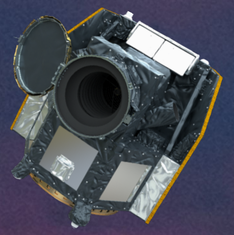


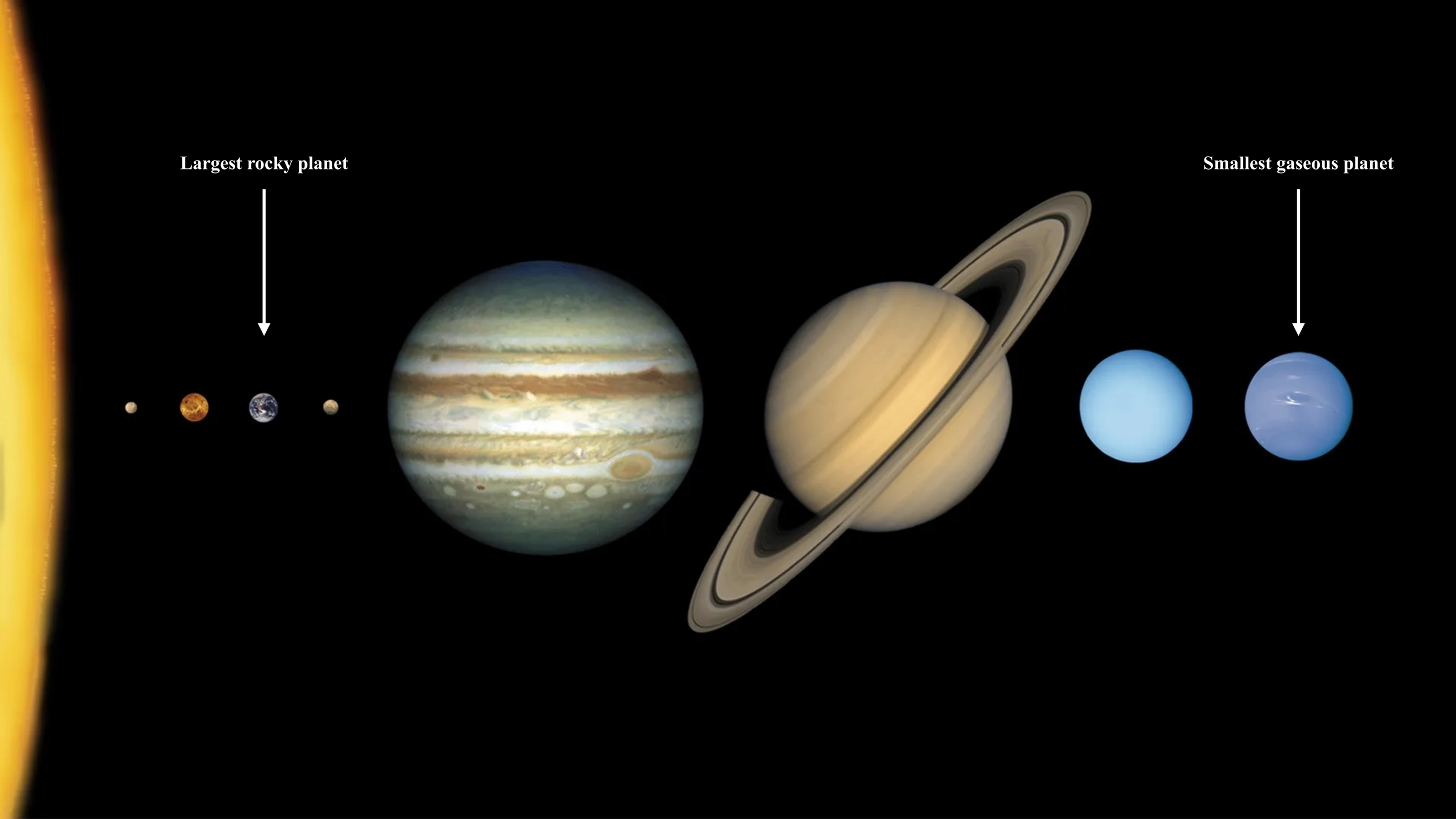
Oxford seminar
September 23, 2024

CHEOPS, HARPS-N

And dynamical considerations to advance our understanding of small planets

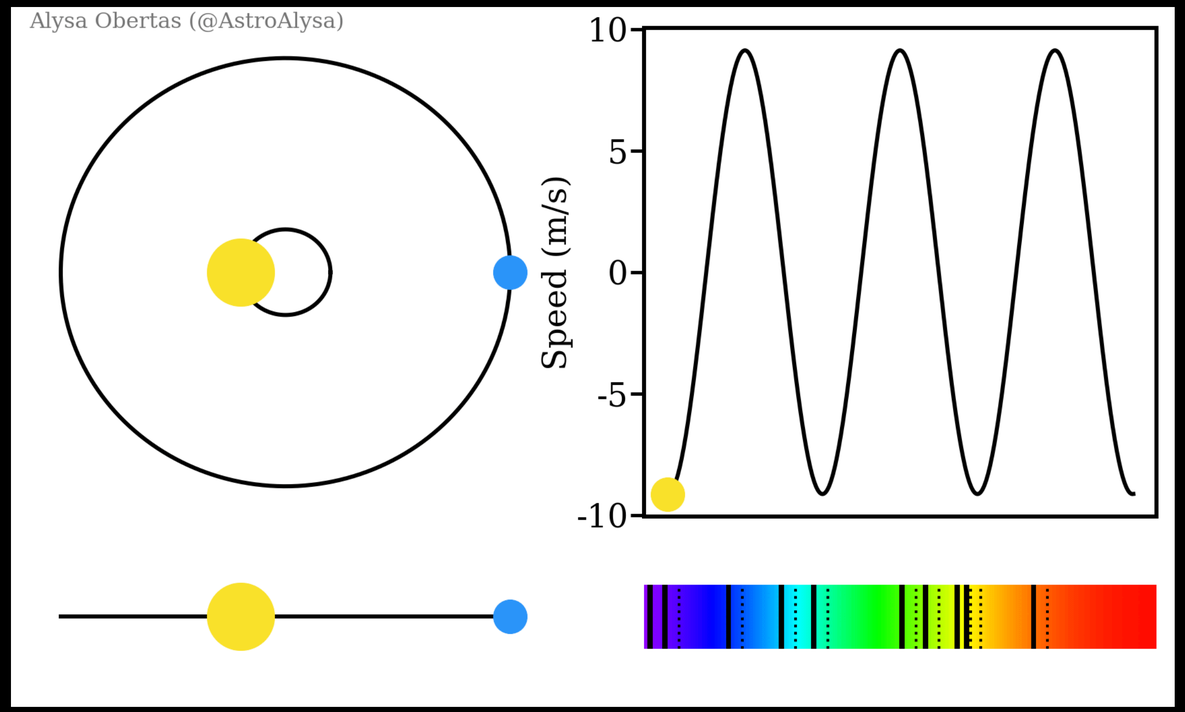
Manu Stalport
Postdoc at the University of Liège

LIÈGE université


Largest rocky planet
Smallest gaseous planet

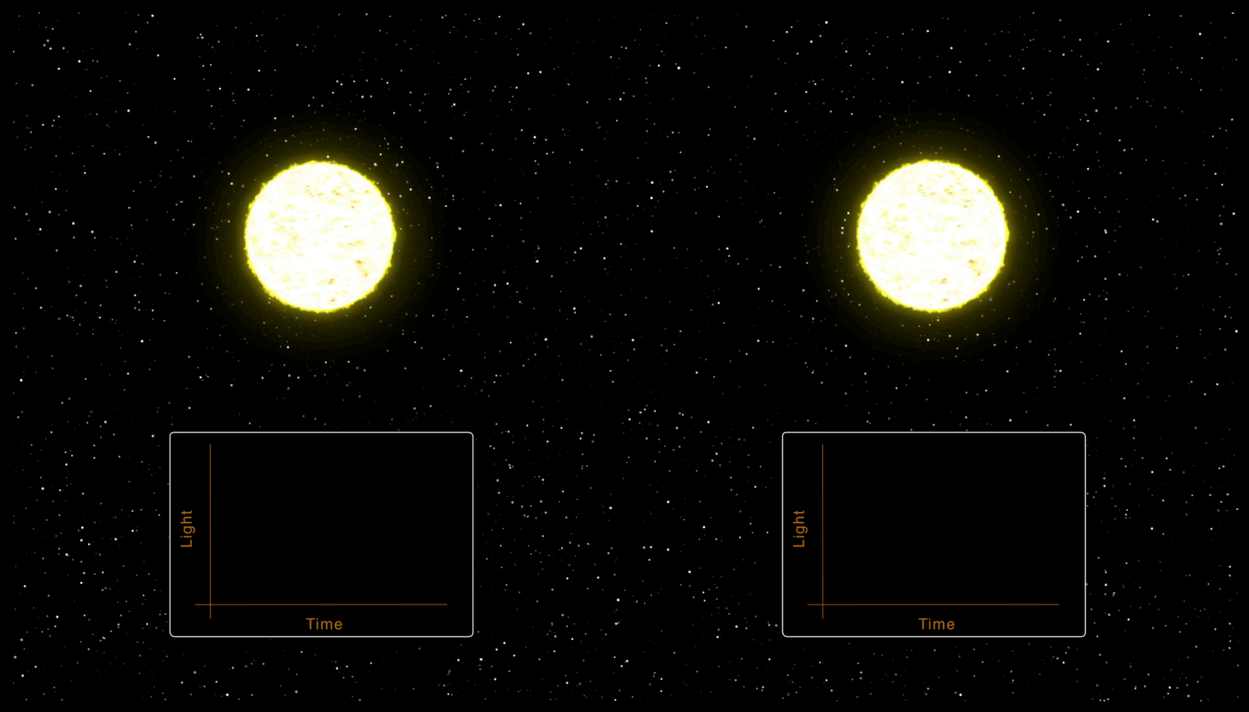
The 2 main techniques of planet detection

