The Diversity of Low-Mass Exoplanets
August 4th 2022
HEDS Seminar @LLNL

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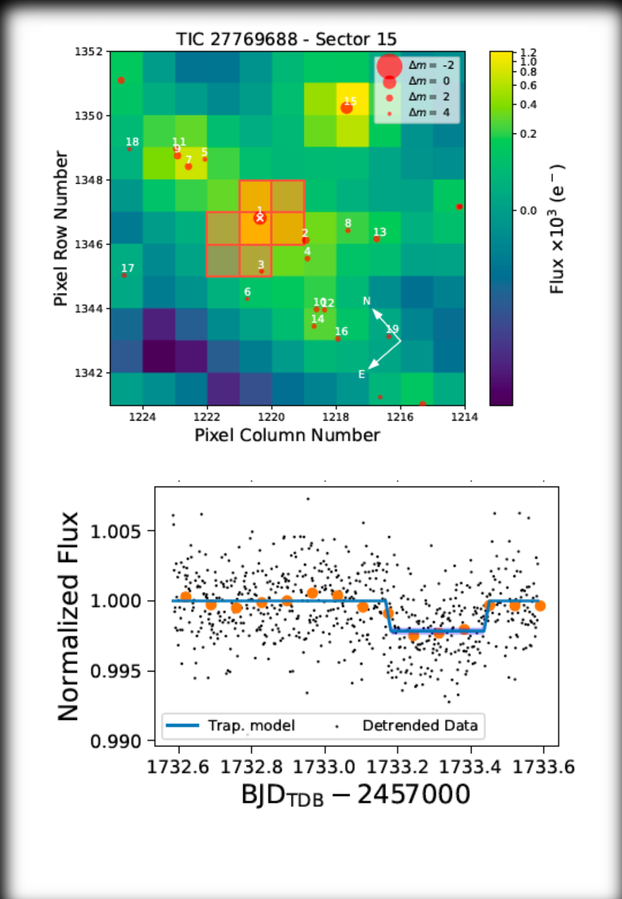
Chapter I

Planet Radii

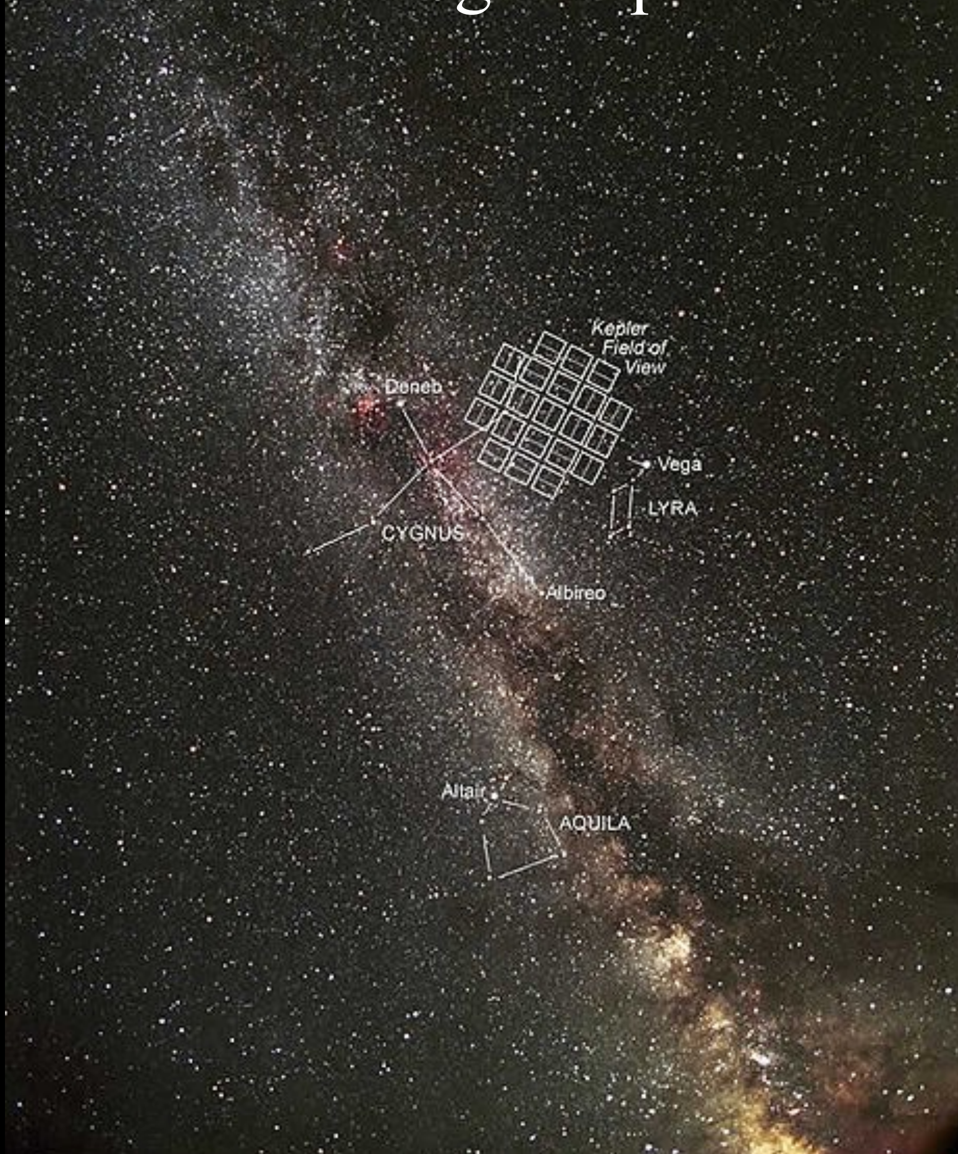


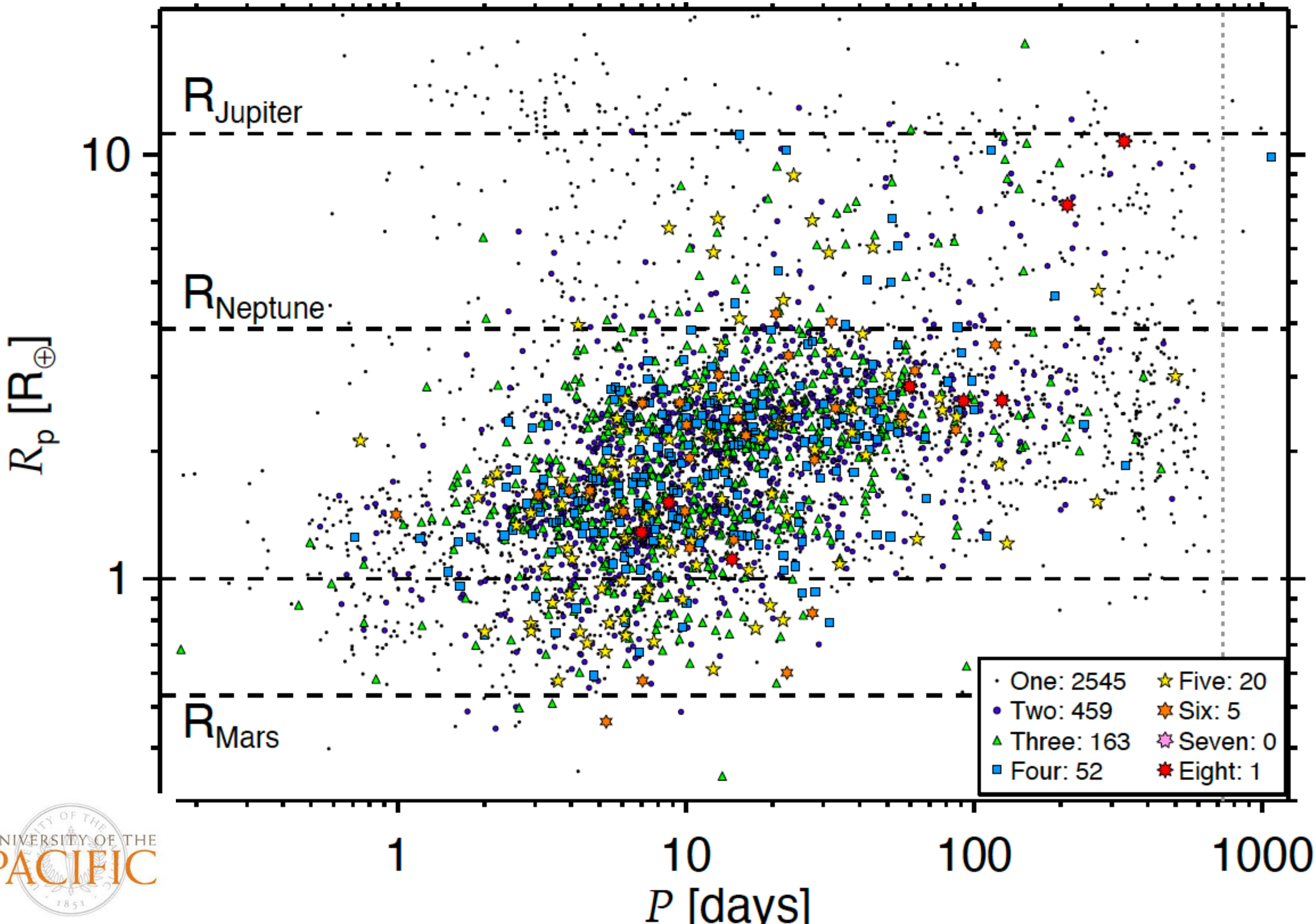
Transiting Exoplanets

Kepler mission

To find an Earth-like planet orbiting a Sun-like star

- Photometry on ~160,000 stars over 4 years
- ~4500 planets discovered
- ~1700 planets in multis





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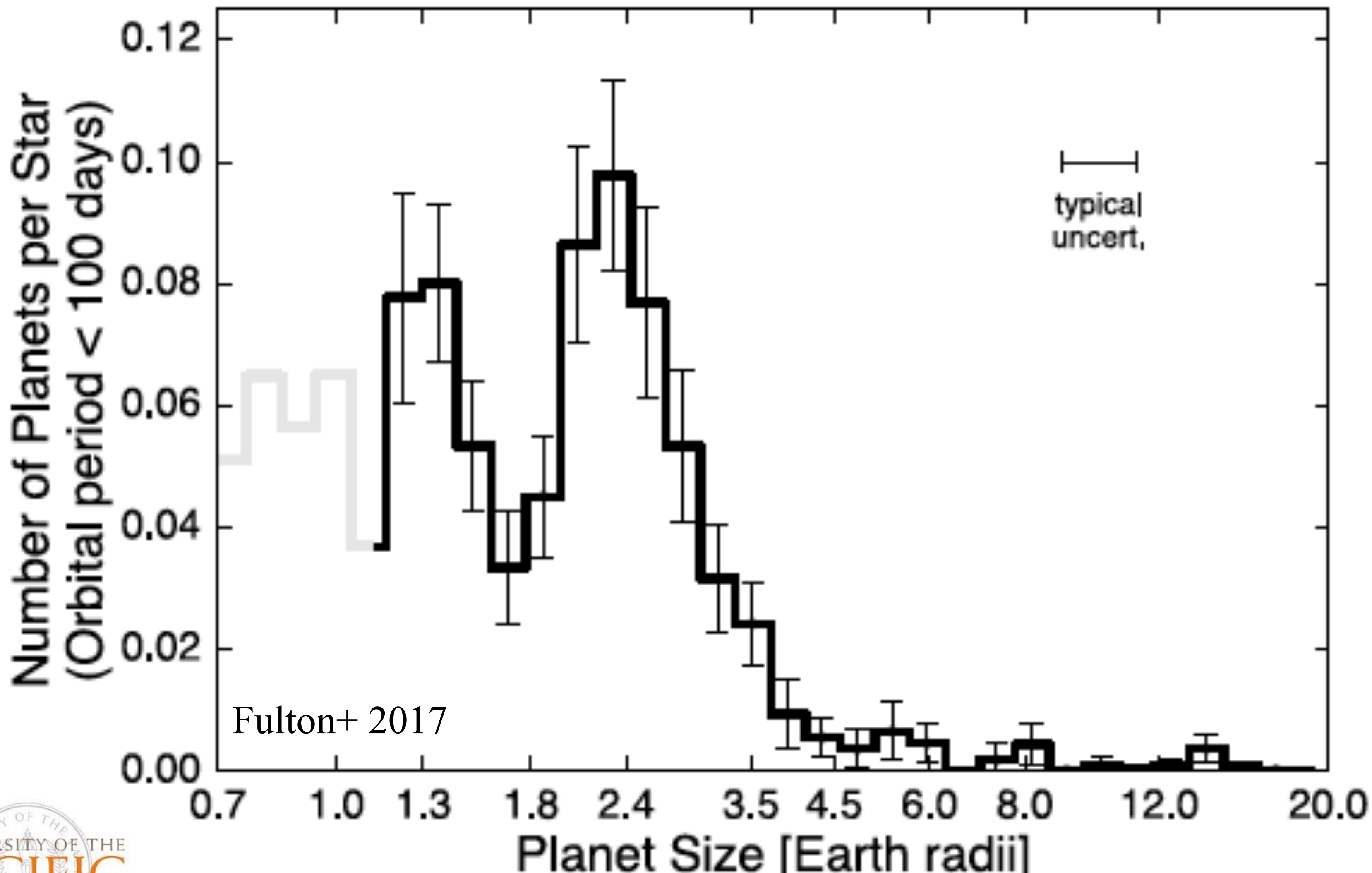
Planet radius valley hints at a transition in composition ~1.8 R_{Earth}



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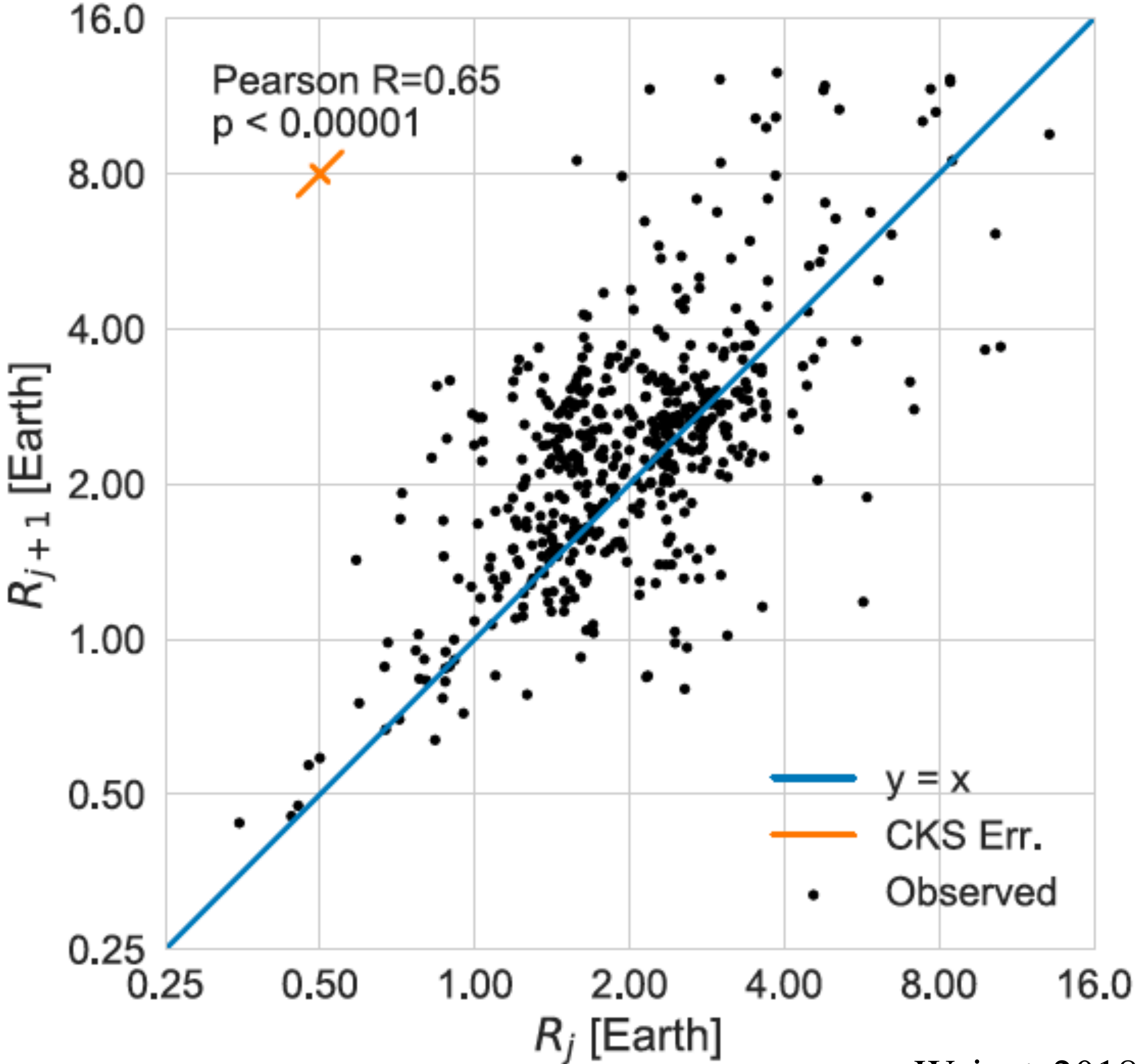
Planet radii in multiplanet systems are strongly correlated.



Weiss+ 2018

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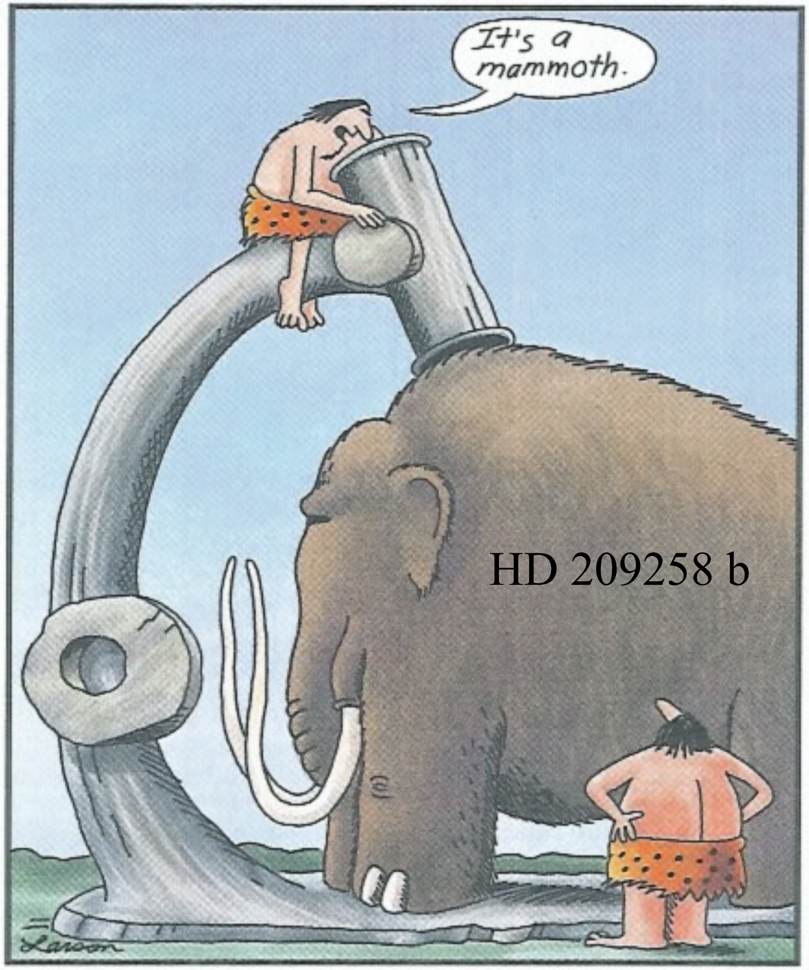
Chapter II

Characterizing Exoplanet Masses



Early microscope

Measuring mass is key.

