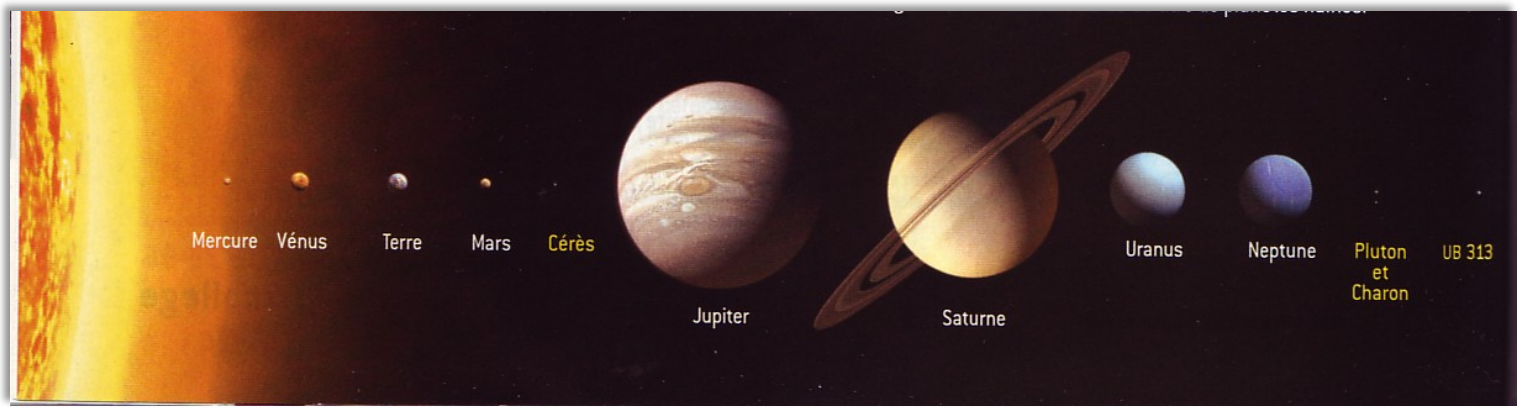
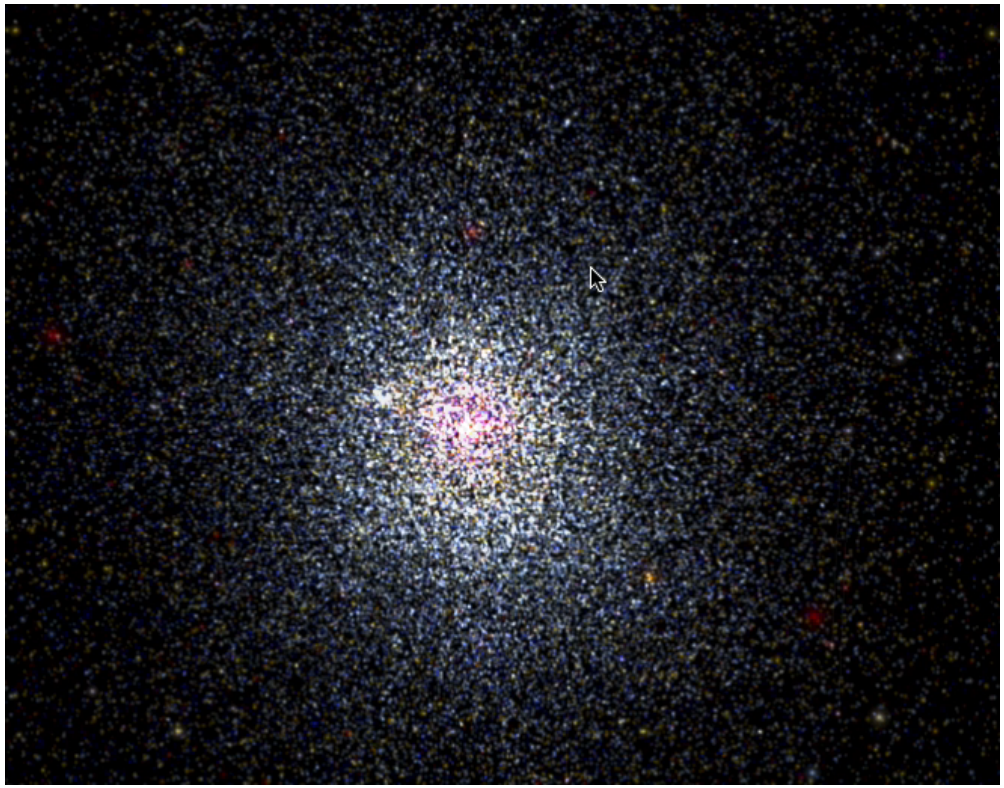
Detecting Exoplanets: a subtle usage of light

How the fine analysis of basic properties of light allows the discovery of exoplanets and/or to characterize them.

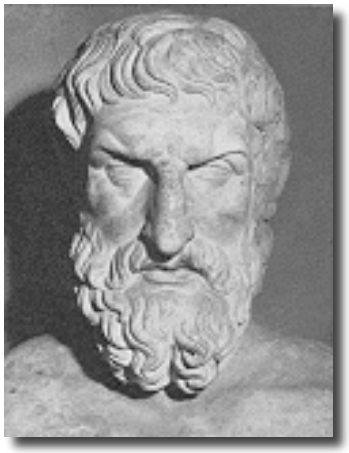
Daniel Rouan – LESIA– Observatoire de Paris

Other planetary systems ?





An ancient concept



Moreover, there is an infinite number of worlds, some like this world, others unlike it.
For the atoms being infinite in number (…), there will be nothing to hinder an infinity of worlds.
Epicurus, letter to Herodote, 300 B.C

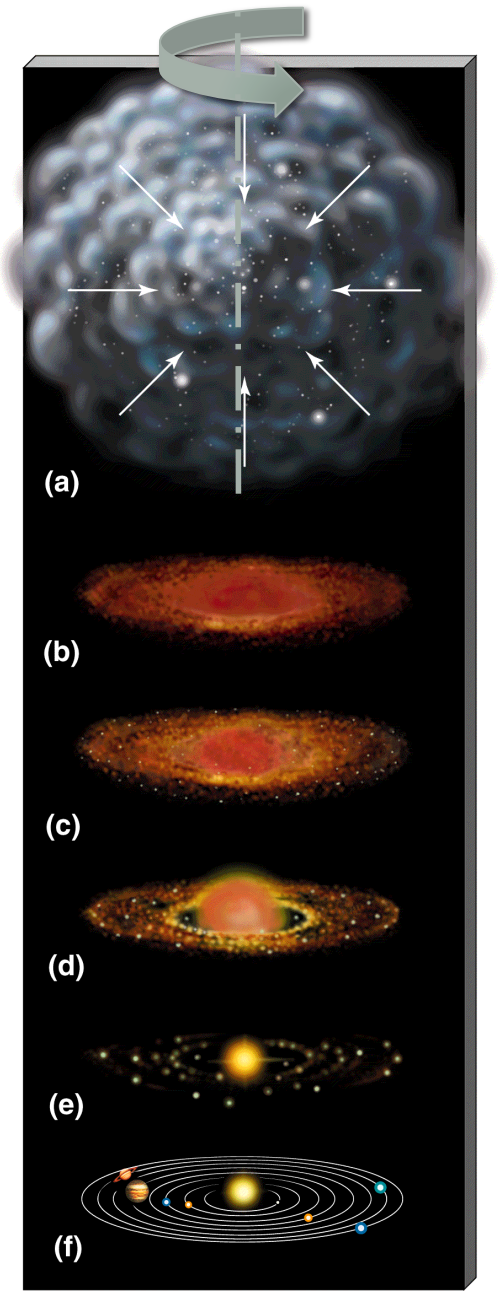
There are countless suns and countless earths all rotating round their suns in exactly the same way as the seven planets of our system
Giordano Bruno, « The infinite, the Universe and the worlds », 1600

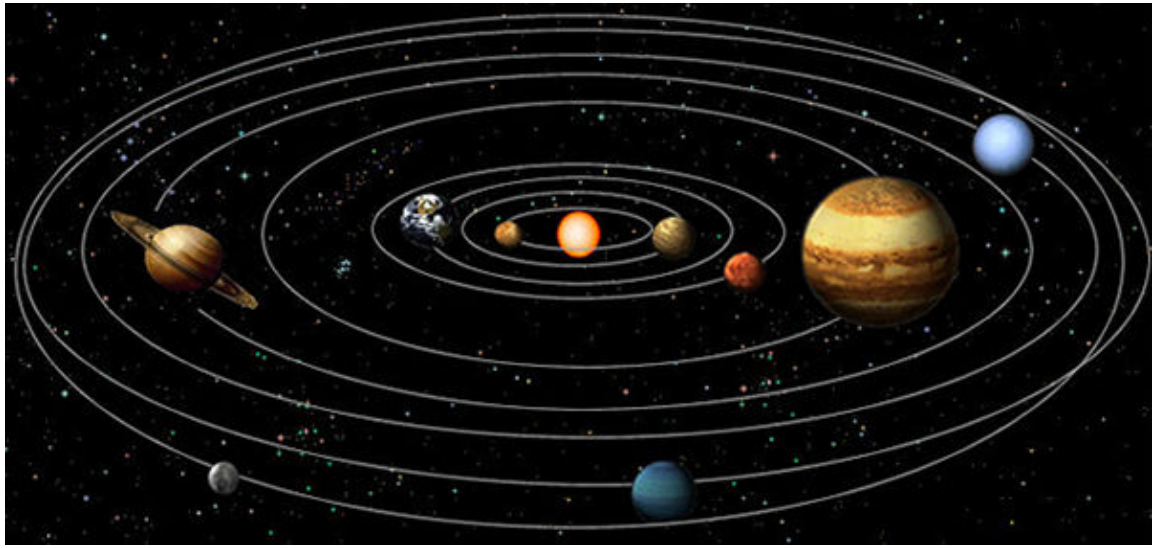
Statistics…

100 billions stars in a galaxy

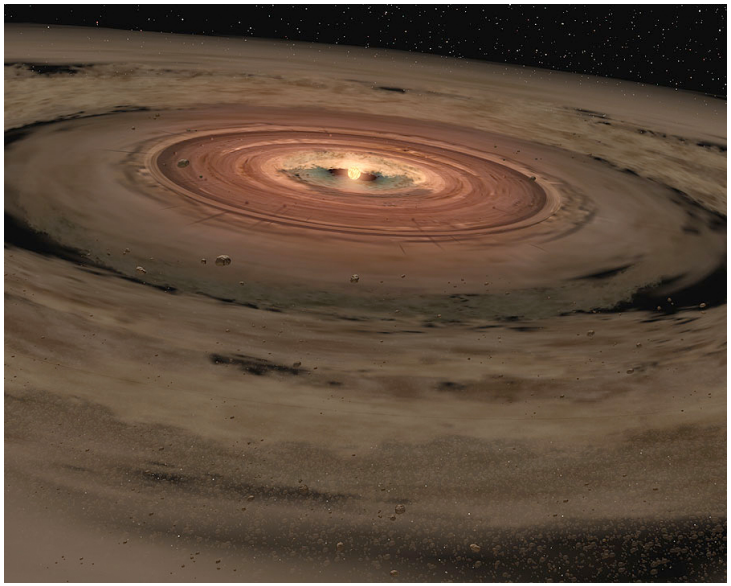
× 100 billions galaxies in the accessible Universe

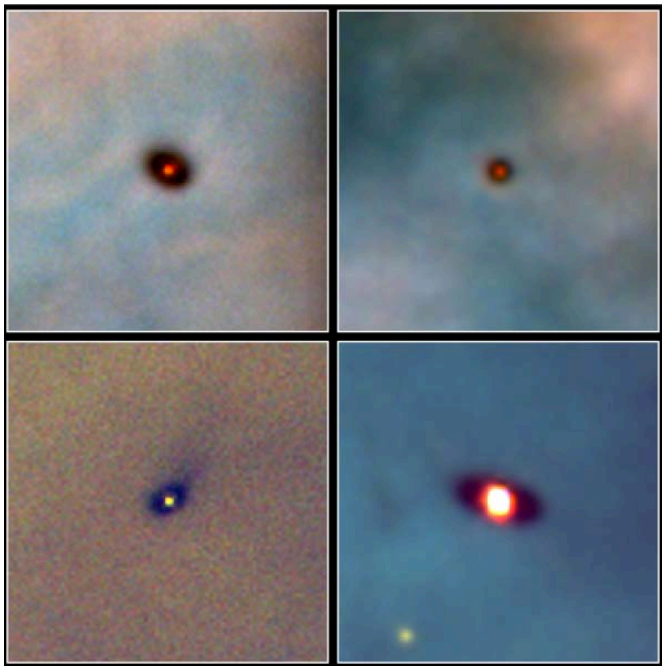
A well understood formation mecanism

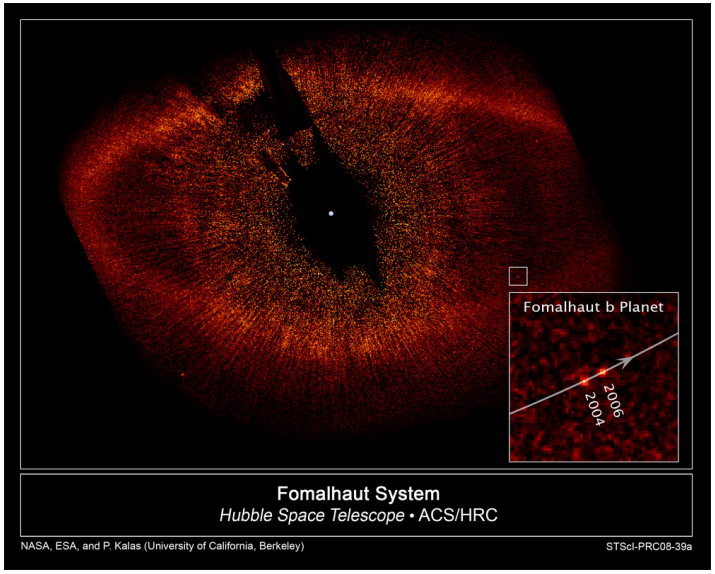


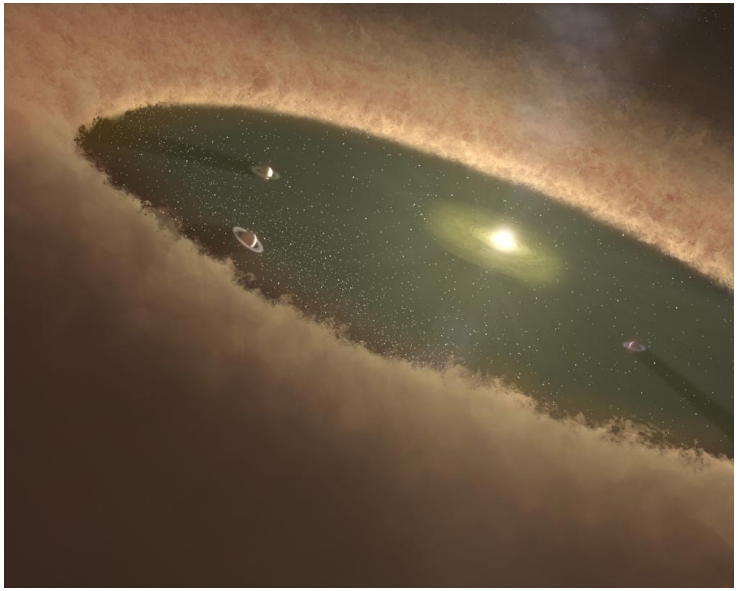


Clues…

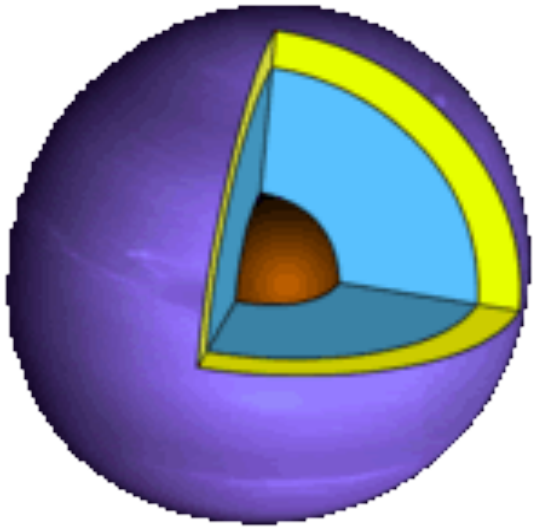





Fomalhaut b Planet
2006
2004
Fomalhaut System
Hubble Space Telescope • ACS/HRC
NASA, ESA, and P. Kalas (University of California, Berkeley)
STScI-PRC08-39a



Definition of a planet ?



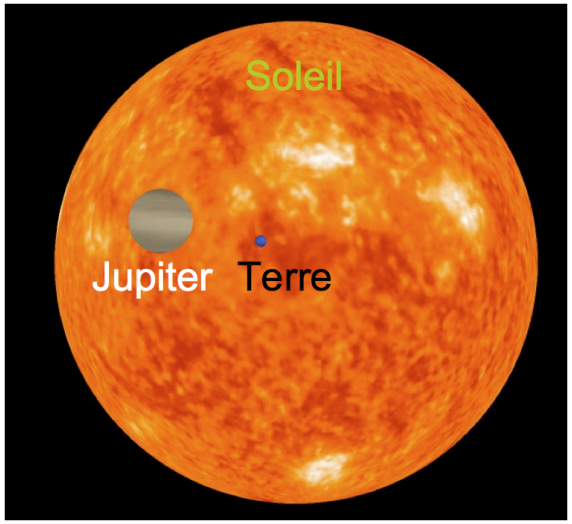
A planet is a celestial body, which

- *a) is orbiting a star,*
- *b) has a mass sufficient so that its gravity wins againts cohesion forces of a solid and maintains equilibrium under a quasi-spherical form,*
- *c) has eliminated all bodies susceptible to be on a close orbit*

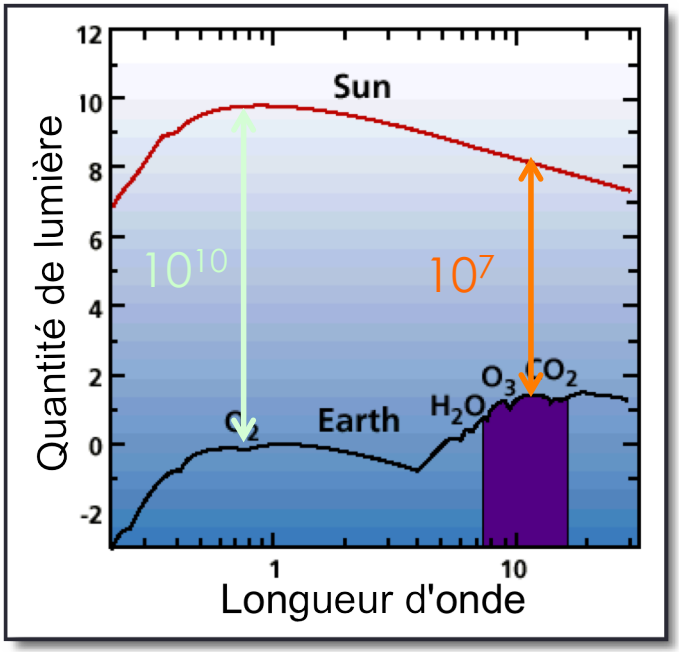
(G.A. International Astronomical Union, 2009)

Detecting a planet ?

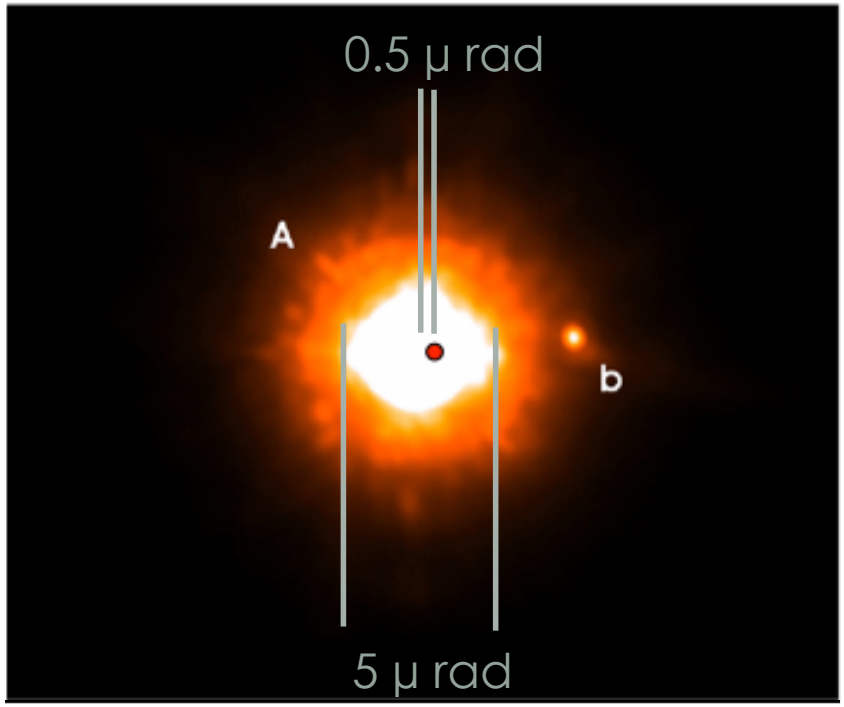
Size / Mass



Contrast



Angular resolution




Detecting *directely* a
planet is a
TERRIBLE task !!!

