

Temperate Giant Planets: Discoveries & Opportunities

Tristan Guillot

Lyu Abe, Karim Agabi, Matteo Beltrame, Philippe Bendjoya, Nicolas Crouzet, Vincent Deloupy, Georgina Dransfield, Maximillian Günther, Djamel Mékarnia, Erika Rea, François-Xavier Schmider, Olga Suarez, Mathilde Timmermans, Amaury Triaud, Xavier Bonfils, Jose Manuel Almenara, Jean-Baptiste Daban, Solène Ulmer-Moll, Mansi Kasliwal, Roger Smith, Tim Greffe

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1. ASTEP

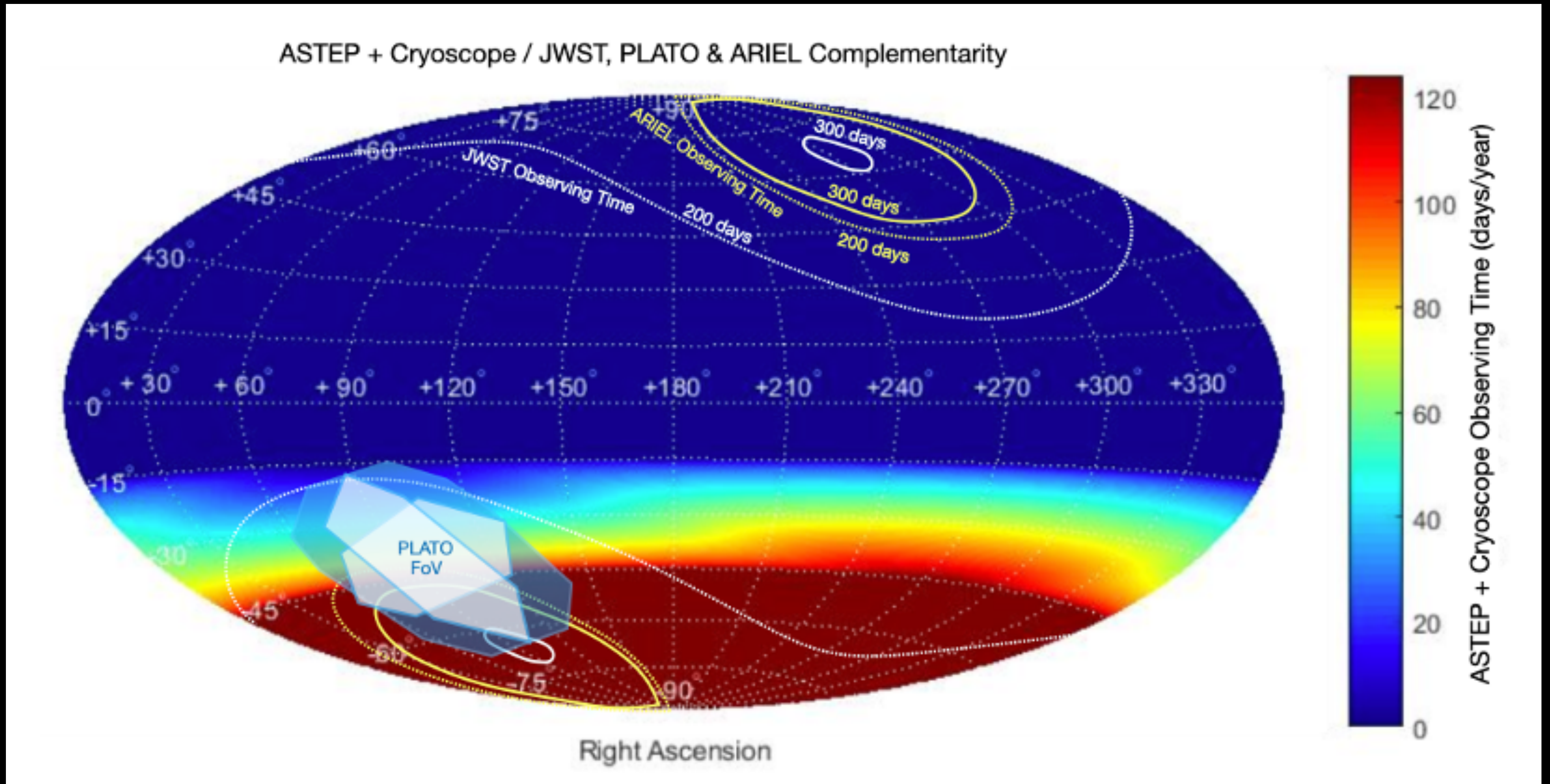








Targets accessible from Concordia



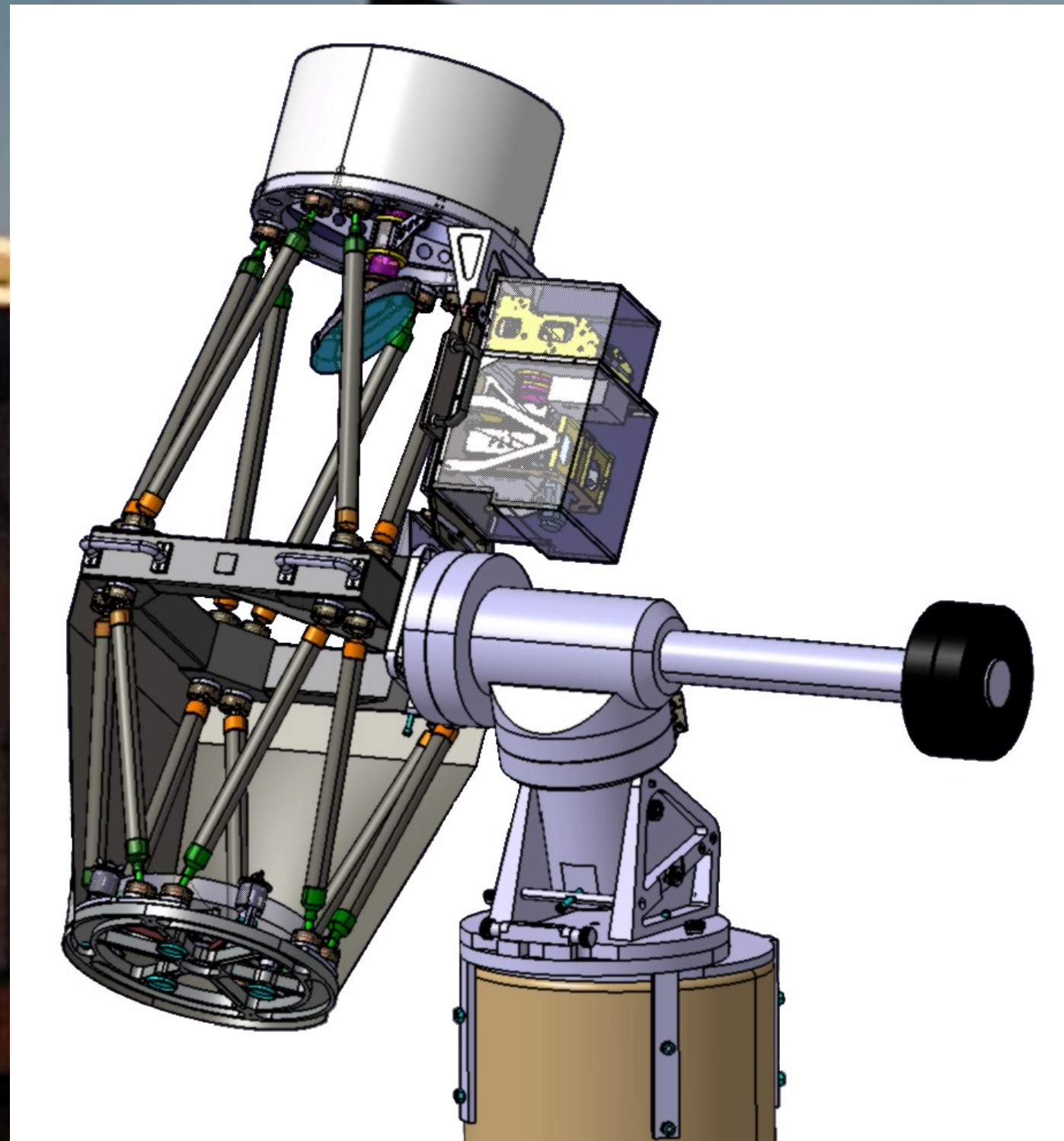


Dome ASTEP West 2023-05-27 LT 12:00

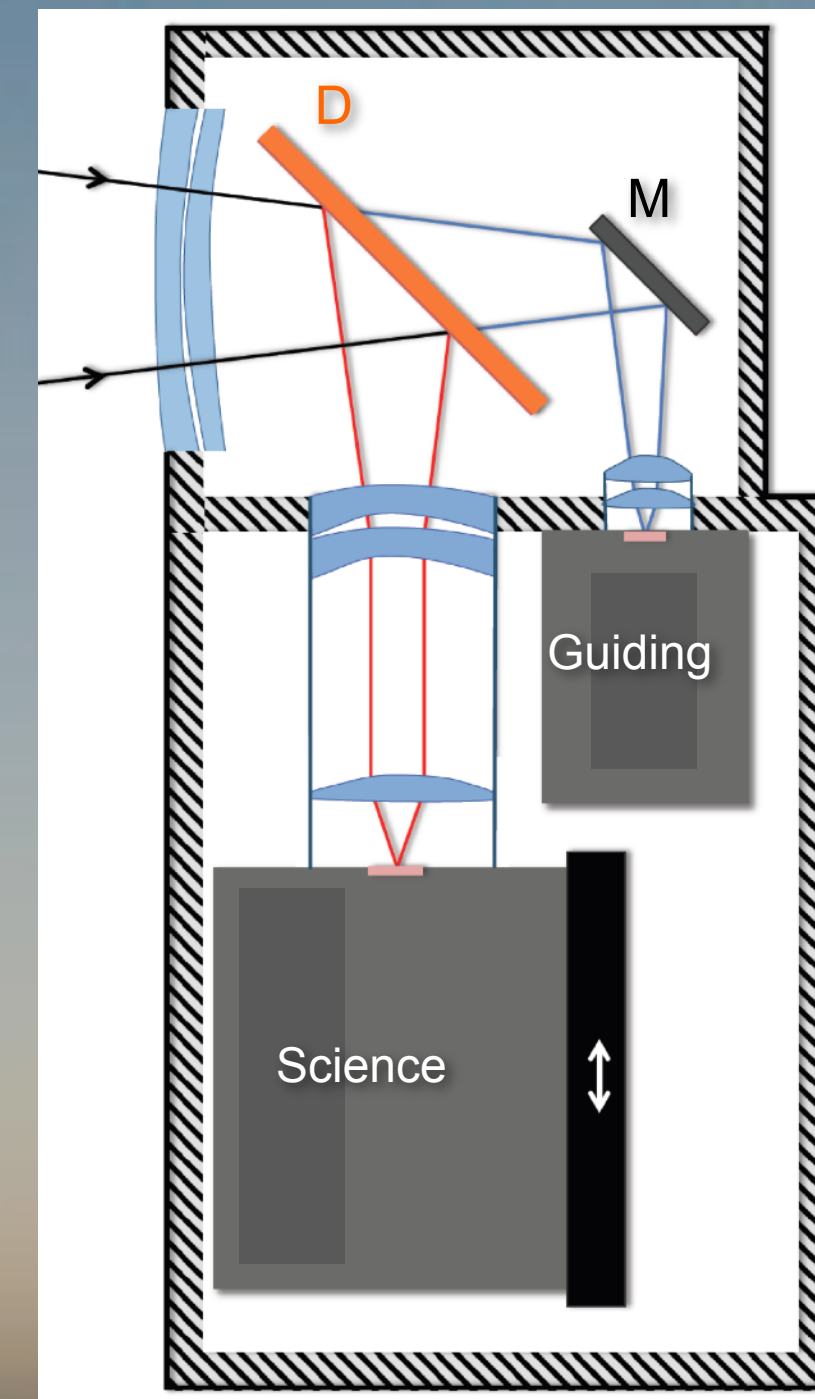
Historical background

- 2006: Proposition of ASTEP (w/ PhD student F. Fressin), ANR funding
- 2009: Tests and installation at Concordia
- 2010-2013: 4 seasons of observation at Concordia
 - Crouzet et al. (2010, 2018): Demonstration of high weather quality (2/3 photometric)
 - Abe et al. (2013): First secondary eclipse of an exoplanet in the visible from the ground
 - Mékarnia et al. (2016): 43 planetary transit candidates from ASTEP
- 2017-2019: A new international campaign to observe Beta Pic
 - Mékarnia et al. (2017): 31 pulsation frequencies (28 new!)
 - Lagrange et al. (2019): Contribution to the detection of Beta Pic c
- Since 2019: Follow-up of TESS planetary transit candidates
- Since 2022: Observations with a new dual-camera system
 - funding from ESA, Univ. Birmingham, INSU, Lagrange Lab.
- In 2024: Installation of a new direct-drive mount
 - funding from ESA, Univ. Birmingham, INSU

ASTEP before 2022



Telescope weight = 83 Kg, including 23 Kg for the focal box



✓ Optical & Mechanical

- 400mm Newton optical design, $f/D=4.6$
- FoV $1^\circ \times 1^\circ$ [Wynne corrector]
- Commercial AP3600 Equatorial Mount

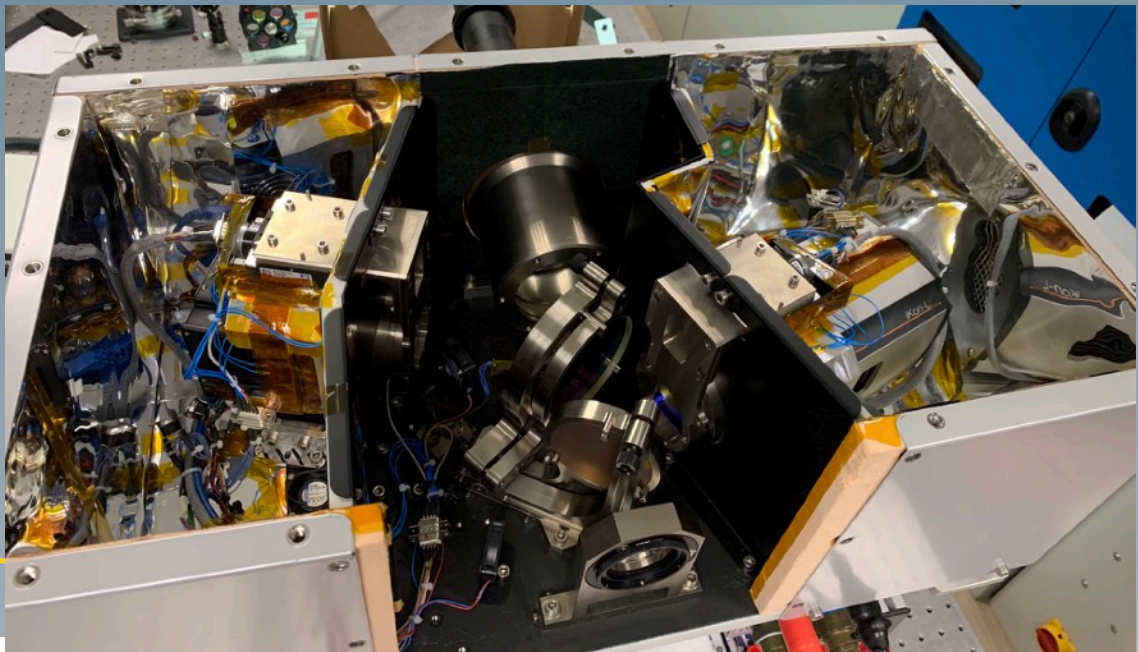
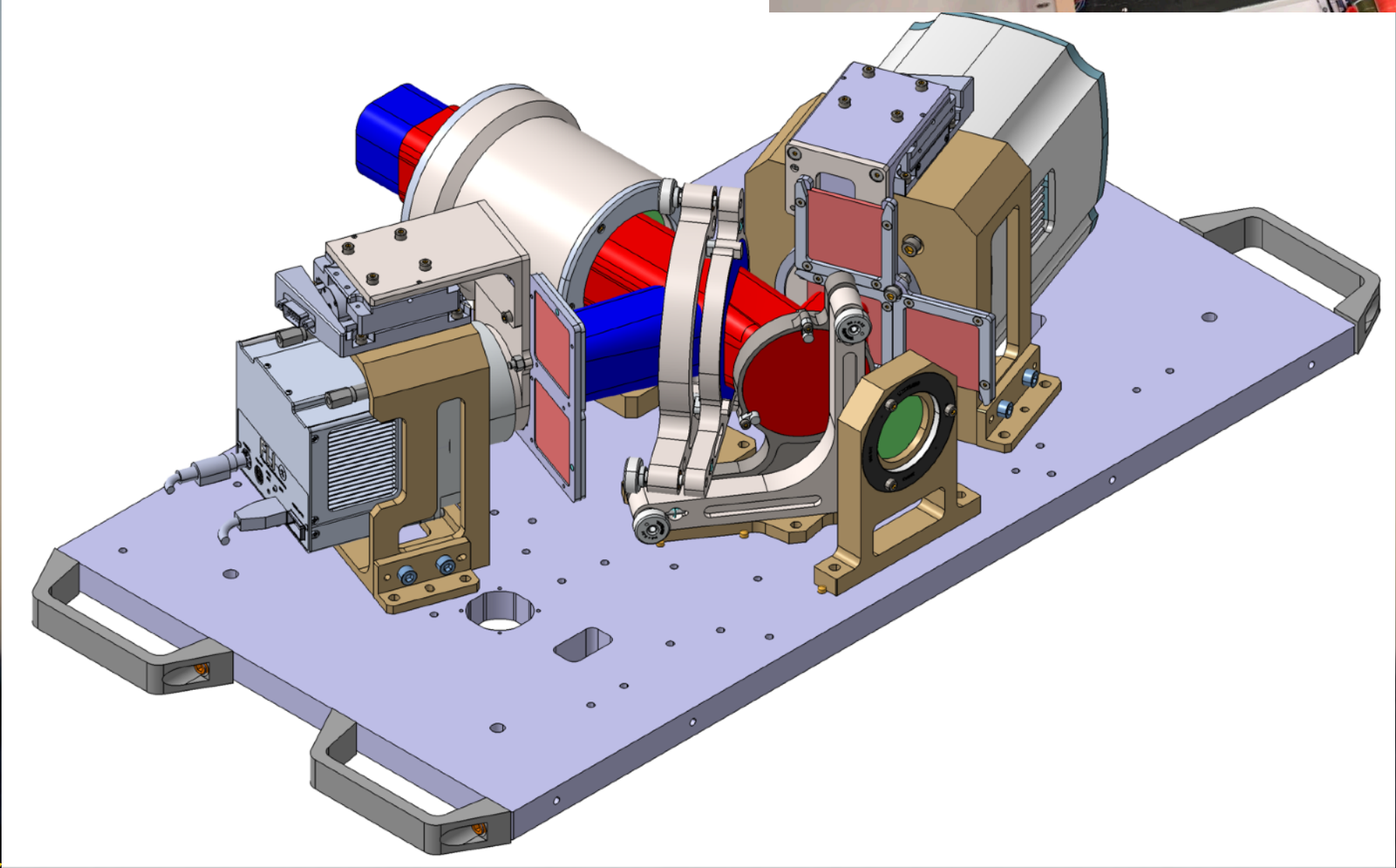
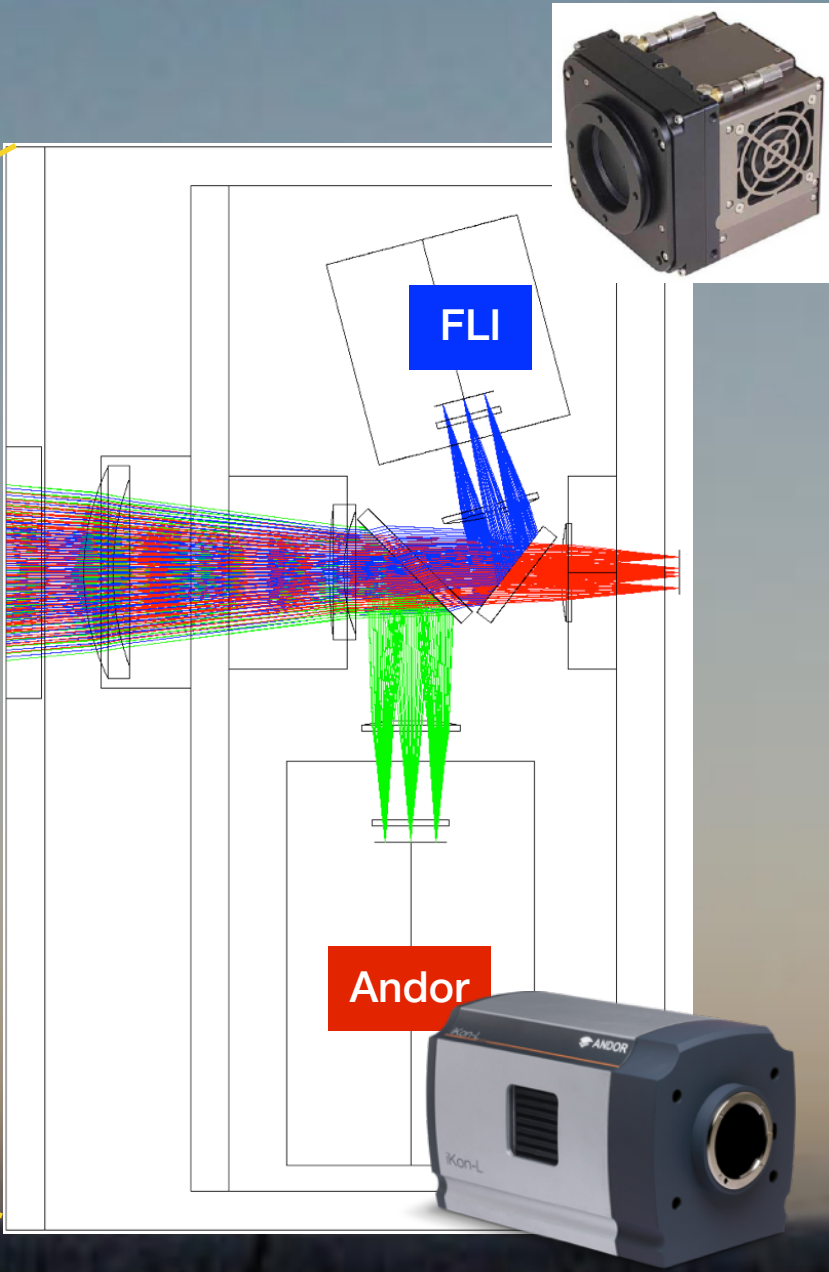
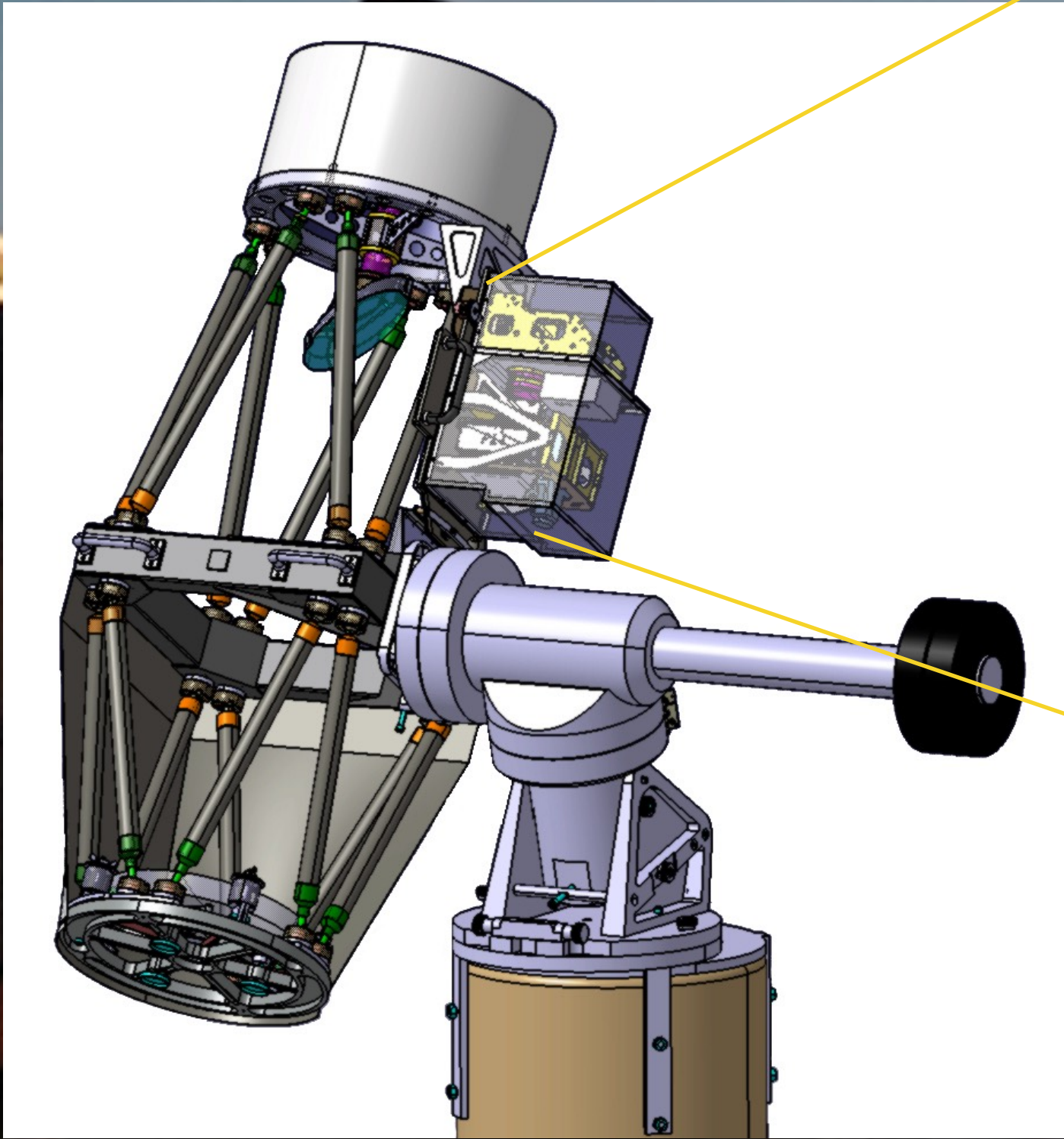
✓ Cameras

- Cooled Science CCD [FLI $4k \times 4k$, $\sim 0.9''/\text{pix}$]
- Cooled Guiding CCD [SBIG]

