

Exoplanets

Fall/Winter 2025/2026

Lecture 2

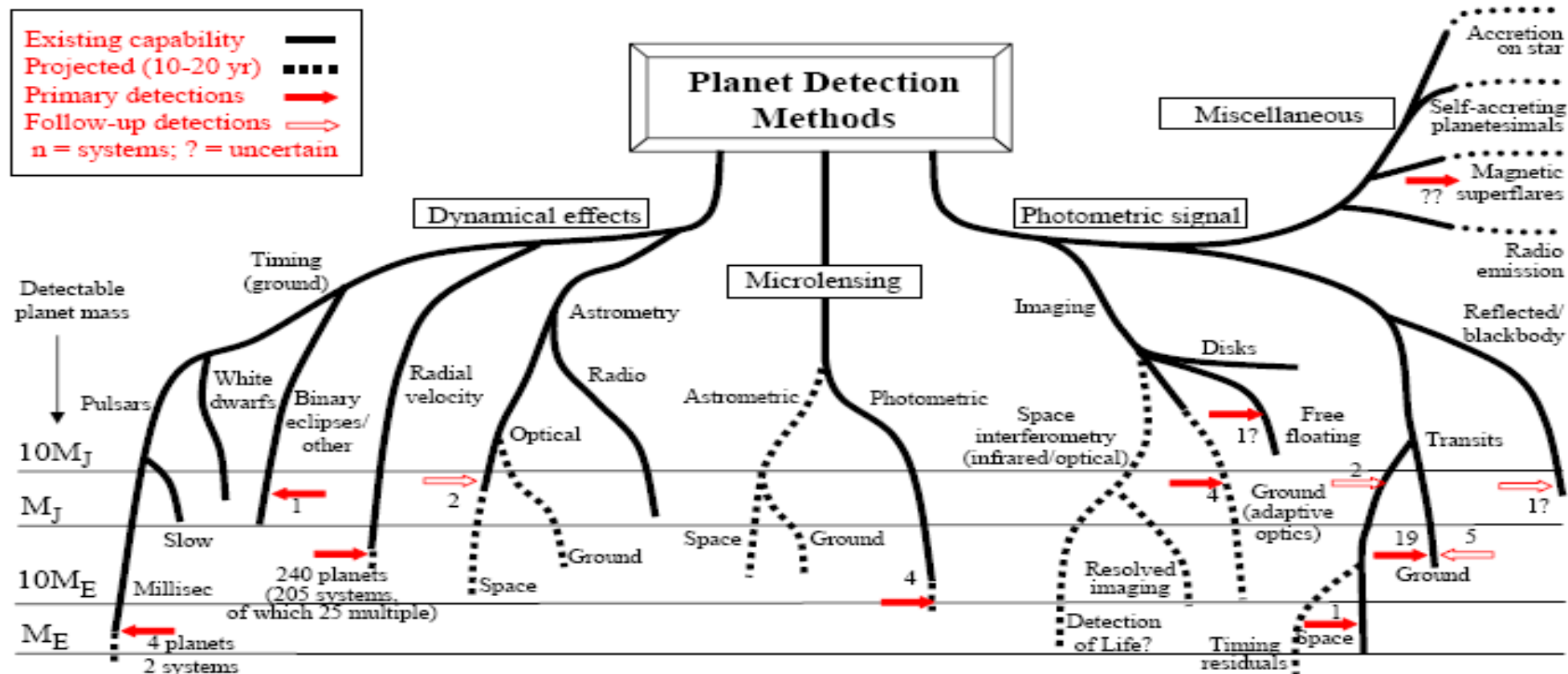
17.10.2025

Outline

- Introduction of detection methods
- Radial velocities
- Transit detection
- Other methods
- Calibration of the spectra

Planet Detection Methods

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



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

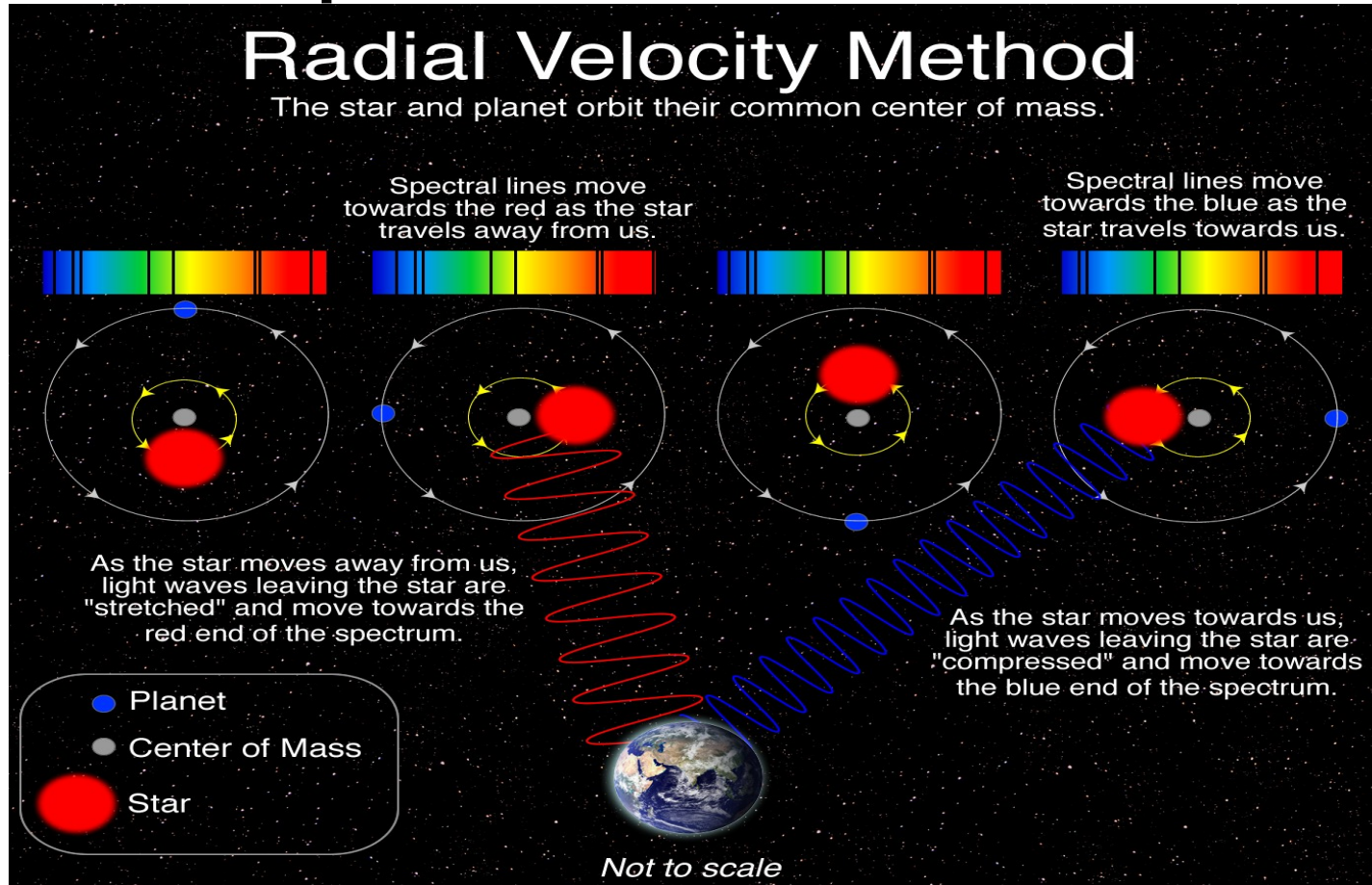
Radial velocities method (RV)

- Spectroscopical method 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 system)
- Measurable quantity is the RV amplitude
- Determines lower mass limit only

Doppler effect

- $\Delta\lambda/\lambda=v/c$ (non relativistic)
- First we need to perfectly calibrate the wavelength
- Then we can measure the velocities, well shifts of spectral lines in wavelength due to the movement of the object
- We are looking at tiny shifts of spectral lines of the star due to planets!

Principle of the RV method



Credit: Las Cumbres Observatory

The first step

- Instrumentation usually very stable Echelle spectrographs to achieve high precision (Lecture 3)
- Obtaining a time series of high res. spectra
- 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)

Results (51 Peg)

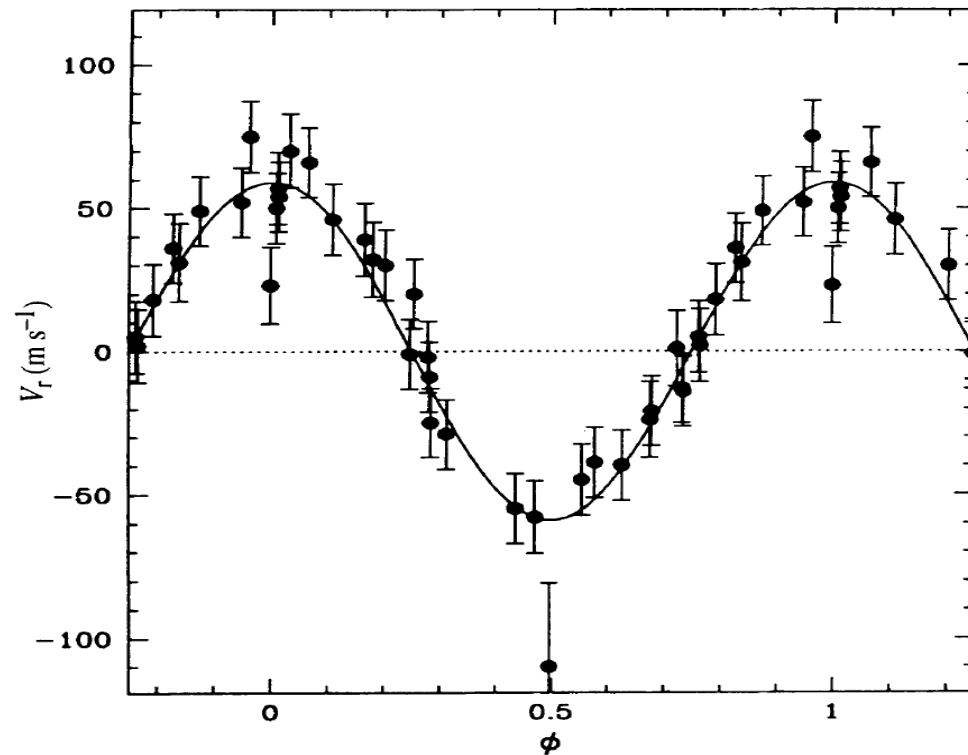
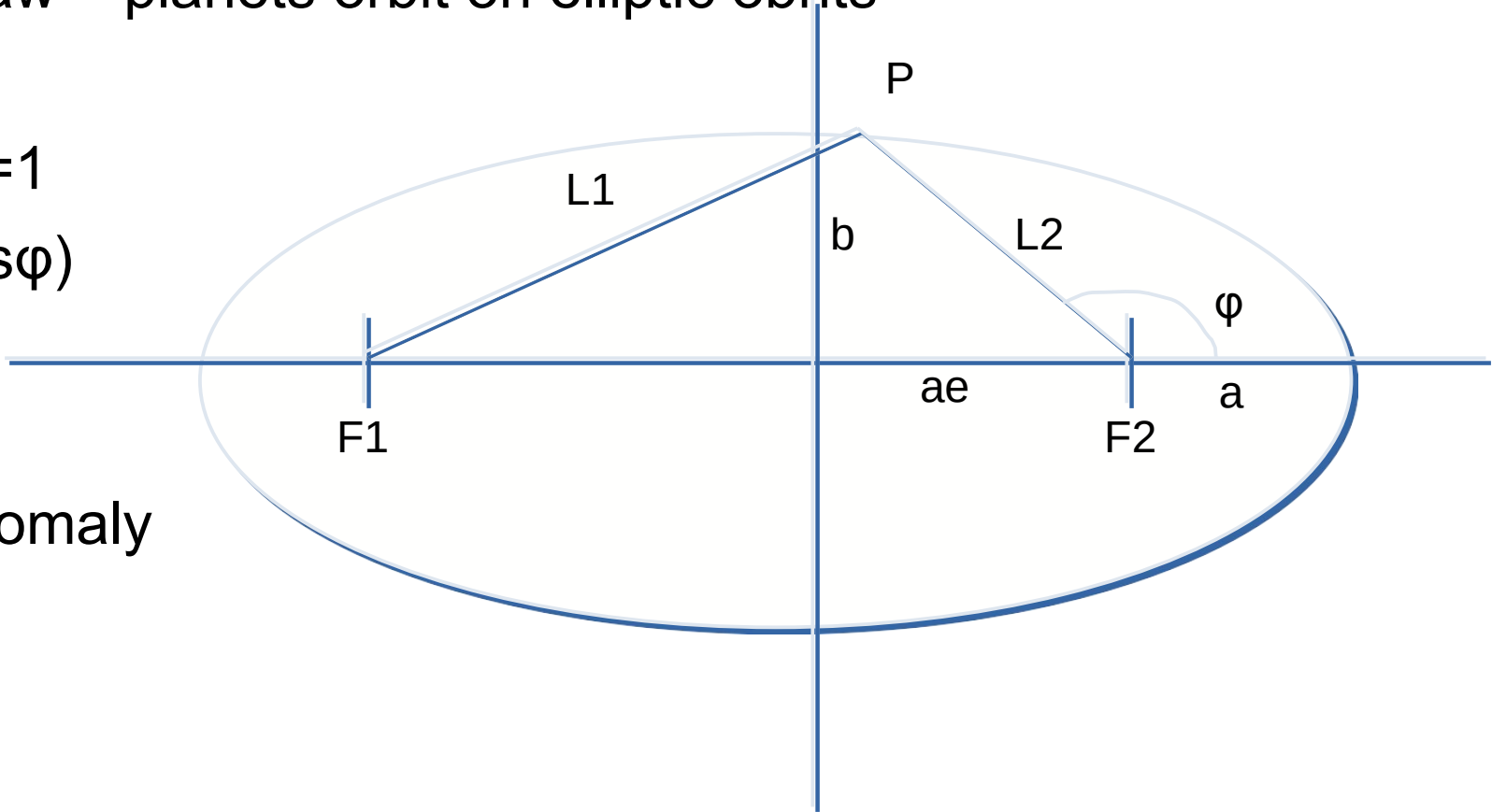


FIG. 4 Orbital motion of 51 Peg corrected from the long-term variation of the γ -velocity. The solid line represents the orbital motion computed from the parameters of Table 1.

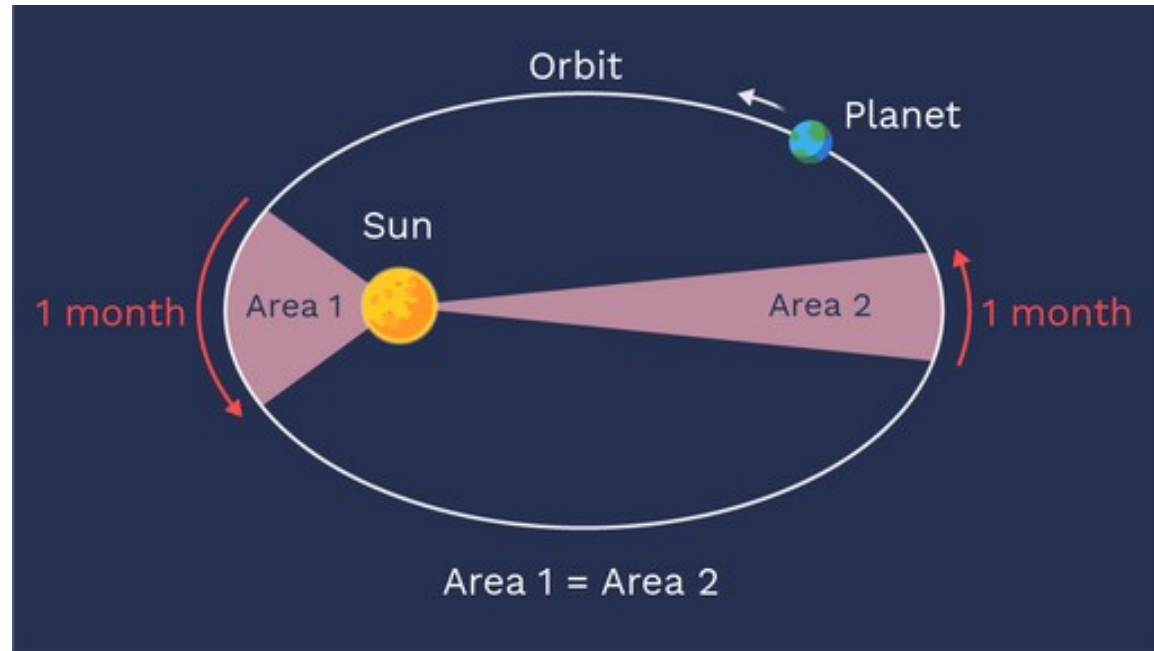
Kepler's laws

- 1st Kepler law – planets orbit on elliptic orbits
- $L_1 + L_2 = 2a$
- $x^2/a^2 + y^2/b^2 = 1$
- $r = p / (1 + \varepsilon \cos \varphi)$
- $p = a(1 - \varepsilon^2)$
- $\varepsilon = e/a$
- φ – true anomaly



Kepler's laws

- 2nd Kepler's law



Kepler`s laws

- 3rd Kepler`s law
- $P^2 \propto a^3$
- All the Kepler laws are applied to obtain the semi-amplitude K for the radial velocities movement of the star due to companion planet

Getting the semi-amplitude K

- http://www.relativitycalculator.com/pdfs/RV_Derivation.pdf
- http://exoplanets.astro.yale.edu/workshop/EPRV/Bibliography_files/Radial_Velocity.pdf

$$V_{r \text{ (star)}} = \frac{2\pi a_1 \sin i}{P\sqrt{1-e^2}} [\cos(\theta + \omega) + e \cos \omega]$$

$$K_1 \equiv \text{radial velocity semi - amplitude of host star} = \frac{2\pi a_1 \sin i}{P\sqrt{1-e^2}}$$

Semi-amplitude K

- 3rd Kepler law

$$P^2 = \frac{4\pi^2}{G(m_1 + m_2)} a_2^3$$

$$K_1 = \frac{m_2}{m_1} \frac{\sin i}{\sqrt{1-e^2}} \left[\frac{8\pi^3 G (m_1 + m_2) P^2}{4\pi^2 P^3} \right]^{\frac{1}{3}}$$

$$= \frac{m_2}{m_1} \frac{\sin i}{\sqrt{1-e^2}} \left[\frac{2\pi G (m_1 + m_2)}{P} \right]^{\frac{1}{3}}$$

$$= \left(\frac{2\pi G}{P} \right)^{\frac{1}{3}} \frac{m_2}{m_1} (m_1 + m_2)^{\frac{1}{3}} \frac{\sin i}{\sqrt{1-e^2}}$$

Simplification – masses difference

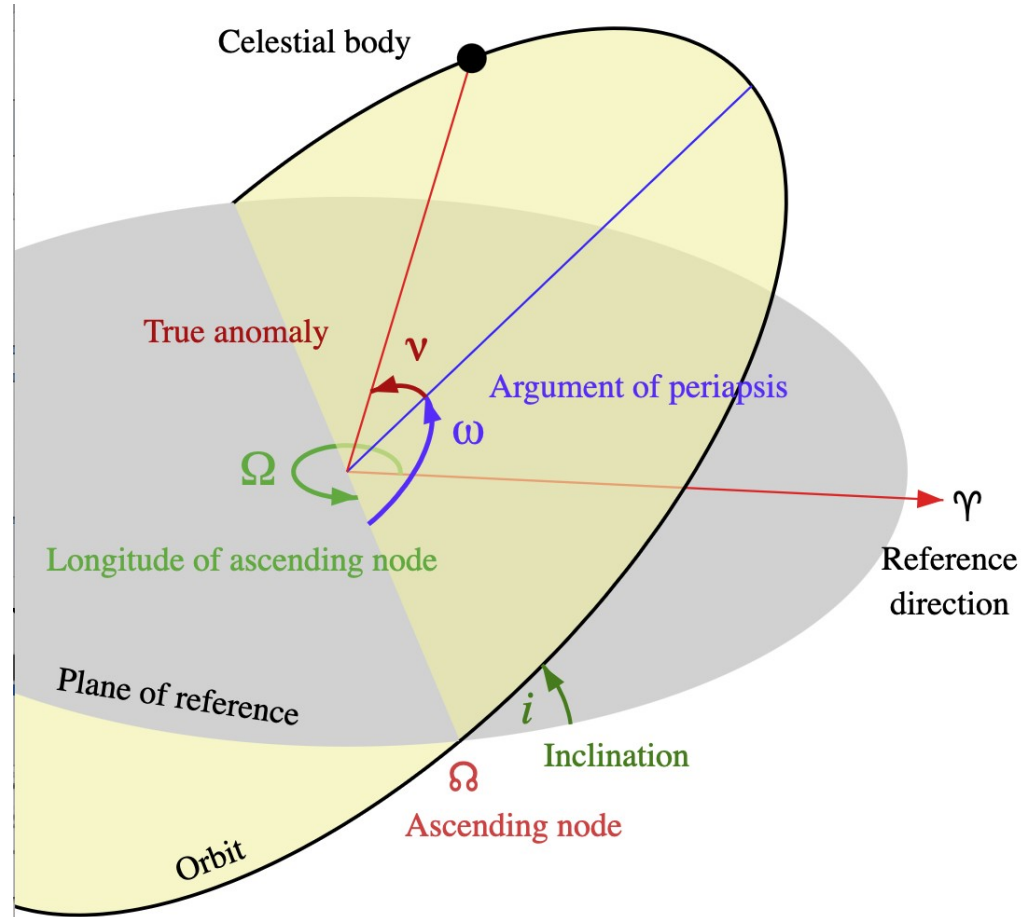
- $m_1 + m_2$ is approx m_1

$$K_1 = \left(\frac{2\pi G}{P} \right)^{\frac{1}{3}} \frac{m_2}{m_1} (m_1)^{\frac{1}{3}} \frac{\sin i}{\sqrt{1-e^2}}$$

$$K_1 = \left(\frac{2\pi G}{P} \right)^{\frac{1}{3}} \frac{m_2 \sin i}{m_1^{2/3}} \frac{1}{\sqrt{1-e^2}}$$

A slight issue

- The radial velocity method can not help with determining the inclination of the orbital plane i
- The mass from RVs is the lower mass limit if i is unknown
- Combination with other methods crucial



Some equations

- Observable semi-amplitude of RV curve K:

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

- Using Kepler law and Newton's law, conservation $\frac{M_p}{(M_p + M_{\star})^{2/3}} = \frac{K_{\star} \sqrt{1-e^2}}{\sin i} \left(\frac{P}{2\pi G} \right)^{1/3}$
- For details see:

