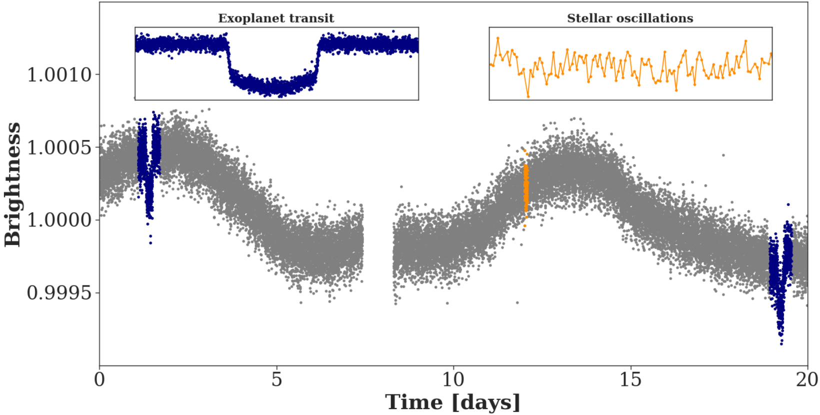
What asteroseismology can do for exoplanets

KITP – Santa Barbara

Vincent Van Eylen

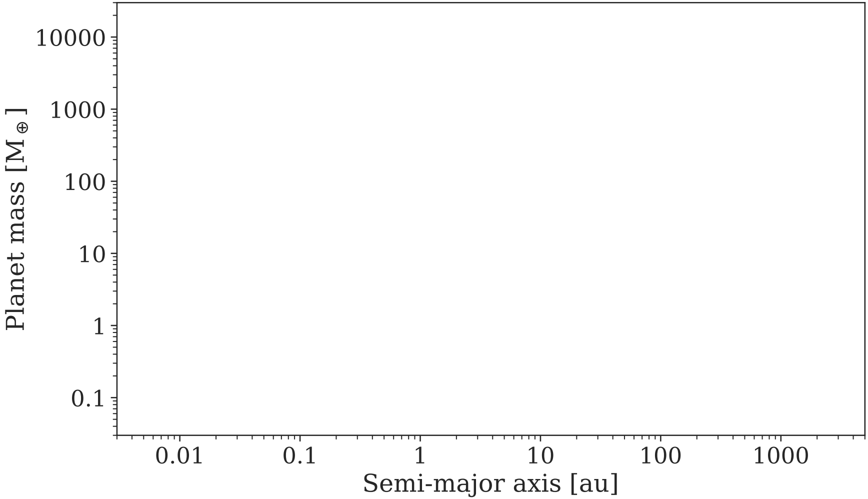
Russell Fellow – Princeton University

Asteroseismology comes ‘for free’ in time series photometry and gives deep knowledge of a star and its planets.



Kepler-410, Van Eylen et al. 2014

Solar system planets show a wide diversity.



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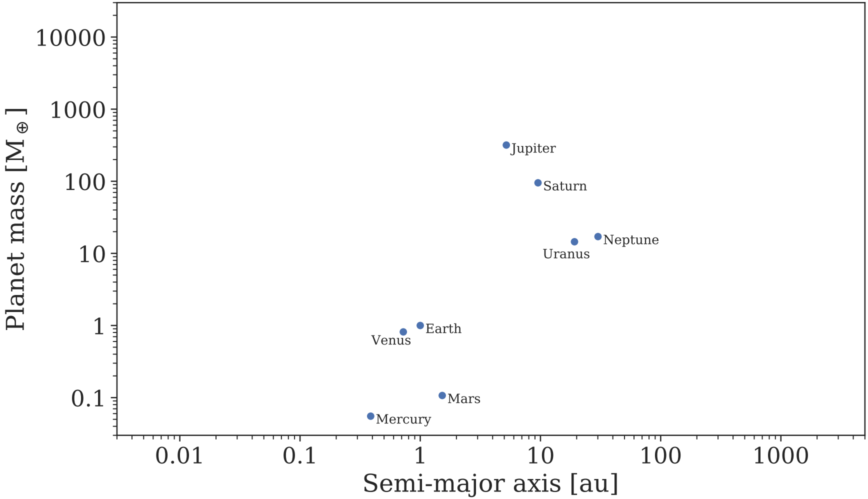

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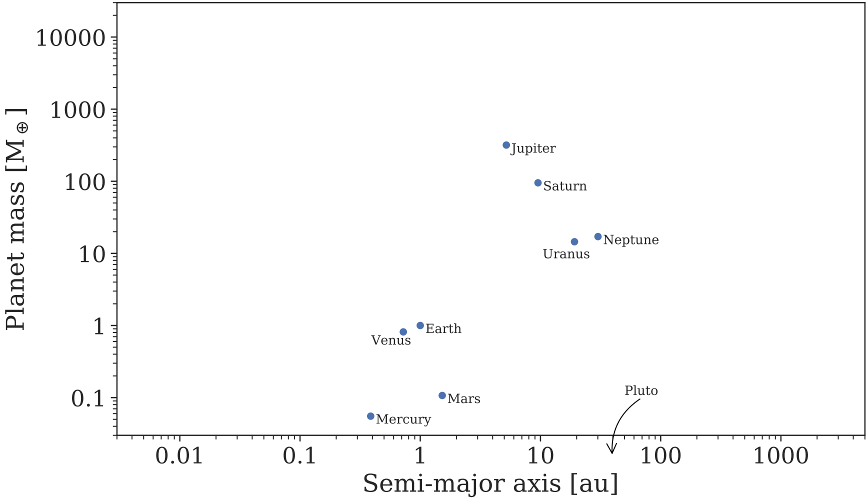
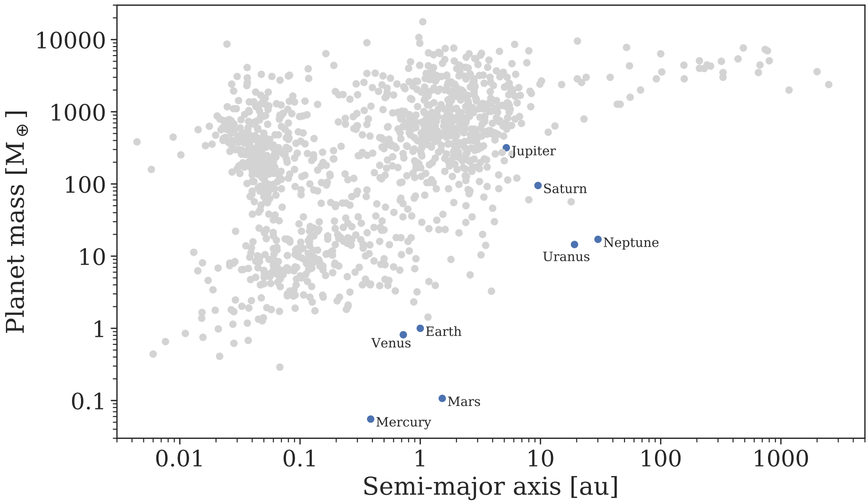


