# Exoplanets

Vybrané kapitoly z astrofyziky
Podzim 2015
AI MFF UK
Přednáška 2
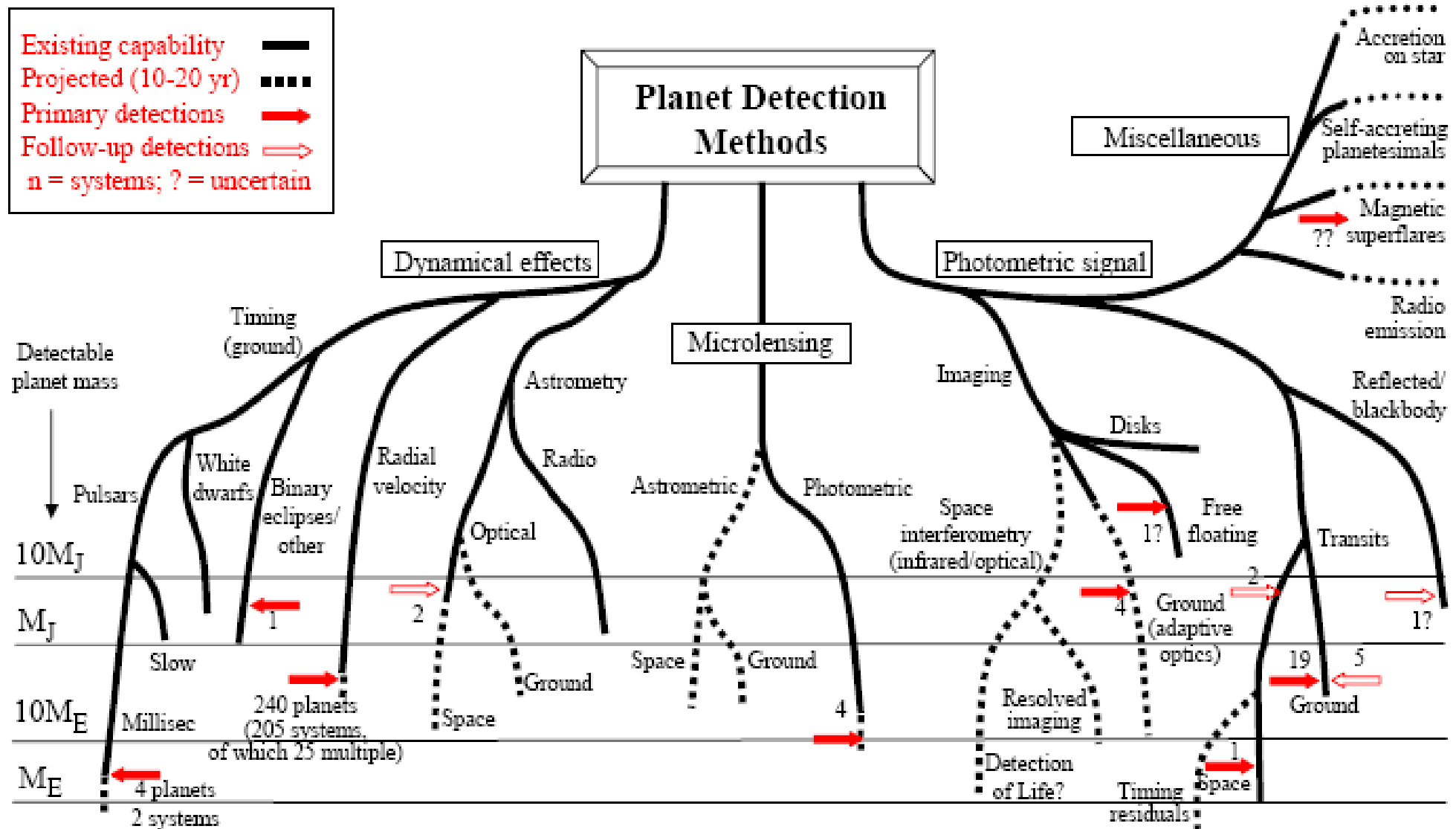14.10.2015

# Outline

- Intorduction of detection methods

- Radial velocities

- Transit detection

- Future prospects

- Statistical sample of planets

# Planet Detection Methods

Michael Perryman, Rep. Prog. Phys., 2000, 63, 1209 (updated 3 October 2007)

Existing capability ——
Projected (10-20 yr) ••••
Primary detections ➡
Follow-up detections ⇨
n = systems; ? = uncertain

**Planet Detection Methods**

Miscellaneous

Dynamical effects

Photometric signal

Microlensing

Detectable planet mass

Timing (ground)

Astrometry

Imaging

Accretion on star

Self-accreting planetesimals

?? Magnetic superflares

Radio emission

Reflected/ blackbody

White dwarfs

Binary eclipses/ other

Radial velocity

Radio

Astrometric

Photometric

Disks

Pulsars

Optical

Space interferometry (infrared/optical)

1? Free floating

Transits

$10M_J$

$M_J$

Slow

2

1

2

Space

Ground

Space

Ground

4

Ground (adaptive optics)

2

1?

$10M_E$

Millisec

240 planets (205 systems, of which 25 multiple)

Space

4

Resolved imaging

19

5

Ground

$M_E$

4 planets 2 systems

Detection of Life?

Timing residuals

1 Space

From: Perryman, Rep. Prog. Phys. 2000, 63, 1209 (updated May 2004)

# Radial velocities method (RV)

- Spectroscopical methood to detect planets

- Making use of the doppler effect

- Star and planet orbiting a center of gravity

- RV curve presents an amplitude due to planets typically about 200 m/s and less (depends on the parameters of the systém)

- Measurable quantitiy is the RV amplitude

- Determines lower mass limit only

# UVES – ESO Paranal

- High resolution (up to 110000), slit, echelle spectrograph
- Red and blue arm 300-1100nm
- RV accuracies to 25 m/s



Credit ESO
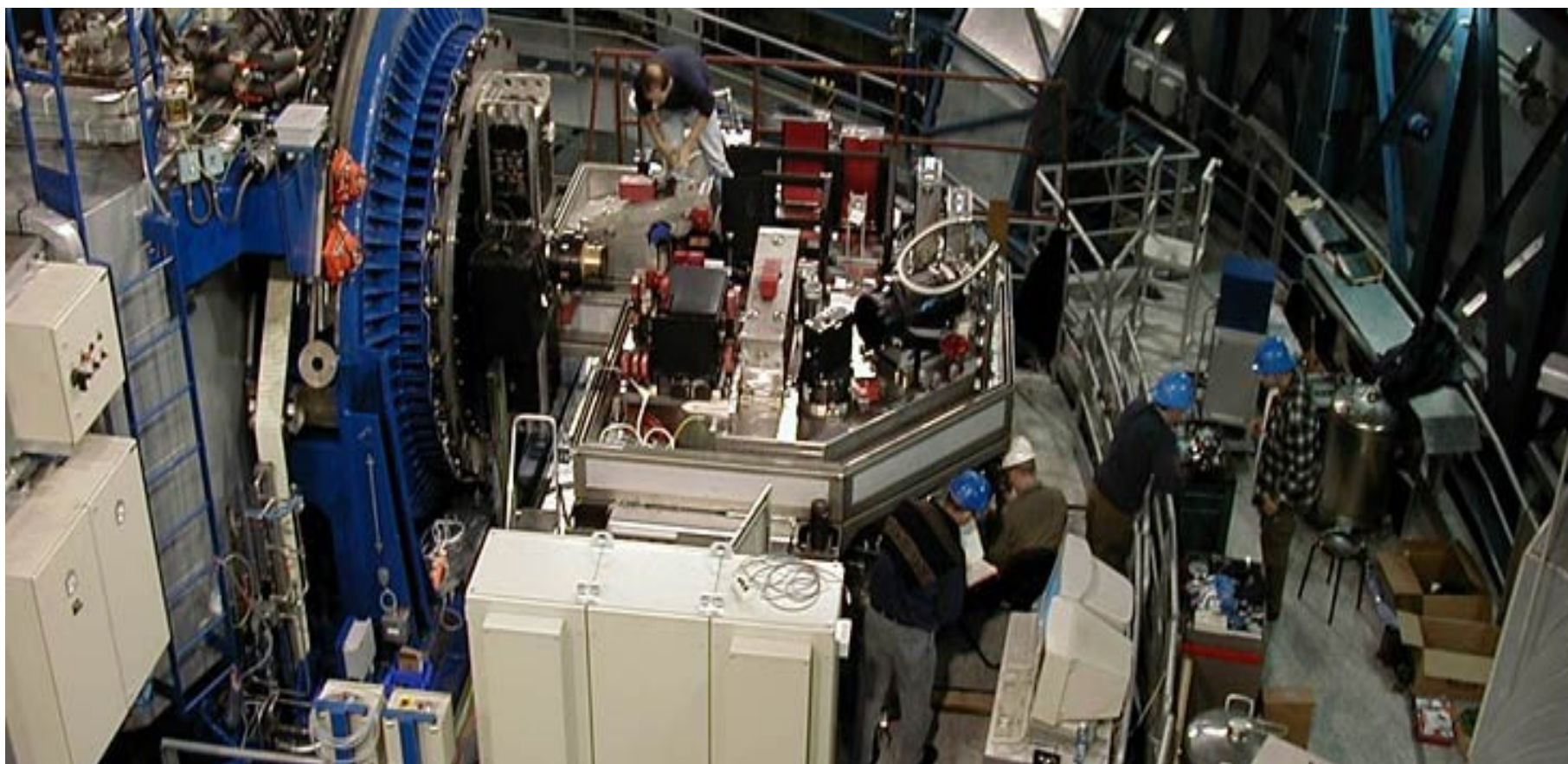
# Spectrograph UVES
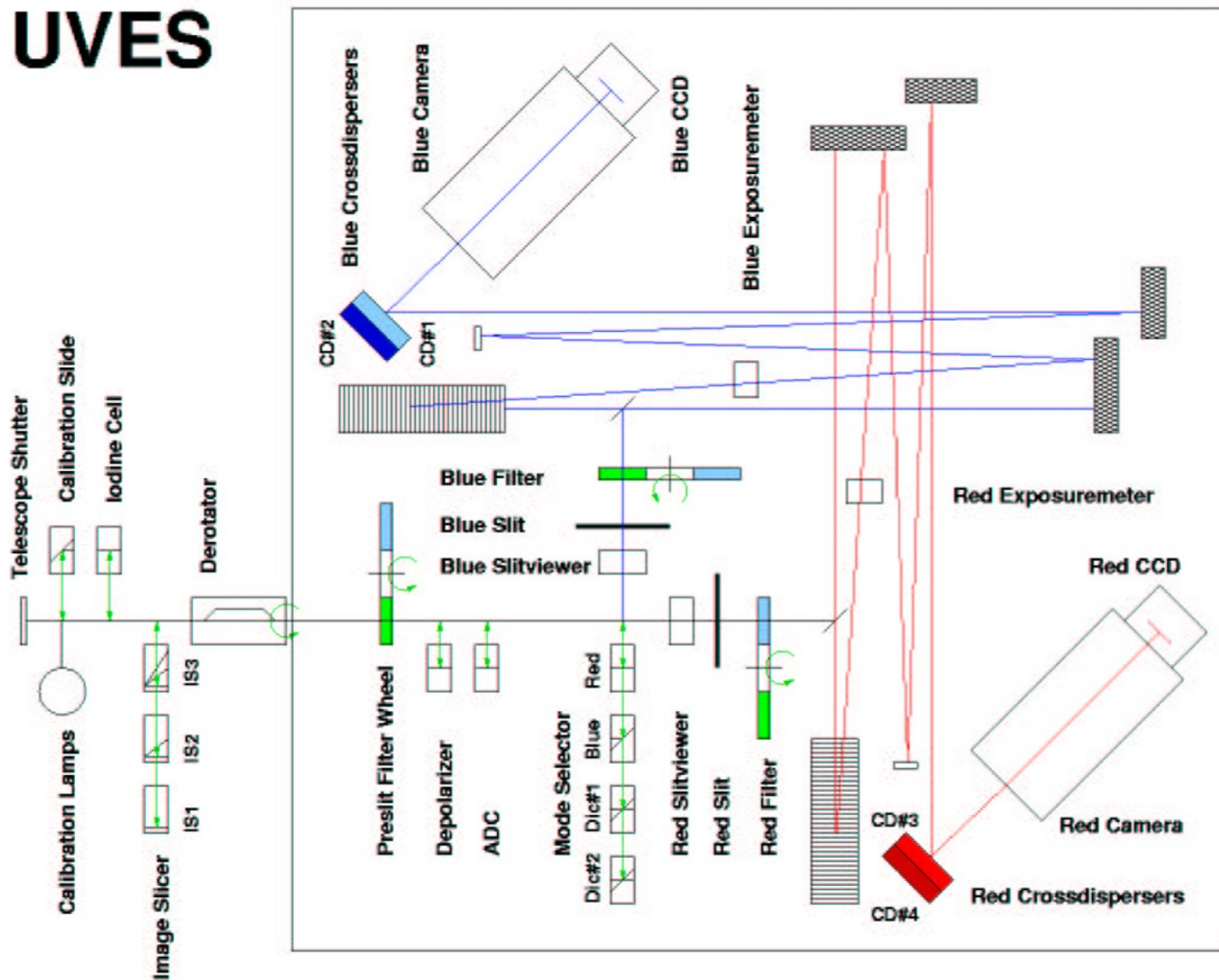


Figure 2.2: Schematic overview of the UVES spectrograph.

# HARPS- ESO La Silla

- High res. Echelle spectrograph (115000), slit, visual light 378-691nm

- RV accuracies to cm/s – extremely stable
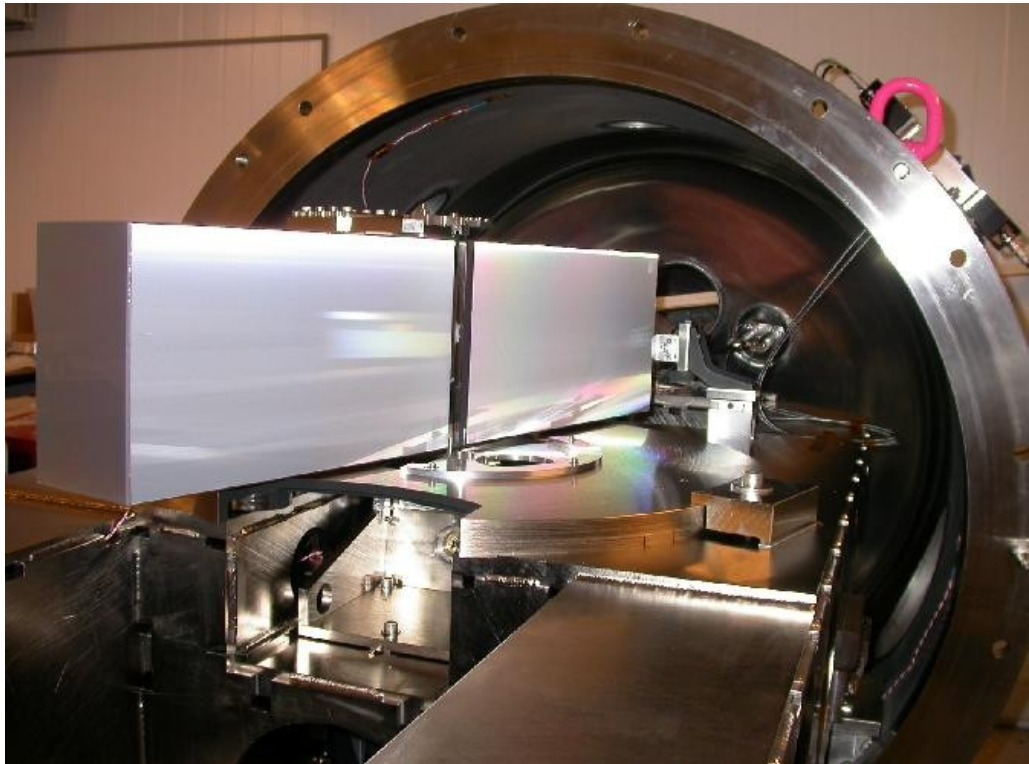
# First step

- Instrumentation usually very stable Echelle spectrographs to achieve high accuracies

- Obtaining a time series of high res. Spectra

  (R 40000 plus)

- Basic spectroscopic reduction, bias, correction of instrument effects, merging the echelle sp.

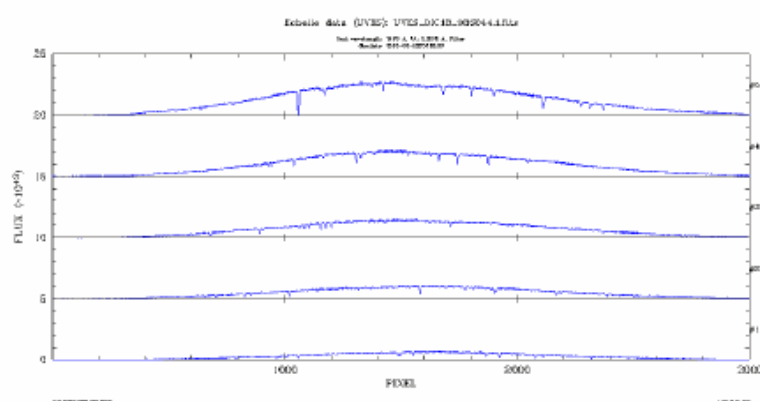- Identification of lines and determination of the profile (by using calibration spectra – e.g. Iodine cell)
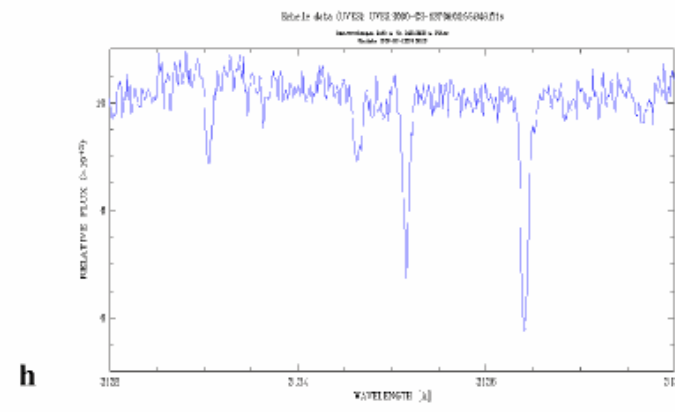
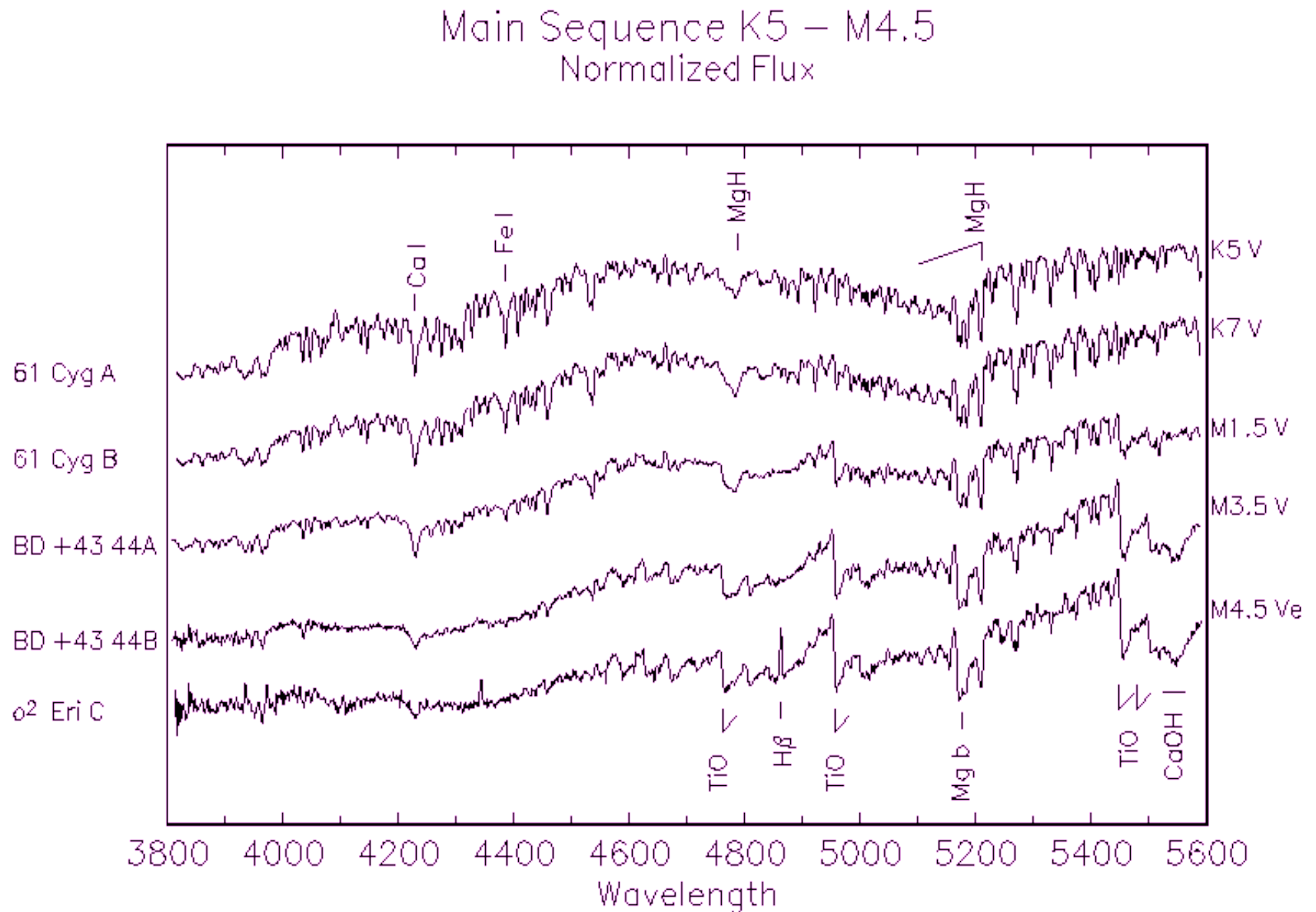# UVES frame example



