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

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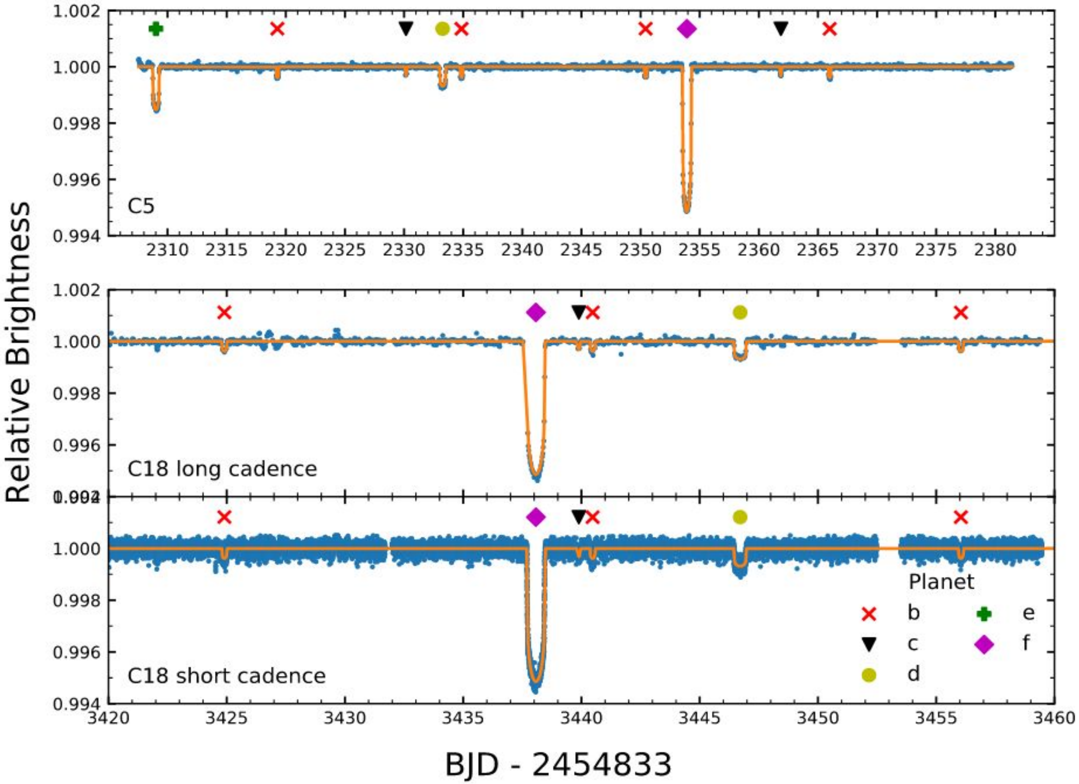
PhD SST
Space Science and Technology