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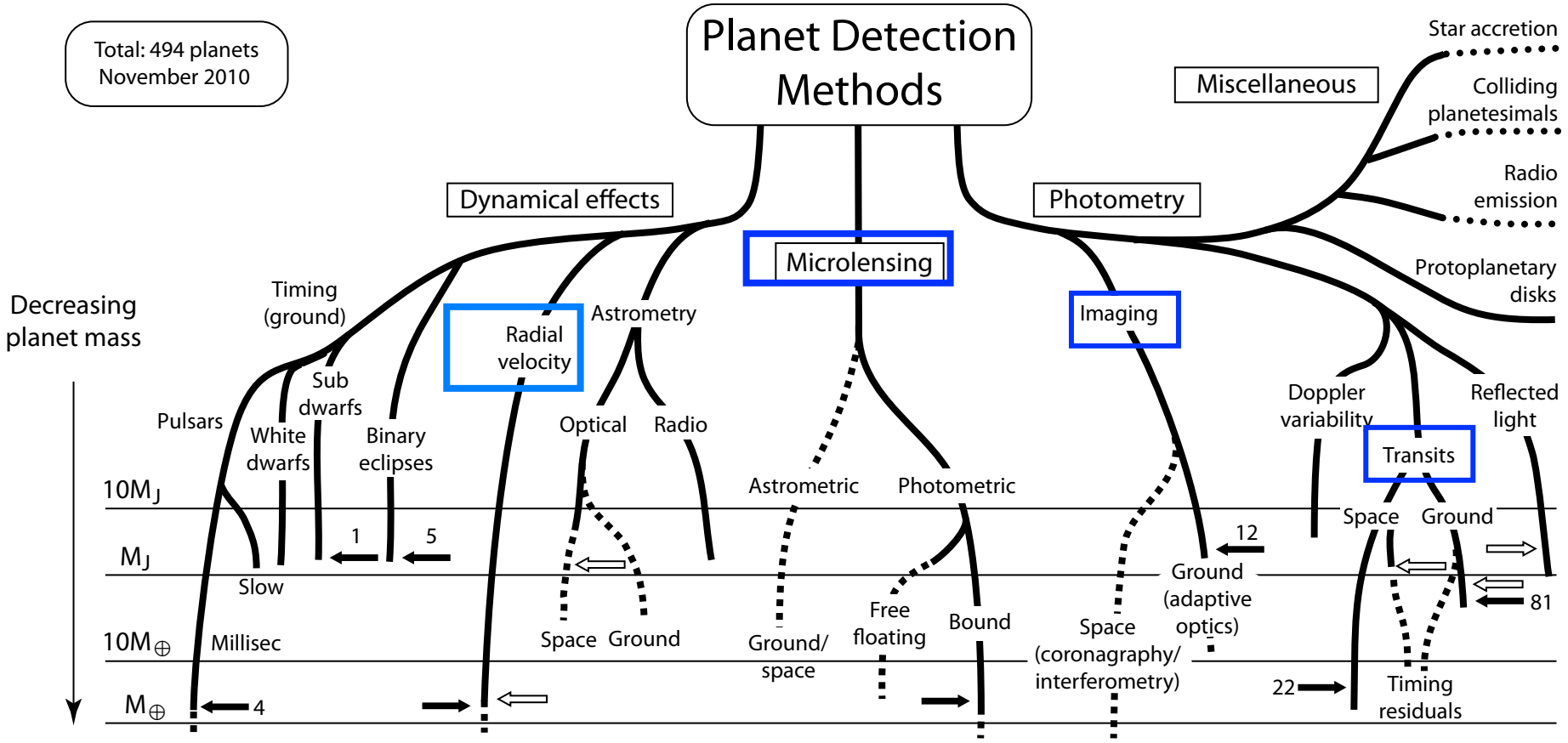
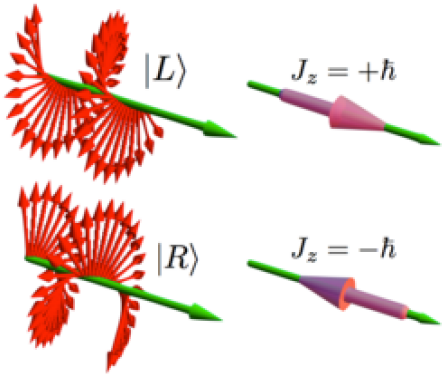
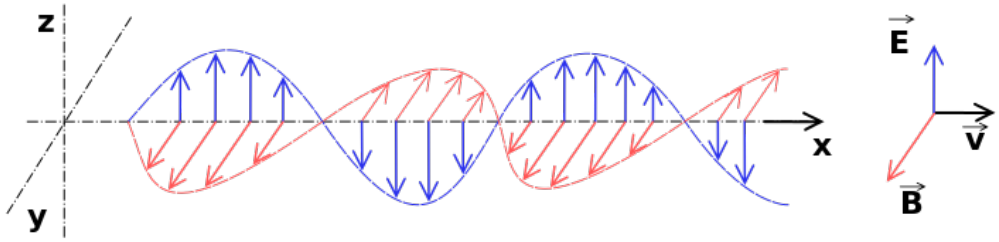
The *tree* of detection methods



Using different properties of light

Photon	Electromagnetic wave	Instrument
Energy (h ν)	Wavelength (λ)	Spectrograph
Number of photons	Intensity	Photometer
Coherence	Spectral purity	Interferometer
Spin state	Polarization	Analyzer / Polarizer
Constant speed	Deviation by a mass: lensing effect	Photometer





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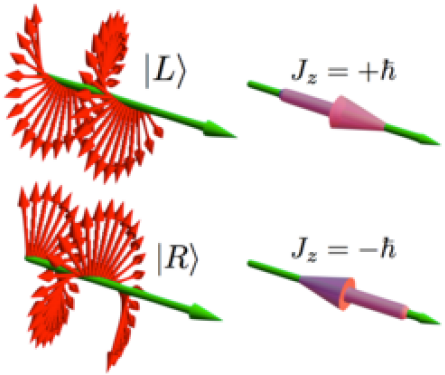

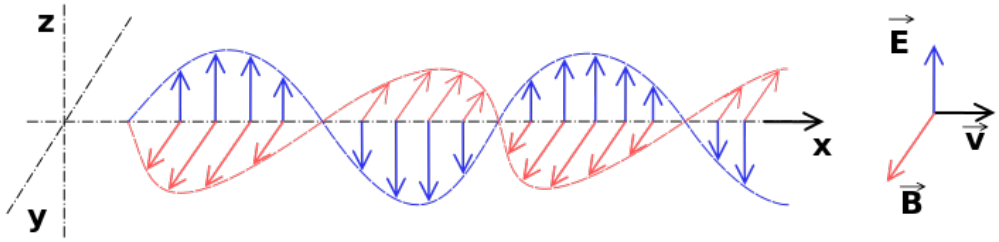

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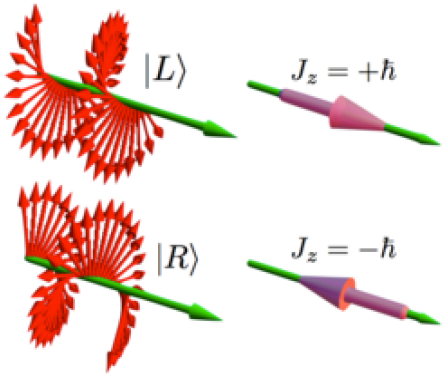

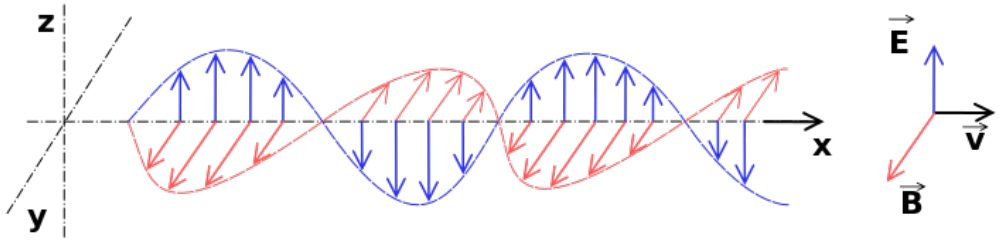

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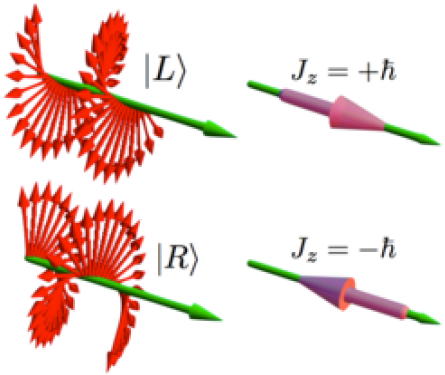

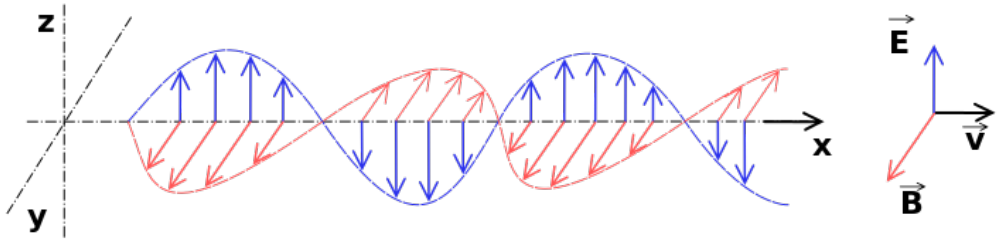

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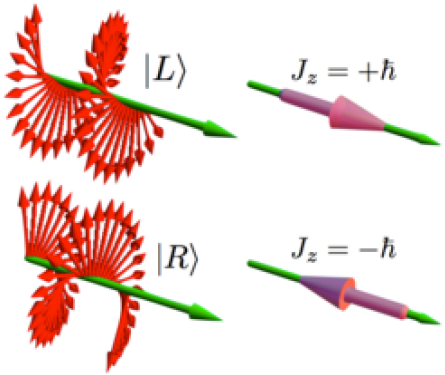
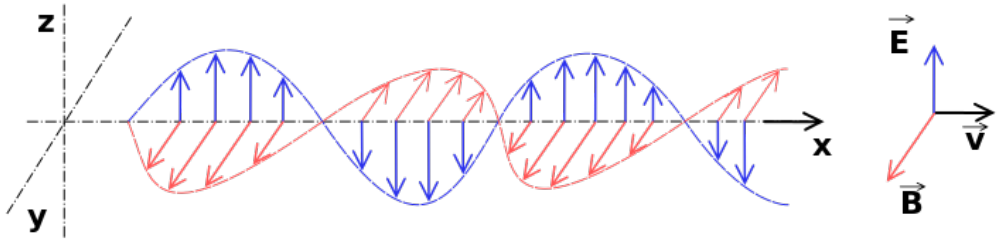
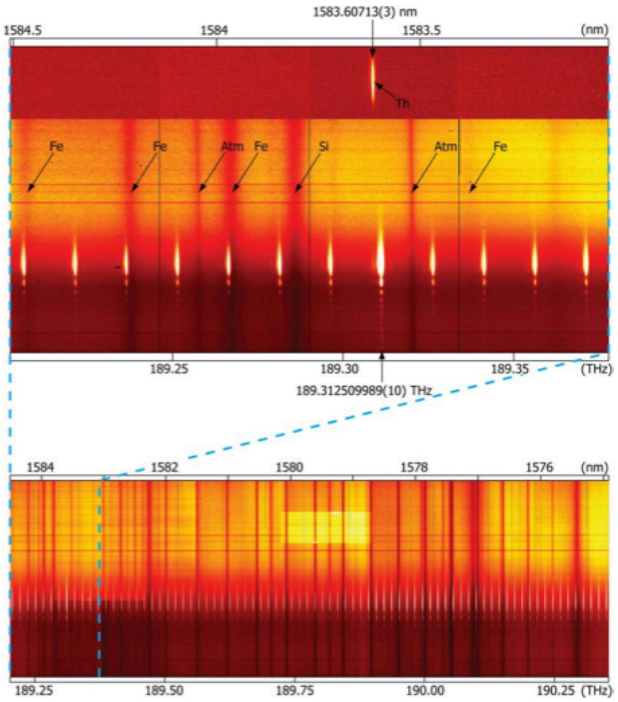




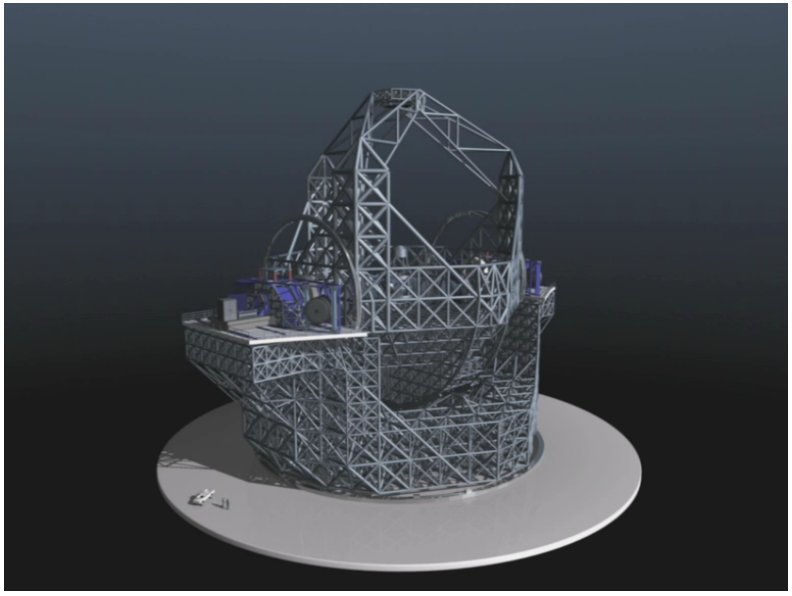
Extreme techniques & *High-tech*

Adaptative optics

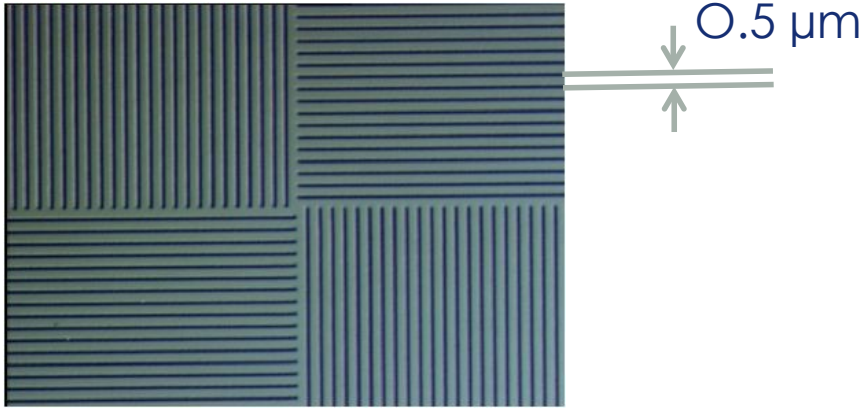
Frequency comb



Giant telescope (10-40 m)



Nanotechnologies

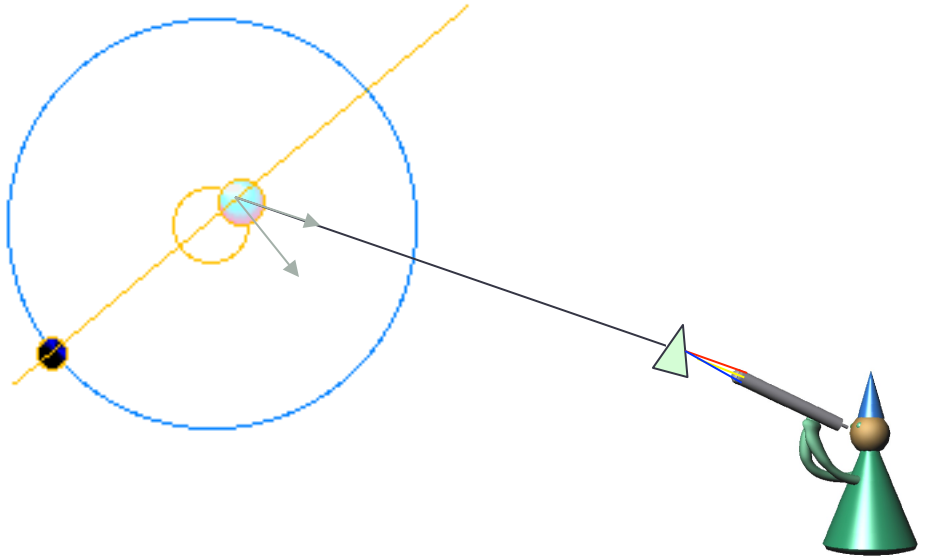


Property 1

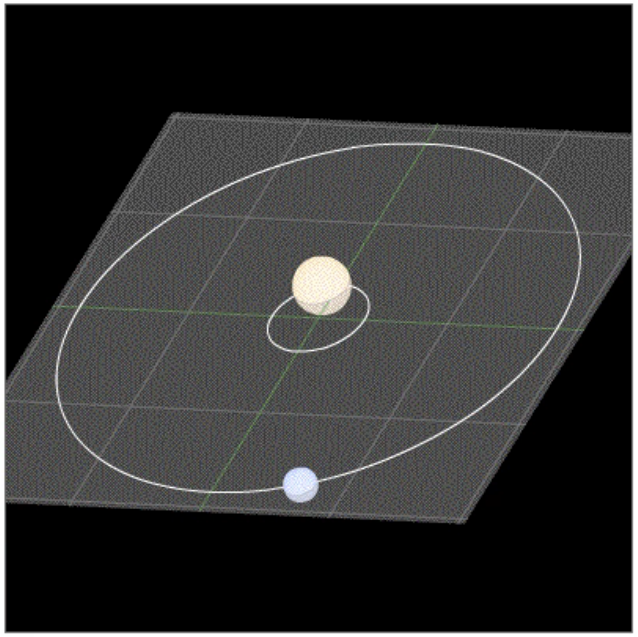
Wavelength

➜

detecting the Doppler shift



The reflex movement

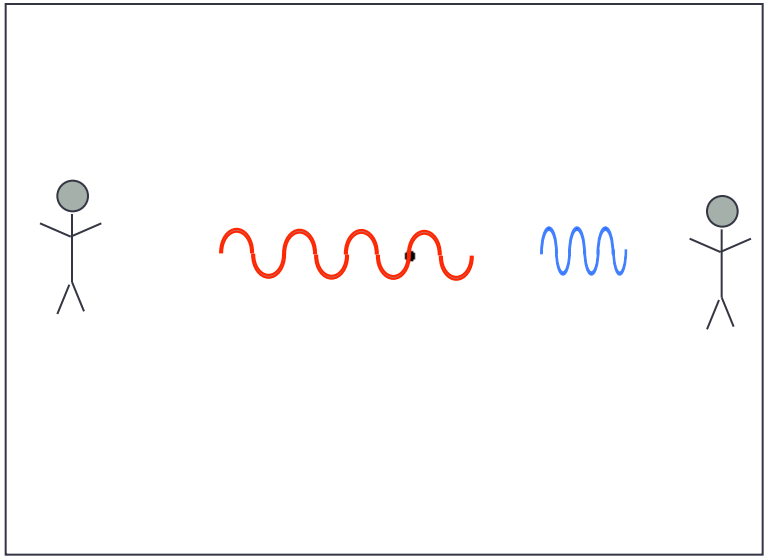


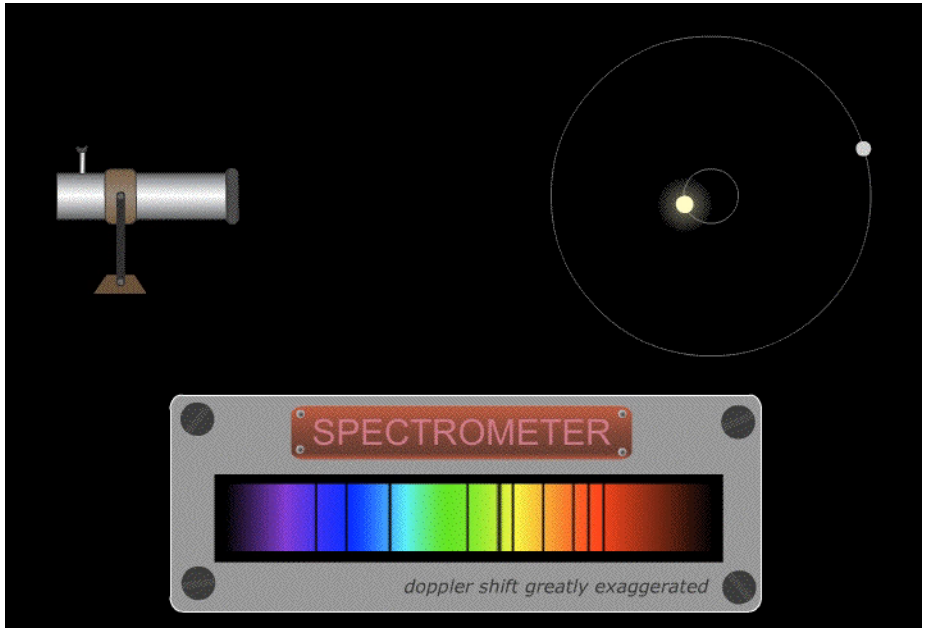
The Doppler effect

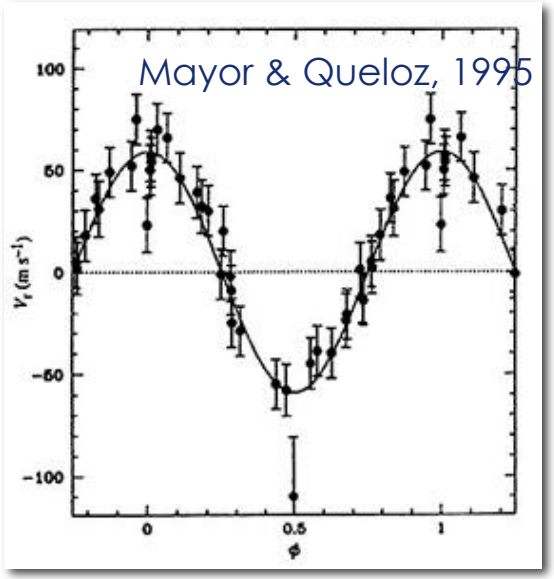
$\Delta \lambda / \lambda_o = 10^{-7} \; M_p \sin i \; (a \, M_*)^{-1/2}$

Earth / Sun: $v_* = 0.1$ m s^{-1} ➜ $\Delta \lambda / \lambda o =$ **3 10^{-10}** !

51 PegB : $v_* = 127$ m s^{-1} ➜ $\Delta \lambda / \lambda o =$ **4 10^{-7}**

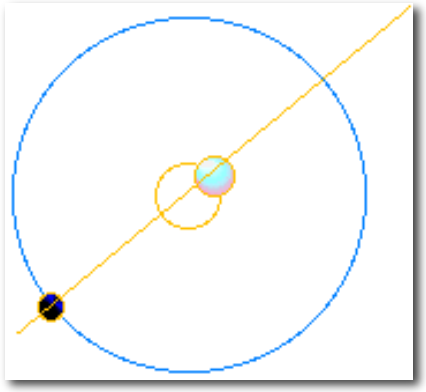






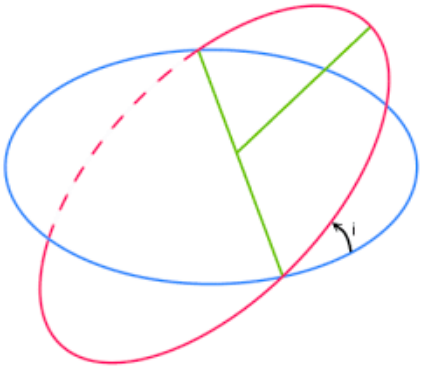
Velocity amplitude ?

