TOI-332: A SUPER-DENSE NEPTUNE FOUND DEEP WITHIN THE HOT NEPTUNIAN DESERT

I. CONTEXT

- ★ To date we have discovered thousands of planets, but there remain regions of parameter space that are still bare: for example, the "Neptunian desert", where planets should be easy to find but discoveries remain few
- ★ Planets in the desert must have undergone unusual / rare formation and evolution processes
  - ★ There are so far only 5 other planets with precise mass determinations located deep in the desert, far from the boundaries: NGTS-4b (West+ 2019), TOI-849b (Armstrong+ 2020), LTT-9779b (Jenkins+ 2020), TOI-2196b (Persson+ 2022), and TOI-1853b (Naponiello 2023).
  - ★ We were looking to find more of these through our "Nomads" programme!

Our "NOMADS" large programme on the HARPS spectrograph aimed to study the nature and origin of the Neptunian Desert by precisely characterising ~30 nomad planets, substantially increasing the current sample of planets with precisely measured masses (better than 20% errors) and radii in the desert, particularly in the 'deep desert' far from the boundaries.

- ★ Need masses to constrain densities and thus infer composition.
- ★ The resulting sample of characterised planets will provide the basis for theoretical studies of the processes that place planets inside the desert, allowing us to push the boundaries of planet formation models and test them against nomad benchmarks.

