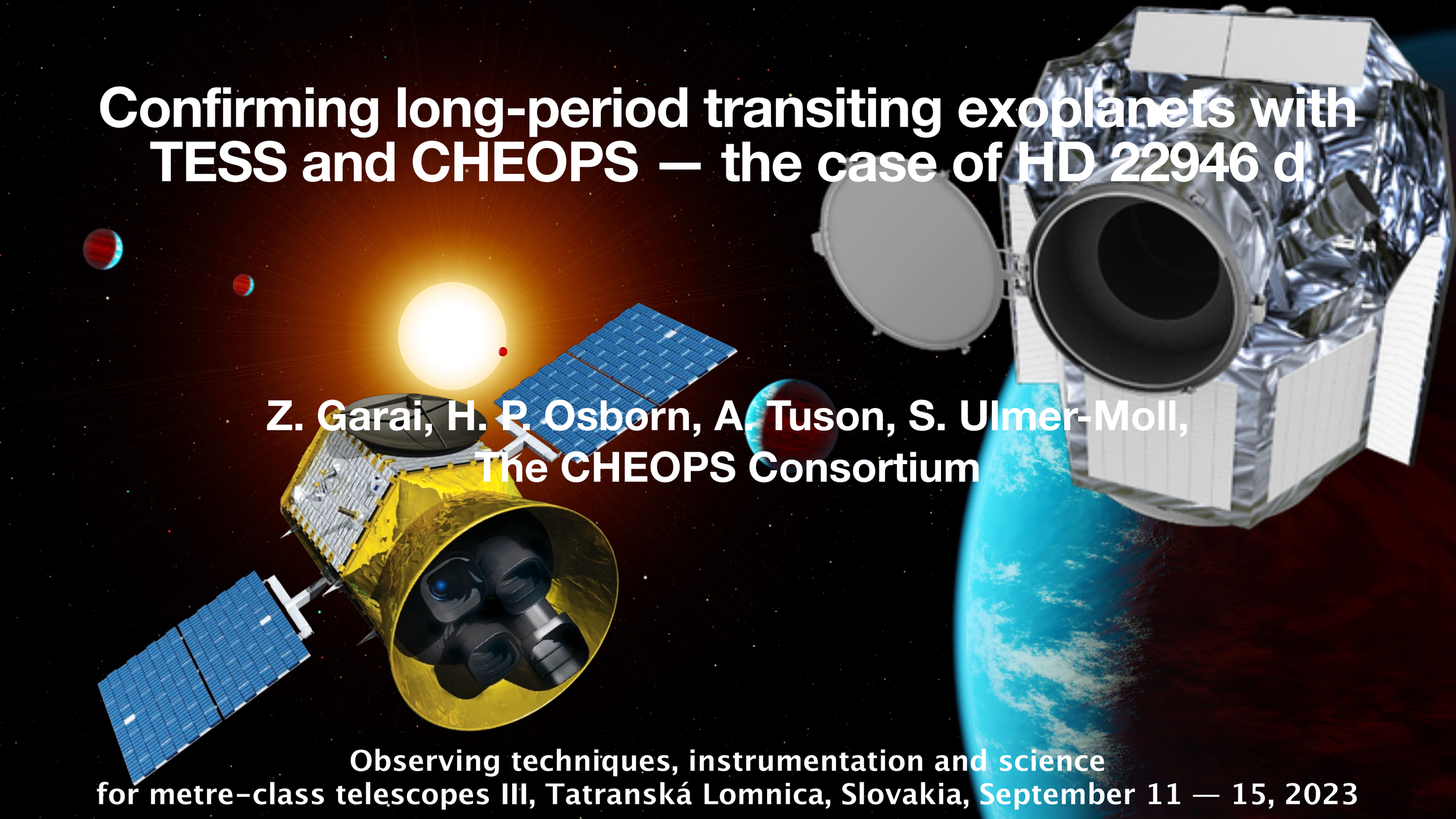
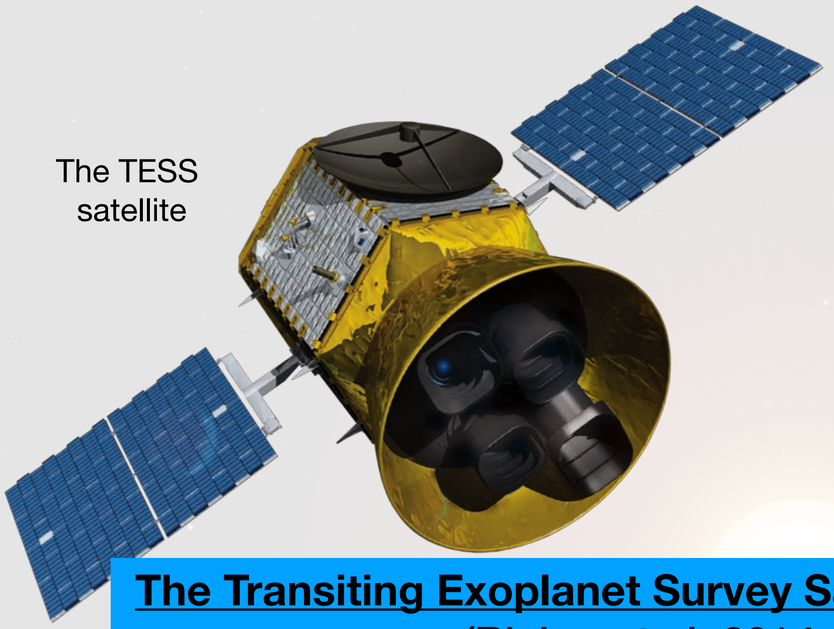
Confirming long-period transiting exoplanets with TESS and CHEOPS — the case of HD 22946 d

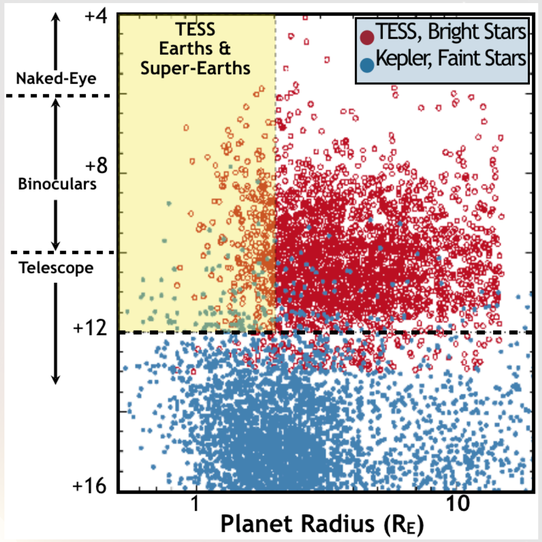


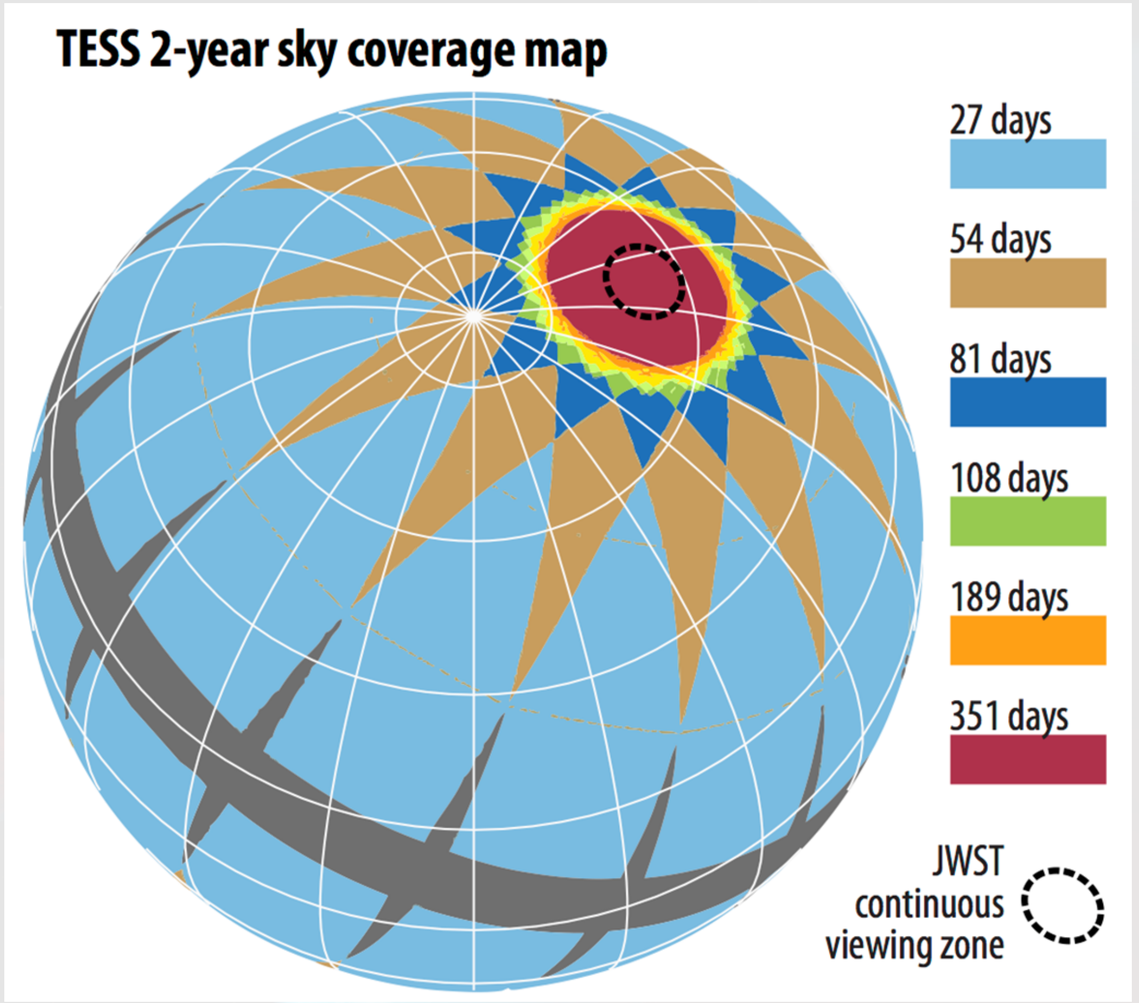
Z. Garai, H. P. Osborn, A. Tuson, S. Ulmer-Moll,
The CHEOPS Consortium

