

EXOPLANETAS

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Heriberto Garzón

Observatório do Valongo
Universidade Federal do Rio de Janeiro



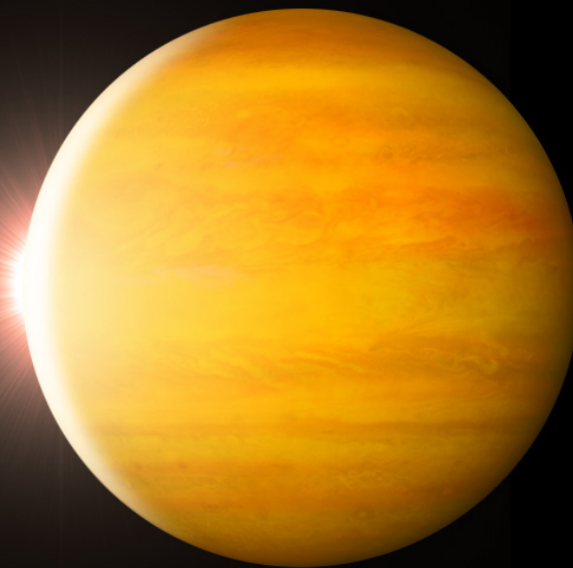
Exoplanetas

- 1995 → Primeira detecção de exoplaneta ao redor de estrela da sequência principal

- Período orbital = 4.2 d → **Júpiter quente.**

- Formação e evolução?

THE FIRST PLANET DISCOVERED AROUND A **SUN-LIKE** STAR



51 Pegasi b

Discovered October 6, 1995

This year we celebrate the discovery of 51 Pegasi b in October, 1995. This giant planet is about half the size of Jupiter and orbits its star in about 4 days. '51 Peg' helped launch a whole new field of exploration.



TEMPERATURE

51 Pegasi b has a temperature of **1000C°/1800F°**.



ORBITAL PERIOD

51 Pegasi b orbits its host star **every 4 days**.

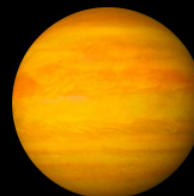


DISTANCE FROM EARTH

51 Pegasi b is **50 light-years** from Earth.

PLANET COMPARISON

51 Pegasi b



Jupiter



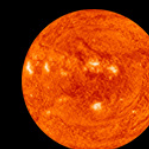
51 Pegasi b is **47% less massive**, but **50% larger** than Jupiter.

STAR COMPARISON

51 Pegasi

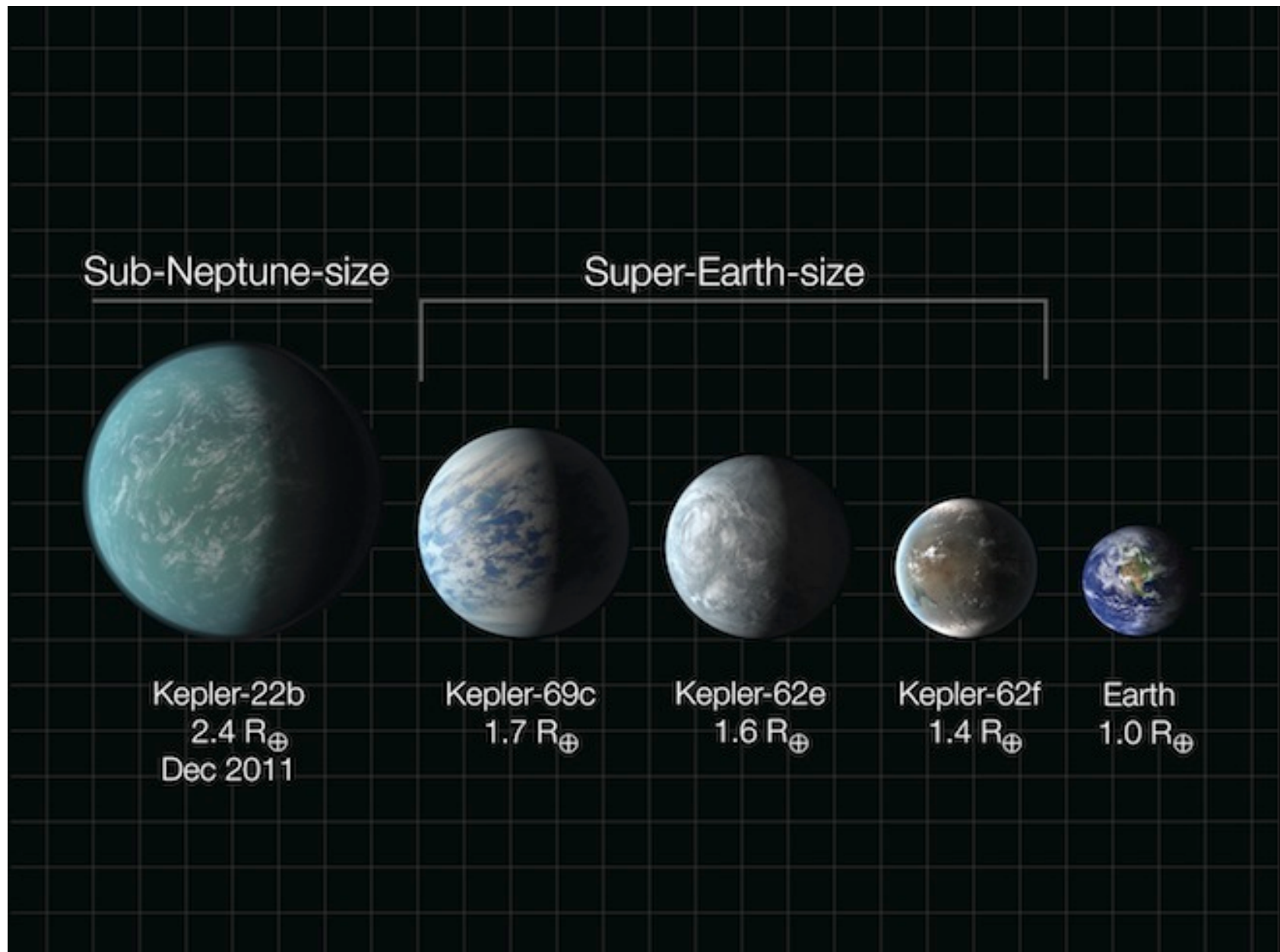


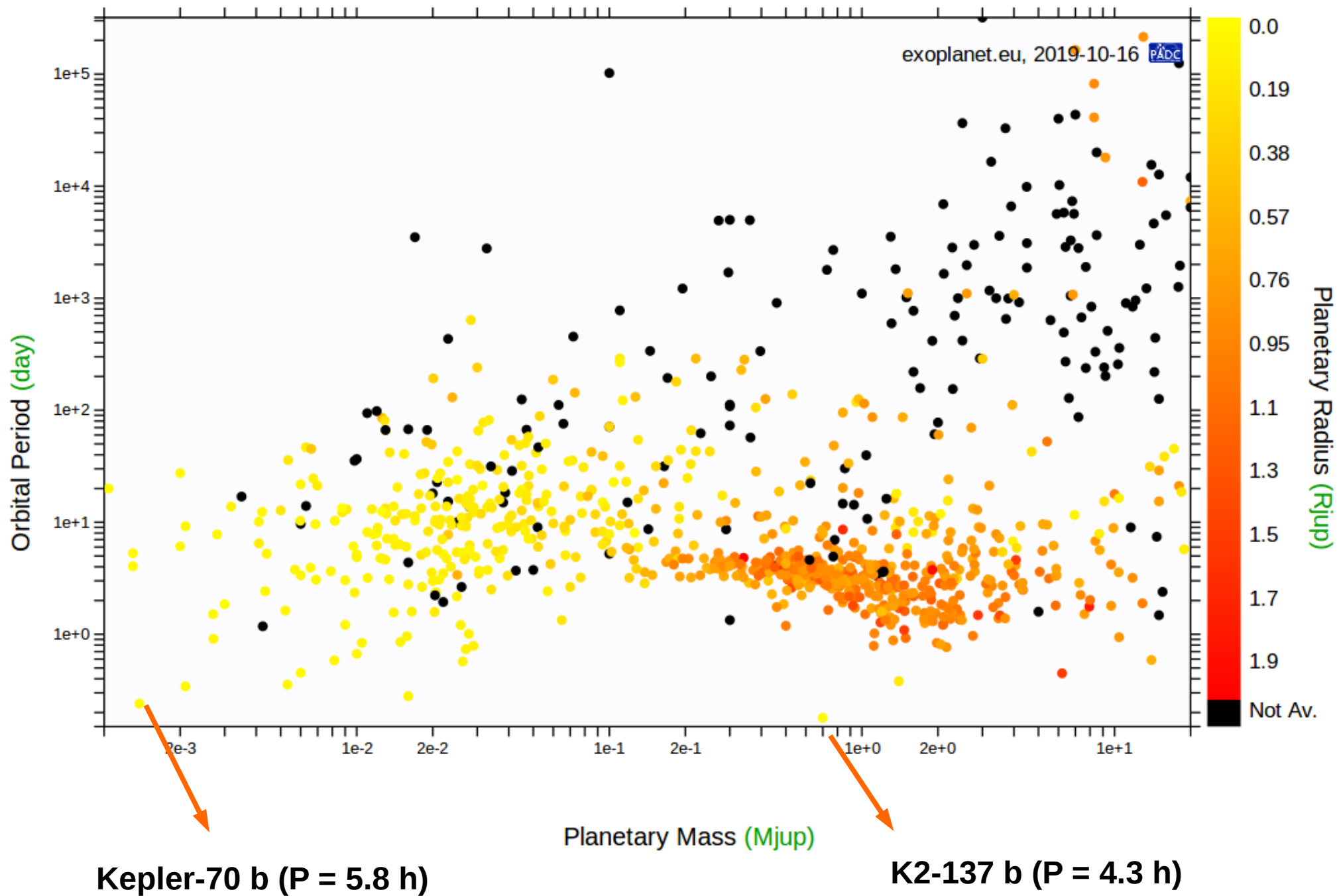
Our sun

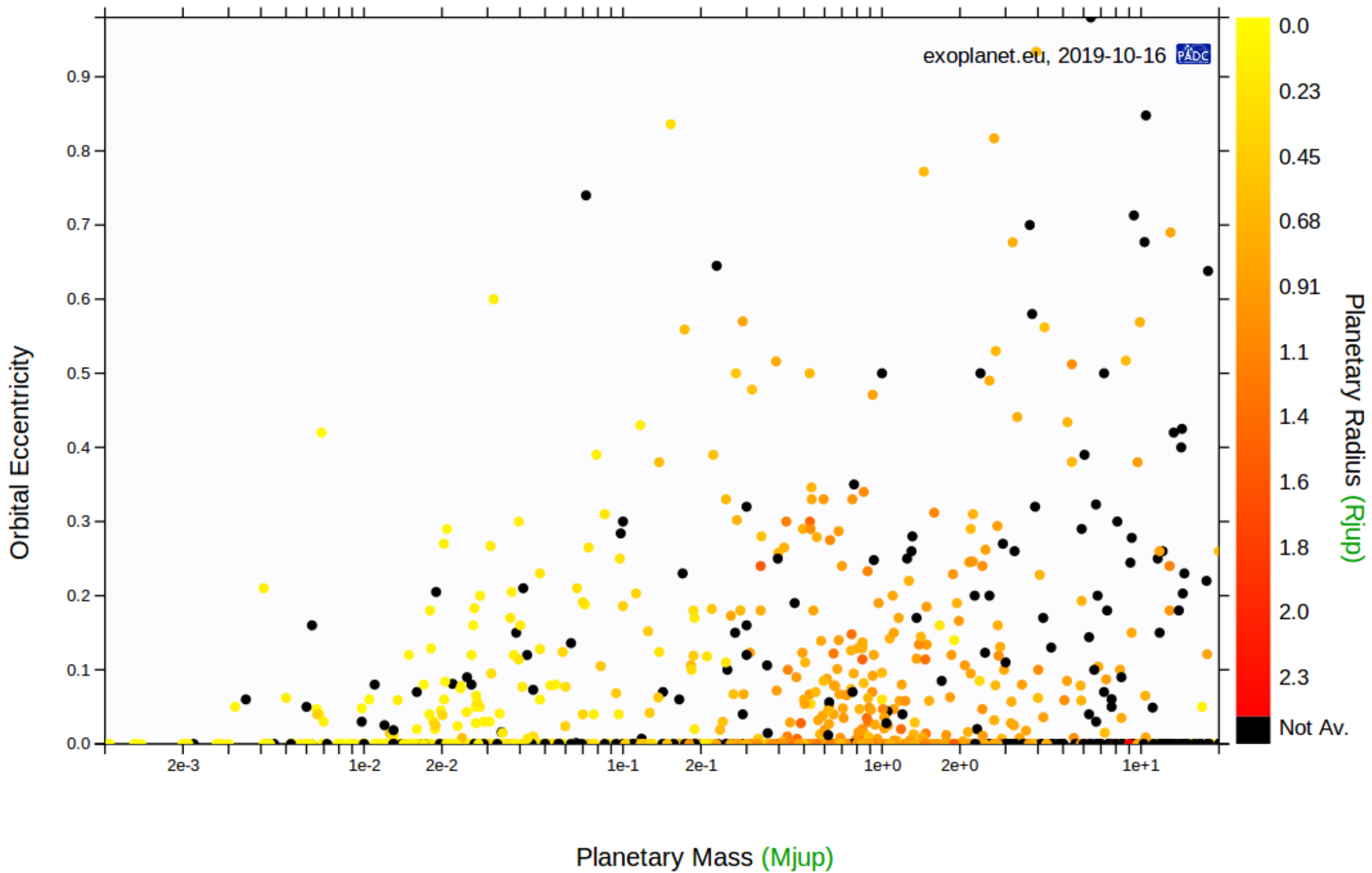


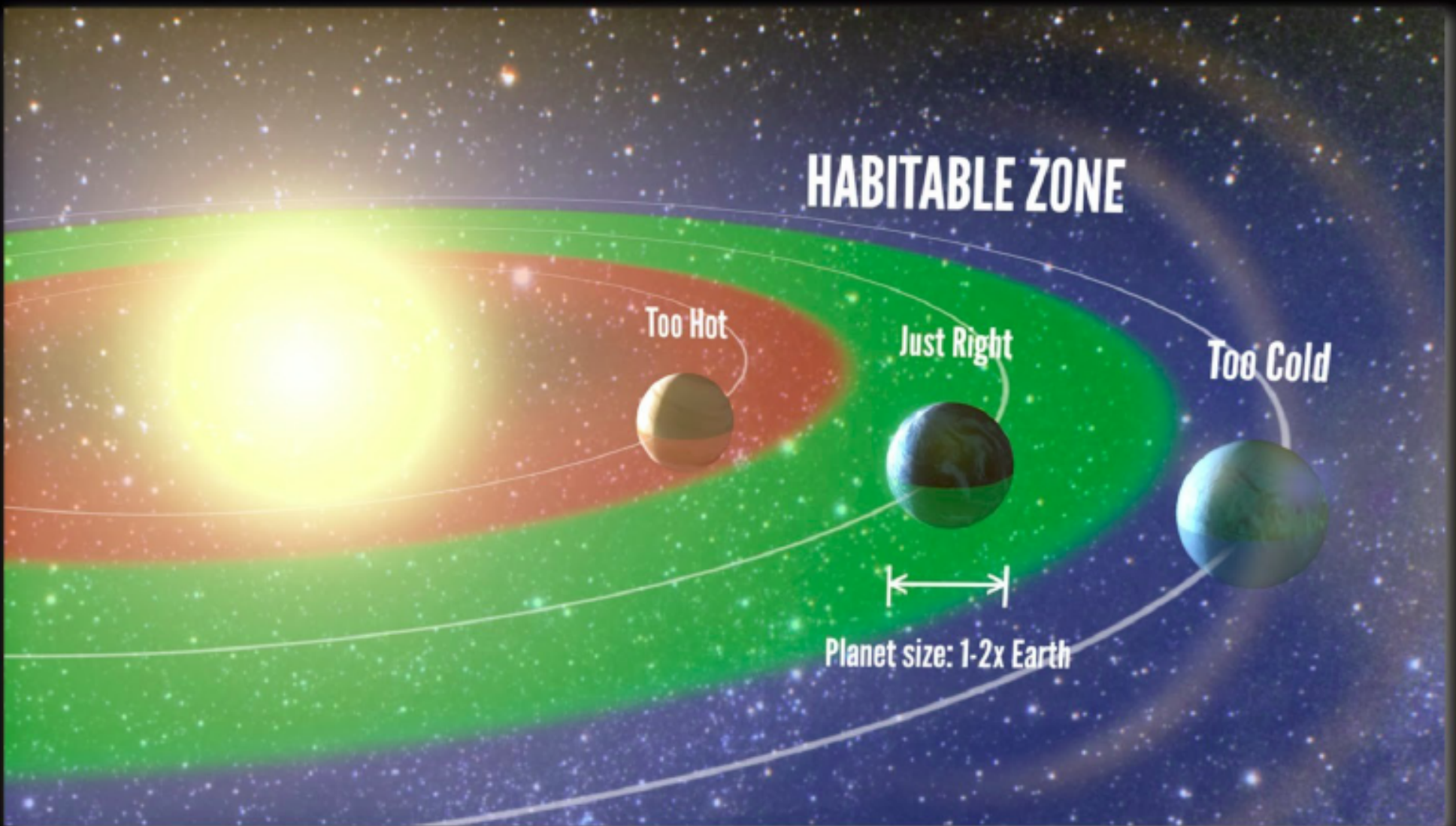
51 Pegasi is **11% more massive** and **23% larger** than our sun.

Exoplanetas



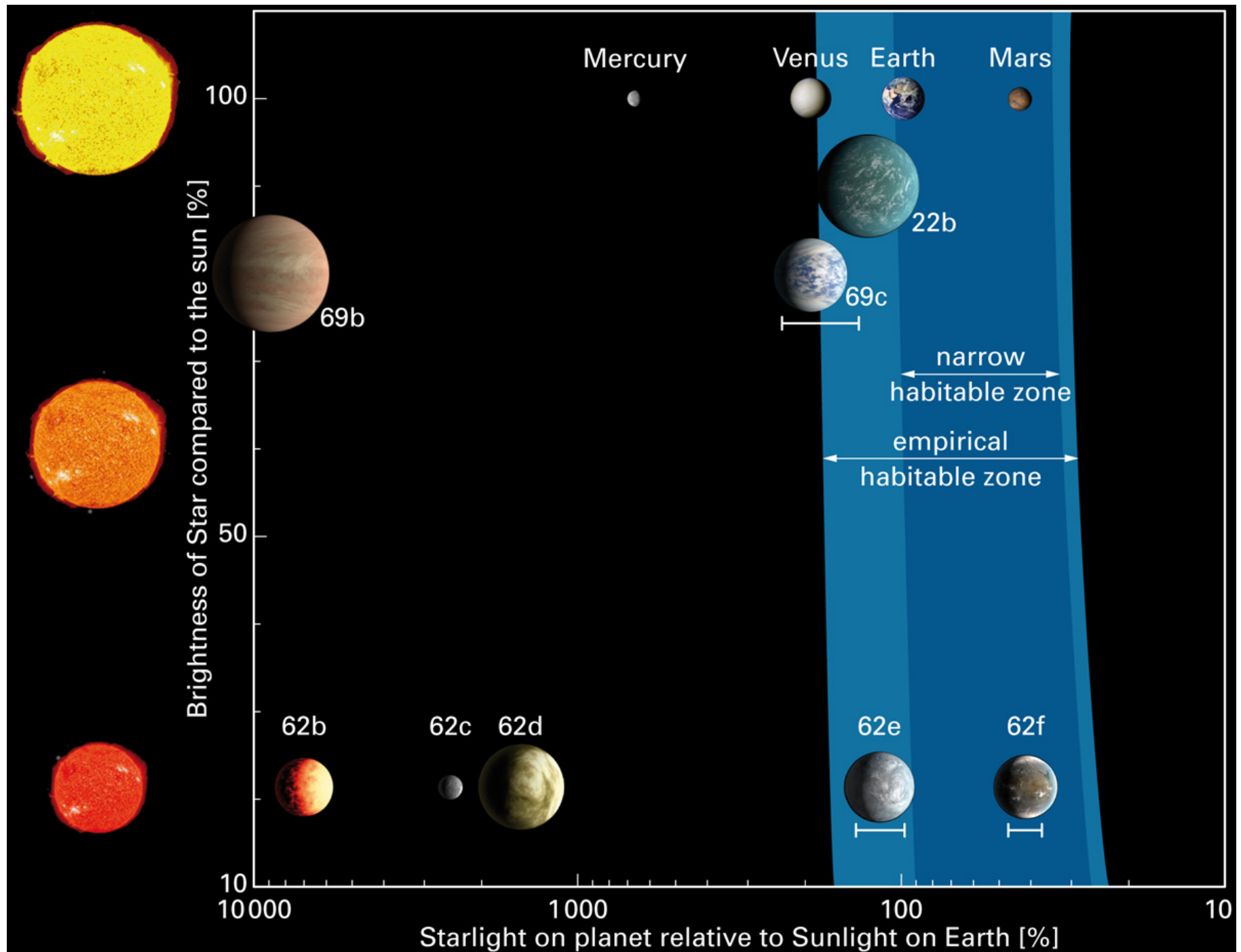






The habitable zone corresponds to the range of orbital distances where liquid water can exist on a planet's surface.