Credit: ESO
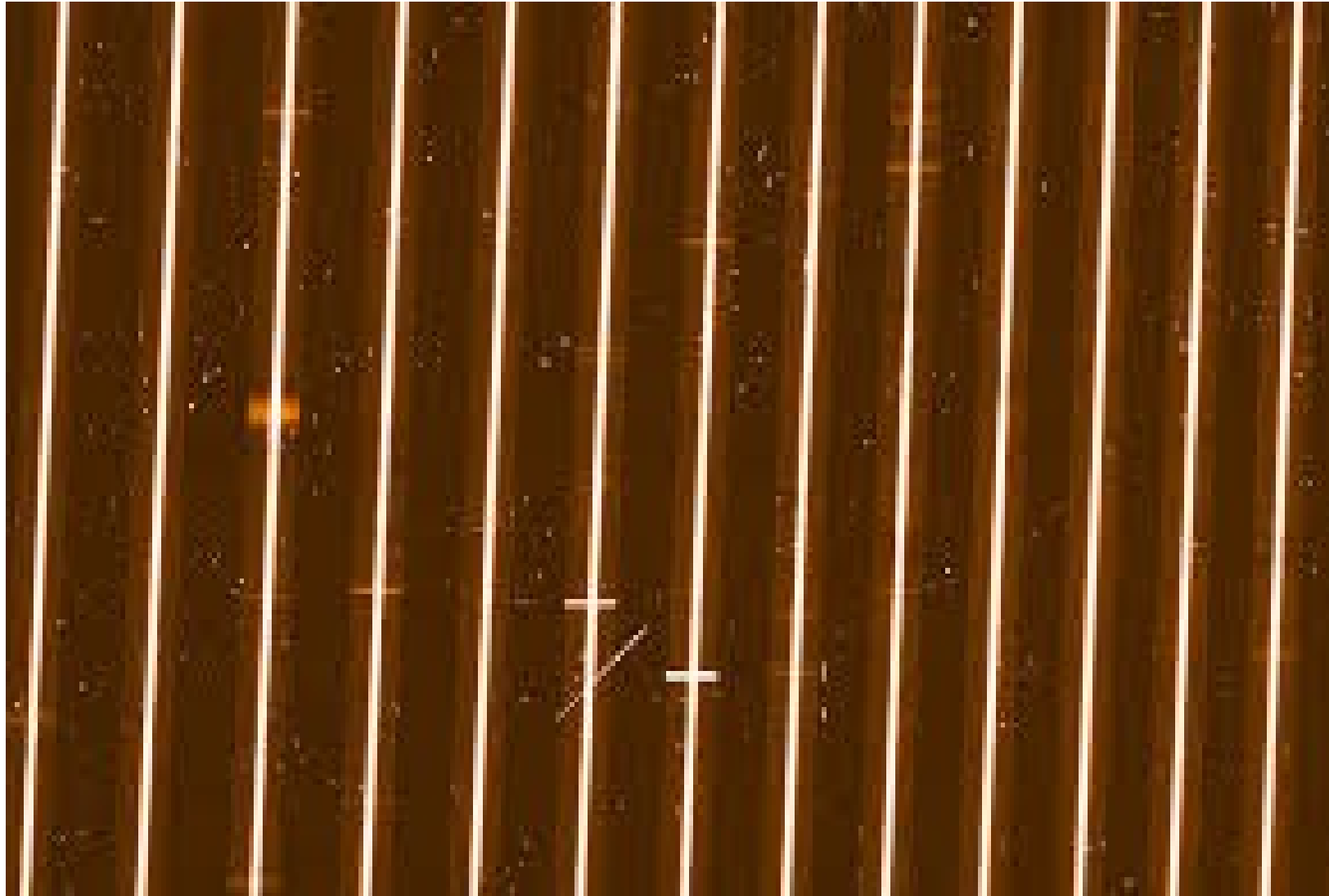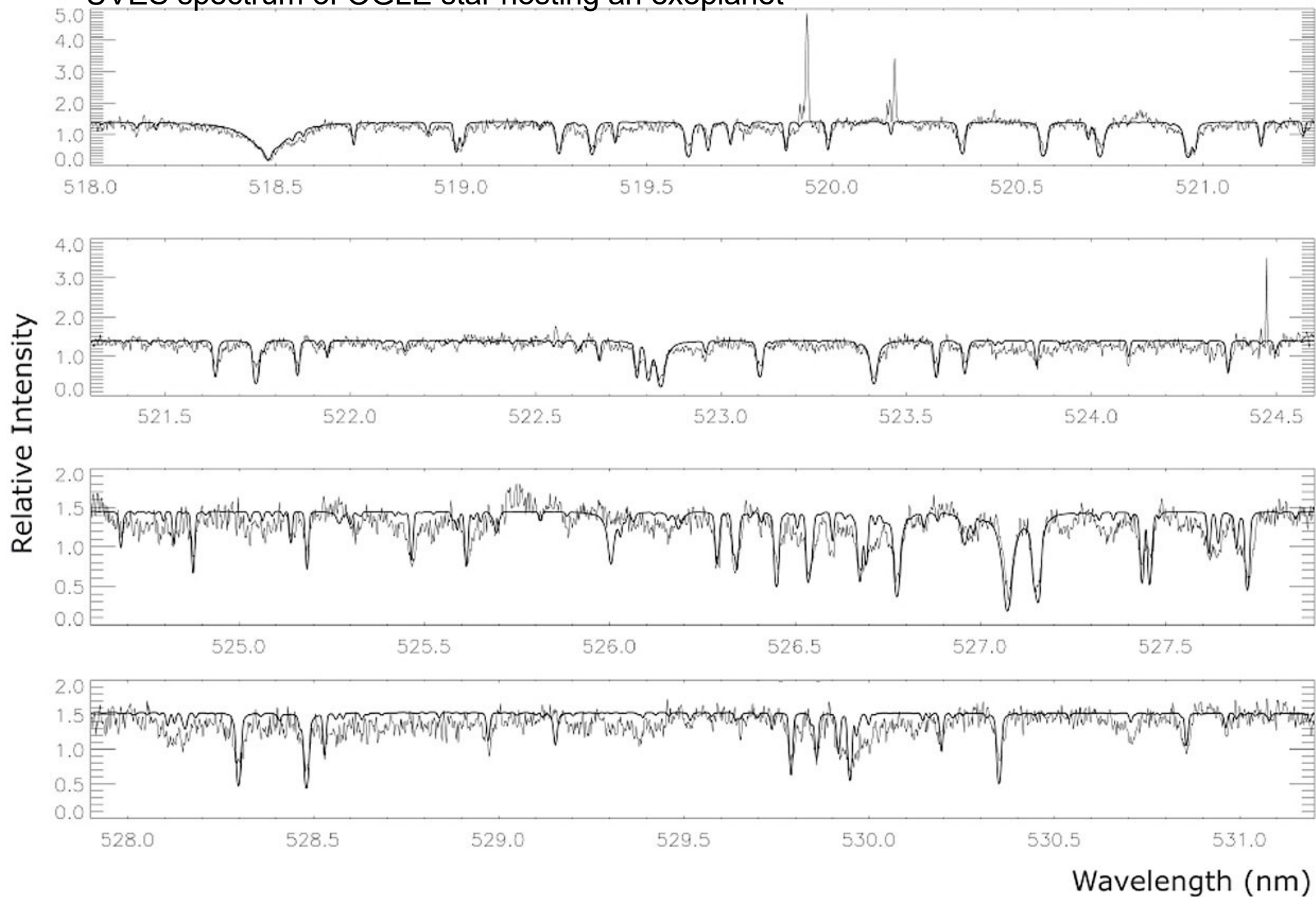
# ESO UVES data reduction process
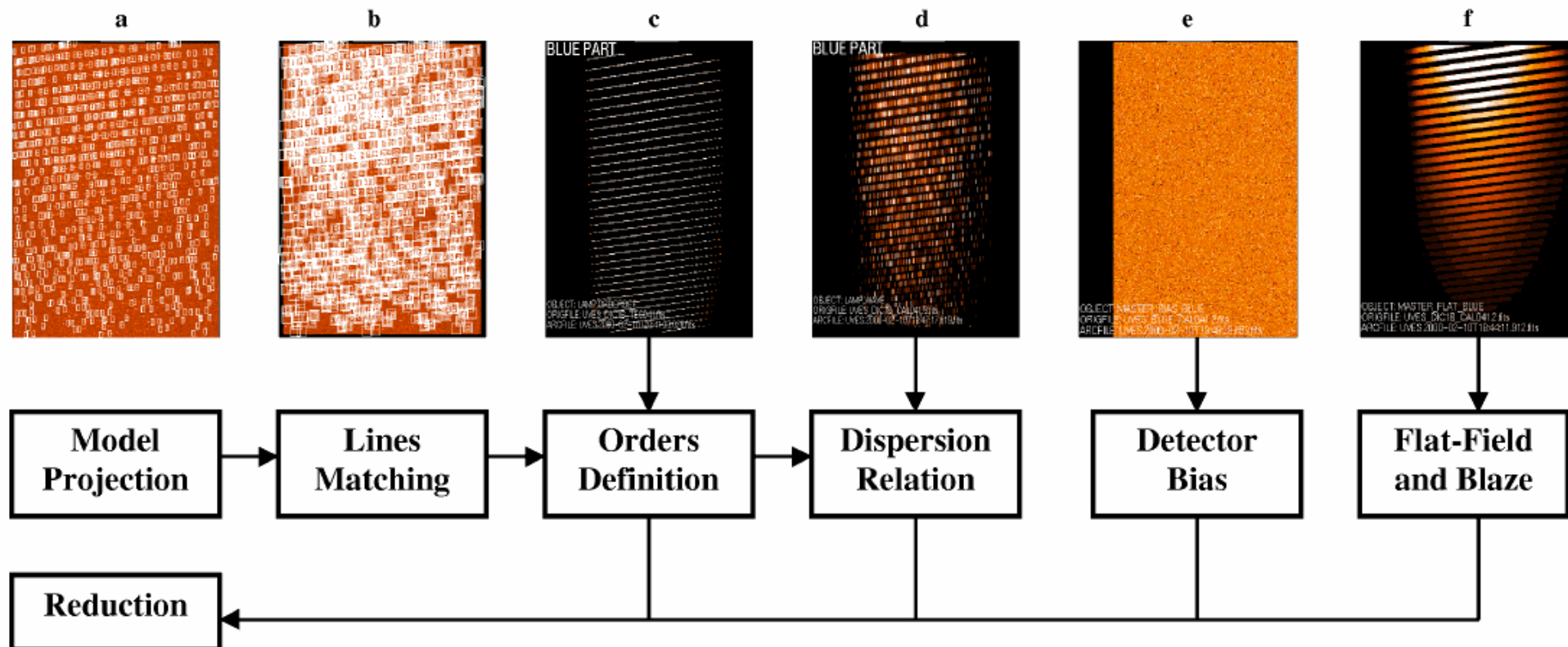


Ballester, et al.
https://www.eso.org/observing/dfo/quality/publ/Messenger/UVES  Messenger  101.html

# Example of main sequence spectra

UVES spectrum of OGLE star hosting an exoplanet

ESO press release http://www.eso.org/public/images/eso0311b/

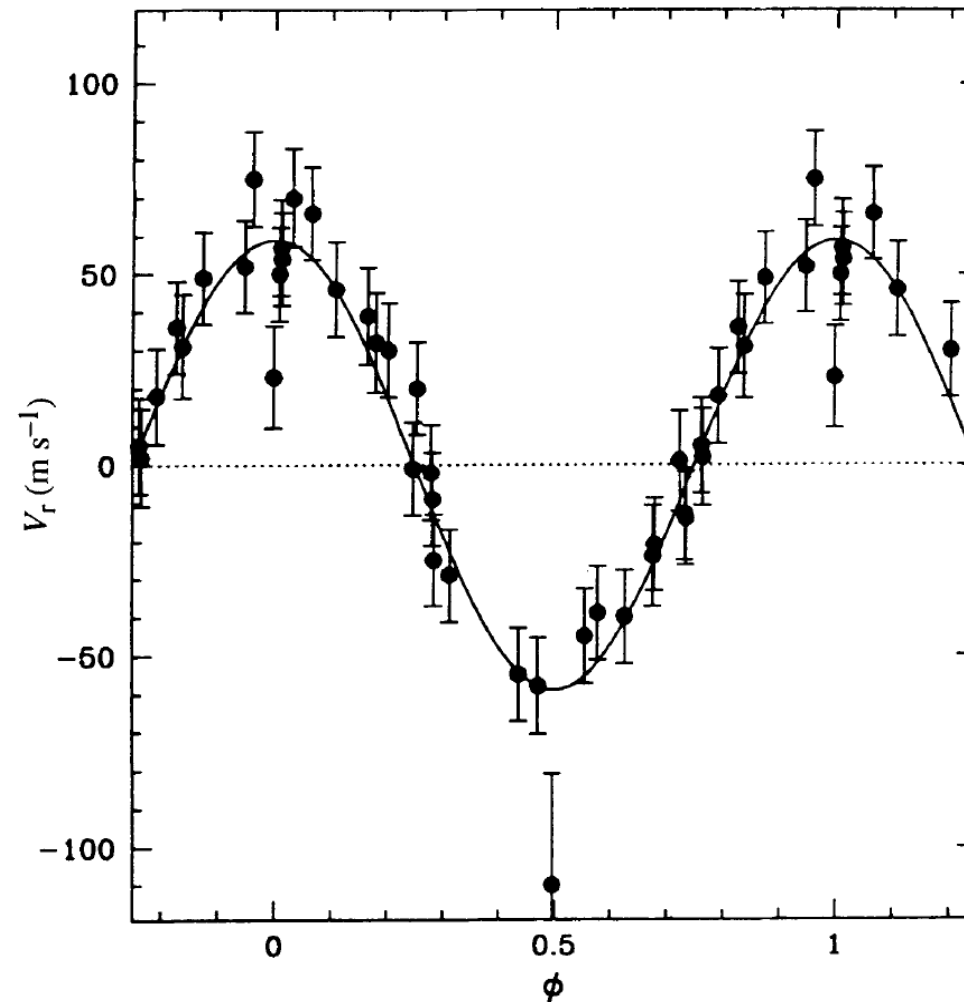# Shapes of lines unveil physics
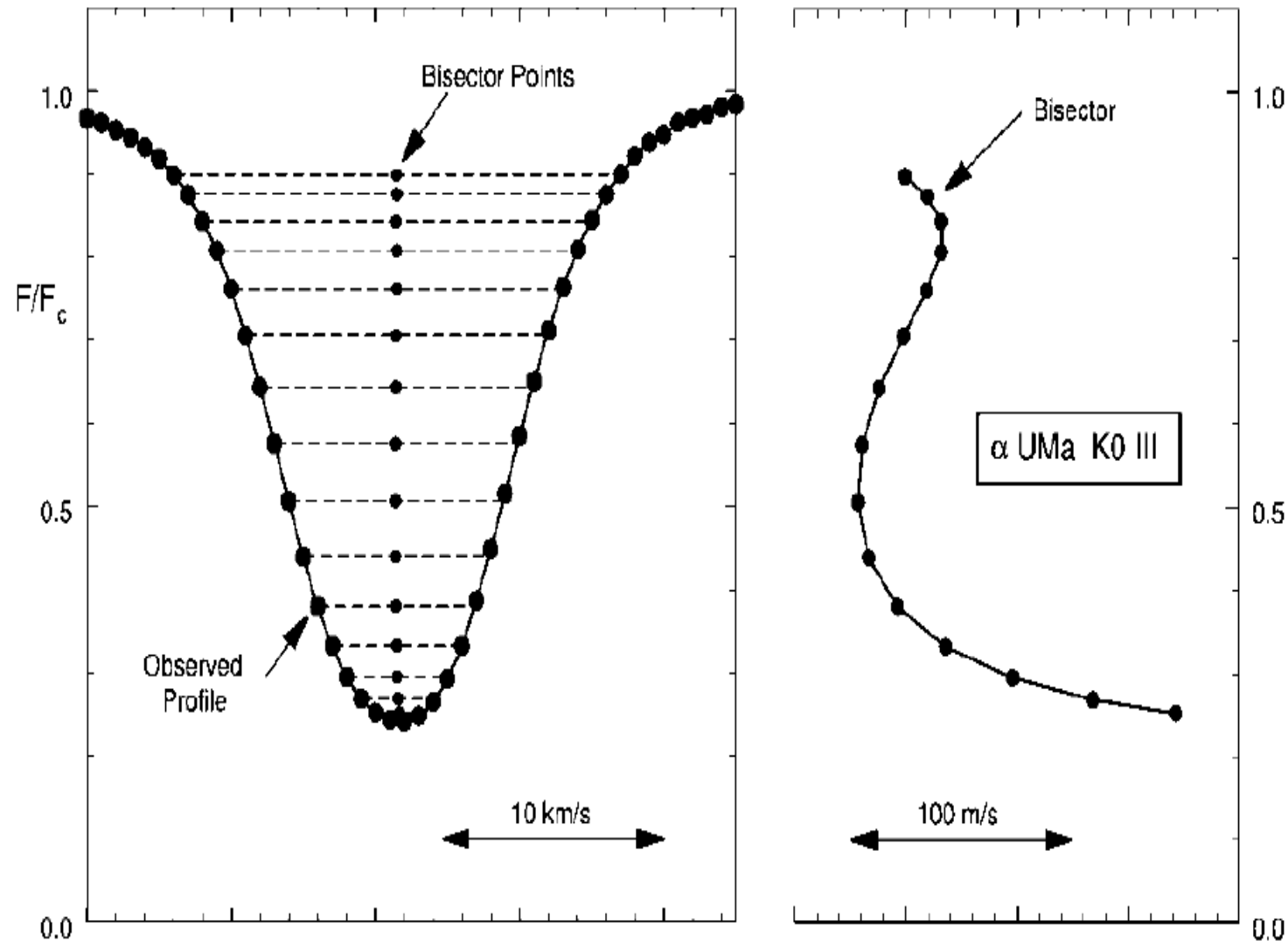
# Results (51 Peg)



FIG. 4 Orbital motion of 51 Peg corrected from the long-term variation of the $\gamma$-velocity. The solid line represents the orbital motion computed from the parameters of Table 1.

