Goals: Understand the Nature of Small Planets (Earth-to-Neptune size)

What is the full diversity of planets?

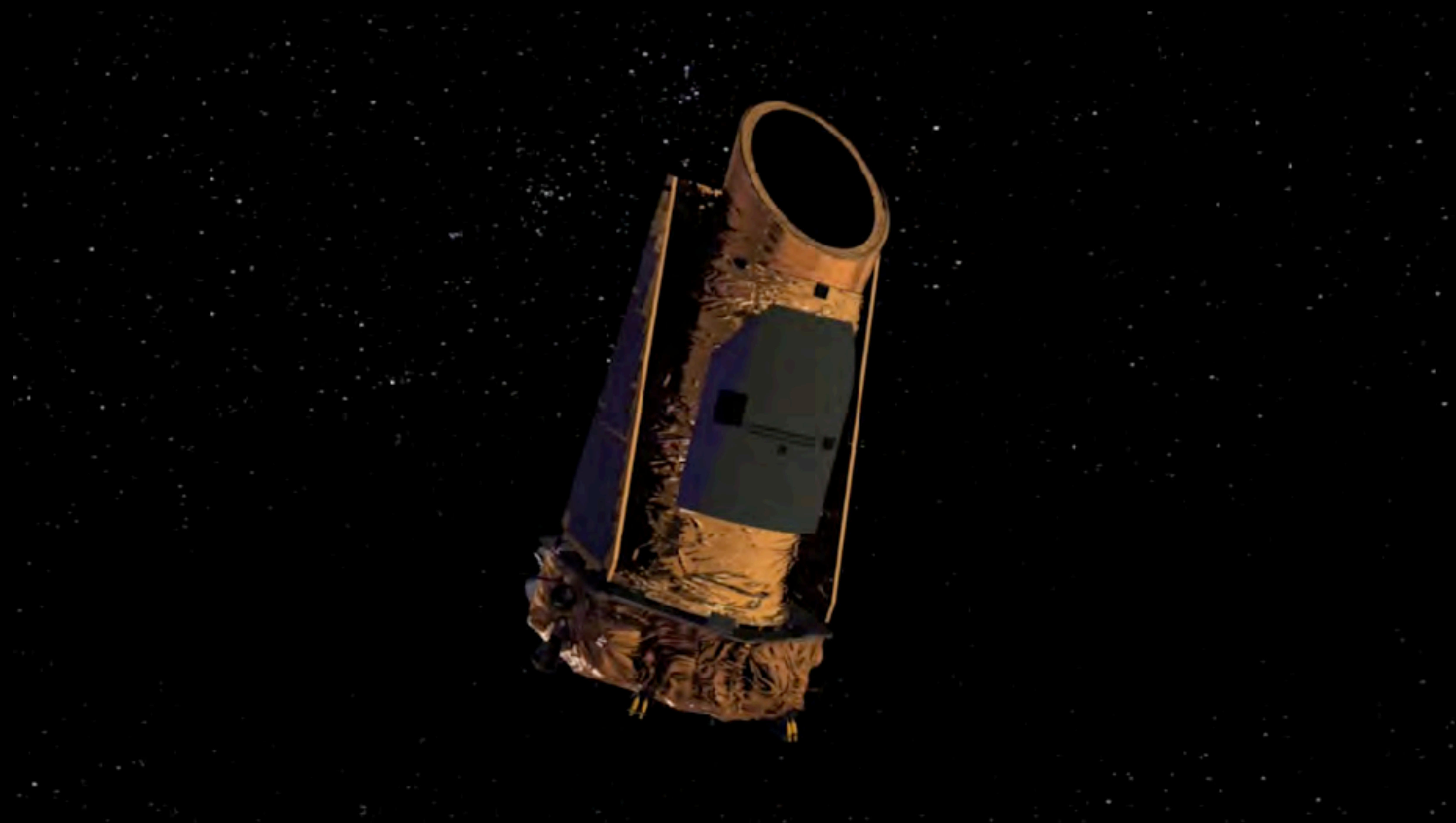
What are super-Earths / sub-Neptunes made of?

How did they form? What are their system architectures?

How common are Earth-size planets?

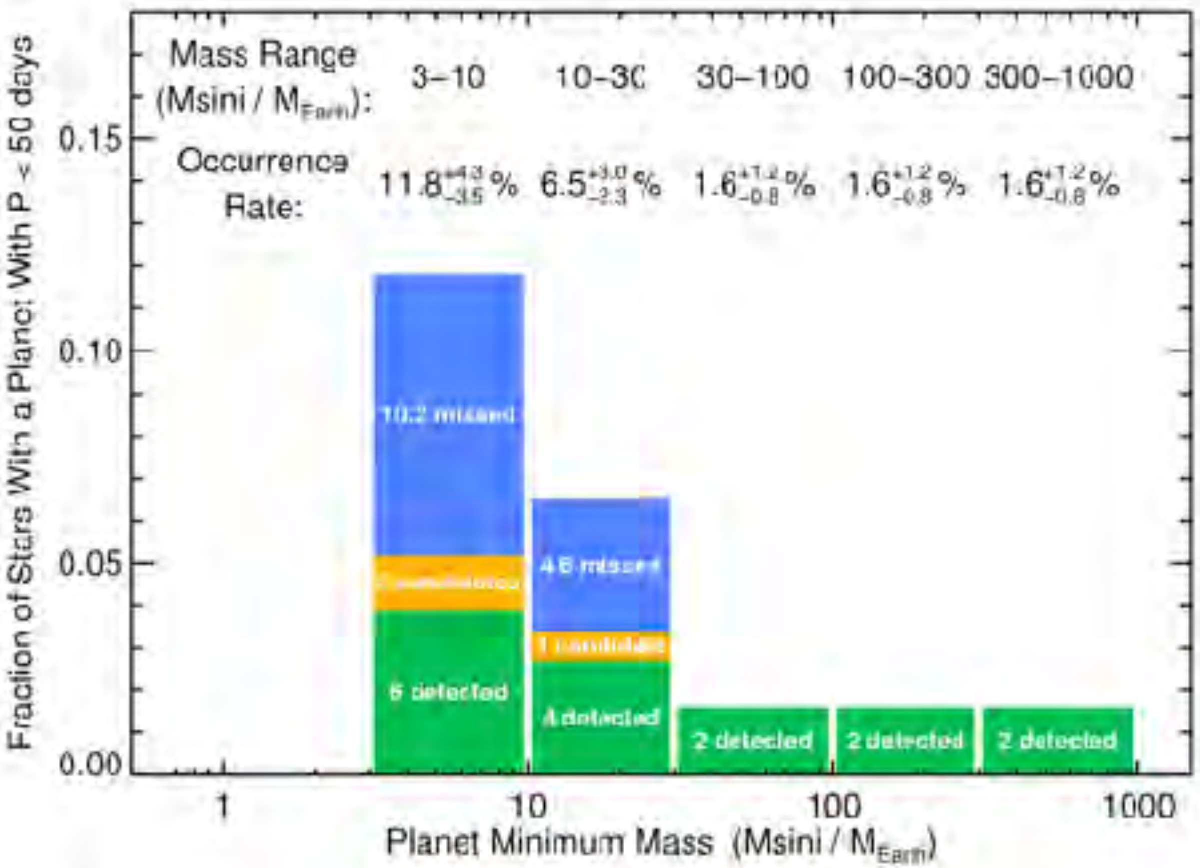
Tools & Projects:

1. Doppler Planet Surveys and Targeted Observations
2. Transiting PlanetS - Demographics & Interesting Planets
3. New Instrumentation - Keck Planet Finder & KPF 2.0


Movie: NASA

Planet Mass Distribution
Eta-Earth Survey (*Doppler*)

Howard et al. 2010, Science, 33, 653



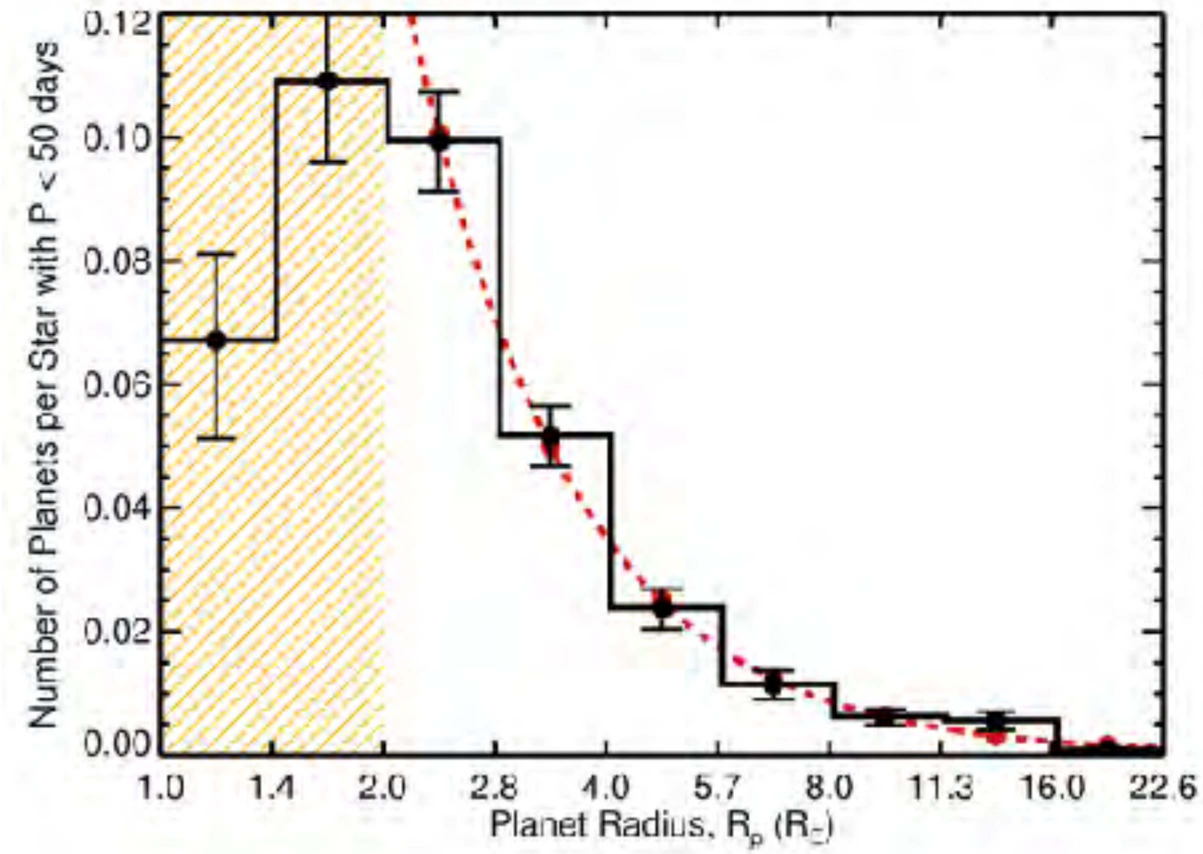
Power Law Mass Function

$df/d\log M = kM^{\alpha}$

$k = 0.39^{+0.27}_{-0.16}$, $\alpha = -0.48^{+0.12}_{-0.14}$

Planet Radius Distribution
Kepler

Howard et al. 2012, ApJ, 330, 653

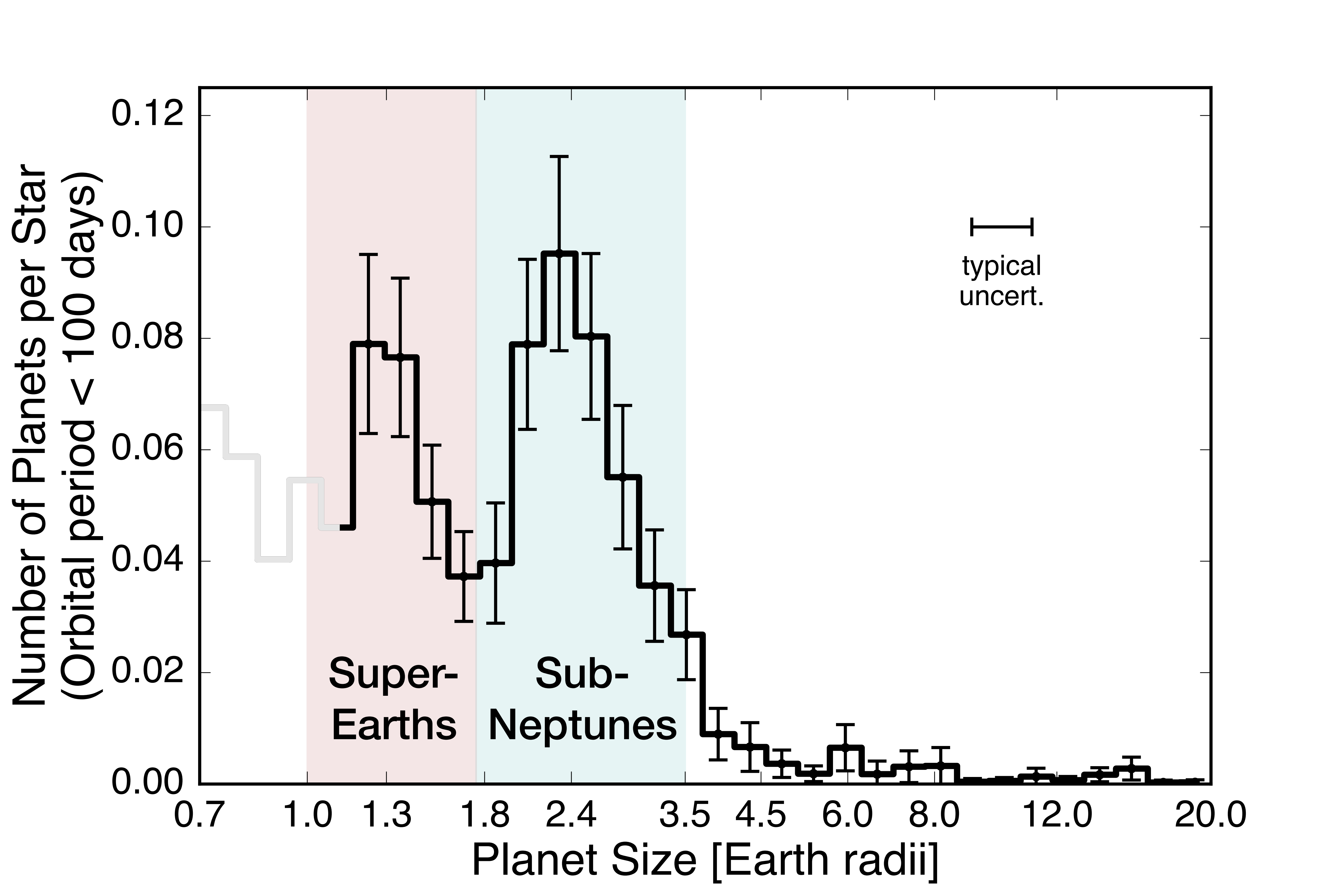


Power Law Radius Function

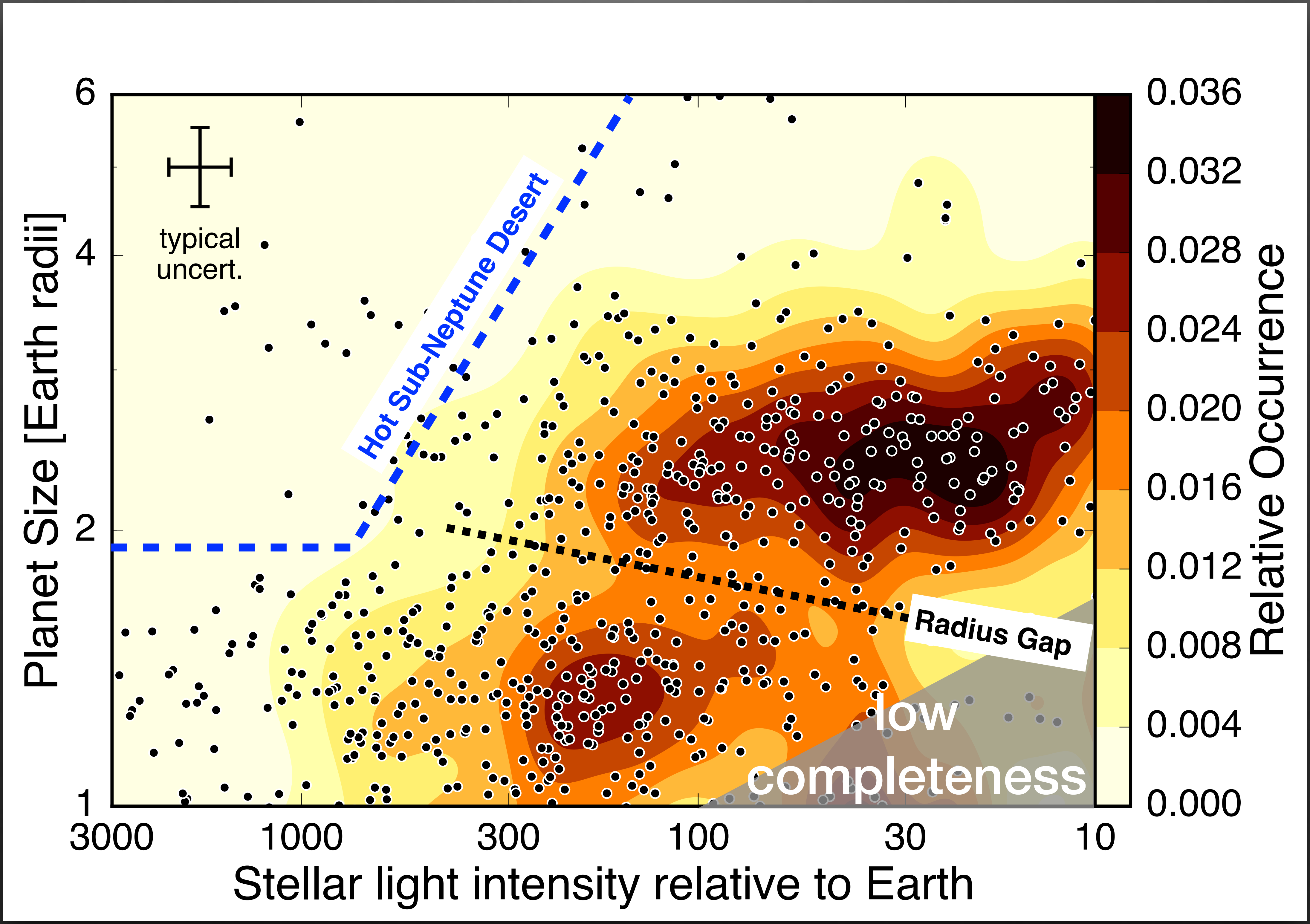
$df/d\log R = kR^{\alpha}$

$k = 2.9\pm0.5$, $\alpha = -1.92\pm0.11$

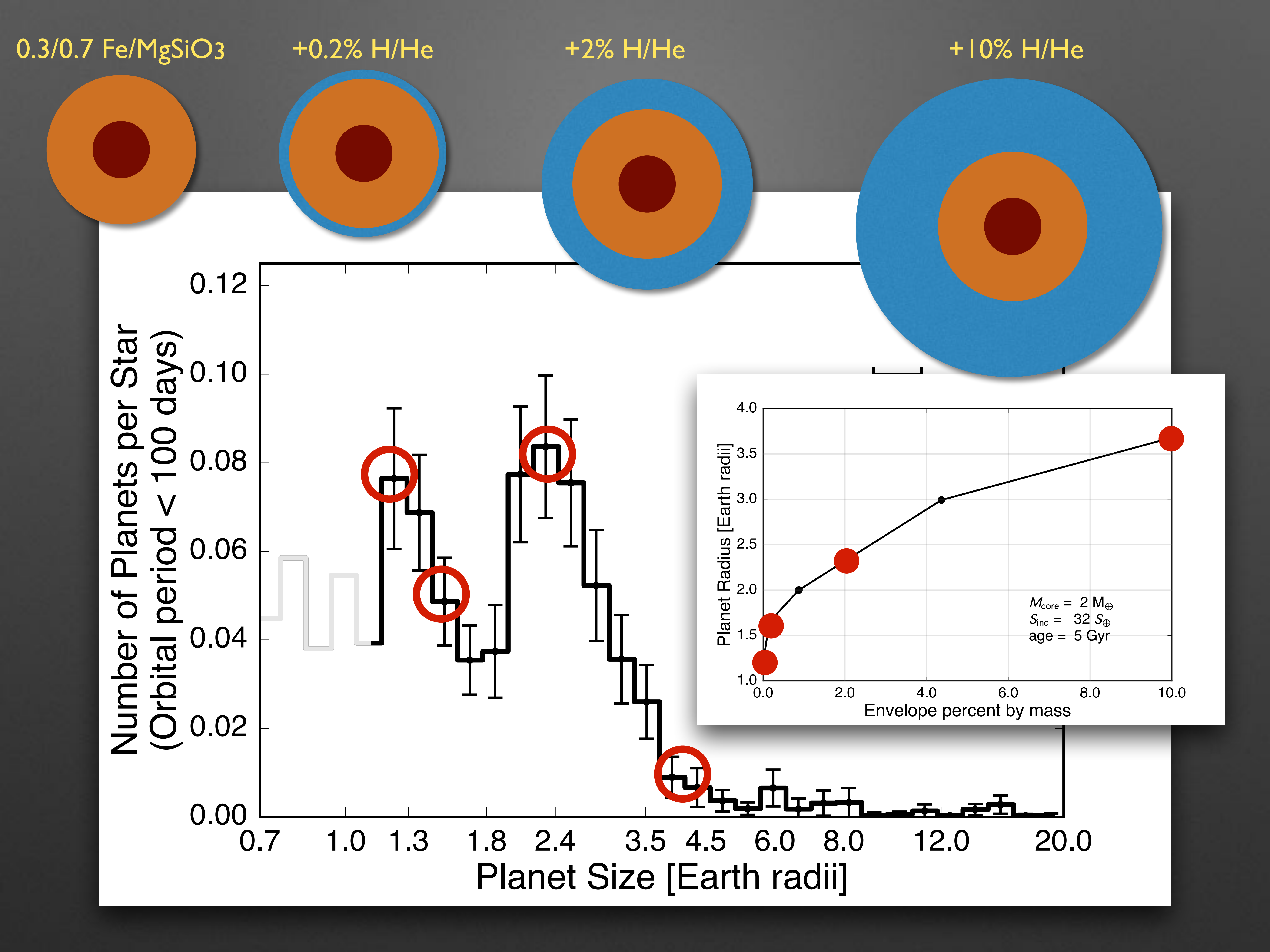
Gap in Planet Radii



Flux Dependency



Fulton, Petigura, et al. (*2017*)

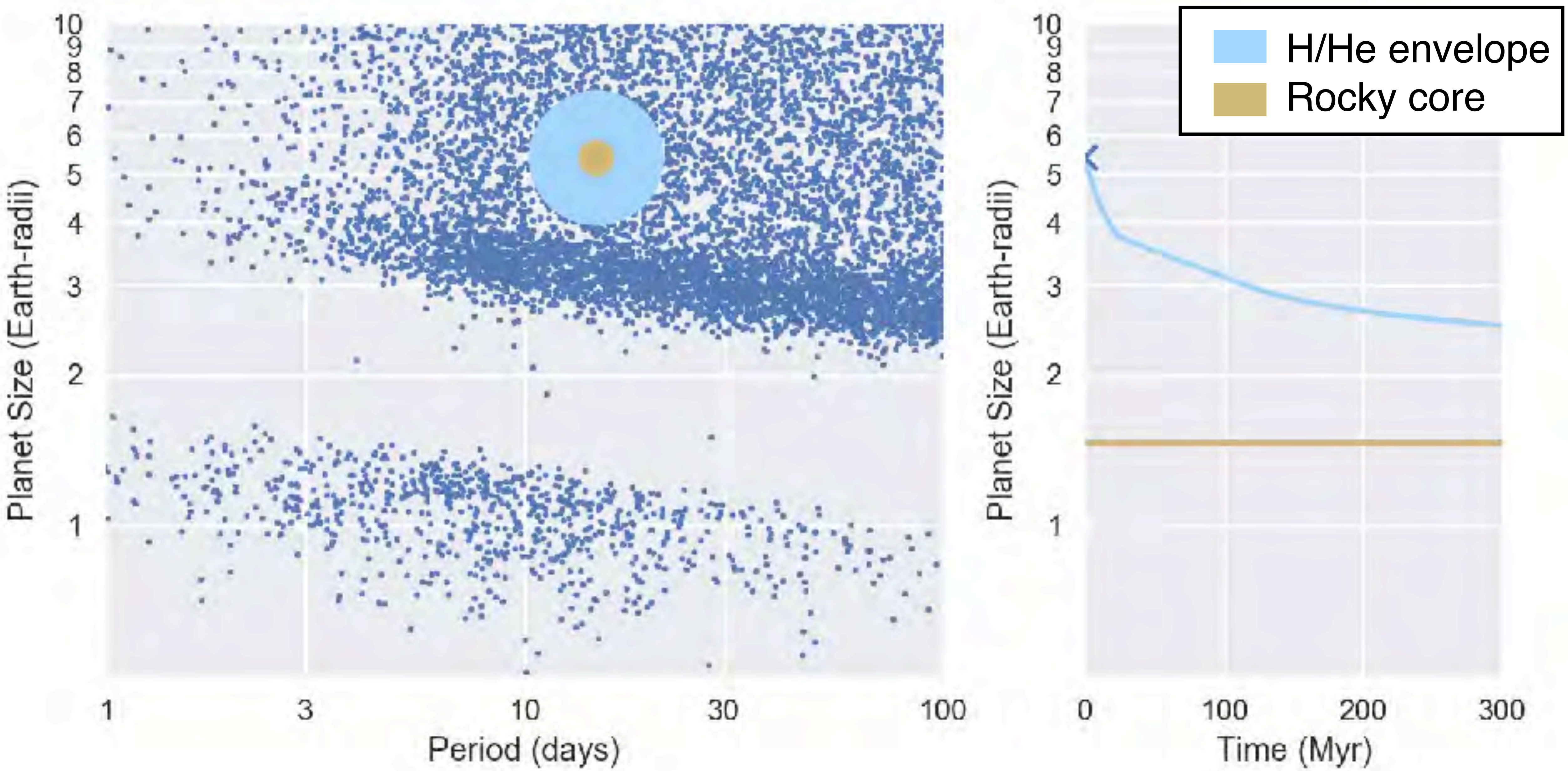


0.3/0.7 Fe/MgSiO3
+0.2% H/He
+2% H/He
+10% H/He
Number of Planets per Star
(Orbital period < 100 days)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.7
1.0
1.3
1.8
2.4
3.5
4.5
6.0
8.0
12.0
20.0
Planet Size [Earth radii]
Planet Radius [Earth radii]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.0
2.0
4.0
6.0
8.0
10.0
Envelope percent by mass
Mcore = 2 M⊕
Sinc = 32 S⊕
age = 5 Gyr