- Doppler Effect : $\Delta\lambda / \lambda_o = (\lambda - \lambda_o)/\lambda_o = v / c$
- Speed of star
  - orbital radius of star $a_* = a\ (M_p / M_*)$
  - Newton-Kepler : $M_p\ (2\pi/P)^2\ a = G\ M_p M_* / a^2$ ➜
    $a_* = (G\ M_*)^{1/3}\ (P/\ 2\pi)^{2/3}\ M_p / M_*$
  - Velocity = orbit length / periode = $2\pi\ a_* / P$
    $= (G\ M_*)^{1/3}\ (P/\ 2\pi)^{-1/3}\ (M_p / M_*)$
  - Projected velocity :
    $= (G\ M_*)^{1/3}\ (P/\ 2\pi)^{-1/3}\ (M_p / M_*)\ \sin i$



In convenient units :

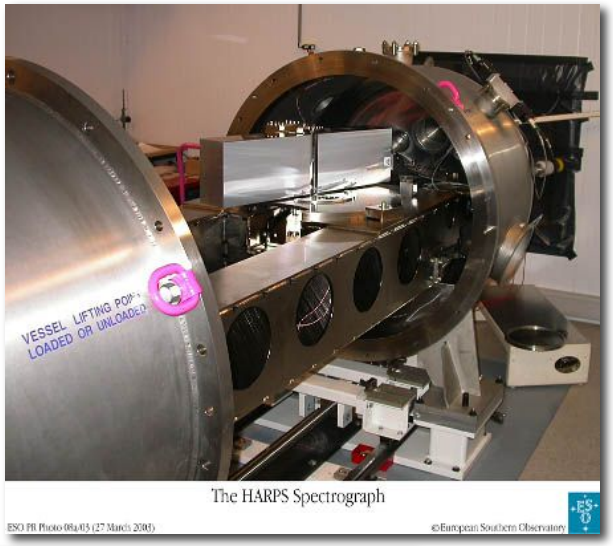
- $\Delta\lambda / \lambda_o = 10^{-7}\ (a/AU)^{-1/2}\ (M_p \sin i/M_J)\ (M_*/M_\odot)^{-1/2}$



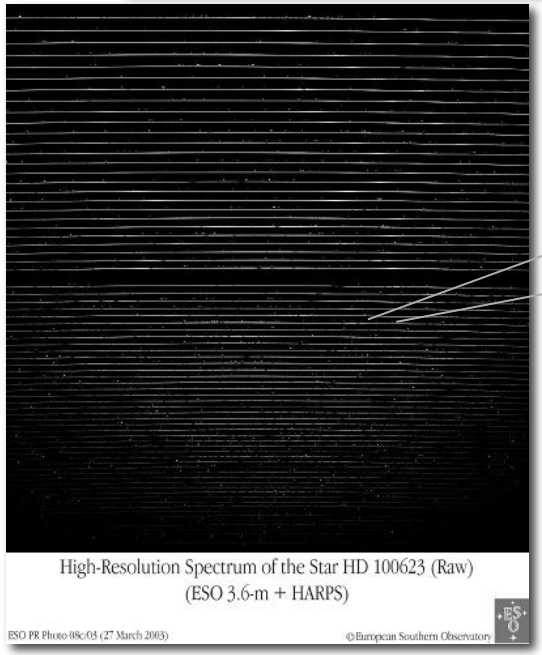
➜ **Mass of the planet !**

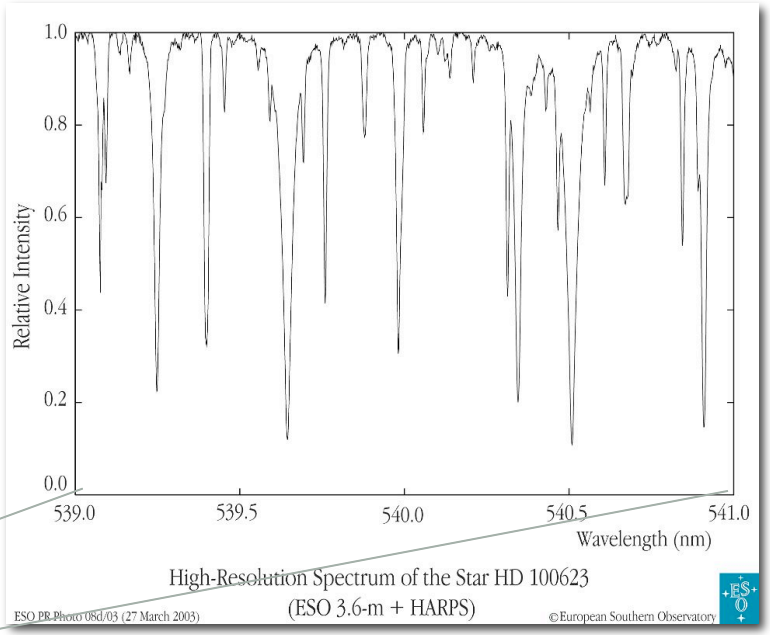
The tool: cross-dispersed échelle spectrograph

HARPS



The HARPS Spectrograph


High-Resolution Spectrum of the Star HD 100623 (Raw)
(ESO 3.6-m + HARPS)

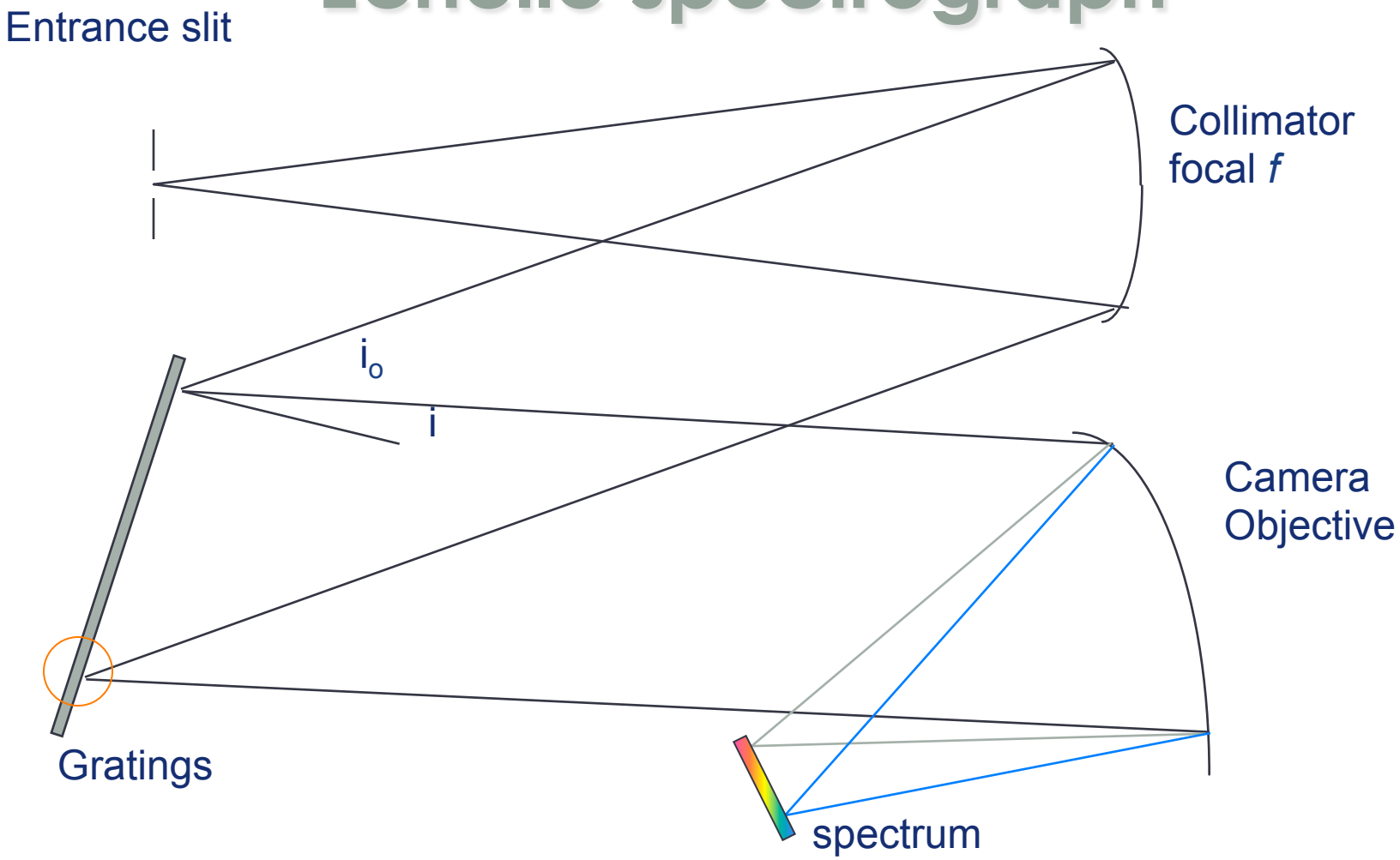


High-Resolution Spectrum of the Star HD 100623
(ESO 3.6-m + HARPS)

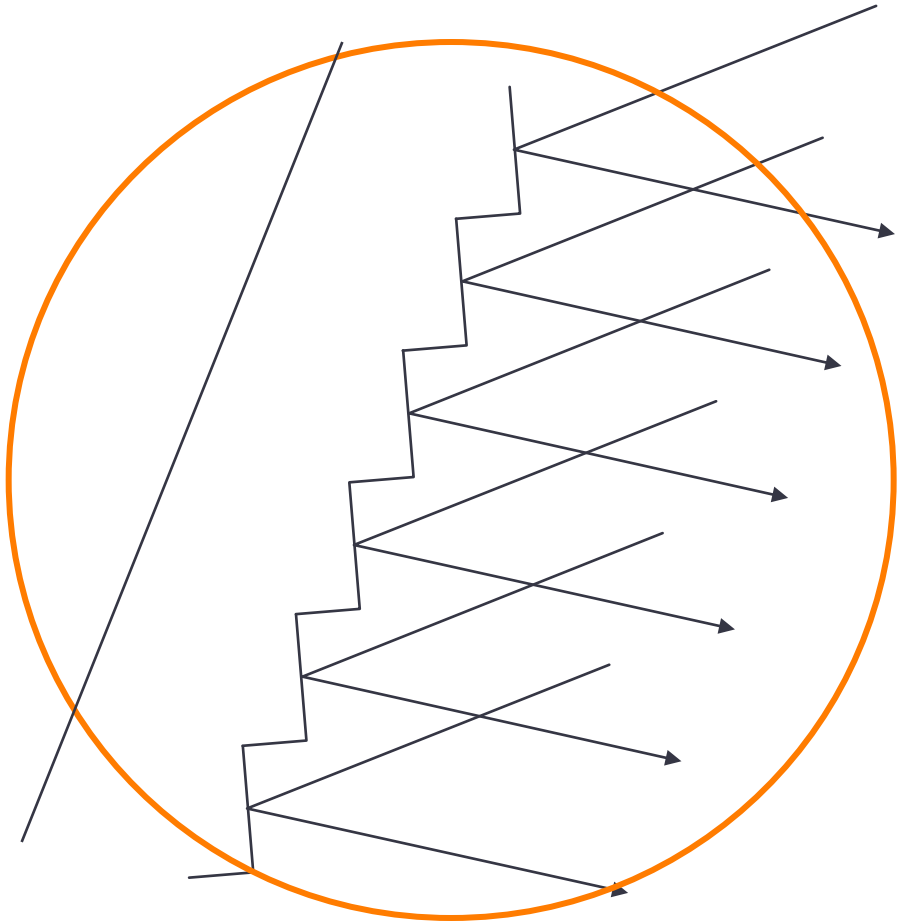
Combines :

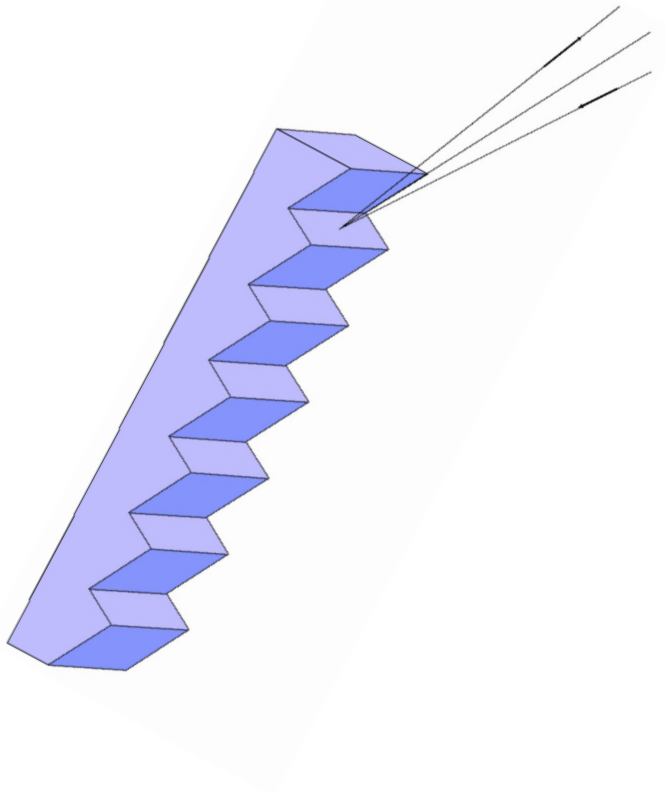
- a very broad spectral domain
- a very high spectral resolution

Échelle spectrograph



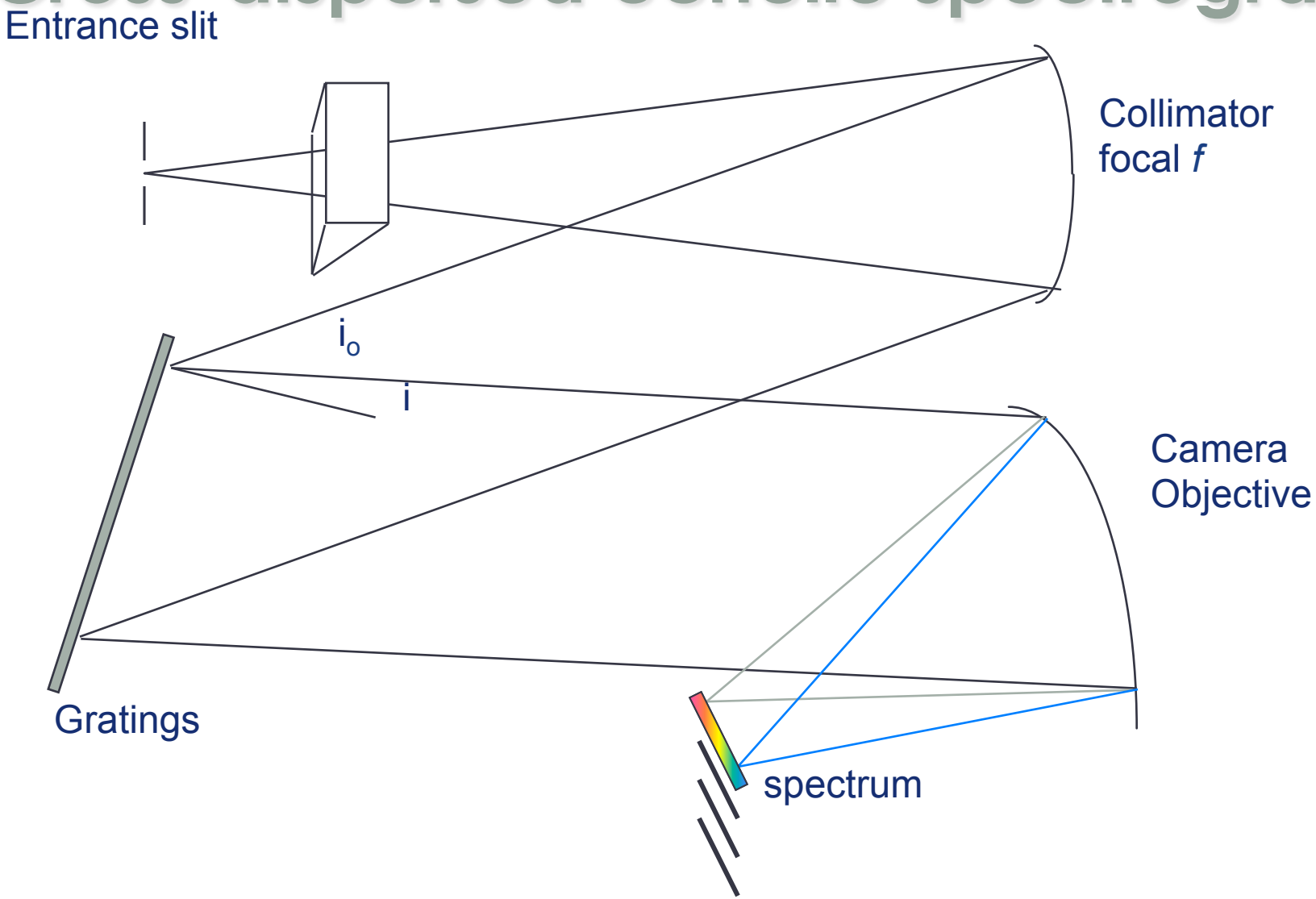
Échelle spectrograph



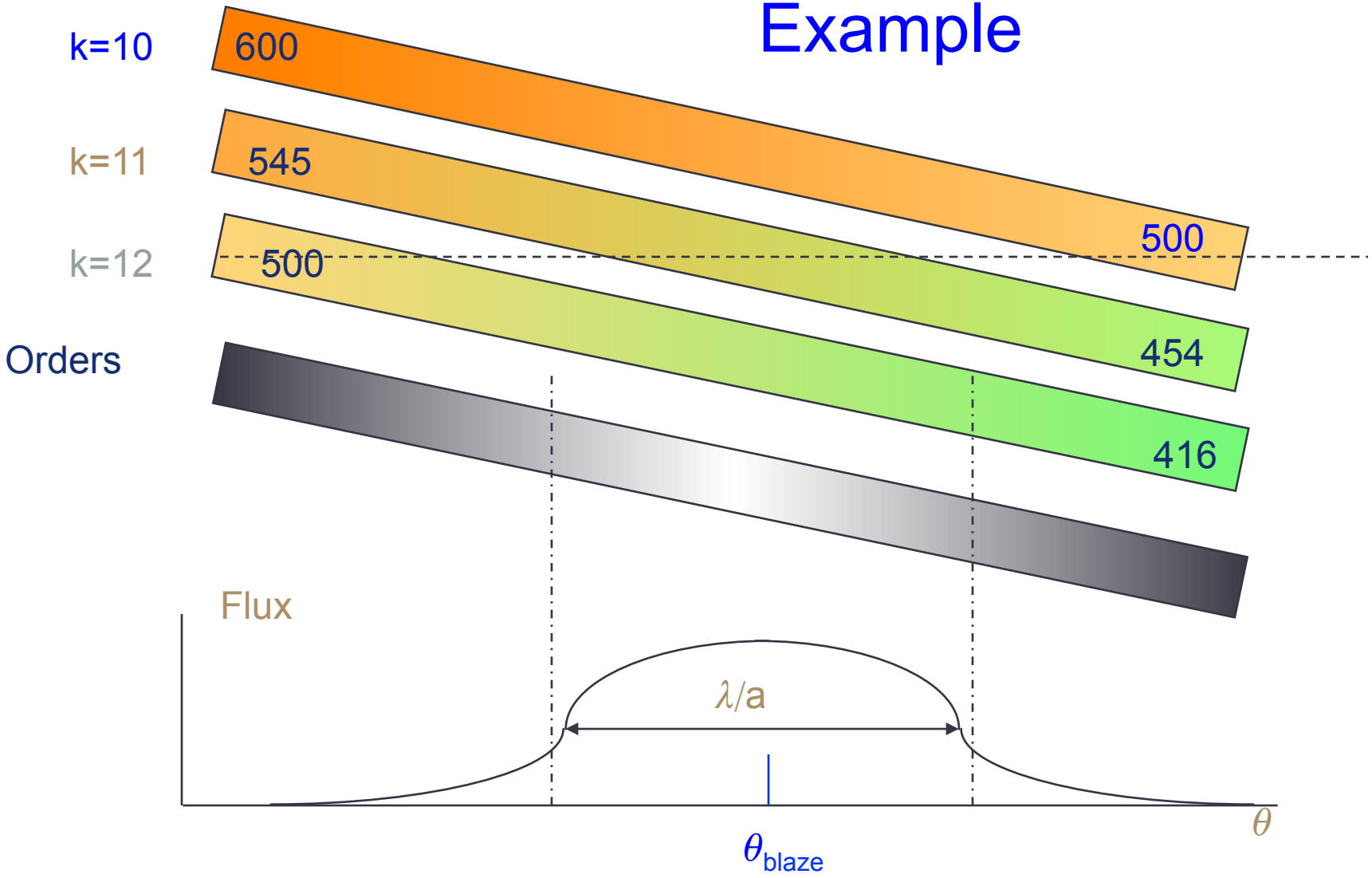


Blazed gratings: reflection = direction of maximum energy

Cross-dispersed échelle spectrograph



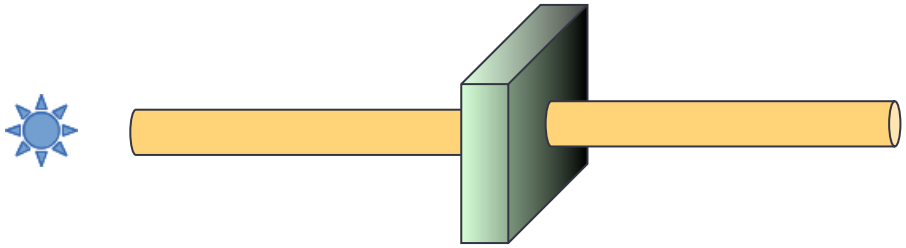
Example



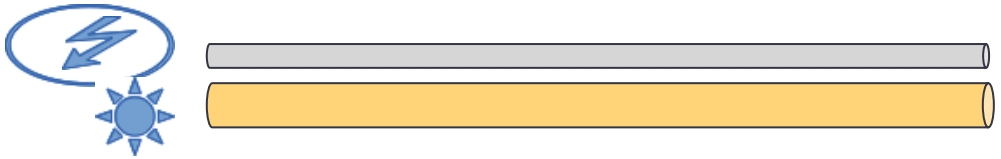
\+ : very broad spectral range on a unique CCD
\- : complex data reduction (tilted spectra, variable resolution..)

