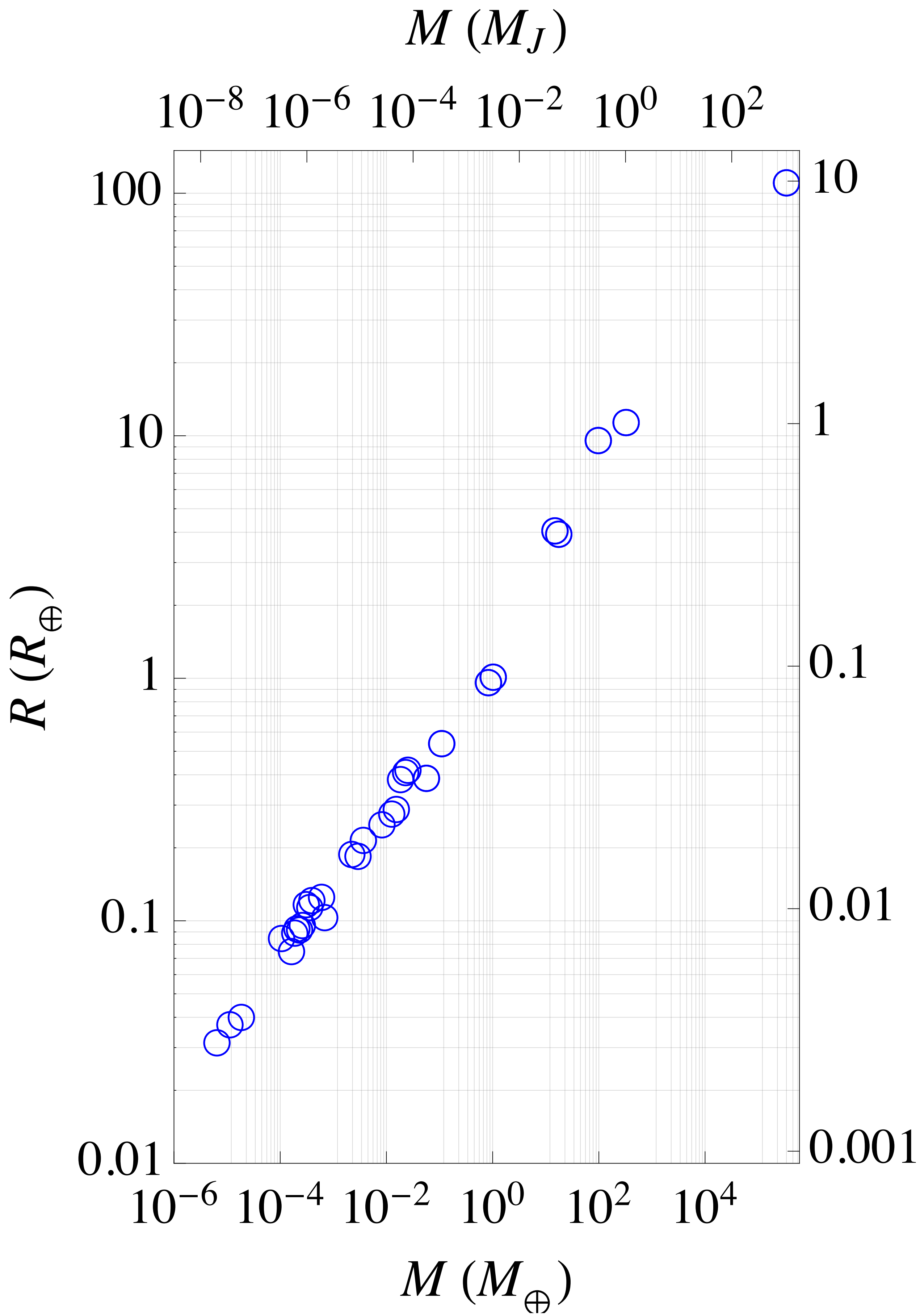
From Super-Earths to Brown Dwarfs: Who's Who? A perspective from the *Solar System*

Jérémy Leconte

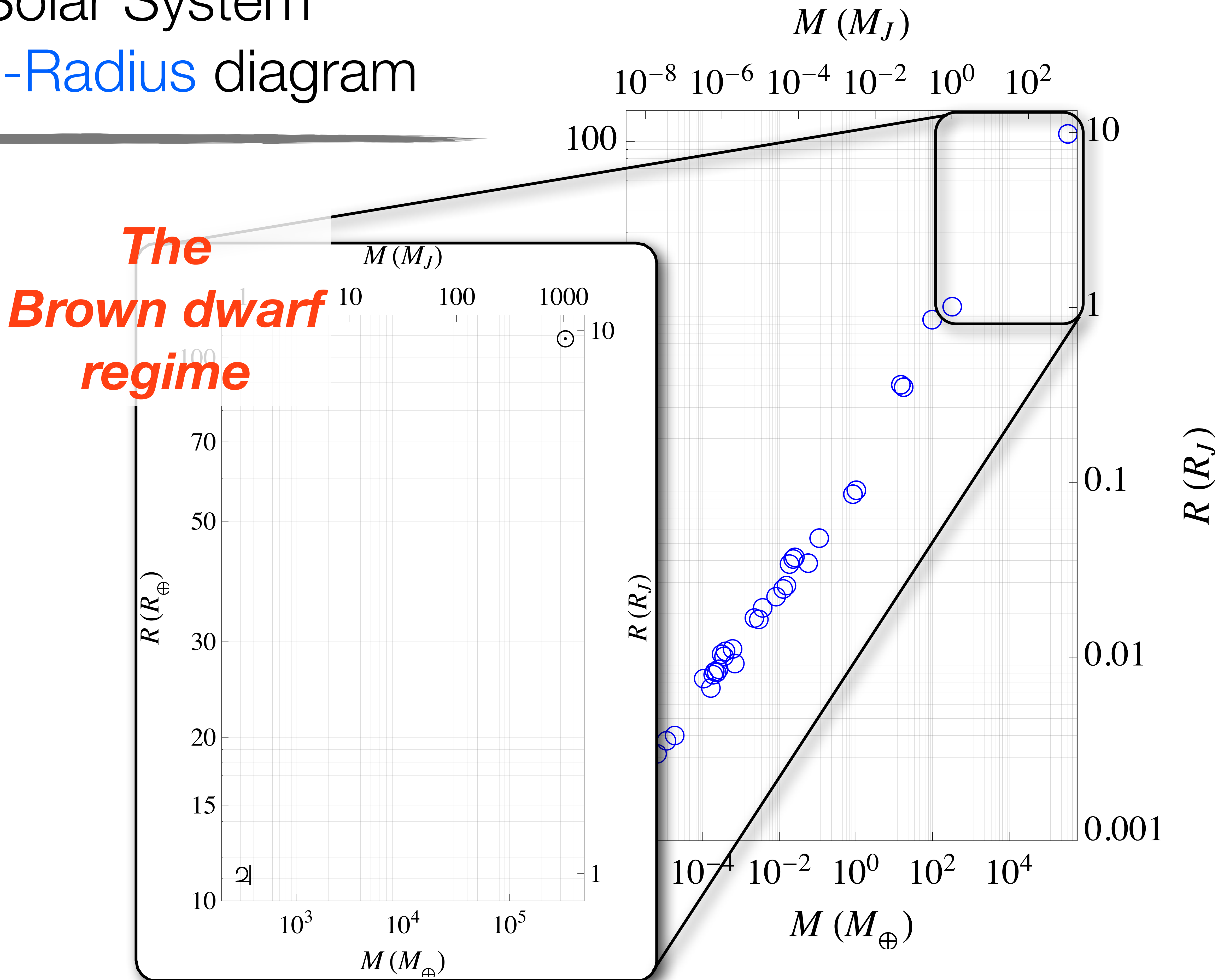
Bourses postdoctorales Banting Postdoctoral Fellowships

CITA–ICAT

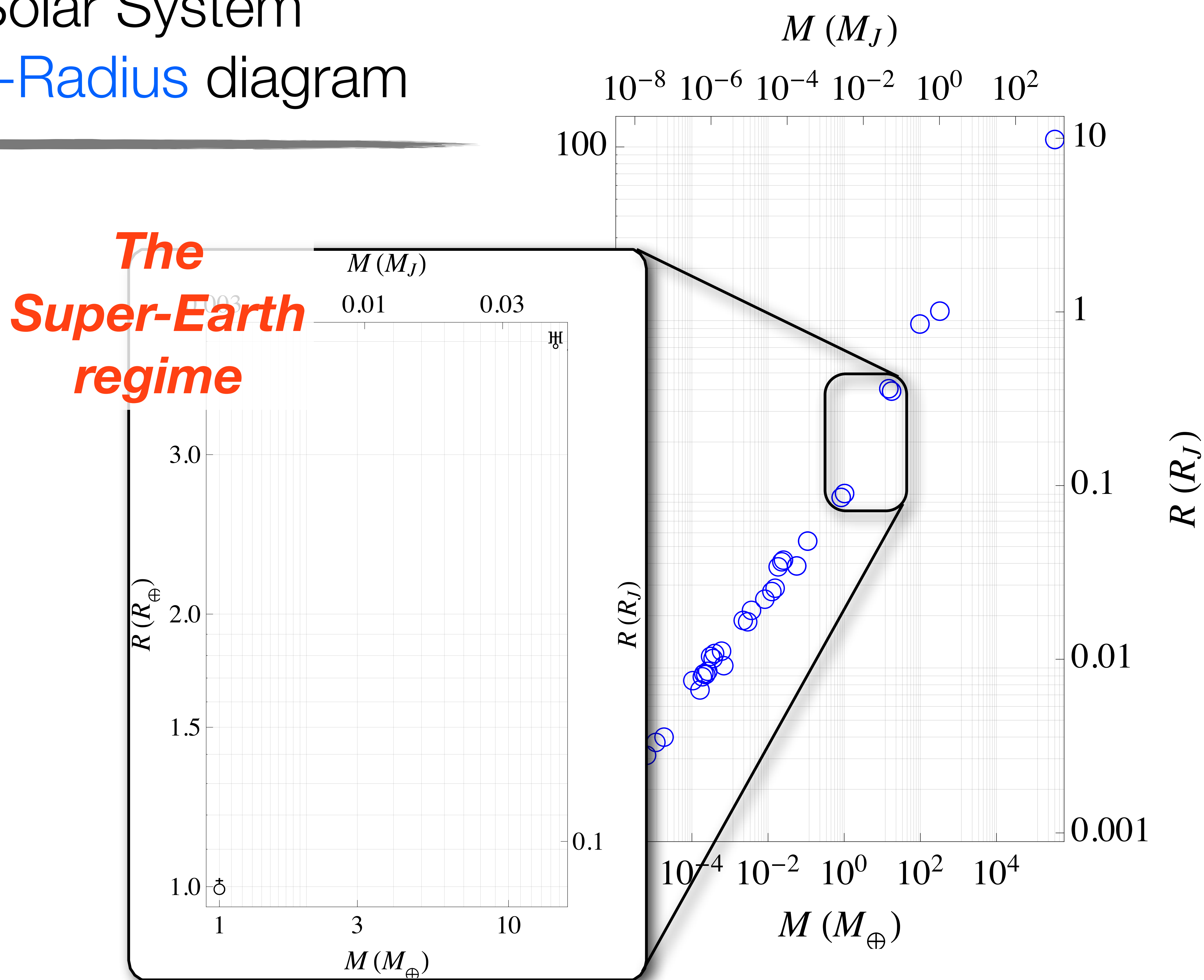
The Solar System
Mass-Radius diagram



The Solar System
Mass-Radius diagram



The Solar System
Mass-Radius diagram



From Super-Earths to Brown Dwarfs: Who's Who? A perspective from the *Solar System*

Jérémy Leconte

Bourses postdoctorales Banting Postdoctoral Fellowships

CITA–ICAT

Who's who:
Does living in the Solar System mislead us?

Jérémy Leconte

Bourses postdoctorales
Banting
Postdoctoral Fellowships

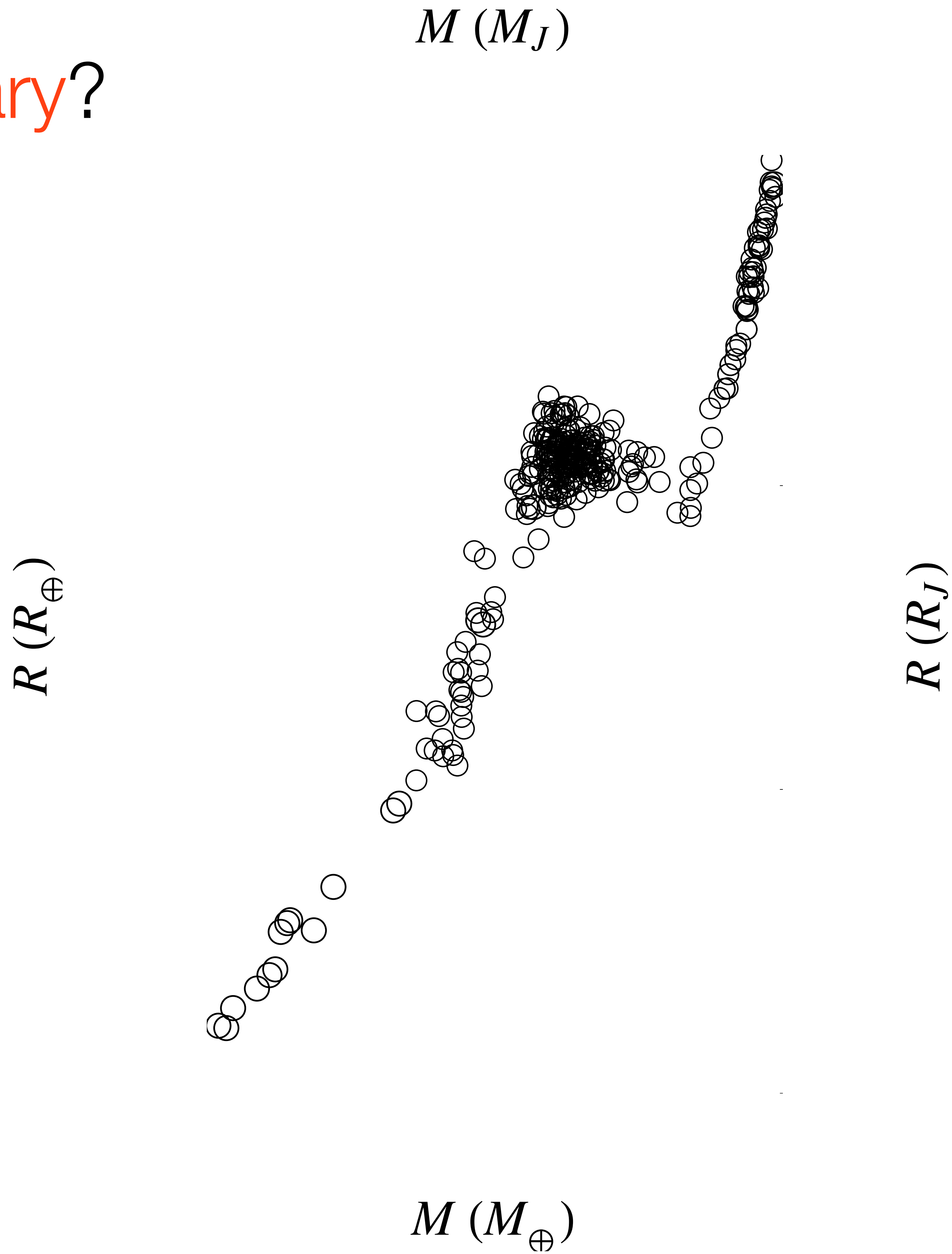
CITA–ICAT

Mass-Radius diagram:
Is there any clear boundary?

- Earth-mass
- Super-Earths
- Mini-Neptunes
- Ice giants
- Gas Giants
- Super-Jupiters
- Brown Dwarfs

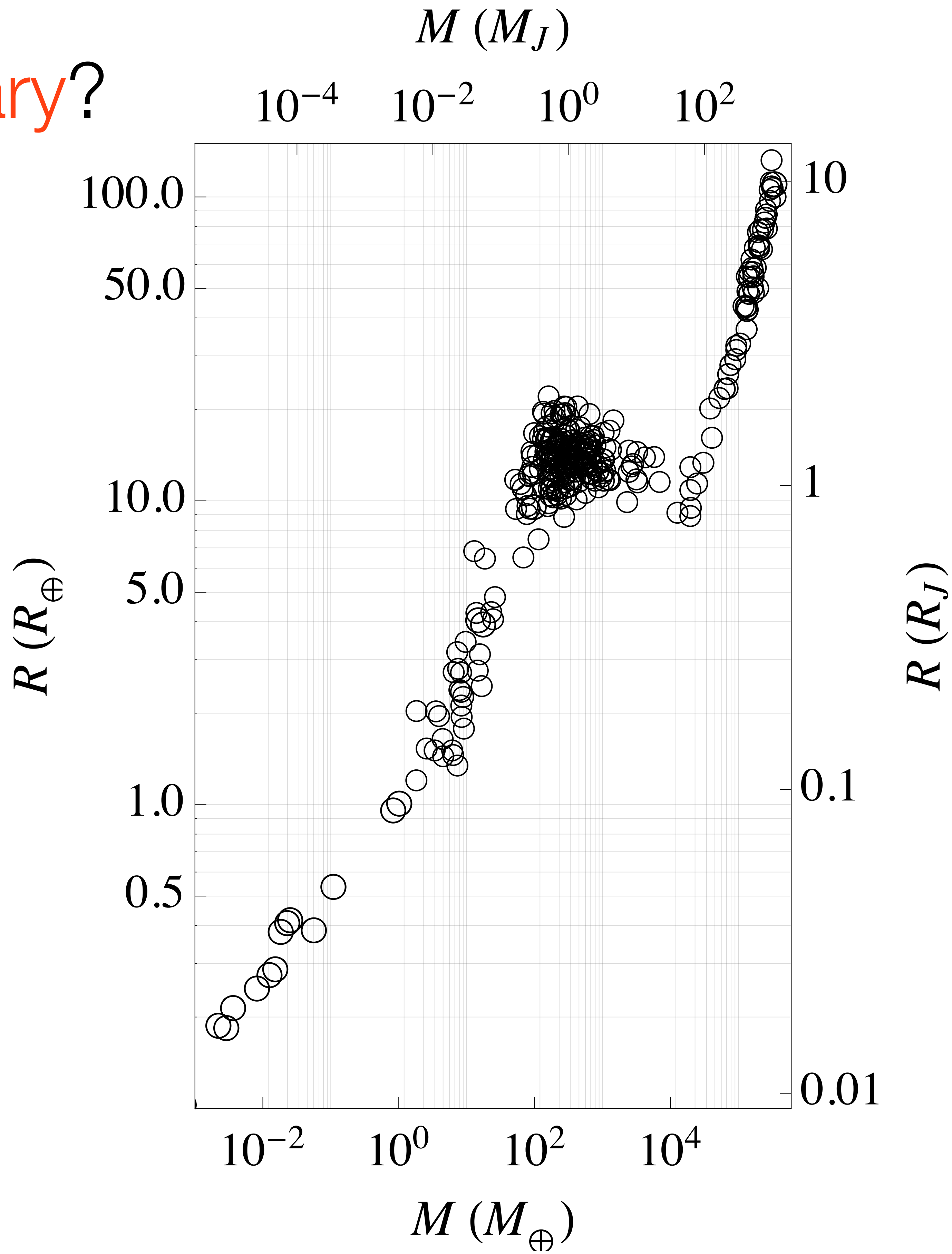
Mass-Radius diagram:
Is there any clear boundary?

- Earth-mass
- Super-Earths
- Mini-Neptunes
- Ice giants
- Gas Giants
- Super-Jupiters
- Brown Dwarfs

