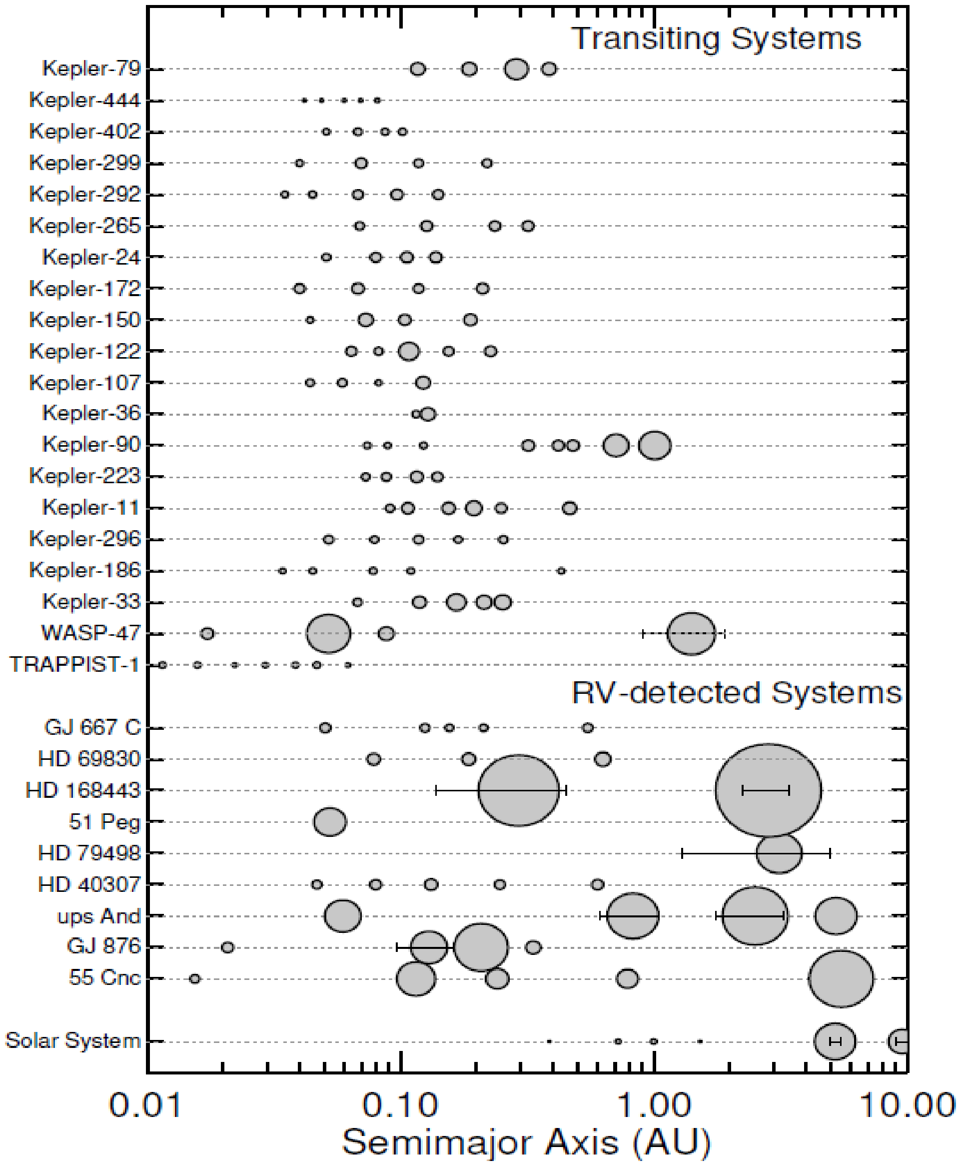


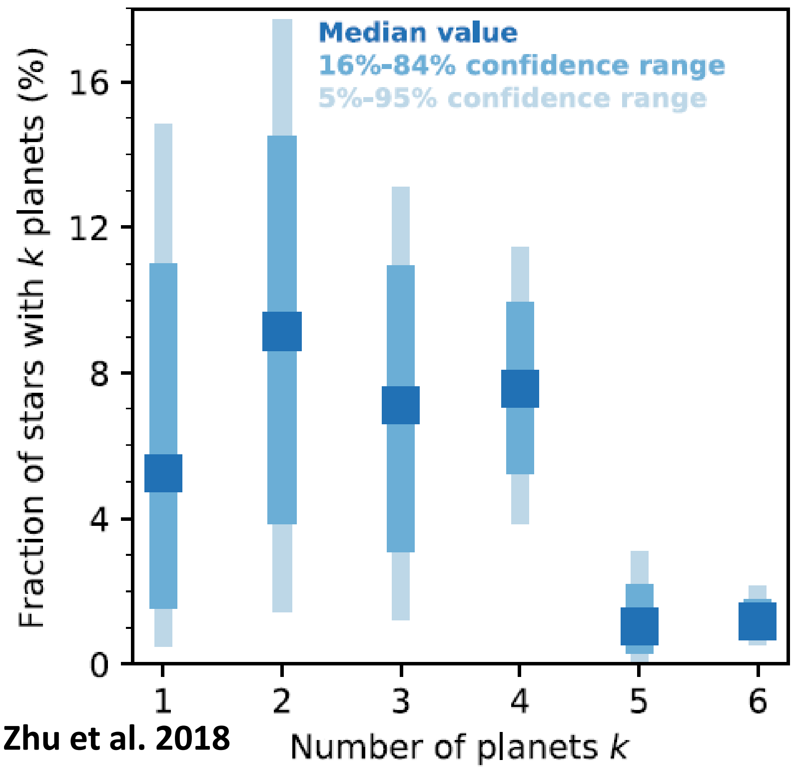


F_p vs [Fe/H]