Observing techniques, instrumentation and science
for metre-class telescopes III, Tatranská Lomnica, Slovakia, September 11 — 15, 2023

The TESS satellite

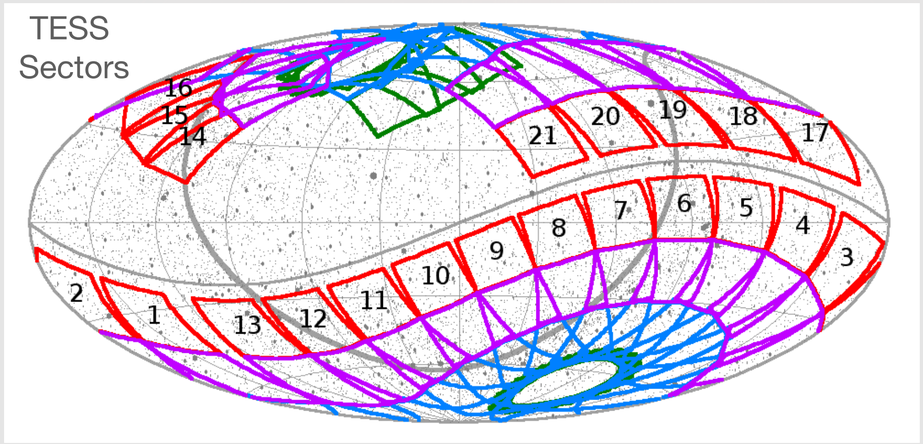






The Transiting Exoplanet Survey Satellite (TESS) mission (Ricker et al. 2014, 2015):

- discoveries: 383 confirmed exoplanets, and 6788 planet candidates (up to August 22, 2023),
- targets: bright stars, brighter than *T* (TESS) = 13 mag, + RV measurements — true masses of the exoplanets,
- observing strategy: this is an all-sky survey in sectors (24 x 96 deg), the sectors are monitored for at least 27 days.



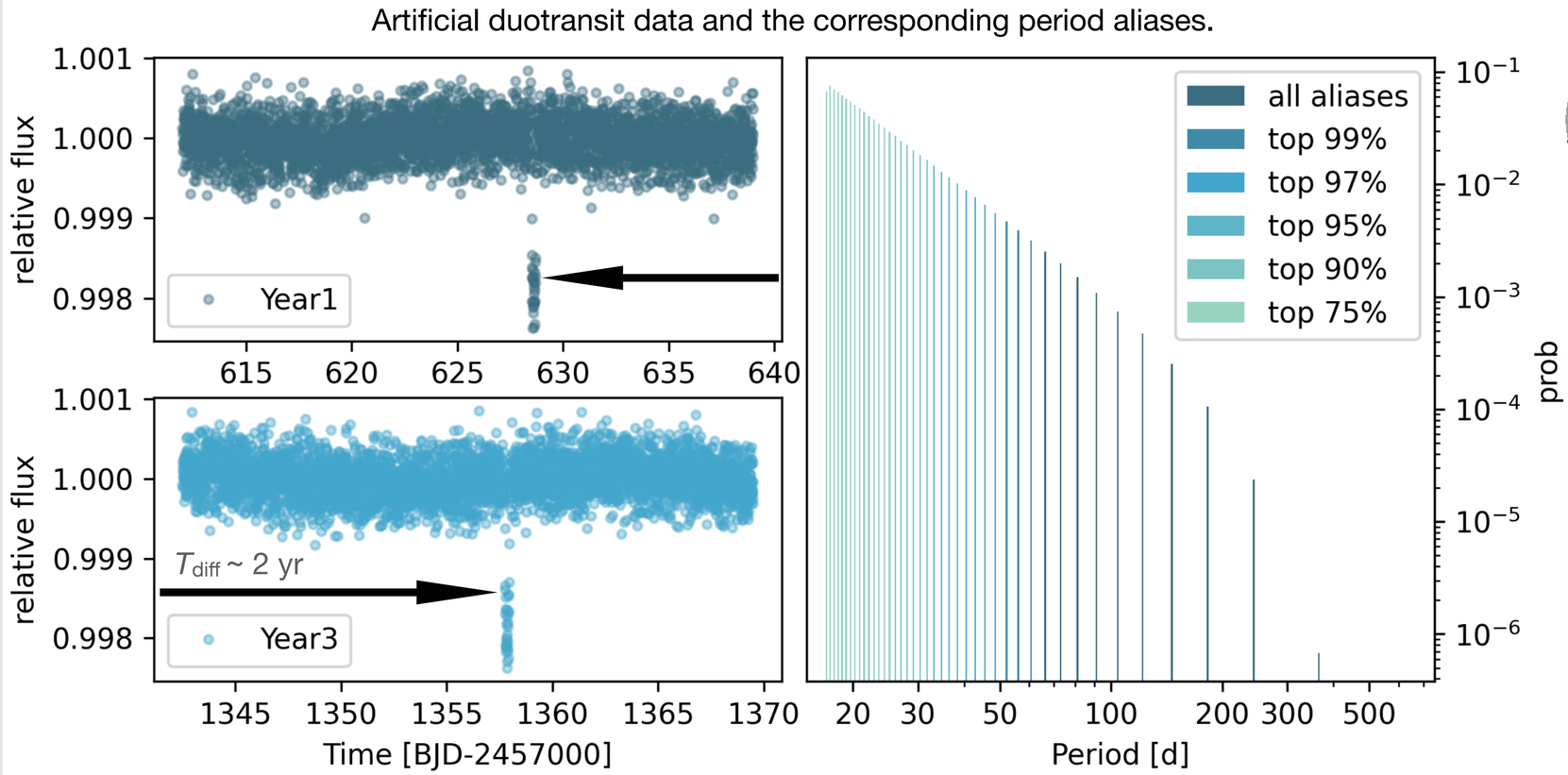
Detecting exoplanets with TESS is biased towards short-period planets:

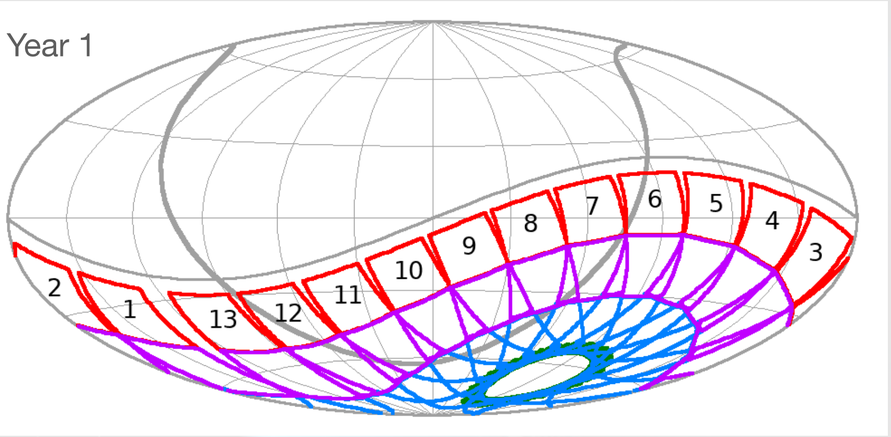
- two-year primary mission: TESS observed the majority of the sky for ~ 27 consecutive days,
- planets with P_{orb} > 27 d would only have been observed to transit once, if at all — "***monotransits***",
- the orbital periods of monotransits are unknown.

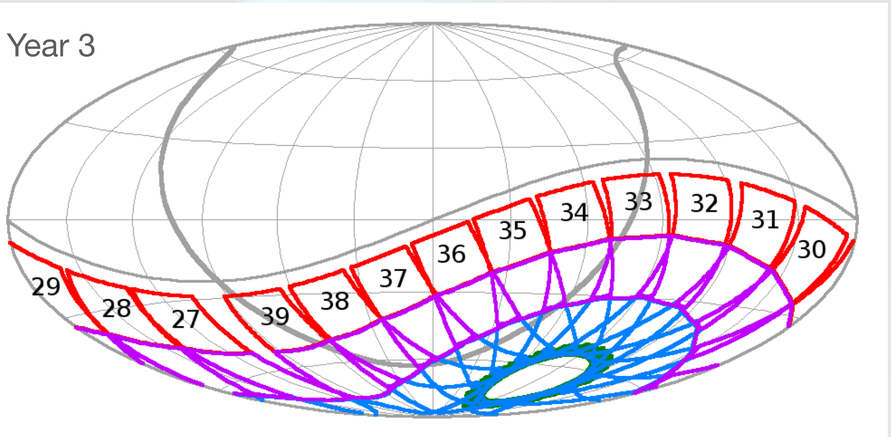
- **Extended mission**: TESS re-observed the same fields 2 yr later — in many cases: a second transit — "*duotransits*" (Osborn et al 2022),
- **duotransits**: **P_{orb} is still unknown, but there now exists a discrete set of allowed period aliases P_n:**

$$P_n = T_{diff}/n,$$

where T_{diff} is the time between the two transit events,
and $n \in \{1, 2, 3 \ldots n_{max}\}$ (n_{max} is determined by the non-detection of a third transit).





