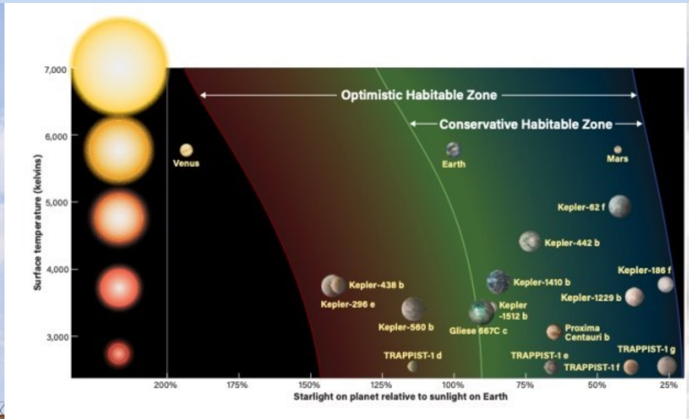
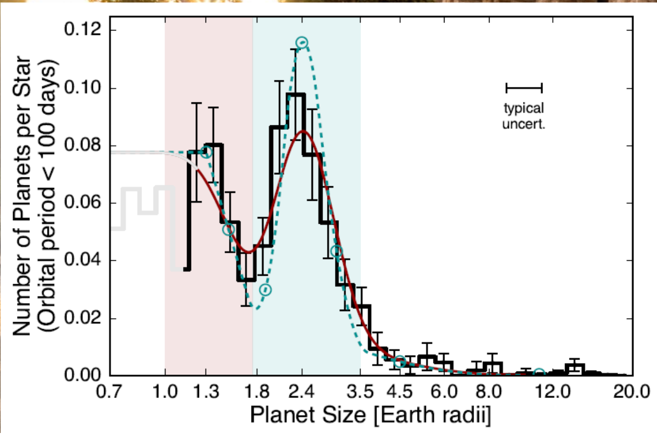
Demographics of Terrestrial Planetary Systems: Now, and in the HWO Era