Spectral calibration

Iodine cell



Thorium Lamp

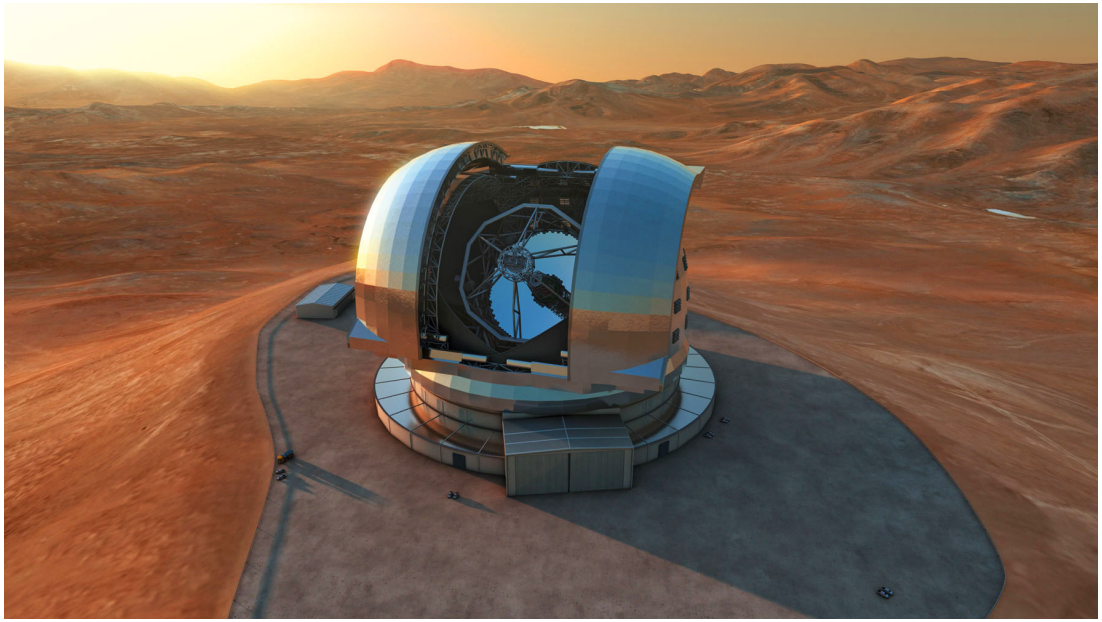


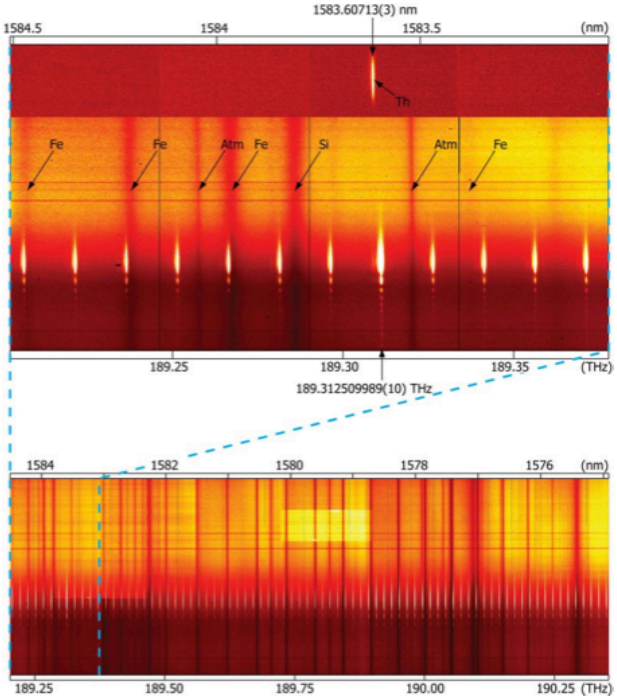
Future instruments

- Better accuracy: frequency combs
- More photons : Extremely Large Telescopes (30 – 40m)

➜

Earth accessible !



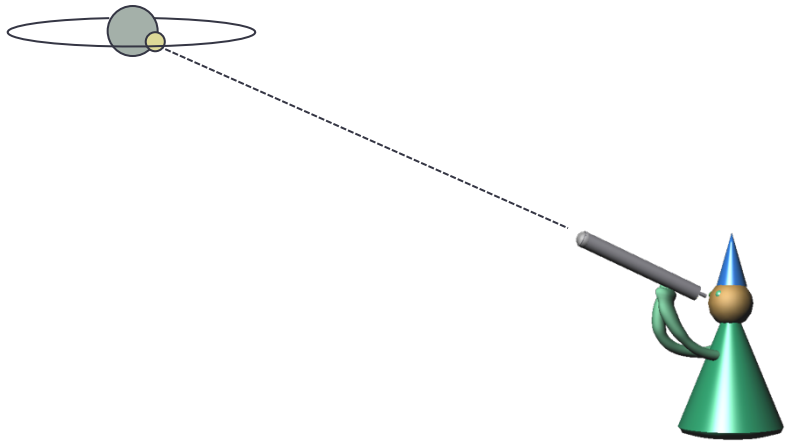


Property 2

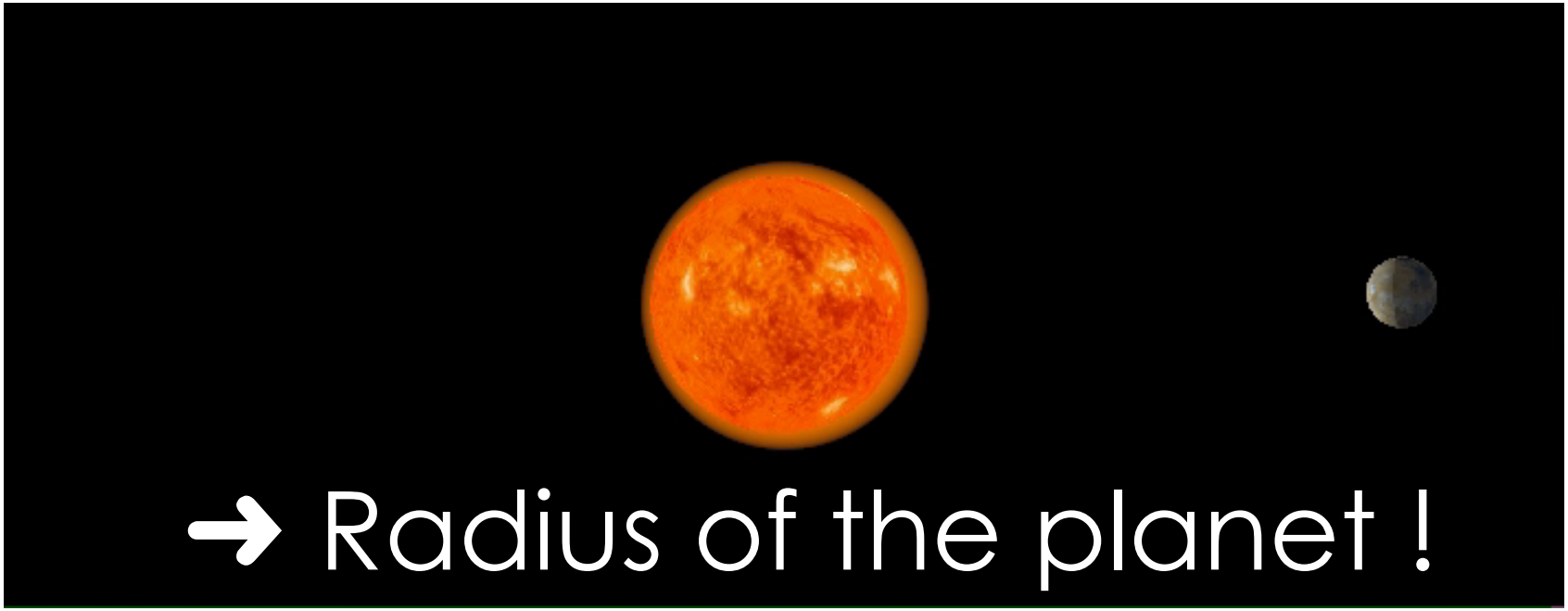
Luminous Intensity

➜

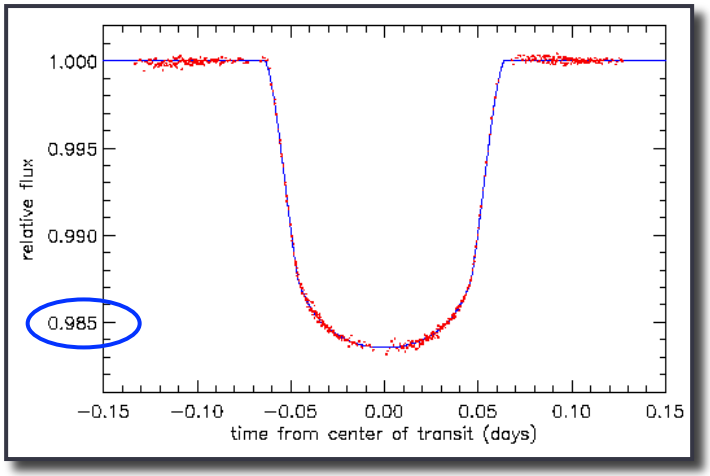
measuring diminutions of brightness during transits



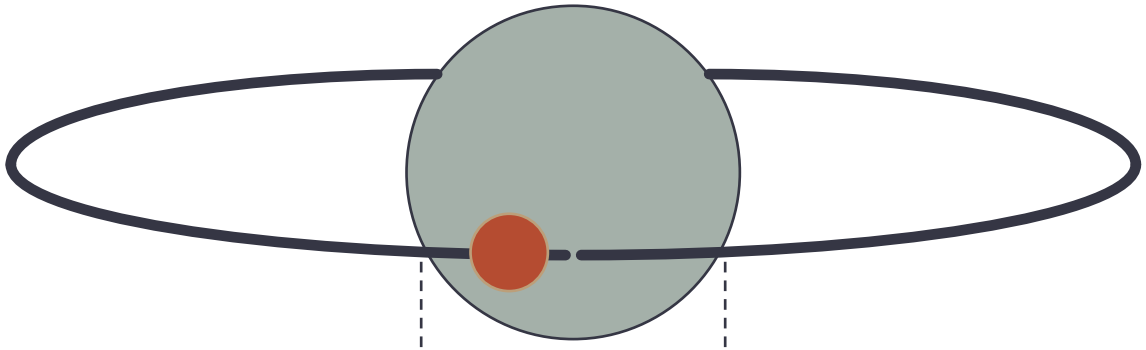
Detection of *transits*



➜ Radius of the planet !

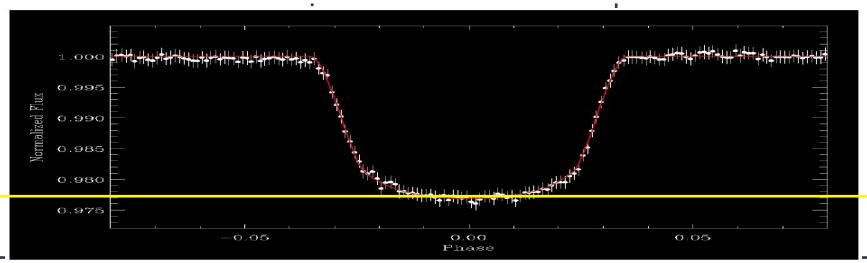


Transit of a planet



ΔF/F

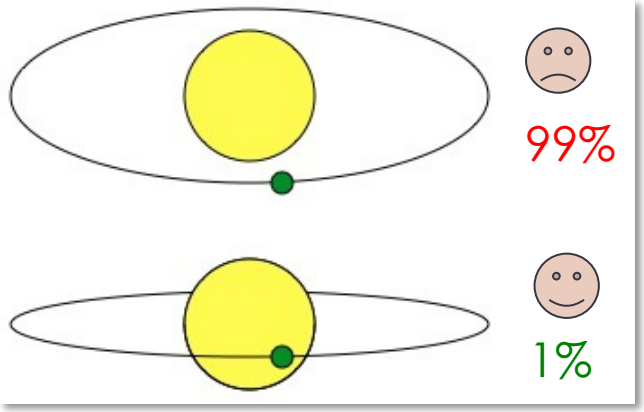
≈ 1 - 30 hrs



0,01 - 3 %

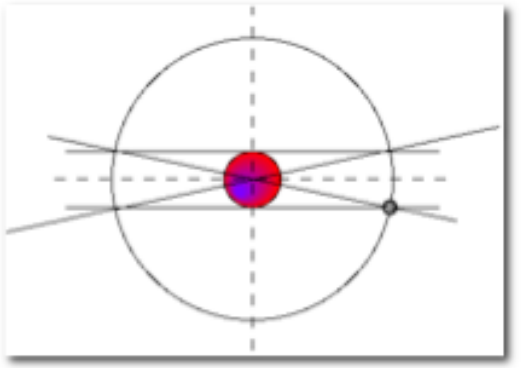
times

Probability



Basic relations

- Probability for an observer to be in the orbital planet's plane :
  Orbit radius = a ; radius of star = R_*
  - $P = W/2p = \sin\theta = R_*/a$

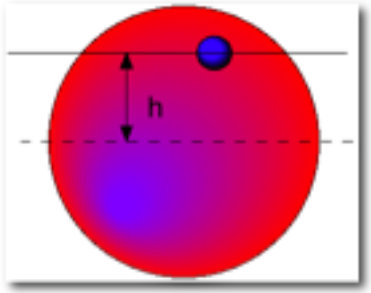


- Transit Duration :

  Orbit and period related by $a^3 = M_* P^2$

  For an impact parameter h

  $t = P\ 2R_* (1-h^2)^{1/2} / (2\pi a)$
  $= 14\ h\ a^{1/2} M_*^{-1/2} R_* (1-h^2)^{1/2}$

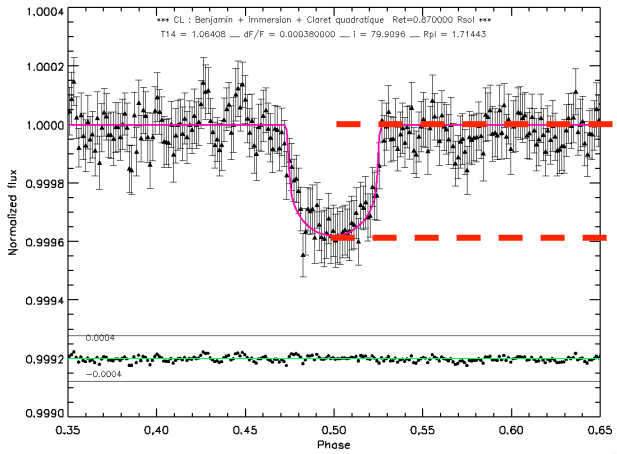


  Ex : Earth : 14h ; Jupiter : 31h ; 51Peg : 3h

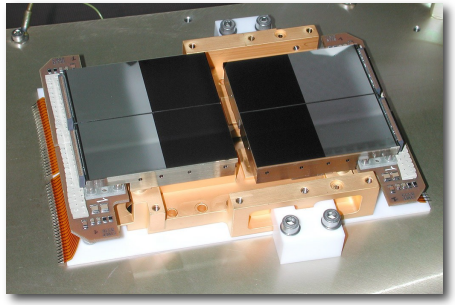
- Number of observed transits : N = Duration of Obs / P : $a^{-3/2}$
- Cumulated Signal : $N\,t \approx a^{-1}$: Favours planets on a tight orbit

The tool: photometric satellite

Corot-7b



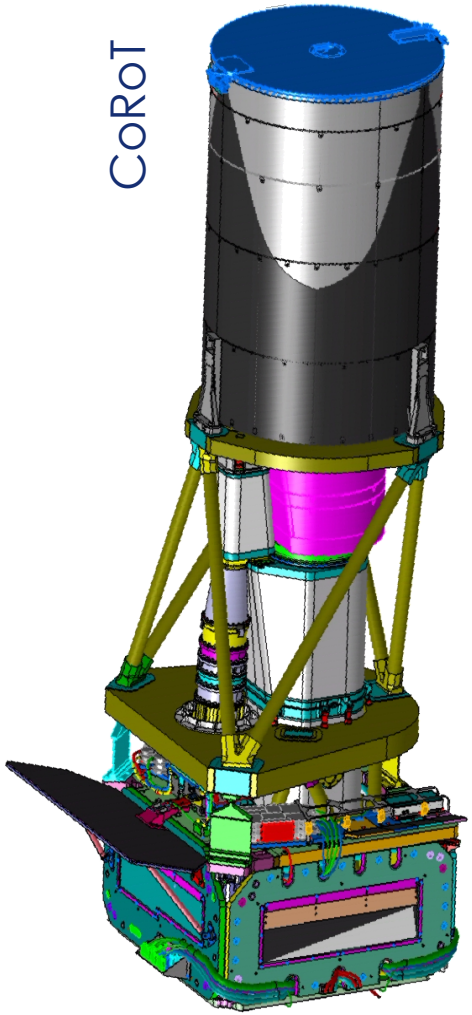
0.035% !



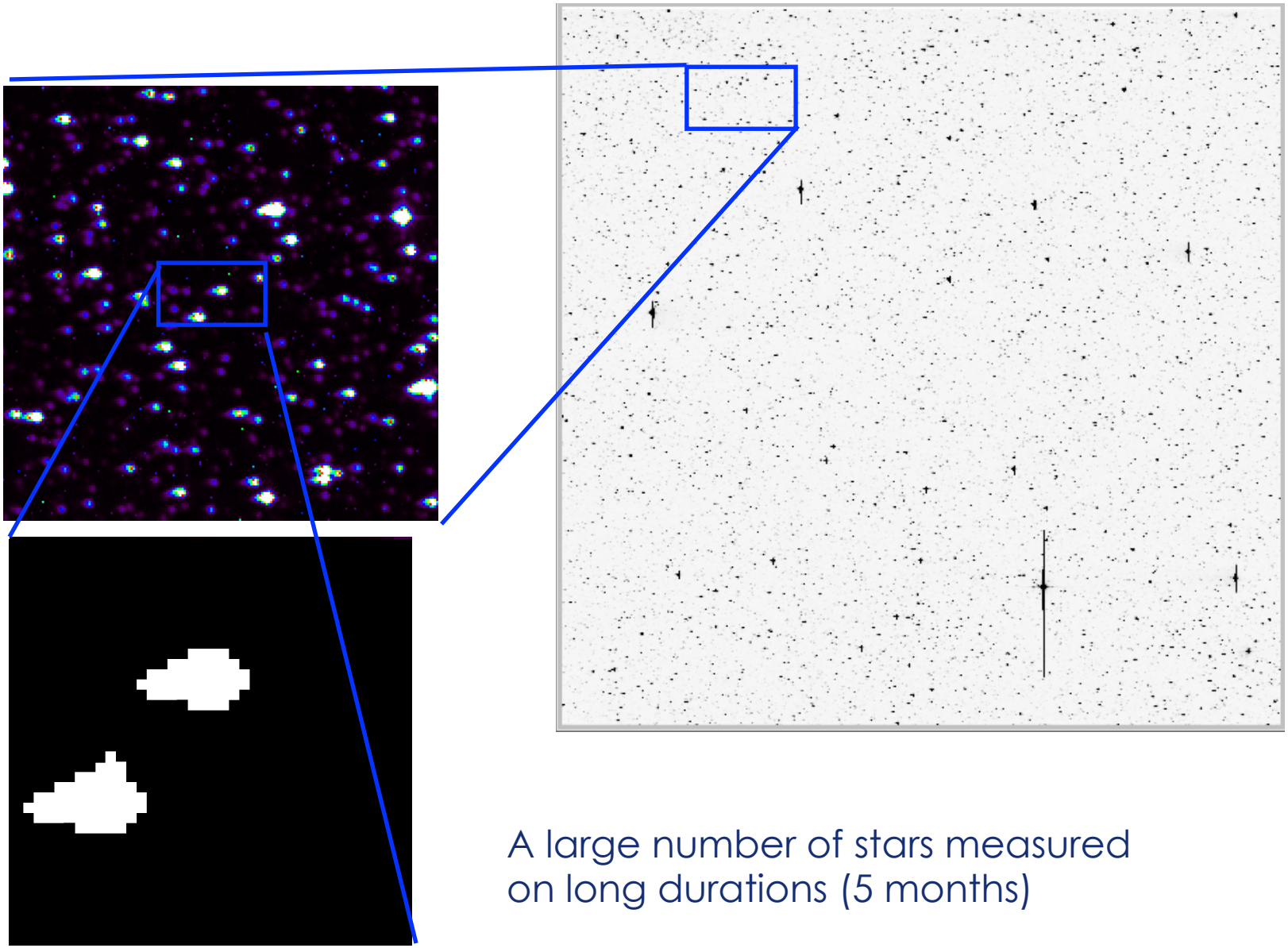
CCD arrays

No atmosphere and control of perturbators ➜ ultra-precise photometry

CoRoT

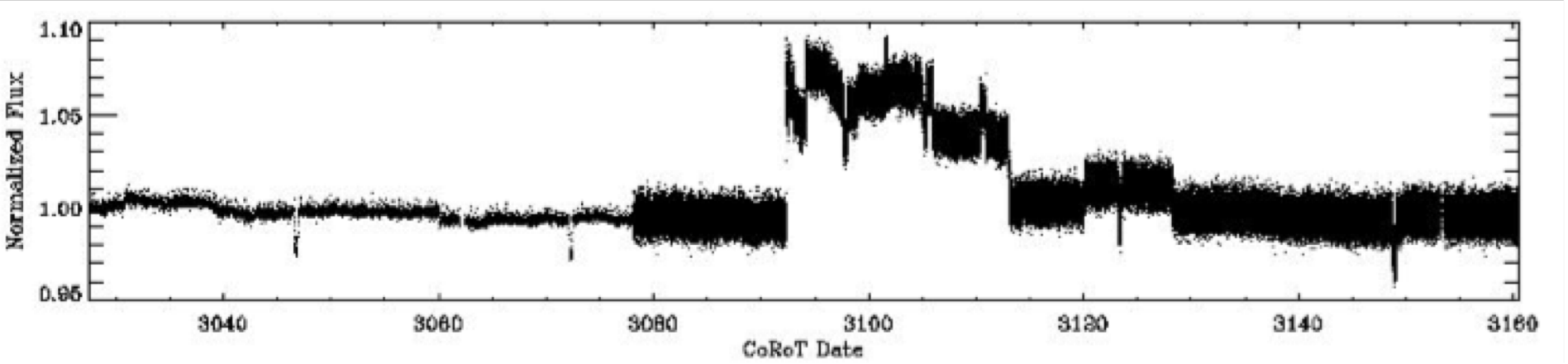


CoRoT Exoplanet field



A large number of stars measured on long durations (5 months)