Exoplanetas (habitabilidad)



Kepler's Small Habitable Zone Planets

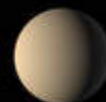
Planets enlarged 25x compared to stars

G Stars



Kepler-452b (Earth)

K Stars



Kepler-442b

155c

235e

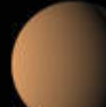
62f

62e

283c

440b

M Stars



Kepler-438b

186f

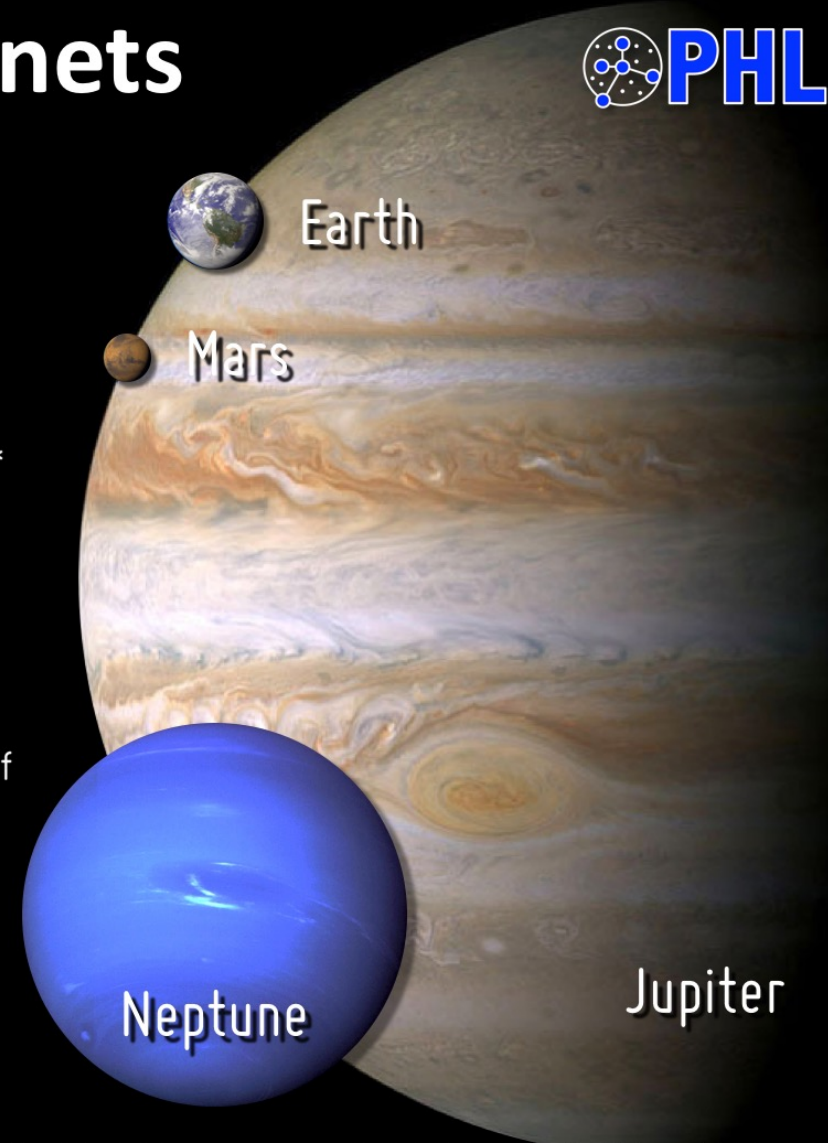
296e

296f

Potentially Habitable Exoplanets



Ranked by Distance from Earth (light years)

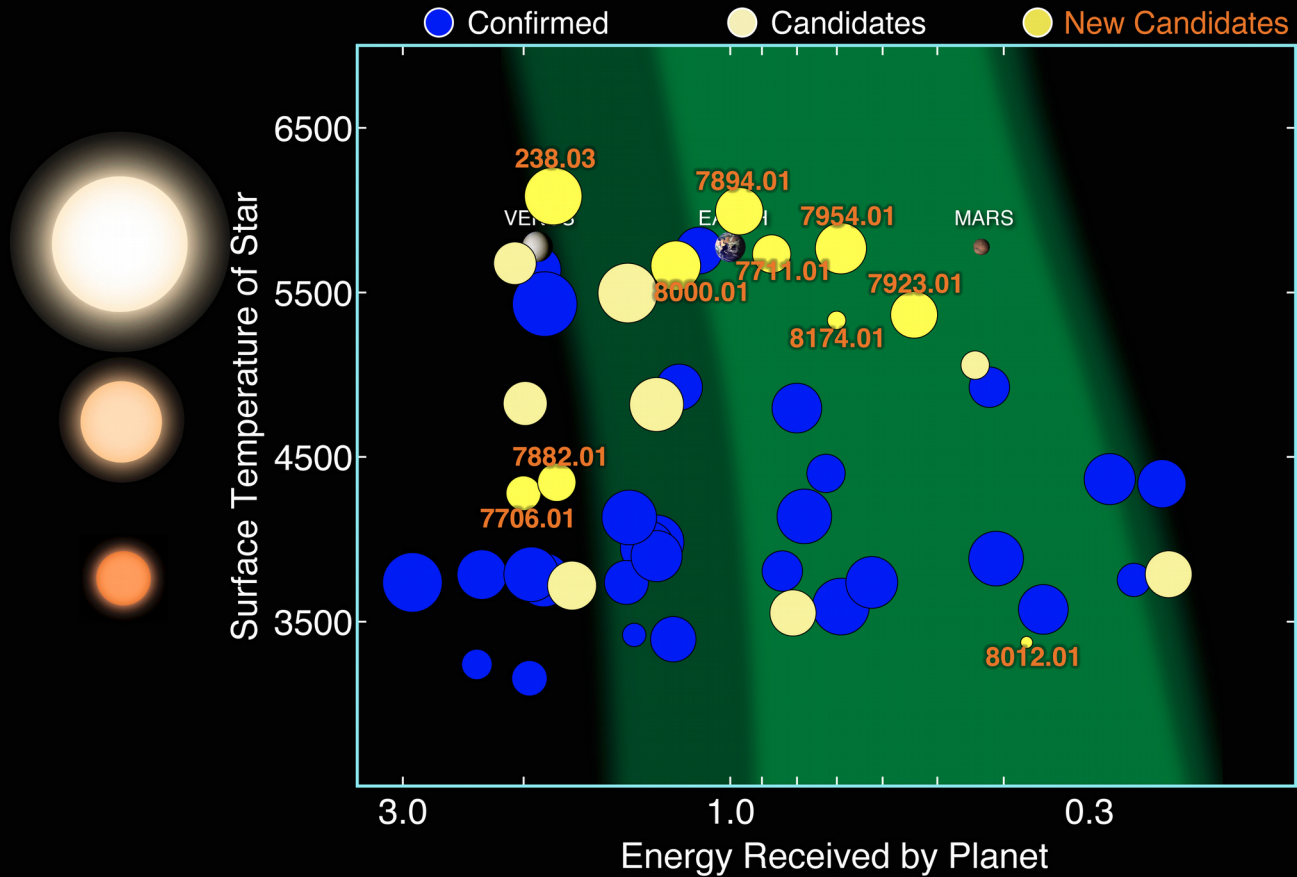


Artistic representations. Earth, Mars, Jupiter, and Neptune for scale. Distance from Earth is between brackets. Planet candidates indicated with asterisks.

CREDIT: PHL @ UPR Arcibo (phl.upr.edu) Jul 2, 2018

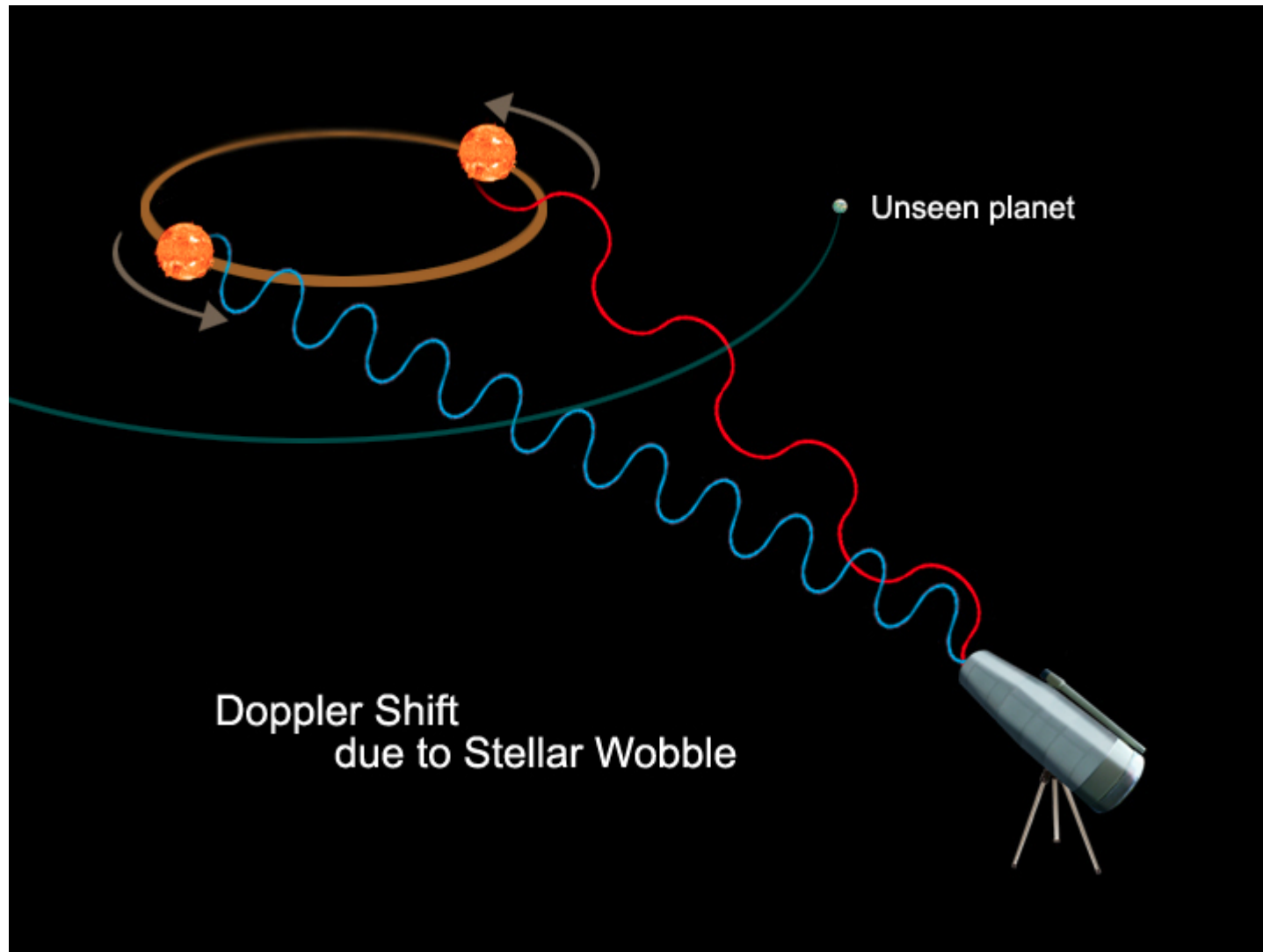
Kepler Habitable Zone Planets

As of June 2017



Exoplanetas (métodos de detecção)

Velocidade Radial

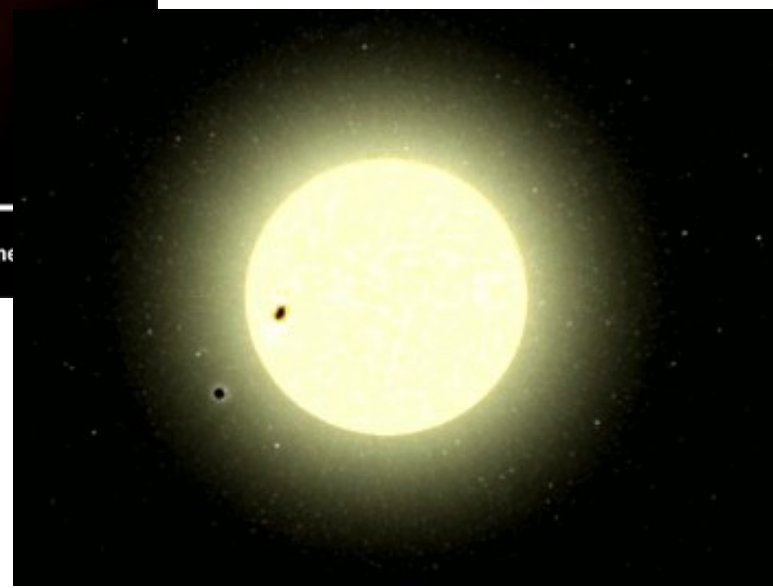
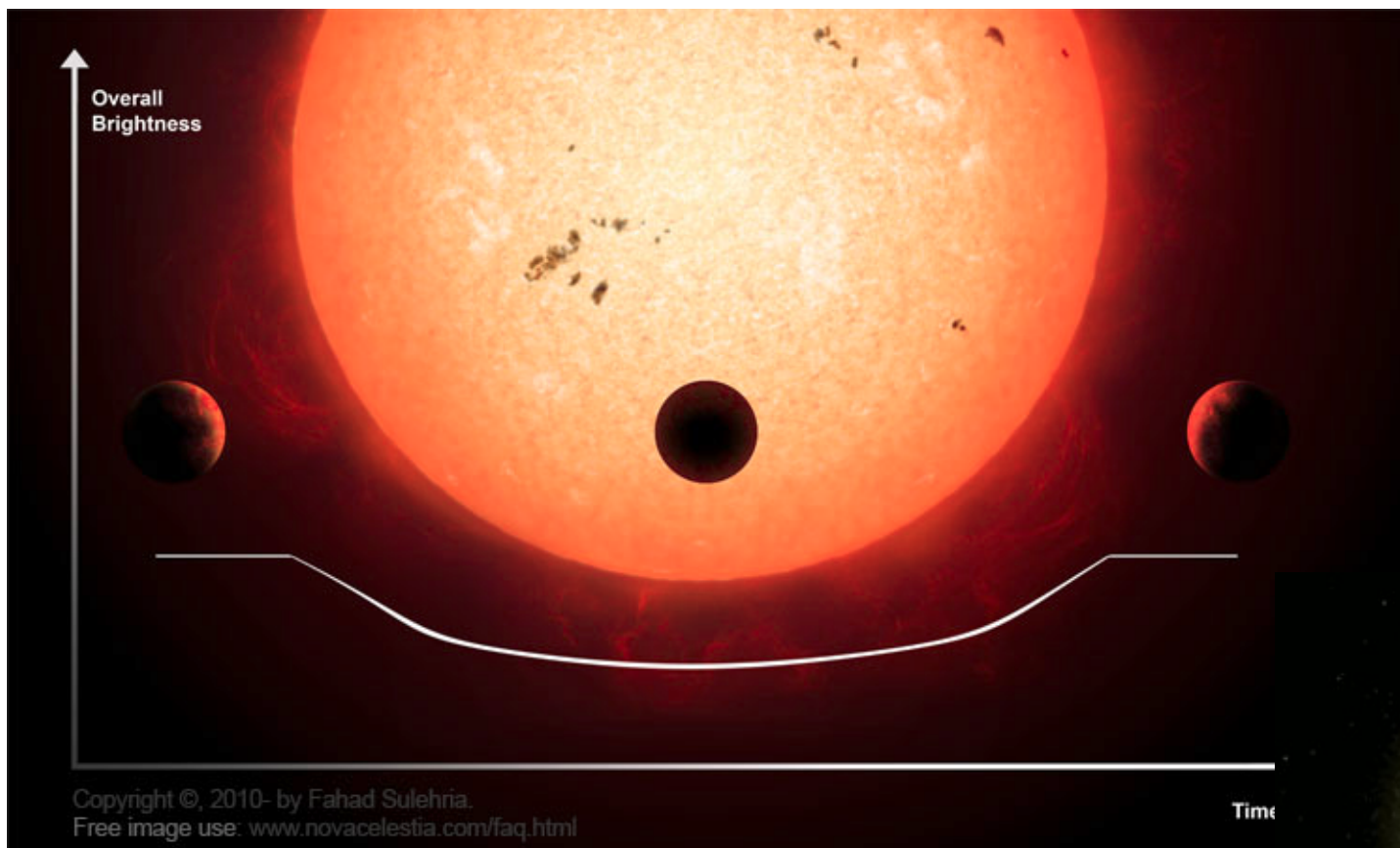


Exoplanetas (métodos de detecção)

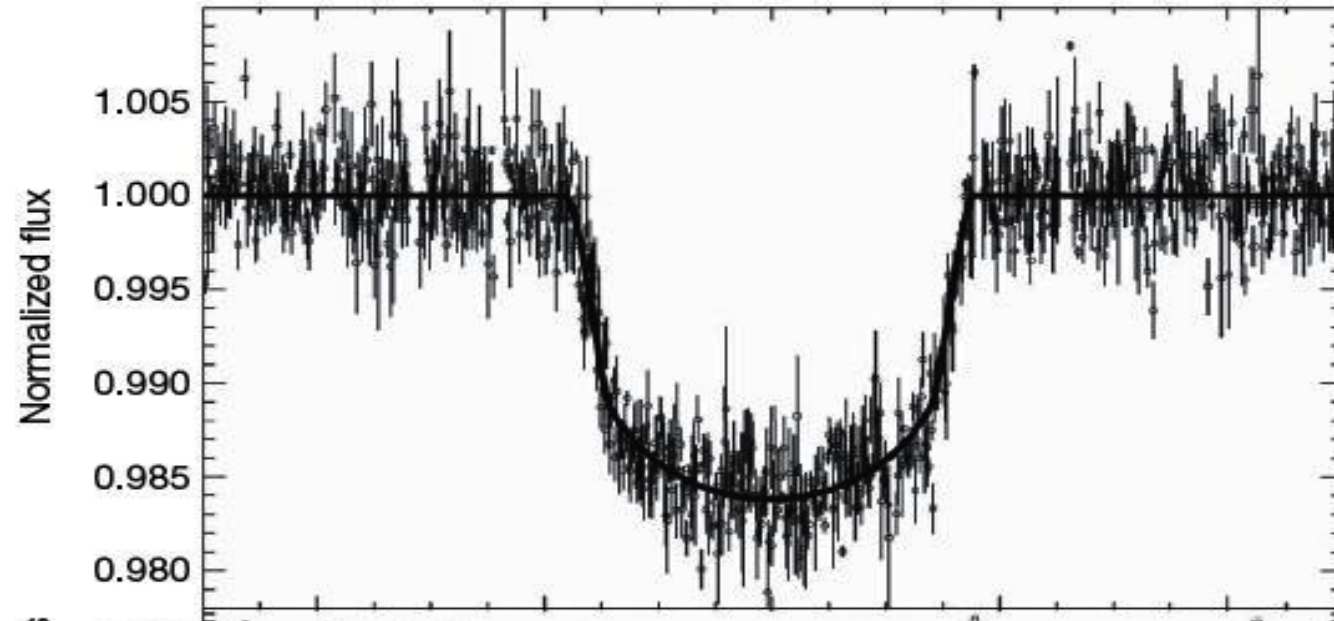
Trânsito

Missões passadas:
CoRoT, KEPLER, K2

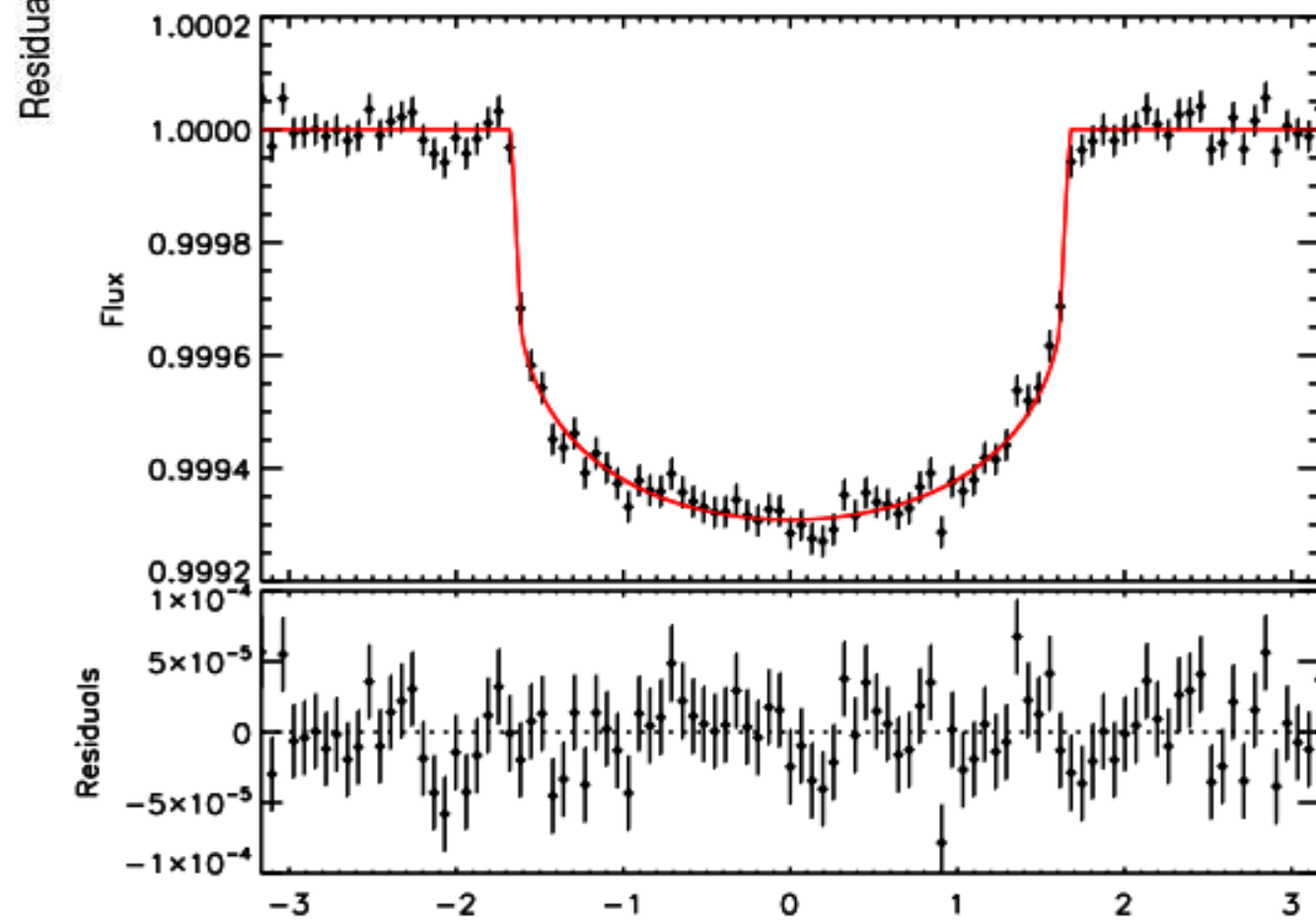
Missões futuras:
TESS (NASA, 2018)
CHEOPS (ESA, 2019)
PLATO (ESA, 2025)