Photoevaporation Creates Radius Gap

Planets are converted into either

- ~2–3 R_E sub-Neptunes (rocky core with ~3% envelope)
- < 1.5 R_E super-Earths (rocky core with no envelope)



Simulation: J. Owen, Animation: E. Petigura

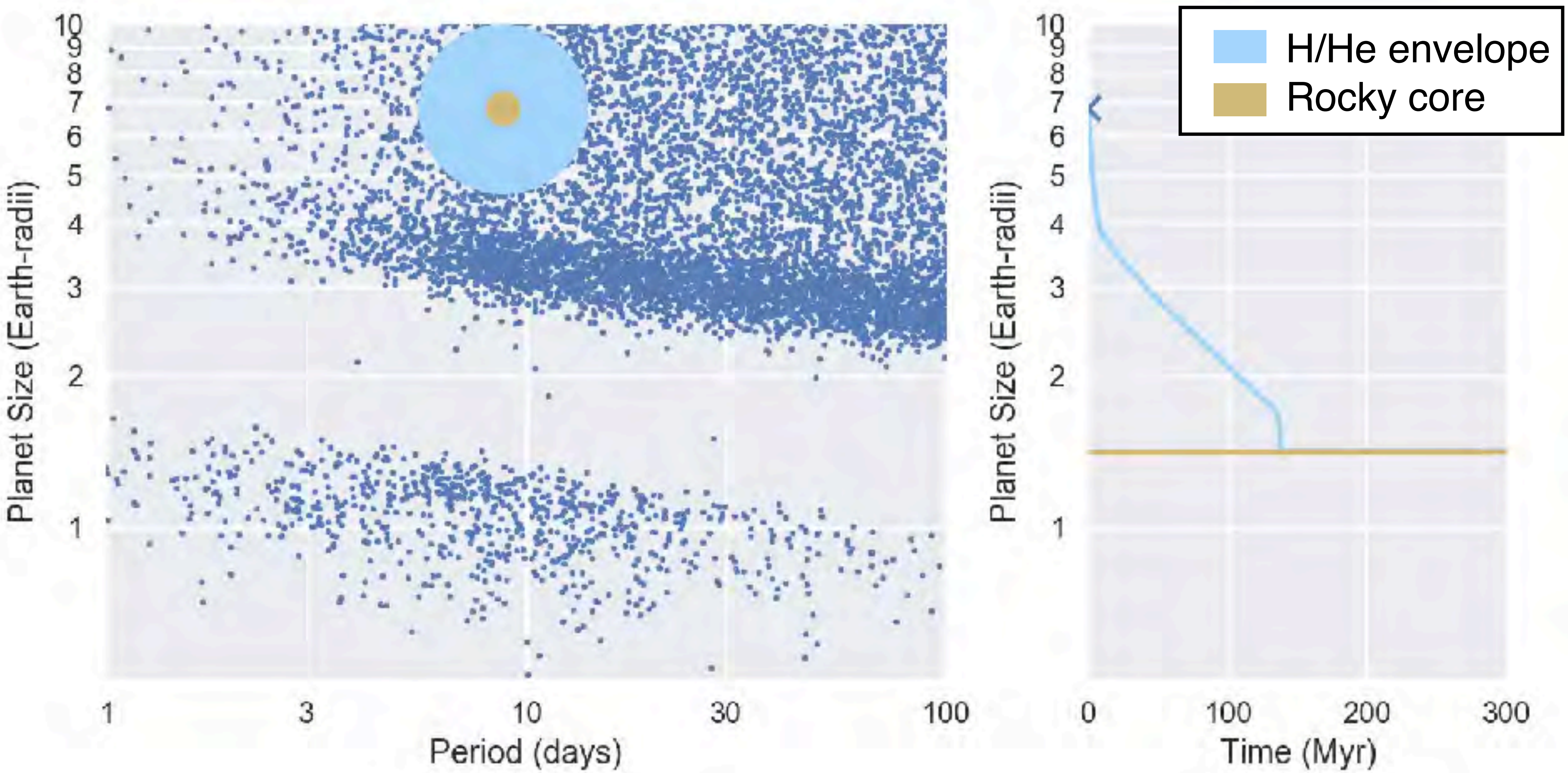
Photoevaporation Creates Radius Gap

Evaporation Timescale:

Light envelopes: short timescale because the planet's radius remains largely constant for tenuous envelopes.

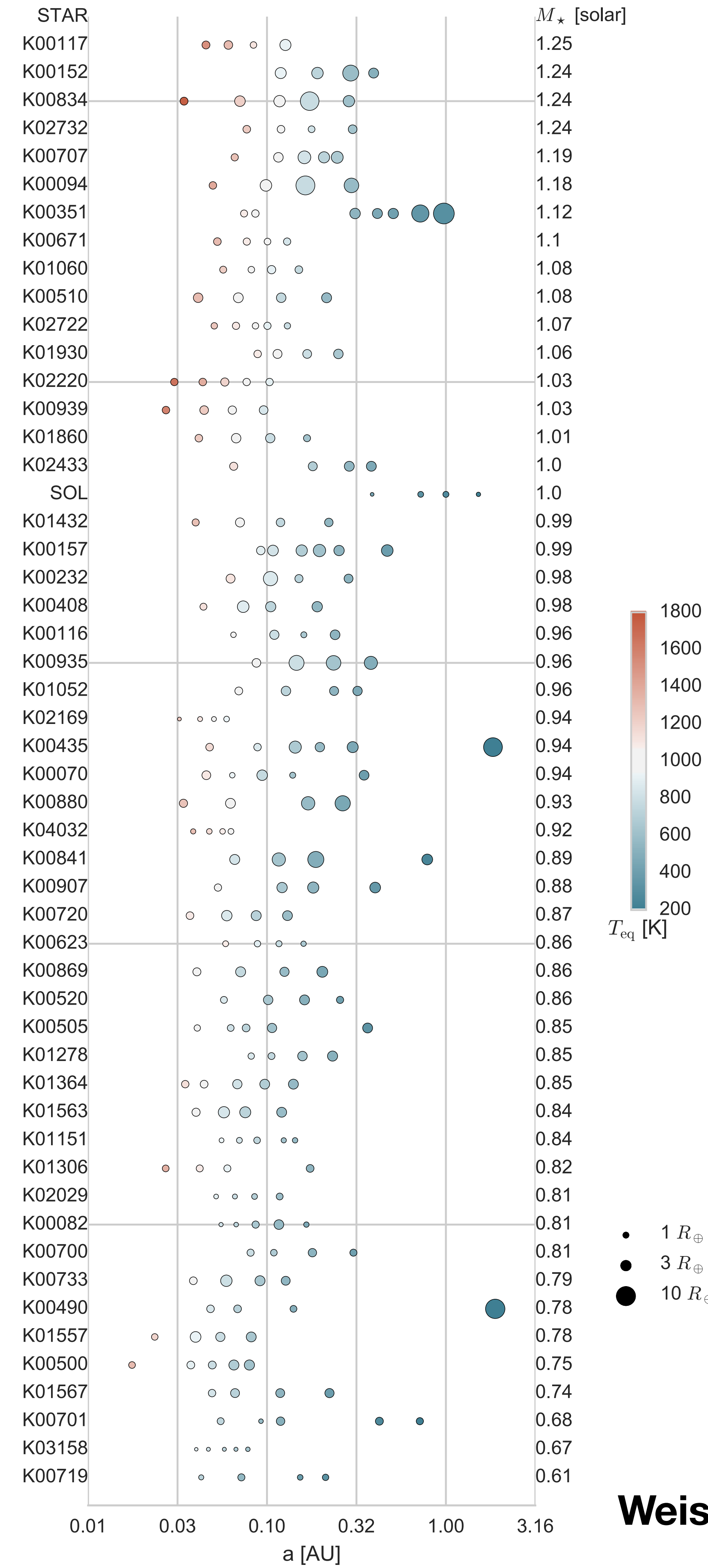
Heavy envelopes: Also decreases vs. Rp because the planet swells faster than the addition of envelope mass.

Photoevaporation therefore herds planets into either bare cores (~1.3 R ⊕) or 2X the core's radius (~2.6 R ⊕).



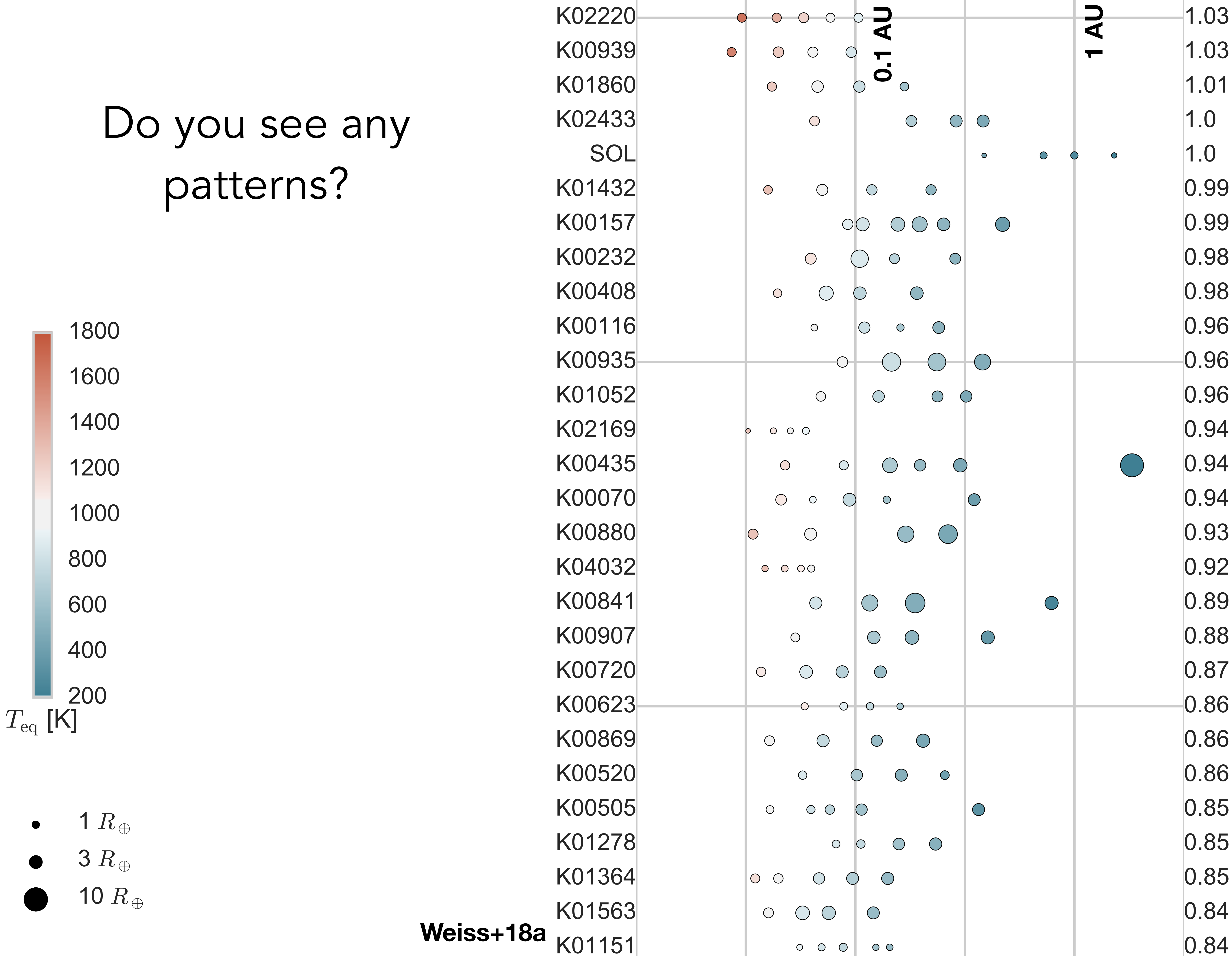
Simulation: J. Owen, Animation: E. Petigura

California Kepler Survey Systems with 4 or more transiting planets



Weiss+18a

Do you see any patterns?



Weiss+18a

Do you see any patterns?

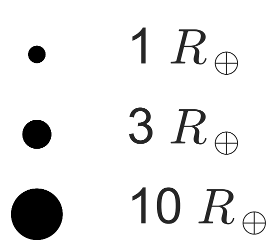
Planets in the same system often have:

Similar Sizes

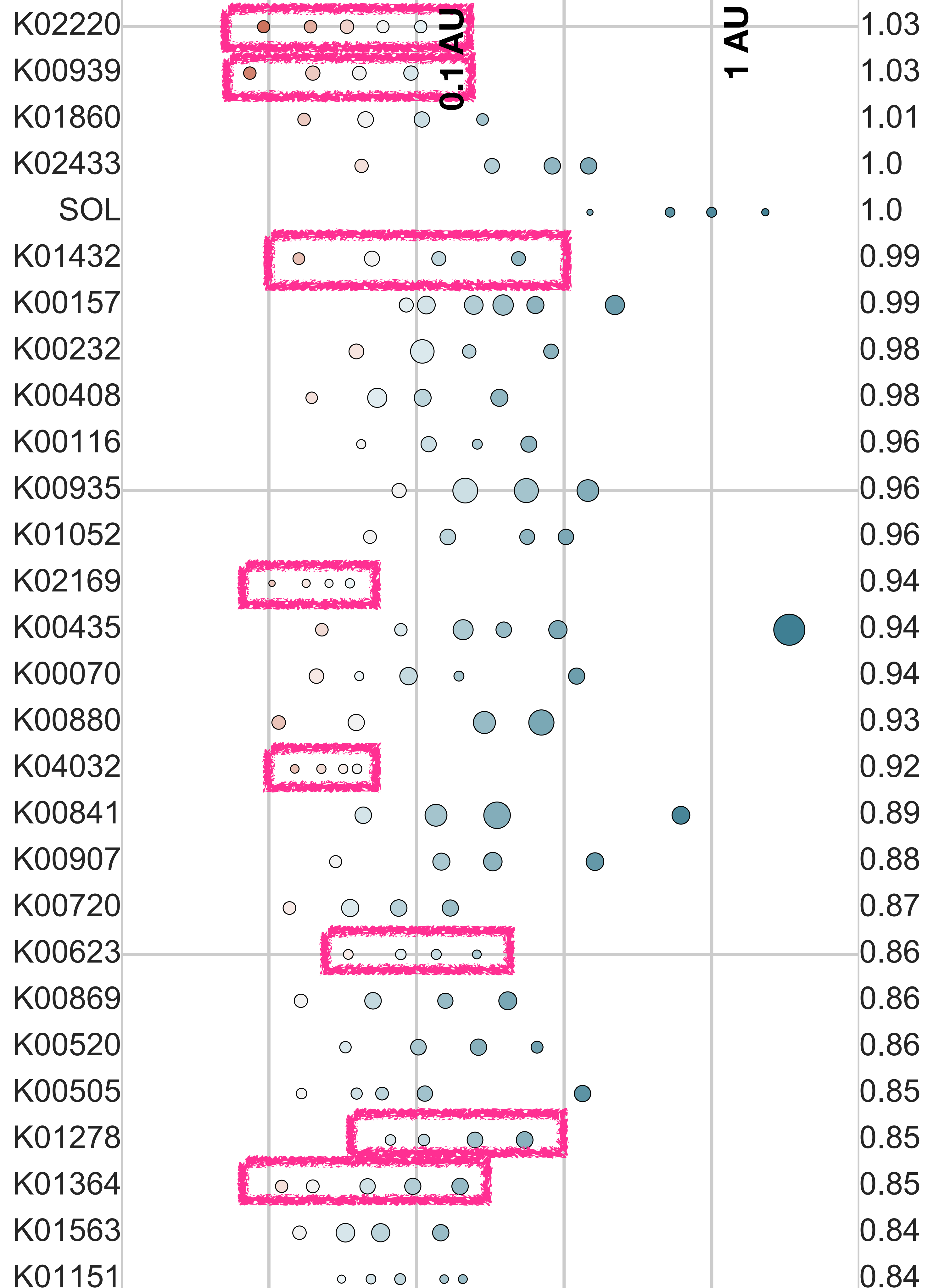
&

Regular Spacing

Weiss+18a



Also: Lissauer+11, Titius & Bode



Do you see any patterns?

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&

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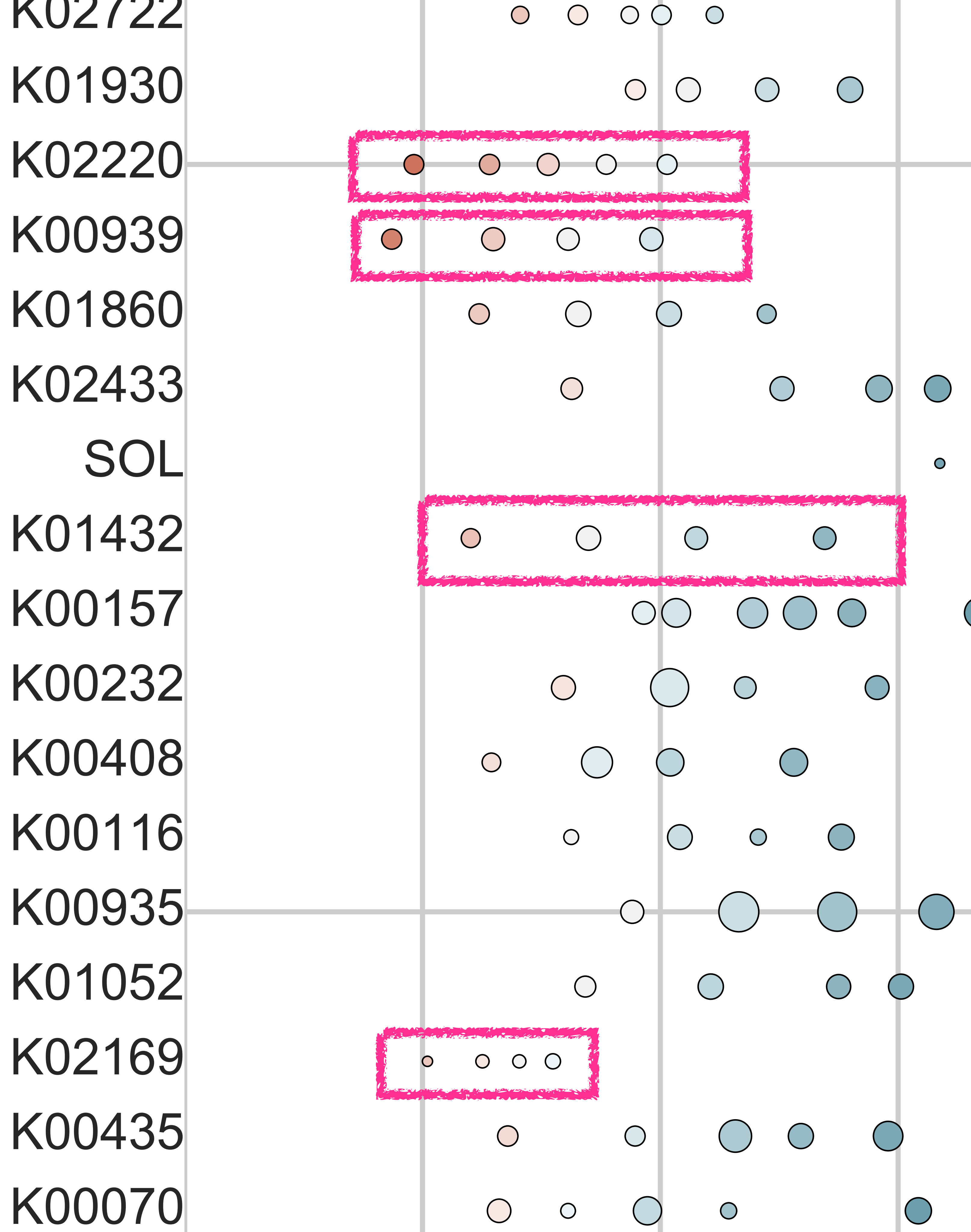
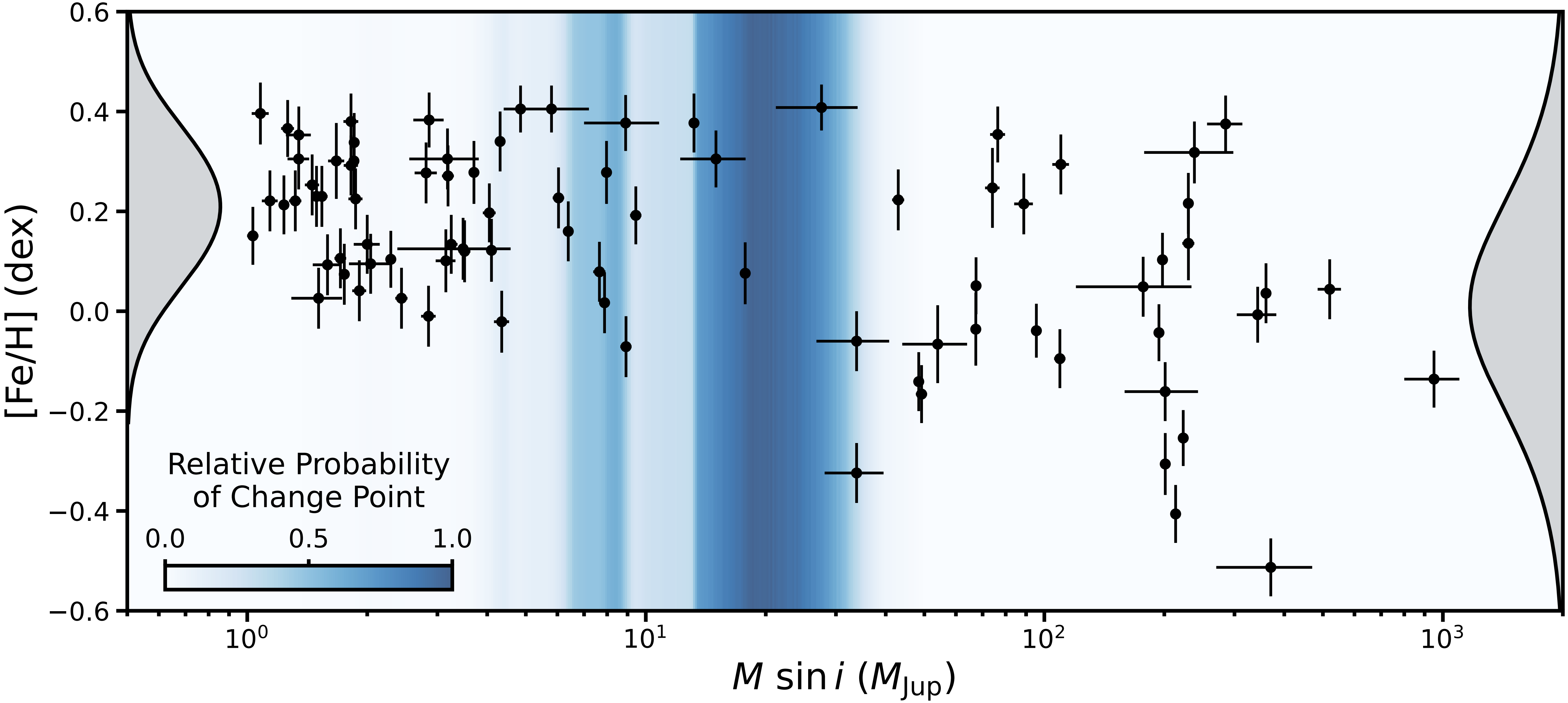
Weiss+18a



• 1 $R_\oplus$
• 3 $R_\oplus$
• 10 $R_\oplus$

Also: Lissauer+11, Titius & Bode

Steven Giacalone - Giant Planets vs. Brown Dwarfs [not submitted yet]