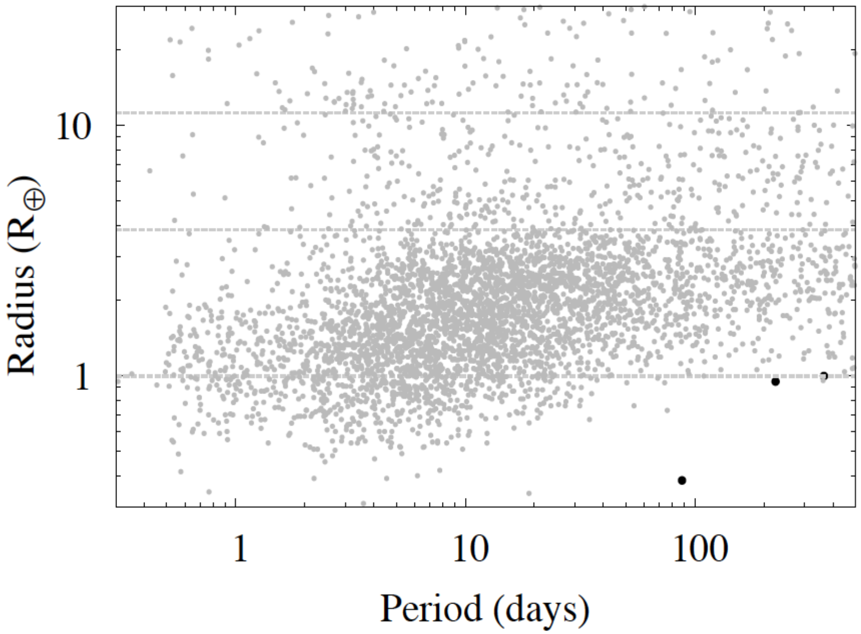
M/R^2 gives surface gravity

- atmospheric scale height

M/R^3 gives bulk density

- we can infer bulk composition: iron, rock, water, hydrogen.

However, the vast majority of transiting planets will not have their masses measured in the near future.



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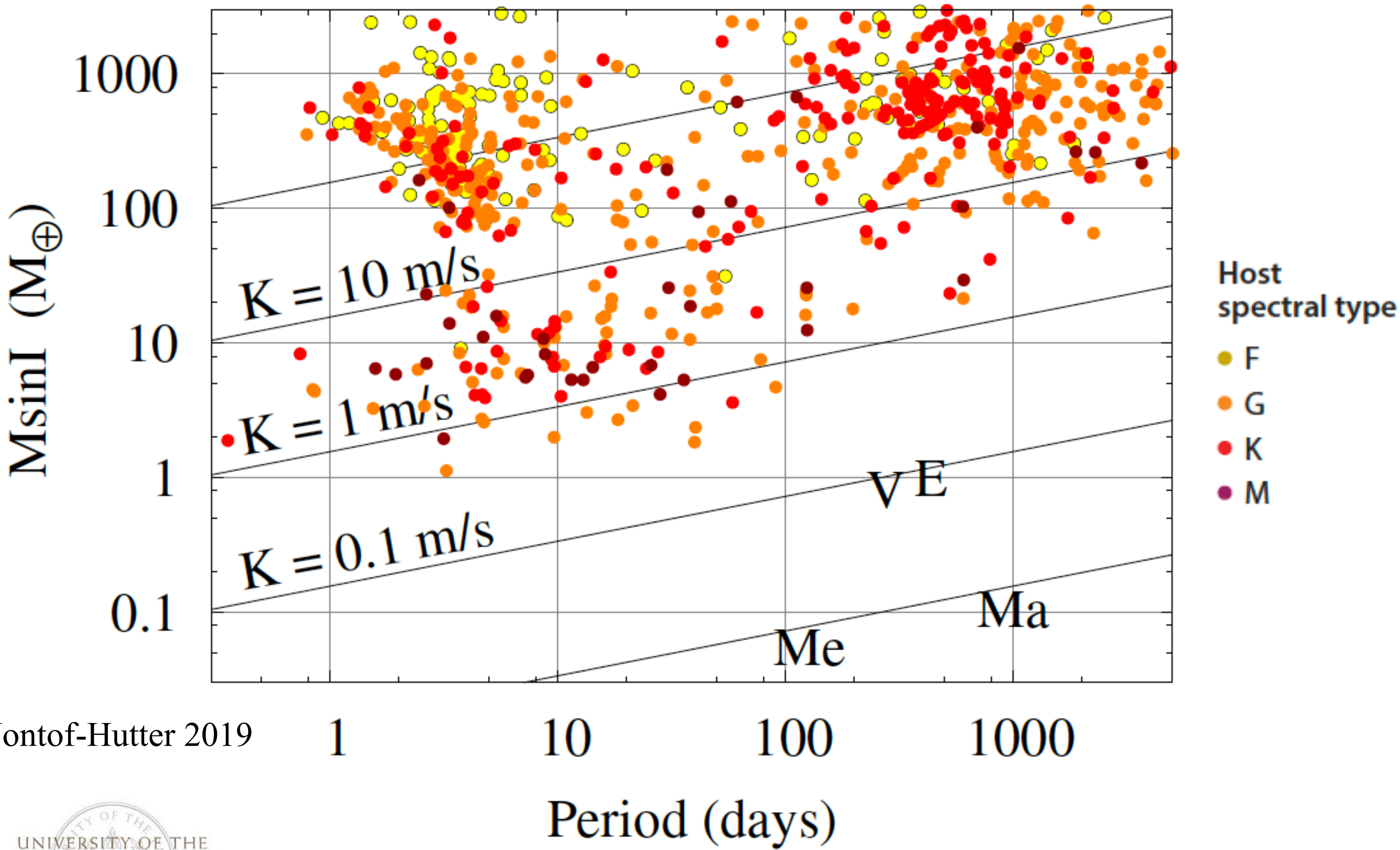
Mass measurement from Radial Velocity Spectroscopy (RV).



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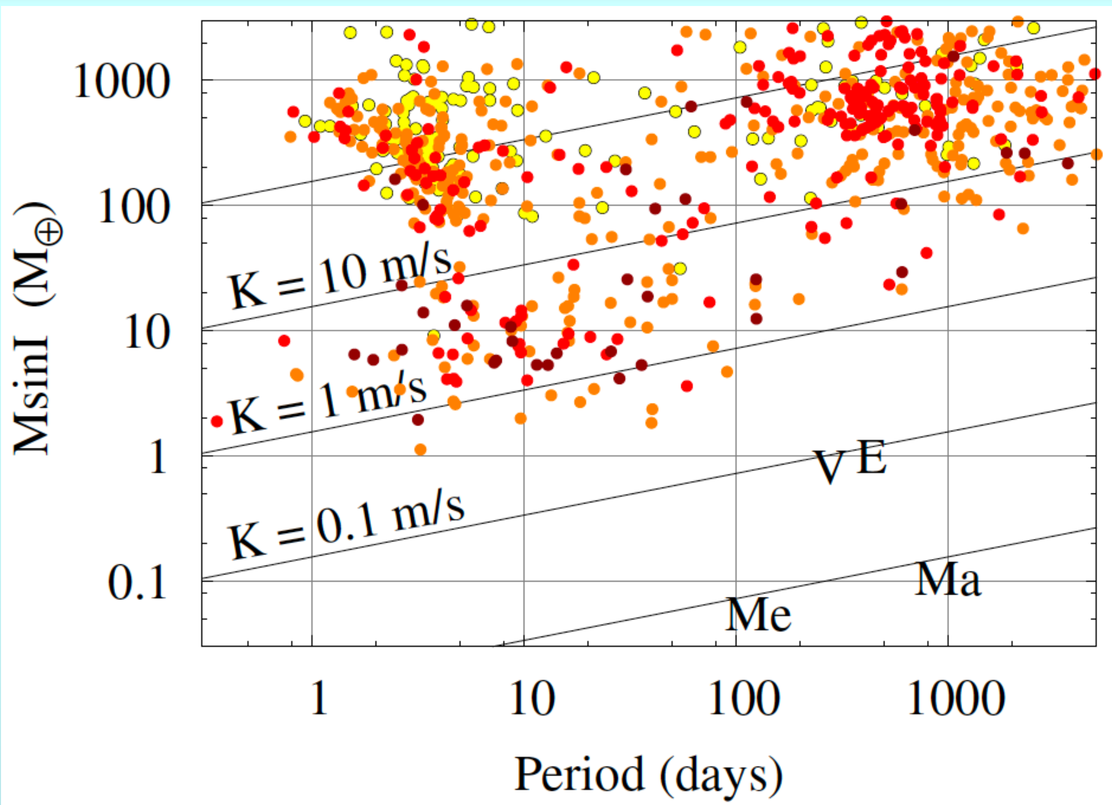
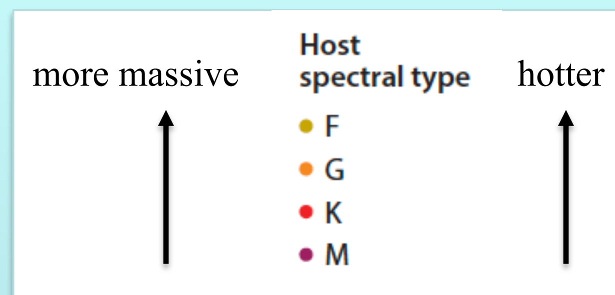
Detection biases of RV

- Higher mass planets at a given size.
- Low mass planets must have short orbital periods.
- Cooler stars are the best targets for RV observations.
- RV surveys have focused on size-limited planet samples.

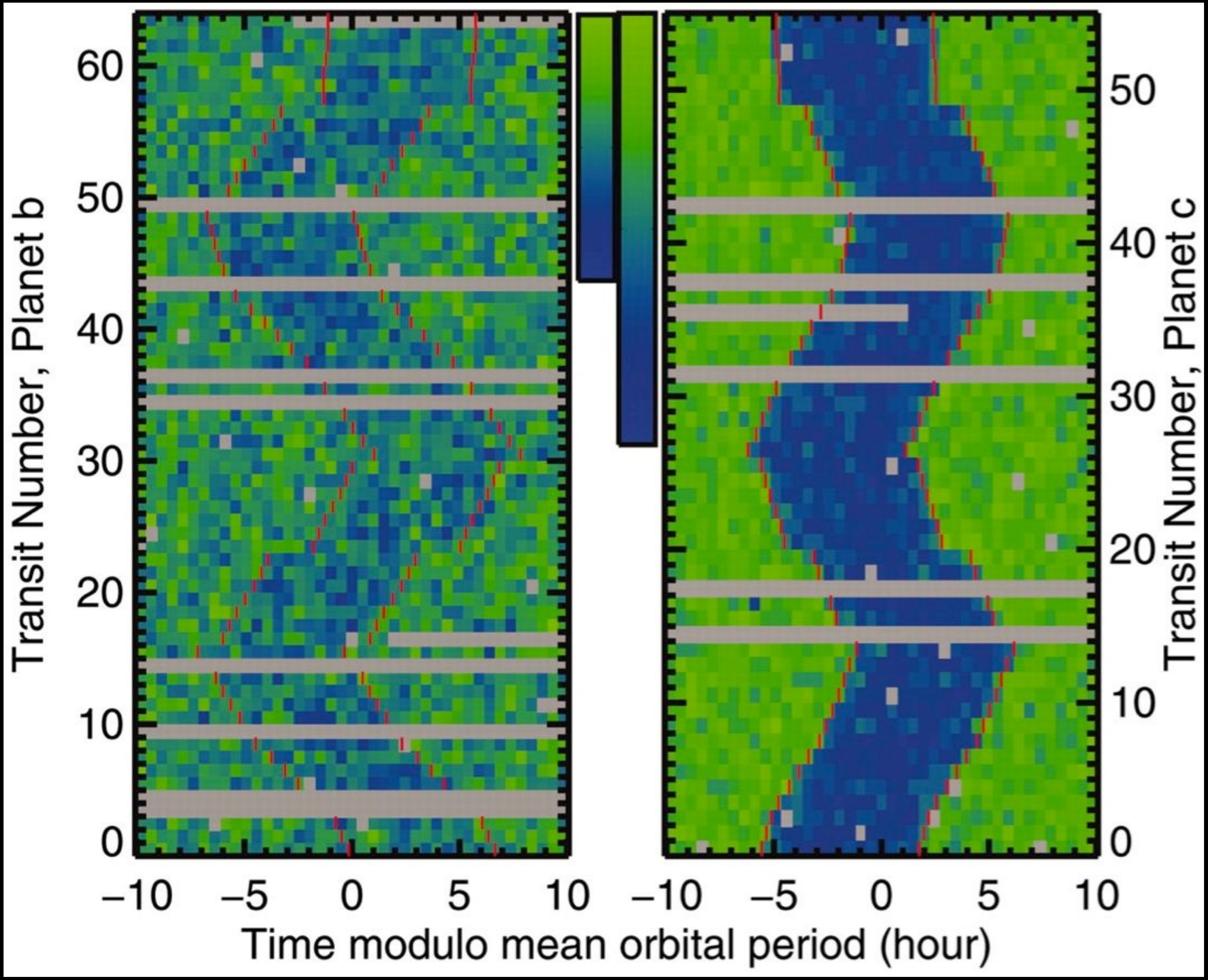


$$K = \frac{0.640\ \mathrm{m/s}^{-1}}{\sqrt{1-e^2}} \frac{m_\mathrm{p} \sin I}{\mathrm{M}_\oplus} \left(\frac{m_\star + m_\mathrm{p}}{\mathrm{M}_\odot}\right)^{-2/3} \left(\frac{P}{1\ \mathrm{day}}\right)^{-1/3}$$

$$\mathrm{SNR}_{\mathrm{RV}} \sim \frac{M_\mathrm{p}}{\sigma_{\mathrm{RV}} P^{1/3}}$$



Transit Timing Variations (TTV)



Carter+ 2012

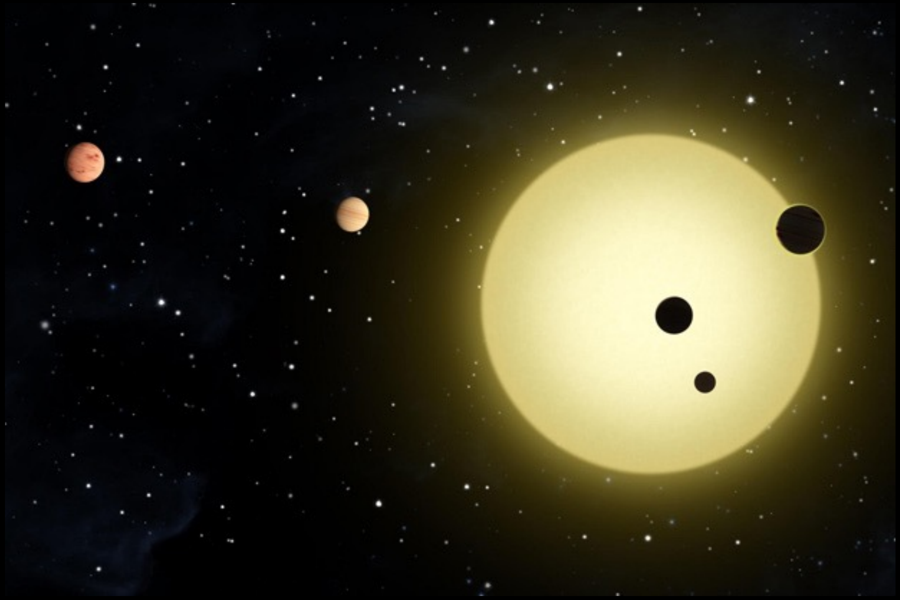
Transit Timing Variations (TTV)

Compact or near-resonant multiplanet systems show TTVs

Near resonance, coherent perturbations add constructively, causing TTVs to build up to minutes to hours.

Near a j:j-1 resonance:

$$\boxed{\frac{1}{P_{TTV}} = \left| \frac{j-1}{P} - \frac{j}{P'} \right|}$$



Theoretical Progress

Agol et al. (2005)

Holman and Murray (2005)

Nesvorný and Morbidelli (2008)

Lithwick et al. (2012)

Nesvorný and Vokrouhlický (2014)

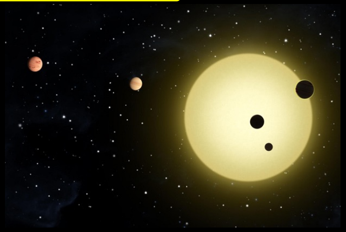
Deck and Agol (2015, 2016)

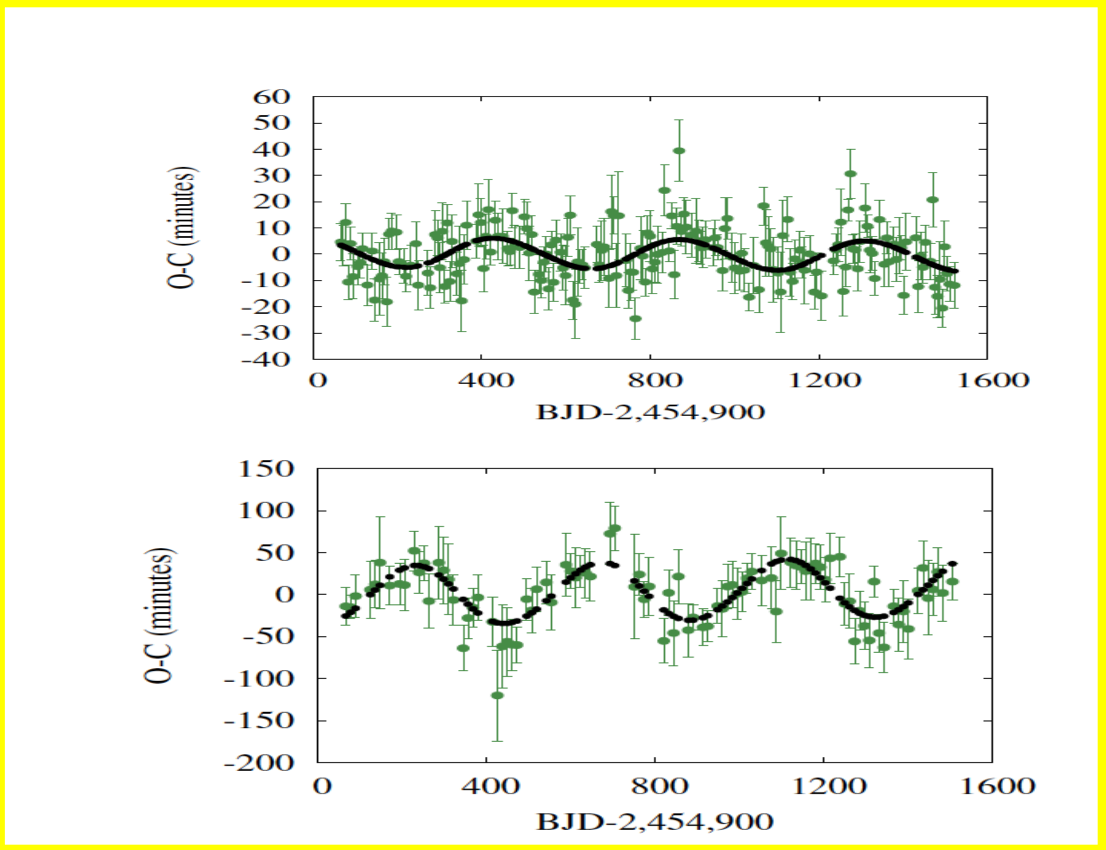
Hadden and Lithwick (2016)

