Planets larger than Neptune have elevated eccentricities

Dr. Greg Gilbert (UCLA)

Know Thy Star 2 | 4 Feb 2025 | Pasadena, CA

Solar system planets come in **three sizes**

Solar system planets have low eccentricity

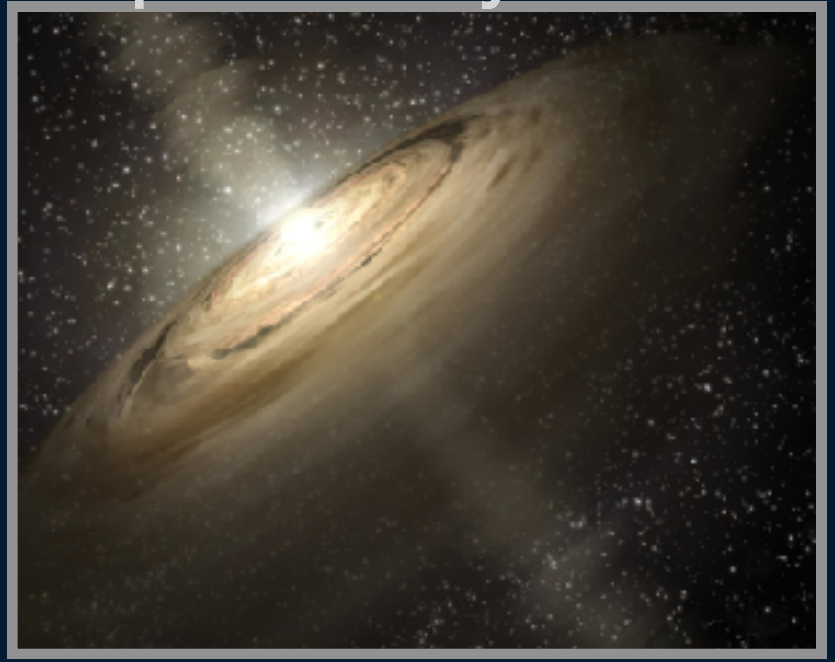
Solar system planets have **low inclination**

A brief **history** of the Solar System

$t \sim 10^4$ yr

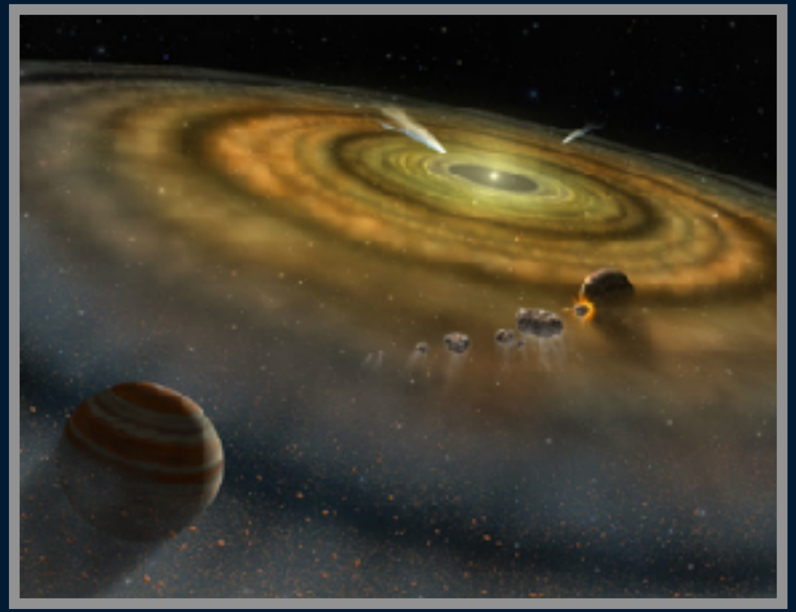
Protostar forms from molecular cloud

Protoplanetary disk forms



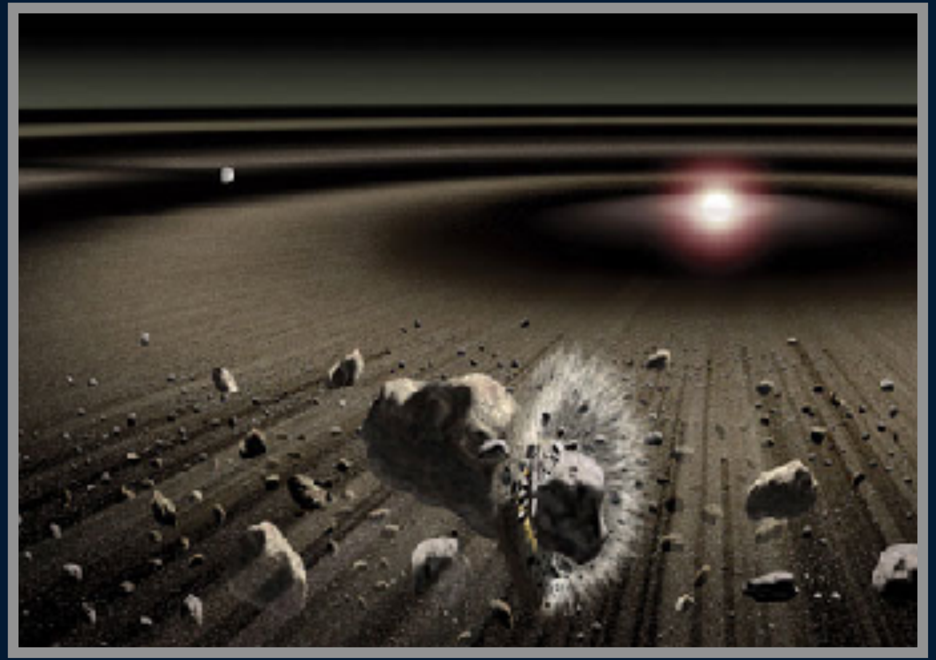
$t \sim 10^6$ yr

$t \sim 10^7$ yr



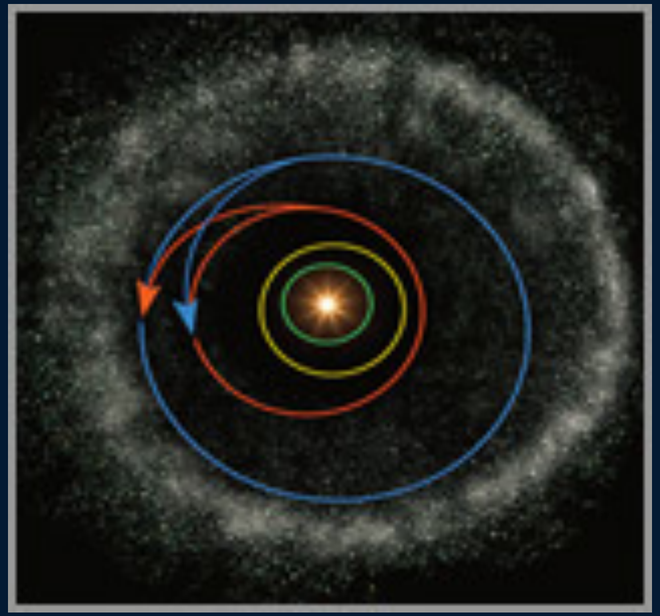
Giant planets form

Terrestrial planets form



$t \sim 10^8$ yr

$t > 10^8$ yr

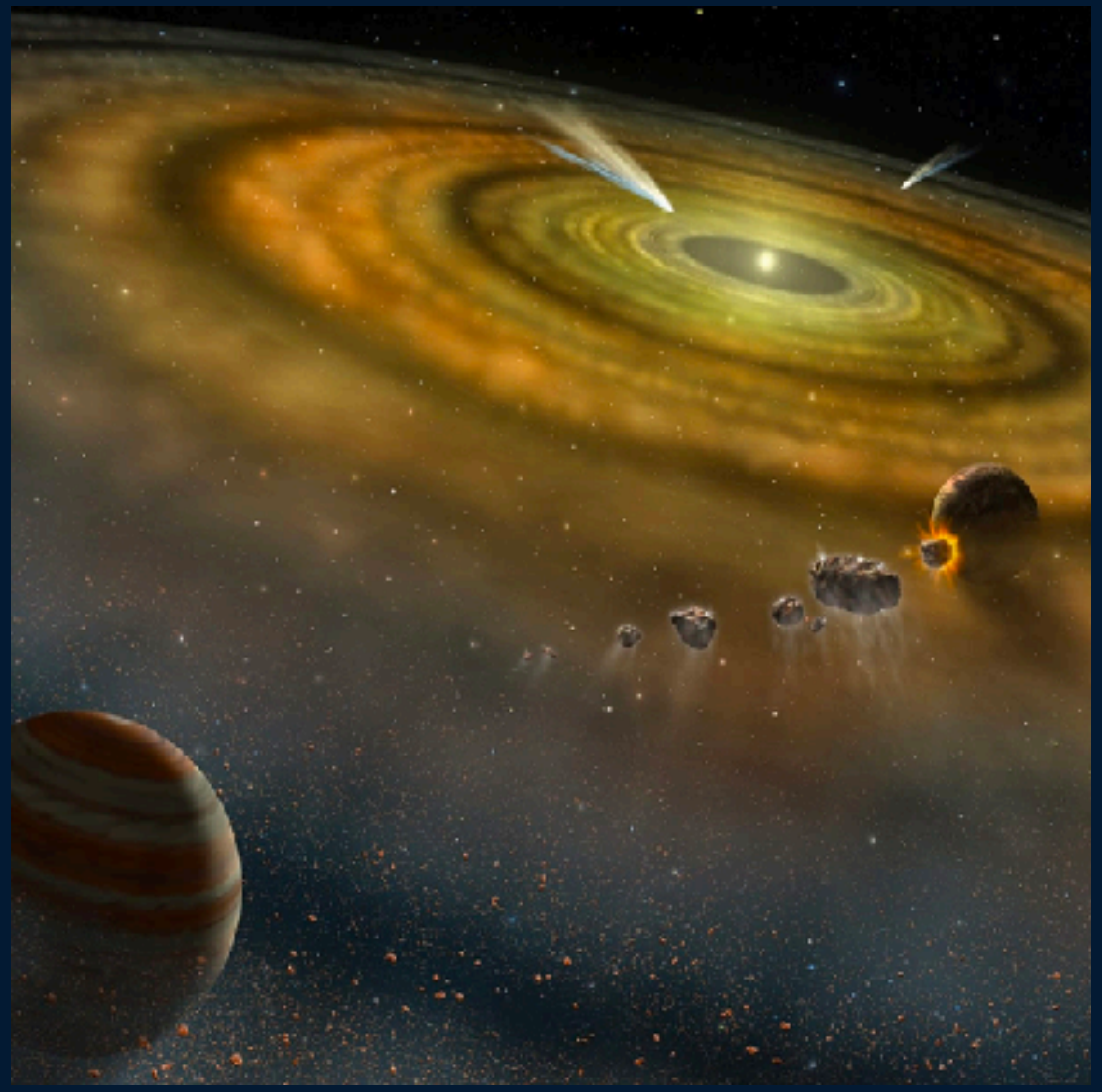


Long timescale dynamical interactions

Dynamical process can either excite or quench inclination and eccentricity

Planet-planet scattering

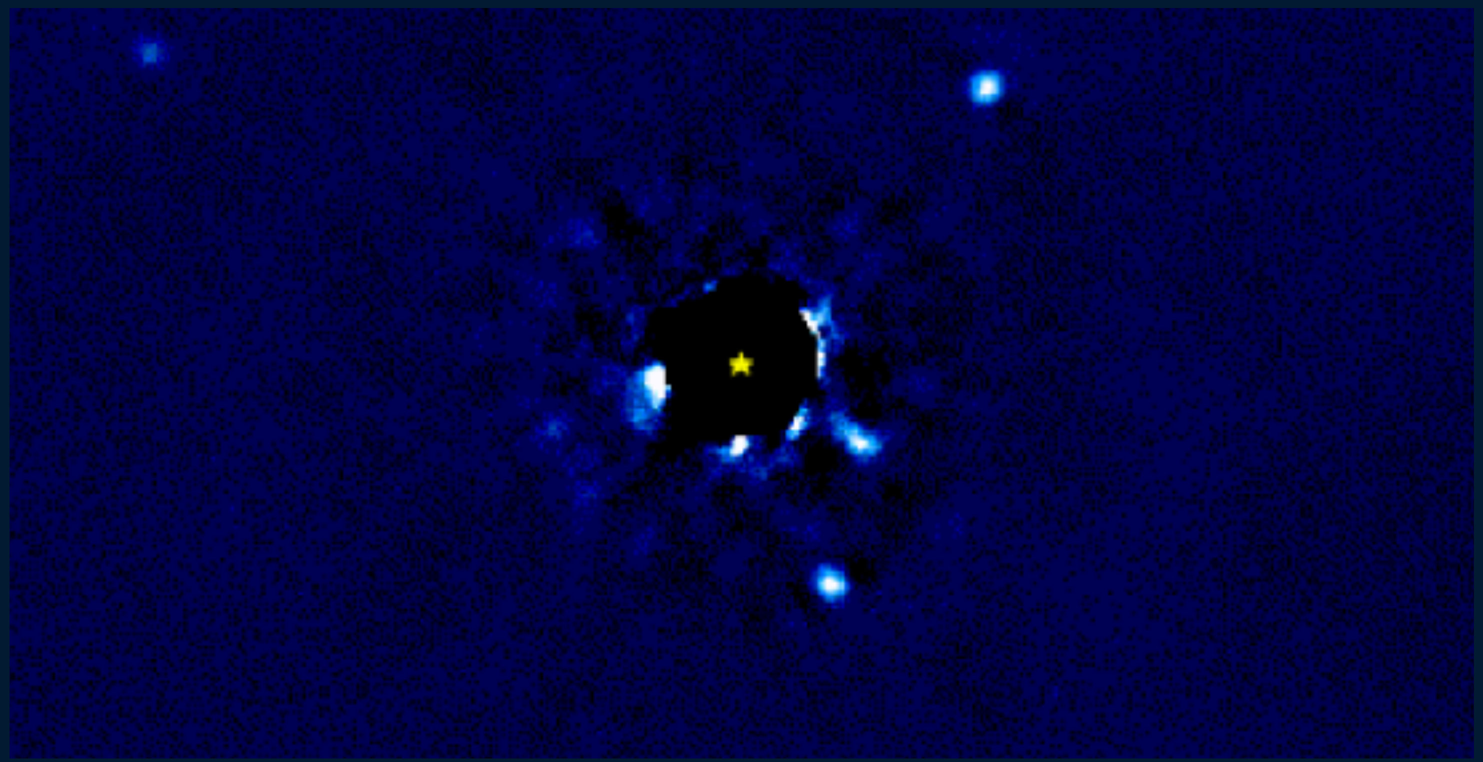
Disk migration



Giant impacts

Transits provide the greatest **statistical power** to investigate populations

Imaging

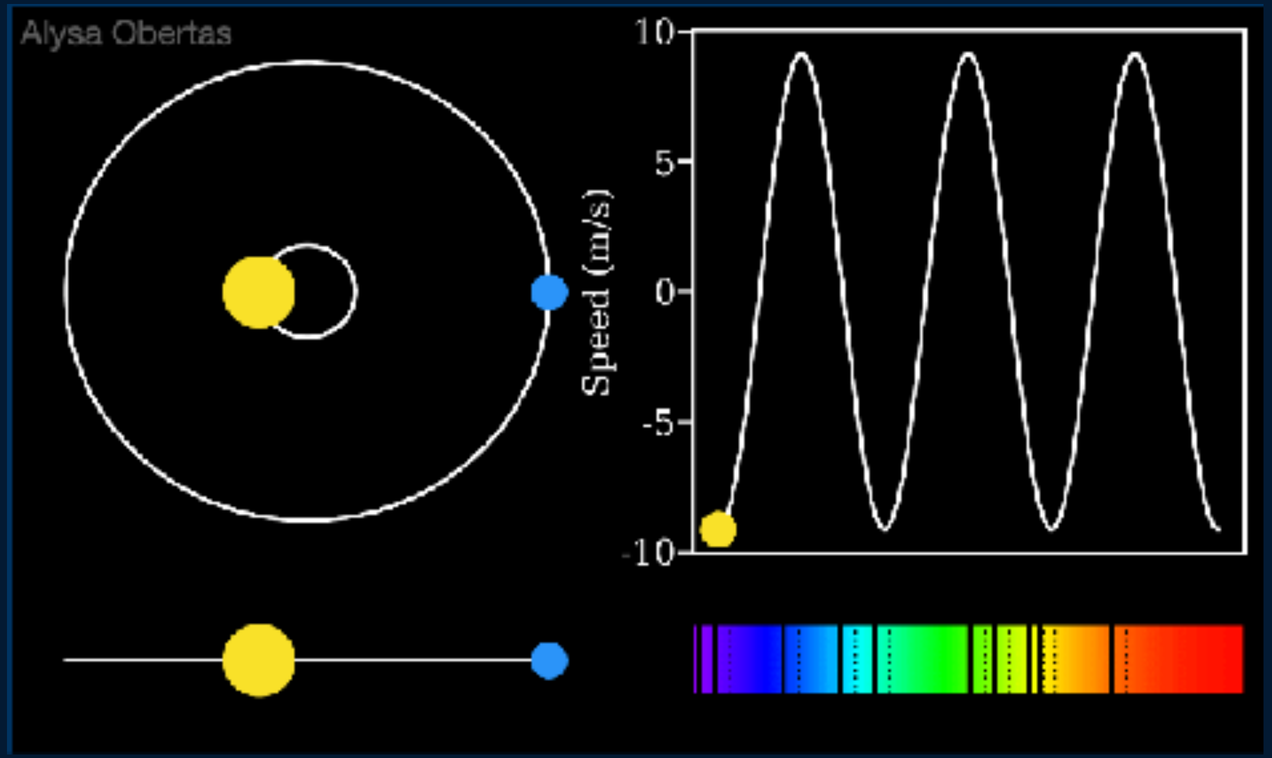


straightforward

small sample (N ~ 10s)

giant planets only

Doppler

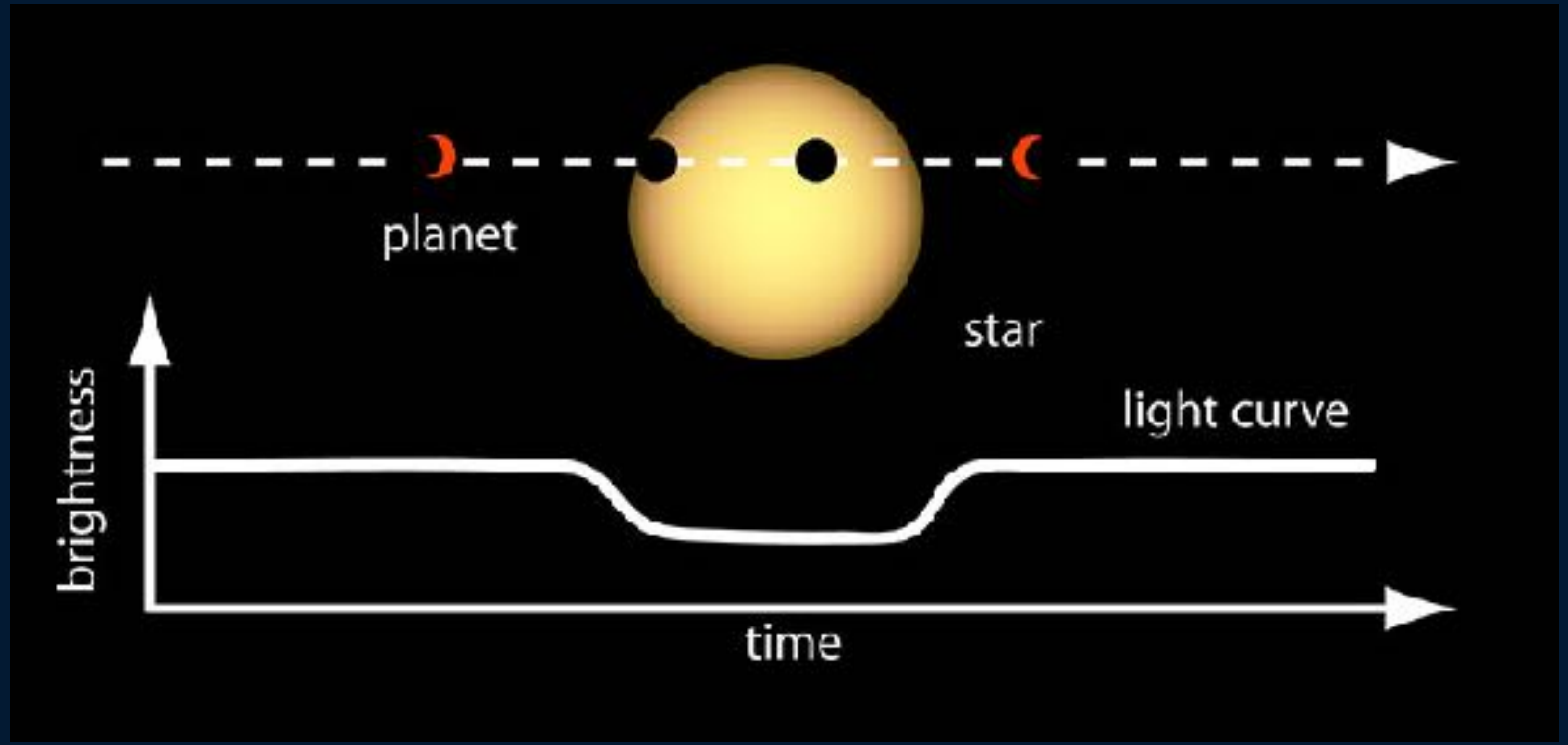


high precision

large sample (N ~ 100s)

large planets only

Transits



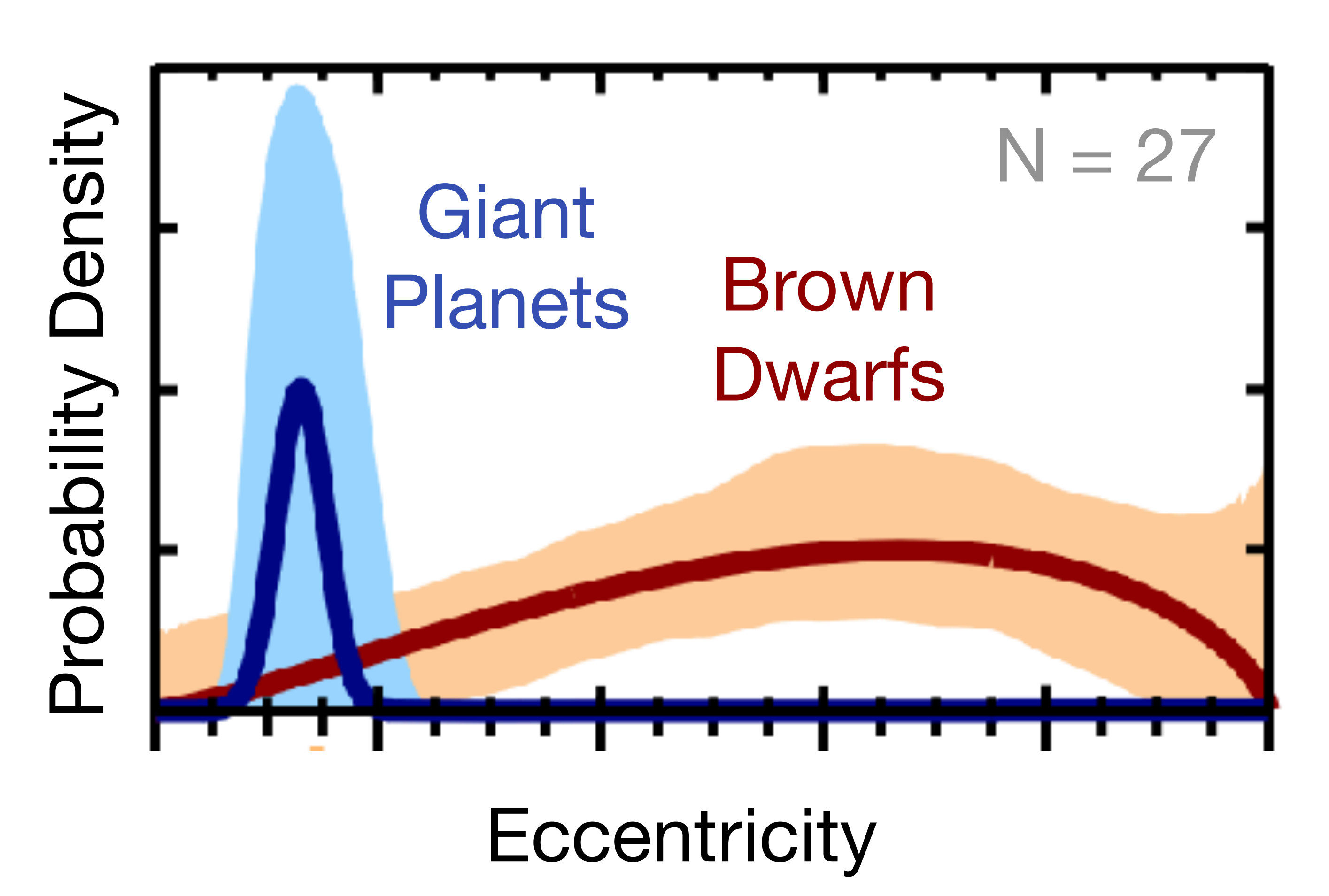
indirect & under-constrained

huge sample (N ~ 1000s)

not limited by planet size

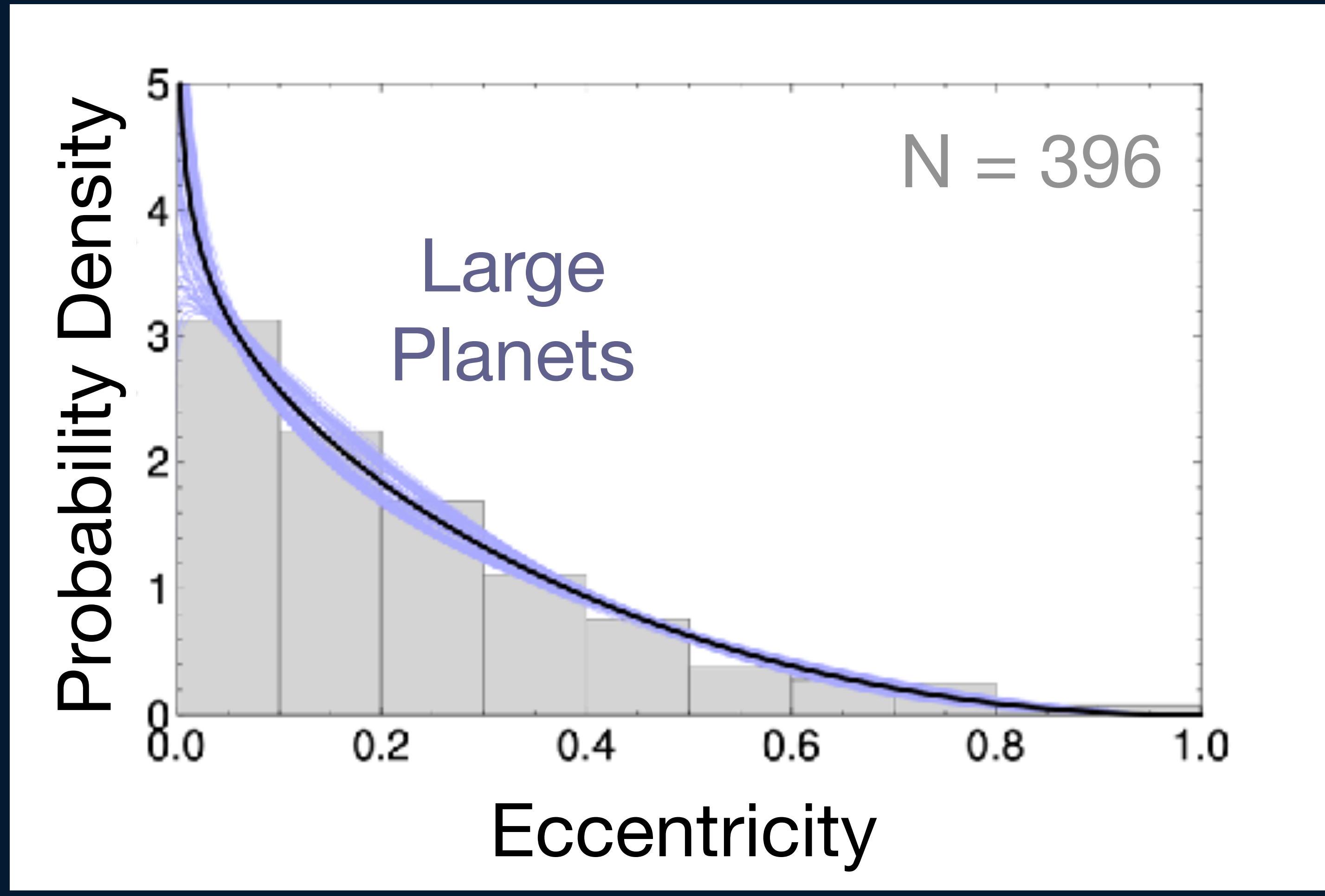
Exoplanet eccentricities tend to be low but span a range of values

Imaging



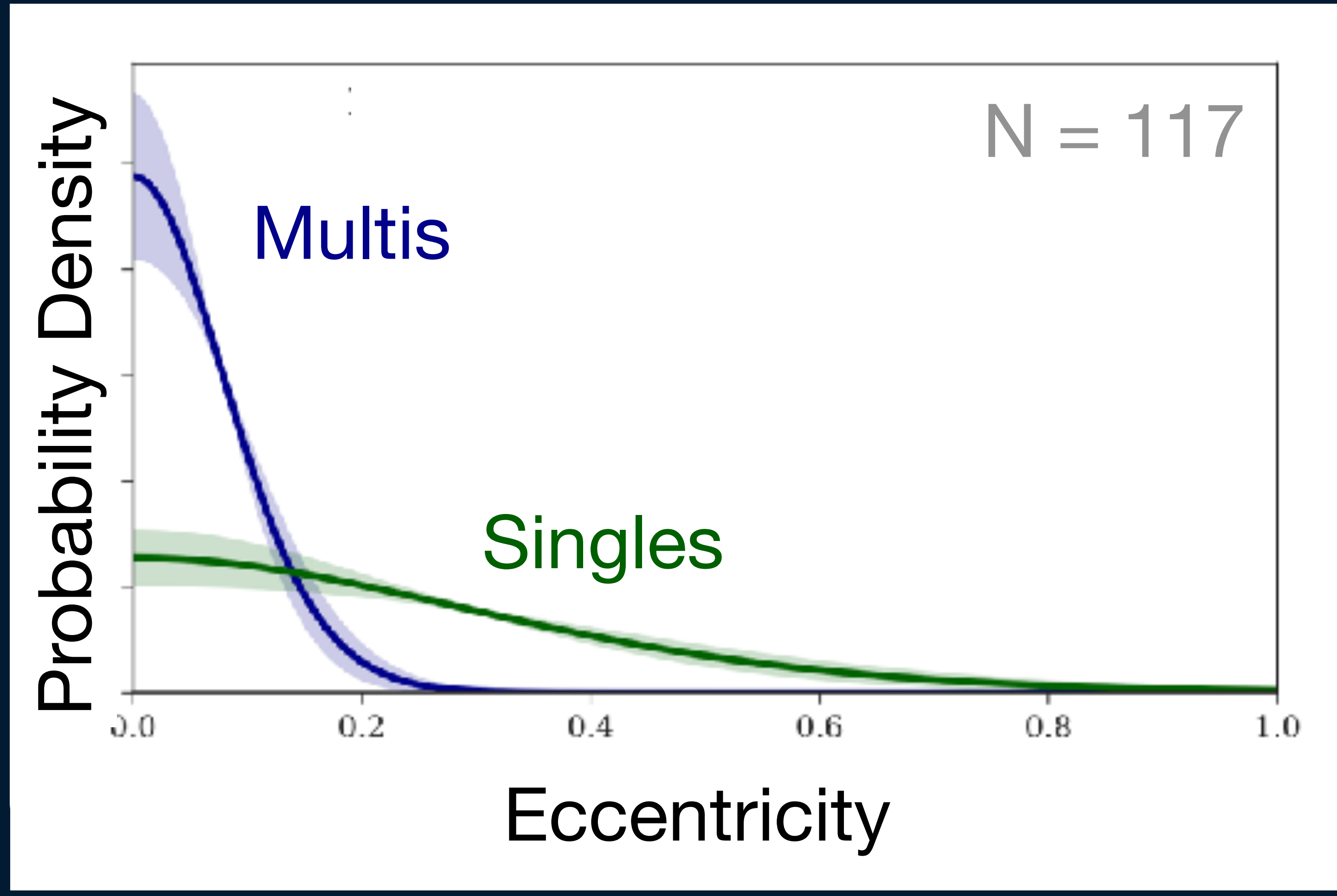
Bowler, Blunt, & Nielsen (2020)

Doppler



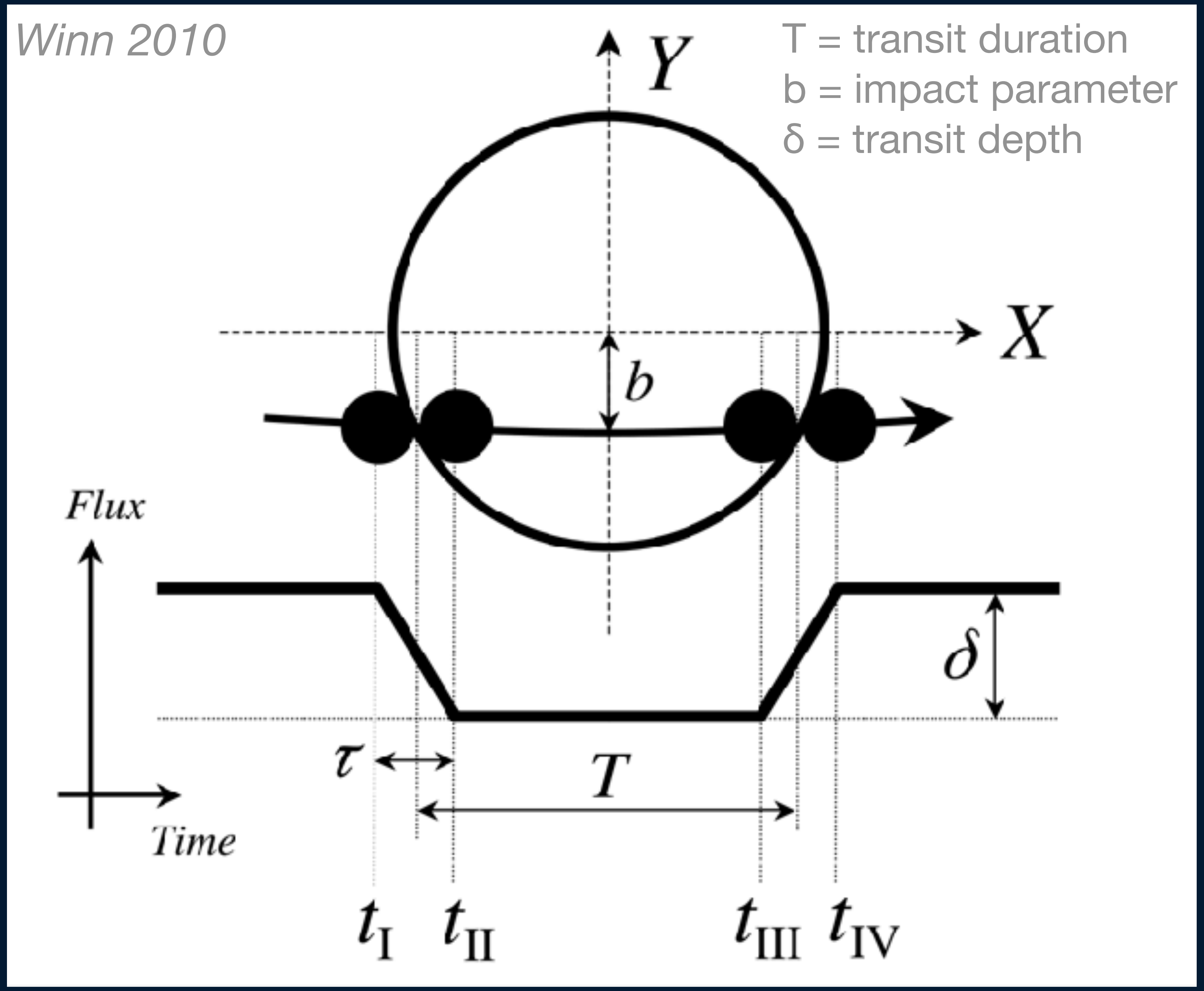
Kipping (2013)