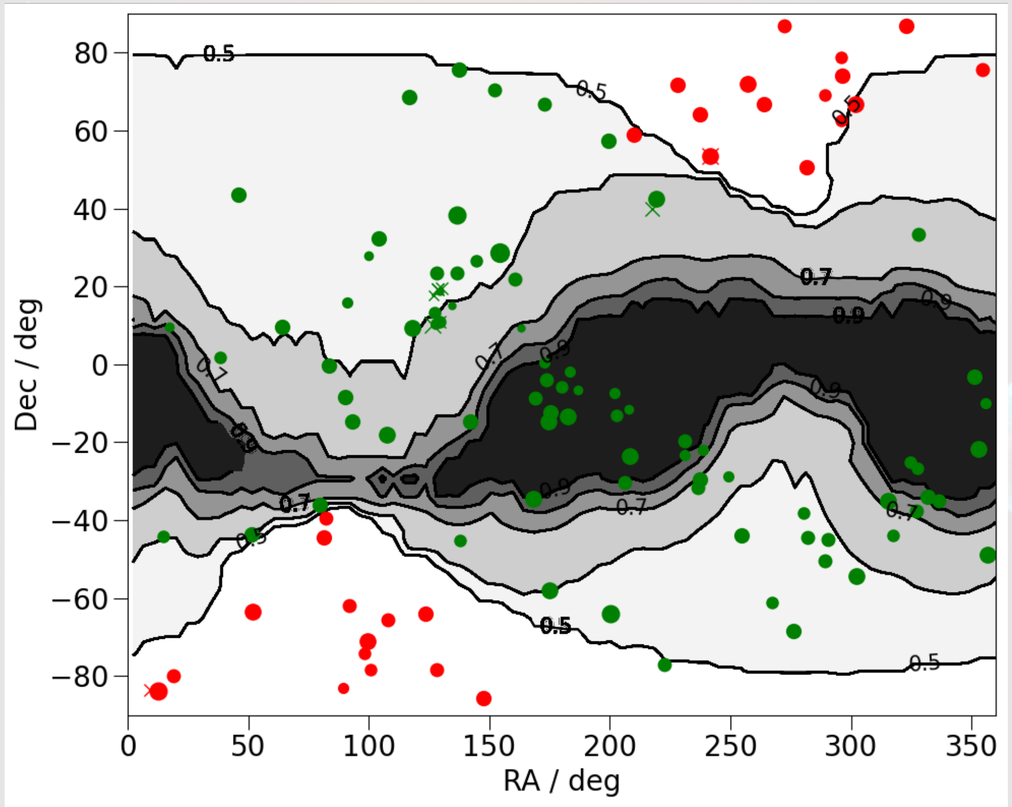


Follow-up of monotransits/duotransits:
follow-up (photometric or spectroscopic) observations of these long-period planets (P_{orb} > 27 d) are required to recover their true P_{orb} and to characterise the planets:

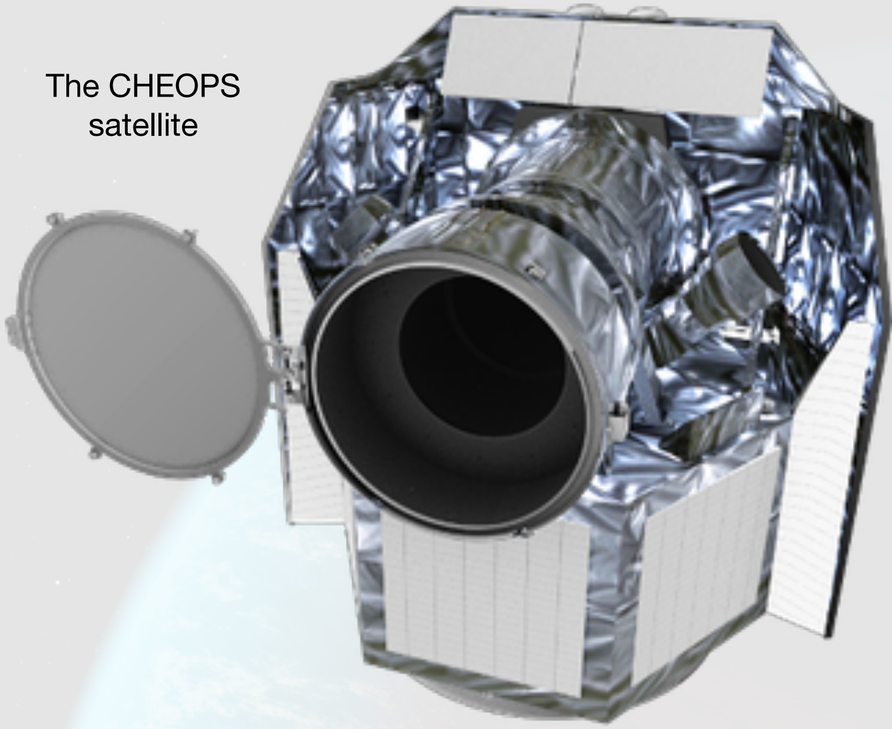
- monotransits — a blind survey approach,
- duotransits — the period aliases allow more targeted observations.

The Duos program:

- Duos is a dedicated CHEOPS Guaranteed Time Observing (GTO) program,
- aims: **to recover the periods of TESS long-period duotransiting planets**, focusing on small planets (*super-Earths, sub-Neptunes*) that cannot be observed from the ground (too shallow /500 - 2500 ppt/ and long /T_{dur} > 6 h/ transits).



The positions of known monotransit and duotransit candidates from TESS and K2 overlaid on the CHEOPS observability map.



The CHEOPS satellite

The Characterising Exoplanet Satellite (CHEOPS)

is an ESA mission (Benz et al. 2021), dedicated to the follow-up of known exoplanets,

- the effective aperture diameter is ~ 30 cm (~ 3x larger than that of TESS /~ 10 cm/), allowing it to achieve higher per-transit *S/N*,
- free pointing ability within the feasible sky area.

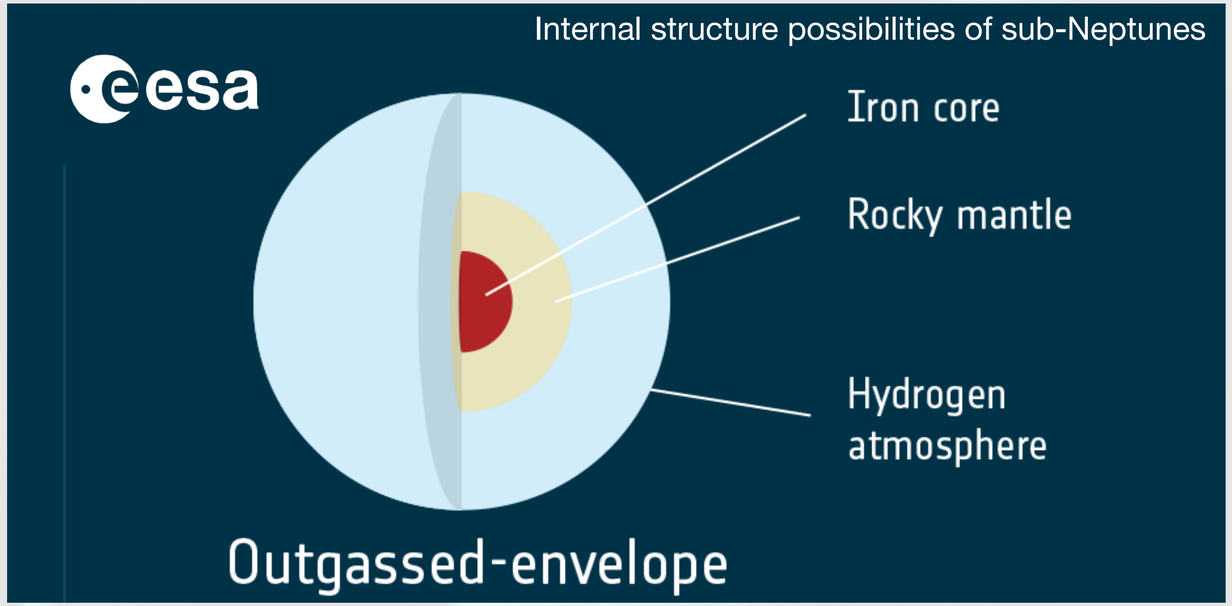
Motivation No. 1: detecting long-period transiting exoplanets is important:

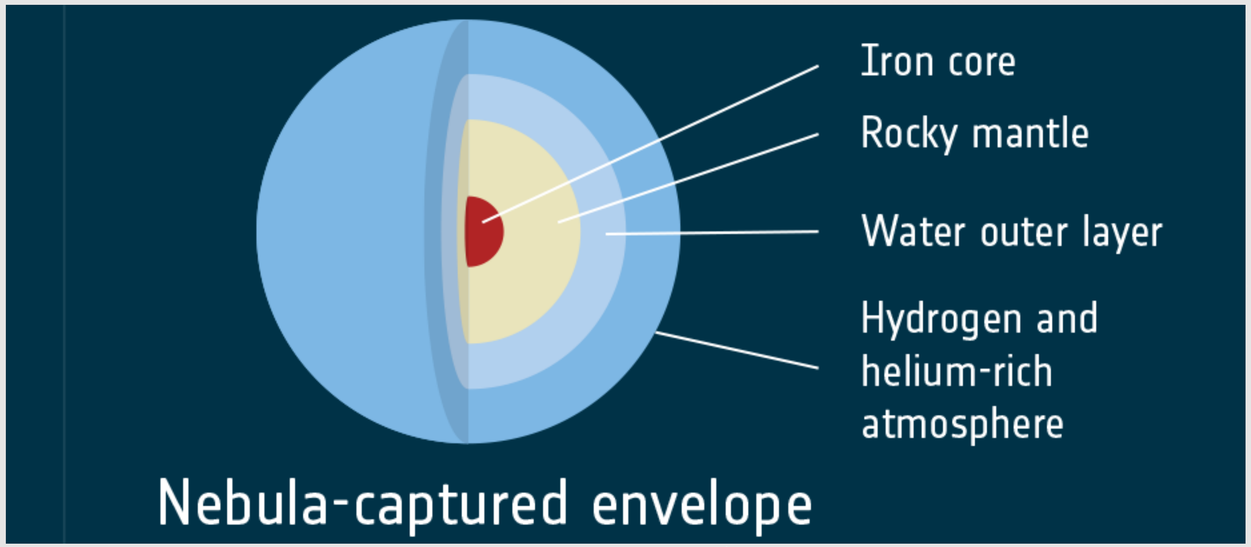
- less affected by radiation — they can retain their *primordial atmospheres* (Owen 2019),
- large Hill spheres — they can have stable *moon or ring systems* (Dobos et al. 2021).