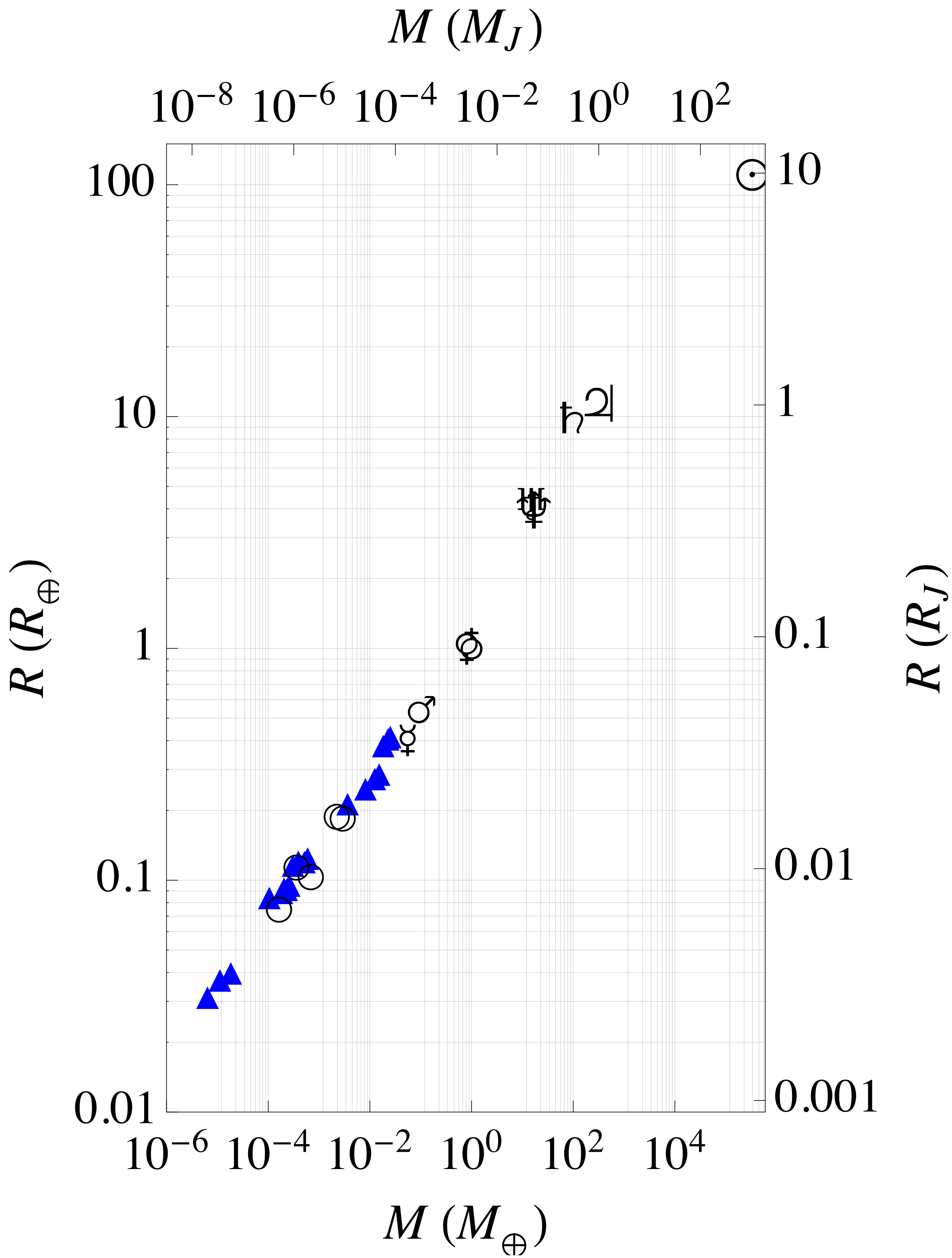


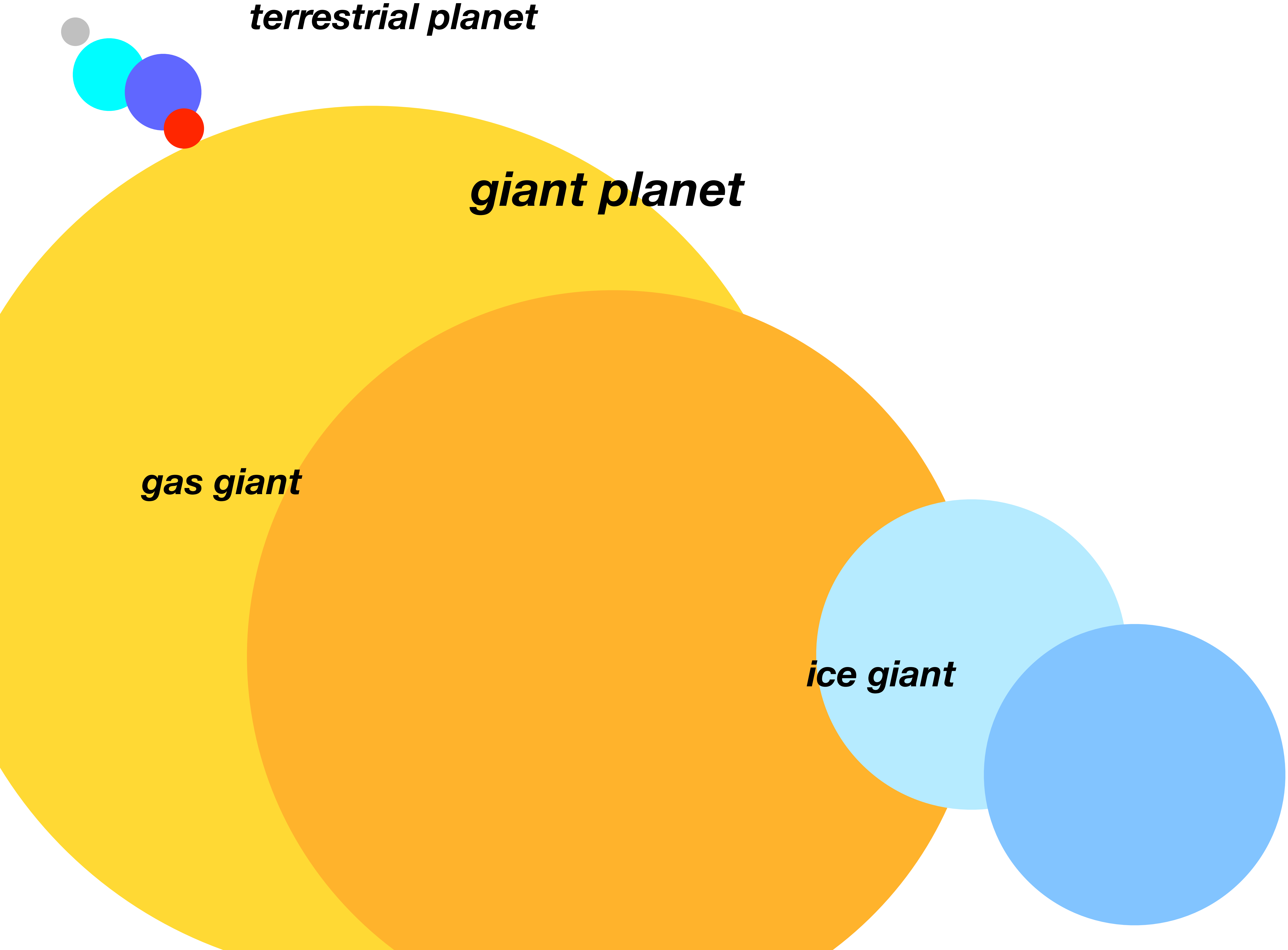
Mass-Radius diagram:
Is there any clear boundary?

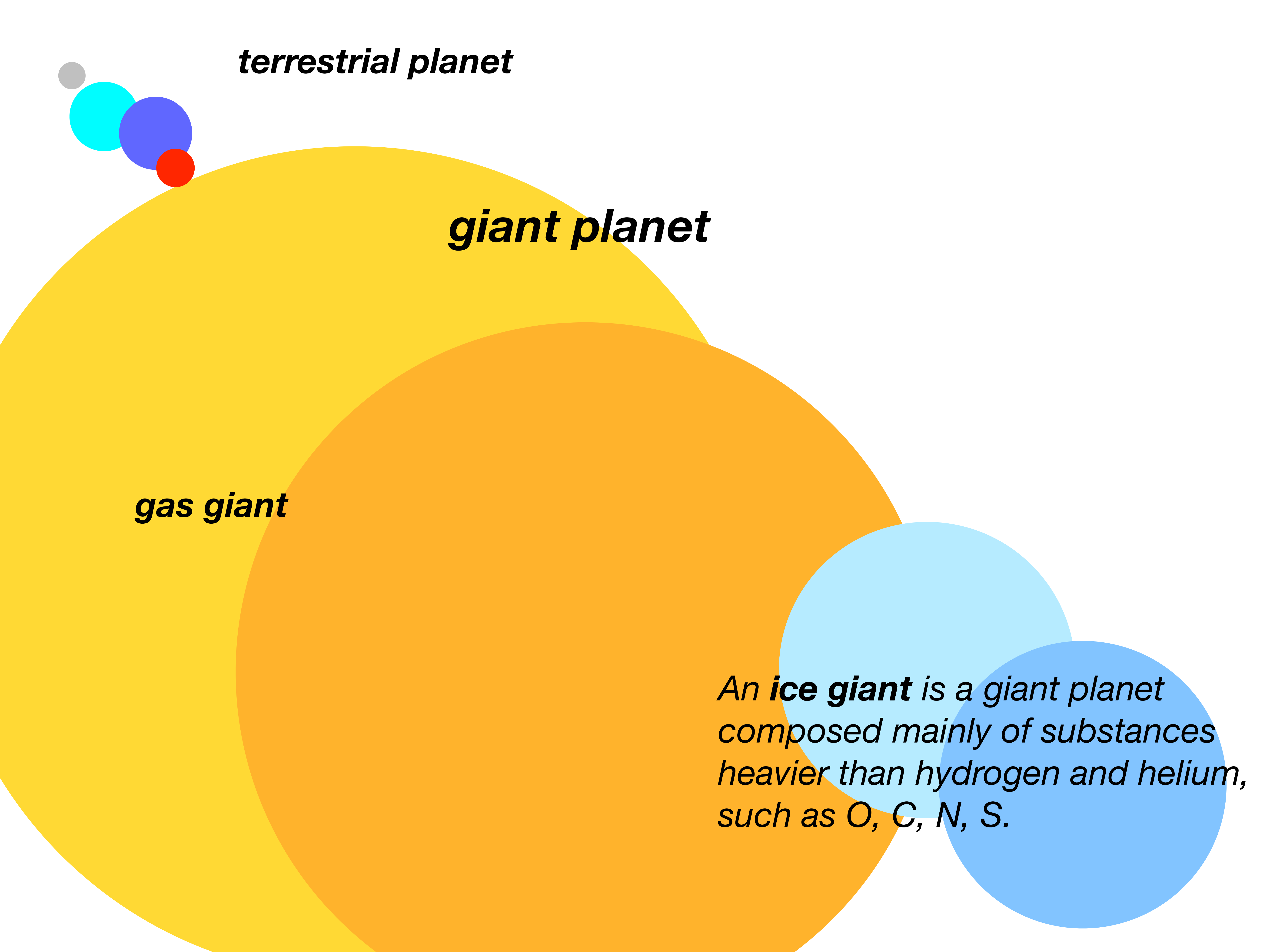
- Earth-mass
- Super-Earths
- Mini-Neptunes
- Ice giants
- Gas Giants
- Super-Jupiters
- Brown Dwarfs

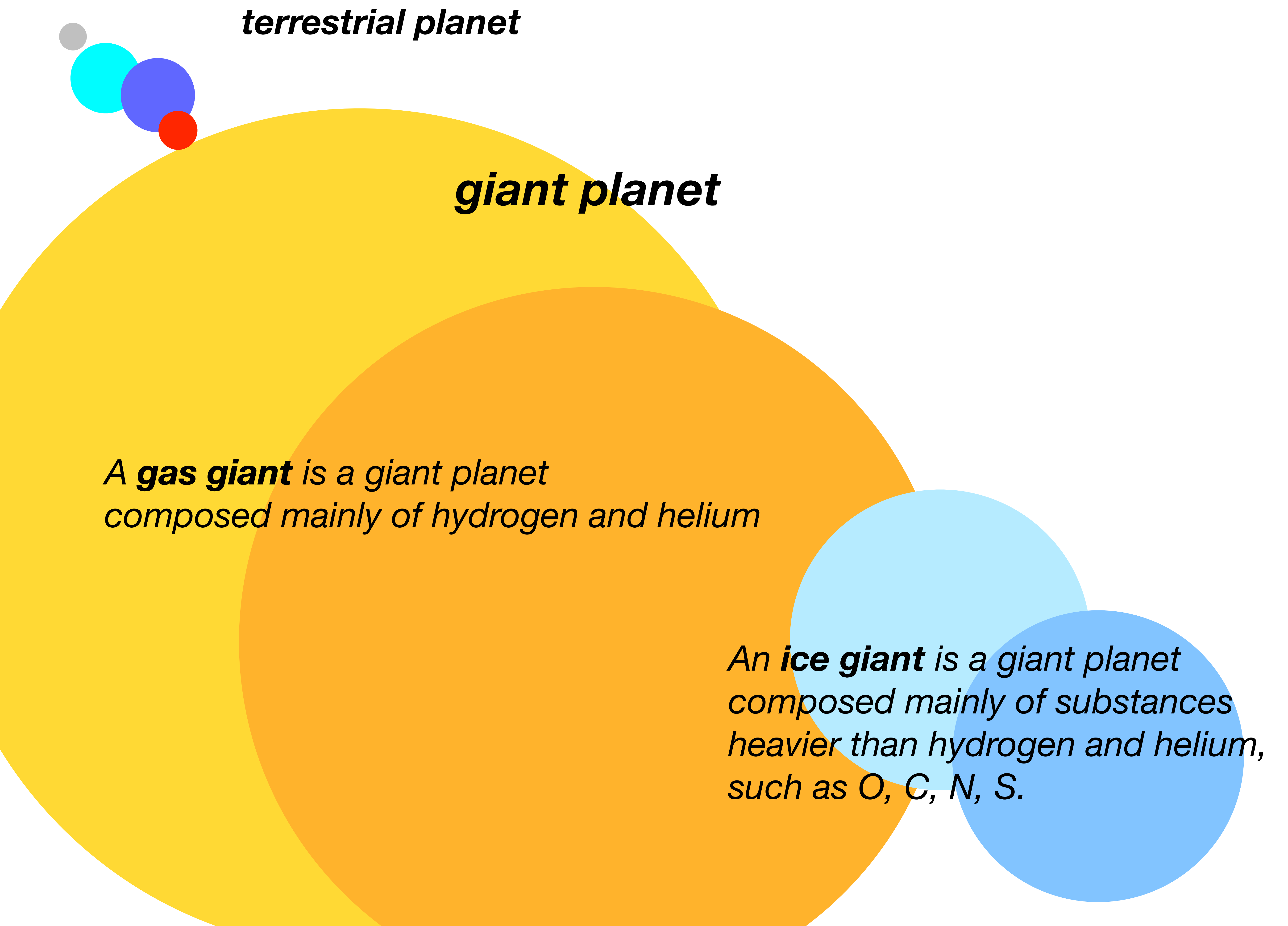


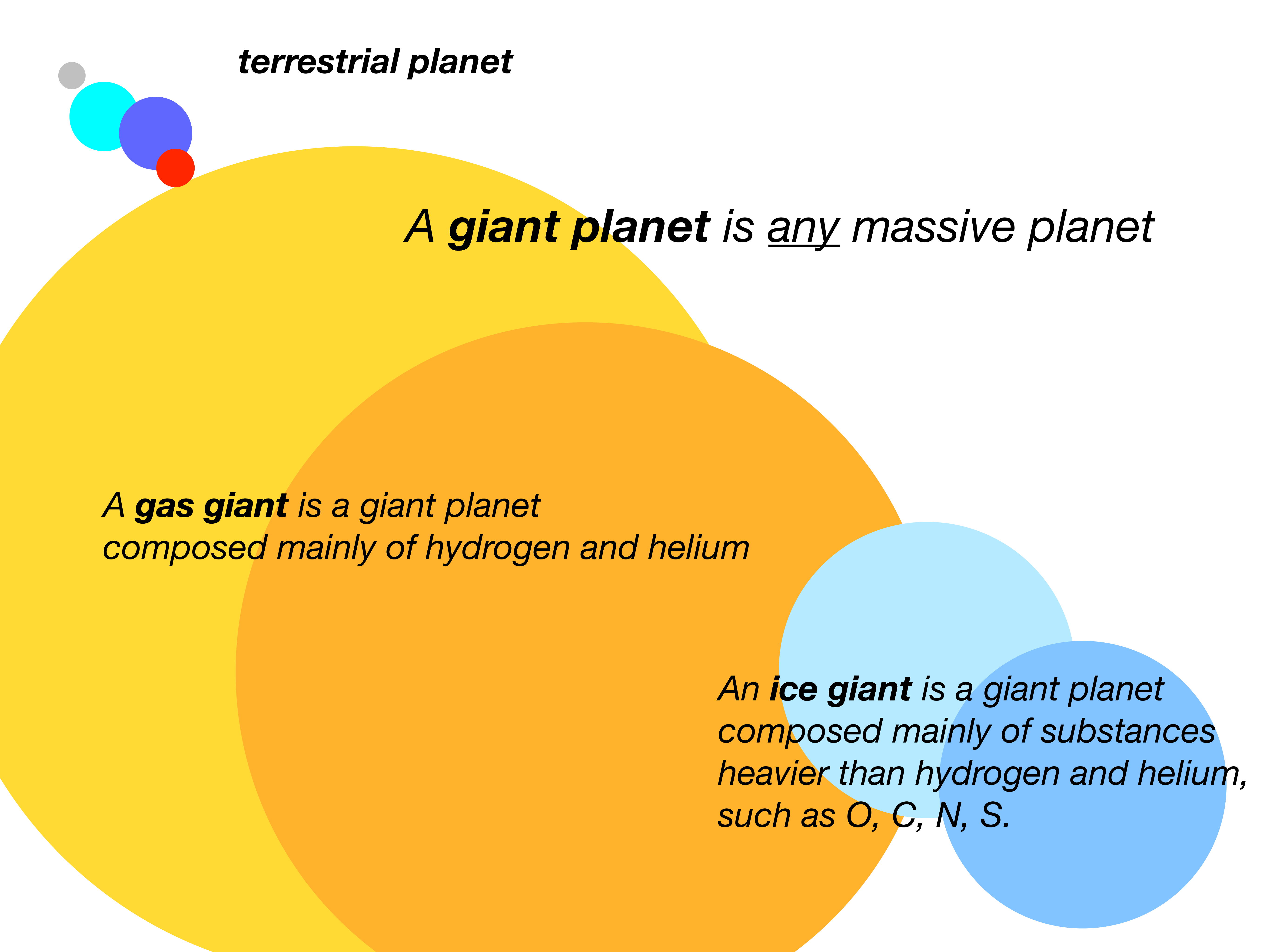
So, where do these definitions come from?



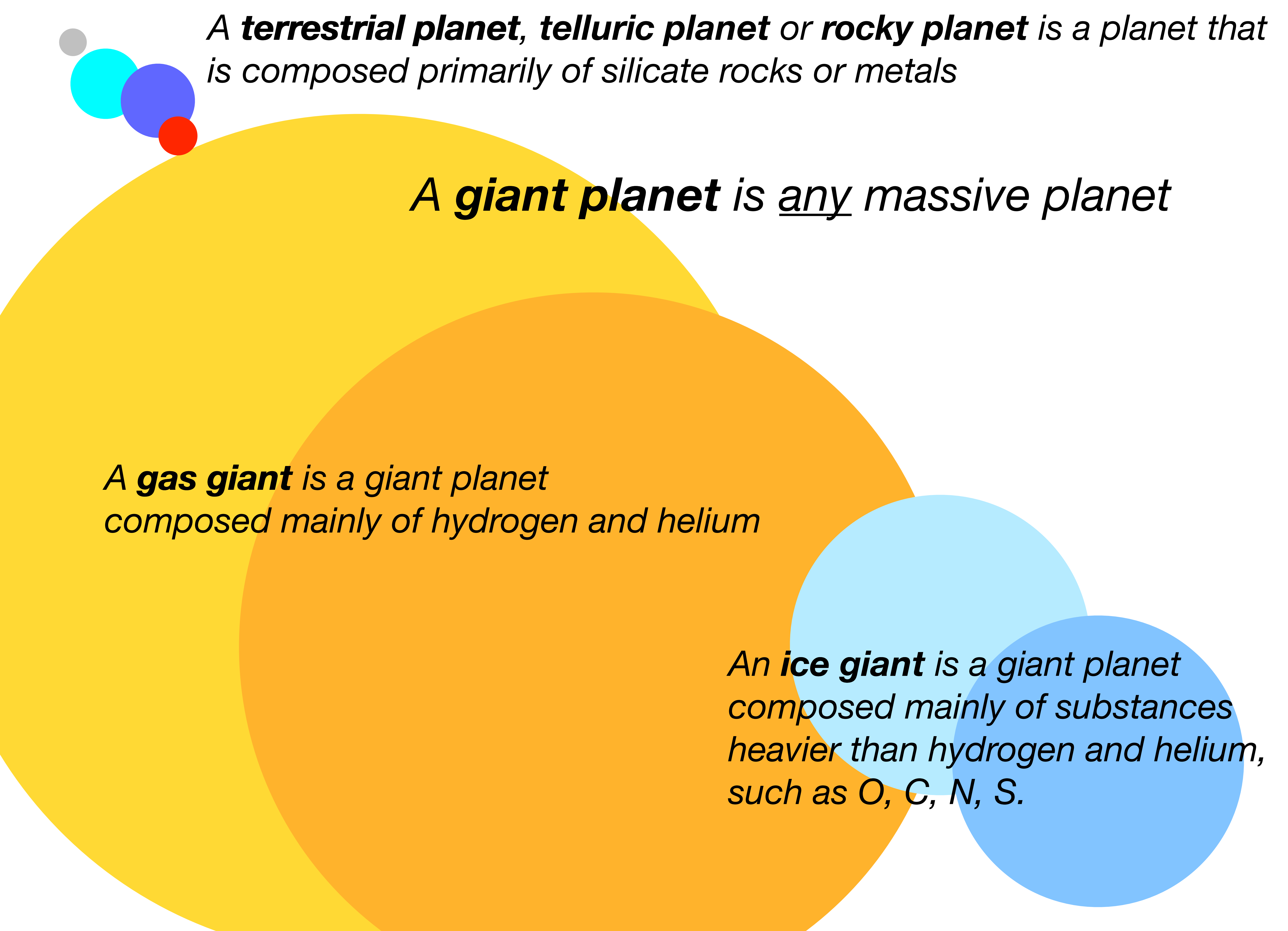

terrestrial planet
giant planet
gas giant
ice giant


terrestrial planet
giant planet
gas giant
An **ice giant** is a giant planet composed mainly of substances heavier than hydrogen and helium, such as O, C, N, S.

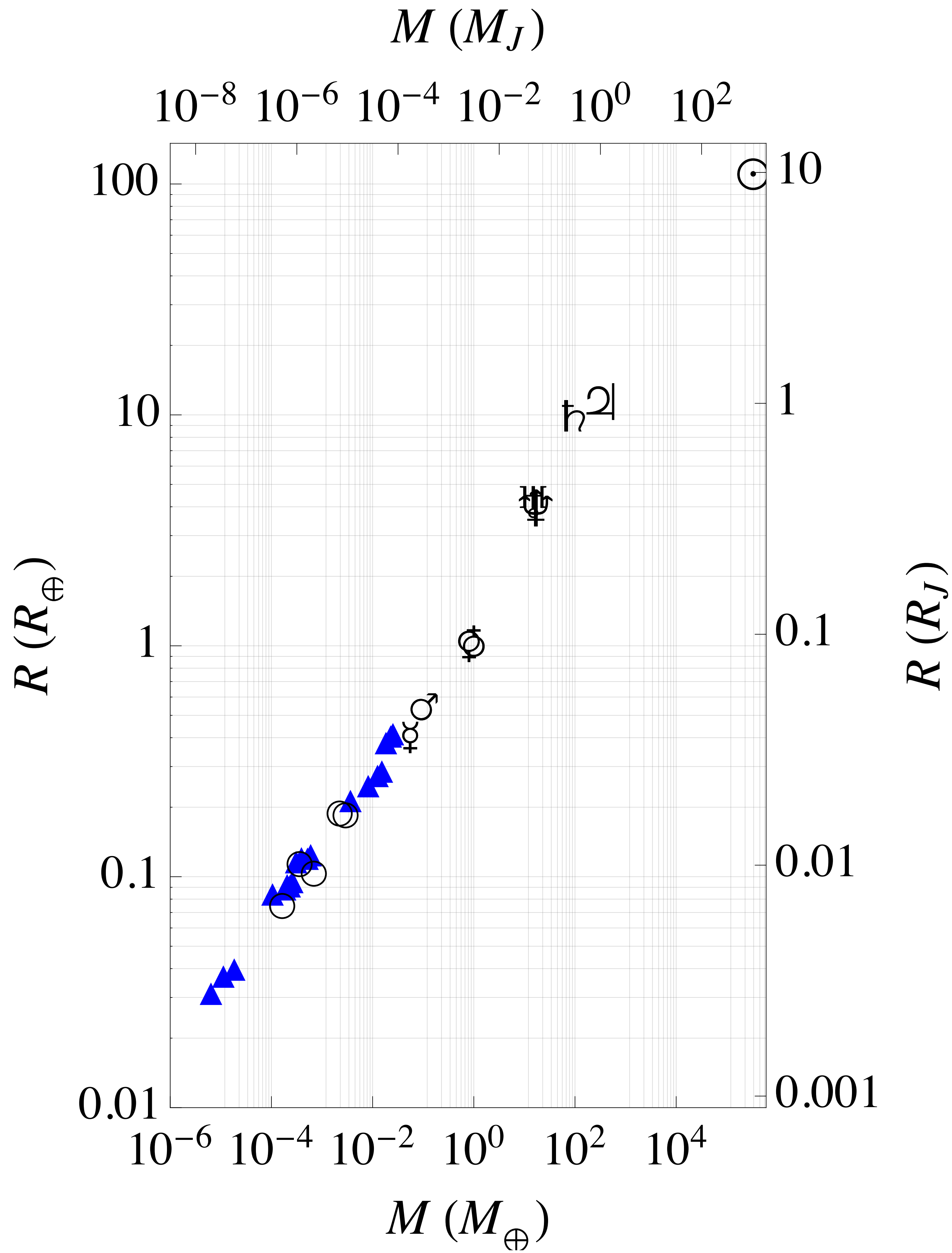

terrestrial planet
giant planet
A gas giant is a giant planet composed mainly of hydrogen and helium
An ice giant is a giant planet composed mainly of substances heavier than hydrogen and helium, such as O, C, N, S.