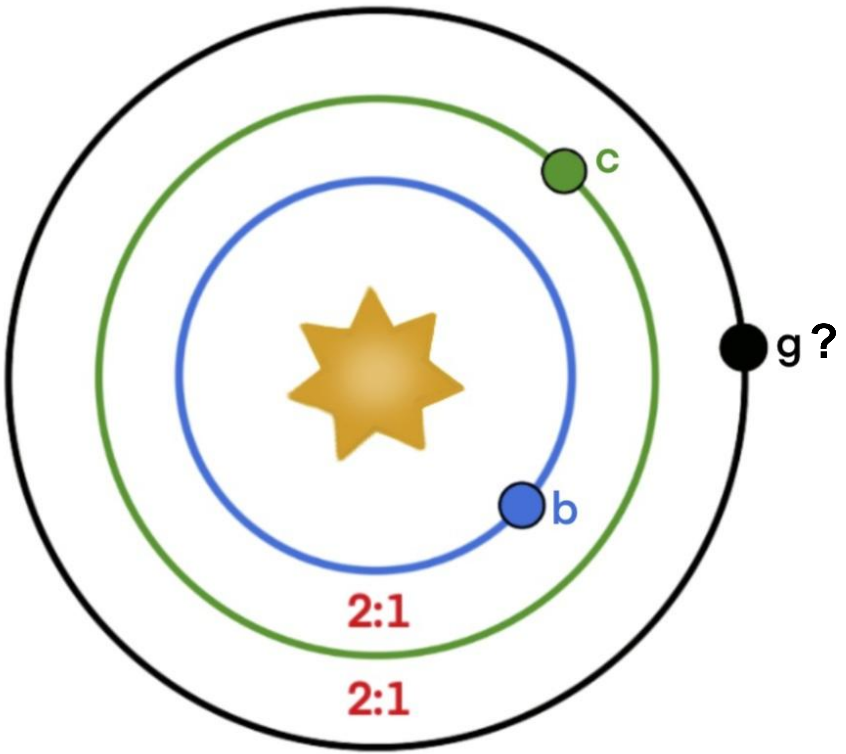
The HIP 41378 system



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

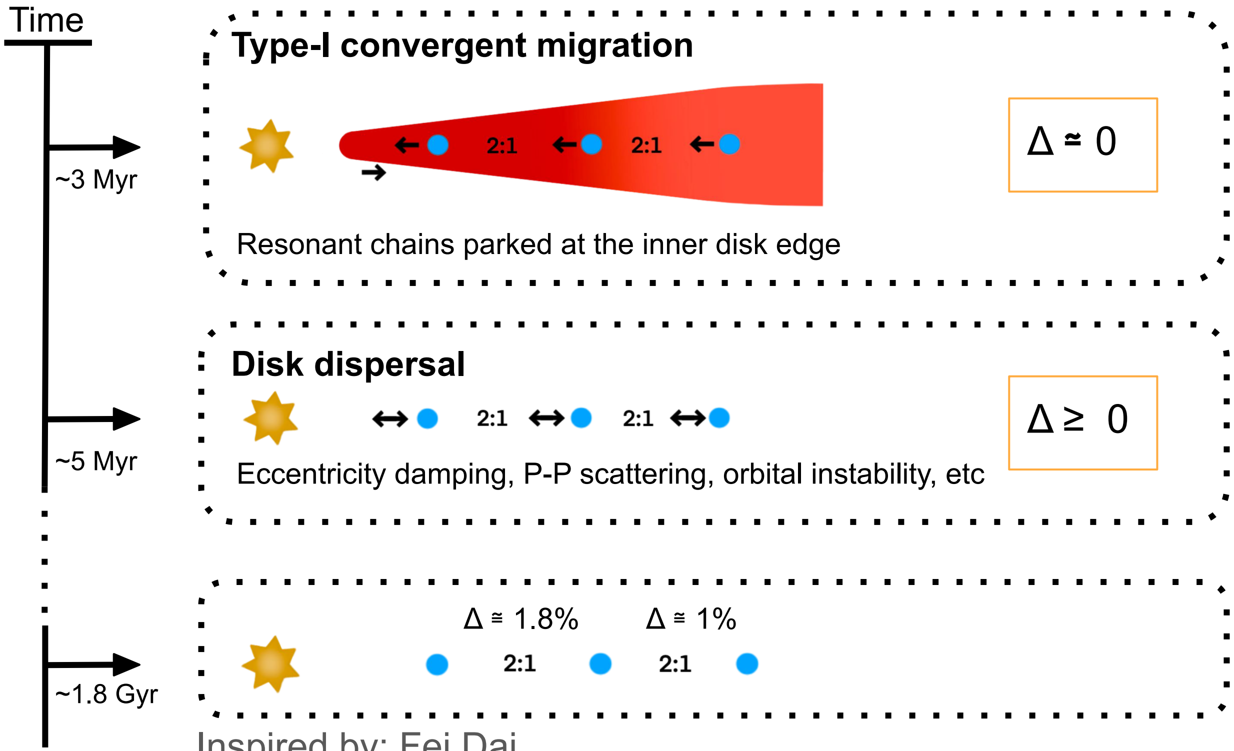
The inner HIP 41378 system



- Two Inner sub-Neptunes close (Δ~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)

HIP 41378: A possible Laplace chain?

Formation of the inner resonant chain



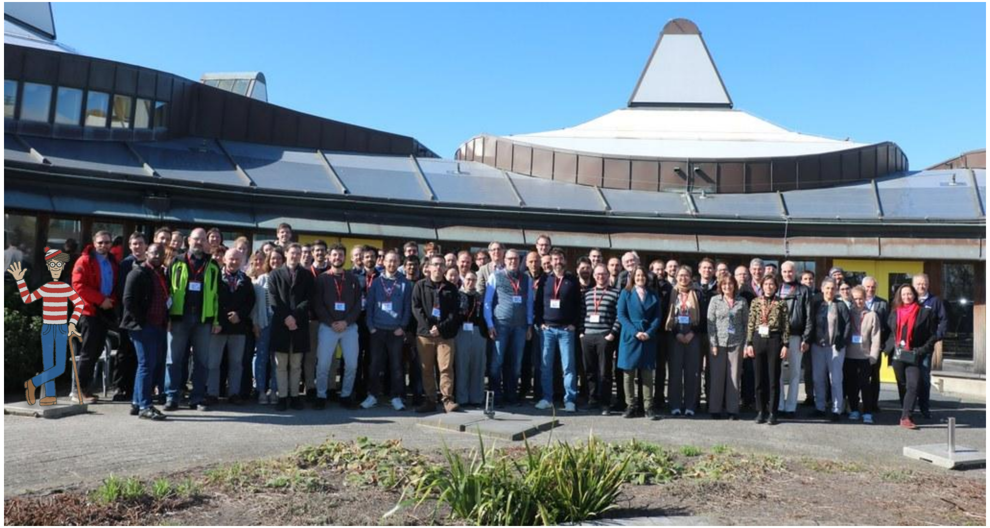
Inspired by: Fei Dai

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

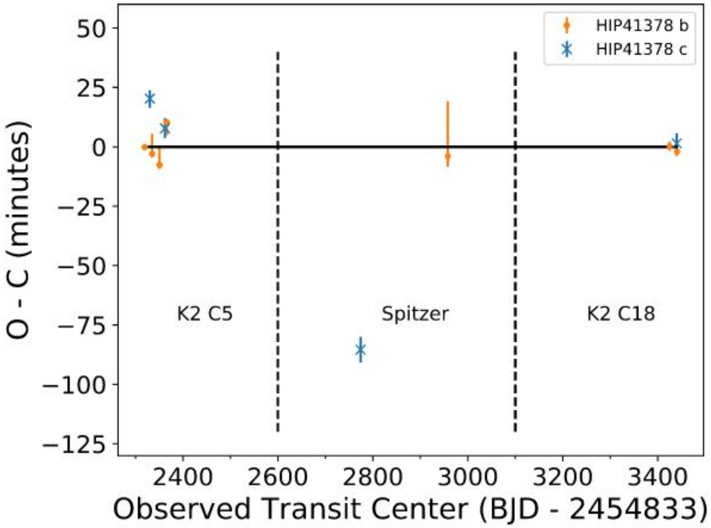
CHEOPS Follow-up on the inner duo

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

  TTVs follow-up observations of resonant multi-planet systems



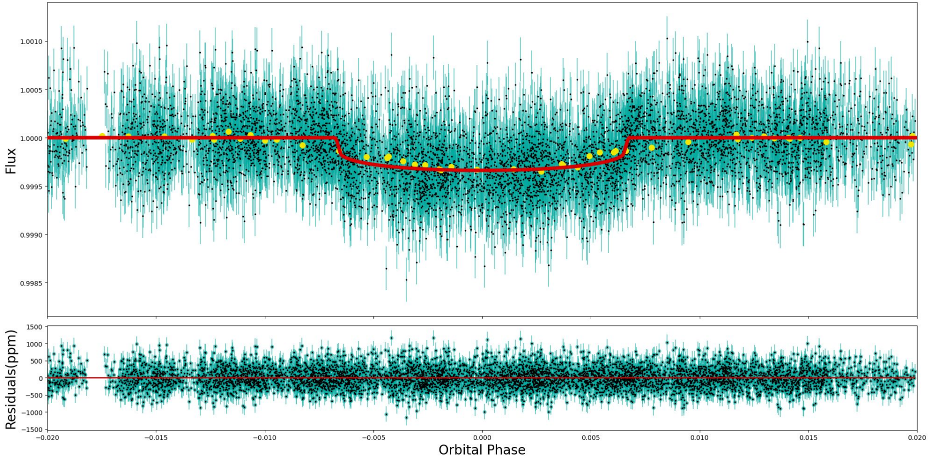
CHEOPS Consortium (Noordwijk, 2025)