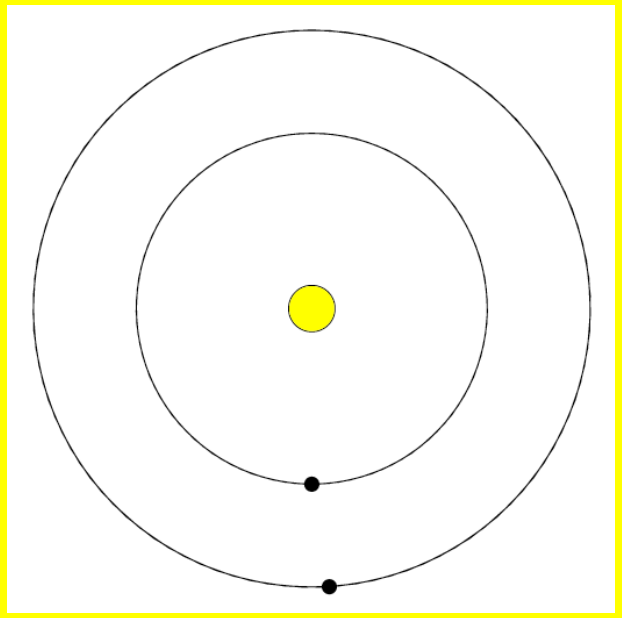
Near a j:j-1 resonance…

$$\frac{1}{P_{TTV}} = \left| \frac{j-1}{P} - \frac{j}{P'} \right|$$

…TTVs are anti-correlated sinusoids

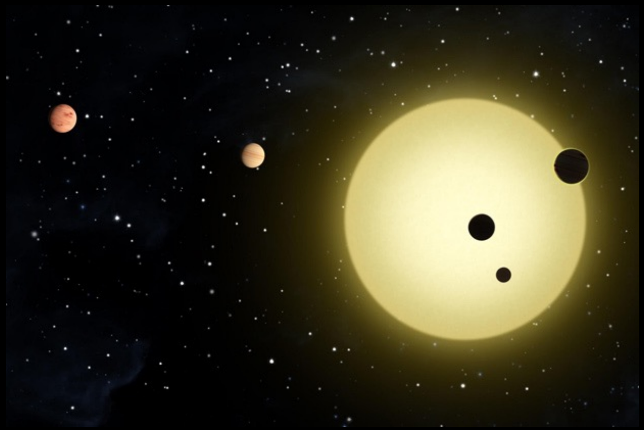






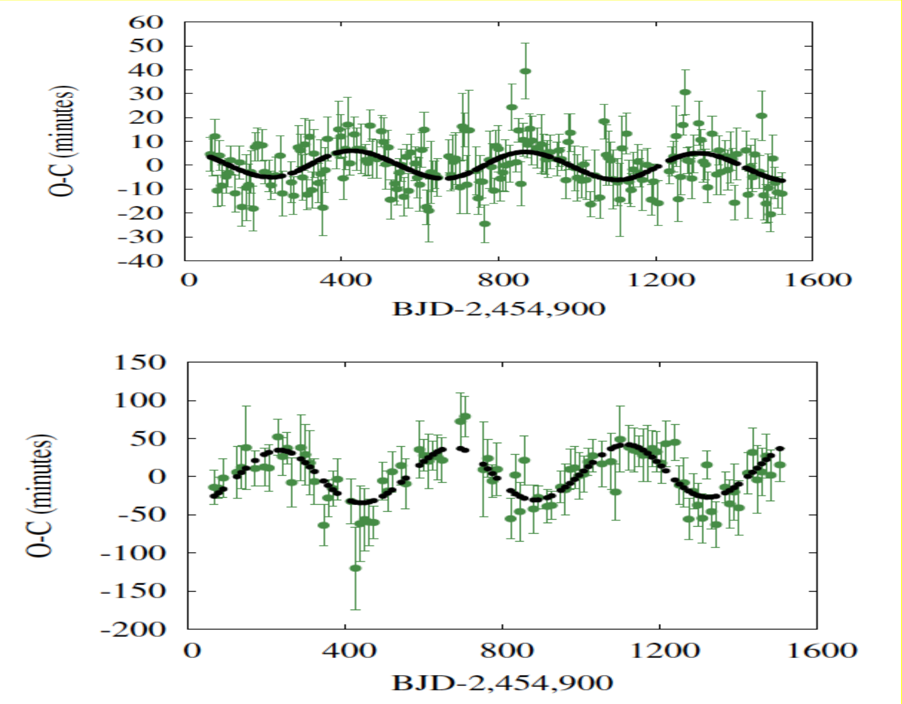
Kepler-57
Jontof-Hutter+ 2016

Near a j:j-1 resonance…



$$\frac{1}{P_{TTV}} = \left| \frac{j-1}{P} - \frac{j}{P'} \right|$$

…an analytical solution exists.

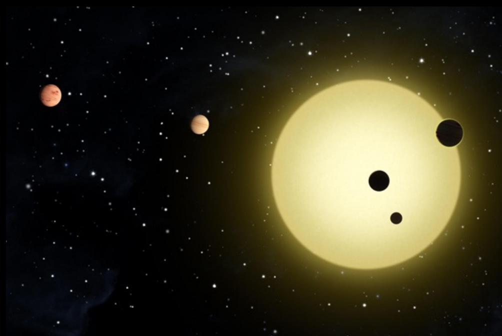


$$|V| \sim P \frac{\mu'}{|\Delta|}\left(1 + \frac{|Z_{\rm free}|}{|\Delta|}\right)$$

$$|V'| \sim P' \frac{\mu}{|\Delta|}\left(1 + \frac{|Z_{\rm free}|}{|\Delta|}\right)$$

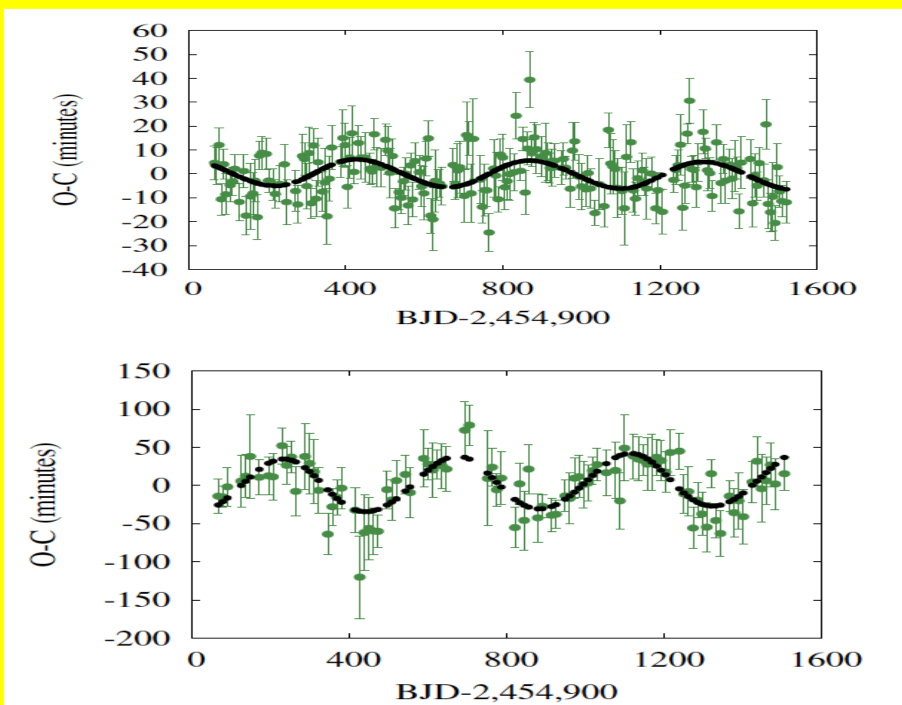
Lithwick et al. 2012

Near a j:j-1 resonance…



$$\frac{1}{P_{TTV}} = \left|\frac{j-1}{P} - \frac{j}{P'}\right|$$

…there is a mass-eccentricity near degeneracy.



$$|V| \sim P\frac{\mu'}{|\Delta|}\left(1 + \frac{|Z_{\mathrm{free}}|}{|\Delta|}\right)$$

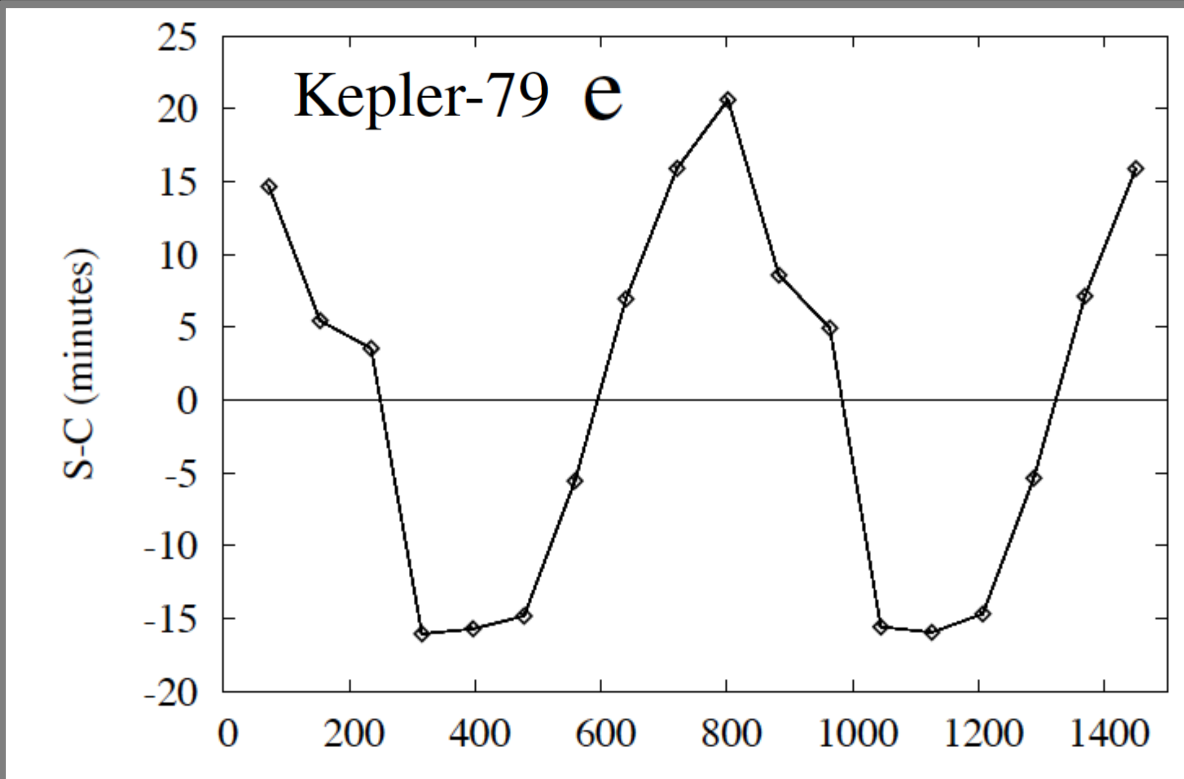
$$|V'| \sim P'\frac{\mu}{|\Delta|}\left(1 + \frac{|Z_{\mathrm{free}}|}{|\Delta|}\right)$$

Lithwick et al. 2012

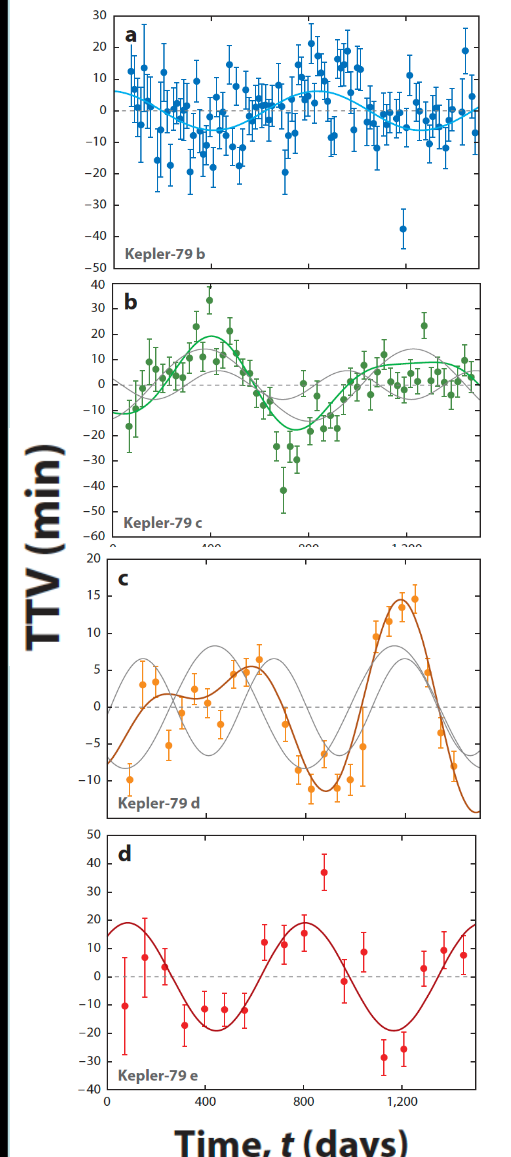
We can break the mass-eccentricity degeneracy if there is more information:

- individual encounters

Due to eccentricity, some conjunctions cause stronger interactions than others.



Jontof-Hutter+ 2014

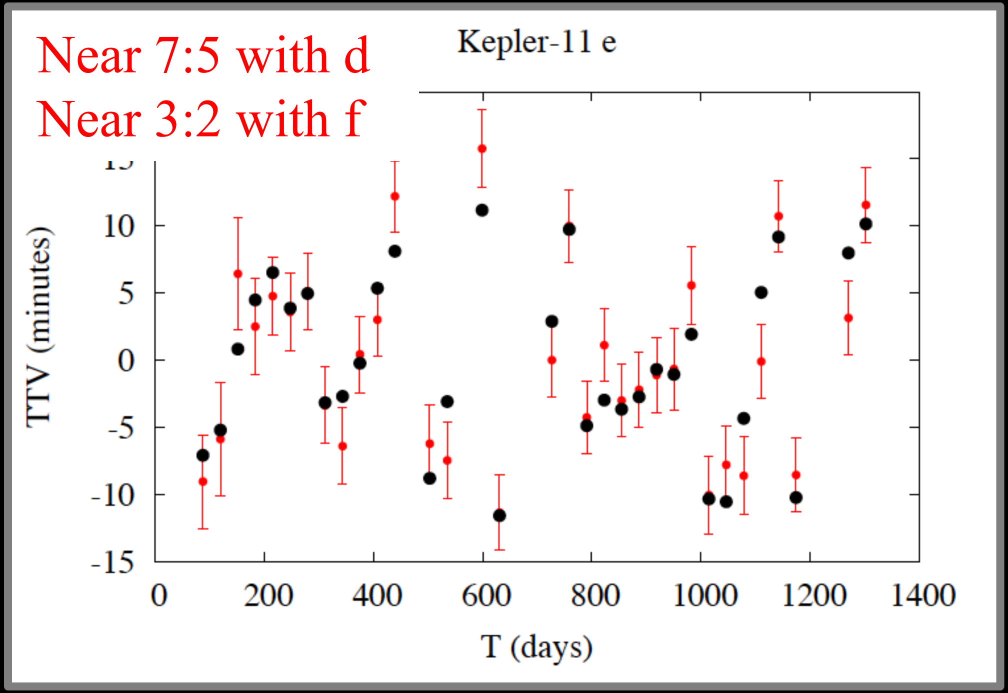


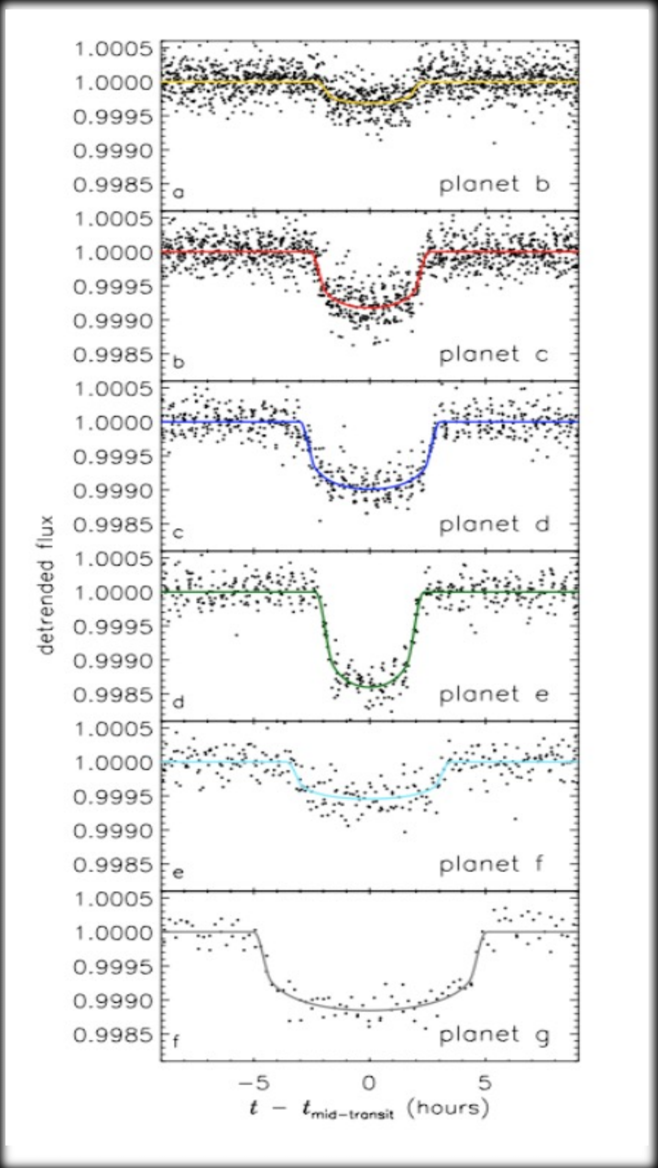
Jontof-Hutter 2019

We can break the mass-eccentricity degeneracy if there is more information:

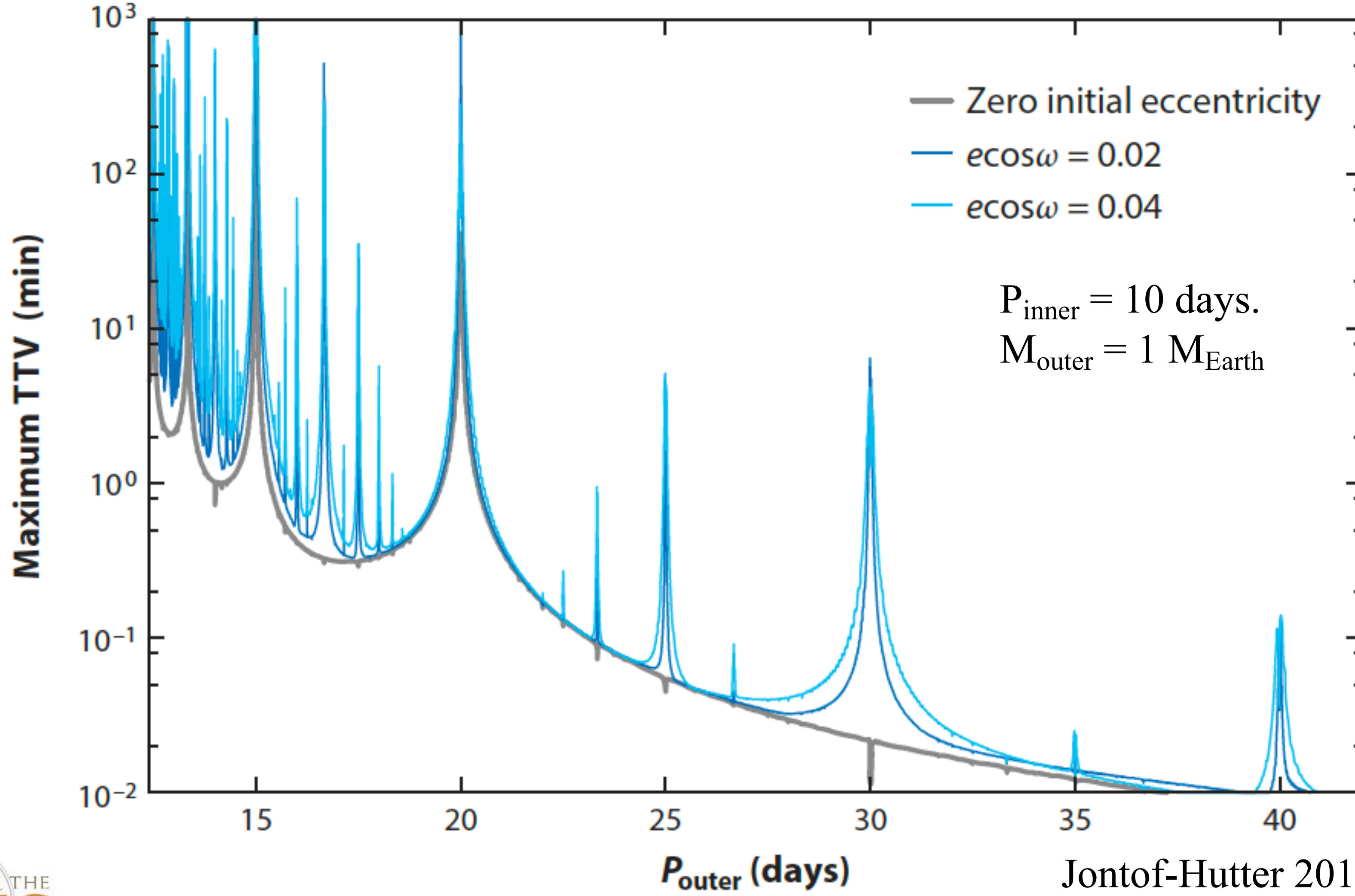
- Individual encounters
- Multi-planet interactions

