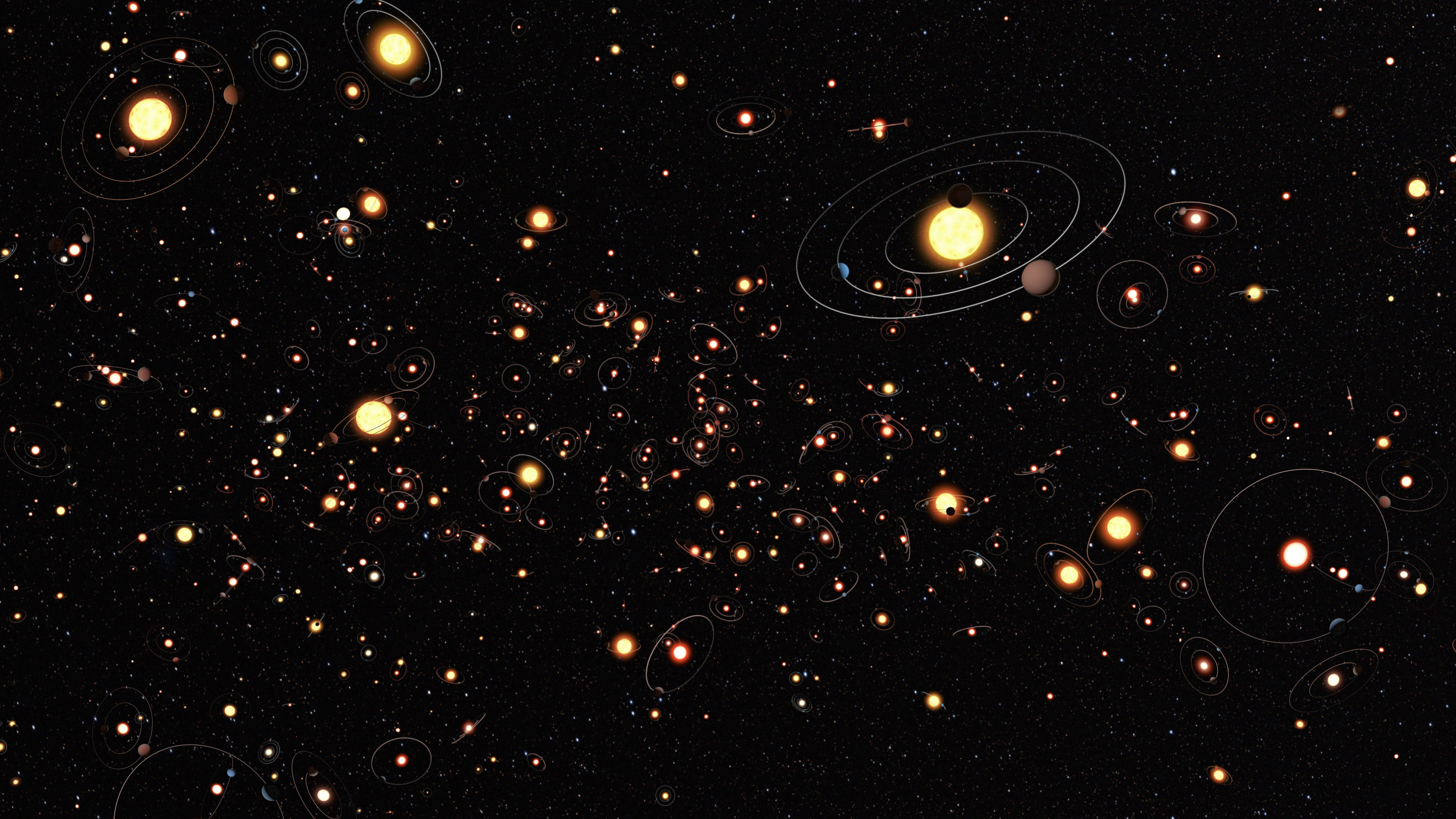
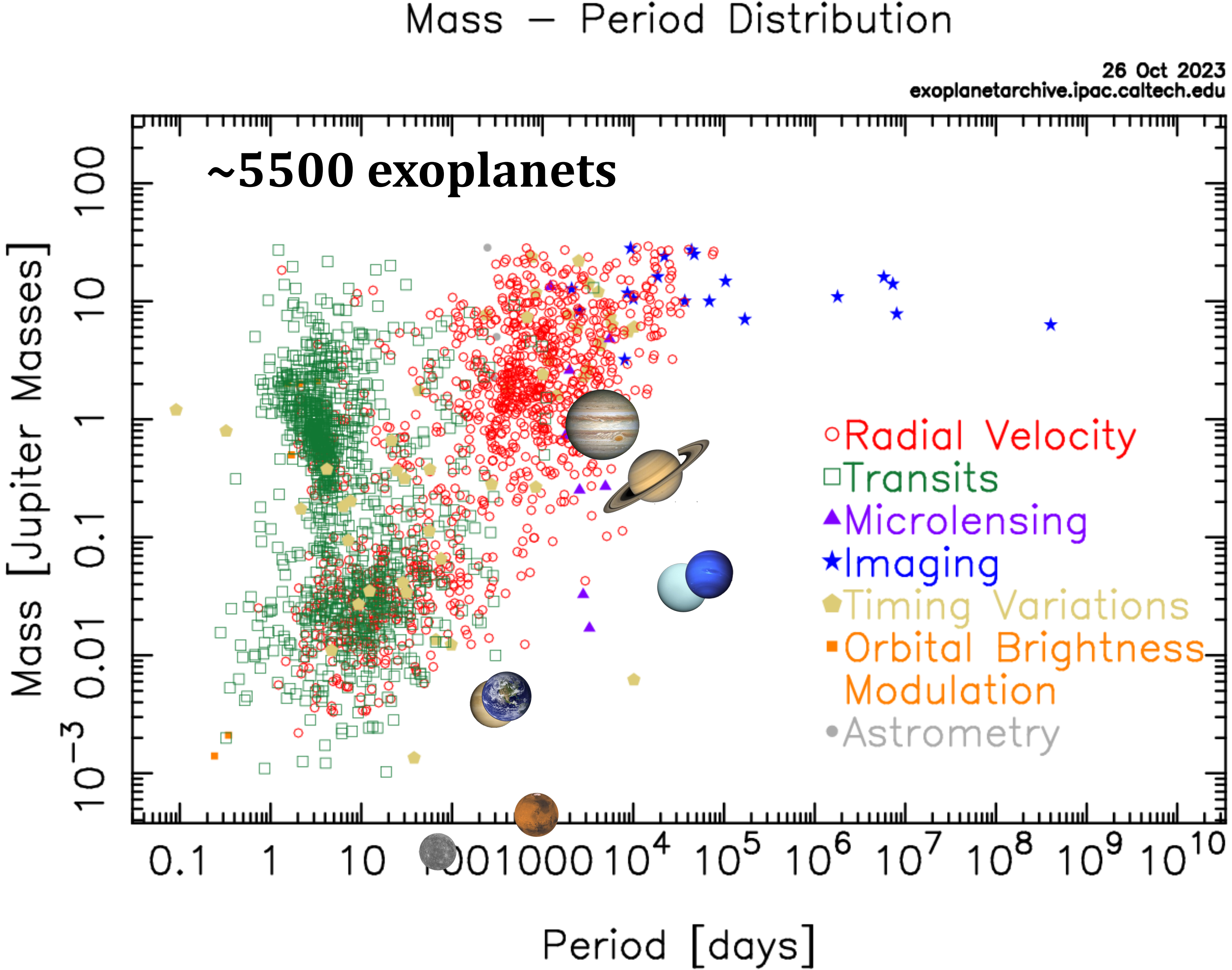
Habitable planets in the solar neighbourhood

Ignasi Ribas
Institut d'Estudis Espacials de Catalunya (IEEC)
Institut de Ciències de l'Espai (ICE, CSIC)

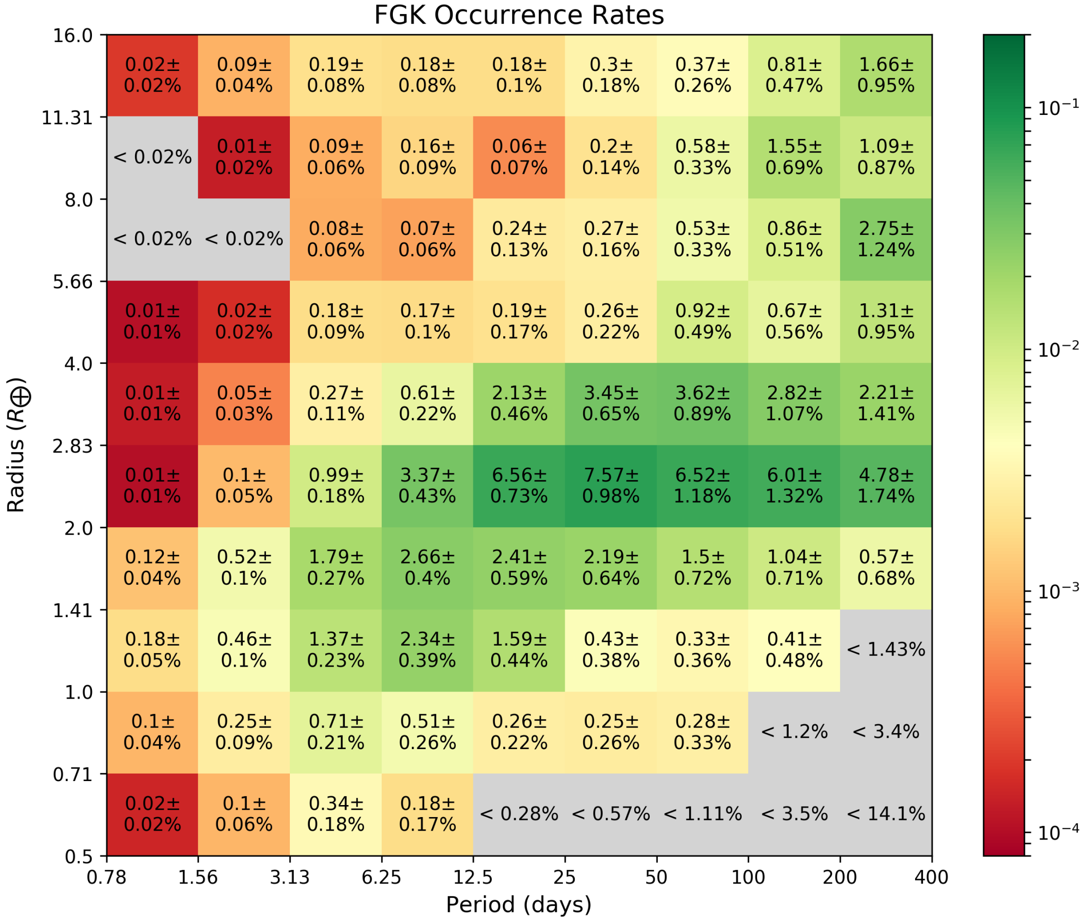
Trobades de la Mediterrània, Maó, November 2023



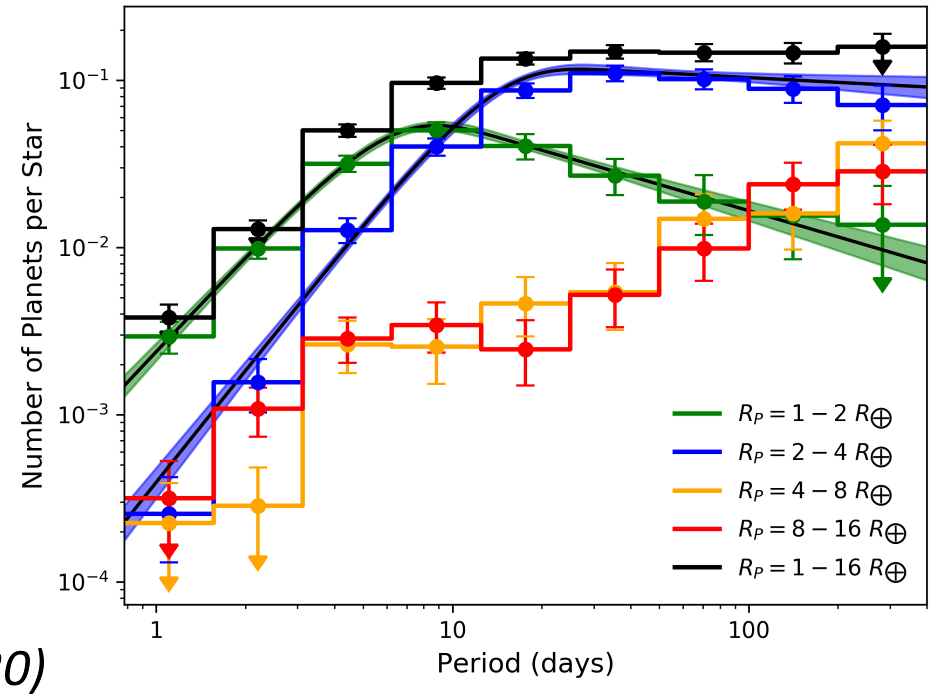

Mass – Period Distribution
26 Oct 2023
exoplanetarchive.ipac.caltech.edu
~5500 exoplanets
Mass [Jupiter Masses]
100
10
1
0.1
0.01
10^{-3}
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness Modulation
Astrometry
0.1
1
10
100
1000
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
Period [days]