CoRoT-9 b

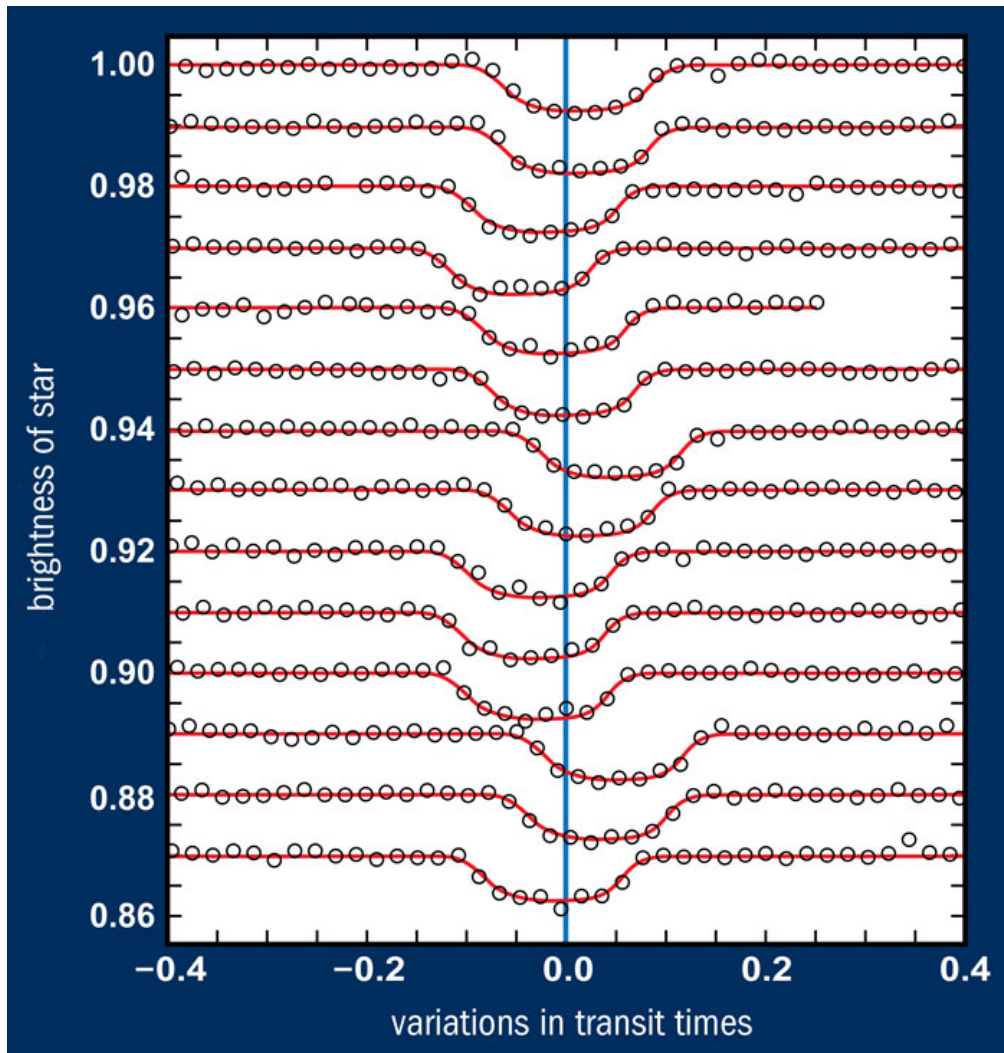


Kepler-19 b

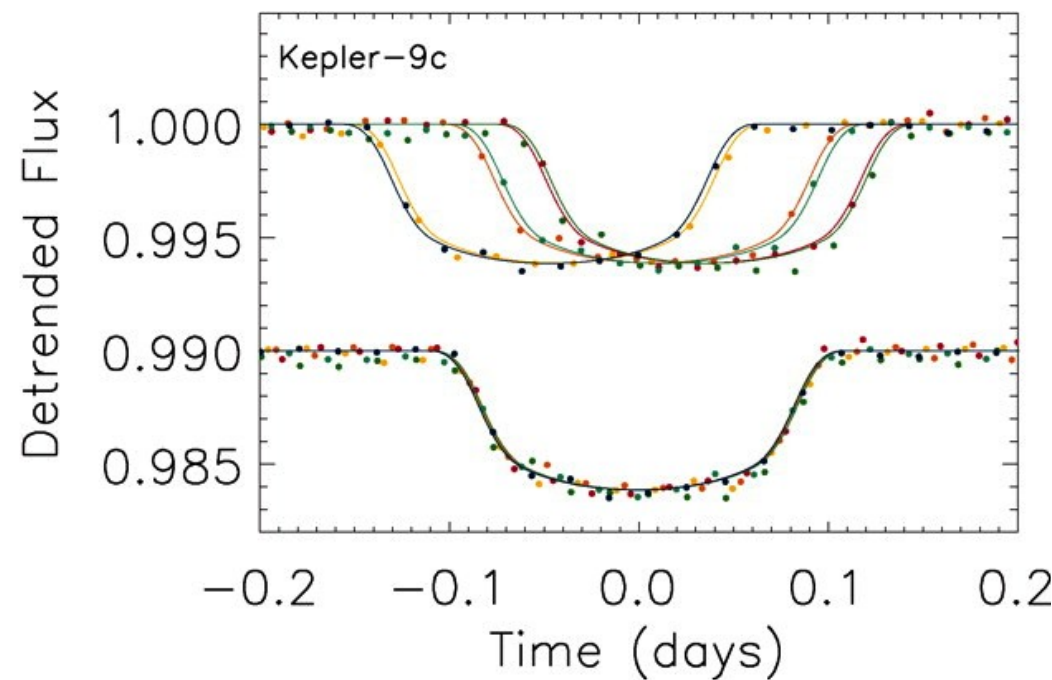
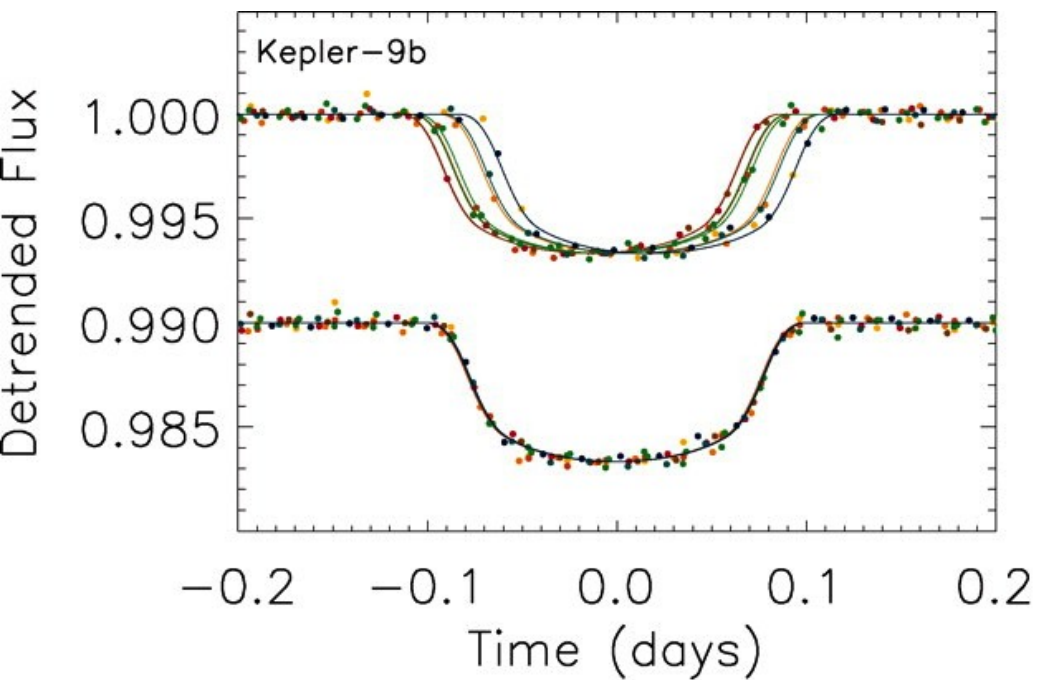
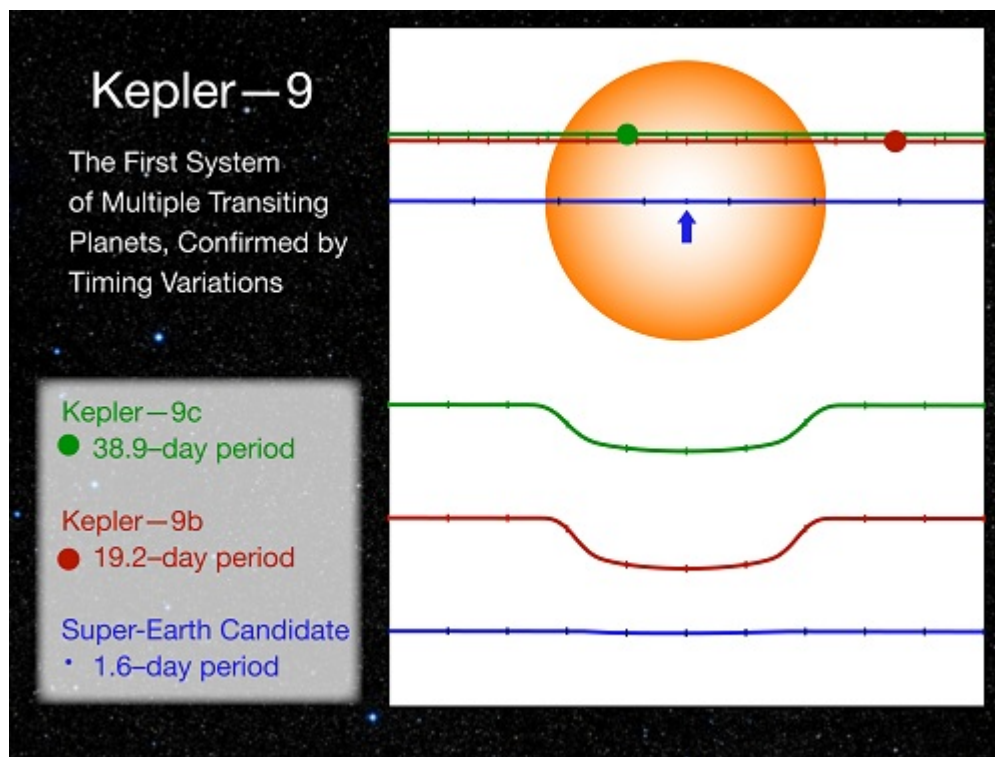


Exoplanetas (métodos de detecção)

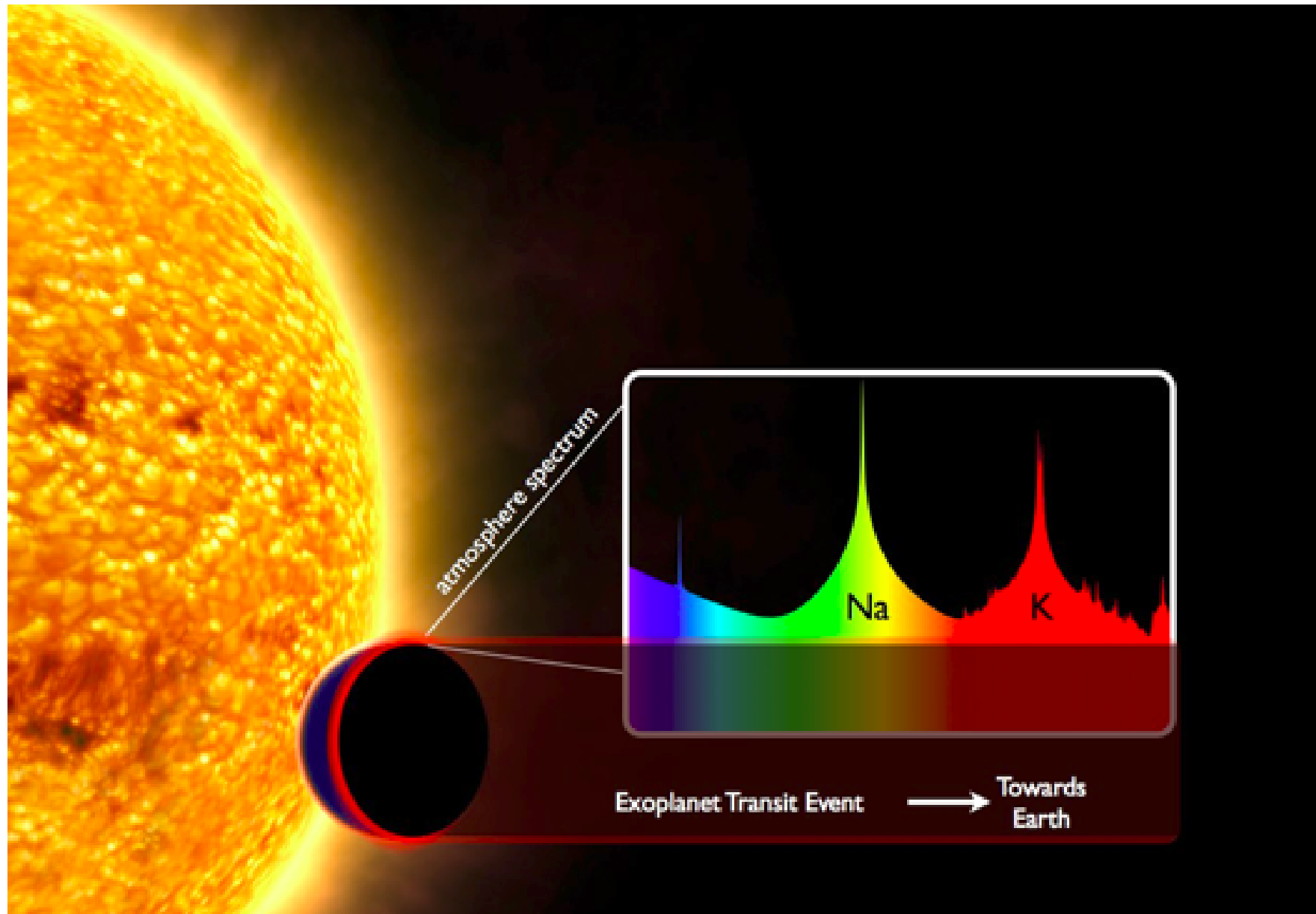
TTV (*Transit Timing Variation*)



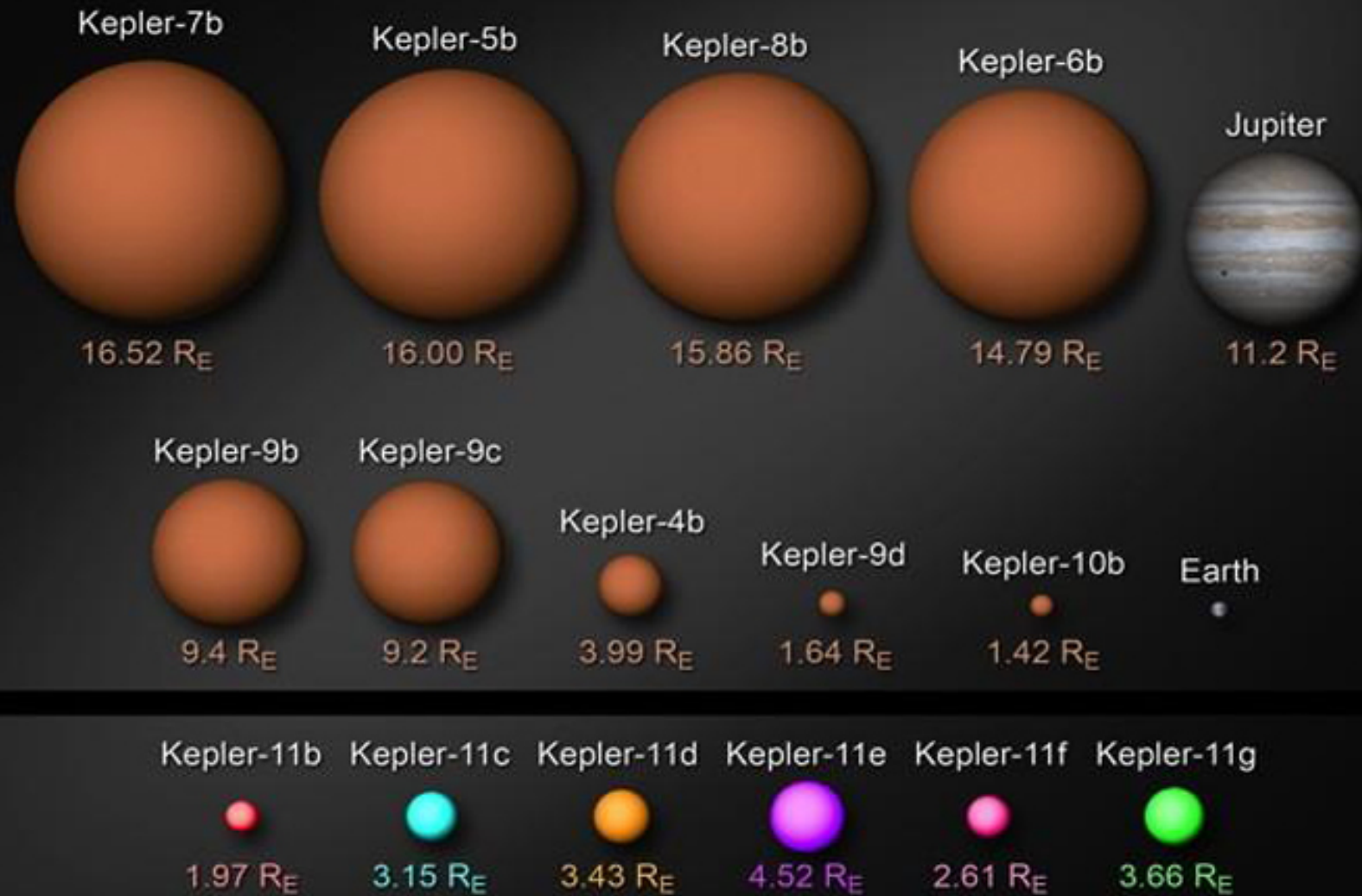
Variação no tempo central do trânsito devido à perturbação de planeta companheiro

