



# Exoplanets

Fall/Winter 2024/2025

Lecture 2

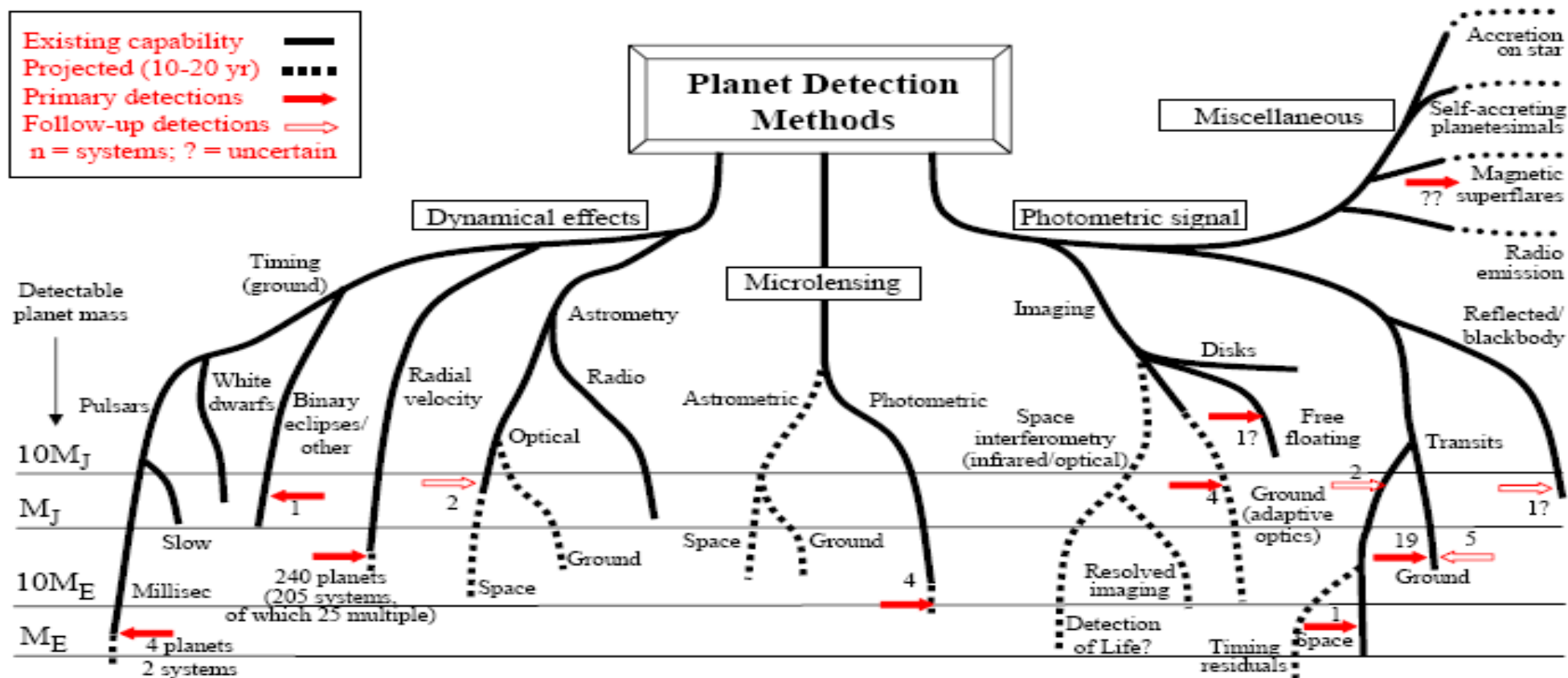
11.10.2024

# 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)



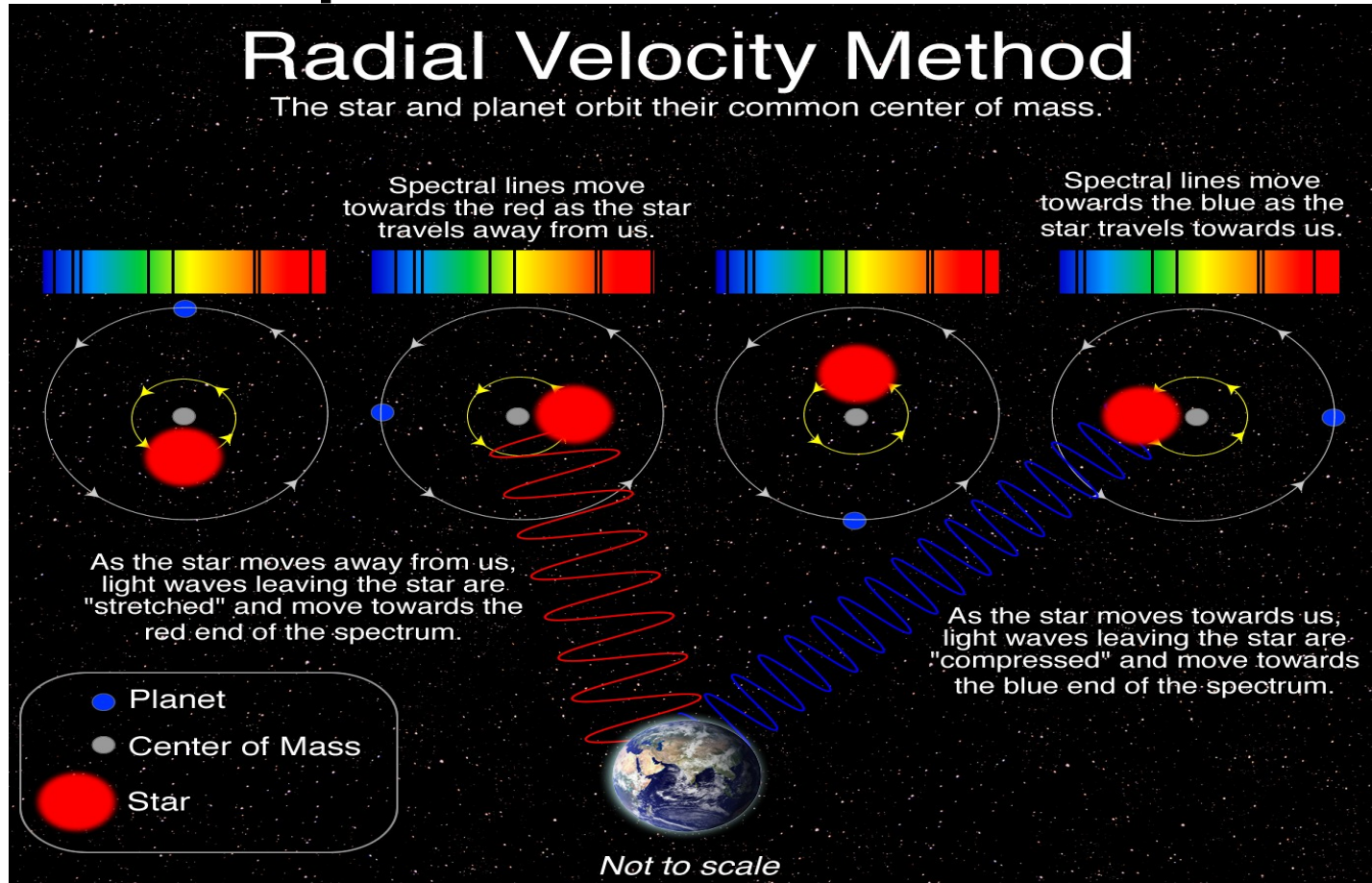
# Radial velocities method (RV)

- 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 (see Lecture 2)
- Then we can measure the velocities, well shifts in wavelength due to the movement of the object
- We are looking at tiny shifts of spectral lines due to planets!

# Principle of the RV method



Credit: Las Cumbres Observatory

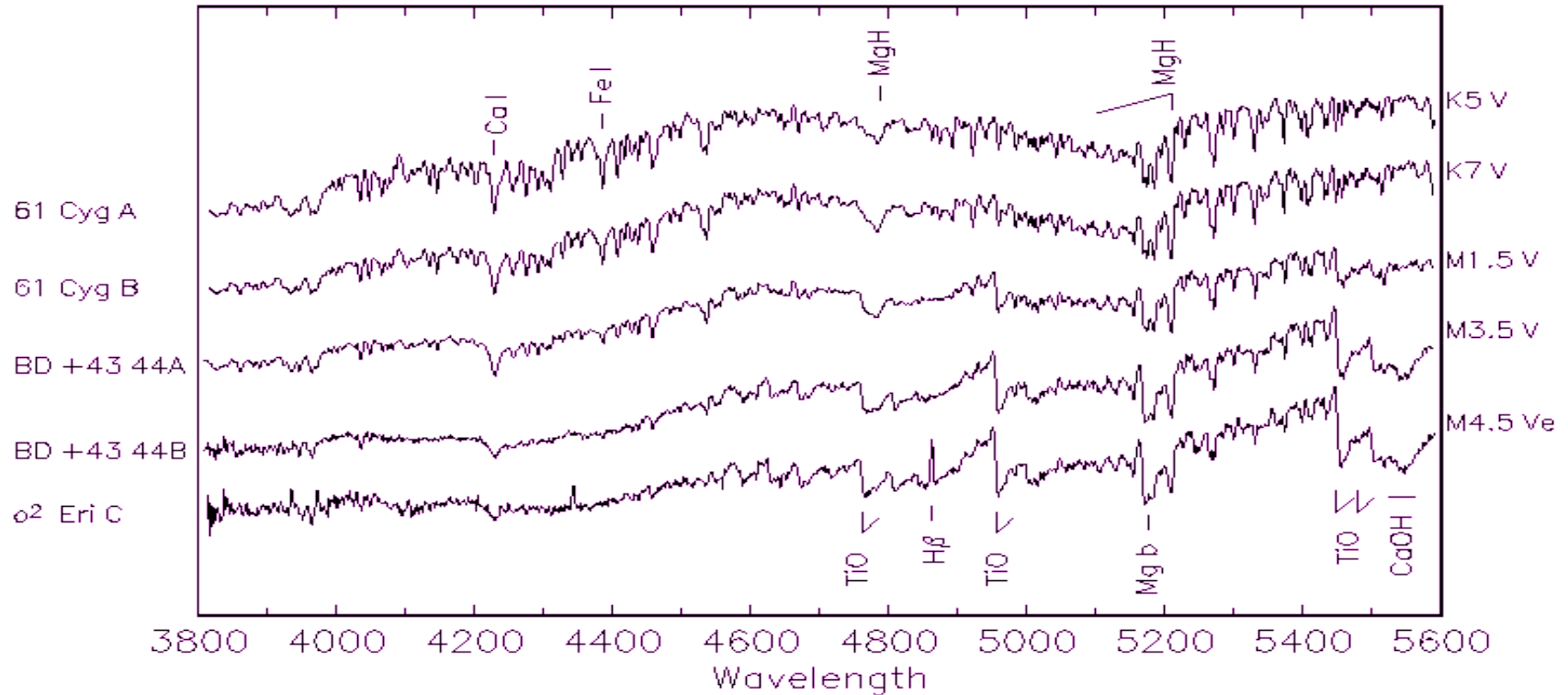
# First step

- Instrumentation usually very stable Echelle spectrographs to achieve high accuracies (Lecture 3)
- 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)