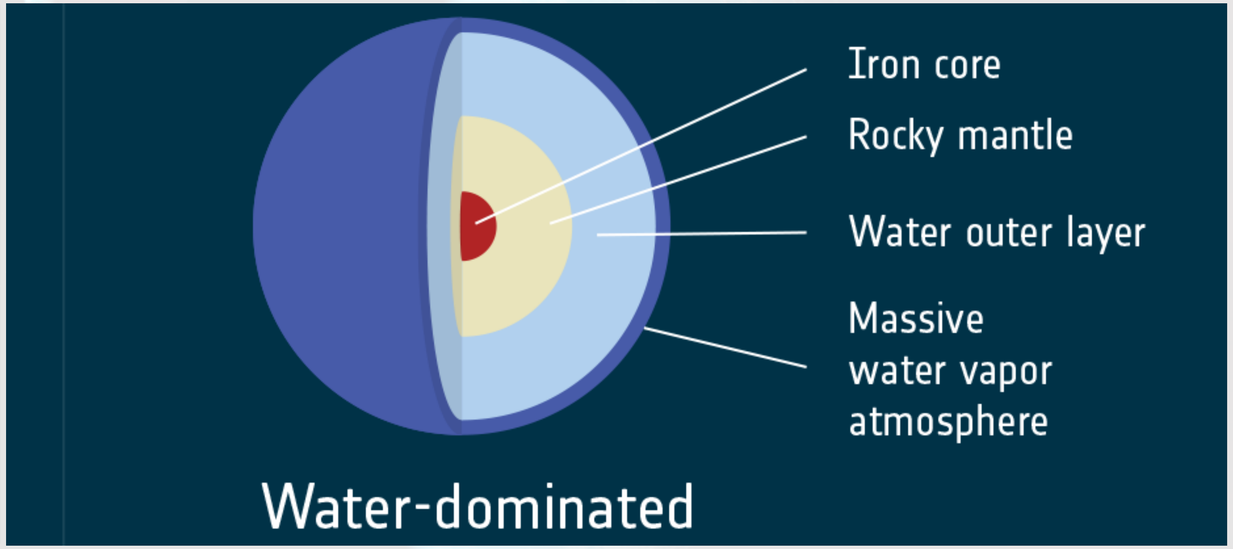
Motivation No. 2: ***warm sub-Neptunes*** **(T_{eq} < 700 K) transiting bright stars (T < 13 mag) are particularly interesting targets for detailed characterisation studies**:

- masses (RV) + radii (TESS, CHEOPS) = bulk density — internal composition,
- spectroscopy (JWST, Ariel) — atmospheric composition.

3 predictions: outgassed envelope, nebula-captured envelope, water-dominated envelope — different envelopes = different formation mechanisms. **This can help distinguish between different formation mechanisms**.

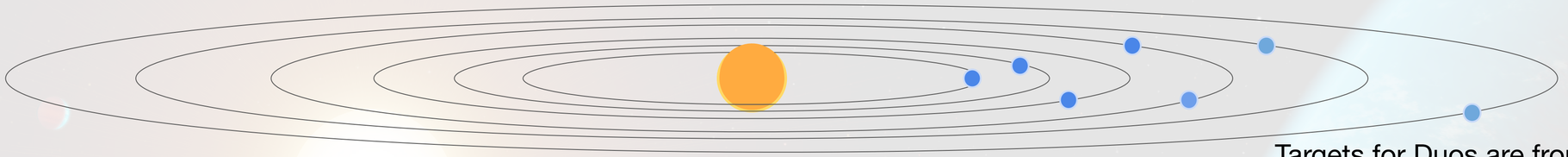






Target selection criteria:

1. "*golden targets*" suitable for future characterisation observations (JWST, Ariel),
2. good CHEOPS visibility and relatively bright planets host stars ($V < 11.5$ mag),
3. transit depth $D < 2500$ ppm, in order to not compete with ground-based programs,
4. **targets with $R_p < 10\ R_{Earth}$ from multi-planet systems — very low false positive probability.**



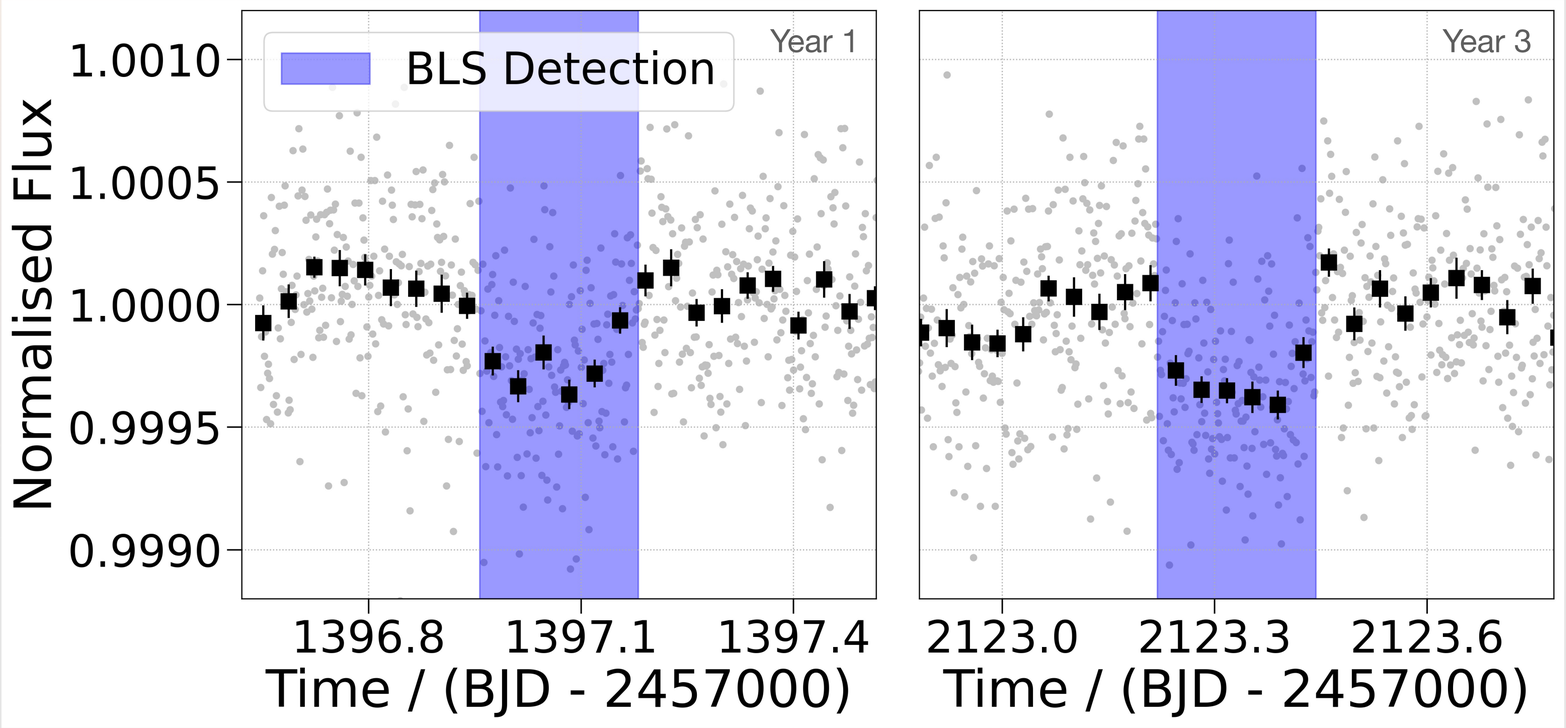
Targets for Duos are from multi-planet systems.

The duotransit pipeline:

(not publicly available; Tuson et al. in prep.)

searches for duotransits in the TESS data:

- input: TESS PDCSAP 2-min LCs or FFI LCs,
- procedure: the pipeline detrends the LCs using a *mean sliding window* and runs a *box least squares* (BLS) transit search (Kovács et al. 2002),
- output: a list of possible duotransit detections.



One of the new TESS duotransits discovered by the pipeline.