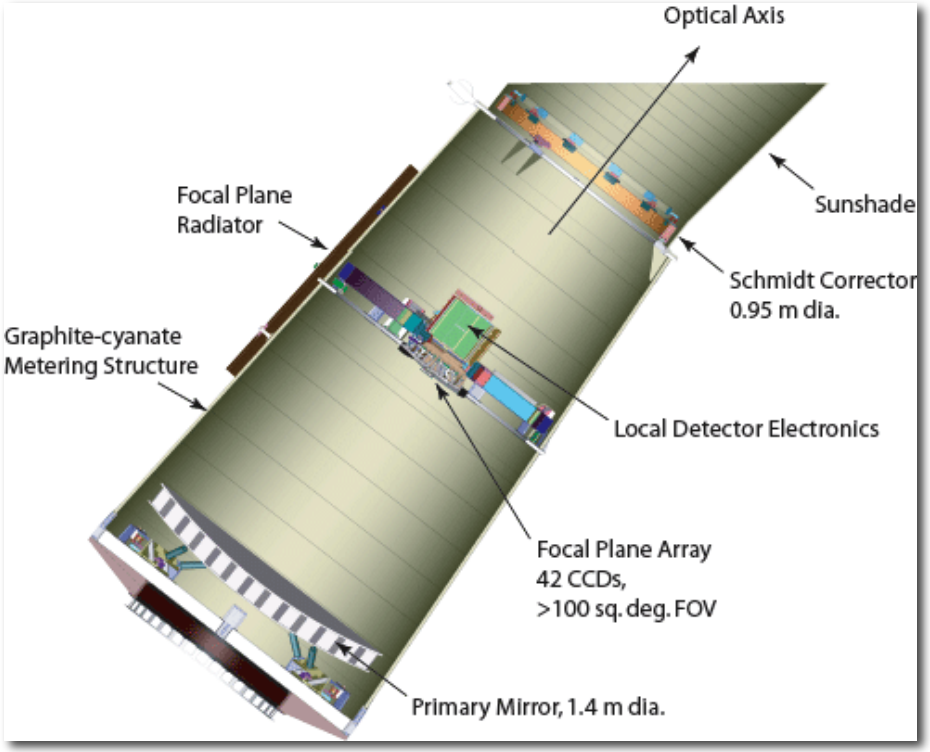
A typical CoRoT Light Curve



KEPLER

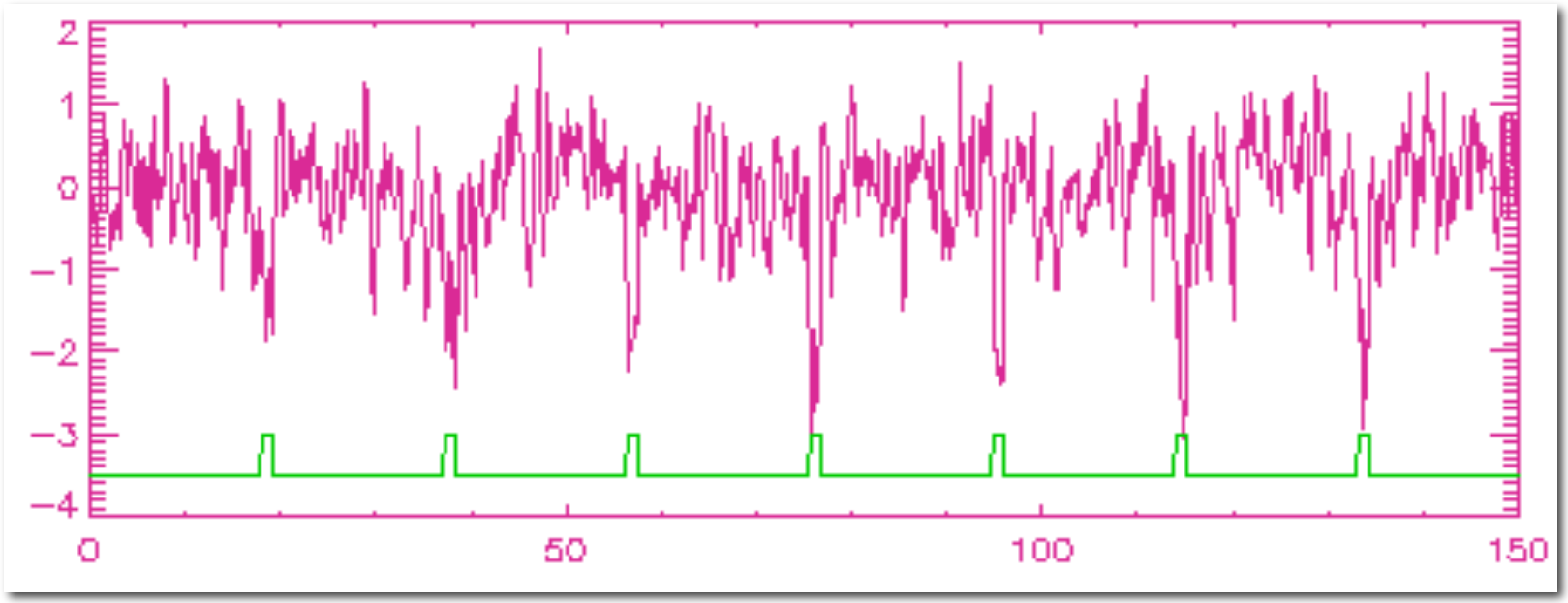
KEPLER : NASA mission

- Same principle as Corot, but
- Larger telescope,
- wider field,
- longer duration
- a unique field
- search for earths in the *habitable zone*



Detection criterion ?

minimum : 3 periodic transits



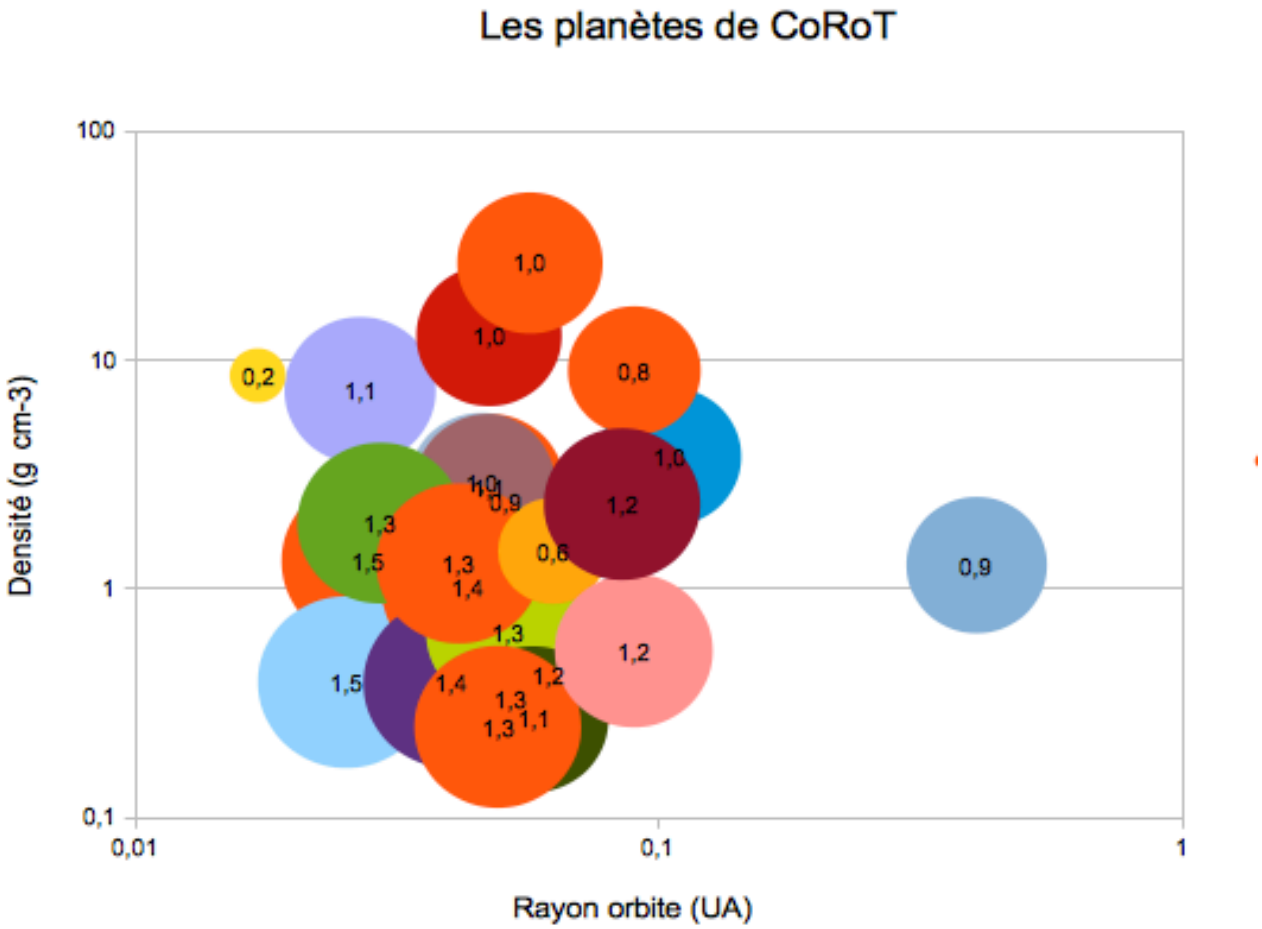
Limit = *photon noise* :

statistical fluctuations of the number of detected photons

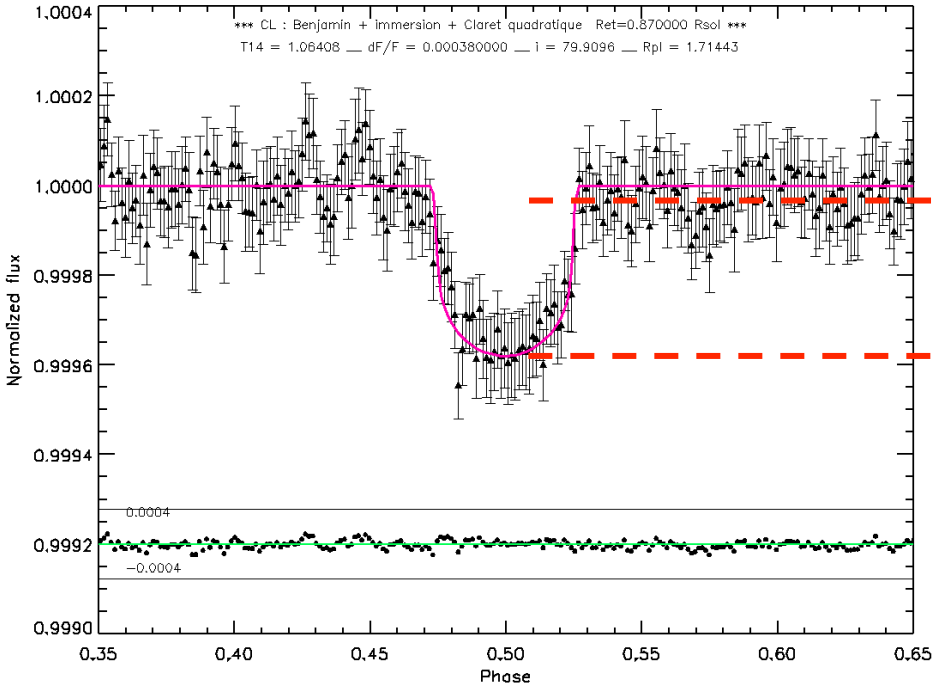
$\delta N_{ph} / N_{ph} = 1/\sqrt{N_{ph}}$ ➜ bright star ➜ *small* planets

The CoRoT planets

- 37 planets discovered
- A **wide variety** among characteristics



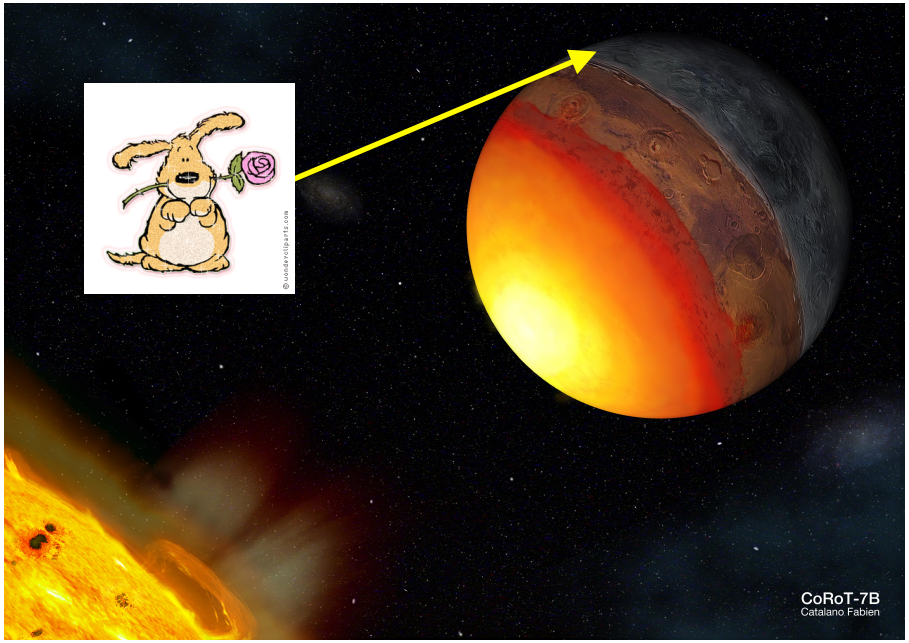
Corot-7b : the first small rocky planet !

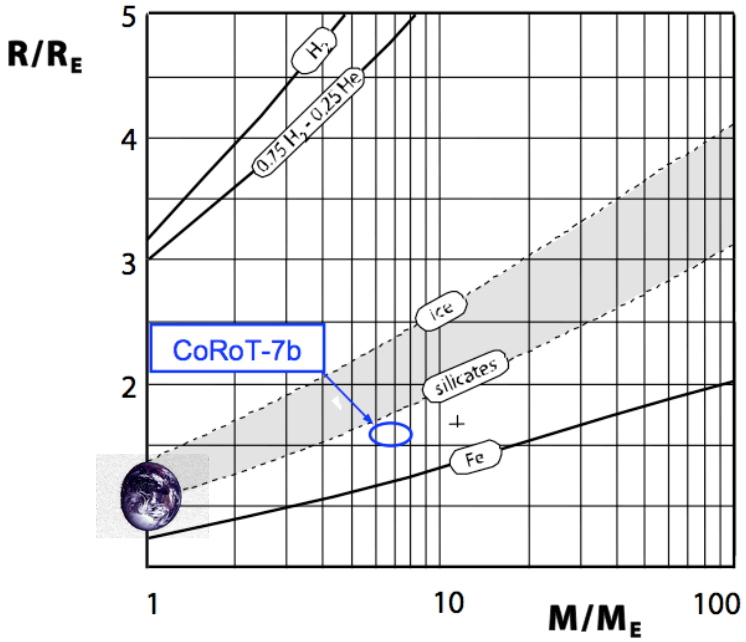


0.035% !

- Radius : 1.7 R_{terre}
- Mass = 7.3 M_{terre}
- A year of 20,5 hours…

Corot-7b: the fire and the ice !

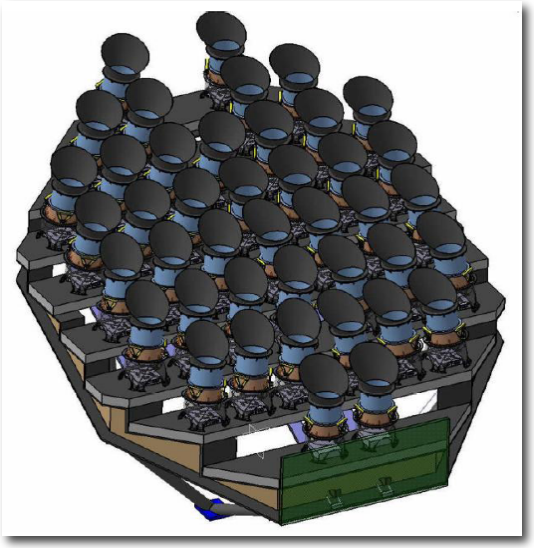




The successor : PLATO

PLATO : decided ESA mission (2023)

- multi-telescope concept to get
- A very wide field monitored: 3600 deg^2
  ➜ bright stars ➜ *earths*
- A large collecting area
  (equivalent to D ~75cm)

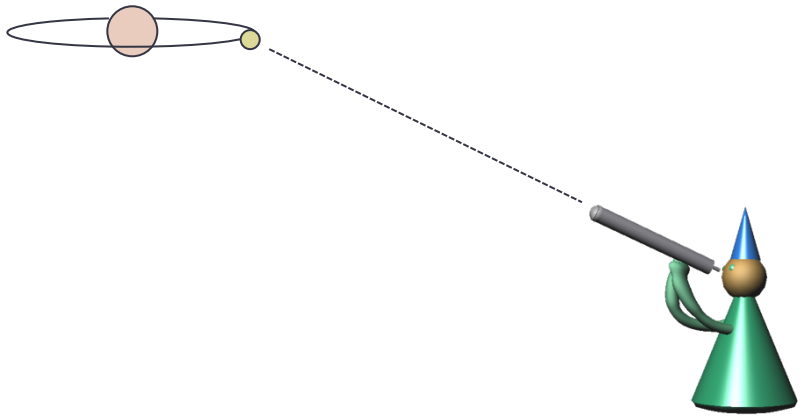


Property 3

Coherence of light

➜

direct detection



Coronagraphy

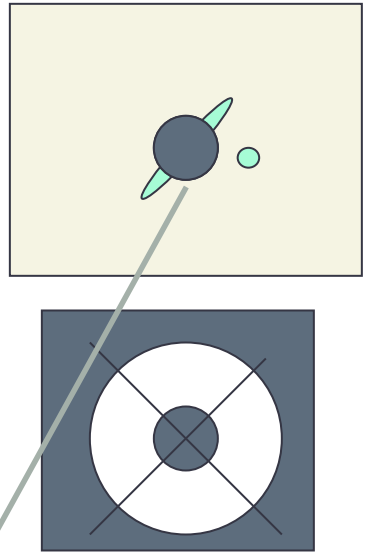
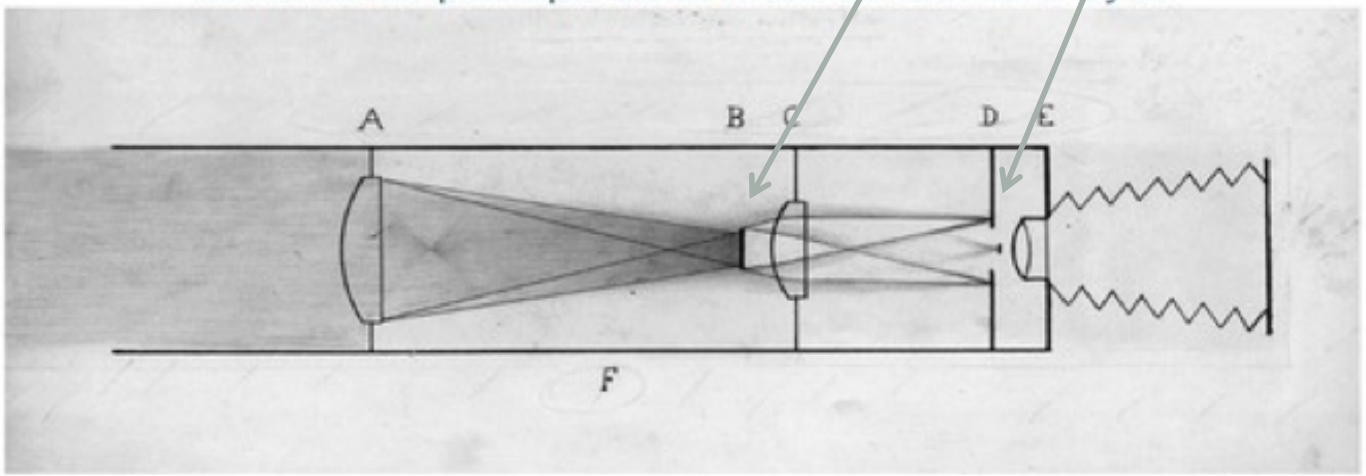
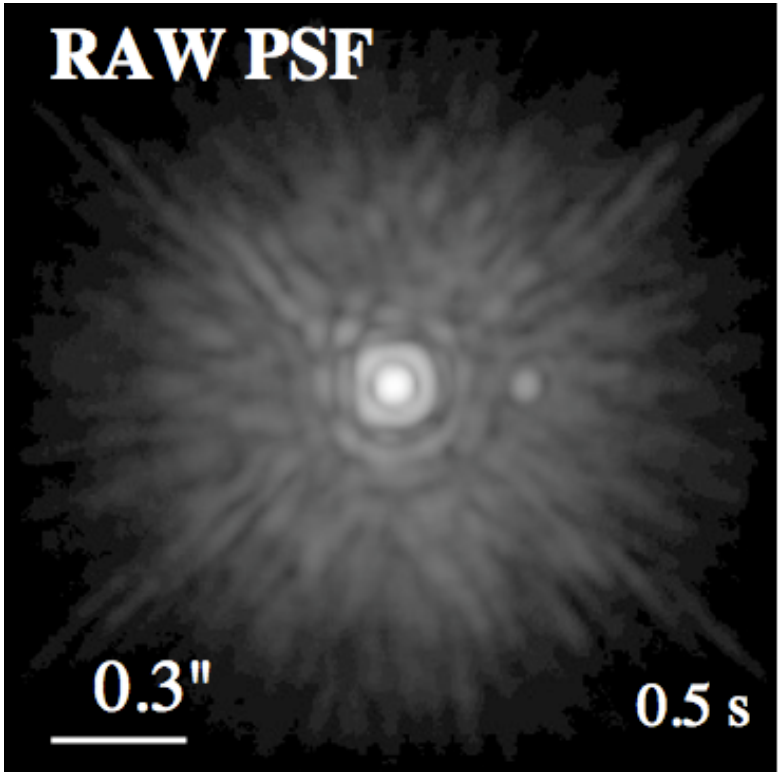


schéma de principe de la main de Bernard Lyot



The ennemy: the speckle !

