Introduction to exoplanetology

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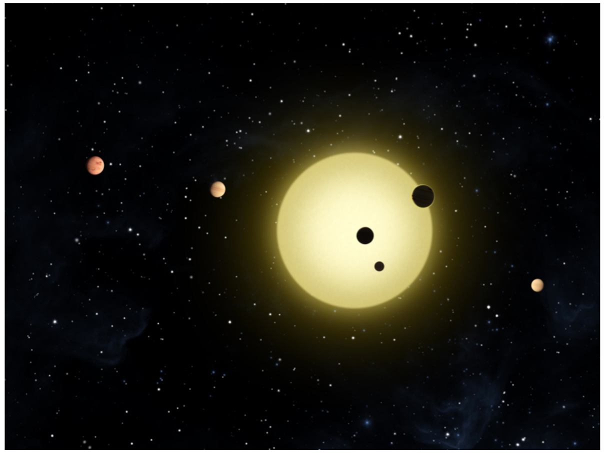
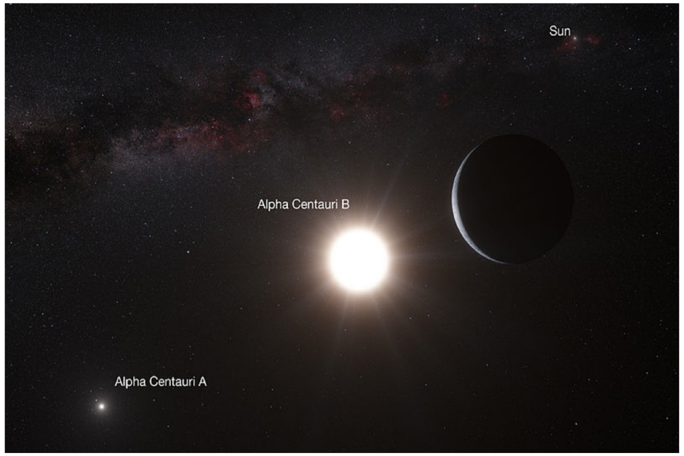
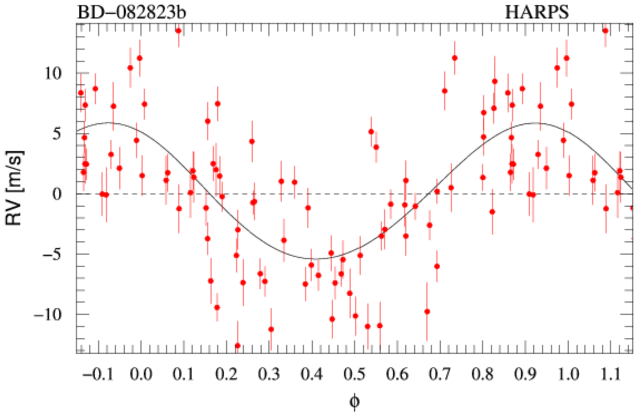
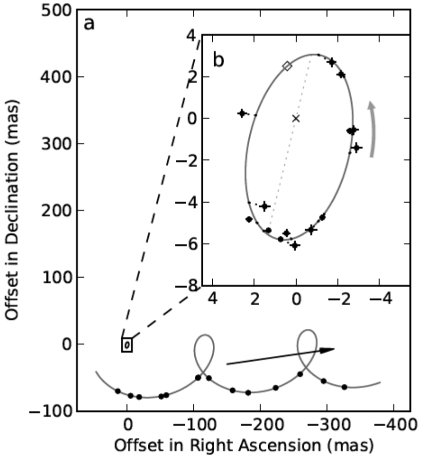


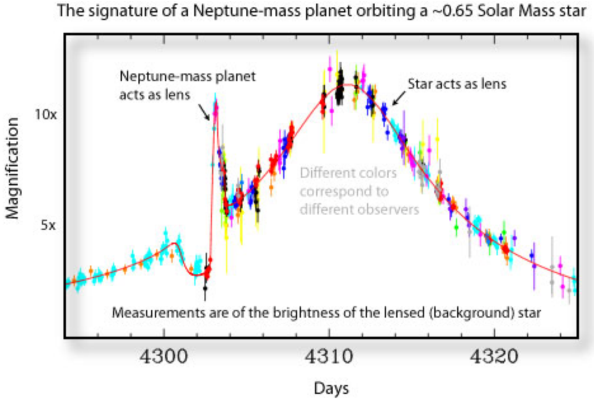


Introduction to exoplanetology. III.

Indirect methods for exoplanet detections







Michaël Gillon

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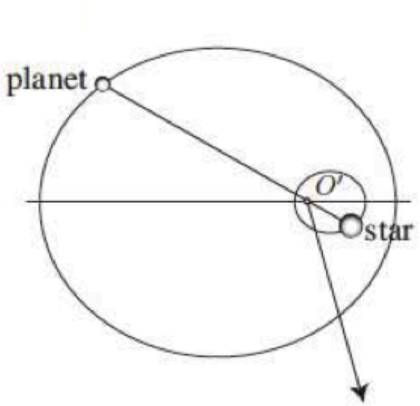
The radial velocity method

Radial motion of a star for an inertial observer (cf. L2)



$$V_r = \underbrace{\gamma_r}_{\text{Systemic velocity}} + \underbrace{K\left(\cos(\omega + f) + e\cos\omega\right)}_{\text{Orbital velocity}}$$

$$K = \frac{28.4329 m/s}{\sqrt{1-e^2}} \frac{m_p \sin i}{M_{Jup}} \left(\frac{m_p + m_*}{M_{Sun}}\right)^{-2/3} \left(\frac{P}{1yr}\right)^{-1/3}$$

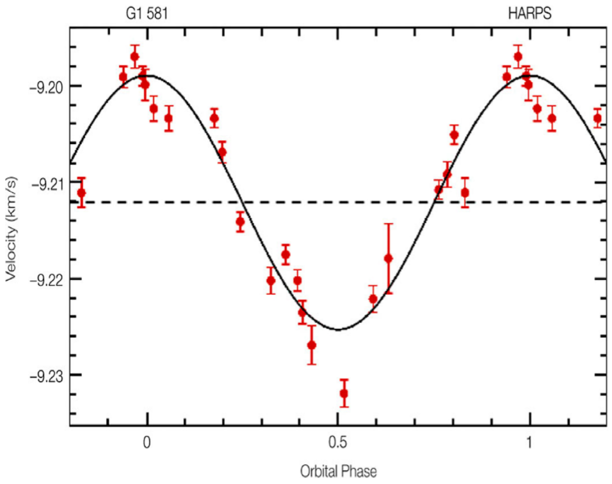
$$K = \frac{28.4329 m/s}{\sqrt{1-e^2}} \frac{m_p \sin i}{M_{Jup}} \left(\frac{m_p + m_*}{M_{Sun}}\right)^{-1/2} \left(\frac{a}{1au}\right)^{-1/2}$$

The radial velocity method

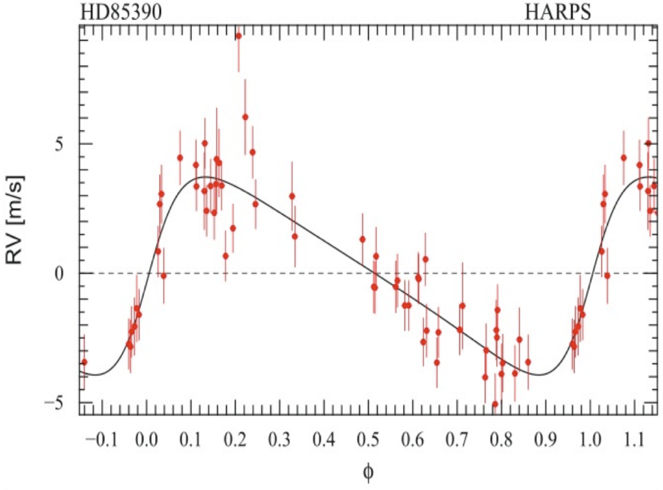
What if N>1 planets?

$$V_r = \gamma_r + \sum_{i=1}^{N} K_i(\cos(\omega_i + f_i) + e\cos\omega_i)$$

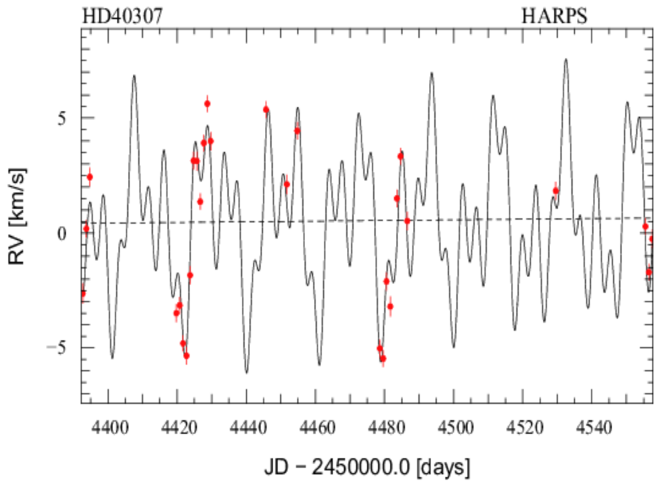
IF planet-planet interactions are negligible (i.e. far from orbital resonance)



1planet
circular orbit



1 planet
eccentric orbit

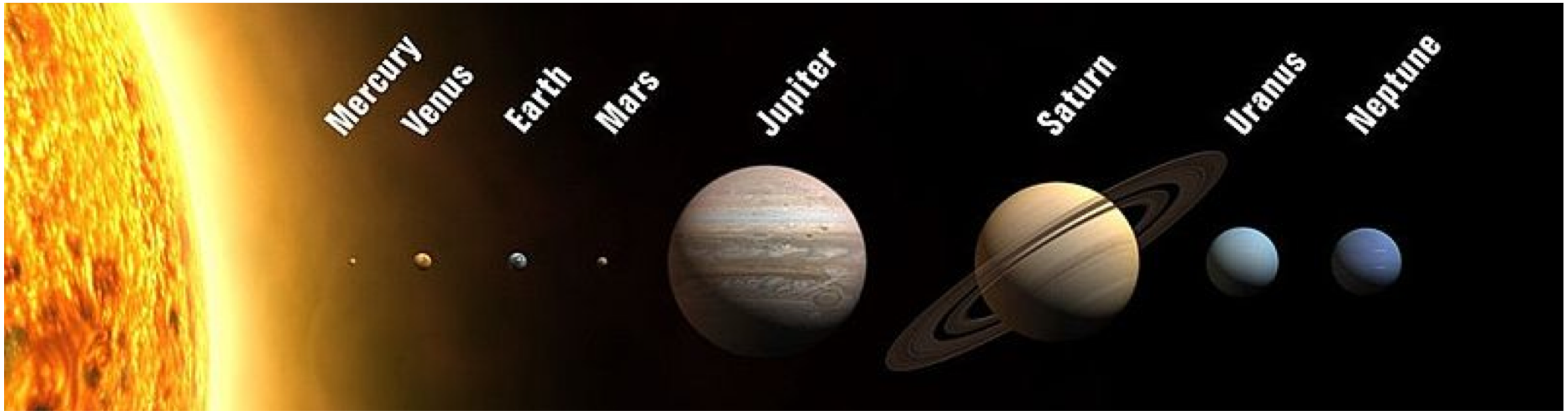


Several planets

Complex systems: modeling includes planet-planet interactions and tidal effects

Criterion of dynamical stability helps constraining the solution

The radial velocity method



P (yr)	0.24	0.62	1	1.9	11.9	29.4	83.7	163.7
K (cm/s) for i=90°	**0.8**	**8.5**	**9**	**0.8**	**1250**	**280**	**28**	**26**

Current best precision ~ 25cm/s = 1 km/h

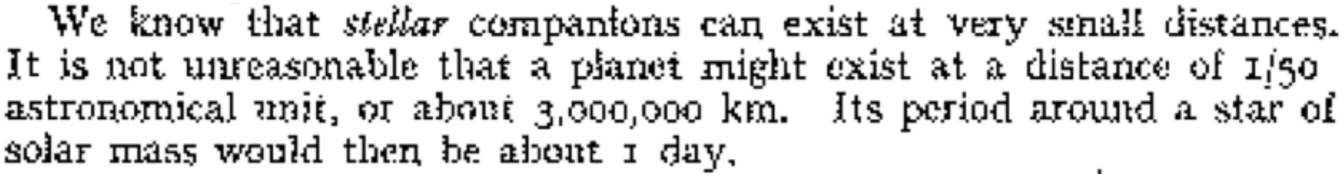
The radial velocity method

1952

Otto Struve (1897-1963)

Proposal for a project of high-precision stellar radial velocity work

The Observatory, Vol. 72, p. 199-200 (1952)

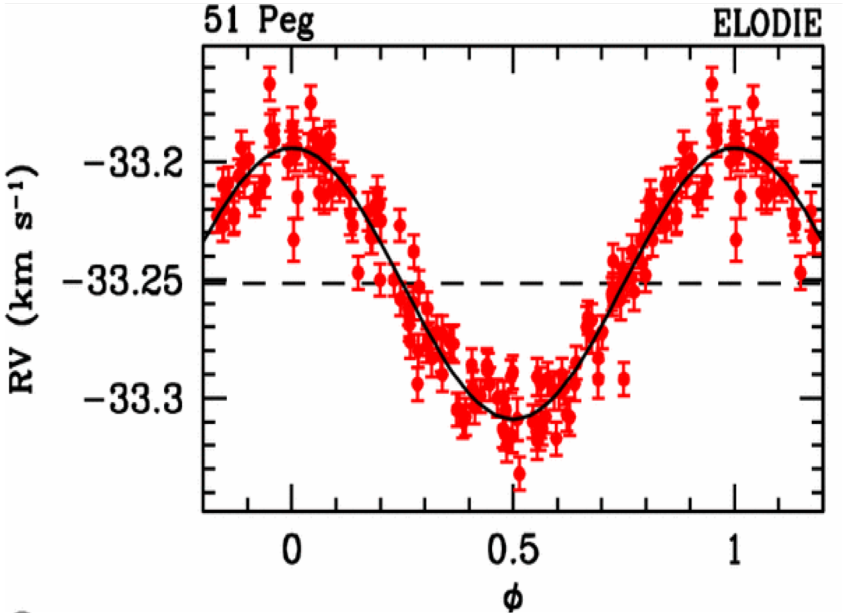


We know that *stellar* companions can exist at very small distances. It is not unreasonable that a planet might exist at a distance of 1/50 astronomical unit, or about 3,000,000 km. Its period around a star of solar mass would then be about 1 day.

Precision at that time ~ 750 m/s

1995

Didier Queloz & Michel Mayor



P = 4.2 days

a = 0.053 au

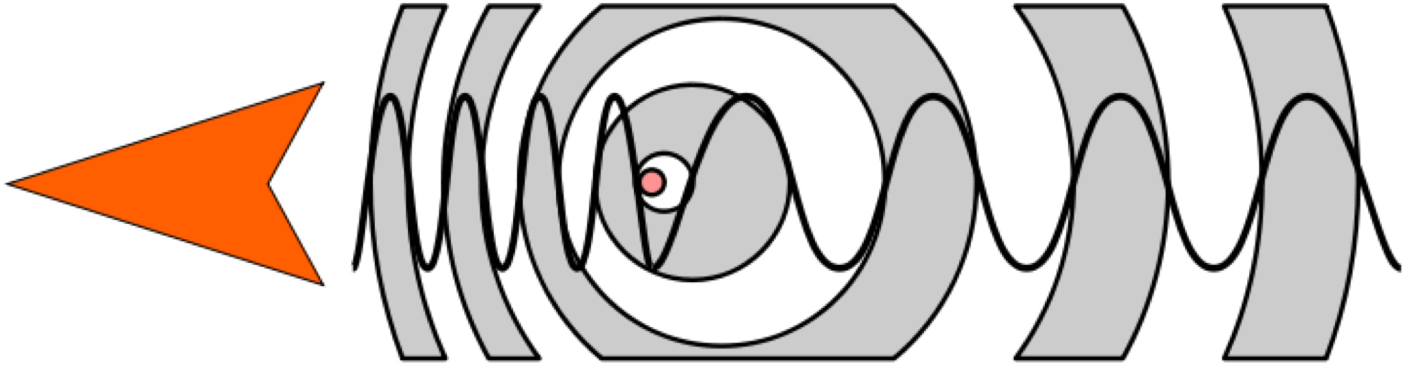
Msini = 0.5 M_{Jup}

The radial velocity method

The Doppler effect

$$\lambda = \lambda' \sqrt{\frac{1+\beta}{1-\beta}}$$

$$\beta = v/c$$



-> **high-resolution spectroscopy** (visible or near-infrared)

-> measurement of the radial velocity by **comparing the observed spectrum to a reference**, e.g.

  * a standard star' spectrum
  * a synthetic spectrum
  * a spectrum of the target

-> For stars that are poor in well-defined lines (hot and/or fast rotating stars), the radial velocity can be measured by fitting a profile on one or a few strong lines.

-> The coldest stars are very rich in lines (molecular bands), resulting in no net continuum

Best targets: metal-rich, slowly rotating stars of type F5 to M5

The radial velocity method

RV error with a single line:

$$\sigma_{RV} \sim \frac{\sqrt{FWHM}}{C \times SNR}$$

with FWHM the full-width at half maximum, SNR the signal-to-noise ratio in the continuum, and C the contrast of the line

Small FWHM: high resolution + slow rotation
High C: strong (but unsatured) lines
High SNR: telescope size, instrumental performances

RV precision for a spectrum:
(Bouchy et al. 2001)

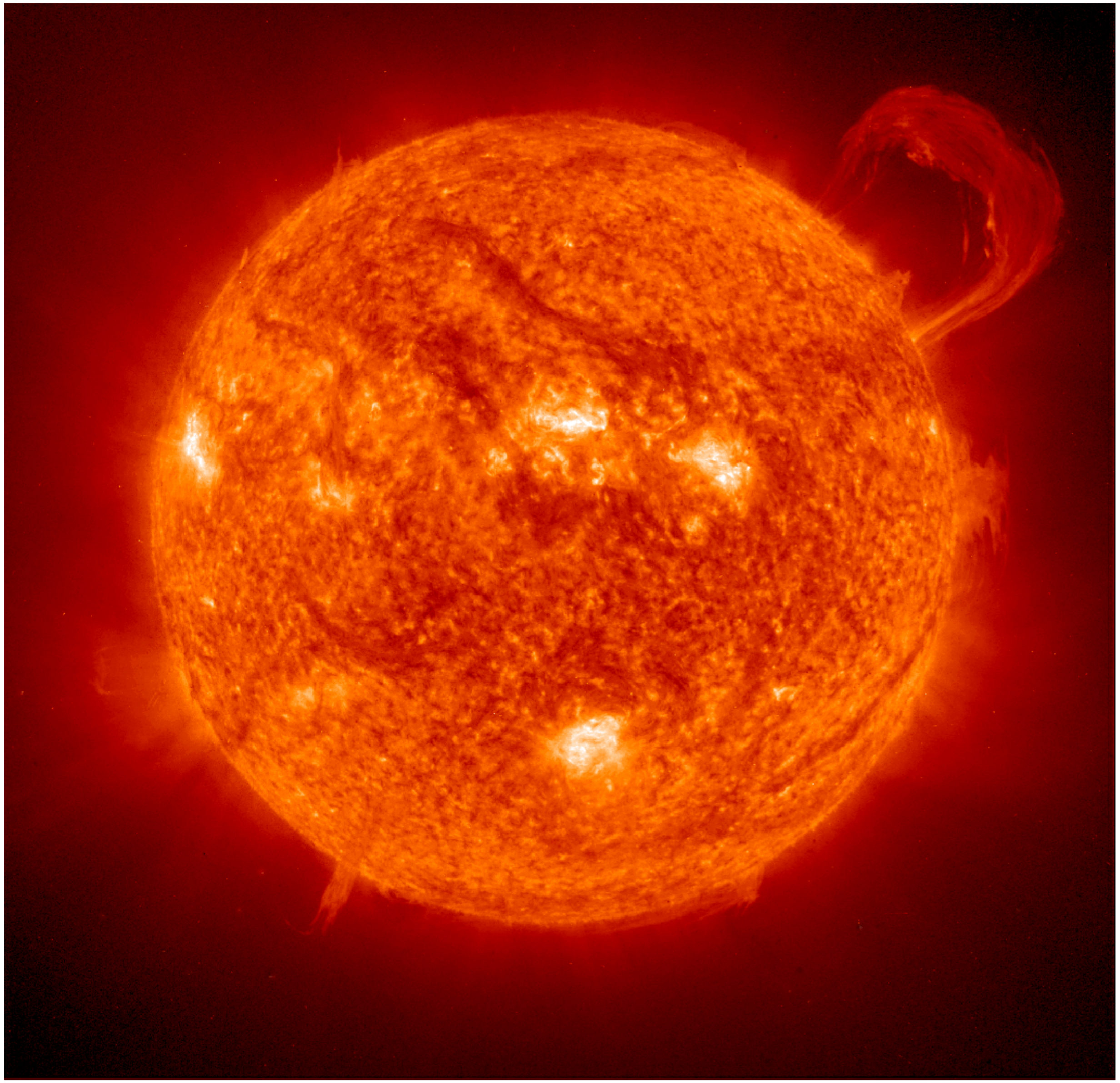
$$\sigma_{RV} = c\left(\sum_i \frac{\lambda_i^2 \left|dA_i / d\lambda\right|^2}{A_i + \sigma_D^2}\right)^{-1/2}$$

i = pixel *i*; λ_i = wavelength; σ_D is the read-out noise (in electrons);
A_i = flux in electrons; *c* = speed of light

Formula valid only for sufficiently strong lines and high SNRs, and neglecting stellar and instrumental systematic noises

The radial velocity method

Stellar noises



The radial velocity method

Stellar noises

Oscillations (p-modes) : star having a convective envelope. Period of a few minutes, increases if stellar density decreases. Amplitude of a few m/s for each mode.
Solution: averaging with exposures of at least 15 min.

The radial velocity method

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Granulation: stars with convective envelope. Amplitude integrated on the stellar disk of the order of m/s. Characteristic timescale ~ 10 min, or more (meso and super-granulation).
Solution: several exposures per night.

The radial velocity method

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Magnetic activity: rotating spots on the photosphere. Amplitude decreases and period increases with age. Amplitude can exceed 100m/s for a young star.
Solution: targeting old stars– observing in the IR – modeling the effect of spots using activity indicators, simultaneous time-series photometry, and/or a priori knowledge of the rotation of the star - strategy adapted to the star to average at best the effects of the activity

The radial velocity method

Stellar noises

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Magnetic cycles: 11 years for the Sun. Not only the RV precision varies with the magnetic phase, but possibly the RV itself too.
Solution: targeting old stars?

« Ultimate » precision ~10 cm/s ?