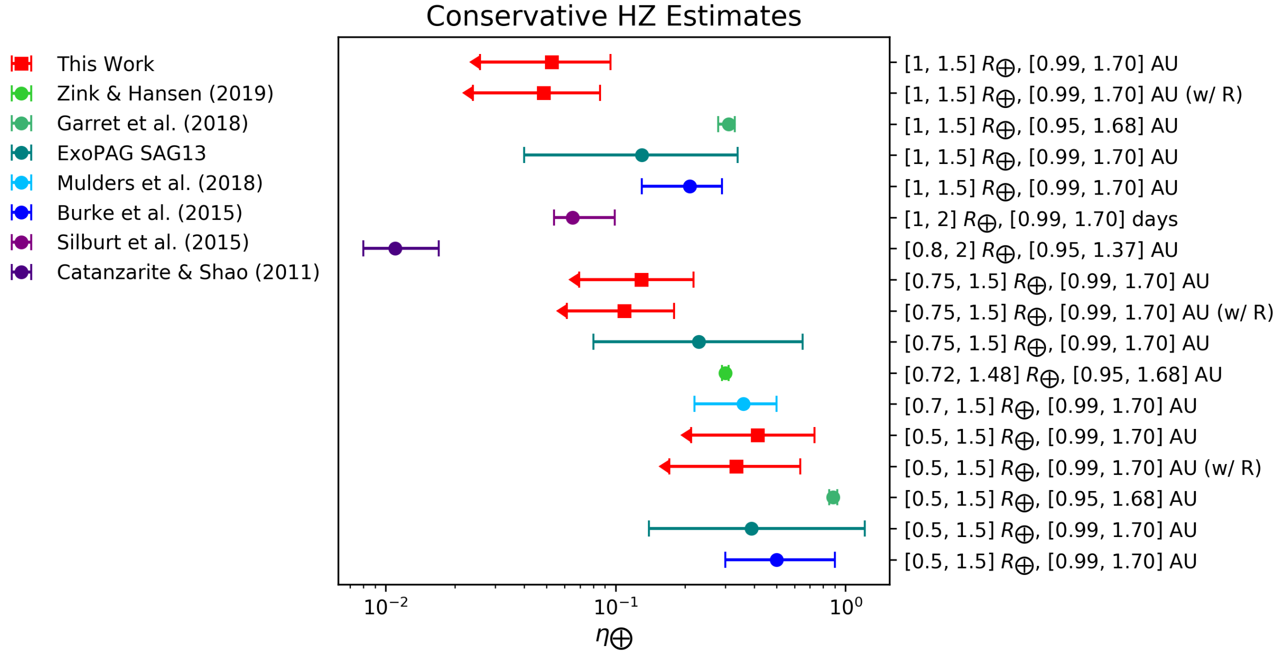
Planet occurrence rates (Sun-like)

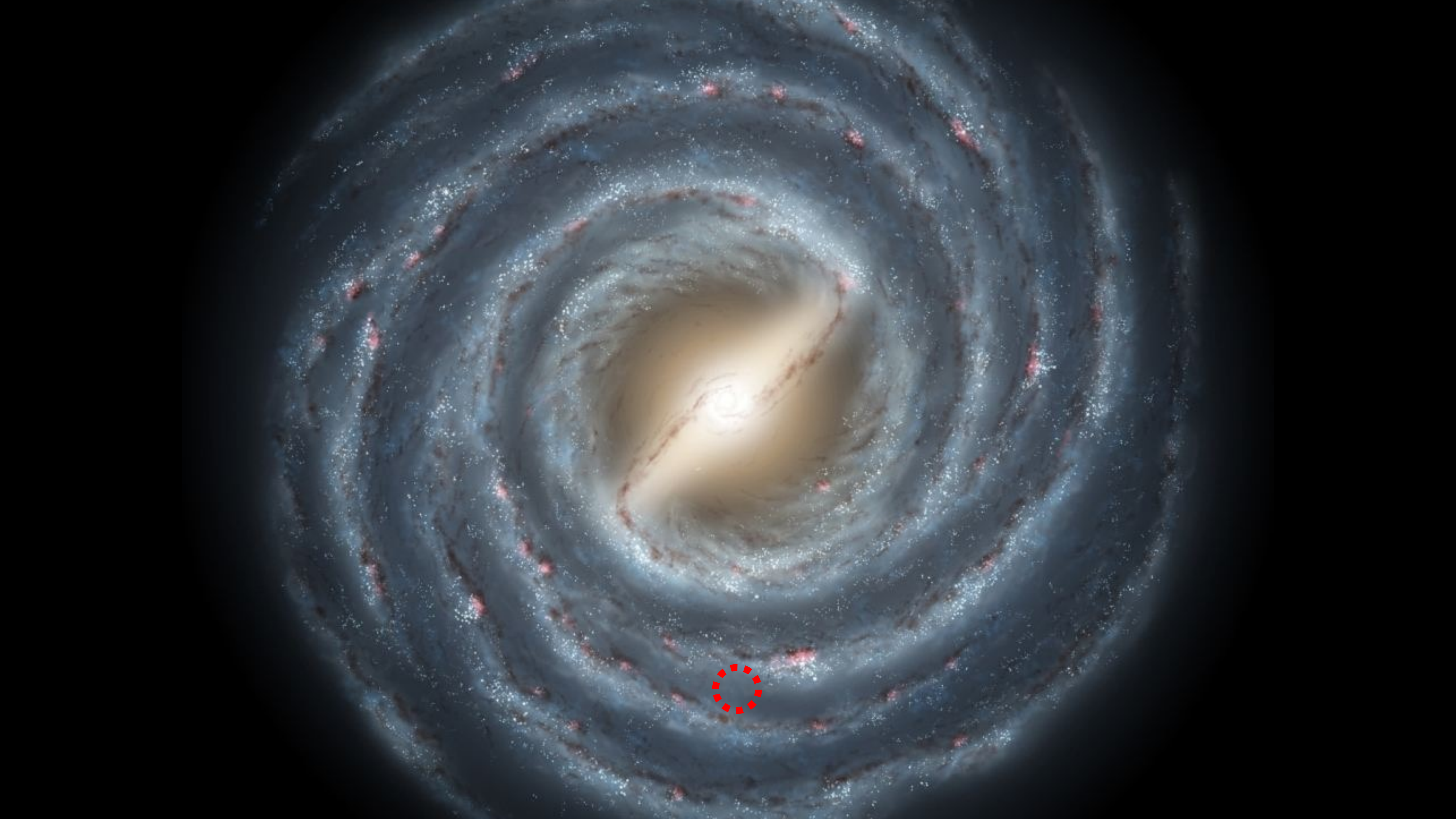
- 200,000 Kepler FGK stars
- ~1 planet per star (0.8-400 d); 0.5-16 $R_\odot$
- $\eta_\oplus$~ 0.1 planets per star (0.75-1.5 $R_\odot$)



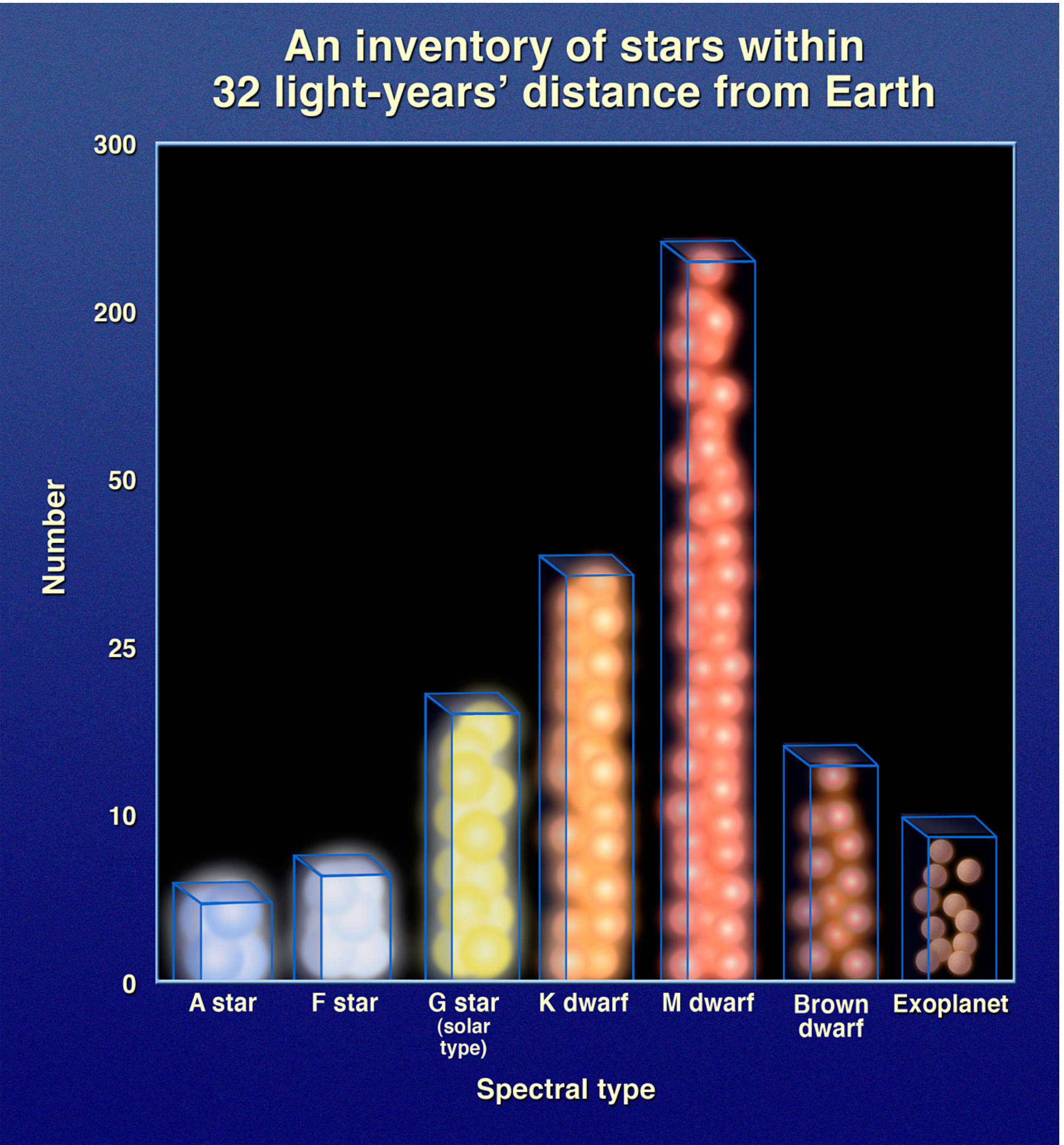
Kunimoto & Matthews (2020)

