Status updates of IRD-SSP

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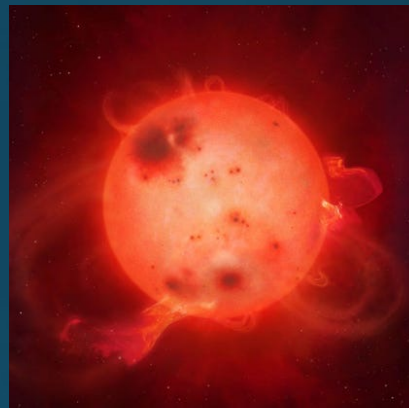
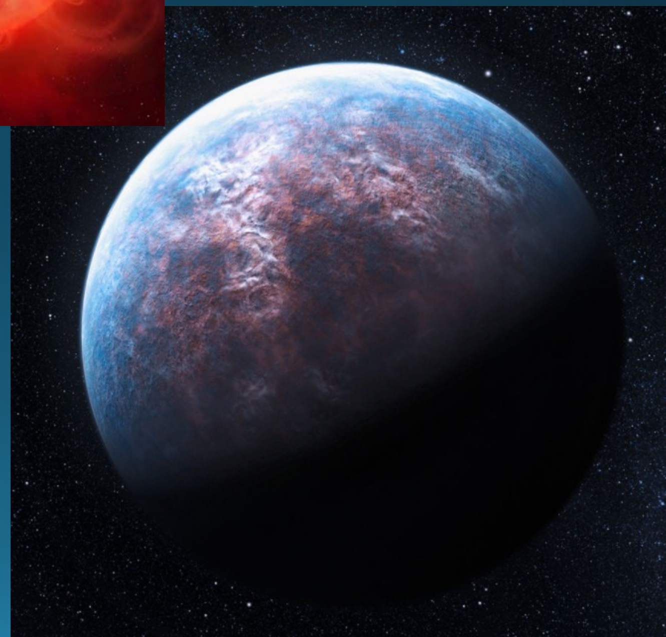
IRD-SSP (original) science goals

1. Search for Earth-mass planets in the habitable zone (HZ)
2. Uncover the distribution of planets (from terrestrial planets to giant planets) both within and beyond the snowline
3. Provide limit to the migration mechanism of small planets and planetary evolution theory

