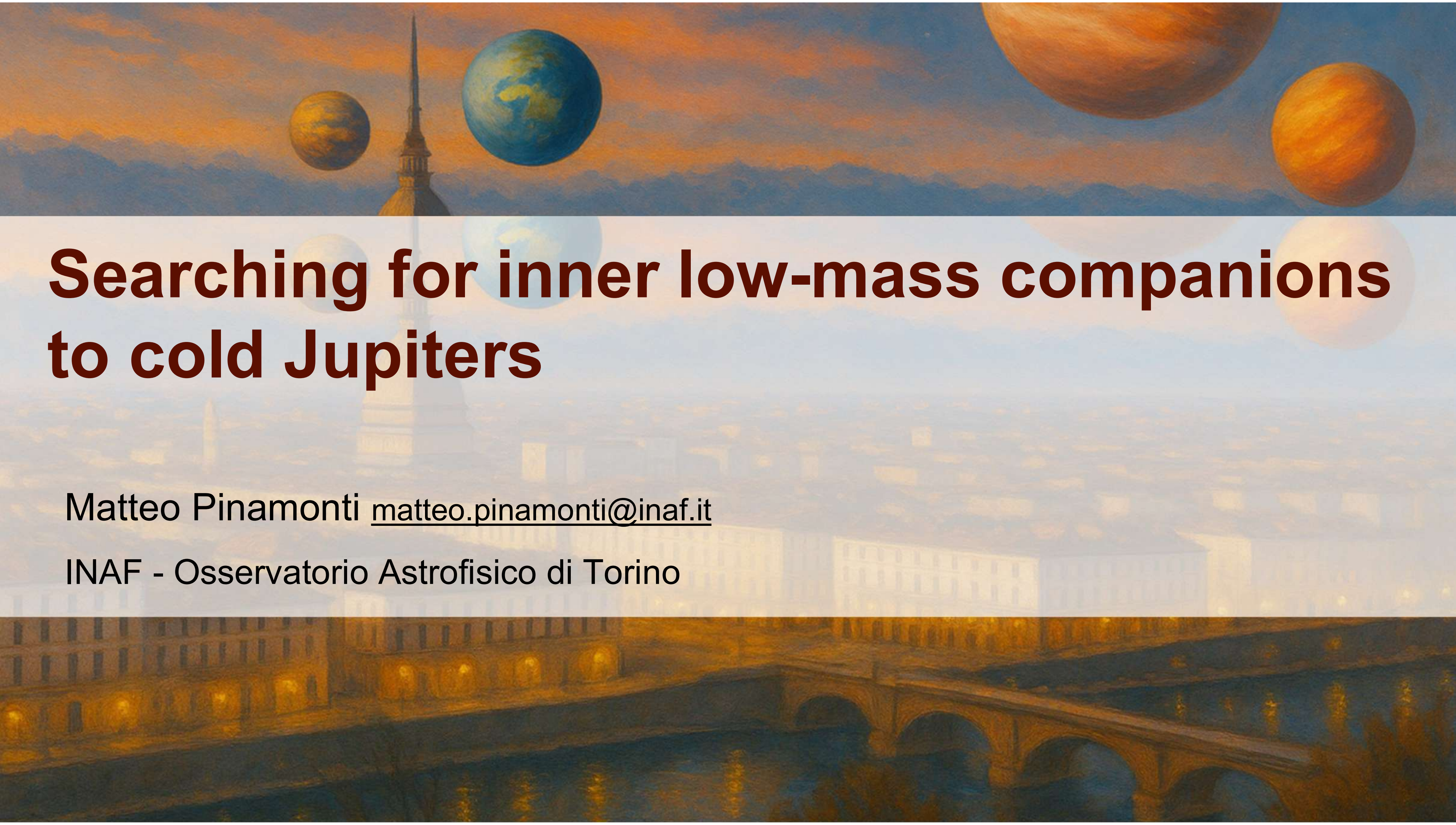
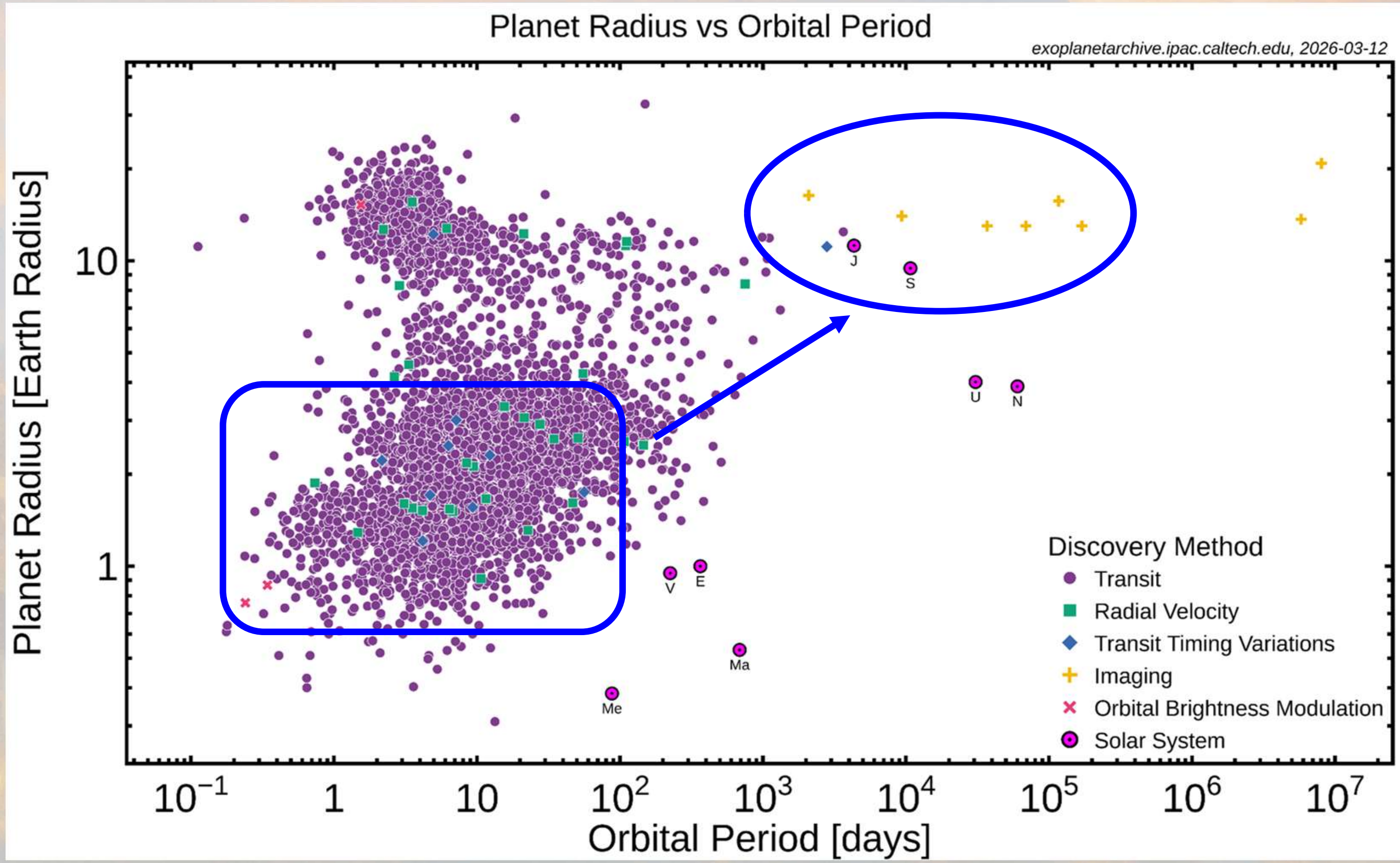


Searching for inner low-mass companions to cold Jupiters

Matteo Pinamonti matteo.pinamonti@inaf.it

INAF - Osservatorio Astrofisico di Torino

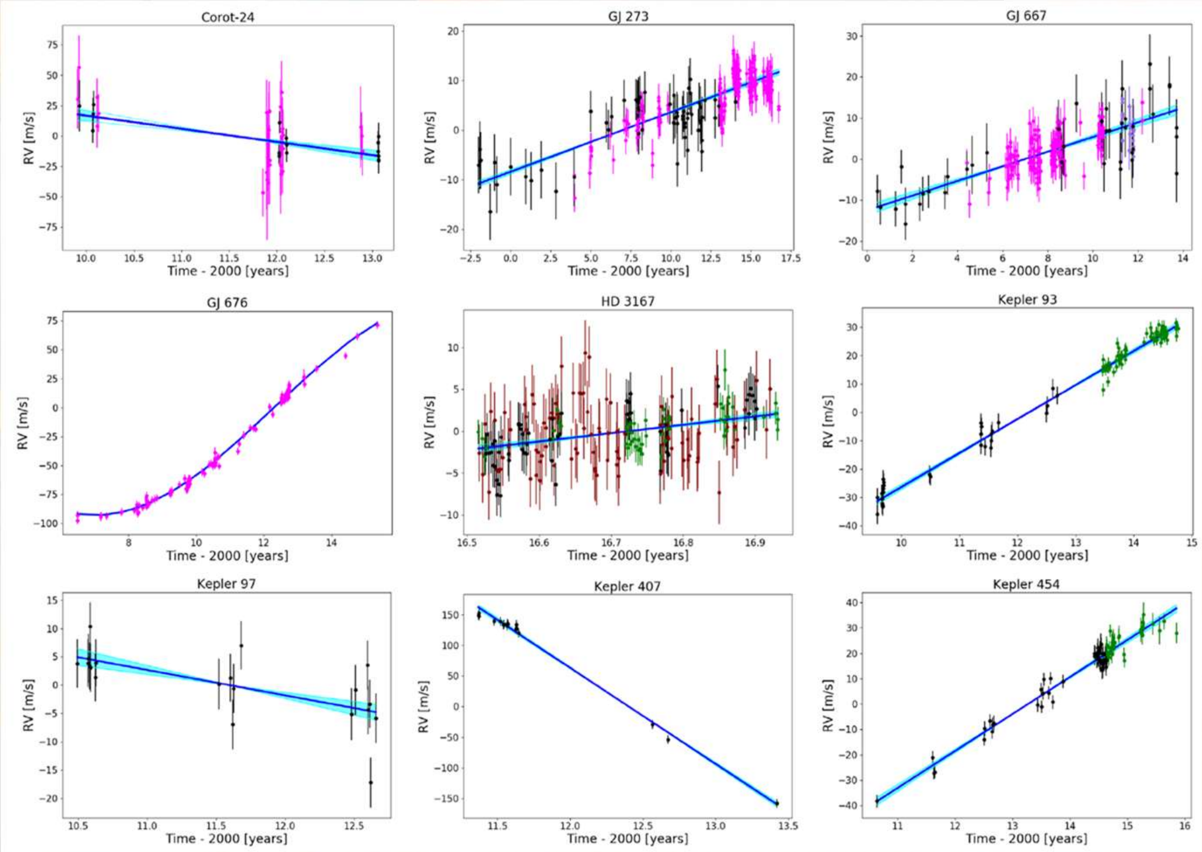
Inside-out (previous session)



Inside-out (previous session)

Detection of outer companions

Bryan et al. 2019



Inside-out: obstacles

Long-period companions difficult to detect with RVs:

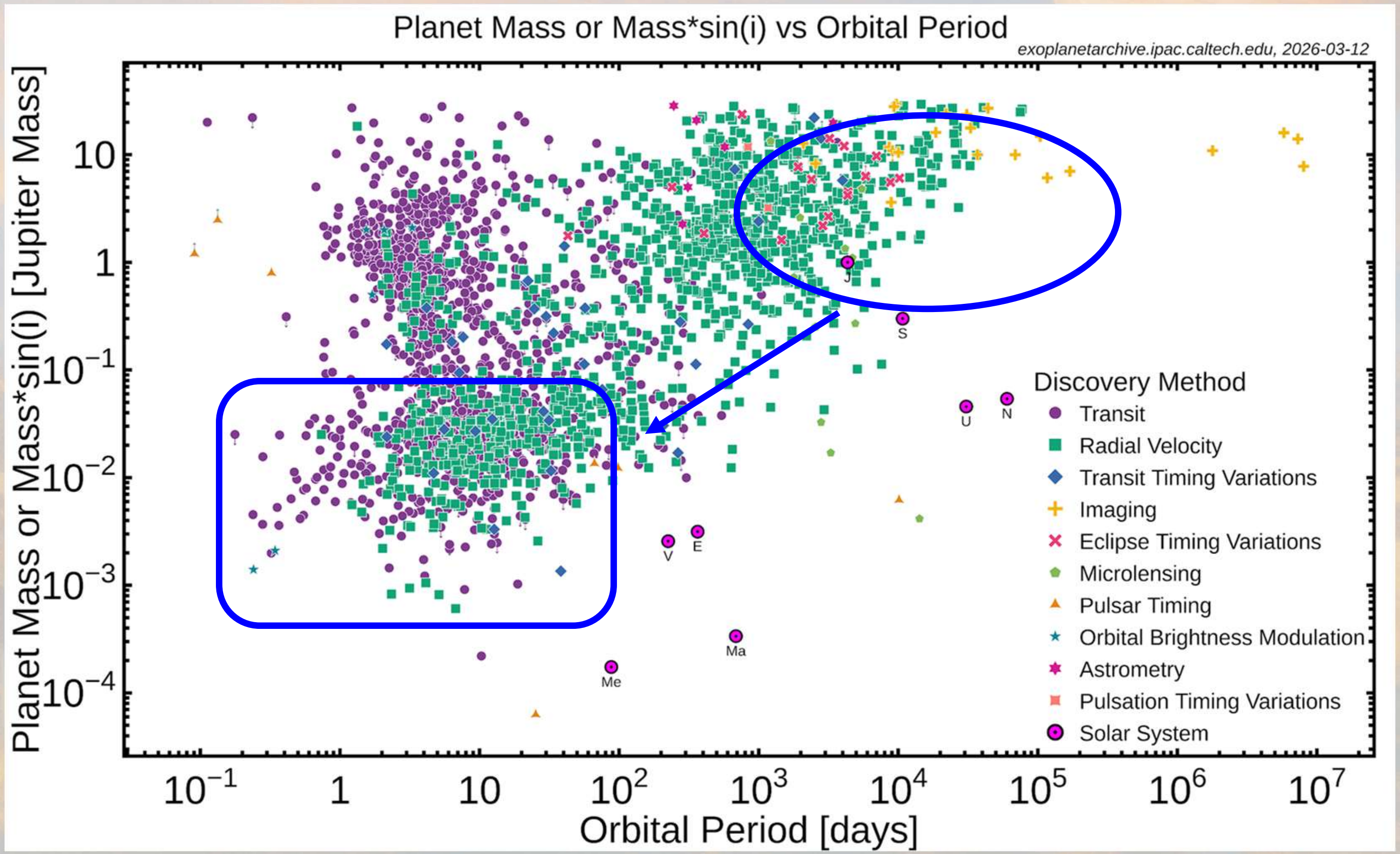
- very large time investment required to detect Jupiter-analogs (*P*=11.86 yr)
- False positives due to:
  - stellar companions
  - magnetic cycles (e.g. the Sun)

See Anne-Marie Lagrange's talk *"Cold Jupiters and the Architecture of Planetary Systems: What We Know and What We Miss"*

External confirmation needed to avoid misinterpretation!

[more on this later]

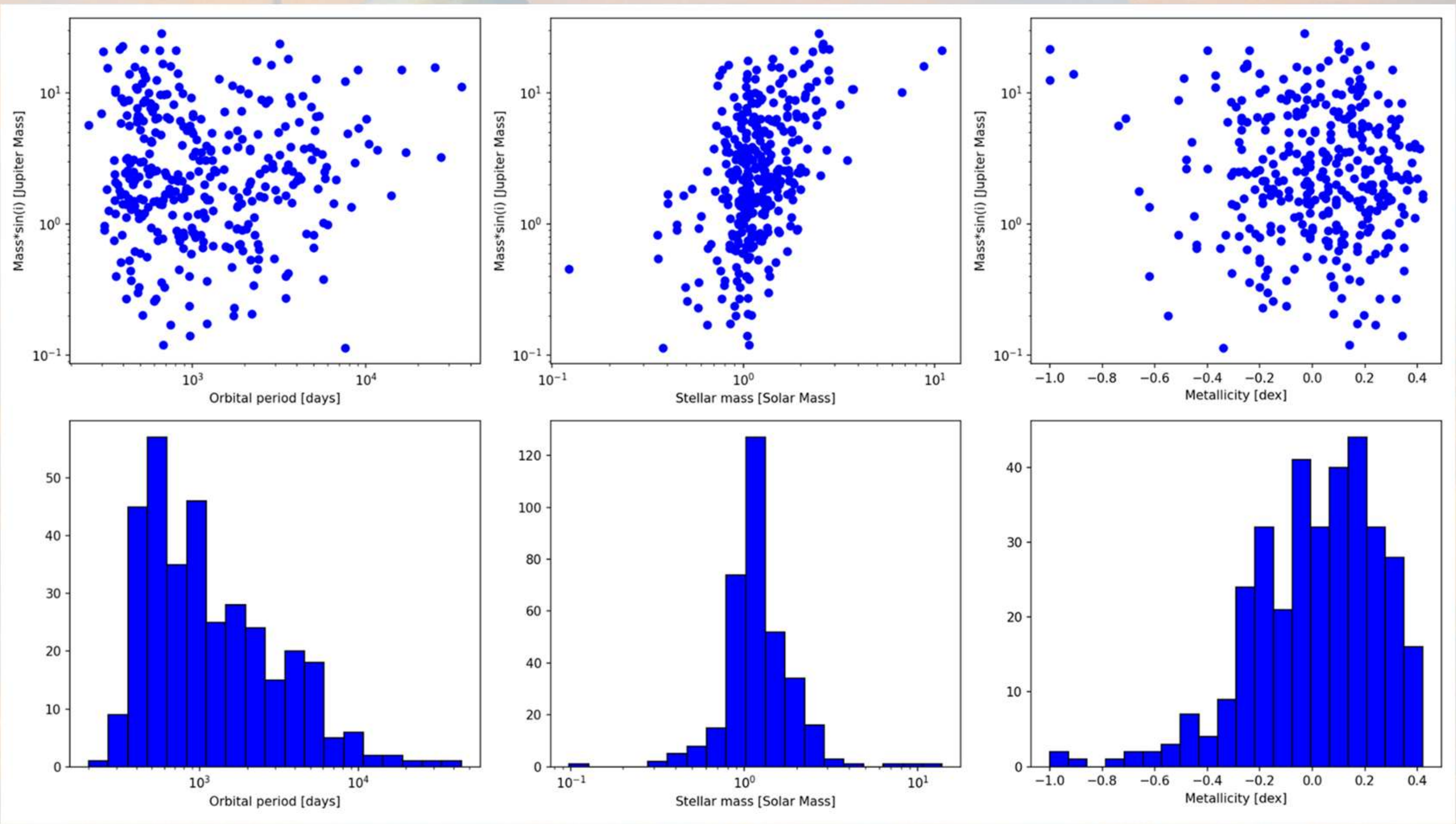
Outside-in



Planet Mass or Mass*sin(i) vs Orbital Period
exoplanetarchive.ipac.caltech.edu, 2026-03-12
Planet Mass or Mass*sin(i) [Jupiter Mass]
Orbital Period [days]
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-1}
1
10
10^2
10^3
10^4
10^5
10^6
10^7
J
S
U
N
V
E
Ma
Me
Discovery Method
Transit
Radial Velocity
Transit Timing Variations
Imaging
Eclipse Timing Variations
Microlensing
Pulsar Timing
Orbital Brightness Modulation
Astrometry
Pulsation Timing Variations
Solar System

Outside-in

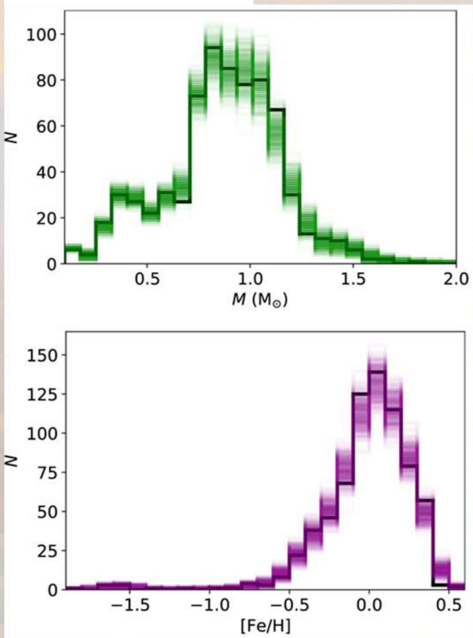
Known RV Cold Jupiters distributions



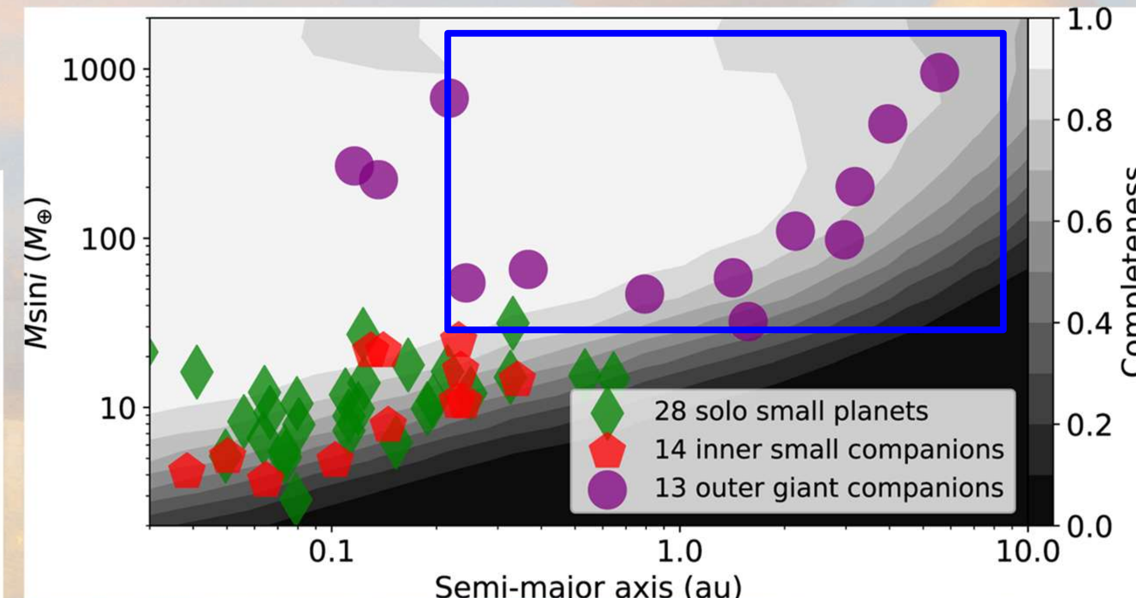
RV population studies

California Legacy survey: 719 FGKM stars

Rosenthal et al. 2021



Condition	$\langle N_P \rangle$
Inner	$0.279^{+0.055}_{-0.053}$
Outer	$0.247^{+0.022}_{-0.023}$
Jupiter	$0.078^{+0.013}_{-0.014}$
Outer|Inner	$0.47^{+0.15}_{-0.12}$
Jupiter|Inner	$0.20^{+0.12}_{-0.08}$
Inner|Outer	$0.69^{+0.19}_{-0.19}$
Inner|Jupiter	$0.34^{+0.24}_{-0.17}$