Multi-planet Systems



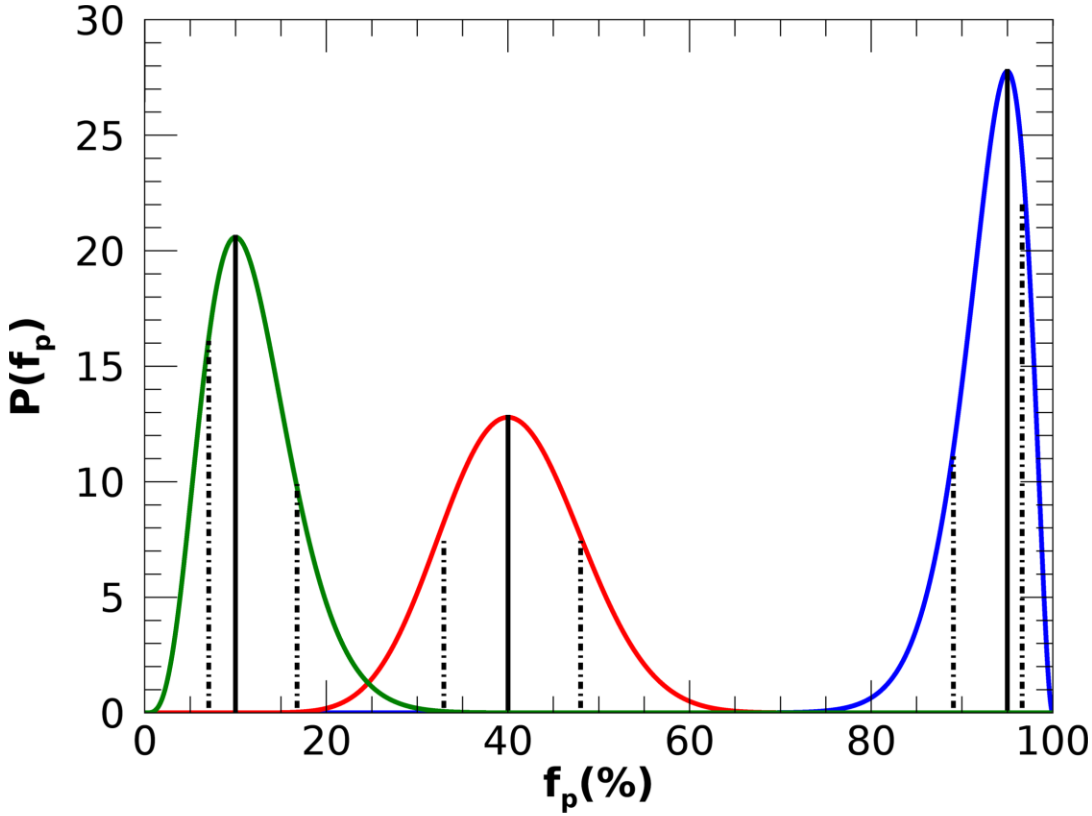


Zhu et al. 2018

Transiting multis are very ‘flat’ and compact systems, with similar sizes

'Ordered' Architectures: Occurrence

Solar-System-type: *inner Super-Earths (SE) and Neptunes (N), outer Jupiters (CJ)*



Barbato et al. 2018

Zhu & Wu 2018

Bryan et al. 2019

Rosenthal et al. 2022

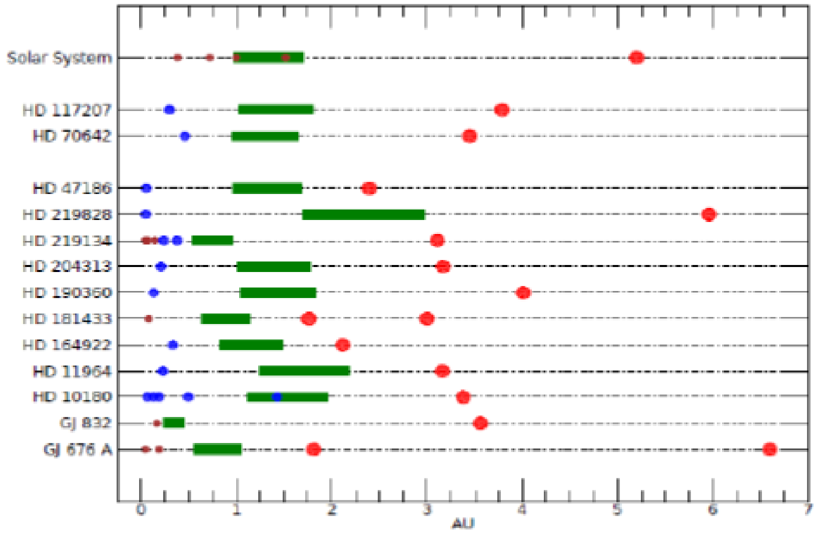
Pinamonti et al. 2023

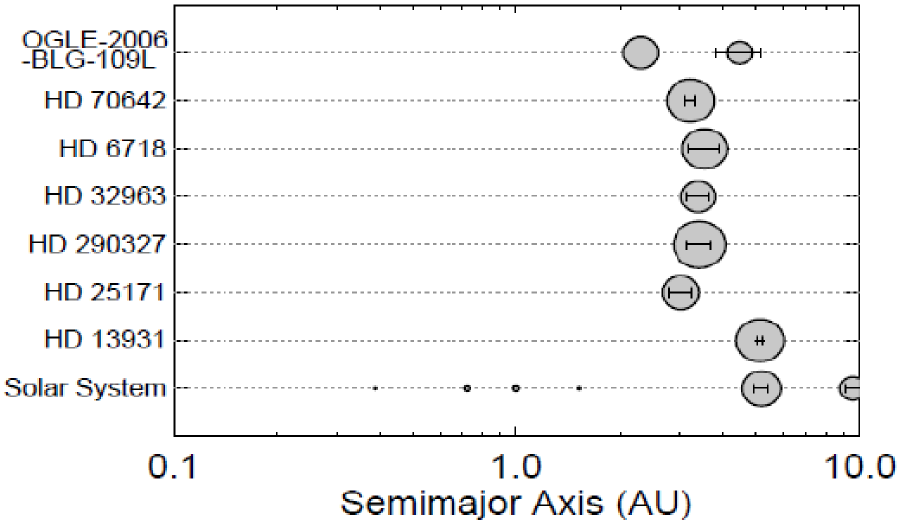
Bonomo et al. 2023

Bryan & Lee 2024

BEWARE: f_p(CJ|SE,N) not necessarily the same as f_p (SE,N|CJ) !

Solar-System-*like* systems?





