

Probing the Six-Planet Architecture of HIP 41378 through TTVs with CHEOPS and TESS

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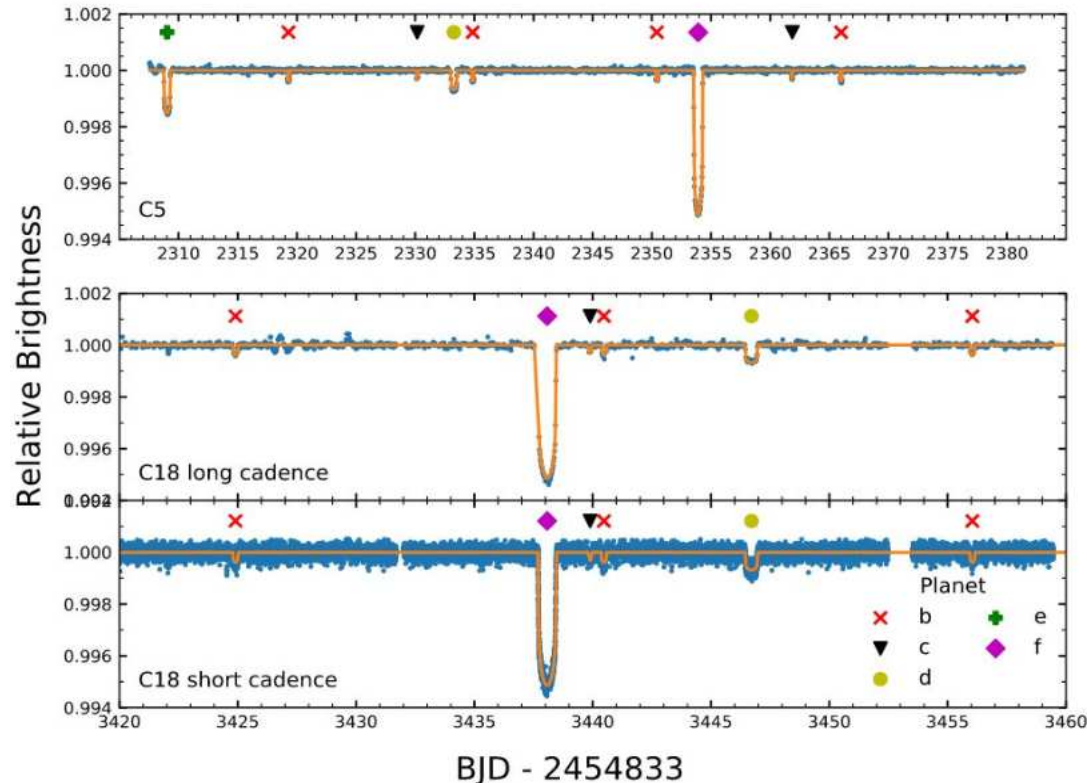


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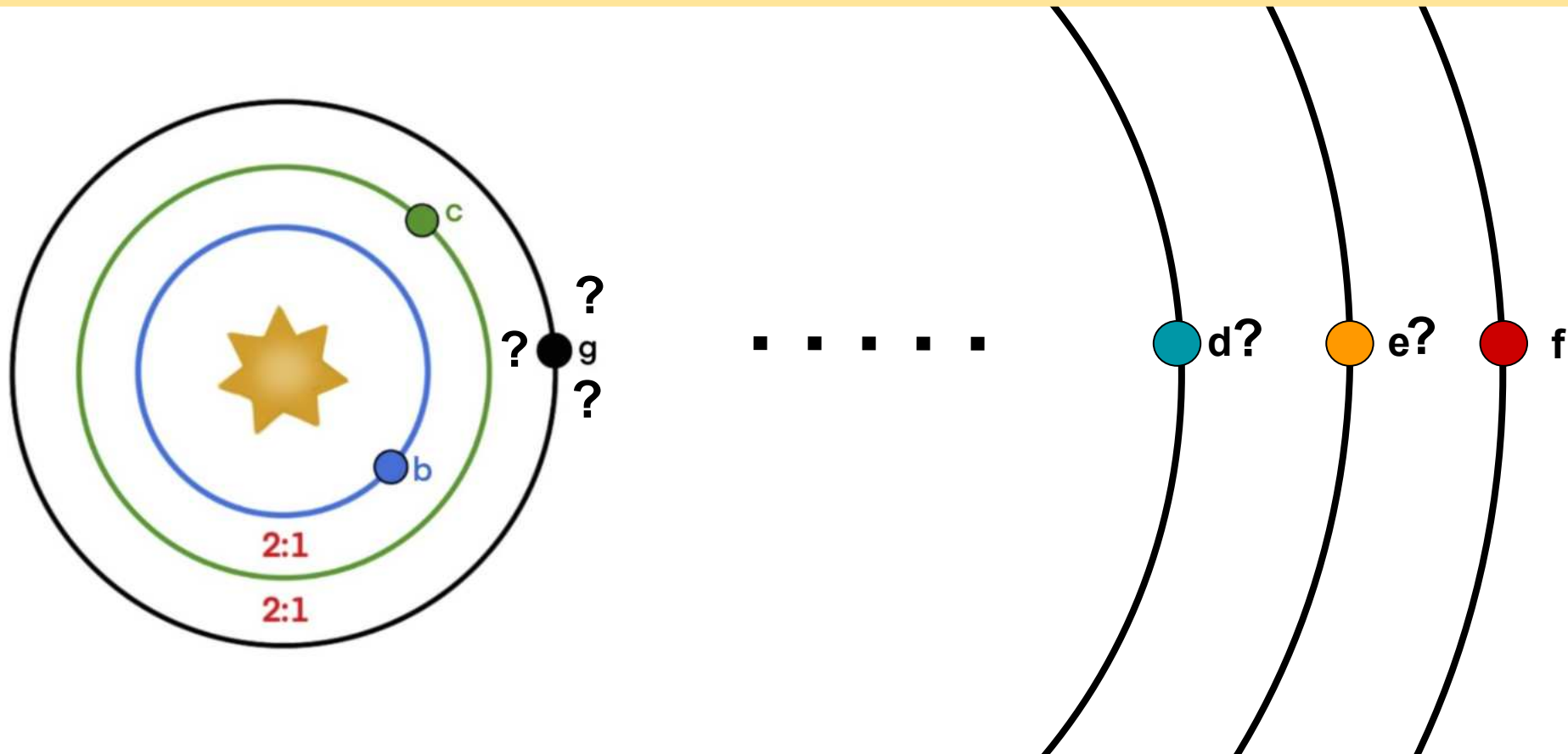
The HIP 41378 system