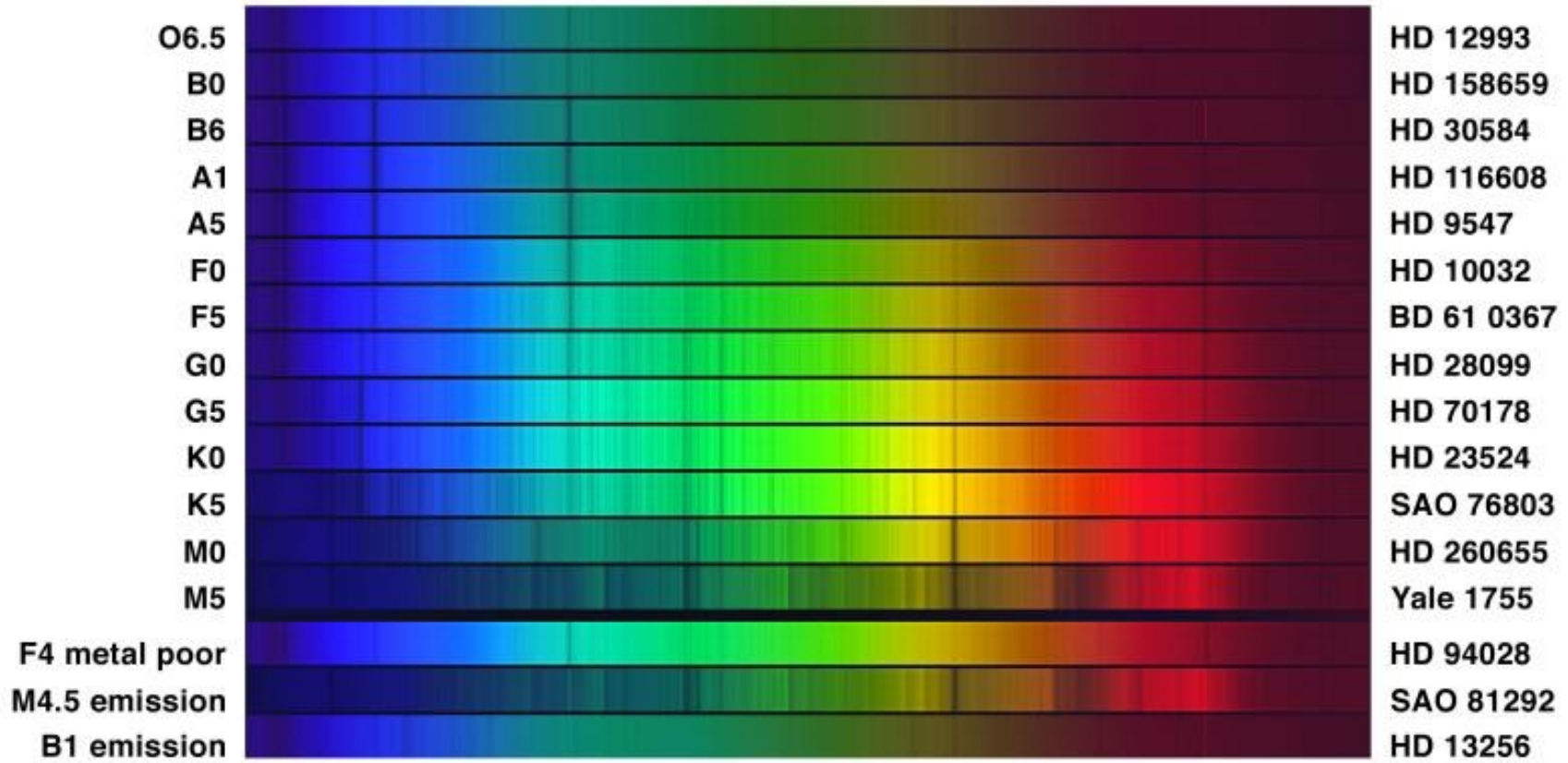


# Example of a main sequence spectra

Main Sequence K5 – M4.5  
Normalized Flux



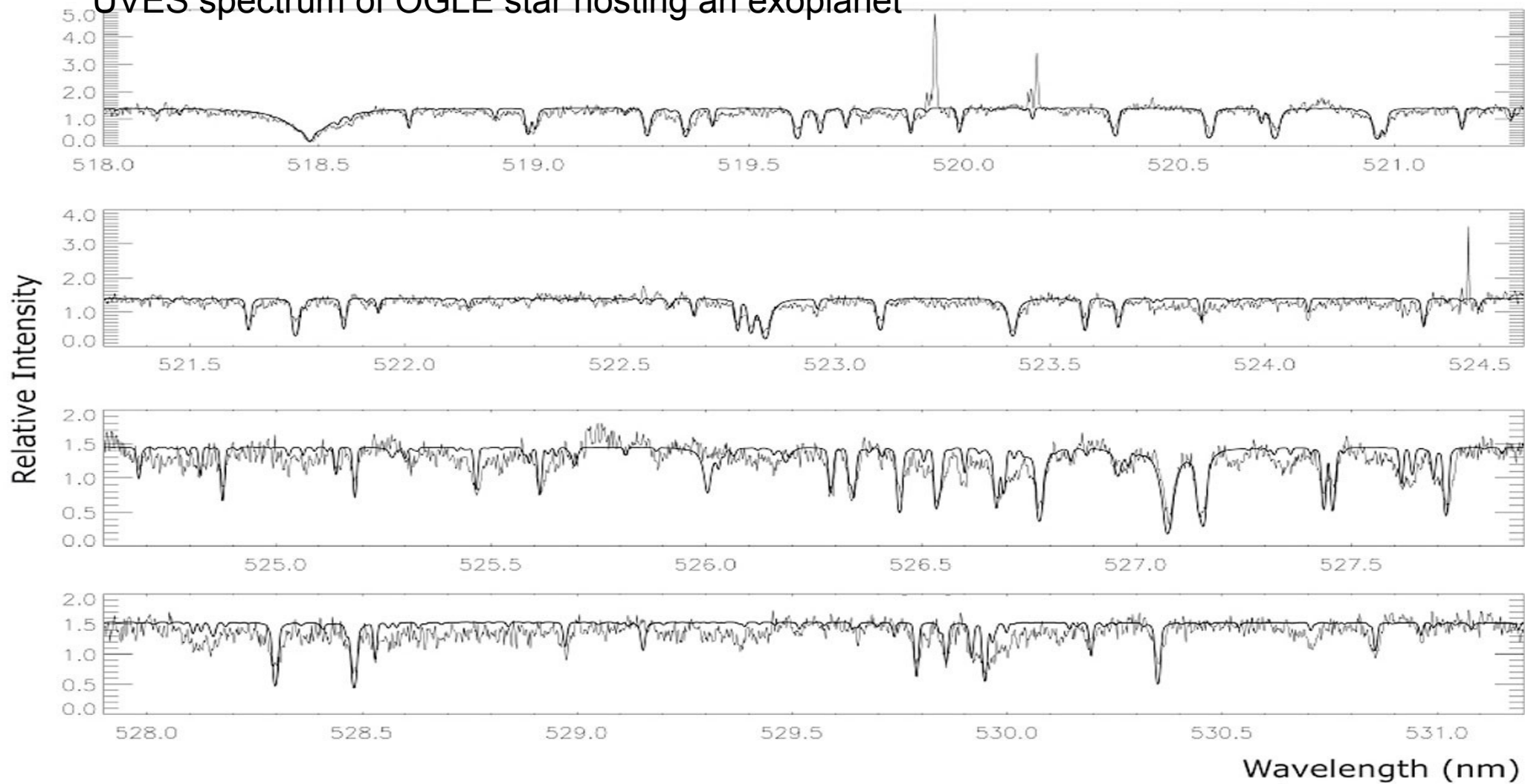
# Various spectral types



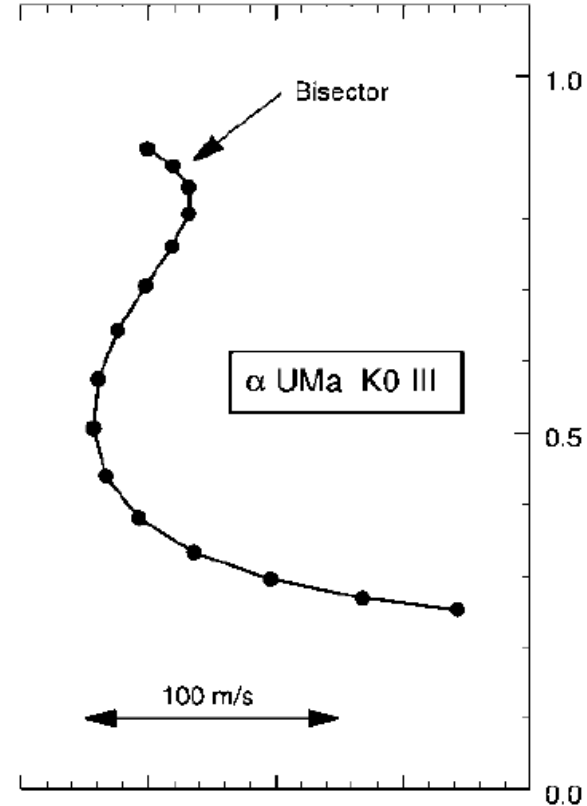
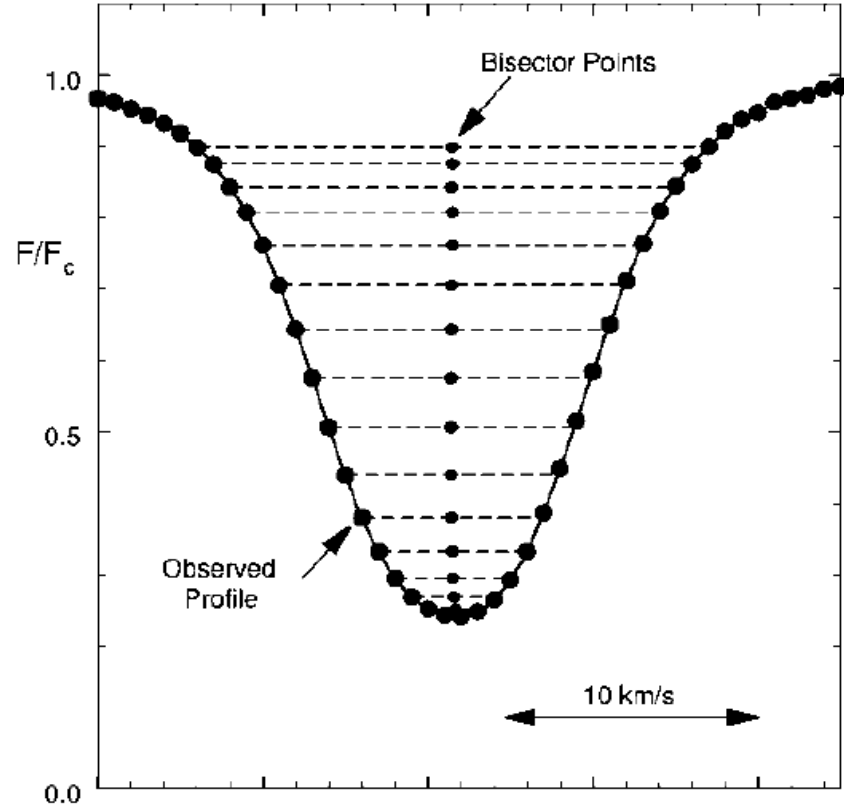
<https://apod.nasa.gov/apod/ap010530.html>

APOD NASA

# UVES spectrum of OGLE star hosting an exoplanet



# Shapes of lines unveil physics



# Results (51 Peg)

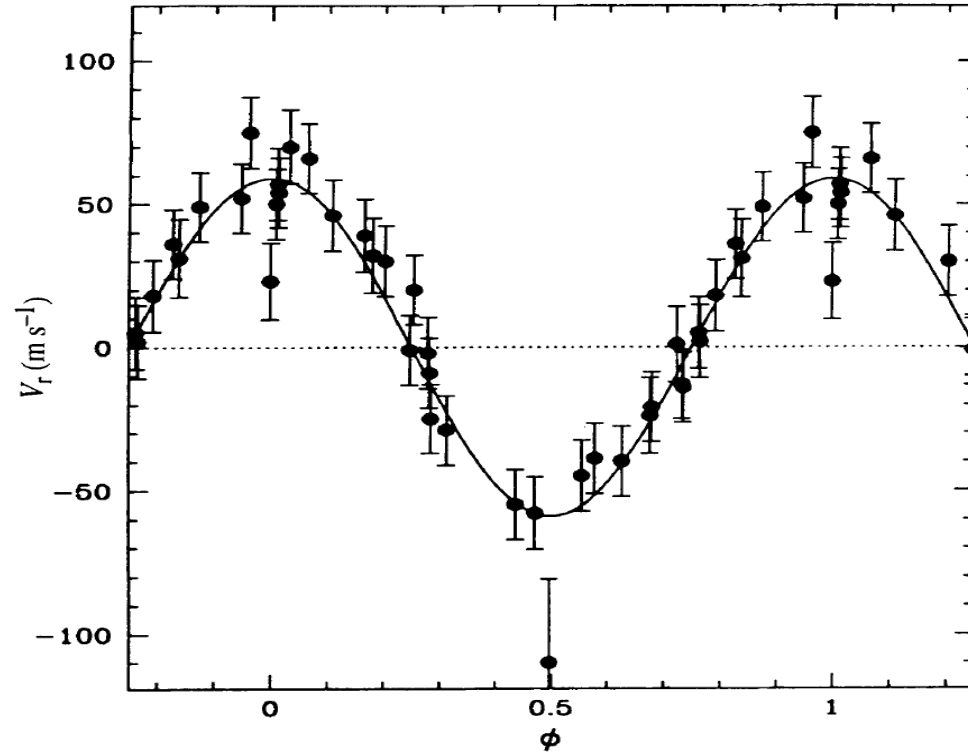
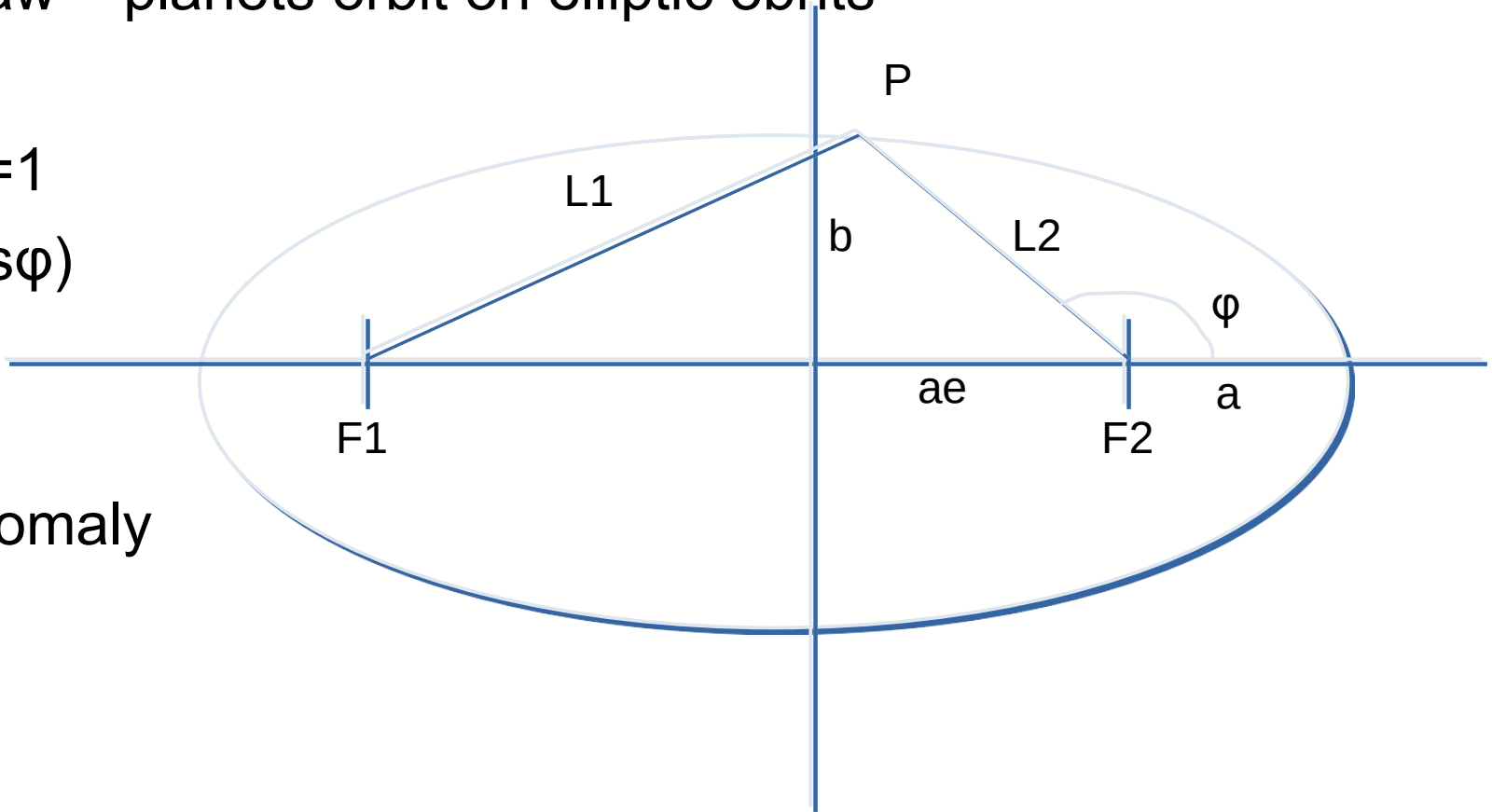


FIG. 4 Orbital motion of 51 Peg corrected from the long-term variation of the  $\gamma$ -velocity. The solid line represents the orbital motion computed from the parameters of Table 1.

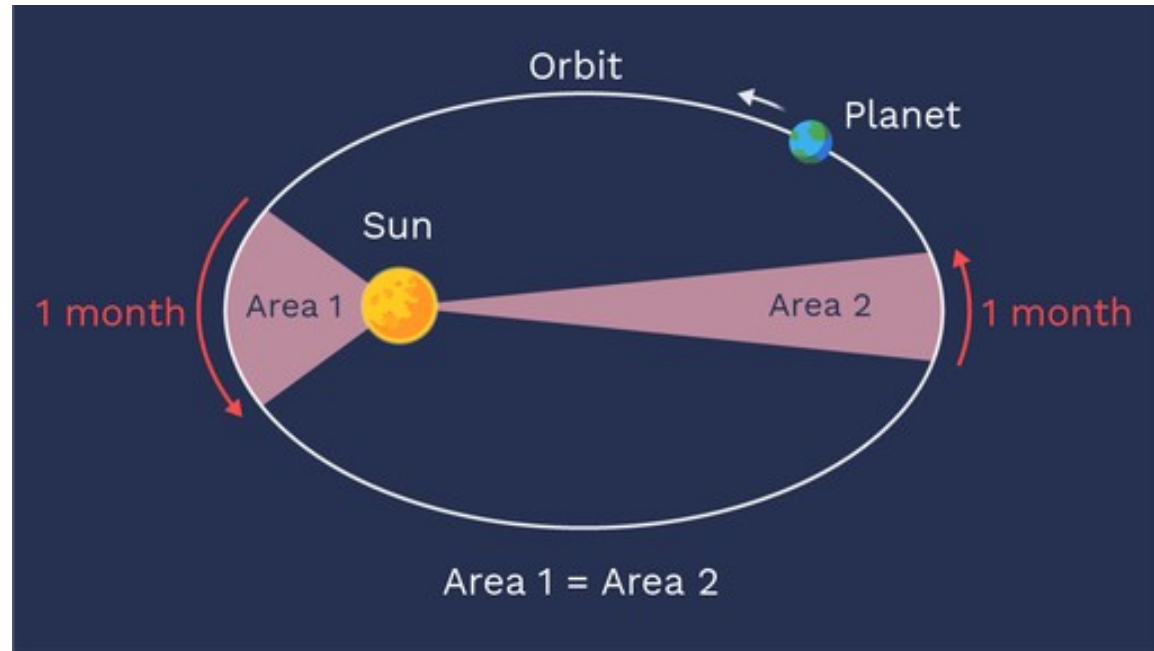
# Kepler's laws

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



# Kepler's laws

- 2<sup>nd</sup> Kepler's law



# Kepler`s laws

- 3<sup>rd</sup> 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://www.relativitycalculator.com/pdfs/RV_Derivation.pdf)
- [http://exoplanets.astro.yale.edu/workshop/EPRV/Bibliography\\_files/Radial\\_Velocity.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

- 3<sup>rd</sup> 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

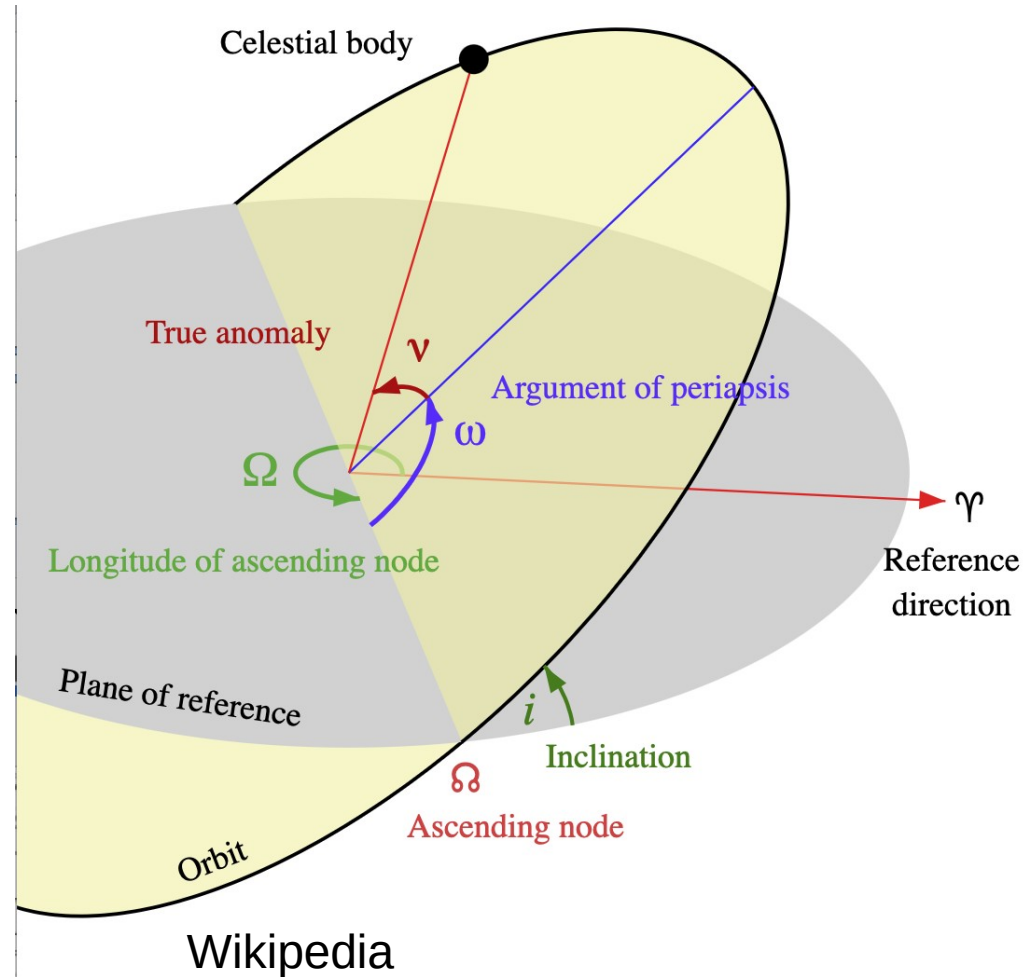
- $m_1+m_2$  is approx  $m_1$

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

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

# 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
- For details see:

$$\frac{M_p}{(M_p + M_{\star})^{2/3}} = \frac{K_{\star} \sqrt{1-e^2}}{\sin i} \left(\frac{P}{2\pi G}\right)^{1/3}$$

# Semi amplitude $K$

Table 1: Radial velocity signals for different kinds of planets orbiting a solar-mass star.

