EXOPLANETS

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EXOPLANETS

Giordano Bruno said that the many stars are like our Sun, with planets like our Earth, inhabited as well (in *de l'infinito universo e mondi* (1574)). He was burnt alive for this claim.

Modern sciences : We expect stars to form together with a protoplanetary disk, in which planets form, but we hadn't seen them, until :

Mayor & Queloz (1995) detected
« *A Jupiter-mass companion to a solar-type star* »

They exist !
This is a revolution of our vision of the Universe.

EXOPLANETS

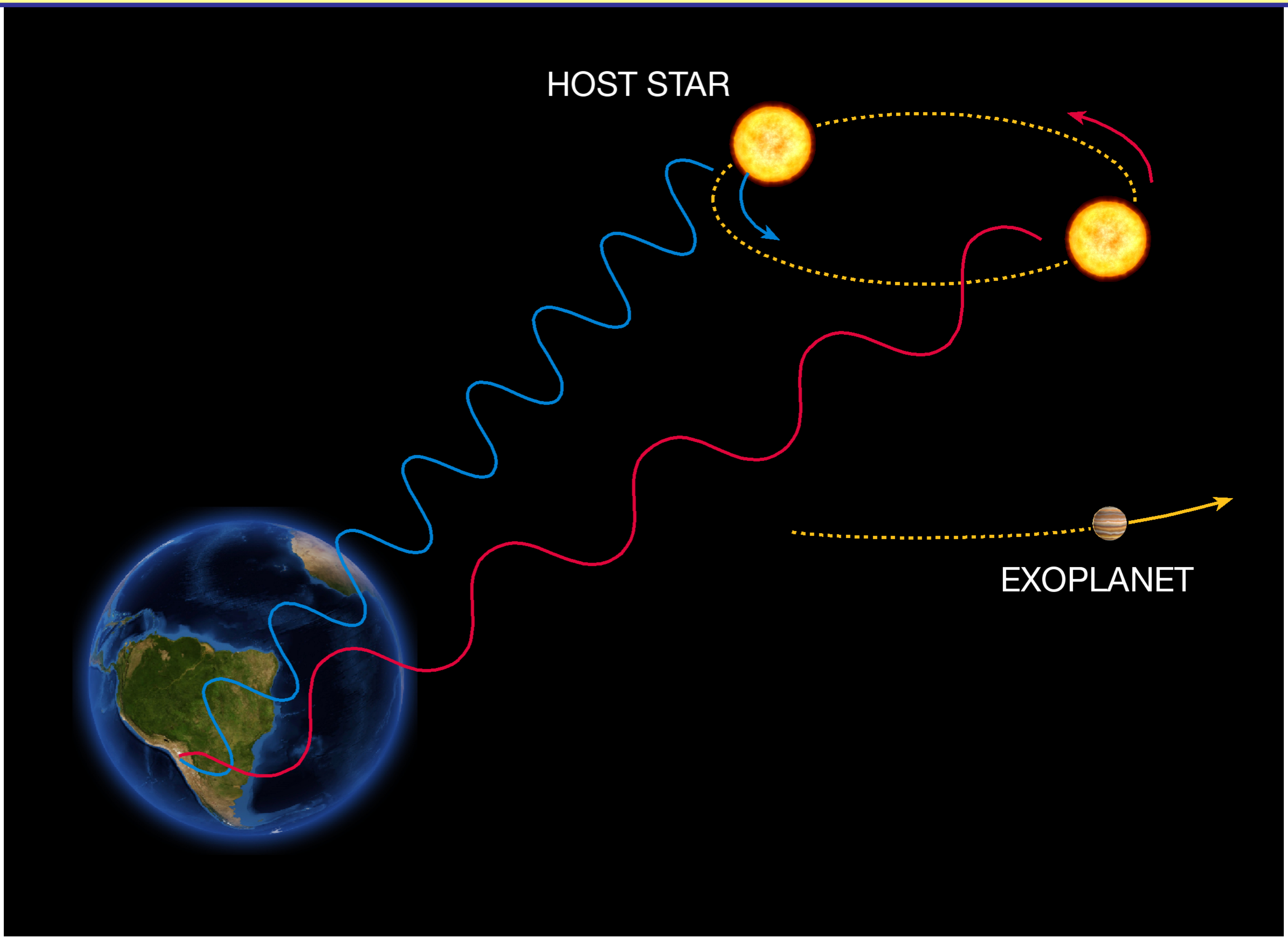
I Detection methods

- Radial velocity (velocimetry)
- Transit (photometry)
- Micro-lensing (photometry)
- Astrometry
- Direct imaging

II Properties and statistics

- Mass, semi major axis, period, eccentricity, radius, metallicity of the host star, density, spectrum...

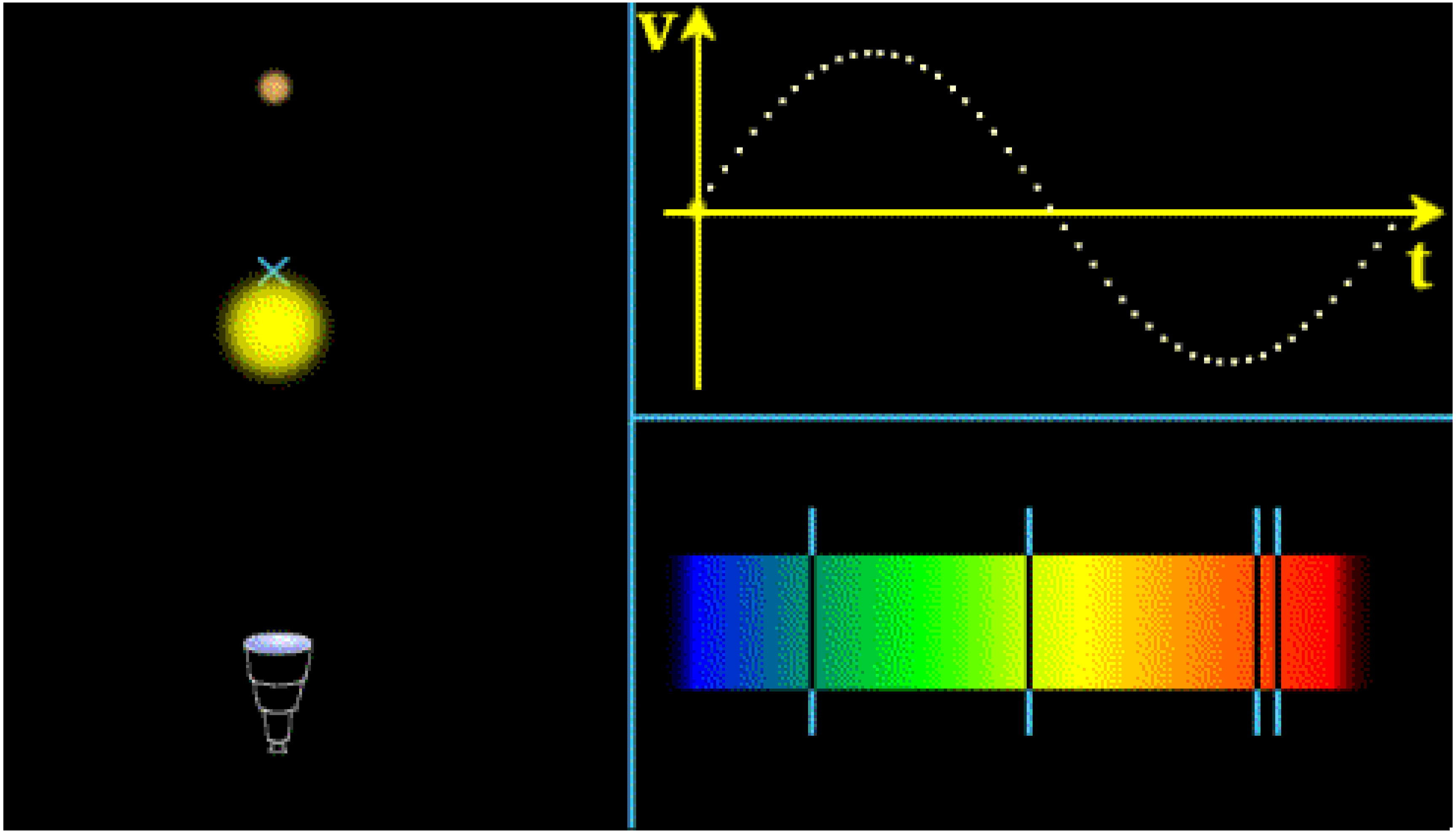
EXOPLANETS Ia) Radial velocity



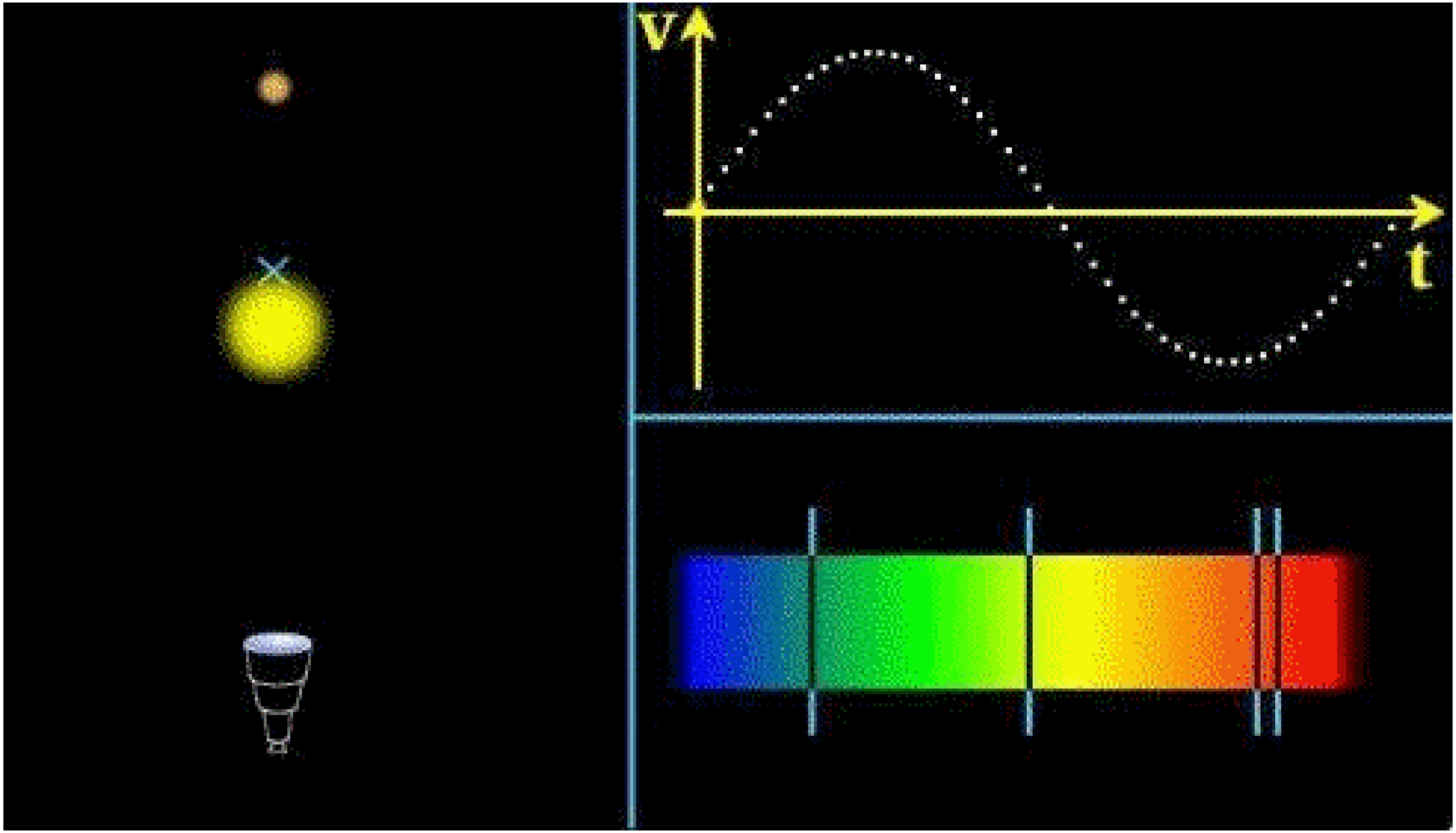
The Radial Velocity Method

ESO Press Photo 22e/07 (25 April 2007)

EXOPLANETS Ia) Radial velocity

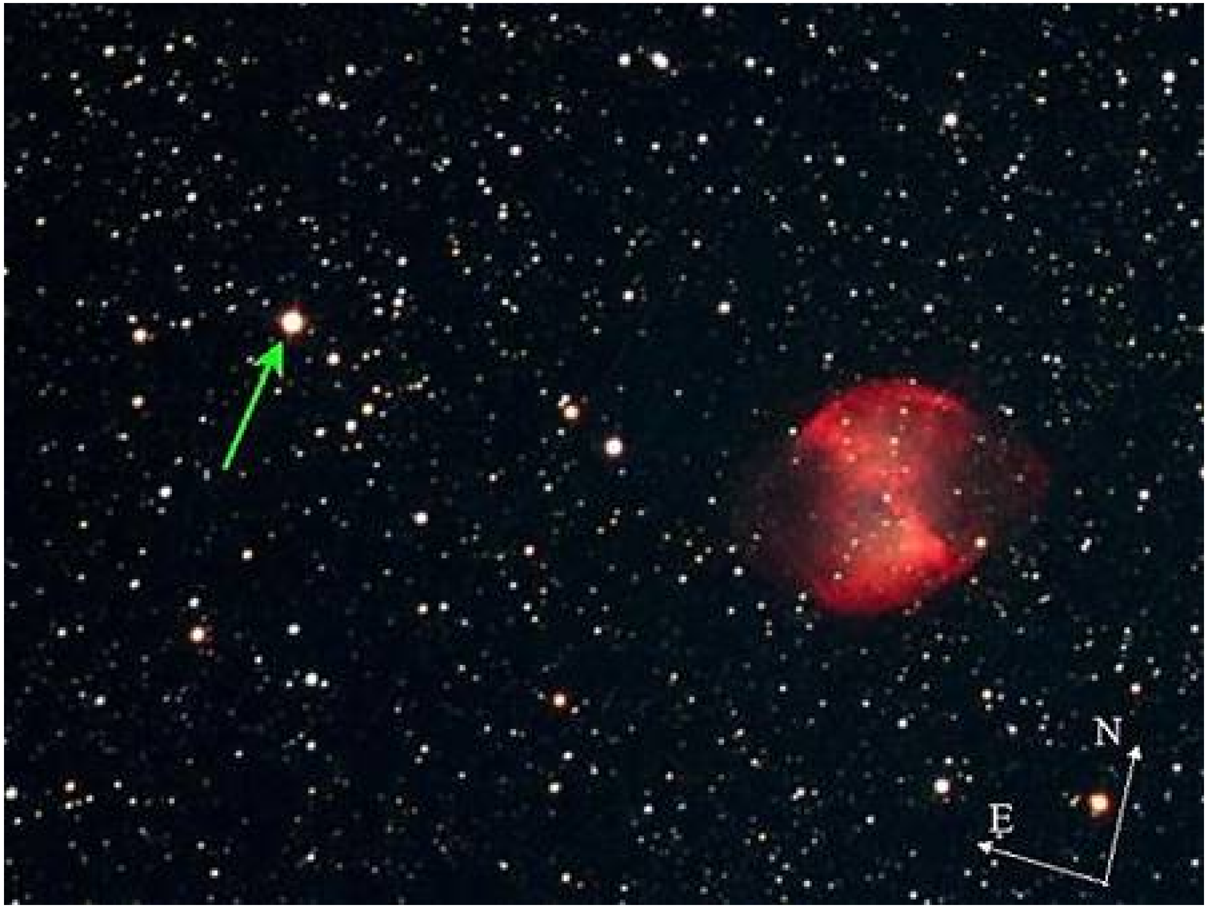


EXOPLANETS Ia) Radial velocity



EXOPLANETS Ia) Radial velocity

Example : HD189733



EXOPLANETS Ia) Radial velocity

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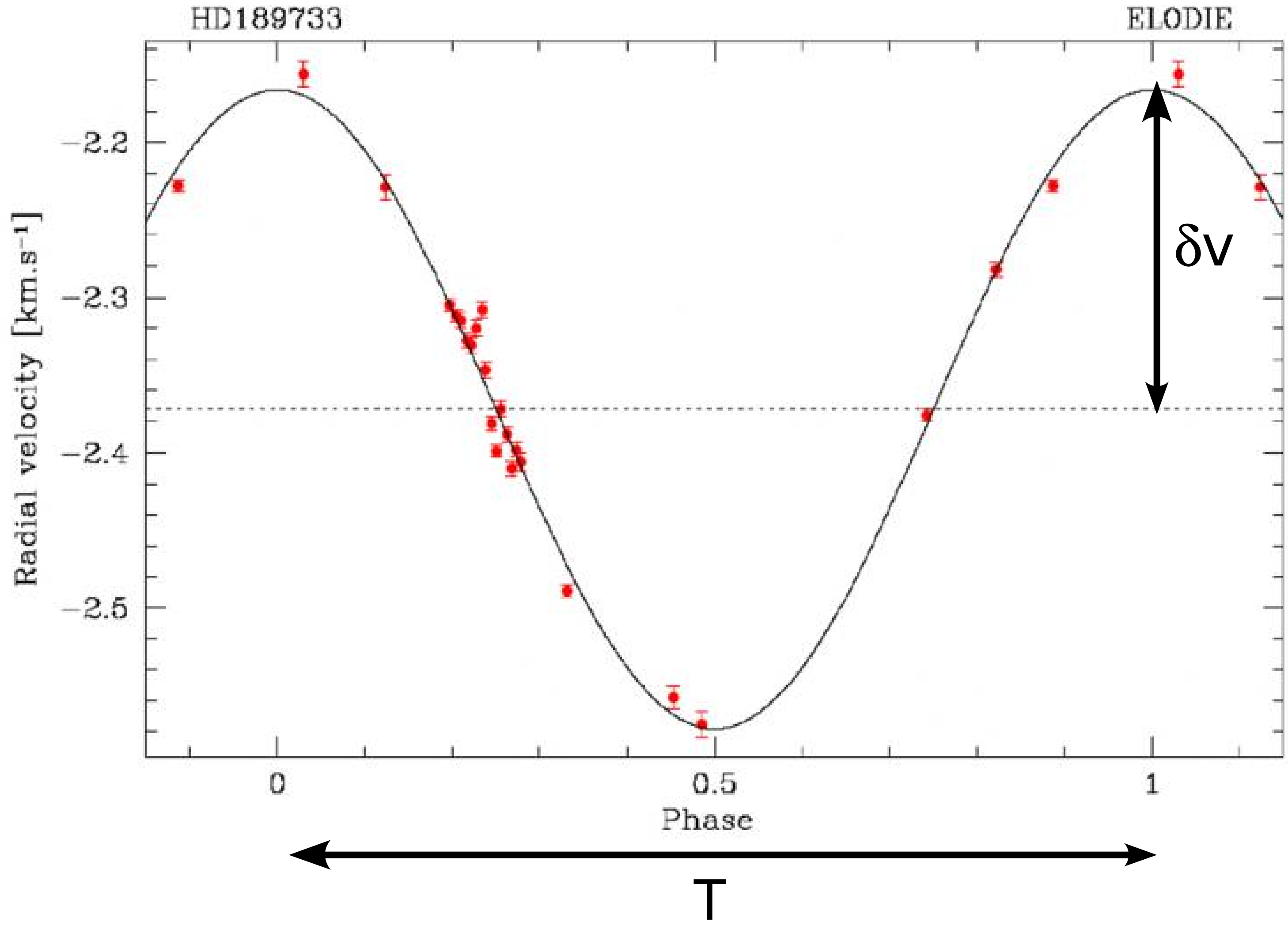
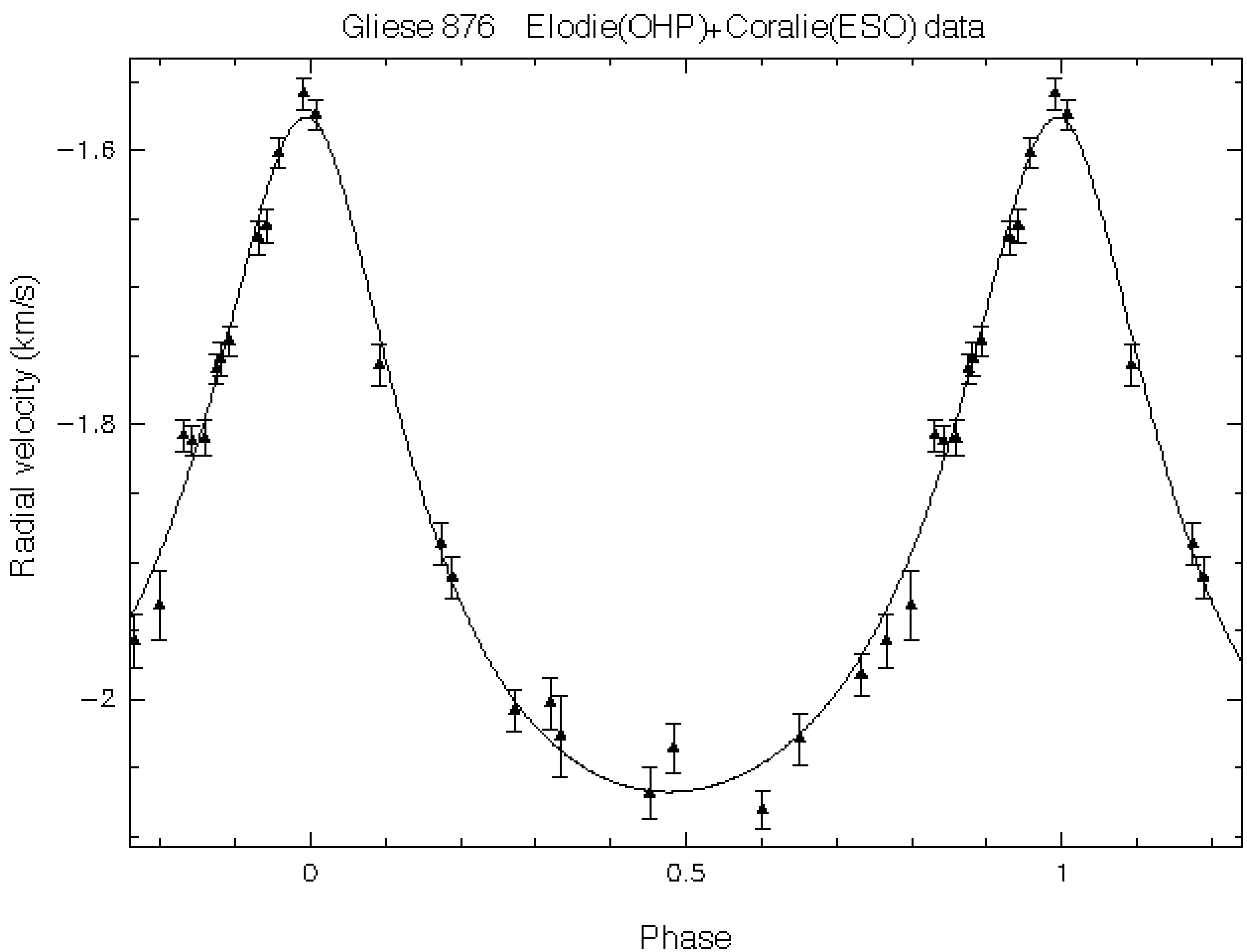


EXOPLANETS Ia) Radial velocity

<u>Example : GJ876b :</u> an eccentric orbit.