The Radial Velocity technique



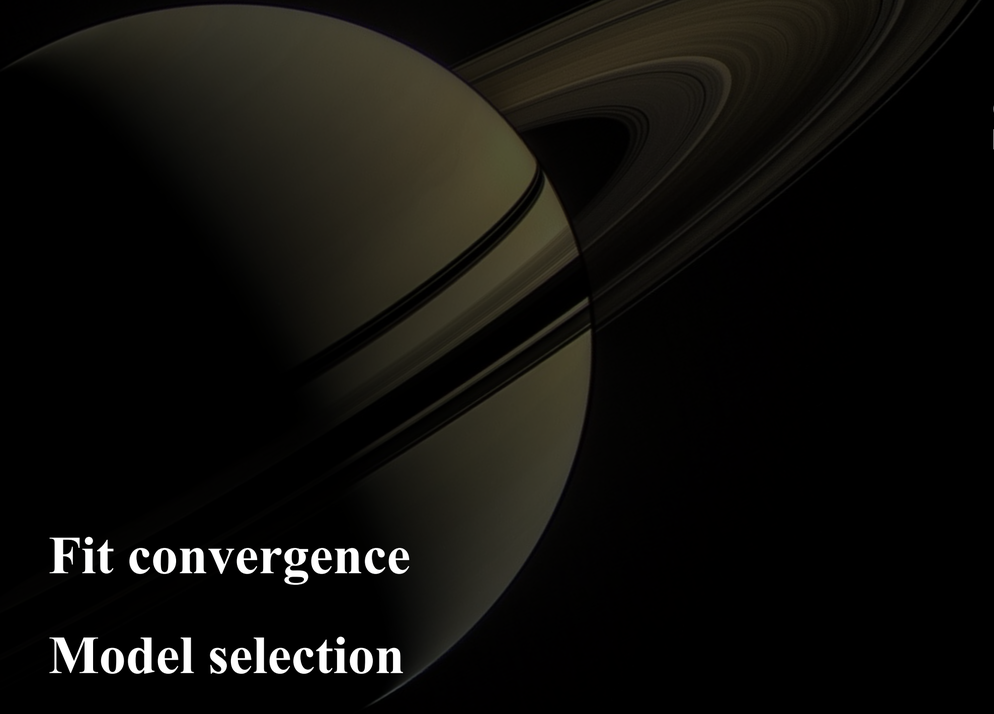
Sensitive to the planetary mass

The transits technique



Sensitive to the planetary radius

Stability analyses

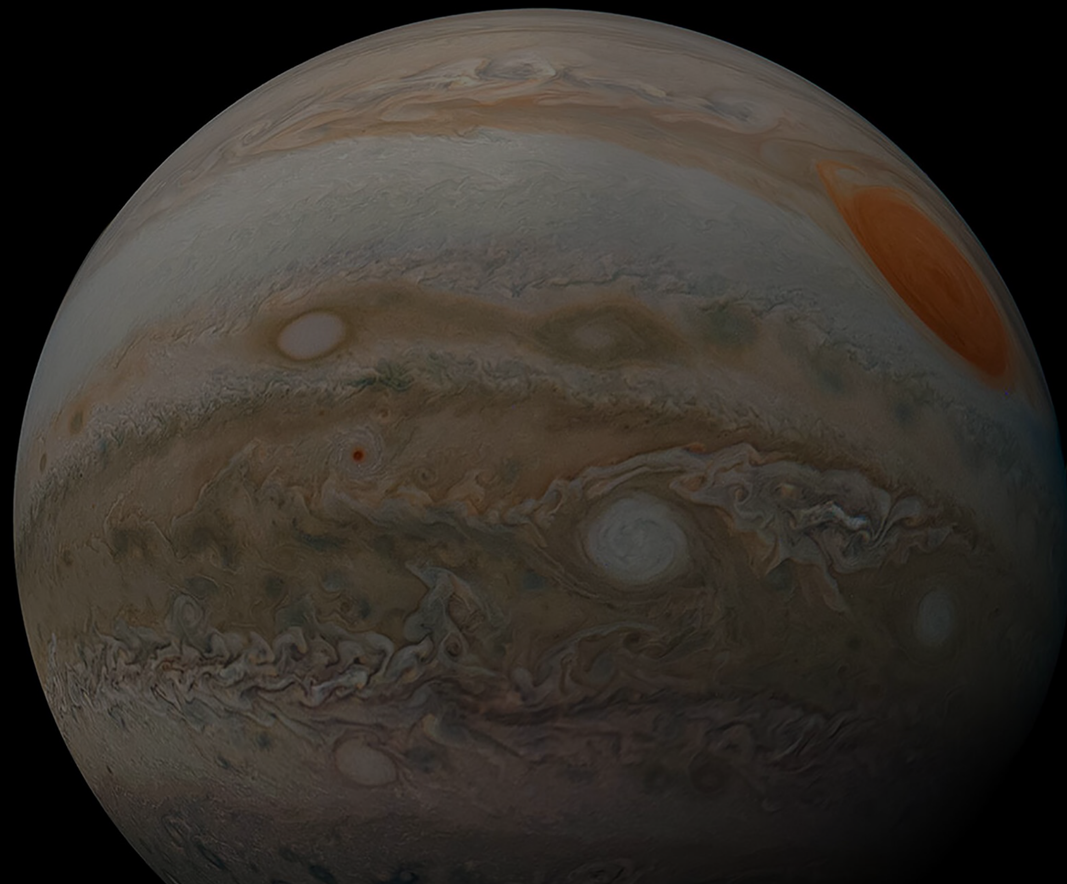


Fit convergence

Model selection

Refine the planet parameters

Investigate mean-motion resonances



Stability analyses

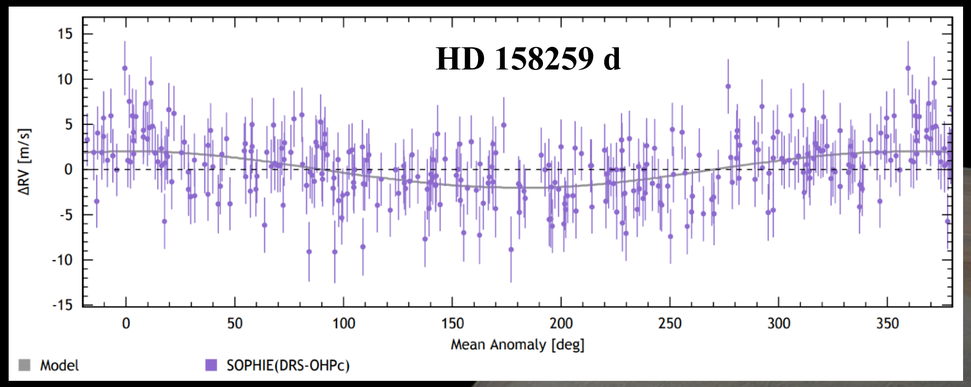
Fit convergence

Model selection

Refine the planet parameters

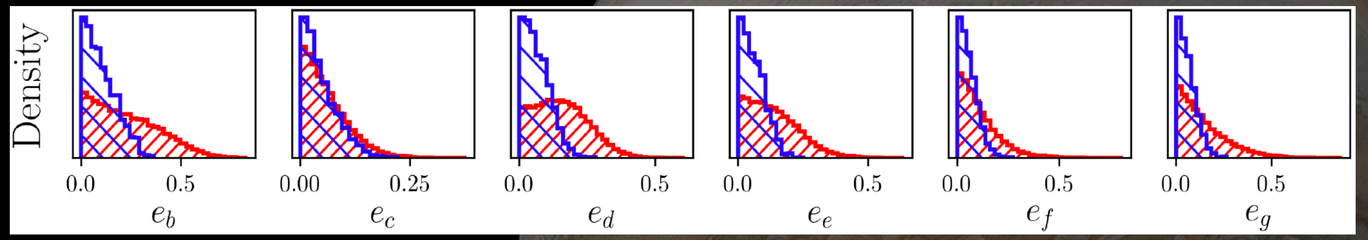
Investigate mean-motion resonances

Small planets = small-amplitude signals



(Hara, et al. 2020)

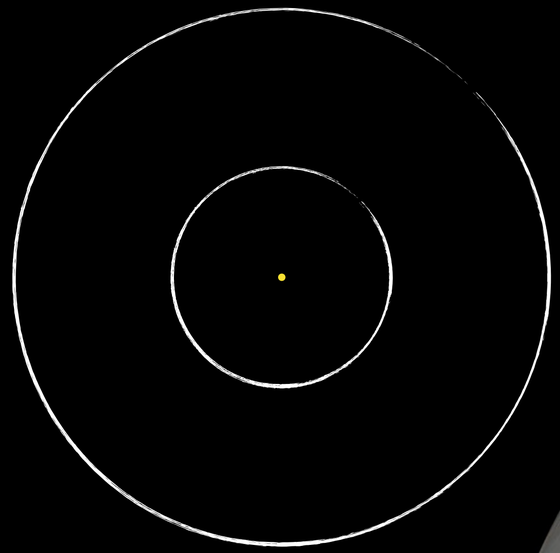
HD 158259
6 planet candidates



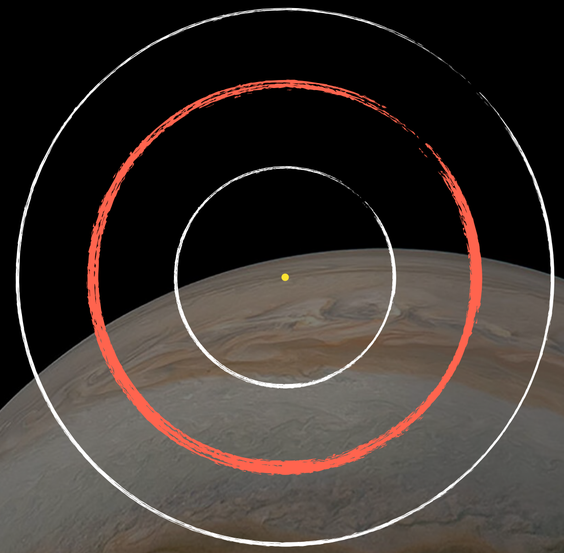
Bayesian framework

Stability analyses

Compare the proportions of stable systems in the posteriors of model 1 vs model 2



Model 1



Model 2

Fit convergence

Model selection

Refine the planet parameters

Investigate mean-motion resonances

Stability analyses

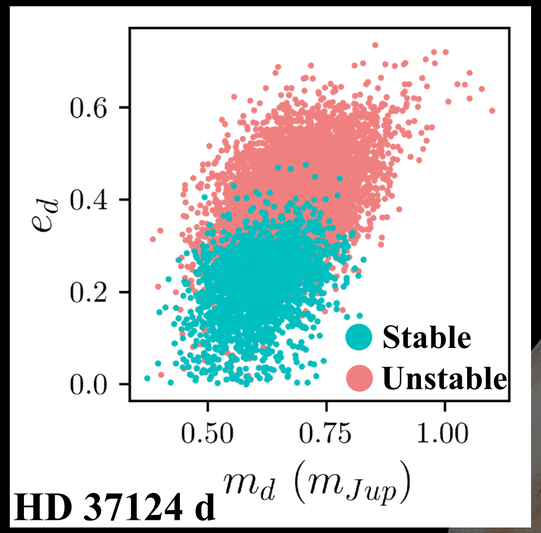
Fit convergence

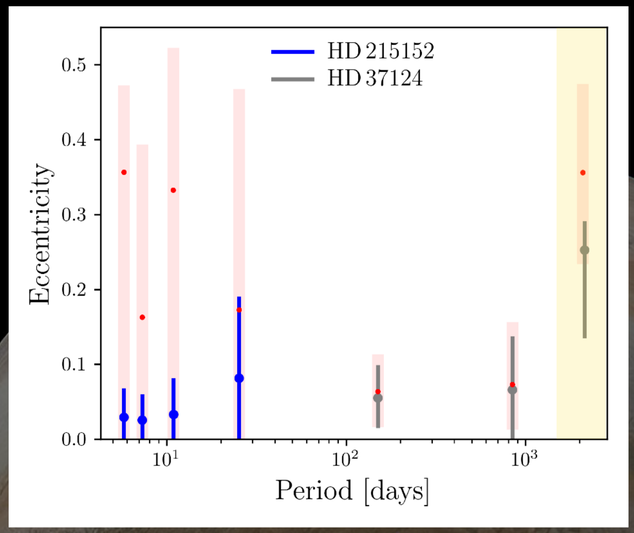
Model selection

Refine the planet parameters

Investigate mean-motion resonances

Stalport, et al. (2022a)





Stability analyses

Inside the MMR: $\frac{P_2}{P_1} \sim \frac{p+q}{p}$ *with* p, q *integers*

Fit convergence

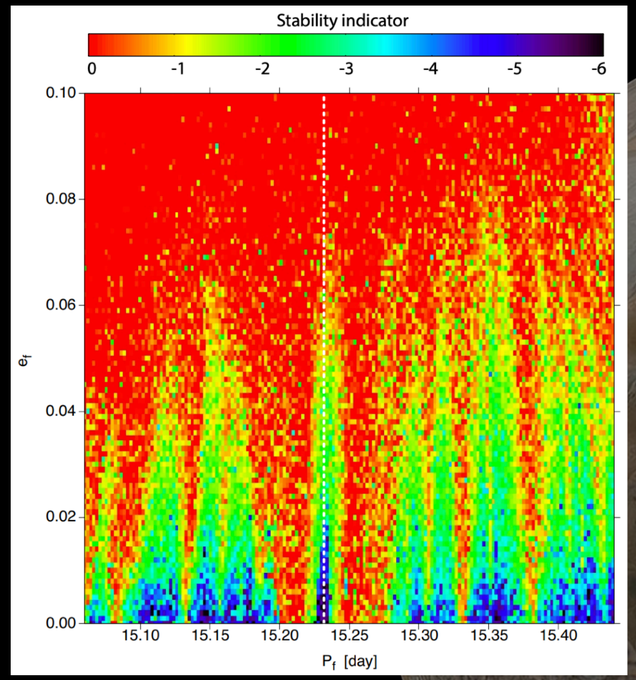
Model selection

Refine the planet parameters

Investigate mean-motion resonances (MMR)

MMR result from the formation processes.
They are direct windows into the past!