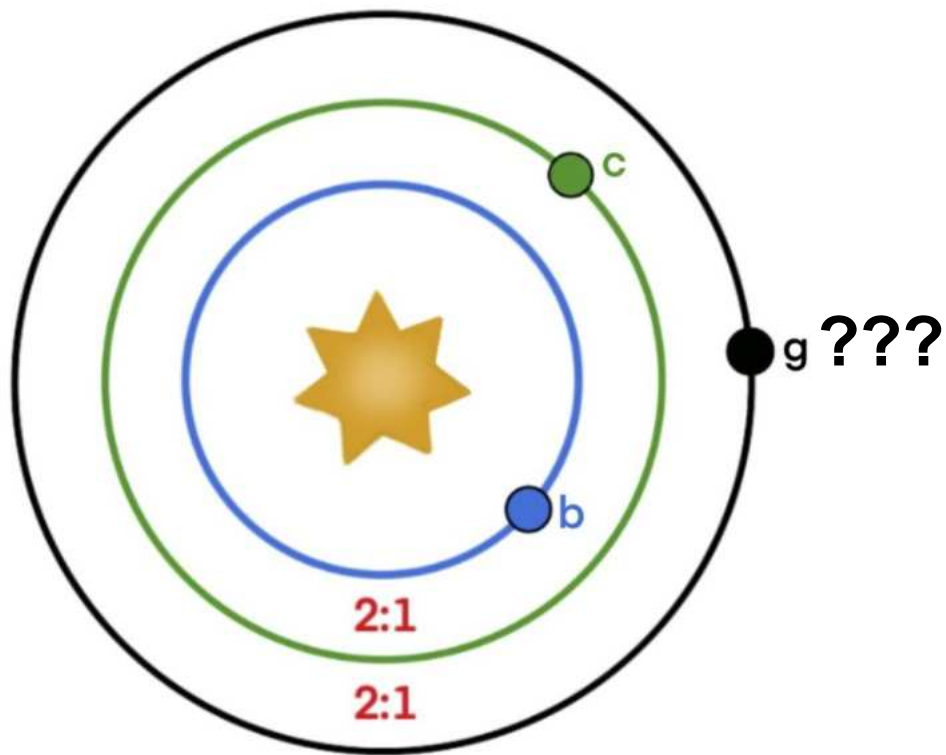
K2 light curves of the system from Berardo et al. 2019

- Five transiting planets confirmed so far with a period ranging from 15 to 542 days.
- Benchmark for multi planet systems with long-period small planets

The HIP 41378 system



The inner HIP 41378 system

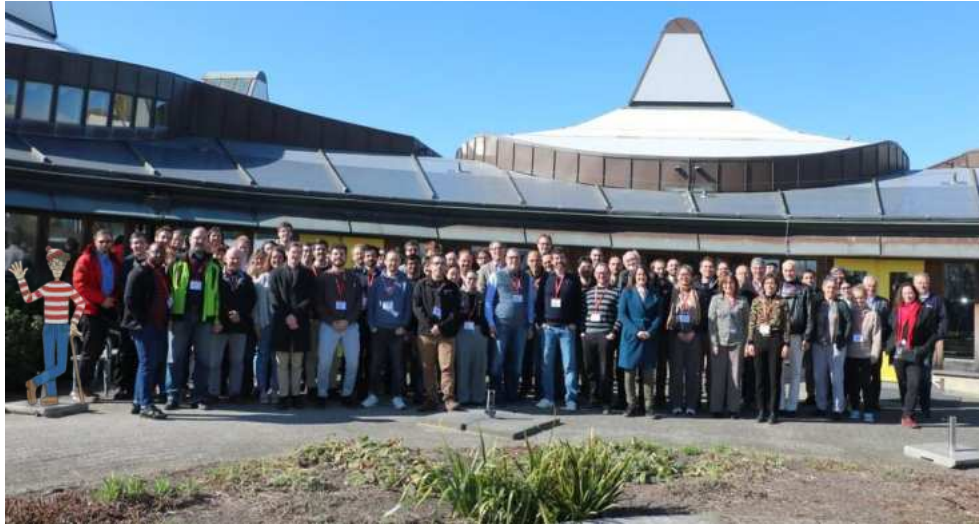


- Two Inner sub-Neptunes close ($\Delta \sim 1.8\%$) to a 2:1 period ratio
- Possible non-transiting outer planet at ~ 62 days close to a 2:1 resonance with planet c (Santerne et al 2019)

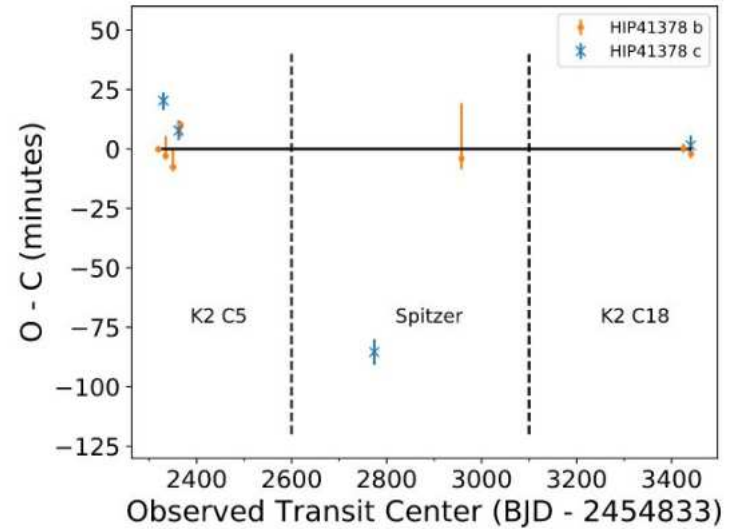
CHEOPS Follow-up on the inner duo

- CHEOPS GTO Programs 25 (PI: Nascimbeni) and 90 (PI: Leleu)

TTVs follow-up observations of resonant multi-planet systems



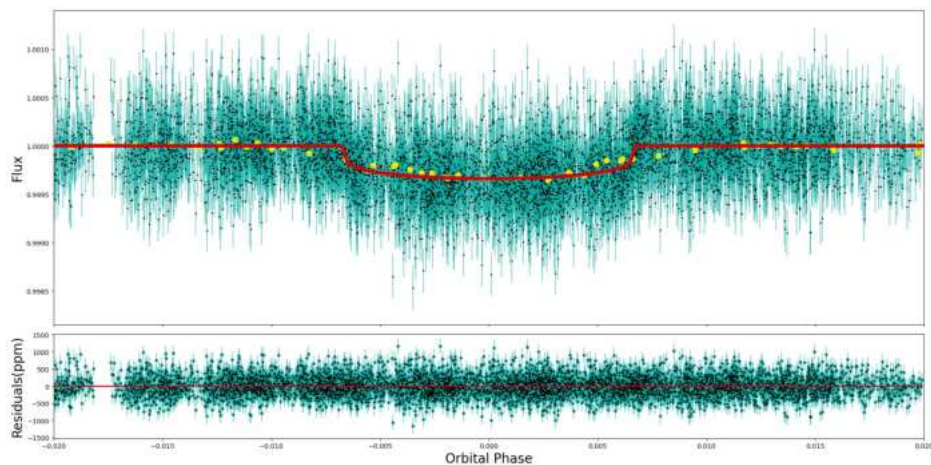
CHEOPS Consortium (Noordwijk, 2025)



Transit timing variations plot for HIP 41378 b and c. Adapted from Berardo et al. 2019