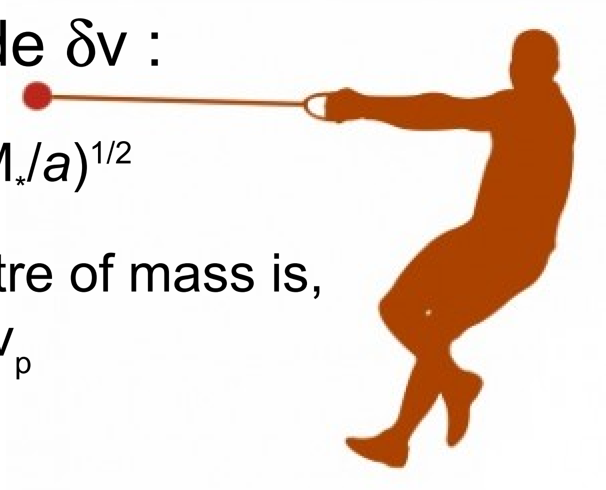


EXOPLANETS Ia) Radial velocity

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

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

The **mass** $\mathbf{q=M_p/M_*}$ is given by the amplitude δv :



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

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

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

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

EXOPLANETS Ia) Radial velocity

EXERCICE :

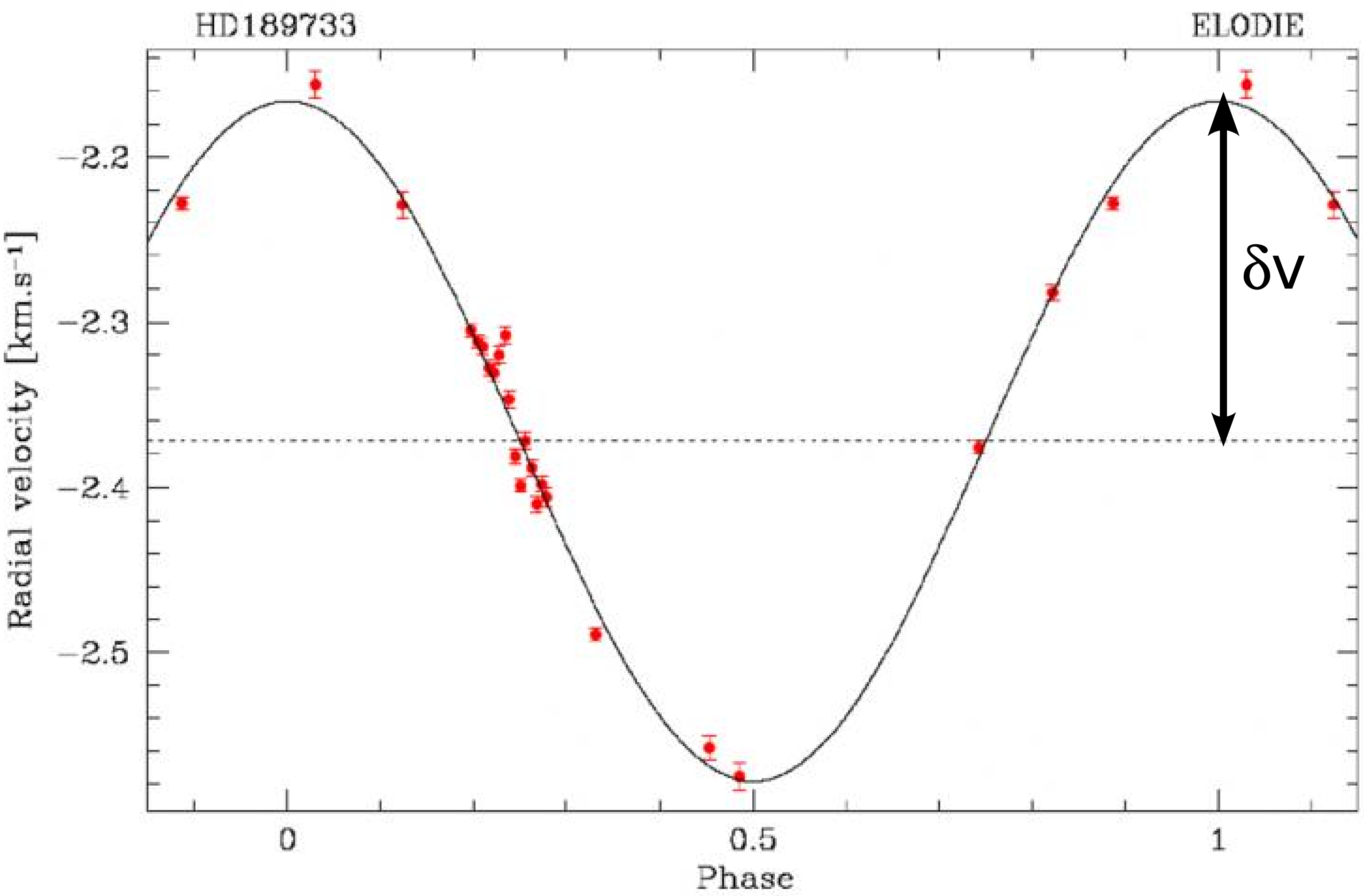
HD189733b :

One gives

T=2,218 days,

$M_{*}=1,6x10^{30}$ kg.

Find q, M_p.



EXOPLANETS Ia) Radial velocity

EXERCICE :

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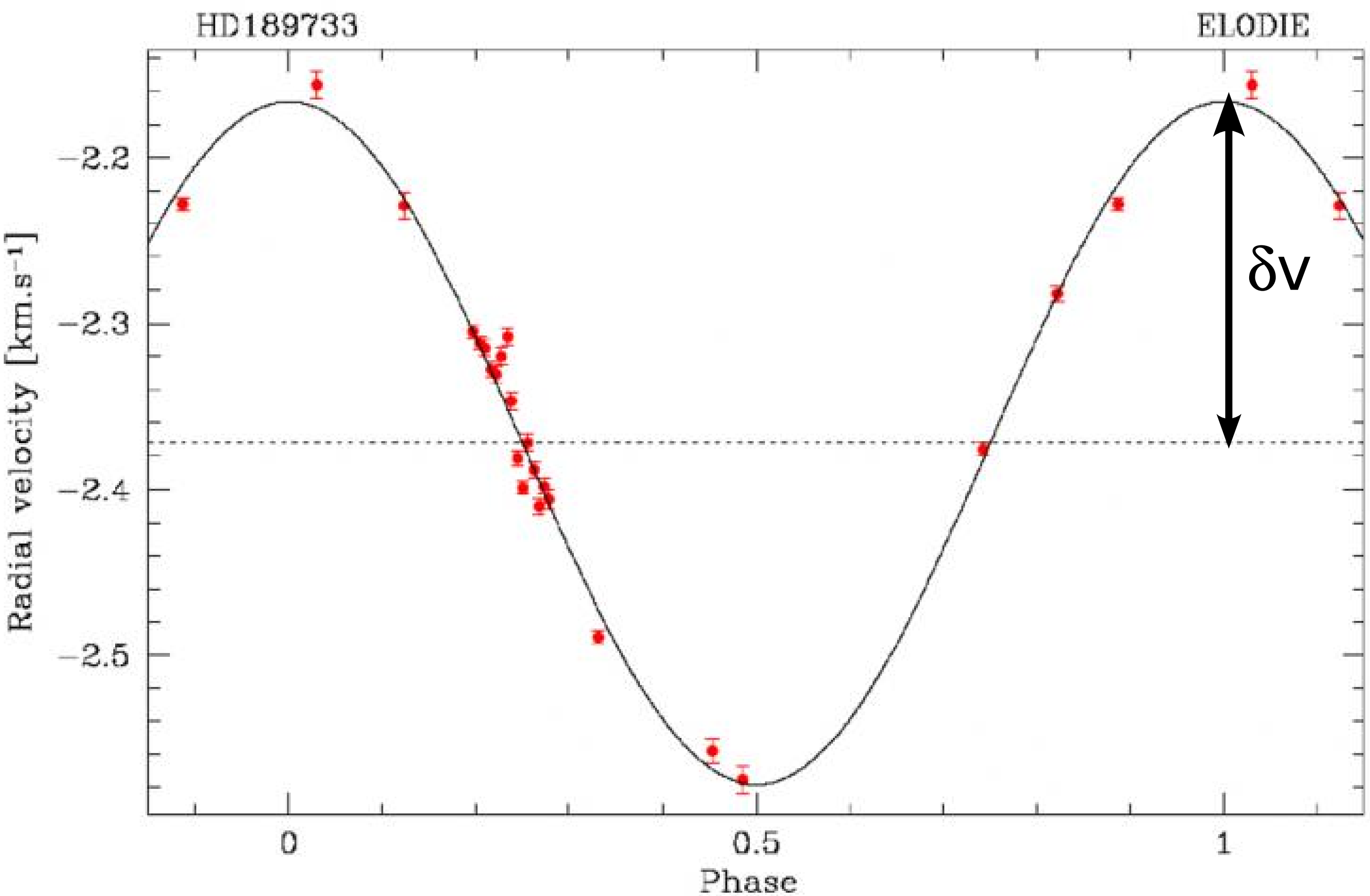


SOLUTION :

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

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

EXOPLANETS Ia) Radial velocity

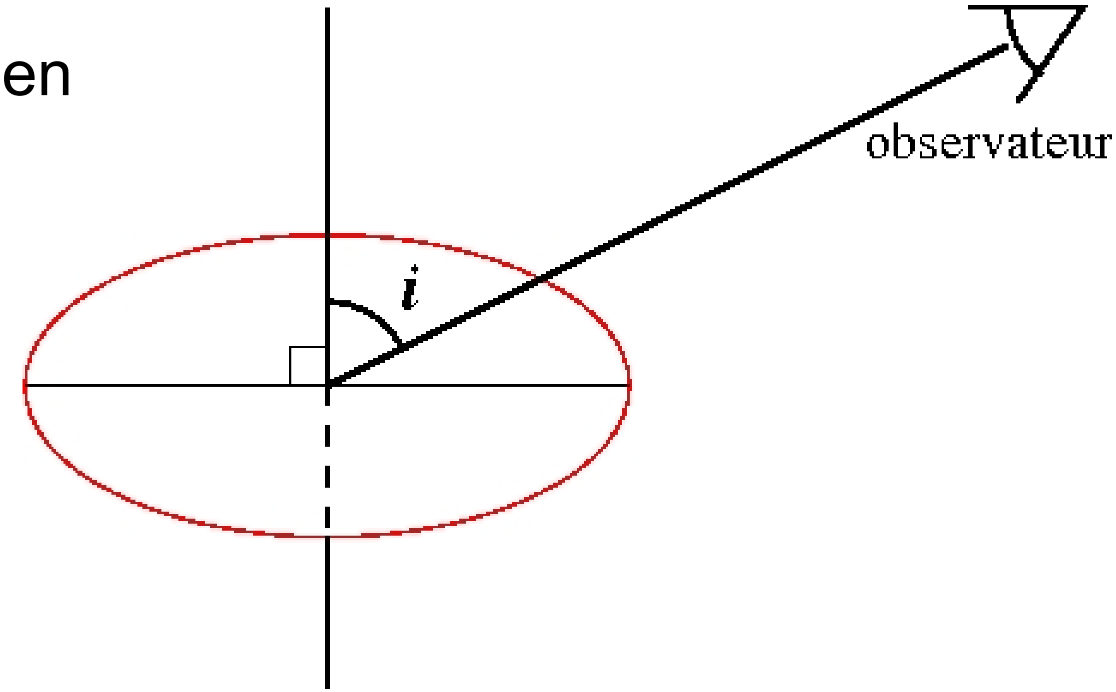
<u>Caution !</u>

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 !

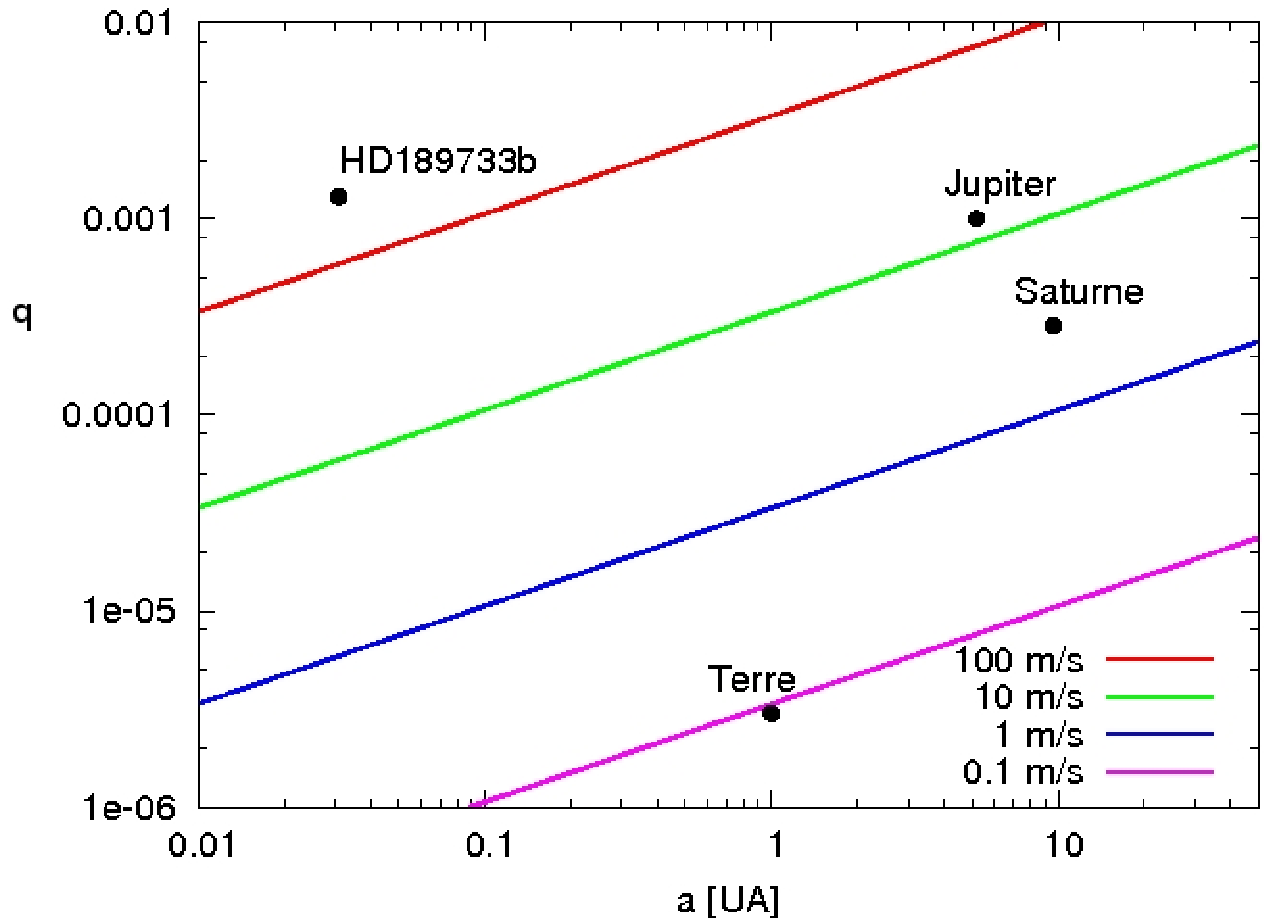
On average, $1/\sin(i)$ is $\pi/2$.

EXOPLANETS Ia) Radial velocity

Nowadays (2014) 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 $\delta\lambda = \lambda_0 v/c$).

<u>Detectability :</u>

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

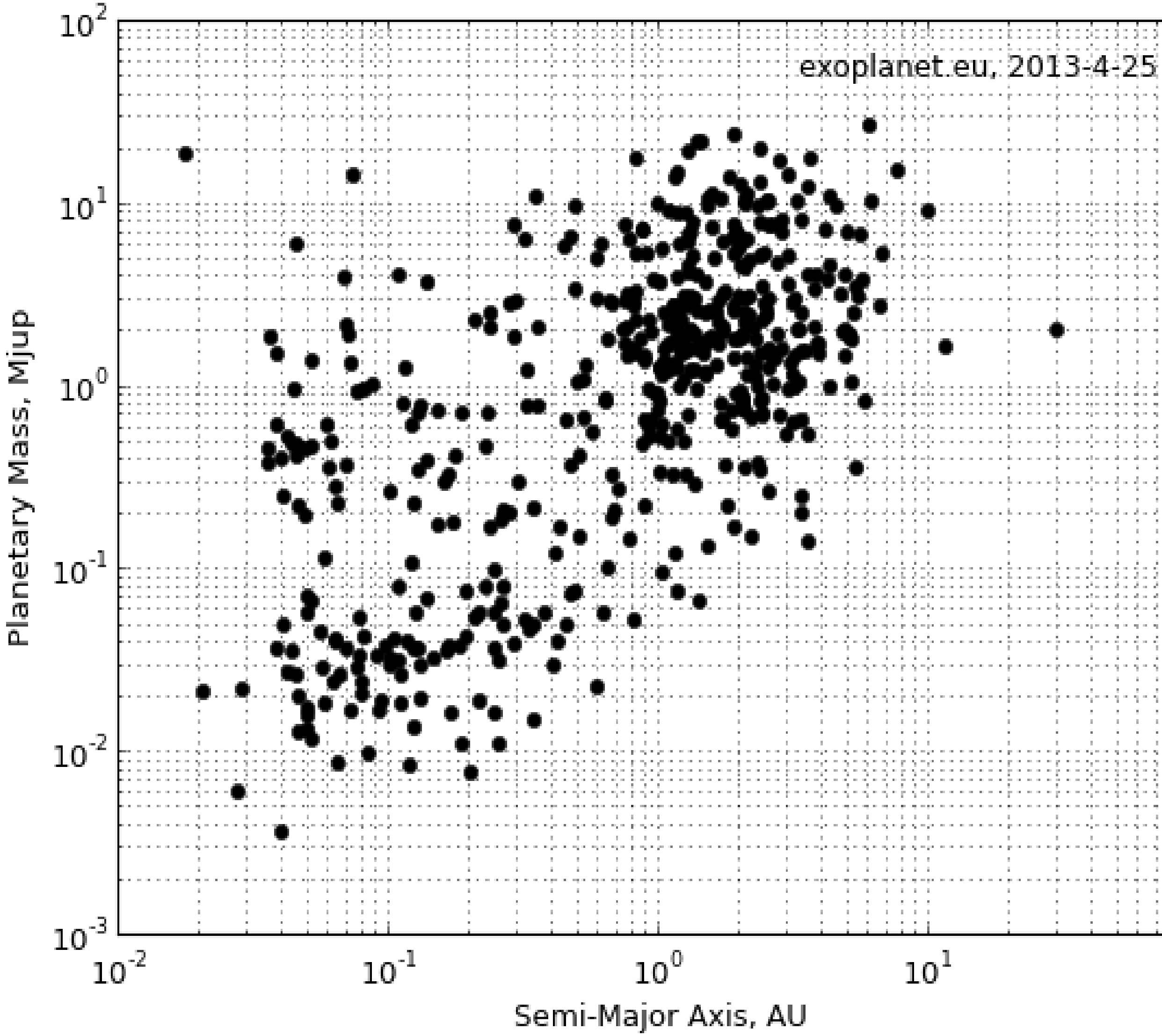


EXOPLANETS Ia) Radial velocity

<u>Detections :</u>

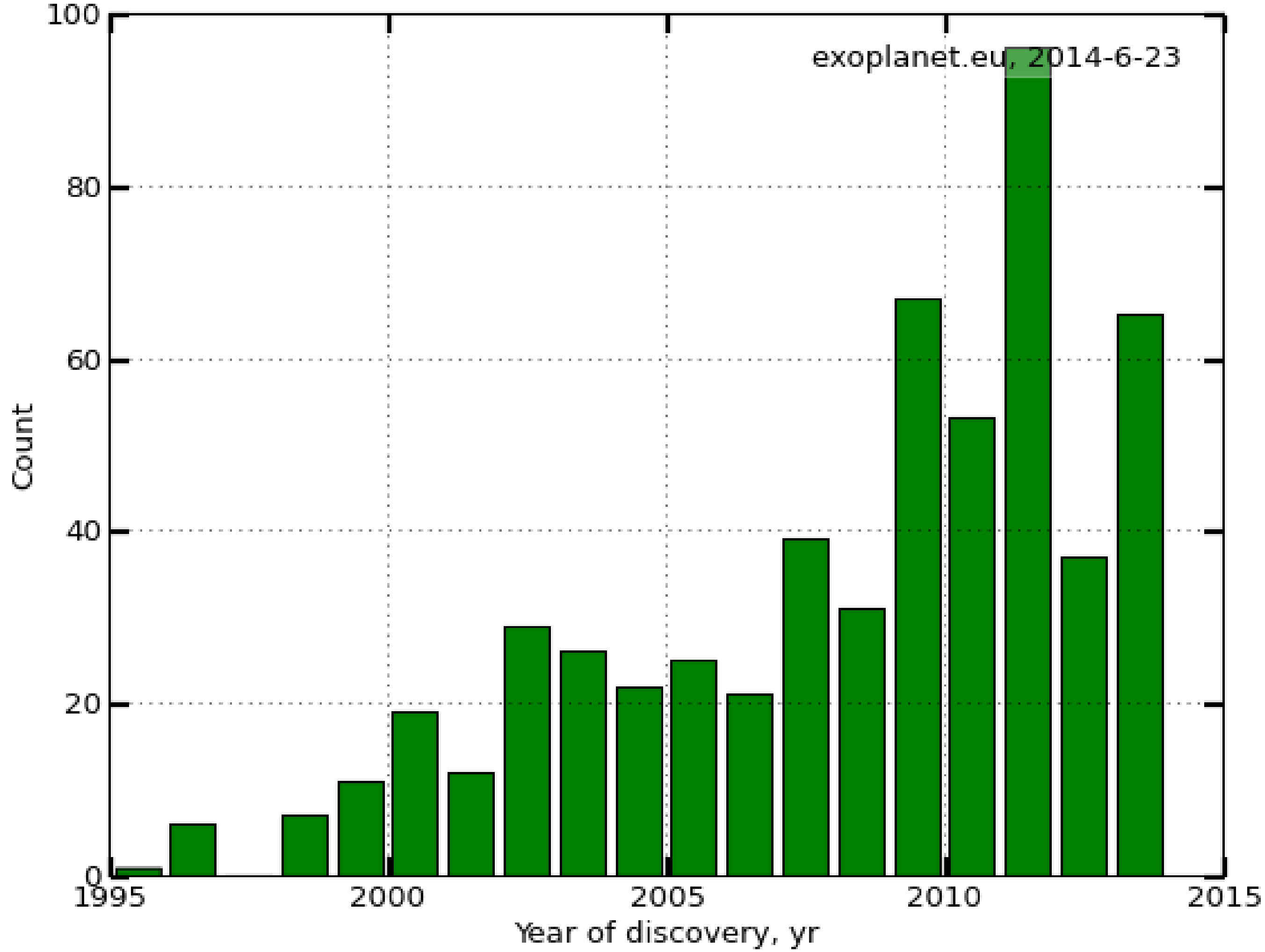
All the planets detected using radial velocity on April, the 25th, 2013.