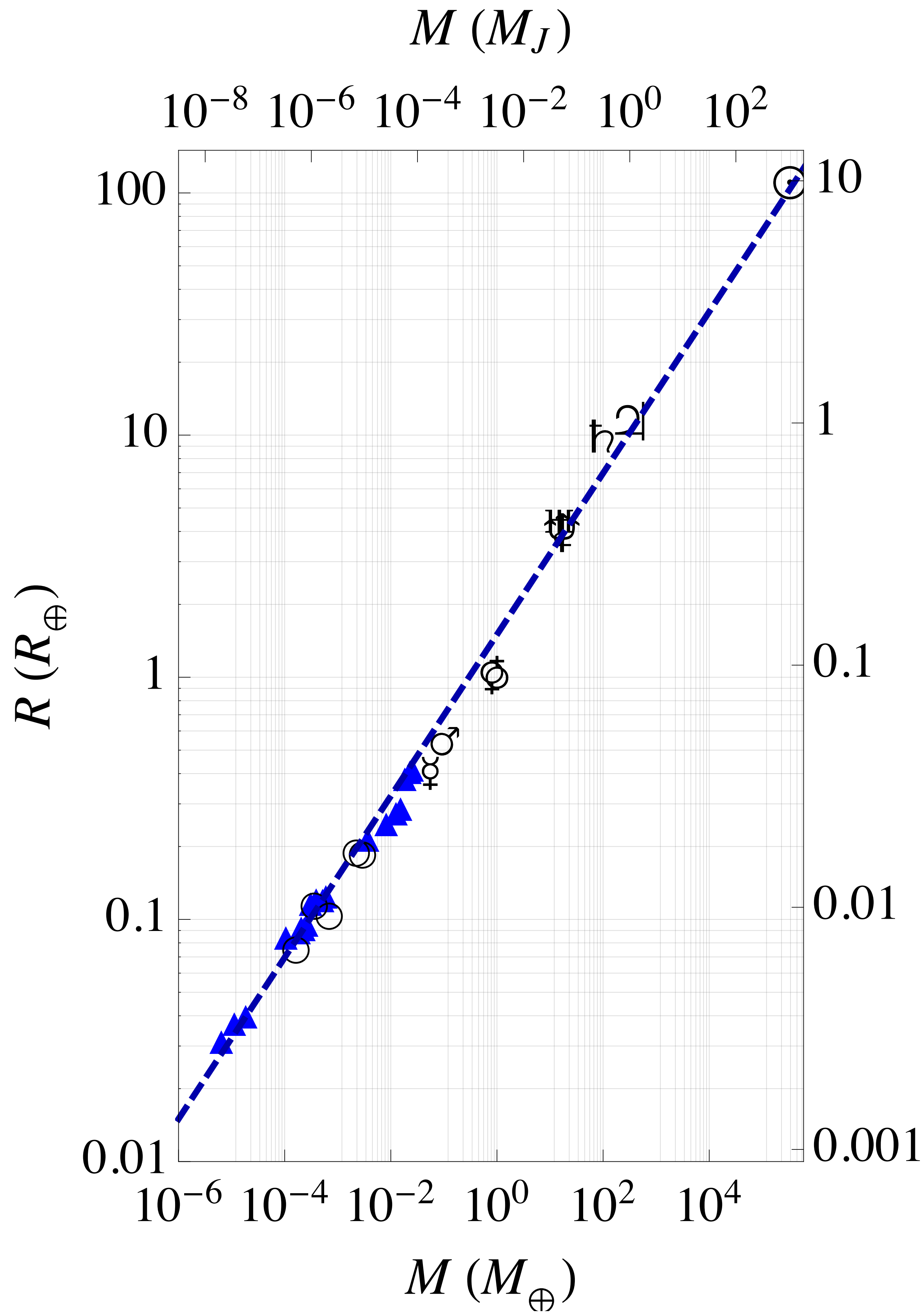
terrestrial planet
A giant planet is any massive planet
A gas giant is a giant planet composed mainly of hydrogen and helium
An ice giant is a giant planet composed mainly of substances heavier than hydrogen and helium, such as O, C, N, S.


A terrestrial planet, telluric planet or rocky planet is a planet that is composed primarily of silicate rocks or metals
A giant planet is any massive planet
A gas giant is a giant planet composed mainly of hydrogen and helium
An ice giant is a giant planet composed mainly of substances heavier than hydrogen and helium, such as O, C, N, S.

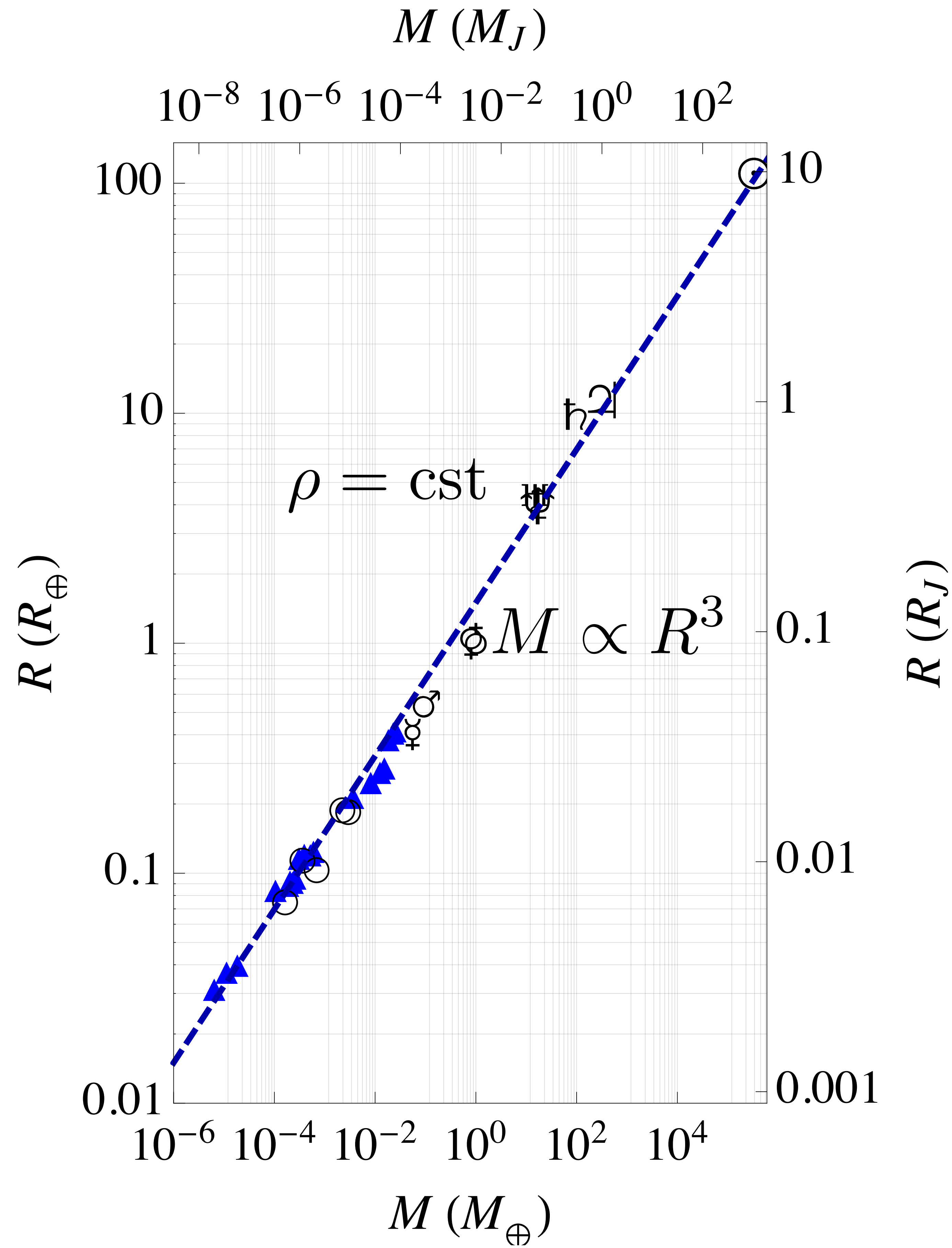
Is there a more rigorous physical basis



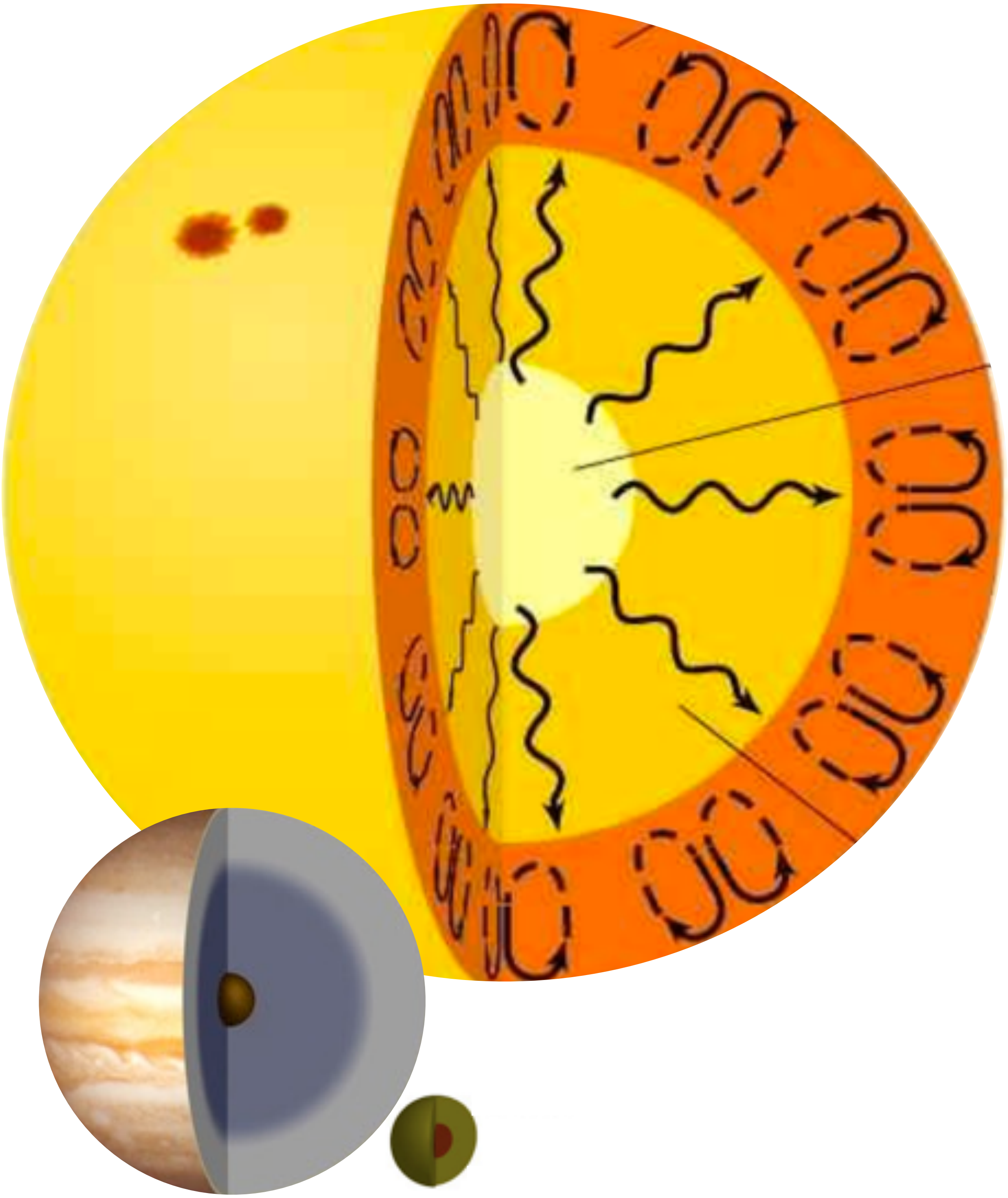
Is there a more rigorous physical basis



Is there a more rigorous physical basis



(Sub)stellar evolution equations

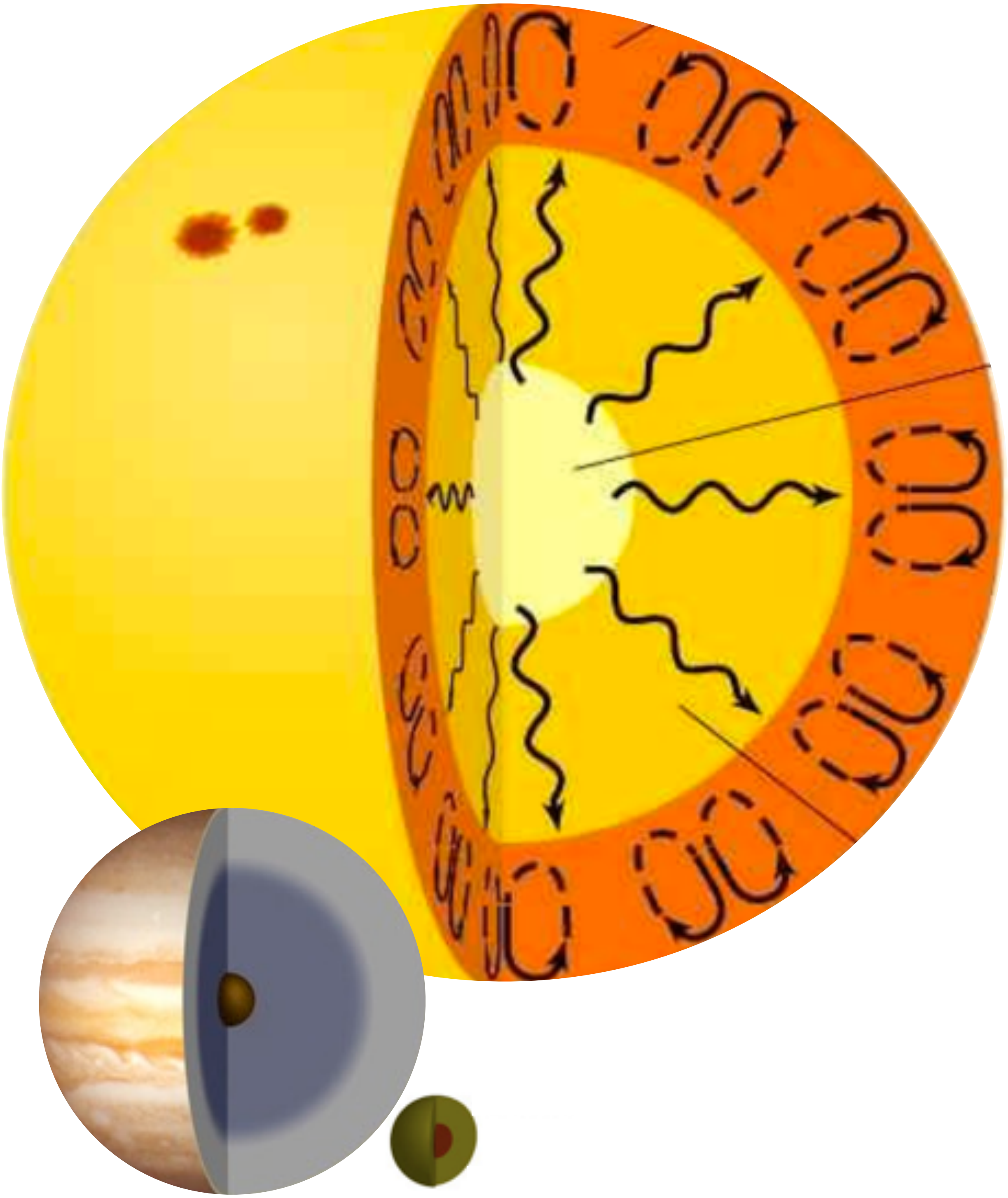


$$\frac{\partial r}{\partial m} = -\frac{1}{4\pi r^2 \rho}$$

$$\frac{\partial P}{\partial m} = -\frac{G m(r)}{4\pi r^4}$$

$$\frac{\partial l}{\partial m} = \epsilon - T\frac{\partial S}{\partial t}$$

(Sub)stellar evolution equations

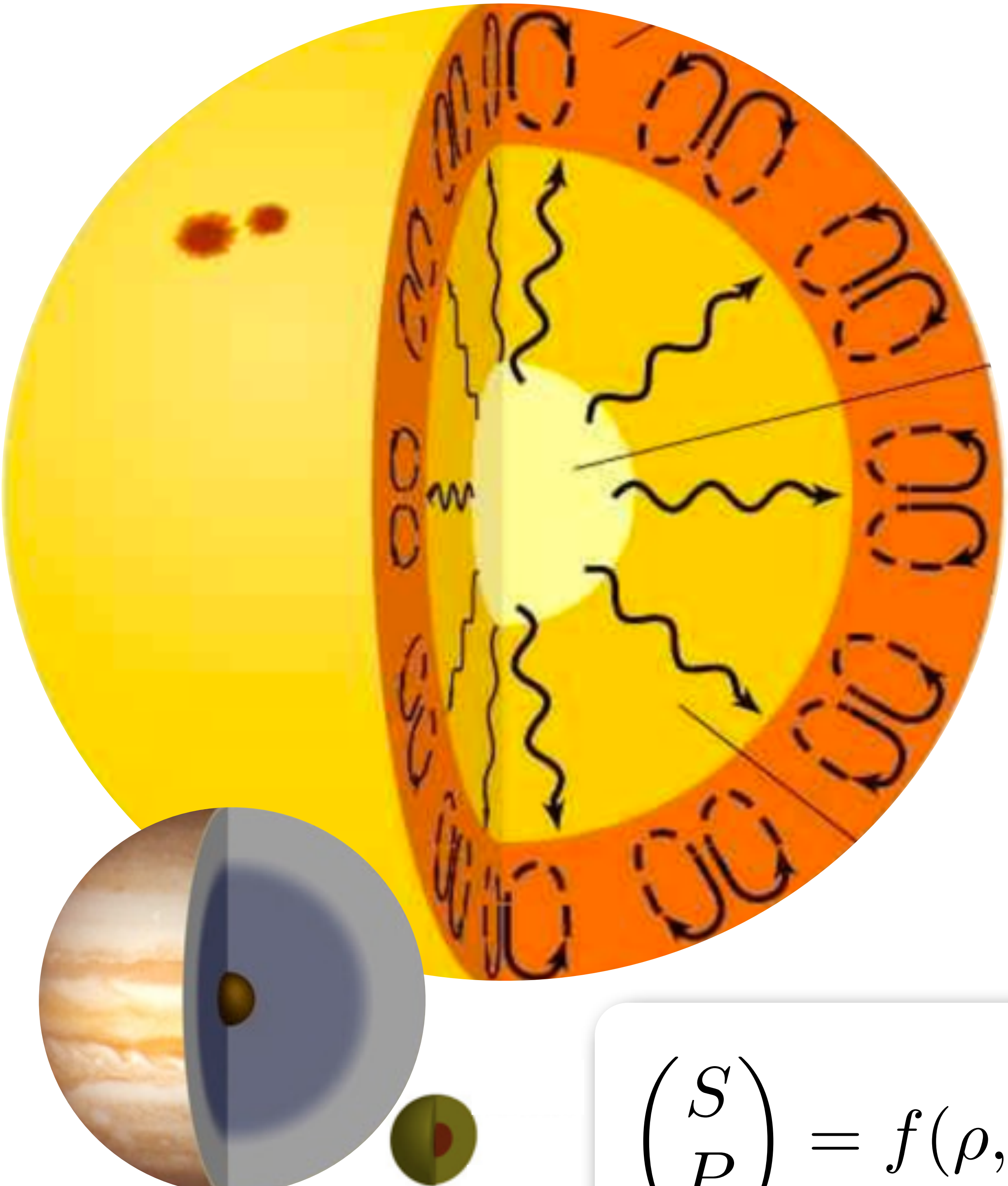


$$\frac{\partial r}{\partial m} = -\frac{1}{4\pi r^2 \rho}$$

$$\frac{\partial P}{\partial m} = -\frac{Gm(r)}{4\pi r^4}$$

$$\frac{\partial l}{\partial m} = \epsilon - T\frac{\partial S}{\partial t}$$

(Sub)stellar evolution equations



$$\frac{\partial r}{\partial m} = -\frac{1}{4\pi r^2 \rho}$$

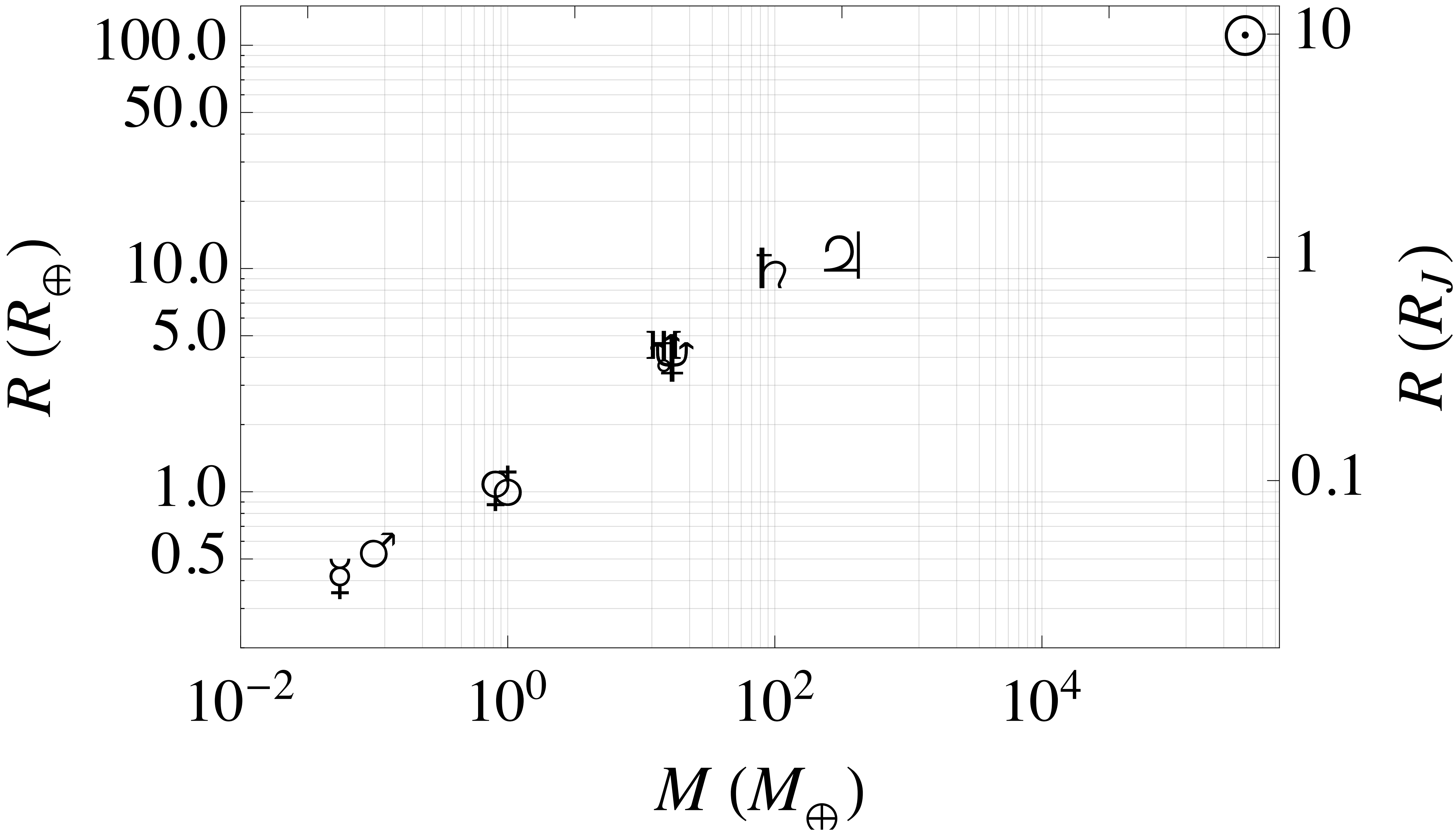
$$\frac{\partial P}{\partial m} = -\frac{Gm(r)}{4\pi r^4}$$

$$\frac{\partial l}{\partial m} = \epsilon - T\frac{\partial S}{\partial t}$$

$$\begin{pmatrix} S \\ P \end{pmatrix} = f(\rho, T) \qquad \frac{\partial \ln T}{\partial \ln P} = \nabla_T \qquad \epsilon = \chi(\rho, T)$$