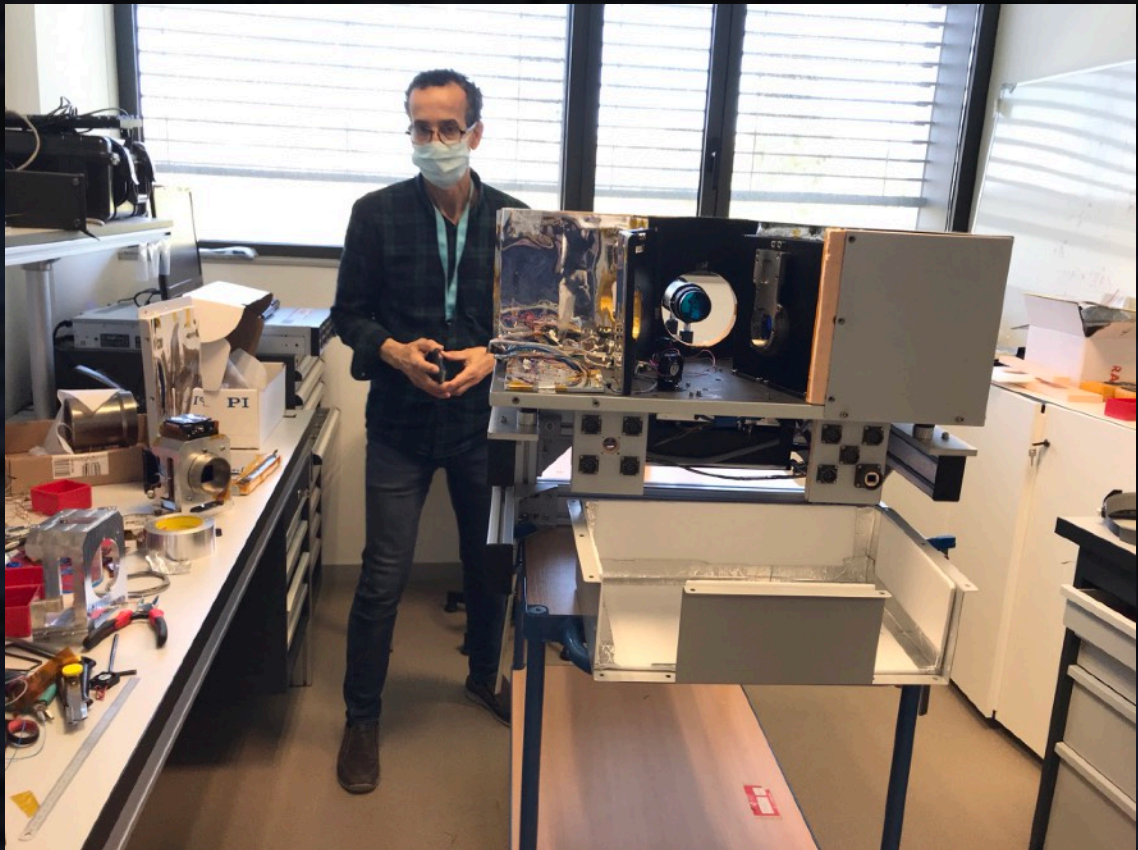
✓ Operation

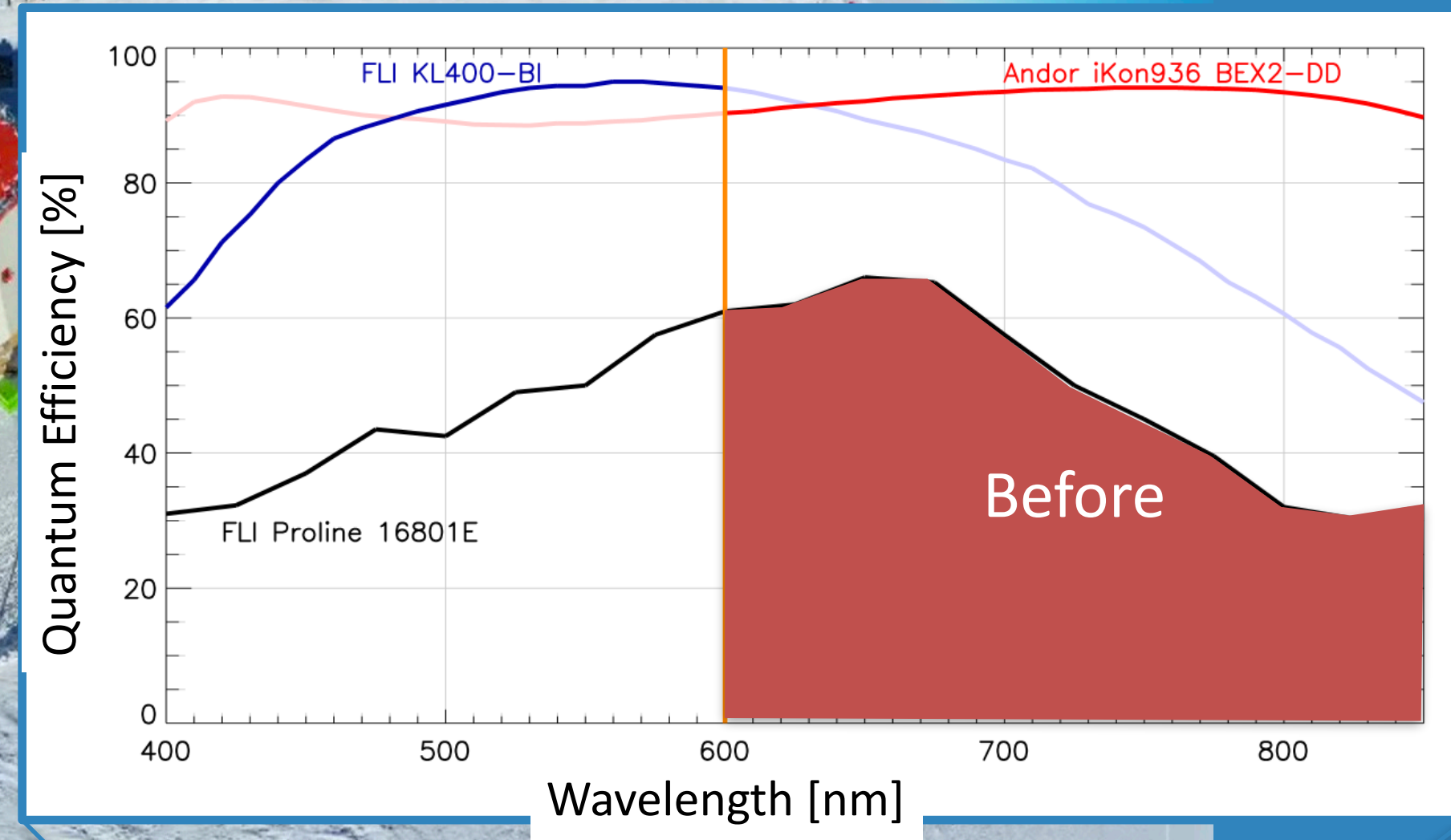
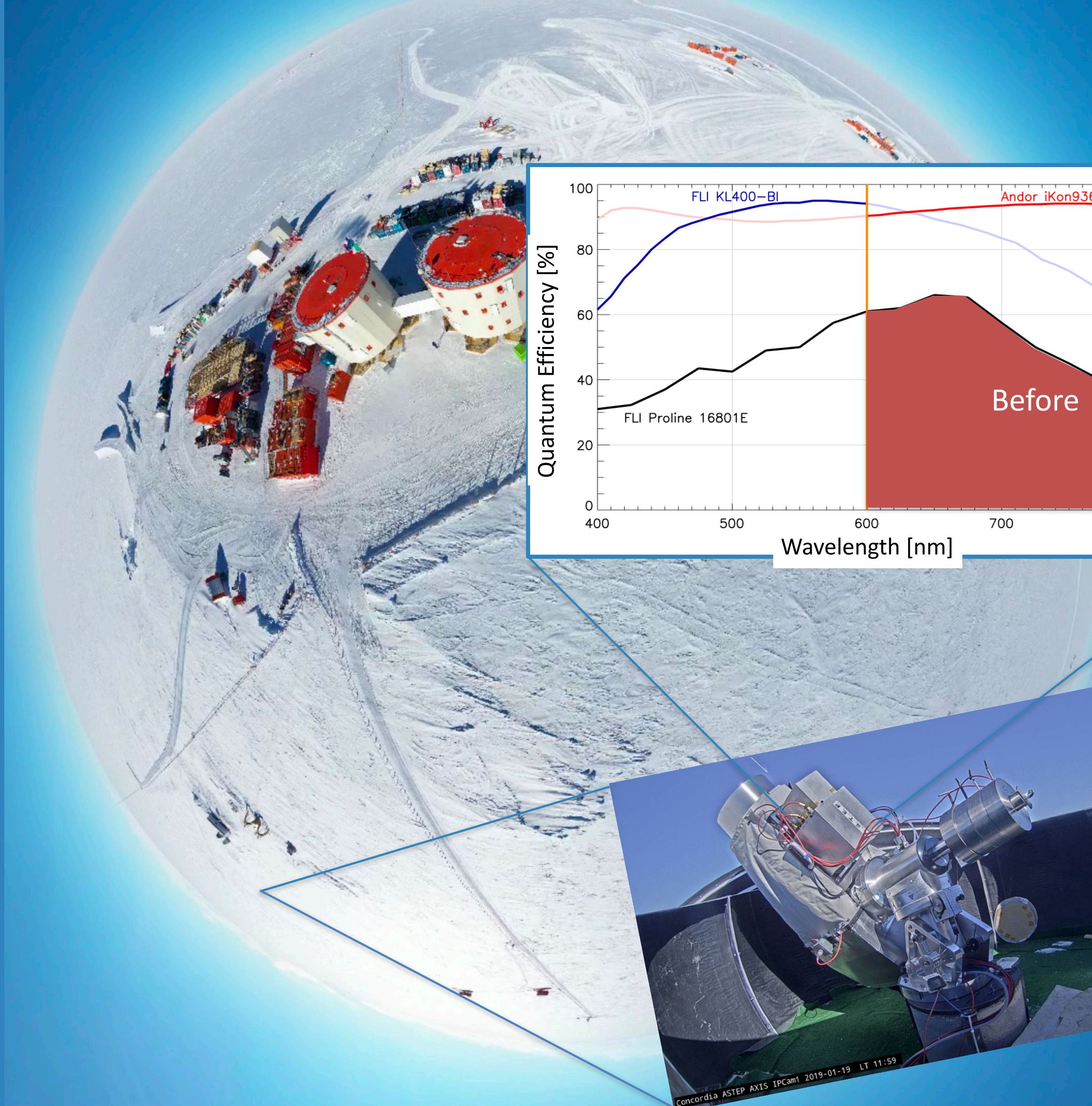
- Automatic mode [scheduler & remote control]

ASTEP since 2022

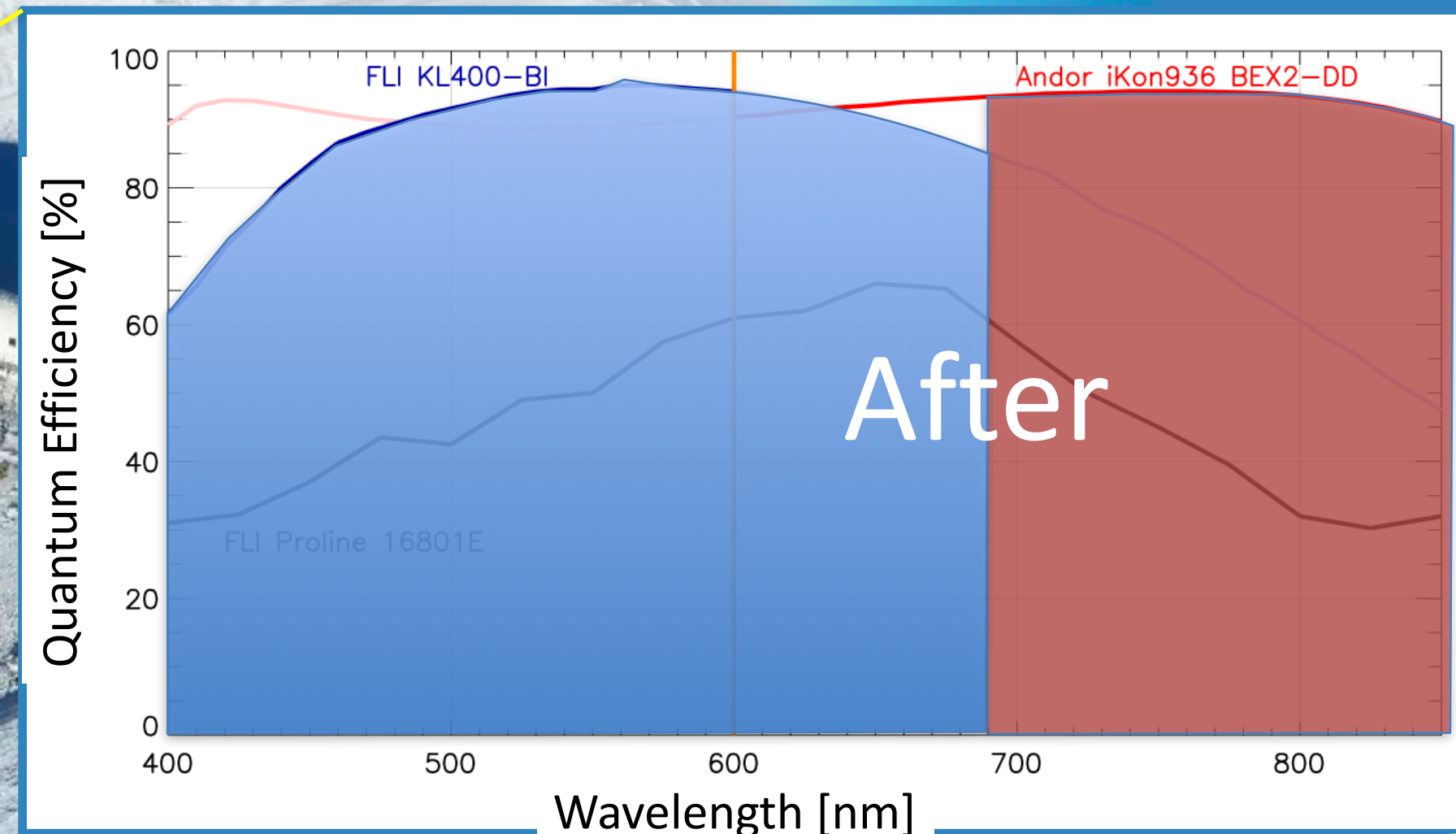


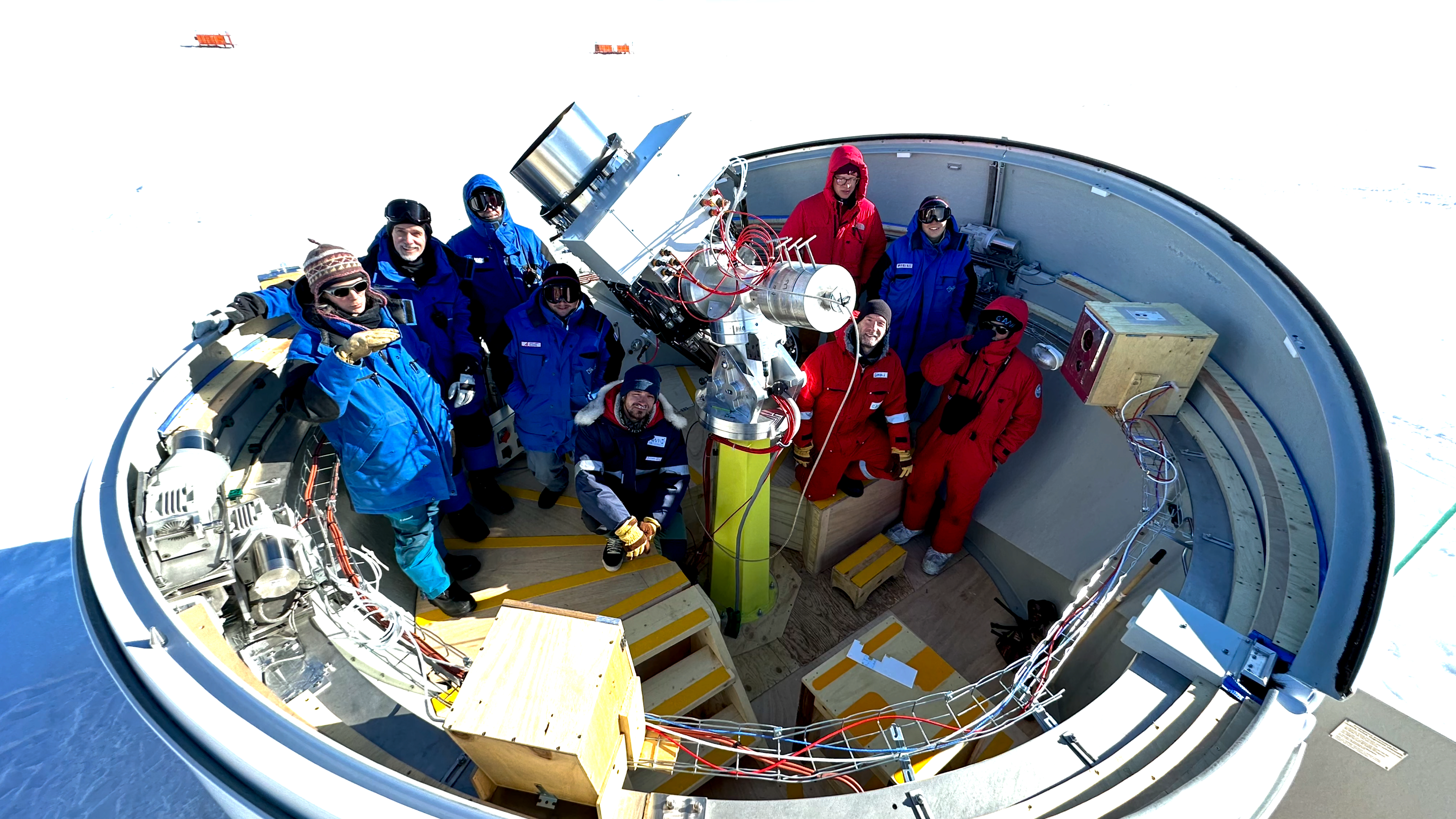
cold chamber tests @ -75°C





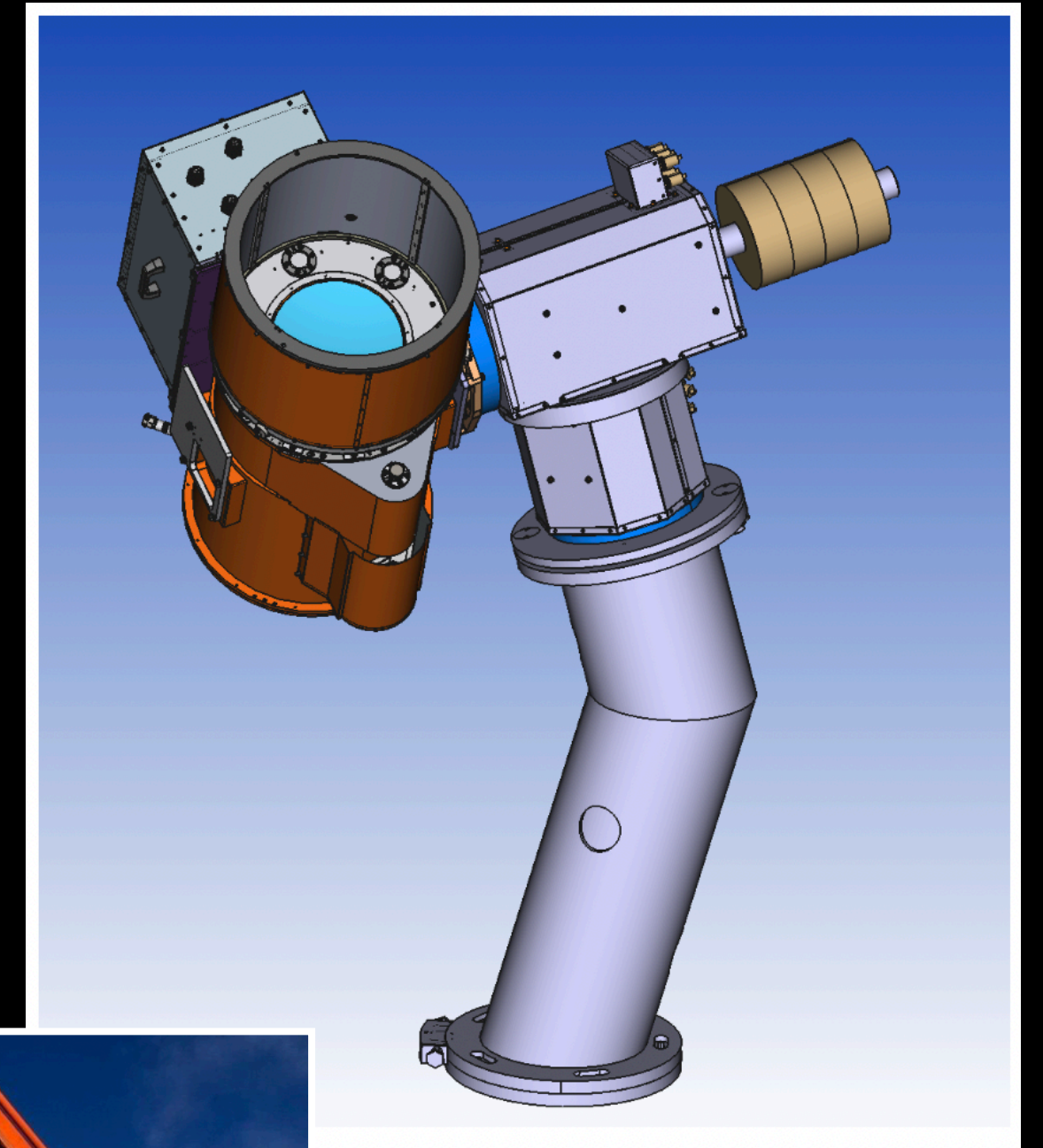
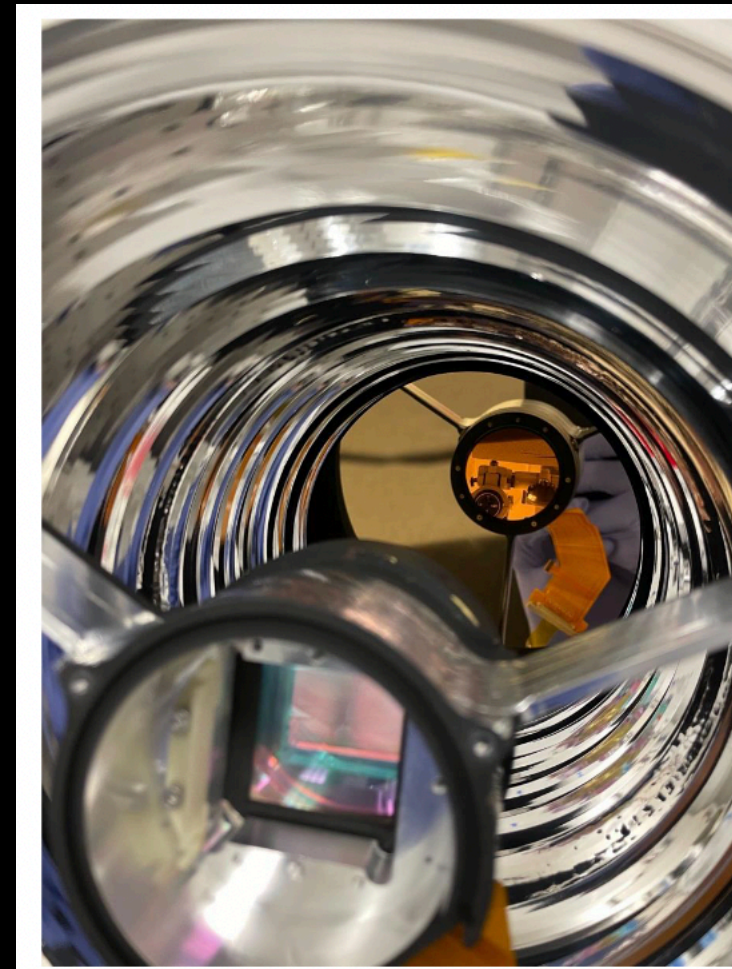
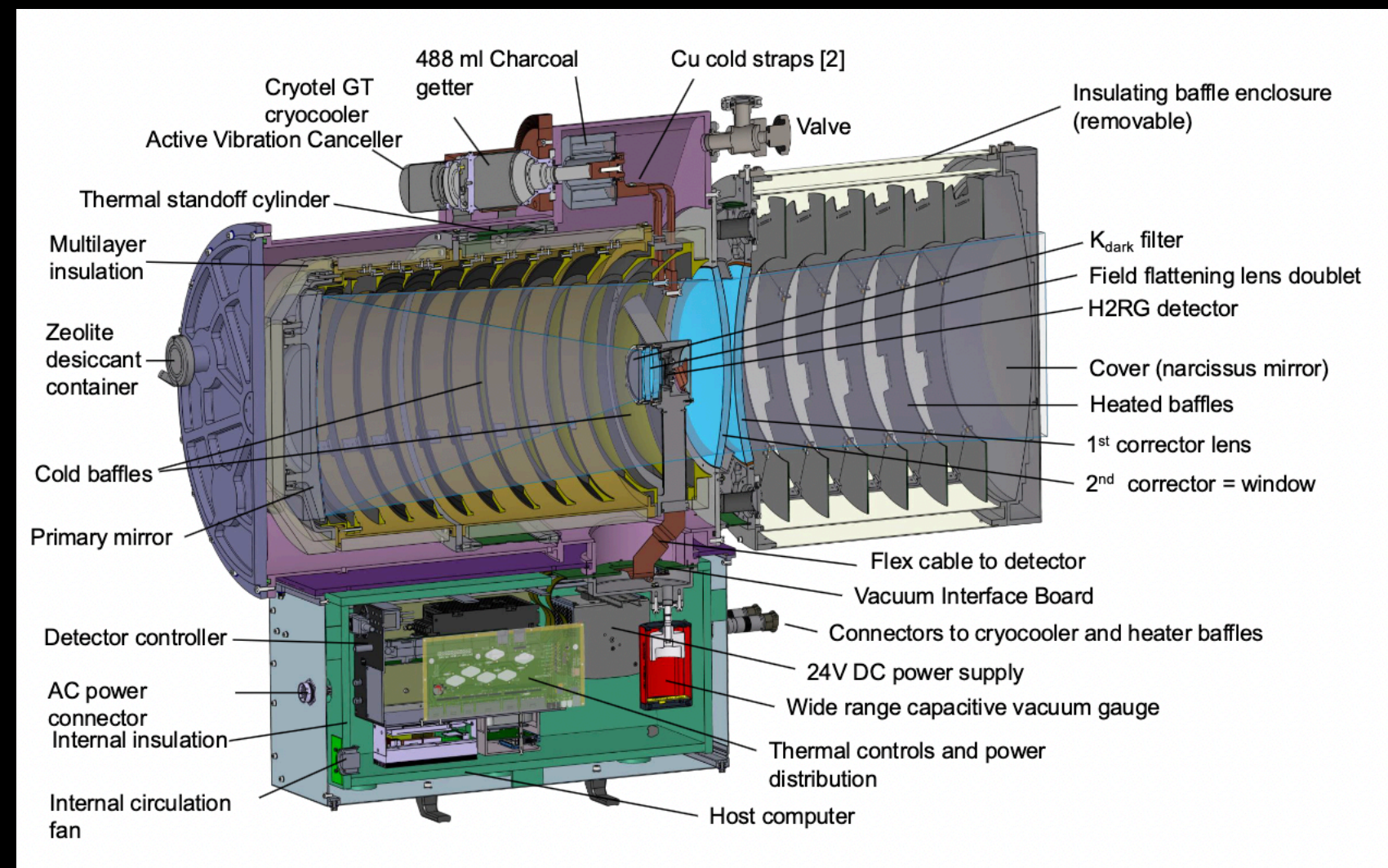
With a new camera box
To capture 3 times more photons
& discover transiting planets around M dwarfs





Cryoscope Pathfinder

- A 26-cm infrared telescope with new optical design
- Cryogenic: In vacuum and cooled to $\sim 100\text{K}$



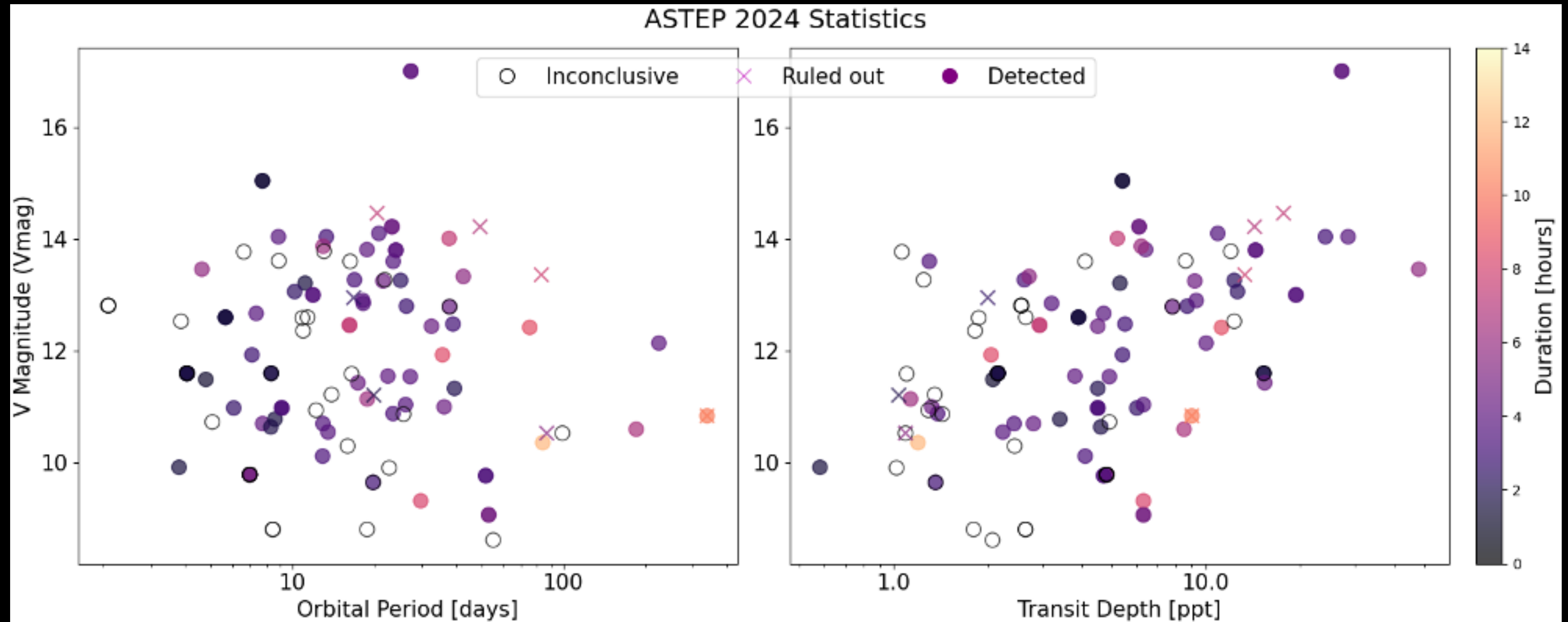
Caltech

- Installation @ Concordia : end of 2026

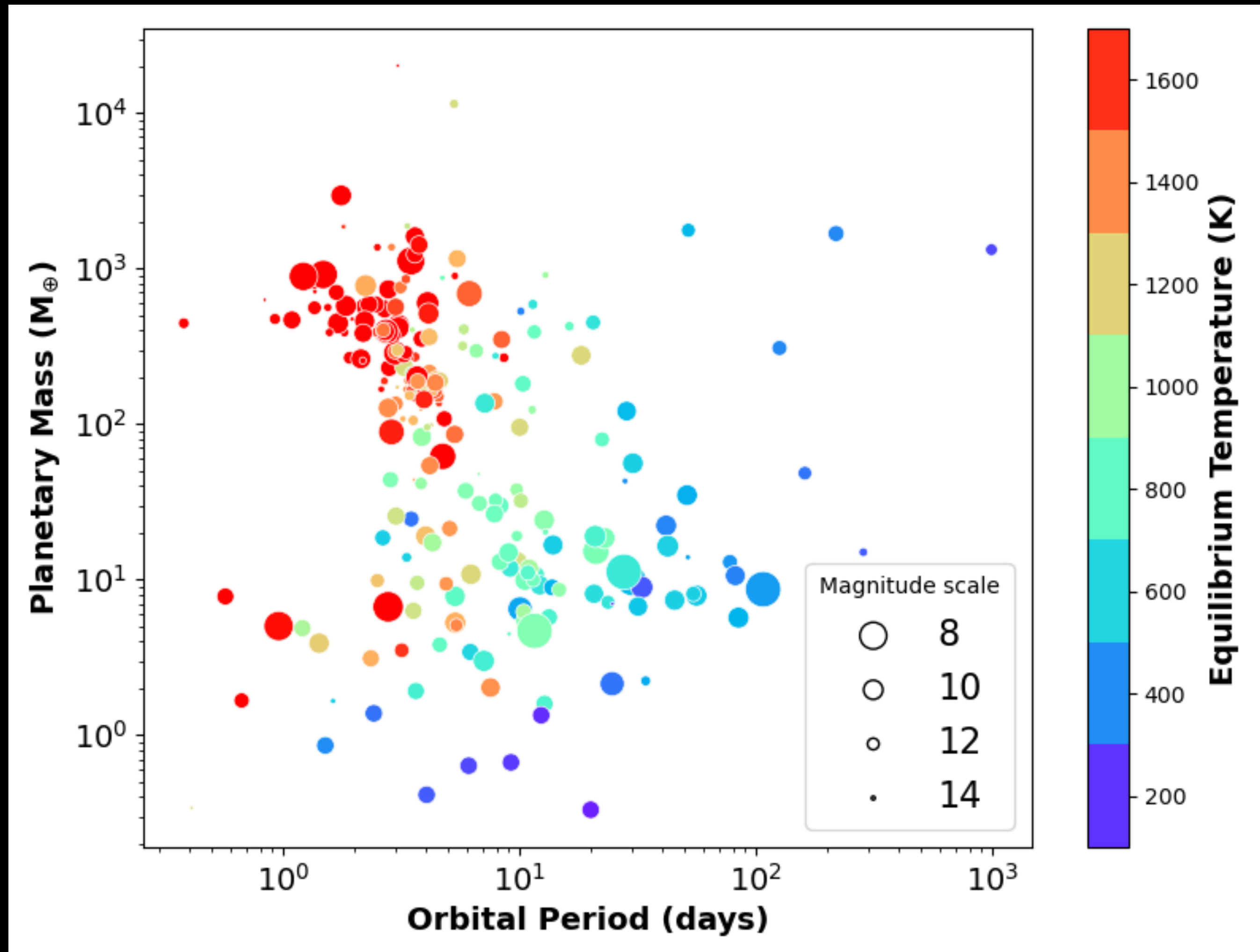
Kasliwal et al. (2025)