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

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

Solar type stars and RVs

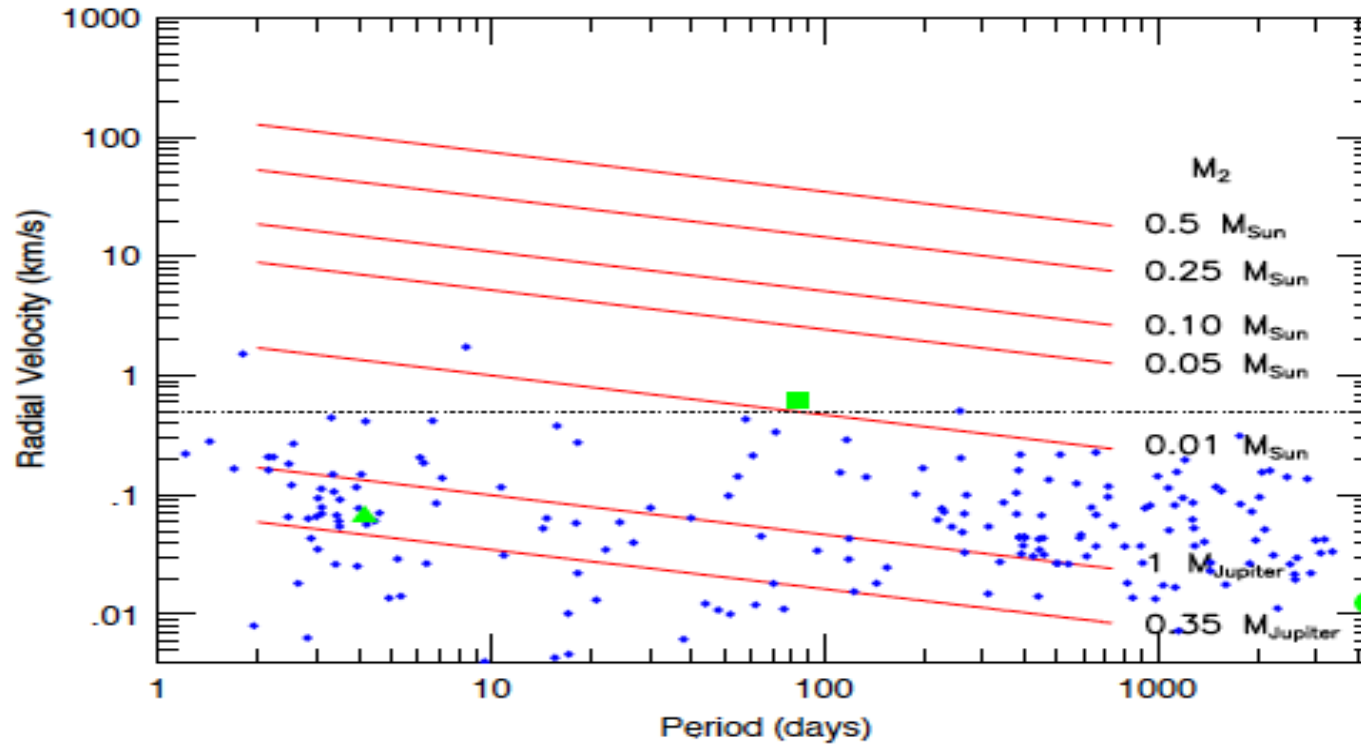
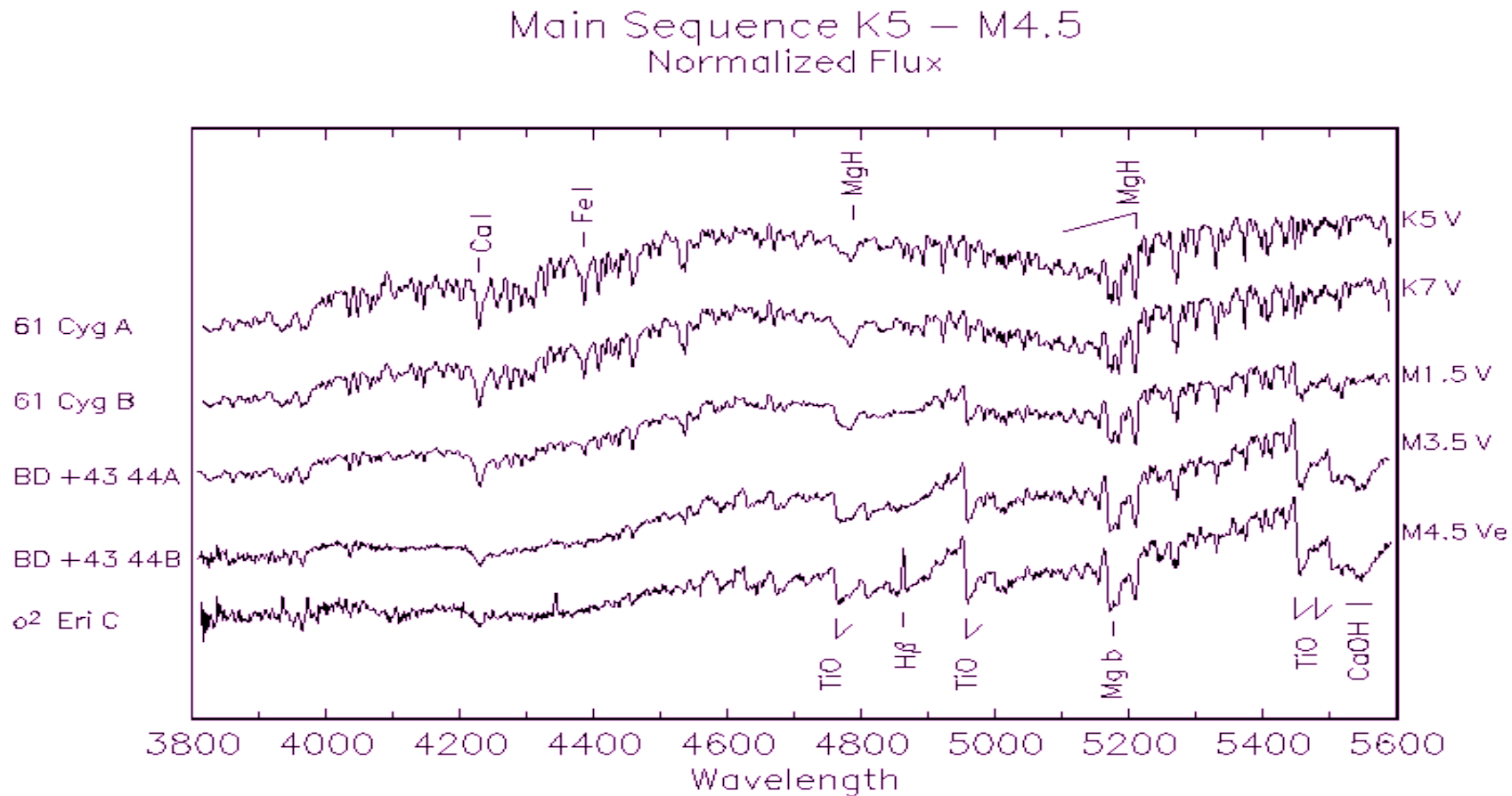
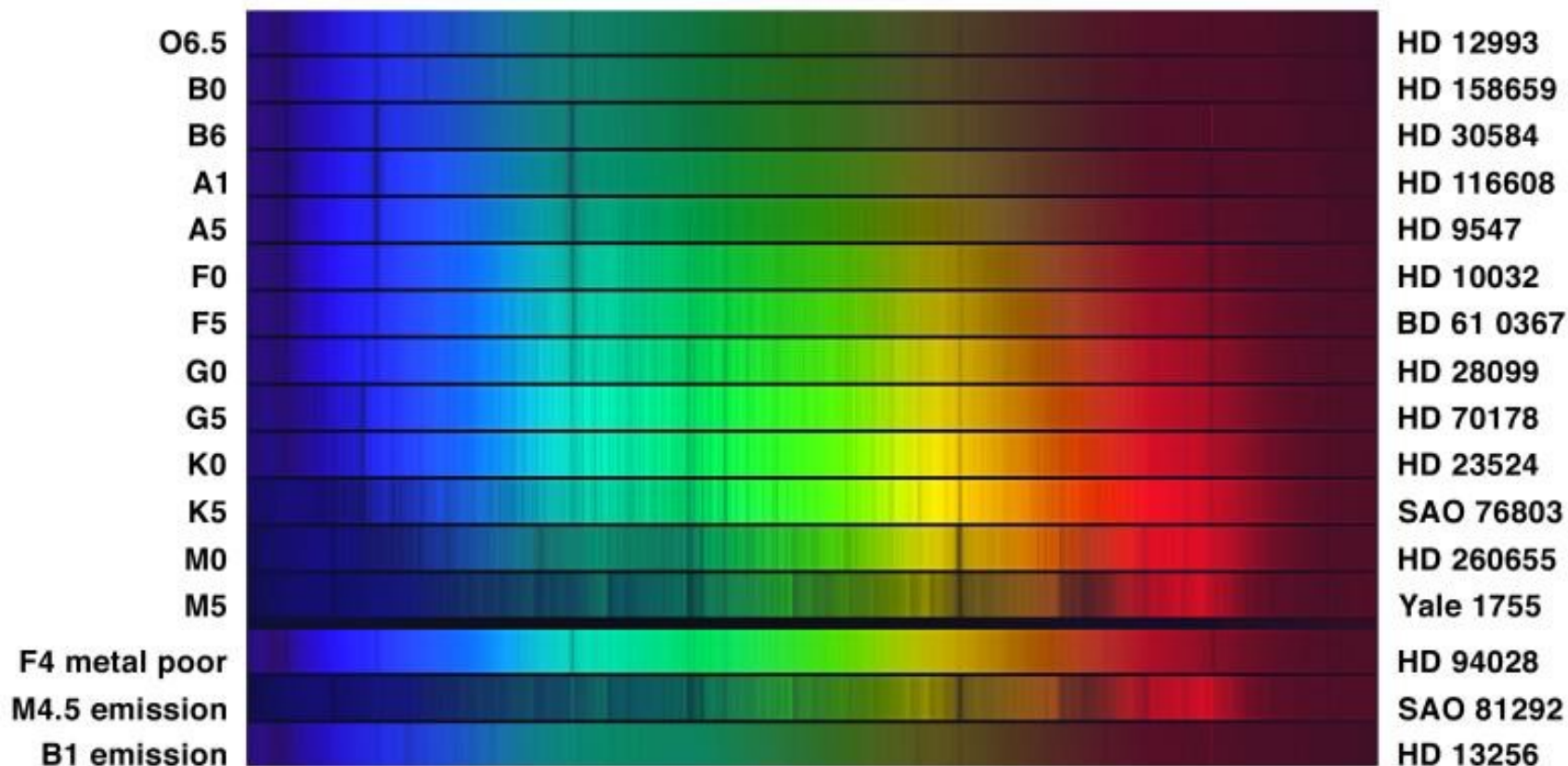


Figure from Hatzes, Cochran, Endl - : Radial velocity of a Solar type star due to a companion

Example of a main sequence spectra



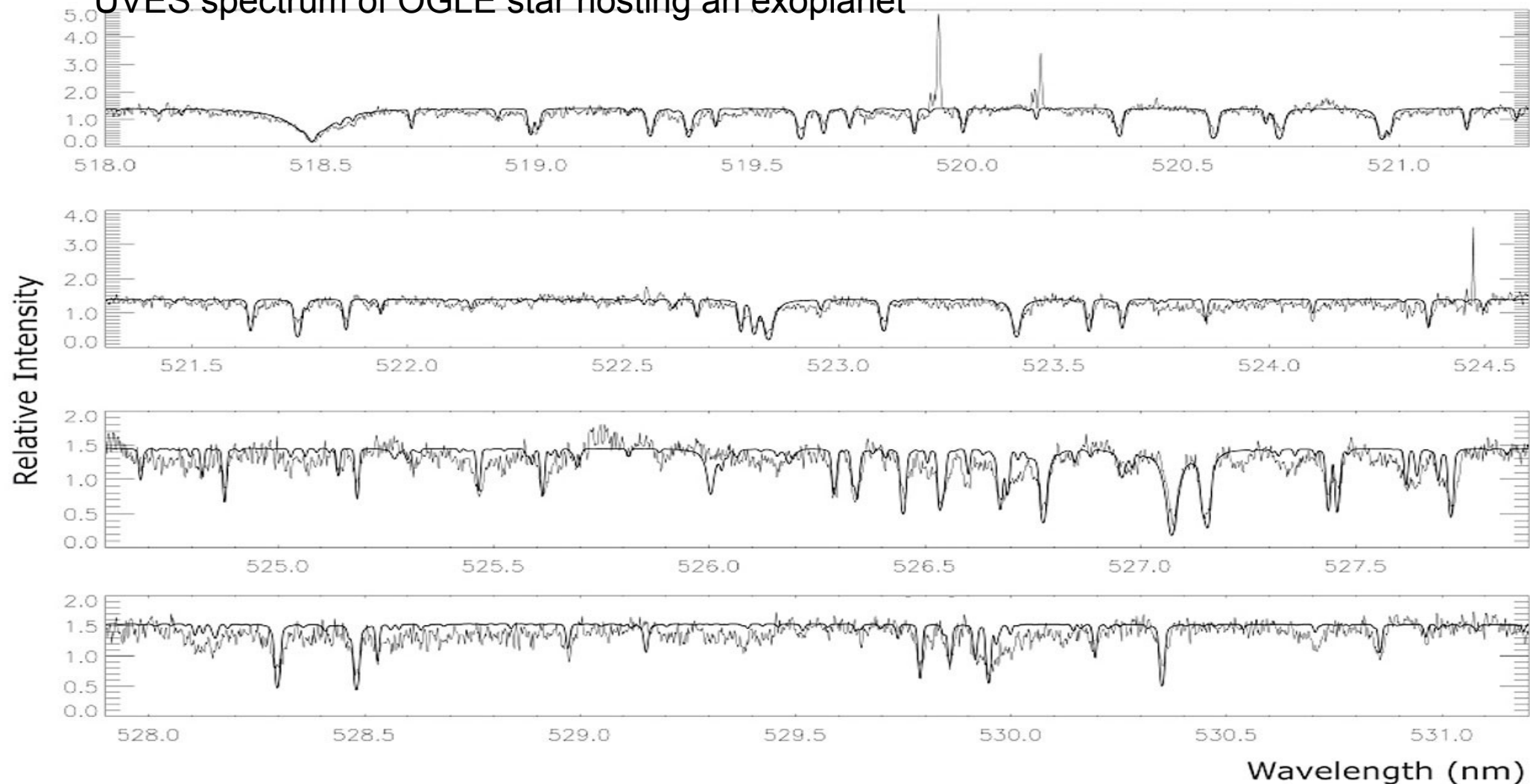
Various spectral types



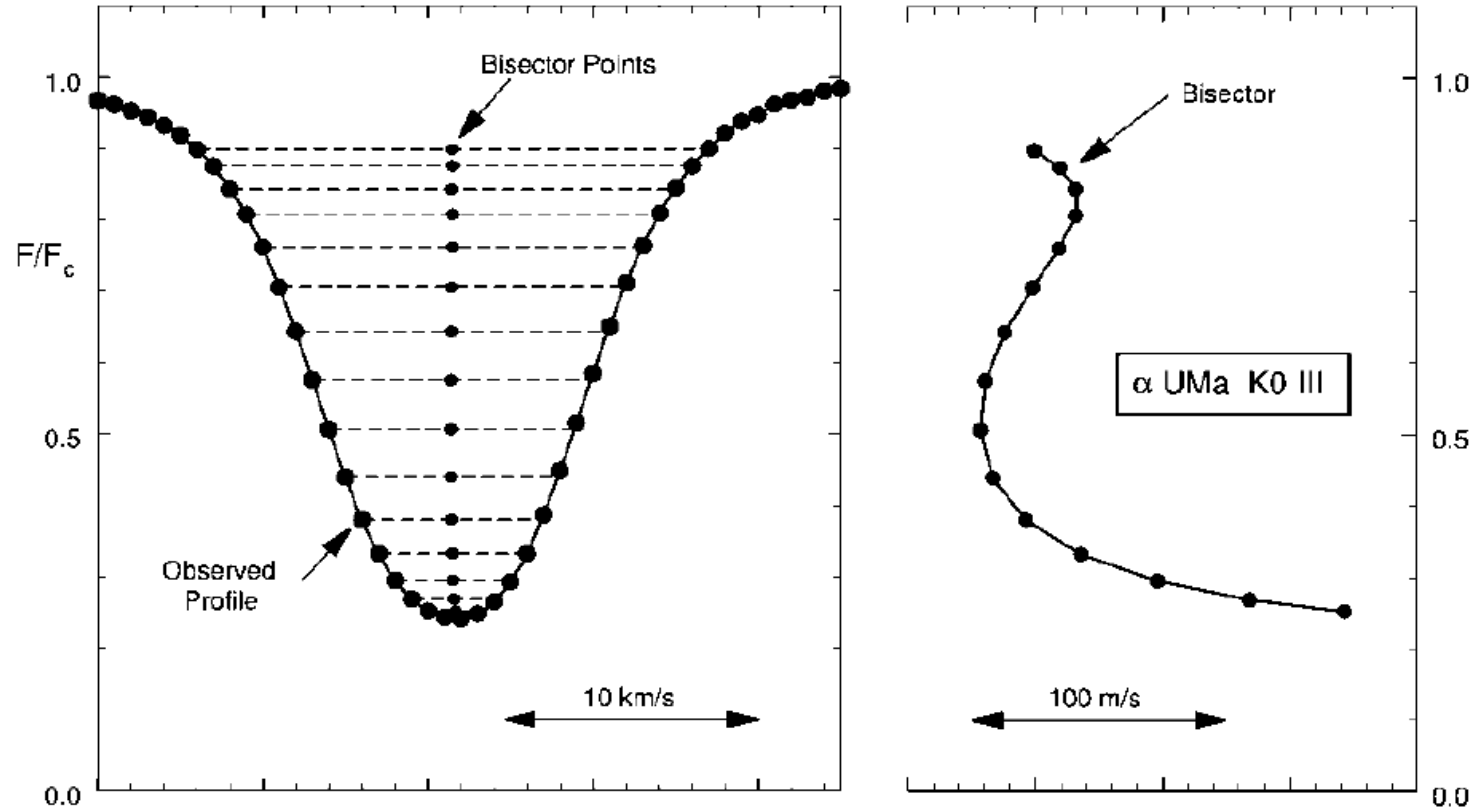
<https://apod.nasa.gov/apod/ap010530.html>

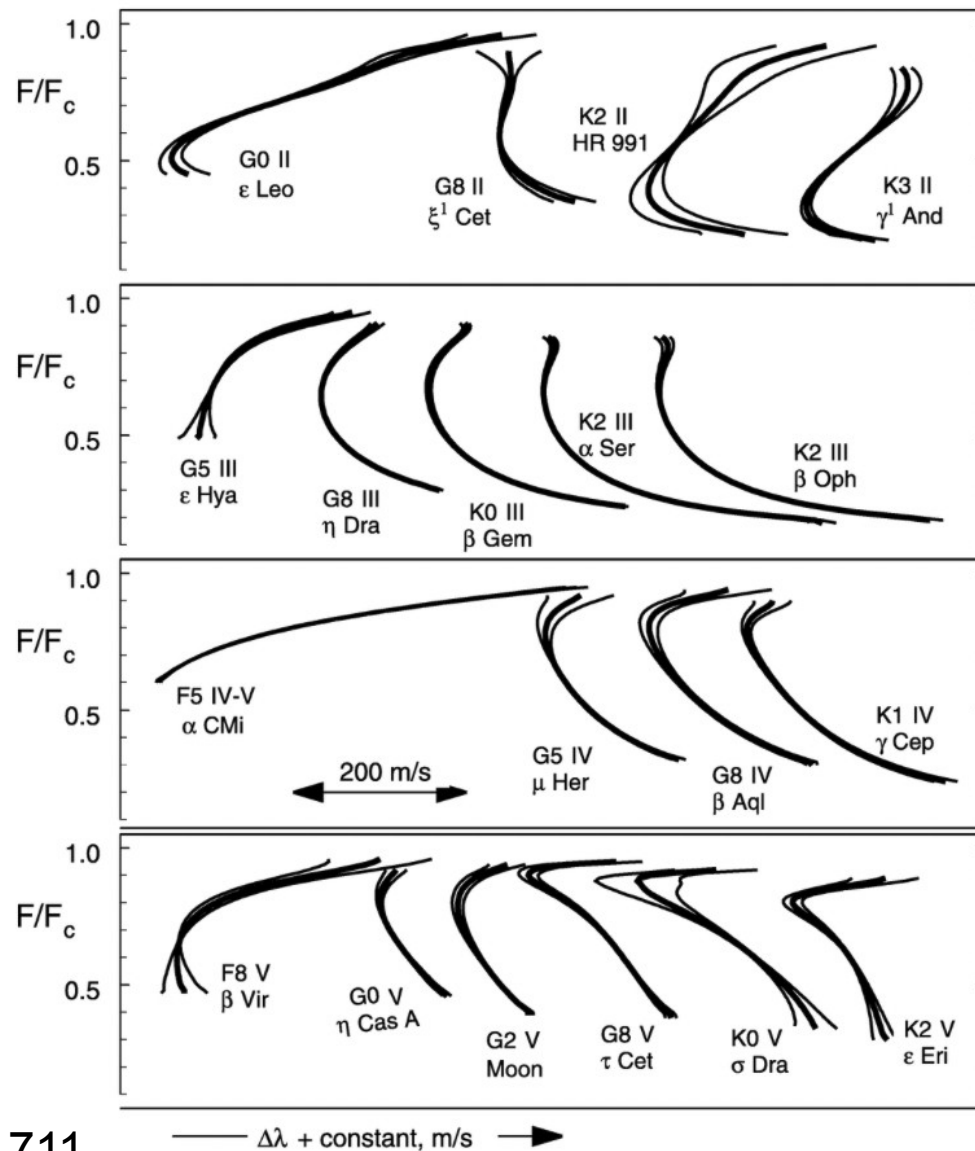
APOD NASA

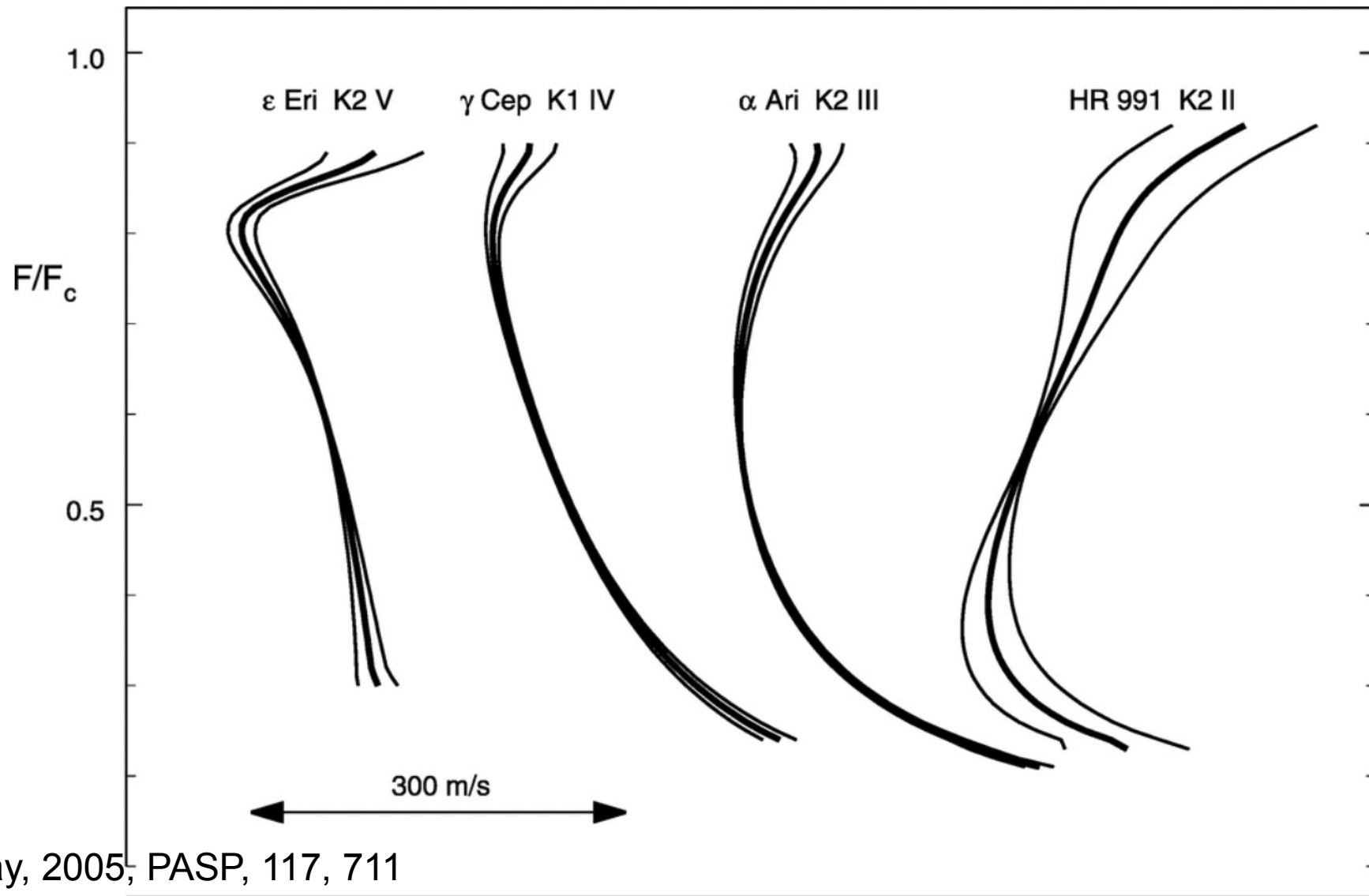
UVES spectrum of OGLE star hosting an exoplanet