The HD 22946 (TOI-411, TIC-100990000) planetary system

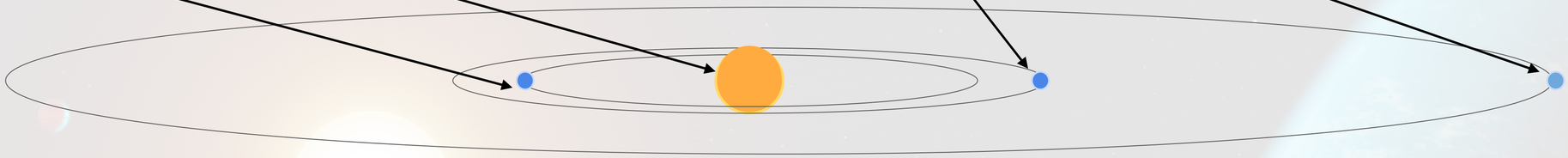
Planet b: a super-Earth, R_p = 1.48 +/- 0.06 R_{Earth}, M_p < 11 M_{Earth}, P_{orb} = 4.0403 d

Host: a late F-type star, G = 8.13 mag

Planet c: a sub-Neptune, R_p = 2.35 +/- 0.08 R_{Earth}, M_p < 14.5 M_{Earth}, P_{orb} = 9.5731 d

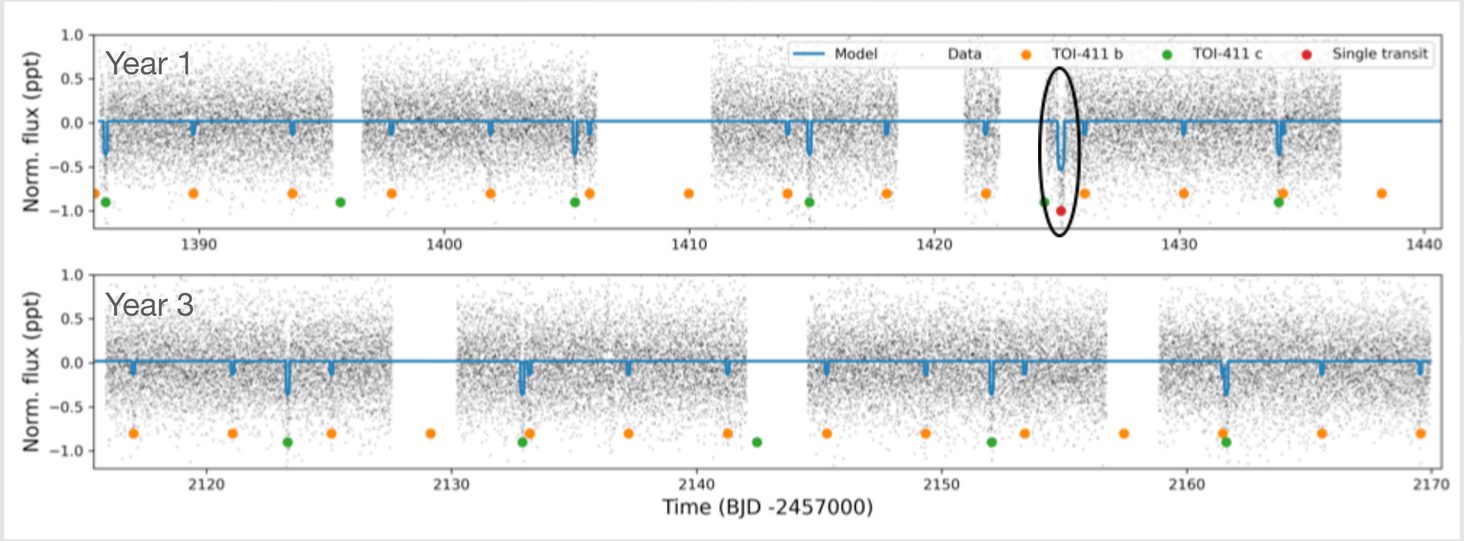
Planet d: a sub-Neptune, R_p = 2.78 +/- 0.13 R_{Earth}, M_p < 24.5 M_{Earth}, P_{orb} = ? d

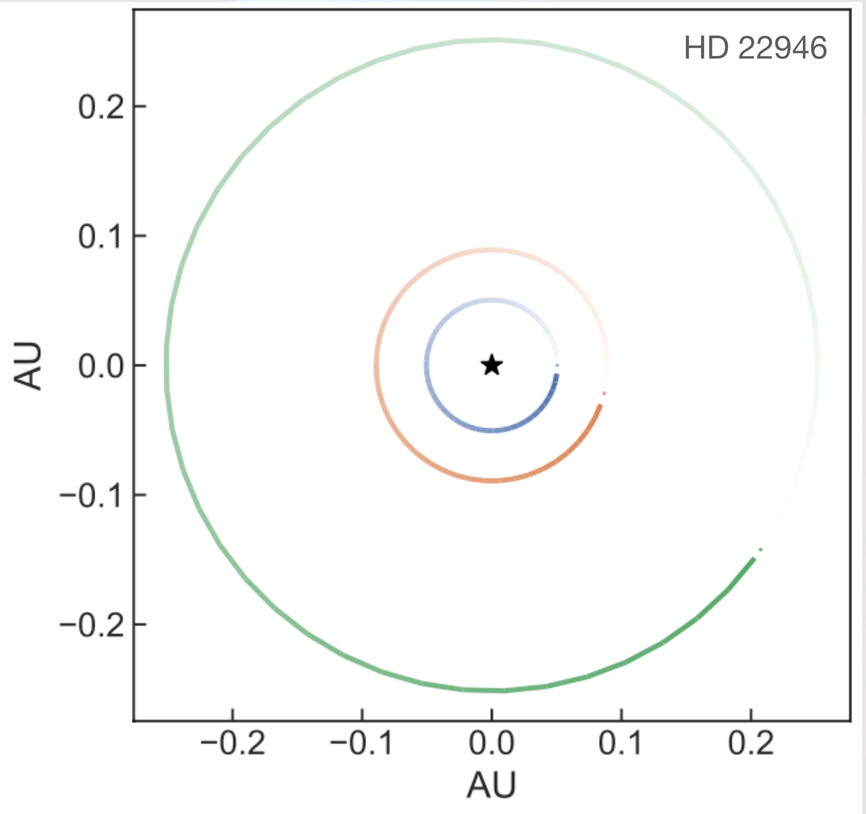
Cacciapuoti et al. (2022)



HD 22946 is a multi-planet system with three transiting planets:

- discovered and validated by Cacciapuoti et al. (2022), based on TESS observations (S3, S4, S30, S31),
- the orbital period of planet d was not found (P_{orb} = 46 +/- 4 d),
- its parameters were determined through a single transit (in TESS S4).