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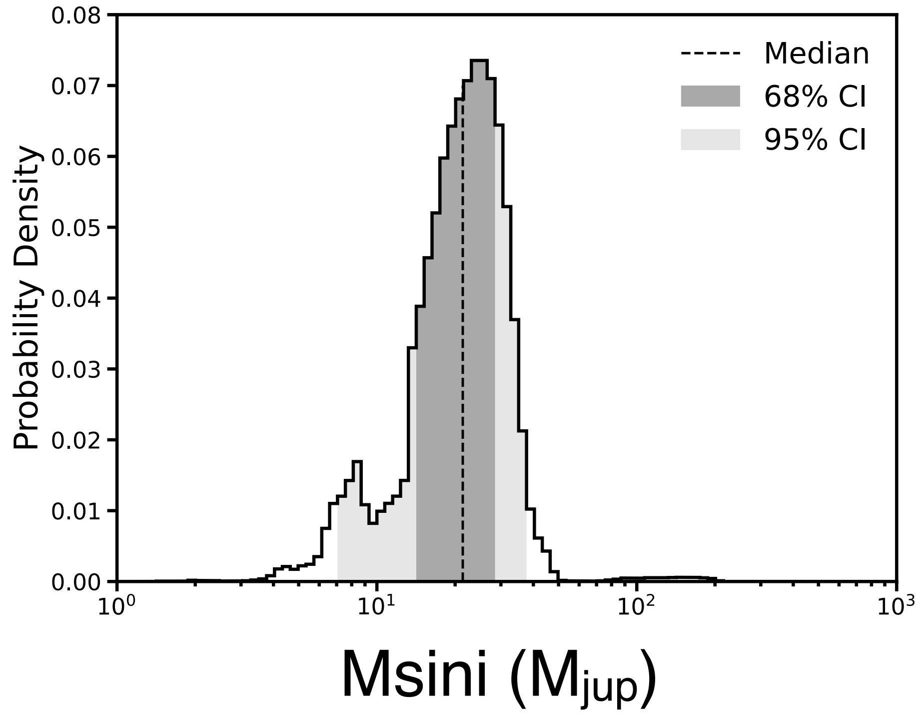
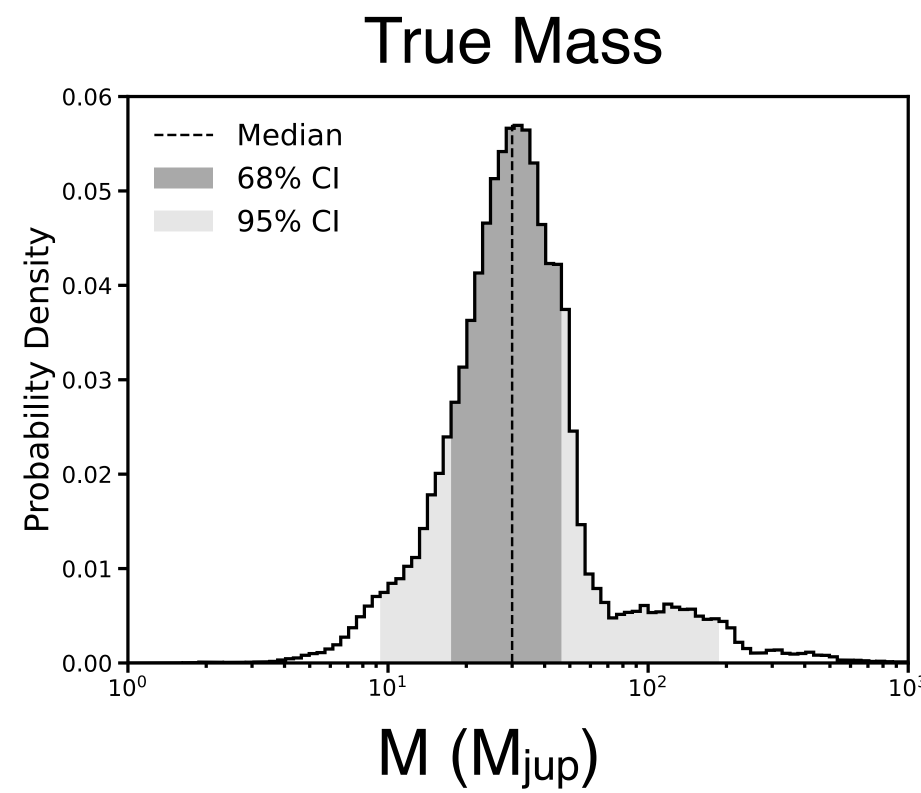
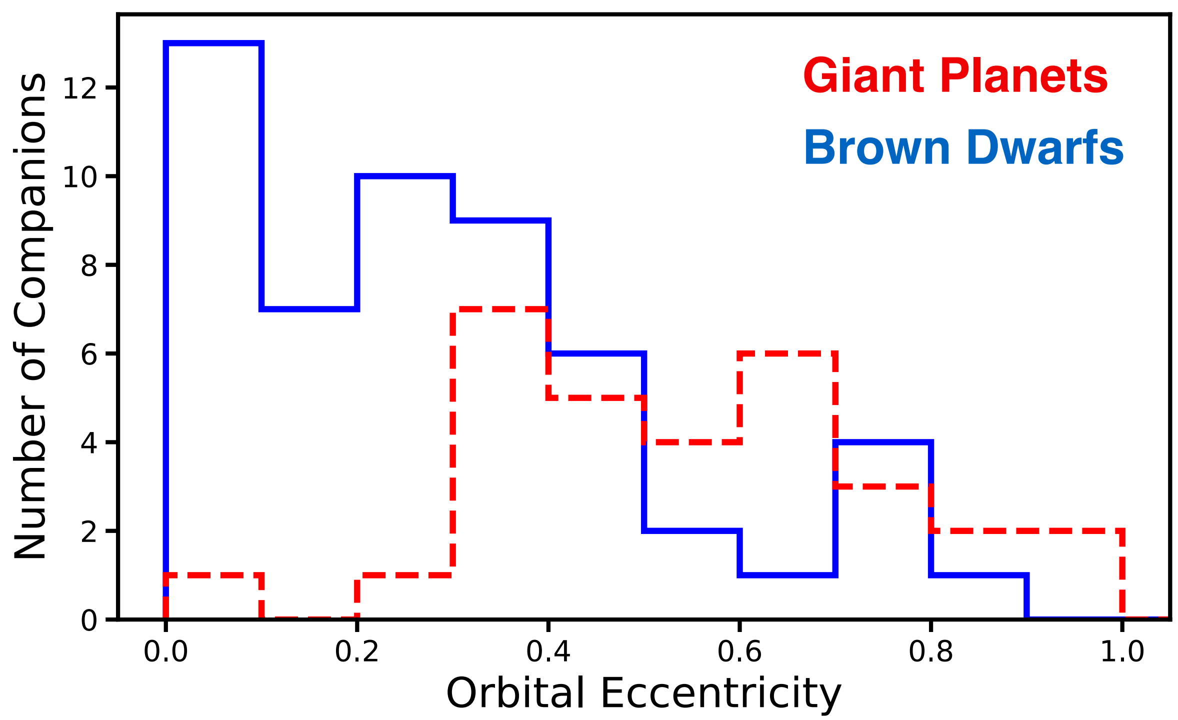
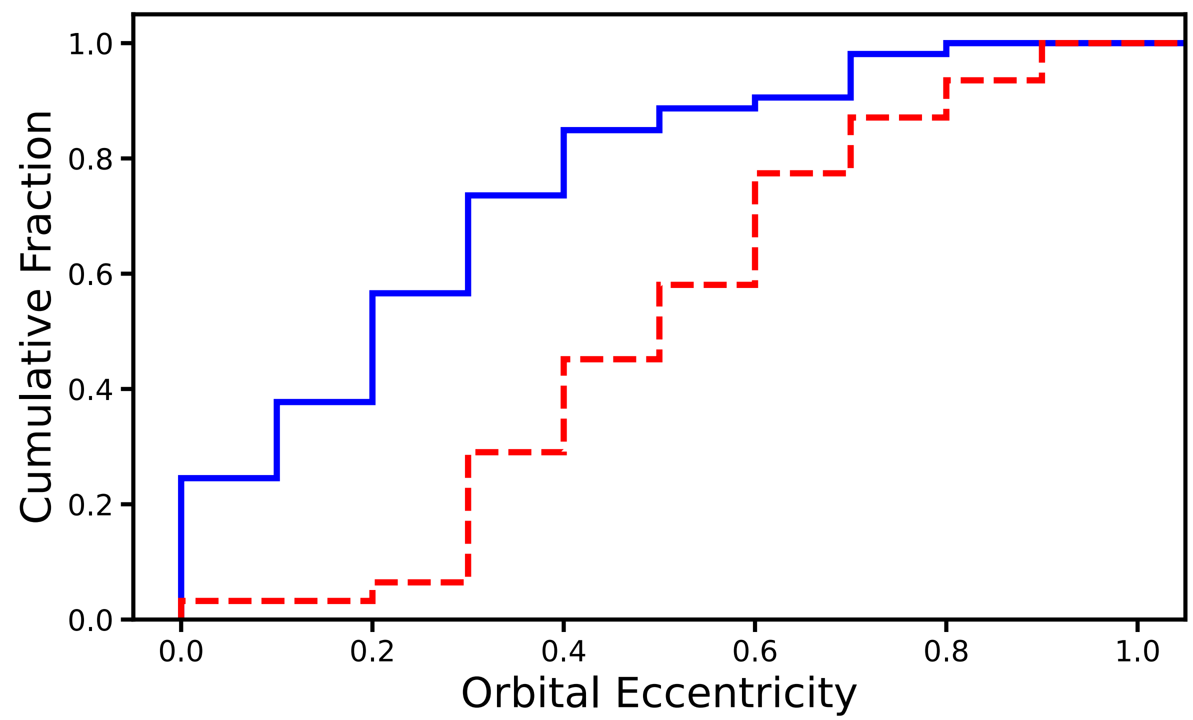


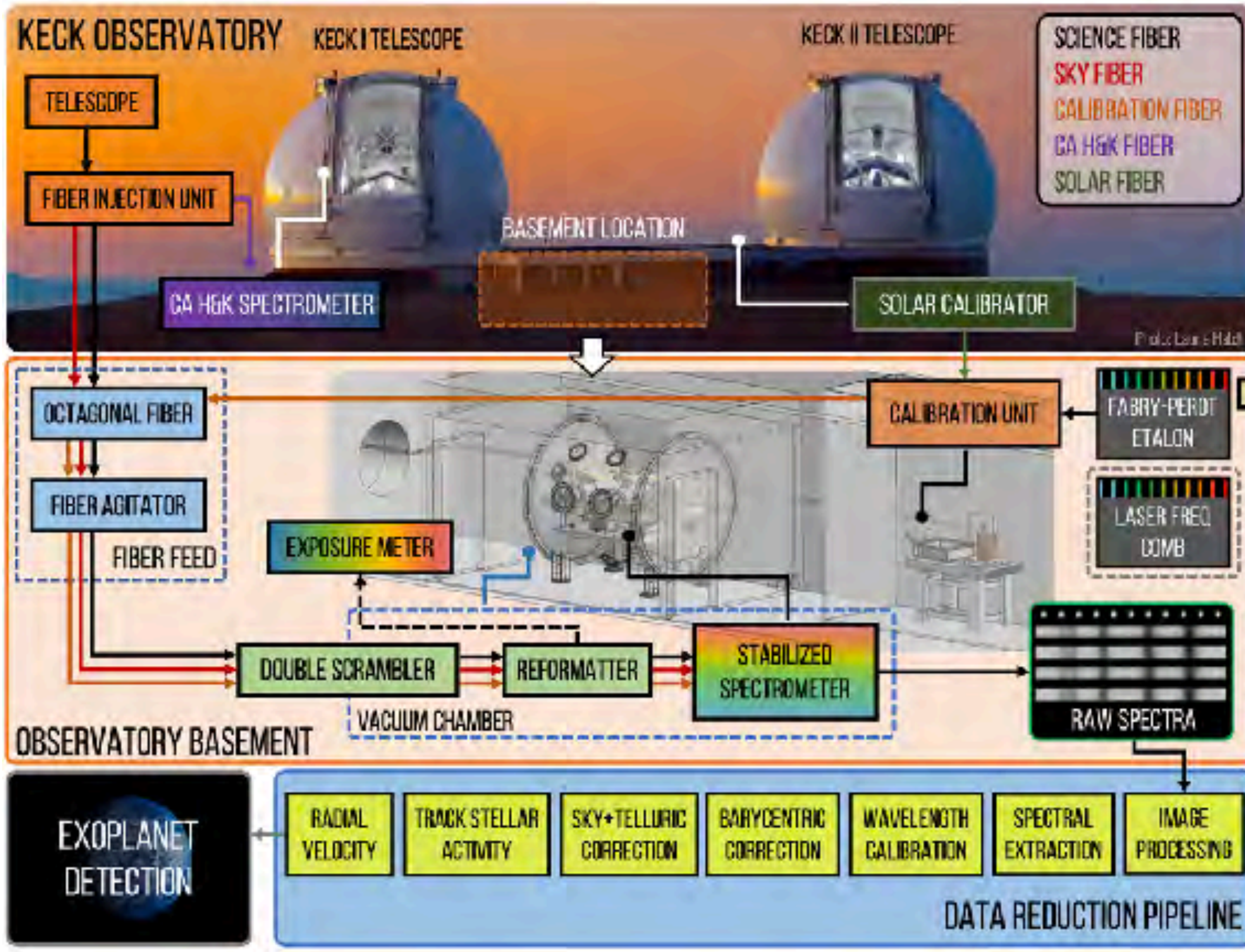


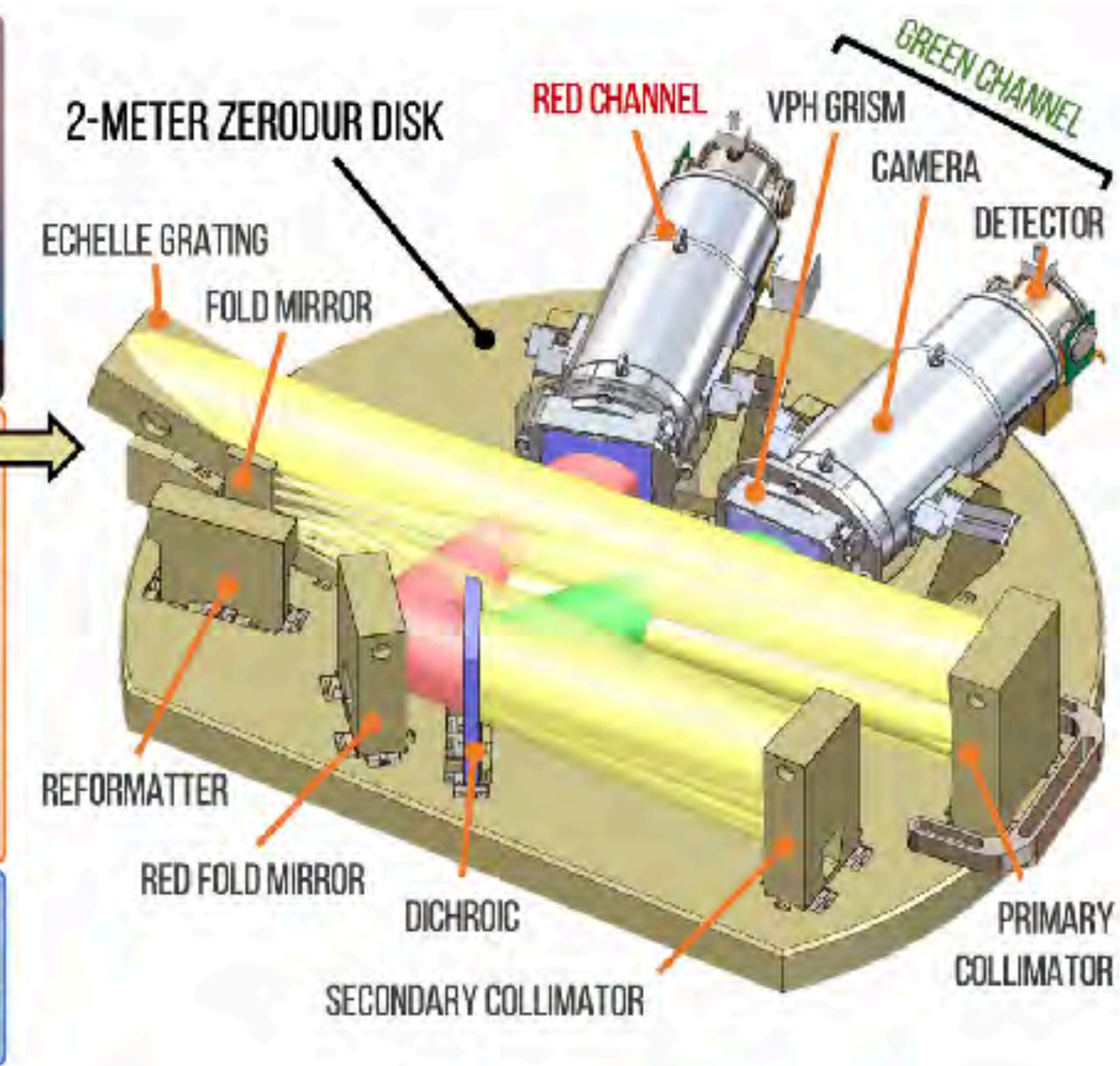




Keck Planet Finder
(KPF)

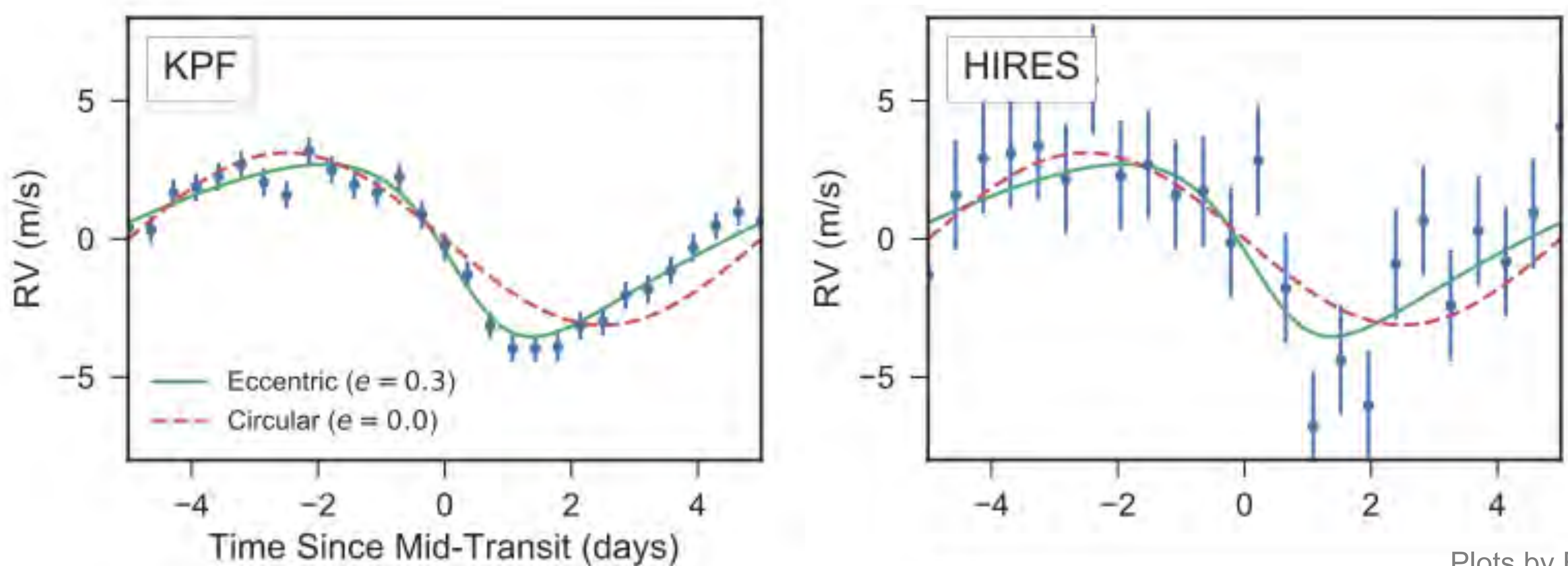
Keck Planet Finder (& KPF 2.0)





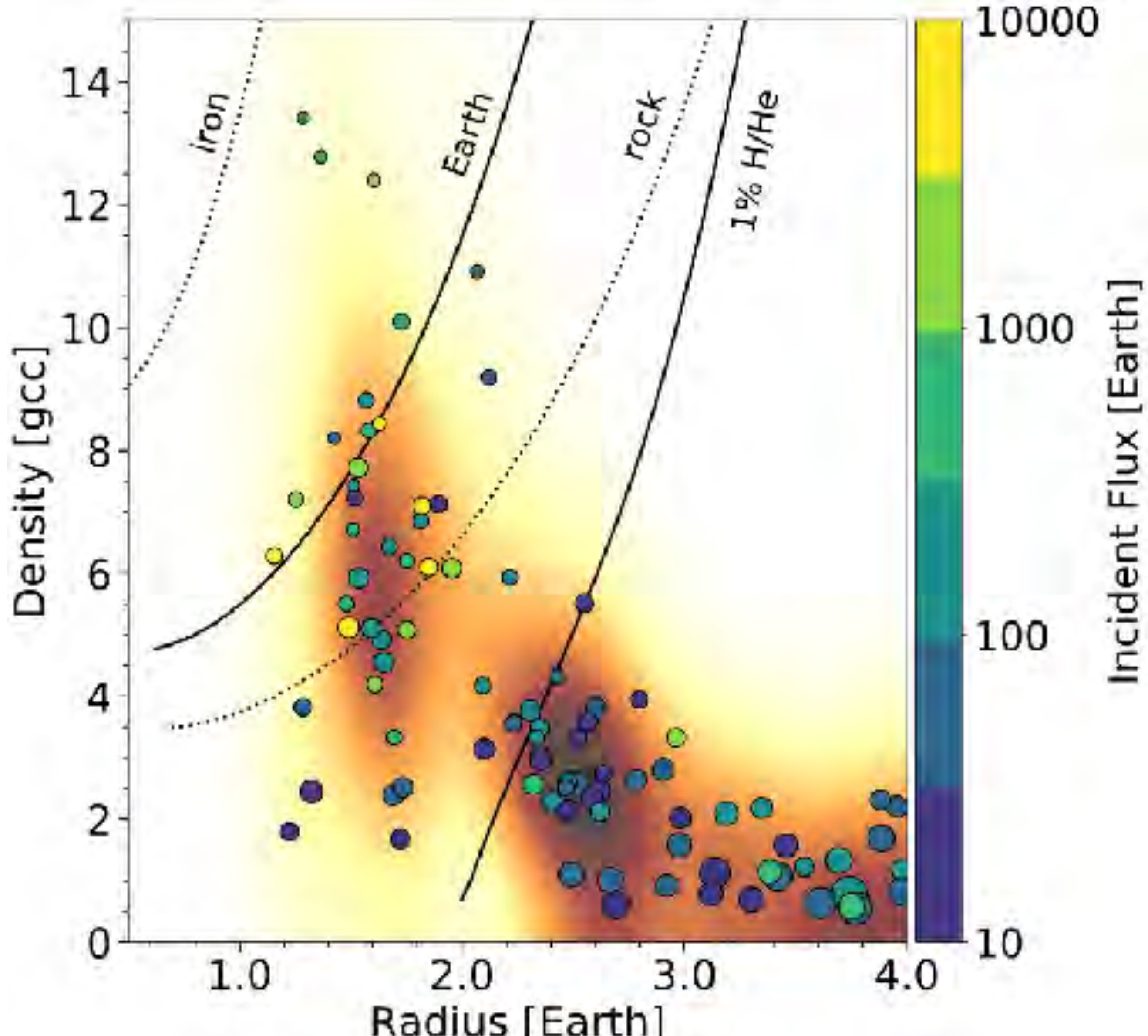
You?

- KPF is superior to HIRES is two key ways:
  - Speed – ~8X faster exposure to a given photon-limited precision
  - Instrumental error floor – KPF: 30 cm/s (goal) – 50 cm/s (requirement)
    HIRES: ~2 m/s

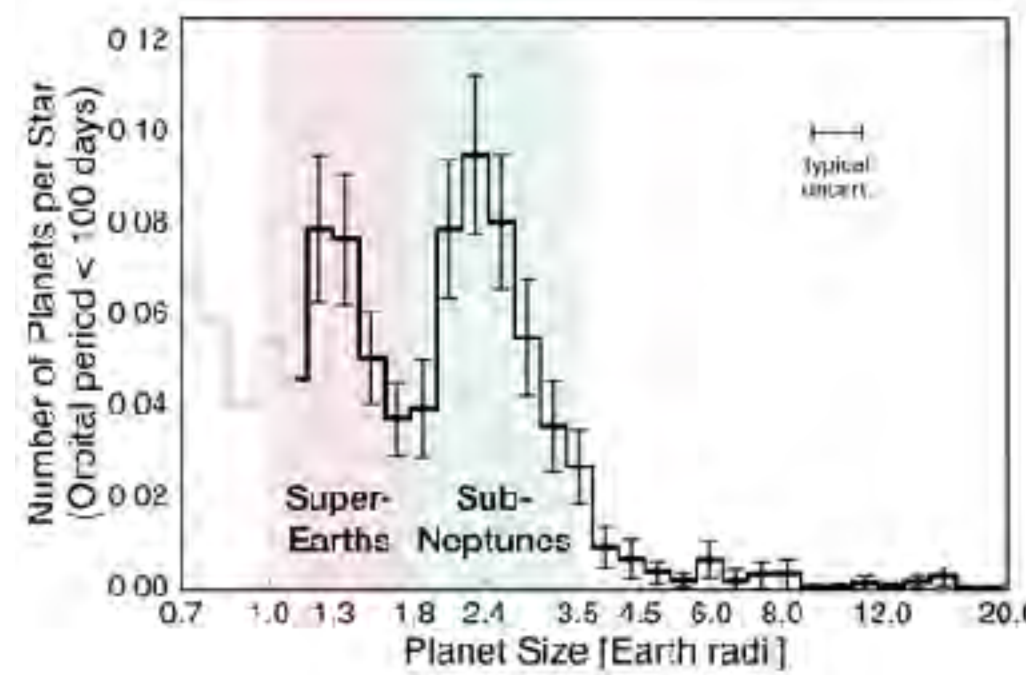


Plots by Erik Petigura

Planet Densities and Radii

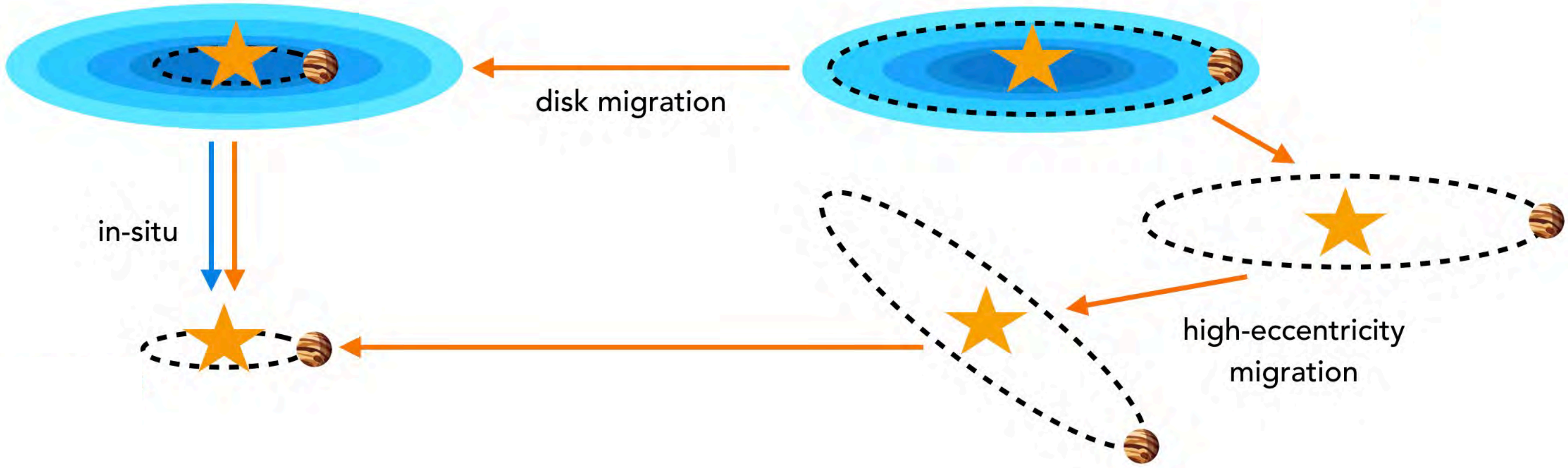


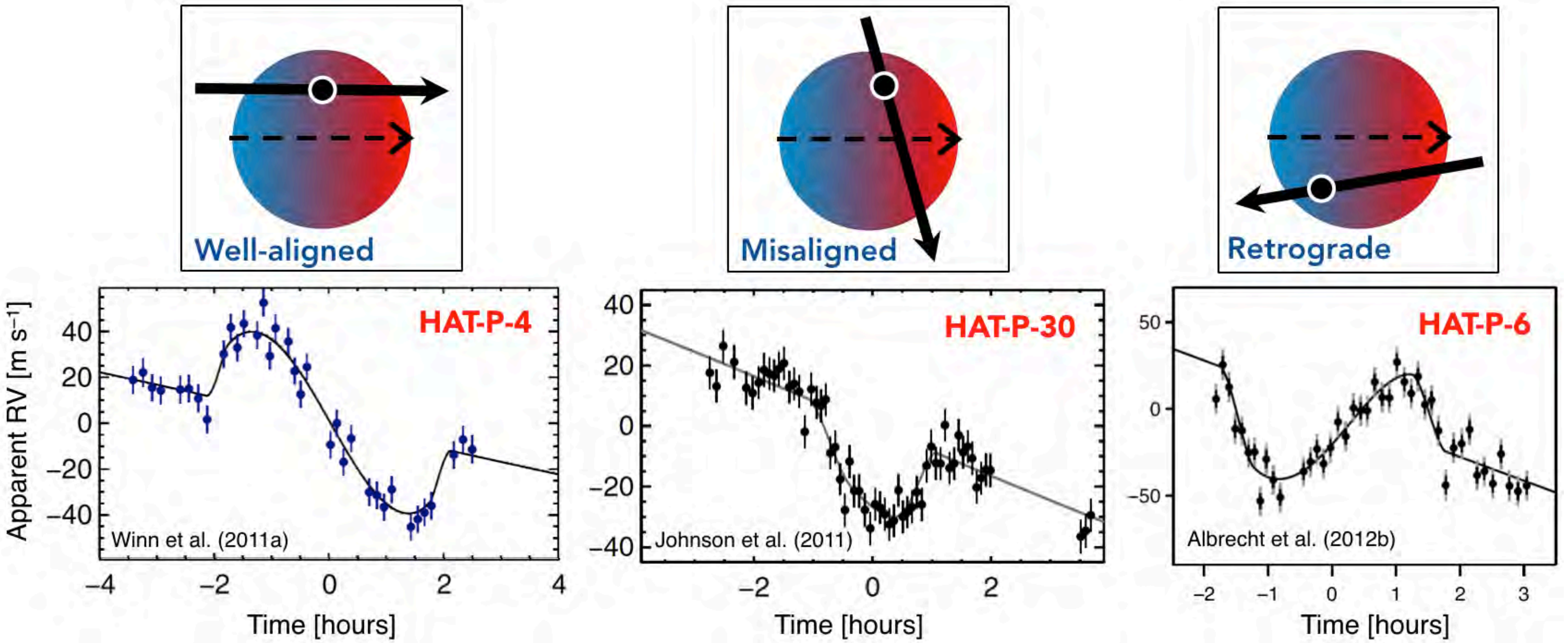
Sinukoff et al. (in prep)