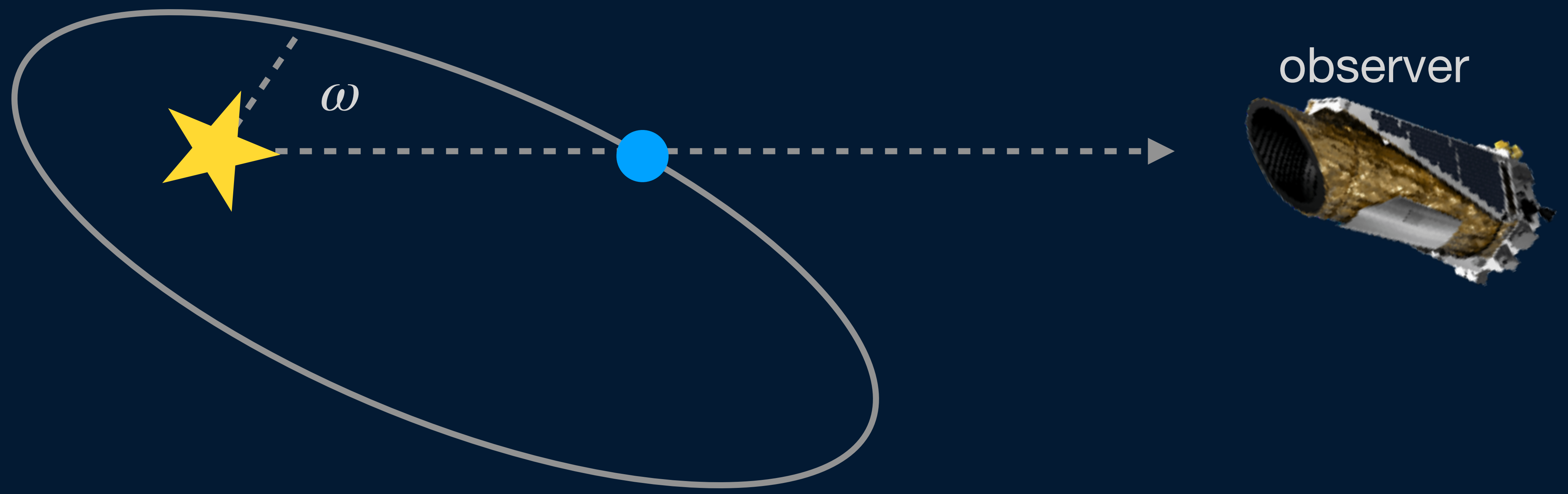
Transits



Van Eylen et. al (2019)

One observable, three unknowns





$$\text{duration} = \frac{\text{transit chord length}}{\text{orbital velocity}}$$

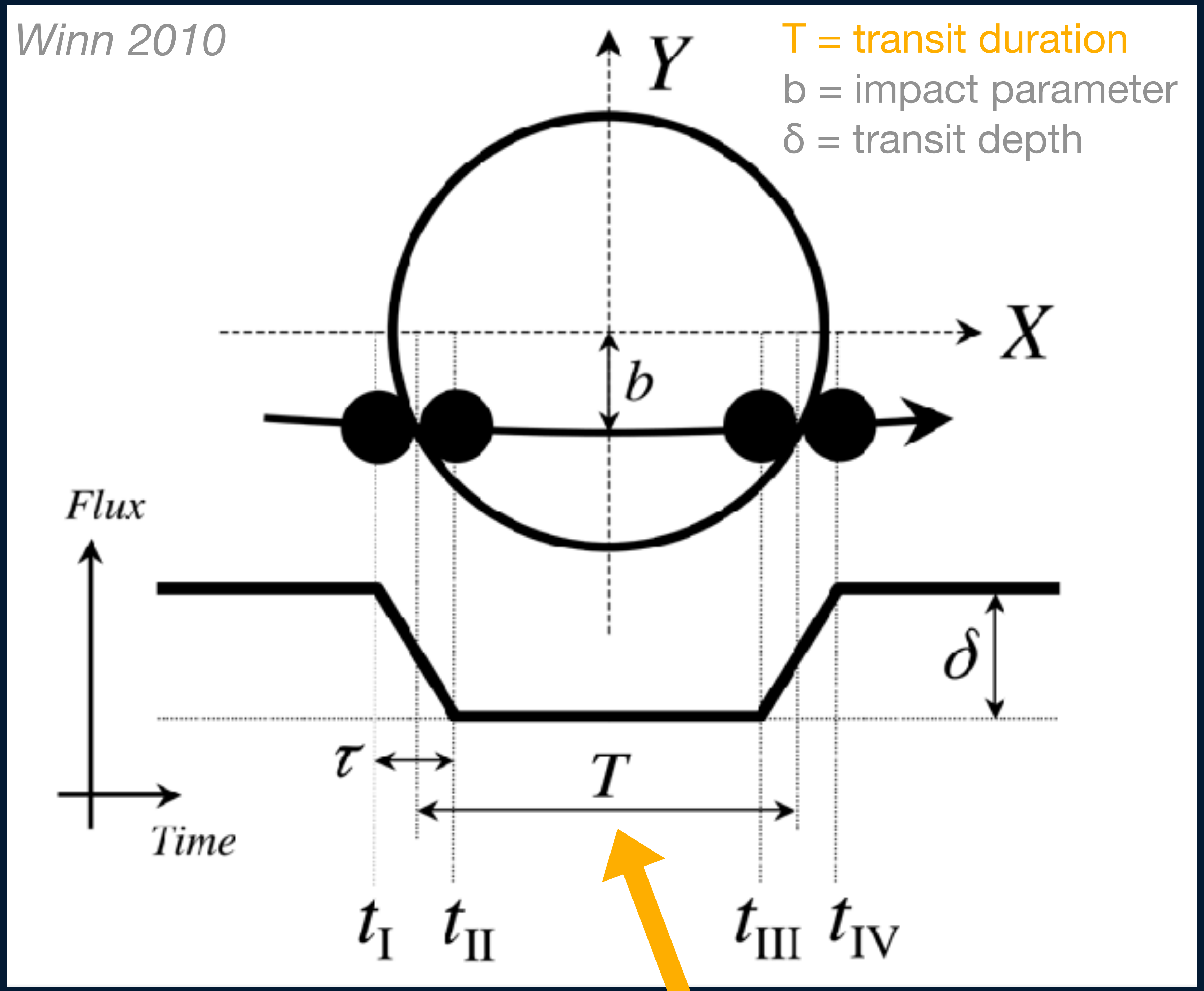
$$T_{14} \approx \frac{PR_\star}{\pi a}\sqrt{1-b^2}\,\frac{\sqrt{1-e^2}}{1+e\sin\omega}$$

compare $\dfrac{T}{T_0}$

T ← observed

T_0 ← predicted for $e=0,\ b=0$

One observable, three unknowns



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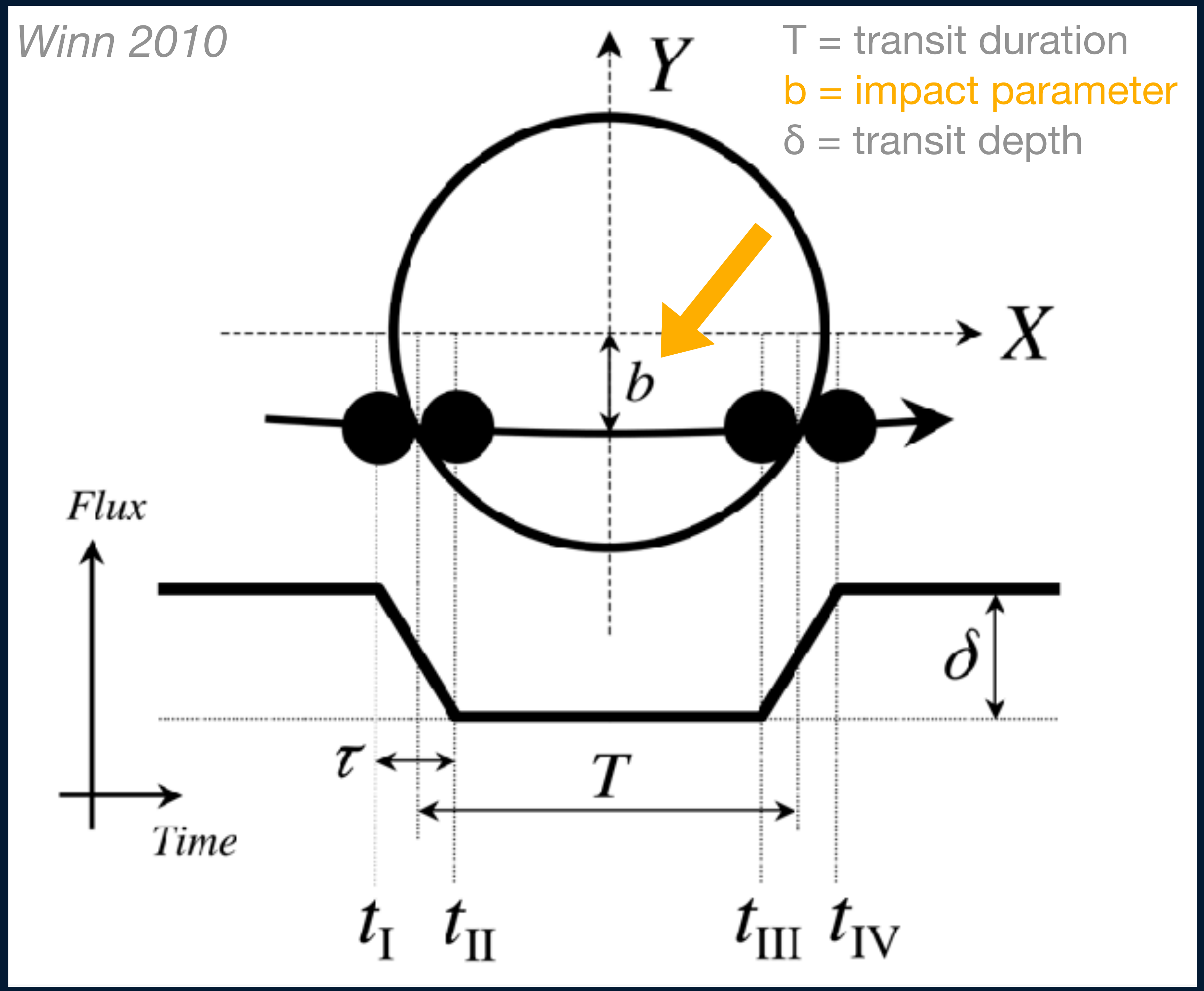

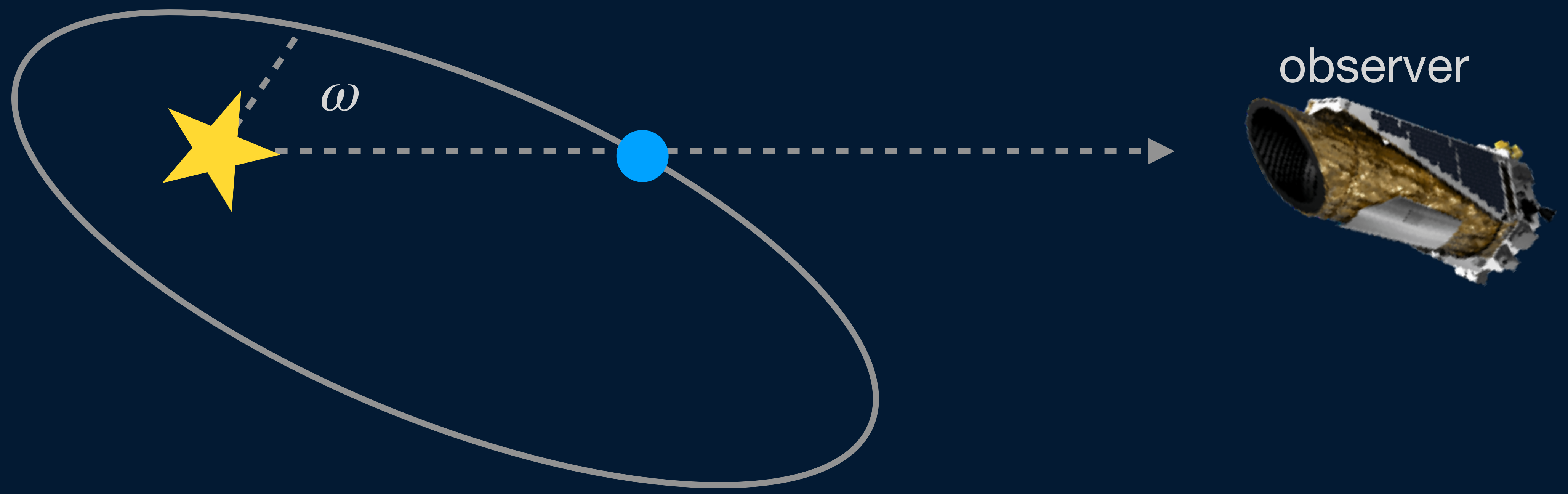

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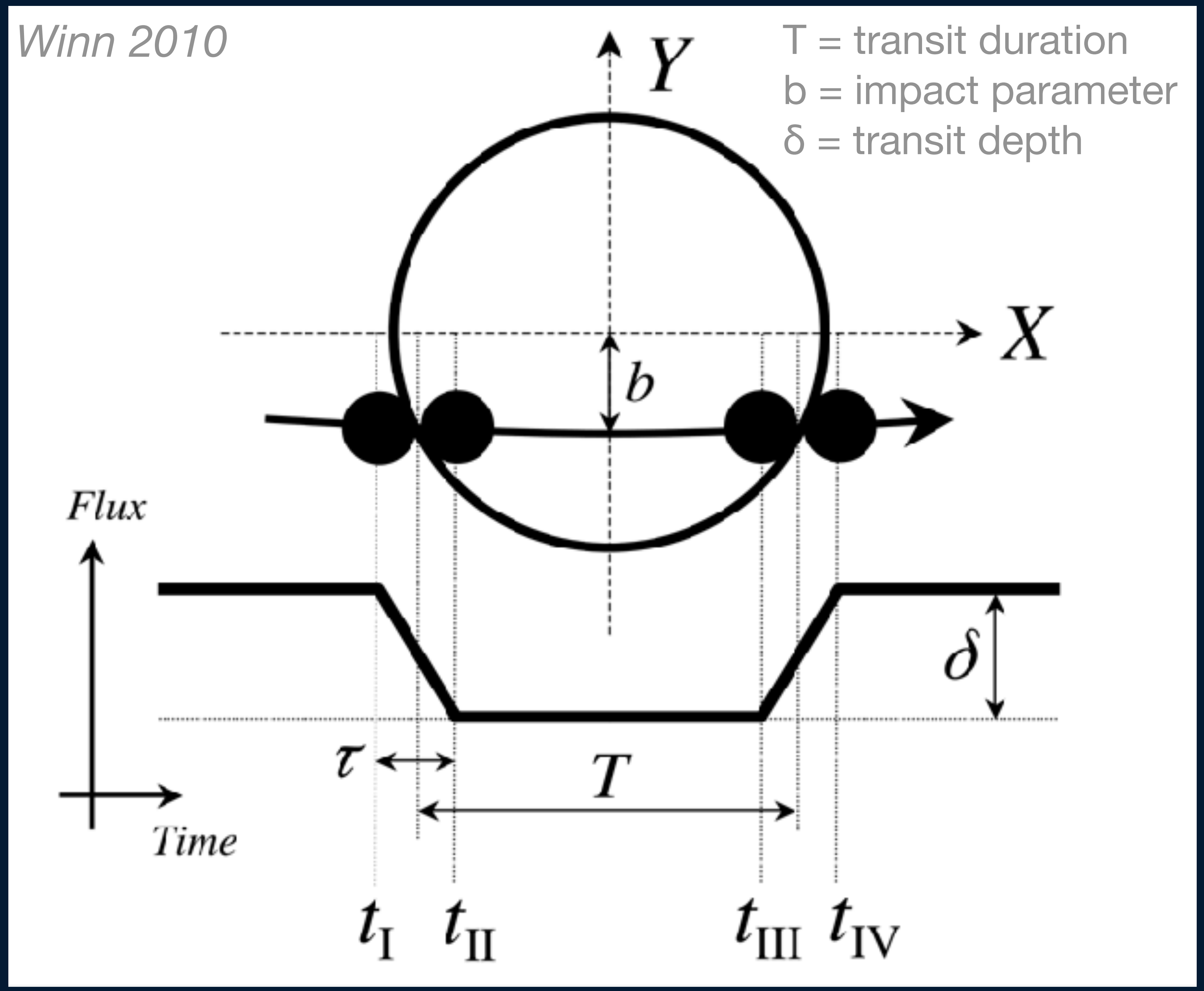

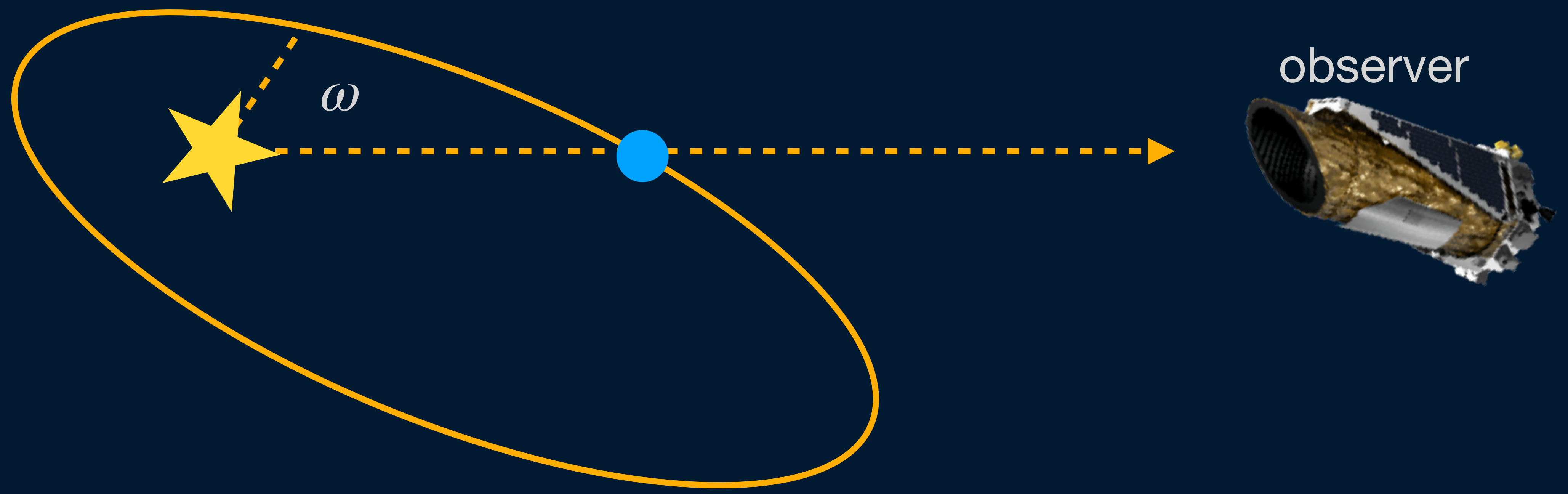

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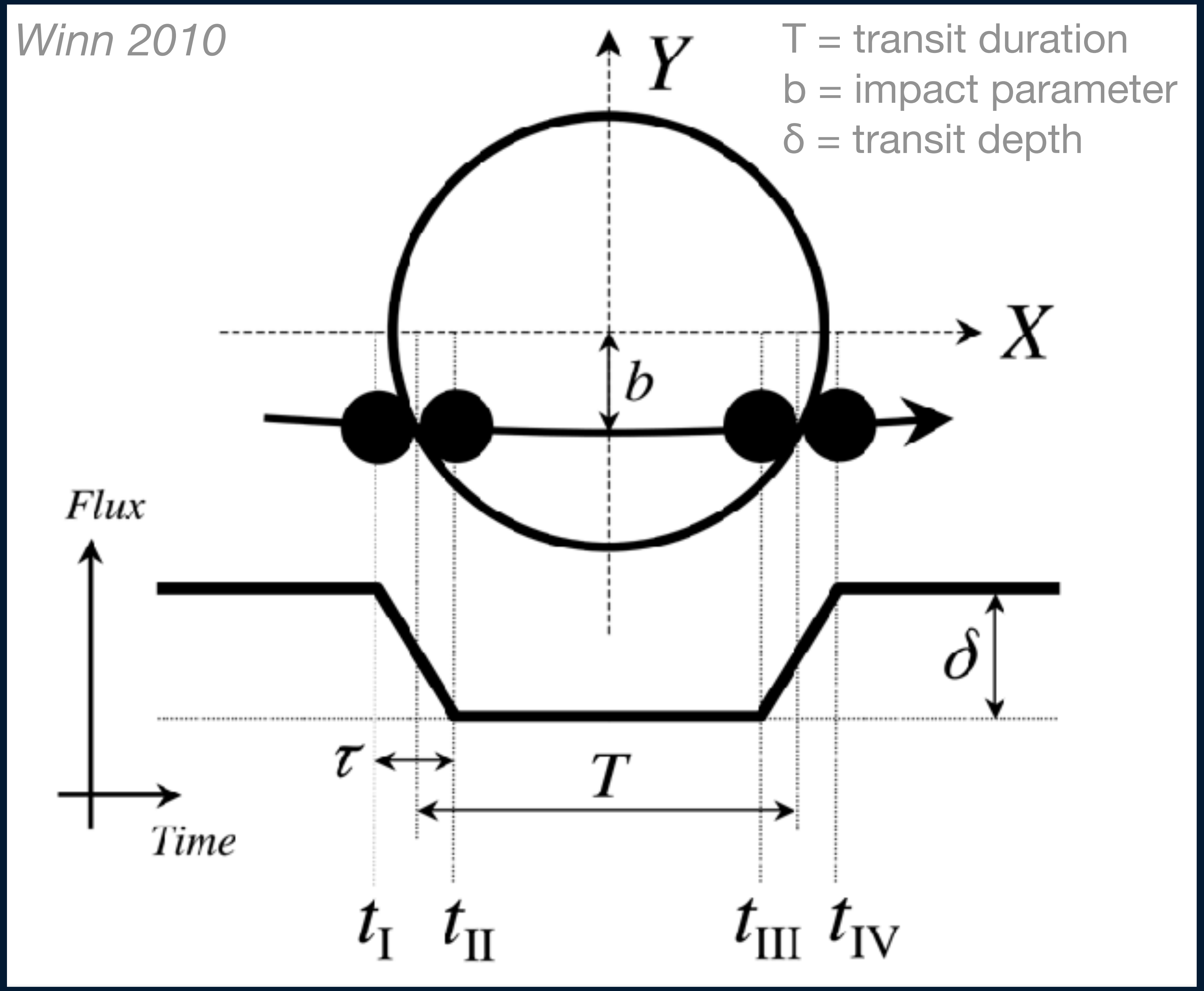

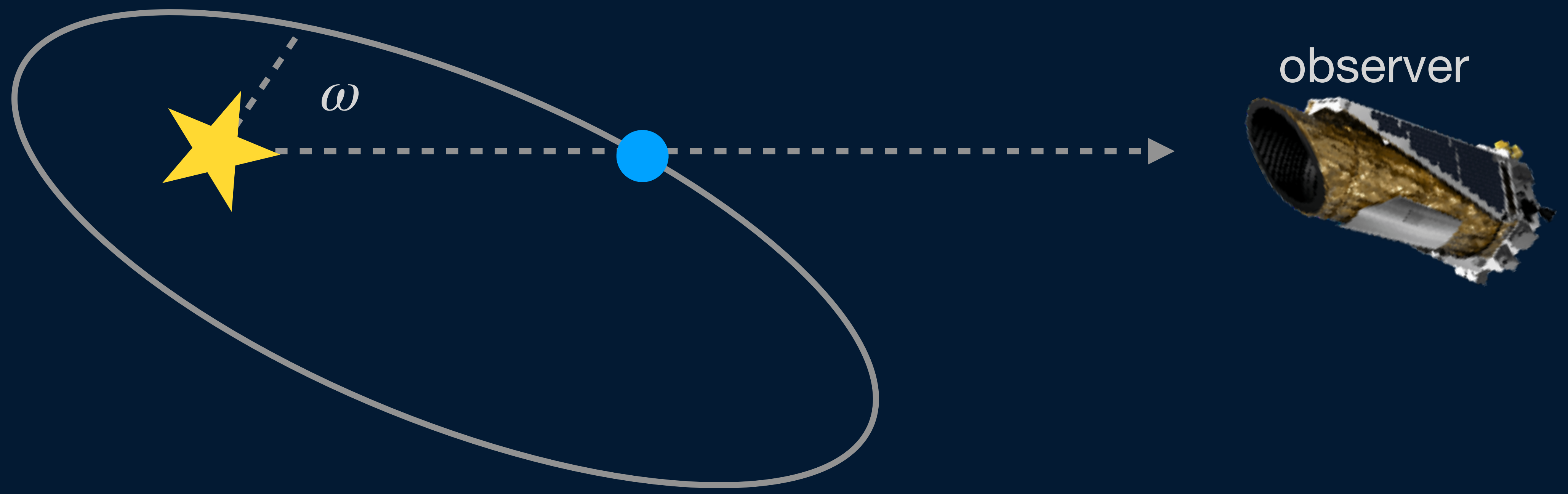

Ford, Quinn, & Veras (2008)
Dawson & Johnson (2012)
Kipping (2014)

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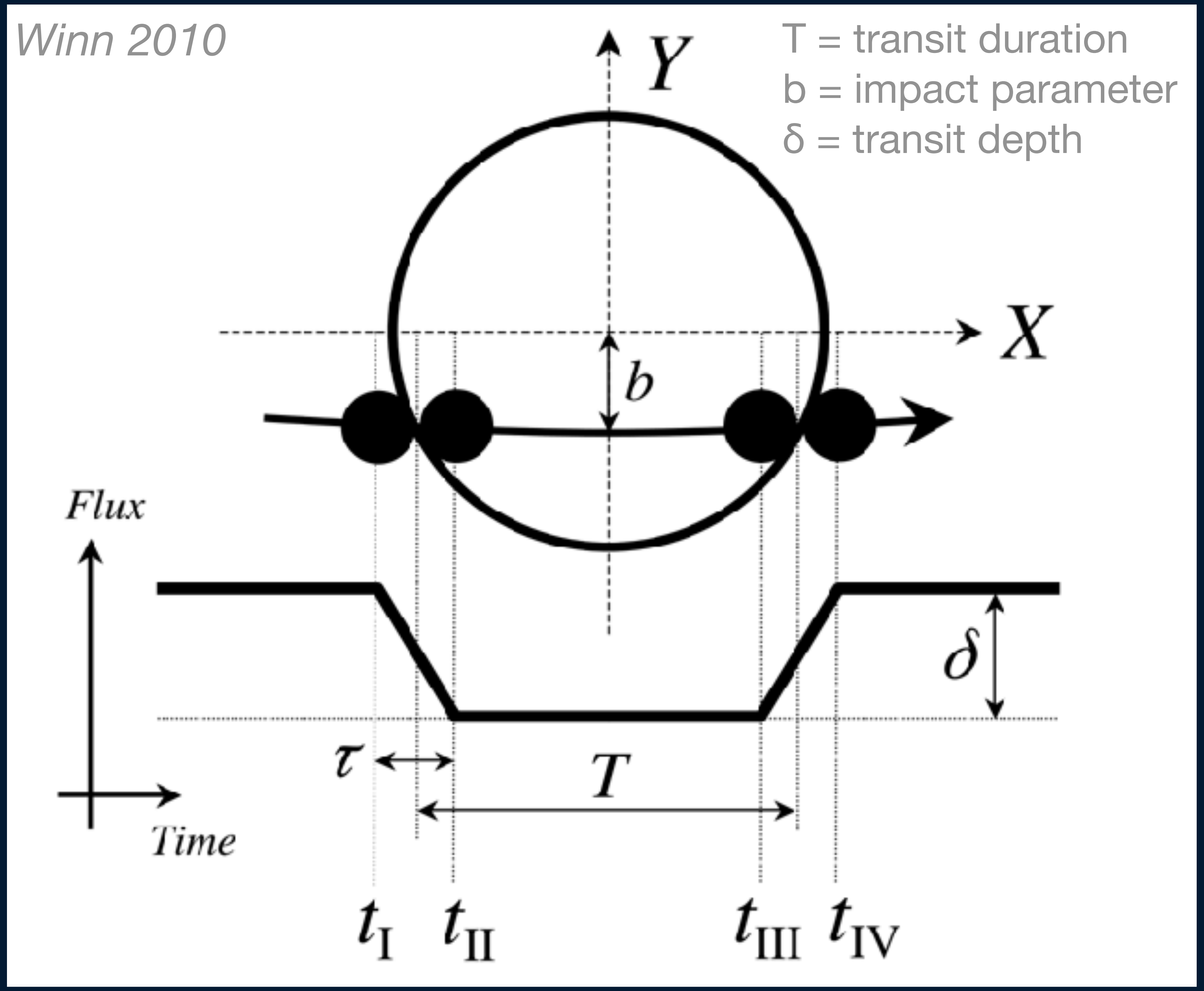
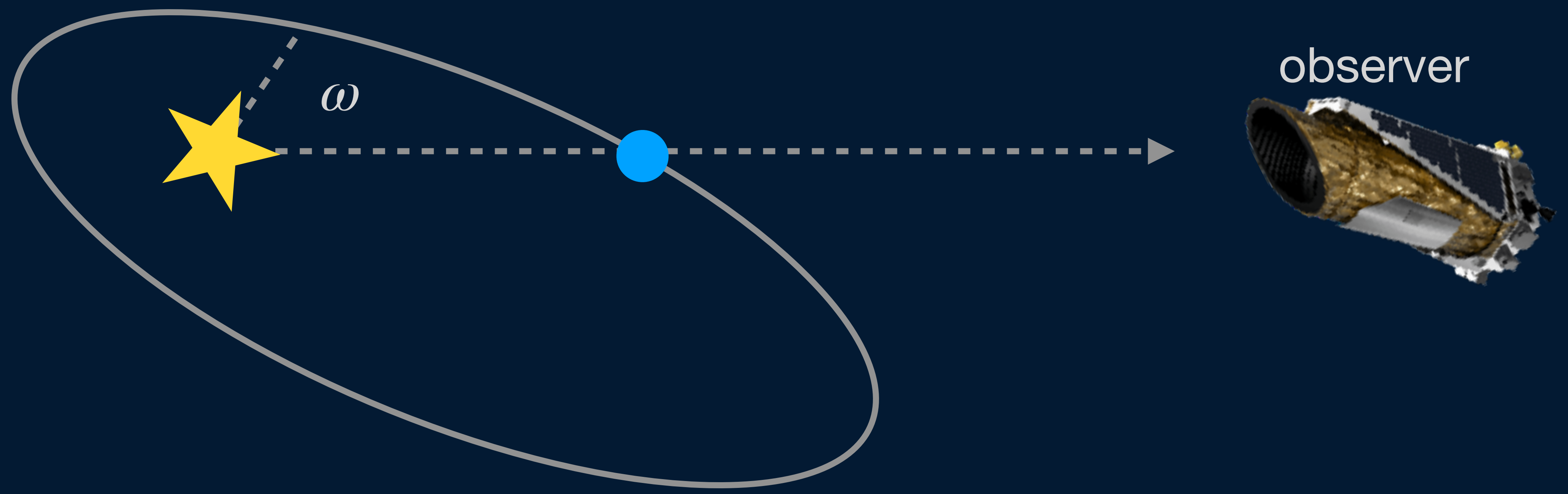




Ford, Quinn, & Veras (2008)
Dawson & Johnson (2012)
Kipping (2014)

$$T_{14} \approx \left(\frac{3P}{\pi^2 G\rho_\star}\right)^{1/3} \sqrt{1-b^2}\,\frac{\sqrt{1-e^2}}{1+e\sin\omega}$$

compare $\dfrac{T}{T_0}$

T ← observed

T_0 ← predicted for $e=0,\ b=0$

We developed a method to generate $\{e, \omega\}$ via **importance sampling** from DR25 chains

Mason MacDougall
UCLA PhD

No lightcurve fitting needed!