The radial velocity method

1 m/s ~ 10^{-5} Å ~ 1/1000th of a pixel for a high-resolution spectrograph

- ➔ **Temperature and pressure** in the spectrograph must be regulated very precisely. 1m/s = 0.01K = 0.01 mbar

- ➔ **Mechanical stability**: flexures can lead to RV drifts > 10m/s

- ➔ **Stability of the illumination** of the spectrograph' slit: internal calibration or use of optical fibers that minimize the illumination effects

- ➔ **Homogeneity and electronical performances of the detector**: ultra-high quality + very thorough calibration are required

- ➔ **Minimizing contamination** by the light of the **Moon**

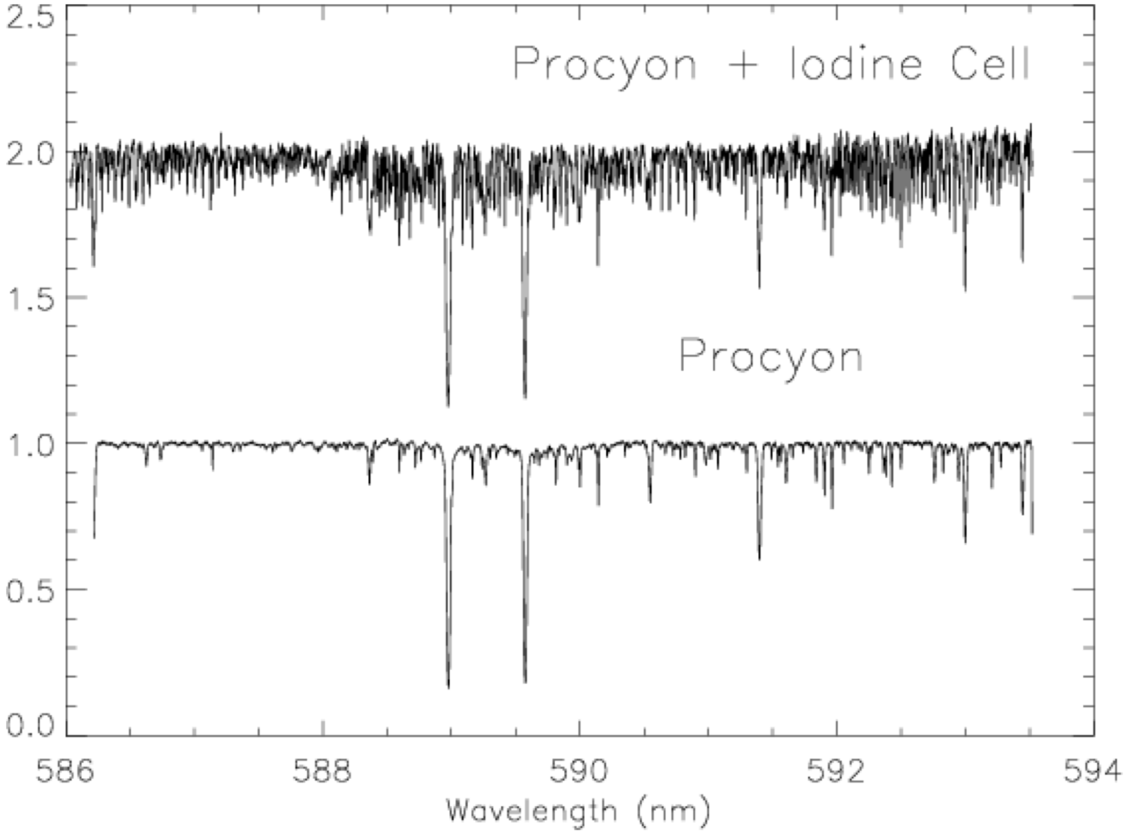
- ➔ **Avoiding the spectral areas rich in telluric lines** (especially in the red and IR) that can be variable

- ➔ **Wavelength calibration**: Iodine cell, Thorium-Argon lamp, laser comb, Fabry-Perot

The radial velocity method

Calibration in λ: the Iodine cell technique

I_2 cell upstream of the spectrograph' slit –> forest of lines between 5000 and 6200 Å

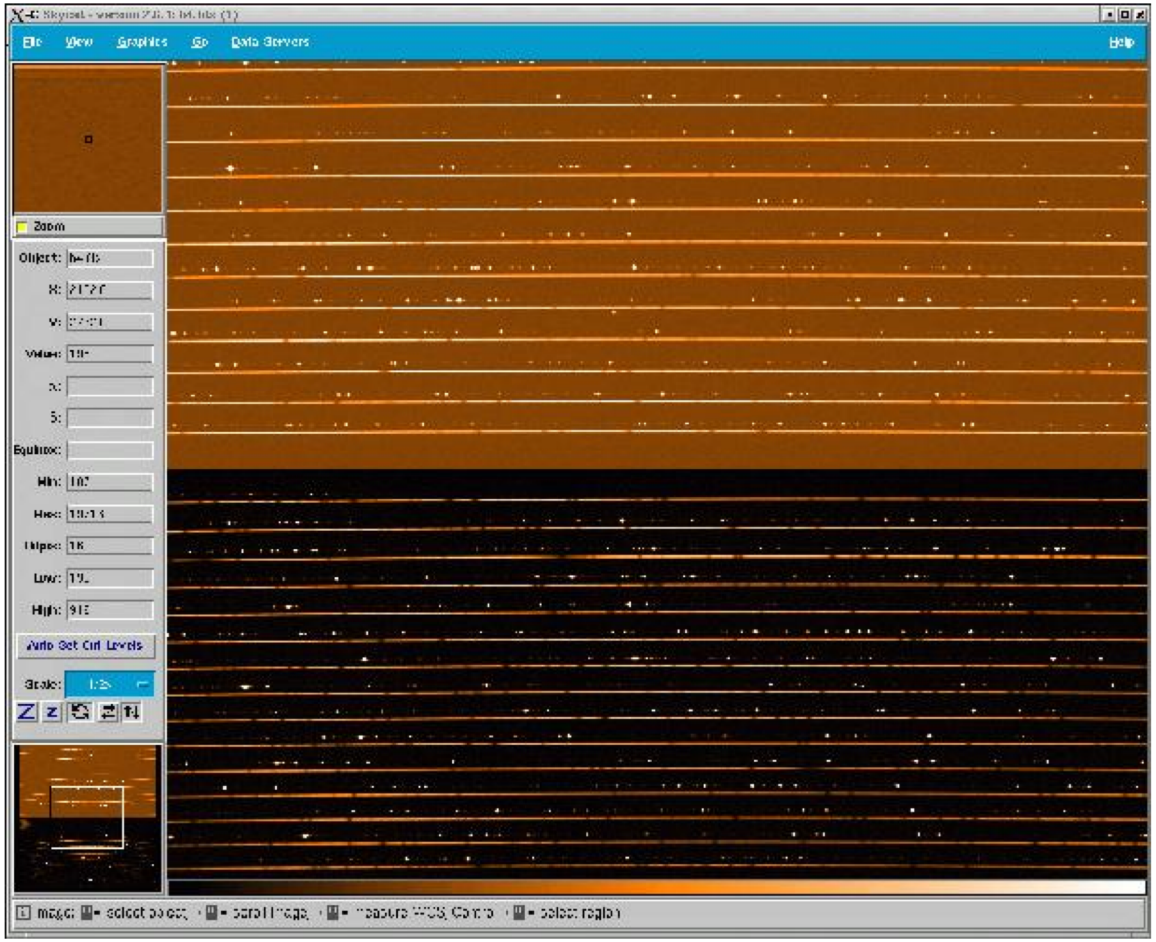


RV measurement by full modeling of the combined star + I_2 spectrum.
Calibration in λ and RV measurement in the same step

The radial velocity method

Calibration in λ: the simultaneous Thorium-Argon technique

Thr-Ar lamp sends light to the telescope focus, and it is then transmitted to the spectrograph through a different fiber than the scientific one.

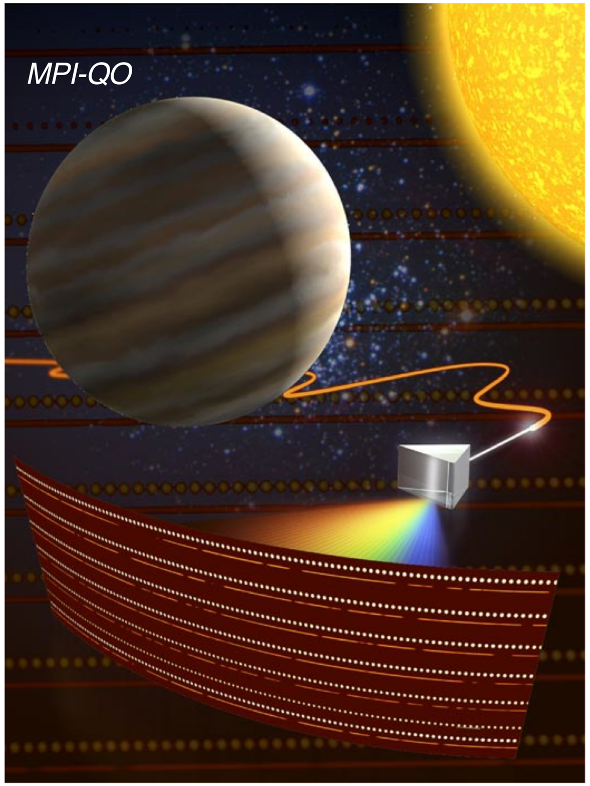


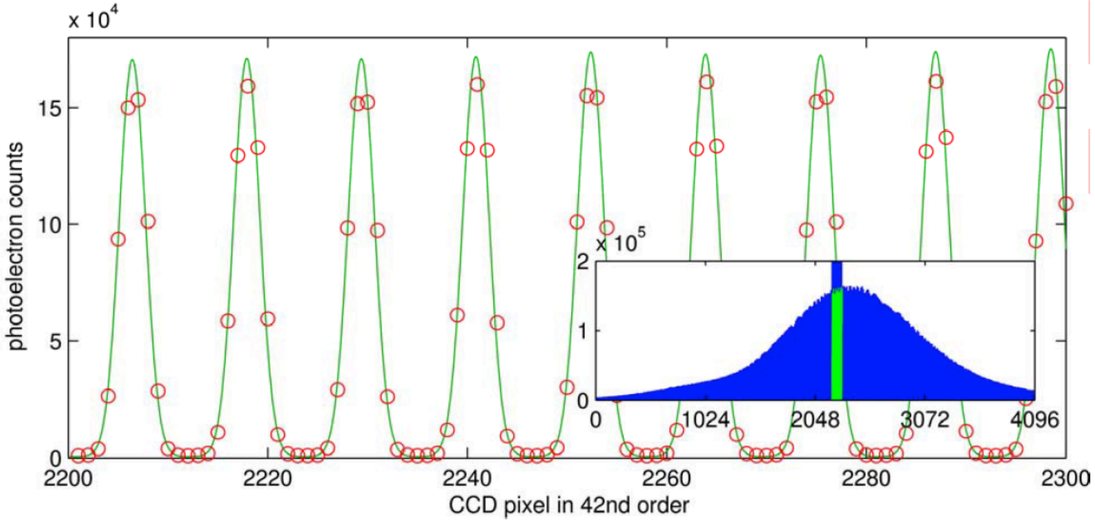
The spectrum is calibrated in wavelength, then the RV is measured by cross-correlation

The radial velocity method

Calibration in λ: the Laser Frequency Comb technique

Laser whose spectrum is a « comb » of lines regularly spaced within a range of λ. The laser's periodic modulations are set by an atomic clock to reach the highest accuracy on the frequencies. In RV, accuracies < 1cm/s can be achieved.
Current problems: lines are too close (Fabry-Perrot), λ-range too small.





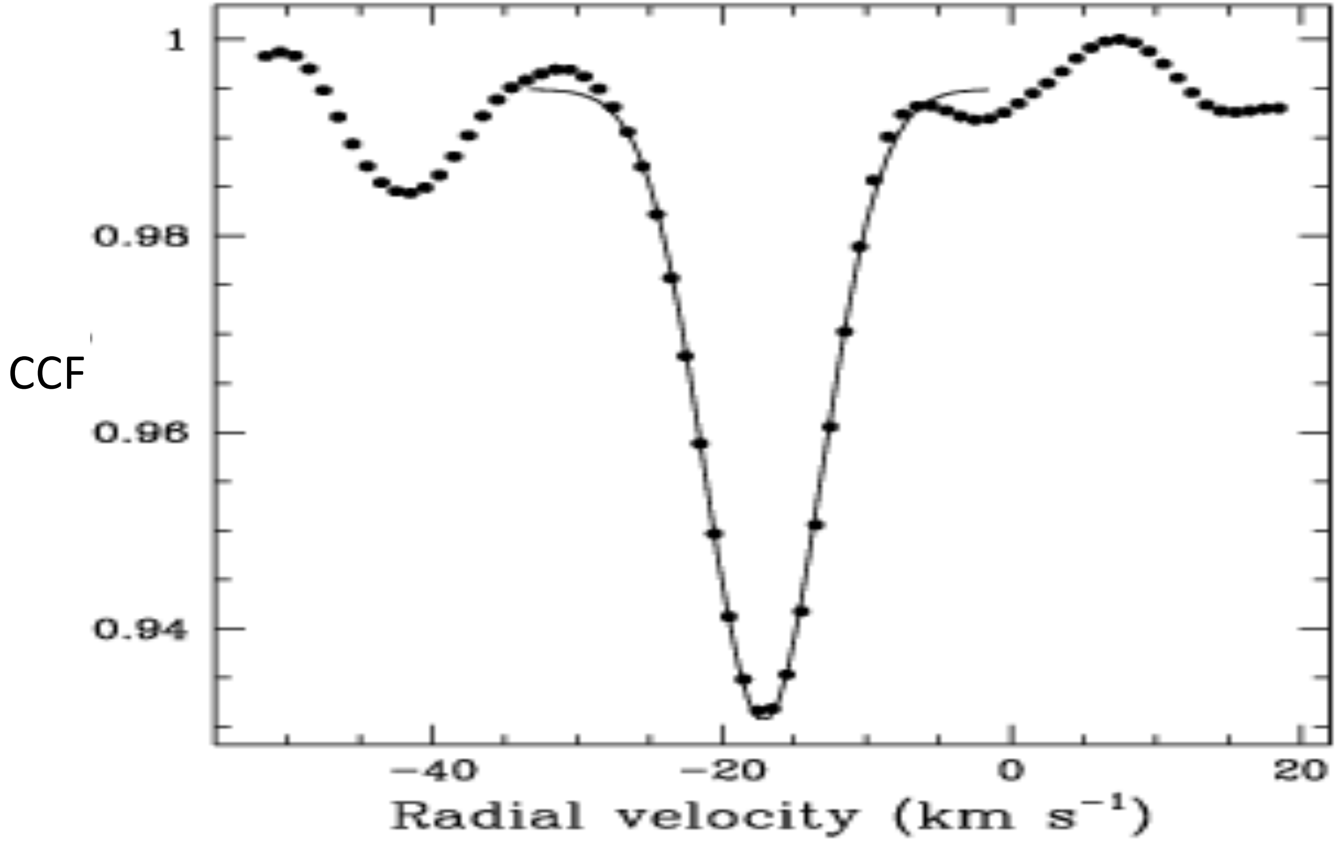
Wilken et al. 2010

The spectrum is calibrated in wavelength, then the RV is measured by cross-correlation

The radial velocity method

The cross-correlation function = CCF

$$\left(s*t\right)\left(\delta\right)=\int_{-\infty}^{+\infty}s(\lambda)t(\lambda+\delta)\,d\lambda$$

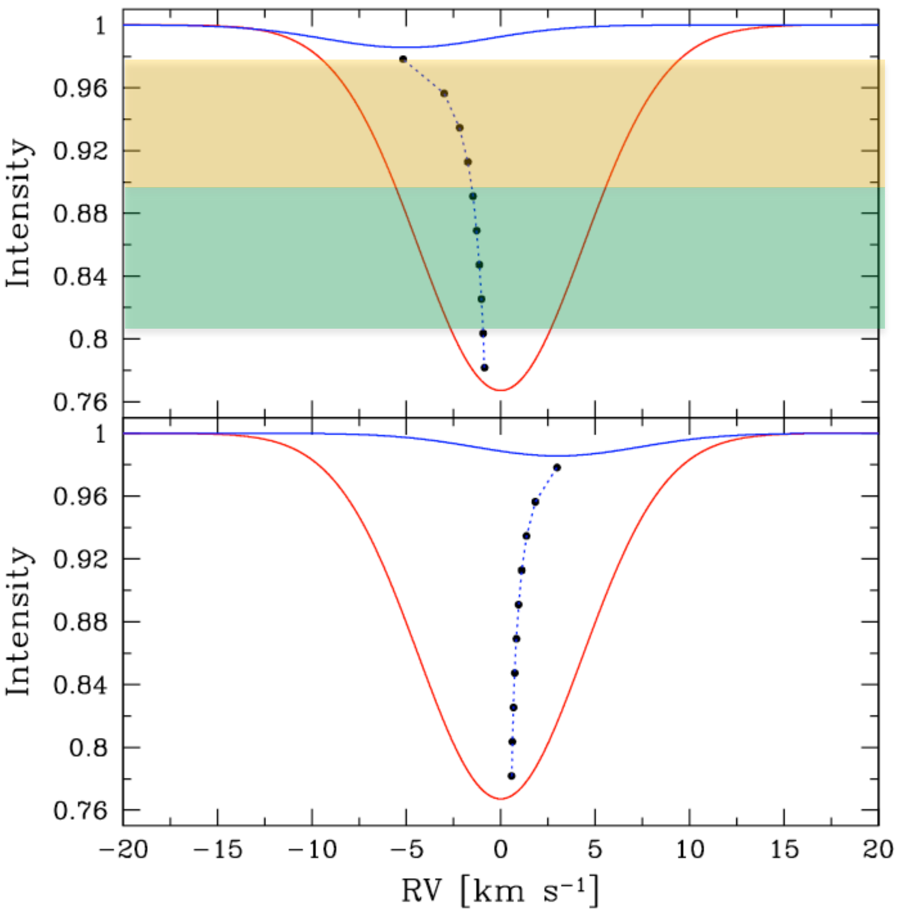


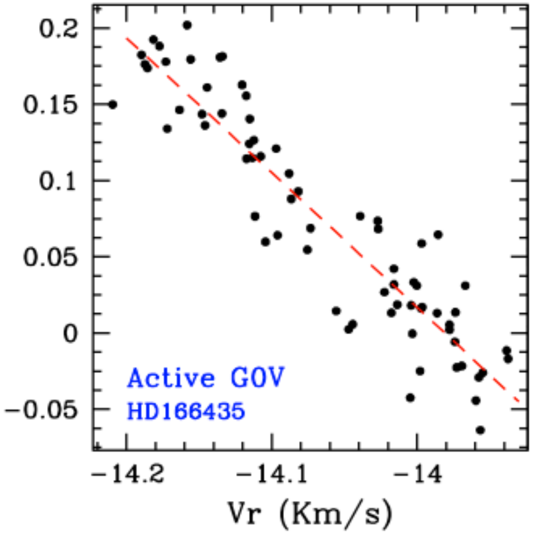
Correlation of the spectrum with a standard, and measurement of the radial velocity by fitting a Gaussian profile on the obtained CCF

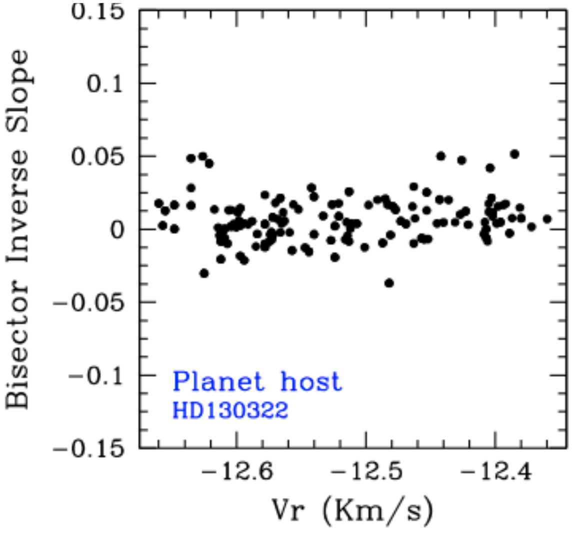
The radial velocity method

The CCF bisector as a mean to identify « false planets »

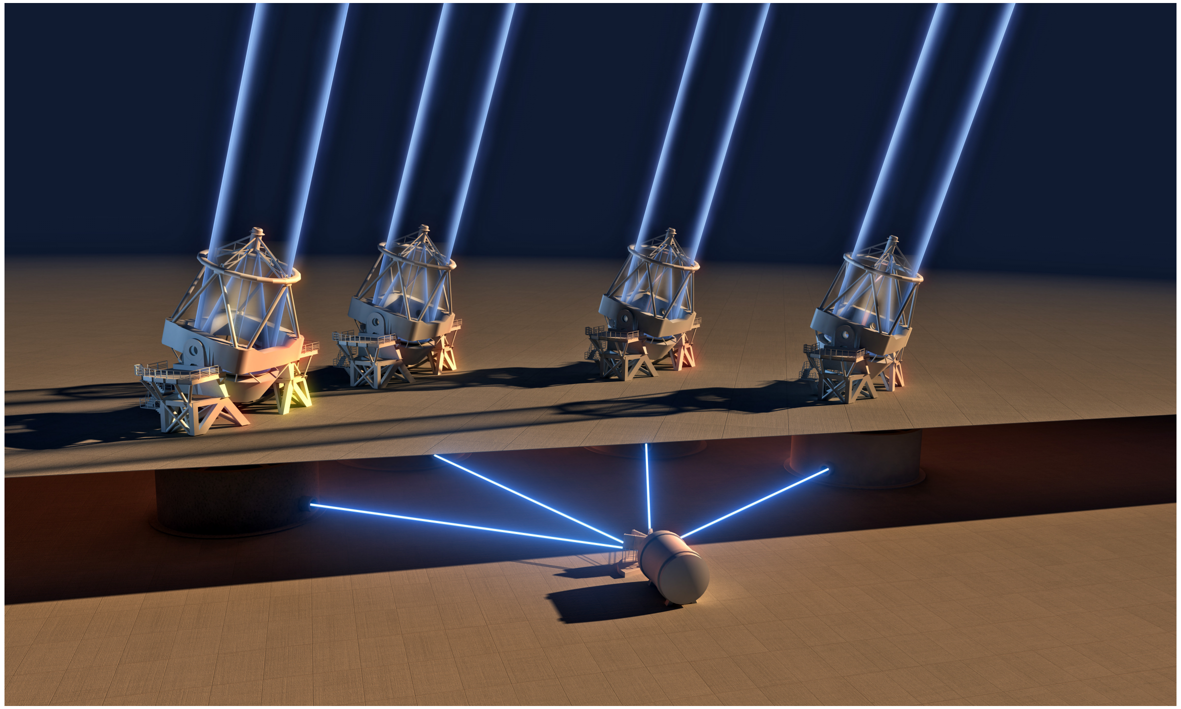
Comparing the average velocity in the ranges 10-40% et 55-90% of the maximum contrast