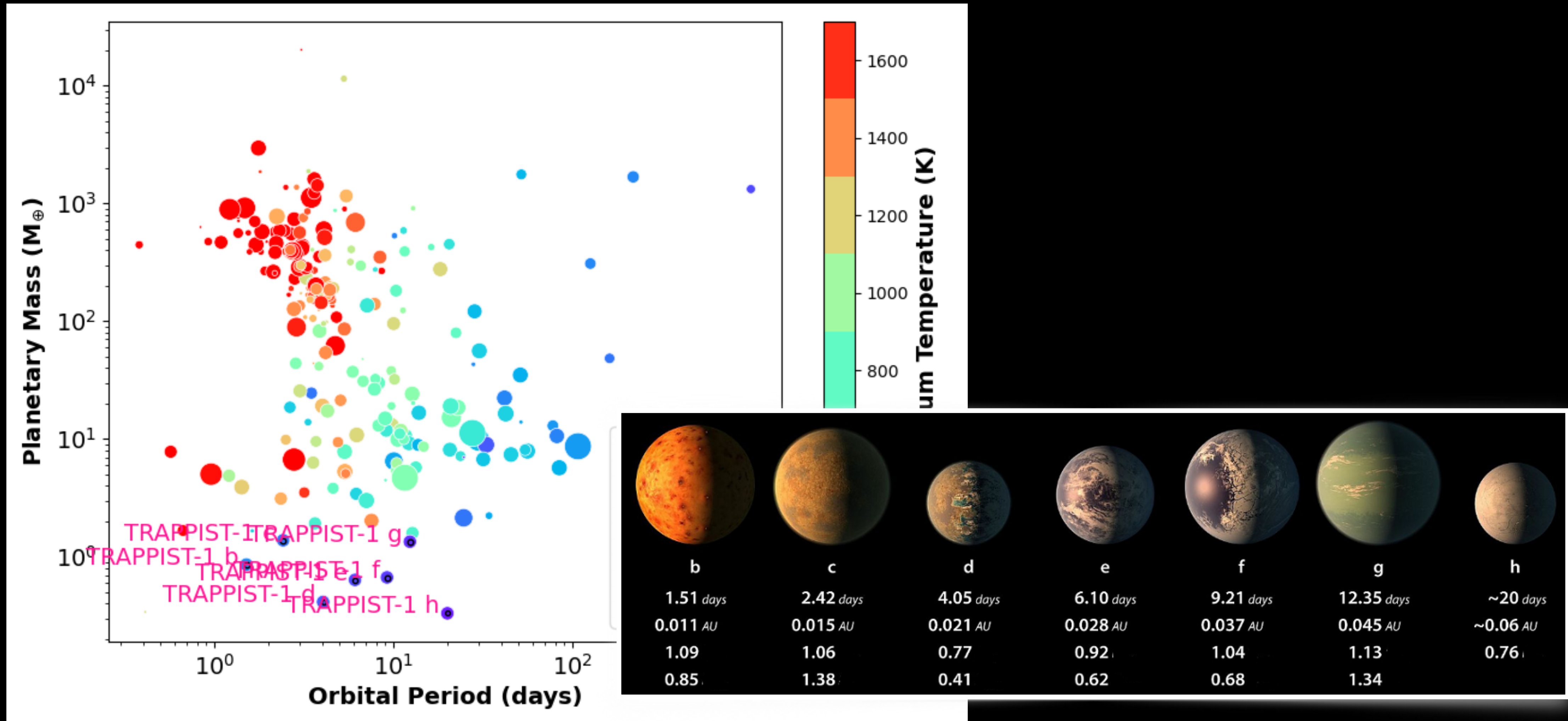
ASTEP observations (2024)



Transiting long period/temperate exoplanets

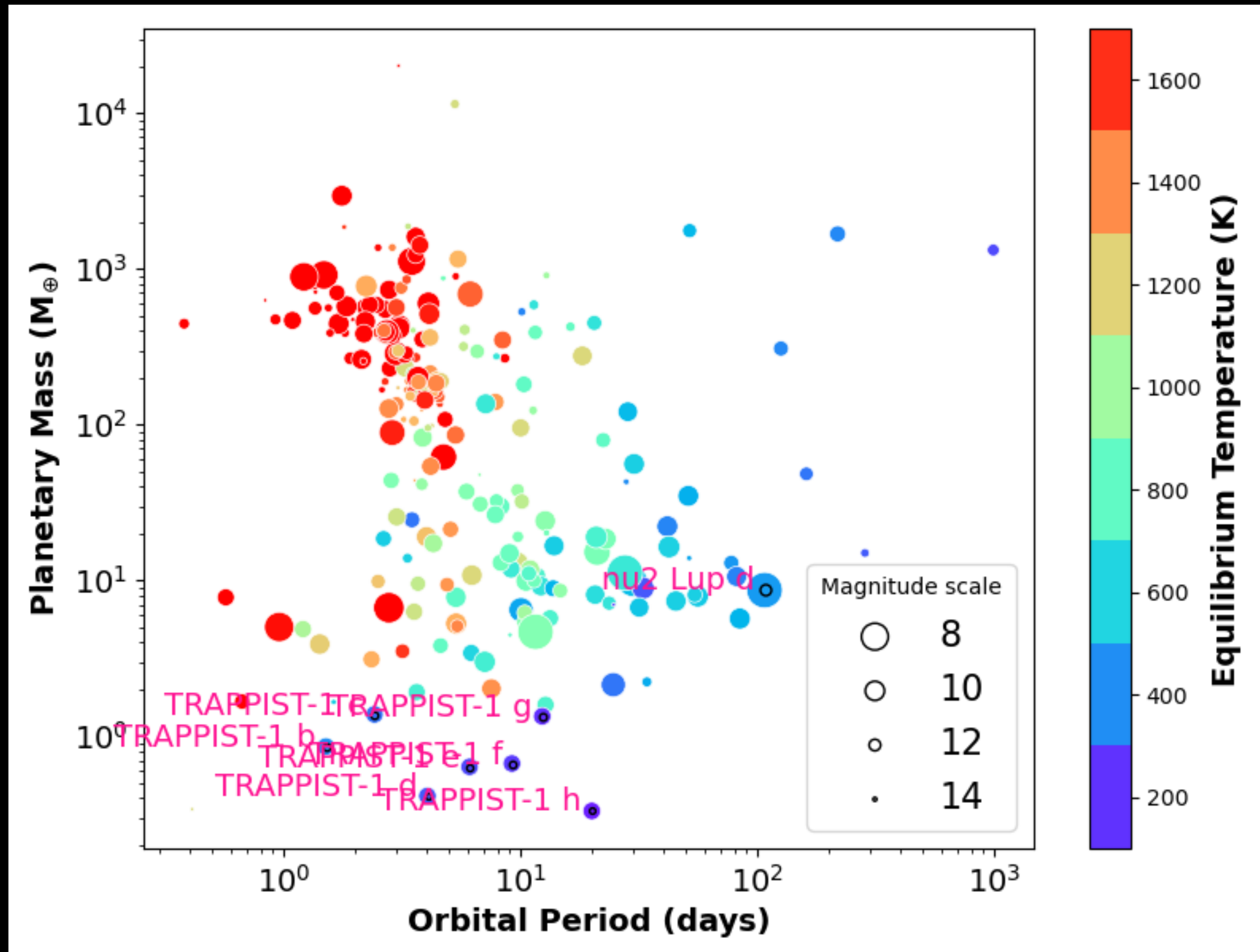


Transiting long period/temperate exoplanets



Gillon et al. Nature (2016, 2017)

Transiting long period/temperate exoplanets



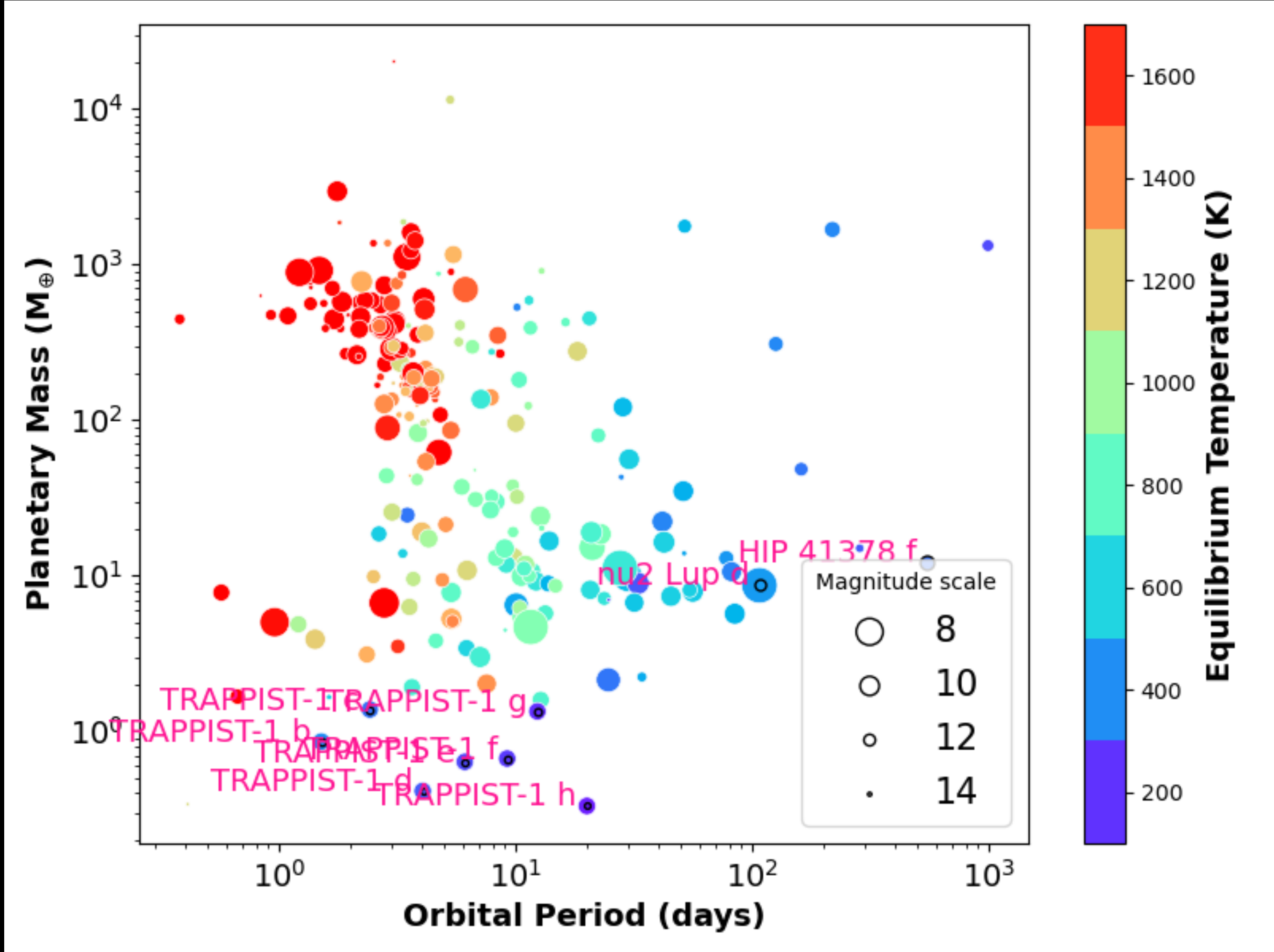
ν^2 Lupi d

Transit detection of the long-period volatile-rich super-Earth ν^2 Lupi d with CHEOPS

[Laetitia Delrez](#) , [David Ehrenreich](#), [Yann Alibert](#), [Andrea Bonfanti](#), [Luca Borsato](#), [Luca Fossati](#), [Matthew](#)

Delrez et al. Nat. Astron. (2021)

Transiting long period/temperate exoplanets



HIP 41378 f

An extremely low-density and temperate giant exoplanet

A. Santerne¹, L. Malavolta², M. R. Kosiarek^{3,4}, F. Dai^{5,6,7}, C. D. Dressing⁸, X. Dumusque⁹,

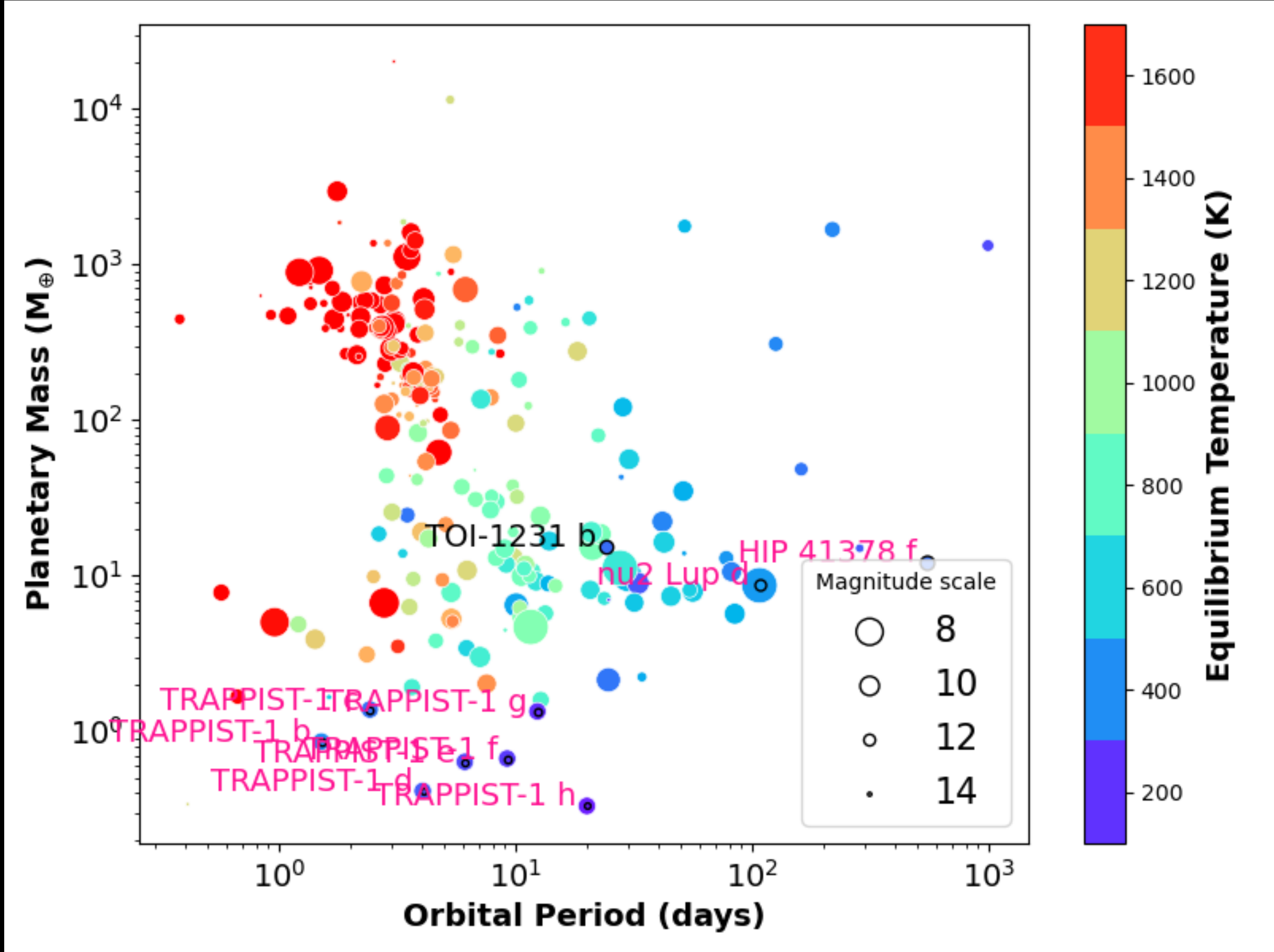
The Dynamical History of HIP-41378 f - Oblique Exorings Masquerading as a Puffy Planet

TIGER LU¹, GONGJIE LI², BEN CASSESE³ AND D.N.C LIN⁴



Santerne et al., Nat. Astron. (2019)
Lu et al., ApJ (2024)
Grouffal et al. A&A (2022, 2025)

Transiting long period/temperate exoplanets



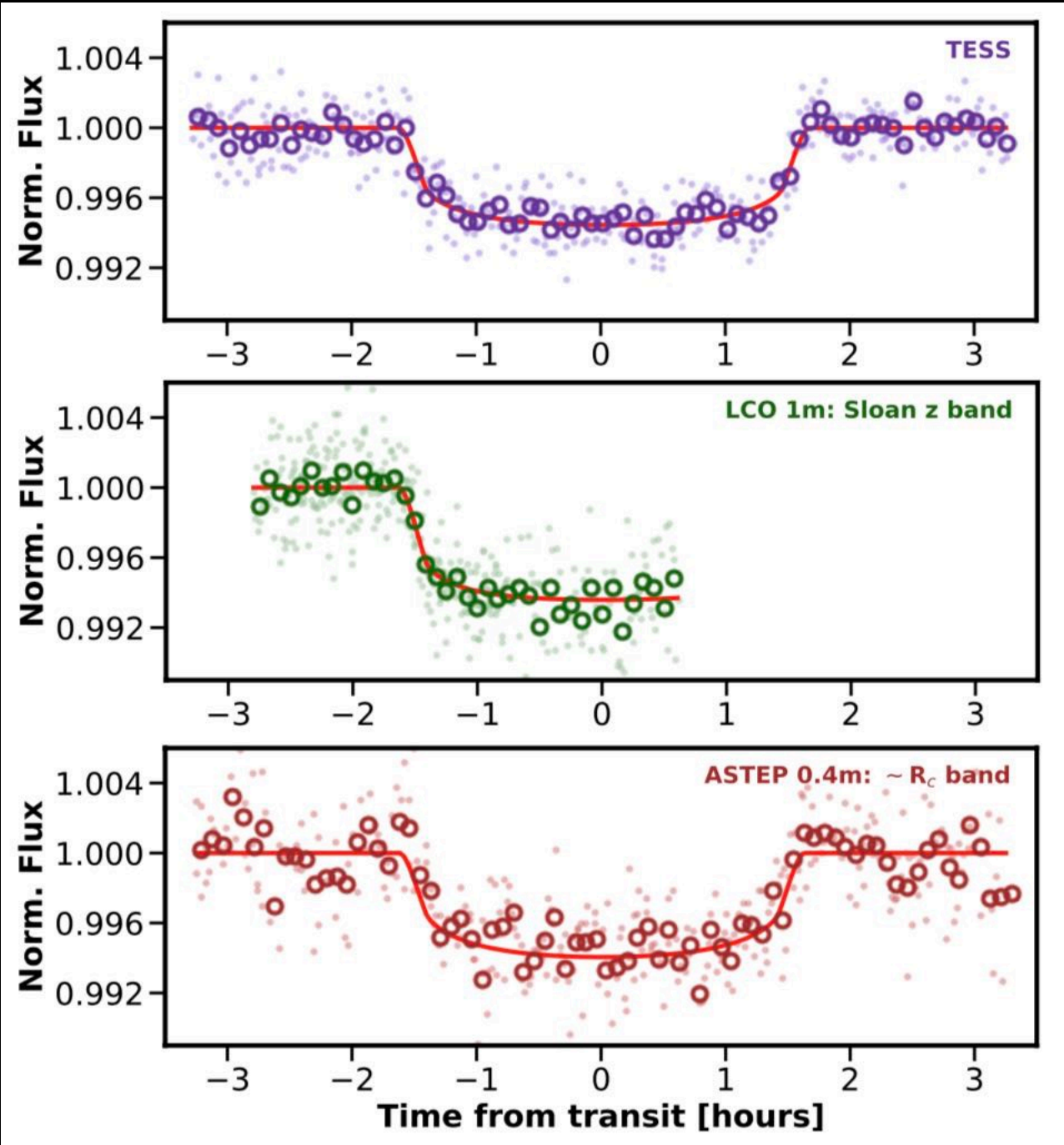
TOI-1231 b

THE ASTRONOMICAL JOURNAL, 162:87 (15pp), 2021 September
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<https://doi.org/10.3847/1538-3881/ac0432>

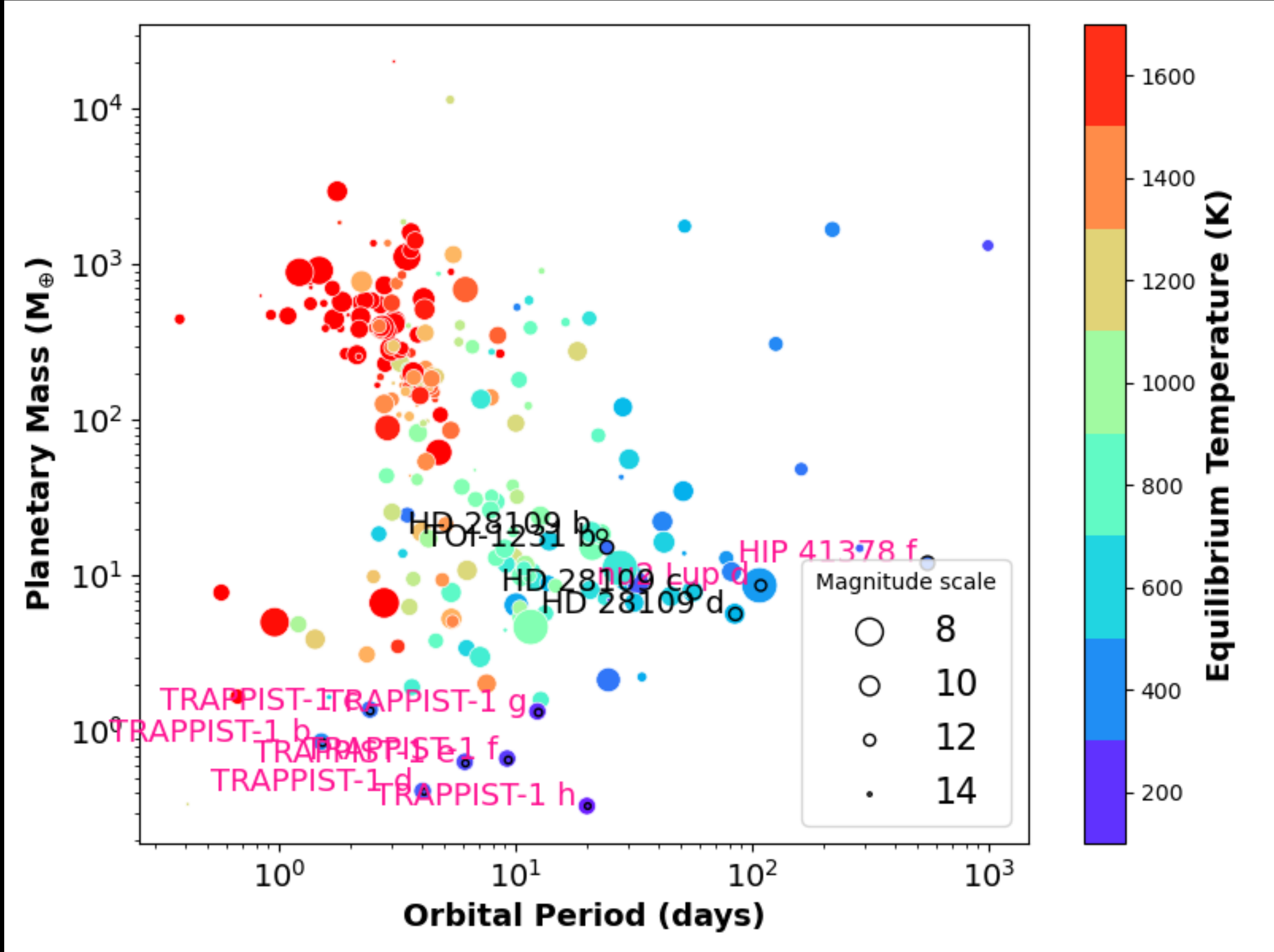
TOI-1231 b: A Temperate, Neptune-sized Planet Transiting the Nearby M3 Dwarf NLTT 24399

Jennifer A. Burt¹, Diana Dragomir², Paul Mollière³, Allison Youngblood⁴, Antonio García Muñoz⁵, John McCann⁶



Burt et al. (incl. ASTEP), ApJ (2021)