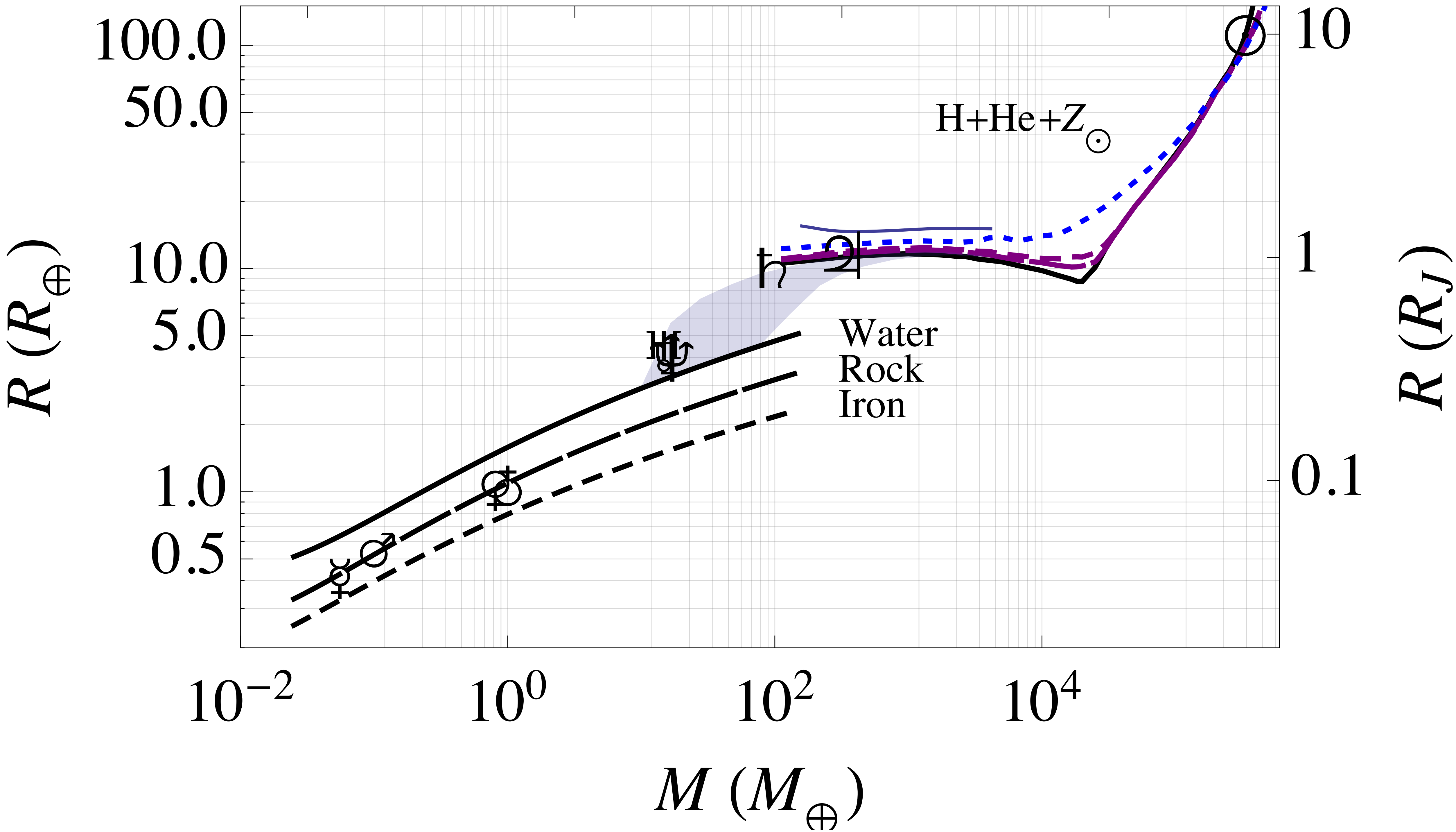
=> *Boundary conditions*

Mass-Radius diagram



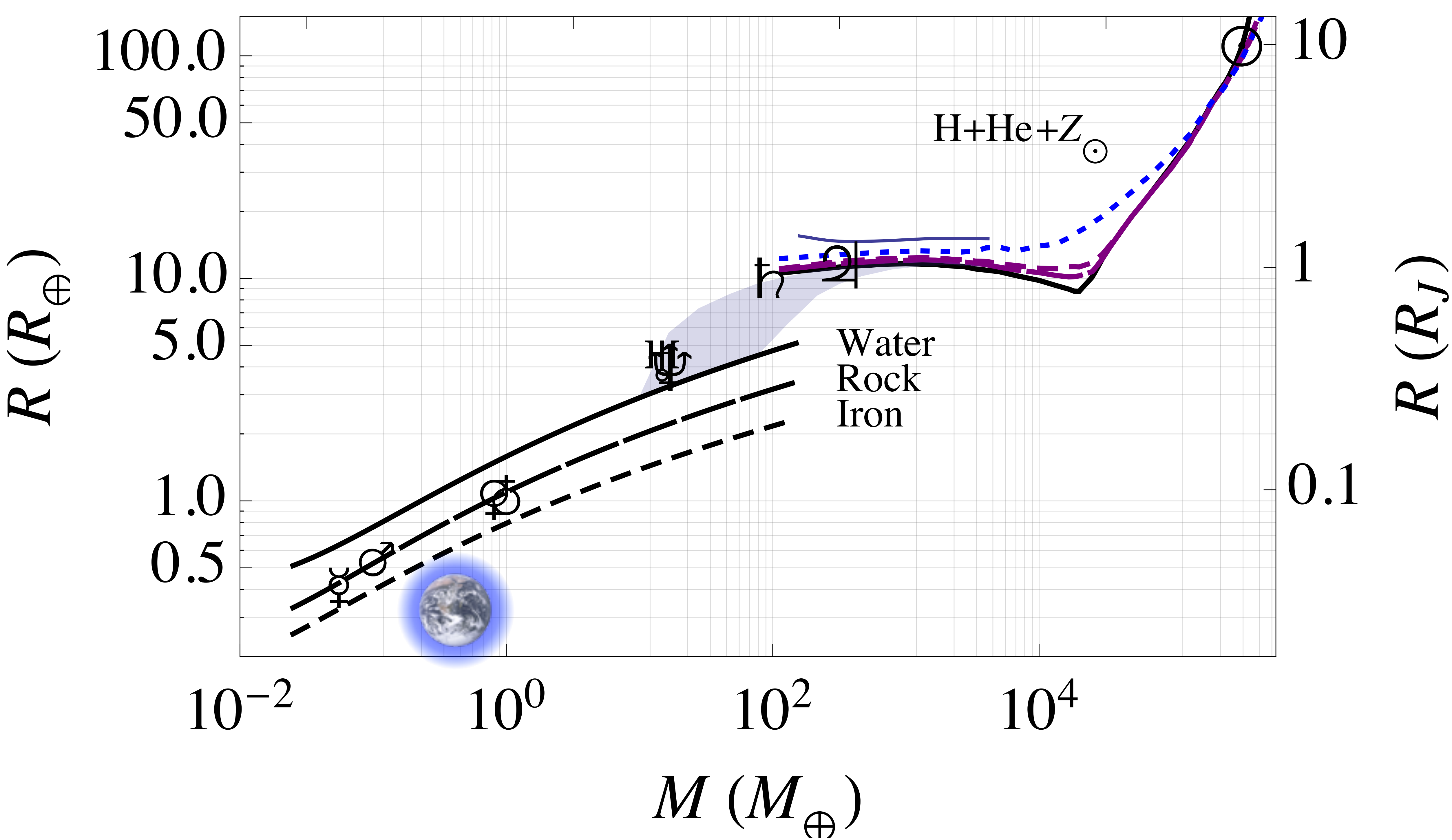
Zapolsky, Salpeter, Stevenson, Hubbard,
Chabrier, Baraffe, Guillot, Fortney, ...

Mass-Radius diagram



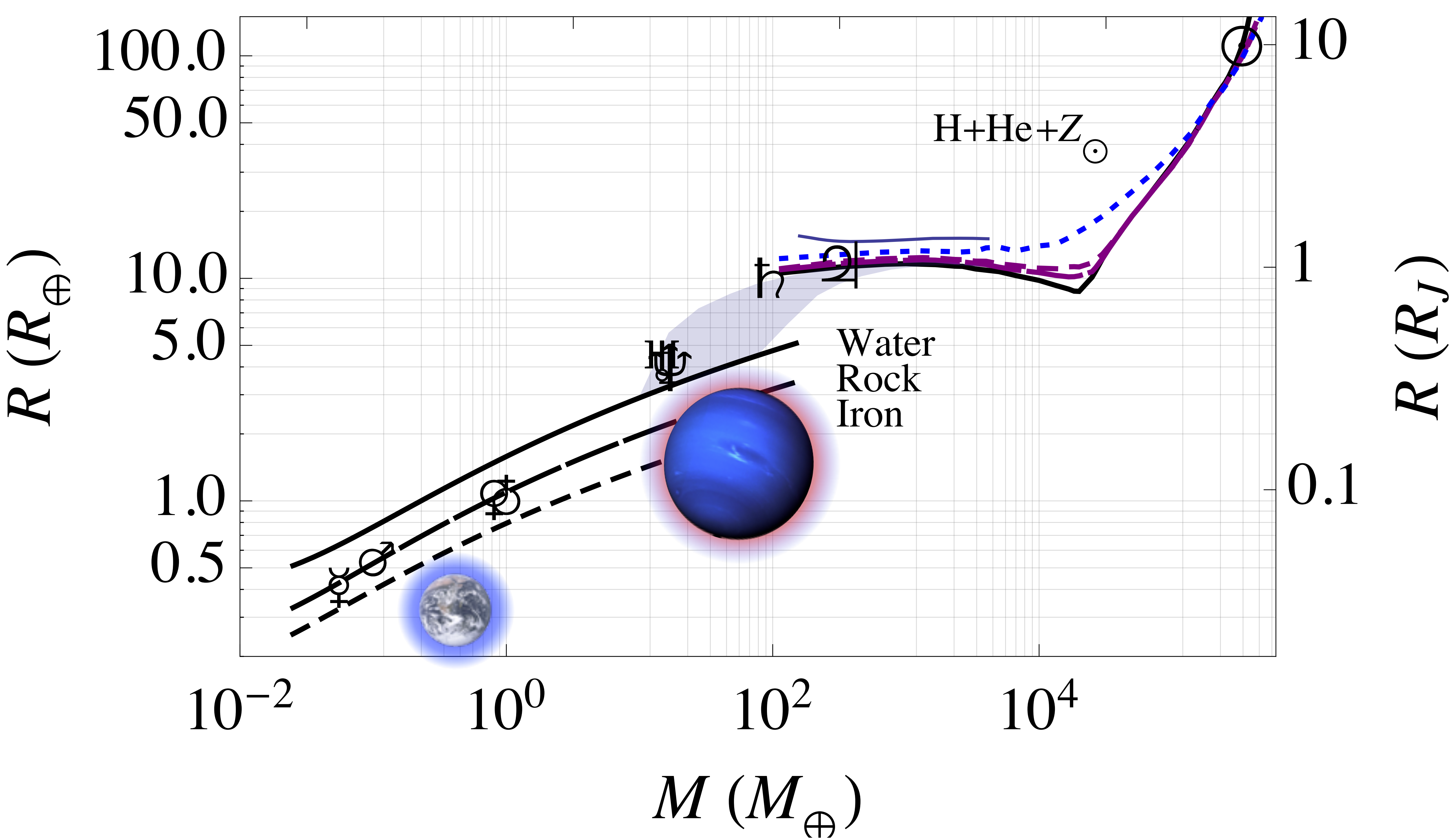
Zapolsky, Salpeter, Stevenson, Hubbard,
Chabrier, Baraffe, Guillot, Fortney, ...

Mass-Radius diagram



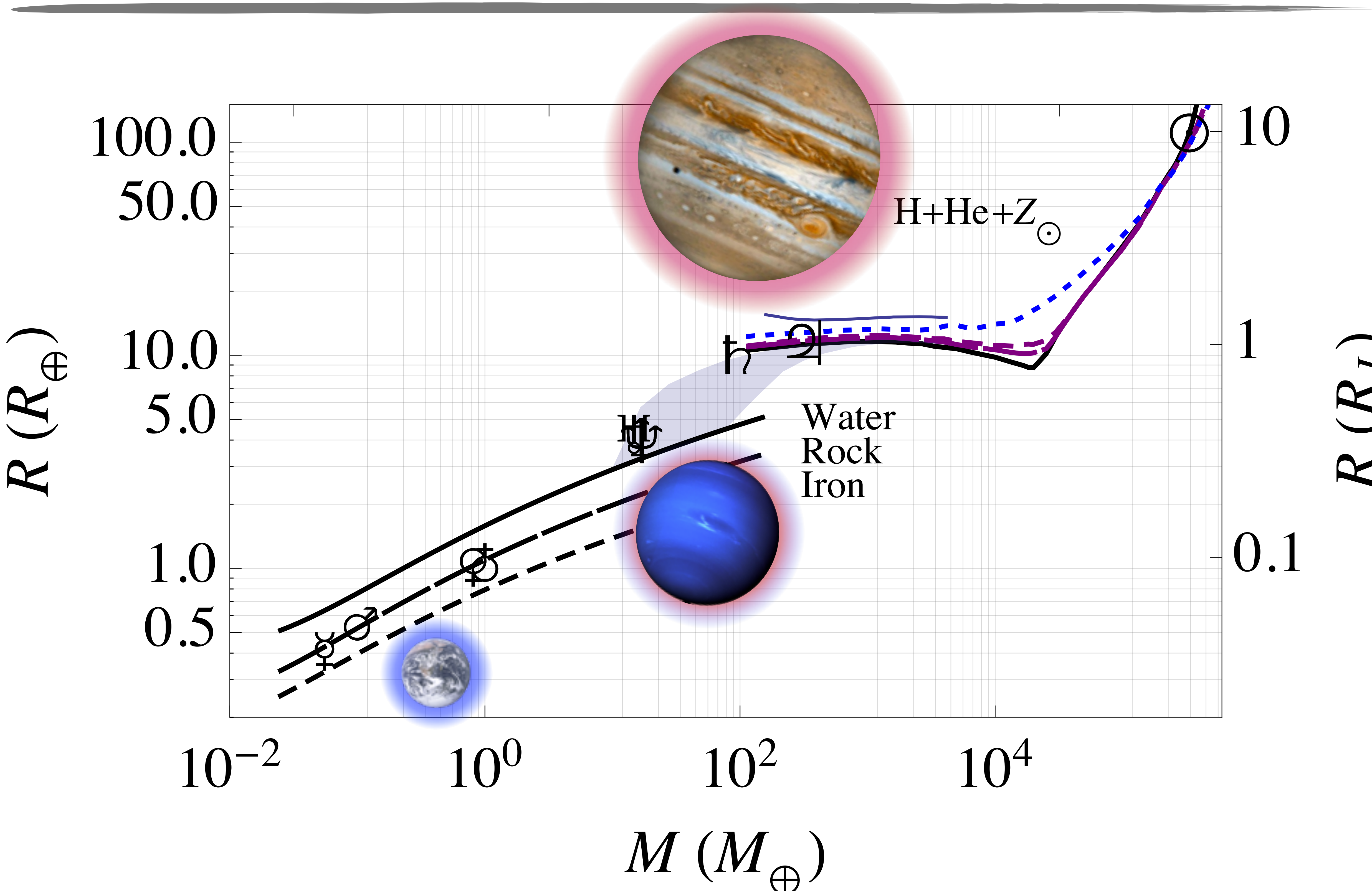
Zapolsky, Salpeter, Stevenson, Hubbard,
Chabrier, Baraffe, Guillot, Fortney, ...

Mass-Radius diagram



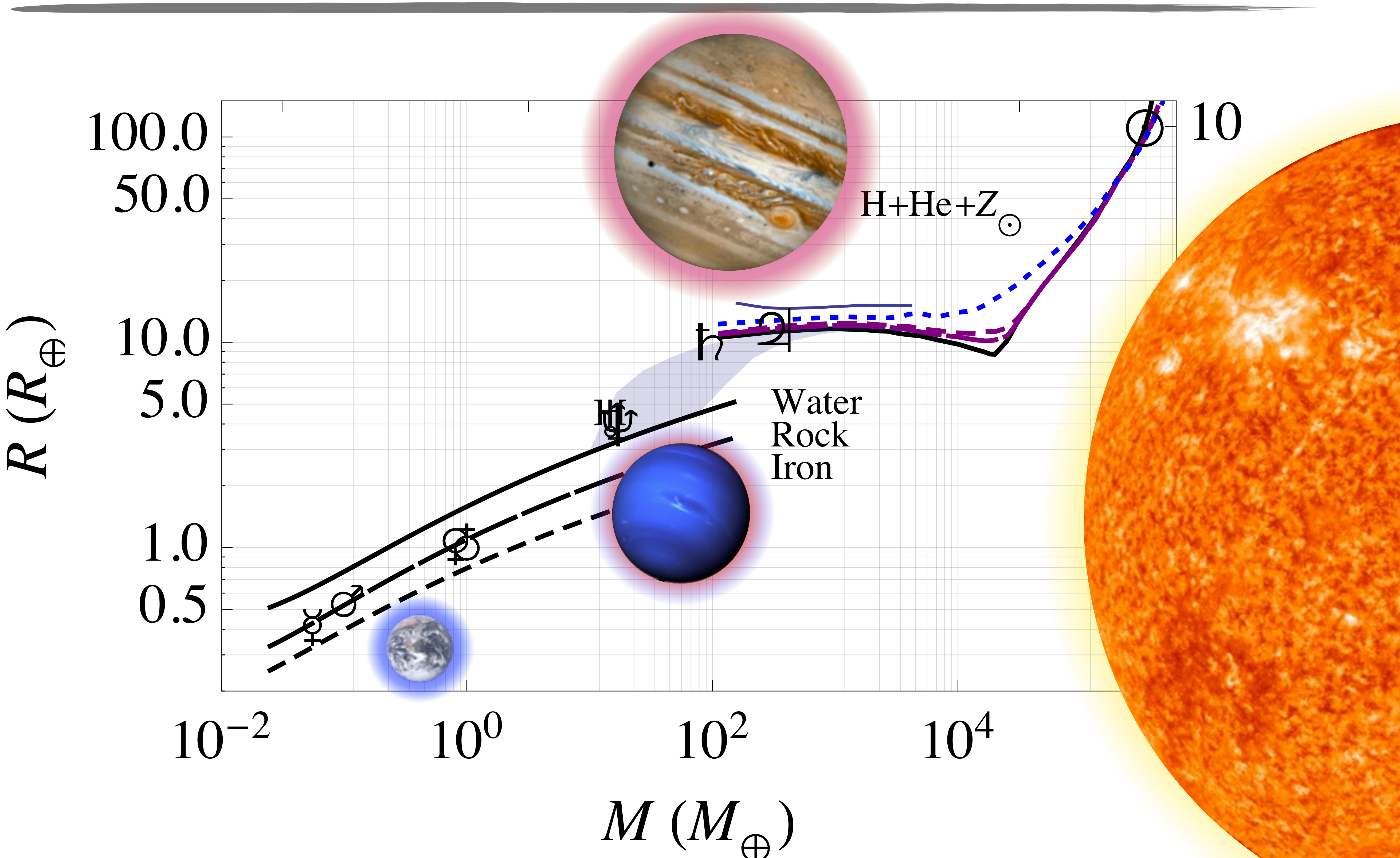
Zapolsky, Salpeter, Stevenson, Hubbard,
Chabrier, Baraffe, Guillot, Fortney, ...

