Nordita Winter School 2017

EXOPLANETS
& Fermi paradox

UNIVERSITÉ CÔTE D'AZUR

Observatoire de la CÔTE d'AZUR

Aurélien CRIDA

« *In space there are countless constellations, suns and planets ;*
we see only the suns because they give light ;
the planets remain invisible, for they are small and dark.
There are also numberless earths circling around their suns, as do the seven planets of our system.

The innumerable worlds of the Univere are not worse and not less inhabitated than our Earth.»

Giordano Bruno,
de l'infinito universo e mondi
(1574)


GIORDA-
NO BRVNO
Nolano.

De l'infinito vniuerſo
et Mondi.

All'illuſtriſsimo Signor di
Mauuiſsiero.

Stampato in Venetia.
Anno. M. D. LXXXIIII.

EXOPLANETS

Stars are a billion times brighter than planets.

EXOPLANETS

Stars are a billion times brighter than planets.
Like a firefly next to a lighthouse...

EXOPLANETS

Stars are a billion times brighter than planets.
Like a firefly next to a lighthouse...

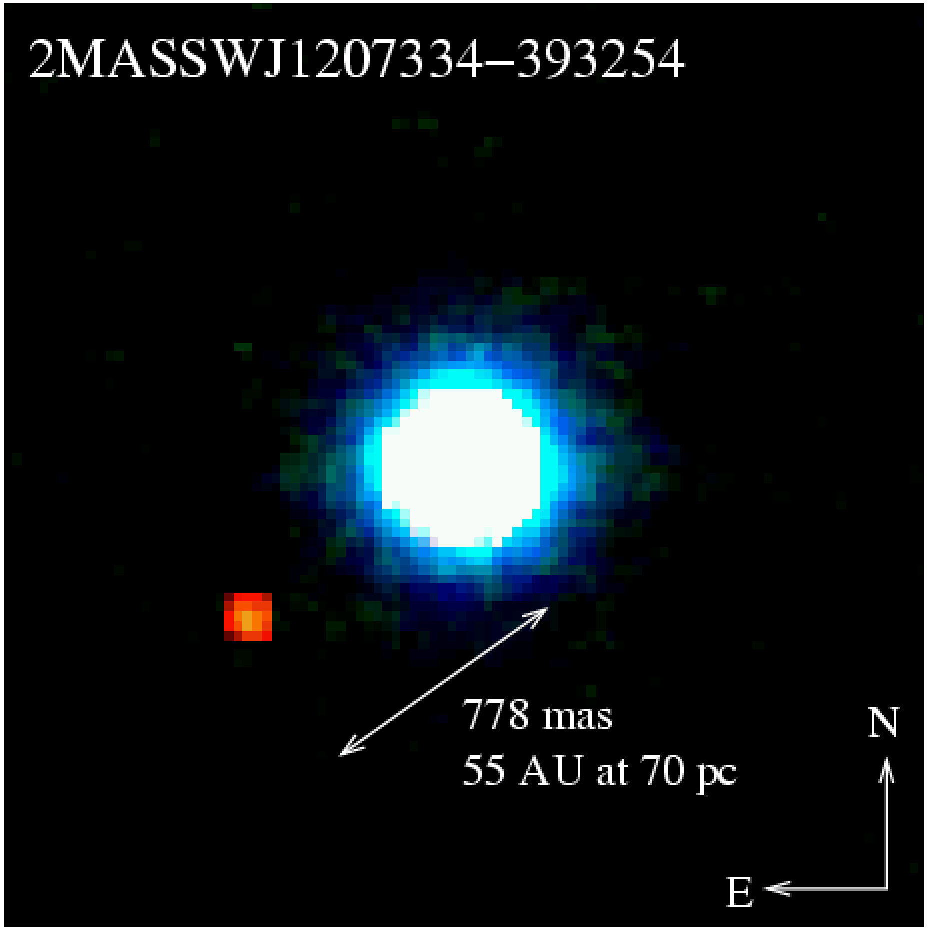
... in New York !
(stars are far, far away)

EXOPLANETS

Sometimes, it works !

One can see directly the planet next to its star, if the latter is faint (e.g. : a brown dwarf).

First image of an exoplanet :
Chauvin et al. (2004)

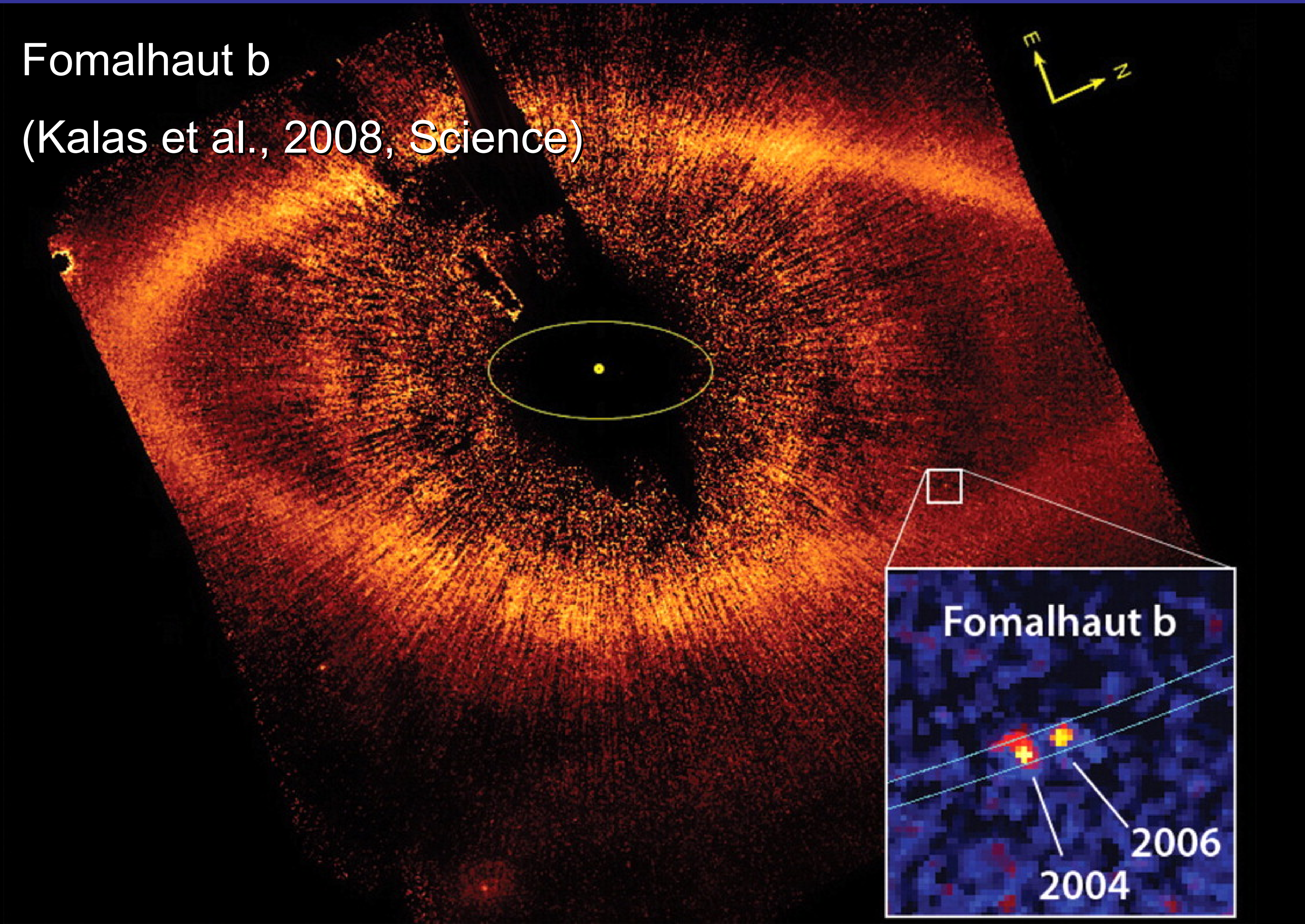


Maybe rather a double brown dwarf ?

EXOPLANETS

Fomalhaut b

(Kalas et al., 2008, Science)

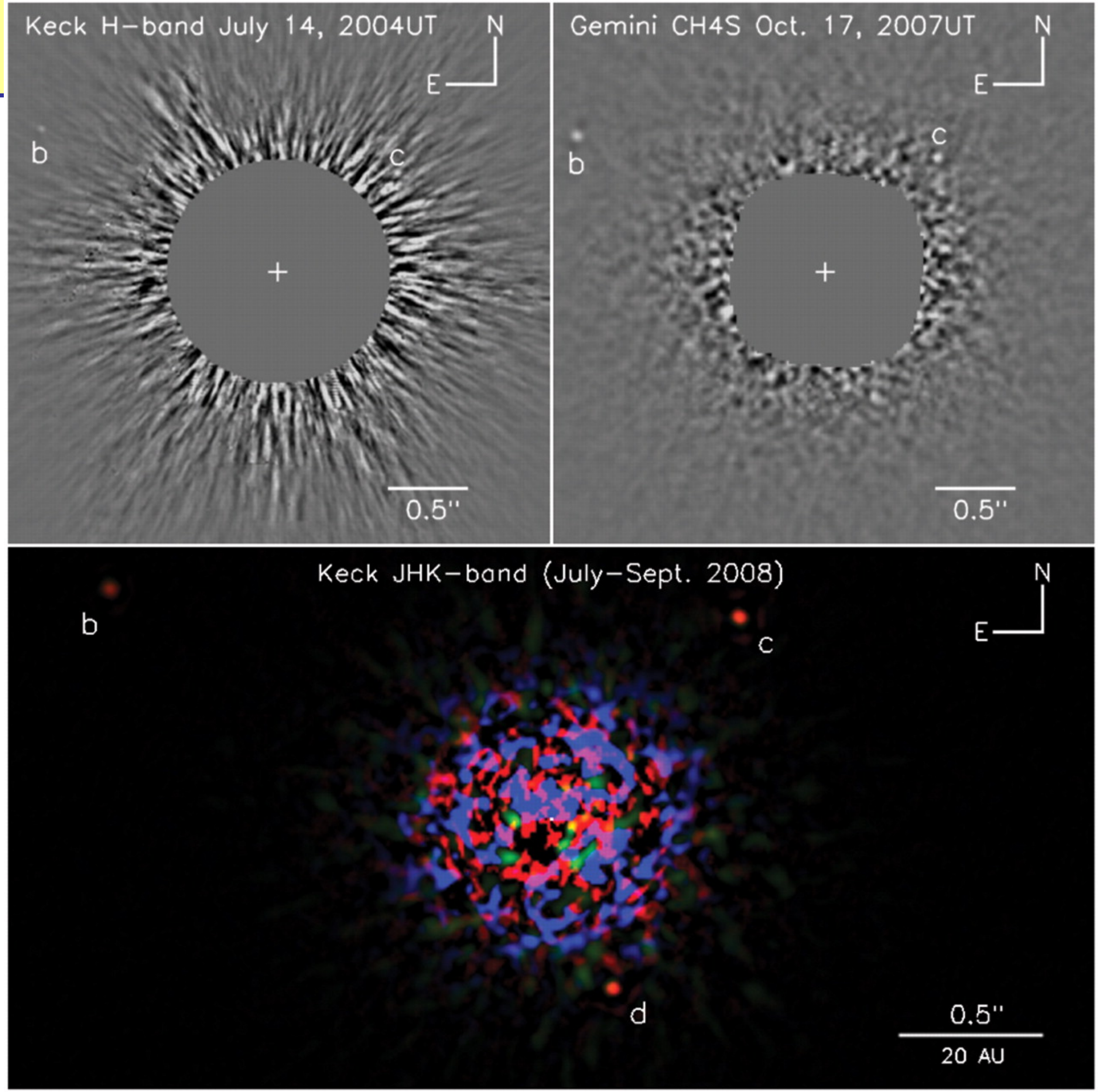


HR8799 :

3 giant planets at 24, 38, 68 AU of the star.

(Marois et al., 2008, Science)

+ 1 fourth one confirmed in november 2010



EXOPLANETS

They exist ! Giordano Bruno was right.

It is a revolution in our understanding / view of the Universe.

1) heliocentrism (Copernic, 1543)

2) island universes = other galaxies (Hubble, 1925)

3) exoplanets (Mayor & Queloz, 1995)

4) extraterrestrial life ?

DRAKE FORMULA

Drake (1971) : divide our ignorance about the number *N* of civilisations having developed an electromagnetic technology in our Galaxy:

$$N = R \times f \times L$$

R = Rate of formation of solar type stars in the Galaxy (~1 / year)

f = fraction of solar type stars of the Galaxy which have a planetary system which hosts an intelligent form of life which has developed electromagnetic communication systems

$$f = f_{planets} * n_{habitable} * f_{life} * f_{intel} * f_{com}$$

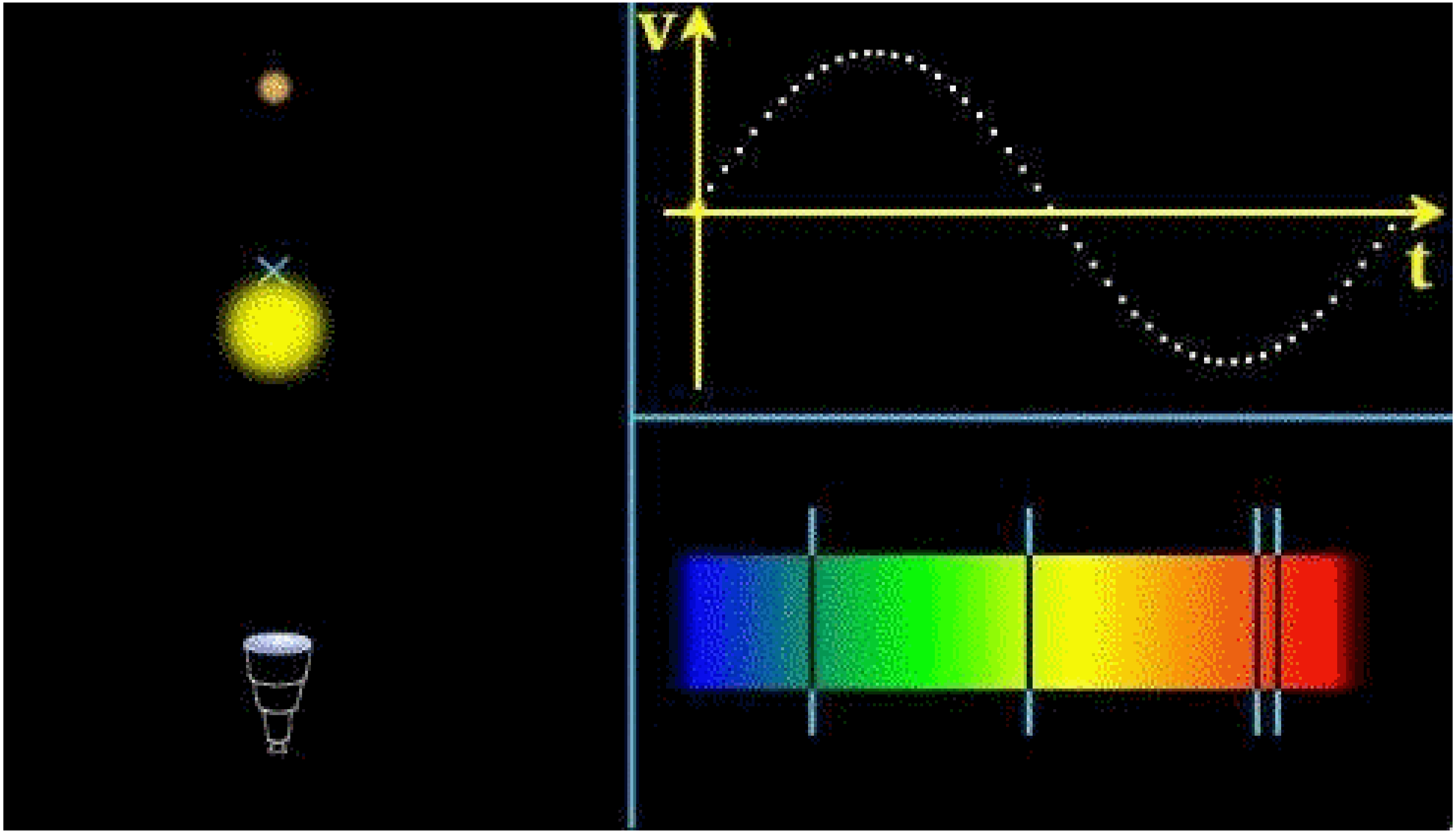
L = Lifetime of these civilisations (*L* > 100 years,apparently) .