Planet	$a$ (AU)	$K_1$ ( $\text{m s}^{-1}$ )
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

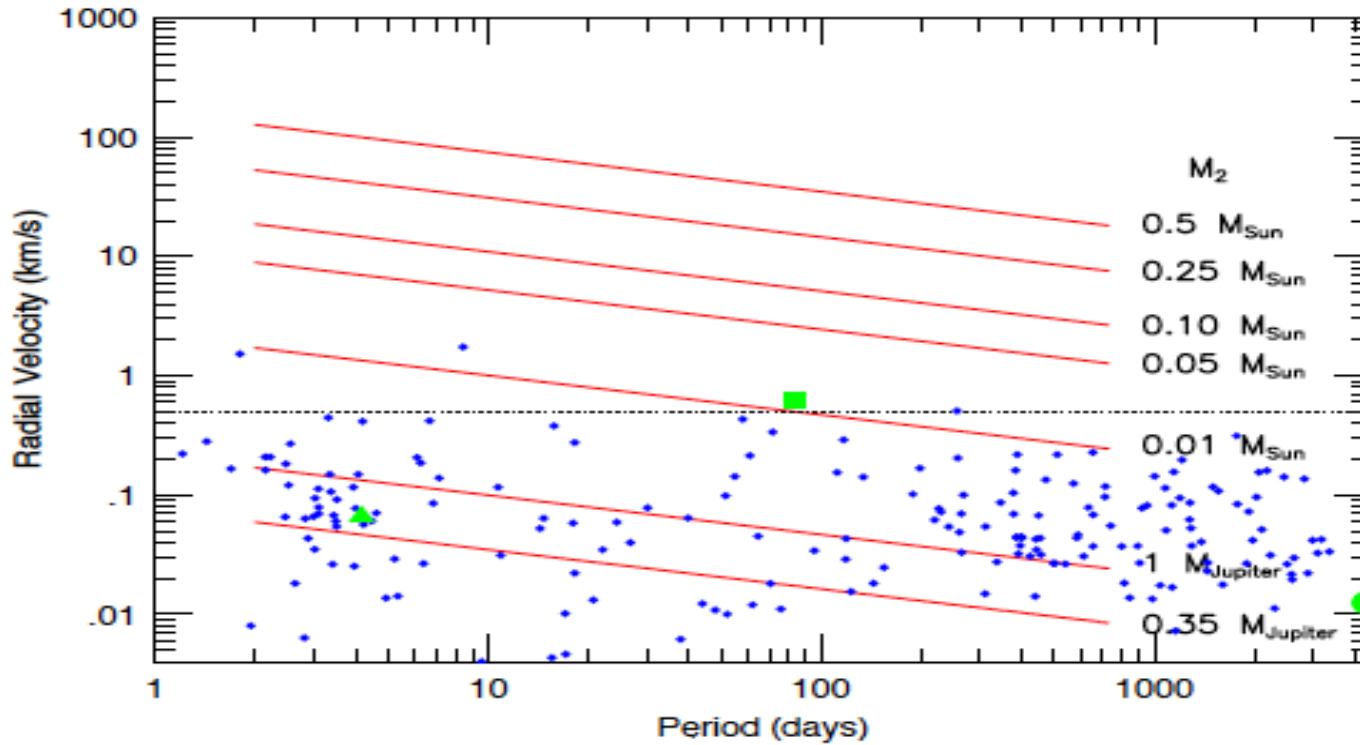


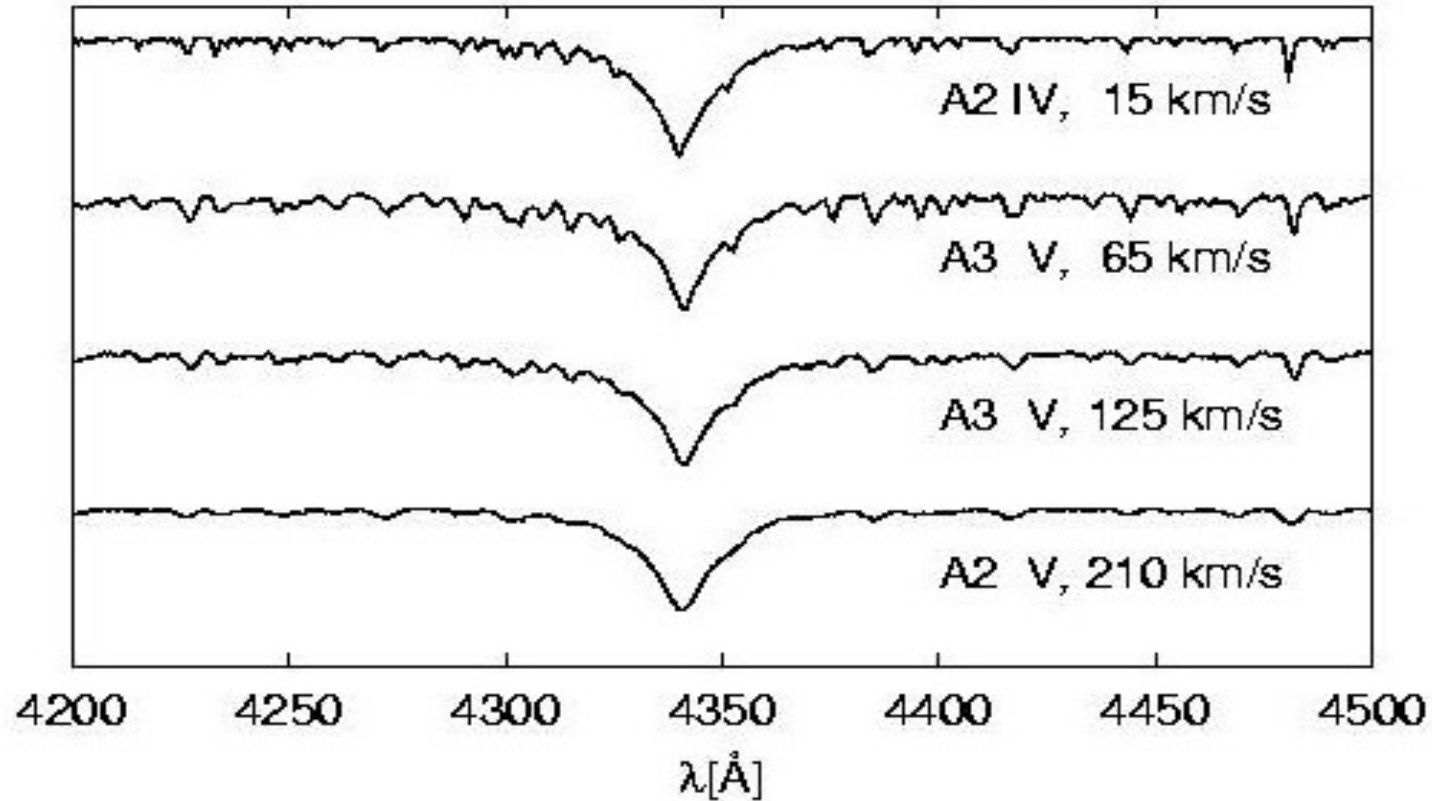
Figure from Hatzes, Cochran, Endl - : Radial velocity of a Solar type star due to a companion

# Problems

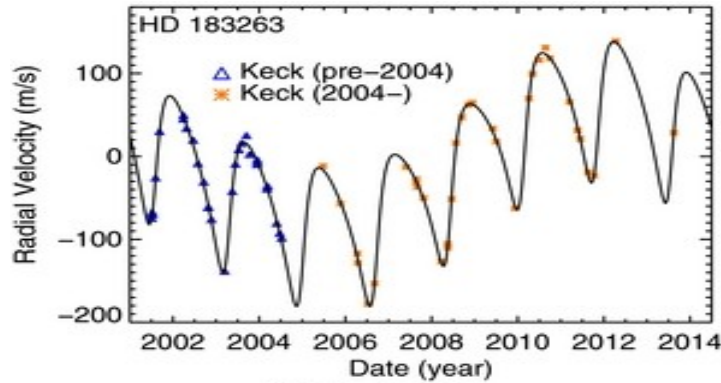
- Mass is a lower limit (unless inclination is known)
- Stellar variability – pulsations (cm/s accuracies)
- Multiplicity of stars – shape of the RV curve
  - difficult RV curves
- Fast rotation of stars – broadening of the lines
  - mimicking planet effect
- Long periodic planets are difficult to detect – due to coverage of the RV curve