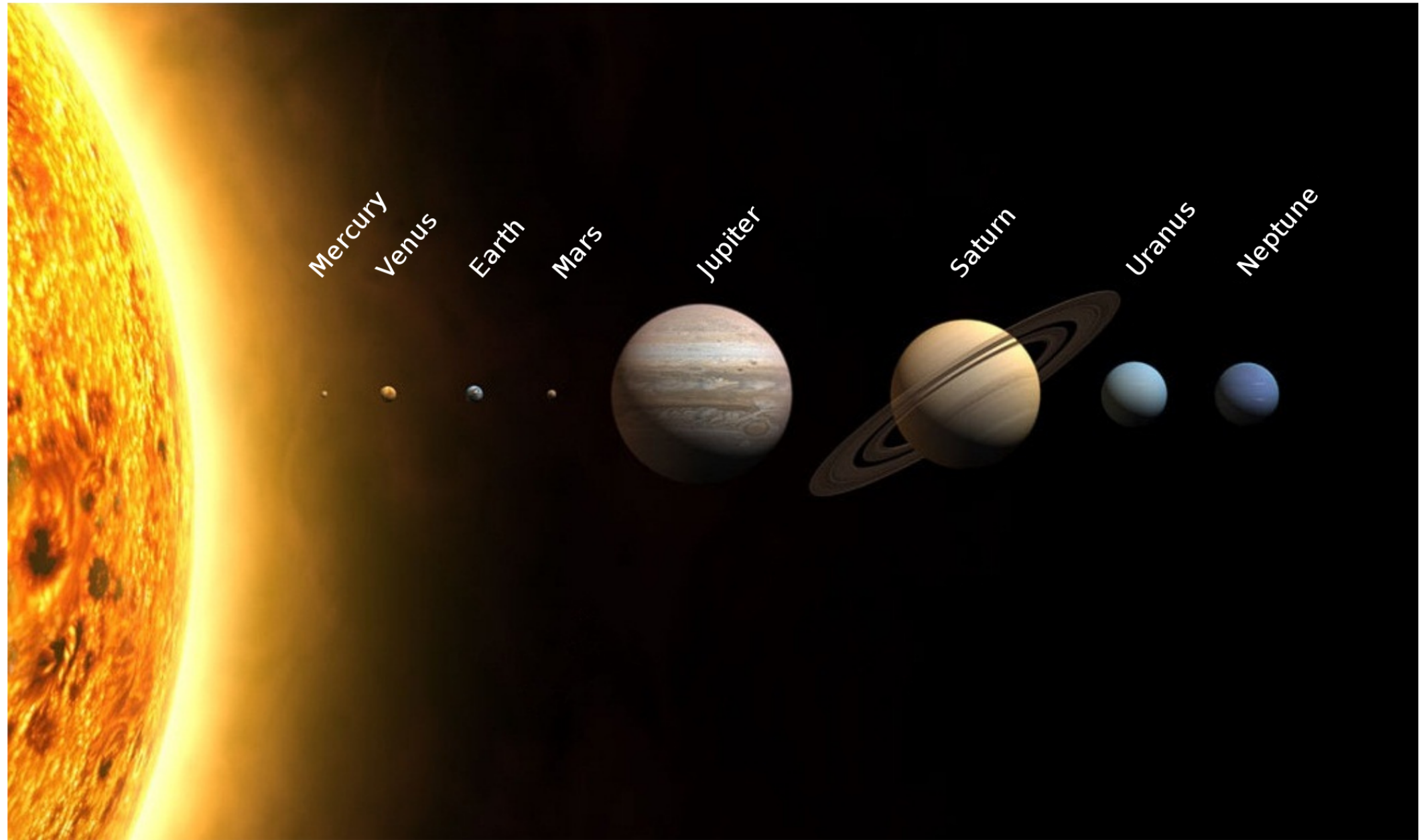


ATMOSFERA



Planet Sizes





Mercury

Venus

Earth

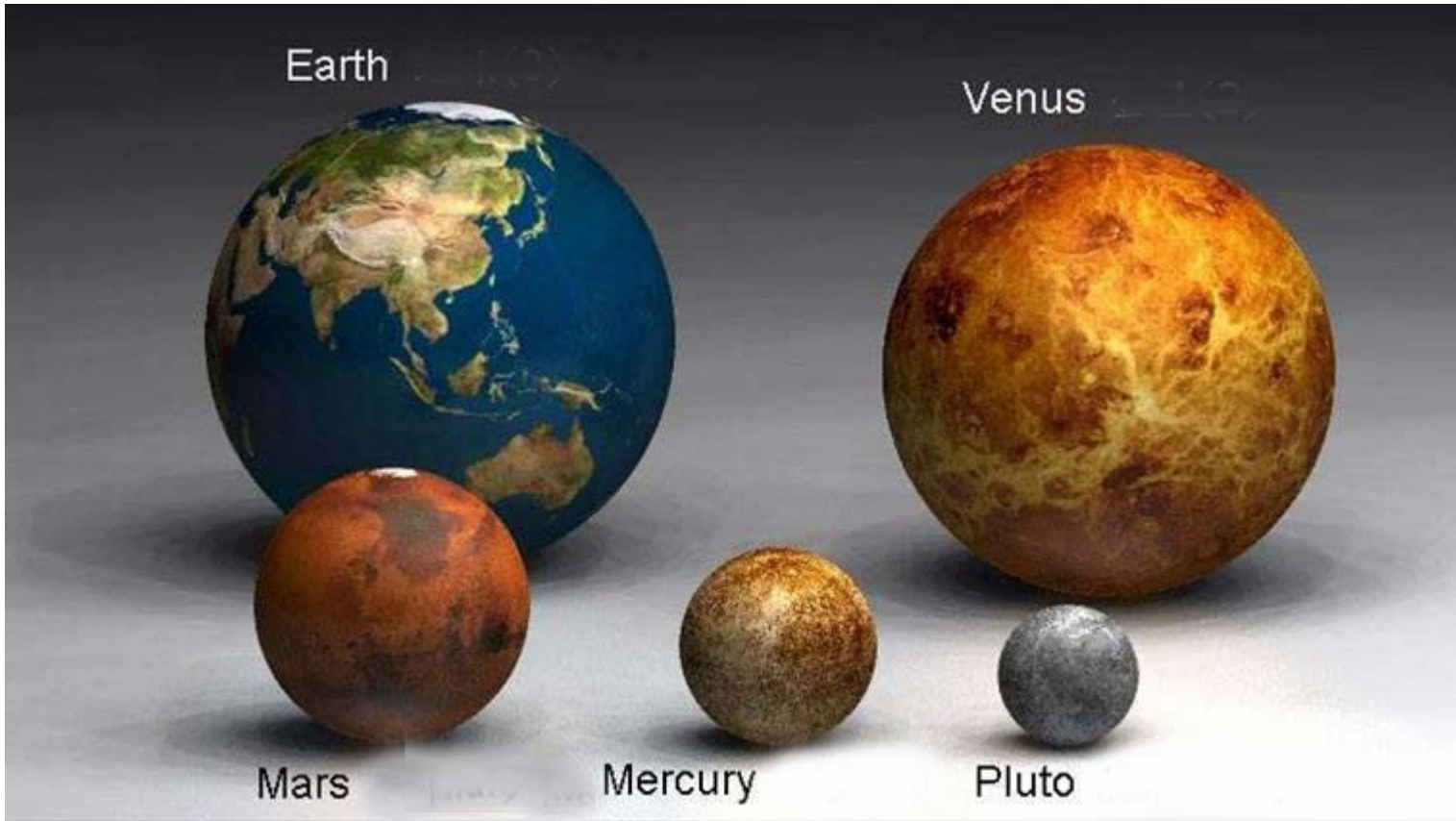
Mars

Jupiter

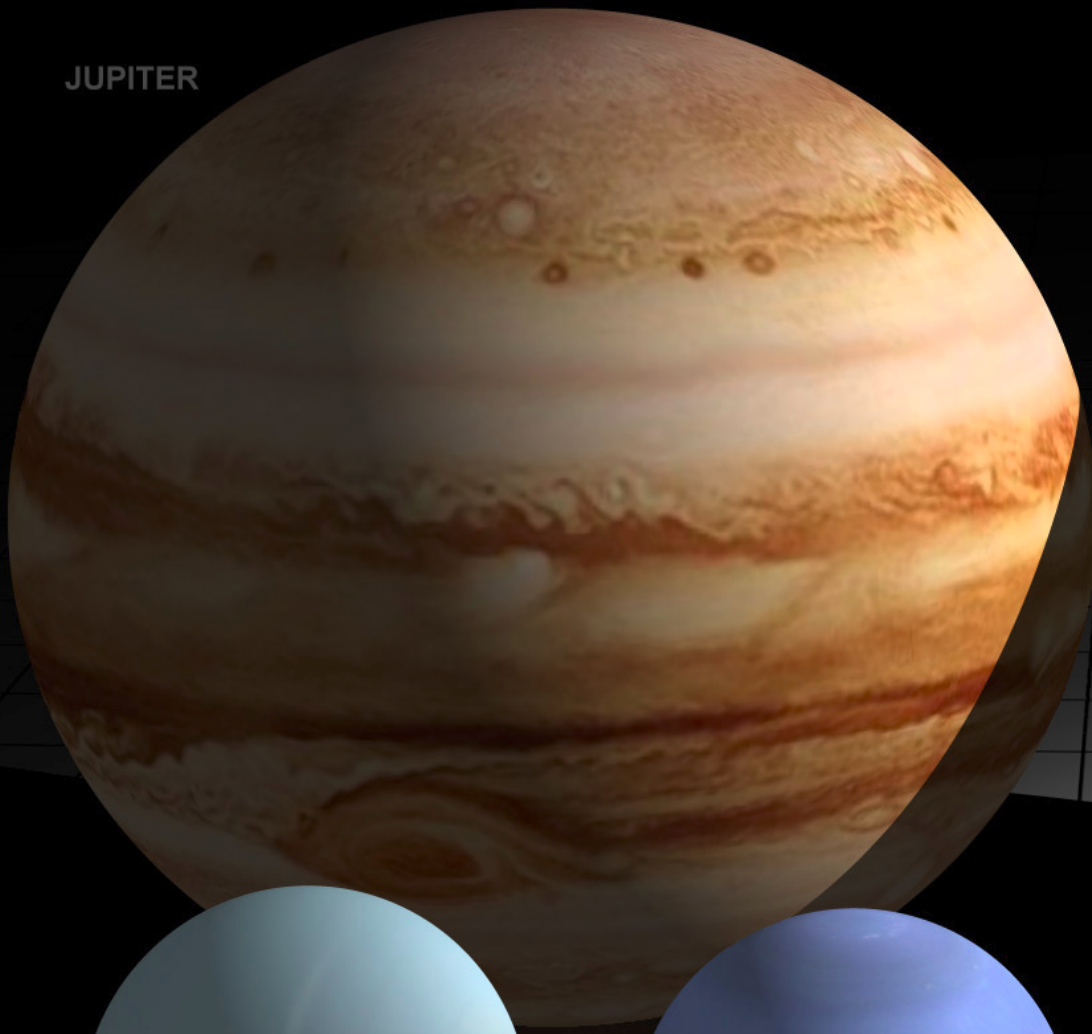
Saturn

Uranus

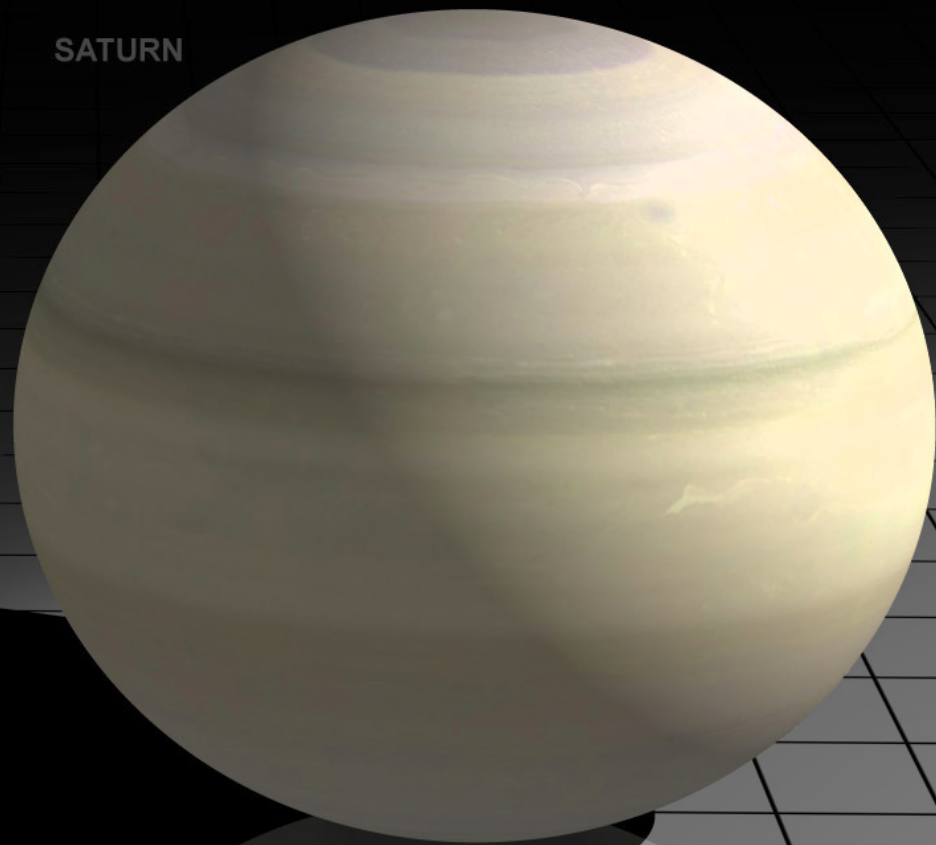
Neptune



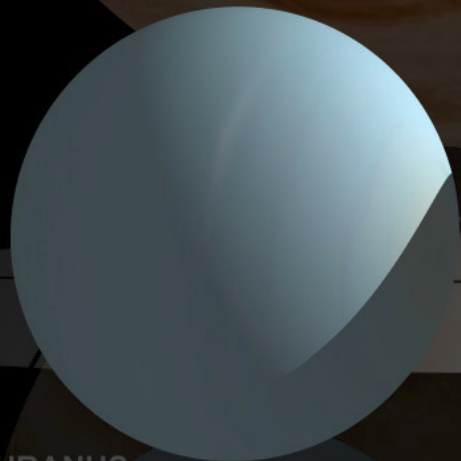
JUPITER



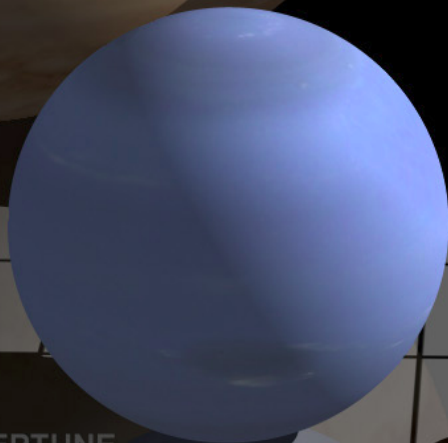
SATURN



URANUS



NEPTUNE



EARTH



VENUS



MERCURY

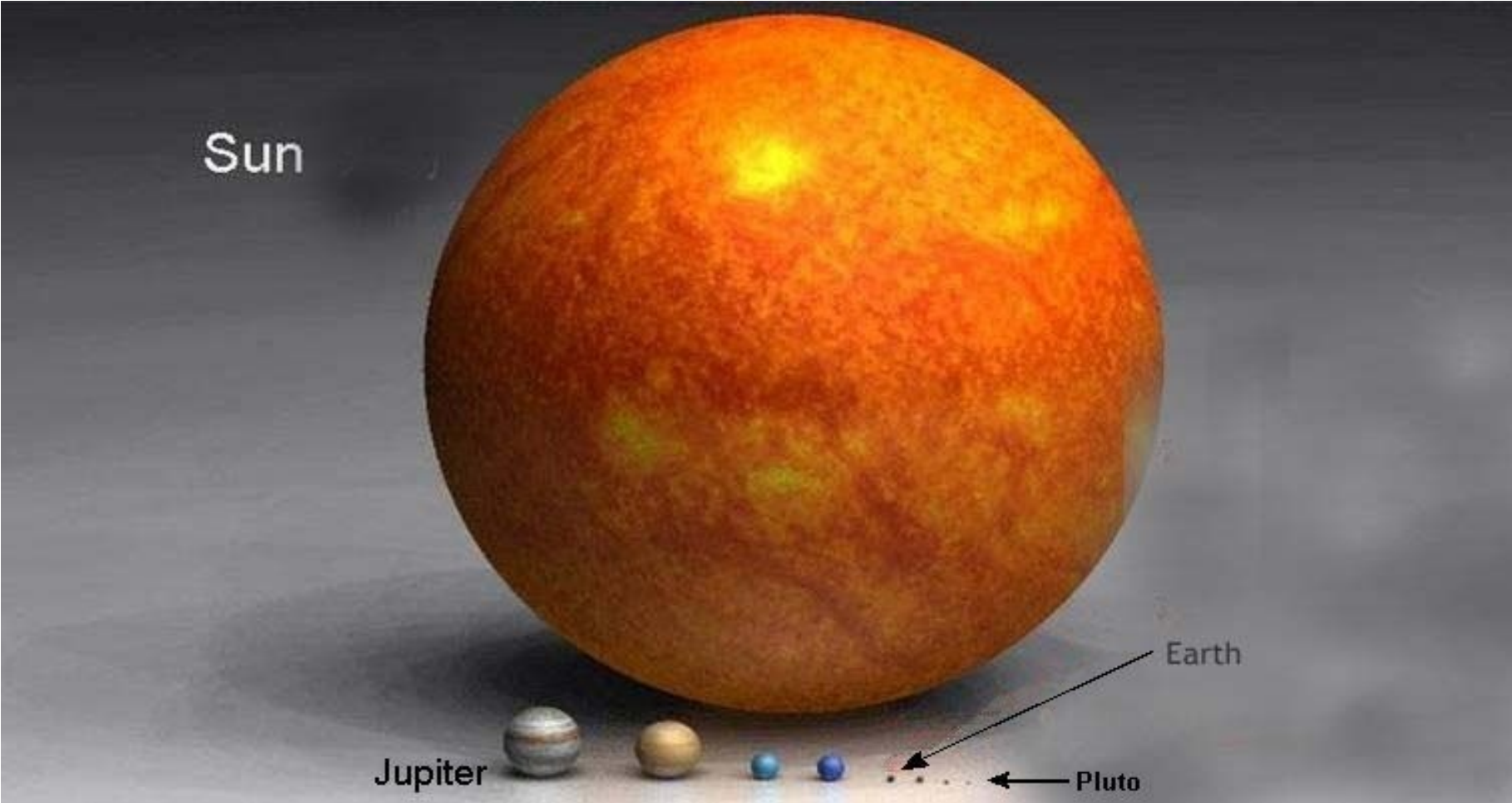


MARS

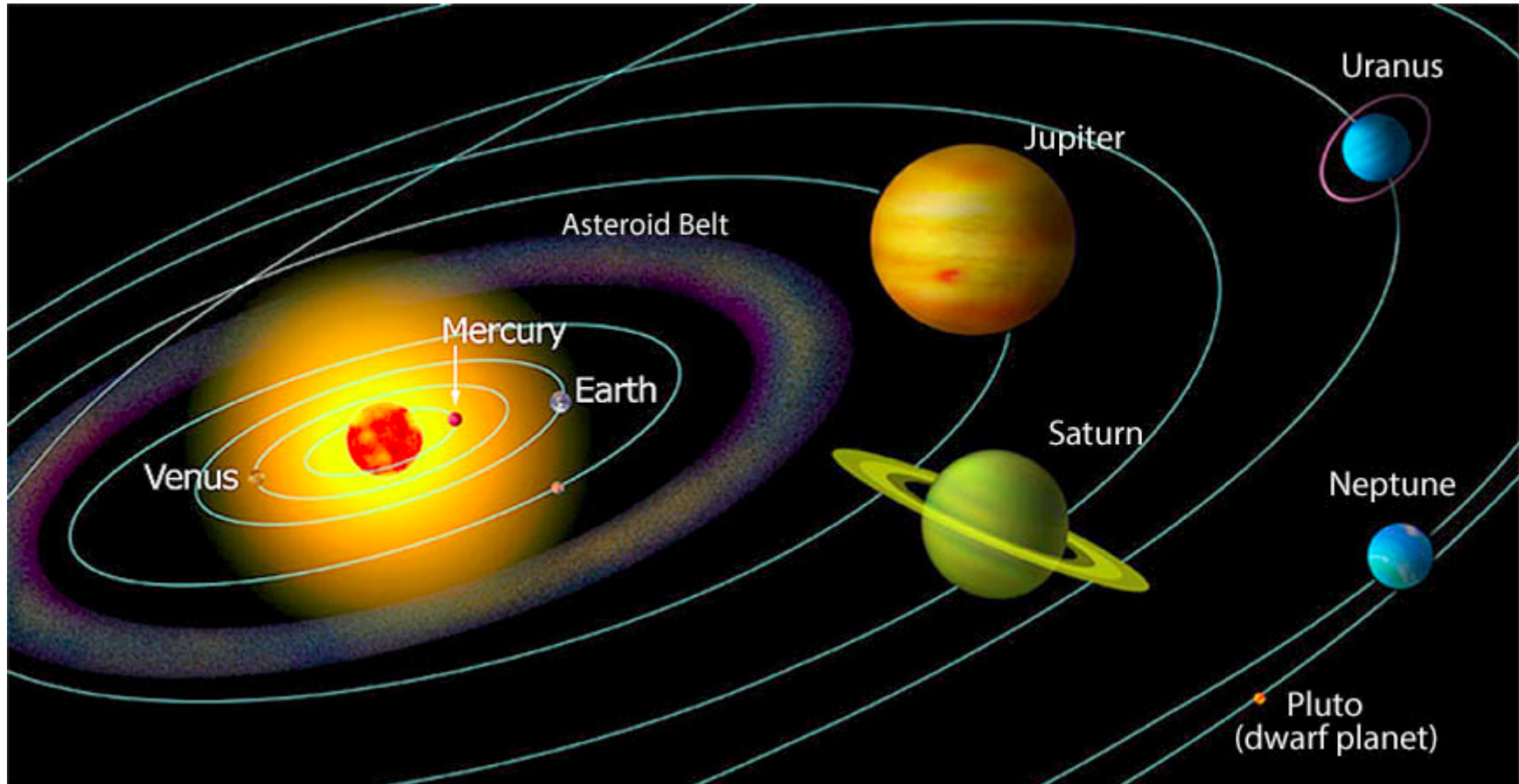


PLUTO





Órbitas



Kepler 80 (“ordenado”)

SPACE.
COM

www.SPACE.com

Crowded Alien Solar System

The Kepler space observatory has spotted a tightly packed, multiplanet system orbiting a star 1,100 light-years from Earth. This is the most crowded system found to date, with all five planets crammed into a region only 1/12 the distance from the Earth to the Sun.

The KOI-500 Star System

| | 1.0 | 3.1 | 4.6 | 7.1 | 9.5 | EARTH TO SCALE |
|----------------------------|-----|-----|-----|-----|-----|----------------|
| ORBIT PERIOD: (EARTH DAYS) | 1.0 | 3.1 | 4.6 | 7.1 | 9.5 | 365.3 |
| DIAMETER: | 1.3 | 1.4 | 1.5 | 2.4 | 2.6 | 1.0 |

STAR KOI-500

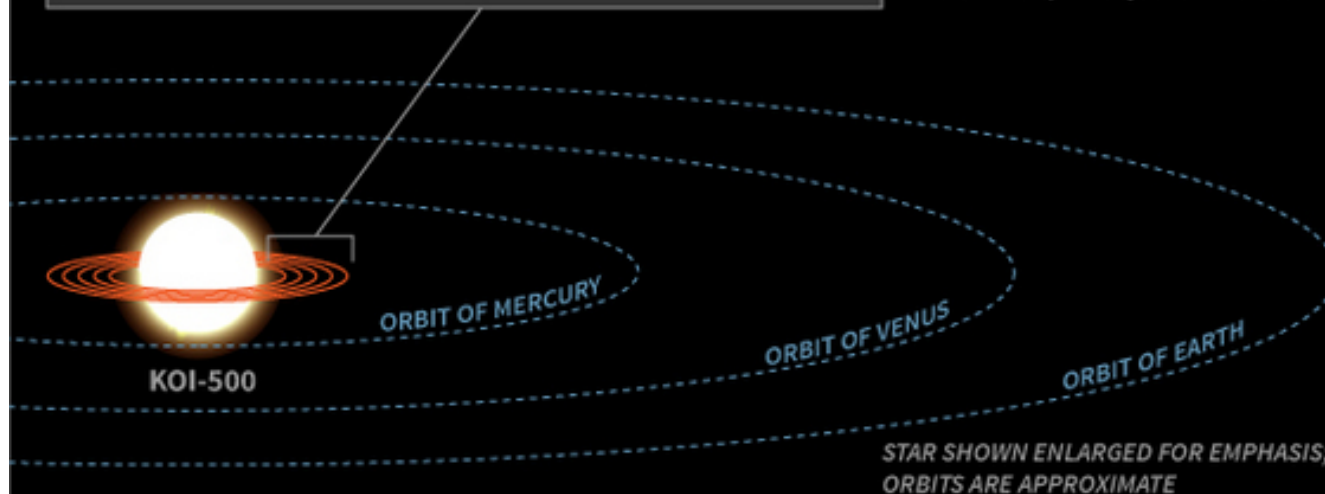
MASS: ABOUT THAT OF THE SUN

DIAMETER: 0.74 THAT OF THE SUN

AGE: ABOUT 1 BILLION YEARS

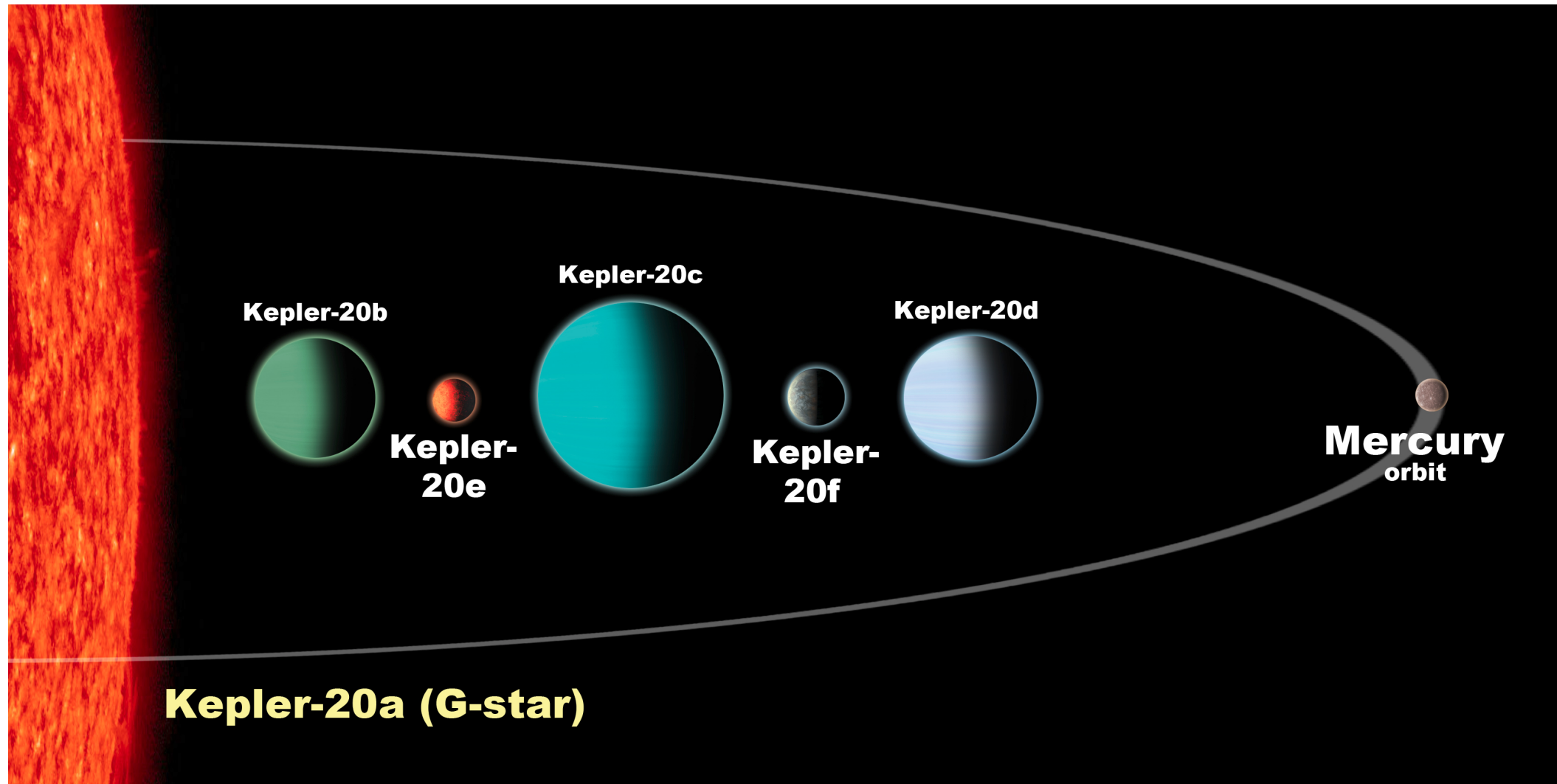
LOCATION: APPROXIMATELY 1,100 LIGHT-YEARS FROM EARTH, IN THE CONSTELLATION LYRA

“KOI” = *Kepler Object of Interest*



STAR SHOWN ENLARGED FOR EMPHASIS;
ORBITS ARE APPROXIMATE

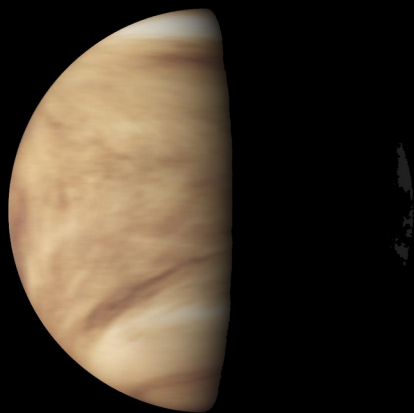
Kepler 20 (“desordenado”)



Kepler-20e



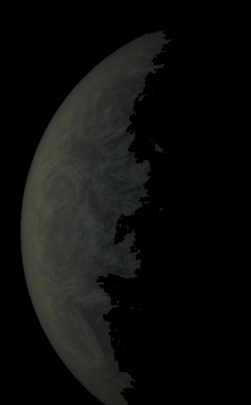
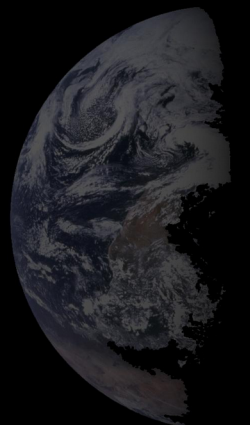
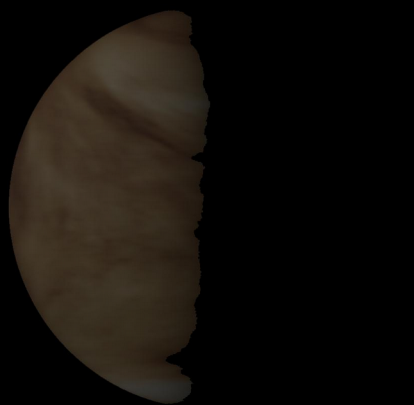
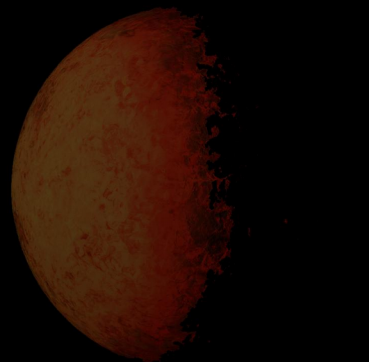
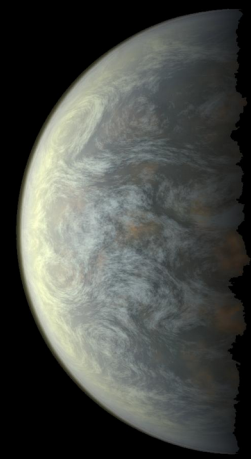
Venus



Earth



Kepler-20f



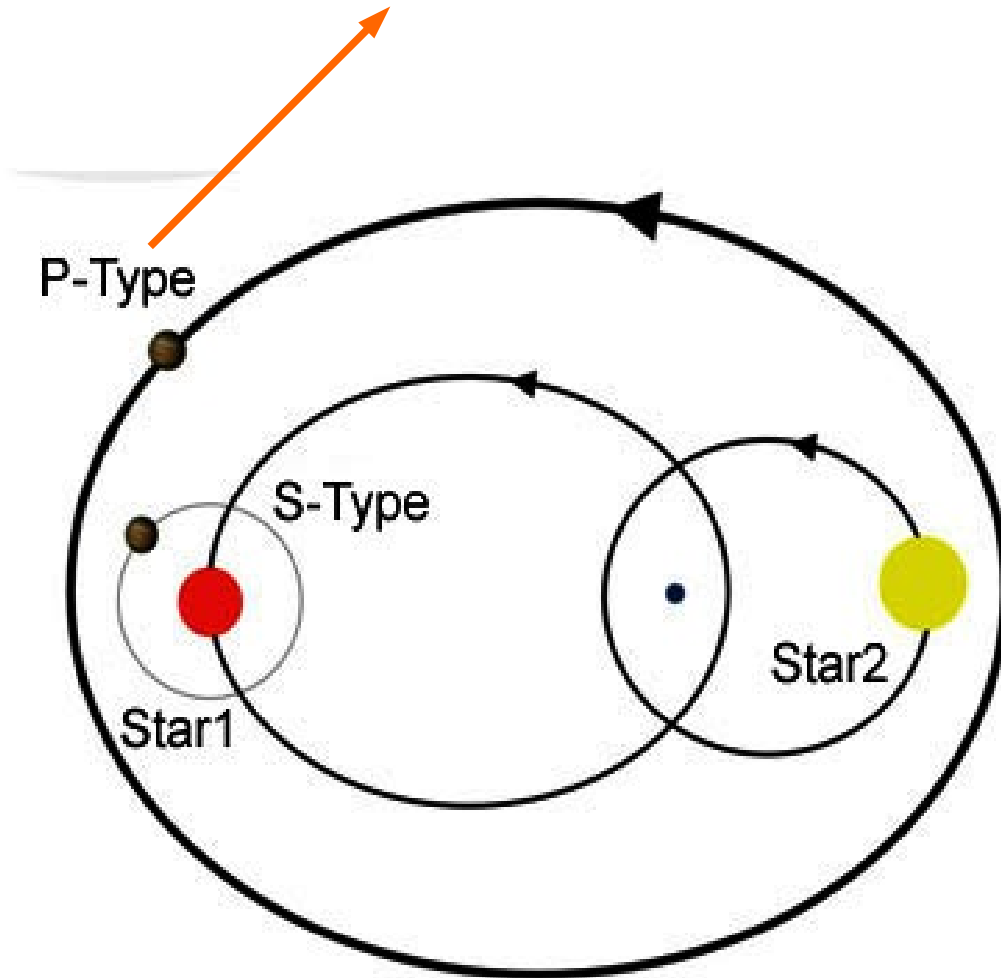
Sistemas multi-estelares

Diversos planetas confirmados pertencem a sistemas de várias estrelas.



