EXOPLANETS

Aurélien CRIDA

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

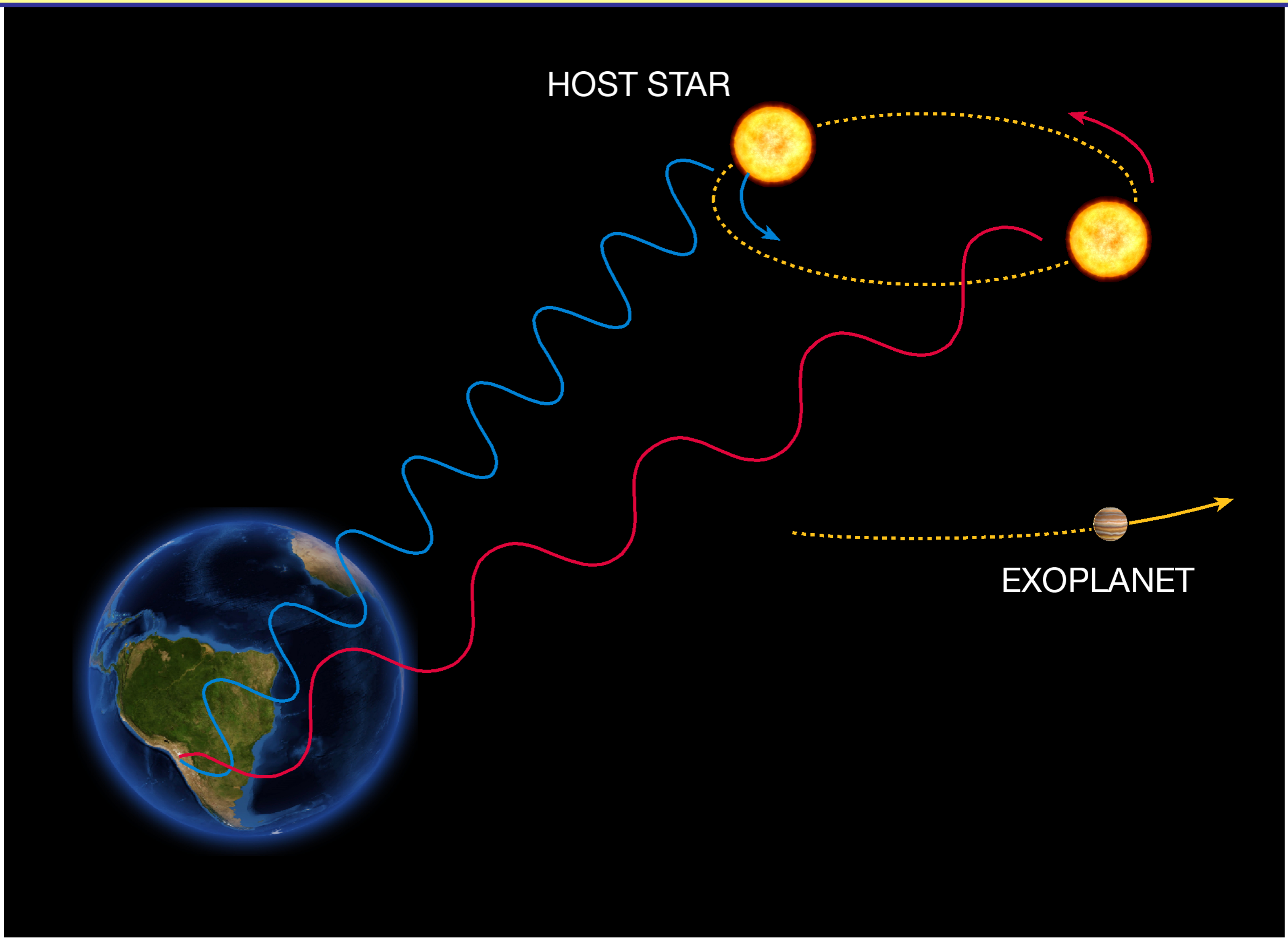
I Detection methods

- 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...

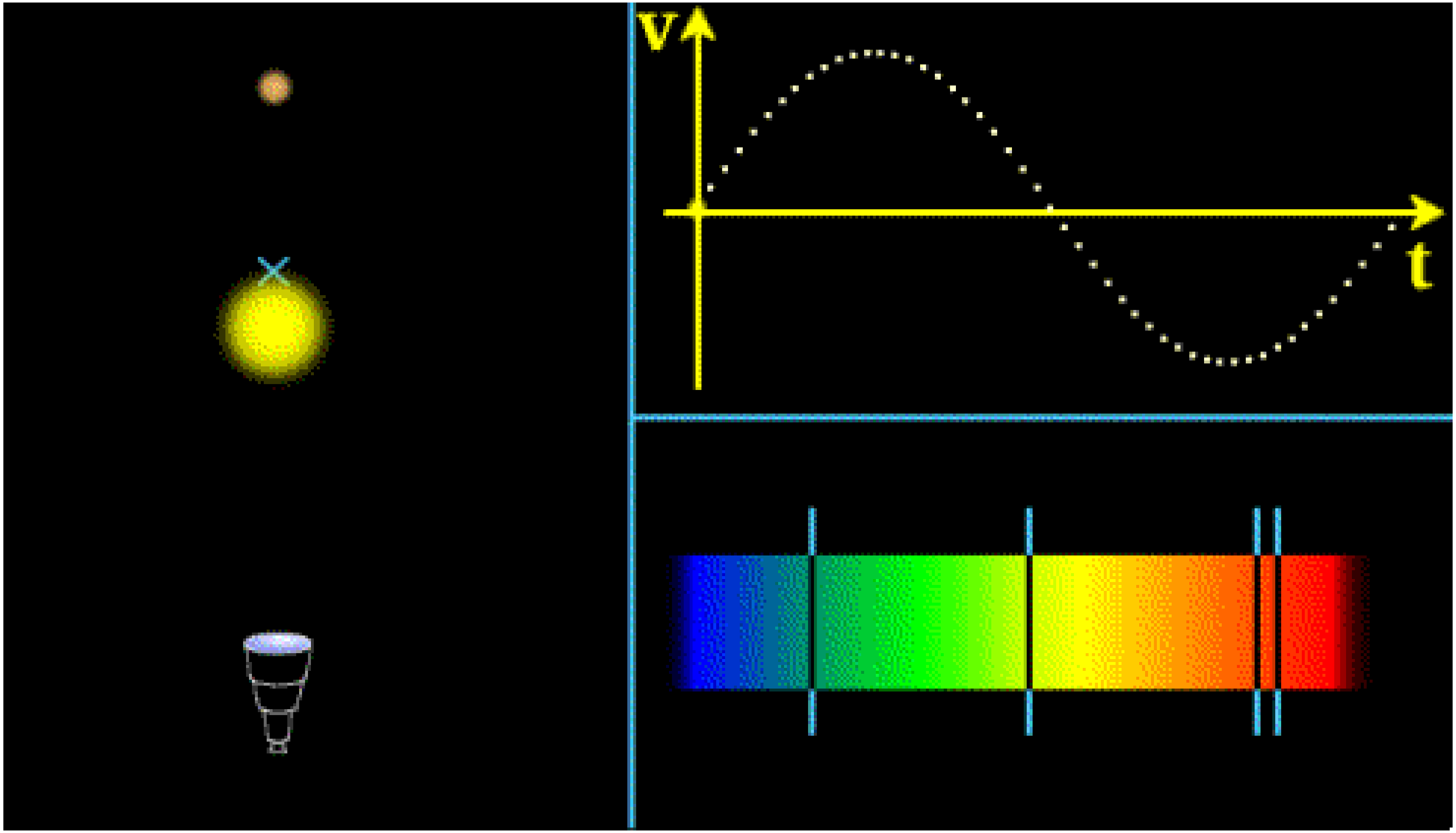
EXOPLANETS Ia) Radial velocity



The Radial Velocity Method

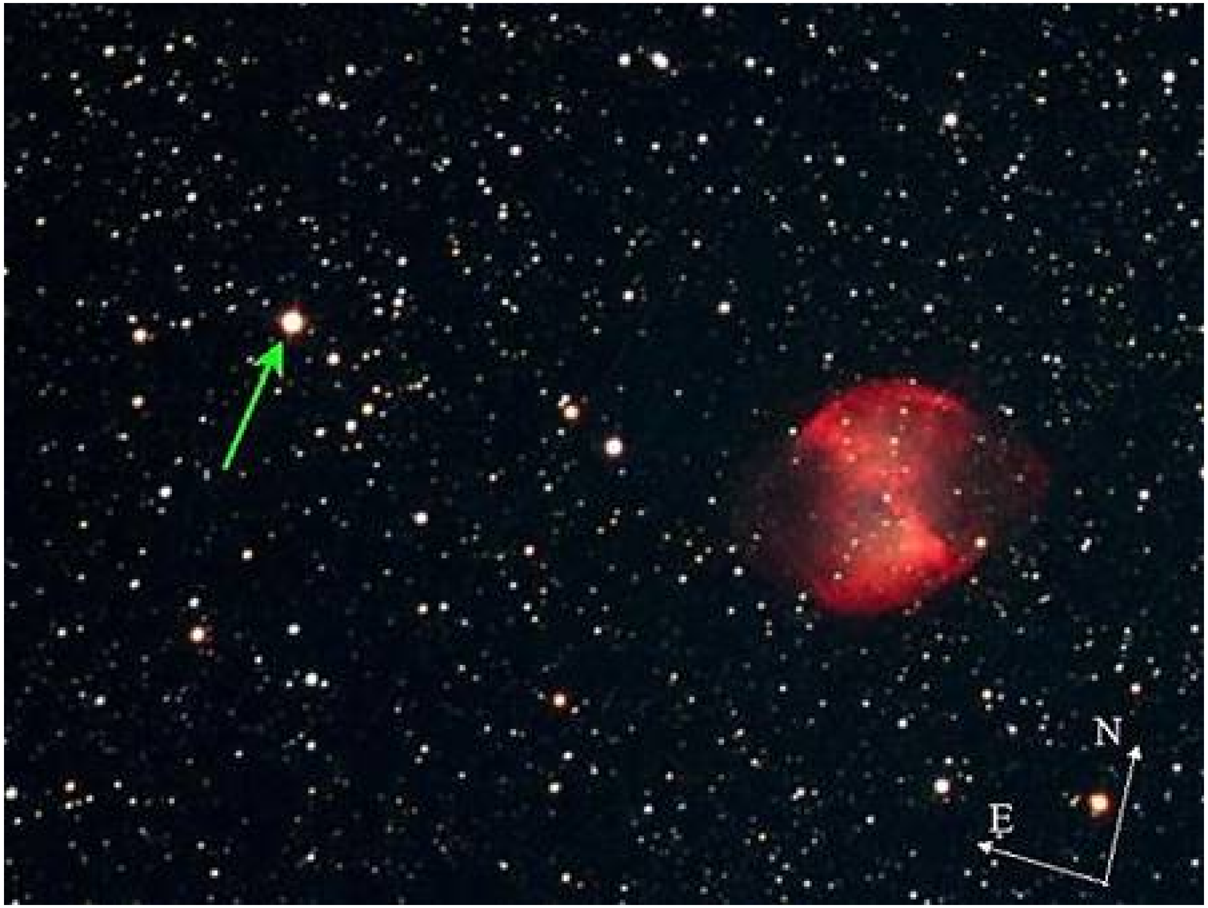
ESO Press Photo 22e/07 (25 April 2007)

EXOPLANETS Ia) Radial velocity



EXOPLANETS Ia) Radial velocity

Example : HD189733



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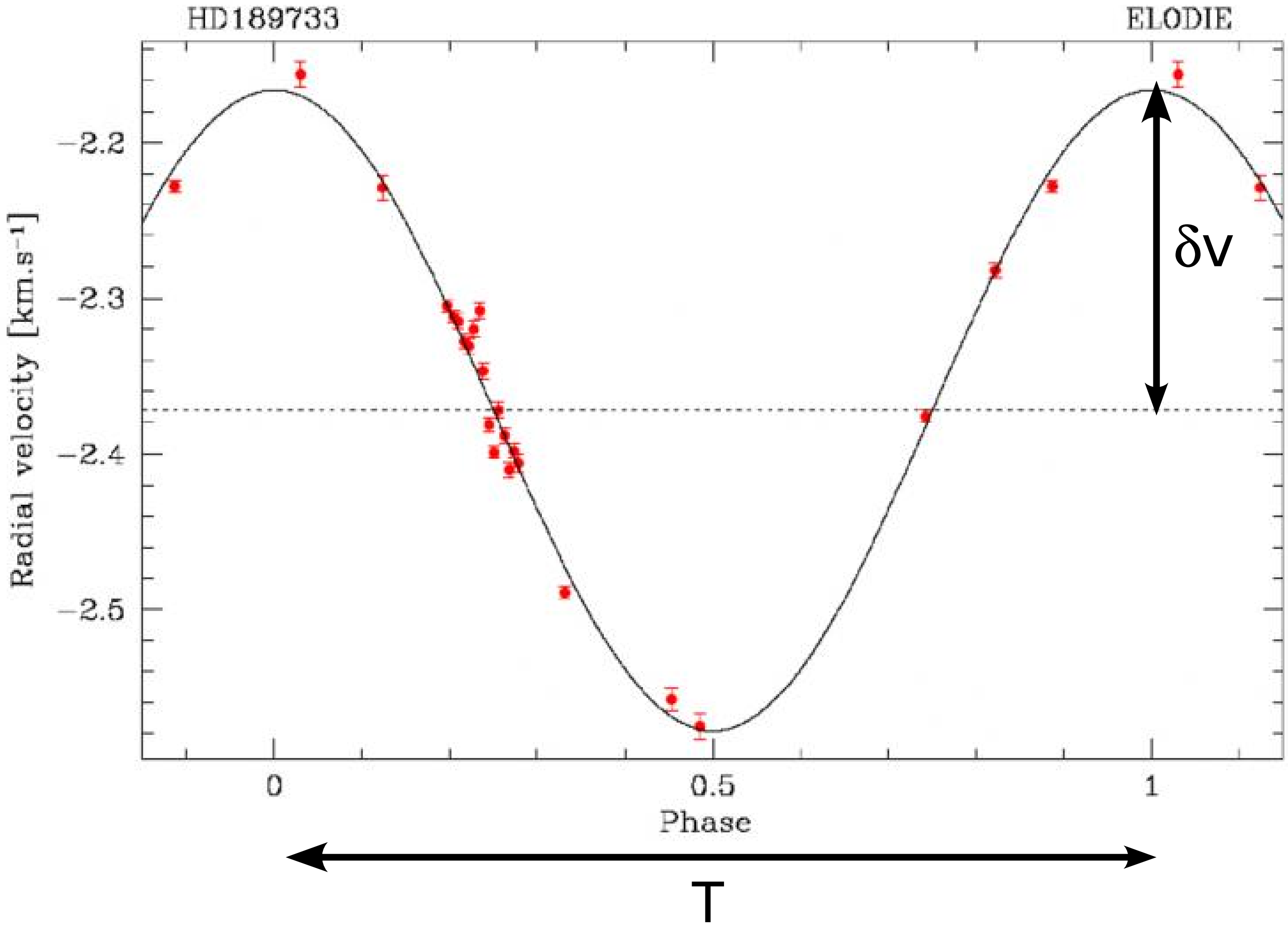
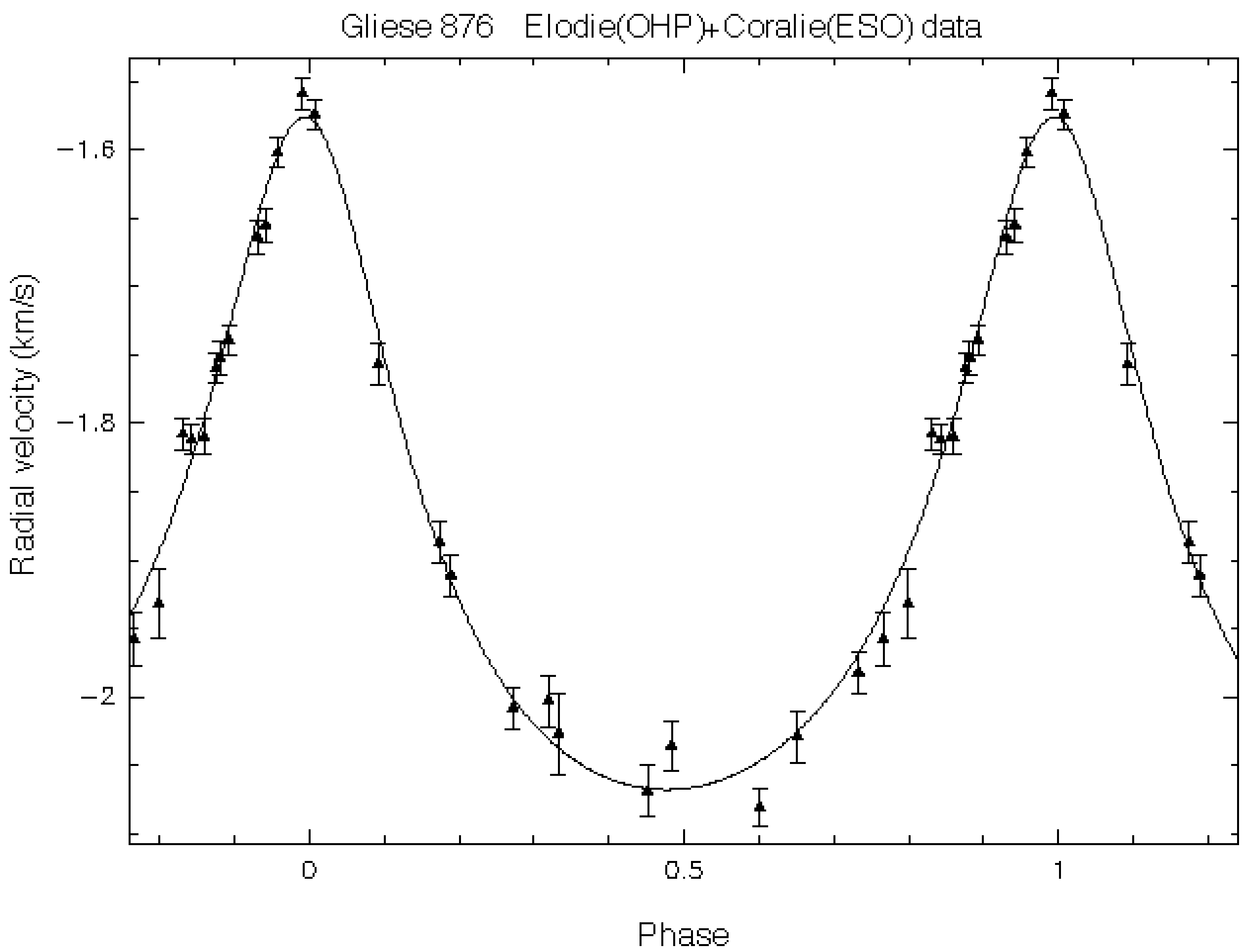


EXOPLANETS Ia) Radial velocity

<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 :