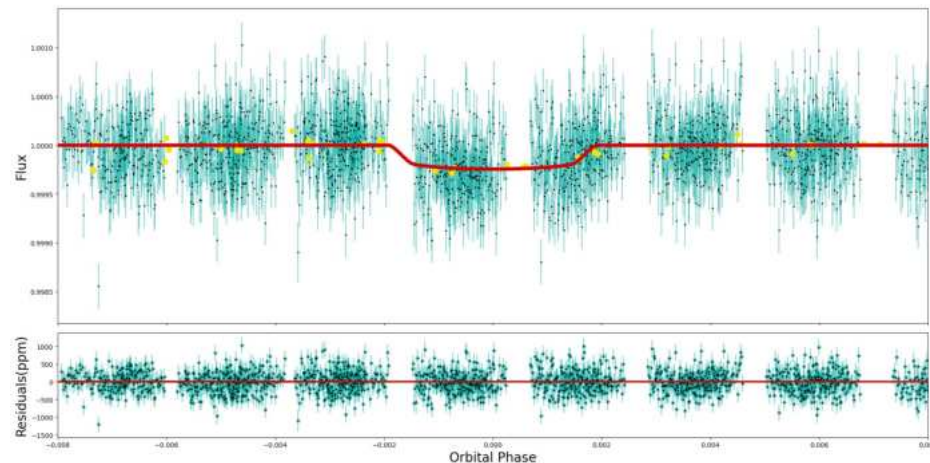
CHEOPS Follow-up on the inner duo

Phase-folded CHEOPS visits



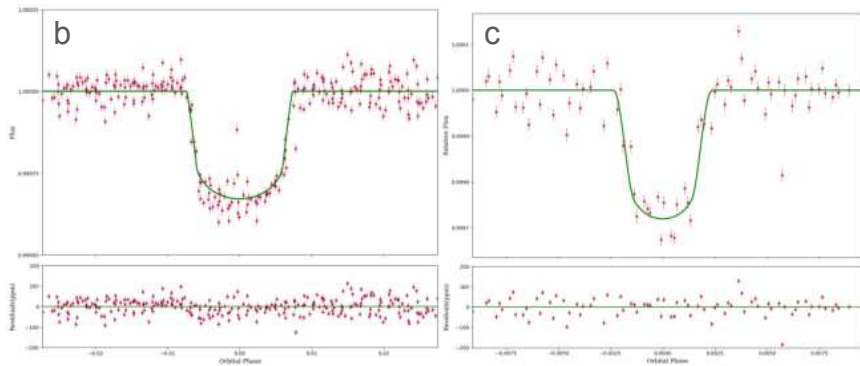
HIP 41378 b

HIP 41378 c

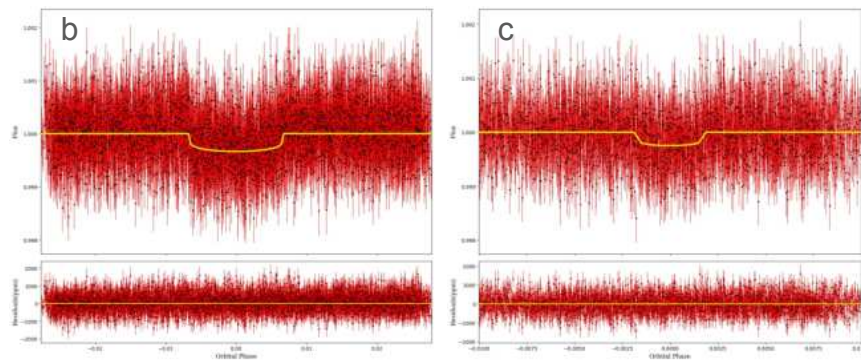


Space-based follow-up with four telescopes

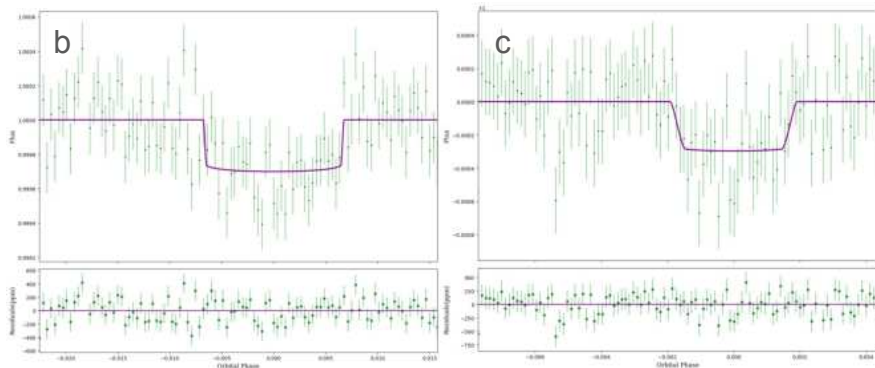
K2