Transiting long period/temperate exoplanets

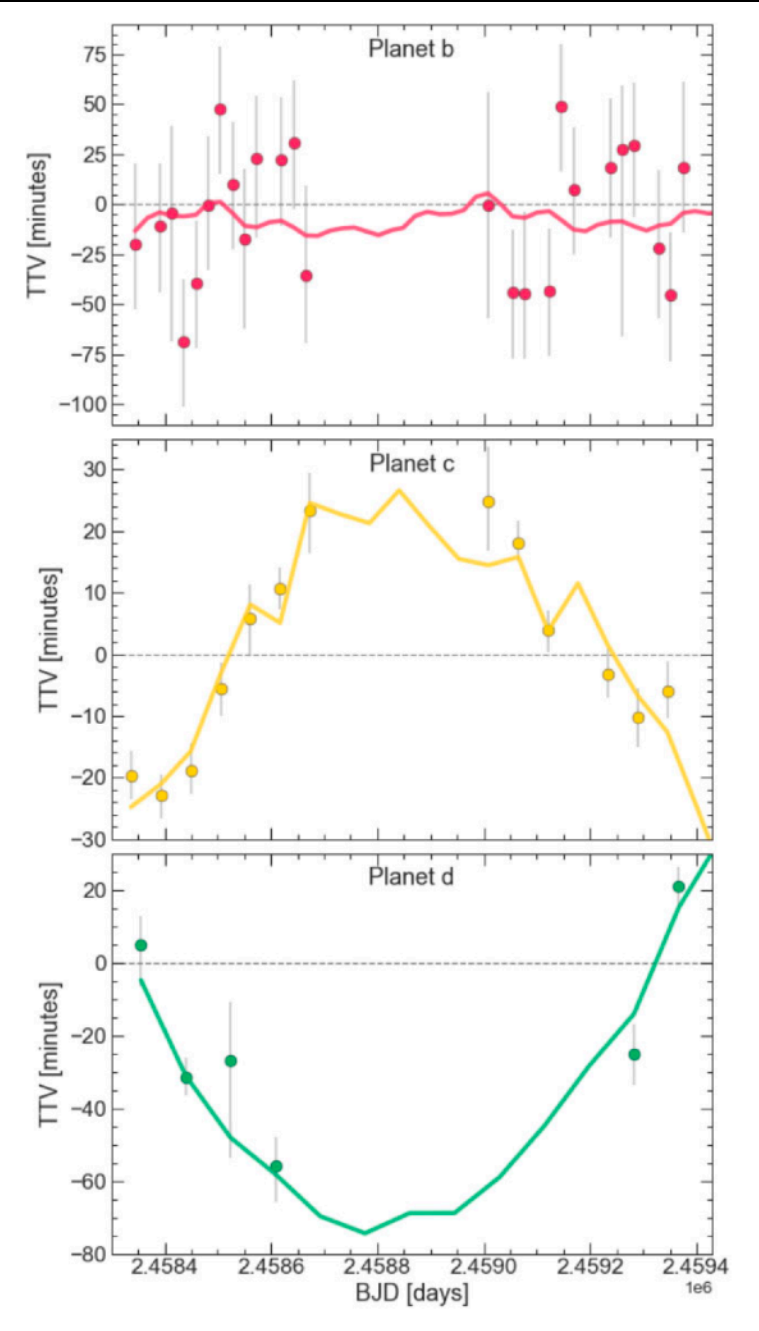


HD 28109 b, c & d

MNRAS 515, 1328–1345 (2022) <https://doi.org/10.1093/mnras/stz300>

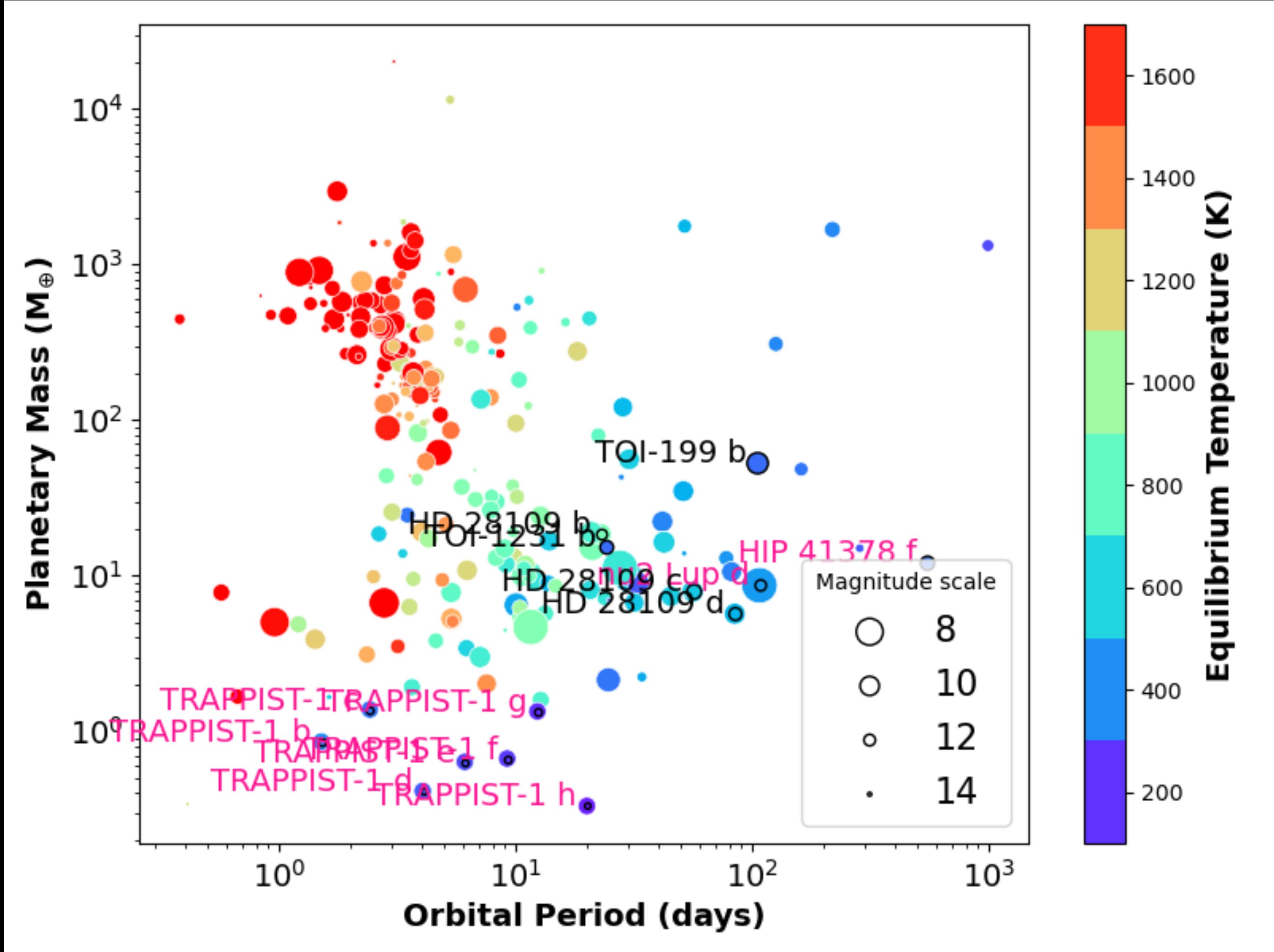
HD 28109 hosts a trio of transiting Neptunian planets including a near-resonant pair, confirmed by ASTEP from Antarctica

Georgina Dransfield¹, Amaury H. M. J. Triaud¹, Tristan Guillot², Djamel Mekarnia²



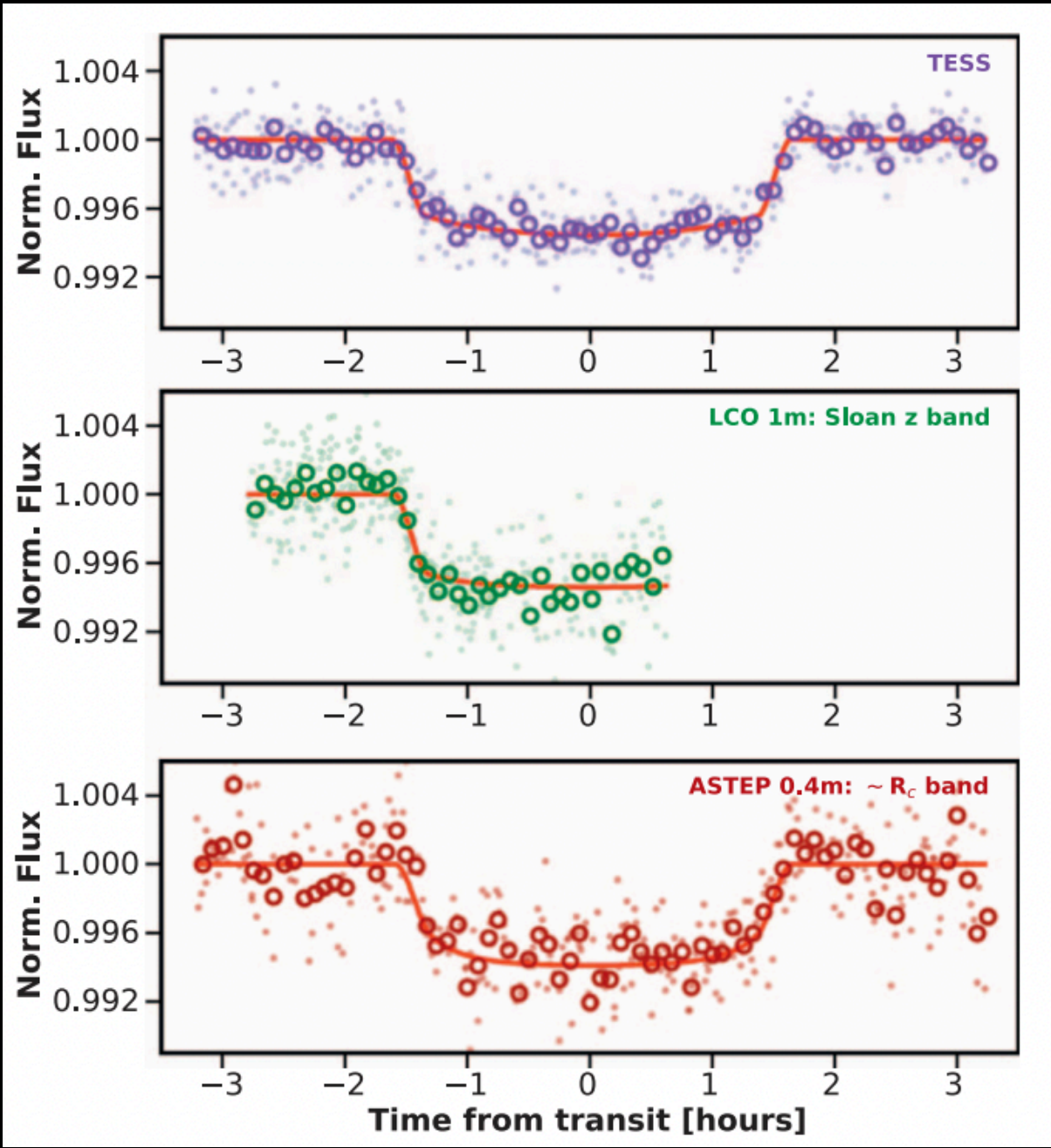
Dransfield et al., MNRAS (2022)

Transiting long period/temperate exoplanets

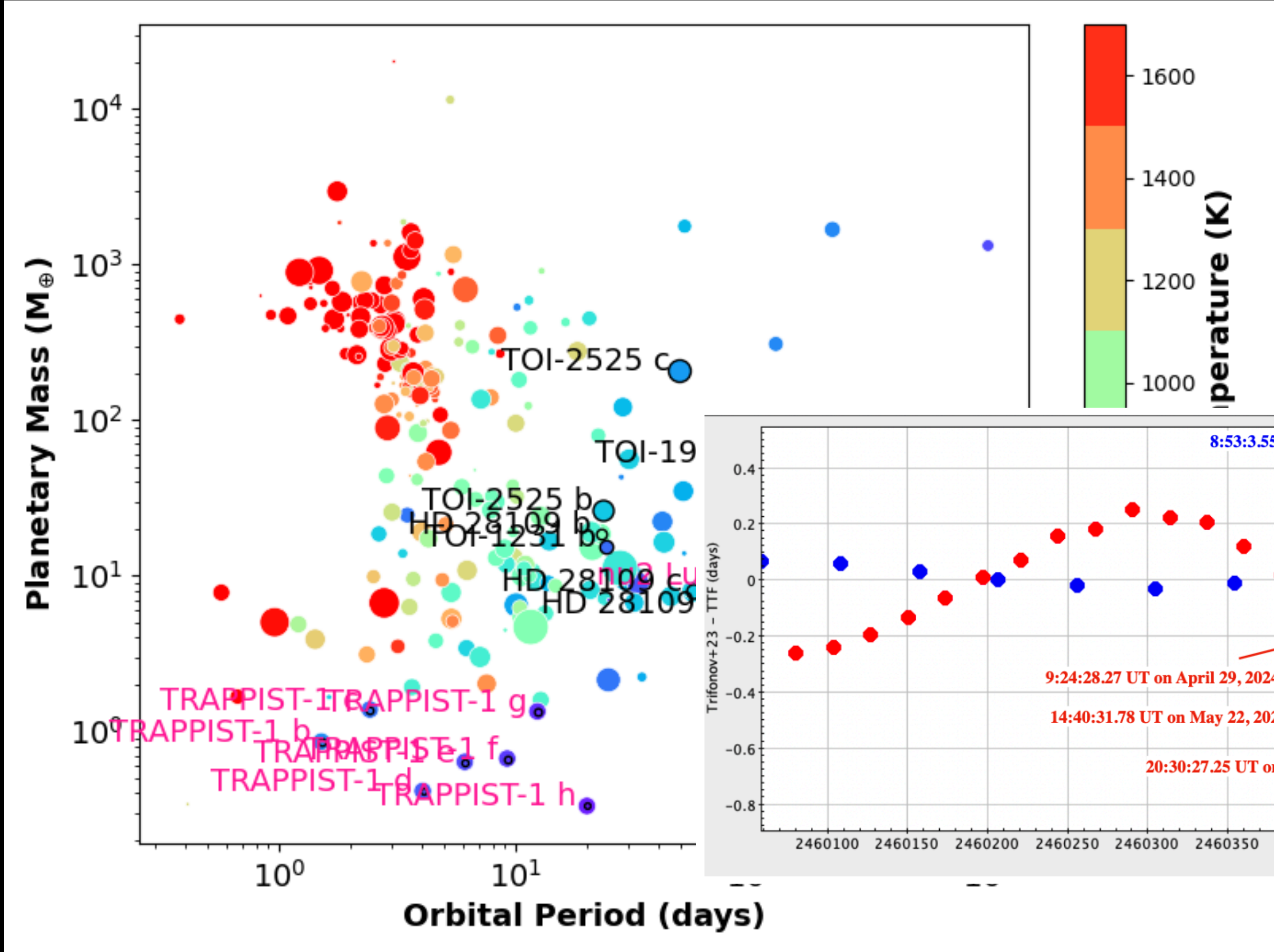


TOI-199 b

THE ASTRONOMICAL JOURNAL, 166:201 (26pp), 2023 November
© 2023. The Author(s). Published by the American Astronomical Society.
OPEN ACCESS
<https://doi.org/10.3847/1538-3881/acfc1d>
TOI-199 b: A Well-characterized 100 day Transiting Warm Giant Planet with TTVs Seen from Antarctica
Melissa J. Hobson^{1,2}, Trifon Trifonov^{1,3,4}, Thomas Henning¹, Andrés Jordán^{2,5}, Felipe Rojas^{2,6}, Nestor Espinoza⁷

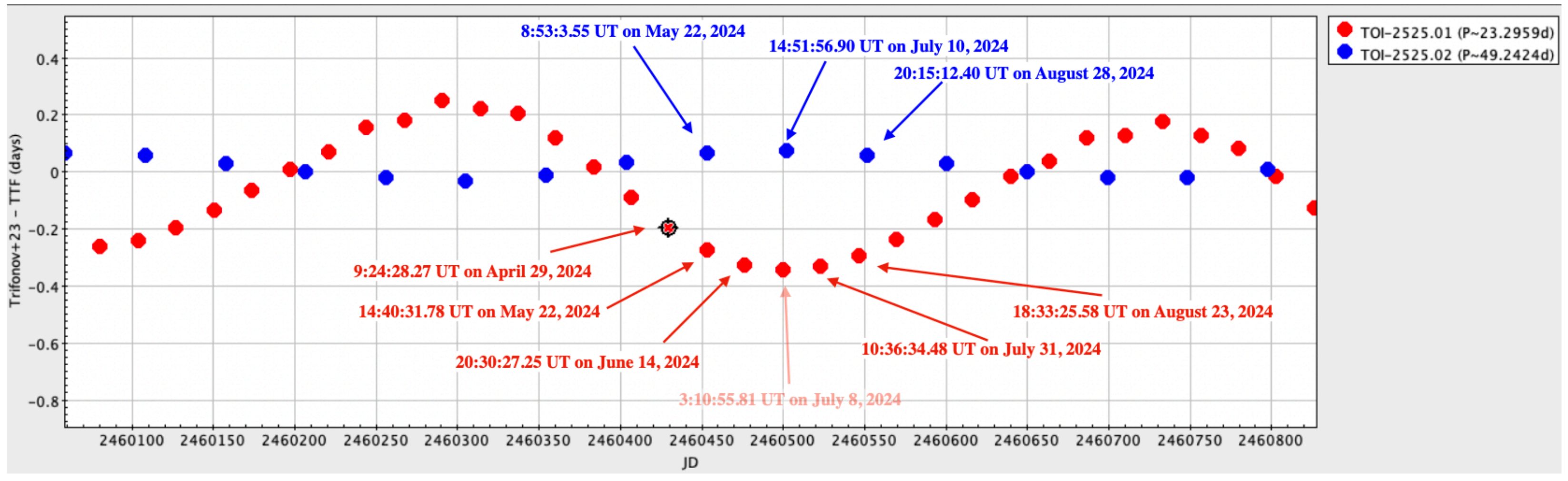


Transiting long period/temperate exoplanets

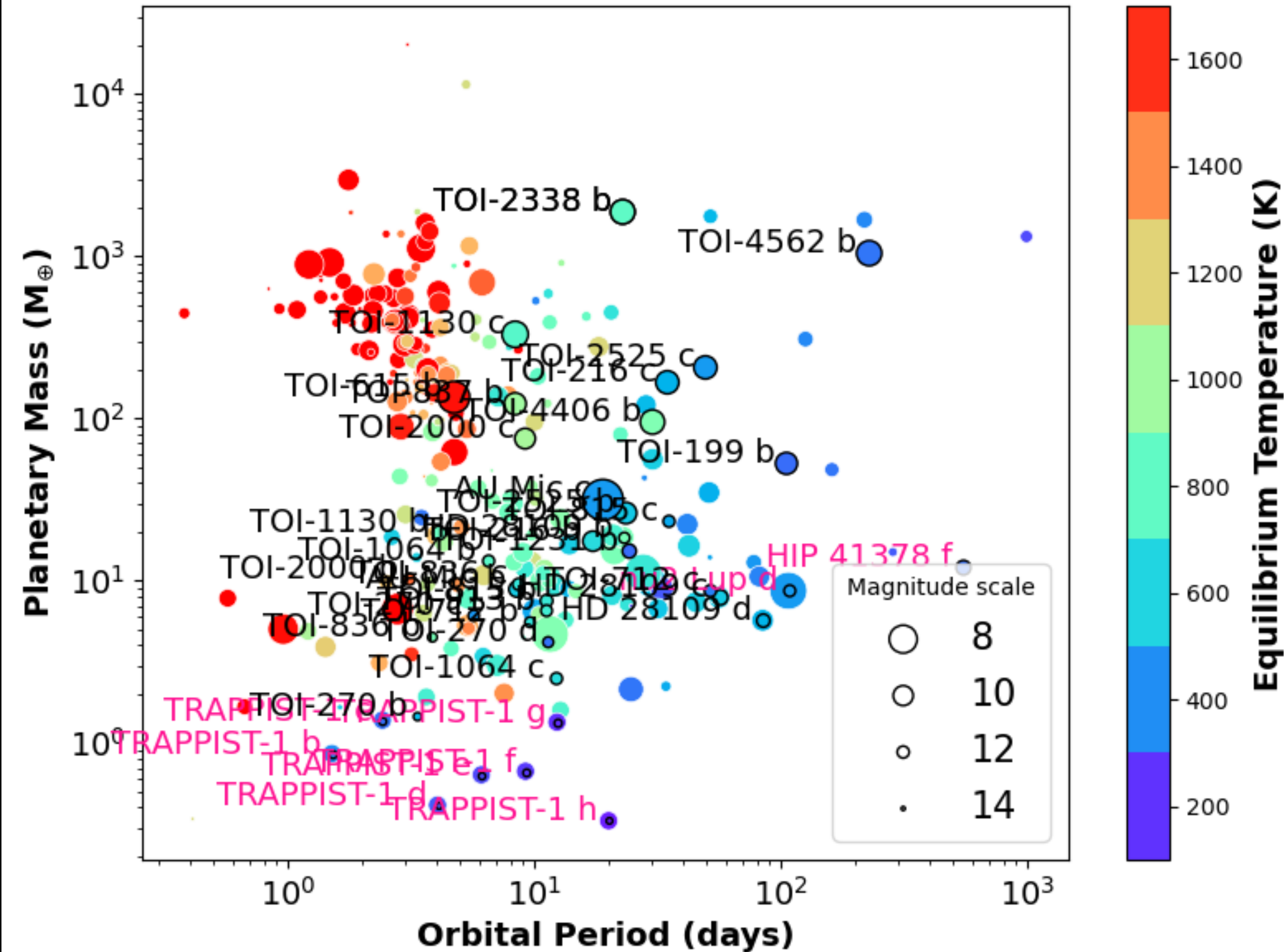


TOI-2525 b & c

THE ASTRONOMICAL JOURNAL, 165:179 (23pp), 2023 April
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OPEN ACCESS
TOI-2525 b and c: A Pair of Massive Warm Giant Planets with Strong Transit Timing Variations Revealed by TESS*
Trifon Trifonov^{1,2}, Rafael Brahm^{3,4,5}, Andrés Jordán^{3,4,5}, Christian Hartogh⁶, Thomas Henning¹, Melissa J. Hobson^{1,4}



Transiting long period/temperate exoplanets



Planets discovered w/ ASTEP

Thao PC, Mann AW, Barber MG, ..., ASTEP authors, et al. "TESS Hunt for Young and Maturing Exoplanets (THYME). X. A Two-planet System in the 210 Myr MELANGE-5 Association." *The Astronomical Journal* **168**, 41 (2024)

Zieba S, Zwintz K, Kenworthy M, ..., ASTEP authors, et al. "The β Pictoris b Hill sphere transit campaign. II. Searching for the signatures of the β Pictoris exoplanets through time delay analysis of the δ Scuti pulsations." *Astronomy and Astrophysics* **687**, A309 (2024)

Psaridi A, Osborn H, Bouchy F, ..., ASTEP authors, et al. "Discovery of two warm mini-Neptunes with contrasting densities orbiting the young K3V star TOI-815." *Astronomy and Astrophysics* **685**, A5 (2024)

Almenara JM, Bonfils X, Guillot T, Timmermans M, Díaz RF, ASTEP authors, et al. "Evidence for transit-timing variations of the 11 Myr exoplanet TOI-1227 b." *Astronomy and Astrophysics* **683**, A96 (2024)

Wittrock JM, Plavchan PP, Cale BL, ..., ASTEP authors, et al. "Validating AU Microscopii d with Transit Timing Variations." *The Astronomical Journal* **166**, 232 (2023)

Kareta T, Thomas C, Li J, ..., ASTEP authors, et al. "Ejecta Evolution Following a Planned Impact into an Asteroid: The First Five Weeks." *The Astrophysical Journal* **959**, L12 (2023)

Eberhardt J, Hobson MJ, Henning T, ..., ASTEP authors, et al. "Three Warm Jupiters around Solar-analog Stars Detected with TESS." *The Astronomical Journal* **166**, 271 (2023)

Hasler SN, Burdanov AY, de Wit J, ..., ASTEP authors, et al. "Small body harvest with the Antarctic Search for Transiting Exoplanets (ASTEP) project." *Monthly Notices of the Royal Astronomical Society* **526**, 3601 (2023)

Hobson MJ, Trifonov T, Henning T, ..., ASTEP authors, et al. "TOI-199 b: A Well-characterized 100 day Transiting Warm Giant Planet with TTVs Seen from Antarctica." *The Astronomical Journal* **166**, 201 (2023)

Travouillon T, Smith RM, Fucik J, ... & Guillot T. "Ultra wide-field infrared astronomy in Antarctica." *Astronomische Nachrichten* **344**, e20230063 (2023)

Sha L, Vanderburg AM, Huang CX, ..., ASTEP authors, et al. "TESS spots a mini-neptune interior to a hot saturn in the TOI-2000 system." *Monthly Notices of the Royal Astronomical Society* **524**, 1113 (2023)

Mistry P, Pathak K, Prasad A, ..., ASTEP authors, et al. "VaTEST. II. Statistical Validation of 11 TESS-detected Exoplanets Orbiting K-type Stars." *The Astronomical Journal* **166**, 9 (2023)

Psaridi A, Bouchy F, Lendl M, ..., ASTEP authors, et al. "Three Saturn-mass planets transiting F-type stars revealed with TESS and HARPS. TOI-615b, TOI-622b, and TOI-2641b." *Astronomy and Astrophysics* **675**, A39 (2023)

Korth J, Gandolfi D, Šubjak J, ..., ASTEP authors, et al. "TOI-1130: A photodynamical analysis of a hot Jupiter in resonance with an inner low-mass planet." *Astronomy and Astrophysics* **675**, A115 (2023)

Vowell N, Rodriguez JE, Quinn SN, ..., ASTEP authors, et al. "HIP 33609 b: An Eccentric Brown Dwarf Transiting a $V = 7.3$ Rapidly Rotating B Star." *The Astronomical Journal* **165**, 268 (2023)

Brahm R, Ulmer-Möll S, Hobson MJ, ..., ASTEP authors, et al. "Three Long-period Transiting Giant Planets from TESS." *The Astronomical Journal* **165**, 227 (2023)

Trifonov T, Brahm R, Jordán A, ..., ASTEP authors, et al. "TOI-2525 b and c: A Pair of Massive Warm Giant Planets with Strong Transit Timing Variations Revealed by TESS." *The Astronomical Journal* **165**, 179 (2023)

Hawthorn F, Bayliss D, Wilson TG, ..., ASTEP authors, et al. "TOI-836: A super-Earth and mini-Neptune transiting a nearby K-dwarf." *Monthly Notices of the Royal Astronomical Society* **520**, 3649 (2023)

Kokori A, Tsiaras A, Edwards B, ..., ASTEP authors, et al. "ExoClock Project. III. 450 New Exoplanet Ephemerides from Ground and Space Observations." *The Astrophysical Journal Supplement Series* **265**, 4 (2023)

Heitzmann A, Zhou G, Quinn SN, ..., ASTEP authors, et al. "TOI-4562b: A Highly Eccentric Temperate Jupiter Analog Orbiting a Young Field Star." *The Astronomical Journal* **165**, 121 (2023)

Dransfield G, Triana AHMJ, Guillot T, Mekarnia D, Nesvorný D, et al. "HD 28109 hosts a trio of transiting Neptunian planets including a near-resonant pair, confirmed by ASTEP from Antarctica." *Monthly Notices of the Royal Astronomical Society* **515**, 1328 (2022)

Vach S, Quinn SN, Vanderburg A, ..., ASTEP authors, et al. "TOI-712: A System of Adolescent Mini-Neptunes Extending to the Habitable Zone." *The Astronomical Journal* **164**, 71 (2022)

Christian S, Vanderburg A, Becker J, ..., ASTEP authors, et al. "A Possible Alignment Between the Orbits of Planetary Systems and their Visual Binary Companions." *The Astronomical Journal* **163**, 207 (2022)

Mann AW, Wood ML, Schmidt SP, ..., ASTEP authors, et al. "TESS Hunt for Young and Maturing Exoplanets (THYME). VI. An 11 Myr Giant Planet Transiting a Very-low-mass Star in Lower Centaurus Crux." *The Astronomical Journal* **163**, 156 (2022)

Kaye L, Vissapragada S, Günther MN, ..., ASTEP authors, et al. "Transit timings variations in the three-planet system: TOI-270." *Monthly Notices of the Royal Astronomical Society* **510**, 5464 (2022)

Wilson TG, Goffo E, Alibert Y, ..., ASTEP authors, et al. "A pair of sub-Neptunes transiting the bright K-dwarf TOI-1064 characterized with CHEOPS." *Monthly Notices of the Royal Astronomical Society* **511**, 1043 (2022)

Burt JA, Dragomir D, Mollière P, ..., ASTEP authors, et al. "TOI-1231 b: A Temperate, Neptune-sized Planet Transiting the Nearby M3 Dwarf NLTT 24399." *The Astronomical Journal* **162**, 87 (2021)

Grievies N, Bouchy F, Lendl M, ..., ASTEP authors, et al. "Populating the brown dwarf and stellar boundary: Five stars with transiting companions near the hydrogen-burning mass limit." *Astronomy and Astrophysics* **652**, A127 (2021)