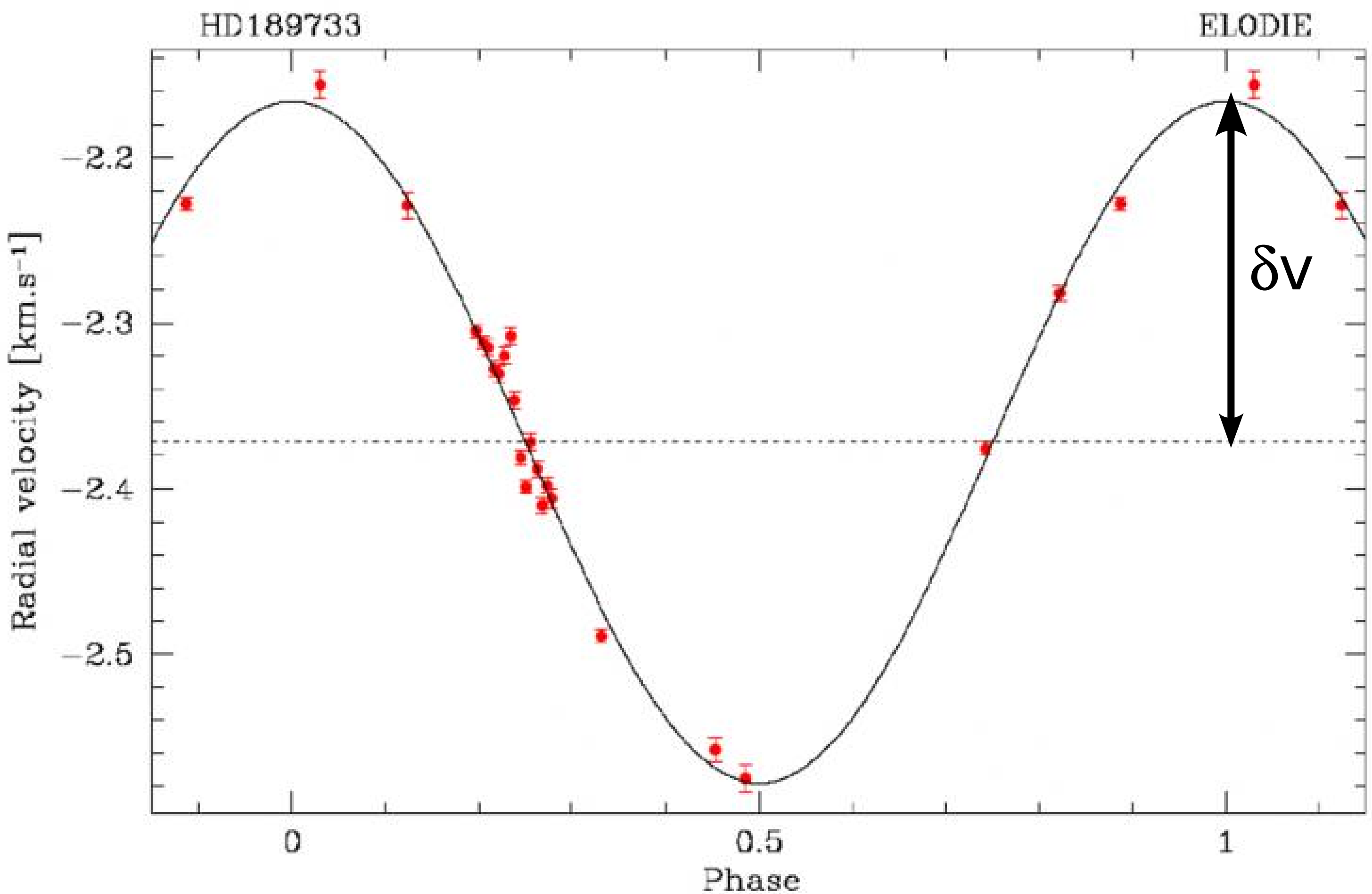
HD189733b :

One gives

T=2,218 days,

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

Find q, M_p.



EXOPLANETS Ia) Radial velocity

EXERCICE :

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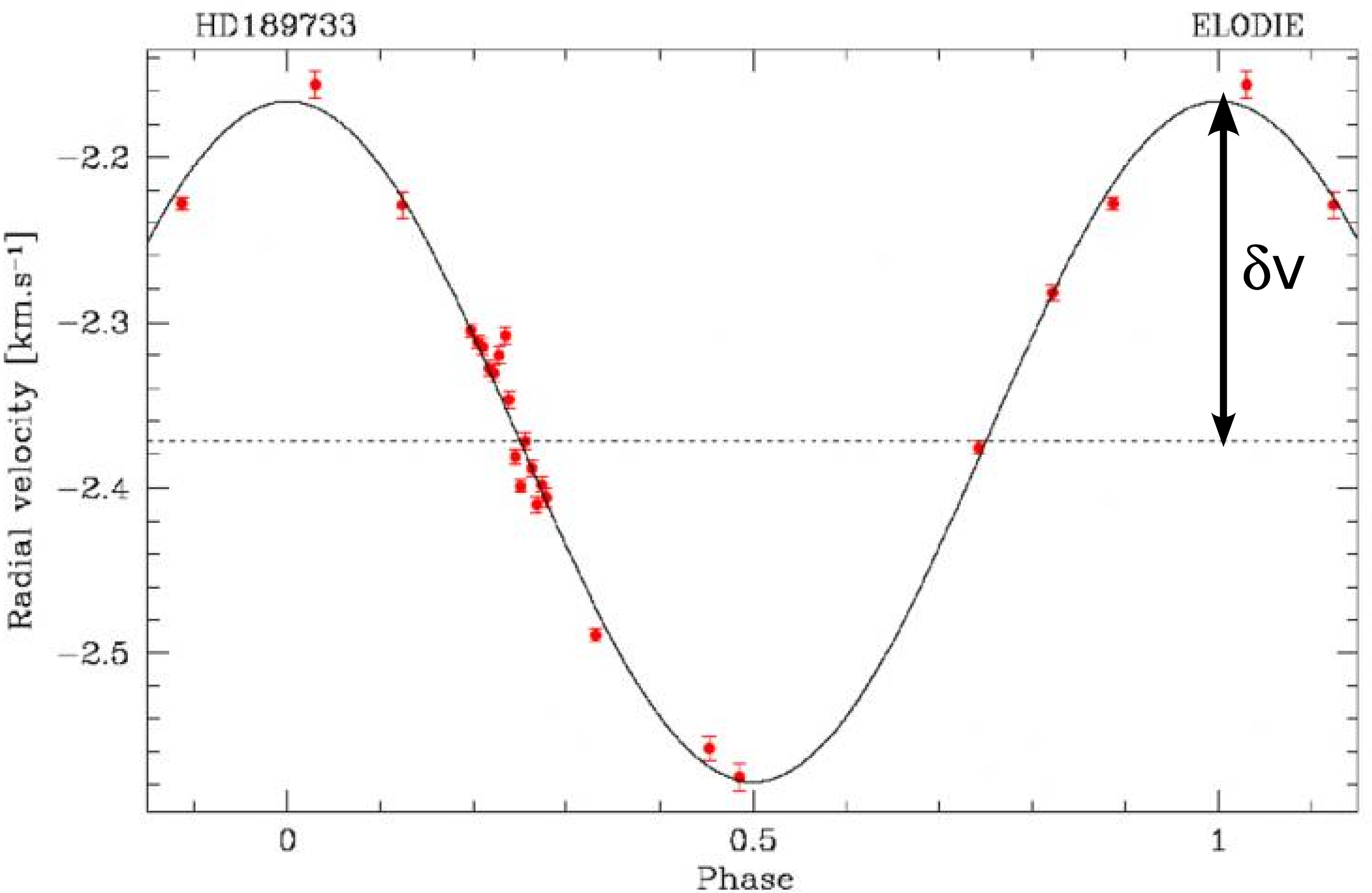


SOLUTION :

a = $4{,}64 \times 10^{9}$ m = 0.031 AU . δv=~200 $m.s^{-1}$.

Thus $q = 1{,}3 \times 10^{-3}$, so $M_p = 1{,}1\ M_{Jup}$.

EXOPLANETS Ia) Radial velocity

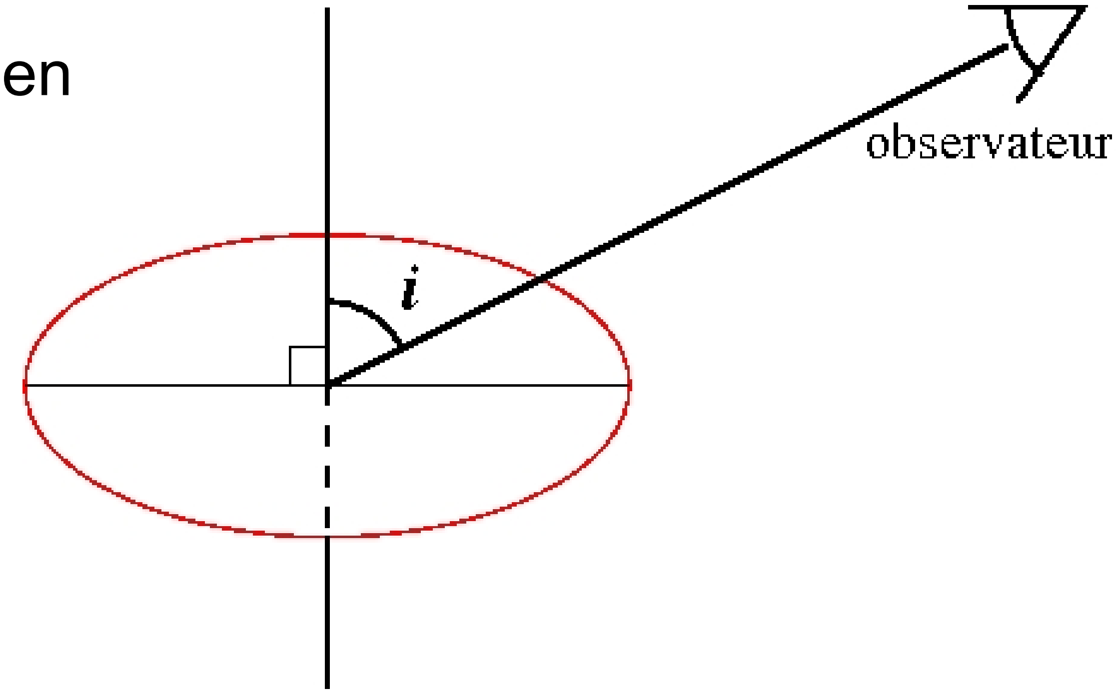
<u>Caution !</u>

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

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 !

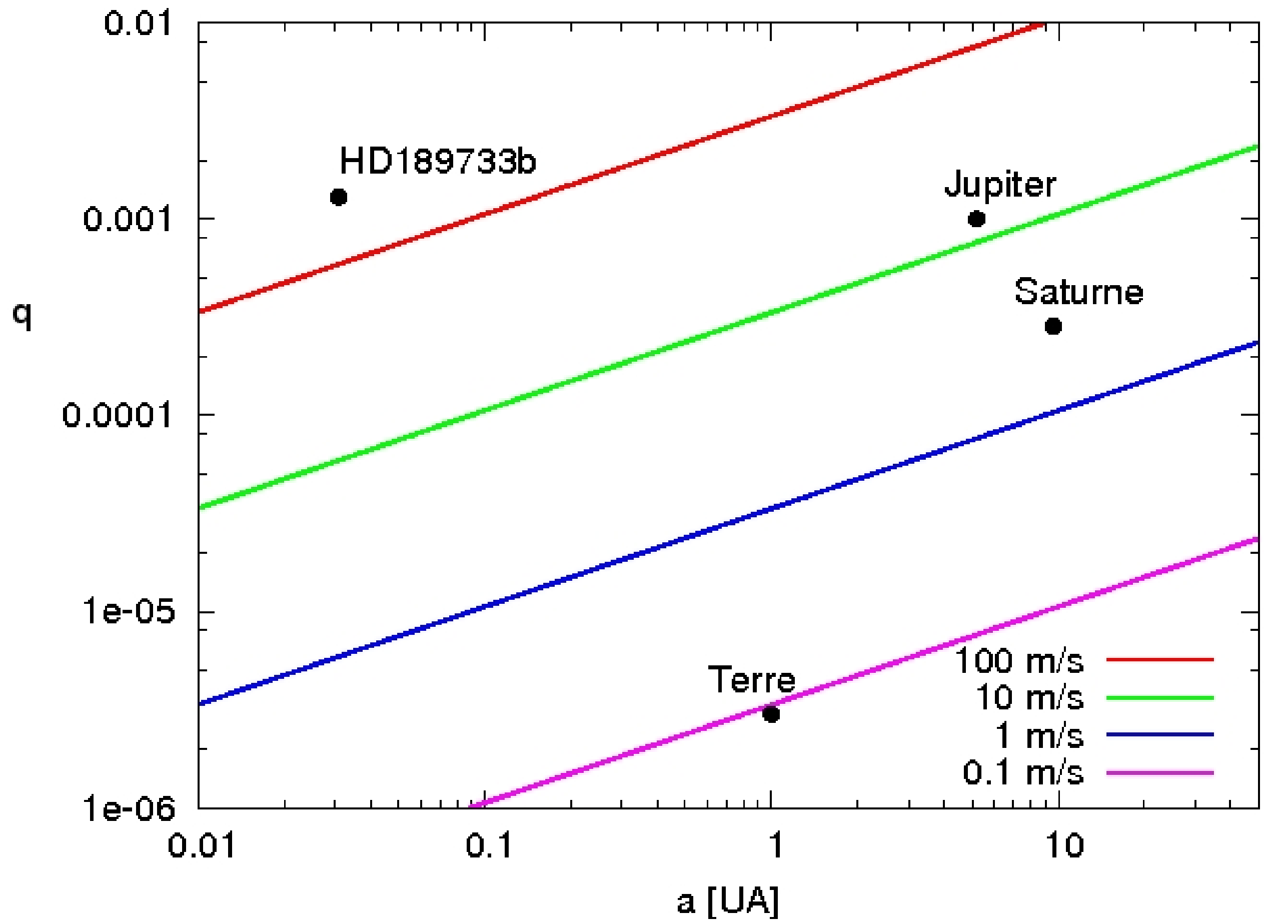
On average, $1/\sin(i)$ is $\pi/2$.

EXOPLANETS Ia) Radial velocity

Nowadays (2012) 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 $\delta\lambda = \lambda_0 v/c$).

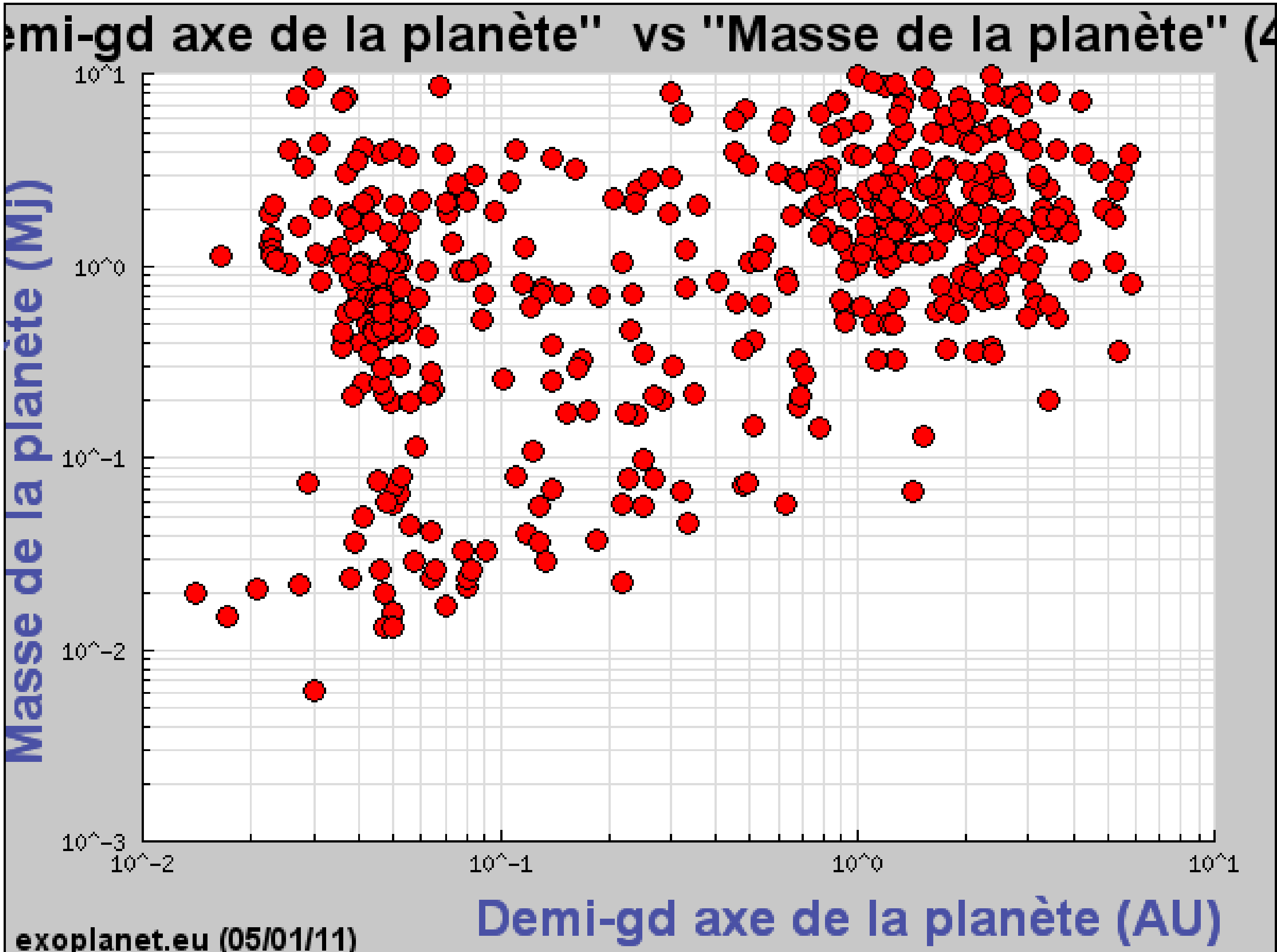
<u>Detectability :</u>

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



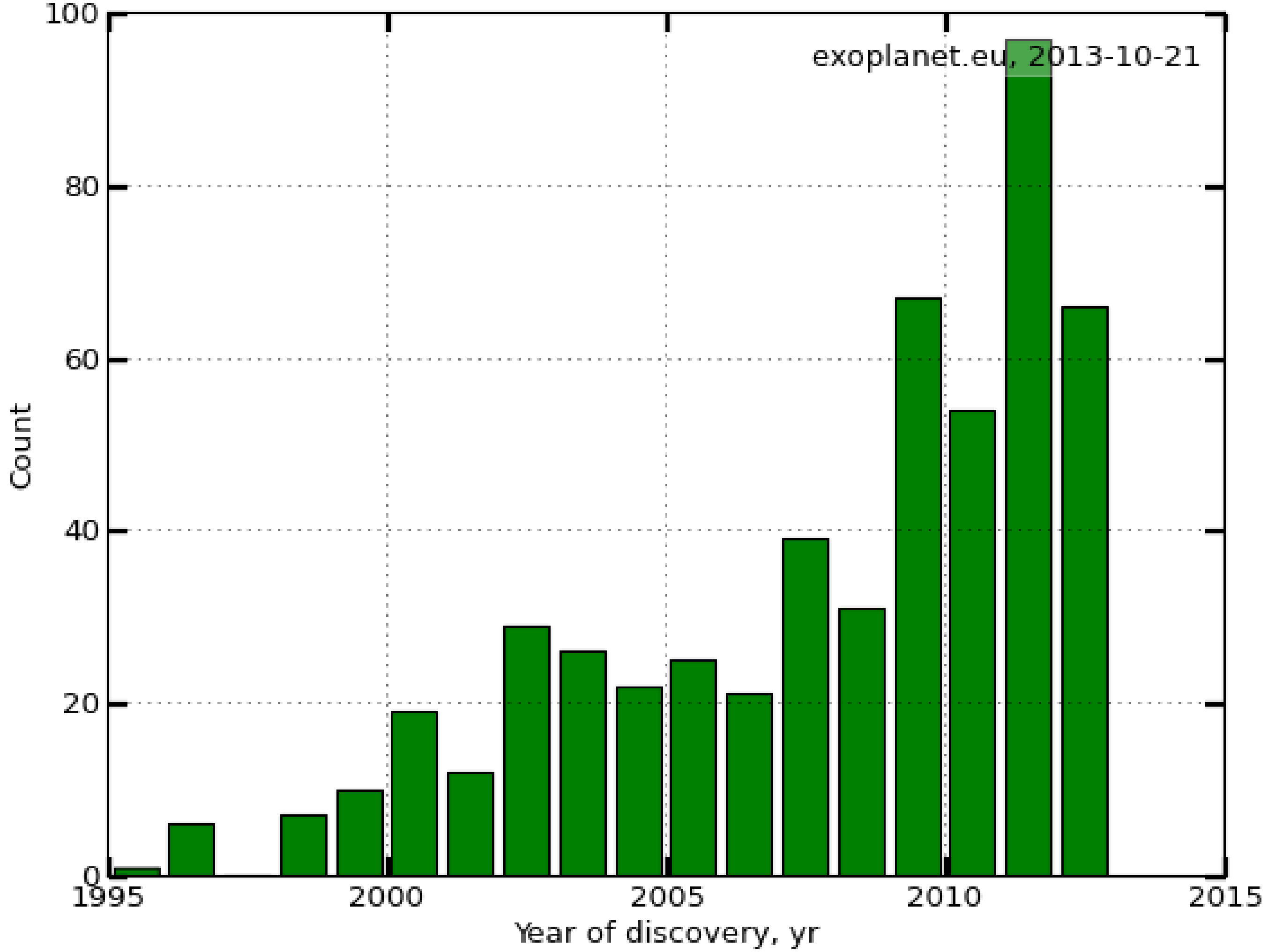
EXOPLANETS Ia) Radial velocity

<u>Detections :</u> The 484 planets detected the 5/1/2011.