R, f_p, n_{hab} = astronomical factors, well known.

f_{vie}, f_{intel} = biological factors.

f_{com}, L = sociological factors.

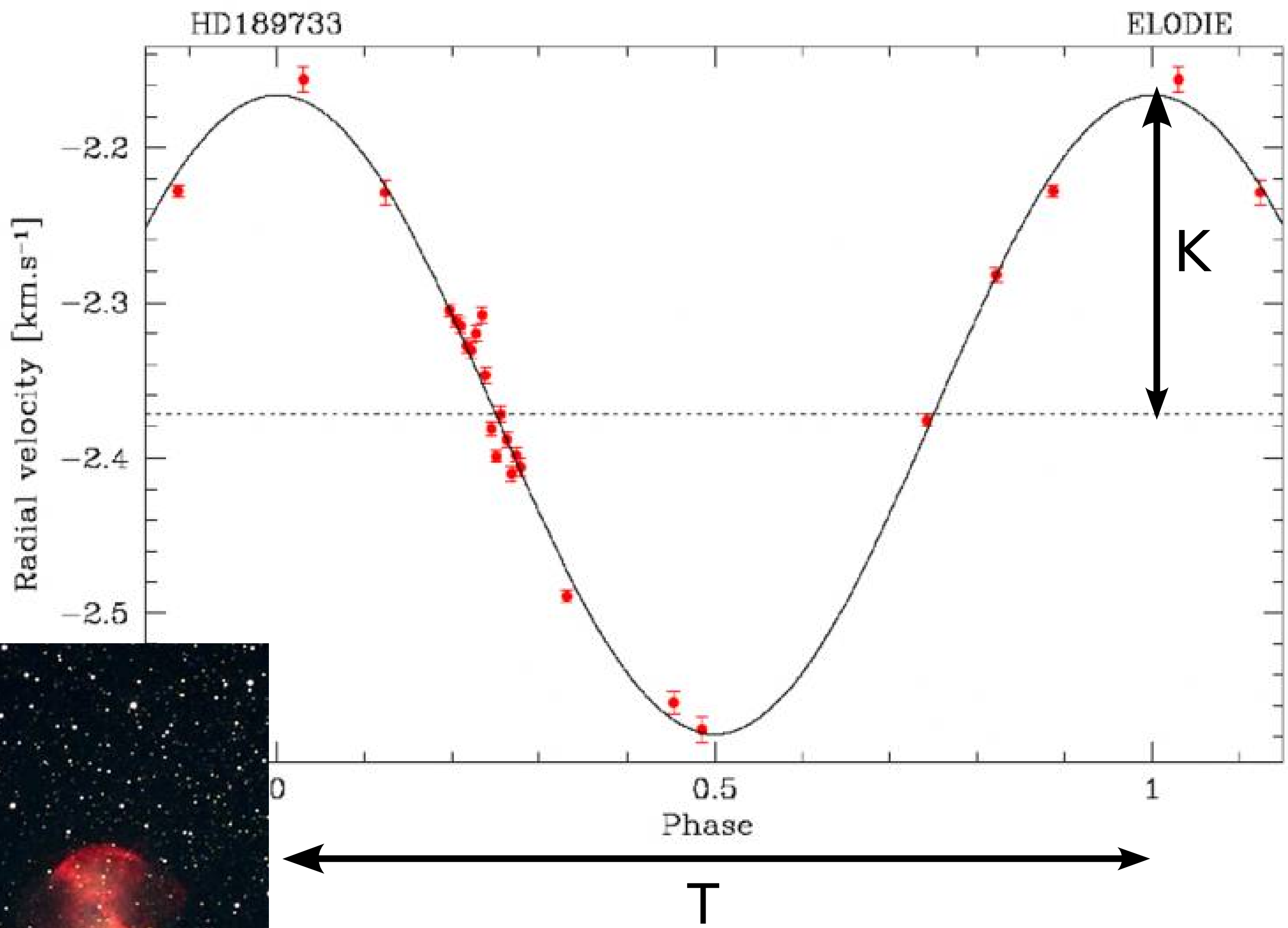
EXOPLANETS Ia) Radial velocity



EXOPLANETS Ia) Radial velocity

Example :

HD189733.

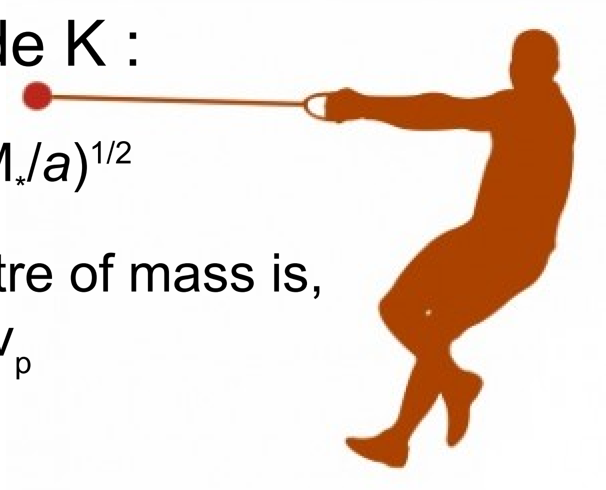


EXOPLANETS Ia) Radial velocity

The **semi major axis** *a* is given by the period T :

$$T^2 = (4\pi^2/GM_*)a^3$$

The **mass $q=M_p/M_*$** is given by the amplitude K :



The velocity of the planet is : $v_p = a\Omega = (GM_*/a)^{1/2}$

Thus the velocity of the star around the centre of mass is, by conservation of the momentum : $v_* = - q\, v_p$

Thus: $q = K\,(a/GM_*)^{1/2}$.

<u>Numerical application :</u> (reminder: $M_{Sun}=2.10^{30}$ kg)

For Jupiter, $q=10^{-3}$, a=5,2 UA, $\delta v = 13\ m.s^{-1}$.

For the Earth, $q=3.10^{-6}$, a=1UA, $\delta v = 0{,}09\ m.s^{-1}$.

EXOPLANETS Ia) Radial velocity

EXERCICE :

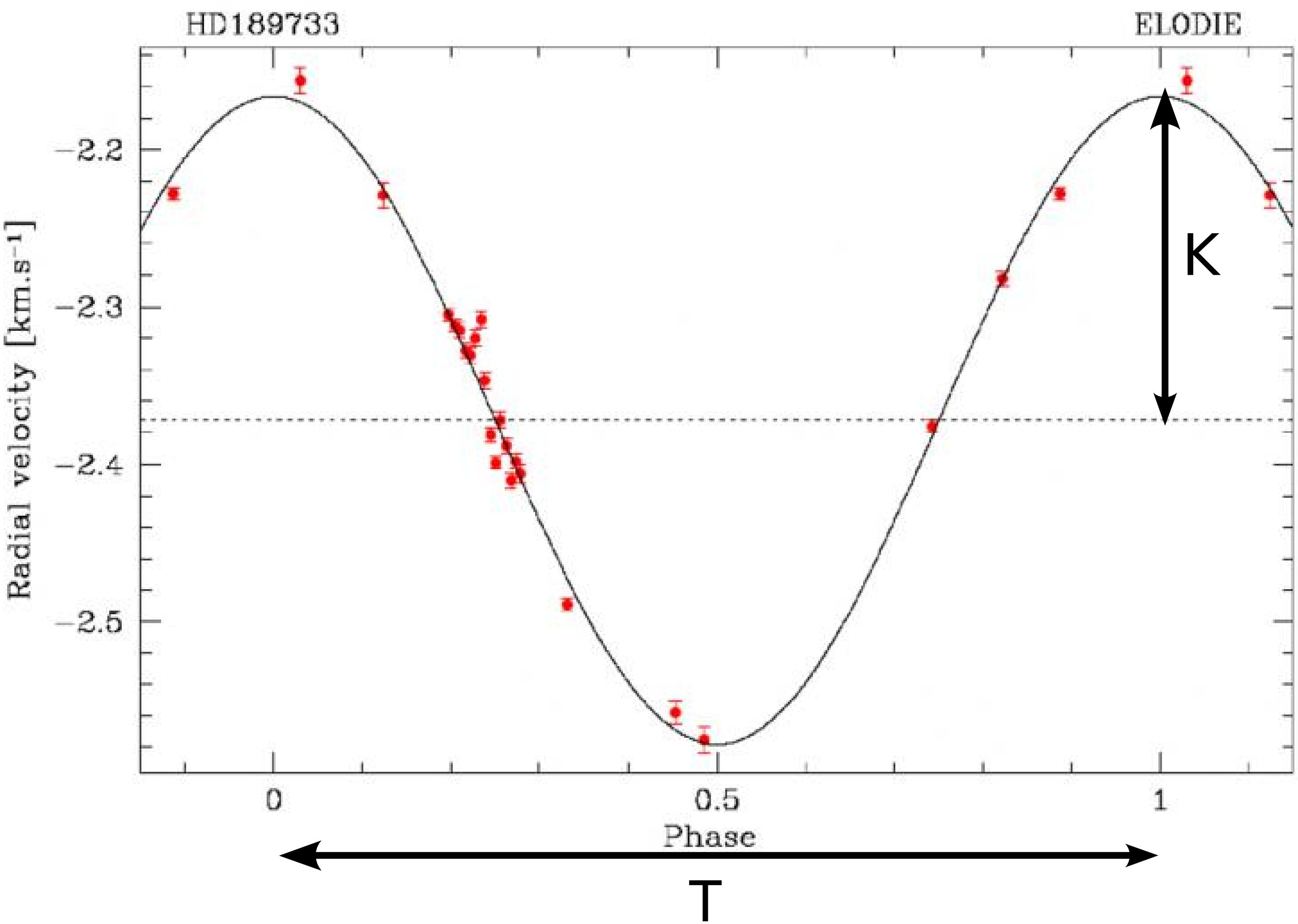
HD189733b :

One gives

T=2,218 days,

$M_* = 1{,}6 \times 10^{30}$ kg.

Find q, M_p.



EXOPLANETS Ia) Radial velocity

EXERCICE :

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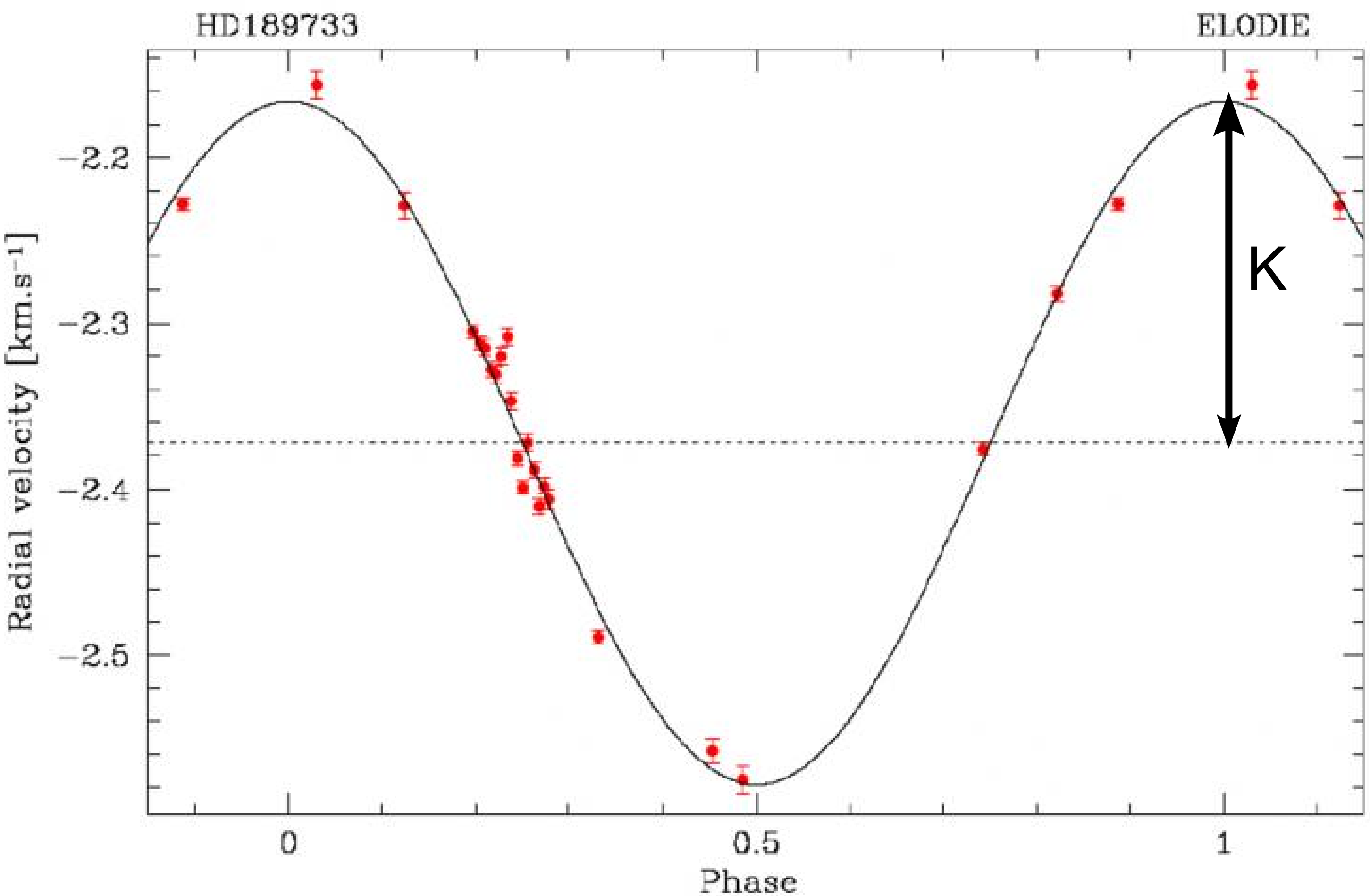


SOLUTION :

a = $4,64\times10^9$ m = 0.031 AU .   K=~200 m.s^{-1}.