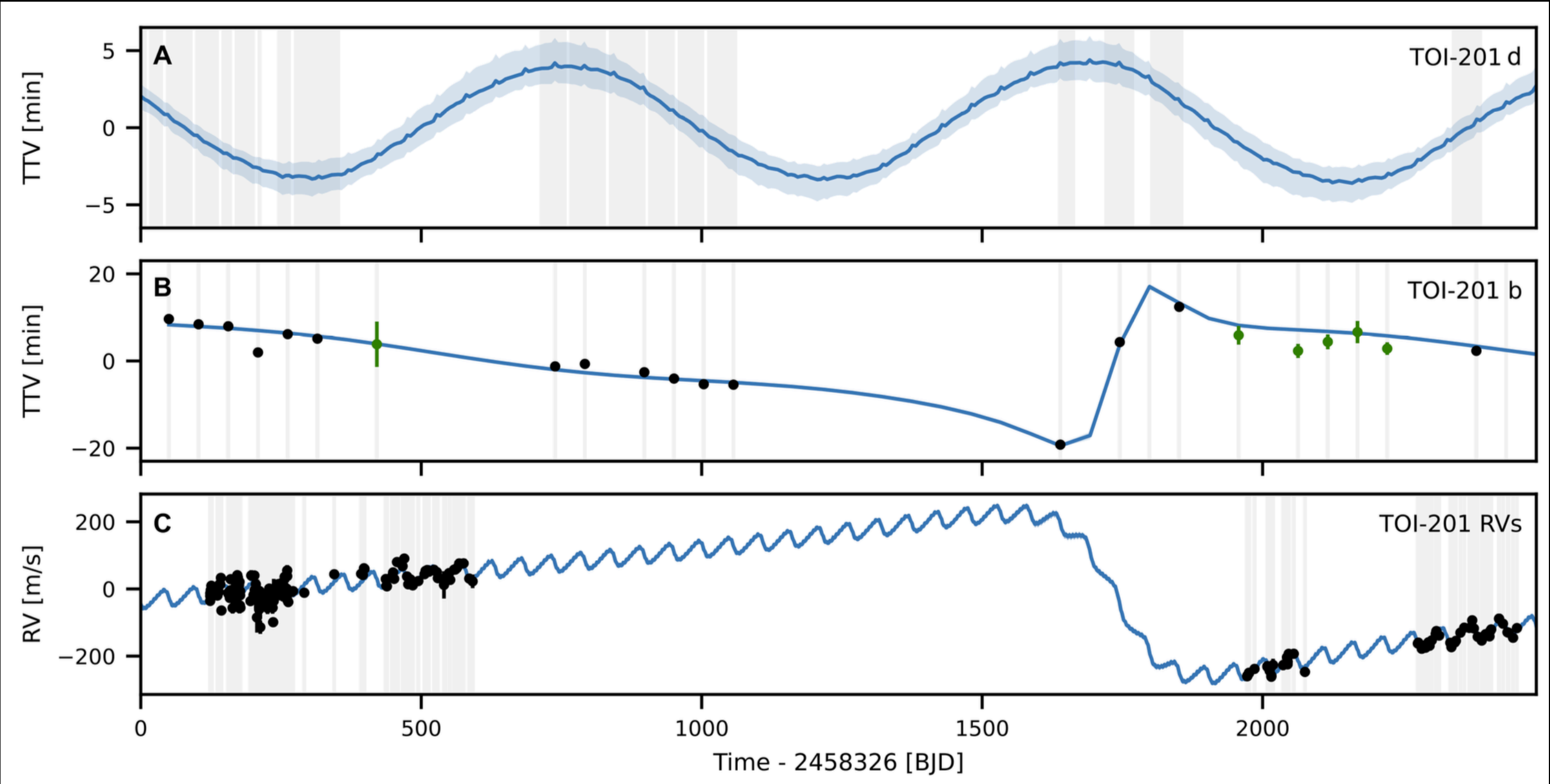
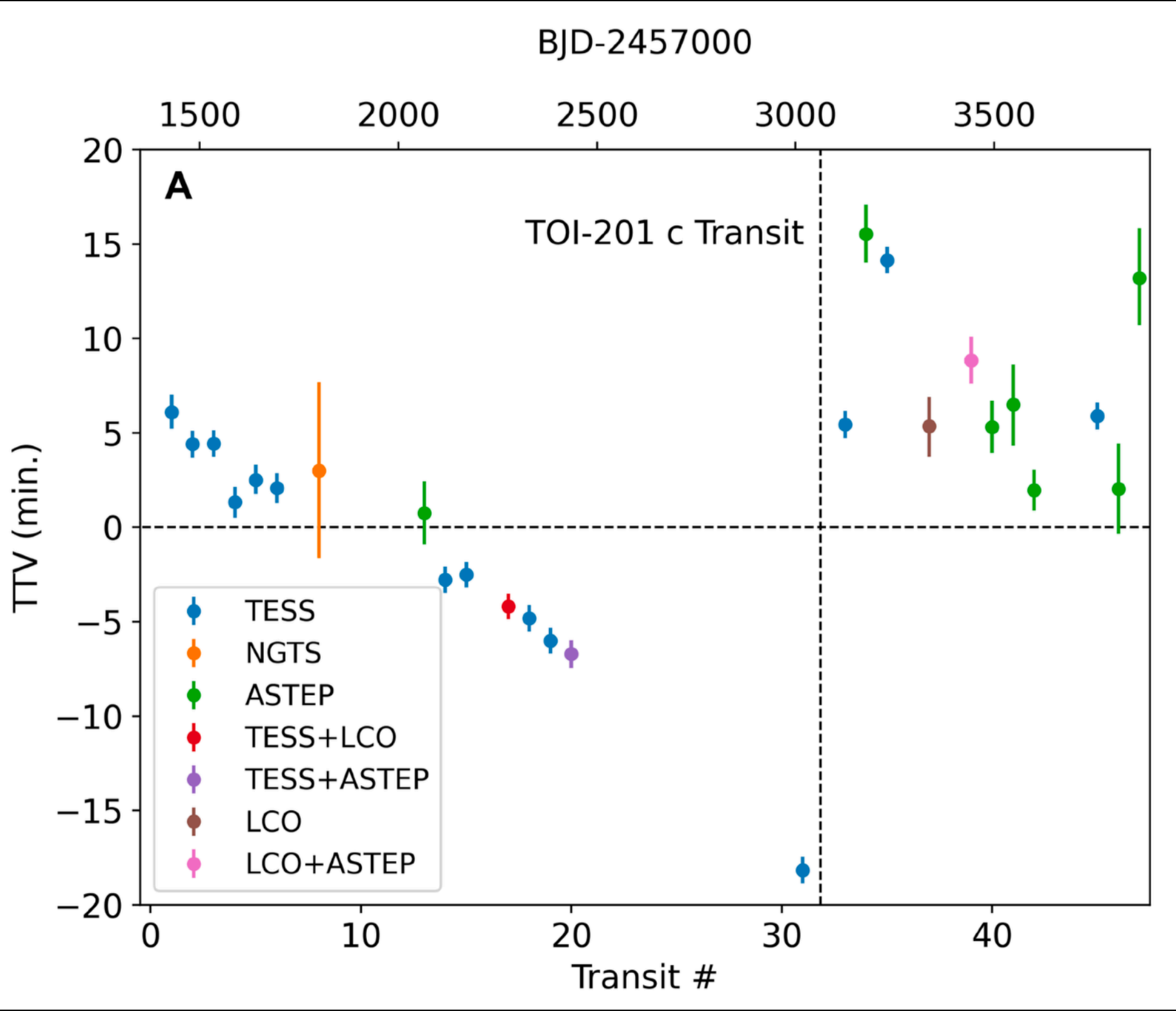
Dong J, Huang CX, Dawson RI, ..., ASTEP authors, et al. "Warm Jupiters in TESS Full-frame Images: A Catalog and Observed Eccentricity Distribution for Year 1." *The Astrophysical Journal Supplement Series* **255**, 6 (2021)

Dawson RI, Huang CX, Brahm R, ..., ASTEP authors, et al. "Precise Transit and Radial-velocity Characterization of a Resonant Pair: The Warm Jupiter TOI-216c and Eccentric Warm Neptune TOI-216b." *The Astronomical Journal* **161**, 161 (2021)

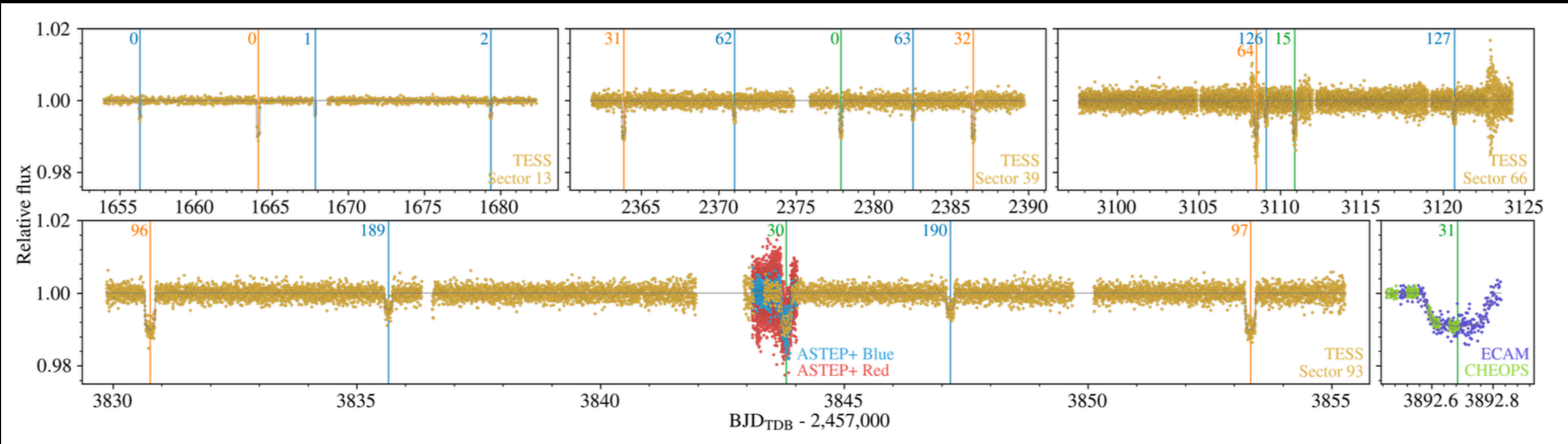
Bouma LG, Hartman JD, Brahm R, ..., ASTEP authors, et al. "Cluster Difference Imaging Photometric Survey. II. TOI 837: A Young Validated Planet in IC 2602." *The Astronomical Journal* **160**, 239 (2020)

+ long-period transits in store up to ~500 days

TOI-201: A 52 days giant with a 2890 day transiting brown dwarf!

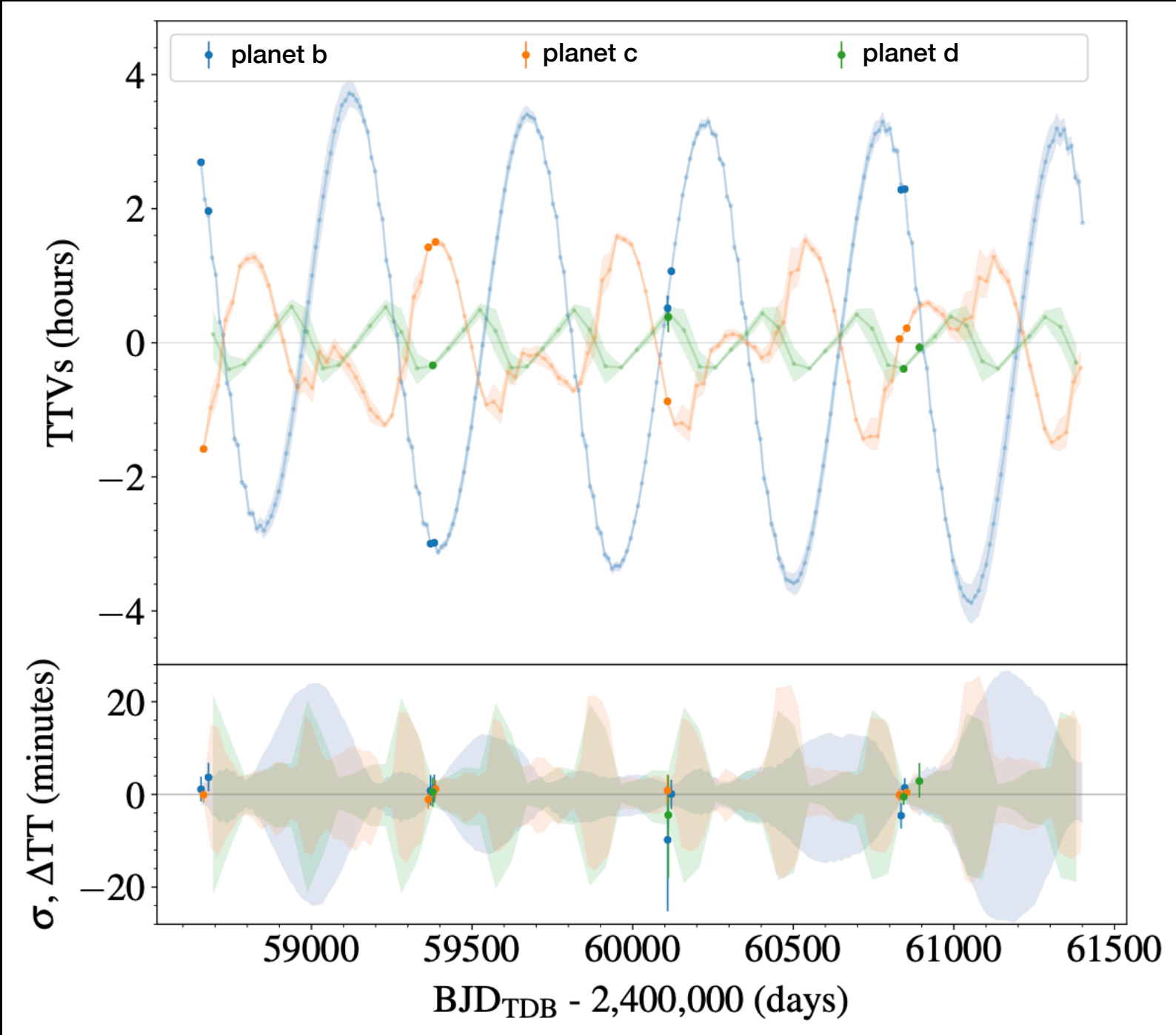


A solar-analog system of three transiting giant planets near a Laplace resonance chain



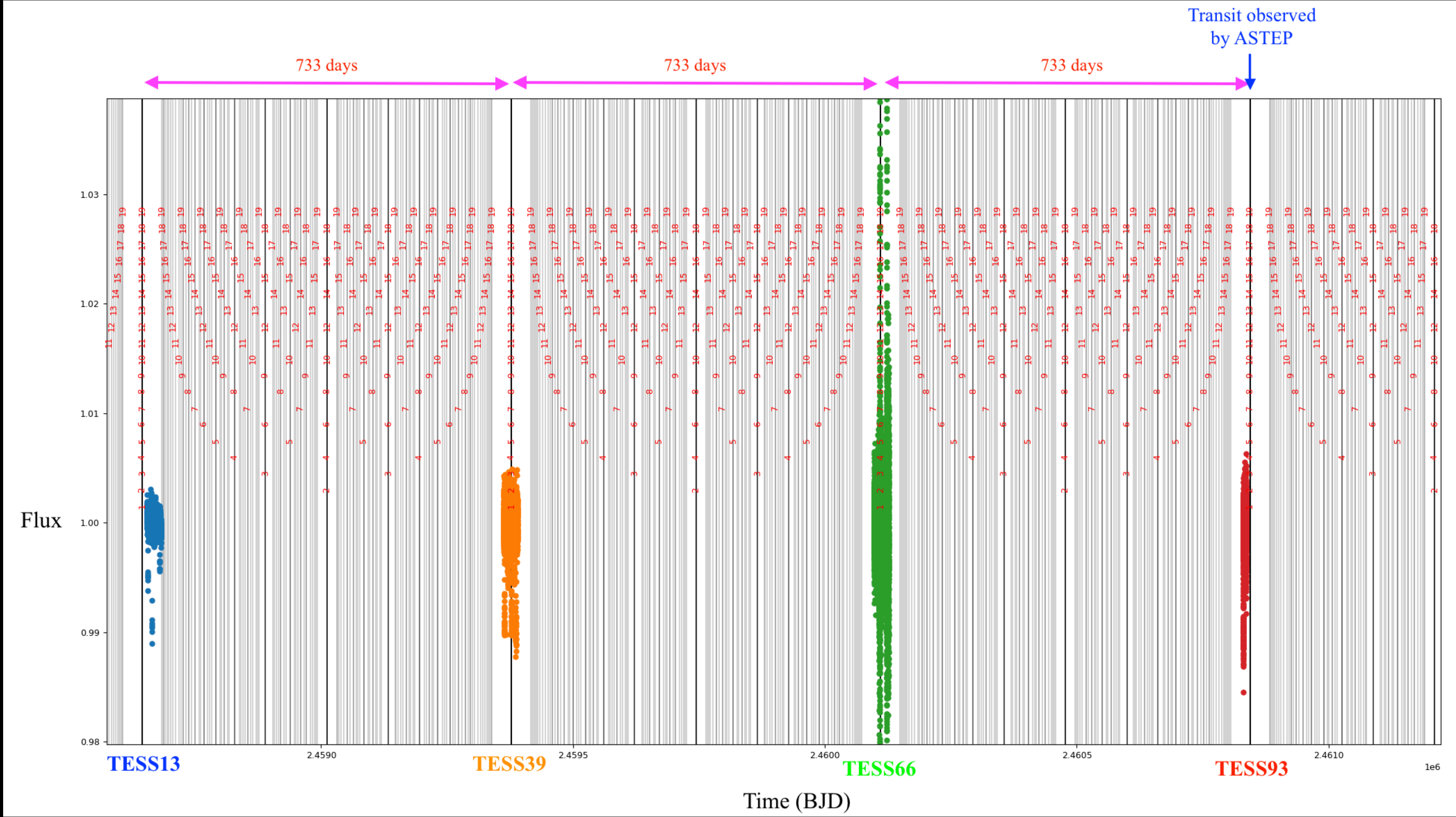
J.M. Almenara¹, A. Leleu¹, T. Guillot², R. Mardling^{3,1}, F. Bouchy¹, T. Forveille⁴, J. Winn⁵, L. Abe², M. Beltrame⁶, P. Bendjoya², X. Bonfils⁴, A. Deline¹, J.-B. Delisle¹, R.F. Díaz^{7,8}, E. Fridén¹, M. Hobson¹, R.M. Hoogenboom¹, J.M. Jenkins⁹, J. Korth¹, M. Lendl¹, D. Mékarnia², A.C. Petit², M. Rosenqvist¹, O. Suárez², A.H.M.J. Triaud¹⁰, and S. Udry¹

We report the confirmation and initial characterization of a compact and dynamically rich multiple giant planet system orbiting the solar analog [redacted]. The system was recently identified as a candidate two-planet system in a machine-learning search of the TESS light curves. Using TESS data and photometric follow-up observations with ASTEP, CHEOPS, and EulerCam, we show that one transit was initially mis-attributed, and that the system consists of three transiting giant planets with orbital periods of 11.5, 22.6, and 48.9 days. The planets have radii of 0.65, 0.96, and 0.94 R_J , making them the largest known trio of transiting planets. The system architecture lies near a 4:2:1 mean motion resonant chain, inducing large transit timing variations for all three planets. Photodynamical modeling gives mass estimates of 0.055, 0.40, and 0.58 M_J , and favors low eccentricities and mutual inclinations. [redacted] is an interesting system for investigating the dynamical interactions and formation histories of compact systems of giant planets.

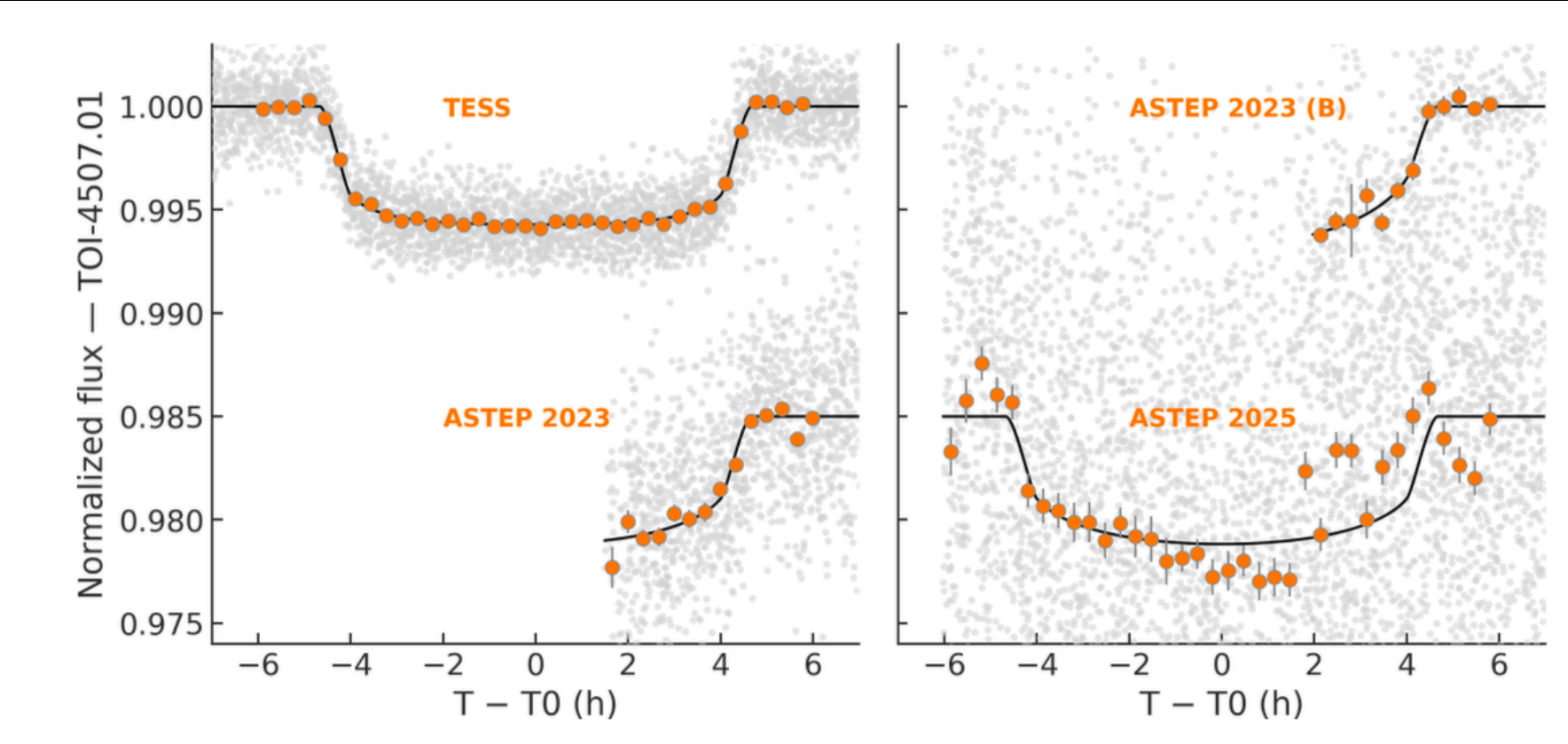
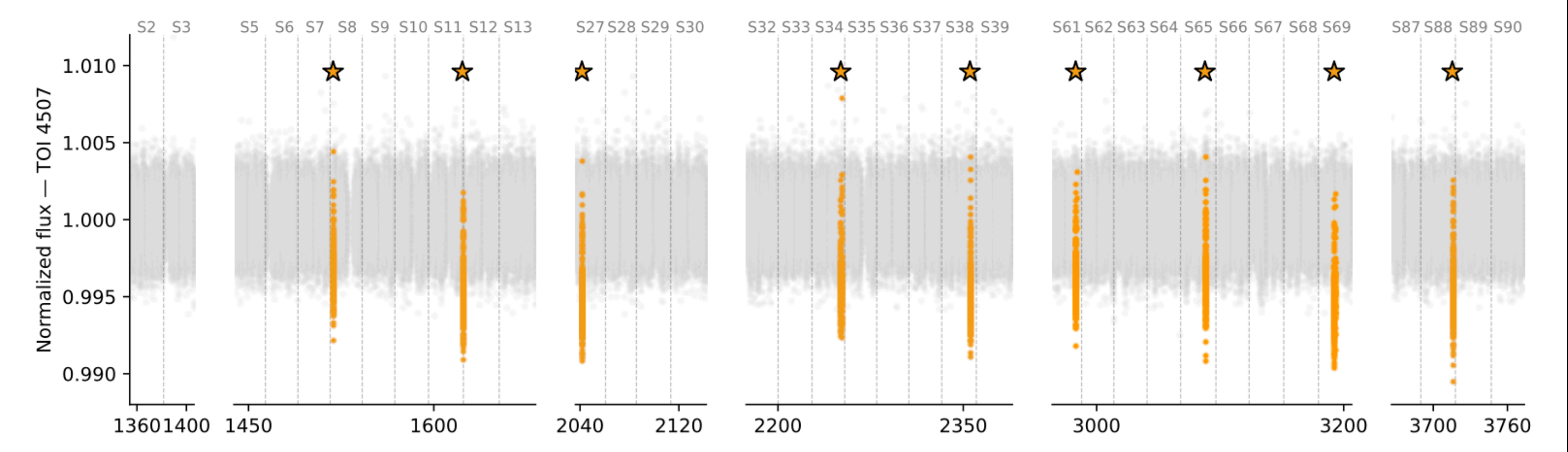


Almenara et al. (submitted)

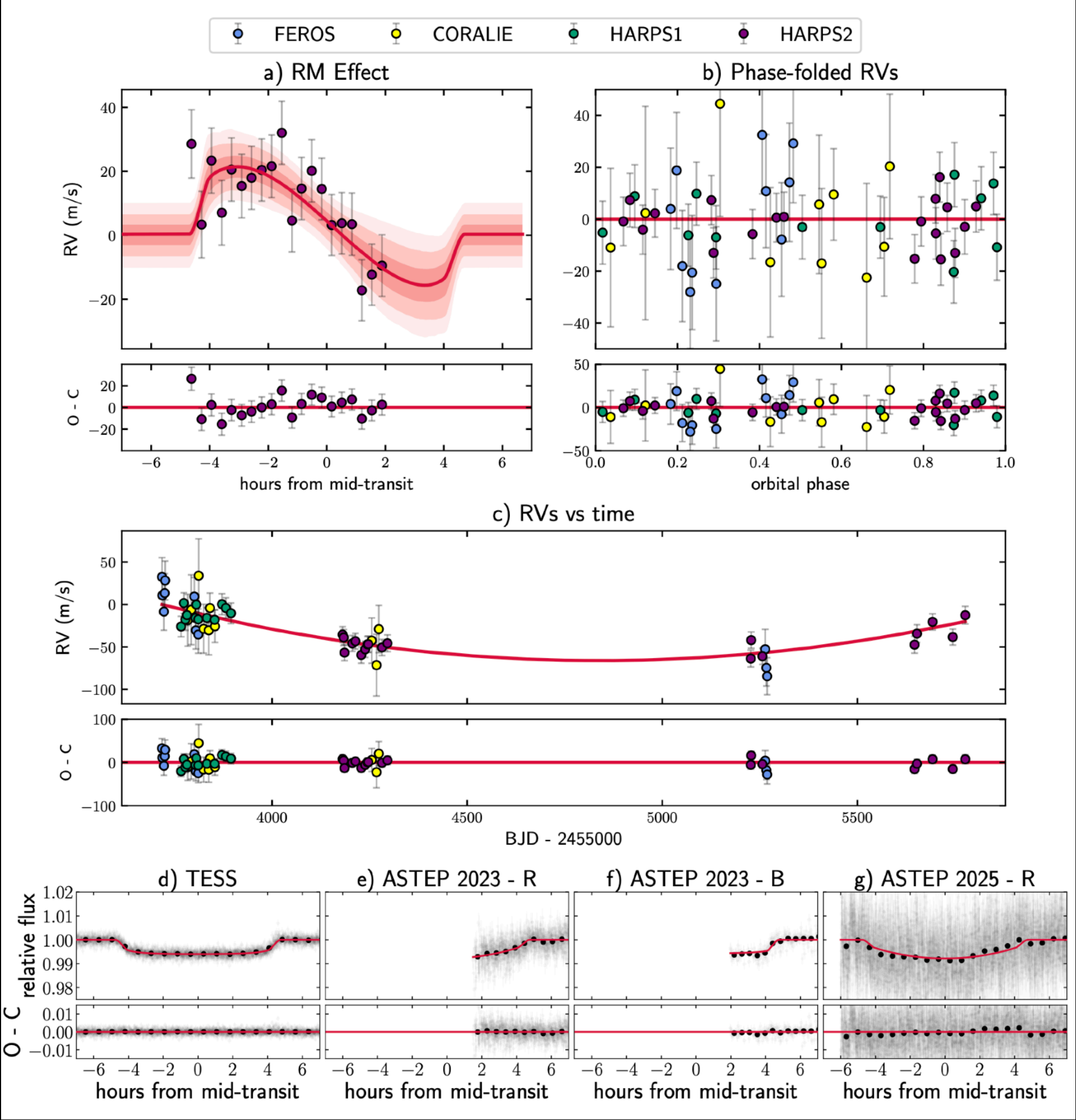
A solar-analog system of three transiting giant planets near a Laplace resonance chain