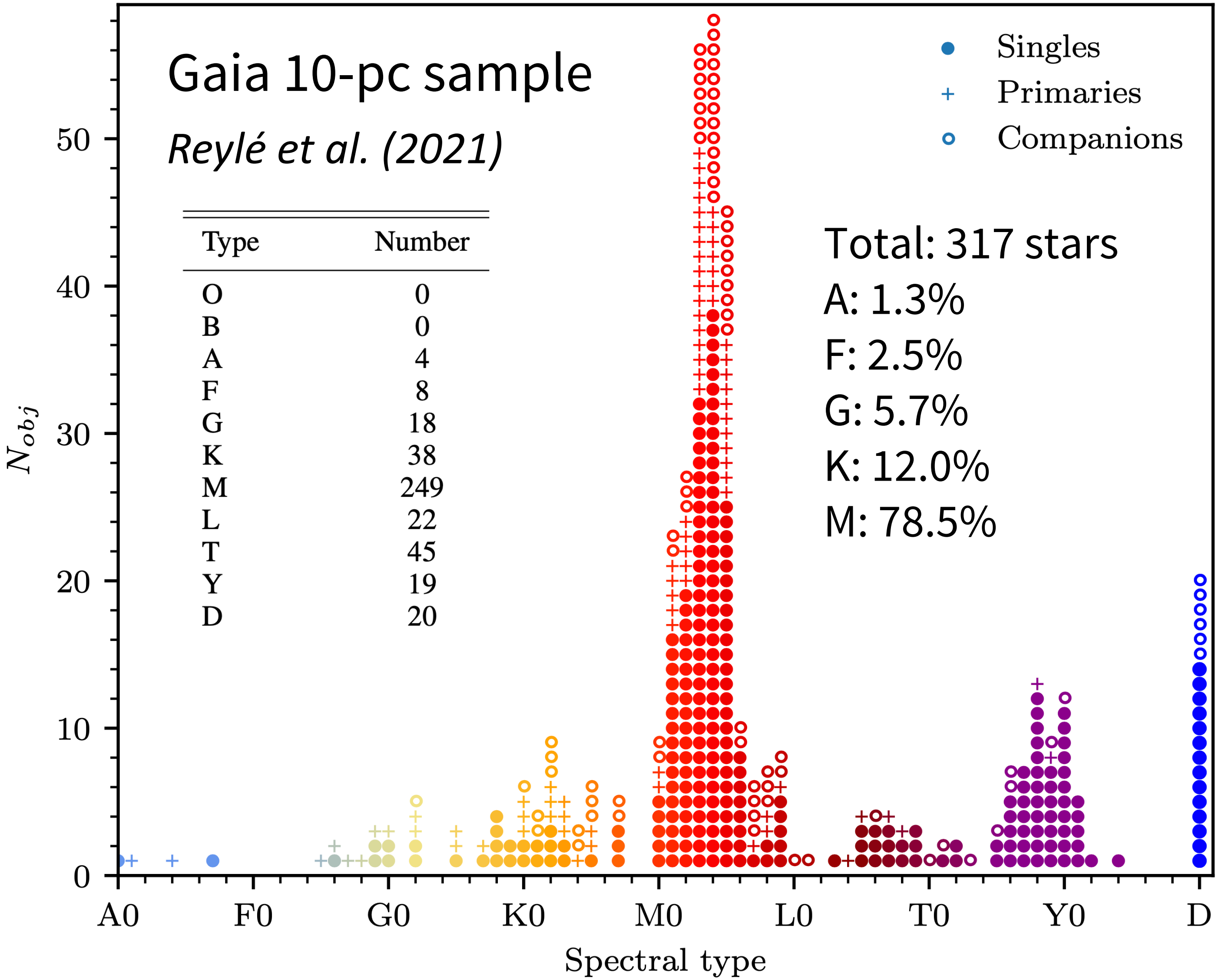






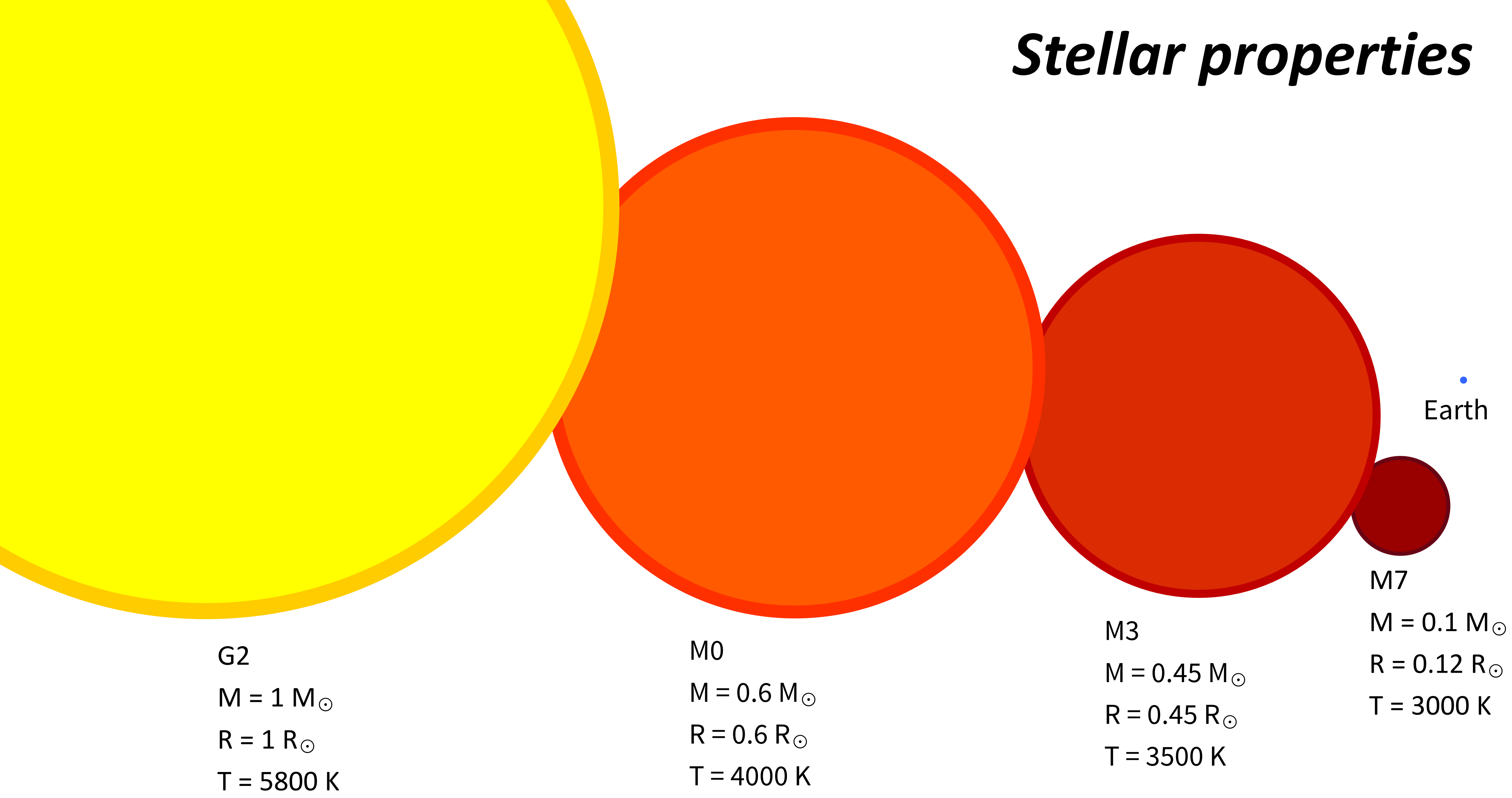
The solar neighbourhood: stellar inventory





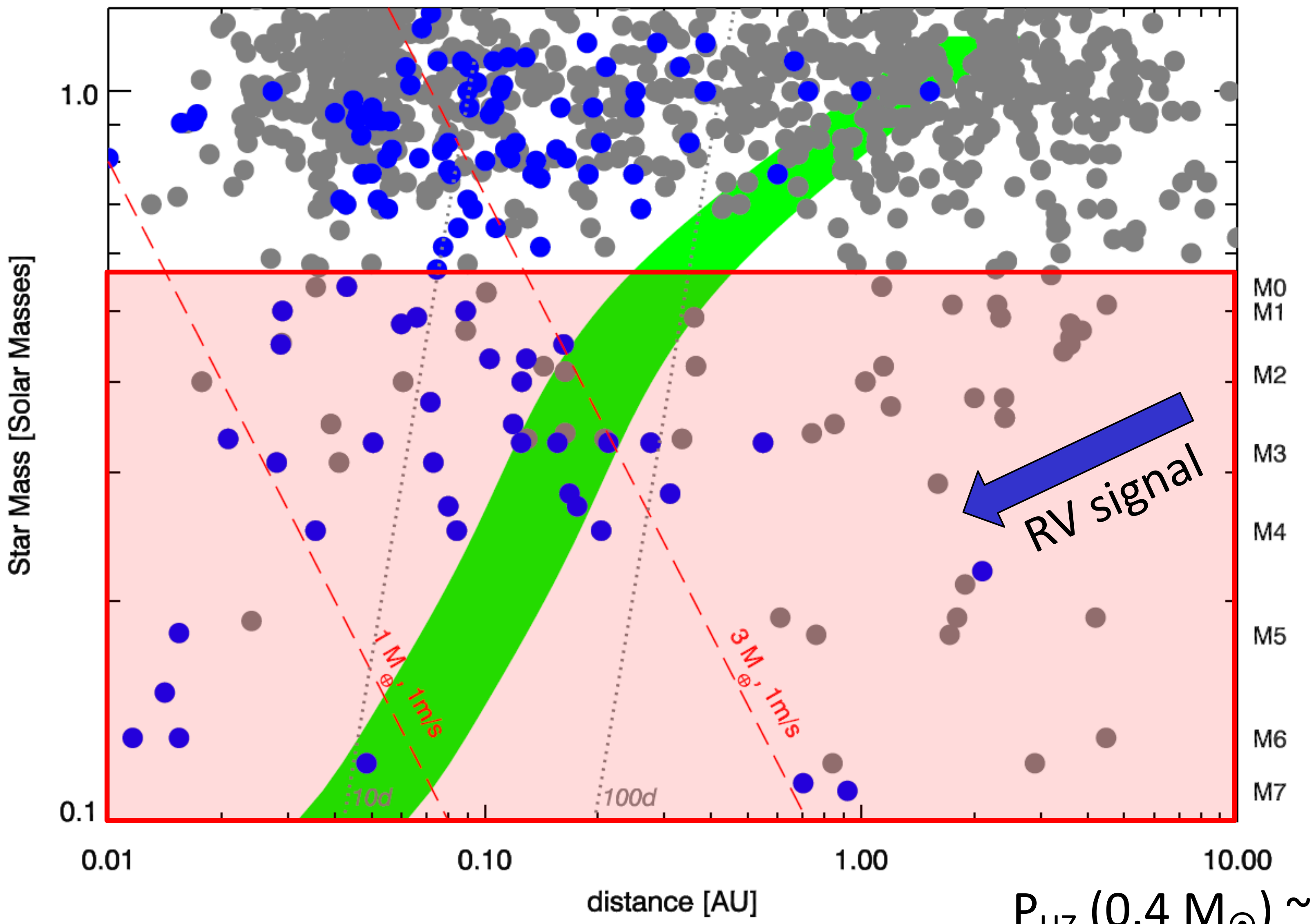
Type	Number
O	0
B	0
A	4
F	8
G	18
K	38
M	249
L	22
T	45
Y	19
D	20

Stellar properties



--sizes to scale--

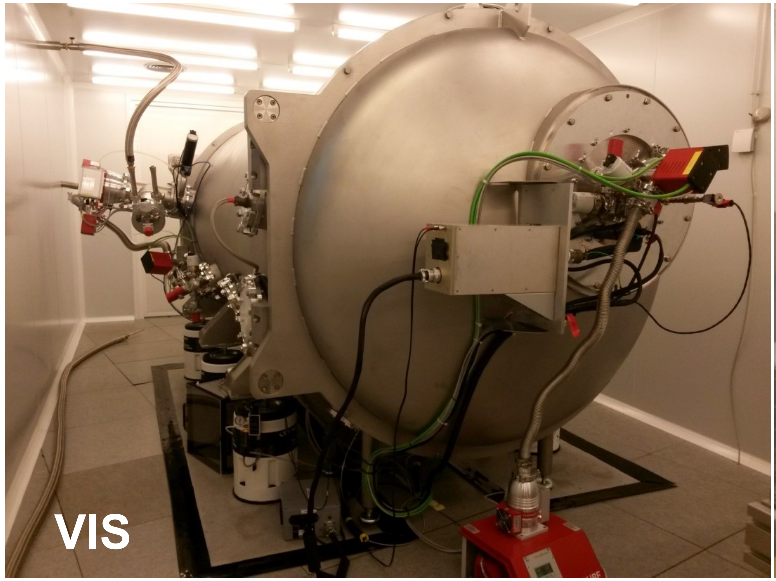
Planets around stars of different types
(as of 2015)

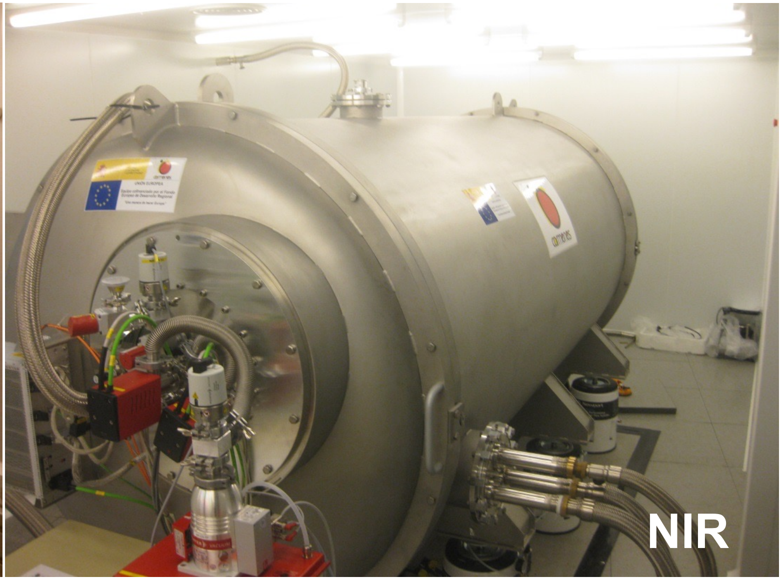


P_{HZ} (0.4 $M_\odot$) ~ 25 d
P_{HZ} (0.3 $M_\odot$) ~ 18 d
P_{HZ} (0.2 $M_\odot$) ~ 12 d

carmenes

- Mounted on 3.5-m @ CAHA
- Consortium: 11 Spanish and German institutions
- GTO: 2016-2020 (750 un)
- CARMENES Legacy-Plus: 2021-2026+ (370 un)