Many planets are unlike those in our solar system.



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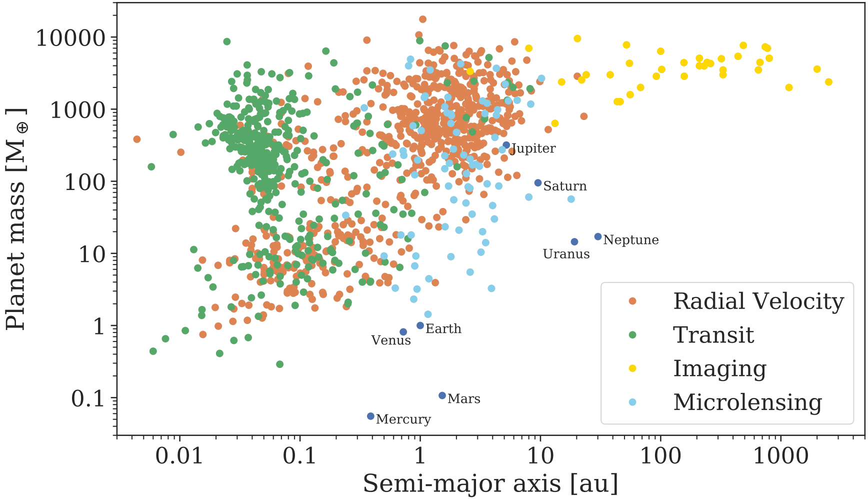

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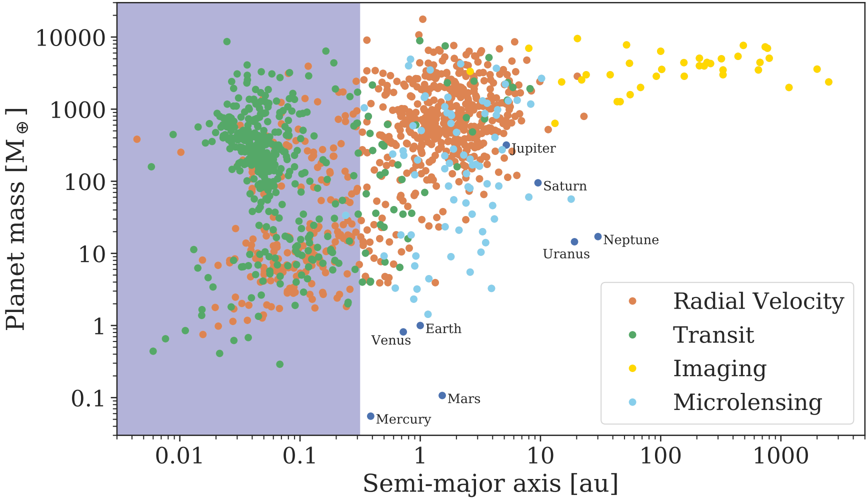

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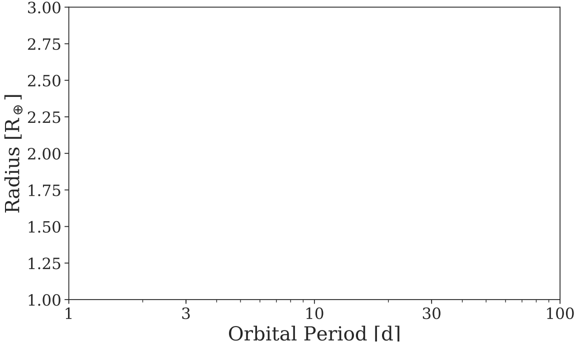
e.g. Lopez & Fortney 2013, Owen & Wu 2013, Jin et al. 2014



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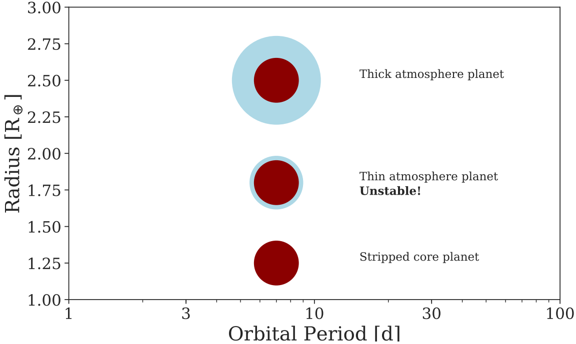

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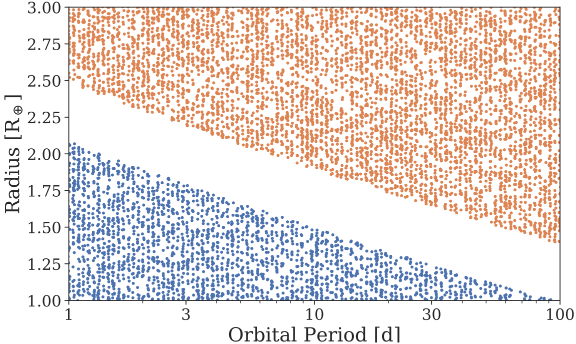