TOI-178 (Leleu et al., 2021)



Chaos maps

2D sections of the parameter space

Visualise the MMR

Small planets: a historical perspective

1995 The first exoplanet orbiting a main-sequence star

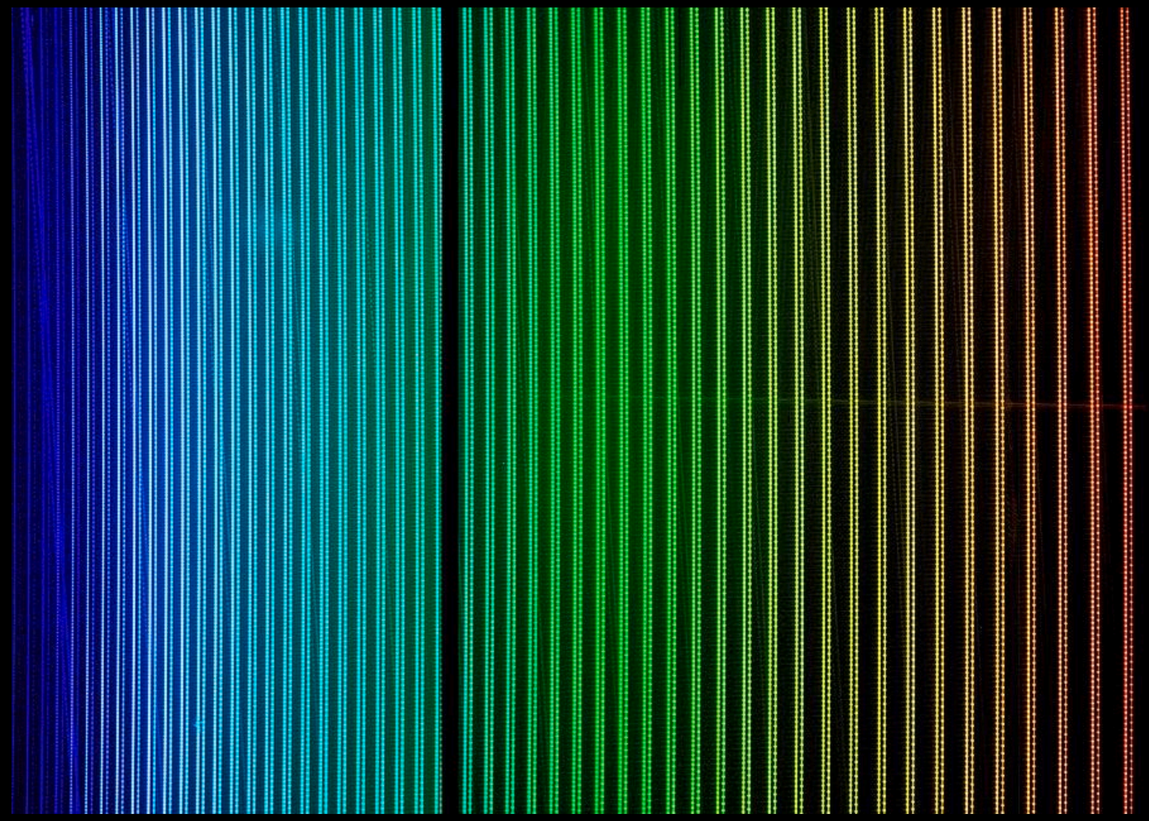
51 Pegasi b

Orbital period = 4.2 days

Mass ~ 0.5 M_J

Small planets: a historical perspective

2003 First light for HARPS!



HARPS

High Accuracy Radial Velocity Planet Searcher

High-resolution spectrograph

Precision ~ 1 m/s

Small planets: a historical perspective

2004 First discovery of an exoplanet less massive than Neptune

A&A 426, L19–L23 (2004)
DOI: 10.1051/0004-6361:200400076

Astronomy & Astrophysics

Letter to the Editor

The HARPS survey for southern extra-solar planets★

II. A 14 Earth-masses exoplanet around μ Arae

N. C. Santos[1,3], F. Bouchy[2], M. Mayor[3], F. Pepe[3], D. Queloz[3], S. Udry[3], C. Lovis[3], M. Bazot[4], W. Benz[5], J.-L. Bertaux[6], G. Lo Curto[7], X. Delfosse[8], C. Mordasini[5], D. Naef[7,3], J.-P. Sivan[2], and S. Vauclair[4]

Mu Area c

2004: detection of a 14 $M_\oplus$ planet

Orbital period = 9.6 days

Small planets: a historical perspective

2009 First indications that small planets are abundant

Transiting Planets
Proceedings IAU Symposium No. 253, 2008
Frédéric Pont, Dimitar Sasselov & Matthews Holman, eds.

doi:10.1017/S1743921308027051

Towards the characterization of the hot Neptune/super-Earth population around nearby bright stars

C. Lovis[1], M. Mayor[1], F. Bouchy[2], F. Pepe[1], D. Queloz[1], S. Udry[1], W. Benz[3] and C. Mordasini[3]

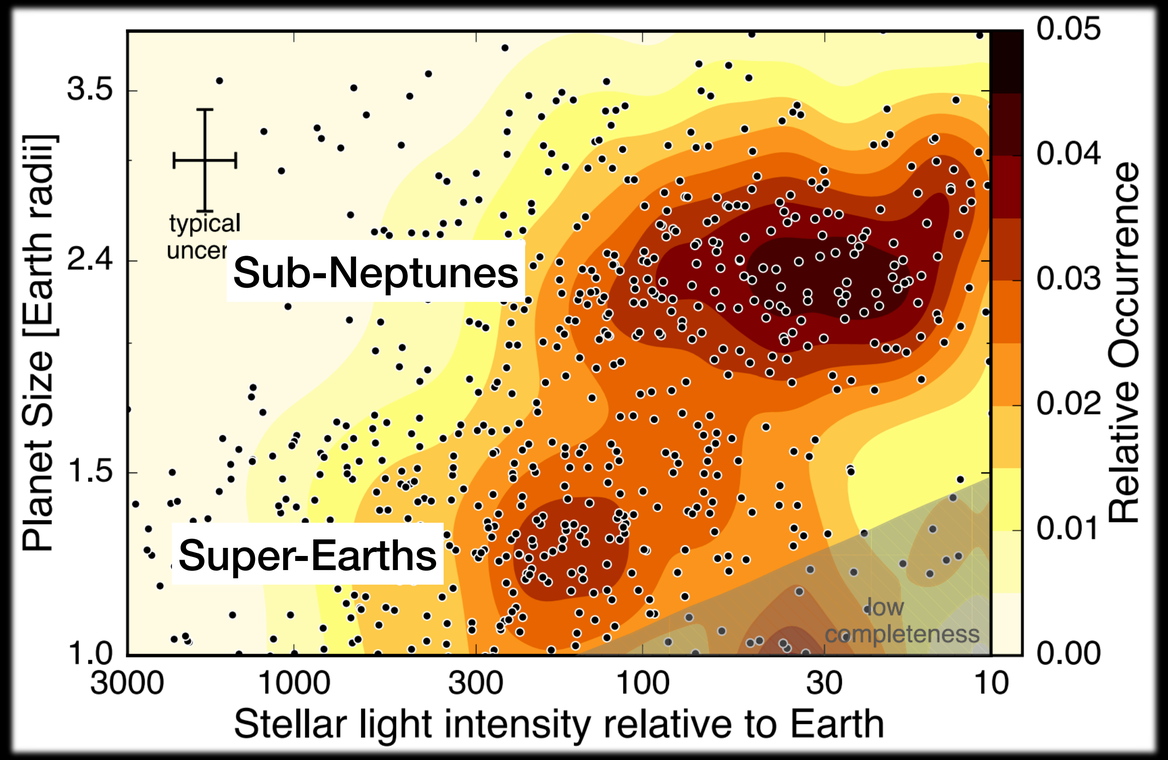
« about 30% of solar-type stars may have close-in, low-mass planets »

Small planets: a historical perspective

2009 First light for Kepler!

Small planets: a historical perspective

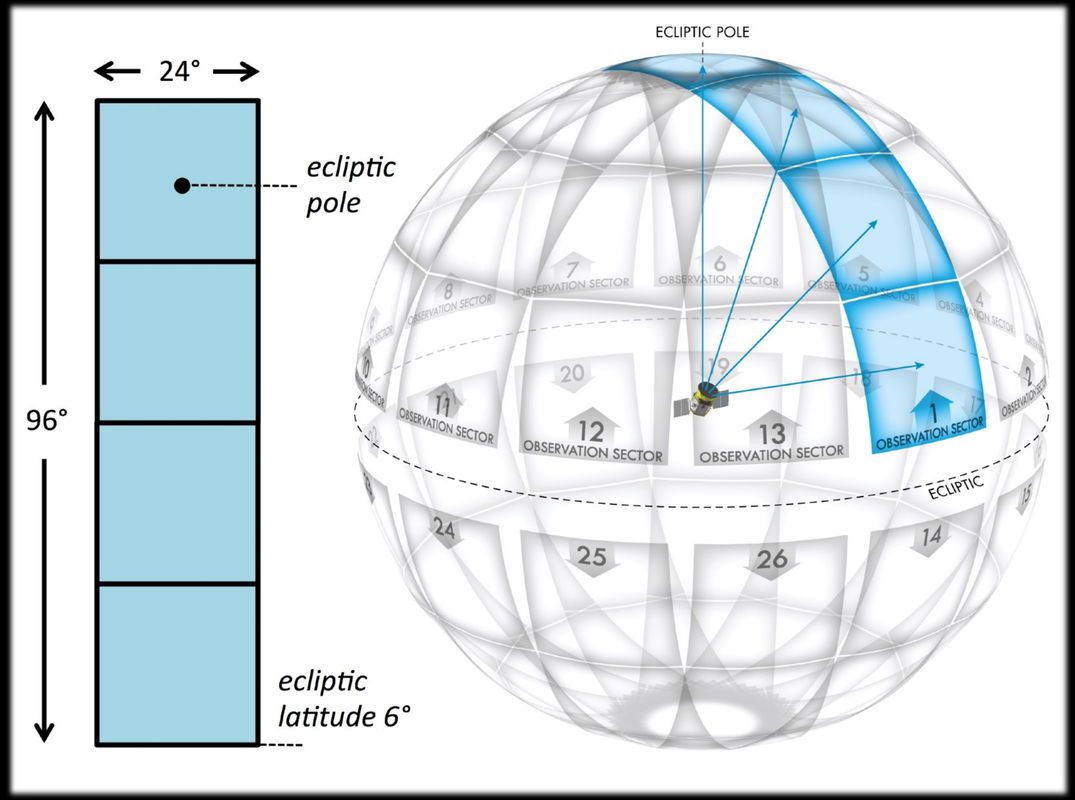
2017 Evidence for a radius valley



Fulton, et al. (2017)

Small planets: a historical perspective

2018 First light for TESS!



HARPS-N

Copy of HARPS in the northern hemisphere

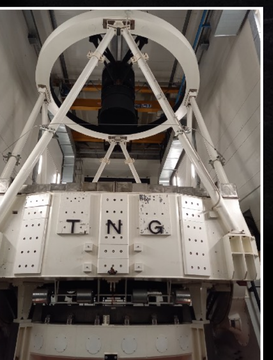
Installed at the 3.6m TNG, La Palma (Spain)

First light in 2012

<u>2 programmes</u>

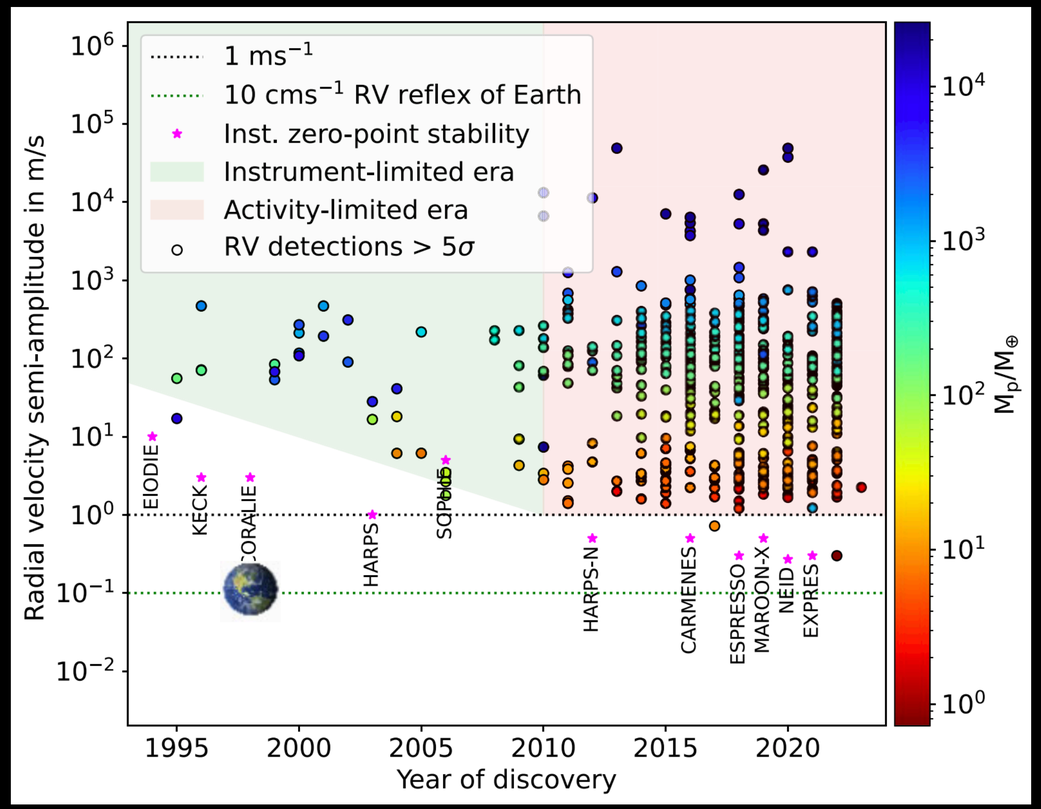
Mass determination of transiting planets
(From Kepler, K2, TESS, CHEOPS)

The Rocky Planet Search programme
(RV blind search for planets around bright stars)

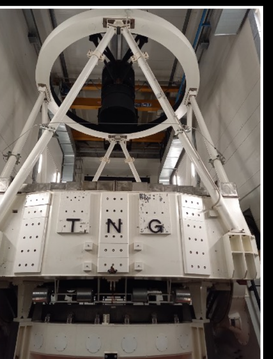


The Rocky Planet Search program

The main obstacle to precise planet mass estimation is stellar activity.