Thus q=$1,3\times10^{-3}$, so M_p=1,1 M_{Jup}.

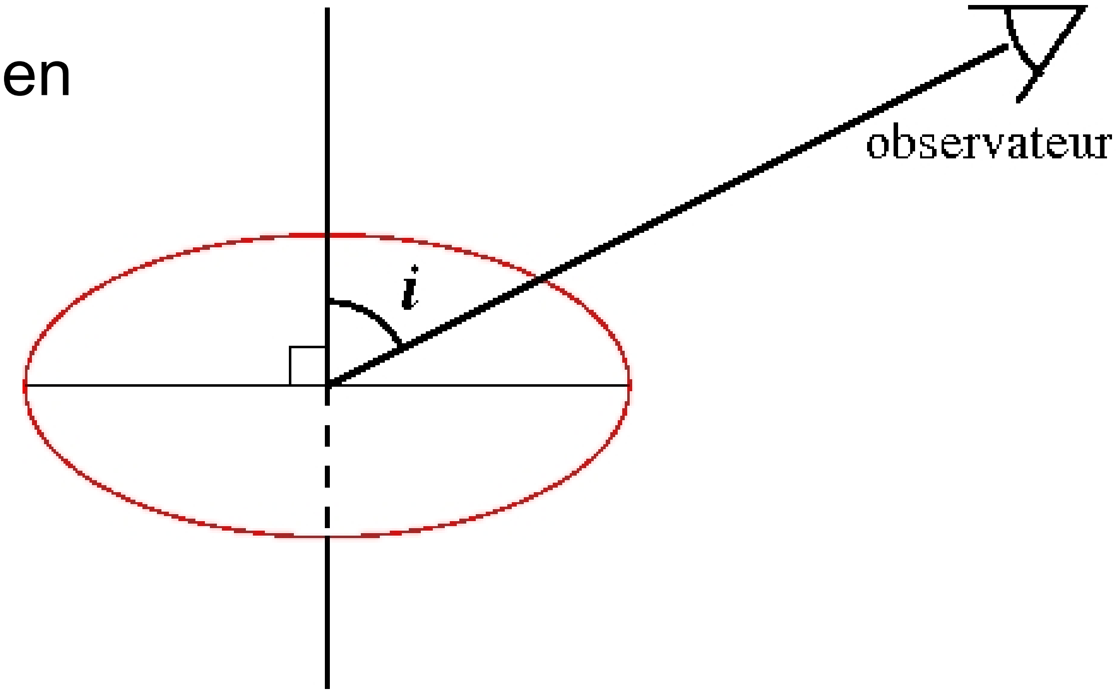
Caution !

The measured velocity is actually $q a_p \Omega_p \sin(i)$,

where i is the angle between the line of sight and the axis of the orbit.

i=0°: seen face-on, planet undetectable.

i=90°: seen edge-on, optimal case.



The obtained mass is actually $M_p \sin(i)$, where i is unknown !

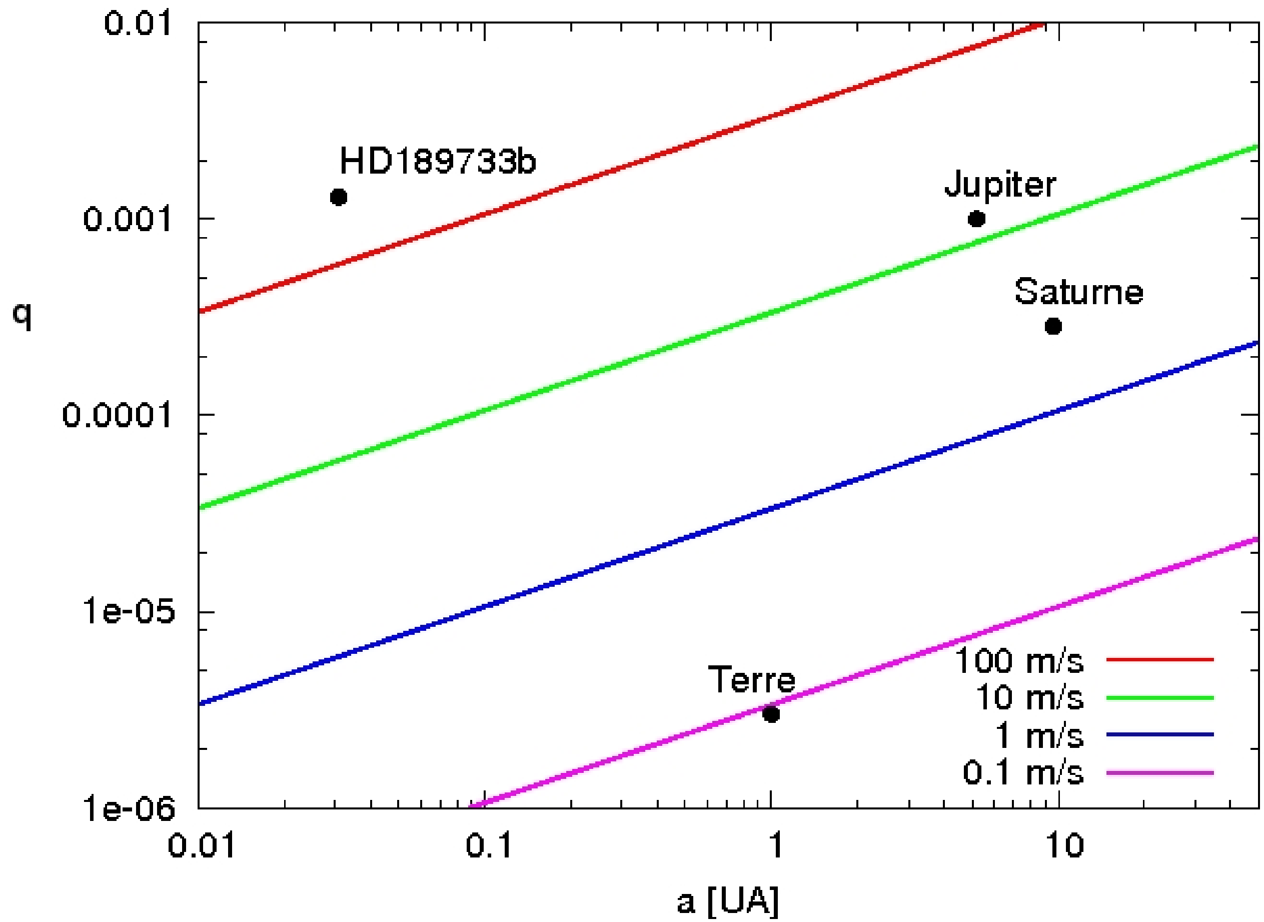
On average, $1/\sin(i)$ is $\pi/2$.

EXOPLANETS Ia) Radial velocity

Nowadays differences in velocity of the order of a few 0.1 m/s can be measured ! It corresponds to a difference in λ smaller than the width of a spectral line (remind $\delta\lambda = \lambda_0 v/c$).

Detectability :

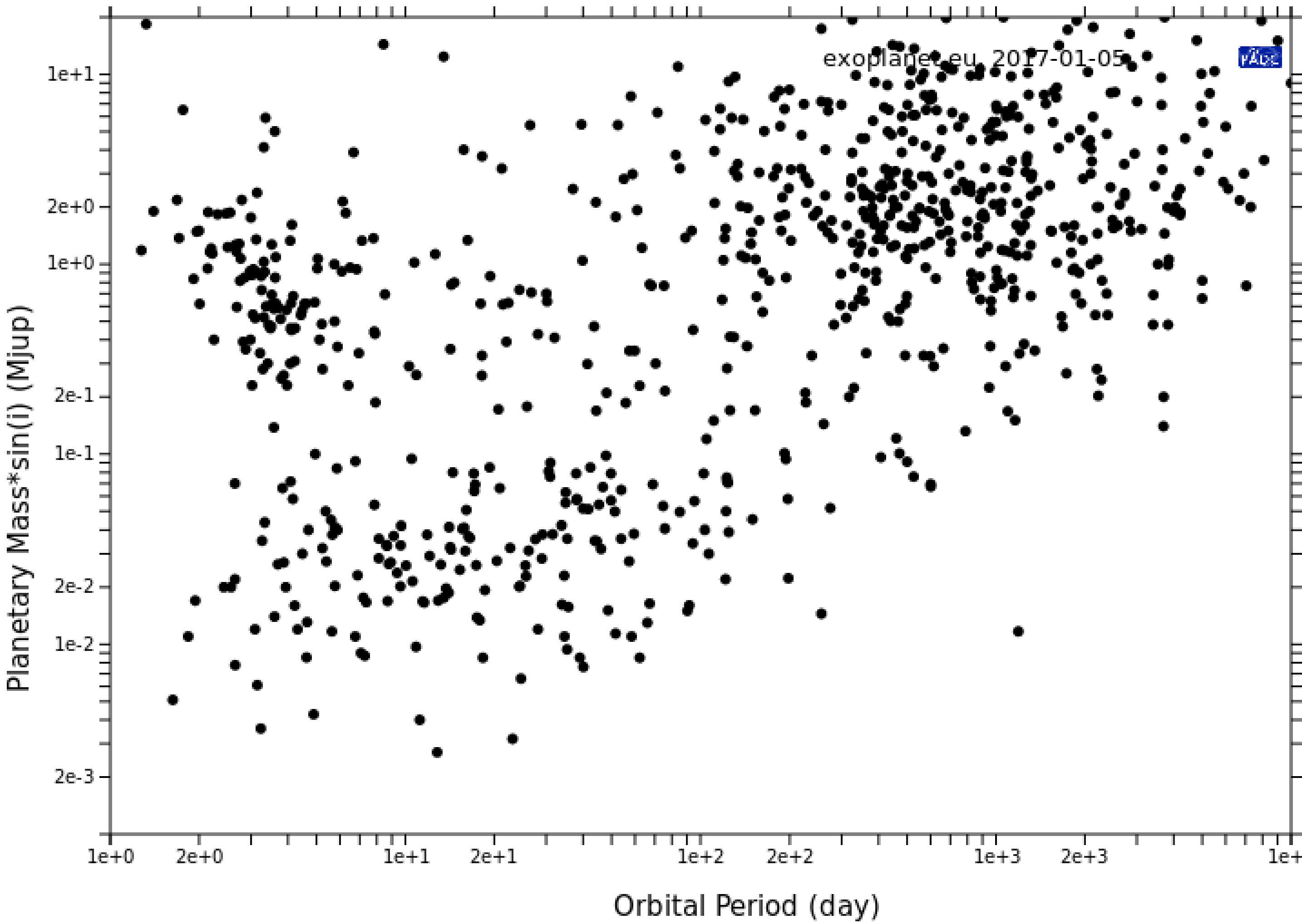
It is much easier to detect a giant planet close to its star.



EXOPLANETS Ia) Radial velocity

Detections :

All 786 planets detected using radial velocity on January 5th, 2017.



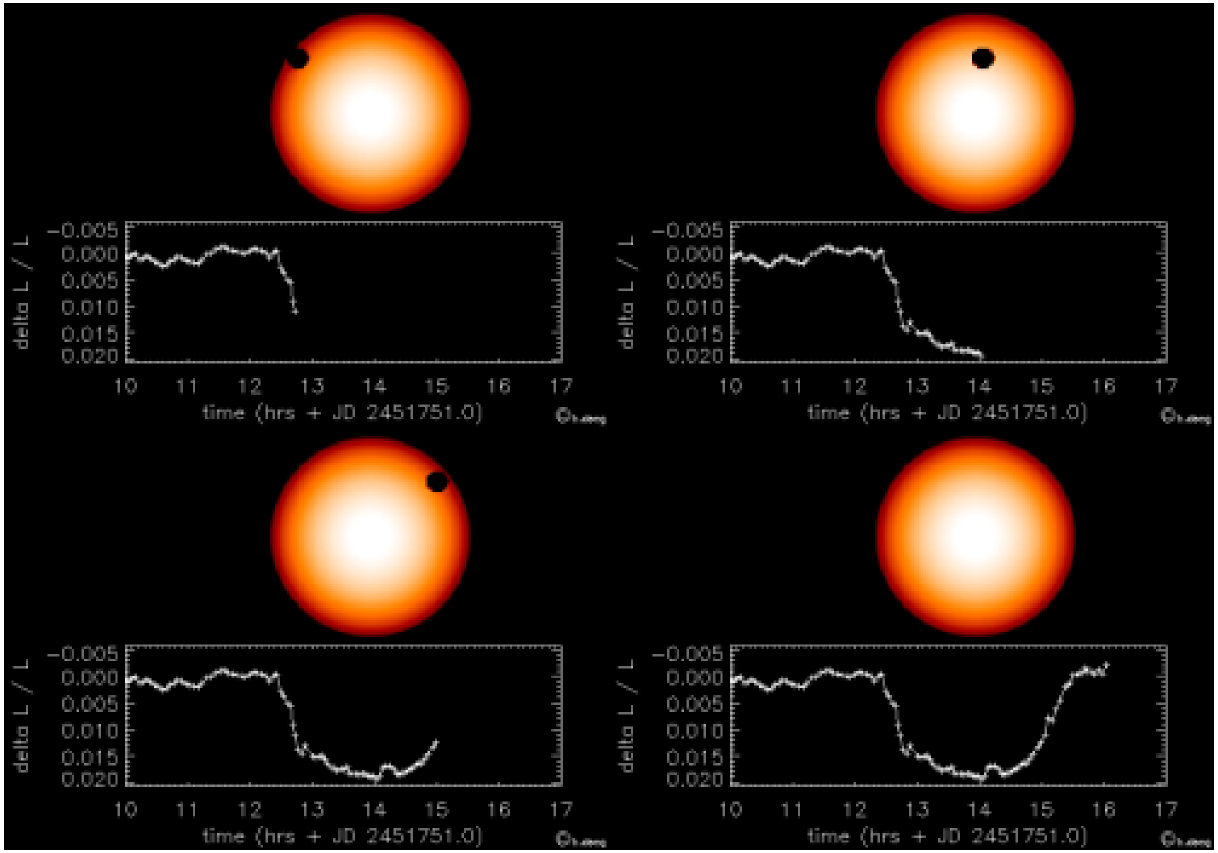
Clearly a biais against large a and small q...