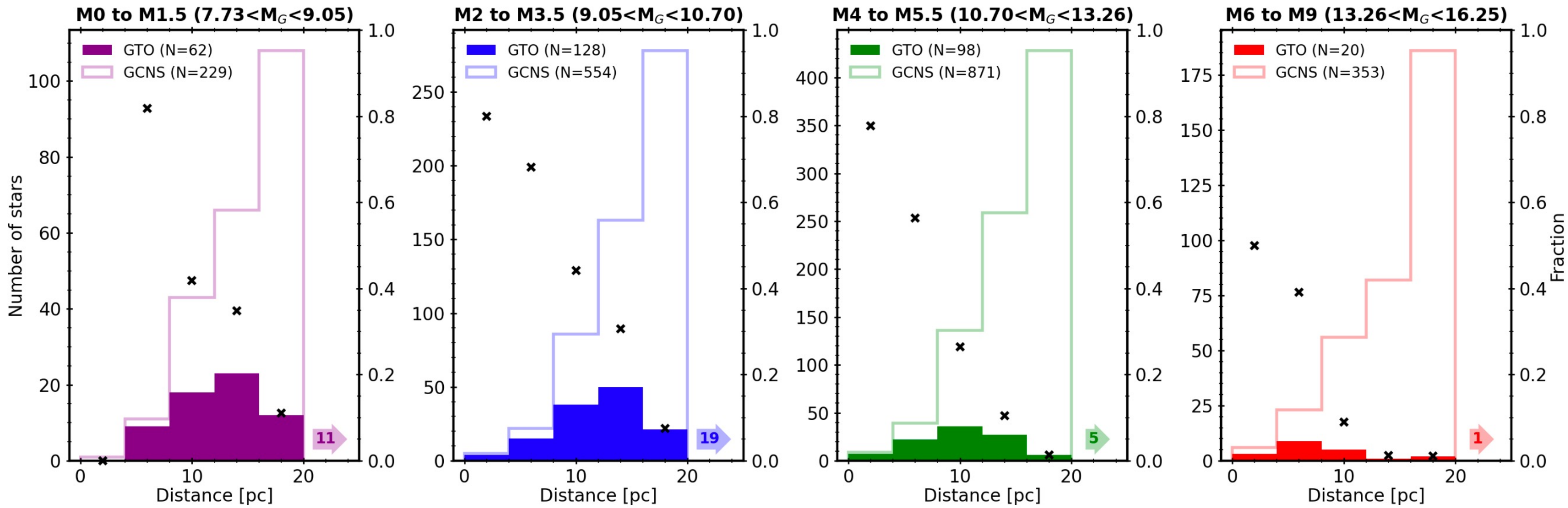




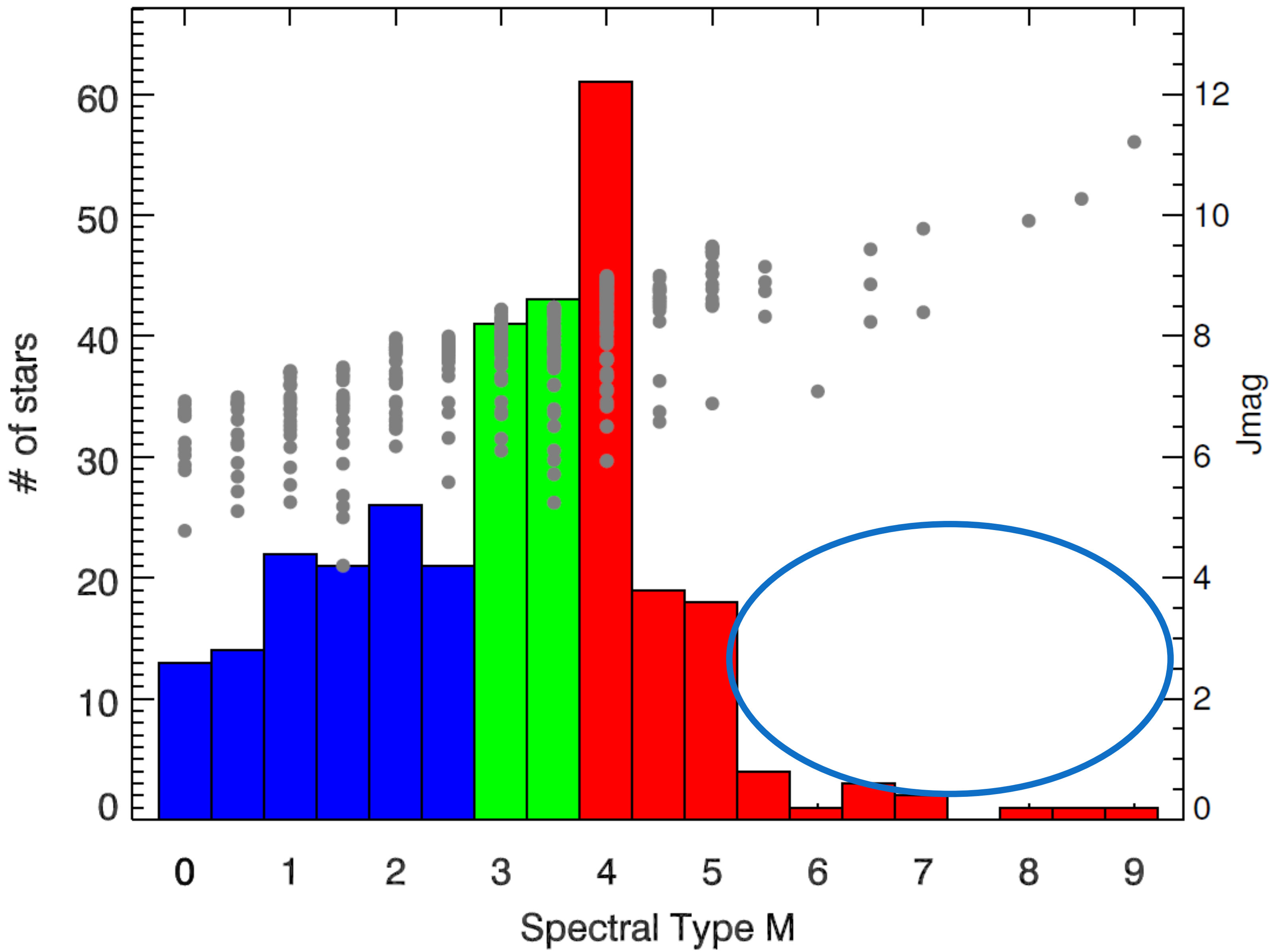
- VIS (520-970 nm) & NIR (970-1710 nm) channels
- Goal: detecting low-mass planets in M-dwarf habitable zones (focus on >M4) ➜ architecture & statistics

CARMENES sample

- 362 stars in total – 11 SB2 & SB3
- Completeness at 20 pc: 15%
- 48% of M dwarfs within 10 pc
- Up to 10 pc, ratio >50% except late Ms (28%)



CARMENES sample

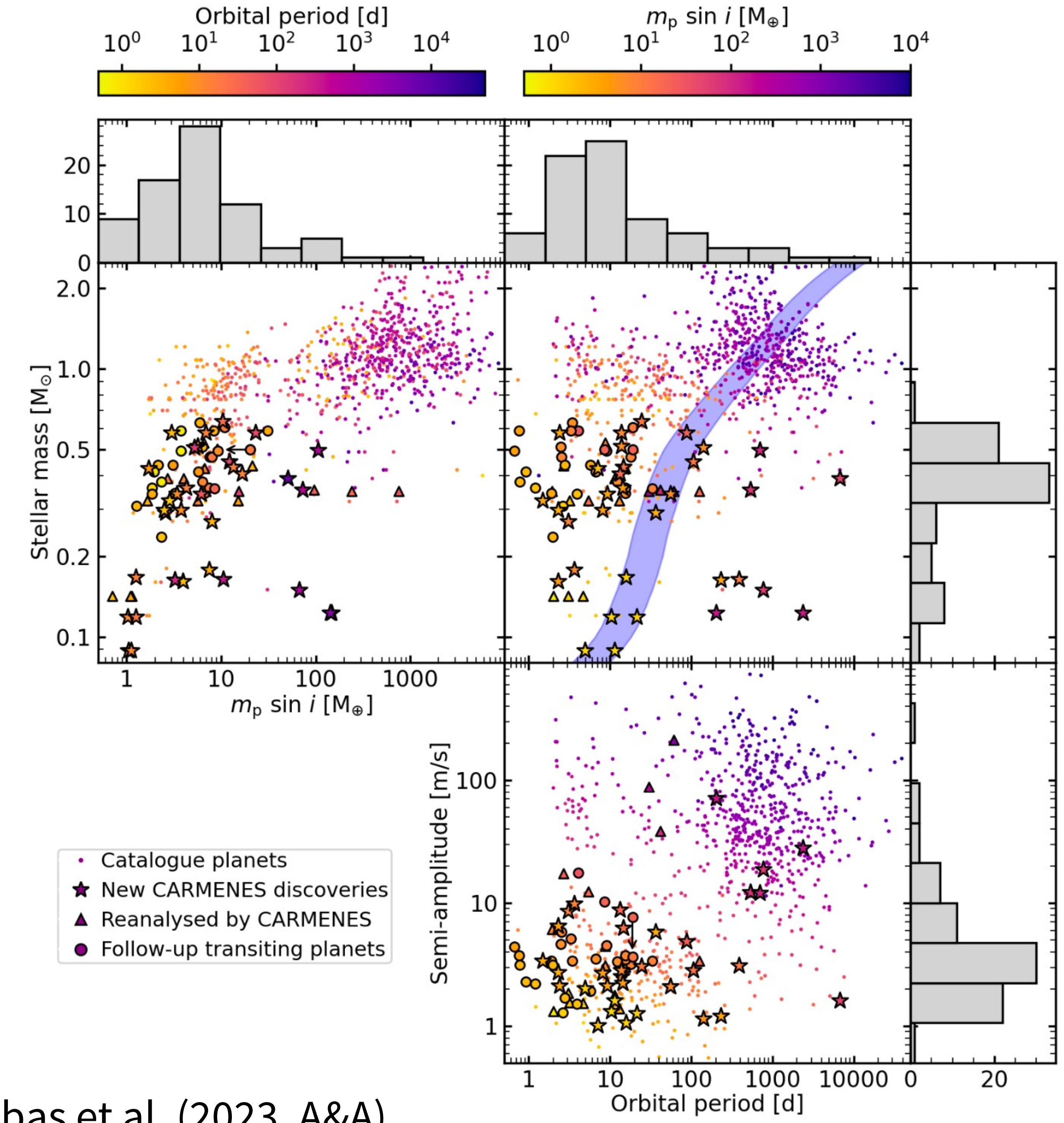


<d> = 13 pc

Typical target:
M3-M4 & J=7-9
(50% of all)

