Investigating stellar structure through orbital decay

Lawrence Berry, UCL

Vincent Van Eylen, Ed Bryant

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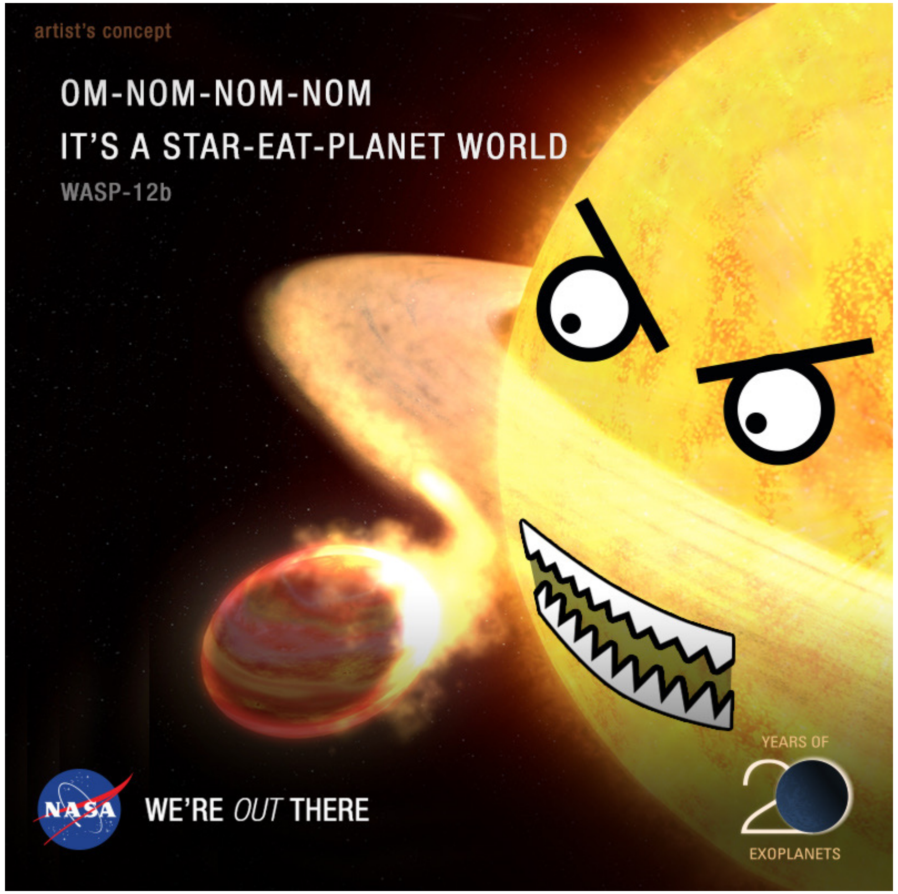

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Figure 1: Exoplanet Exploration, NASA/JPL-Caltech

Stellar and planetary composition and structure

- Tools for stellar structure:

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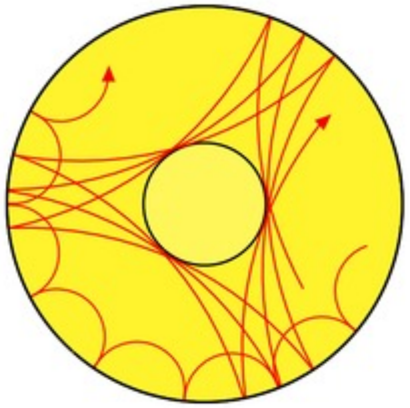

Asteroseismology

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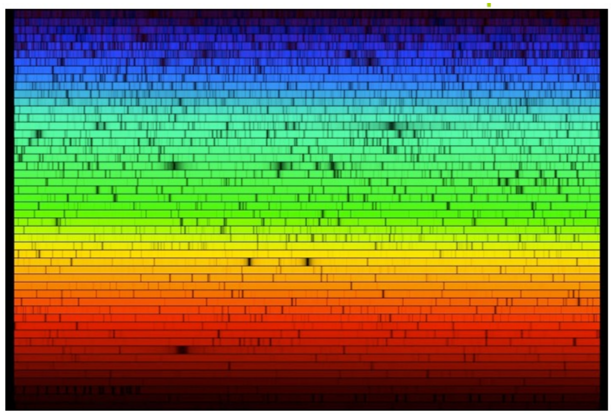

Stellar spectra

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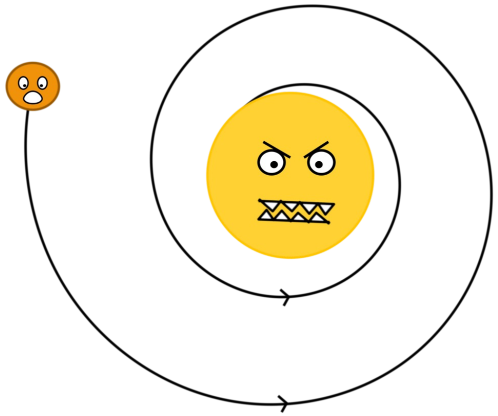

Tidal decay

- Planetary structure?

Figure 2: Asteroseismology wiki page, Tosaka, Figure 3: Classification of stellar spectra lecture notes, Burros, Figure 4: Berry

What is tidal decay?

