UNIVERSITY OF BIRMINGHAM

AMAURY TRIAUD
PHYSIC WEST G32
A.TRIAUD@BHAM.AC.UK
OFFICE HOURS: MON 1-2PM
VEVOX.APP 137-795-664

EXOPLANETS

year 3 & year 4

22 lectures

+ 2 supervisions

A few remarks first

office hours Mon 1-2 pm. At other times, send a mail first

reasonable arrangements tell me what I can do to help

exams before 2023, half are on asteroseismology

live polling have a device with web-access ready

support session 9am Friday 06 Feb and 27 Mar

continuous assessment for Y3: two quizzes during term

lecture notes Latex notes are mostly done, but in progress

Syllabus

Week 1	-	Exoplanet introduction
Week 2	-	Planet formation - gap formation
Week 2/3	-	Planet formation - ice-line, runaway accretion
Week 3	-	The two-body problem
Week 4	-	Detection methods - radial-velocities
Week 5	-	Detection methods - transits
Week 6	-	Detection methods - other methods
Week 7	-	Atmospheres
Week 8	-	Know thy star
Week 9	-	Planetary migration
Week 10	-	non-Keplerian effects

TextBooks

Exoplanets, by Sara Seager

The Exoplanet Handbook 2nd edition, by Michael Perryman

Planetary Sciences 2nd Edition, by de Pater & Lissauer

List available on ***http://resourcelists.bham.ac.uk***

In addition, I will post a few research papers for your interest.

Practice during the term

Exercices	Available on Canvas, with and without solutions. Suggestions of further work as well.
Support session	2 tutorials on 06 Feb and 27 Mar 9-10am (Watson B)
Assessment 1	Quiz on Canvas. The quiz will open on **10 February,** and needs to be in by **24 February**.
Assessment 2	Quiz on Canvas about a scientific paper. The quiz will open on **10 March**, and needs to be in by **24 March**.

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Amaury Triaud
Physic West G32
a.triaud@bham.ac.uk
office hours: Mon 1-2pm
Vevox.app 137-795-664

ExoPlanets

Introduction

What is a Planet?

The definition of what a planet is has changed throughout history

~500 BCE	a moving star.
~1500 CE	something orbiting the Sun.
~1850 CE	a large body orbiting the Sun.
~2000 CE	a body - in orbit about the Sun - with enough mass to be spherical - that has cleared its orbit

This definition is not sufficient and will need to be revised
e.g., exoplanets, but also free-floating planets (or are they planets?)

What is an Exoplanet?

Usually, a planet orbiting a star other than the Sun.

We also call them extrasolar planets.

quiz #1

go to vevox.app

6 questions

Why we are interested in Exoplanets

- We have probably finished the census of the Solar System.

  few objects to work with: only 8 planets

  are all systems similar to the Solar system?

- We want to understand planet formation

  can look at **different** environments: younger & older

  can look at different stars, properties (like binary stars)

- To measure how frequently biology exists in the Cosmos.

APPENDIX A USEFUL PLANETARY DATA

Table A1 Basic data on the planets (including the Moon).

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Mass										
$/10^{24}$ kg	0.330	4.87	5.97	0.074	0.642	1900	569	86.8	102	0.013
/Earth masses	0.055	0.815	1.00	0.012	0.107	318	95.2	14.4	17.1	0.002
Orbital semimajor axis[a]										
$/10^6$ km	57.91	108.2	149.6	149.6	227.9	778.4	1427	2871	4498	5906
/AU	0.39	0.72	1.00	1.00	1.52	5.20	9.54	19.19	30.07	39.48
Orbital eccentricity	0.206	0.007	0.017	0.055	0.093	0.048	0.054	0.047	0.009	0.249
Orbital inclination /degrees	7.0	3.4	0.0	5.2	1.9	1.3	2.5	0.8	1.8	17.1
Orbital period[b]	88.0 days	224.7 days	365.0 days	27.3 days	686.5 days	11.86 yr	29.42 yr	83.75 yr	163.7 yr	248.0 yr
Axial rotation period[b]/days	58.6	243	0.997	27.3	1.03	0.412	0.444	0.718	0.671	6.39
Axial inclination /degrees	0.1	177.3	23.5	6.7	25.2	3.1	26.7	97.9	29.6	119.6
Polar radius/km	2440	6052	6357	1738	3375	66 850	54 360	24 970	24 340	1137
Equatorial radius/km	2440	6052	6378	1738	3397	71 490	60 270	25 560	24 770	1137
Mean radius[c]/km	2440	6052	6371	1738	3390	69 910	58 230	25 360	24 620	1137
Density/10^3 kg m^{-3}	5.43	5.20	5.51	3.34	3.93	1.33	0.69	1.32	1.64	2.1
Surface gravity/m s^{-2}	3.7	8.9	9.8	1.6	3.7	23.1	9.0	8.7	11.1	0.7
Mean surface temperature/K	443	733	288	250	223					≥40
Effective cloud-top temperature/K						120	89	53	54	
Temperature at 1 bar pressure/K						165	135	75	70	
Rings	0	0	0	0	0	few	many	several	few	0
Satellites	0	0	1		2	≥39	≥30	≥21	≥8	1
Atmospheric surface pressure/bar[d]	$\approx 10^{-15}$	92.1	1.01	$\approx 10^{-14}$	6.3×10^{-3}					$\approx 10^{-5}$
Atmospheric surface density/kg m^{-3}	$\approx 10^{-13}$	67	1.293	$\approx 10^{-13}$	0.018					$\approx 10^{-4}$

Relative sizes in Solar System

Units & Orders of Magnitude

Remembering these values will speed your calculations, and help checking whether your results are sensible

$$M_\odot \sim 2\,10^{30}\,\mathrm{kg}$$

$$R_\odot \sim 700,000\,\mathrm{km} \sim 5\,10^{-3}\,\mathrm{AU}$$

$$M_{\mathrm{Jup}} \sim 2\,10^{27}\,\mathrm{kg} \sim 10^{-3}\,M_\odot \sim 300\,M_\oplus$$

$$R_{\mathrm{Jup}} \sim 70,000\,\mathrm{km} \sim 0.1\,R_\odot \sim 10\,R_\oplus$$

$$M_{\mathrm{Nep}} \sim 15\,M_\oplus$$

$$R_{\mathrm{Nep}} \sim 4R_\oplus$$

$$1\,\mathrm{AU} \sim 150,000,000\,\mathrm{km}$$

$$1\,\mathrm{pc} \sim 200,000\,\mathrm{AU}$$

Exoplanet History

- **Struve** (1952) describes how one could detect exoplanets with radial-velocities & transits.
- **van der Kamp** (1969) claims an astrometric detection, on Proxima Centauri - since disproved.
- **Campbell et al.** (1988) suspected planetary signal - retracted but shown to be true in 2002.
- **Latham et al.** (1989), an 11 M_{jup} object orbits HD114762 - suspected brown dwarf, confirmed as such in 2019.
- **Wolszczan & Frail** (1992), exoplanets orbiting a pulsar.
- **Mayor & Queloz** (1995), Jupiter-mass planet orbiting a Sun-like star, on a four-day orbit, 51 Peg b - **2019 Nobel prize in Physics**.

Exoplanet Rationales & Results

We search for exoplanets for:

To find out how Earth and the solar system **compare** to the rest of creation.