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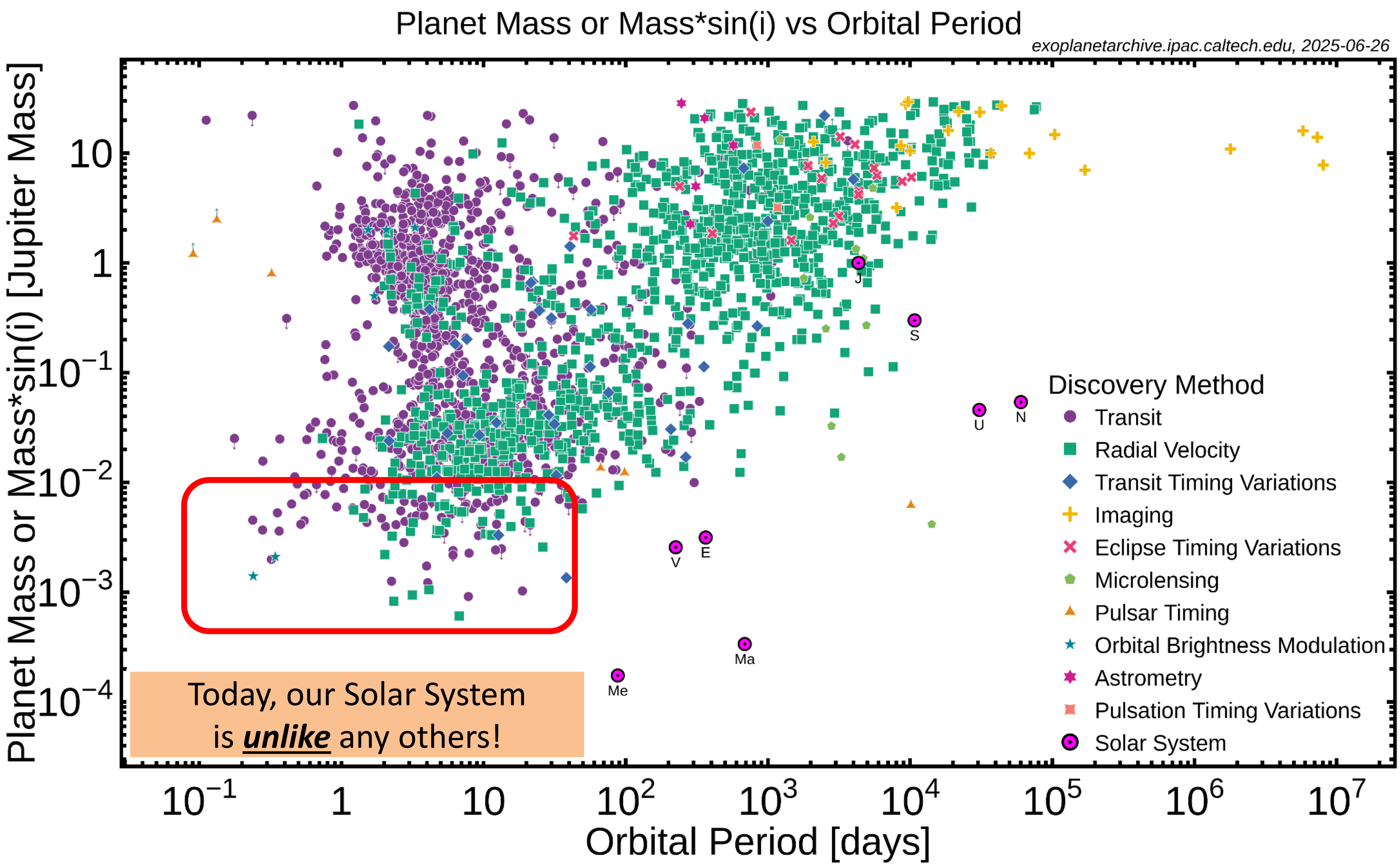
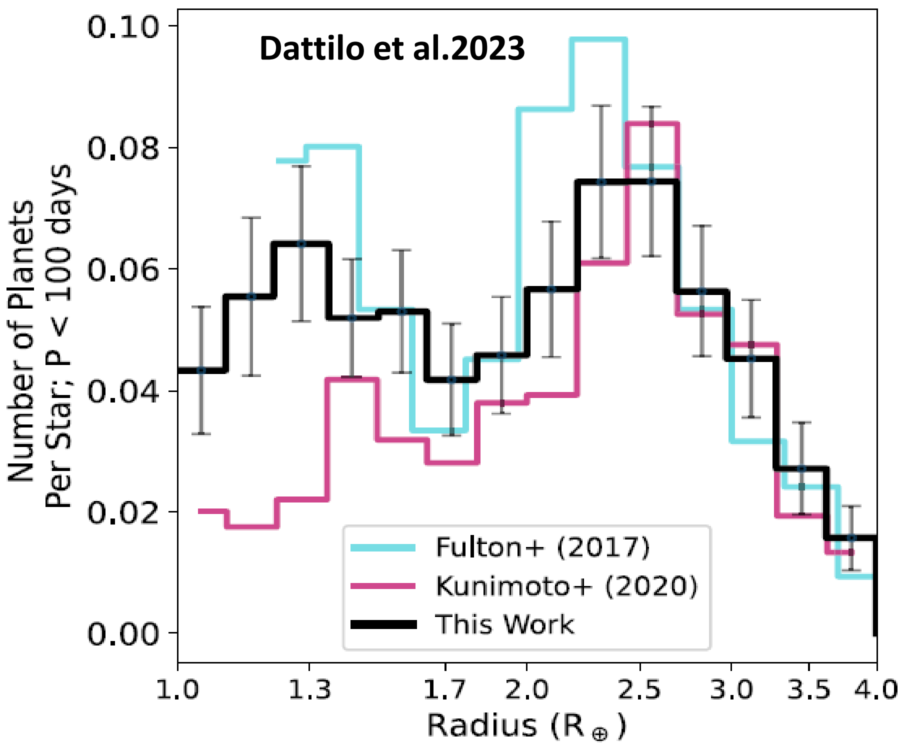
Exoplanet Demographics



Today, our Solar System is ***unlike*** any others!