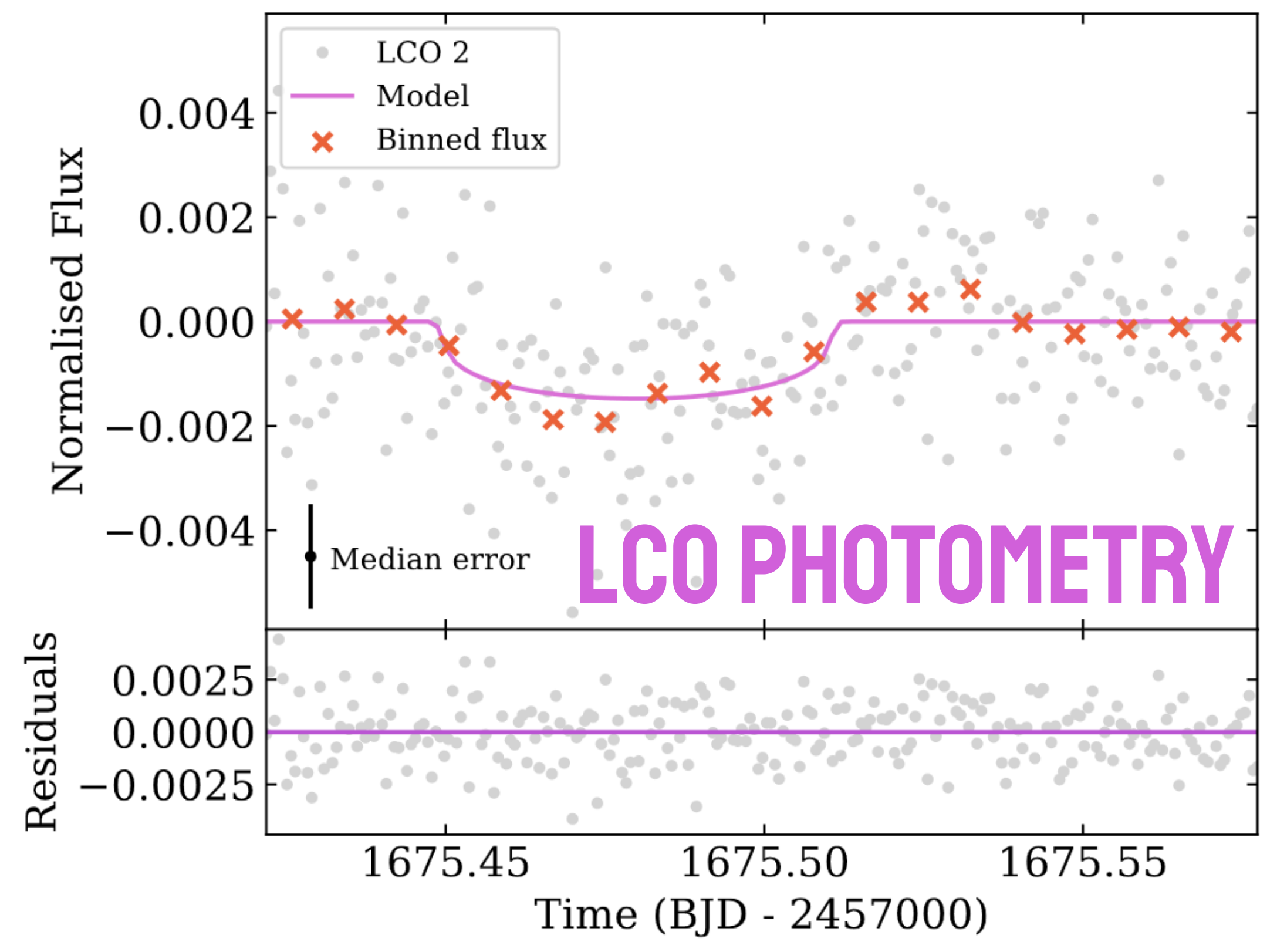

Fig. 2: 1 of the 6 LCO transits, observed with SAAO

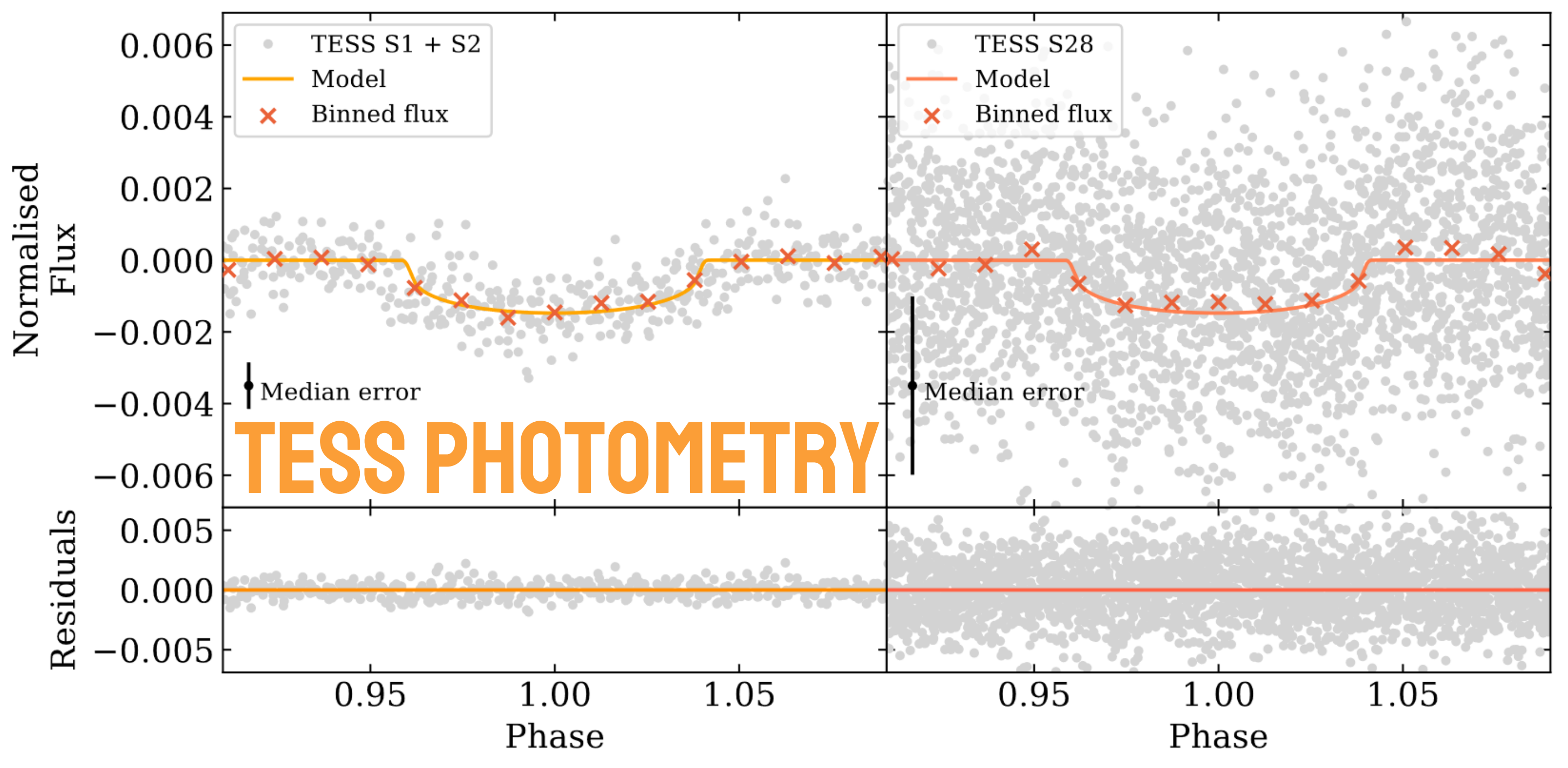

Fig. 1: phase folds of the TESS S1+S2 (left) and S28 (right) photometry

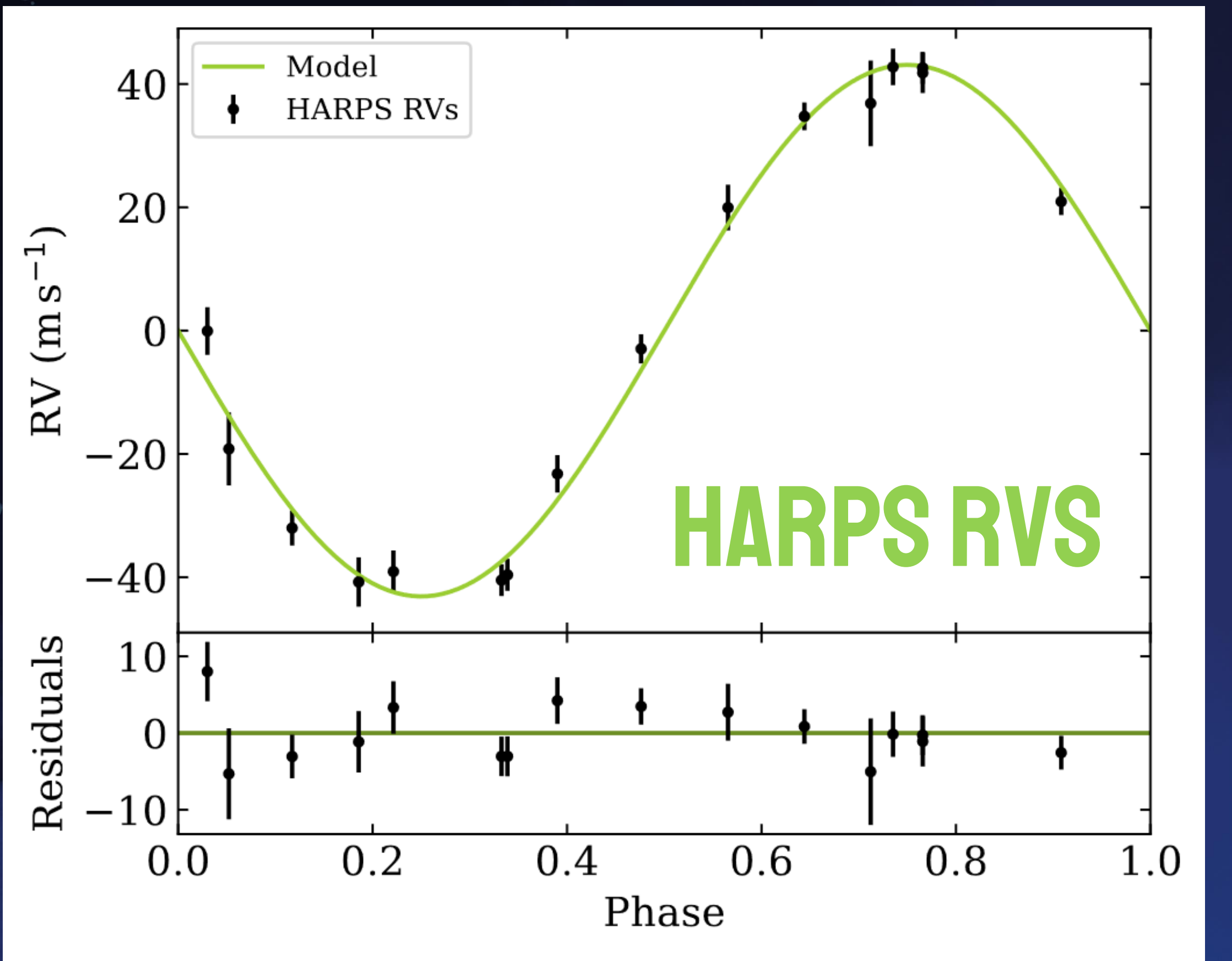

Fig. 3: the HARPS RV data, phase folded

2. OBSERVATIONS

- ★ TESS: 2 sectors (S1+S2) at 30 min cadence; 1 sector (S28) at 2 min (Fig. 1)
- ★ LCO: 6 transits, 5 full, 1 partial (Fig. 2)
- ★ PEST: 1 partial transit, ruined by weather
- ★ WASP: monitoring over 7 years, transit detection tentative
- ★ HARPS: 16 RV spectra from the Nomads program (Fig. 3)
- ★ Gemini/Zorro and VLT/NaCo: HR imaging excludes companion stars

👉 TESS, LCO, + HARPS data is joint fit with the Python package exoplanet

System

Semi-major axis	0.0159 AU
Impact param.	0.26
Inclination	86.2 °
Eccentricity	0 (fixed)

TOI-332

Spectral type	K0V	
Stellar radius	0.86	$R_\odot$
Stellar mass	0.88	$M_\odot$
Effective temp.	5251	K
[Fe/H]	0.26	Dex
Age	5.0	Gyr

3. SYSTEM DETAILS

TOI-332 b is 1 of 6 planets with a precise mass determination located deep within the Neptunian desert (Fig. 4)

TOI-332 b

Period	0.78	d	→ Ultra-short period
Radius	3.21	$R_\oplus$	→ Radius smaller than that of Neptune
Mass	57.0	$M_\oplus$	→ Mass more than half that of Saturn
Bulk density	9.5	g cm^{-3}	→ One of the densest planets of those the size of Neptune or greater found thus far
Equ. temp.	1869	K	