Mass-Radius diagram



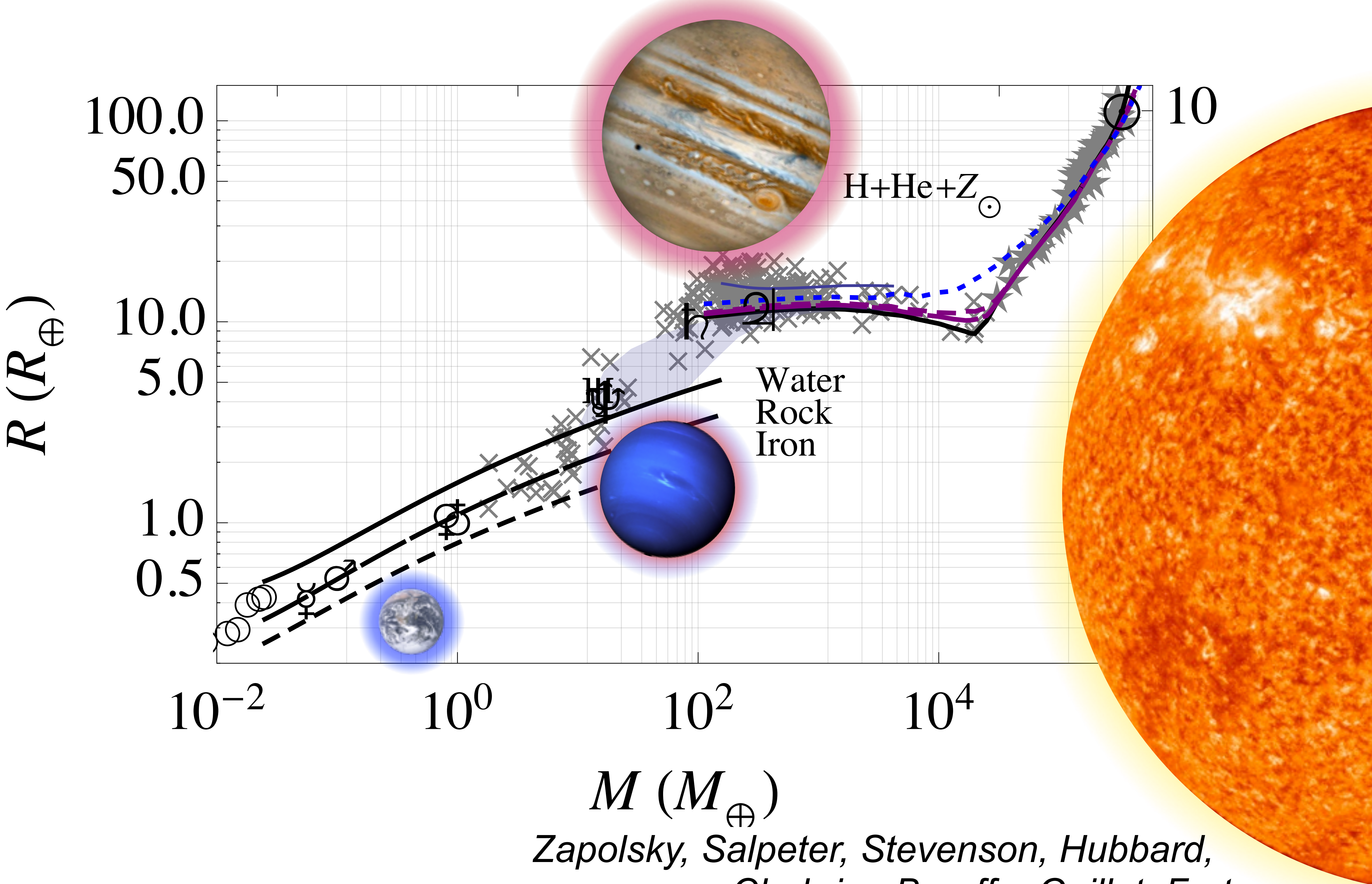
Zapolsky, Salpeter, Stevenson, Hubbard, Chabrier, Baraffe, Guillot, Fortney, ...

Mass-Radius diagram



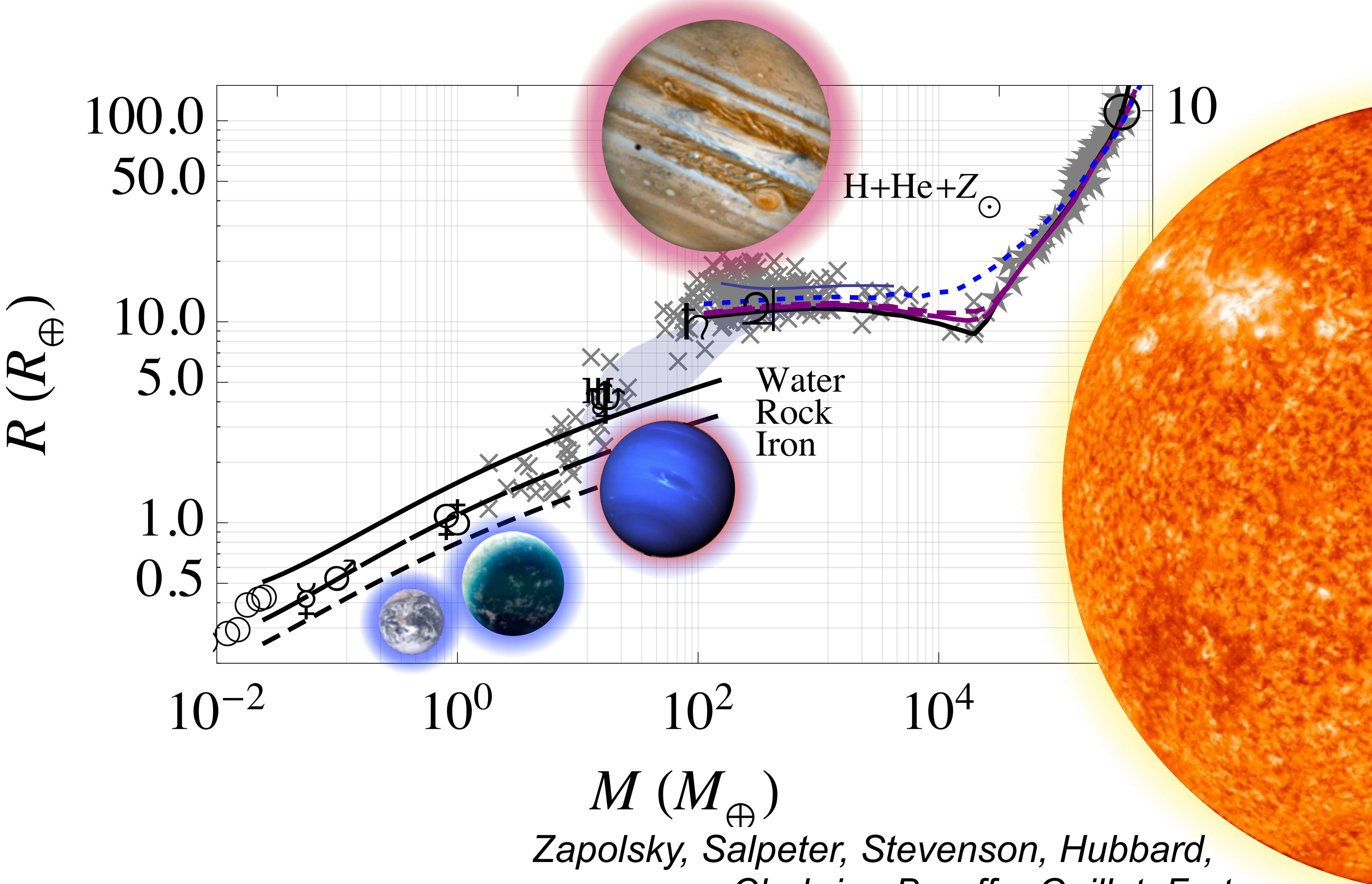
Zapolsky, Salpeter, Stevenson, Hubbard,
Chabrier, Baraffe, Guillot, Fortney, ...

Mass-Radius diagram: the good news



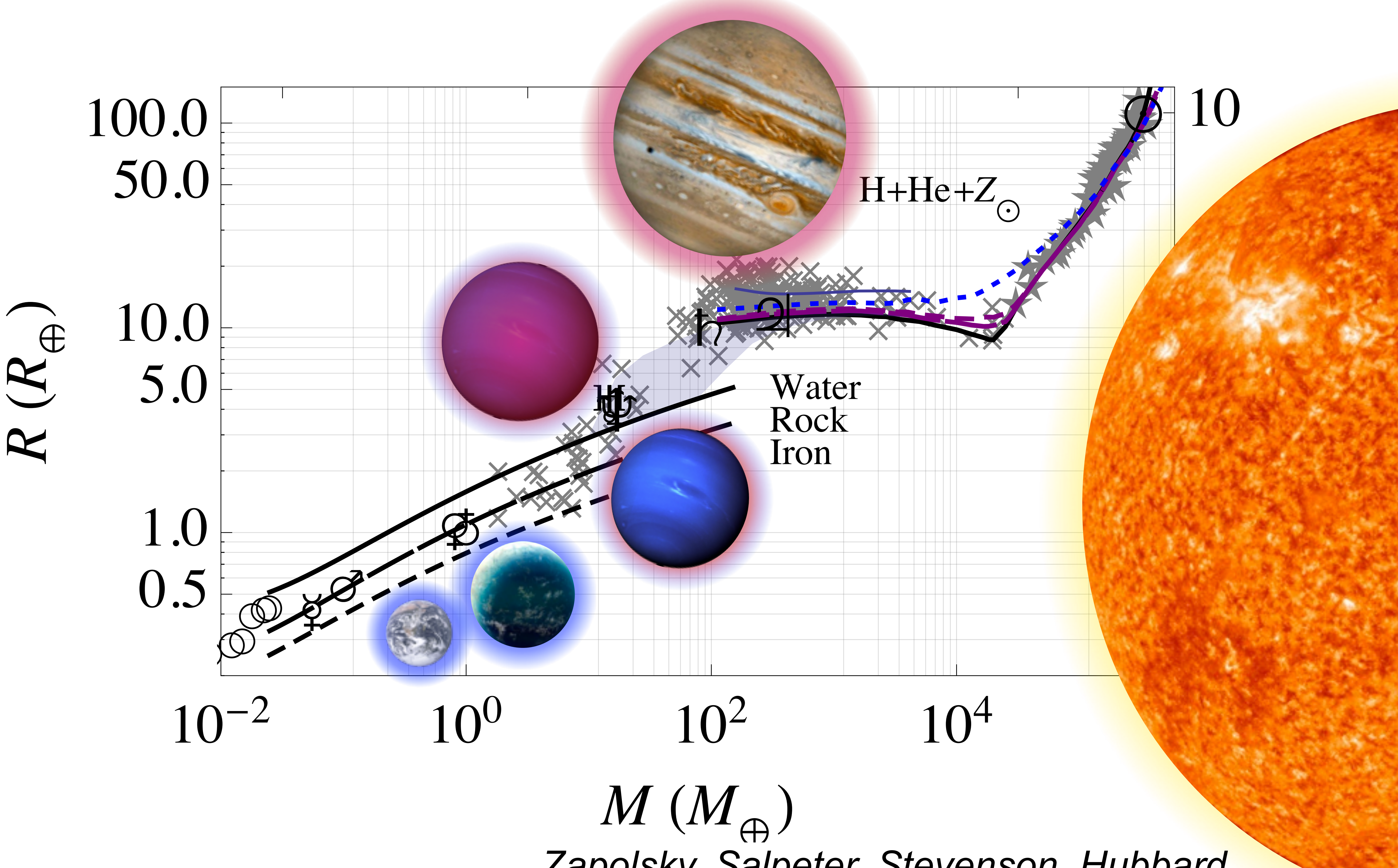
Zapolsky, Salpeter, Stevenson, Hubbard, Chabrier, Baraffe, Guillot, Fortney, ...

Mass-Radius diagram: the good news



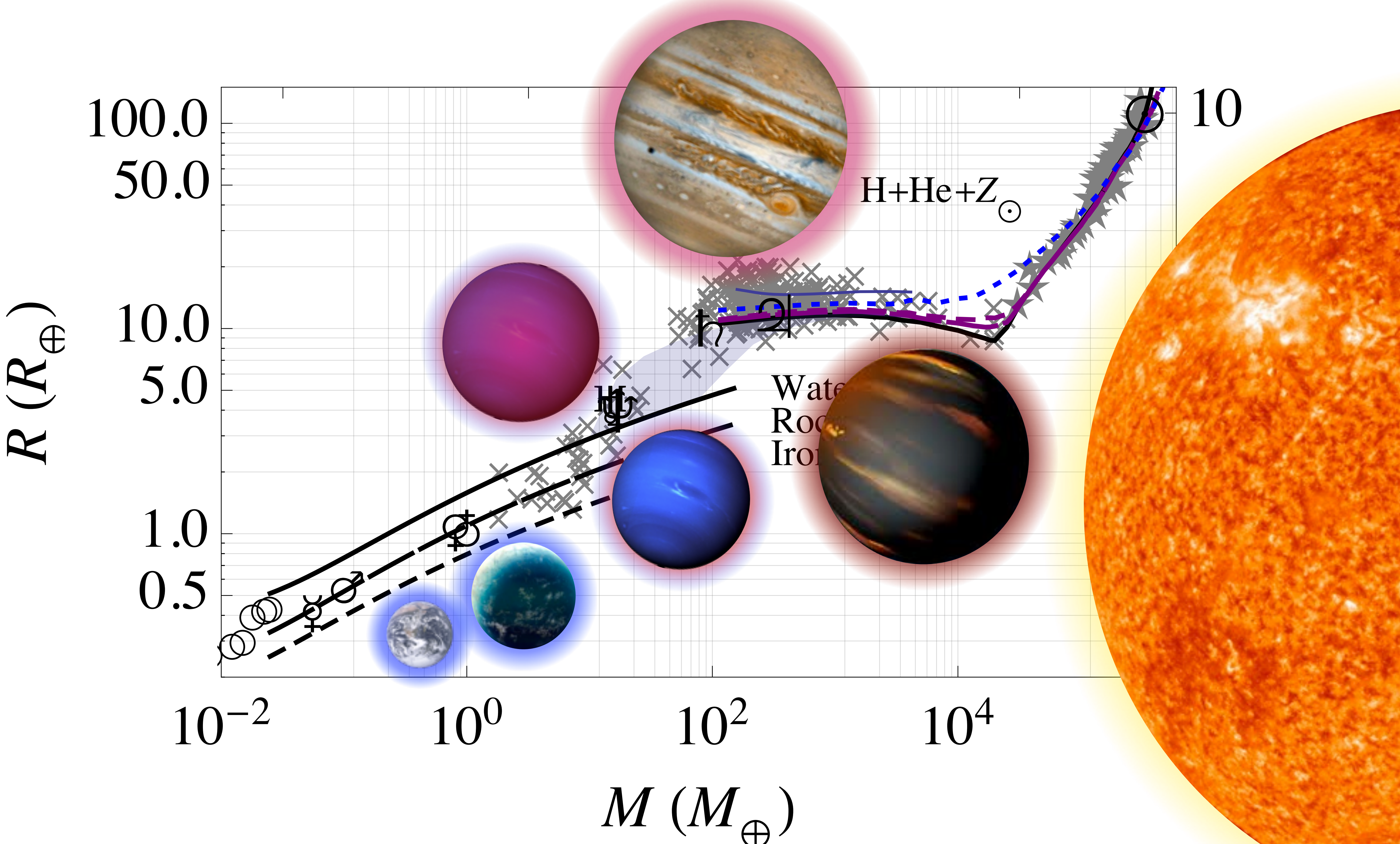
Zapolsky, Salpeter, Stevenson, Hubbard, Chabrier, Baraffe, Guillot, Fortney, ...

Mass-Radius diagram: the good news



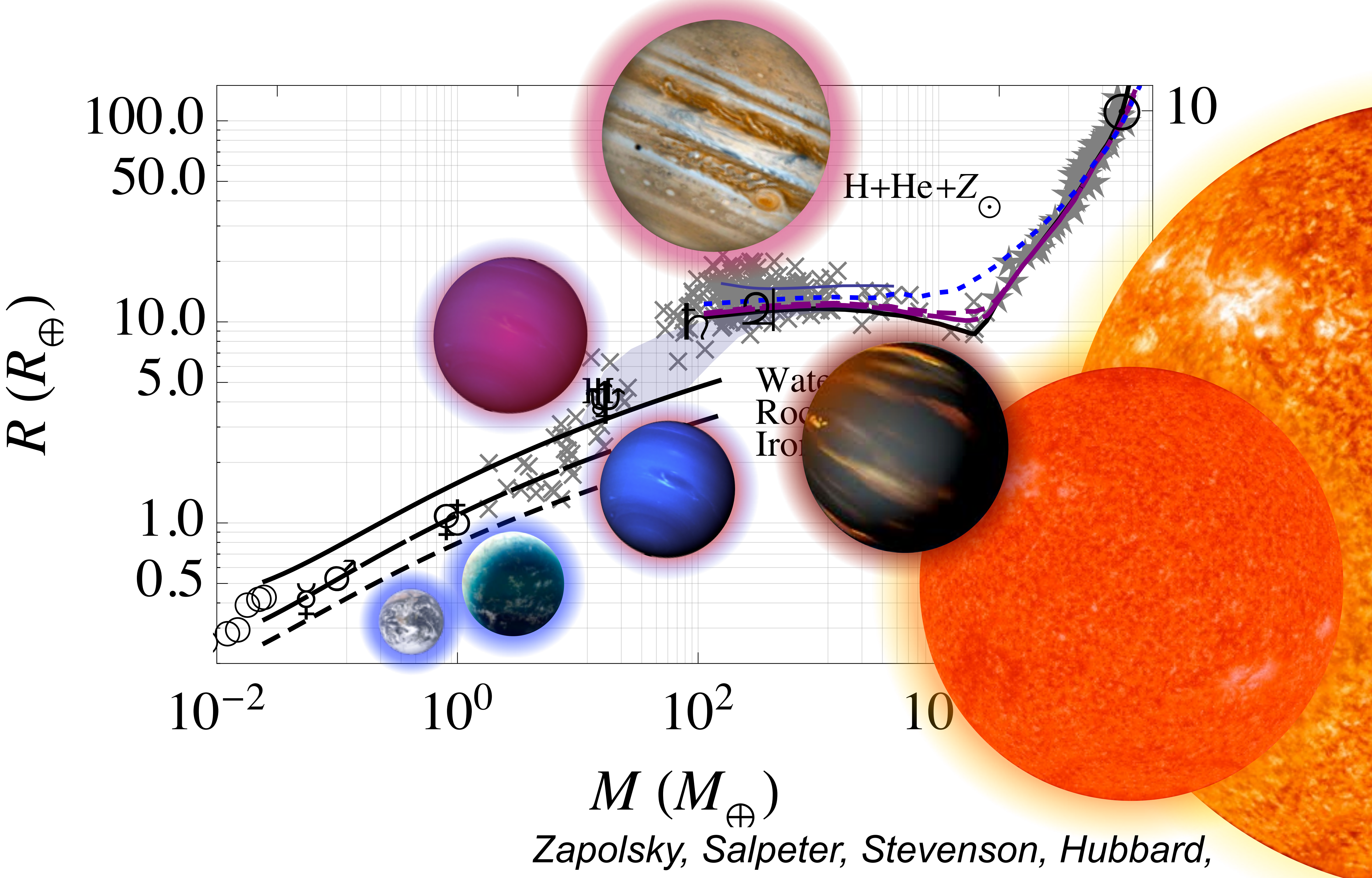
Zapolsky, Salpeter, Stevenson, Hubbard,
Chabrier, Baraffe, Guillot, Fortney, ...

Mass-Radius diagram: the good news



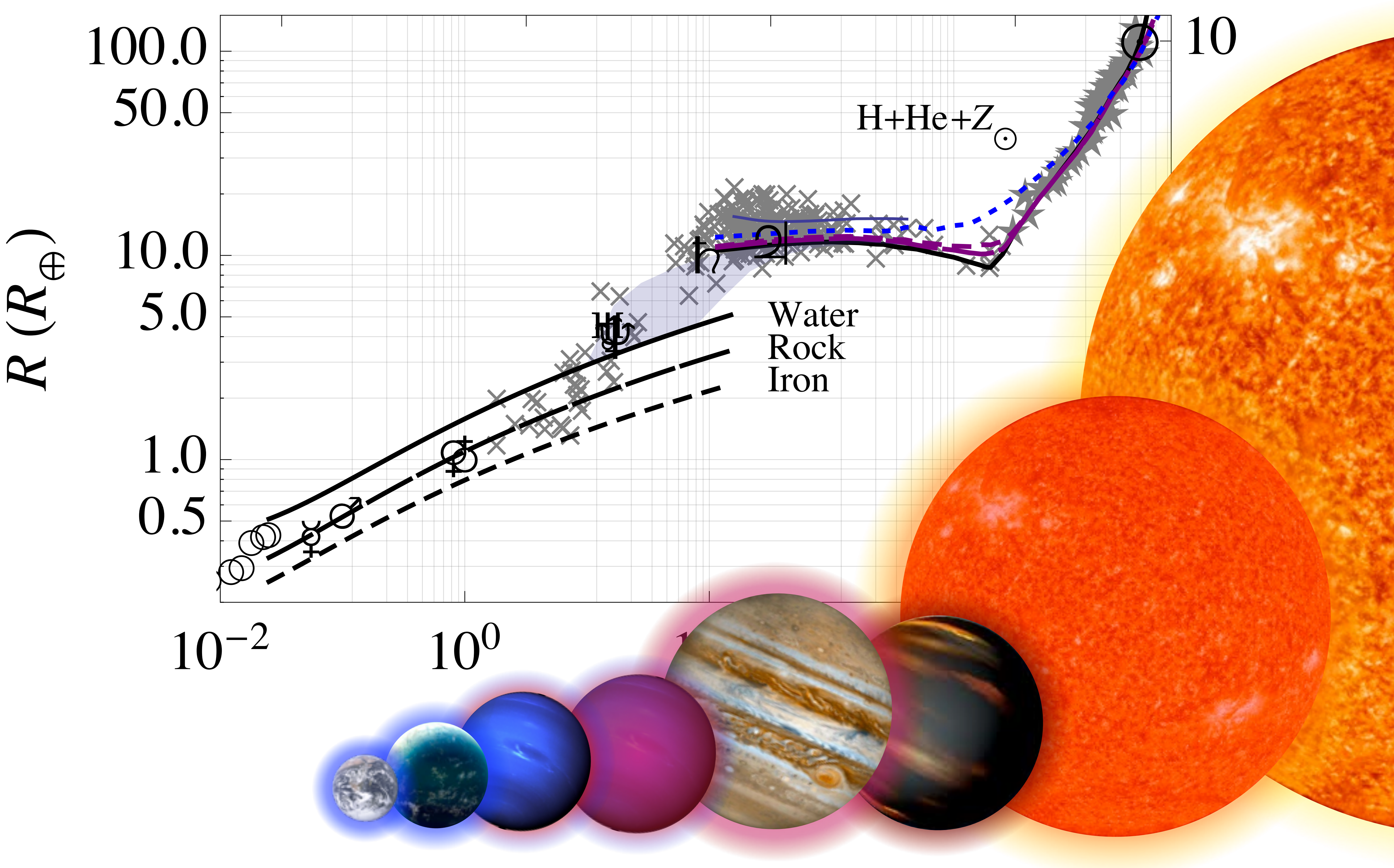
Zapolsky, Salpeter, Stevenson, Hubbard, Chabrier, Baraffe, Guillot, Fortney, ...

Mass-Radius diagram: the good news



Zapolsky, Salpeter, Stevenson, Hubbard, Chabrier, Baraffe, Guillot, Fortney, ...

Only one big family?