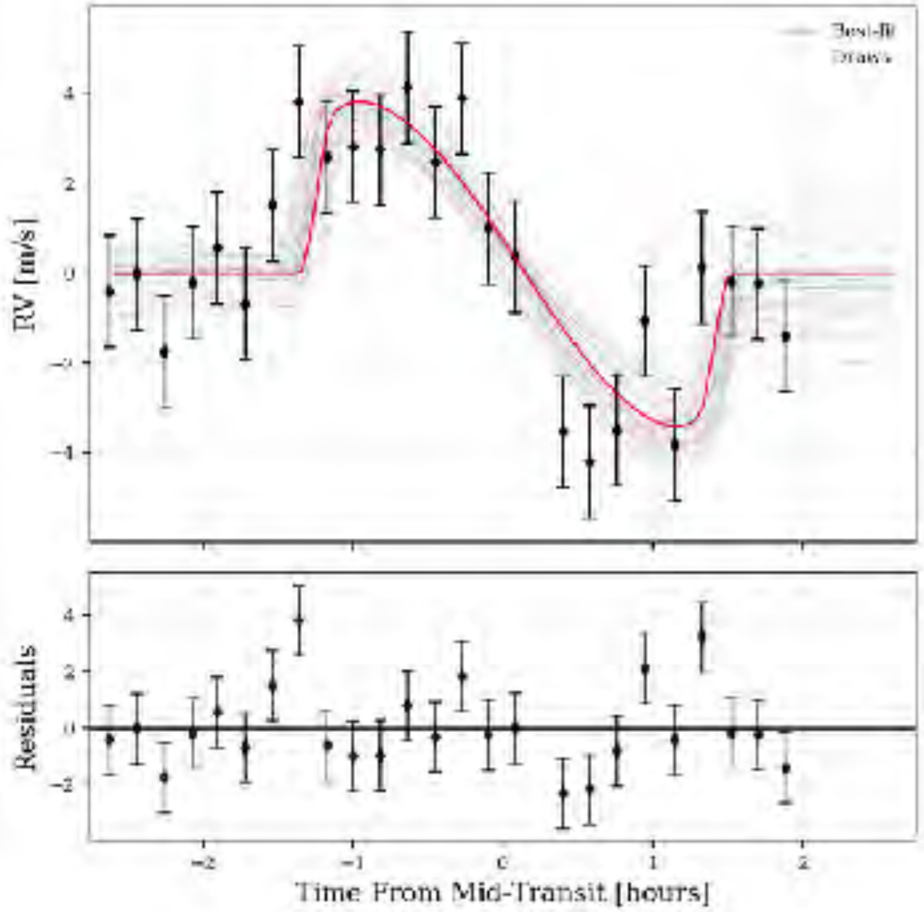
Fulton et al. (2017)

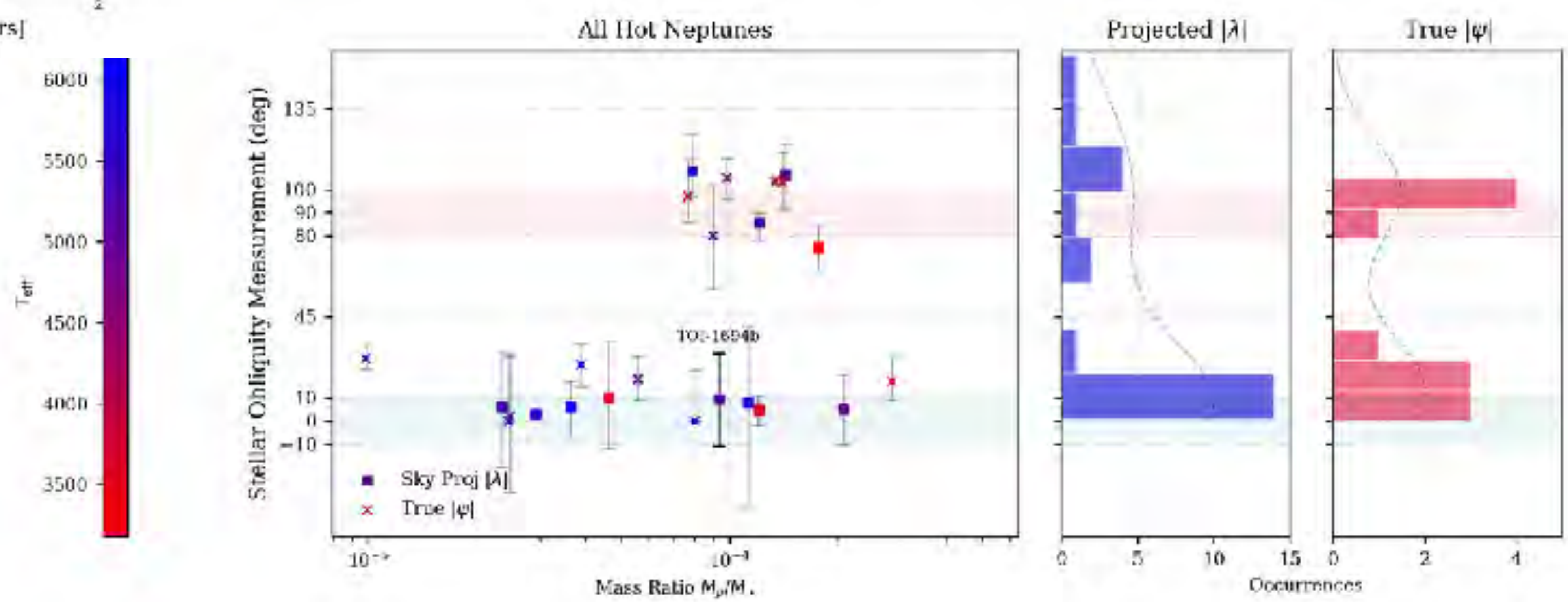
Obliquities





Luke Handley - Obliquities





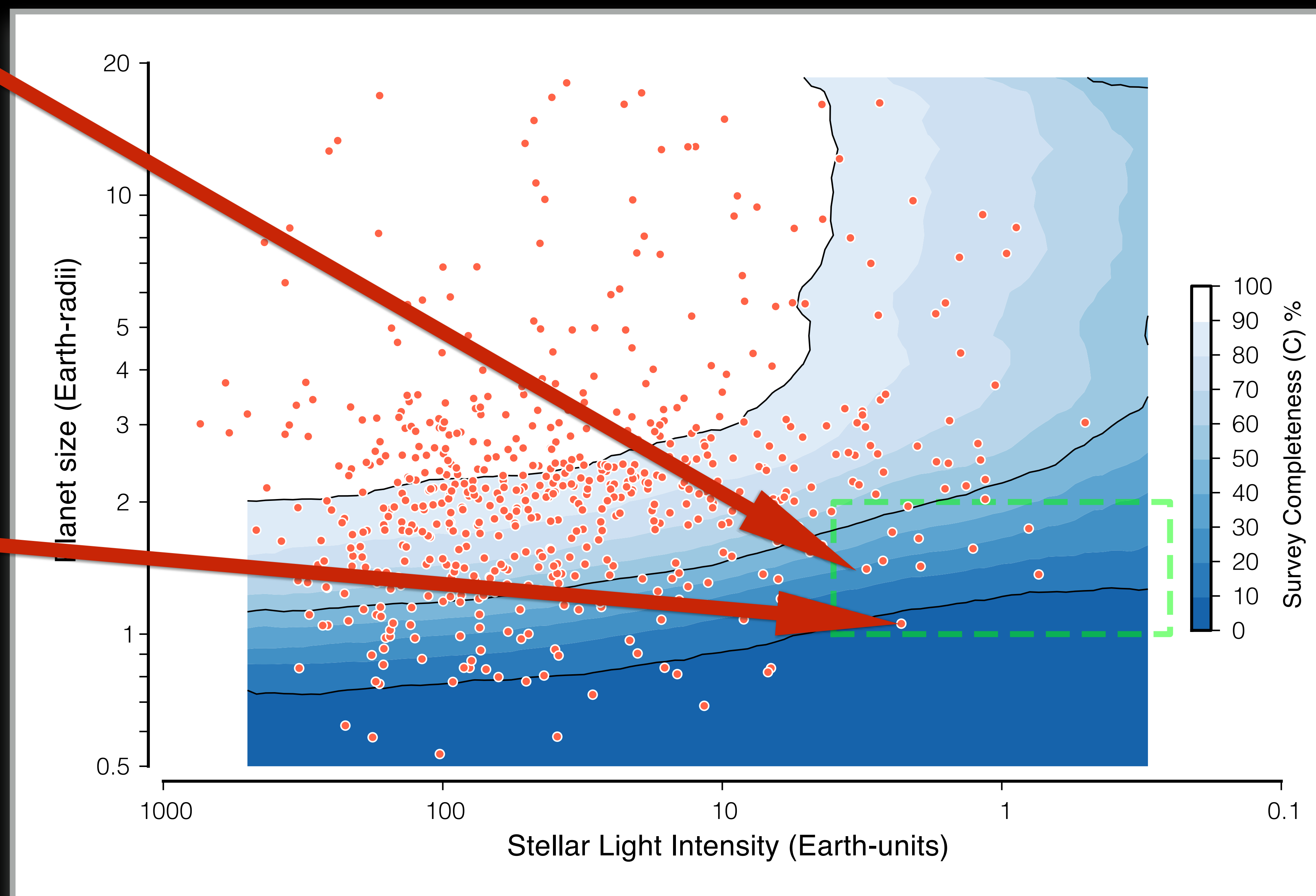
Rocky

or

Puffy?

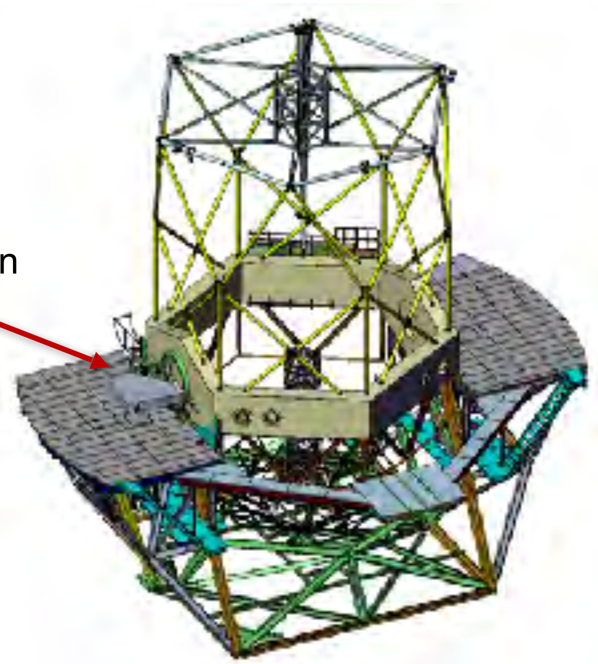
Determine if cool Earth-size planets are rocky.

Earth-size planets known from Kepler



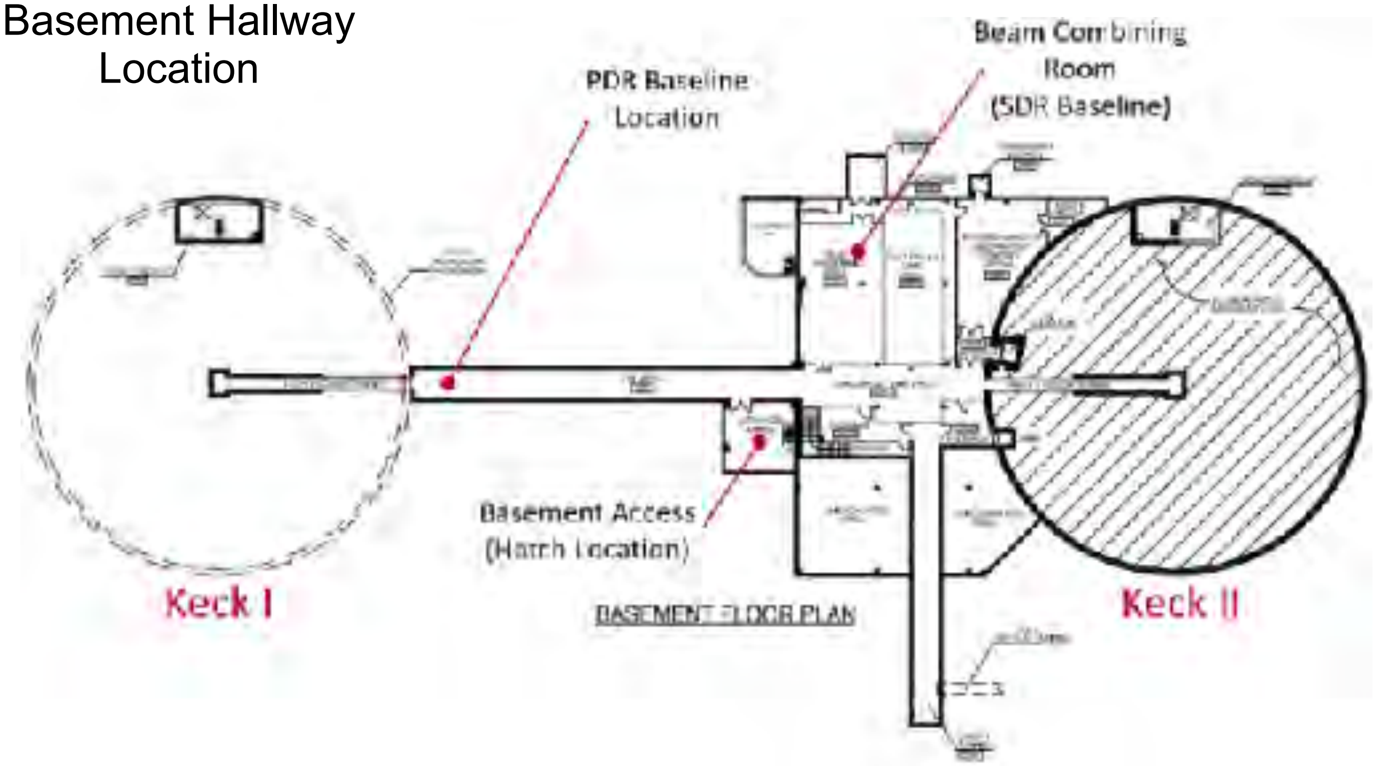
Petigura, Howard, & Marcy (2013)