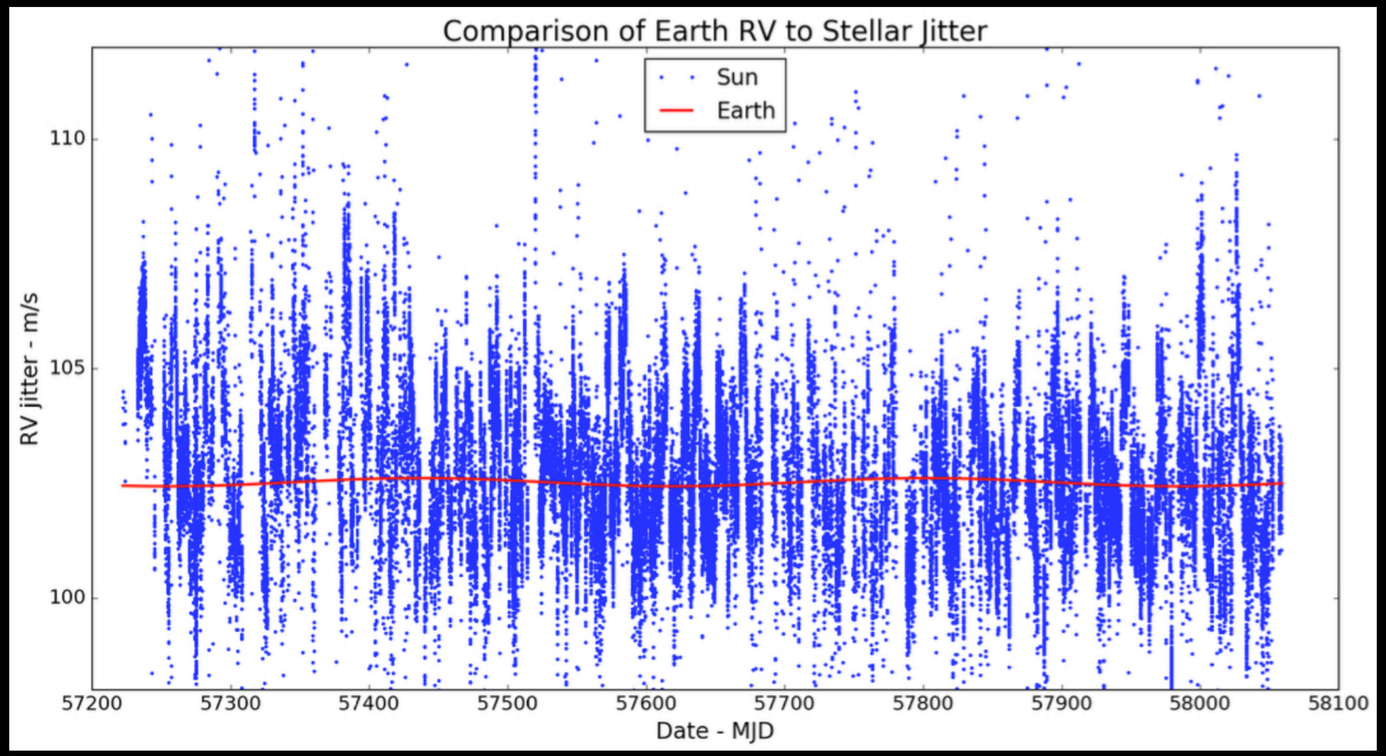


Anna John, et al. (2023)

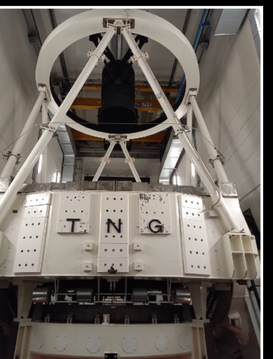


The Rocky Planet Search program

The main obstacle to precise planet mass estimation is stellar activity.



HARPS-N Solar data



The Rocky Planet Search program

The main obstacle to precise planet mass estimation is stellar activity.

Rocky Planet Search (RPS) program

Dataset: close-by bright stars in the northern hemisphere with low activity.

Program started in 2012: 10+ years timespan of high-cadence observations.

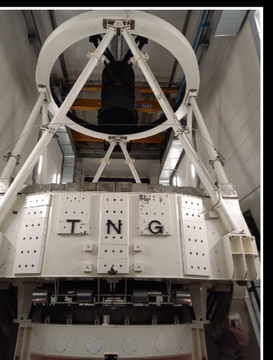
This dataset provides the ideal testbed for new activity mitigation techniques

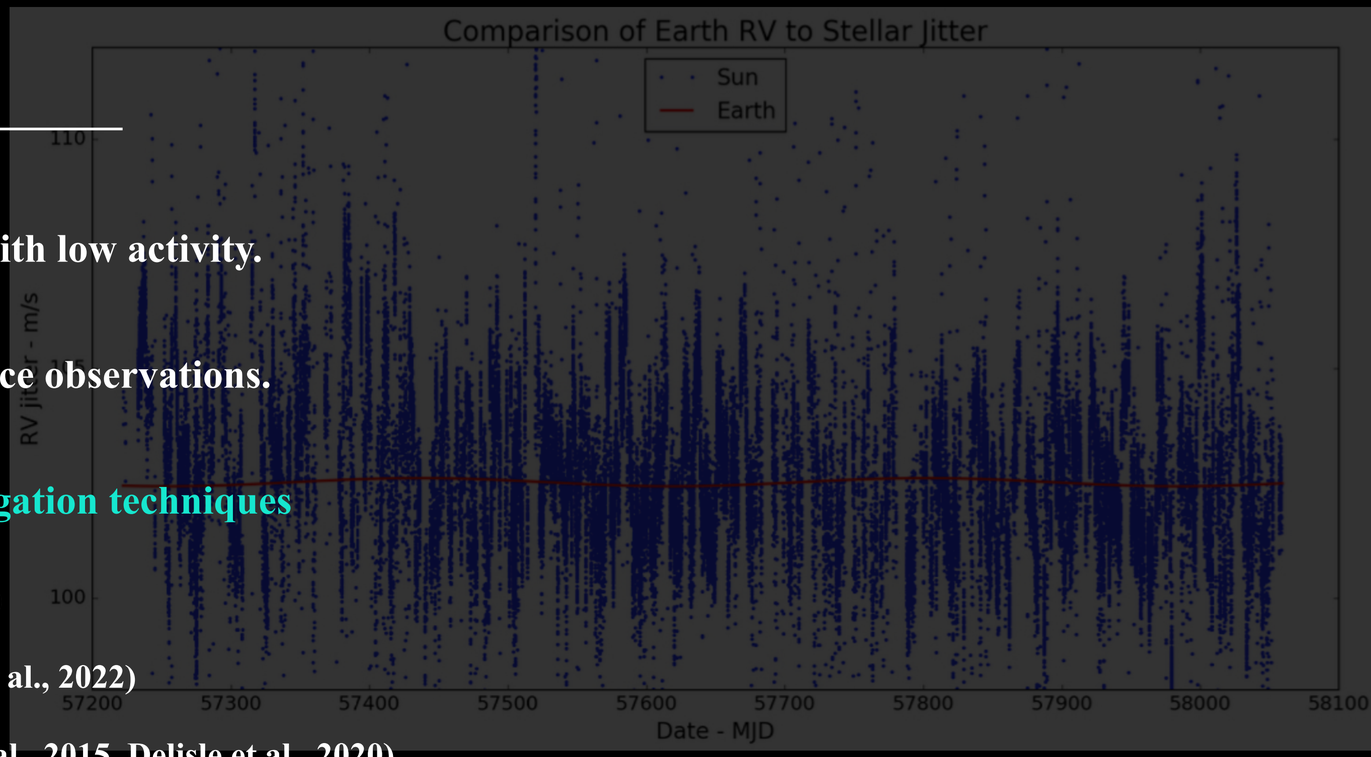
YARARA (Cretignier et al., 2021 ; Cretignier et al., 2023)

SCALPELS (Collier-Cameron et al., 2021 ; Anna John et al., 2022)

Gaussian Processes (e.g. Aigrain et al., 2012 ; Rajpaul et al., 2015, Delisle et al., 2020)