Breaking the degeneracy opens up a whole system to precise masses and eccentricities





TTV induced on an inner planet



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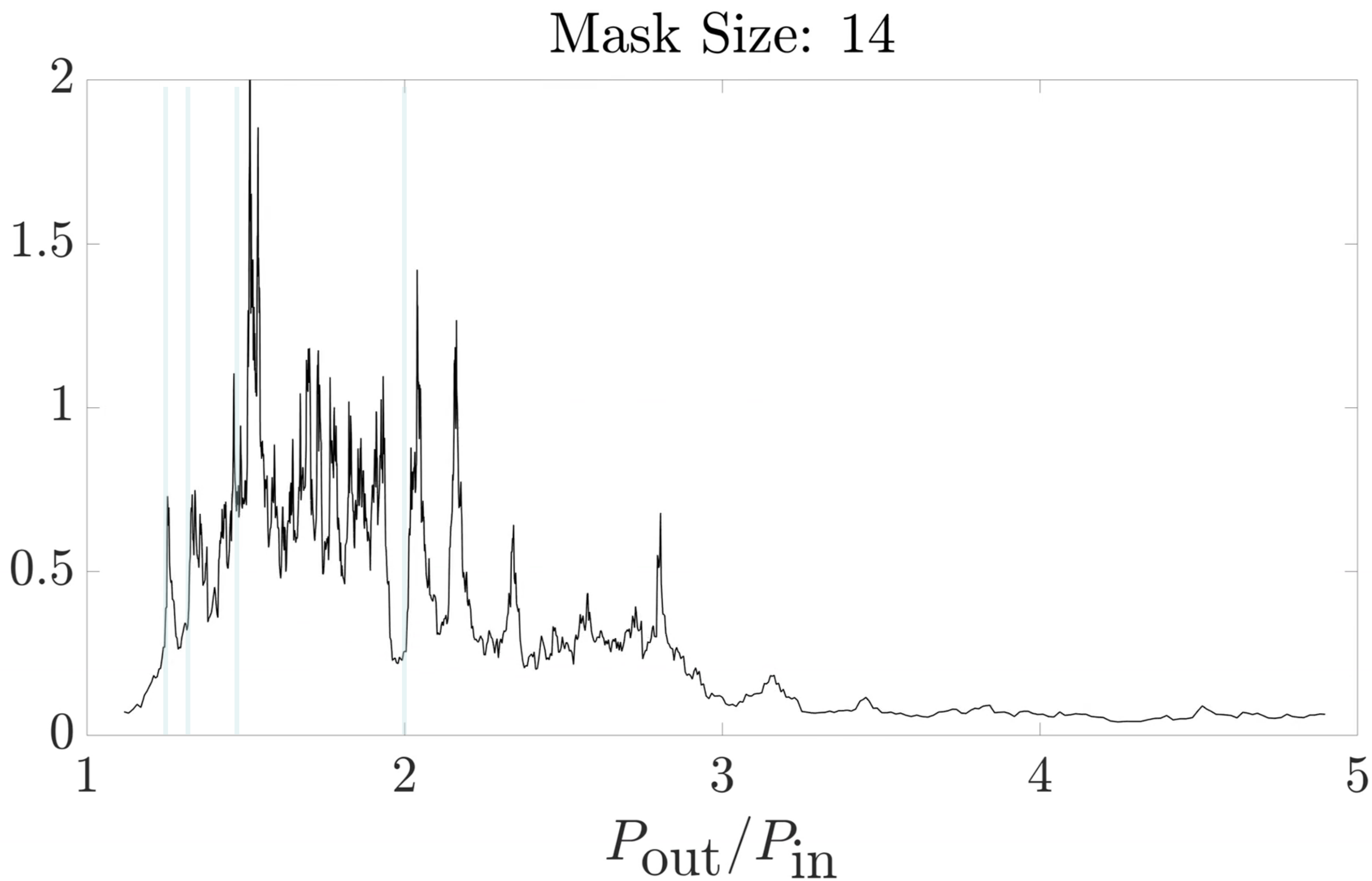
The ratio of orbital periods between adjacent planets.

Kernel Density Estimators of Period Ratios of Kepler Multis.



credit: Kadri Nizam.

Detection biases of TTV

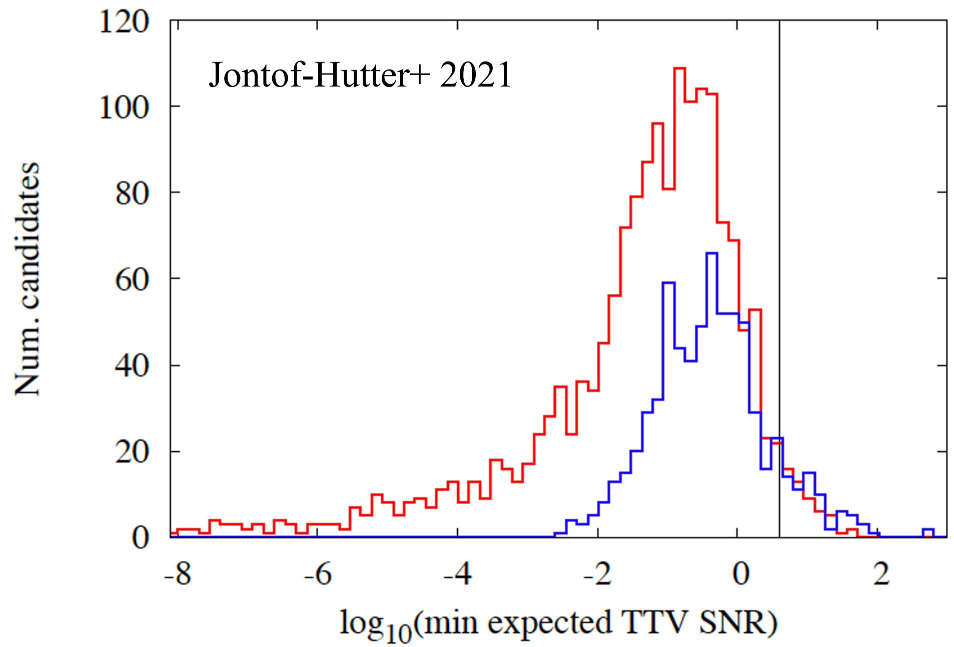
$$\mathrm{SNR_{TTV}} \sim \frac{M_p R_p^{3/2} P^{5/6}}{\sigma_{\mathrm{TTV}}}$$

- Compact multis near resonance.
- TTVs scale with orbital period.
- For a given mass, TTV planets have larger radii.
- Deeper transits permit better transit timing precision.
- TTVs are biased towards lower bulk densities.

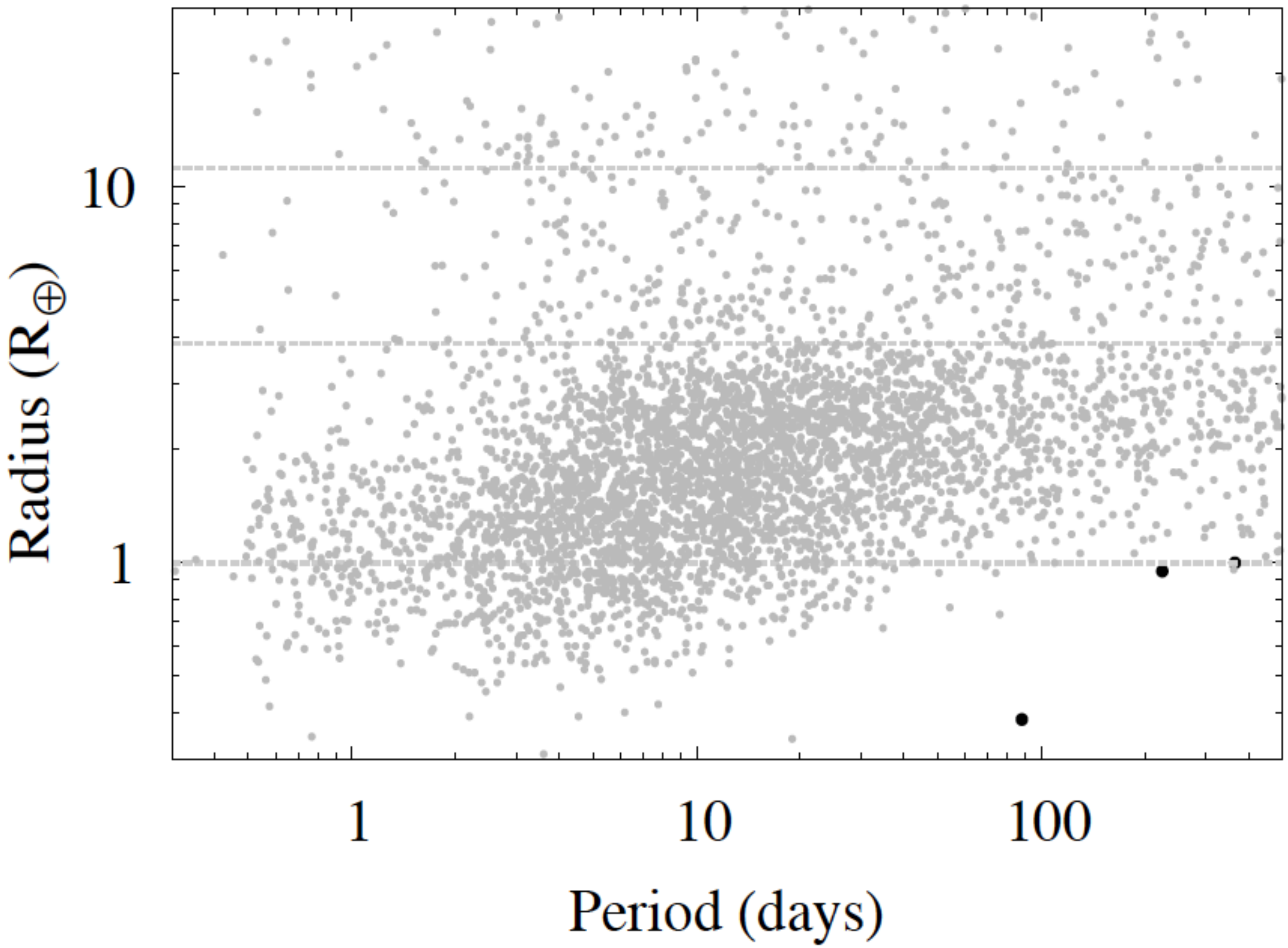
Expected number of planets with mass determined by TTVs in the Kepler field.

----- Near resonant TTVs

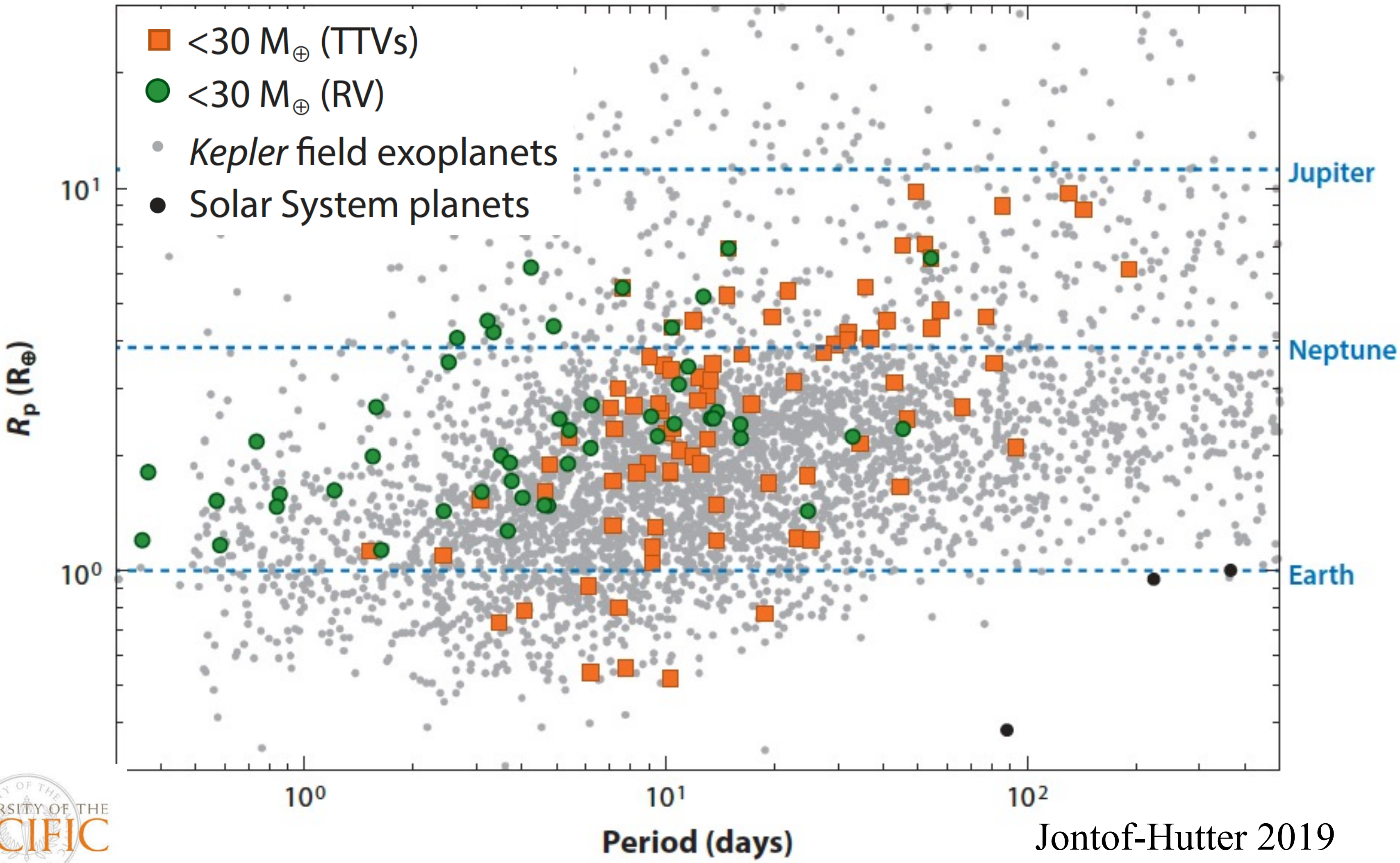
----- Non-resonant TTVs



Transiting Exoplanet Period-Radius Distribution



Transiting exoplanets with characterized masses.



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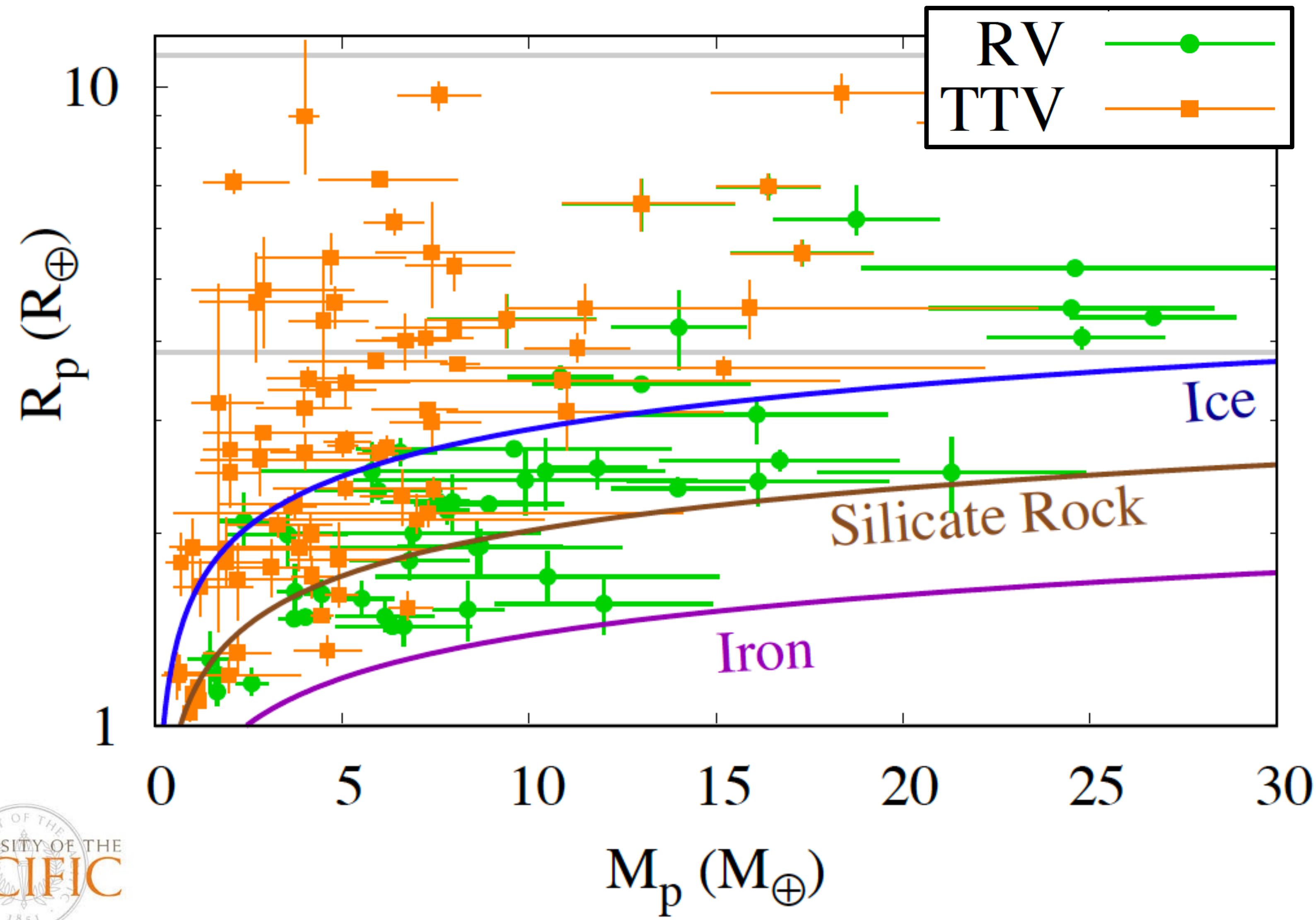
Chapter III
Mass-Radius diagram

What have TTVs done for us?