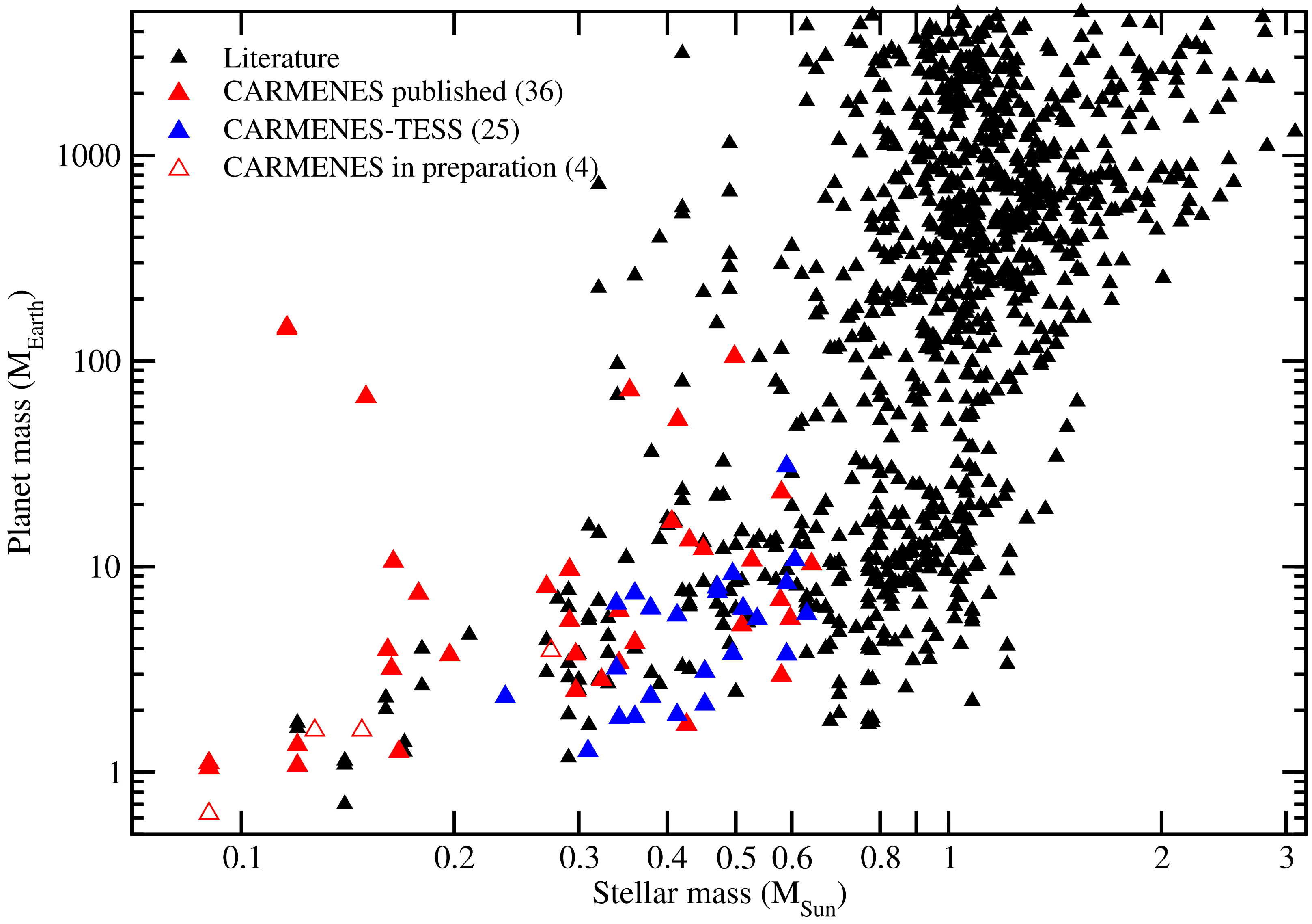
CARMENES planets

- 50% of all known RV planets with stellar hosts below 0.2 $M_\odot$ have been discovered by CARMENES
- Majority of CARMENES planets are super-Earth to Neptune-mass
- In spite of low occurrence rate, CARMENES has discovered 6 Saturn- and Jupiter-mass planets
- Most CARMENES planets have P from a few days to a few 10s of days
- 5 new CARMENES low-mass planets orbit within the liquid-water HZ
- Killed a few planets…



Ribas et al. (2023, A&A)

CARMENES planets

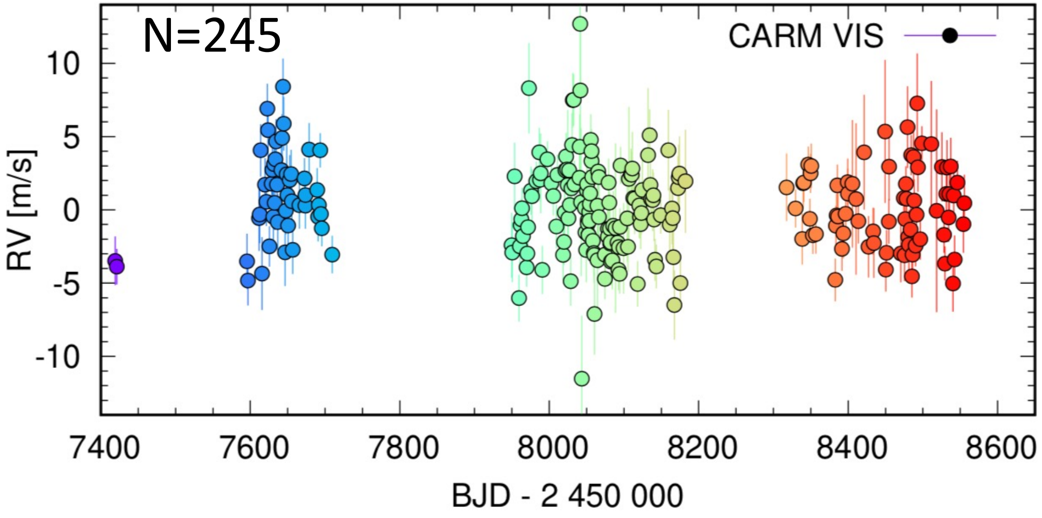


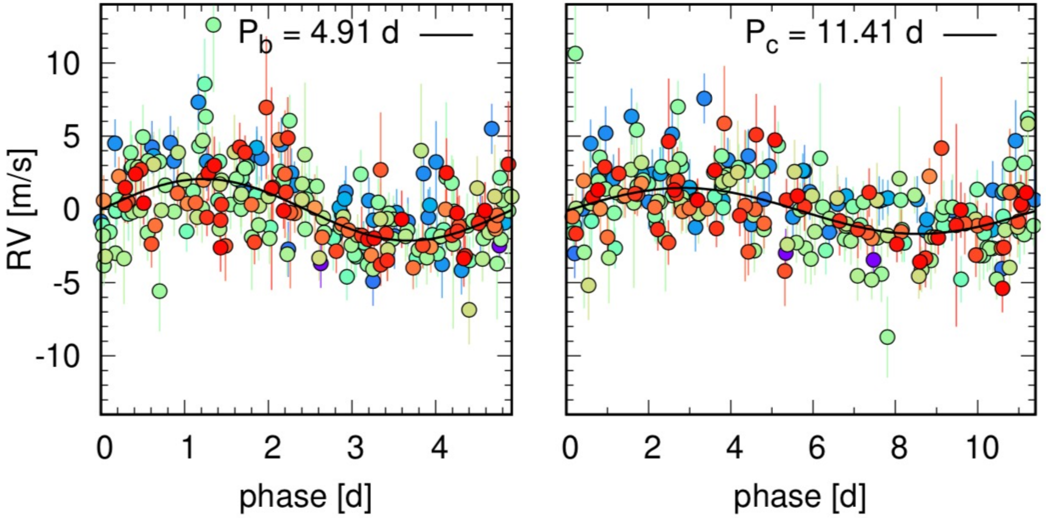
Planet zoo

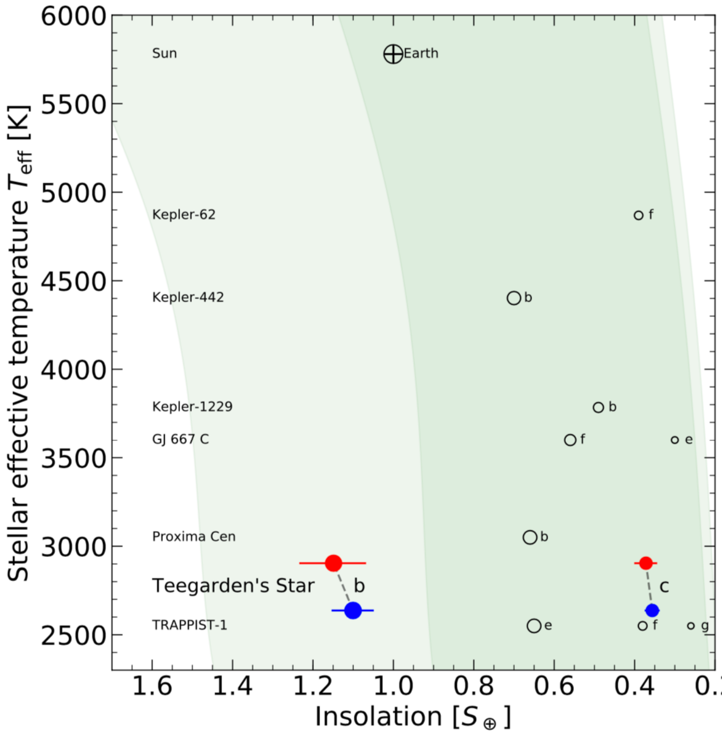
- Neptunes in temperate orbits
- Close-in eccentric
- With active star hosts
- Nearby systems with transits
- …

Teegarden's Star b & c: Earth twins

Zechmeister et al. (2019, A&A)

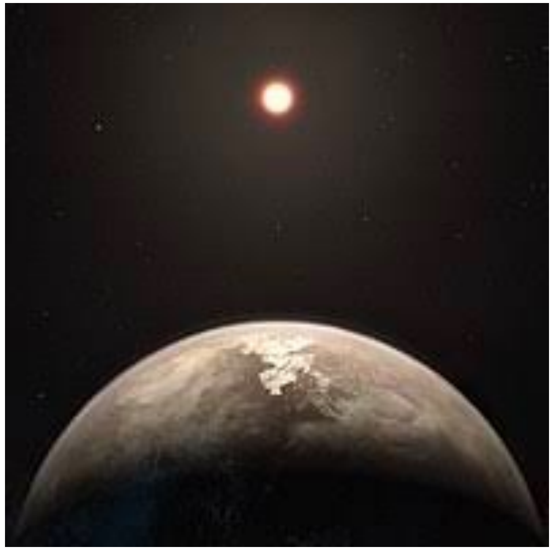






Keplerian parameters	Planet b	Planet c
P [d]	$4.9100^{+0.0014}_{-0.0014}$	$11.409^{+0.009}_{-0.009}$
K [m/s]	$2.02^{+0.19}_{-0.20}$	$1.61^{+0.19}_{-0.19}$
e^a	$0.00^{+0.16}$	$0.00^{+0.16}$
ω [deg]	77^{+52}_{-79}	286^{+101}_{-74}
$t_p - 2\,458\,000$ [d]	$52.3^{+0.7}_{-1.1}$	$53.2^{+3.2}_{-2.3}$
Derived parameters		
a [au]	$0.0252^{+0.0008}_{-0.0009}$	$0.0443^{+0.0014}_{-0.0015}$
$m \sin i$ [$M_\oplus$]	$1.05^{+0.13}_{-0.12}$	$1.11^{+0.16}_{-0.15}$
m [$M_\oplus$]^b	$1.25^{+0.68}_{-0.22}$	$1.33^{+0.71}_{-0.25}$
$\sin i^b$	$0.87^{+0.12}_{-0.31}$	
F [$S_\oplus$]^c	$1.15^{+0.08}_{-0.08}$	$0.37^{+0.03}_{-0.03}$

carmenes



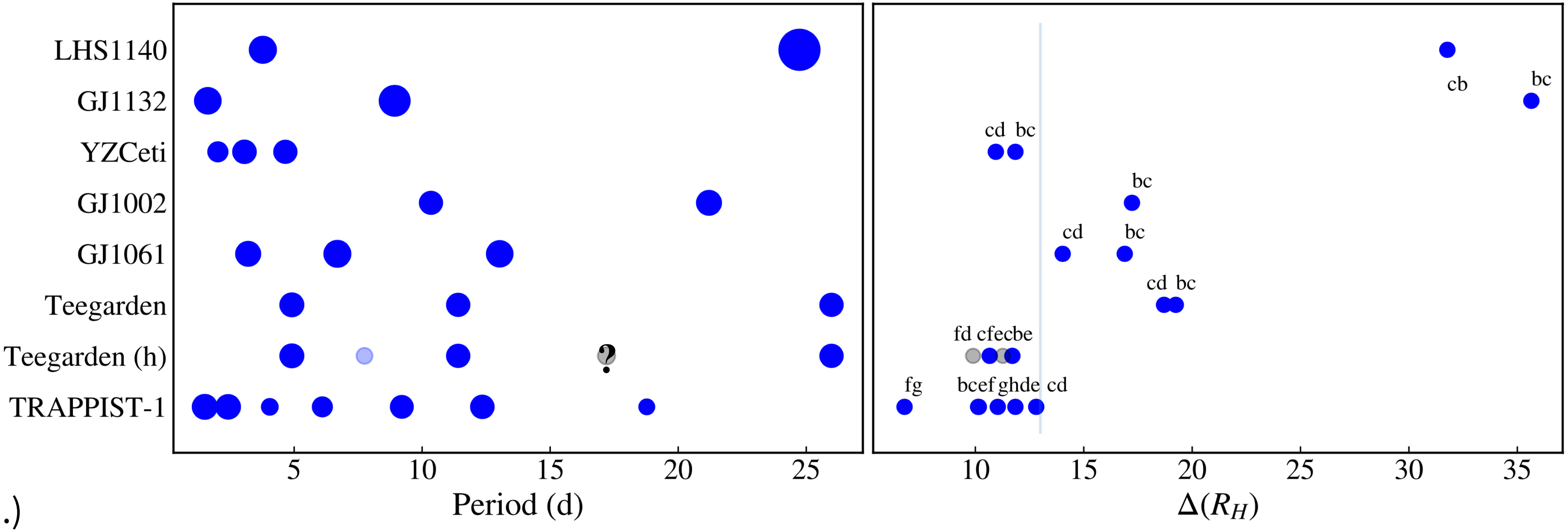
HZ planets around an ultracool dwarf (M7) with dynamical masses, at 3.8 pc

More Teegarden planets!