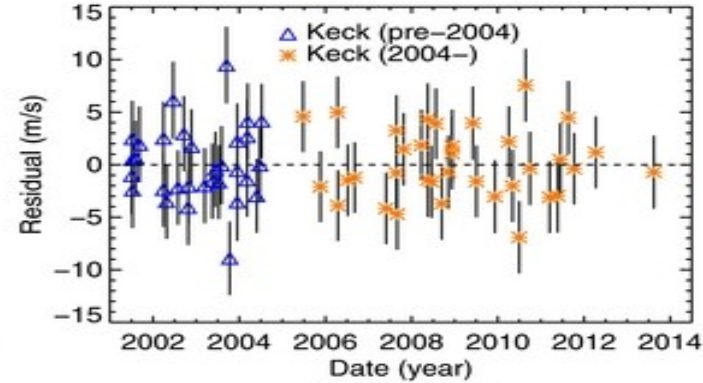
# Line broadening, rotation



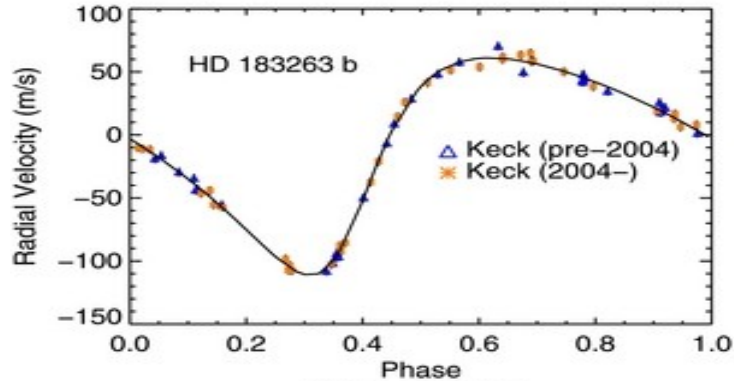
# Multiple system



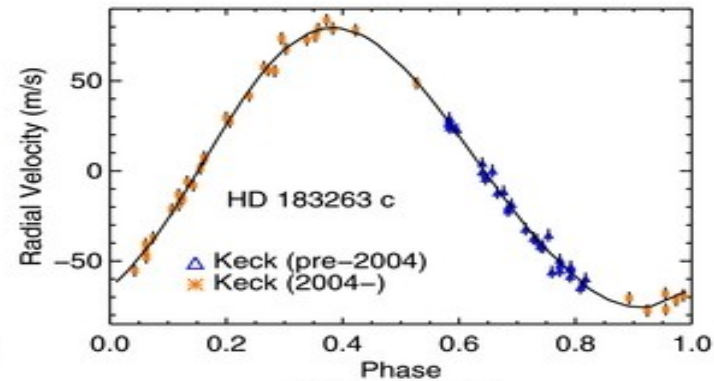
(a) HD 183263 system



(b) Residuals

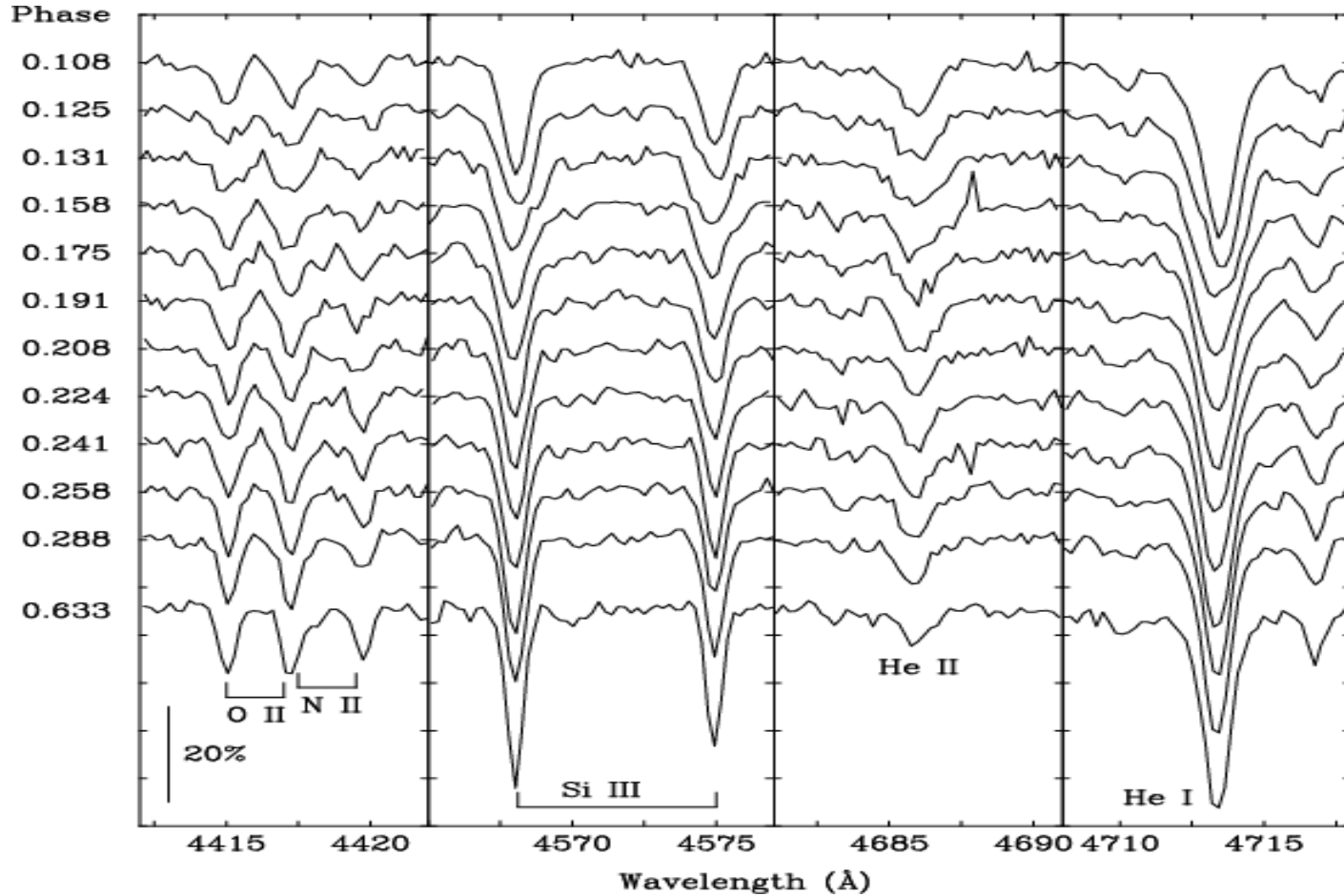


(c) HD 183263 b



(d) HD 183263 c

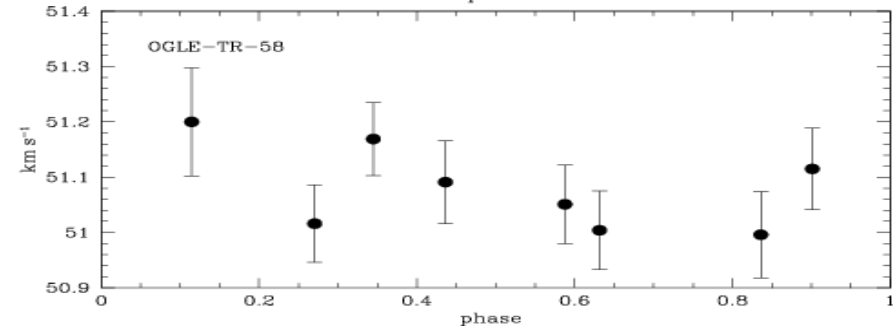
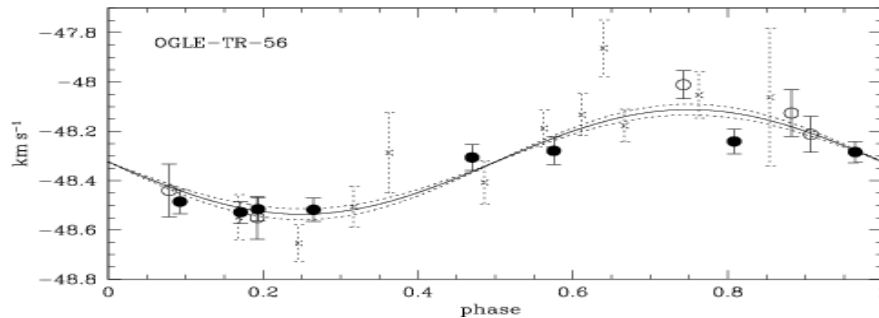
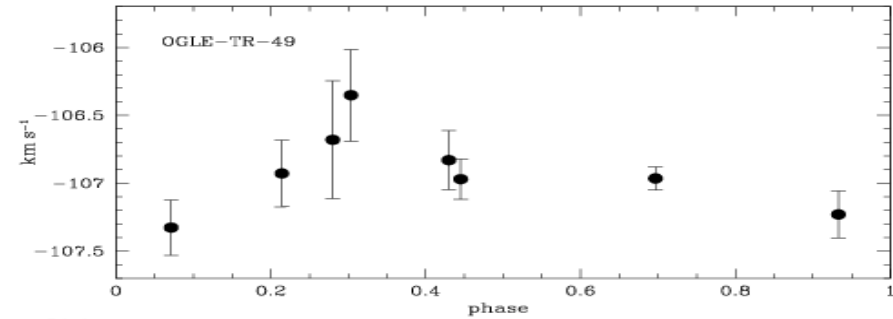
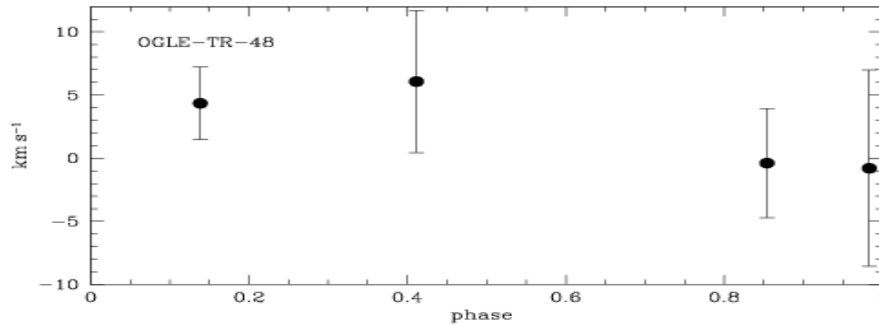
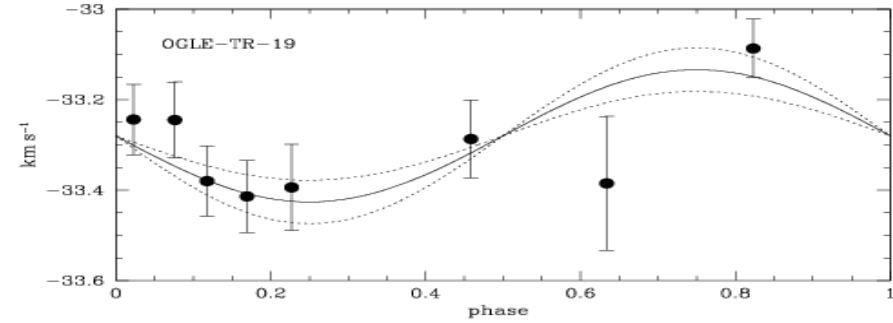
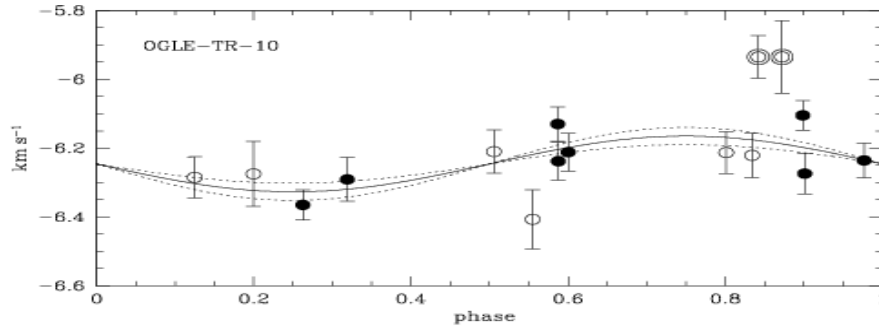
# Pulsations



Jeffery et al., A&A 376, 497-517 (2001)

<http://www.aanda.org/articles/aa/full/2001/35/aah2647/aah2647.right.html>

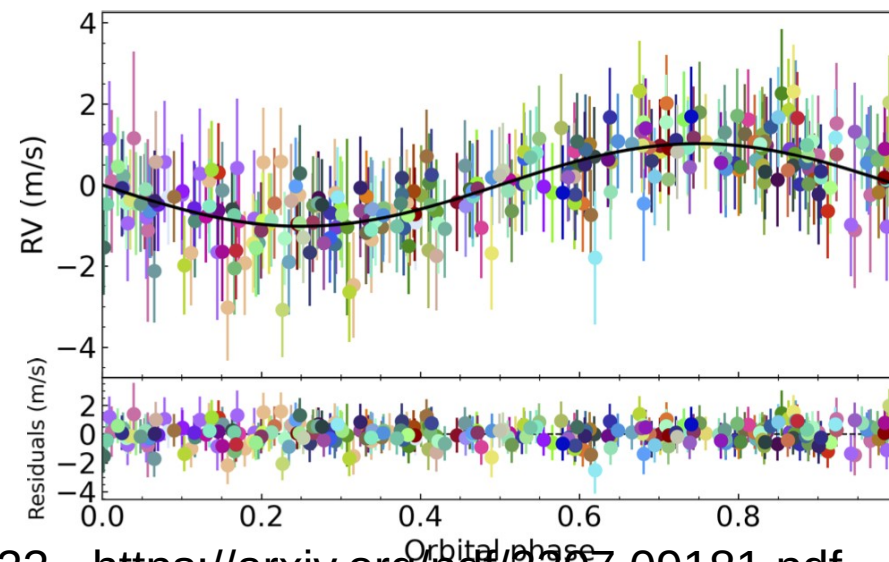
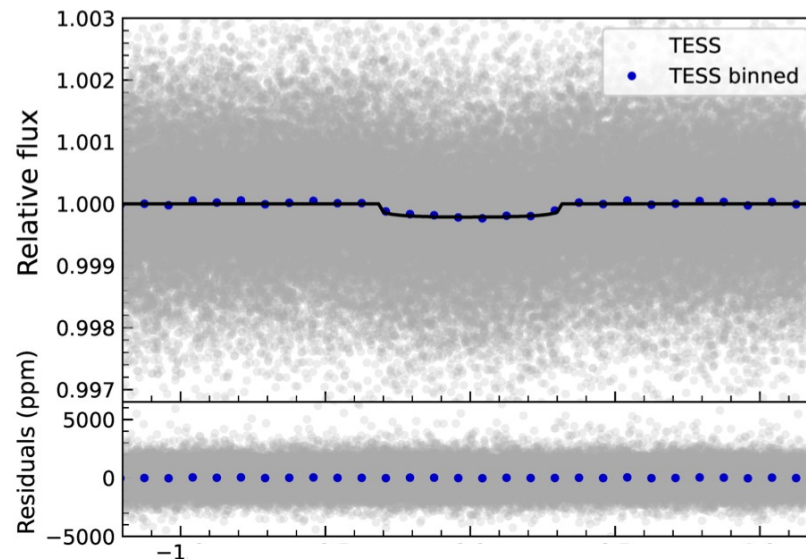
# Unresolved cases RV



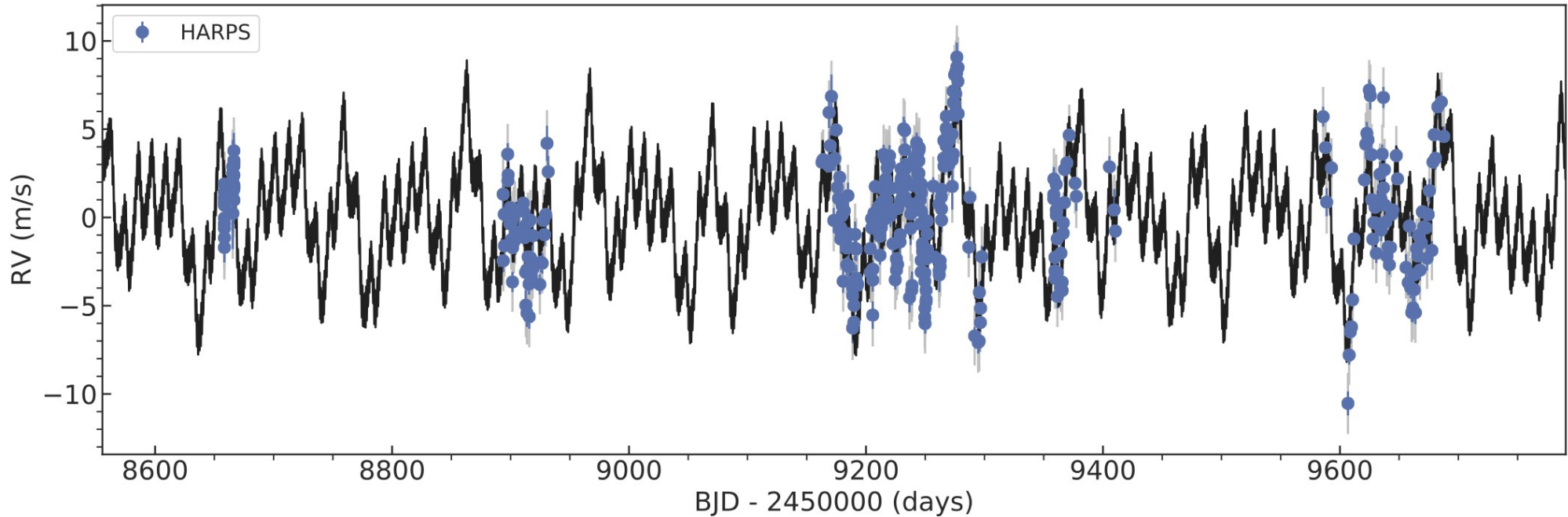
# GJ 367 b - example

Table 1. Fundamental parameters of GJ 367.

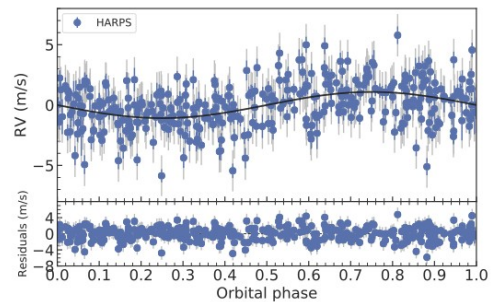
Parameter	Value	Reference
Name	GJ 367	
	TOI-731	
	TIC 34068865	
R.A. (J2000)	09:44:29.15	[1]
Decl. (J2000)	-45:46:44.46	[1]
TESS-band magnitude	$8.032 \pm 0.007$	[2]
V-band magnitude	$10.153 \pm 0.044$	[3]
Parallax (mas)	$106.173 \pm 0.014$	[1]
Distance (pc)	$9.413 \pm 0.003$	[1]
Star mass $M_*$ ( $M_\odot$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



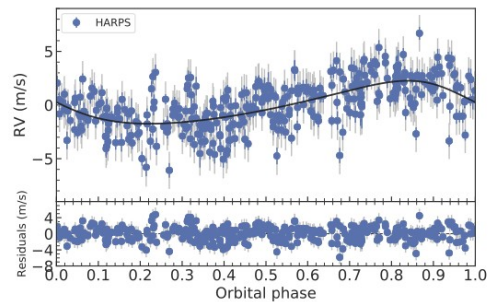
# But there are more planets .....



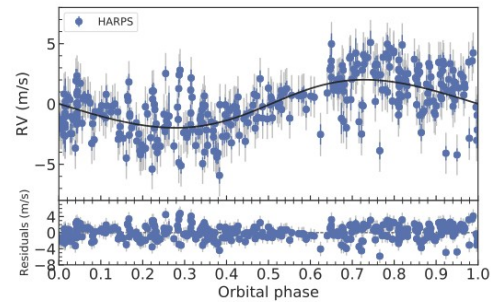
Goffo et al. 2023 - <https://arxiv.org/pdf/2307.09181.pdf>



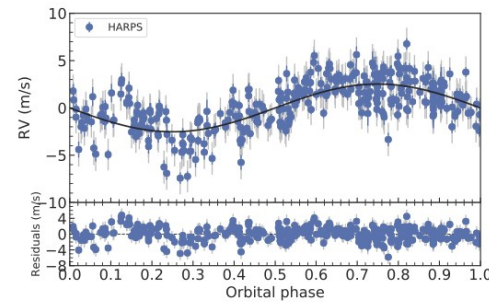
(a)



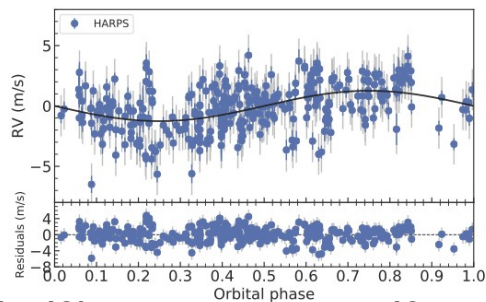
(b)



(c)



(d)



(e)



# System parameters

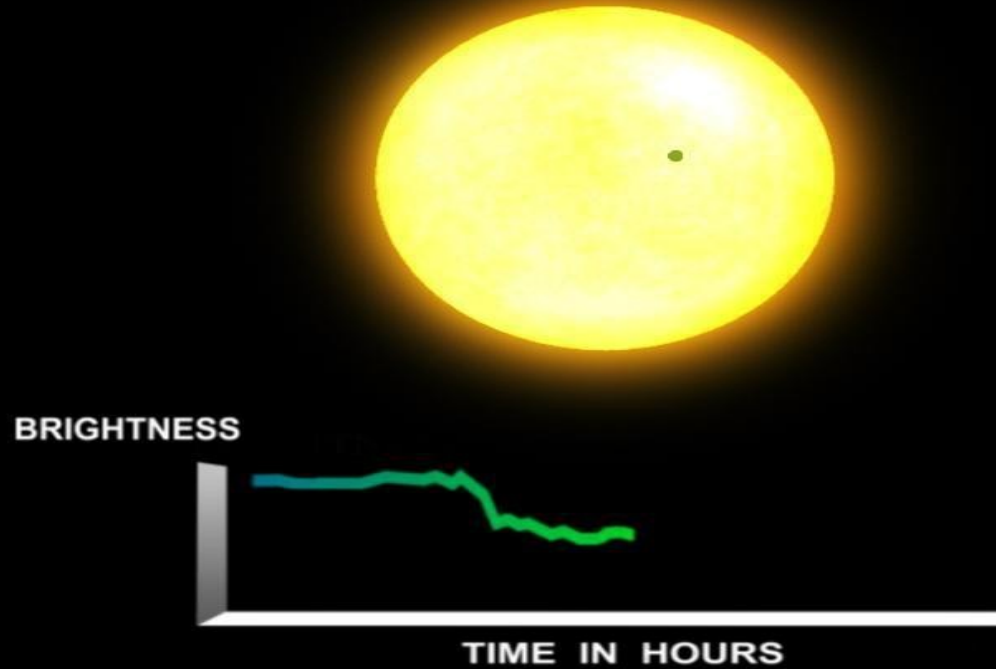
Goffo et al. 2023 -  
<https://arxiv.org/pdf/2307.09181.pdf>

