Exceptionally Large Transit Timing Variations in TOI-4504: A Tale of Resonance and Complexity

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WINE The Warm Giants with TESS Collaboration

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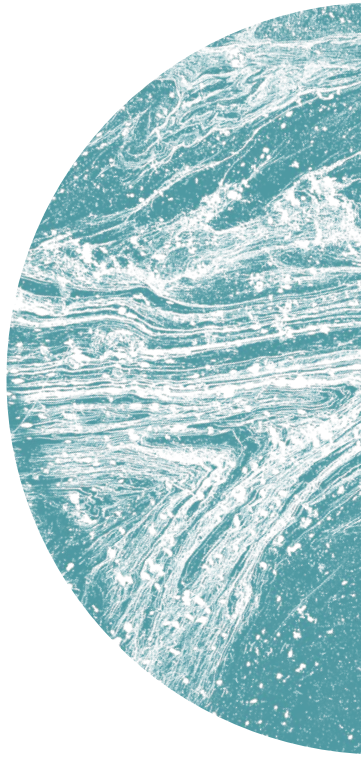
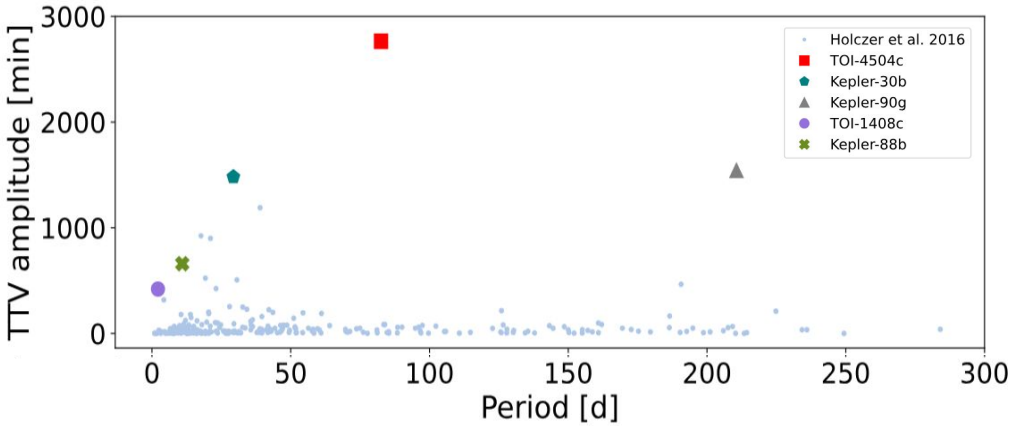
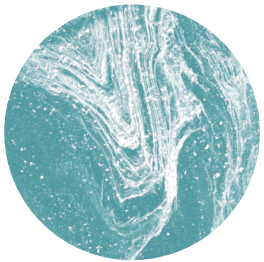
Why TOI-4504 Matters: *Resonant Worlds & Extreme TTVs*

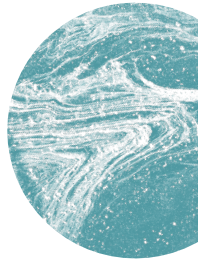
- TTVs reveal hidden planets and gravitational interactions
- Large TTVs signal strong planet–planet dynamics
- Resonant giant planets constrain migration and formation
- TOI-4504 c shows the largest TTV amplitude ever observed

