TOI-332: THE DENSEST KNOWN NEPTUNE FOUND DEEP WITHIN THE HOT NEPTUNIAN DESERT

1. 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 (see Nomads poster)
  - ★ Planets in the desert must have undergone unusual / rare formation and evolution processes
  - ★ There are only 4 planets with precise mass determinations located deep in the desert, far from the boundaries: TOI-849b (Armstrong+ 2020), NGTS-4b (West+ 2019), LTT-9779b (Jenkins+ 2020), and TOI-2196b (Persson+ 2022).
- ★ We present here the discovery of TOI-332b and its follow-up with the Nomads program:
  - ★ Ultra-short period of 0.78d
  - ★ Radius of 3.21 $R_\oplus$, smaller than that of Neptune
  - ★ Mass of 57.4 $M_\oplus$, more than half that of Saturn
  - ★ Density of 9.5 g cm^{-3}, approaching that of pure iron, and the densest planet of those the size of Neptune or greater found thus far
  - ★ The 5th planet with a precise mass determination located deep within the Neptunian desert (Fig. 4)

2. OBSERVATIONS

- ★ TESS: 2 sectors (S1+S2) at 30m cadence; 1 sector (S28) at 2m (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

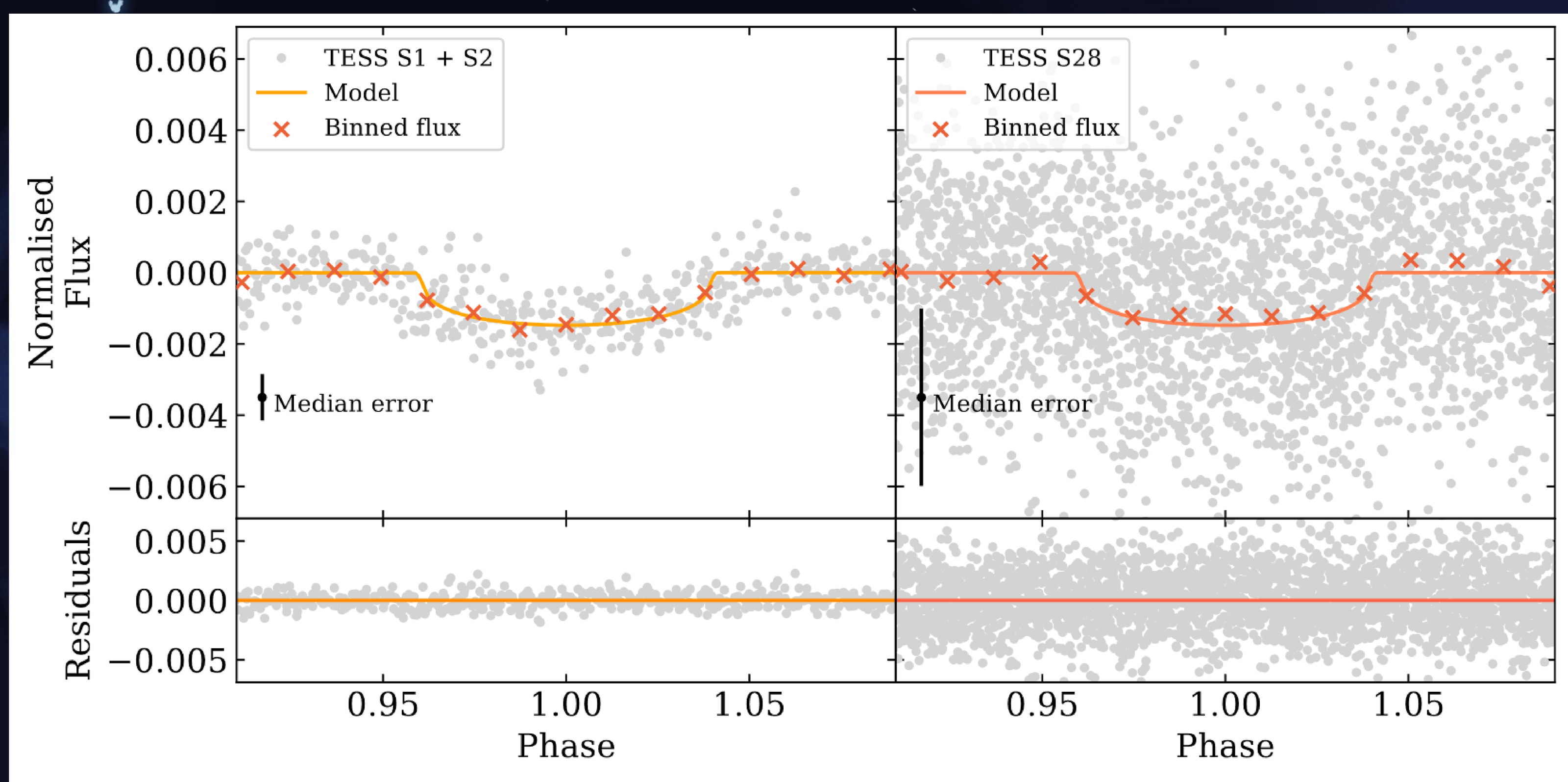

Fig. 1: phase folds of the TESS S1+S2 (left) and S28 (right) photometry