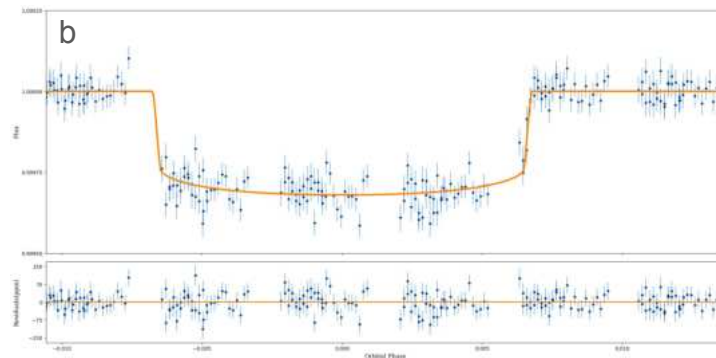
TESS



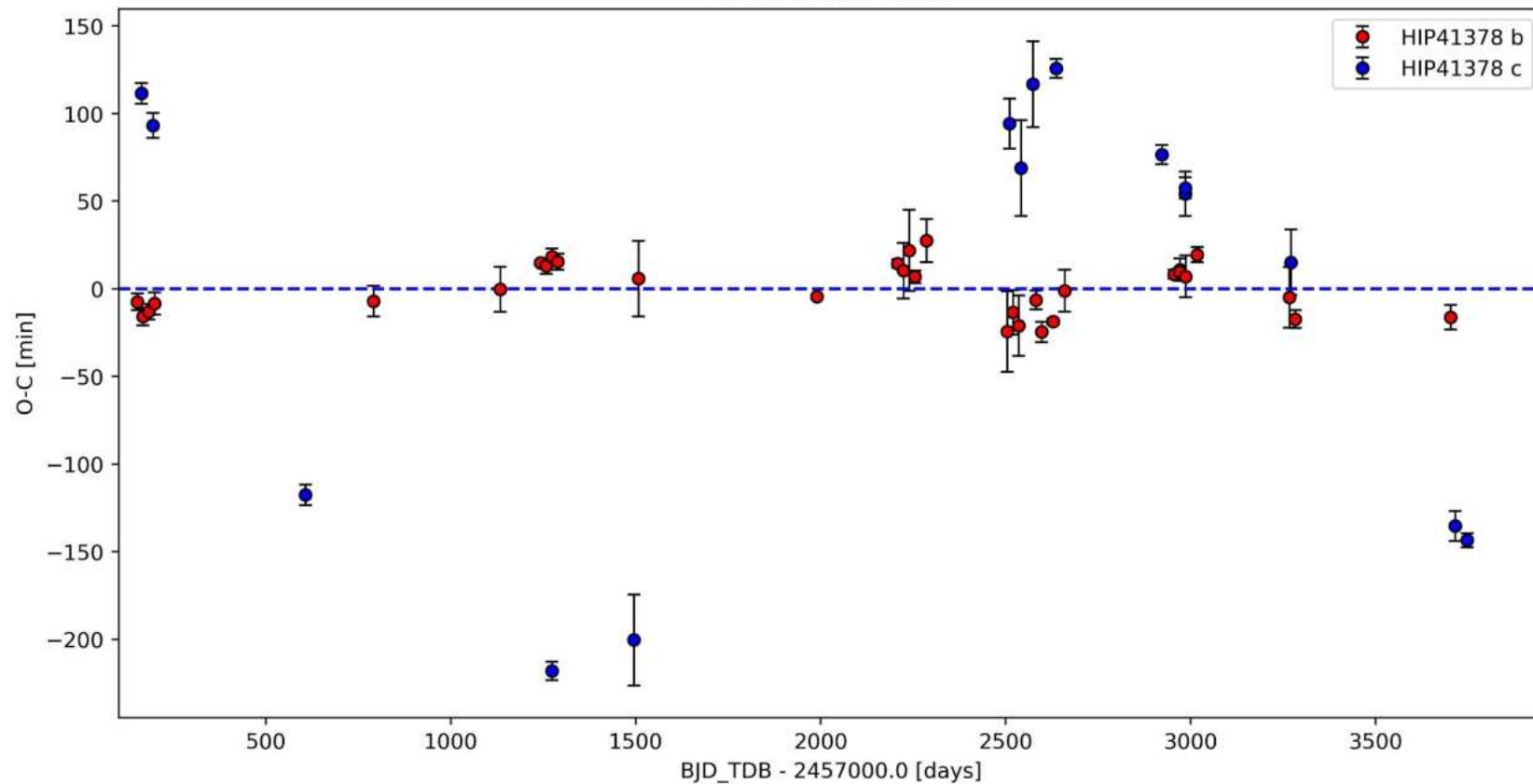
Spitzer



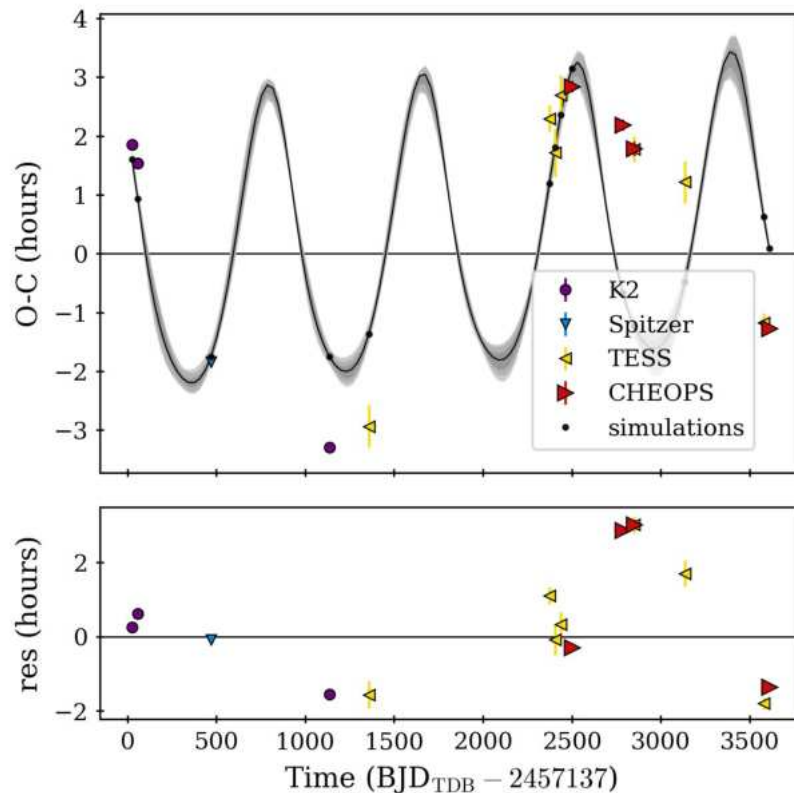
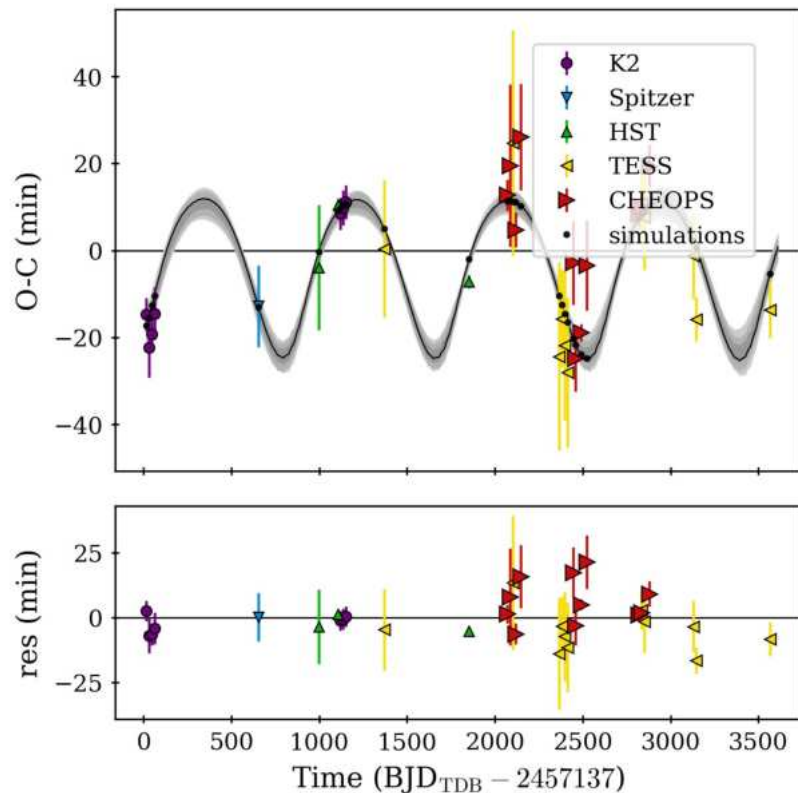
HST



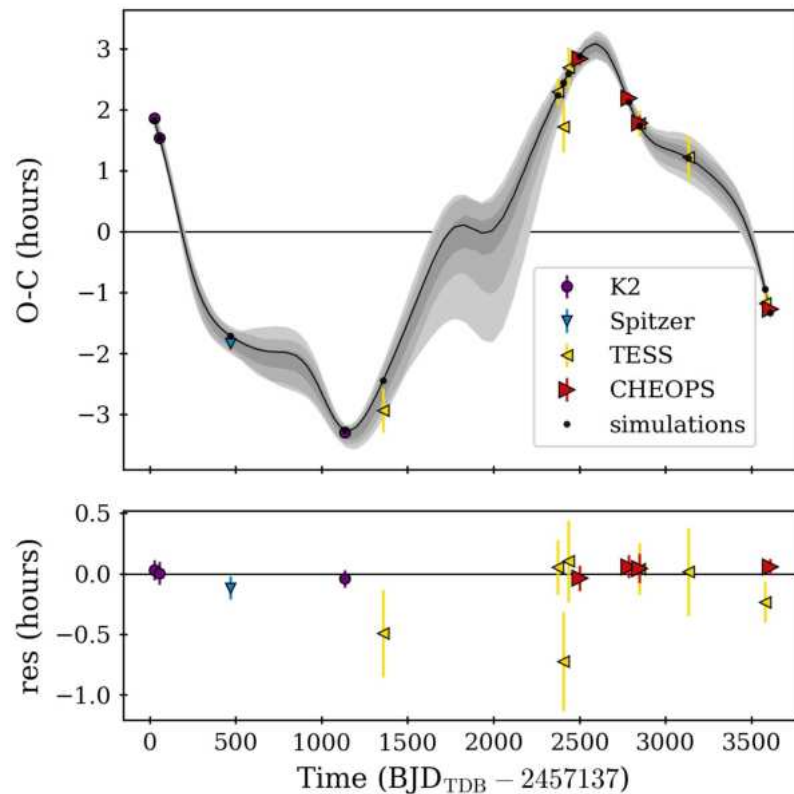
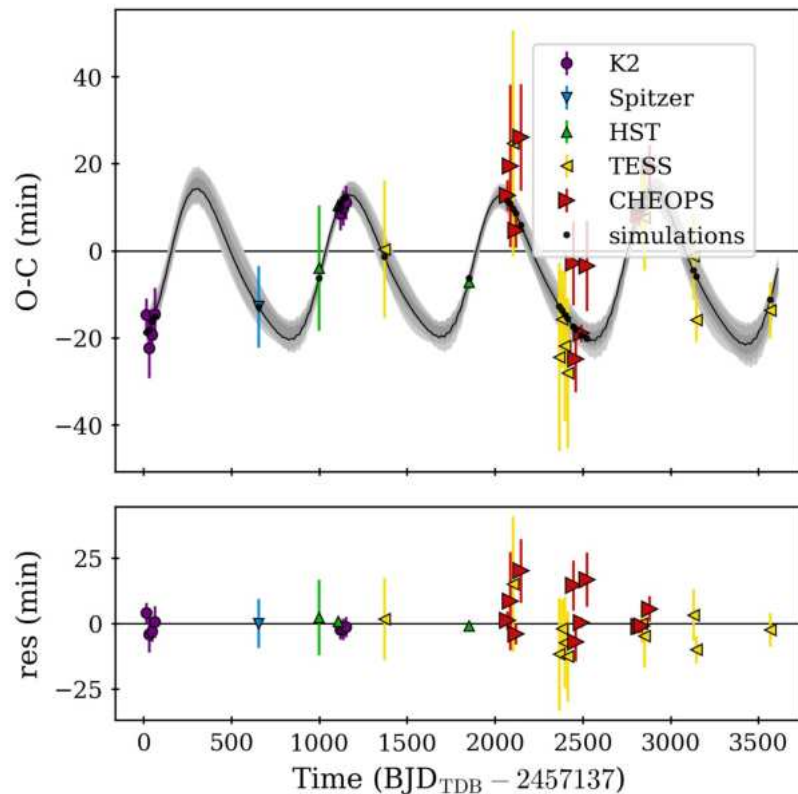
O-C diagram of HIP 41378 b & c