1. A planet exerts a gravitational force on its host star creating a tidal bulge
2. The tidal bulge creates a non-Keplerian potential
3. If the planet orbits faster than the star spins, it experiences a decelerating torque

$$\dot{a} \propto \frac{1}{Q'_*}$$

Stellar tidal dissipation factor

Depends on **rigidity** and **elastic modulus** of the star

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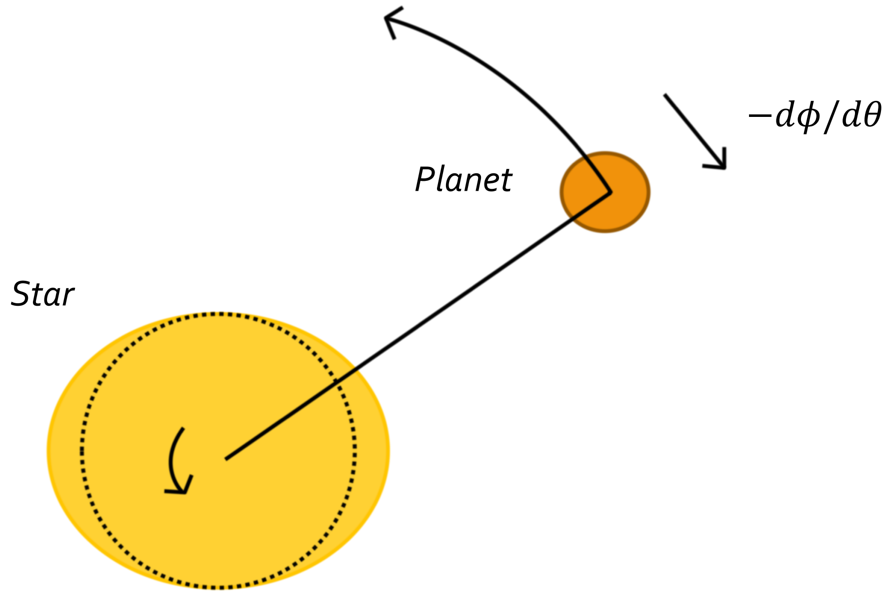
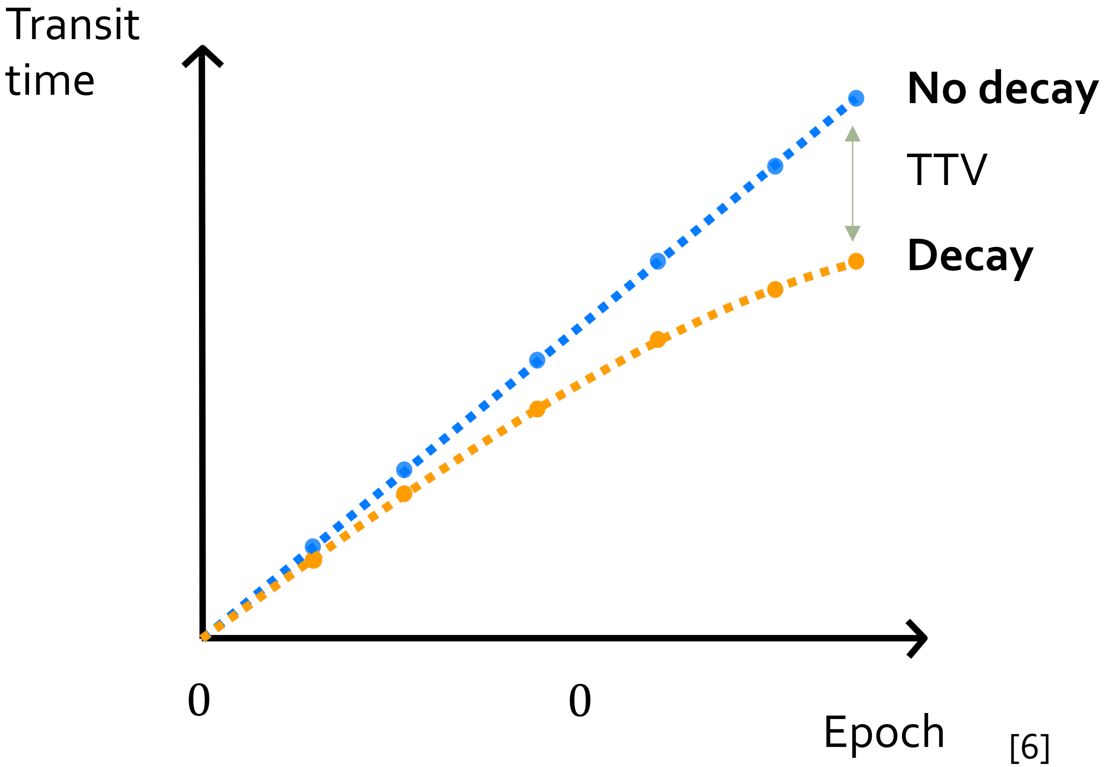


Tidal decay is a consequence of **stellar (and planetary) composition and structure**. Decay rates could tell you something about what the star and planet are made of!

Figure 5: Berry

How do we measure tidal decay?

- Indirectly via orbital distributions
- Or: transit timing variations aka **TTVs**



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Overlayed light curves of KOI-872