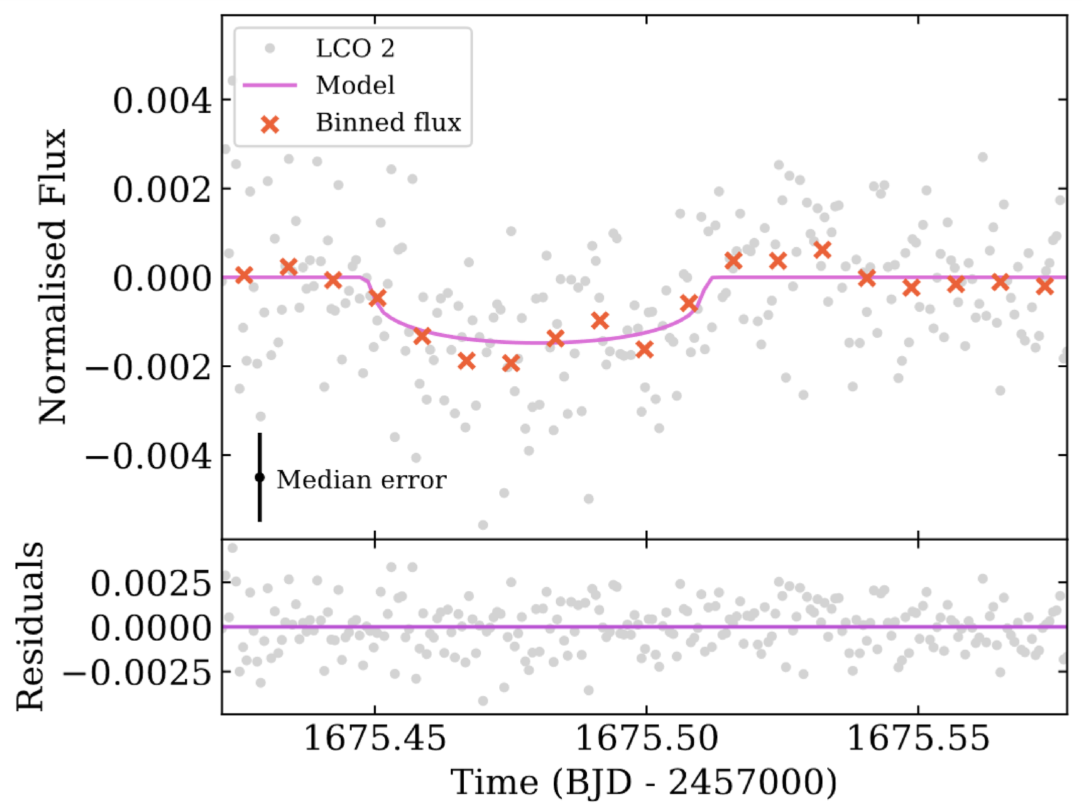

Fig. 2: 1 of the 6 LCO transits, observed with SAAO

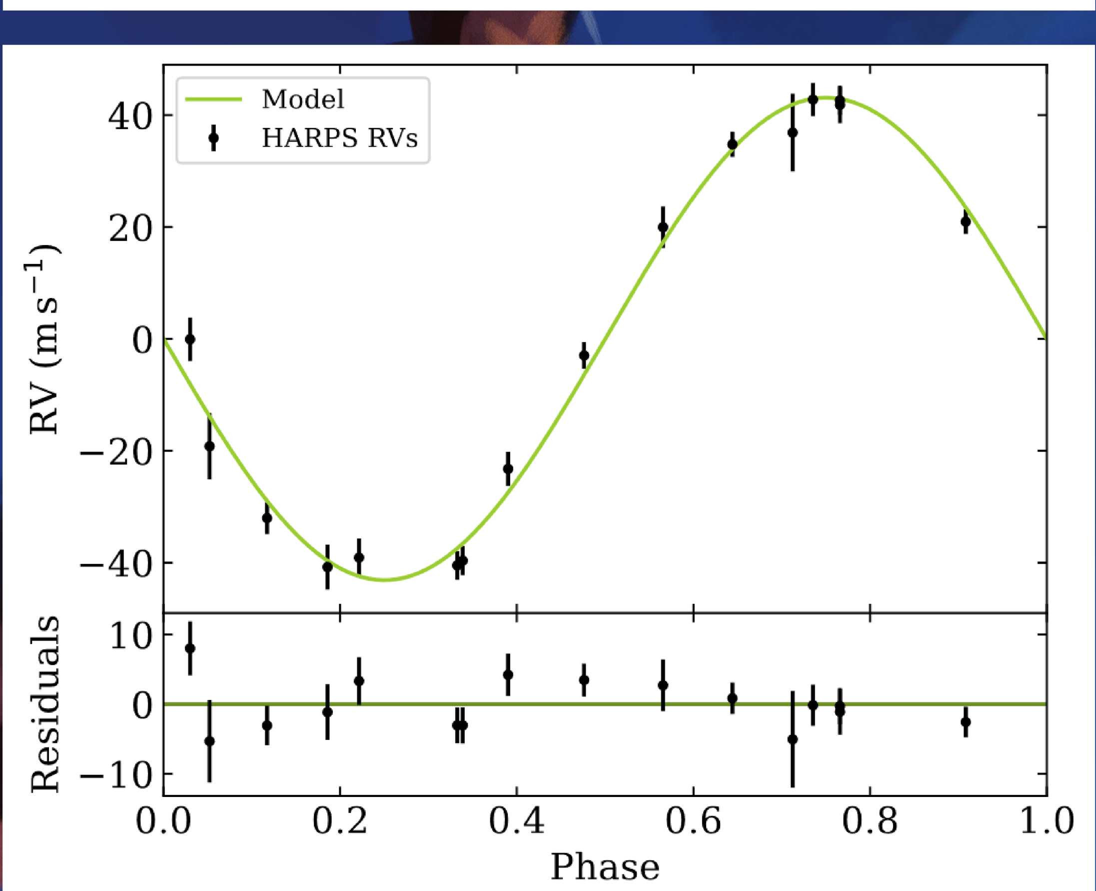

Fig. 3: the HARPS RV data, shown as a time series in the top panel, phase folded in the bottom panel.

3. SYSTEM DETAILS

Host star	
Spectral type	K0V
Stellar radius	0.86 $R_\odot$
Stellar mass	0.88 $M_\odot$
Effective temp.	5251 K
Metallicity [Fe/H]	0.256 dex
Age	9.88 Gyr

Planet	
Semi-major axis	0.0159 AU
Period	0.78 d
Radius	3.21 $R_\oplus$
Impact param.	0.26
Inclination	86.2 °
Eccentricity	0 (fixed)
Mass	57.0 $M_\oplus$
Bulk density	9.5 g cm^{-3}
Equilibrium temp.	1869 K