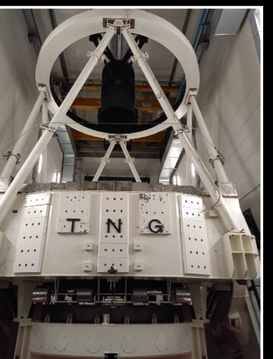
And many more…

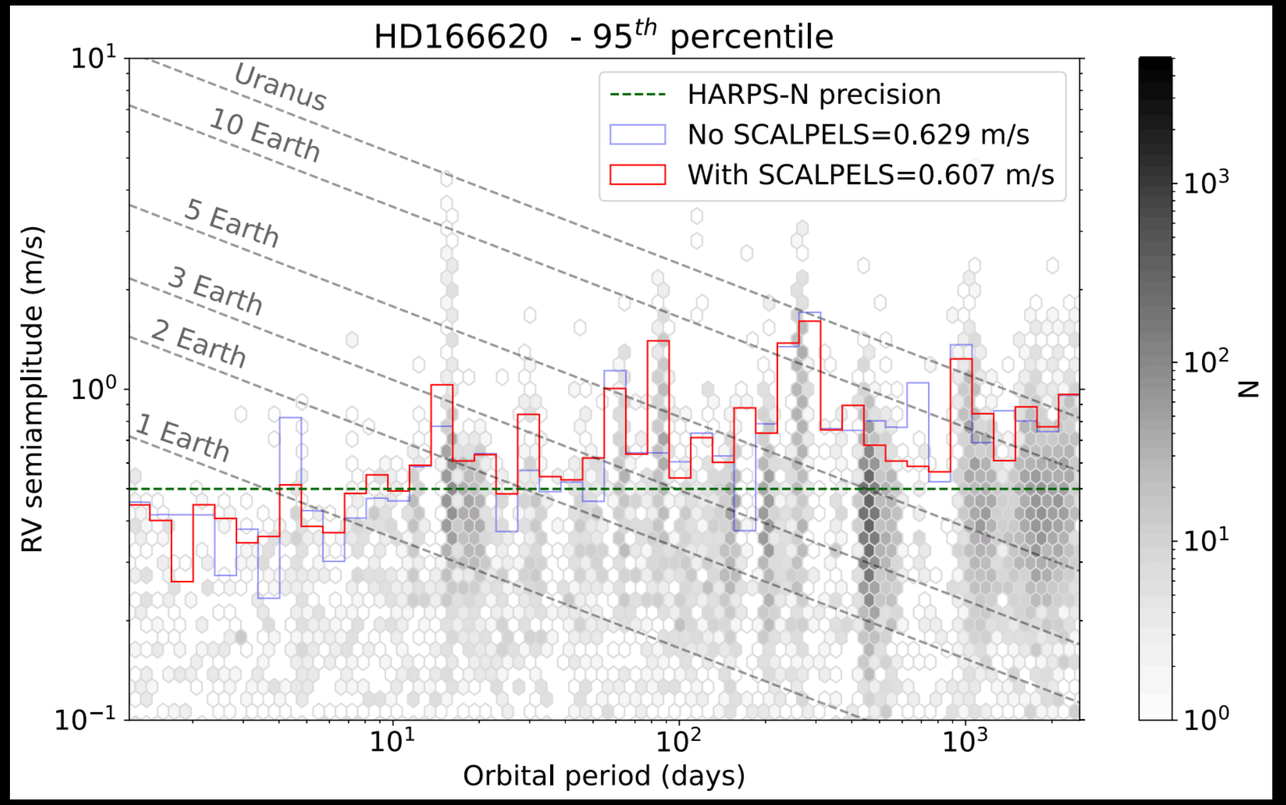




The Rocky Planet Search program

Reaching the sub-m/s RV precision



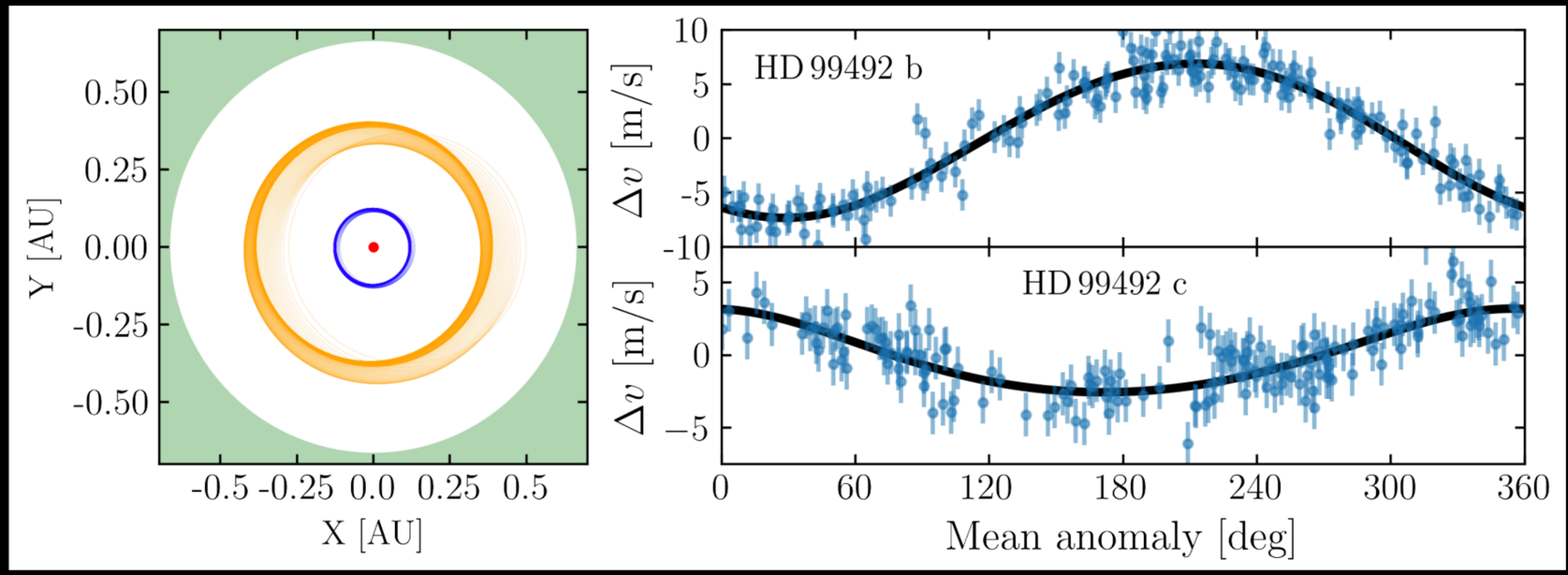


Anna John, et al. (2023)

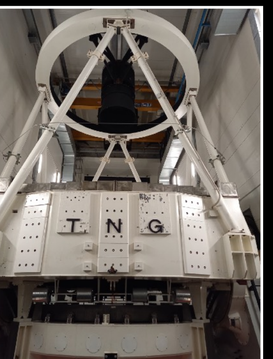
The Rocky Planet Search program

Reaching the sub-m/s RV precision

Detection of additional planets in known systems



Stalport, et al. (2023)

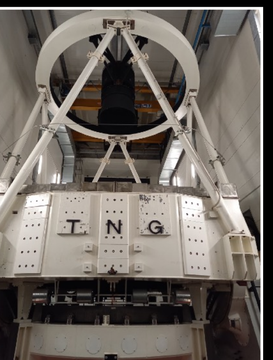


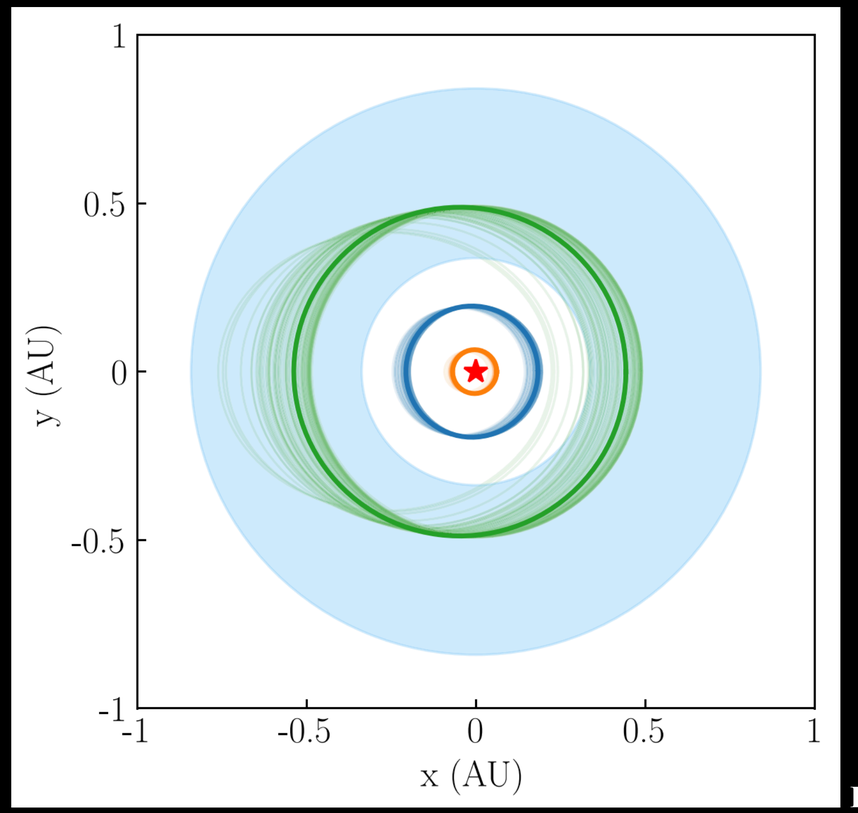
The Rocky Planet Search program

Reaching the sub-m/s RV precision

Detection of additional planets in known systems

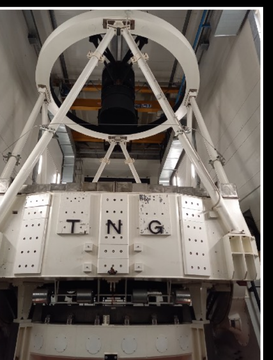
Detection of 3 super-Earths around HD48948

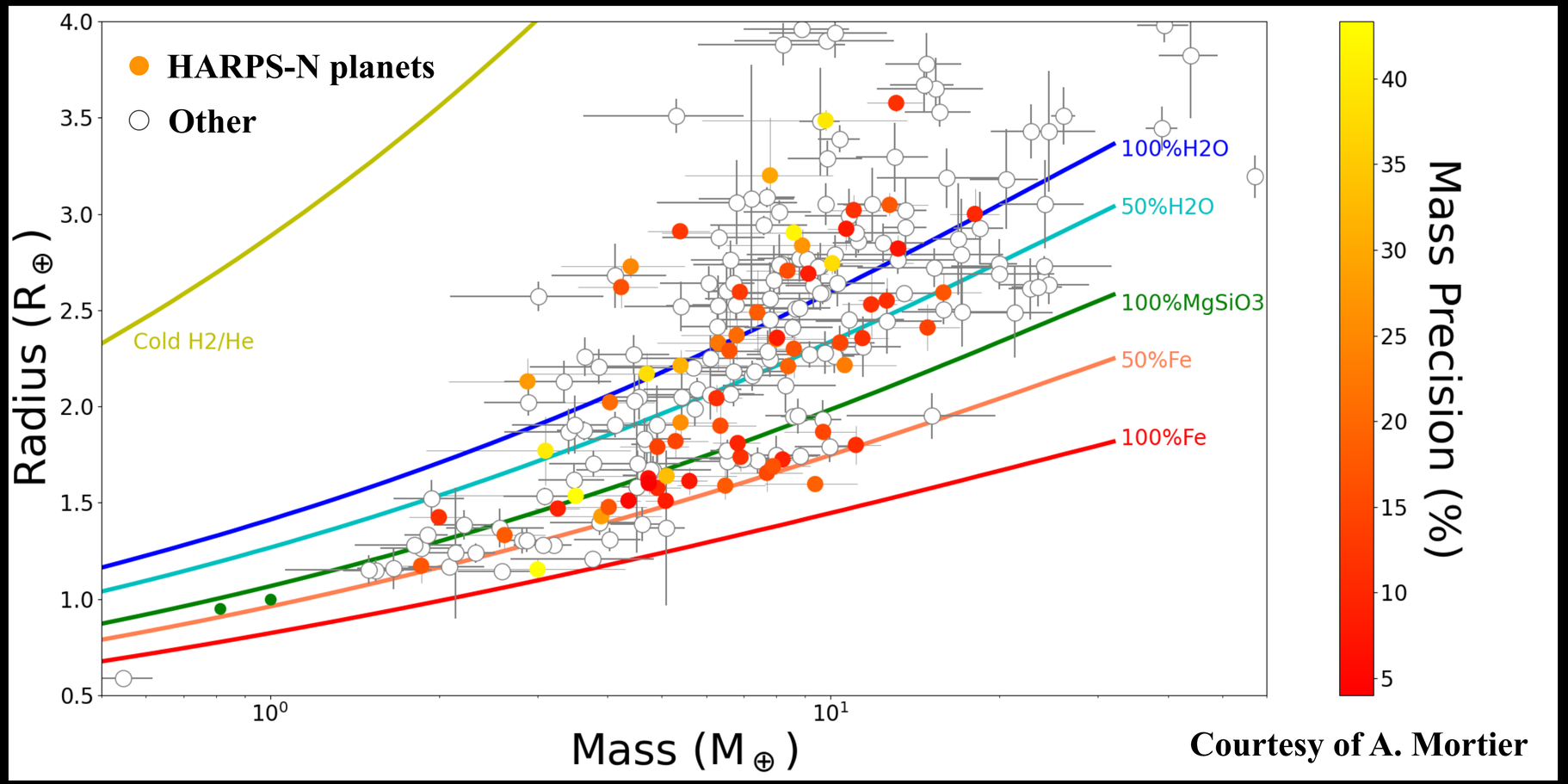




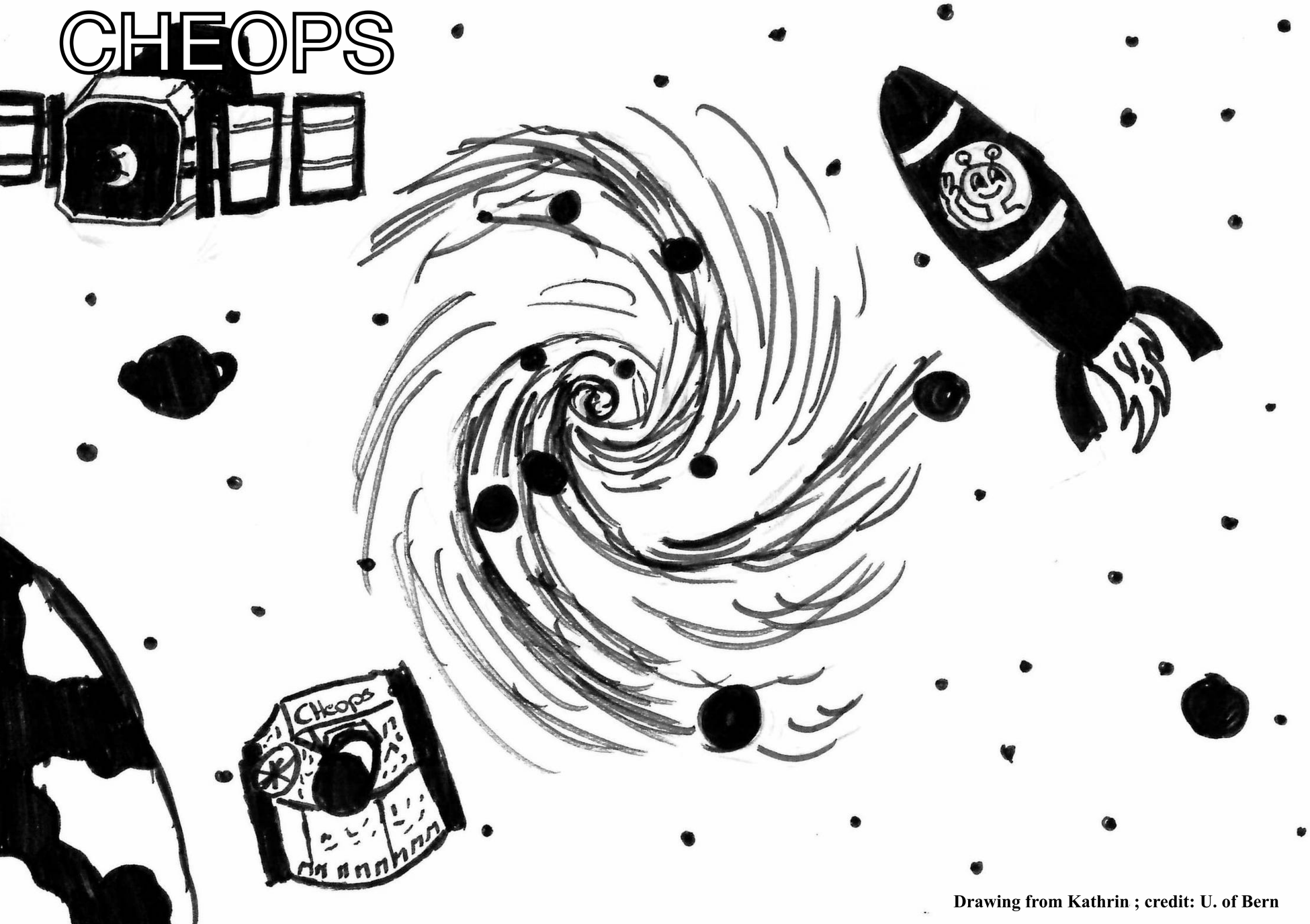
Dalal, et al. (2024)