Kepler samples $\{P, R_p/R_\star, b, \tilde{\rho}\}_i$

$\{P, R_p/R_\star, b, T_{14}\}_i$

$\{e, \omega\}_i$ Uniform draws

$\rho_\star$ Gaia

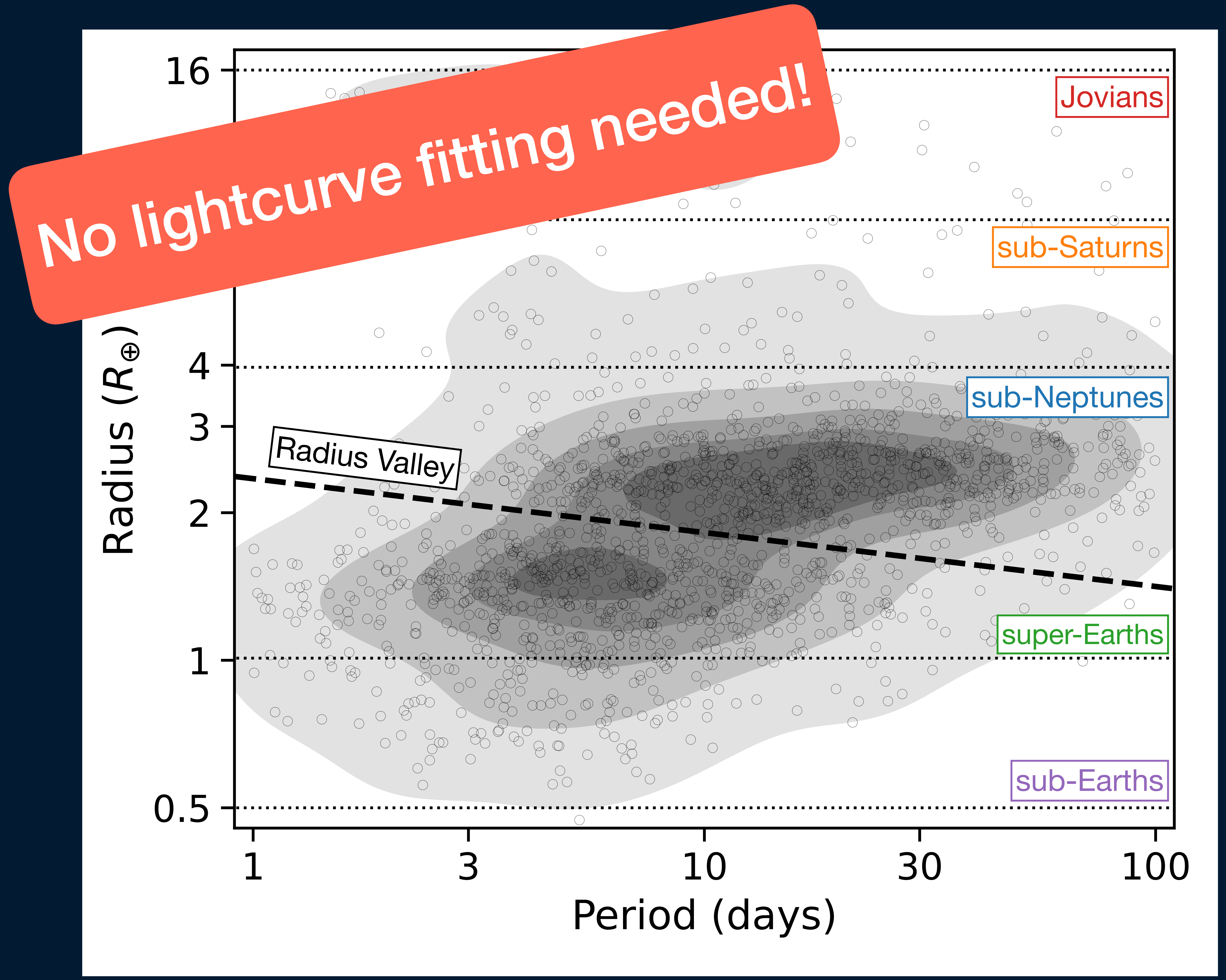
Importance samples $\{P, R_p/R_\star, b, \rho_\star, e, \omega\}_i$

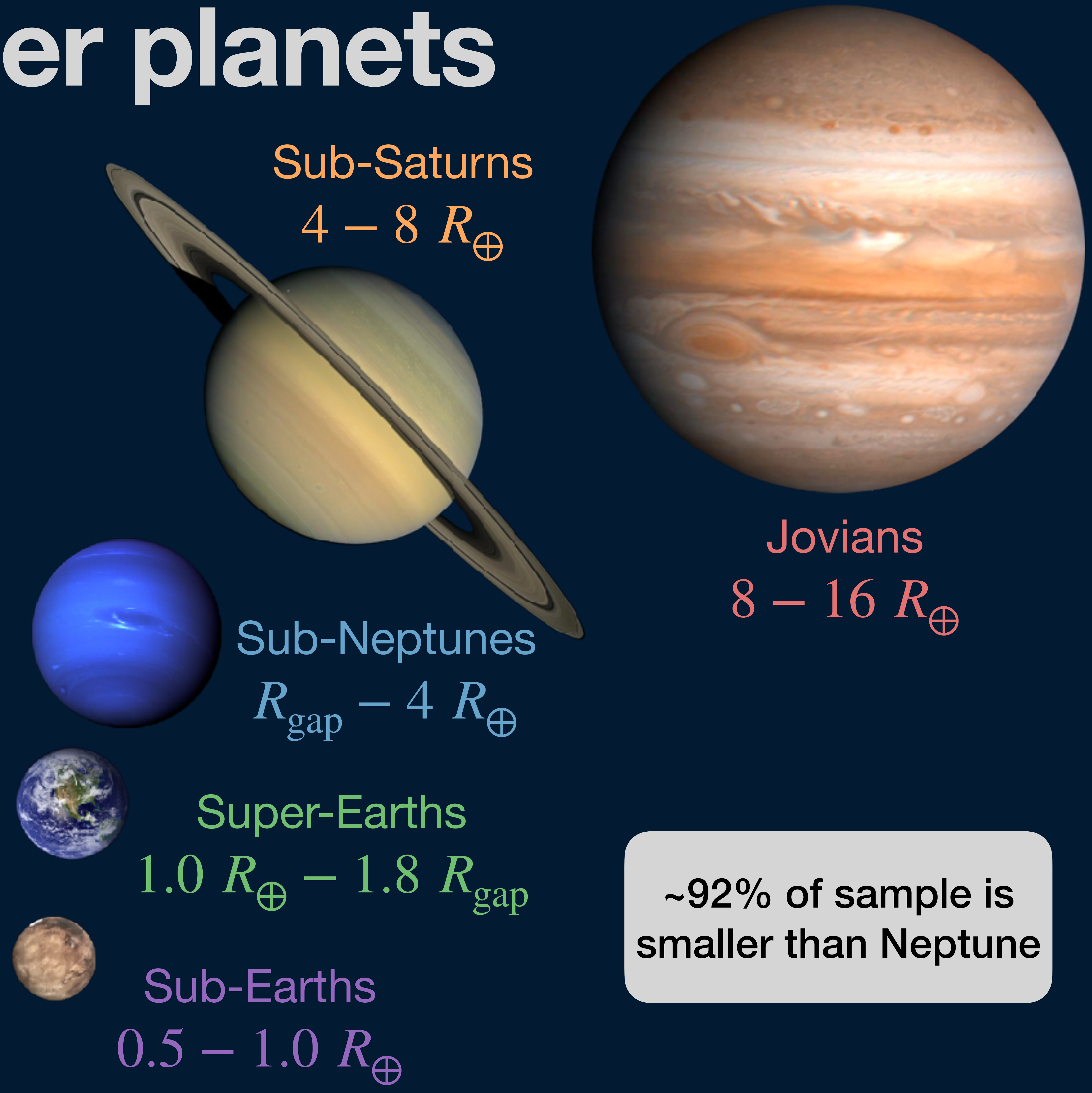
$$\log \mathcal{L}_i = -\frac{1}{2}\left(\frac{\rho_{\star,\mathrm{samp},i} - \rho_\star}{\sigma_{\rho_\star}}\right)^2 \longrightarrow \boxed{w_i = \frac{\mathcal{L}_i}{\sum \mathcal{L}_i}}$$

Importance weights

MacDougall, Gilbert, & Petigura (2023)

We analyzed ~1600 Kepler planets





~92% of sample is smaller than Neptune

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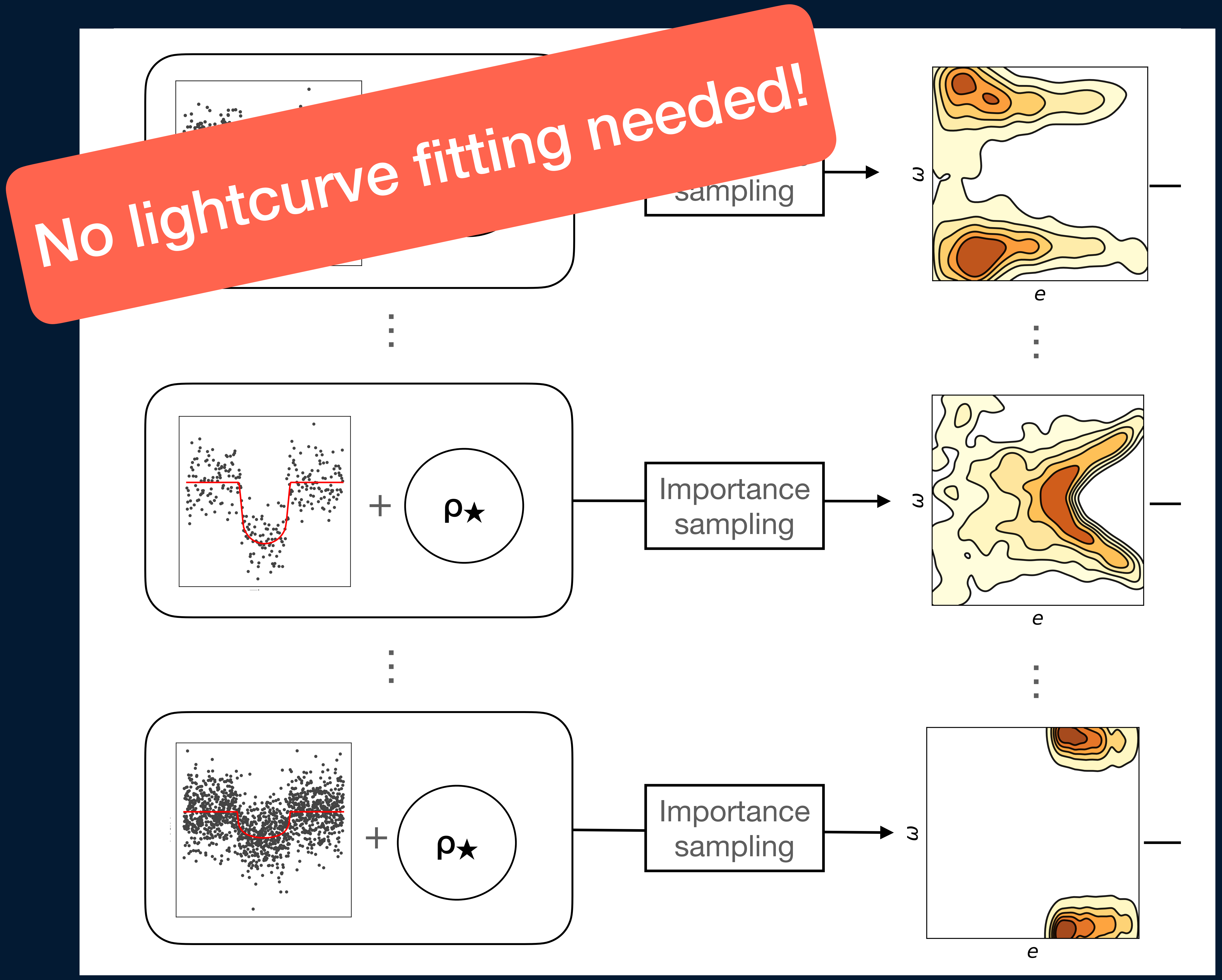
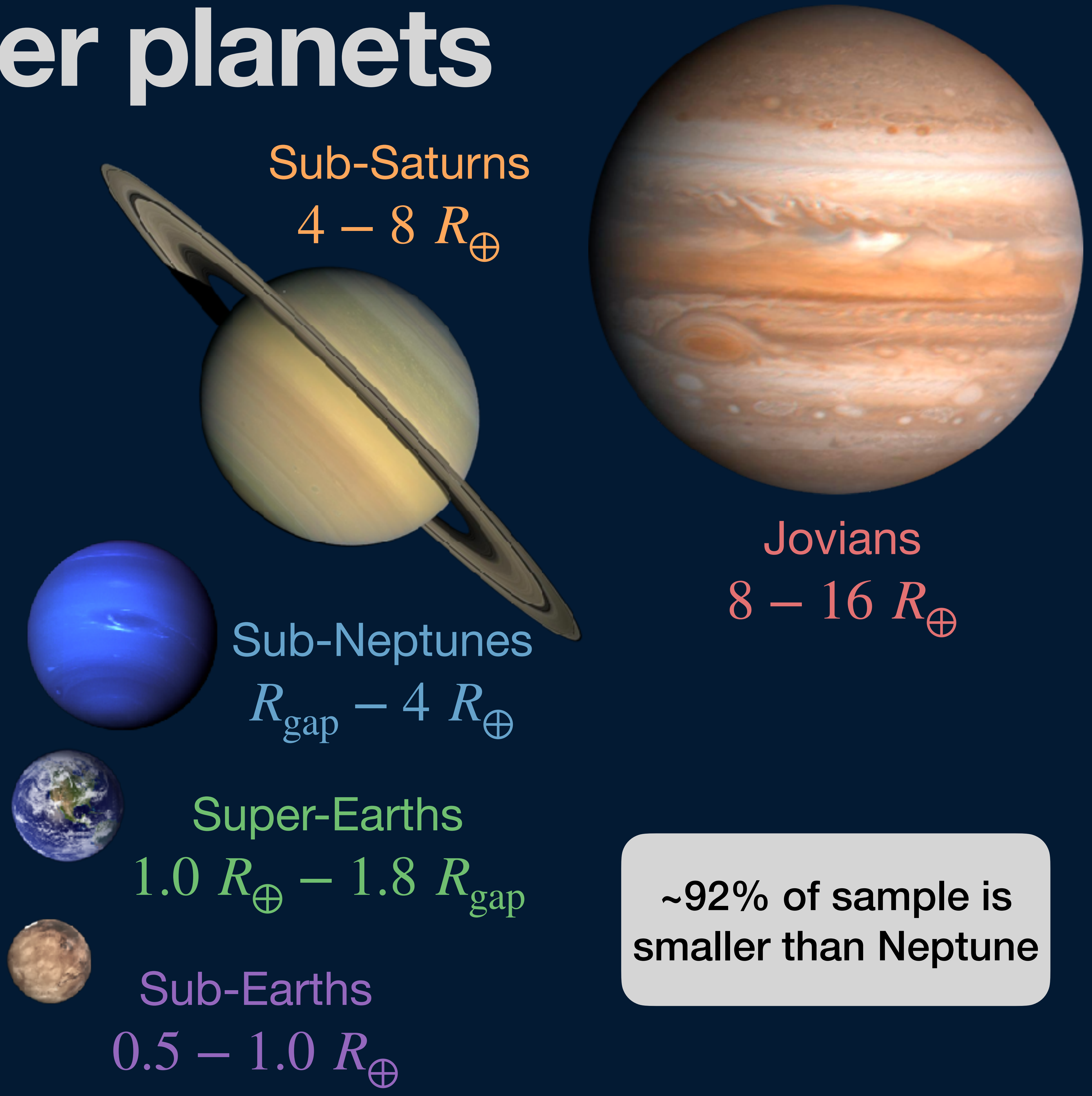
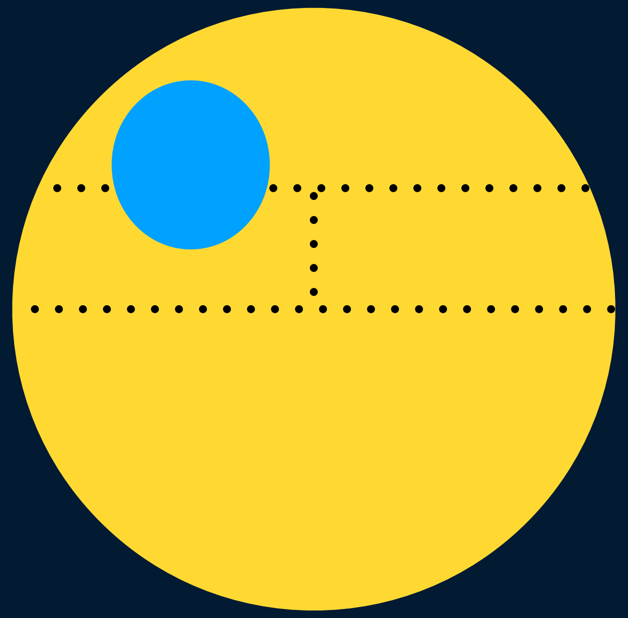




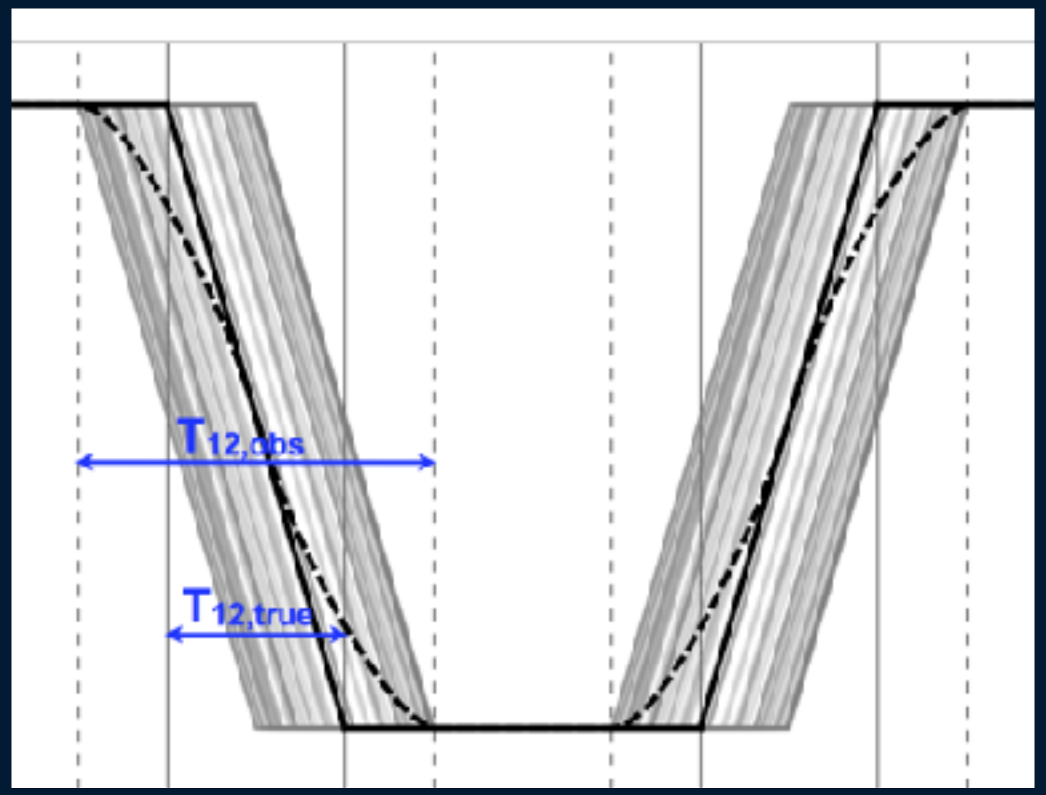
~92% of sample is smaller than Neptune

No lightcurve fitting needed?

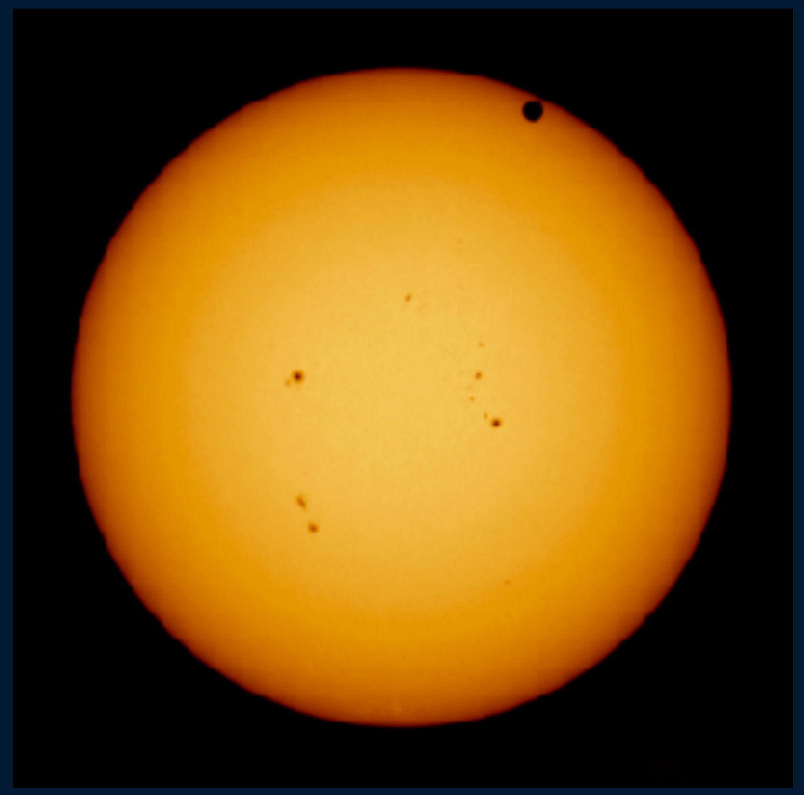
We refit 1600 Kepler light curves to address these issues



Impact Parameter

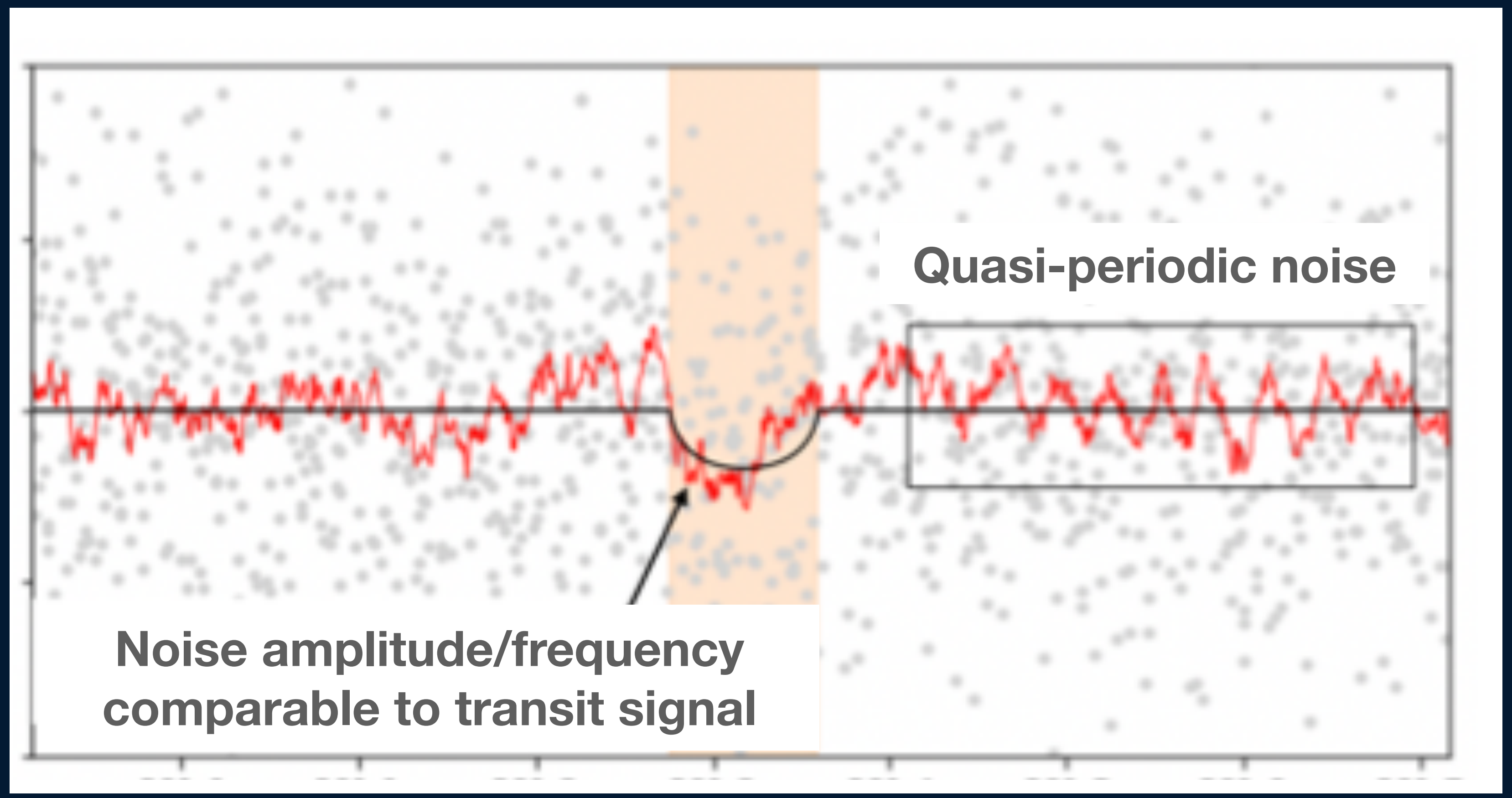


Transit Timing Variations



Stellar Limb Darkening

Sampler's ability to navigate narrow covariances



Correlated Noise

Model specification and prior choice

Introducing the ALDERAAN pipeline

Automated Lightcurve Detrending, Exoplanet Recovery, and Analysis of Autocorrelated Noise

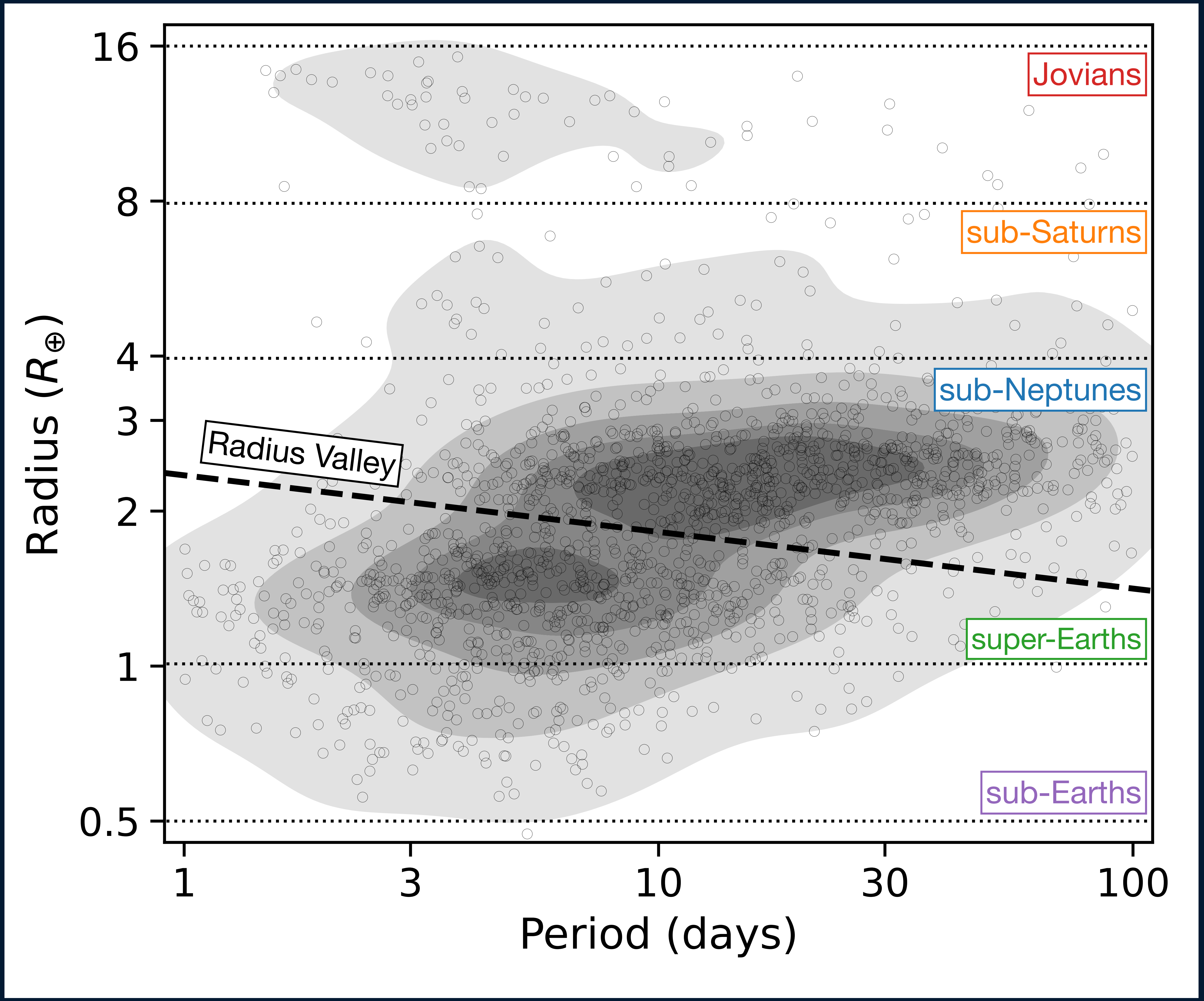
www.github.com/gjgilbert/alderaan

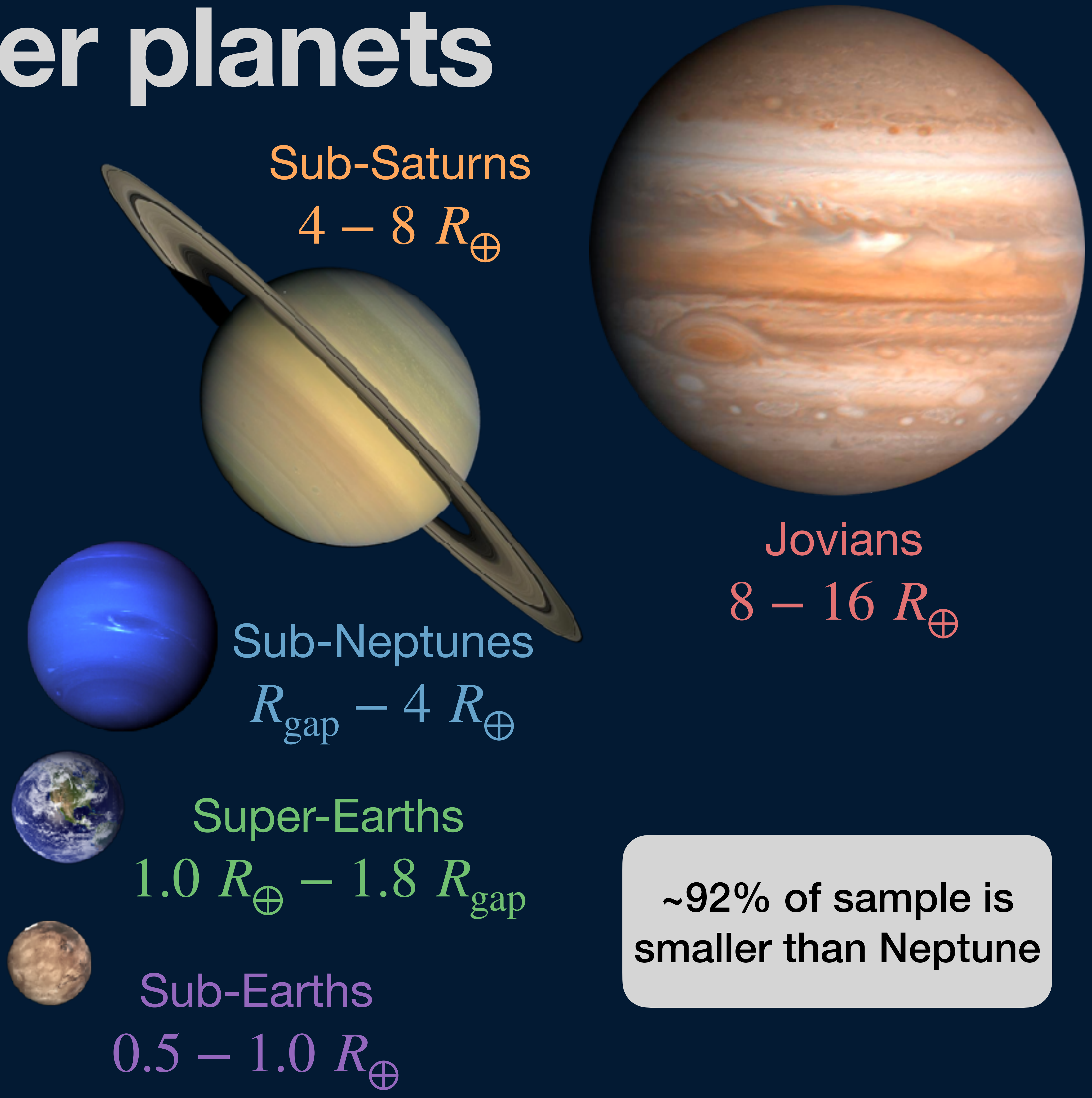
Paige Entrican
UCLA Undergrad

Project: data visualization software and manual validation of 1600 model fits

www.github.com/pentrican10/alderaan-viewer

We analyzed ~1600 Kepler planets





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Gilbert, Petigura, & Entrican (*accepted to PNAS*)

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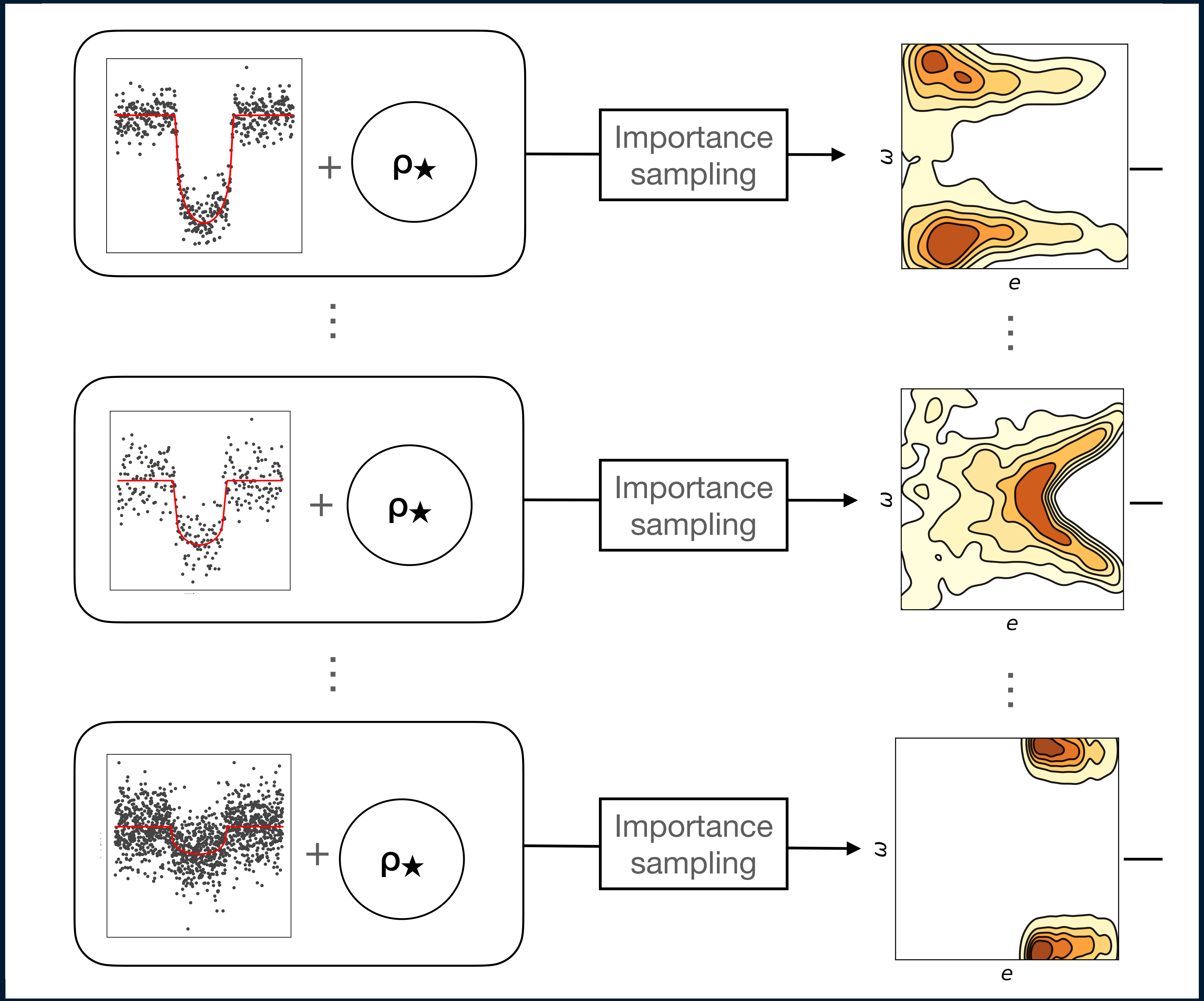