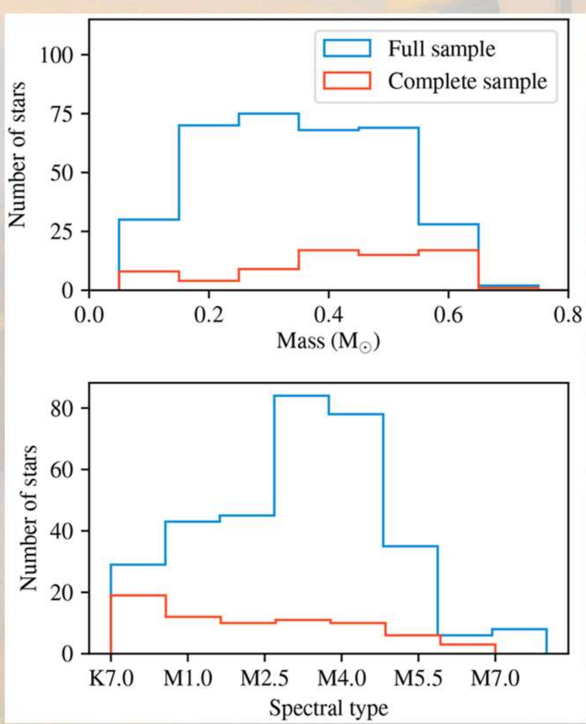


Rosenthal et al. 2022

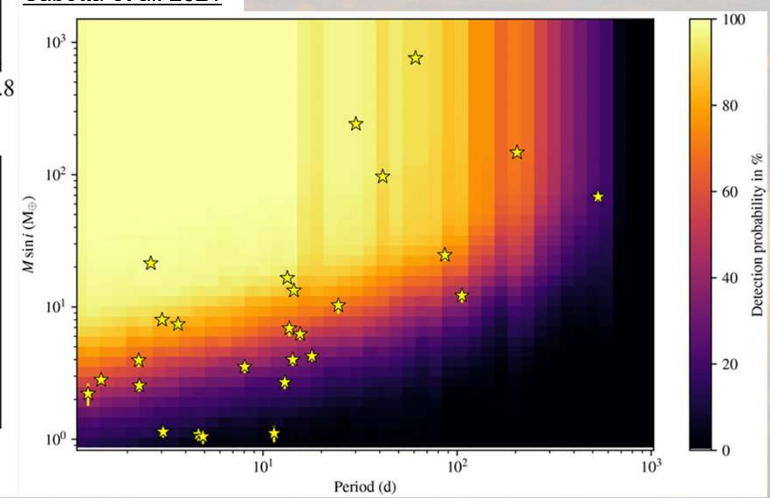
RV population studies

Stellar mass dependence: CARMENES survey 71 M dwarfs

Strong dependence on stellar mass:
low-mass short-period planets (msini<10 $M_\oplus$, P<50 d): $f_M = 1.18^{+0.31}_{-0.27}$
3x than around G-type stars (f_G=0.41±0.16)



Sabotta et al. 2021



Cold Jupiter frequency:

$$\overline{n}_{pl} = 0.05^{+0.04}_{-0.03}$$

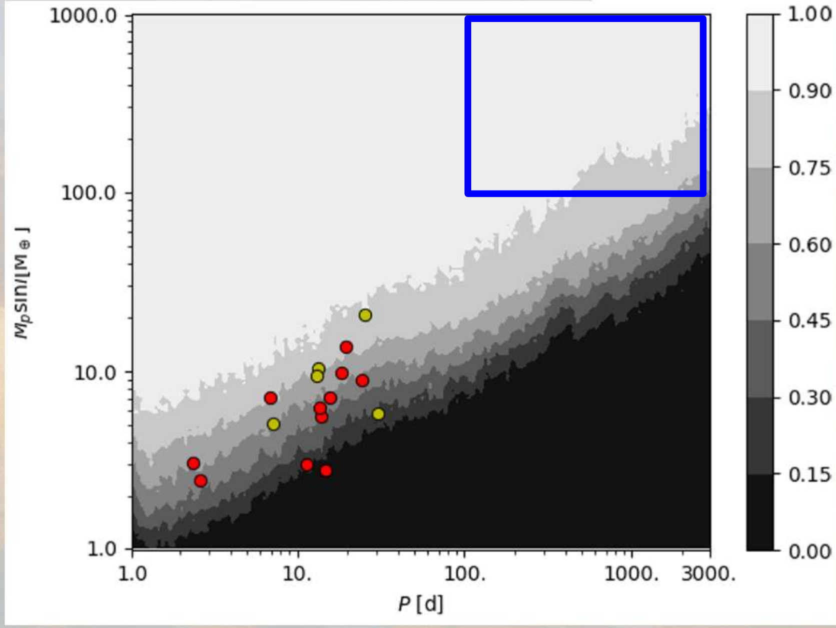
(<<FGK)

RV population studies

Stellar mass dependence: HADES survey 56 early-M dwarfs

$m_p \sin i$ ($M_\oplus$)	Period [d] [1, 10]	$[10, 10^2]$	$[10^2, 10^3]$	$[10^3, 3\times10^3]$
$[10^2, 10^3]$	$k_p = 0$	$k_p = 0$	$k_p = 0$	$k_p = 0$
–	$n = 56.0$	$n = 55.8$	$n = 54.4$	$n = 51.7$
–	$f_{occ} < 0.02$	$f_{occ} < 0.02$	$f_{occ} < 0.02$	$f_{occ} < 0.02$
$[10, 10^2]$	$k_p = 0$	$k_p = 1$	$k_p = 0$	$k_p = 0$
–	$n = 55.0$	$n = 49.3$	$n = 33.2$	$n = 14.9$
–	$f_{occ} < 0.02$	$f_{occ} = 0.02^{+0.05}_{-0.01}$	$f_{occ} < 0.04$	$f_{occ} < 0.08$
$[1, 10]$	$k_p = 3$	$k_p = 7$	$k_p = 0$	$k_p = 0$
–	$n = 29.0$	$n = 8.2$	$n = 0.7$	$n = 0.4$
–	$f_{occ} = 0.10^{+0.10}_{-0.03}$	$f_{occ} = 0.85^{+0.46}_{-0.21}$	$f_{occ} < 1.65$	$f_{occ} < 2.70$

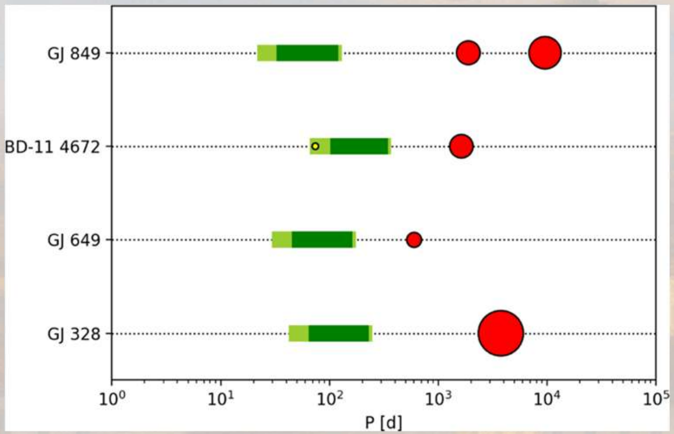
Pinamonti et al. 2022



RV population studies

GAPS late-type CJ survey

Pinamonti et al. 2023 vs Pinamonti et al. 2022



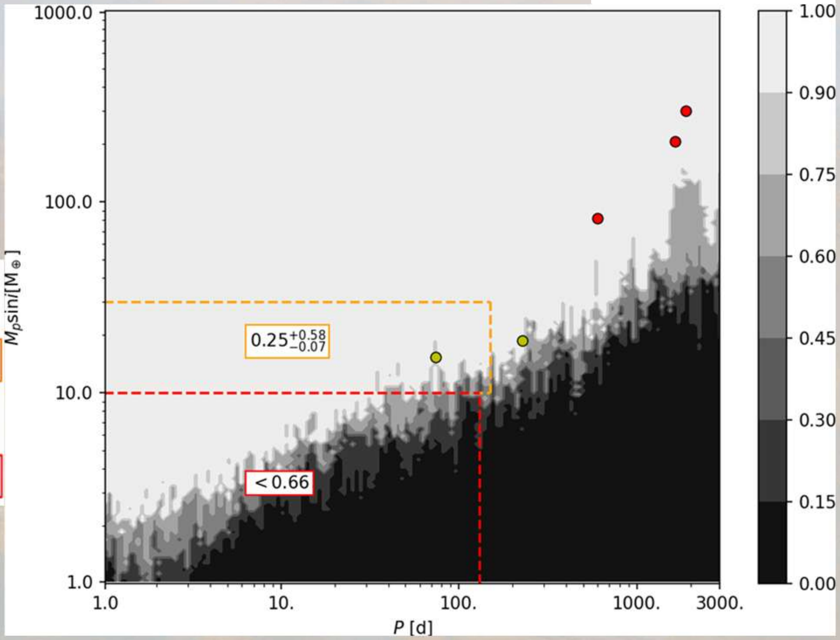
Field M dwarfs SP freq.:

$0.06^{+0.06}_{-0.02}$

Pinamonti et al. 2022

$0.74^{+0.27}_{-0.15}$

Pinamonti et al. 2023



RV population studies

GAPS Known-Planets programme

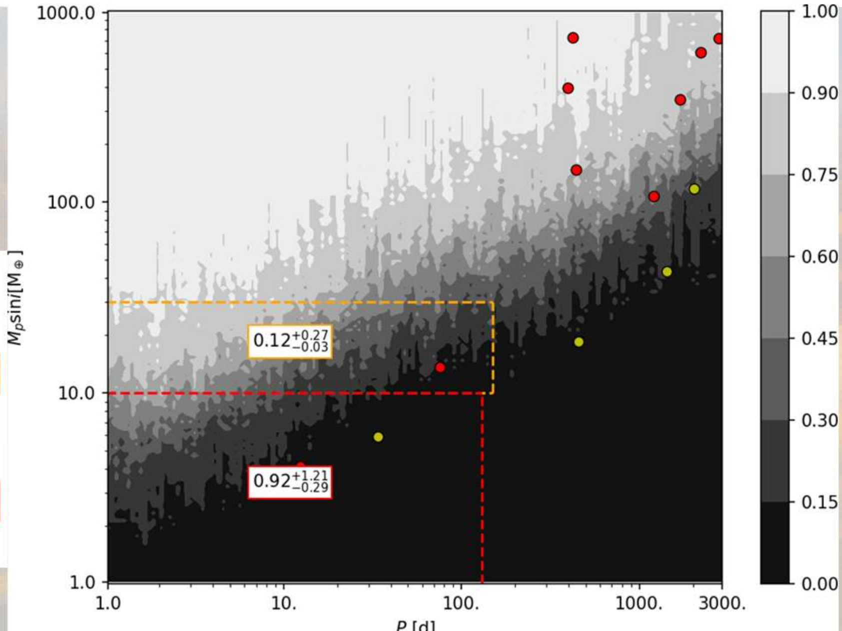
17 FGK CJ-hosts observed with HARPS-N @ TNG

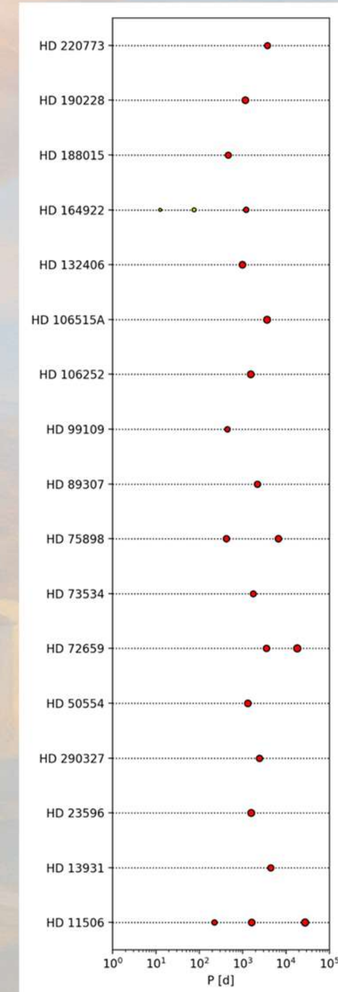
See Silvano Desidera's talk *"A new scaled Solar-System analog around a nearby bright star"*