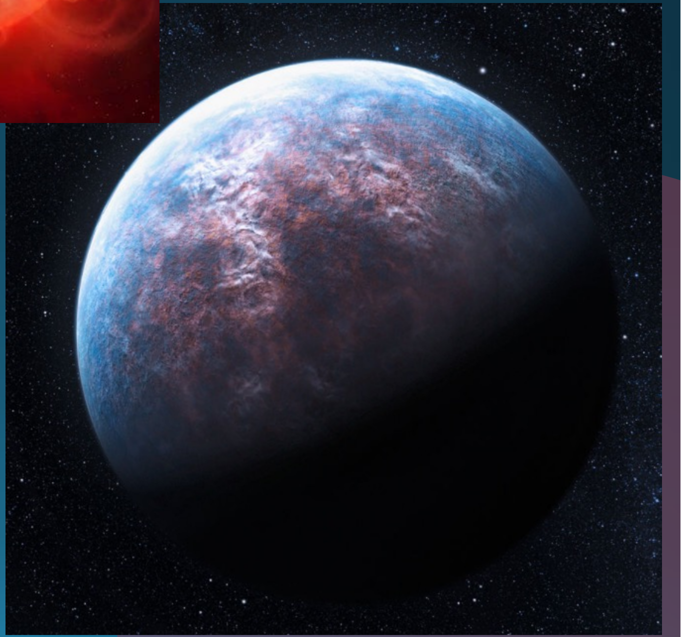


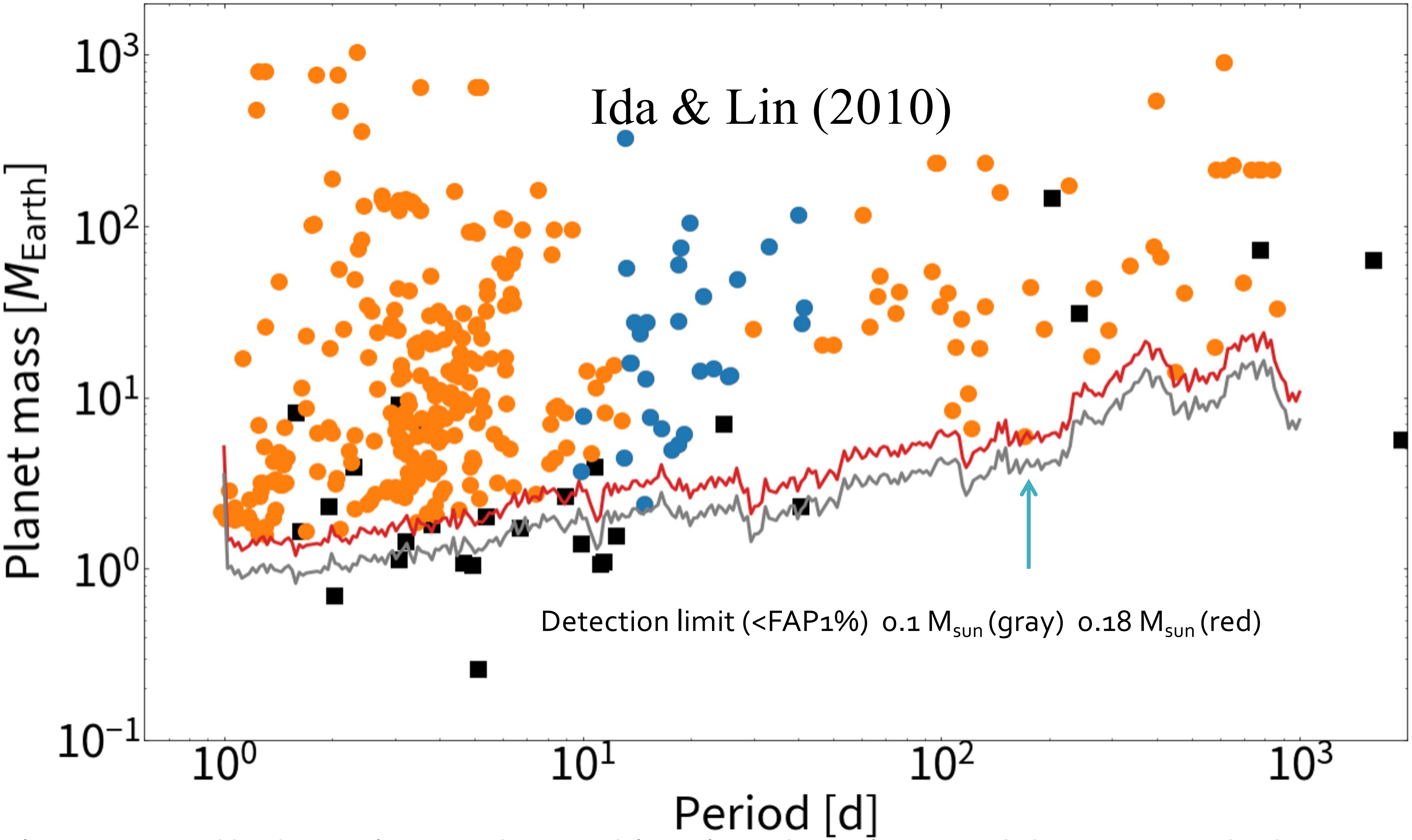


Re-defined science objectives in response to review comments and suggestions from the SSP interim review in 2022, by considering the latest planetary formation models