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

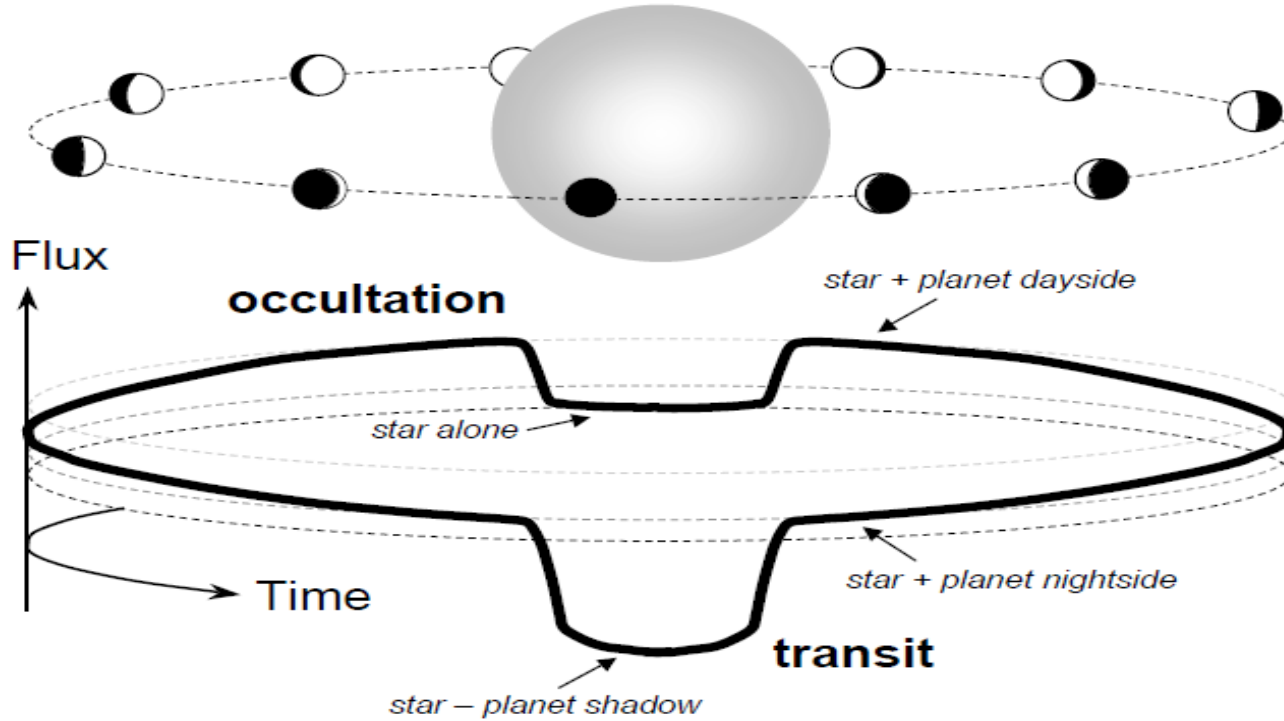
Parameter	Prior	Derived value
<b>GJ 367 b</b>		
<i>Model parameters</i>		
Orbital period $P_{\text{orb,b}}$ [days]	$\mathcal{N}[0.3219225, 0.0000002]$	$0.3219225 \pm 0.0000002$
Transit epoch $T_{0,b}$ [BJD <sub>TDB</sub> -2,450,000]	$\mathcal{N}[8544.1364, 0.00004]$	$8544.13632 \pm 0.000040$
$\sqrt{e_b} \sin \omega_{*,b}$	$\mathcal{U}[-1.0, 1.0]$	$-0.23^{+0.30}_{-0.23}$
$\sqrt{e_b} \cos \omega_{*,b}$	$\mathcal{U}[-1.0, 1.0]$	$-0.07 \pm 0.13$
Radial velocity semi-amplitude variation $K_b$ [ $\text{m s}^{-1}$ ]	$\mathcal{U}[0.00, 0.05]$	$1.10 \pm 0.14$
<i>Derived parameters</i>		
Planet mass $M_b$ [ $M_{\oplus}$ ] <sup>(*)</sup>	–	$0.699 \pm 0.083$
Orbit eccentricity $e_b$	–	$0.10^{+0.14}_{-0.07}$
Argument of periastron of stellar orbit $\omega_{*,b}$ [deg]	–	$251^{+23}_{-102}$
<b>GJ 367 c</b>		
<i>Model parameters</i>		
Orbital period $P_{\text{orb,c}}$ [days]	$\mathcal{U}[11.4858, 11.5858]$	$11.543 \pm 0.005$
Time of inferior conjunction $T_{0,c}$ [BJD <sub>TDB</sub> -2,450,000]	$\mathcal{U}[9152.6591, 9154.6591]$	$9153.46 \pm 0.21$
$\sqrt{e_c} \sin \omega_{*,c}$	$\mathcal{U}[-1, 1]$	$0.38^{+0.10}_{-0.13}$
$\sqrt{e_c} \cos \omega_{*,c}$	$\mathcal{U}[-1, 1]$	$0.27^{+0.11}_{-0.14}$
Radial velocity semi-amplitude variation $K_c$ [ $\text{m s}^{-1}$ ]	$\mathcal{U}[0.00, 0.05]$	$2.01 \pm 0.15$
<i>Derived parameters</i>		
Planet minimum mass $M_c \sin i_c$ [ $M_{\oplus}$ ]	–	$4.08 \pm 0.30$
Orbit eccentricity $e_c$	–	$0.23 \pm 0.07$
Argument of periastron of stellar orbit $\omega_{*,c}$ [deg]	–	$55 \pm 18$
<b>GJ 367 d</b>		
<i>Model parameters</i>		
Orbital period $P_{\text{orb,d}}$ [days]	$\mathcal{U}[34.0016, 34.6016]$	$34.39 \pm 0.06$
Time of inferior conjunction $T_{0,d}$ [BJD <sub>TDB</sub> -2,450,000]	$\mathcal{U}[9179.2710, 9183.2710]$	$9180.90^{+0.70}_{-0.81}$
$\sqrt{e_d} \cos \omega_{*,d}$	$\mathcal{U}[-1, 1]$	$-0.10^{+0.20}_{-0.18}$
$\sqrt{e_d} \sin \omega_{*,d}$	$\mathcal{U}[-1, 1]$	$0.16^{+0.16}_{-0.20}$
Radial velocity semi-amplitude variation $K_d$ [ $\text{m s}^{-1}$ ]	$\mathcal{U}[0.00, 0.05]$	$1.98 \pm 0.15$
<i>Derived parameters</i>		
Planet minimum mass $M_d \sin i_d$ [ $M_{\oplus}$ ]	–	$5.93 \pm 0.45$
Orbit eccentricity $e_d$	–	$0.08^{+0.07}_{-0.05}$
Argument of periastron of stellar orbit $\omega_{*,d}$ [deg]	–	$277^{+58}_{-242}$
<b>Stellar activity induced RV signal</b>		
Rotation period $P_{*,\text{Rot}}$ [days]	$\mathcal{U}[50.0903, 52.0903]$	$51.30 \pm 0.13$
Rotation RV semi-amplitude $K_{*,\text{Rot}}$ [ $\text{m s}^{-1}$ ]	$\mathcal{U}[0.00, 0.05]$	$2.52 \pm 0.13$
Active region evolution period $P_{*,\text{Evol}}$ [days]	$\mathcal{U}[103.1797, 163.1797]$	$138 \pm 2$
Active region evolution RV semi-amplitude $K_{*,\text{Evol}}$ [ $\text{m s}^{-1}$ ]	$\mathcal{U}[0.00, 0.05]$	$1.25 \pm 0.14$
<b>Additional model parameters</b>		
Systemic velocity $\gamma_{\text{HARPS}}$ [ $\text{m s}^{-1}$ ]	$\mathcal{U}[47.806, 48.025]$	$47.91674 \pm 0.00013$
Radial velocity jitter term $\sigma_{\text{RV,HARPS}}$ [ $\text{m s}^{-1}$ ]	$\mathcal{J}[0, 100]$	$1.59 \pm 0.07$



# The transit method

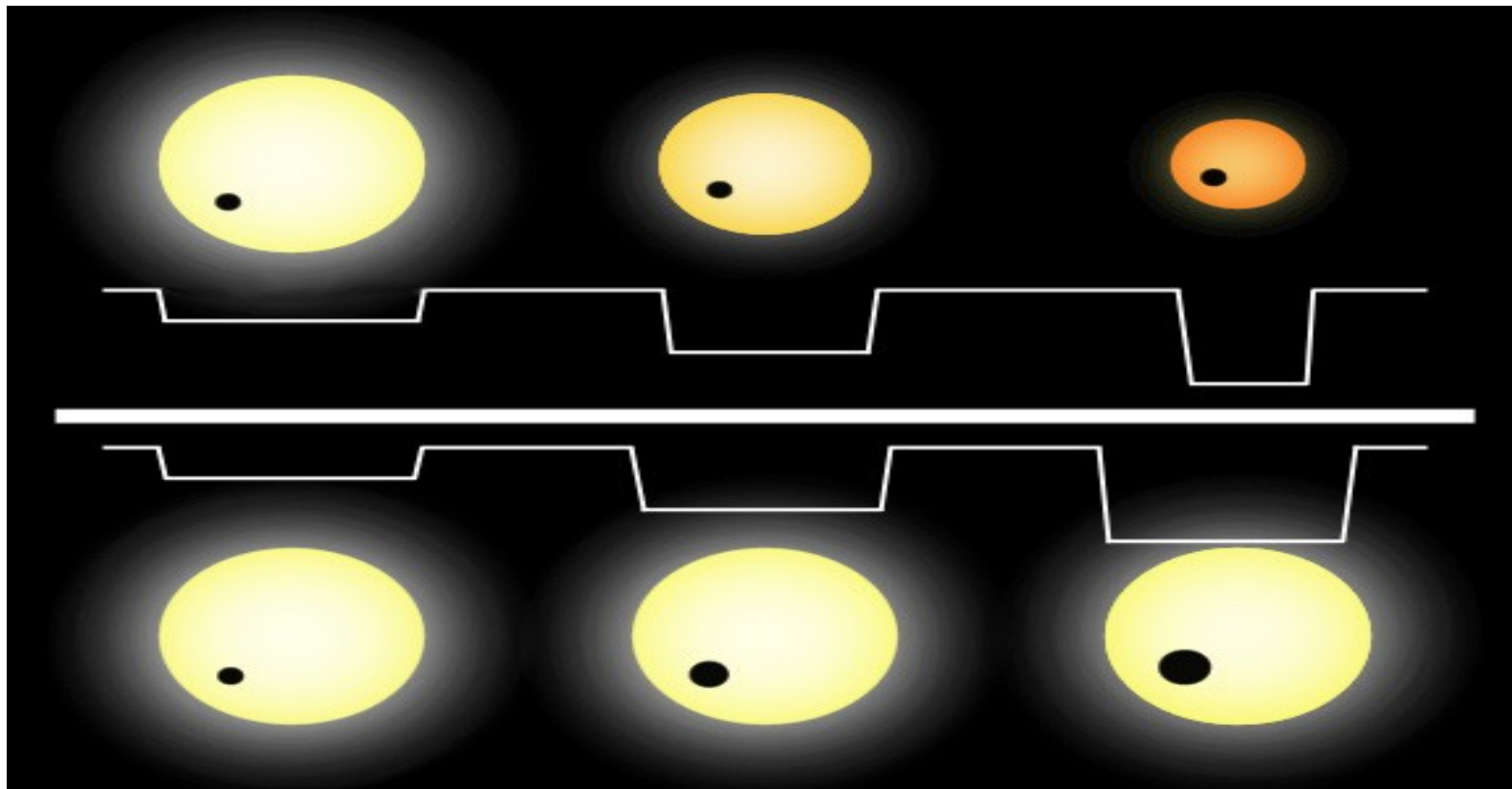


# Eclipses/transits



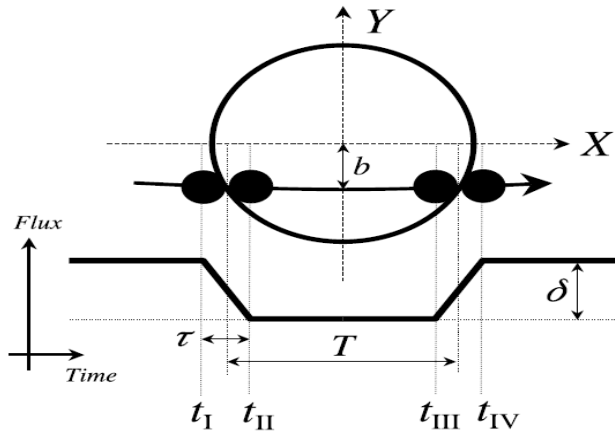
From Winn, 2010, <http://arxiv.org/pdf/1001.2010v5.pdf>

# The transit method



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

# Obtainable parameters



- 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:

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

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

# Limb darkening

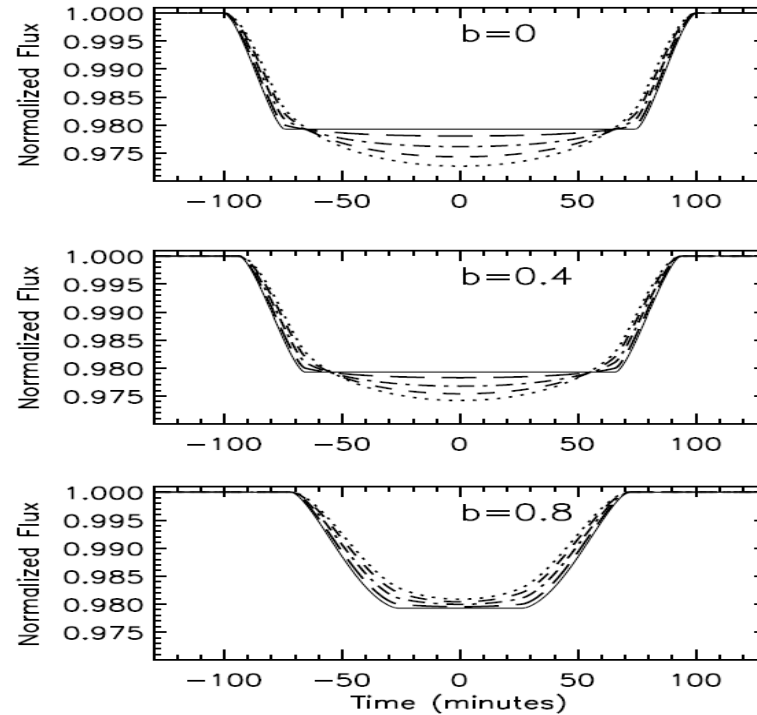


Fig. 3.— Solar limb darkening dependence of a planet transit light curve. In these theoretical light curves the planet has  $R_p = 1.4R_J$  and  $a = 0.05$  AU and the star has  $R_* = R_\odot$  and  $M_* = M_\odot$ . The solid curve shows a transit light curve with limb darkening neglected. The other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

# Problems

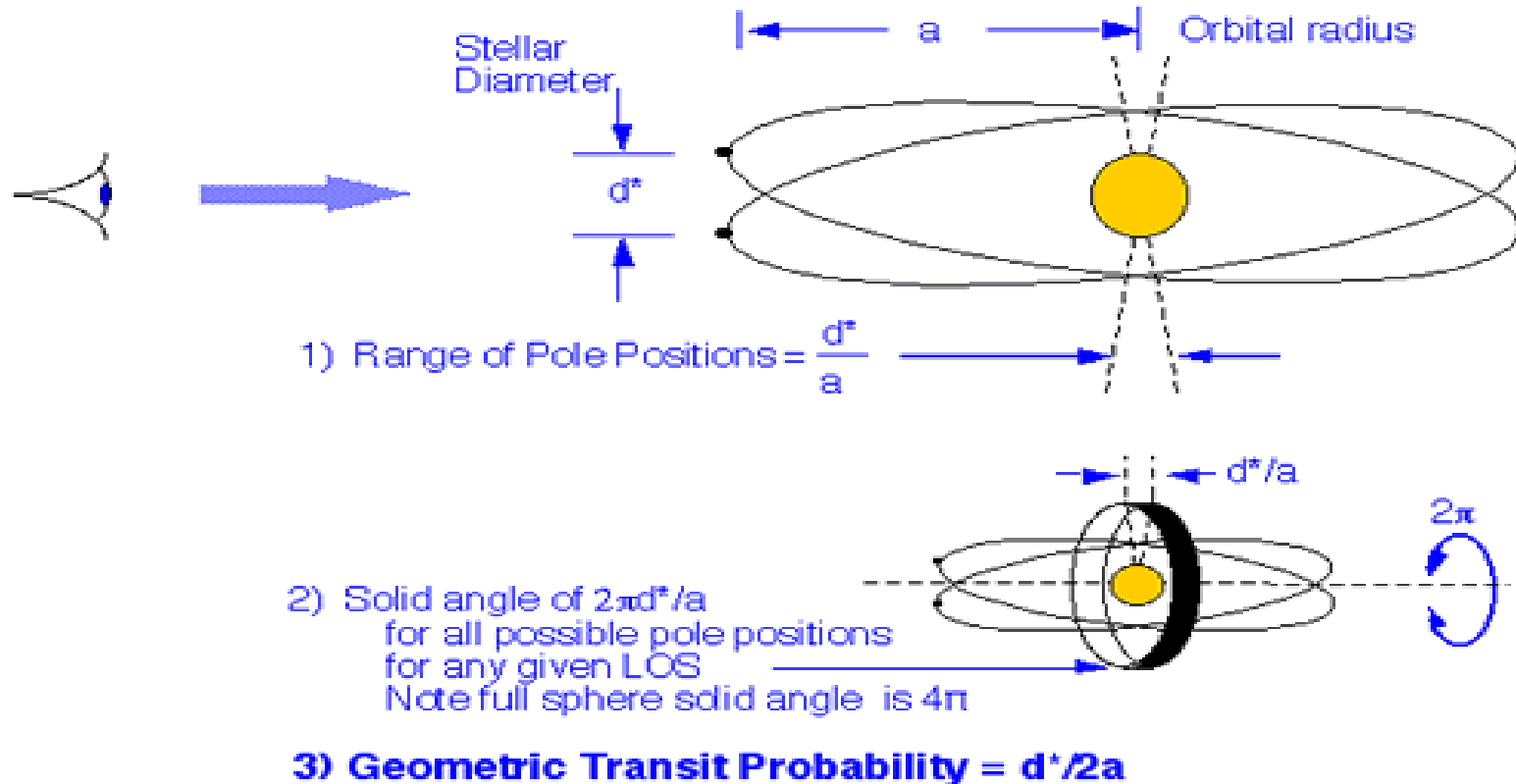
- Systematic noise hiding the transit
- High photometric accuracy needed in mmag range
- Transits due to background binaries
- Star parameters needed to fully characterize the system – SPECTROSCOPY NEEDED