Low mass exoplanet Mass-Radius Diagram



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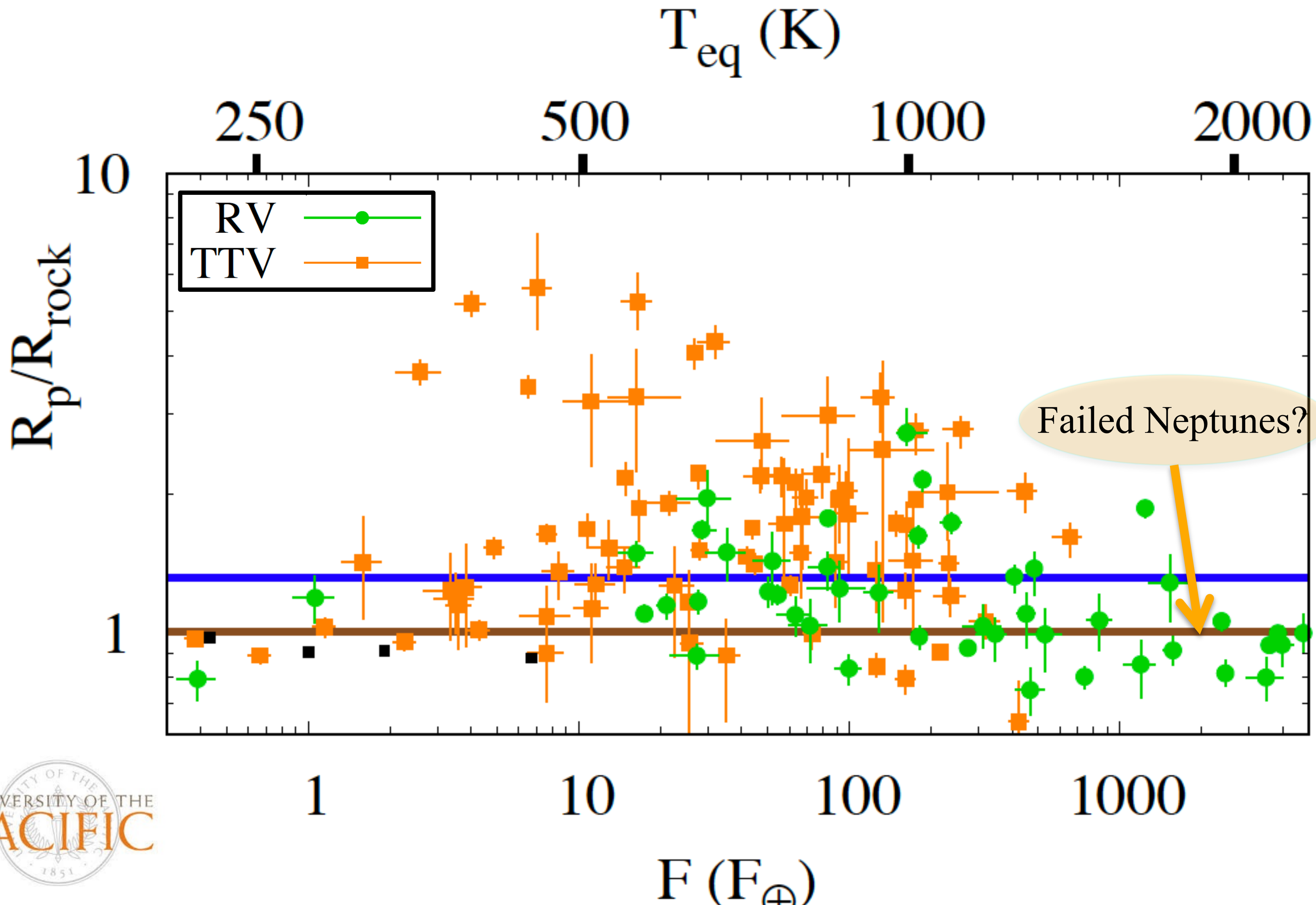
Low mass exoplanet Composition-Flux Diagram



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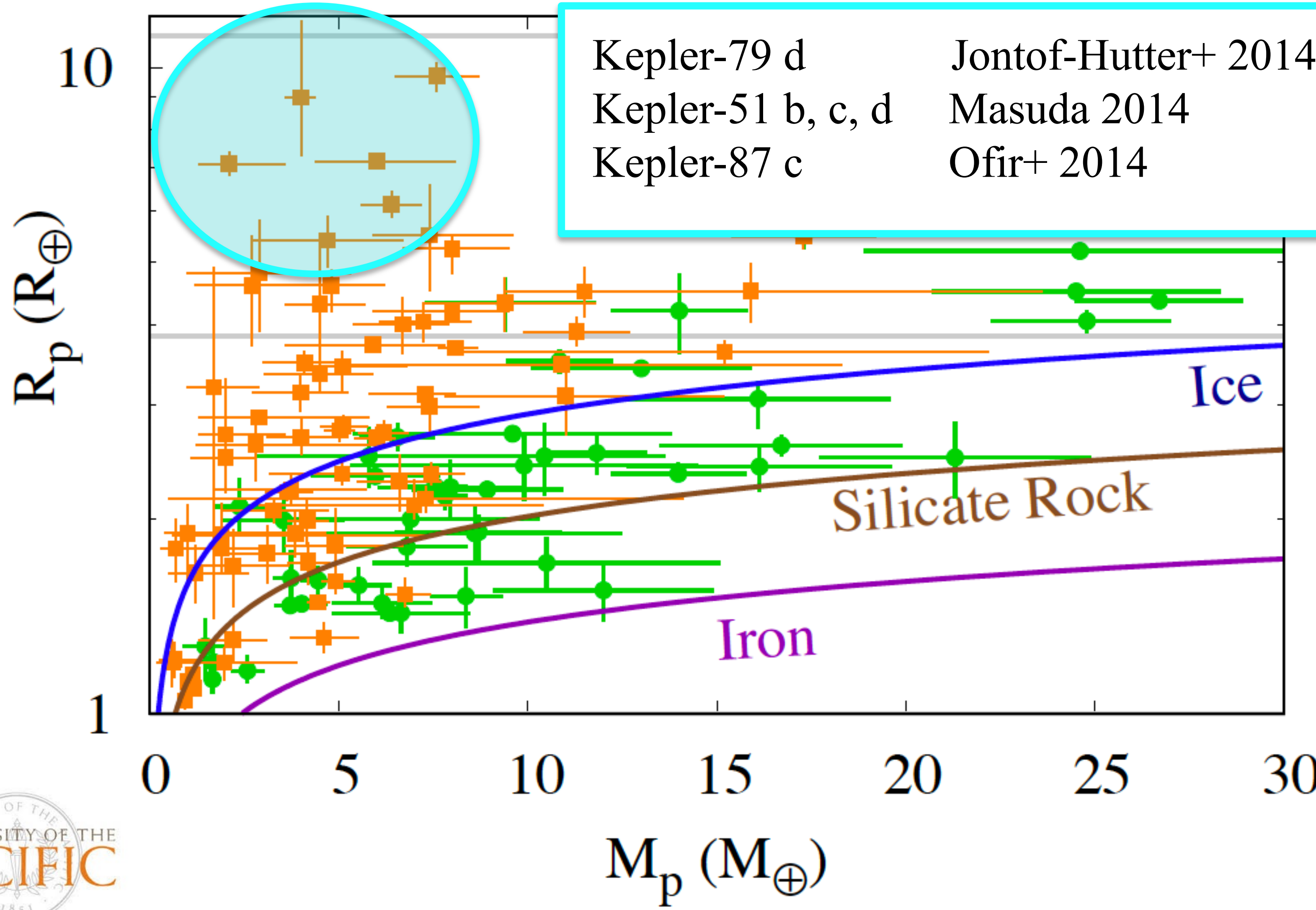
Superpuffs



Kepler-79 d	Jontof-Hutter+ 2014
Kepler-51 b, c, d	Masuda 2014
Kepler-87 c	Ofir+ 2014

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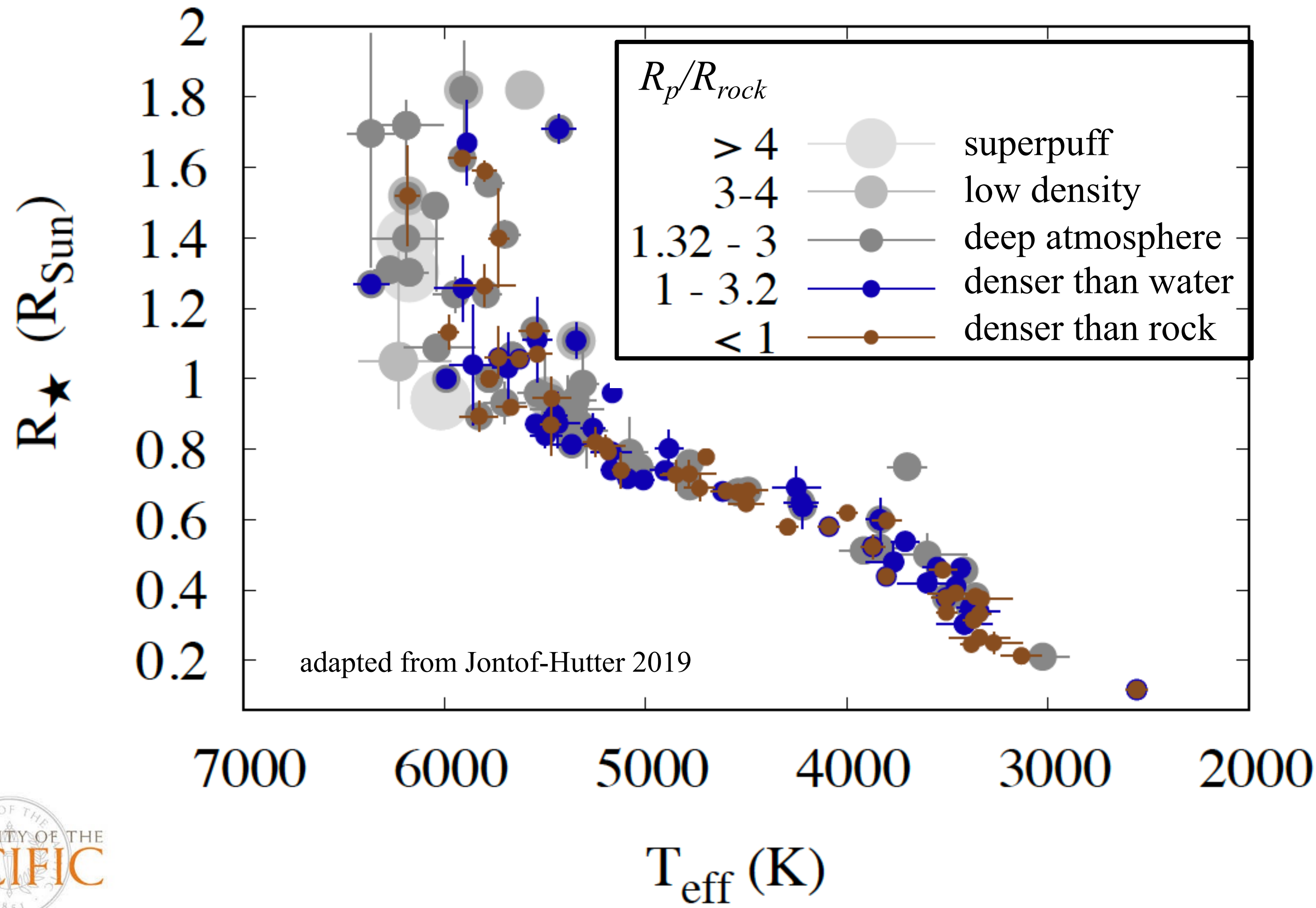
Stellar hosts of low-mass exoplanets and planet compositions



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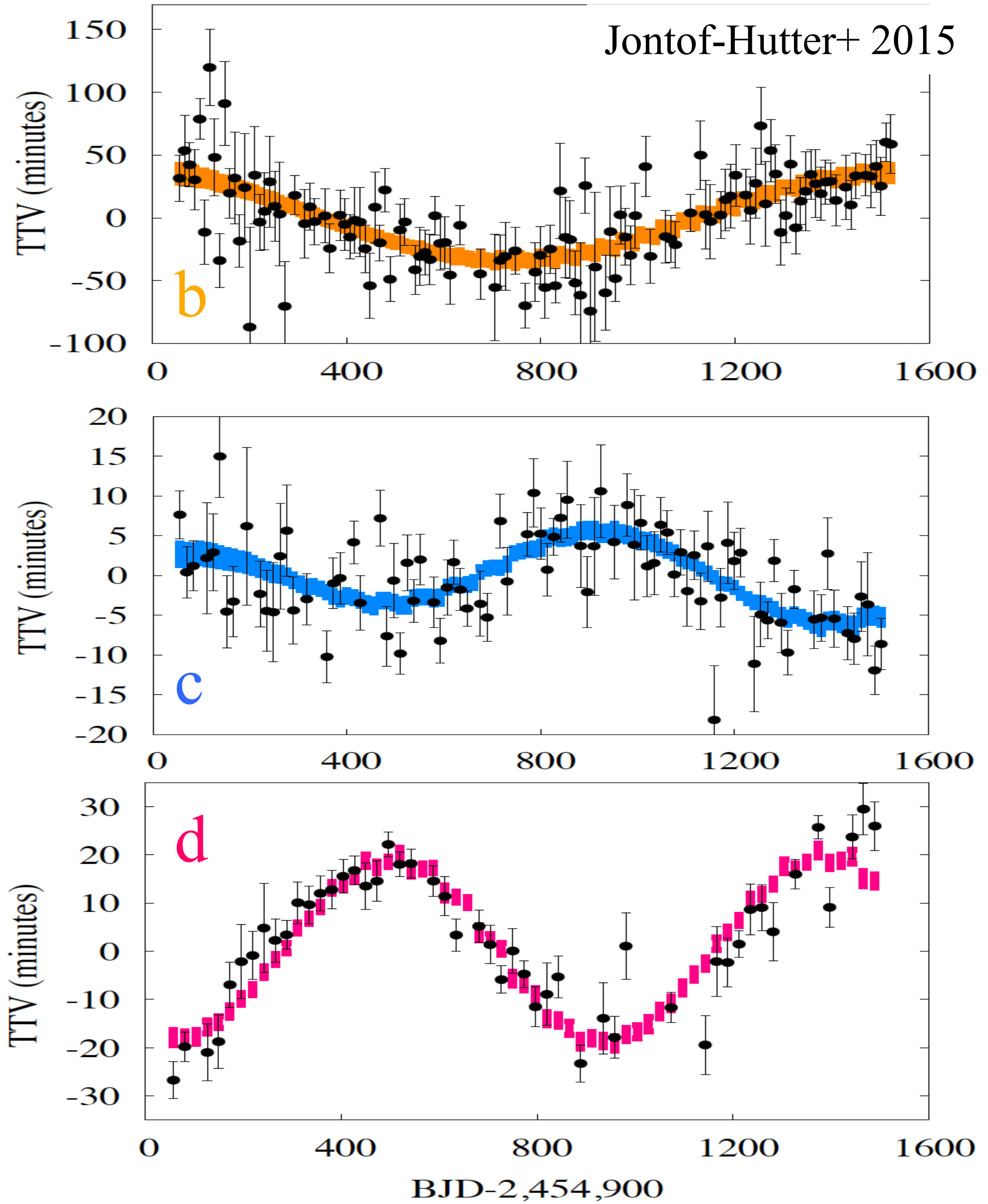
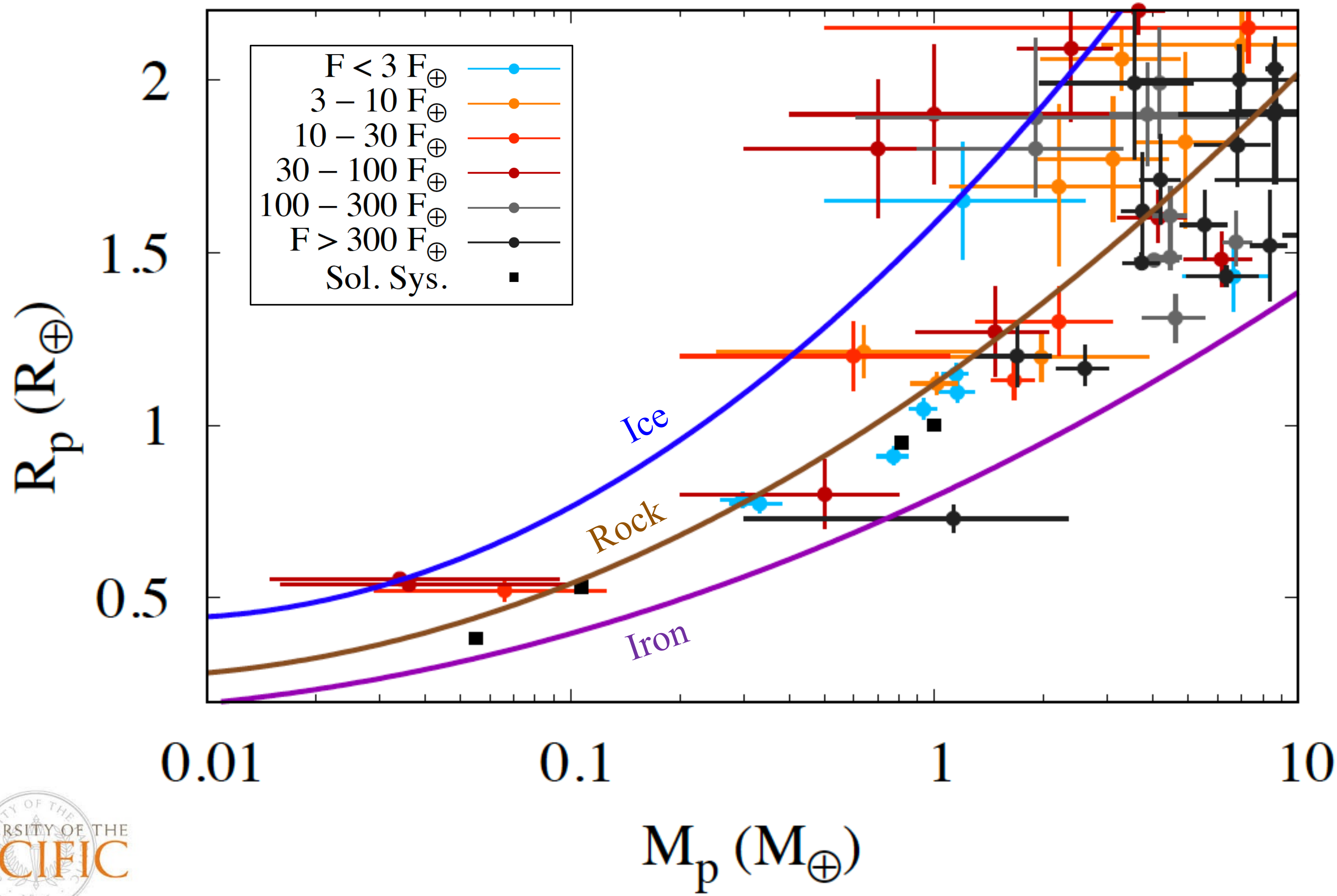
The Terrestrial Regime