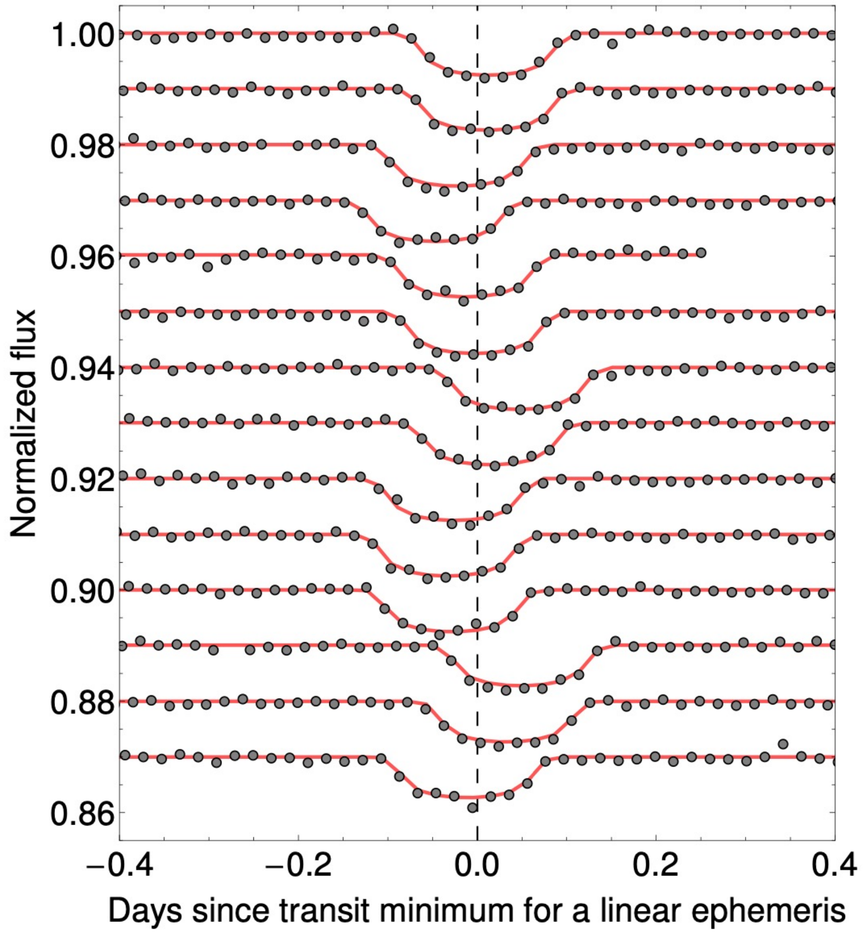

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Figure 6: Berry, Figure 7: Nesvorny et al, 2012

Aims of my project

1. Let's model all systems for which we have transit observations
2. Build an empirical distribution of stellar tidal dissipation factors
3. Test stellar structure theory by analysing how other stellar properties relate to the tidal dissipation factors we observe

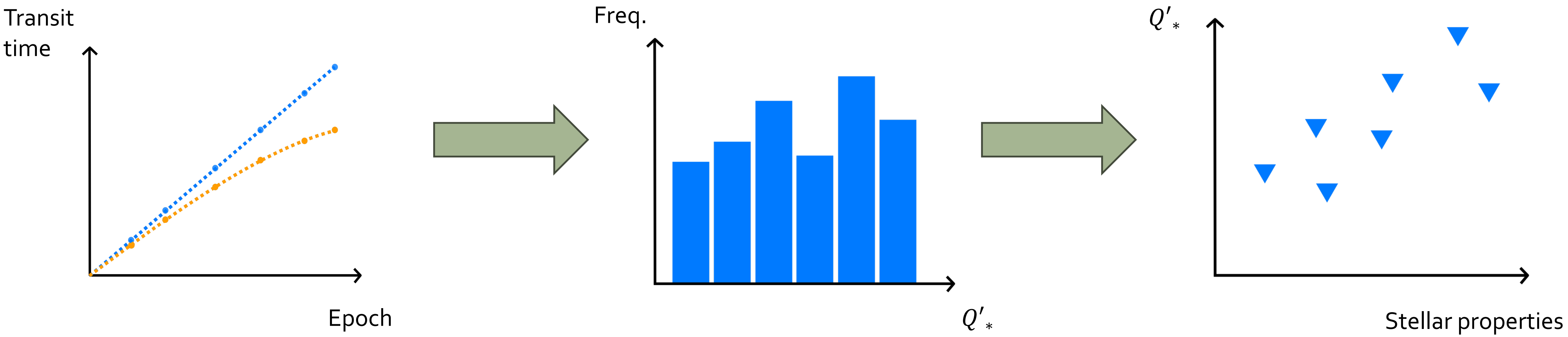

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Figure 8: Berry

Method

- **Inputs**:

Transit timing en masse

[9] [10] [11]