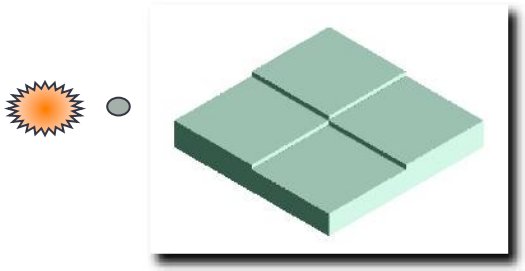
- No wavefront can be perfect ➜ speckles !
- They can easily be confused with a faint planet

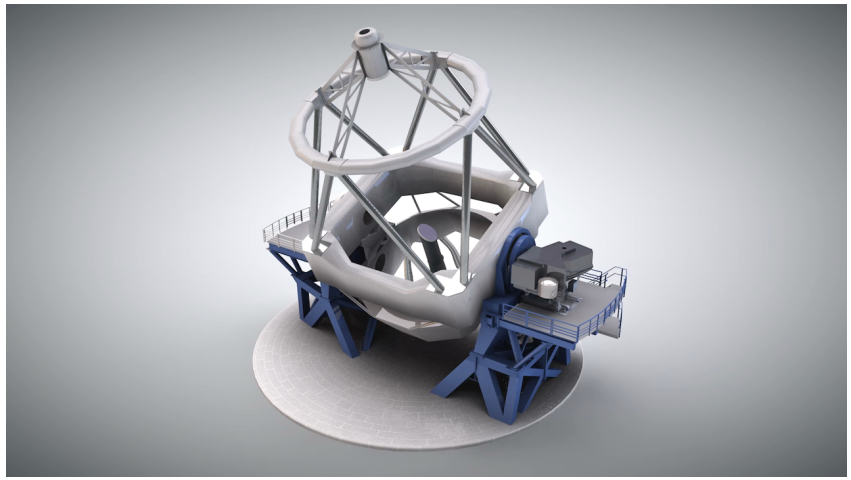


Modern coronagraphy

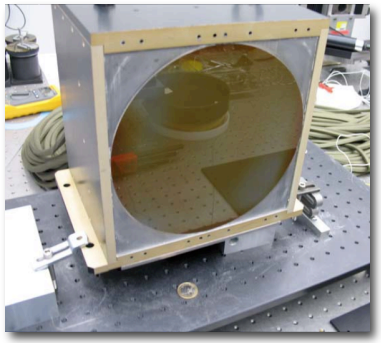
- Optics as perfect as possible:
  corrected by adaptative optics
- Very large telescopes (8m – 40m) :
  excellent resolution $\theta = \lambda /D = 10^{-7}$ rds
- Coherence ➜ destructive interferences
  using a phase mask (transparent)
- Differential methods (spectral, rotation, reference…)

A transparent mask !



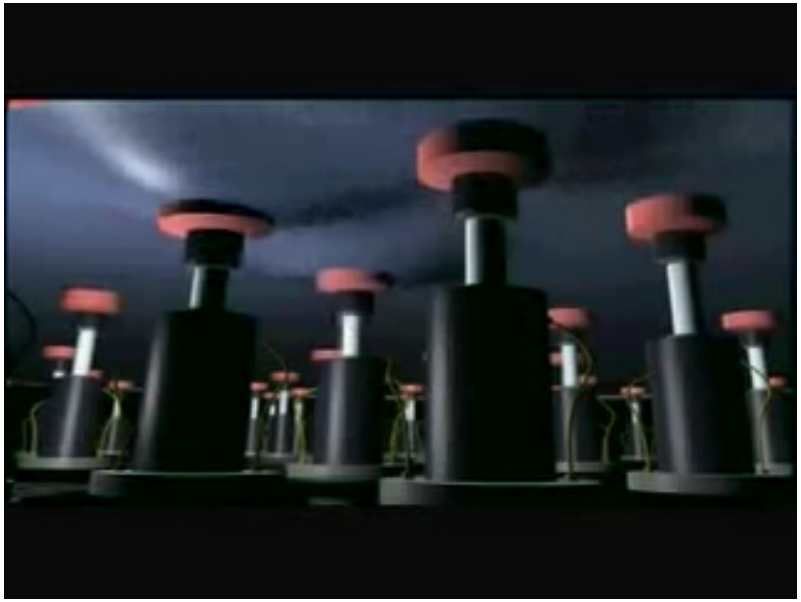


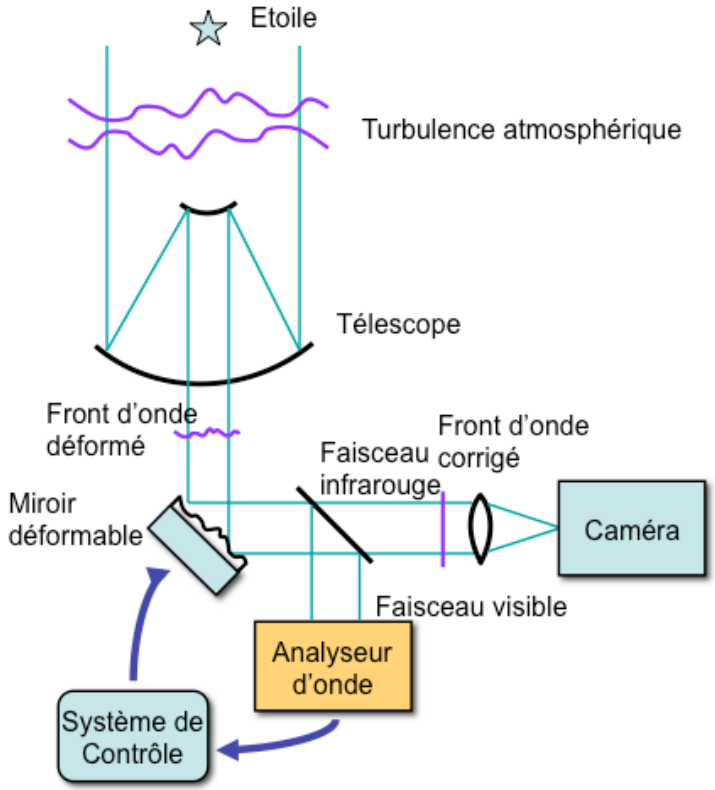
Adaptive optics



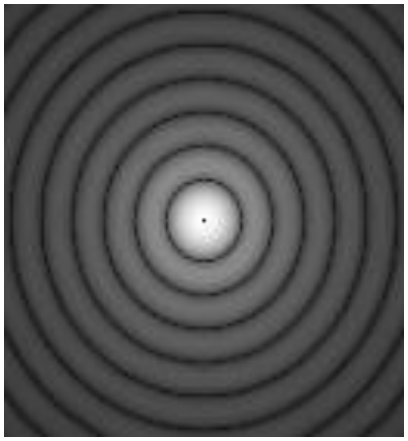
- A loop including a deformable mirror and

a wavefront analyzer to *debump* the wavefront deformed by the atmospheric turbulence

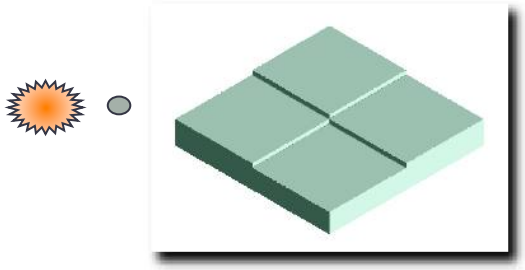


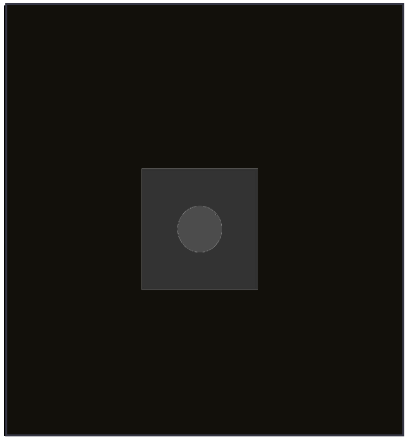


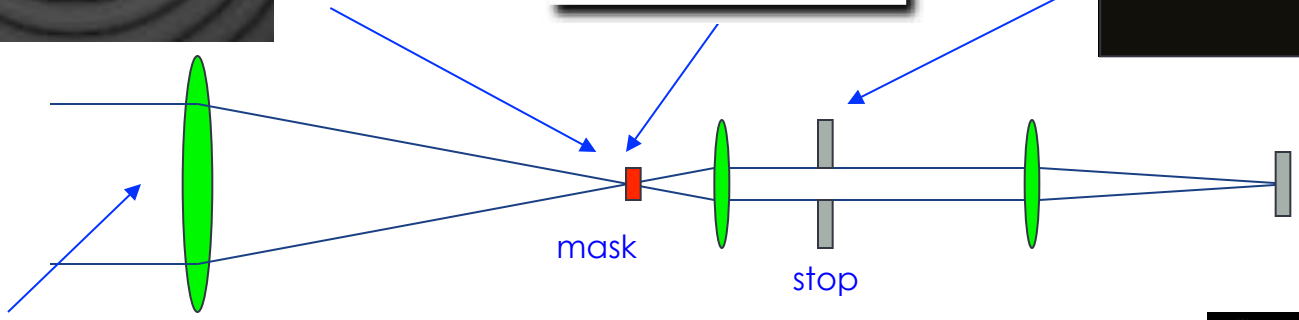
4 Quadrants Phase Mask coronagraph

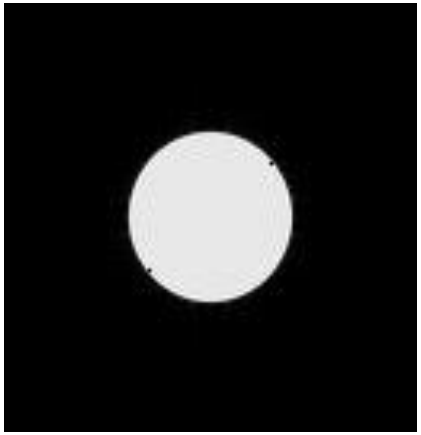


A transparent mask !

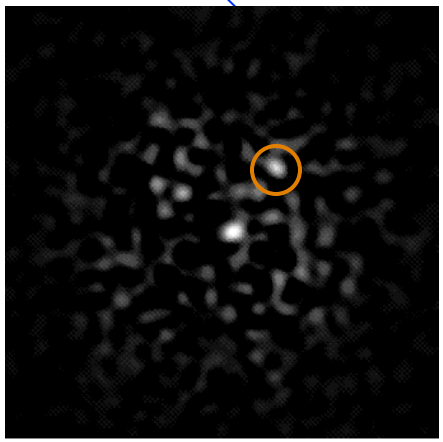




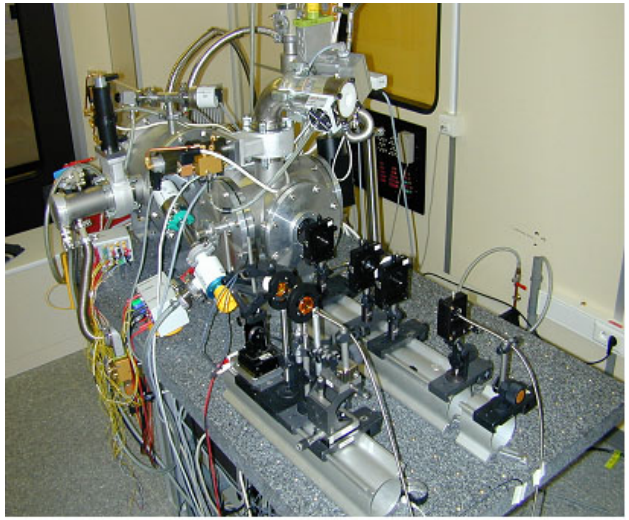


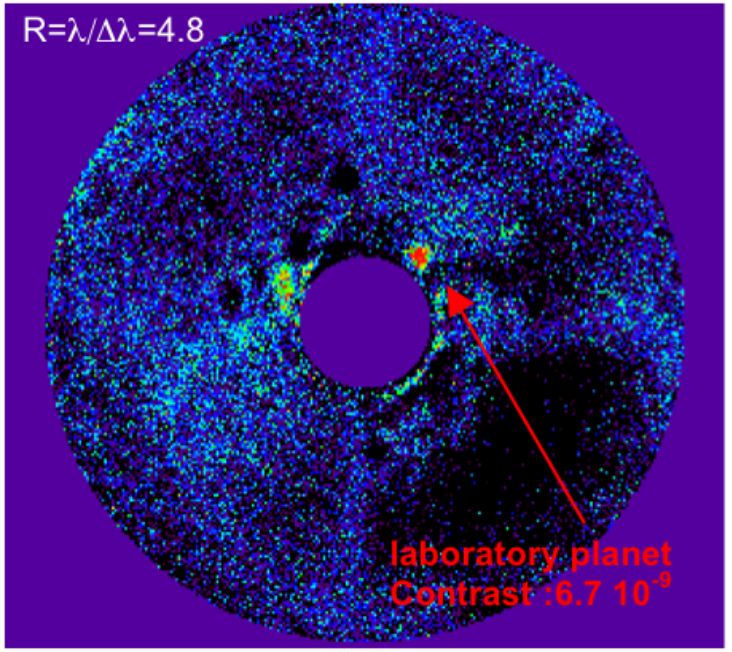


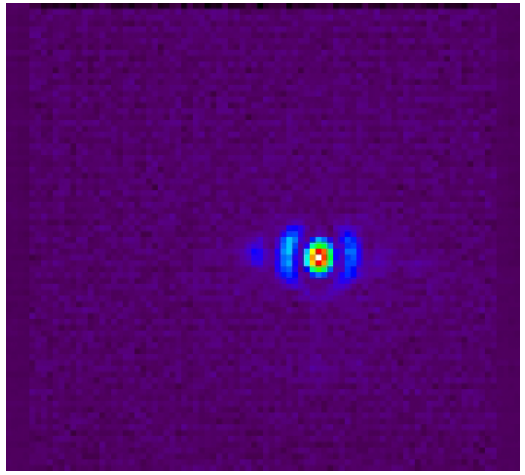
Produces destructive interferences on the star only



Performances

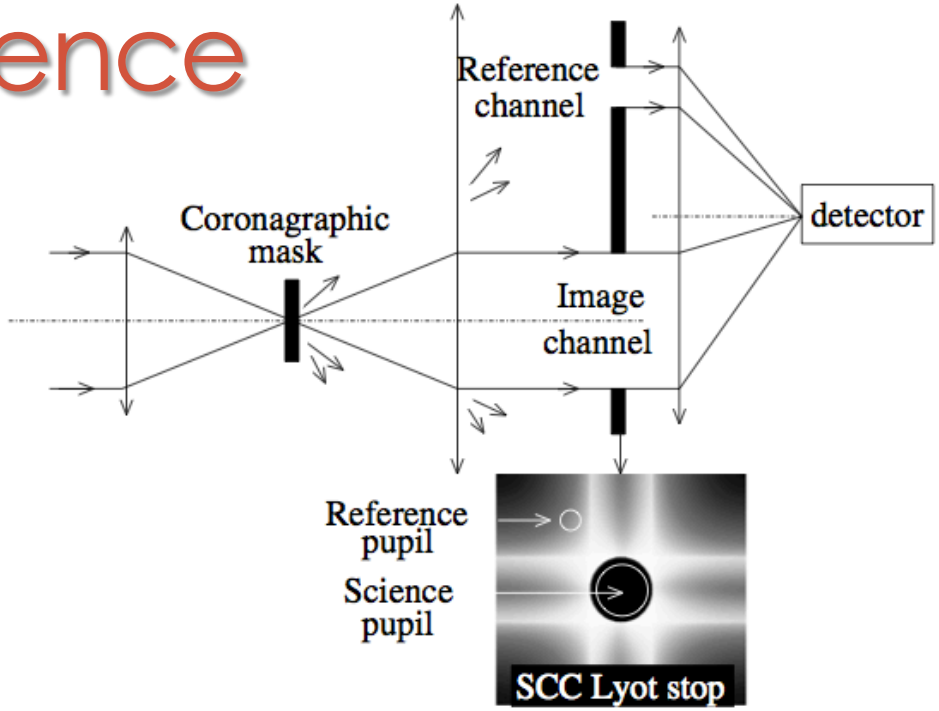


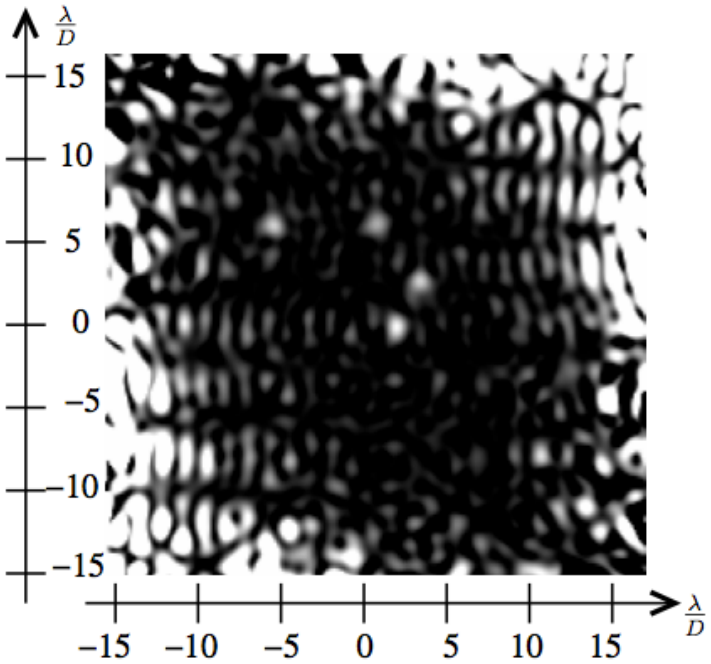


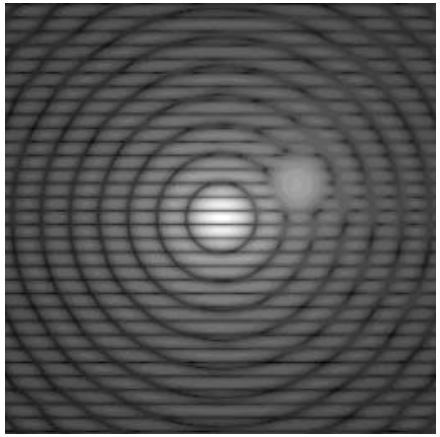


2nd level of coherence

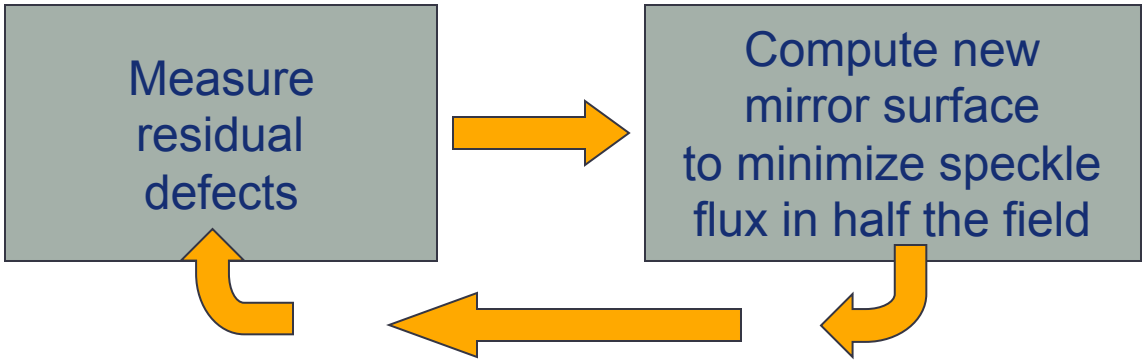
Interferences : the planet has no fringes (non-coherence star/planet)
➜ *self-coherent camera* (P. Baudoz)