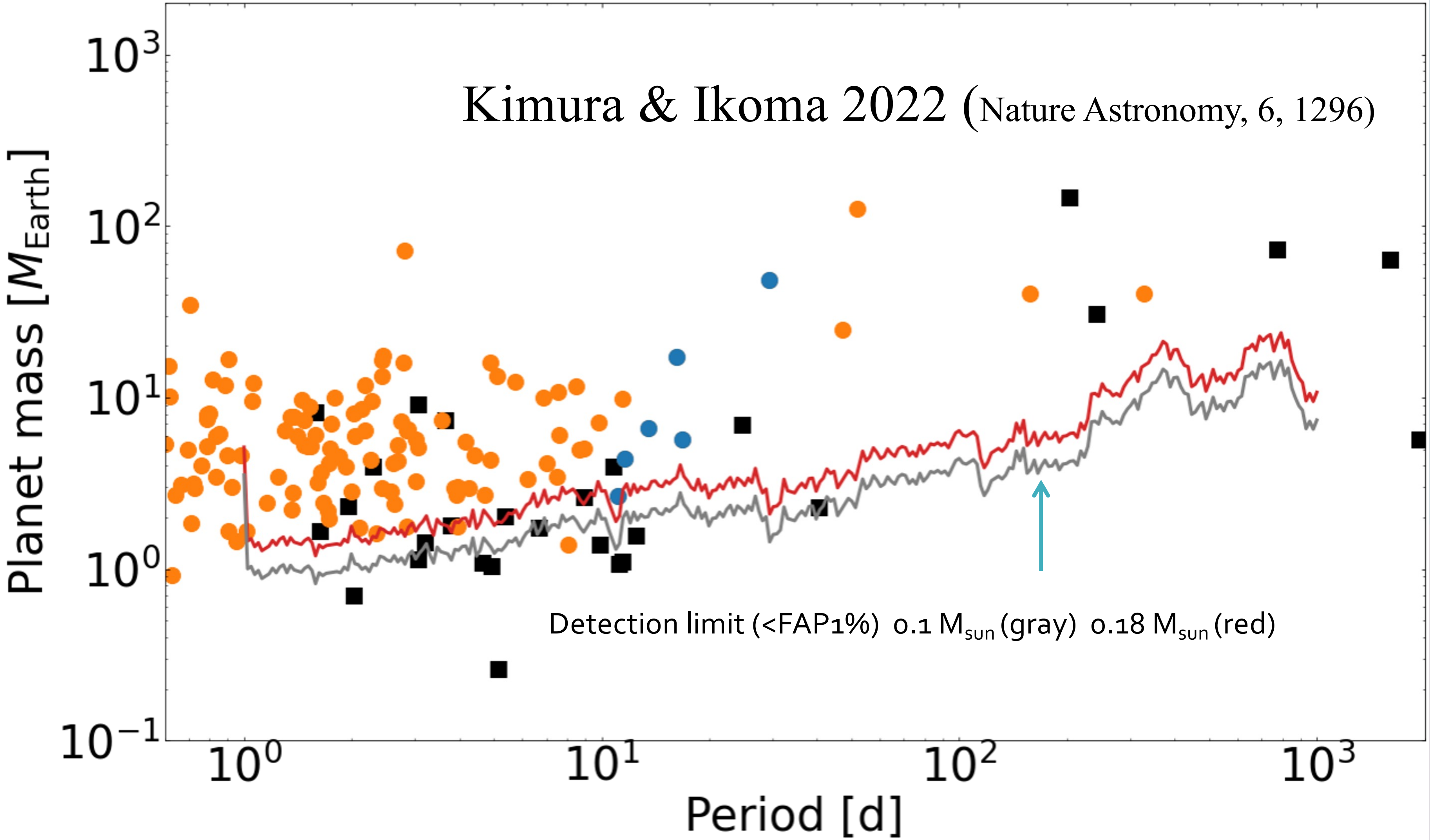
Redefinition of science goals

- Minimum Success
  - **Detection of >1 terrestrial planets (m sini = 1 -10 M_{Earth})**
  - Limit on the distribution of giant planets (> a few 10 MEarth), located up to ~0.1 a.u. for >40 stars that can be compared to the result of gravitational microlensing planet.
  - Provide an upper limit on the frequency of HZ planets, >3 MEarth
- Full Success:
  - **Discover at least one HZ planet with m sini = 1-10 M_{Earth}**
  - Limit the distribution of short-period (orbital period < 10 days), planets >3 M_{Earth}
  - Limit the frequency of existence of low-mass planets (>3 MEarth), including HZ planets
- Extra Success:
  - **Discovery of one or more HZ planets of about Earth mass (m sini= 1-3 M_{Earth})**
  - Obtain frequency of existence for terrestrial planets (>1 MEarth), including Earth-mass HZ planets
  - Discover Earth-like planets that can be followed up (transit photometry) to understand the atmospheres and internal compositions (e.g. mass-radius relationship)