EXOPLANETS : Ib) Transit

EXOPLANETS : Ib) Transit

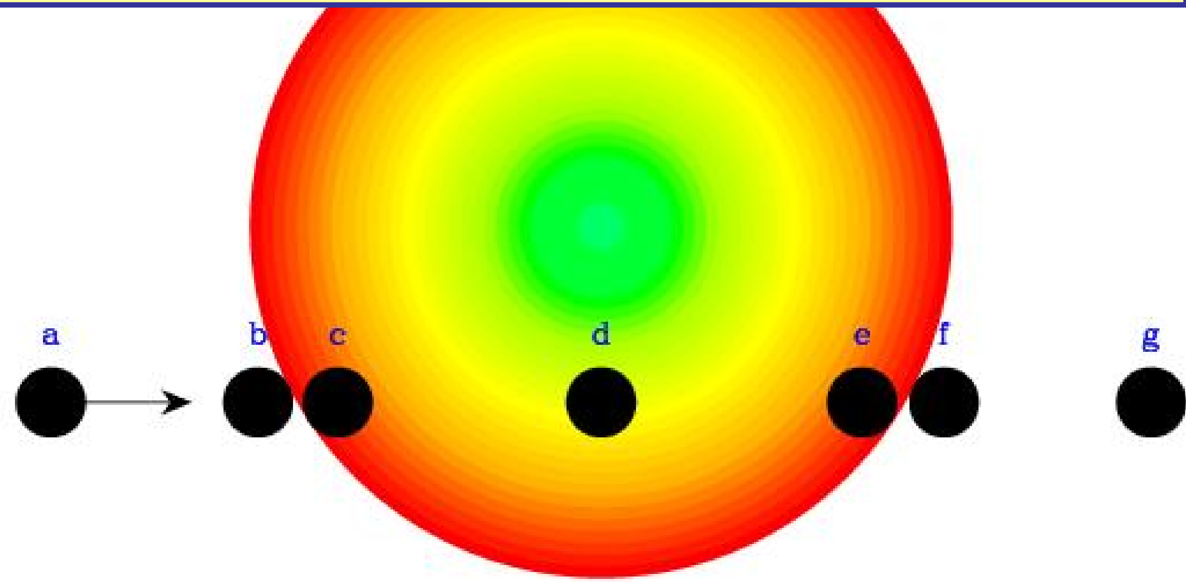
Like Venus in front of the Sun in 2004 and 2012, sometimes, an exoplanet moves in front of its star, this is a **transit**.

Then, on sees a decrease of the luminosity of the star :

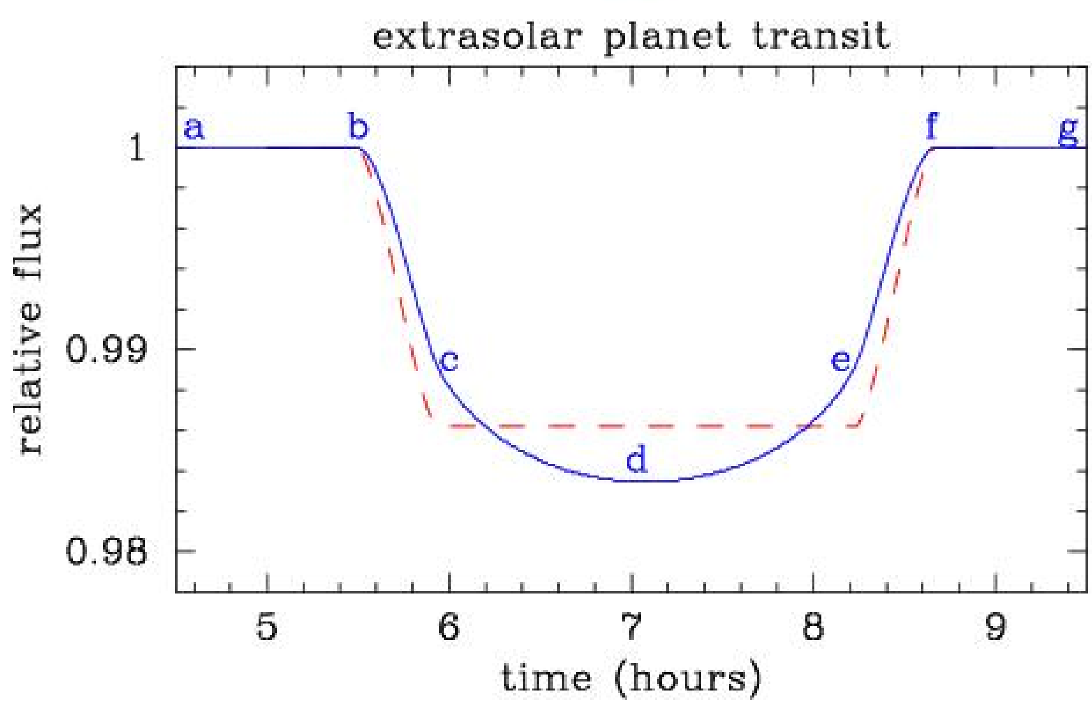


EXOPLANETS : Ib) Transit

Limb darkening effect : the bottom of the transit isn't flat.



A transit lasts a few hours.

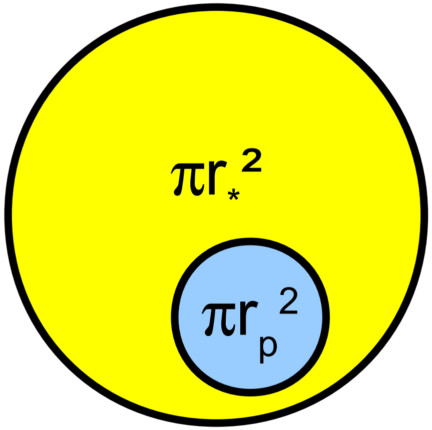


EXOPLANETS : Ib) Transit

<u>Advantages of the transit method :</u>

The amplitude of the transit gives the radius of the planet :

$$\delta L/L = \pi r_p^2 / \pi r_*^2 = (r_p/r_*)^2$$



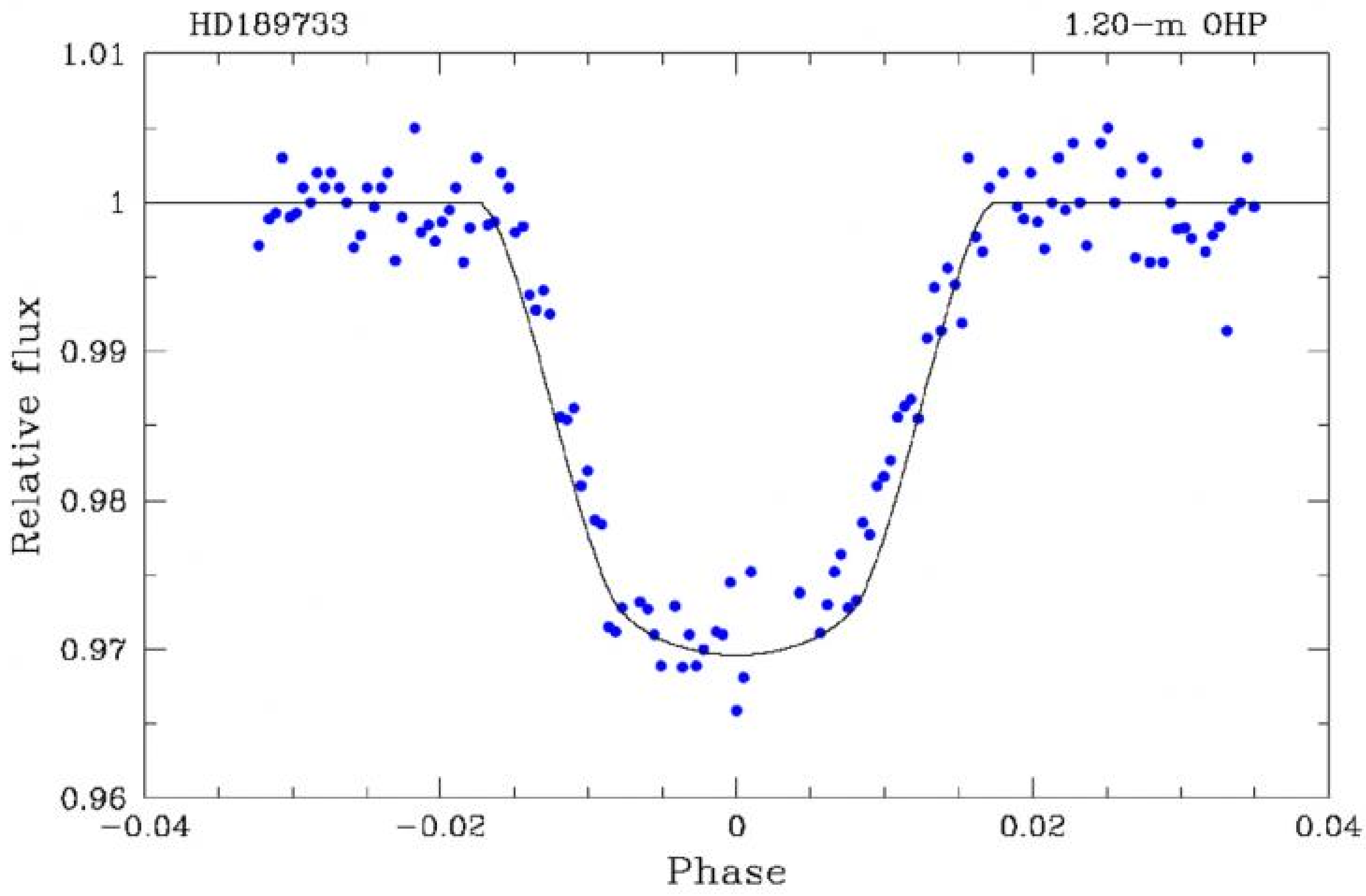
The period of the transit gives the semi major axis (Képler's law).

The radial velocity gives the real mass : i=90°.

One derives the density of the planet !

EXOPLANETS : Ib) Transit

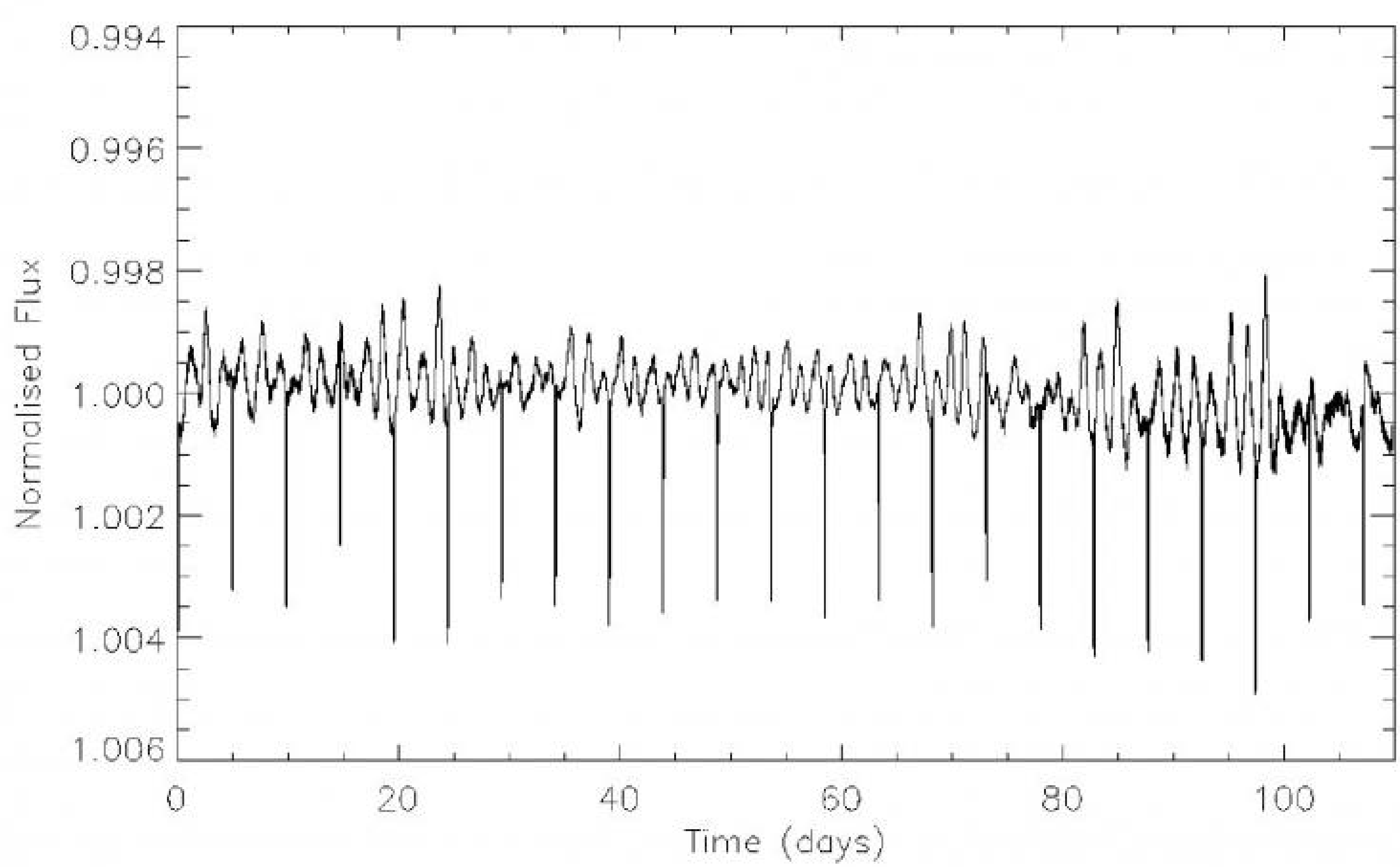
Ex: HD 189733b, seen in radial velocity, also has a transit :



EXOPLANETS : Ib) Transit

Note : a planetary transit should be periodic.