The radial velocity method: the state-of-the-art



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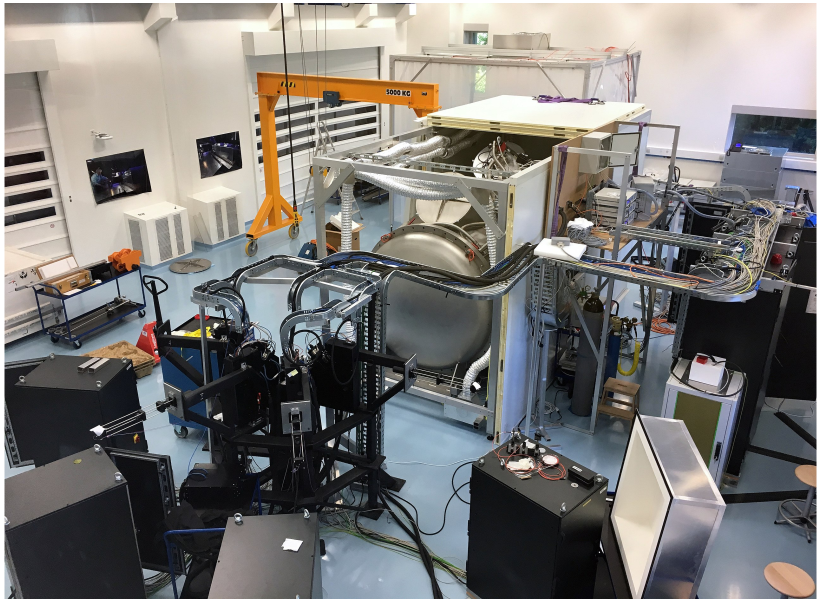
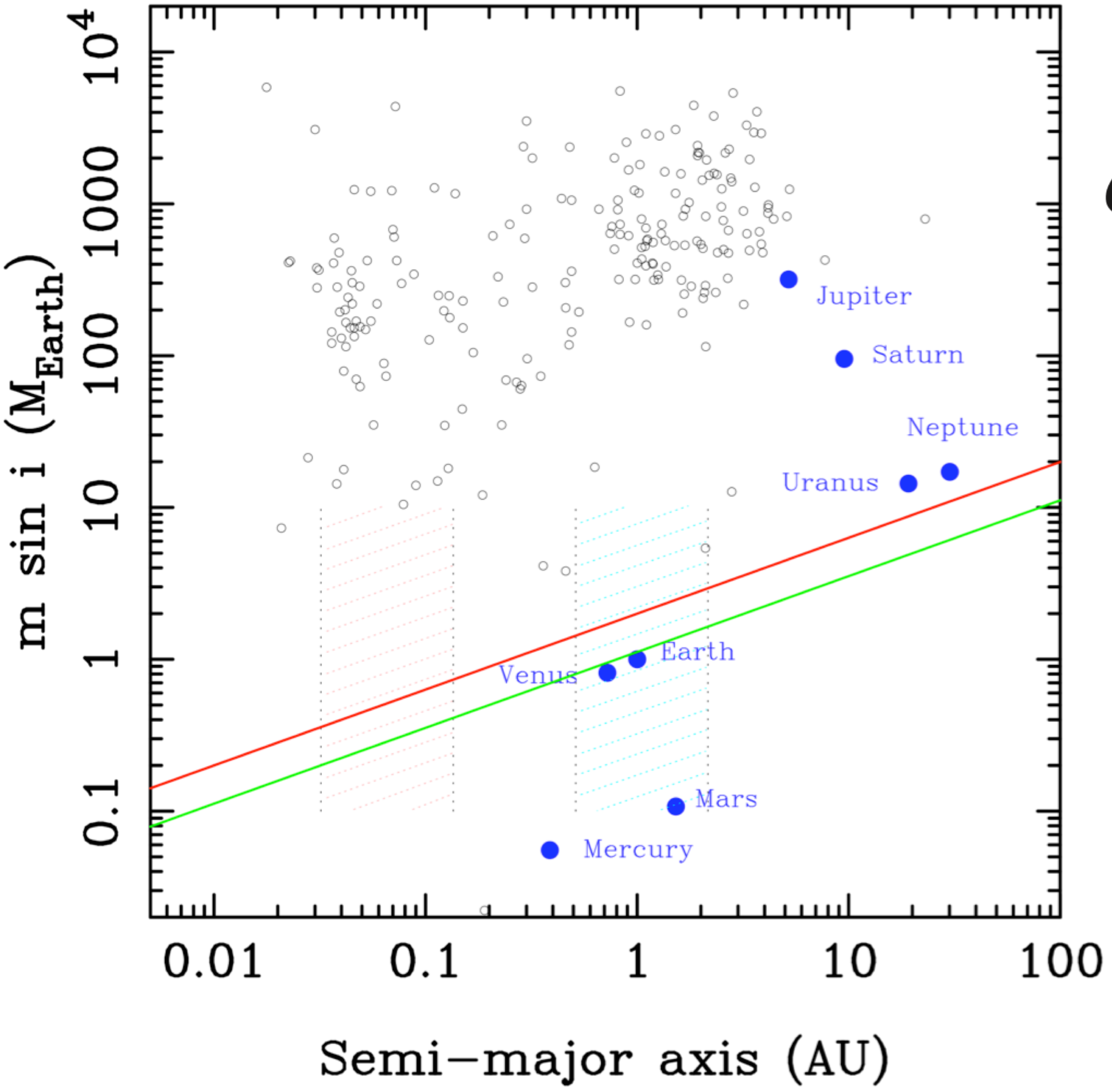


Up to 4x8.m telescopes at ESO Paranal, Chile
Echelle spectrograph
R up to 190,000
380-788nm
Thorium-Argon + Laser-Comb
Extreme instrumental stability
RV stability <10 cm/s

The radial velocity method: the state-of-the-art



Radial velocities: results

1988 : first exoplanet: γ Cep b (Campbell et al.), confirmed only in 2002

1989 : first brown dwarf (or exoplanet?): HD114762b (Latham et al.)

1995: first confirmed exoplanet around a main-sequence star: 51 Peg b (Mayor & Queloz)
Discovery of hot Jupiters

1997: first multiple exoplanetary system: Upsilon Andromedae (Butler et al.)

2000: HD209458b, first transiting planet (Mazeh et al., Charbonneau et al.)

2004: first « Neptune » and « Super-Earth » (Butler et al., Mc Arthur et al.)

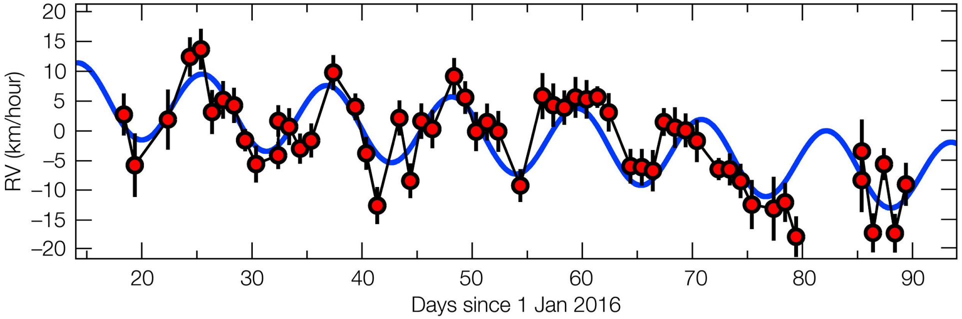
2006: first multiple Neptunes system (Lovis et al.)

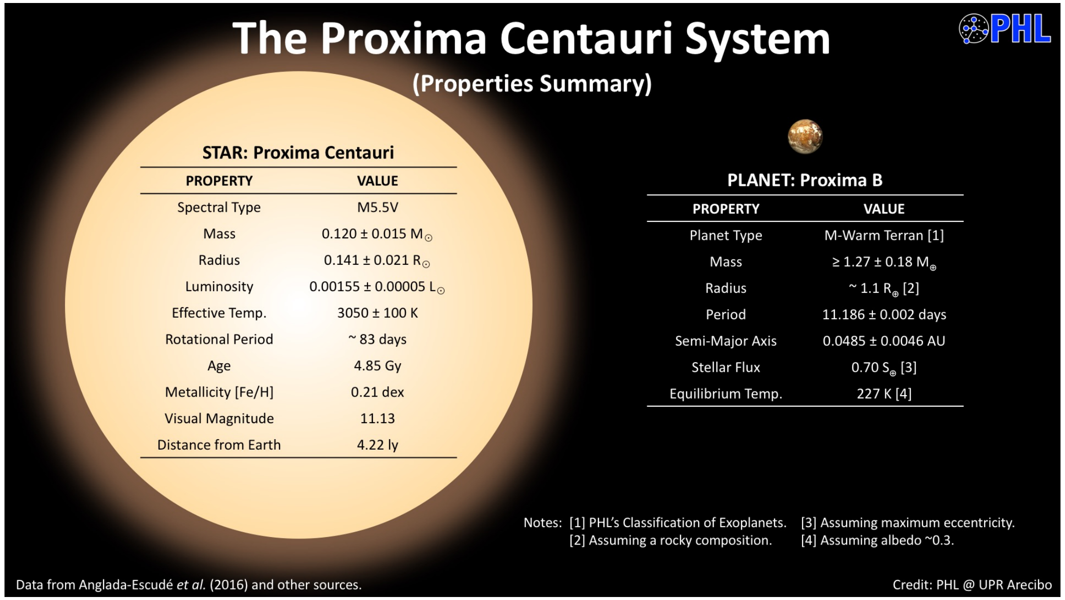
2007: first super-Earth in the habitable zone, first multiple super-Earths system (Udry et al.)

~~2013: Earth-mass planet around Alpha Cen B! (Dumusque et al) K=50cm/s!~~

2015 (Rajpaul et al.)

Radial velocities: results





The Proxima Centauri System

(Properties Summary)

PHL

STAR: Proxima Centauri

PROPERTY	VALUE
Spectral Type	M5.5V
Mass	$0.120 \pm 0.015\ M_\odot$
Radius	$0.141 \pm 0.021\ R_\odot$
Luminosity	$0.00155 \pm 0.00005\ L_\odot$
Effective Temp.	3050 ± 100 K
Rotational Period	~ 83 days
Age	4.85 Gy
Metallicity [Fe/H]	0.21 dex
Visual Magnitude	11.13
Distance from Earth	4.22 ly

PLANET: Proxima B

PROPERTY	VALUE
Planet Type	M-Warm Terran [1]
Mass	$\geq 1.27 \pm 0.18\ M_\oplus$
Radius	$\sim 1.1\ R_\oplus$ [2]
Period	11.186 ± 0.002 days
Semi-Major Axis	0.0485 ± 0.0046 AU
Stellar Flux	$0.70\ S_\oplus$ [3]
Equilibrium Temp.	227 K [4]

Notes: [1] PHL's Classification of Exoplanets. [3] Assuming maximum eccentricity.
[2] Assuming a rocky composition. [4] Assuming albedo ~0.3.

Data from Anglada-Escudé *et al.* (2016) and other sources.

Credit: PHL @ UPR Arecibo

Anglada-Escudé et al. (2016)

Radial velocities: results

Proxima Centauri d - K = 39+-7 cm/s - Msini = 0.26+-0.5 Mearth

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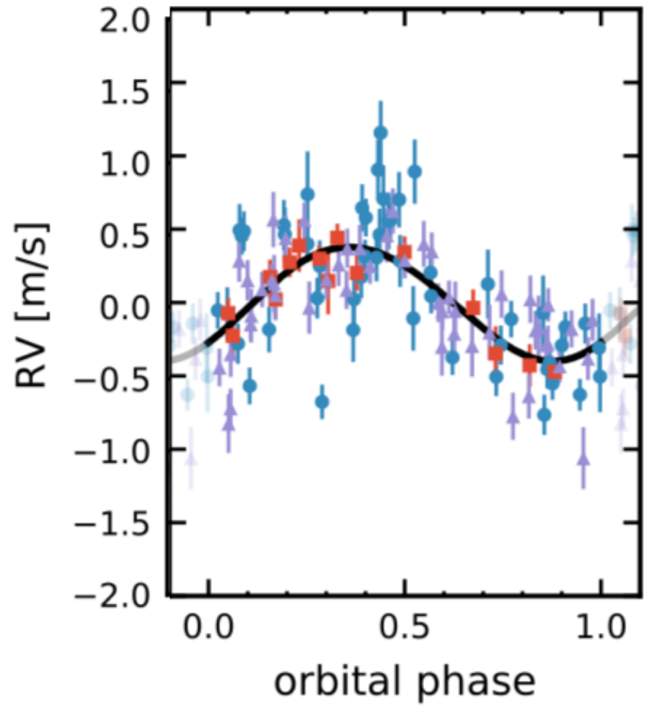
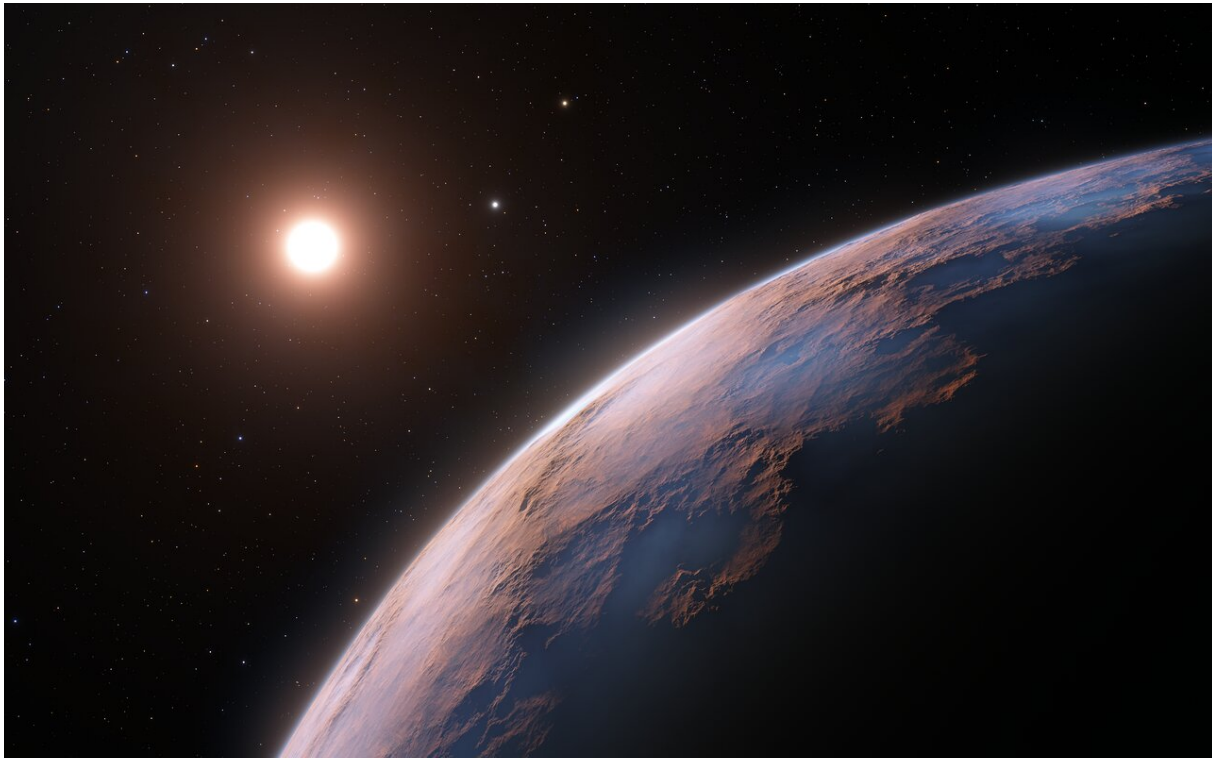
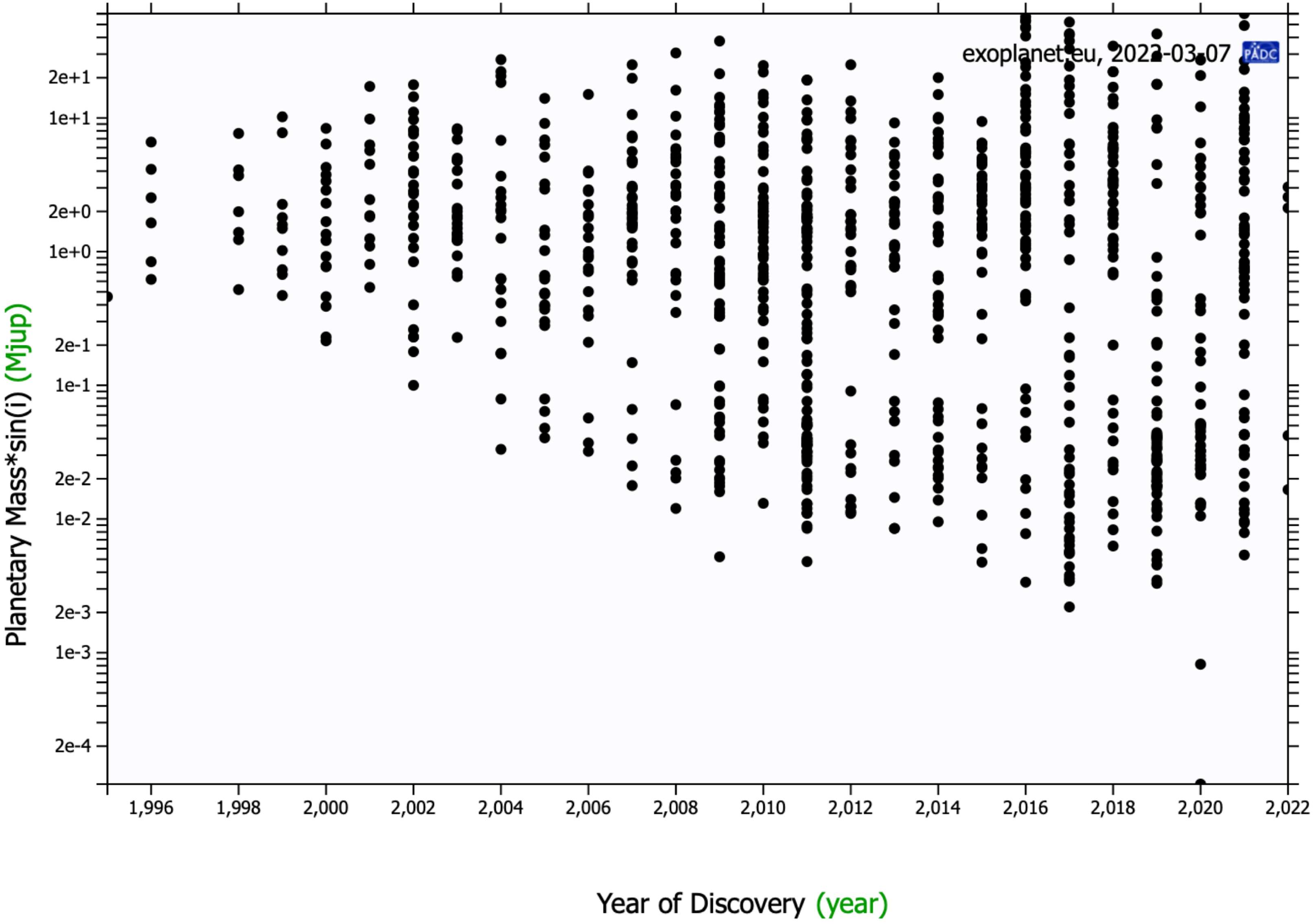




Faria et al. (2016)