	Planet b	Planet c	Planet d
P (d)	4.9063 ± 0.0004	11.416 ± 0.003	26.13 ± 0.02
K (m/s)	2.09 ± 0.15	1.42 ± 0.15	0.86 ± 0.17
m sin i ($M_\oplus$)	1.16 ± 0.11	1.05 ± 0.13	0.82 ± 0.17
a (au)	0.0259 ± 0.0009	0.0455 ± 0.0015	0.0791 ± 0.0026
S ($S_\oplus$)	1.08 ± 0.08	0.35 ± 0.02	0.12 ± 0.01

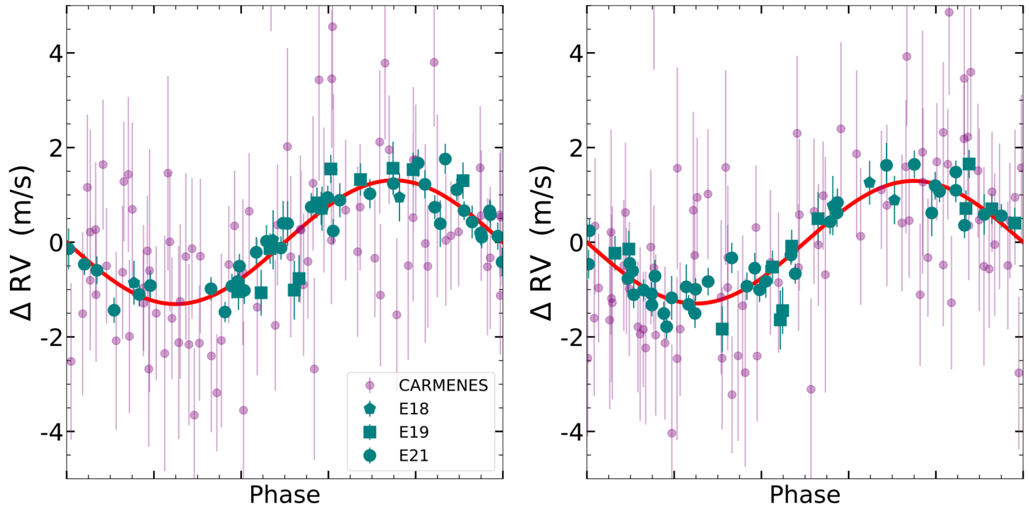
P (d)	172	96	7.7	1.104
K (m/s)	1.3	1.0	~0.5	~0.5
m sin i ($M_\oplus$)	2.3		~0.5	~0.3
Notes	Activity?	Rotation	Planet?	Planet?

- $M_\star < 0.2\ M_\odot$
- $N_{pl} > 1$
- Dynamical masses (RVs or TTVs)
- $M_{pl} < 2\ M_\oplus$ (at least 1)

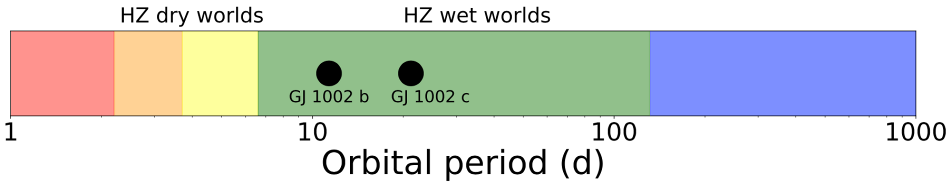


Dreizler et al. (subm.)

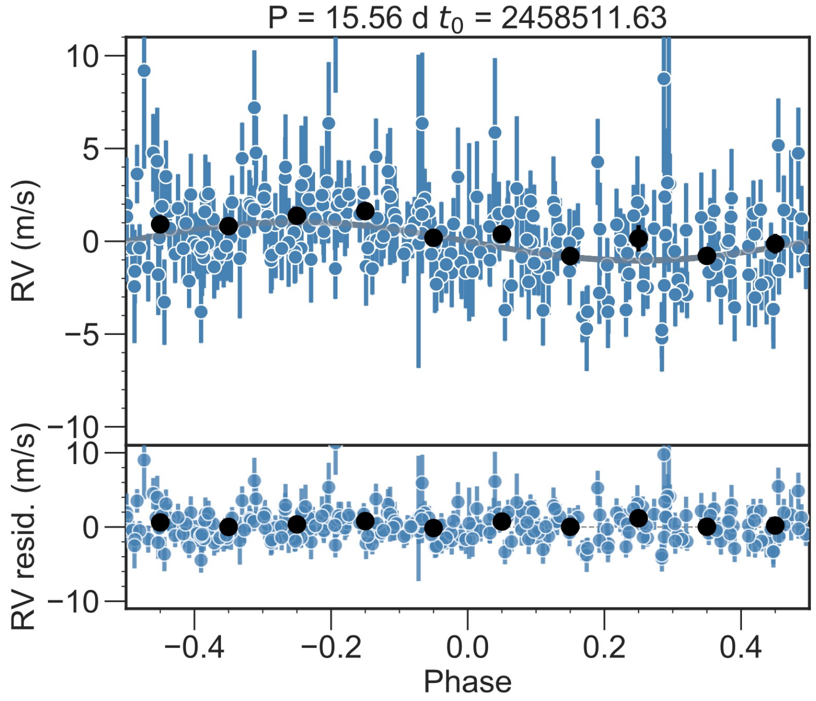
GJ 1002 b,c & Wolf 1069 b



Parameter	GJ 1002 b	GJ 1002 c
$T_0 - 2450000$ [d]	8583.27 ± 0.22	8585.54 ± 0.50
P_{orb} [d]	10.3465 ± 0.027	21.202 ± 0.013
K_p [m s^{-1}]	1.31 ± 0.14	1.30 ± 0.14
$m_p \sin i$ [M⊕]	1.08 ± 0.13	1.36 ± 0.17
a [au]	0.0457 ± 0.0013	0.0738 ± 0.0021
Incident flux [F⊕]	0.670 ± 0.039	0.257 ± 0.015
Eq. Temp.$_{A=0.3}$ [K]	230.9 ± 6.7	181.7 ± 5.2

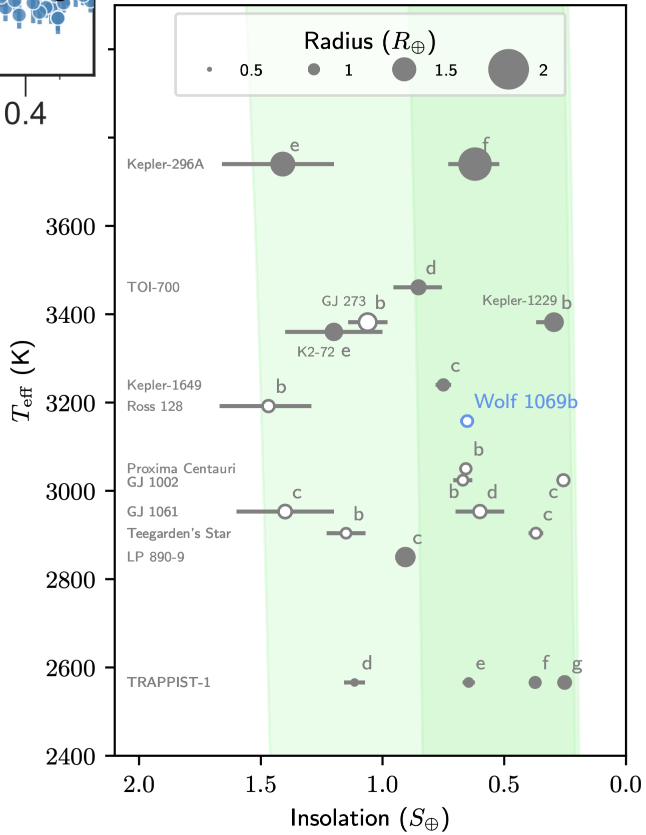


Suárez-Mascareño et al. (2023, A&A)



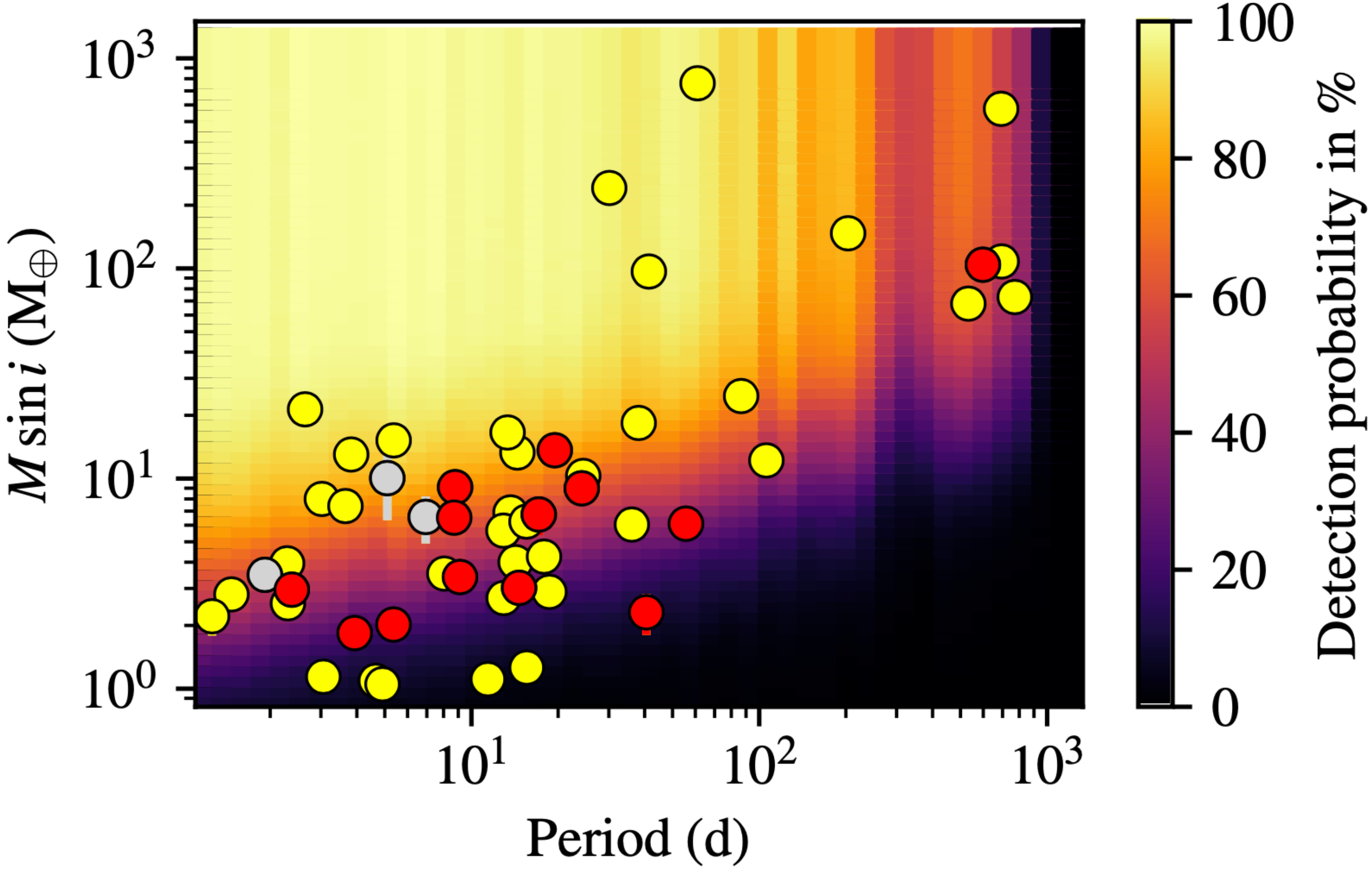
Parameter name	Posterior[(a)] b	Unit
P_p	$15.564^{+0.015}_{-0.015}$	d
$t_{0,p}$ (BJD)	$2458511.63^{+0.45}_{-0.46}$	d
K_p	$1.07^{+0.17}_{-0.17}$	m s^{-1}
$S_{1,p} = \sqrt{e_p} \sin \omega_p$	0.0 (fixed)	. . .
$S_{2,p} = \sqrt{e_p} \cos \omega_p$	0.0 (fixed)	. . .
$M \sin i_p$	$1.26^{+0.21}_{-0.21}$	$M_\oplus$
a_p	$0.0672^{+0.0014}_{-0.0014}$	au
T_{eq}[(b)]	$250.1^{+6.6}_{-6.5}$	K
S_p	$0.652^{+0.029}_{-0.027}$	$S_\oplus$