EXOPLANETS Ia) Radial velocity

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

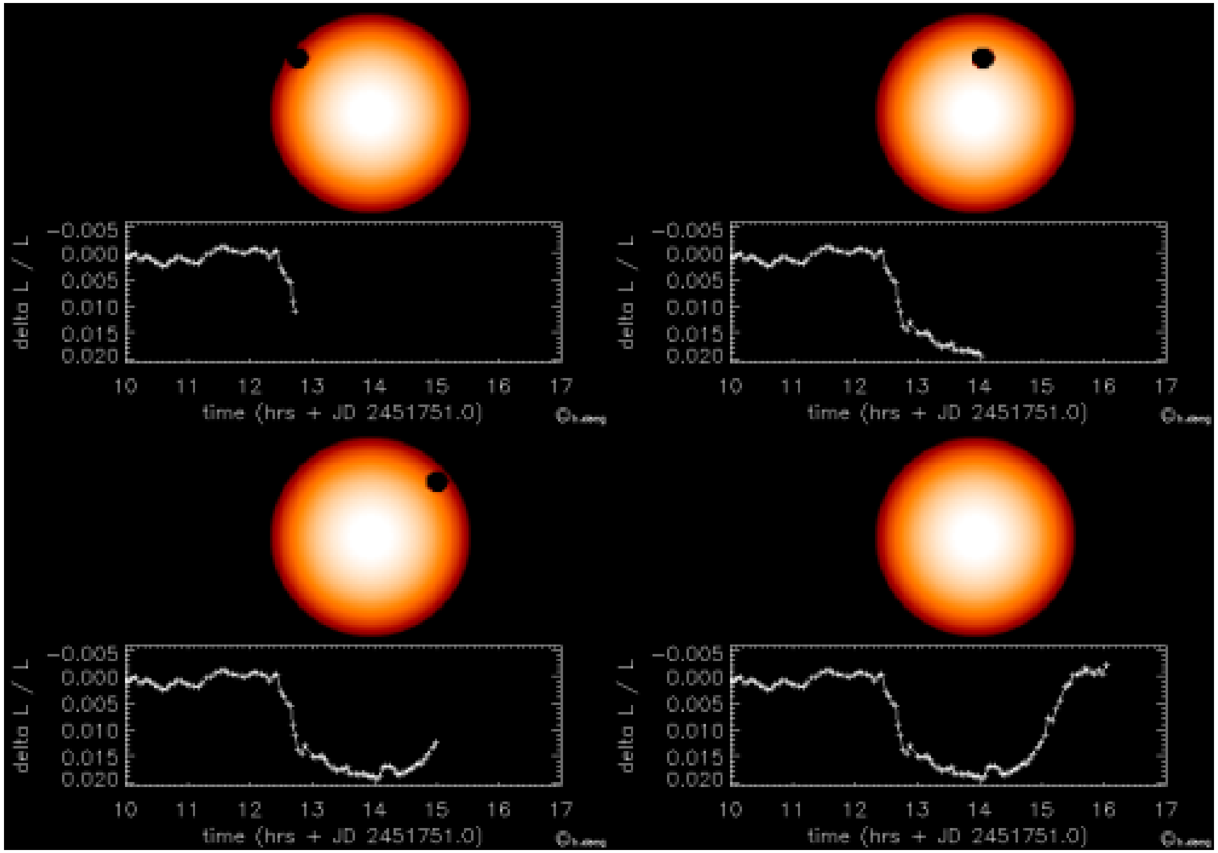


EXOPLANETS : Ib) Transit

EXOPLANETS : Ib) Transit

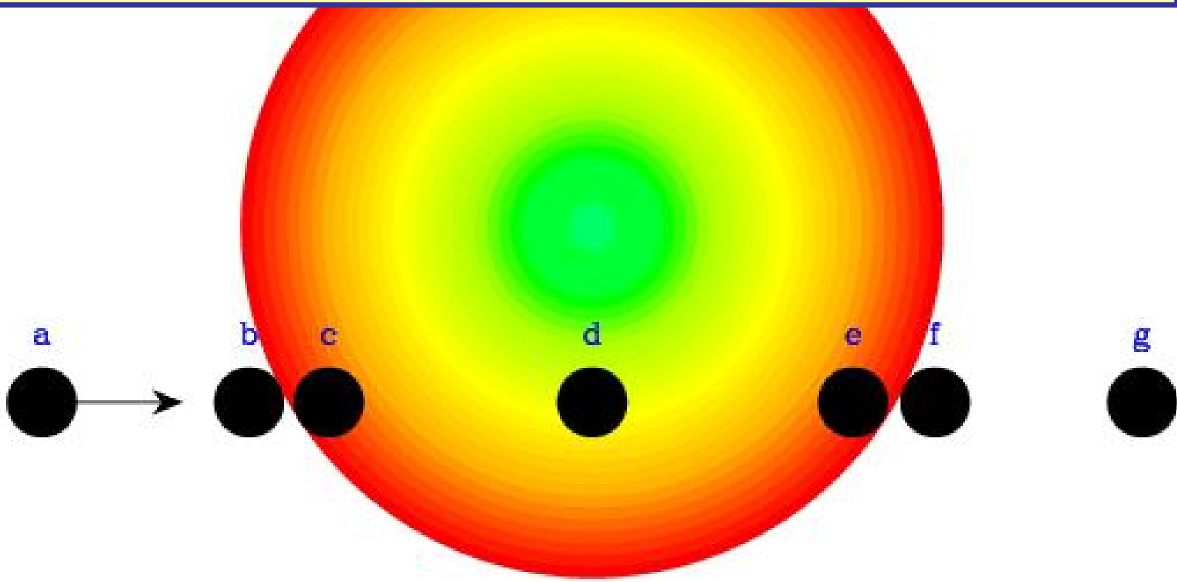
Like Venus in front of the Sun in 2004 and 2012, sometimes, an exoplanet moves in front of its star, this is a **transit**.

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

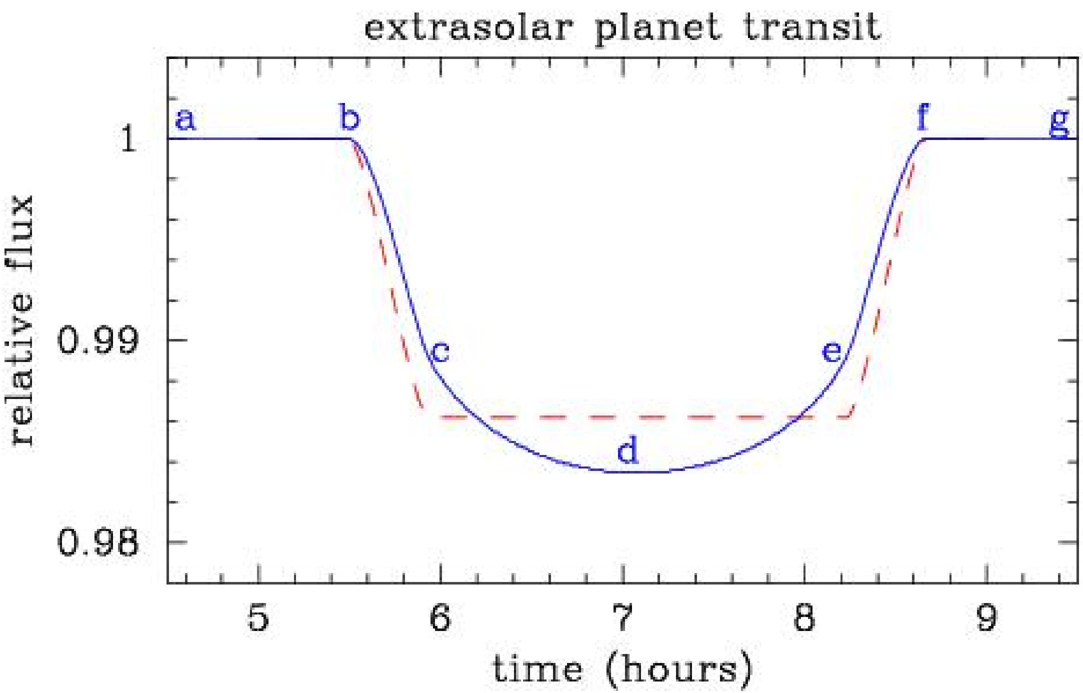


EXOPLANETS : Ib) Transit

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

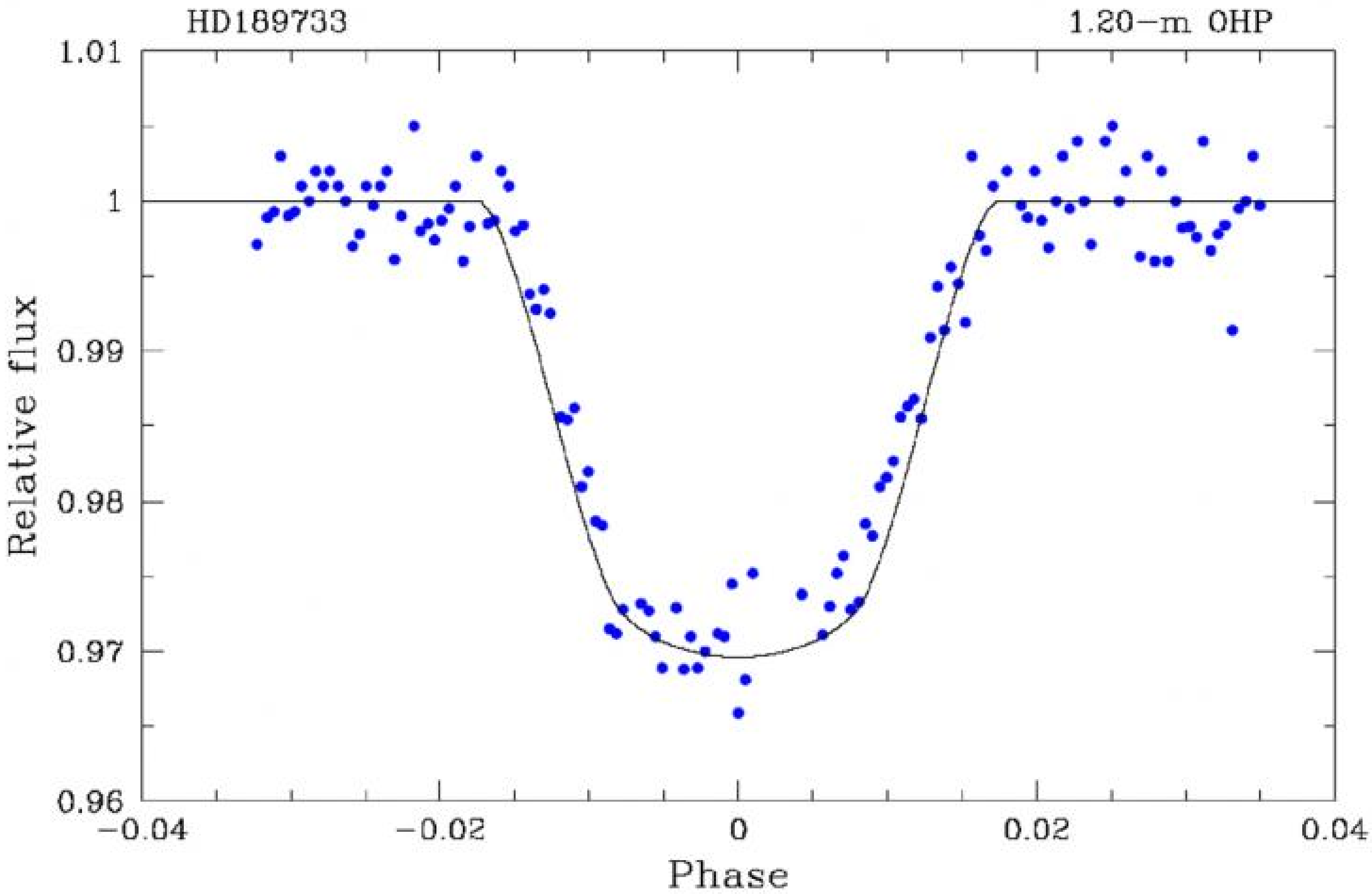


A transit lasts a few hours.



EXOPLANETS : Ib) Transit

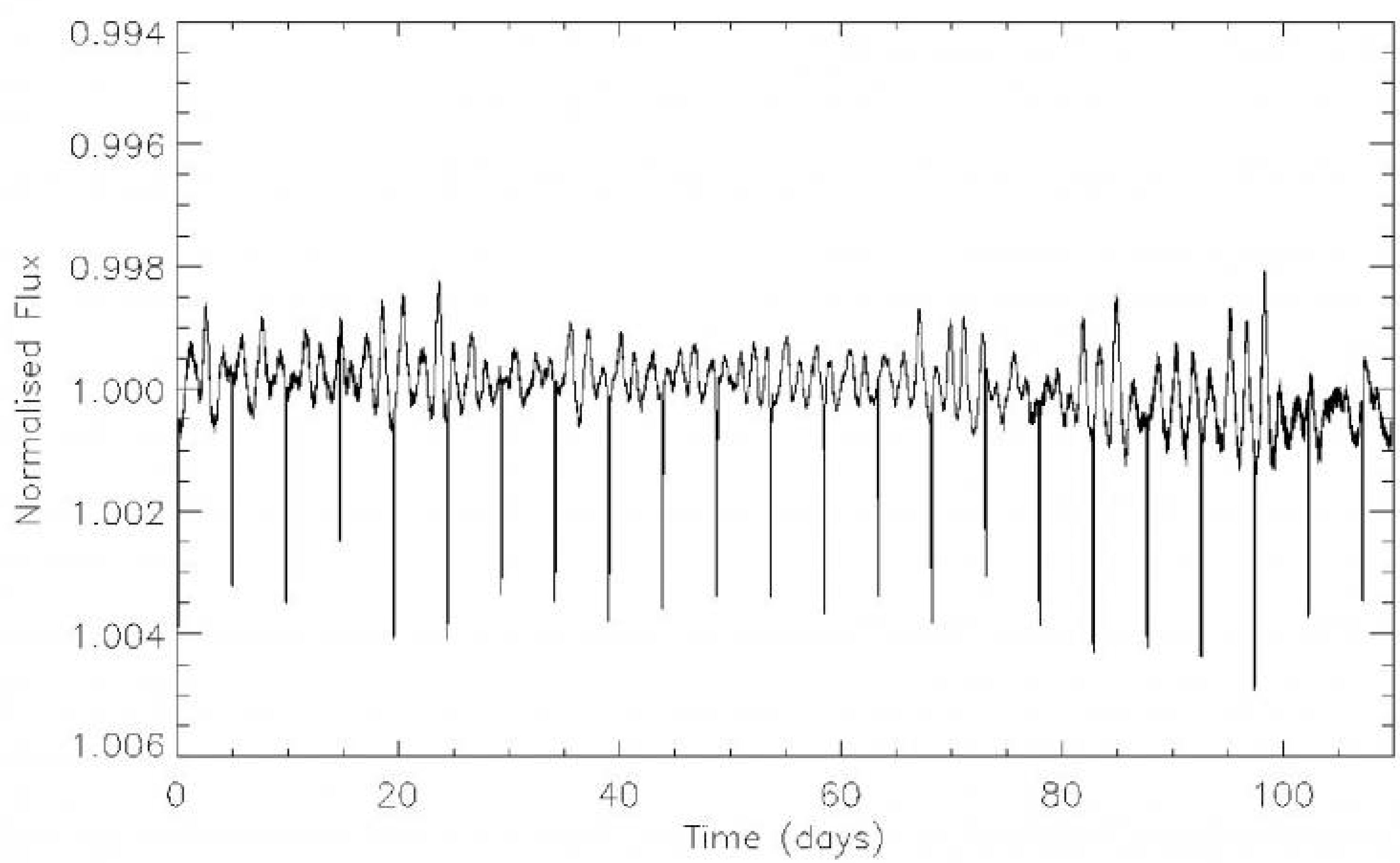
Ex: HD 189733b, seen in radial velocity, also has a transit :



EXOPLANETS : Ib) Transit

A planetary transit should be periodic.