# 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

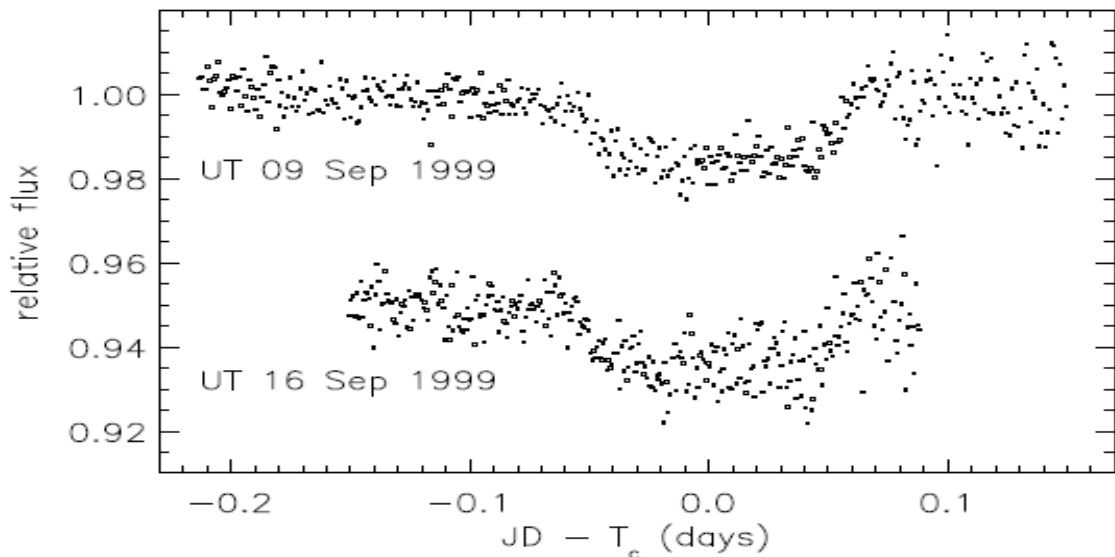




## Transit Properties of Solar System Objects

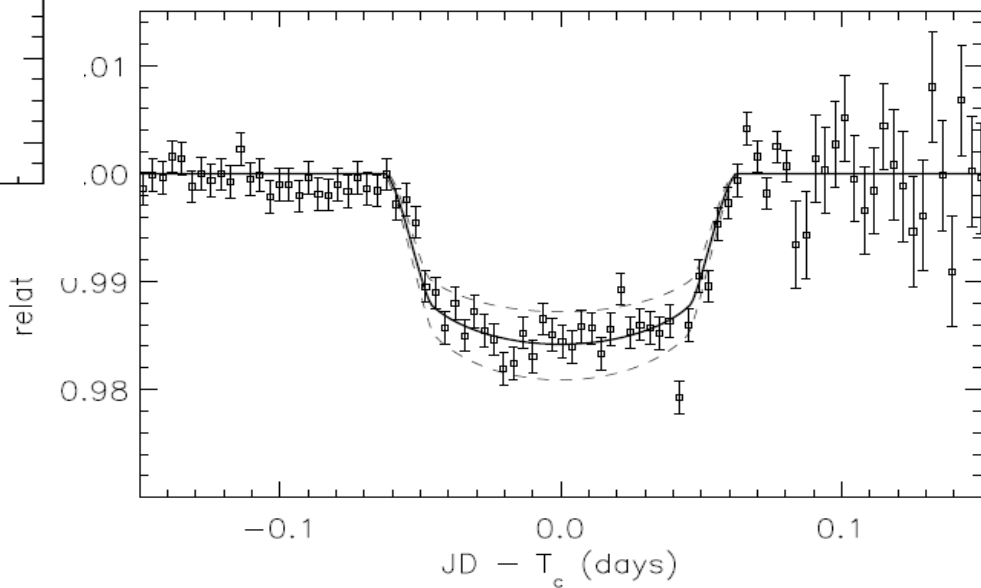
Planet	Orbital Period P (years)	Semi-Major Axis a (A.U.)	Transit Duration (hours)	Transit Depth (%)	Geometric Probability (%)	Inclination Invariant Plane (deg)
Mercury	0.241	0.39	8.1	0.0012	1.19	6.33
Venus	0.615	0.72	11.0	0.0076	0.65	2.16
Earth	1.000	1.00	13.0	0.0084	0.47	1.65
Mars	1.880	1.52	16.0	0.0024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

# First transiting exoplanet



HD209458b

Charbonneau et al. 2000



# HD209458b

- Parameters

- Mass : 0.69M<sub>J</sub>

- Radius : 1.38 R<sub>J</sub>

- O. period : 3.5 days

- Star: G0V

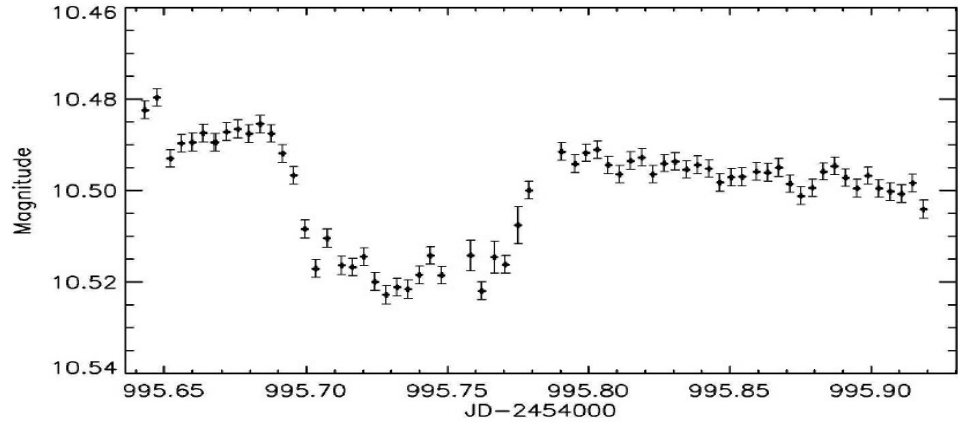
- brightness: 7 mag (V)

- T<sub>eff</sub>: 6092 K

- Metallicity: 0.02

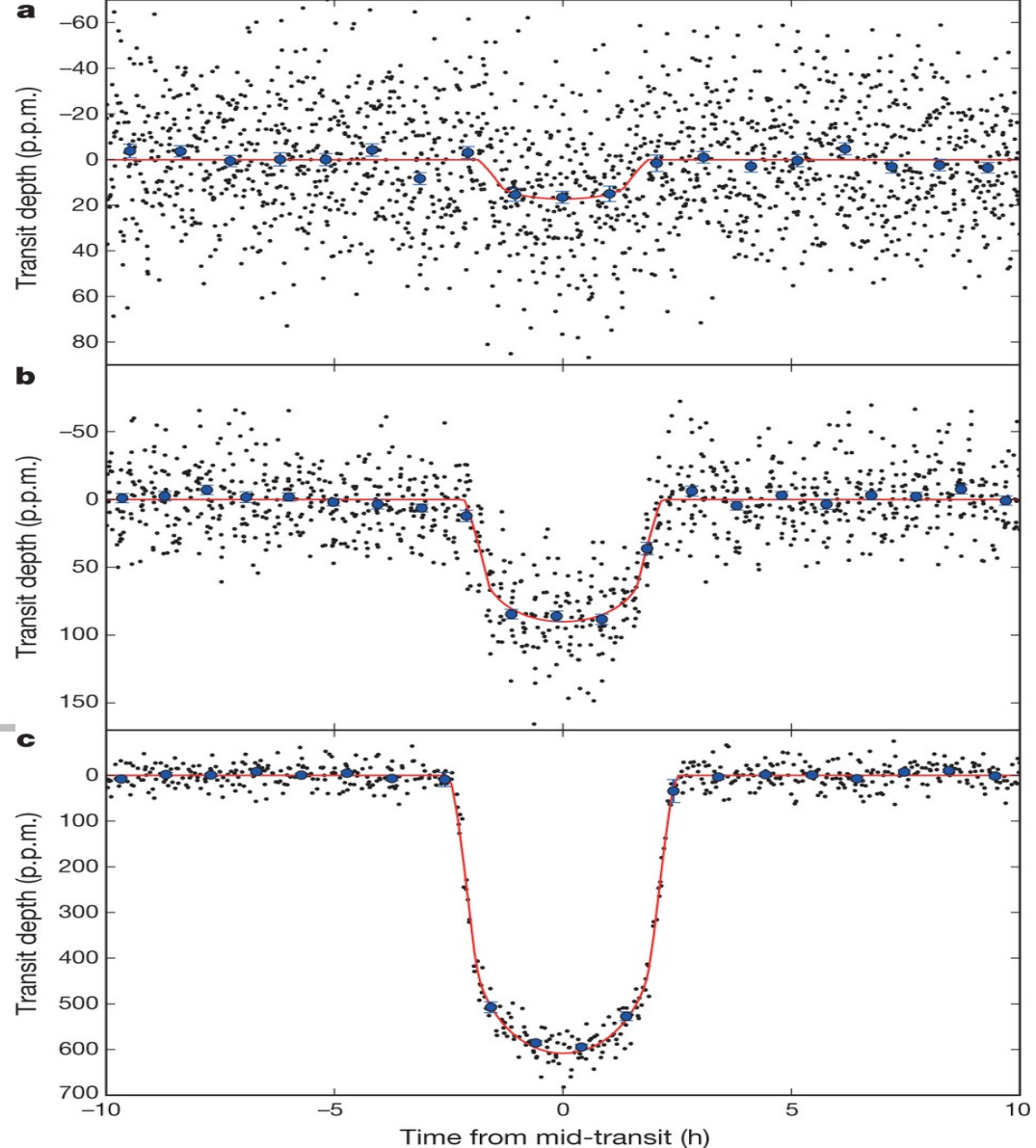
# Nice light curves

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

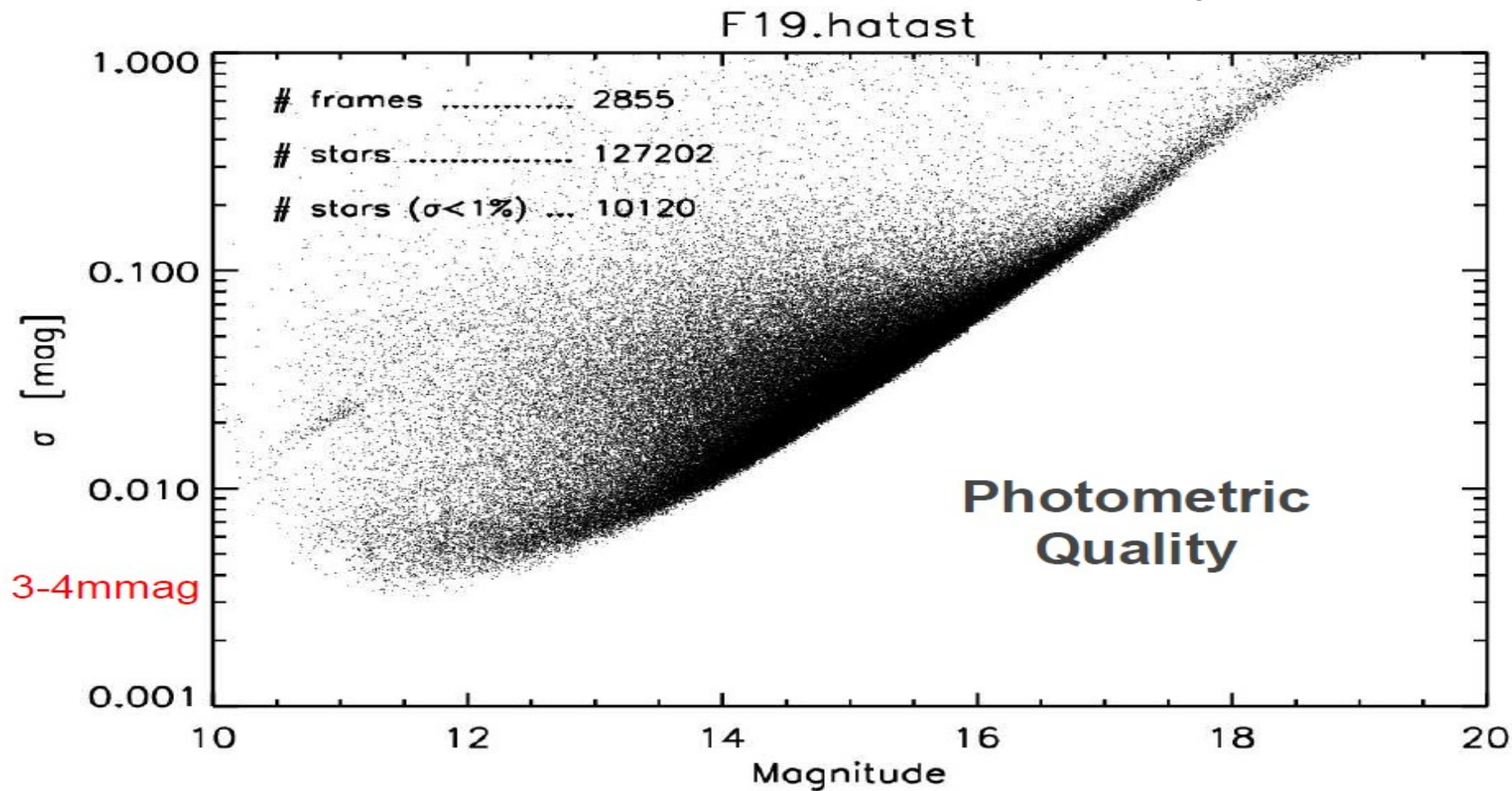


## Specifications:

Telescope	:	BRC - 250
Aperture	:	25 cm
Focal ratio	:	$f/5.0$
Instrument	:	FLI IMG-1680 CCD
Size	:	4096 x 4096 pixels
Pixel size	:	9 $\mu\text{m}$
Pixel scale	:	1.5 arcsec/pixel
Field of view	:	1.7° x 1.7°

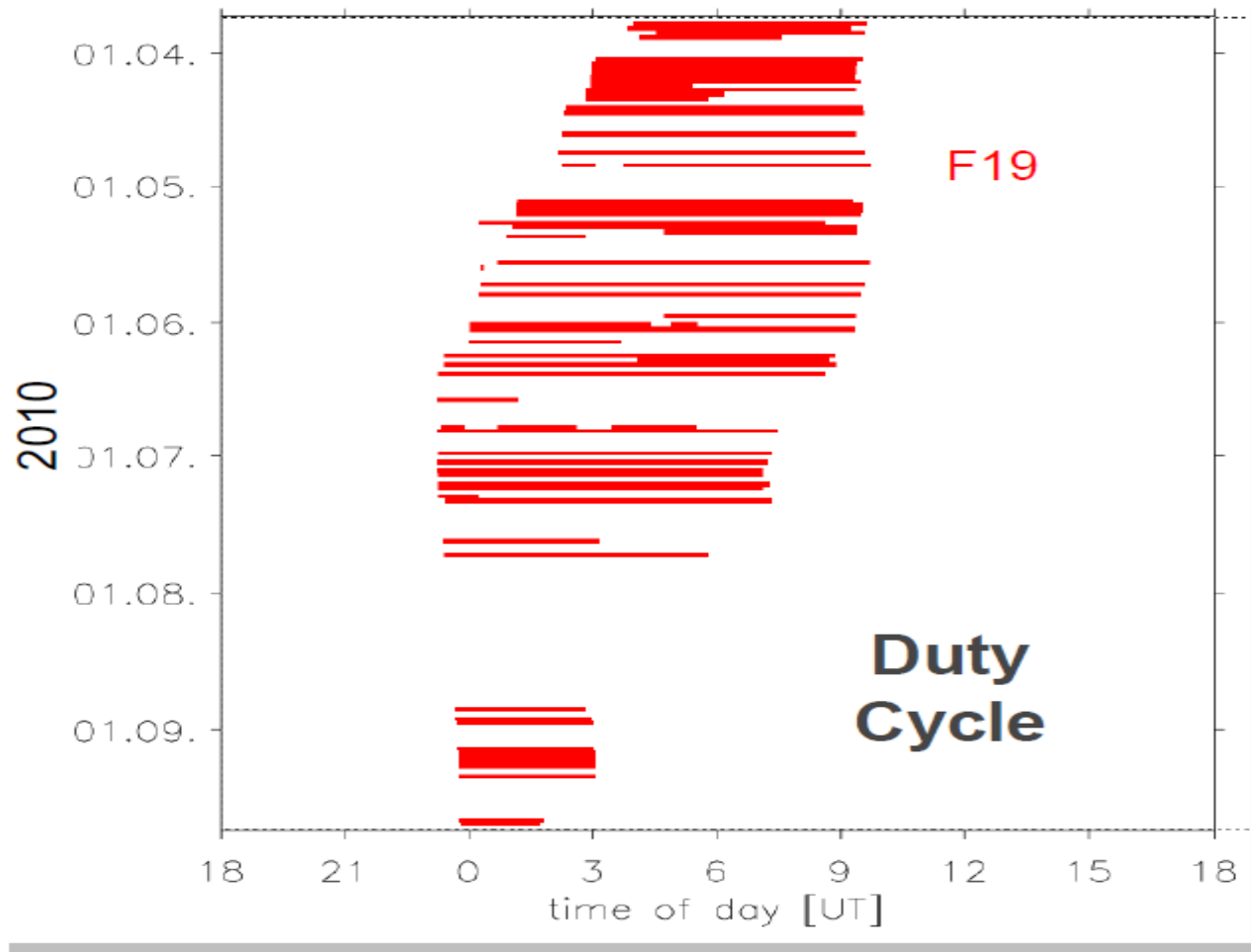


# Photometric quality





# 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

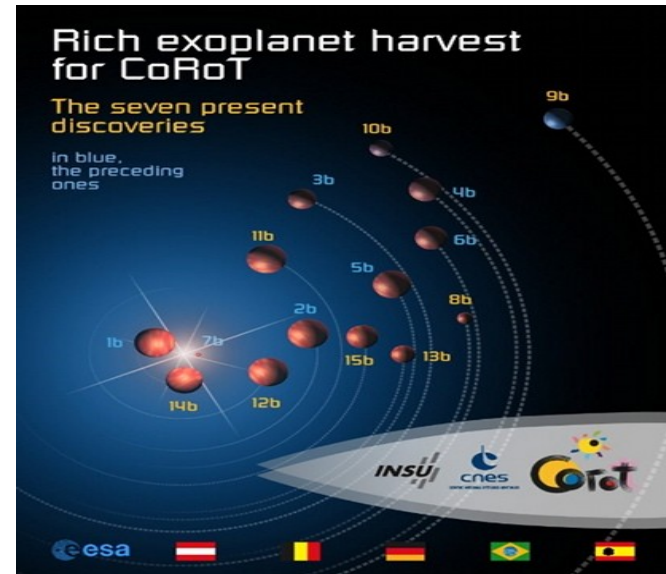
Convection, Rotation and planetary Transits

Launched 2006 – mission end 2013

28cm mirror, 4 detectors of 1,5x1,5deg

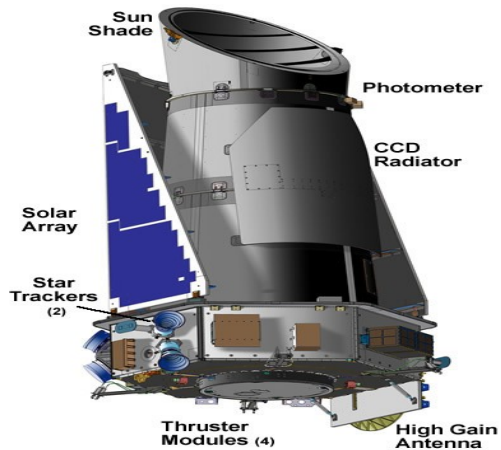


ESA webpages



# 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 about 5000 planets

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

# Microlensing

The lens/Earth configuration does not repeat (usually)