Mayor and Queloz, 1995, Nature

# Some equations

- Observable semi-amplitude of RV curve K:

$$K_1 = \sqrt{\frac{G}{(1-e^2)}}\, m_2 \sin i\, (m_1+m_2)^{-1/2}\, a^{-1/2} \qquad K_1 = \frac{28.4329\,\mathrm{m\,s^{-1}}}{\sqrt{1-e^2}} \frac{m_2 \sin i}{M_{\mathrm{Jup}}} \left(\frac{m_1+m_2}{M_\odot}\right)^{-2/3} \left(\frac{P}{1\,\mathrm{yr}}\right)^{-1/3}$$

- Using Kepler law $\dfrac{M_p}{(M_p+M_\star)^{2/3}} = \dfrac{K_\star \sqrt{1-e^2}}{\sin i}\left(\dfrac{P}{2\pi G}\right)^{1/3}$ mentum conservation

- For details see:

http://adsabs.harvard.edu/full/1913PASP...25..208P

http://w.astro.berkeley.edu/~kclubb/pdf/RV_Derivation.pdf

http://exoplanets.astro.yale.edu/workshop/EPRV/Bibliography_files/Radial_Velocity.pdf

# Semi amplitude K

Table 1: Radial velocity signals for different kinds of planets orbiting a solar-mass star.
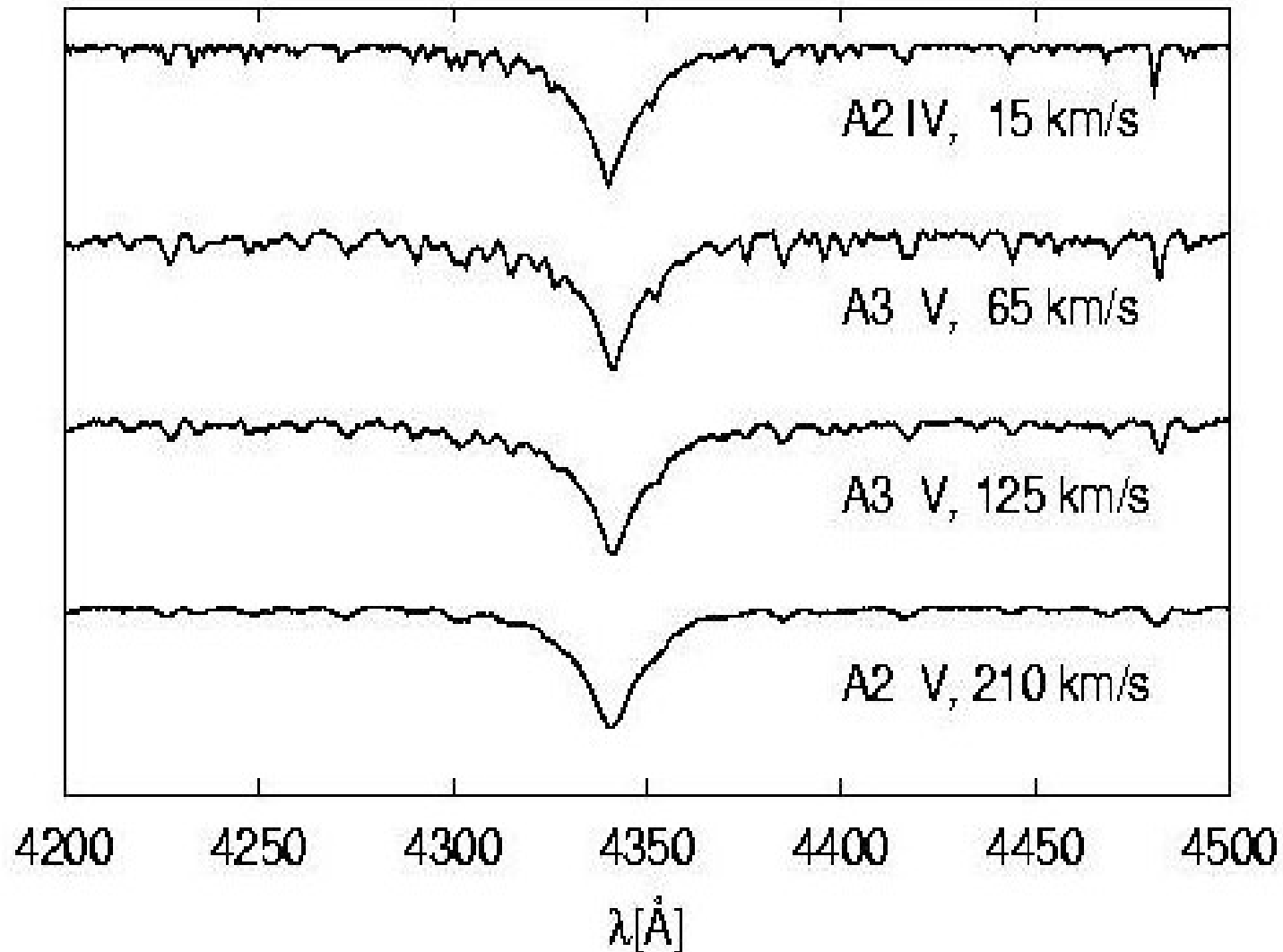
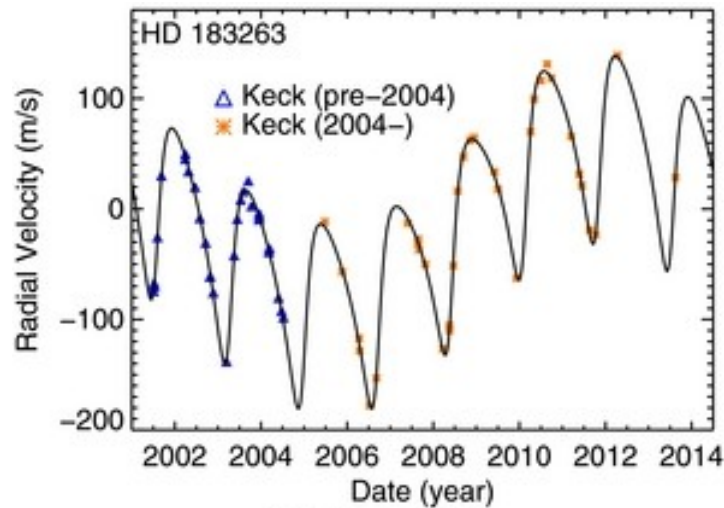| Planet | $a$ (AU) | $K_1$ (m s$^{-1}$) |
|---|---|---|
| Jupiter | 0.1 | 89.8 |
| Jupiter | 1.0 | 28.4 |
| Jupiter | 5.0 | 12.7 |
| Neptune | 0.1 | 4.8 |
| Neptune | 1.0 | 1.5 |
| Super-Earth (5 $M_\oplus$) | 0.1 | 1.4 |
| Super-Earth (5 $M_\oplus$) | 1.0 | 0.45 |
| Earth | 0.1 | 0.28 |
| Earth | 1.0 | 0.09 |

2

# Problems

- Mass is lower limit (unless inclination is known)
- Stellar variability – pulsations (cm/s accuracies)
- Multiplicity of stars – shape of the RV curve

  - difficult RV curves

- Fast rotation of stars – broadening of the lines

  - mimicking planet effect

- Long periodic planets are difficult to detect – due to covergae of the RV curve
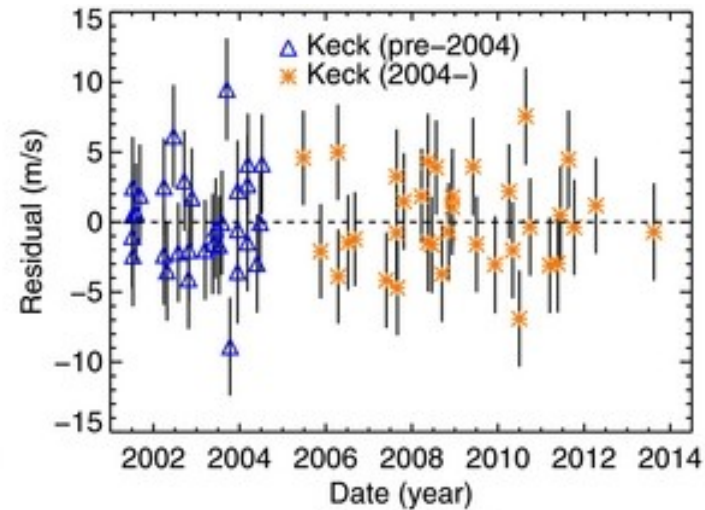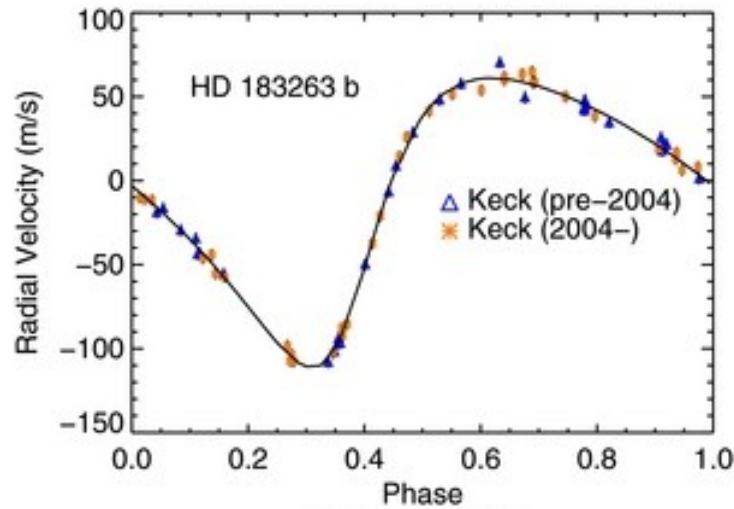
# Line boradening, rotation



A2 IV, 15 km/s

A3 V, 65 km/s

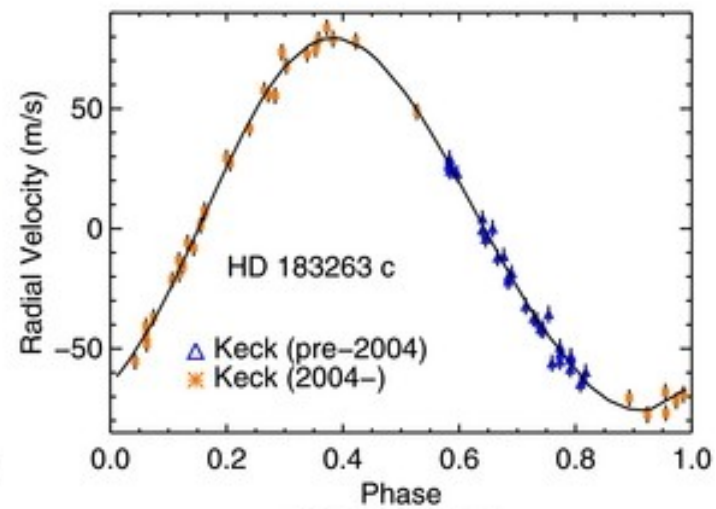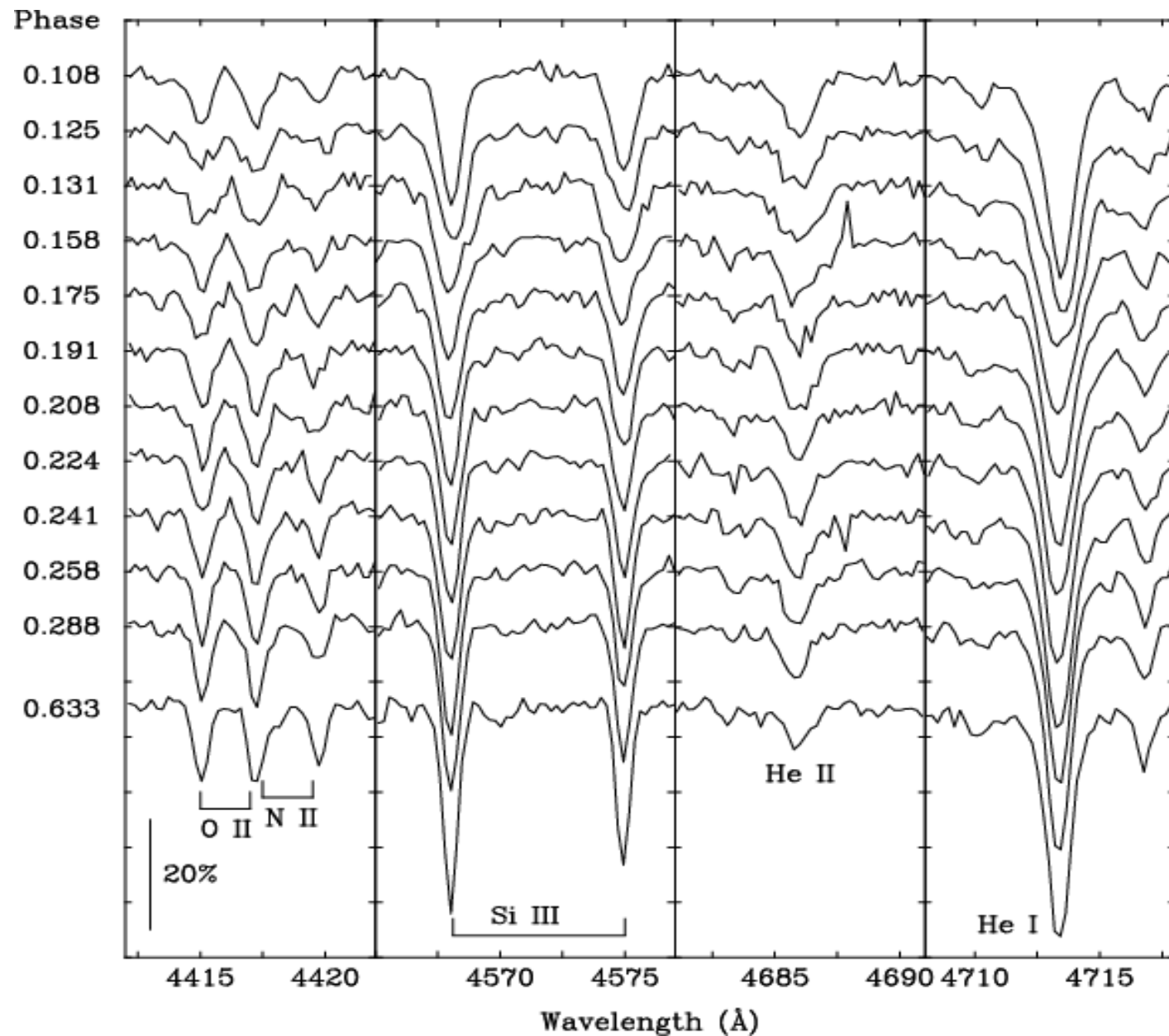A3 V, 125 km/s

A2 V, 210 km/s

$\lambda [\AA]$

# Multiple system



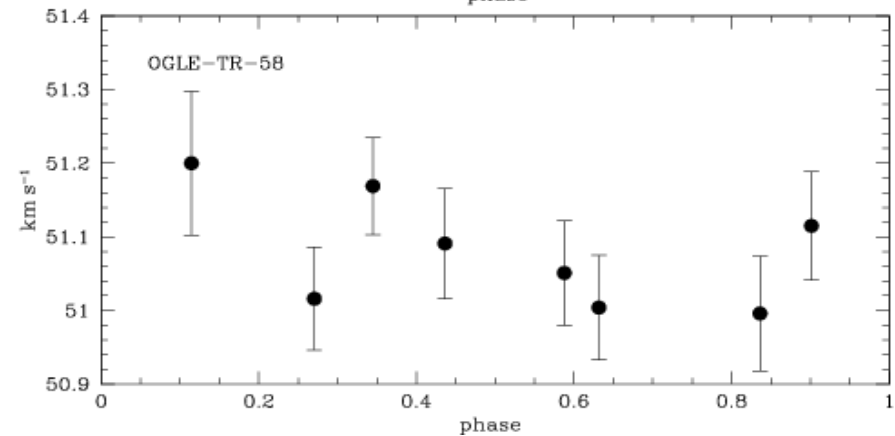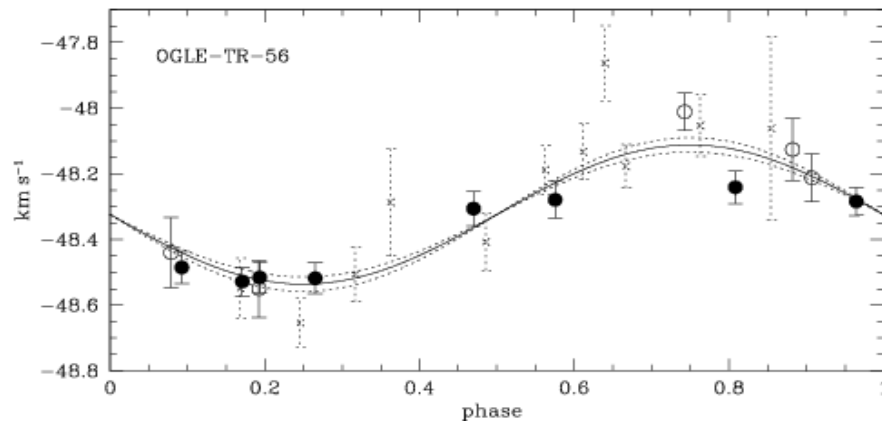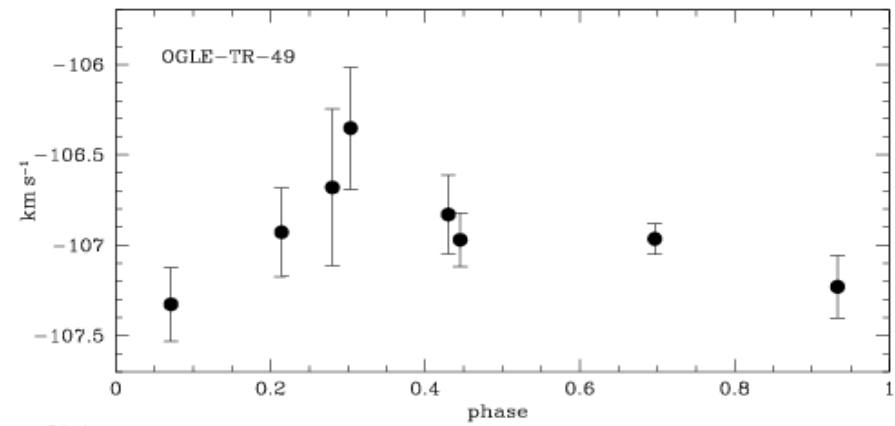(a) HD 183263 system