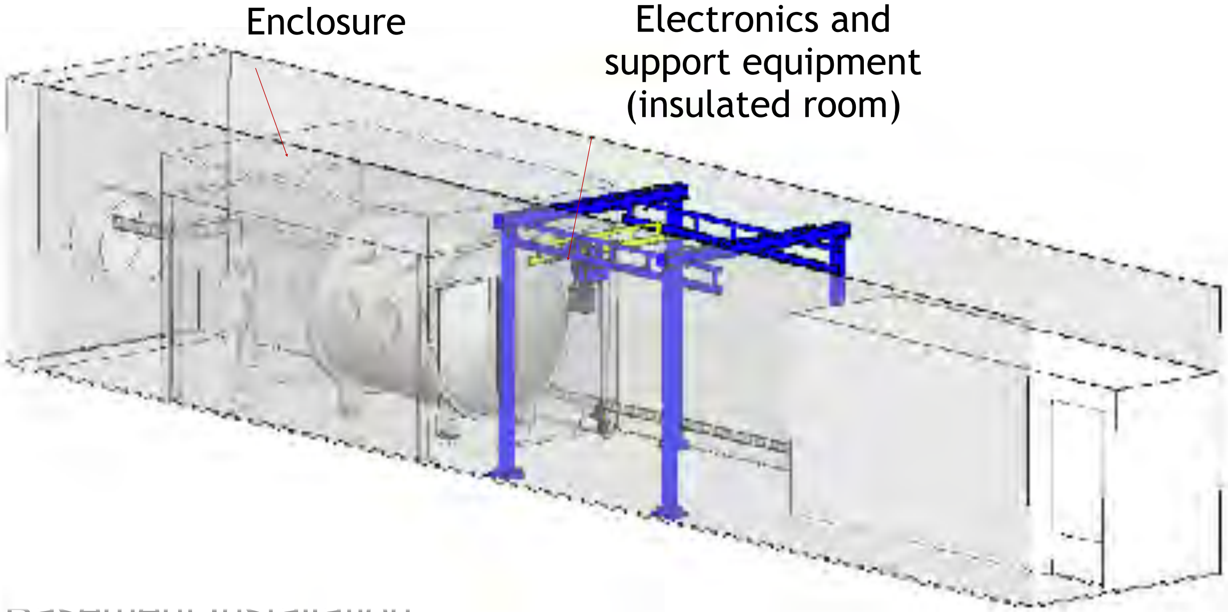
KPF System Overview



Keck I Telescope

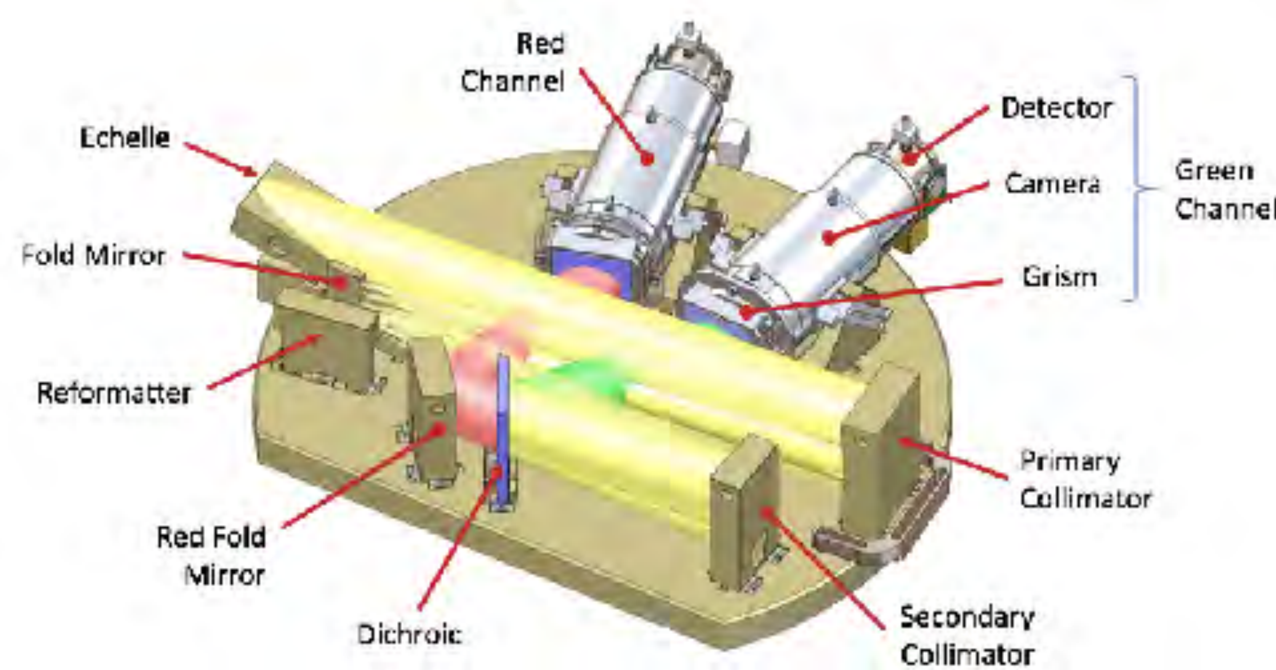
Basement Hallway Location



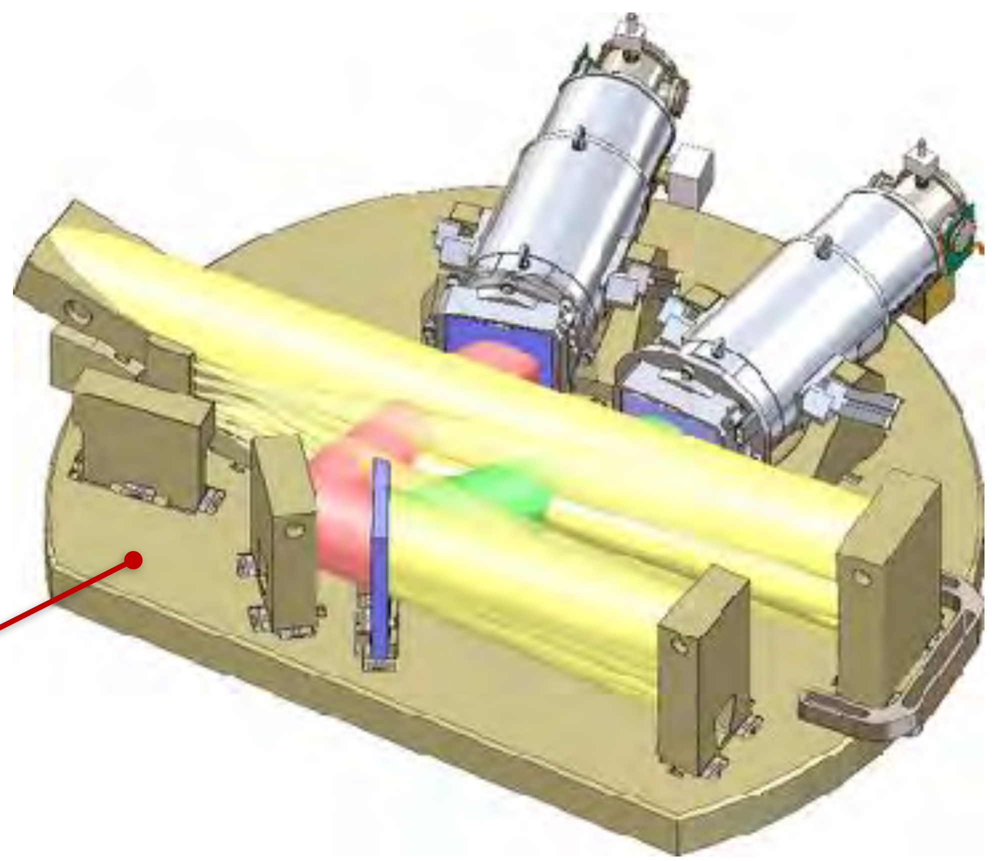


Basement Installation

Spectrometer



Mechanical Stability: Zerodur Optical Bench

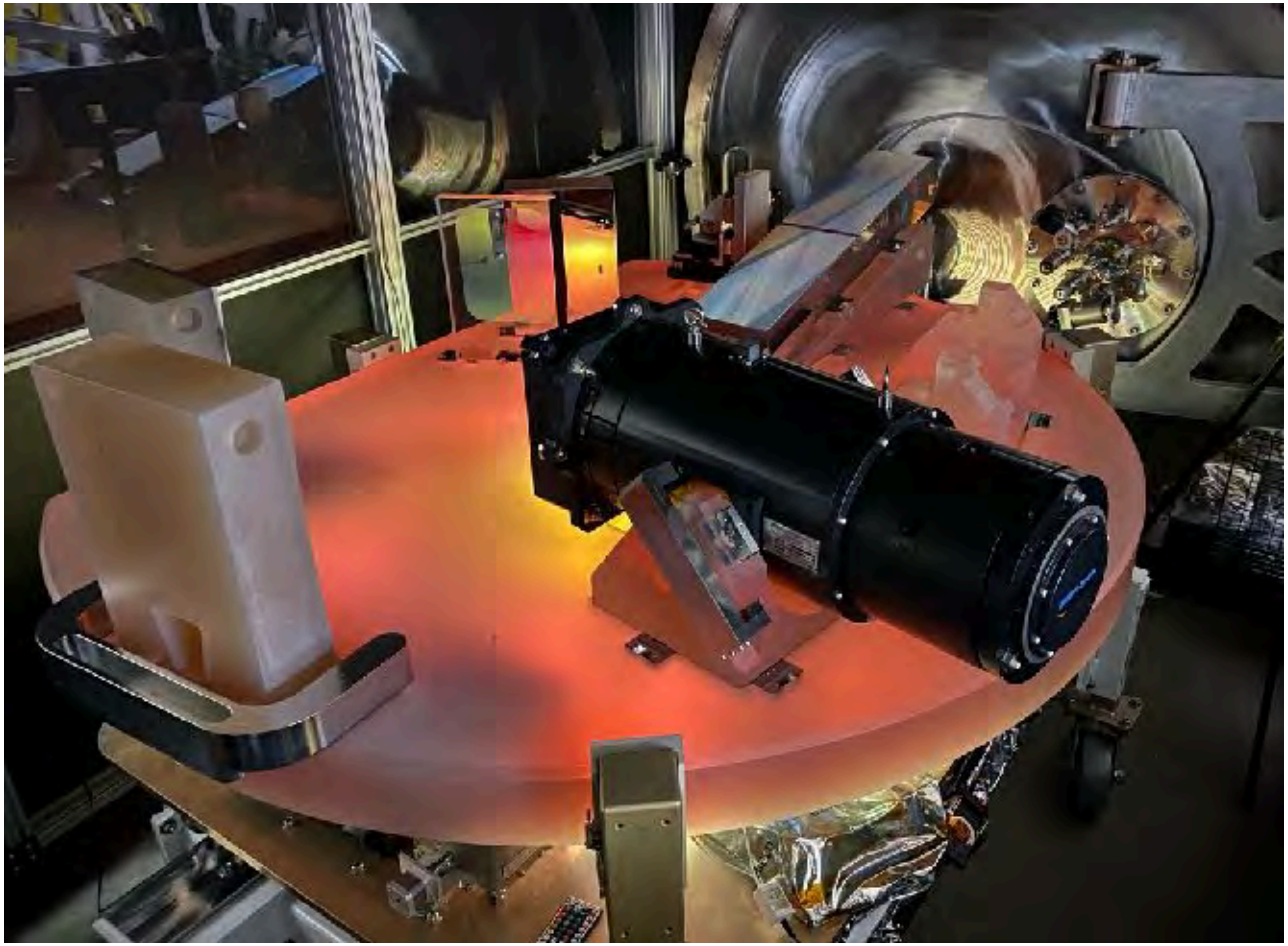


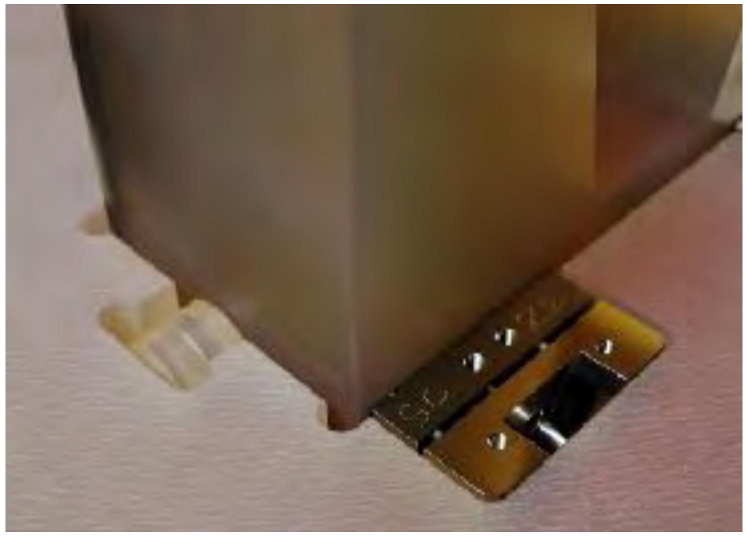
Primary advantage is very low CTE:

Material	CTE [10-6 K-1]	Relative to KPF Zerodur
Zerodur (KPF disk)	< 0.005	1x
Invar 36	1.0	200x
Stainless 416	8.5	1700x
Stainless 304	14.7	2940x

- Unique opportunity: availability of 2 m x 0.4 m Zerodur disk
  (purchased, but not used by, another project at SSL)

KPF System Overview





Above: Zerodur optical bench with integral mount and optic

Zerodur's thermal expansion (CTE) is 1000x lower than invar

Zerodur Optical Bench

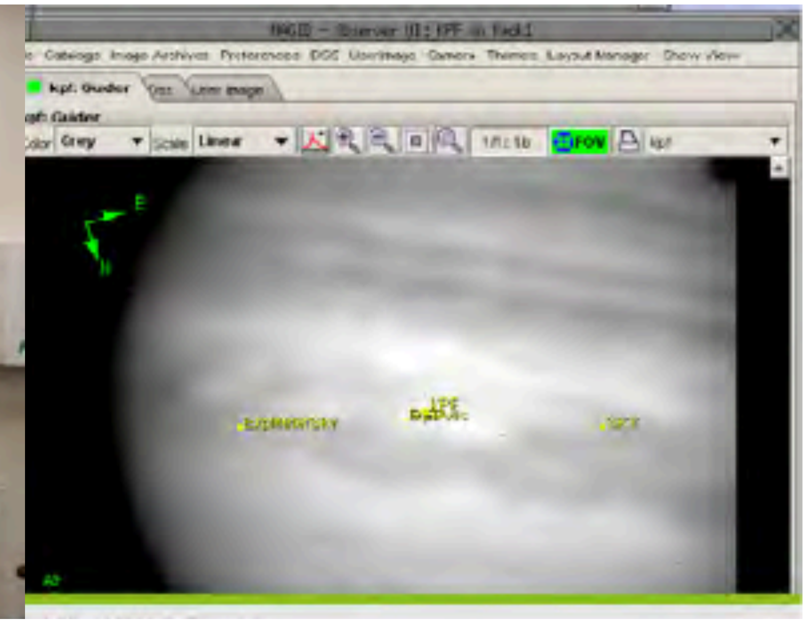
Spectrometer optical bench being lifted onto isolation frame

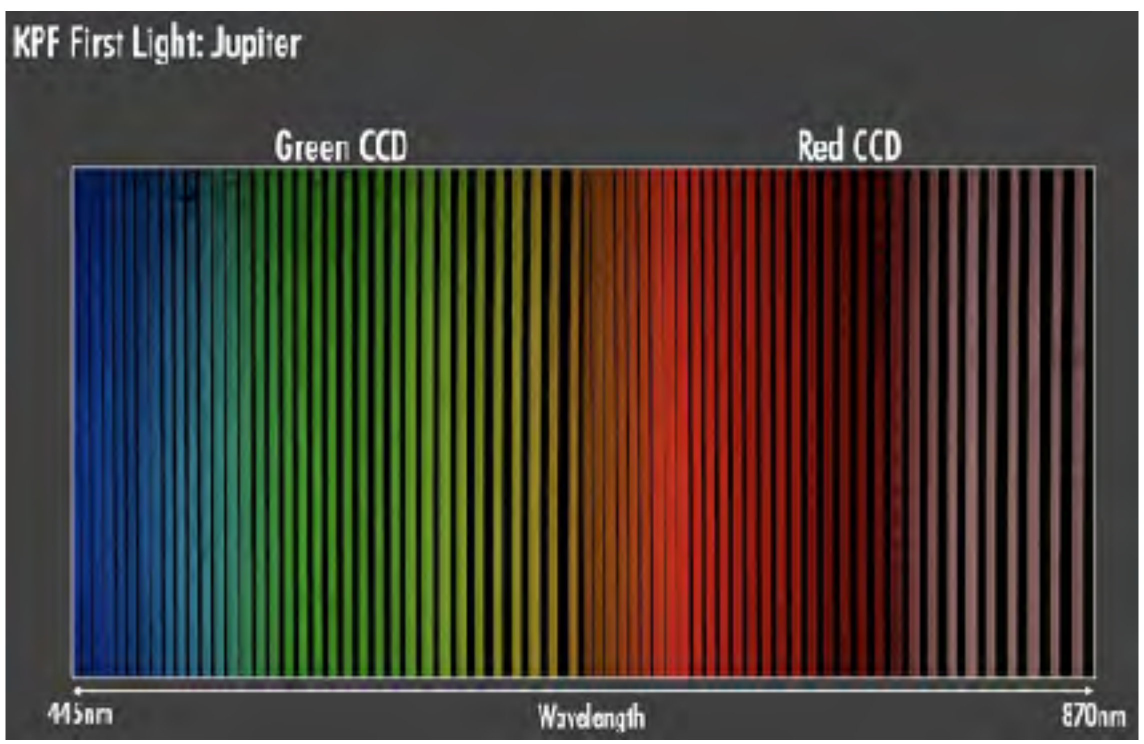
KPF Arrives at Keck Observatory

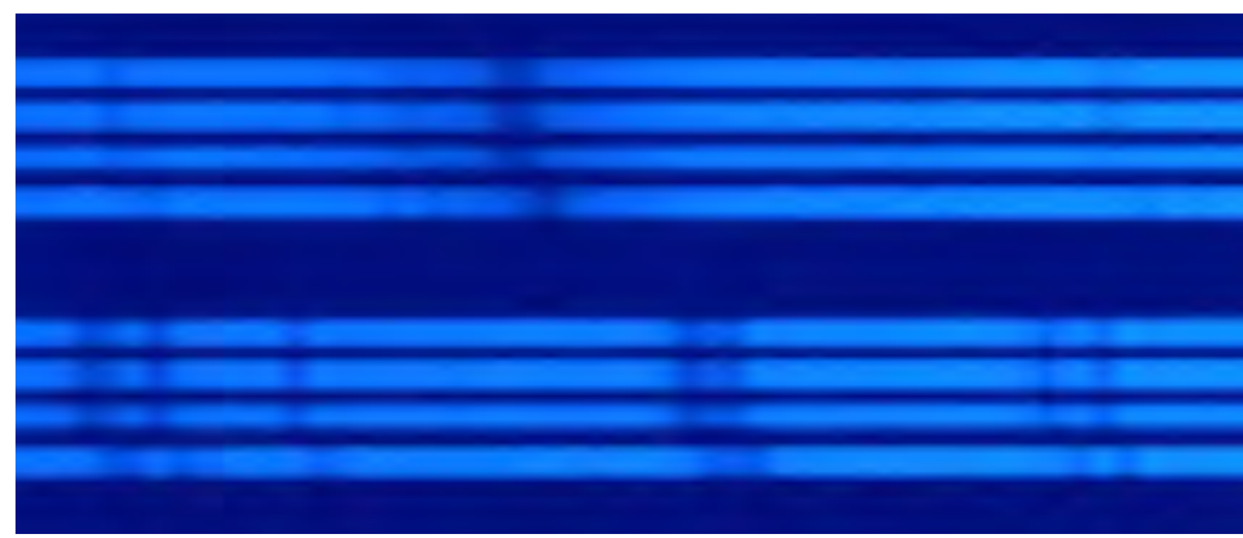
Reassembling the KPF Spectrometer

Solar Calibrator Now Installed

First Light in November, 2022

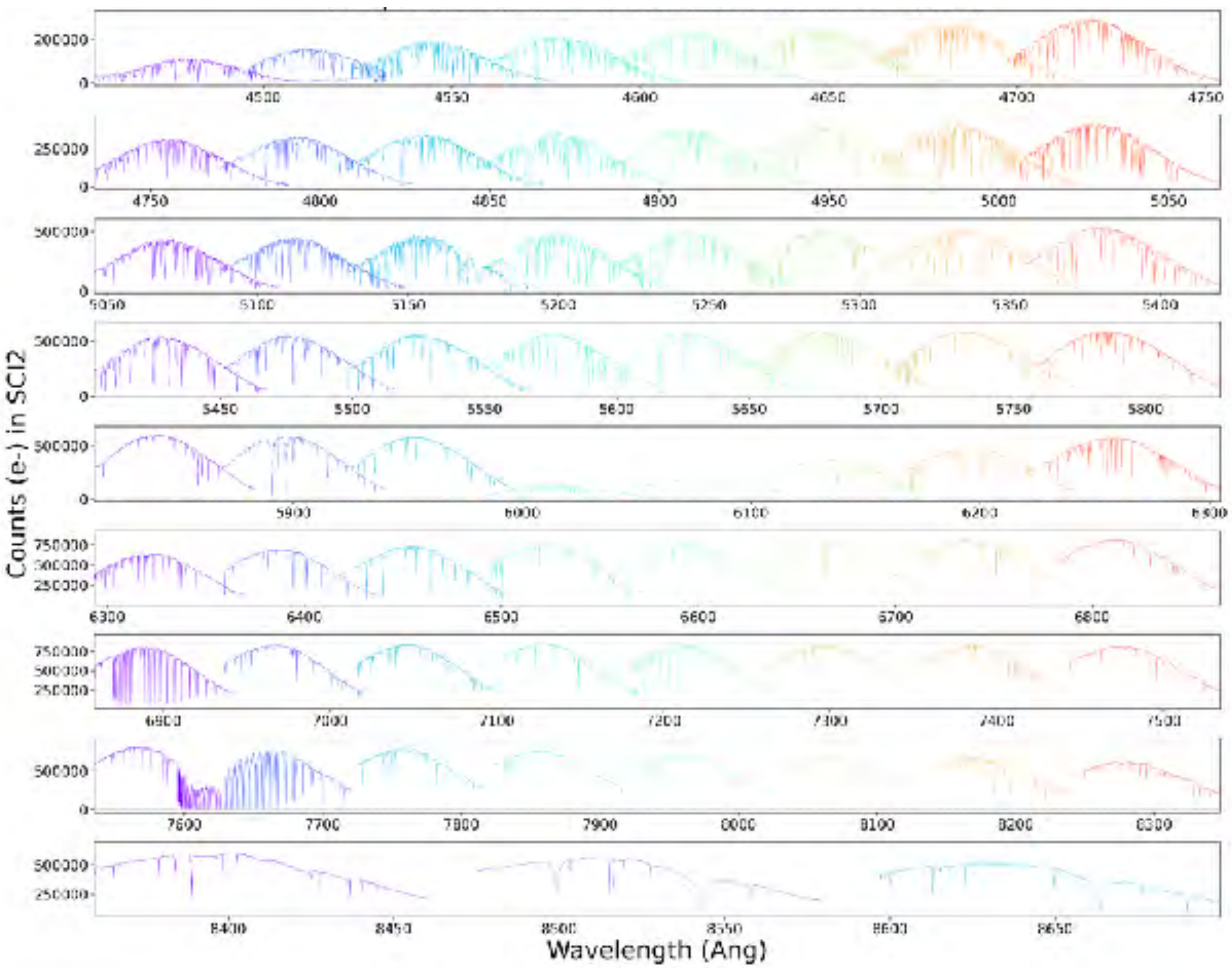


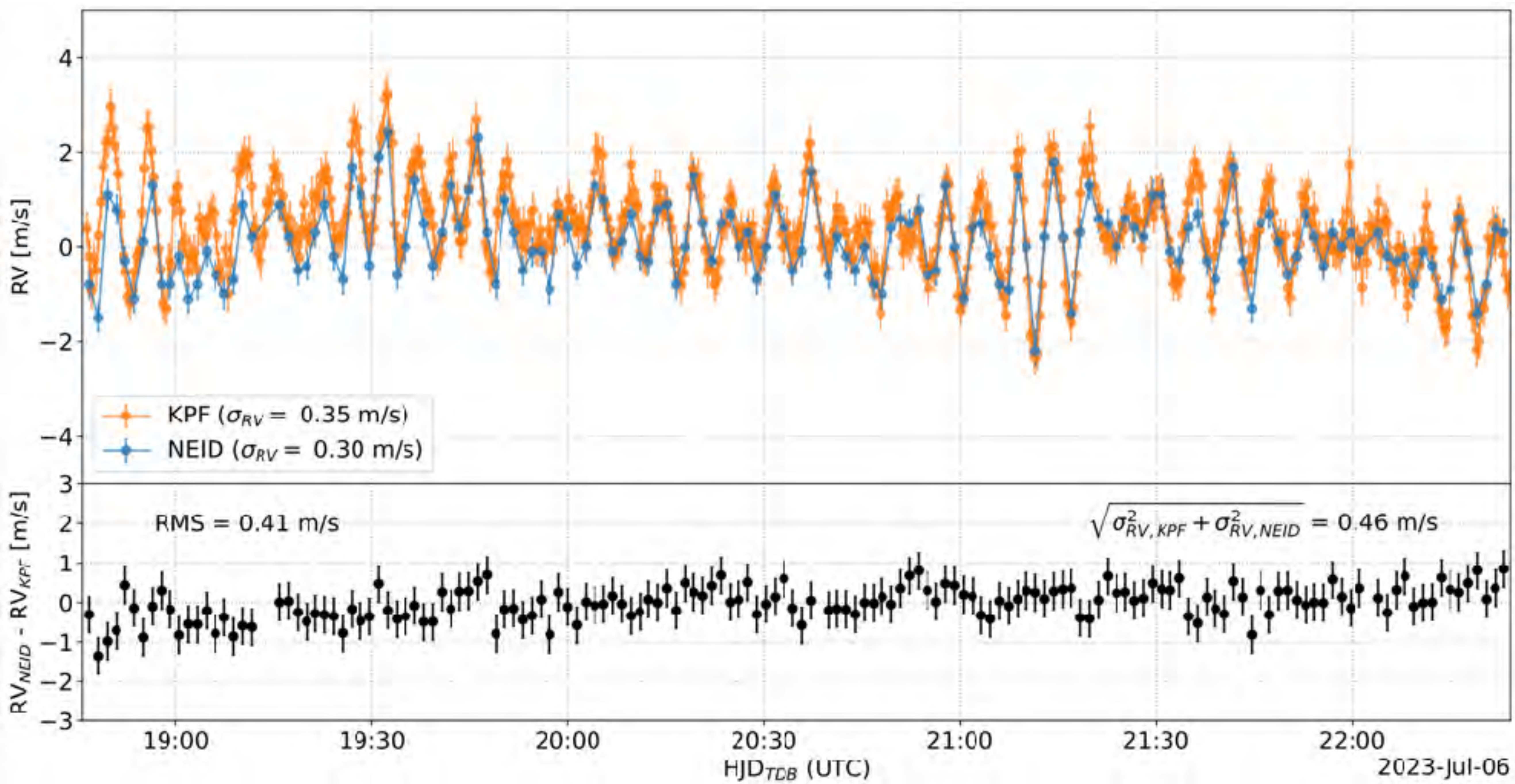




Raw spectrum - Jupiter

KPF Data Products: Beautiful Spectra



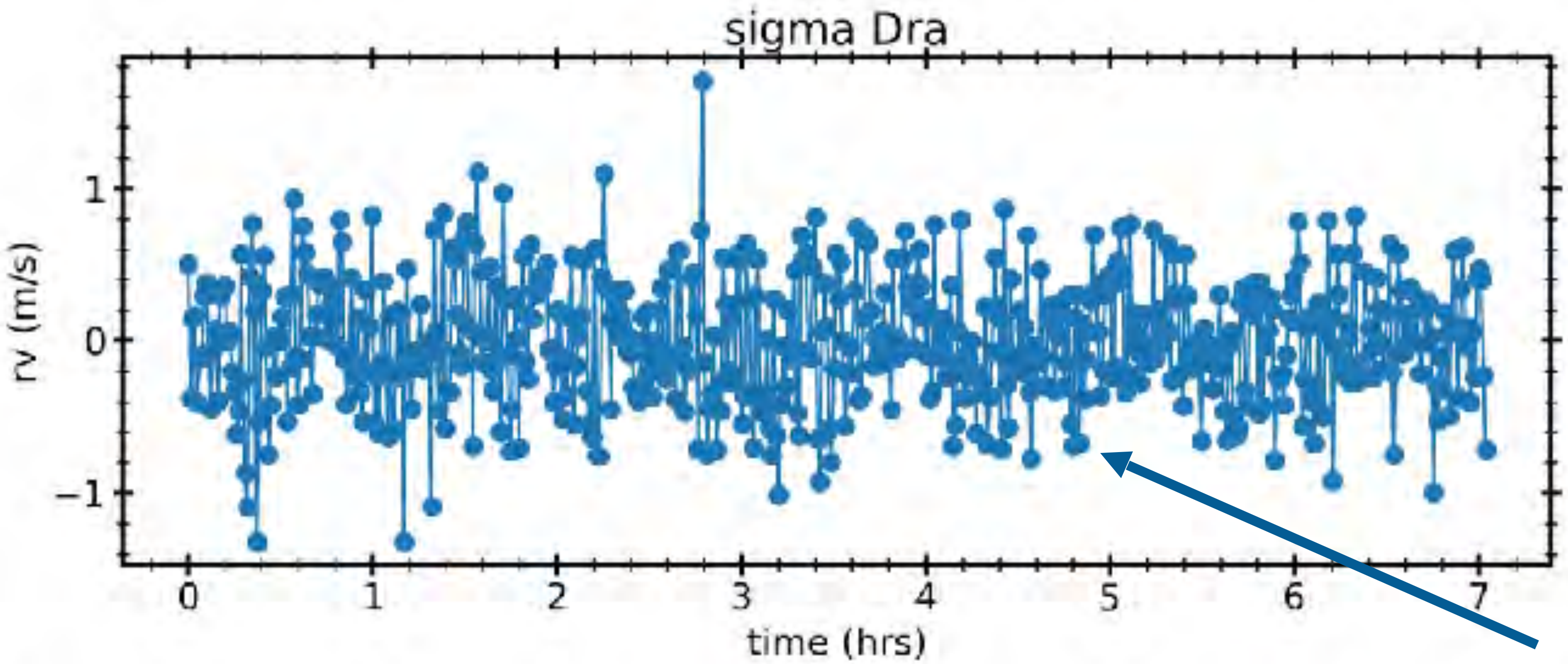


KPF + SoCal: 21 sec cadence:
5s exposures +
16 sec (!) readout

NEID: 85 sec cadence:
55s exposures +
30 sec readout

Rubenzahl et al. (submitted)

KPF Science Examples – Asteroseismology



Sigma Draconis:

K0V, V=4.7

560 exposures:

30s exposures + 15s readout

41 cm/s over 7 hours (including signal!)