Field stars SP frequencies:

mini-Neptunes $0.39^{+0.07}_{-0.07}$
Barbato et al. 2018

super-Earths ~ 0.30
Bryan et al. 2019



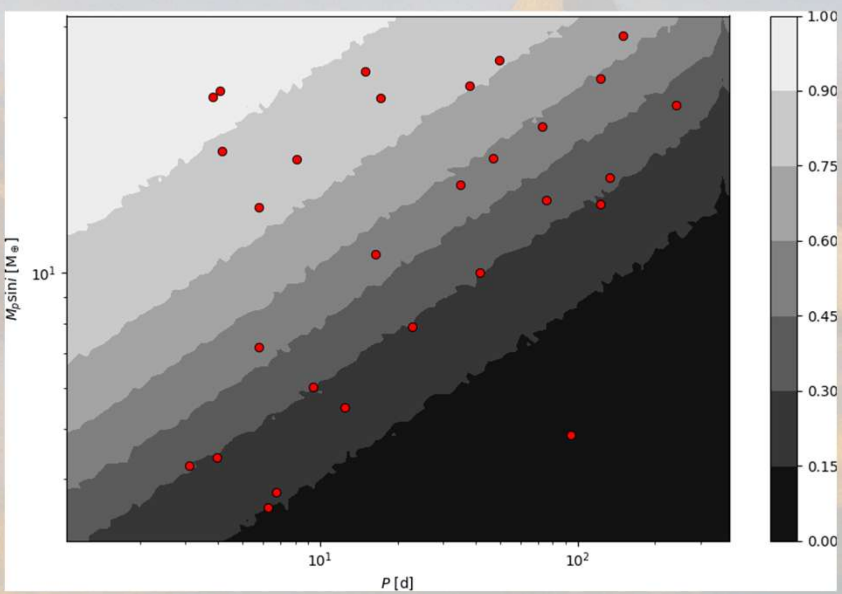


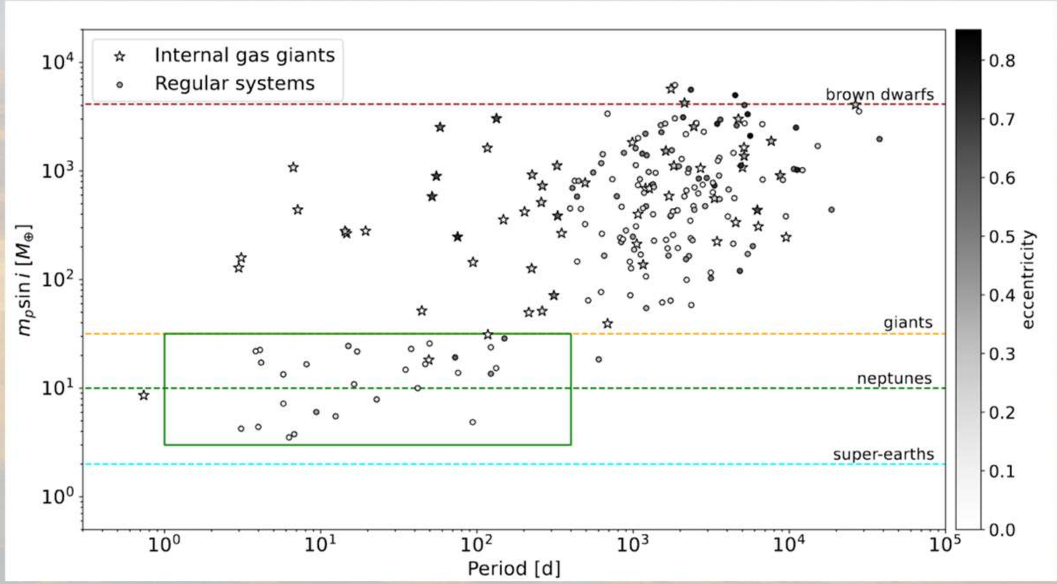
RV population studies

115 FGK stars hosting RV-detected CJs

Extension of the GAPS-KP program to include other known systems and literature data

See Alessandro Ruggieri's talk "*Occurrence rates of small close-in planets in the presence of cold Jupiters*"



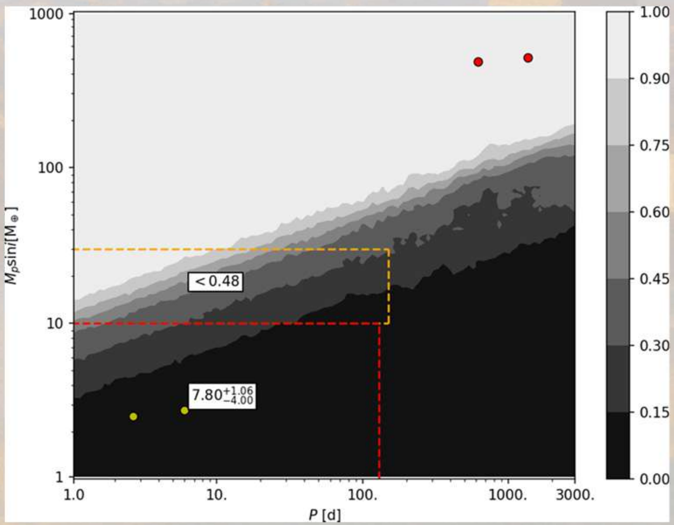


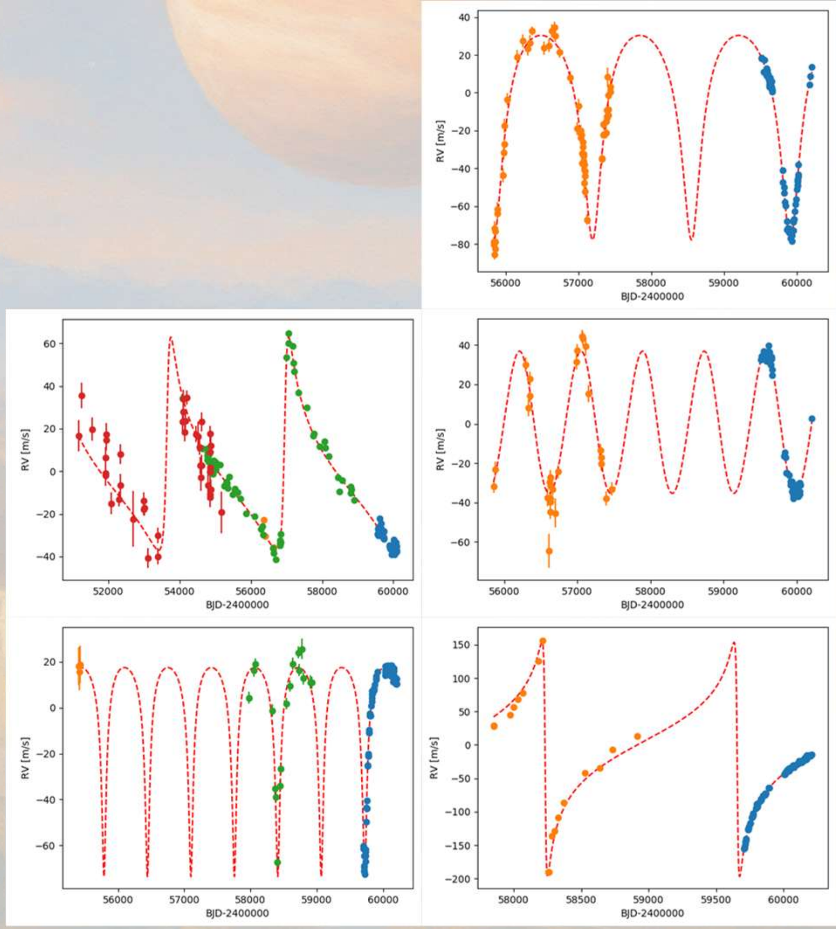
RV population studies

K-dwarf ITP survey:

Sample of 5 late-G to K dwarfs (Teff<5500), observed with HARPS-N and FIES@NOT within the ITP observing program *“Deep search for jumping super Earths around nearby K dwarfs”*.

One inner compact system of SP detected (Barbato, Pinamonti, et al., in prep.)





RV population studies

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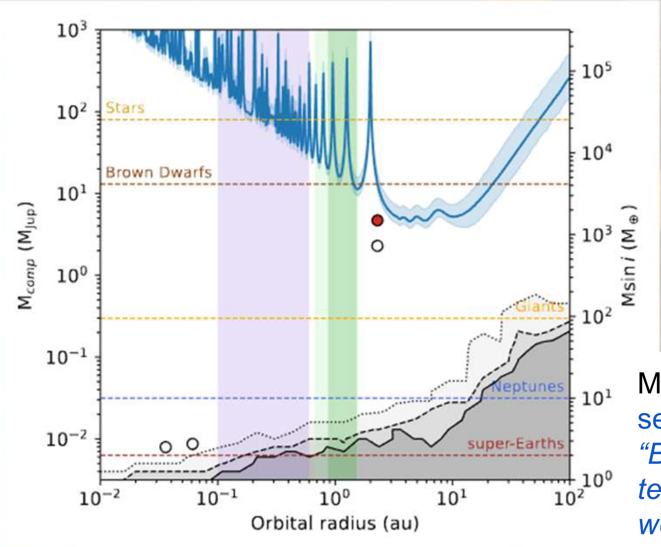
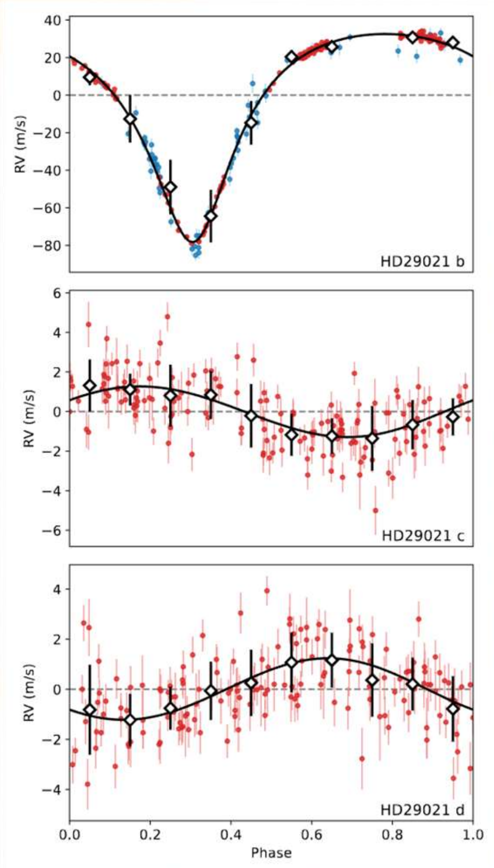


Multi-technique completeness map, see Domenico Barbato’s talk *“Bridging discovery spaces: a multi-technique view on inner and outer worlds”*