A Cold and Super-Puffy Planet on a Polar Orbit

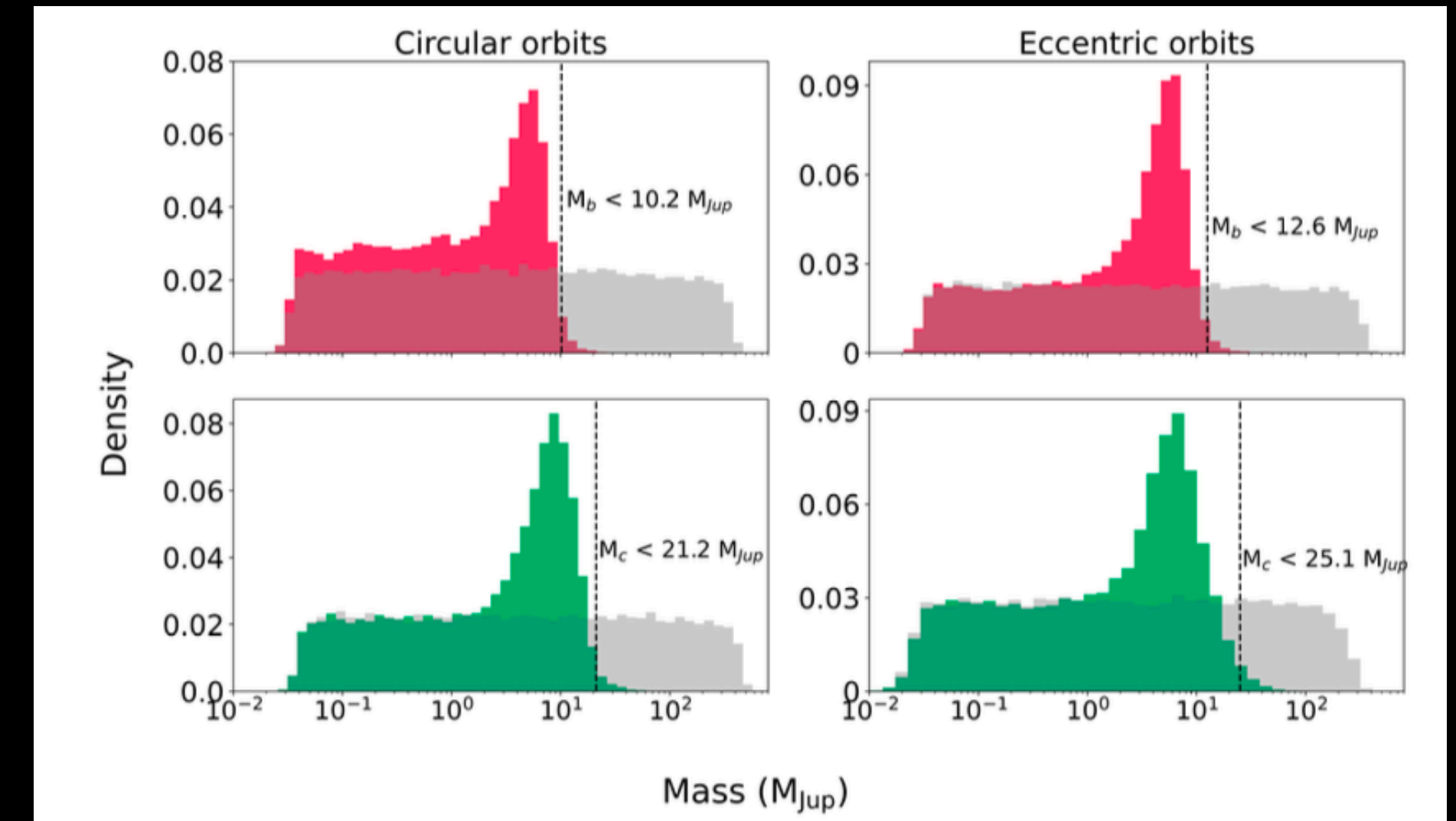
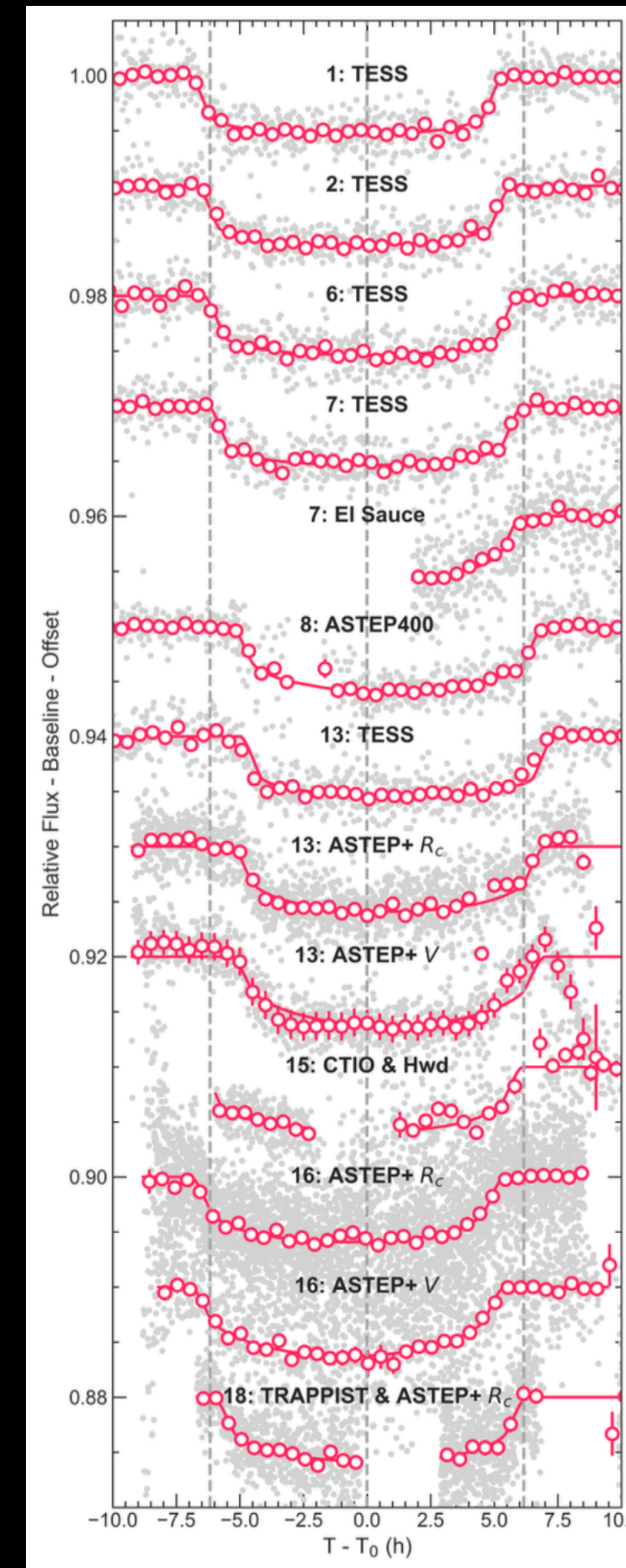
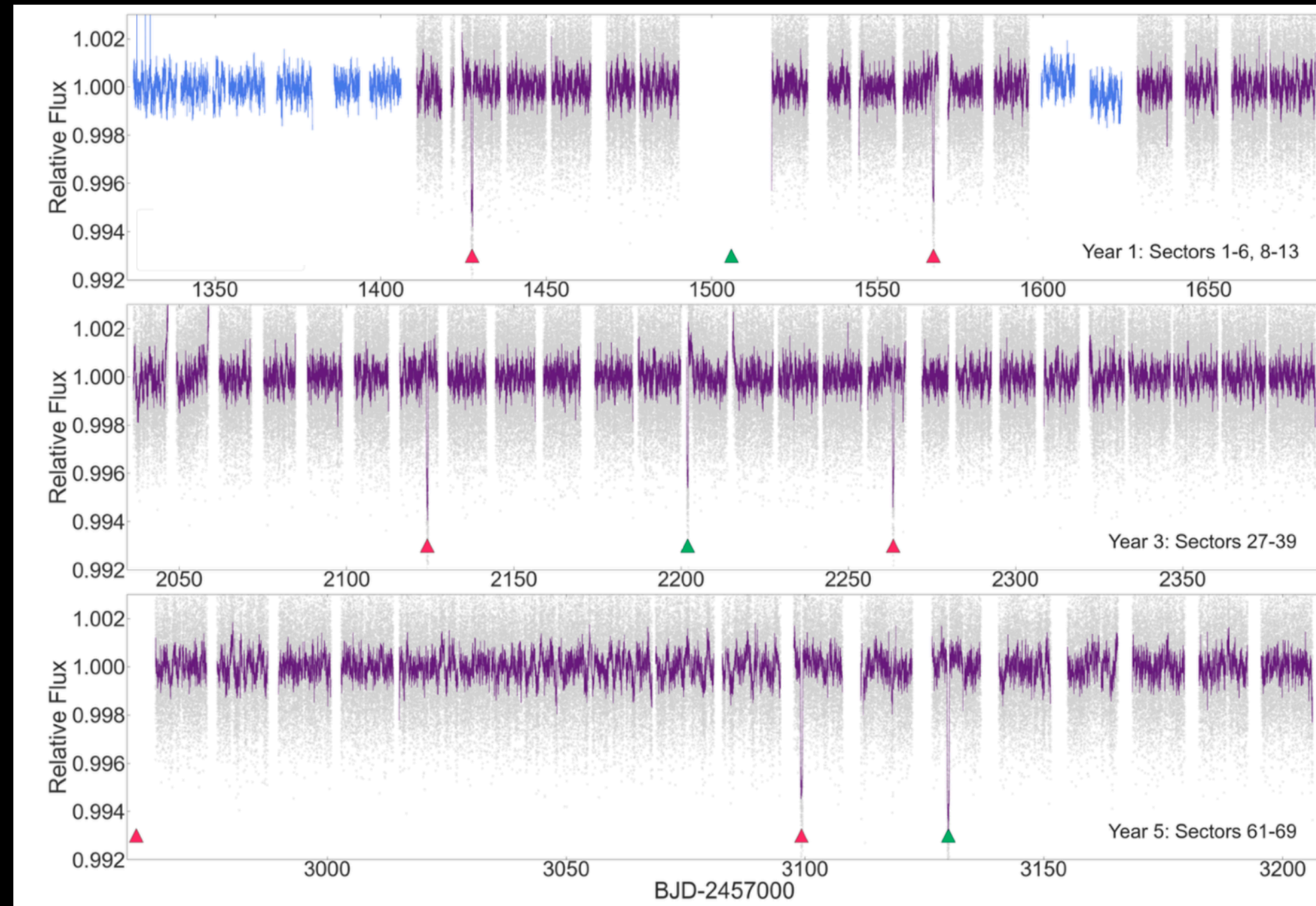


105 days period
sub-Saturn
polar orbit



Rea et al. + Espinoza-Retamal et al. A&A (submitted)

A pair of long-period Jupiter-sized planets with extremely low densities

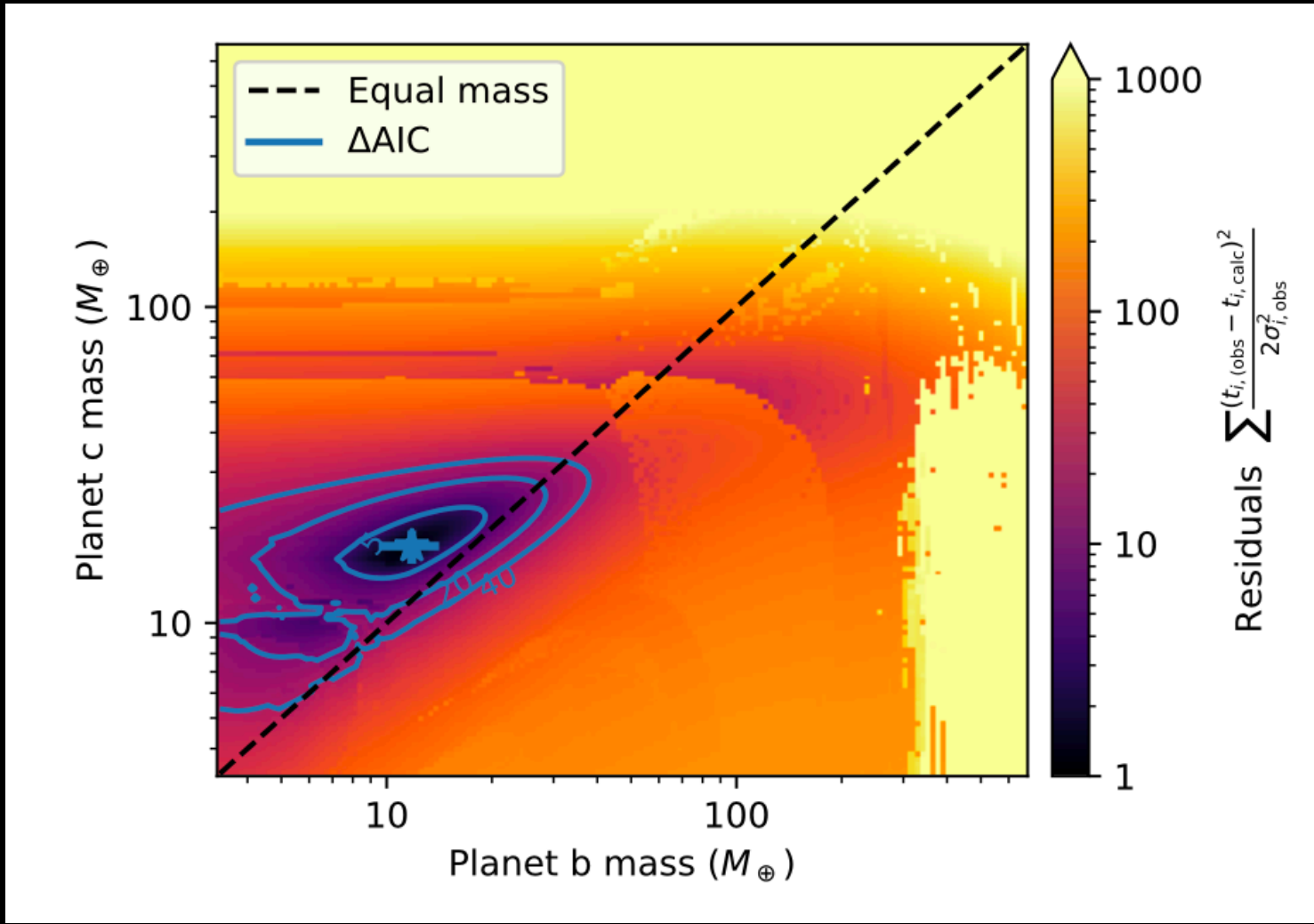
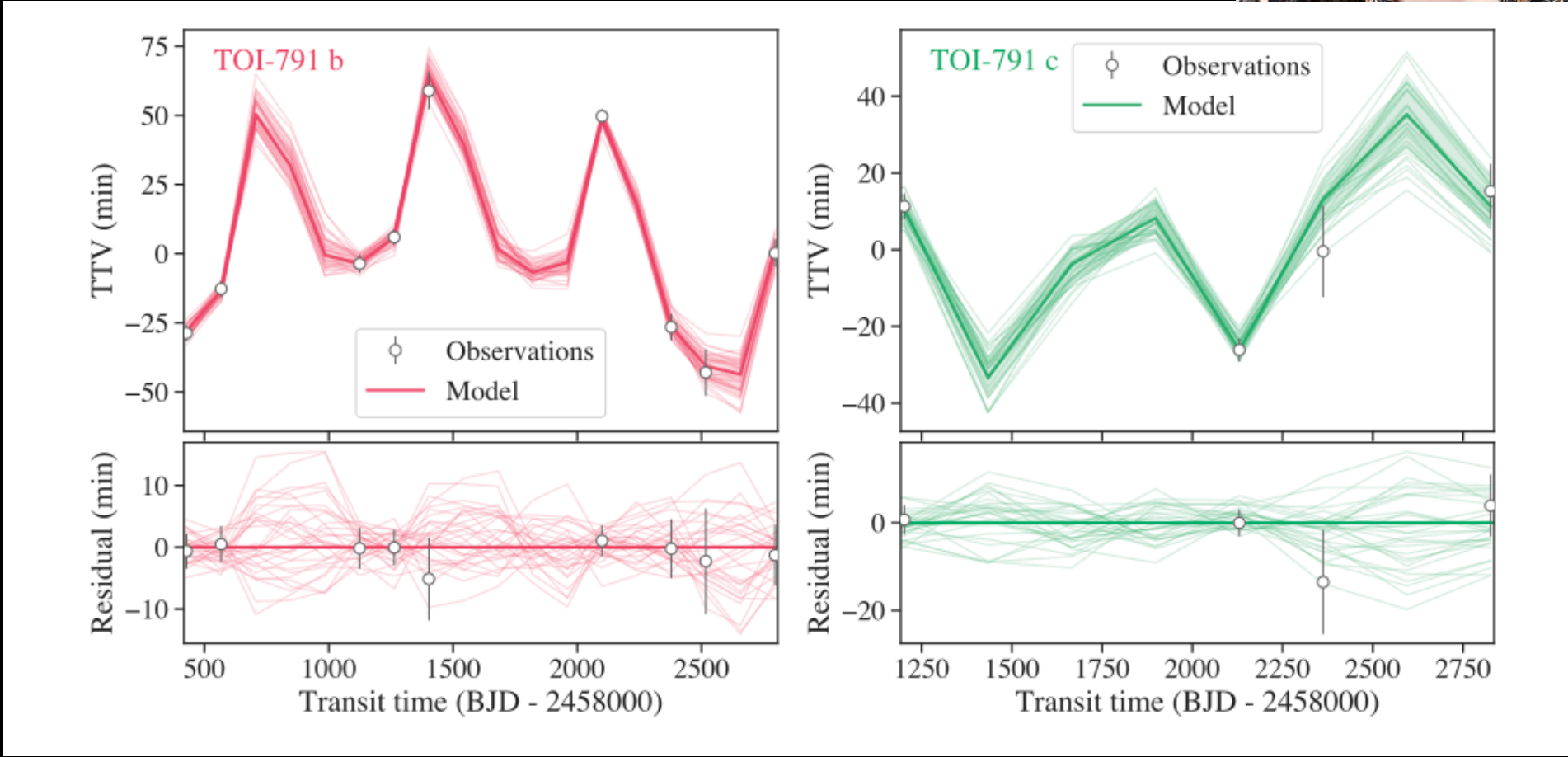
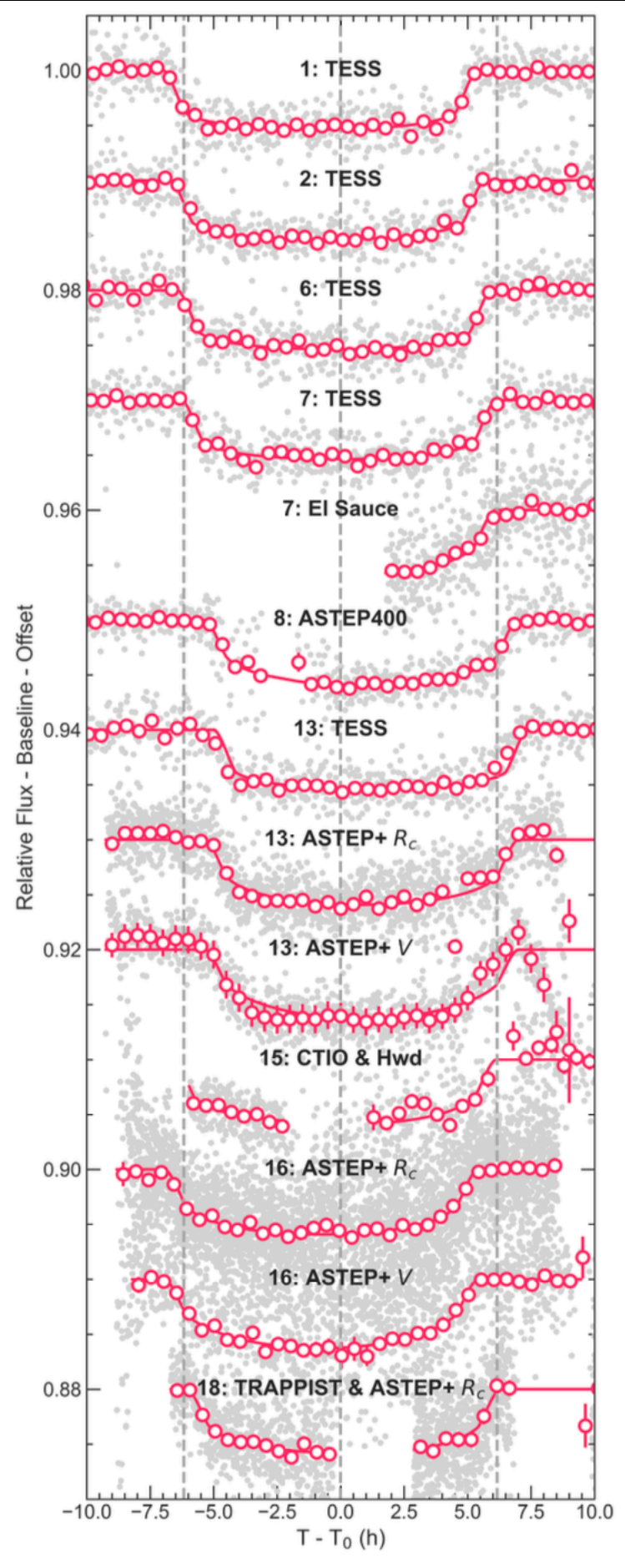
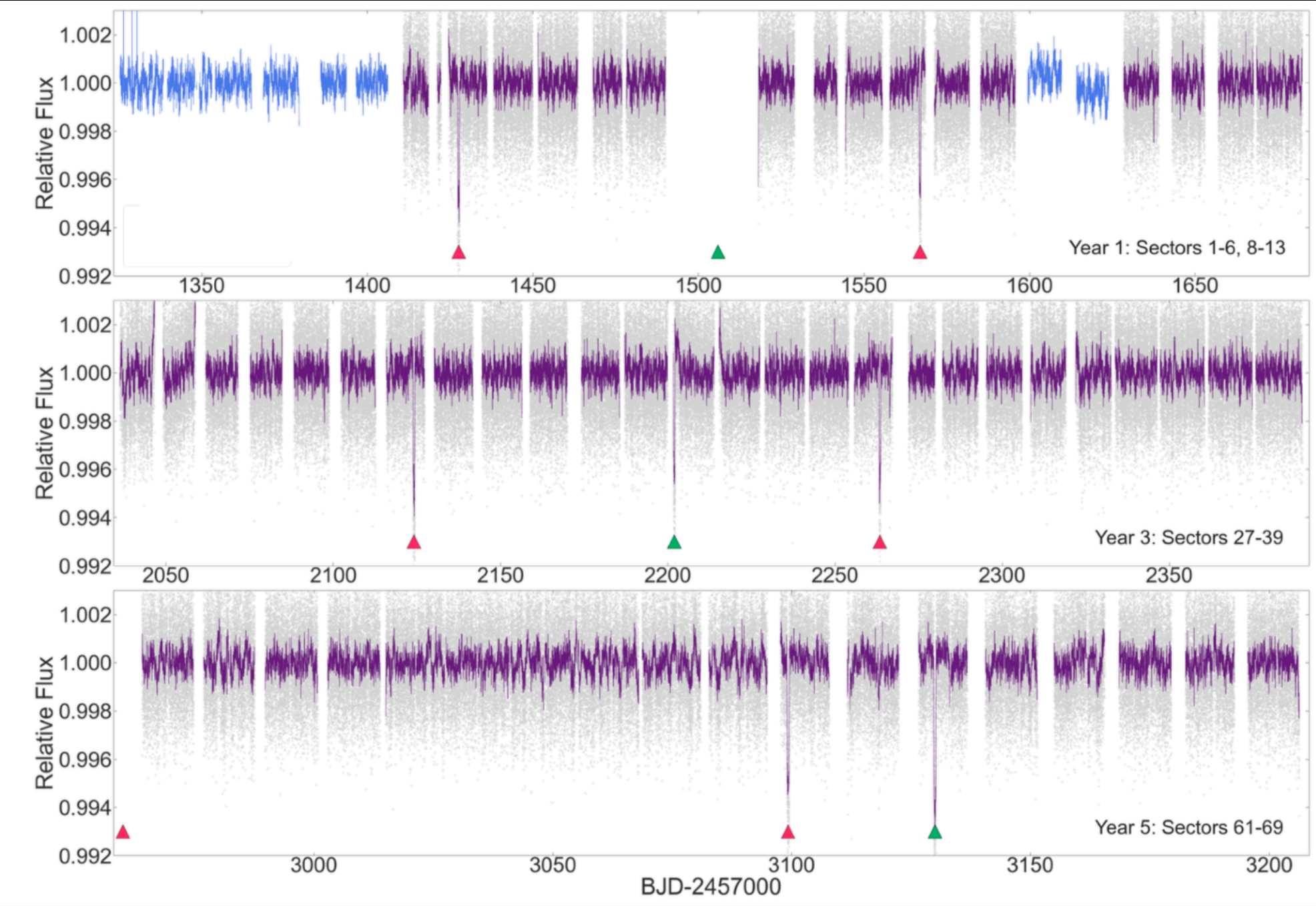


Periods : 139 and 232 days
5:3 resonance
Radii: 1.00 and 1.16 R_{Jup}



Dransfield et al. MNRAS (in revision)

A pair of long-period Jupiter-sized planets with extremely low densities



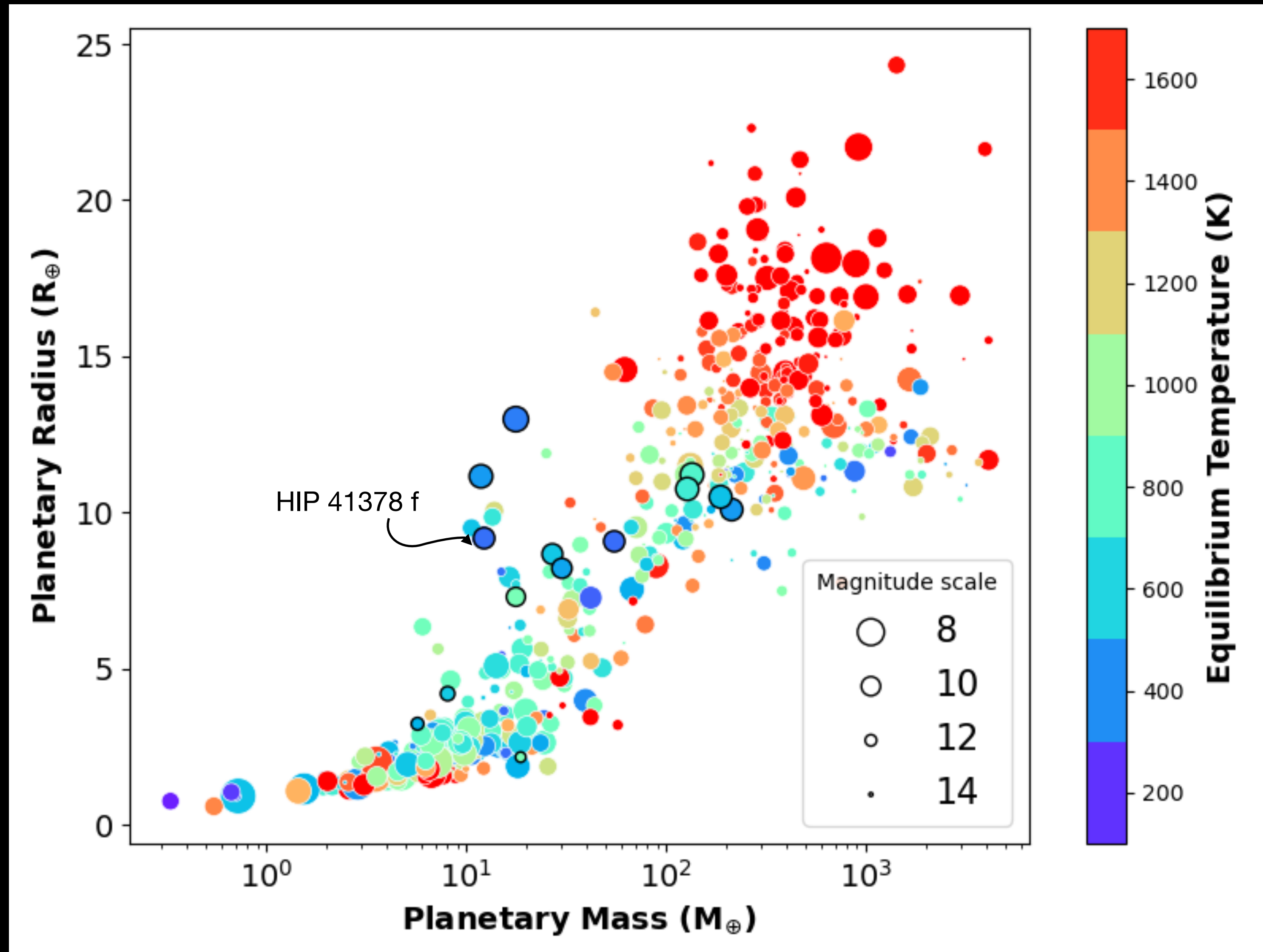
Periods : 139 and 232 days
5:3 resonance
Radii: 1.00 and 1.16 R_{Jup}