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



EXOPLANETS Ia) Radial velocity

<u>Detections :</u> Time evolution of the detection rate.

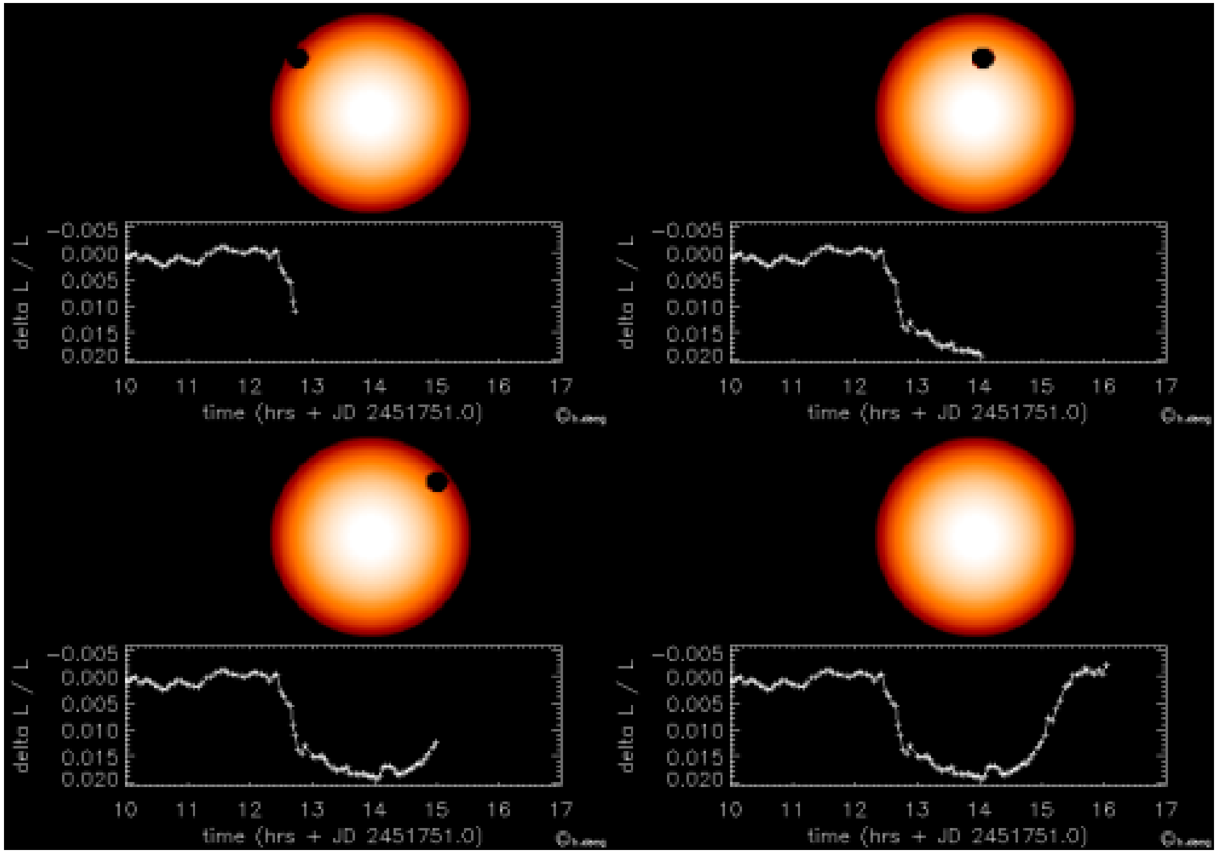


EXOPLANETS : Ib) Transit

EXOPLANETS : Ib) Transit

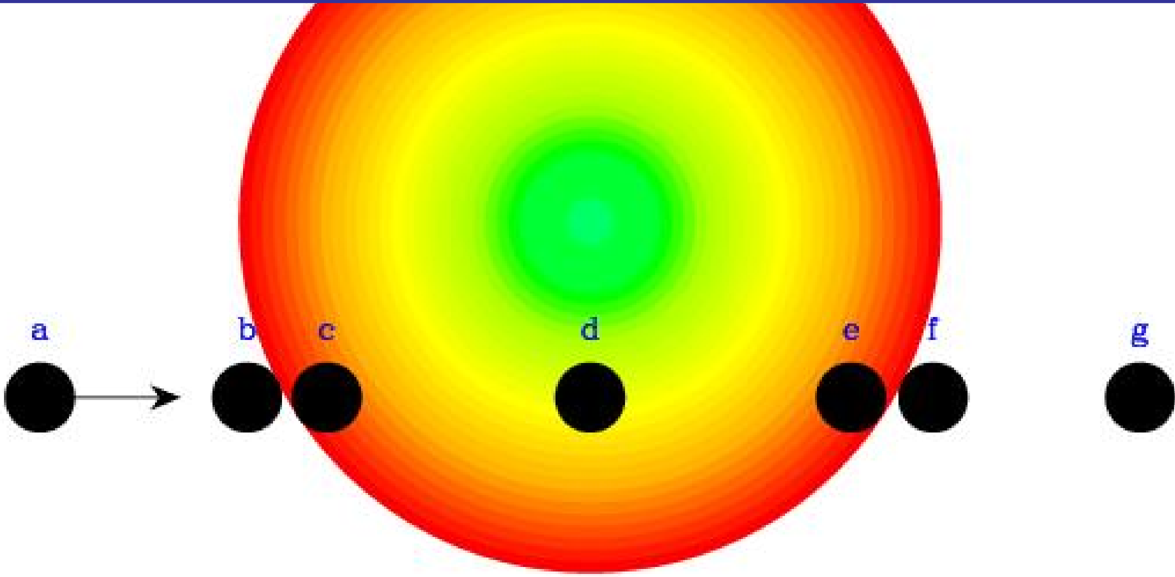
Like Venus in front of the Sun in 2004 and 2012, sometimes, an exoplanet moves in front of its star, this is a **transit**.

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

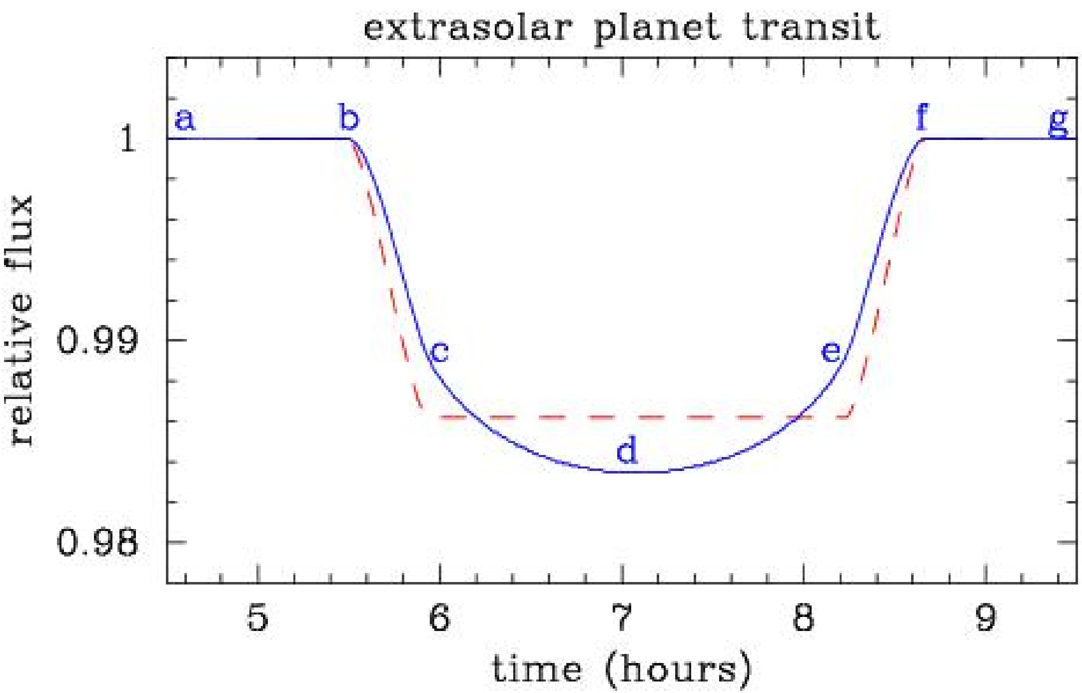


EXOPLANETS : Ib) Transit

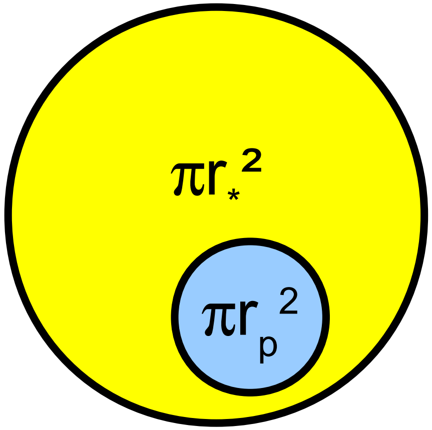
Limb darkening effect : the bottom of the transit isn't flat.



A transit lasts a few hours.



EXOPLANETS : Ib) Transit



Advantages of the transit method :

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

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

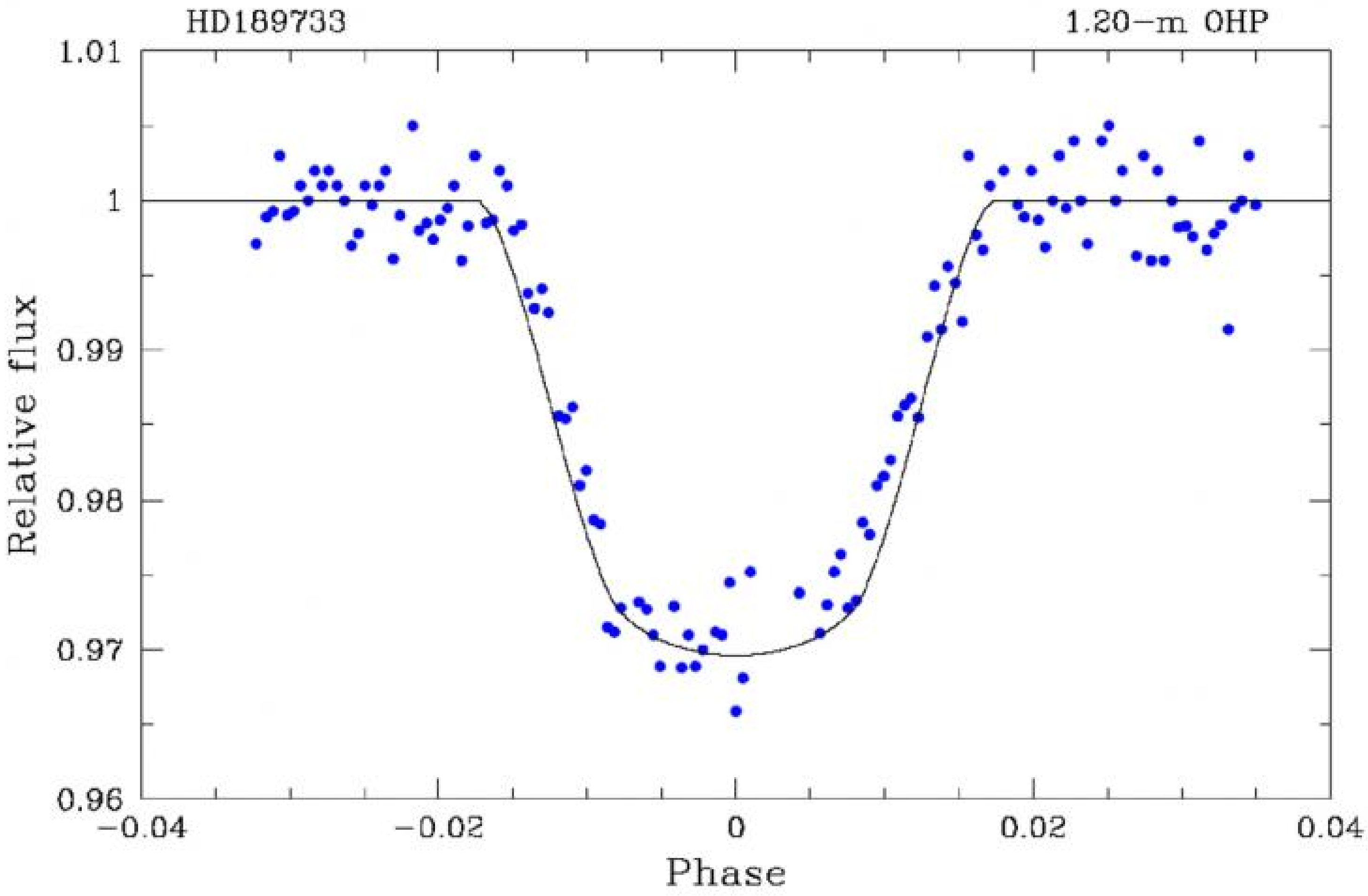
The period of the transit gives the semi major axis (Képler's law).

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

One derives the density of the planet !

EXOPLANETS : Ib) Transit

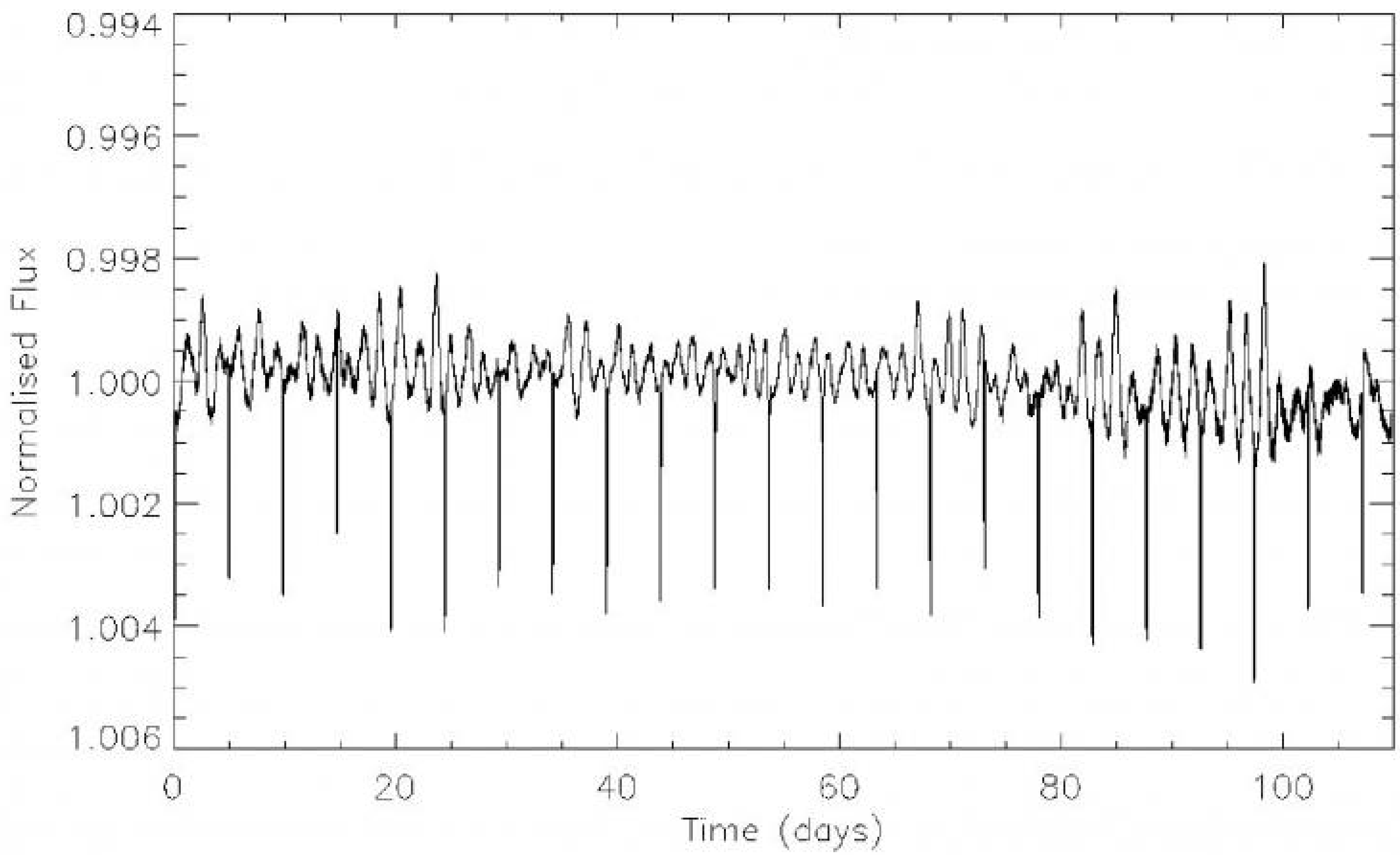
Ex: HD 189733b, seen in radial velocity, also has a transit :



EXOPLANETS : Ib) Transit

A planetary transit should be periodic.

Ex: light curve of a star observed by Corot :

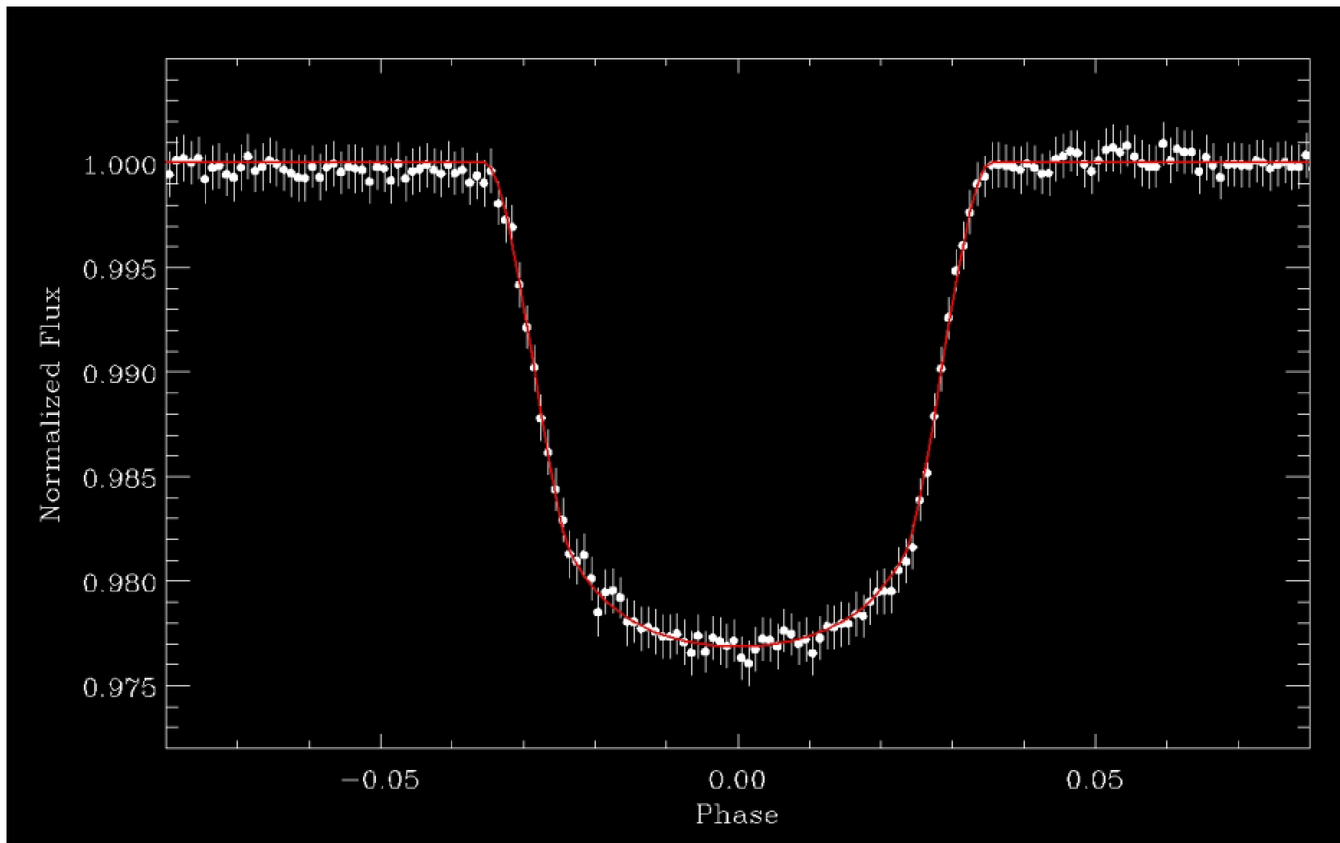


EXOPLANETS : Ib) Transit

Corot : COnvection ROtation, et Transits planétaires.

satellite of the CNES (70%), launched on 26/12/06, which tracks luminosity variations of thousands of stars during many months in a row.

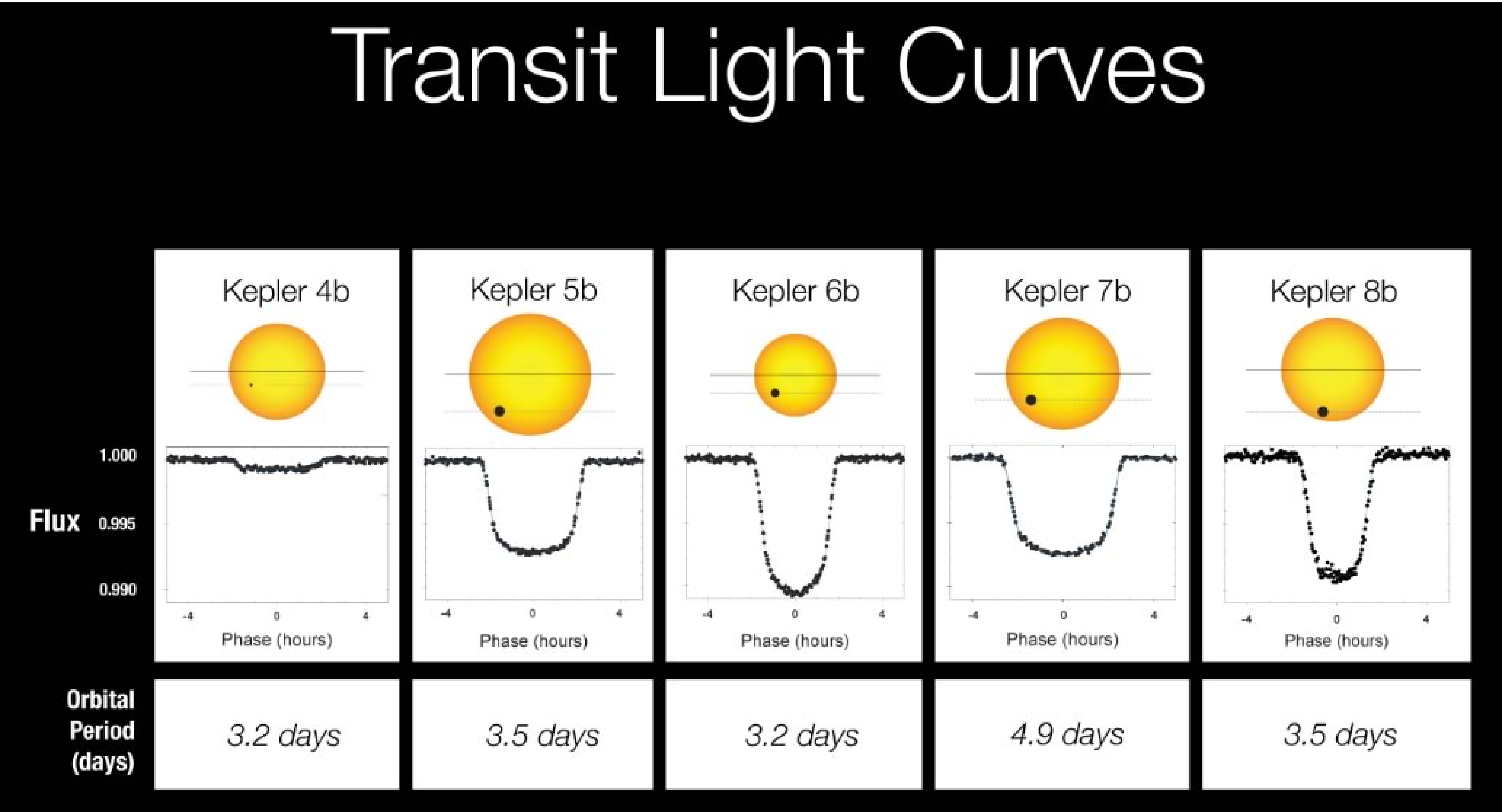
Ex: The first exoplanet discovered by Corot:



Copyright Corot

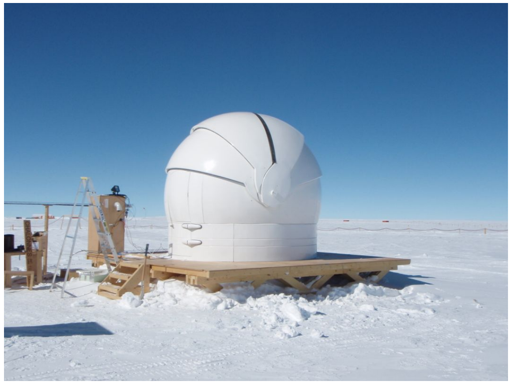
EXOPLANETS : Ib) Transit

KEPLER (NASA), launched on 7/3/2009, now degraded.
~2000 planet candidates !
But not all confirmed, faint host stars...