(b) Residuals

(c) HD 183263 b

(d) HD 183263 c

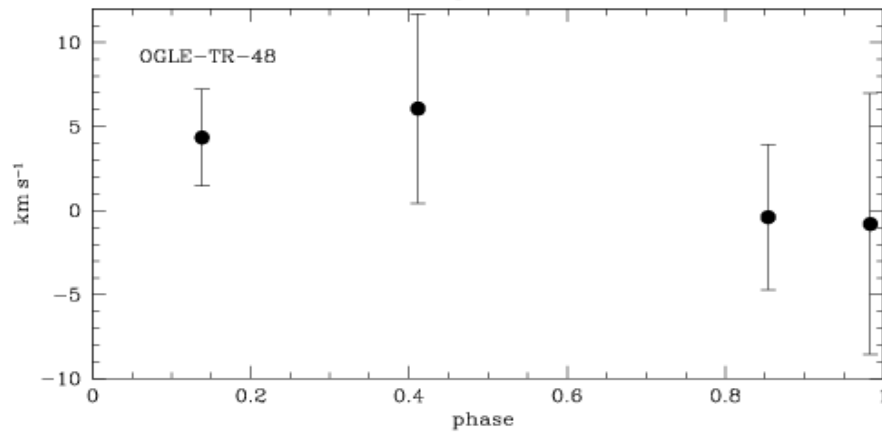Feng et al. 2015, http://iopscience.iop.org/article/10.1088/0004-637X/800/1/22/pdf
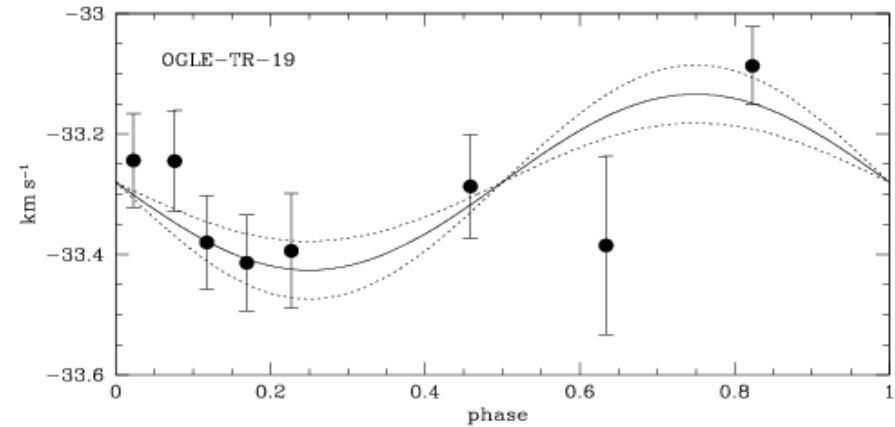
# Pulsations



Jeffery et al., A&A 376, 497-517 (2001)
http://www.aanda.org/articles/aa/full/2001/35/aah2647/aah2647.right.html

# Unresolved cases RV
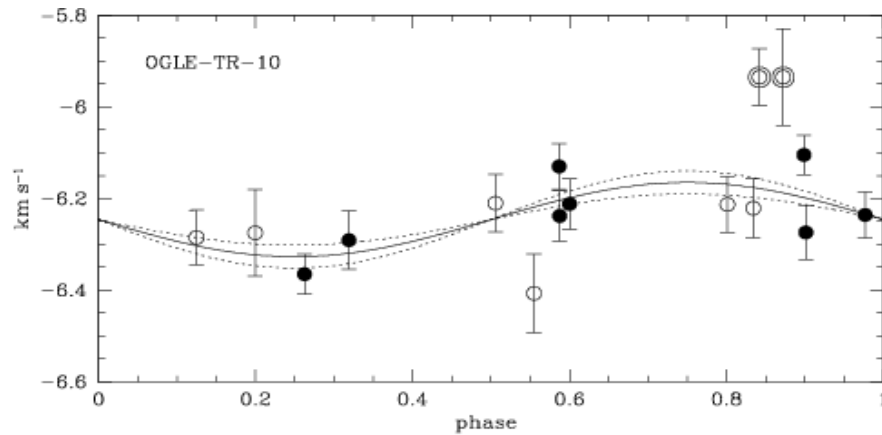
# Transit method
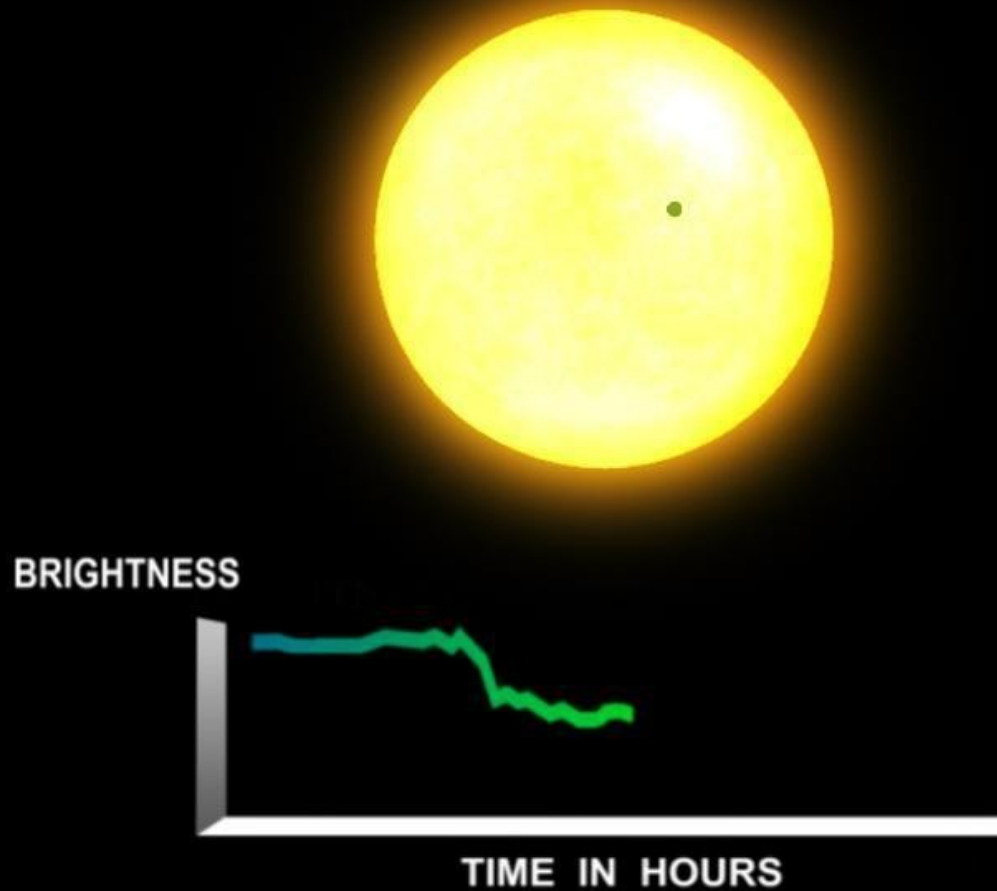
# Eclipses/transits



From Winn, 2010, http://arxiv.org/pdf/1001.2010v5.pdf
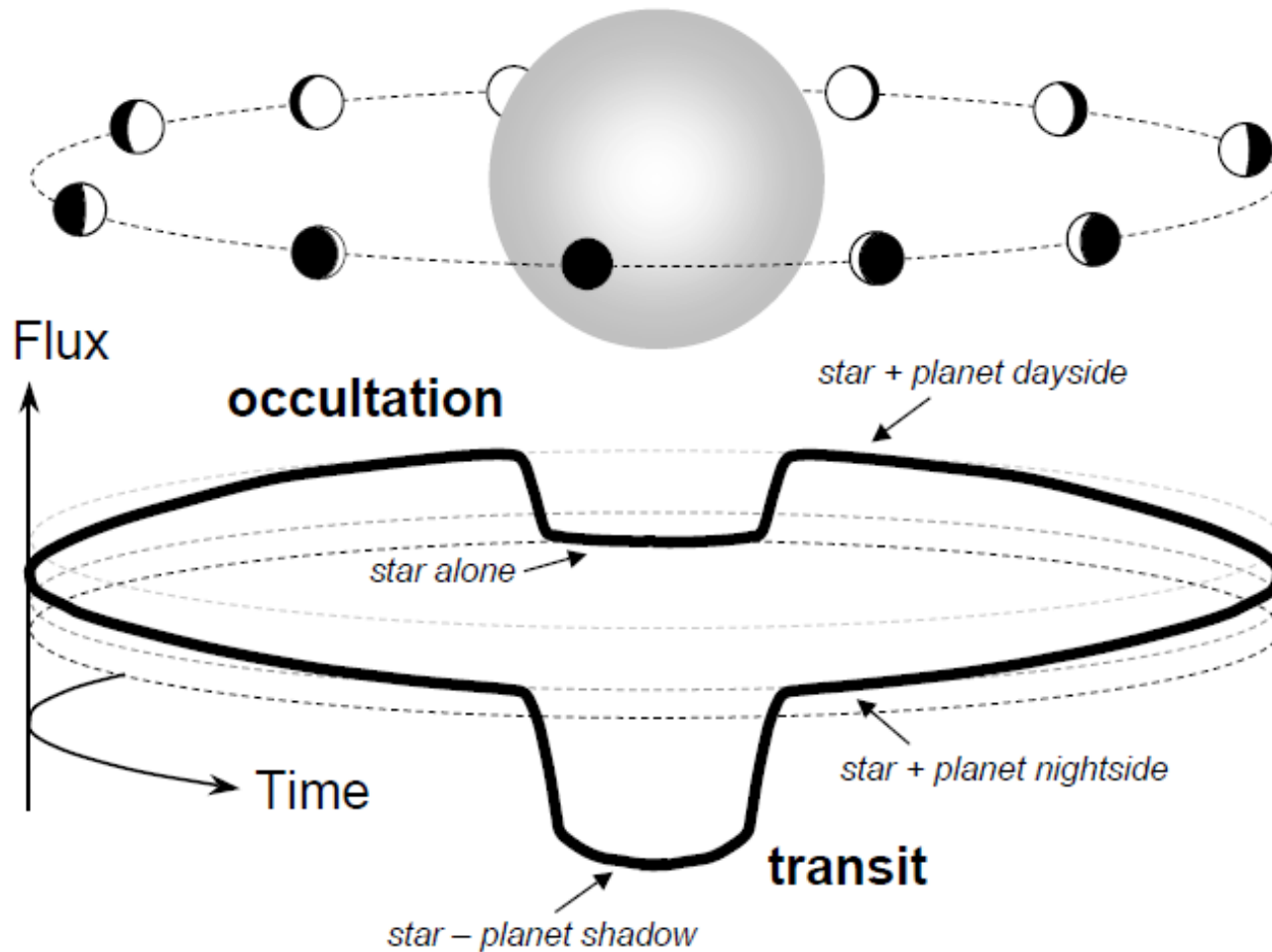
# The transit method



$$\delta \propto \Delta I = \frac{I_{out} - I_{transit}}{I_{out}} \propto \frac{R^2_{planet}}{R^2_{star}}$$

# Obtainable parameters
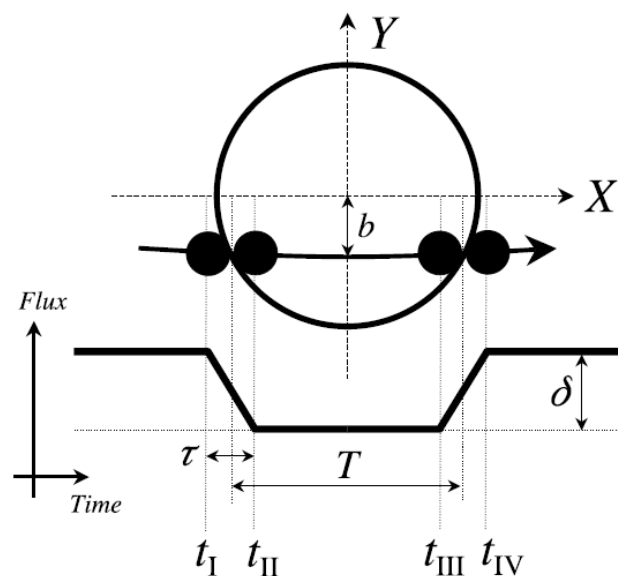


Winn, 2010, http://arxiv.org/abs/1001.2010

- Transit depth:

$$\delta \propto \Delta I = \frac{I_{out} - I_{transit}}{I_{out}} \propto \frac{R_{planet}^2}{R_{star}^2}$$

- Transit shape:

$$L(p,z) = \begin{cases} ( \quad I(p,z) = 1 - L(p,z) & 1 + p < z \\ \frac{1}{\pi}\left[ p^2 \kappa_0 + \kappa_1 - \sqrt{\frac{4z^2 - (1+z^2-p^2)^2}{4}} \right] & |1-p| << \leq |1+p| \\ p^2 & z \leq 1 - p \\ 1 & z \leq p - 1 \end{cases}$$

- Inclination:

$$i = \cos^{-1}\left( b\frac{R_*}{a} \right)$$

- Transit duration:

$$t_T = \frac{P R_*}{\pi a}\sqrt{\left(1 + \frac{R_p}{R_*}\right)^2 - \left(\frac{a}{R_*}\cos i\right)^2}$$

# Limb darkening



Fig. 3.— Solar limb darkening dependence of a planet transit light curve. In these theoretical light curves the planet has $R_p = 1.4R_J$ and $a = 0.05$ AU and the 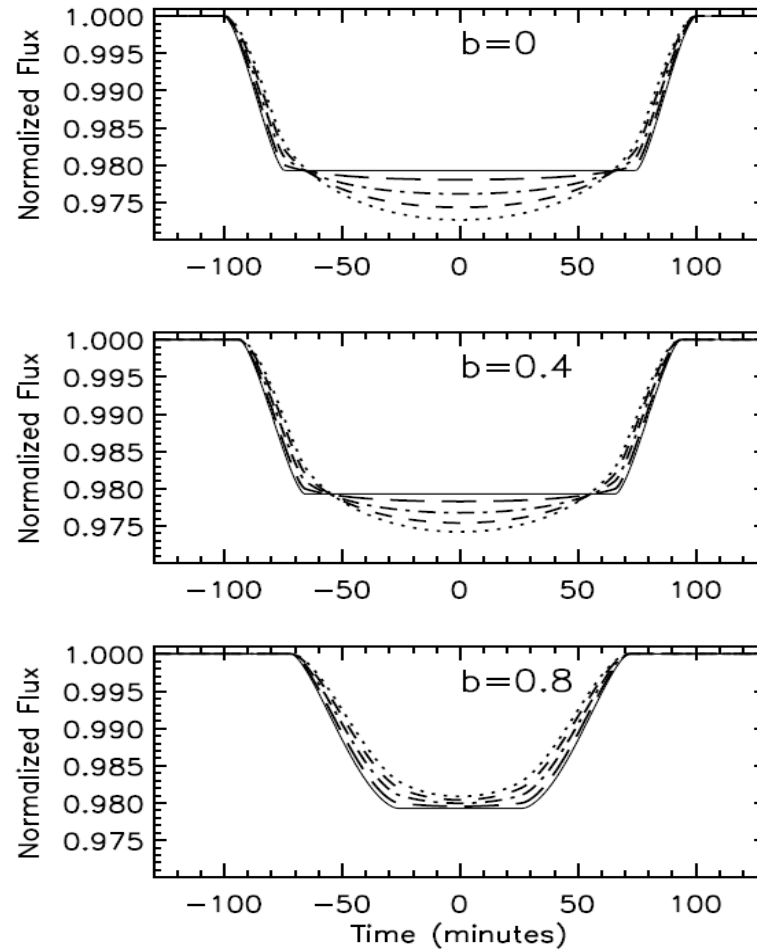star has $R_* = R_\odot$ and $M_* = M_\odot$. The solid curve shows a transit light curve with limb darkening neglected. The other planet transit light curves have solar limb darkening at wavelengths (in $\mu$m): 3, 0.8, 0.55, 0.45. From top to bottom the panels show transits with different impact parameters $b$, which correspond to inclinations $\cos i = bR_*/a$. Although the transit depth changes at different wavelengths, the ingress and egress slope do not change significantly; the different slopes are generally equivalent within typical observational errors. The ingress and egress slope mainly depend on the time it takes the planet to cross the stellar limb.

From Seager and Ornella, http://arxiv.org/pdf/astro-ph/0206228v1.pdf

# Problems

- Systematic noise hiding the transit

- Hihg photometric accuracy needed in mmag range

- Transits due to background binaries

- Star parameters needed to fully characterize the system – SPECTROSCOPY NEEDED

# How to detect a transit

- Observing large number of stars – wide-field photometry

- Accurate photometry – accuracy 1 percent and better

- Understanding of the systematic errors of photometry

- Limitation due to RV follow-up requirements

- Observables are decrease of flux due to an eclipse, mid-time of transit, duration of transit and durations of ingress and egress

# Geometrical probability



**GEOMETRY FOR TRANSIT PROBABILITY**

Stellar Diameter

a — Orbital radius

$d^*$

1) Range of Pole Positions $= \dfrac{d^*}{a}$

$d^*/a$

2) Solid angle of $2\pi d^*/a$ for all possible pole positions for any given LOS Note full sphere solid angle is $4\pi$

$2\pi$

3) **Geometric Transit Probability** $= d^*/2a$

Credit: NASA Kepler
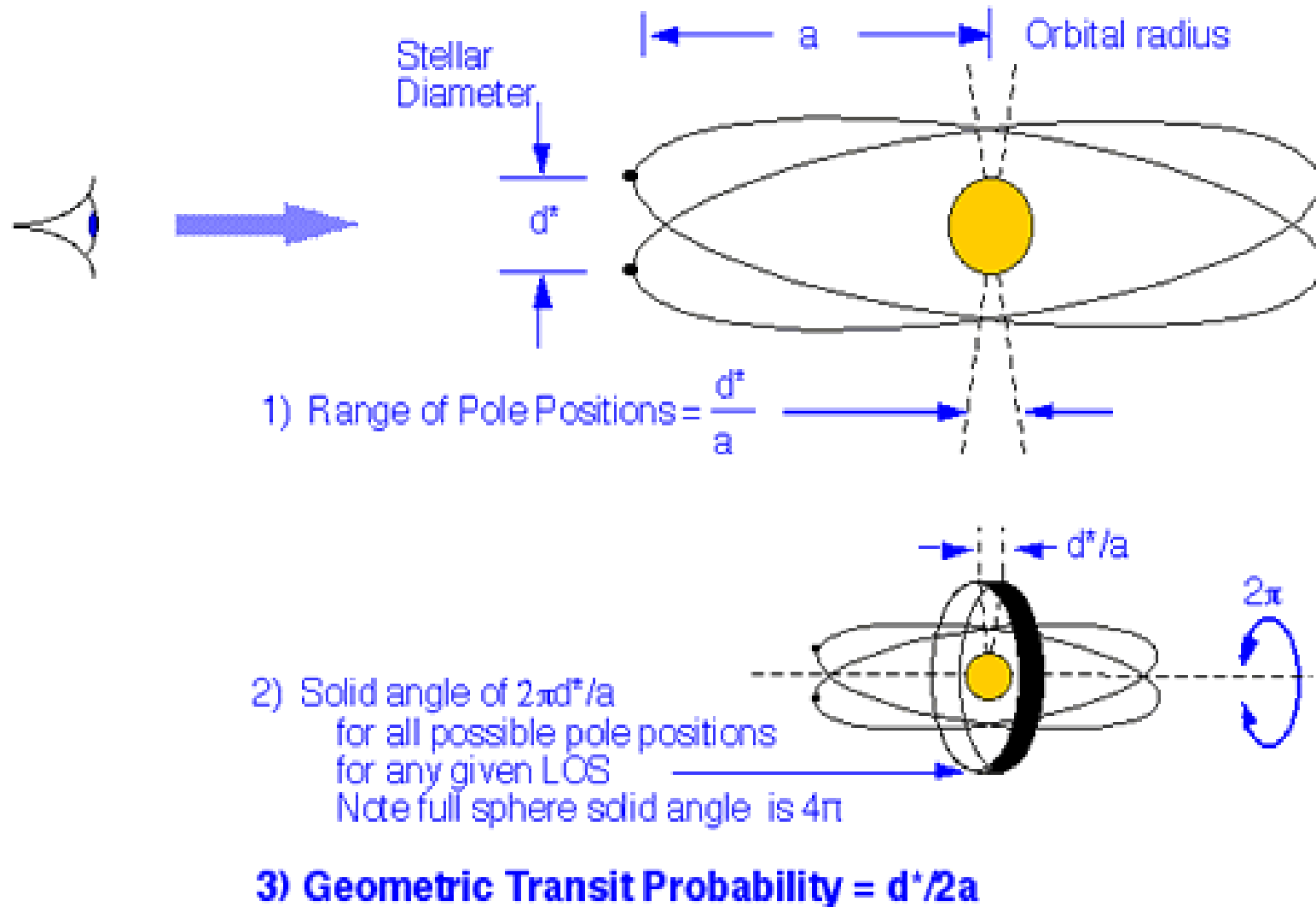
# Transit Properties of Solar System Objects

| Planet | Orbital Period P (years) | Semi-Major Axis a (A.U.) | Transit Duration (hours) | Transit Depth (%) | Geometric Probability (%) | Inclination Invariant Plane (deg) |
|---|---|---|---|---|---|---|
| Mercury | 0.241 | 0.39 | 8.1 | 0.0012 | 1.19 | 6.33 |
| Venus | 0.615 | 0.72 | 11.0 | 0.0076 | 0.65 | 2.16 |
| Earth | 1.000 | 1.00 | 13.0 | 0.0084 | 0.47 | 1.65 |
| Mars | 1.880 | 1.52 | 16.0 | 0.0024 | 0.31 | 1.71 |
| Jupiter | 11.86 | 5.20 | 29.6 | 1.0100 | 0.089 | 0.39 |
| Saturn | 29.5 | 9.5 | 40.1 | 0.75 | 0.049 | 0.87 |
| Uranus | 84.0 | 19.2 | 57.0 | 0.135 | 0.024 | 1.09 |
| Neptune | 164.8 | 30.1 | 71.3 | 0.127 | 0.015 | 0.72 |
| | $P^2M^* = a^3$ | | $13\sqrt{a}$ | $\% = (d_p/d^*)^2$ | $d^*/D$ | phi |