Shapes of lines unveil physics







Stellar parameters

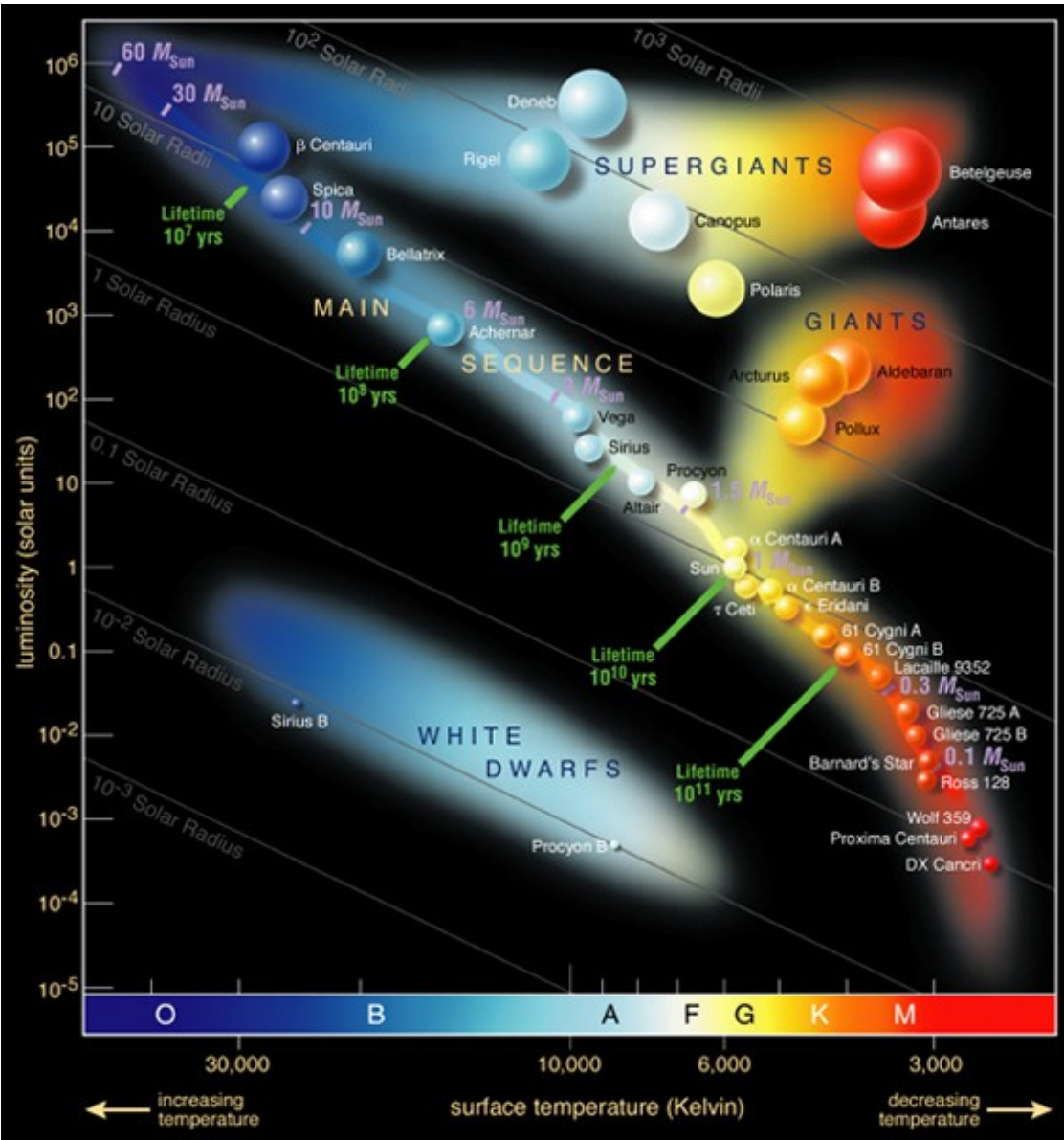
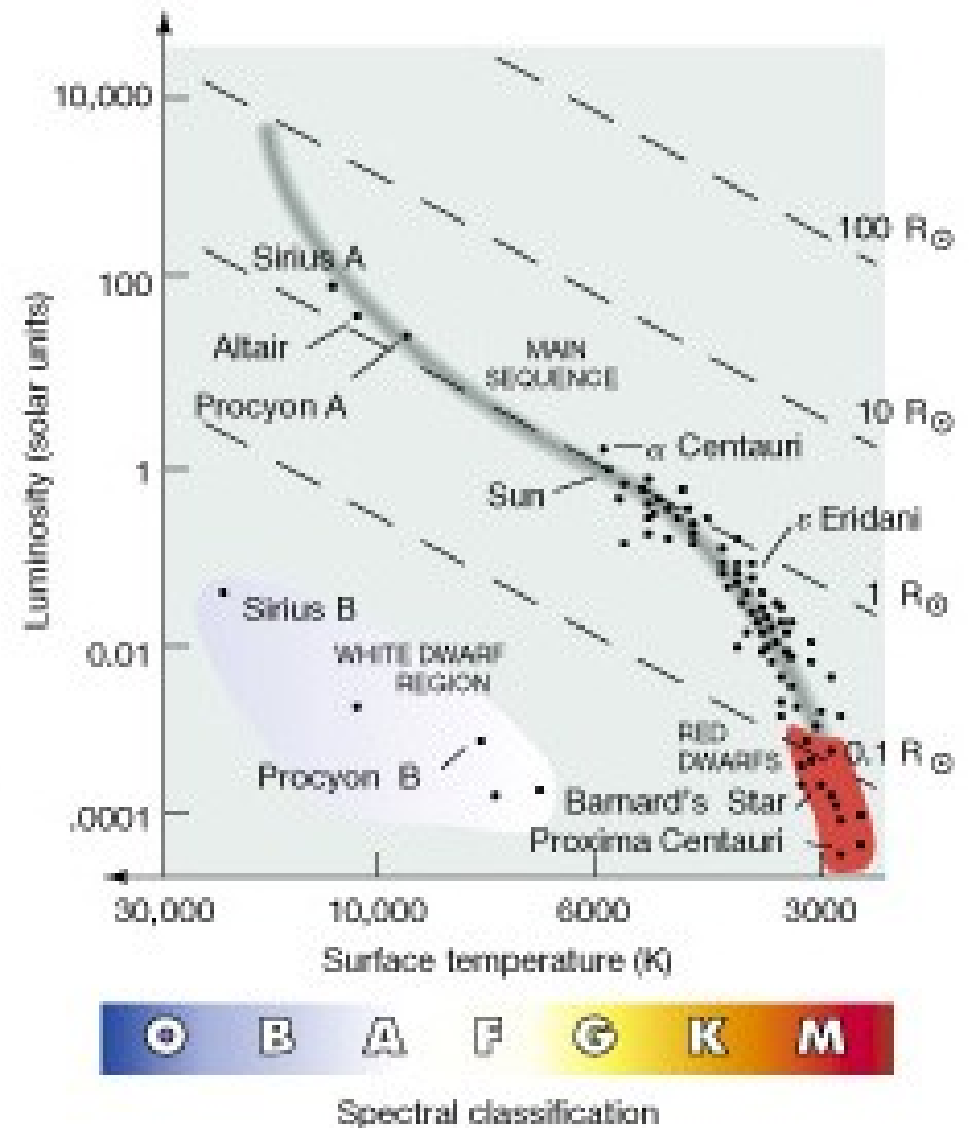
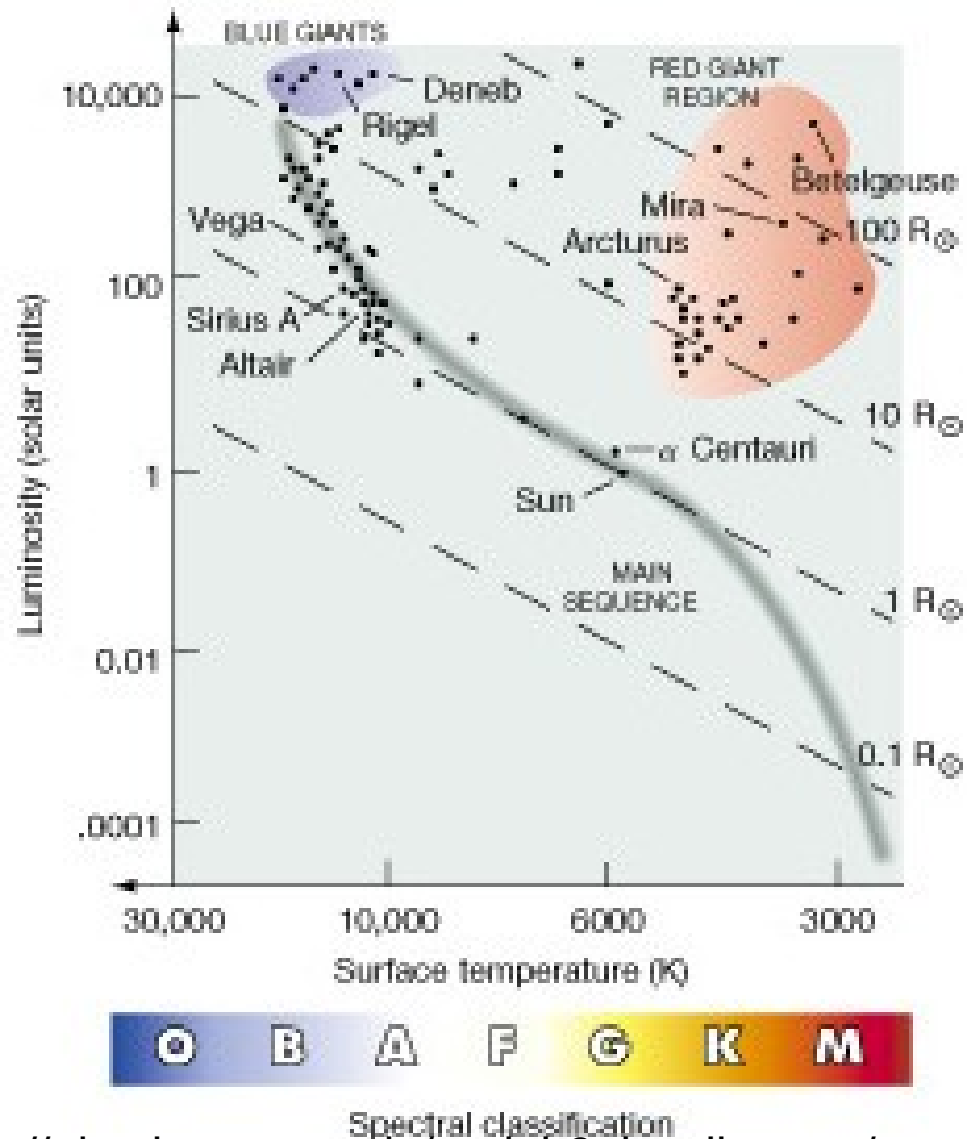


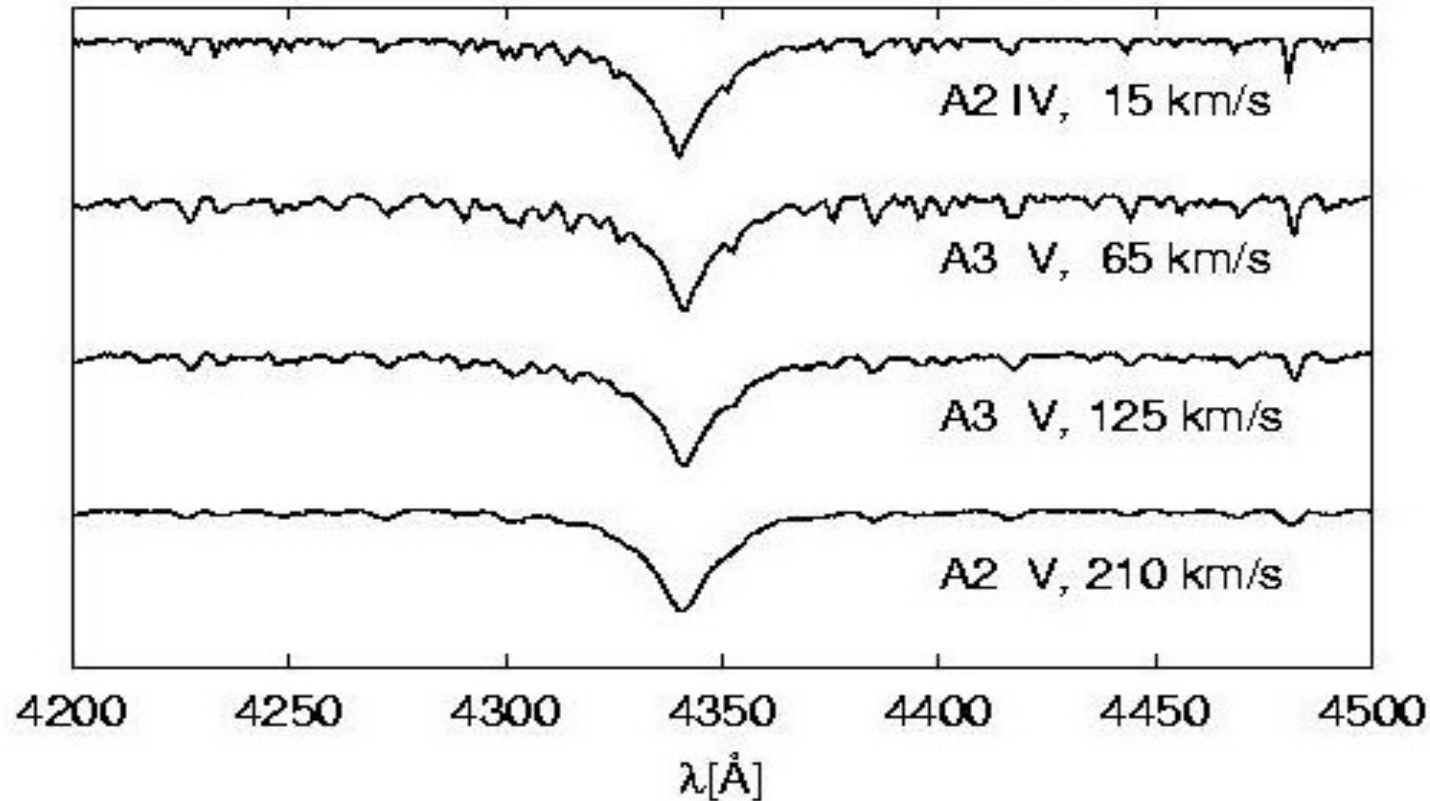
Image: ESA



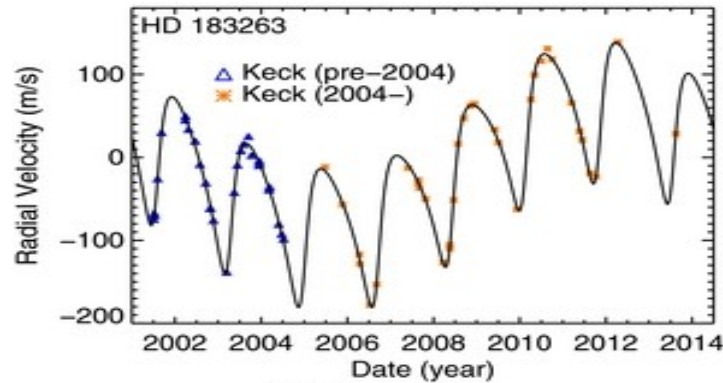
Problems

- Mass is a 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 coverage of the RV curve

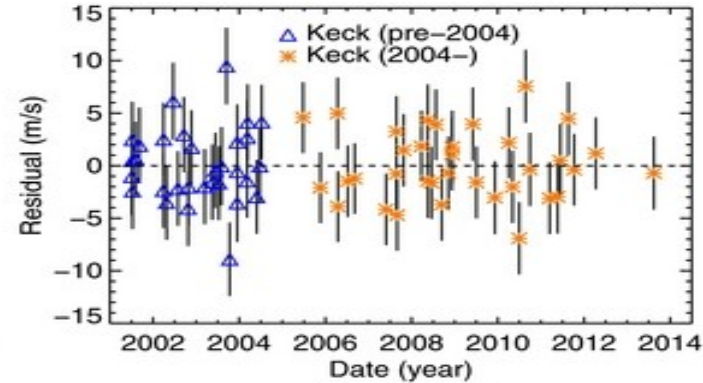
Line broadening, rotation



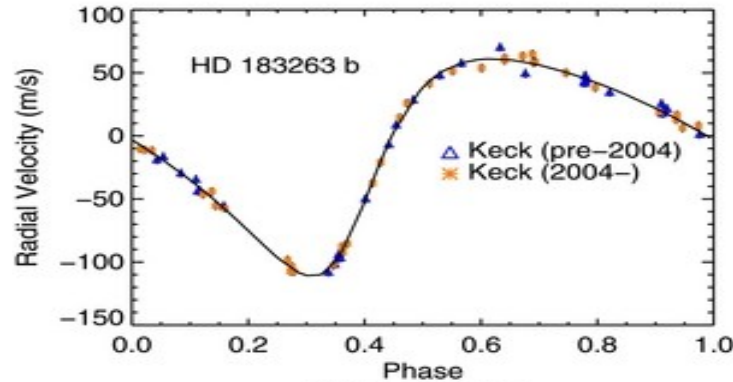
Multiple system



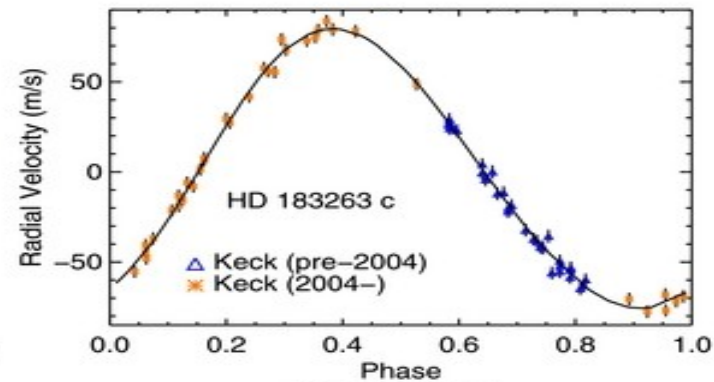
(a) HD 183263 system



(b) Residuals

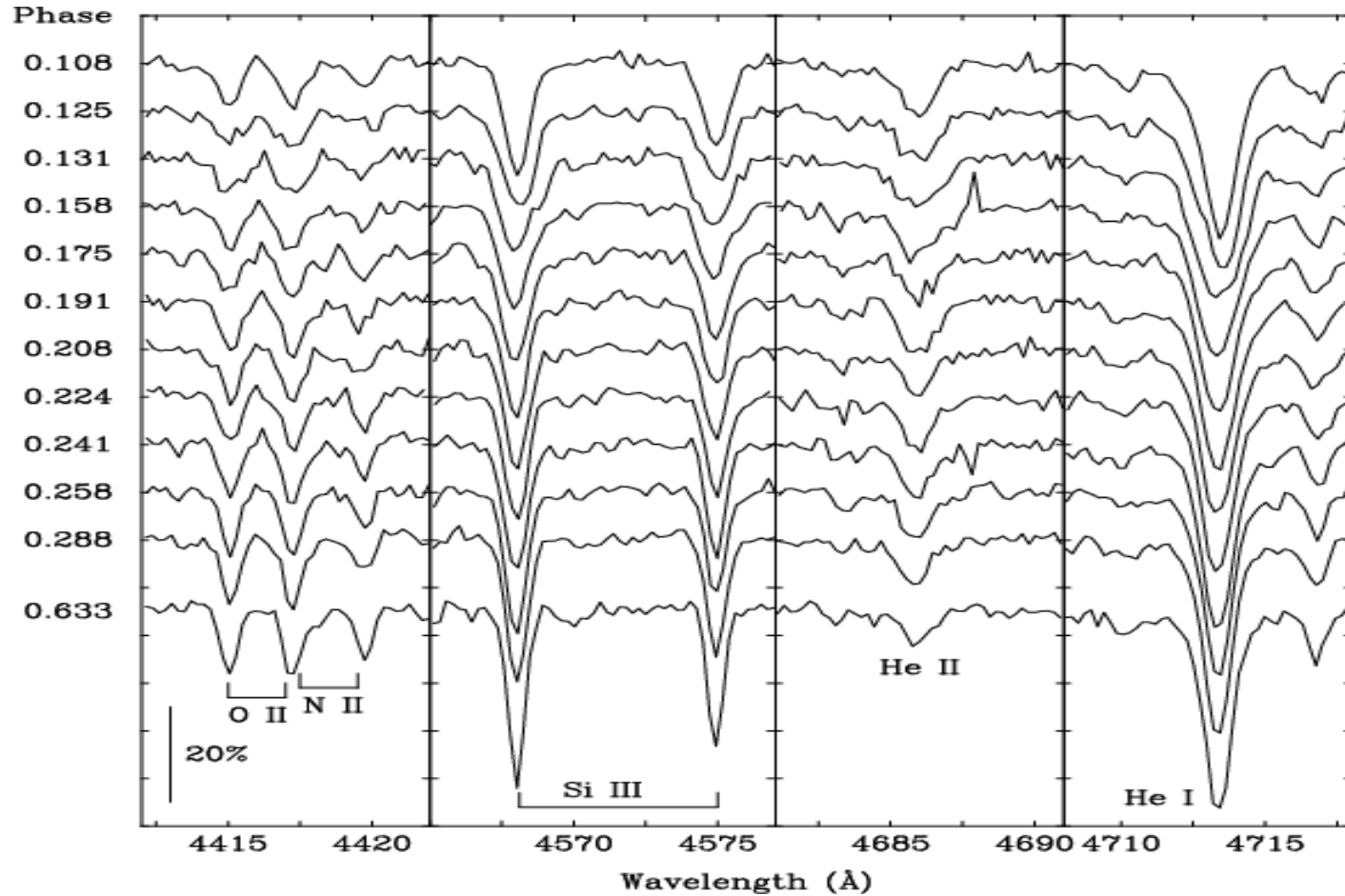


(c) HD 183263 b



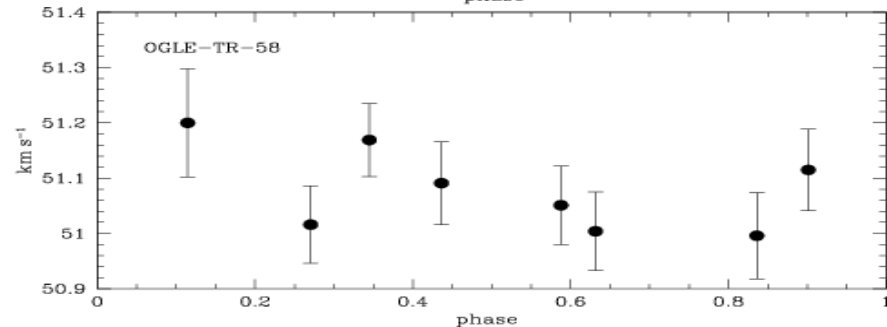
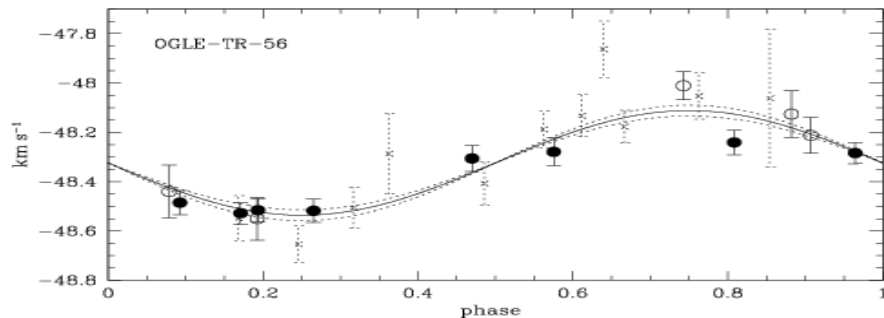
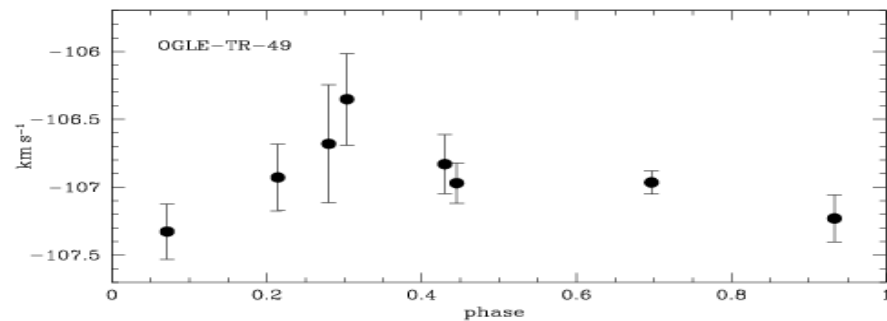
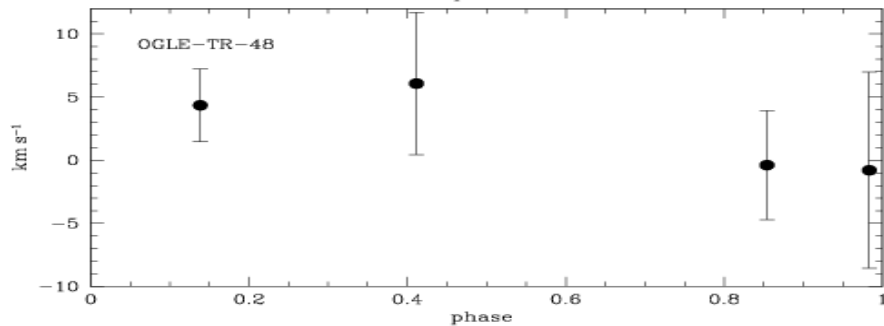
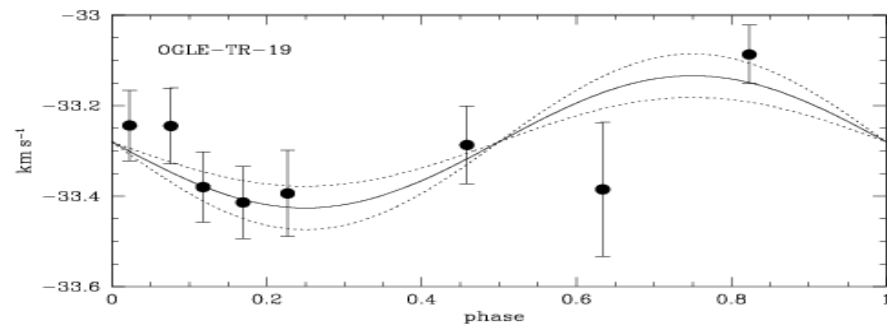
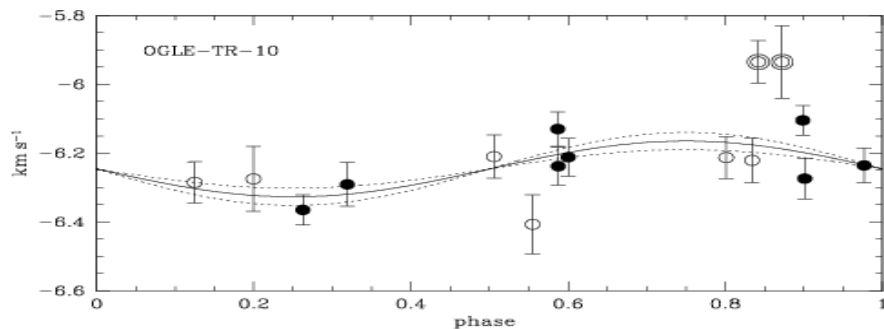
(d) HD 183263 c

Pulsations



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

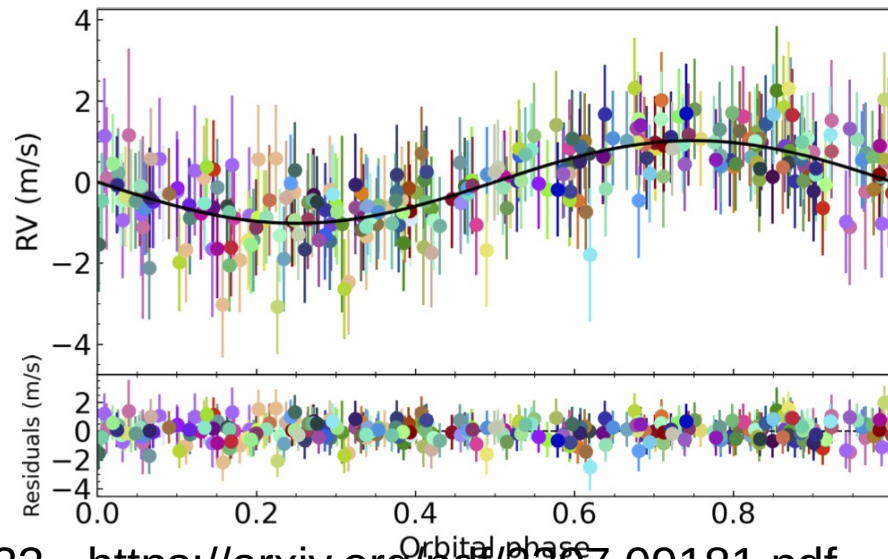
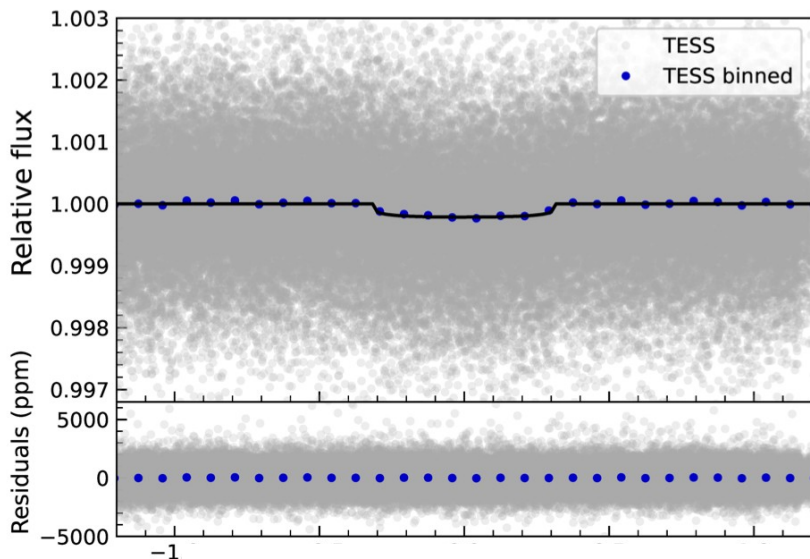
Unresolved cases RV



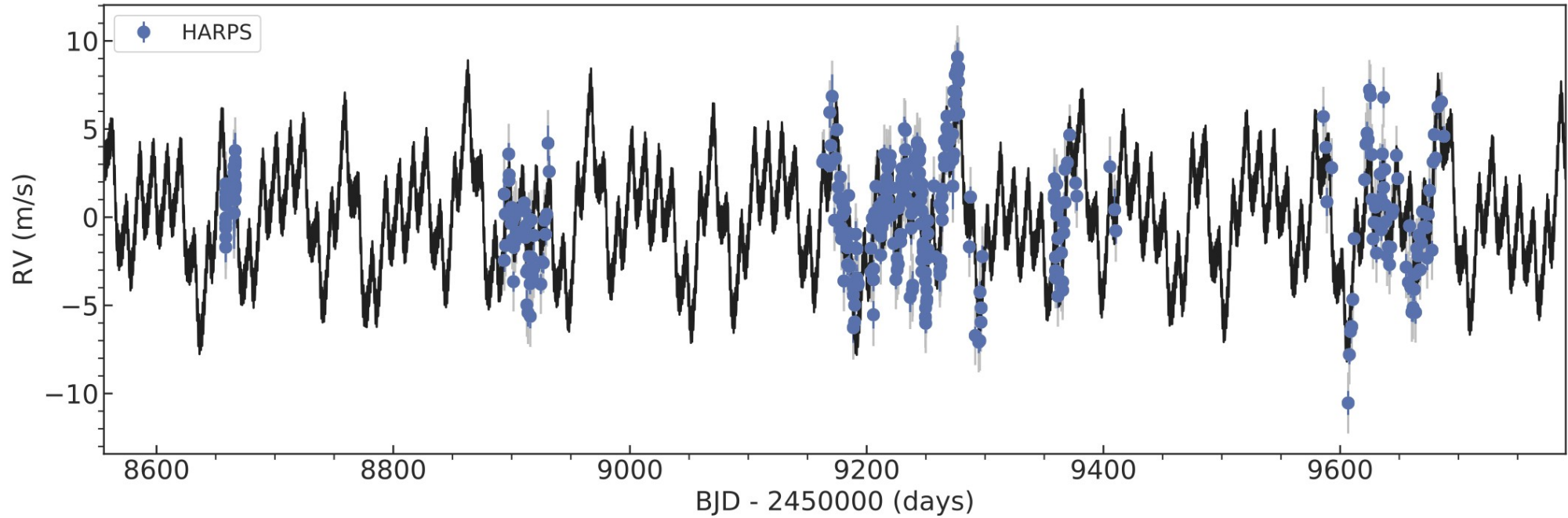
GJ 367 b - example

Table 1. Fundamental parameters of GJ 367.