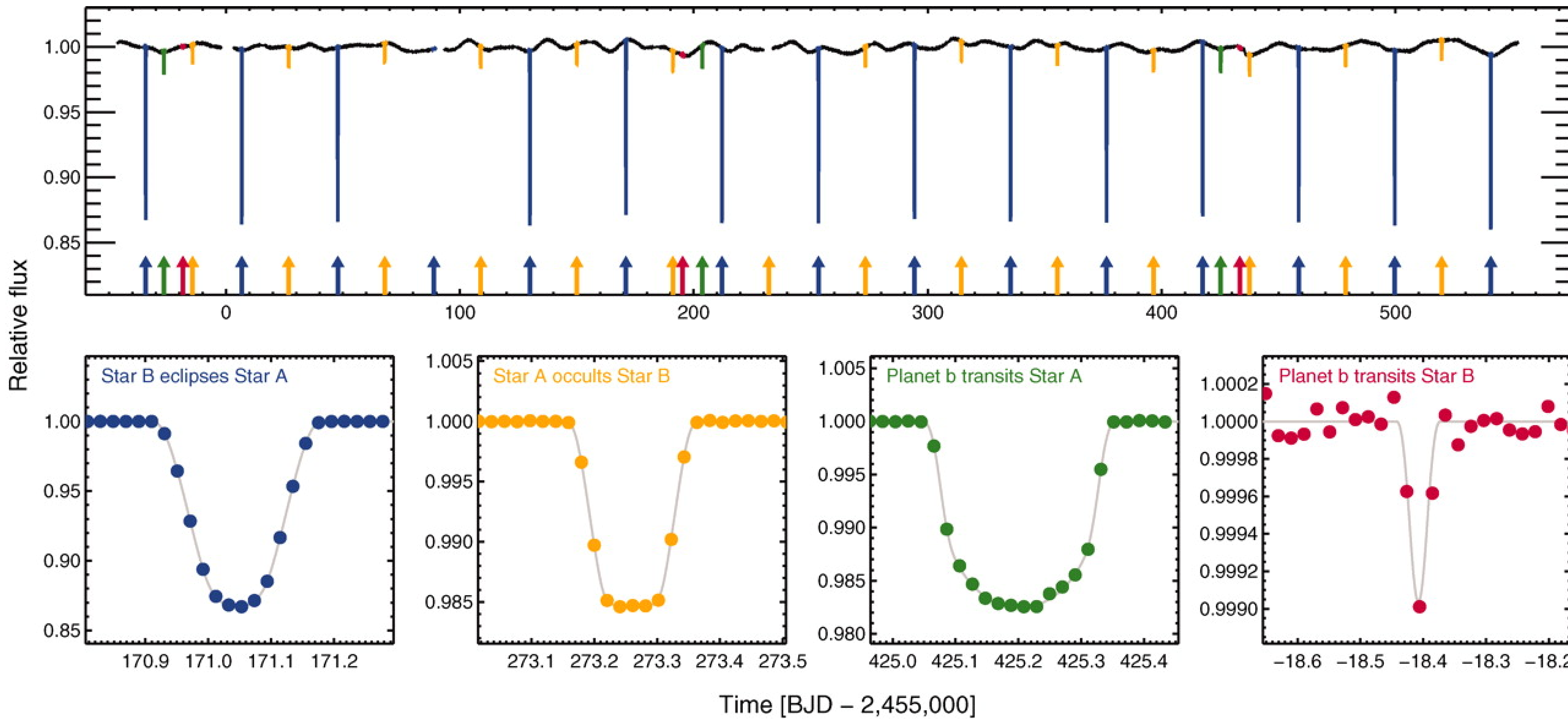
Ex: light curve of a star observed by Corot :



EXOPLANETS : Ib) Transit

Note : a planetary transit should be periodic.

Ex: light curve of a double star with a planet.

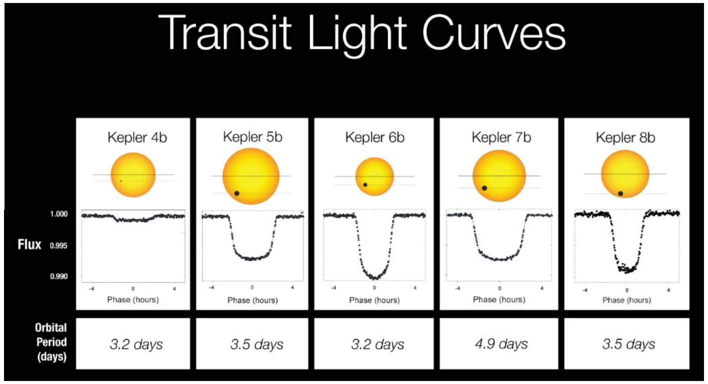


EXOPLANETS : Ib) Transit

<u>Transit dedicated missions :</u>

Corot (2006-2014)

Kepler (2009-2013)



CHEOPS

TESS

PLATO : PLAnetary Transits and Oscillations of stars

Future M3 mission of ESA (launch 2024).
Aims at bright stars.

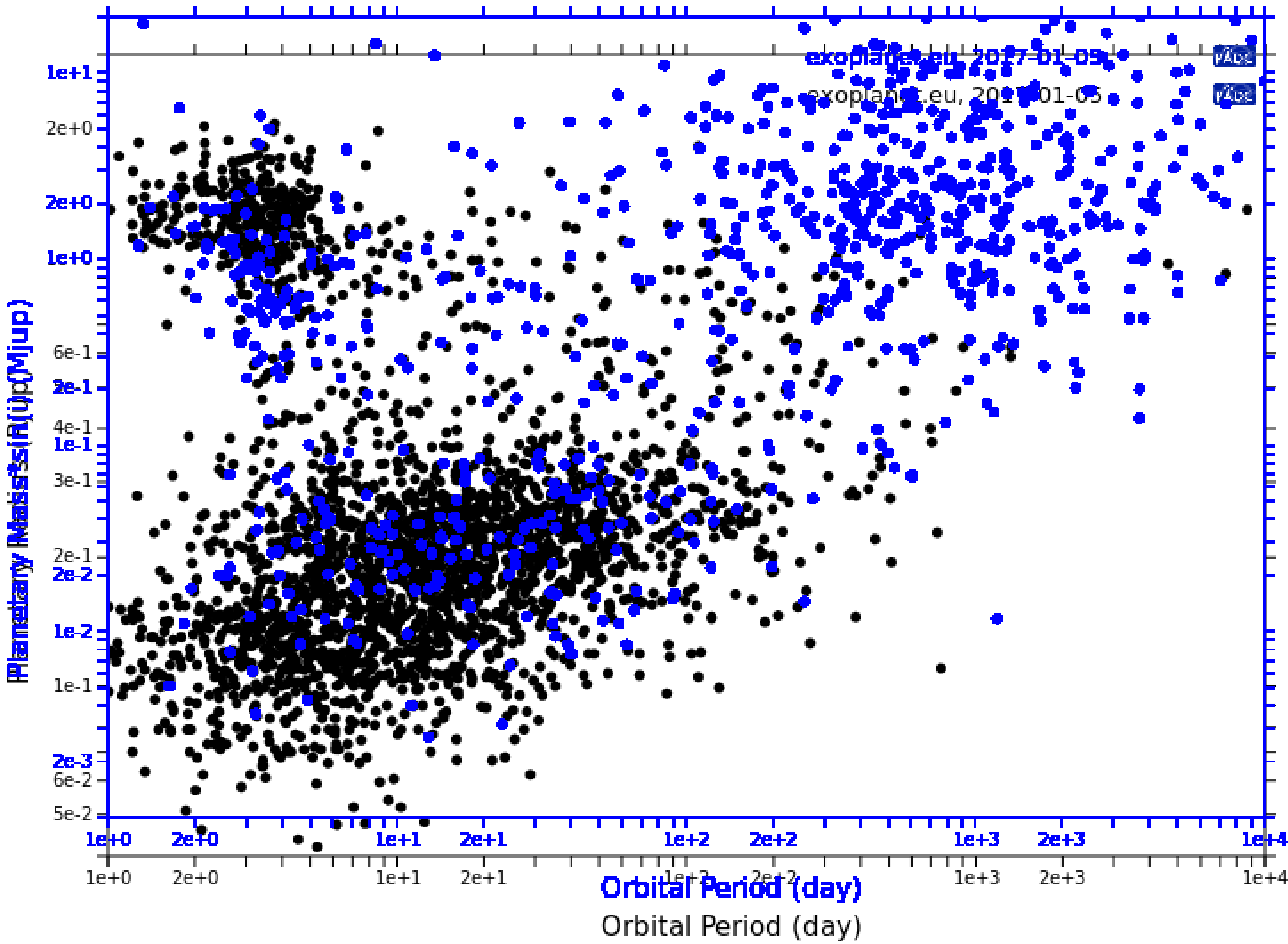
European Space Agency
Agence spatiale européenne

EXOPLANETS : Ib) Transit

Detections :

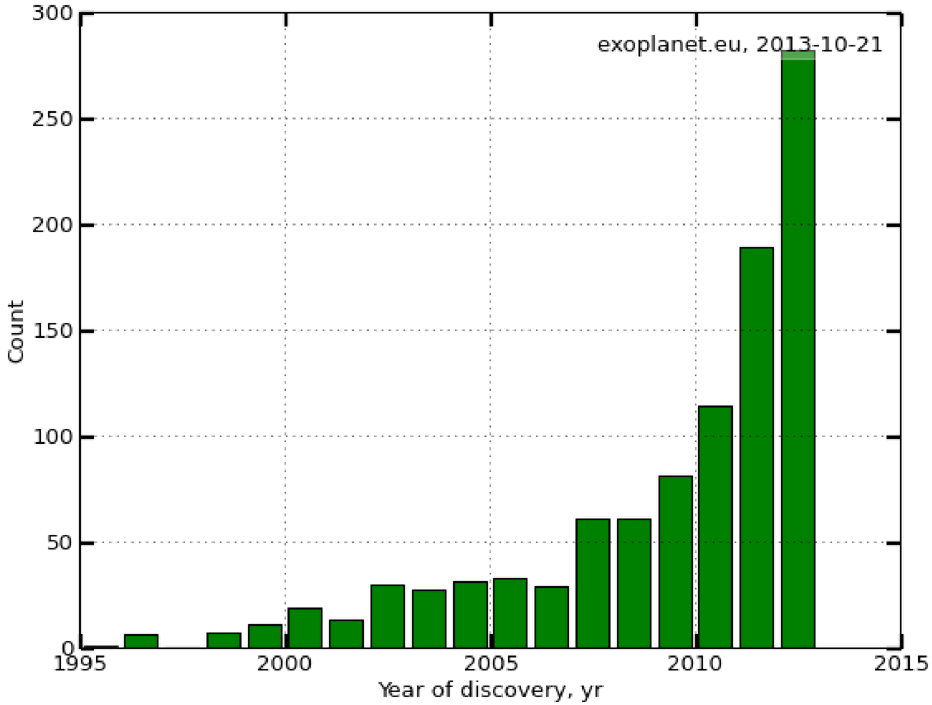
All 2648 planets detected by transit on January 5th, 2017.

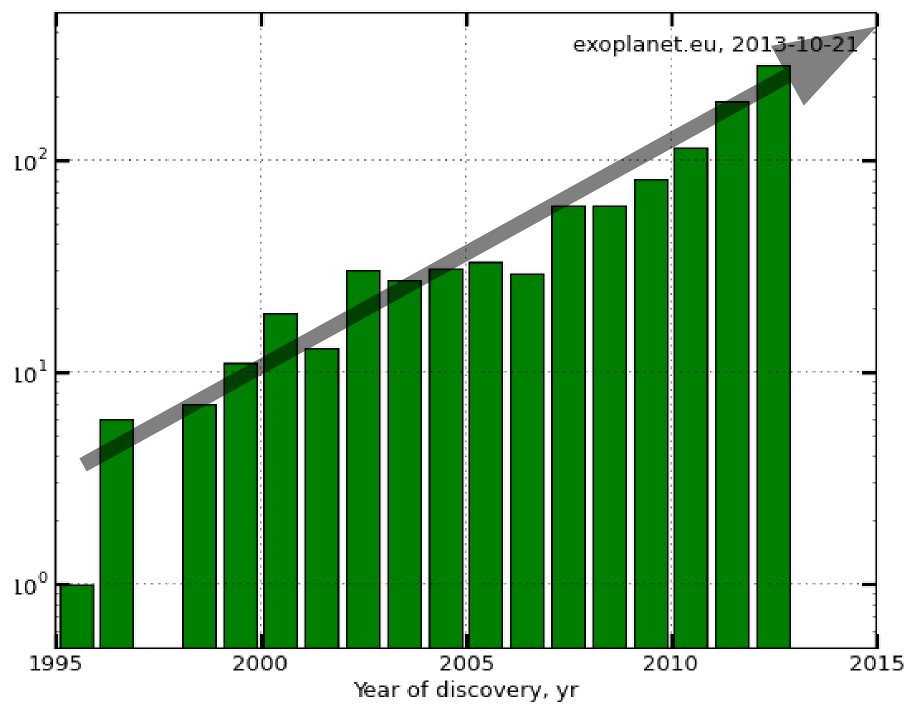
Clearly a biais against long T and small R...