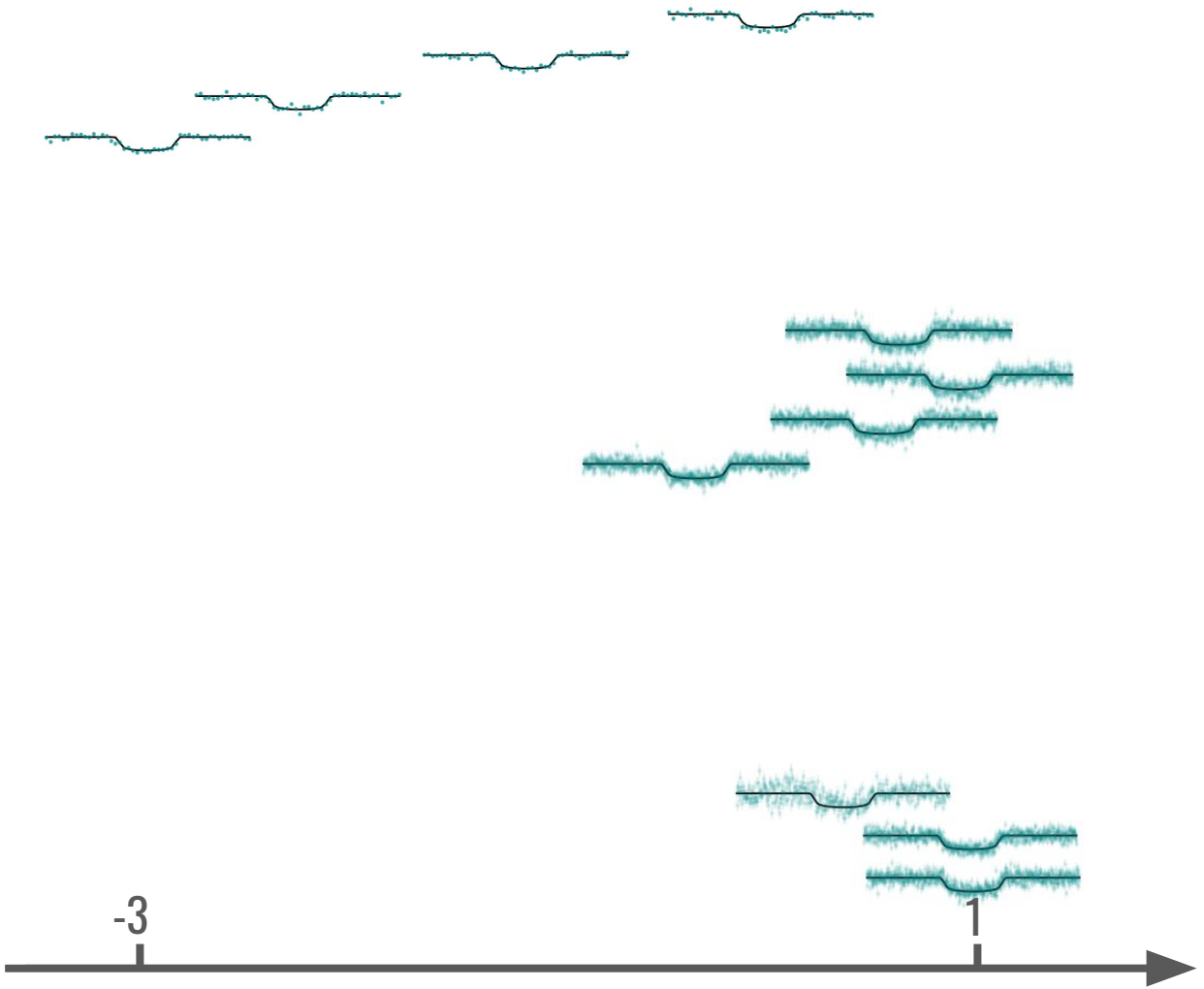




What TESS Saw: *From light curves to chaos—transits that don't show up on time*

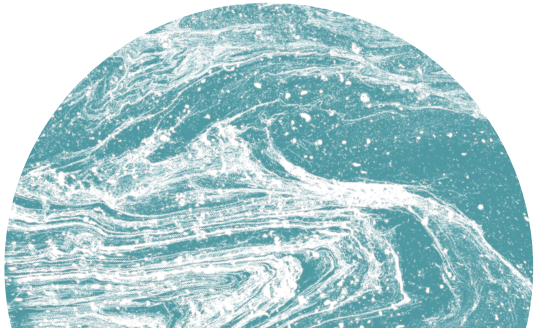


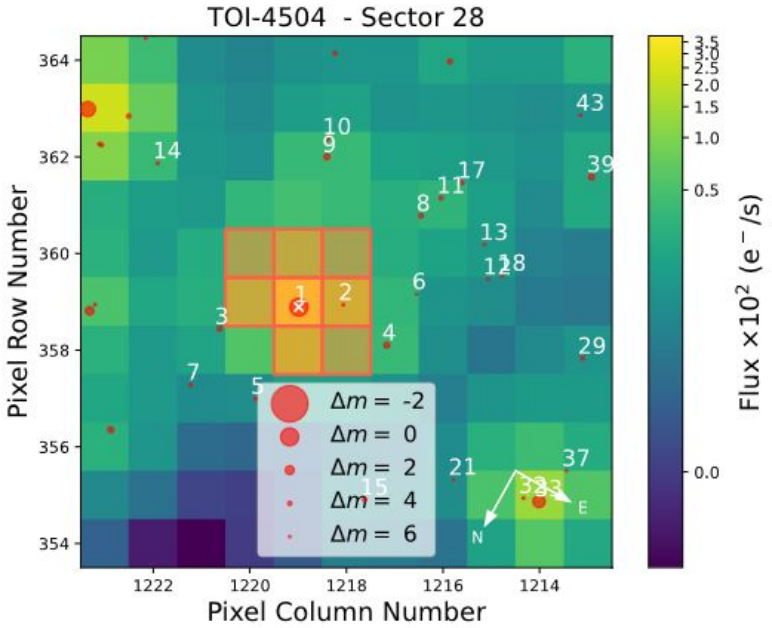



-3
1
O-C [days]