Planets generated by the population synthesis model simulation (10 trials, 48 stars) that are expected to be detected (●) and HZ planets (●) 。■ is RV detected planets around a star <0.25M_{sun}



Planets generated by the population synthesis model simulation (10 trials, 48 stars) that are expected to be detected (●) and HZ planets (●) 。■ is RV detected planets around a star <0.25M_{sun}

Observation progress

- A total of 175 nights allocated for S19A~S23B period
- 149.5 nights were used for IRD-SSP by January 2024
- Success rate is particularly not good in November – February
- 25.5 nights lost due to troubles (telescope, detector, COVID-19) need to be compensated in S24A or later (7 nights in S24A and 7 nights in S24B are already approved) in order to ensure the minimum success.

	Number of night
Allocated night（S23B）	175.0
Number of nights used for IRD-SSP	149.5
Number of nights that need to be compensated	25.5
Telescope trouble, COVID-19	19.5
Detector trouble in 2020/1~2	6.0
Number of nights to be compensated in S24A	7.0
Number of nights needs to be compensated in S24B or later	18.5

Publications

1. "A Super-Earth Orbiting Near the Inner Edge of the Habitable Zone around the M4.5-dwarf Ross 508", Harakawa et al. 2022, PASJ, 74, 904
2. "Elemental Abundances of nearby M Dwarfs Based on High-resolution Near-infrared Spectra Obtained by the Subaru/IRD Survey: Proof of Concept", Ishikawa et al. 2022, AJ, 163, 72
3. "An Earth-sized Planet around an M5 Dwarf Star at 22 pc", Hirano et al. 2023, AJ, 165, 131
4. "Direct Imaging Explorations for Companions around Mid-Late M Stars from the Subaru/IRD Strategic Program", Uyama et al. 2023, AJ, 165, 162
5. "Planetary companions orbiting the M dwarfs GJ 724 and GJ 3988: A CARMENES and IRD collaboration", Gorrini et al. 2023, A&A, 680, 28

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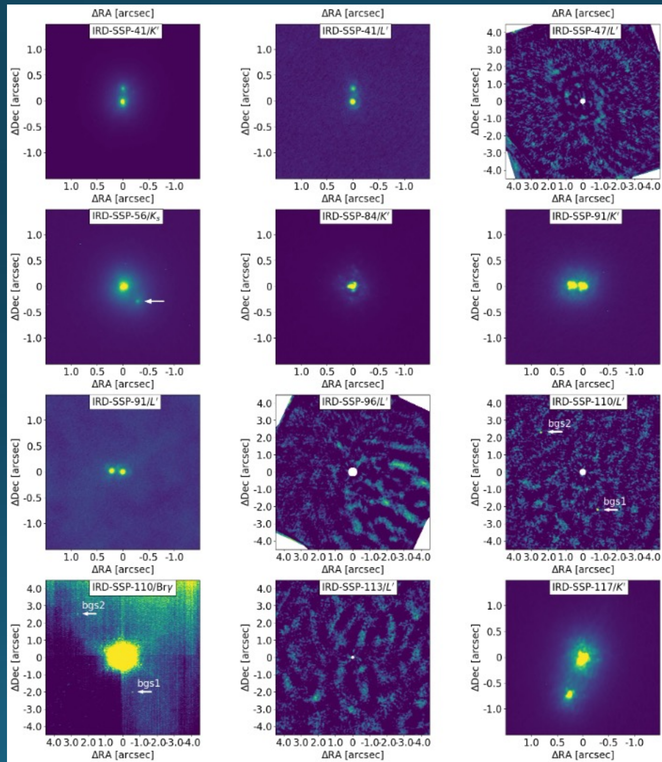
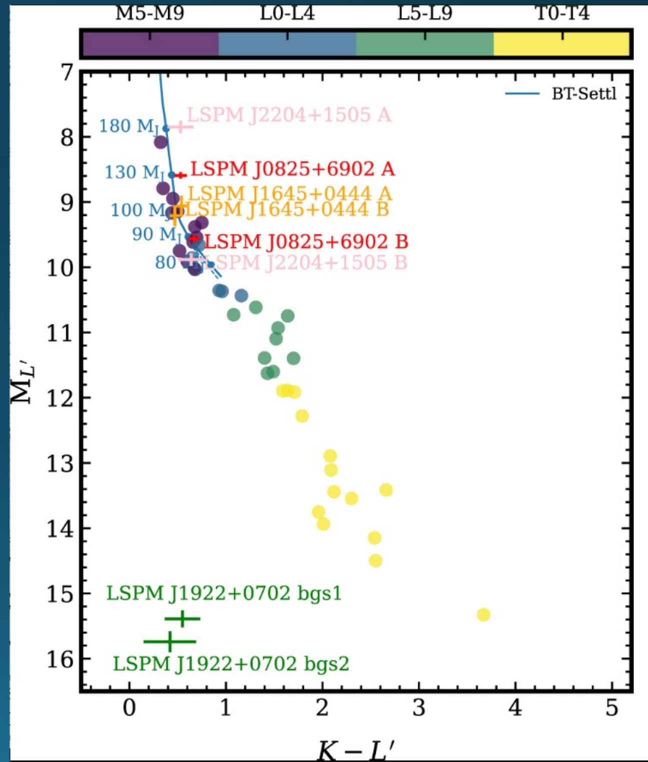
6. A paper on the discovery of "a nearby temperate Earth-sized planet ideal for JWST spectroscopy" from IRD-SSP, TESS, and MuSCAT2&3 collaboration is now under review