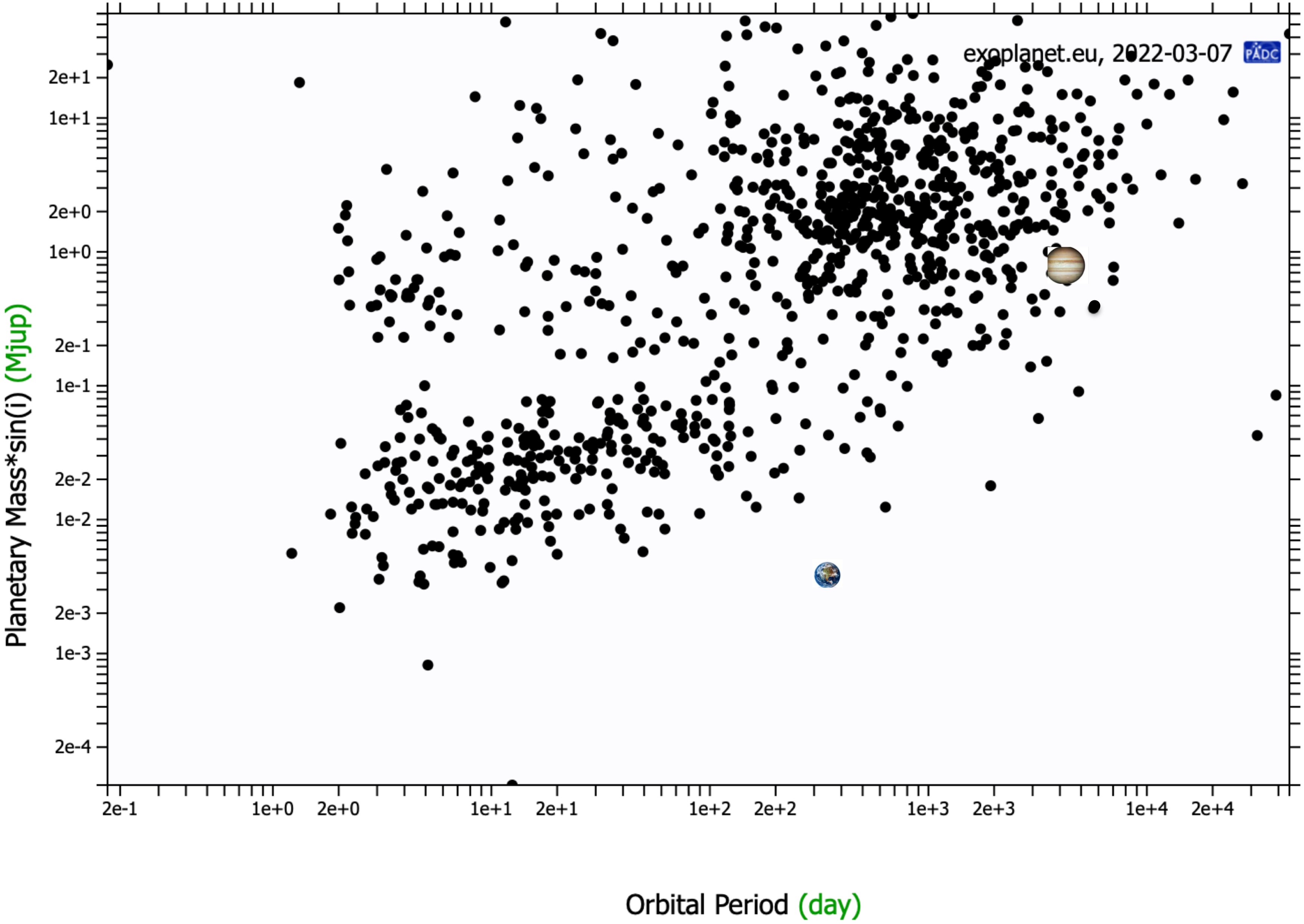
Radial velocities: results

>900 planets

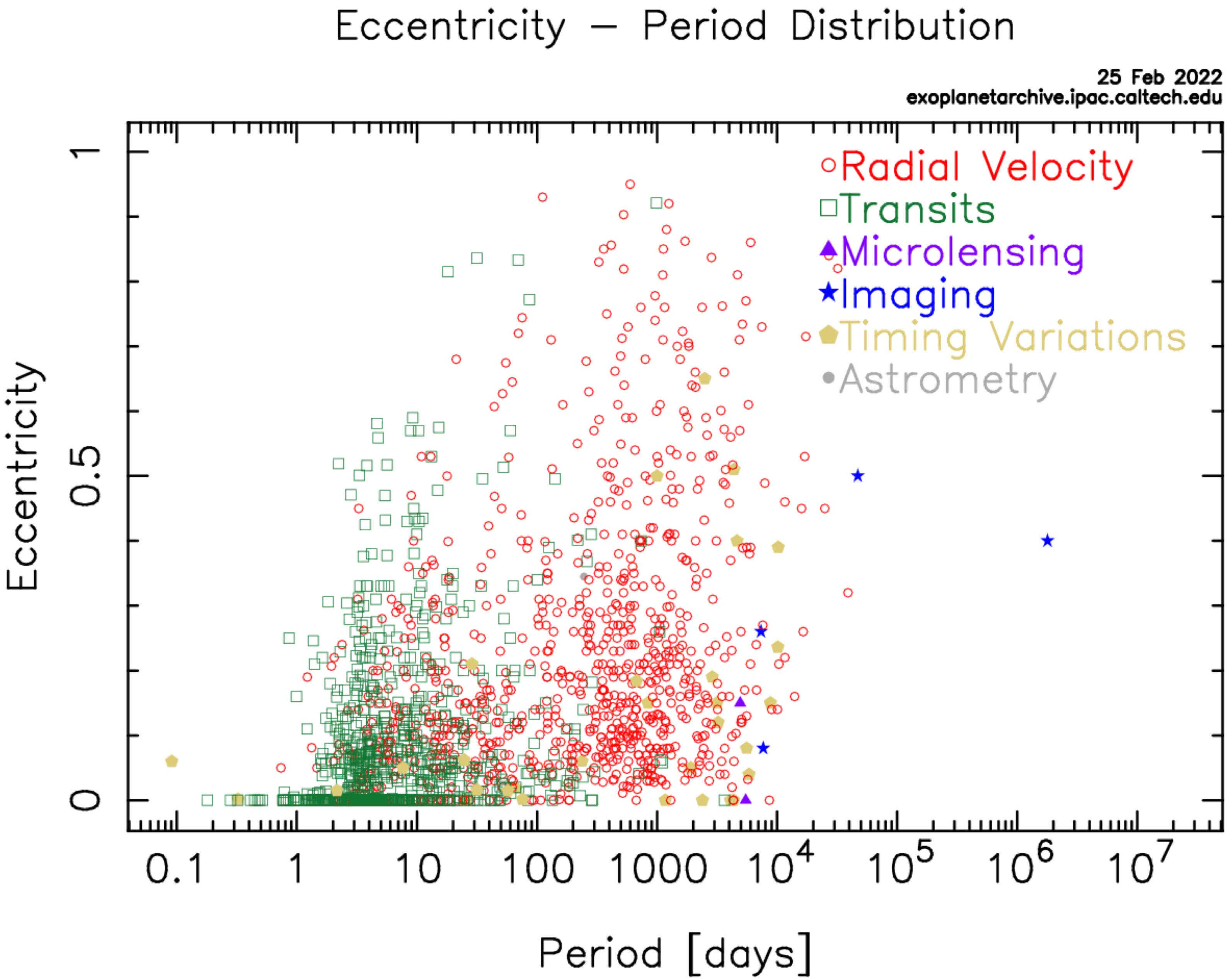


Radial velocities: results

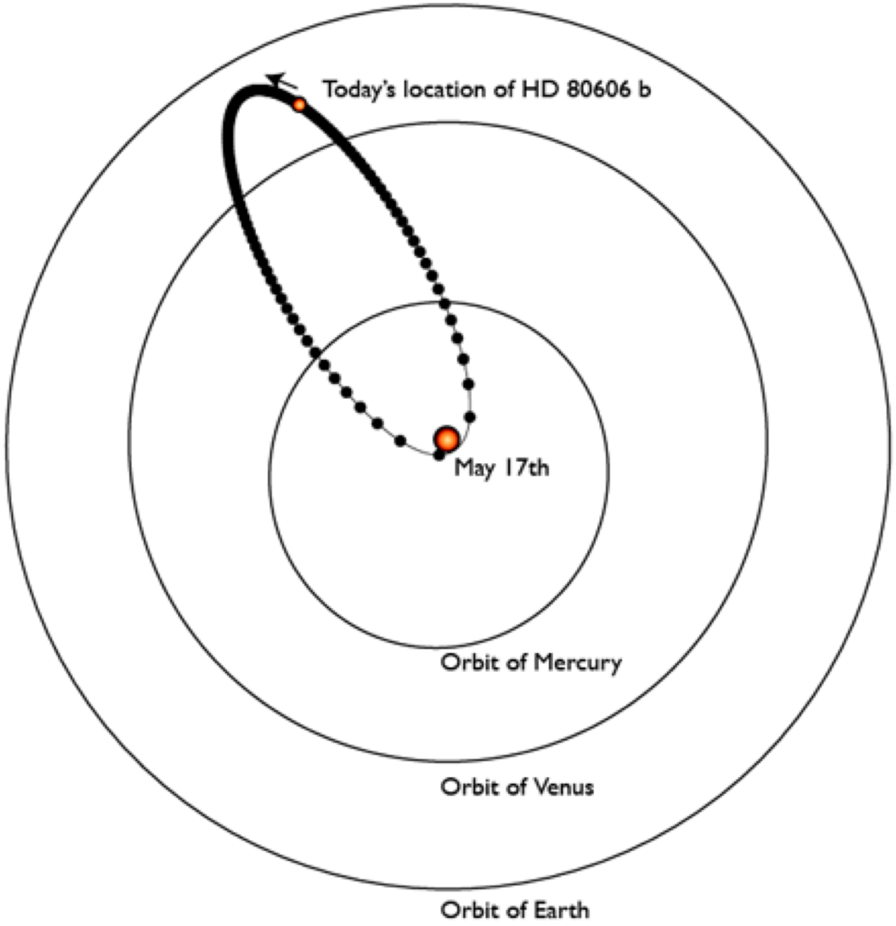
>900 planets

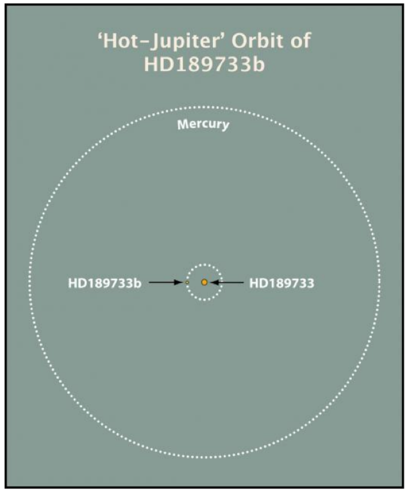


Radial velocities: results



Radial velocities: results





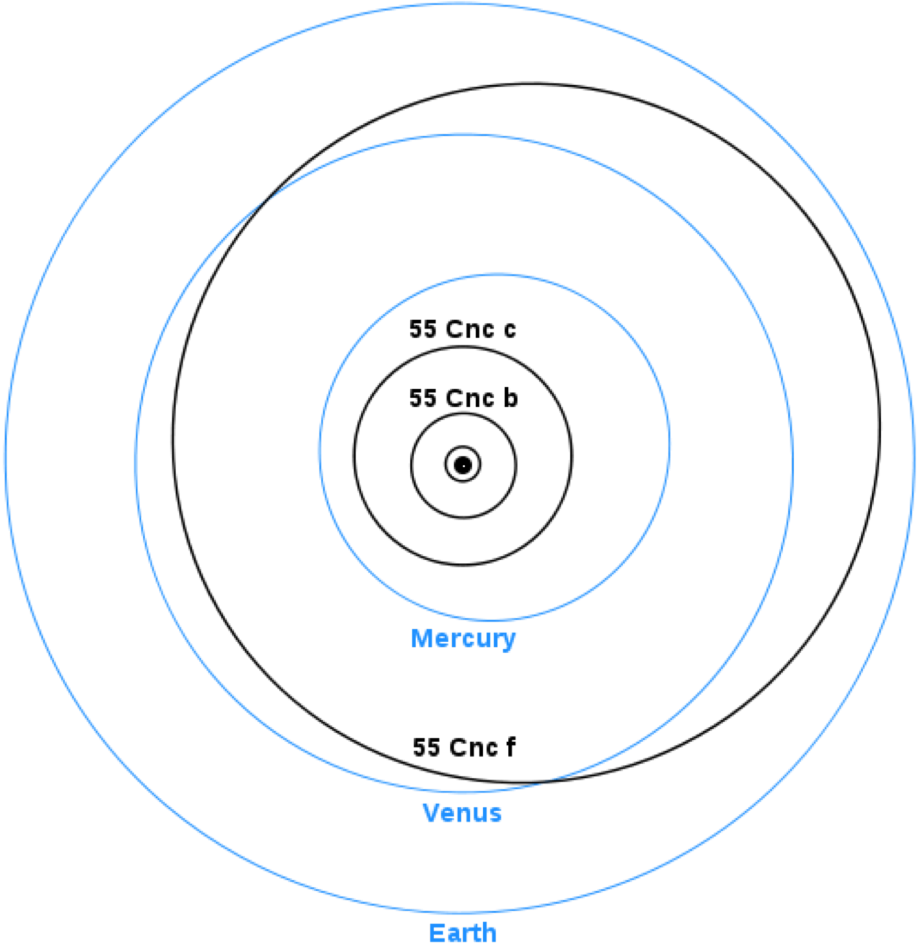
Giant planets in orbits shorter than Jupiter's: eccentric and warm/hot Jupiters

A few % of solar-type stars

Eccentric warm Jupiters: planet-planet scattering and/or Kozai resonance followed by tidal migration?

Radial velocities: results

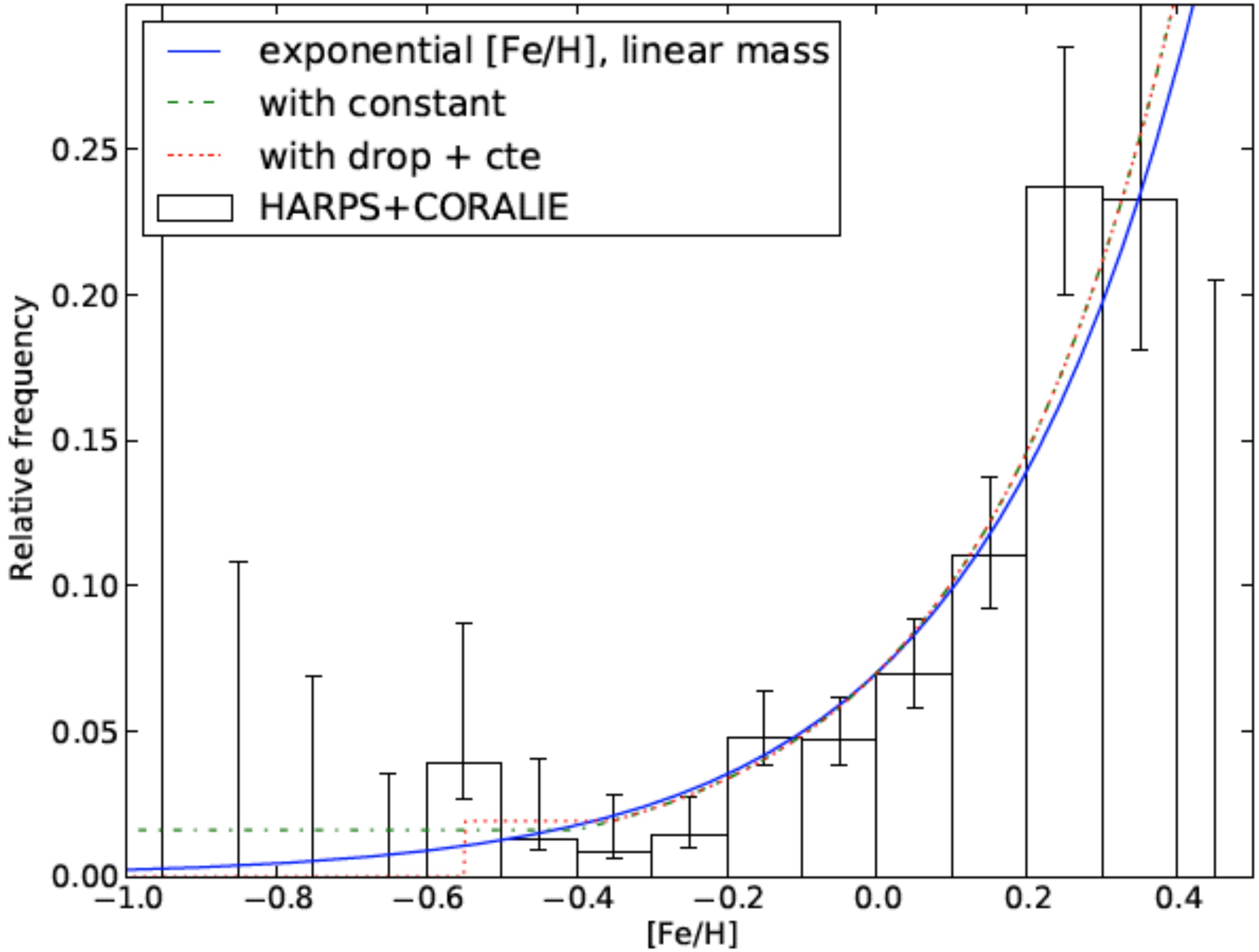
Systems of short-period giant planets in or close to orbital resonances



55 Cnc e: 8 M_{Earth}, P = 19h
55 Cnc b: 0.8 M_J, P = 15 days
55 Cnc c: 0.2 M_J, P = 45 days
55 Cnc f: 0.15 M_J, P = 260 days

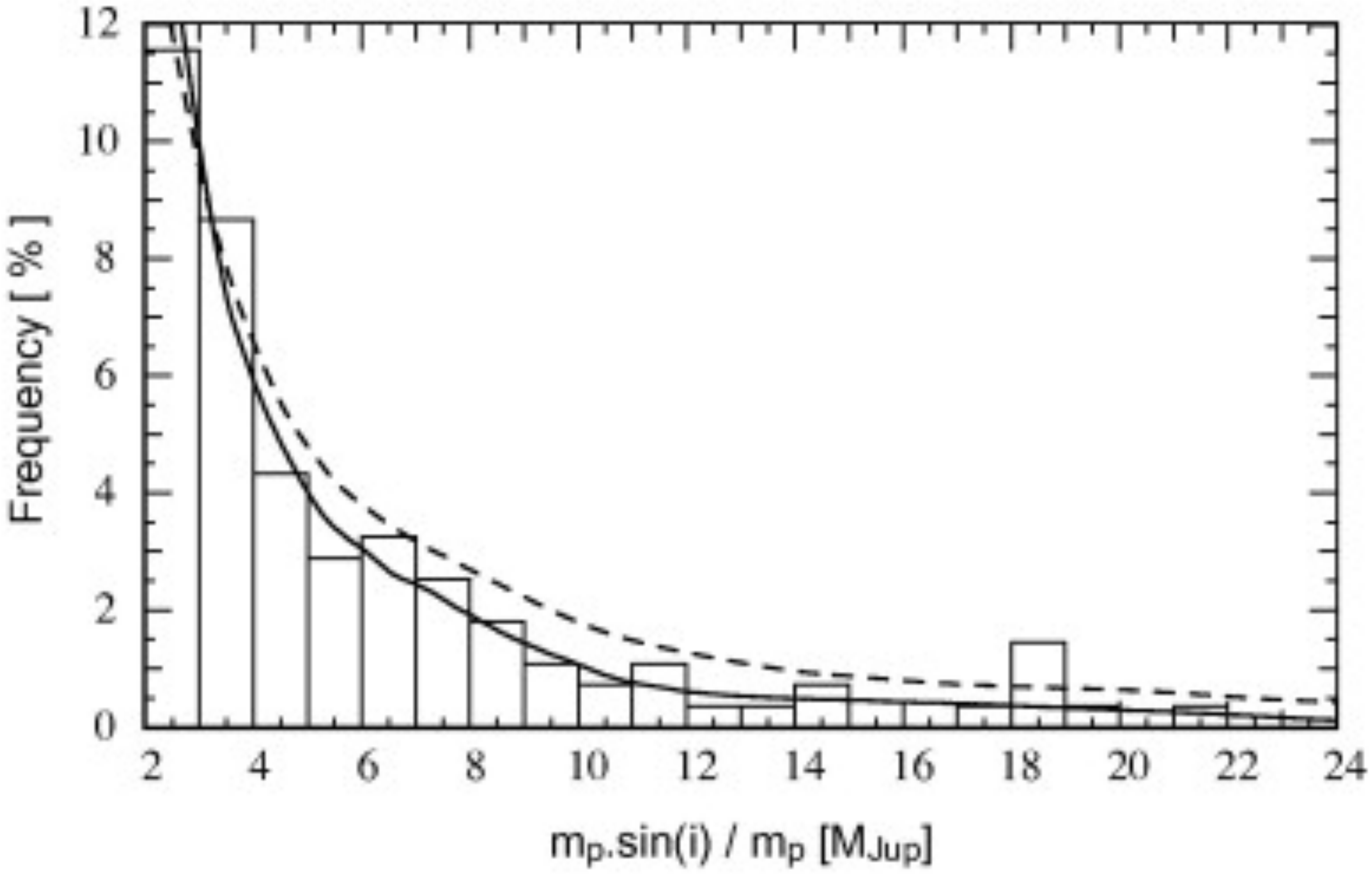
Proofs of disk-driven migration?

Radial velocities: results



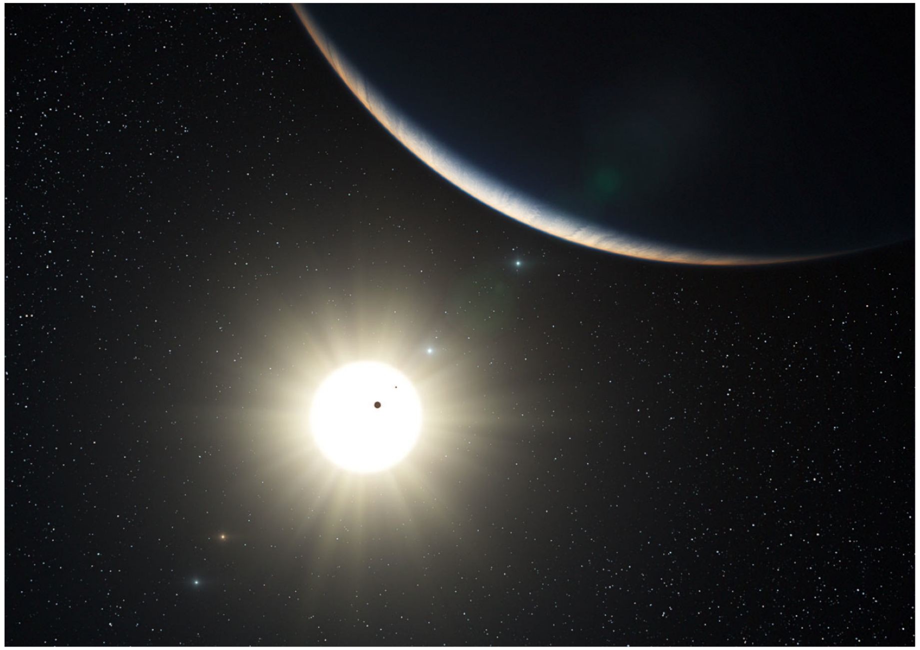
The frequency of giant planets increases with the metallicity of hot stars

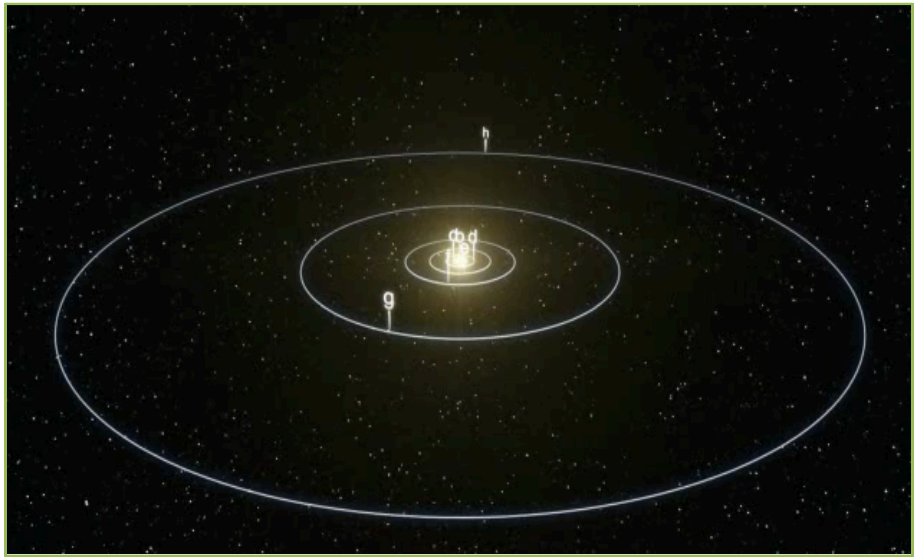
Radial velocities: results



The frequency of planets decreases for bigger masses

Radial velocities: results





HD10180

Solar-type star

7 planets

- HD10180b, ≥1.4 M_{Earth}, P = 1.2 days
- HD10180c, ≥0.75 $M_{Neptune}$, P = 5.8 days
- HD10180d, ≥0.7 $M_{Neptune}$, P = 16 days
- HD10180e, ≥1.5 $M_{Neptune}$, P = 50 days
- HD10180f, ≥1.4 $M_{Neptune}$, P = 123 days
- HD10180g, ≥1.2 $M_{Neptune}$, P = 1.6 years
- HD10180h, ≥0.7 $M_{Saturne}$, P = 6 years

Multiplanetary system with short-period super-Earths and Neptunes

Radial velocities: results

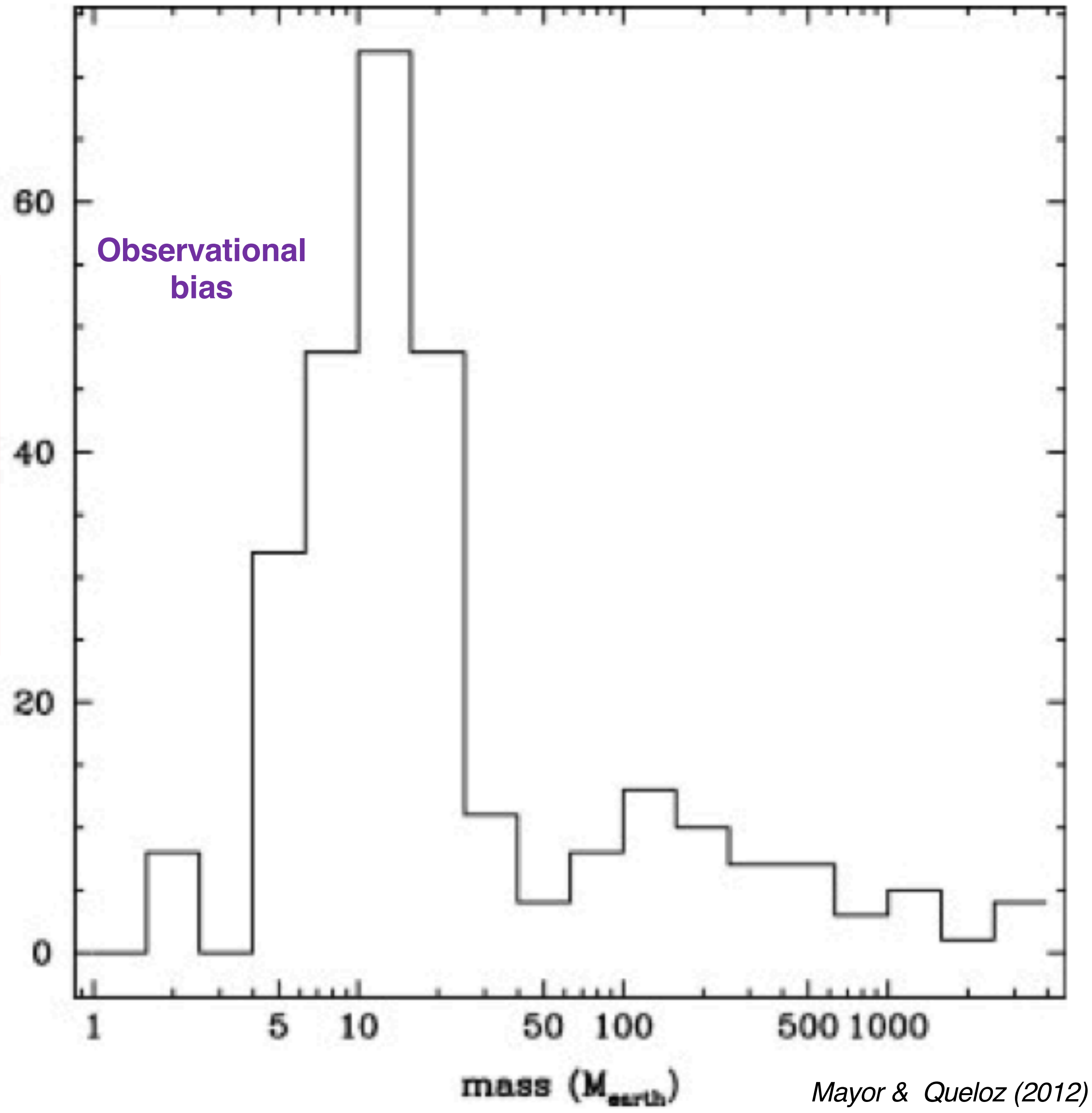
P < 100 days

Population distinct of hot Jupiters

30-50% of solar-type stars have one or several planets of a few M_{Earth} in short-period orbits (Mercury's or shorter)

