Water Worlds?
Water Worlds!

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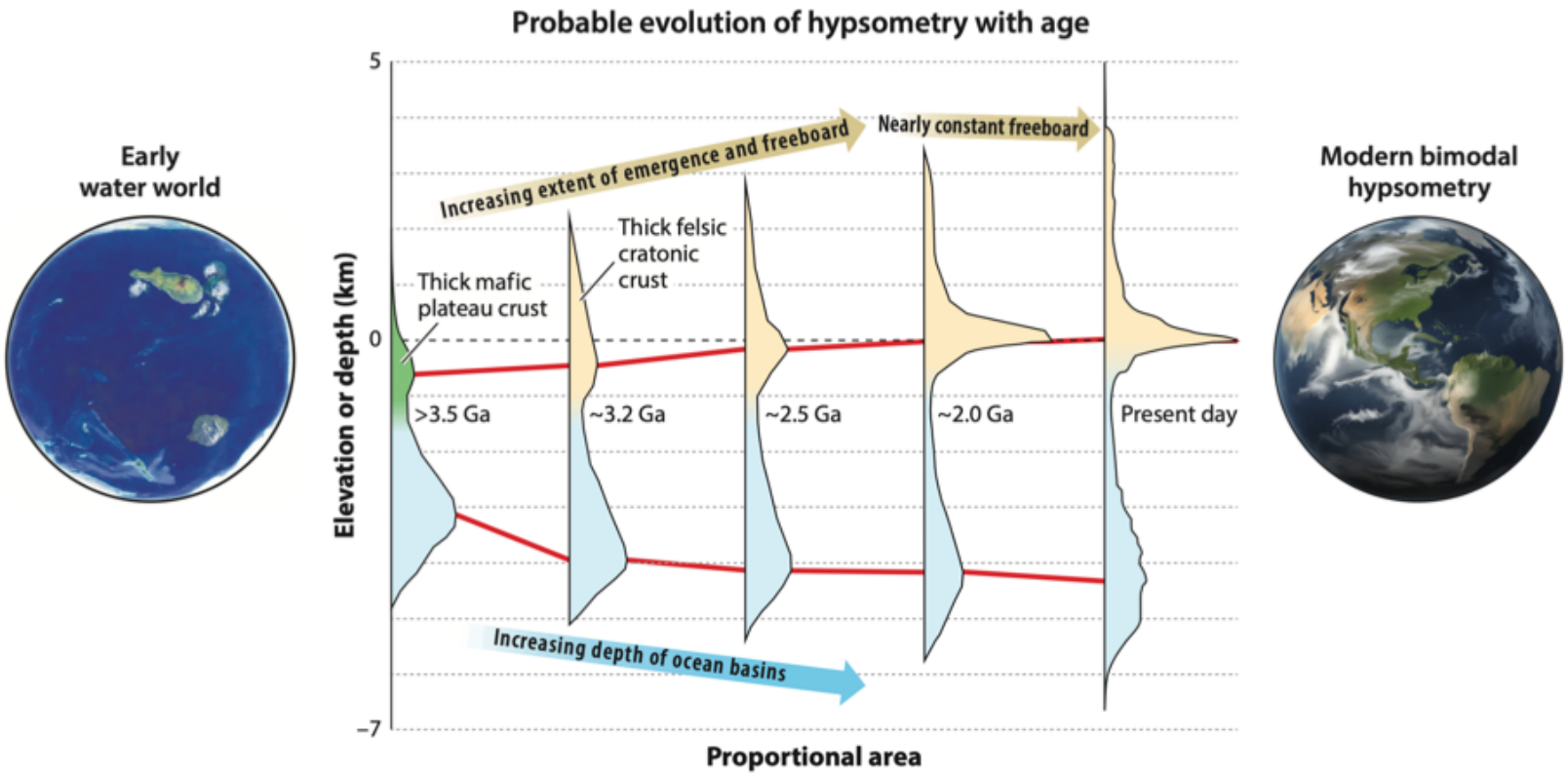
Water Worlds:

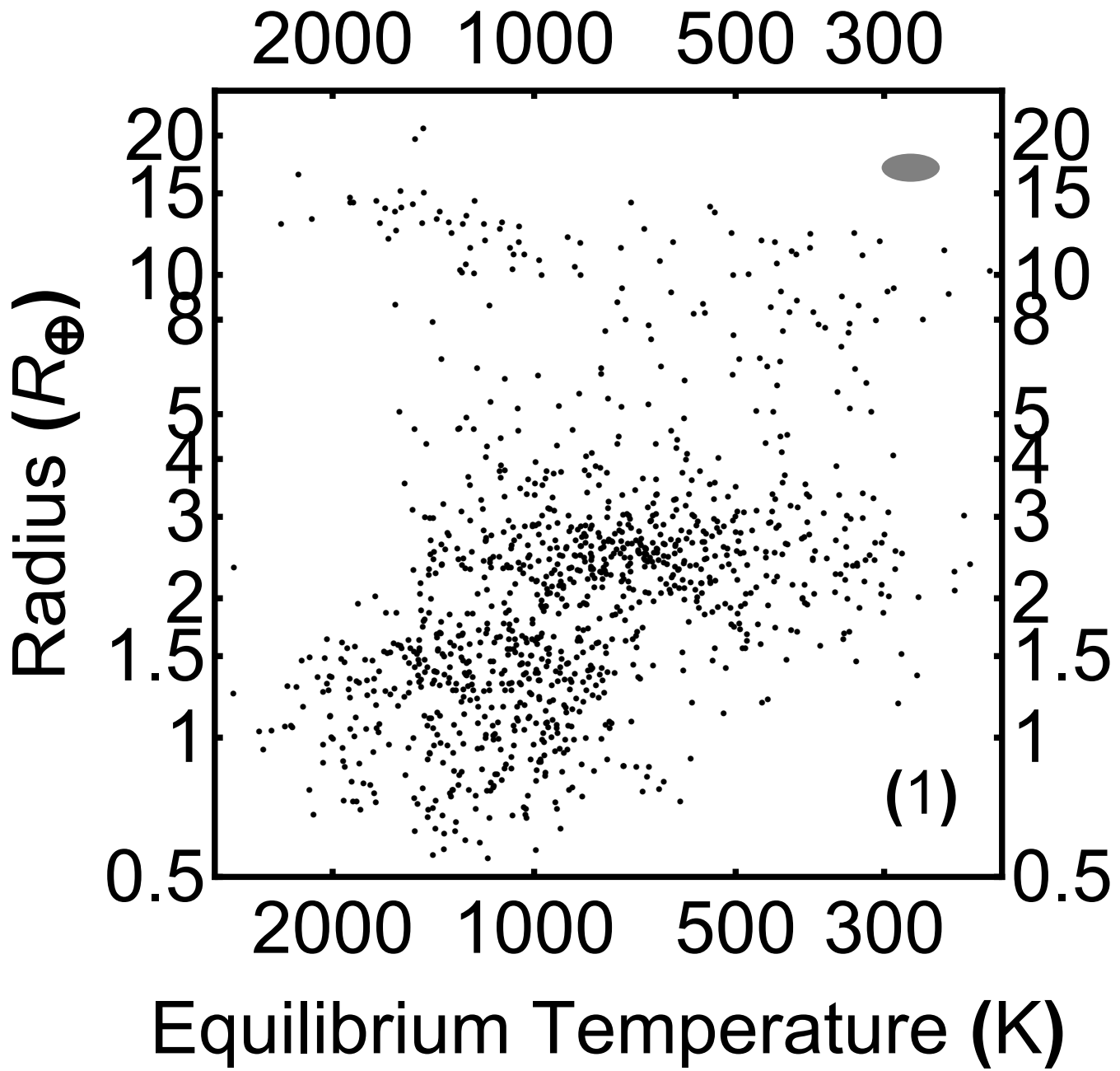
- **Earth may have begun as a water world, but has gradually evolved into a planet with both continents and oceans. Other exoplanets, if they start with more water budget, could they remain water worlds for ever…**
- **What is the evidence from current exoplanet sciences?**

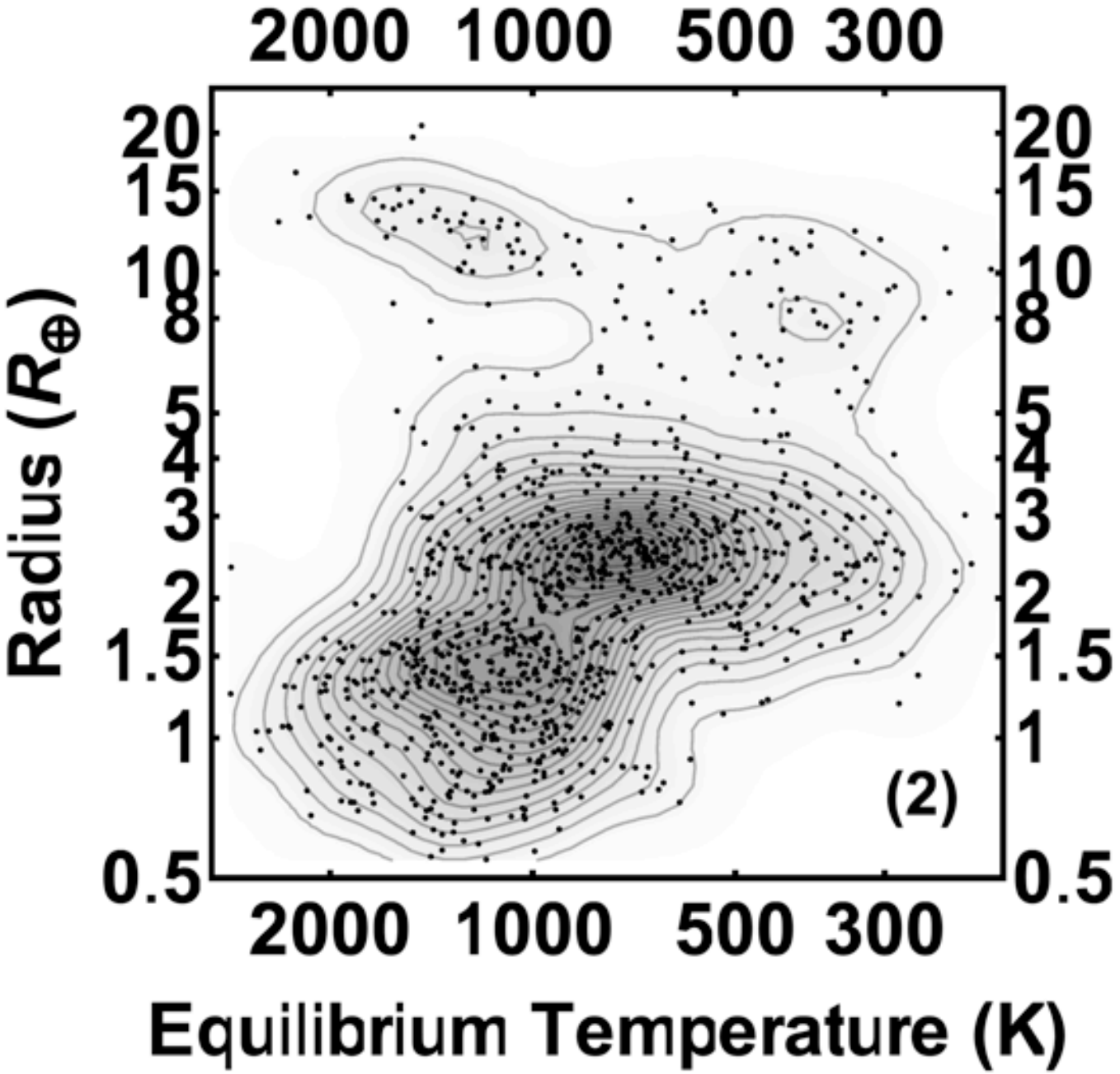


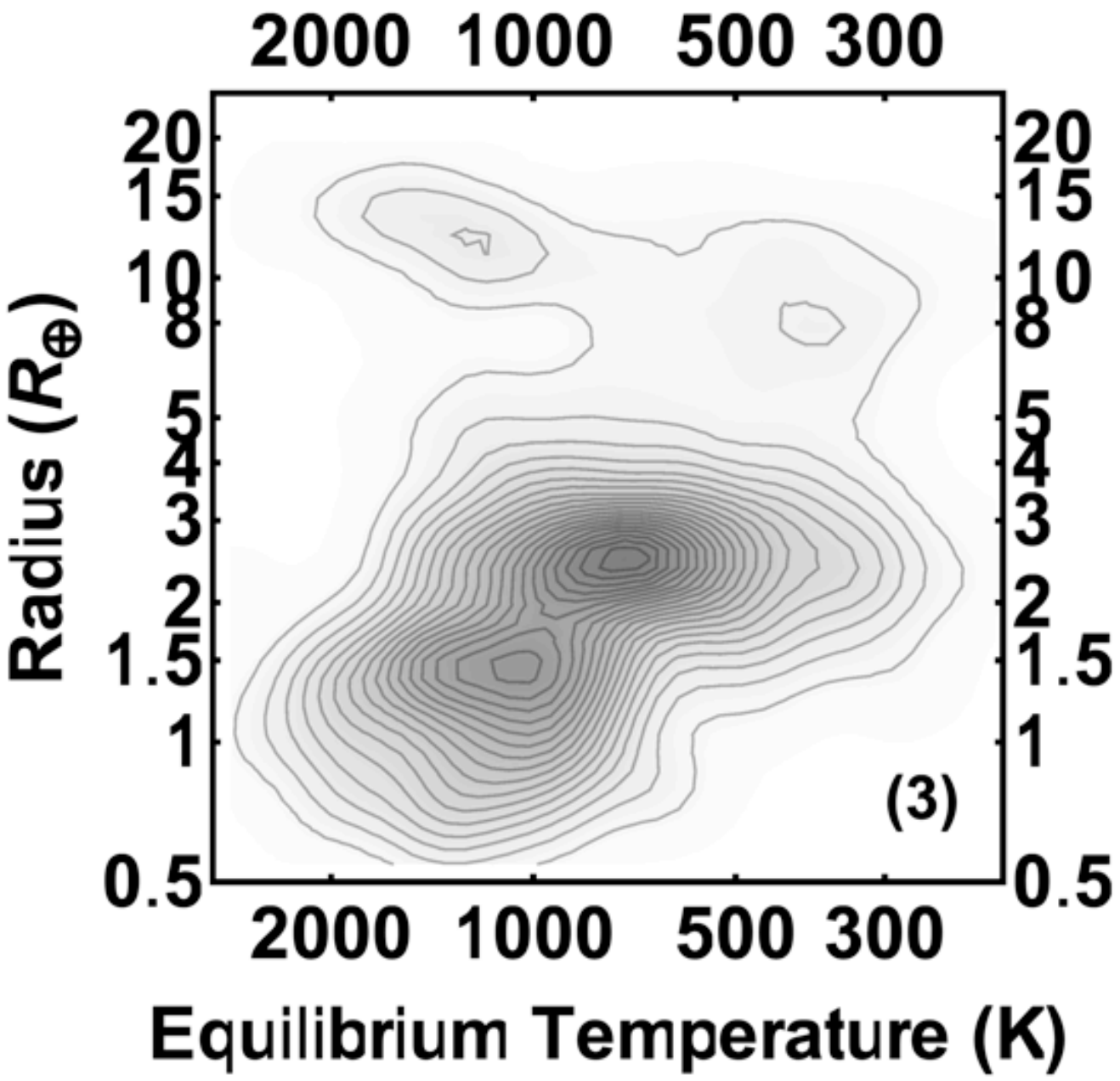
Annual Review of Earth and Planetary Sciences 2025
Subaerial Emergence of Continents on Archean Earth
Priyadarshi Chowdhury, Peter A. Cawood, and Jacob A. Mulder