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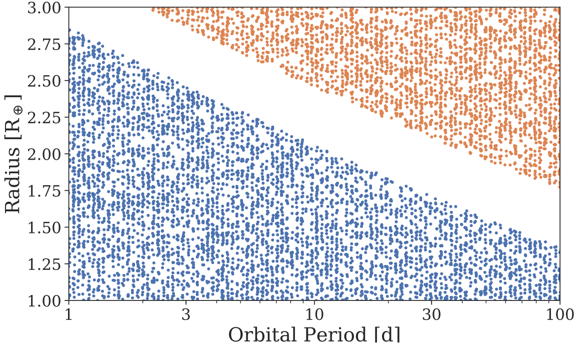

Photo-evaporation results in:

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2. valley depends on planet composition and orbital period

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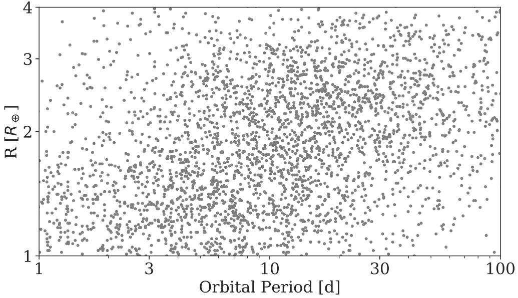

Early Kepler (Q12 table)

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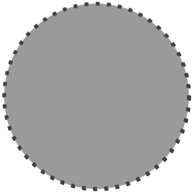
Early Kepler
25% precision



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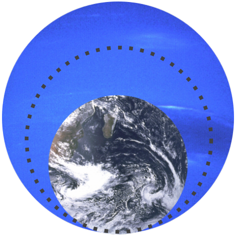

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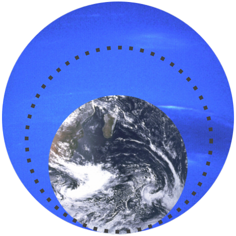

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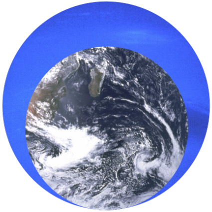
Spectroscopy & Gaia
<10% precision



Fulton et al. 2017
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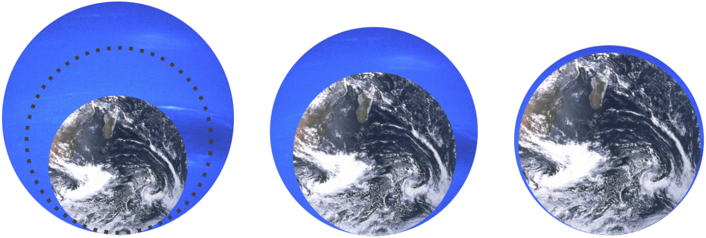

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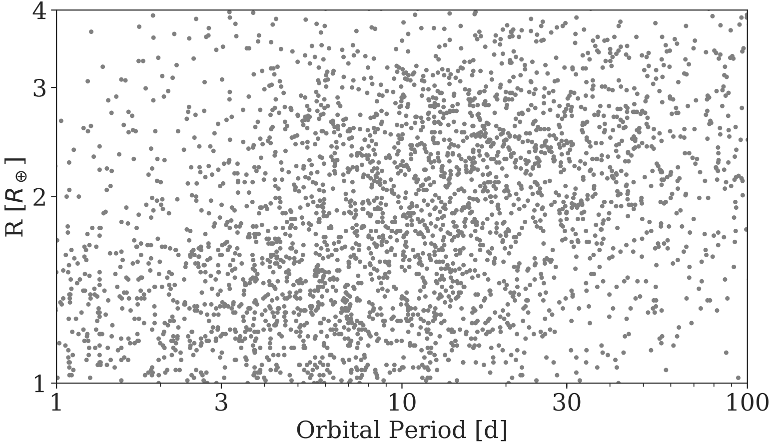

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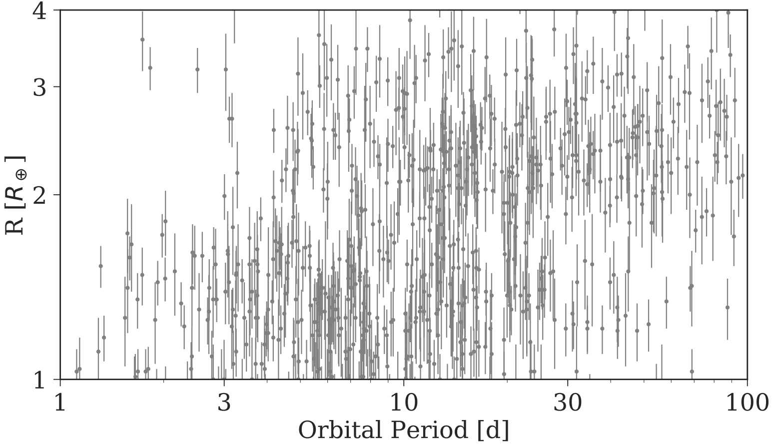
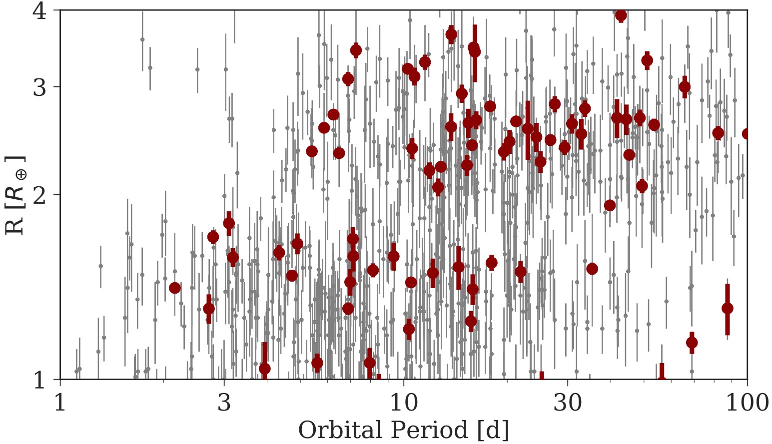
Precise stellar and planetary parameters bring the radius valley into view: spectroscopy + Gaia.