OCCURRENCE ESTIMATES:

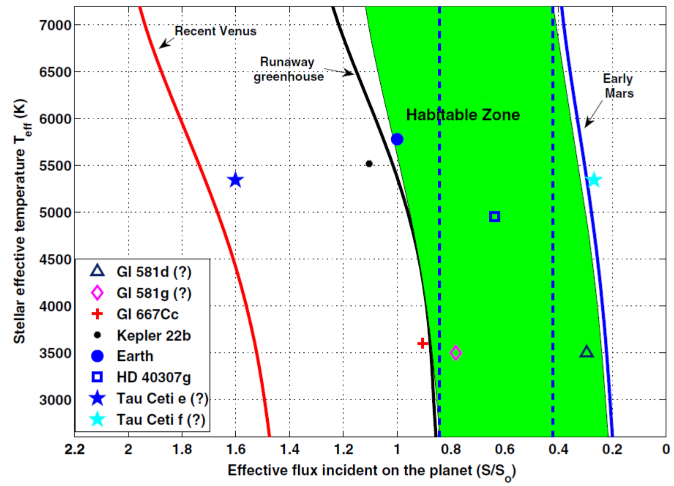
- Rowan et al. (2016): **3%** (cold giants beyond the snow line, F-G-K primaries)
- Fernandes et al. (2019) **1.5%** (cold giants beyond the snow line, F-G-K primaries)
- Wittenmyer et al. (2020): **7%** (cold giants beyond the snow line, F-G-K primaries)
- Fulton et al. (2021): **13%** (cold giants beyond the snow line, F-G-K primaries)

BEWARE: the occurrence of true Solar System analogs remains unknown!

Planet type (planet-radius range in $R_\oplus$)	$\eta_\oplus$ (planets per star)	Reference	Notes
0.5 – 1.5	$0.37^{+0.48}_{-0.21} - 0.60^{+0.90}_{-0.36}$	Bryson et al. (2021)	F G K dwarfs[a]
0.5 – 1.5	$0.58^{+0.73}_{-0.33} - 0.88^{+1.28}_{-0.51}$	Bryson et al. (2021)	F G K dwarfs[b]
0.75 – 1.5	$0.13^{+0.09}_{-0.06} - 0.11^{+0.07}_{-0.05}$	Kunimoto & Matthews (2020)	G dwarfs[a,b]
0.5 – 1.5	$0.302^{+0.181}_{-0.113}$	Bryson et al. (2020a)	G K dwarfs[a,c]
0.5 – 1.5	$0.126^{+0.095}_{-0.055}$	Bryson et al. (2020a)	G K dwarfs[a,d]
0.7 – 1.5	$0.11^{+0.06}_{-0.04}$	Pascucci et al. (2019)	F G K dwarfs[a,f]
0.7 – 1.5	$0.05^{+0.07}_{-0.03}$	Pascucci et al. (2019)	F G K dwarfs[a,g]
0.75 – 1.5	$0.33^{+0.10}_{-0.12}$	Hsu et al. (2020)	M dwarfs[a]
0.75 – 1.5	0.04 – 0.40	Hsu et al. (2019)	G K dwarfs[e]
0.85 – 1.4	0.33	Hsu et al. (2019)	G K dwarfs[a]
0.72 – 1.7	0.34 ± 0.02	Zink & Hansen (2019)	G dwarfs[a]
1.0 – 1.5	$0.41^{+0.29}_{-0.12}$	Hsu et al. (2018)	G K dwarfs[h]
1.0 – 1.5	$0.31^{+0.02}_{-0.03}$	Garrett et al. (2018)	G dwarfs[a]
0.5 – 1.5	$0.88^{+0.04}_{-0.03}$	Garrett et al. (2018)	G dwarfs[a]
0.5 – 1.0	$0.215^{+0.148}_{-0.099}$	Kopparapu et al. (2018)	G dwarfs[i]
1.0 – 1.75	$0.145^{+0.071}_{-0.0.061}$	Kopparapu et al. (2018)	G dwarfs[j]
0.7 – 1.5	0.36 ± 0.14	Mulders et al. (2018)	G stars[a]
1.0 – 1.5	$0.16^{+0.17}_{-0.07}$	Dressing & Charbonneau (2015)	M dwarfs[a]
1.5 – 2.0	$0.12^{+0.10}_{-0.05}$	Dressing & Charbonneau (2015)	M dwarfs[a]
1.0 – 1.5	$0.21^{+0.08}_{-0.08}$	Burke et al. (2015)	G dwarfs[k]
0.5 – 1.5	$0.50^{+0.40}_{-0.20}$	Burke et al. (2015)	G dwarfs[k]
1.0 – 2.0	$0.064^{+0.034}_{-0.011}$	Silburt et al. (2015)	F G K dwarfs[l]
0.6 – 1.7	$0.017^{+0.018}_{-0.009}$	Foreman-Mackey et al. (2014)	G dwarfs[a]
1.0 – 2.0	0.00059	Schlaufman (2014)	G stars[m,n]
1.0 – 2.0	$0.057^{+0.022}_{-0.017}$	Petigura et al. (2013b)	G stars[m]
0.5 – 1.4	$0.15^{+0.13}_{-0.06}$	Dressing & Charbonneau (2013)	M dwarfs[a]
0.5 – 1.4	$0.48^{+0.12}_{-0.24}$	Kopparapu (2013)	M dwarfs[a]
0.5 – 2.0	0.34 ± 0.14	Traub (2012)	F G K dwarfs[o]
0.8 – 2.0	$0.028^{+0.019}_{-0.009}$	Catanzarite & Shao (2011)	F G K dwarfs[p]
0.5 – 3.0	2.75 ± 0.33	Youdin (2011)	G dwarfs[q]