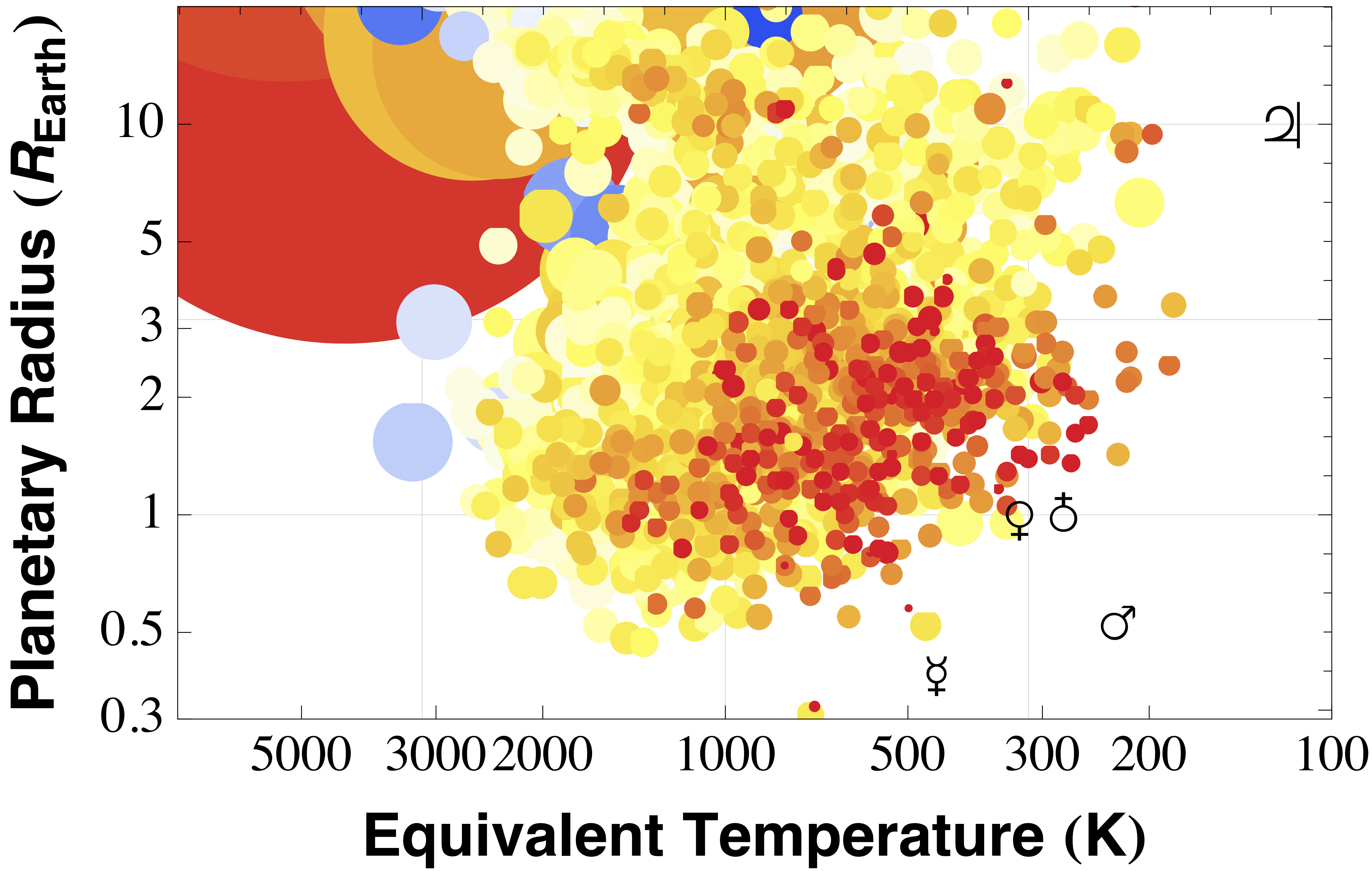
Do we need precise definitions?

No

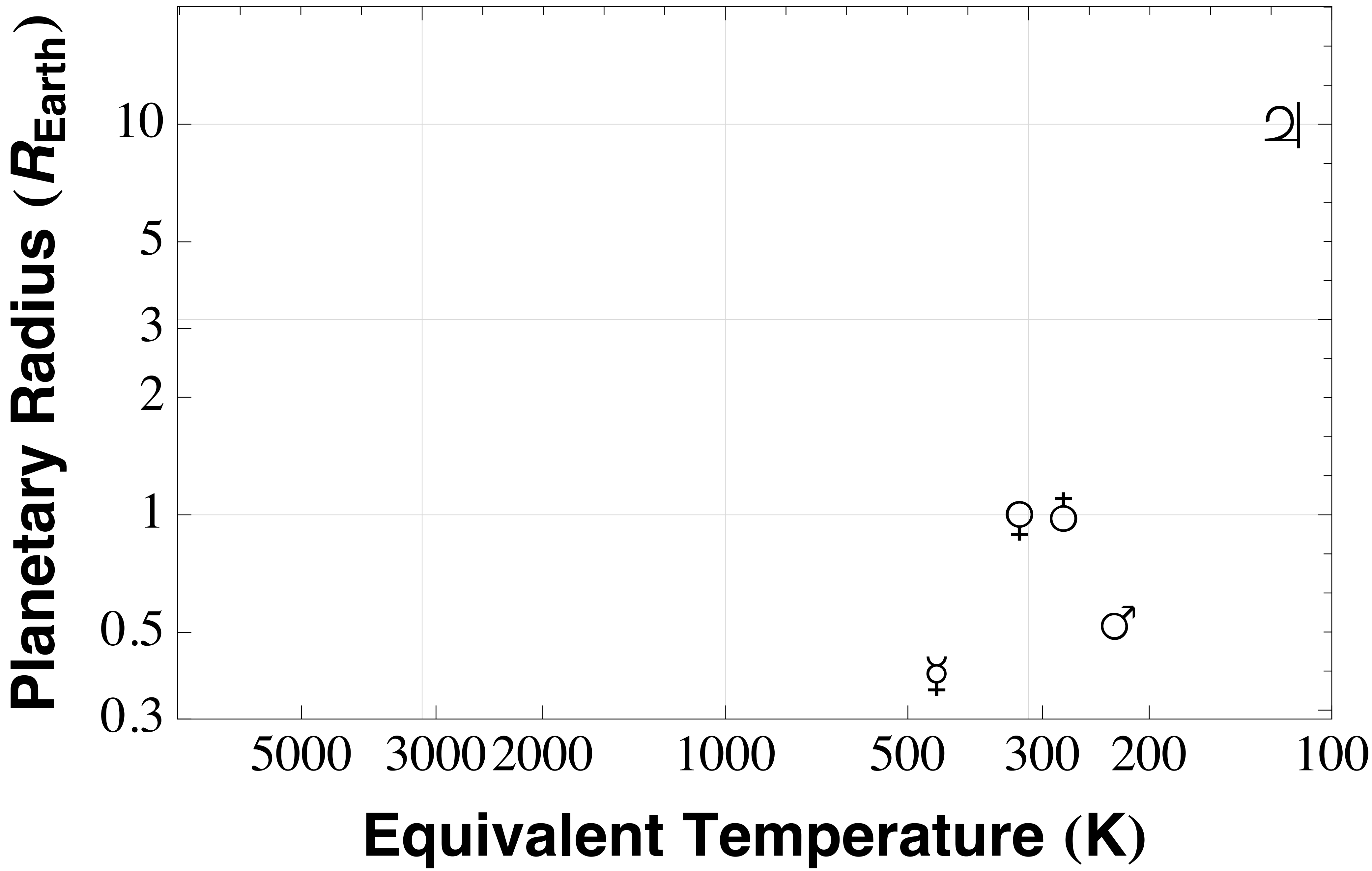

POOR
PLUTO
MATHIASPEDERSEN.COM


POOR PLUTO
SIZE DOESN'T MATTER
PROTEST FOR PLUTO
MATTER
PROTEST

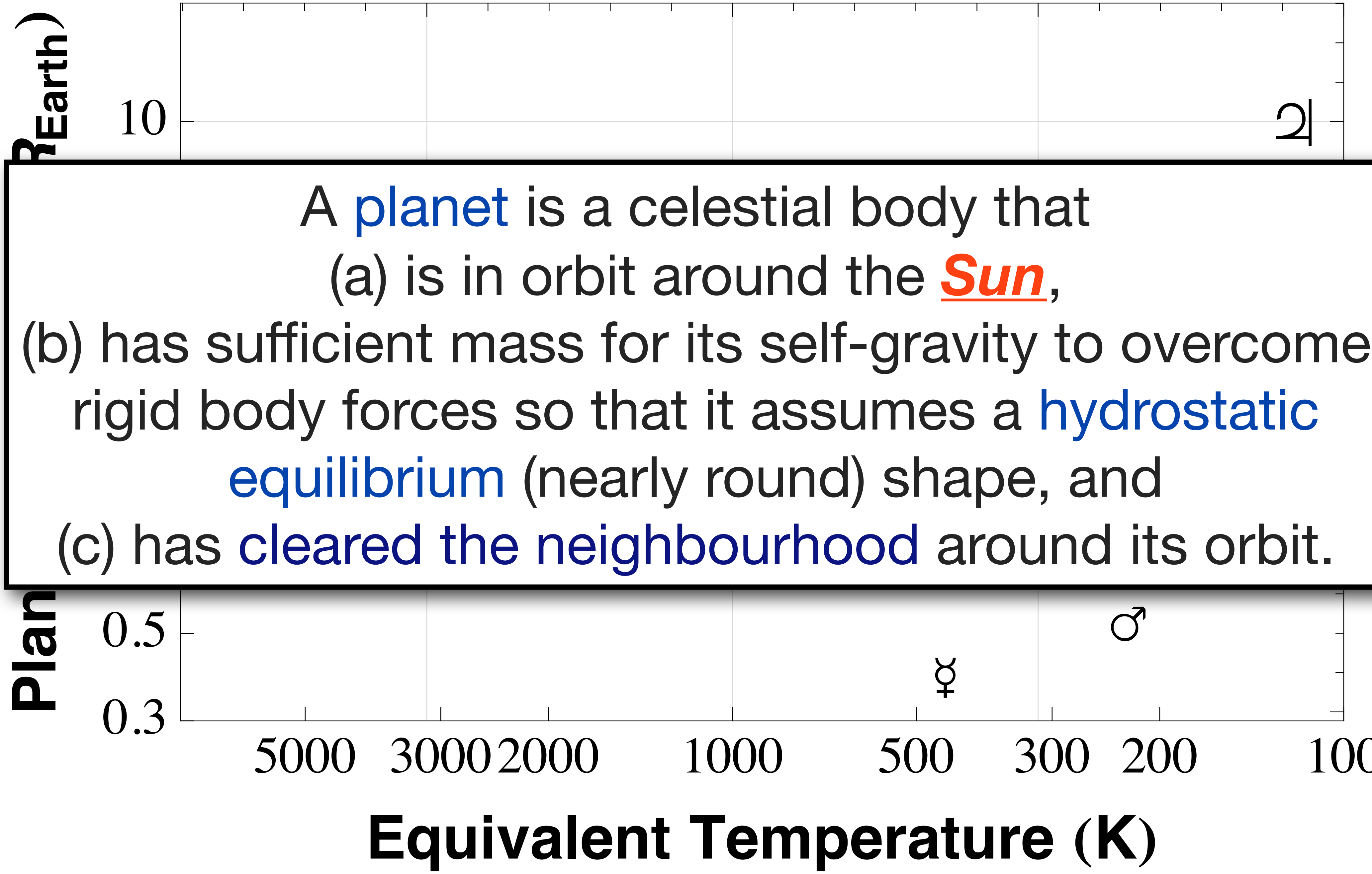
How many exoplanets fall into IAU's definition?



How many exoplanets fall into IAU's definition?



How many exoplanets fall into IAU's definition?



A planet is a celestial body that
(a) is in orbit around the ***Sun***,
(b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and
(c) has cleared the neighbourhood around its orbit.

But naming things is important...

Rationality is for economists as pornography was to the US Supreme Court, undefinable but nonetheless easily identified; and yet, like the Justices of the Court, no two economists share a common definition. This article details some of the common meanings of individual (as

The Palgrave Dictionary of Economics

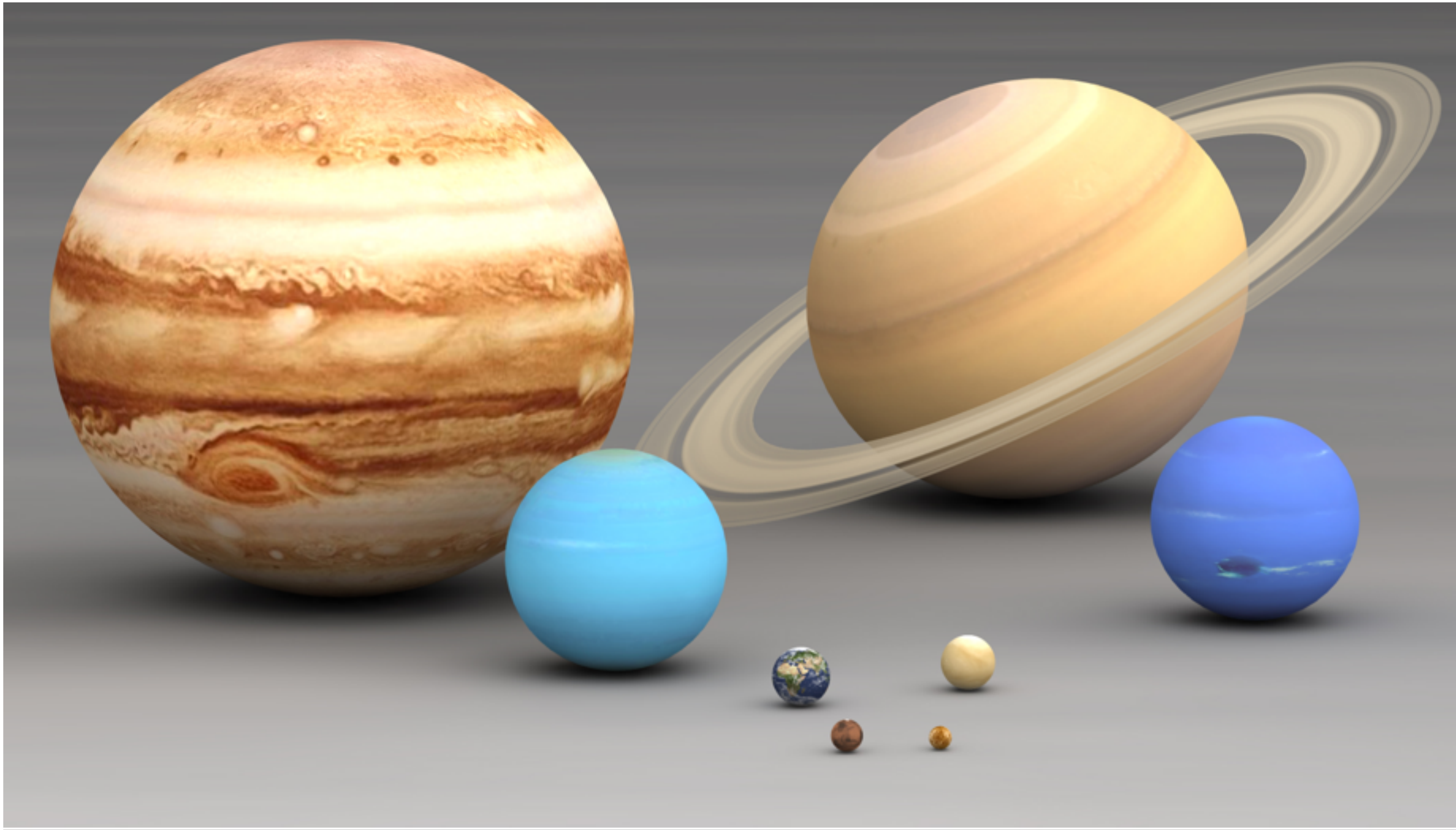
Rationality is for economists as pornography was to the US Supreme Court, undefinable but nonetheless easily identified; and yet, like the Justices of the Court, no two economists share a common definition. This article details some of the common meanings of individual (as

It's not the definition,
it's the concept that matters

- *the geologists never bothered to define a «continent»*
- *We always have the numbers to be specific!*

The Palgrave Dictionary of Economics

The eight «concepts» of the Solar System

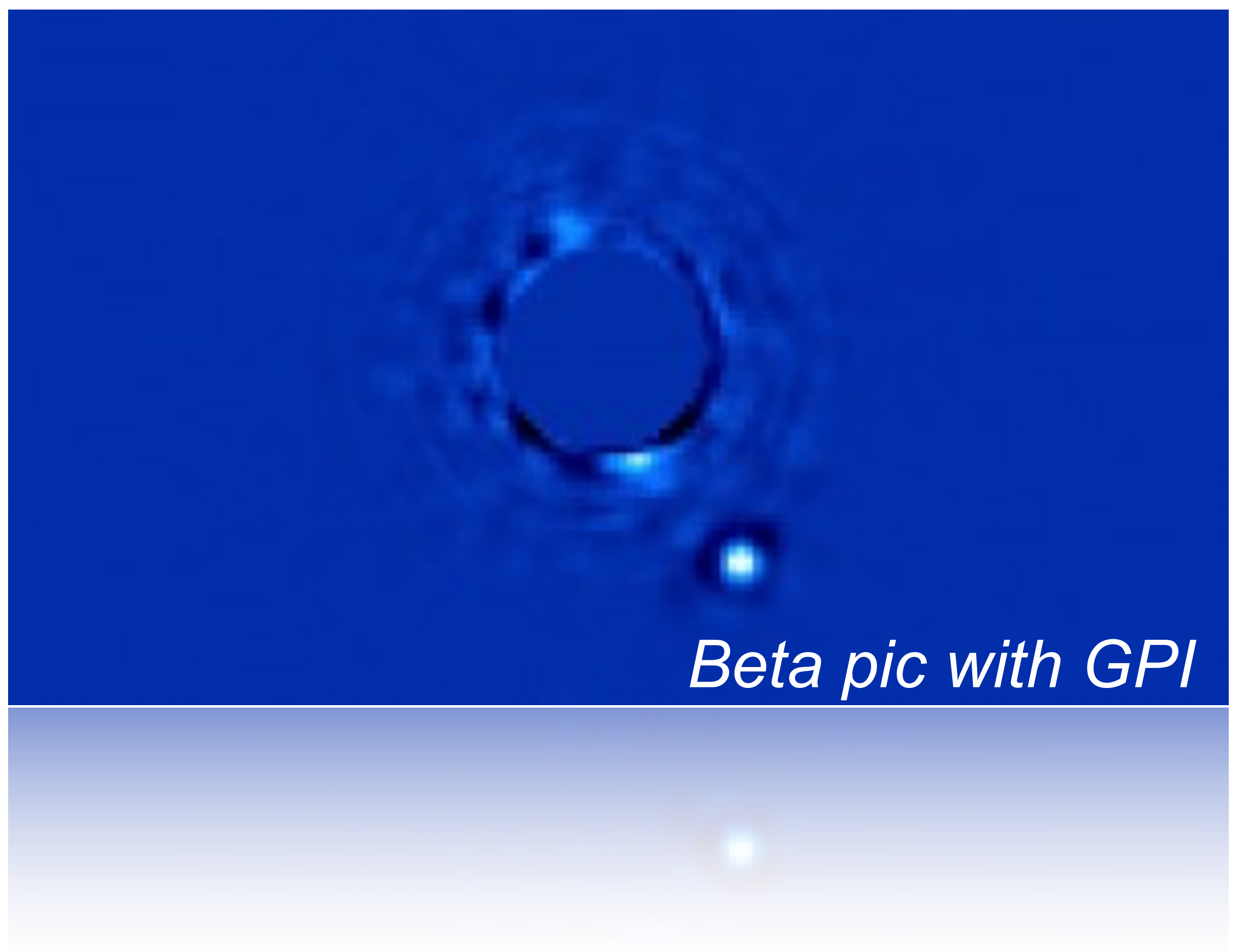


What we would forget without the Solar System

- Planets are more than a data point in a mass-radius diagram
  - We can resolve Solar System planets
  - Many different, exquisite observational constraints

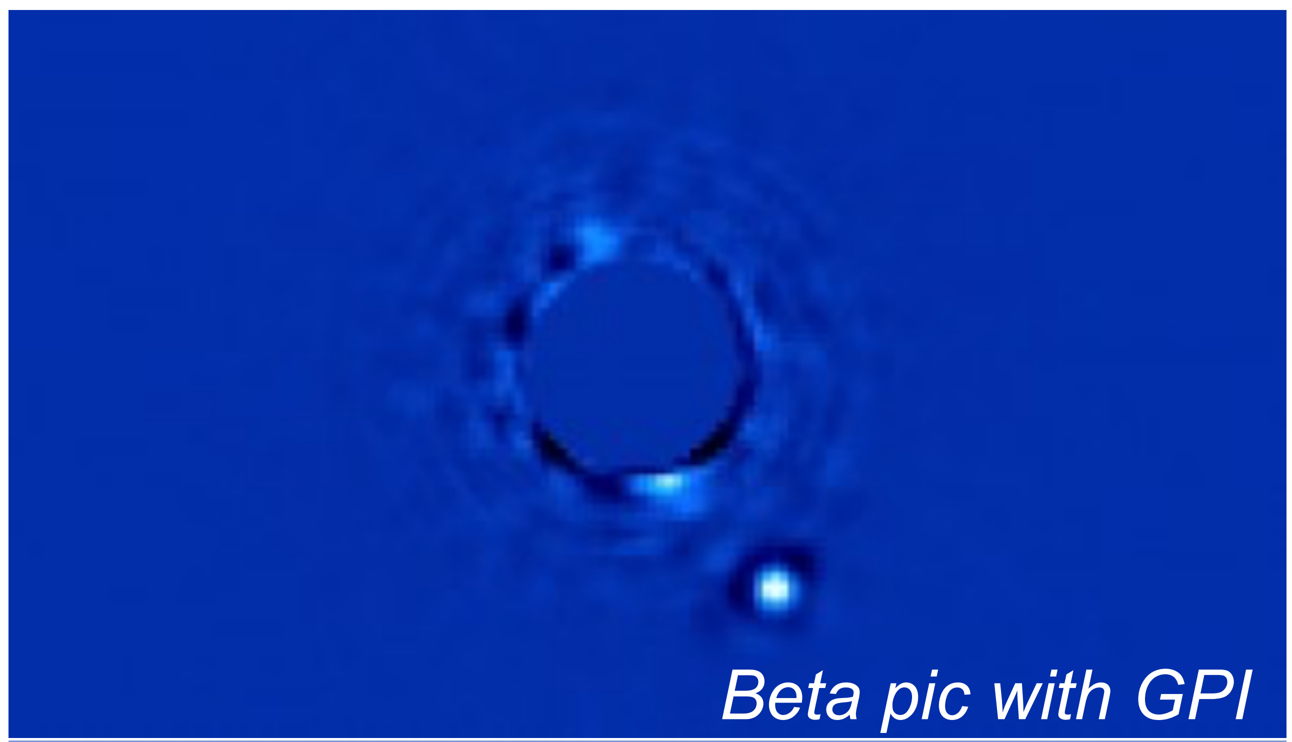
What we would forget without the Solar System

- Planets are more than a data point in a mass-radius diagram
    - We can resolve Solar System planets
    - Many different, exquisite observational constraints



What we would forget without the Solar System

- Planets are more than a data point in a mass-radius diagram
  - We can resolve Solar System planets
  - Many different, exquisite observational constraints

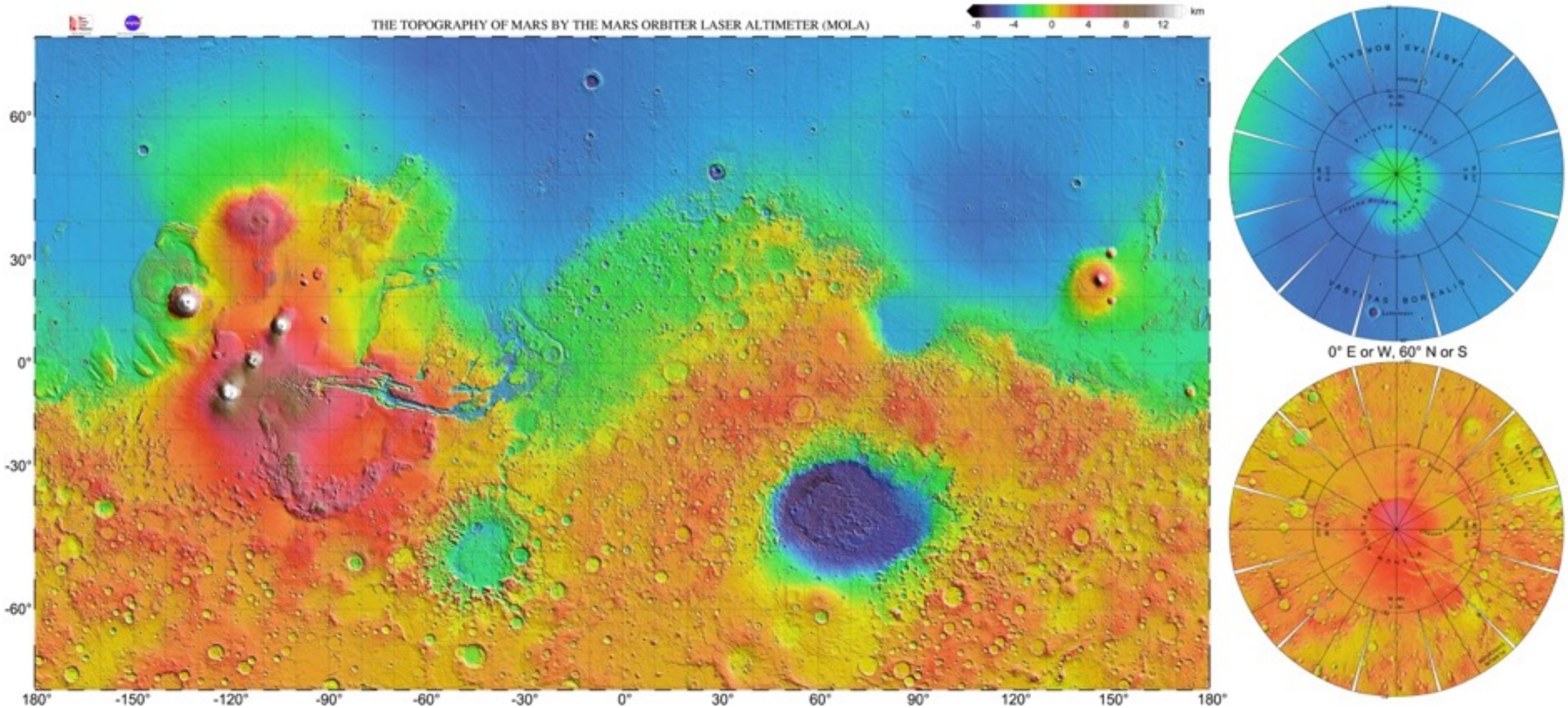


  - We can even go there...