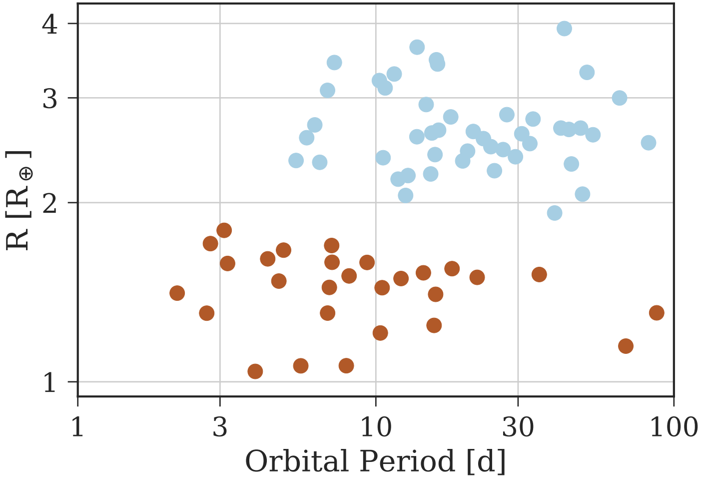
Adapted from Fulton et al. 2017

See also Fulton & Petigura 2018, Berger et al. 2018

Precise stellar and planetary parameters bring the radius valley into view: asteroseismology!

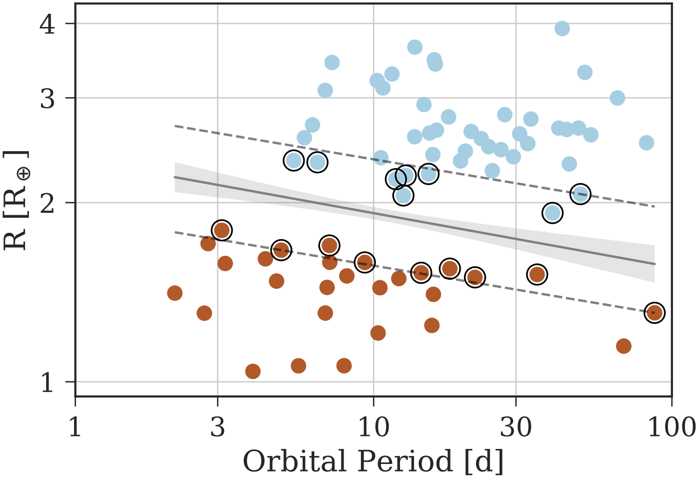


Van Eylen et al. 2018b



Van Eylen et al. 2018b

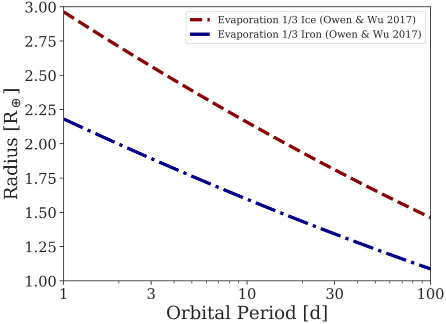
- We find a **very empty radius valley.**



Van Eylen et al. 2018b

- We find a **very empty radius valley.**
- Using support vector machines, we measure its precise **location & slope**: $\log_{10}(\mathbf{R}) = -0.09^{+0.02}_{-0.04} \log_{10}(\mathbf{P}) + 0.37^{+0.04}_{-0.02}$.

Comparing the slope to photo-evaporation models reveals core composition (+ evaporation physics).



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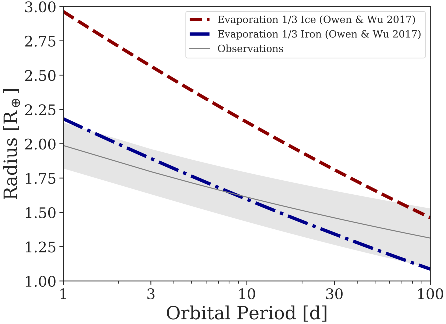

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- Location matches terrestrial core composition (in situ formation?)
- Valley's emptiness suggests homogeneous core composition

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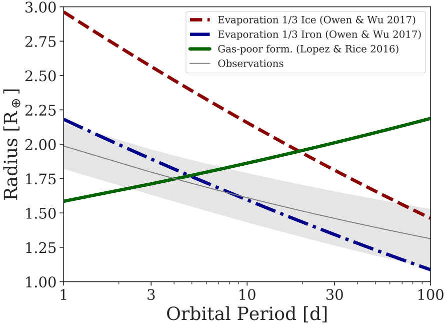