The transiting planet follow-up program

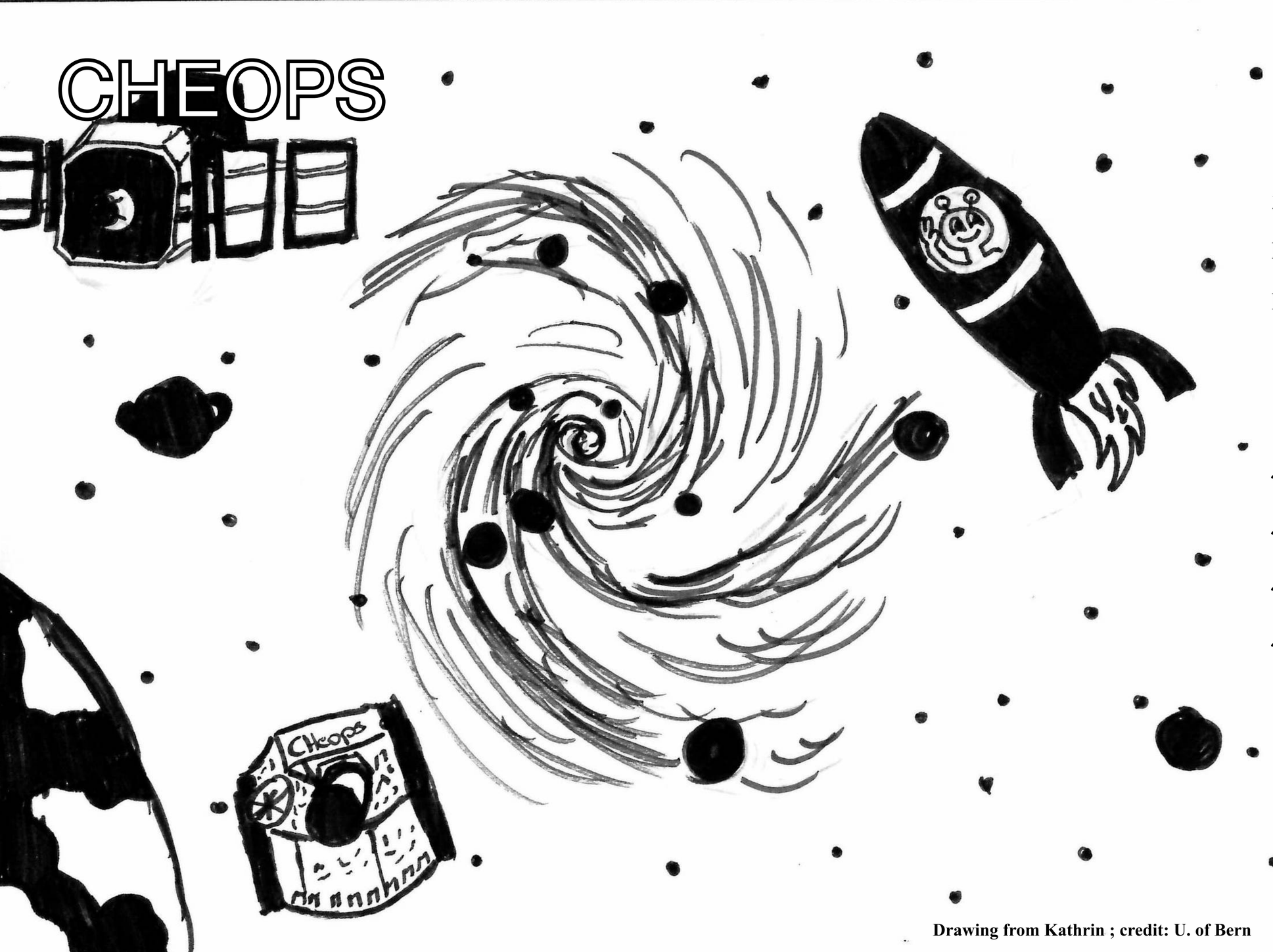




CHEOPS



Drawing from Kathrin ; credit: U. of Bern



CHEOPS

Characterising Exoplanets Satellite

30cm telescope launched in 2019

First mission extension until 31.12.2026

P_{orb} = 98.7 min

Exoplanet follow-up mission

- Refine planetary radii
- Detect additional planets
- TTV characterisation
- Exomoons, exocomets, tides

Drawing from Kathrin ; credit: U. of Bern

CHEOPS

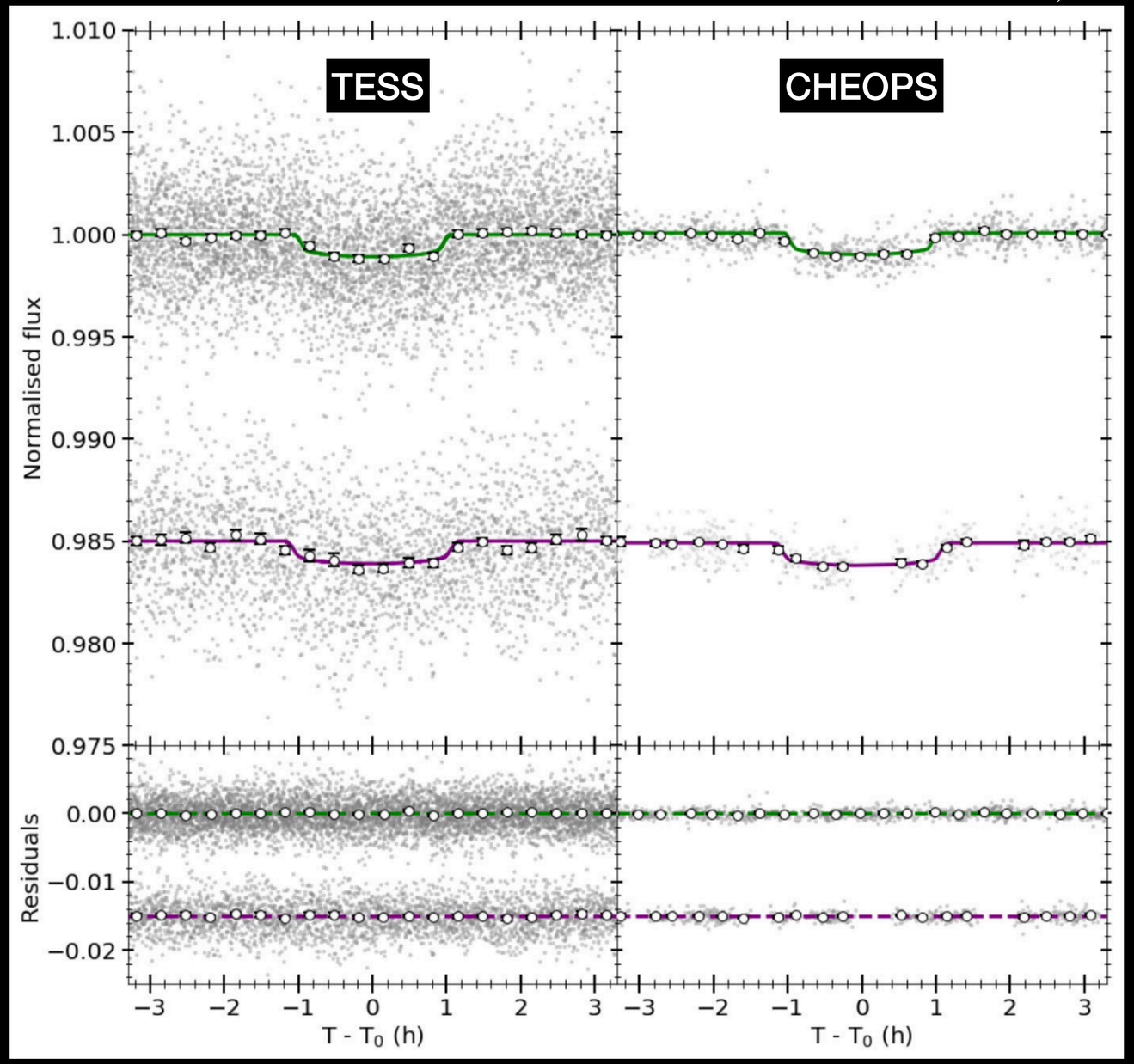
Wilson et al., 2022

2 sub-Neptunes around TOI-1064

Transit depth of TOI-1064 b ~ 1070 ppm
TOI-1064 c ~ 1120 ppm

TOI-1064 is a K-type main-sequence star.

Mag(V) = 10.95



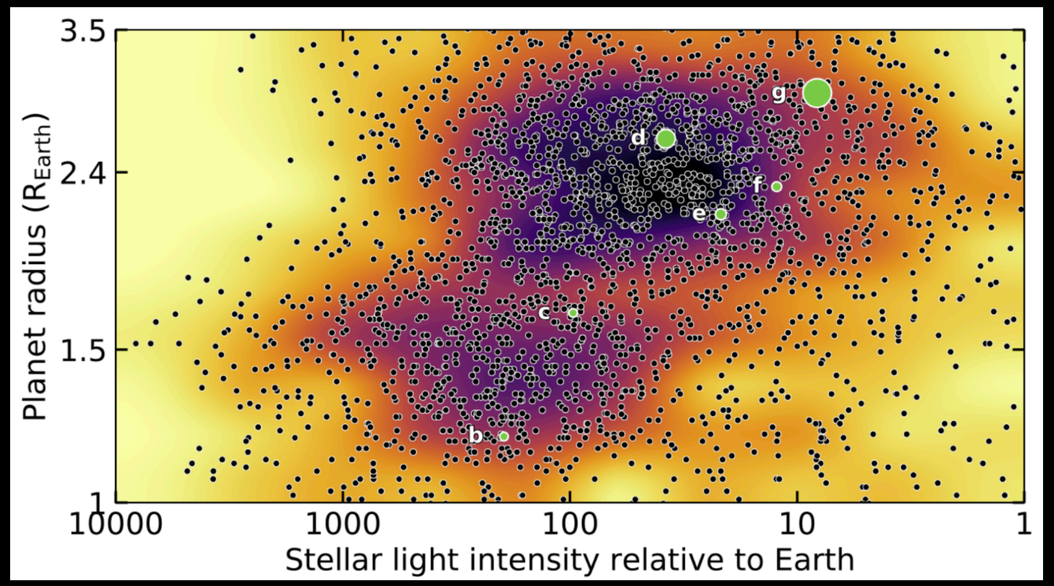
CHEOPS and the sub-Neptunes

TOI-178 and HD 110067

2 planetary systems in chains of mean-motion resonance (MMR)