What TESS Saw: *From light curves to chaos—transits that don't show up on time*

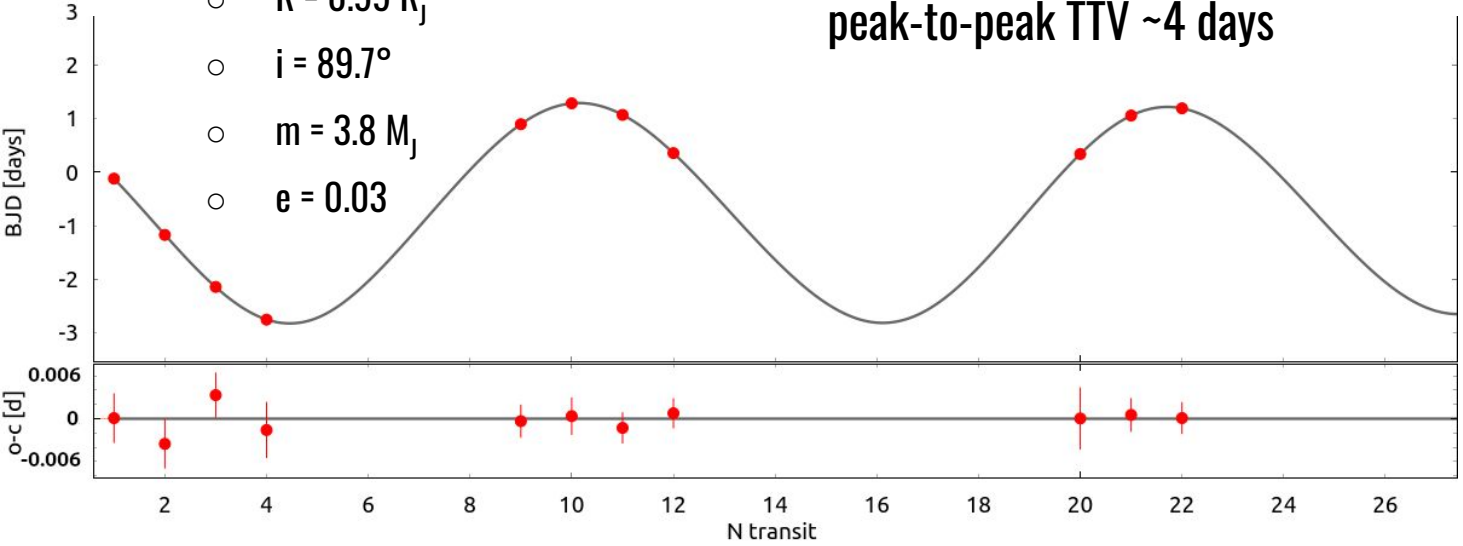
- Observed in 30-min and 2-min cadence
- Favourable position of the star in the TESS field (multiple sectors during first, third and fifth year of the mission) - 11 transits of planet c
- Transits of two planets (b & c)
- Large TTVs made ground-based transit observation of c complicated

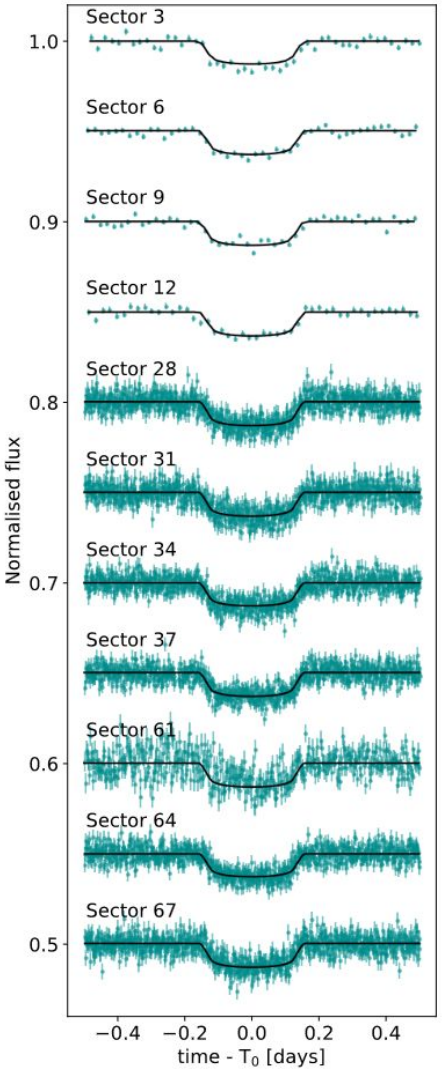




Timing is Everything: *A 4-day swing reveals a hidden world*

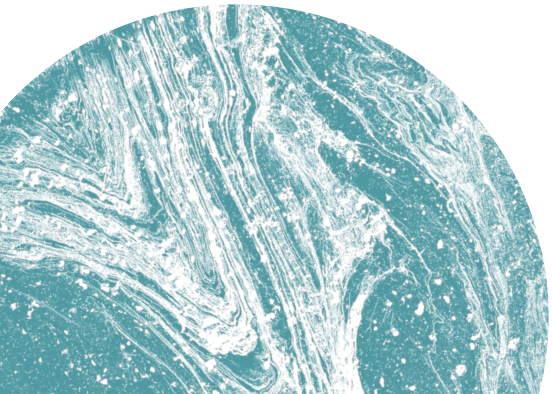
- *Juliet* (Espinoza+ 2019)
- TOI-4504 c: warm Jupiter
  - P = 82.972 days
  - R = 0.99 R_J
  - i = 89.7°
  - m = 3.8 M_J
  - e = 0.03
- TOI-4504 c: transit times show huge sinusoidal TTVs
- Superperiod ~930 days, peak-to-peak TTV ~4 days