Van Eylen et al. 2018b

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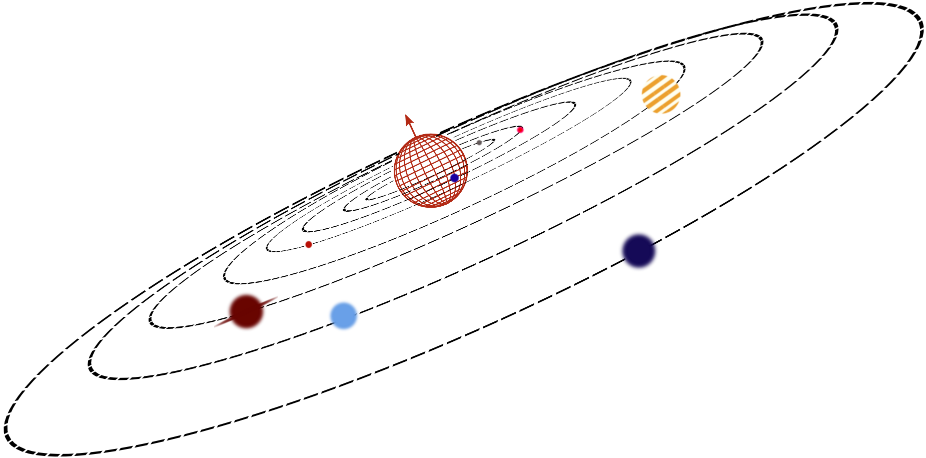
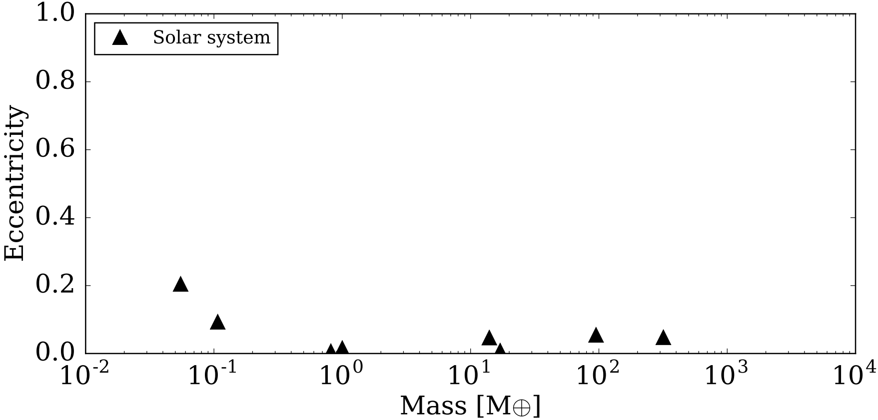
- Alternatives. Slope inconsistent with late gas poor formation, but perhaps *core-powered mass-loss: see e.g. Gupta & Schlichting 2019*

Our solar system is flat and planet orbits are nearly circular.



What are the eccentricities of exoplanets?



Eccentricities from RV detections from exoplanets.org.

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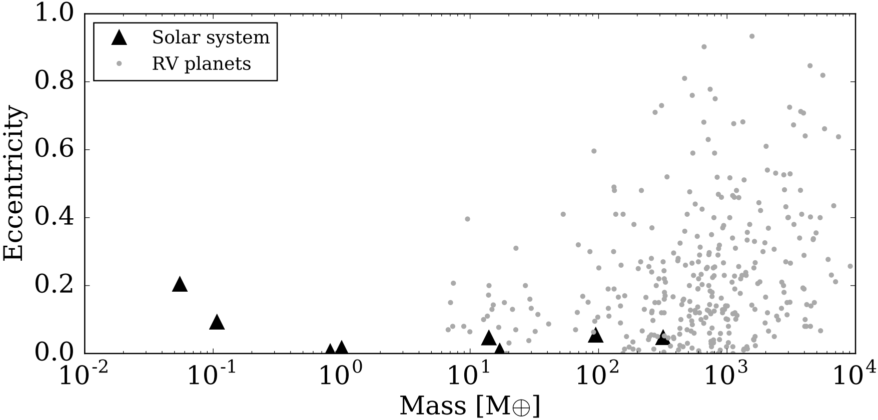

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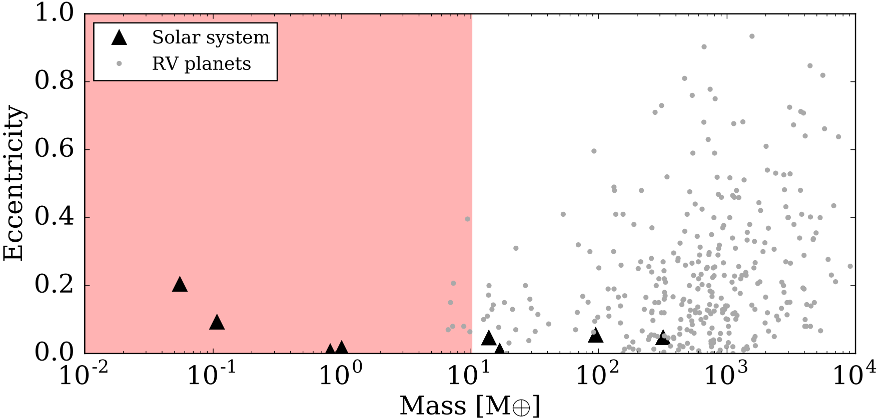

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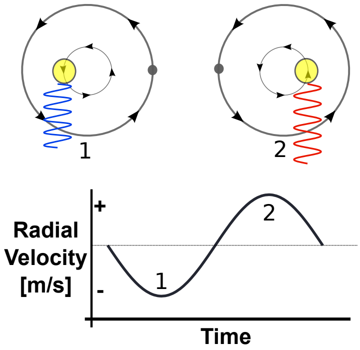
How to observe eccentricity?

- Using radial velocities



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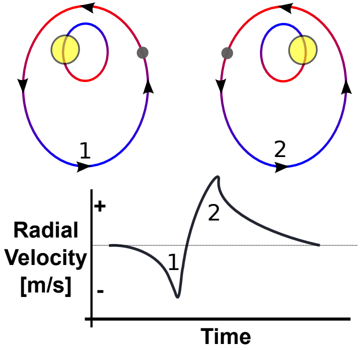

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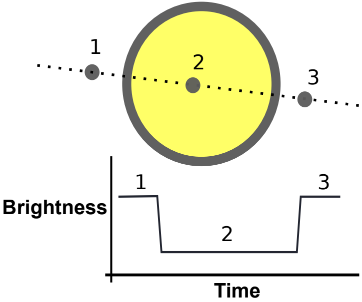

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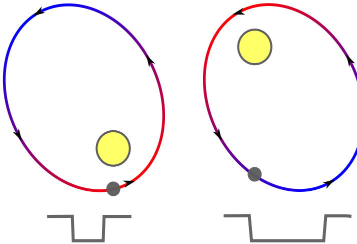

Calibration: transit durations are proportional to the **mean stellar density**, as well as the planetary orbit.