Planetas circumbinários

Movimento planetário em sistemas binários



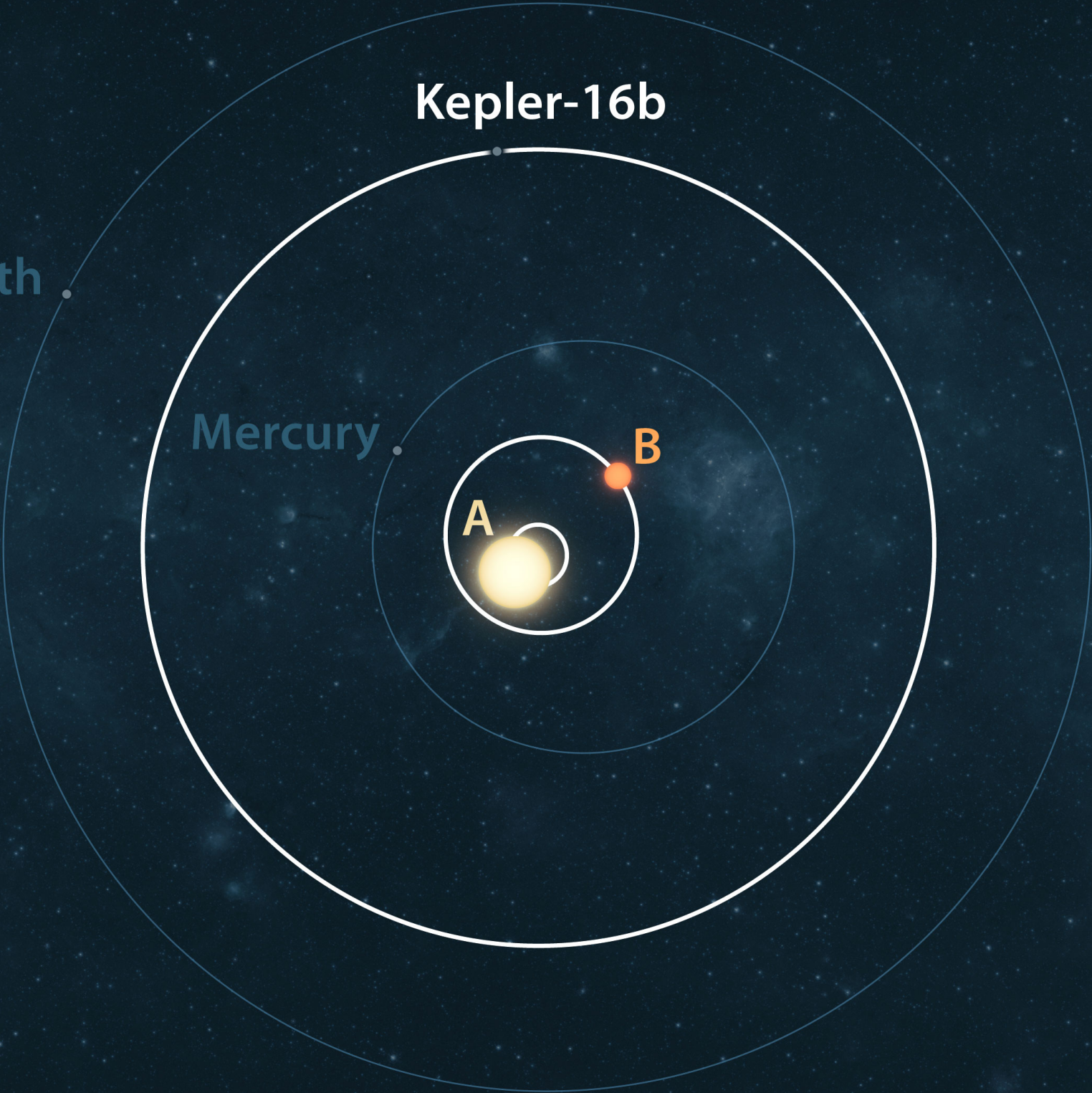
Kepler-16b

Earth

Mercury

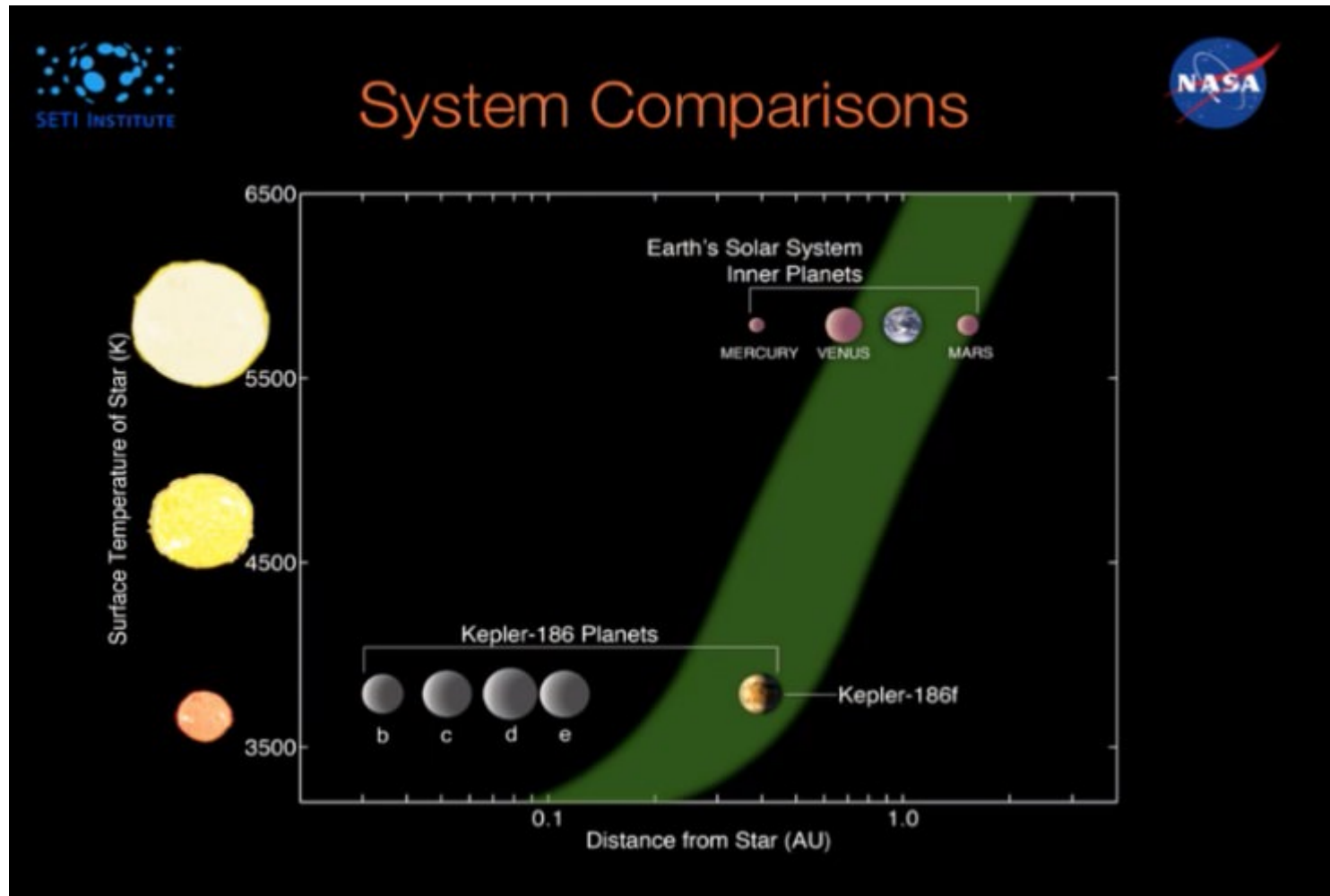
A

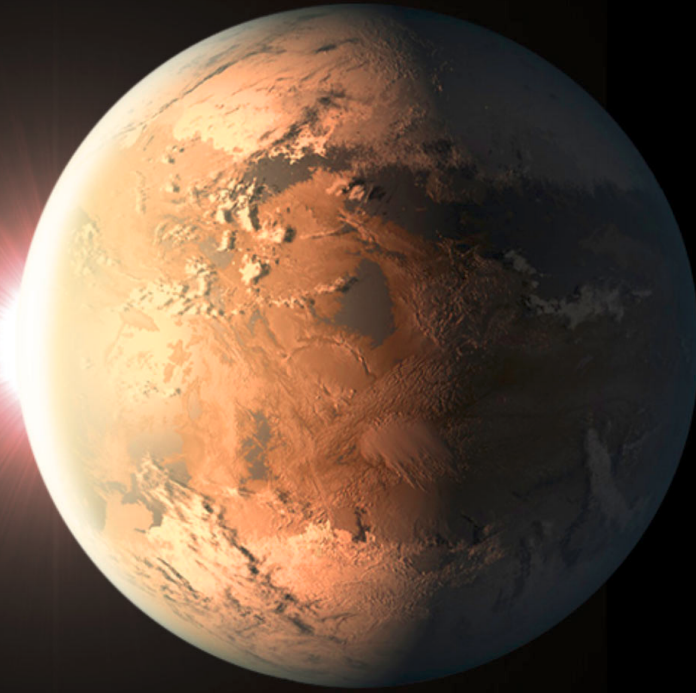
B



KEPLER – 186 f : primeiro planeta similar à Terra na região de habitabilidade

- $R=1.1 R_T$; $0.3 M_T < M < 3.8 M_T$ (água ou ferro puros) ; $P_{orb}=130$ d
- Estrela = tipo M (anã vermelha) ; distância = 500 anos luz.





Kepler-186f

Discovered April 17, 2014

Kepler-186f was the first validated Earth-size planet to orbit a distant star in the habitable zone—a range of distance from a star where liquid water might pool on the planet's surface. Its discovery confirmed that Earth-size planets exist in the habitable zones of other stars.



TEMPERATURE

The temperature of Kepler-186f is **unknown**.



ORBITAL PERIOD

Kepler-186f orbits its host star every **130 days**.



DISTANCE FROM EARTH

Kepler-186f is **492 light-years** from Earth.

PLANET COMPARISON

Kepler-186f



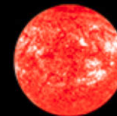
Earth



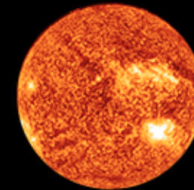
Kepler-186f has the **same mass** as Earth, but is **17% larger**.

STAR COMPARISON

Kepler-186



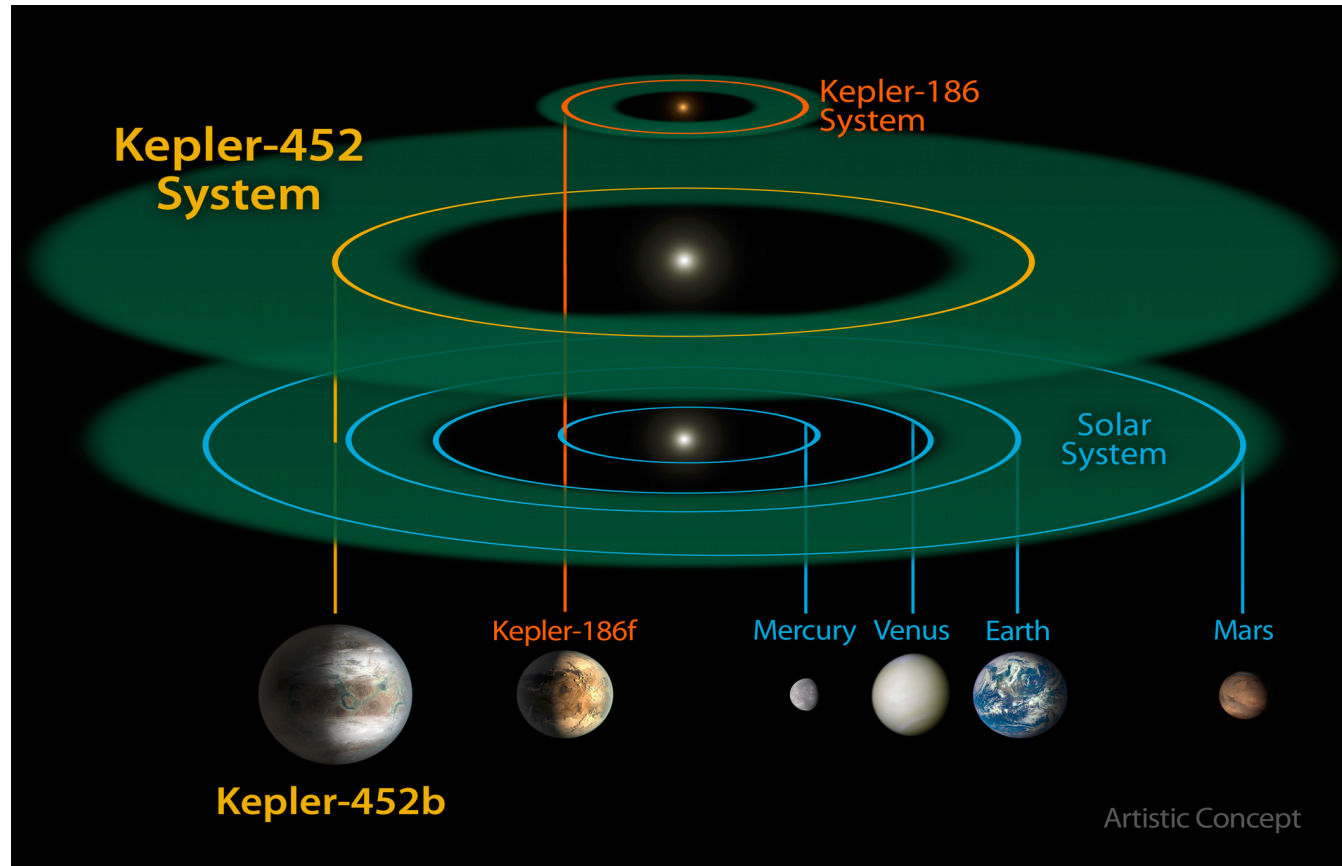
Our Sun



Kepler-186 is **48% less massive** and **47% smaller** than our Sun.

KEPLER – 452 b : sistema análogo ao Sol – Terra !

- $R = 1.6 R_T$; $M = 5 M_T$ (?) ; $P_{orb} = 385 \text{ d}$; Estrela = Tipo G (~ Sol)
- 1.5 vezes mais velho que a Terra (maior tempo para vida desenvolver)
- Distância = 1400 anos luz (26 mil anos para chegar lá com velocidade da New Horizons)

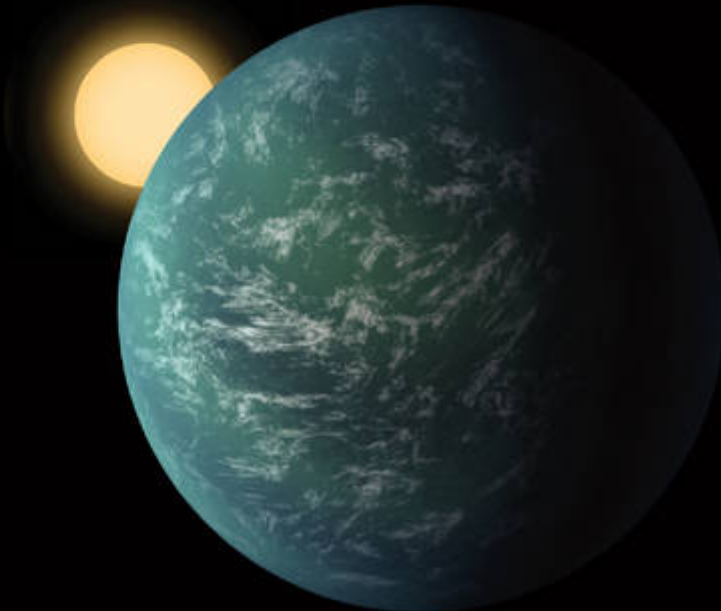


Searching for Habitable Worlds

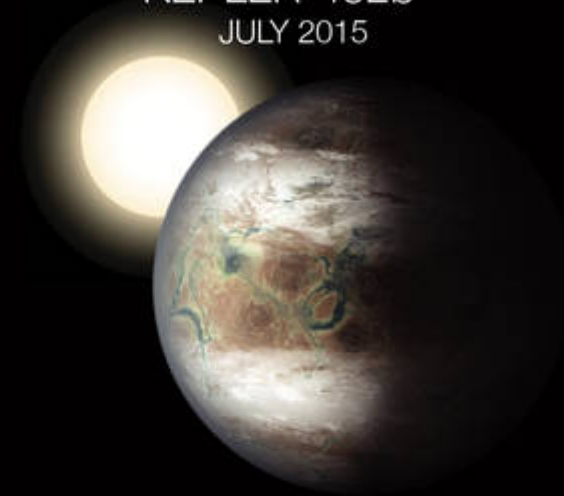
KEPLER-20e
DECEMBER 2011



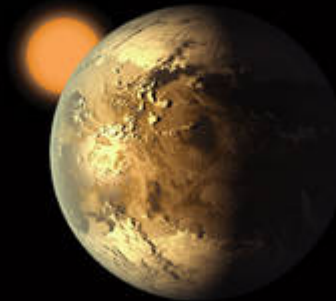
KEPLER-22b
DECEMBER 2011



KEPLER-452b
JULY 2015



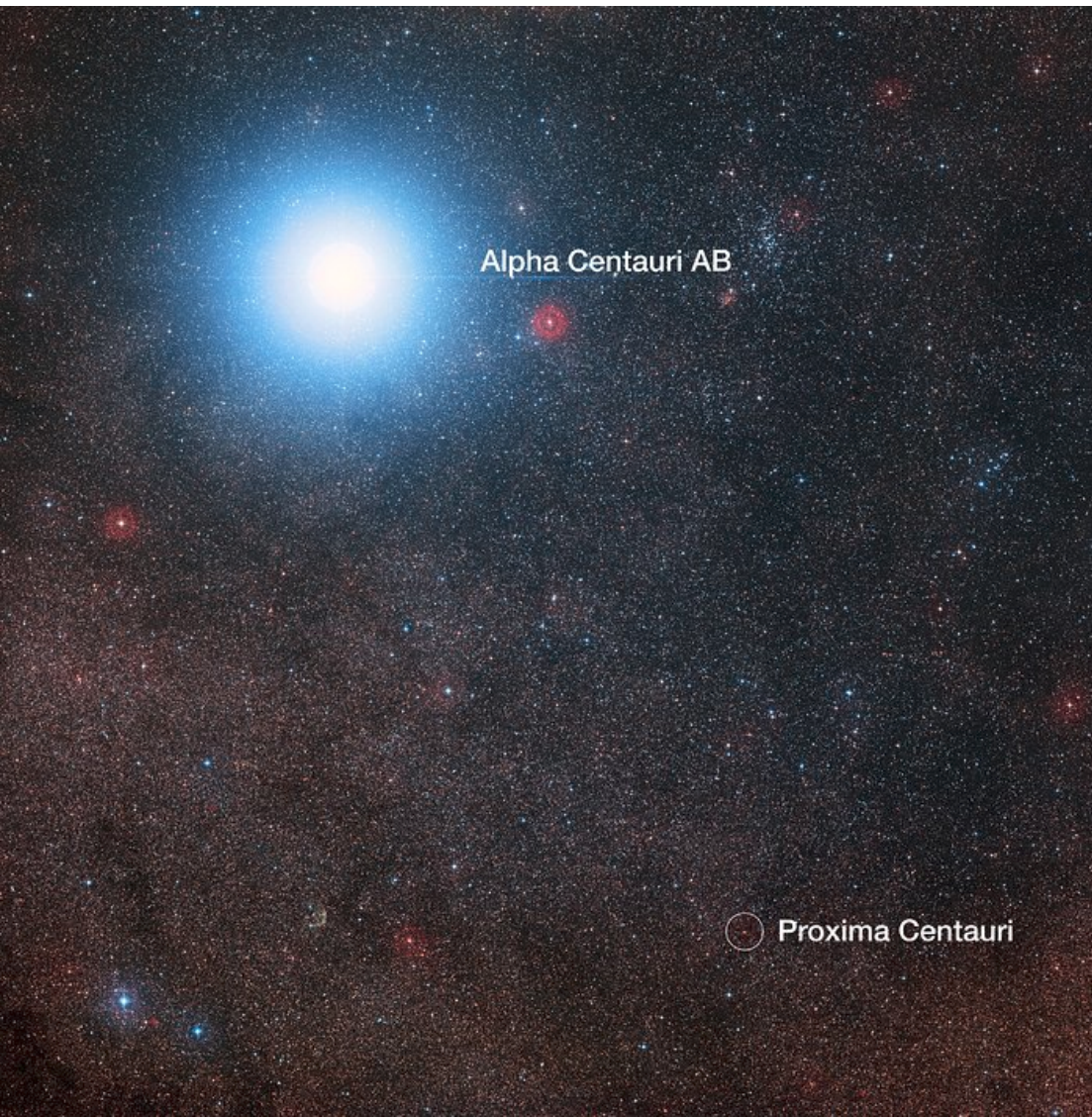
KEPLER-186f
APRIL 2014

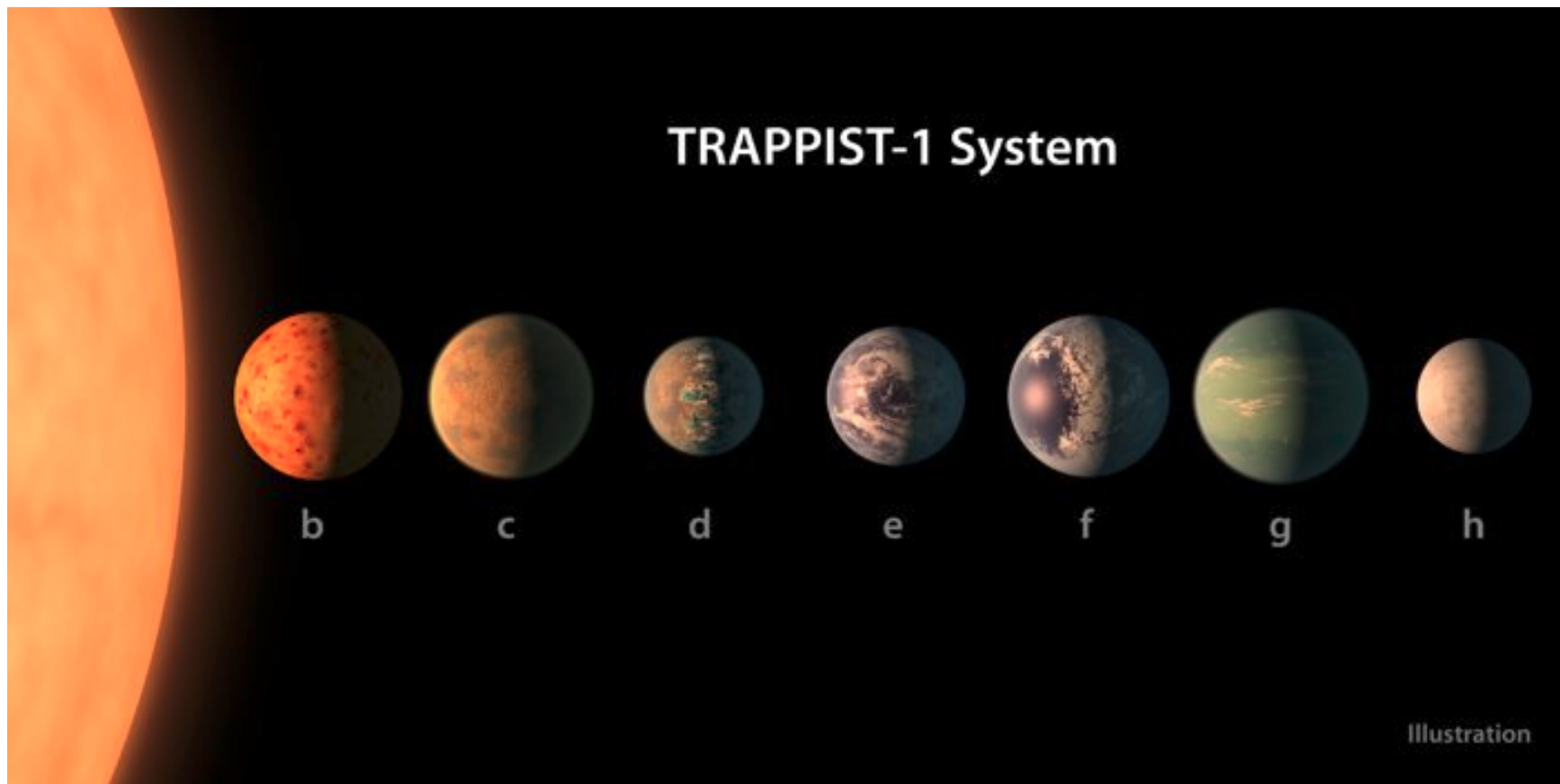


ARTISTIC CONCEPT



Proxima b: planeta rochoso mais próximo do Sistema Solar (4.2 anos-luz), orbitando, com um período de 11 dias, na zona de habitabilidade de estrela anã vermelha.