EXOPLANETS : I Detections summary

The number of detections per year seems to grow exponentially :



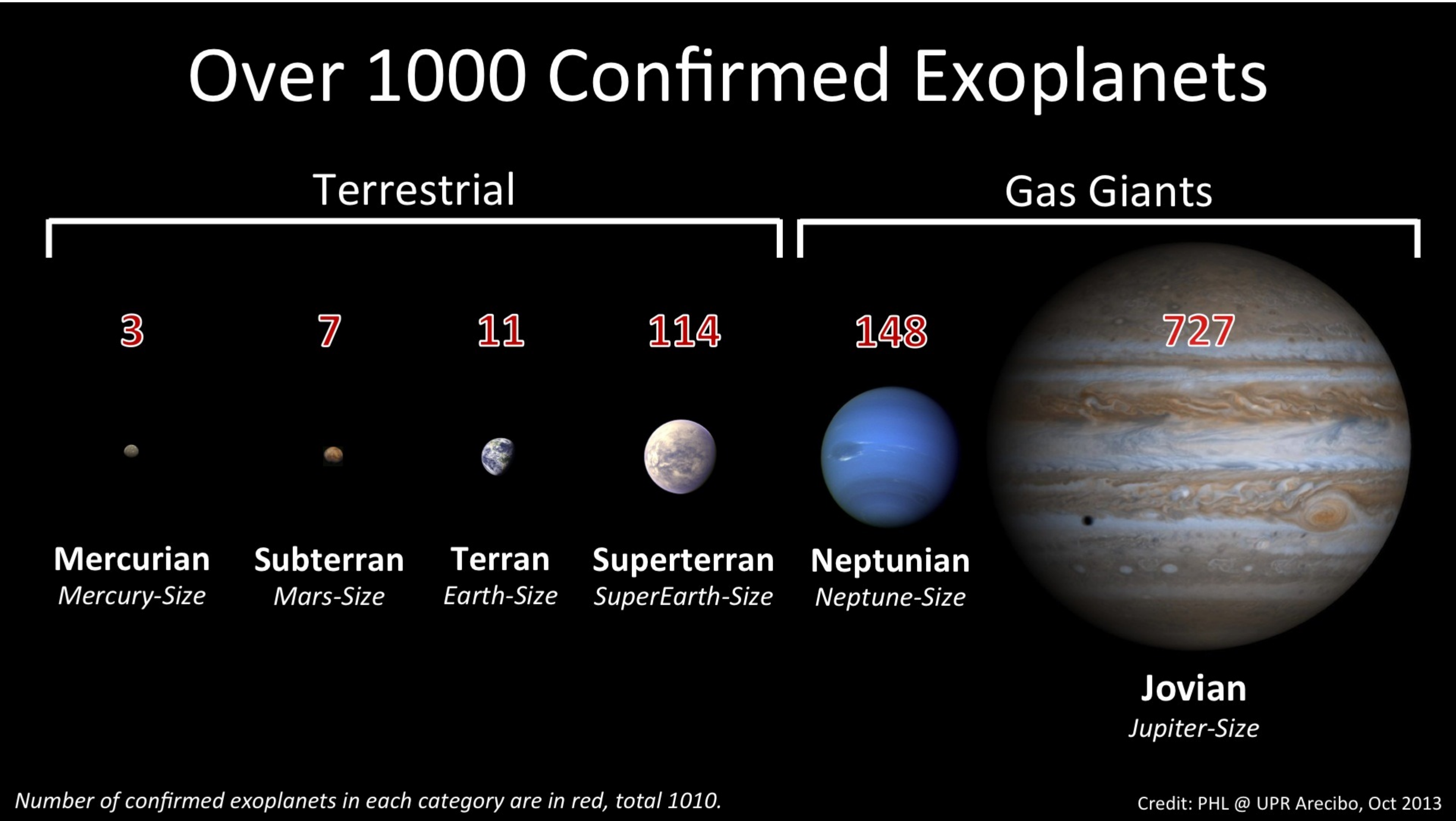


Life is in logscale...

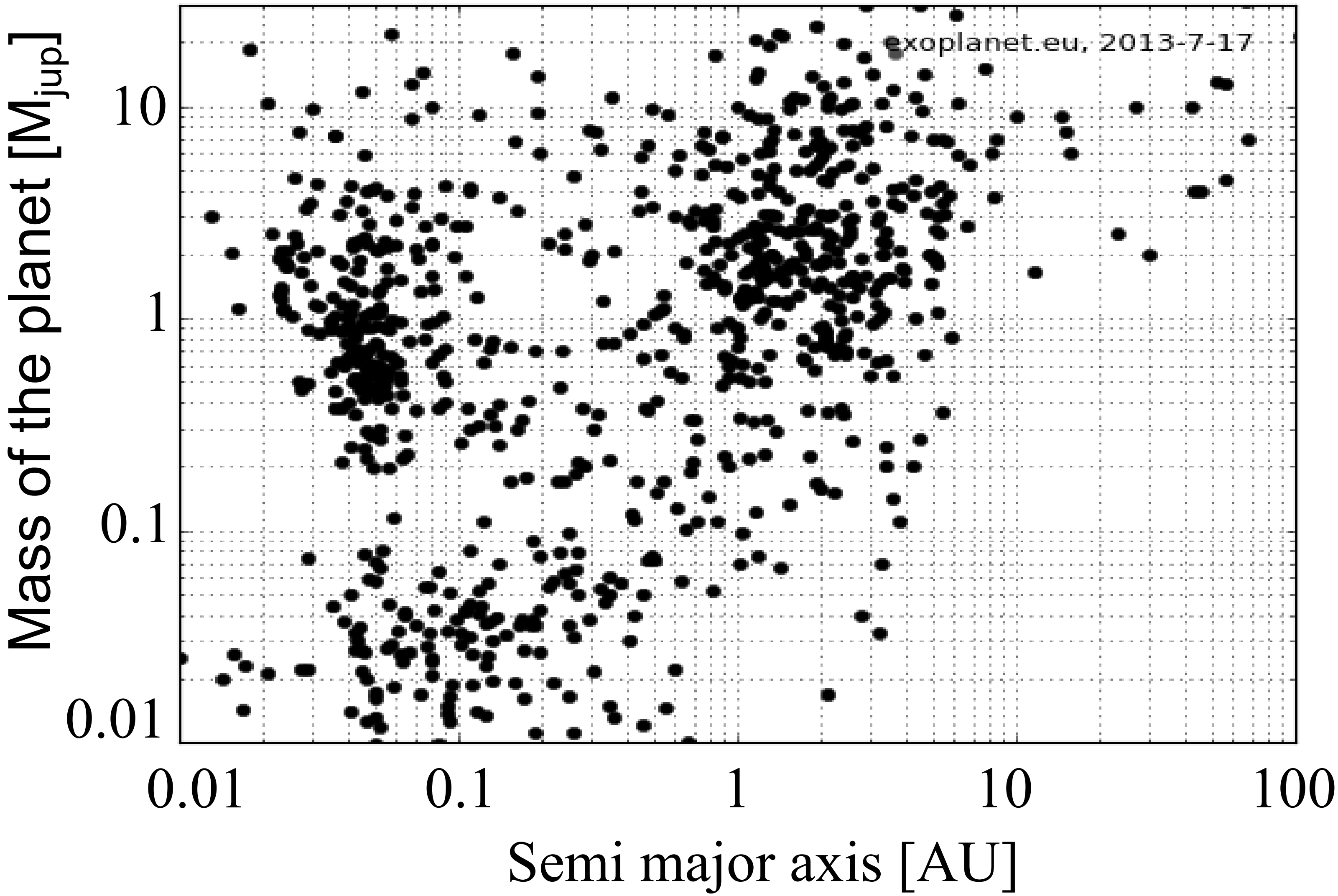
EXOPLANETS : II) Statistics

See www.exoplanet.eu :

data, statistics, correlations, ...



EXOPLANETS : II) Statistics



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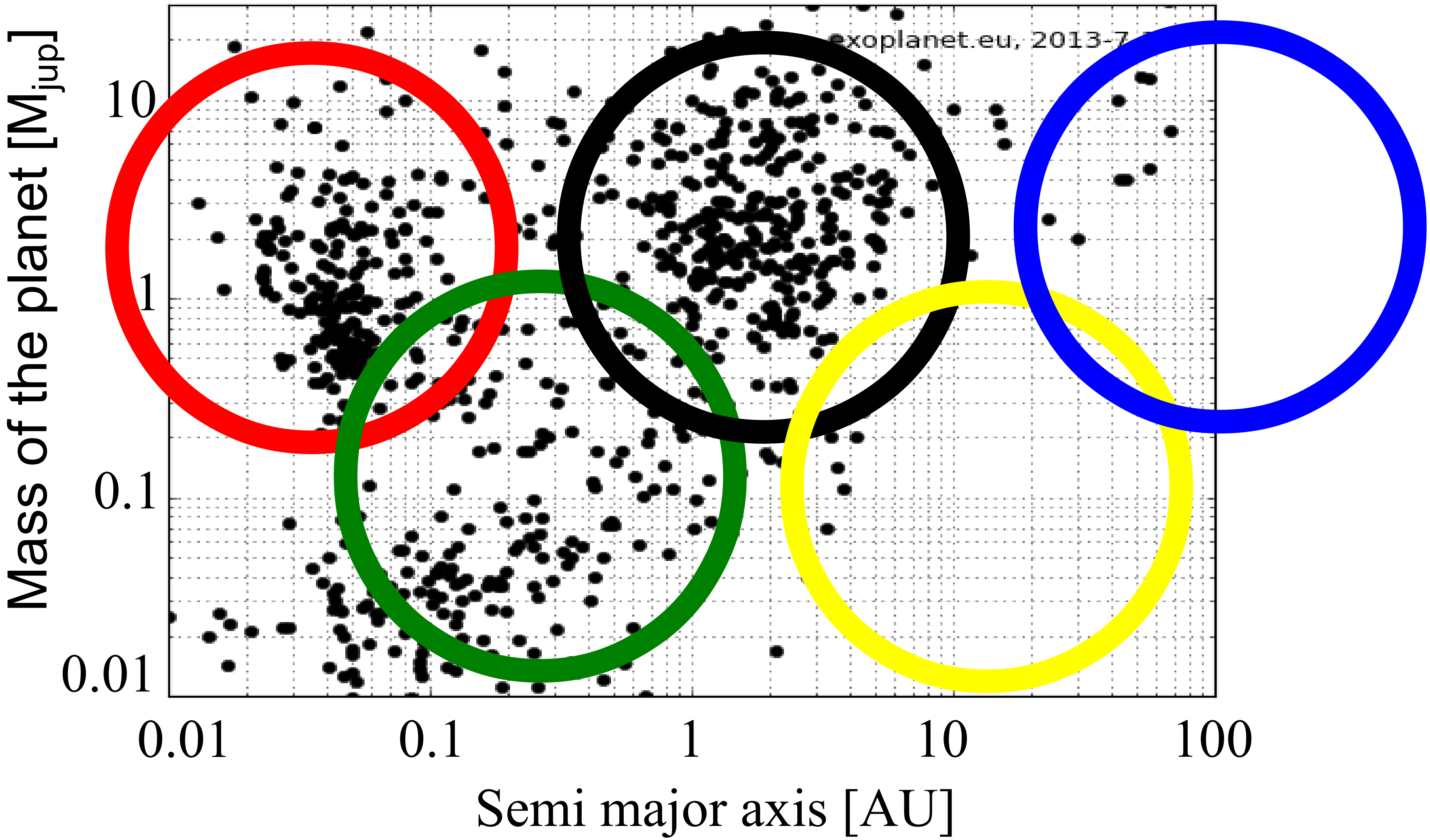