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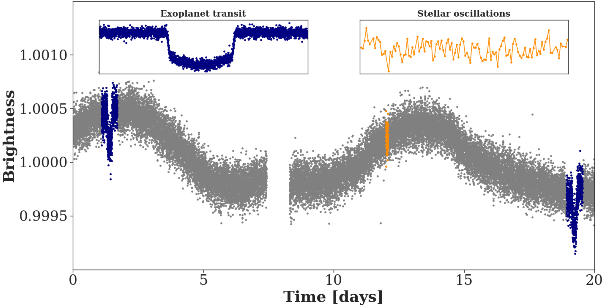
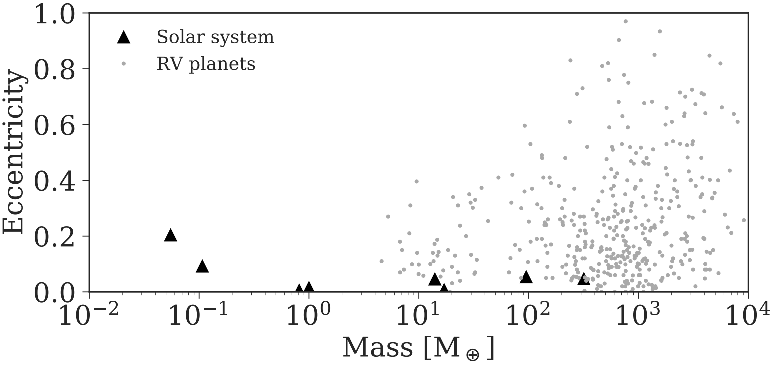


Kepler-410, Van Eylen et al. 2014

Combining precise **stellar mean densities from asteroseismology** with careful transiting modeling, we can get orbital eccentricities.

The orbital eccentricity of small planets



Only $P > 5$ days plotted

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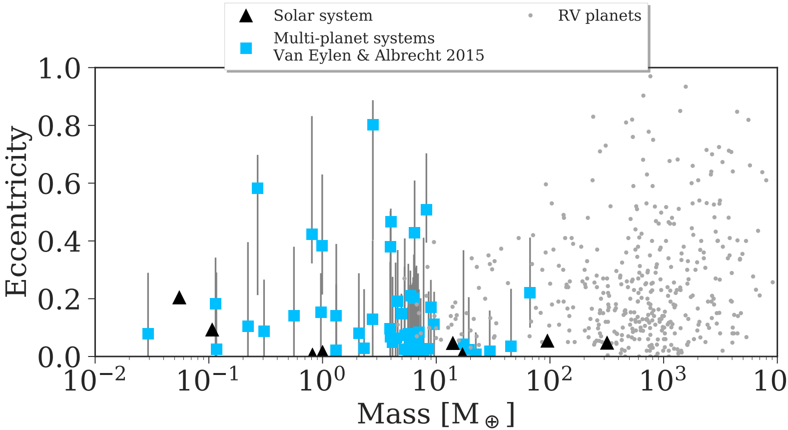

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Van Eylen & Albrecht 2015

Multi-planet systems are near-circular, like the solar system.

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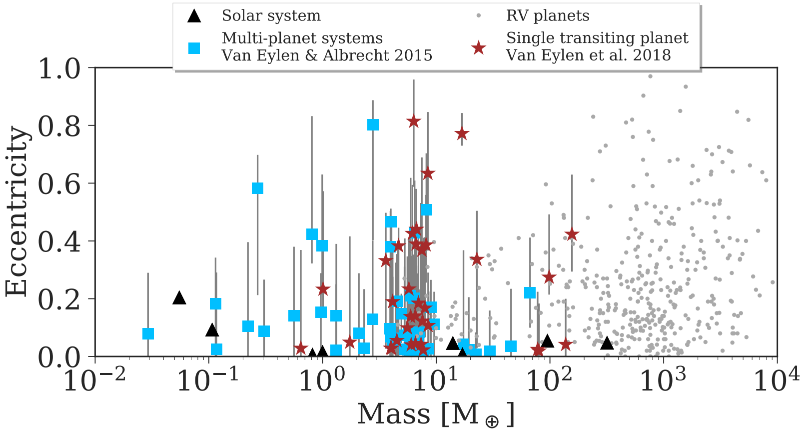

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Van Eylen et al. 2019

Single-transiting-planet systems have moderate eccentricities.

See also Xie et al. 2016 (LAMOST), Mills et al. 2019 (CKS)

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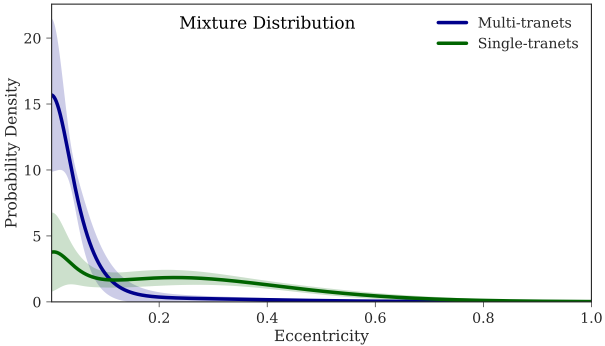