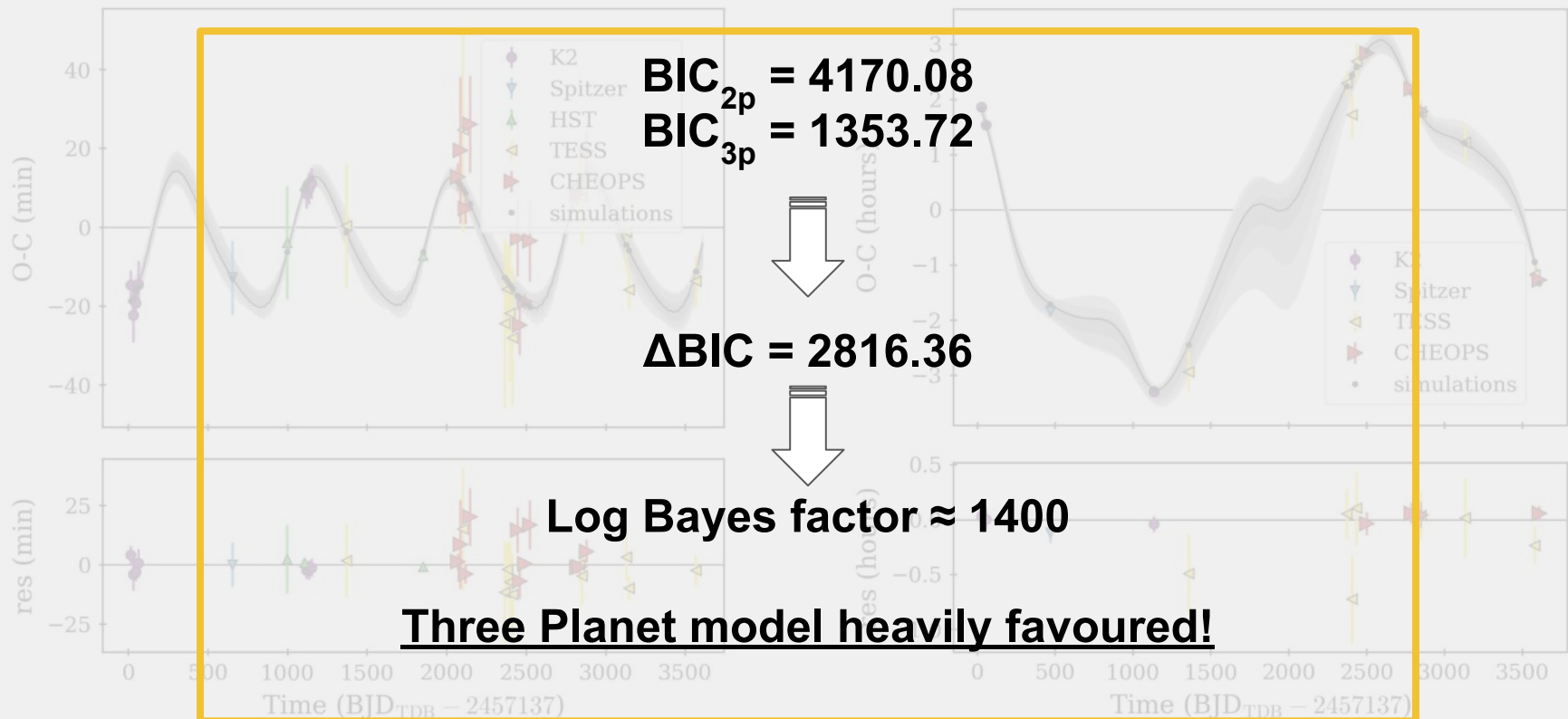
Dynamical Modeling (TTVs + RVs): 2-planet model



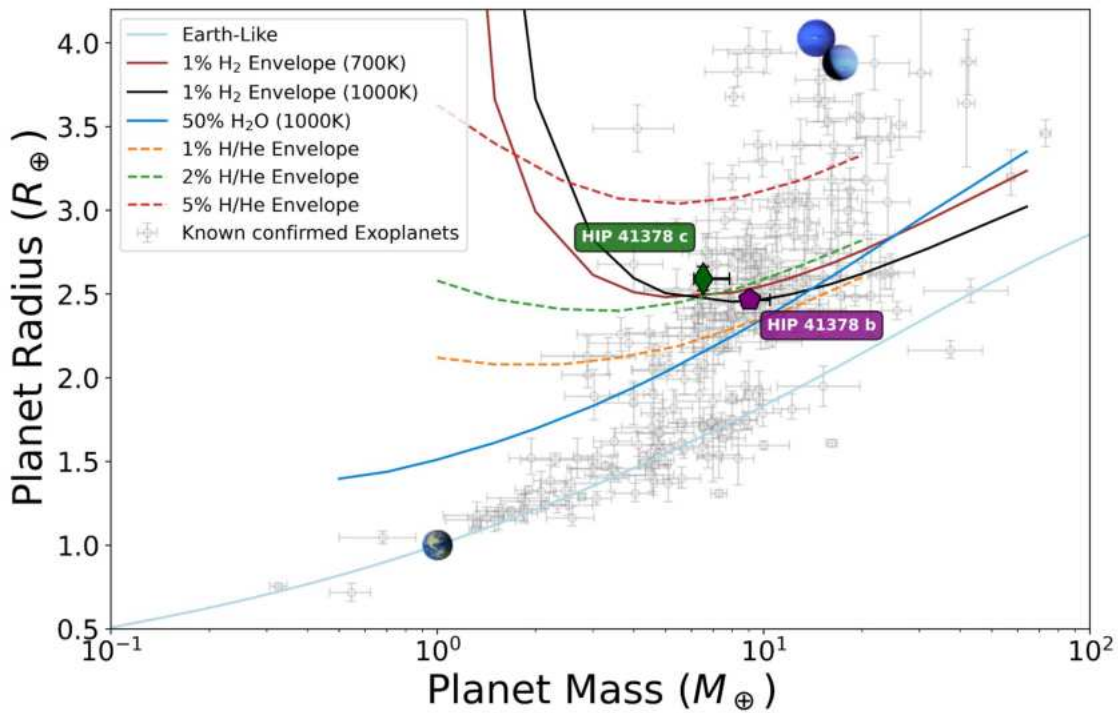
Dynamical Modeling (TTVs + RVs): 3-planet model