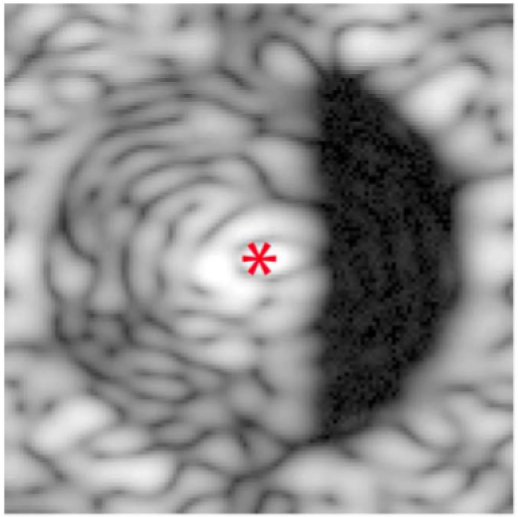


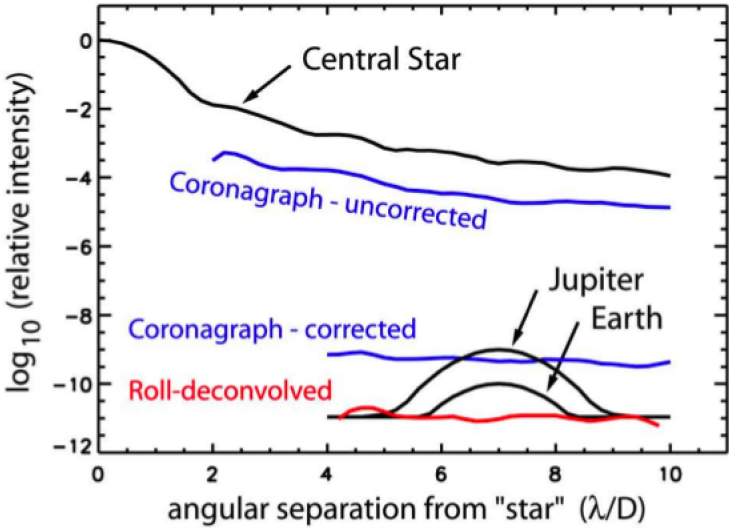




Active control of the wavefront



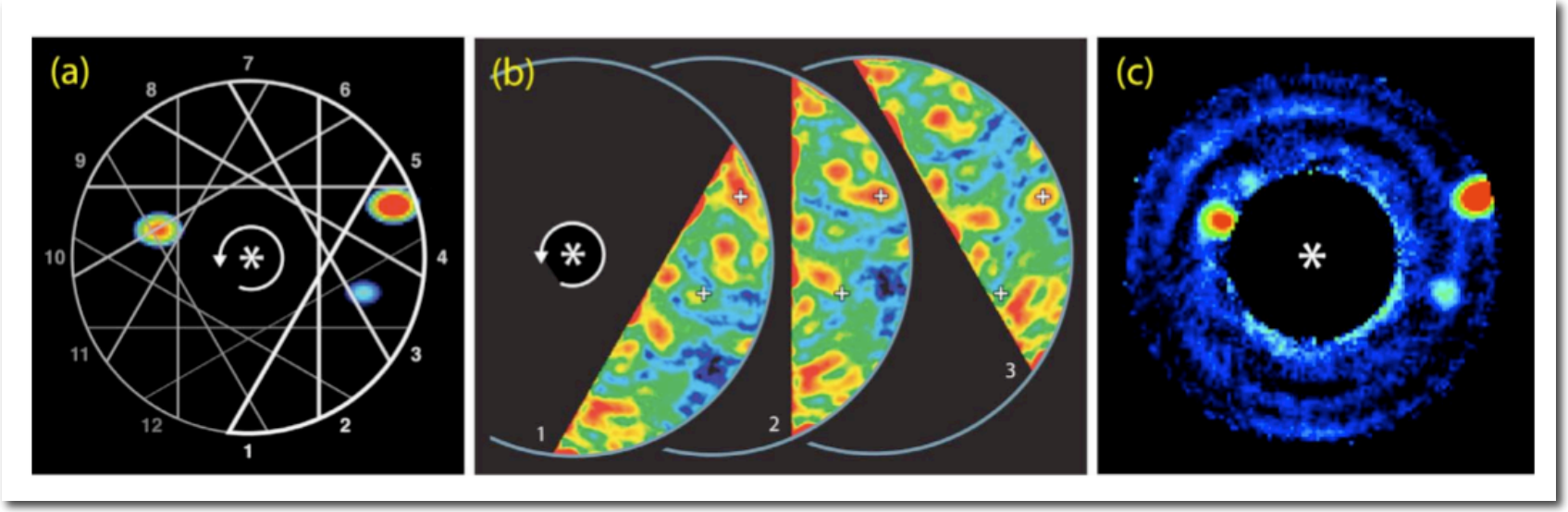




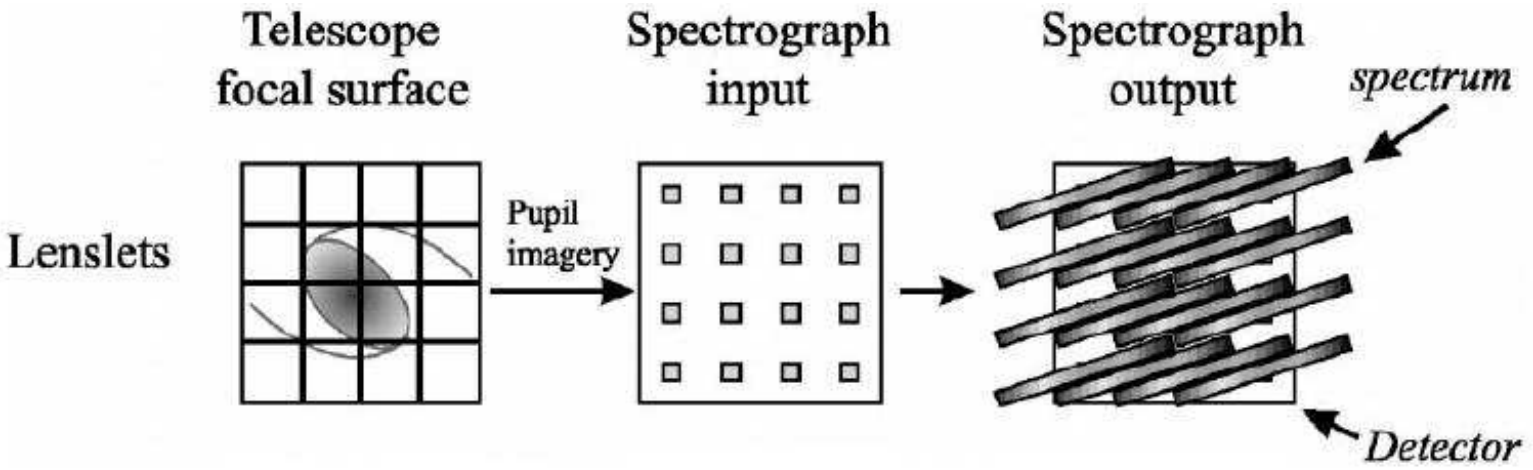
Angular Differential Imaging (ADI)

- *static* speckles bound to optics : they *turn* with it, not the image of the planet

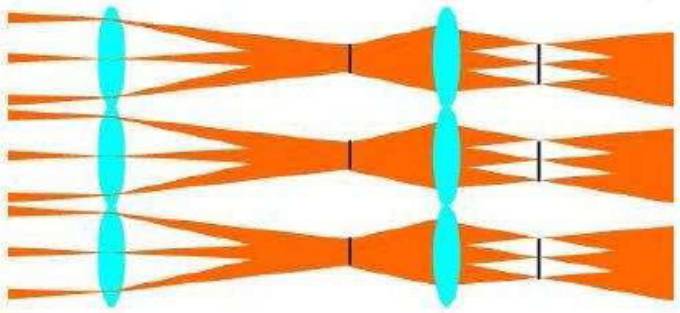
- Several images ➜ smart substraction

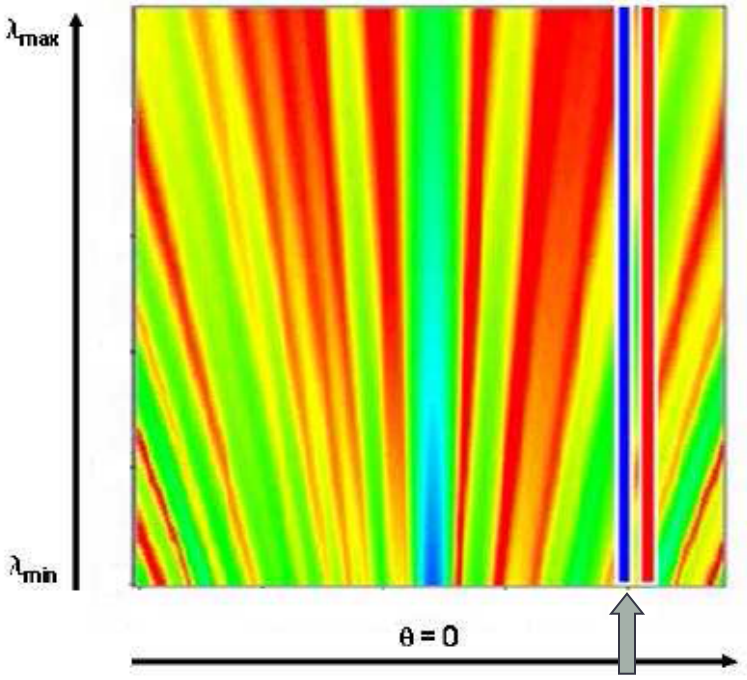


Integral field spectroscopy



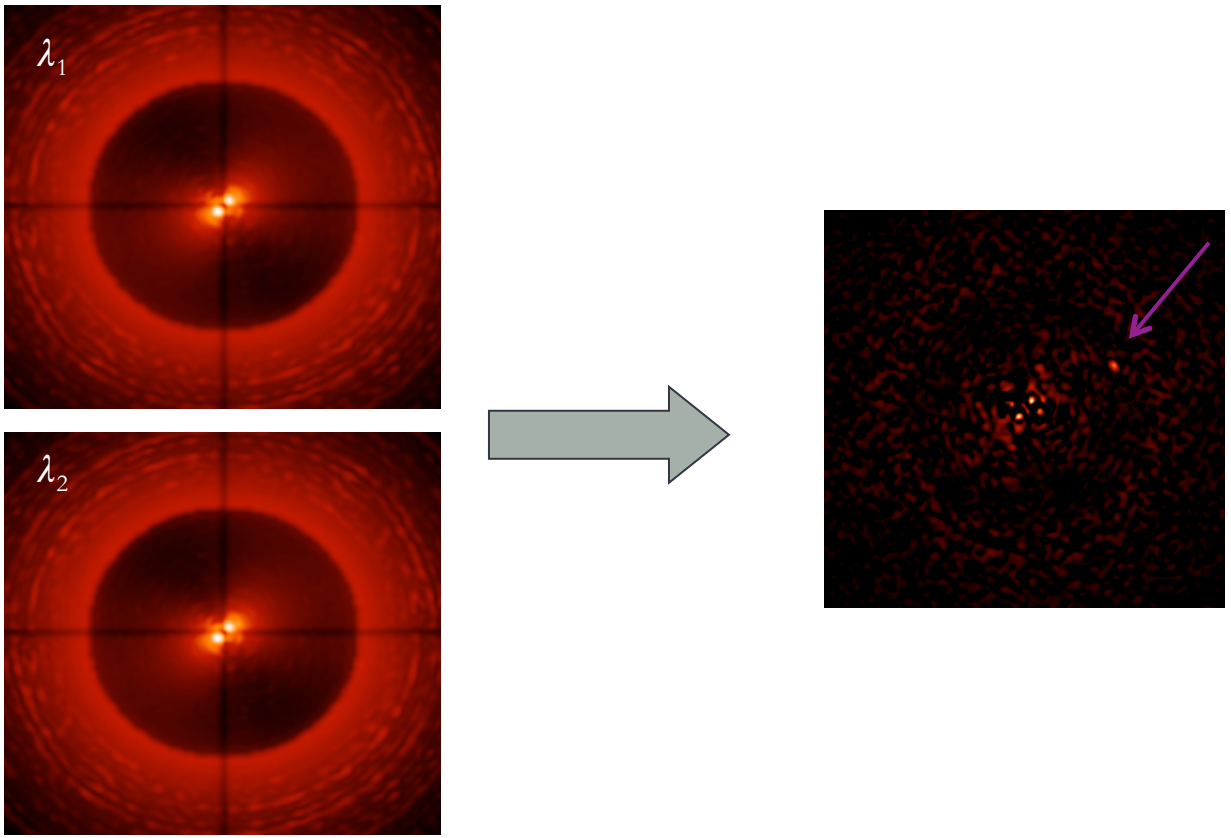
Speckles size/location evolves with λ
Planet image does not





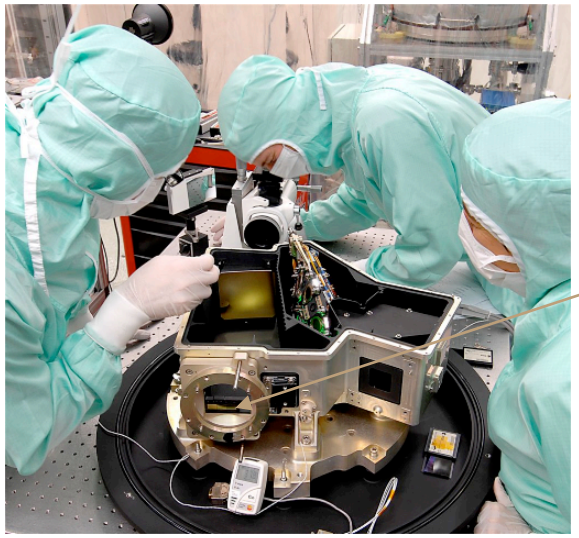
Differential spectral imaging

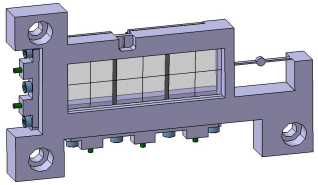
- Make images at two neaby wavelengths, one being proper to a planetary spectral feature (e.g. methane, ammonia lines)
- Rescale the two images to take into account diffraction pattern vs λ
- Substract the two images

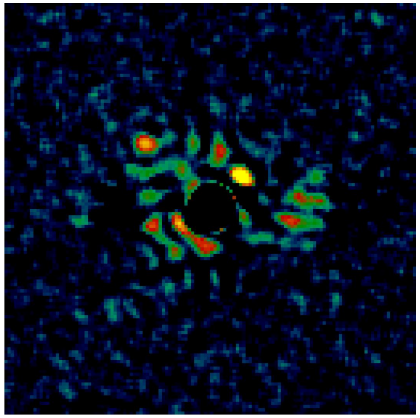


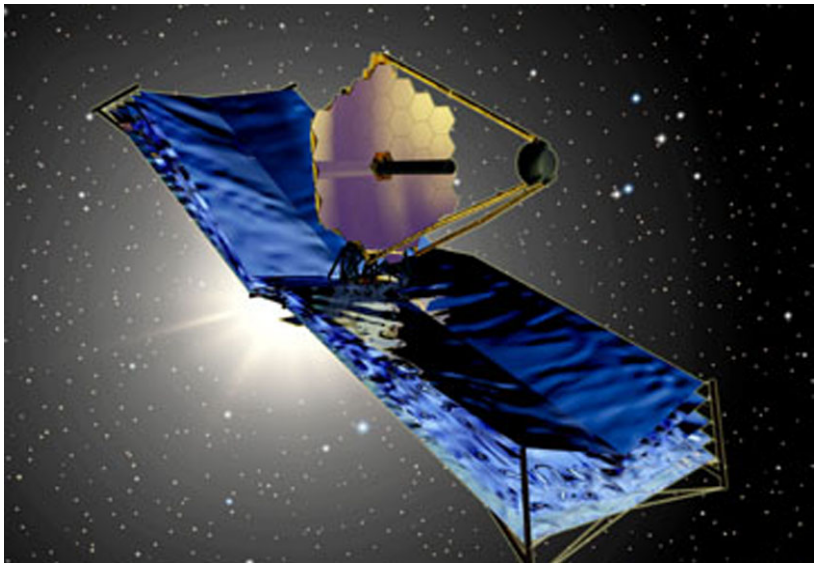
The tool : coronagraphic cameras

In space : european camera ***MIRI*** onboard the J. Webb Space Telescope

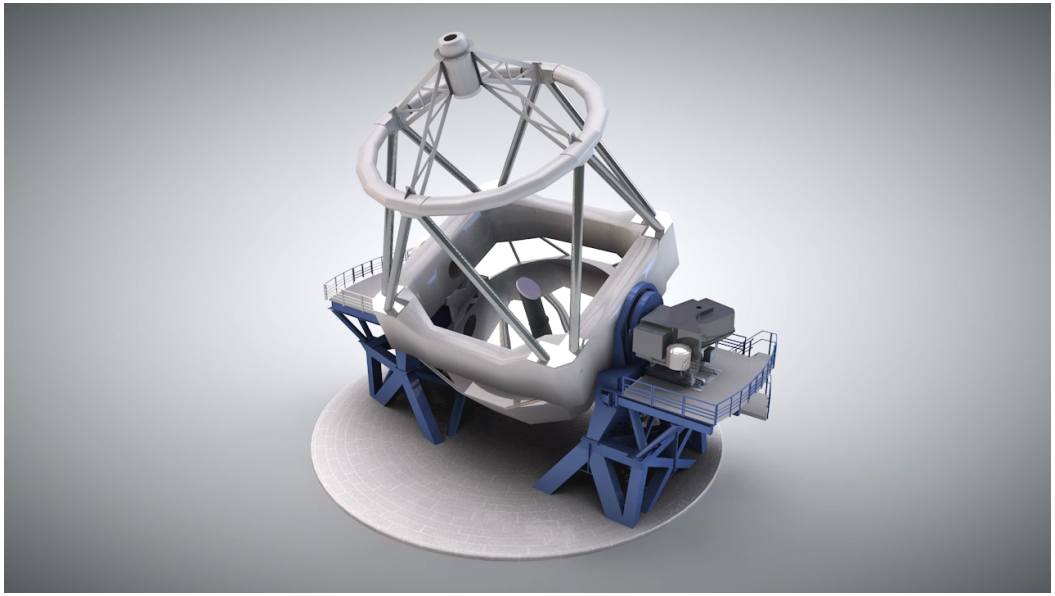


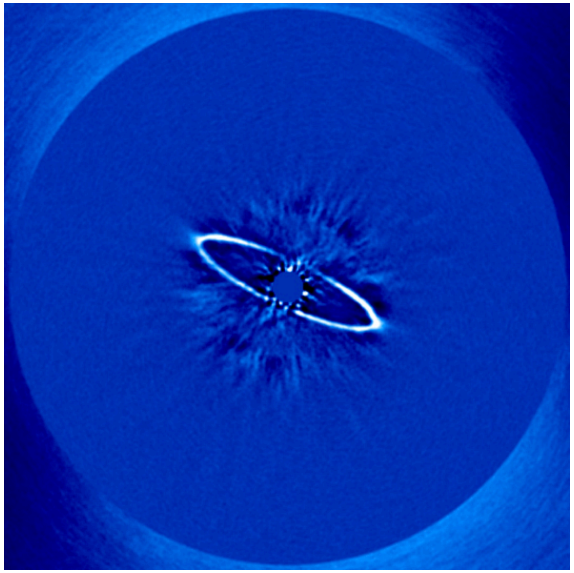




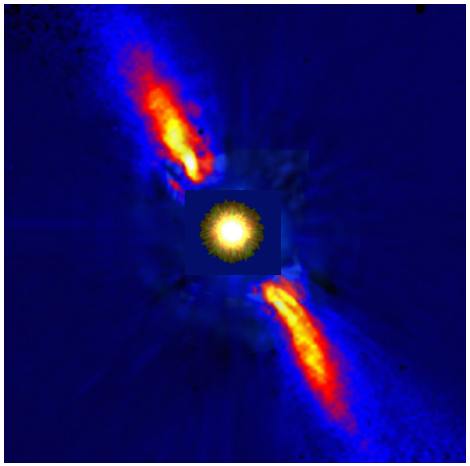


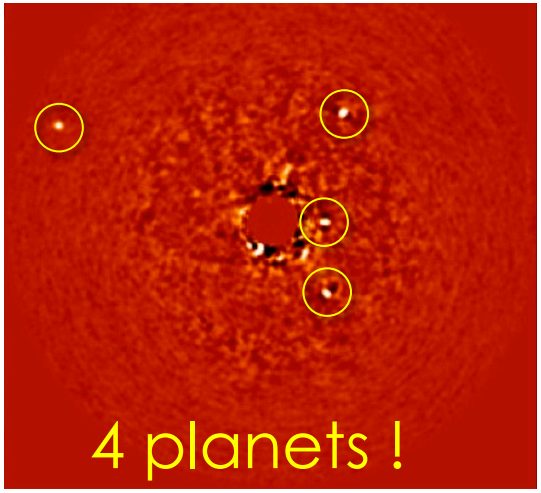
The tool : coronagraphic cameras





On ground: the instrument ***SPHERE*** on the european VLT





The winning team

Optics : off-axis, super-polished

VLT, ELT or Space

Smart achromatic coronagraph

Active control of the wavefront

Several differential techniques

Residuals measured on science image

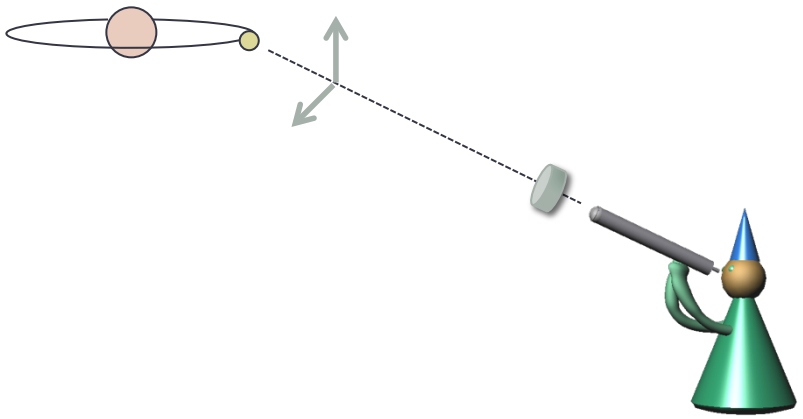
Combine all differential techniques : spectral (monochromatic images or IFS), polarimetric, rotation