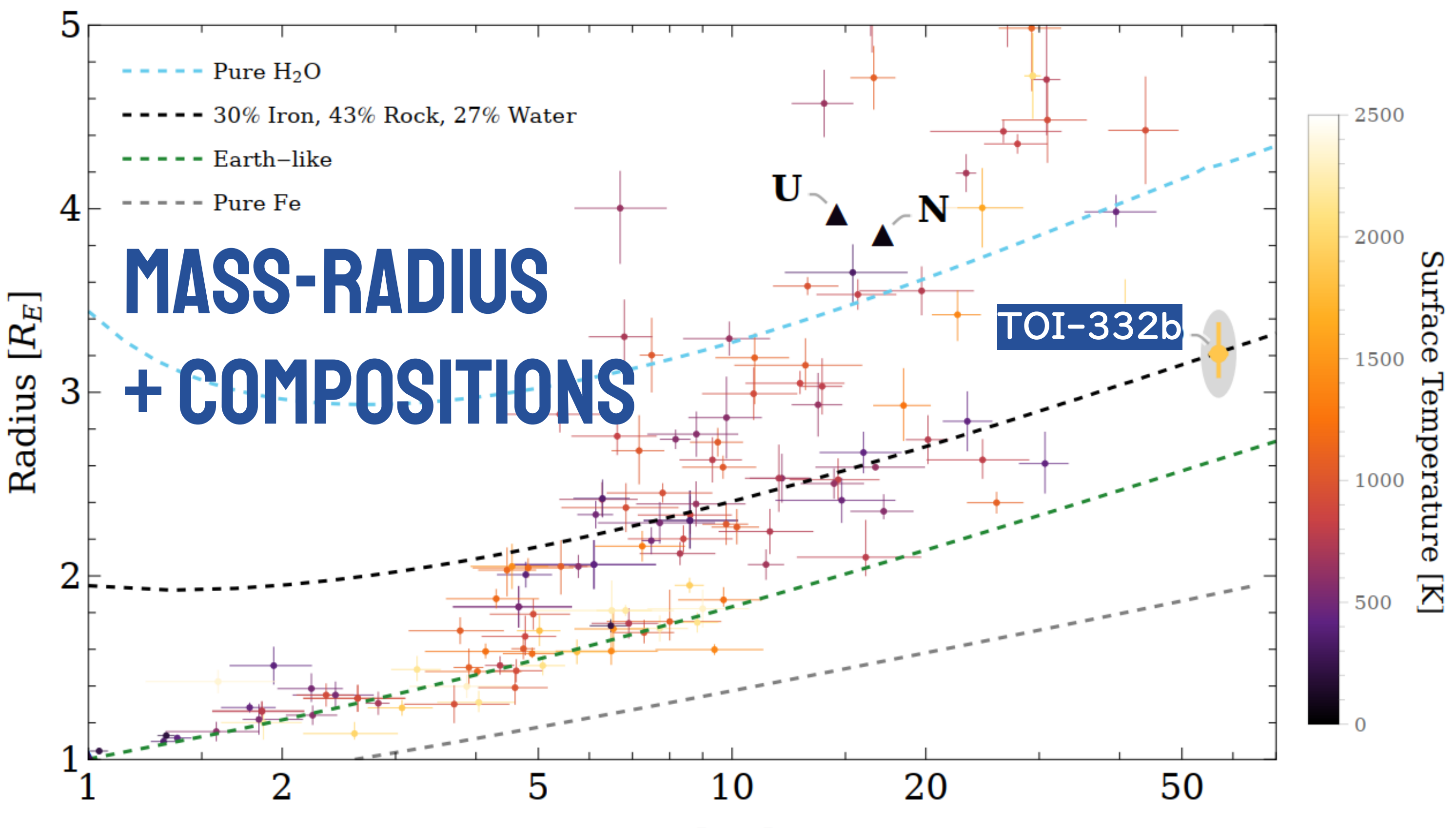

Fig. 5: mass-radius diagram of the exoplanets in Otegi+ 2022, showing mass-radius relations for several compositions, including the composition of TOI-332b (see Section 4)