Dynamical Modeling (TTVs + RVs): Model choice



Three sub-Neptunes close to a 1:2:4 resonant chain



Planet b:

Period = 15.57128 ± 0.00020 days

Radius = $2.466 \pm 0.029 R_{\oplus}$

Mass = $9.06 \pm 1.41 M_{\oplus}$

Eccentricity = 0.0213 ± 0.0099

Planet c:

Period = 31.71076 ± 0.00179 days

Radius = $2.592 \pm 0.071 R_{\oplus}$

Mass = $6.53 \pm 1.33 M_{\oplus}$

Eccentricity = 0.0678 ± 0.0097

Planet g:

Period = 64.067 ± 0.067 days

Mass = $6.81 \pm 1.14 M_{\oplus}$

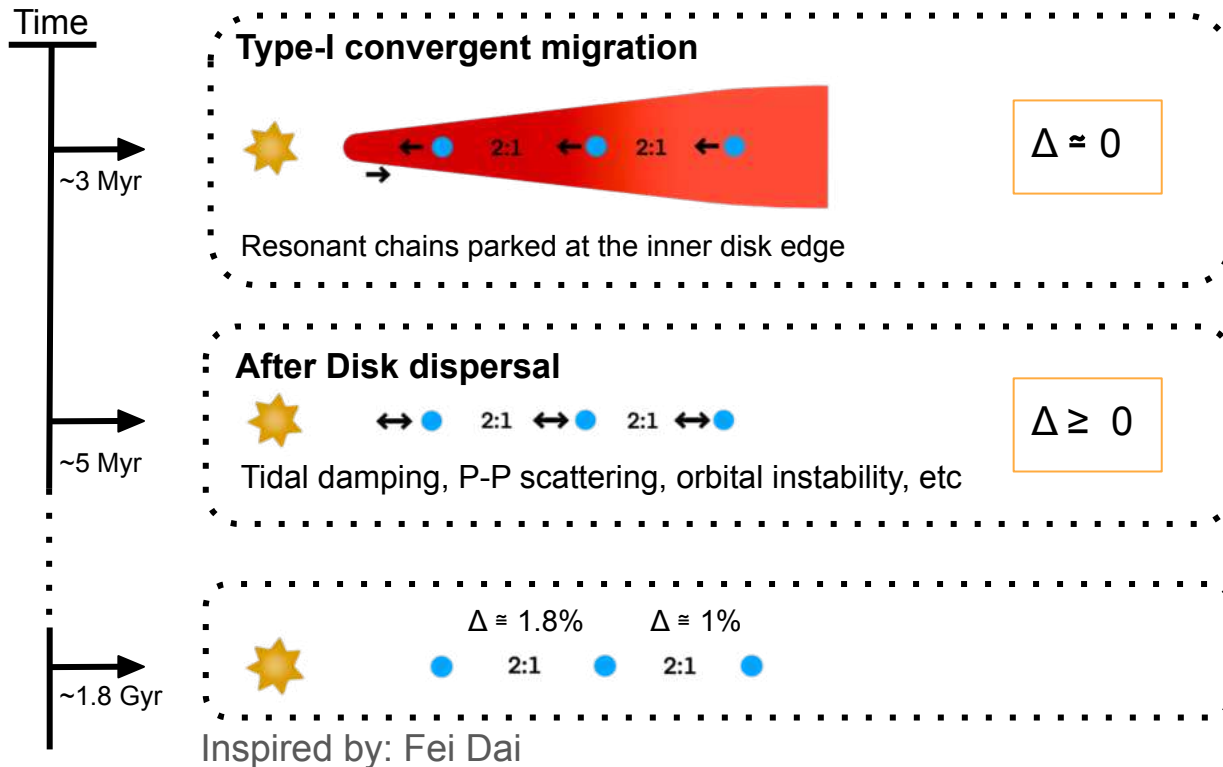
Eccentricity = 0.010 ± 0.010

Inclination = 95°

The color-coded lines show different theoretical mass–radius relations corresponding to the planet compositions taken from Zeng et al. (2019) (solid lines) and Lopez & Fortney (2014) (dashed lines; 1 Gyr, solar metallicity and incident flux of $10 S_{\oplus}$). Also shown are Earth, Uranus and Neptune, for reference.

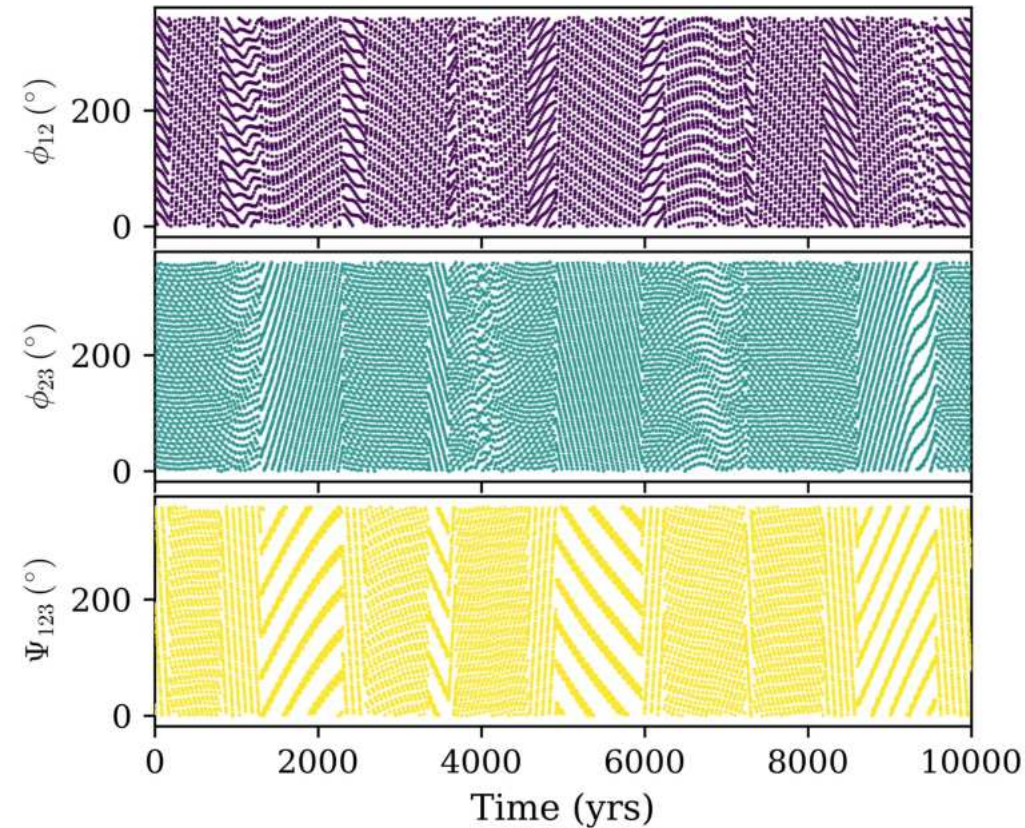
HIP 41378: A possible Laplace chain?

Formation of the inner resonant chain



- Constrain **formation and migration histories**
- **Long-term stability**
- Use **TTVs** to estimate masses, eccentricities, and possible additional (non-transiting) companions.

Are the inner planets in a 1:2:4 Laplace MMR?