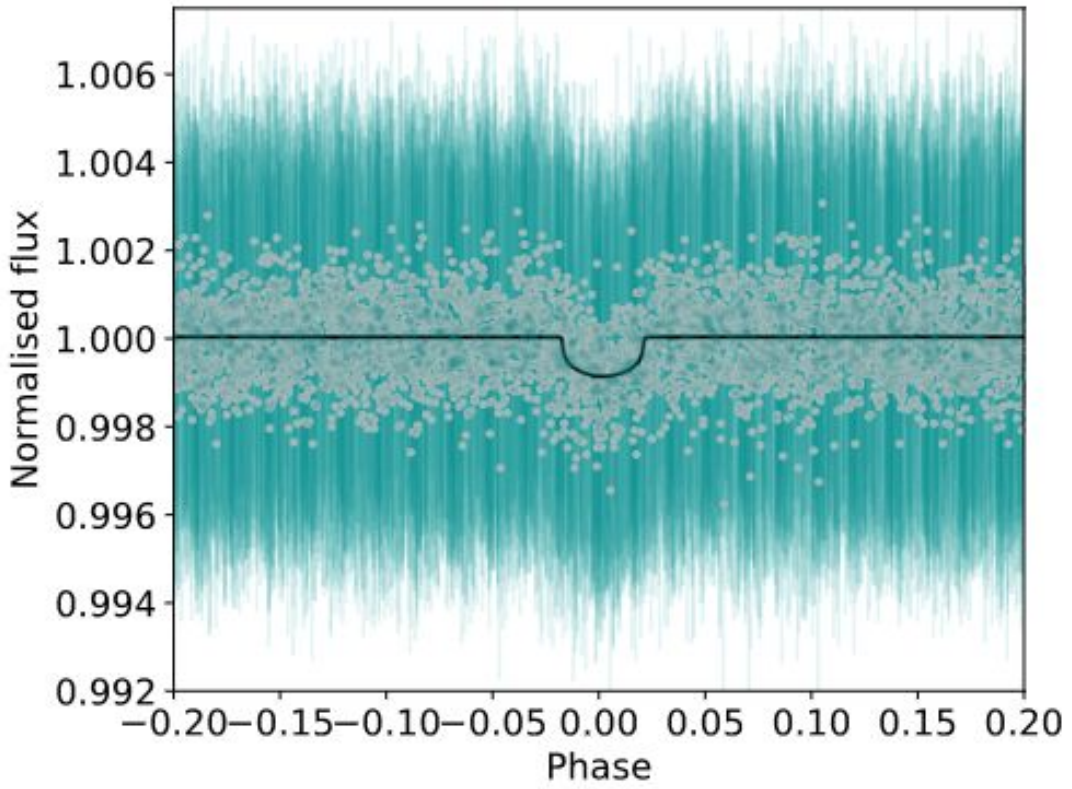




Second signal in TESS lightcurve: *Another player in the game*

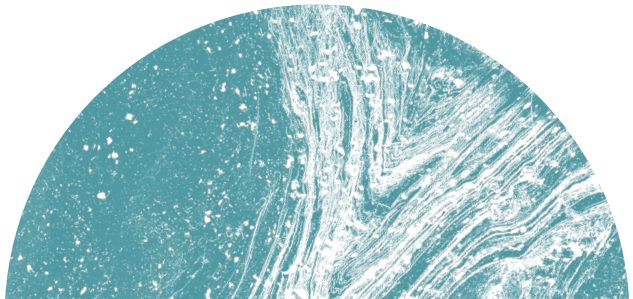
- *Juliet* (Espinoza+ 2019)
- TOI-4504 b: sub-Neptune
  - P = 2.4261 days
  - R = 2.69 $R_{\oplus}$
  - i = 87.4°