Several more papers are in preparation.

Direct imaging explorations for companions around Mid-Late M stars

- Binarity study of IRD-SSP sample by Keck/NIRC2 and IRD/FIM
- "Deprioritized" IRD-SSP targets that have signatures of long-term RV trends and/or large RUWE values from the Gaia catalog suggesting unresolved systems
- Detected 7, including 4 new, companions at projected separations between ~ 2 – 20 au from the target stars
- Non-detection makes the objects promising targets for further RV monitoring





Uyama et al. 2023, AJ, 165, 162

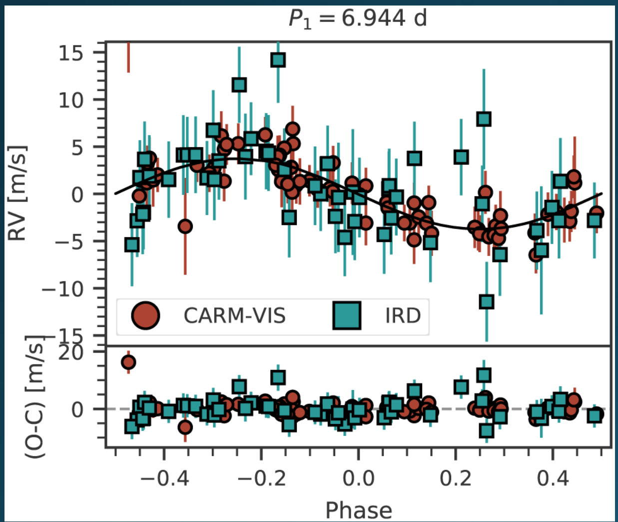
Collaboration with CARMENES

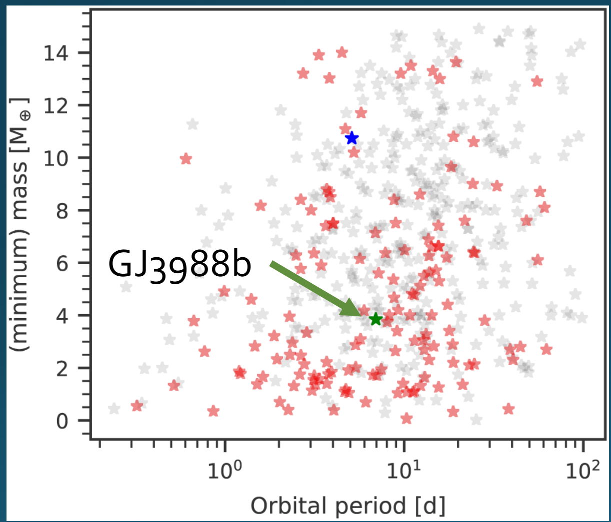
- New collaboration with the CARMENES team from 2022/09 to maximize science output of IRD-SSP
  - CARMENES project: visible & NIR RV survey of M-dwarfs started in 2016 (750-night exoplanet survey targeting ~300 M dwarfs)
  - Sharing a target list and RV data, coordinated observations, data reduction, activity analysis, etc.