What we would forget without the Solar System

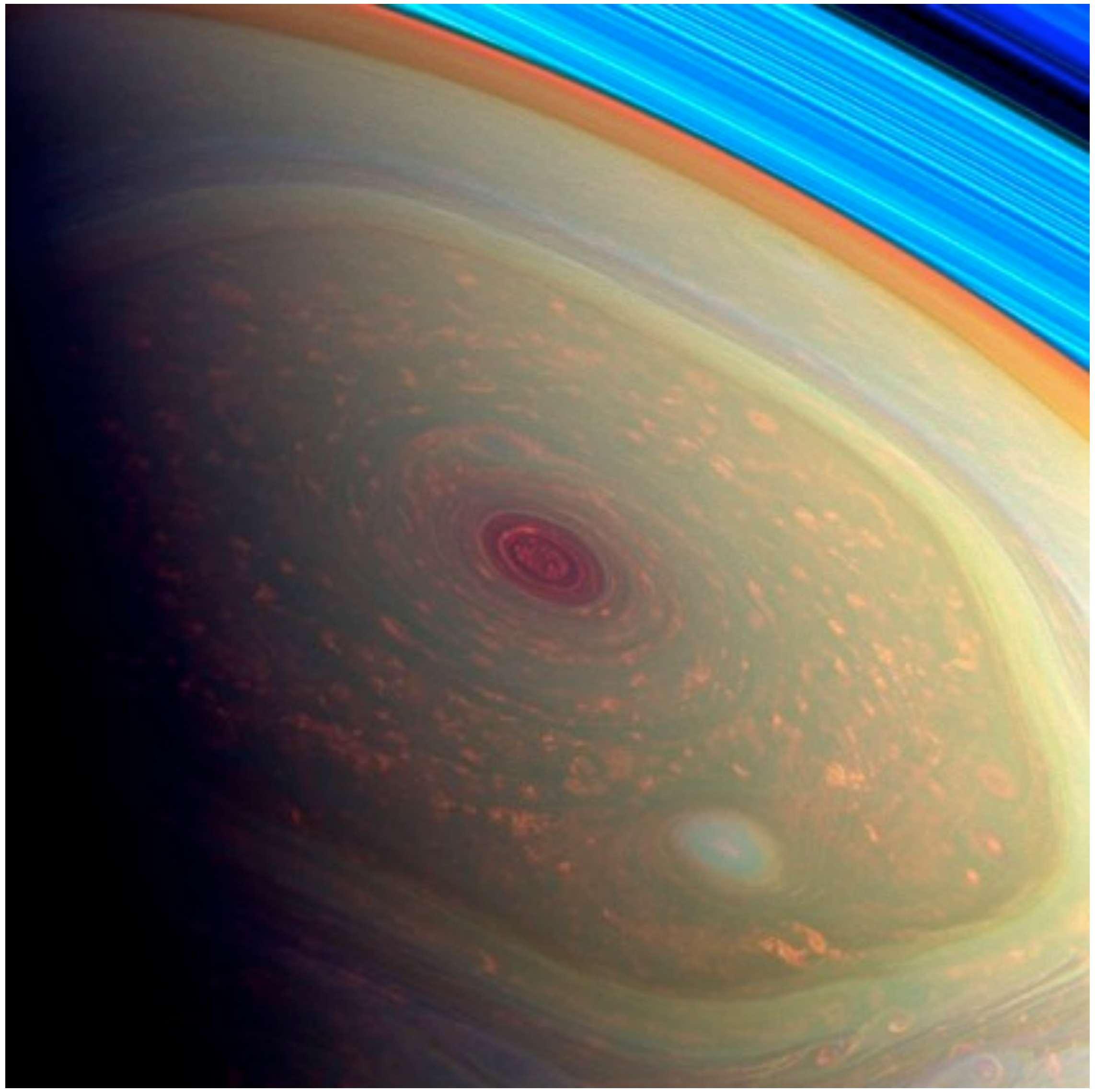
What we would forget without the Solar System

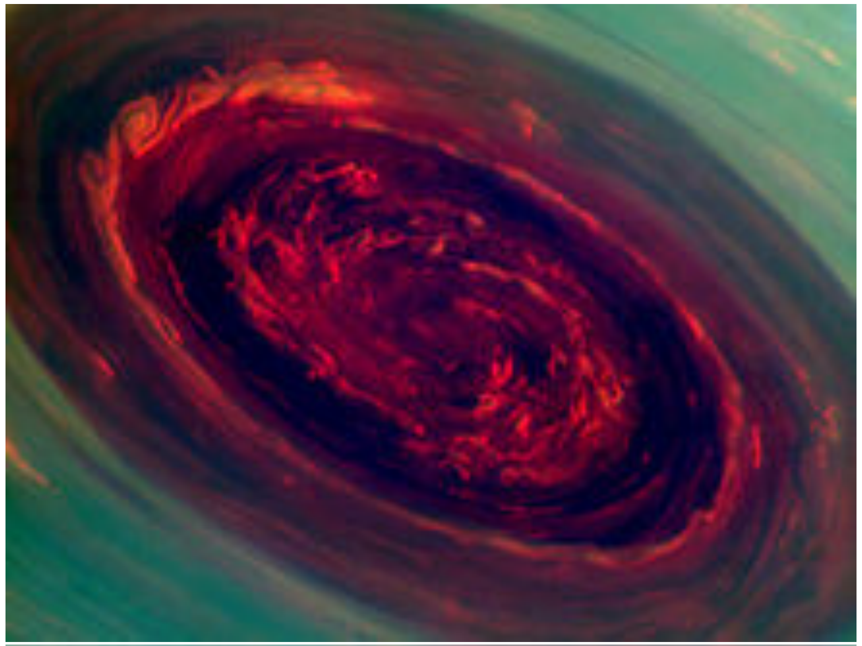
- Planets are not spherically symmetric

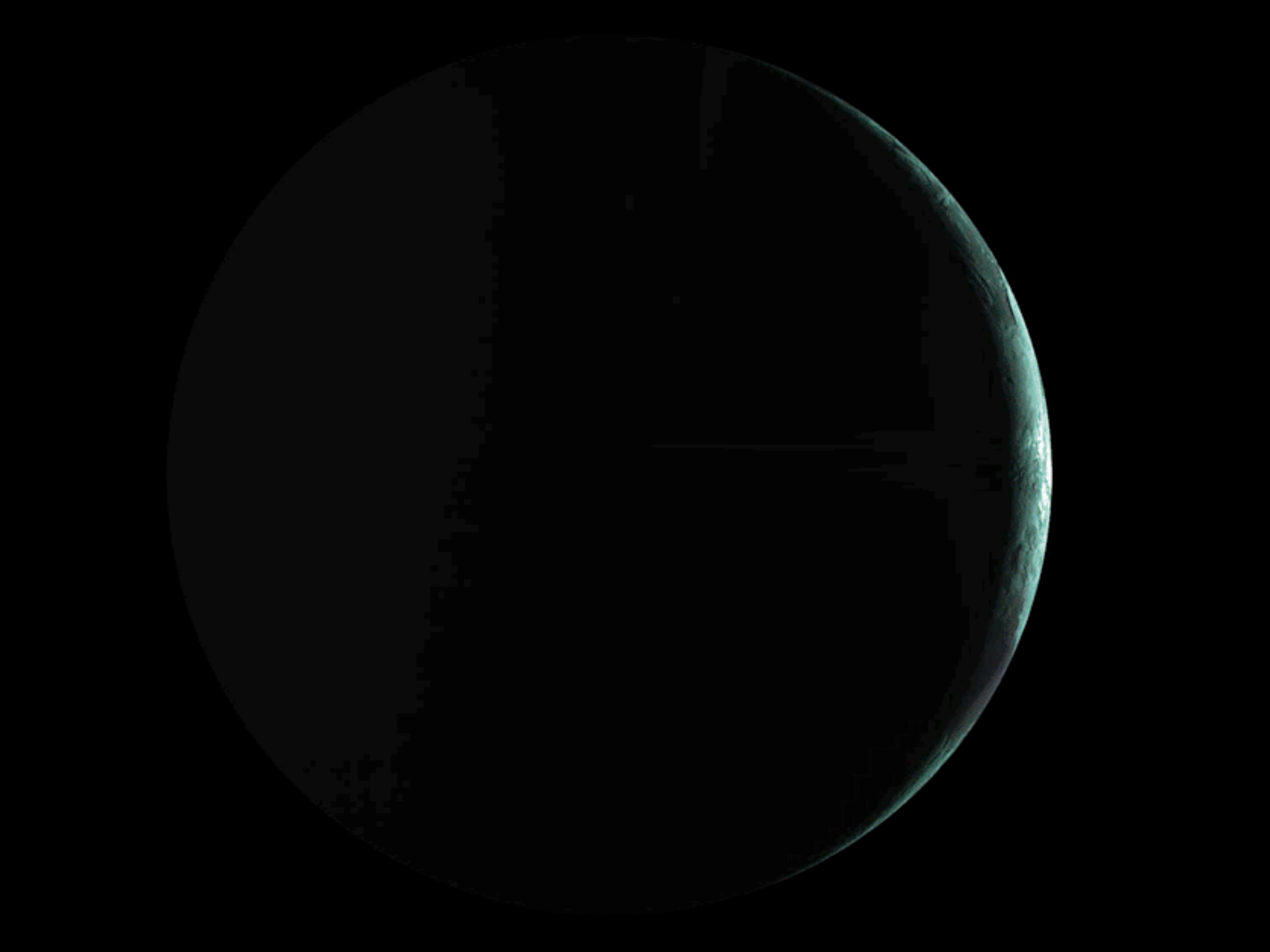


What we would forget without the Solar System

- Planets are not spherically symmetric
- Planets (and their atm) are actually 3D dynamical objects (at all scales)







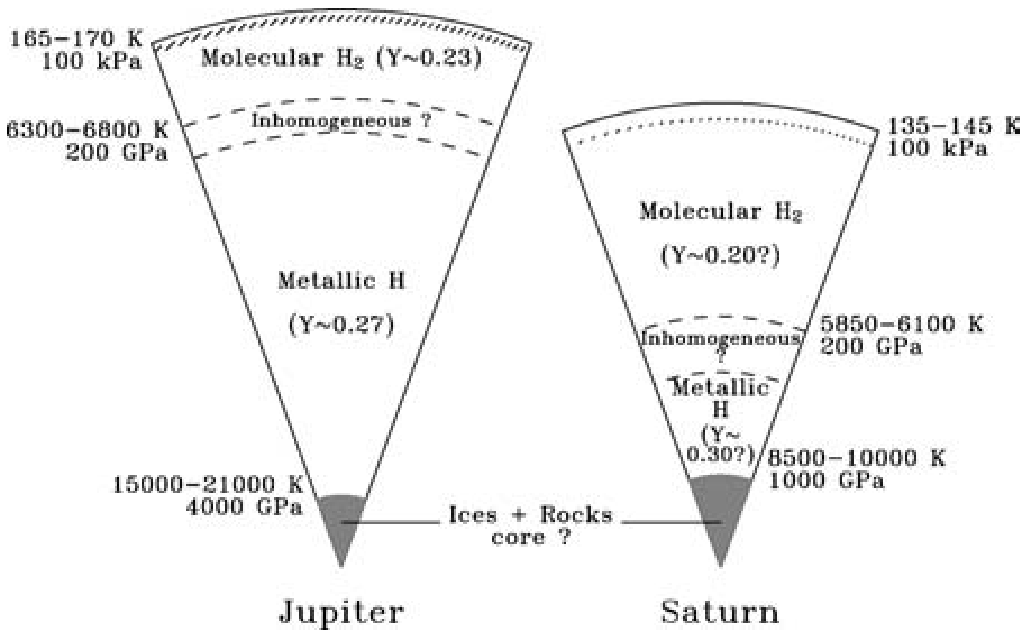
What we would forget without the Solar System

- Planets are not spherically symmetric
- Planets (and their atm) are actually 3D dynamical objects (at all scales)
- Moons are common

What we would forget without the Solar System

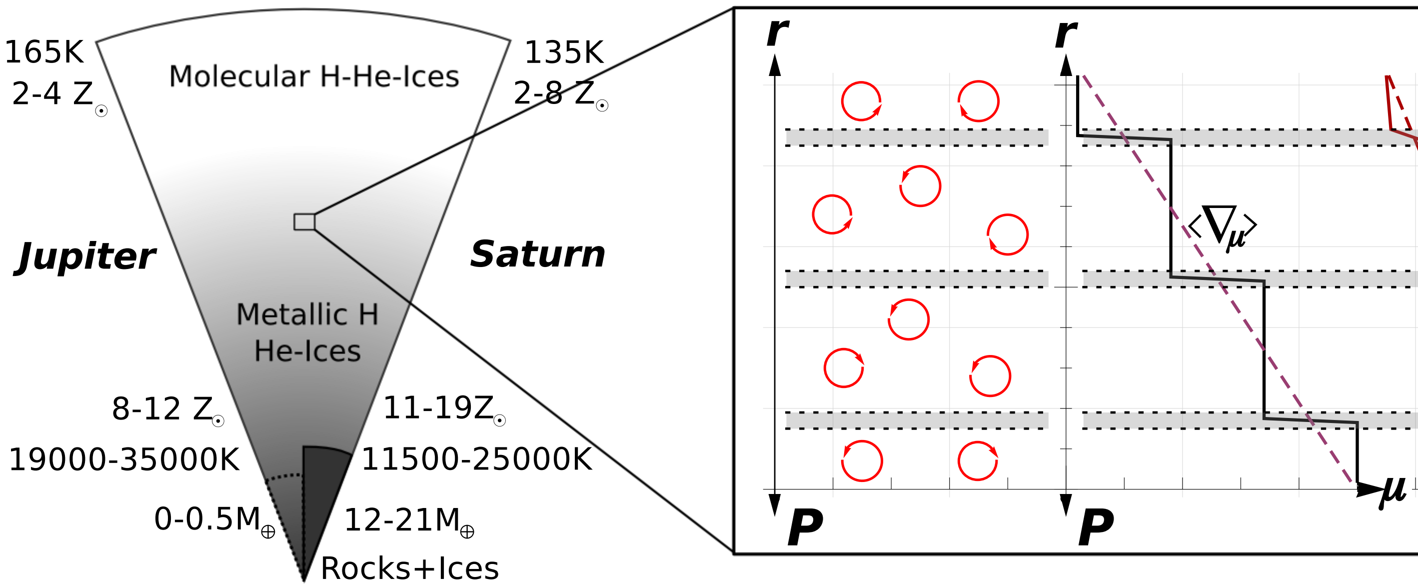
- Planets are not spherically symmetric
- Planets (and their atm) are actually 3D dynamical objects (at all scales)
- Moons are common
- Planetary interiors are not fully mixed (or fully stratified)

What we would forget without the Solar System



from a review by T. Guillot (2005)

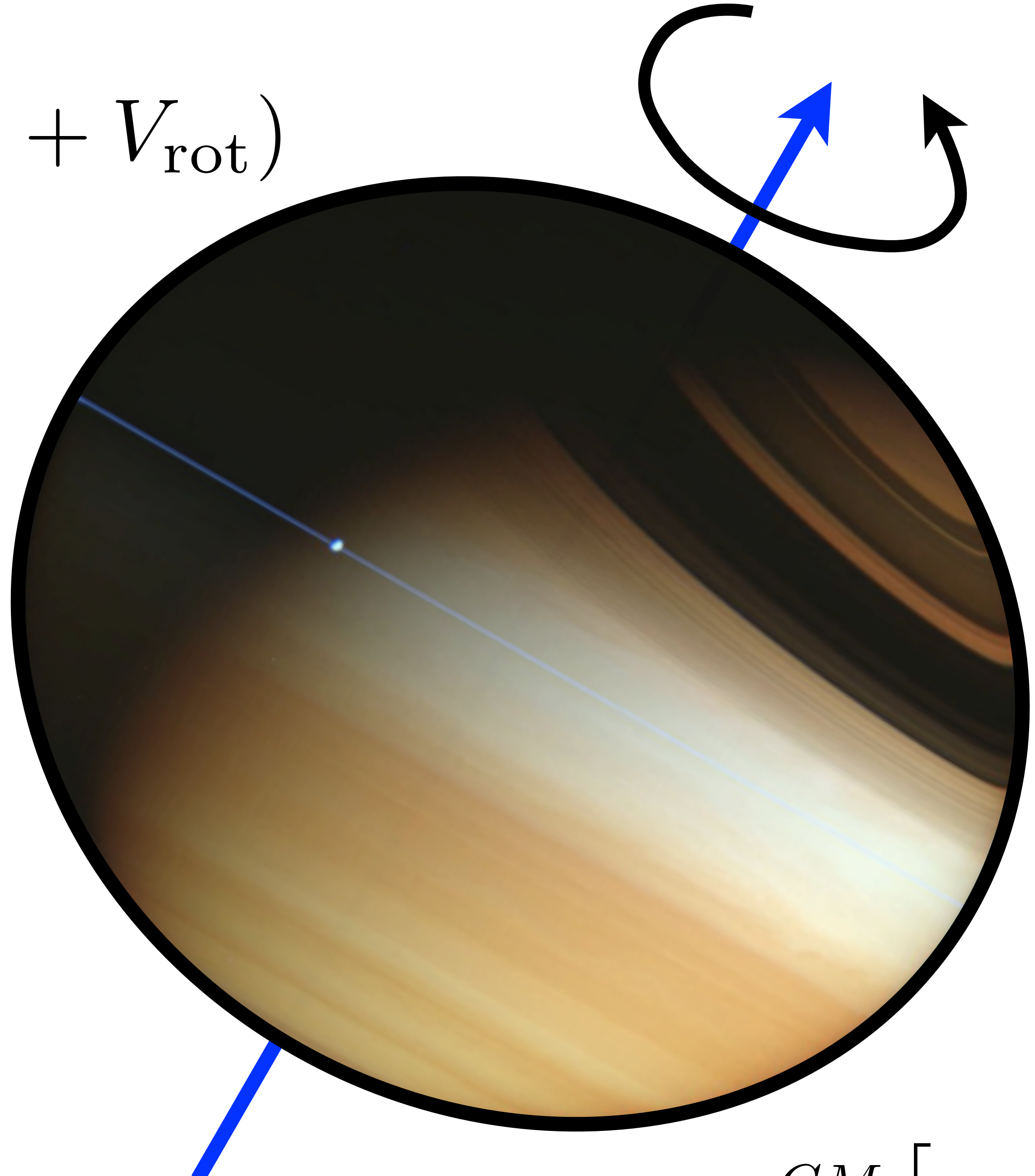
Assumption of large homogeneous/well mixed layers often done because of the lack of constraints!