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

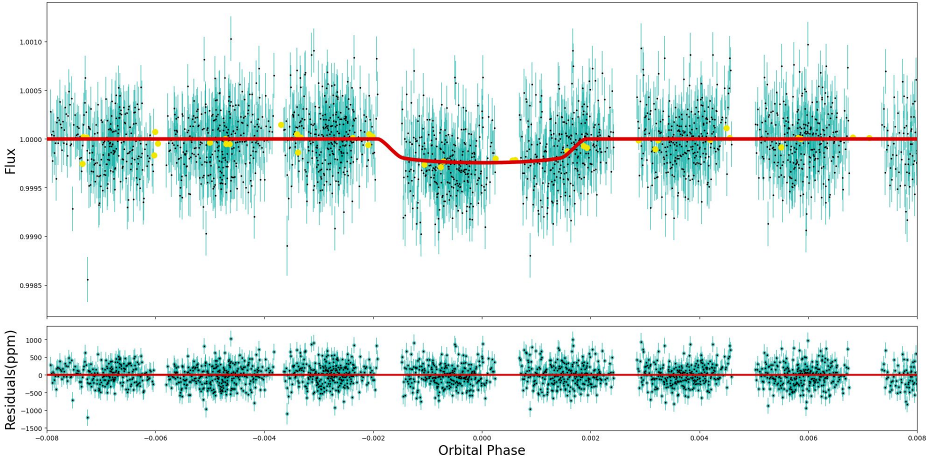
CHEOPS Follow-up on the inner duo

Phase-folded CHEOPS visits



HIP 41378 b

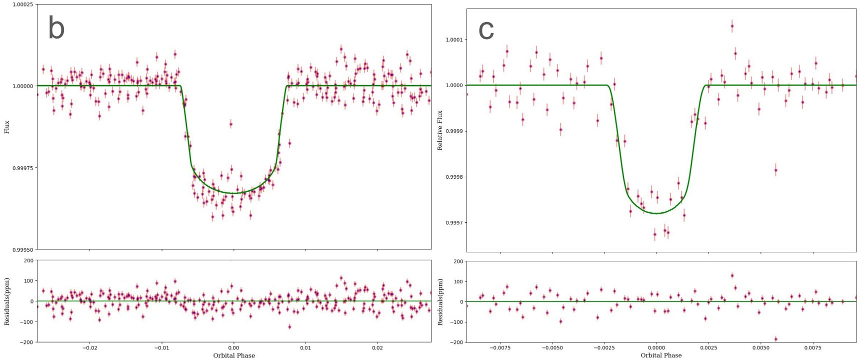
HIP 41378 c



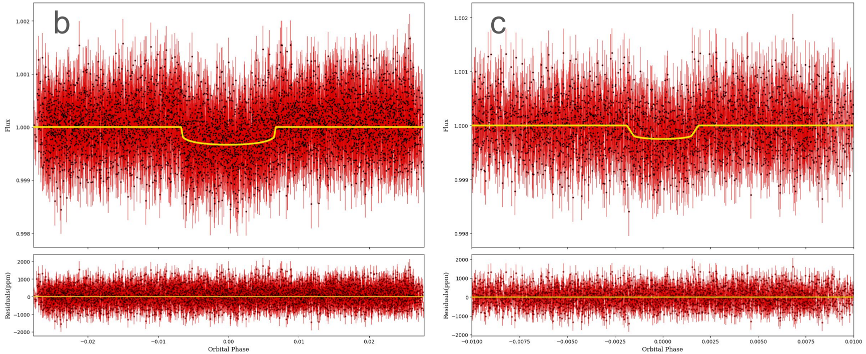
Detrending + Photometric fit done with PyORBIT (Malavolta et al. 2016; 2018)