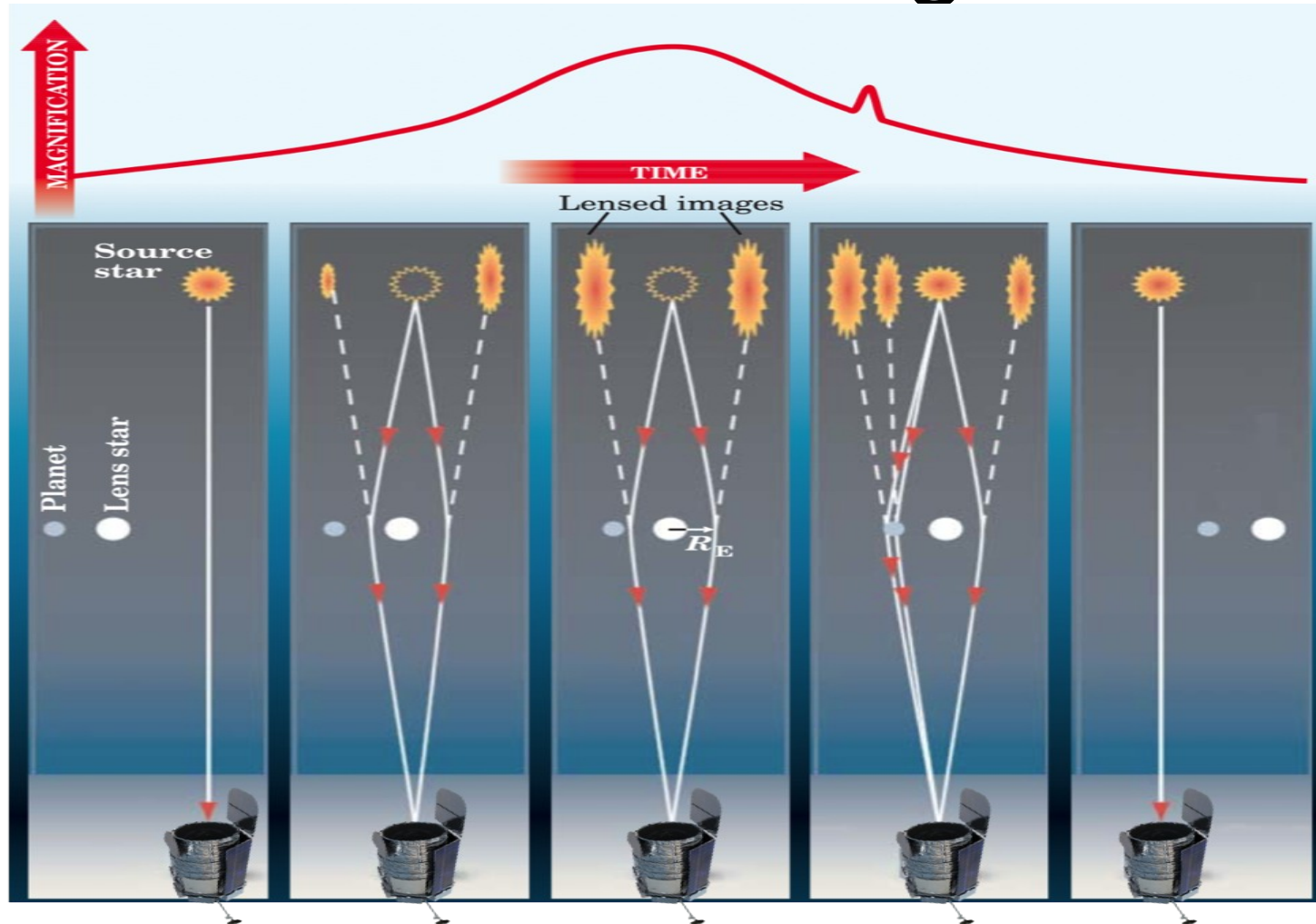
It is difficult to confirm such planets

OGLE – Optical gravitational lensing experiment

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



# Micro lensing



# 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  $\mu\text{as}$  and less
- For some planets (Jupiters), detectable by Gaia (Gaia has 2 exoplanets detected 2024)

# Astrometry

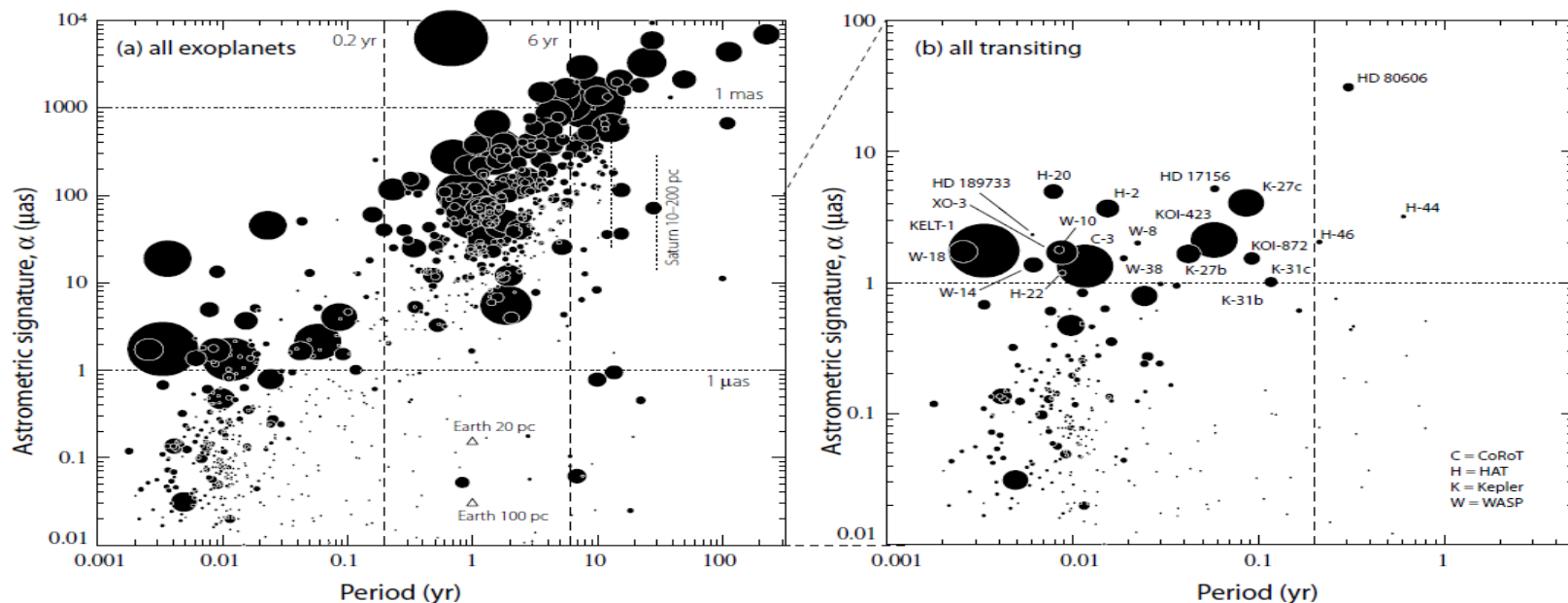


Fig. 1.— Astrometric signature versus period calculated for the objects listed in `exoplanet.eu` at 2014 September 1 for all 1821 confirmed planets (left), and for the subset of 1129 transiting planets with appropriately known data (right). Note the different scales in abscissa and ordinate. Circle sizes 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,  $\alpha$  would increase by a factor 2, but their astrometric motion would remain undetectable by Gaia.

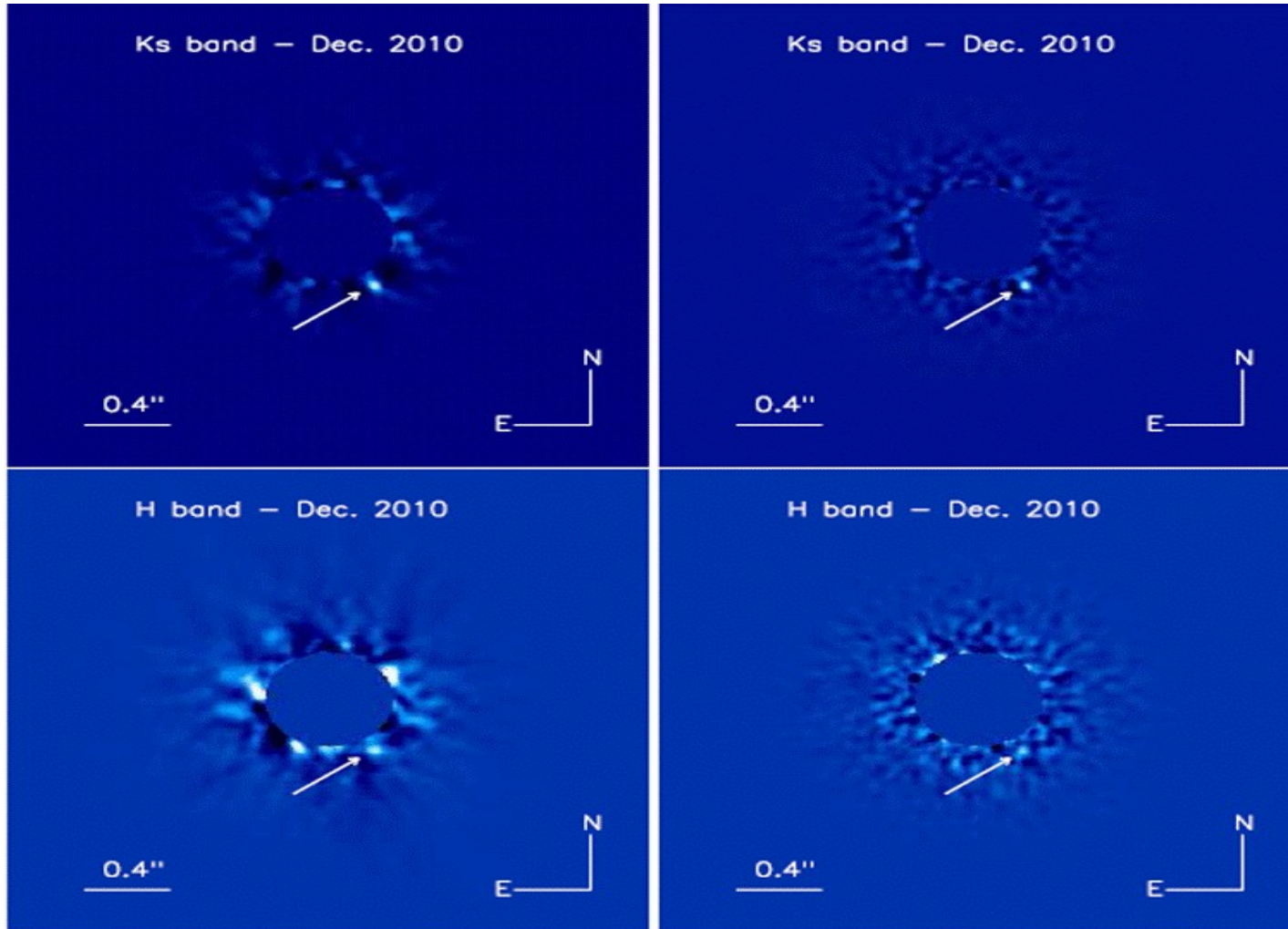


# Direct imaging

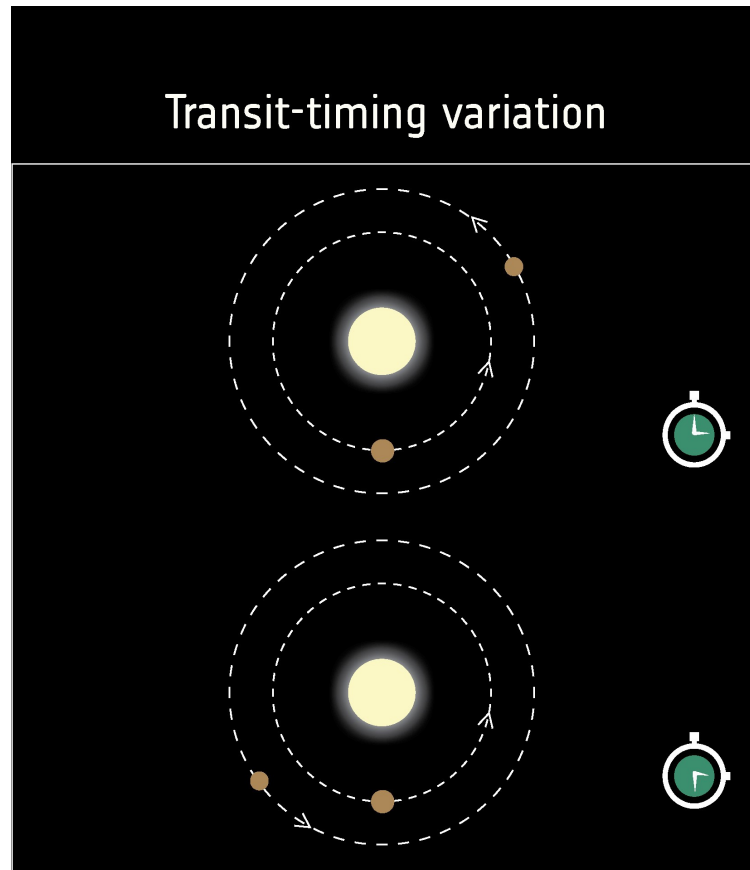
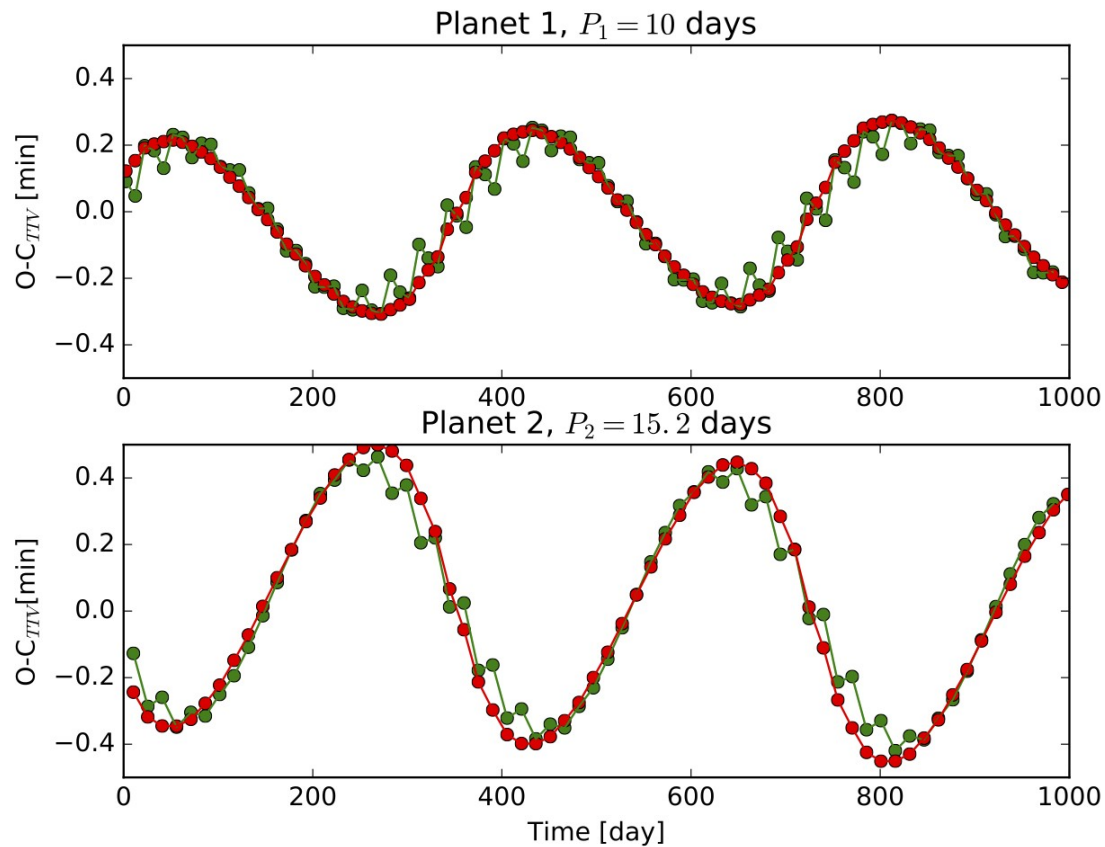
- Difficult due to the contrast of star planet
- Difficult because of Earth atmosphere
- Use of adaptive optics is a must
- Only planets in large distance from the host