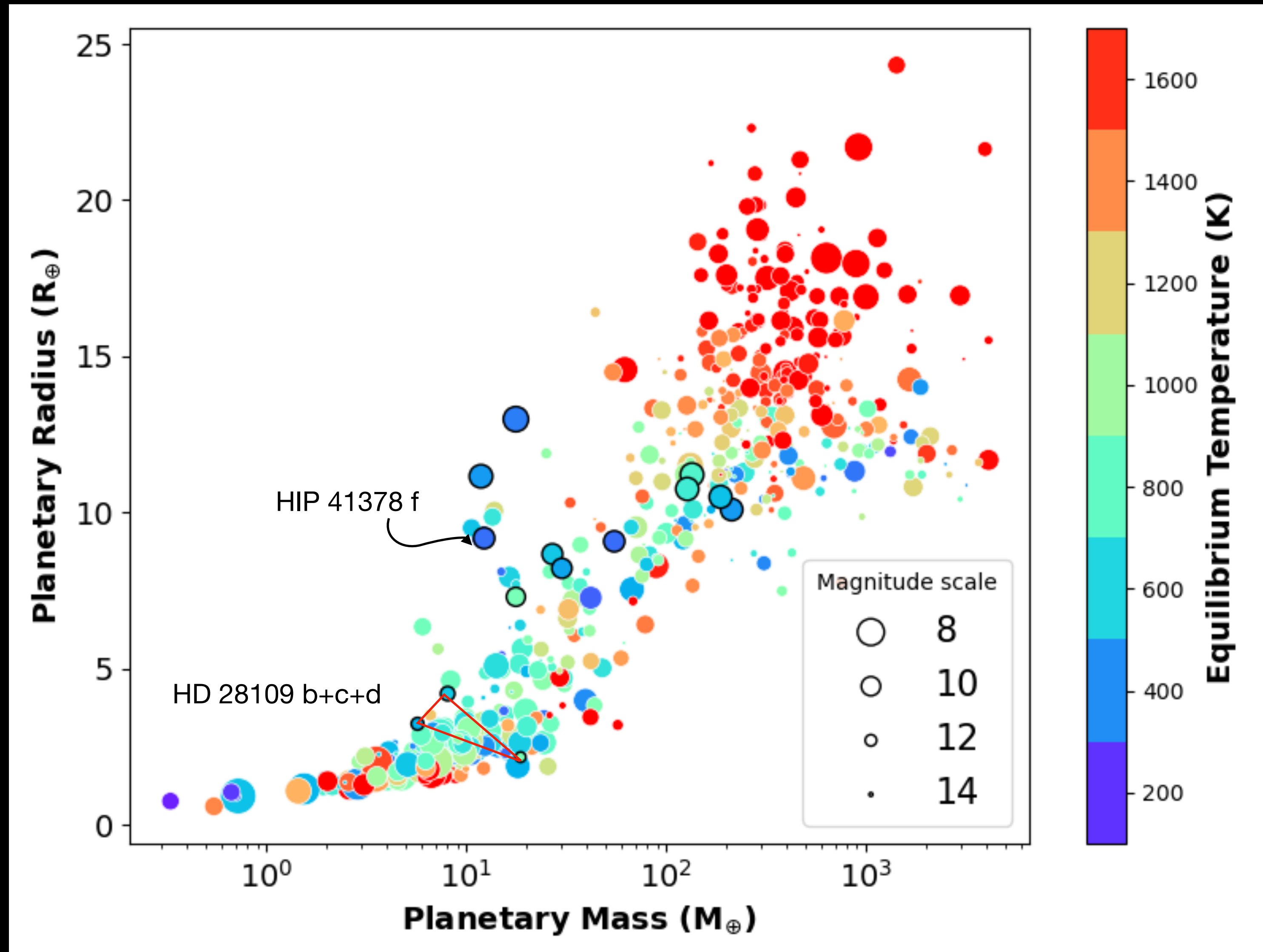
2. M-R diagram and super-puffs

Mass radius diagram

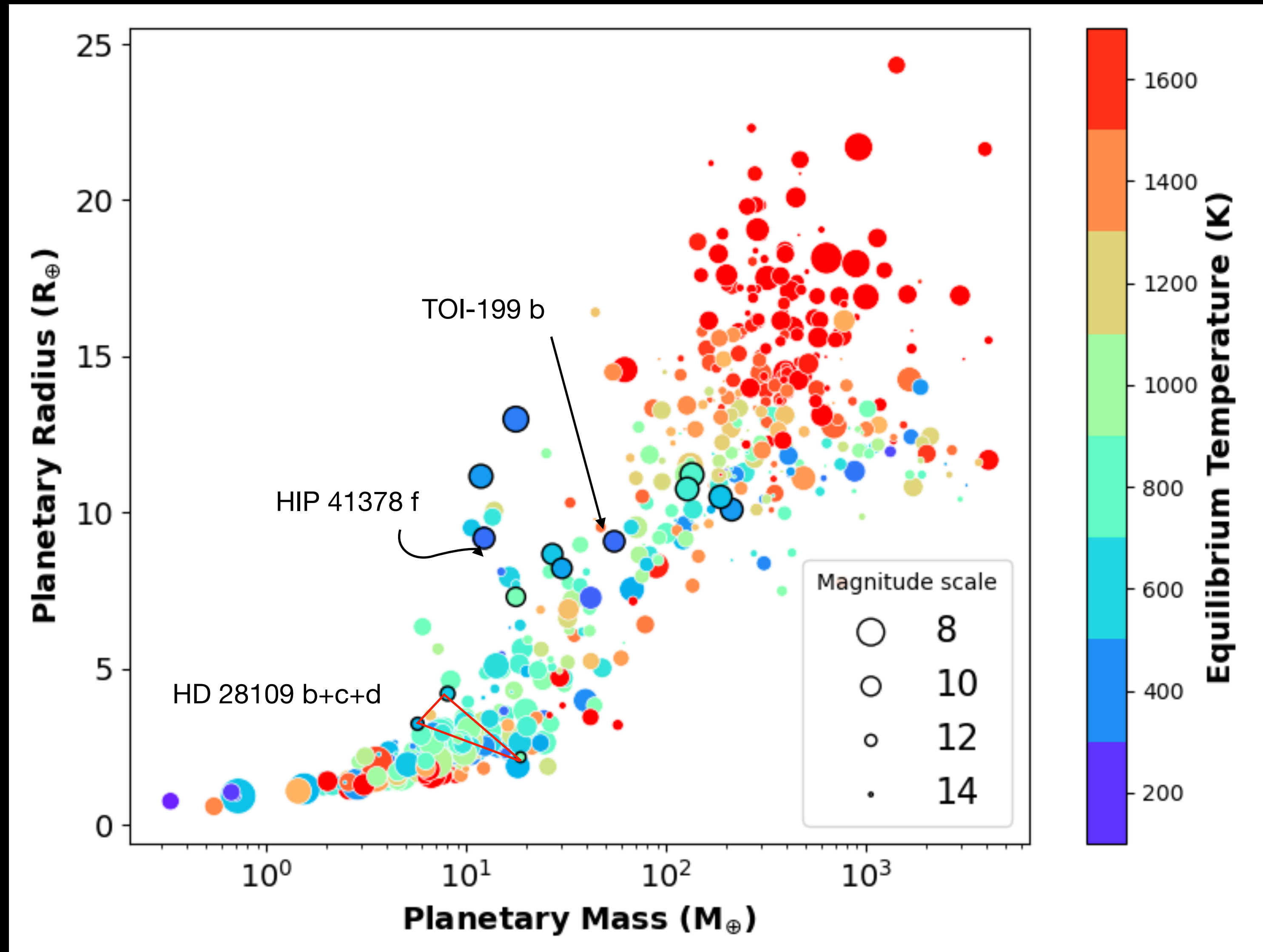


Santerne et al., Nat. Astron. (2019)
Grouffal et al. A&A (2022, 2025)

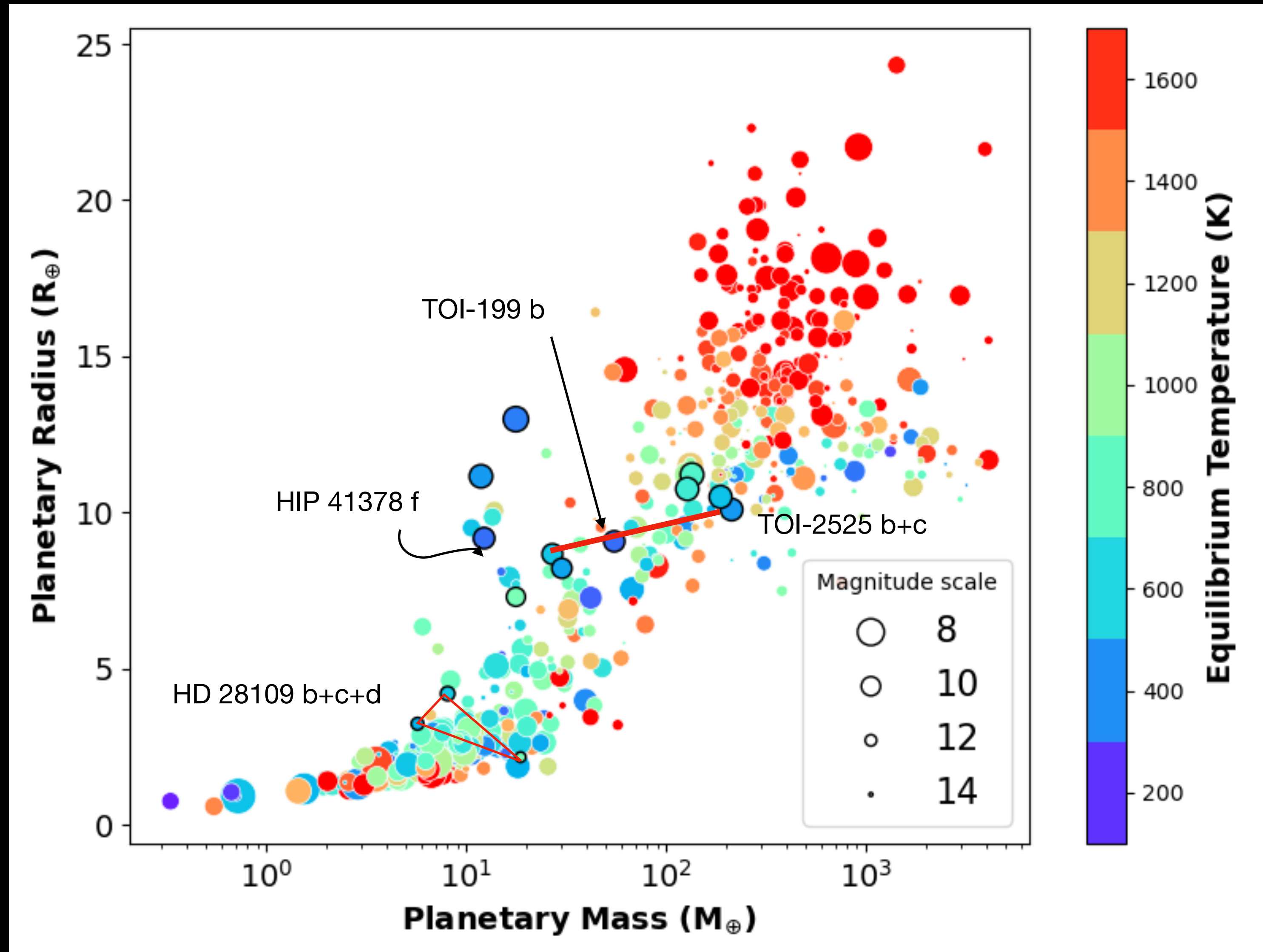
Mass radius diagram



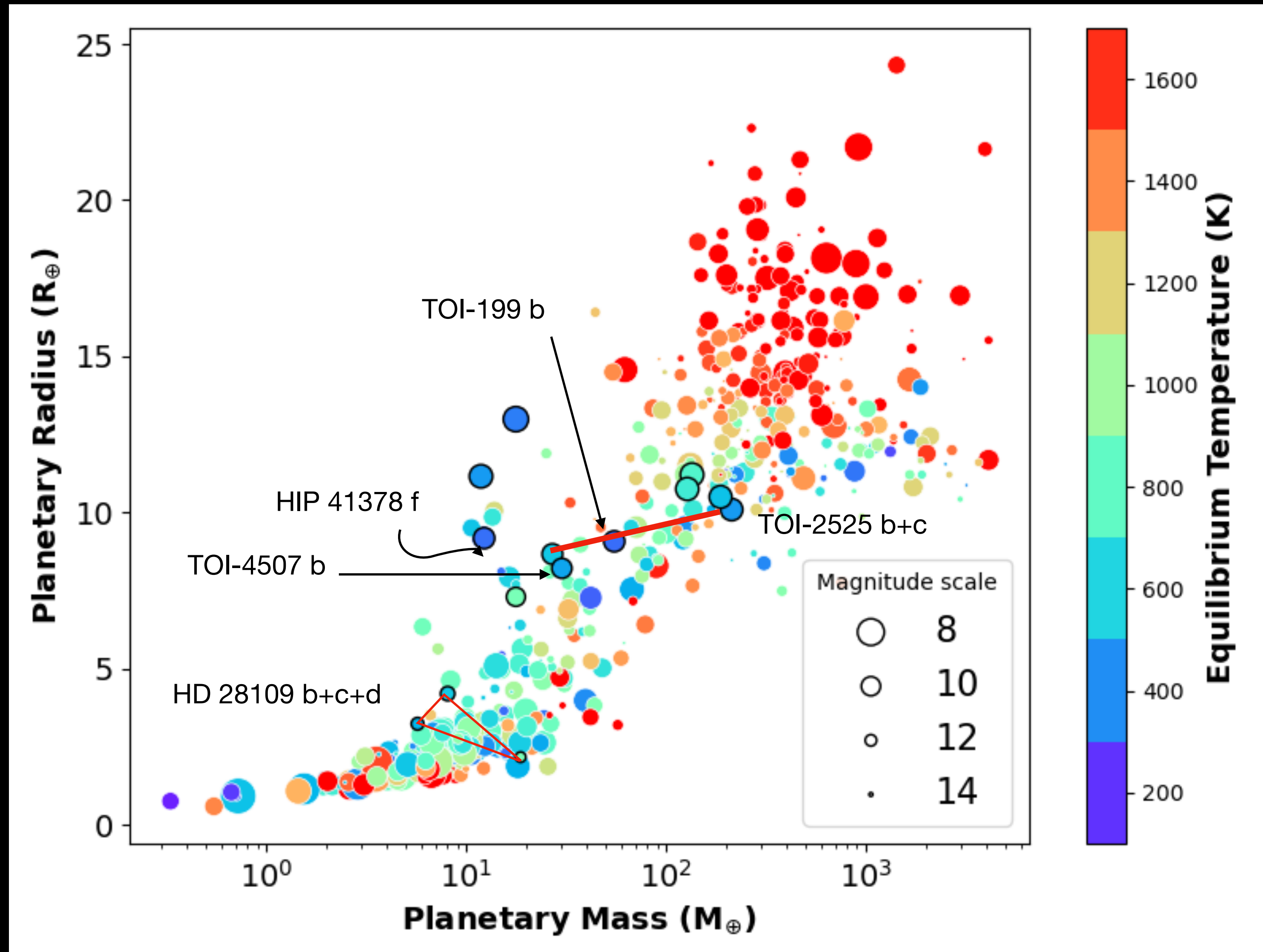
Mass radius diagram



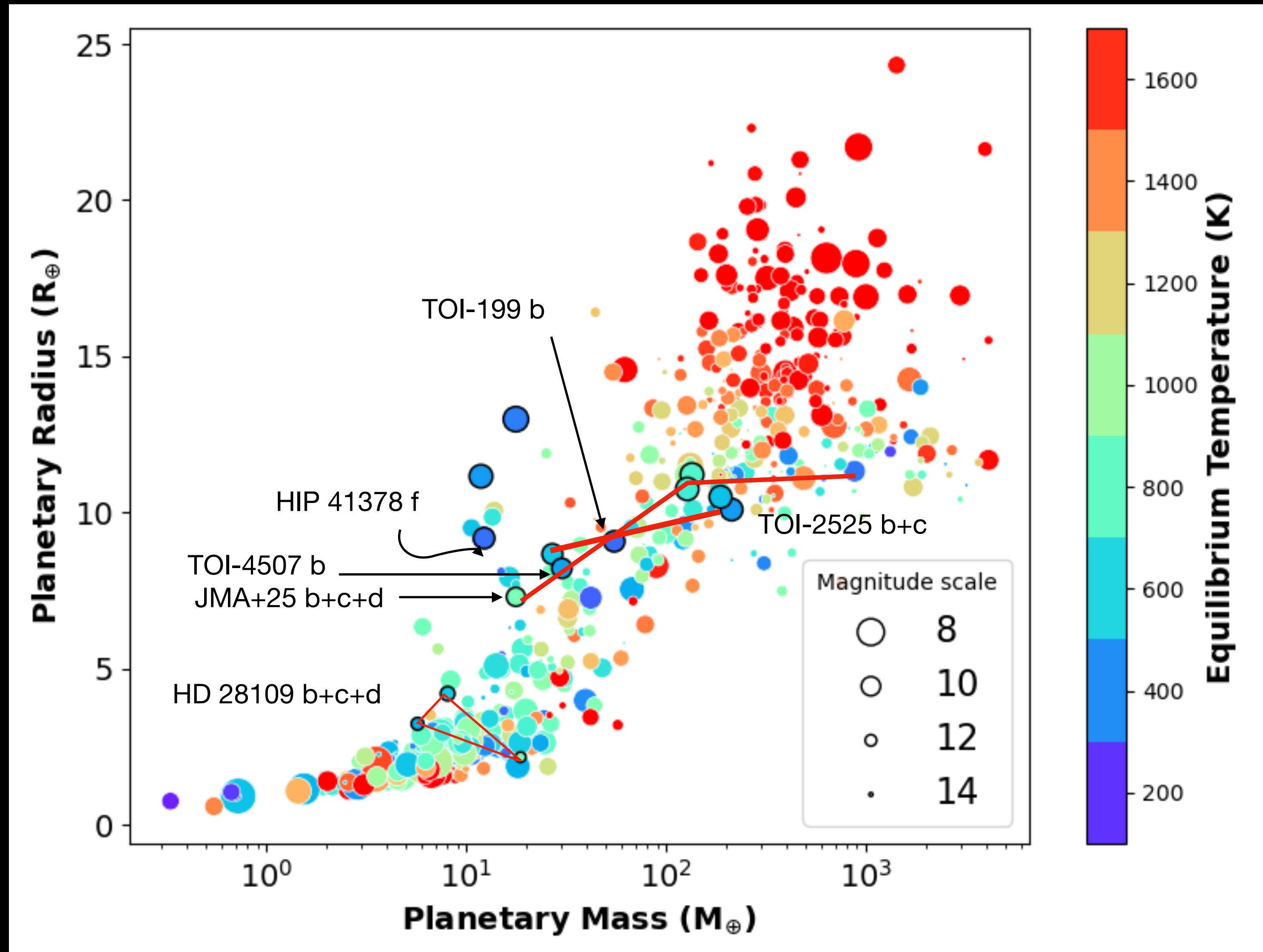
Mass radius diagram



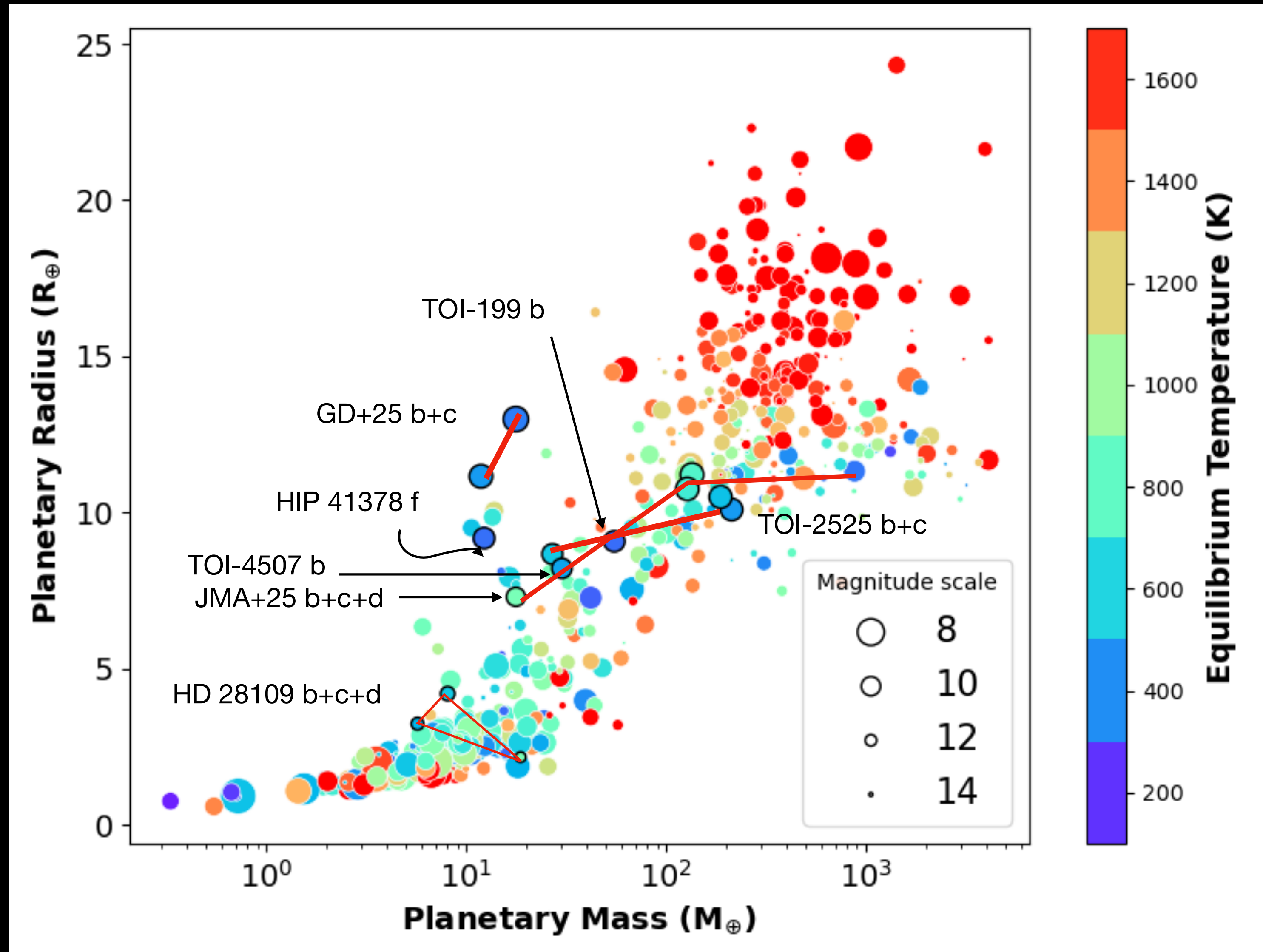
Mass radius diagram



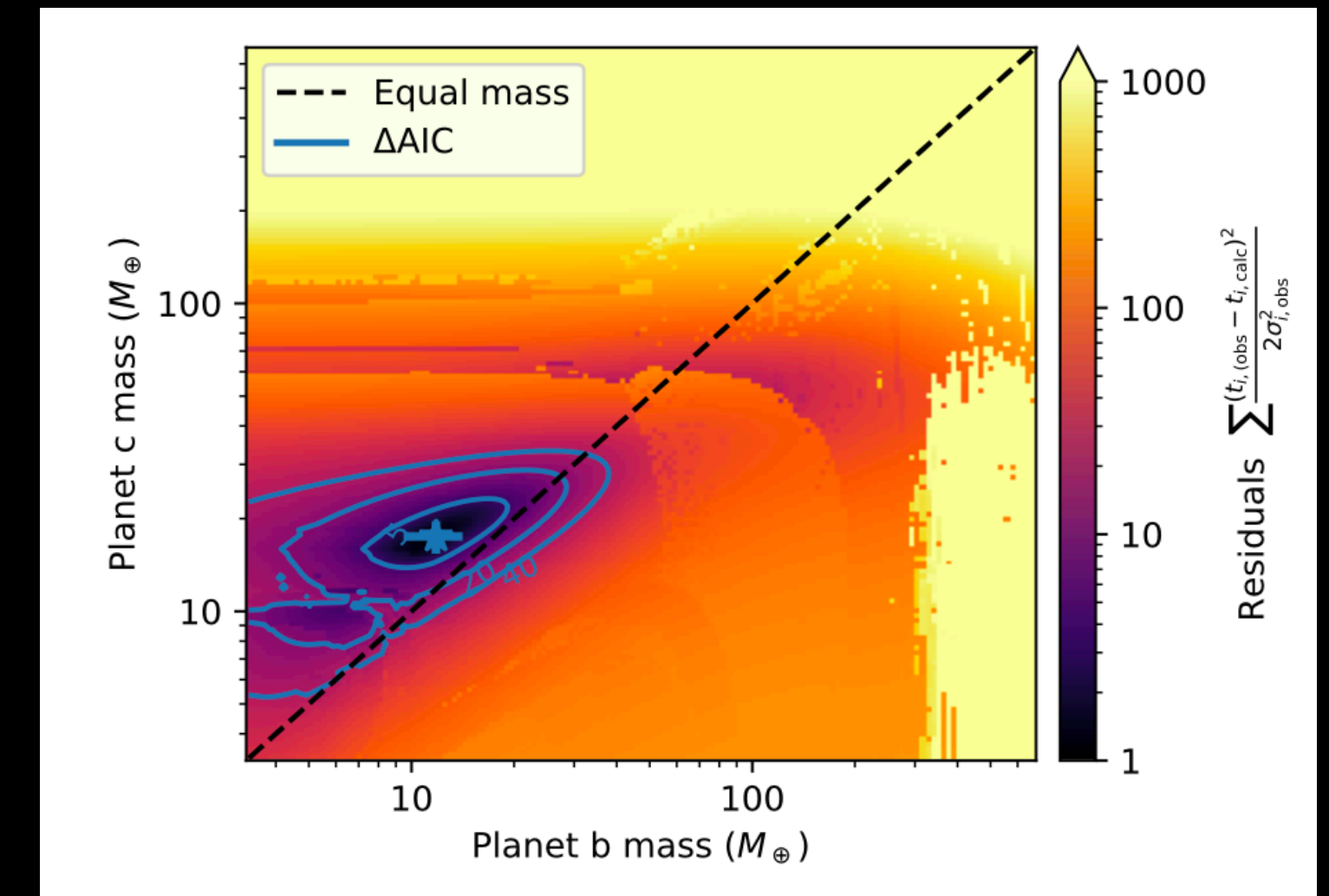
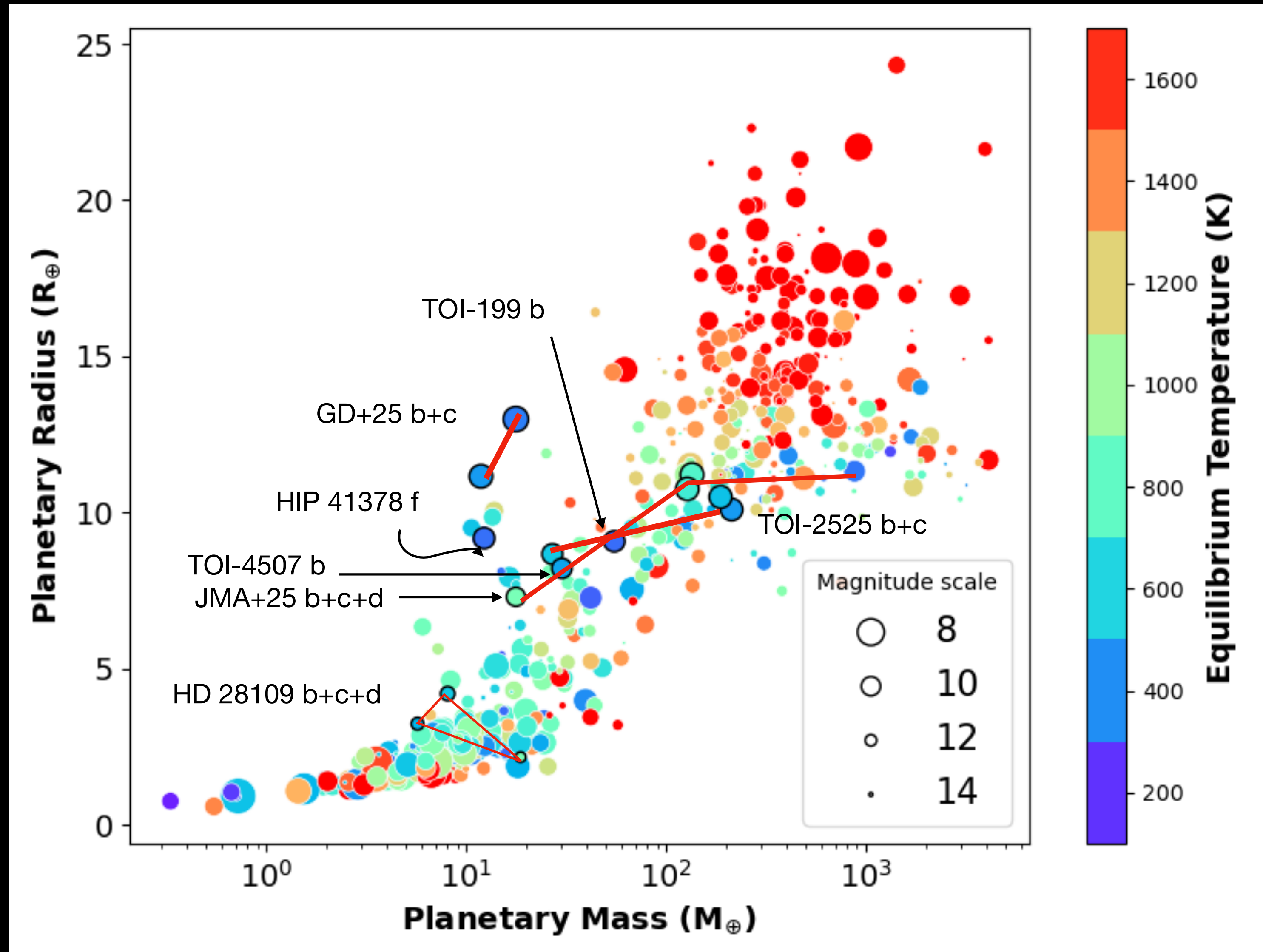
Mass radius diagram