- **Model:**

$$y_i = T_0 + P_0 E + \frac{1}{2}\frac{dP}{dE}E^2 + \epsilon_i$$

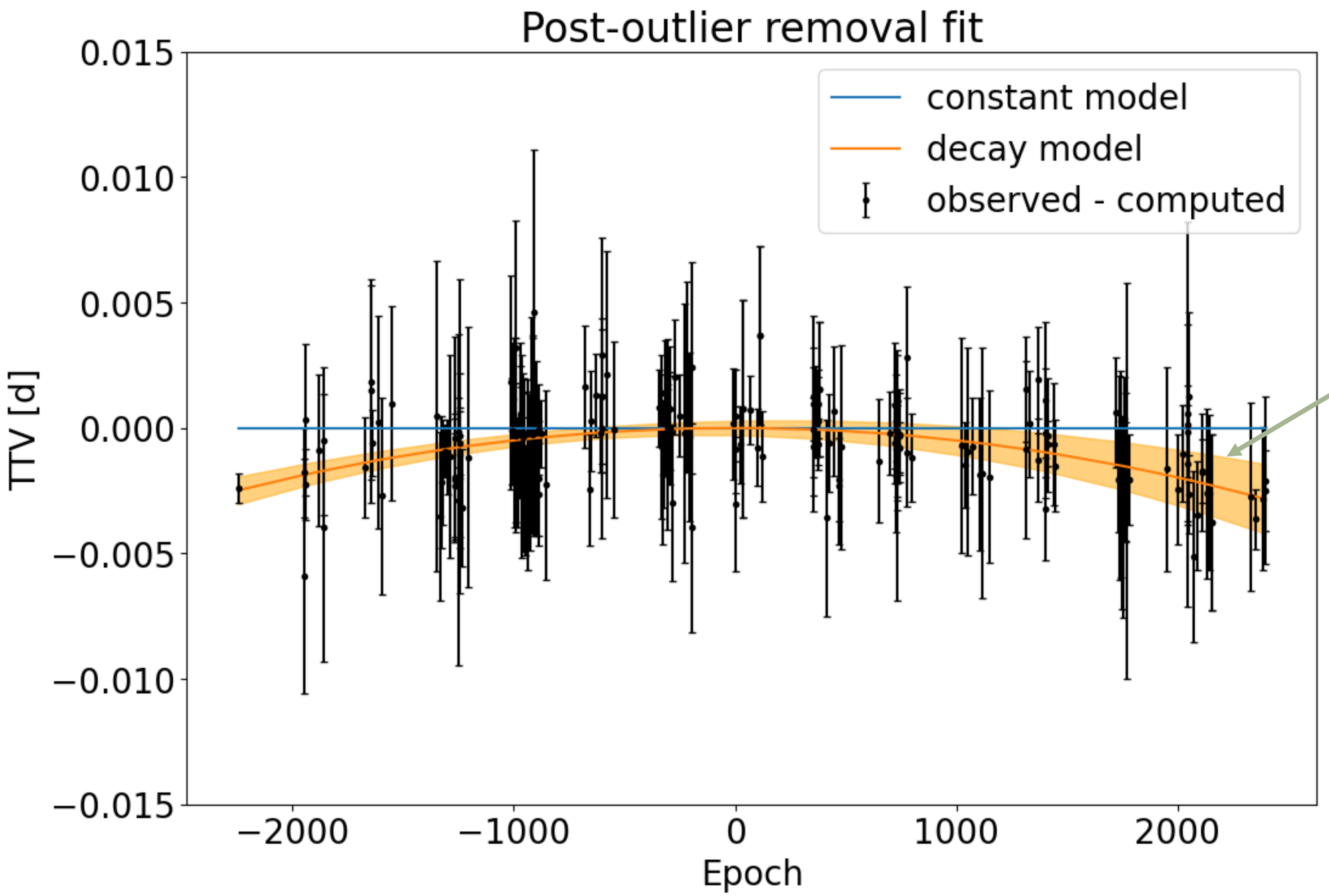
Measured transit time	Reference time	Constant period component	Decay rate per orbit	Measurement noise

- **Fitting procedure**:
  - Bayesian linear regression
  - Parameterise uncertainty in individual transit time measurements

Figure 9: ExoClock, ARIEL Ephemerides Working Group, Figure 10: ETD, Czech Astronomical Society, Figure 11: Transit timing en masse, Ivshina & Winn

Example: WASP-12b

A curve fits better than a straight line!



3σ posterior model error

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Figure 12: Berry

Observations vs theory (442 planets)