Kossakowski et al. (2023, A&A)



CARMENES occurrence rates

- Update to Sabotta et al. (2021) – from 71 to 238 stars
- 53 planets in 43 systems



Ribas et al. (2023, A&A)

CARMENES occurrence rates

	P (d) 1–10	10–100	100–1000	1–1000
(a) Planets with 100 $M_\oplus \sin i < M_{pl} < 1000 M_\oplus$				
$N_{pl,det}$	0	2	4	6
$\bar{n}_{pl}$	<0.006	$0.010^{+0.010}_{-0.005}$	$0.03^{+0.01}_{-0.01}$	$0.03^{+0.02}_{-0.01}$
N_h	0	1	4	5
F_h	<0.006	$0.006^{+0.005}_{-0.005}$	$0.03^{+0.01}_{-0.01}$	$0.03^{+0.01}_{-0.01}$
(b) Planets with 10 $M_\oplus < M_{pl} \sin i < 100 M_\oplus$				
$N_{pl,det}$	4	7	3	14
$\bar{n}_{pl}$	$0.02^{+0.02}_{-0.01}$	$0.04^{+0.02}_{-0.01}$	$0.04^{+0.02}_{-0.02}$	$0.09^{+0.03}_{-0.02}$
N_h	4	7	2	13
F_h	$0.02^{+0.02}_{-0.01}$	$0.04^{+0.02}_{-0.01}$	$0.03^{+0.02}_{-0.02}$	$0.09^{+0.02}_{-0.03}$
(c) Planets with 1 $M_\oplus < M_{pl} \sin i < 10 M_\oplus$				
$N_{pl,det}$	18	15	0	33
$\bar{n}_{pl}$	$0.39^{+0.10}_{-0.07}$	$0.67^{+0.18}_{-0.15}$	< 0.40	$1.37^{+0.24}_{-0.24}$
N_h	15	10	0	25
F_h	$0.33^{+0.08}_{-0.07}$	$0.47^{+0.13}_{-0.13}$	< 0.40	$0.89^{+0.08}_{-0.11}$
(d) Planets with 1 $M_\oplus < M_{pl} \sin i < 1000 M_\oplus$				
$N_{pl,det}$	22	24	7	53
$\bar{n}_{pl}$	$0.37^{+0.09}_{-0.07}$	$0.63^{+0.14}_{-0.12}$	$0.54^{+0.23}_{-0.17}$	$1.44^{+0.20}_{-0.20}$
N_h	19	18	6	43
F_h	$0.32^{+0.07}_{-0.07}$	$0.47^{+0.13}_{-0.09}$	$0.47^{+0.20}_{-0.16}$	$0.94^{+0.04}_{-0.09}$

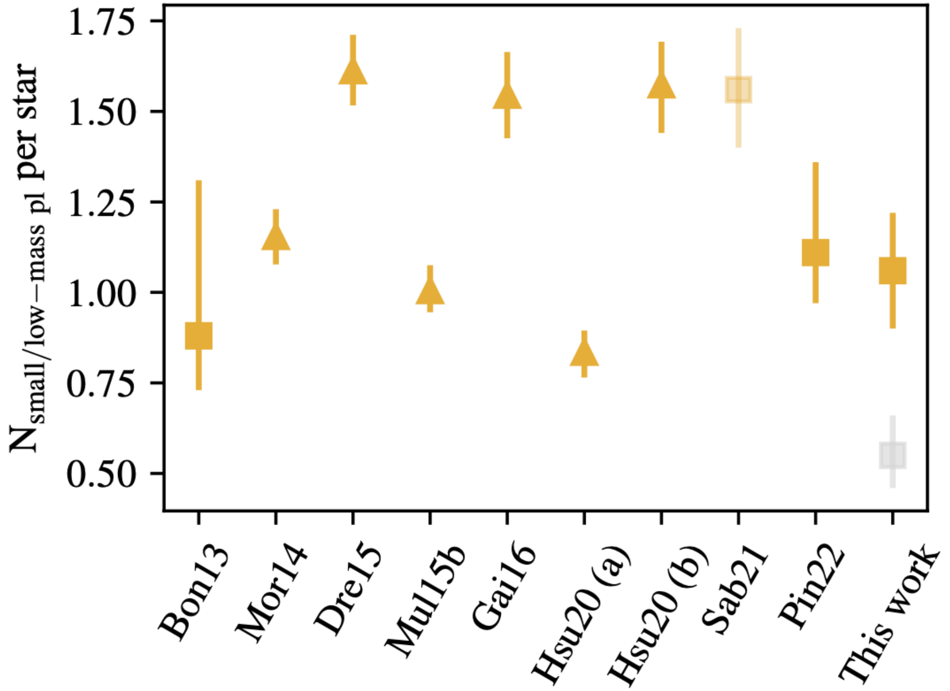
- Planets of any mass (1-1000 $M_\oplus$) & period (1-1000 d) around M dwarfs:
  - 1.44 planets per star
  - 94% of stars have planets
- Results in good agreement with Bonfils et al. (2013), Pinamonti et al. (2022) but more precise (larger sample)
- Excess of giant planets compared with theoretical expectations

Ribas et al. (2023, A&A)

CARMENES occurrence rates

	P (d)			
	1–10	10–100	100–1000	1–1000
(a) Planets with $100\,M_\oplus \sin i < M_{pl} < 1000\,M_\oplus$				
$N_{pl,det}$	0	2	4	6
$\bar{n}_{pl}$	<0.006	$0.010^{+0.010}_{-0.005}$	$0.03^{+0.01}_{-0.01}$	$0.03^{+0.02}_{-0.01}$
N_h	0	1	4	5
F_h	<0.006	$0.006^{+0.005}_{-0.005}$	$0.03^{+0.01}_{-0.01}$	$0.03^{+0.01}_{-0.01}$
(b) Planets with $10\,M_\oplus < M_{pl} \sin i < 100\,M_\oplus$				
$N_{pl,det}$	4	7	3	14
$\bar{n}_{pl}$	$0.02^{+0.02}_{-0.01}$	$0.04^{+0.02}_{-0.01}$	$0.04^{+0.02}_{-0.02}$	$0.09^{+0.03}_{-0.02}$
N_h	4	7	2	13
F_h	$0.02^{+0.02}_{-0.01}$	$0.04^{+0.02}_{-0.01}$	$0.03^{+0.02}_{-0.02}$	$0.09^{+0.02}_{-0.03}$
(c) Planets with $1\,M_\oplus < M_{pl} \sin i < 10\,M_\oplus$				
$N_{pl,det}$	18	15	0	33
$\bar{n}_{pl}$	$0.39^{+0.10}_{-0.07}$	$0.67^{+0.18}_{-0.15}$	< 0.40	$1.37^{+0.24}_{-0.24}$
N_h	15	10	0	25
F_h	$0.33^{+0.08}_{-0.07}$	$0.47^{+0.13}_{-0.13}$	< 0.40	$0.89^{+0.08}_{-0.11}$
(d) Planets with $1\,M_\oplus < M_{pl} \sin i < 1000\,M_\oplus$				
$N_{pl,det}$	22	24	7	53
$\bar{n}_{pl}$	$0.37^{+0.09}_{-0.07}$	$0.63^{+0.14}_{-0.12}$	$0.54^{+0.23}_{-0.17}$	$1.44^{+0.20}_{-0.20}$
N_h	19	18	6	43
F_h	$0.32^{+0.07}_{-0.07}$	$0.47^{+0.13}_{-0.09}$	$0.47^{+0.20}_{-0.16}$	$0.94^{+0.04}_{-0.09}$

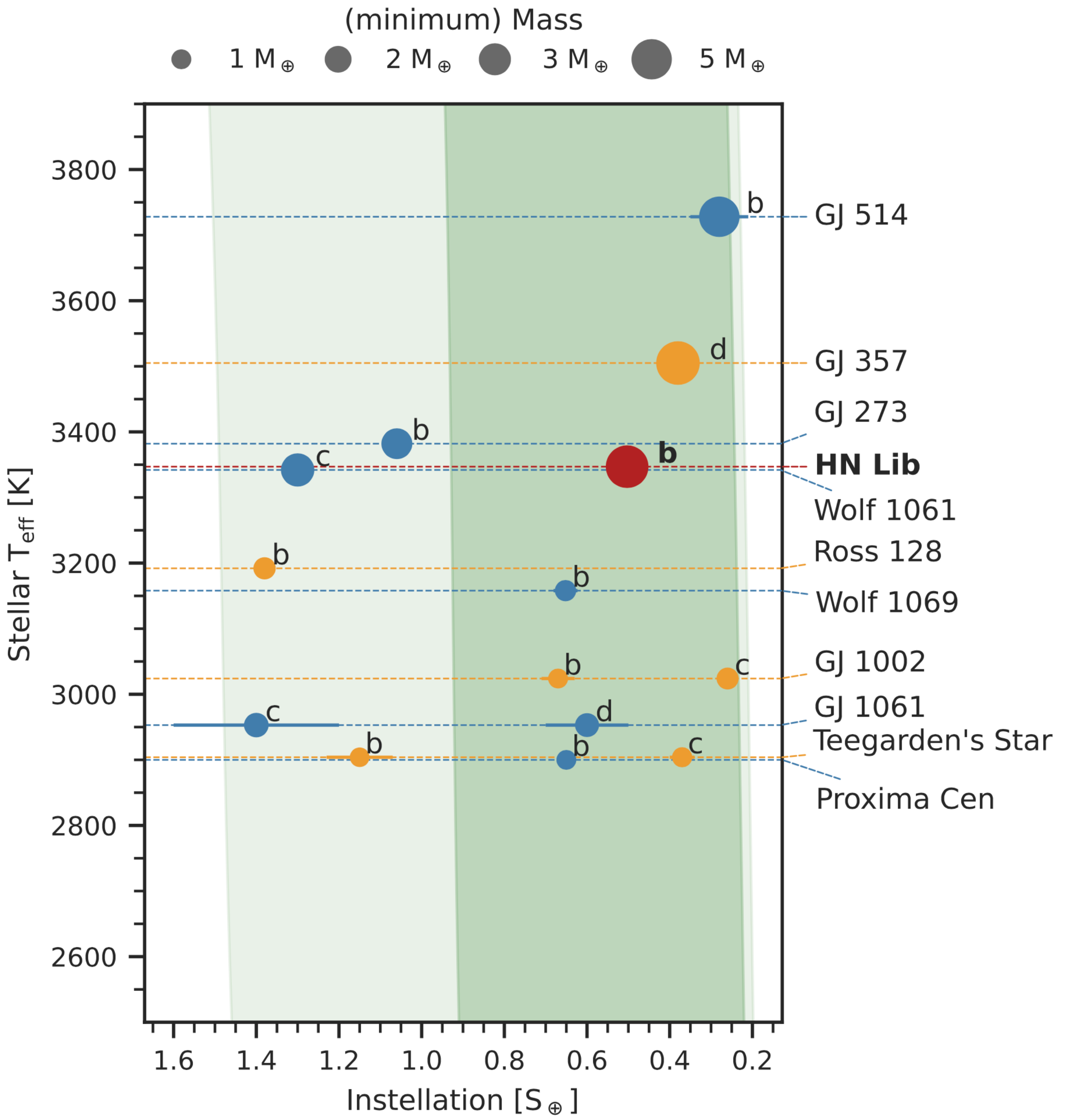
- Criteria: 1 d < P_{orb} < 100 d, 1 $M_\oplus$ < M sin i < 10 $M_\oplus$ or 1.3 $R_\oplus$ < R < 3.7 $M_\oplus$
- Different assumptions on planet mass distribution: log-uniform vs. power law
- $\eta_\oplus$~>0.3 planets per star



Ribas et al. (2023, A&A)