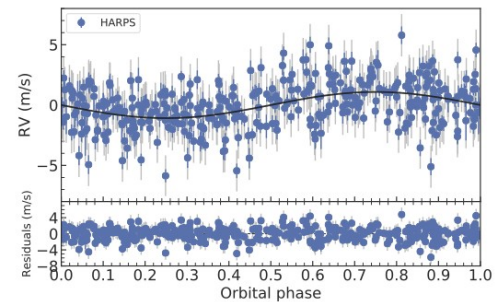
Parameter	Value	Reference
Name	GJ 367	
	TOI-731	
	TIC 34068865	
R.A. (J2000)	09:44:29.15	[1]
Decl. (J2000)	−45:46:44.46	[1]
TESS-band magnitude	8.032 ± 0.007	[2]
V-band magnitude	10.153 ± 0.044	[3]
Parallax (mas)	106.173 ± 0.014	[1]
Distance (pc)	9.413 ± 0.003	[1]
Star mass M_* (M_\odot)	0.455 ± 0.011	[4]
Star radius R_* (R_\odot)	0.458 ± 0.013	[4]
Effective temperature T_{eff} (K)	3522 ± 70	[4]
Stellar density ρ_* (ρ_\odot)	$4.75^{+0.44}_{-0.39}$	[4]
Metallicity [Fe/H]	-0.01 ± 0.12	[4]
Surface gravity $\log g_*$	4.776 ± 0.026	[4]
Luminosity L_* (L_\odot)	$0.0289^{+0.0029}_{-0.0027}$	[4]
$\log R'_{HK}$	-5.169 ± 0.068	[4]
Spectral type	M1.0 V	[5]



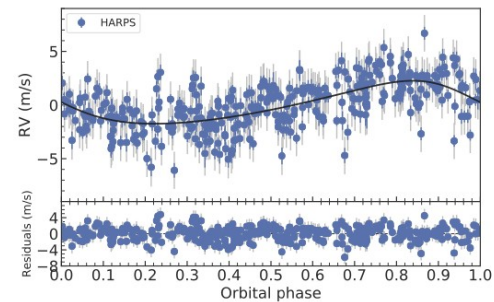
But there are more planets



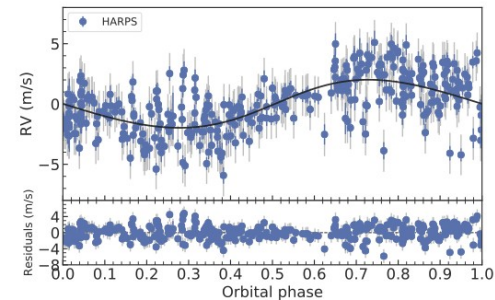
Goffo et al. 2023 - <https://arxiv.org/pdf/2307.09181.pdf>



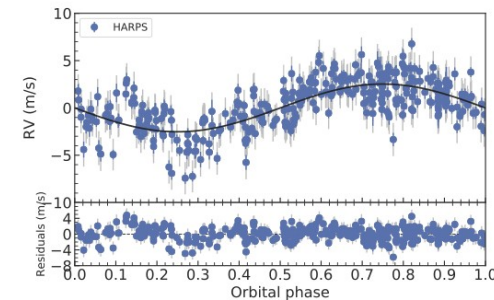
(a)



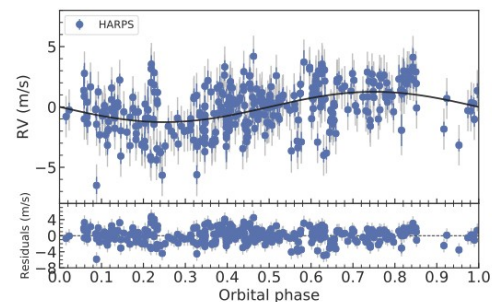
(b)



(c)



(d)



(e)

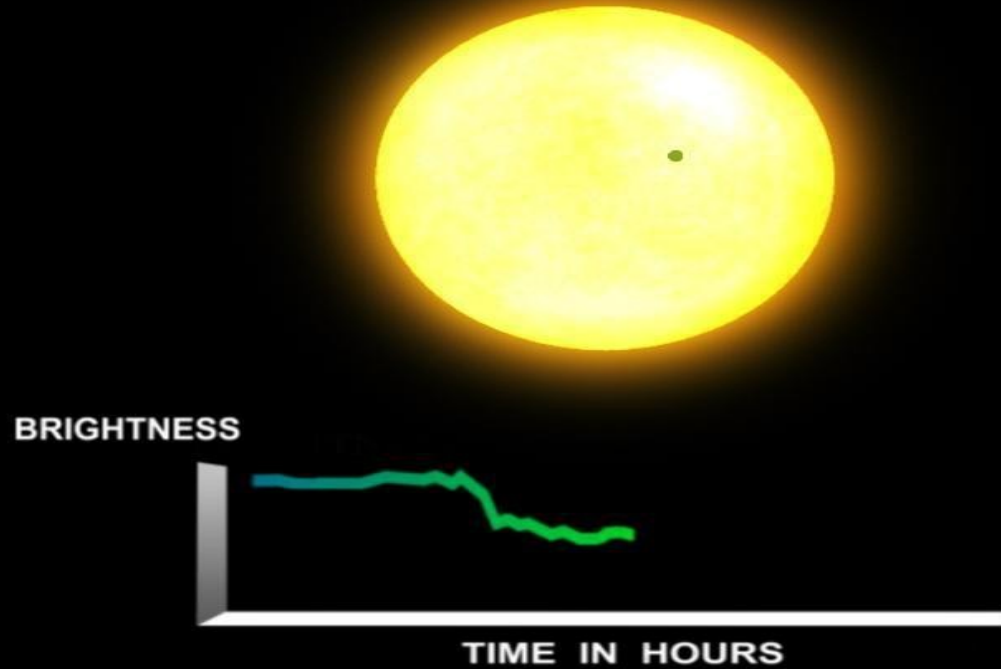
System parameters

Goffo et al. 2023 -
<https://arxiv.org/pdf/2307.09181.pdf>

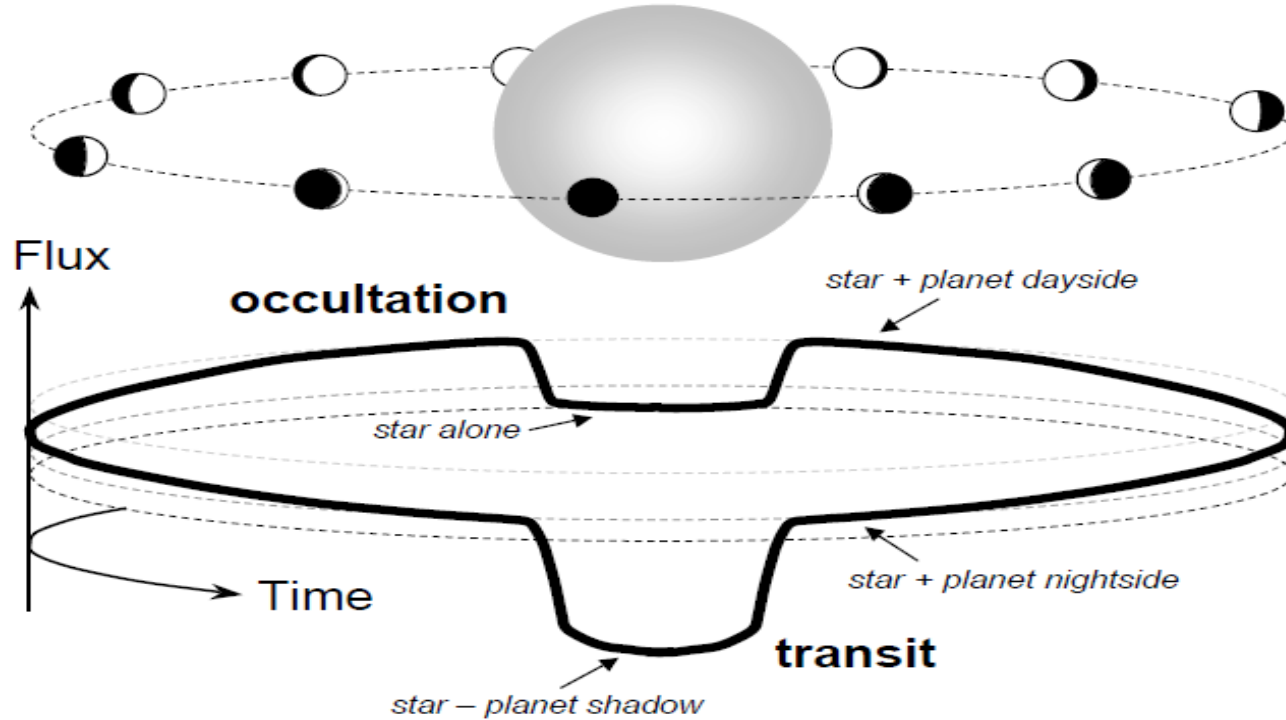
Table 3. System parameters as derived modeling the stellar signals with two sine functions.

Parameter	Prior	Derived value
GJ 367 b		
<i>Model parameters</i>		
Orbital period $P_{\text{orb,b}}$ [days]	$\mathcal{N}[0.3219225, 0.0000002]$	0.3219225 ± 0.0000002
Transit epoch $T_{0,\text{b}}$ [BJD _{TDB} -2,450,000]	$\mathcal{N}[8544.1364, 0.0004]$	8544.13632 ± 0.00040
$\sqrt{e_{\text{b}}} \sin \omega_{*,\text{b}}$	$\mathcal{U}[-1.0, 1.0]$	$-0.23^{+0.30}_{-0.23}$
$\sqrt{e_{\text{b}}} \cos \omega_{*,\text{b}}$	$\mathcal{U}[-1.0, 1.0]$	-0.07 ± 0.13
Radial velocity semi-amplitude variation K_{b} [m s ⁻¹]	$\mathcal{U}[0.00, 0.05]$	1.10 ± 0.14
<i>Derived parameters</i>		
Planet mass M_{b} [M _⊕](*)	—	0.699 ± 0.083
Orbit eccentricity e_{b}	—	$0.10^{+0.14}_{-0.07}$
Argument of periastron of stellar orbit $\omega_{*,\text{b}}$ [deg]	—	251^{+23}_{-102}
GJ 367 c		
<i>Model parameters</i>		
Orbital period $P_{\text{orb,c}}$ [days]	$\mathcal{U}[11.4858, 11.5858]$	11.543 ± 0.005
Time of inferior conjunction $T_{0,\text{c}}$ [BJD _{TDB} -2,450,000]	$\mathcal{U}[9152.6591, 9154.6591]$	9153.46 ± 0.21
$\sqrt{e_{\text{c}}} \sin \omega_{*,\text{c}}$	$\mathcal{U}[-1, 1]$	$0.38^{+0.10}_{-0.13}$
$\sqrt{e_{\text{c}}} \cos \omega_{*,\text{c}}$	$\mathcal{U}[-1, 1]$	$0.27^{+0.11}_{-0.14}$
Radial velocity semi-amplitude variation K_{c} [m s ⁻¹]	$\mathcal{U}[0.00, 0.05]$	2.01 ± 0.15
<i>Derived parameters</i>		
Planet minimum mass $M_{\text{c}} \sin i_{\text{c}}$ [M _⊕]	—	4.08 ± 0.30
Orbit eccentricity e_{c}	—	0.23 ± 0.07
Argument of periastron of stellar orbit $\omega_{*,\text{c}}$ [deg]	—	55 ± 18
GJ 367 d		
<i>Model parameters</i>		
Orbital period $P_{\text{orb,d}}$ [days]	$\mathcal{U}[34.0016, 34.6016]$	34.39 ± 0.06
Time of inferior conjunction $T_{0,\text{d}}$ [BJD _{TDB} -2,450,000]	$\mathcal{U}[9179.2710, 9183.2710]$	$9180.90^{+0.70}_{-0.81}$
$\sqrt{e_{\text{d}}} \cos \omega_{*,\text{d}}$	$\mathcal{U}[-1, 1]$	$-0.10^{+0.20}_{-0.18}$
$\sqrt{e_{\text{d}}} \sin \omega_{*,\text{d}}$	$\mathcal{U}[-1, 1]$	$0.16^{+0.16}_{-0.20}$
Radial velocity semi-amplitude variation K_{d} [m s ⁻¹]	$\mathcal{U}[0.00, 0.05]$	1.98 ± 0.15
<i>Derived parameters</i>		
Planet minimum mass $M_{\text{d}} \sin i_{\text{d}}$ [M _⊕]	—	5.93 ± 0.45
Orbit eccentricity e_{d}	—	$0.08^{+0.07}_{-0.05}$
Argument of periastron of stellar orbit $\omega_{*,\text{d}}$ [deg]	—	277^{+58}_{-242}
Stellar activity induced RV signal		
Rotation period $P_{*,\text{Rot}}$ [days]	$\mathcal{U}[50.0903, 52.0903]$	51.30 ± 0.13
Rotation RV semi-amplitude $K_{*,\text{Rot}}$ [m s ⁻¹]	$\mathcal{U}[0.00, 0.05]$	2.52 ± 0.13
Active region evolution period $P_{*,\text{Evol}}$ [days]	$\mathcal{U}[103.1797, 163.1797]$	138 ± 2
Active region evolution RV semi-amplitude $K_{*,\text{Evol}}$ [m s ⁻¹]	$\mathcal{U}[0.00, 0.05]$	1.25 ± 0.14
Additional model parameters		
Systemic velocity γ_{HARPS} [m s ⁻¹]	$\mathcal{U}[47.806, 48.025]$	47.91674 ± 0.00013
Radial velocity jitter term $\sigma_{\text{RV,HARPS}}$ [m s ⁻¹]	$\mathcal{J}[0, 100]$	1.59 ± 0.07

The transit method

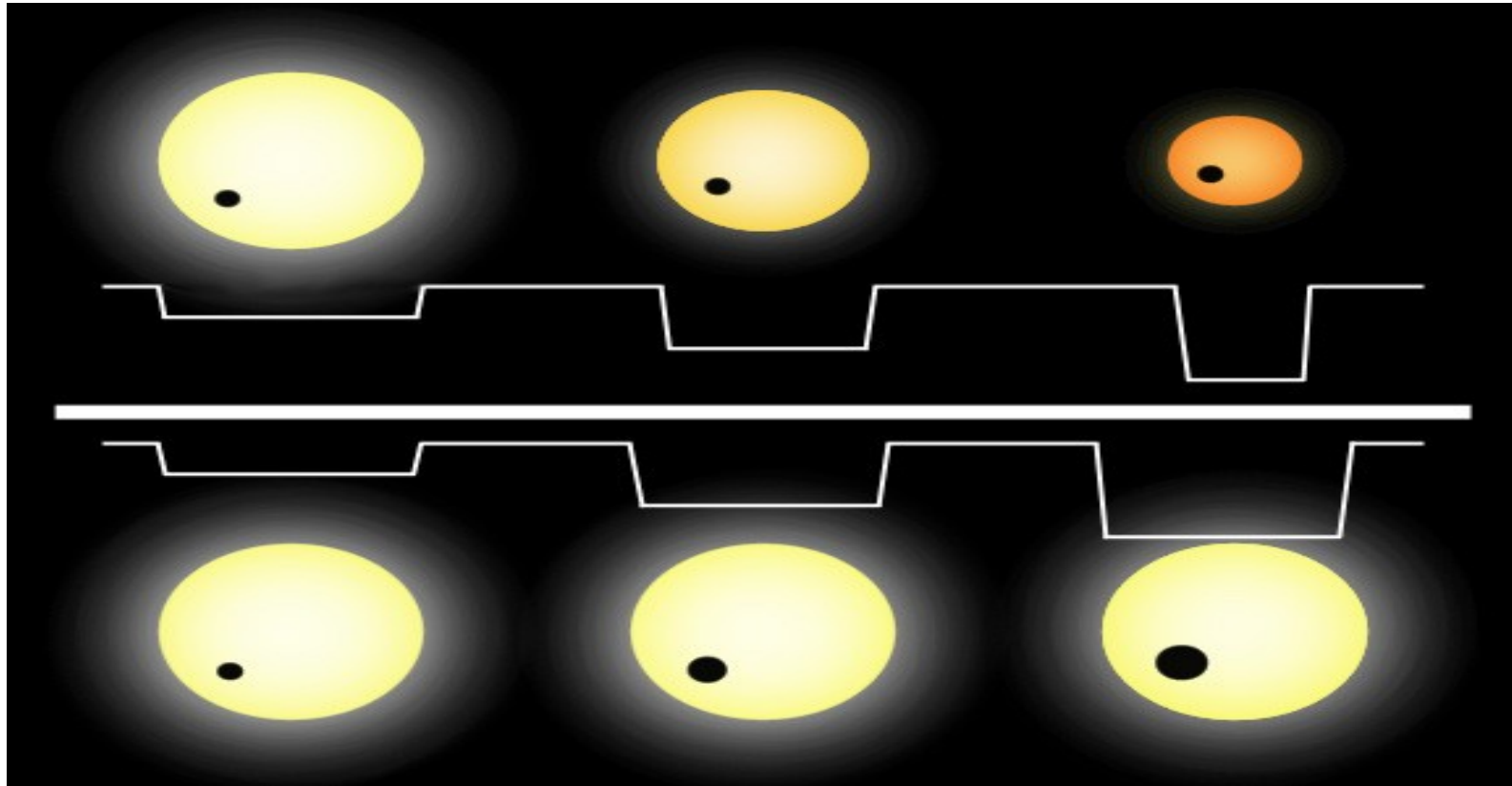


Eclipses/transits



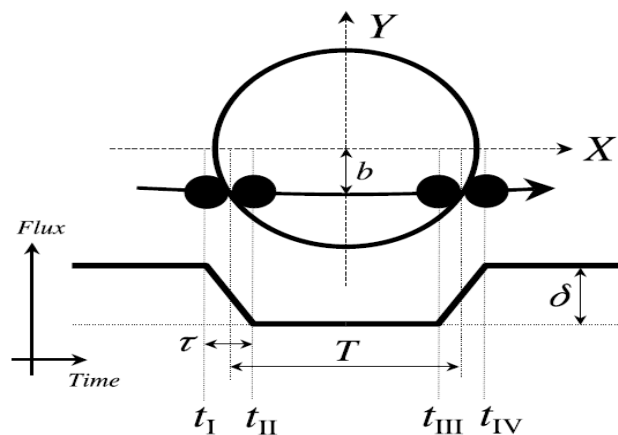
From Winn, 2010, <http://arxiv.org/pdf/1001.2010v5.pdf>

The transit method



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

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:

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

- Inclination:

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

- Transit duration:

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

Limb darkening

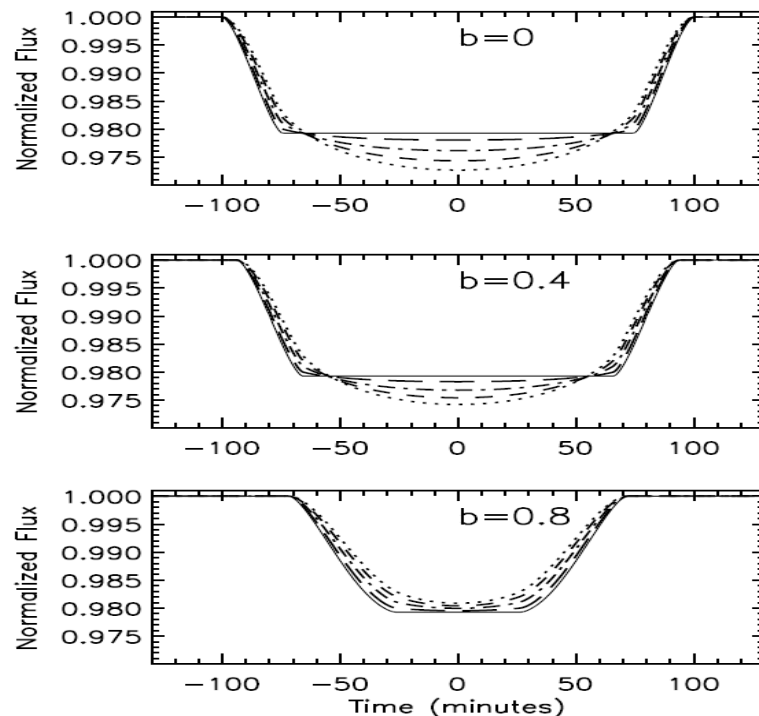


Fig. 3.— Solar limb darkening dependence of a planet transit light curve. In these theoretical light curves the planet has $R_p = 1.4R_J$ and $a = 0.05$ AU and the star has $R_* = R_\odot$ and $M_* = M_\odot$. The solid curve shows a transit light curve with limb darkening neglected. The other planet transit light curves have solar limb darkening at wavelengths (in μm): 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.

Problems

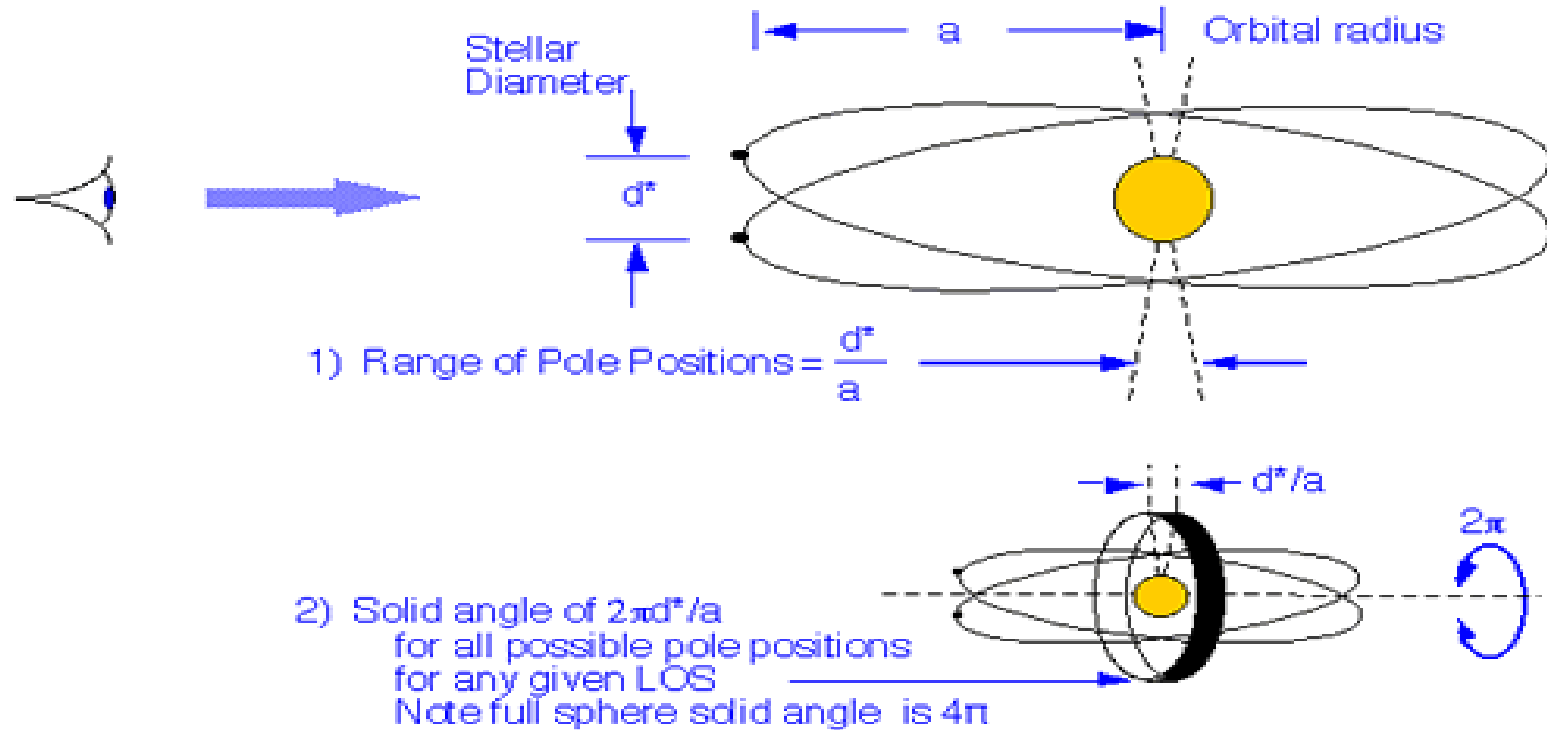
- Systematic noise hiding the transit
- High photometric accuracy needed in mmag range
- Transits due to background binaries
- Star parameters needed to fully characterize the system – SPECTROSCOPY NEEDED