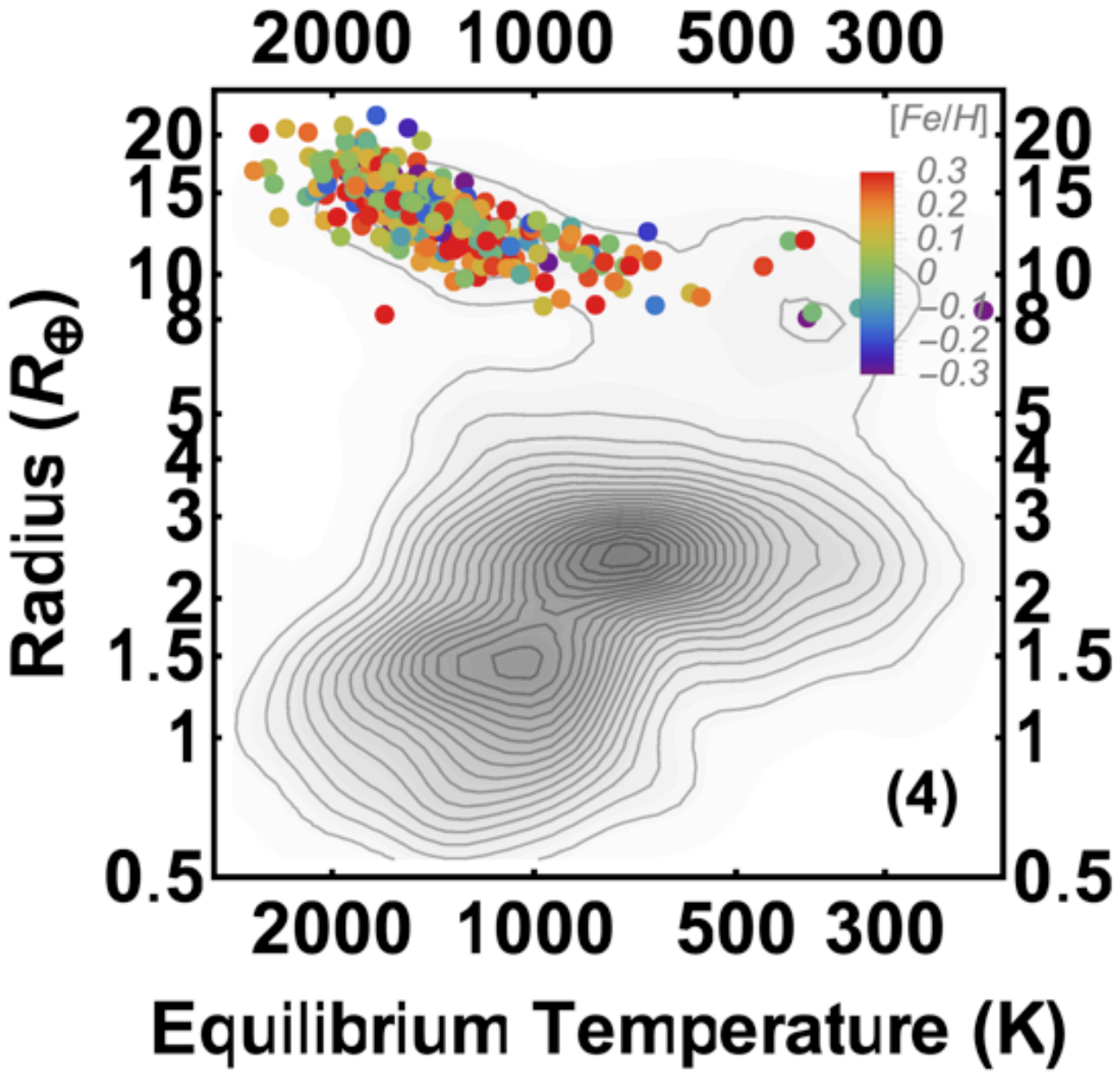
Kepler Survey Result

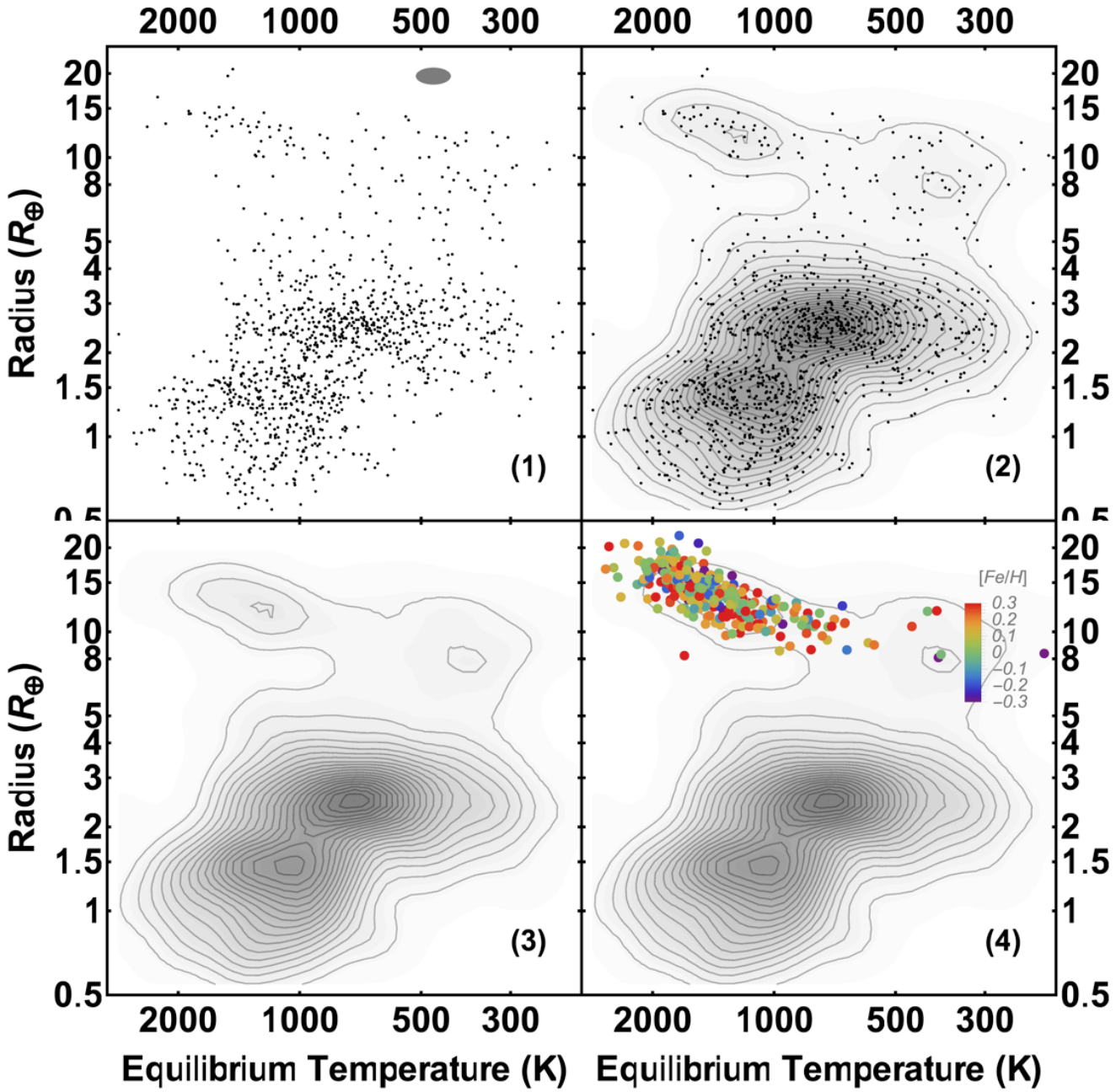
- Selection criteria:
  - Teff: 5000-6500 K
  - σRp/Rp < 0.1


2000
1000
500
300
20
15
10
8
5
4
3
2
1.5
1
0.5
Radius ($R_\oplus$)
(1)
Equilibrium Temperature (K)

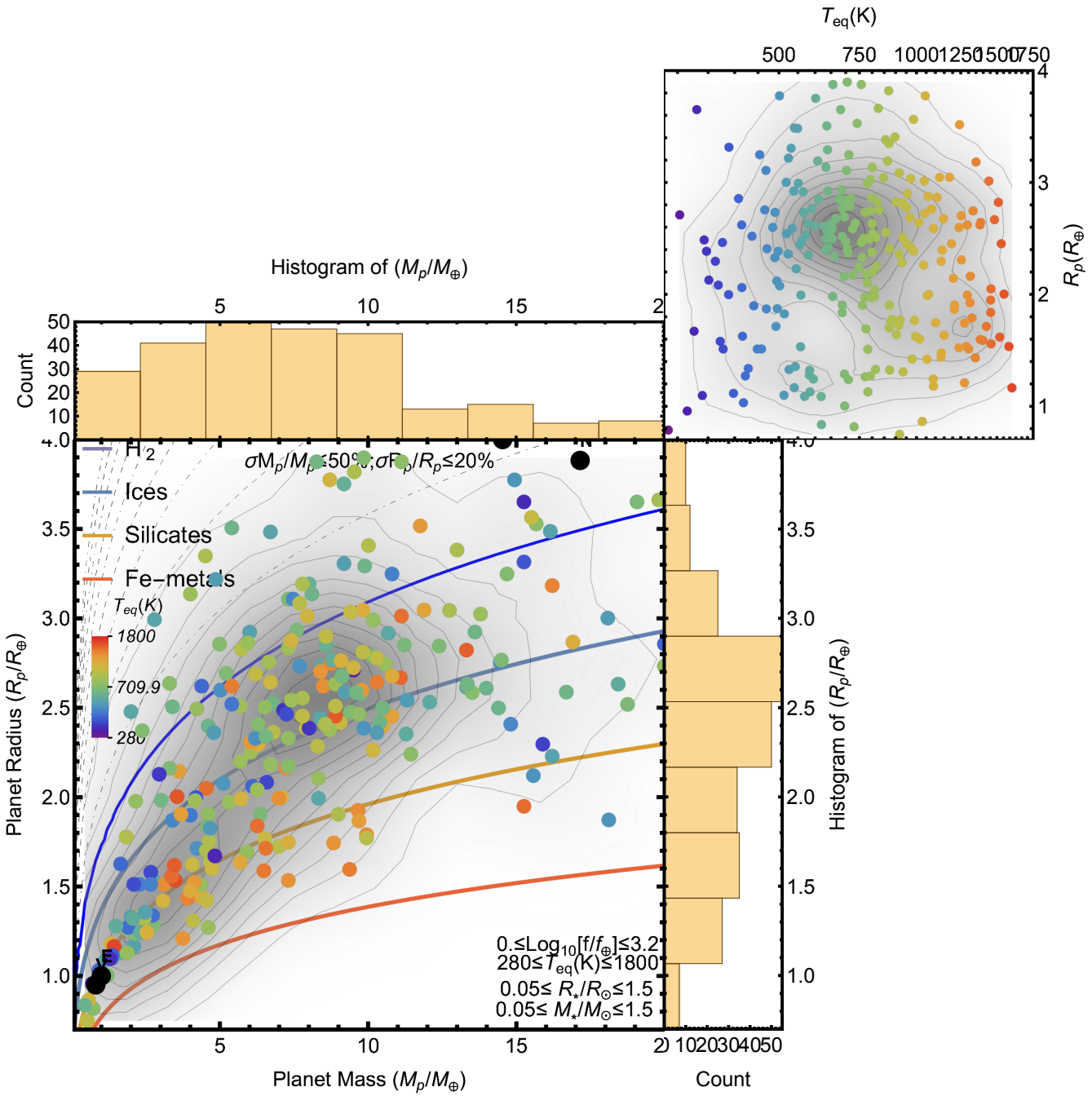

2000 1000 500 300
20
15
10
8
5
4
3
2
1.5
1
0.5
Radius ($R_\oplus$)
(2)
2000 1000 500 300
Equilibrium Temperature (K)