Ex: light curve of a star observed by Corot :

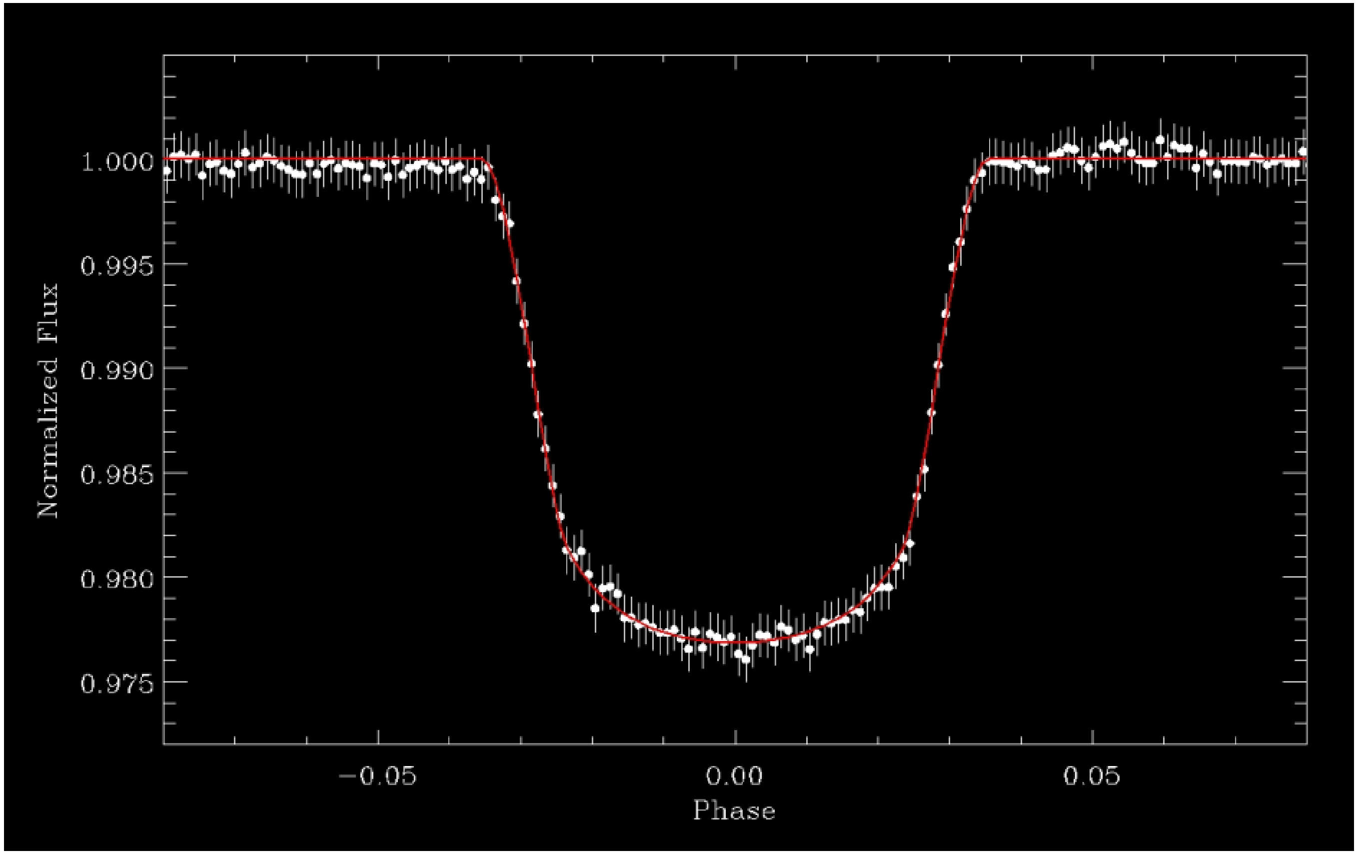


EXOPLANETS : Ib) Transit

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

Other transit detection projects :

Kepler (NASA), launched on 7/3/09.
already 1200 planet candidates !
But only candidates...

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

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

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

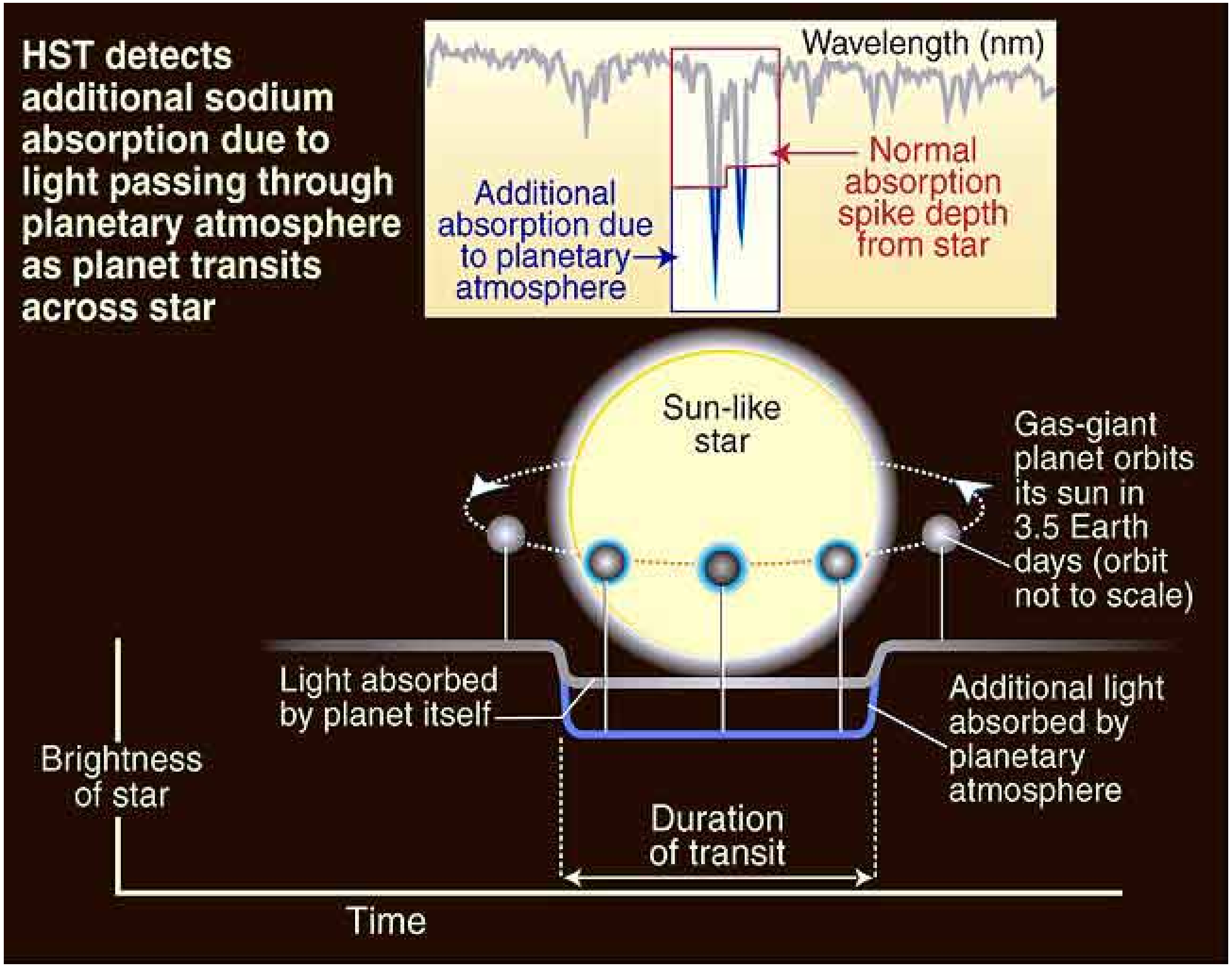
Possible surprises...

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

EXOPLANETS : Ib) Transit

Advantages of the transit method :

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



EXOPLANETS : Ib) Transit

<u>Conditions for a transit :</u>

The planet must pass in front of the star.

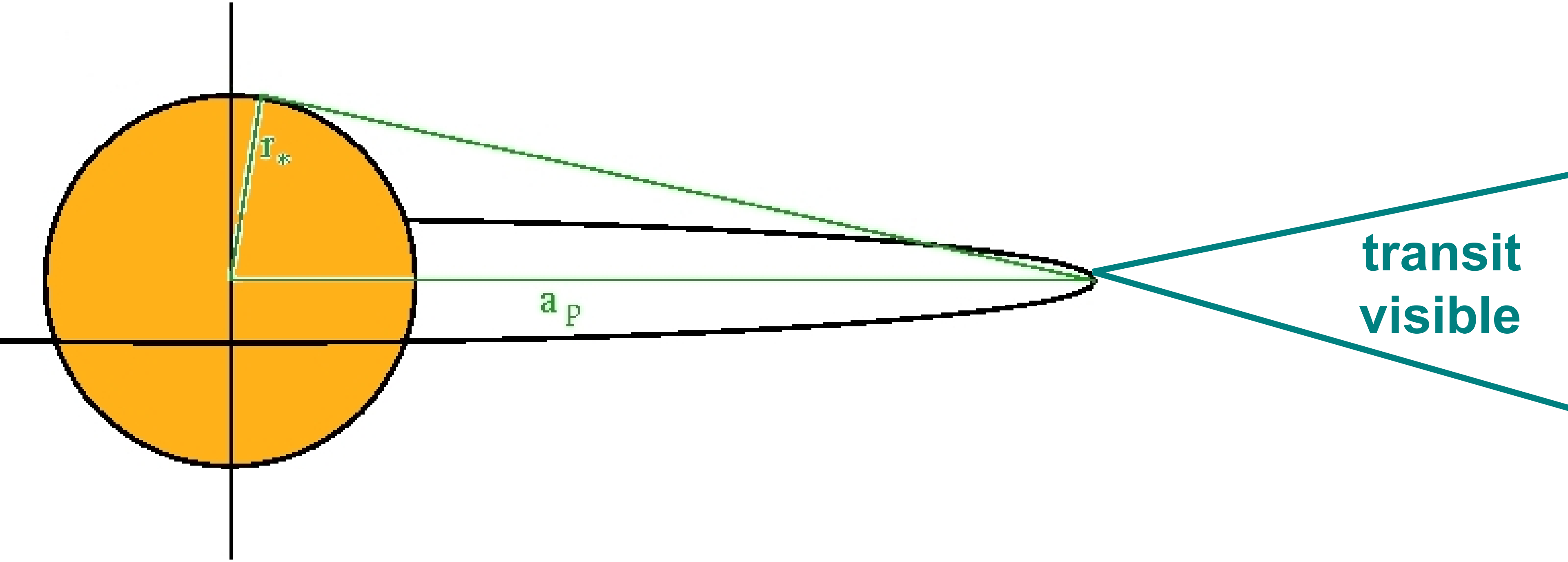
Condition on i ?

EXOPLANETS : Ib) Transit

<u>Conditions for a transit :</u>

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 $i \sim \pi/2$)

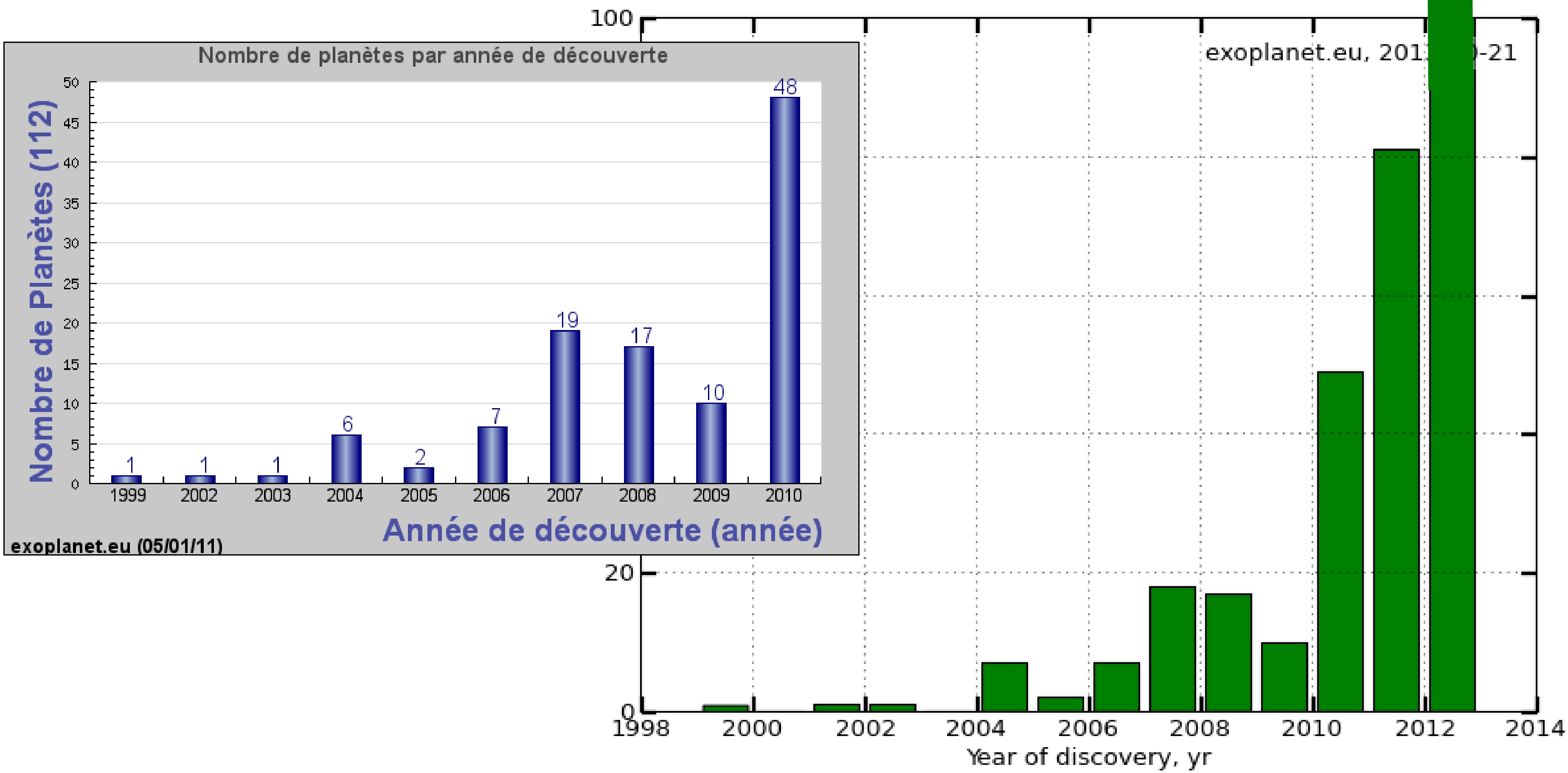


Short period planets are favoured.

EXOPLANETS : Ib) Transit

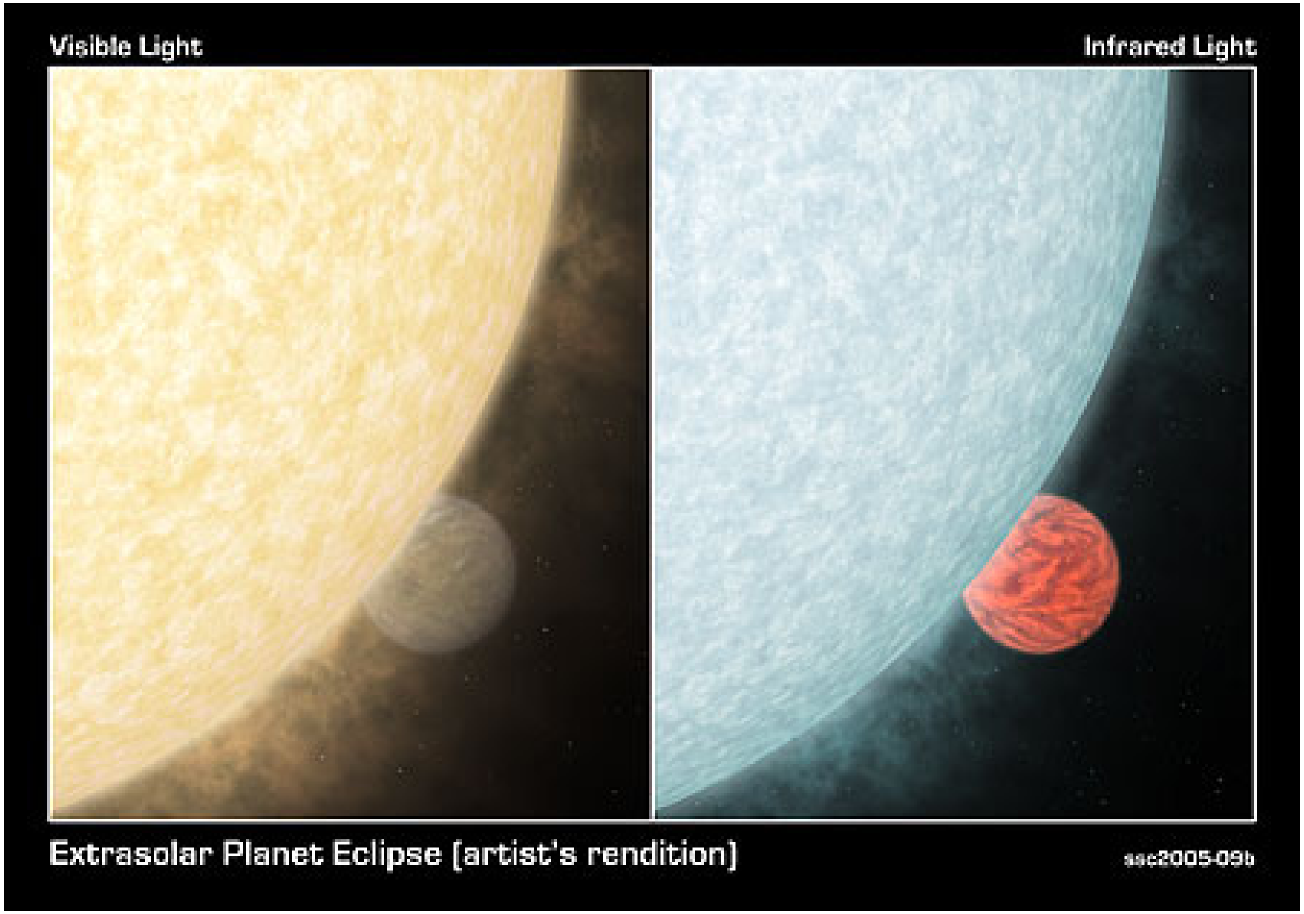
Detections :