Radius Distribution



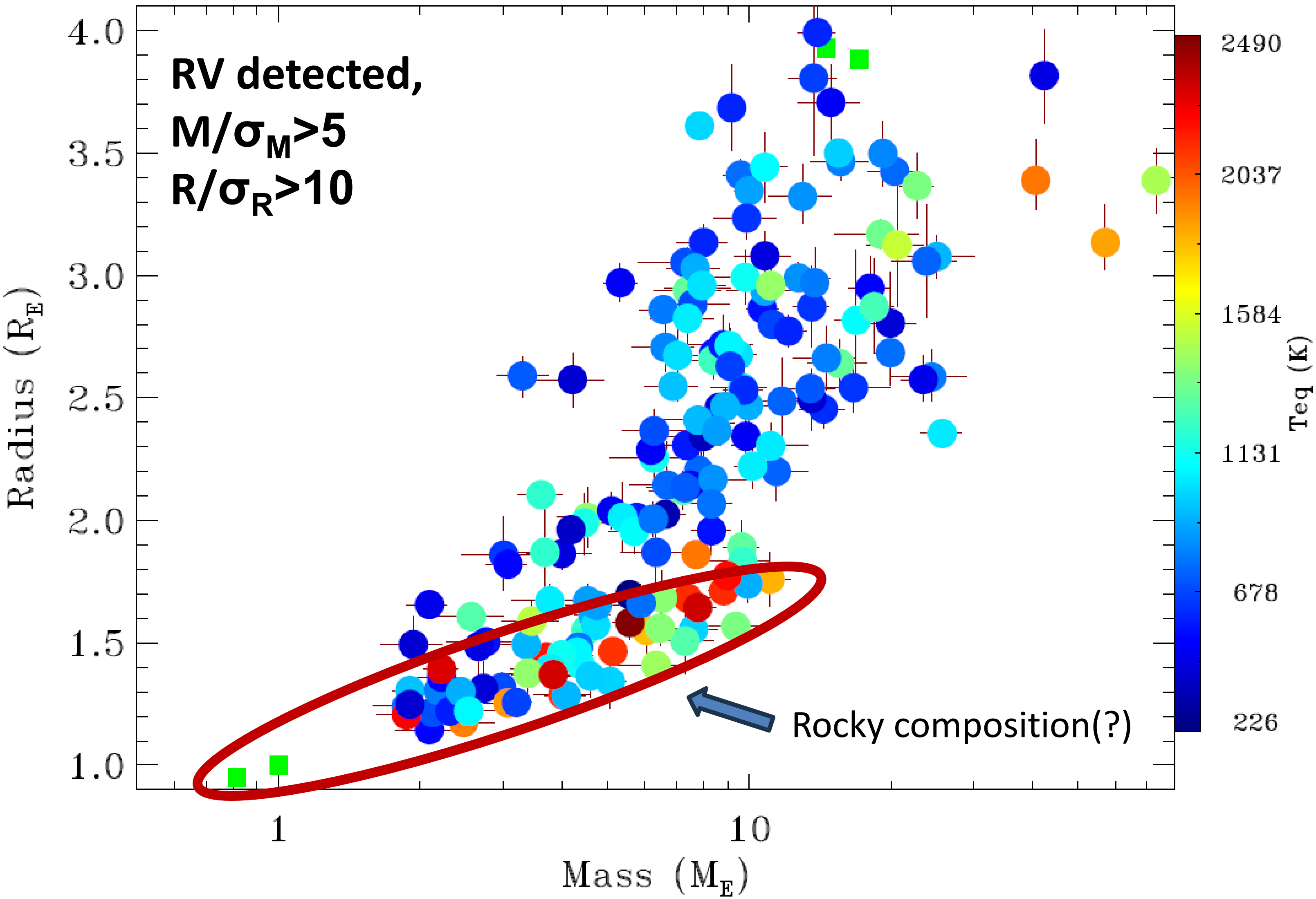
Clearly bimodal: Radius 'Valley' or 'Gap'

Two classes of close-in (P < 100 d or so) small planets:

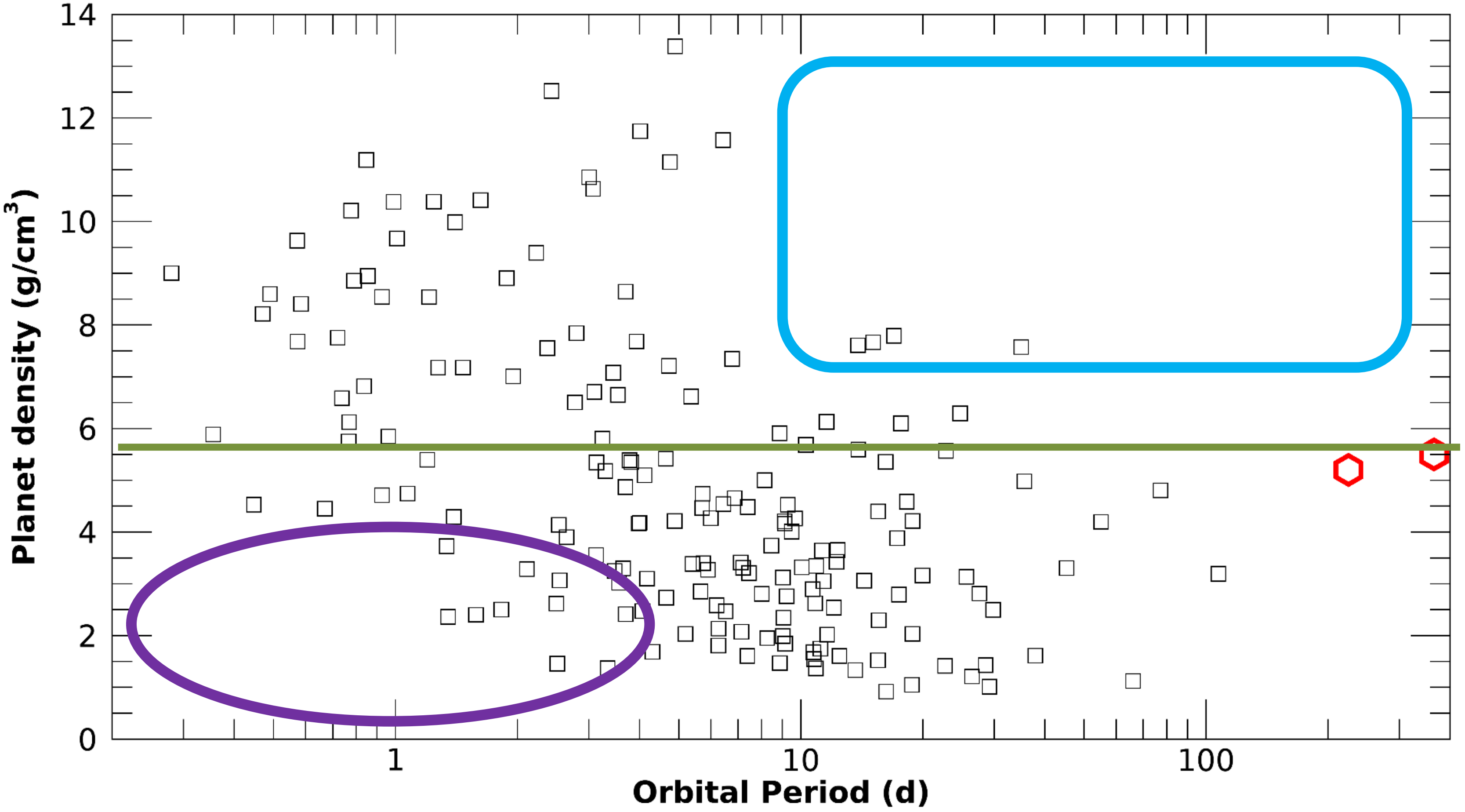
a) **(mostly) rocky super-Earths**

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

M-R Relation: Small Planets

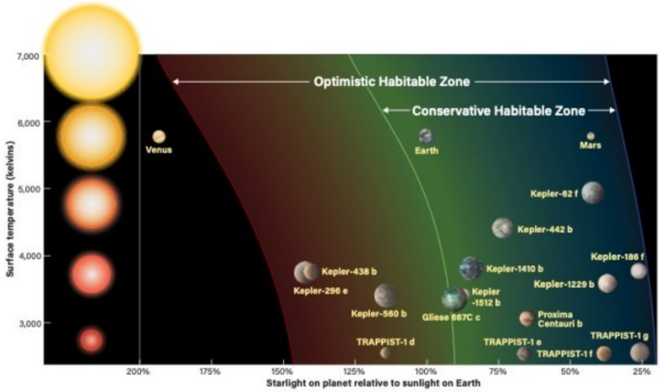


From Ultra-Short to ‘Long’ Periods



Earth Twins: Occurrence Rates

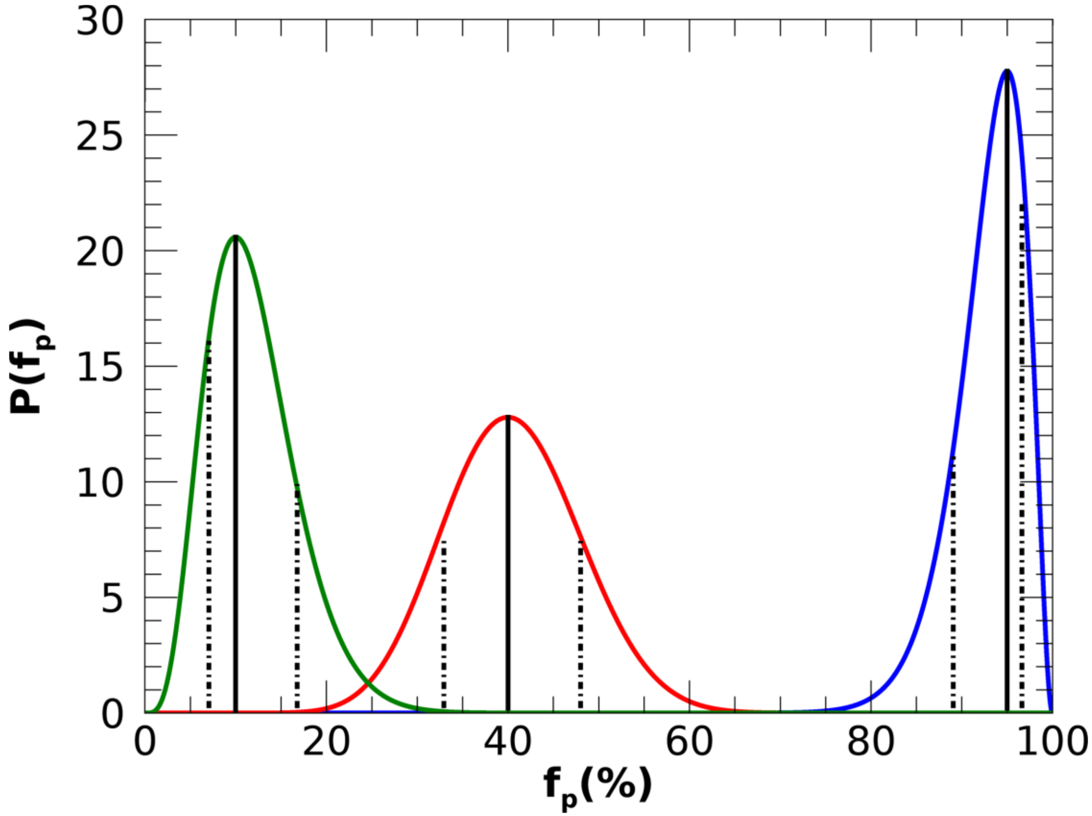
Planet type (planet-radius range in $R_\oplus$)	$\eta_\oplus$ (planets per star)	Reference	Notes
0.5 – 1.5	$0.37^{+0.48}_{-0.21} - 0.60^{+0.90}_{-0.36}$	Bryson et al. (2021)	F G K dwarfs[a]
0.5 – 1.5	$0.58^{+0.73}_{-0.33} - 0.88^{+1.28}_{-0.51}$	Bryson et al. (2021)	F G K dwarfs[b]
0.75 – 1.5	$0.13^{+0.09}_{-0.06} - 0.11^{+0.07}_{-0.05}$	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]



Within 1-2 sigma:
$\eta_\oplus$ may be 9%, or 90%...
...and just an extrapolation!