Kepler-138



Artwork: Danielle Futselaar



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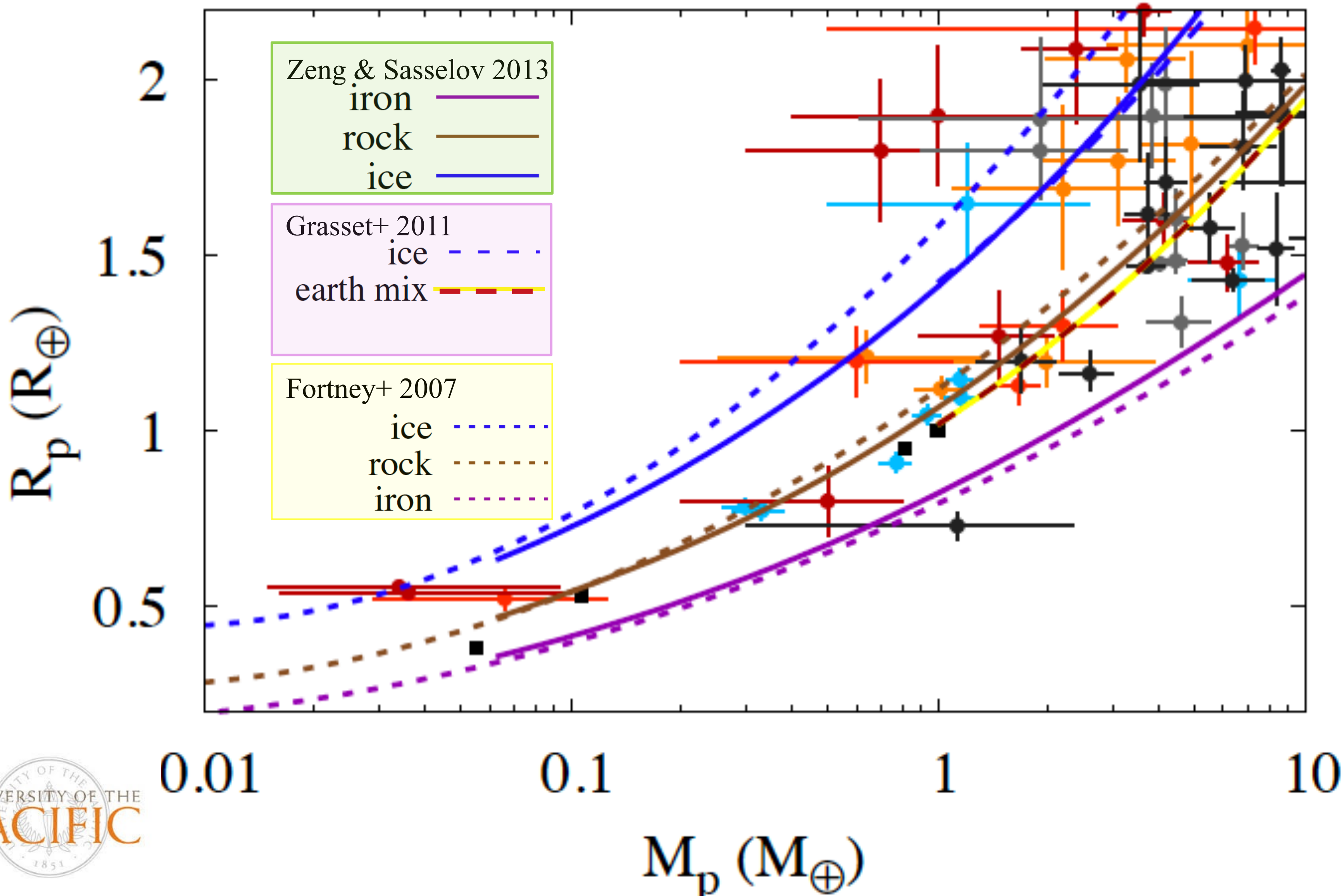
Chapter IV
Theoretical Uncertainties



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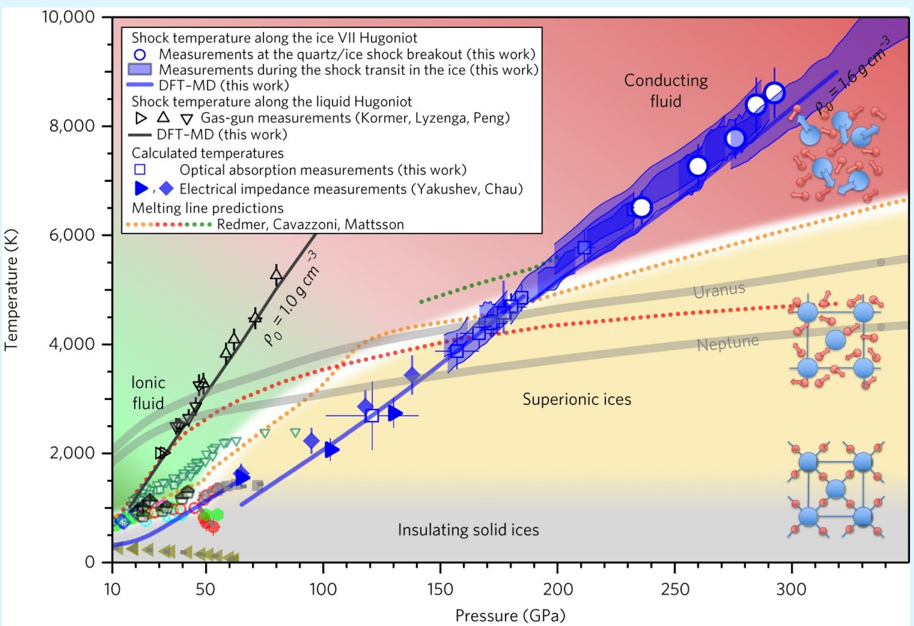
Complications on Planetary Structure models.

Temperatures are unknown. States are unknown.

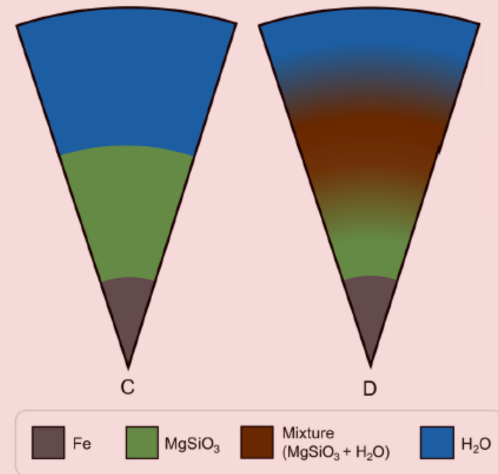
Water (and gas) models require either an assumed thermal profile or a detailed cooling model.

High pressure equations of state are beginning to explore the states of water rich planetary interiors.

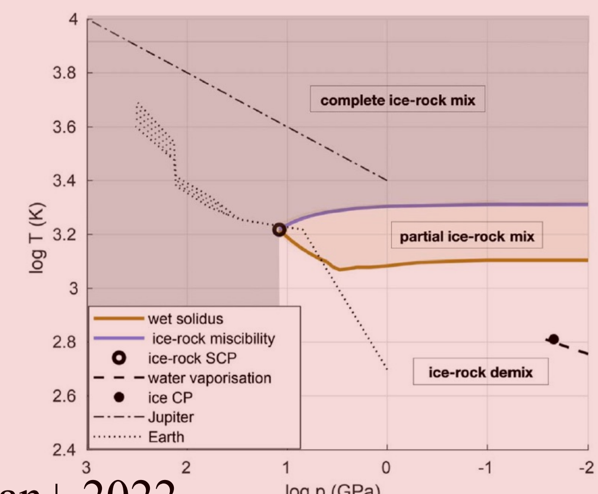


Millot+ 2018

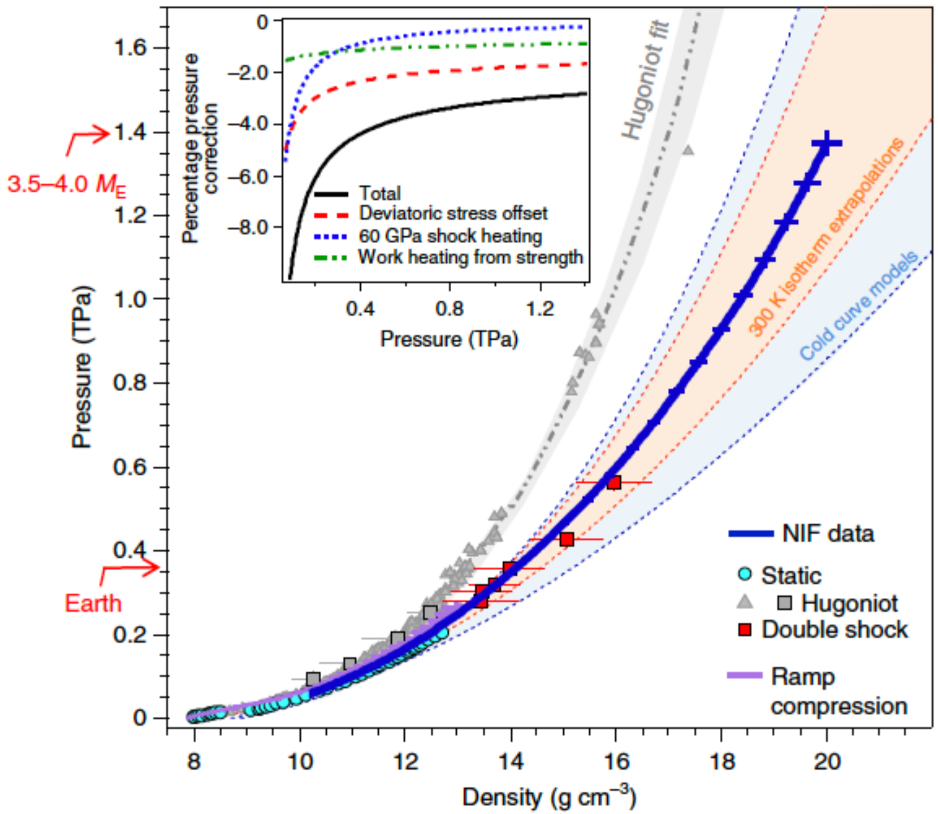
Assumed boundaries between cores and mantles are not real.

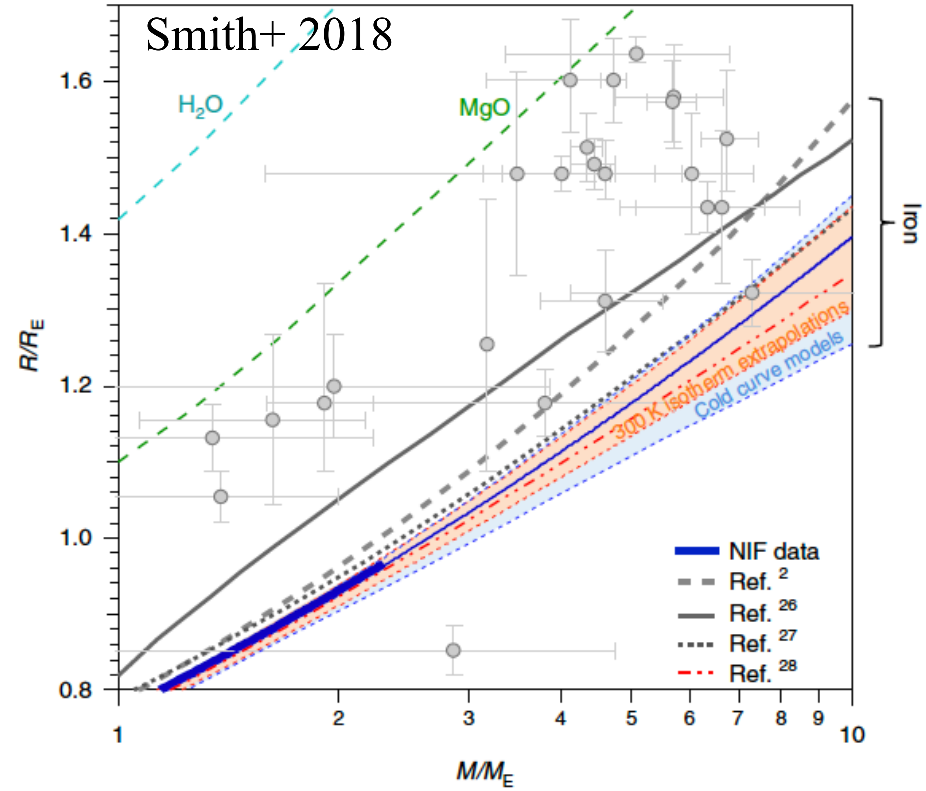


Kovacevic+ 2022



Vazan+ 2022



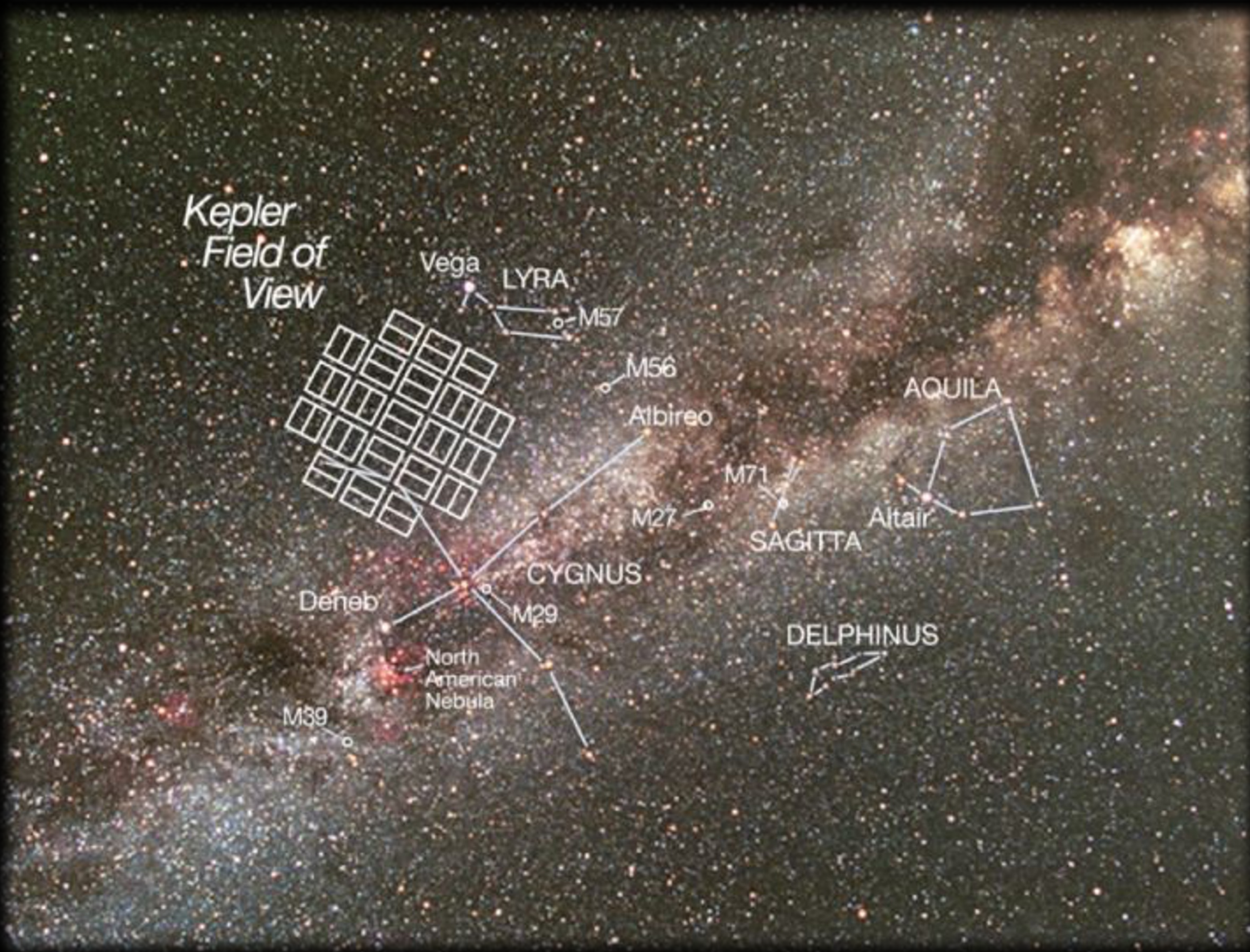


Prior models for Iron had a gap in high pressure equations of state from 0.2 TPa to the high pressure limit ~10 TPa.

Recent progress at NIF ensures the entire regime of rocky planet cores is supported by high pressure data.

Chapter V

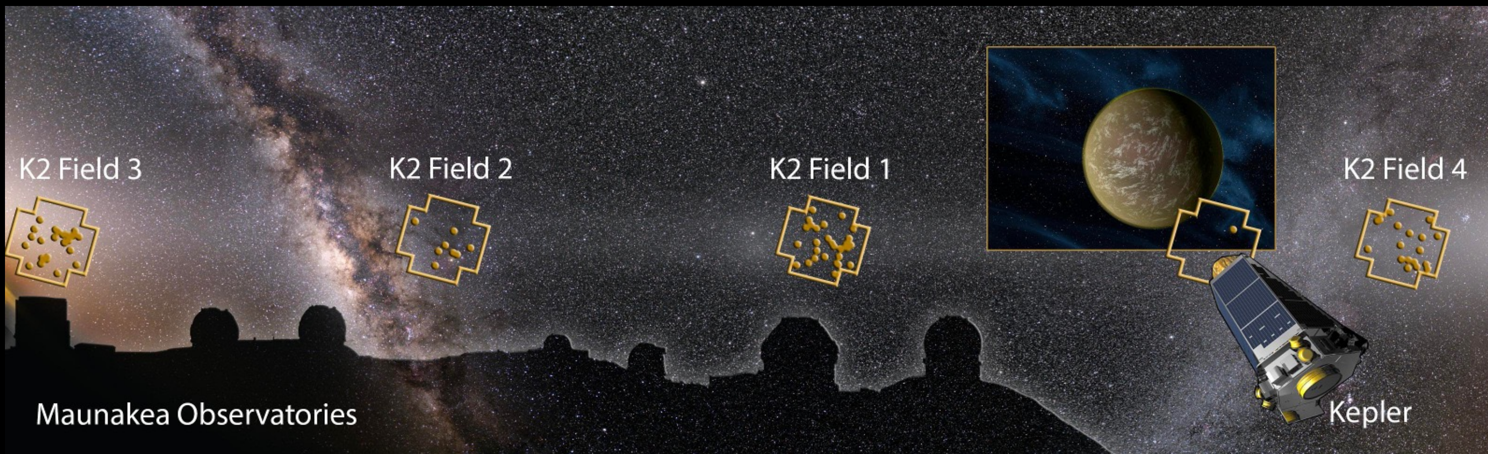
Post-Kepler missions

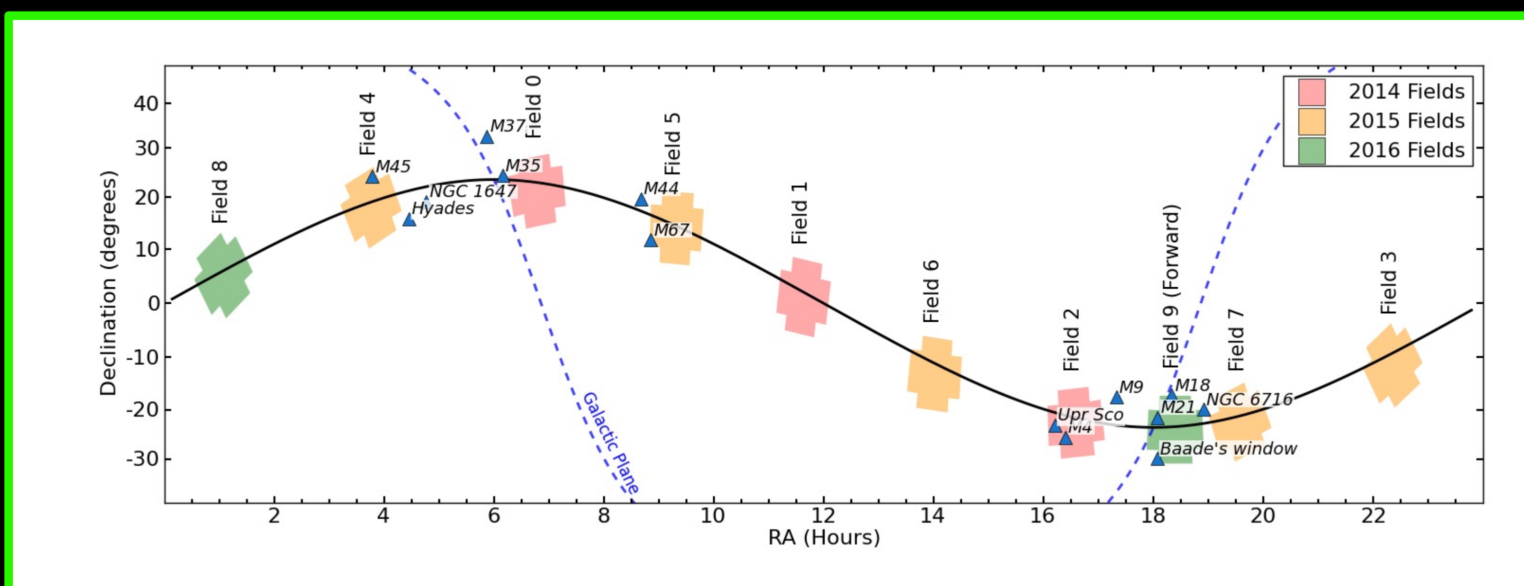


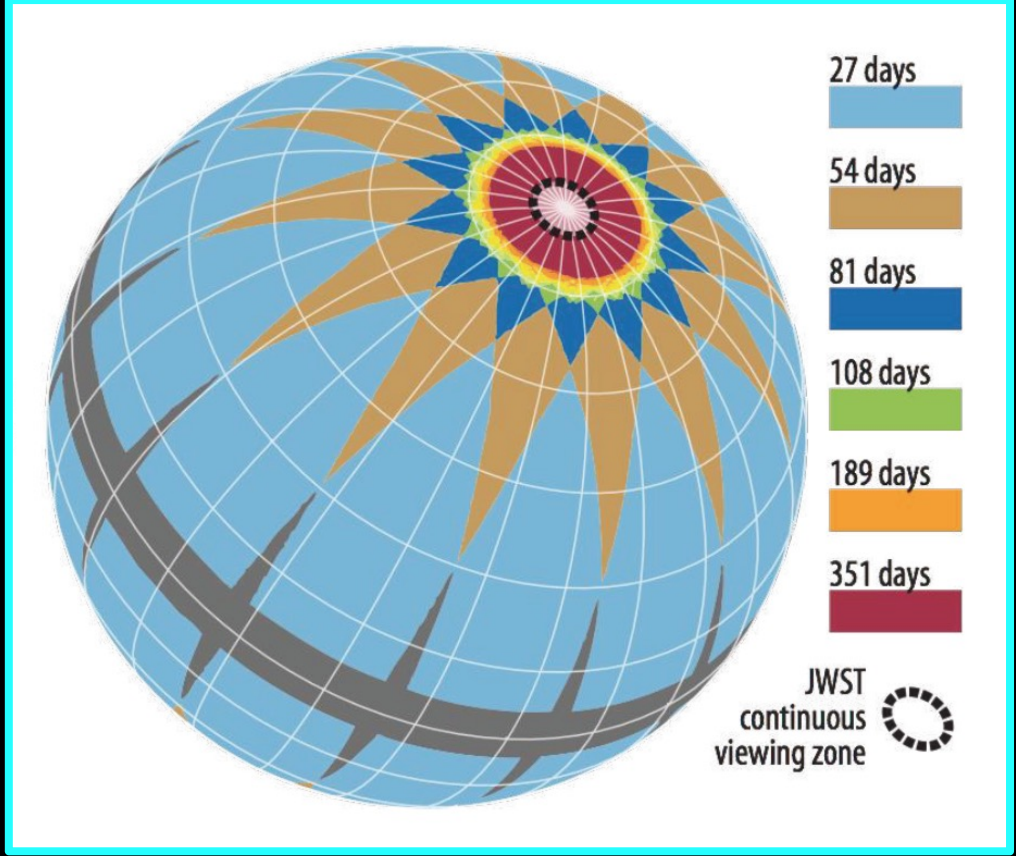
K2: The Kepler mission was repurposed in 2013 after two reaction wheels failed.