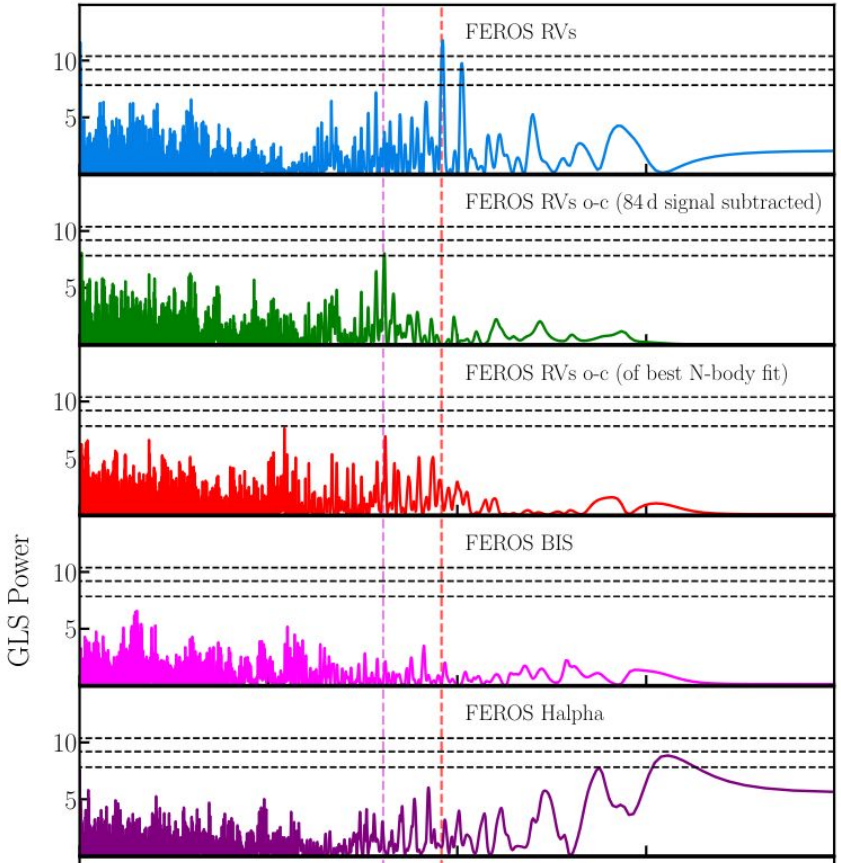




Chasing Signals with FEROS: *Confirming the giants, revealing the unseen*

- 39 RVs with FEROS (La Silla), S/N ~40
- Strong 84-day signal from TOI-4504 c
- Weaker ~41-day signal consistent with TOI-4504 d
- No strong stellar activity periodicities
- Remaining jitter in RV ~ 100 m/s

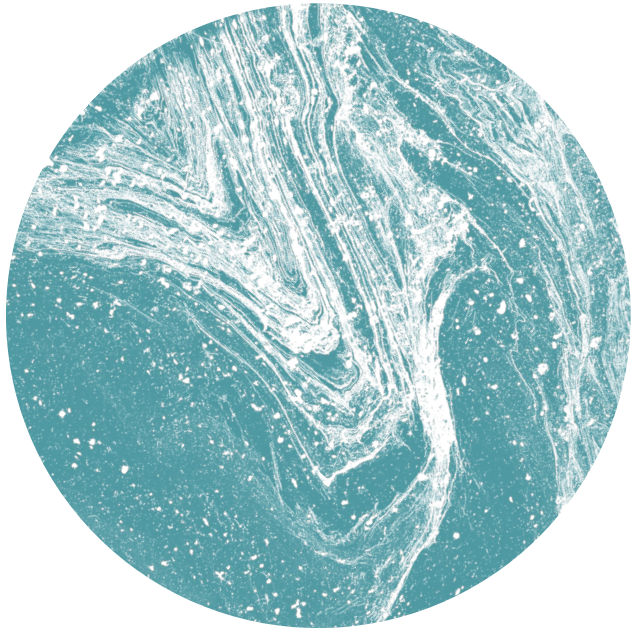




Know Your Planets Like You Know Your Star: *Exoplanet Exploration Begins with Knowing the Star*

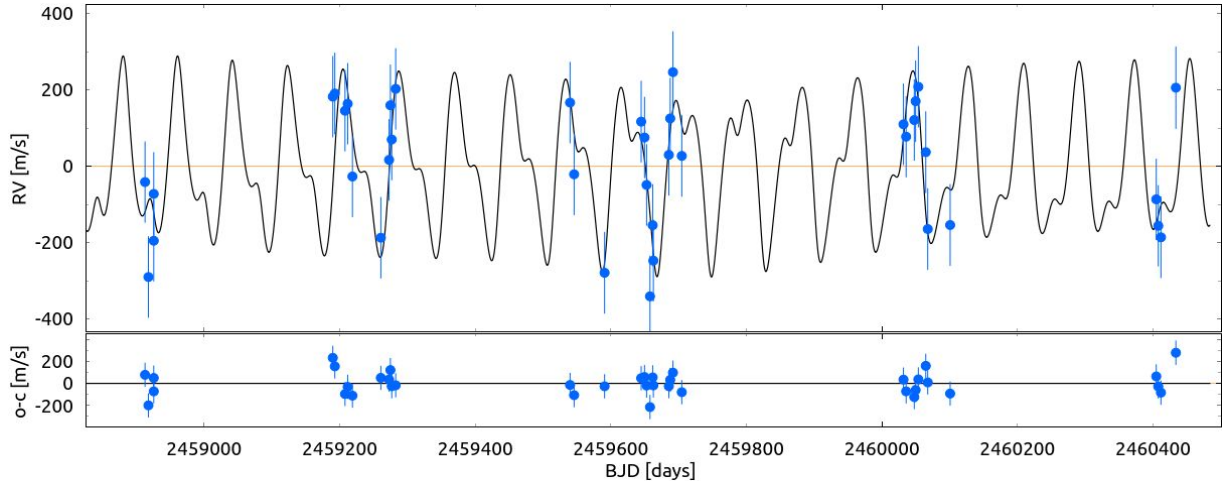
- *ZASPE* (Brahm+ 2017b)

- Spectral type K1V
- V = 13.4 mag
- Teff: 5315 ± 60 K
- R_*: 0.92 ± 0.04 R_{sun}
- M_*: 0.89 ± 0.05 M_{sun}
- L_*: 0.62 ± 0.03 L_{sun}
- ρ_*: 1607 ± 79 kg m^{-3}
- [Fe/H]: 0.16 ± 0.05 dex
- v sini: 1.9 ± 0.5 km s^{-1}
- Age: 10.0 ± 3.3 Gyr