Earth Twins: Occurrence Rates

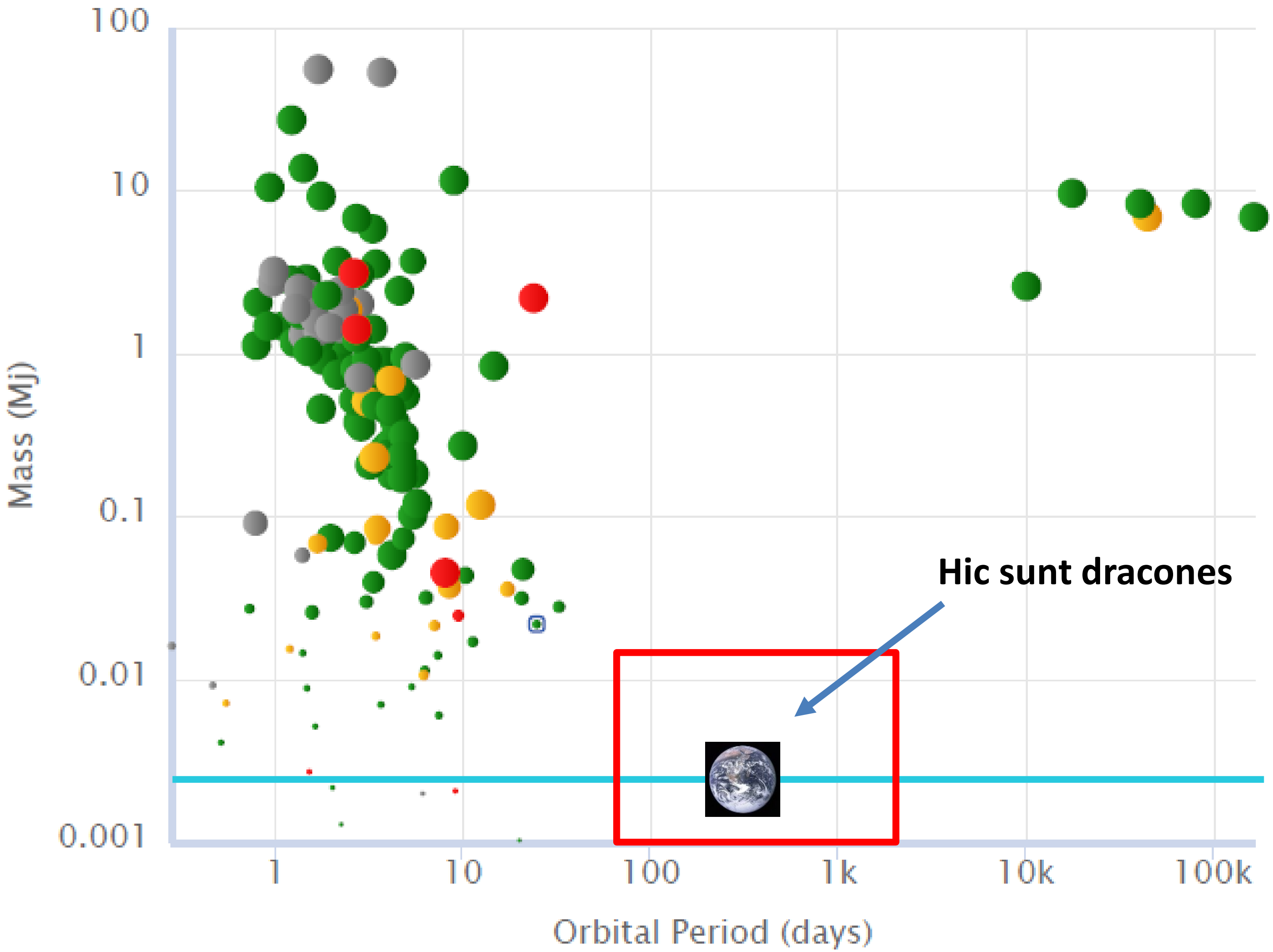
Kopparapu et al. 2013



Within 1-2 sigma:
it could be 9%, or 90%...

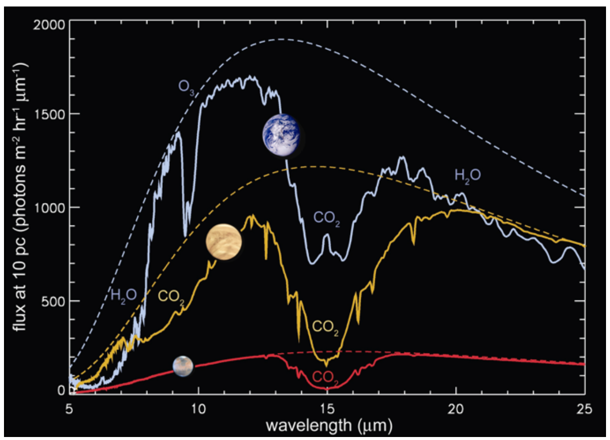
IAP PARIS (FRANCE), 13/09/2024

Atmospheres: Atoms & Molecules



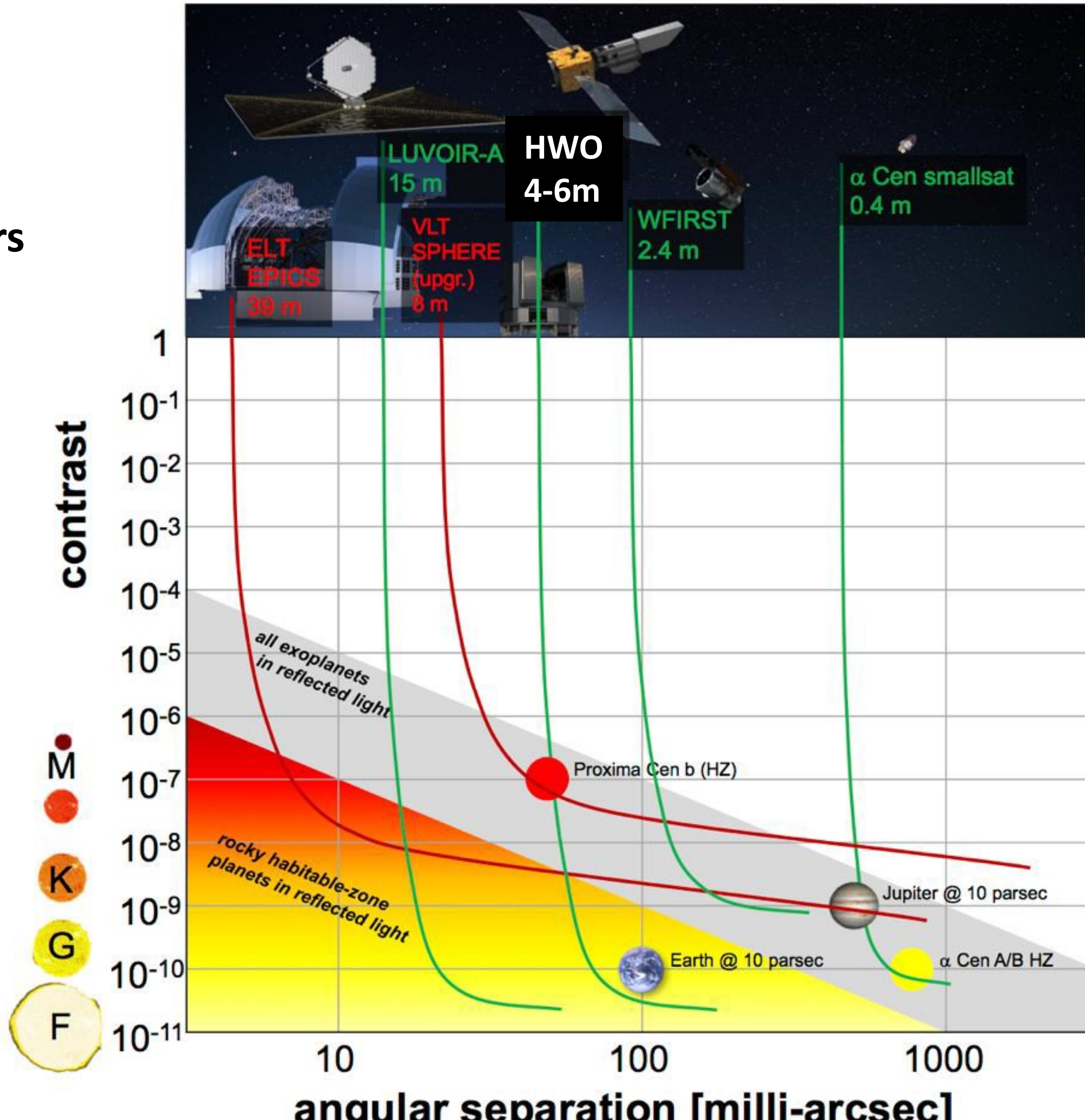
Earth-*Like* Planets: The Ultimate Frontier