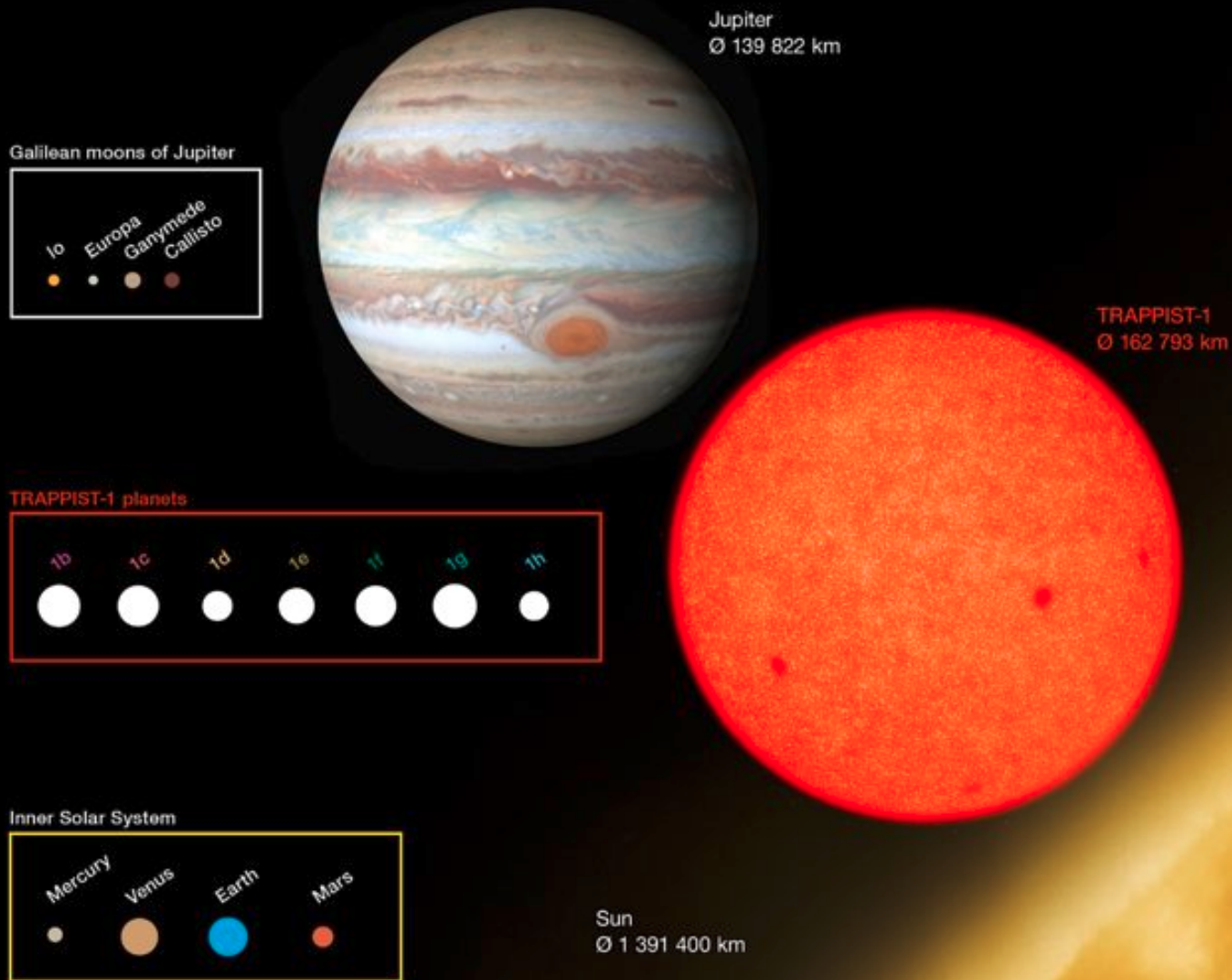




TRAPPIST – 1: sistema com maior número de planetas do tamanho da Terra e maior número de mundos que podem abrigar água líquida na superfície (e, f, g).

Size Comparison

between TRAPPIST-1 system, Galilean moons of Jupiter and the inner Solar System



TRAPPIST-1 System



b

c

d

e

f

g

h

Orbital Period
days

1.51 days

2.42 days

4.05 days

6.10 days

9.21 days

12.35 days

~20 days

Distance to Star
Astronomical Units (AU)

0.011 AU

0.015 AU

0.021 AU

0.028 AU

0.037 AU

0.045 AU

~0.06 AU

Planet Radius
relative to Earth

1.09 R_{Earth} 1.06 R_{Earth} 0.77 R_{Earth} 0.92 R_{Earth} 1.04 R_{Earth} 1.13 R_{Earth} 0.76 R_{Earth}

Planet Mass
relative to Earth

0.85 M_{Earth} 1.38 M_{Earth} 0.41 M_{Earth} 0.62 M_{Earth} 0.68 M_{Earth} 1.34 M_{Earth}

-

Solar System Rocky Planets



Mercury

Venus

Earth

Mars

Orbital Period
days

87.97 days

224.70 days

365.26 days

686.98 days

Distance to Star
Astronomical Units (AU)

0.387 AU

0.723 AU

1.000 AU

1.524 AU

Planet Radius
relative to Earth

0.38 R_{Earth} 0.95 R_{Earth} 1.00 R_{Earth} 0.53 R_{Earth}

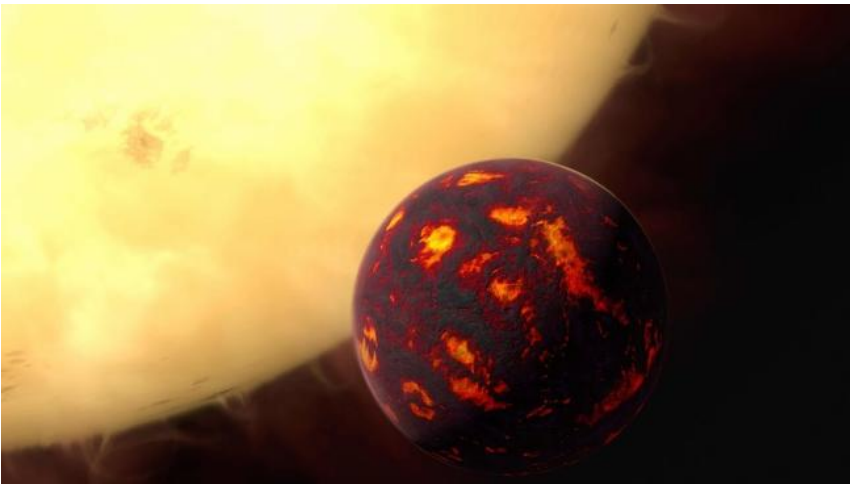
Planet Mass
relative to Earth

0.06 M_{Earth} 0.82 M_{Earth} 1.00 M_{Earth} 0.11 M_{Earth}

Marés



- Evolução primordial: Interação planeta-disco induz **migração orbital**.
- Em alguns casos, devido aos curtos períodos orbitais, o efeito de maré entre o planeta e a estrela é muito intenso.
- Júpiter e super-Terras quentes são fortemente afetados pela força de maré.



Qual o efeito das marés na órbita e na rotação de planetas quentes?

Marés

Órbita:

$$\langle \dot{a} \rangle = -\frac{2}{3}na^{-4}[(2 + 46e^2)\hat{s} + 7e^2\hat{p}],$$

$$\langle \dot{e} \rangle = -\frac{1}{3}nea^{-5}(18\hat{s} + 7\hat{p}).$$

$$\frac{\hat{p}}{\hat{s}} = 2 \frac{k_{dp}}{k_{d*}} \frac{Q_*}{Q_p} \left(\frac{m_*}{m_p} \right)^2 \left(\frac{R_p}{R_*} \right)^5$$

Interação de maré provoca **decaimento orbital** e **circularização**.

Evolução em sistemas de um planeta

CoRoT-20:

$M = 4.2 M_{\text{Jup}}$

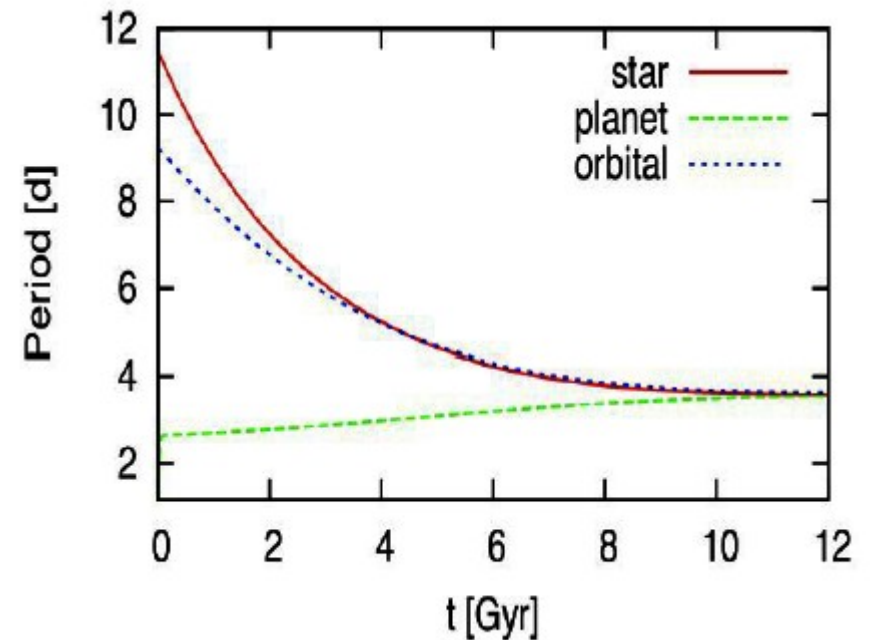
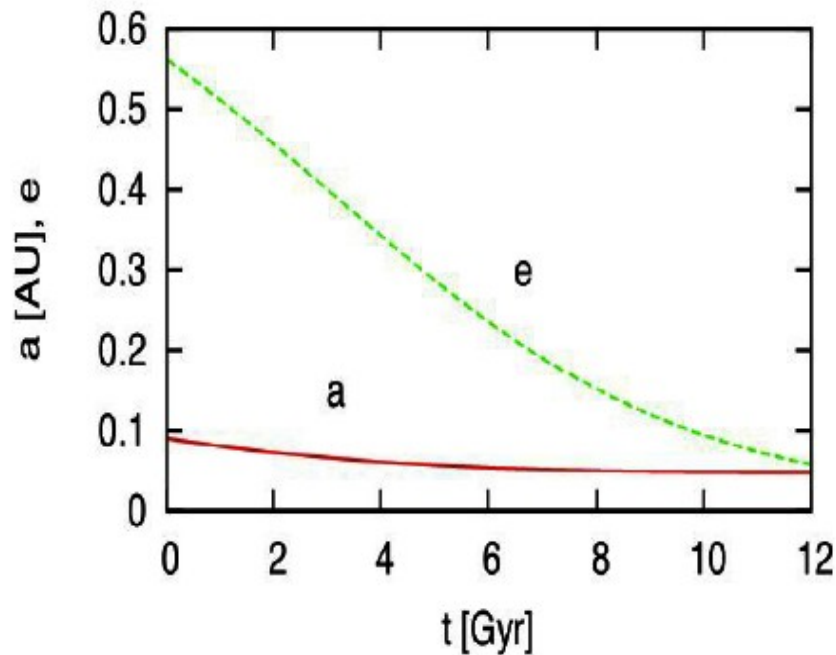
$P = 9.2 \text{ d}$

$e = 0.56$

$P_{\text{rot}} = 11.2 \text{ d}$

- A interação de maré com um planeta gigante conduz à **aceleração** da rotação da estrela.

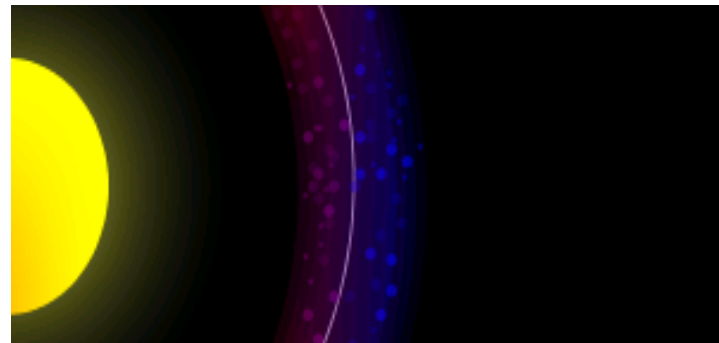
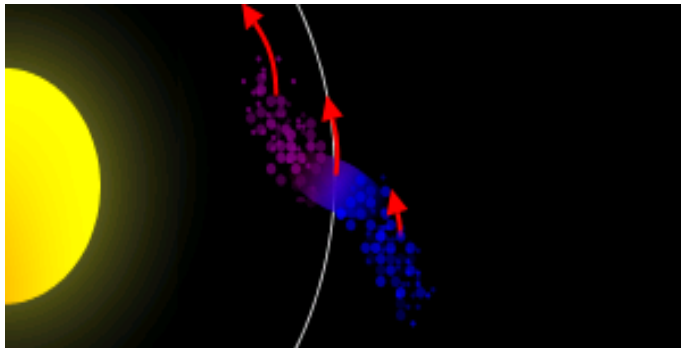
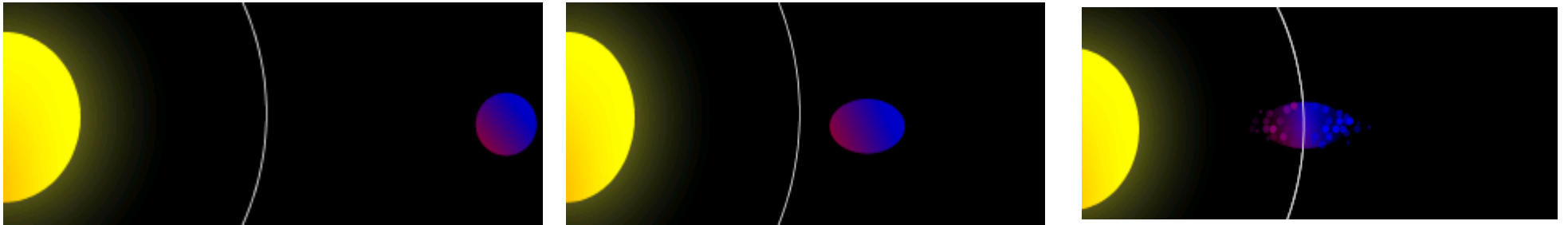
- Em alguns casos, o estado de duplo **duplo sincronismo** pode ser atingido.



Deleuil et al. (2012)

O Limite de Roche

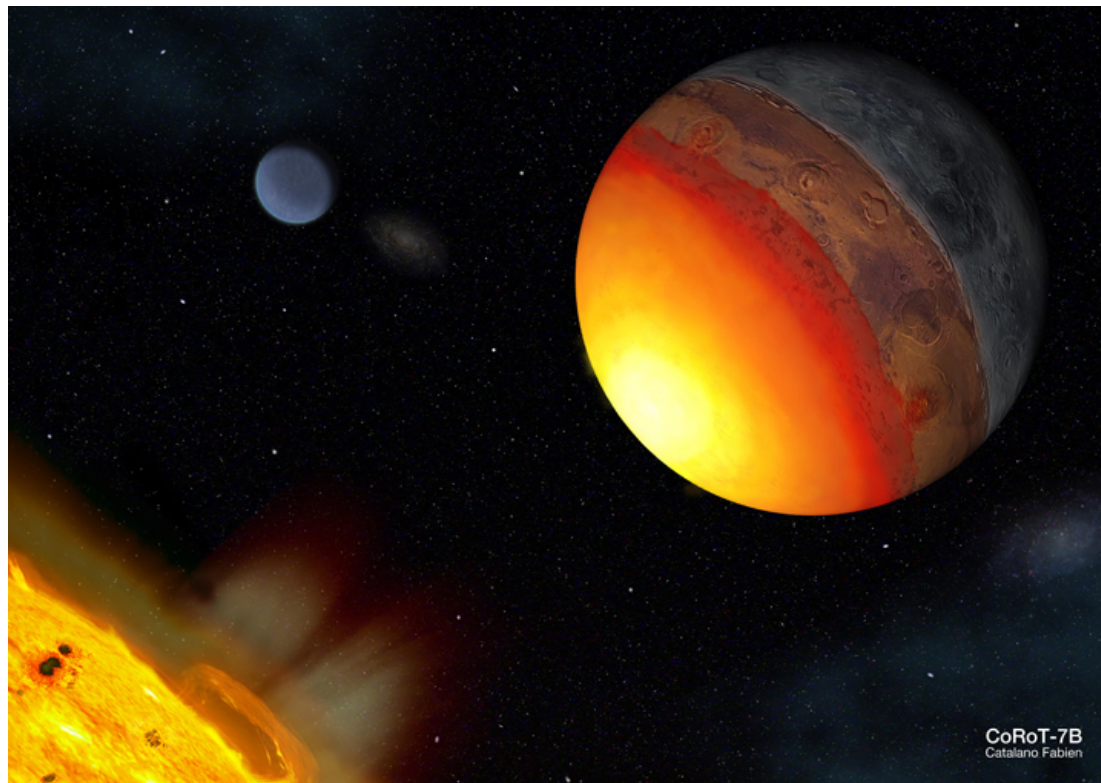
Distância crítica de aproximação sem ser **destruído** pela ação da maré.



Marés

Rotação:




A rotação de planetas quentes tende ao **sincronismo** com o movimento orbital.



Exoluas

THE ASTRONOMICAL JOURNAL

HEK. VI. On the Dearth of Galilean Analogs in *Kepler*, and the Exomoon Candidate Kepler-1625b I

A. Teachey¹ , D. M. Kipping¹ , and A. R. Schmitt² 

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[The Astronomical Journal](#), Volume 155, Number 1

2018

DETECTING EXOMOONS VIA DOPPLER MONITORING OF DIRECTLY IMAGED EXOPLANETS

ANDREW VANDERBURG^{1,†}, SAUL A. RAPPAPORT², AND ANDREW W. MAYO^{3,4}

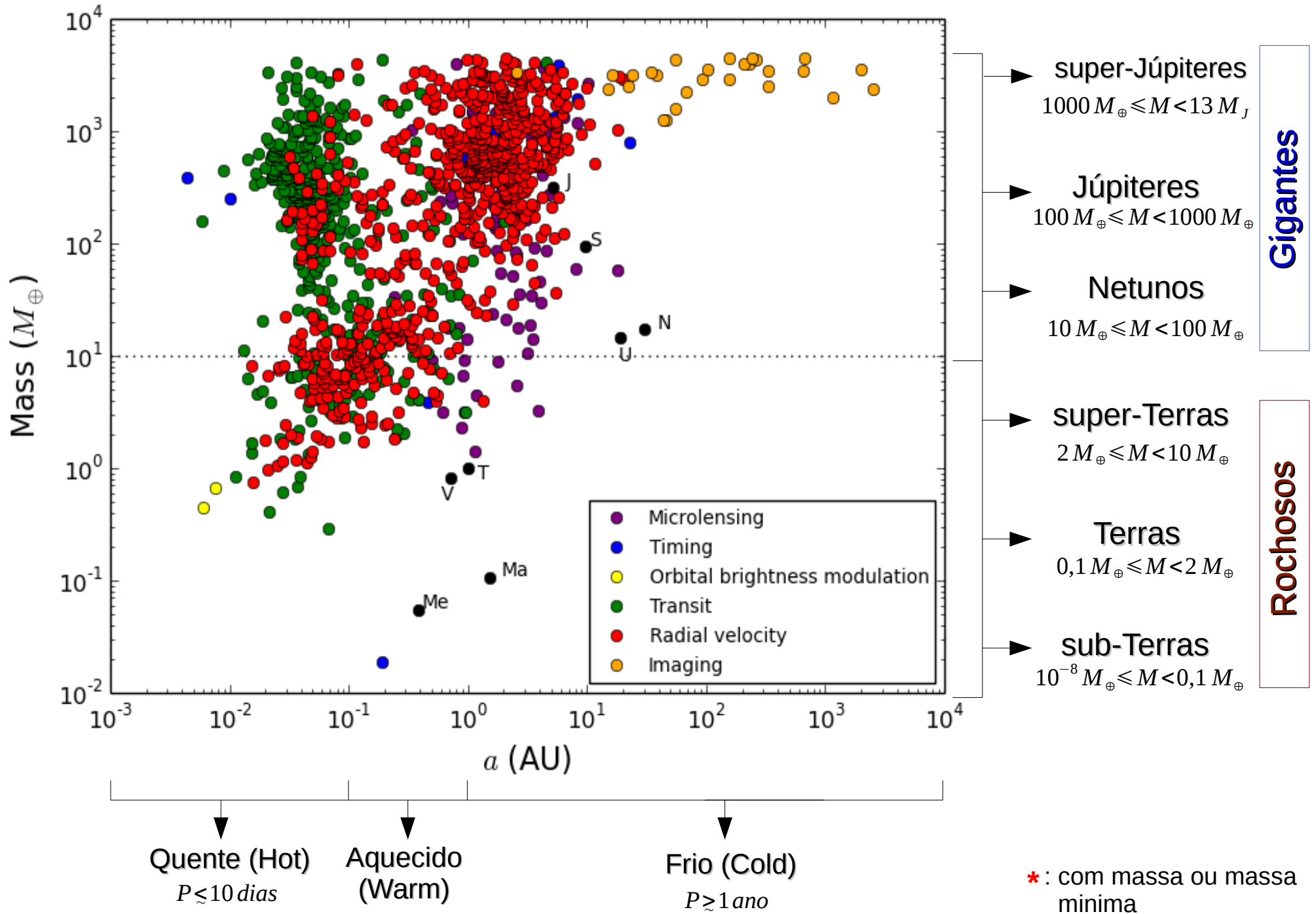
ABSTRACT

Recently, Teachey, Kipping, and Schmitt (2018) reported the detection of a candidate exomoon, tentatively designated *Kepler*-1625b I, around a giant planet in the *Kepler* field. The candidate exomoon would be about the size and mass of Neptune, considerably larger than any moon in our Solar System, and if confirmed, would be the first in a new class of giant moons or binary planets. Motivated by the large mass ratio in the *Kepler*-1625b planet and satellite system, we investigate the detectability of similarly massive exomoons around directly imaged exoplanets via Doppler spectroscopy. The candidate moon around *Kepler*-1625b would induce a radial velocity signal of about 200 ms^{-1} on its host planet, large enough that similar moons around directly imaged planets orbiting bright, nearby stars might be detected with current or next generation instrumentation. In addition to searching for exomoons, a radial velocity survey of directly imaged planets could reveal the orientations of the planets' spin axes, making it possible to identify Uranus analogs.