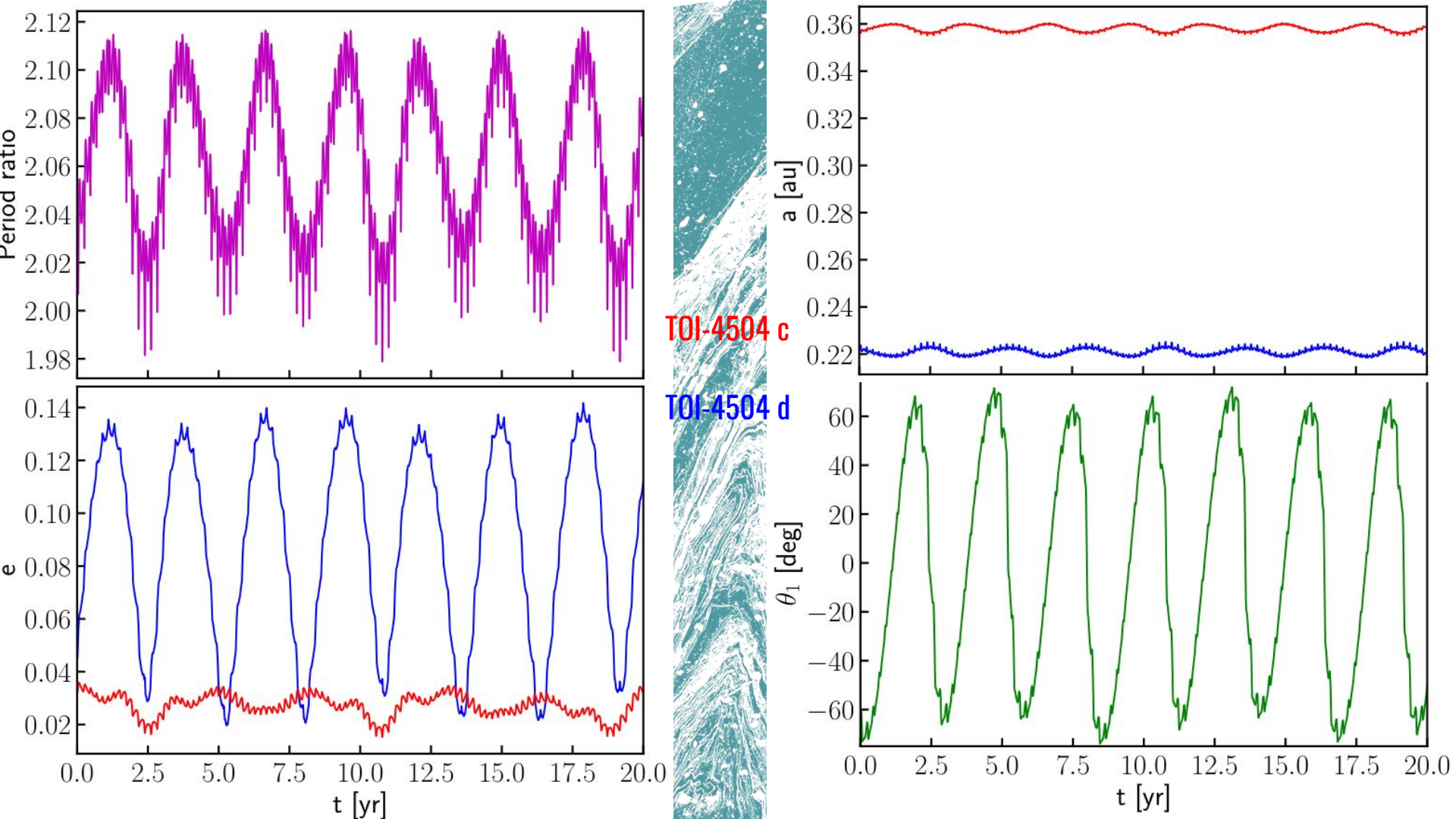


Unmasking the Architect: *TTVs + RVs = The orbit of an invisible giant*

- *Exo-Striker* (Trifonov 2019)
- Fit both RVs and TTVs jointly
- Best-fit solution places d interior to c, in 2:1 MMR
- Mutual inclination ~4.7°