Stevenson (1979); Chabrier & Baraffe (2007); Leconte et al. (2013, 2014)

Gravitational sounding

$$\nabla P = -\rho \nabla (V_G + V_{\rm rot})$$



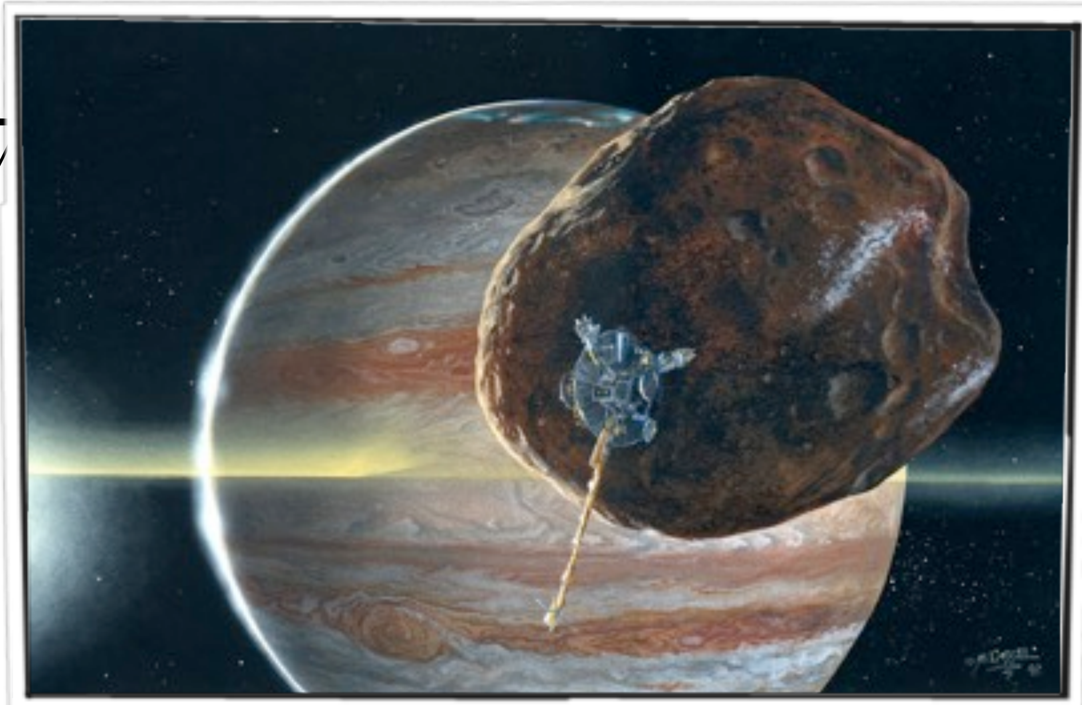
$$V_{\rm ext}(r,\theta) = -\frac{GM}{r}\left[1 - \sum_{\rm n=1}^{\infty}\left(\frac{a}{r}\right)^{\rm 2n} J_{\rm 2n} P_{\rm 2n}(\cos\theta)\right]$$

$$J_{\rm 2n} = -\frac{1}{M_1 R_{\rm eq}^{\rm 2n}} \iiint \rho(r,\theta)\, r^{\rm 2n} P_{\rm 2n}(\cos\theta)\, {\rm d}^3\mathbf{r}$$

Clairaut, Radau, ...
Zharkov & Trubitsyn
(1973,1979,1980)

Gravitational sounding

∇



	Jupiter	Saturn
M_p [10^{26}kg]	18.986112(15)	5.684640(30)
R_eq [10^7m]	7.1492(4)	6.0268(4)
R_pol[10^7m]	6.6854(10)	5.4364(10)
P_rot [10^4s]	3.57297(41)	3.83577(47)
$J_2 \times 10^2$	1.4697(1)	1.6332(10)
$J_4 \times 10^4$	-5.84(5)	-9.19(40)
$Z_\mathrm{atm}/Z_\odot$	2-4	2-8
$(Y/(X+Y))_\mathrm{atm}$	0.238(50)	0.215(35)

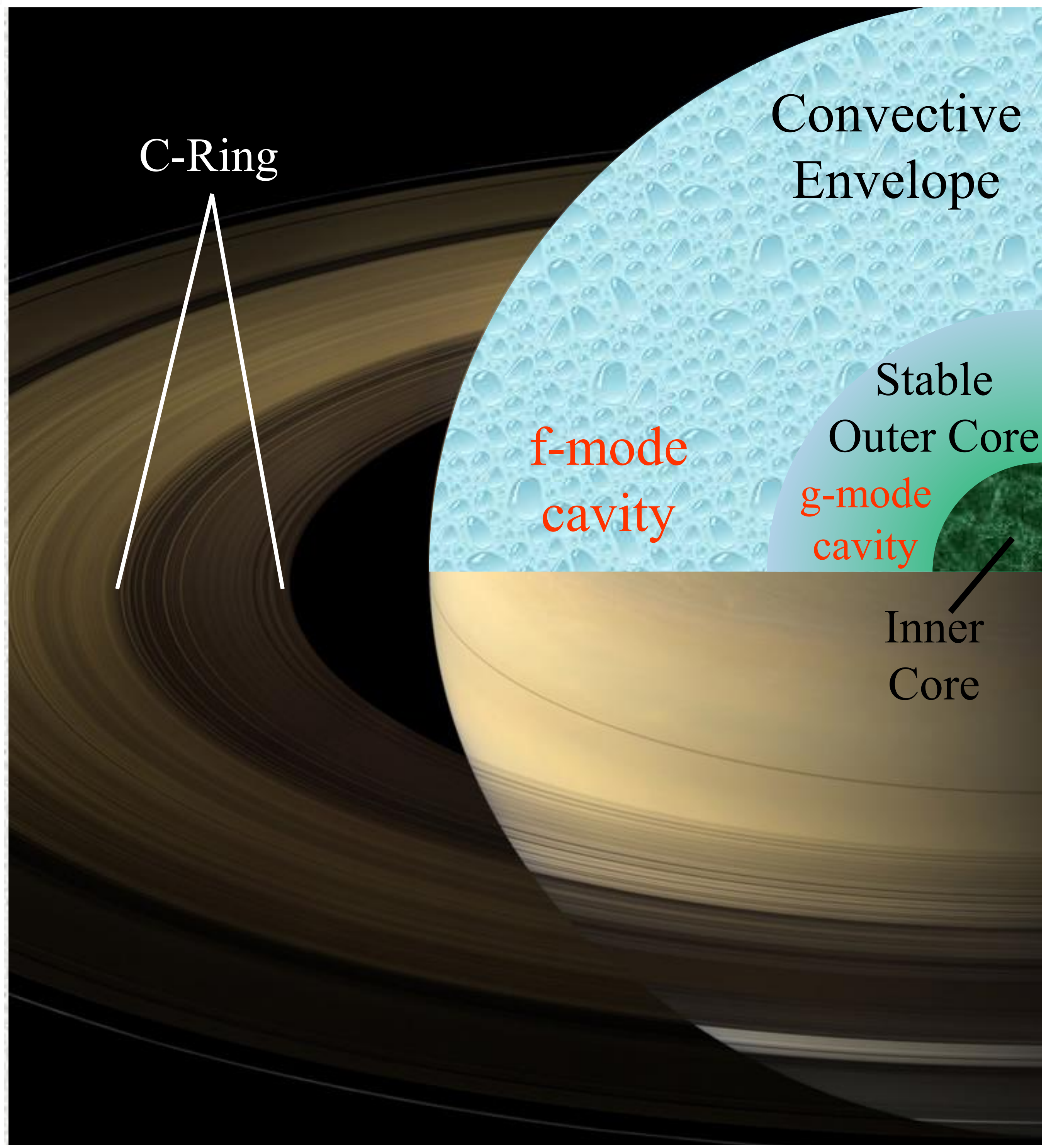
$$\left(\frac{a}{r}\right)^{2\mathrm{n}} J_{2\mathrm{n}} P_{2\mathrm{n}}(\cos\theta)\Big]$$

$$, \theta)\, r^{2\mathrm{n}} P_{2\mathrm{n}}(\cos\theta)\, \mathrm{d}^3\mathbf{r}$$

$$M_1 R_{\mathrm{eq}} \int\int\int$$

Voyager, Pioneer, Galileo, Cassini-Huygens

An independent confirmation from ring seismology



Fuller (Icarus, 2014)

but there is hope for exoplanets...

What we would forget without the Solar System

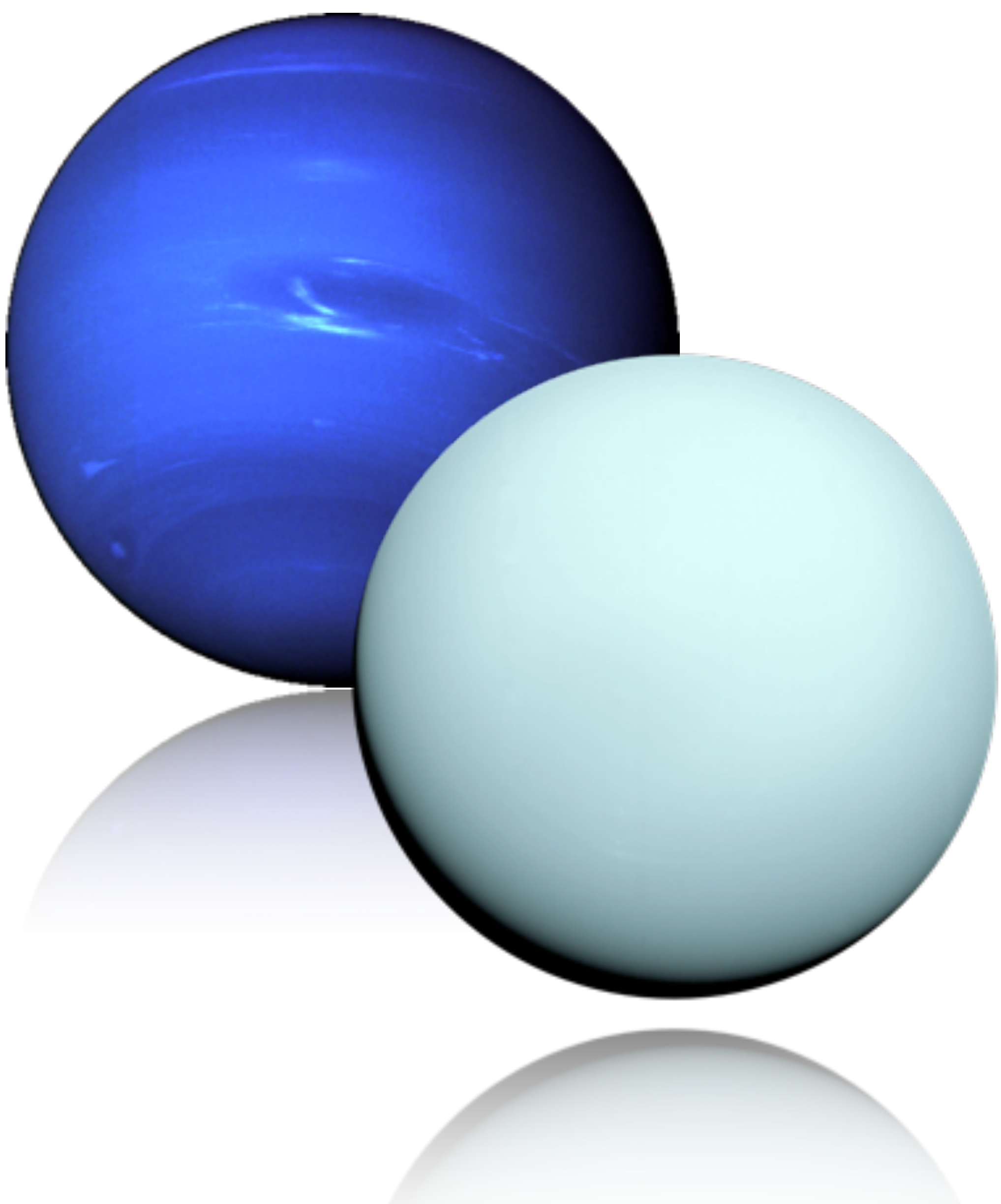
- Planets are not spherically symmetric
- Planets (and their atm) are actually 3D dynamical objects (at all scales)
- Planetary interiors are not homogeneous (or fully stratified)

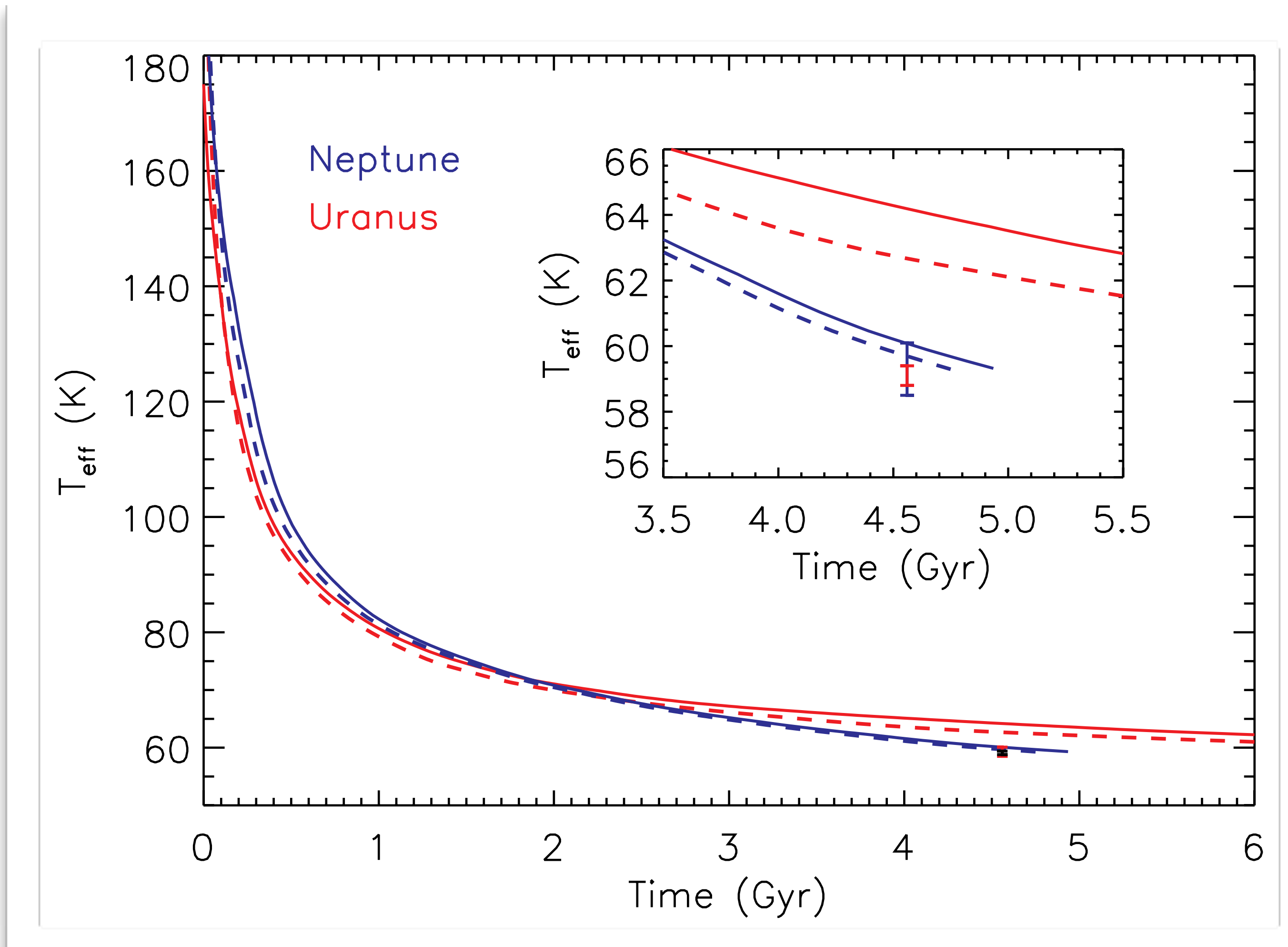
What we would forget without the Solar System

- Planets are not spherically symmetric
- Planets (and their atm) are actually 3D dynamical objects (at all scales)
- Planetary interiors are not homogeneous (or fully stratified)
- Planets can be very diverse...

What we would forget without the Solar System

- Planets are not spherically symmetric
- Planets (and their atm) are actually 3D dynamical objects (at all scales)
- Planetary interiors are not homogeneous (or fully stratified)
- Planets can be very diverse... even when they look alike





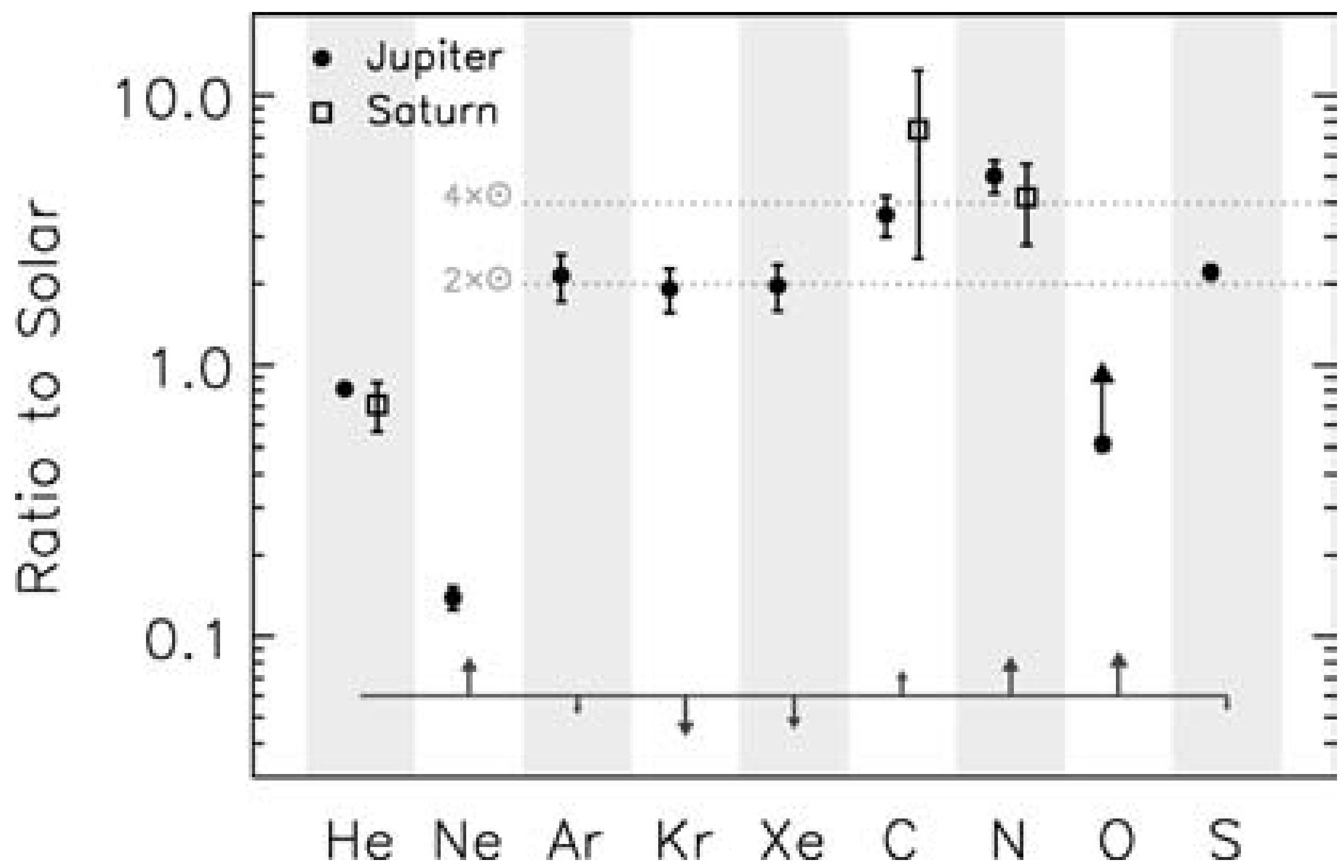
Fortney et al. (ApJ, 2011)

What we would forget without the Solar System

- Planets are not spherically symmetric
- Planets (and their atm) are actually 3D dynamical objects (at all scales)
- Planetary interiors are not homogeneous (or fully stratified)
- Planets can be very diverse... even when they look alike

What we would forget without the Solar System

- Planets are not spherically symmetric
- Planets (and their atm) are actually 3D dynamical objects (at all scales)
- Planetary interiors are not homogeneous (or fully stratified)
- Planets can be very diverse... even when they look alike
- Atmospheric (and interior) compositions are not scaled up solar metallicites (important to understand formation and evolution)



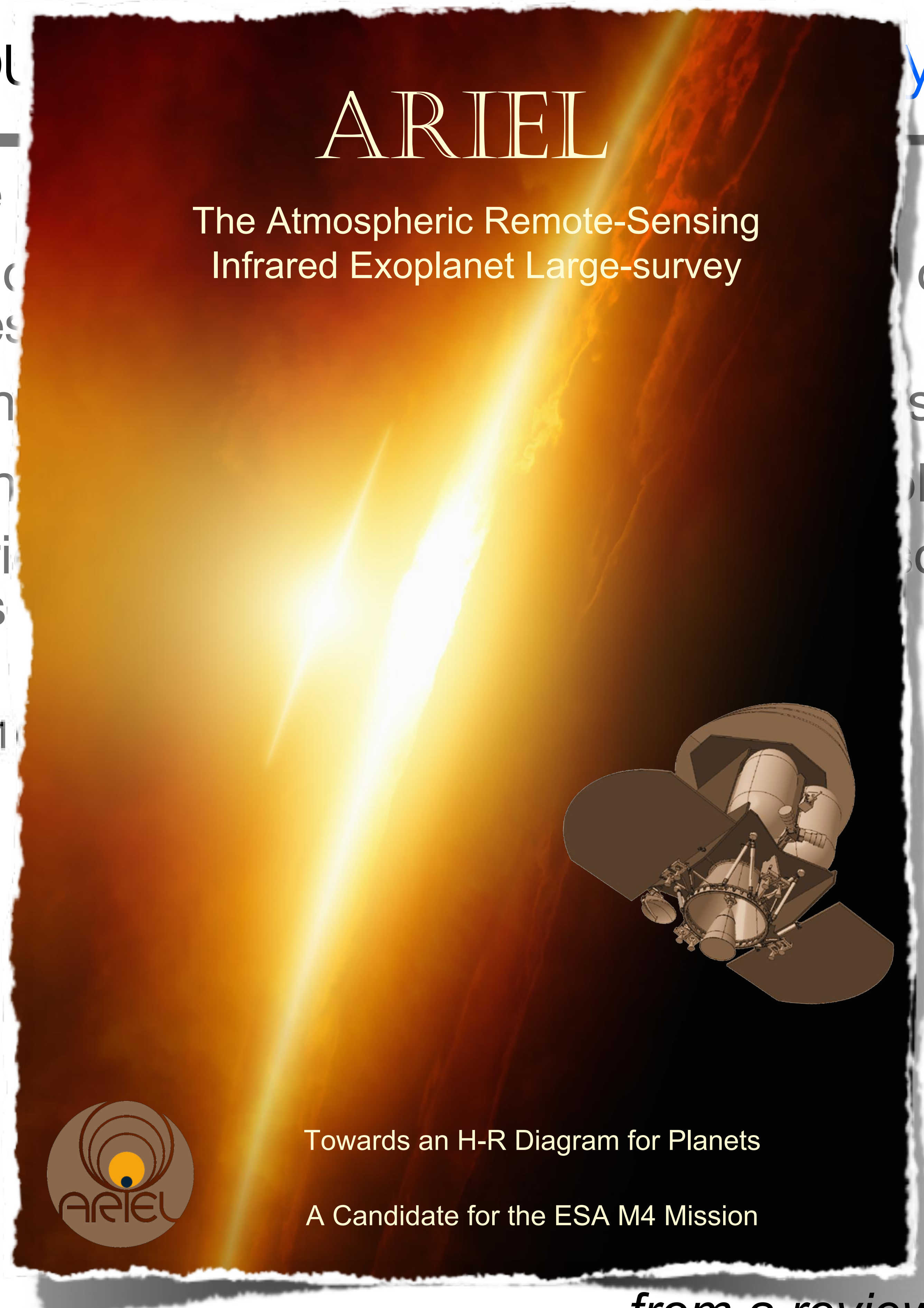
from a review by T. Guillot (2005)

What we wou... ...ystem

- Planets are ...
- Planets (and ... objects (at all scales ...
- Planetary in... ...stratified)
- Planets can ... ...k alike
- Atmospheri... ...caled up solar metallicites ...

1

Ratio to Solar



from a review by T. Guillot (2005)

Largest known trans-Neptunian objects (TNOs)

Largest known trans-Neptunian objects (TNOs)