Space-based follow-up with four telescopes

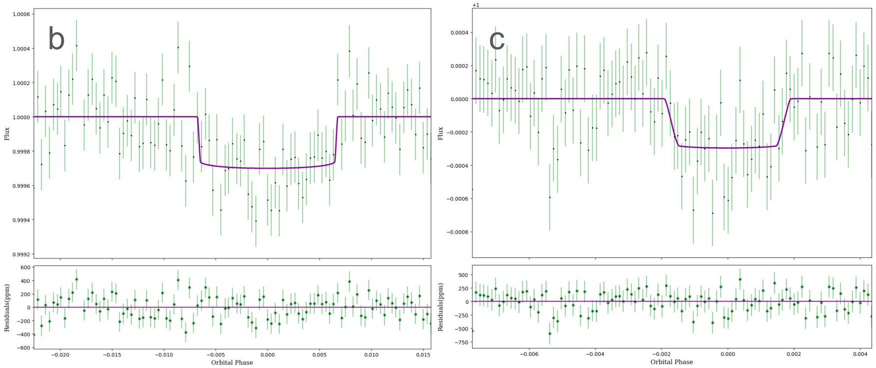
K2



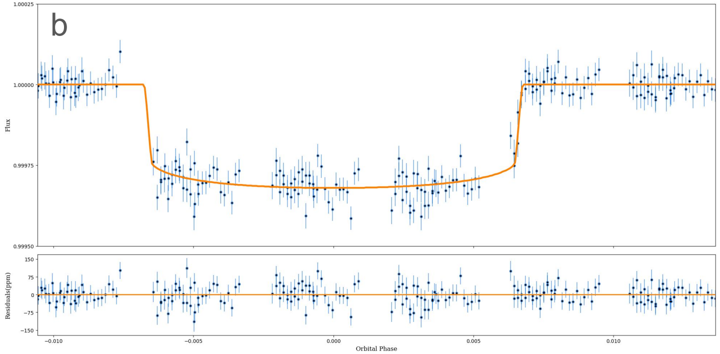
TESS



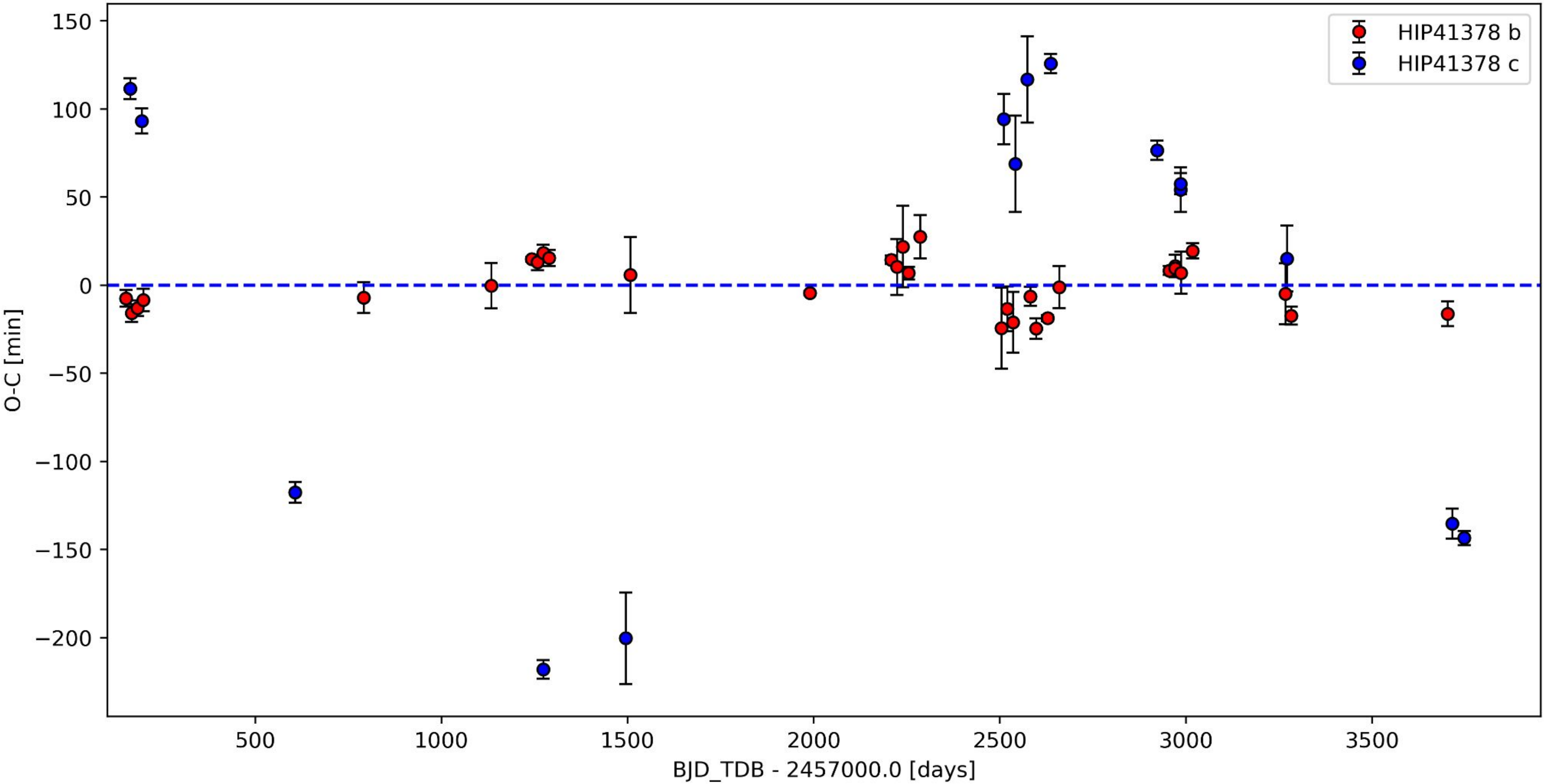
Spitzer



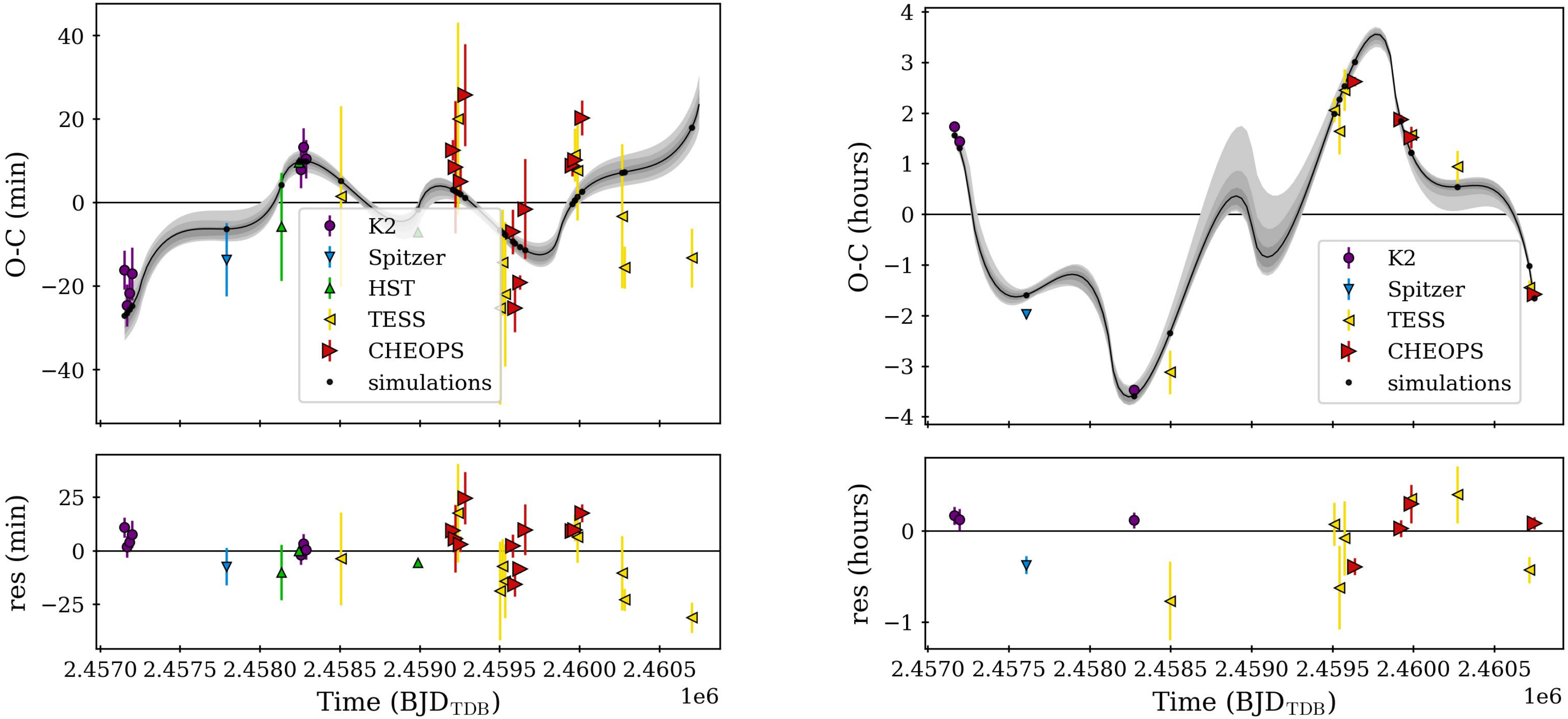
HST



O-C diagram of HIP 41378 b & c

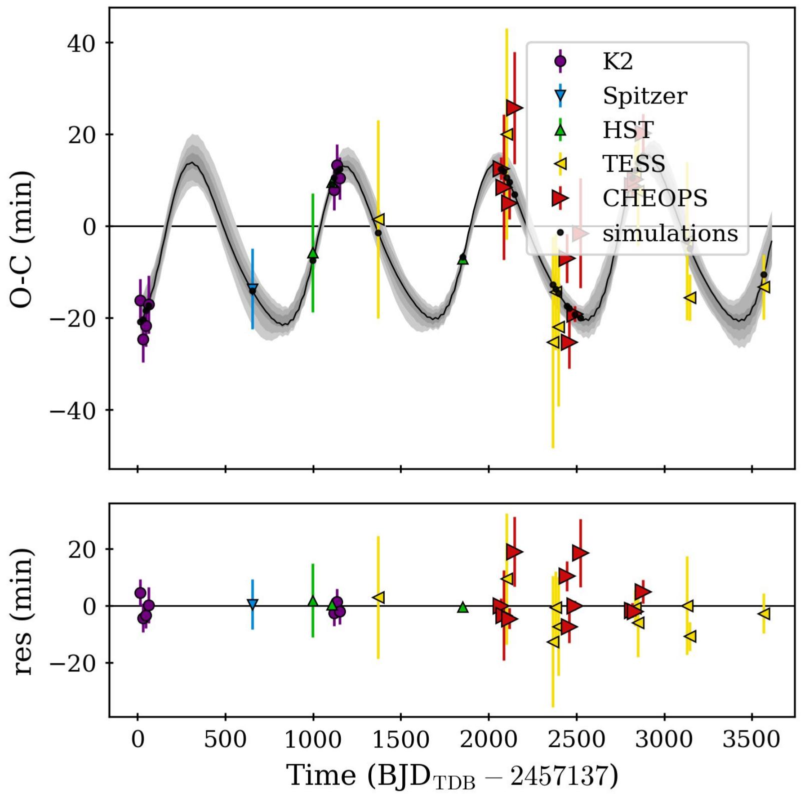