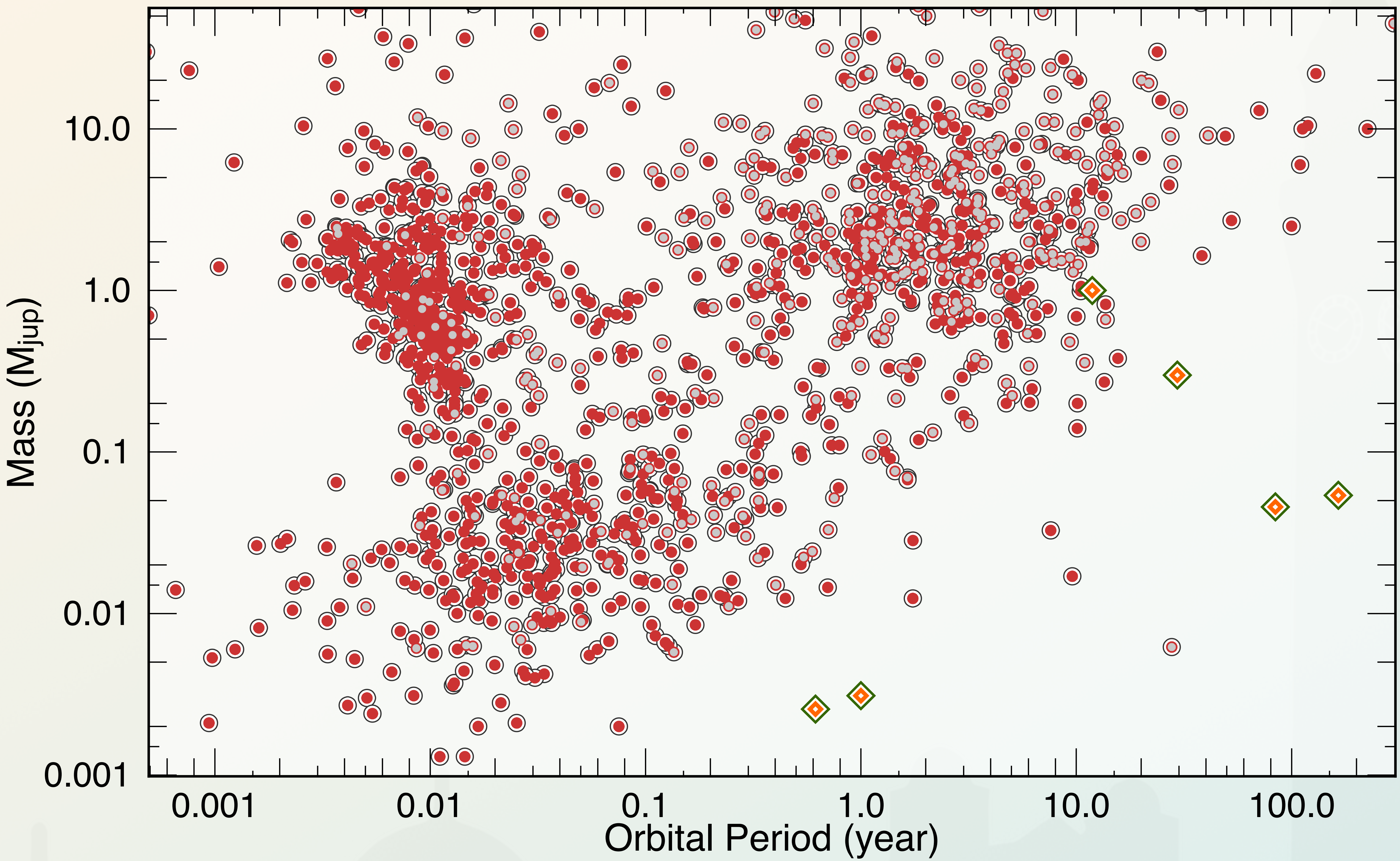
To **understand** planet formation processes and derive new laws of physics that might govern this process in a universal ways.

To find evidence of biology elsewhere, and **measure** how frequently and under which condition life happens.

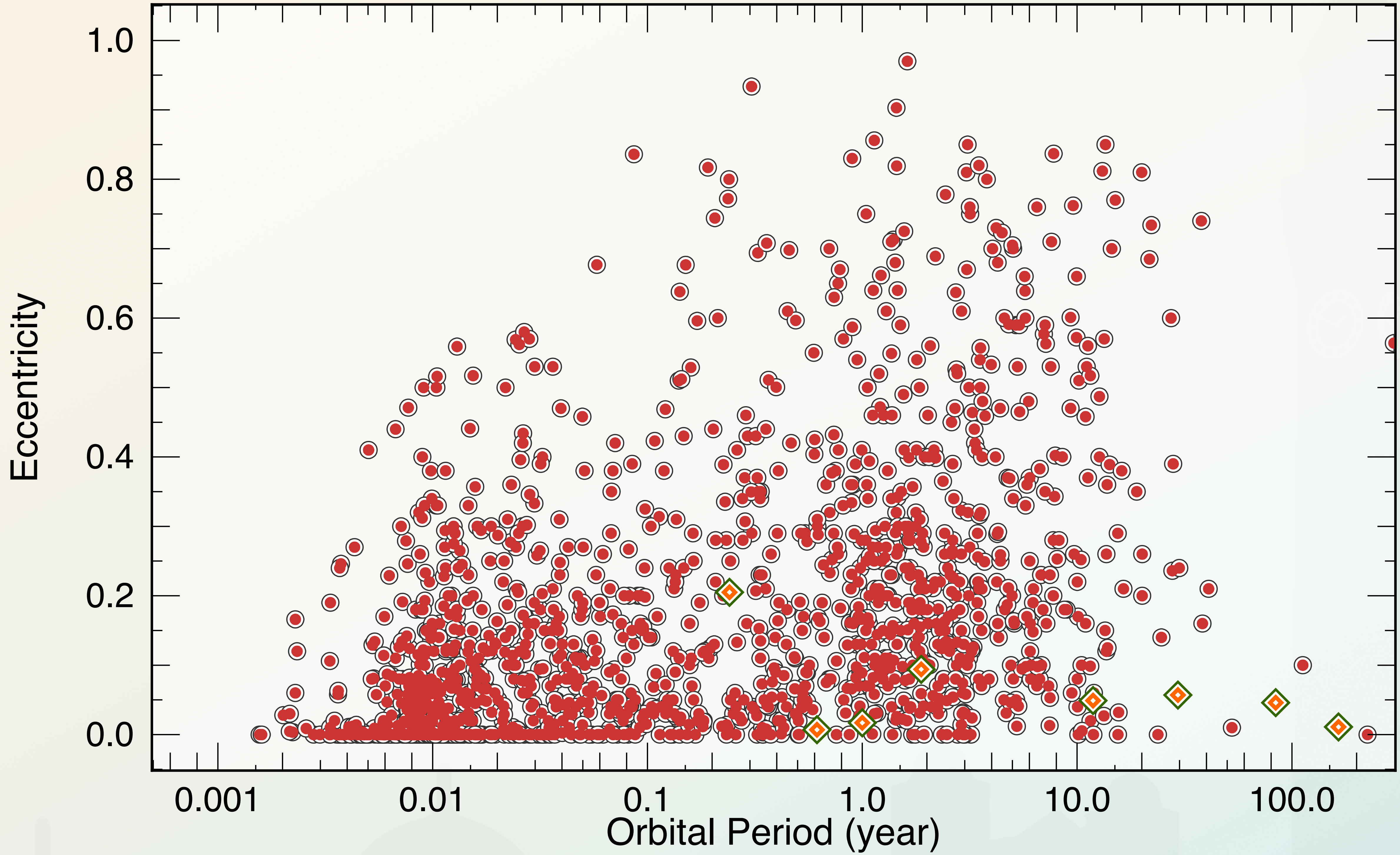
The biggest result so far is:

The discovery of exoplanet diversity

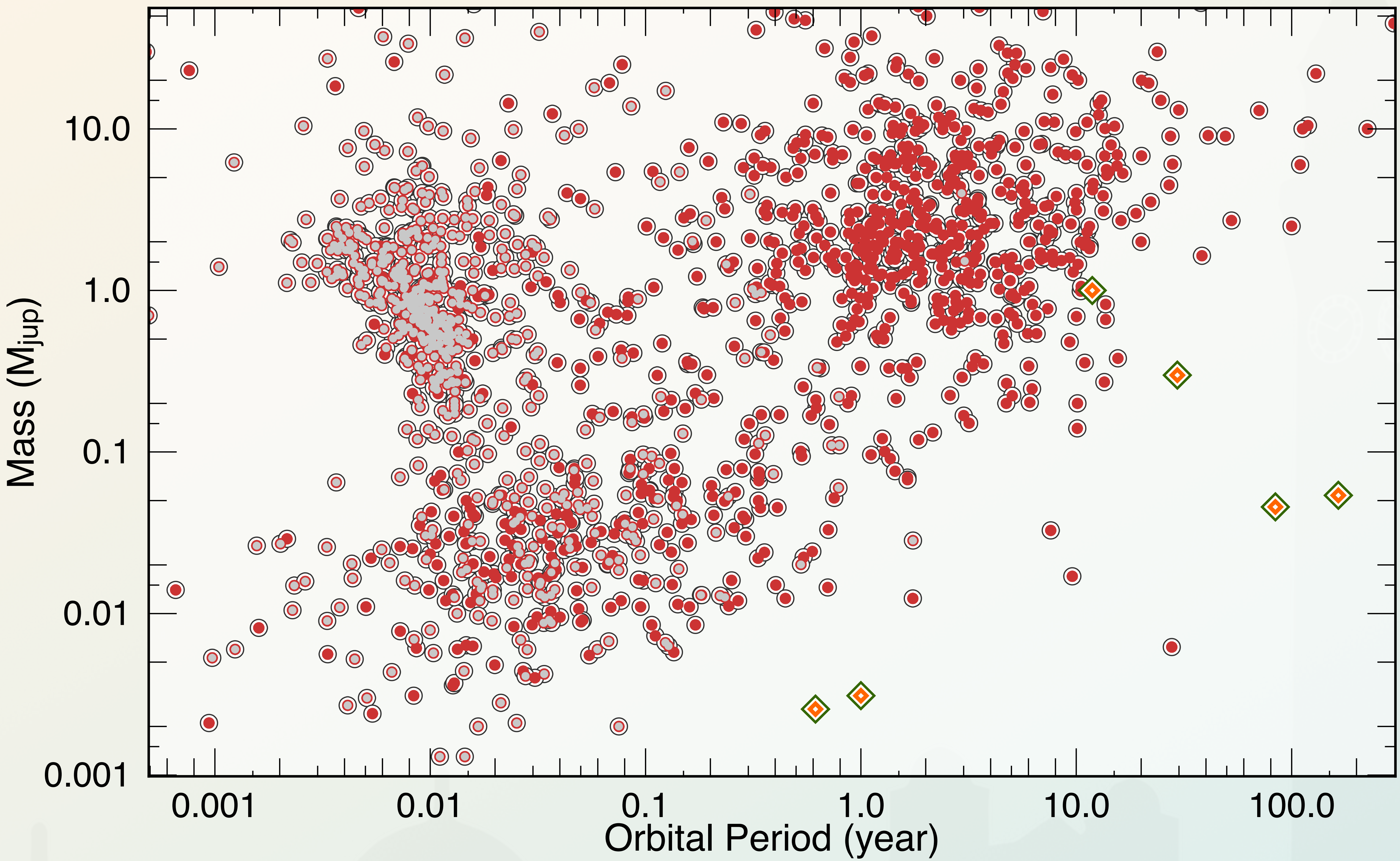
Exoplanet Diversity



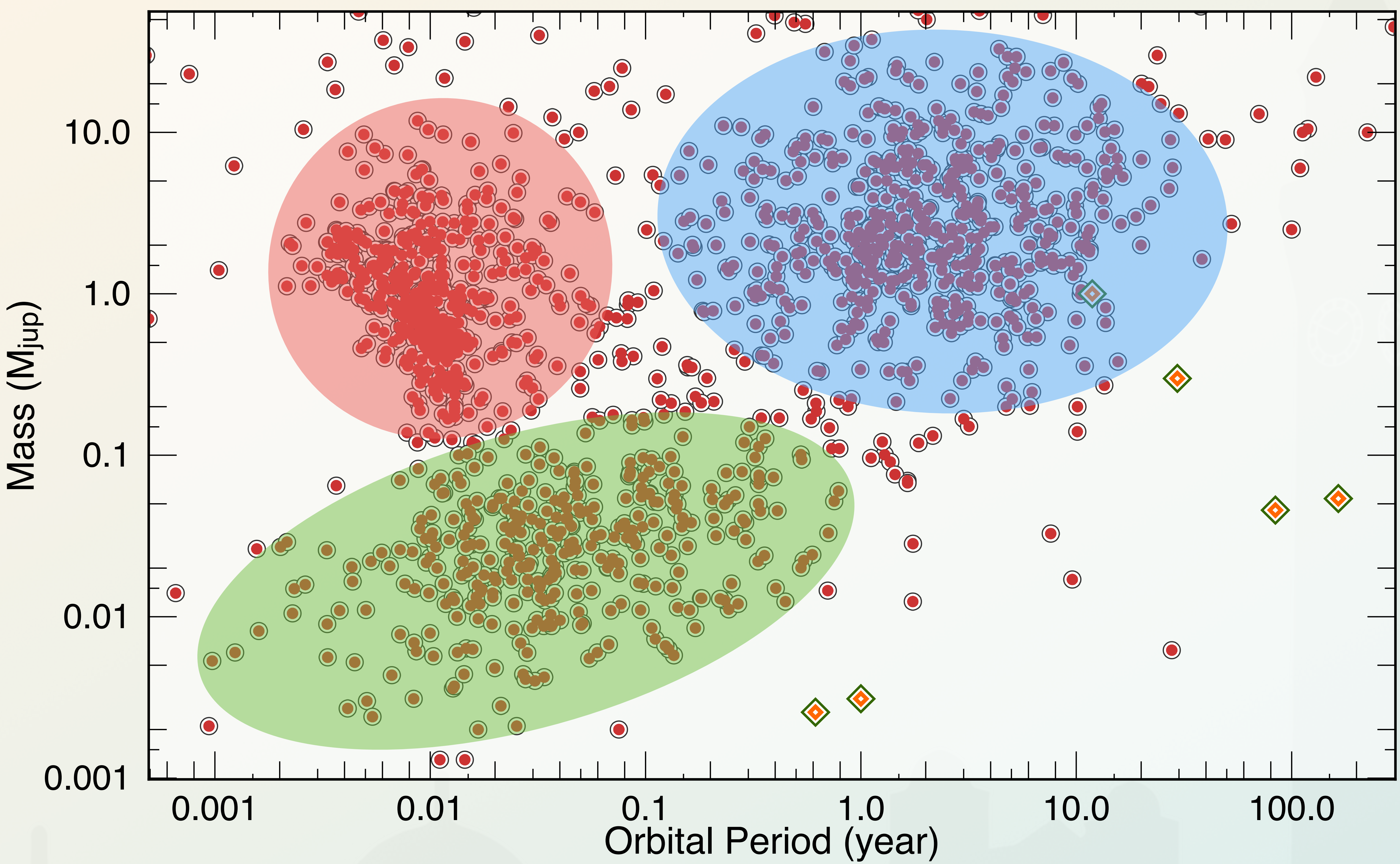
Exoplanet Diversity



Exoplanet Diversity