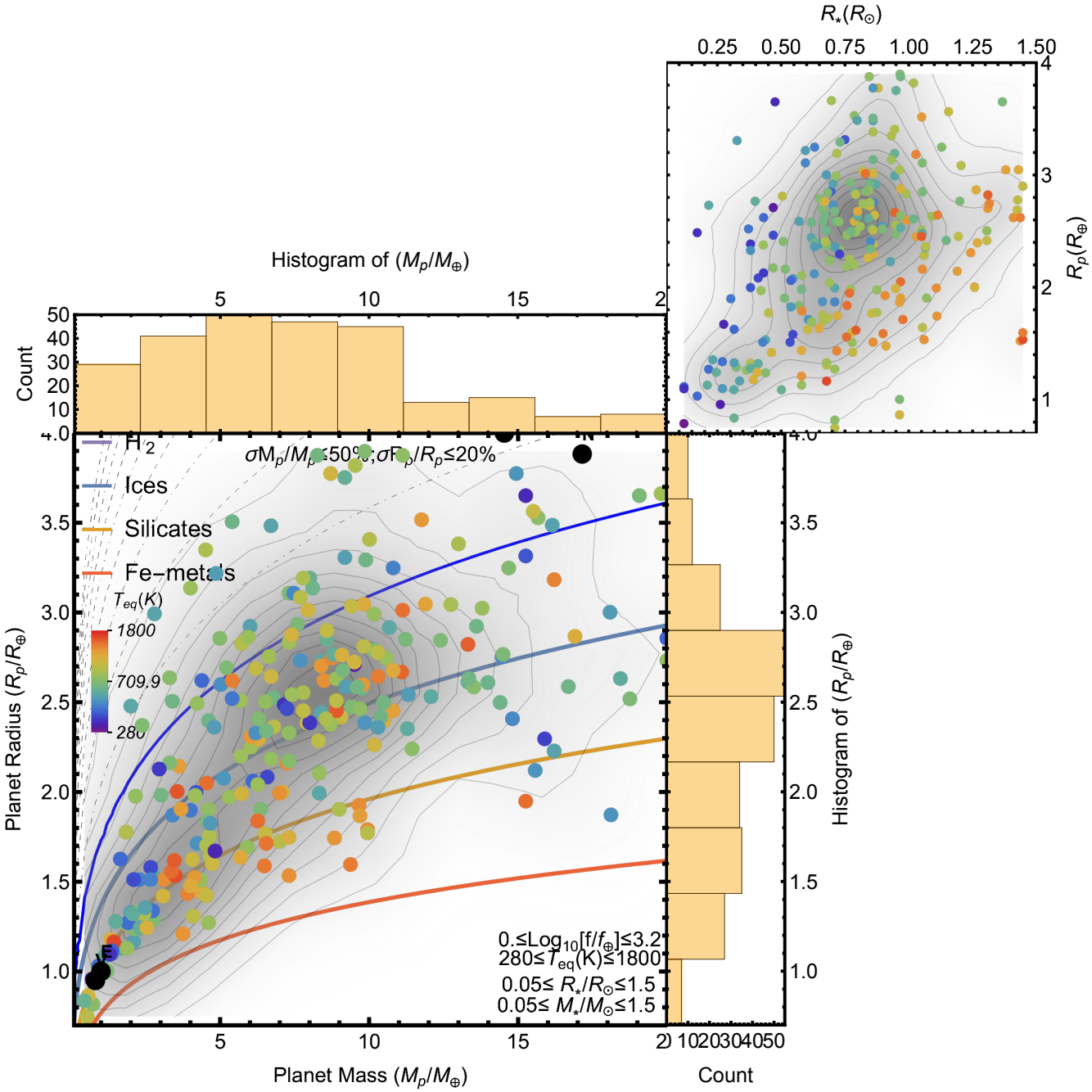

2000
1000
500
300
20
15
10
8
5
4
3
2
1.5
1
0.5
Radius ($R_\oplus$)
(3)
Equilibrium Temperature (K)

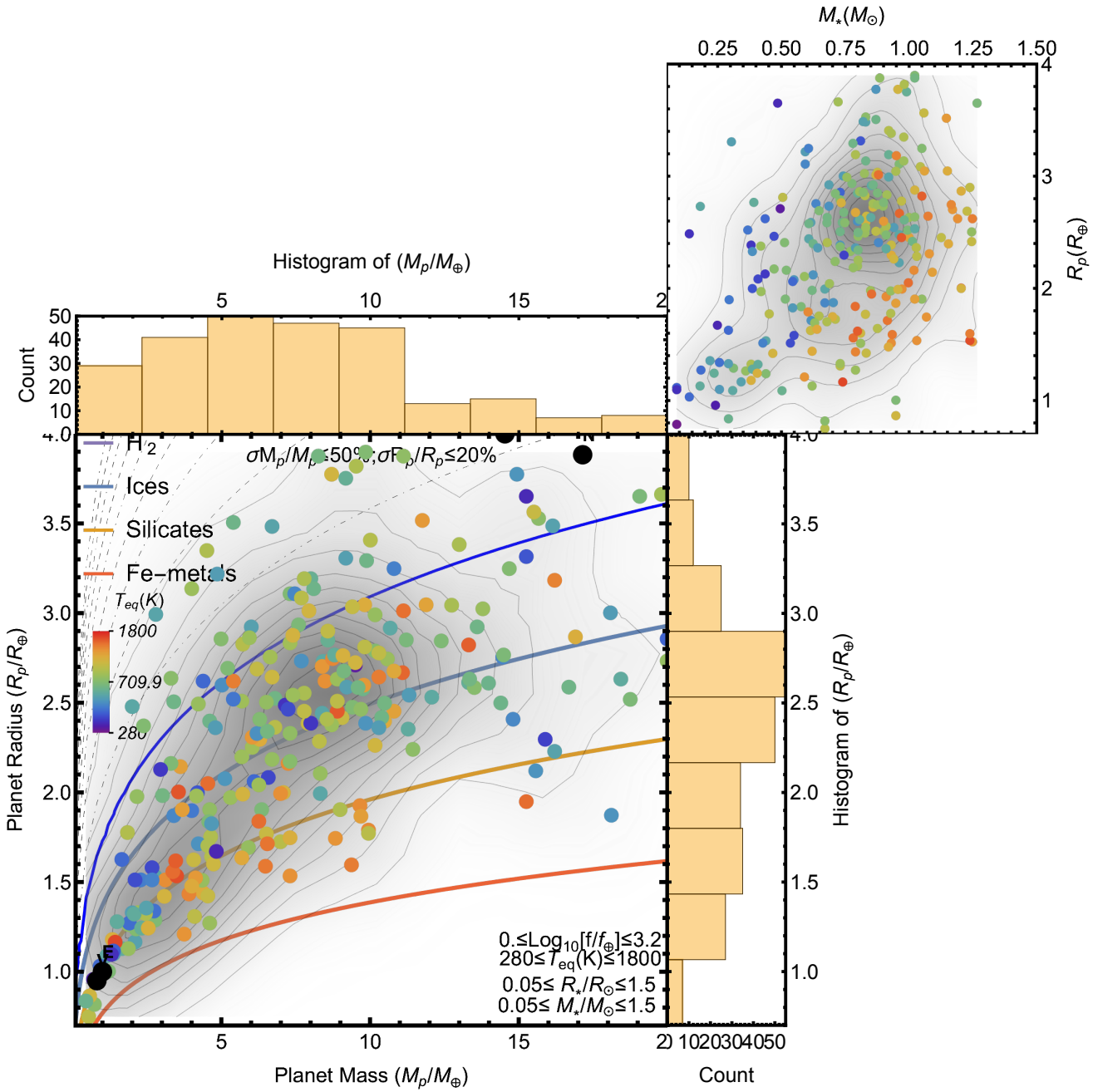

2000 1000 500 300
20
15
10
8
5
4
3
2
1.5
1
0.5
Radius ($R_\oplus$)
[Fe/H]
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
(4)
2000 1000 500 300
Equilibrium Temperature (K)

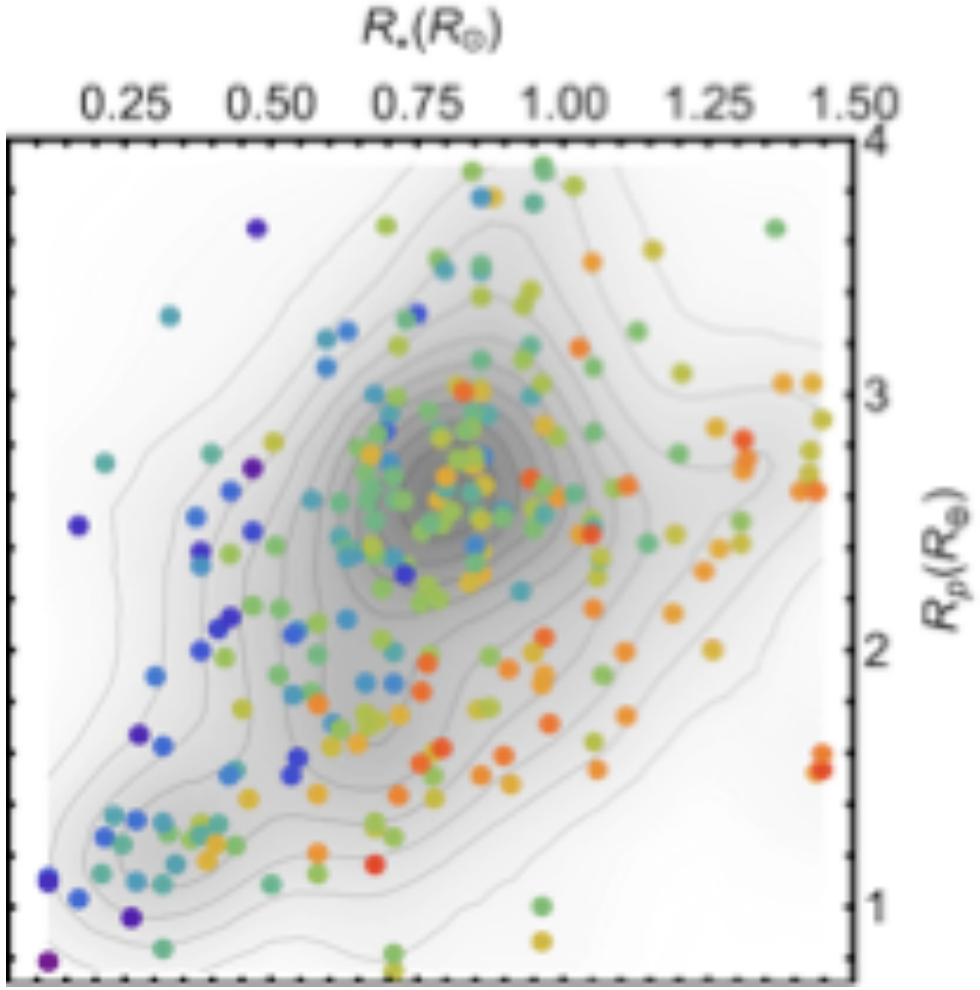

2000
1000
500
300
Radius ($R_\oplus$)
20
15
10
8
5
4
3
2
1.5
1
0.5
(1)
(2)
(3)
(4)
[Fe/H]
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
Equilibrium Temperature (K)