# First transiting exoplanet
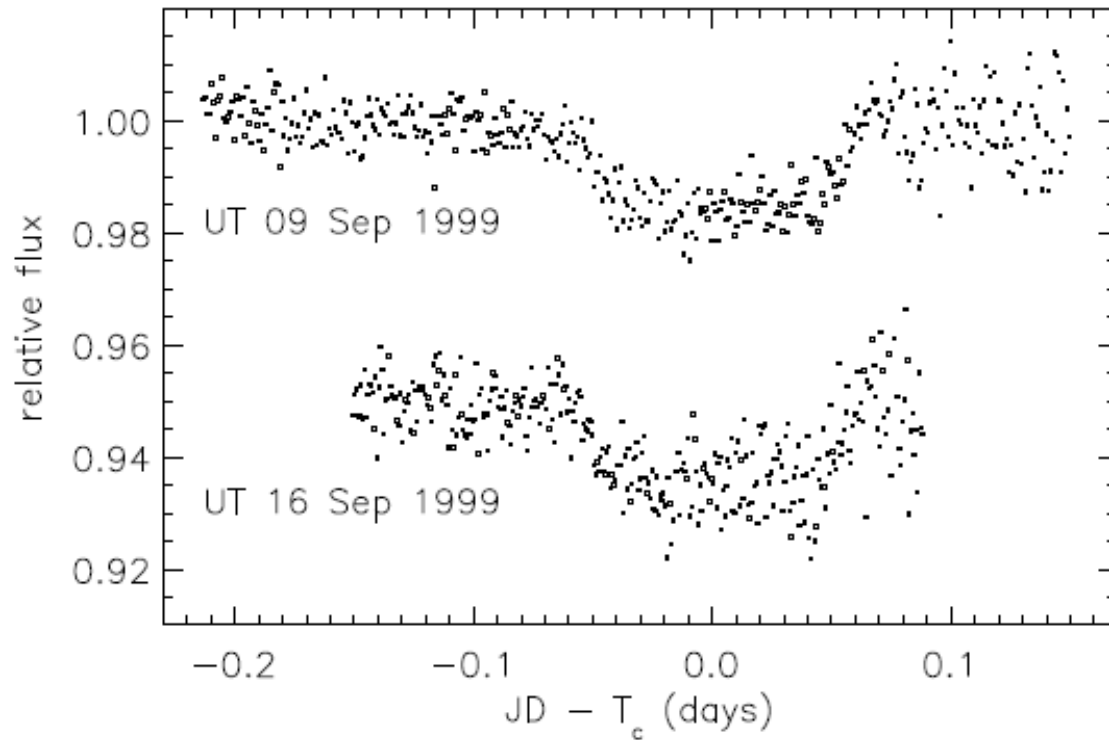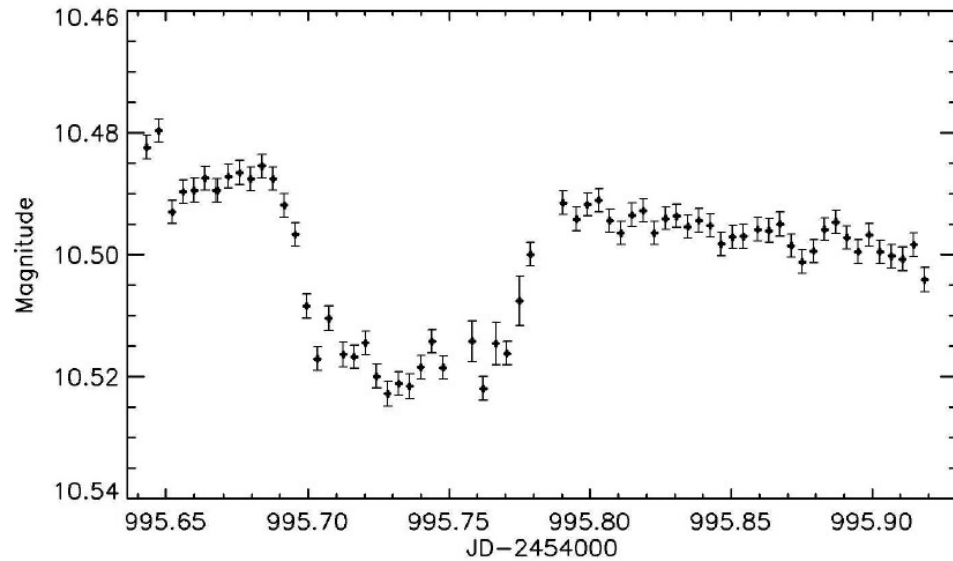


HD209458b

**Charbonneau et al. 2000**
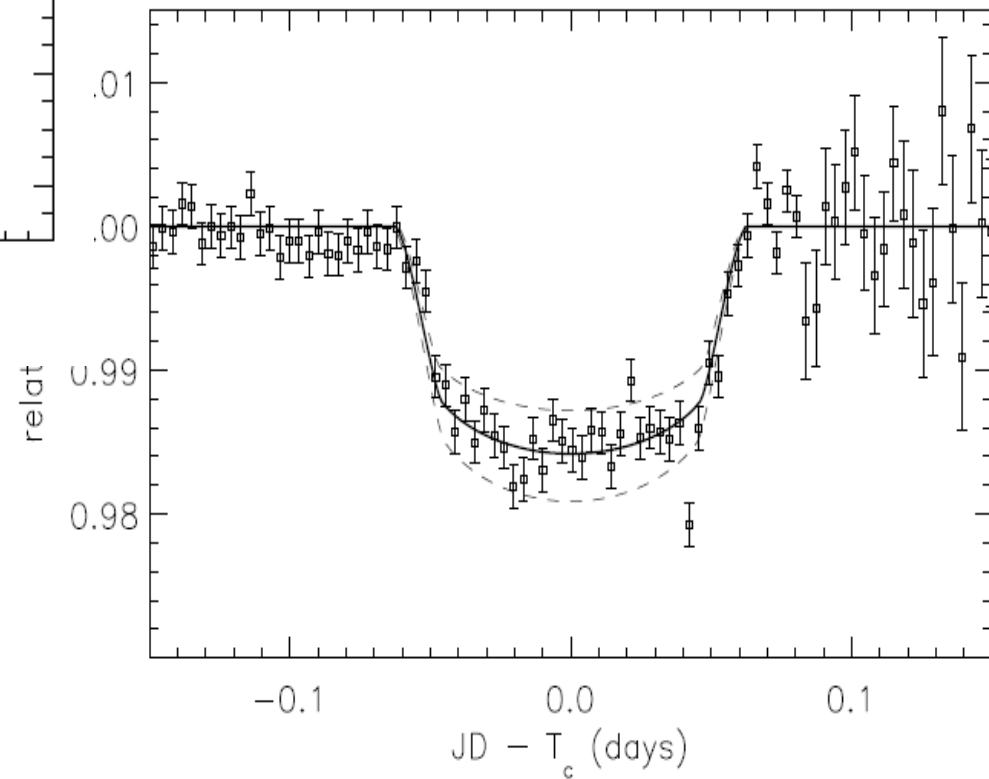
# HD209458b

- Parameters

  - Mass : 0.69Mj

  - Radius : 1.38 Rj

  - O. period : 3.5 days

- Star: G0V

  brightness: 7 mag (V)

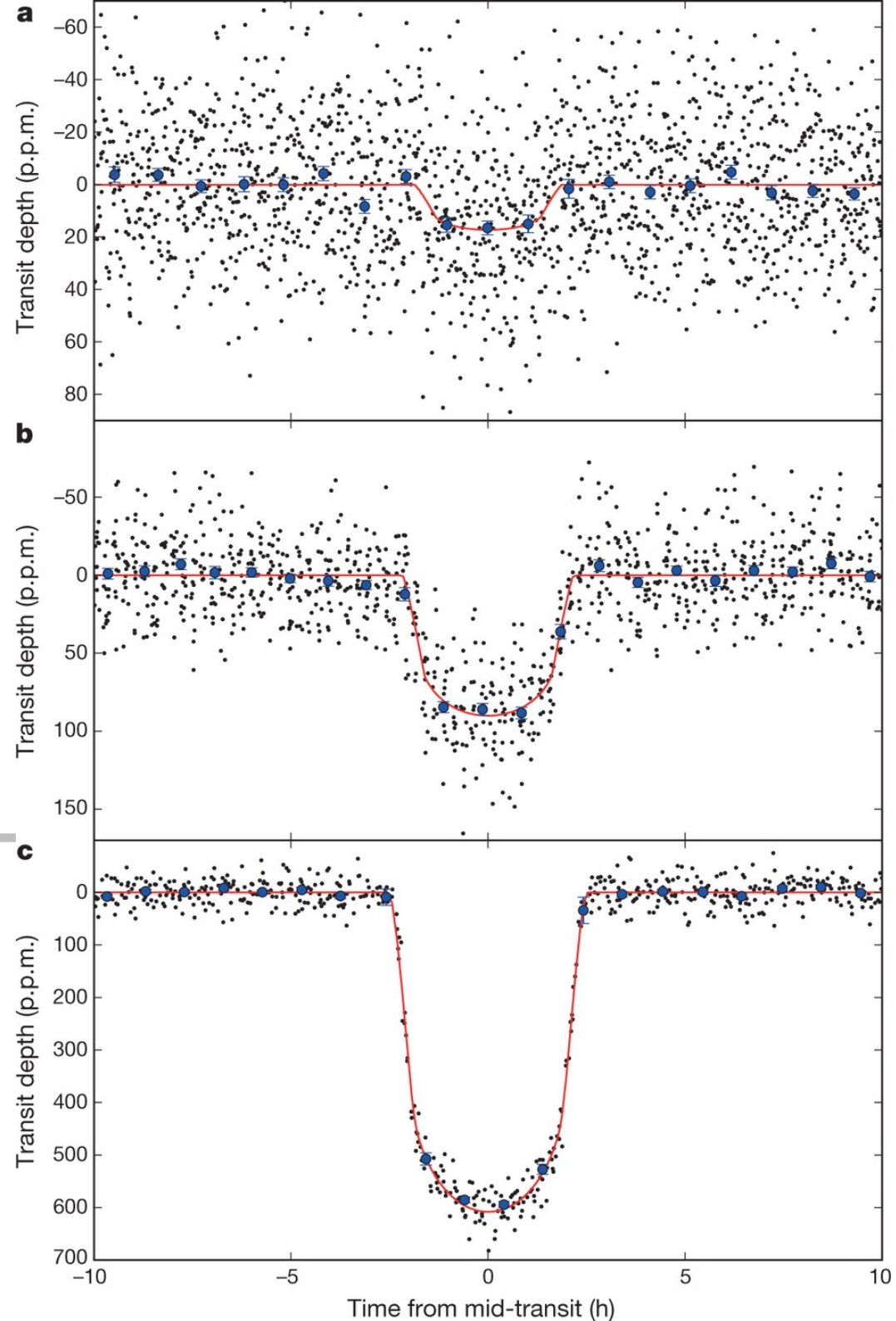  Teff: 6092 K

  Metallicity: 0.02

# Nice light curves

BEST II @ CoRoT-2



DLR, Thomas Fruth

Kepler: A sub-Mercury-sized exoplanet,
Barclay et al., 2013, Nature, 494, 452

# Transit surveys

# Ground based transit survey projects

SuperWasp – the most successful ground based survey operated by UK universities

2 robotic observatories – La Palma, Spain and South Africa

Each site consists of 8 telescopes with wide angle CCDs
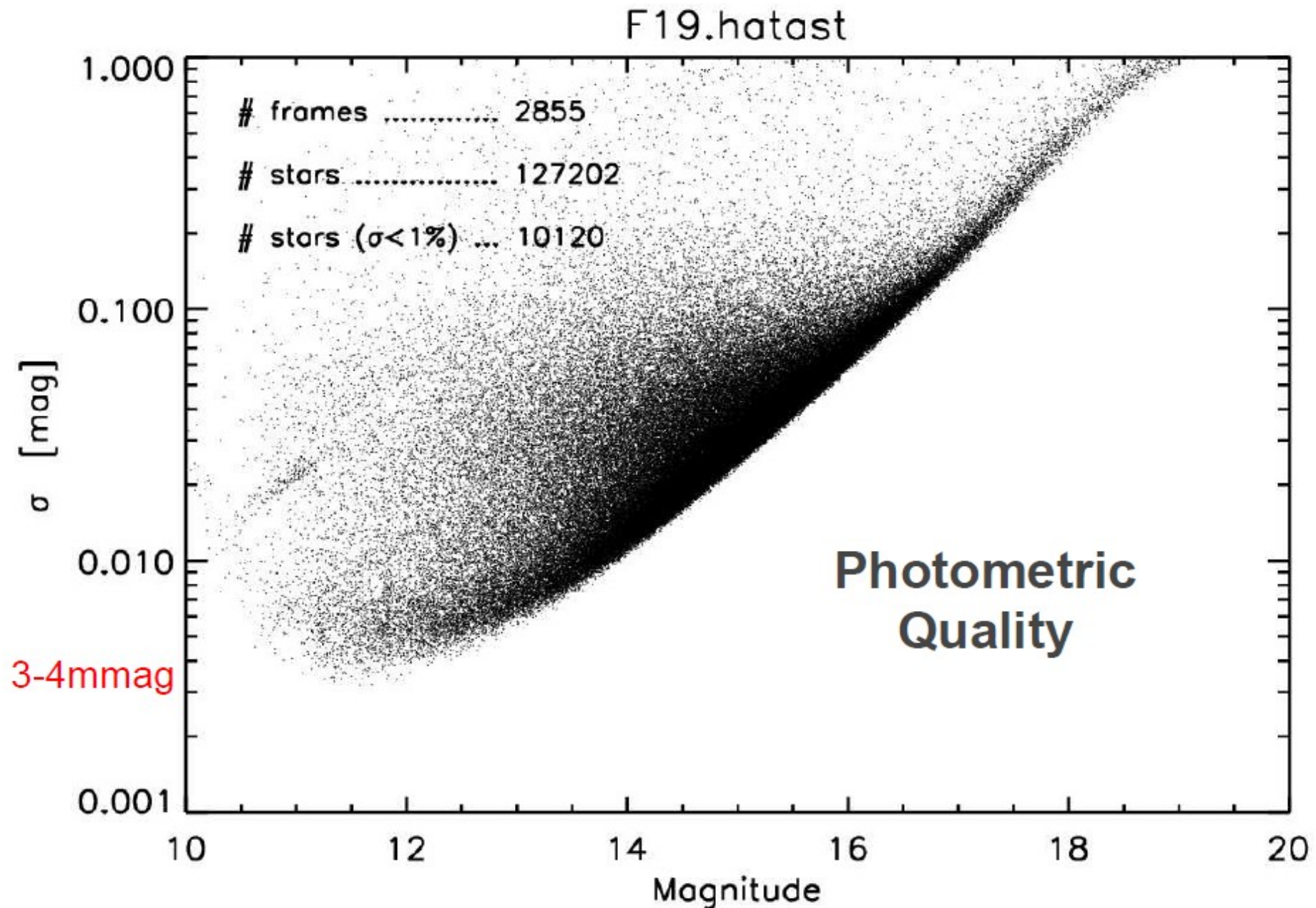
More than 100 planets discovered

since 2002

http://www.superwasp.org/index.html

# BEST II



Observatorio Cerro Armazones, Chile



## Specifications:

| | | |
|---|---|---|
| Telescope | : | BRC - 250 |
| Aperture | : | 25 cm |
| Focal ratio | : | *f/5.0* |
| Instrument | : | FLI IMG-1680 CCD |
| Size | : | 4096 x 4096 pixels |
| Pixel size | : | 9 µm |
| Pixel scale | : | 1.5 arcsec/pixel |
| Field of view | : | 1.7° x 1.7° |