Habitability and atmospheric biosignatures of temperate terrestrial exoplanets around the nearest _solar-type_ stars



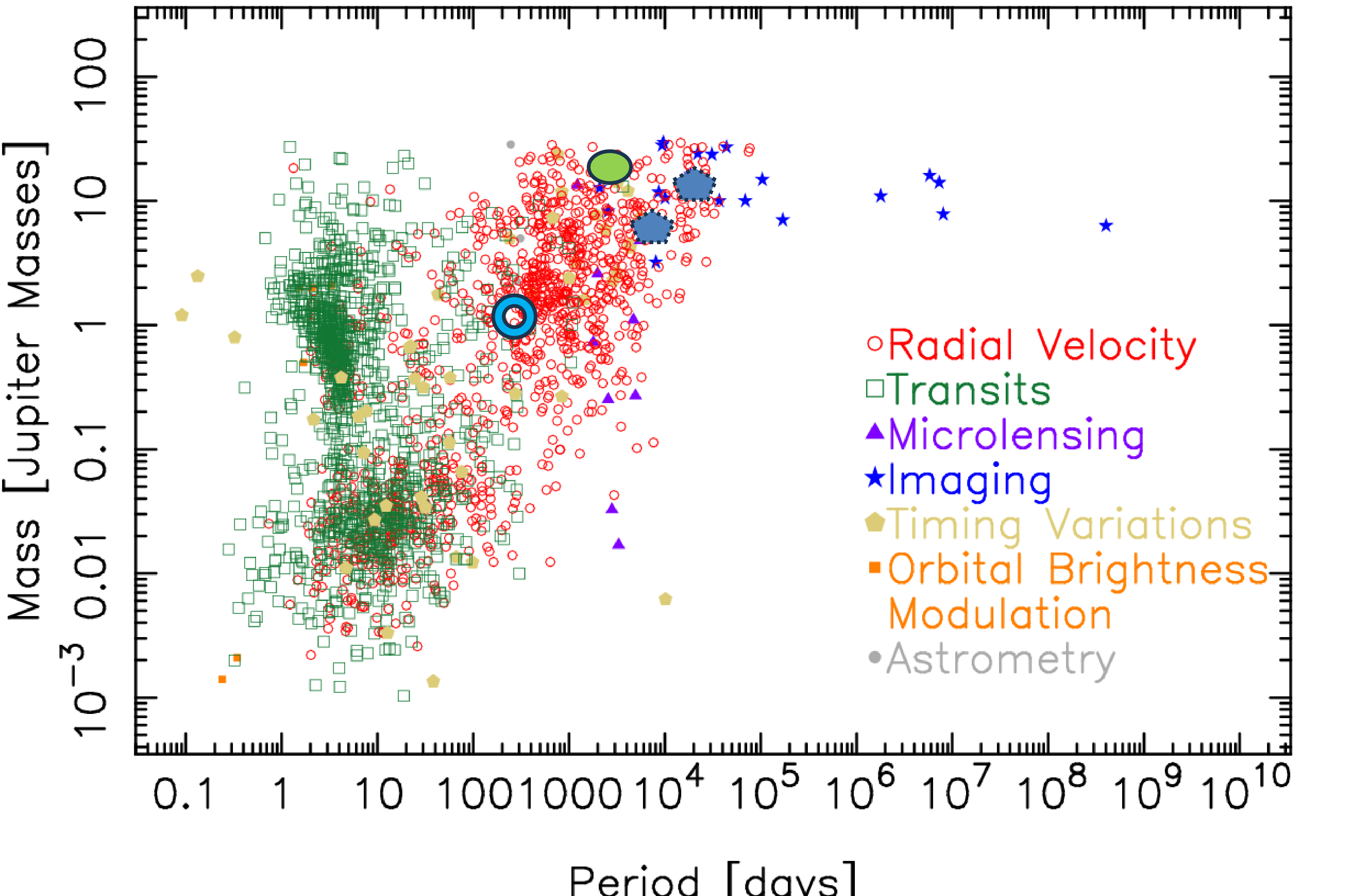
Finding the targets FIRST is <u>mandatory</u> in order to maximize science return