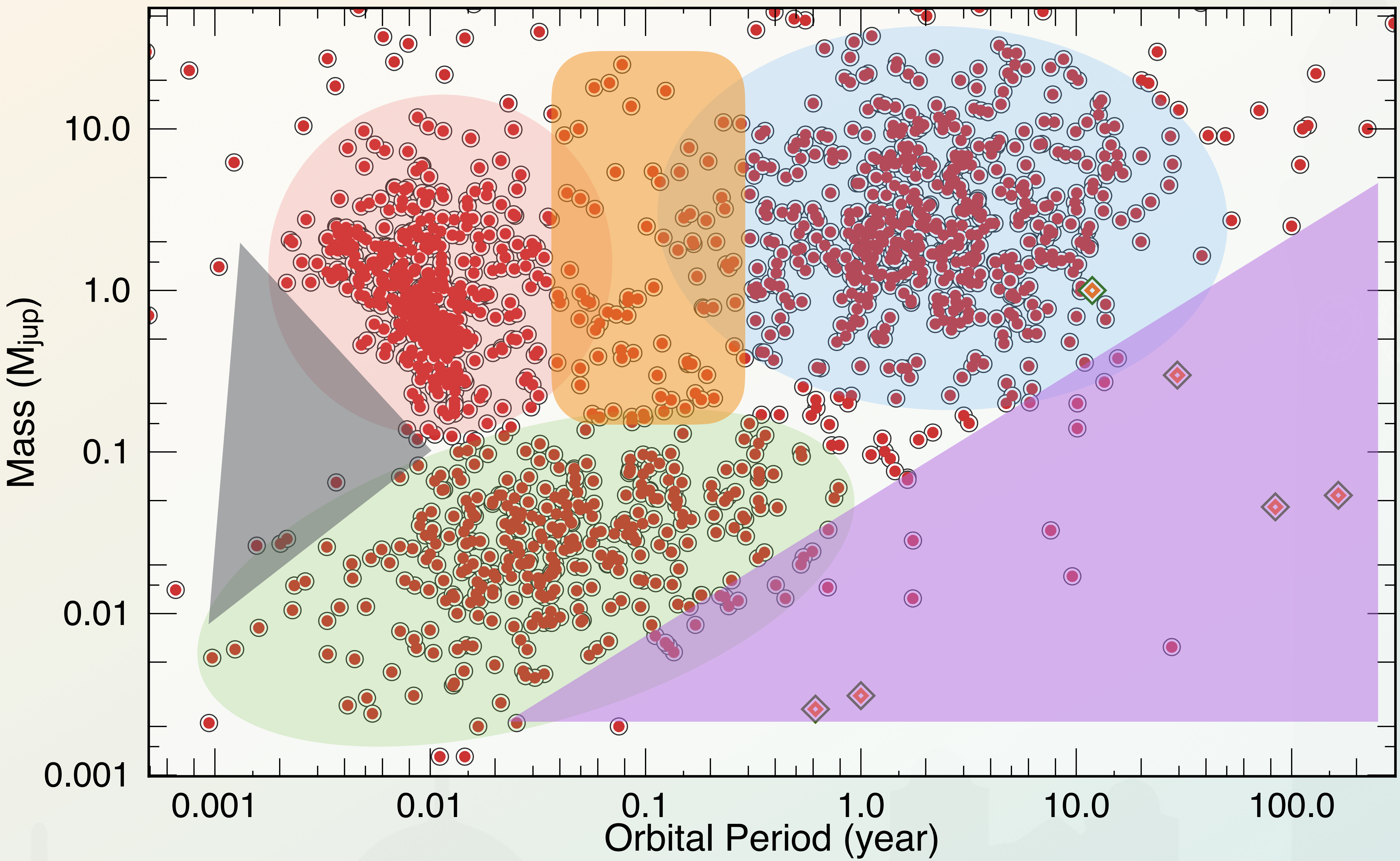


Exoplanet Nomenclature



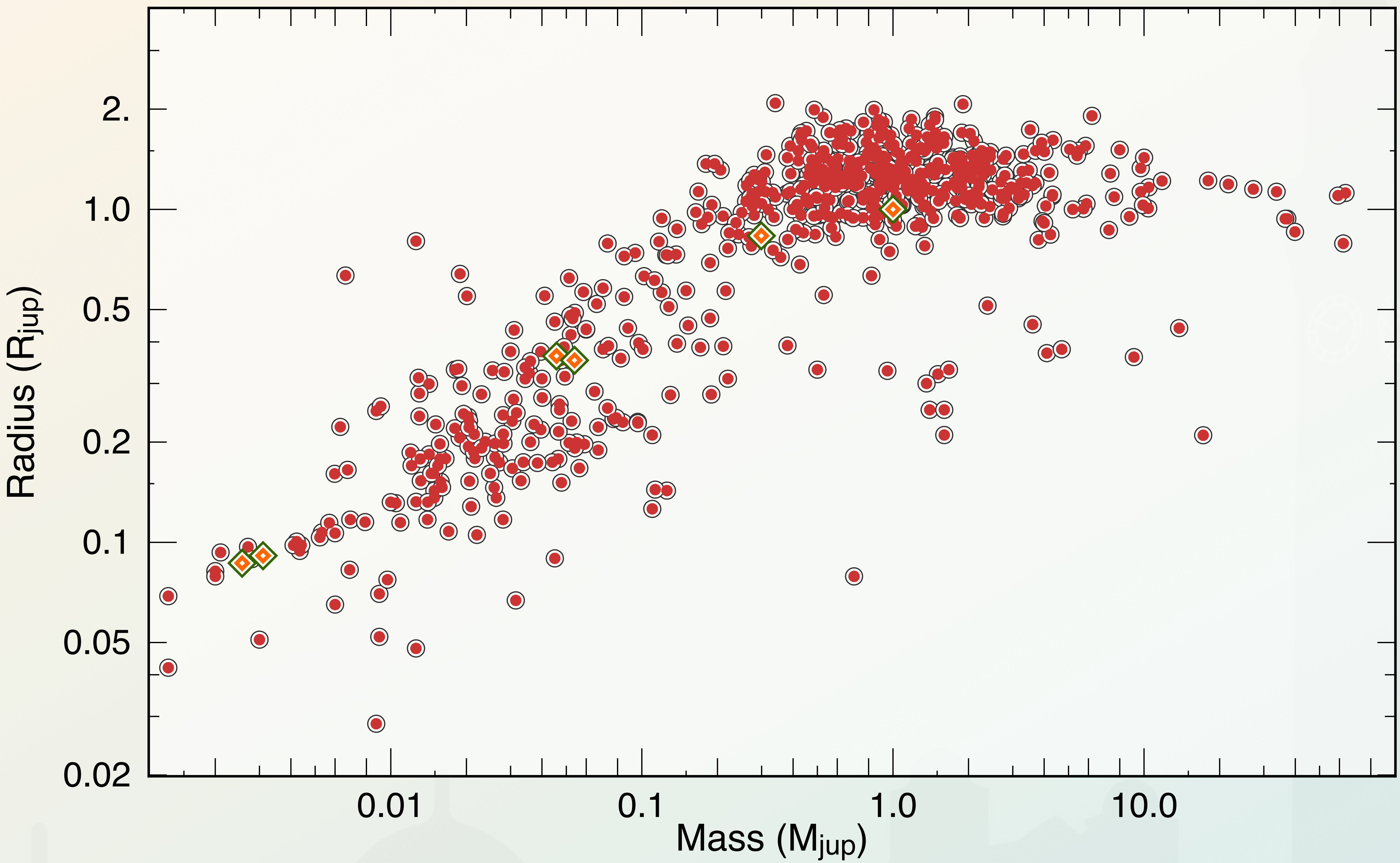
Hot Jupiters - warm and cold Jupiters - super Earths & sub Neptunes