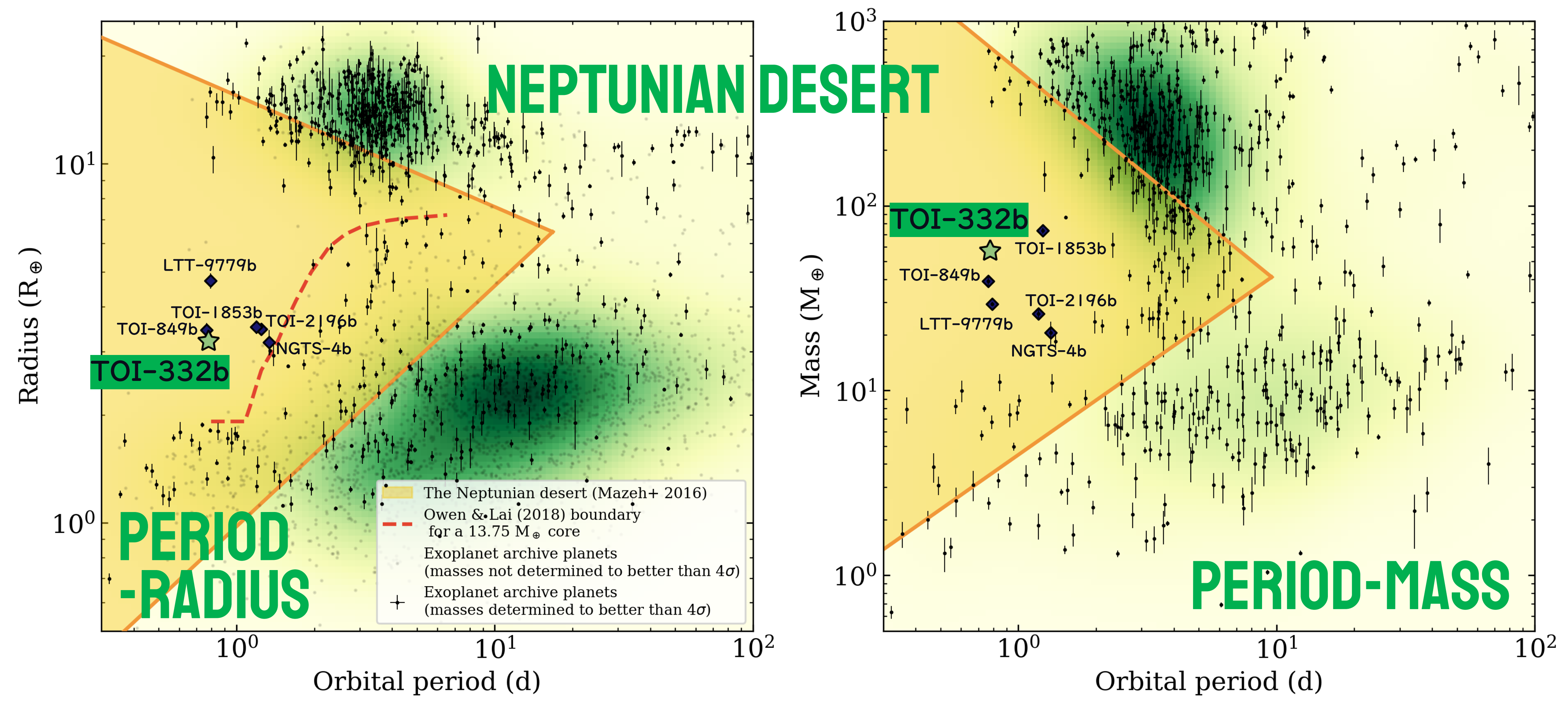

Fig. 4: the Neptunian desert, shown in period-radius space (left) and period-mass space (right), with TOI-332b and the other deep desert planets marked (see Section 1)

4. FORMATION & EVOLUTION

- ★ TOI-332b occupies a unique and unpopulated spot in the MR diagram (Fig. 5)
  - ★ Use a layered interior model to determine a composition of 30% iron core, 43% rock mantle, 27% water, and a negligible H-He envelope
- ★ With such a large core mass and little envelope, TOI-332b does not fit with the theory of planet formation via core-accretion
  - ★ It either avoided runaway accretion or accreted a large envelope which is subsequently lost
- ★ Looking at photoevaporation histories for TOI-332b, we find a narrow range of upper limits on the initial envelope mass fraction of less than 10% - TOI-332b starting out as a Jupiter-sized planet is inconsistent with photoevaporation as the only mechanism for mass loss
- ★ Given its unusually high density, we also rule out a co-orbital scenario consisting of a pair of planets in a 1:1 resonance where only one of the planets transits, which may mimic the appearance of a single, more massive planet.
  - ★ Other explanations?
    - ★ An initially large envelope may have been removed by high-eccentricity migration and subsequent tidal thermalization, or giant planet collisions
    - ★ Runaway accretion could have been initially avoided by gap opening in the protoplanetary disk

5. FUTURE OBSERVATIONS?

Further observations will be needed to deduce more about the formation and evolutionary history and the current composition of TOI-332b.

- ★ Rossiter-McLaughlin observations: measures the sky-projected obliquity of a system, important for constraining formation scenarios: disk-migration is expected to conserve alignment, but misalignment could imply planet-planet/planet-star scattering, high-eccentricity migration or tidal disruption.
- ★ High equilibrium temperature could lead to evaporation of volatiles and a secondary atmosphere that contains core materials, which could be measured
  - ★ A phase curve would constrain its dayside and nightside temperatures and any phase offset, its Bond albedo, and heat recirculation efficiency

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Work done as a PhD at the University of Warwick
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