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

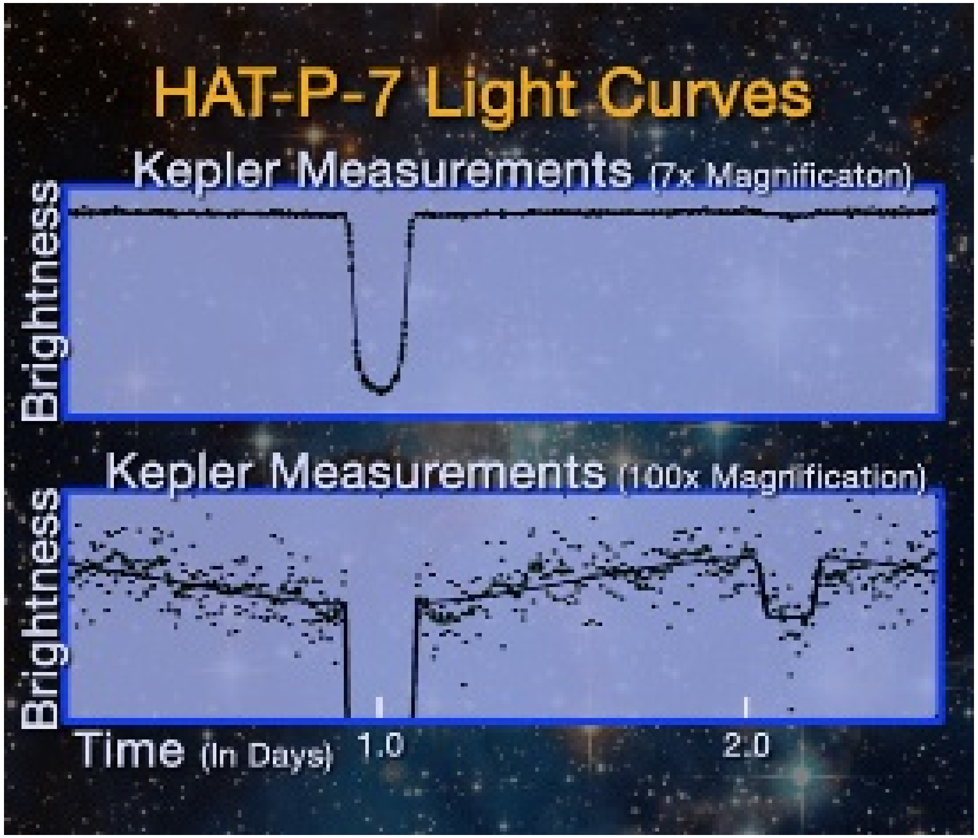


EXOPLANETS : Ib') Secondary transit

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



EXOPLANETS : I c) Microlensing

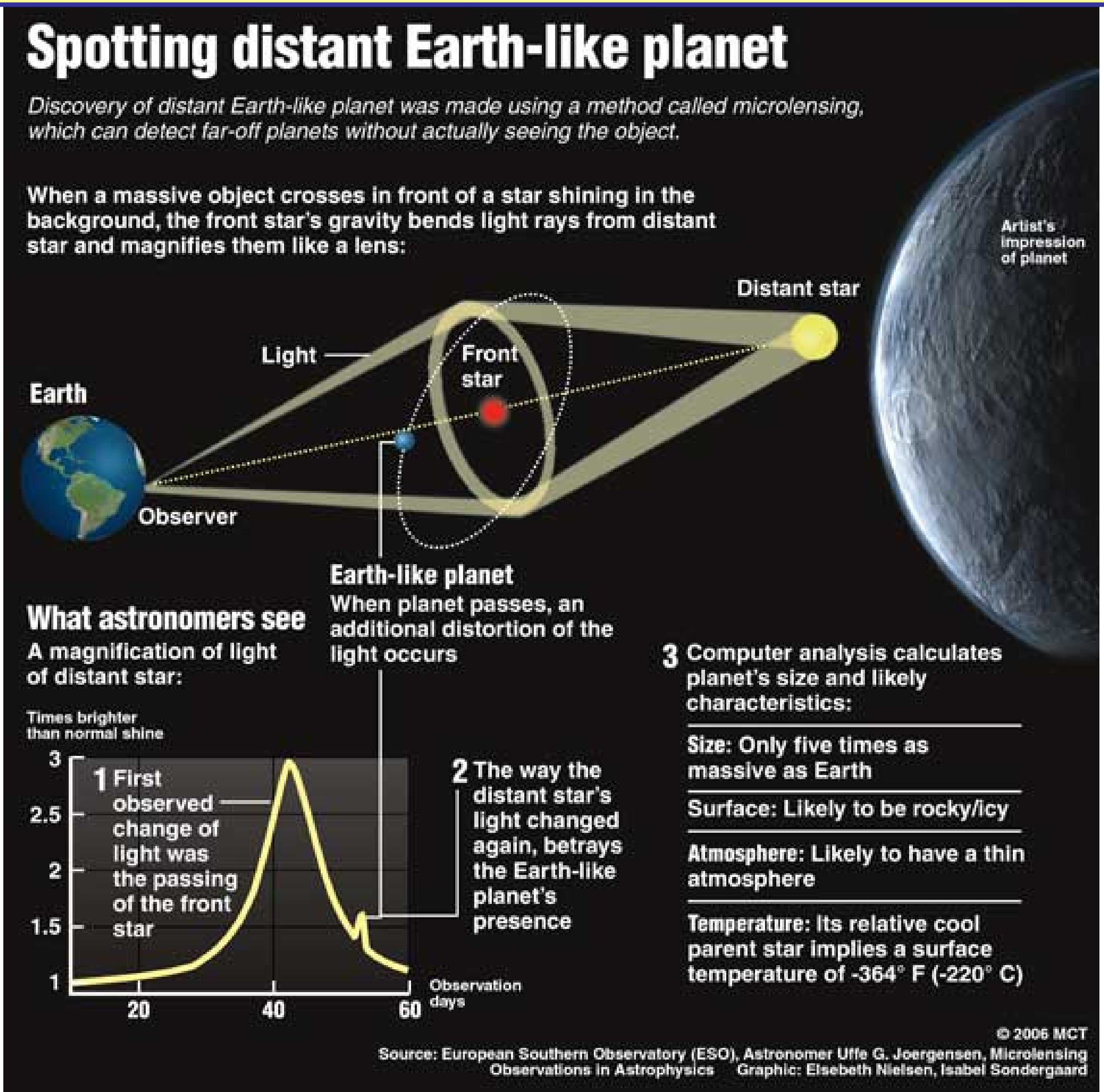
Gravitational lense :

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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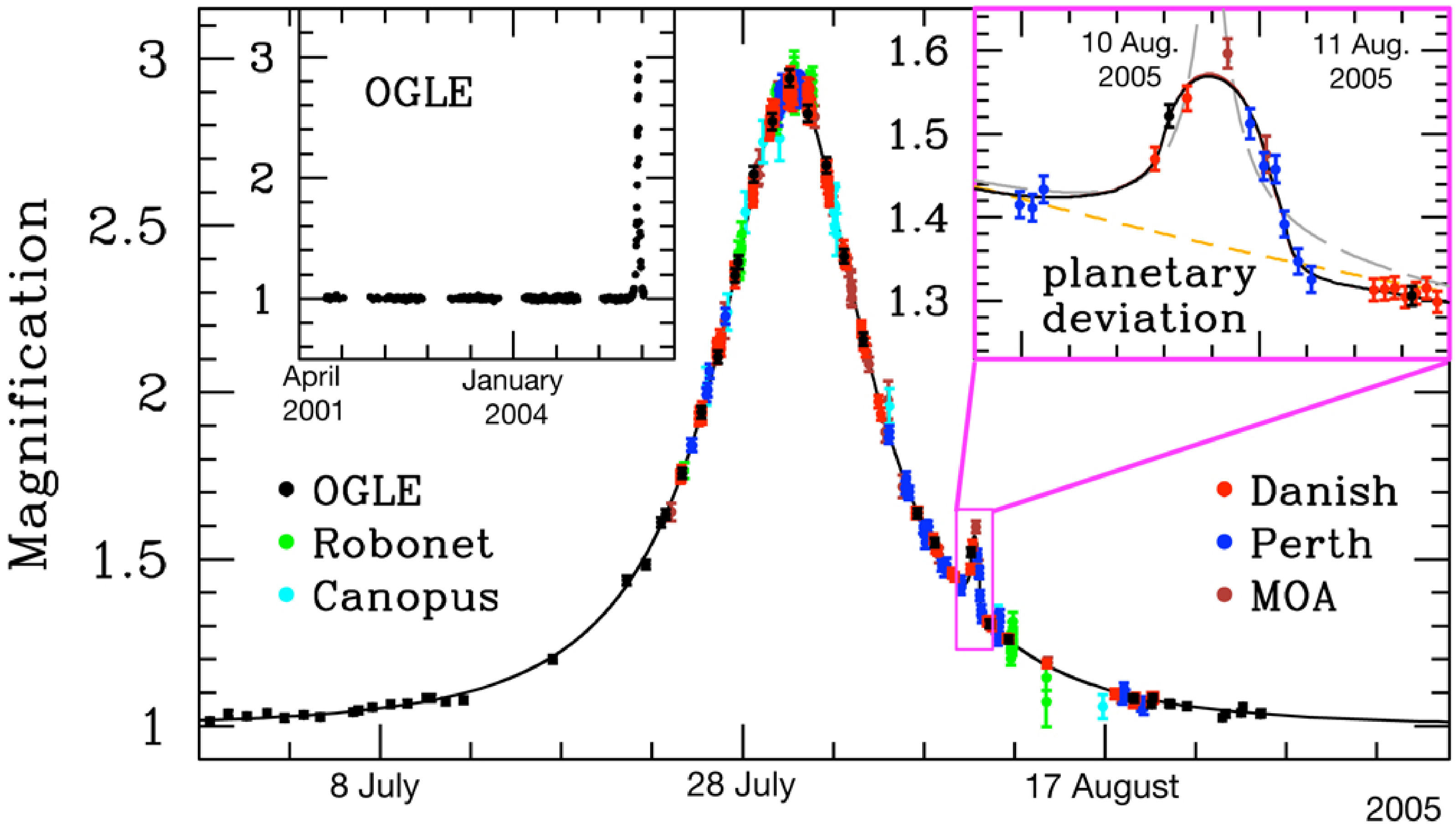


Light Curve of OGLE-2005-BLG-390

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

EXOPLANETS : I c) Microlensing

Big planets far from their host stars are favoured.

Drawbacks:

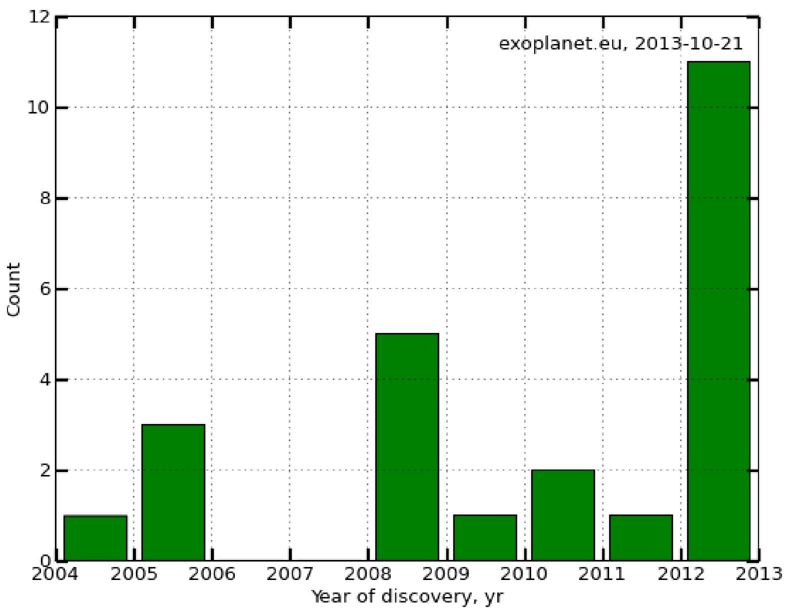
We don't see the host star.

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 astrométry.

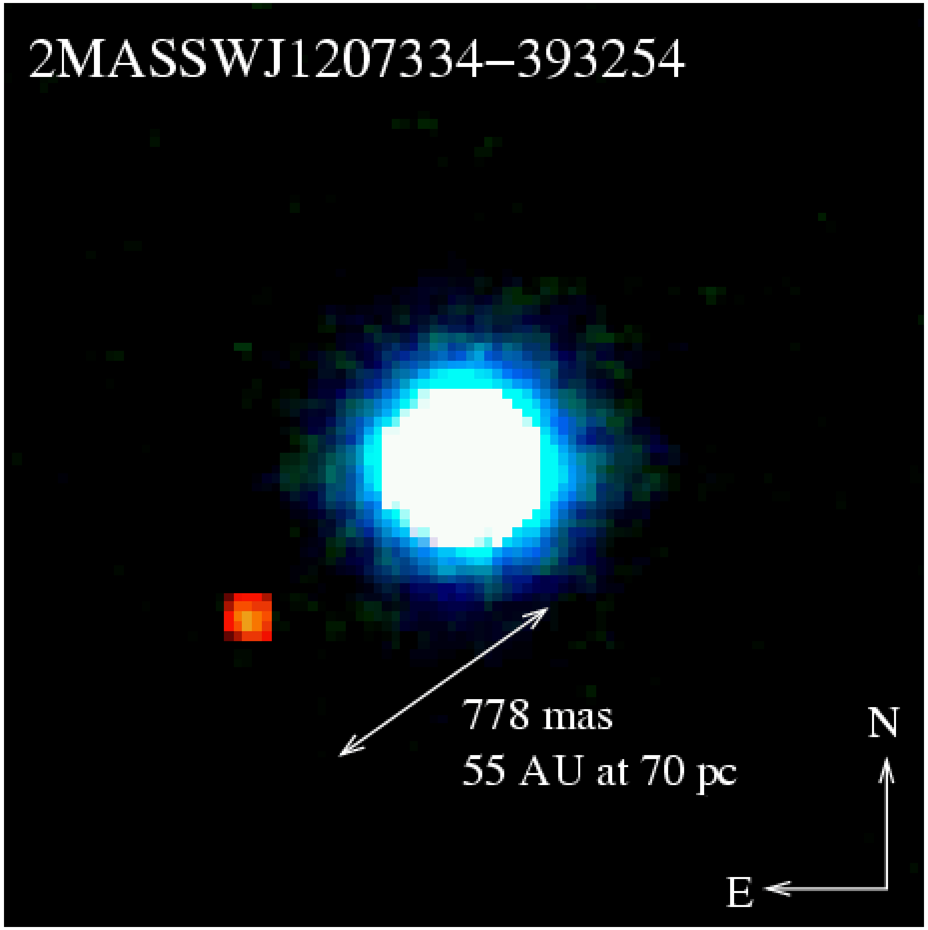
<u>Advantages :</u>

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)

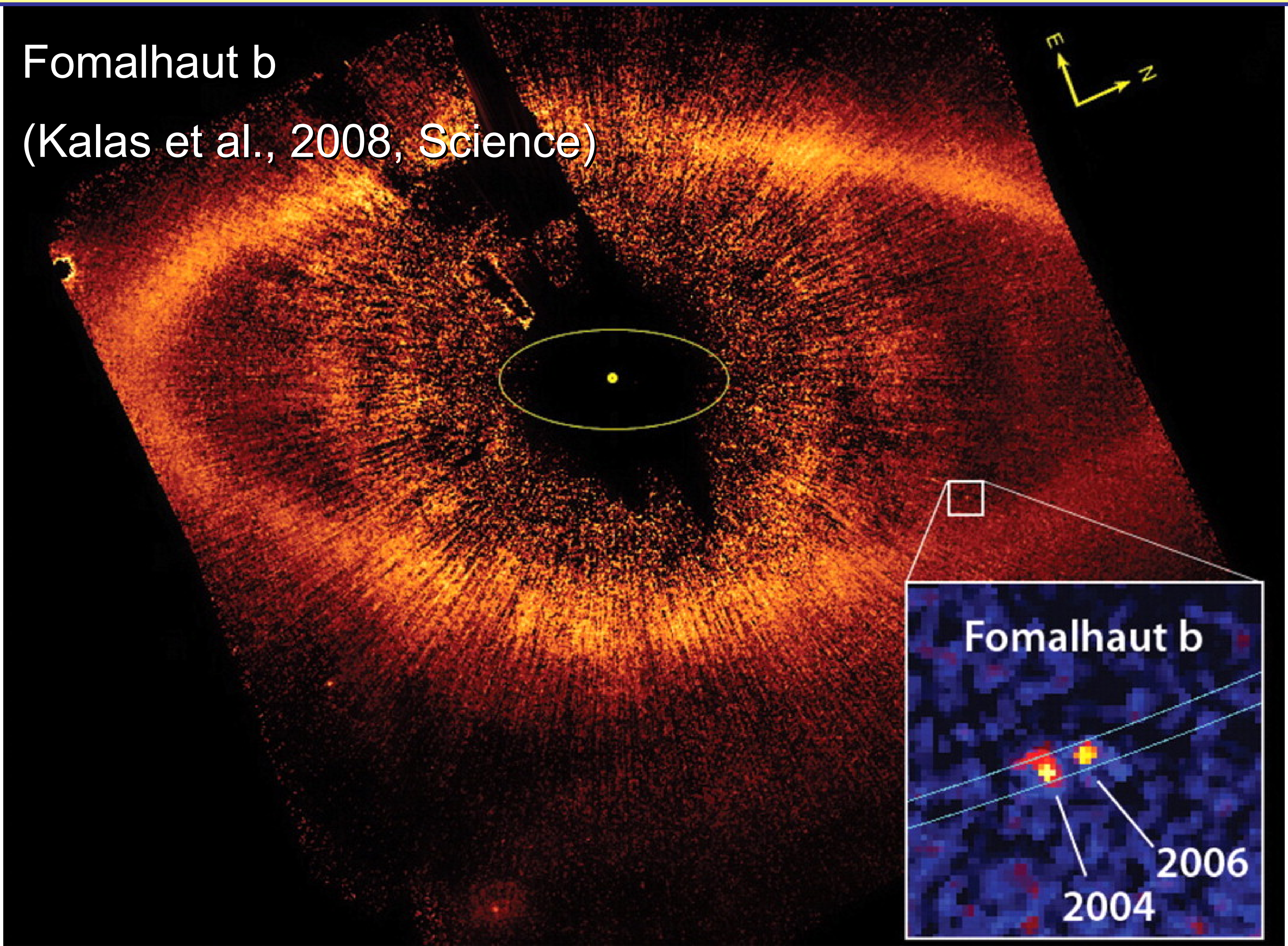


Or is it a double brown dwarf ?