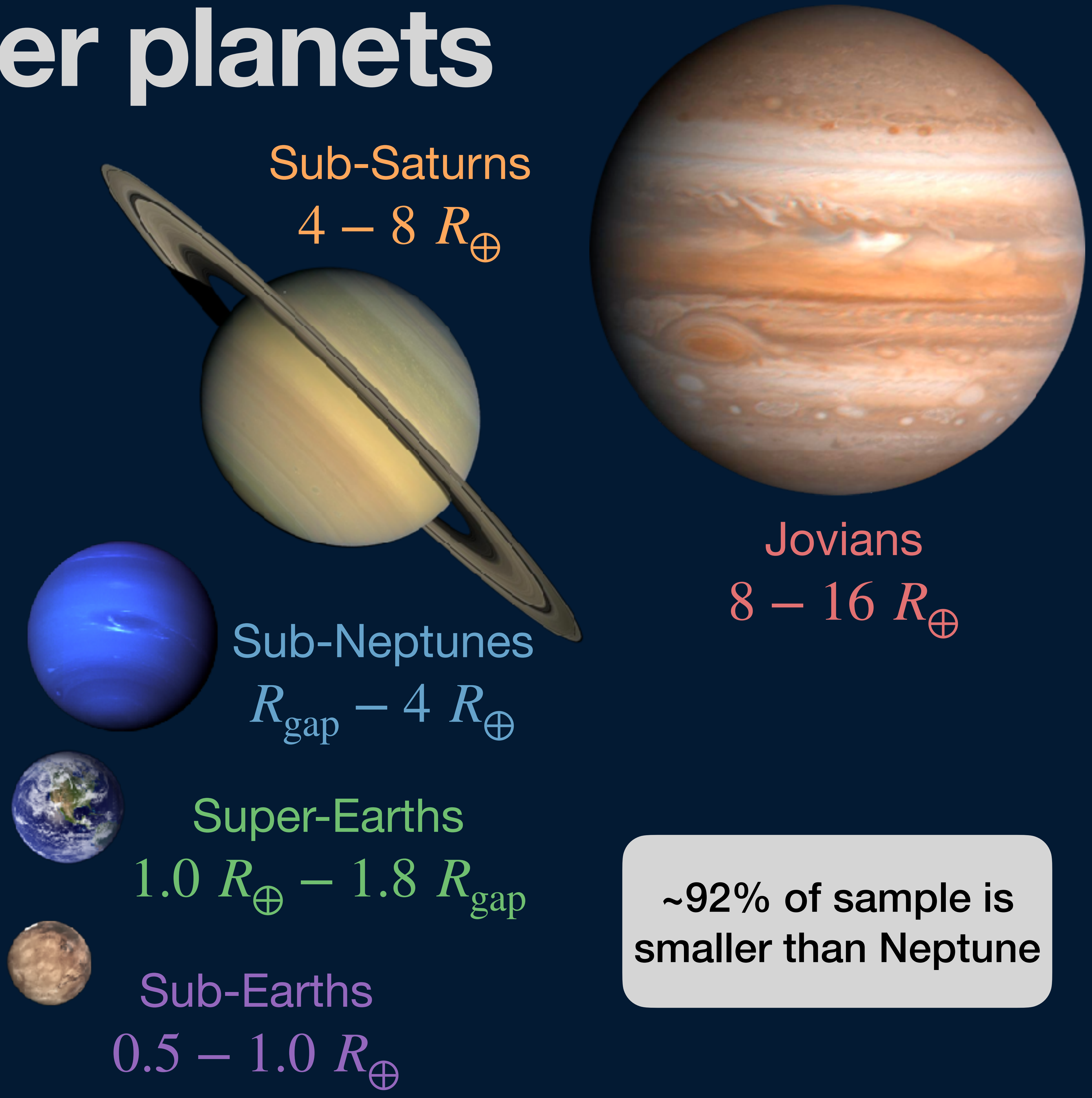

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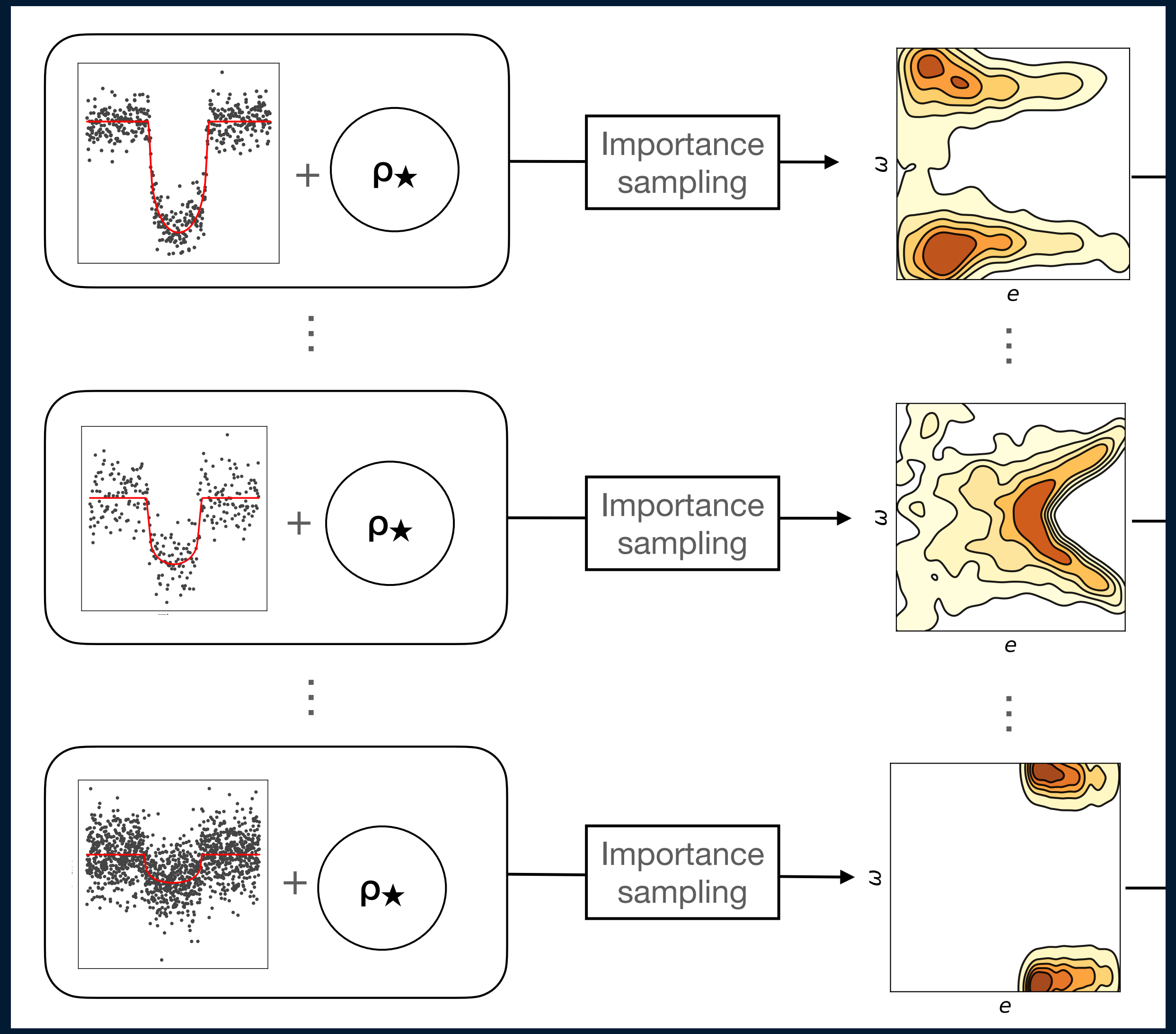
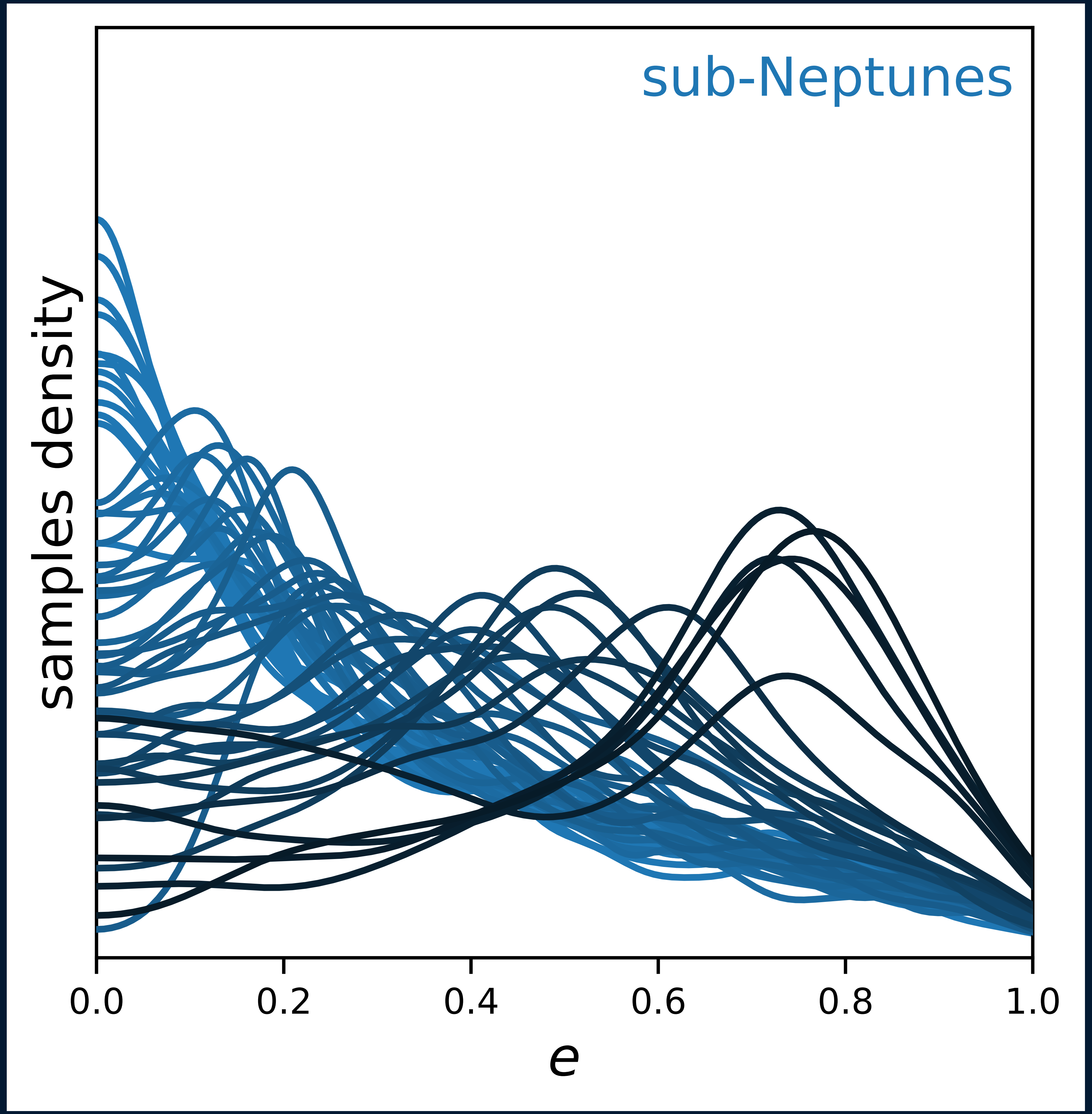
Gilbert, Petigura, & Entrican (*accepted to PNAS*)

Individual $\{e\}_i$ posteriors are asymmetric

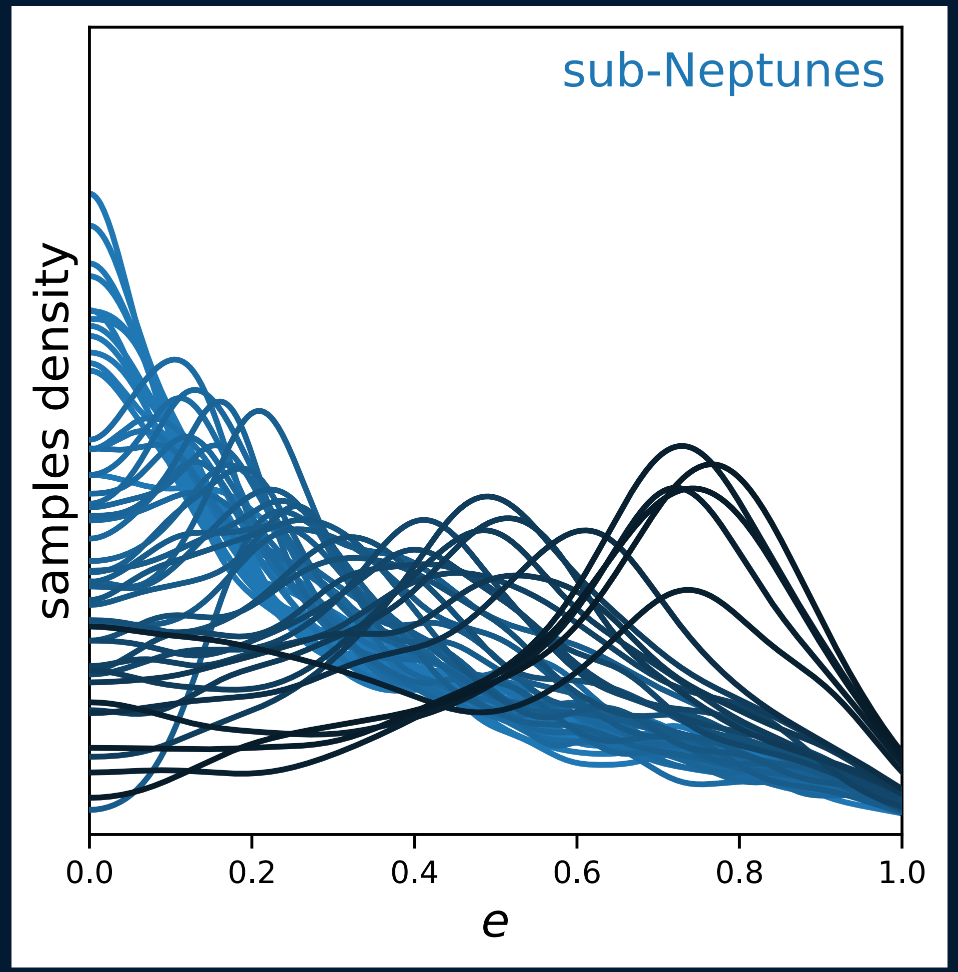


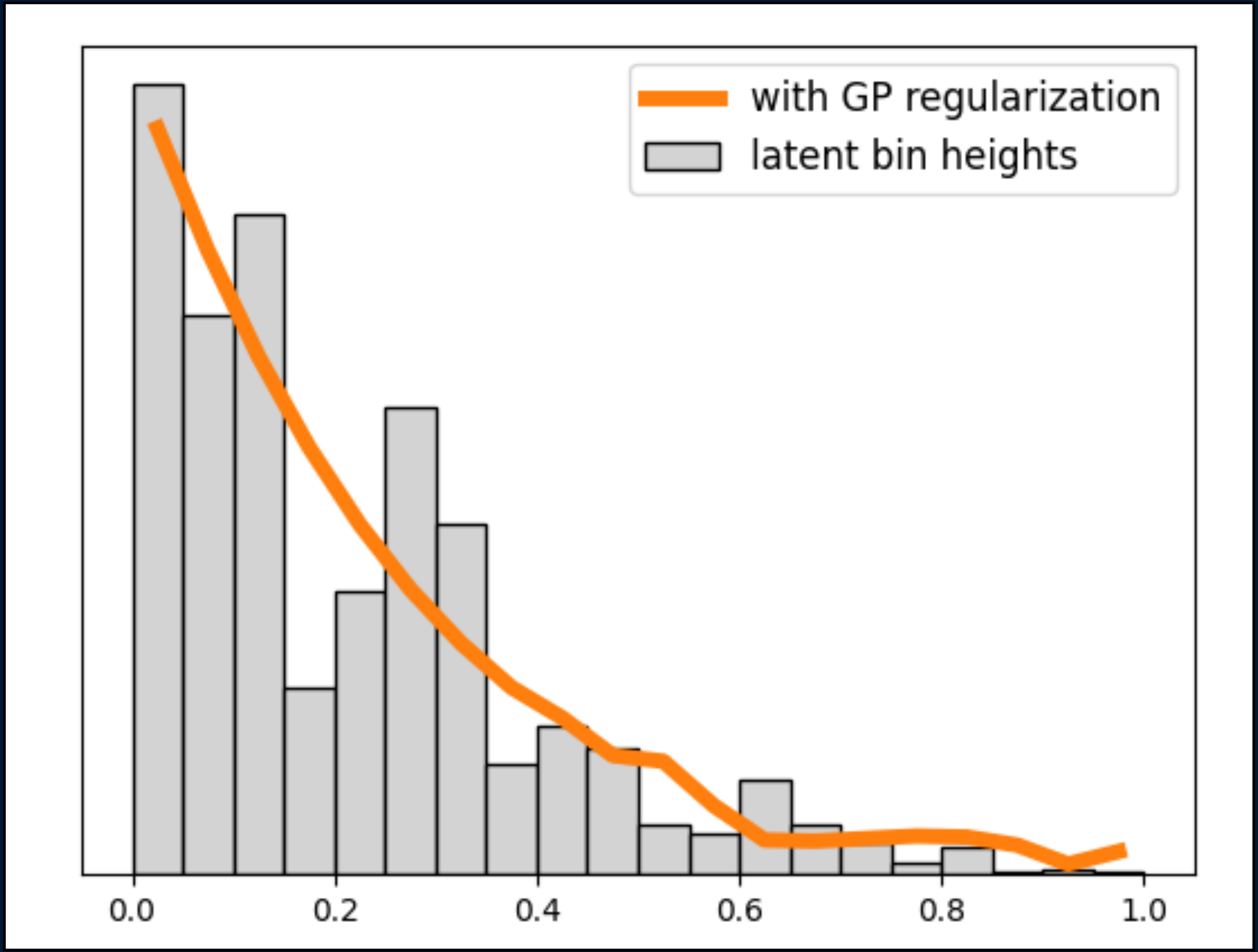
x 1600



Gilbert, Petigura, & Entrican (*accepted to PNAS*)

We infer **population** $f(e)$ from **individual** $\{e\}_i$ with a Hierarchical Bayesian Model





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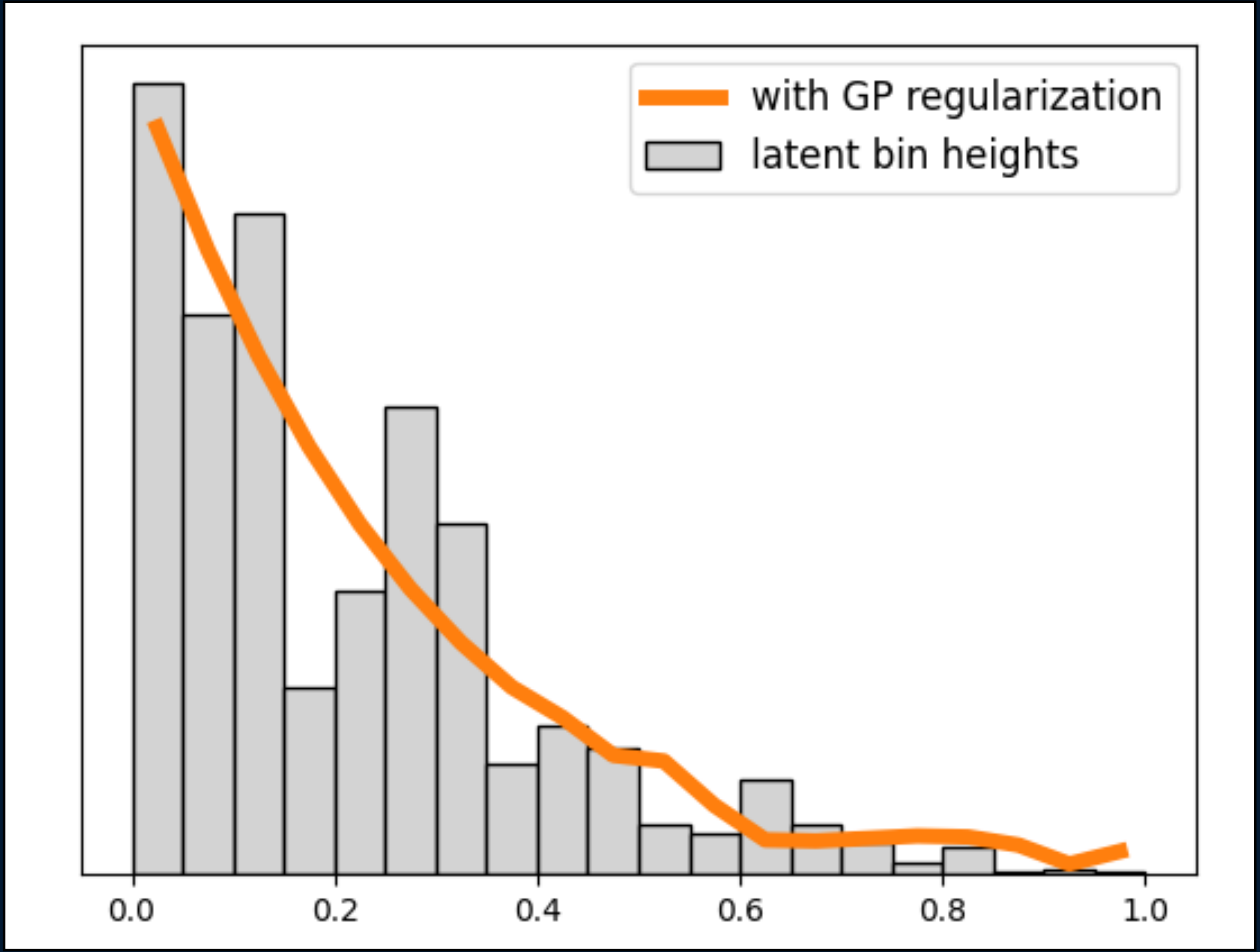

Empirical Histogram

- 25 bins $\rightarrow \Delta e \sim 0.04$
- GP regularization enforces smoothness
- Agnostic to underlying distribution shape

Hogg+ (2010) | Foreman-Mackey+ (2014)
Van Eylen+ (2019) | Bowler+ (2020)
Masuda+ (2022) | Sagear & Ballard (2023)

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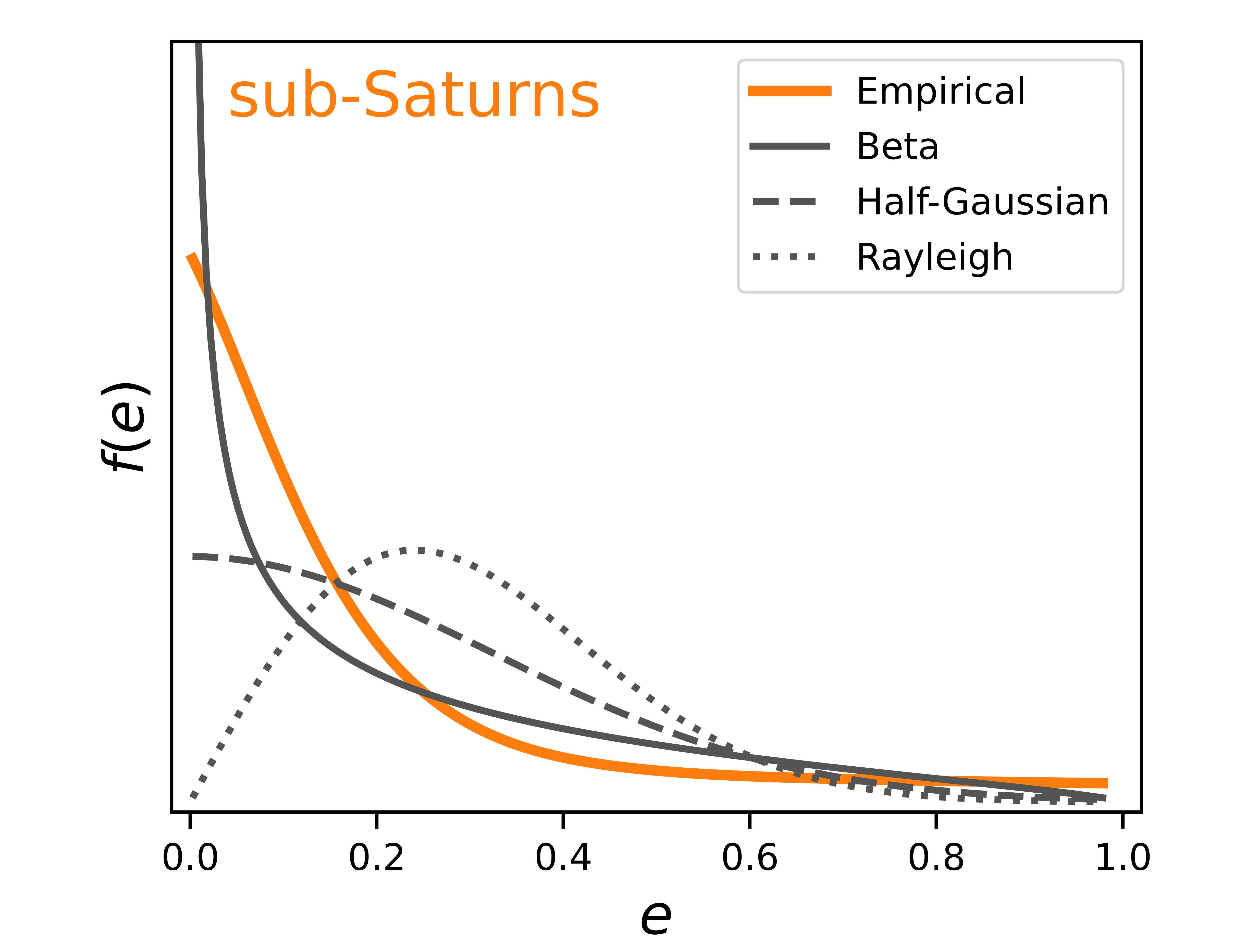

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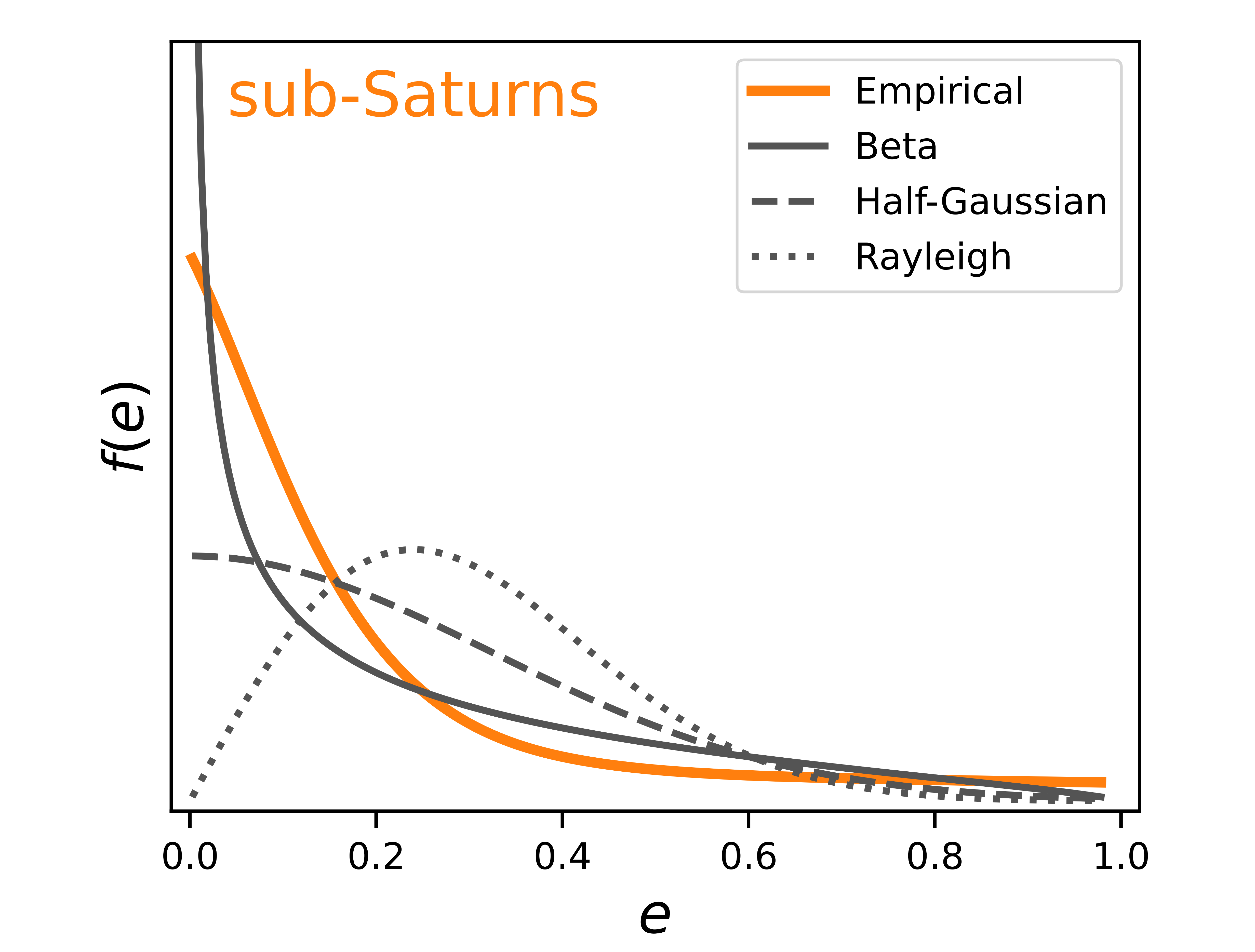

- Monotonic
- Peaked at $e = 0$

Gilbert, Petigura, & Entrican (*accepted to PNAS*)