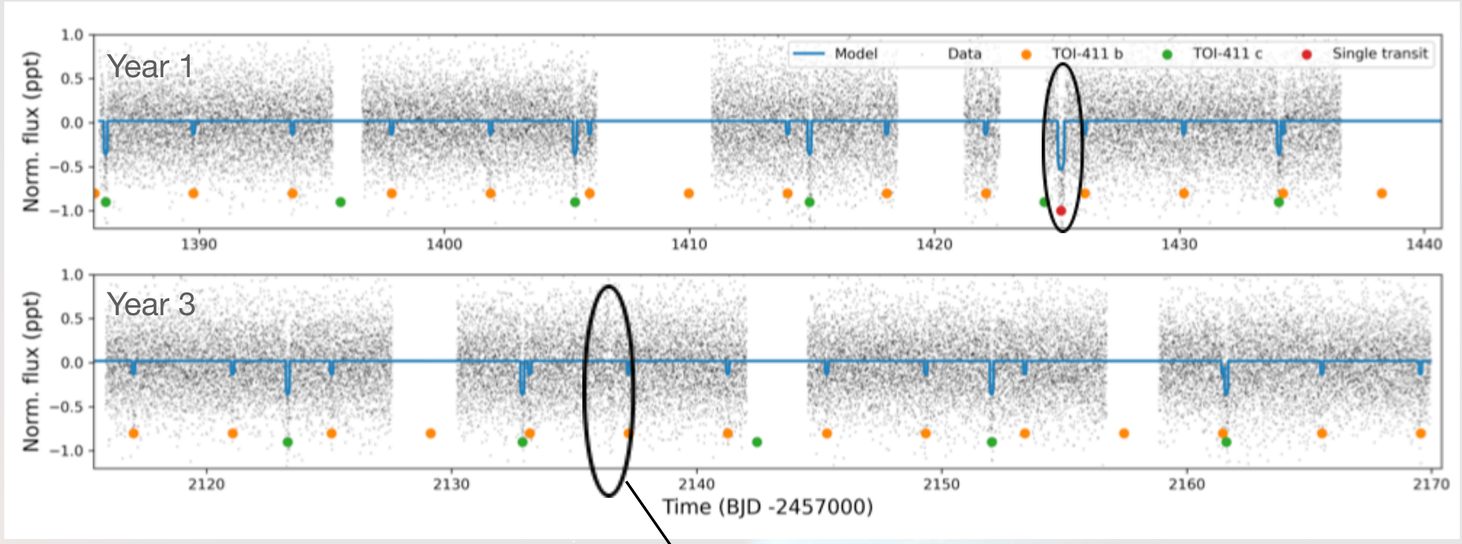




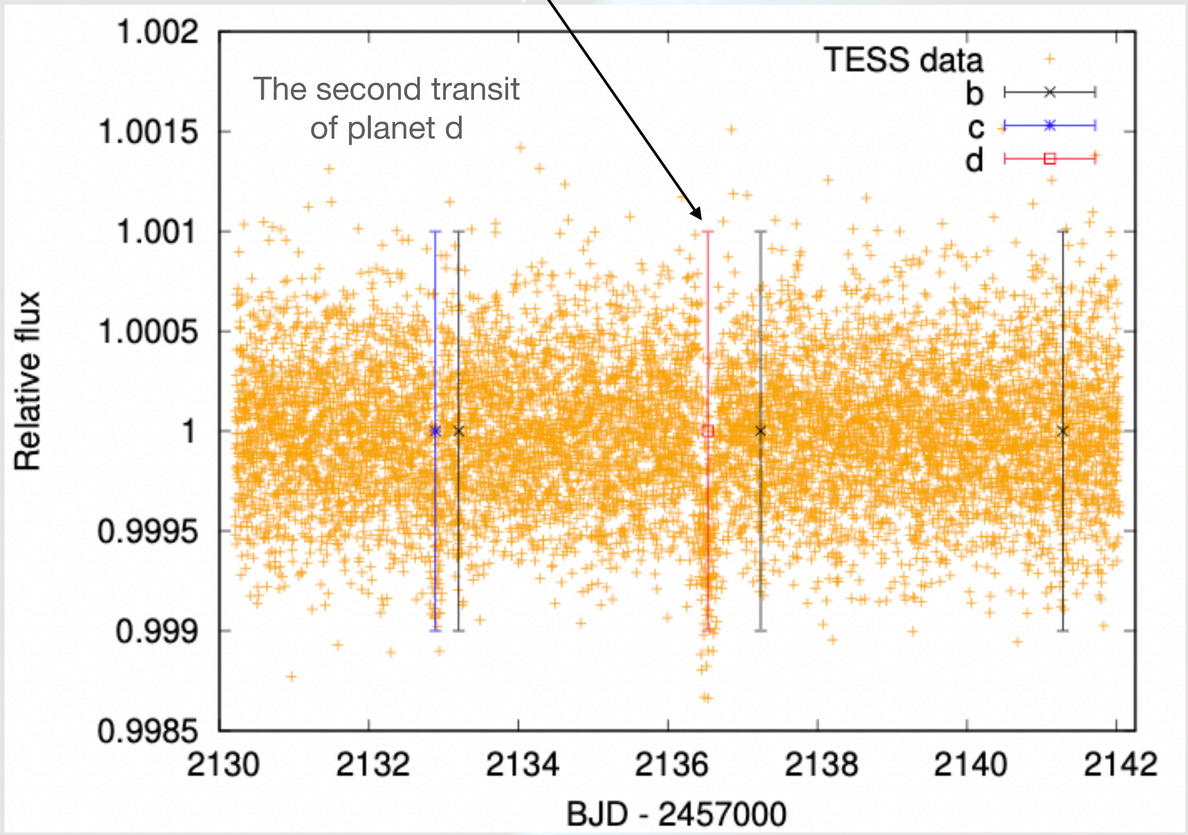
- Cooke et al. (2019, 2021): 65 - 80% of single transits from year 1 will re-transit in year 3:
- **we visually inspected the TESS year 3 data and found a second dip in TESS S30**

with near identical transit depth and duration,

- this 2nd event was excluded by the discoverers from their analysis as an instrumental artifact.



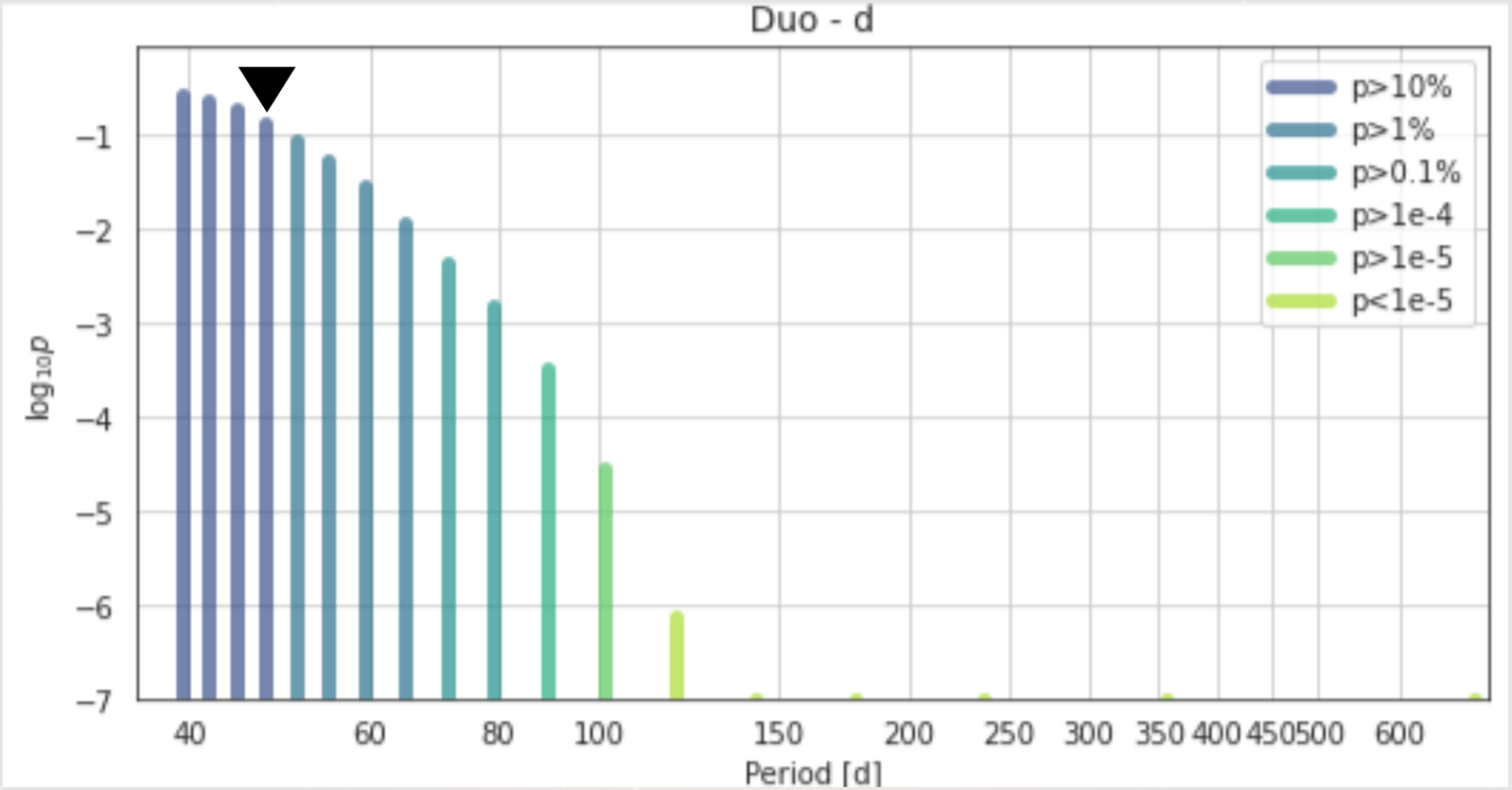
Conclusion: planet d = duotransit – period aliases.



Follow-up observation with CHEOPS is possible:

aims:

1. to uncover the true P_{orb} of planet d with CHEOPS,
2. to refine the parameters of the system with TESS + CHEOPS photometric observations + + spectroscopic observations.



Orbital period aliases of planet d calculated by the MonoTools package from TESS data alone.

Table 5. Orbital period aliases of the planet HD 22946d.

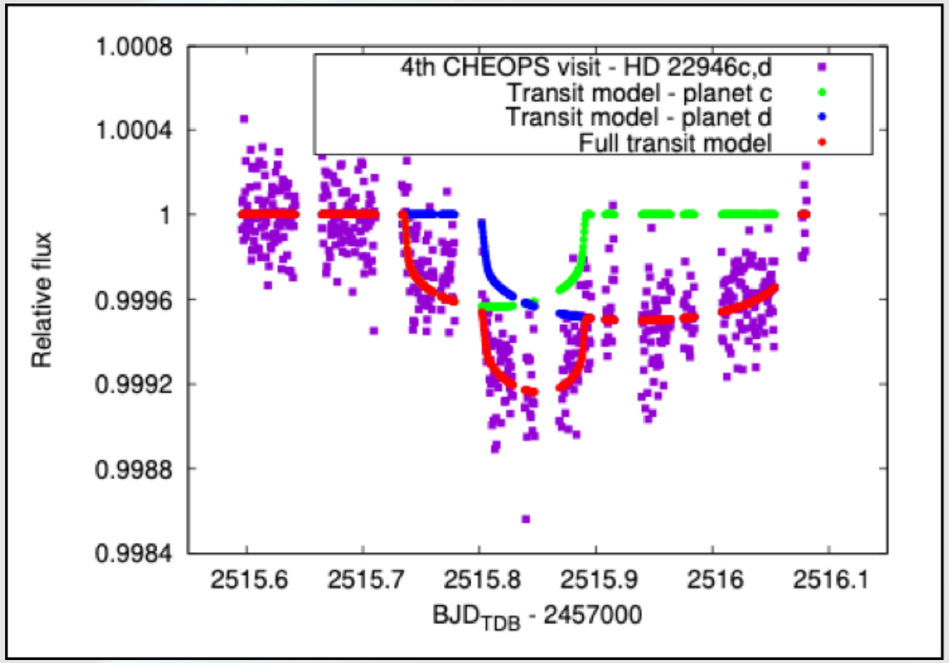
Alias No.	Period alias (P) (days)	Probability (p) (%)
1	39.5206	17.420
~~2~~	~~41.8454~~	~~20.078~~
3	44.4607	20.341
4	47.4248	18.113
5	50.8122	13.445
6	54.7209	7.061
7	59.2809	2.756
8	64.6701	~1.0

Notes. Only the period aliases with a probability of $p > 1\%$ are listed here, as calculated by the `MonoTools` package from TESS data alone, i.e. before CHEOPS observations.

Period aliases from the TESS data and CHEOPS observations:

- the MonoTools package* (Osborn et al. 2022): 18 period aliases,
- CHEOPS observation No. 1 of planet d (2021-10-25): no transit detection, but the period alias No. 2 was excluded from the list of aliases,
- CHEOPS observation No. 2 of planet d (2021-10-28): successful transit detection, the period alias No. 4 was confirmed as the true P_{orb} of planet d.