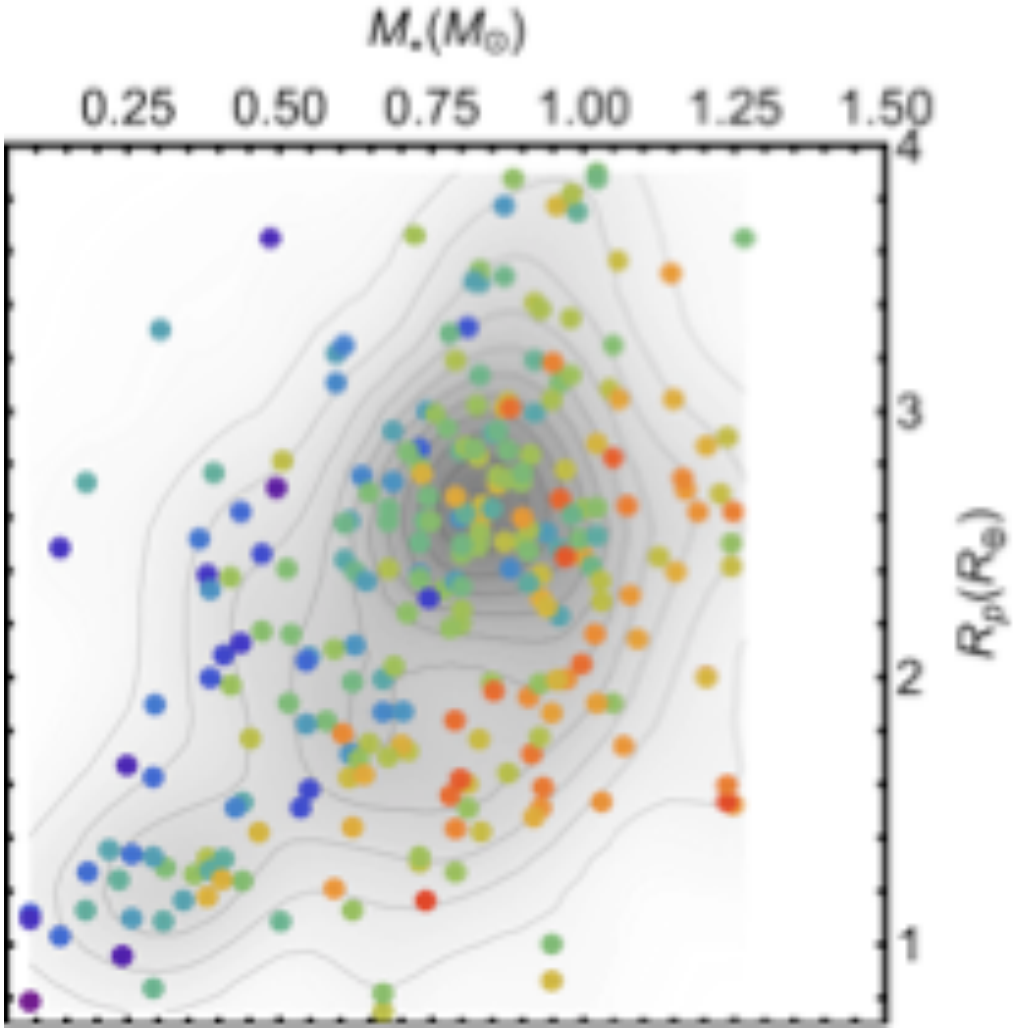
Mass-Radius and other parameters…

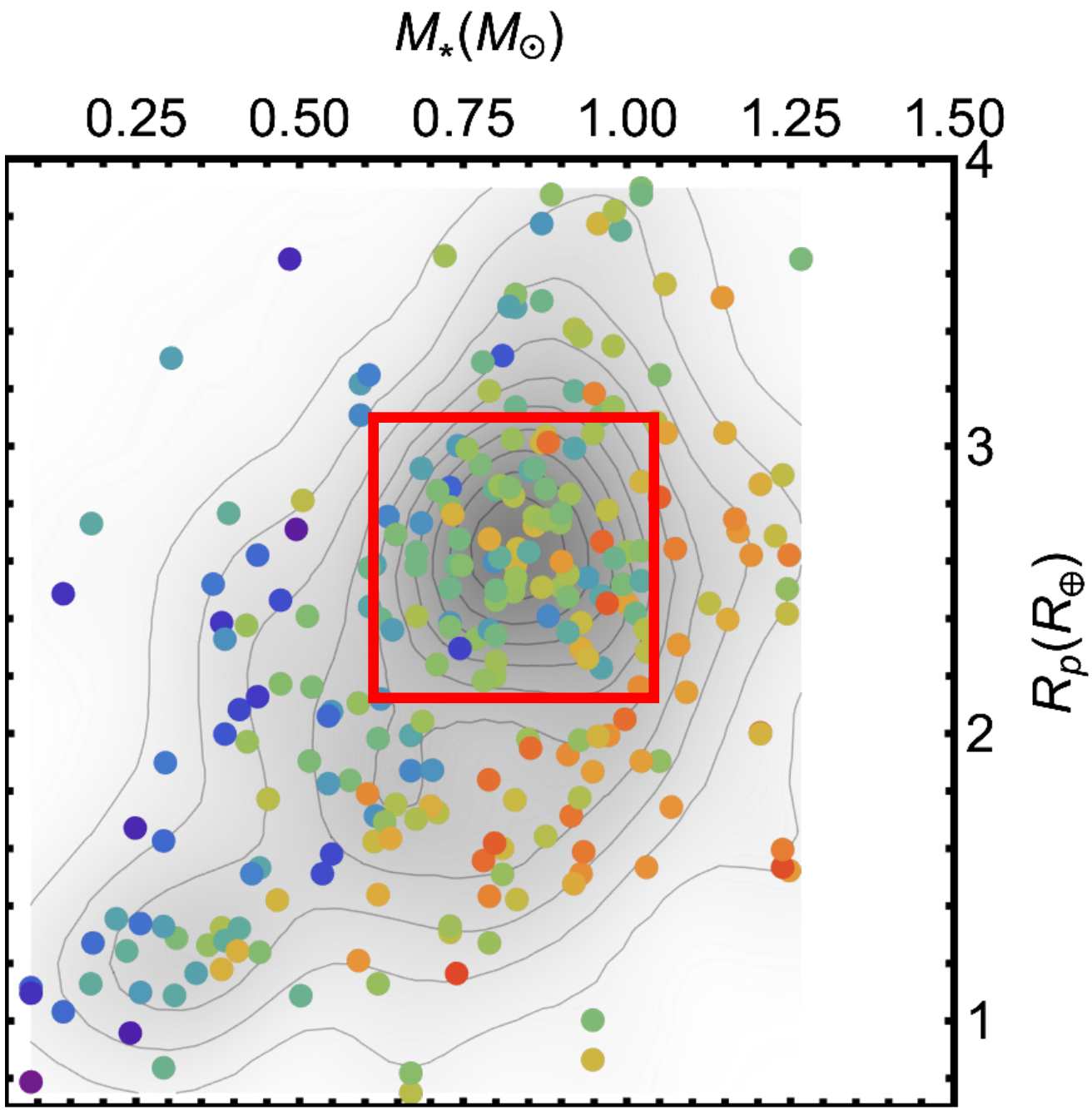

T_{eq}(K)
500
750
1000
1250
1500
750
$R_p(R_\oplus)$
Histogram of ($M_p/M_\oplus$)
Count
H_2
Ices
Silicates
Fe-metals
$T_{eq}(K)$
1800
709.9
280
$\sigma M_p/M_p \leq 50\%; \sigma R_p/R_p \leq 20\%$
$0.\leq \mathrm{Log}_{10}[f/f_\oplus] \leq 3.2$
$280 \leq T_{eq}(\mathrm{K}) \leq 1800$
$0.05 \leq R_*/R_\odot \leq 1.5$
$0.05 \leq M_*/M_\odot \leq 1.5$
Planet Radius ($R_p/R_\oplus$)
Histogram of ($R_p/R_\oplus$)
Planet Mass ($M_p/M_\oplus$)
Count


$R_*(R_\odot)$
0.25 0.50 0.75 1.00 1.25 1.50
$R_p(R_\oplus)$
1 2 3 4
Histogram of $(M_p/M_\oplus)$
5 10 15 2
Count
10 20 30 40 50
H_2
Ices
Silicates
Fe–metals
$T_{eq}(K)$
1800
709.9
280
$\sigma M_p/M_p \leq 50\%;\sigma R_p/R_p \leq 20\%$
Planet Radius $(R_p/R_\oplus)$
1.0 1.5 2.0 2.5 3.0 3.5 4.0
Histogram of $(R_p/R_\oplus)$
$0.\leq Log_{10}[f/f_\oplus] \leq 3.2$
$280 \leq T_{eq}(K) \leq 1800$
$0.05 \leq R_*/R_\odot \leq 1.5$
$0.05 \leq M_*/M_\odot \leq 1.5$
5 10 15 2
Planet Mass $(M_p/M_\oplus)$
10 20 30 40 50
Count


$M_*(M_\odot)$
0.25 0.50 0.75 1.00 1.25 1.50
$R_p(R_\oplus)$
Histogram of $(M_p/M_\oplus)$
Count
H_2
Ices
Silicates
Fe–metals
$T_{eq}(K)$
1800
709.9
280
$\sigma M_p/M_p \leq 50\%; \sigma R_p/R_p \leq 20\%$
$0.\leq \mathrm{Log}_{10}[f/f_\oplus] \leq 3.2$
$280 \leq T_{eq}(K) \leq 1800$
$0.05 \leq R_*/R_\odot \leq 1.5$
$0.05 \leq M_*/M_\odot \leq 1.5$
Planet Radius $(R_p/R_\oplus)$
Planet Mass $(M_p/M_\oplus)$
Histogram of $(R_p/R_\oplus)$
Count


$R_\star(R_\odot)$
0.25
0.50
0.75
1.00
1.25
1.50
4
3
2
1
$R_p(R_\oplus)$

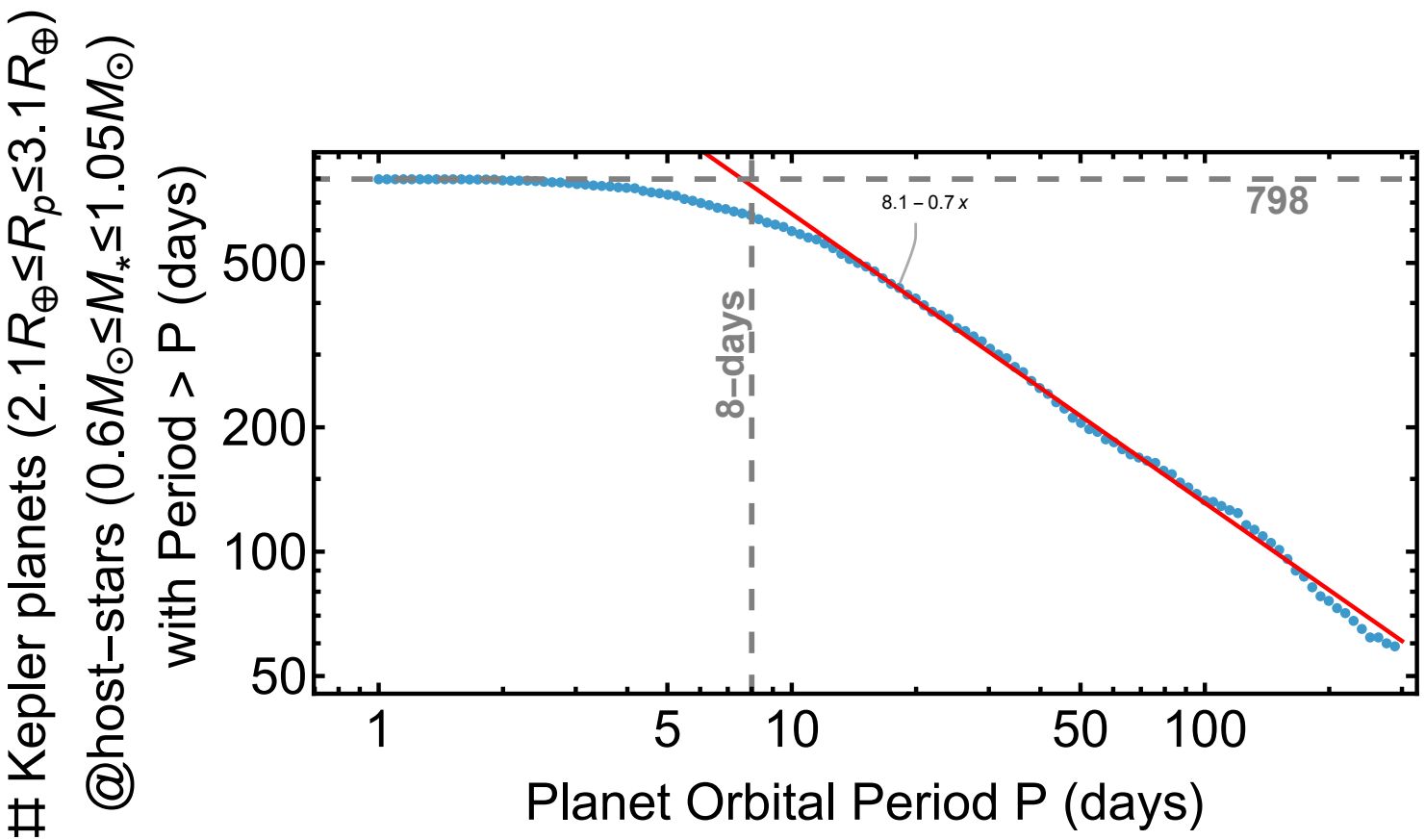

$M_*(M_\odot)$
0.25
0.50
0.75
1.00
1.25
1.50
4
3
2
1
$R_p(R_\oplus)$

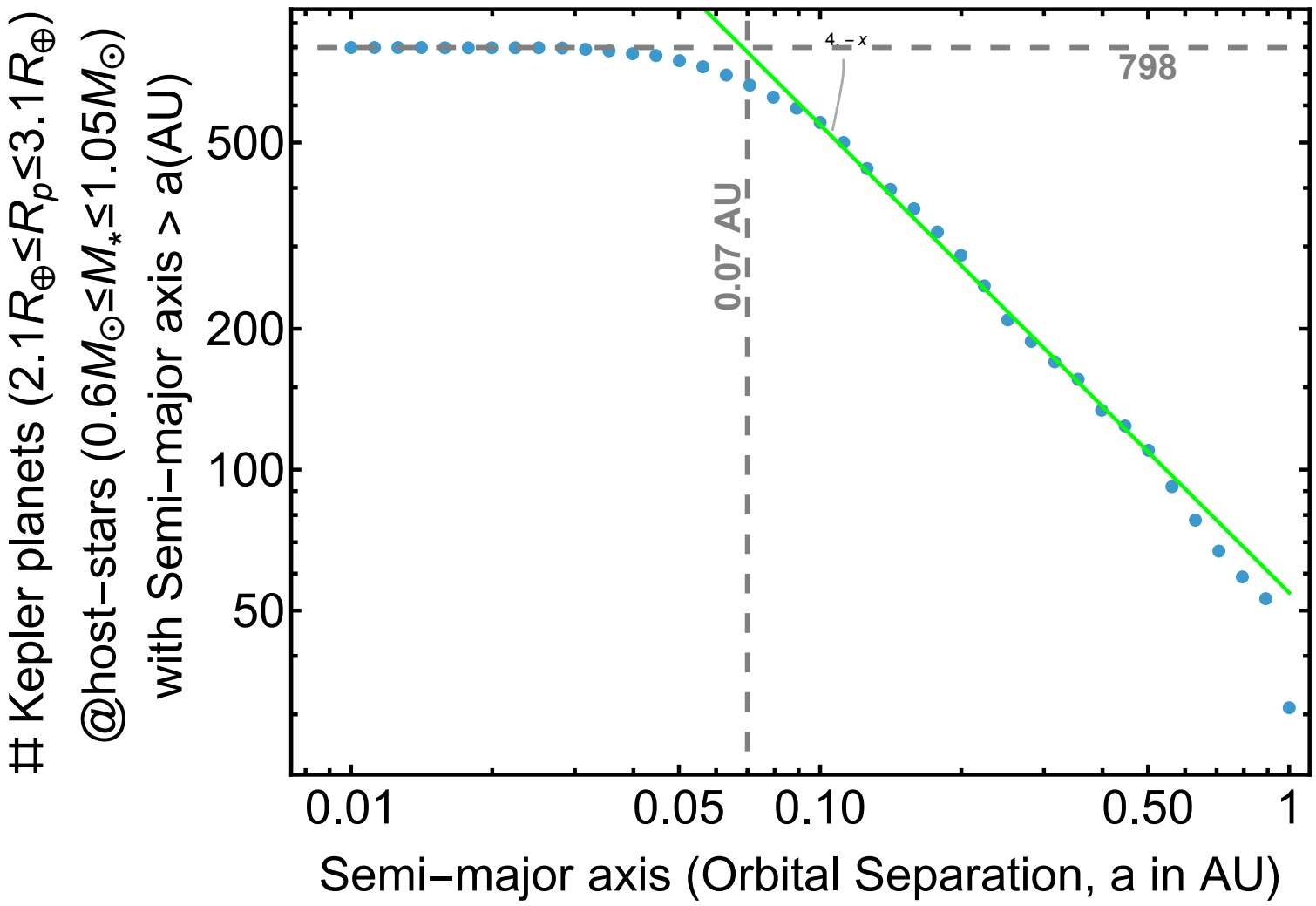

$M_*(M_\odot)$
0.25
0.50
0.75
1.00
1.25
1.50
4
3
2
1
$R_p(R_\oplus)$

Kepler target stars

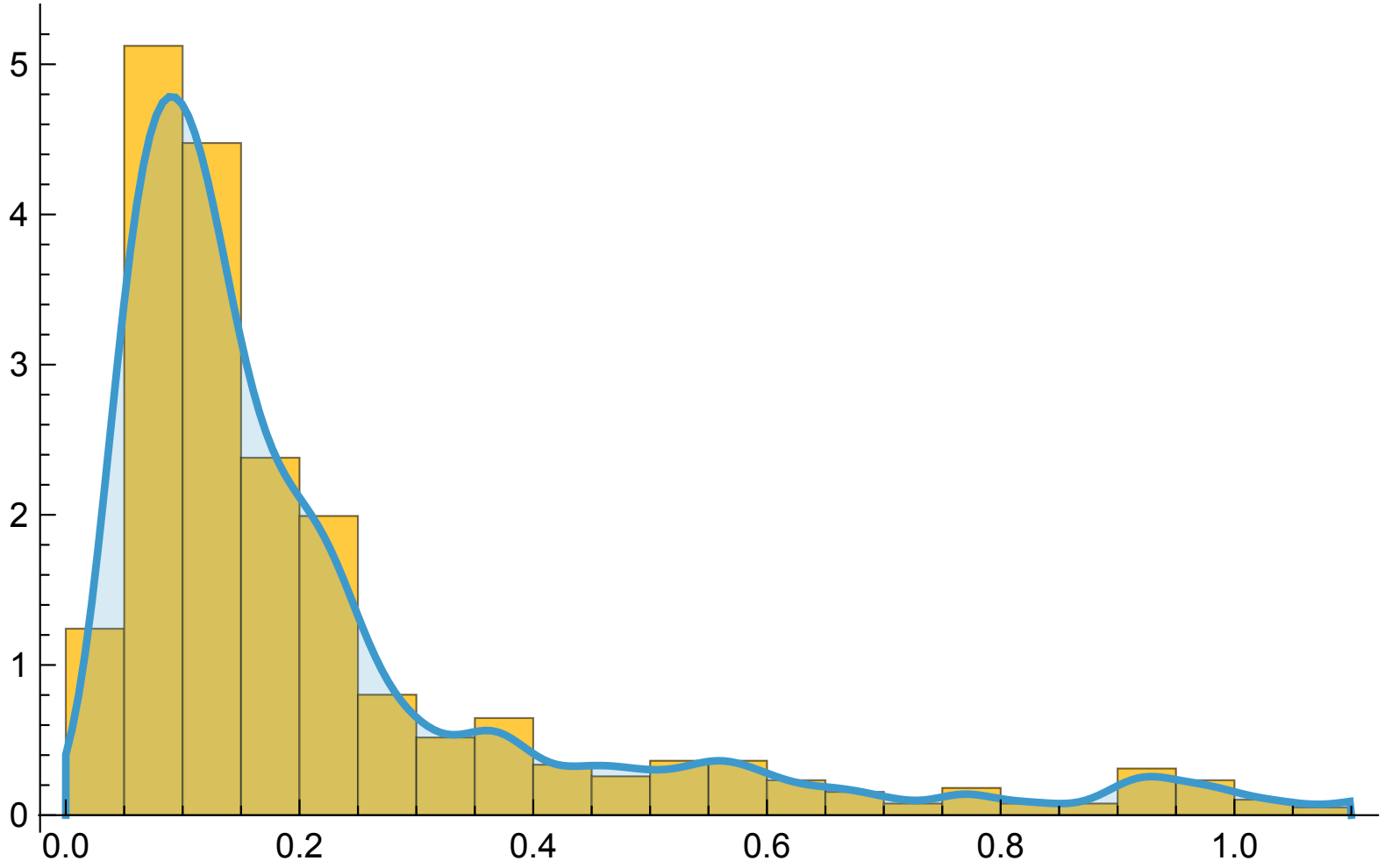
Mag/T_e(K)	10500	9500	8500	7500	6500	5500	4500	3500	Total
7.5	2	8	8	8	8	7	0	0	41
8.5	8	20	26	24	50	16	7	8	159
9.5	9	31	81	65	117	88	11	4	406
10.5	27	37	100	209	405	362	40	9	1189
11.5	24	58	172	396	1495	1356	157	39	3697
12.5	33	43	230	678	4148	4761	625	62	10580
13.5	34	51	170	737	9250	15841	2218	159	28460
14.5	3	0	0	0	4791	29291	4401	552	39038
15.5	7	3	0	0	4261	43132	11188	1828	60419
Total	147	251	787	2117	24525	94854	18647	2661	143989