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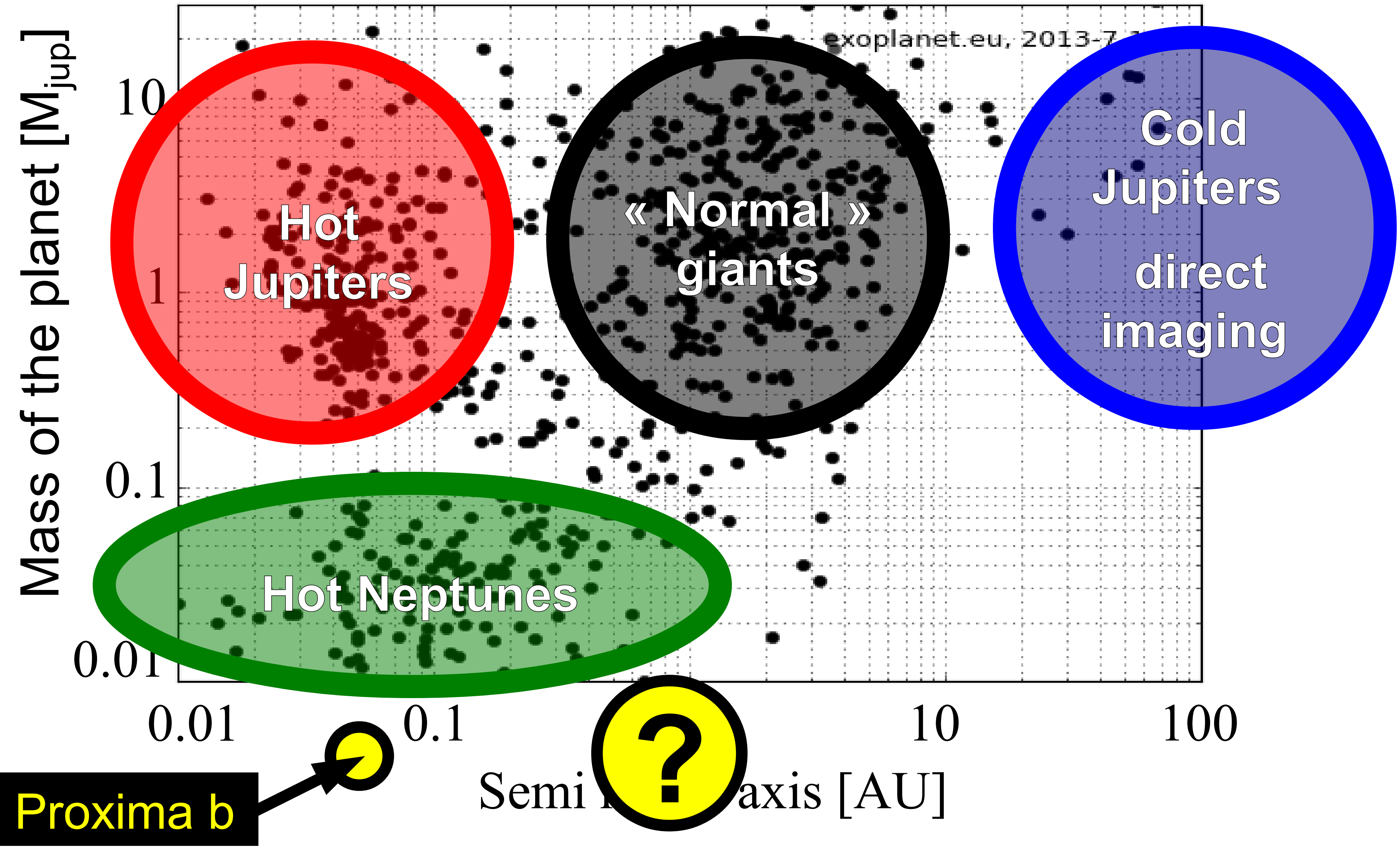
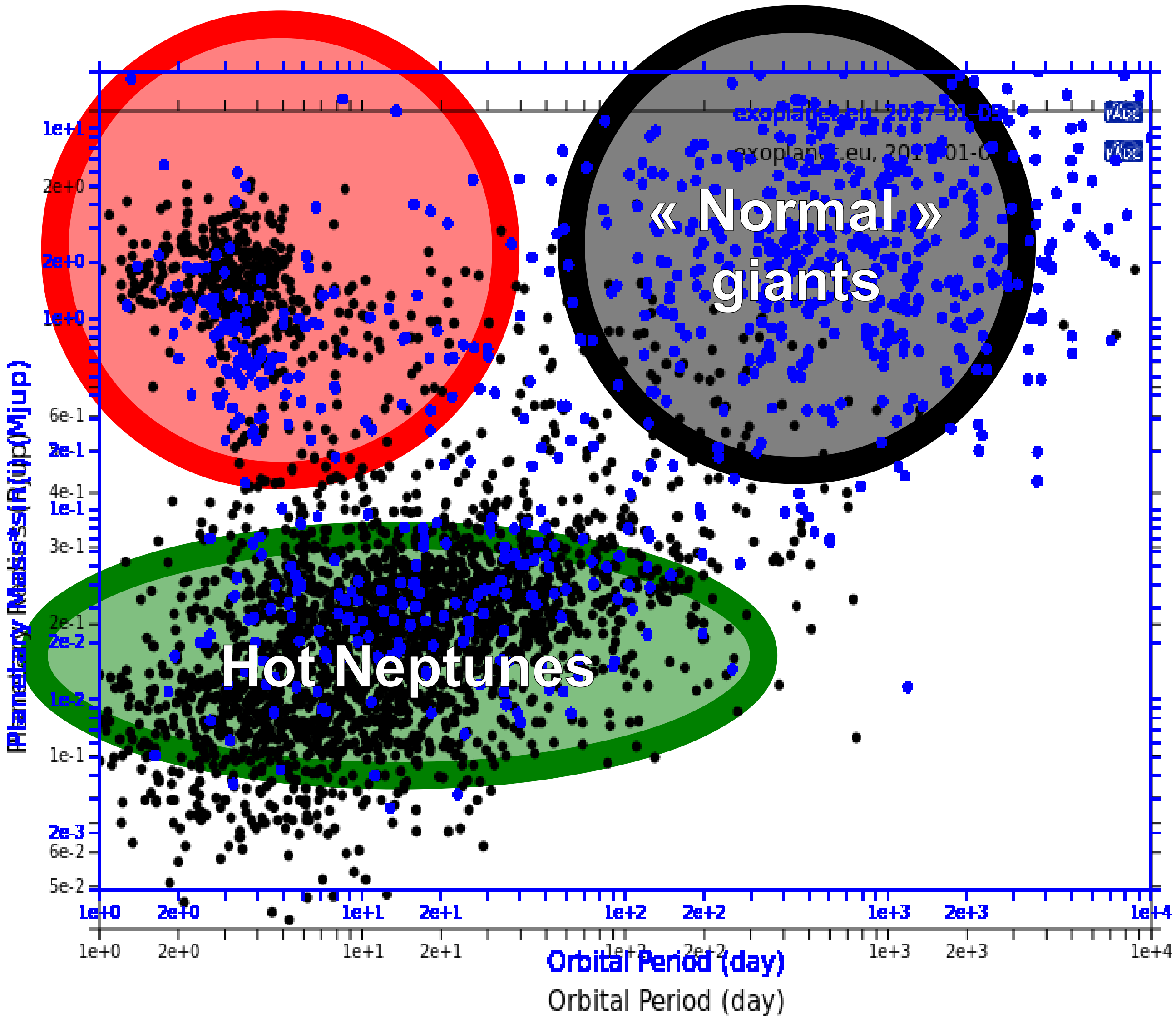


EXOPLANETS : II) Statistics

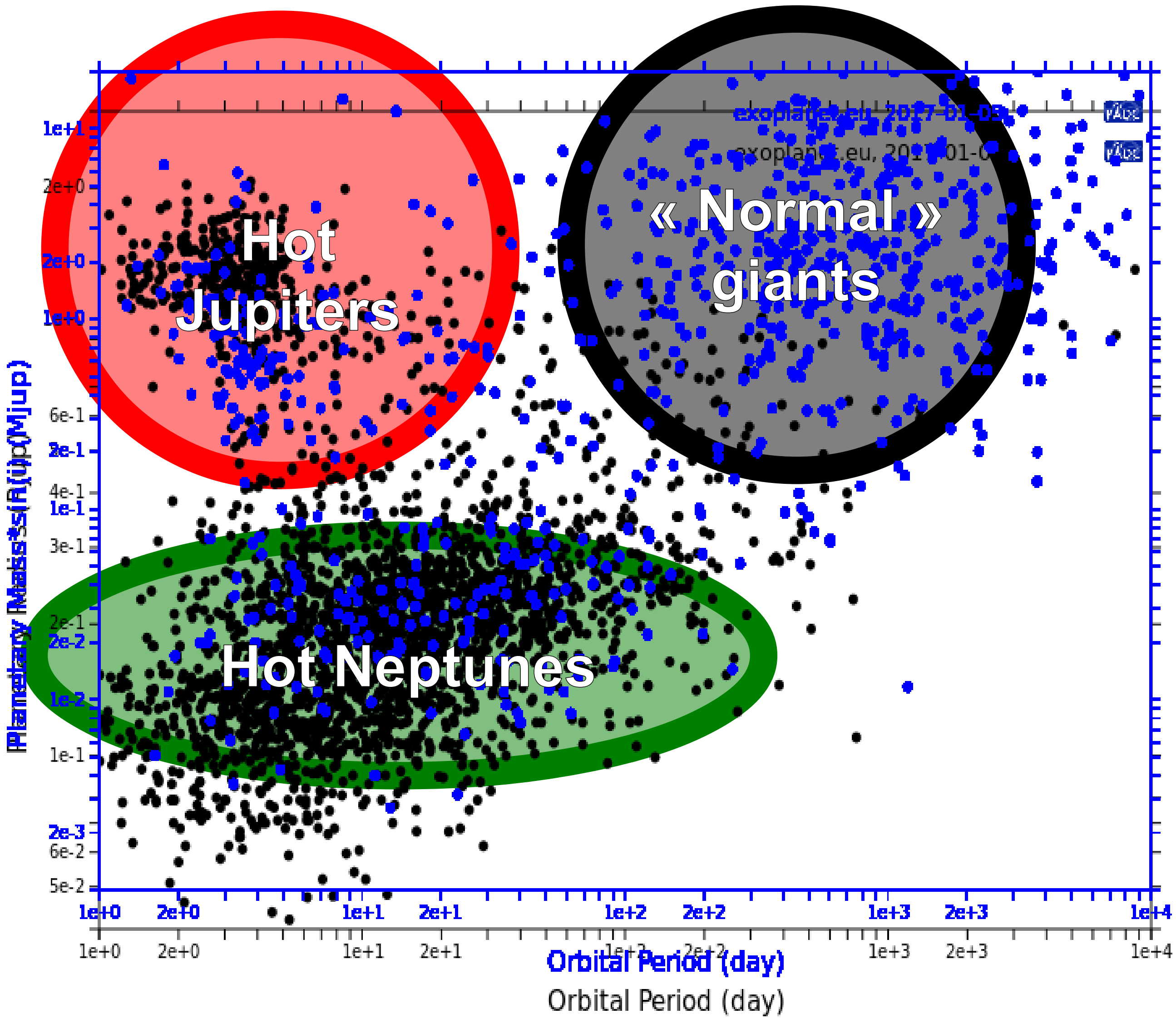


Hot Jupiters are not as massive as large → less dense than Jupiter :
« inflated hot Jupiters »

Formation ?

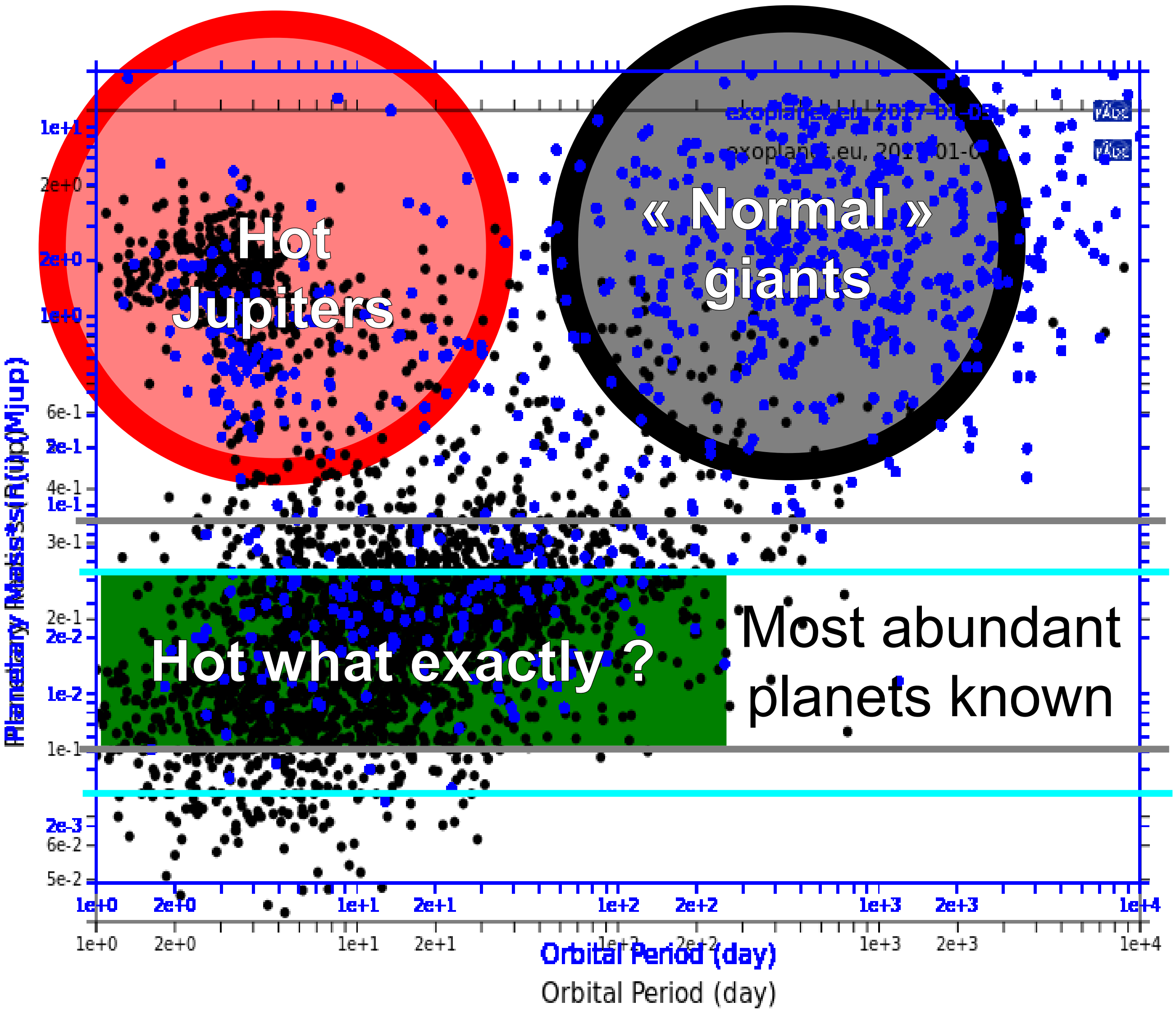
Evolution ?

EXOPLANETS : II) Statistics



0.2 R_{Jup} → 0.022 M_{Jup}. Hot Neptunes are ~3 times denser than Jupiter, as is Neptune.

EXOPLANETS : II) Statistics



Neptune's radius

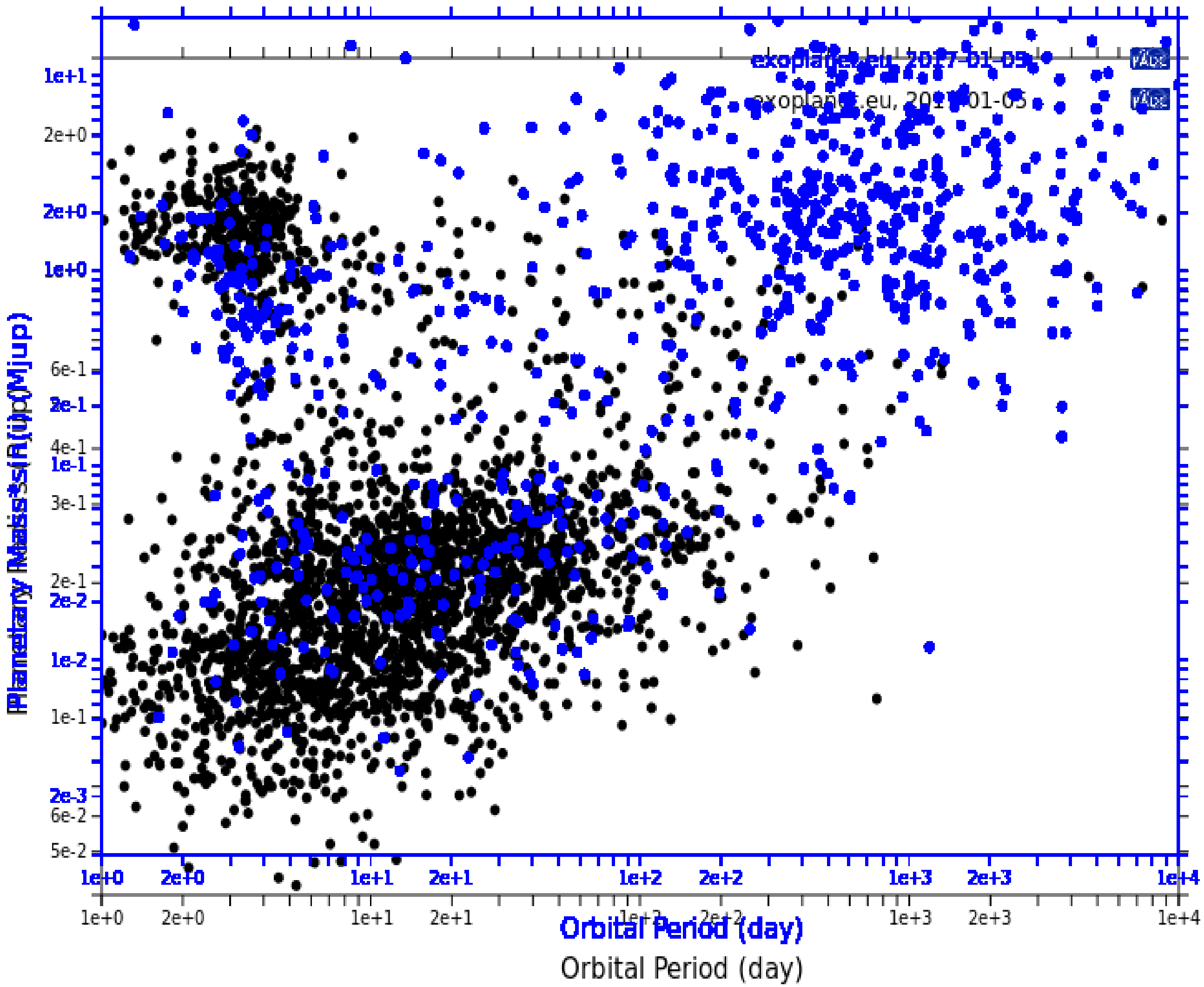
Uranus' mass

Earth radius

Earth mass

0.2 RJup → 0.022 MJup. Hot Neptunes are ~3 times denser than Jupiter, as is Neptune.

EXOPLANETS : II) Statistics



Local formation close to the stars ?