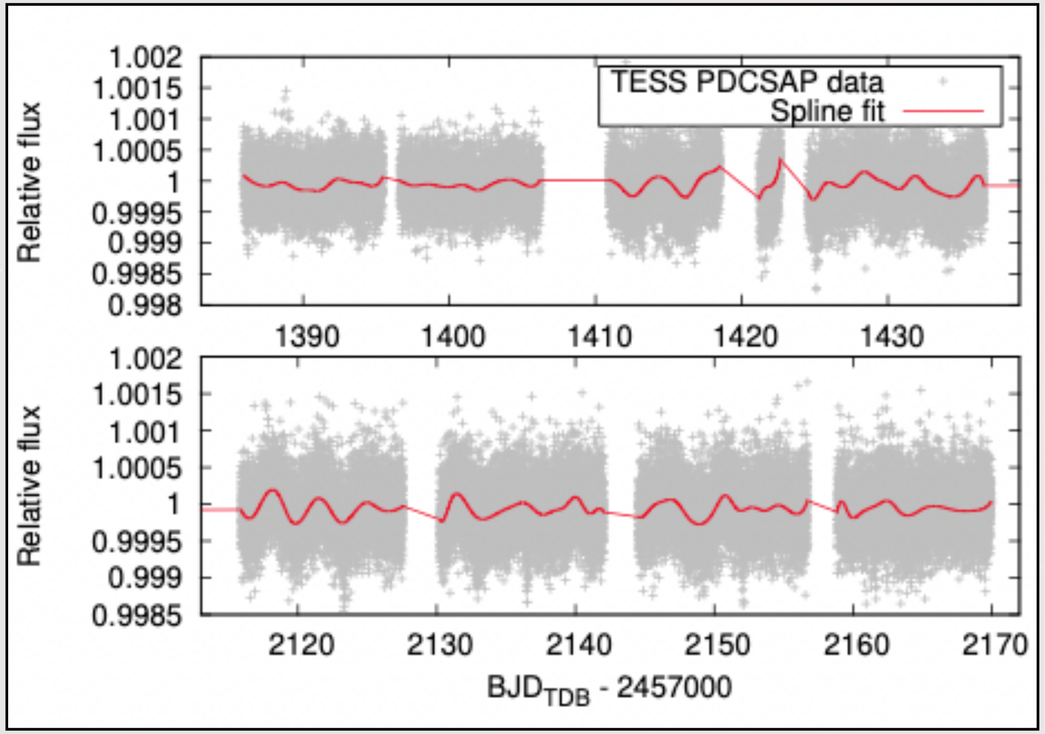
*See: https://github.com/hposborn/MonoTools

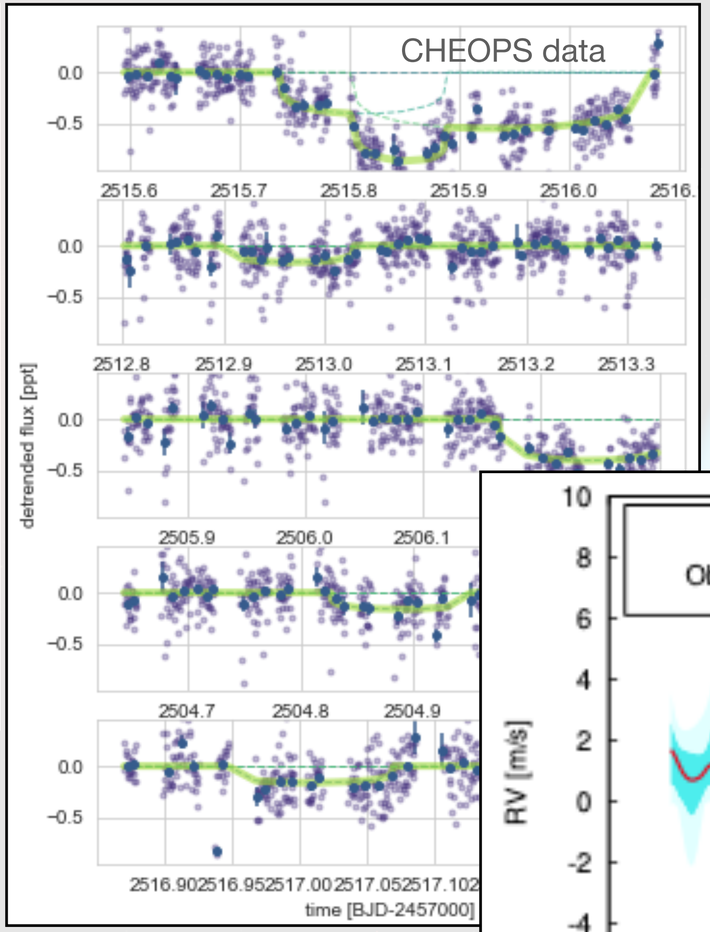


The successful transit detection of planet d with CHEOPS.

Combined analysis:

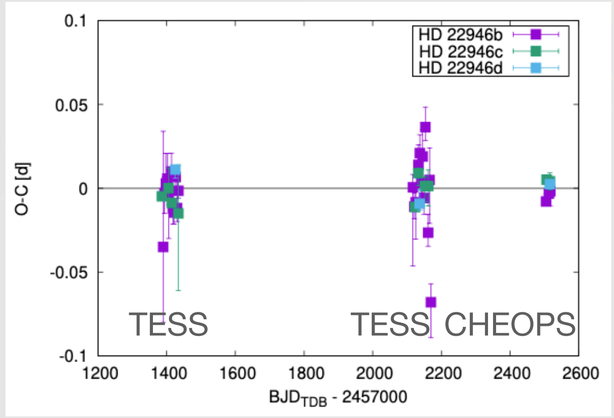
TESS + CHEOPS photometric observations + VLT/ESPRESSO spectroscopic observations (14 RV observations + combined spectrum): the combined model was built using the *PyMC3* (Salvatier et al. 2021) package, with Keplerian orbits modelled with *exoplanet* (Foreman-Mackey et al. 2017) package.



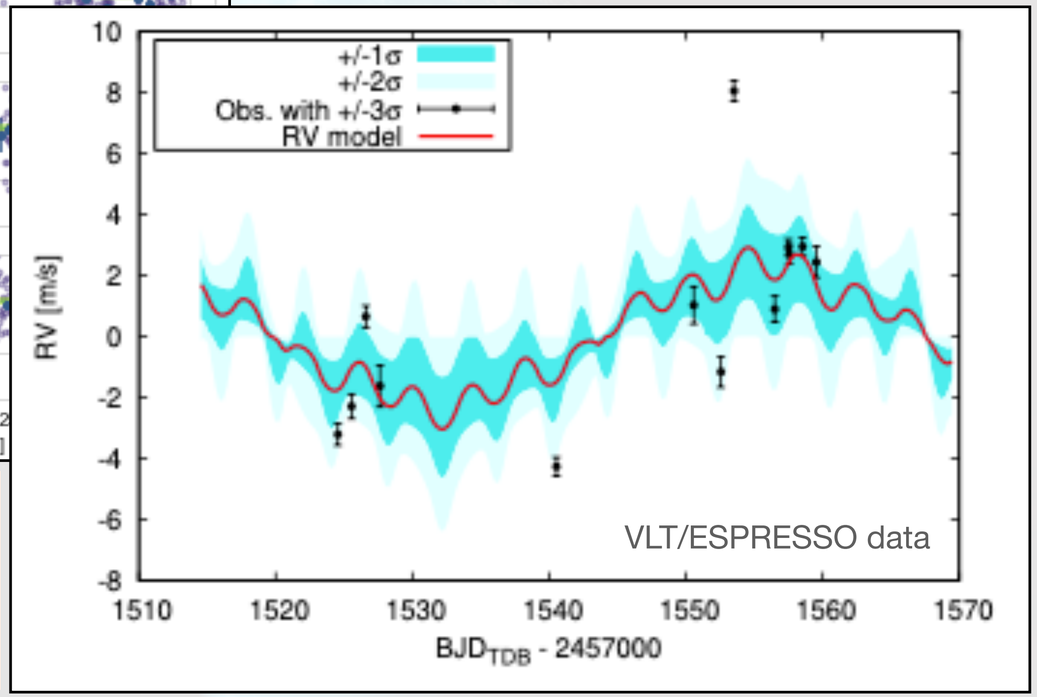


Result No. 1:

- new ephemerides of the planetary orbits,
- the true orbital period of planet d: P_{orb} = 47.42489 +/- 0.00011 d, prediction of the discoverers: P_{orb} = 46 +/- 4 d — confirmed.



Result No. 2:
no significant TTVs are present in the system.



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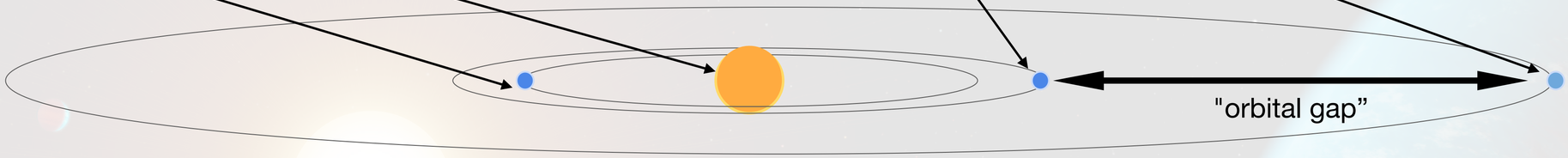
R_p = 1.362 +/- 0.040 R_{Earth}, M_p < 13.71 M_{Earth}, P_{orb} = 4.0403 d