True Earth twin: K = 9 cm/s

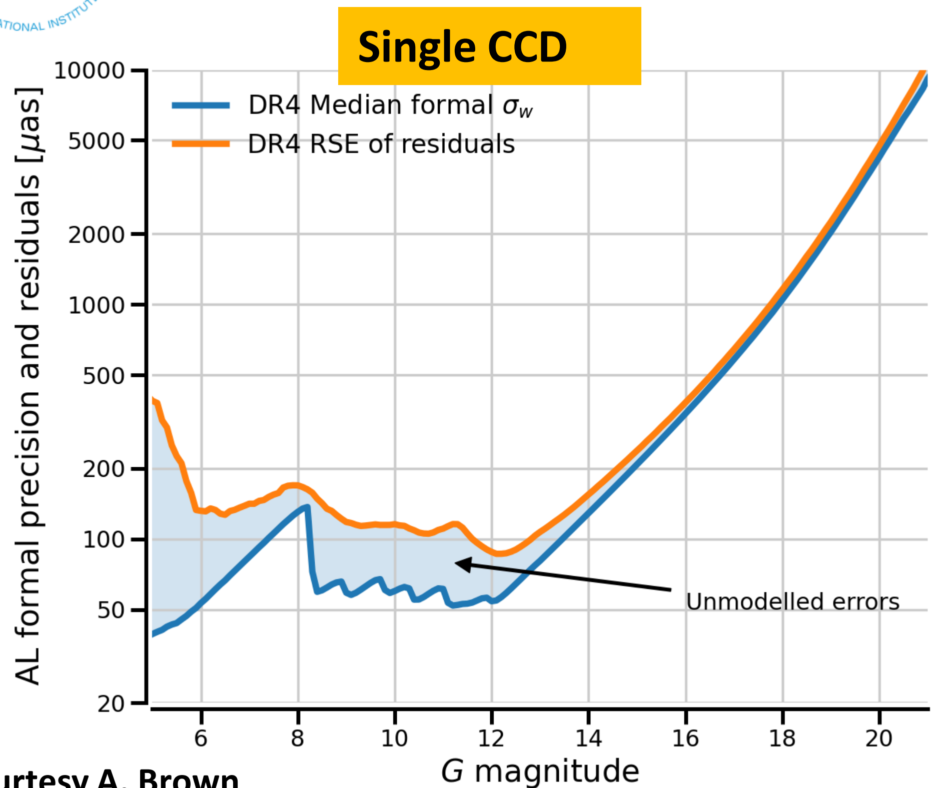


A FUTURE SPACE MISSION FOR VERY HIG

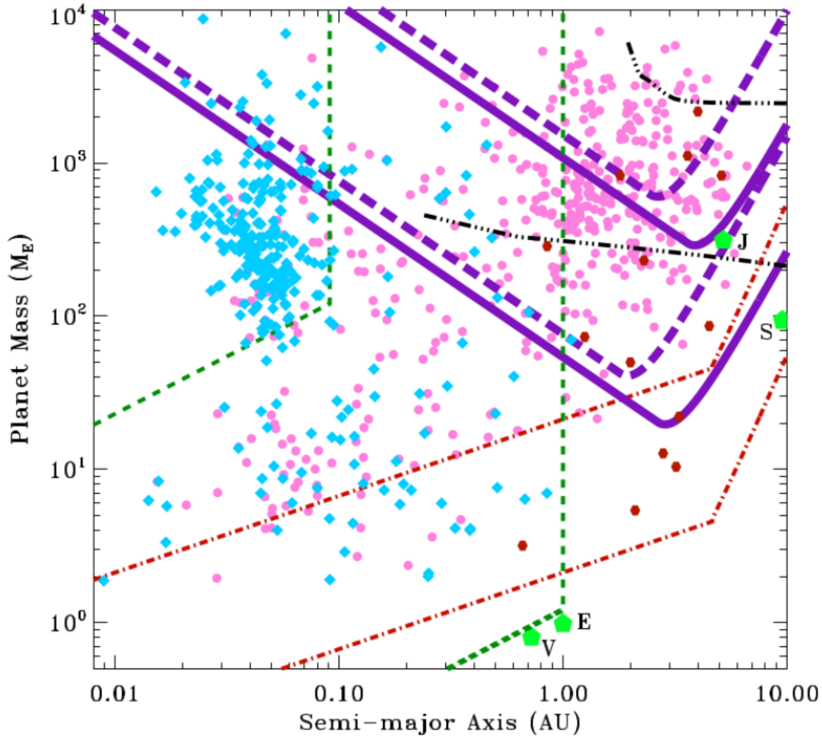
Exoplanet Demographics: DIRECT Astrometry Contribution



Gaia DR4 (2026) and DR5 (2030)



Courtesy A. Brown

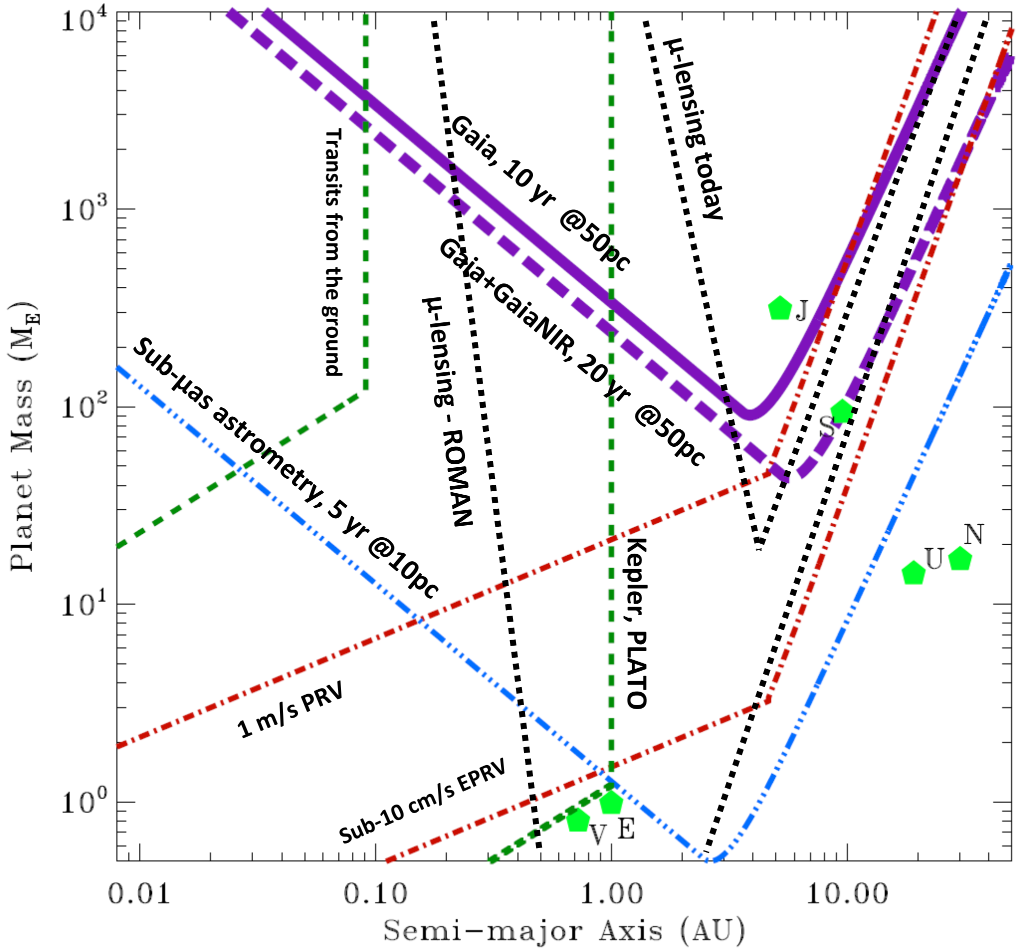


Yield: > 10000 of cold (1<a<5 au) Jupiters

(Lattanzi+2000; Casertano+2008; Sozzetti+2014; Perryman+2014)