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



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

Transit Properties of Solar System Objects

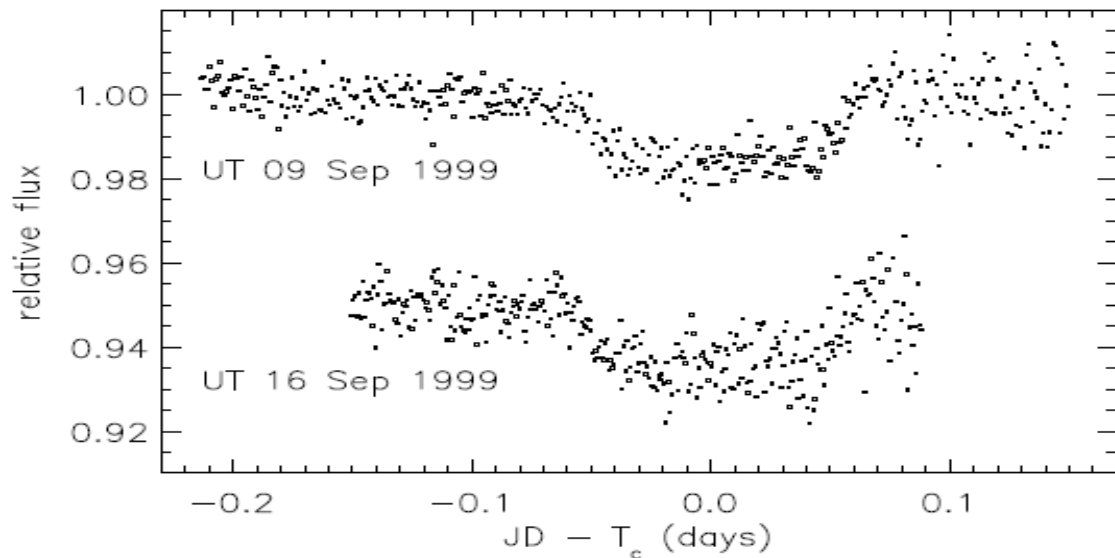
Planet	Orbital Period P (years)	Semi- Major Axis a (A.U.)	Transit Duration (hours)	Transit Depth (%)	Geometric Probability (%)	Inclination Invariant Plane (deg)
Mercury	0.241	0.39	8.1	0.0012	1.19	6.33
Venus	0.615	0.72	11.0	0.0076	0.65	2.16
Earth	1.000	1.00	13.0	0.0084	0.47	1.65
Mars	1.880	1.52	16.0	0.0024	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
	$P^2 M^* = a^3$		$13\sqrt{a}$	$\% = (d_p/d^*)^2$	d^*/D	ϕ

<https://web.njit.edu/~gary/320/Lecture10.html>

OBSERVE AS MANY STAR AS POSSIBLE TO FIND TRANSITS

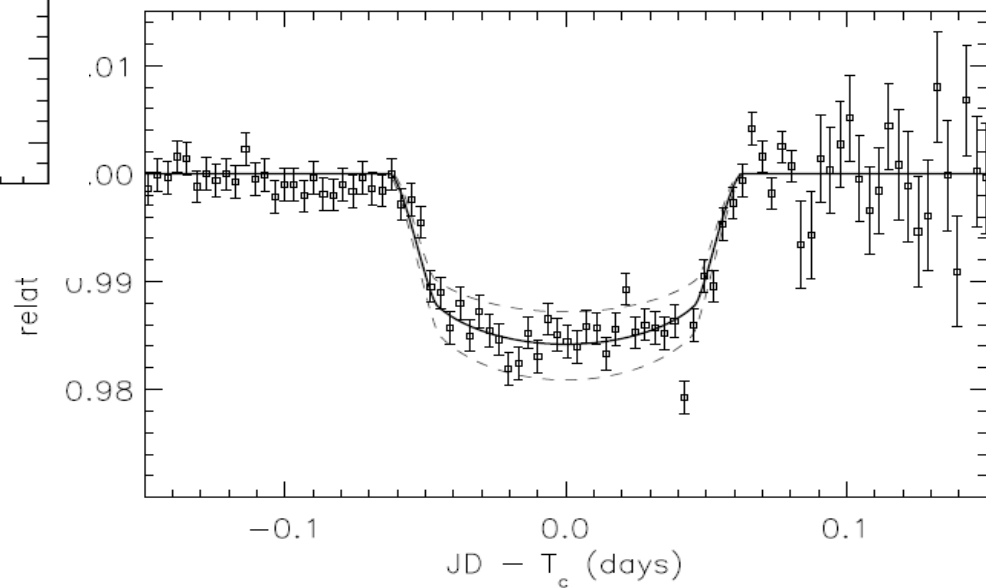


First transiting exoplanet



HD209458b

Charbonneau et al. 2000



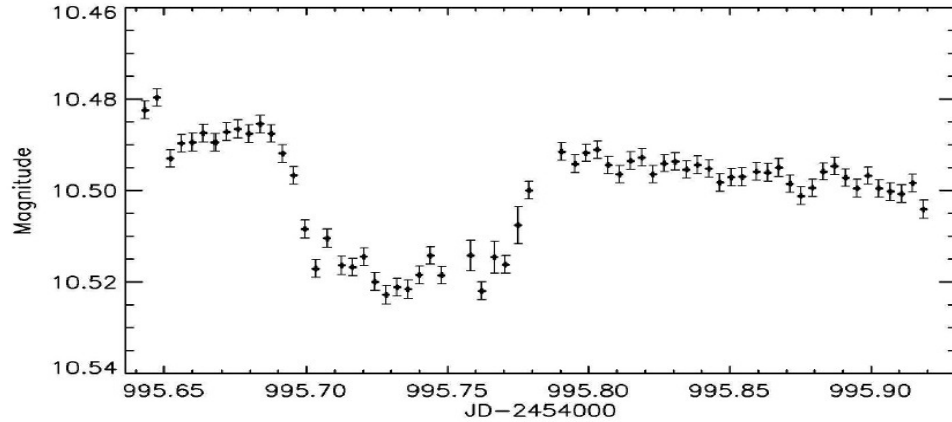
HD209458b

- Parameters
 - Mass : 0.69M_J
 - Radius : 1.38 R_J
 - O. period : 3.5 days

- Star: G0V
brightness: 7 mag (V)
T_{eff}: 6092 K
Metallicity: 0.02

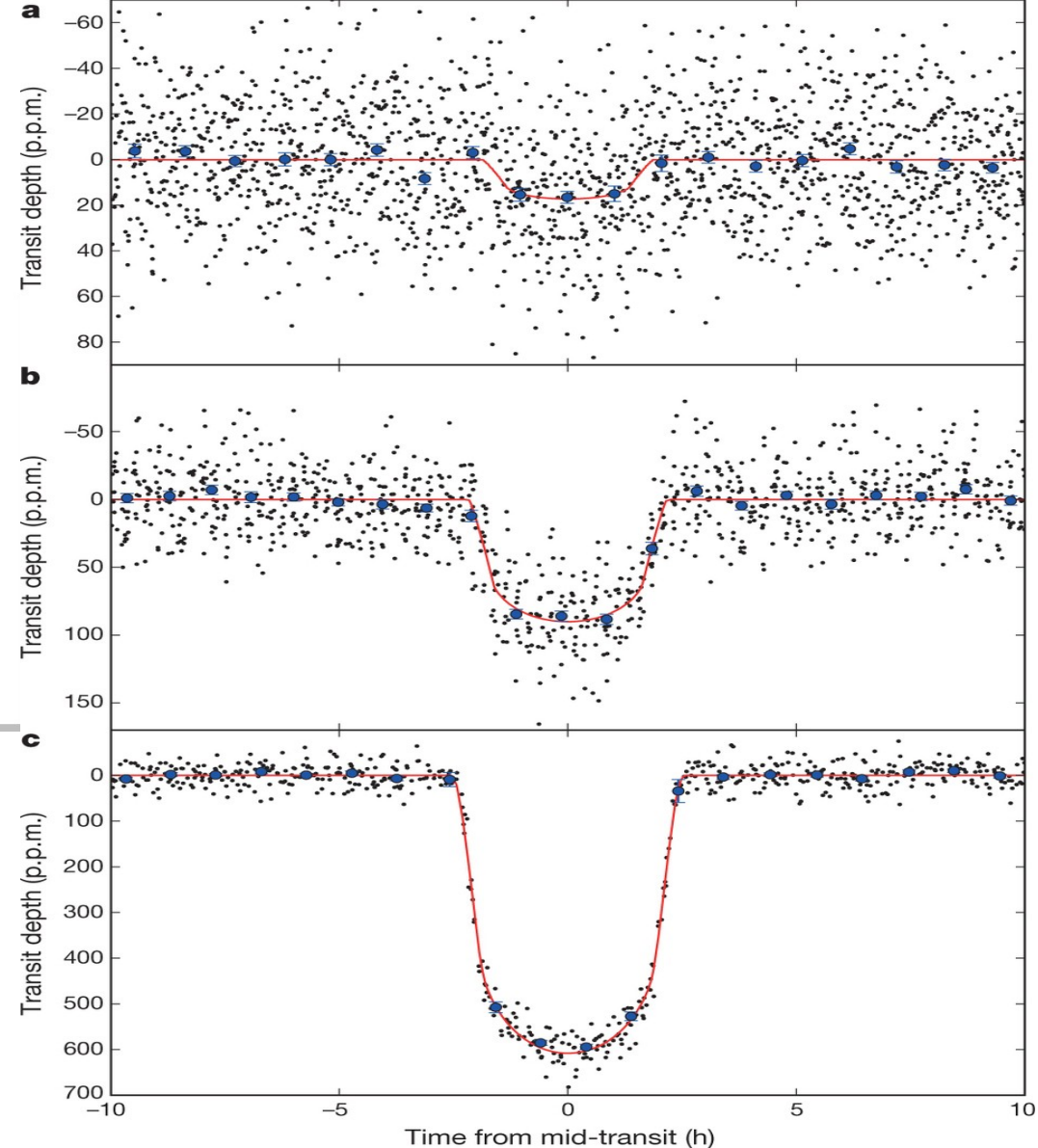
Nice light curves

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



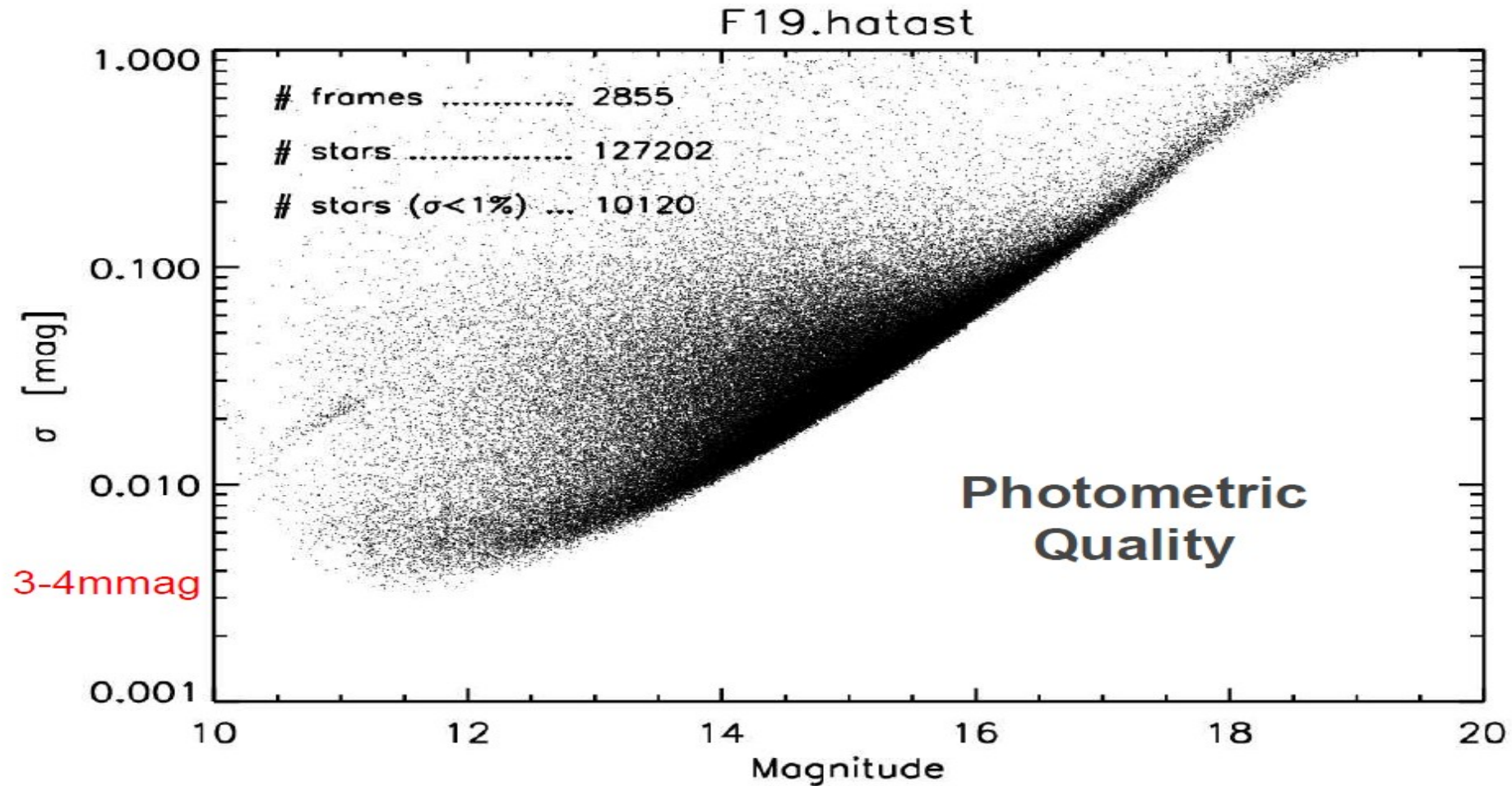
Observatorio Cerro Armazones, Chile



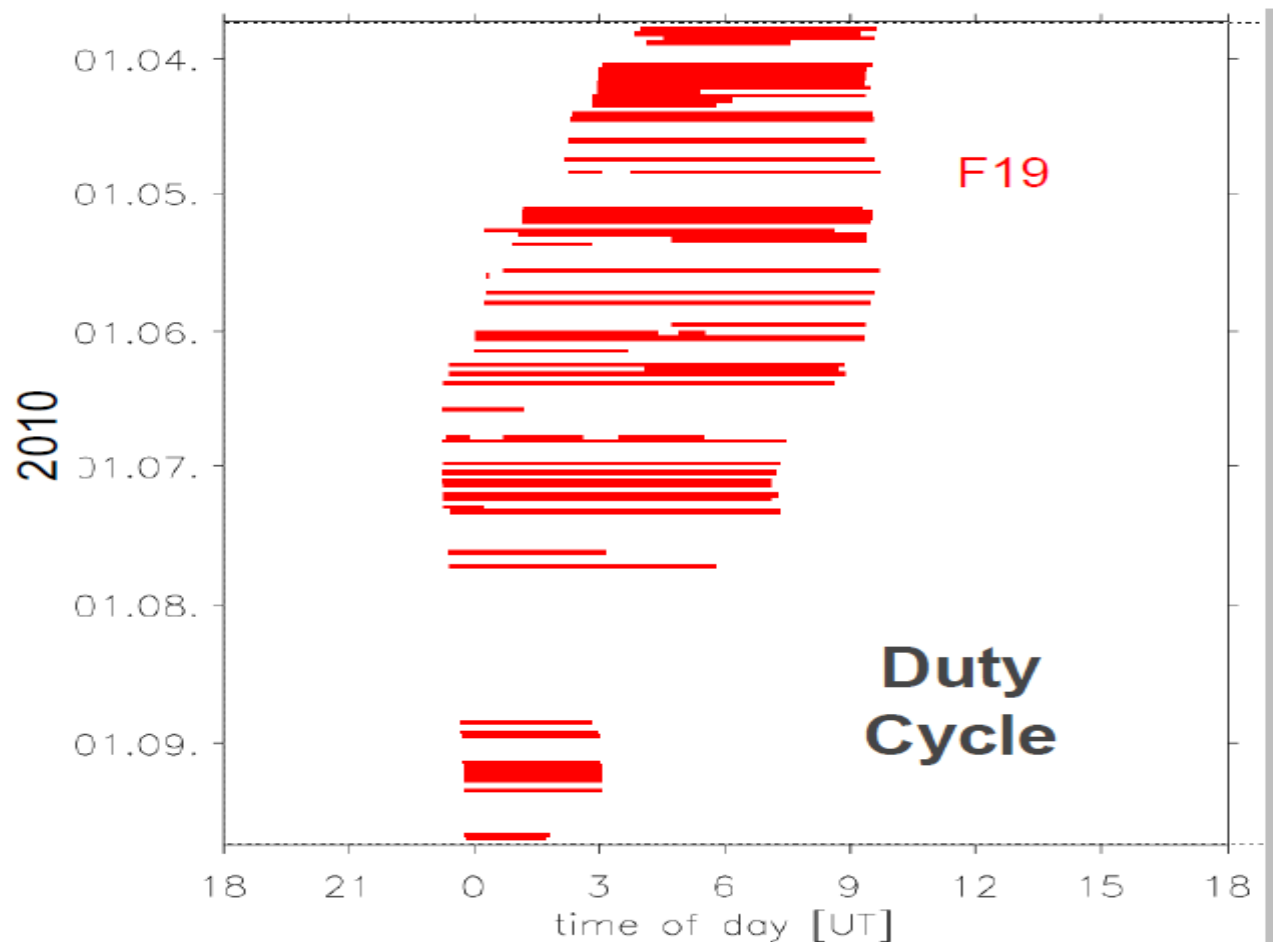
Specifications:

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	: $1.7^\circ \times 1.7^\circ$

Photometric quality



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

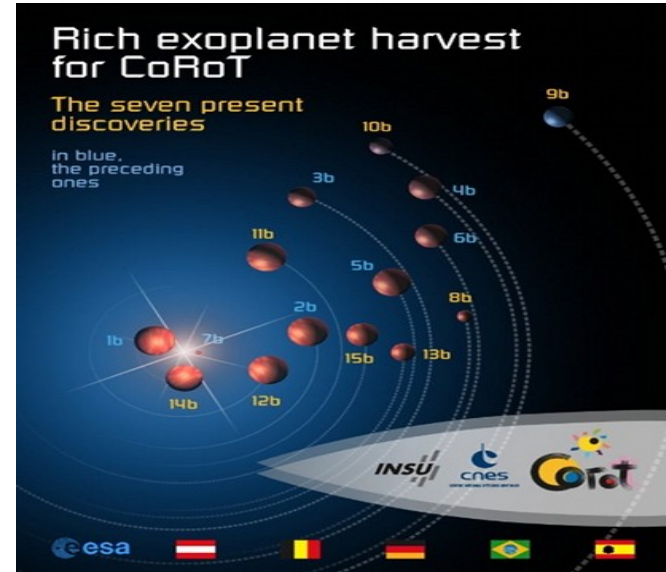
Convection, Rotation and planetary Transits

Launched 2006 – mission end 2013

28cm mirror, 4 detectors of $1,5 \times 1,5$ deg

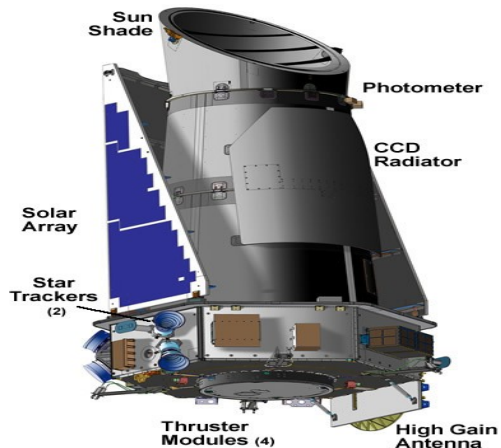


ESA webpages



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 about 5000 planets

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



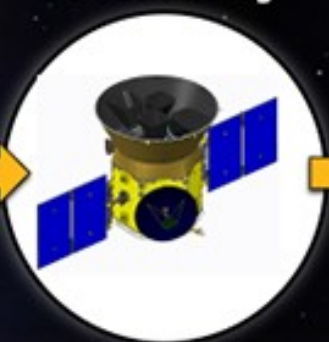
Transiting Exoplanet Survey Satellite

Launch Vehicle



- SpaceX Falcon 9 v1.1
- High Earth Orbit (HEO)
- 2:1 Resonance with Moon's Orbit

Observatory



- Orbital LEOStar-2
- Instrument-in-the-loop attitude control

Science Instrument



- Four Wide Field-of-View CCD Cameras
- 24"x 24" Field-of-View
- Well defined spacecraft interfaces

Project Overview

- Transiting exoplanet discovery mission
- 2 month Commissioning period
- 2 year all-sky survey (3 year science mission)
- Identifies best targets for follow-up characterization
- Deep Space Network (DSN) primary support
- Category II, Class C
- Planned Launch Readiness Date: August 2017
- PI Cost Cap: \$228.3 M (RYS)



MIT KAVLI INSTITUTE



Orbital ATK

PLATO searching for another Earth

Sun

New ESA mission
will launch in 2026

150 million km

PLATO will provide
the key information on planets
(planet radii, mean densities,
stellar irradiation, and architecture
of planetary systems) needed to
determine habitability

The satellite will have 26 onboard
telescopes to observe thousands
of stars and changes in light caused
by orbiting planets.

Earth

Moon

The satellite is kept
in stable position
as it follows the earth's
orbit around the sun

1.5 million km

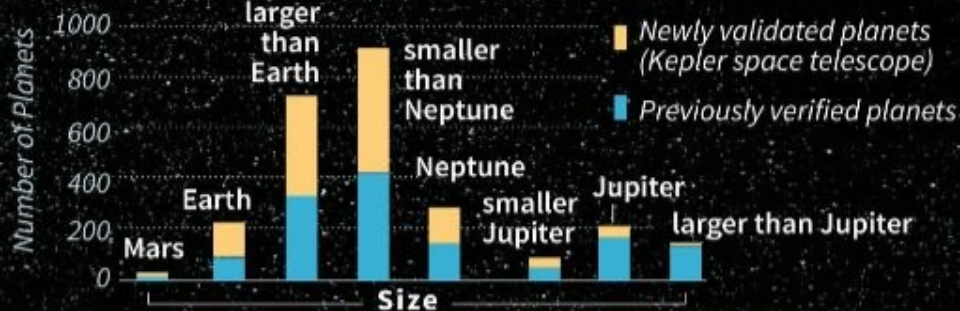
Known planets orbiting
stars like our Sun

Planet sizes in our Solar system

Mars Earth

Neptune

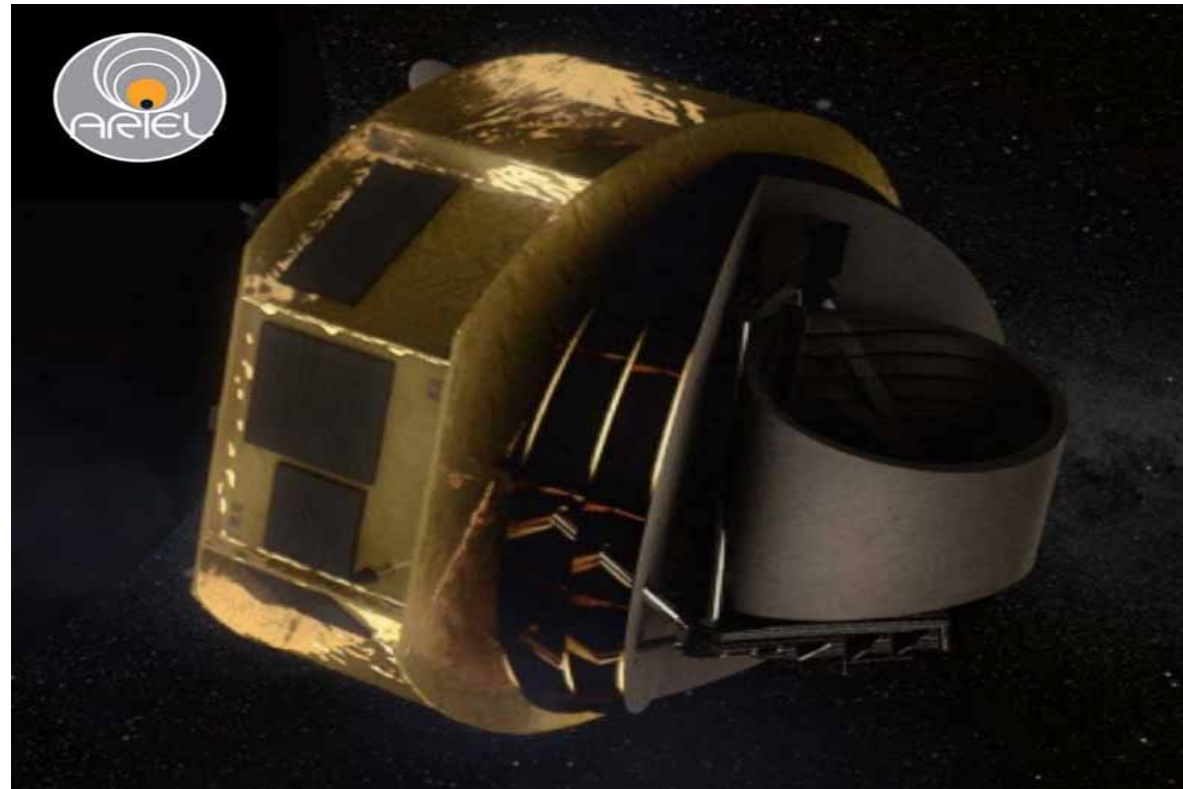
Jupiter



Will join NASA's
Kepler space
telescope in the hunt
for earth-like planets

Participation in Ariel

- CZ contribution is being defined
- Leaders:
ÚFCHJH
S. Civis and
M. Ferus
- P. Kabath is in
WG Stellar charac.