IRD Infrared Doppler

carmenes

A planet orbiting the M dwarf GJ 3988 (M4.5V, 0.18M_{sun}): A CARMENES and IRD collaboration





Gorrini et al. 2023, A&A, 680, A28

Parameter [a]	GJ 724	GJ 3988
Planetary posteriors		
P_b (d)	$5.101\,284^{+0.000\,090}_{-0.000\,077}$	$6.9442^{+0.0010}_{-0.0010}$
$t_{0,b}$ (BJD)	$2\,457\,509.766^{+0.050}_{-0.049}$	$2\,457\,509.78^{+0.26}_{-0.25}$
K_b (m s^{-1})	$7.48^{+0.90}_{-0.67}$	$3.83^{+0.37}_{-0.37}$
$\sqrt{e_b}\cos\omega_b$	$0.635^{+0.050}_{-0.055}$	0 (fixed)
$\sqrt{e_b}\sin\omega_b$	$0.416^{+0.060}_{-0.065}$	0 (fixed)
Derived parameters [b]		
$M_b \sin i$ ($M_\oplus$)	$10.75^{+0.96}_{-0.87}$	$3.69^{+0.42}_{-0.41}$
a_b (au)	$0.046\,85^{+0.000\,77}_{-0.000\,79}$	$0.0405^{+0.0011}_{-0.0012}$
e_b	$0.577^{+0.055}_{-0.052}$	0 (fixed)
ω_b (deg)	$33.2^{+5.7}_{-5.5}$	0 (fixed)
$\langle S_b$ ($S_\oplus$)$\rangle$	$23.32^{+0.82}_{-0.77}$	$2.45^{+0.15}_{-0.13}$
$\langle T_{eq,b}$ [c] (K)$\rangle$	611^{+20}_{-19}	348^{+17}_{-16}
$T_{eq,b}$ [d] (K)	643^{+30}_{-26}	349^{+19}_{-17}
GP posteriors		
$P_{GP,rv}$ (d)	$29.50^{+0.88}_{-1.46}$	$115.28^{+3.24}_{-3.06}$
$\sigma_{GP,rv,CARM-VIS}$ (m s^{-1})	$3.09^{+1.14}_{-0.72}$	$3.30^{+1.20}_{-0.85}$
$\sigma_{GP,rv,HARPS}$ (m s^{-1})	$3.00^{+1.17}_{-0.86}$	...
$\sigma_{GP,rv,IRD}$ (m s^{-1})	...	$4.36^{+2.20}_{-1.50}$
$f_{GP,rv}$	$0.70^{+0.21}_{-0.31}$	$0.65^{+0.24}_{-0.31}$
$Q_{0,GP,rv}$	$5.4^{+15.4}_{-4.5}$	$0.46^{+1.10}_{-0.29}$
$dQ_{GP,rv}$	23^{+3193}_{-23}	$561.36^{+19\,571.86}_{-560.55}$
Instrumental posteriors		
$\gamma_{CARM-VIS}$ (m s^{-1})	$0.79^{+0.40}_{-0.43}$	$0.30^{+0.61}_{-0.59}$
$\sigma_{CARM-VIS}$ (m s^{-1})	$1.18^{+0.67}_{-0.69}$	$1.27^{+0.49}_{-0.50}$
γ_{HARPS} (m s^{-1})	$-0.80^{+0.66}_{-0.63}$	...
σ_{HARPS} (m s^{-1})	$0.65^{+0.70}_{-0.45}$	...
γ_{IRD} (m s^{-1})	...	$-0.12^{+1.04}_{-1.50}$
σ_{IRD} (m s^{-1})	...	$3.17^{+0.77}_{-0.72}$

The 3rd terrestrial planet from IRD-SSP