Nearby HZ planets

- d < 10 pc
- M sin i < 10 $M_\oplus$

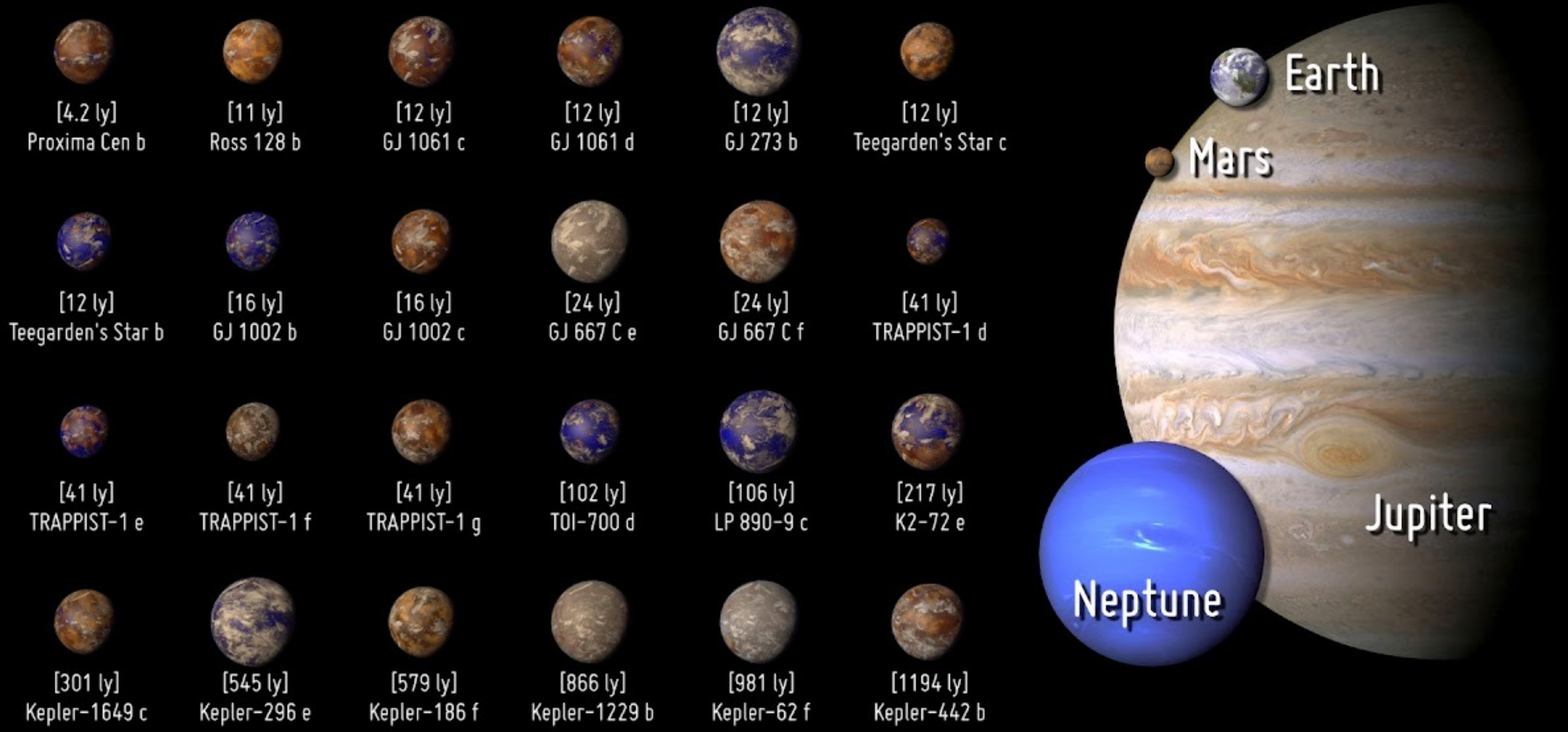


González-Álvarez et al.
(2023, A&A)

Potentially Habitable Exoplanets

Sorted by Distance from Earth

PHL

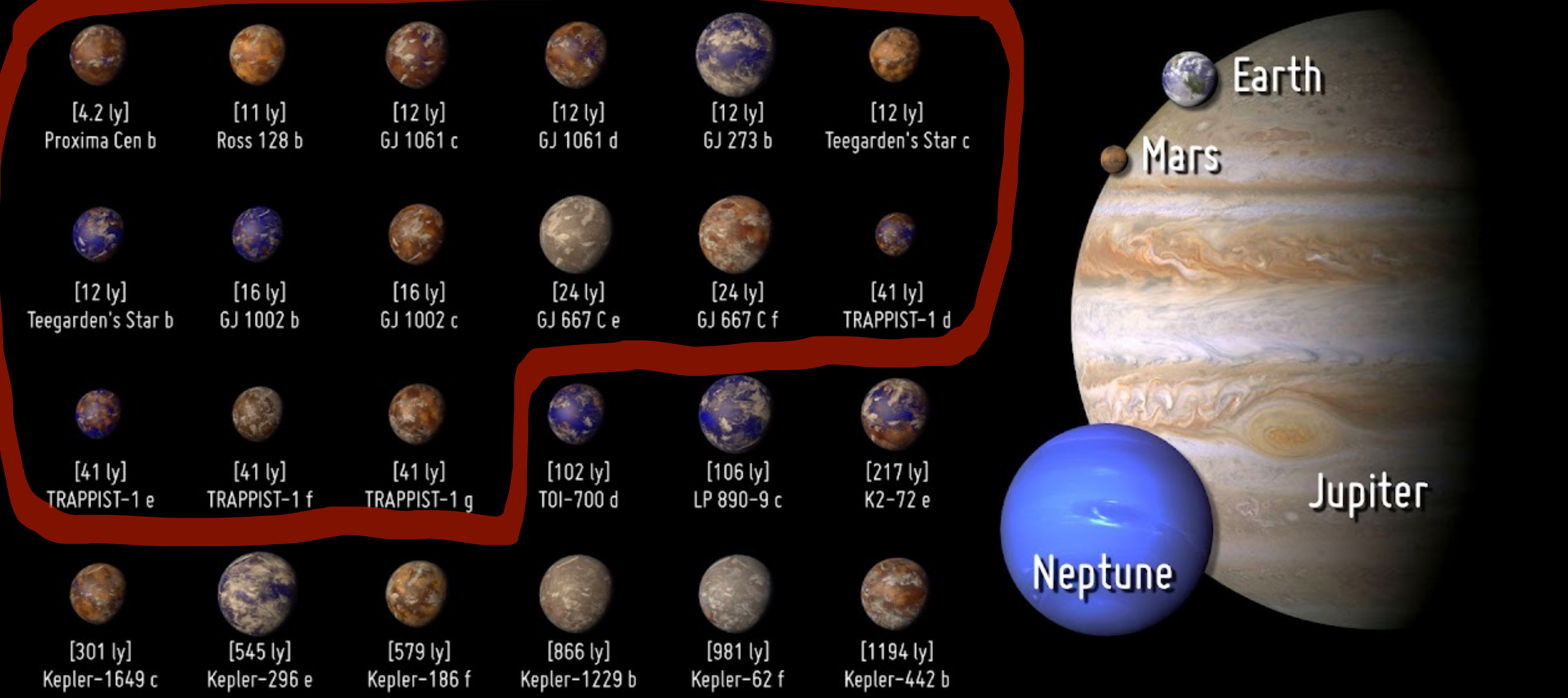


Artistic representations. Earth, Mars, Jupiter, and Neptune for scale. Distance from Earth in light years (ly) is between brackets.

CREDIT: PHL @ UPR Arecibo (phl.upr.edu) Jan 5, 2023

Potentially Habitable Exoplanets

Sorted by Distance from Earth



Artistic representations. Earth, Mars, Jupiter, and Neptune for scale. Distance from Earth in light years (ly) is between brackets.

CREDIT: PHL @ UPR Arecibo (phl.upr.edu) Jan 5, 2023

Potentially habitable

(within the habitable zone and rocky)

25-50

(0.5-1% of all)

Habitable

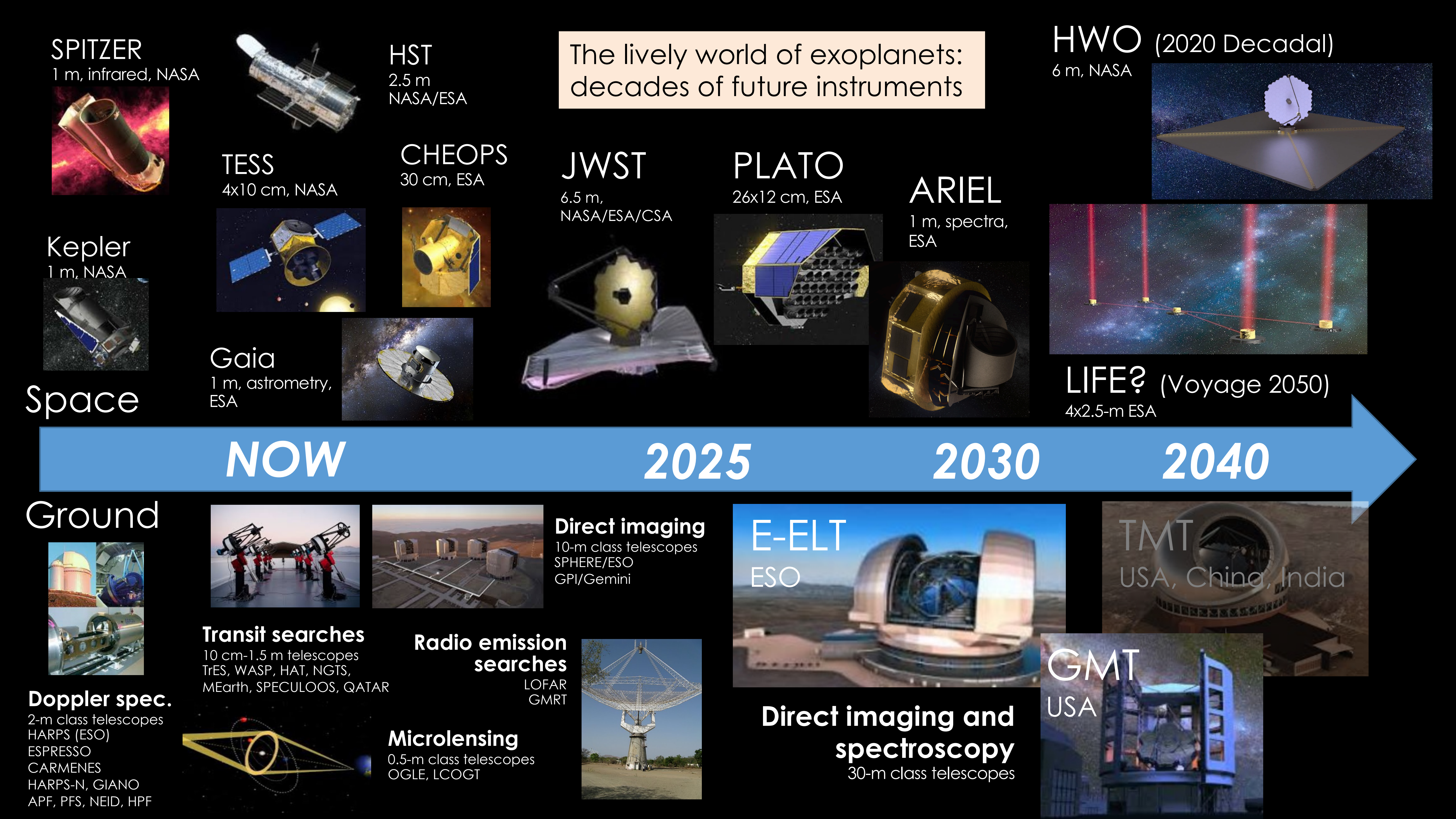
(with surface liquid water)

?

Inhabited

(with a biosphere)

?



The lively world of exoplanets: decades of future instruments
SPITZER
1 m, infrared, NASA
HST
2.5 m
NASA/ESA
HWO (2020 Decadal)
6 m, NASA
TESS
4x10 cm, NASA
CHEOPS
30 cm, ESA
JWST
6.5 m,
NASA/ESA/CSA
PLATO
26x12 cm, ESA
ARIEL
1 m, spectra,
ESA
Kepler
1 m, NASA
Gaia
1 m, astrometry,
ESA
Space
LIFE? (Voyage 2050)
4x2.5-m ESA
NOW
2025
2030
2040
Ground
Direct imaging
10-m class telescopes
SPHERE/ESO
GPI/Gemini
E-ELT
ESO
TMT
USA, China, India
Transit searches
10 cm-1.5 m telescopes
TrES, WASP, HAT, NGTS,
MEarth, SPECULOOS, QATAR
Radio emission searches
LOFAR
GMRT
GMT
USA
Doppler spec.
2-m class telescopes
HARPS (ESO)
ESPRESSO
CARMENES
HARPS-N, GIANO
APF, PFS, NEID, HPF
Microlensing
0.5-m class telescopes
OGLE, LCOGT
Direct imaging and spectroscopy
30-m class telescopes