Observation ≠ theory: **perhaps something else is going on?**

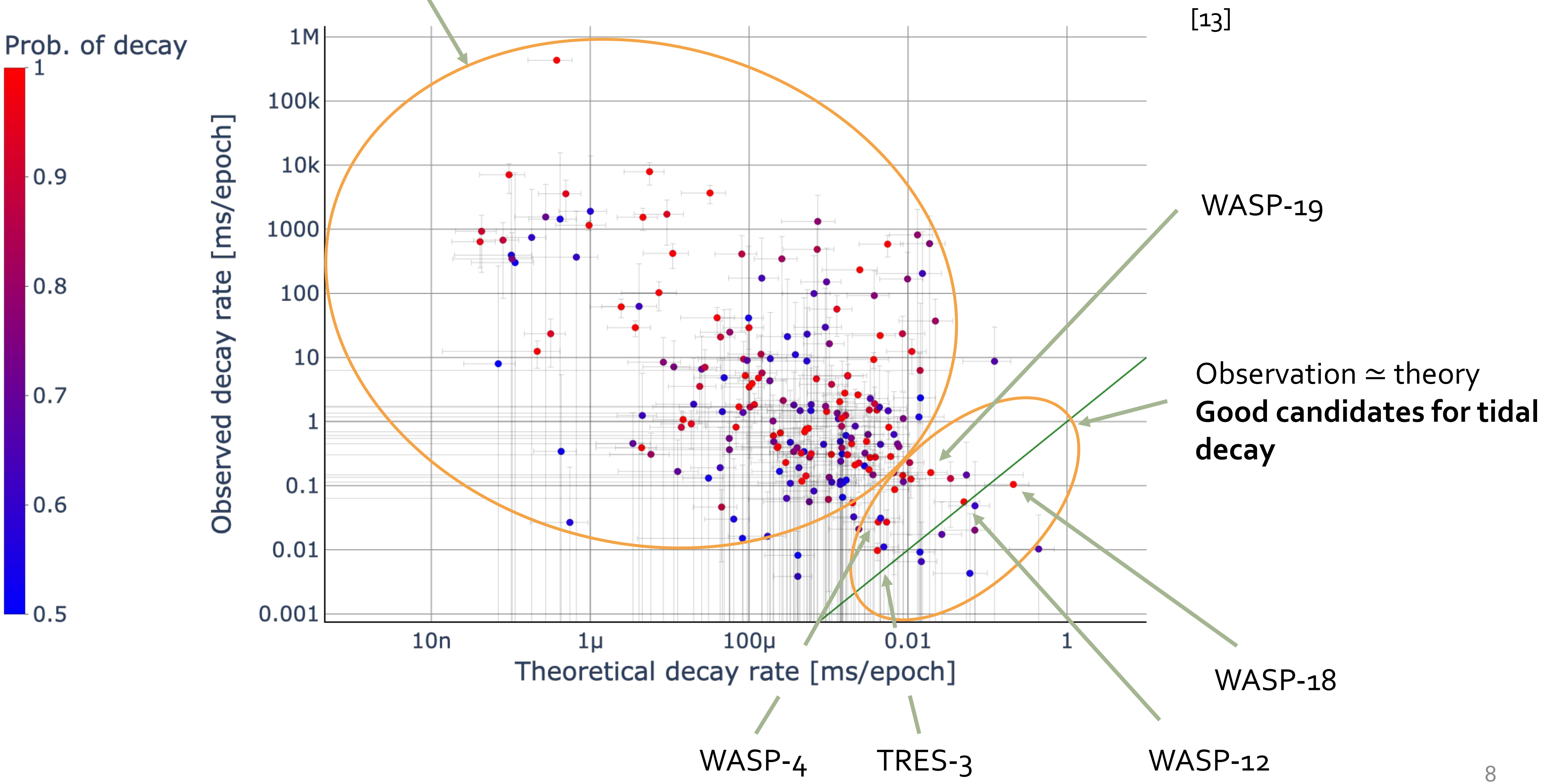

Figure 13: Berry

Empirical distribution of Q'_*

Filtered to:
- Single planet systems
- > 10 transits
- $< 1\ ms/epoch$ error

Literature > 10^5 (e.g. *Ogilvie, 2014*)

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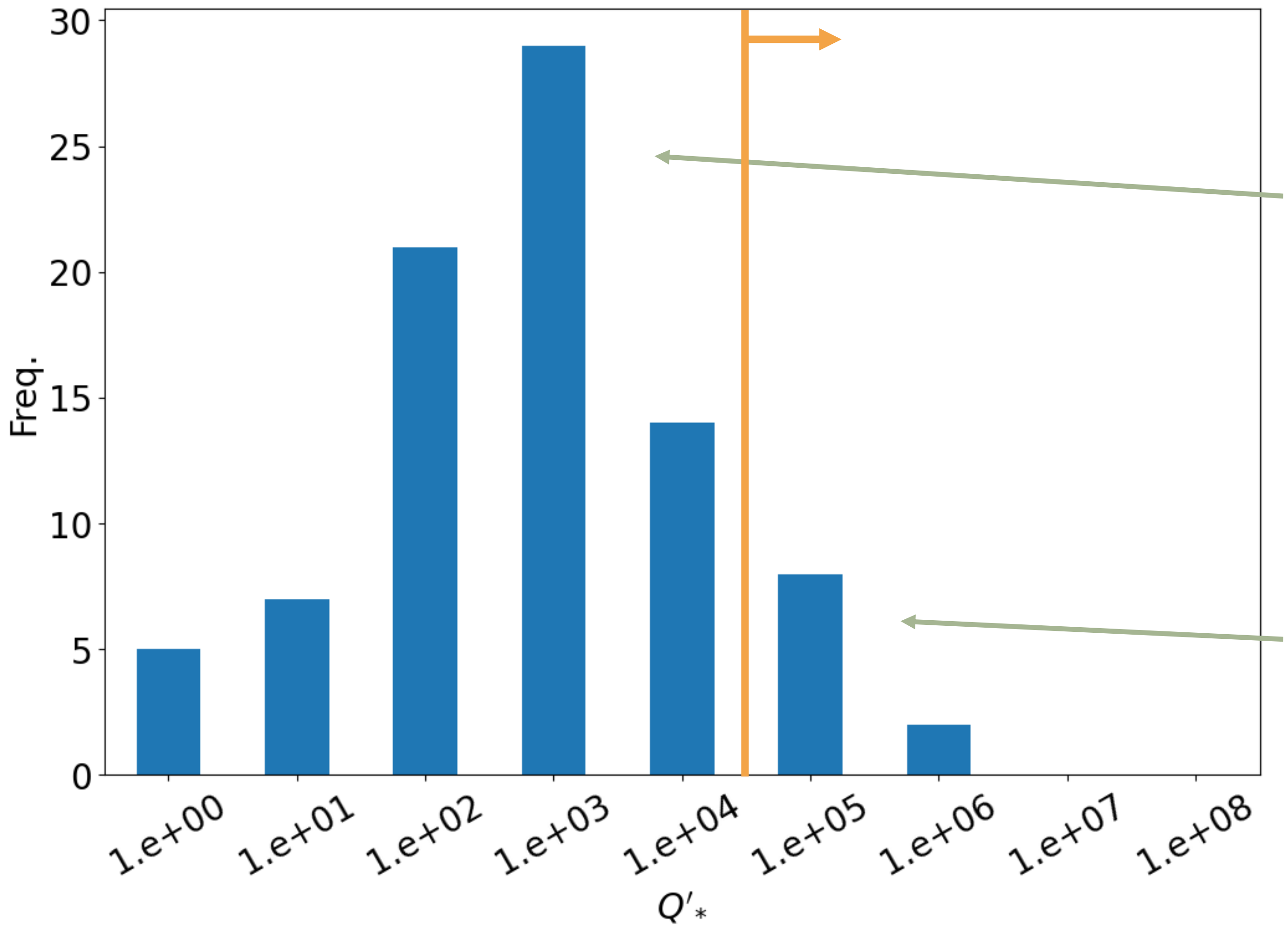

Smaller Q'_* than typically quoted in theoretical literature

WASP-12 falls in the 10^5 bucket

Figure 14: Berry

How does Q'_* relate to stellar properties?