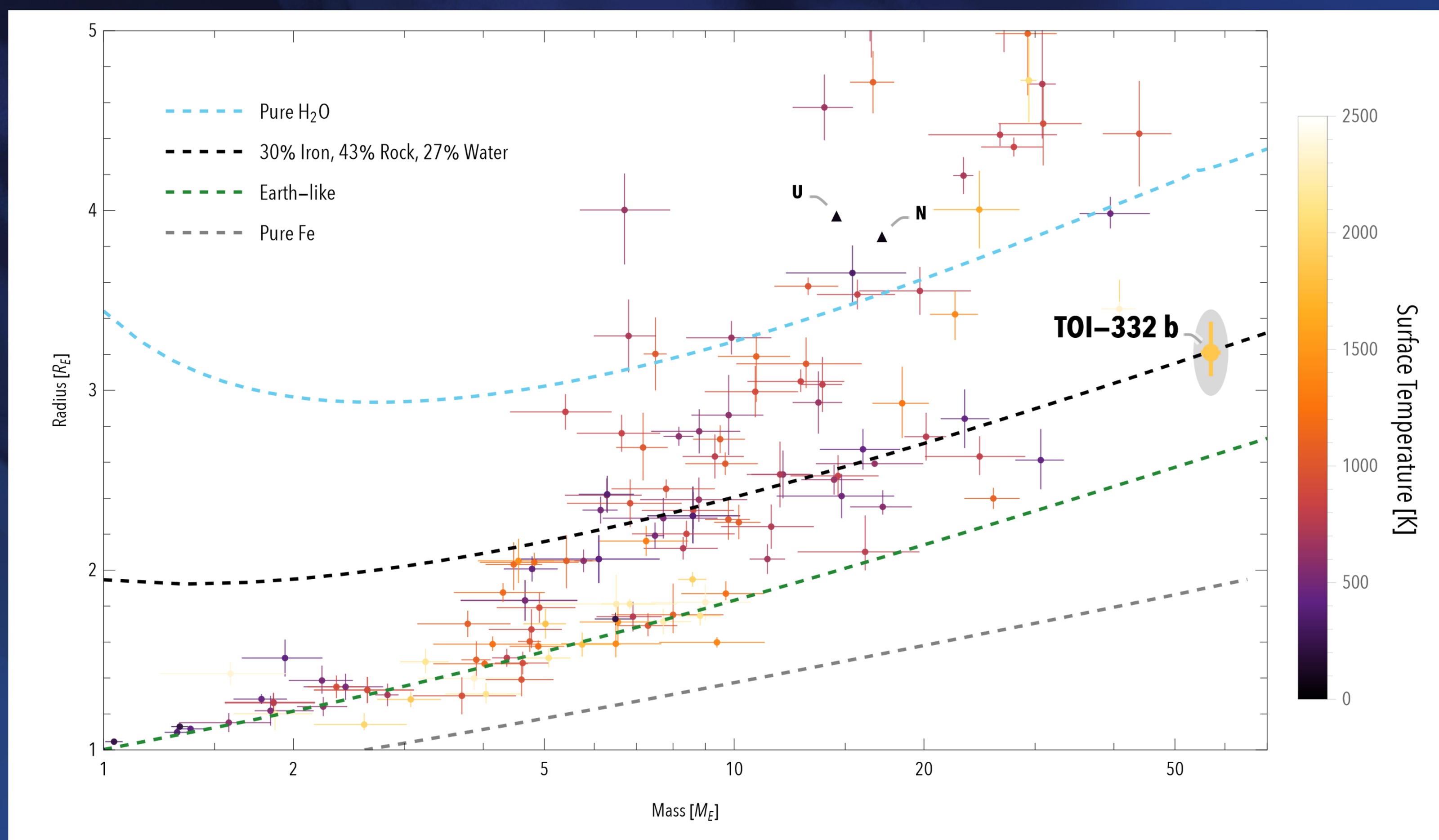

Fig. 4: mass-radius diagram of the exoplanets in Otegi+ 2022, showing mass-radius relations for several compositions, including the composition of TOI-332b (see Section 4)