‘Ordered’ Architectures: Occurrence

Solar-System-type: *inner small planets (SP), outer, cold 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

Zhu 2024

Bryan & Lee 2025

Bonomo et al. 2025

Many attempts to determine (primarily) f_p(CJ|SP) or f_p (SP|CJ)!

Occurrence **η_{SS}** of true Solar-System-like architectures is today ***unknown…***

The BIG Questions

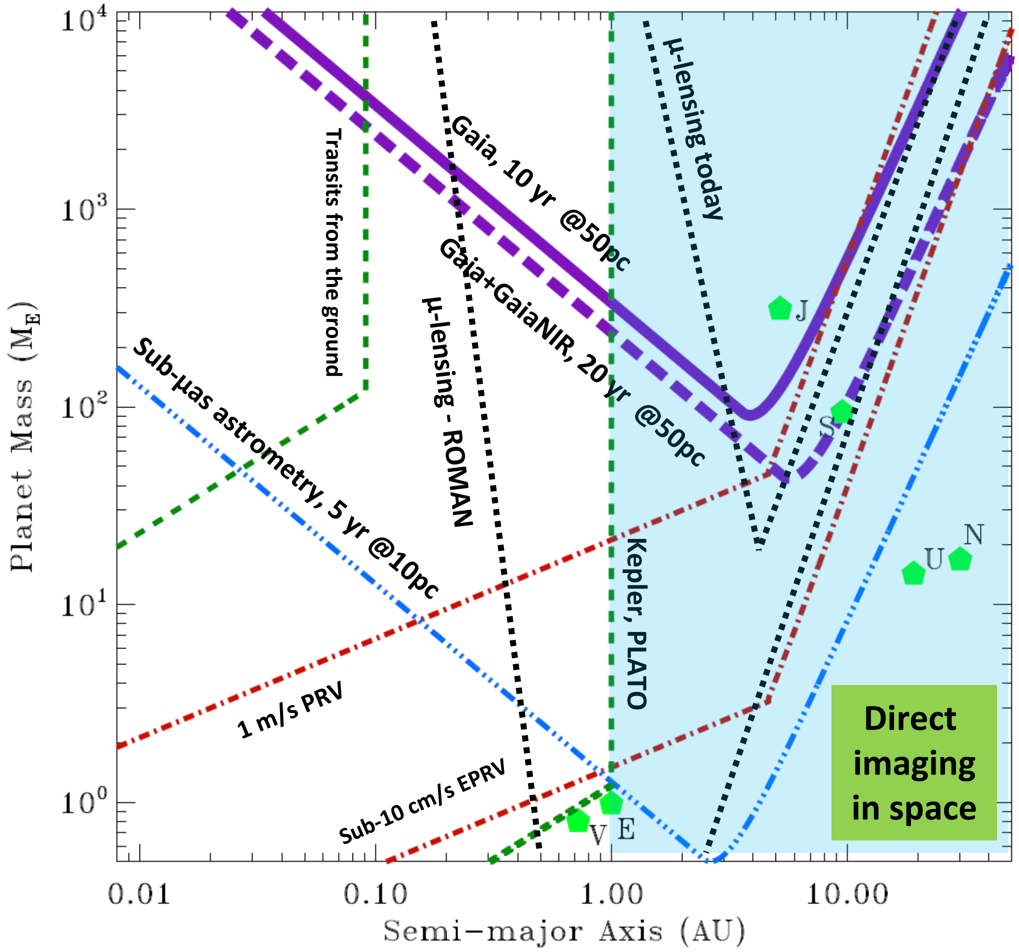
A) What is the diversity of planets and *planetary system architectures*?

B) How do the physical and *architectural properties* depend on stellar and environmental properties?

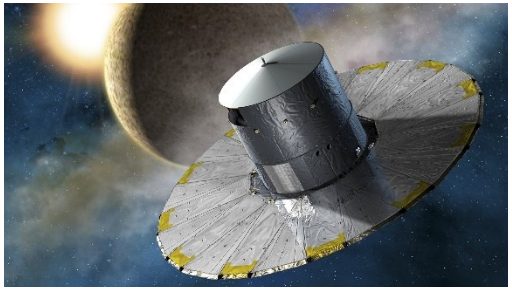
C) How common are *true* Solar System analogs?

D) Where are the nearest Earth-*like* planets?