Three-body Laplace resonant angles

$$\Phi_{12} = 2\lambda_c - \lambda_b - \tilde{\omega}_c$$

$$\Phi_{23} = 2\lambda_g - \lambda_c - \tilde{\omega}_c$$

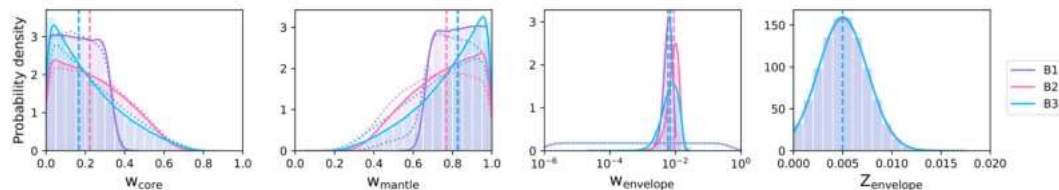
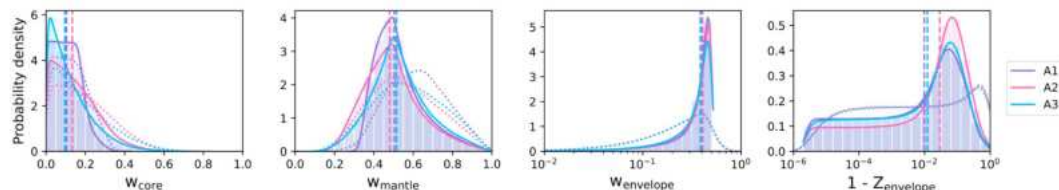
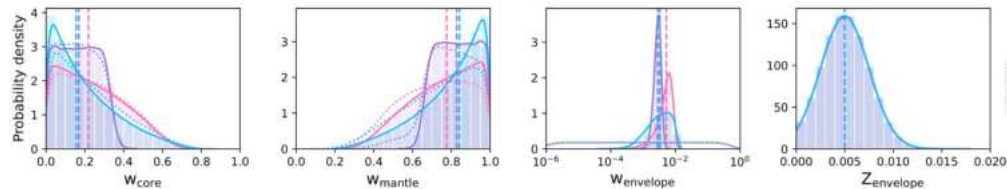
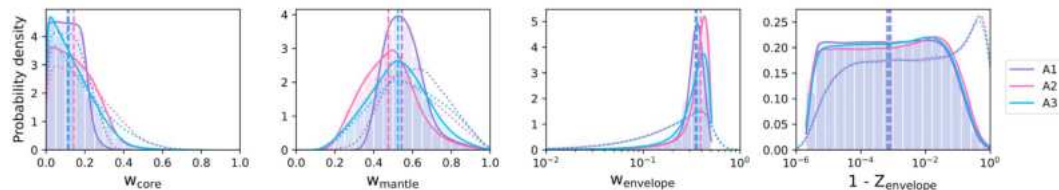


$$\Psi_{123} = \Phi_{12} - \Phi_{23}$$

$$= 3\lambda_c - \lambda_b - 2\lambda_g$$

What Are HIP 41378 b & c Made Of?

Work done by:
Jo Ann Egger



HIP 41378 b

HIP 41378 c

Results of plaNETic:

- Tested **six different prior scenarios**, reflecting different formation histories (e.g., forming inside or beyond the ice line).
- We also varied assumptions about bulk rock composition (e.g., same as the star vs. enriched in iron).
- The core and mantle layers remain **poorly constrained** due to degeneracies.

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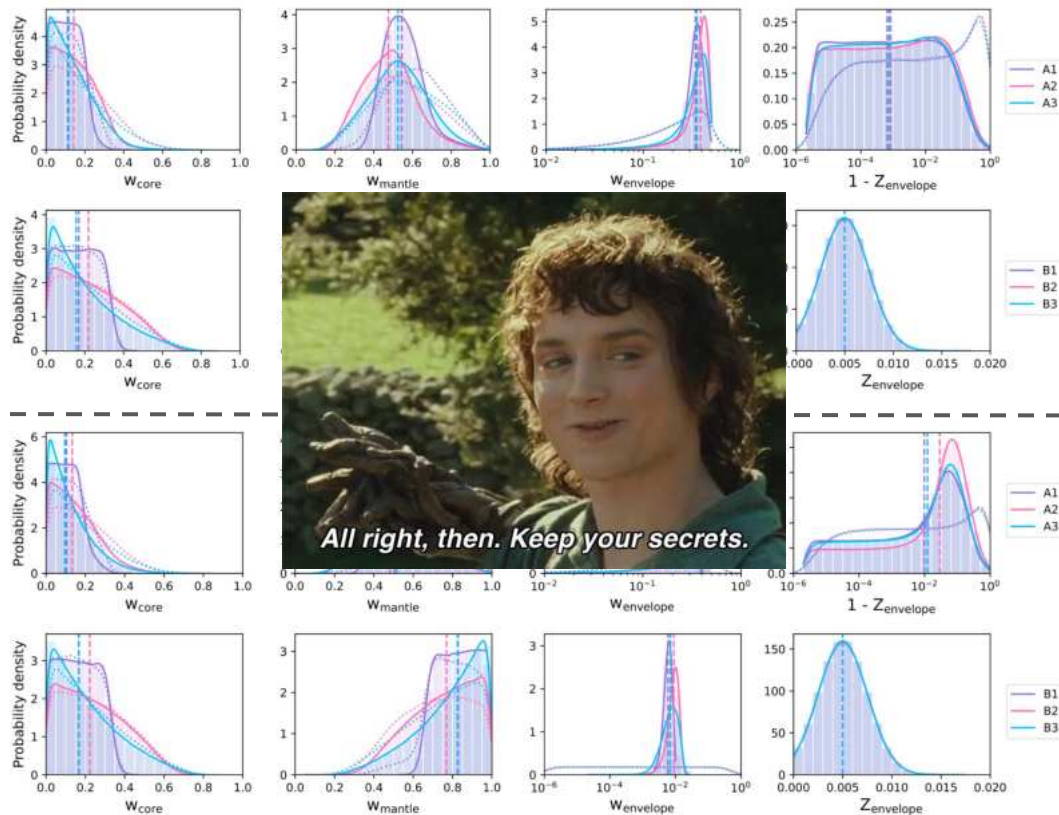
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HIP 41378 b

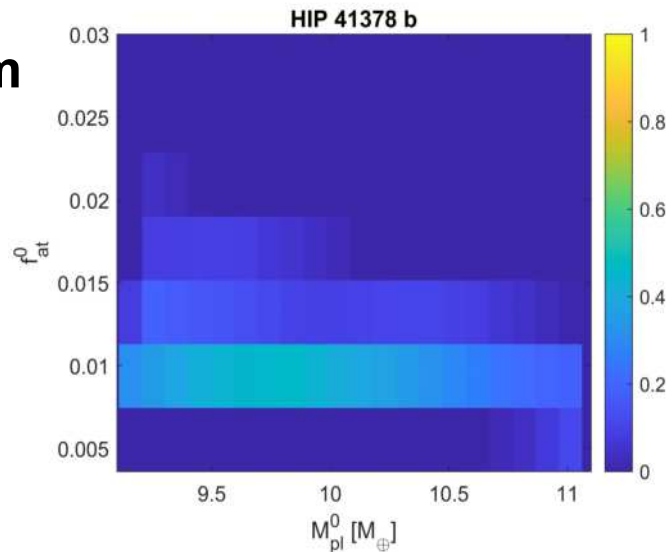
HIP 41378 c



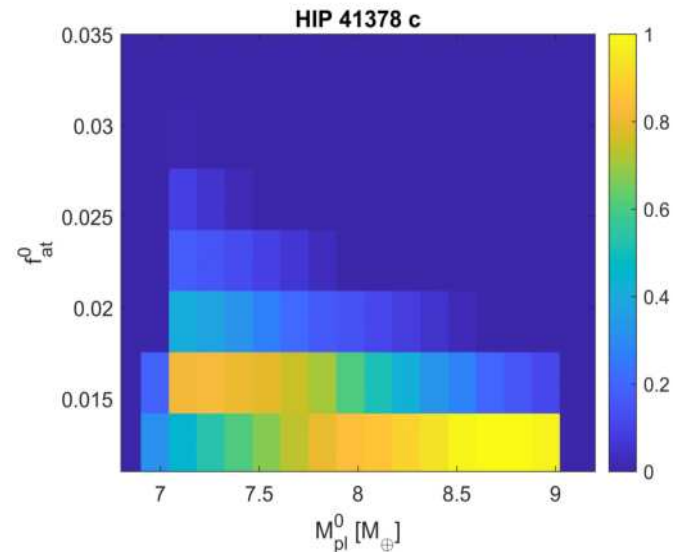
Primordial Atmospheric Evolution of HIP 41378 b & c