14 cm/s peak amplitude

2 cm/s noise (per mode)

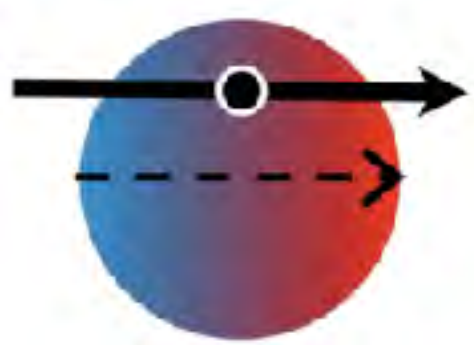
Huber et al. (in prep)

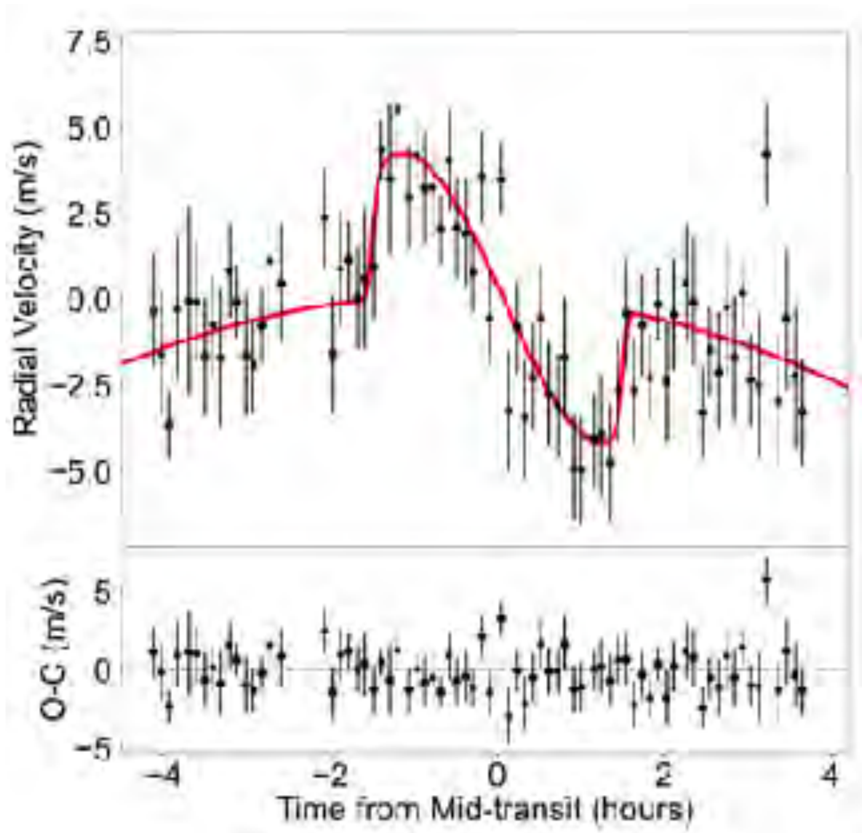
KPF Science Examples – Stellar Obliquity

TOI-4495:

Young Planetary System with two planets

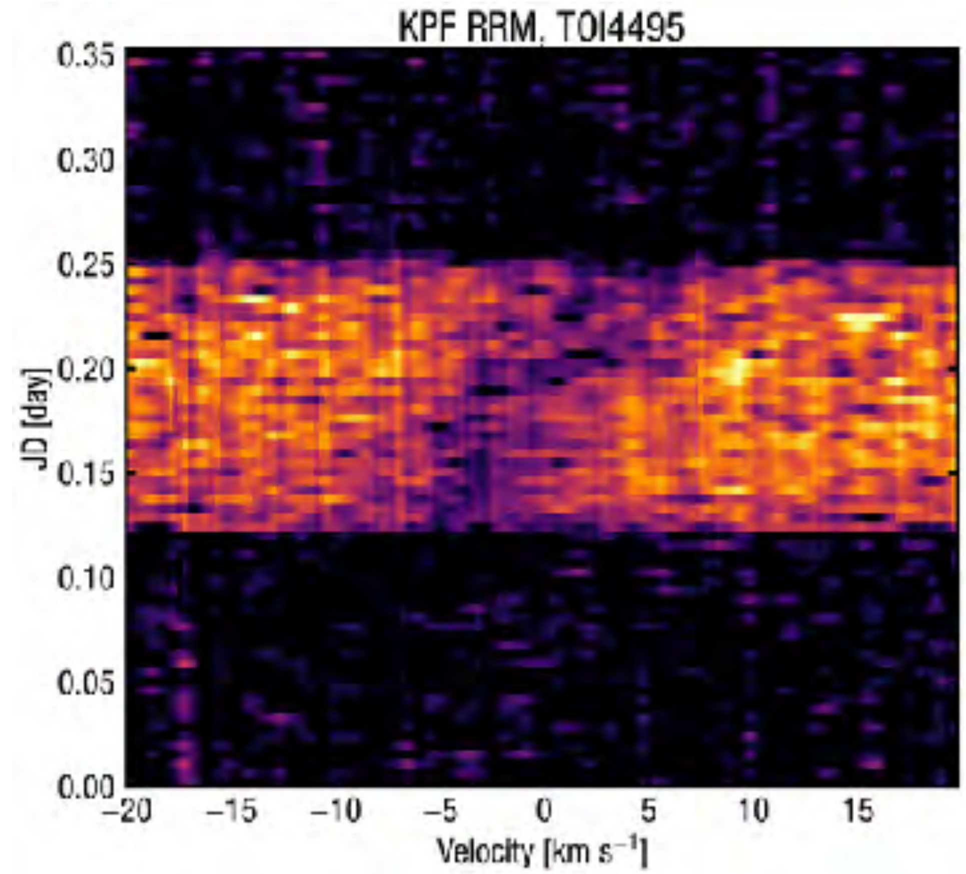
Obliquity Measurement with KPF





Rossiter-McLaughlin analysis

RM amplitude ~ 3 m/s, easily detected



Reloaded R-M

Signal is ~400 ppm, one of the lowest ever recorded

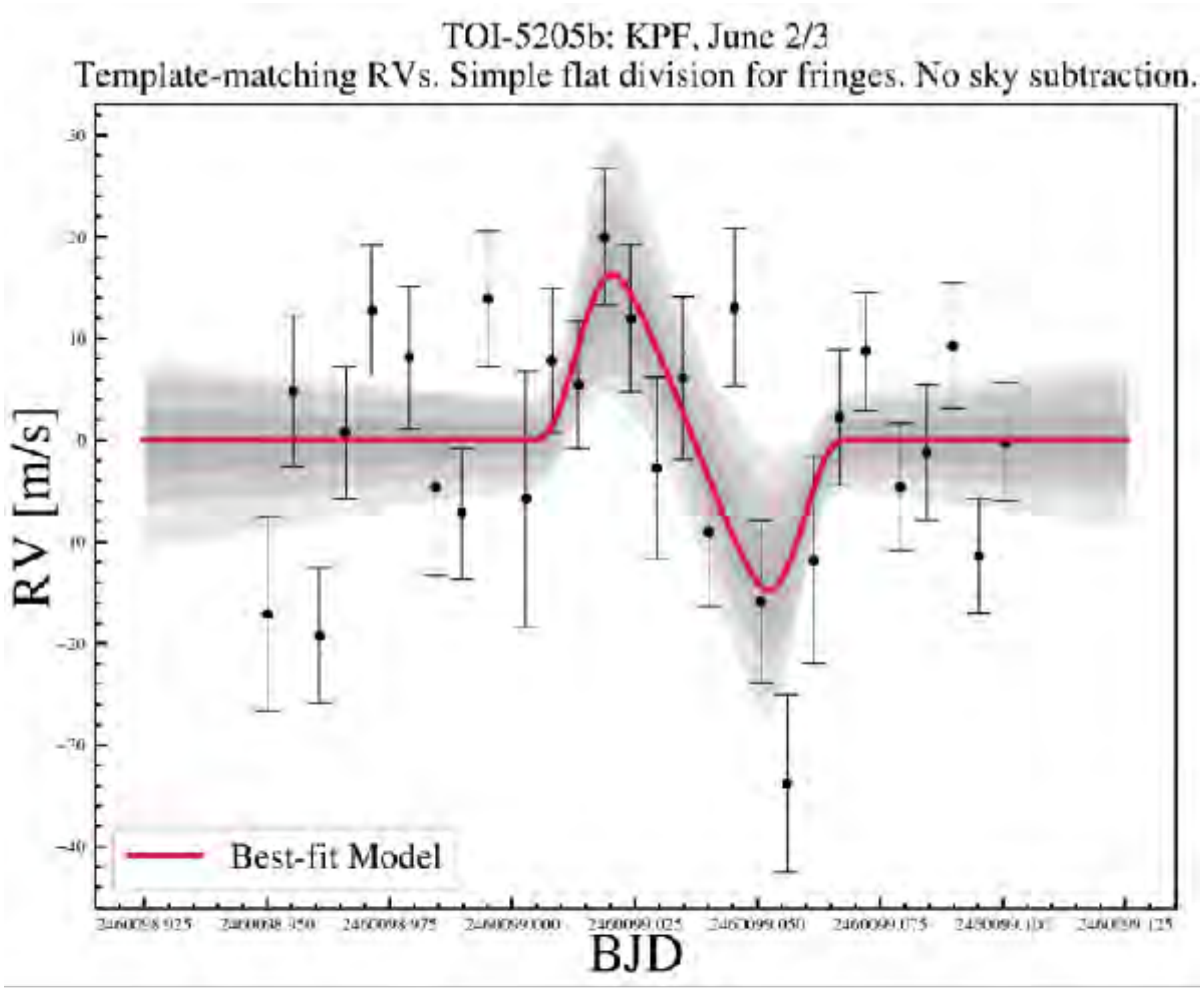
Dai et al. (in prep); plot from S. Halverson

KPF Science Examples – Stellar Obliquity

TOI-5205b:
First Hot Jupiter around
M dwarf

Obliquity Measurement
with KPF
Upcoming JWST atmos.
observations

Very faint: V = 15.9 !
(most signal comes from
red optical spectrum)

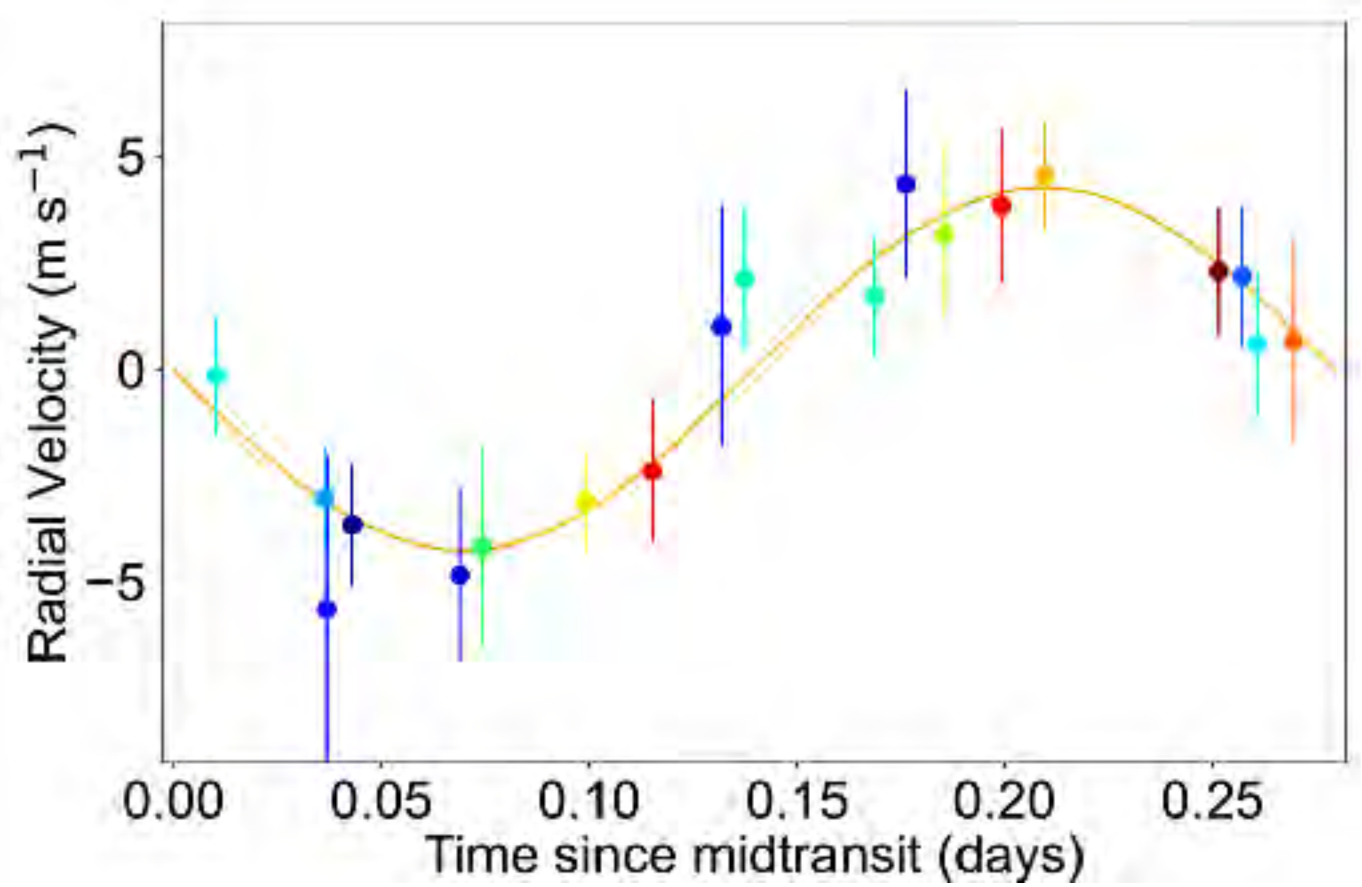


Stefansson et al. (in prep)

KPF Science Examples – Measuring Planet Masses

TOI-6324b:

Earth-size planet (1.0 Earth-radii)
ultrashort-period orbit (0.28 days)
RVs are phasing up! →



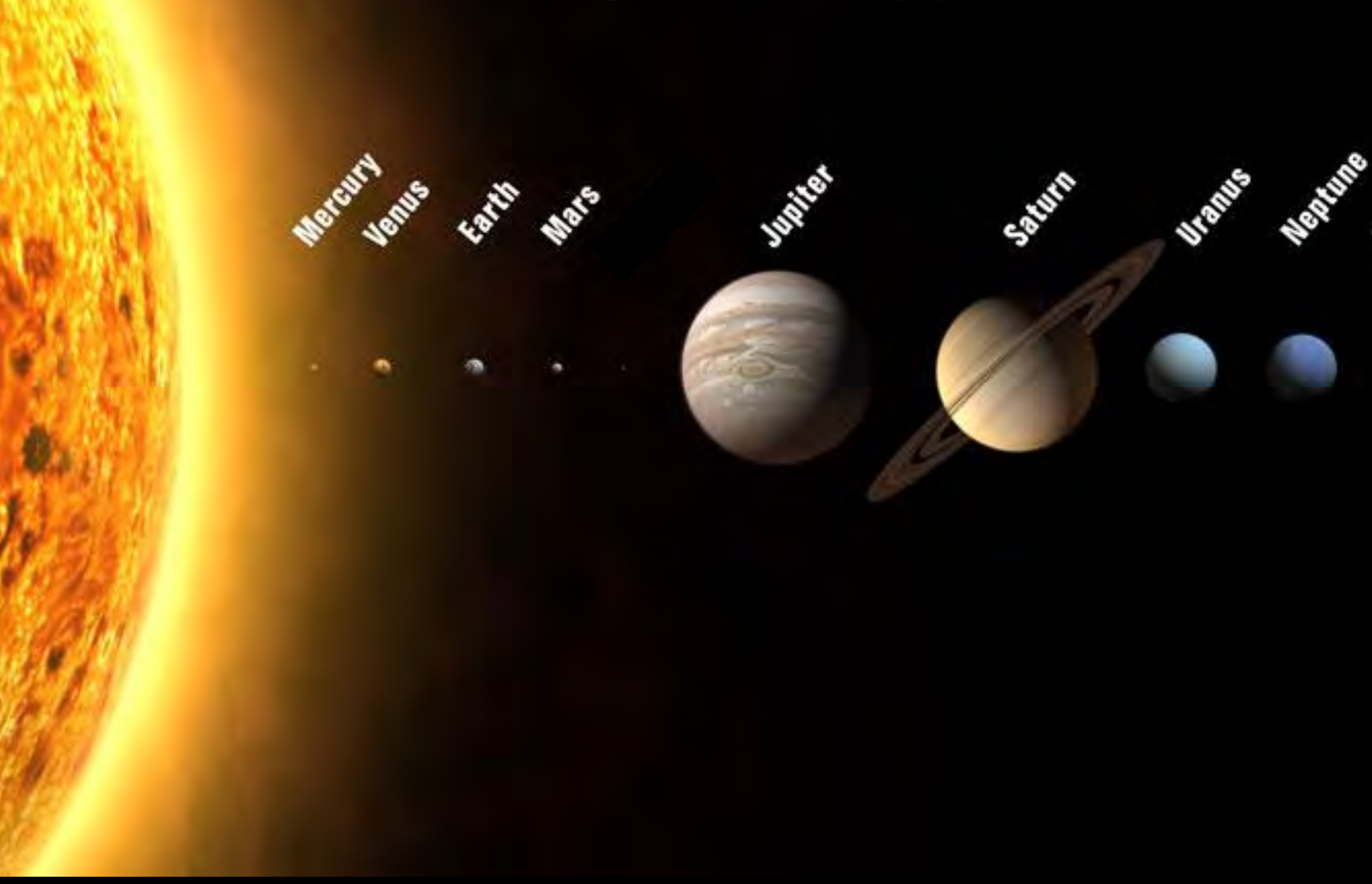
Excellent JWST target to determine surface mineralogy

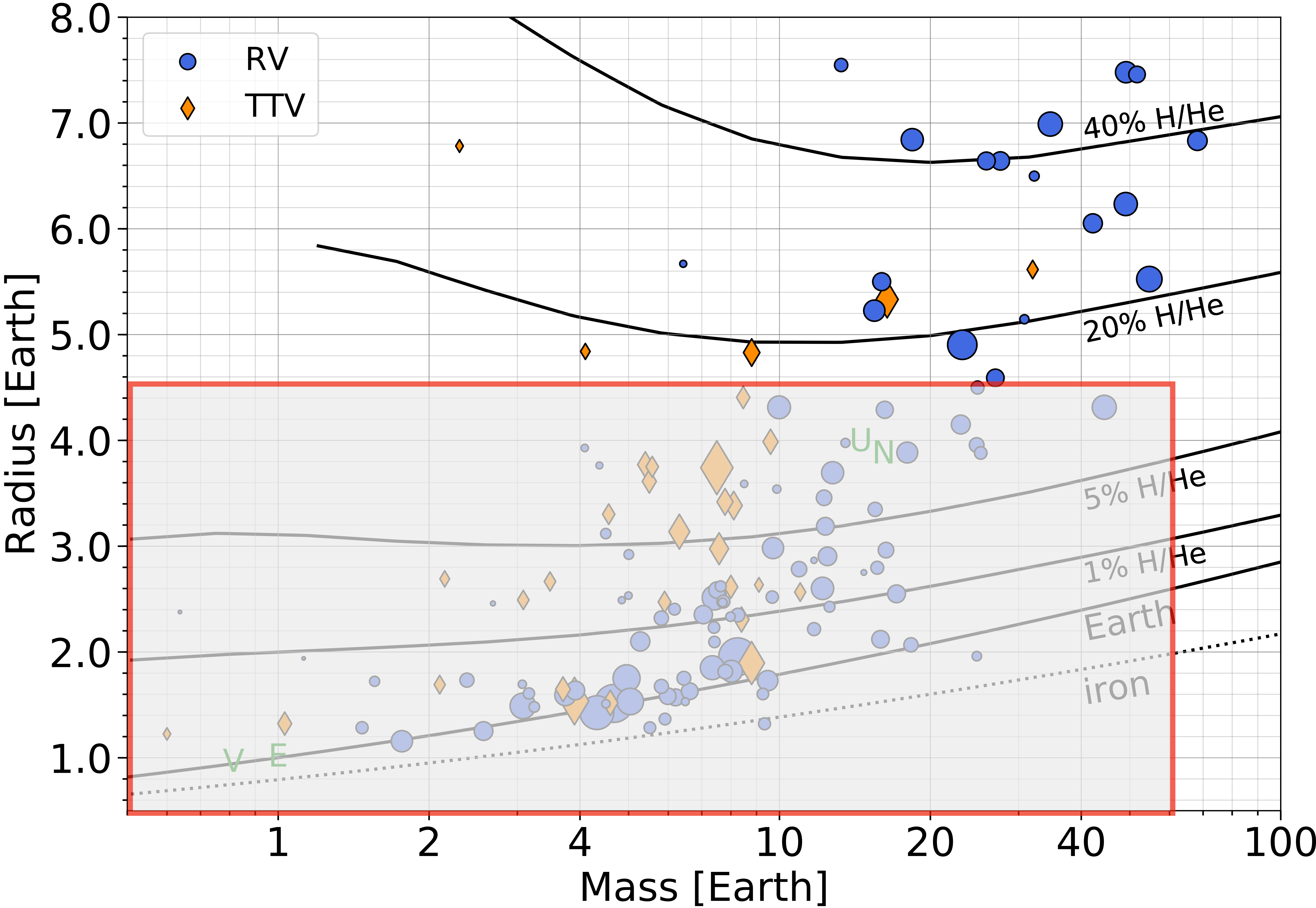
part of ongoing NASA KSMS program;
PI: Fei Dai

Dai et al. (in prep)

Time for Extra Slides on Planet Architectures?

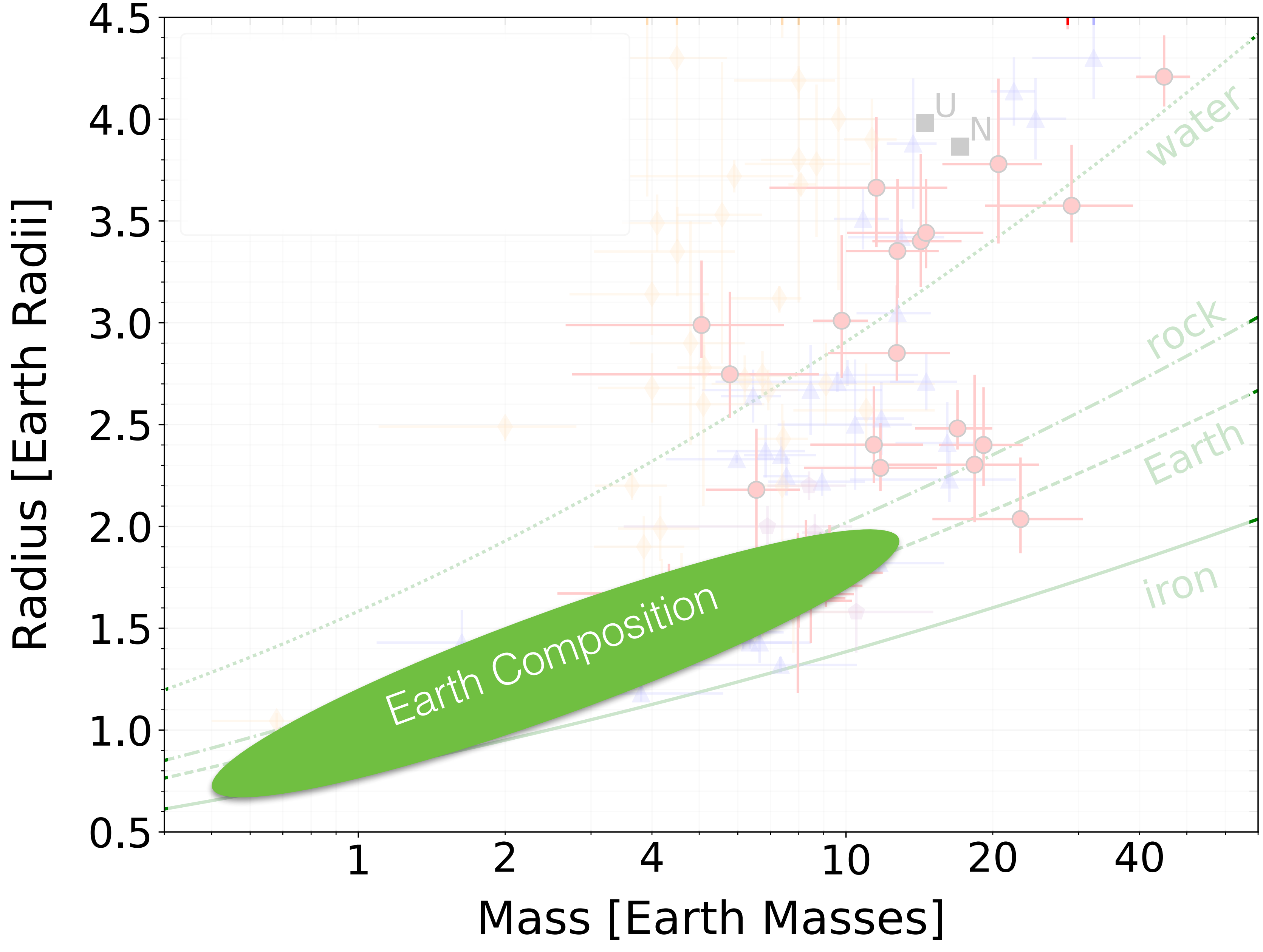
Planetary Archetypes





8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
Radius [Earth]
RV
TTV
40% H/He
20% H/He
5% H/He
1% H/He
Earth
iron
U
N
V
E
1
2
4
10
20
40
100
Mass [Earth]

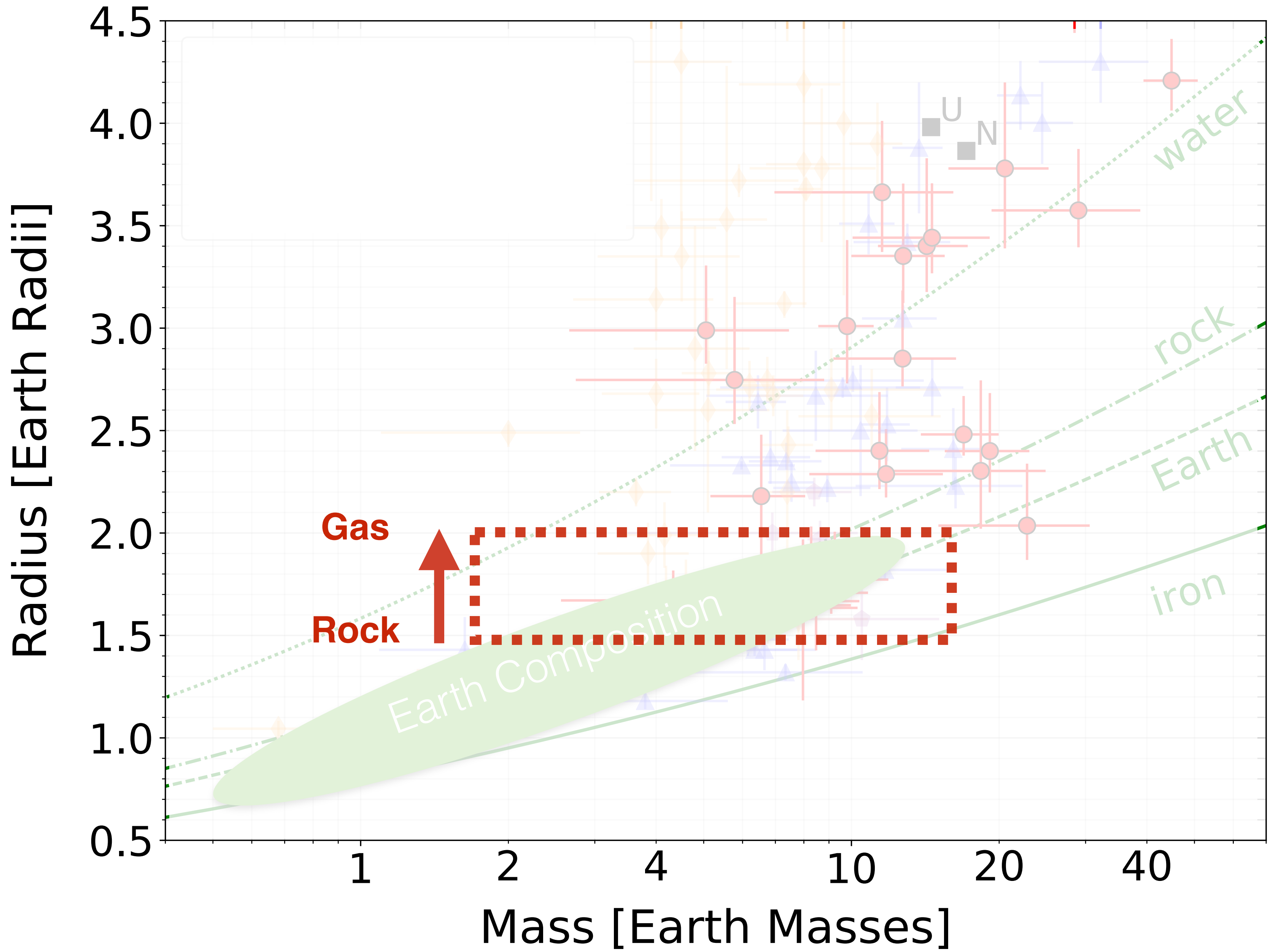
Planetary Archetypes



Earth Composition Planets

- “Super-Earths"
- Max size: ~1.8 R_E
- Max mass: ~10 M_E
- Straddle Earth and Rock M-R curves
- Probed by USP population
- Shaped by photo-evaporation