The K2 mission consisted of ~80 day campaigns along the ecliptic.

~1800 planet candidates discovered.

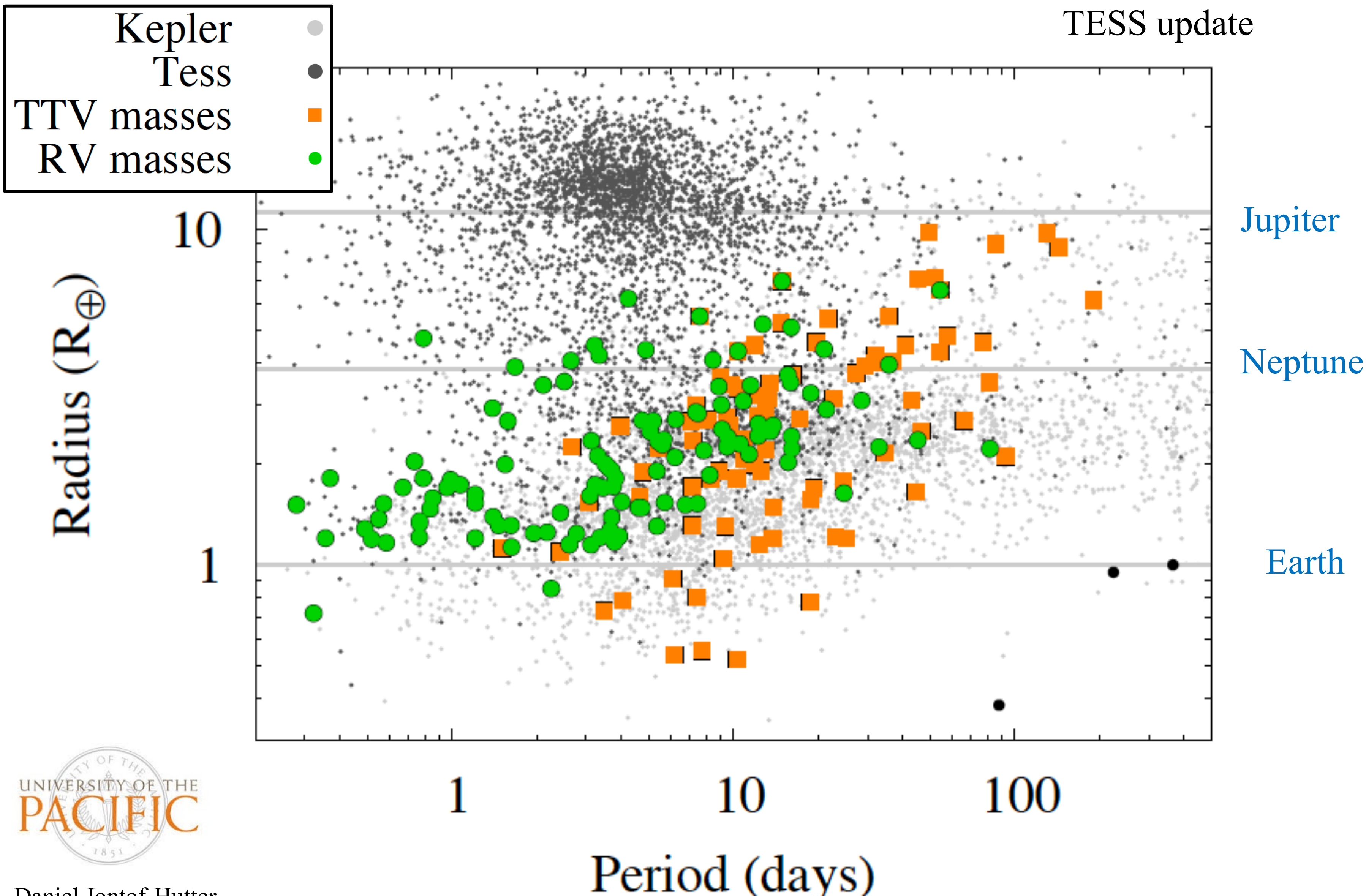






TESS is less sensitive than Kepler but has observed more bright stars.
TESS has been running since 2018: ~4000 exoplanet candidates so far.

Transiting exoplanets with characterized masses.



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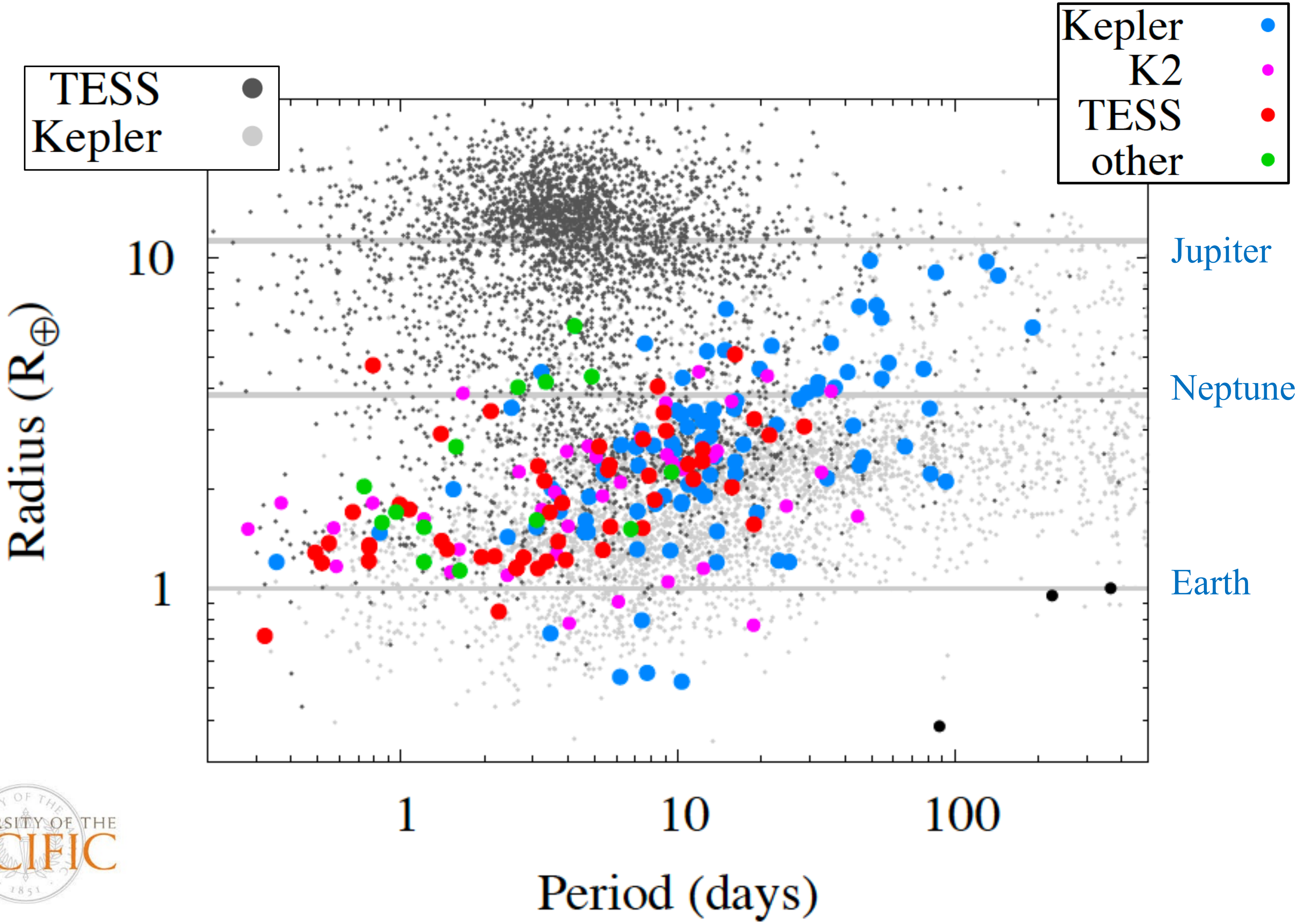
Planet candidates with measured masses < 30 M_{Earth}.



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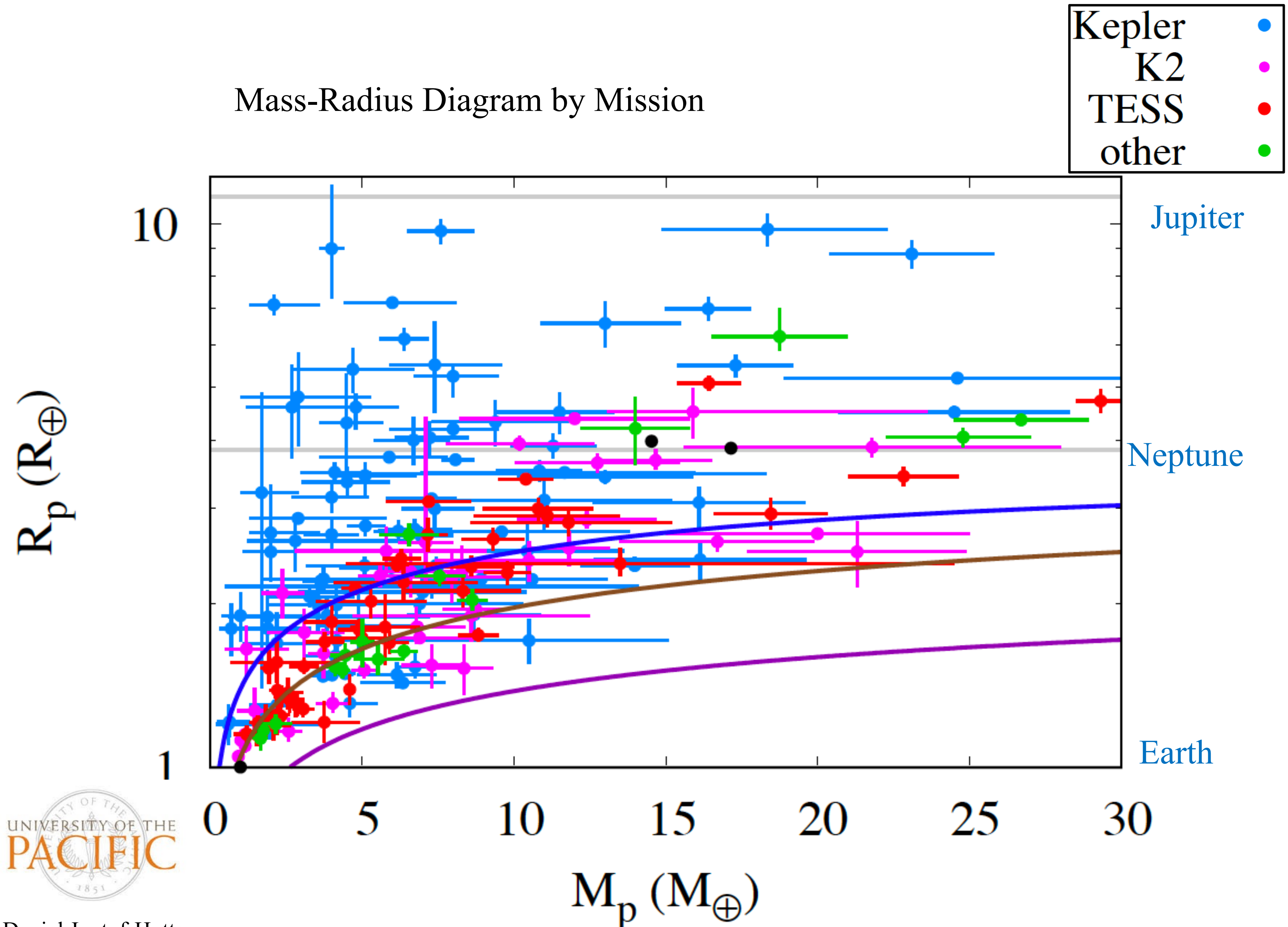
Mass-Radius Diagram by Mission



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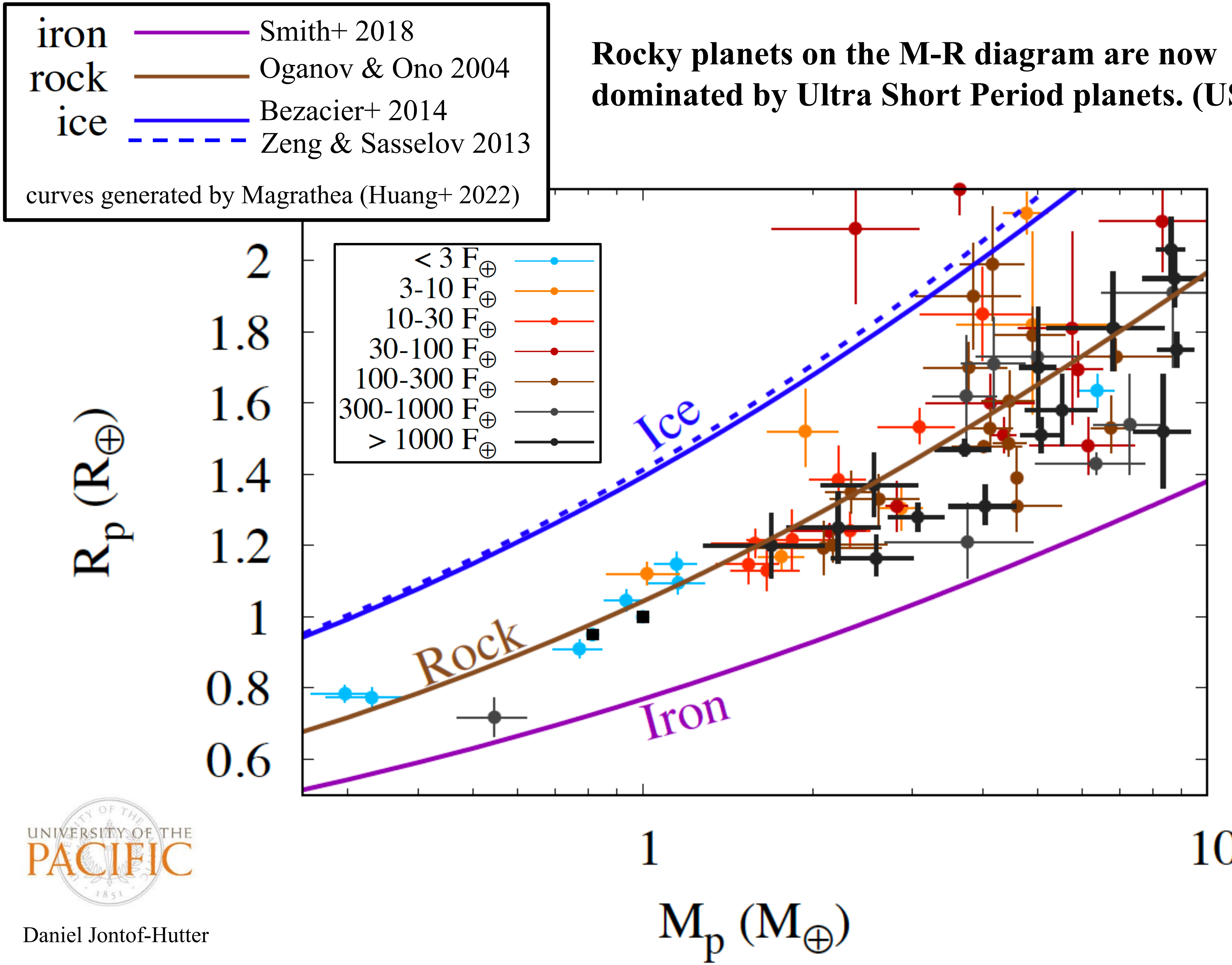
Rocky planets on the M-R diagram are now dominated by Ultra Short Period planets. (USPs).