**Simulated long-term
primordial
atmospheric
evolution**

**MESA +
hydrodynamic
escape models.**



Planet b: narrow range of initial atmospheres \rightarrow low loss



Planet c: two possible outcomes (compact or puffy) depending on mass

Work done by:
Daria Kubyshkina

Atmospheric characterization prospects with JWST

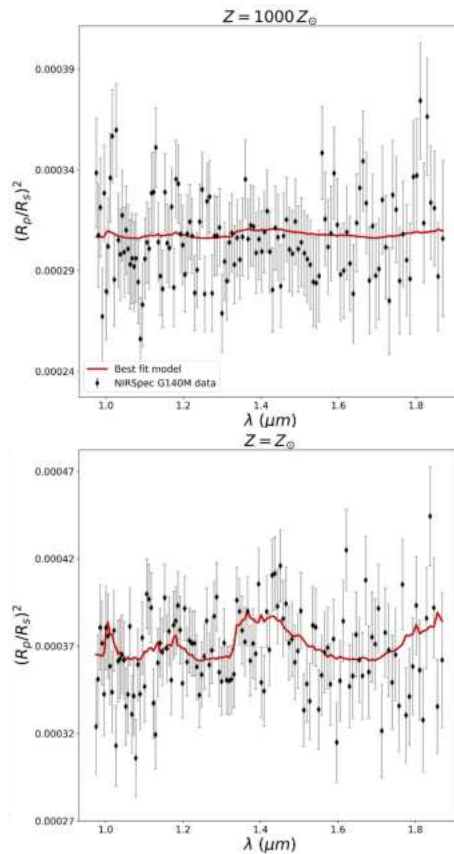


Simulated JWST/NIRSpec spectra

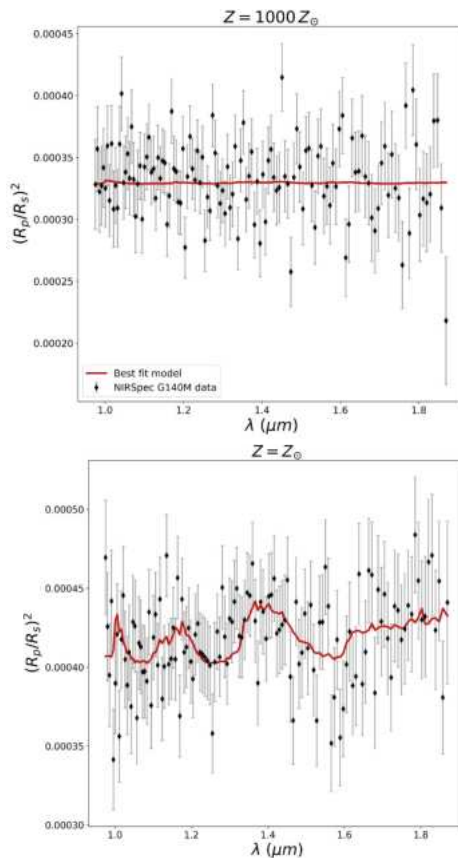
Bayes factor > 10

→ Strong evidence that JWST can differentiate light vs heavy atmospheres

HIP 41378 b



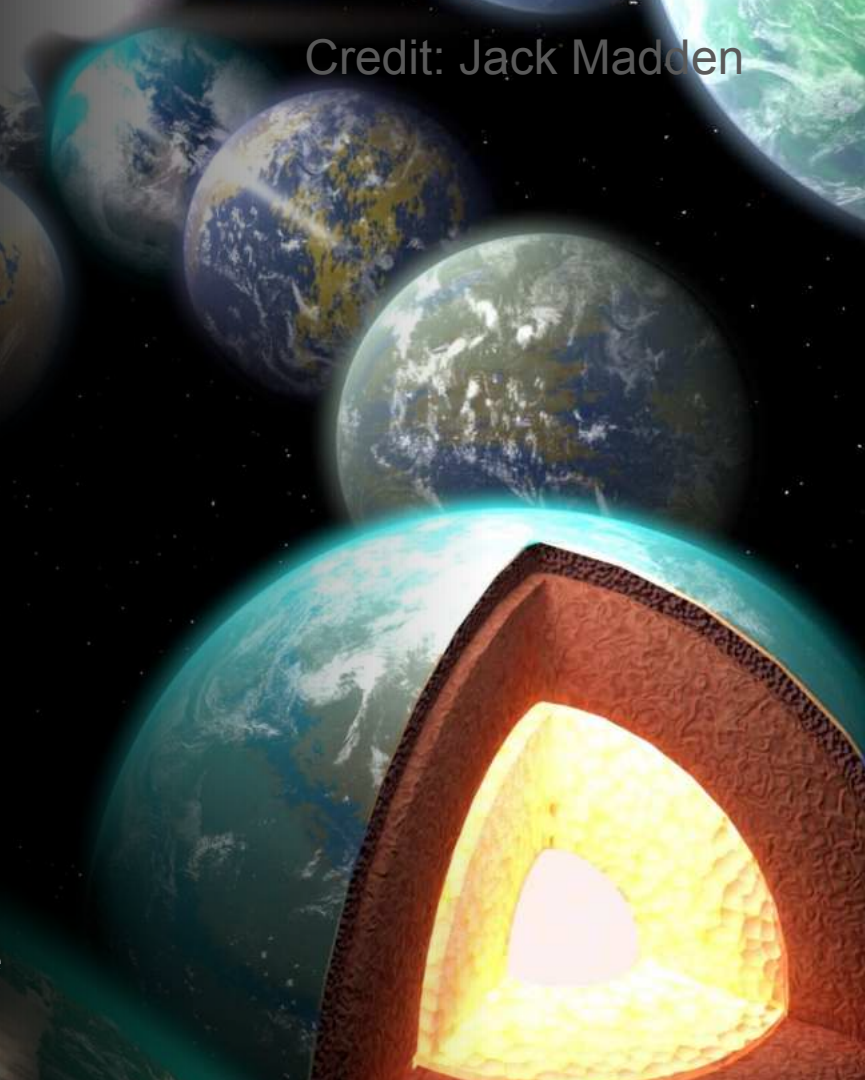
HIP 41378 c



Work done by:
Leonardo Pagliaro

TAKE HOME MESSAGE

- Confirmed the non-transiting planet HIP 41378 g using TTVs + RVs
- Refined the **masses and eccentricities** of: HIP 41378 b, HIP 41378 c and HIP 41378 g
- No Laplace resonance of the inner planets
- Insights into the **interior composition** and **atmospheric** evolution and future characterization.



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I am finishing my PhD in October!

Do you have a Post-Doc, good sir?