Subject headings: planetary systems, planets and satellites: detection

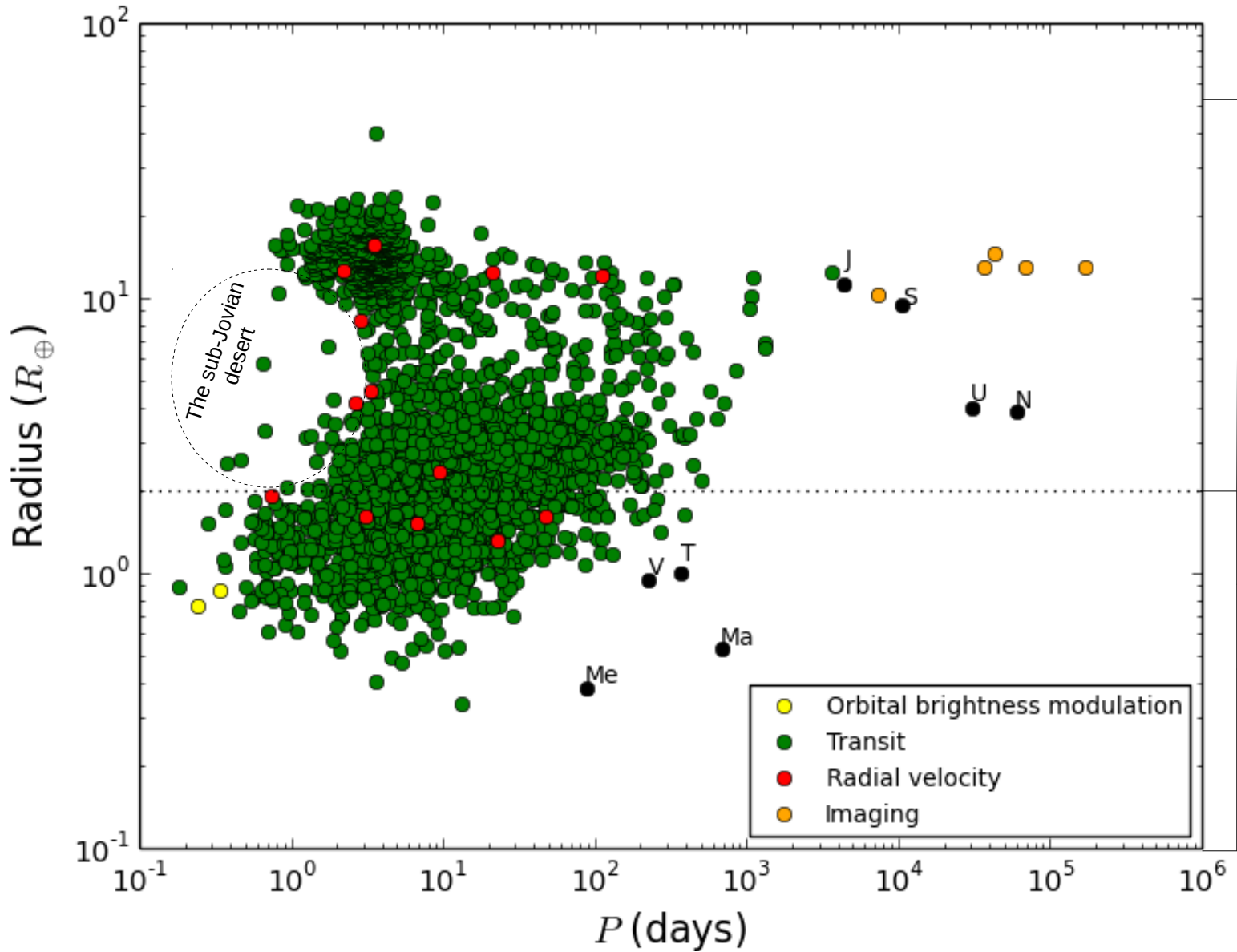
* Total: 1310 (NASA Exoplanet Archive) – Data: 15/10/2019

$1 M_J = 317,8 M_\oplus$



Total: 3137 (NASA Exoplanet Archive) – Data: 15/10/2019

$$1 R_J = 11,2089 R_\oplus$$



- ▶ Júpiteres
 $R \geq 6 R_\oplus$
- ▶ Netunos
 $2 R_\oplus \leq R < 6 R_\oplus$
- ▶ super-Terras
 $1,25 R_\oplus \leq R < 2 R_\oplus$
- ▶ Terras
 $1 R_\oplus \leq R < 1,25 R_\oplus$
- ▶ sub-Terras
 $R < 1 R_\oplus$

Gigantes

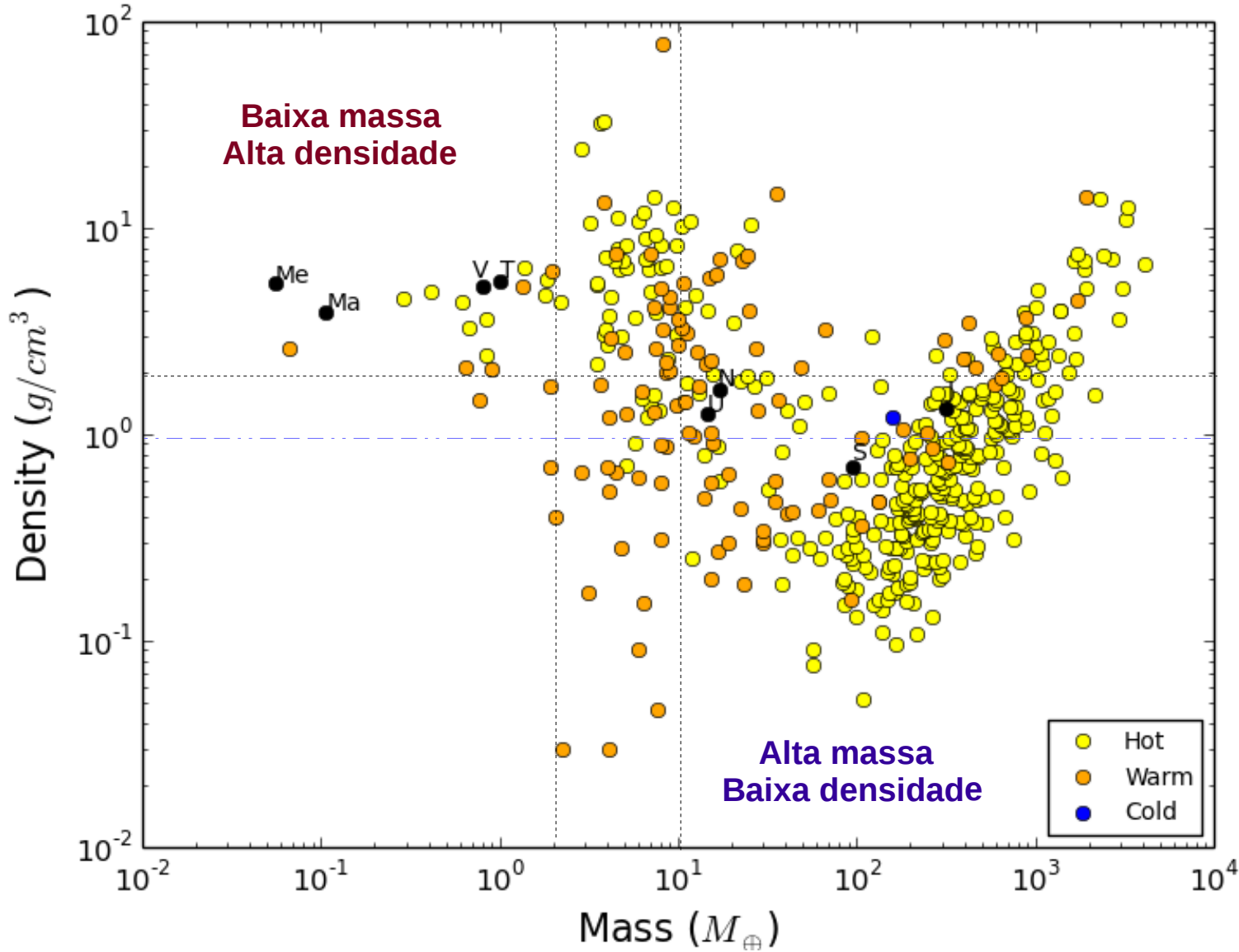
Rochosos

Quente (Hot)

Aquecido (Warm)

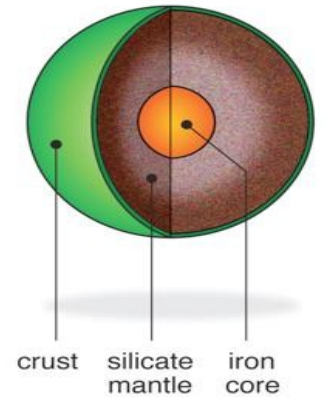
Frio (Cold)

Total: 480 (NASA Exoplanet Archive) – Data: 15/10/2019

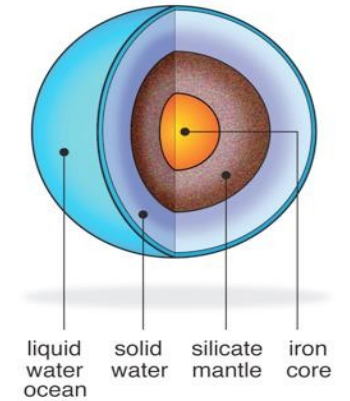


super-Terras

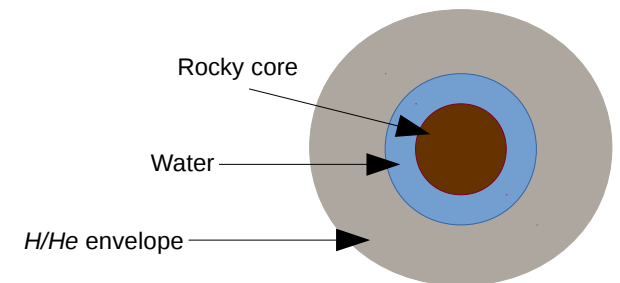
Alta densidade



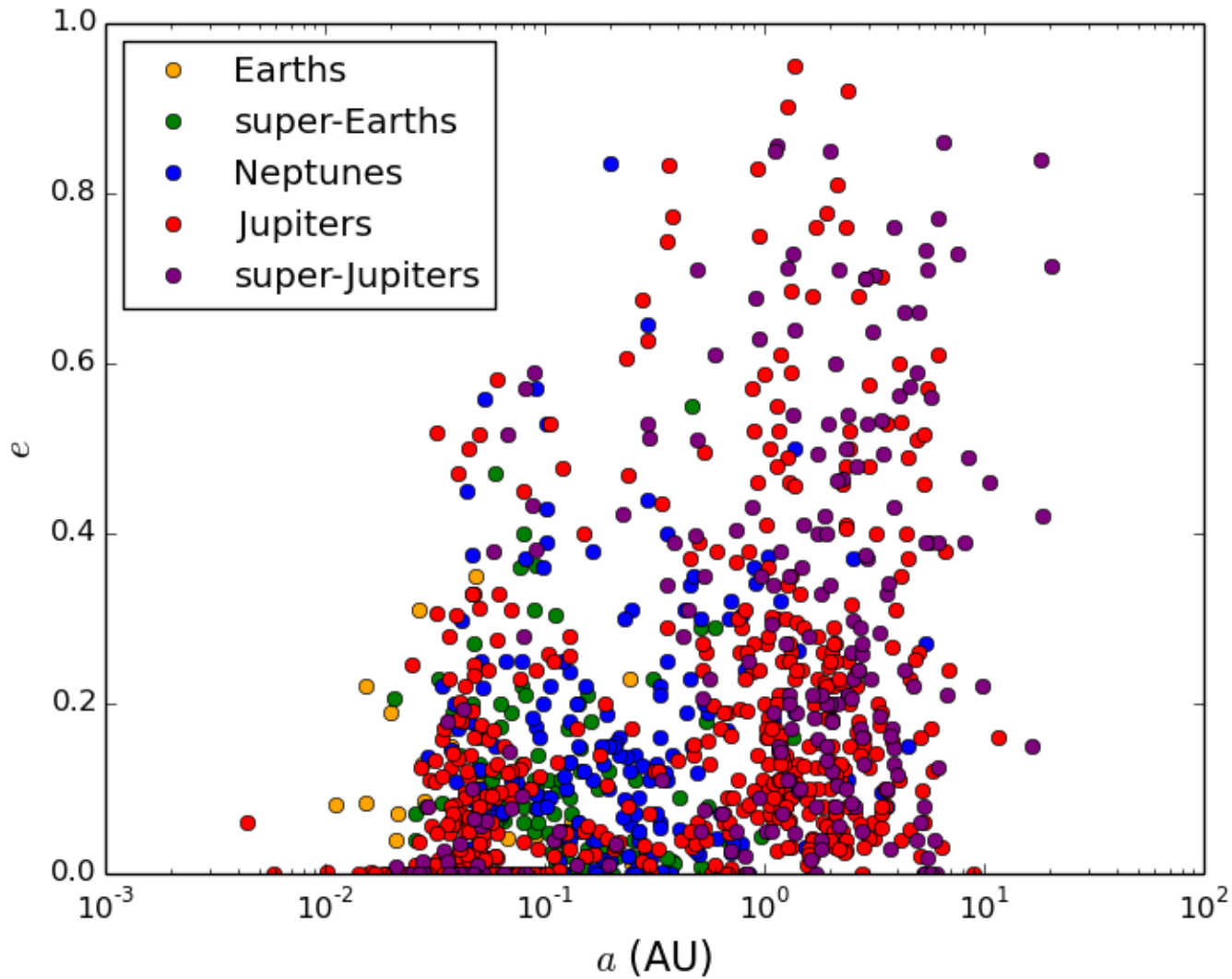
Densidade intermediária (planetas oceanos)



Baixa densidade (mini-Netunos)



Total: 1108 (NASA Exoplanet Archive) – Data: 15/10/2019



Sistema solar

| | |
|----------------|---------------|
| Mercúrio: | 0,2056 |
| Vênus: | 0,0068 |
| Terra: | 0,0167 |
| Marte: | 0,0068 |
| Júpiter: | 0,0484 |
| Saturno: | 0,0557 |
| Urano: | 0,0472 |
| Netuno: | 0,0086 |
| Cometa Halley: | 0,967 |

$e=0$
(201)

- sub-Terras: **1**
- Terras: **7**
- super-Terras: **31**
- Netunos: **35**
- Júpiteres: **110**
- super-Júpiteres: **17**

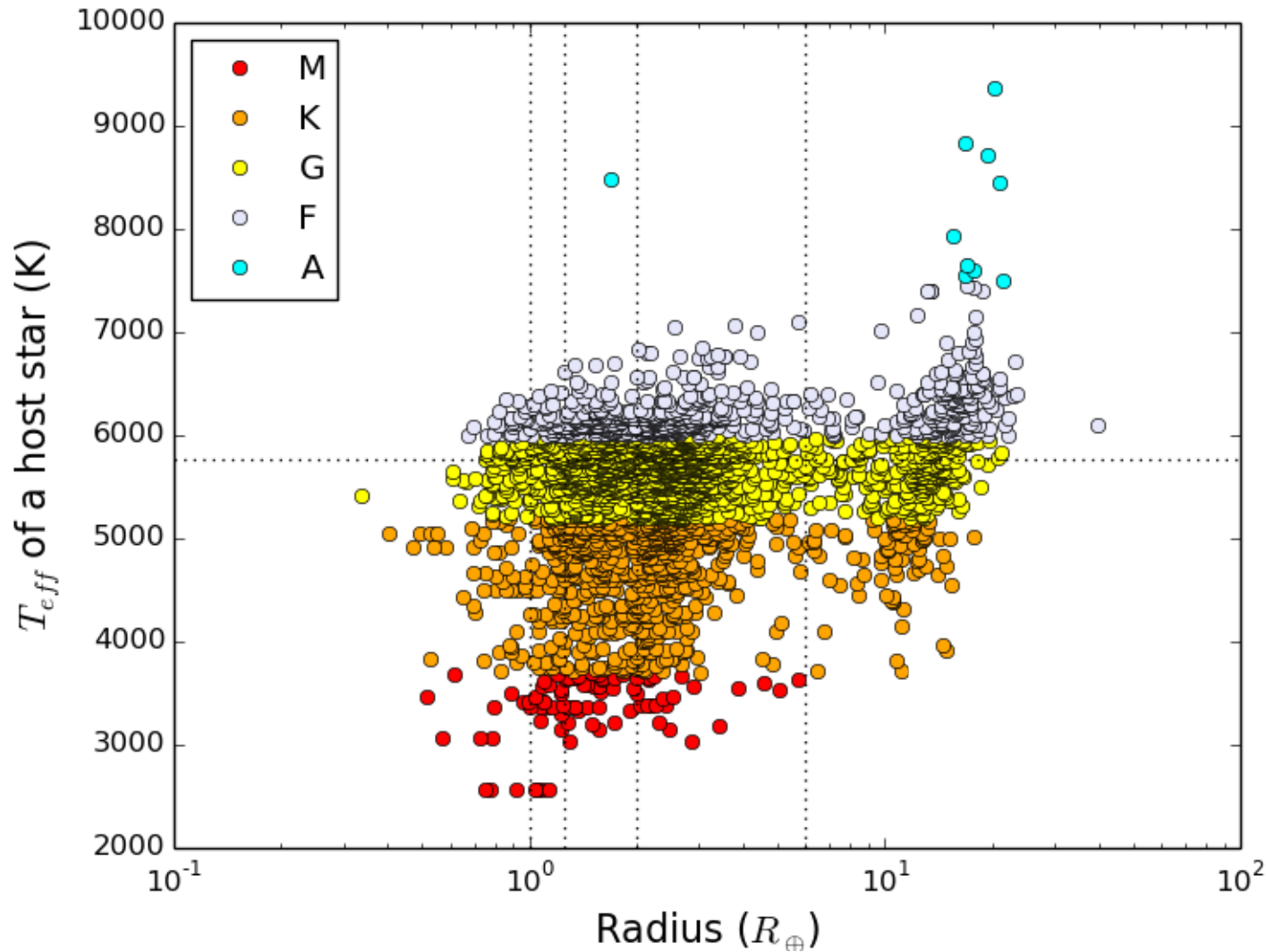
$0 < e \leq 0.4$
(778)

- sub-Terras: **0**
- Terras: **21**
- super-Terras: **91**
- Netunos: **158**
- Júpiteres: **373**
- super-Júpiteres: **135**

$e > 0.4$
(129)

- sub-Terras: **0**
- Terras: **0**
- super-Terras: **2**
- Netunos: **9**
- Júpiteres: **62**
- super-Júpiteres: **56**

Total: 3075 (NASA Exoplanet Archive) – Data: 15/10/2019



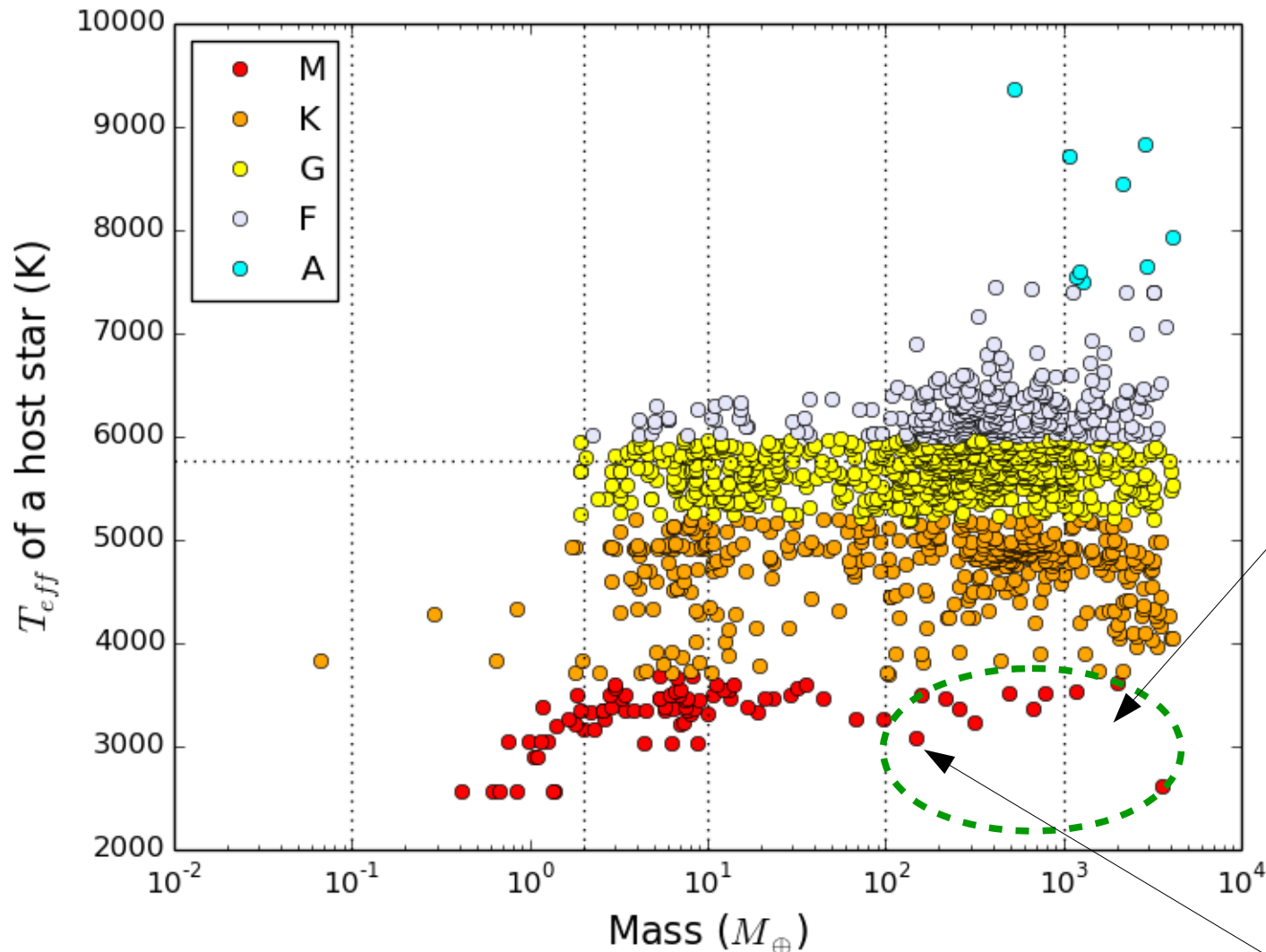
$T_{eff \odot} = 5772$ K

Na vizinhança solar:

- Tipo **A**: **0,625 %**
- Tipo **G**: **7,6 %**
- Tipo **M**: **76 %**

1. Estrelas Tipo **A0** – **F6**:
 - Poucas linhas espectrais e alta velocidade de rotação.
 - Alta luminosidade.
2. Estrelas Tipo **M**:
 - Espectro difícil de identificar (muitas bandas moleculares).
 - Baixa luminosidade.