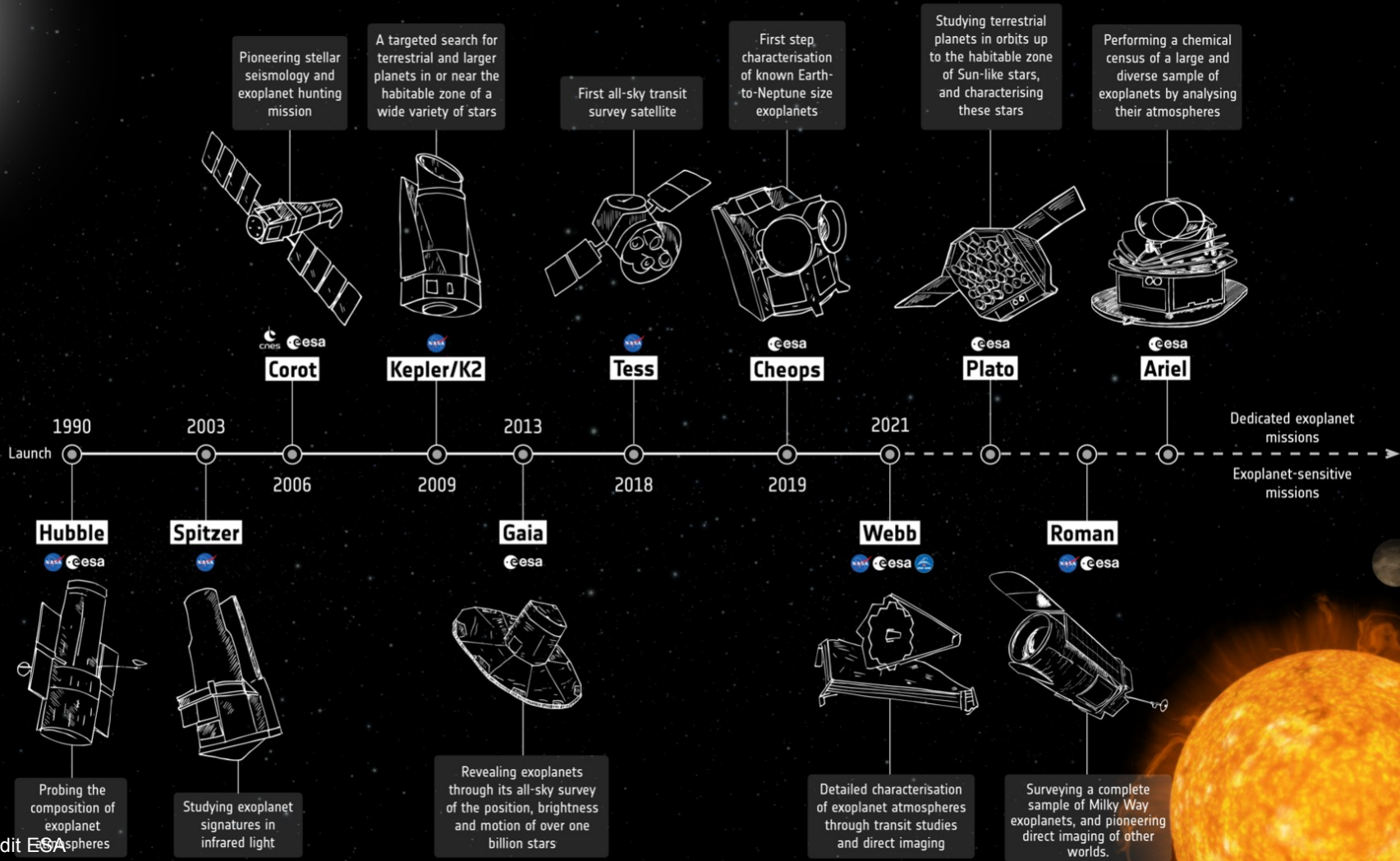


Elliptical primary mirror: 1.1 x 0.7 metres



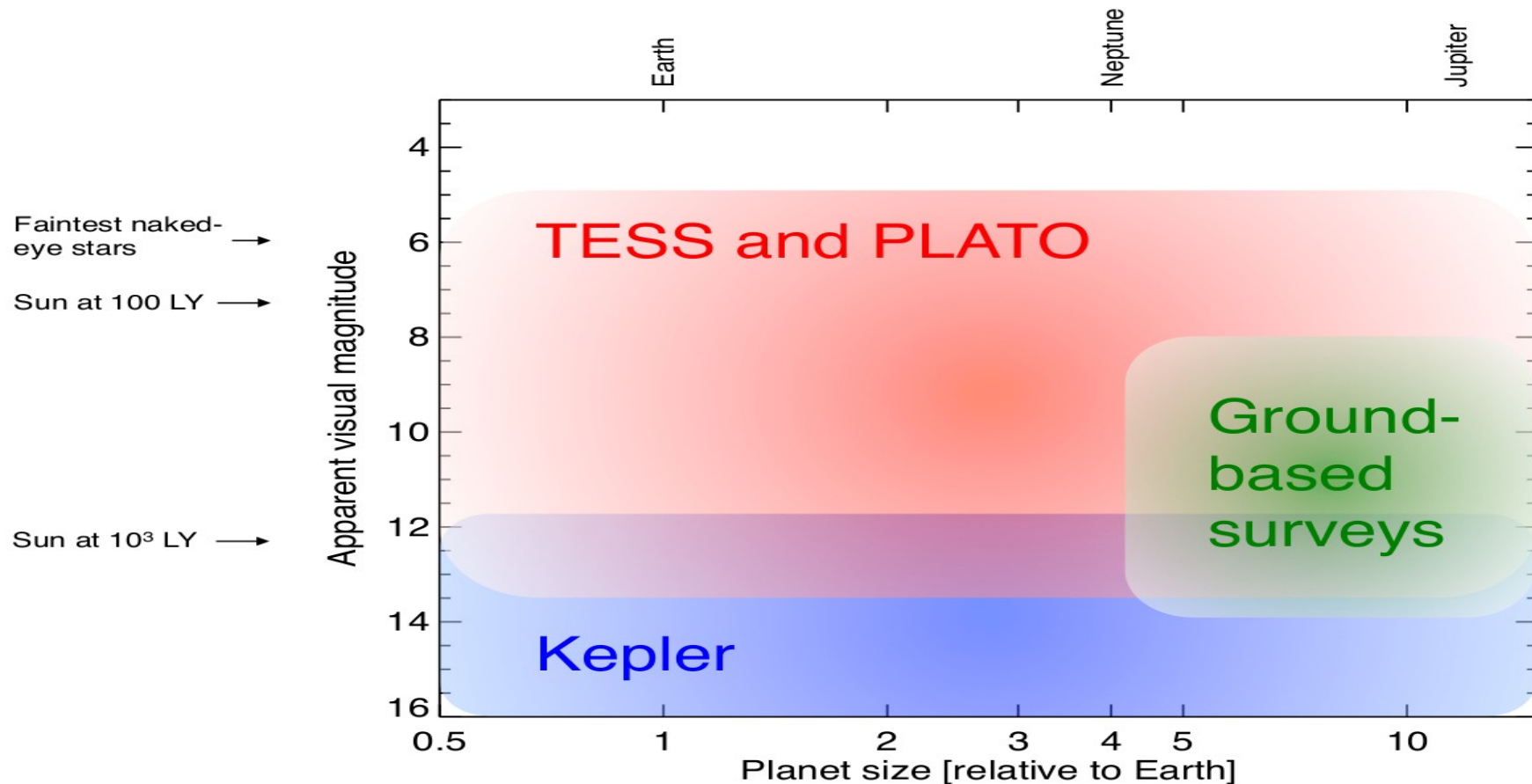
Ground-based observatories

First discoveries of exoplanets in the 1990s opened up the field of exoplanet research. New innovations and discoveries continue to this day



Credit ESA

Space missions compared



Microlensing

The lens/Earth configuration does not repeat (usually)

It is difficult to confirm such planets

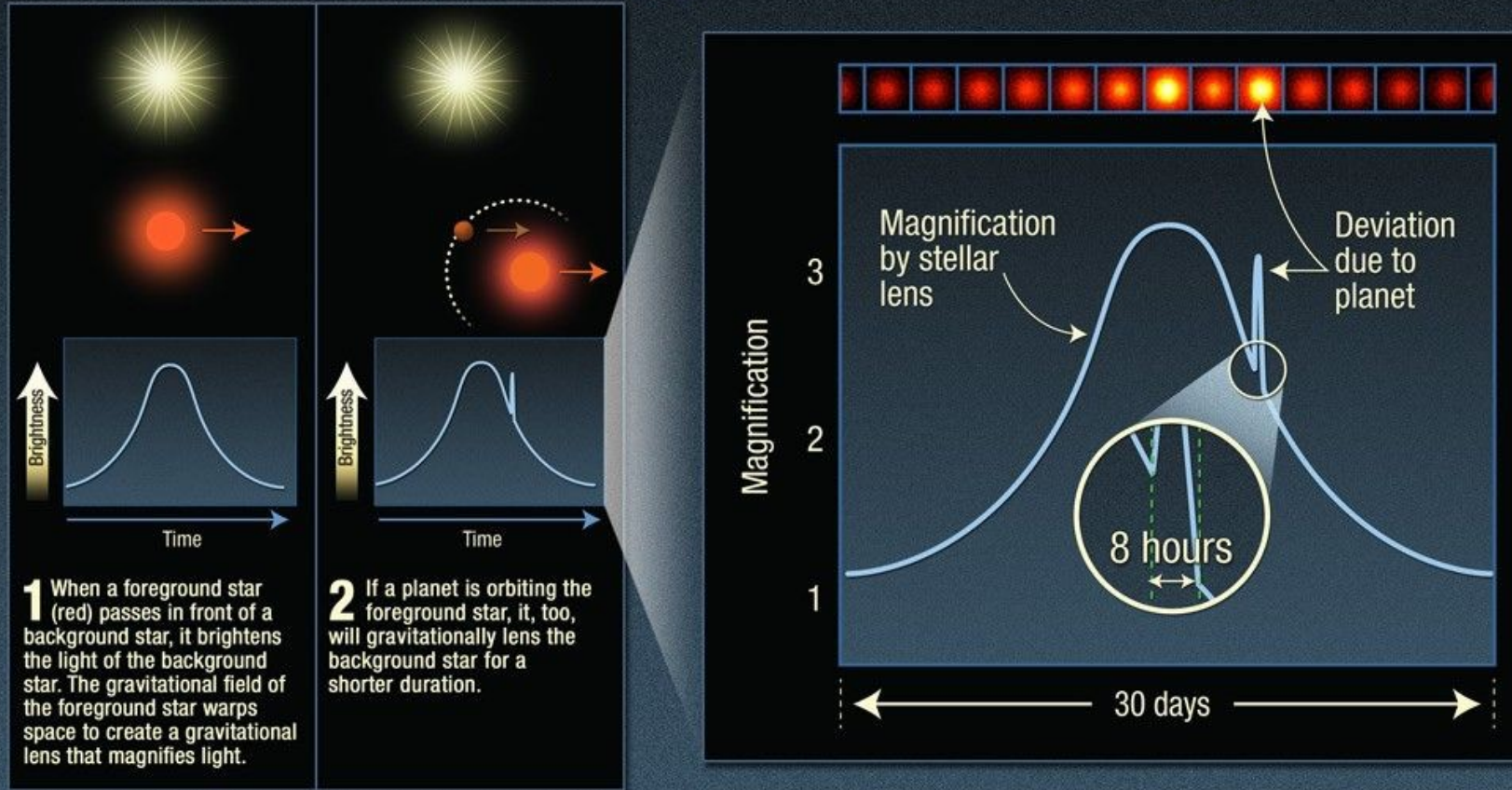
OGLE – Optical gravitational lensing experiment

- 1.3m Las Campanas, Warsaw Univ.
- discovered planets by transit and microlensing (about 20)
- typically fainter stars



Microlensing

Extrasolar planet detected by gravitational 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 (Gaia has 2 exoplanets detected 2024)

Astrometry

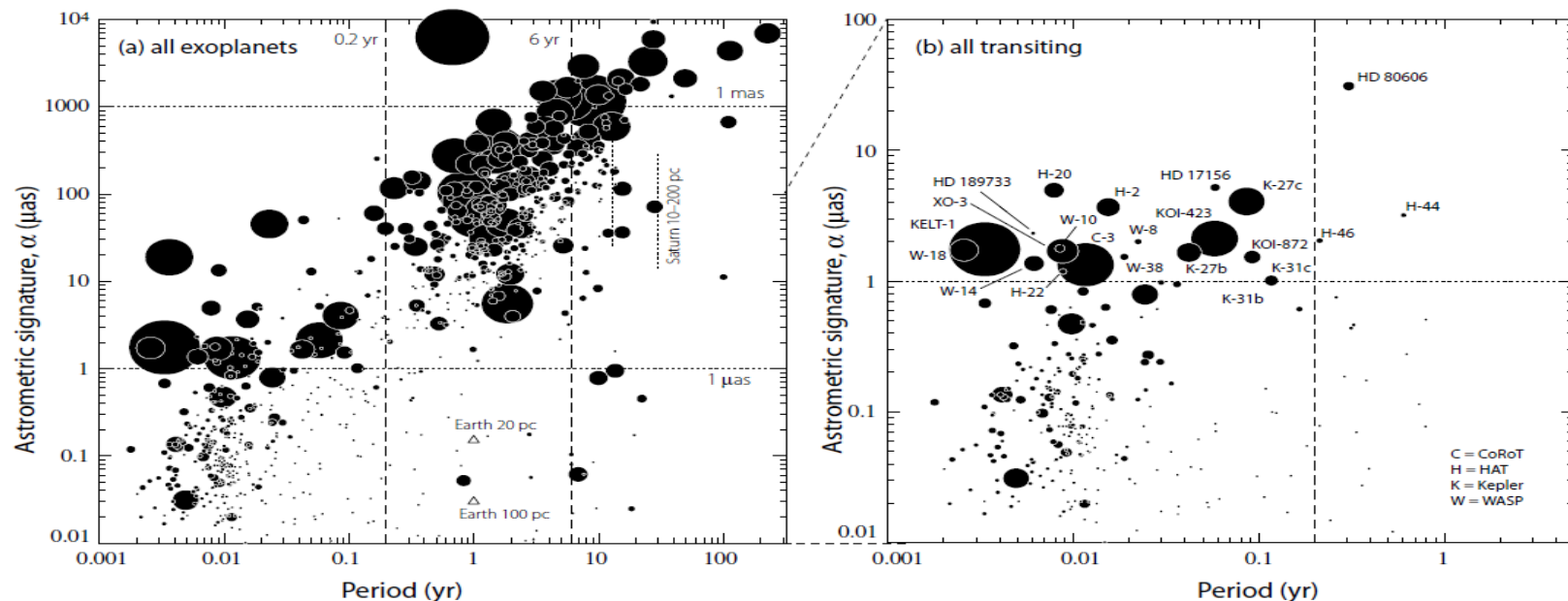
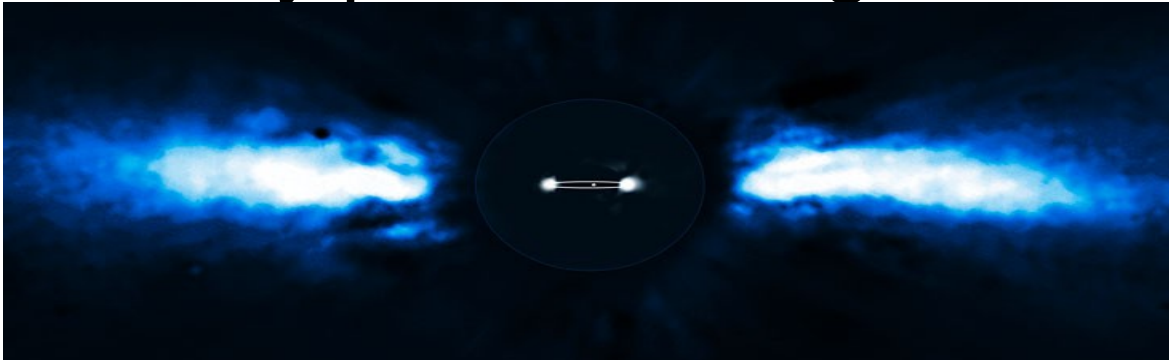


Fig. 1.— Astrometric signature versus period calculated for the objects listed in `exoplanet.eu` at 2014 September 1 for all 1821 confirmed planets (left), and for the subset of 1129 transiting planets with appropriately known data (right). Note the different scales in abscissa and ordinate. Circle sizes are proportional to planet mass; the prominent object (left) at $P = 0.7$ yr, $\alpha = 6300 \mu\text{as}$, is the $28.5 M_J$ astrometric detection DE0823–49 b. Unknown distances are set to $d = 1000$ 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 $d = 500$ pc, α would increase by a factor 2, but their astrometric motion would remain undetectable by Gaia.

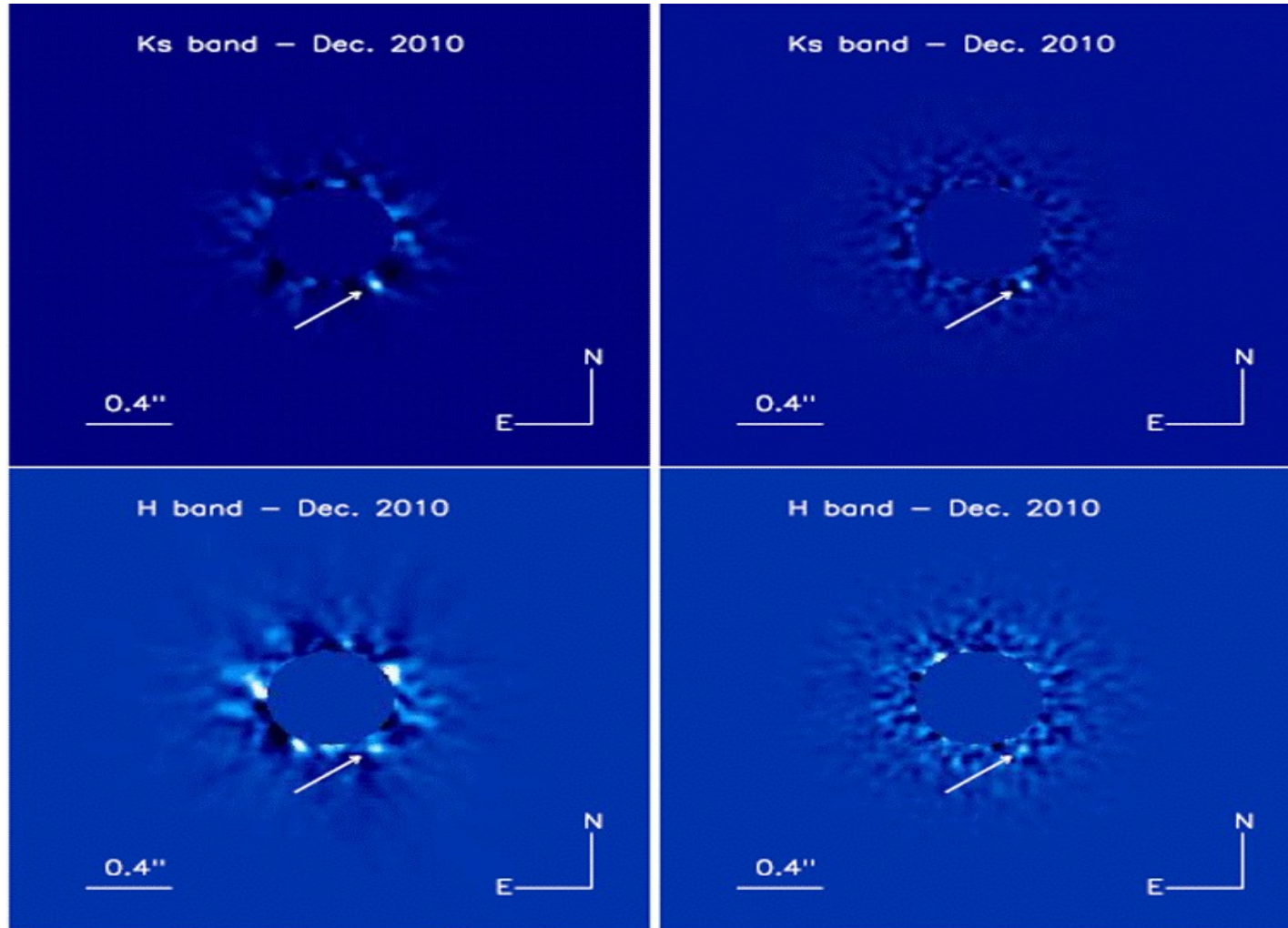
Direct imaging

- Difficult 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

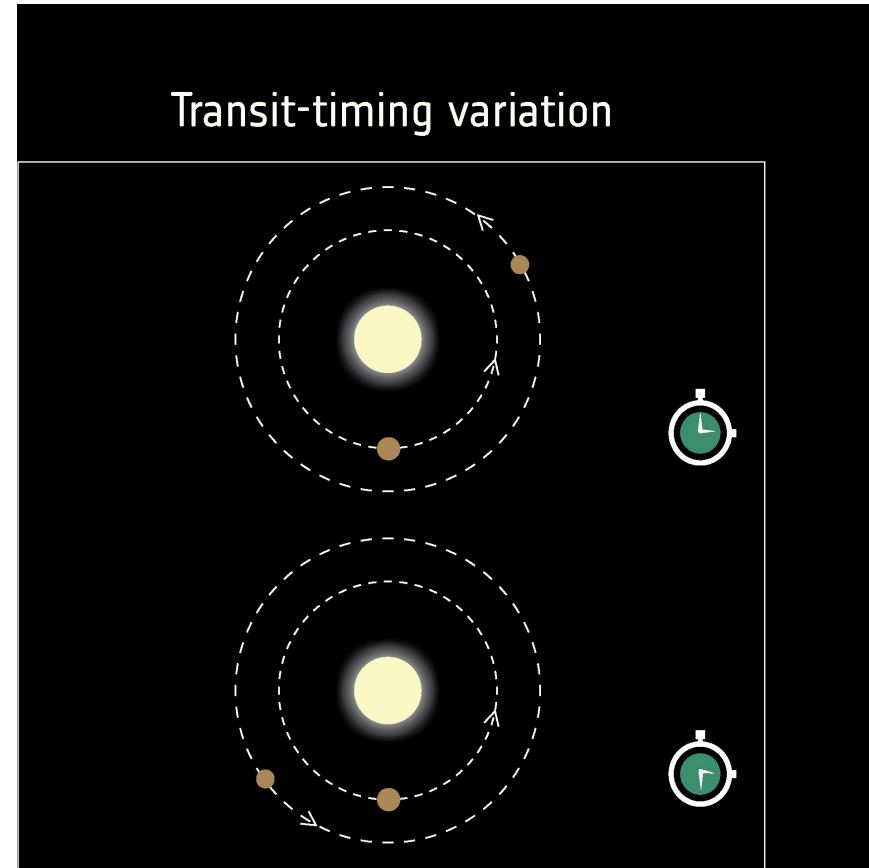
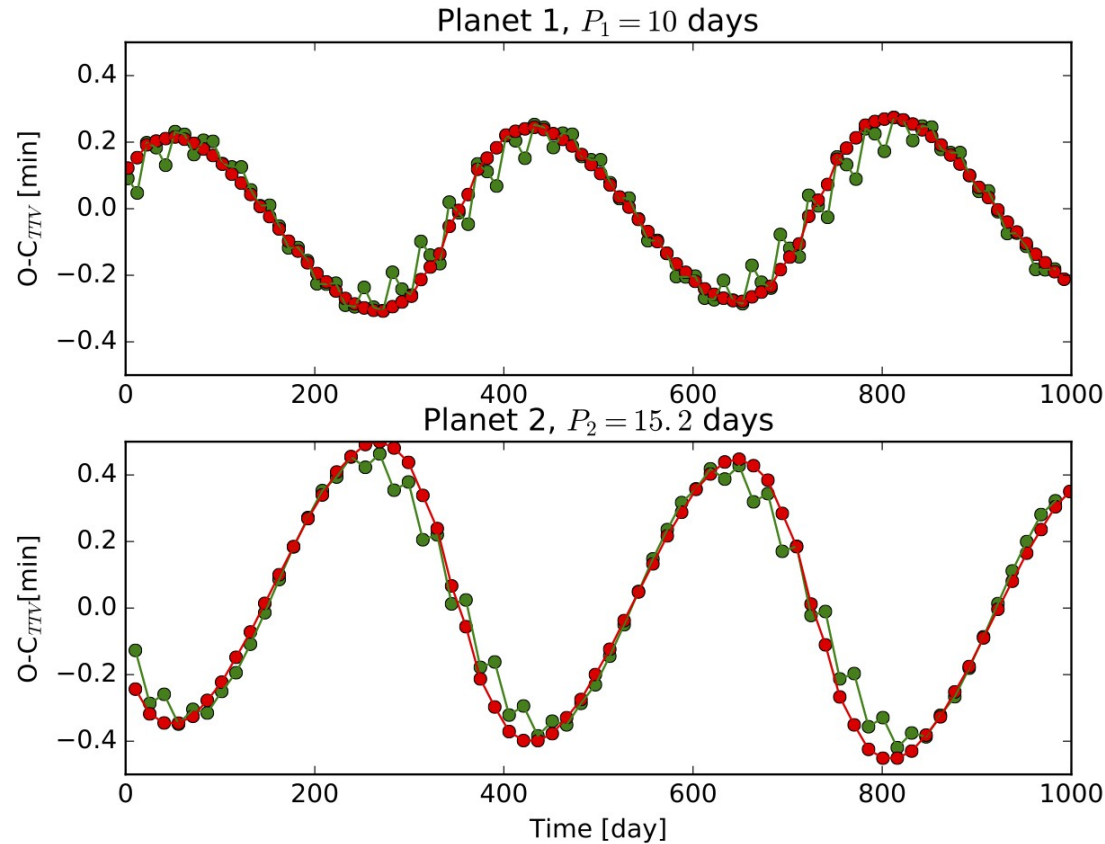


Credit : ESO press release (Beta Pic, A. Lagrange)