# Photometric quality



F19.hatast

# frames ............... 2855
# stars ............... 127202
# stars ($\sigma < 1\%$) ... 10120

**Photometric Quality**

3-4mmag

DLR – Thomas Fruth

Deutsches Zentrum
DLR für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

Slide 13
PhD Introduction :: 10.12.2009

# Duty cycle
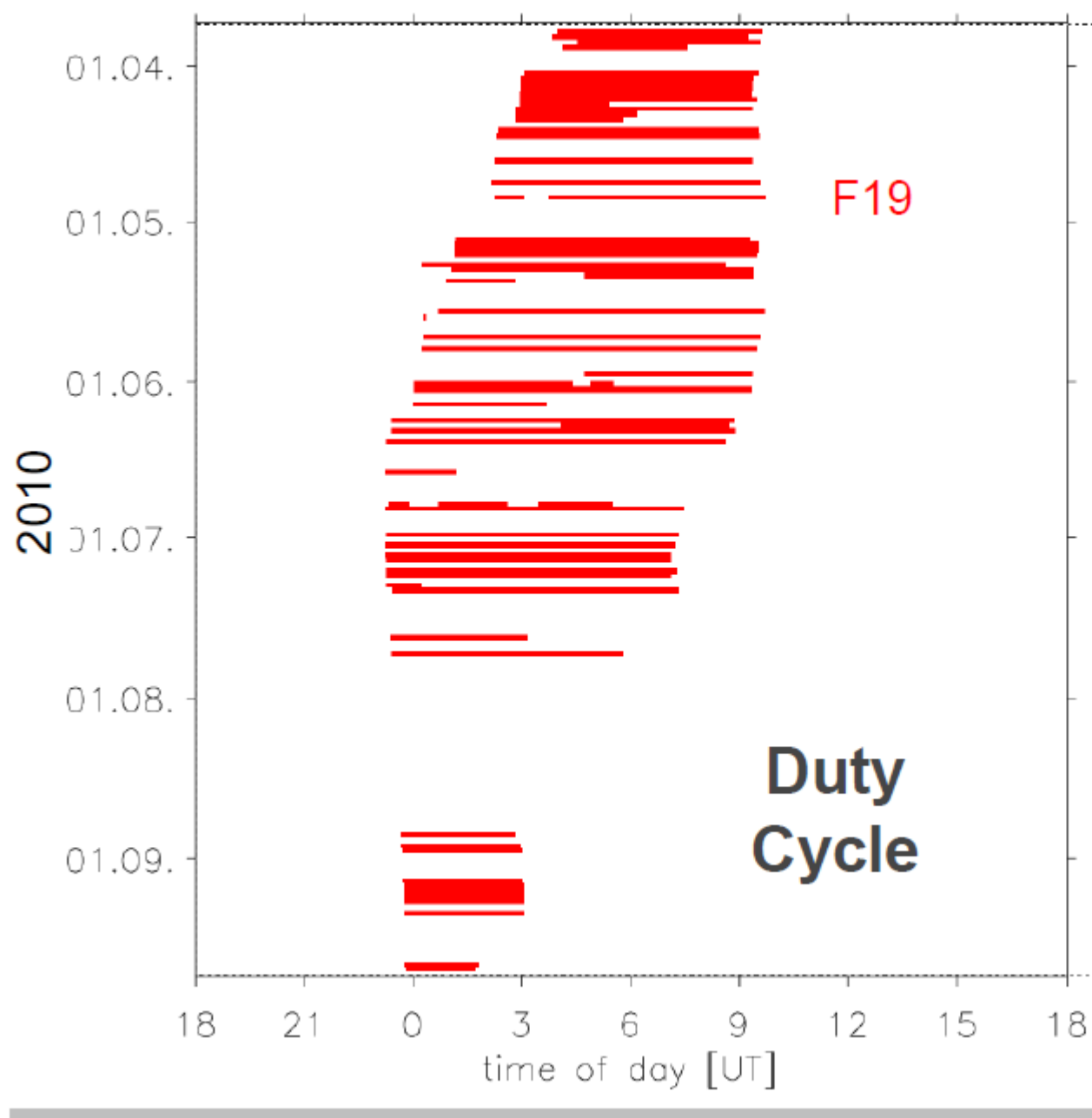
# HAT-South (child of HAT)

- Locations: Chile, Australia, Namibia

- Robotic 2x4x0.18m telescope each side

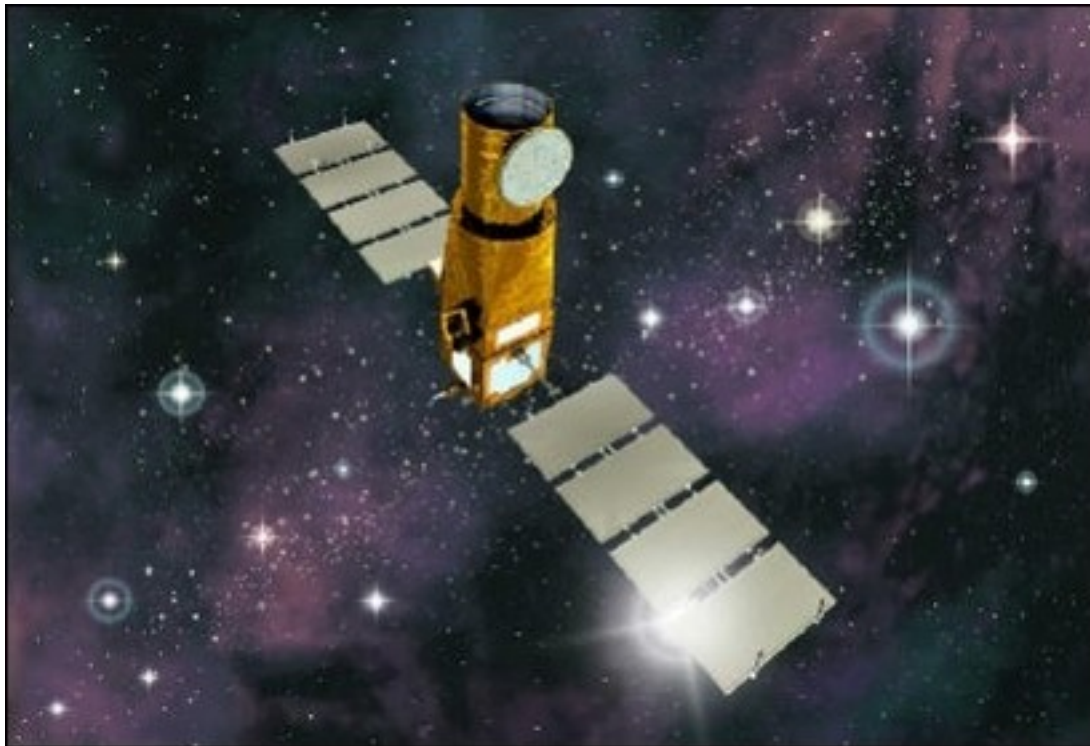- FOV 8x8deg

- Near round a clock monitoring



AIM:

Increasing the statistics of transiting
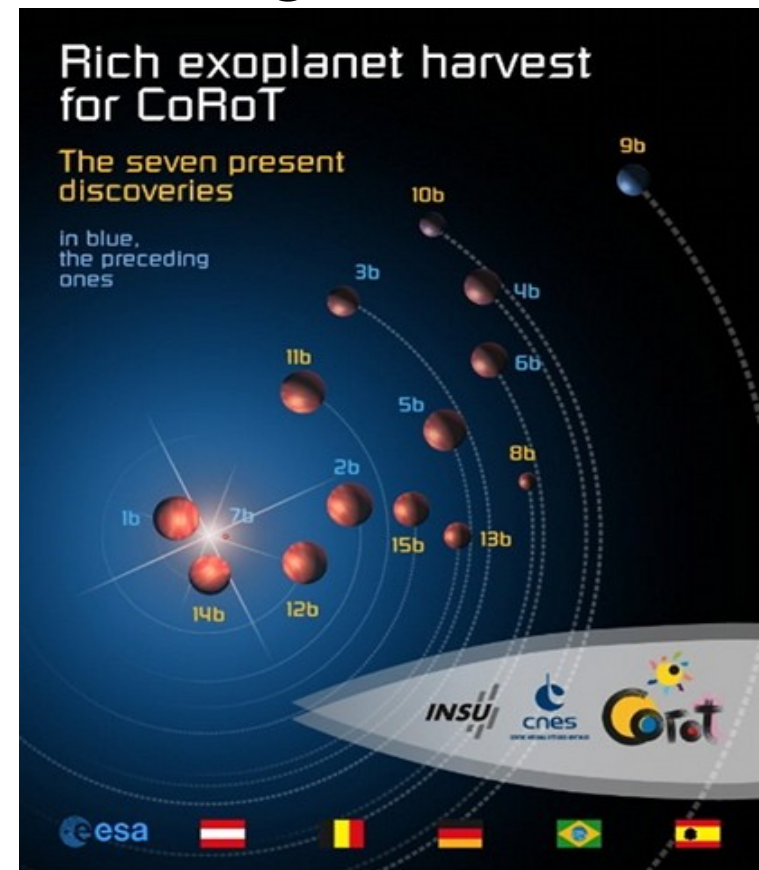
exoplanets around bright stars

# CoRoT

Convection, Rotation and planetary Transits

Launched 2006 – mission end 2013
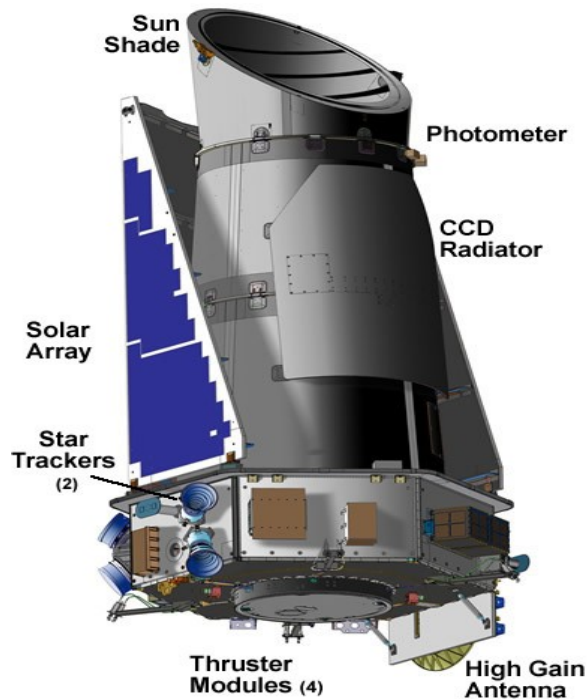
28cm mirror, 4 detectors of 1,5x1,5deg



ESA webpages

# Kepler

- 1.4-m mirror, telescope equipped with an array of 42 CCDs, each of 50x25 mm CCD has 2200x1024 pixels.

- launch March 2009, now continuing as K2

Monitored 100k stars in Cygnus constellation

Detected 1030 confirmed planets
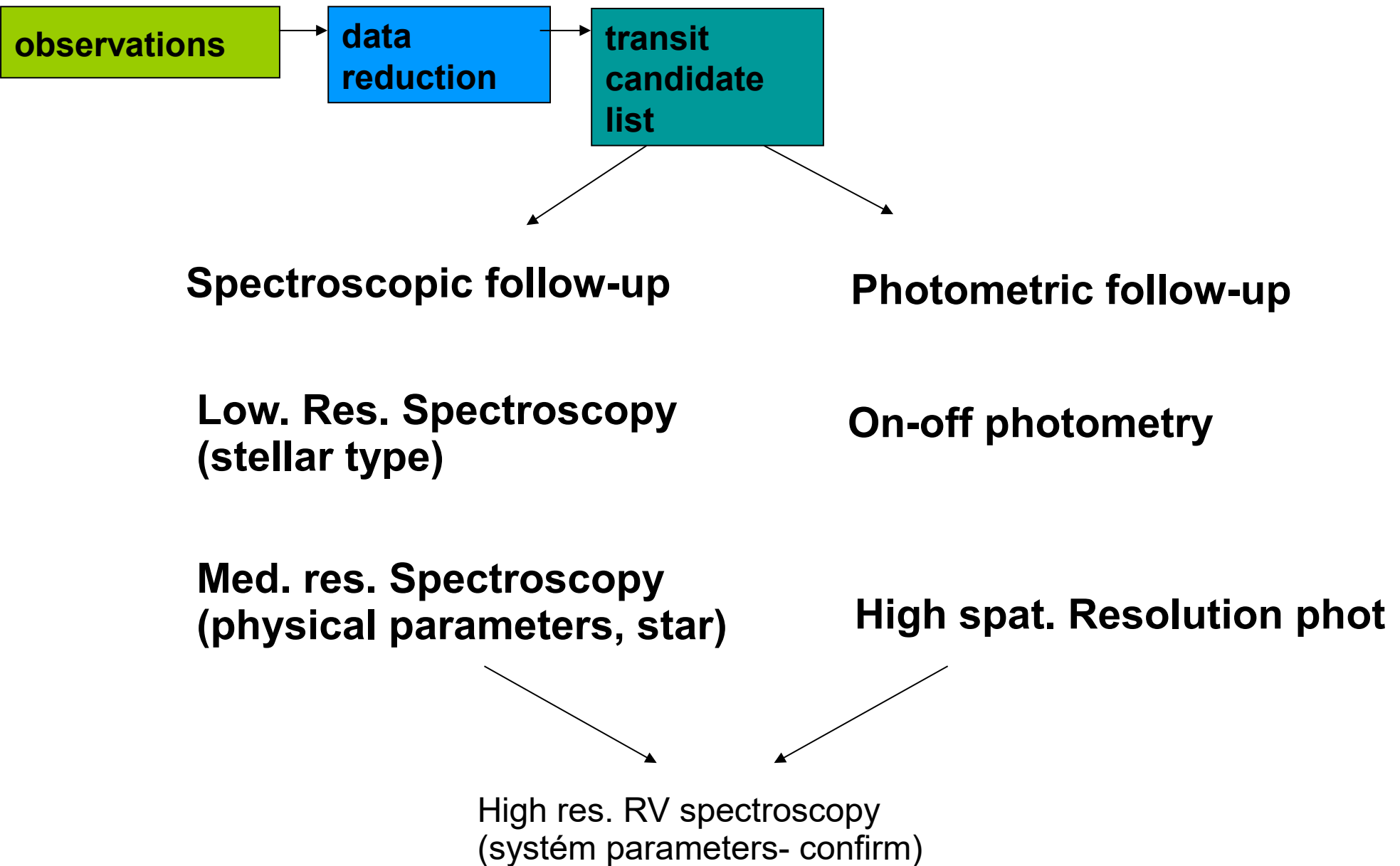
More to come from K2

Kepler webpage - http://kepler.nasa.gov/

Sun Shade

Photometer

CCD Radiator

Solar Array

Star Trackers (2)

Thruster Modules (4)

High Gain Antenna

# Planet confirmation process (Transits and RV combined)

# Transiting planets and their detection

```
observations ──▶ data reduction ──▶ transit candidate list
```

**Spectroscopic follow-up**

**Photometric follow-up**

**Low. Res. Spectroscopy (stellar type)**

**On-off photometry**

**Med. res. Spectroscopy (physical parameters, star)**

**High spat. Resolution phot**

High res. RV spectroscopy
(systém parameters- confirm)

# Other methods

# Microlensing

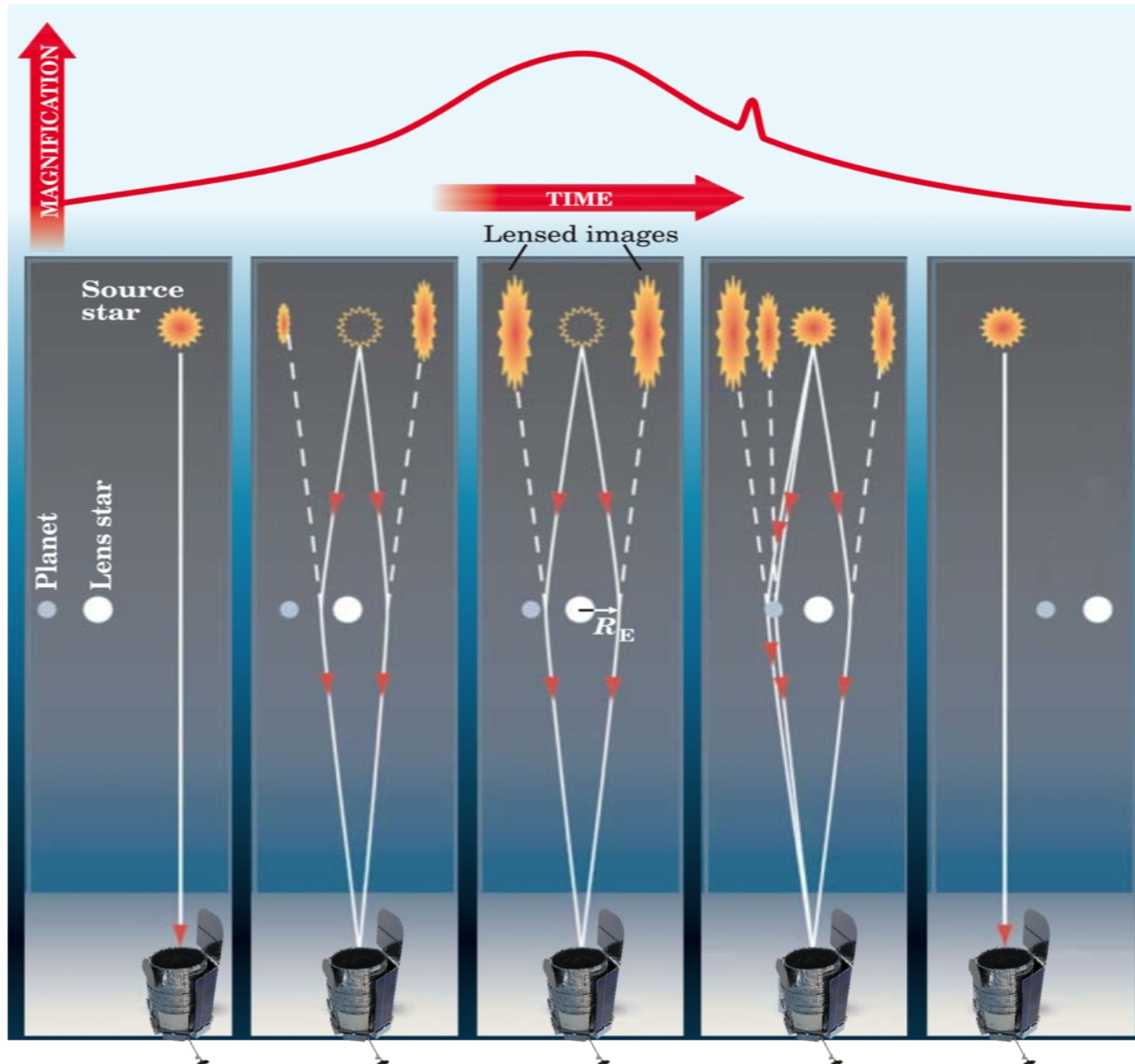The lense/Earth configuration does not repat (usually)

It is difficult to confirm such planets

OGLE – Optical gravitational lensing experiment



- 1.3m Las Campanas, Warsaw Univ.

- discovered planets by transit and microlensing (about 20)

- typically fainter stars

# Microlensing

# Astrometry

- Astrometric signature on sky measurable:

$$\alpha = \left(\frac{M_p}{M_\star}\right)\left(\frac{a_p}{1\text{ AU}}\right)\left(\frac{d}{1\text{ pc}}\right)^{-1}\text{arcsec}$$

- Astrometric signature of planets usually 10 μas and less

- For some planets (Jupiters), detectable by Gaia

# Astrometry



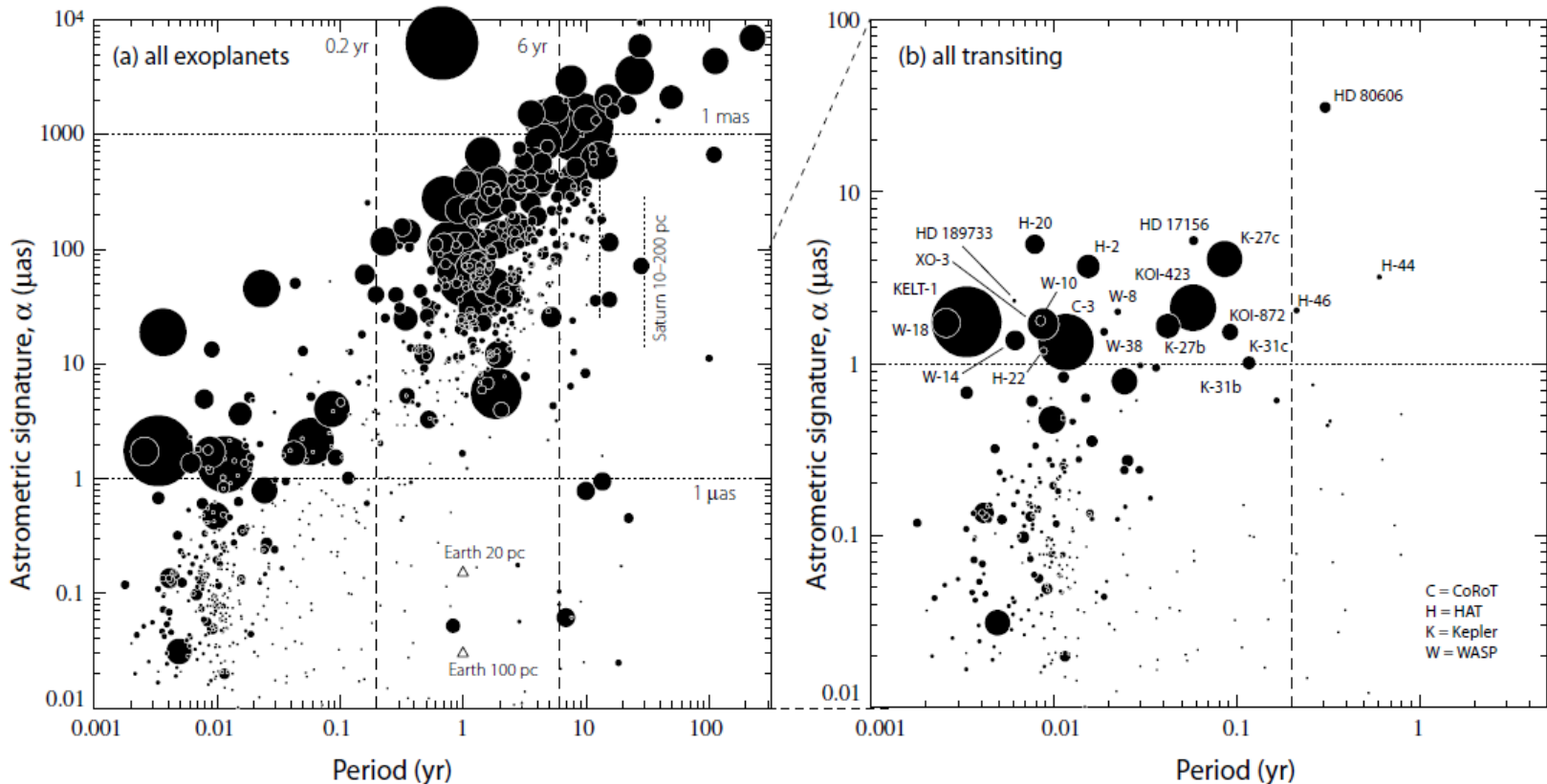Fig. 1.— Astrometric signature versus period calculated for the objects listed in exoplanet.eu at 2014 September 1 for all 1821 confirmed planets (left), and for the subset of 1129 transiting planets with appropriately known data (right). Note the different scales in abscissa and ordinate. Circle sizes are proportional to planet mass; the prominent object (left) at $P = 0.7\,\text{yr}$, $\alpha = 6300\,\mu\text{as}$, is the $28.5 M_\text{J}$ astrometric detection DE0823–49 b. Unknown distances are set to $d = 1000\,\text{pc}$. Transiting planets with $\alpha > 1\,\mu\text{as}$ are labelled by (abbreviated) star name, indicating the discovery instrument, both ground (H = HAT, W = WASP) and space (C = CoRoT, K = Kepler). For the transiting planets above this threshold, the unknown distance affects only Kepler–27 b and c, and Kepler–31 b and c. Assuming $d = 500\,\text{pc}$, $\alpha$ would increase by a factor 2, but their astrometric motion would remain undetectable by Gaia.