Mass radius diagram

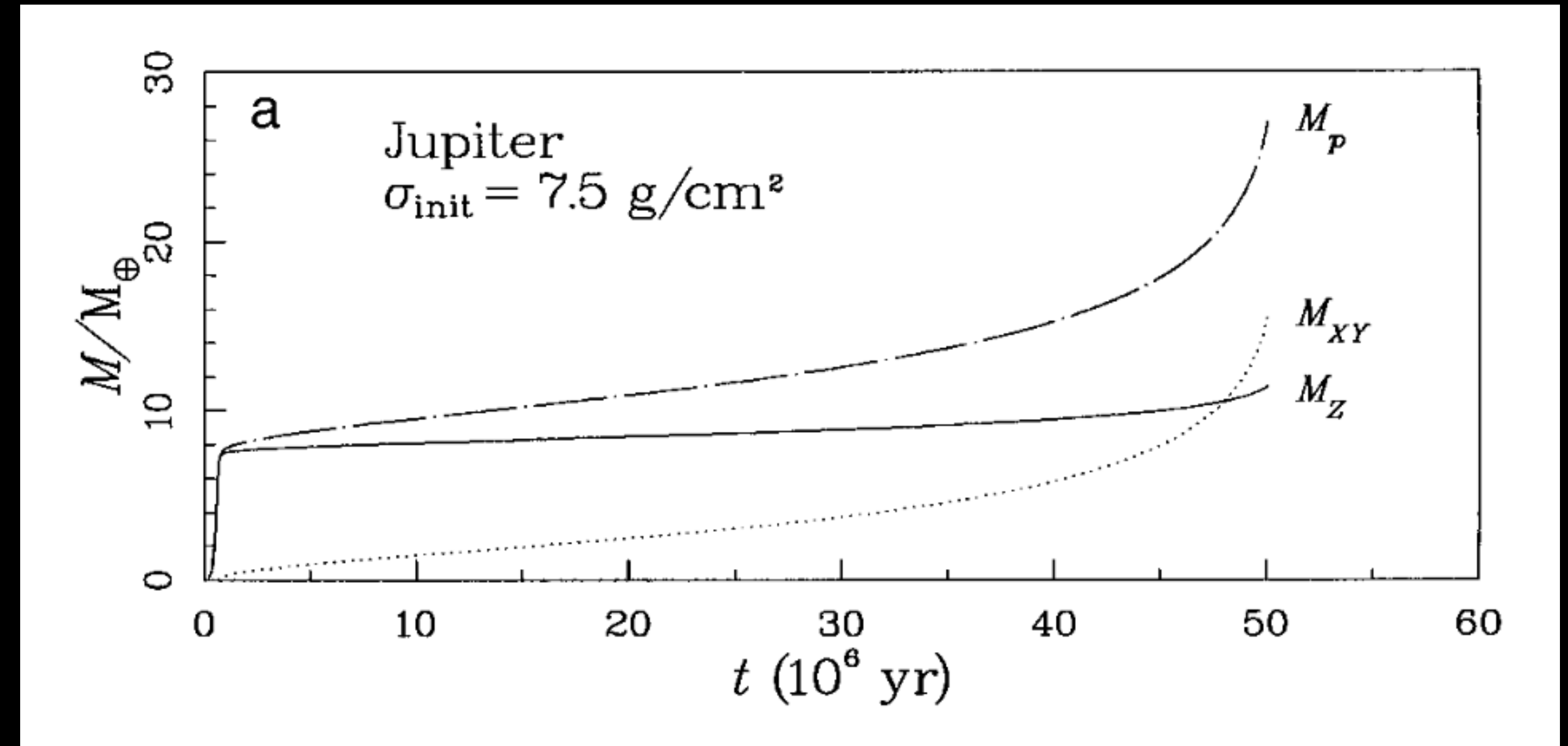
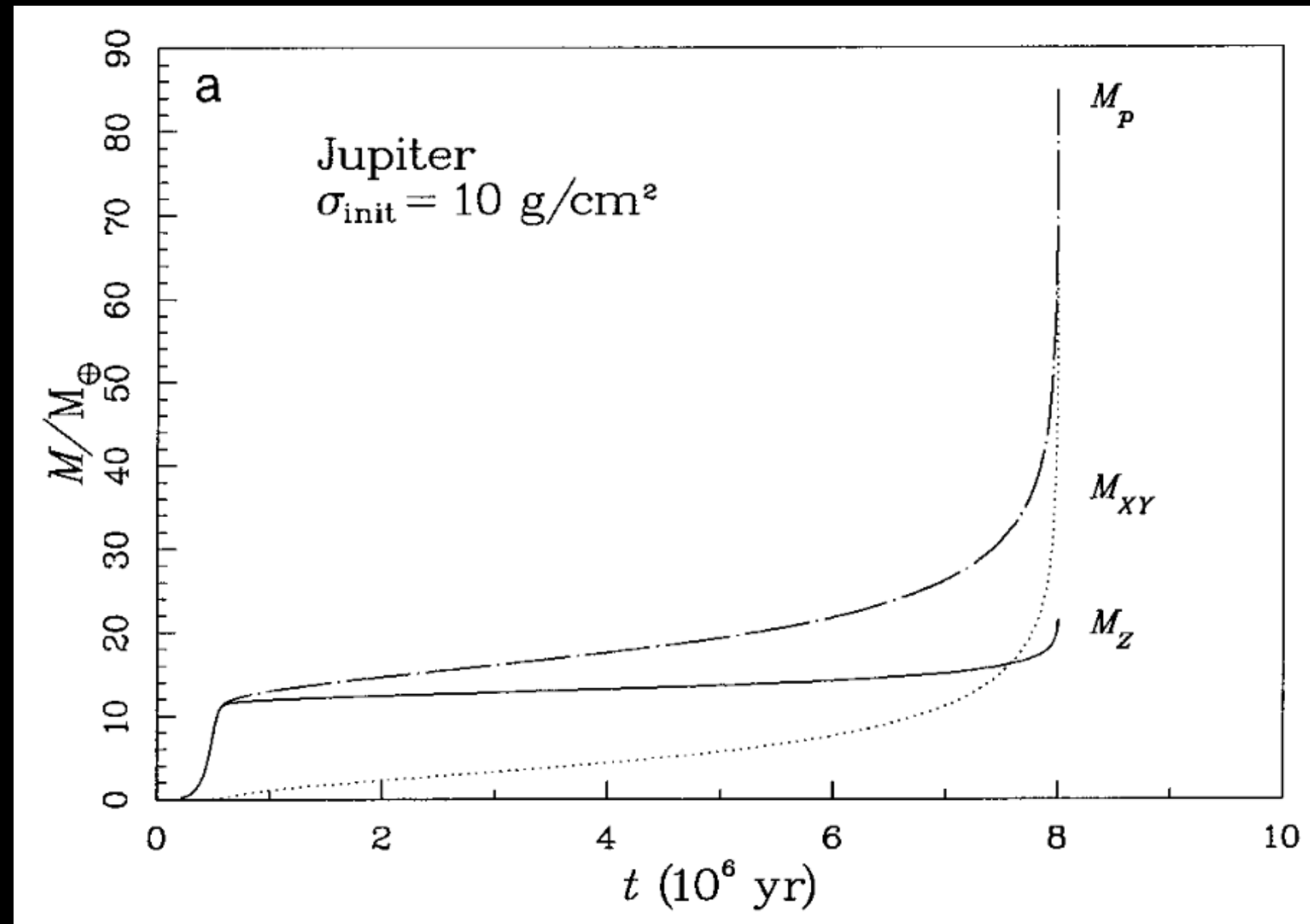


Mass radius diagram

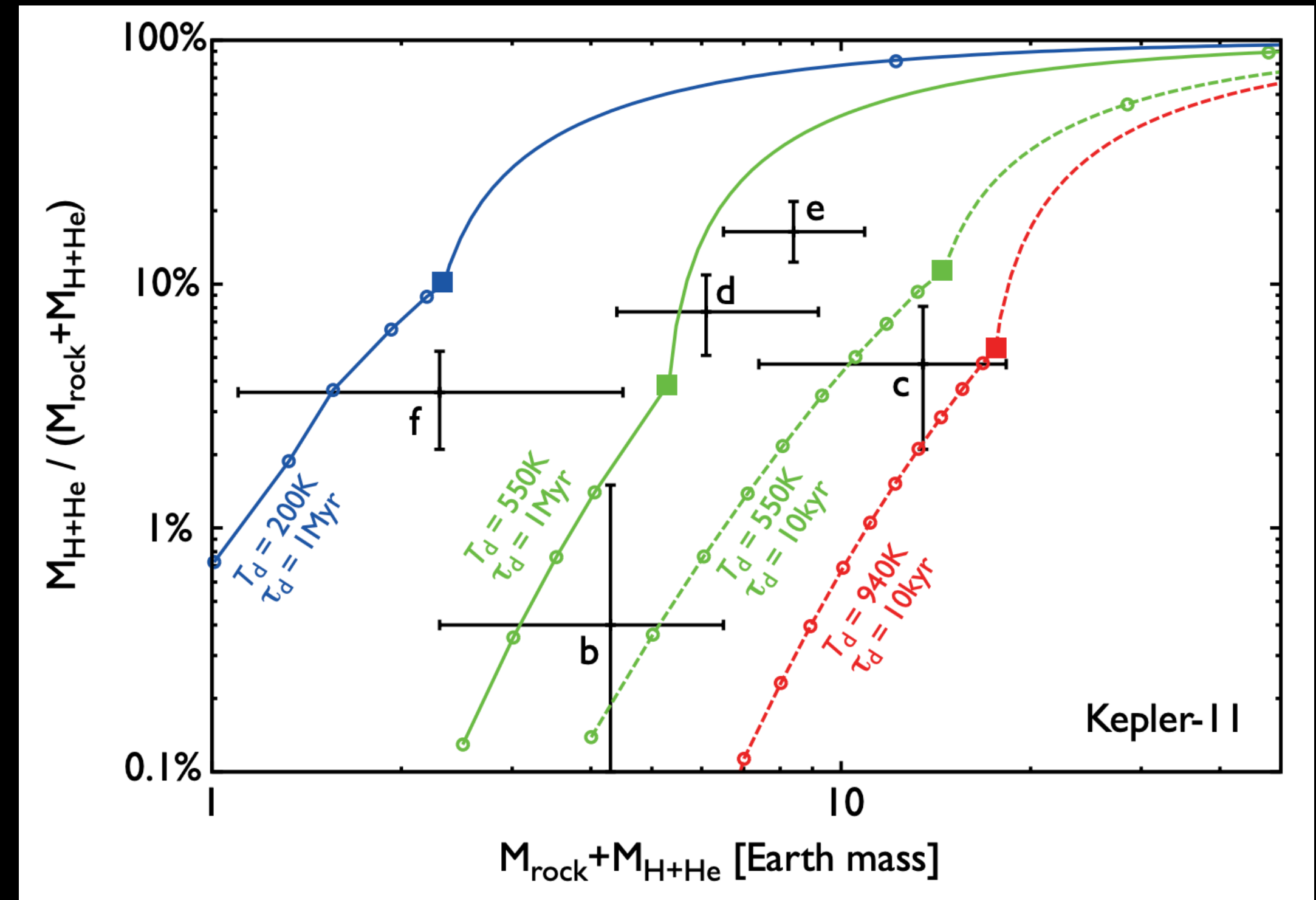
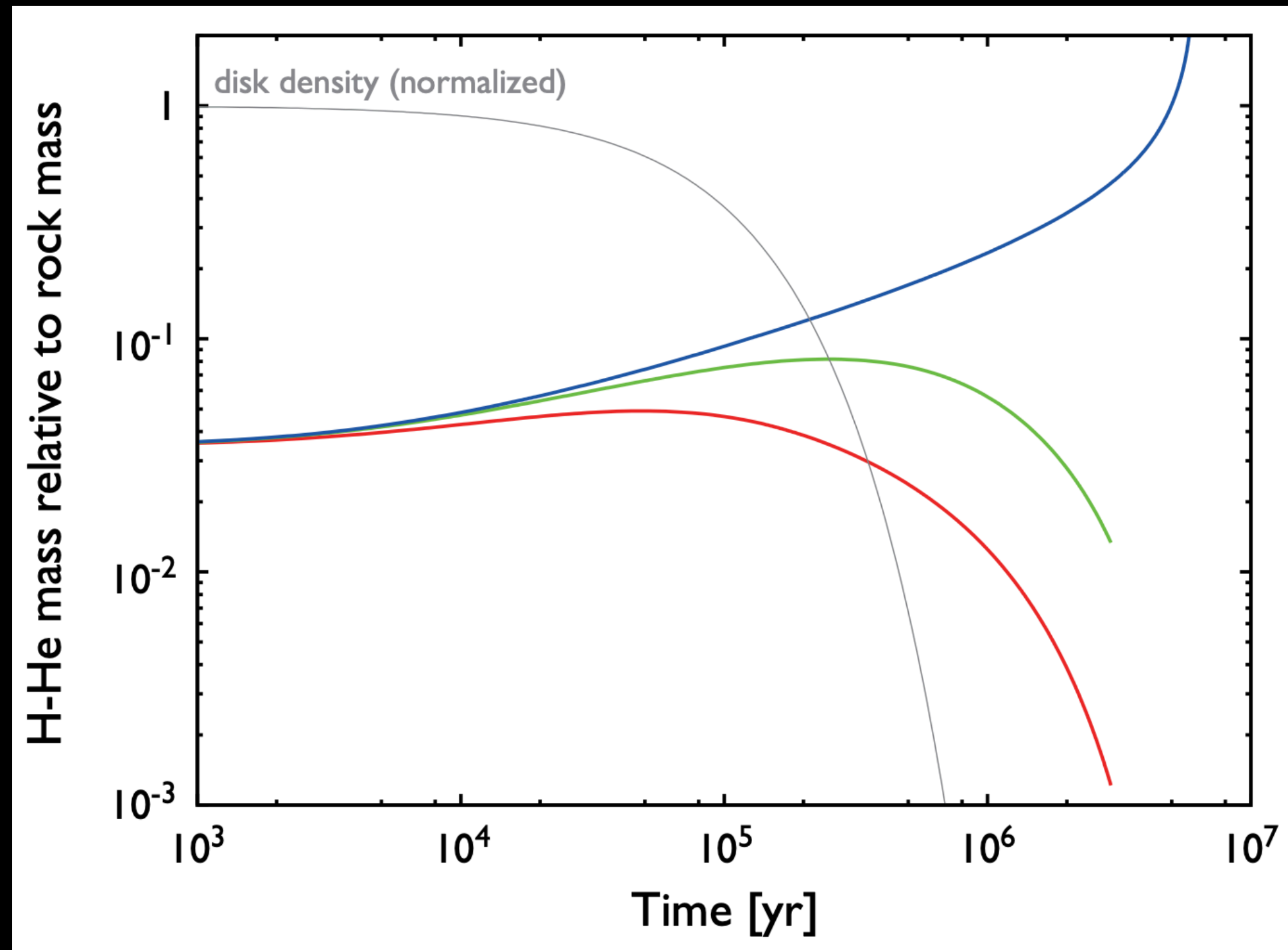


Dransfield et al. (submitted)

Super-puffs



Super-puffs



A wide-angle photograph of Earth from space. The horizon is a thin blue line separating the dark, starry void of space from the bright, sunlit surface of the planet. The sun is a large, glowing yellow-orange orb positioned just above the horizon, casting a brilliant light across the scene. The atmosphere is visible as a thin, hazy layer above the surface. Below the horizon, the landscape is a vast, dark expanse of land and water, with numerous clouds and smoke plumes rising from the surface, suggesting a volcanic or post-apocalyptic environment. The overall color palette is dominated by the deep blues of space, the bright yellows and oranges of the sun, and the dark, textured browns and greys of the planet's surface.

3. On temperate planets and cooling

Temperate planets (& in the HZ)

- Will come in all kinds of masses, radii, compositions
 - Earth-like planets, with an H₂O ocean and 1 bar of N₂ and O₂
 - Earth-like planets, with vastly different atmospheres (and perhaps an H₂O ocean)
 - Super-Earths (with perhaps an H₂O ocean)
 - Mini-Neptunes (with perhaps an H₂O ocean)
 - Ice giants (with perhaps an H₂O ocean)
 - Gas giants & brown dwarfs

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 - Mini-Neptunes (with perhaps an H₂O ocean)
 - Ice giants (with perhaps an H₂O ocean)
 - Gas giants & brown dwarfs
- Their atmospheres too
 - Different masses and extent:
 - No atmosphere
 - Optically thin to moderately thick atmosphere
 - Abyssal atmosphere
 - Different compositions:
 - Light (with a significant amount of hydrogen)
 - Moderately heavy (with e.g., N₂ or CO₂)

Moist convection inhibition

In the presence of condensation, the mean molecular weight gradient ∇_μ depends on how the humidity changes with pressure.

The medium is convective if:

$$(1 - \varpi\beta f)(\nabla_T - \nabla_T^*) > 0$$

1 for Jupiter
-0.5 for Earth

$$\beta = L/RT \sim 20$$

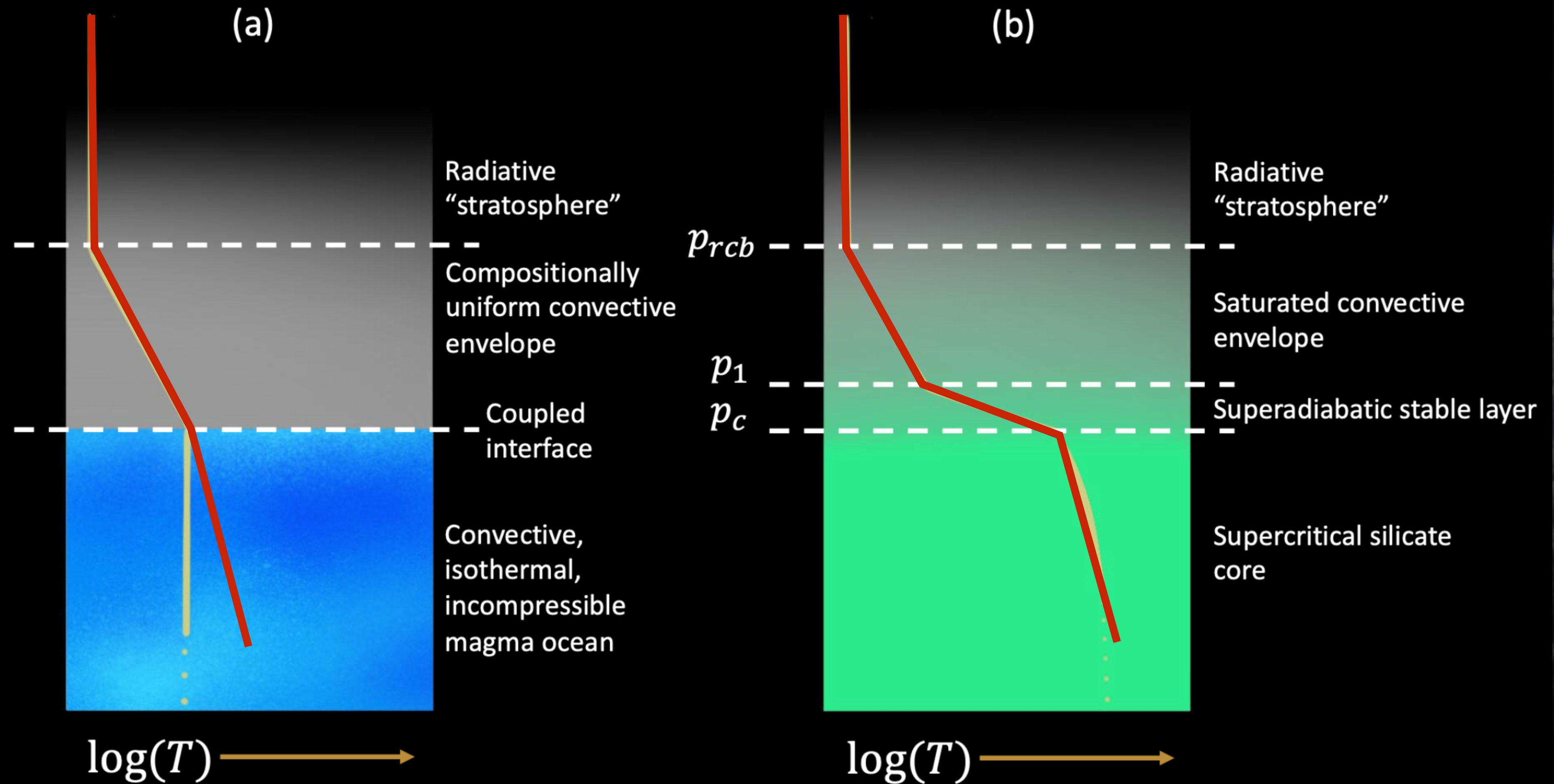
mass mixing ratio
of condensing species

This *never* occurs if: $f > f_0 \equiv \frac{1}{\varpi\beta}$ → Enrichments in: $\text{H}_2\text{O} \gtrsim 10 \times \odot$
 $\text{CH}_4 \gtrsim 40 \times \odot$

Leconte et al. (2017) further demonstrate that double-diffusive convection is also inhibited

Guillot (Science 1995)

Moist convection inhibition: consequences



Markham, Guillot & Stevenson (2022)
(see also Leconte et al. 2017)

Moist convection inhibition: cases

- In Uranus & Neptune, due to CH_4 condensation
 - Guillot (1995), Ge et al. (2024), Clément et al. (2024)
- In Jupiter & Saturn
 - Linked to H_2O condensation, possibly: Li & Ingersoll (2017), Hyder et al. (2024)
 - Linked to helium rain: Markham & Guillot (2024)
- In K2-18b
 - Leconte et al. (2024)
- In Earth-like planets with a water ocean and a hydrogen atmosphere
 - If the ocean temperature is $>300\text{K}$: Seeley & Wordsworth (2025)
- In magma-ocean planets
 - Markham, Guillot & Stevenson (2023)

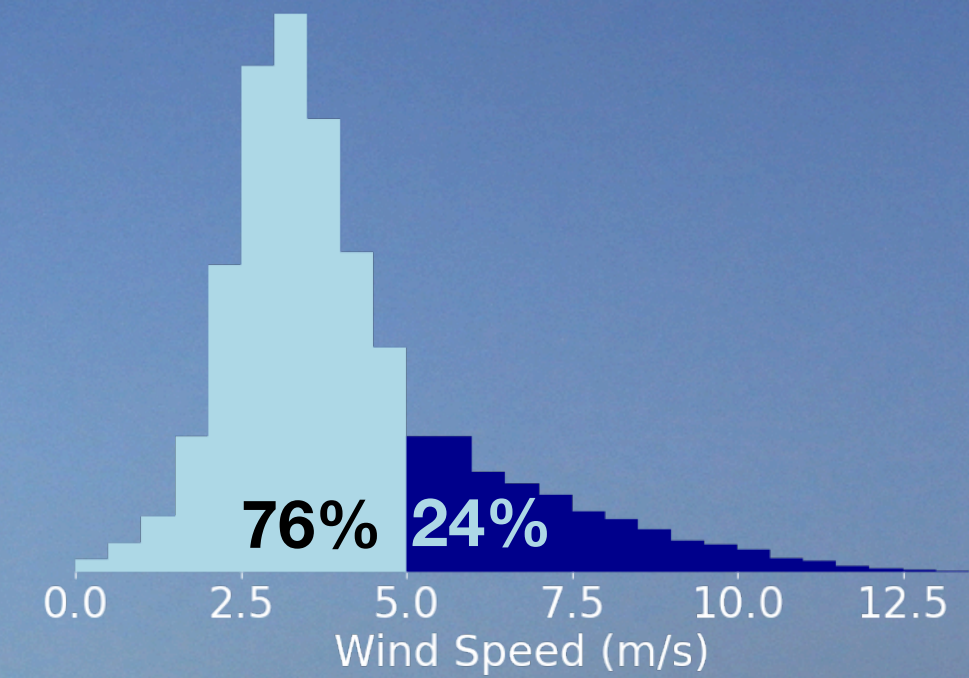
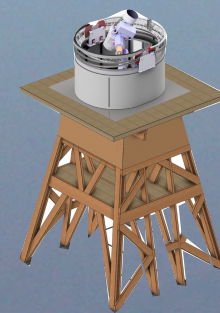
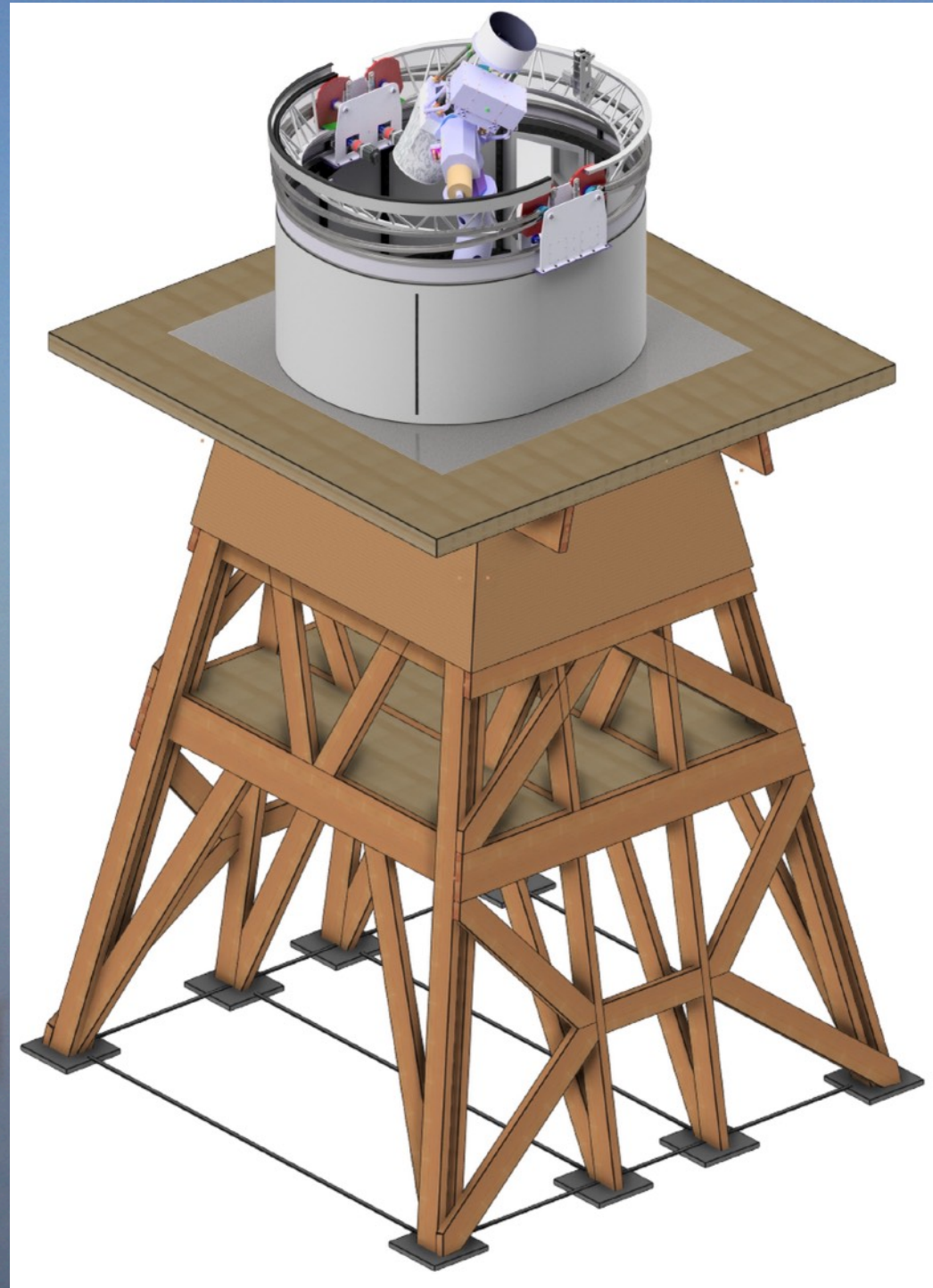
Moist convection inhibition & PLATO

- This will yield slower cooling, higher internal temperatures
 - Will modify inferred bulk abundances
 - Very difficult to check against composition degeneracies, particularly in small planets
 - Age information may be a game changer but this is to be quantified
 - Problem yet to be tackled with evolution models in the context of WP116100
- Testing this requires observations of enriched exoplanetary atmospheres
 - Constraints on disequilibrium species abundances
 - Linking bulk and atmospheric compositions.
 - Long-period temperate planets (w/ water condensation) are especially interesting
- Characterizing planets in the HZ is essential
 - With water condensation & inhibition, convection becomes very intermittent
 - We will need many targets & many observations!

Opportunities



Une tour astronomique pour Concordia



Station Concordia , 18 Novembre 2013

Température : -41.5 °C

Vent : 8 m/s