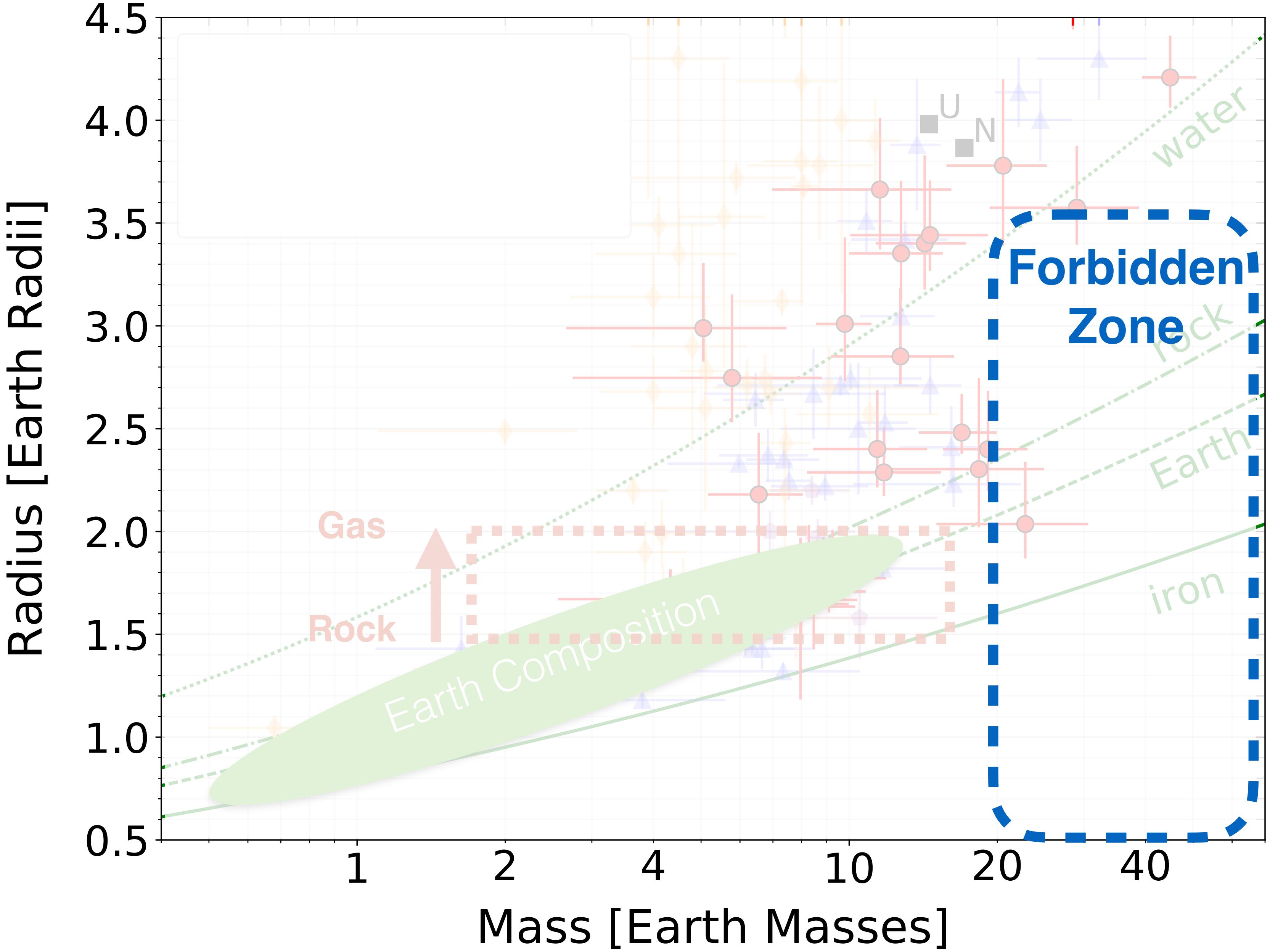
Planetary Archetypes



Rock → Gas Transition Zone

- Transition radius: 1.5-2.0 R_E
- No rocky planets > 10 M_E
- Consistent with:
  - Radius-Density studies (Weiss & Marcy 2014)
  - Gap in Planet Radius Distribution (Fulton et al. 2017)

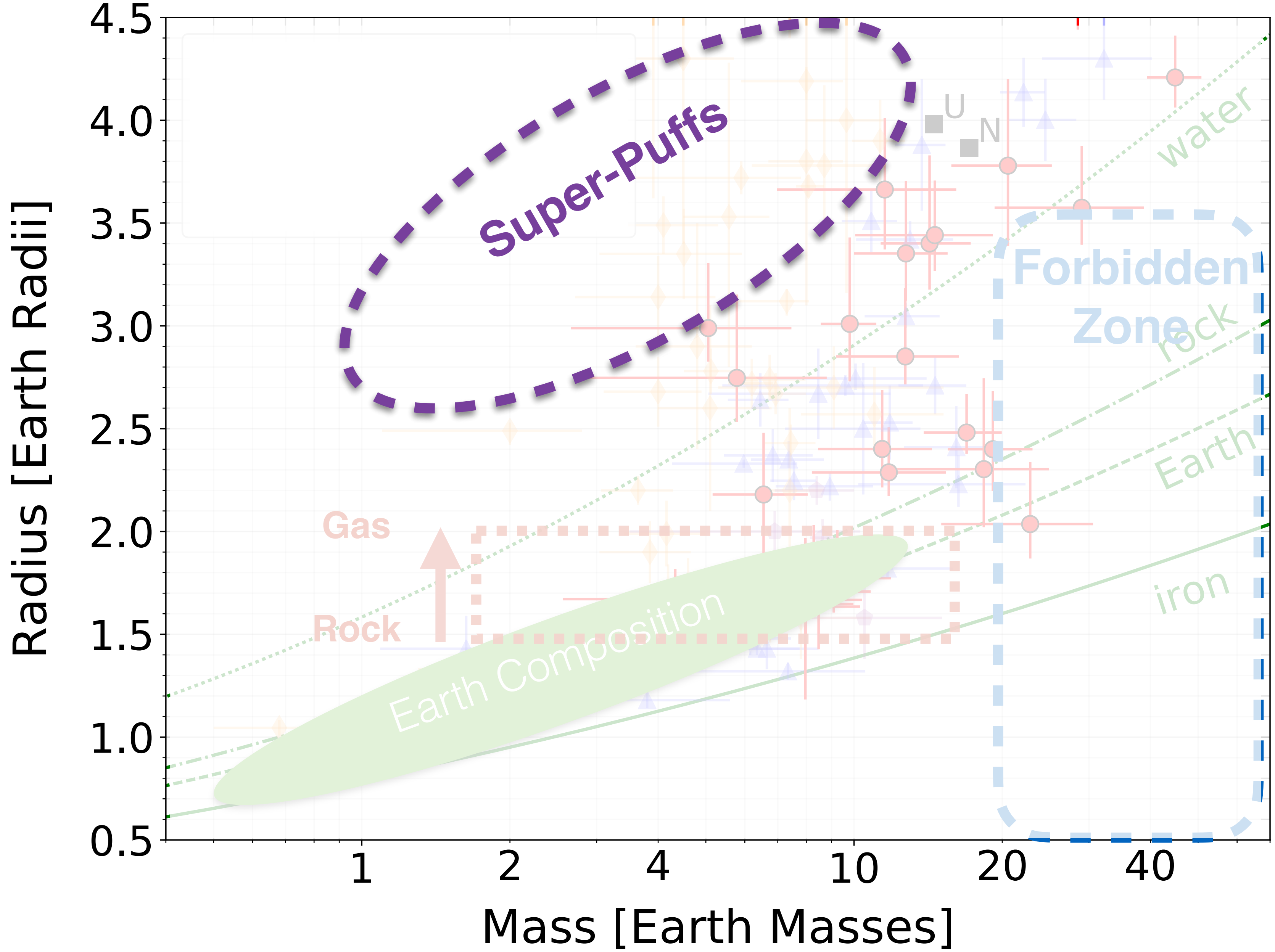
Planetary Archetypes



Forbidden Zone

- Maximum mass of a sub-Neptune is ~10-15 M_E
- Constraint on core-size distribution

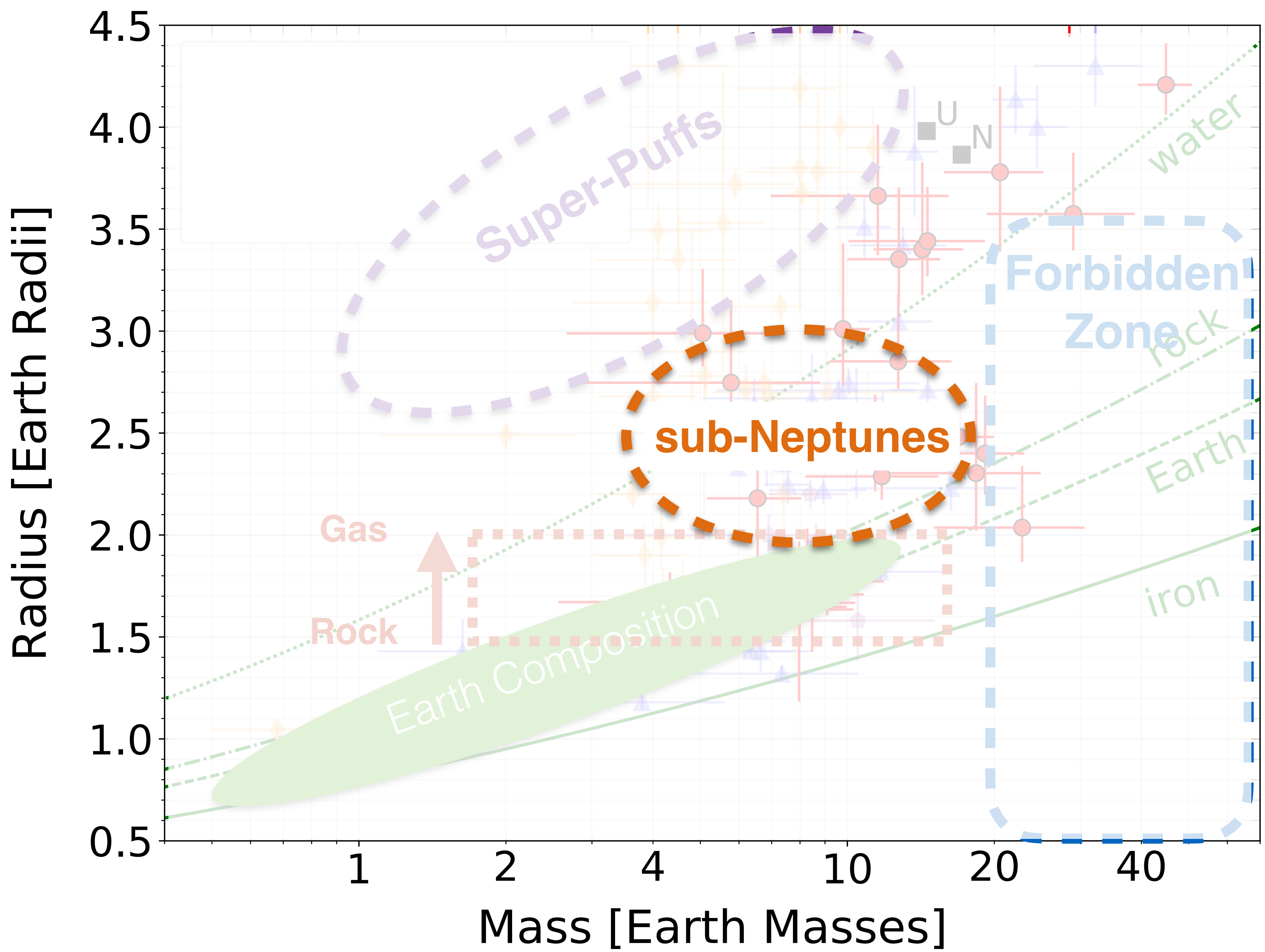
Planetary Archetypes



Super-Puffs

- Very low density → lots of H/He
- Typical core masses (~2-8 M_E)
- Poorly constrained; no super-puffs with well-measured masses

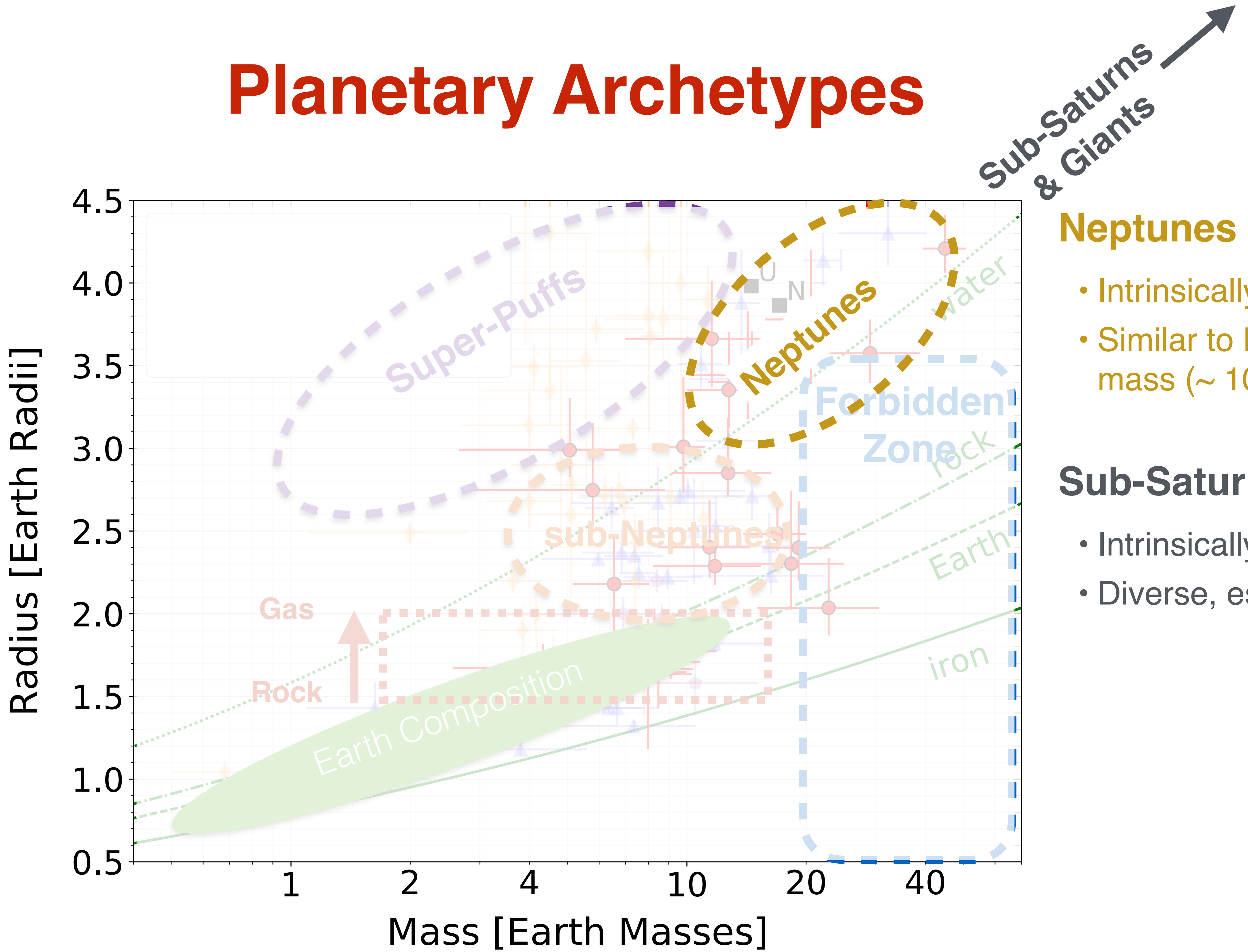
Planetary Archetypes



Sub-Neptunes

- Common planet type!
- Size: ~2-3 R_E
- Few percent H/He by mass needed to explain size & mass

Planetary Archetypes



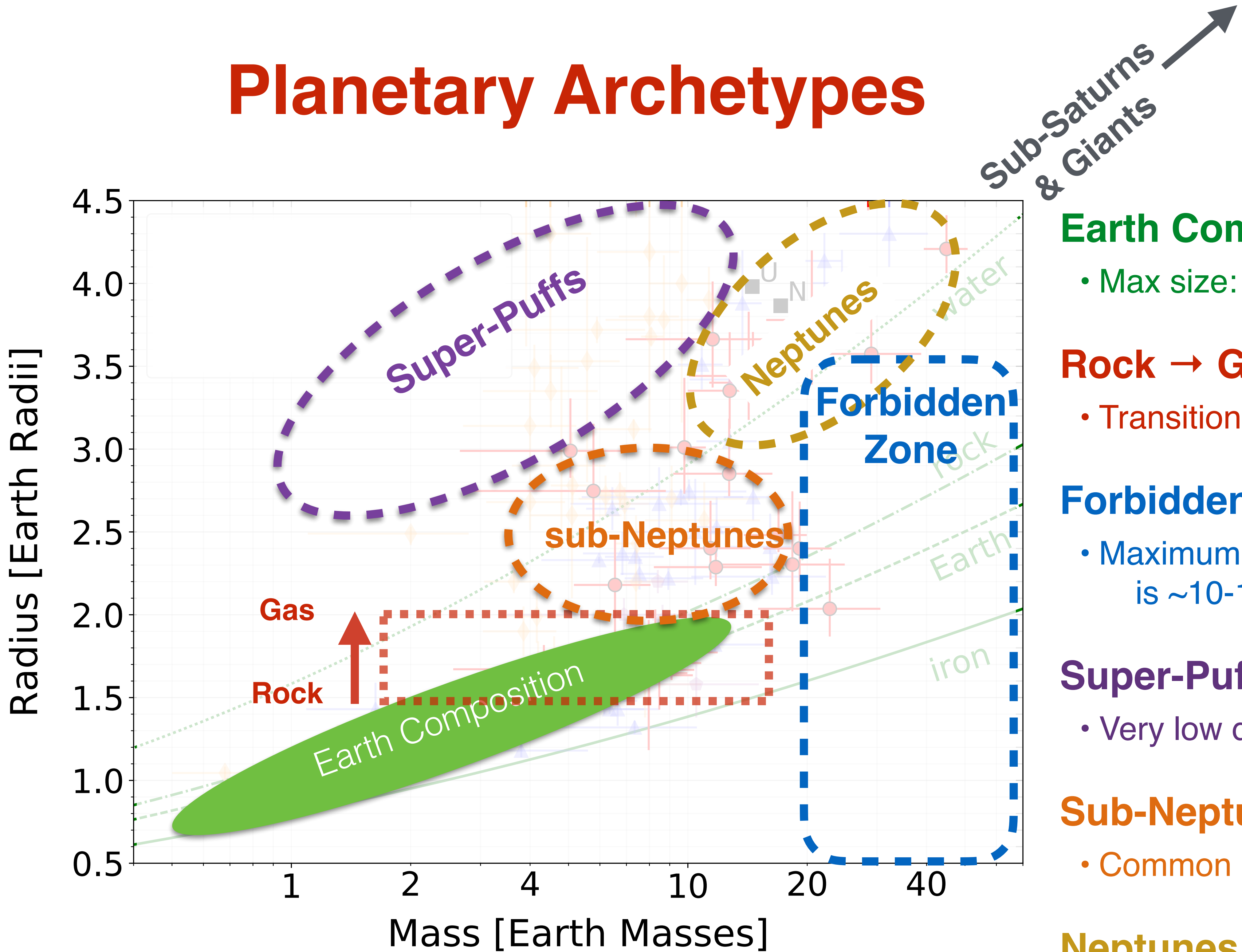
Neptunes

- Intrinsically rare
- Similar to Neptune/Uranus in mass (~ 10-40 M_E) & radius (~ 4 R_E)

Sub-Saturns & Giants

- Intrinsically rare
- Diverse, especially sub-Saturns

Planetary Archetypes



Earth Composition Planets

- Max size: ~1.8 R_E

Rock → Gas Transition Zone

- Transition radius: 1.5-2.0 R_E

Forbidden Zone

- Maximum mass of a sub-Neptune is ~10-15 M_E

Super-Puffs

- Very low density → lots of H/He

Sub-Neptunes

- Common planet type!

Neptunes

- Intrinsically rare; typically ~ 10-40 M_E

Sub-Saturns & Giants

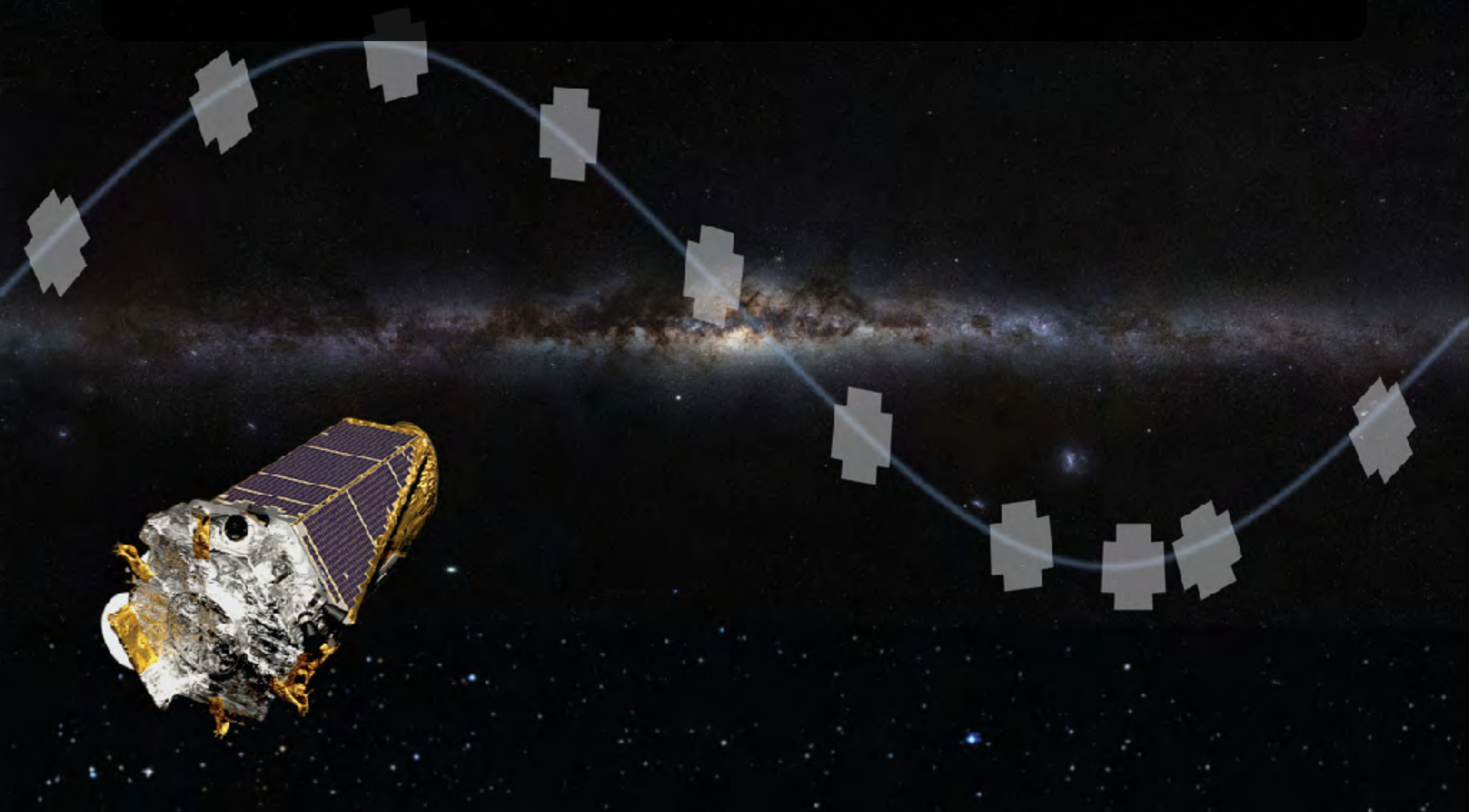
- Intrinsically rare & diverse

Resources

- *Radvel* (on github) - RV fitting - Fulton, Petigura, Blunt (2018)
- *Papers*: Mass catalog (Howard et al. in prep.)
  Mass-radius interpretation (Sinukoff et al. in prep.)