Host: a late F-type star, G = 8.13 mag

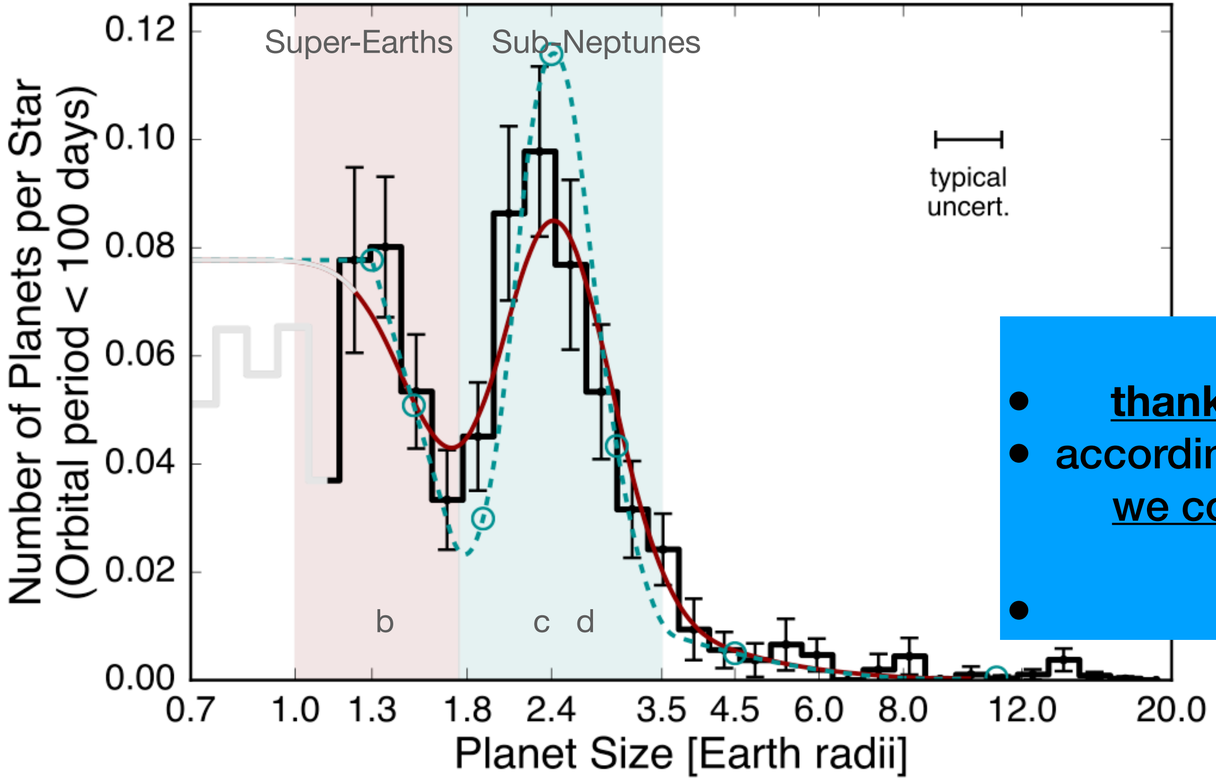
Planet c: a sub-Neptune, R_p = 2.35 +/- 0.08 R_{Earth}, M_p < 14.5 M_{Earth}, P_{orb} = 9.5731 d
R_p = 2.328 +/- 0.039 R_{Earth}, M_p < 9.72 M_{Earth}, P_{orb} = 9.5731 d

Planet d: a sub-Neptune, R_p = 2.78 +/- 0.13 R_{Earth}, M_p < 24.5 M_{Earth}, P_{orb} = ? d
R_p = 2.607 +/- 0.060 R_{Earth}, M_p < 26.57 M_{Earth}, P_{orb} = 47.4249 d

Cacciapuoti et al. (2022)
Garai et al. (2023)



The radius valley (Fulton et al. 2017)



Result No. 3:

- the improved ratios of the orbital periods are: $P_{orb,c}/P_{orb,b}$ = 2.37, and $P_{orb,d}/P_{orb,c}$ = 4.95,
- **the seemingly large orbital gap between planets c and d is not anomalous — falls into statistics** (based on the *Kepler* database; Steffen & Hwang 2015).

Result No. 4:

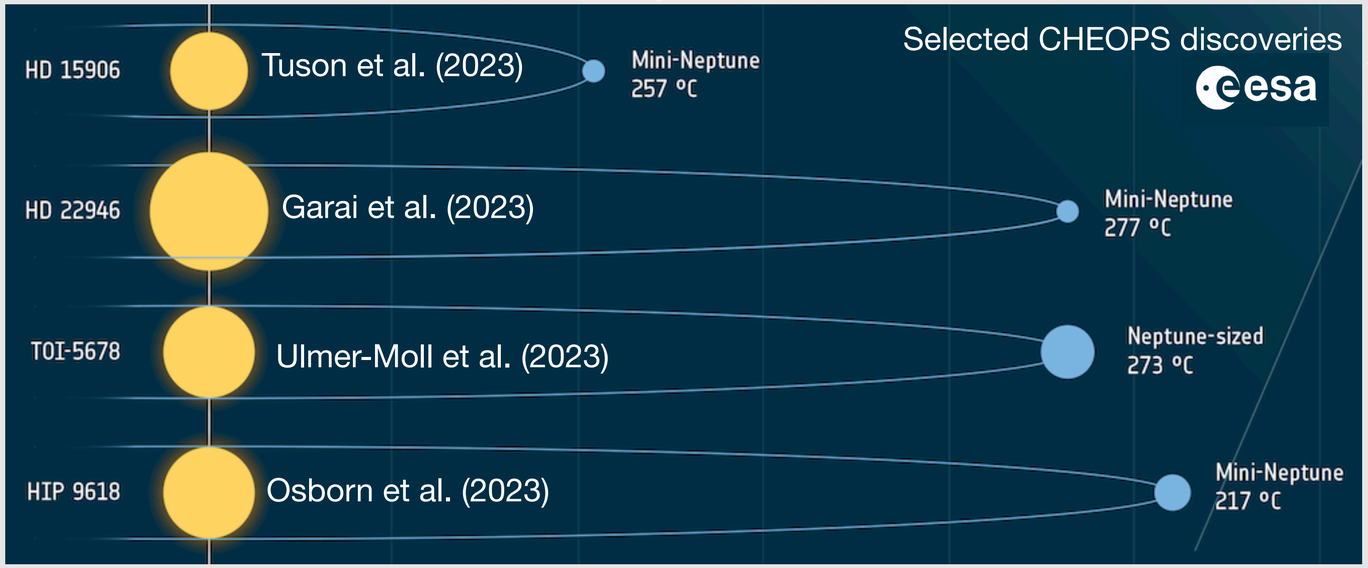
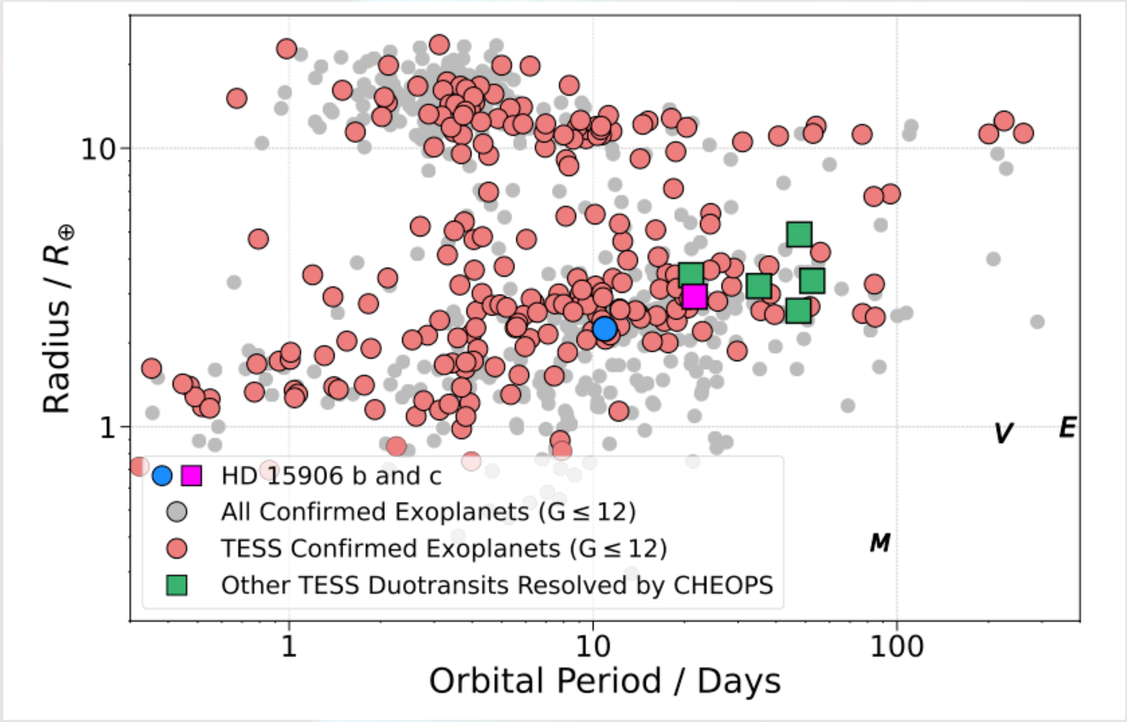
- **thanks to the CHEOPS observations: precise radii of the planets,**
- according to the radius valley at ~ 1.5 - 2.0 R_{Earth} (e.g. Fulton et al. 2017): **we confirmed that planet b is a super-Earth, and planets c and d are sub-Neptunes,**
- new 3-sigma upper limits for the planet masses.

Conclusions:

- Only ~ 14% of planets confirmed by TESS have periods longer than 20 d.

CHEOPS can be used to follow-up TESS duotransits to expand the sample of long-period planets.

- **Through the CHEOPS GTO Duos program we have contributed to the discovery of 6 planets** (see Osborn et al. 2022, 2023; Tuson et al. 2023; Ulmer-Moll et al. 2023; Garai et al. 2023) **with periods longer than 20 d**, radii smaller than 5 R_{Earth}, and host stars brighter than G = 12 mag. There are only ~ 18 other planets confirmed by TESS in this parameter space.

- **HD 22946 d is a warm sub-Neptune**. There are only a few similar confirmed exoplanets to date. **Such objects are worth investigating in the future**: atmosphere, composition, internal structure…

Thank you for your attention!