Exoplanet Nomenclature

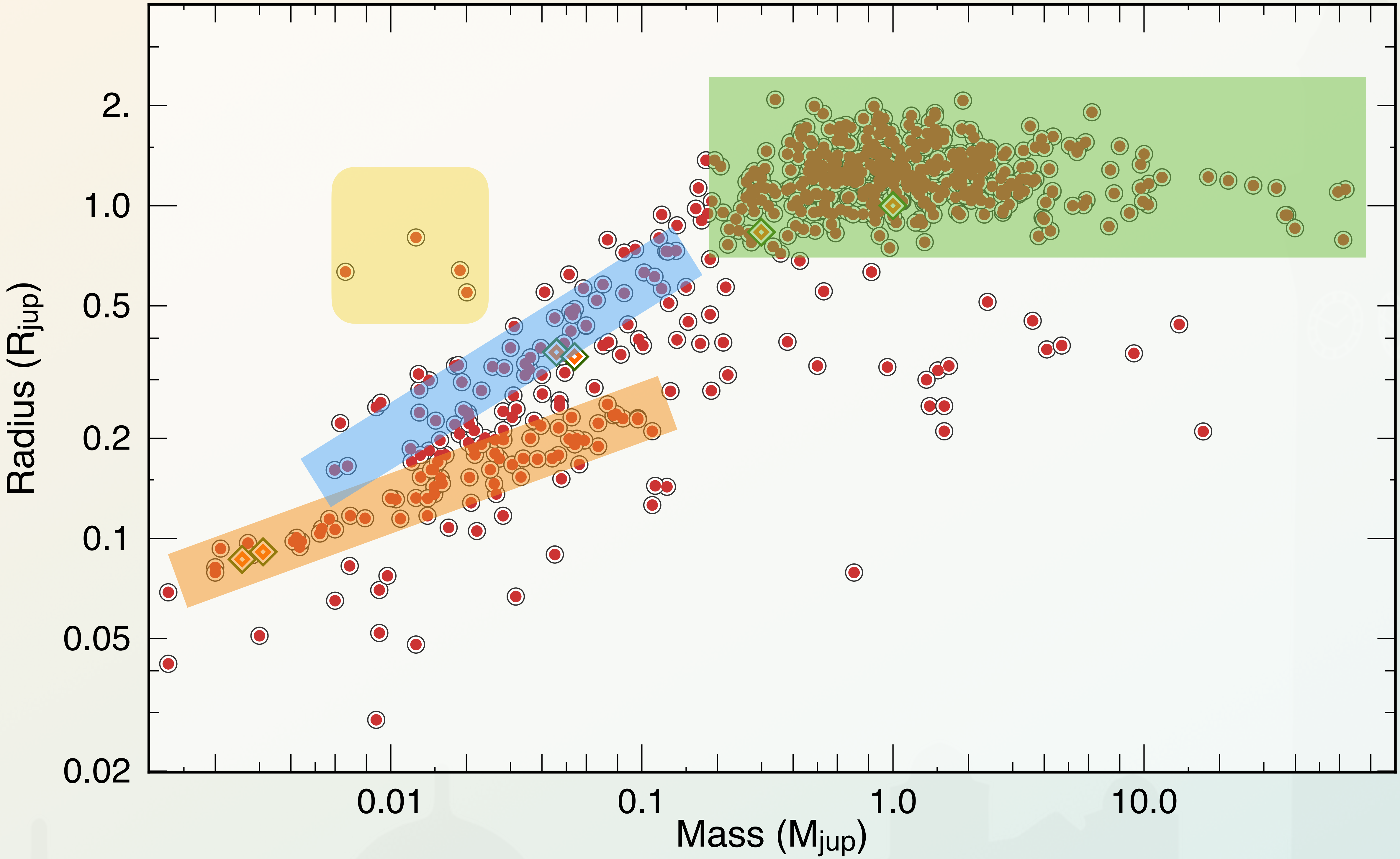


hot neptune desert - the period valley - detection inefficiency

Exoplanet Diversity

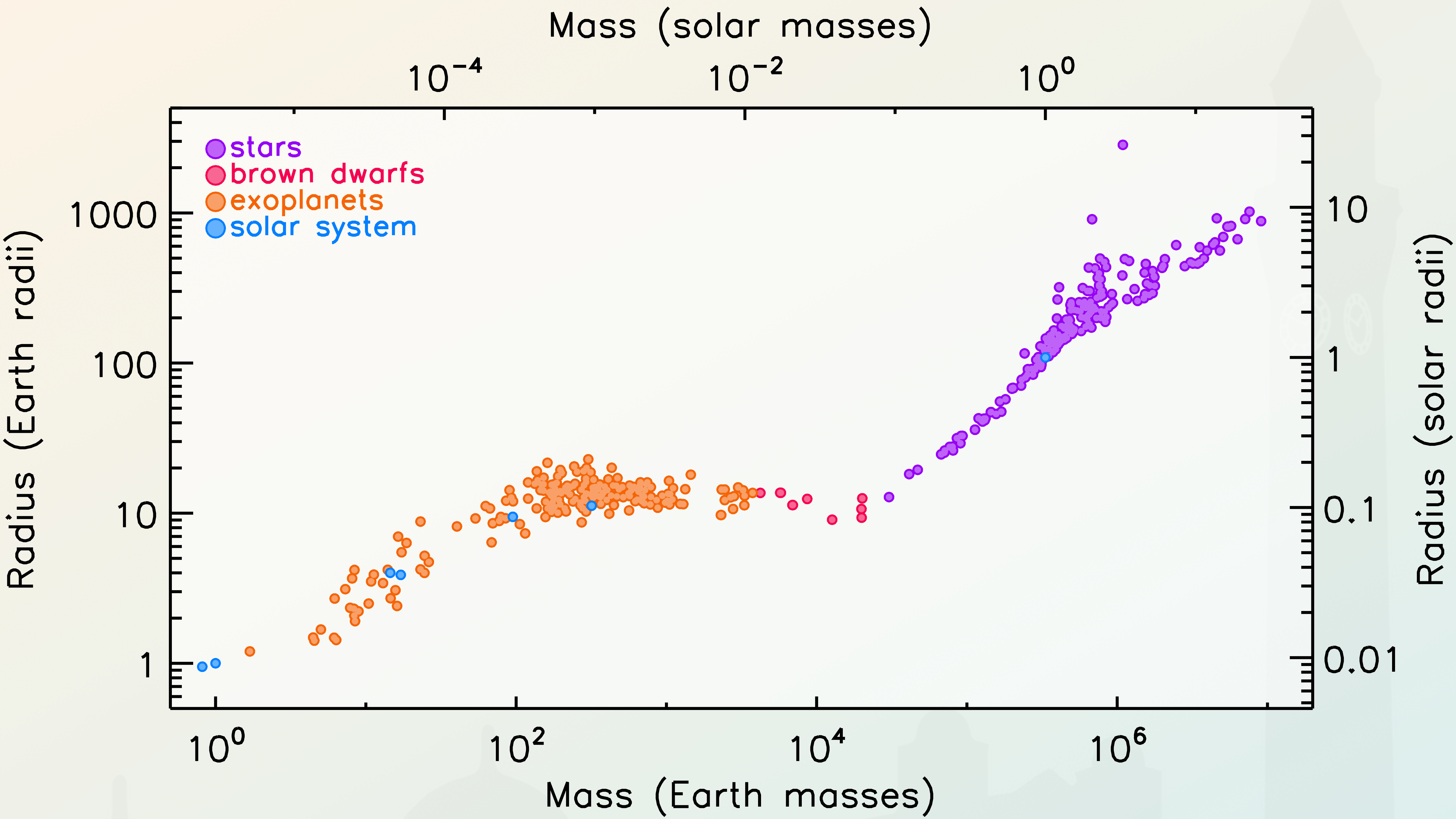


Exoplanet Nomenclature



Rocky - volatile-rich - gas-giants - super puffs

Exoplanet Diversity



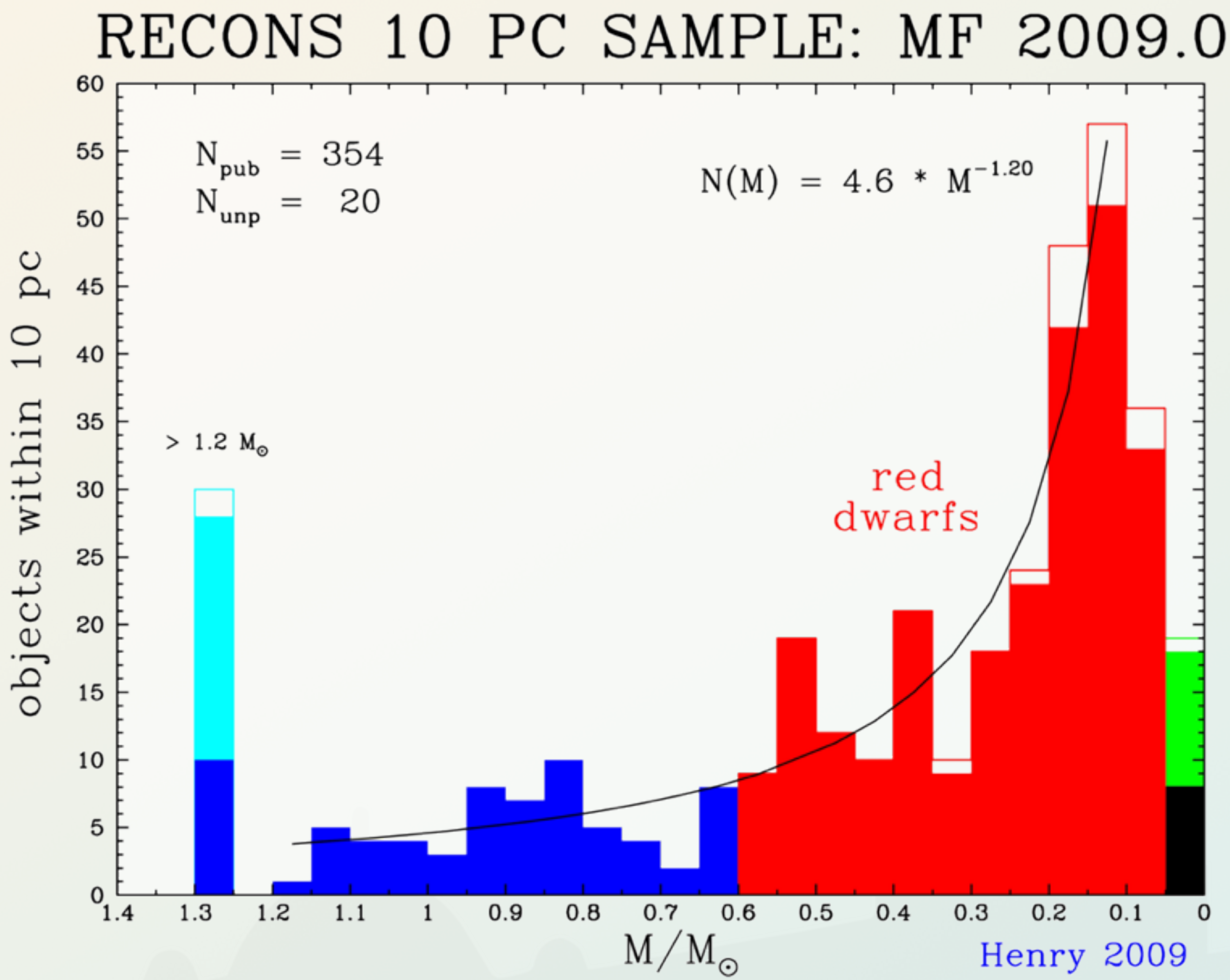
Courtesy Zach Berta-Thompson

Stellar Nomenclature

Sun-like star	Typically with a mass between 0.8 and 1.2 $M_\odot$
K dwarf	Typically with a mass between 0.55 and 0.8 $M_\odot$
M dwarf	Typically with a mass between 0.072 and 0.55 $M_\odot$
Fully convective star	Typically with a mass between 0.072 and 0.3 $M_\odot$
Brown dwarf	Typically with a mass between 0.012 and 0.072 $M_\odot$
Ultra-cool dwarf	Typically with a mass between 0.012 and 0.15 $M_\odot$
Hydrogen burning limit	Mass below which Hydrogen fusion is not possible: 0.072 $M_\odot$ (80 M_{jup})
Deuterium burning limit	Mass below which Deuterium fusion is not possible: 0.012 $M_\odot$ (13 M_{jup})
Binary star	Two stars orbit one another.