Exoplanet Architectures: Now and By 2040-2045



The Gaia-RV-PLATO Synergy



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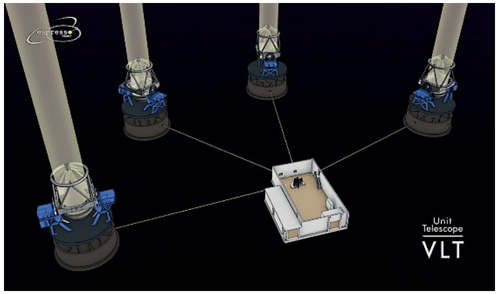

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Take $2x10^4$ P1 PLATO targets (bright, nearby FGK dwarfs):

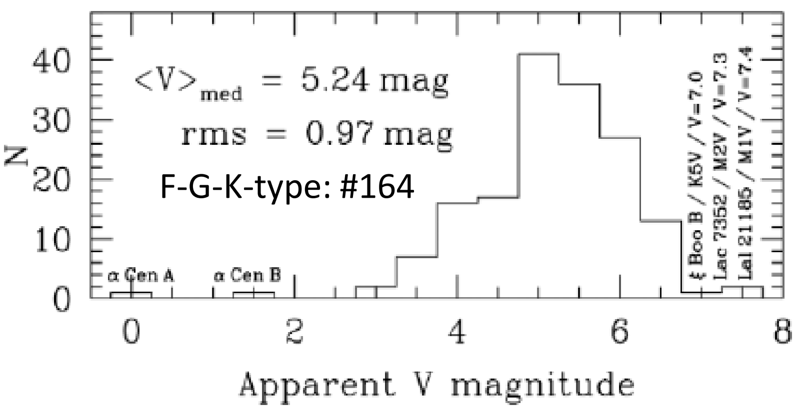
- Achieve homogeneous sensitivity to Earth-like transiting planets
- EPRV follow-up for mass confirmation for all of them
- Gaia DR4 & DR5 deliver homogeneous sensitivity to gas giants on Jupiter-like orbits

Determine $\eta_{\oplus}$ and η_{SS} for the first time without extrapolations!

Earth-*Like* Planets: The Ultimate Frontier

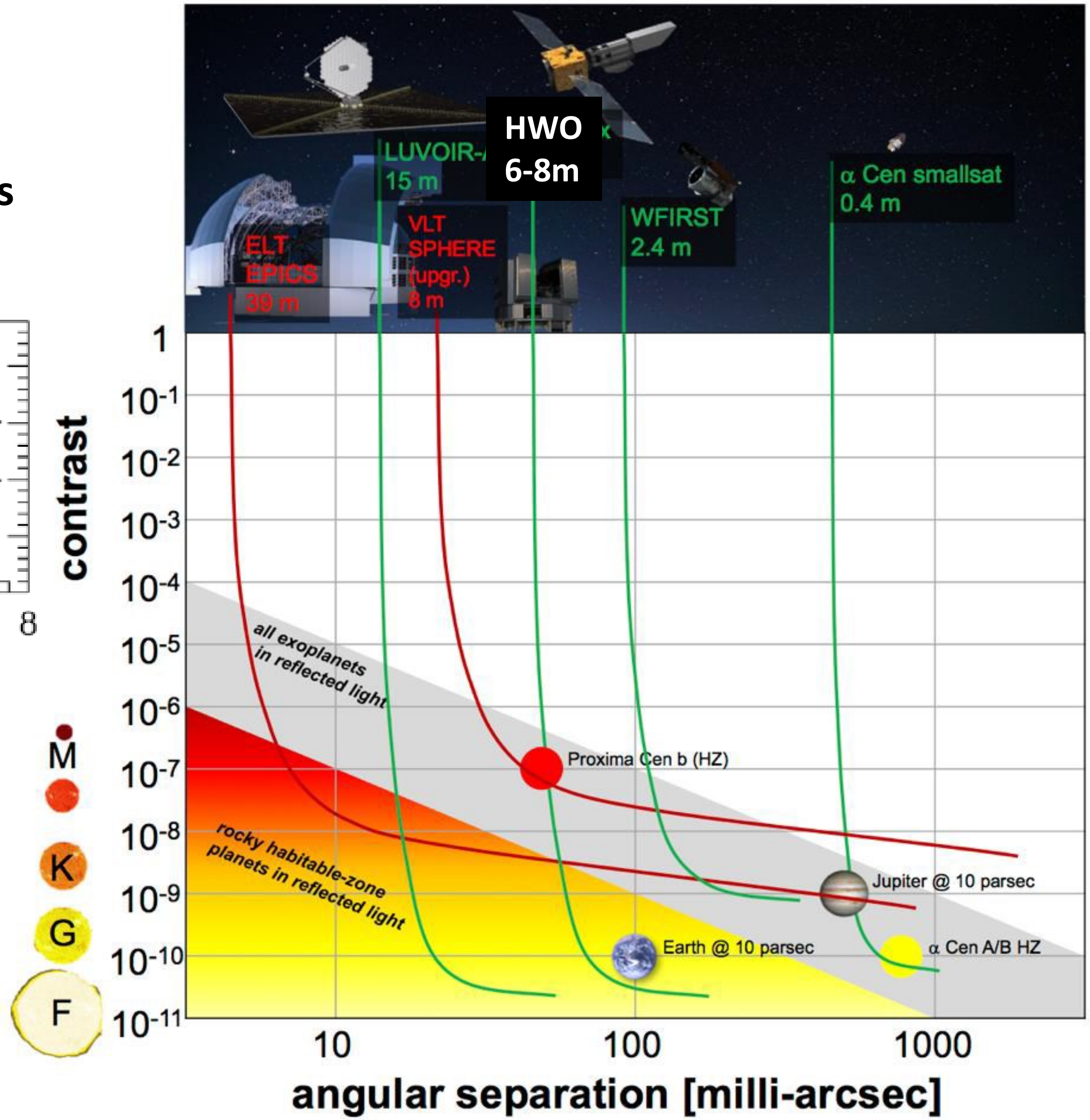
Habitability and atmospheric biosignatures of temperate terrestrial exoplanets around the <u>*nearest*</u> <u>*solar-type*</u> stars