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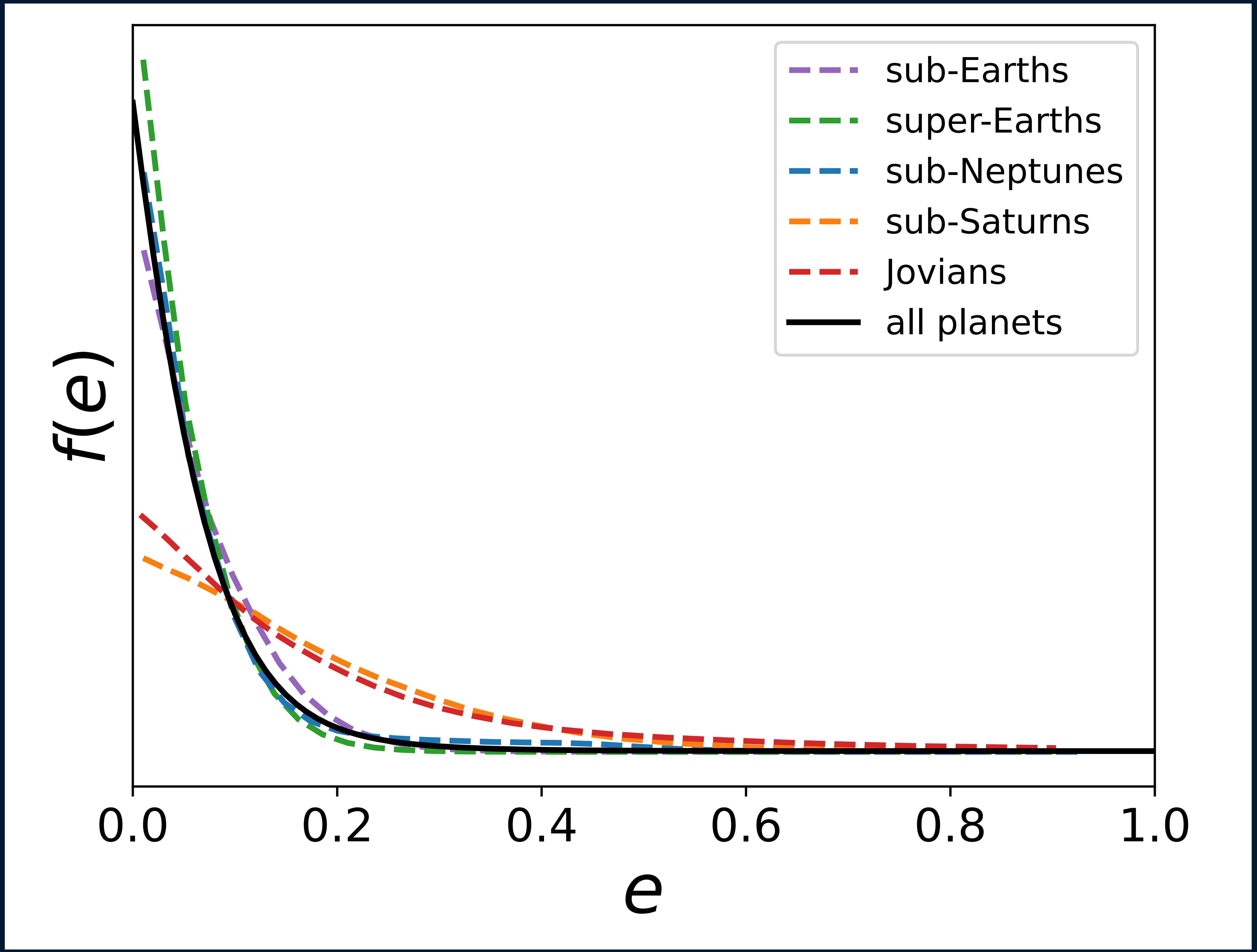
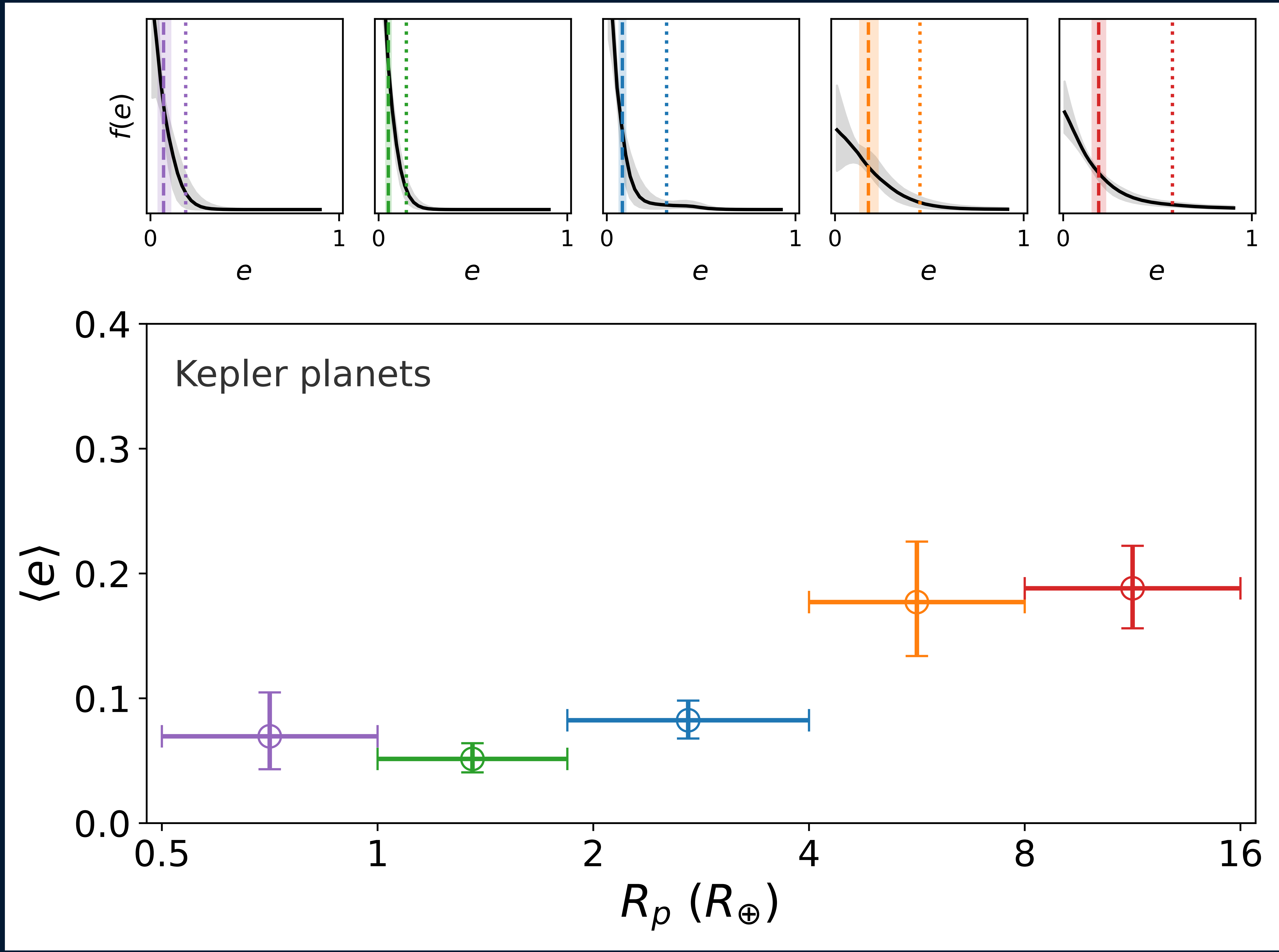


- Monotonic
- Peaked at $e = 0$
- Self-similar across planet sizes

Gilbert, Petigura, & Entrican (*accepted to PNAS*)

Eccentricity as a function of planet radius



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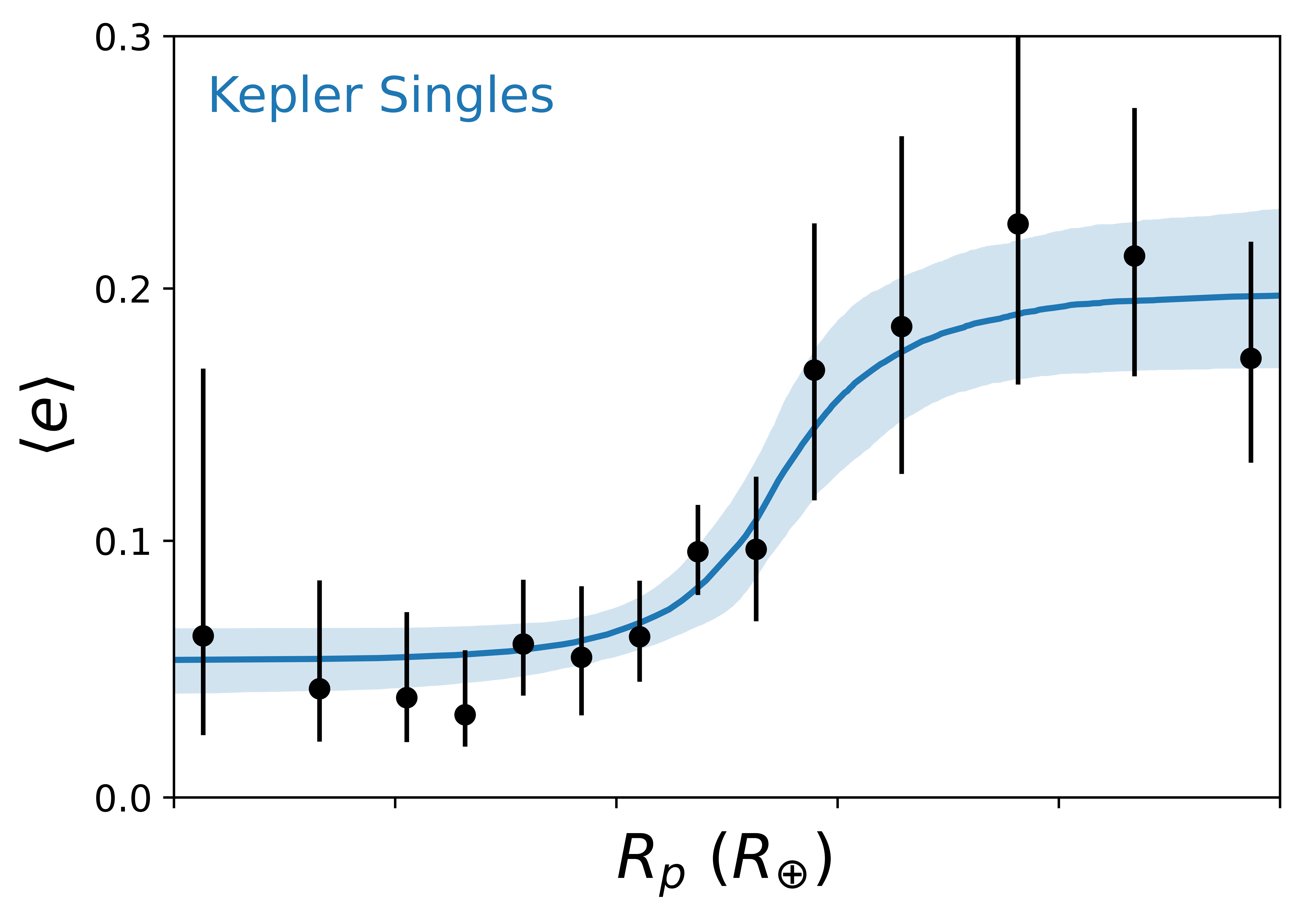
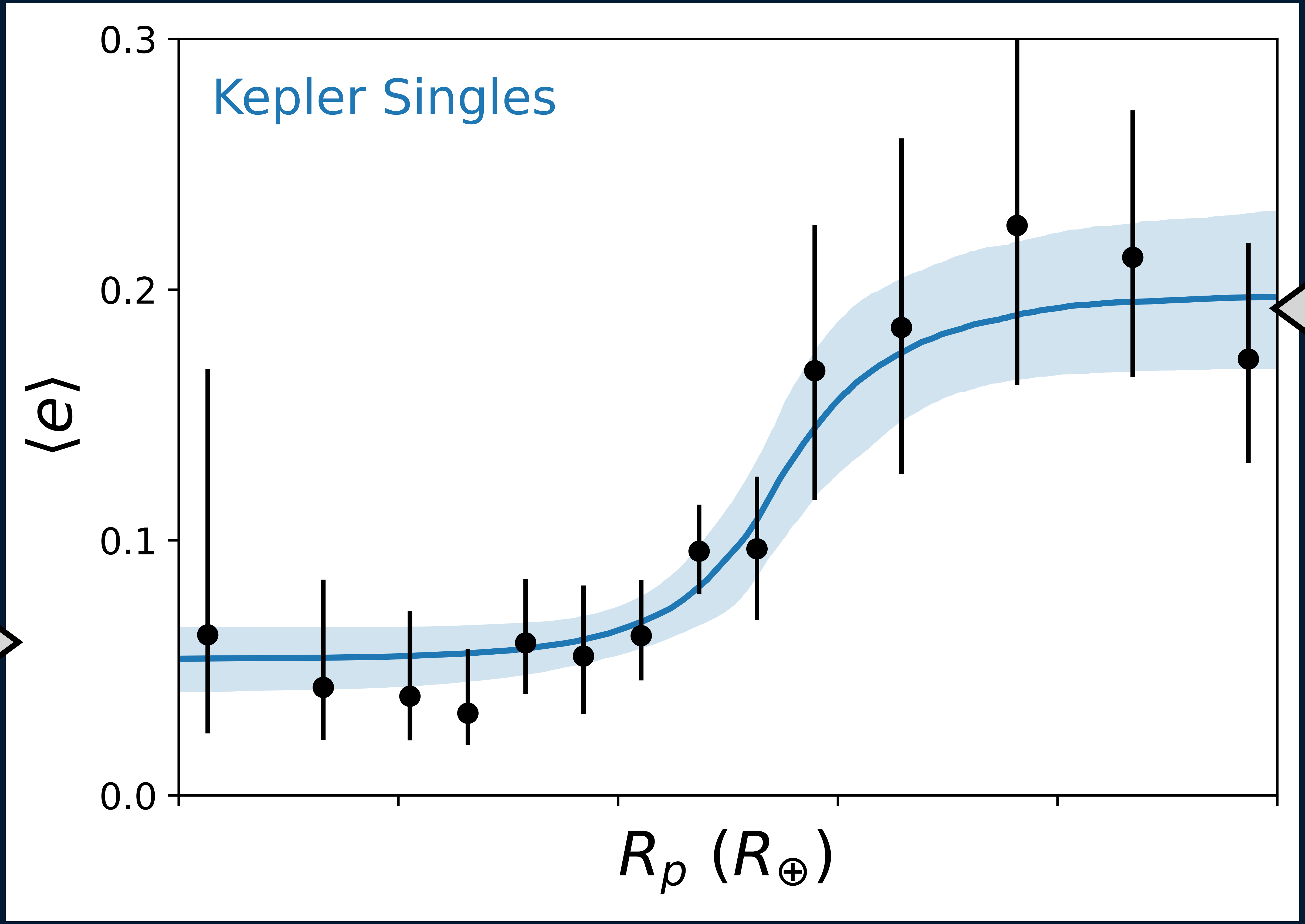


Gilbert, Petigura, & Entrican (*accepted to PNAS*)

Small planets have low $\langle e \rangle$

$\langle e \rangle_{\text{small}} \sim 0.05$

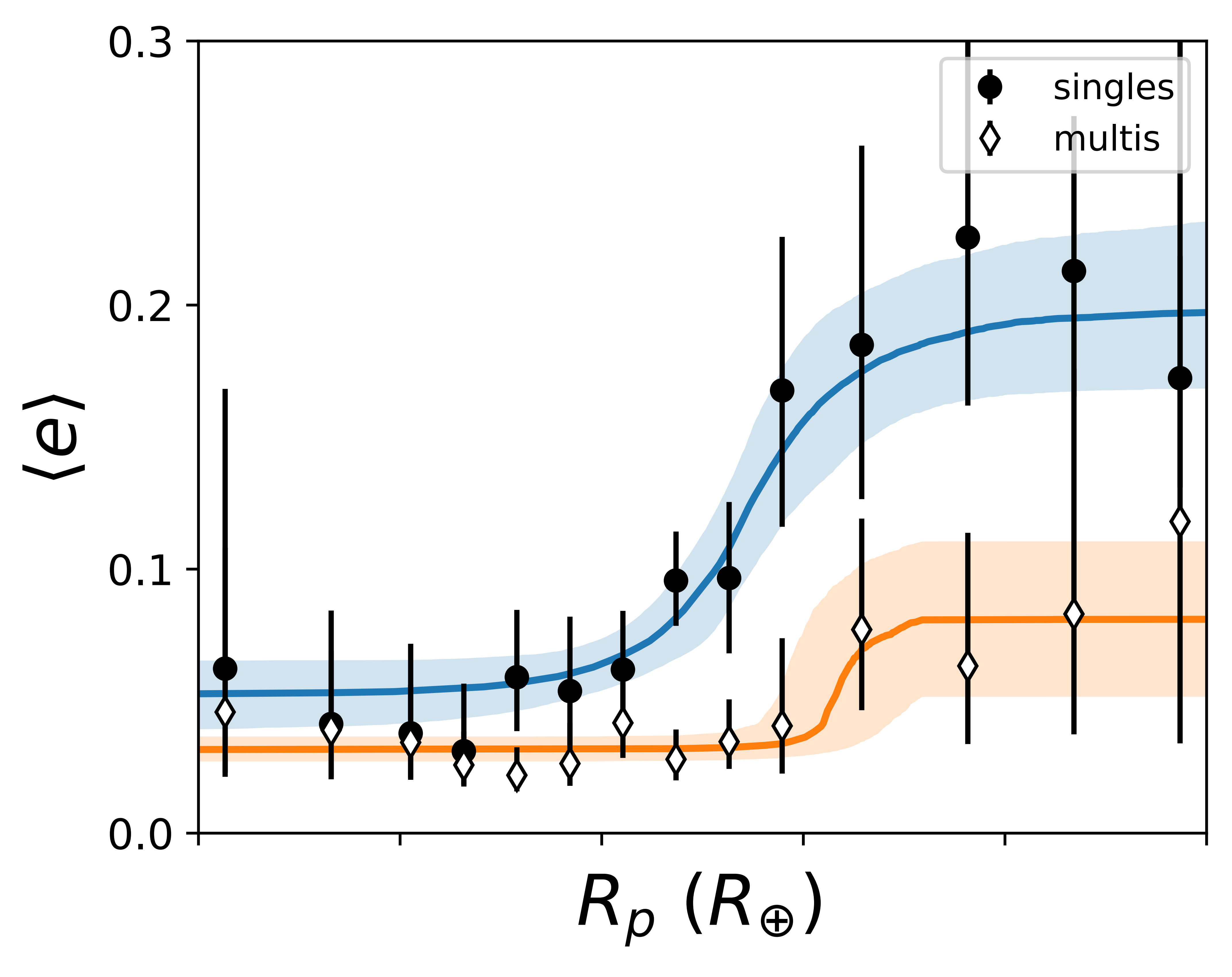


$\langle e \rangle_{\text{large}} \sim 0.2$

large planets have elevated $\langle e \rangle$

Gilbert, Petigura, & Entrican (*accepted to PNAS*)

Singles and **multis** have the same $\langle e \rangle - R_p$ relationship



← Singles

← Multis

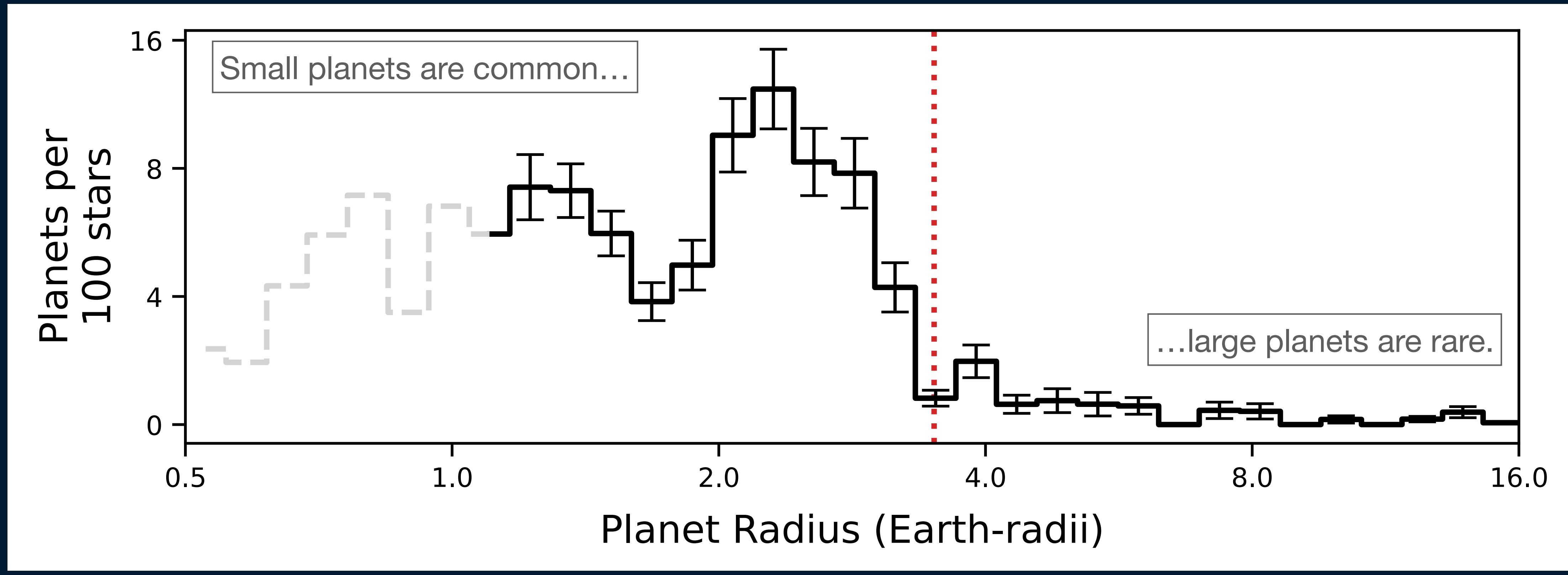
$$\boxed{\langle e \rangle_{\rm singles} / \langle e \rangle_{\rm multis} \approx 2.5}$$

Gilbert, Petigura, & Entrican (*accepted to PNAS*)

The population of small planets is demographically distinct compared to the population of large planets

The population of small planets is demographically distinct compared to the population of large planets

Common



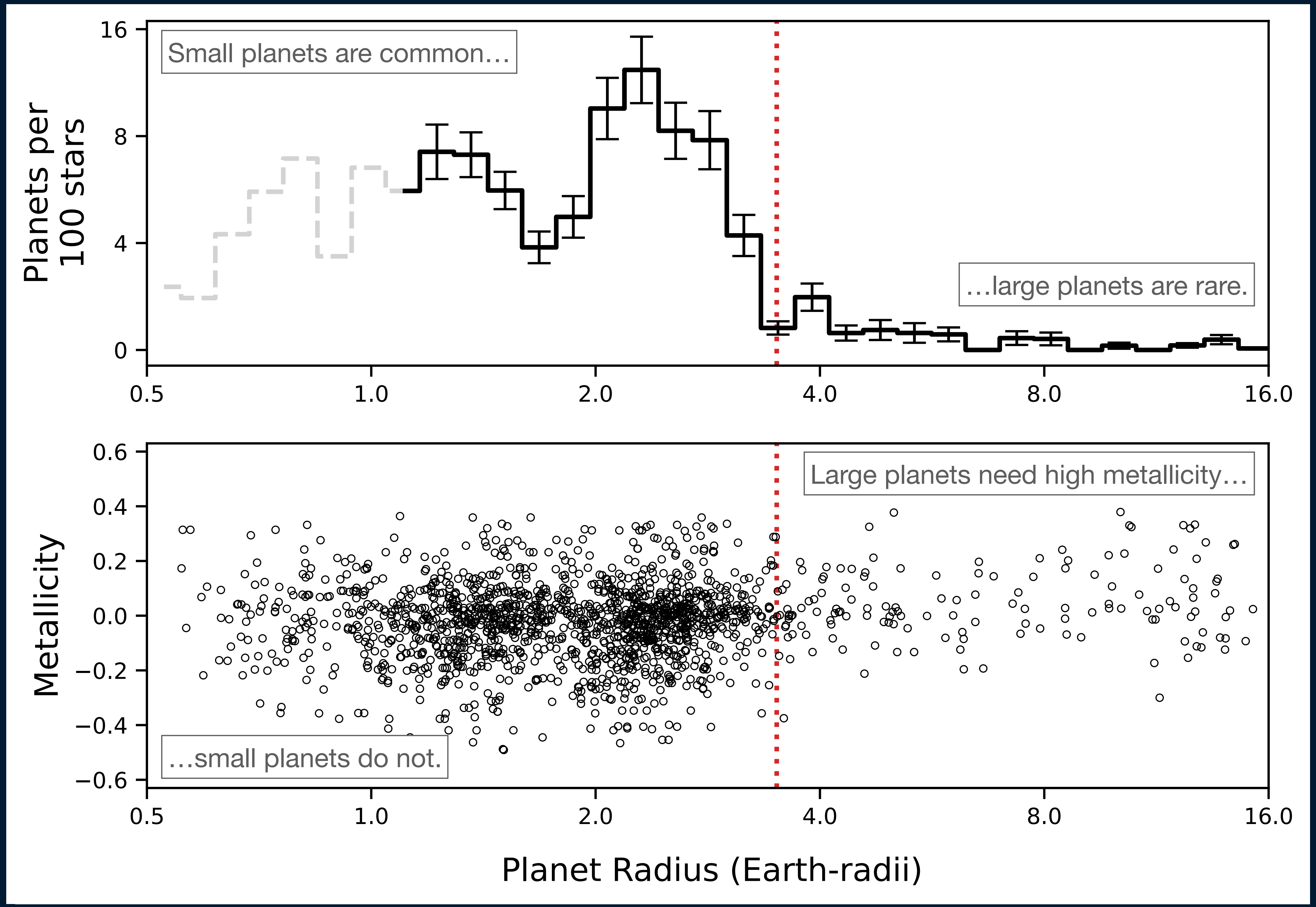
Rare

Fulton et. al (2017), Fulton & Petigura (2018)

The population of small planets is demographically distinct compared to the population of large planets

Common

No [Fe/H] dependance



Buchhave et al. (2012)

Rare

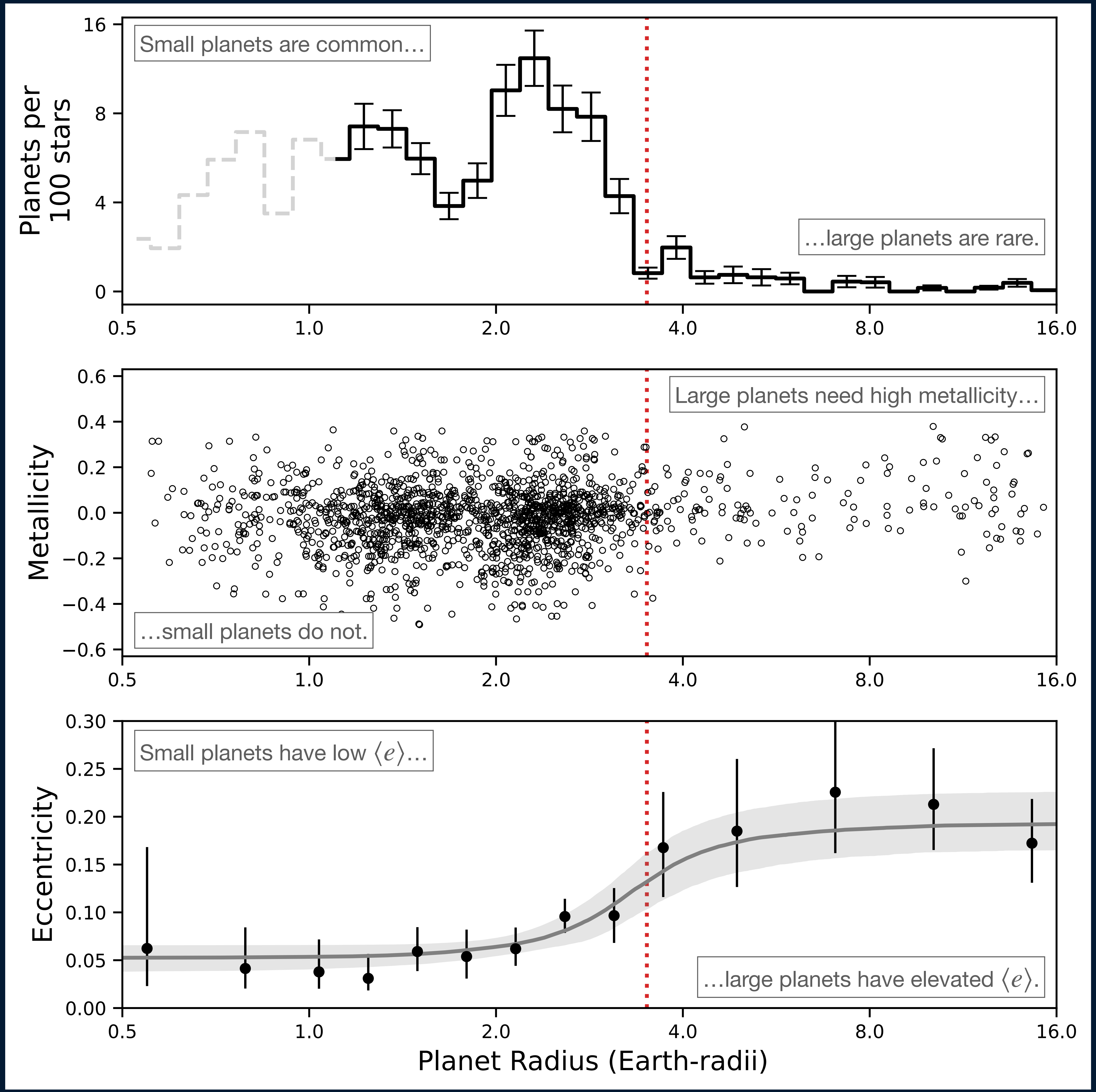
High [Fe/H] host stars

The population of small planets is demographically distinct compared to the population of large planets

Common

No [Fe/H] dependance

Low $\langle e \rangle$



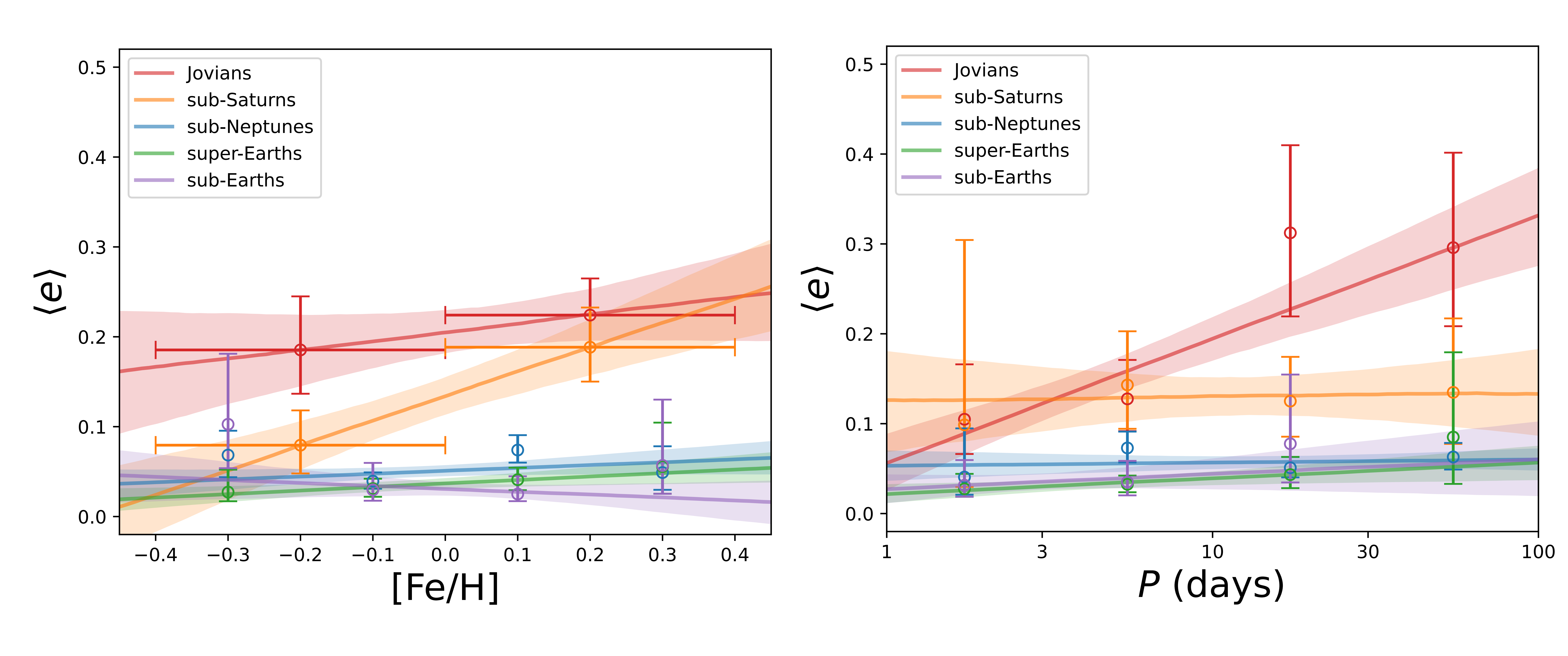
Rare

High [Fe/H] host stars

Elevated $\langle e \rangle$

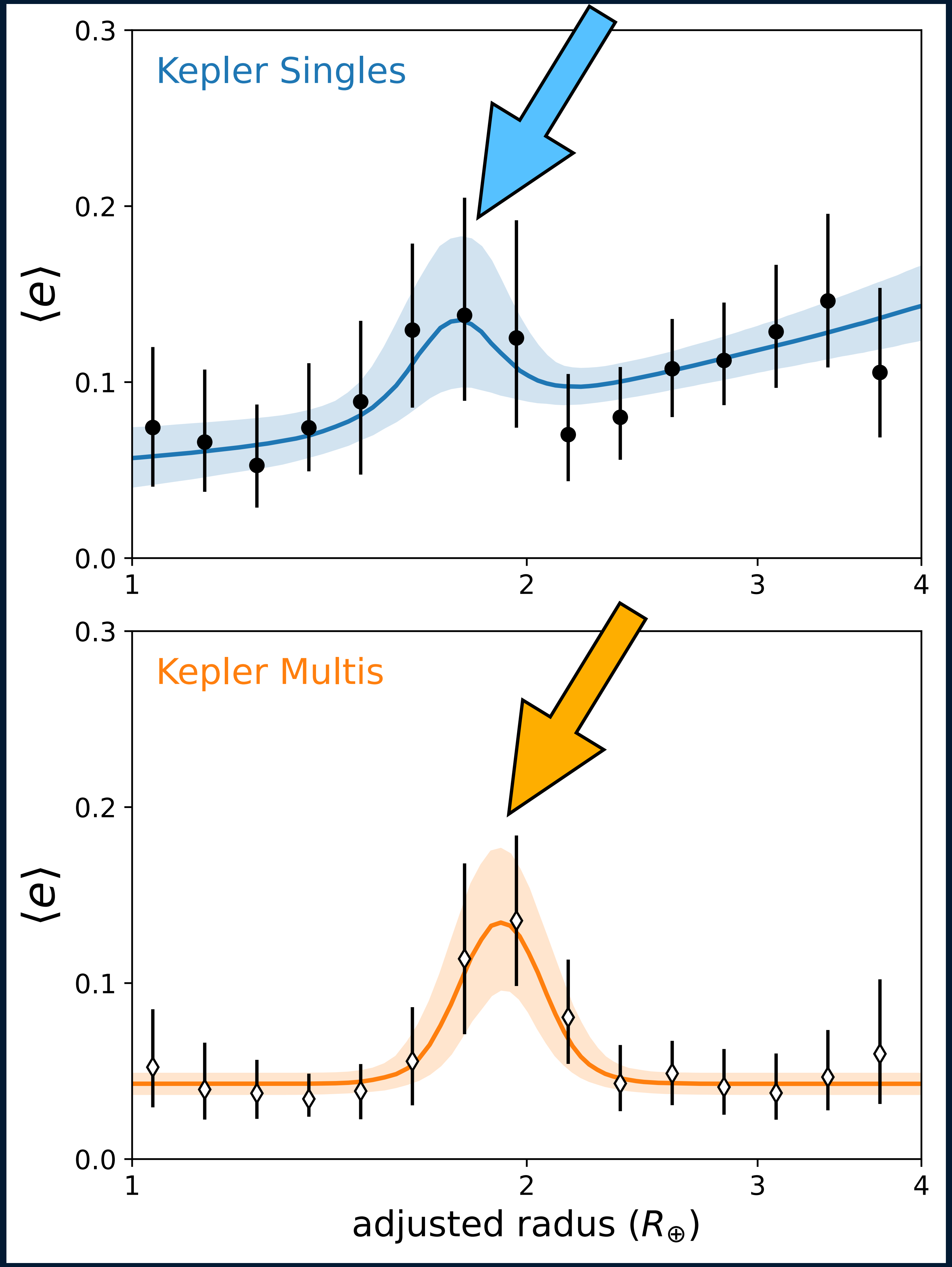
Gilbert, Petigura, & Entrican (*accepted to PNAS*)