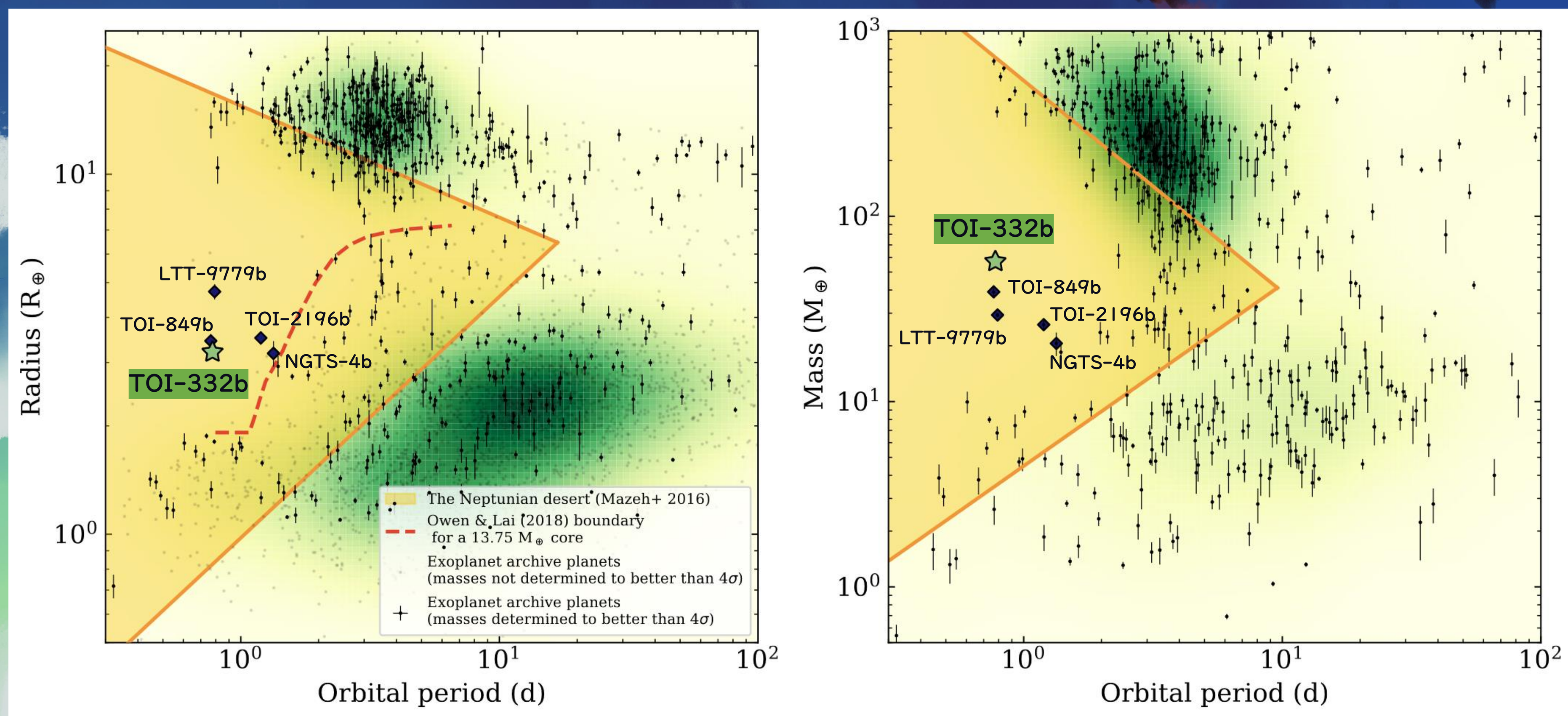

Fig. 4: the Neptunian desert, shown in period-radius space (left) and period-mass space (right), with TOI-332b and the other deep desert planets marked (see Section 1)

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
  - ★ Even in a model with no water (an extreme case), the H-He envelope is max. 1.8%
- ★ 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 between the angular momentum of a disk and planetary orbits, 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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I'm currently looking for a postdoc!

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Background illustration by Ares