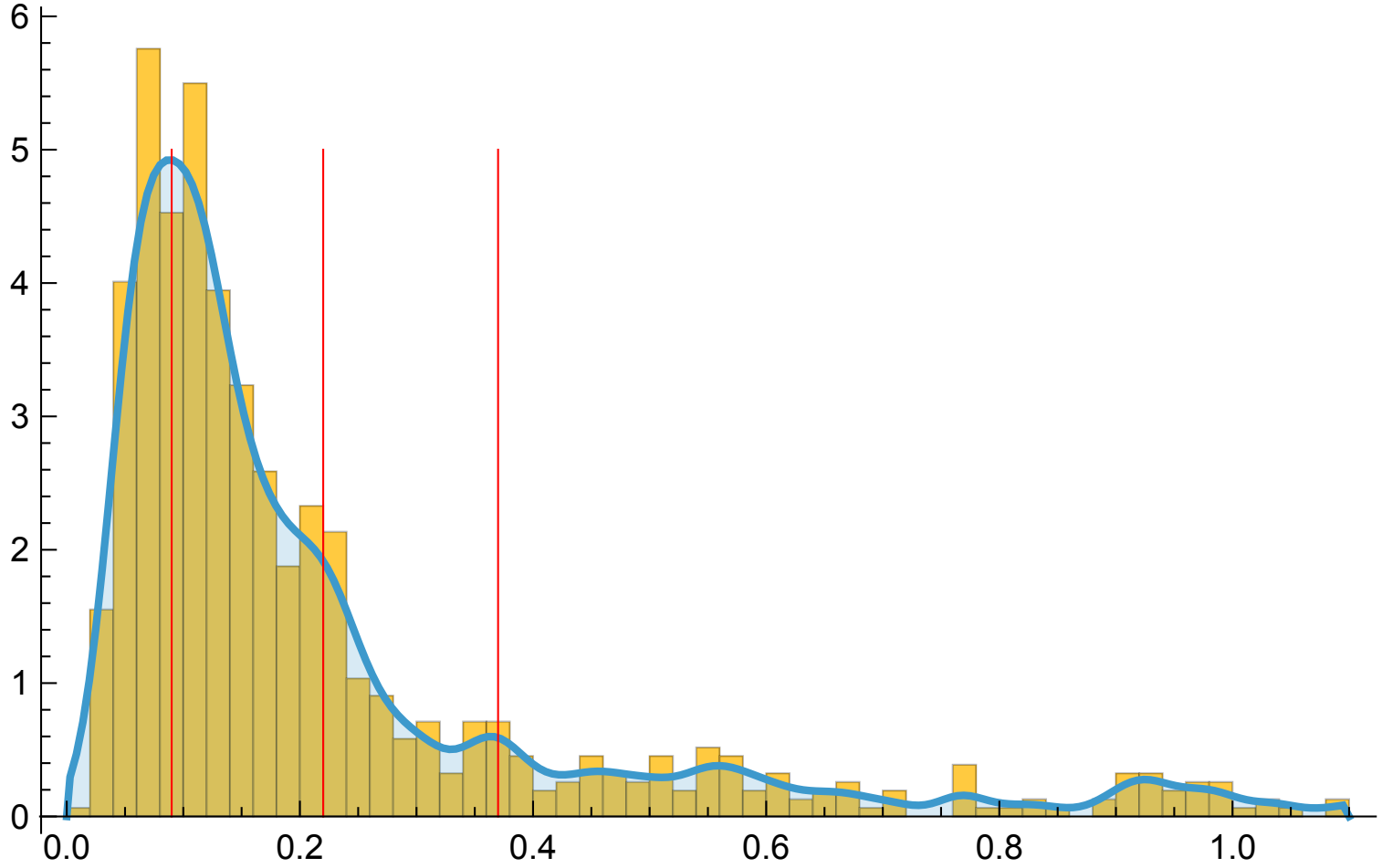
Credit: Dave Latham

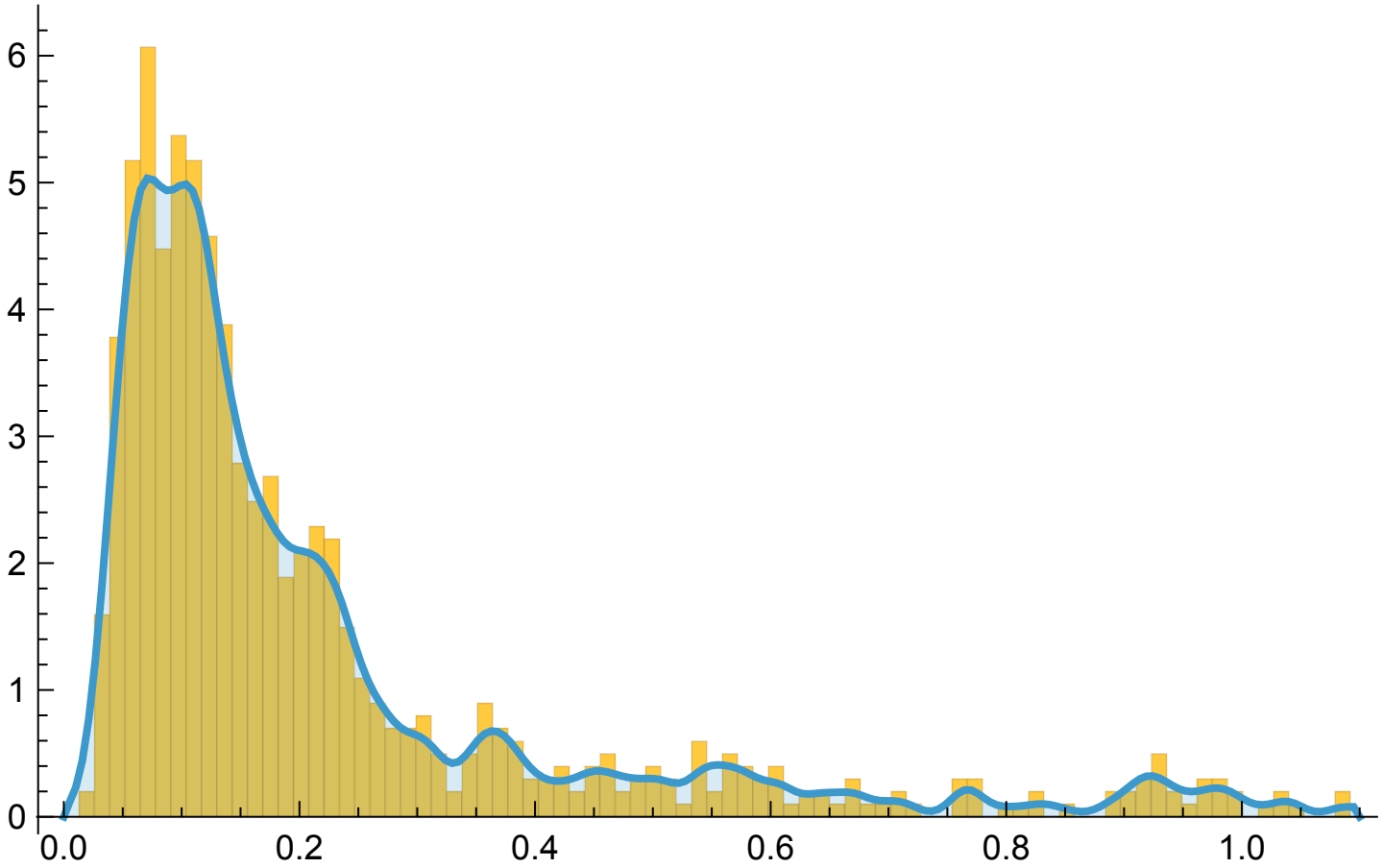

Kepler planets ($2.1R_\oplus \leq R_p \leq 3.1R_\oplus$)
@host–stars ($0.6M_\odot \leq M_* \leq 1.05M_\odot$)
with Period > P (days)
500
200
100
50
1
5
10
50
100
Planet Orbital Period P (days)
8–days
8.1 – 0.7 x
798

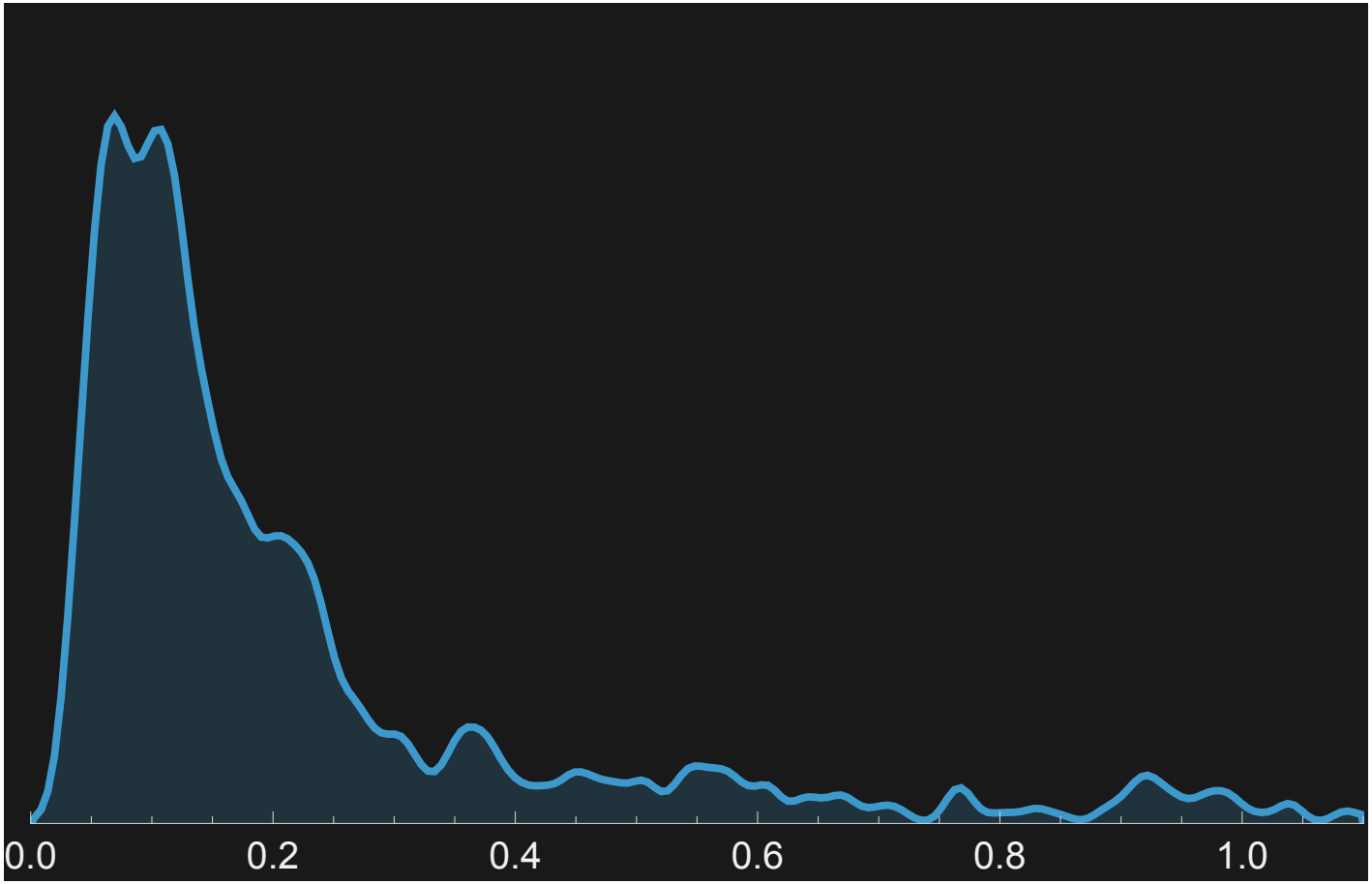

Kepler planets (2.1$R_\oplus \leq R_p \leq$3.1$R_\oplus$)
@host−stars (0.6$M_\odot \leq M_* \leq$1.05$M_\odot$)
with Semi−major axis > a(AU)
500
200
100
50
798
0.07 AU
0.01
0.05
0.10
0.50
1
Semi−major axis (Orbital Separation, a in AU)