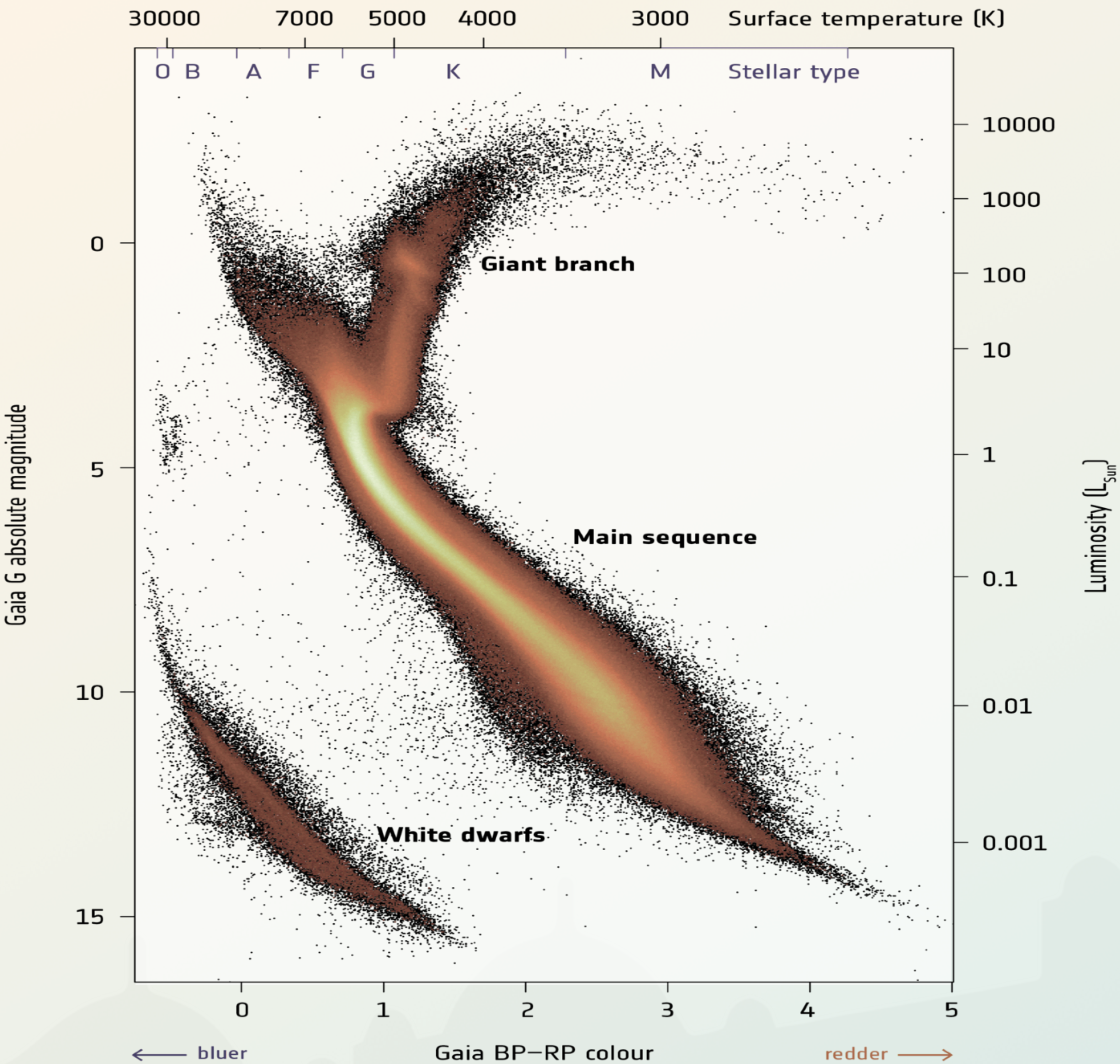
Stellar Diversity

Stars are also diverse themselves



Henry+ 2009

STELLAR DIVERSITY



Most stars in the **main sequence**.

Stars are born above the main sequence, then settle on it.

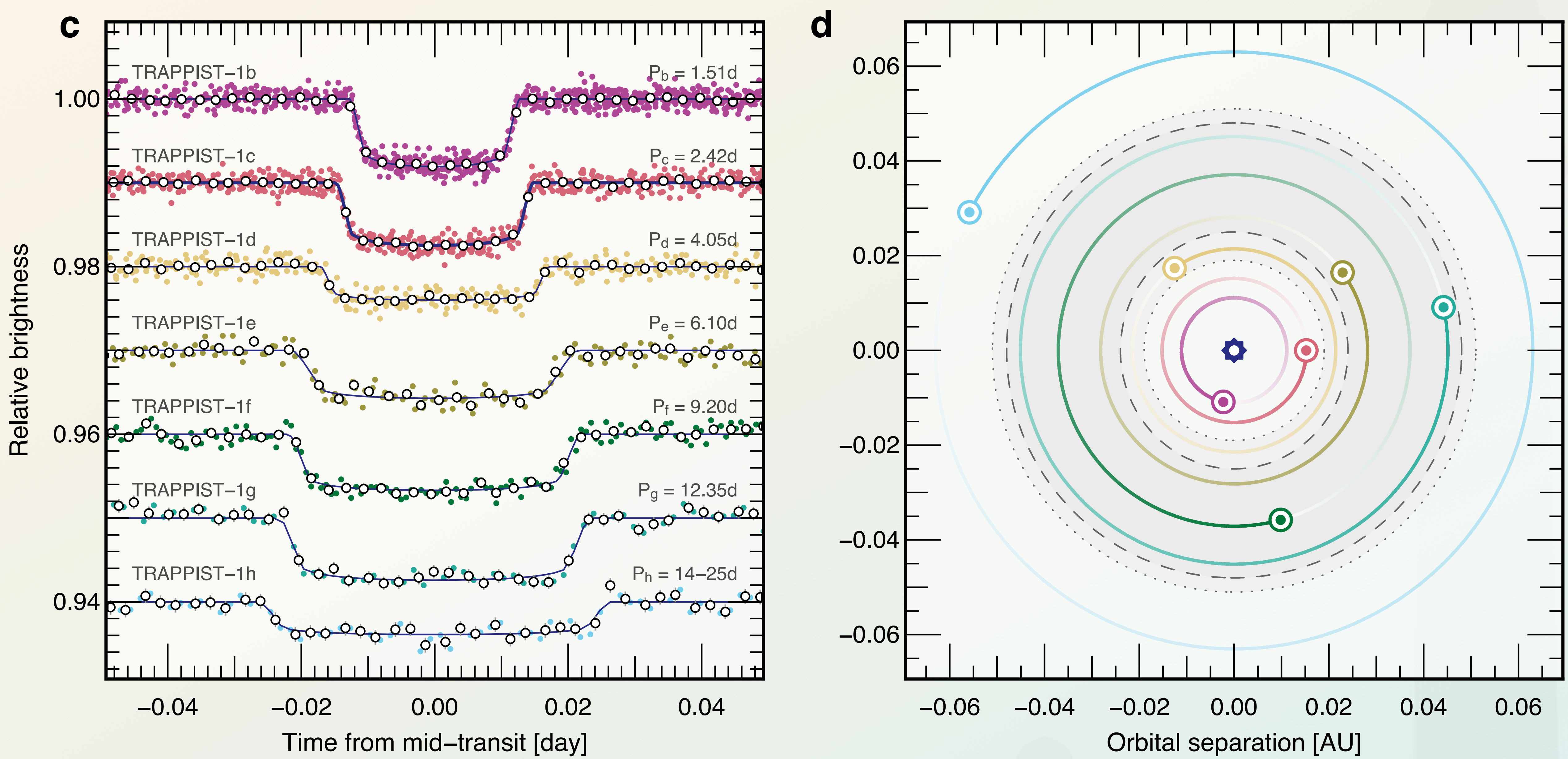
They evolve into giant stars, and stars $< 5\ M_\odot$ turn into white dwarfs (stellar remnants)