EXOPLANETS : Ib) Transit

Other transit detection projects :



A-STEP : Antartica Search for Transiting Extrasolar Planets,
automatic telescope of 40cm at Dome C, at Concordia (University of Nice).

PLATO : PLAnetary Transits and Oscillations of stars

esa
European Space Agency
Agence spatiale européenne

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

Theory meeting last week in London.

EXOPLANETS : Ib) Transit

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

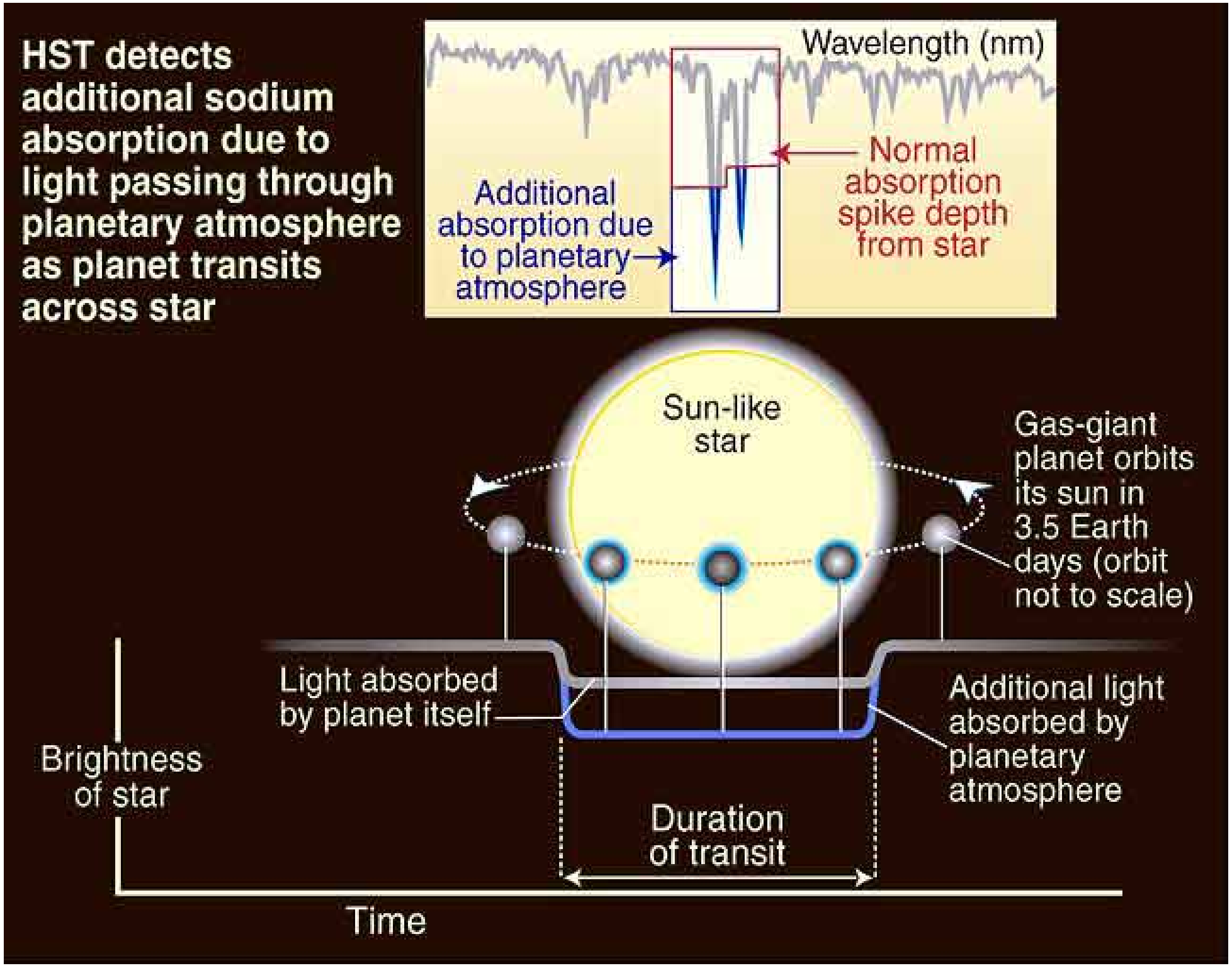
Possible surprises...

Ex: HD209458b :
huge absorbtion in Lyα during the transit, as if an atmosphere of H large as ~$r_*/3$ surrounding the planet.

EXOPLANETS : Ib) Transit

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

If the atmosphere of the planet makes absorbtion lines, composition !



EXOPLANETS : Ib) Transit

Conditions for a transit :

The planet must pass in front of the star.

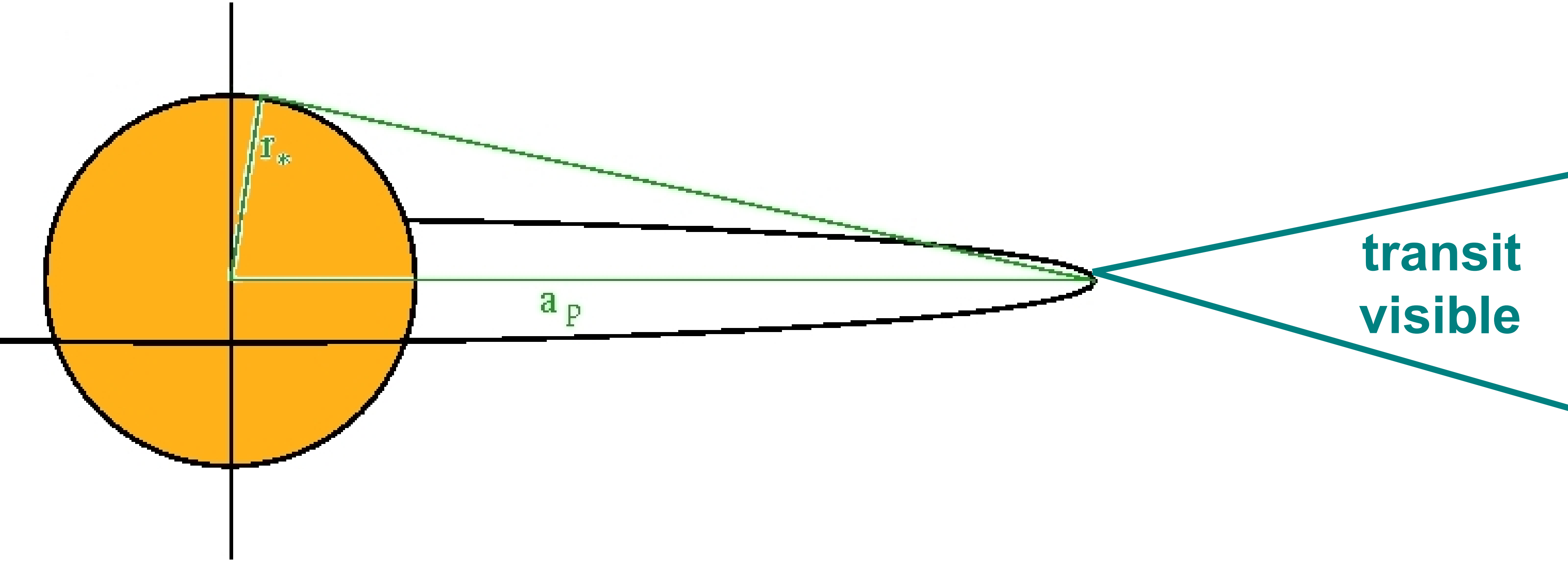
Condition on i ?

EXOPLANETS : Ib) Transit

Conditions for a transit :

The planet must pass in fron of the star, that is :

$| \pi/2 - i | < \arcsin(r_*/a_p)$ ou: $a_p < r_*/|i-\pi/2|$ (pour $i \sim \pi/2$)

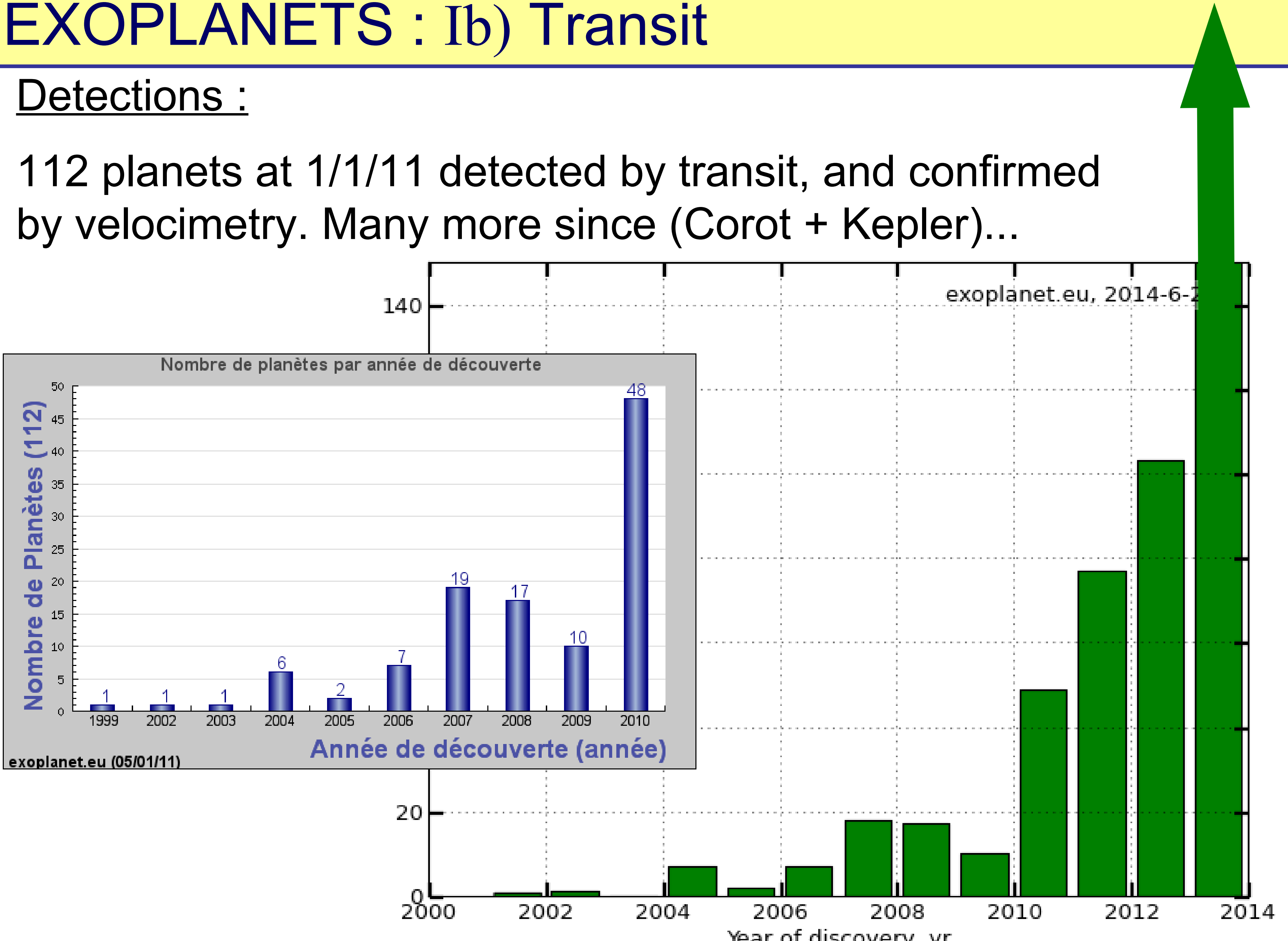


Short period planets are favoured.

EXOPLANETS : Ib) Transit

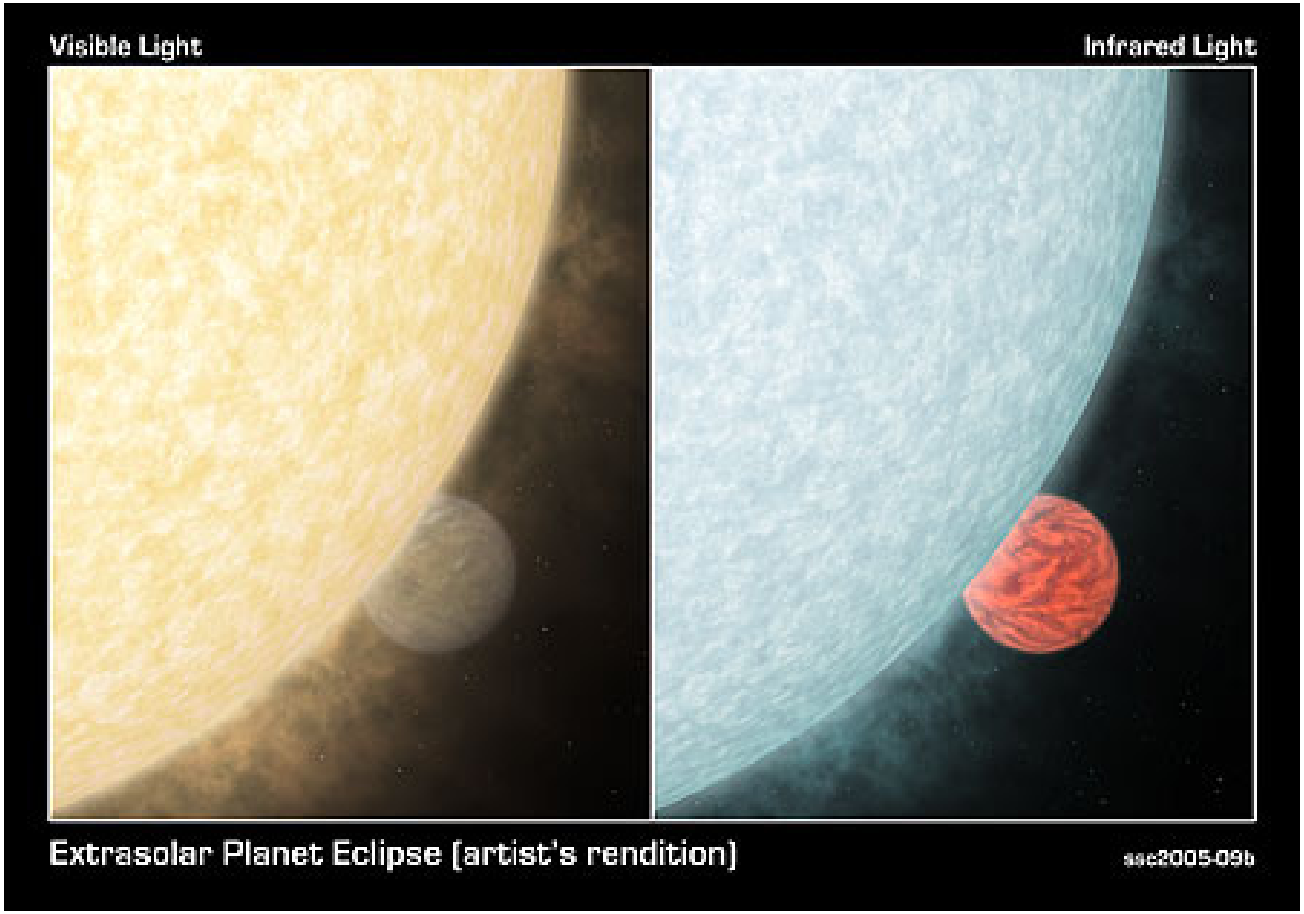
Detections :

112 planets at 1/1/11 detected by transit, and confirmed by velocimetry. Many more since (Corot + Kepler)...

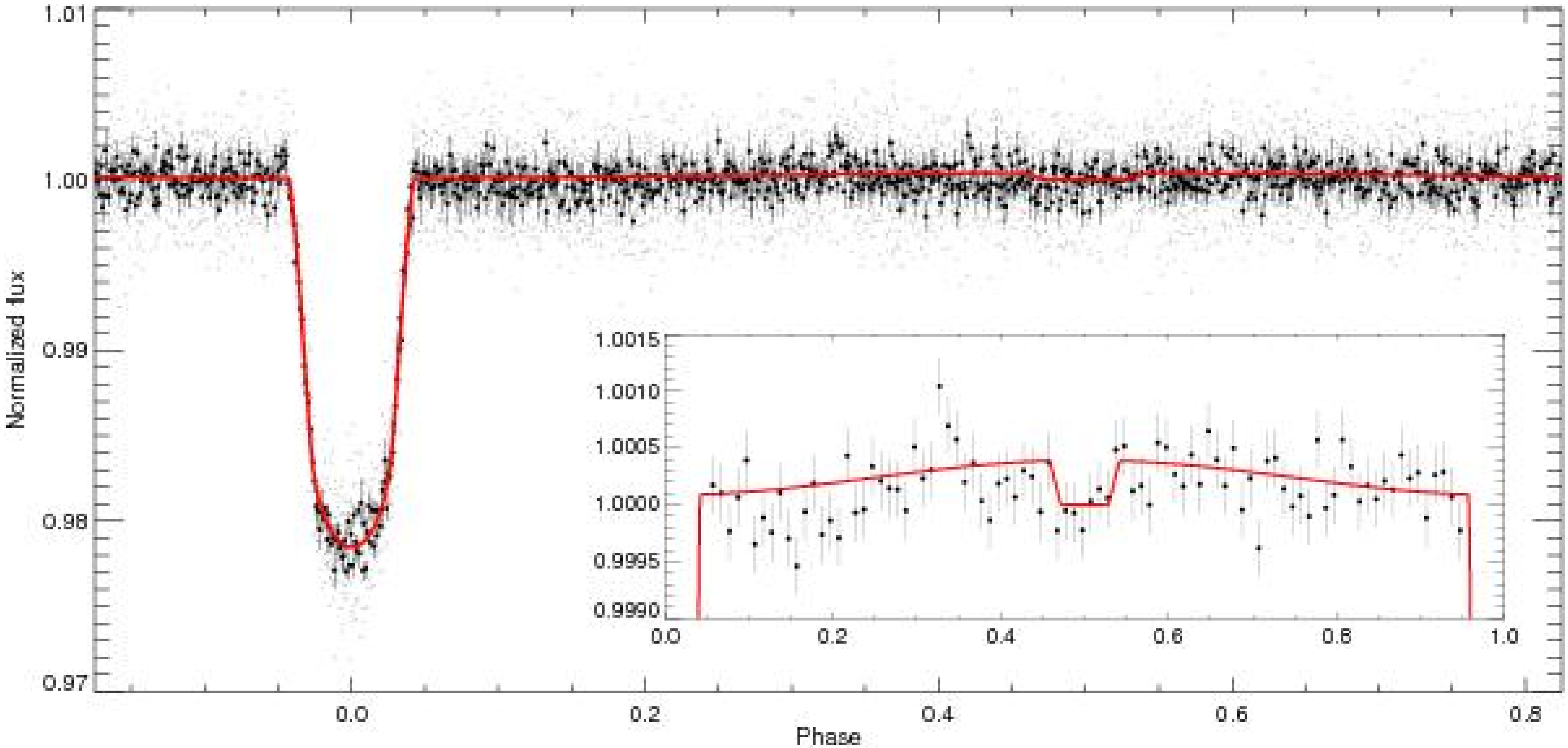


EXOPLANETS : Ib') Secondary transit

When the planet goes behind its star, its light is masked. By substraction, one can (almost) find the spectrum of the planet, thus its temperature...



EXOPLANETS : Ib') Secondary transit



Ex : Courbe de lumière de WASP-19 observée par A-STEP.

→ la température de la planète WASP-19-b est ~2000°C.