Property 4

Polarization of light

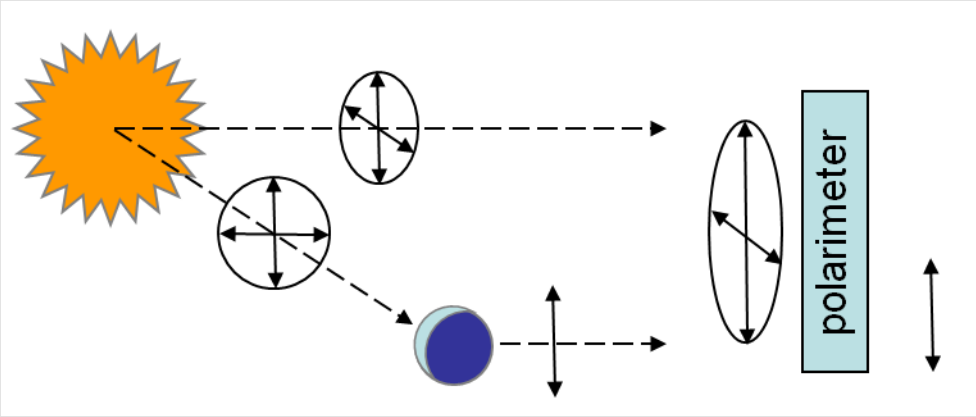
➜

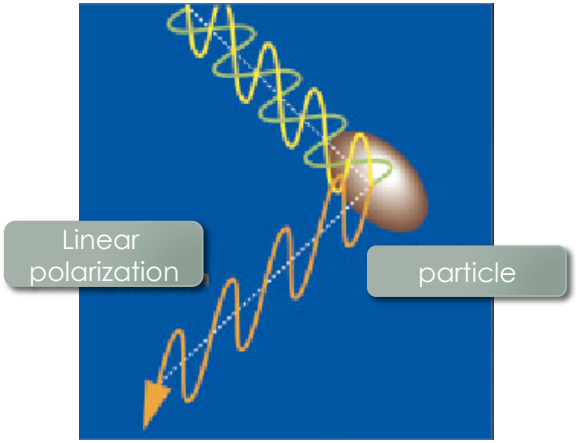
Differential polarimetry



Light from planets is polarized

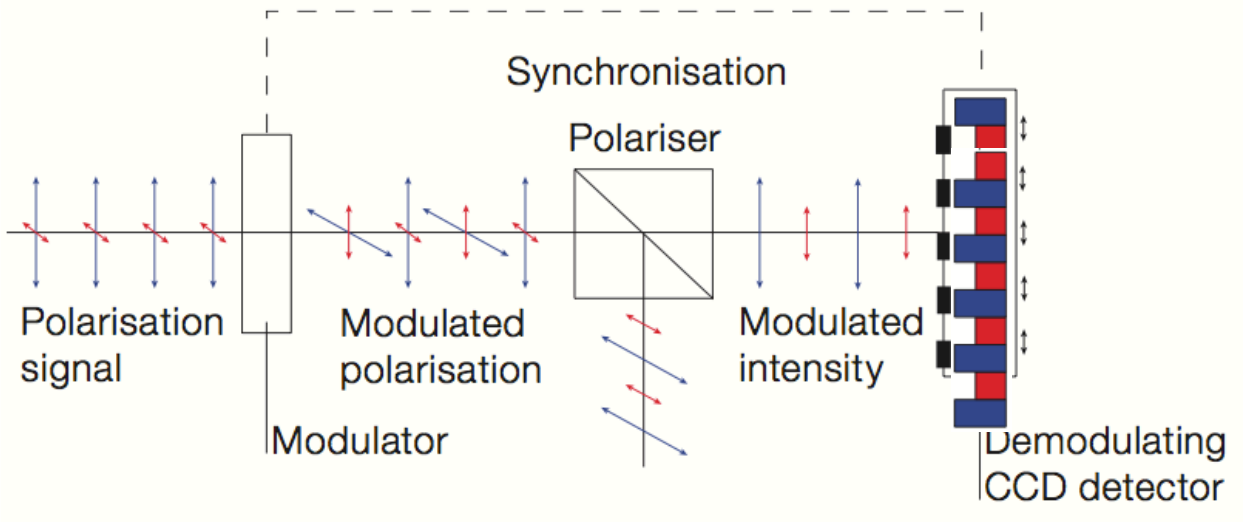
- Starlight is not polarized: P = 0
- Planet light is polarized through scattering: P = 5 - 50 %
- Mixing: $P < 10^{-5}$





An ultra-precise polarimeter

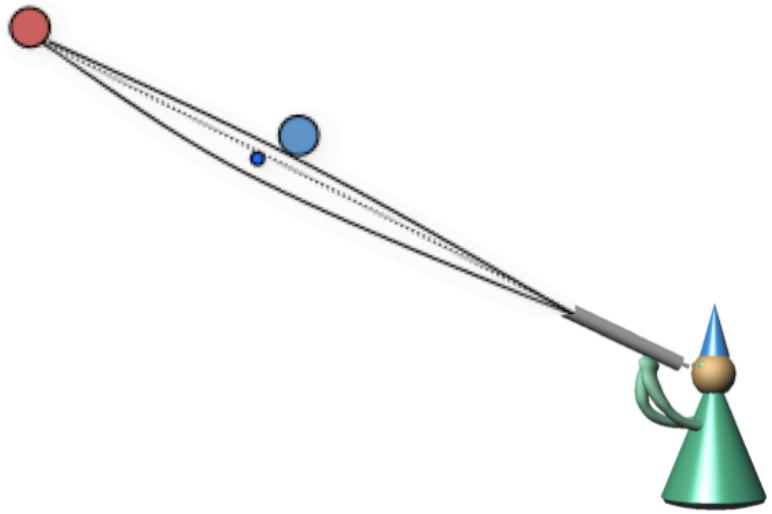
- A CCD array where one pixel over two is blind



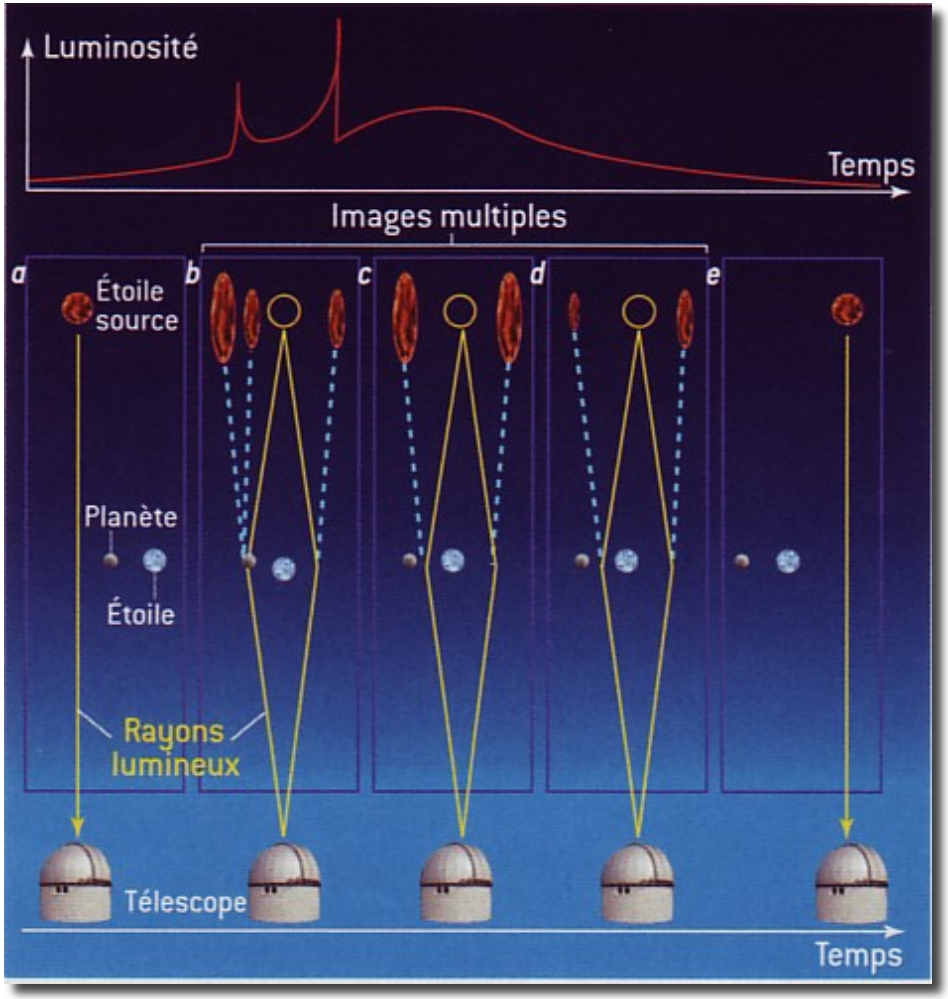
- A fast modulation of polarization, synchronous with *ping-pong* transfer of photo-charges in the CCD
- The ZIMPOL instrument in SPHERE (ETH Zürich)

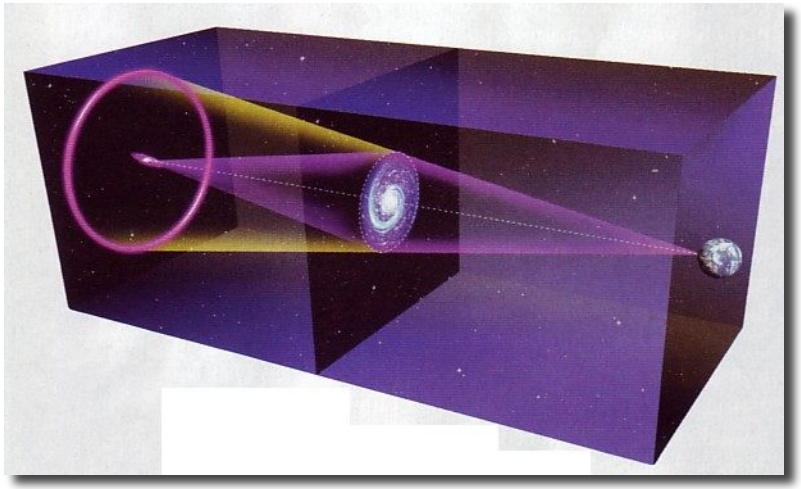
Property 5

Constancy of light speed
➜
Gravitational amplification



Gravitational Lense

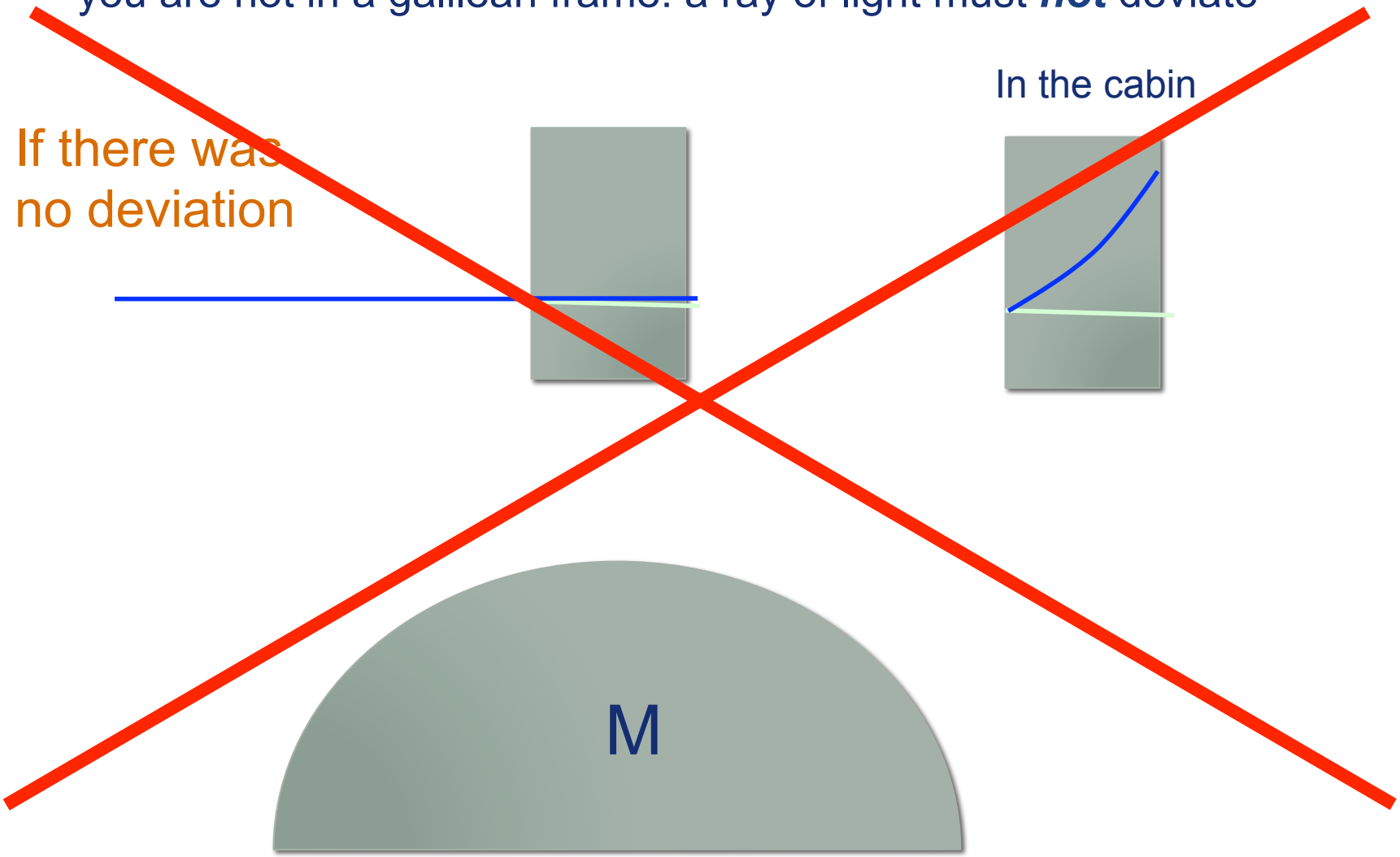




Bending of luminous rays predicted by general relativity (Einstein 1915)

(simplified) bending of light

General relativity ➜ in a free-falling cabin, no way to know that you are not in a galilean frame: a ray of light must ***not*** deviate

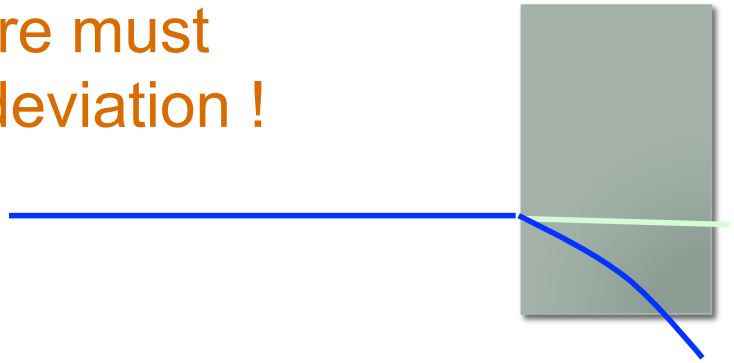


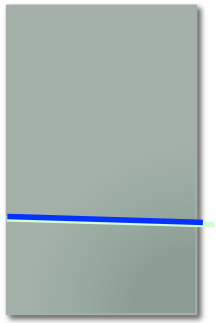
(simplified) bending of light

General relativity ➜ in a free-falling cabin, no way to know that you are not in a galilean frame: a ray of light must ***not*** deviate

In the cabin

There must be deviation !





Gravitational Amplification

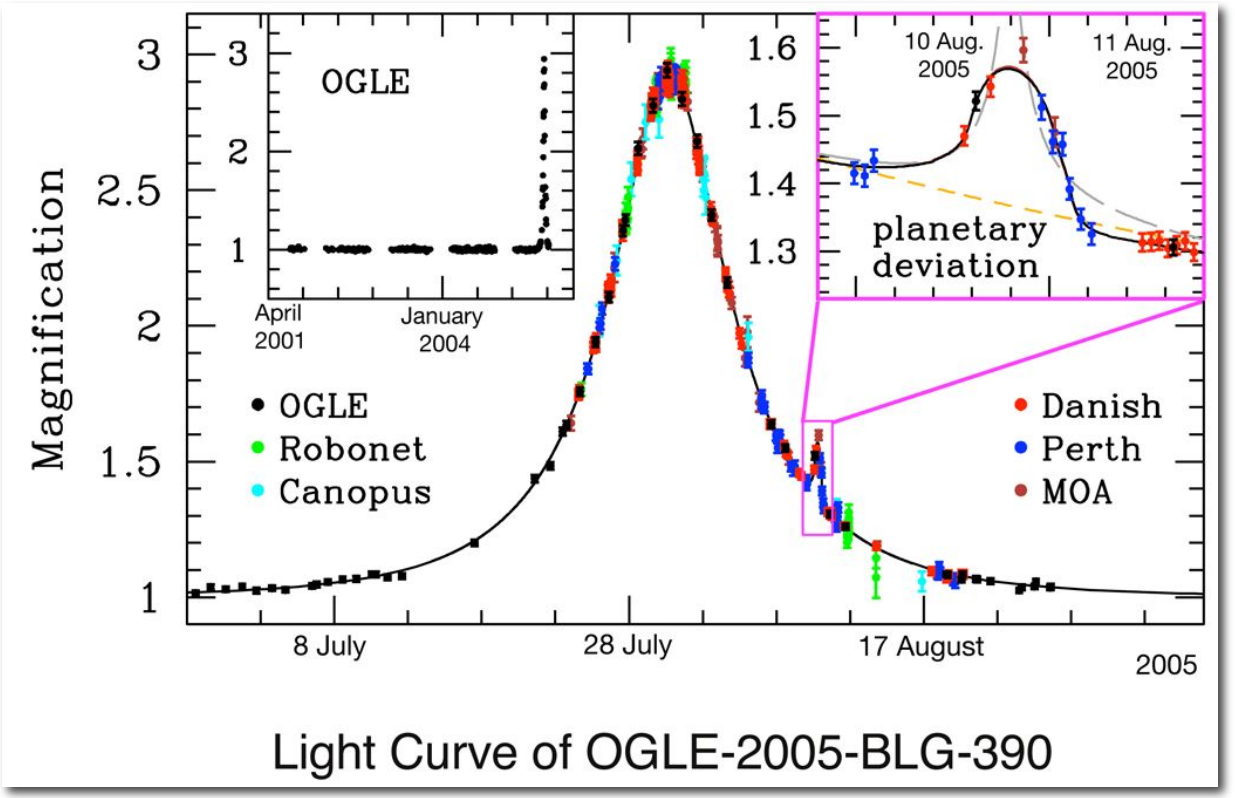
- Bending of light ➜ lensing effect
- One looks for the trace of the gravitational lense: an amplification of light from a distant star when a couple star/ planet (the lense) passes exactly between it and us.

Amplification : $A(t) = (u + 2/u)/(u^2+4)1/2$
With u = projected distance between lense and distant source

Example : u = 1 ➜ A = 1.34 ; u = .1 ➜ A = 10

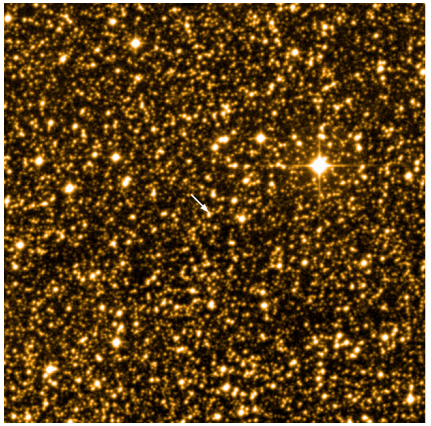
Example

- Star OGLE-2005-BLG-390Lb shows a quasi-certain planetary signature : a very small mass planet:
  - $M_p = 5.5\ M_{earth}$!
  - T = 10 years
  - a = 2.7 AU



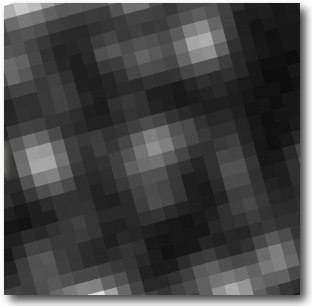
The tool: monitoring of millions of stars

- On ground network of dedicated telescopes

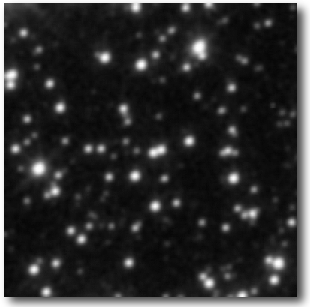


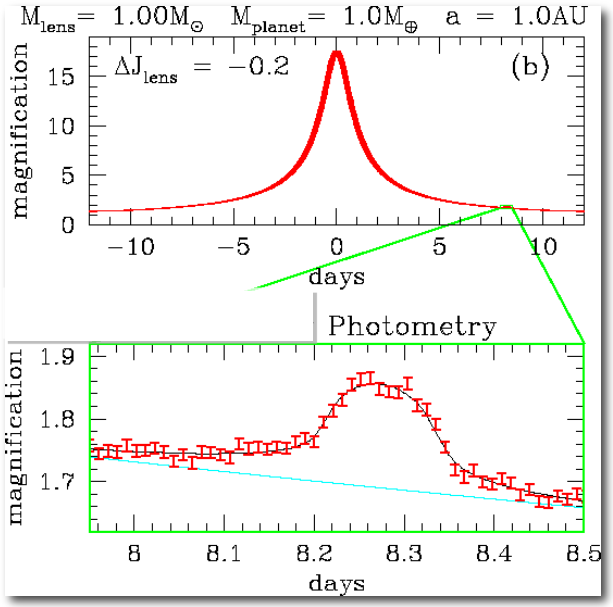
- In space the Euclid satellite (?)

Ground



Space



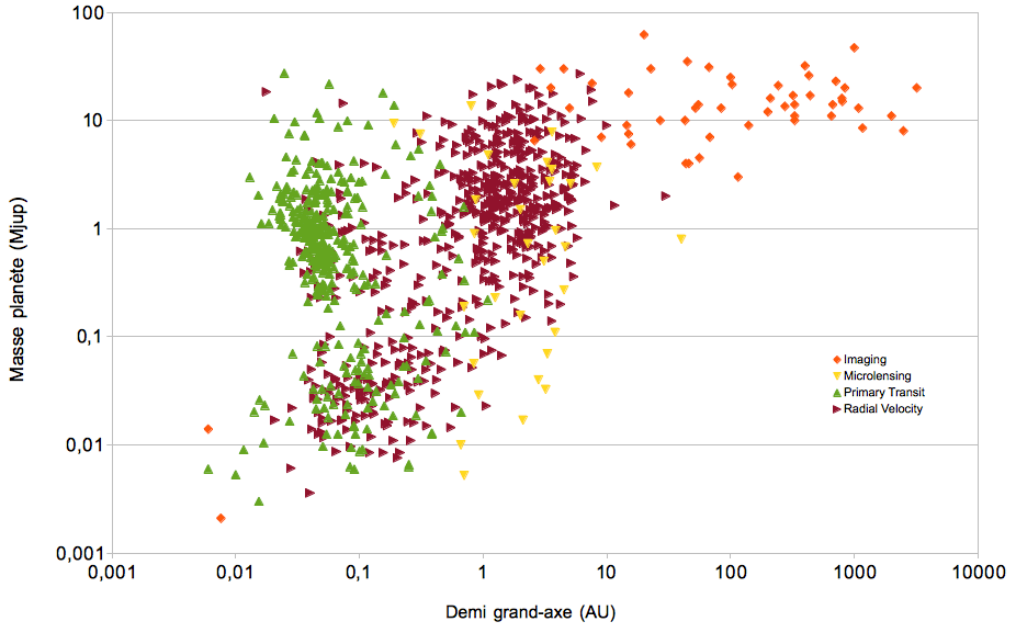


Census today

1901 planets

in

1199 systems




THE END
A
UNIVERSAL-INTERNATIONAL PICTURE