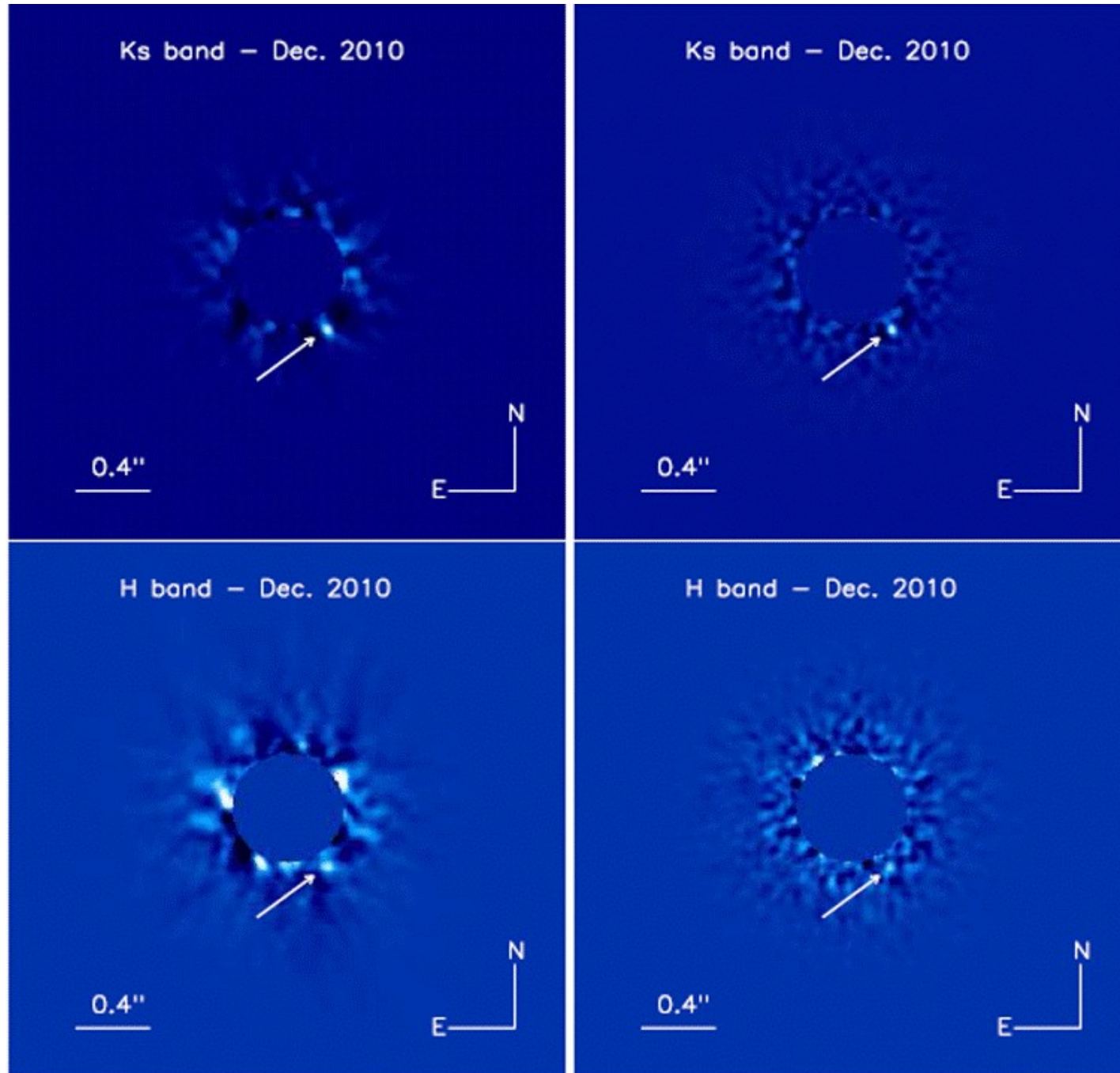Perryman et al. 2014, http://arxiv.org/pdf/1411.1173v1.pdf

# Direct imaging

- Diffcult due to the contrast of star planet

- Difficult because of Earth atmosphere

- Use of adaptive optics is a must

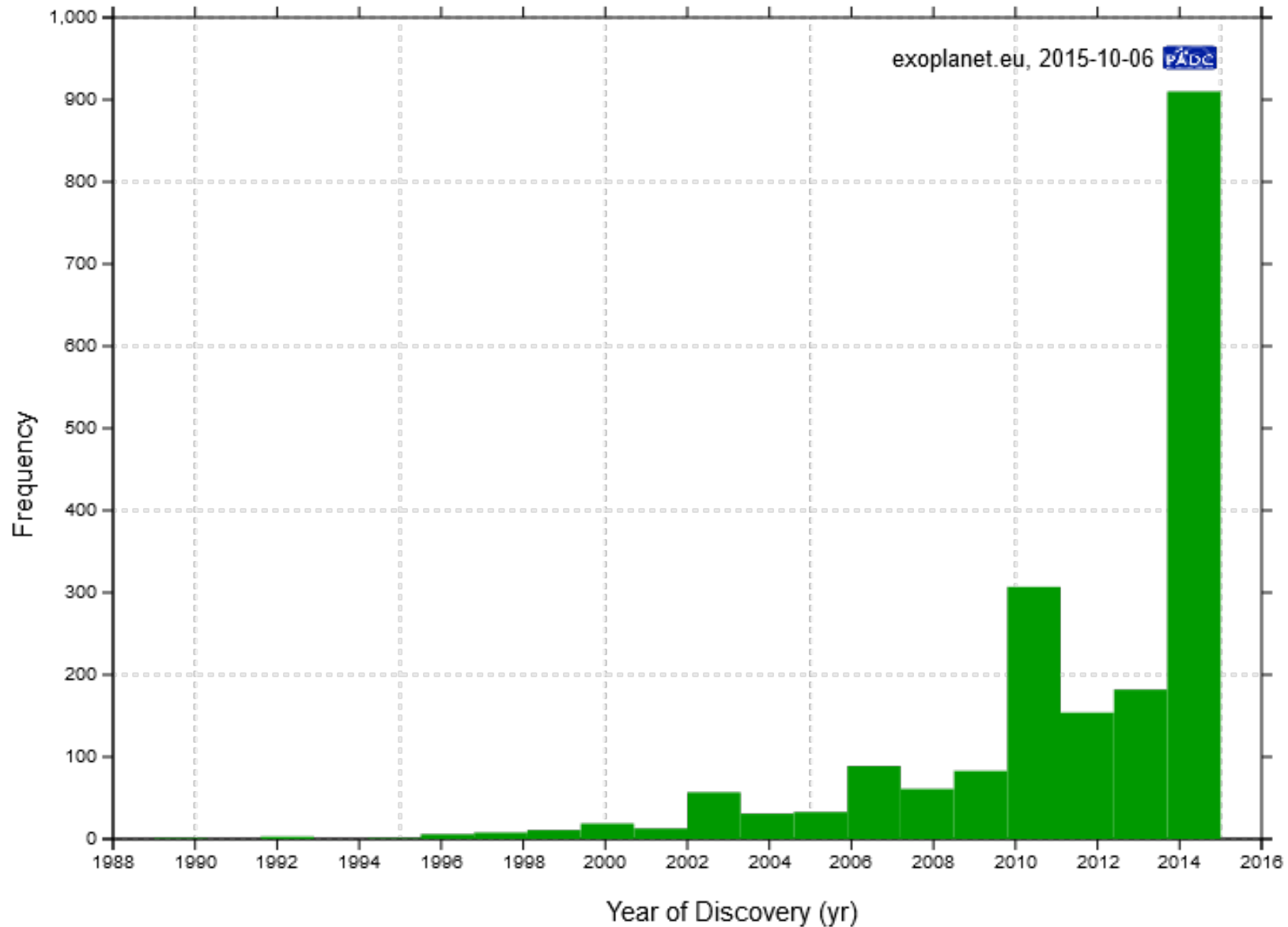- Only planets in large distance from the host star
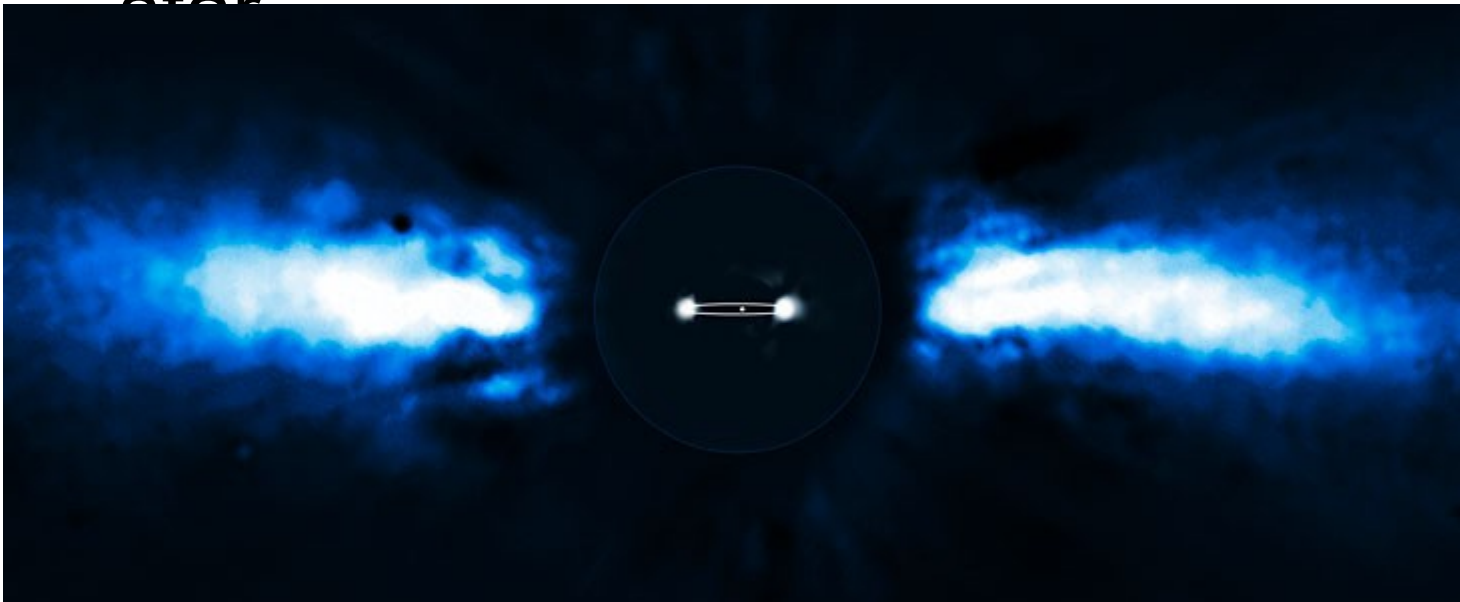


Credit : ESO press release (Beta Pic, A. Lagrange)
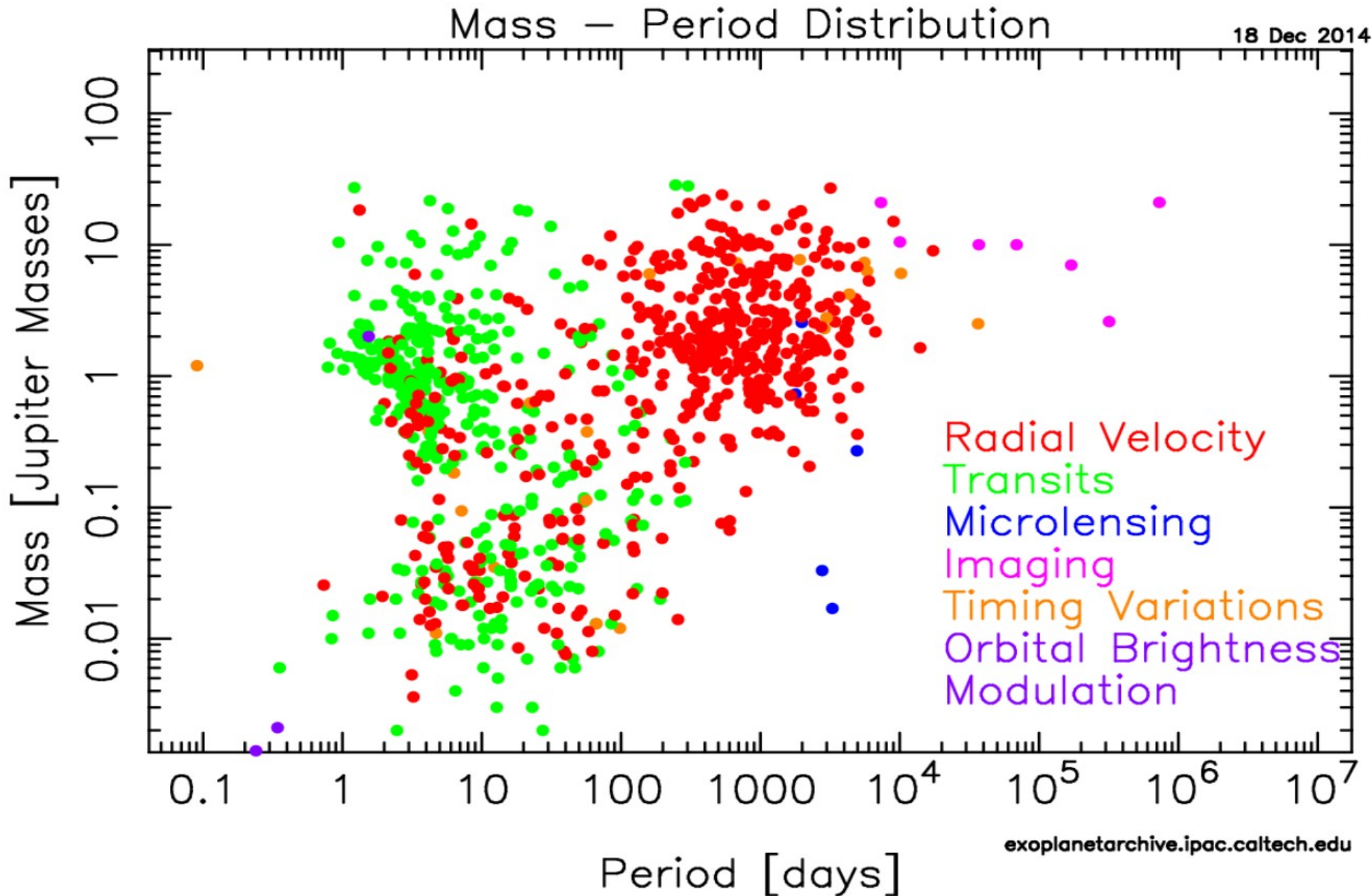
# And here is a detail
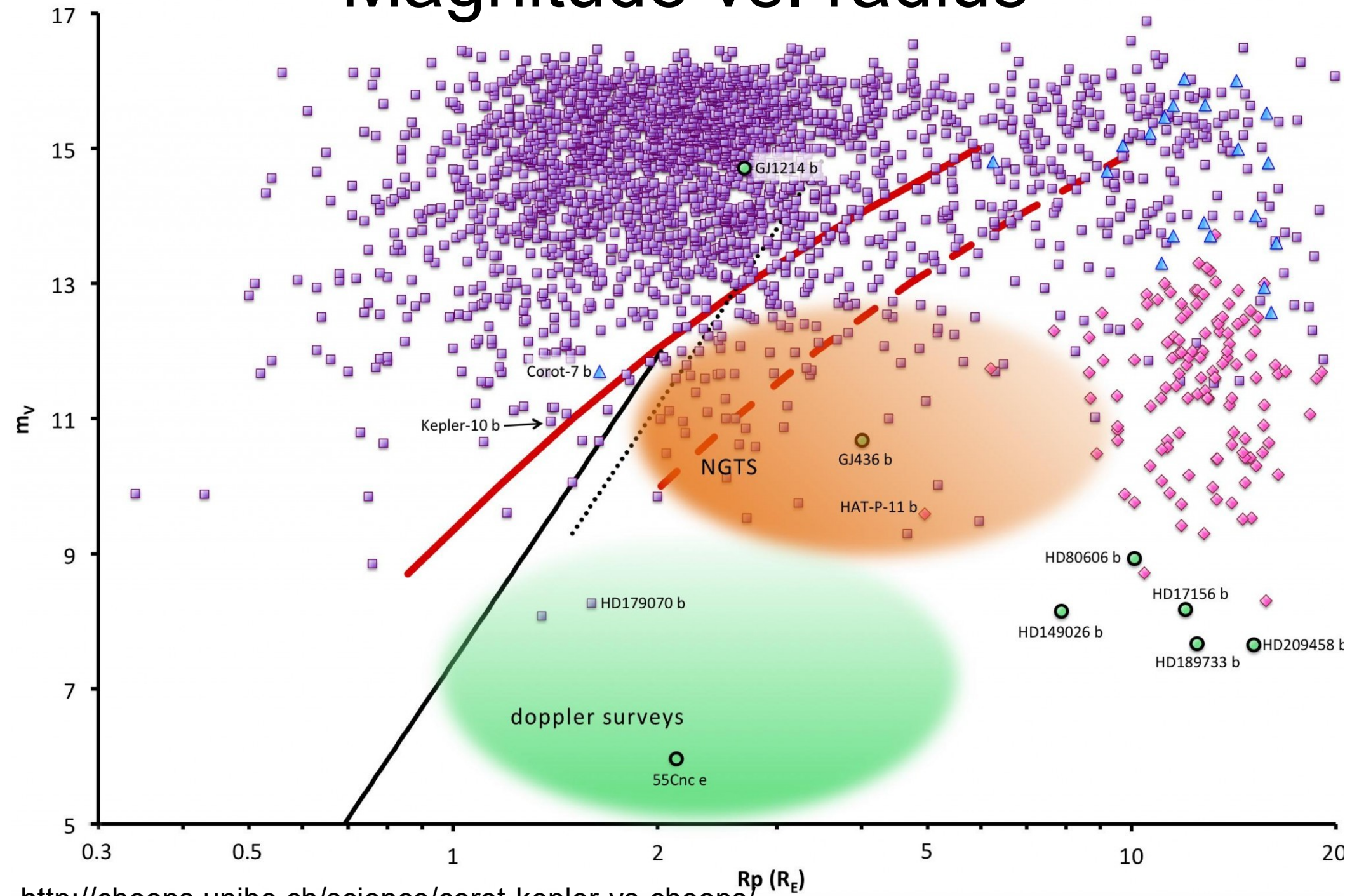
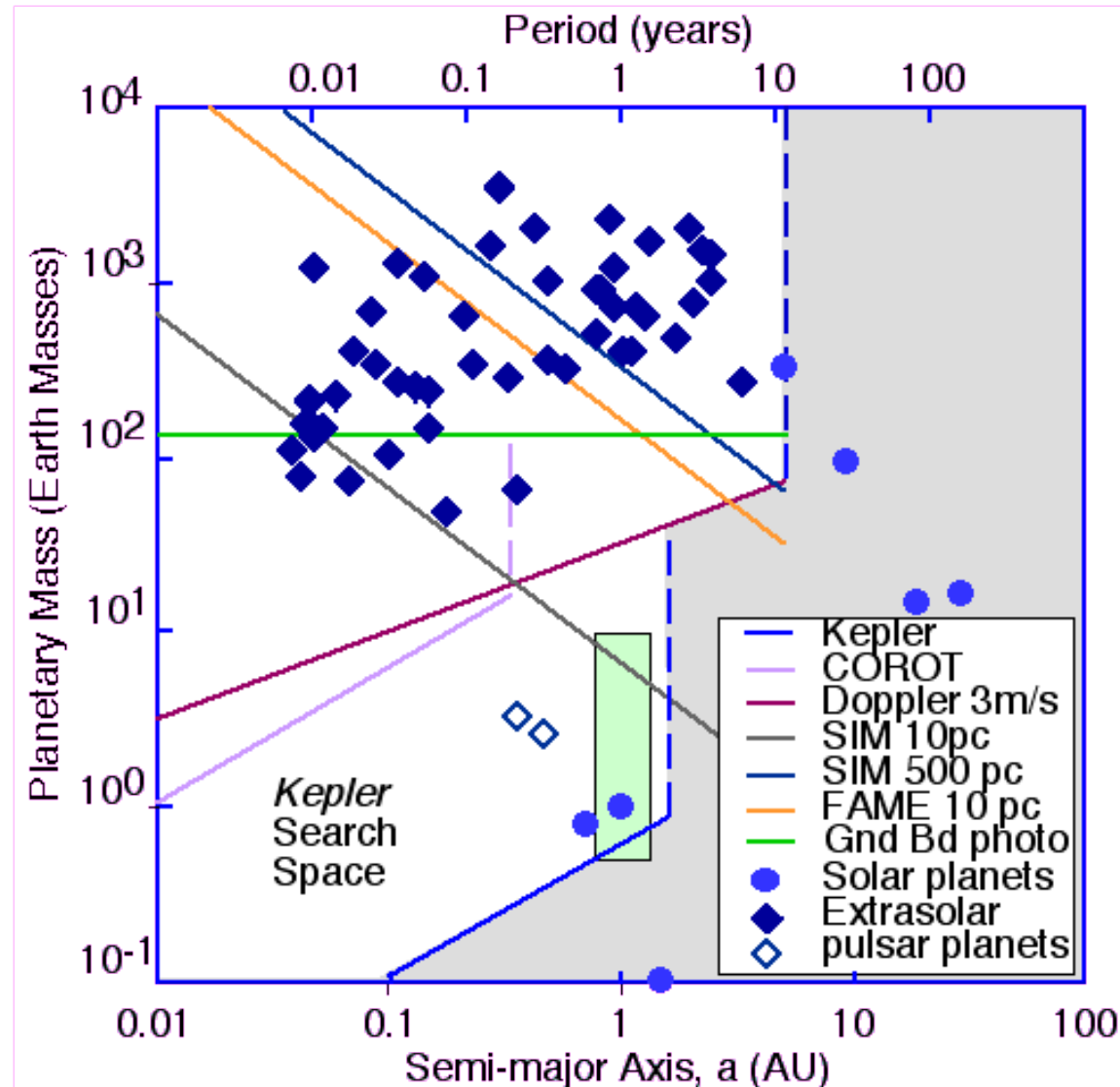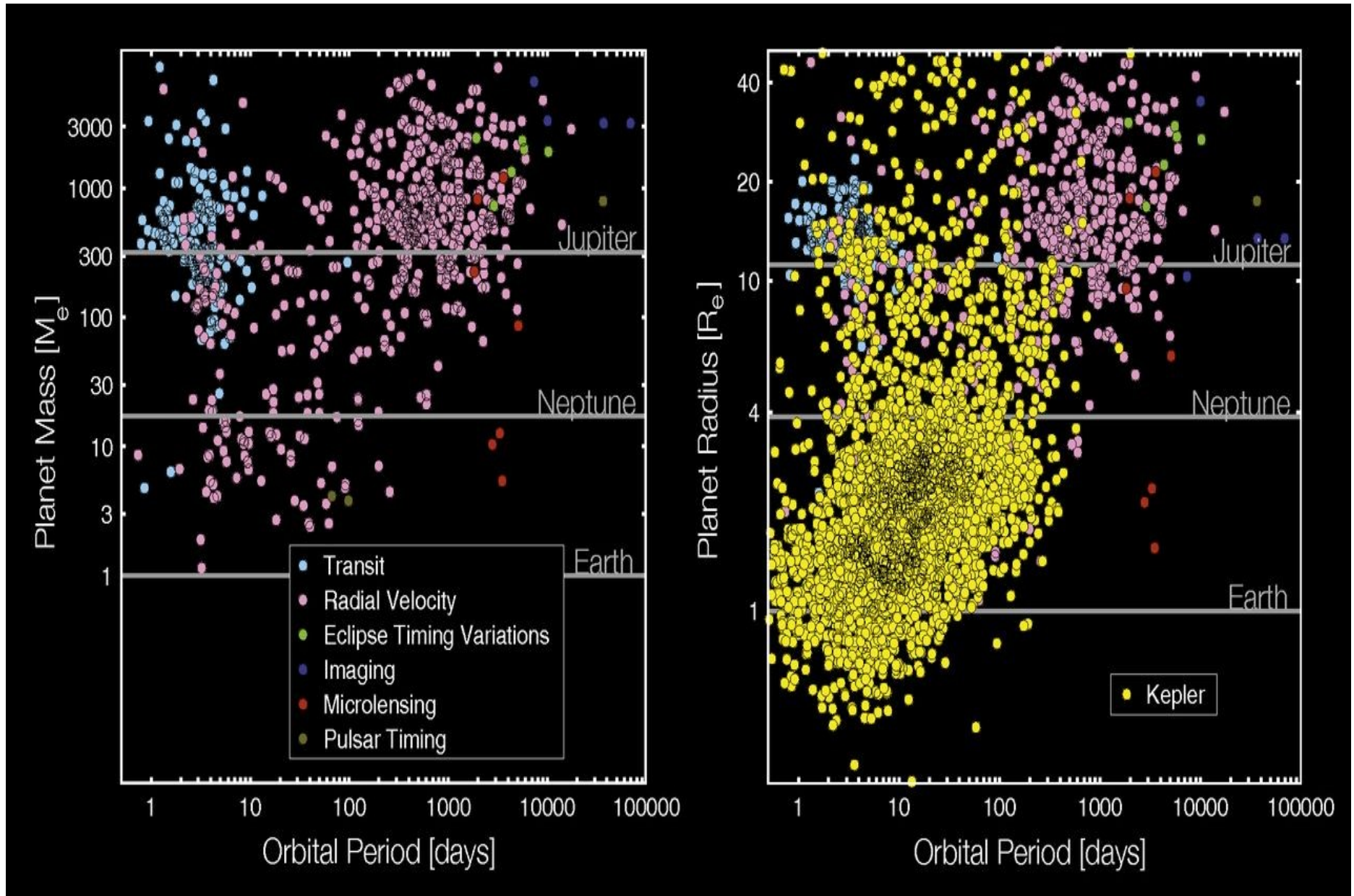# Some statstics
# Completeness of surveys