(figure tirée de : L. Abe et al. 2013, voir film)

EXOPLANETS : I c) Microlensing

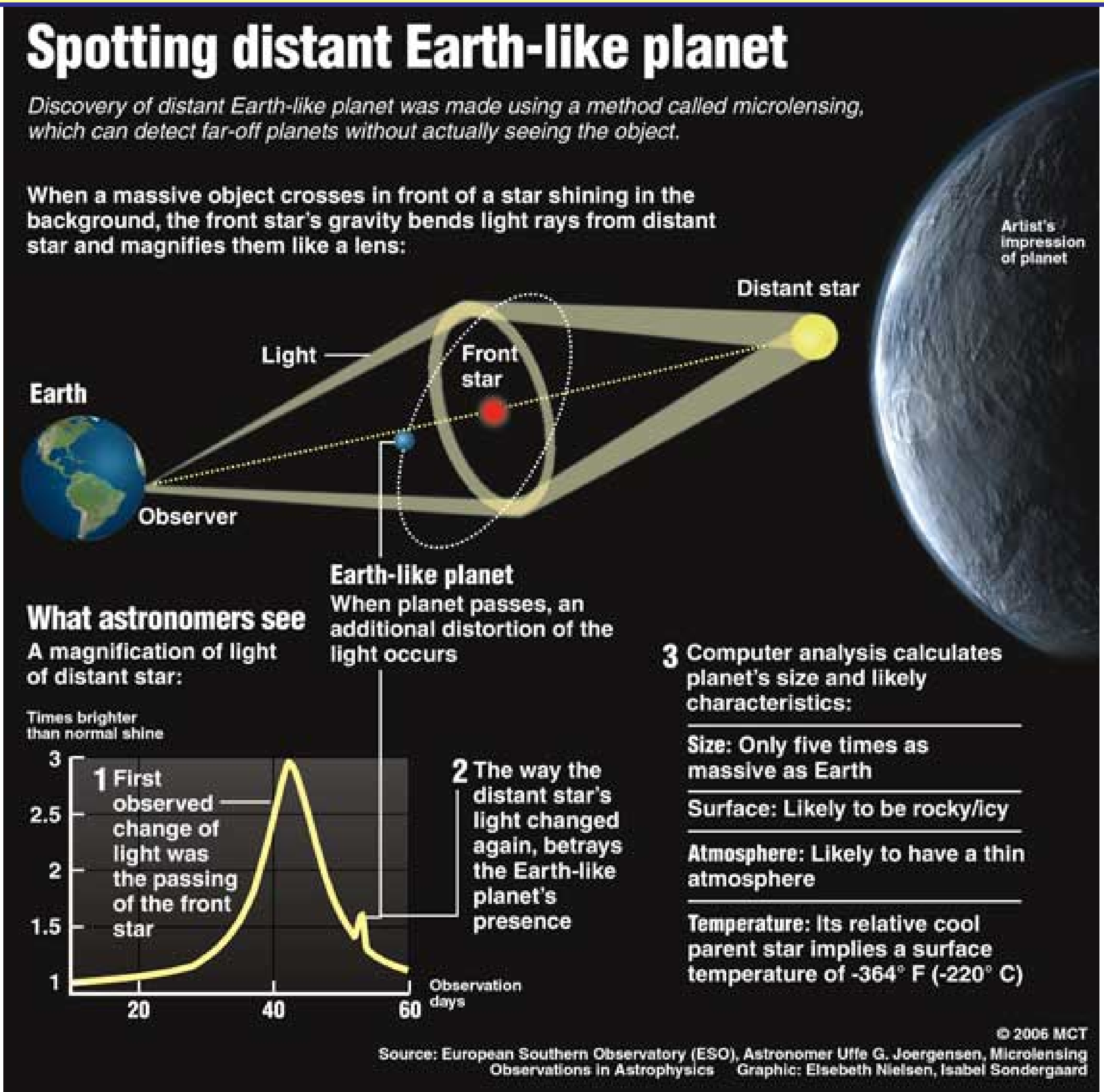
<u>Gravitational lense :</u>

When a star passes exactly infront of an other star, it deviates the light rays, like a lense (Einstein). One sees a peak in the luminosity.

A secondary peak betrays the presence of a planet.

The luminosity of stars in the core of the Milky Way is followed carefully (dense region).

EXOPLANETS : I c) Microlensing



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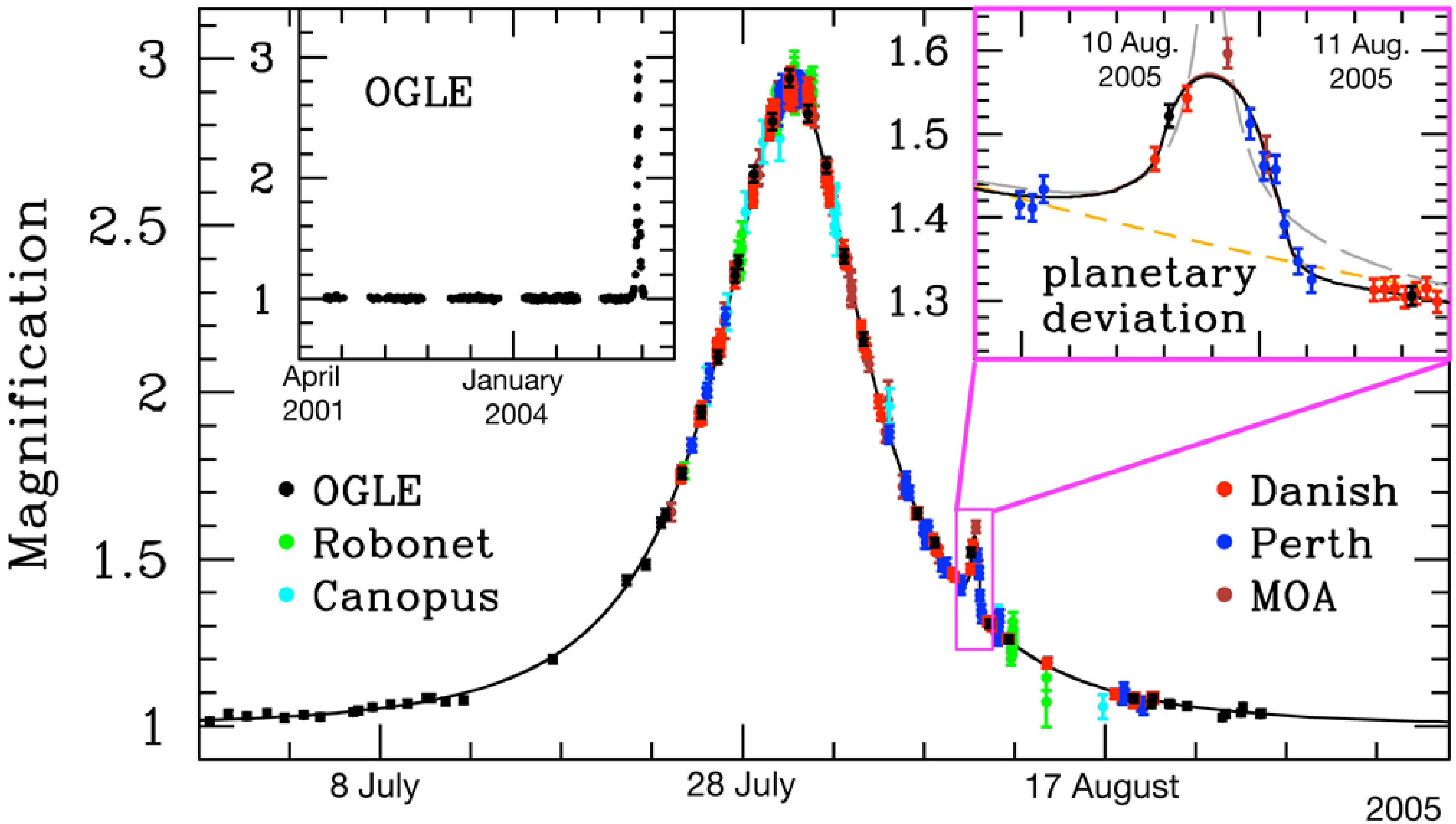


Light Curve of OGLE-2005-BLG-390

ESO PR Photo 03b/06 (January 25, 2006)

EXOPLANETS : I c) Microlensing

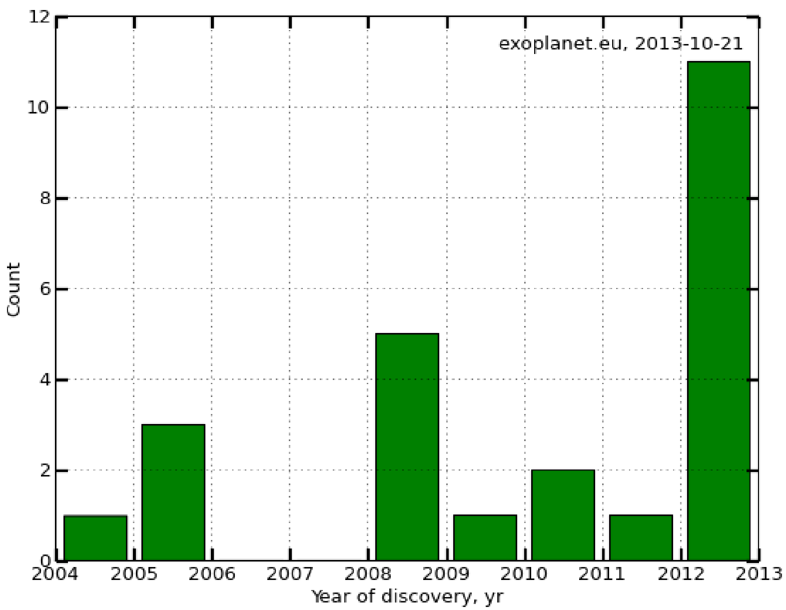
Big planets far from their host stars are favoured.

Drawbacks:

We don't see the host star.

Unique observation, not periodic, impossible to redo.

Orbital parameters unknown (only the distance to the host star times sin(i) at one moment is known).



Total :

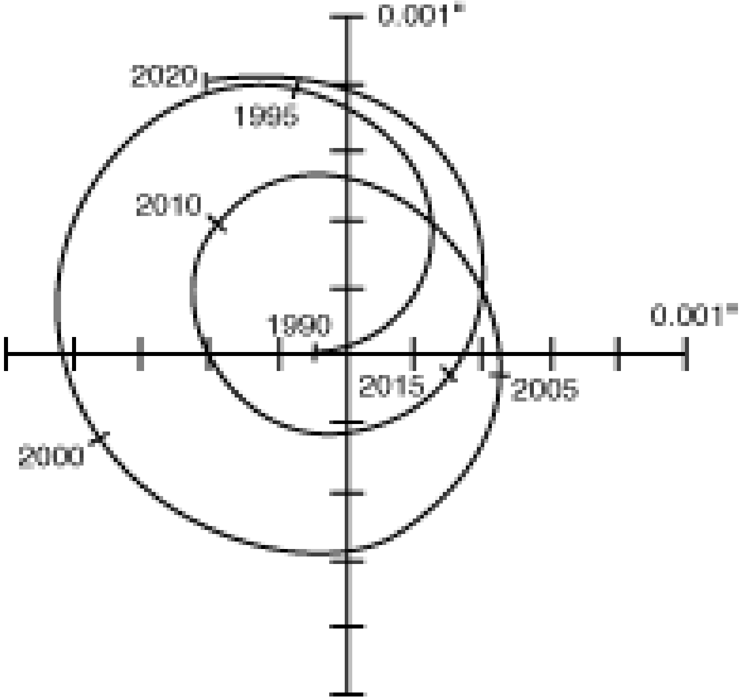
24 detections upto 2013.

EXOPLANETS : I d) Astrometry

The star is directly seen orbiting around the centre of mass, on the background of distant stars.

Caution : parallax and proper movement of the star add up to the orbit around the centre of mass.

Bright future for this technique, with GAIA : precision astrometry.



Ex : le mouvement du Soleil, vu d'une distance de 10pc.

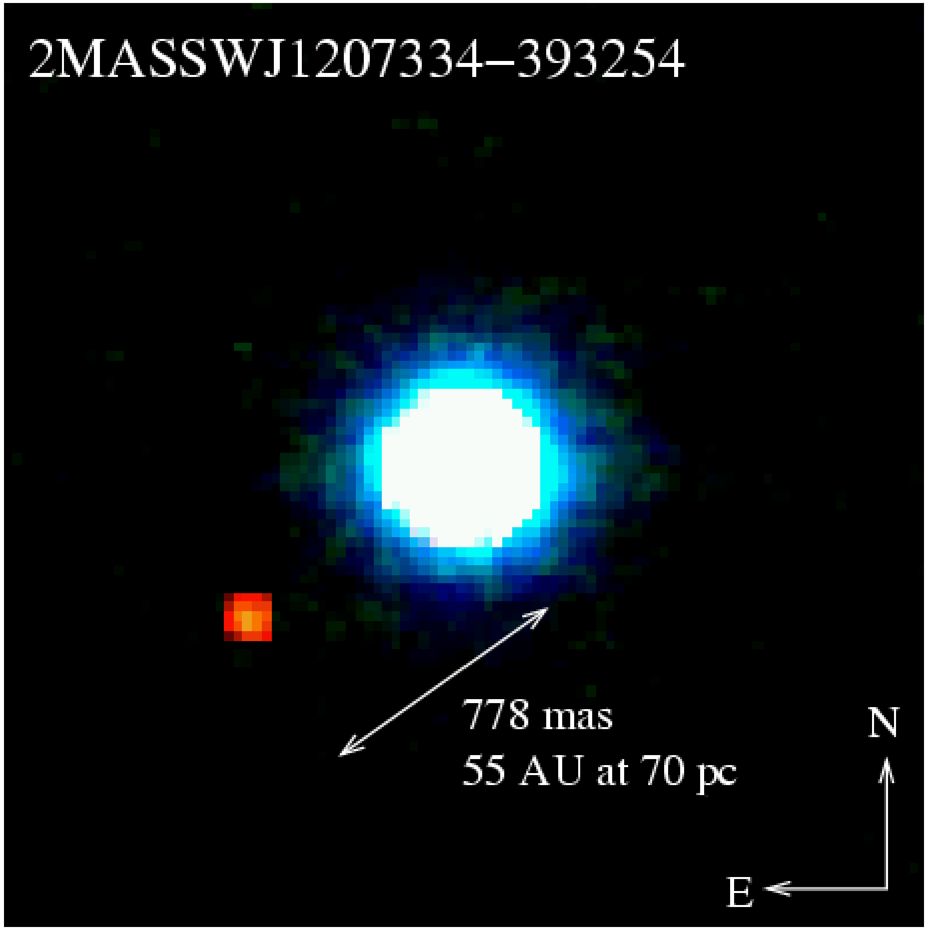
<u>Advantages :</u>

One gets directly i, a_p, e_p, M_p.

EXOPLANETS : I e) Direct imaging

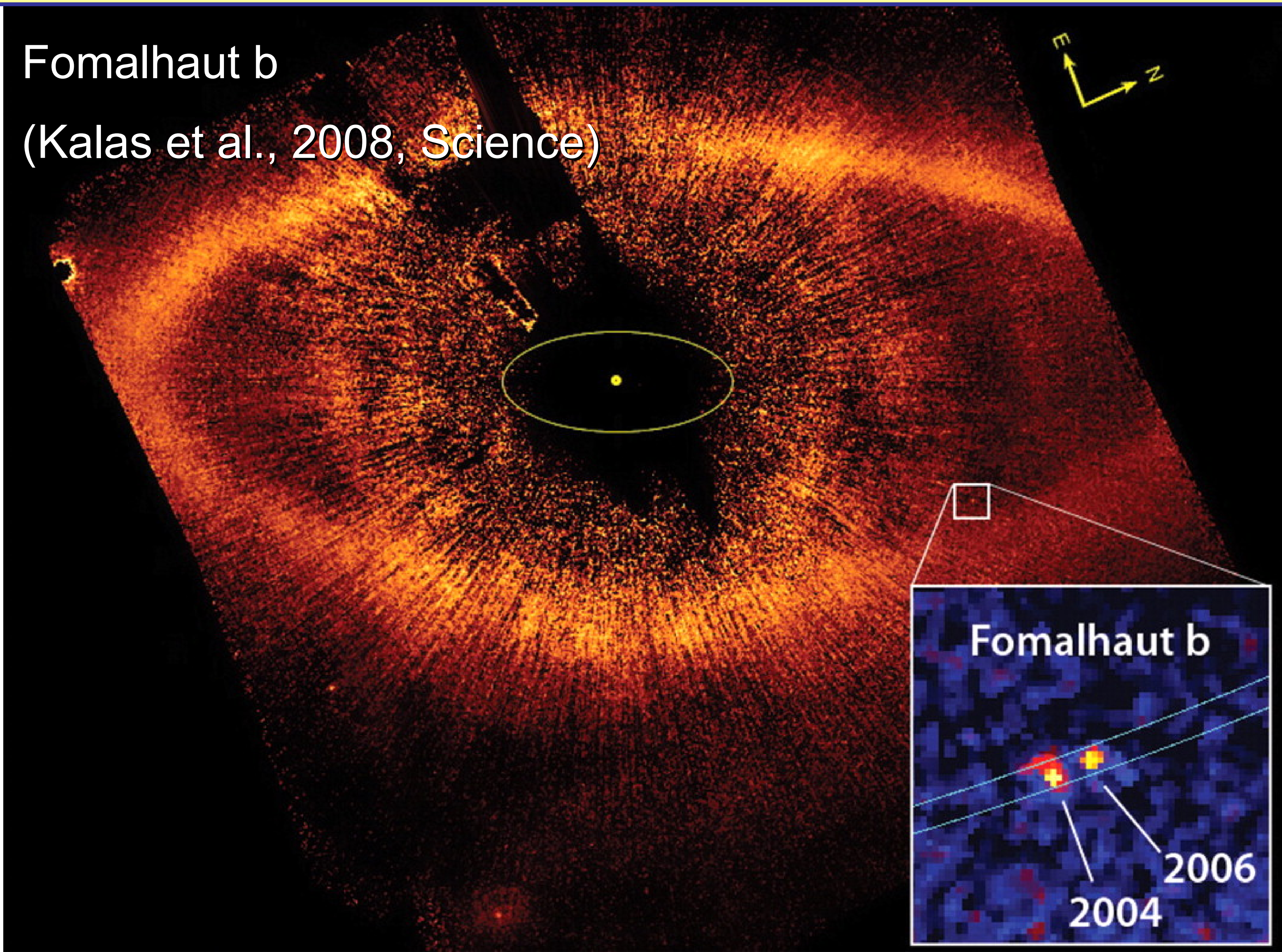
The planet is directly observed around the star, which can be shut down by a coronograph if needed.

First ever image of an extra-solar planet : Chauvin et al. (2004)



Or is it a double brown dwarf ?

EXOPLANETS : I e) Direct imaging



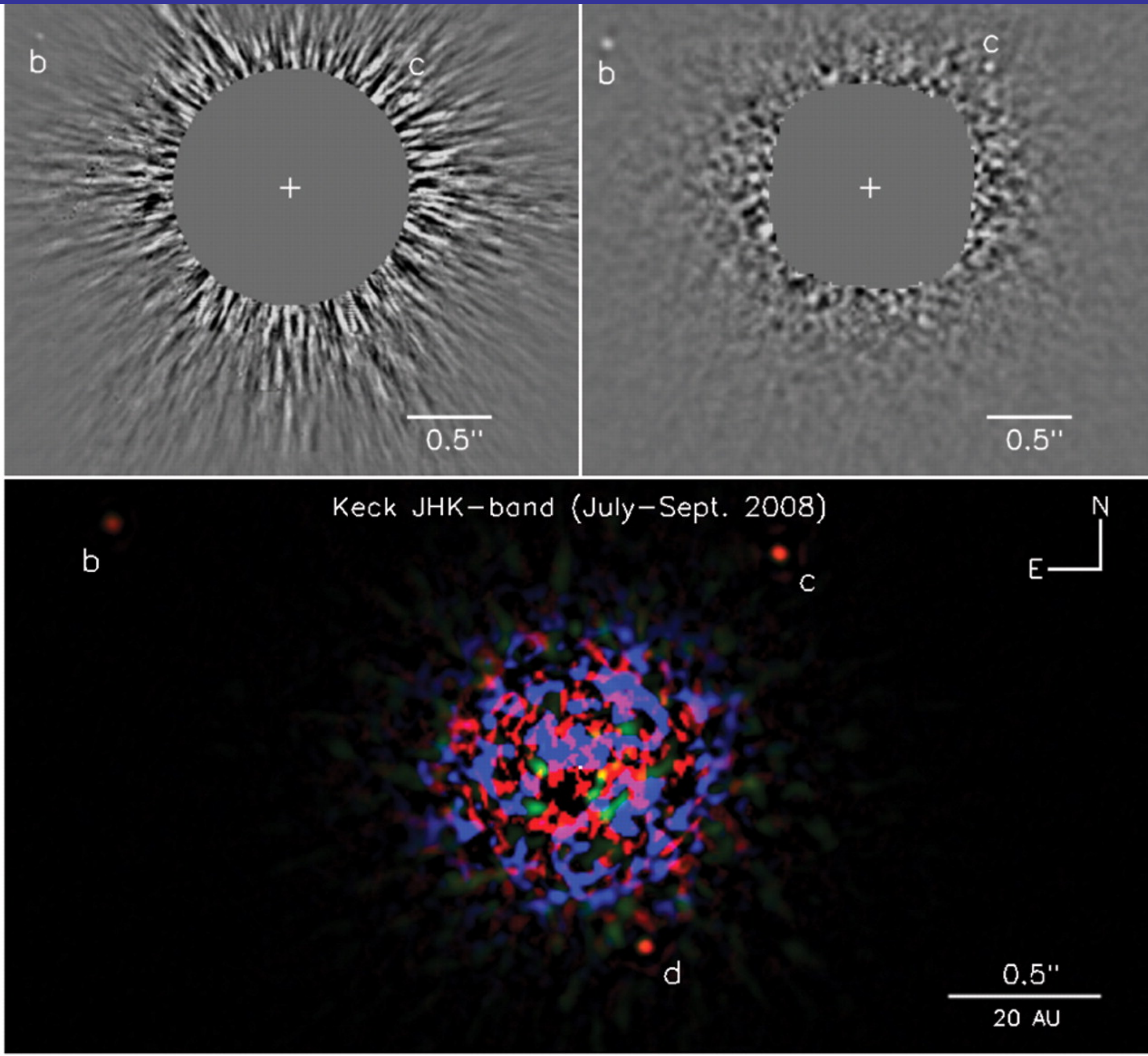
EXOPLANETS : I e) Direct imaging

<u>HR8799 :</u>

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

(Marois et al., 2008, Science)

+ 1 fourth one confirmed in november 2010



EXOPLANETS : I e) Direct imaging

SPectropolarimetric **H**igh-contrast **E**xoplanet **RE**search:
Un nouvel instrument au VLT
pour voir le voisinage très proche des étoiles.

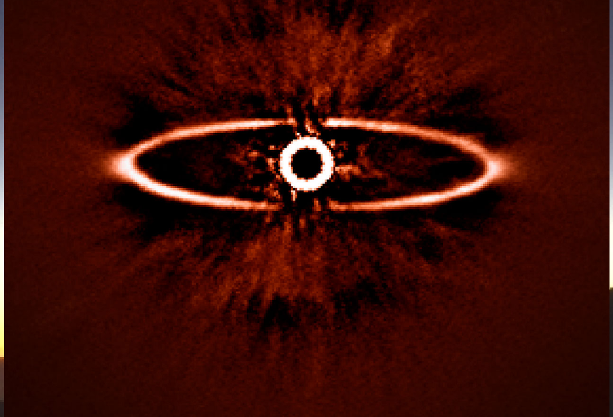
EXOPLANETS : I e) Direct imaging

SPectropolarimetric **H**igh-contrast **E**xoplanet **RE**search:
Un nouvel instrument au VLT
pour voir le voisinage très proche des étoiles.

Laboratoire pilote: IPAG (Grenoble).

Implication de LAGRANGE: Éric Lagadec, Patrice Martinez, Thierry Lanz, Zeinab Khorrami, Farrokh Vakili, Andrea Ferrari, Lyu Abe, Marcel Carbillet, Djamel Mekarnia...