EXOPLANETS : I e) Direct imaging

Fomalhaut b

(Kalas et al., 2008, Science)



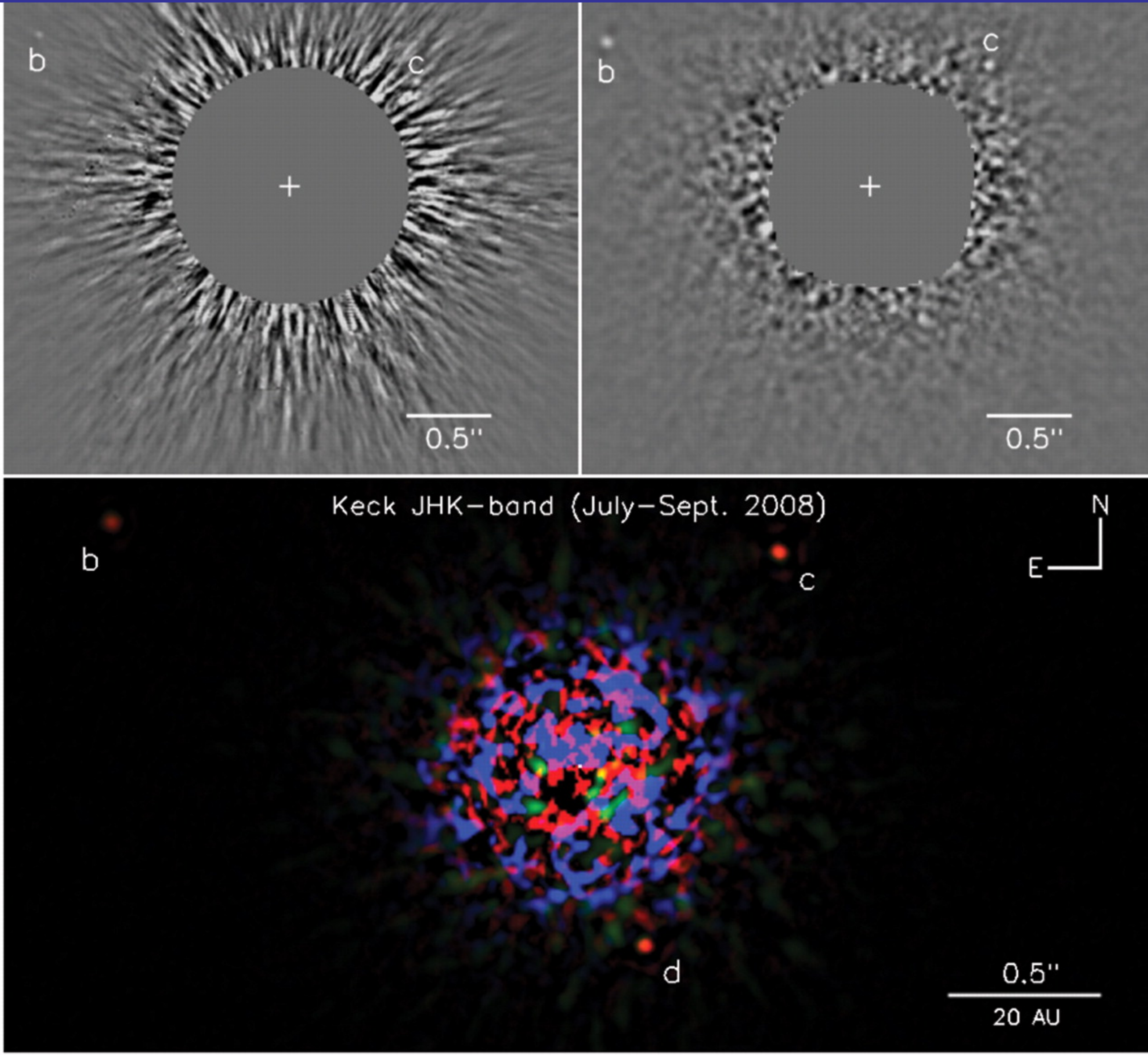
EXOPLANETS : I e) Direct imaging

<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

<u>Total :</u> 32 planets detected this way (at the end of 2012).

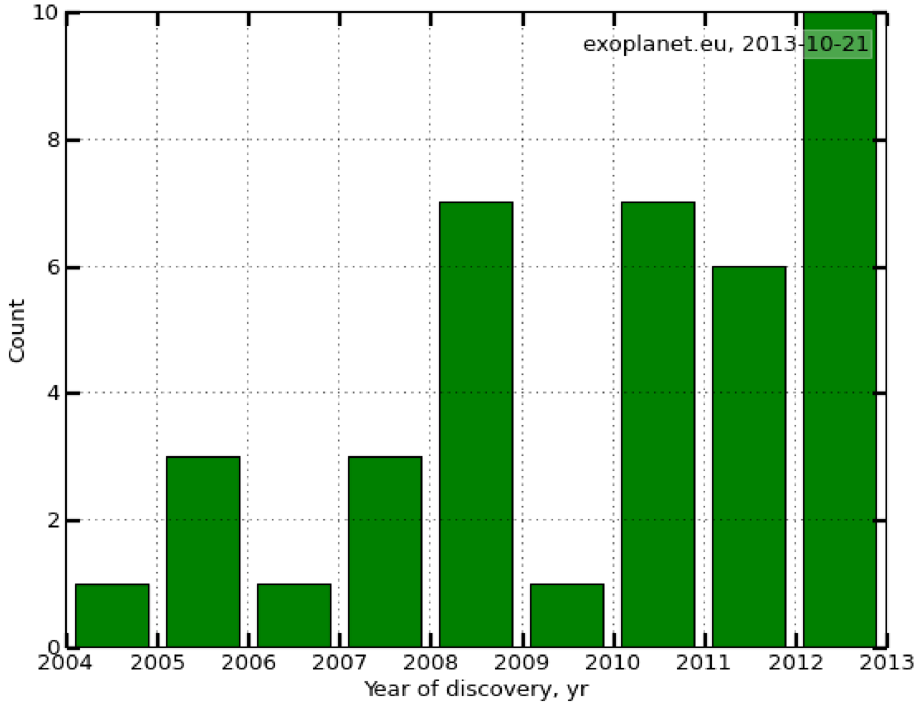
This method favors giant planets, far from their stars, which are not accessible by velocimetry or transits.

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

<u>Advantages:</u>

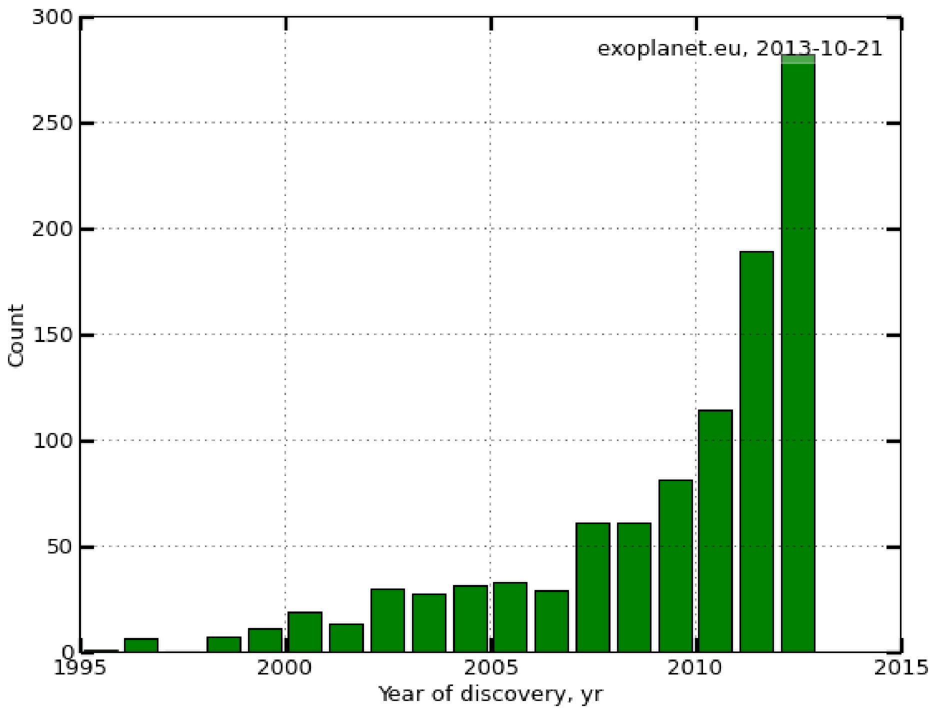
Direct proof of existence

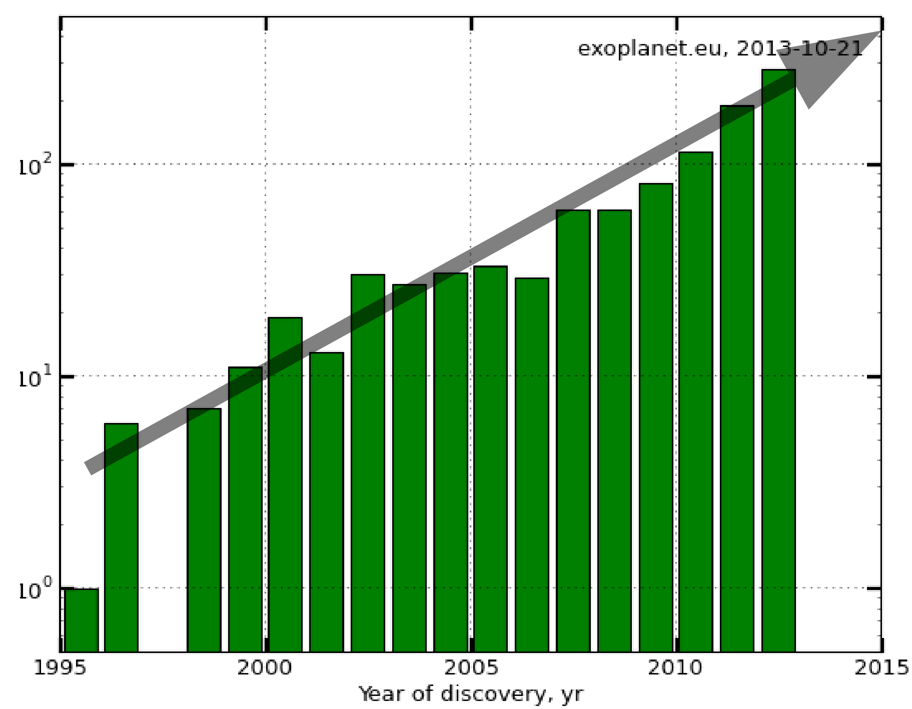
Possibility of spectroscopy...



EXOPLANETS : I Detections summary

The number of detections per year seems to grow exponentially :





Life is in logscale...

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- Radial velocity (velocimetry)
- Transit (photometry)
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- Astrometry
- 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 hunderds ! 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.

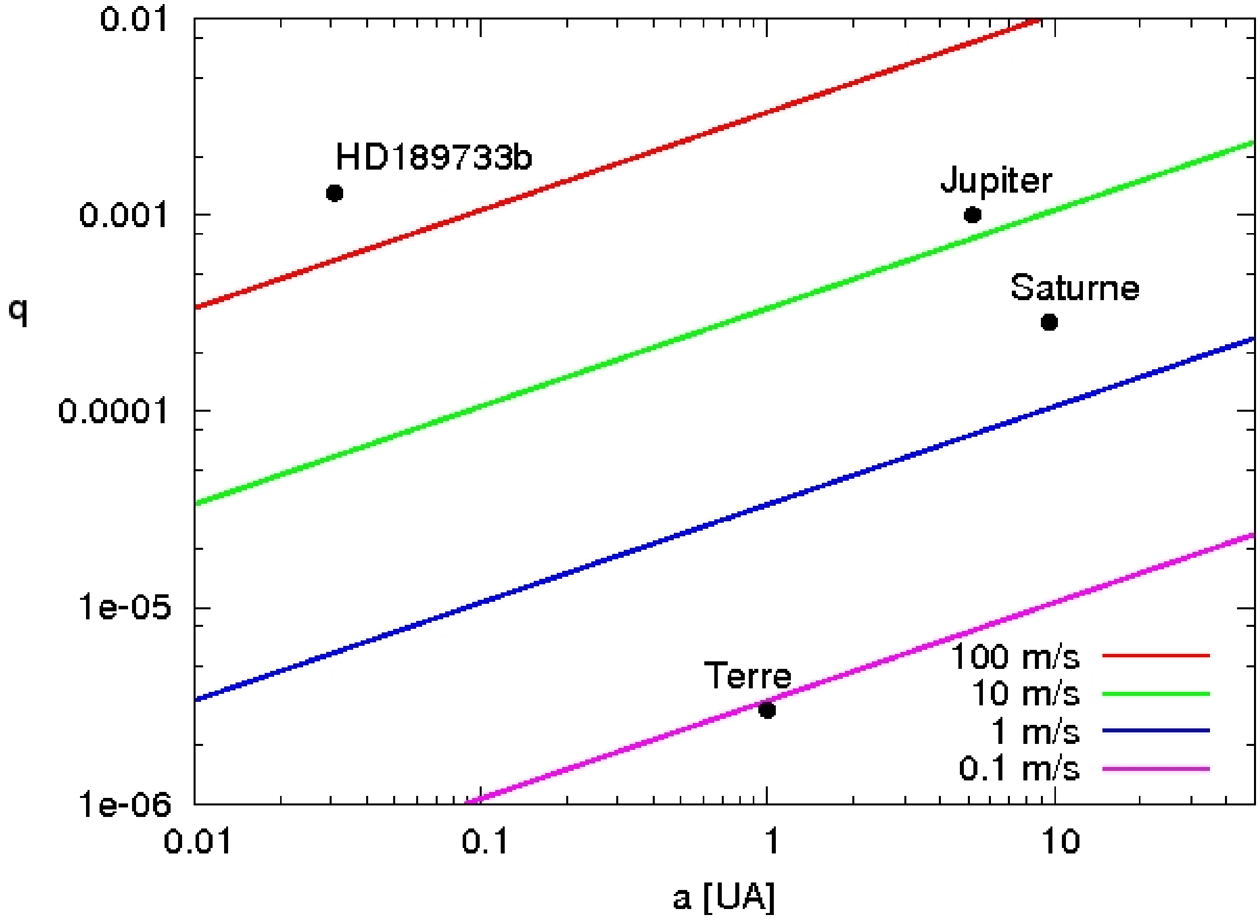
EXOPLANETS : II) Statistics

Nowadays (2012) 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 $\delta\lambda = \lambda_0 v/c$).

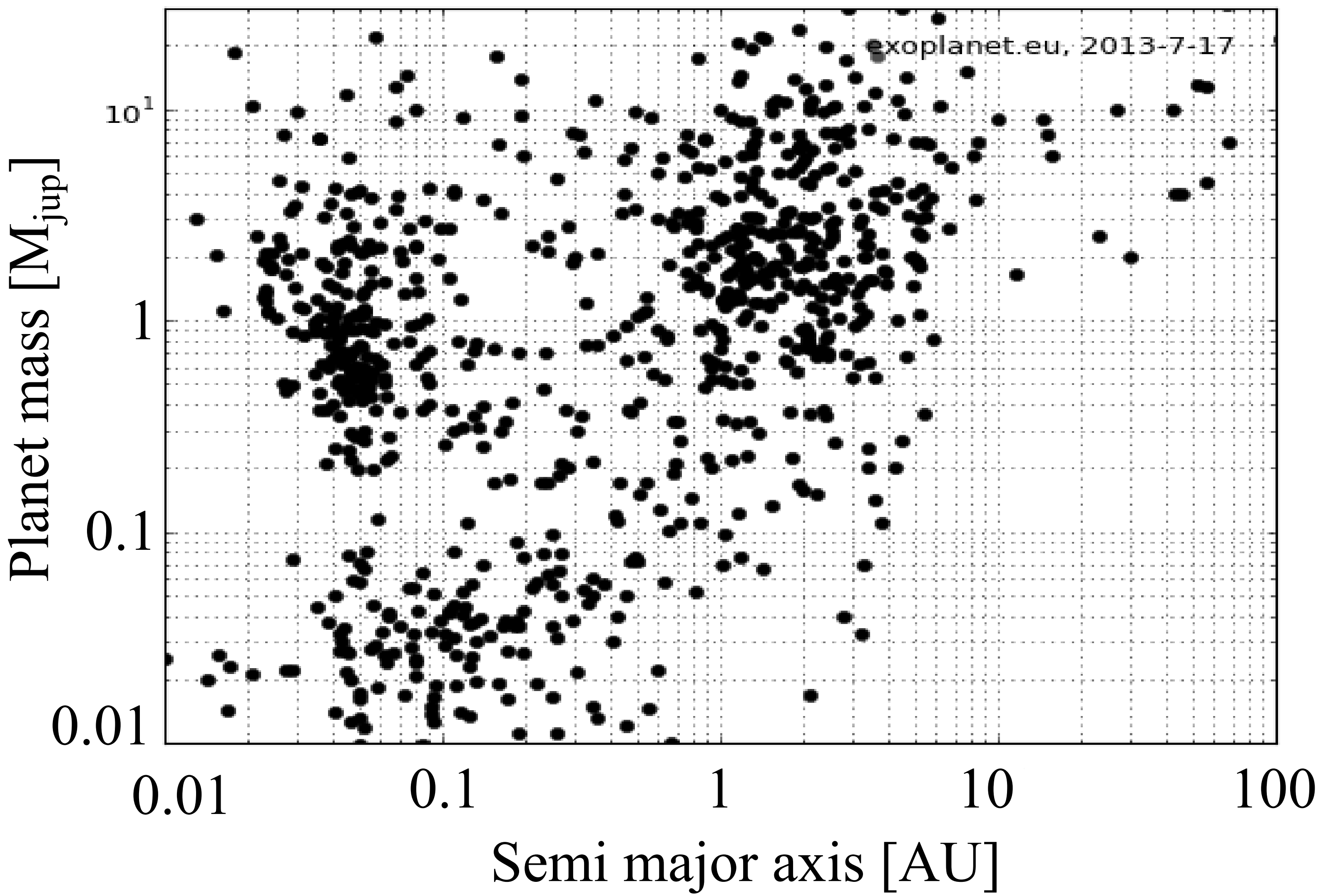
<u>Detectability :</u>

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

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



EXOPLANETS : II) Statistics



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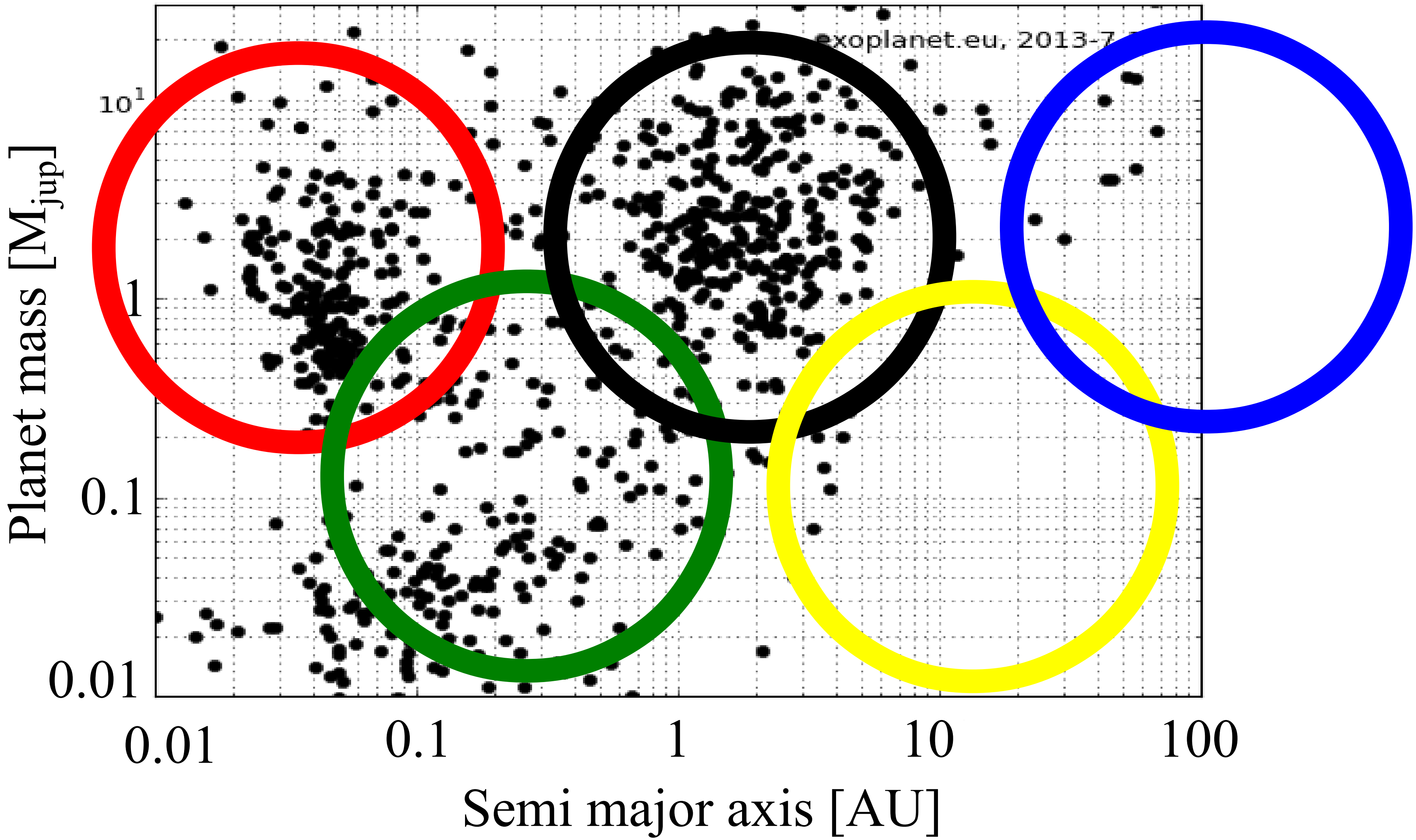