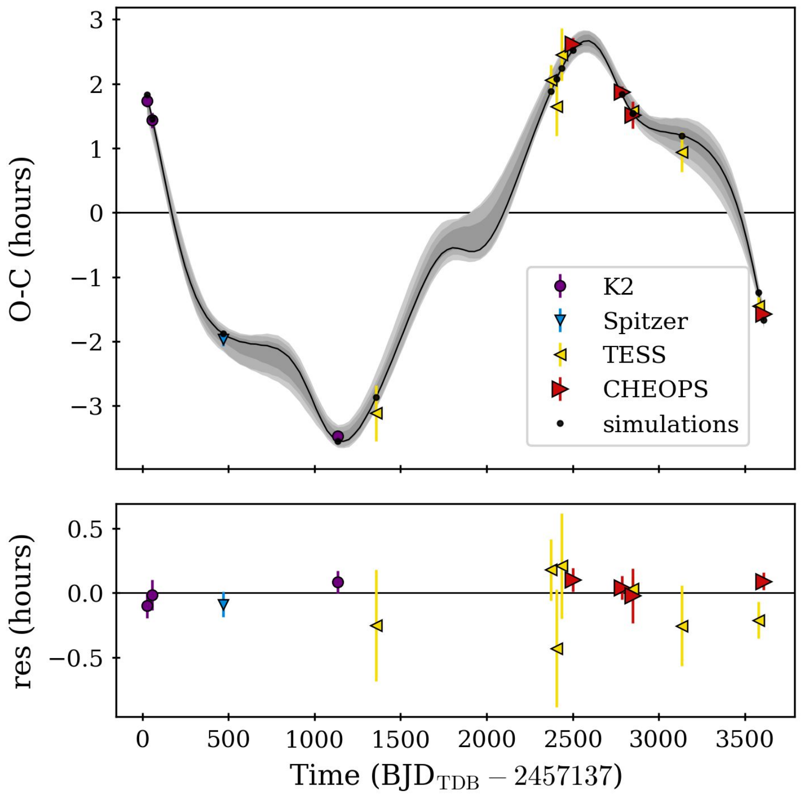
Dynamical Modeling (TTVs + RVs): 2-planet model



Dynamical modeling done with TRADES (Borsato et al. 2014; 2019, 2021)

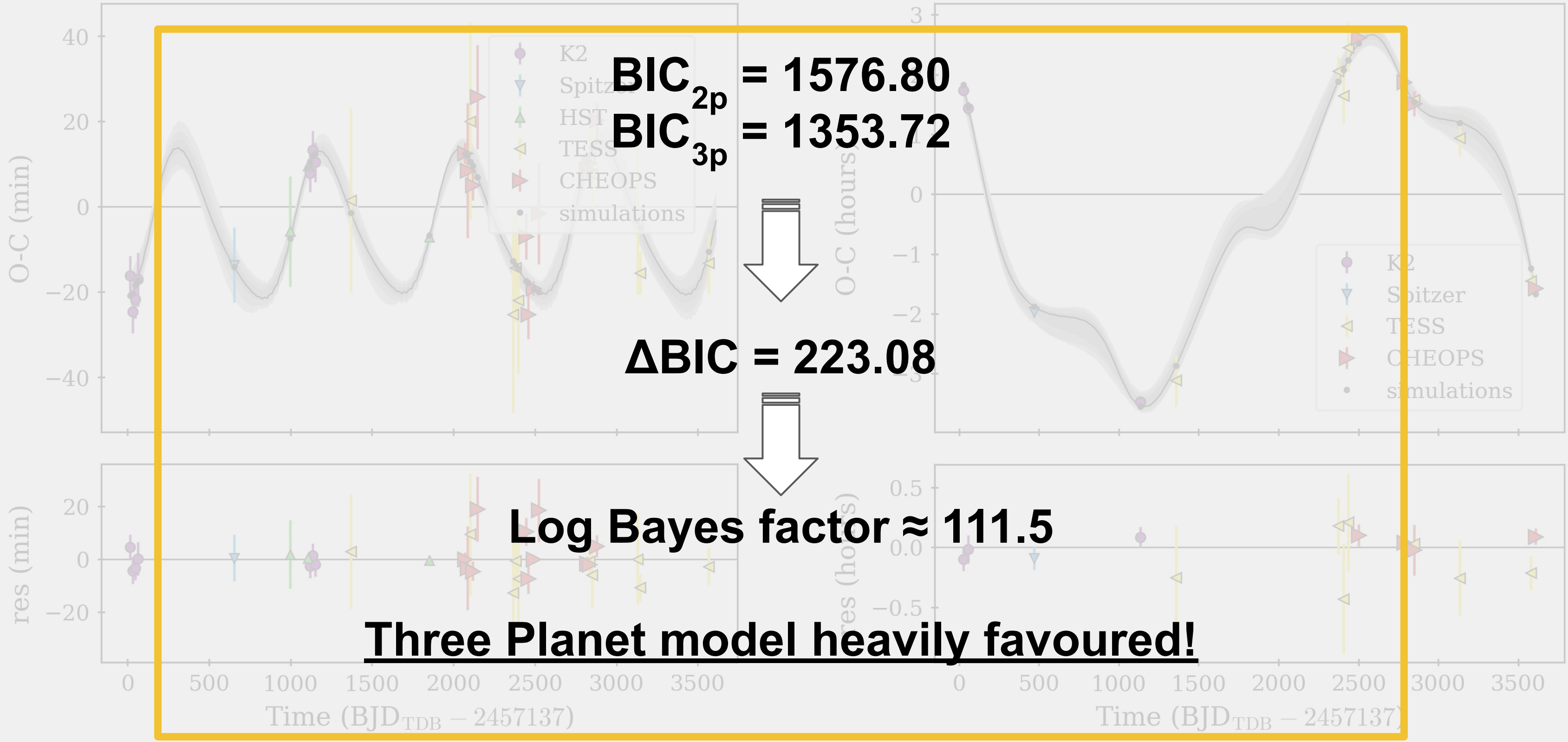
Dynamical Modeling (TTVs + RVs): 3-planet model





Dynamical modeling done with TRADES (Borsato et al. 2014; 2019, 2021)