P_c = 2.67 d
$M_c \sin i$ = 2.52 $M_\oplus$

P_d = 5.94 d
$M_d \sin i$ = 2.76 $M_\oplus$



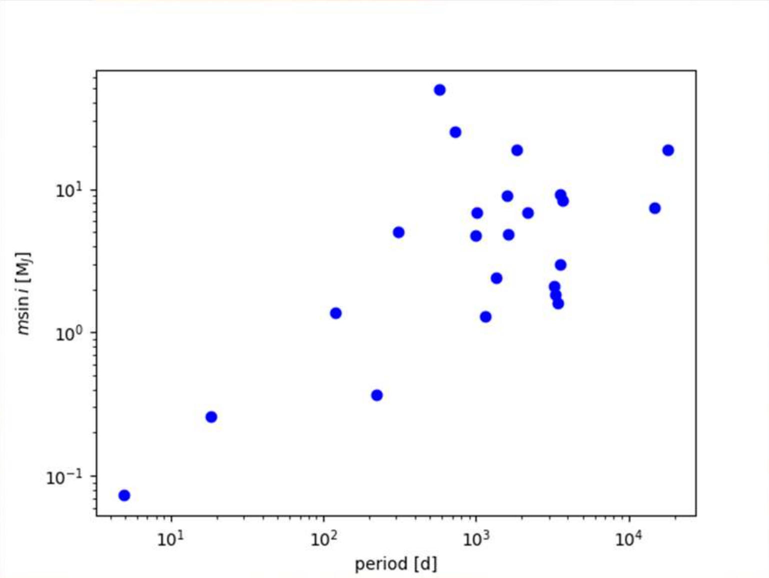
GAPS - Gaia Follow Up

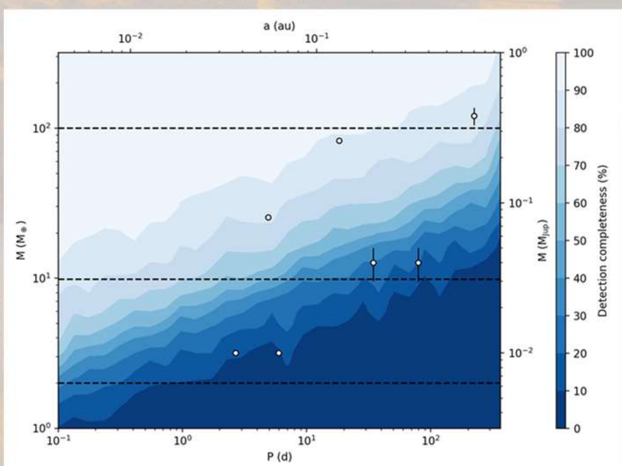
The Great HARPS-N hunt for super-Earths and Neptunes interior to outer giant planets detected by Gaia

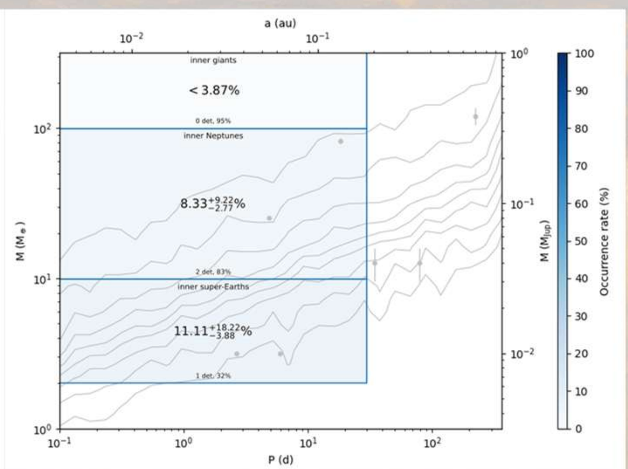
Long program at TNG to monitor around 40 stars known to host long-period giant planets and brown dwarfs from RVs and Gaia Astrometry.

(some false-positive contamination by SB2s, Barbato et al., submitted to A&A)

See also Adriana Barbieri's poster *"Follow-up analysis of HIP 105707"*







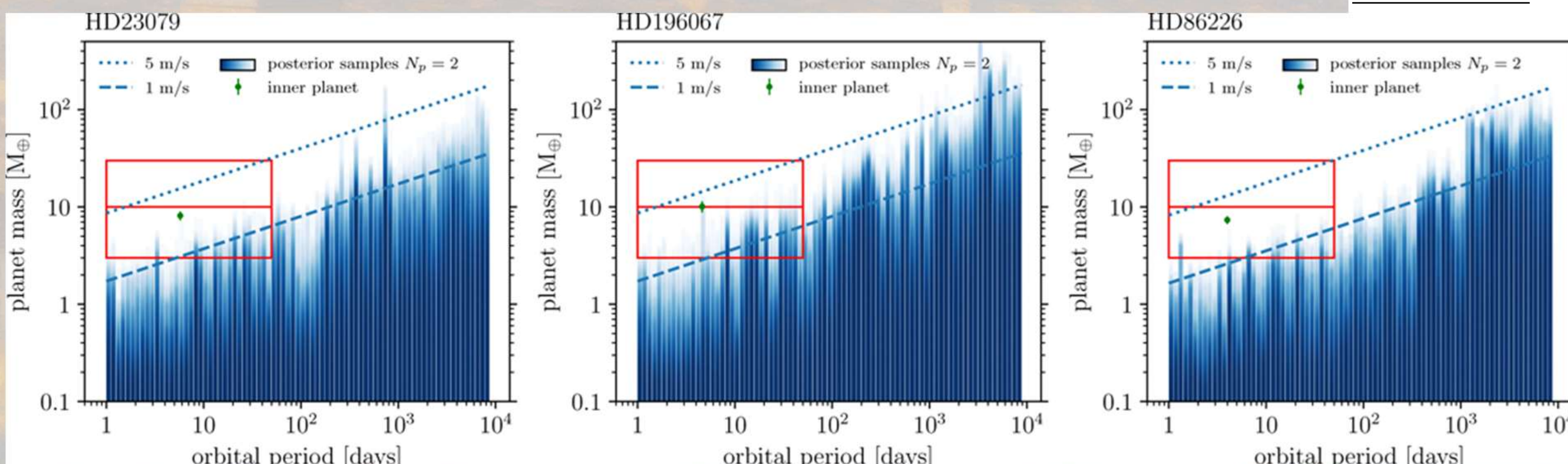
RV population studies

Architecture of planetary systems with and without outer giant planets

Long-term survey with CORALIE, HARPS, and ESPRESSO of systems with and without CJs (Delisle et al. 2025)

Homogeneous samples and **uniform observations** to avoid "*observer-excitement bias*"

Delisle et al. 2025



Cold-Jupiter detection

Long-period companions difficult to detect with RVs:

- very large time investment required to detect Jupiter-analogs (*P*=11.86 yr)
- False positives due to:
    - stellar companions
    - magnetic cycles (e.g. the Sun)

External confirmation needed to avoid misinterpretation!

[continue]

Astrometry

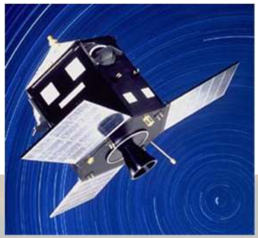
Cold-Jupiters mass determination

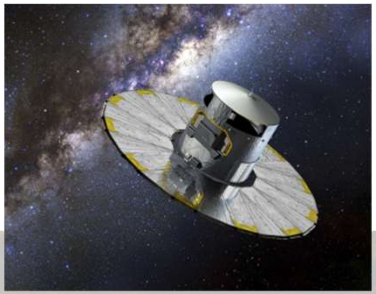
From RVs only $m_p \sin i$ is measured.
No inclination, **no** true planetary mass.

Astrometry can solve this!

Two possible approaches:

1. **Gaia Astrometric time series** (DR3, DR4 simulations);
2. **Proper Motion Anomaly** (PMA), between Hipparcos and Gaia



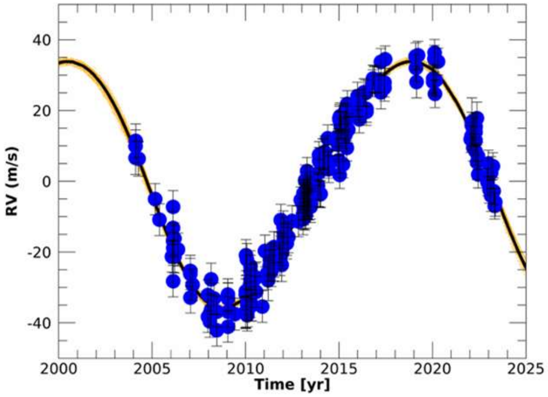


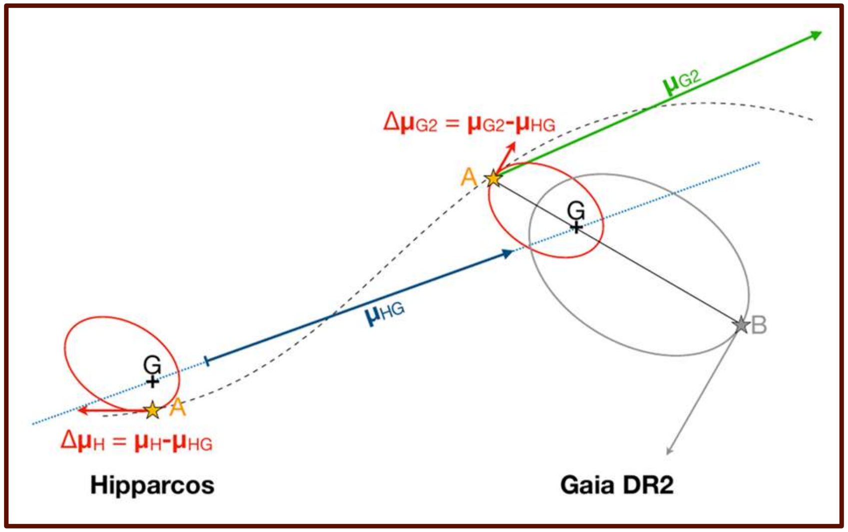
Angular semi-major axis $\propto M_p * a$
RV semi-amplitude $\propto M_p * a^{-1/2}$

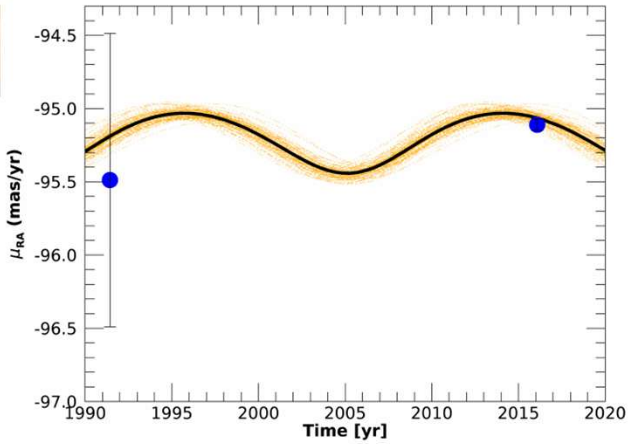
Astrometry: PMA applications

HD 75898c

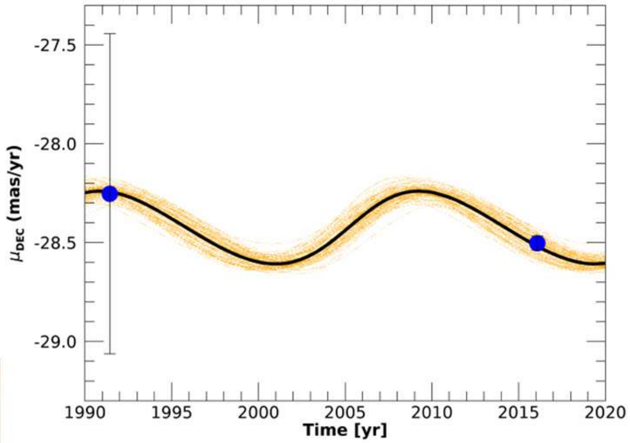
RV detected Cold-Jupiter
P = 18 yr
$m_p \sin i$ = 3.78 M_J