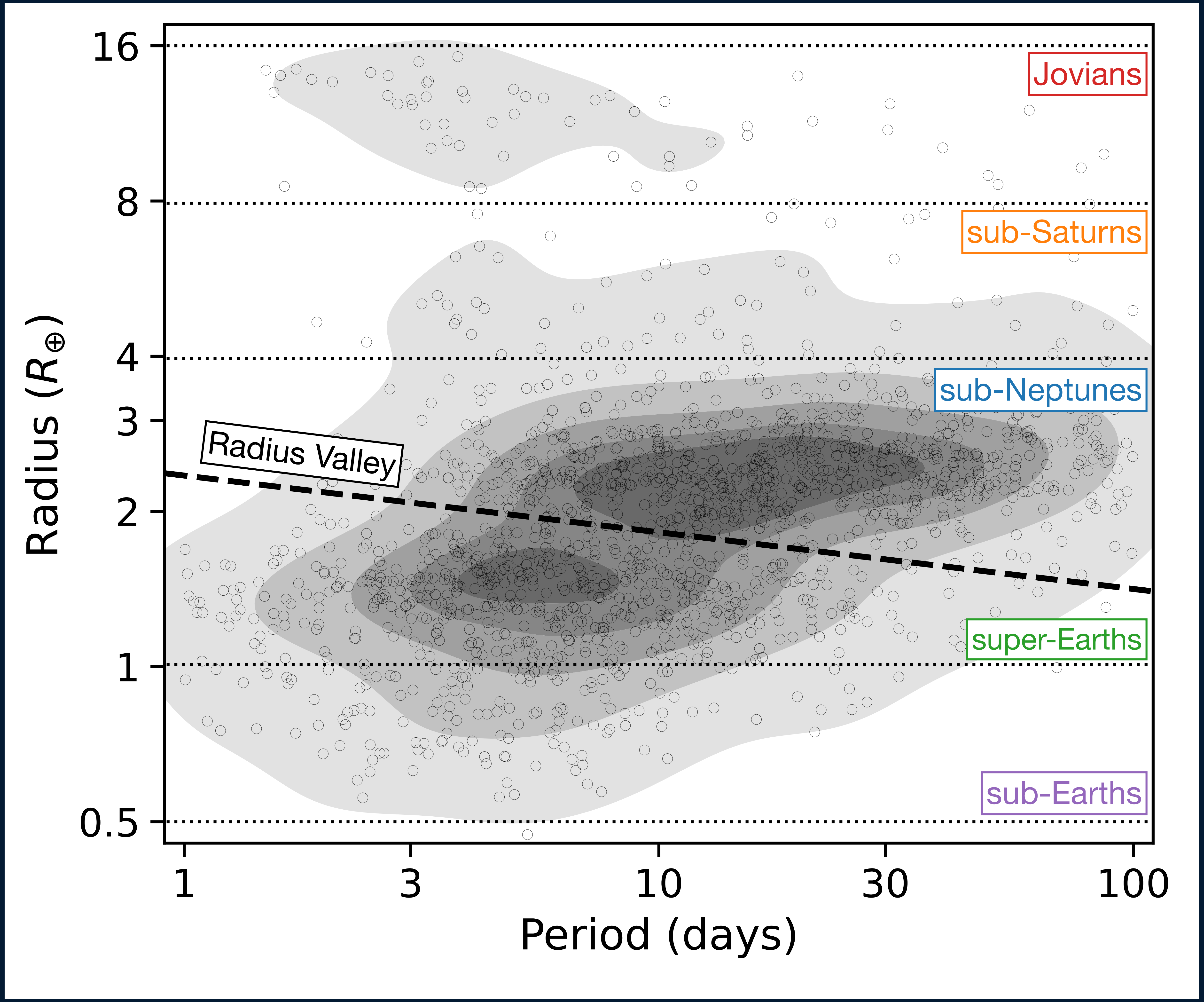
Eccentricity as a function of period and metallicity



Gilbert, Petigura, & Entrican (*accepted to PNAS*)

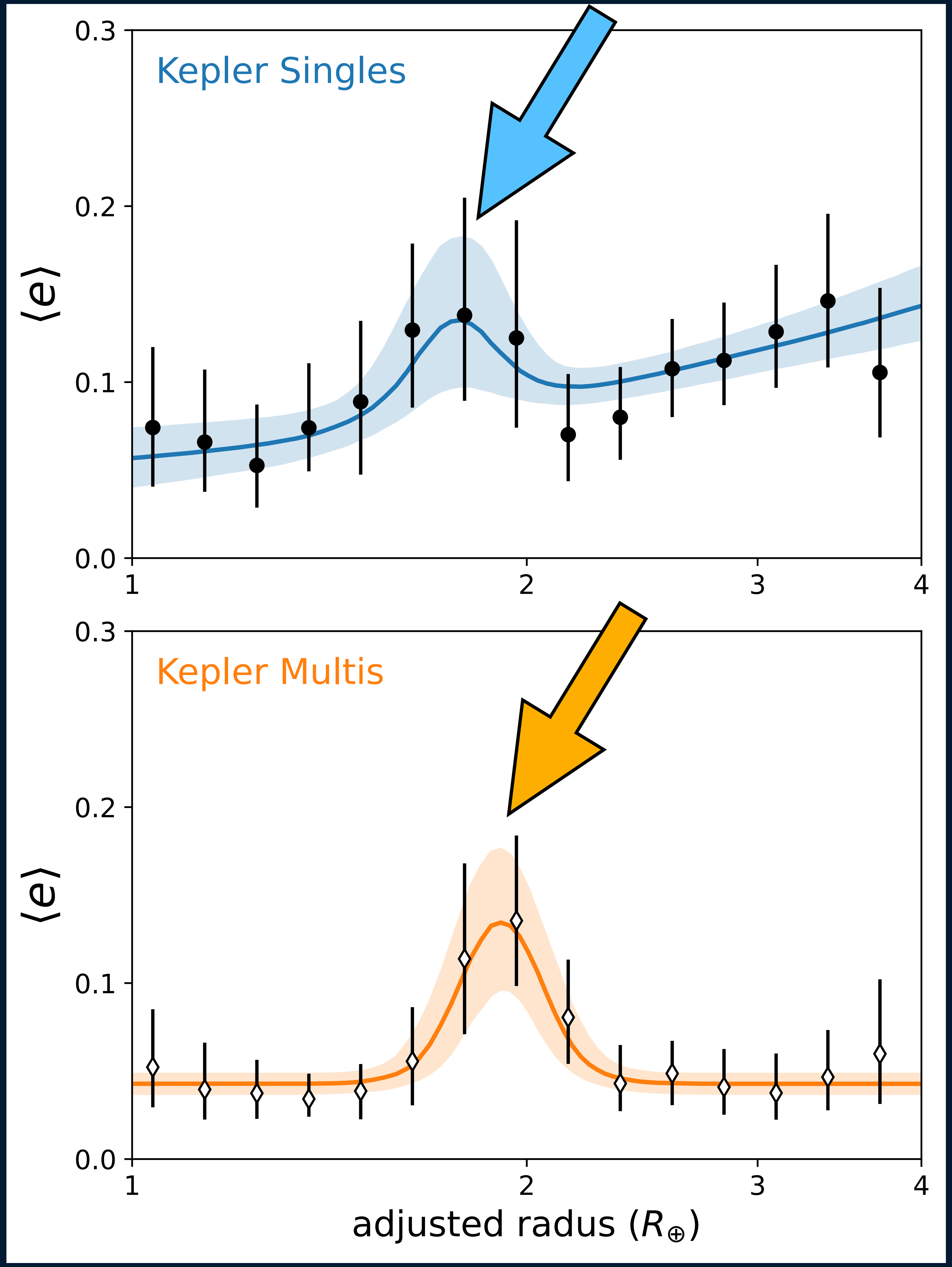
There is an eccentricity peak in the radius valley





Gilbert, Petigura, & Entrican (*accepted to PNAS*)

What causes the eccentricity peak in the radius valley?



Hypothesis #1: Measurement Error

TTVs?

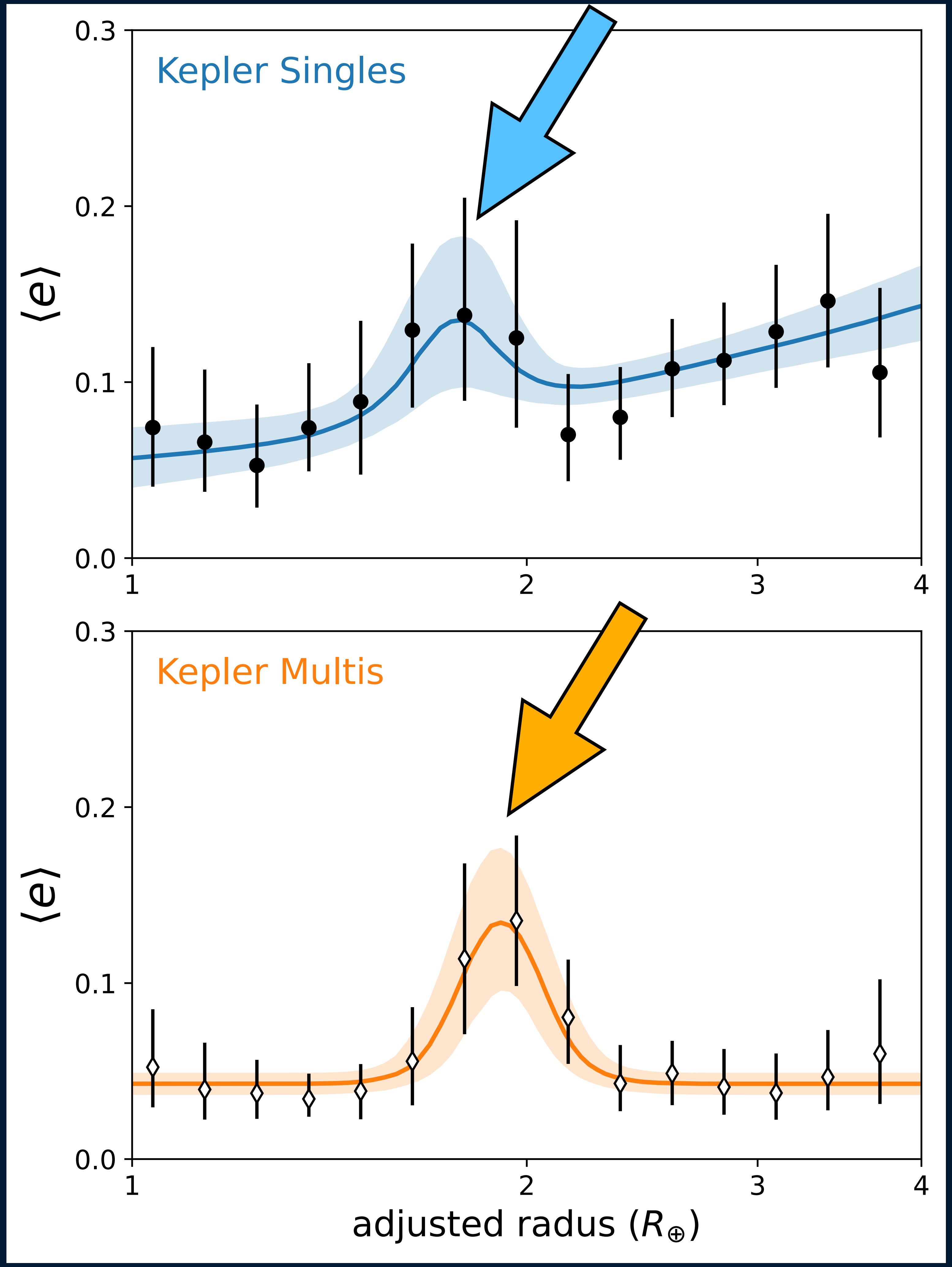
Flux contamination?

Sampler convergence?

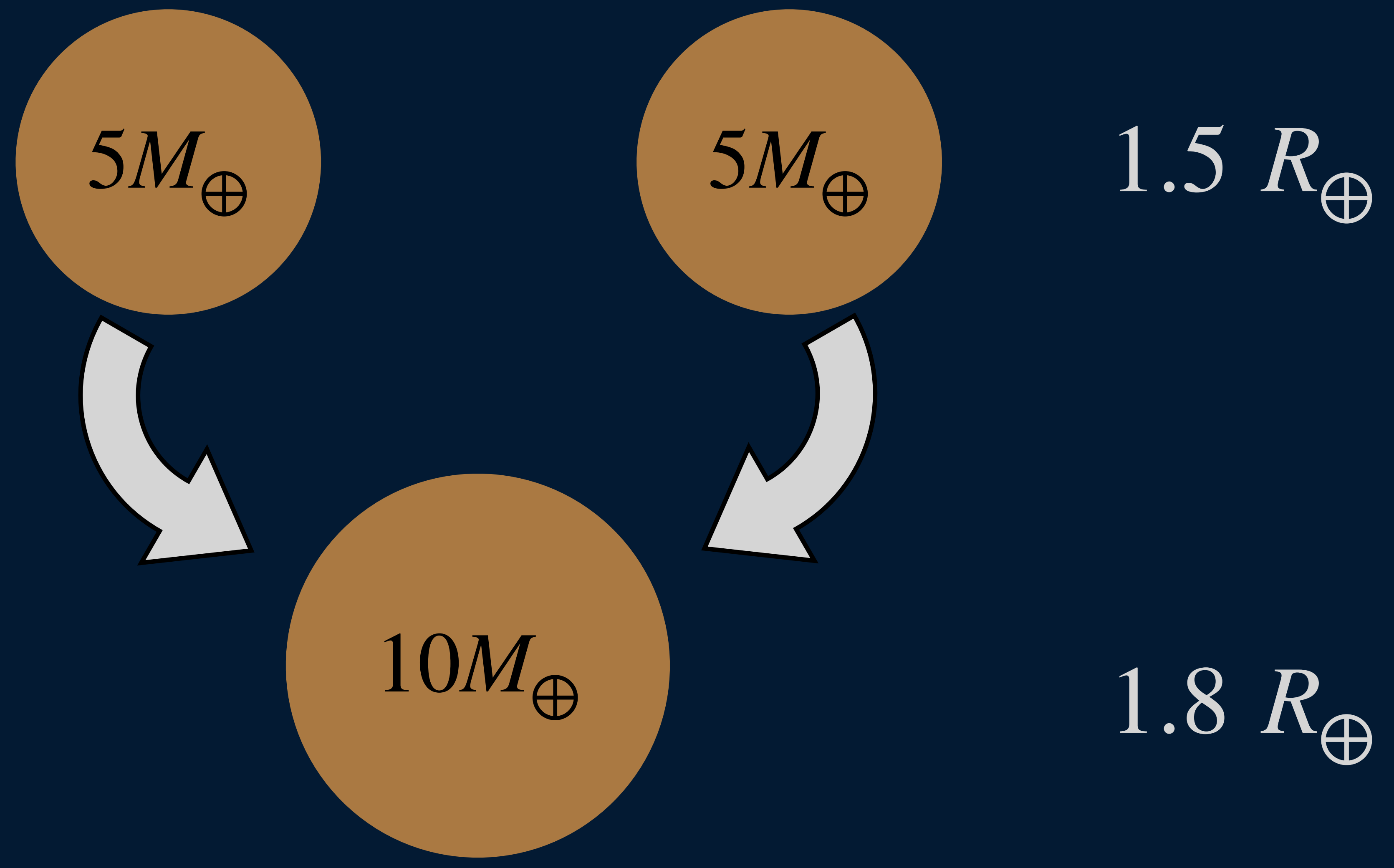
Photometric detrending?

Gilbert, Petigura, & Entrican (*accepted to PNAS*)

What causes the eccentricity peak in the radius valley?

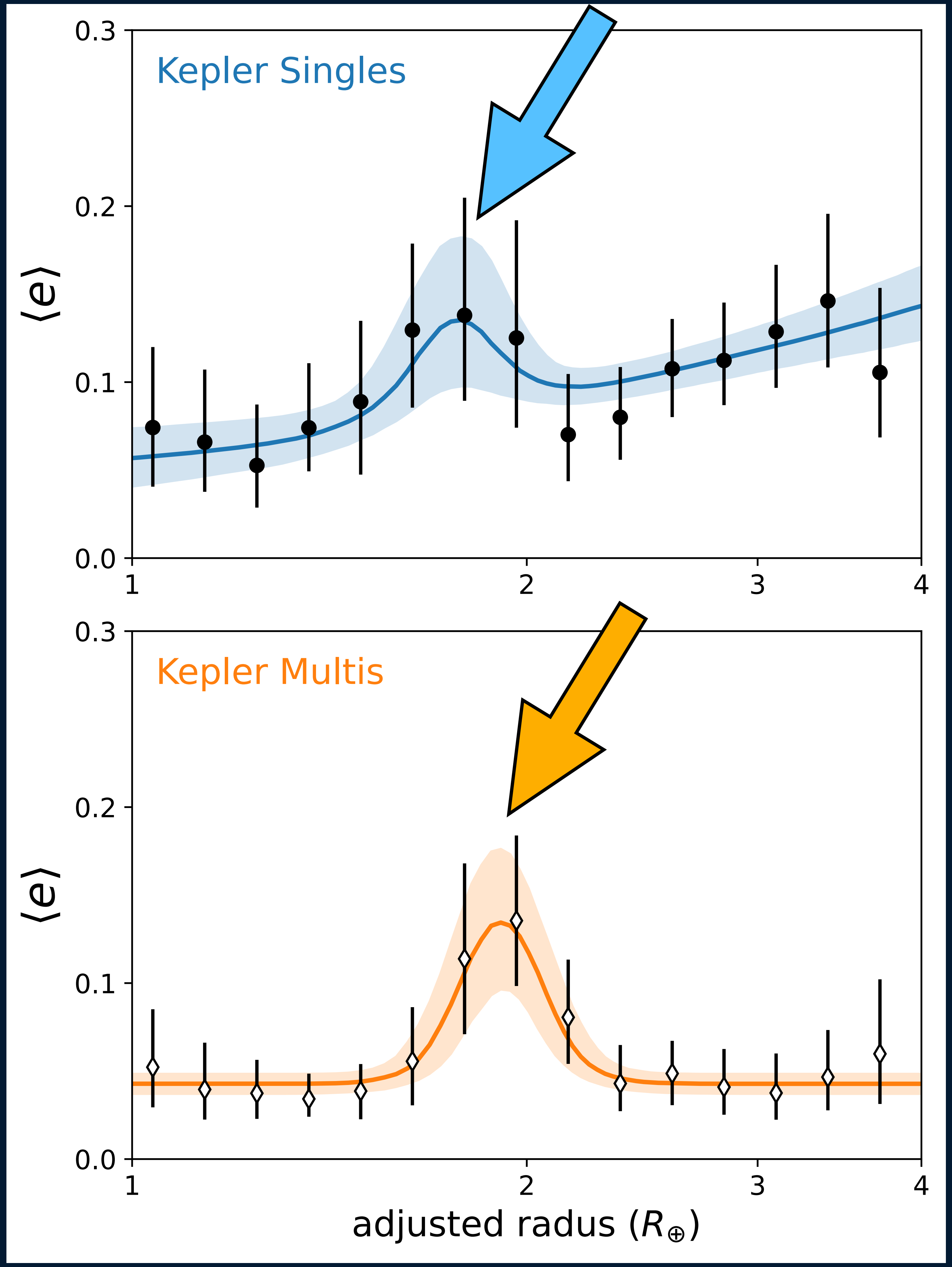


Hypothesis #2a: Mergers

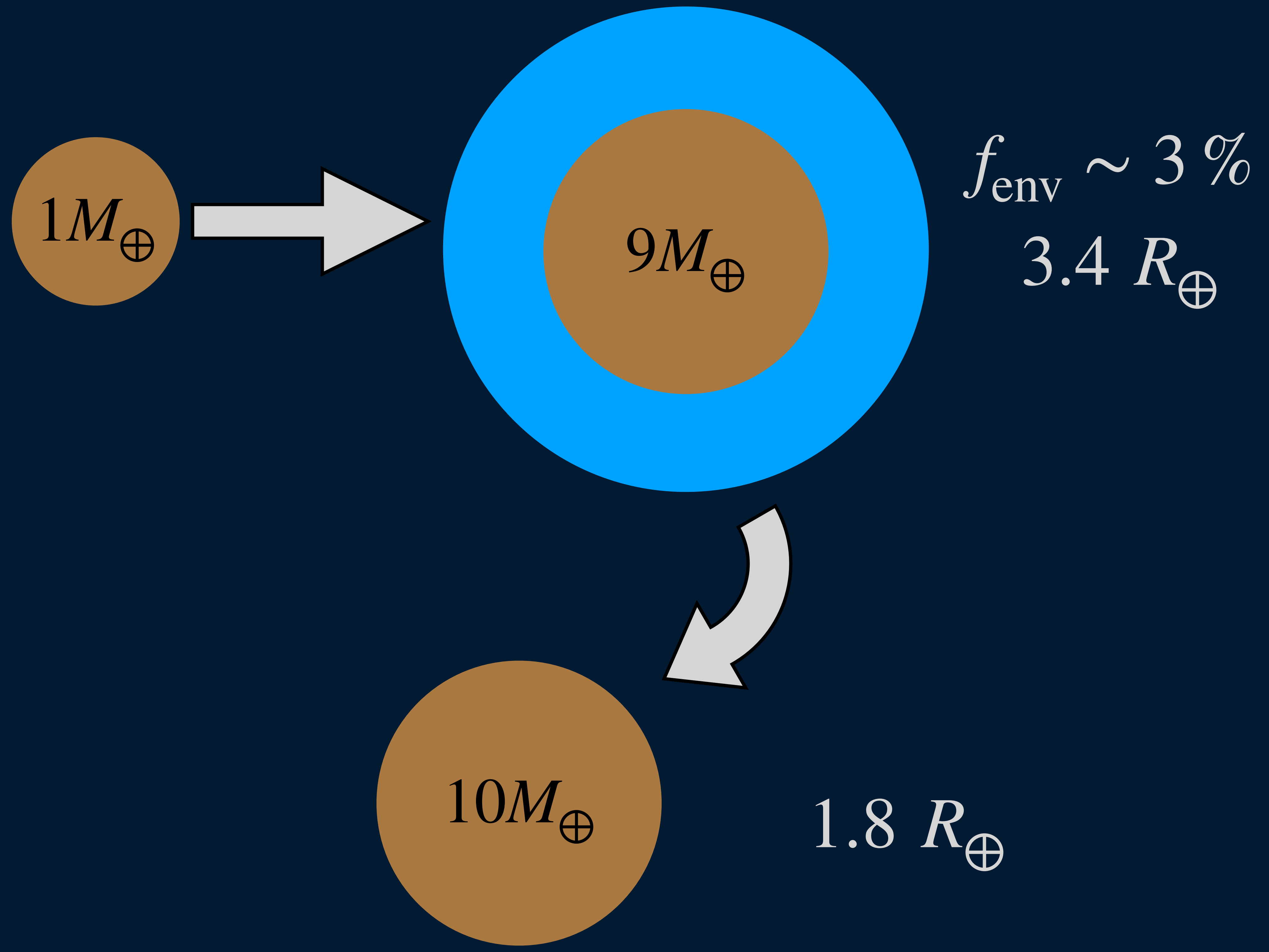


Gilbert, Petigura, & Entrican (*accepted to PNAS*)

What causes the eccentricity peak in the radius valley?

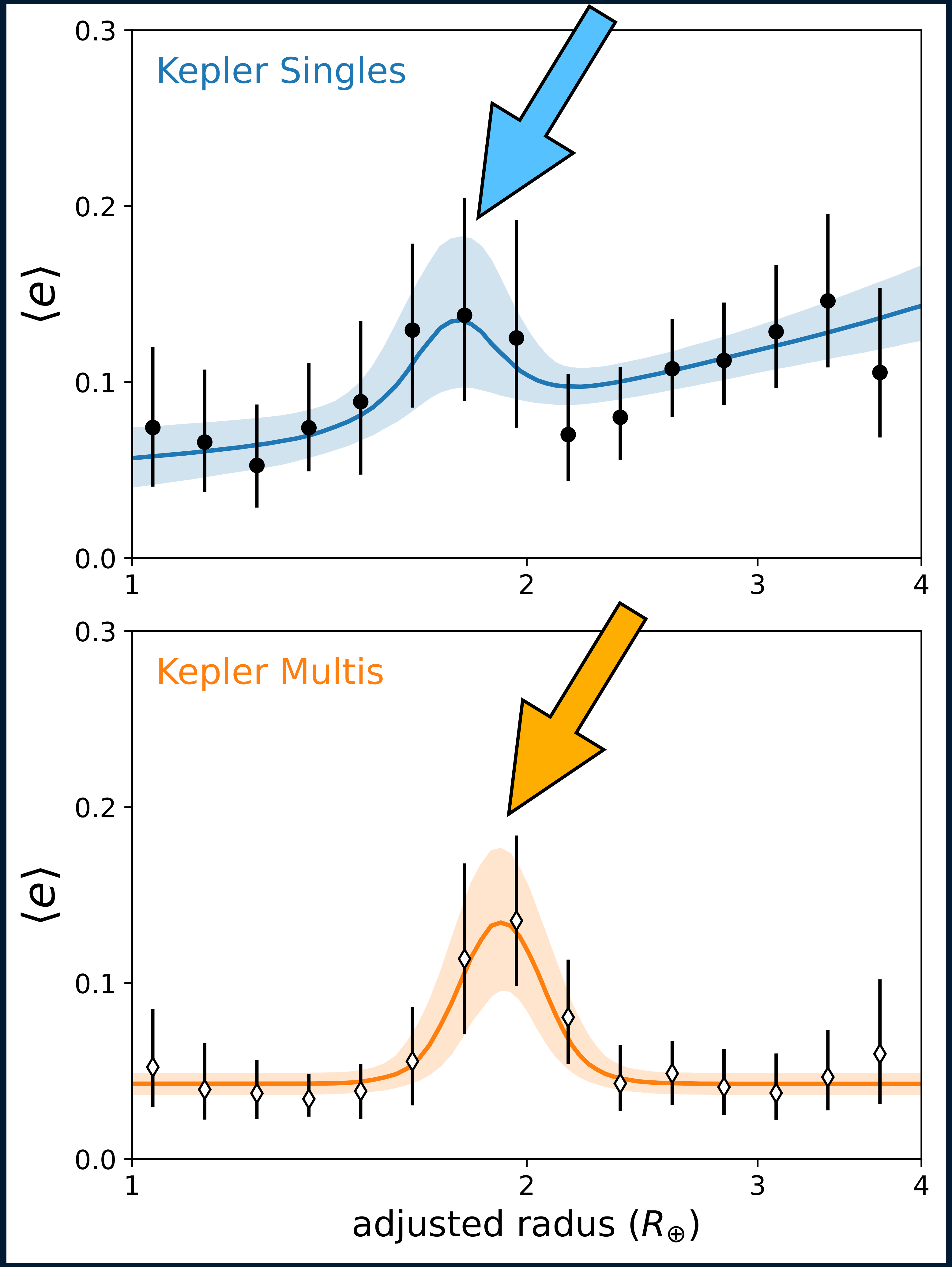


Hypothesis #2b: Atmospheric Stripping



Gilbert, Petigura, & Entrican (*accepted to PNAS*)

What causes the eccentricity peak in the radius valley?



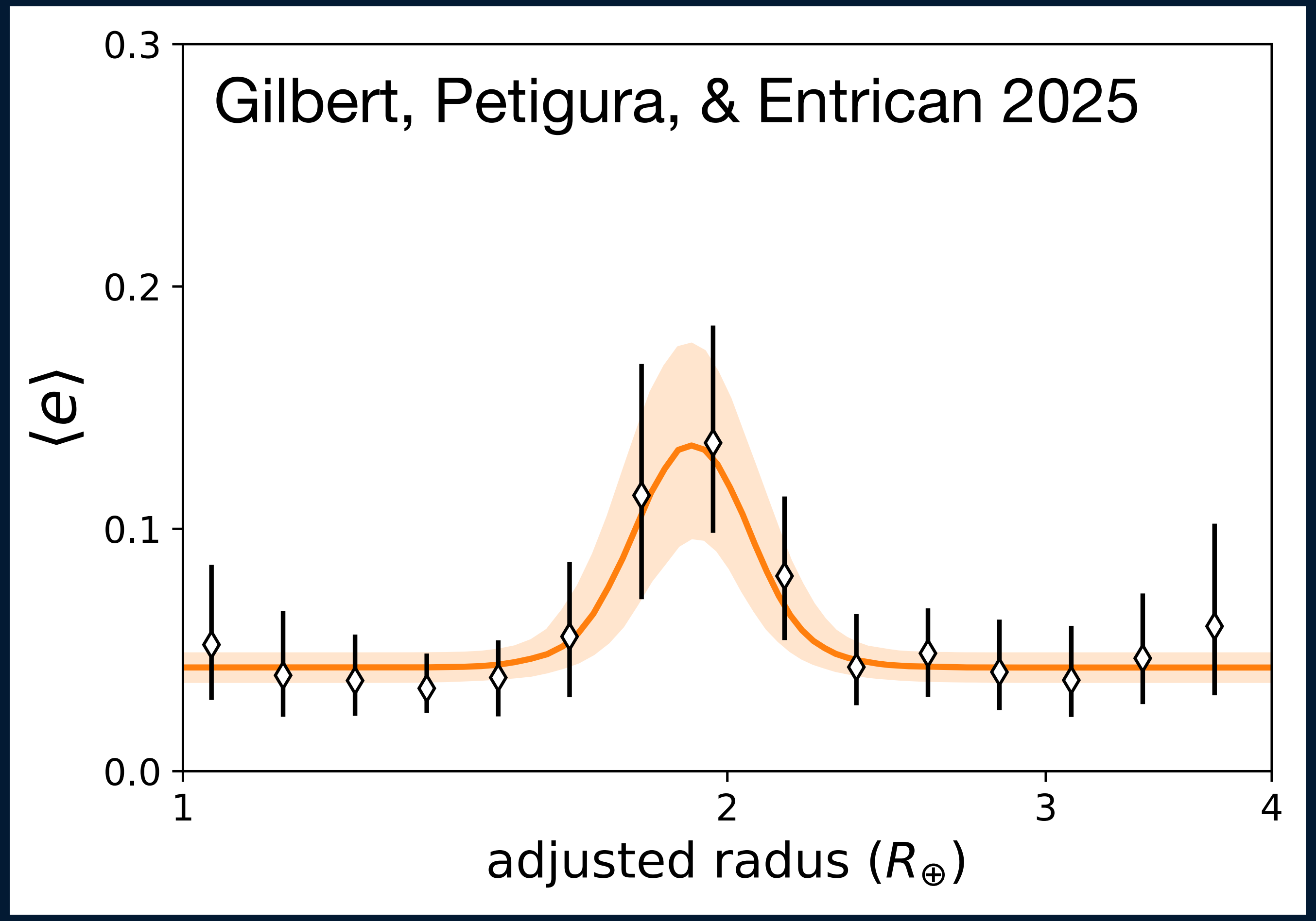
Hypothesis #3: Any Ideas?