# Exoplanets today



Encyclopedia of extrasolar planets

# Mass vs. period



Mass – Period Distribution

18 Dec 2014

Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation

Mass [Jupiter Masses]

Period [days]

exoplanetarchive.ipac.caltech.edu

# Magnitude vs. radius

# Mass vs. Semi-m. Axis (before Kepler)



Credit: NASA

# And similar with Kepler
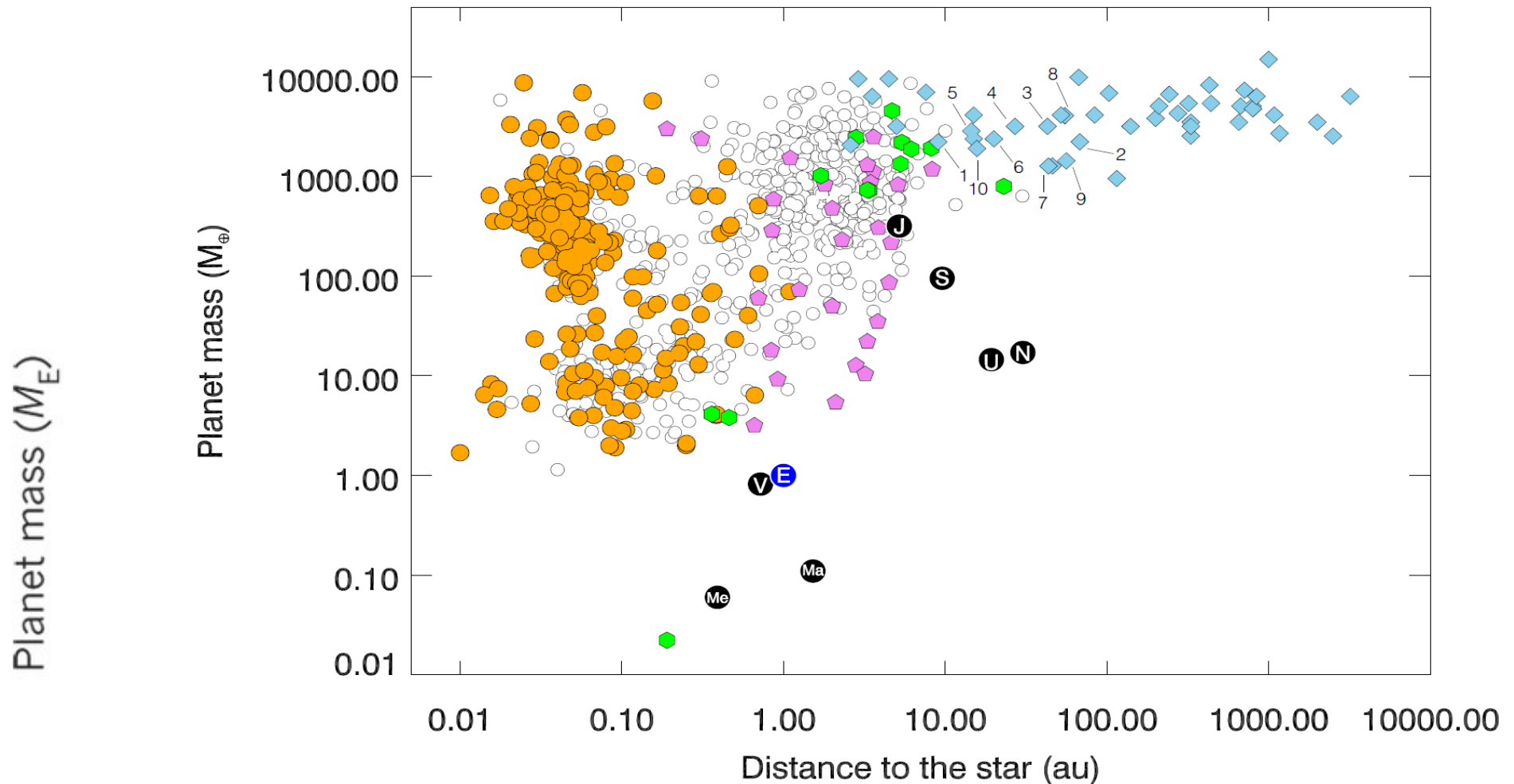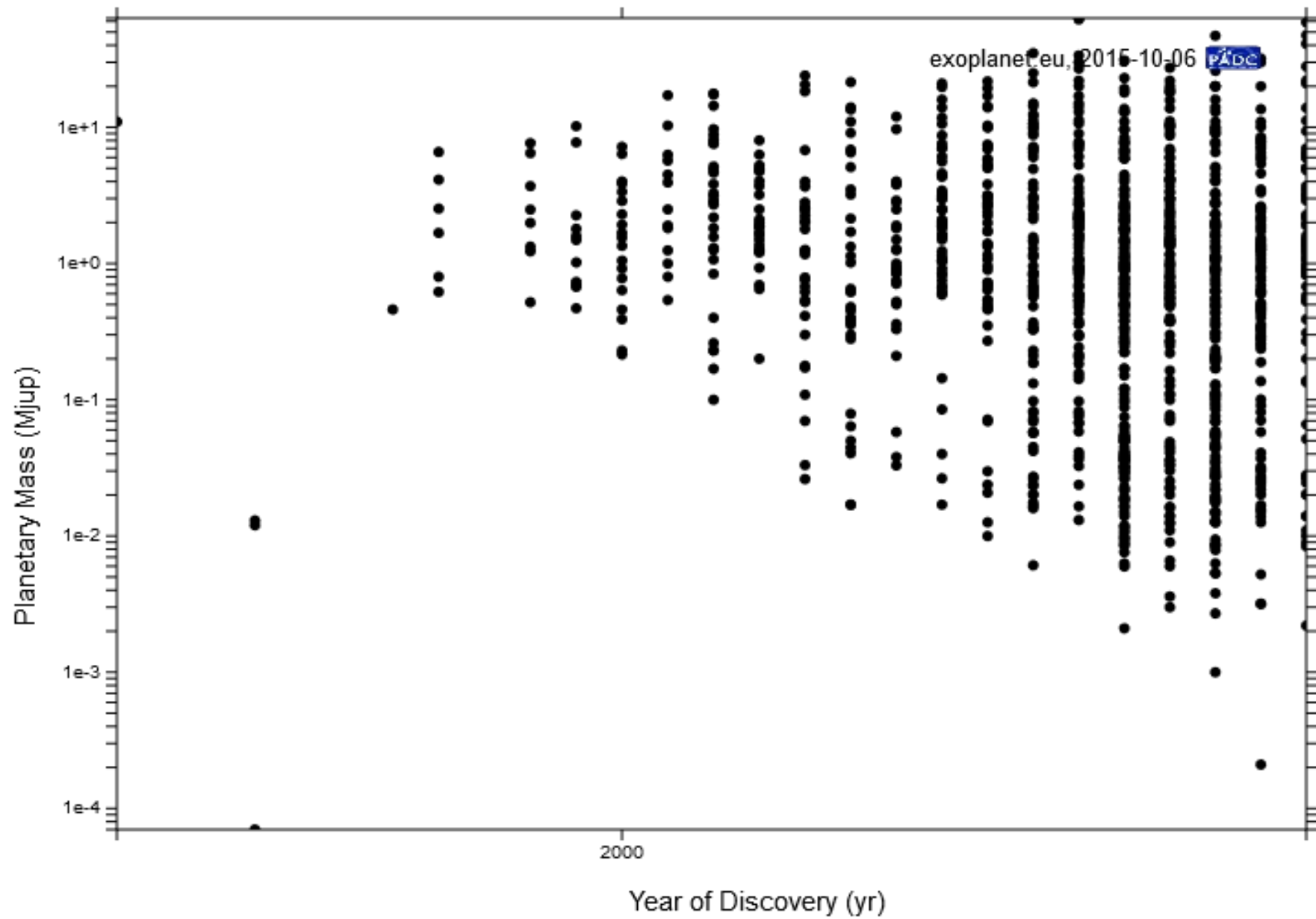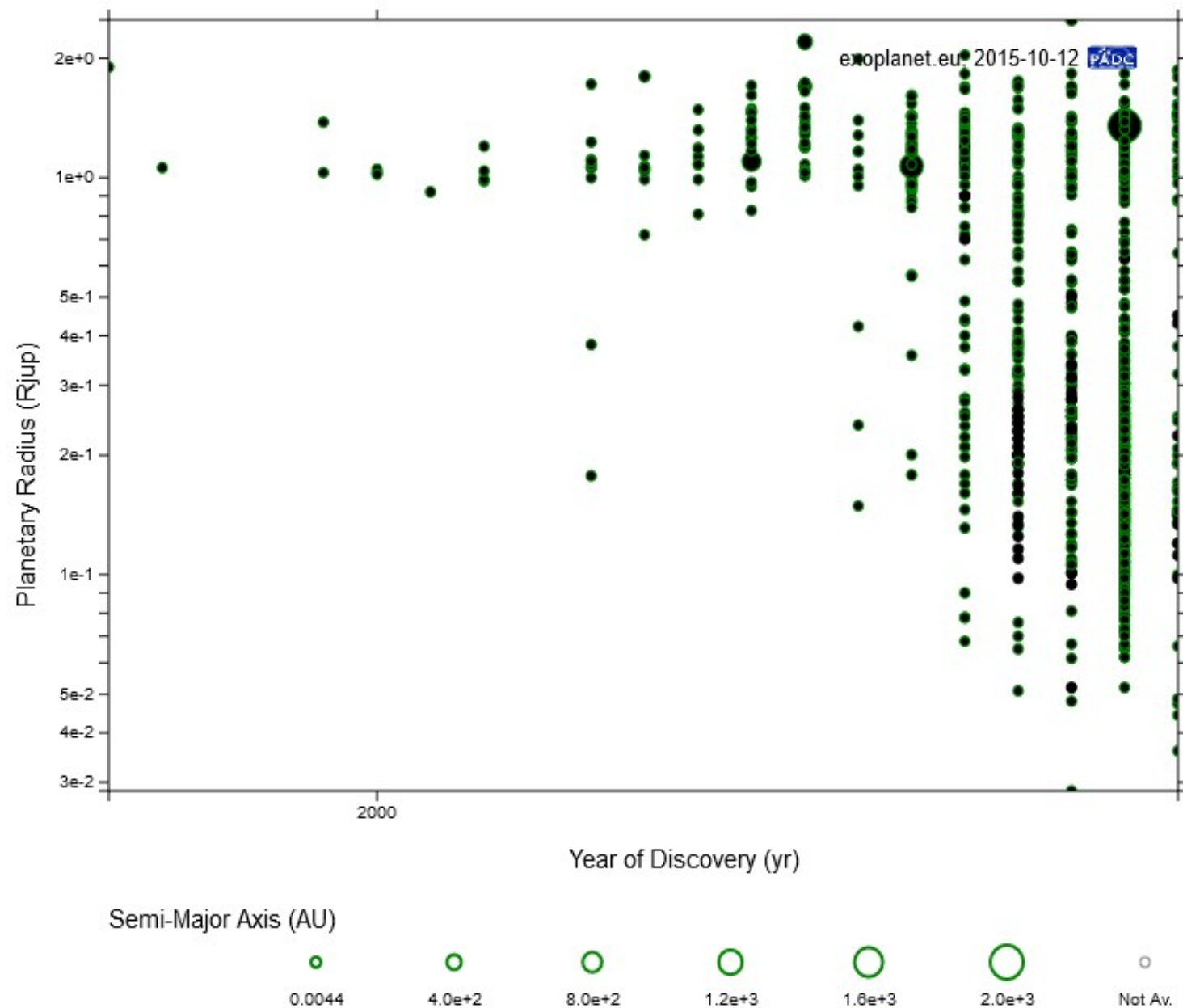
# Mass. vs. distance to star



Figure 3: *Mass and semi-major axis of known planets.* **Planetary mass is plotted as a function of semi-major axis (the distance to the host star). Solar-system planets are shown by black circles, the Earth in blue. Exoplanets detected with different techniques and instrumentation are represented by different symbols: Doppler velocimetry (white circles), transit with a measured mass (orange circles), direct imaging (sky blue diamonds), microlensing (violet pentagons), and pulsation timing (green hexagons). Among the direct-imaging planets only ten were found within 100 au from their host and a mass ratio between the companion and its host star $q < 0.02$: beta Pic b, HR 8799e, PZ Tel b, HR 8799 d, HR 8799 c, GJ 504 b, kappa And b, HD 95086 b, HR 8799 b and LkCa 15b. Data underlying this plot were retrieved from the Exoplanet Encyclopaedia[196].**

Pepe, et al. 2014 http://arxiv.org/ftp/arxiv/papers/1409/1409.5266.pdf

# Smaller and smaller



exoplanet.eu, 2015-10-06

# And the radius

# Next week

- Types of planets

- Physical characterization

- Exoplanetary atmospheres

- Towards smaller planets

- Biomarkers

Thank you for your attention and see you nex tweek