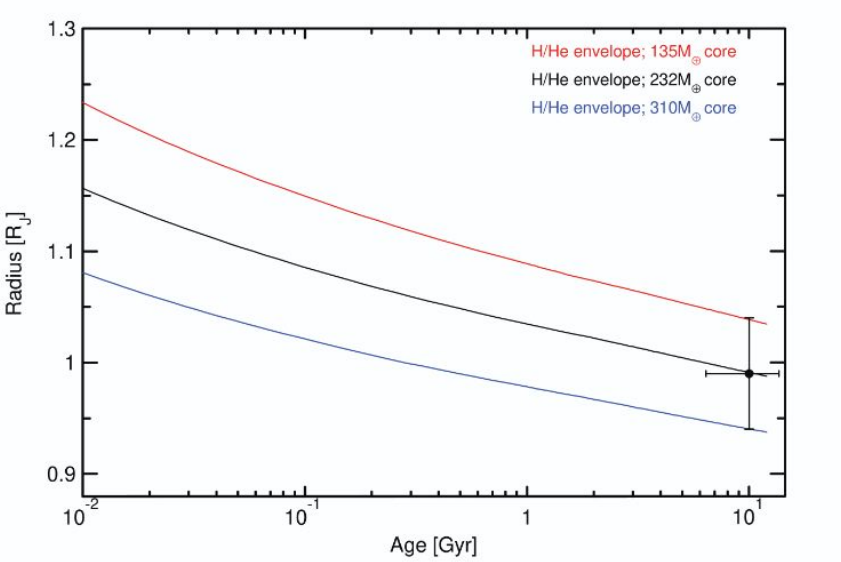


- TOI-4504 d: warm Jupiter
  - P = 40.6 days
  - i = 85°
  - m = 1.4 M_J
  - e = 0.04


Period ratio
2.12
2.10
2.08
2.06
2.04
2.02
2.00
1.98
e
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
t [yr]
TOI-4504 c
TOI-4504 d
a [au]
0.36
0.34
0.32
0.30
0.28
0.26
0.24
0.22
θ_1 [deg]
60
40
20
0
−20
−40
−60
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
t [yr]

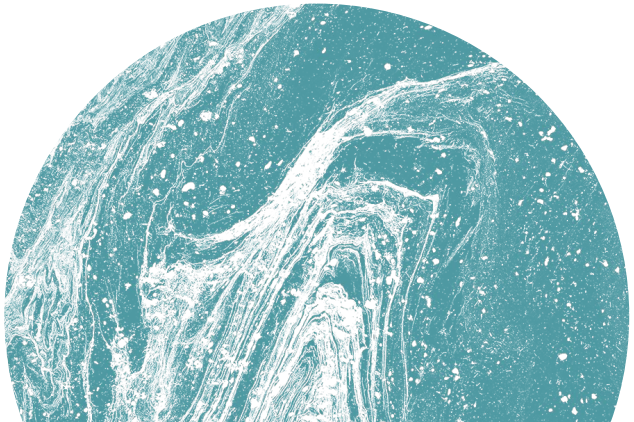
What's Under the Clouds?: *Core-heavy, metal-rich*

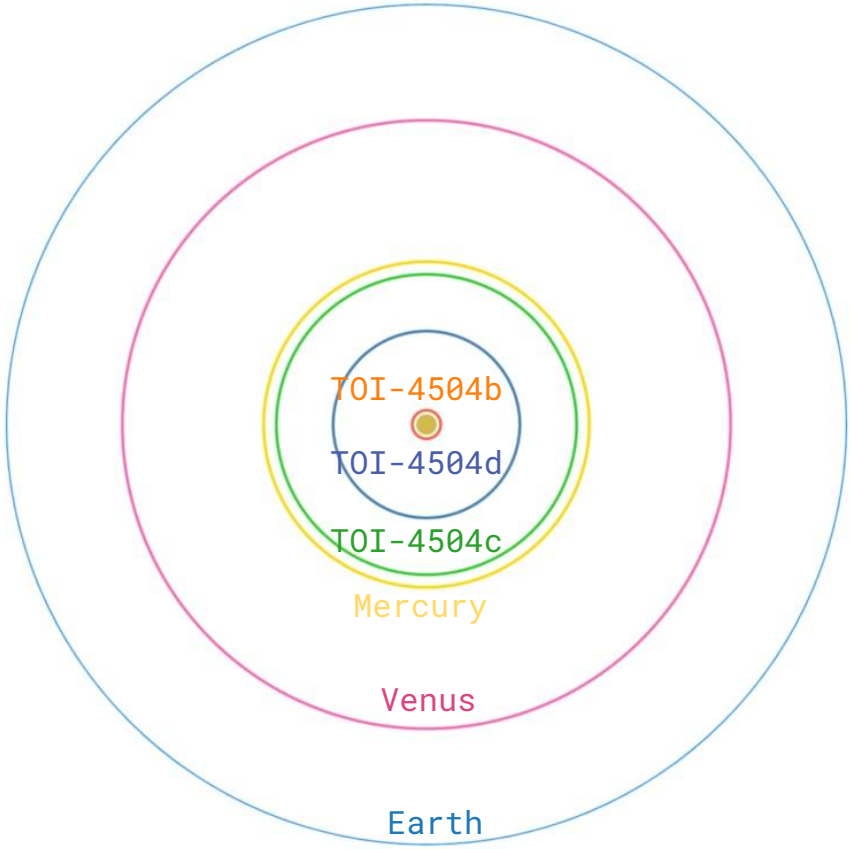
- Interior modeled with *MESA*
- Metallicity $Z_p \approx 0.21 \rightarrow Z_p/Z_* \sim 10$
- Consistent with heavy-element-enriched warm Jupiter
- No significant inflation