Please, let's speculate

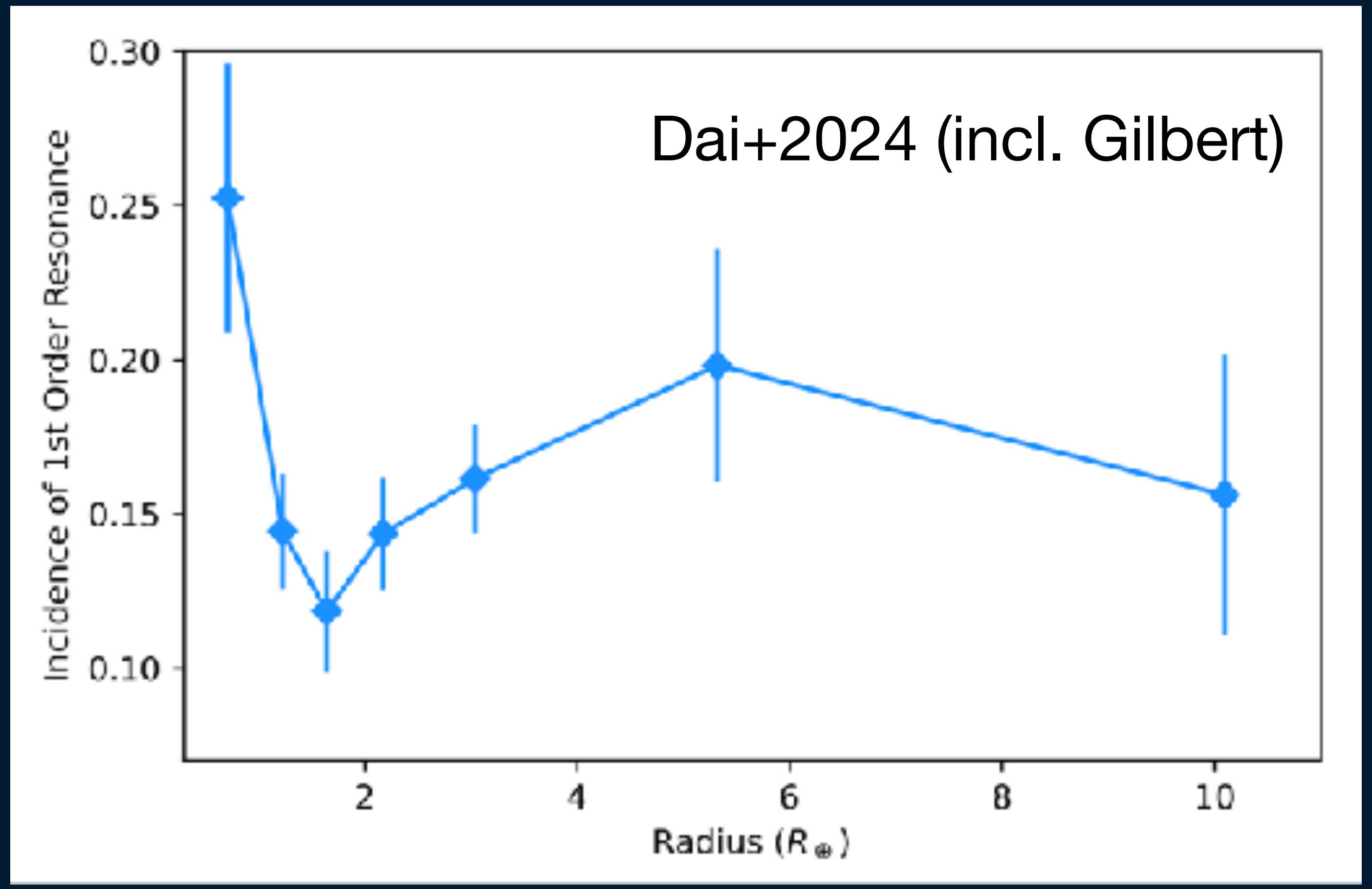
Gilbert, Petigura, & Entrican (*accepted to PNAS*)

Planets in the radius gap are weird

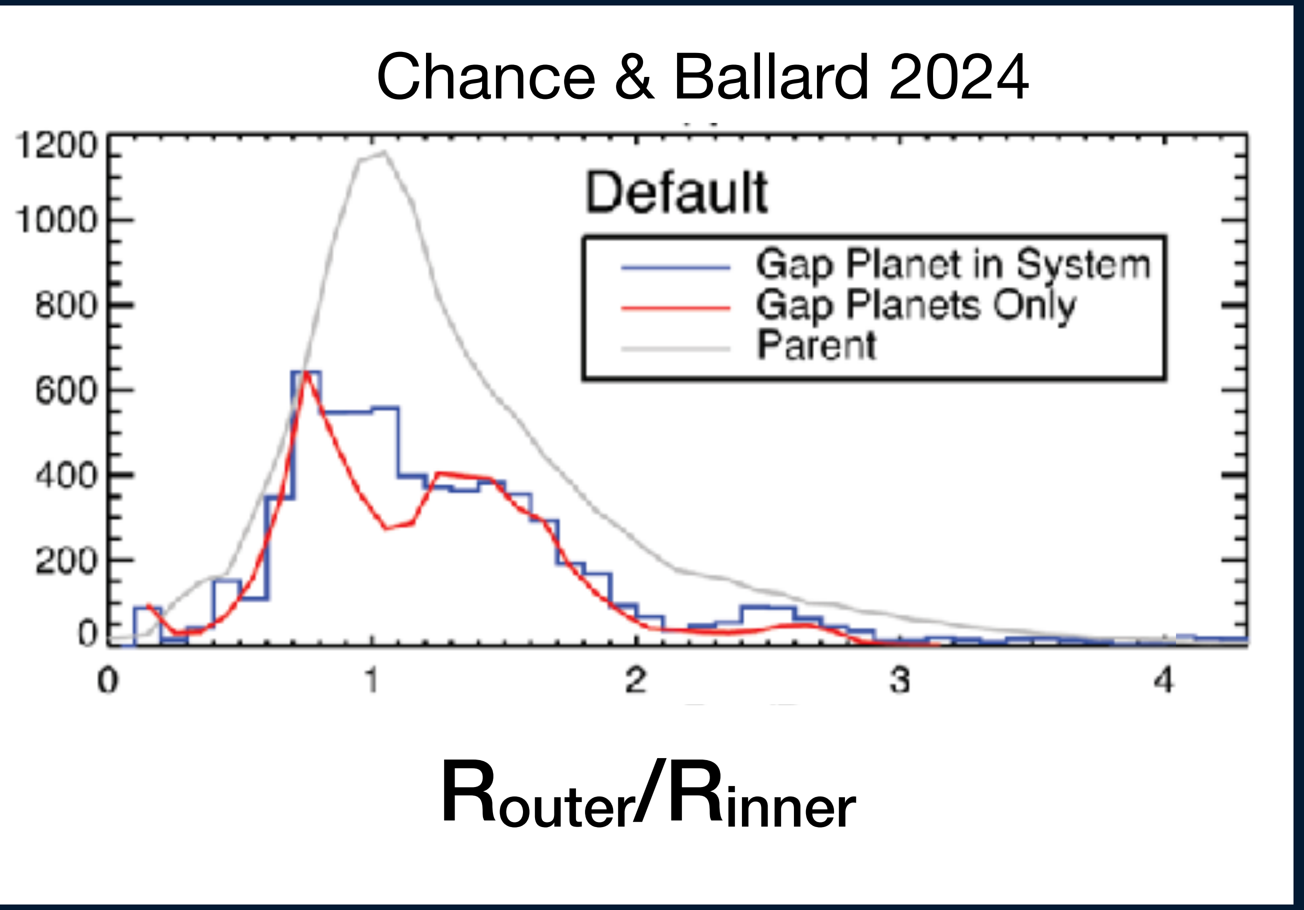
Elevated Eccentricity



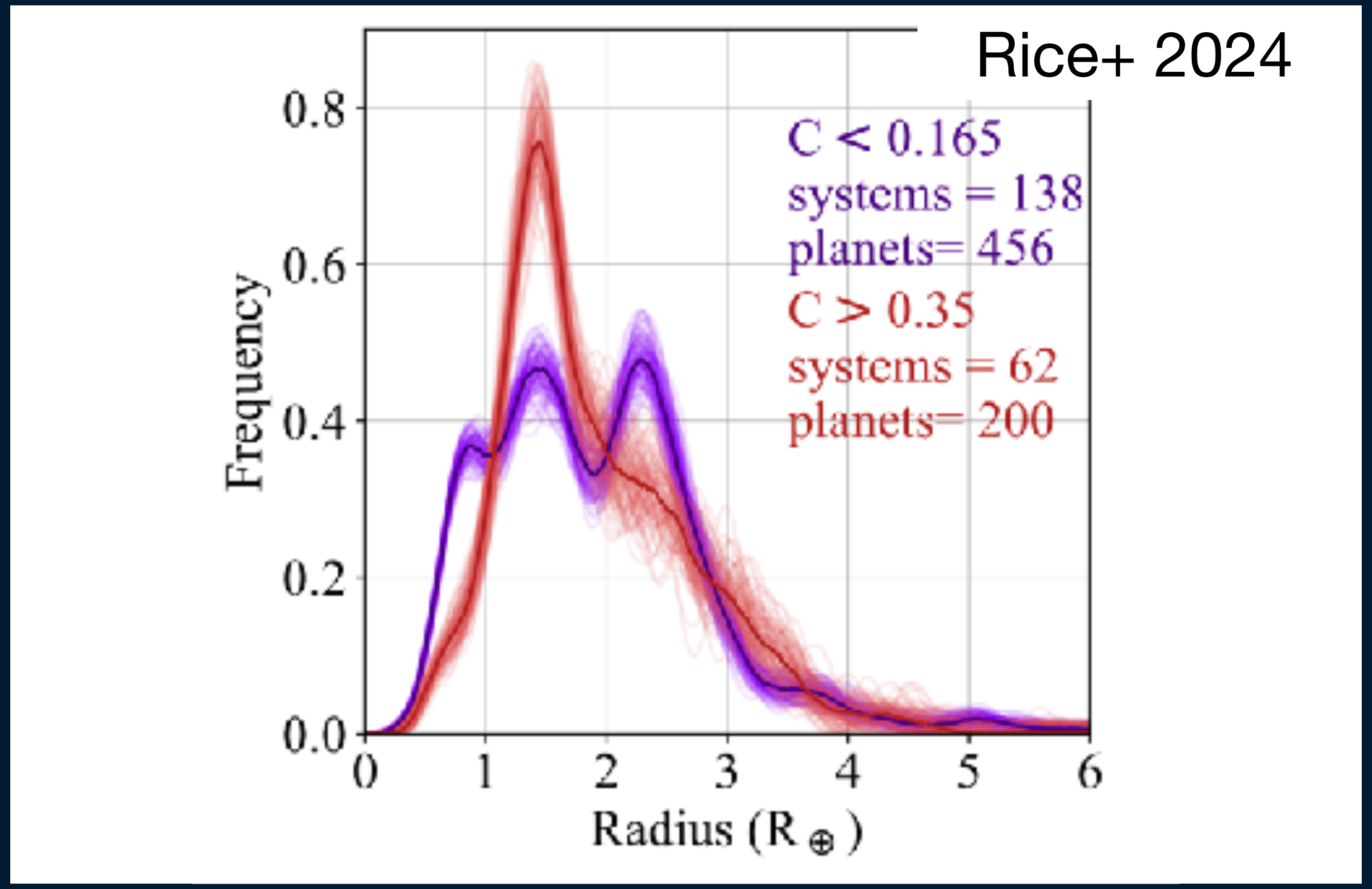
Fewer Resonances



Non-uniform sizes



High Gap Complexity



The emerging picture of planet formation

- Planets form on nearly circular orbits, perhaps in or near mean motion resonance
- High metallicity raises likelihood of forming giant planets
- Systems with giant planets experience greater dynamical excitation
- Atmospheric mass loss driven by XUV radiation erodes H/He atmospheres of sub-Neptunes, creating the radius gap
- Some sub-Neptunes experience giant impacts, which strip atmospheres and populates the radius gap

Next steps — eccentricity as a function of…

Stellar properties: $M_\star$, T_{eff}, $[\mathrm{Fe/H}]$

Mutual inclinations

Period ratios

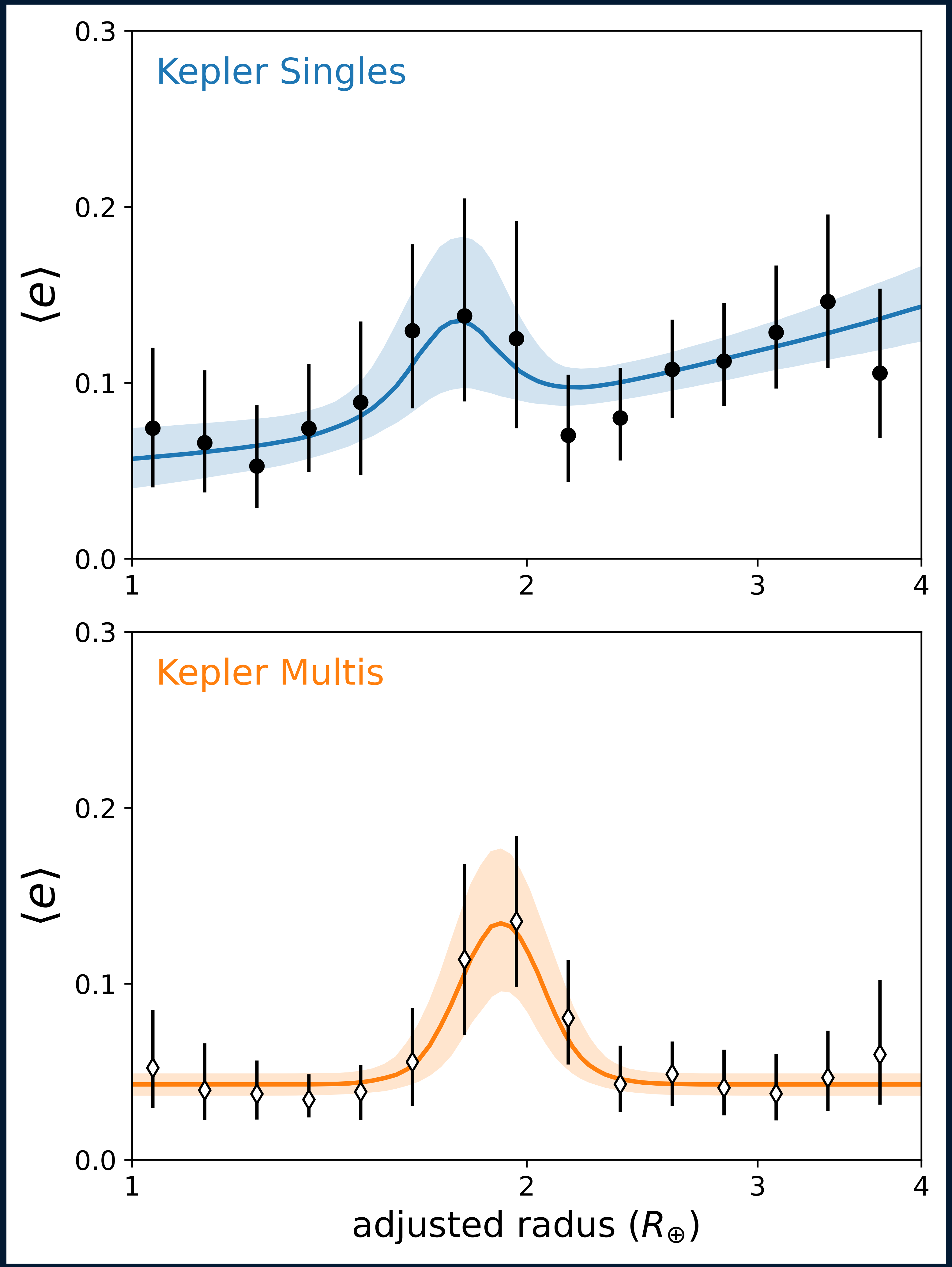
Architectural complexity

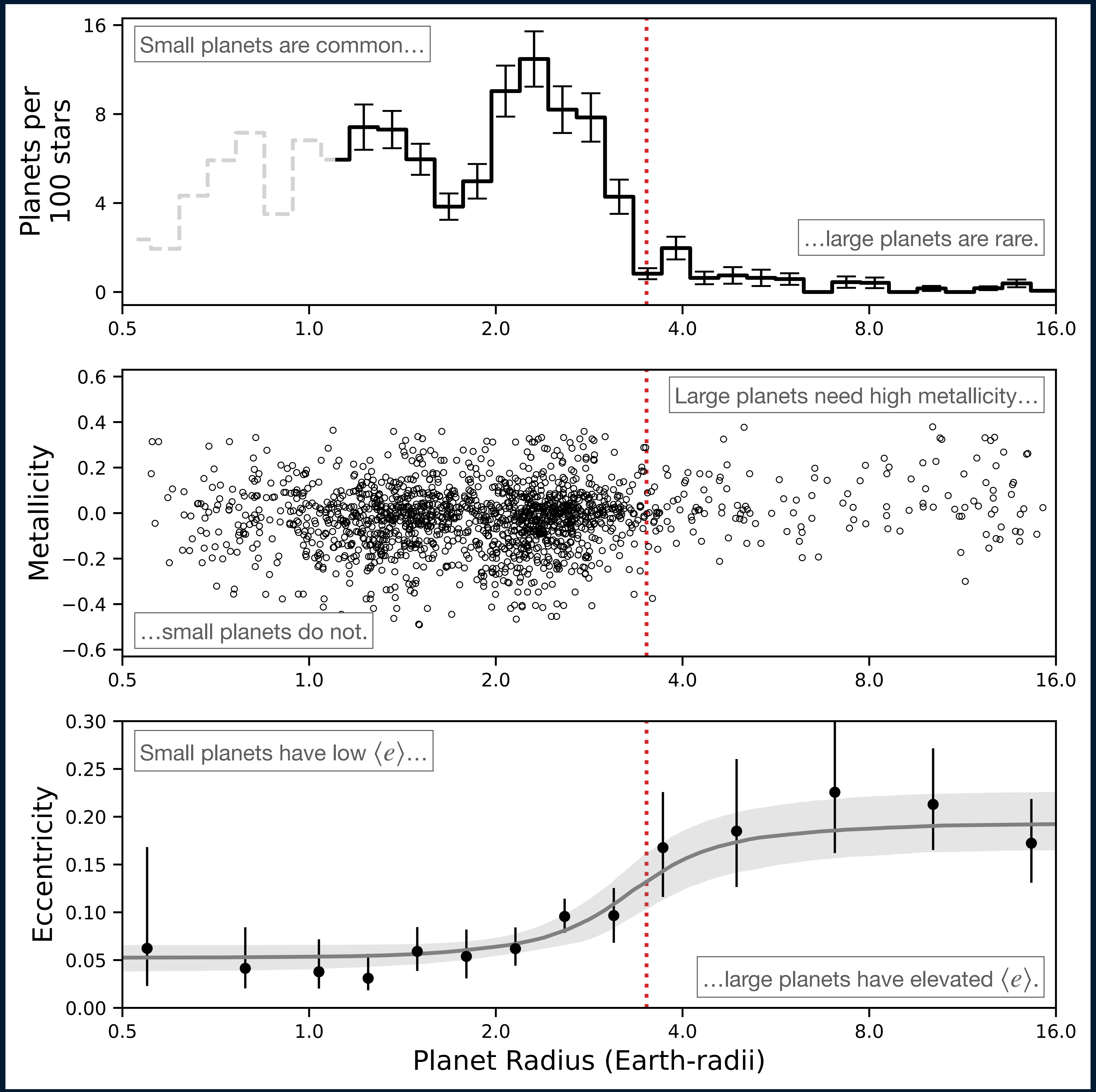
System multiplicity

Outer companion status

And more!

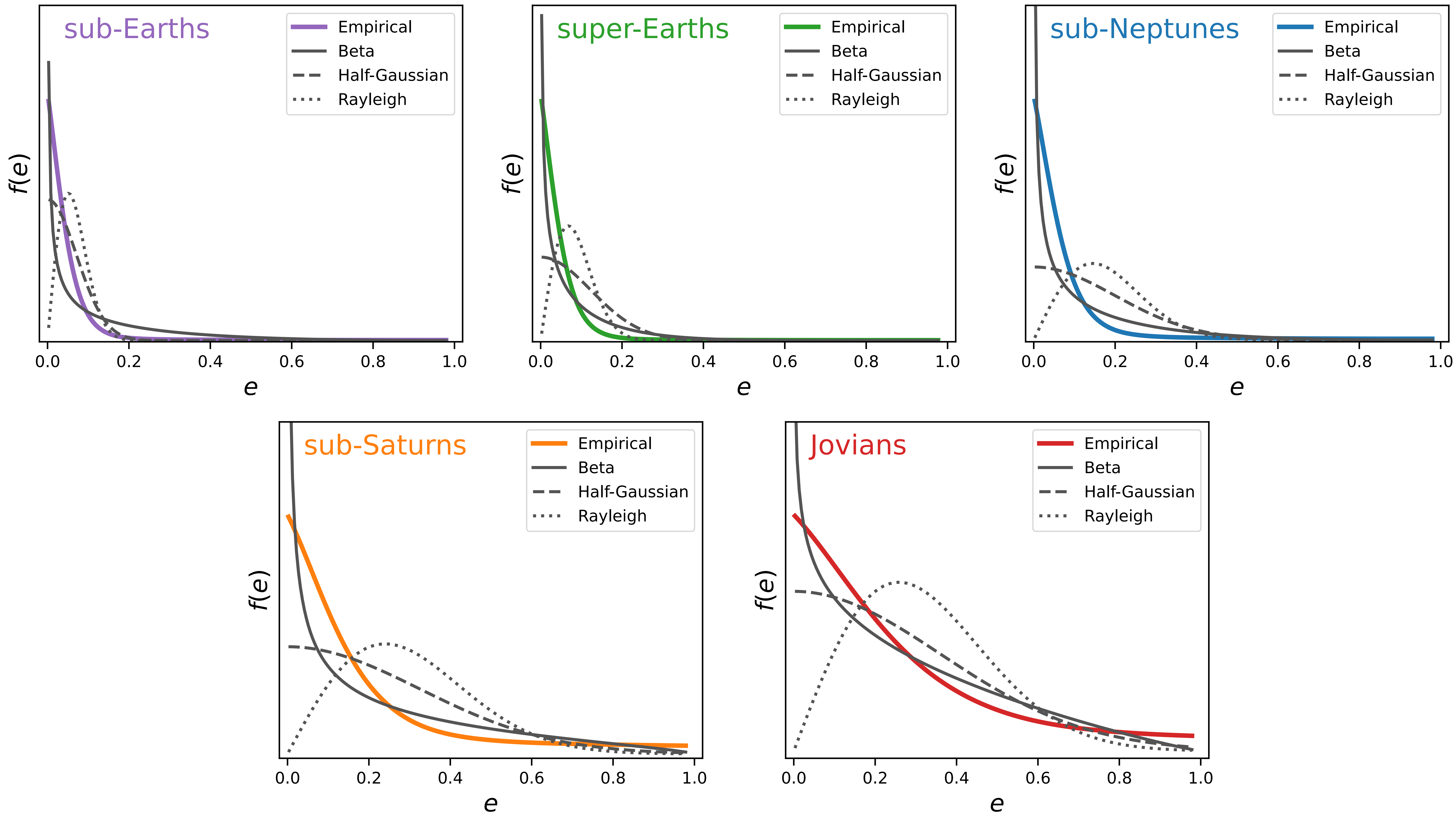
Eccentricity (and soon inclination) demographics point the way toward better planet formation models



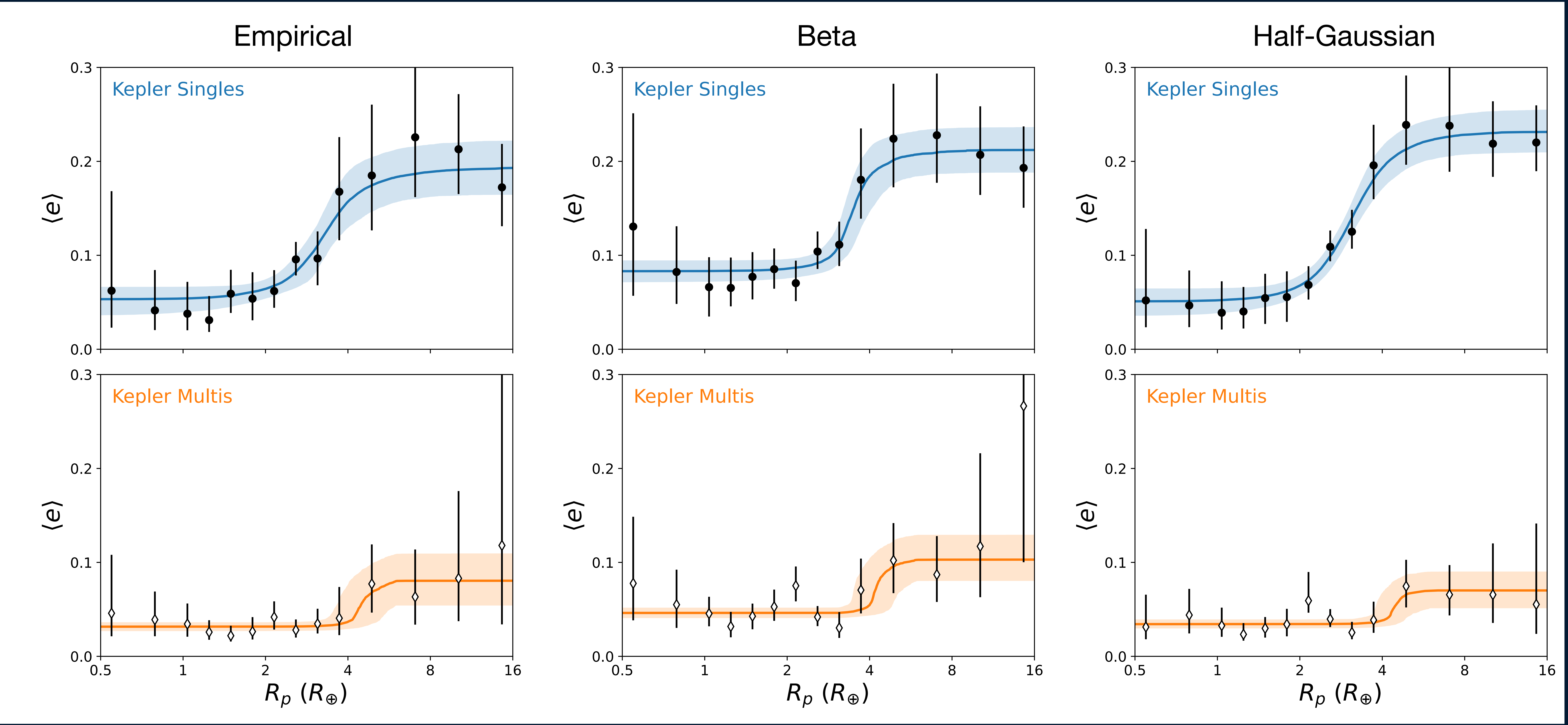


Gilbert, Petigura, & Entrican (*accepted to PNAS*)

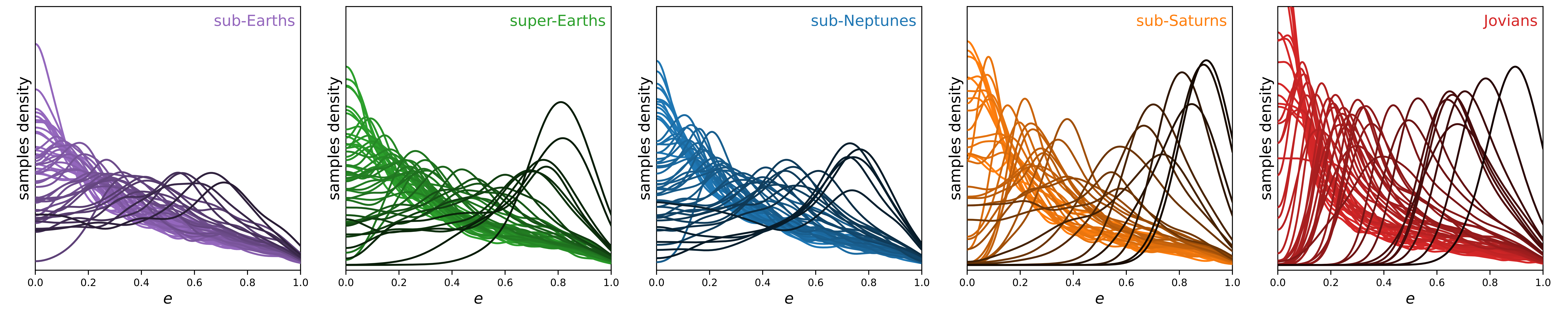
EXTRA SLIDES



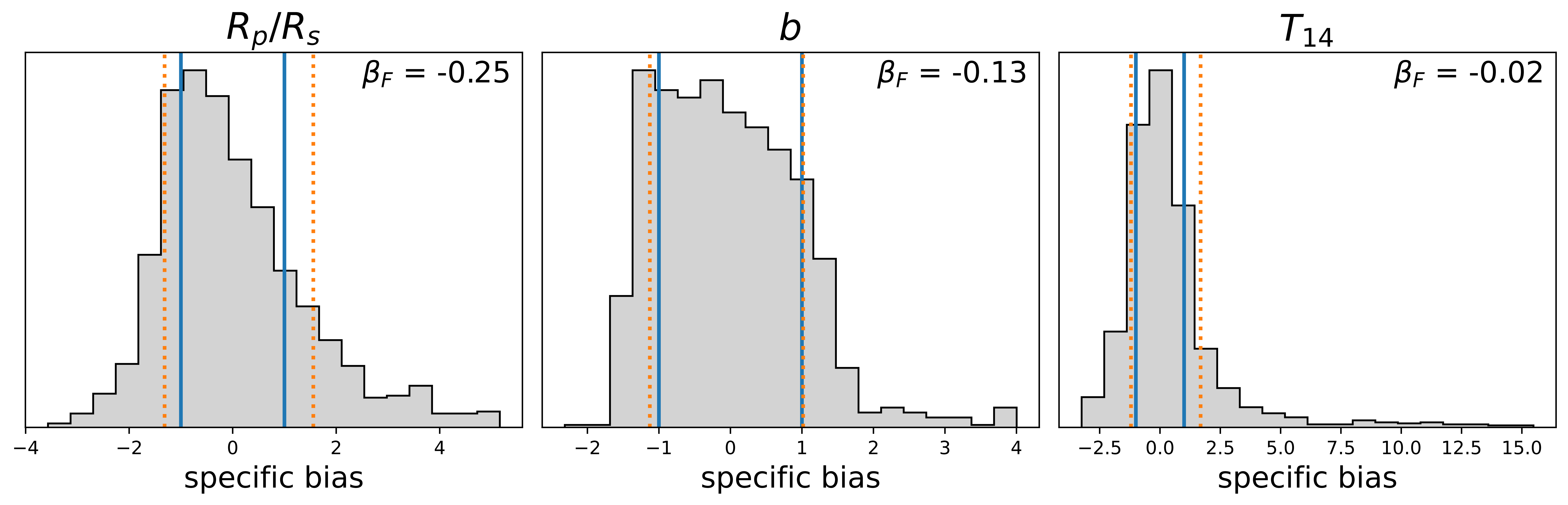
Gilbert & Petigura (*in review*)



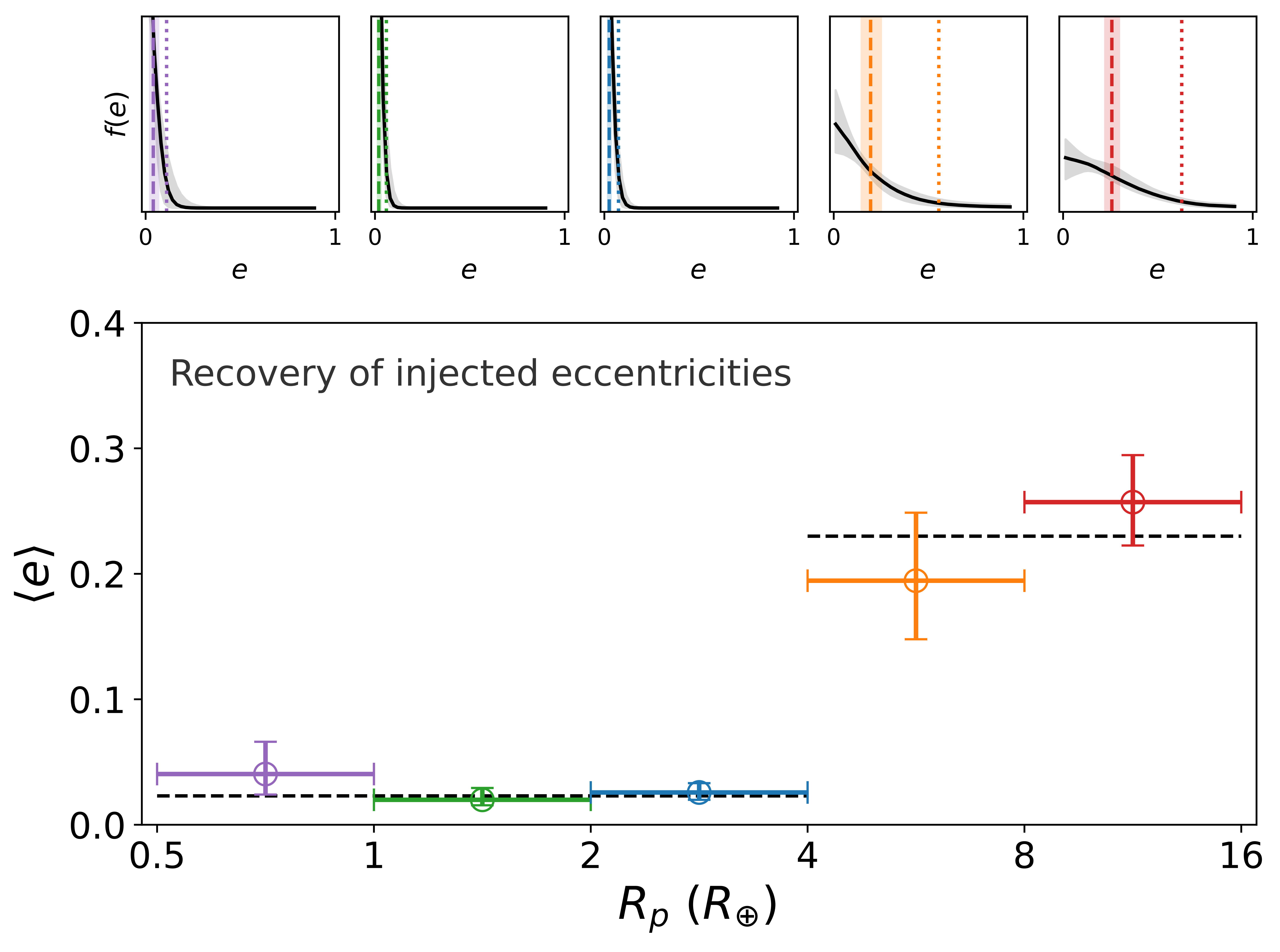
Gilbert, Petigura, & Entrican (*in review*)

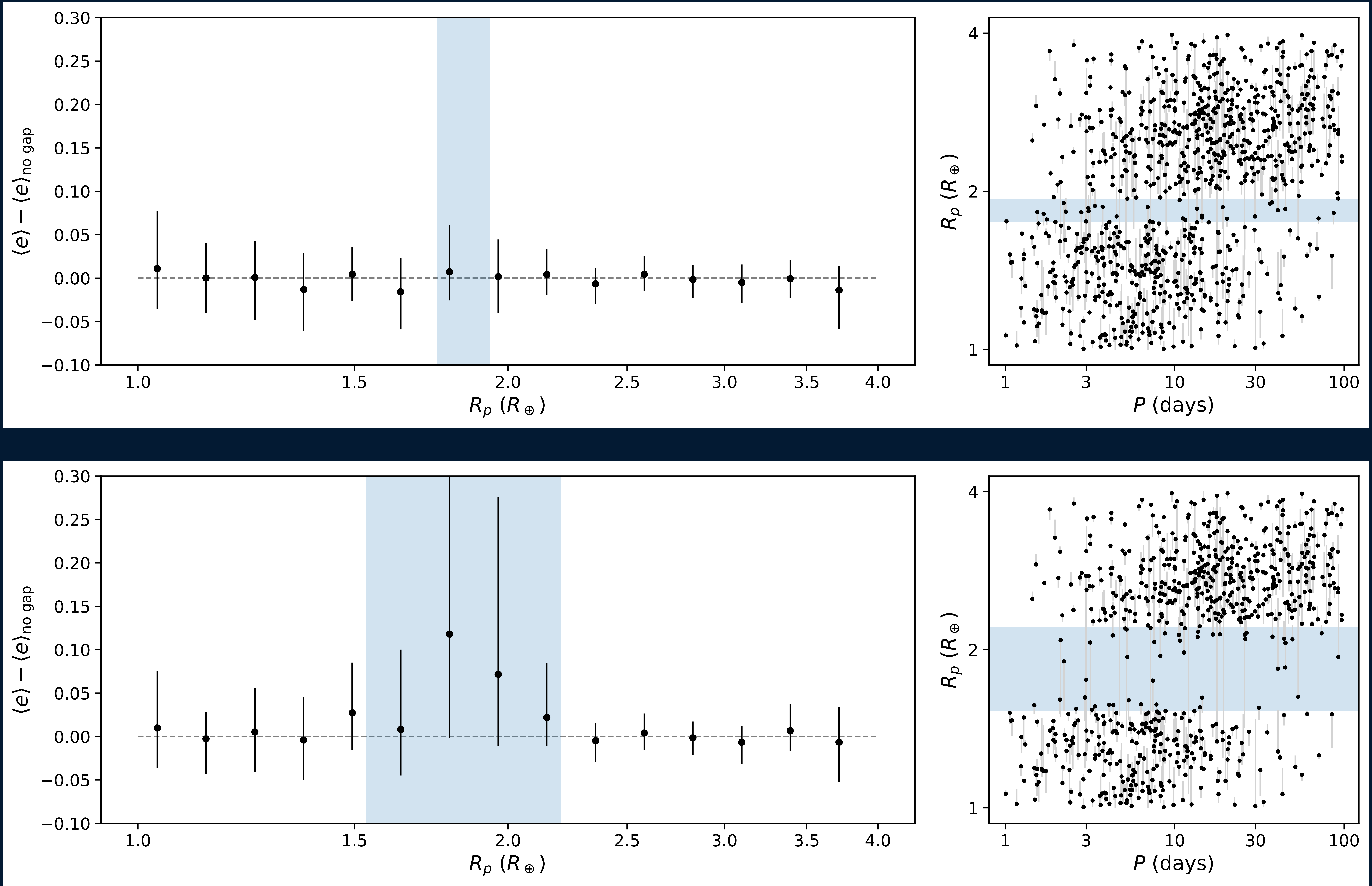


Gilbert & Petigura (*in review*)