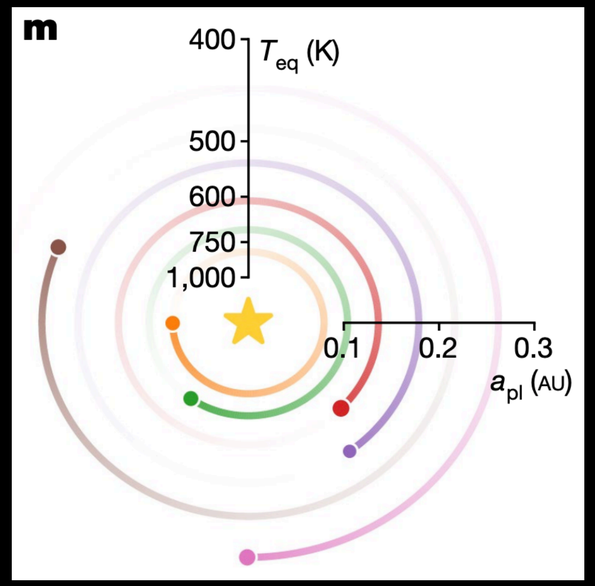
Inside the MMR: $\frac{P_2}{P_1} \sim \frac{p+q}{p}$ *with* p, q *integers*

TOI-178 (Leleu et al., 2021)



From c to g: 2/1 - 3/2 - 3/2 - 3/2

HD 110067 (Luque et al., 2023)



From b to g: 3/2 - 3/2 - 3/2 - 4/3 - 4/3

CHEOPS and the sub-Neptunes

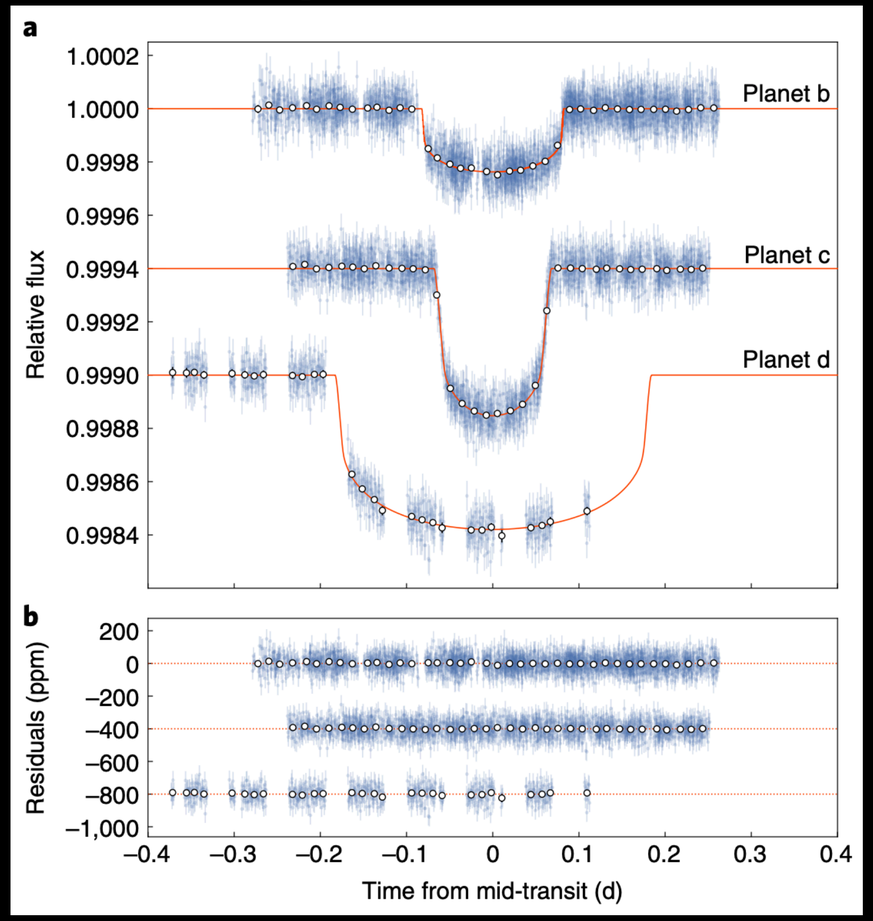
TOI-178 and HD 110067

2 planetary systems in chains of mean-motion resonance

ν^2 Lupi d

A transiting sub-Neptune on a 107-d orbit

ν^2 Lupi d (Delrez et al., 2021)



CHEOPS and the sub-Neptunes

TOI-178 and HD 110067

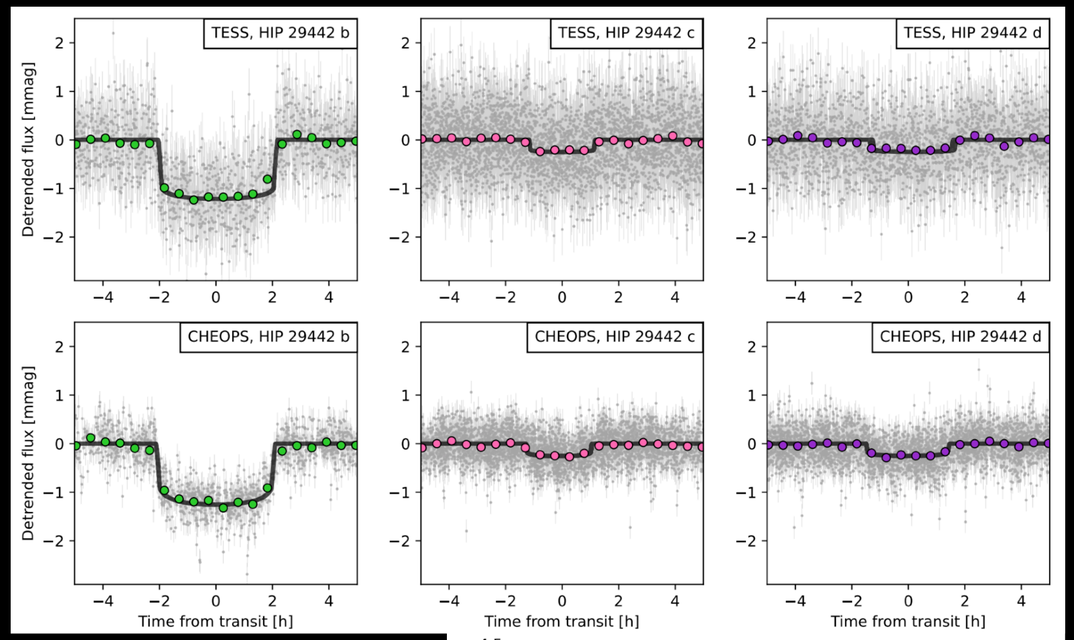
2 planetary systems in chains of mean-motion resonance

ν^2 Lupi d

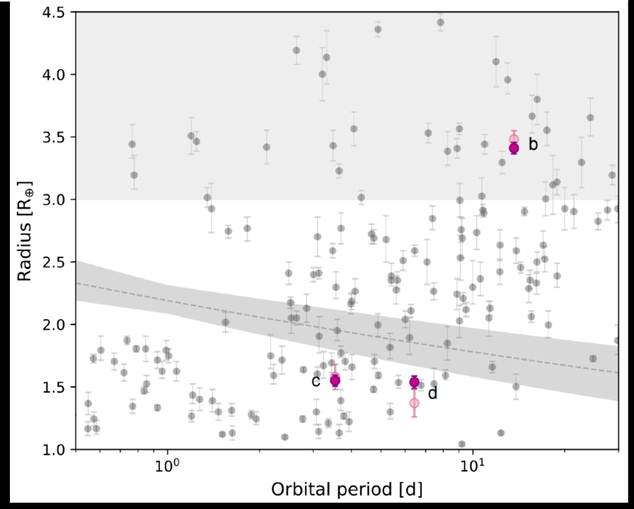
A transiting sub-Neptune on a 107-d orbit

HIP 29442

3 small planets spanning the radius valley



HIP 29442 (Egger et al., 2024)



CHEOPS and the sub-Neptunes

TOI-178 and HD 110067

2 planetary systems in chains of mean-motion resonance

ν^2 Lupi d

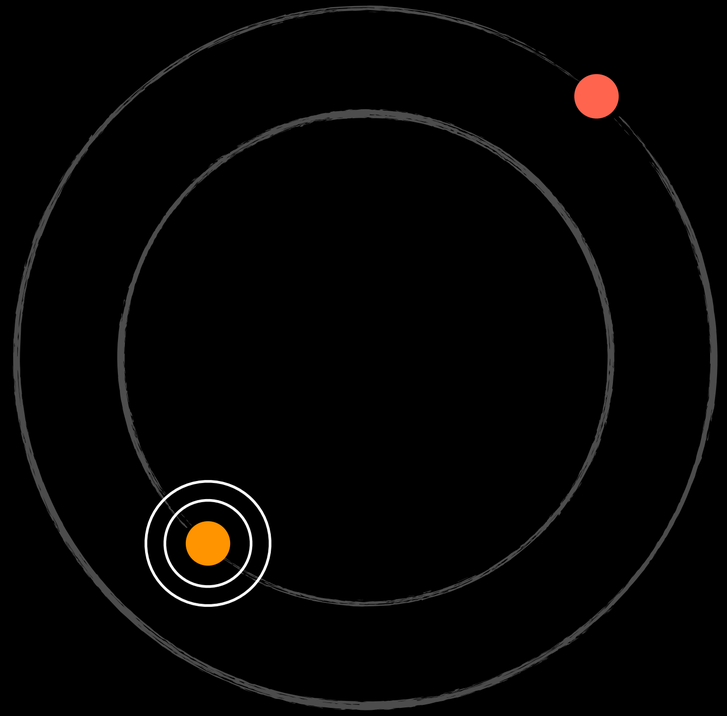
A transiting sub-Neptune on a 107-d orbit

HIP 29442

3 small planets spanning the radius valley

S-Valley

Towards a characterisation of the radius valley in binary systems



Joint CHEOPS - HARPS-N efforts

TOI-561

Orbital periods of TOI-561 [days]

.01: 0.45 ; .02: 10.8 ; .03: 16.3

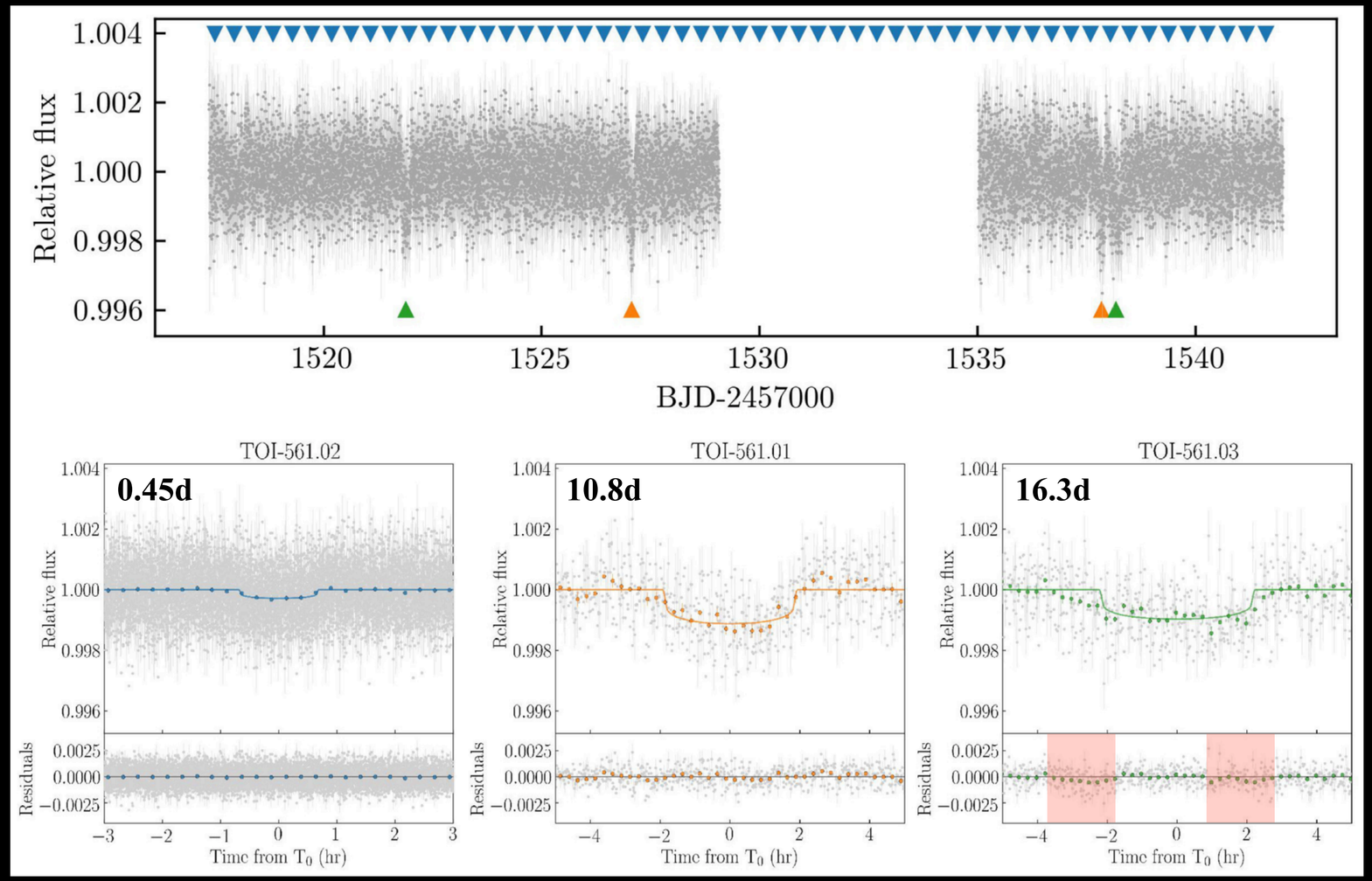
HARPS-N RV follow-up

Revealed 4 signals, at 0.4, 10, 25, 77 days

Is the 16d signal real?