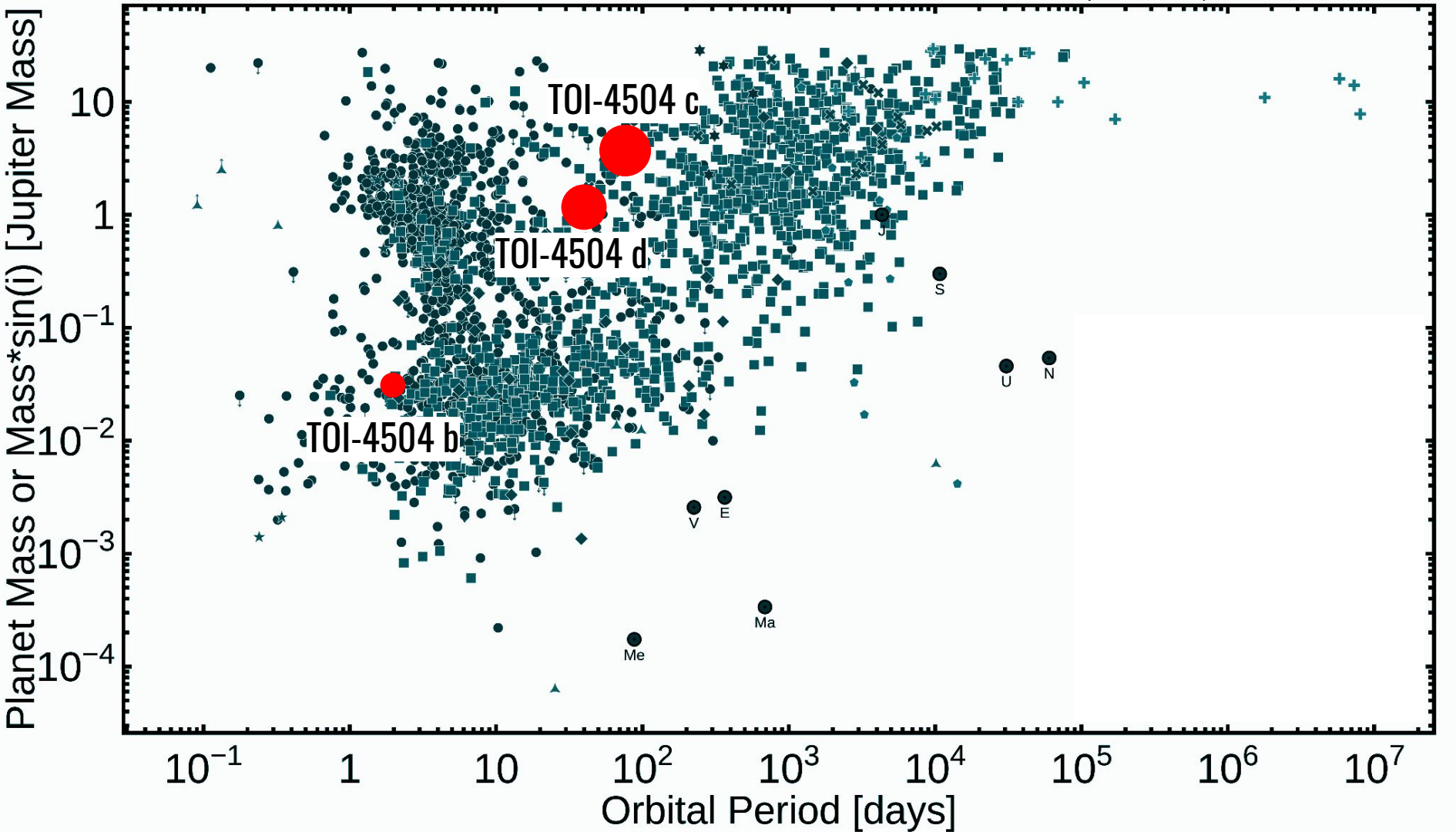


Three Planets, One Puzzle: *A hot sub-Neptune and two warm Jupiters in motion*

- TOI-4504 b: hot sub-Neptune (2.7 $R_{\oplus}$, ~10 $M_{\oplus}$)
- TOI-4504 c: warm Jupiter (0.99 R_J, 3.77 M_J)
- TOI-4504 d: warm, nontransiting Jupiter (1.42 M_J)
- c & d in 2:1 mean-motion resonance (MMR)






TOI-4504 c
TOI-4504 d
TOI-4504 b
J
S
U
N
V
E
Ma
Me
Planet Mass or Mass*sin(i) [Jupiter Mass]
Orbital Period [days]
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}

What We've Learned: *A dynamically rich system that rewrites the TTV record books*

- Resonant pair of warm Jupiters + hot sub-Neptune
- Largest TTVs ever observed
- Joint TTV+RV modeling to derive masses
- Demonstrates the power of multi-method exoplanet discovery

What's Next for TOI-4504?: *From RV precision to JWST atmospheres and new TESS data*

- Continue RV monitoring (planet b mass, long-term trends)
- TOI-4504 b: TSM ~20, excellent JWST target
- Focus more on the dynamics of the resonant duo, photodynamical model
- New TESS data reveal something ...

Shortest way to the paper:

Scan me!

Thank You
Let’s Talk Planets!

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