Van Eylen et al. 2019

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- **Self-excitation:** gravitational scattering increases inclination/eccentricity
  e.g. Moriarty & Ballard 2016, Dawson, Lee & Chiang 2016
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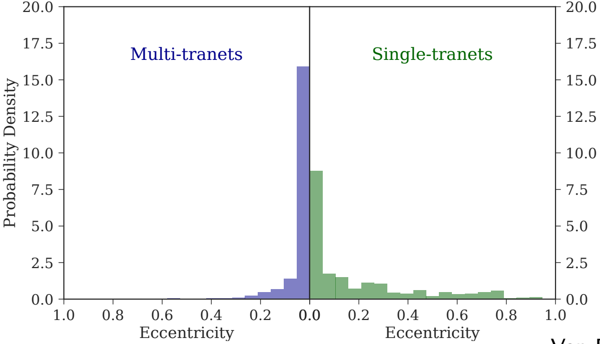

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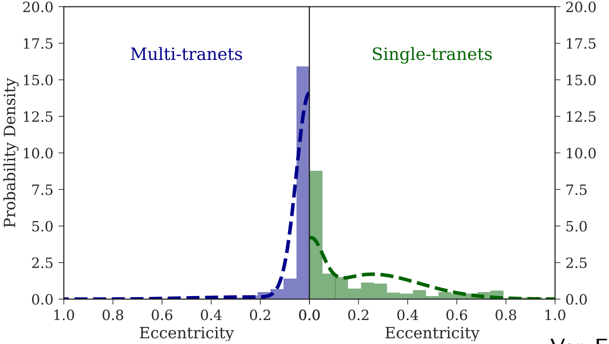

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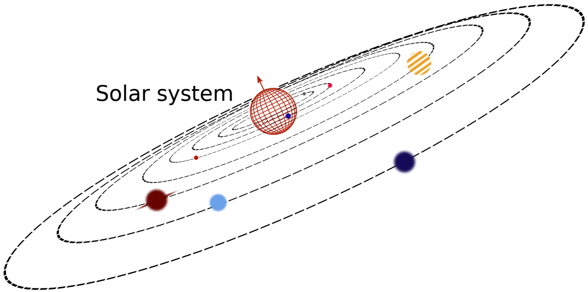

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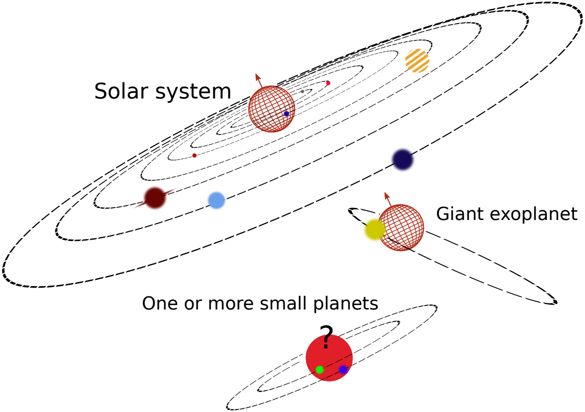

Giant planets can be highly eccentric, systems with small planets are often like the solar system, but not always.

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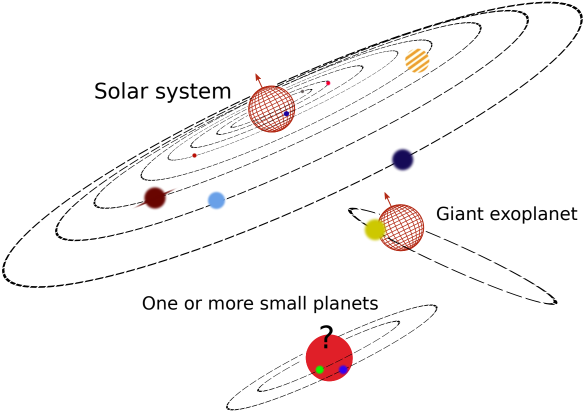

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What about the alignment of the stellar rotation?

How can we measure the obliquity?

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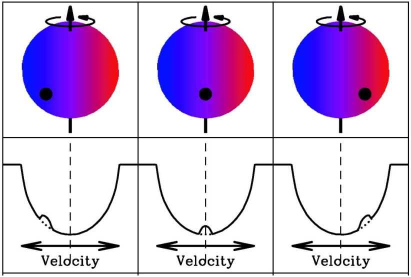
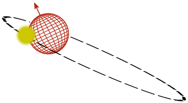
Rossiter-McLaughlin effect



Large planets



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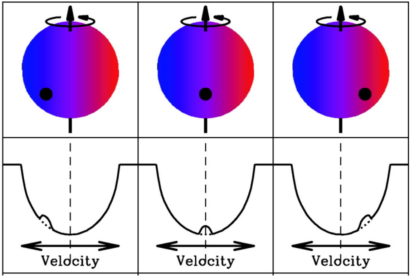

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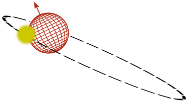
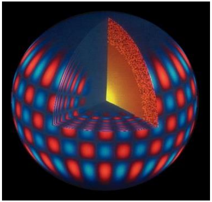


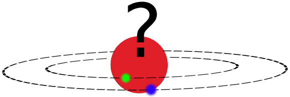
Asteroseismology

Accurate mass, radius, age, ...

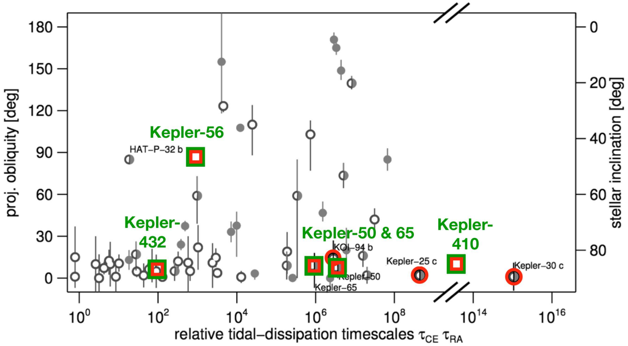


... and stellar inclination!