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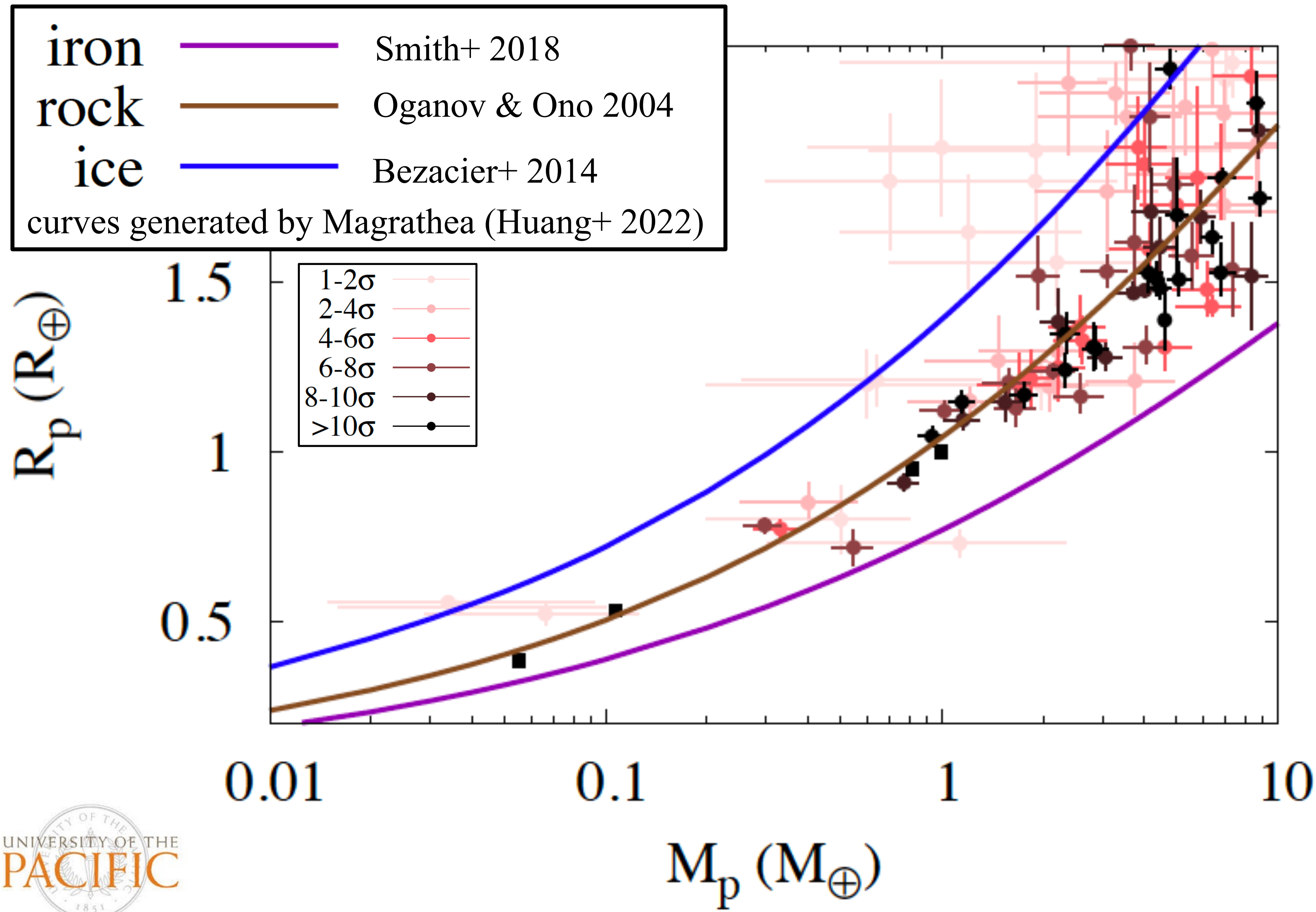

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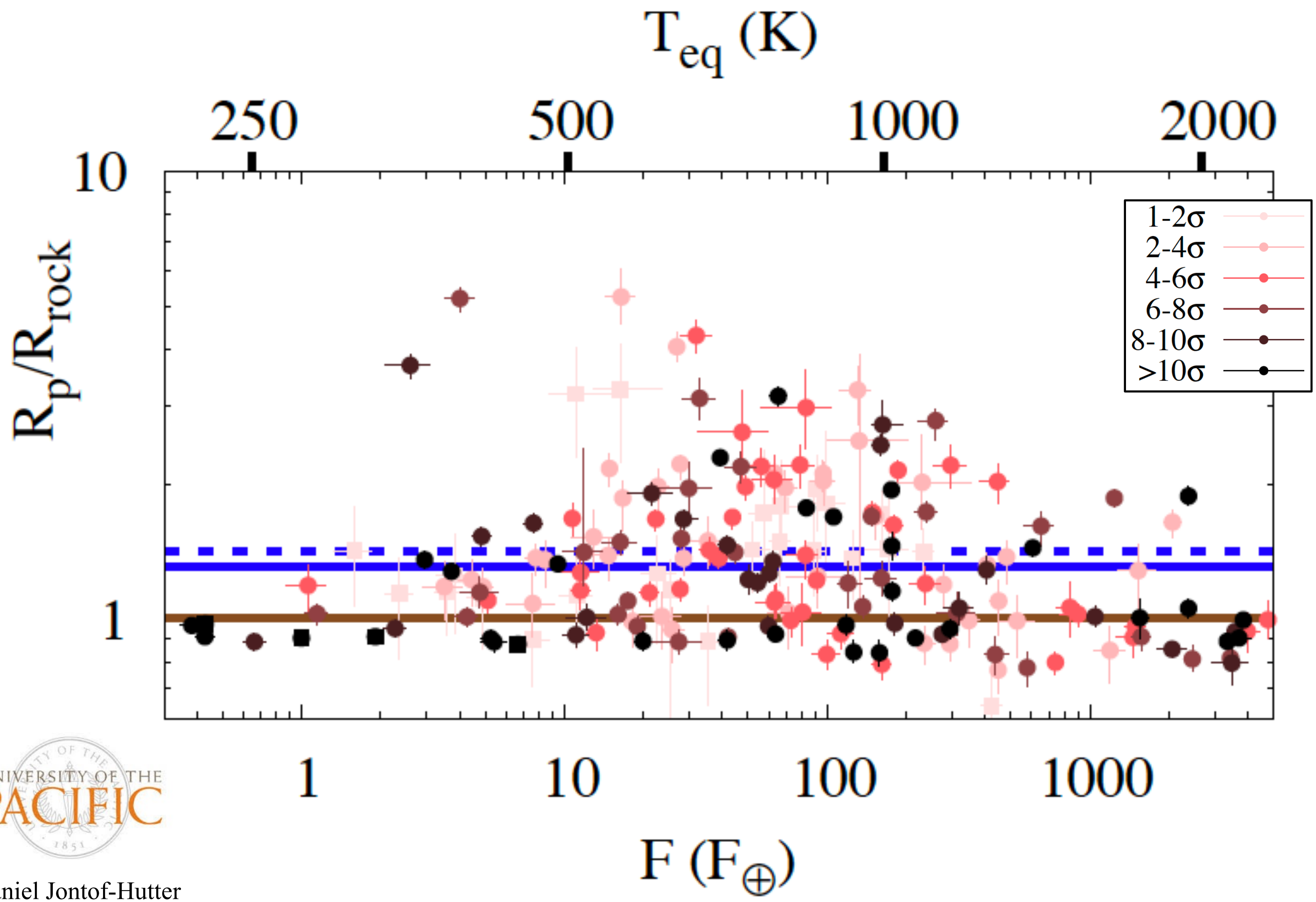
Low mass exoplanet Composition-Flux Diagram



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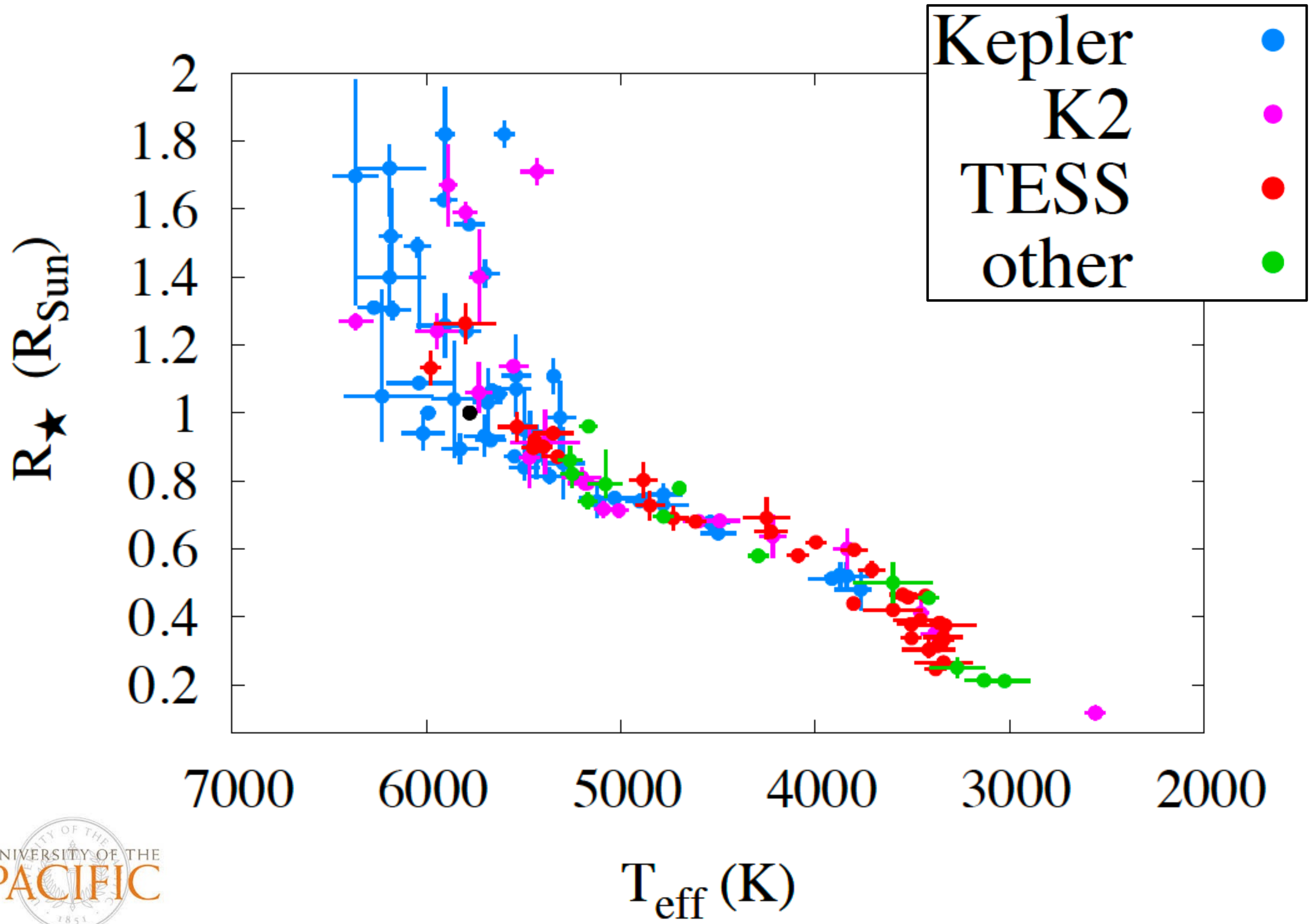

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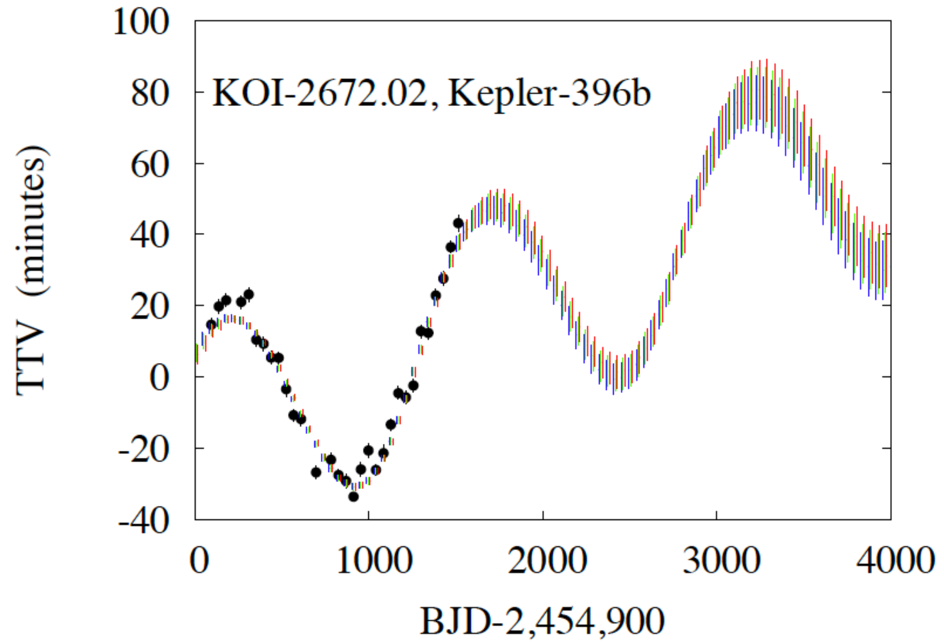
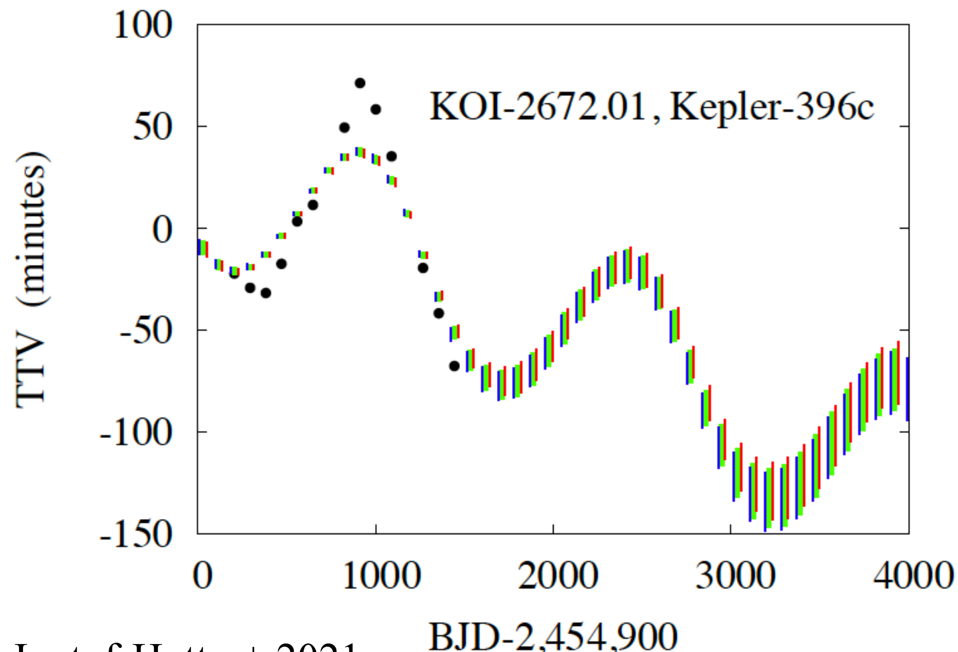
TTVs with TESS

With short baselines, and few multis, it will take some time before TTVs with TESS data will add many planets to the mass-radius diagram.

Here is an exception, KOI-2672 (Kepler-396) is in the Kepler field and has been visited by TESS.

The Kepler data show anticorrelated TTVs in Kepler-396 b and c.





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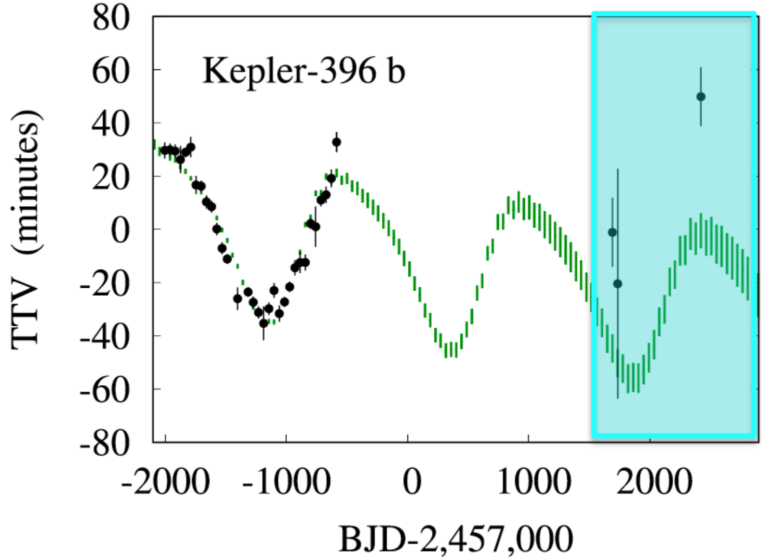
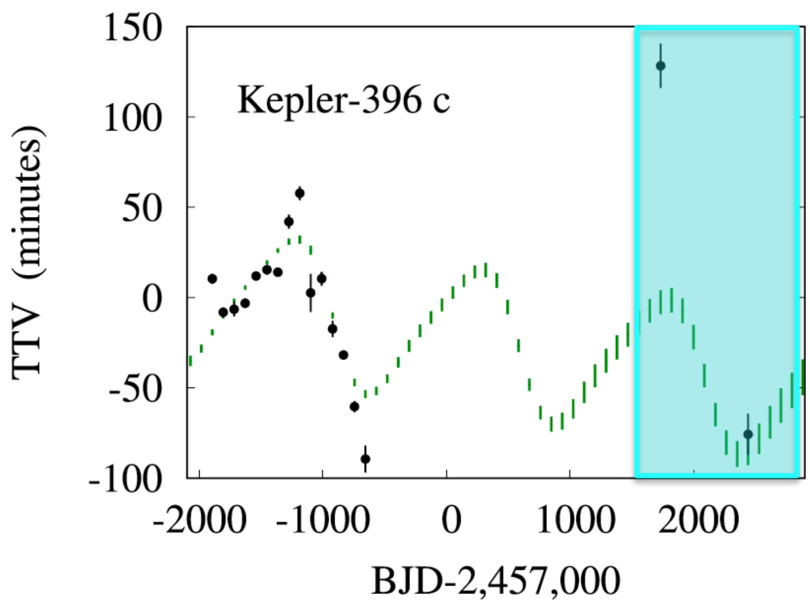
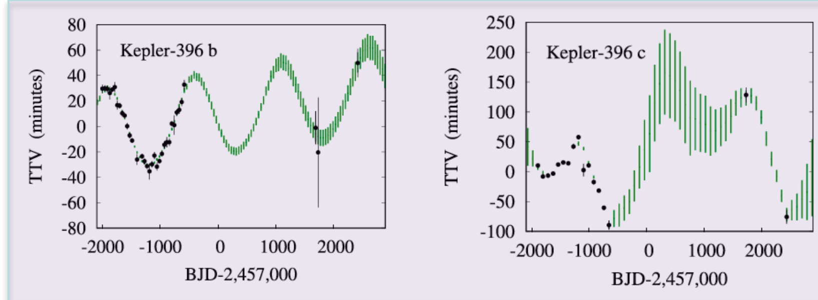
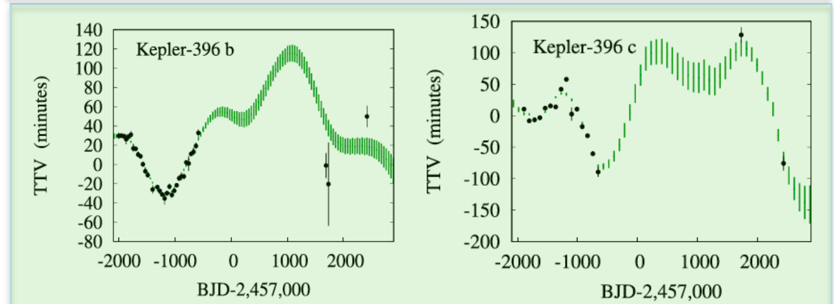
The 2-planet model is ruled out by TESS.





A third planet can explain the TTVs.





KOI	P (days)	$\frac{M_p}{M_\oplus}$
2672.02	$42.9921^{+0.0002}_{-0.0002}$	$9.5^{+1.2}_{-1.1}$
2672.01	$88.5168^{+0.0005}_{-0.0005}$	$11.8^{+1.8}_{-1.6}$
2672.02	$42.9926^{+0.0002}_{-0.0002}$	$5.60^{+2.82}_{-1.51}$
2672.01	$88.5231^{+0.0025}_{-0.0015}$	$4.64^{+1.53}_{-1.14}$
2672x	$140.9352^{+0.0781}_{-0.0867}$	<5.99
2672.02	$42.9919^{+0.0002}_{-0.0002}$	$6.54^{+0.99}_{-0.92}$
2672x	$57.3666^{+0.0085}_{-0.0082}$	$0.19^{+0.03}_{-0.03}$
2672.01	$88.5173^{+0.0006}_{-0.0006}$	$5.05^{+0.64}_{-0.61}$

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Conclusions

The sample of rocky planets is increasing rapidly with TESS discoveries.

Precisions on rocky planet masses and radii are approaching the accuracy of planet models.

More data on low density planets in compact systems awaits longer baseline photometry with TESS.

TESS TTVs at Kepler-396 hint at a possible planet missed from the Kepler mission.

Earth analogs are not yet accessible, but habitable rocky planets around cool stars are.