Mamajek & Stapelfeldt 2024



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

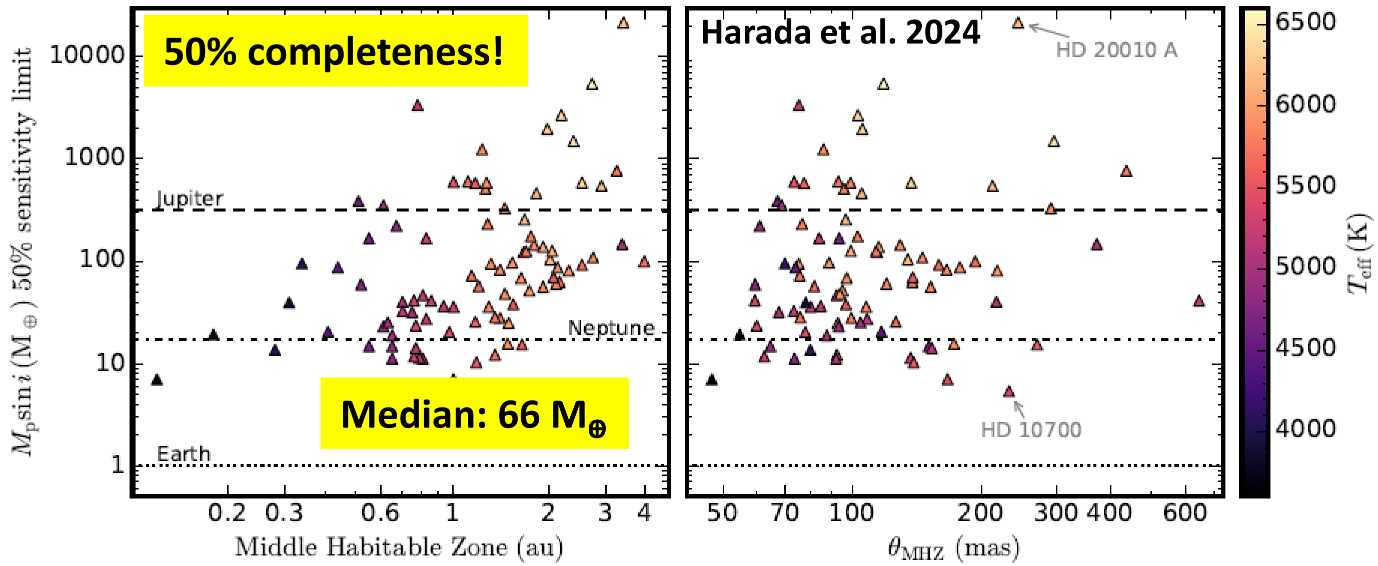
True Earth twin:
K = 9 cm/s, α@10pc = 0.3 μas



EPRVs: The Challenge

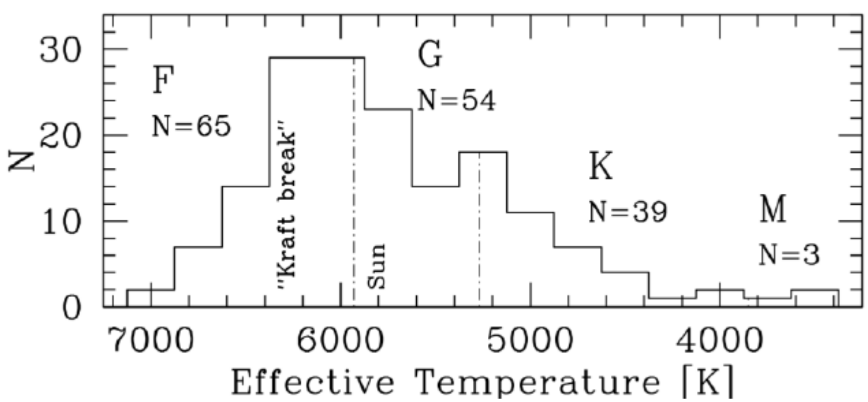
20-yr@1 m/s:
Not nearly enough!