Dynamical Modeling (TTVs + RVs): Model Choice



BIC_{2p} = 1576.80
BIC_{3p} = 1353.72

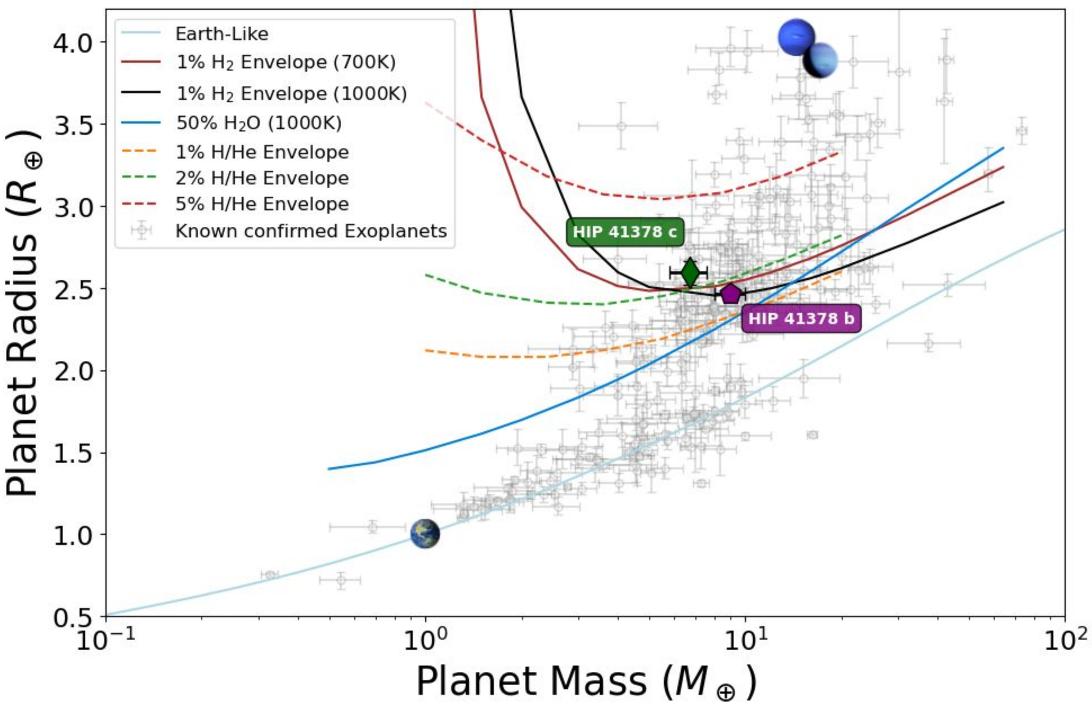
ΔBIC = 223.08

Log Bayes factor ≈ 111.5

<u>Three Planet model heavily favoured!</u>

Dynamical modeling done with TRADES (Borsato et al. 2014; 2019, 2021)

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



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.

Planet b:

Period = 15.57128 ± 0.00020 days
Radius = 2.466 ± 0.029 $R_\oplus$
Mass = 9 ± 1 $M_\oplus$
Eccentricity = 0.0229± 0.0090

Planet c:

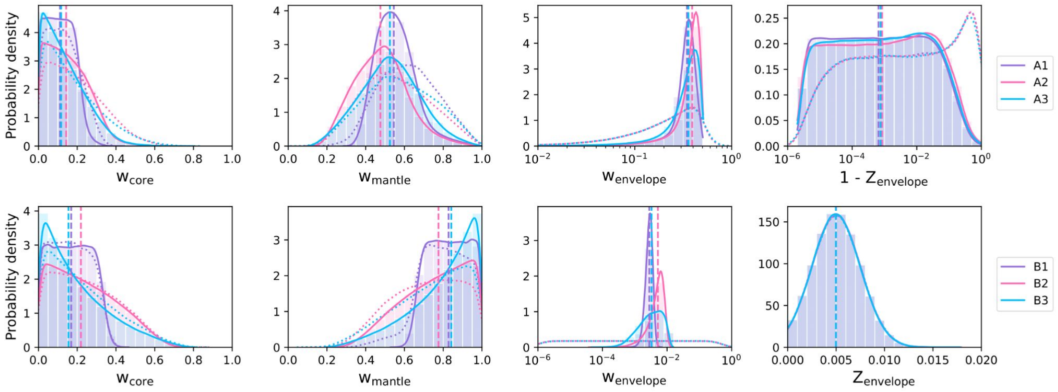
Period = 31.71076 ± 0.00179 days
Radius = 2.592 ± 0.071 $R_\oplus$
Mass = 6.72 ± 0.91 $M_\oplus$
Eccentricity = 0.0642 ± 0.0104

Planet g:

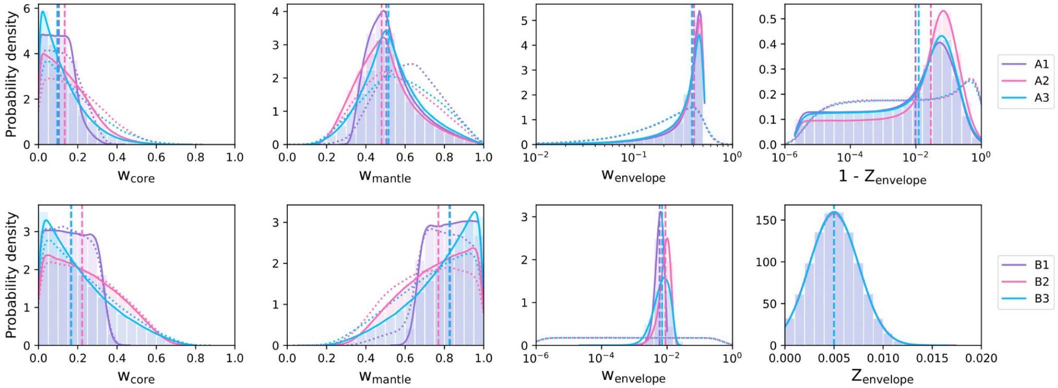
Period = 64.061 ± 0.00179 days
Mass = 7 ± 1 $M_\oplus$
Eccentricity = 0.013 ± 0.036
Inclination = 86°

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.

What Are HIP 41378 b & c Made Of?