Migration ?

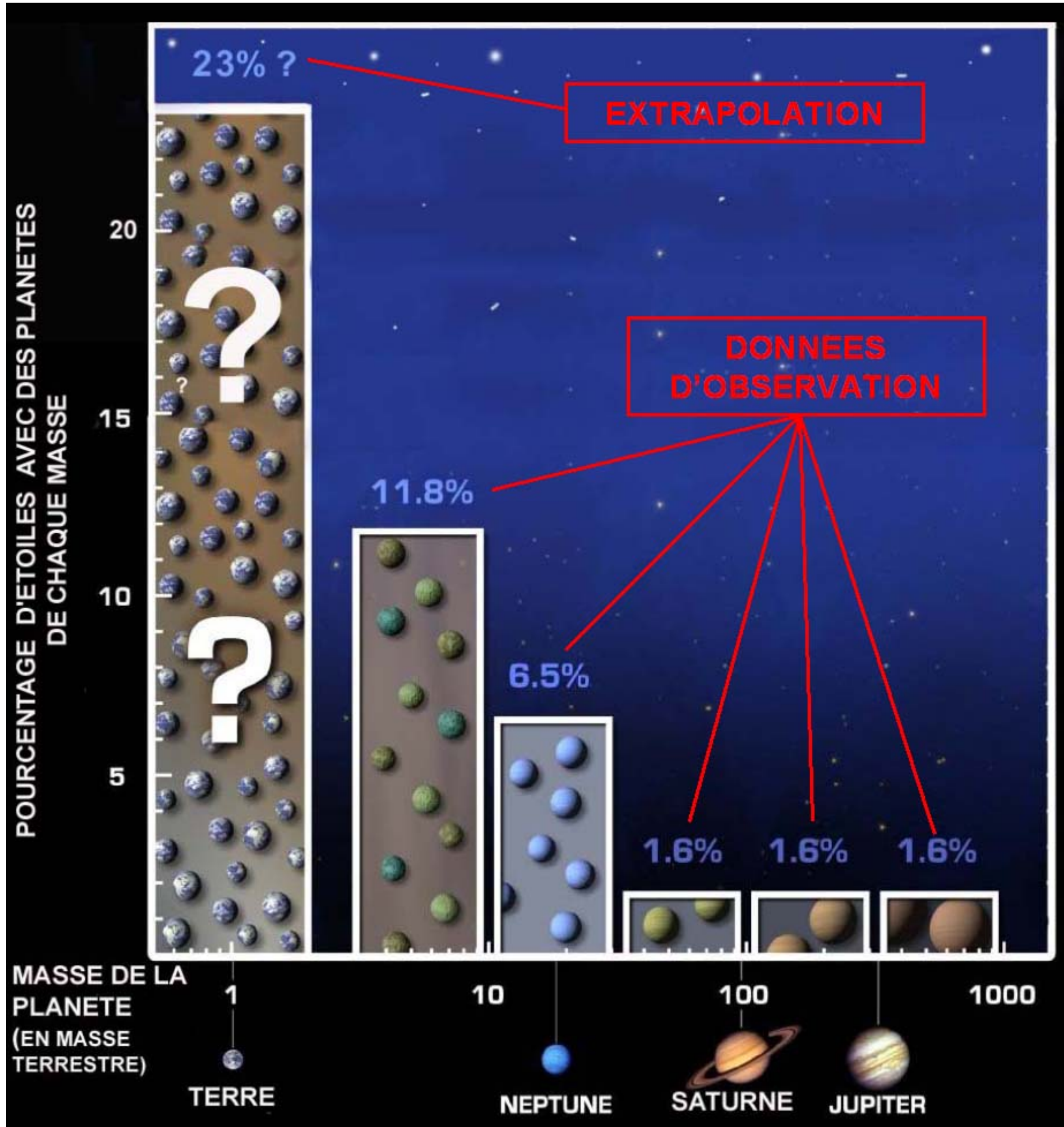
Amazing variety → most likely various paths to a planet...

EXOPLANETS : II) Statistics

25% of stars have (at least) a planet.

Let's extrapolate : there is at least 46 billion terrestrial planets in our own galaxy !

<u>Note:</u> Incredible variety, with planets of type unknown in the Solar System (hot Jupiters, super-Earths...) → more work for theorists :-) .



BACK to DRAKE FORMULA

$$\mathbf{N = R \times f_p \times n_{hab} \times f_v \times f_i \times f_c \times L}$$

$\mathbf{N} = N_p \times f_v \times f_i \times f_c \times f_t = \mathbf{N_p} \times \boldsymbol{\varepsilon}$

$N_p \approx 46\ 000\ 000\ 000$, and $N \geq 1$.

So, we know that $\varepsilon > 0{,}000\ 000\ 000\ 022...$

What if $\varepsilon = 0{,}000\ 000\ 000\ 05$? Then, $N>2$!

It seems very unlikely that intelligent life appeared only once.

And $N_p \times f_v >> N_p \times \varepsilon \geq 1$.

There may be life everywhere !

A LITTLE CHRONOLOGY OF LIFE

14 billion years : Big Bang, birth of the Universe.

4,5 billion years : Formation of the Earth.

480 million years : First terrestrial plants.

65 millions years:End of the dinosaurs, rise of mammals.

3 millions years : Australopithecs.

400 000 years : prehistoric humans master fire.

CHRONOLOGY of TRANSPORTATION

-4500 : Domestication of the horse.

1520 : Magellan('s ship) circles the world.

1782 : Montgolfière.

1906 : First flight with a plane.

1947 : A plane faster than sound speed.

1961 : Gagarine in space.

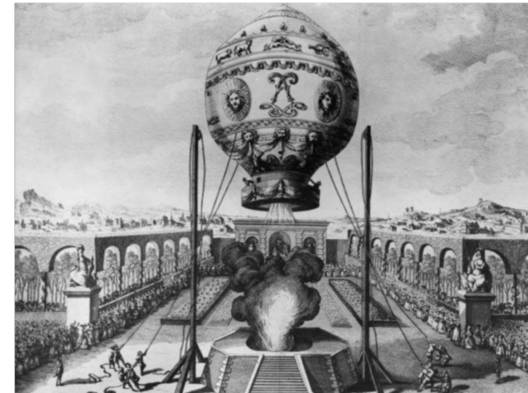
1969 : Man on the Moon.

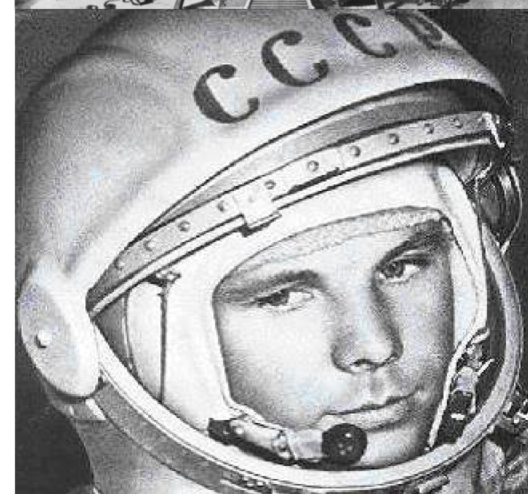
1975 : *Viking* on Mars.

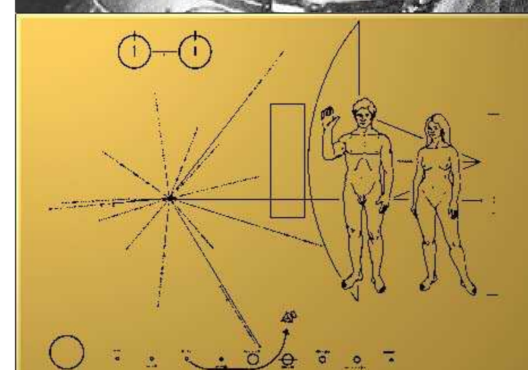
2004 : *Cassini* orbits Saturn.

2012 : *Voyager* leaves the Solar System.

10 000 : Man conquests the Galaxy ???







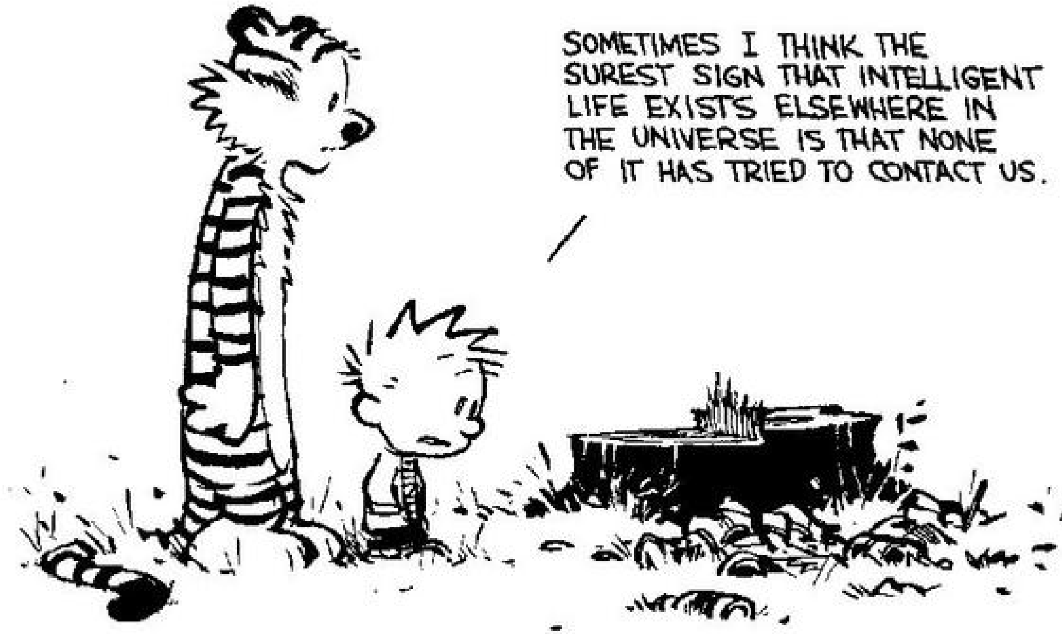
FERMI's PARADOX

If we continue our development, we will conquer the whole Milky Way in a snap on the Universe's clock.

Why, among the 46 billion terrestrial planets isn't one 10000 years ahead of us ? Formed just 4500,01 million years ago ?

Where are they ?

Is there a fluke
in this reasoning ?



FERMI's PARADOX

In my humble opinion :

An exponential development is not possible indefinitely.

<u>1) physical limits :</u>

- speed of light unreachable

- limited ressources

FERMI's PARADOX

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An exponential development is not possible indefinitely.

<u>1) physical limits :</u>

Consider a 2% growth per year :

100 → 102 → 104,04 → 106,16 → 108,24 → 110,41 → 112,62 → 114,87 → 117,17 → 119,51 → 121,90 = 21,9% in 10 years

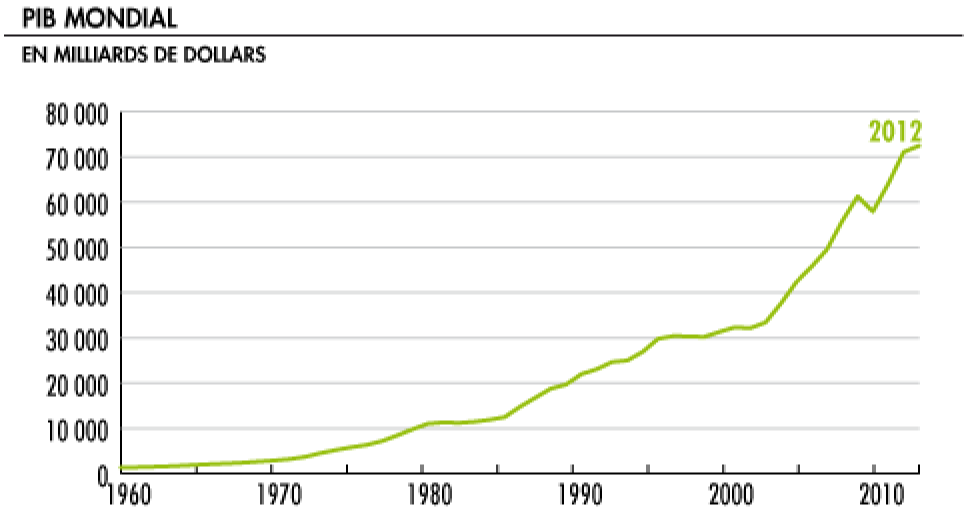
In 100 years ? 100 → 121,9 → 148,6 → 181 → 221 → … → 724,46 !!!

In 200 years ? x 50.

In 350 years ? x 1000.

In 1000 years ? x 400 millions.

In 1047 years → x 1 billion !



FERMI's PARADOX

In my humble opinion :

An exponential development is not possible indefinitely.

<u>2) Social limits :</u>

The factor L in Drakes equation may not be so long...

- remember the cold war

- how do civilisations collapse ? Generally at least one of 3 key factors : inequalities, shortage in ressources, climate change...

→ **2 possibilities, now :**

Either we try and we exhaust/burn our planet, or we admit we can't grow for ever and we look for an alternative model...


Looking at other stars and planets
brings you back on Earth...
The more planets
we find, the more
we realize we should
protect ours, and
share it fairly...