10-yr@10 cm/s:
Coming up!
(ESPRESSO, EXPRES, MAROON-X, HARPS3)



Present Record Holders:

Proxima d: P=5d, ***K= 40 cm/s***, ***$M_p sin(i)$ = 0.3 M_E***
Barnard e: P=7d, ***K= 22 cm/s***, ***$M_p sin(i)$ = 0.2 M_E***



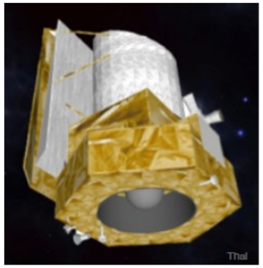
Expected RV jitter from activity:
Between a few and 10-15 m/s

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

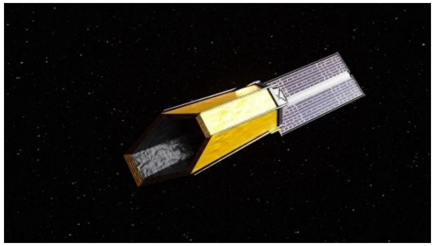
Ways of mitigating the problem:
- directly on the spectra
- on the RVs/activity indicators

Astrometry: Post-Gaia Outlook

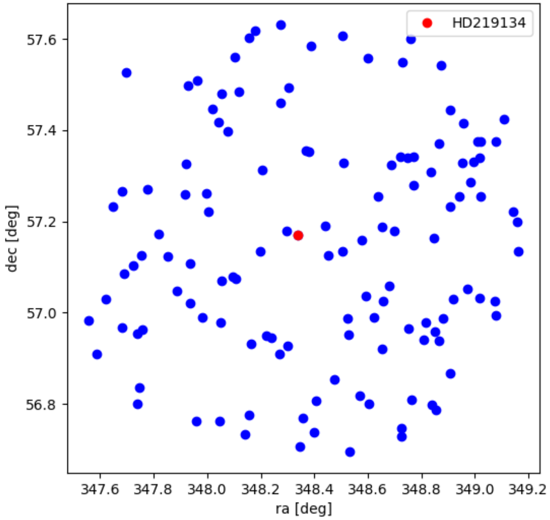
- Relative astrometry, visible wavelengths
- Precision 30x better than Gaia’s



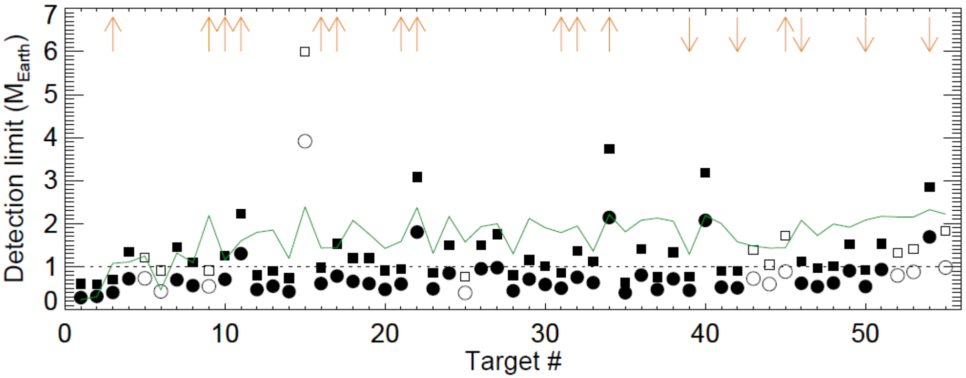
Theia (?)



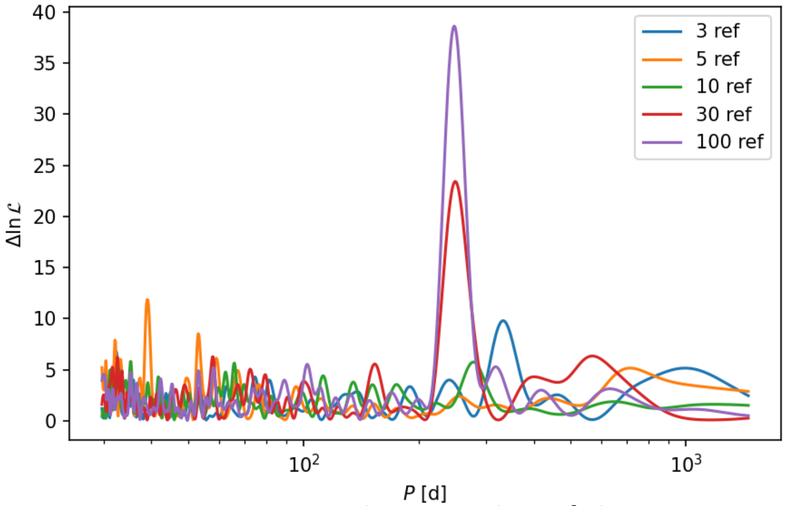
HWO



- Stellar activity: not much of an issue!
- Trade-offs: FOV size, systematics



Meunier & Lagrange 2022



Pinamonti et al. in prep.