End

From Kepler to K2



K2 Discovery & Characterization

Propose K2 Targets → Generate Time Series Photometry → Planet Search

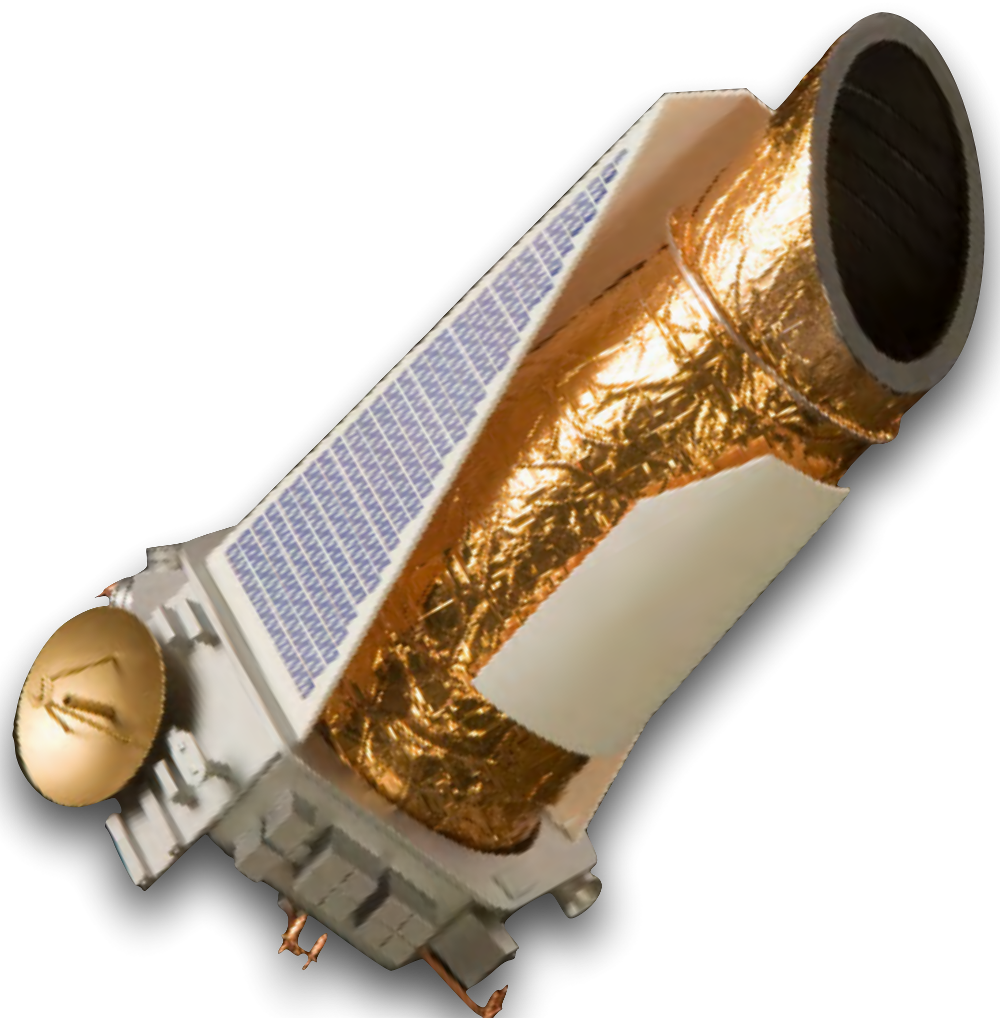
Planet Search → Candidate Vetting

Planet Search → Generate Planet Catalog

Crossfield+ (2016)
Sinukoff+ (2016)
Petigura+ (2017)

Generate Planet Catalog → Measure Planet Masses/ Densities

Sinukoff+ (2016, 2017a,b)
Petigura+ (2016, 2017)
Christiansen+ (2017)
Dressing+ (in prep)
[more …]

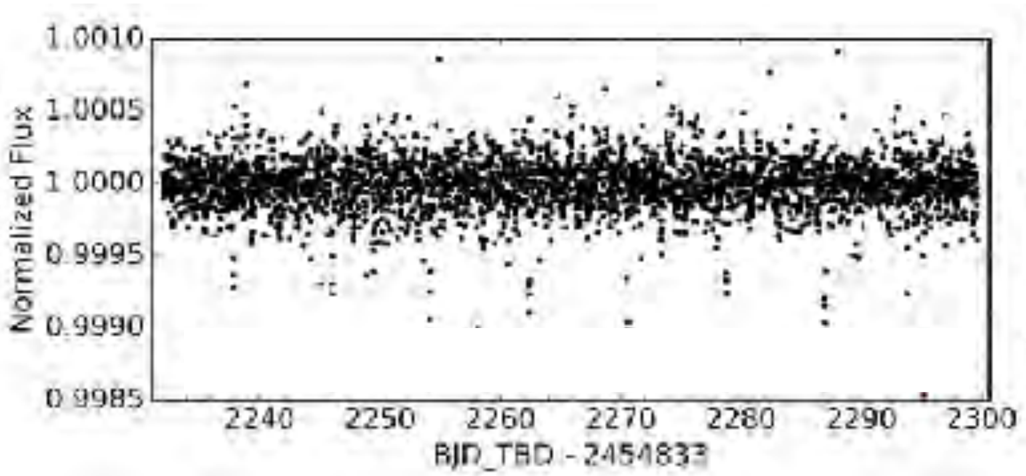


K2 Discovery & Characterization

Propose K2 Targets → **Generate Time Series Photometry** → **Planet Search**

Planet Search → **Candidate Vetting**

Planet Search → **Generate Planet Catalog** → **Measure Planet Masses/ Densities**



Crossfield+ (2016)

Generate Planet Catalog:

Crossfield+ (2016)

Sinukoff+ (2016)

Petigura+ (2017)

Measure Planet Masses/ Densities:

Sinukoff+ (2016, 2017a,b)

Petigura+ (2016, 2017)

Christiansen+ (2017)

Dressing+ (in prep)

[more …]

K2 Discovery & Characterization

Propose K2 Targets → **Generate Time Series Photometry** → **Planet Search** → **Candidate Vetting**

Generate Planet Catalog

Crossfield+ (2016)

Sinukoff+ (2016)

Petigura+ (2017)

Measure Planet Masses/ Densities

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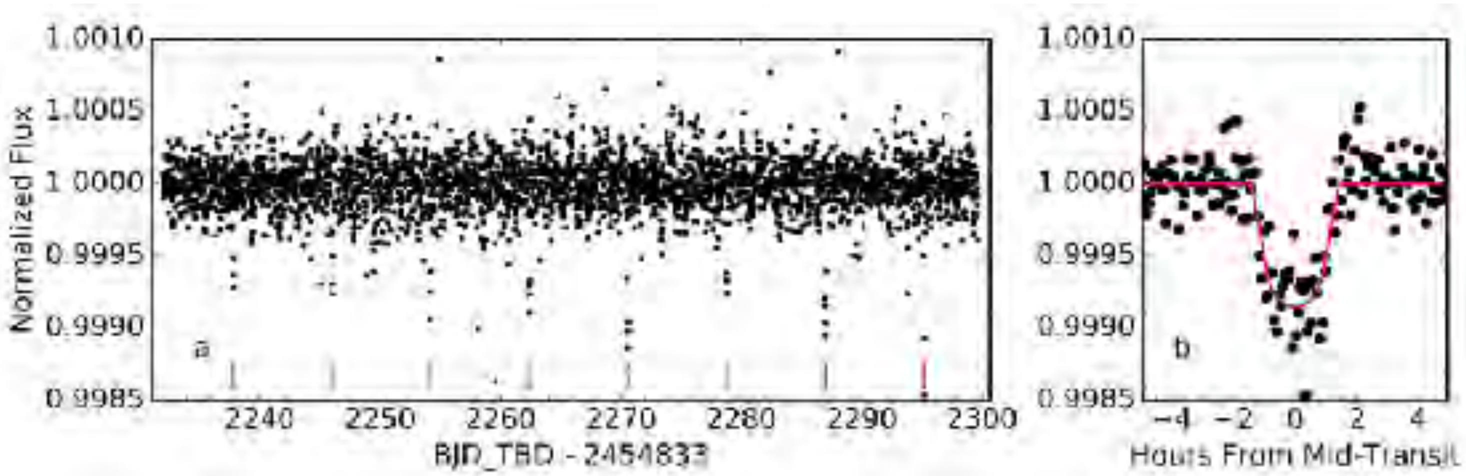
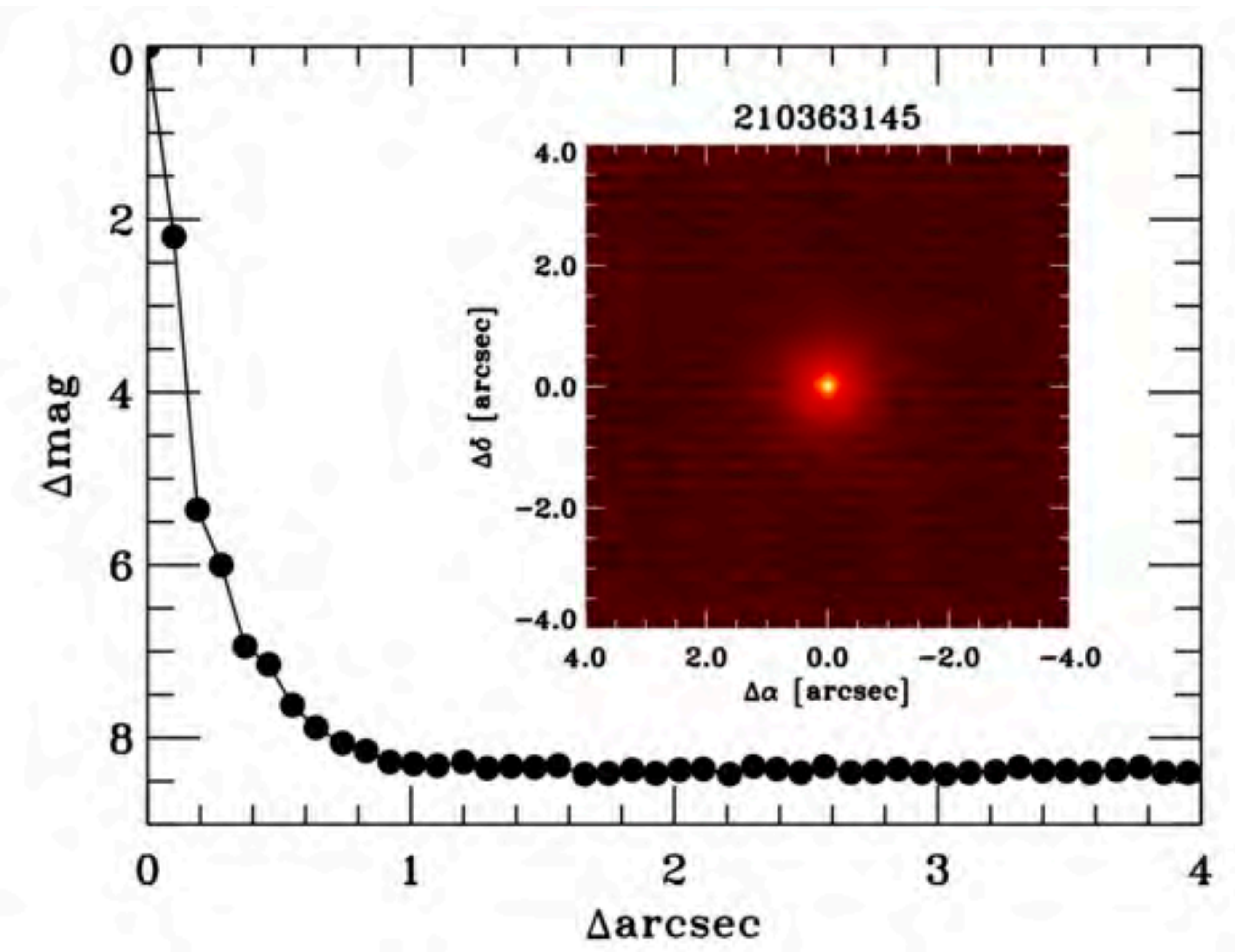
[more …]



Crossfield+ (2016)

K2 Discovery & Characterization

- Propose K2 Targets →
- Generate Time Series Photometry →
- Planet Search ⇢ Candidate Vetting
- ↓ Generate Planet Catalog
- ↓ Measure Planet Masses/ Densities



Crossfield+ (2016)

Generate Planet Catalog:

Crossfield+ (2016)

Sinukoff+ (2016)

Petigura+ (2017)

Measure Planet Masses/ Densities:

Sinukoff+ (2016, 2017a,b)

Petigura+ (2016, 2017)

Christiansen+ (2017)

Dressing+ (in prep)

[more …]

K2 Discovery & Characterization

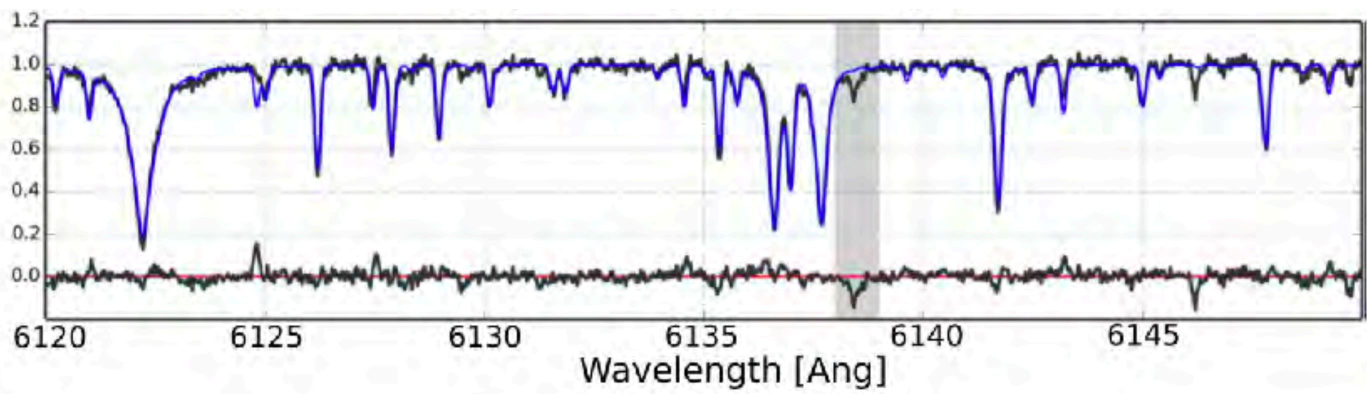
Propose K2 Targets → **Generate Time Series Photometry** → **Planet Search** → **Candidate Vetting**

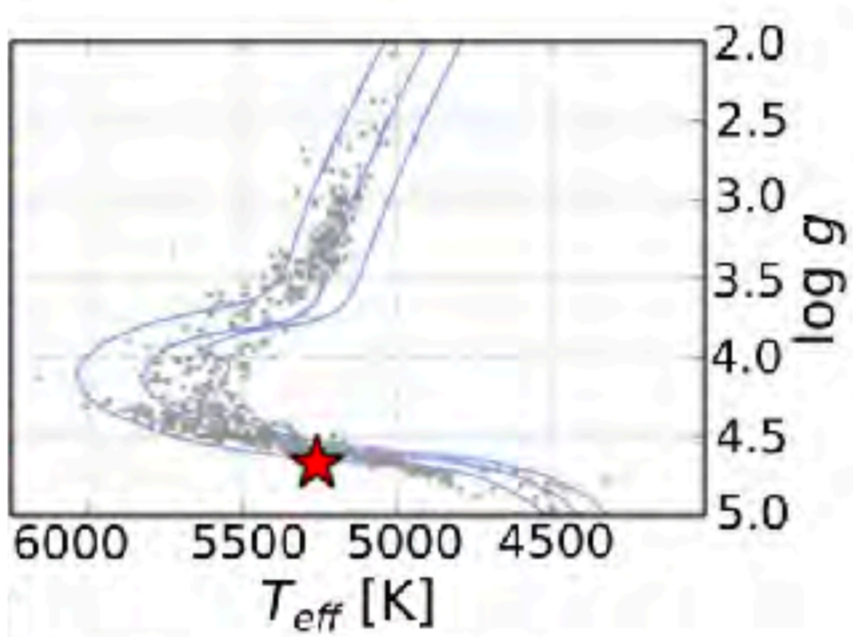
Planet Search → **Generate Planet Catalog**

Crossfield+ (2016)
Sinukoff+ (2016)
Petigura+ (2017)

Generate Planet Catalog → **Measure Planet Masses/ Densities**

Sinukoff+ (2016, 2017a,b)
Petigura+ (2016, 2017)
Christiansen+ (2017)
Dressing+ (in prep)
[more …]





Crossfield+ (2016)

K2 Discovery & Characterization

Propose K2 Targets → Generate Time Series Photometry → Planet Search

Planet Search → Generate Planet Catalog (with Candidate Vetting)

Generate Planet Catalog → **Measure Planet Masses/ Densities**

Candidate Vetting

Generate Planet Catalog:
Crossfield+ (2016)
Sinukoff+ (2016)
Petigura+ (2017)

Measure Planet Masses/ Densities:
Sinukoff+ (2016, 2017a,b)
Petigura+ (2016, 2017)
Christiansen+ (2017)
Dressing+ (in prep)
[more …]

Photo: Ethan Tweedie

Keck Observatory
Mass measurements using HIRES

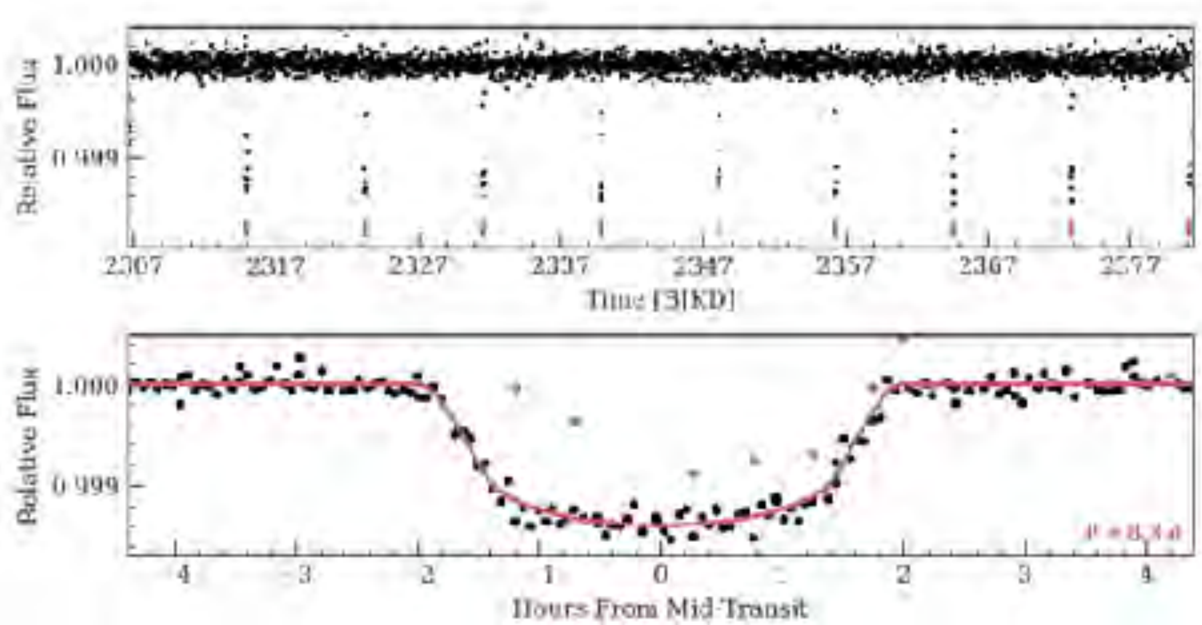
K2-105

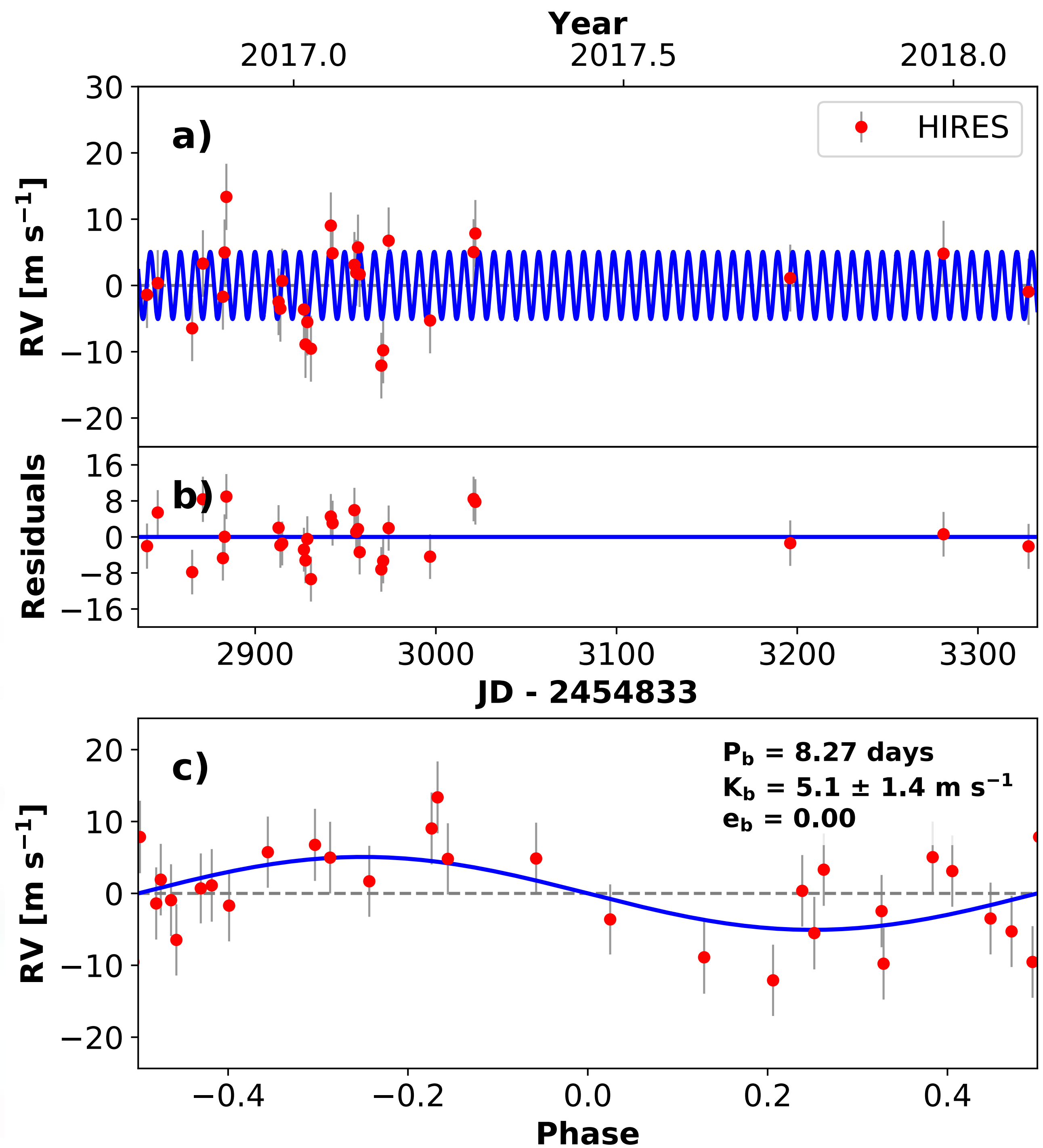
Star

T_{eff} = 5370 K
logg = 4.45
[Fe/H] = +0.22

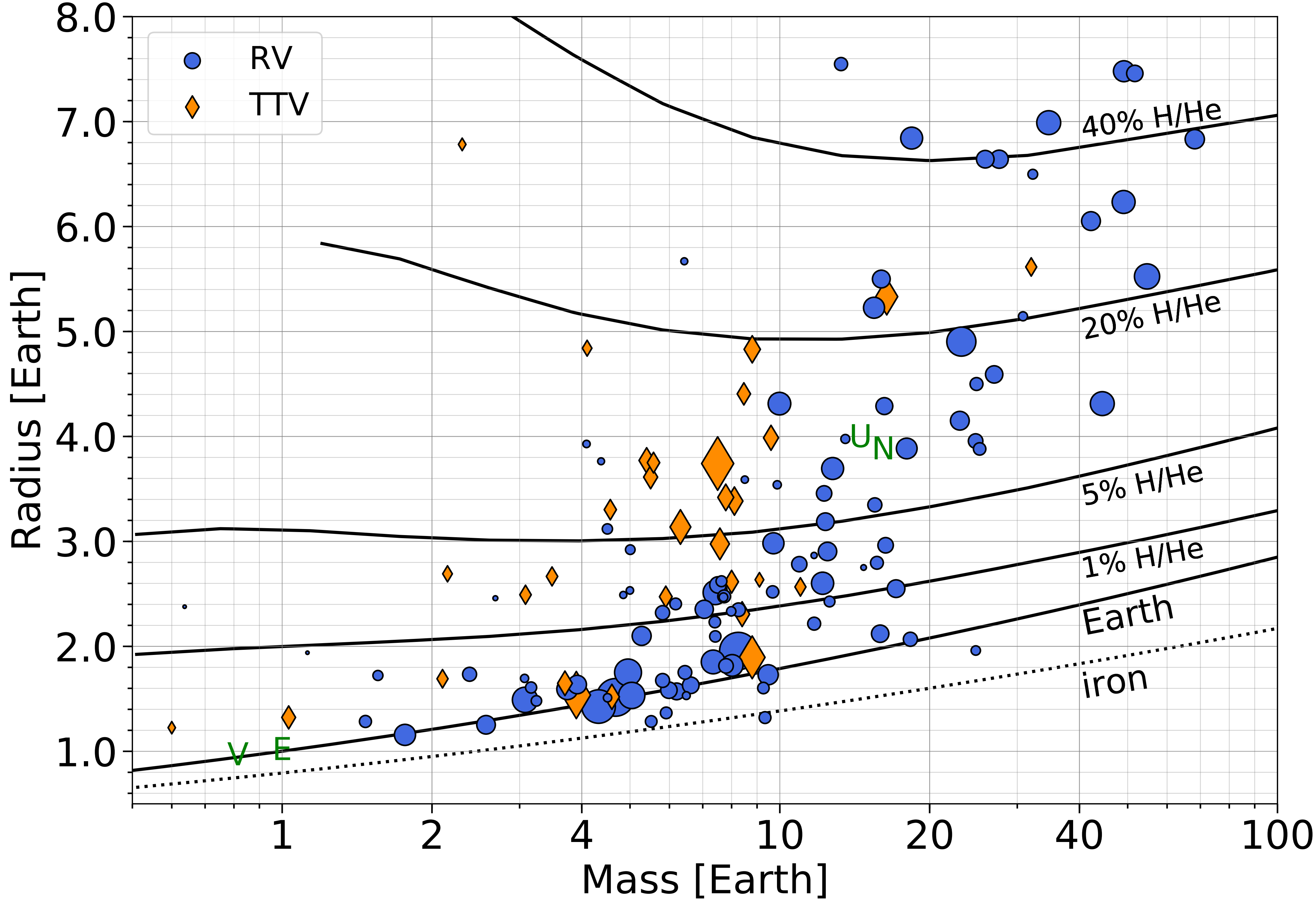
Planet b:

P = 8.3 days
R_p = 3.4 ± 0.2 $R_\oplus$
M_p = 15.3 ± 4.3 $M_\oplus$





Mass-radius Diagram



A gap in small planet composition

Mass uncertainty > 30% excluded