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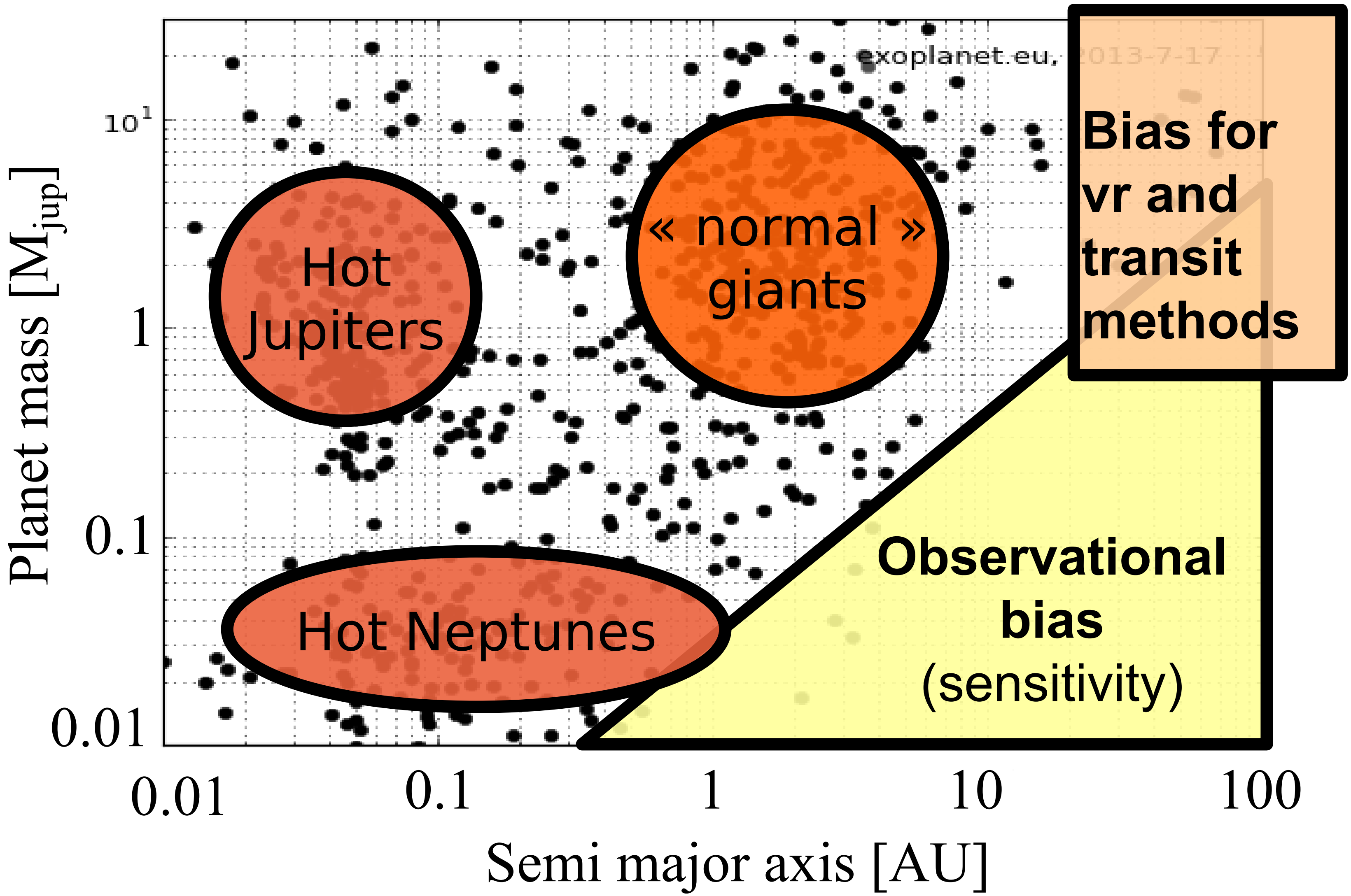
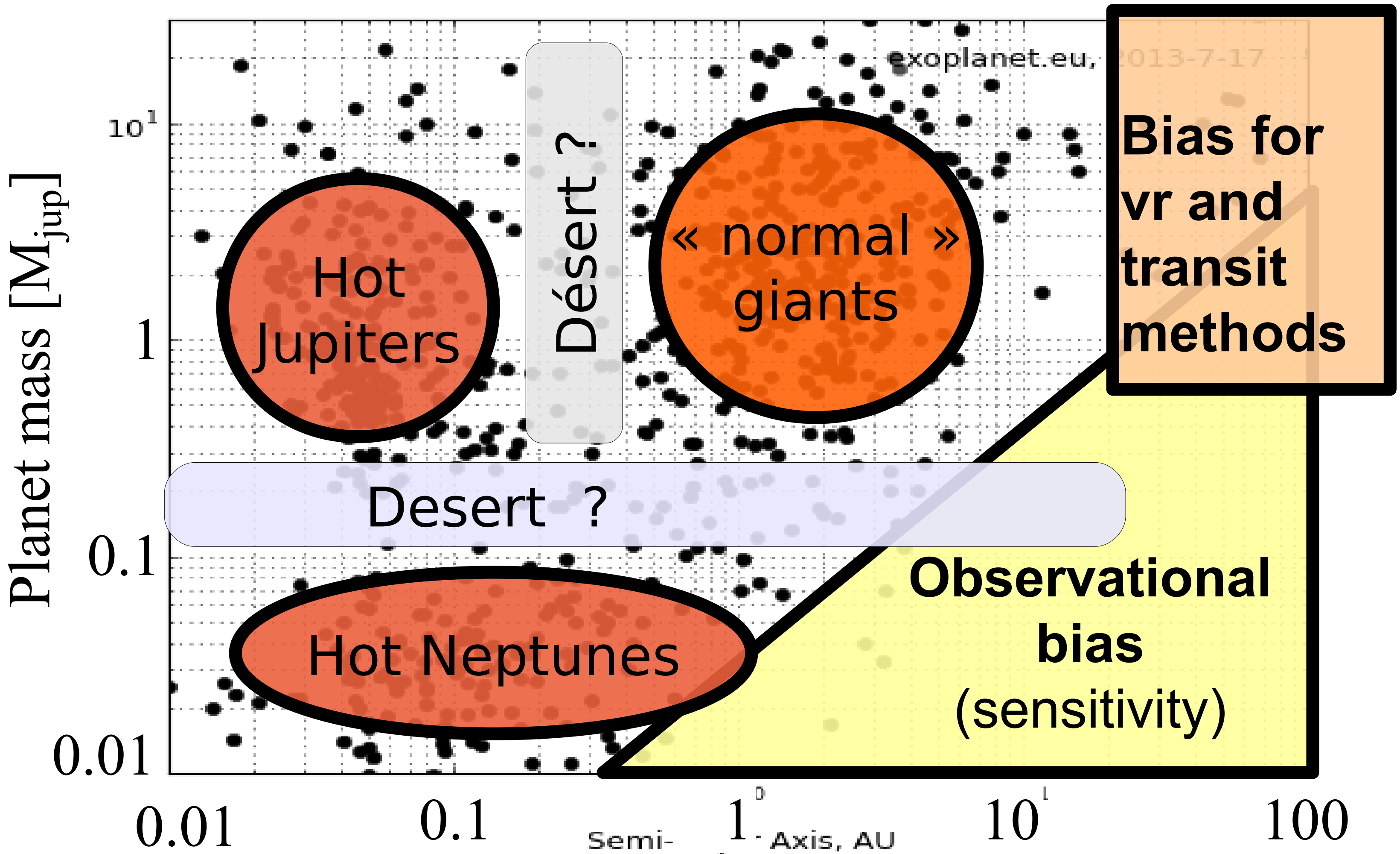


EXOPLANETS : II) Statistics



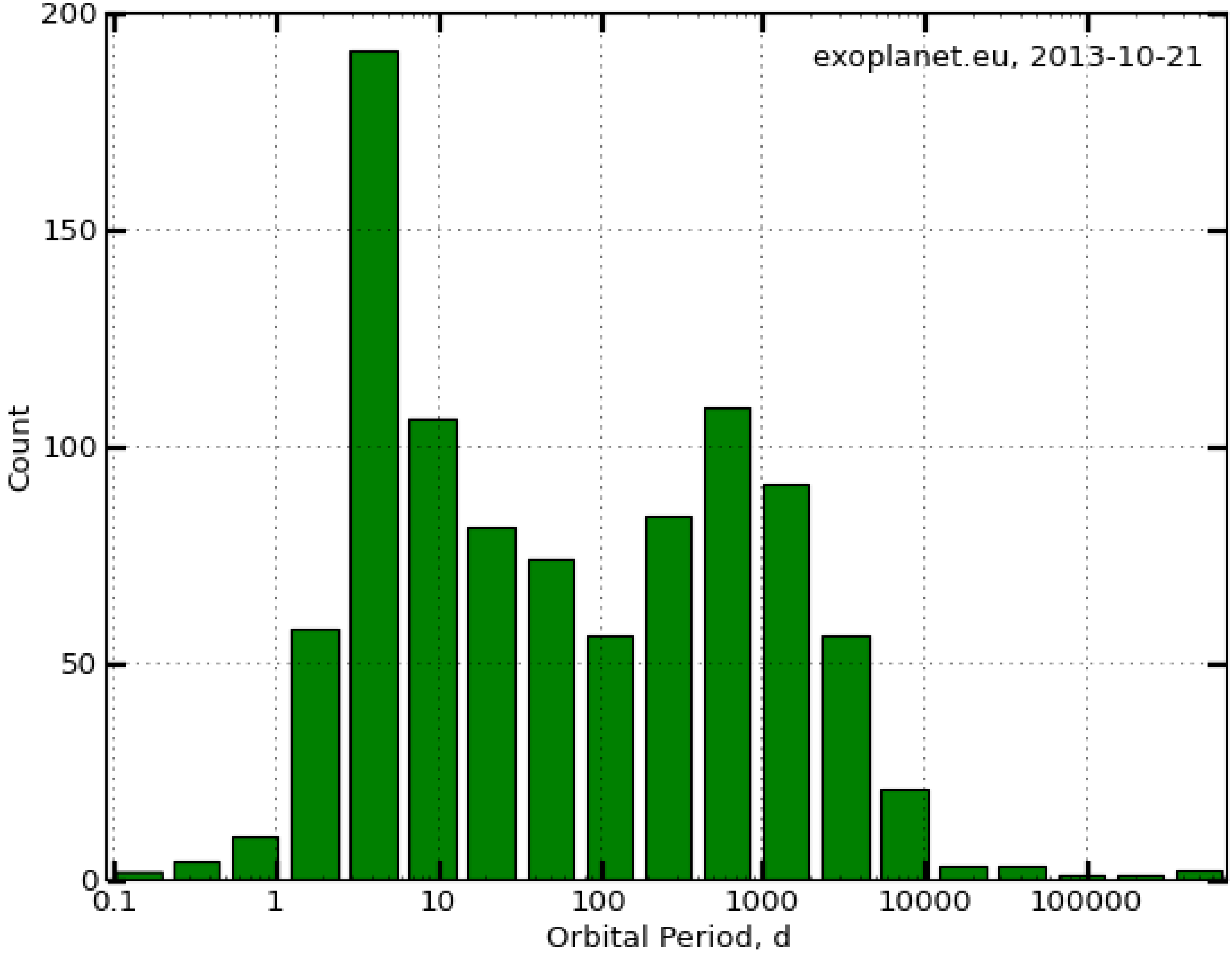
In spite of obs-ervationnal biases, one sees 3 populations, separated by 2 deserts.

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.

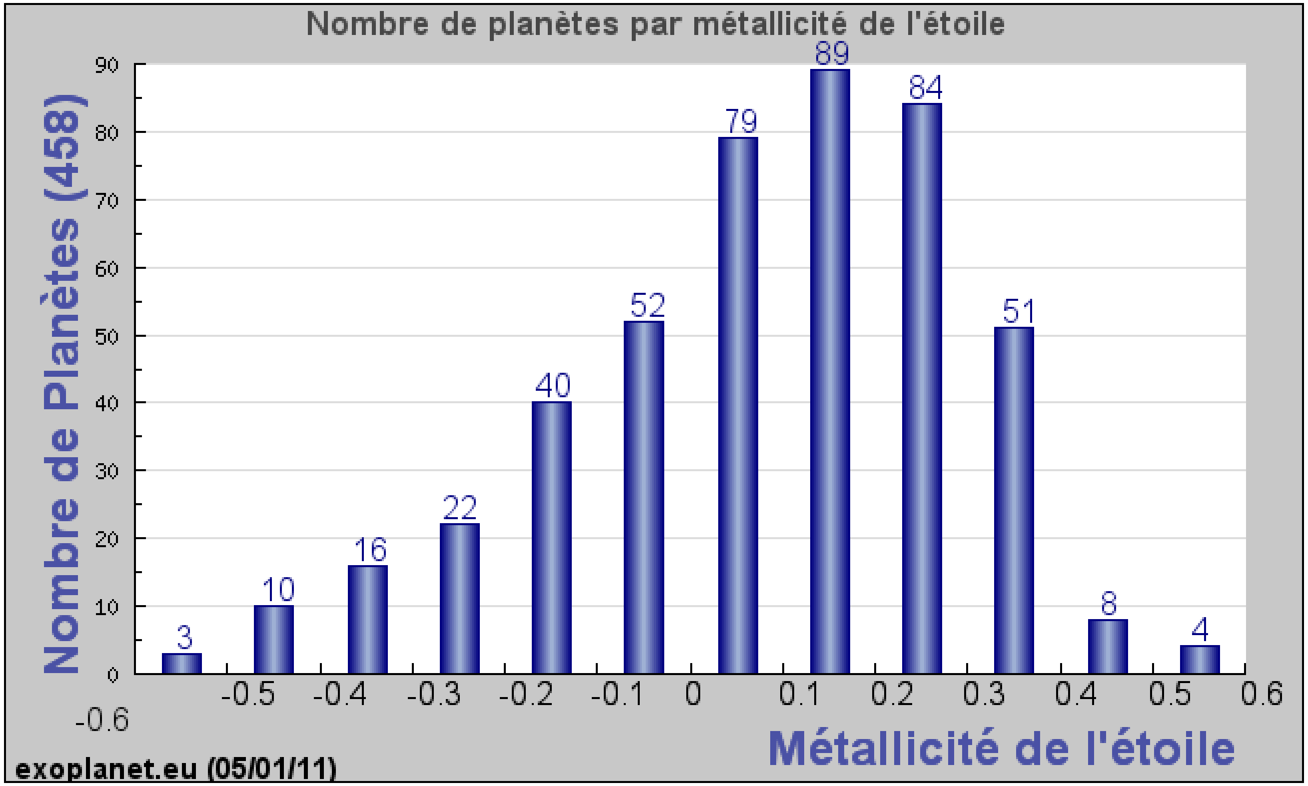
Either the disk life-time is enough to form a Jupiter-like gas giant, or it isn't, and one only gets an icy core with smaller atmosphere, like Neptune

EXOPLANETS : II) Statistics



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

EXOPLANETS : II) Statistics



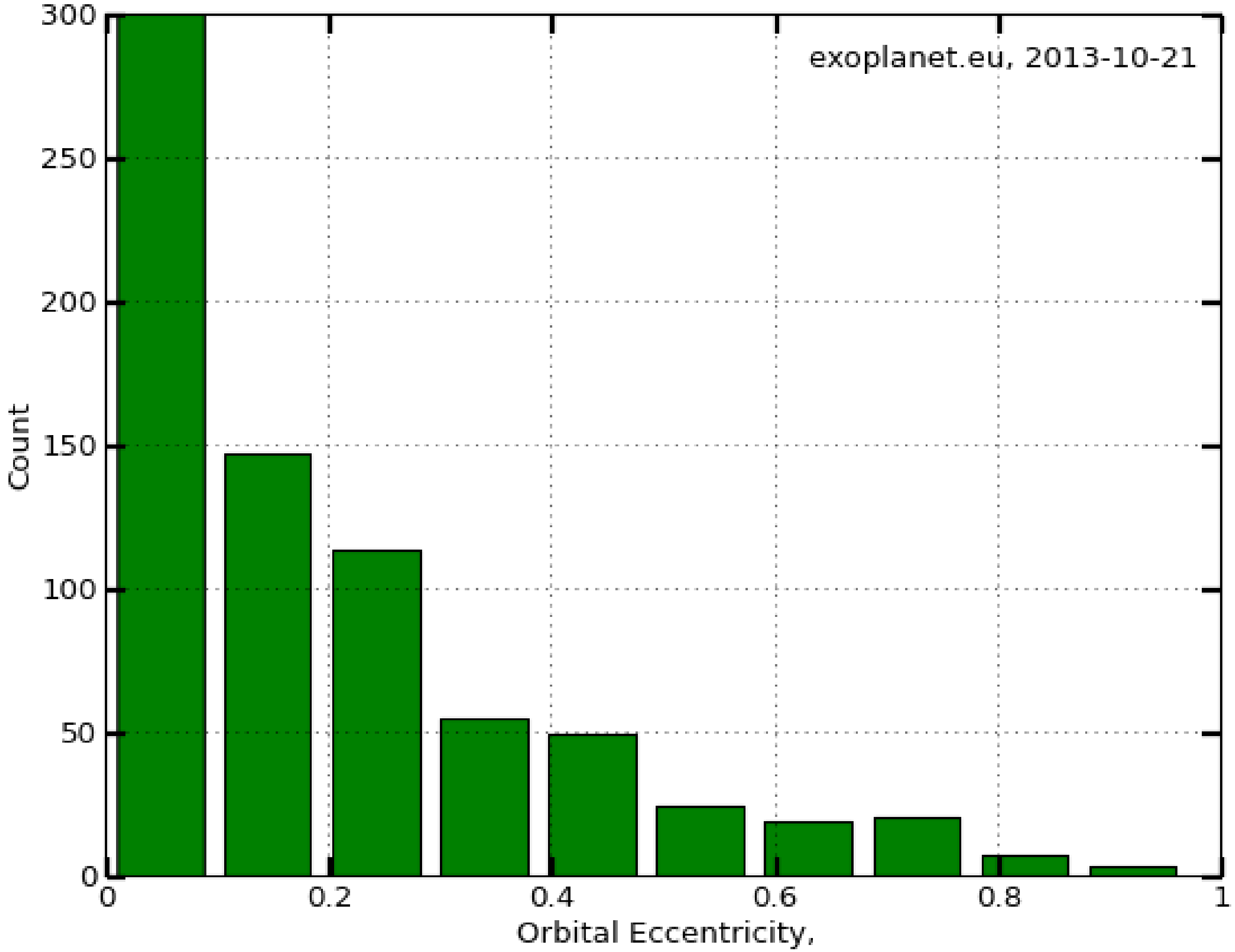
Strong influence of the metalicity of the host star !