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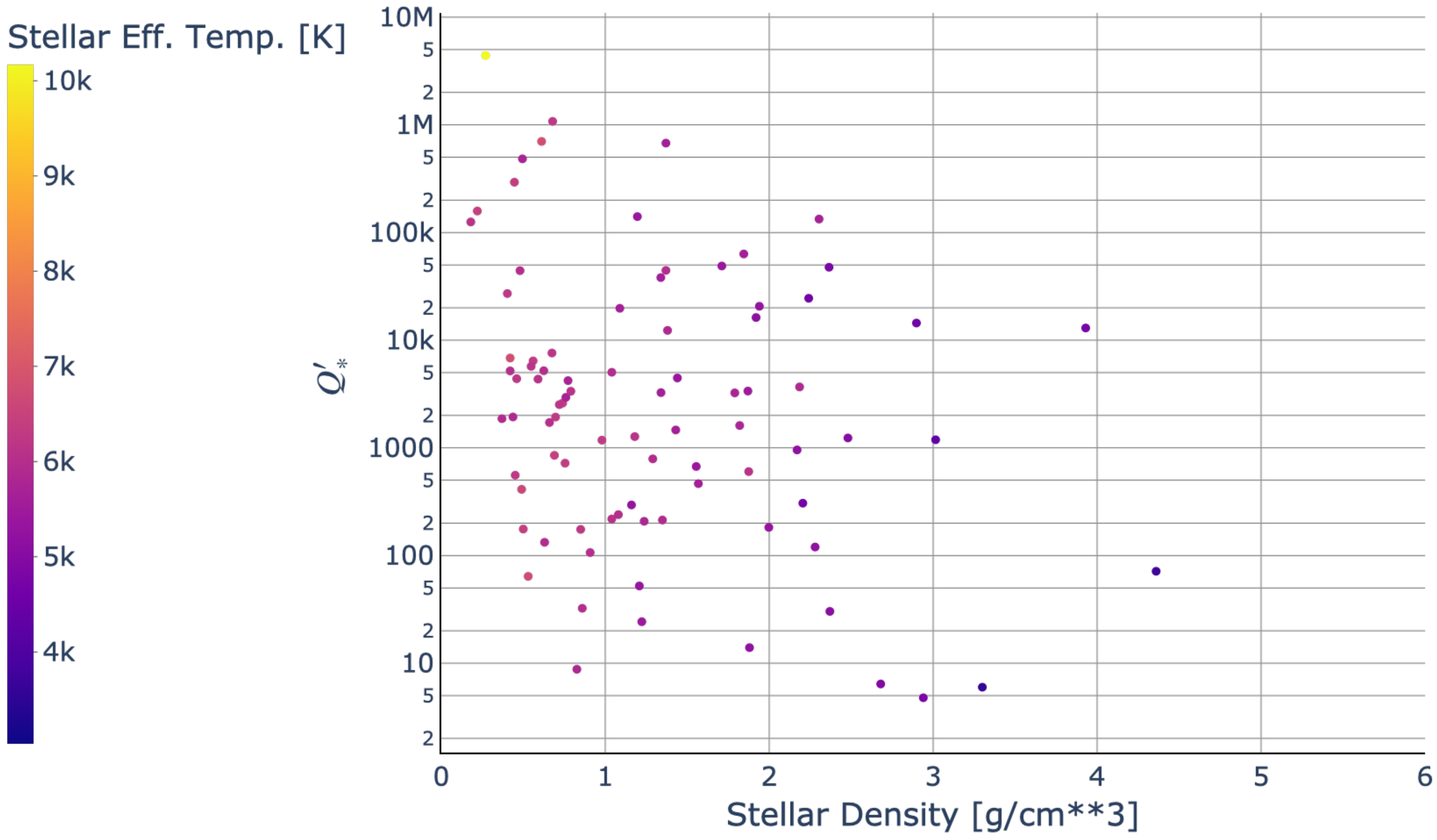

Figure 15: Berry

Future work

- Are these relationships real? Are our assumptions okay?
  - Other physical phenomena might be at play
    - e.g. we might accidentally be catching sinusoidal TTVs due to precession
  - Is decay rate constant per epoch?
  - Are mid transit times unbiased and Gaussian?
- Once we gain confidence in the results, let's connect these observations with stellar structure theory
- These techniques can also help inform which planets we should observe in future

Summary

- Measuring tidal decay for a large ensemble of stars provides new opportunities for studying stellar structure
- Initial results suggest a relationship exists between stellar density/ temperature and the size and lag of a star's tidal bulge
- Understanding these relationships better could help determine the structure of stars!

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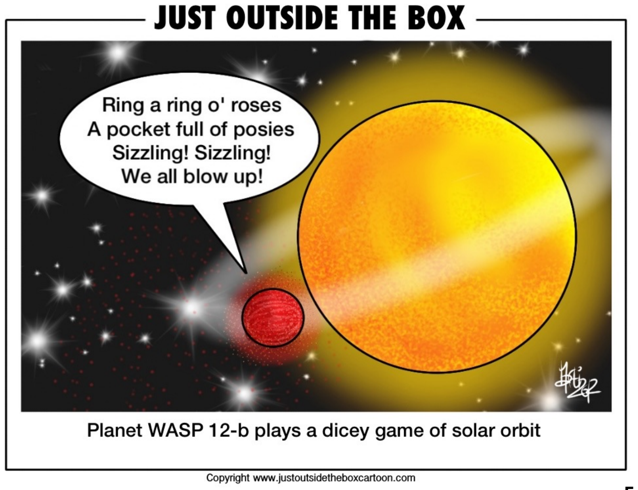