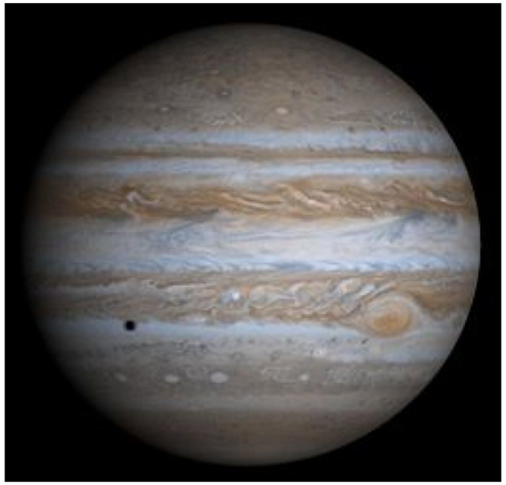
No metallicity effect

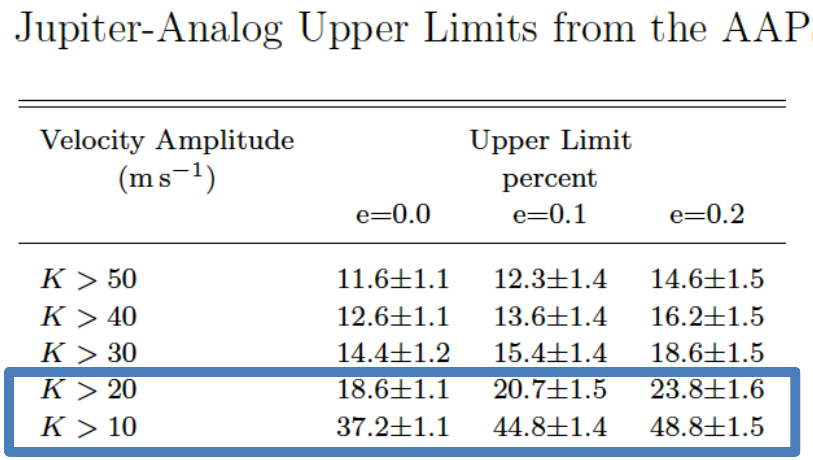
>70% = multiple systems



Mayor & Queloz (2012)

Radial velocities: results





Jupiter-Analog Upper Limits from the AAPS Sample

Velocity Amplitude ($\mathrm{m\,s^{-1}}$)		Upper Limit percent	
	e=0.0	e=0.1	e=0.2
$K > 50$	11.6±1.1	12.3±1.4	14.6±1.5
$K > 40$	12.6±1.1	13.6±1.4	16.2±1.5
$K > 30$	14.4±1.2	15.4±1.4	18.6±1.5
$K > 20$	18.6±1.1	20.7±1.5	23.8±1.6
$K > 10$	37.2±1.1	44.8±1.4	48.8±1.5

Wittenmeyer et al. (2011)

Jupiter analog:

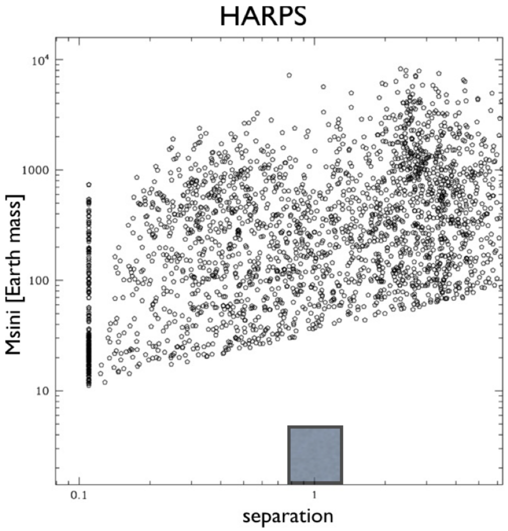
Now estimated to be less than 5% of solar-type stars!

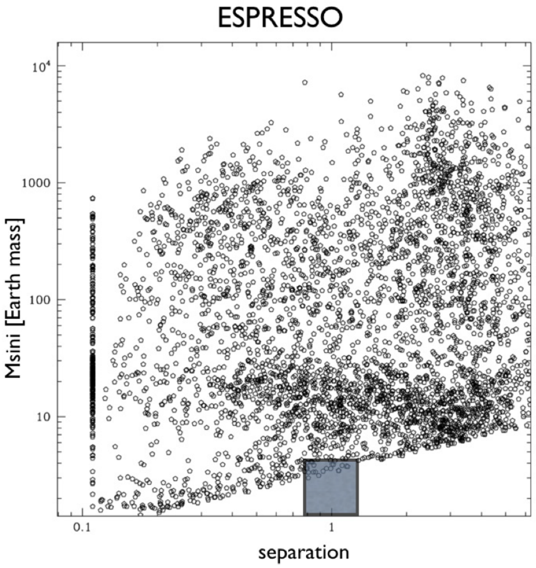
Rowan et al. (2016)

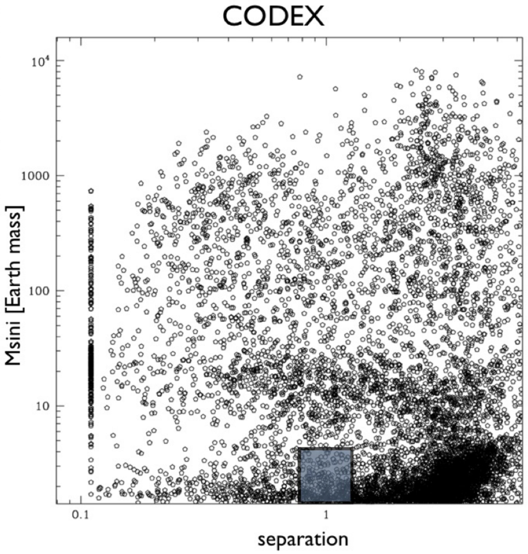
Radial velocities: the future

ESPRESSO@VLT: 1 to 4 telescopes of 8.2m
precision ~10cm/s for bright solar-type stars

HIRES@E-ELT: telescope of 39m
precision of 2 cm/s for bright solar-type stars







Radial velocities: the future

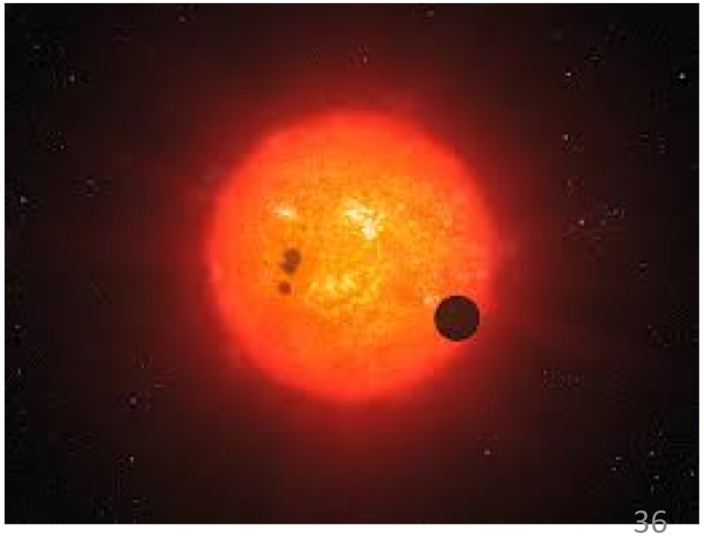
IR spectrographs to search for small planets around ultra-cool stars, e.g.

Carmenes @ Calar Alto, 3.5m telescope
precision of 1m/s for ~300 ultra-cool stars (>M4)

SPIROU @ CFHT 3.6m telescope
precision of 1m/s for ultra-cool stars

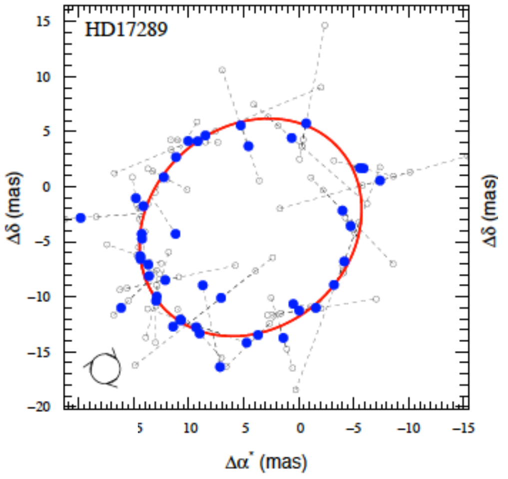
Habitable Zone planet Finder (HPF) @ Hobby-Eberly 10m telescope
precision <1m/s for ultra-cool stars

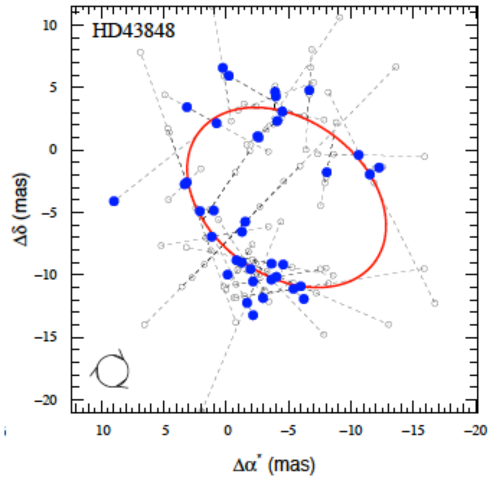
Etc…

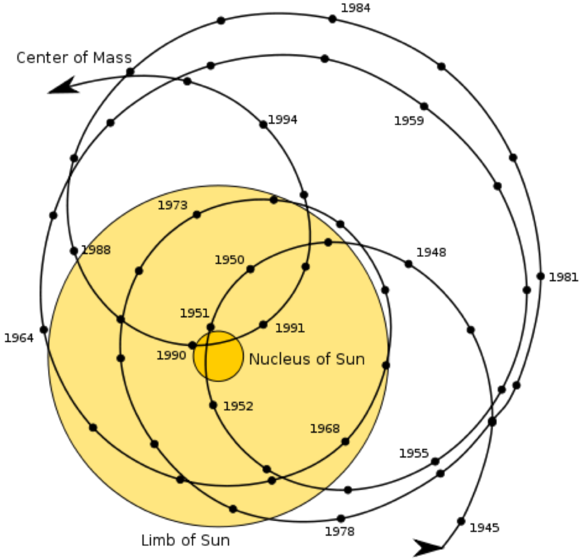


The astrometric method

Motion of the star in the plane of the sky (circular orbit)







$$\boxed{\theta = \frac{a}{d}\frac{m_p}{m_*}} = \left(\frac{G}{4\pi^2}\right)^{1/3}\frac{m_p}{m_*^{2/3}}\frac{P^{2/3}}{d}$$

$$\boxed{\theta = 5mas}\frac{m_p}{M_J}\left(\frac{m_*}{M_{sun}}\right)^{-2/3}\left(\frac{P}{11.8yr}\right)^{2/3}\left(\frac{d}{pc}\right)^{-1}$$

Jupiter

$$\boxed{\theta = 3\mu as}\frac{m_p}{M_\oplus}\left(\frac{m_*}{M_{sun}}\right)^{-2/3}\left(\frac{P}{1yr}\right)^{2/3}\left(\frac{d}{pc}\right)^{-1}$$

Earth

$m_p << m_*$

The astrometric method: results

~~1855: **first exoplanet detected** around the binary star 70 Ophiuchu (Jacobs)~~

~~1943: detection of massive exoplanets (Strand; Reyl & Holmberg)~~

~~1963: detection of an exoplanet of 1.6 M_J around **Barnard's star**, the second closest stellar system (van de Kamp)~~

~~Years 1960-1980: other planets (and brown dwarfs) detected, notably by Peter van de Kamp~~

All these detections have been ruled out and imputed to systematic effects

Typical precision for modern CCD imagery ~ 1-10 mas

Decrease in 1/d

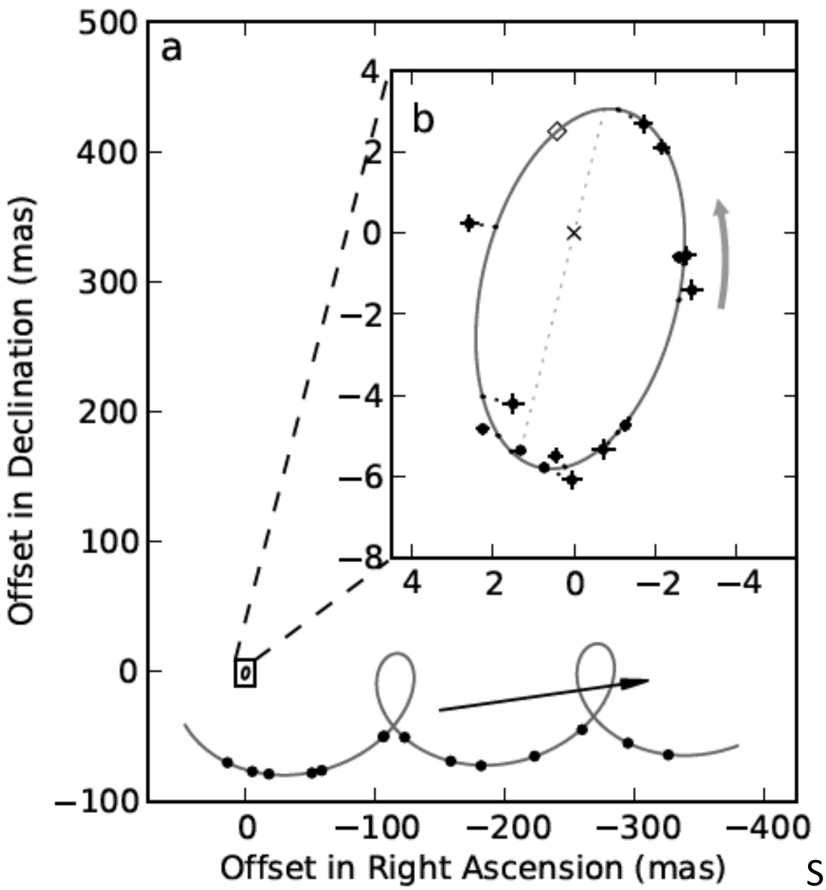
Favors long-period massive planets

The astrometric method

Ground-based CCD imagery

Main source of error = atmospheric turbulence

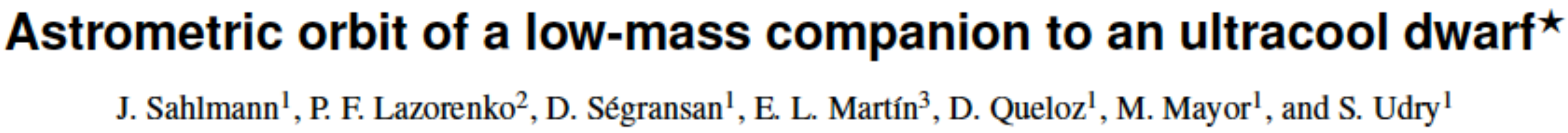
Solution = differential astrometry in a small field (a few arcmins) with a large aperture telescope. Needs many reference stars nearby.



Salhmann et al. (2013)

σ = 0.1 mas for a 10 min exposure with a 10m telescope

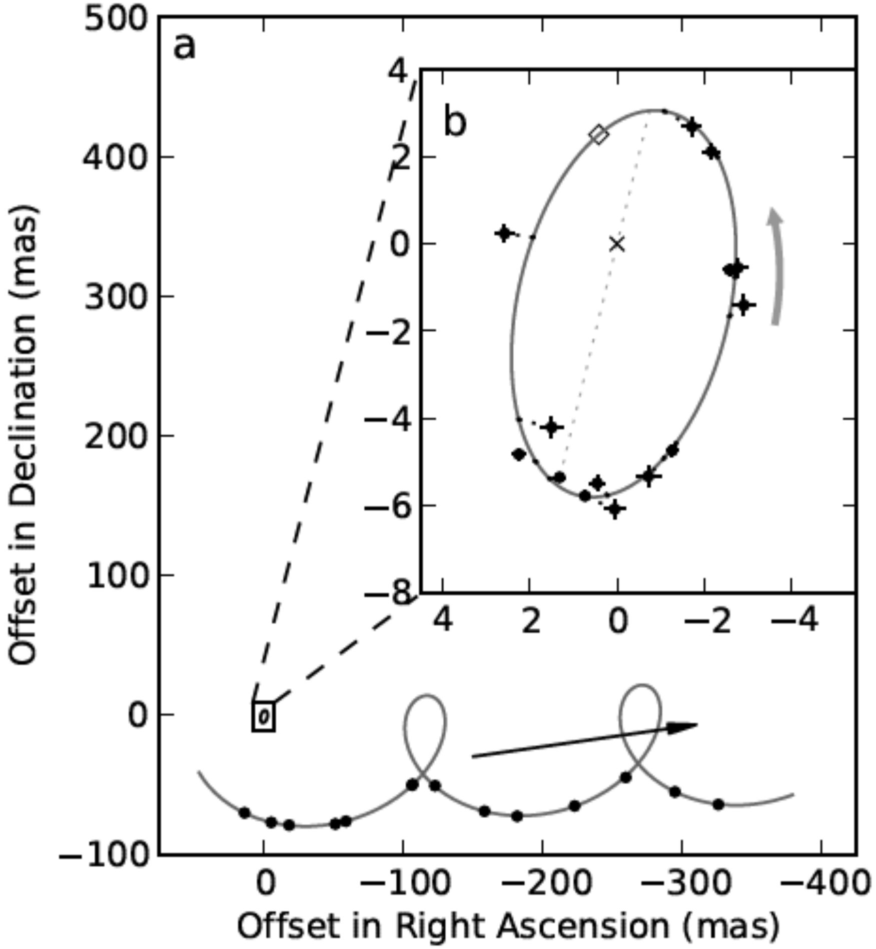
The astrometric method: results



Astrometric orbit of a low-mass companion to an ultracool dwarf★

J. Sahlmann[1], P. F. Lazorenko[2], D. Ségransan[1], E. L. Martín[3], D. Queloz[1], M. Mayor[1], and S. Udry[1]

Astronomy and Astrophysics, 556, 133 (2013)



P = 245 days
e = 0.35
a = 0.36 au
M_1 = 78.4+-7.8 M_{Jup}
M_2 = 28.5+-1.9 M_{Jup}

A pair of brown dwarfs at 20 parsec

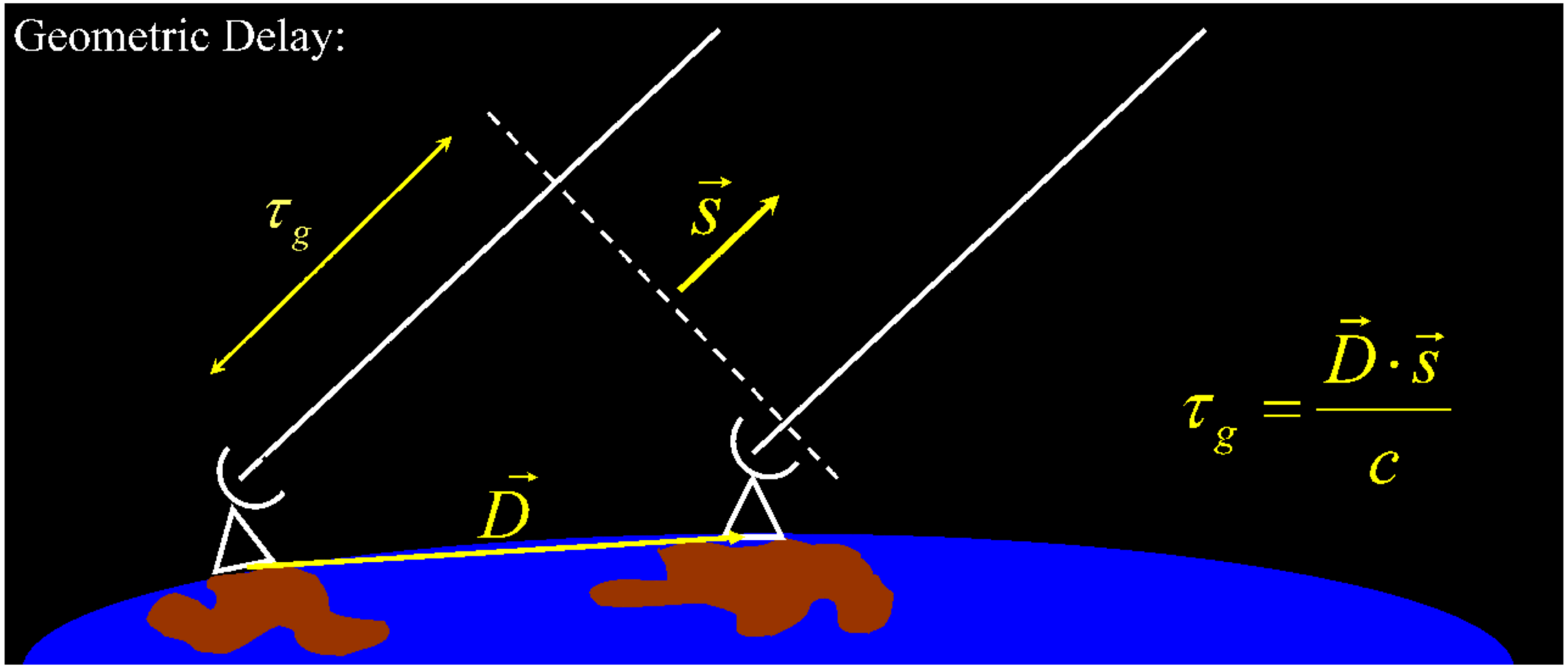
Promising approach for nearby very-low-mass stars and brown dwarfs

The astrometric method

Ground-based interferometry

For two stars at > 0.5°, the differential astrometric precision with CCD ground-based astrometry does not depend any more of the size of the telescope and is fully given by the atmospheric turbulence.