Stars have **spectral types**: O B A F G K M, which they are referred to often

~ 50 % of stars are binary stars

Gaia Collaboration+ 2022

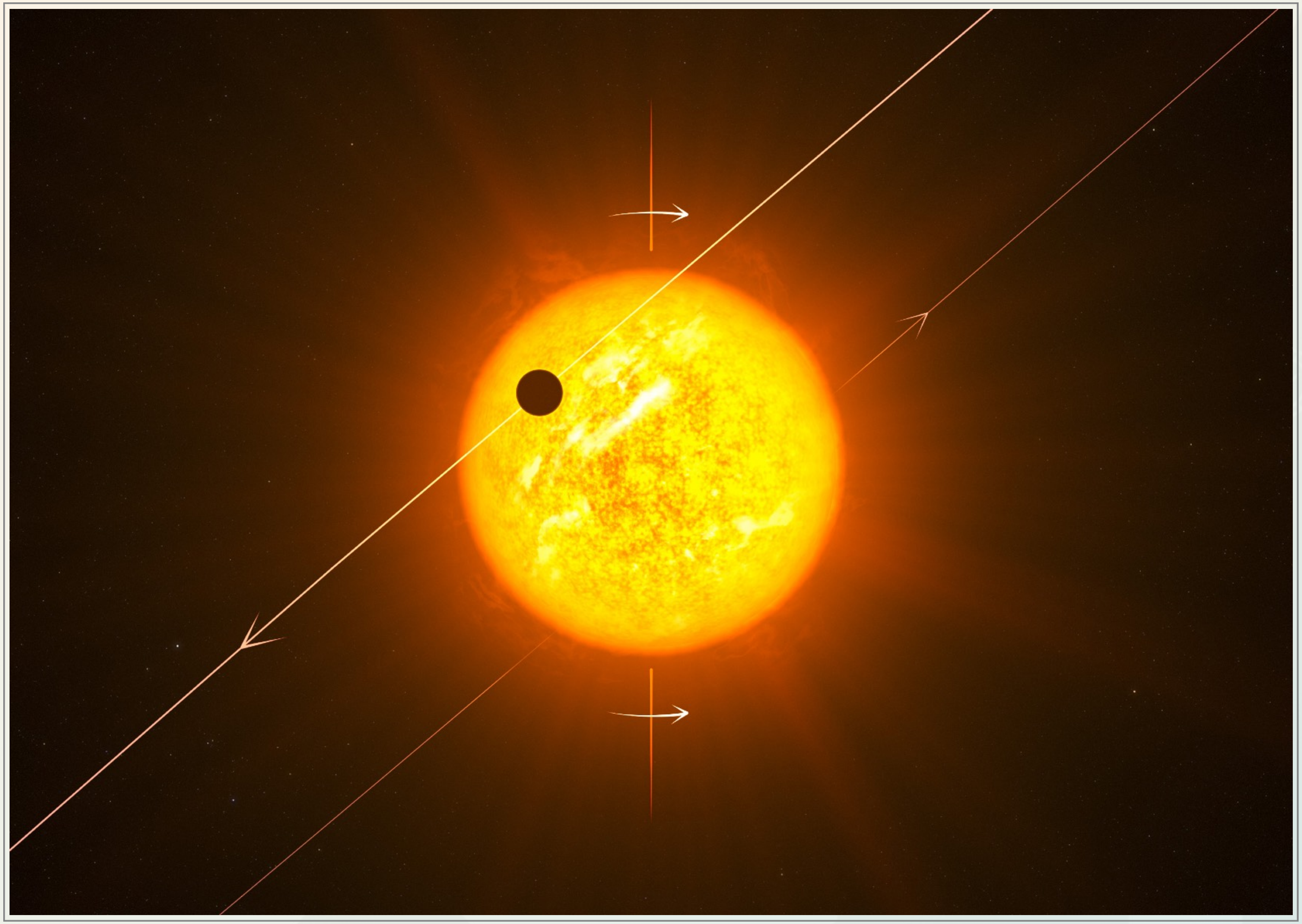
Exoplanet Diversity



7 rocky Earth-like planets orbiting an **ultra-cool dwarf**

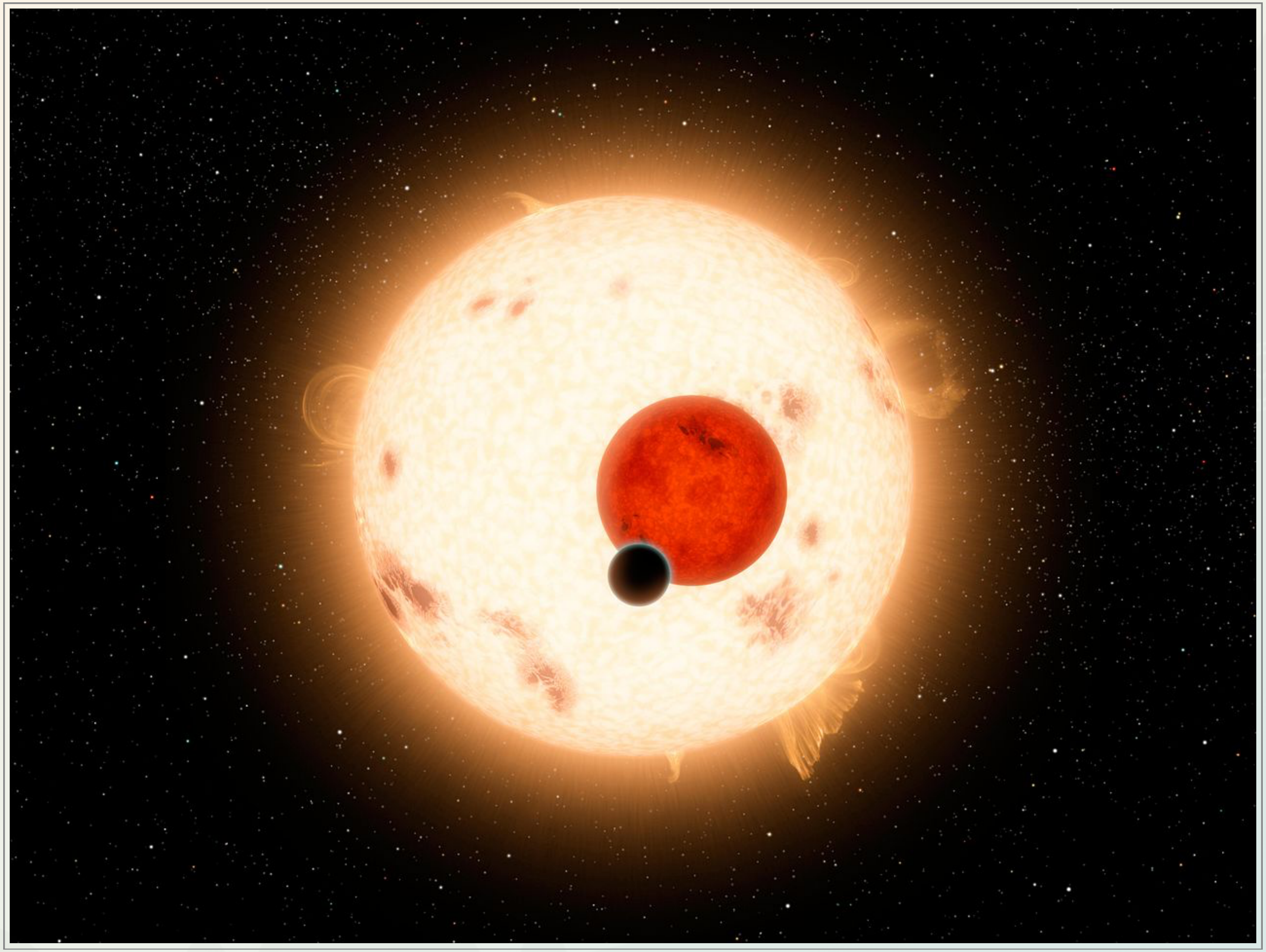
Gillon, Triaud+ 2017

Exoplanet Diversity



Queloz+ 2008

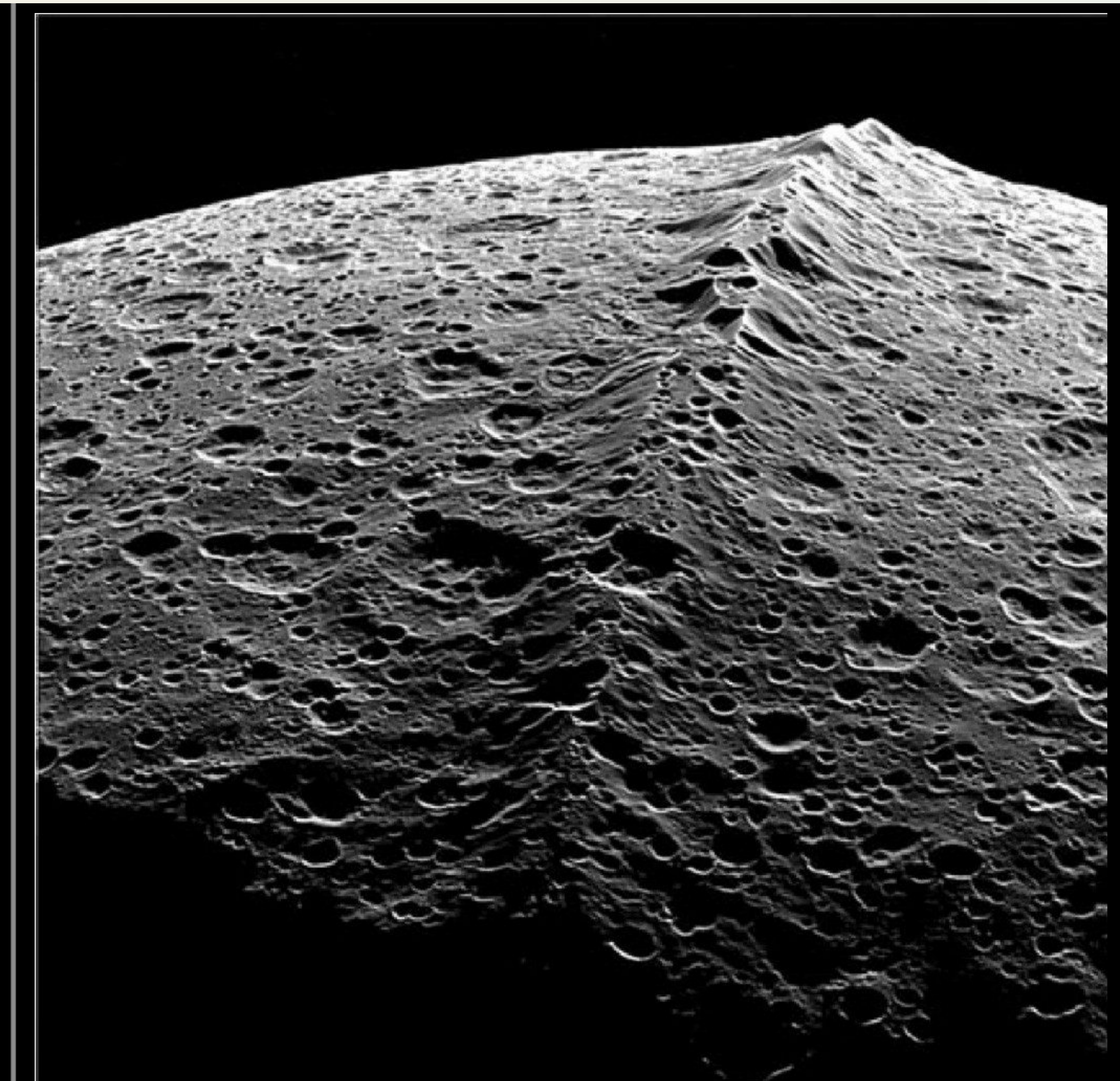
A Circumbinary System



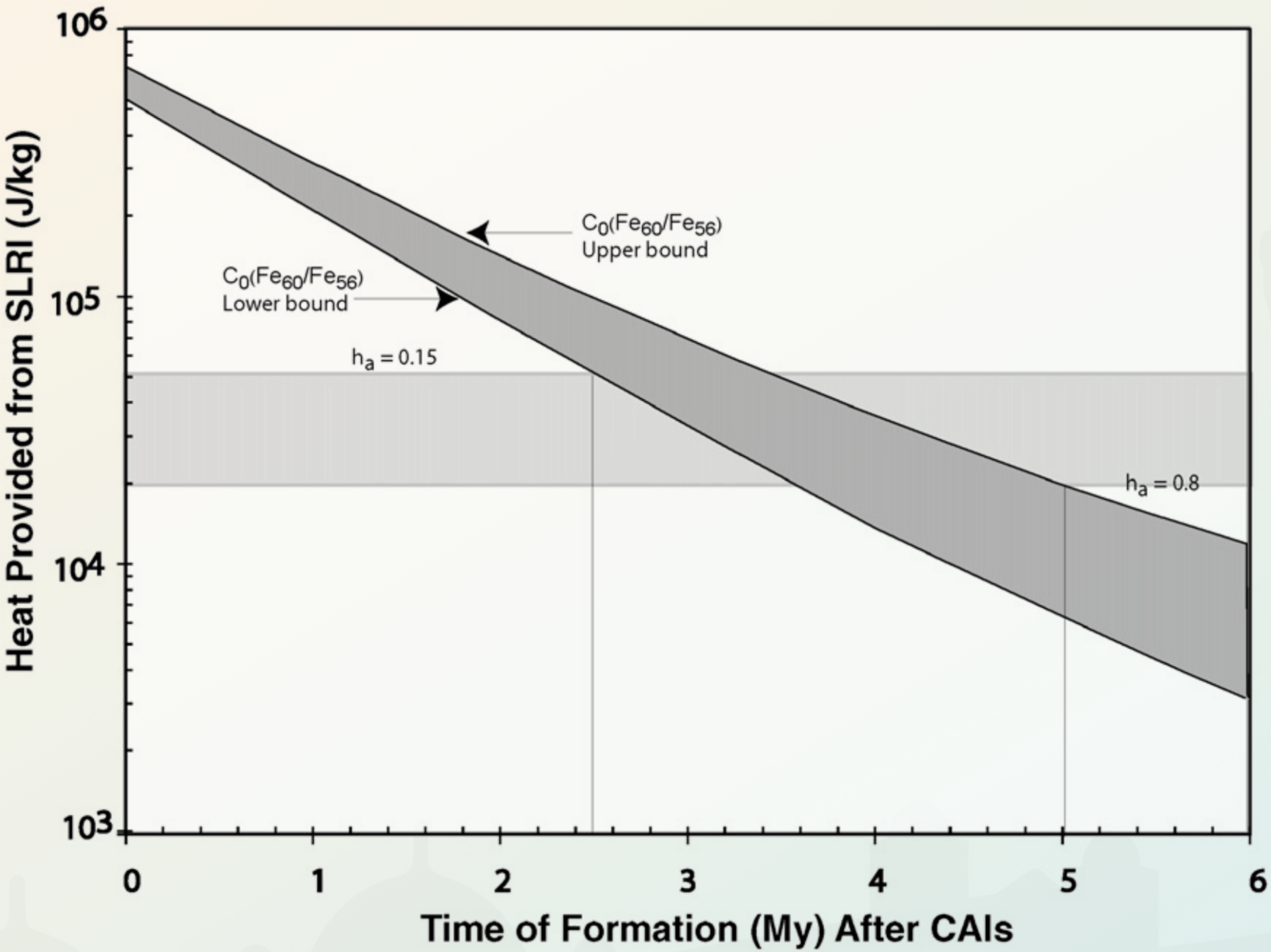
Doyle+ 2011

Age of Saturn, thanks to Iapetus

paper by Castillo-Rogez 2007