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

Why ?

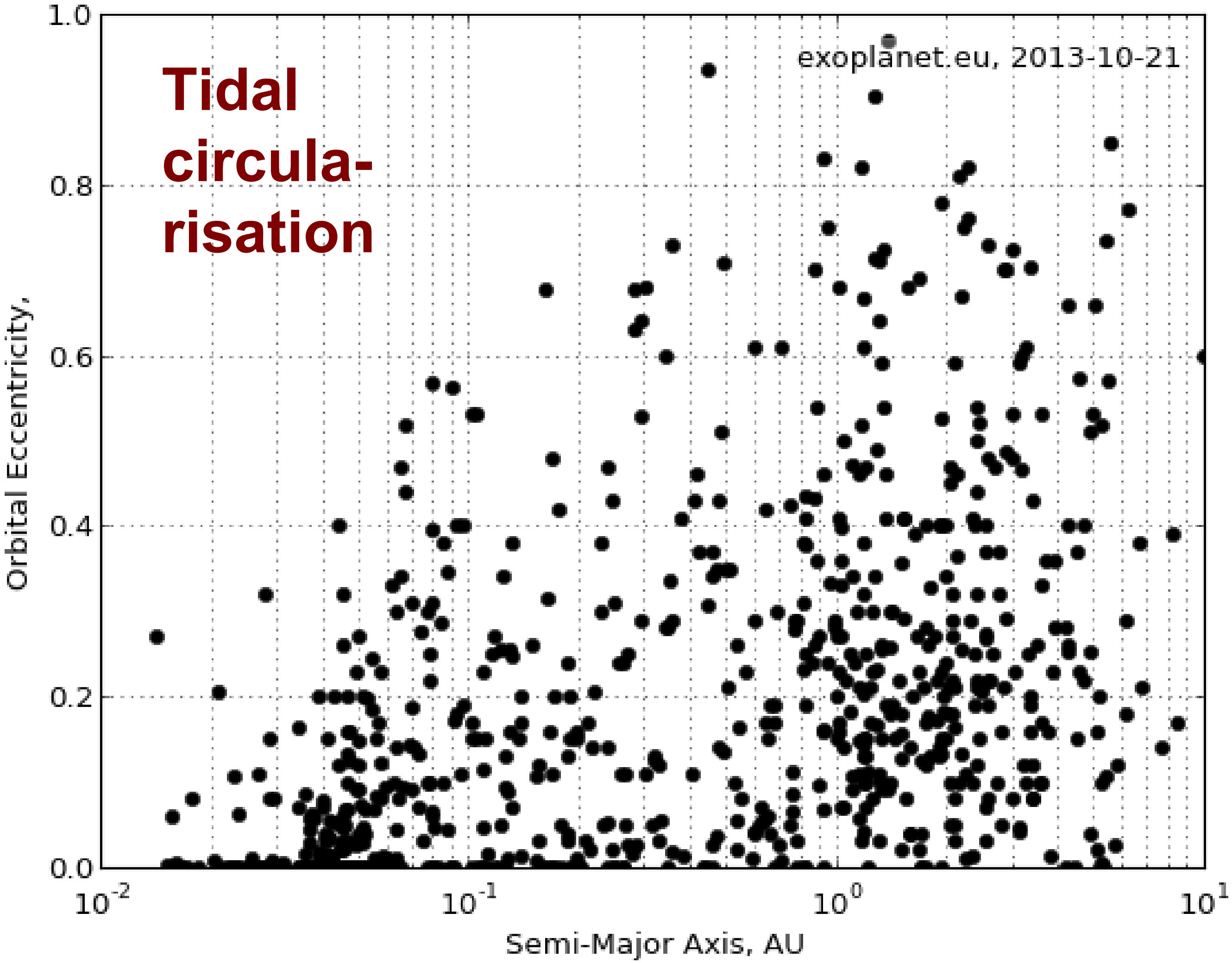
EXOPLANETS : II) Statistics

Excentricities : great variety !



EXOPLANETS : II) Statistics

Correlation a – e ?



EXOPLANETS : II) Planet Population Synthesis

Planet Population Synthesis :

Kitchen recipe including all the ingredients we have seen in the *planet formation* Chapter :

accretion, disk evolution, migration, and so on.

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

Repeat this operatino for a whole distribution of initial conditions.

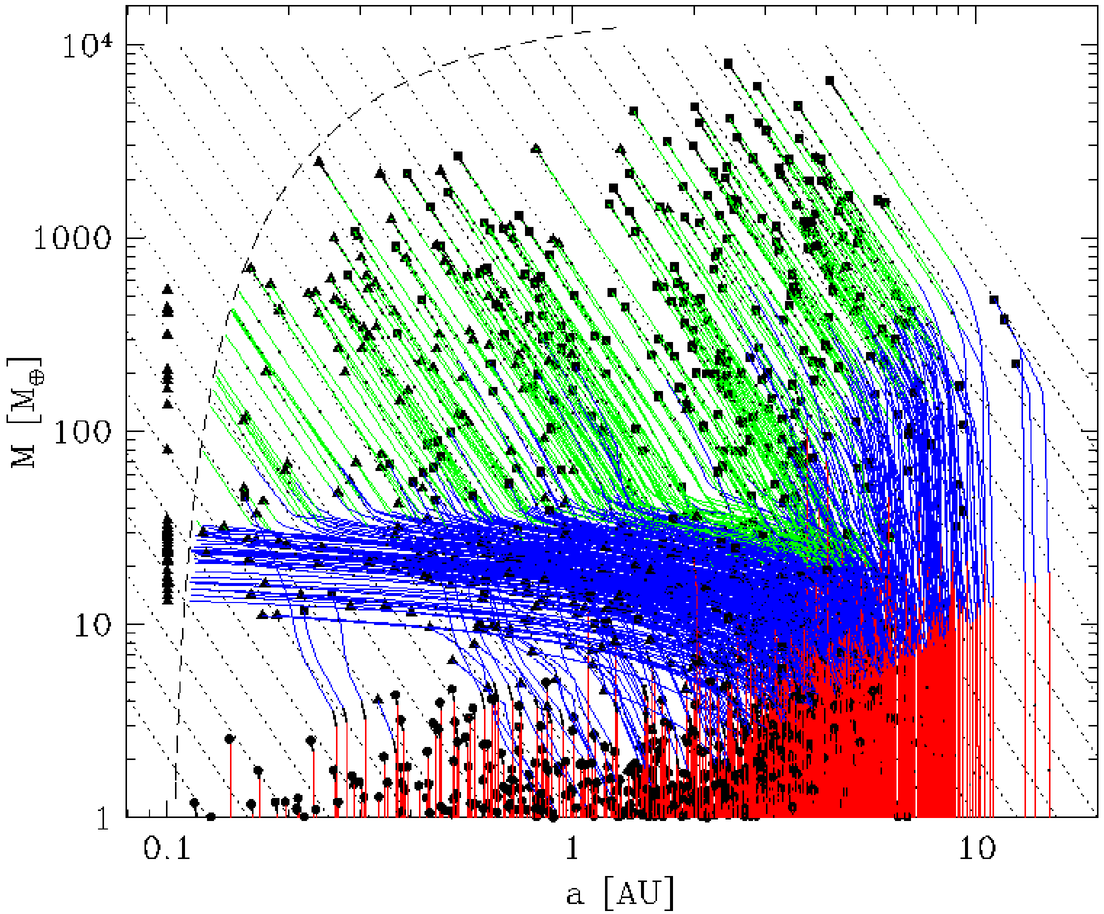
Look at the final distribution.

Compare with the statistics of the observations.

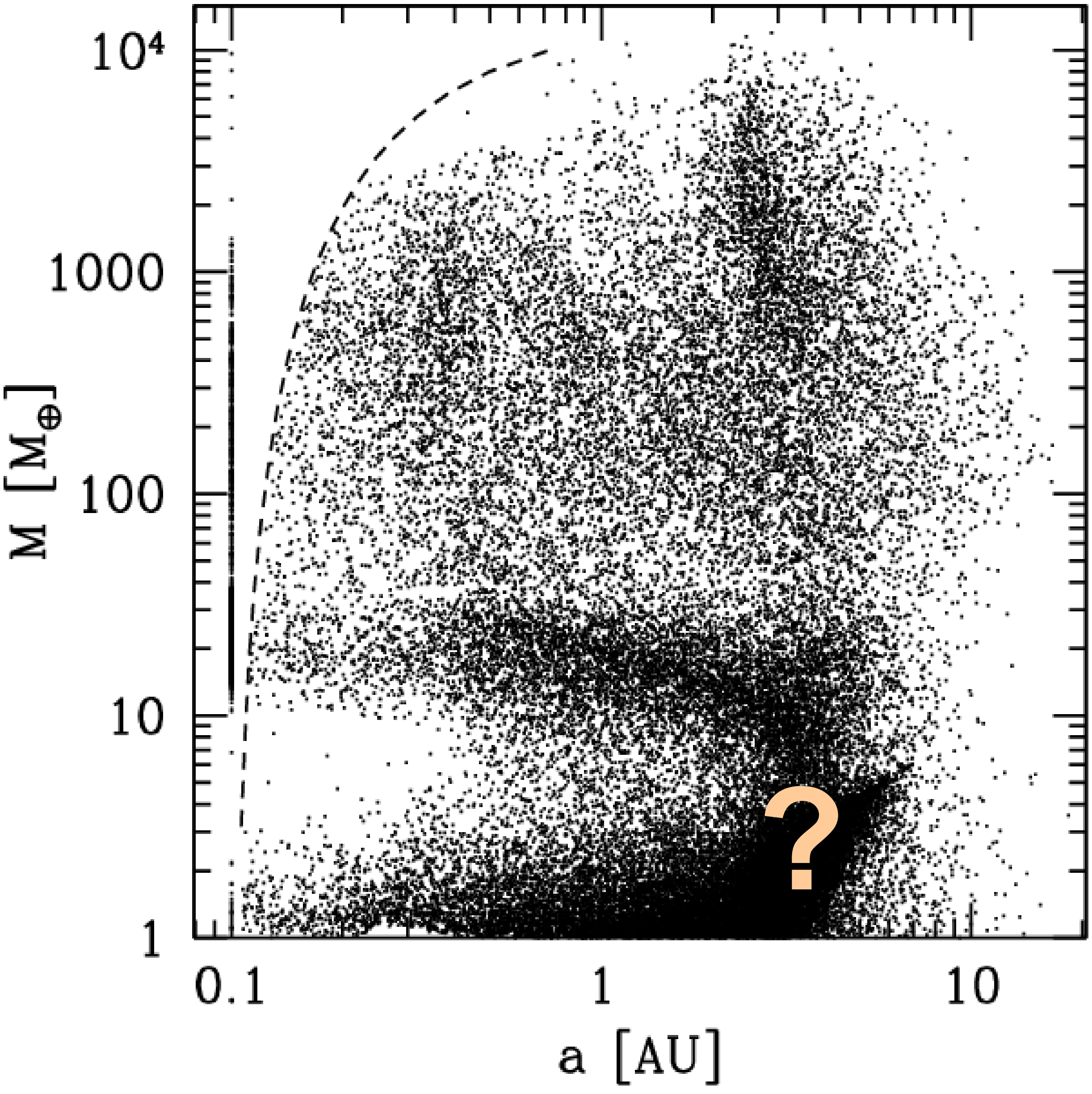
EXOPLANETS : II) Planet Population Synthesis

Plant Population Synthesis

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



EXOPLANETS : II) Planet Population Synthesis



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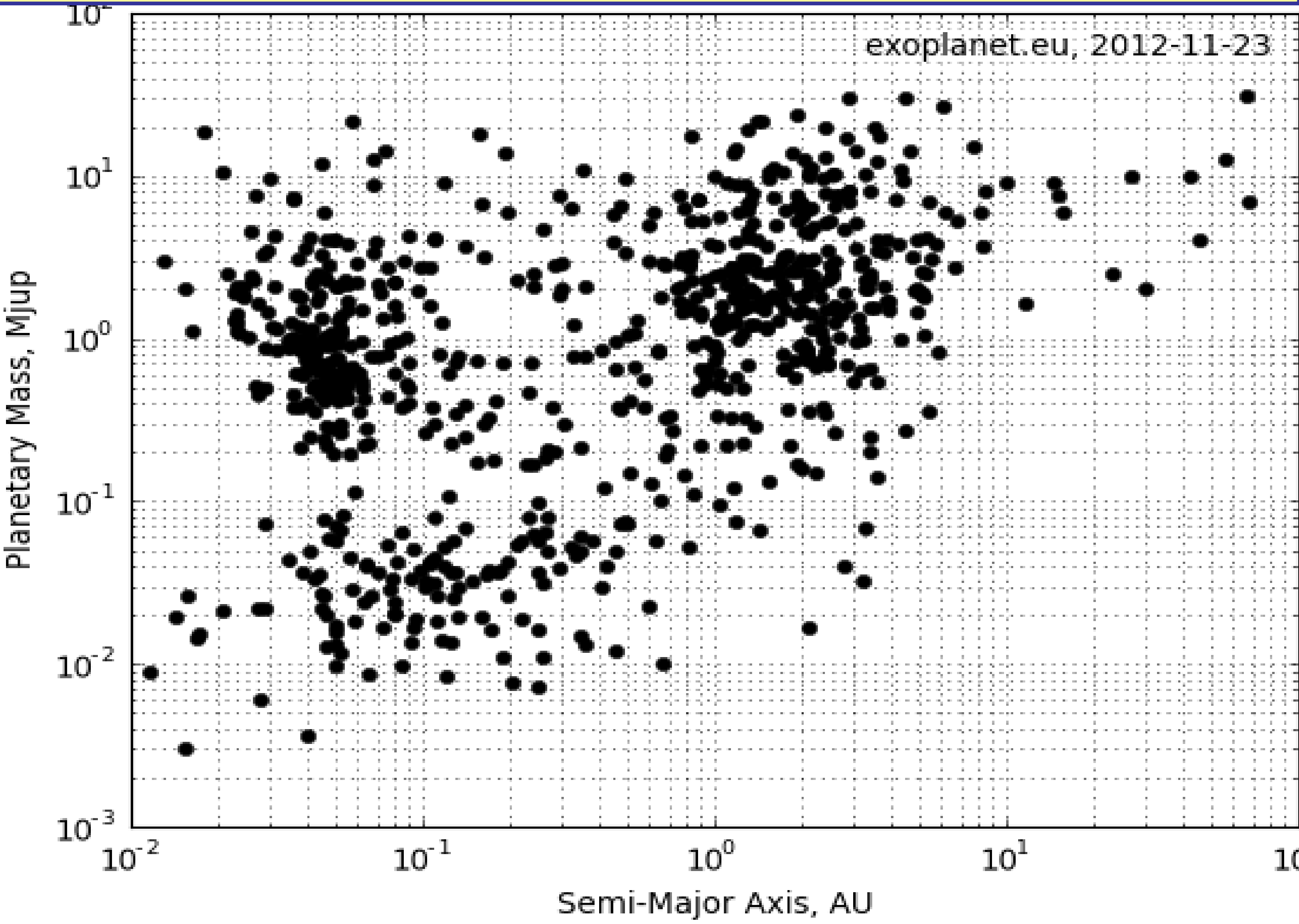
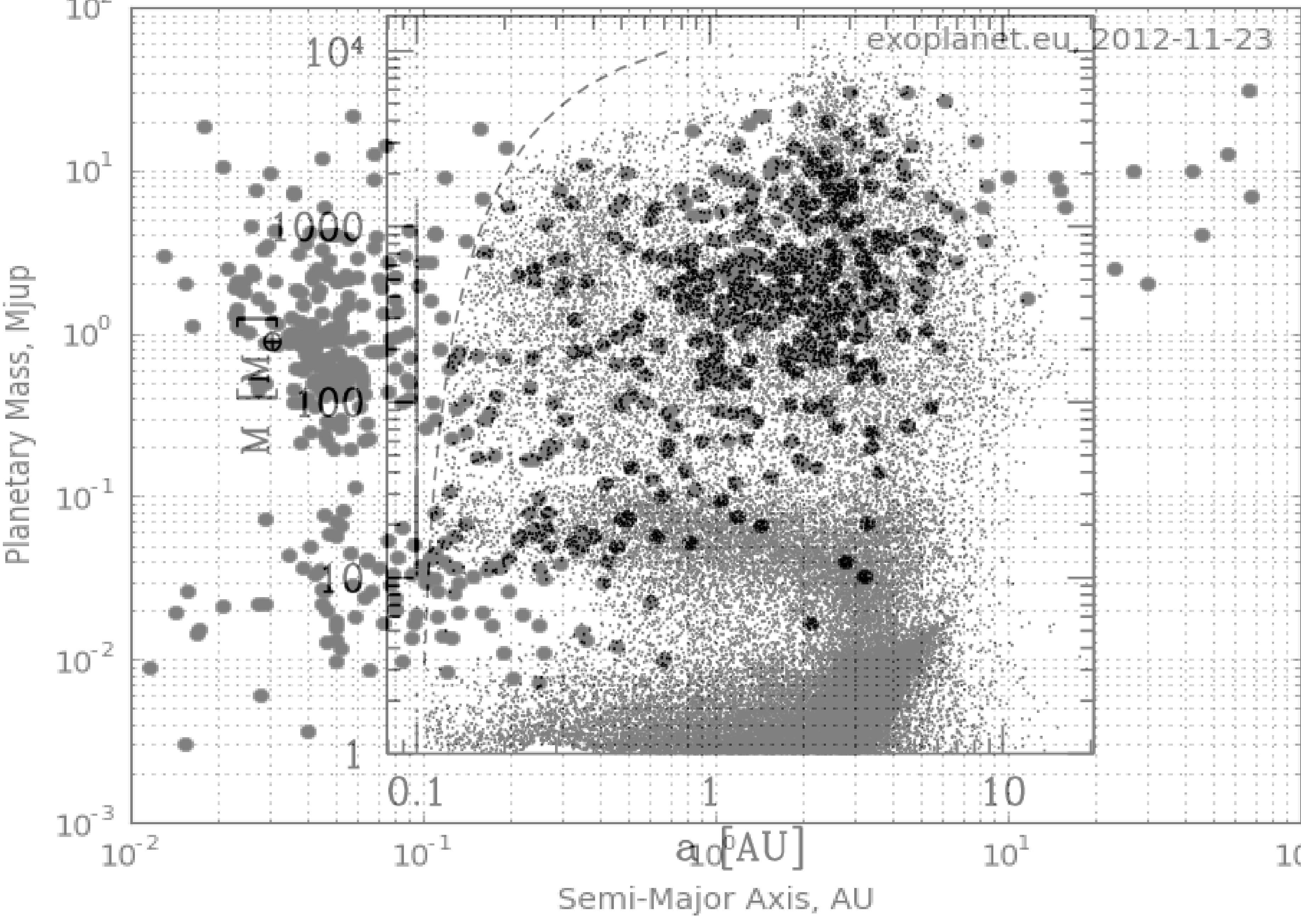


EXOPLANETS : II) Statistics



EXOPLANETS

See www.exoplanet.eu :

data, statistics, correlations, ...

Habitability ?