Gaia will test the fine structure of GP parameters distributions and frequencies (including the GP/BD transition), and investigate their changes as a function of stellar mass, metallicity, age, and multiplicity with unprecedented resolution

Exoplanet Demographics: Now and Beyond



GaiaNIR – Exoplanet Science

- *Cold giant planets around* stars Gaia can hardly see (*heavily reddened young stars within 200-300 pc*) or cannot see at all (*L and T dwarfs within 20 pc*)

- Detection of *gas giants at Saturn-like distances*, combined with Gaia: the *demographics of exoplanets at 5-10 au around solar-type stars* is still vastly unexplored/uncertain

- First-ever estimate of the *frequency of planetary systems* with *BOTH Jupiters AND Saturns*

- *Cold Neptunes and Super Earths beyond the snowline around* the nearest low-mass *M dwarfs* (proper motion anomaly)

Theia – Exoplanet Science

- Determine the *true mass function of temperate 1–5 $M_\oplus$ rocky planets around solar-type stars,* which is today *completely unknown*

- Measure *the true masses and 3-d architecture in multiple systems* to allow for the first time full *demographics studies* of planetary systems in the presence of *temperate telluric planets* around the nearest Sunlike stars, in high *synergy* with *Gaia* and *Doppler surveys*

Stellar type	Number of stars	Number of B comp.
F	16	2
G	17	1
K	22	9

Meunier & Lagrange 2022

- Revised estimates of Theia sensitivity indicate that the median detectable mass across the full HZ for this stellar sample is$\simeq$1.1 $M_\oplus$.

- Very low impact of stellar activity

Jupiter+Saturn analogs: Can RV surveys Do The Job?

1) The sample size accessible to Gaia+GaiaNIR is about two-three orders of magnitude larger

2) Saturn's signal: 3 m/s (sin(i) =1), 30-yr period. Instrumental systematics and activity cycles might prevent detection (Lagrange et al. 2023)

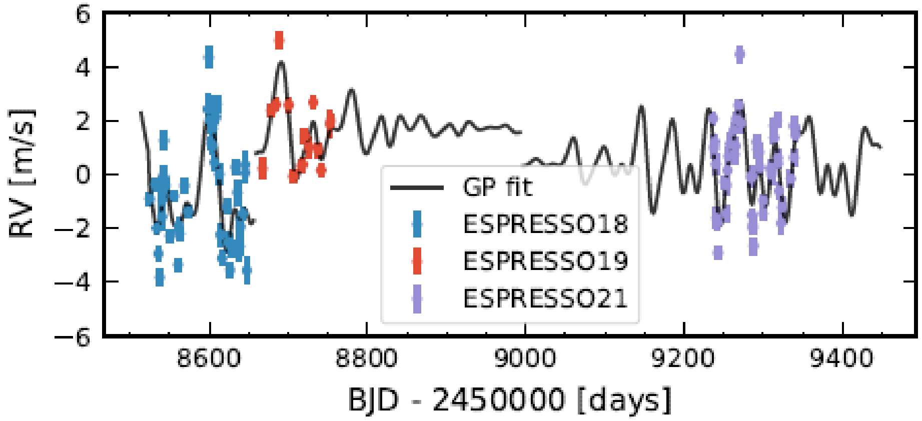
Earth analogs:
Will EPRVs Do The Job?

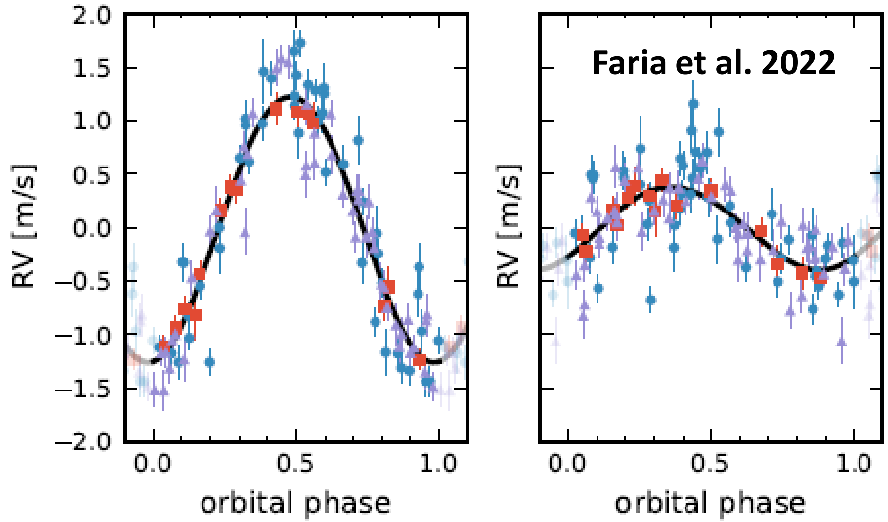
- Stellar activity the major limitation (m/s-level)

- Many approaches for mitigating the problem:
  - directly on the spectra
  - on the RVs/activity indicators

- A plethora of solar telescopes now operating:
  - fantastic sampling (not replicable to other stars), great insights on activity (but all stars are different)

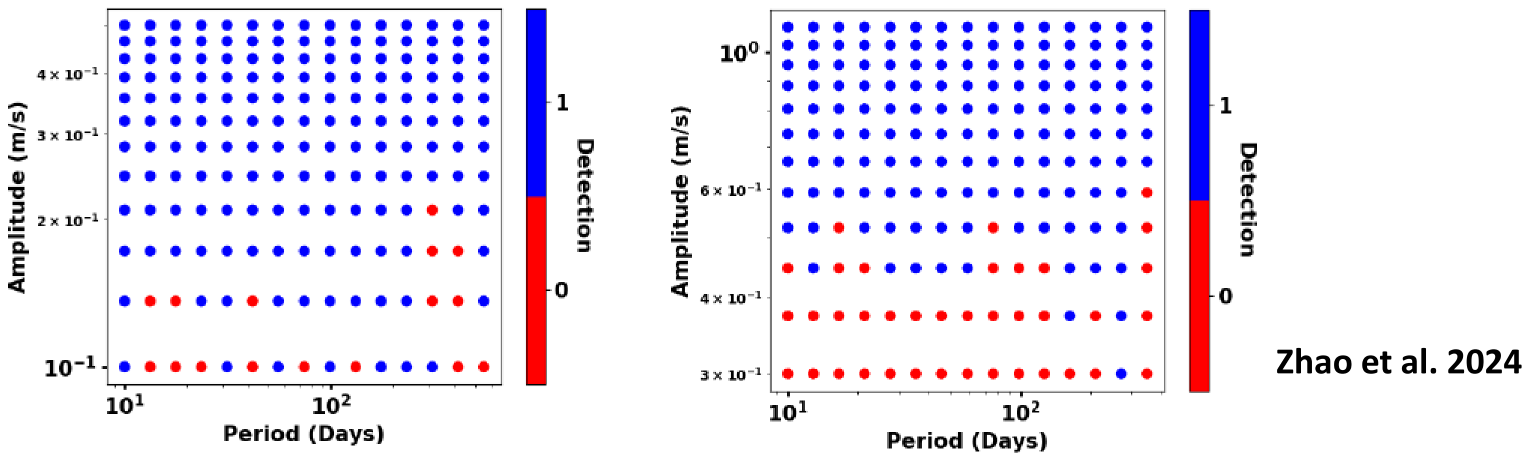
Where Do We Stand (2024)?