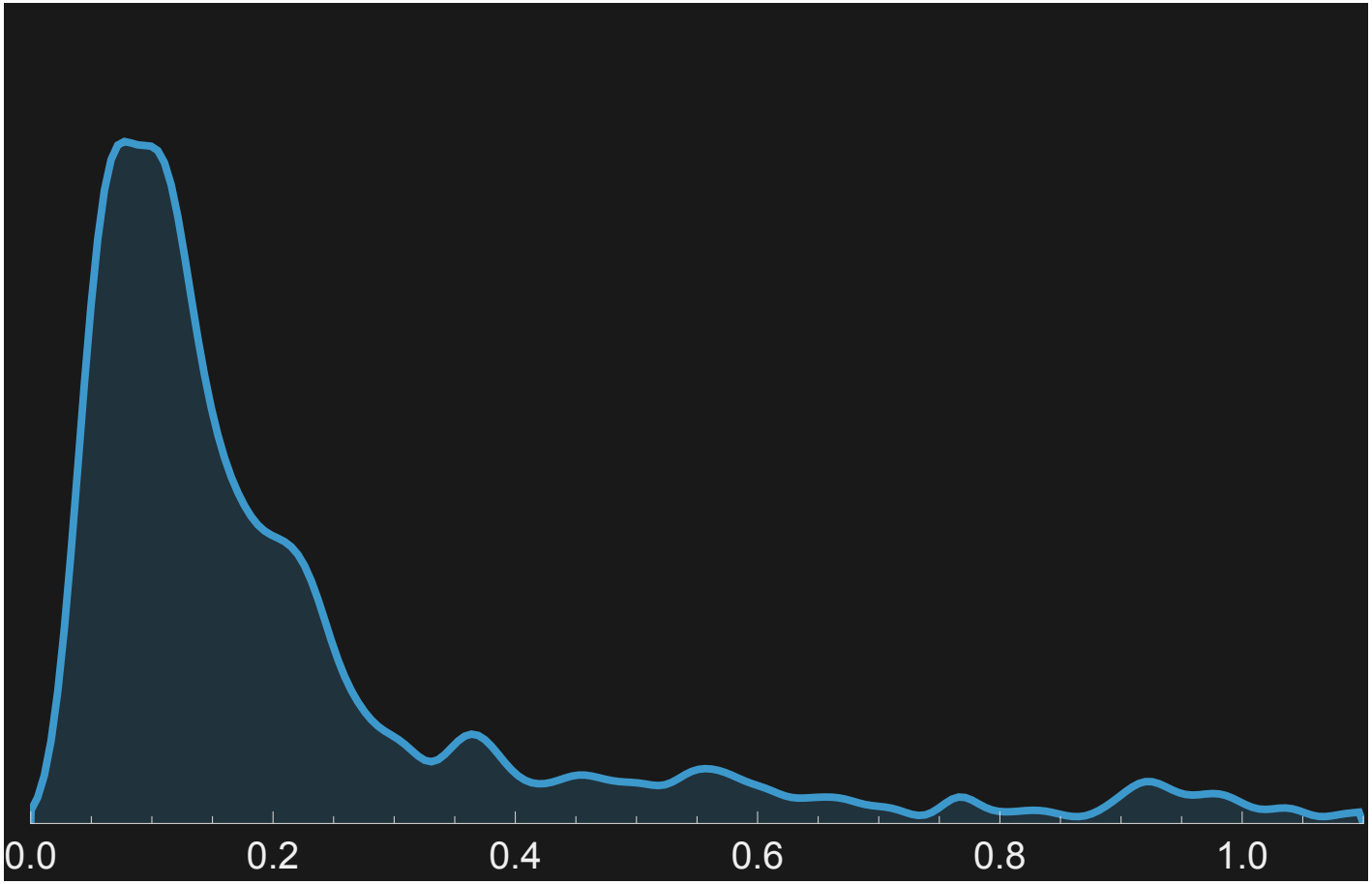
Oscillatory behavior…

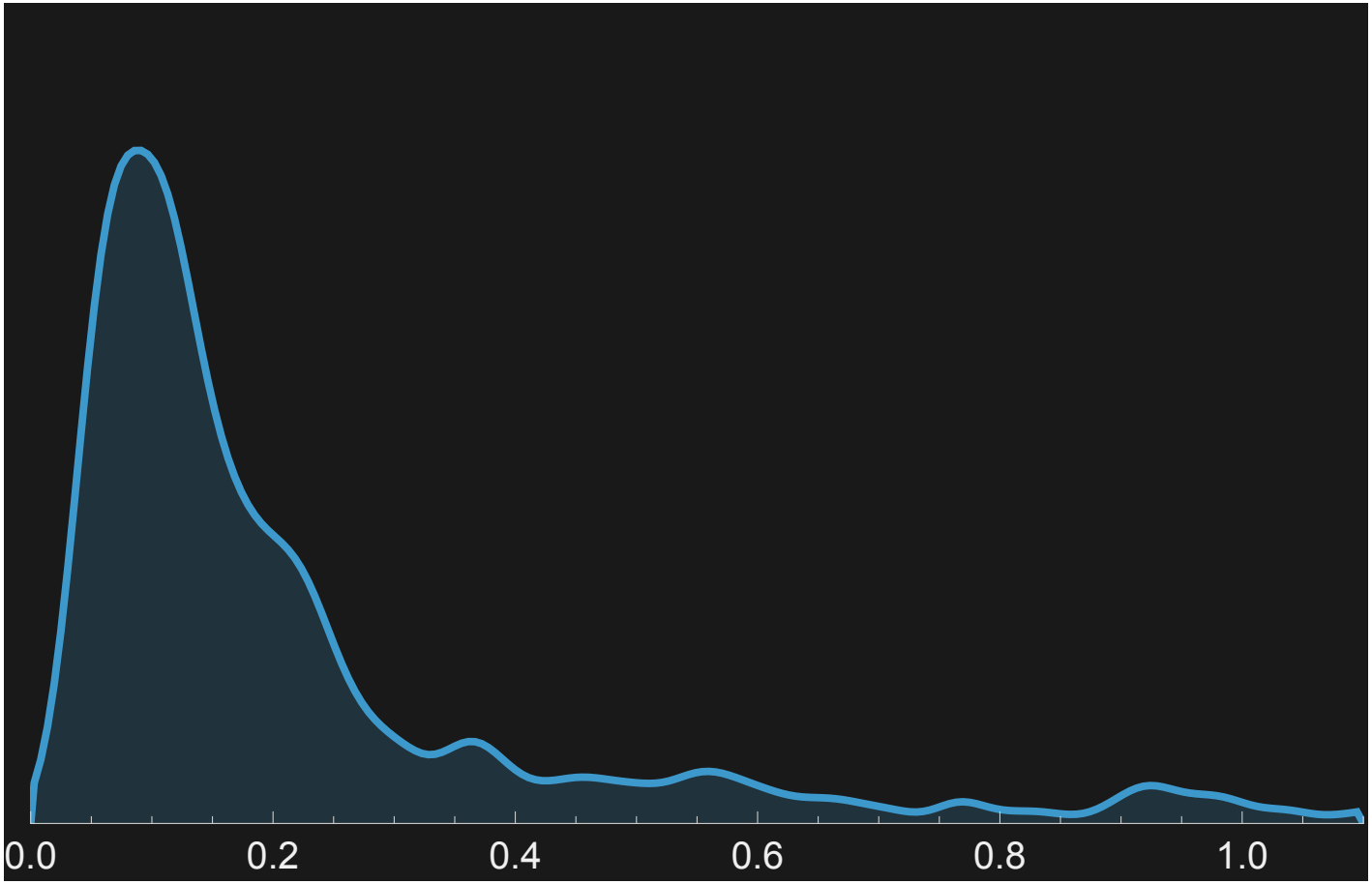


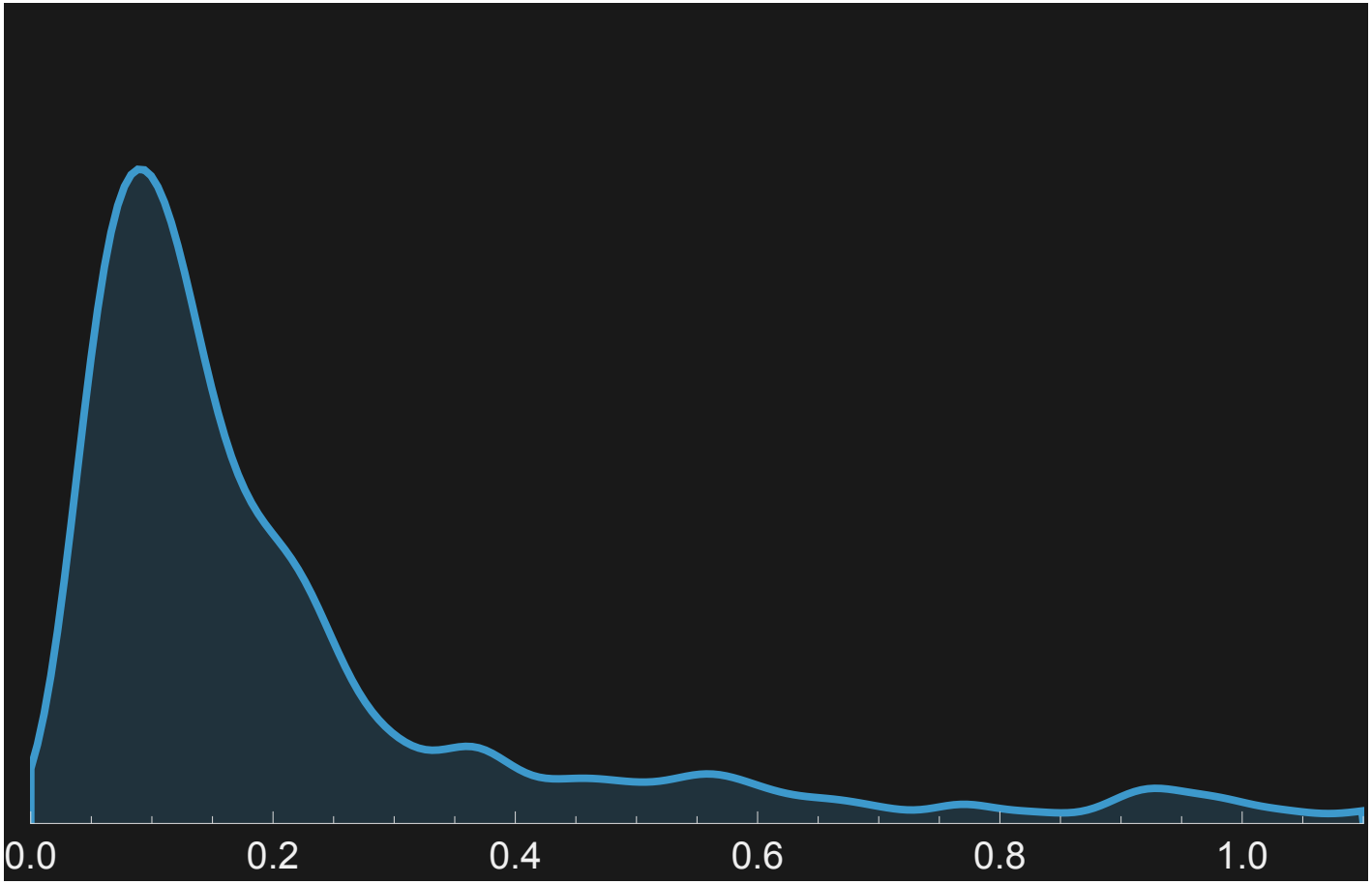

6
5
4
3
2
1
0
0.0
0.2
0.4
0.6
0.8
1.0

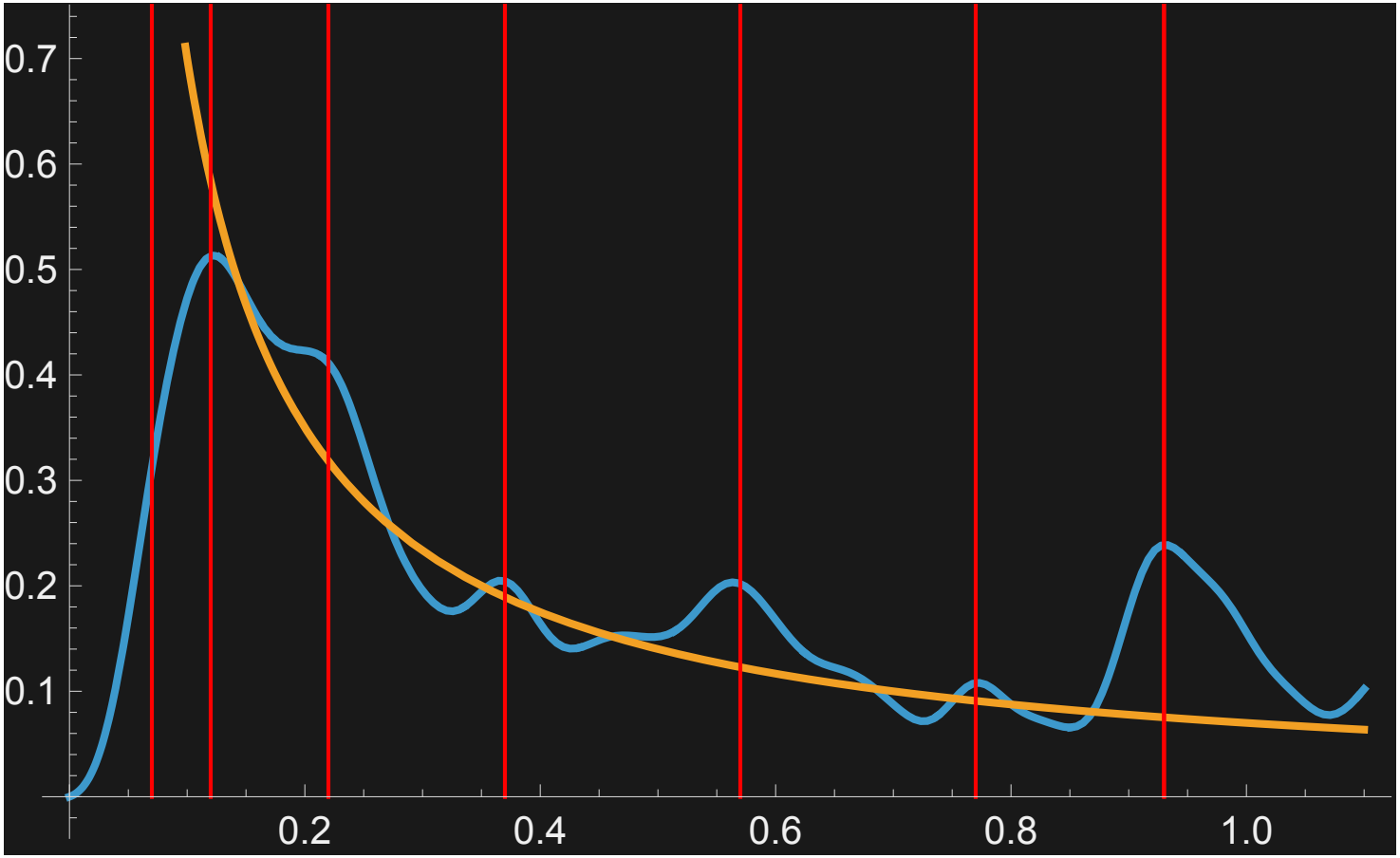

6
5
4
3
2
1
0
0.0
0.2
0.4
0.6
0.8
1.0

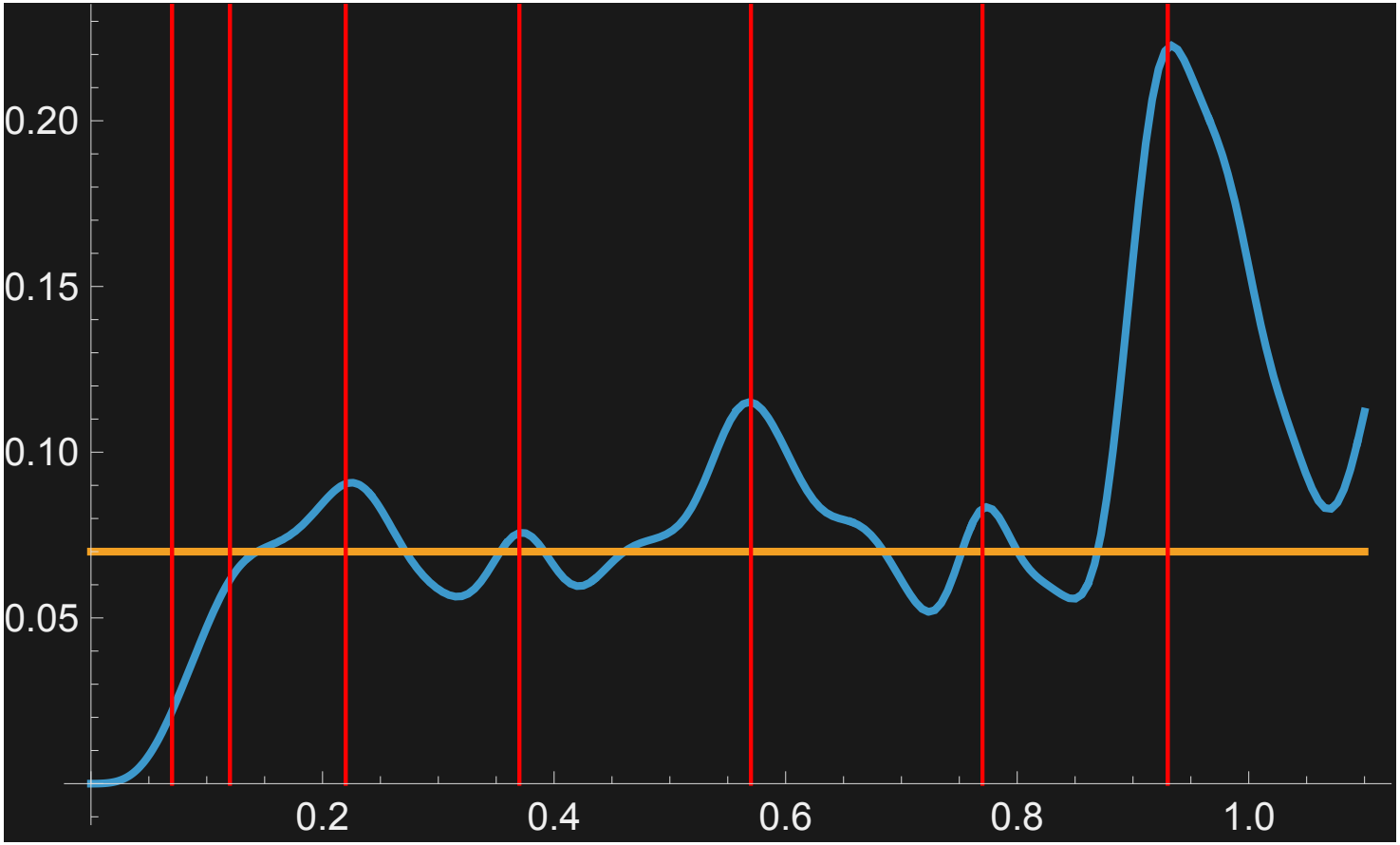

0.0
0.2
0.4
0.6
0.8
1.0


0.0
0.2
0.4
0.6
0.8
1.0

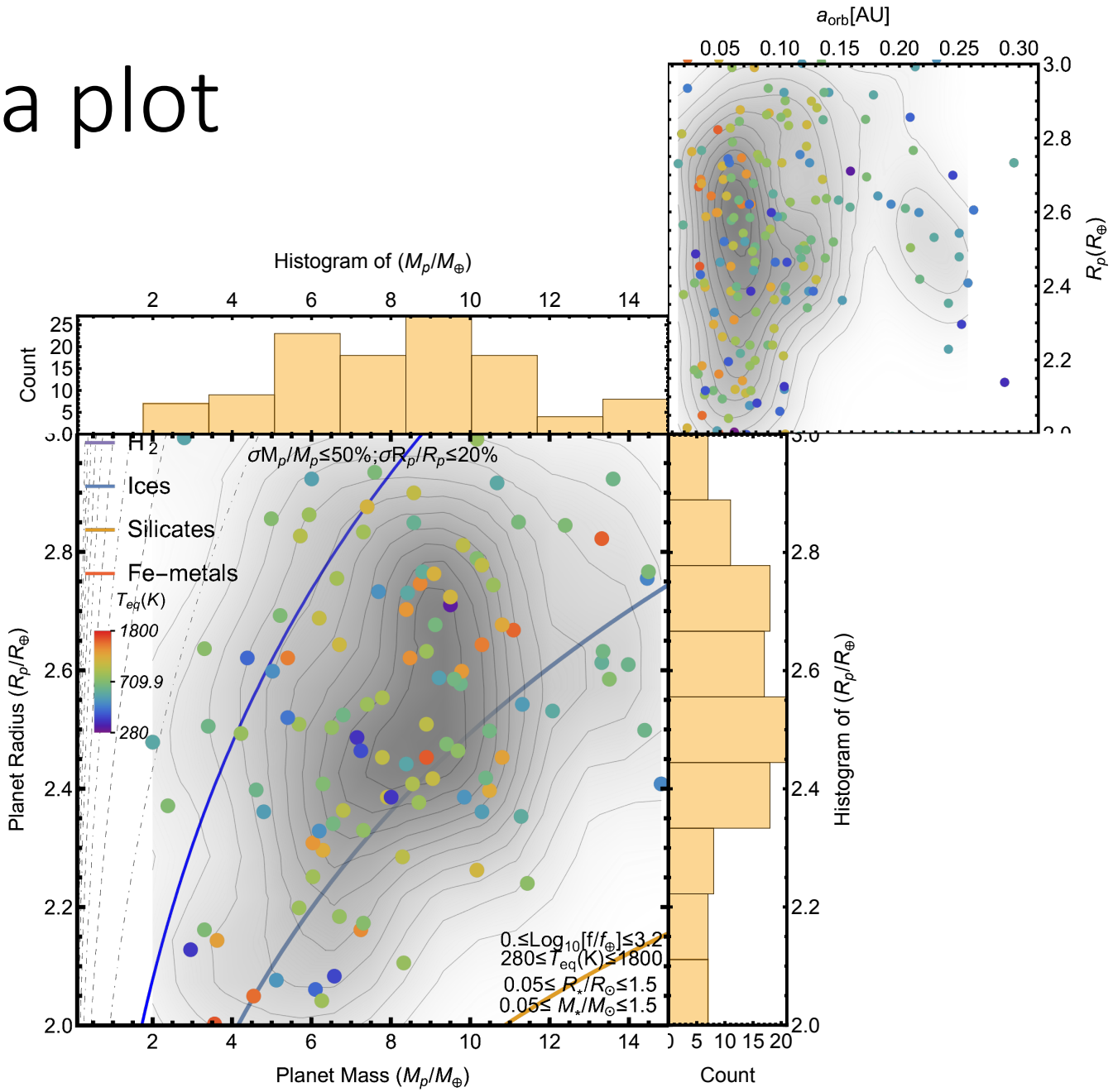

0.0
0.2
0.4
0.6
0.8
1.0


0.0
0.2
0.4
0.6
0.8
1.0

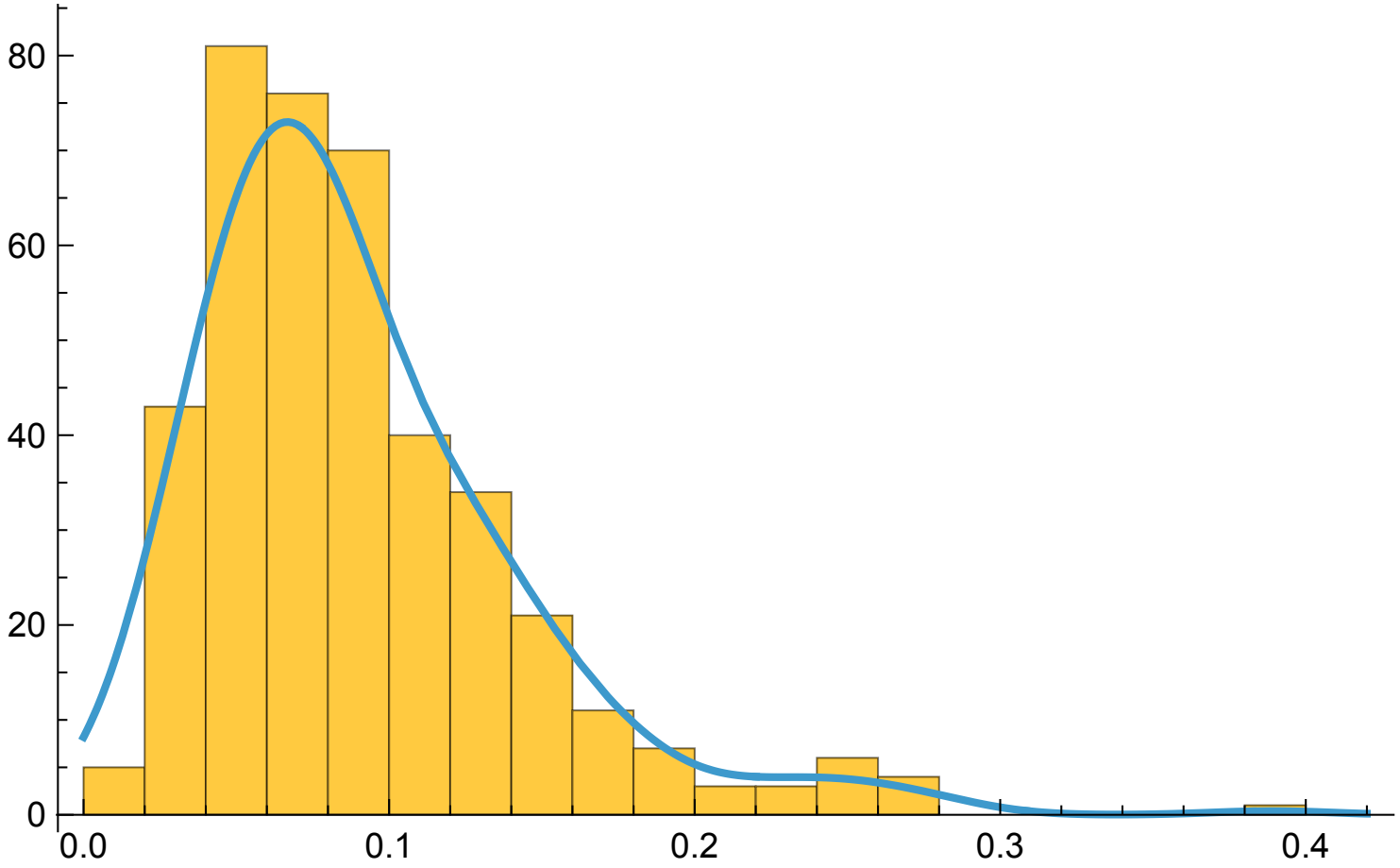

0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.2
0.4
0.6
0.8
1.0

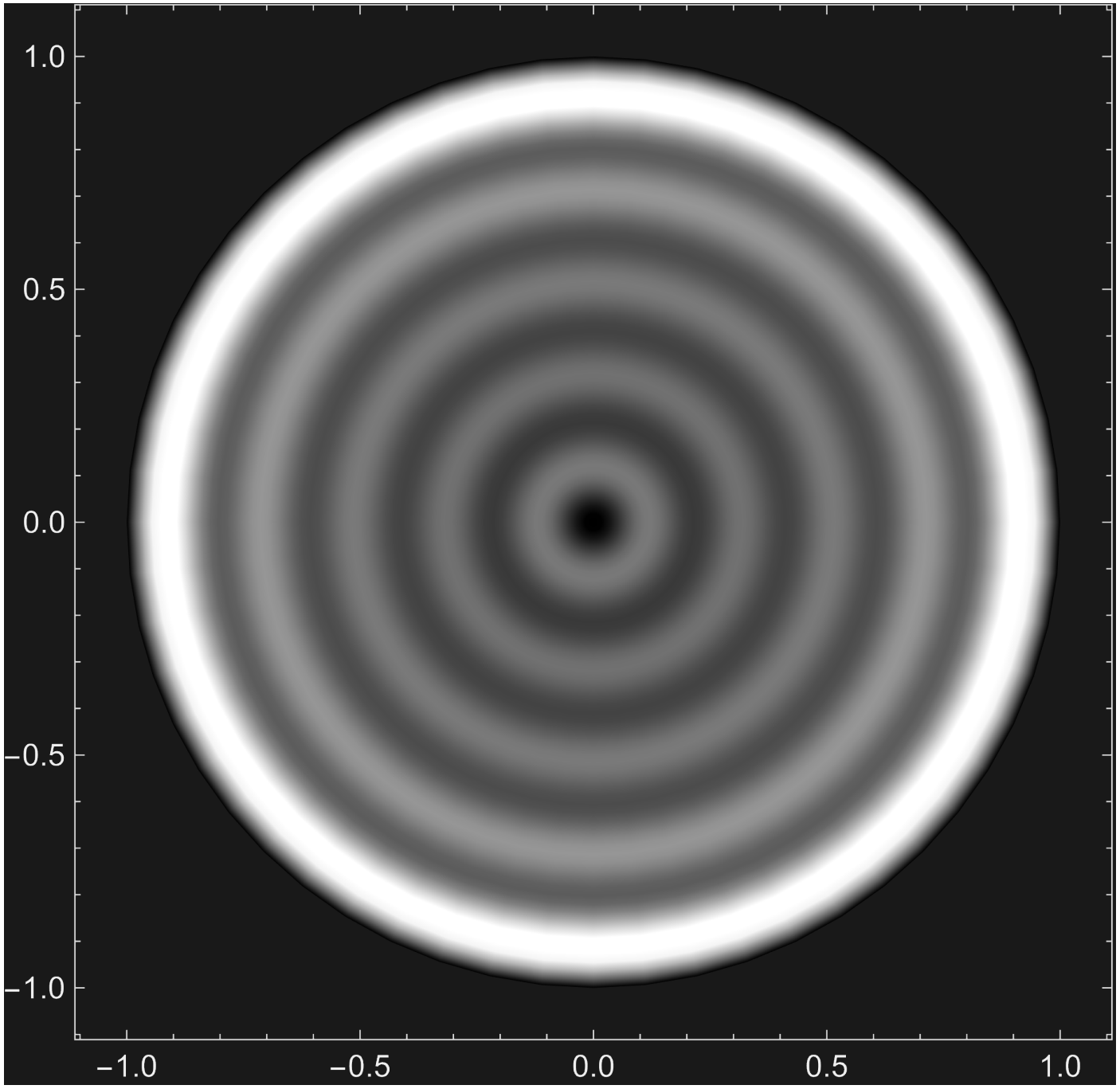

0.20
0.15
0.10
0.05
0.2
0.4
0.6
0.8
1.0

Rp-a plot

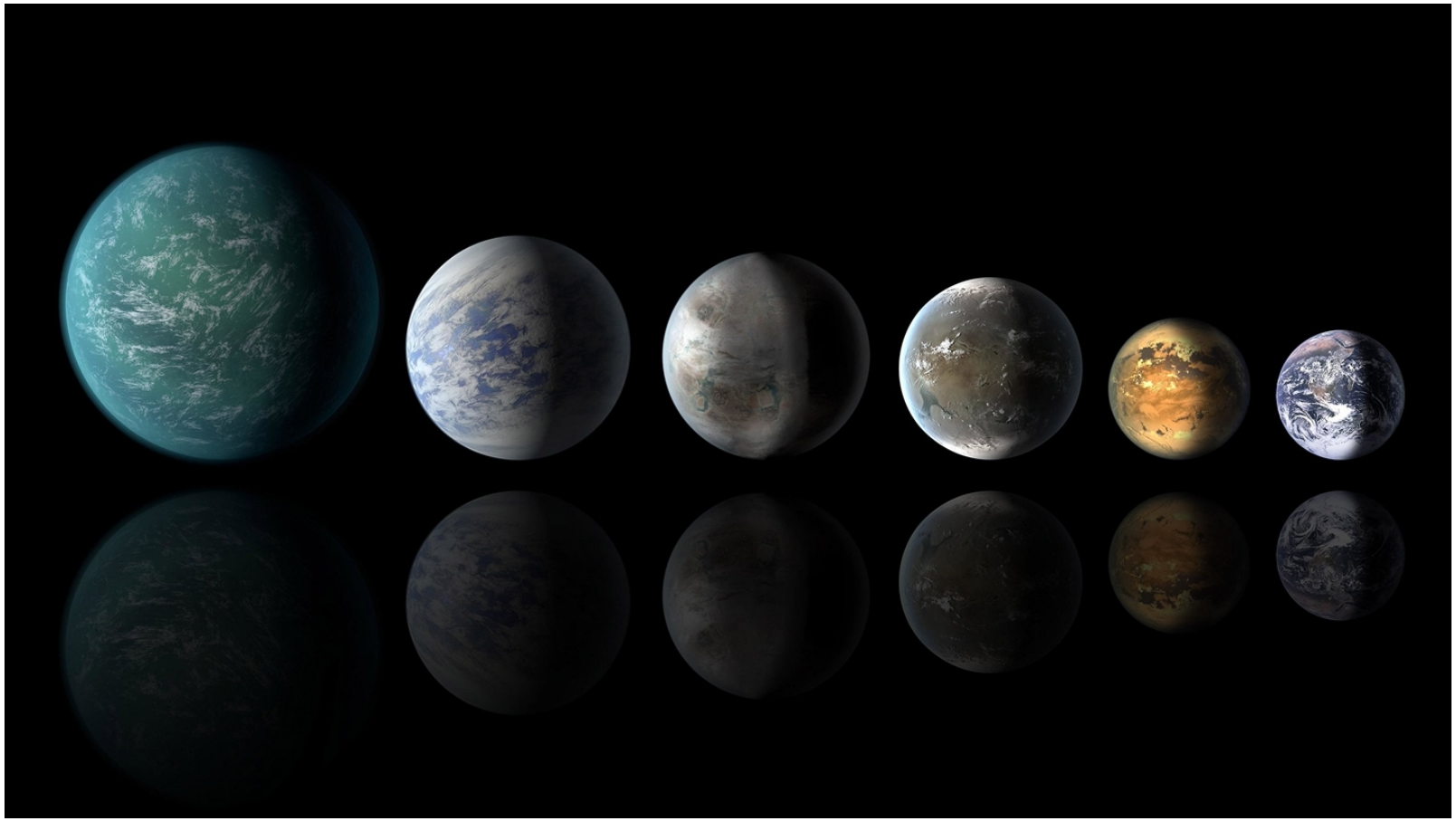

a_{orb}[AU]
0.05 0.10 0.15 0.20 0.25 0.30