Ruggieri et al. 2024



Astrometry: PMA examples

HD 75898c

RV detected Cold-Jupiter

P = 18 yr

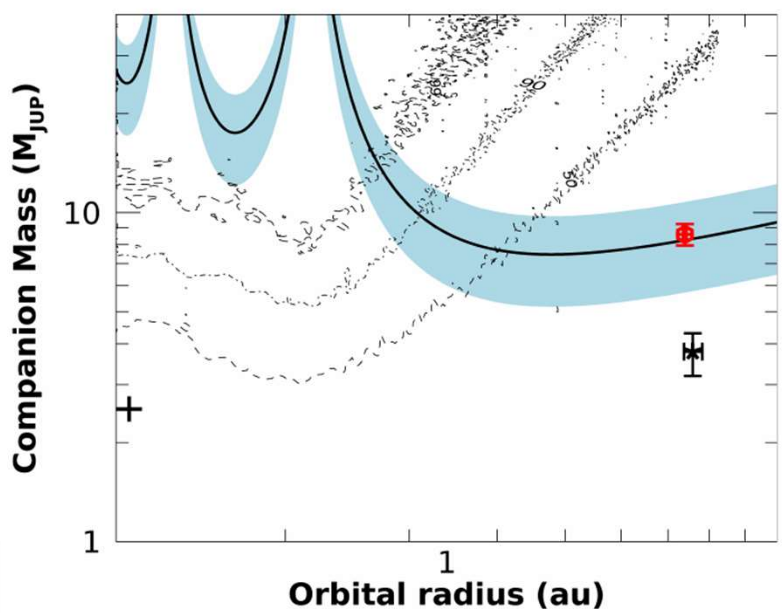
$m_p \sin i$ = 3.78 M_J

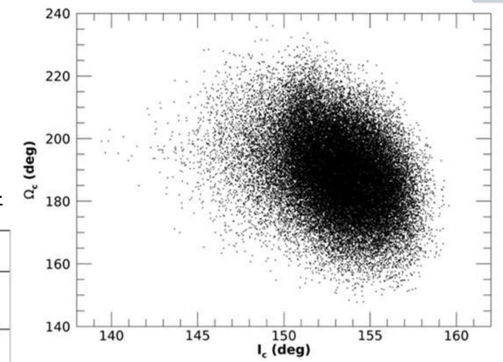
RV+PMA

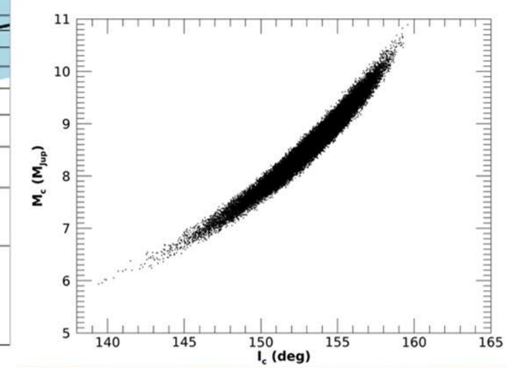
i = 153°

m_p = 8.5 M_J

Ruggieri et al. 2024







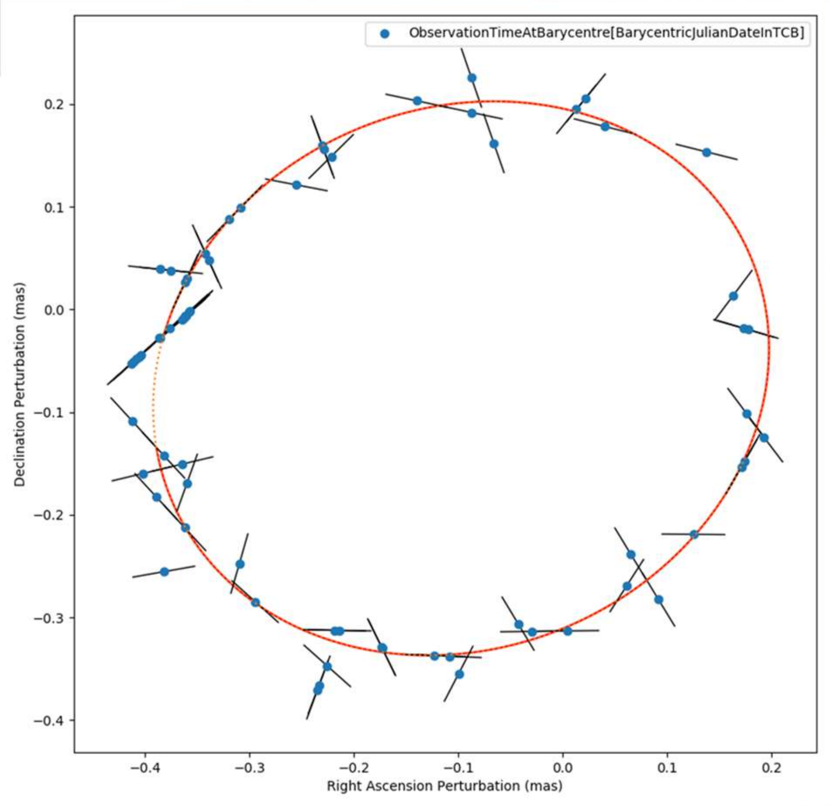
Astrometry: Gaia candidates

HD 128717 / Gaia-ASOI-009

Gaia DR3 solution

m_p = 10 M_J
P_b = 1090 d
e_b = 0.39

Simulation of Gaia DR3 time series:



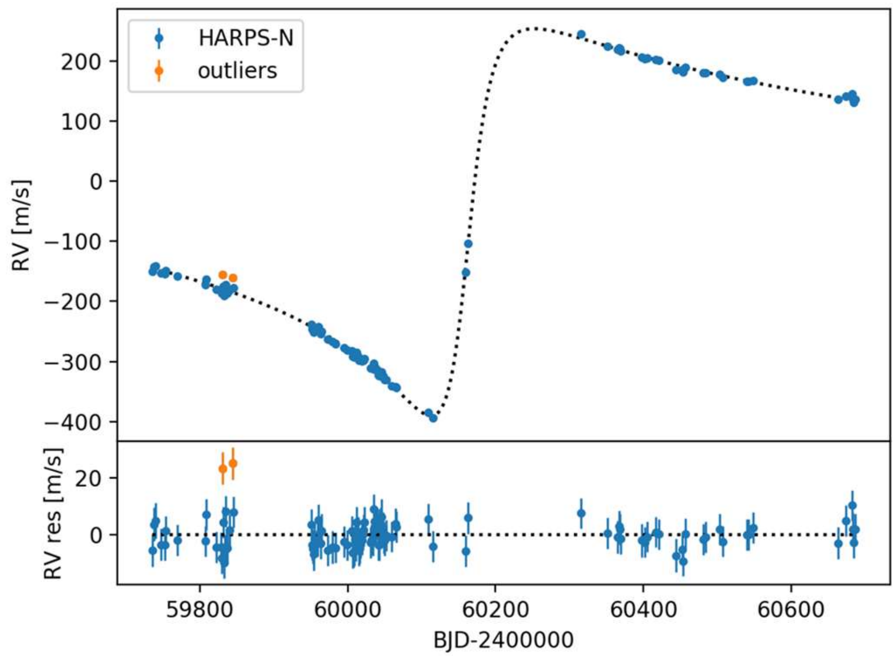
Pinamonti et al. 2026

Astrometry: Gaia candidates

HD 128717 / Gaia-ASOI-009

~~**Gaia DR3 solution**~~
~~m_p = 10 M_J~~
~~P_b = 1090 d~~
~~e_b = 0.39~~

HARPS-N RV solution
m_p = 14.7 M_J
P_b = 2600 d
e_b = 0.80

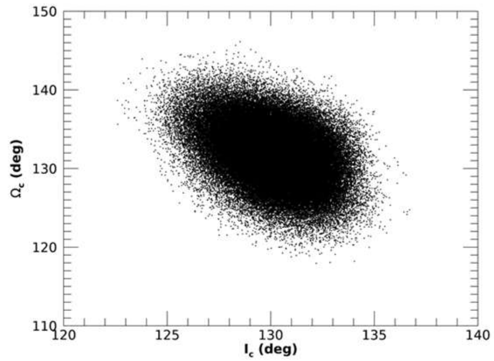


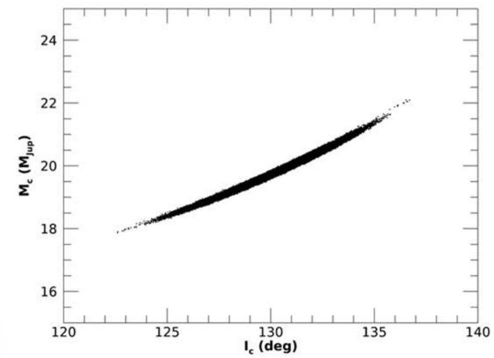
Incompatible solutions!
Period-eccentricity degeneracy in astrometry (P_b>T_{obs})

Pinamonti et al. 2026

Astrometry: Gaia candidates

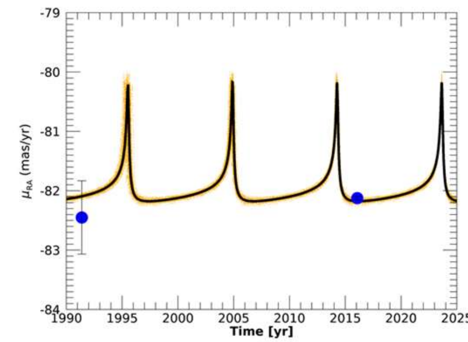
HD 128717 / Gaia-ASOI-009

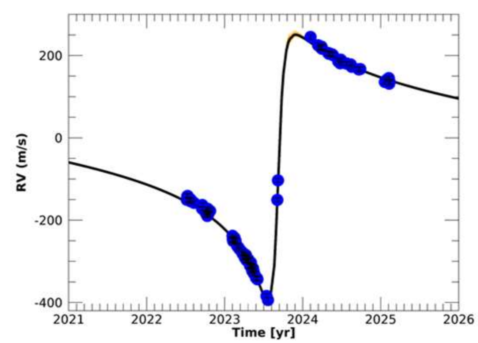


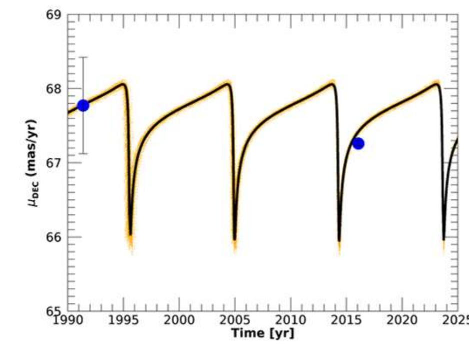


Agreement between RV and astrometry (PMA)

Low-mass brown dwarf: M = 19.8 M_J
(Gaia-6 B)







Pinamonti et al. 2026

Gaia DR4: outer companions to known SP?