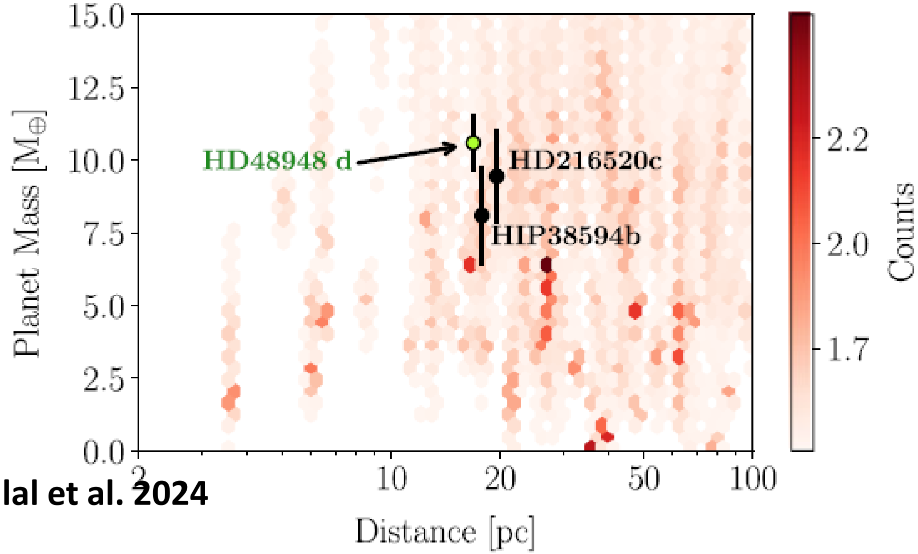


Proxima b (HZ): P=11d, K= 1.3 m/s, $M_p$sin(i) = 1.1 M_E

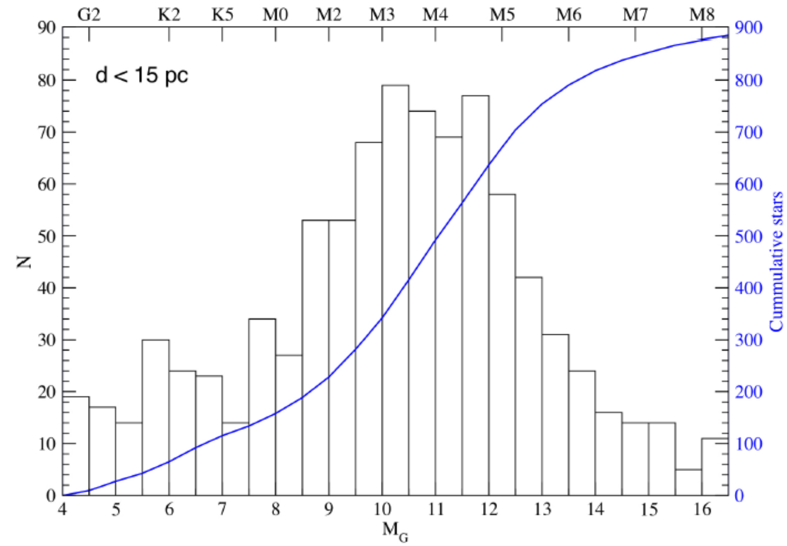
Proxima d: P=5d***, K= 40 cm/s***, ***$M_p$sin(i) = 0.3 M_E***

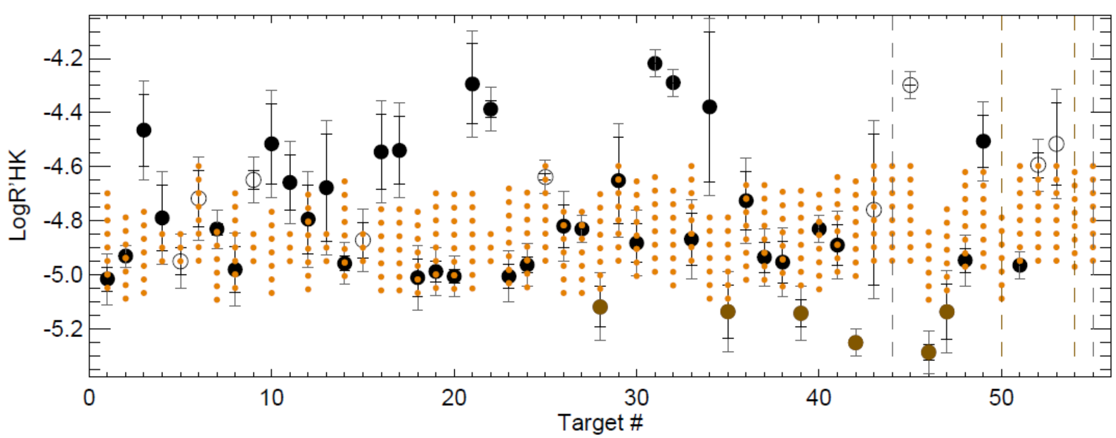


The EPRV Challenge



Dalal et al. 2024





Meunier & Lagrange 2022

Expected RV jitter:
Between a few and 10-15 m/s

From >10 to >100 times larger than the signal we seek!

Astrometry: Post-Gaia Outlook

GaiaNIR (2045-2050)

- NIR global astrometry
- Gaia-like precision

Exoplanet demographics

Census of Jupiter+Saturn-like systems around stars of varied M, age, [Fe/H]

Frequency of true Solar-System analogs

Theia (2040+)

- Visible differential astrometry
- Precision 30x better than Gaia's

Exoplanet demographics

Census of temperate terrestrial planets around the nearest solar-type stars

Precursor science for HWO or LIFE to search for atmospheric biomarkers

For binaries, TOLIMAN/SHERA

Or, using HWO itself, or both