Solution for« distant» stars: **Long-base interferometry**. The size of the virtual telescope is larger than the separation of the light rays at the top of the atmosphere (~100m)
Expected precision: down to 0.01 mas (ex. VLT/PRIMA)



The astrometric method

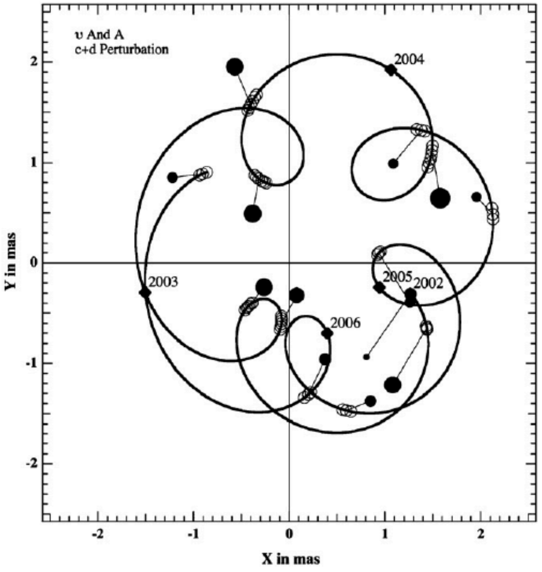
Ground-based interferometry: very difficult

The astrometric method: results

Space: follow-up of exoplanets detected by RVs

HST Fine Guidance Sensors (interferometry) :

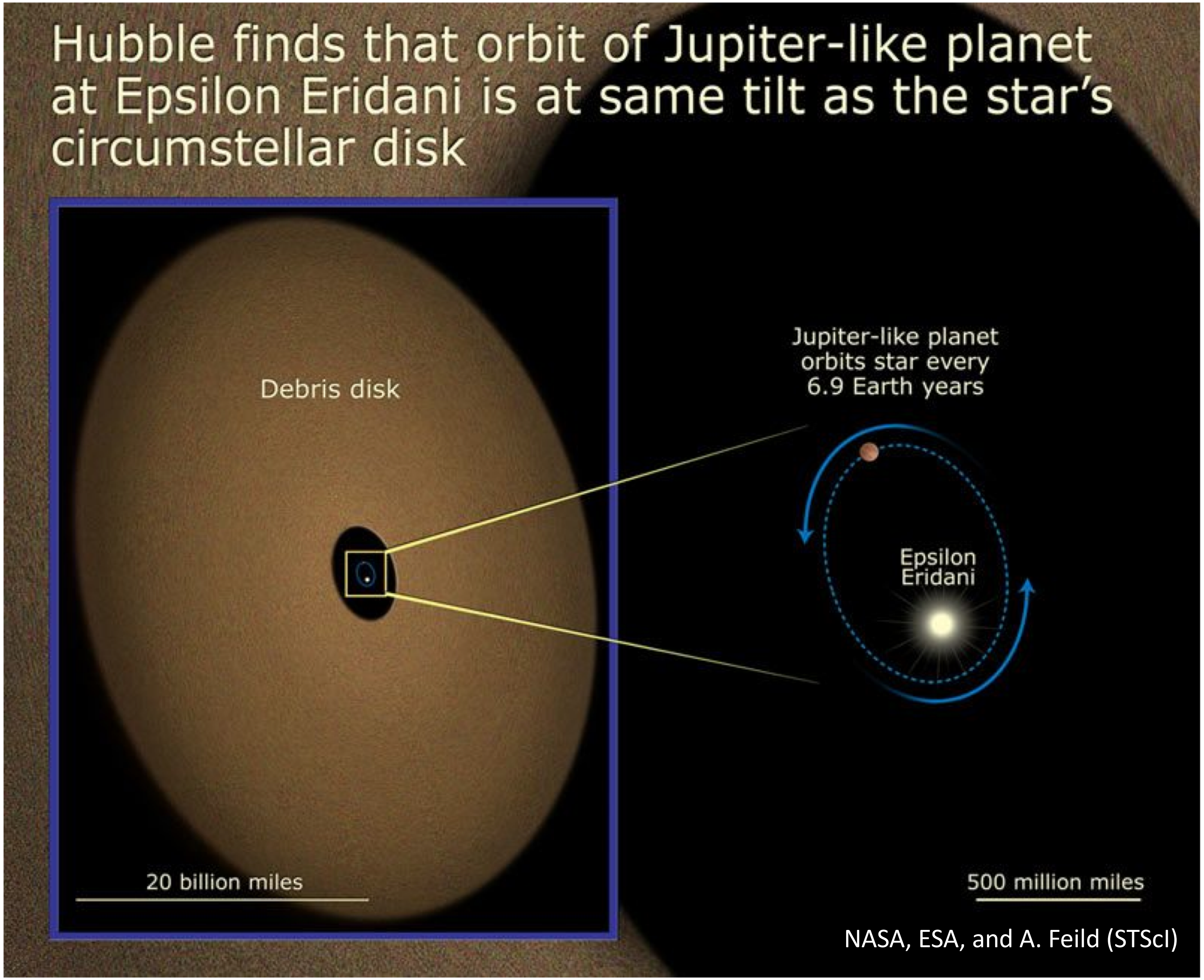
- **Gl 876 b (5 pc)** : P=60d, Msini~2 M_{jup} ➔ M_p=2.6 M_{Jup} (Benedict et al. 2002; Bean & Seifarth 2009)
- **ε Eri b (3 pc)** : P=2500d, Msini~1.2M_{Jup} ➔ M_p=1.6 M_{Jup} (Benedict et al. 2006)
- **HD 33636 b (29 pc)** : P=2130 d, Msini~9 M_{Jup} ➔ M_2=0.14 M_{Sun} (Bean et al. 2007)
- **u And c and d (14 pc)** : $M_c$sini=2M_{jup}, P_c=241j + $M_d$sini=4.3 M_{jup}, P_d=1282 ➔ M_c=14 M_{jup}, M_d=10 M_{jup}, i_{mut}=30° (Mac Arthur et al. 2010)



+ a few upper limit on M_2 from Hipparcos data

The astrometric method: results

Space: follow-up of exoplanets detected by RVs

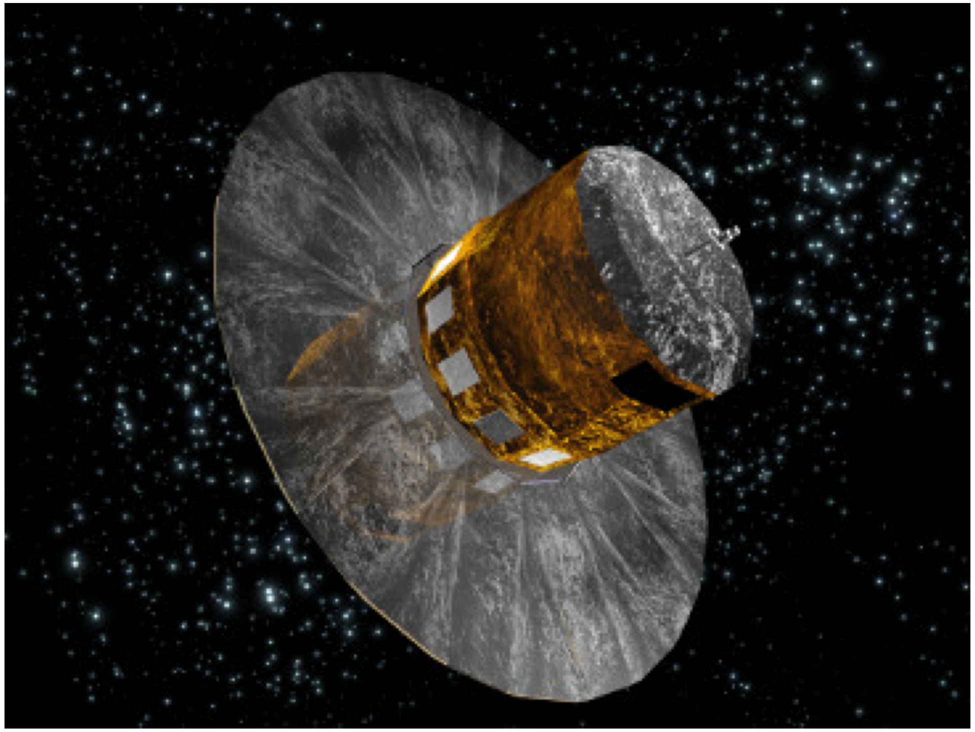


NASA, ESA, and A. Feild (STScI)

The astrometric method: the future

The ESA Gaia mission

ESA mission
Launched on Dec 19th 2013
2 telescopes of 1.45m aperture
1 third telescope for spectroscopy
Orbit: Earth-Sun L2 point
Photometry + astrometry + RV for 10^6 stars
Maximum magnitude ~ 20 (or less ?)
For each star: ~70 measurements over 5 years
Expected astrometric precisions:
20 µas @ mag 15
200 µas @ mag 20 (?)



Expected harvest: ~1000 long-period massive planets
Strong constraints on the frequency of Jupiter analogs

The timings method

Principle: delay or advance of a periodic signal due to the orbital motion of the source and the finite speed of light (*light travel time*)

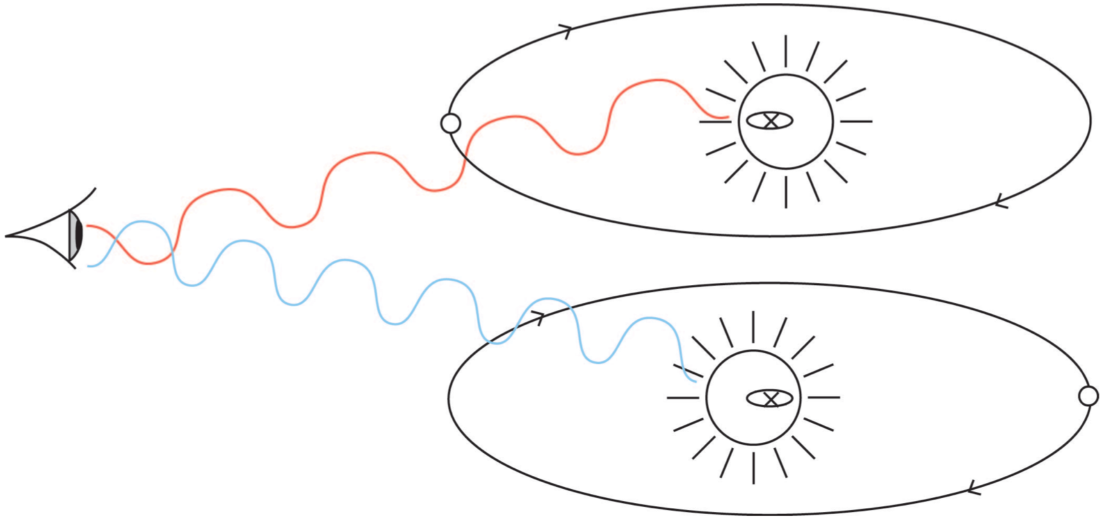
Targets = source with a very stable periodic signal:

pulsars
pulsating stars
eclipsing binaries

Amplitude :

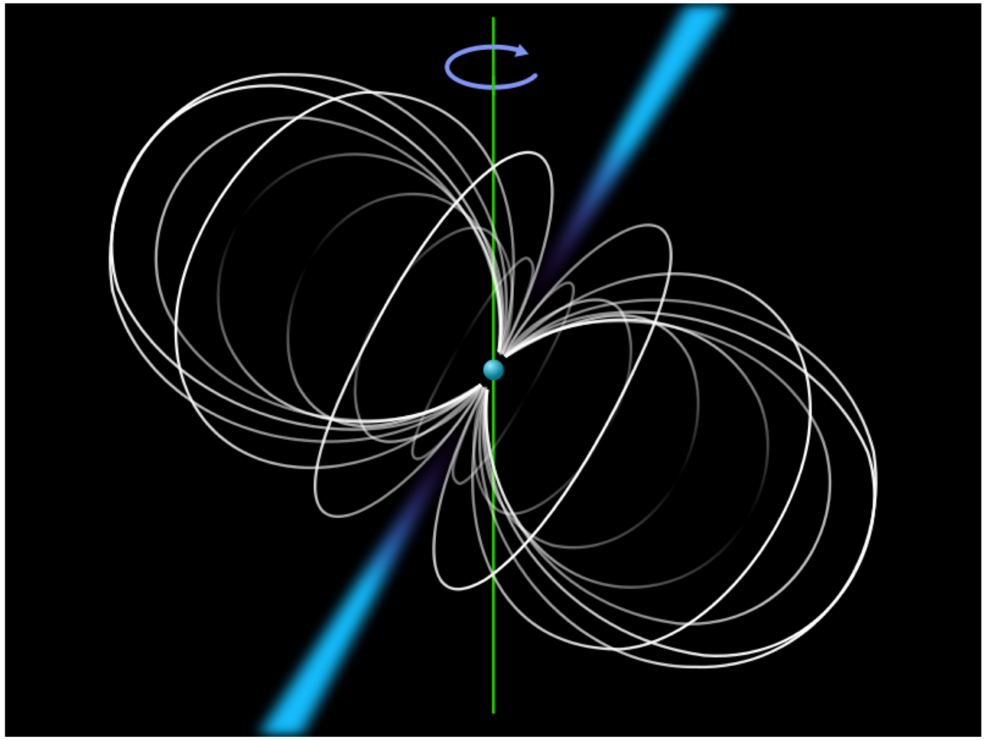
$$\boxed{\Delta t = \frac{1}{c}\frac{a \times M_p \sin i}{M_*}}$$

Earth + Sun = 1.5 ms
Jupiter + Sun = 2.5 s



The timings method: pulsars

Pulsar: neutron star in fast rotation and with its dipolar magnetic axis inclined with respect to its rotation axis. Radio emission beam in the direction of the magnetic axis sweeps Earth once per rotation
~1700 known pulsars



Two classes of pulsars: « regular » with P~1s, and millisecond (~10%).
Millisecond pulsars: hyper-stables, and precision on the period down to µs
Precision high enoug to detect a big asteroid!

The timing method: pulsars

Pulsar PSR B1257+12: d~300pc, P~6.2ms, M_{*}~1.35M_{Sun}

1990 : Arecibo radiotelescope shows periodicity departures

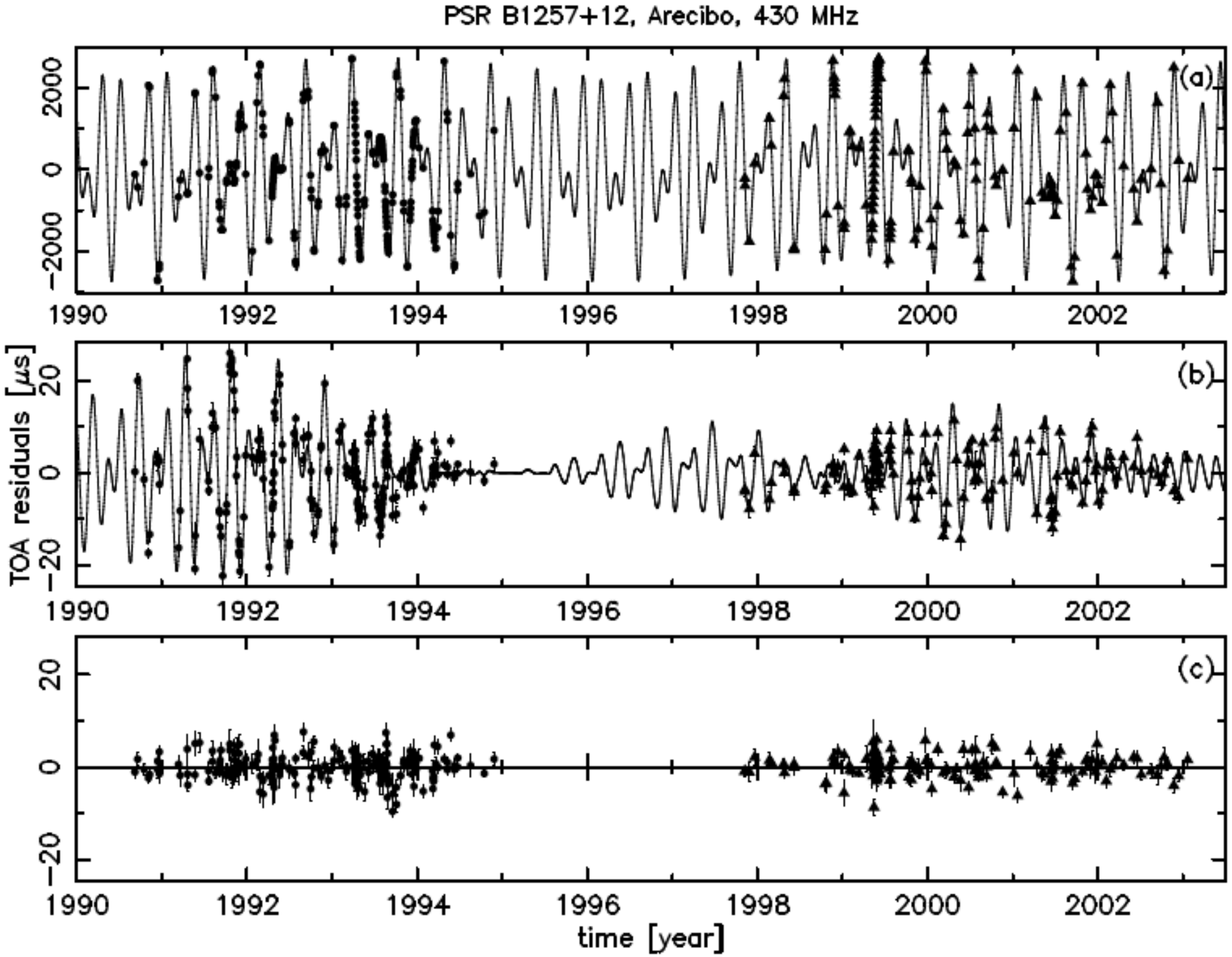
1992 : announcement of 2 planets of a few M_{Earth} (Wolszczan & Frail)

1994 : 3rd planet with $M_p < 2M_{Moon}$ (Wolszczan)

	A	B	C
$M(M_E)$	0.020	4.3	3.9
P(d)	25.3	66.5	98.2
a(AU)	0.19	0.36	0.46

Stable system

Formation ?

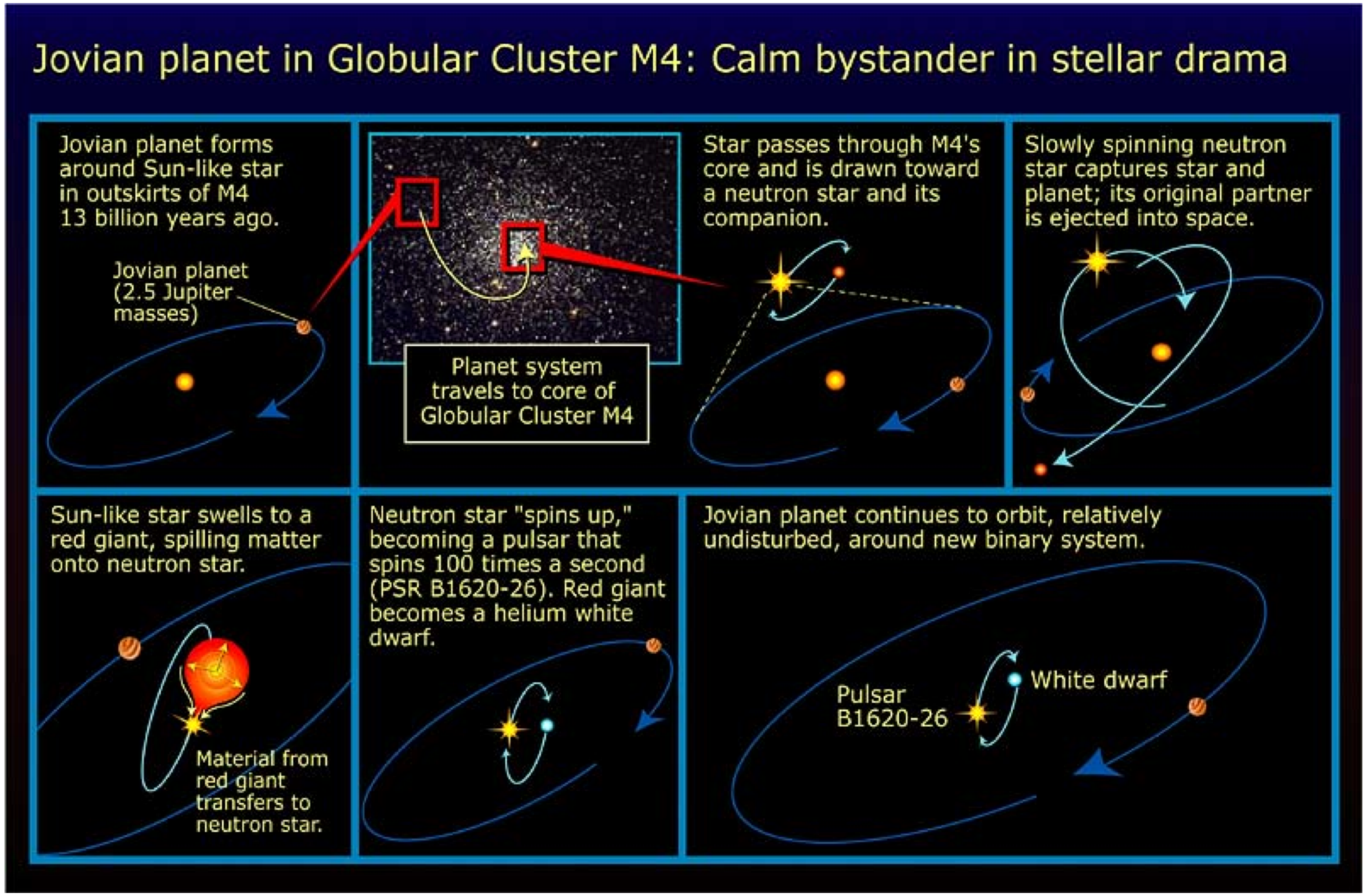


(Konacki & Wolszczan, 2003)

The timing method: pulsars

Pulsar PSR B1620-26: d~380pc, in the globular cluster M4. Binary system with a pulsar (~1.35 M_{sun}, P~11ms) + white dwarf (0.3 M_{sun}), with P=191d.

1993 (confirmed in 2003) : discovery of a circumbinary planet of 2.5 M_{jup} *(Thorsett et al.)* a~23 au, P~100 yrs. **Age: up to 13 Gyrs**



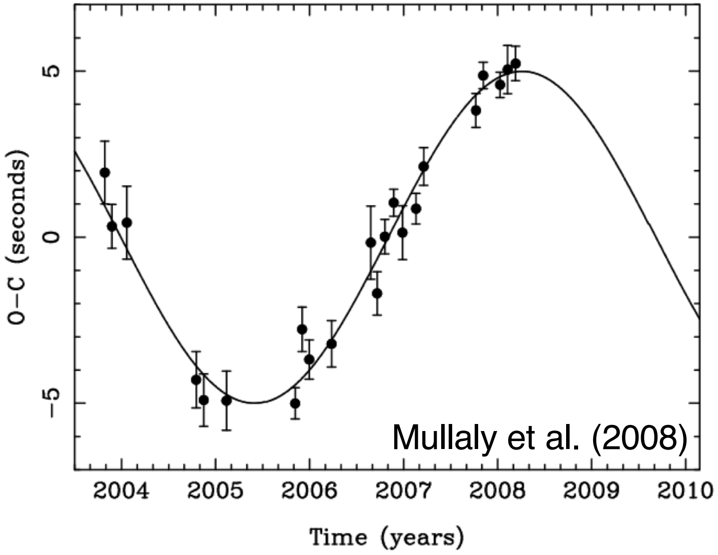
The timing method: pulsations

Two type of very stable pulsators:

1/ White dwarfs of classes GW Vir, DBV, DAV. g-type pulsations, related to the partial ionization of C/O, He et H. P=100-1000s

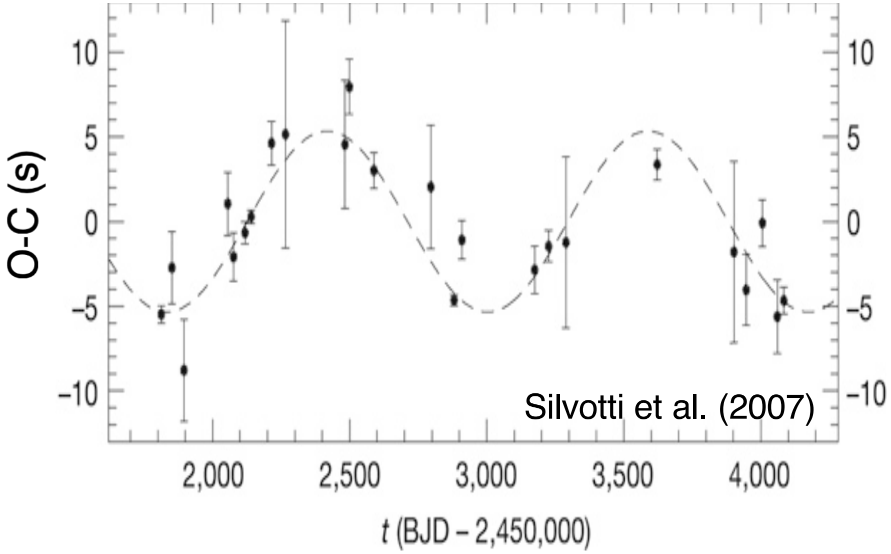
2/ Sub-dwarf stars of type sdB = red giant having lost its hydrogen envelop. p-type pulsations, with P of a few 100s.