Premiers tests très satisfaisants :

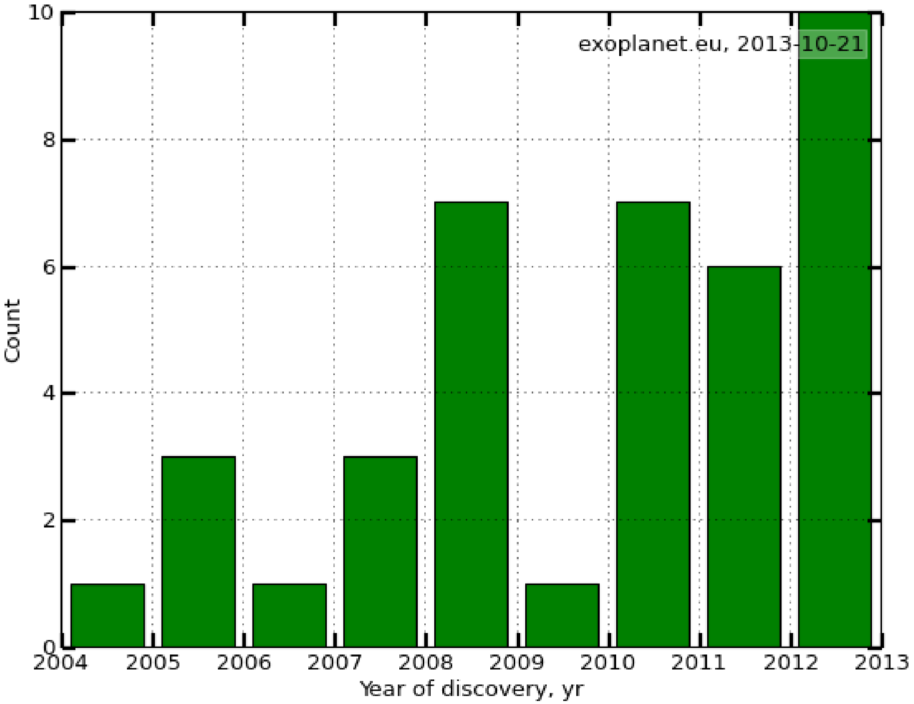


EXOPLANETS : I e) Direct imaging

Total : 32 planets detected this way (at the end of 2012).

This method favors giant planets, far from their stars, which are not accessible by velocimetry or transits.

Needs for refined observations techniques (interferometry, coronography, ...).



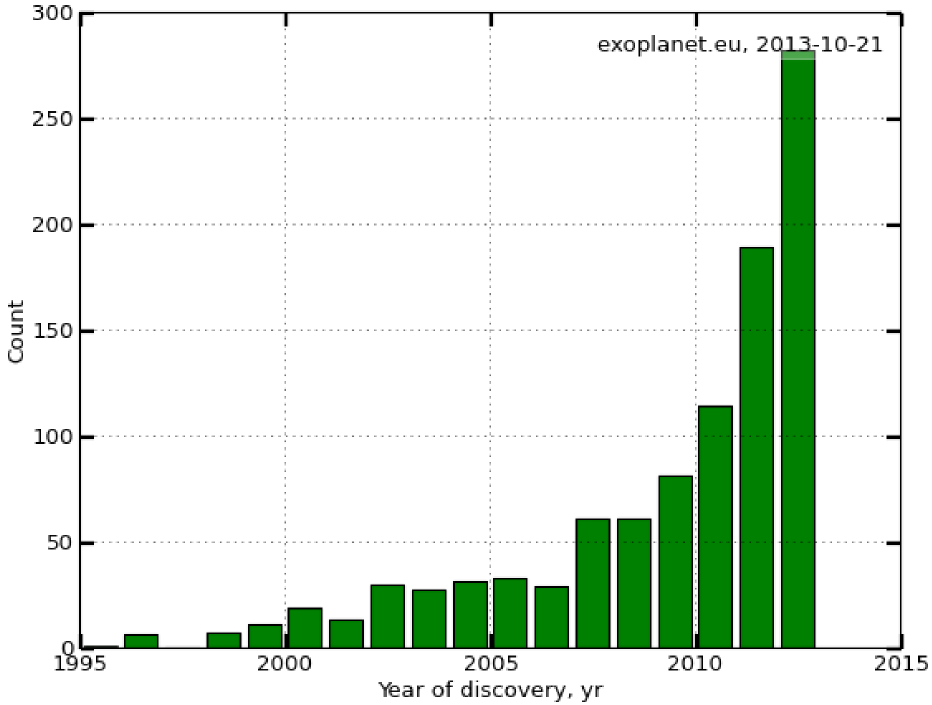
Advantages:

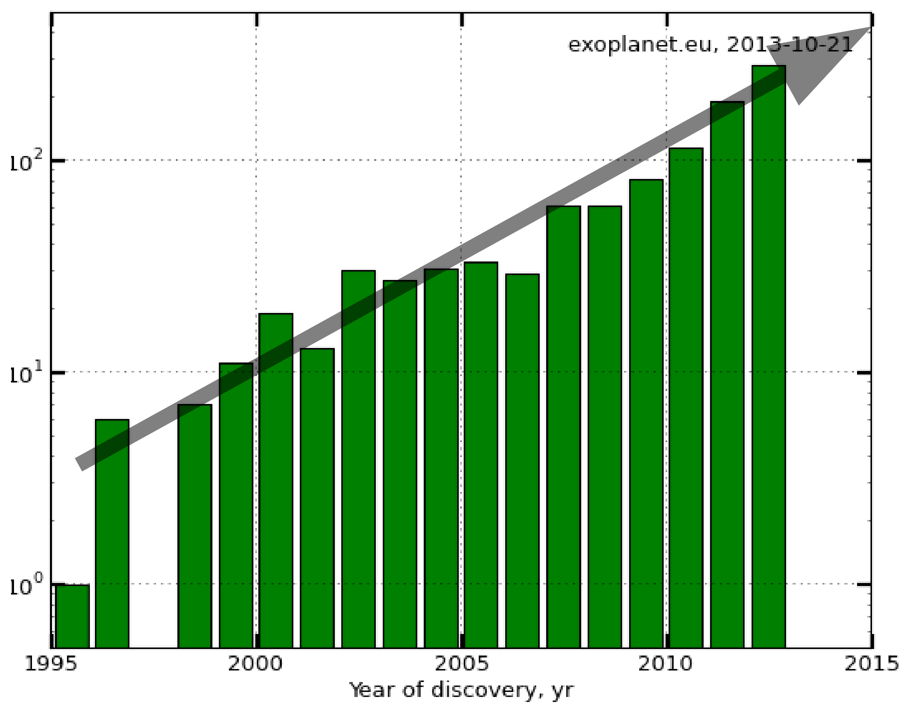
Direct proof of existence

Possibility of spectroscopy...

EXOPLANETS : I Detections summary

The number of detections per year seems to grow exponentially :





Life is in logscale...

EXOPLANETS

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- Direct imaging

II Properties and statistics

- Mass, semi major axis, period, eccentricity, radius, metallicity of the host star, density, spectrum...

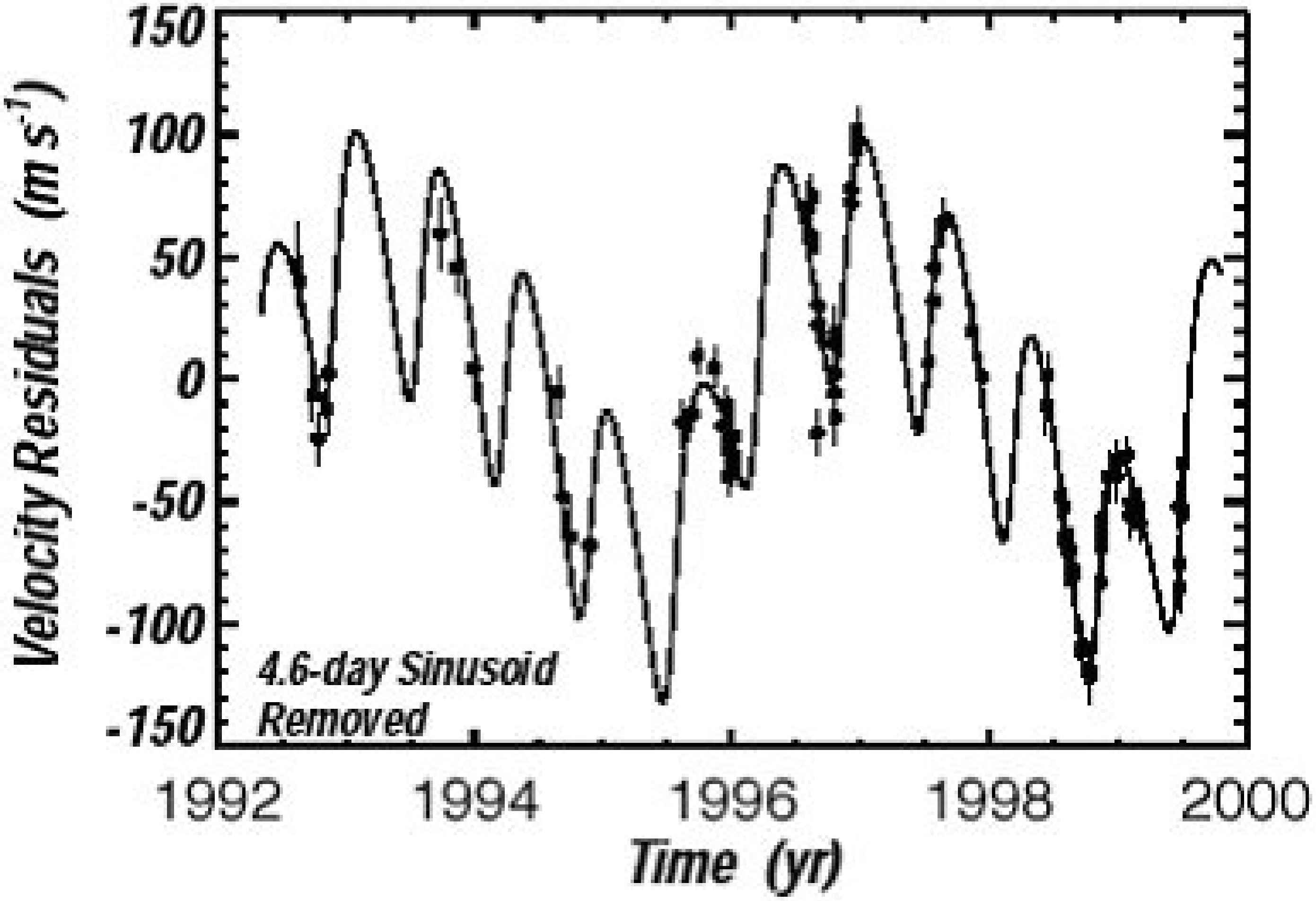
EXOPLANETS : II) Statistics

We don't have only 1 system at hand, but hundreds ! The planetary formation models must take this diversity into account, and explain the observed properties.

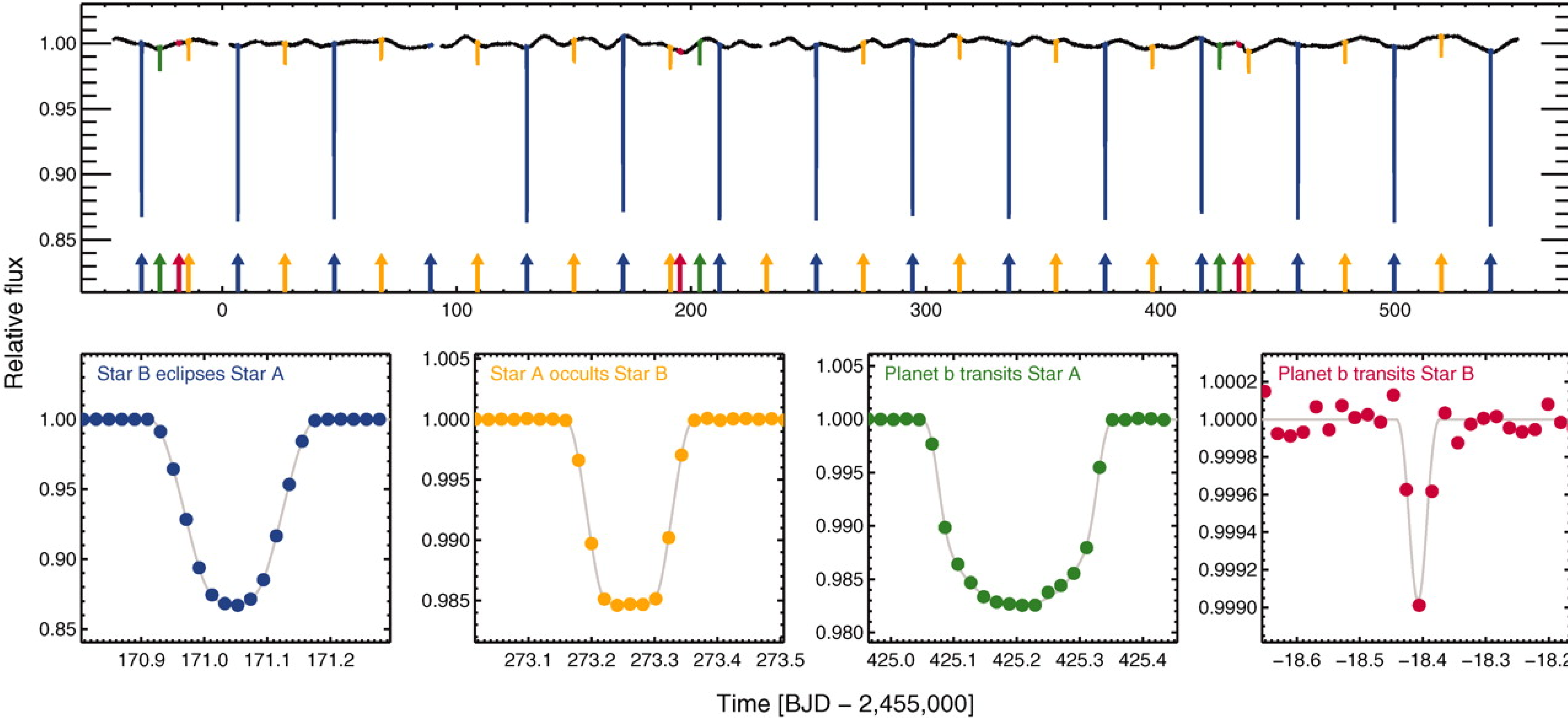
Caution : every method has its biases.

Be aware of that when doing statistics.