$R_p(R_\oplus)$
Histogram of $(M_p/M_\oplus)$
Count
H_2
Ices
Silicates
Fe−metals
$T_{eq}(K)$
1800
709.9
280
$\sigma M_p/M_p \leq 50\%; \sigma R_p/R_p \leq 20\%$
$0.\leq \mathrm{Log}_{10}[f/f_\oplus] \leq 3.2$
$280 \leq T_{eq}(K) \leq 1800$
$0.05 \leq R_*/R_\odot \leq 1.5$
$0.05 \leq M_*/M_\odot \leq 1.5$
Planet Radius $(R_p/R_\oplus)$
Planet Mass $(M_p/M_\oplus)$
Histogram of $(R_p/R_\oplus)$
Count

TESS result comparison…

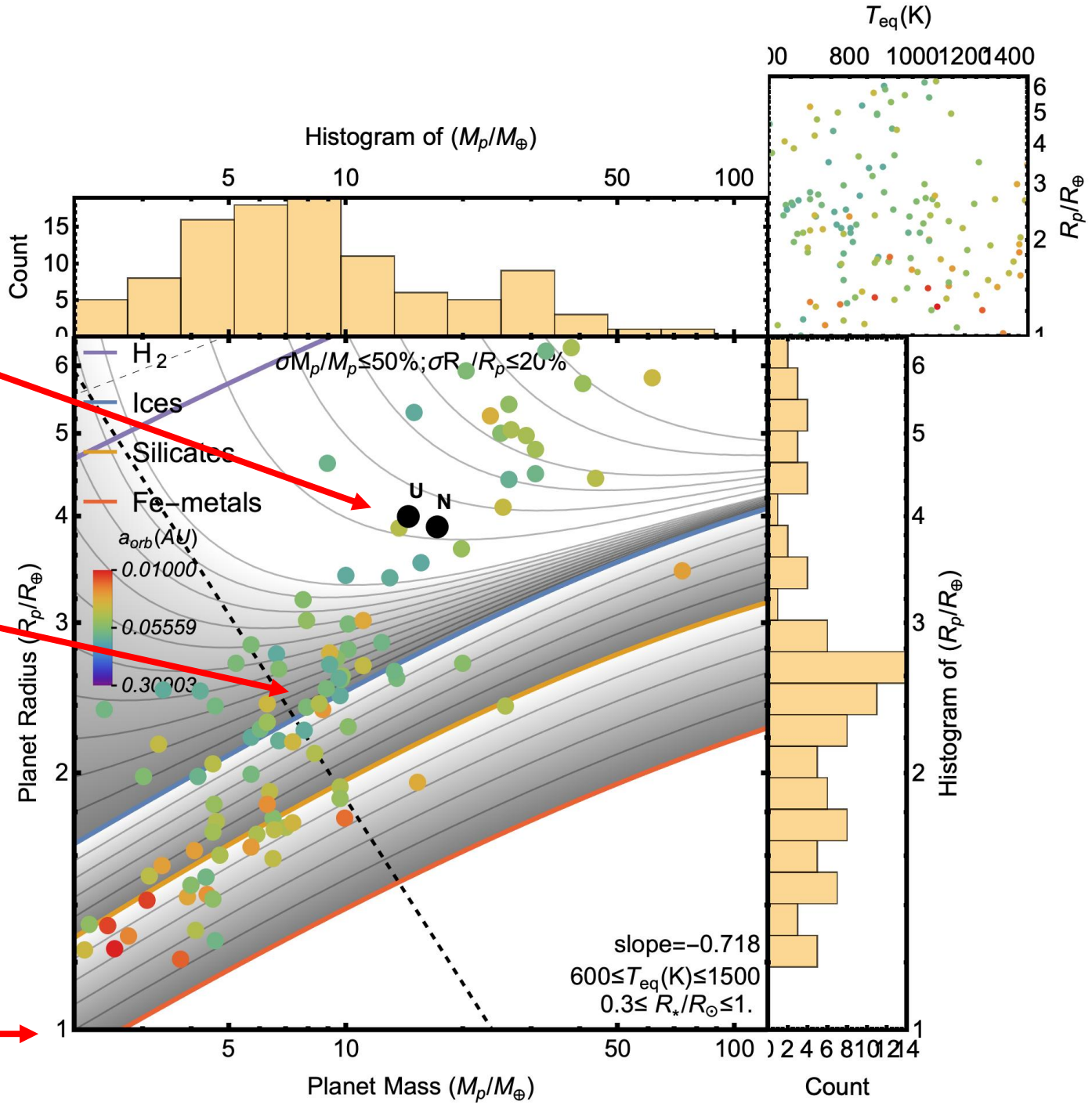



1.0
0.5
0.0
−0.5
−1.0
−1.0
−0.5
0.0
0.5
1.0

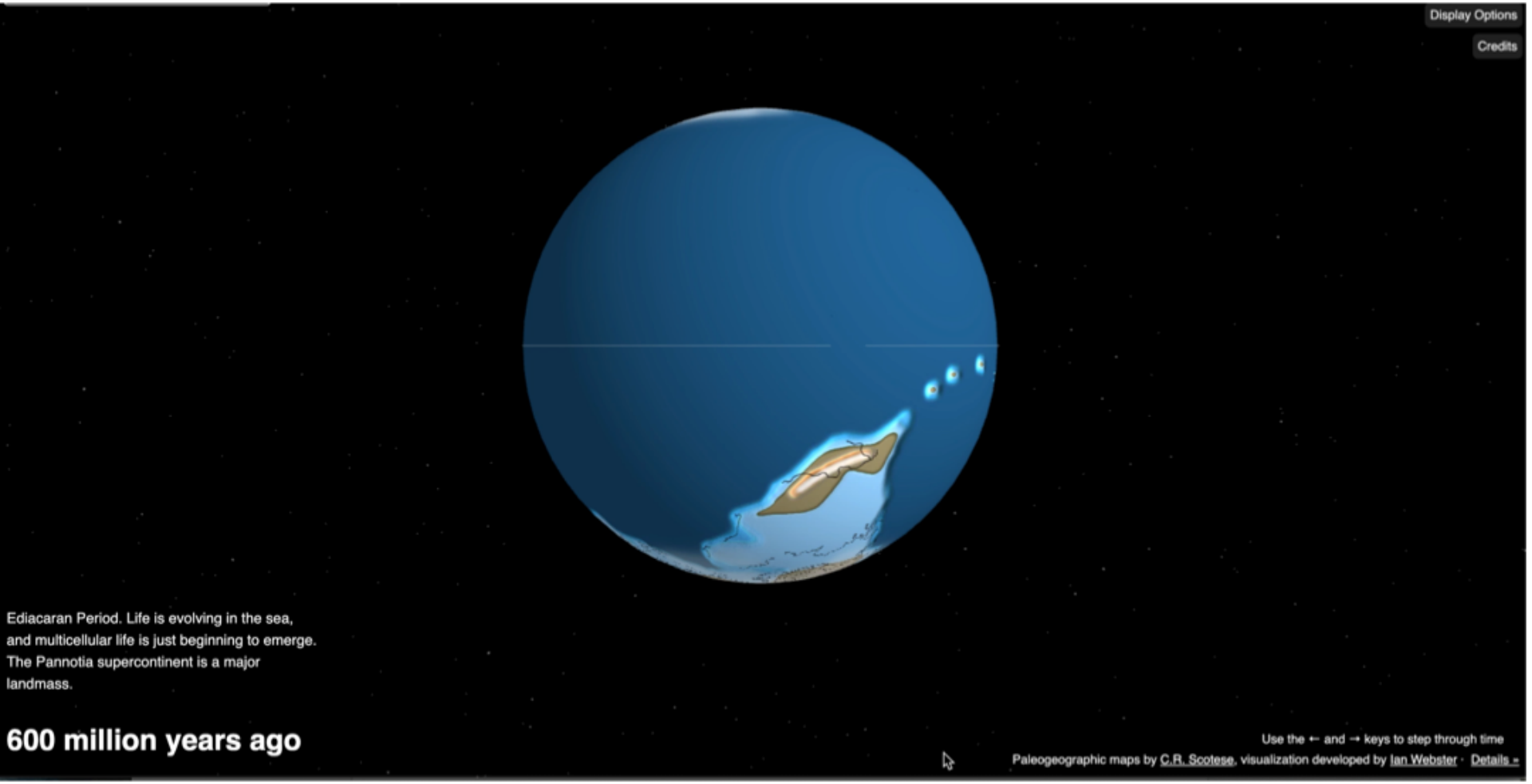
Matter Held Together by Gravity



Goldschmidt Conference 2018 Press Release @ Li Zeng
https://phys.org/news/2018-08-water-worlds-common-exoplanets-vast-amounts.html


T_{eq}(K)
Histogram of ($M_p/M_\oplus$)
Count
$R_p/R_\oplus$
H_2
Ices
Silicates
Fe-metals
$\sigma M_p/M_p \leq 50\%; \sigma R_p/R_p \leq 20\%$
U
N
a_{orb}(AU)
0.01000
0.05559
0.30003
Planet Radius ($R_p/R_\oplus$)
Histogram of ($R_p/R_\oplus$)
slope=−0.718
$600 \leq T_{eq}(K) \leq 1500$
$0.3 \leq R_*/R_\odot \leq 1.$
Planet Mass ($M_p/M_\oplus$)
Count

Phys.org



Credit: www.smithsonianmag.com, Christopher Scotese and Ian Webster

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- Support from Stephanie C. Werner, Trond Torsvik, Trine Sannesmoen and Hedda Susanne Molland,
- Support from Stein B. Jacobsen and my fellow group members at Harvard University Department of Earth & Planetary Sciences

references

- https://arxiv.org/abs/2604.08428
- https://arxiv.org/abs/2604.08406