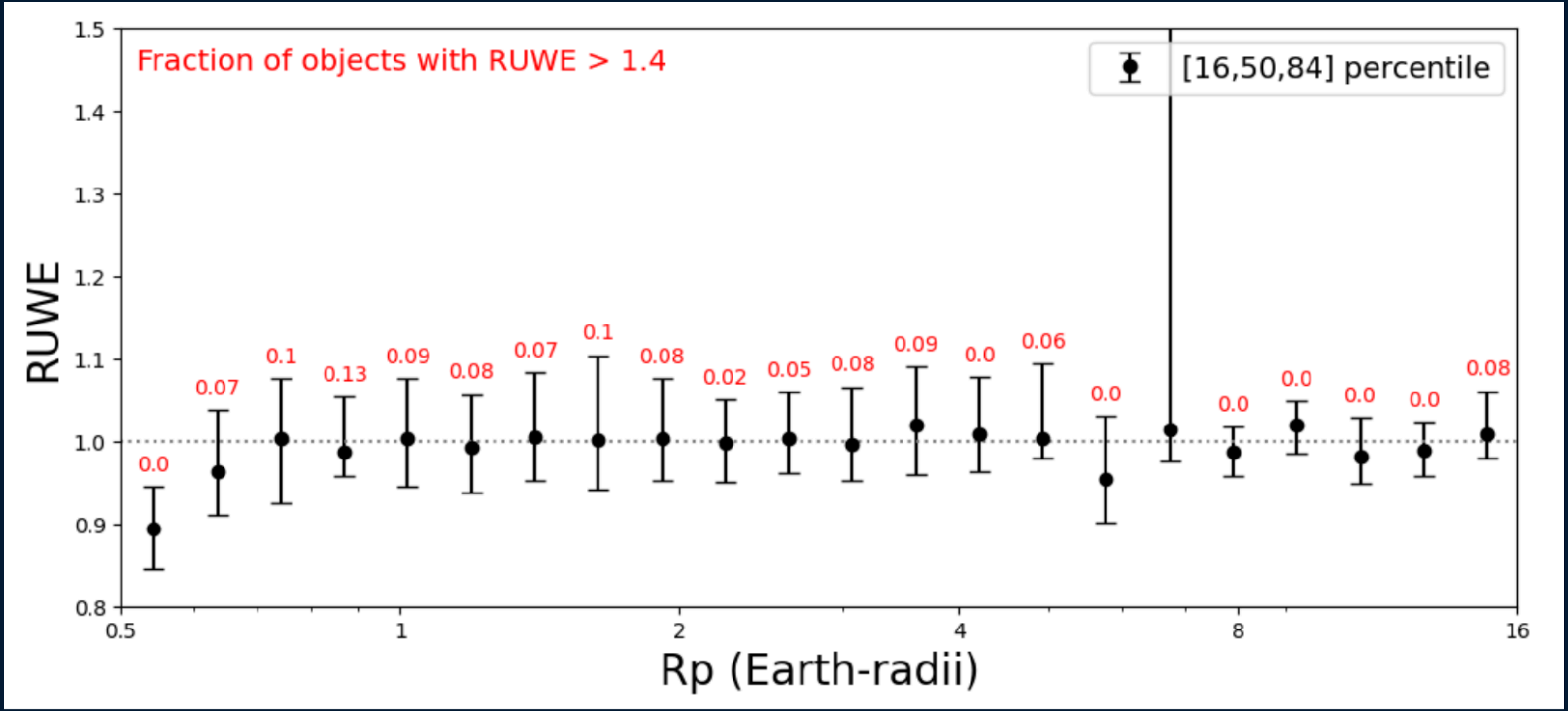
R_p/R_s
β_F = -0.25
b
β_F = -0.13
T_{14}
β_F = -0.02
−4 −2 0 2 4
−2 −1 0 1 2 3 4
−2.5 0.0 2.5 5.0 7.5 10.0 12.5 15.0
specific bias
specific bias
specific bias


f(e)
0
1
e
0.4
0.3
0.2
0.1
0.0
⟨e⟩
Recovery of injected eccentricities
0.5
1
2
4
8
16
R_p (R_⊕)



⟨e⟩ − ⟨e⟩no gap
Rp (R⊕)
P (days)
Rp (R⊕)
⟨e⟩ − ⟨e⟩no gap
Rp (R⊕)
P (days)
Rp (R⊕)

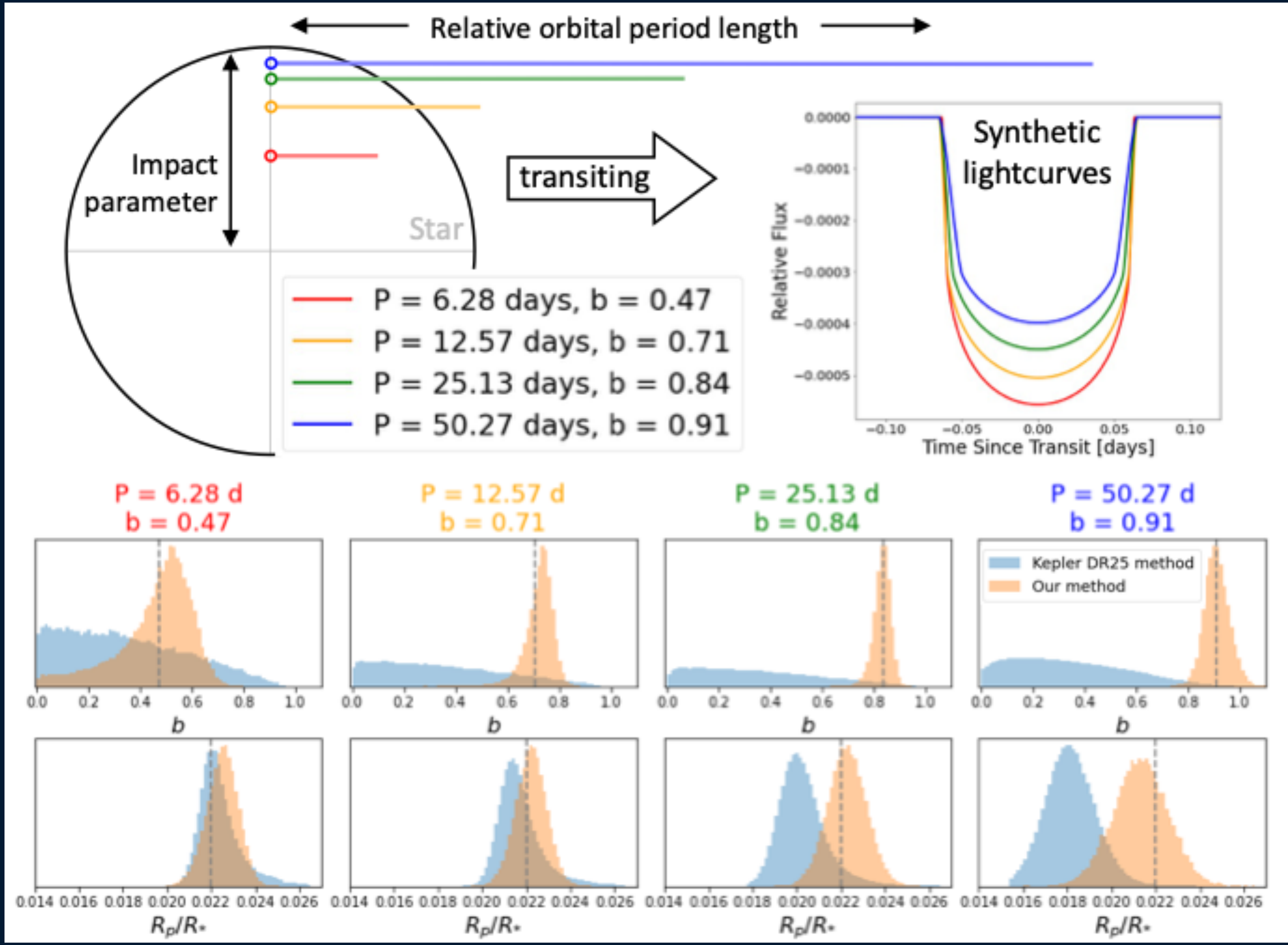
Gaia RUWE as a function of R_p rules out stellar contamination



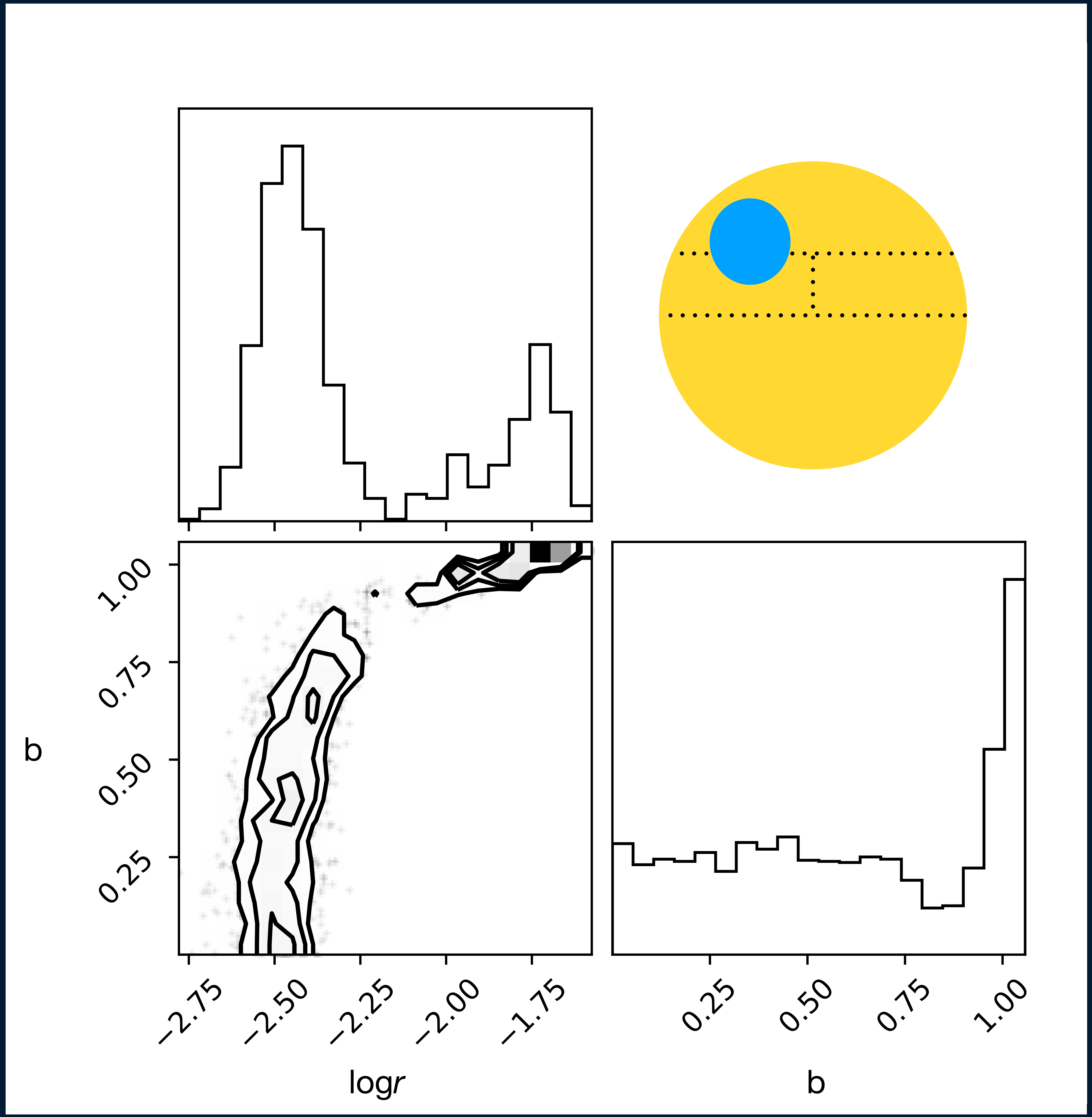

Small planets are common…
…large planets are rare.
Low e
High e
Low e
Planets per 100 stars
16
8
4
0
0.5
1.0
2.0
4.0
8.0
16.0
Planet Radius (Earth-radii)

Small planets are common…
…large planets are rare.
Low e
Low e
High e
Planets per 100 stars
16
8
4
0
0.5
1.0
2.0
4.0
8.0
16.0
Planet Radius (Earth-radii)

Hierarchical shrinkage produces improved b and R_p estimates



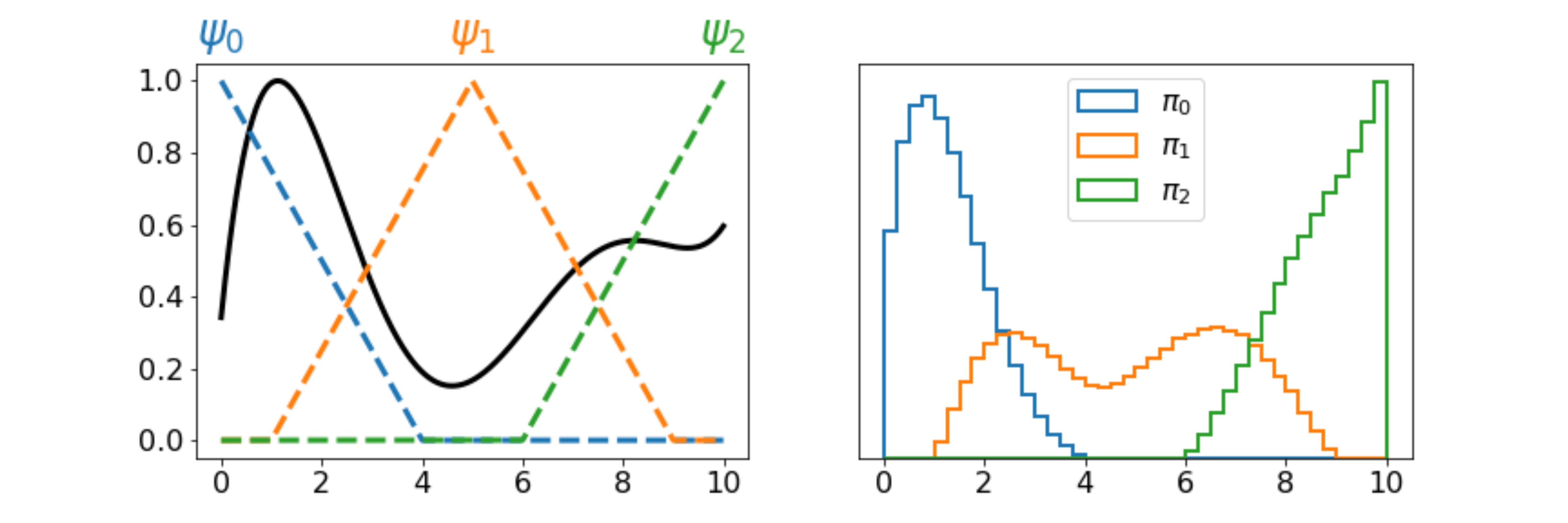
Impact parameters are challenging to measure



Gilbert (2021)

MCMC samplers get "stuck" at the transition from grazing to non-grazing geometries

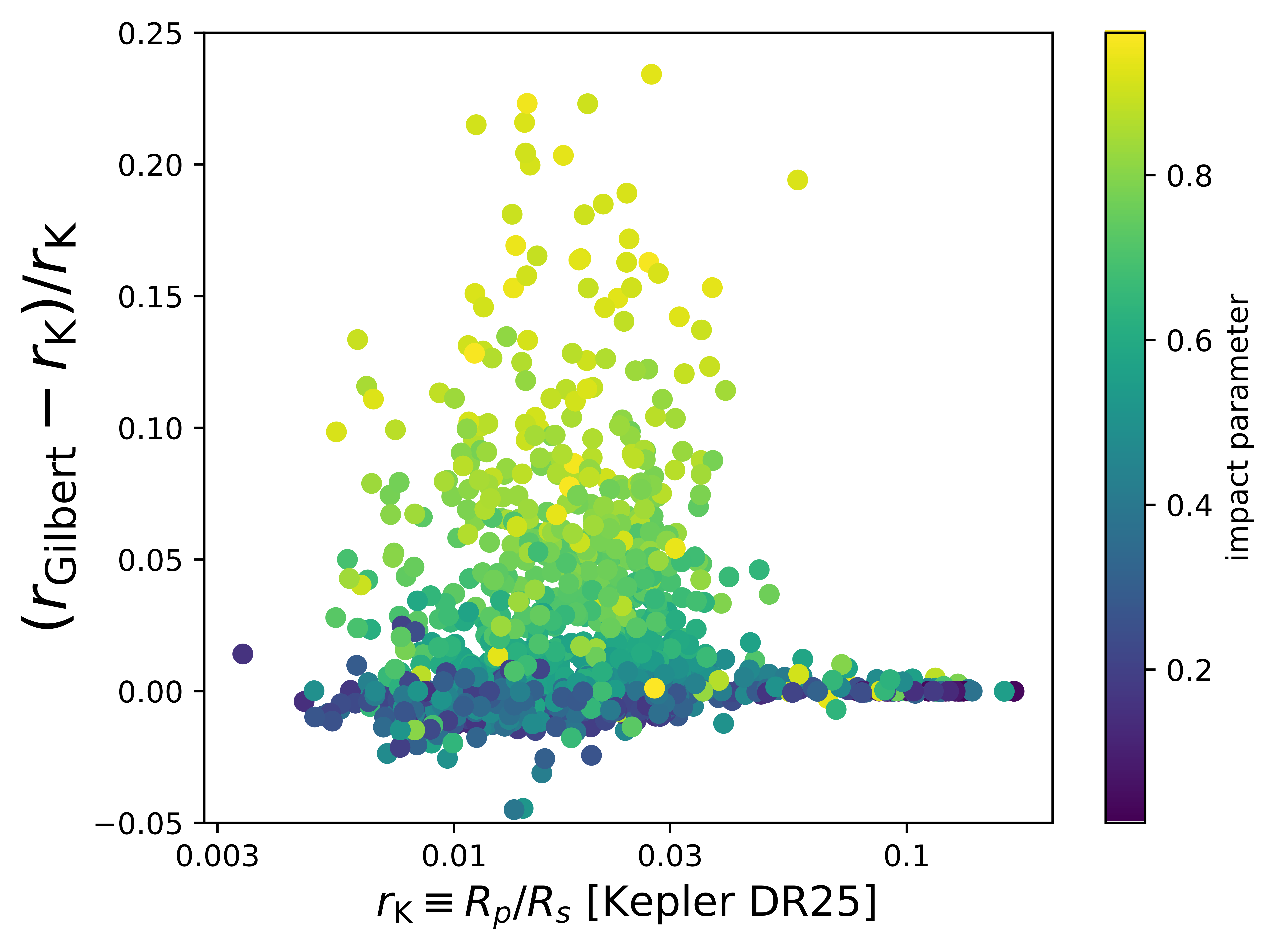
Solution: Umbrella Sampling



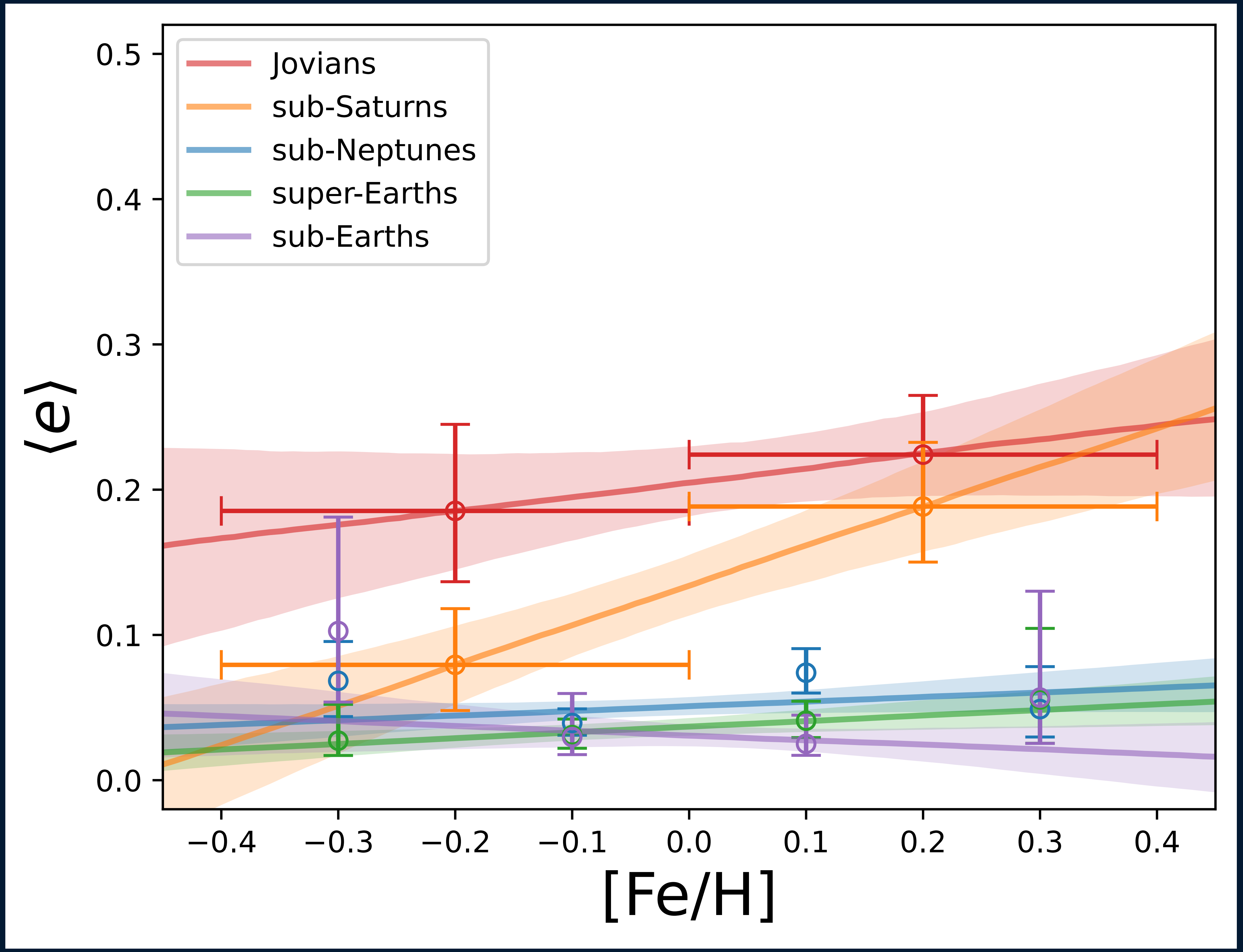
Torrie & Valleau (1977) | Matthews+ 2018 | Gilbert 2021

gjgilbert.github.io/tutorials/umbrella_sampling/

Hierarchical shrinkage produces improved b and R_p estimates



Why don't we see a strong $\langle e \rangle - [\mathrm{Fe/H}]$ correlation?



Small planets are common (1 per star)

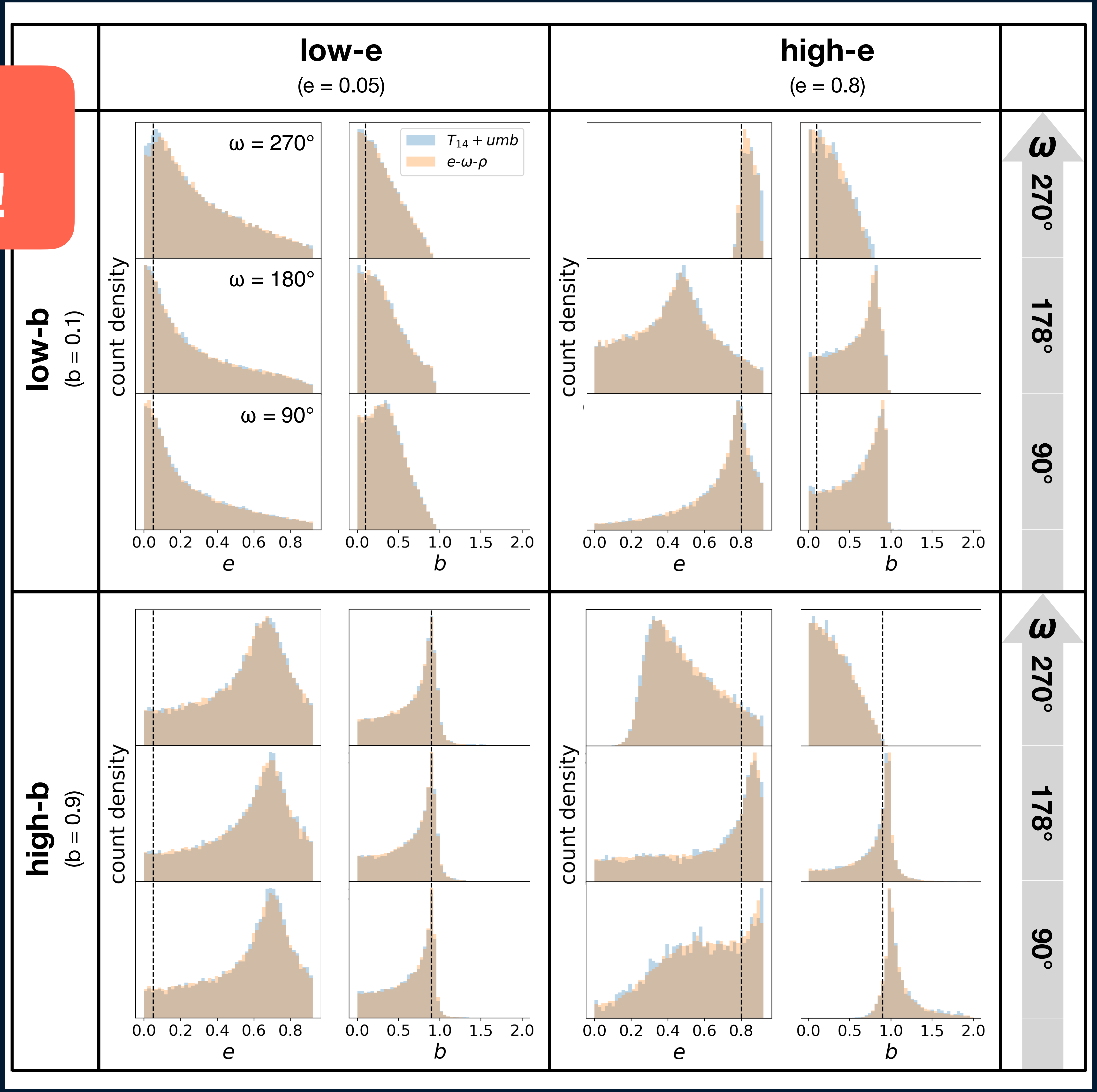
Large planets are rare (~10% at [Fe/H] = 0.25)

Only some large planets have elevated eccentricity (~50%)

$\langle e \rangle - [\mathrm{Fe/H}]$ is "diluted" by the abundant population of $e \approx 0$ small planets

Posteriors on b and e are degenerate

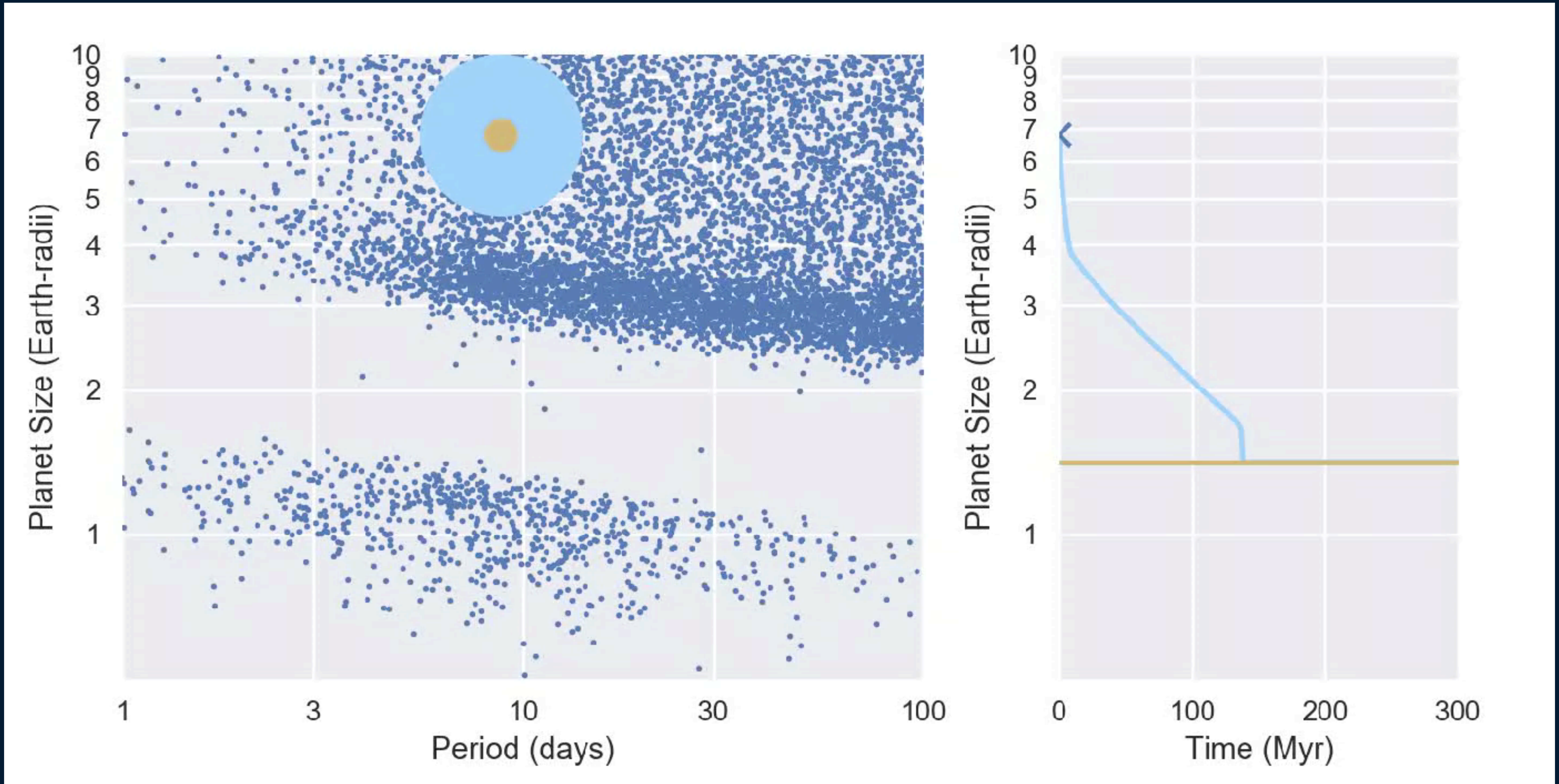
No lightcurve fitting needed!



Mason MacDougall
UCLA PhD

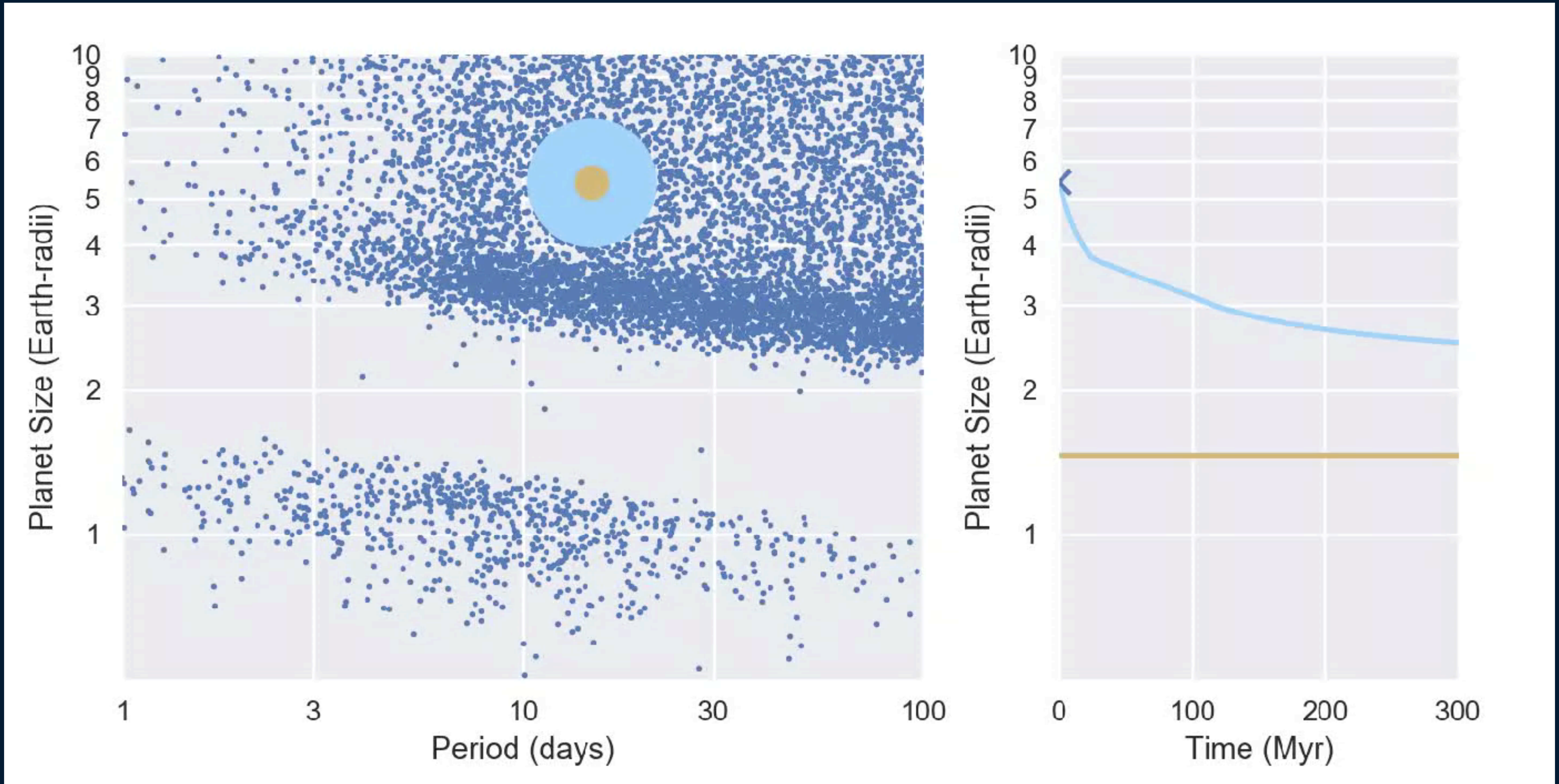
MacDougall, Gilbert, & Petigura (2023)

Photo-evaporation creates the radius valley



Simulation: J. Owen | Animation: E. Petigura

Photo-evaporation creates the radius valley



Simulation: J. Owen | Animation: E. Petigura