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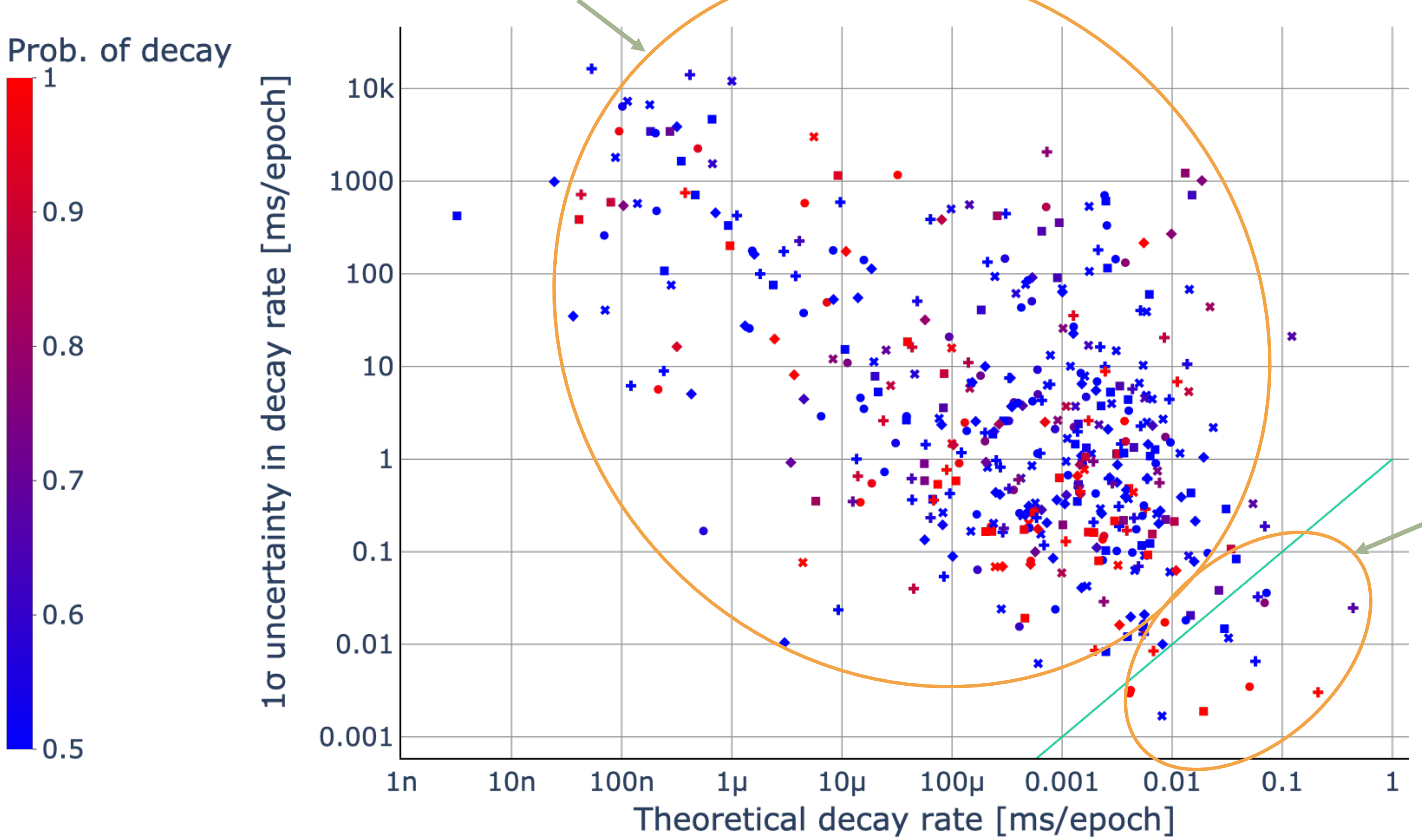
[18]

Figure 16: Solar System Comics, Figure 17: Just Outside The Box Cartoons, Figure 18: Deviant Art

Appendix A: which planets should we follow up on?

Uncertainty > theory: **these planets need further observing**



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TRES-3, WASP-4, WASP-12, WASP-18, WASP-19

Figure 19: Berry

Appendix B: tidal decay equations

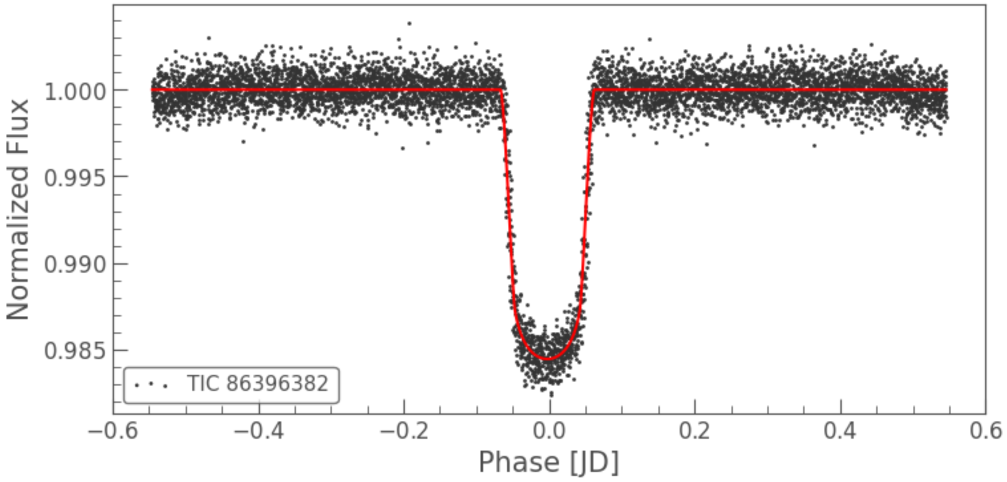
$$\frac{1}{a}\frac{\mathrm{d}a}{\mathrm{d}t} = -\left(\frac{63}{2}(GM_*^3)^{1/2}\frac{R_p^5}{Q'_p M_p}e^2 + \frac{9}{2}(G/M_*)^{1/2}\frac{R_*^5 M_p}{Q'_*} \times\left(1+\frac{57}{4}e^2\right)\right)a^{-13/2}$$