And here is a detail

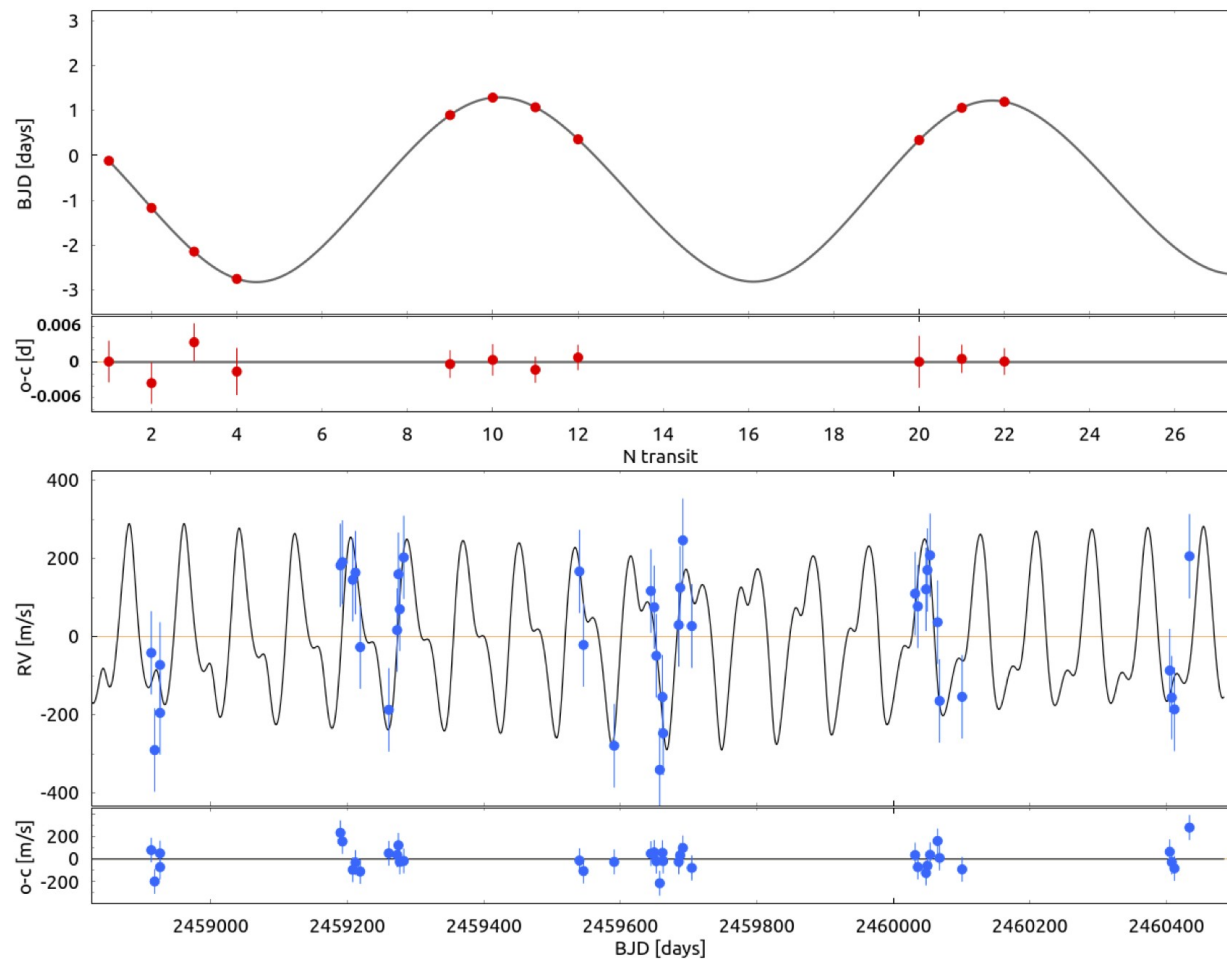


Transit timing variations - TTV



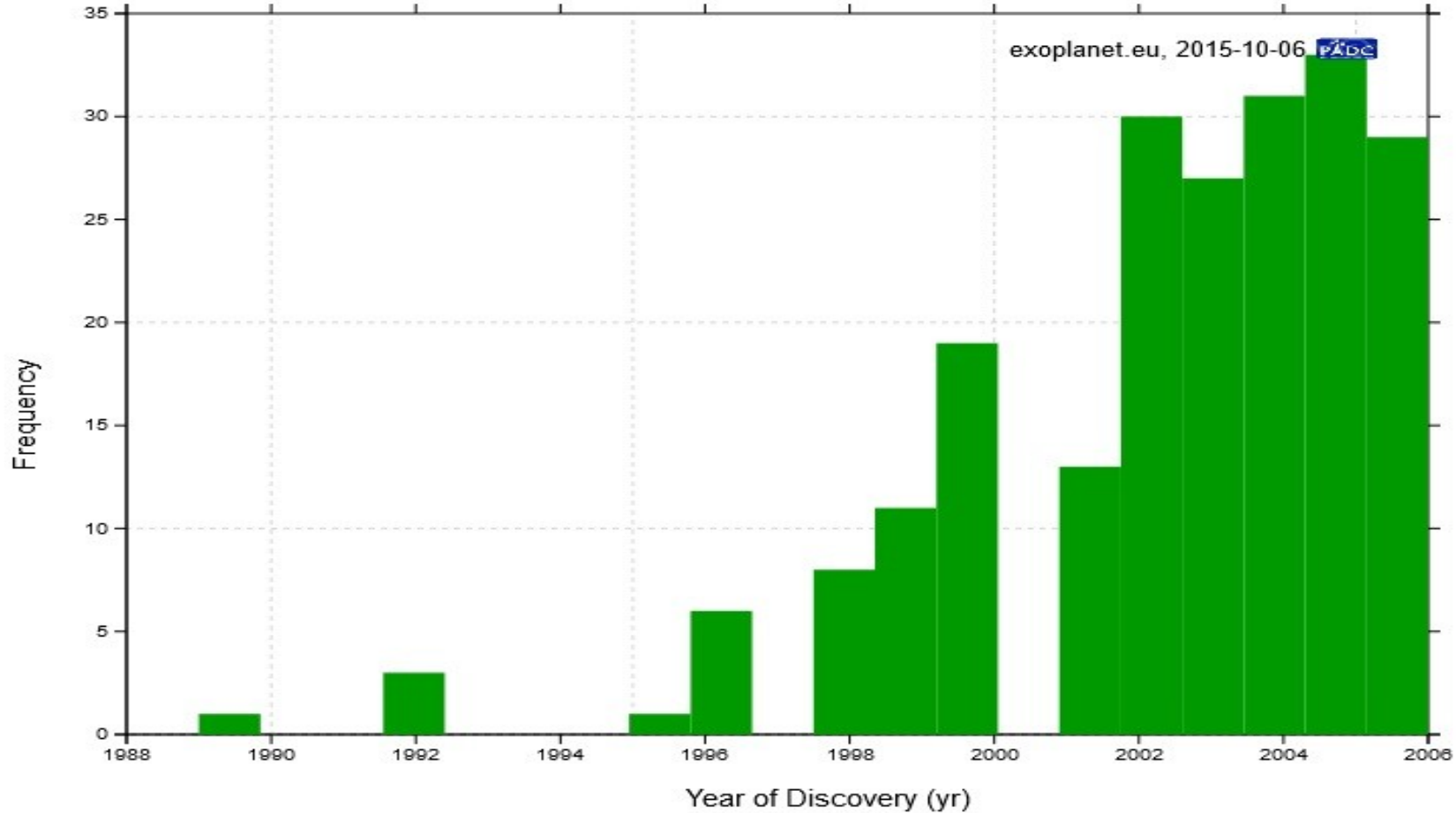
Transit timing variations - TTV

- Vitkova et al. 2024 (ApJL)
- TTVs of order of days
- Multiplanet system

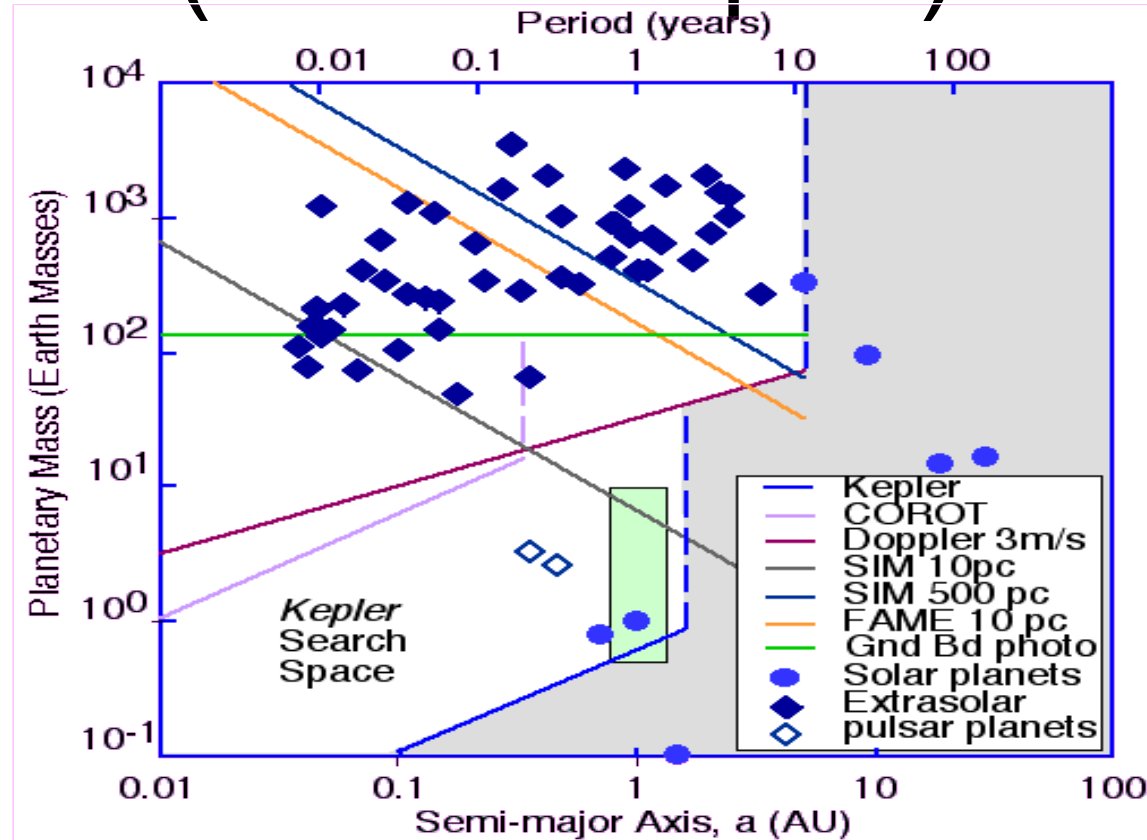


Some statistics
Completeness of surveys

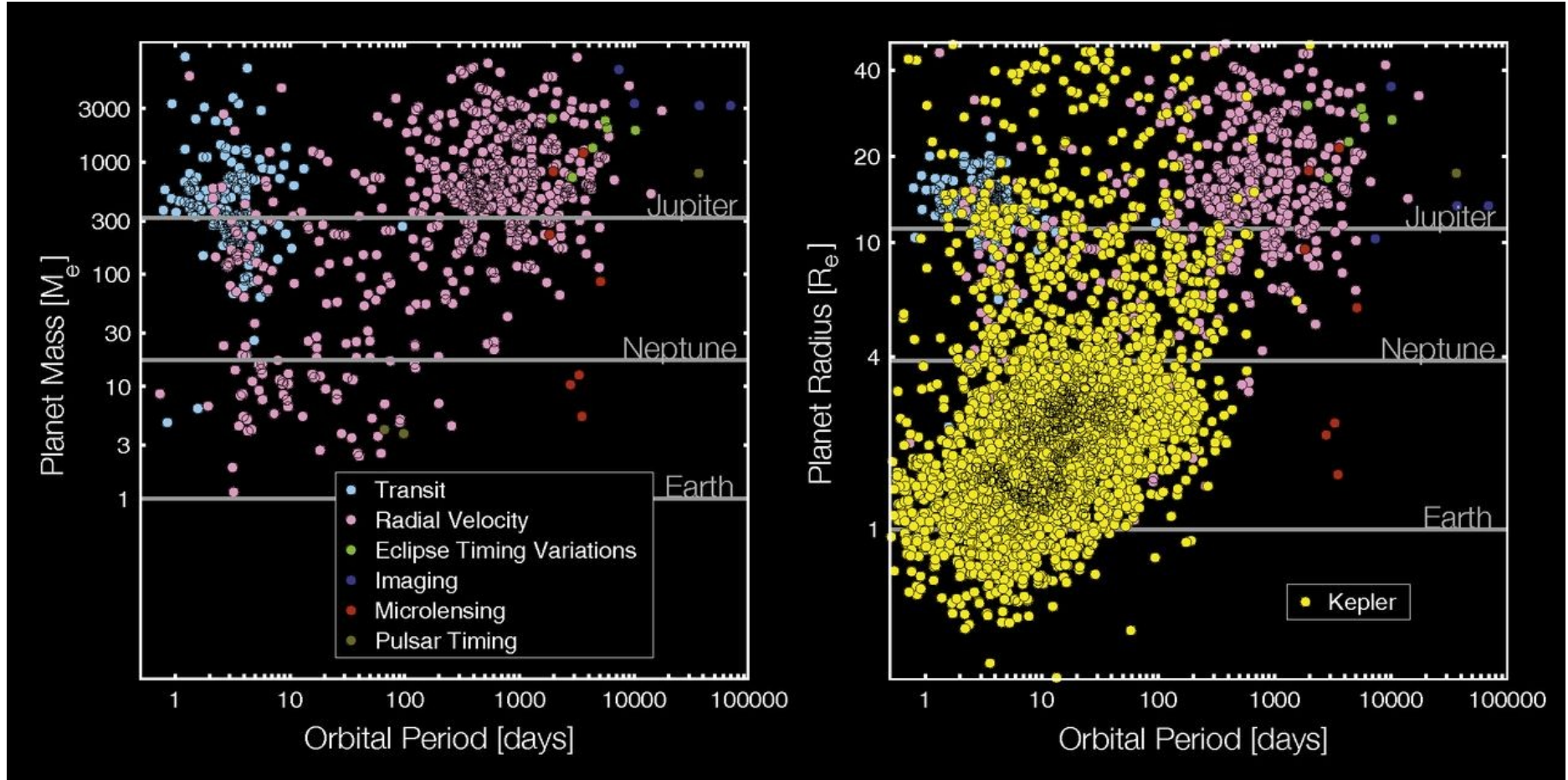
How many stars do have planets? (2006)

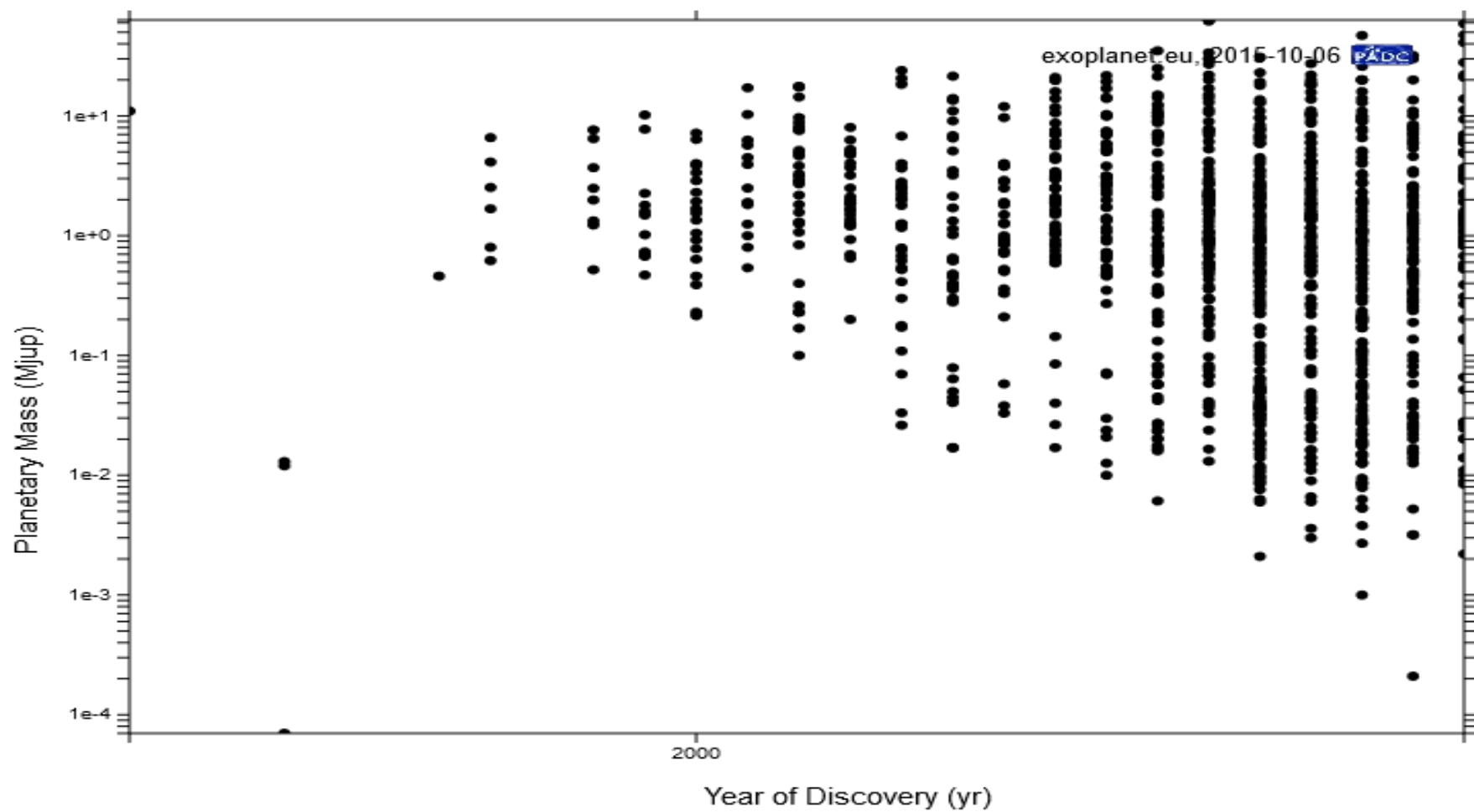


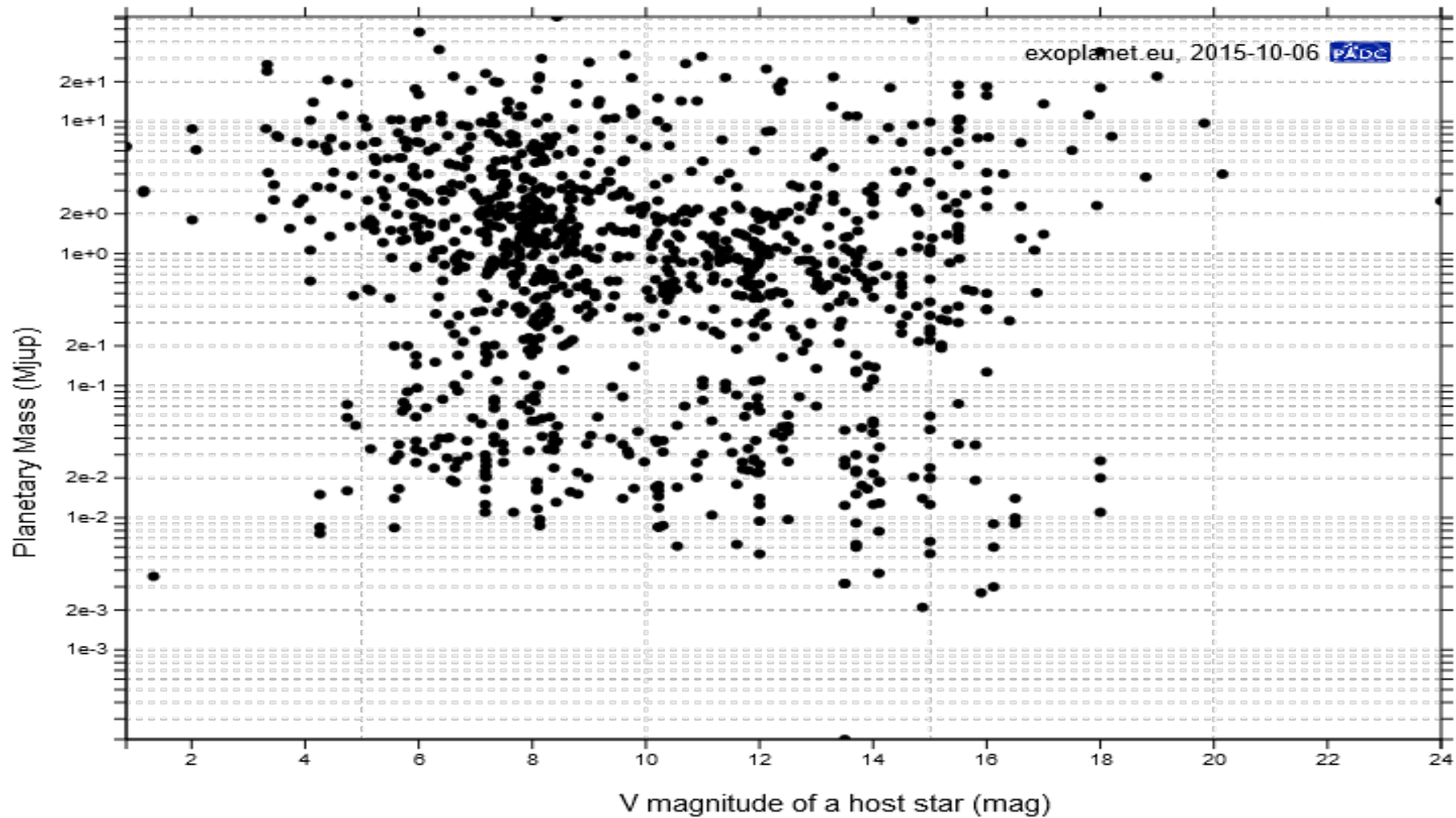
Mass vs. Semi-m. Axis (before Kepler)