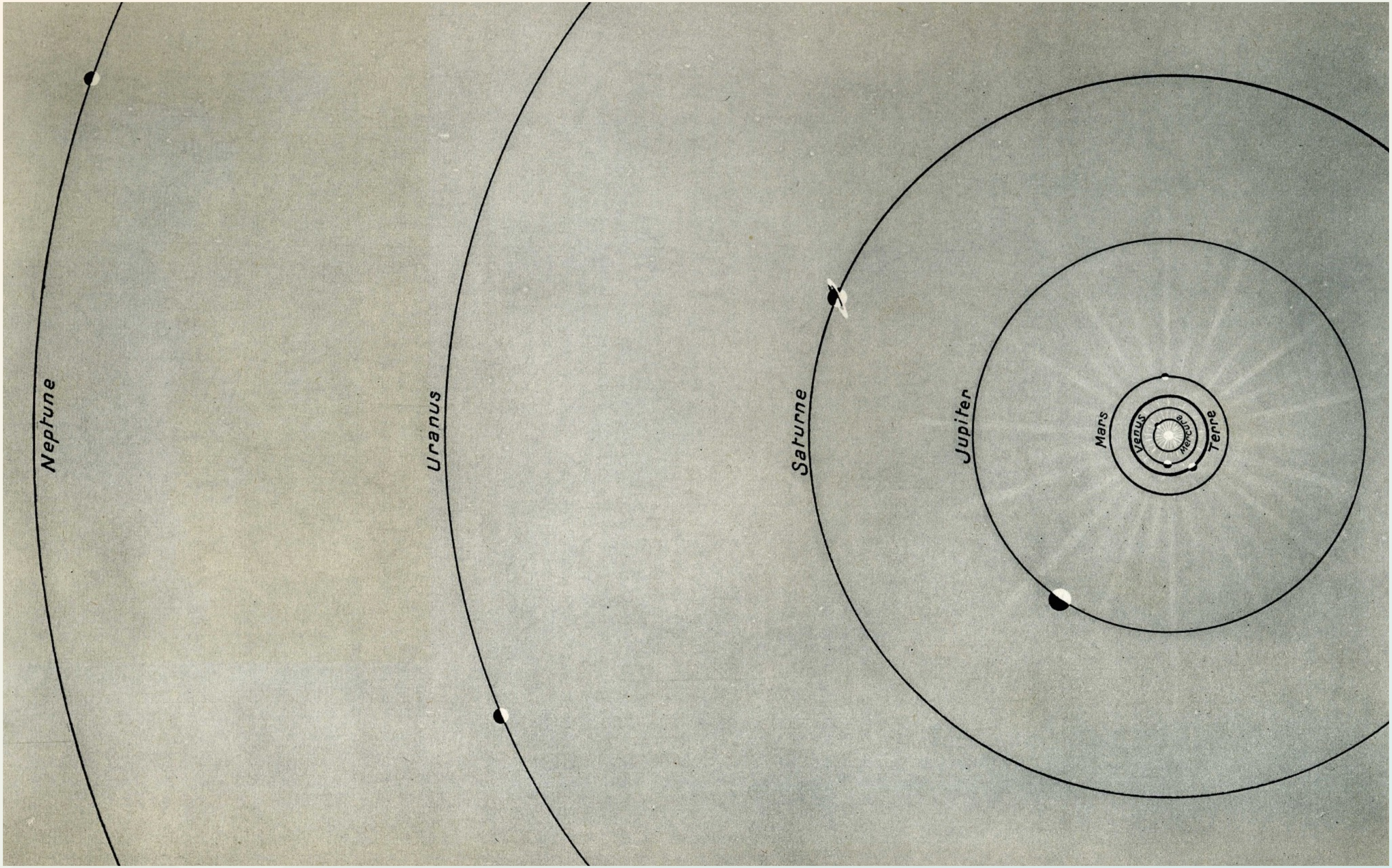


Age of Saturn, thanks to Iapetus



Castillo Rogez+ 2007

Solar System



Inventory

- The Sun: 99.8% of the mass, <2% of the angular momentum
  Removing the Sun: Jupiter is 70% of the mass, 60% of angular momentum

- Gas giants: Jupiter & Saturn

  Ice giants: Uranus & Neptune

  Rocky planets: Mercury, Venus, Earth & Mars

- A plethora of small bodies

  dwarf planets, satellites, asteroids, comets, ring systems
  Main Belt, Kuiper Belt, Oort Cloud

without the solar system's example, we could not invent all that