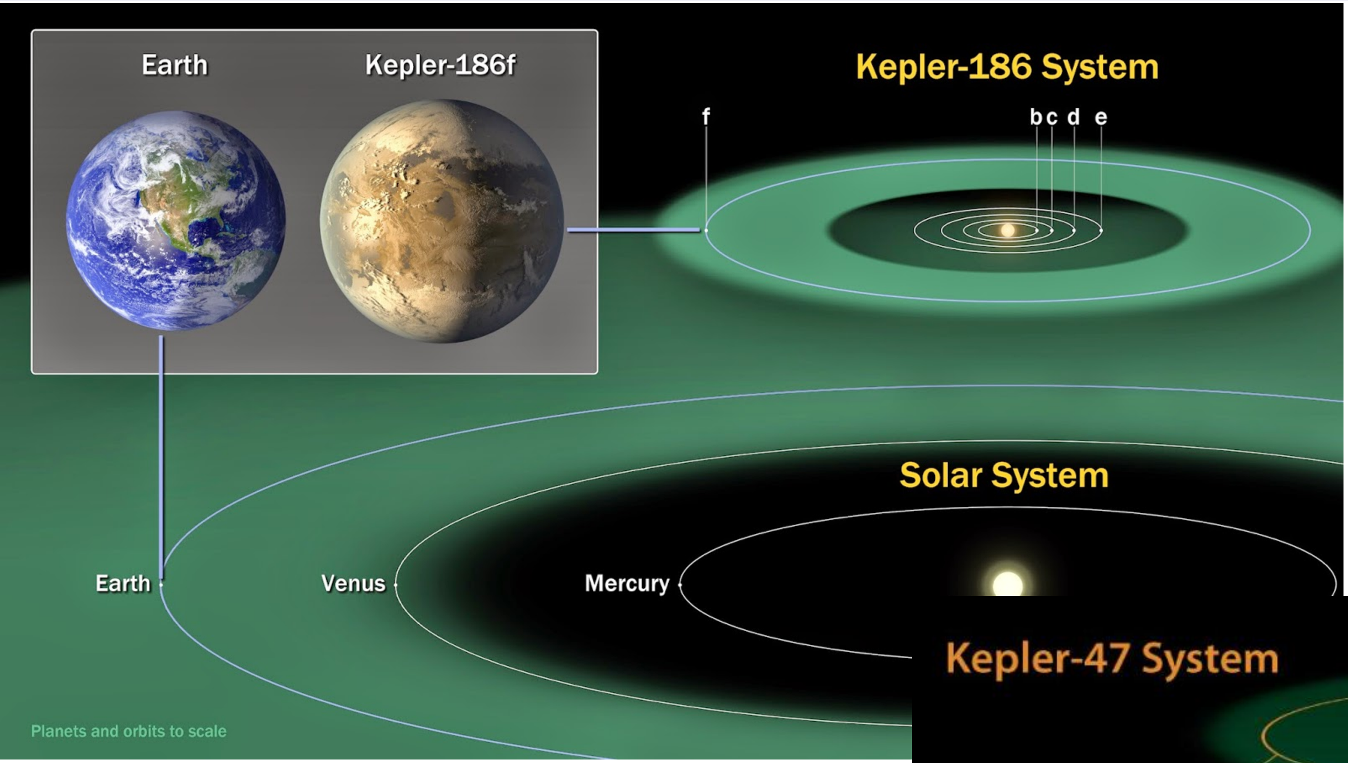
EXOPLANETS : II) Systems

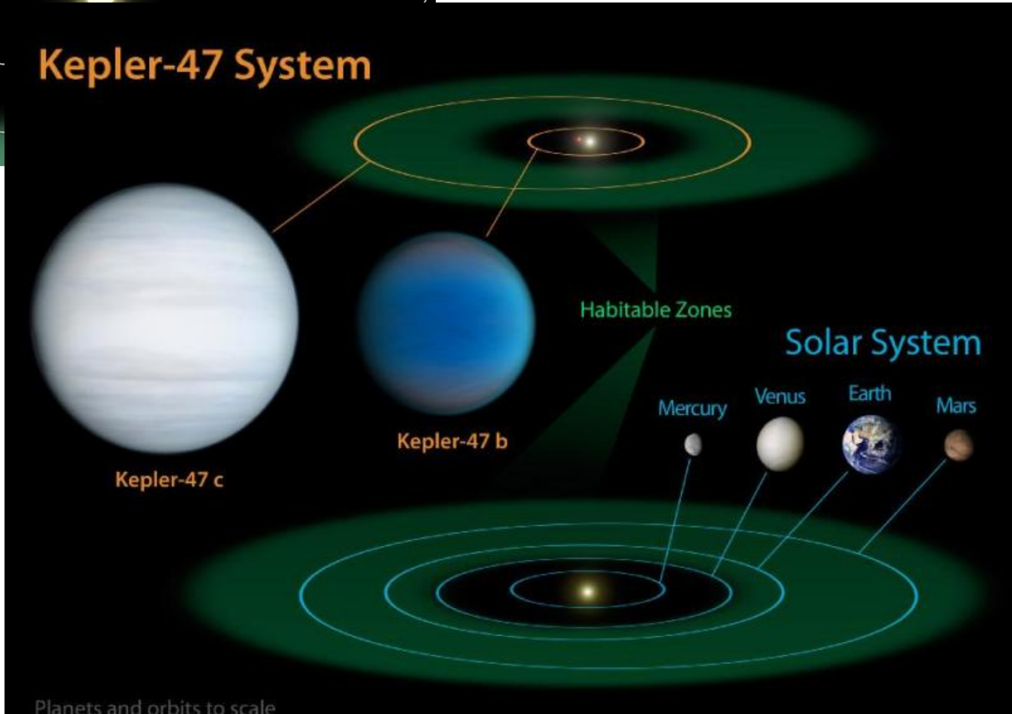


EXOPLANETS : II) Systems

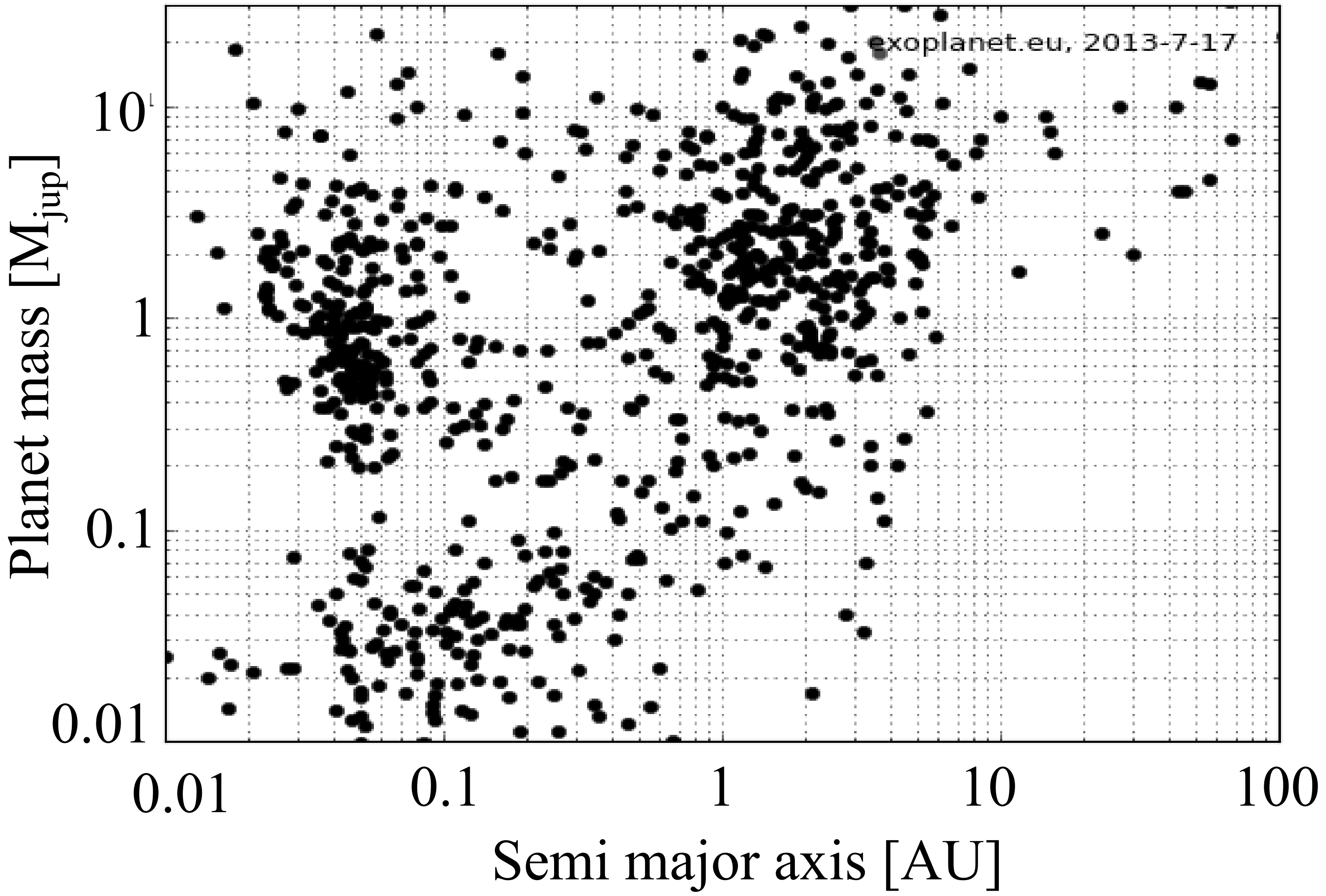


EXOPLANETS : II) Systems

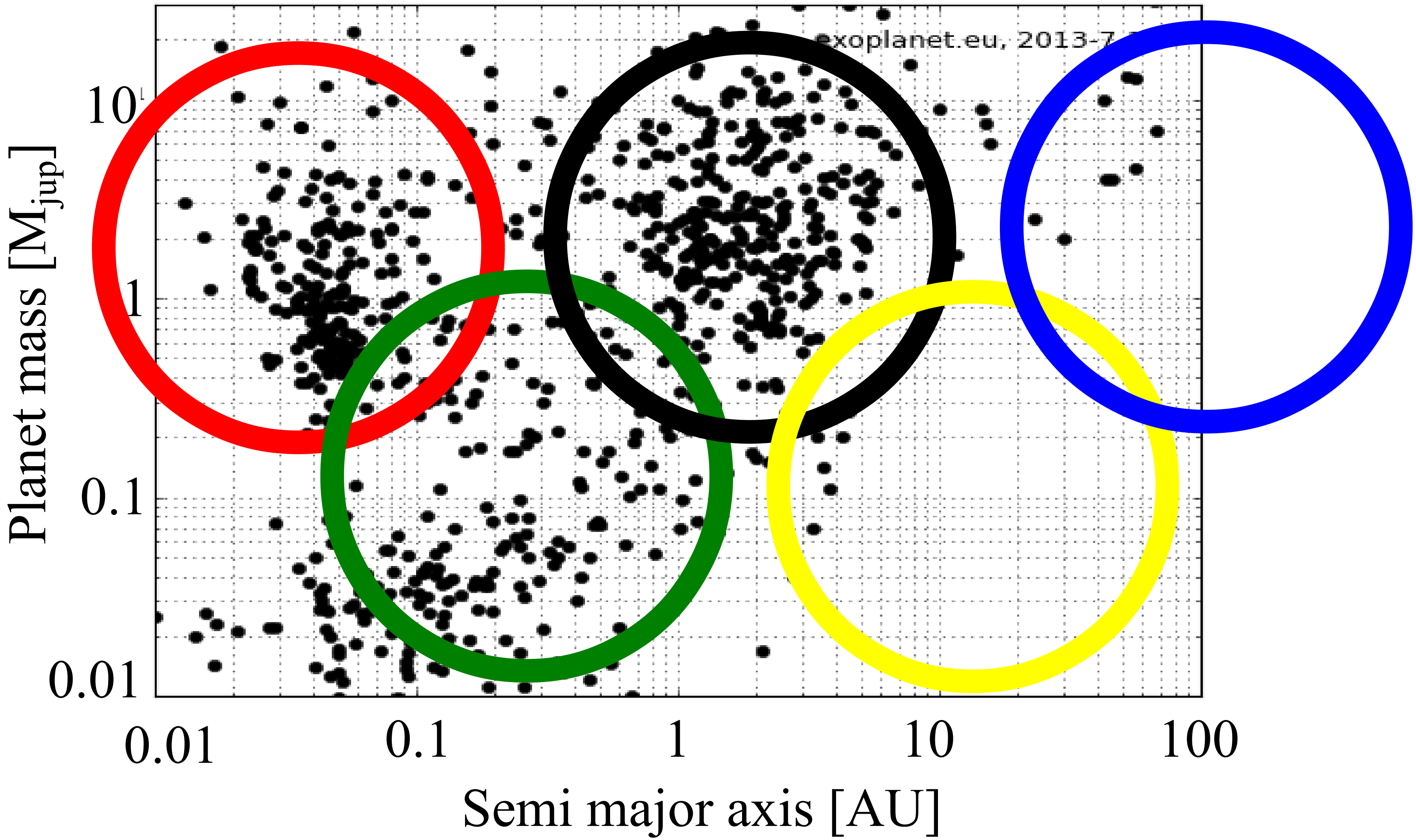




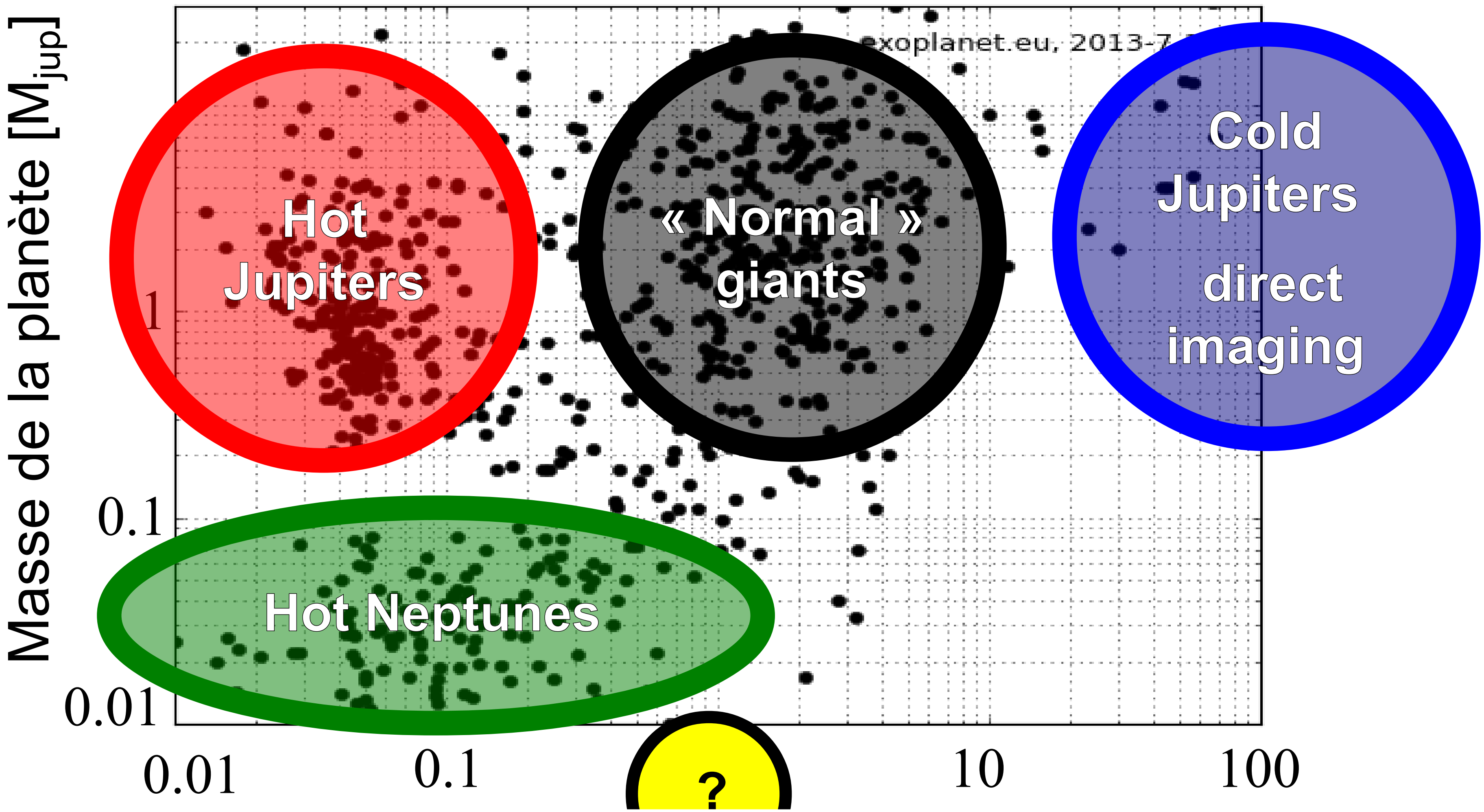
EXOPLANETS : II) Statistics



EXOPLANETS : II) Statistics



EXOPLANETS : II) Statistics



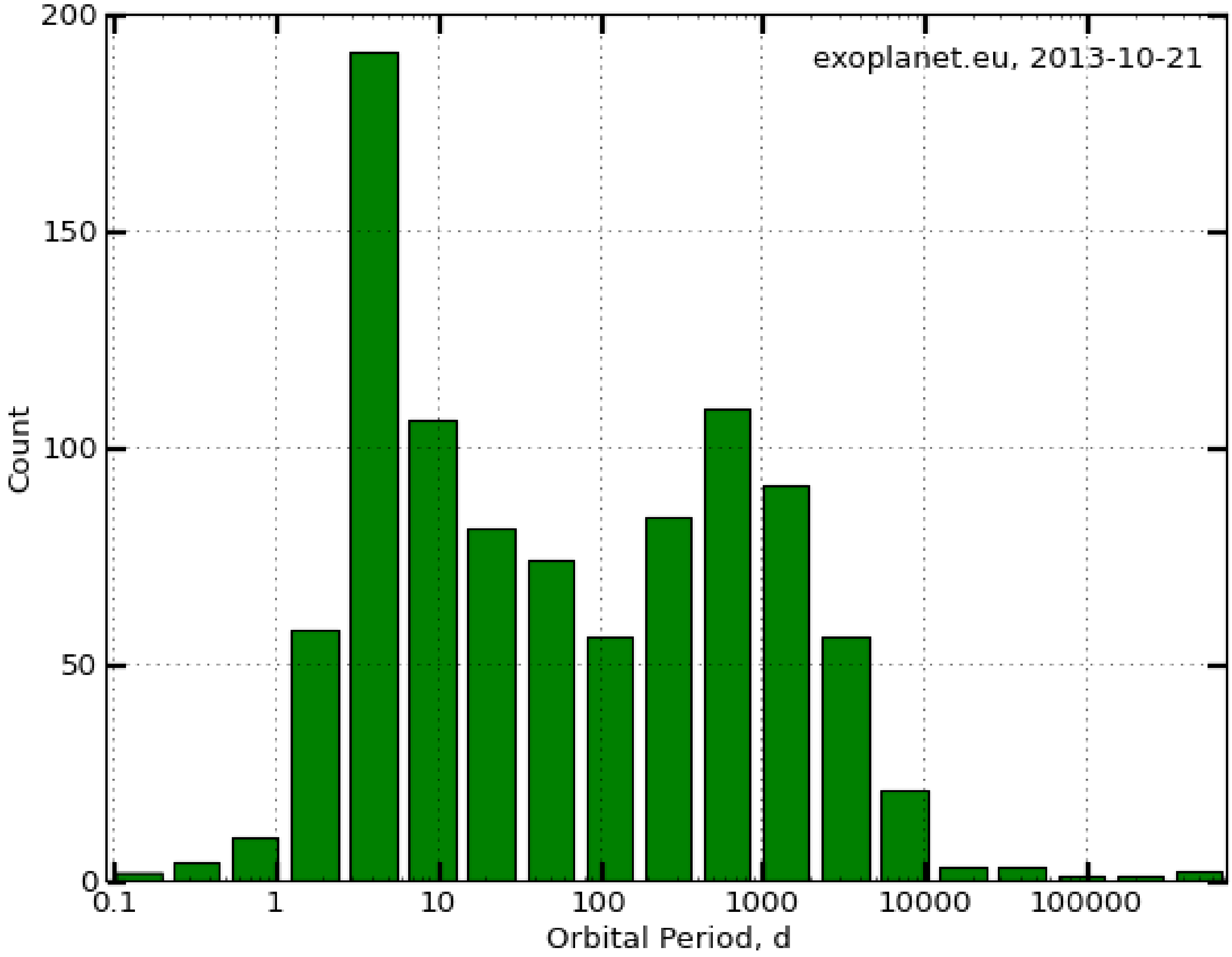
In spite of observationnal biases, one sees 3 populations, separated by 2 deserts.

EXOPLANETS : II) Statistics

The desert between neptune mass planets and Jupiter mass planets is consistent with the core accretion model for the formation of giant planets : the growth from Neptune mass to Jupiter mass is extremely fast.

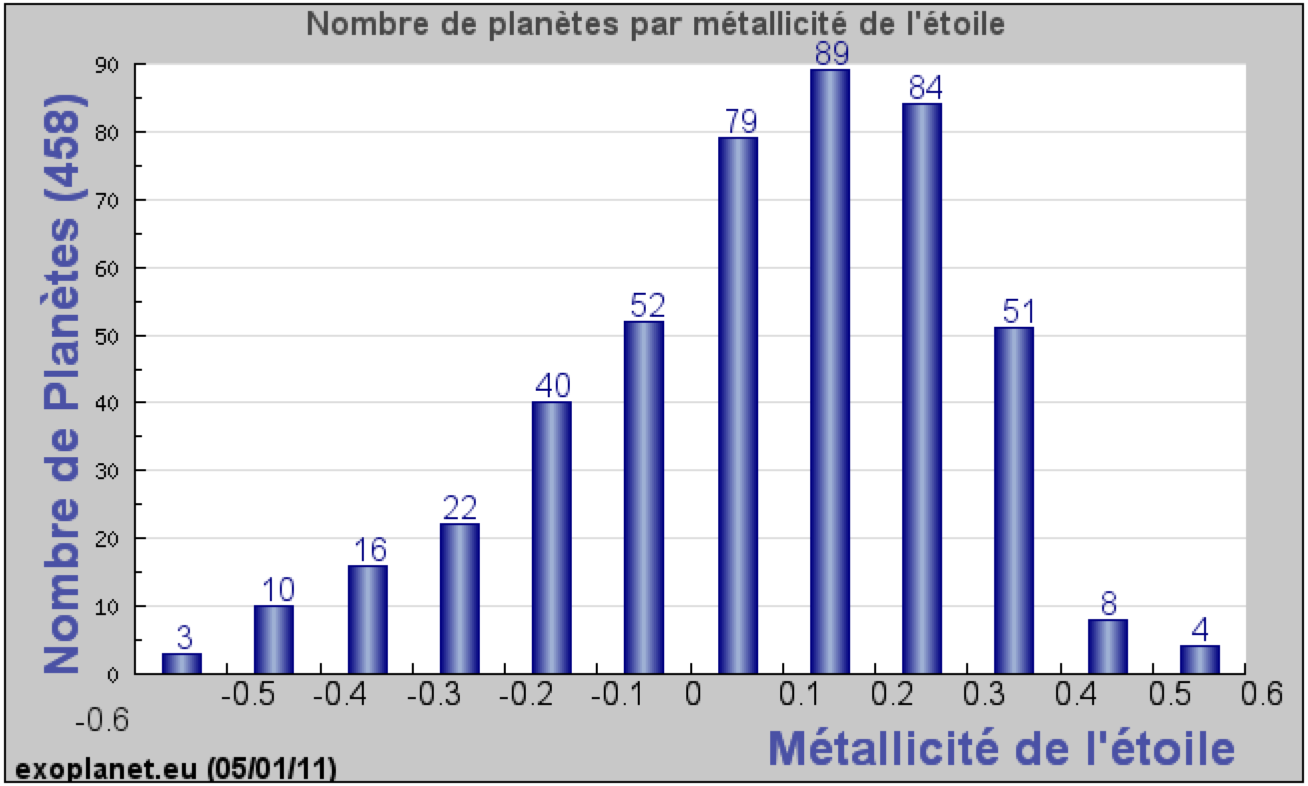
Either the disk life-time is enough to form a Jupiter-like gas giant, or it isn't, and one only gets an icy core with smaller atmosphere, like Neptune

EXOPLANETS : II) Statistics



Statistics in period suggest that migration plays a big role...
but not always !

EXOPLANETS : II) Statistics



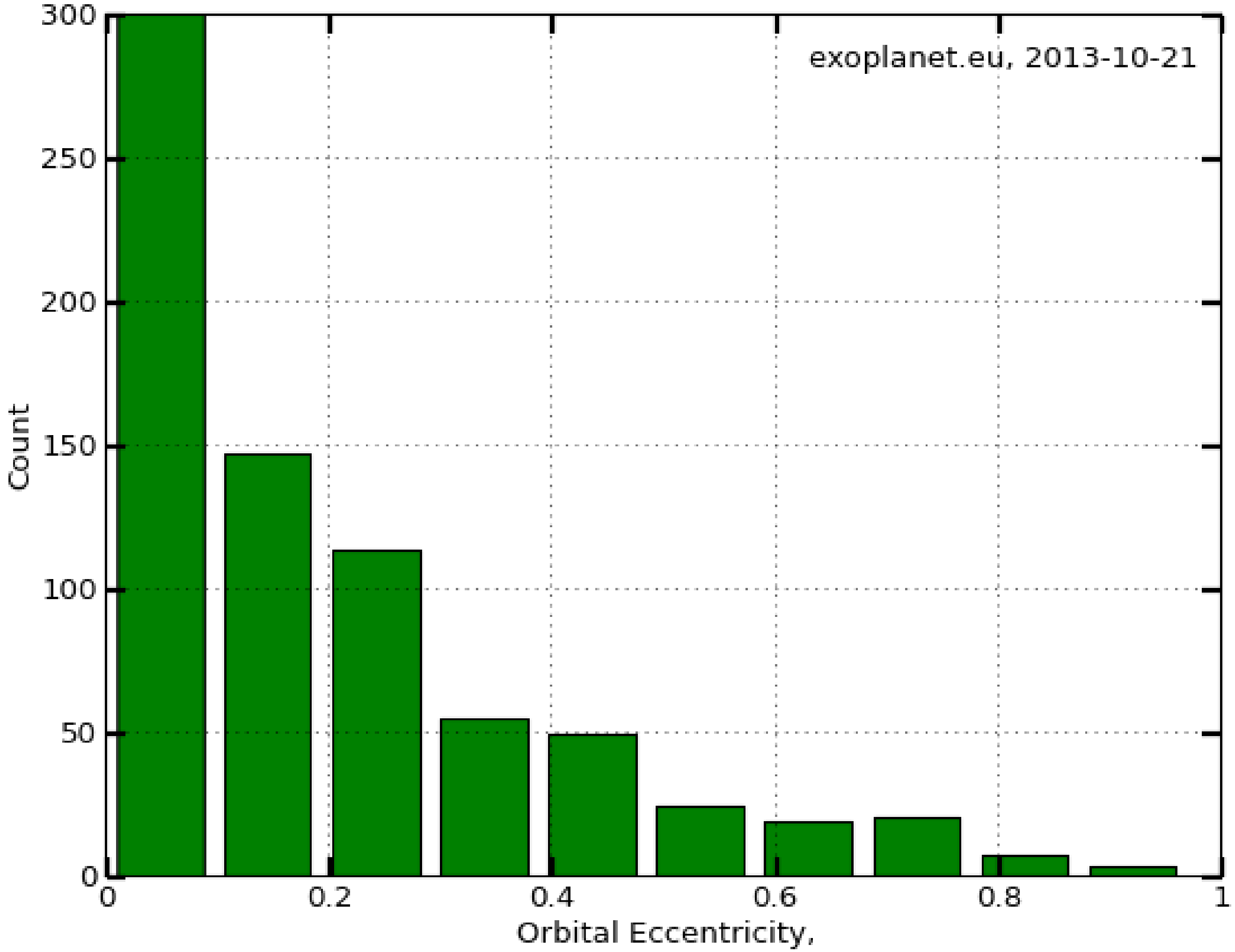
Strong influence of the metalicity of the host star !

The likelyhood of the presence of planet(s) increases with Z.

Why ?

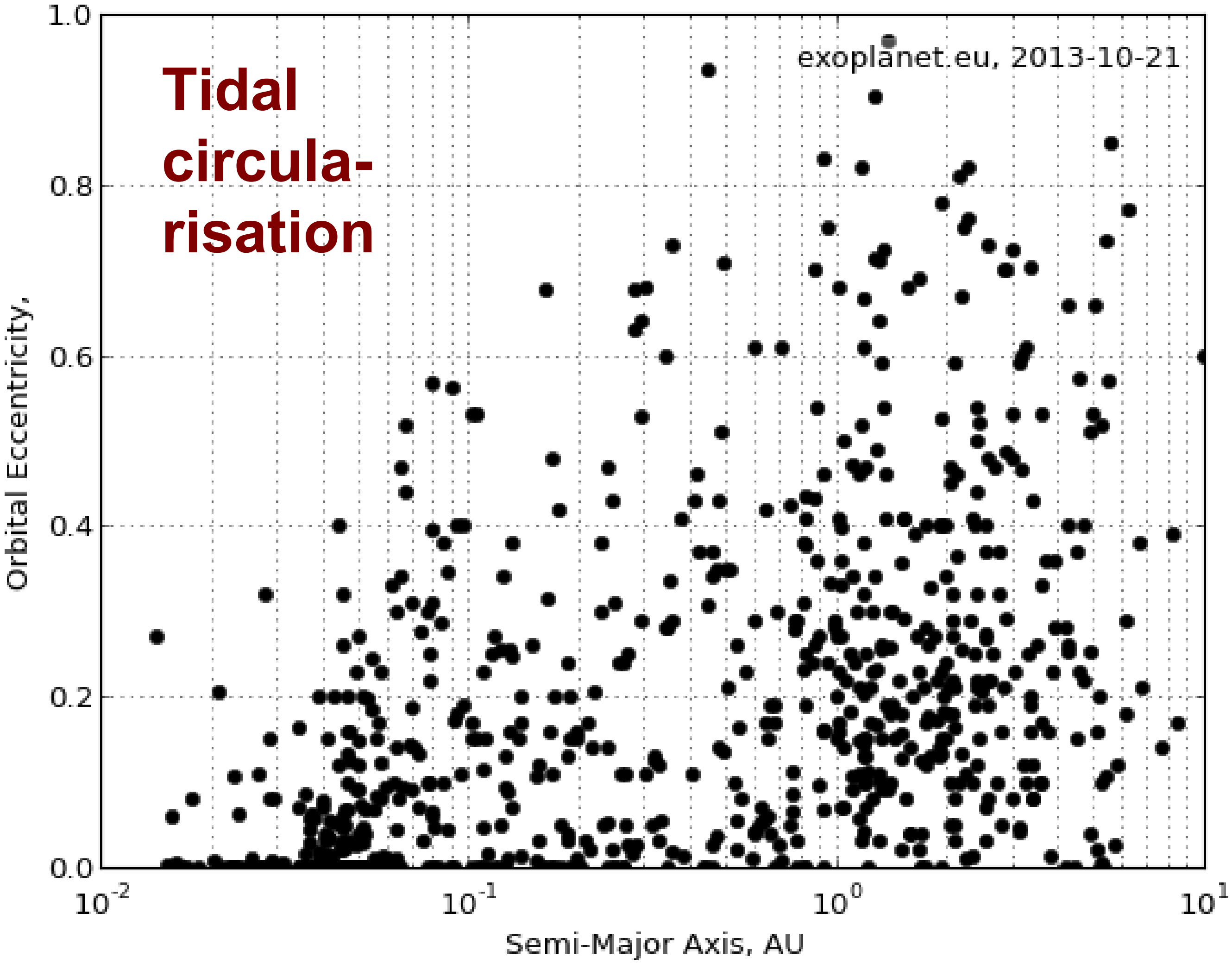
EXOPLANETS : II) Statistics

Excentricities : great variety !



EXOPLANETS : II) Statistics

Correlation a – e ?



EXOPLANETS : II) Planet Population Synthesis

Planet Population Synthesis :

Kitchen recipe including all the ingredients we will see in the *planet formation* Chapter :

accretion, disk evolution, migration, and so on.

Programm the evolution of 1 embryo, starting from an initial mass and semi-major axis.