And similar with Kepler



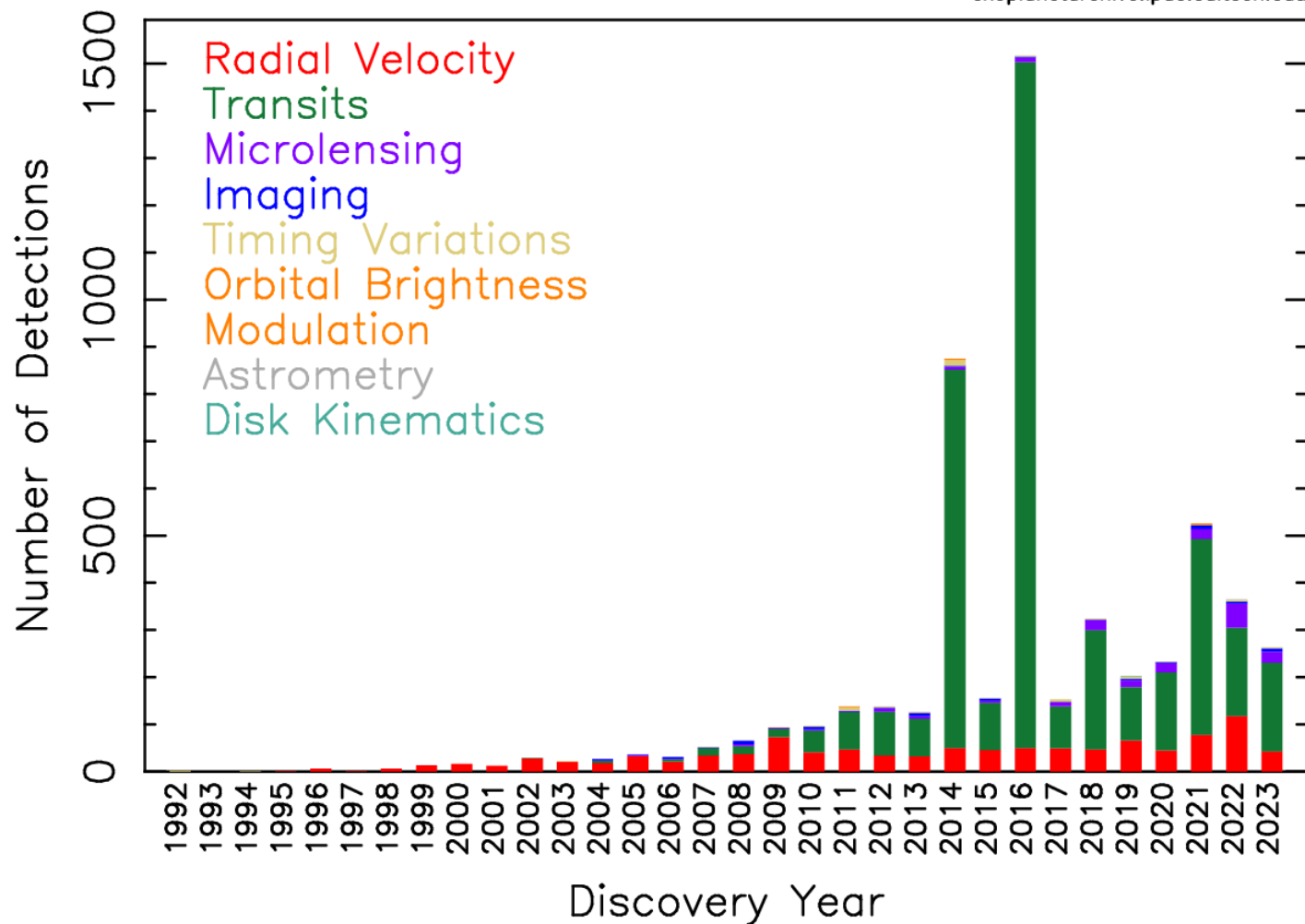




Detections Per Year

12 Oct 2023

exoplanetarchive.ipac.caltech.edu

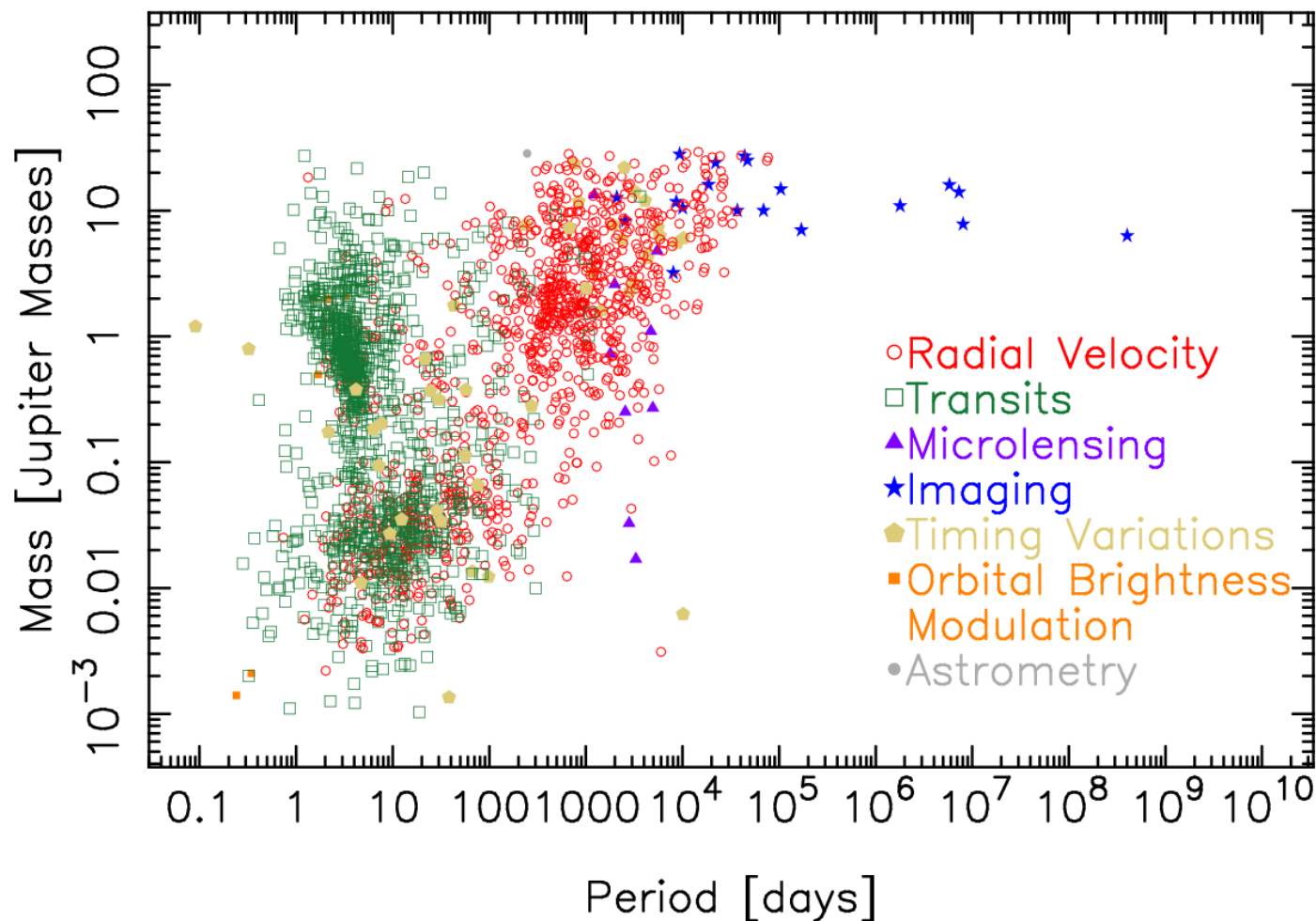


https://exoplanetarchive.ipac.caltech.edu/exoplanetplots/exo_dischist.png

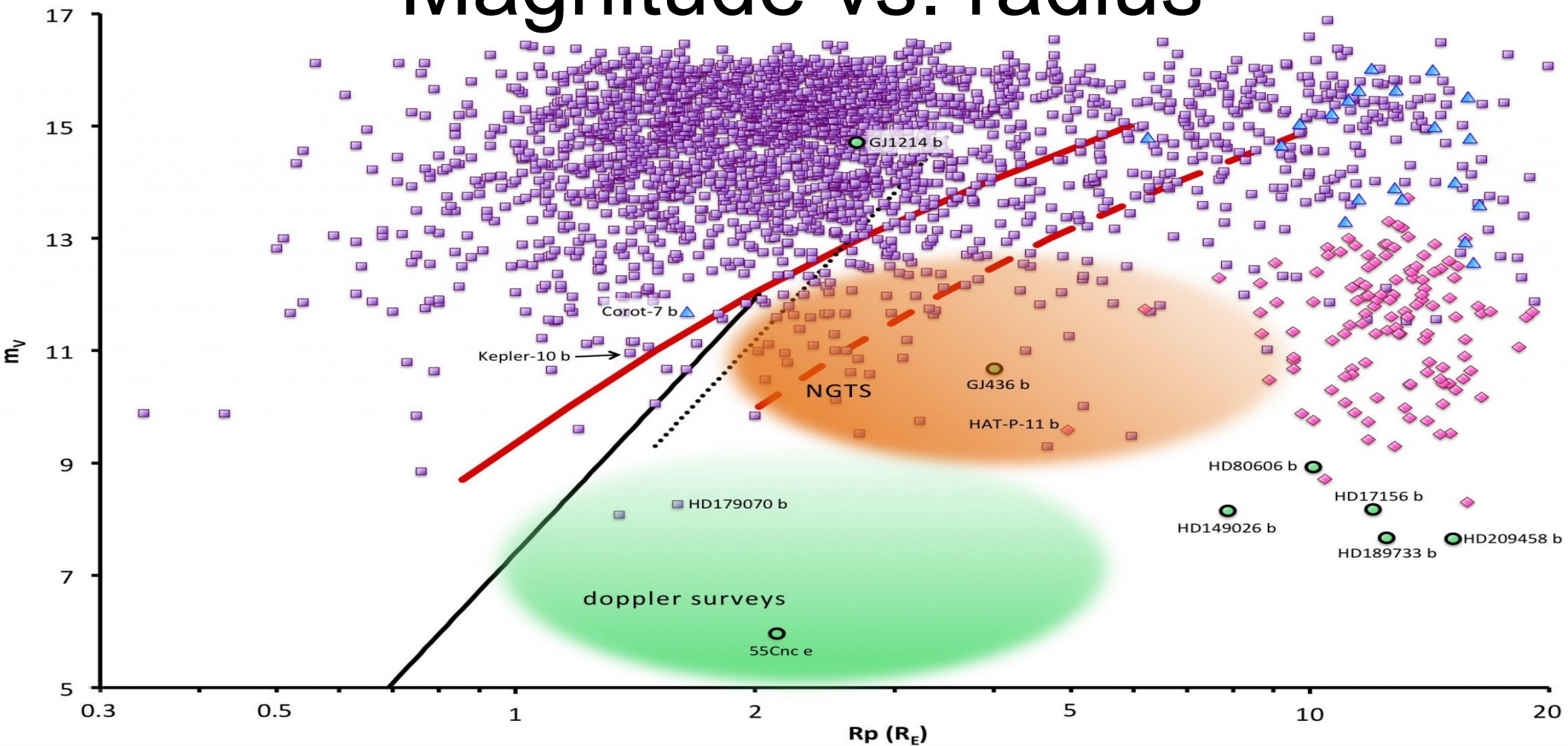
Mass – Period Distribution

12 Oct 2023

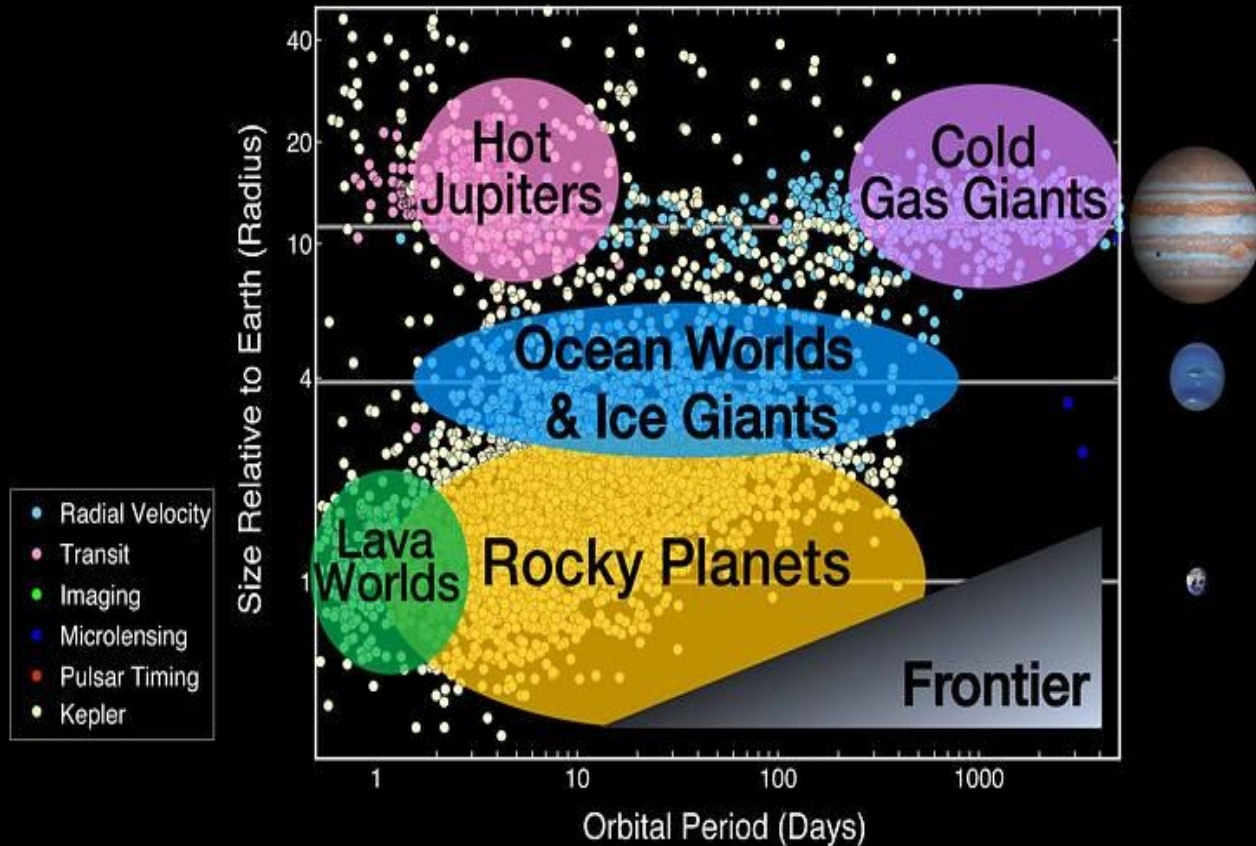
exoplanetarchive.ipac.caltech.edu



Magnitude vs. radius



Exoplanet Populations



<https://www.nasa.gov/image-article/exoplanet-populations/>

Mass. vs. distance to star

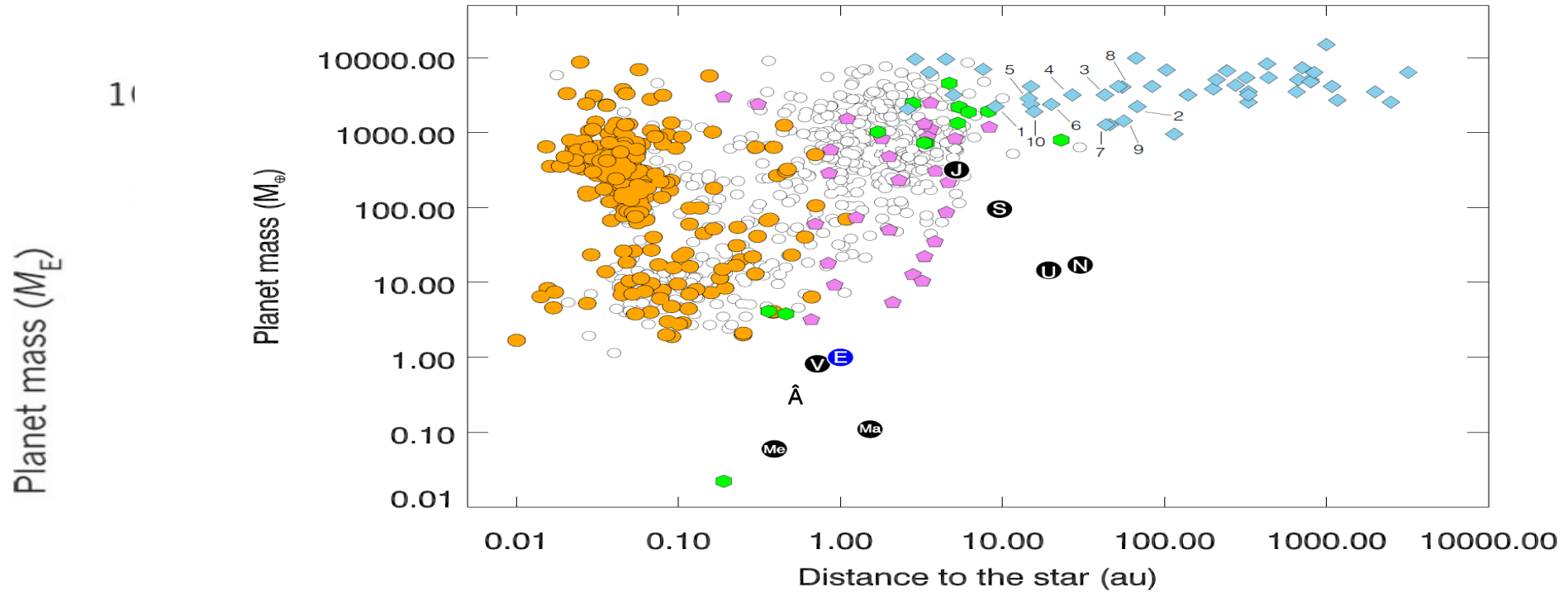
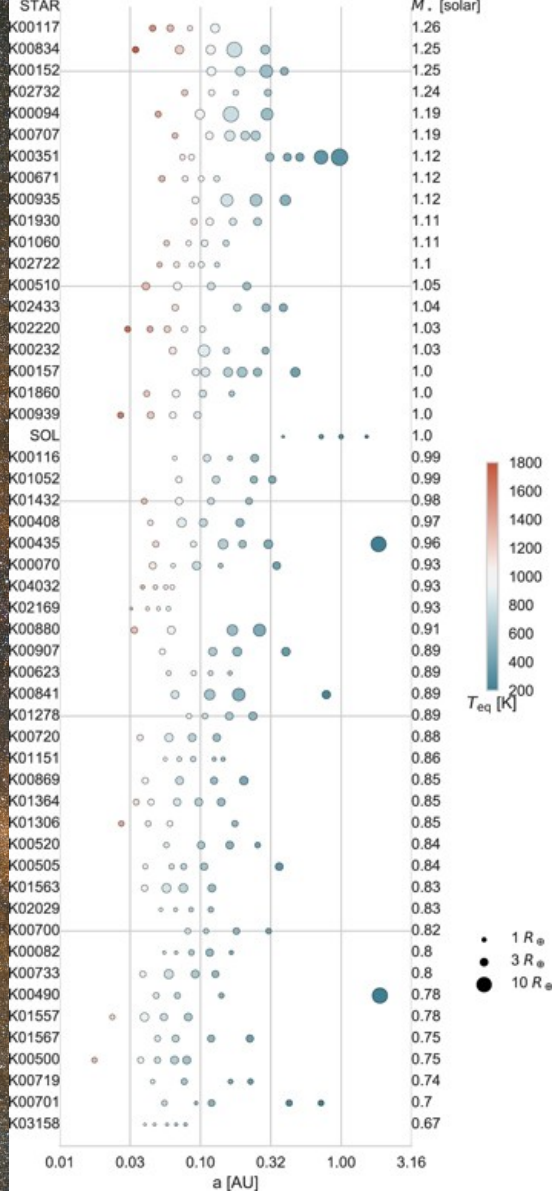
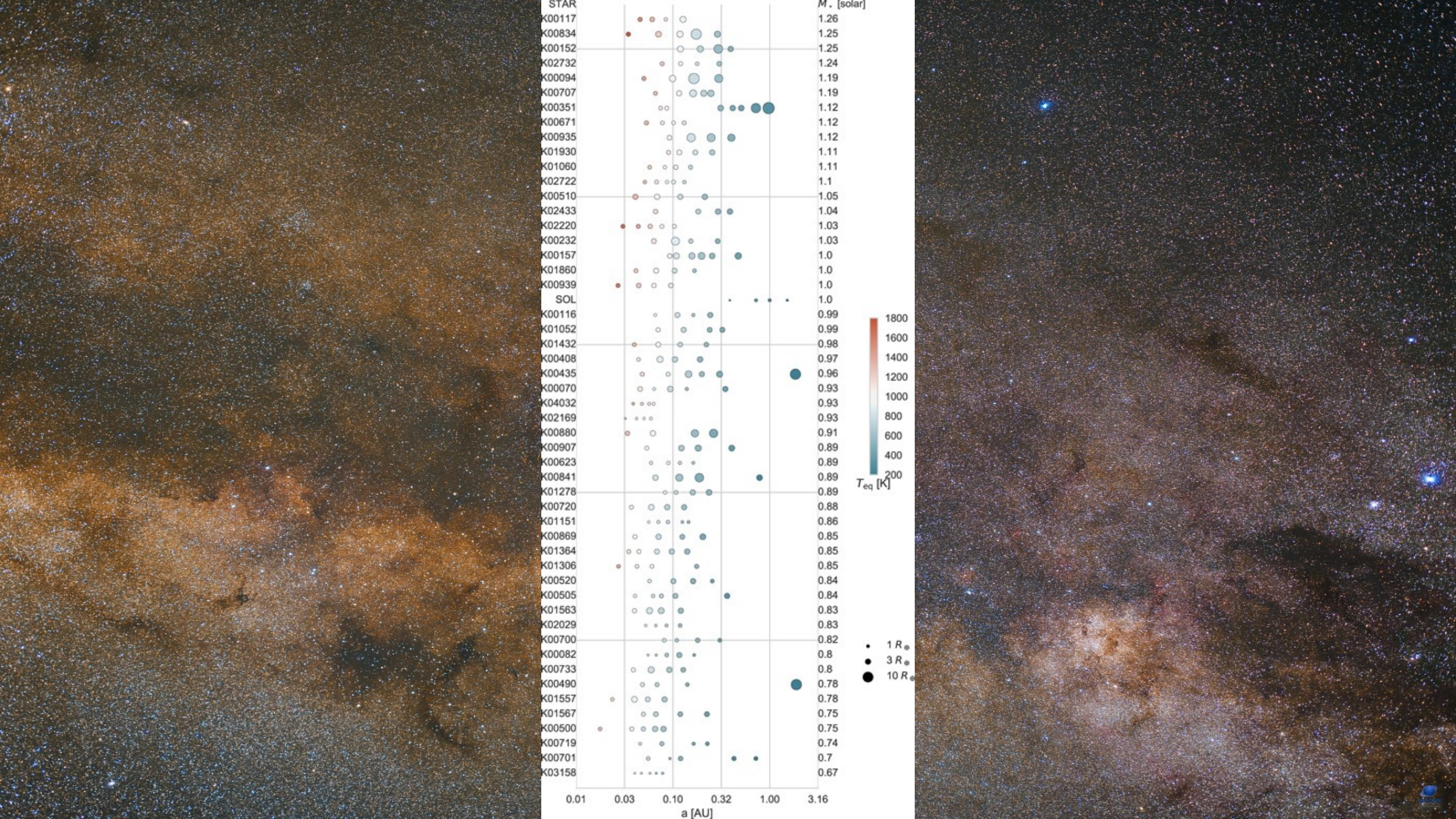
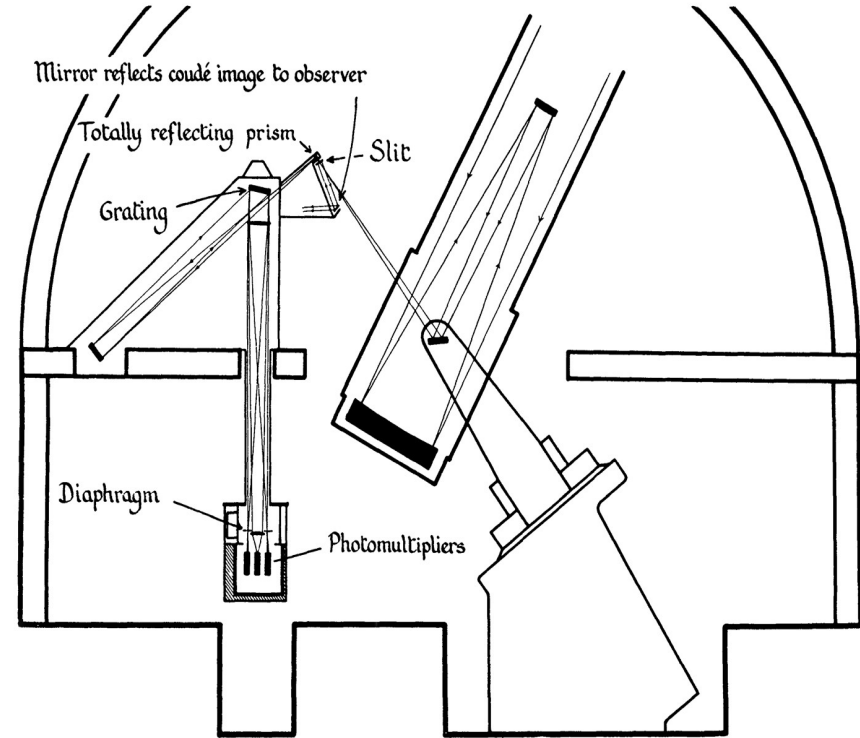
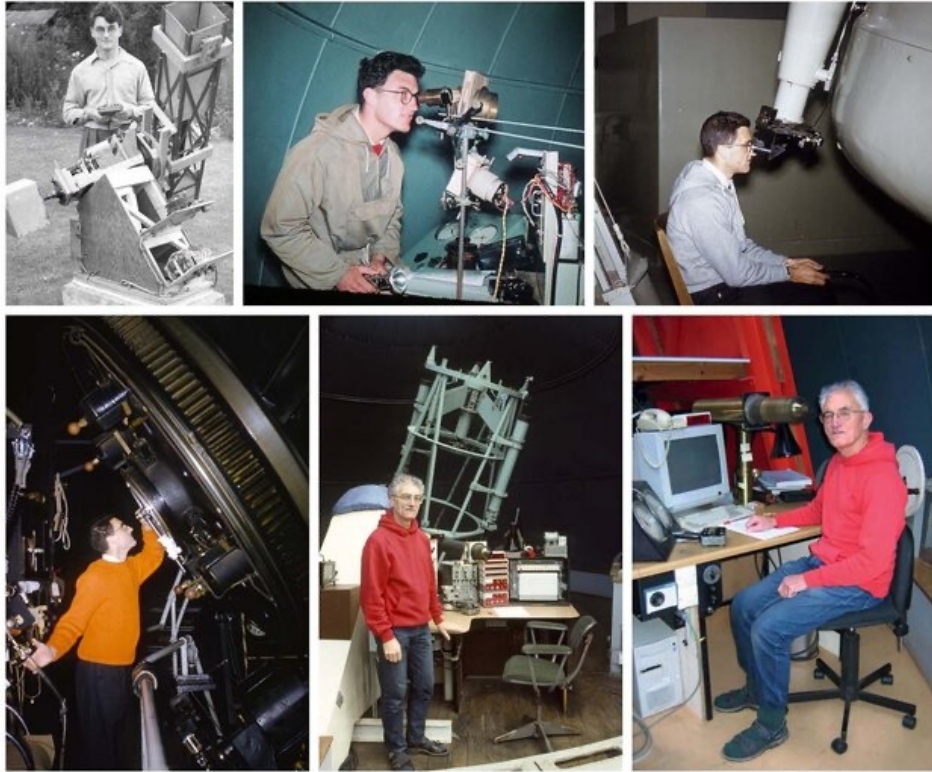


Figure 3: *Mass and semi-major axis of known planets.* Planetary mass is plotted as a function of semi-major axis (the distance to the host star). Solar-system planets are shown by black circles, the Earth in blue. Exoplanets detected with different techniques and instrumentation are represented by different 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 Encyclopaedia¹⁹⁶.



First high dispersing spectrograph



Roger Griffin - <https://ui.adsabs.harvard.edu/abs/1967ApJ...148..465G/abstract>

Roger F. Griffin – University of Cambridge

Long way towards exoplanets

- CORAVEL - precise RVs down to 250 m/s
- Installed at ESO Danish telescope in 1969
- First atlas of stellar parameters



Image: ESO

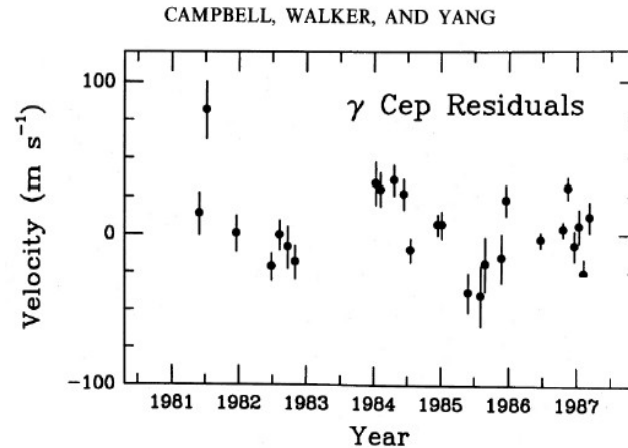
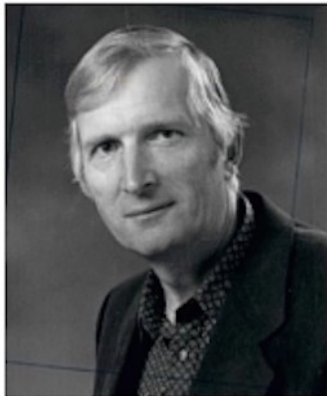
Bruce Campbell and Gordon Walker

- First spectroscopic exoplanet survey 1971
- Hydrogen Fluoride cell for calibration
- The goal is to convert pixel scale (detector) into wavelength as accurately as possible
- <http://articles.adsabs.harvard.edu/pdf/1979PASP...91..540C>



Gordon Walker & Bruce Campbell

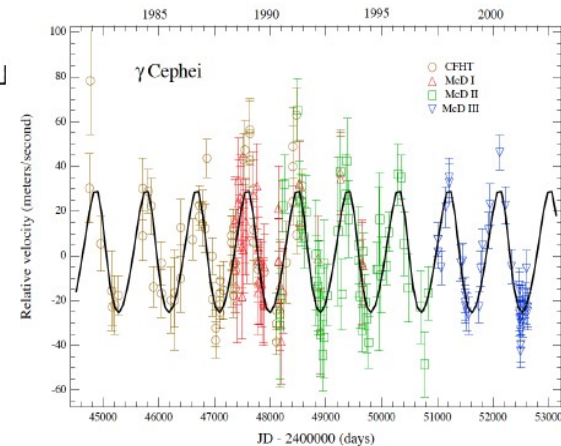
- Started around 1971, calibration with HF lamp
- First real planet but retracted
- RVs down to 3 m/s
- Gamma Cephei story



Campbell, Walker and Yang, 1988, ApJ

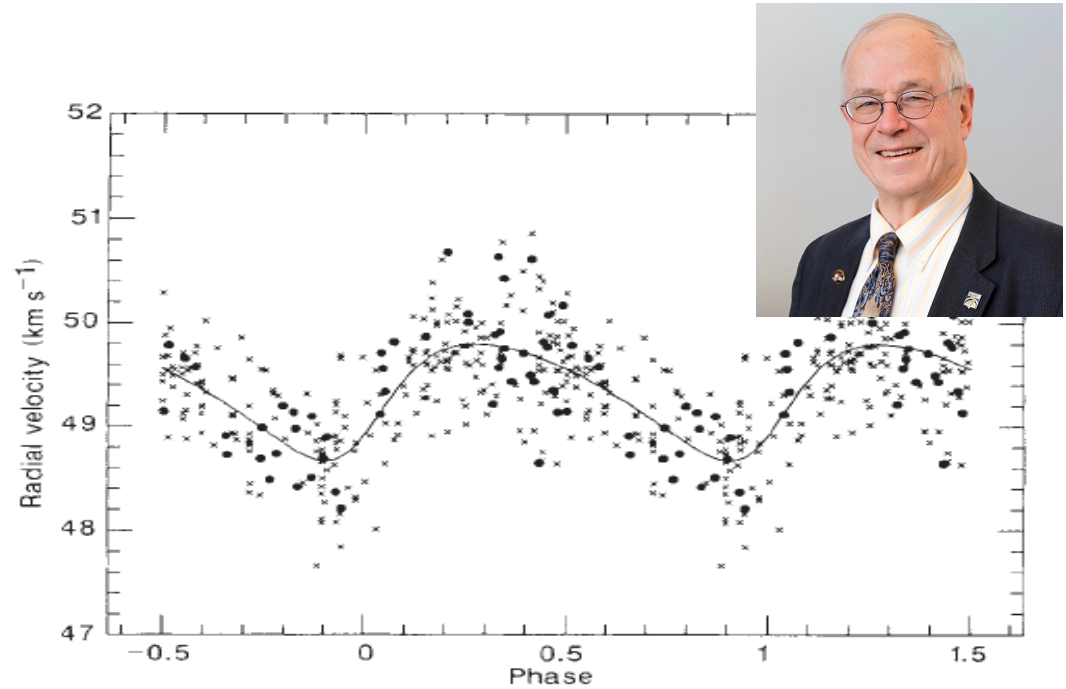
$P = 903$ days
Mass = $1.85 \text{ M}_{\text{jupiter}}$

Hatzes et al. 2003, ApJ



The Case of Dave Latham's planet

- HD114762
- A BD? A planet?
- 11- 65 Jupiter Masses?
- Or more or less?
- Mass of 107 Jup. confirmed
- very low inclination
- Flavien, A&A



From Latham et al. 1989, Nature

- <https://arxiv.org/abs/1910.07835>

Next week

- Instrumentation for detection of exoplanets

Thank you for your attention and see you next week

Reading

http://www.astro.unipd.it/ScuolaNazionale2013/lectures/Hatzes_RV_Detections_Chapter_1.pdf

<https://arxiv.org/abs/1001.2010>

<https://arxiv.org/pdf/astro-ph/0305110.pdf>

<http://articles.adsabs.harvard.edu/pdf/1979PASP...91..540C>

<http://articles.adsabs.harvard.edu/pdf/1988ApJ...331..902C>

<http://spiff.rit.edu/classes/resceu/refs/339038a0.pdf>