$$\frac{1}{e}\frac{\mathrm{d}e}{\mathrm{d}t} = -\left(\frac{63}{4}(GM_*^3)^{1/2}\frac{R_p^5}{Q'_p M_p} + \frac{225}{16}(G/M_*)^{1/2}\frac{R_*^5 M_p}{Q'_*}\right)a^{-13/2}$$

[Goldreich 1963, Jackson 2009]

Appendix C: why is this a hard problem?

- Uncertainty in the transit time measurements is **large**
  - Fundamental lower limit ~ sampling rate
  - Noisy citizen-science data
  - Inhomogeneous sources
  - Different physical phenomena at play
- Often **of the same order** as the timing variation we're trying to measure



[20]

We're talking about things that vary **milliseconds** per epoch and this scale is in **days**!

But decay compounds with time $TTV \approx \frac{1}{2}\frac{dP}{dE}\frac{t^2}{P_0^2} \sim 300s$ for WASP-12b over 10 years

Figure 20: Berry, using TESS data

Appendix D: Q'_* vs stellar mass

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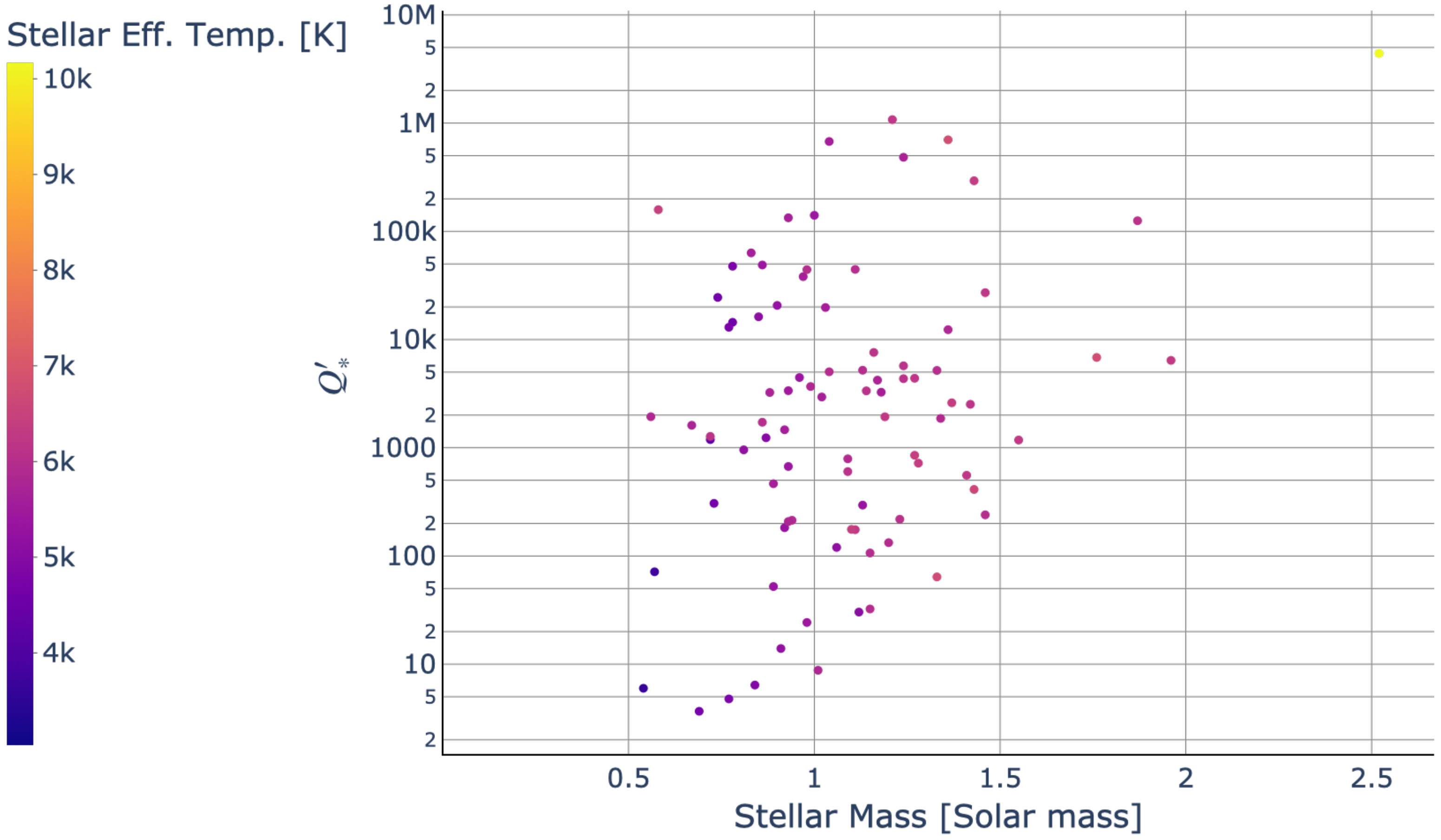

Figure 21: Berry