Independent of planet



What do obliquities tell us?



Albrecht et al. 2013, adapted by Huber 2017, including data from Sanchis-Ojeda et al. 2012, Hirano et al. 2012
Chaplin et al. 2013, Huber et al. 2013, Van Eylen et al. 2014, Benomar et al. 2014
See also ensemble studies: e.g. Morton & Winn 2014, Mazeh et al. 2015, Campante et al. 2016, Winn et al. 2017

1. Giant planets, in grey: often misaligned
2. Systems with (multiple) small planets, in color: more aligned?
   Green points from asteroseismology! *Done with Kepler, waiting for TESS/PLATO...*
   .. but see Kepler-408; Kamiaka et al. 2019

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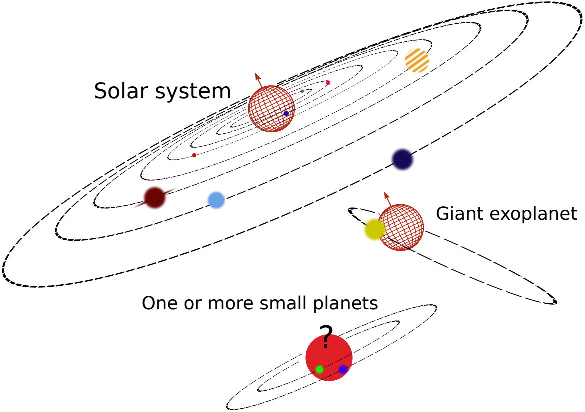

Giant planets can be highly eccentric, systems with small planets are often like the solar system, but not always.

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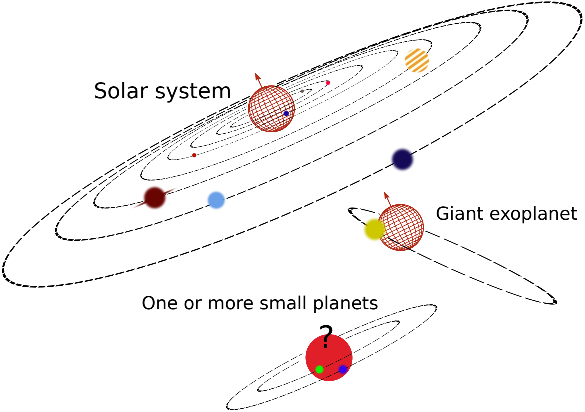

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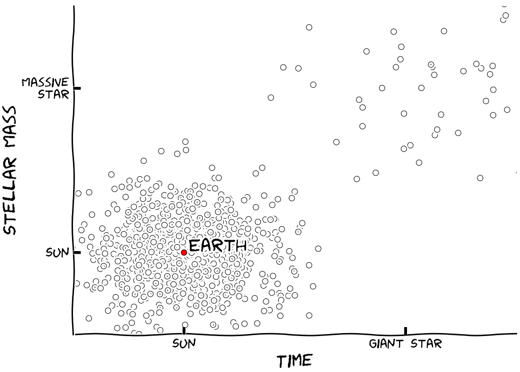
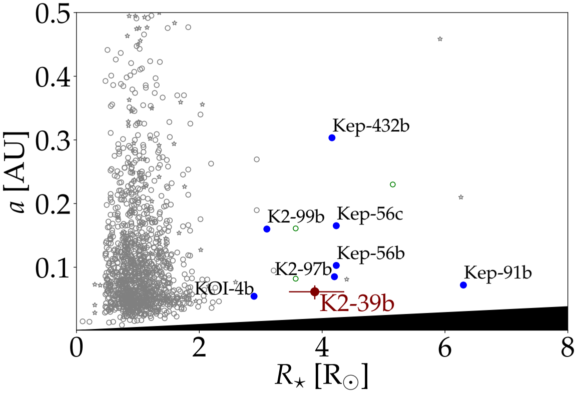
Giant planets often misaligned, small planets maybe – *TESS/PLATO?*.

Do planets orbit all kinds of stars?



1. **Formation**: around which stars do planets form?
   e.g. Burkert & Ida 2007, Kretke et al. 2009, Currie 2009
2. **Evolution**: as stars evolve, what happens to planetary systems?
   e.g. Rasio et al. 1996, Villaver & Livio 2009, Schlaufman & Winn 2013

Short-period planets around evolved stars: search ongoing



K2-99 (Smith et al. 2017), Kepler-432 (Ortiz et al. 2015, Ciceri et al. 2015, Quinn et al. 2015),
Kepler-91 (Lillo-Box et al. 2014a, Sliski & Kipping 2014, Lillo-Box et al. 2014b, Barclay et al. 2015),
Kepler-56 (Huber et al. 2013), K2-97 (Grunblatt et al. 2016, 2017), **K2-39 (Van Eylen et al. 2016c)**
KOI-4 (Chontos et al. 2018).
More evolved? Occurrence constraints on planets orbiting **white dwarfs**: van Sluijs & Van Eylen 2018

Asteroseismic parameters of evolved stars e.g. Hjørringgaard+ 2017, Stello+ 2017, North+ 2017, Campante+ 2017

We've answered many questions, but as many remain open. Luckily, asteroseismology & exoplanets have a bright future!

Kepler & K2

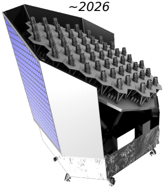
2009-2018

TESS

2018-...

PLATO

~2026



1. **Accurate stellar radius and mass $\rightarrow$ planet radius and mass**
   e.g. radius gap: how to form close-in planets, which ones have atmospheres
2. **Mean stellar density $\rightarrow$ orbital eccentricity**
   e.g. formation history, single-tranets have higher eccentricity
3. **Rotational splitting $\rightarrow$ obliquities**
   e.g. obliquity of systems with multiple / small planets
4. **Evolutionary stage, age $\rightarrow$ ...?**
   e.g. planets around evolved stars, ...?