V361 Aur
DAV@51 pc
0.65 M_{Sun}, 0.013 R_{sun}
12000K



M>2.4MJup, a=2.8au, P=5.7yr

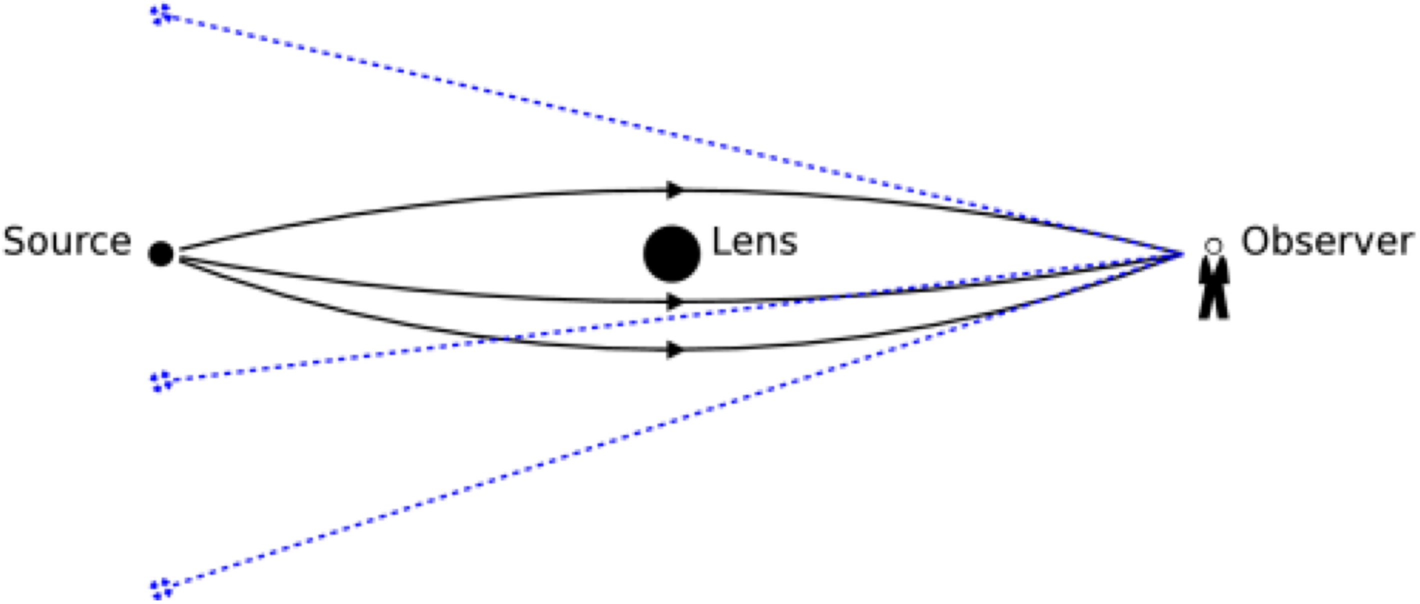
V391 Peg
sdB@1400 pc
0.5 M_{Sun}, 0.23 R_{Sun}
29000K



M>3.2MJup, a=1.7au, P=3.2yr

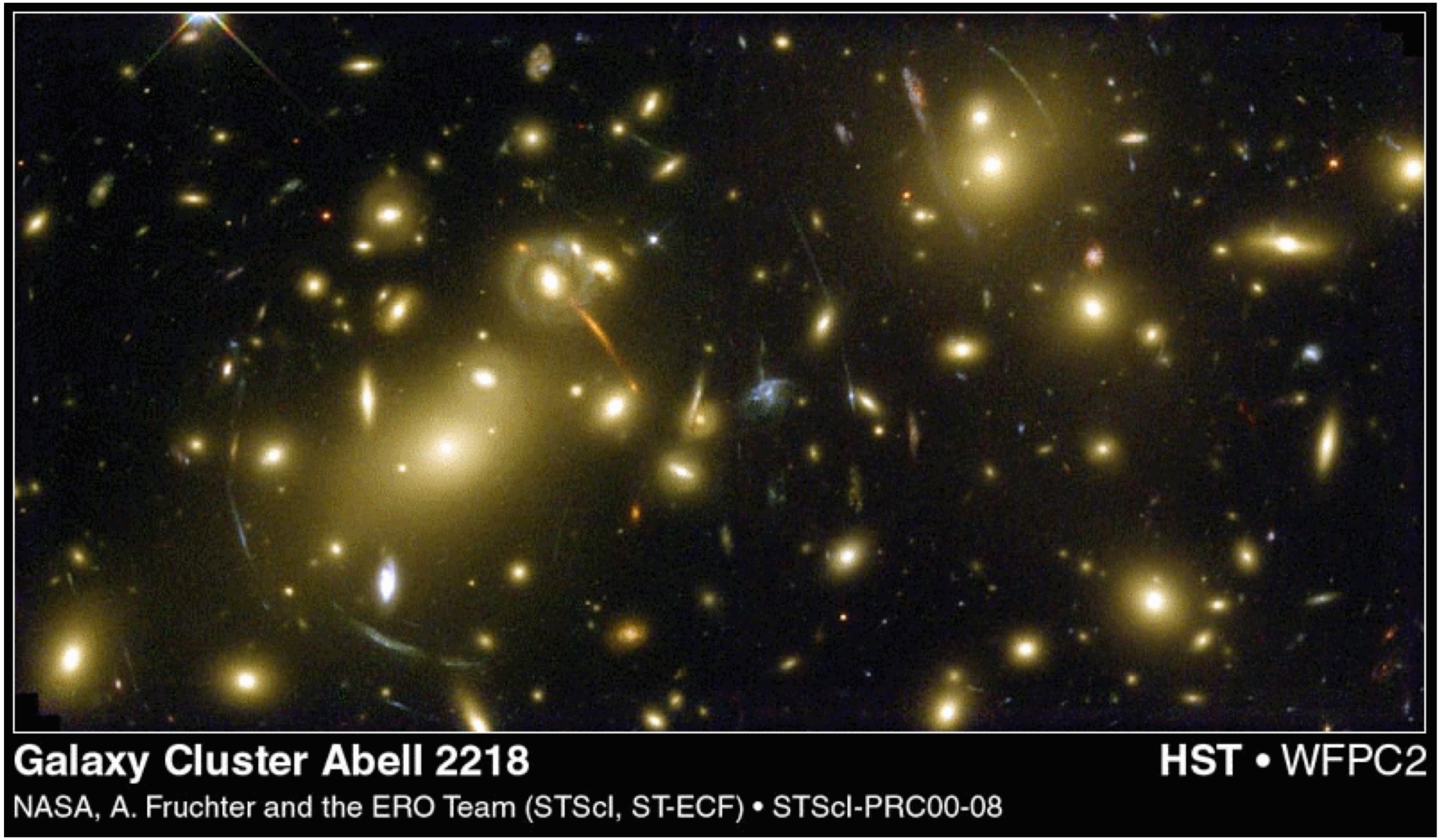
The gravitational microlensing method

Principle : general relativity predicts that light rays are deflected by matter/energy. The light of a distant source grazing a lens (e.g. star, planet) can be deflected towards Earth. The source appears then brighter.



The gravitational microlensing method

Macrolensing: the different images of the source can be observed as point sources or arcs.



The gravitational microlensing method

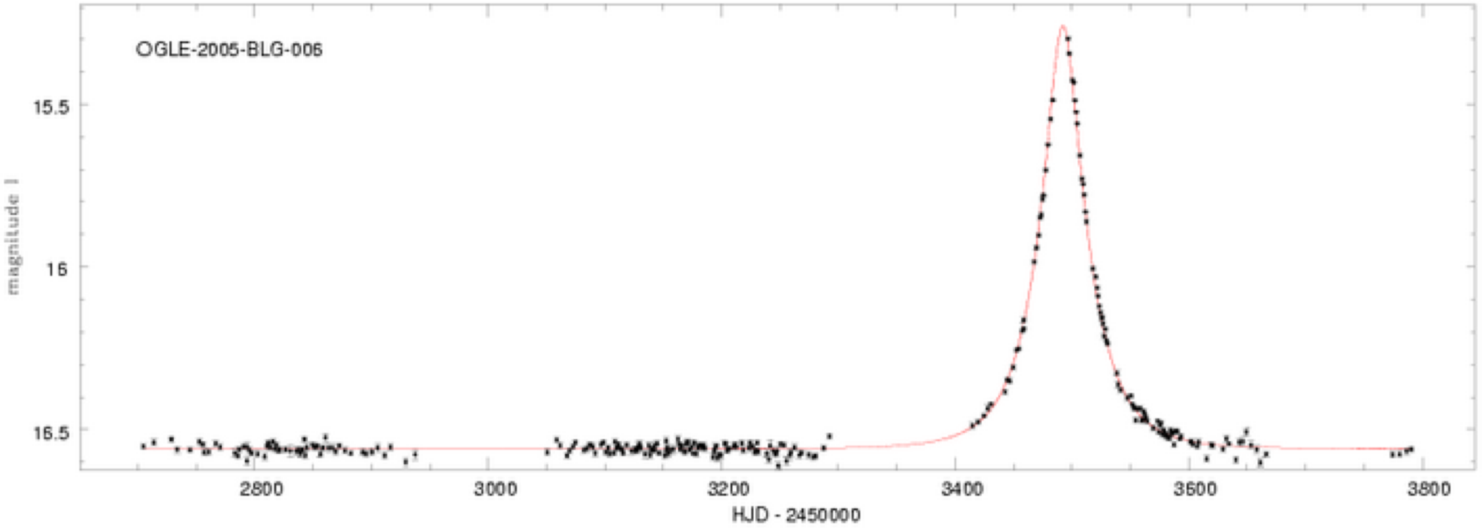
Microlensing: the different images of the source are not resolved. The most significant effect is photometric.

- **Required alignement** ~1 mas -> very rare. Detection of stellar microlensing makes necessary to observe very dense stellar fields.

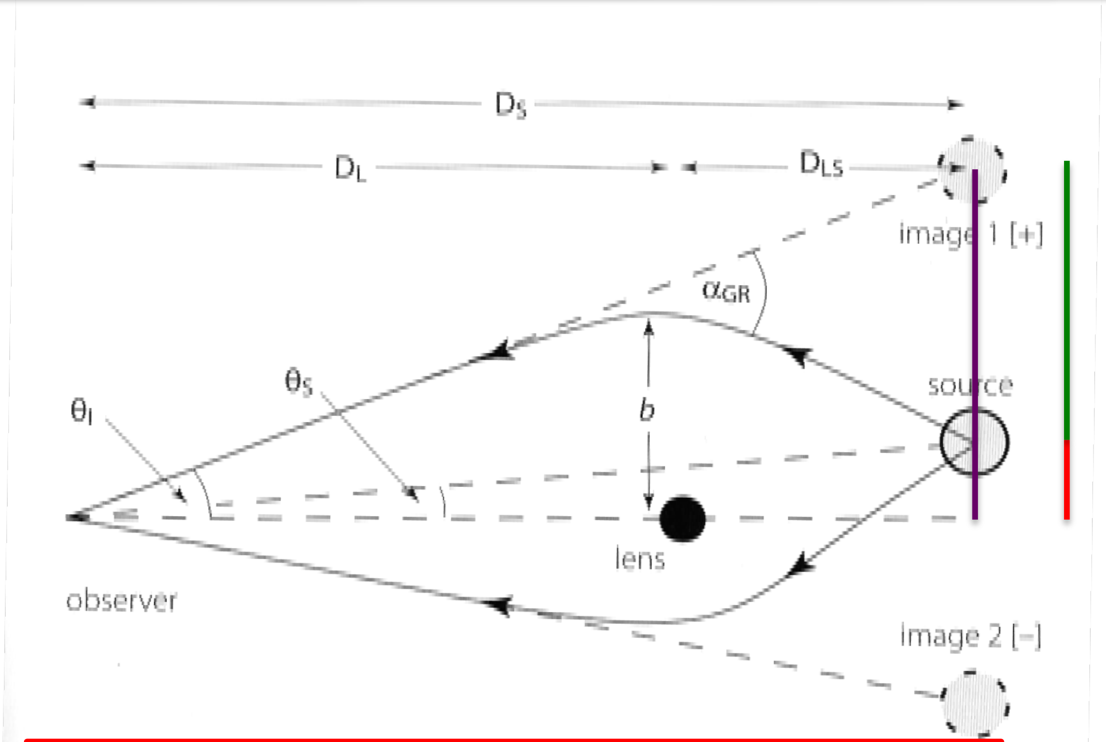
- **Typical source:** 1 star of the galactic bulge at ~8kpc

- **Typical lens:** 1 star of the galactic disk ~4kpc

- **Typical duration:** determined by the relative motion of the two stars. Typically a few weeks to a few months.



The gravitational microlensing method



$$\boxed{\alpha_{GR}=\frac{4GM_L}{c^2 b}=\frac{2R_{Sc,L}}{b} \qquad \text{with } b \gg R_{Sc,L}}$$

$$\underline{\theta_S D_S}=\underline{\theta_I D_S}-\underline{\alpha_{GR} D_{LS}}$$

$$b=\theta_I D_L$$

$$\Rightarrow \quad \theta_s=\theta_I-\frac{2R_{Sc,L}}{b}\frac{D_{LS}}{D_S}=\theta_I-2R_{Sc,L}\frac{D_{LS}}{D_S D_L}\frac{1}{\theta_I}$$

Lens equation

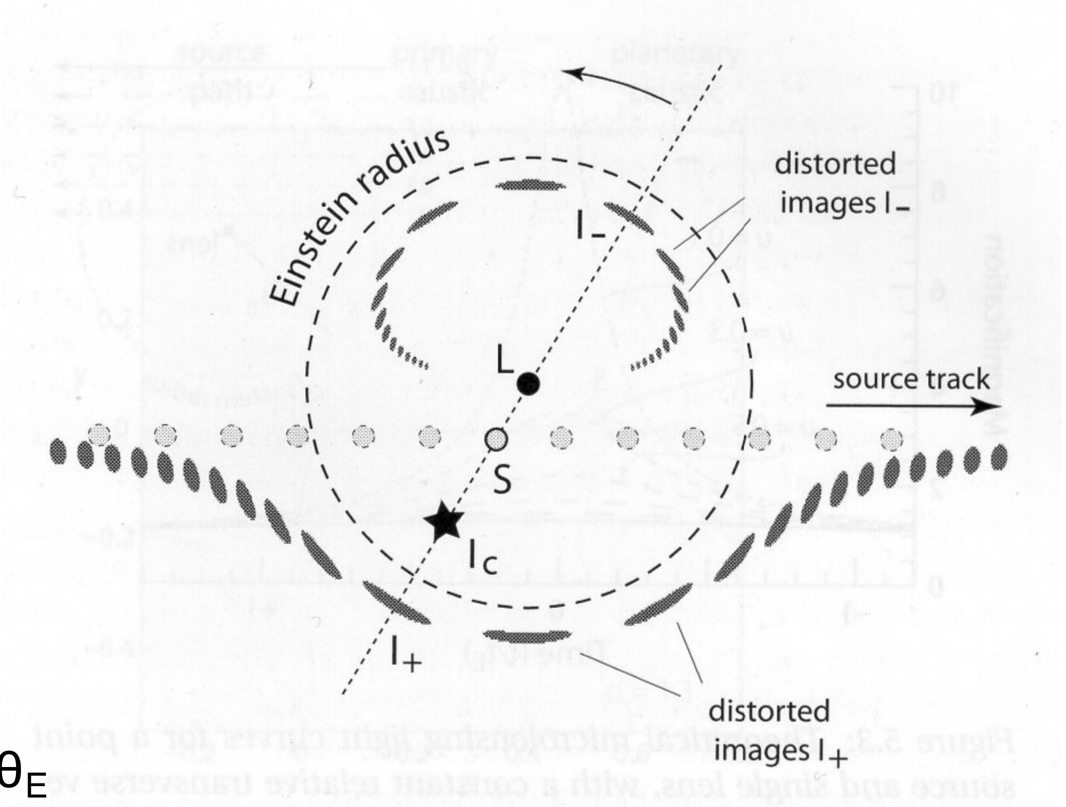
The gravitational microlensing method

$$\theta_s = \theta_I - \frac{2R_{Sc,L}}{b}\frac{D_{LS}}{D_L} = \theta_I - 2R_{Sc,L}\frac{D_{LS}}{D_S D_L}\frac{1}{\theta_I}$$

Let's define the **Einstein radius :** $\theta_E = \sqrt{2R_{Sc,L}\frac{D_{LS}}{D_S D_L}}$ **= limit angle for high magnification**

Lens equation becomes $\theta_I^2 - \theta_S\theta_I - \theta_E^2 = 0$

2 solutions : $\theta_{+,-} = \frac{1}{2}\left(\theta_S \pm \sqrt{\theta_S^2 + 4\theta_E^2}\right)$



If perfect alignement(θ_S=0)
images make an **Einstein ring** of radius θ_E

The gravitational microlensing method

In numbers…

$$\theta_E \approx 0.4\left(\frac{M_L}{0.3M_{Sun}}\right)^{1/2}\left(\frac{D_L}{2kpc}\right)^{-1/2}\left(\frac{D_{LS}}{D_S}\right)^{1/2} mas,$$

$$R_E = \theta_E D_L \approx 2.2\left(\frac{M_L}{0.3M_{Sun}}\right)^{1/2}\left(\frac{D_L}{2kpc}\right)^{1/2}\left(\frac{D_{LS}}{D_S}\right)^{1/2} au$$

For a typical stellar lens, the Einstein ring corresponds to the size of a planetary system

Amplification A ?

$$A = \frac{u^2+2}{u\sqrt{u^2+4}}, u \equiv \frac{\theta_S}{\theta_E}$$

$A \approx \frac{\theta_E}{\theta_S}$ if $\theta_S << \theta_E$

$A \approx 1$ if $\theta_S >> \theta_E$

Maximum recorded: A=3000 (delta mag = 8.7)

The gravitational microlensing method

Duration = Einstein time t_E

$$t_E = \frac{R_E}{v_\perp} \approx 21 \left(\frac{M_L}{0.3M_{Sun}}\right)^{1/2} \left(\frac{D_L}{2kpc}\right)^{1/2} \left(\frac{D_{LS}}{D_S}\right)^{1/2} \left(\frac{v_\perp}{200kms^{-1}}\right)^{-1} days,$$

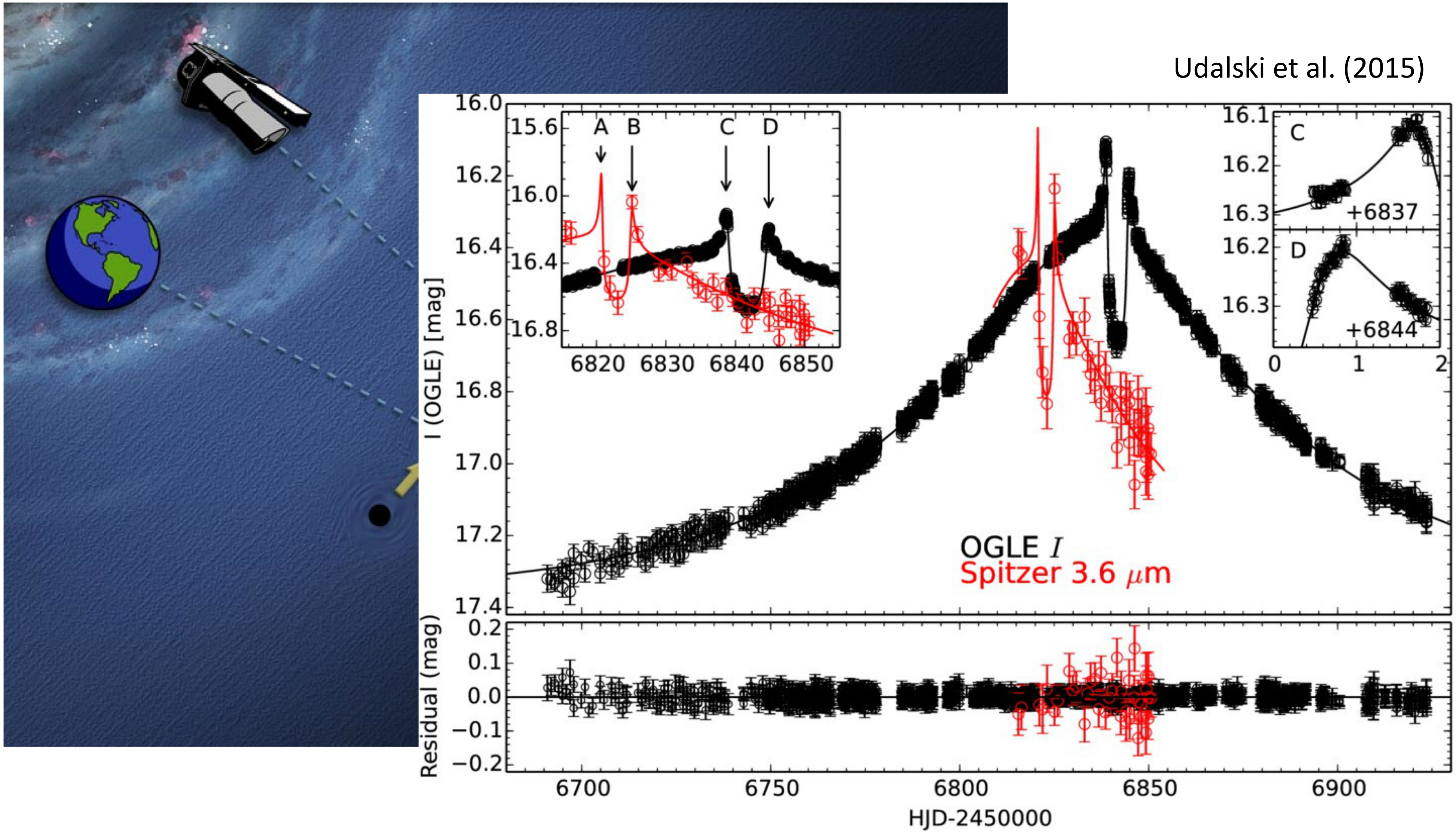
If the lens is not visible, *a priori* probability distributions for its **transversal velocity and distance** must generally be taken from a galactic model. Another option is based on finite source effects, that constrain the ratio R_E/R_S, and the microlens parallax that constrains the distance to the lens

In angular units

$$t_E = \frac{\theta_E}{\mu_{LS}} \longrightarrow \text{Relative proper motion}$$

The gravitational microlensing method

Microlens parallax



Udalski et al. (2015)

+ finite source effects (high amplification): distance and mass of the invisible lens

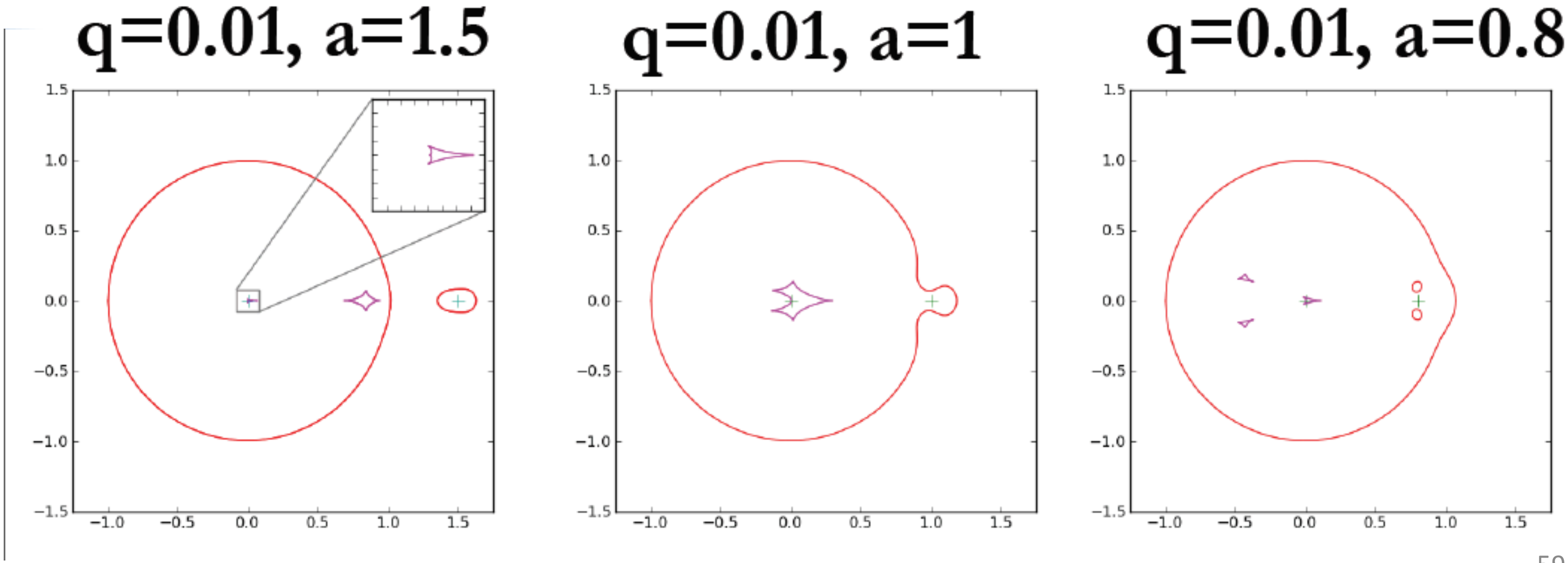
The gravitational microlensing method

Star + planet?