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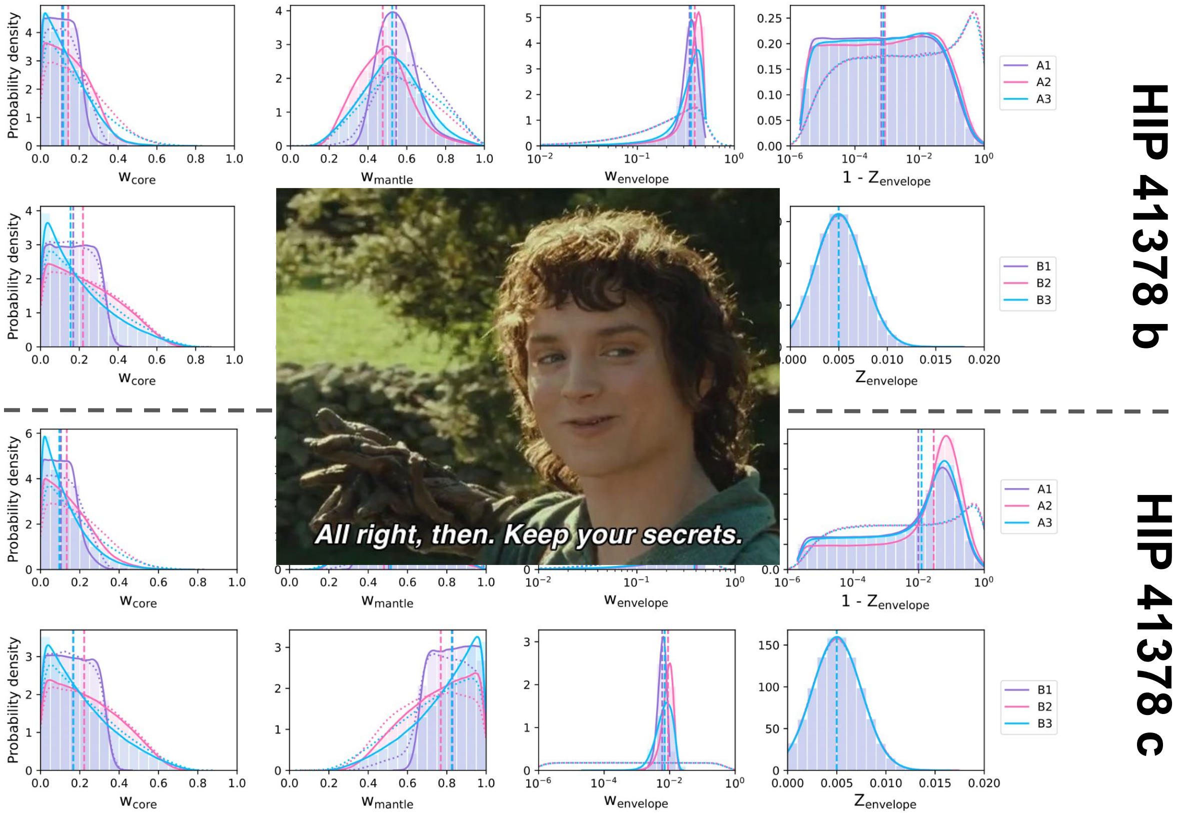

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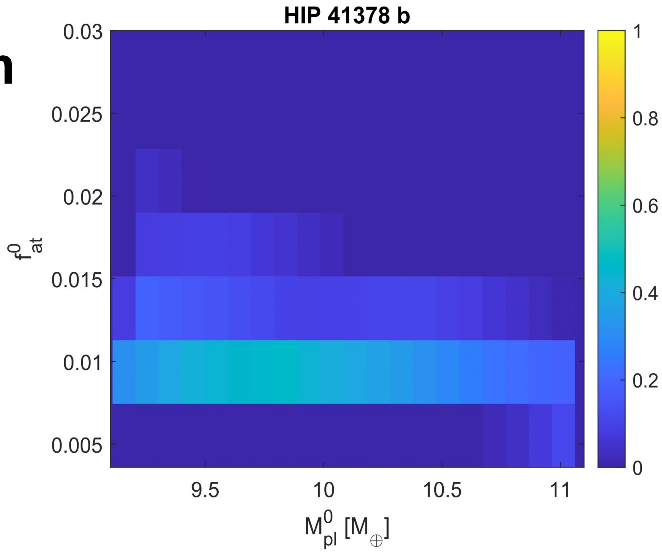
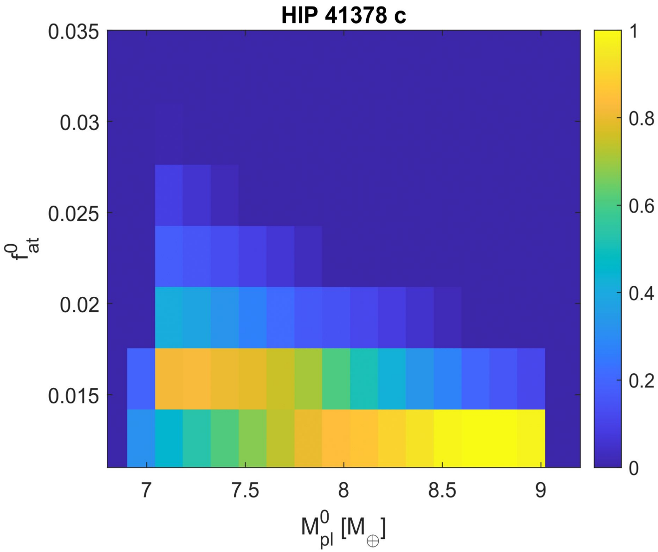
Modeling the Atmospheric Evolution of HIP 41378 b & c

Simulated long-term primordial atmospheric evolution (MESA + hydrodynamic escape models.





Planet b: narrow range of initial atmospheres → low loss

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

Work done by:
Daria Kubyshkina

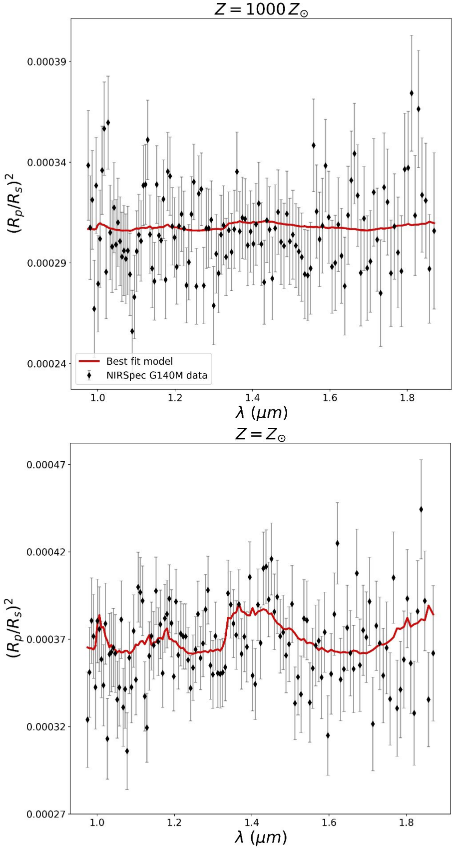
Atmospheric characterization prospects with JWST