Repeat this operation for a whole distribution of initial conditions.

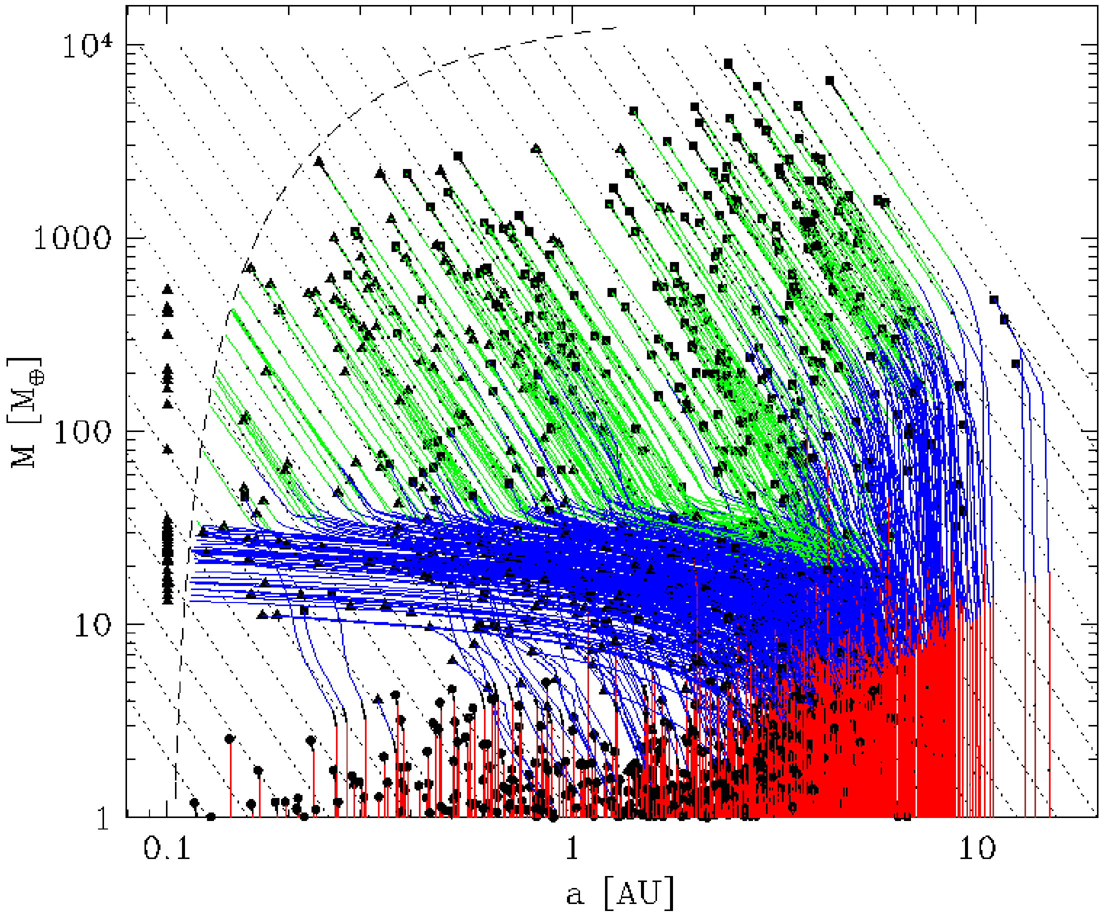
Look at the final distribution.

Compare with the statistics of the observations.

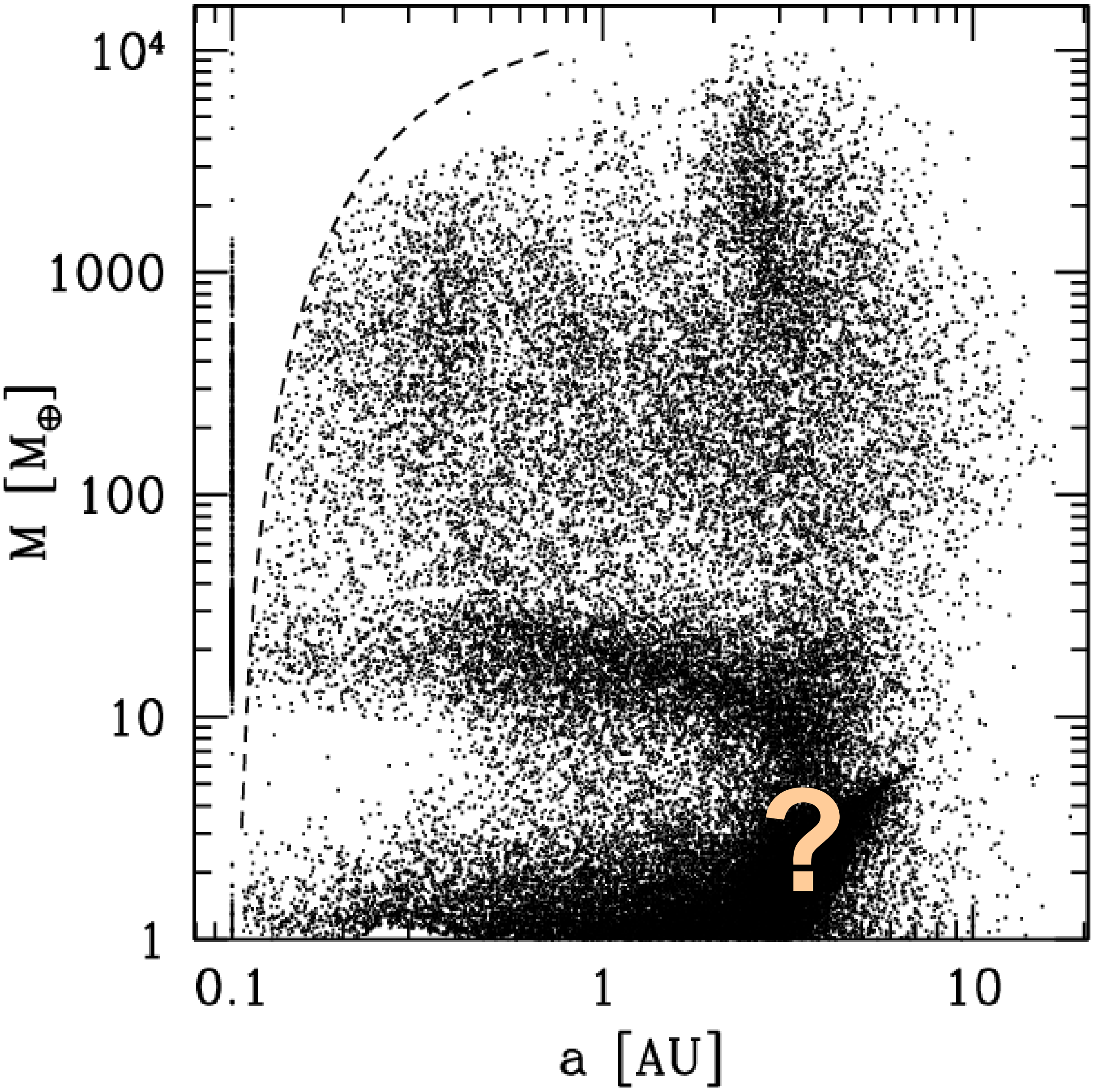
EXOPLANETS : II) Planet Population Synthesis

Plant Population Synthesis

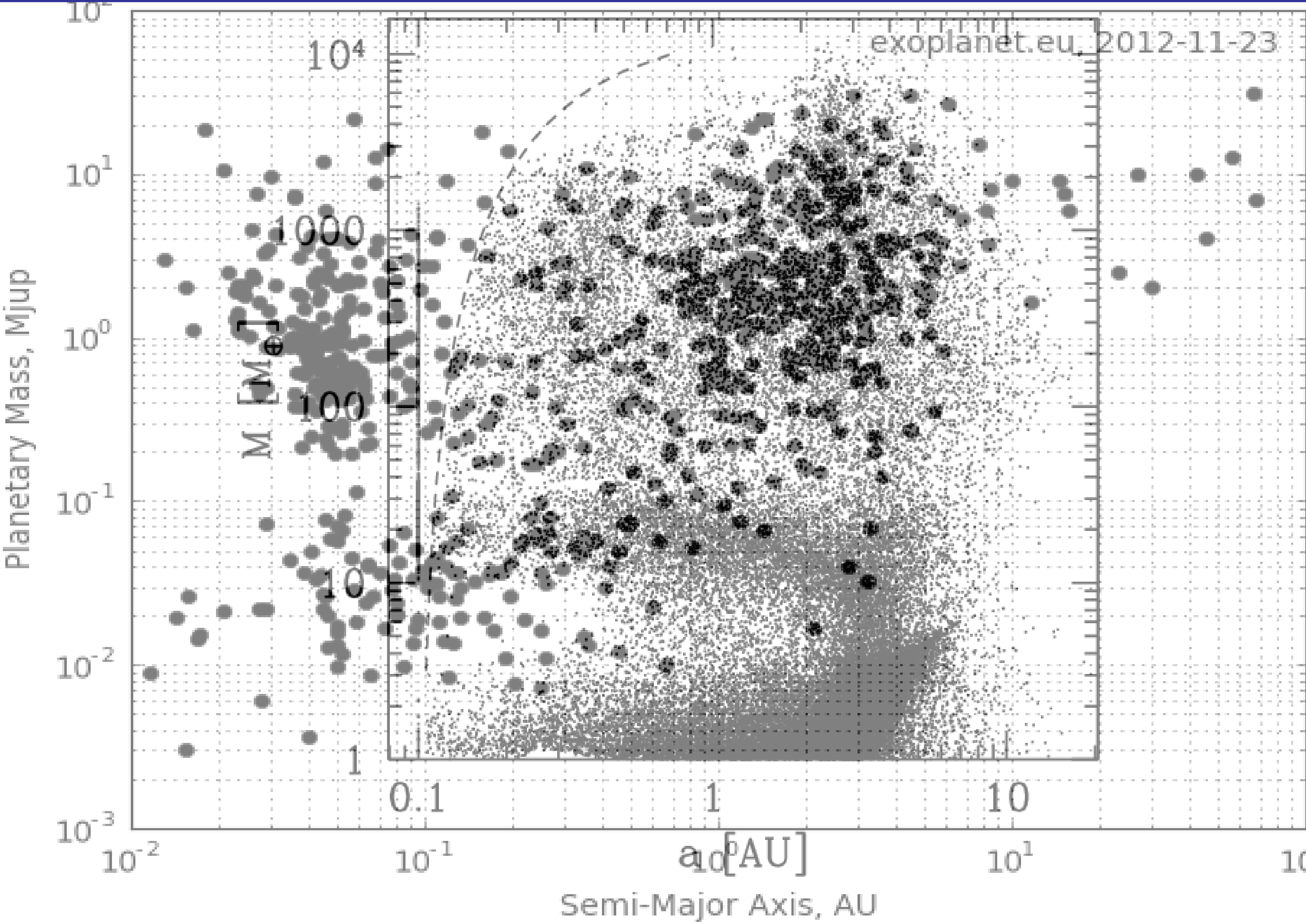
(Mordasini, Alibert, Benz, Naef, 2009).



EXOPLANETS : II) Planet Population Synthesis



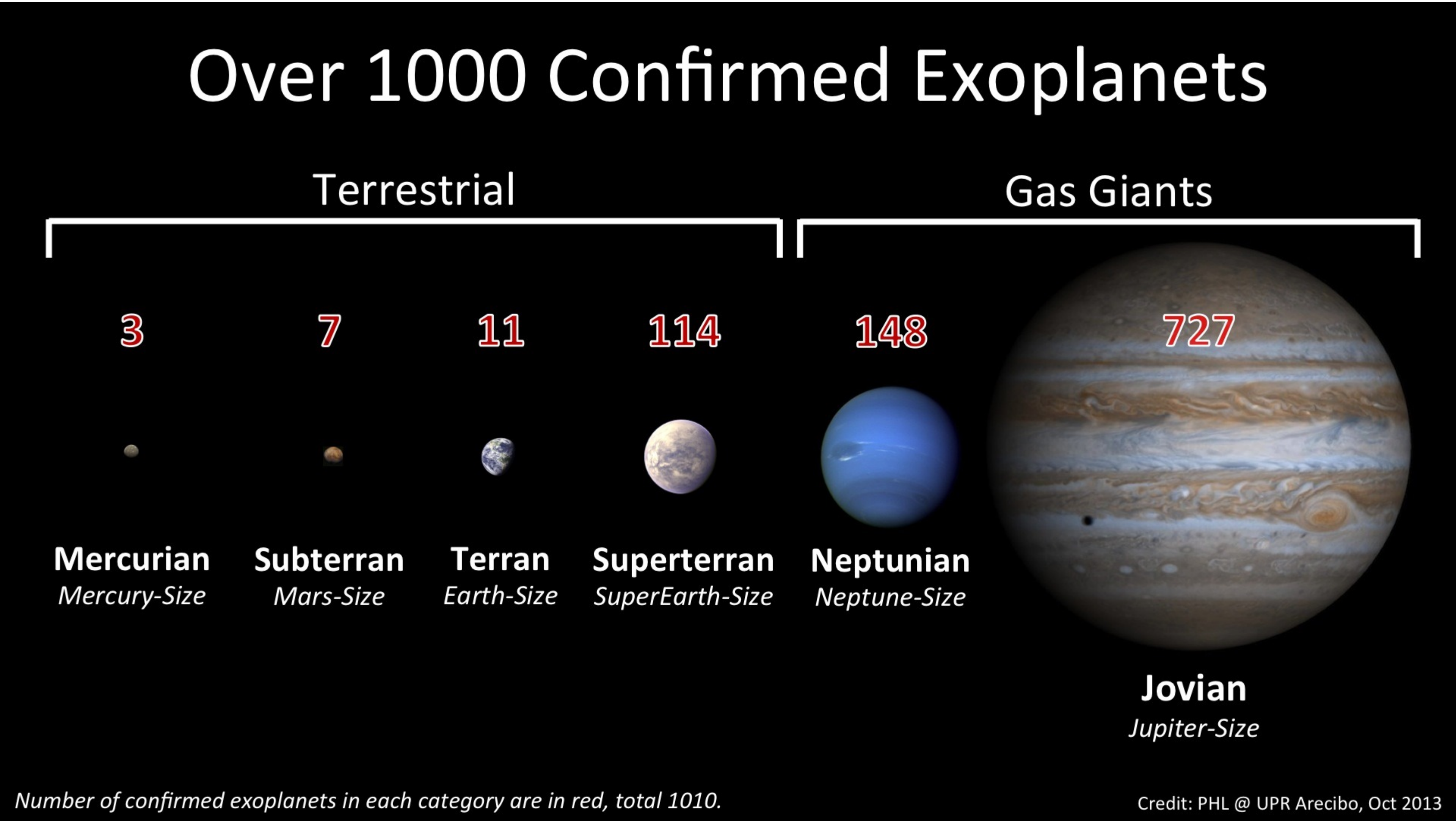
EXOPLANETS : II) Statistics



EXOPLANETS

See www.exoplanet.eu :

data, statistics, correlations, ...

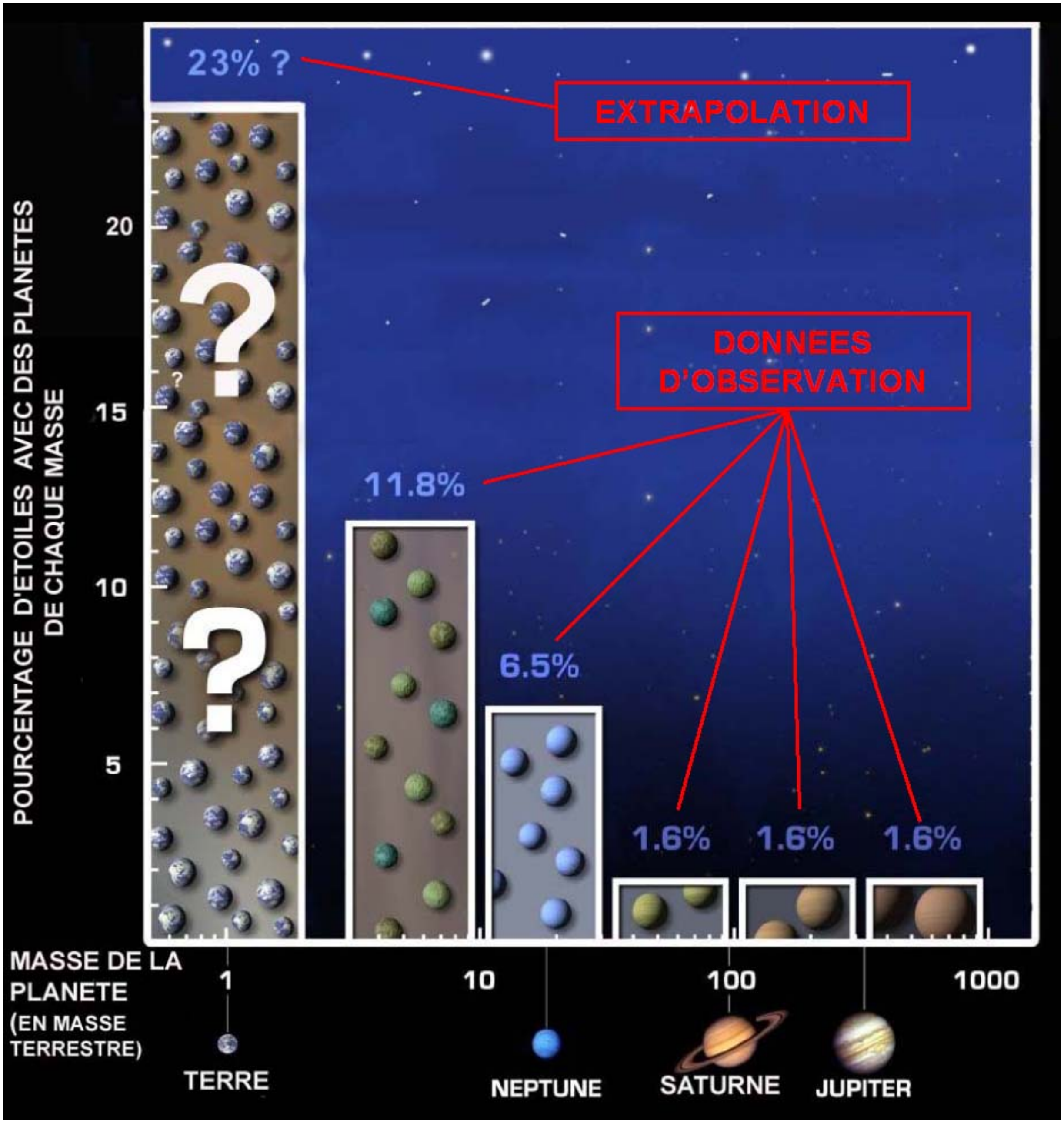


EXOPLANÈTES : Statistiques

25% des étoiles ont 1 planète (au moins).

On peut extrapoler :
il y a au moins 46 milliards de planètes de type terrestre dans notre Galaxie !

NB : Variété extraordinaire, avec planètes de type inconnu (Jupiters chauds, super terres) → du travail pour les théoriciens !



CHRONOLOGIE de la VIE

14 milliards d'années : Big Bang, naissance de l'Univers.

4,5 milliards d'années : Formation de la Terre.

3,8 milliards d'années : Première forme de vie (unicellulaire).

3,0 milliards d'années : Photosynthèse.

1,2 milliards d'années : Première forme de vie pluri-cellulaire.

0,6 milliards d'années : Explosion cambrienne.

480 millions d'années : Premières plantes terrestres.

220 millions d'années : Premiers mammifères.

65 millions d'années : Fin des dinosaures.

3 millions d'années : Australopithèques

400 000 ans : maîtrise du feu.

CHRONOLOGIE des TRANSPORTS

-4500 : Domestication du cheval.

1520 : Magellan fait le tour du monde.

1782 : Montgolfière.

1906 : Premier vol en avion.

1947 : Franchissement du mur du son.

1961 : Gagarine dans l'espace.

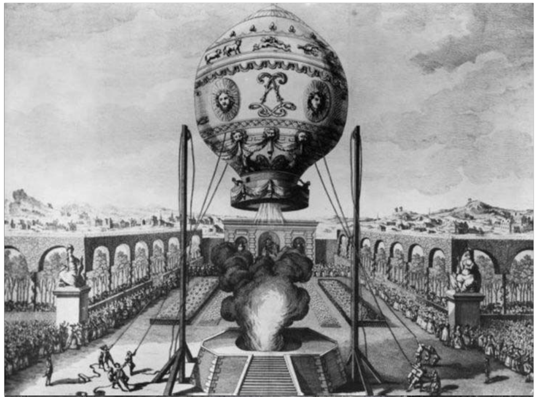
1969 : L'homme sur la Lune.

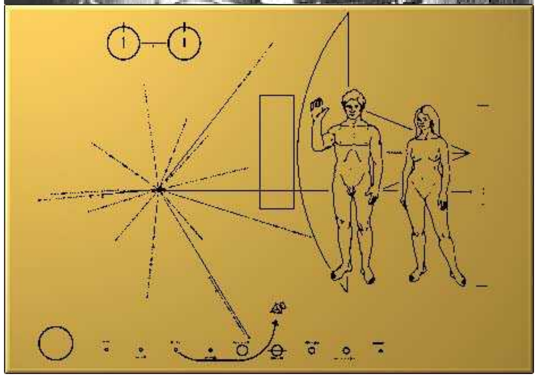
1975 : *Viking* sur Mars.

2004 : *Cassini* en orbite autour de Saturne.

2012 : *Voyager* quitte le système solaire.

10 000 : L'homme conquiert la Galaxie ???





PARADOXE de FERMI

A l'échelle de l'Univers, nous aurons conquis la Galaxie en un claquement de doigts, si nous continuons notre développement.

Pourquoi, parmi les 46 milliards de planètes terrestres n'y en aurait-il pas une qui a 10000 ans d'avance sur nous ? Formée il y a 4500,01 millions d'années ?

Où sont-ils ?

Y a-t-il une faille dans le raisonnement ?

PARADOXE de FERMI

à mon humble avis :

Un développement exponentiel n'est pas possible indéfiniment.

<u>1) limites physiques :</u>

- vitesse de la lumière indépassable
- ressources limitées

PARADOXE de FERMI

à mon humble avis :

Un développement exponentiel n'est pas possible indéfiniment.

<u>2) limites sociétales :</u>

Le facteur L de Drake n'est peut-être pas très grand...

- Guerre froide...

- Nouvelle étude (financée par la NASA) : HANDY.

Notre civilisation va bientôt disparaître :
inégalités, épuisement des ressources, changement climatique

« Si ces scénarios paraissent difficiles à éviter, les scientifiques mettent en avant la nécessité urgente de "réduire les inégalités économiques afin d'assurer une distribution plus juste des ressources, et de réduire considérablement la consommation de ressources en s'appuyant sur des ressources renouvelables moins intensives et sur une croissance moindre de la population." »

http://www.rtbf.be/info/societe/detail_une-etude-de-la-nasa-met-en-garde-contre-la-chute-de-l-empire-occidental?id=8223283

En ayant la tête dans les étoiles, on retombe sur Terre...

On a beau connaître 1000 exo-planètes on se rend compte qu'on ferait mieux de protéger la notre, et de tout faire pour bien y vivre ensemble...