3 important parameters: $q=M_p/M_*$, $a(R_E)$, angle source-binary α

Additional structures of relative duration ≈ $q^{0.5}$

Each amplification maximum corresponds in the lens plane to a minimal distance between the source and a **caustic = maximal amplification zone**

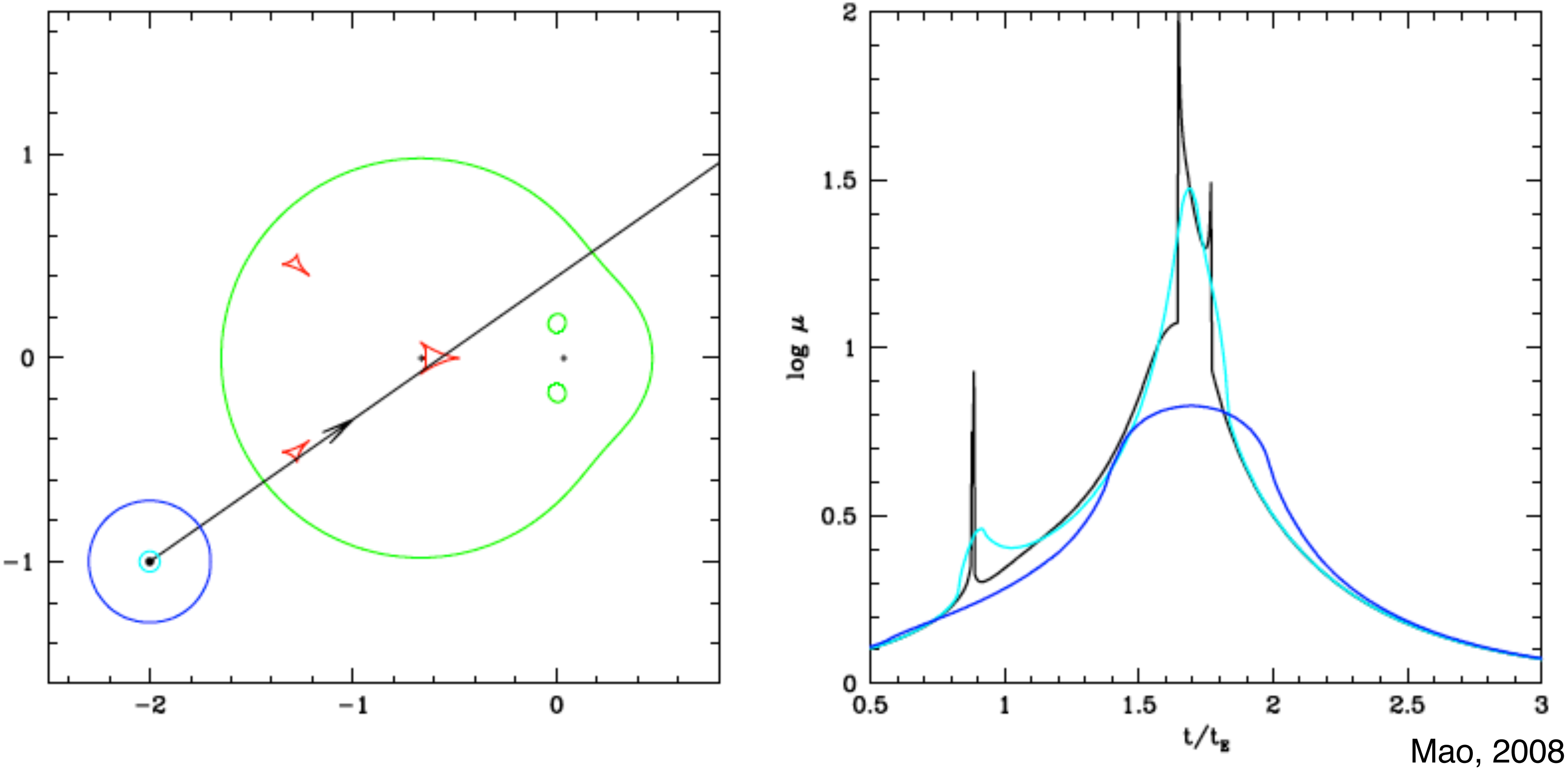

q=0.01, a=1.5

q=0.01, a=1

q=0.01, a=0.8

Erl & Schneider, 1993

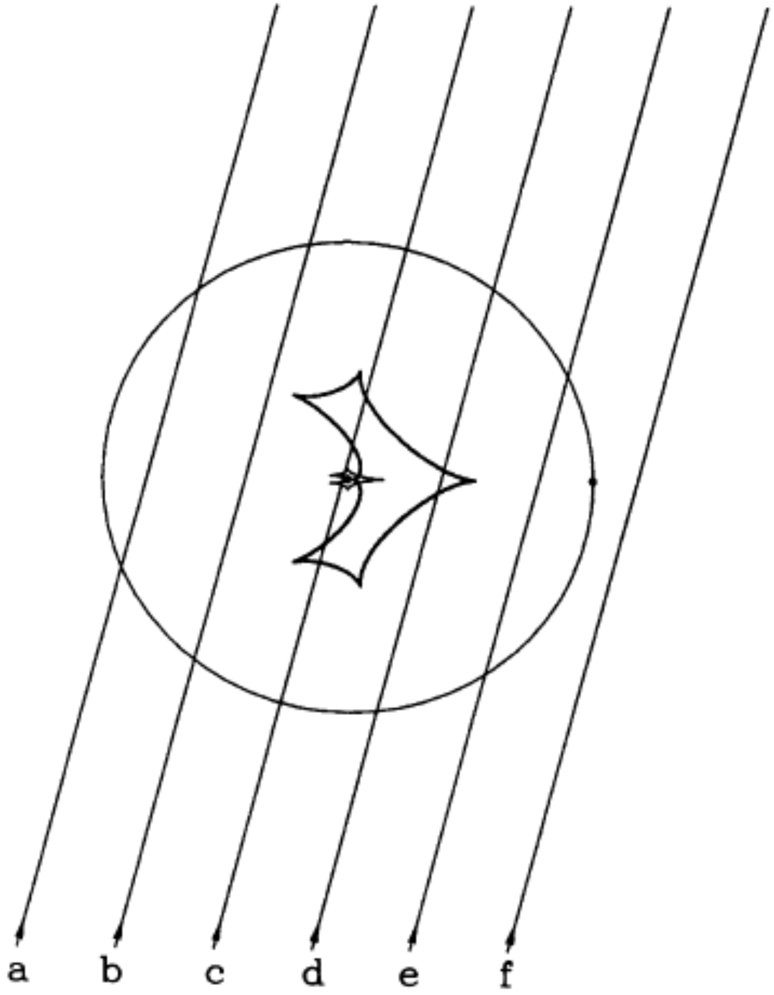
The gravitational microlensing method

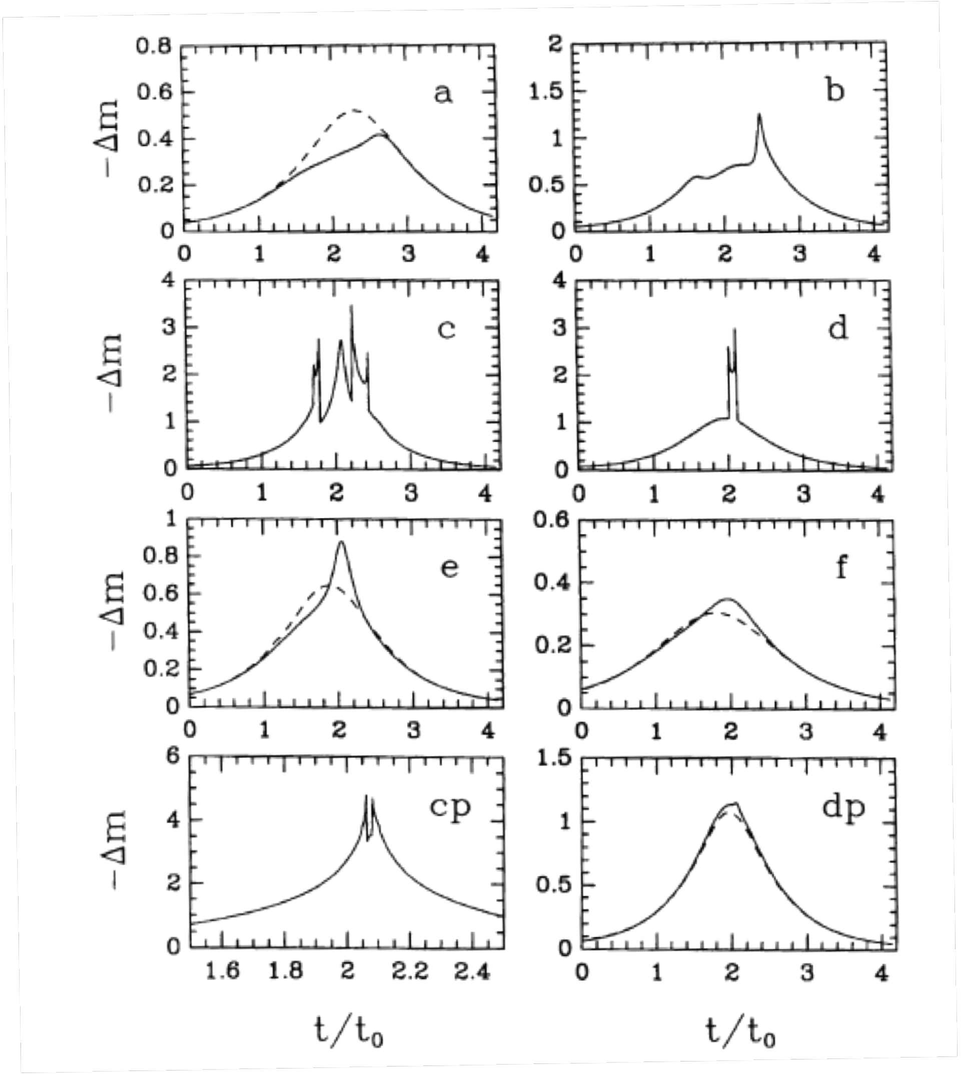


Mao, 2008

Anomalies last days for giant planets, hours for terrestrial planets
If the source’s path crosses a caustic, the amplification can be high even for terrestrial planets

The gravitational microlensing method





Mao & Paczynski 1991

The gravitational microlensing method

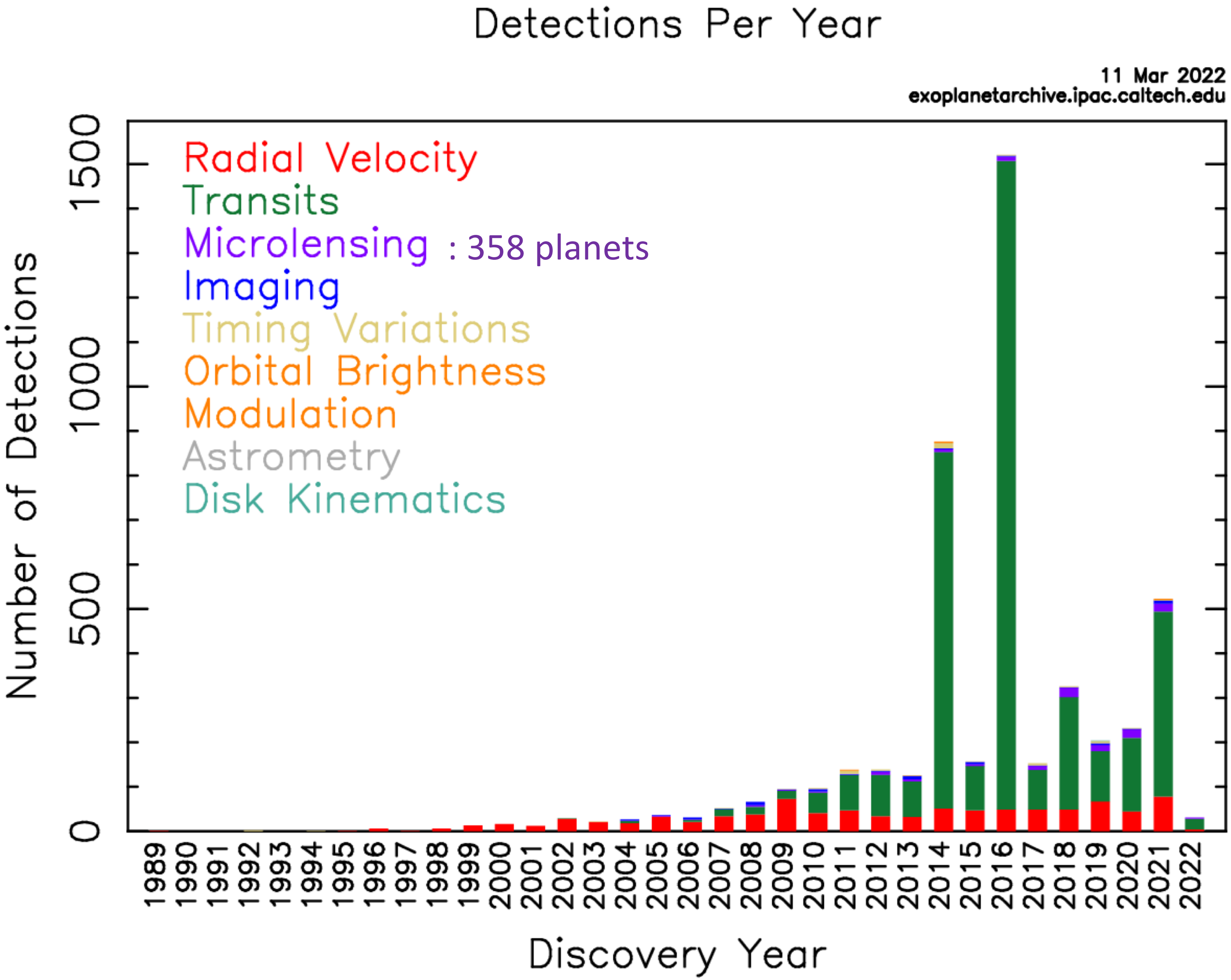
The advantages of the method

- Detection of planets around stars very far away: other area of the Galaxy explored
- Detection of free-floating planets
- Detection of multi-planetary systems
- Sensitive to planets at a few au of their stars, or less (red dwarfs)
- Sensitive to terrestrial planets (if high amplification)
- Permits to determine the mass of the lens and of the planet
- Insensitive to the activity of the host star
- Could in theory detect planets in M31

The drawbacks of the method

- Unique detection, no further possibility of confirmation and follow-up
- Distance of the system can behard to constrain if host star is not visible
- Complex modelling and models degeneracy
- No information on the structure and atmospheric properties of the planet

The gravitational microlensing method



: 358 planets

The gravitational microlensing method

Key discoveries

2005 : first planet detected by µlensing (Bond et al.)
OGLE-2003-BLG-235Lb – 5.8kpc – a~4.3 au – M_1~0.6 M_{Sun}- M_2~2.6 M_{jup}

2006 : first 'super-Earth' detected by µlensing (Beaulieu et al.)
OGLE-2005-BLG-390Lb – 6.6kpc – a~2.6 au – M_1~0.22 M_{Sun}- M_2~5.5 M_{Earth}

2008 : First multiple system detected by µlensing (Gaudi et al.)
OGLE-2005-BLG-109Lb – 1.5kpc – a~2.3 au – M_1~0.5 M_{Sun}- M_2~0.7 M_{Jup}
OGLE-2005-BLG-109Lc a~4.6 au M_2~0.3 M_{jup}

2009 : first planet around an ultra-cool dwarf (Bennett et al.)
OGLE-2005-BLG-192Lb – 0.66kpc – a~0.65 au – M_1~0.085 M_{Sun}- M_2~3.2 M_{Earth}

2011 : First free-floating planets (Sumi et al.)

2013 : two compact binary low-mass brown dwarfs (Choi et al.)
OGLE-2009-BLG-151L – 0.4kpc – a~0.3 au – M_1~19 M_{Jup}- M_2~8 M_{Jup}
OGLE-2011-BLG-0420L – 2kpc - a~0.2 au – M_1~26 M_{Jup}- M_2~10 M_{Jup}

« planet » around a brown dwarf (Han et al.)
OGLE-2012-BLG-0358Lb – 1.8kpc – a~0.9 au – M_1~23 M_{Jup}- M_2~2 M_{Jup}

2015 : First microlensing parallax measured at 2.5% precision (Udalski et al.)

The gravitational microlensing method

Important statistical results

1. Beyond the ice line, Neptunes and Super-Earths are ~7 times more frequent than Jupiters *(Sumi et al. 2010)*

2. Less than 20% of solar-type stars host a planetary system similar to ours *(Gould et al. 2010)*

3. There should be ~ twice more free-floating planets than main-sequence stars in the Milky Way *(Sumi et al. 2011)*

4. $17^{+6}_{-9}\%$ of stars have a Jupiter between 0.5 and 10 au *(Cassan et al. 2012)*
   $52^{+22}_{-29}\%$ Neptune
   $62^{+35}_{-37}\%$ Super-Earth

↓

In average, each star of the Galaxy hosts at least one planet $>5M_{\text{Earth}}$ between 0.5 and 10 au.

The gravitational microlensing method

In practice

1/ Detection of lensing anomalies by ground-based surveys OGLE (Chile) et MOA (New Zealand)

2/ Follow-up of anomalies by the multi-longitude networks PLANET/RoboNET, MicroFUN and MiNDSTEp

MicroFUN

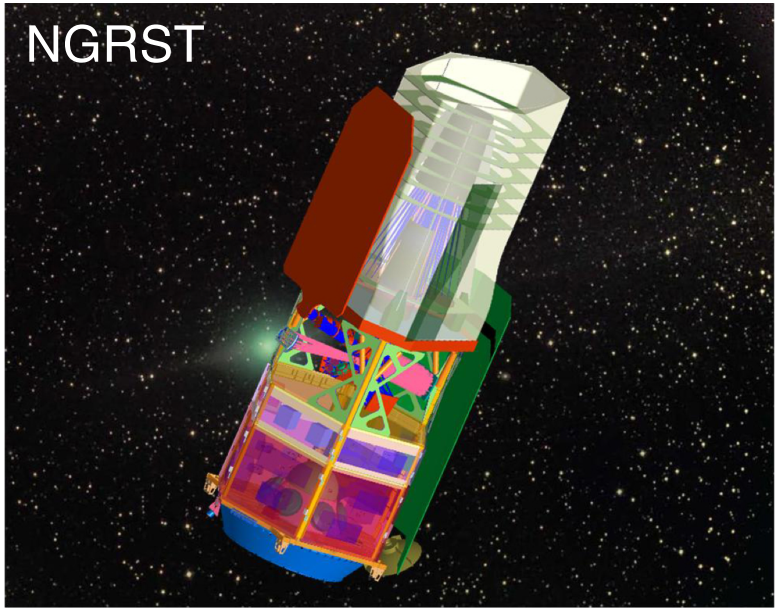
MICROLENSING FOLLOW-UP NETWORK

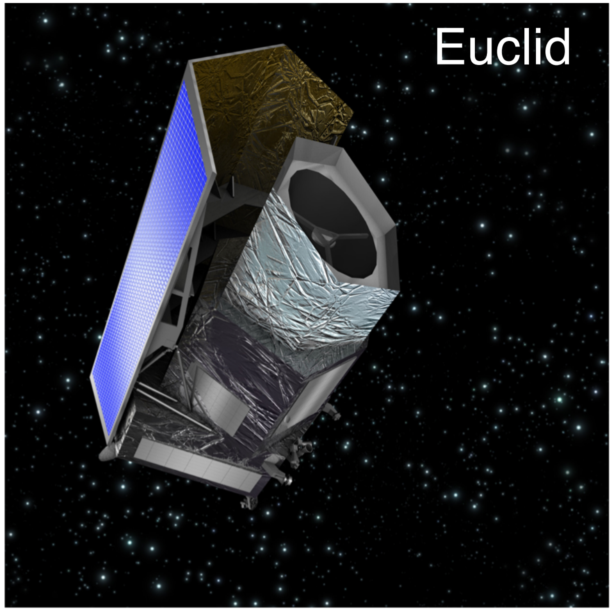
MiNDSTEp

Microlensing Network for the Detection of Small Terrestrial Exoplanets

The gravitational microlensing method

The future: space





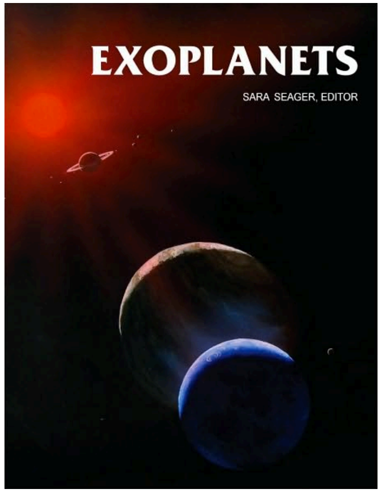
NASA
Nancy Grace Roman SpaceTelescope
Telescope of 2.4m – IR – 5 yrs
Earth-Sun L2 orbit
Launch in 2027
Expected harvest for NGRST
(Spergel et al. 2013) :

- 3000 planets
- 300 Earths – 40 Mars
- a few dozens of free-floating Earths

ESA
Telescope of 1.2m – Vis + IR – 6 yrs
Earth-Sun L2 orbit
Launch in 2023
Expected harvest for Euclid:
(Penny et al. 2013)

- Several hundreds of planets
- 50 Earths – 5 Mars
- a few free-floating Earths

References



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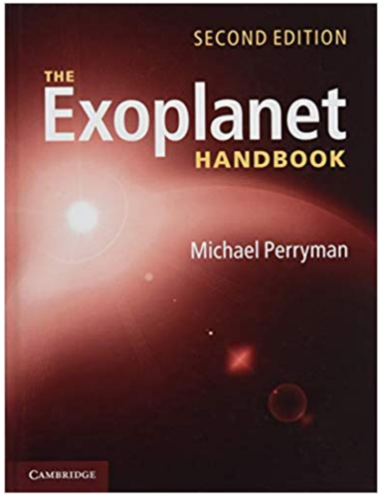
University of Arizona Press
Chapitres 3, 5, 7, 8



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Chapitres 2, 3, 4, 5