From TESS observations: 3 transiting planet candidates

Lacedelli et al., 2021



Joint CHEOPS - HARPS-N efforts

TOI-561

Orbital periods of TOI-561 [days]

.01: 0.45 ; .02: 10.8 ; .03: 16.3

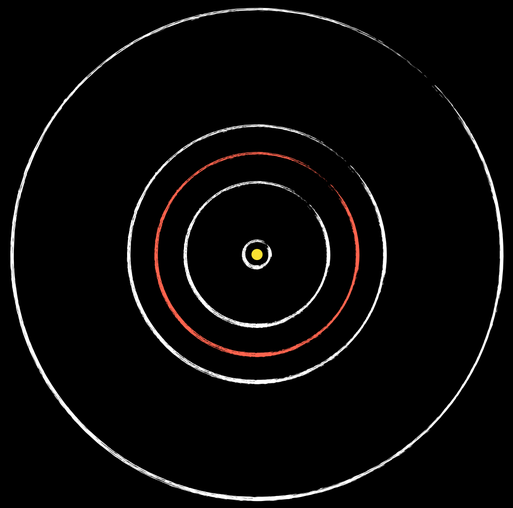
HARPS-N RV follow-up

Revealed 4 signals, at 0.4, 10, 25, 77 days

Is the 16d signal real?

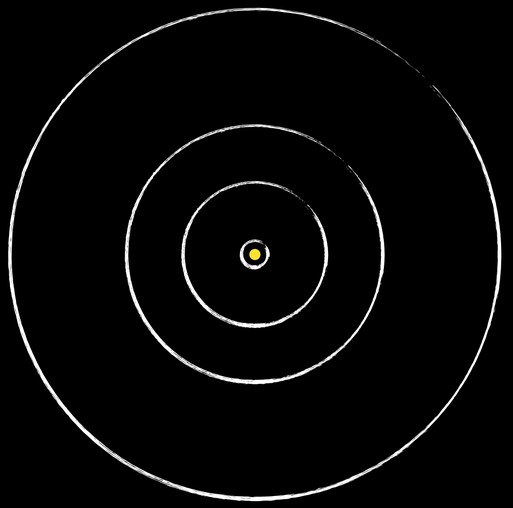
Model 1

5 planets (0.4, 10, 16, 25, 77 d)



Model 2

4 planets (0.4, 10, 25, 77 d)



Stability analysis

Model 1 was widely unstable

Model 2 was widely stable

Joint CHEOPS - HARPS-N efforts

TOI-561

Orbital periods of TOI-561 [days]

b: 0.45 ; c: 10.8 ; d: 25.6 ; e: 77.2

Thanks to the RV data, an alternative model is favoured.

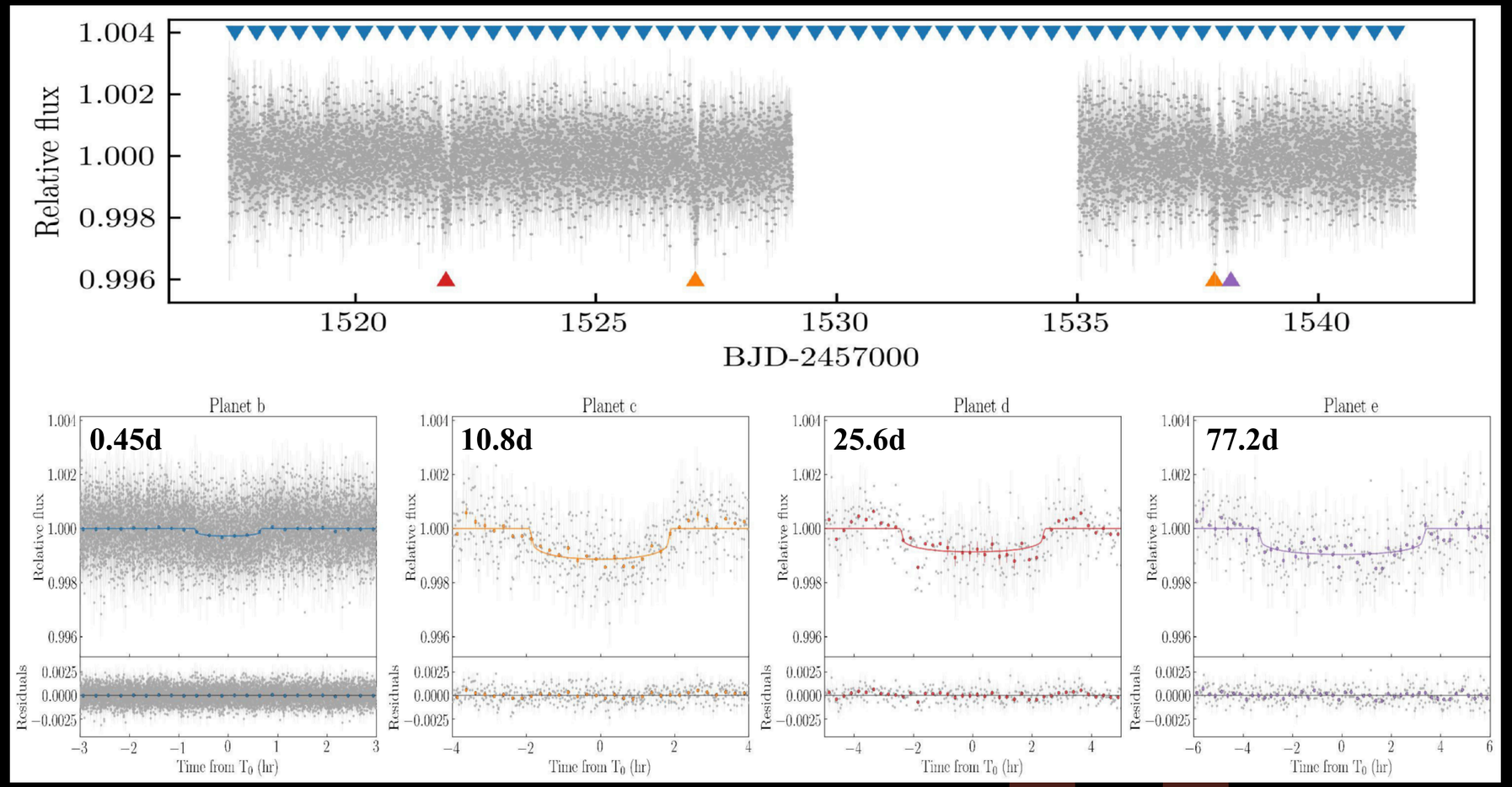
4 planets!

All have signatures in RV data

Single transits for planets d and e

Needs confirmation…

Lacedelli et al., 2021



Joint CHEOPS - HARPS-N efforts

TOI-561

Orbital periods of TOI-561 [days]

b: 0.45 ; c: 10.8 ; d: 25.6 ; e: 77.2

Confirmation of TOI-561 d!

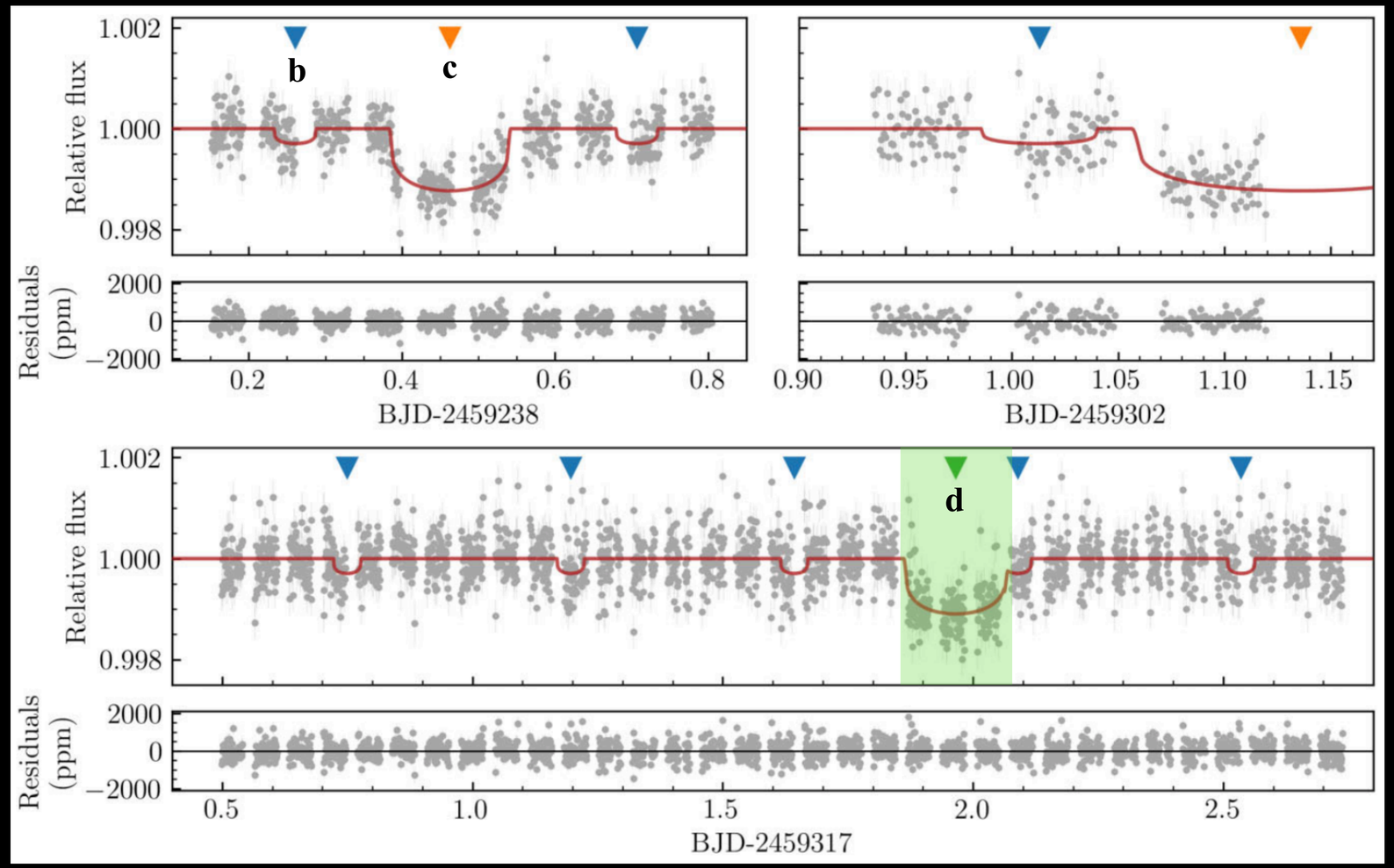
This was possible thanks to:

- HARPS-N dataset which signaled this candidate

- the high flexibility of CHEOPS to perform targeted observations

Follow-up observations with CHEOPS

Lacedelli et al., 2022



Joint CHEOPS - HARPS-N efforts

HD 110067 (TOI-1835)

Luque et al., 2023

6 planets in a chain of mean-motion resonances

CHEOPS led to the detection of the system, while HARPS-N measured the mass of the 3 inner planets.

HD 77946 (TOI-1778)

Palethorpe et al., 2024

Precise characterisation of a sub-Neptune around this F5 star

CHEOPS and HARPS-N were crucial to provide precise mass and radius measurements.

Monitoring stellar activity

Ongoing analyses…

Parallel CHEOPS and HARPS-N observation campaigns on a bright K-type star

The CHEOPS photometry should provide insights into the activity patterns observed in HARPS-N data.

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Where do the super-Earths and sub-Neptunes come from?

CHEOPS + HARPS-N

Measuring the bulk density of super-Earths and sub-Neptunes

Dynamical characterisation:

Fit convergence

Model selection

Refine the planet parameters

Investigate MMR

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