Total: 1405 (NASA Exoplanet Archive) – Data: 15/10/2019



Instabilidade do disco

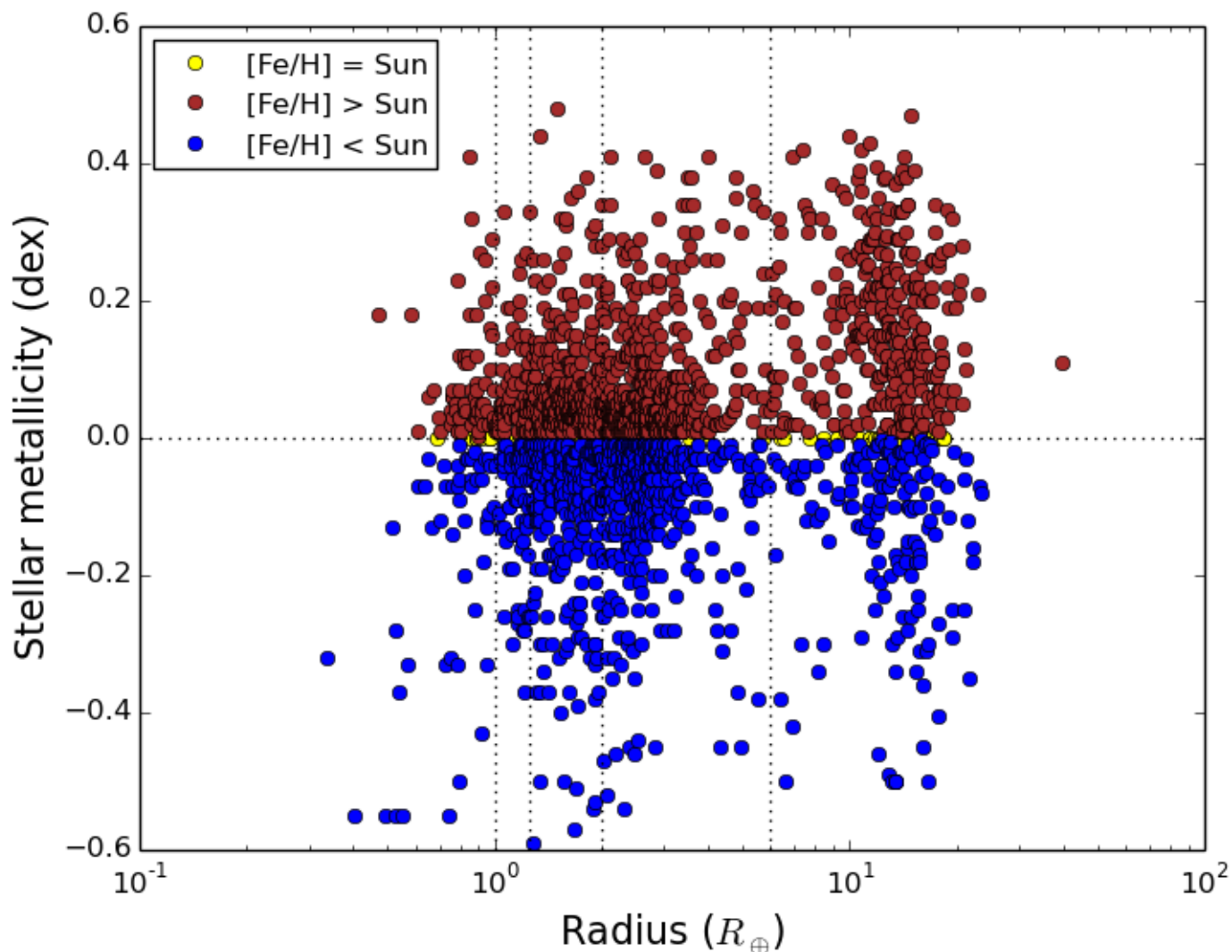
É mais provável que os gigantes tipo Júpiteres tenham se formado quando parte do disco entrou em colapso devido a sua própria gravidade.

GJ 3512 b

$$M \sin(i) = (0,463 \pm 0,023) M_J$$
$$e = 0,4356 \pm 0,0052$$
$$P = (203,59 \pm 0,14) \text{ dias}$$

Paper: *A giant exoplanet orbiting a very low-mass star challenges planet formation models.*
Morales et al. 2019. *Science*, 365, 1441.

Total: 2200 (NASA Exoplanet Archive) – Data: 15/10/2019



Rochosos

[Fe/H] = 0 : 37 (1,68 %)
 [Fe/H] < 0 : 368 (16,73 %)
 [Fe/H] > 0 : 417 (18,95 %)

(([Fe/H] > 0) - ([Fe/H] < 0))
2,23 %

Total: 822

Gigantes

[Fe/H] = 0 : 75 (3,4 %)
 [Fe/H] < 0 : 540 (24,54 %)
 [Fe/H] > 0 : 763 (34,68 %)

(([Fe/H] > 0) - ([Fe/H] < 0))
10,14 %

Total: 1378

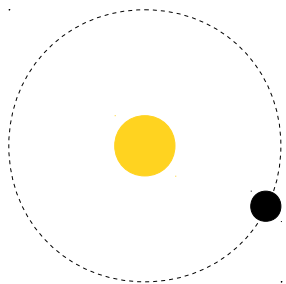
Netunos: (([Fe/H] > 0) - ([Fe/H] < 0))
4,21 %

Júpiteres: (([Fe/H] > 0) - ([Fe/H] < 0))
11,97 %

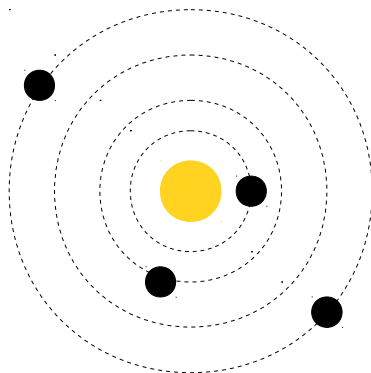
← **Estrelas com maior metalicidade do que o Sol têm maior probabilidade de abrigar Júpiteres.**

↑ **Estrelas com maior metalicidade do que o Sol têm maior probabilidade de abrigar planetas gigantes.**

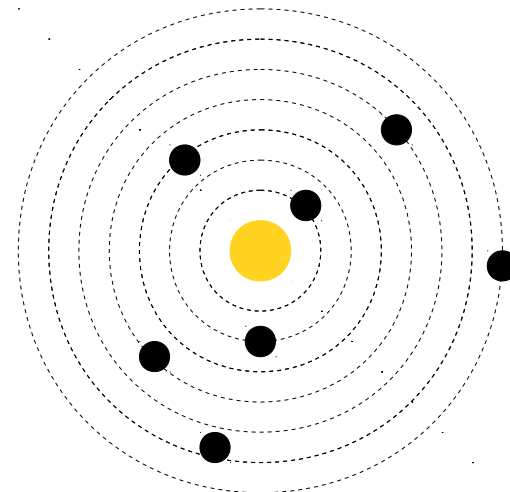
Total: **2858** sistemas



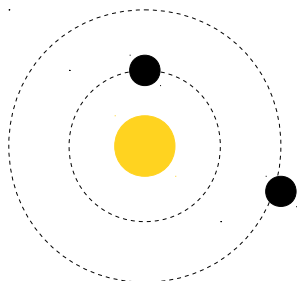
2207 (**77,22 %**)



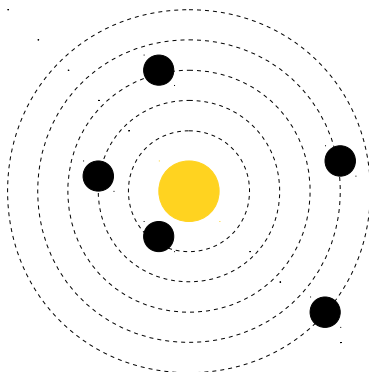
54 (**1,89 %**)



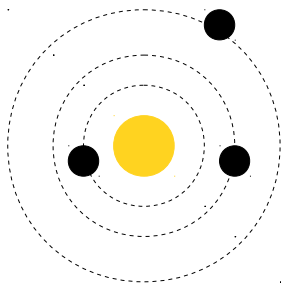
1 (**0,04 %**)



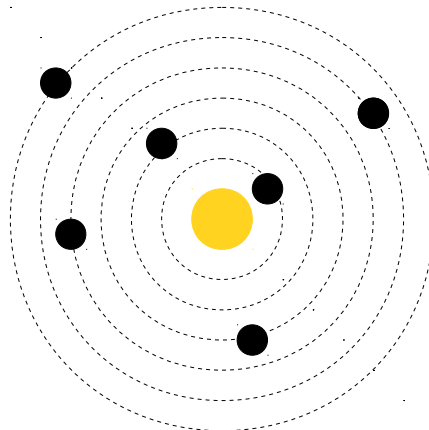
436 (**15,26 %**)



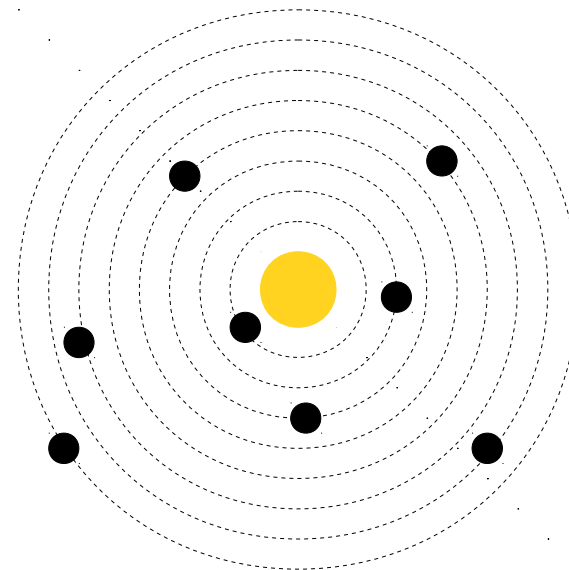
18 (**0,63 %**)



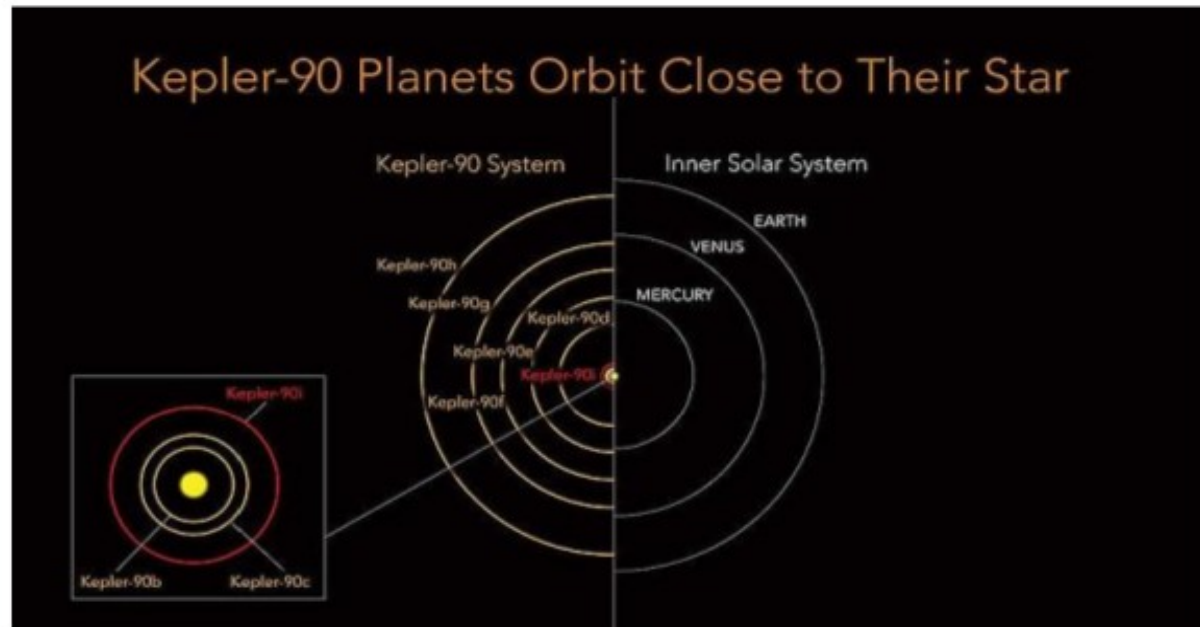
136 (**4,76 %**)



5 (**0,17 %**)

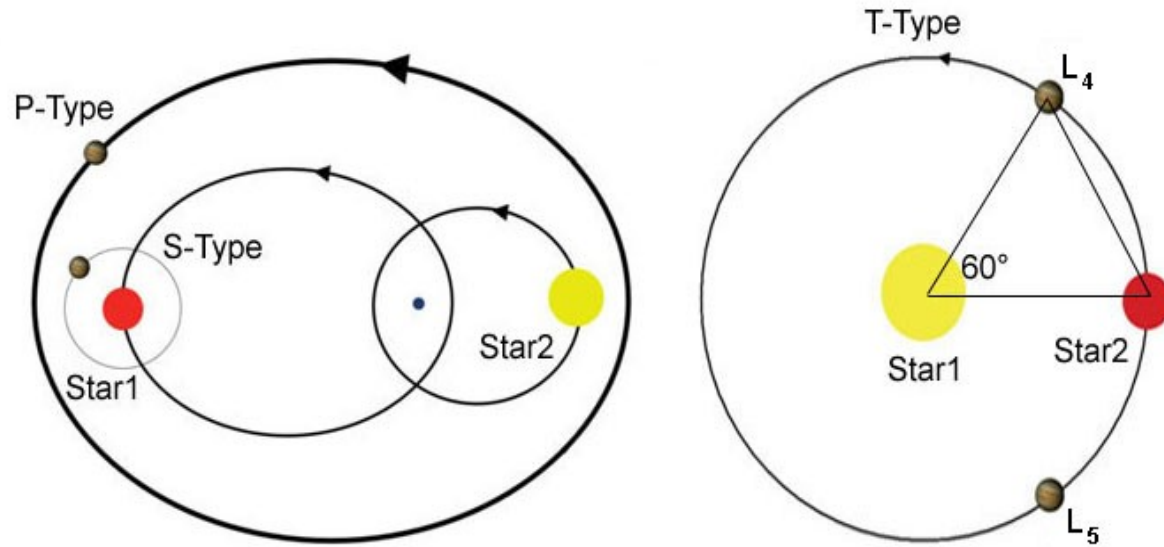


1 (**0,04 %**)

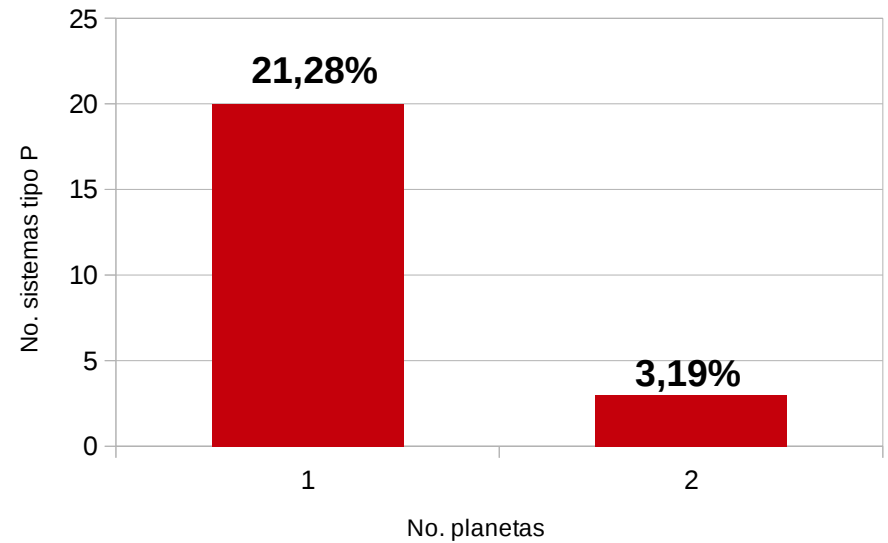
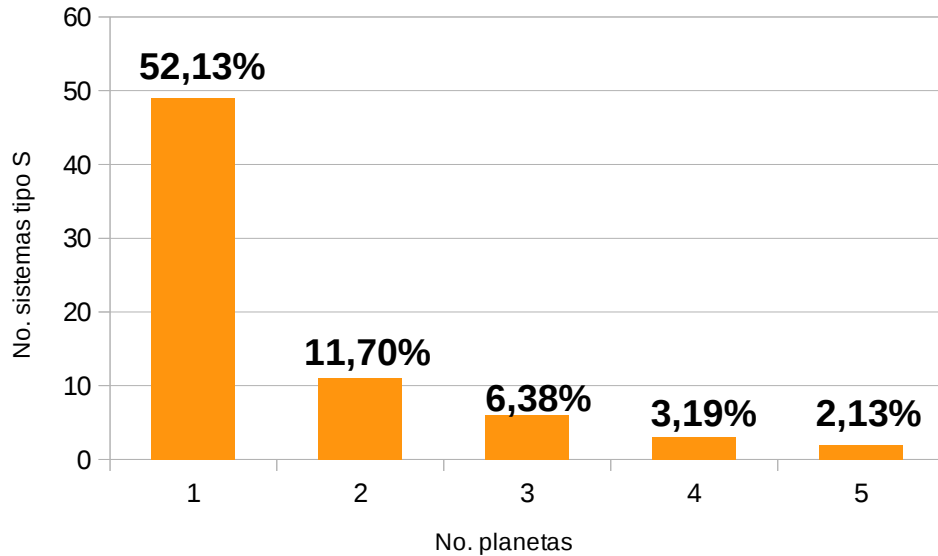


2013, 2017

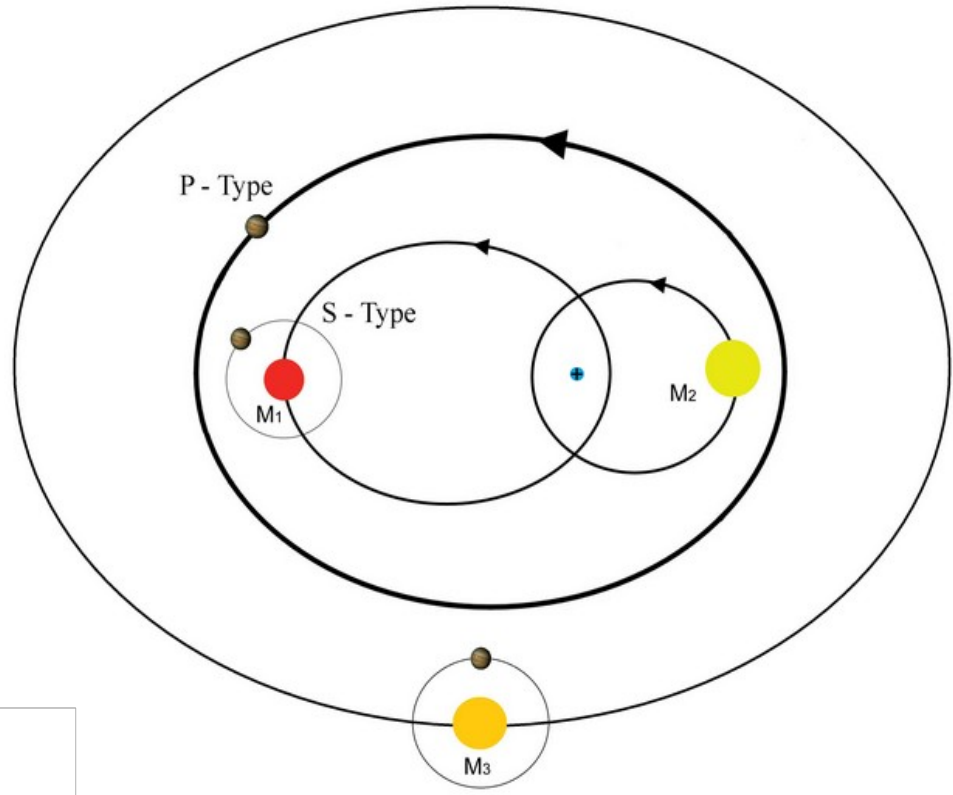
Total: **94** sistemas (www.univie.ac.at/adg/schwarz/multiple.html)



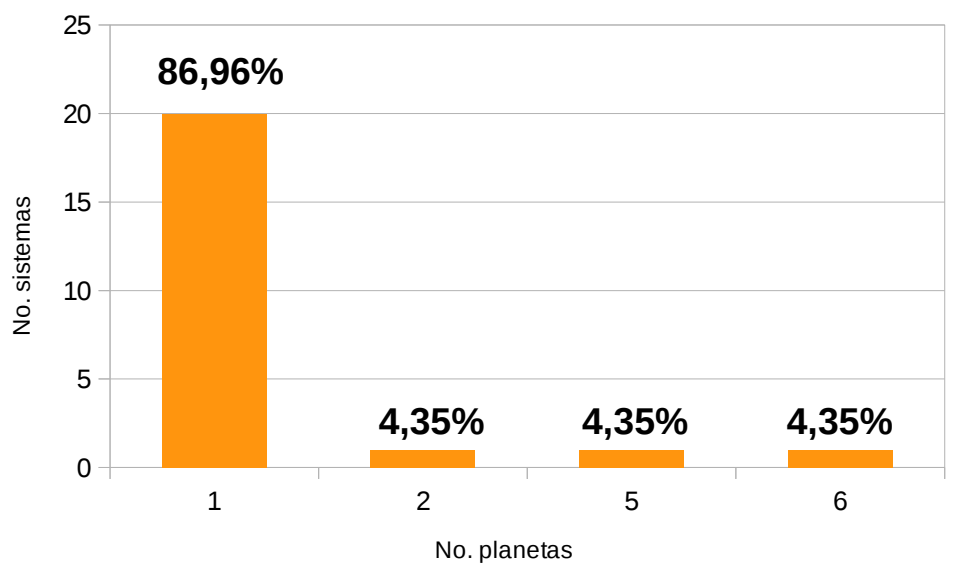
Schwarz et al. 2011



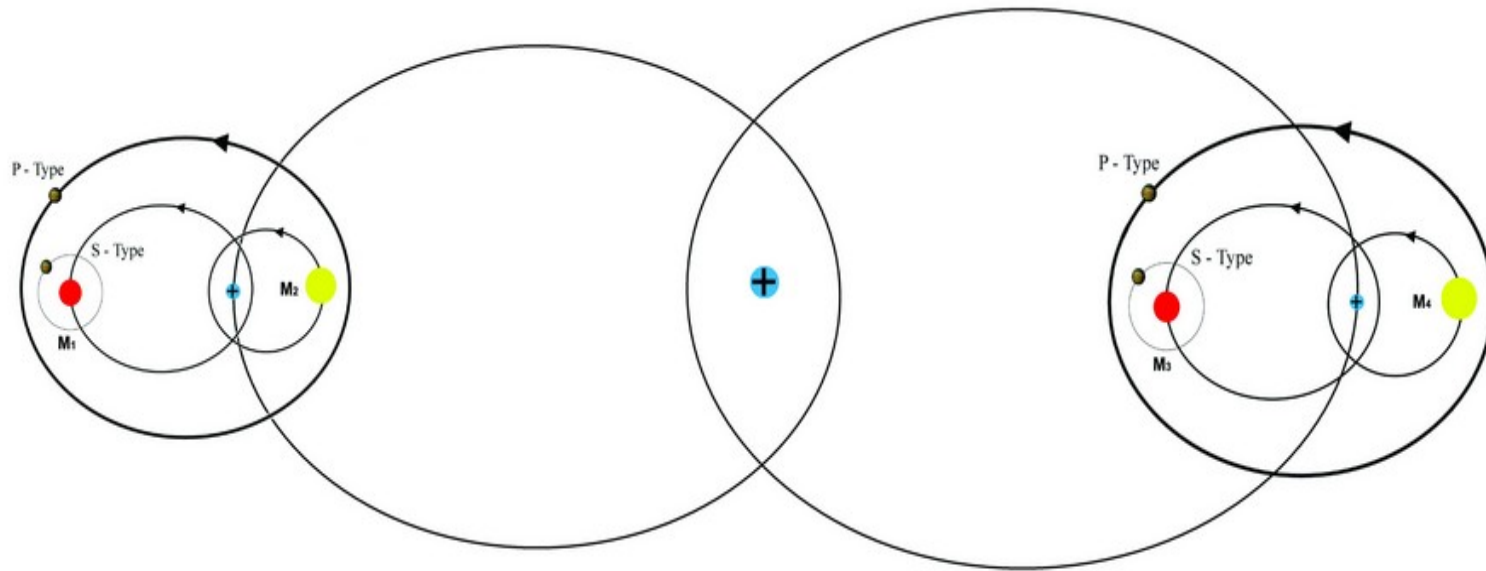
Total: **23** sistemas



Schwarz et al. 2011



Total: **2** sistemas de 1 planeta



Schwarz et al. 2011

Resultado:

Aprox. 96% dos exoplanetas confirmados pertencem a sistemas de 1 estrela, 3% a sistemas de binárias, e 1% a sistemas de estrela múltipla.