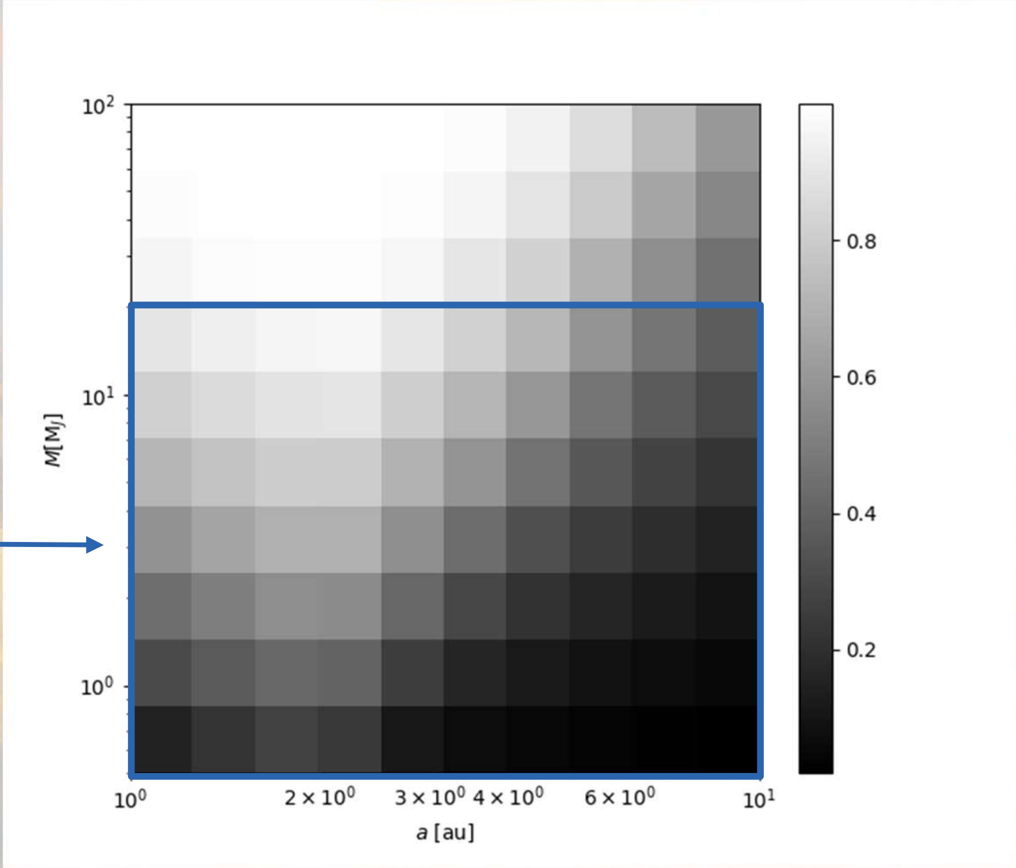
SP: $P \lesssim 100$ d, $1 < M_p < 20\ M_\oplus$

CJ: $1 < a < 10$ AU, $0.5 < M_p < 20\ M_{Jup}$

(Bonomo et al. 2025)

Detection MAP on SP sample from Bonomo et al. 2025: **240 systems** with detected transit/RV SP

Completeness to CJ = 44.9%



Summary

Small planets and cold Jupiters Outside-in observations:

- f(SP|CJ): RV surveys suggest that small planets (3-30 $M_\oplus$) might be more abundant in CJ systems around Solar-type stars (Rosenthal+2022, Ruggieri+, submitted to A&A). This might be different around M dwarfs (very low statistics) (Pinamonti+2023)
- Super-Earths / mini-Neptunes: are they affected in the same way?
- Metallicity dependence?

Many open questions: increasing number of statistical studies thanks to ever larger exoplanet sample!

Many surveys presented today:

- Diana Dragomir: *JAS: a Jovian Architectures Survey to uncover the links between outer giant planets and their inner systems*;
- Alessandro Ruggieri: *Occurrence rates of small close-in planets in the presence of cold Jupiters*;
- Etienne Lefèvre Florján: *Only the least massive outer-giant planets occur more frequently in the presence of inner super-Earths*;
- Alex Polanski: *Digger Deeper into Jovian-Host Systems with the Extreme Precision Spectrograph: Preliminary Survey Results*;

Take-home messages:

- large statistical samples required for precise measurements;
- many parameters involved, difficult to distinguish different effects;
- Different techniques can be complementary to each other (but don't always agree);

THANK YOU

BACK-UP

Detection techniques: RV

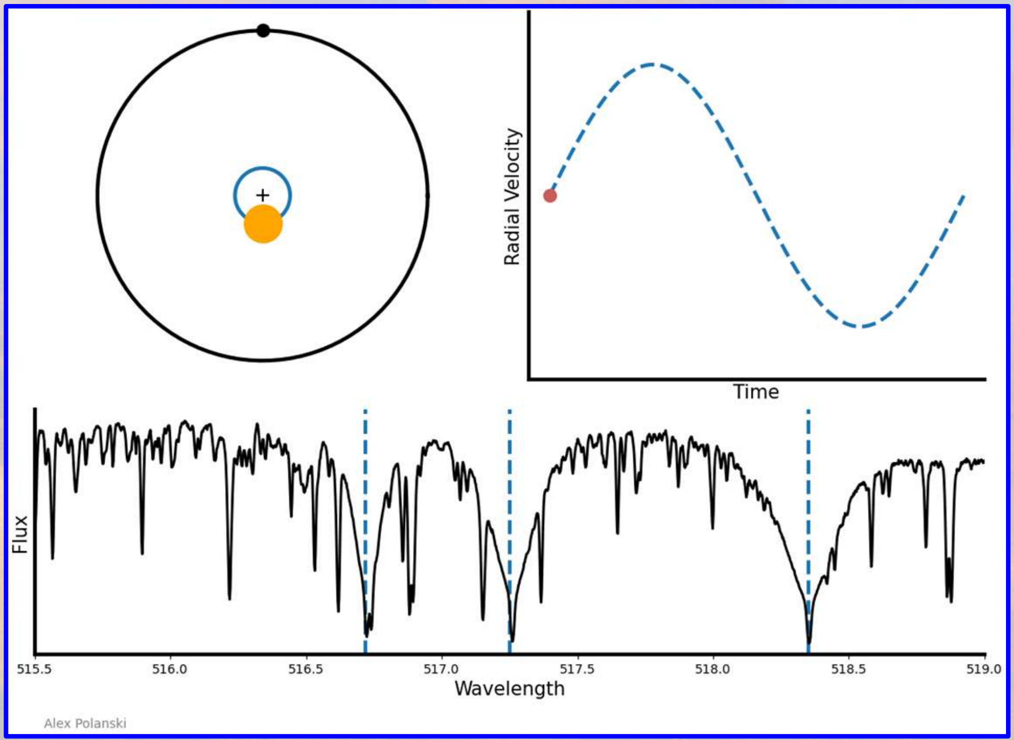
Radial Velocity method

$$K = \frac{M_p \sin i}{(M_s + M_p)^{2/3}} \cdot \frac{(2\pi G)^{1/3}}{P^{1/3}\sqrt{1-e^2}}$$

Biased towards:

- high-mass planets
- low-mass stars
- short-periods

(long-period detection possible, limited by obs duration)



Detection techniques: RV

HARPS-N@TNG (σ_{RV} ~ 1 m/s)
Canary islands

HARPS@ESO (σRV ~ 1 m/s)
Chile

ESPRESSO@VLT (σRV ~ 0.3 m/s)
Chile

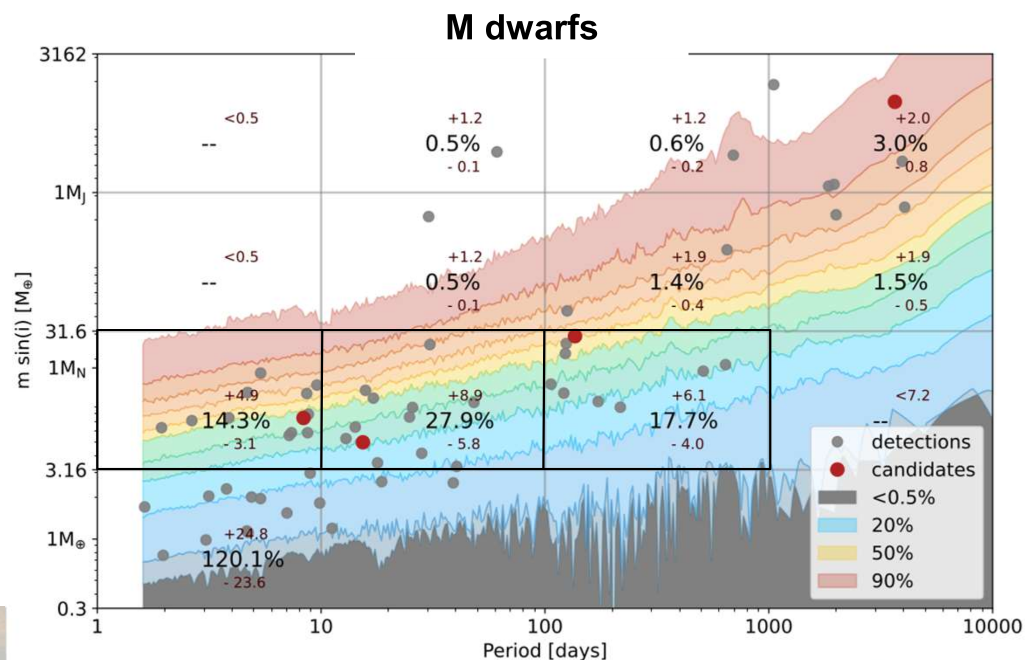
CARMENES@Calar Alto (σRV ~ 1 m/s)
Spain

HIRES@Keck (σRV ≤ 1 m/s)
Hawaii

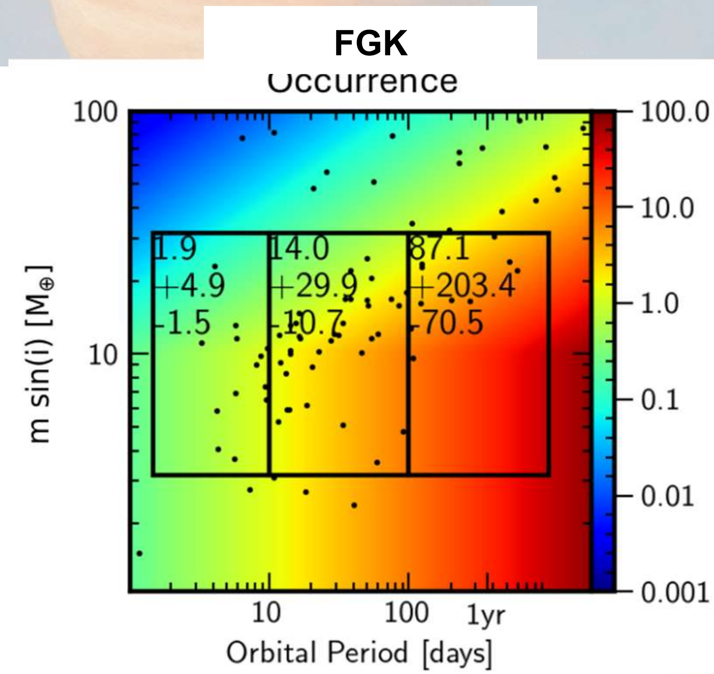
Low-mass (small) planets population

Dependance on stellar type:

HARPS: 197 M-dwarf within 26 pc, 0.1-0.75 $M_\odot$



Mignon et al. 2025



Mayor et al. 2011
Mulders et al. 2018
Mignon et al. 2025

Low-mass (small) planets population

From observations to occurrence rates

Definitions:

- $\langle n_P \rangle = n_p / n_\star$ = average number of planets per star
- $F_p = n_{syst} / n_\star$ = fraction of stars with planets

$n_{obs} \neq n_p$ not all planets are detected

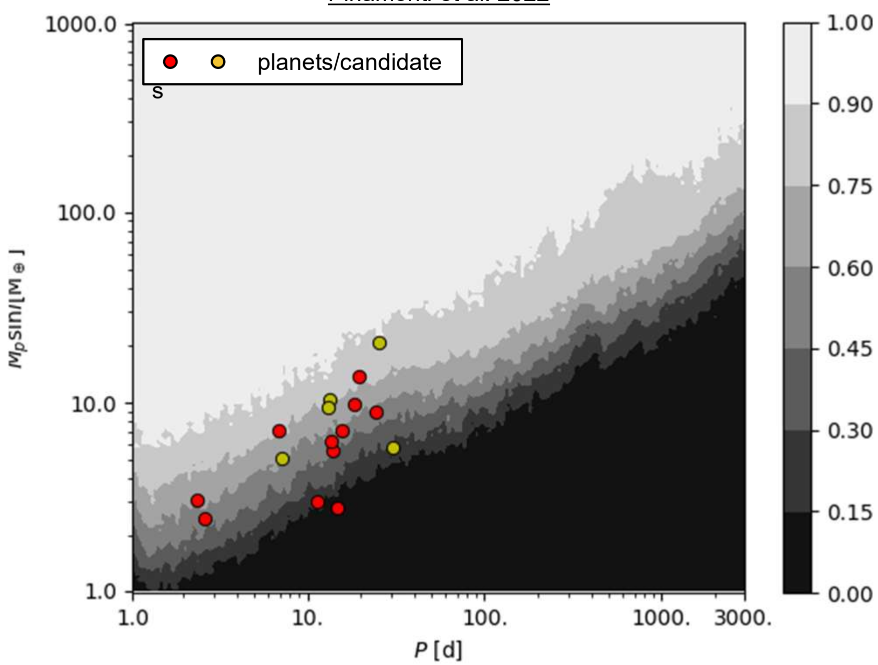
$n_{obs} = n_p \cdot \boldsymbol{C}$ (detection function or completeness)

C is function of many things: observing survey, type of planet, stellar activity,...