Simulated JWST/NIRSpec spectra

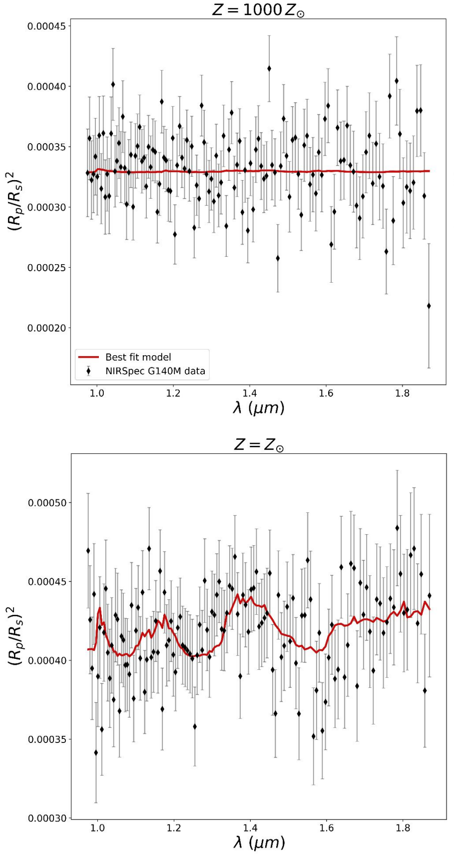
Bayes factor > 10

→ Strong evidence that JWST can differentiate light vs heavy atmospheres

HIP 41378 b



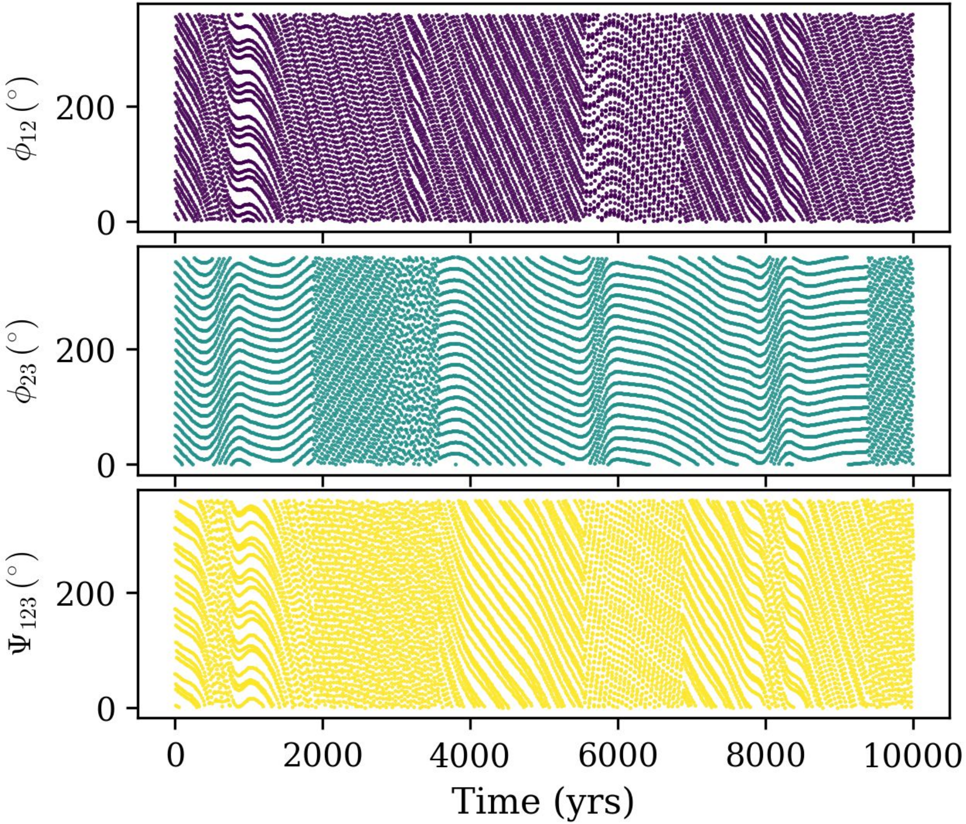
HIP 41378 c



Work done by:
Leonardo Pagliaro

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

Work done by:
L.Pietro



Three-body Laplace resonant angles

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

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

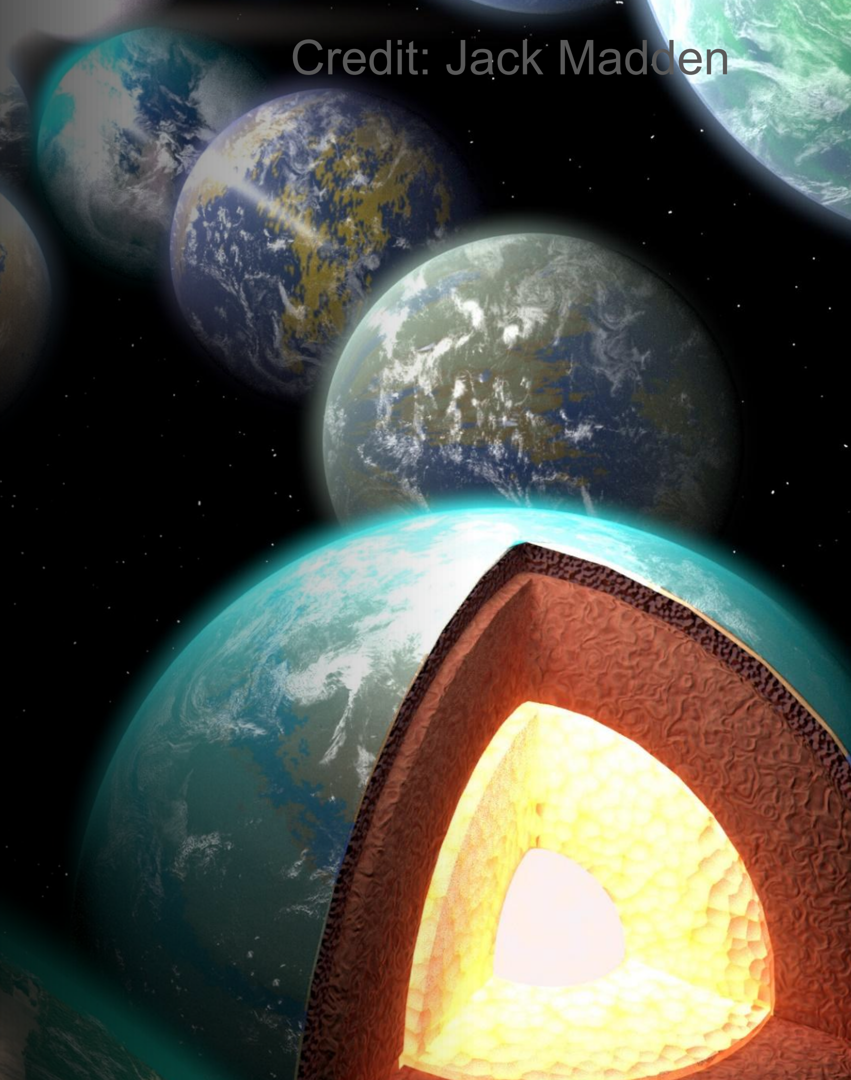
$$\Rightarrow$$

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

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

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.



Credit: Jack Madden