Example: HADES - RV survey of early-M dwarfs

56 stars, several planets detections. What are occurrence rates?

Pinamonti et al. 2022



Low-mass (small) planets population

Occurrence rates from HADES

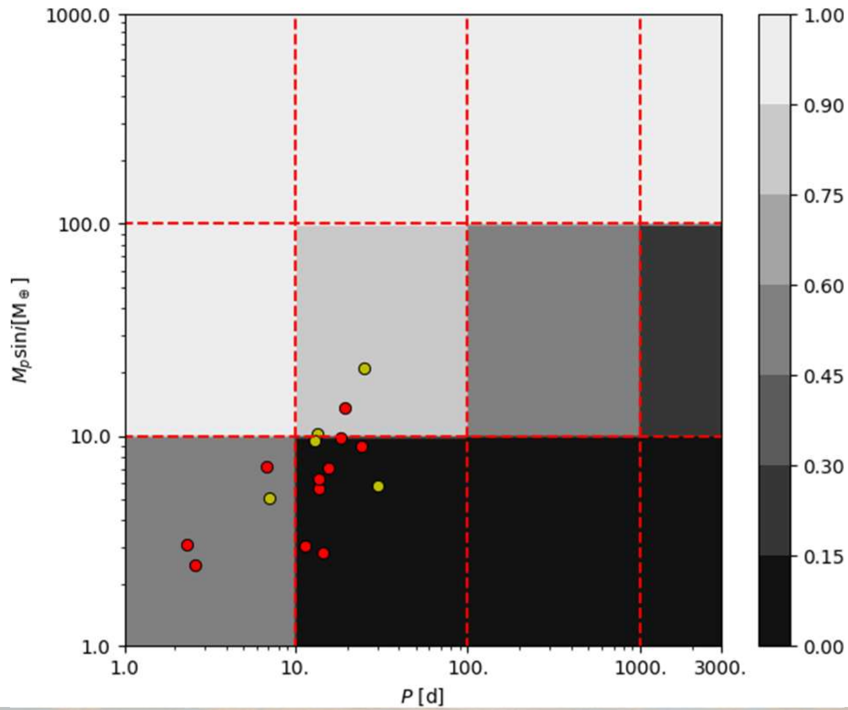
56 early-M dwarfs

k_p = detected planets,
$n = n_{\star} \cdot C$ = sensitive targets

$m_p \sin i$ [M$_\oplus$]	Period [d] [1, 10]	$[10, 10^2]$	$[10^2, 10^3]$	$[10^3, 3\cdot10^3]$
$[10^2, 10^3]$	$k_p = 0$	$k_p = 0$	$k_p = 0$	$k_p = 0$
-	$n = 56.0$	$n = 55.8$	$n = 54.4$	$n = 51.7$
-	$f_{occ} < 0.02$	$f_{occ} < 0.02$	$f_{occ} < 0.02$	$f_{occ} < 0.02$
$[10, 10^2]$	$k_p = 0$	$k_p = 1$	$k_p = 0$	$k_p = 0$
-	$n = 55.0$	$n = 49.3$	$n = 33.2$	$n = 14.9$
-	$f_{occ} < 0.02$	$f_{occ} = 0.02^{+0.05}_{-0.01}$	$f_{occ} < 0.04$	$f_{occ} < 0.08$
$[1, 10]$	$k_p = 3$	$k_p = 7$	$k_p = 0$	$k_p = 0$
-	$n = 29.0$	$n = 8.2$	$n = 0.7$	$n = 0.4$
-	$f_{occ} = 0.10^{+0.10}_{-0.03}$	$f_{occ} = 0.85^{+0.46}_{-0.21}$	$f_{occ} < 1.65$	$f_{occ} < 2.70$

$$\mathcal{P}(k \mid n, f_{occ}) = \frac{(n f_{occ})^k e^{-n f_{occ}}}{k!},$$

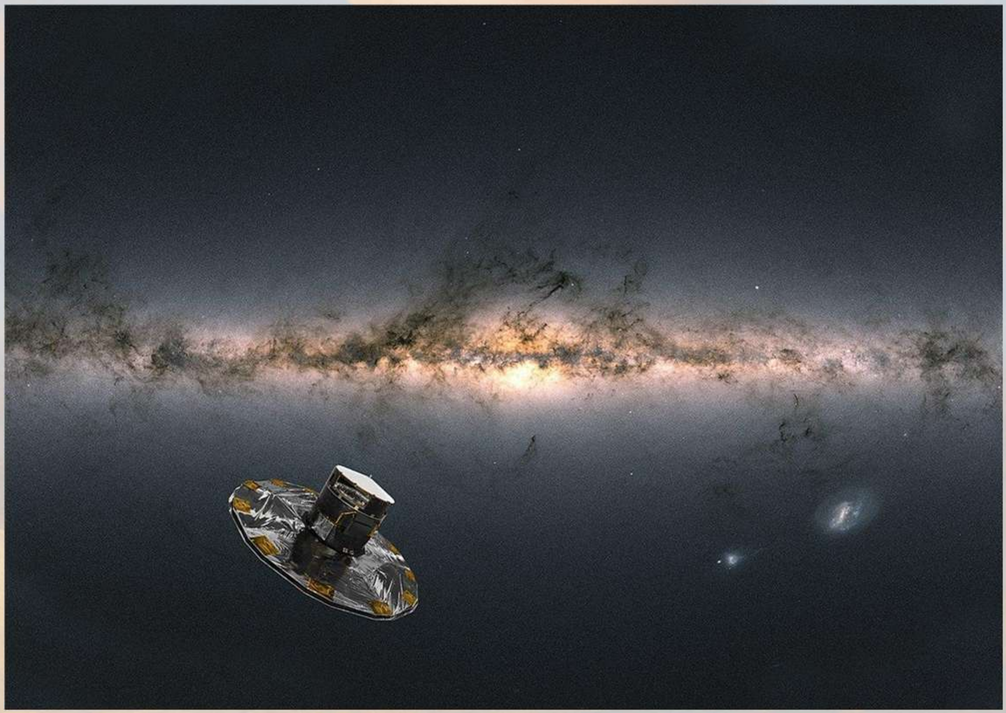
Pinamonti et al. 2022



Astrometry: Gaia DR4

Coming in 2026

- 66 months of data (almost 2x DR3)
- 2x astrometric precision
- Full time series released
- Extensive exoplanet candidate list



Gaia DR4: huge statistical samples!

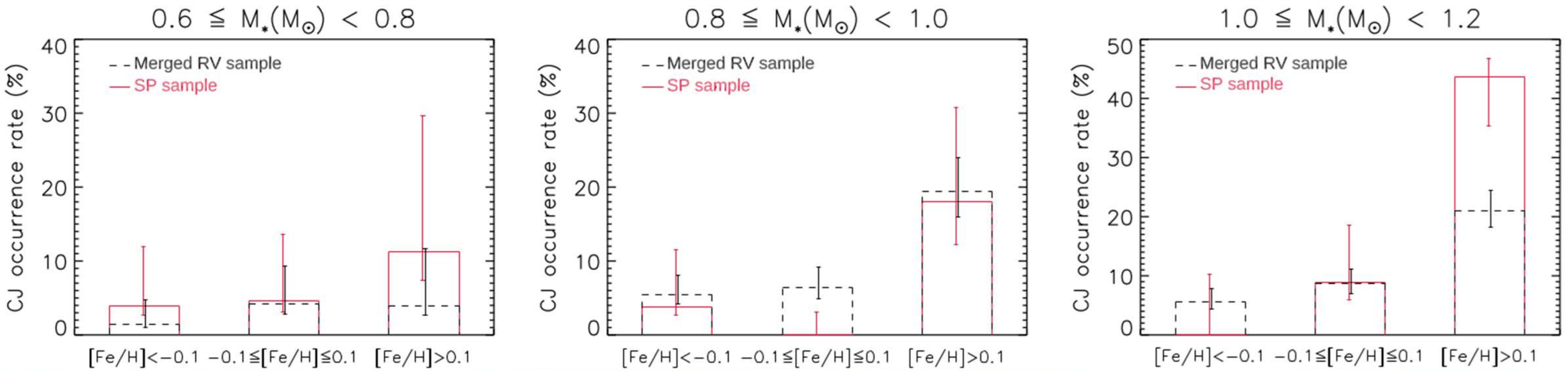
(Bonomo et al. 2025)

[Fe/H]	$M_p = 0.3 - 13\,M_{Jup}$ $N_\star \mid d$	C	f_{CJ} [%]	$M_p = 0.5 - 20\,M_{Jup}$ $N_\star \mid d$	C	f_{CJ} [%]
Small planet (transit+radial velocity) sample						
$\overline{[Fe/H]} = -0.011 \pm 0.005$	217 | 27	0.928	$13.4^{+2.8}_{-2.0}$	217 | 23	0.958	$11.1^{+2.5}_{-1.8}$
[Fe/H] < −0.1	64 | 2	0.943	$3.3^{+4.1}_{-1.1}$	64 | 2	0.969	$3.2^{+4.0}_{-1.0}$
−0.1 ≤ [Fe/H] ≤ +0.1	86 | 6	0.918	$7.6^{+4.1}_{-2.0}$	86 | 3	0.952	$3.7^{+3.3}_{-1.1}$
[Fe/H] > +0.1	67 | 19	0.923	$30.7^{+6.4}_{-5.2}$	67 | 18	0.954	$28.2^{+6.2}_{-4.9}$
[Fe/H] ≤ 0	102 | 3	0.932	$3.2^{+2.9}_{-1.0}$	102 | 3	0.961	$3.1^{+2.8}_{-0.9}$
[Fe/H] > 0	115 | 24	0.923	$22.6^{+4.5}_{-3.5}$	115 | 20	0.954	$18.2^{+4.2}_{-3.1}$
Merged (AAT+CLS+HARPS) radial velocity comparison sample						
$\overline{[Fe/H]} = -0.072 \pm 0.009$	1167 | 118	0.974	$10.4^{+1.0}_{-0.8}$	1167 | 113	0.988	$9.8^{+0.9}_{-0.8}$
[Fe/H] < −0.1	430 | 22	0.974	$5.2^{+1.3}_{-0.9}$	430 | 21	0.988	$4.9^{+1.3}_{-0.8}$
−0.1 ≤ [Fe/H] ≤ +0.1	413 | 31	0.971	$7.7^{+1.5}_{-1.1}$	413 | 31	0.986	$7.6^{+1.5}_{-1.1}$
[Fe/H] > +0.1	324 | 65	0.977	$20.5^{+2.4}_{-2.1}$	324 | 61	0.990	$19.0^{+2.4}_{-2.0}$
[Fe/H] ≤ 0	624 | 33	0.973	$5.4^{+1.1}_{-0.8}$	624 | 32	0.988	$5.2^{+1.0}_{-0.7}$
[Fe/H] > 0	543 | 85	0.974	$16.1^{+1.7}_{-1.5}$	543 | 81	0.988	$15.1^{+1.7}_{-1.4}$

d<200 pc, DR3 Mass, [Fe/H]

[Fe/H] = -0.077	220 000
[Fe/H] < -0.1	88 000
-0.1 < [Fe/H] < 0.1	70 000
[Fe/H] > 0.1	58 000

Gaia DR4 observational constraints



Bonomo et al. 2025

No very strong additional constraints on *f*(CJ|SP)

Very strong additional constraints on ***f*(CJ)**