# And here is a detail

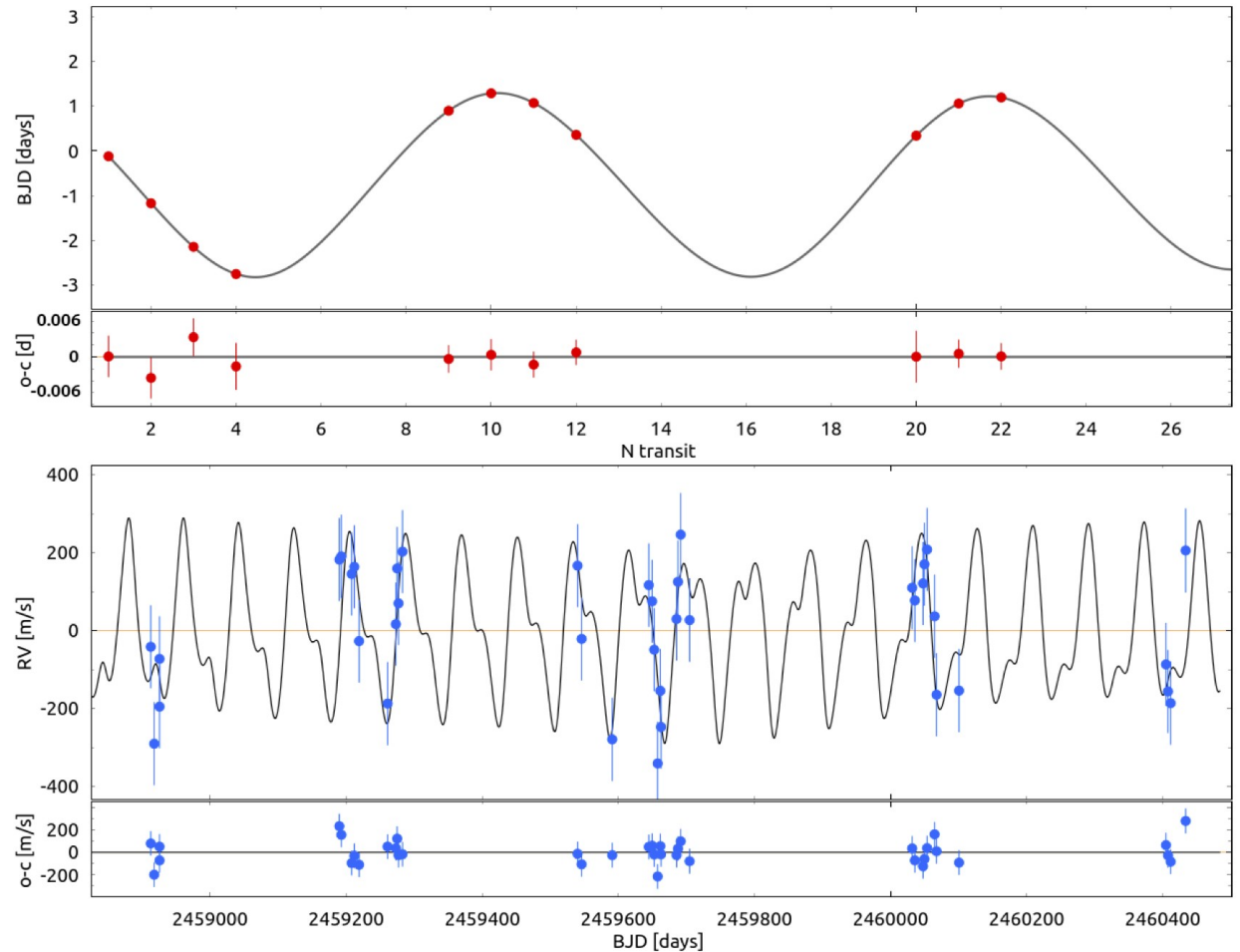


# Transit timing variations - TTV



# Transit timing variations - TTV

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

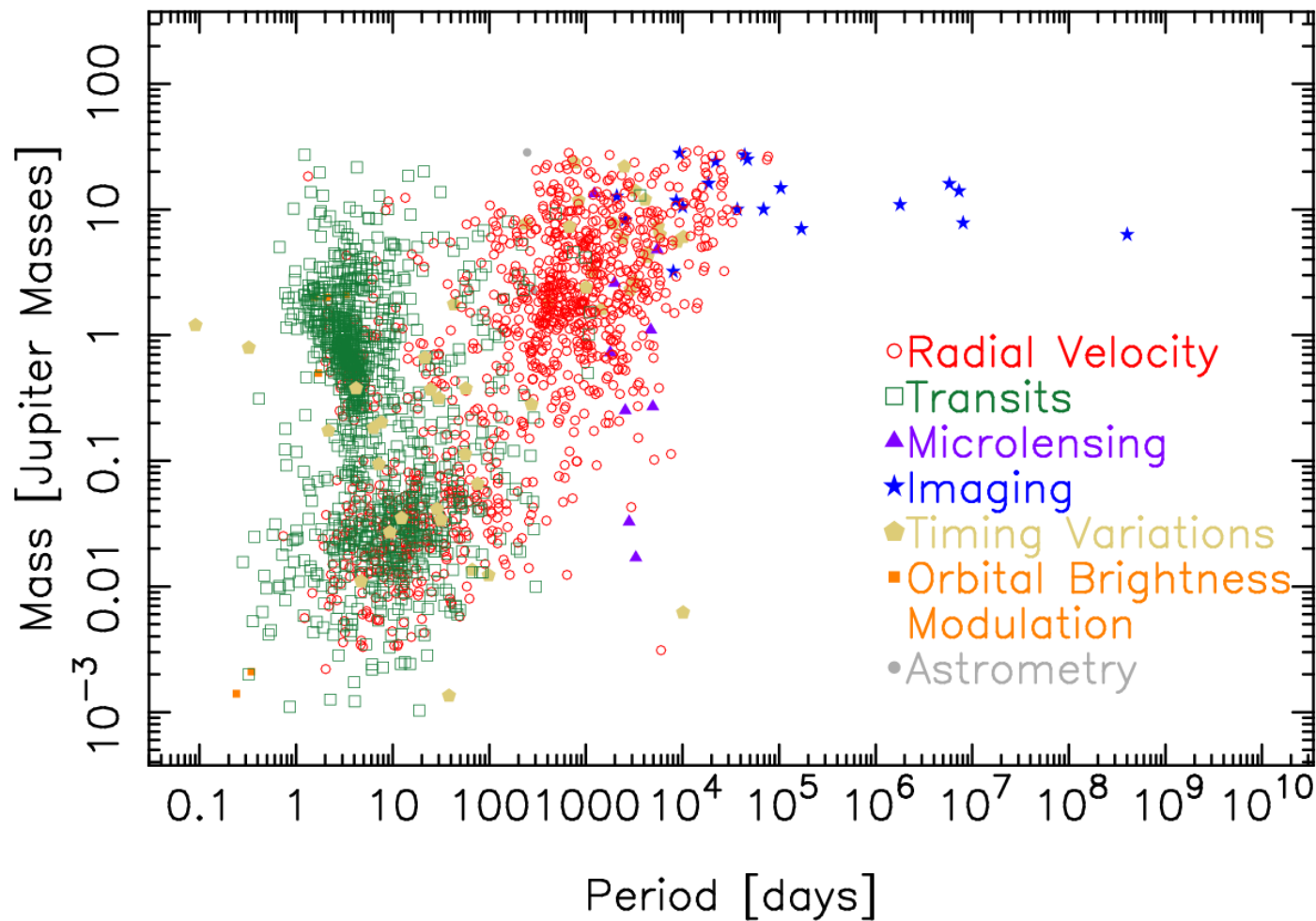


Some statistics  
Completeness of surveys

# Mass – Period Distribution

12 Oct 2023

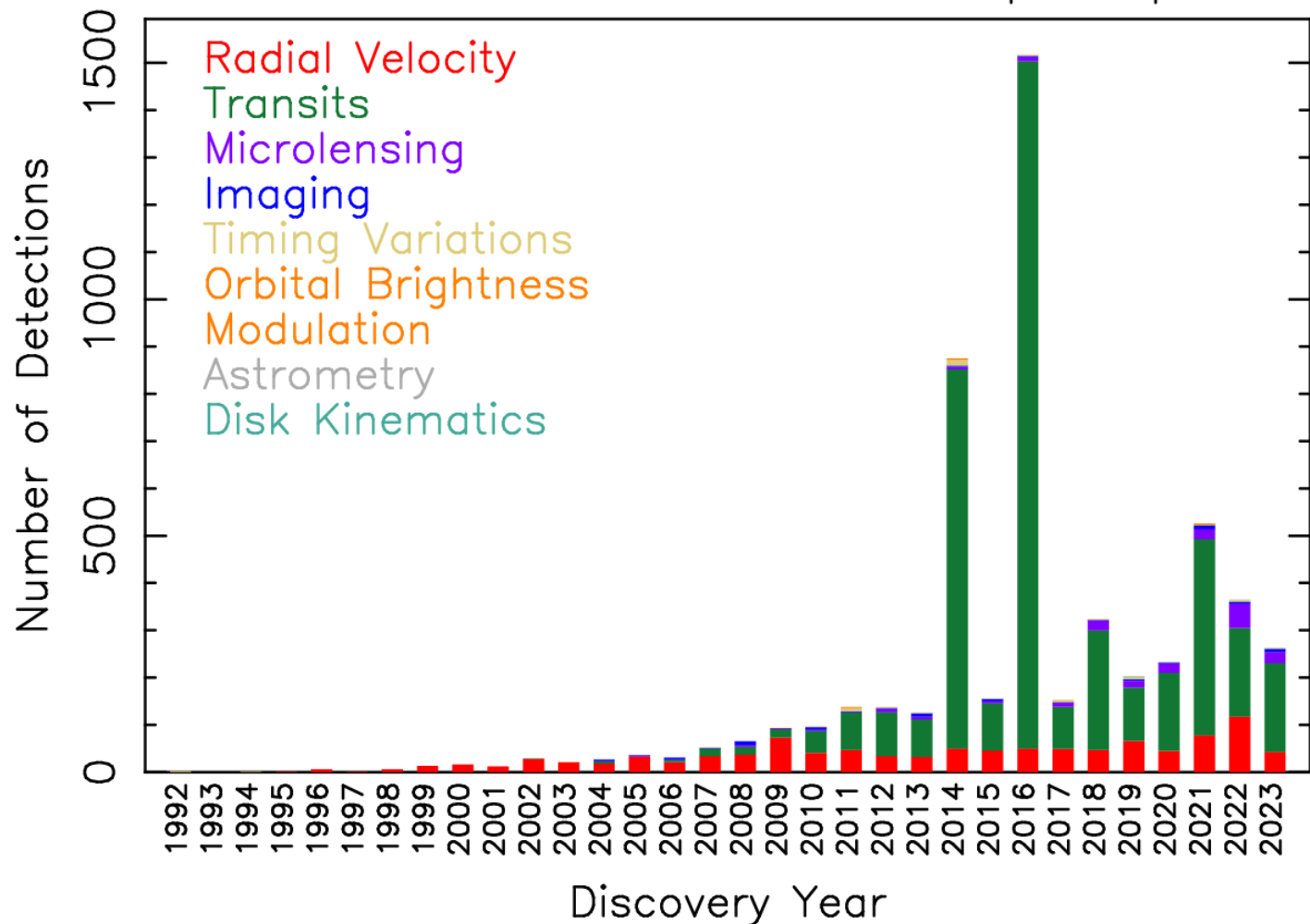
exoplanetarchive.ipac.caltech.edu



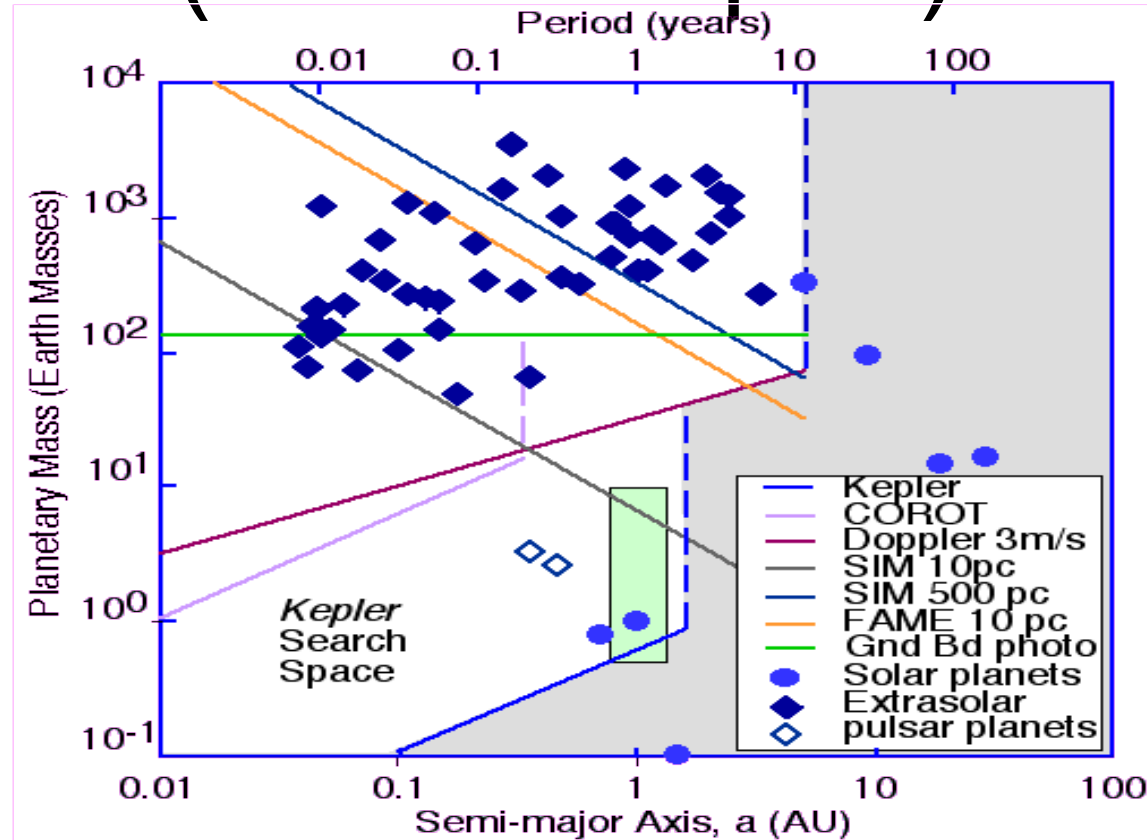
# Detections Per Year

12 Oct 2023

exoplanetarchive.ipac.caltech.edu

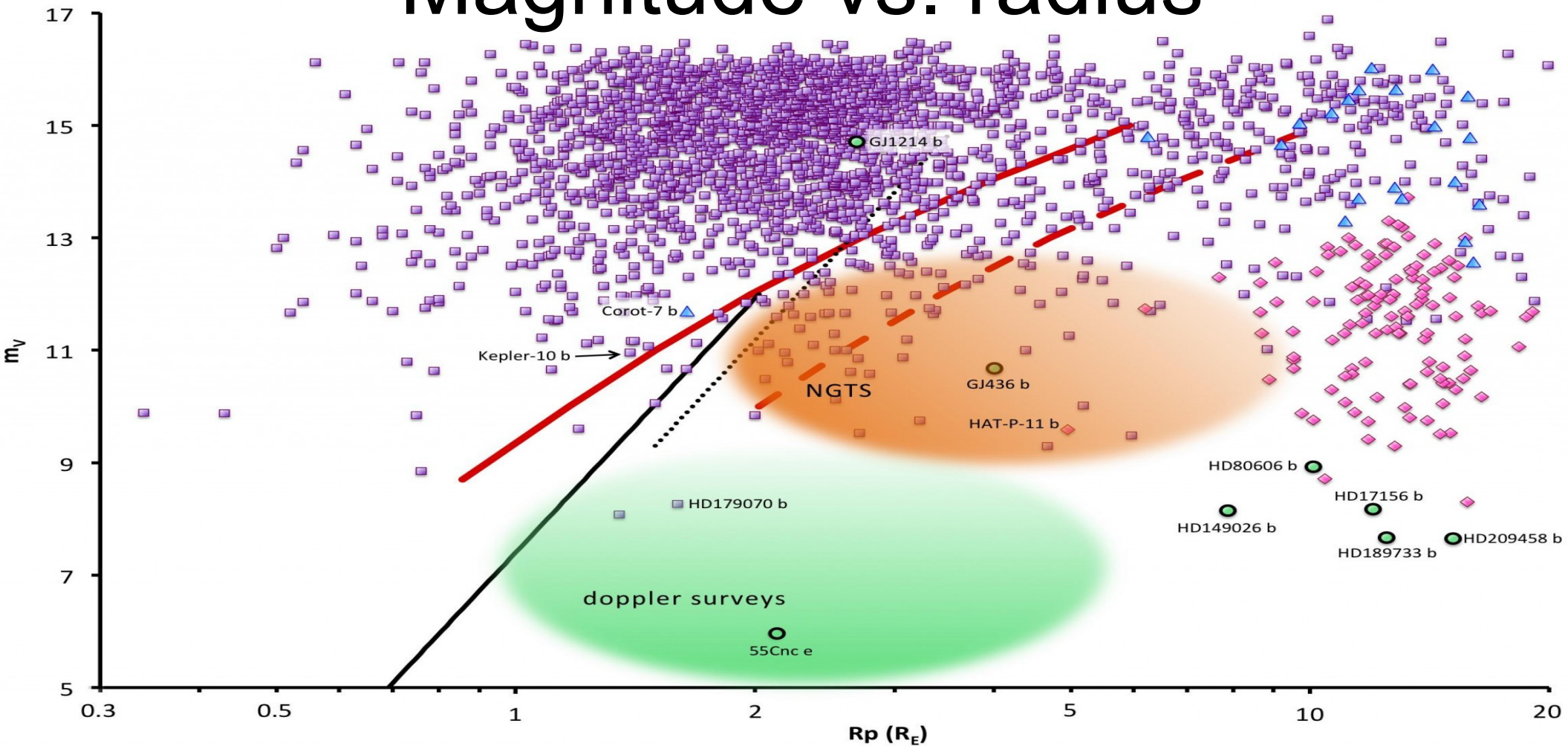


# Mass vs. Semi-m. Axis (before Kepler)

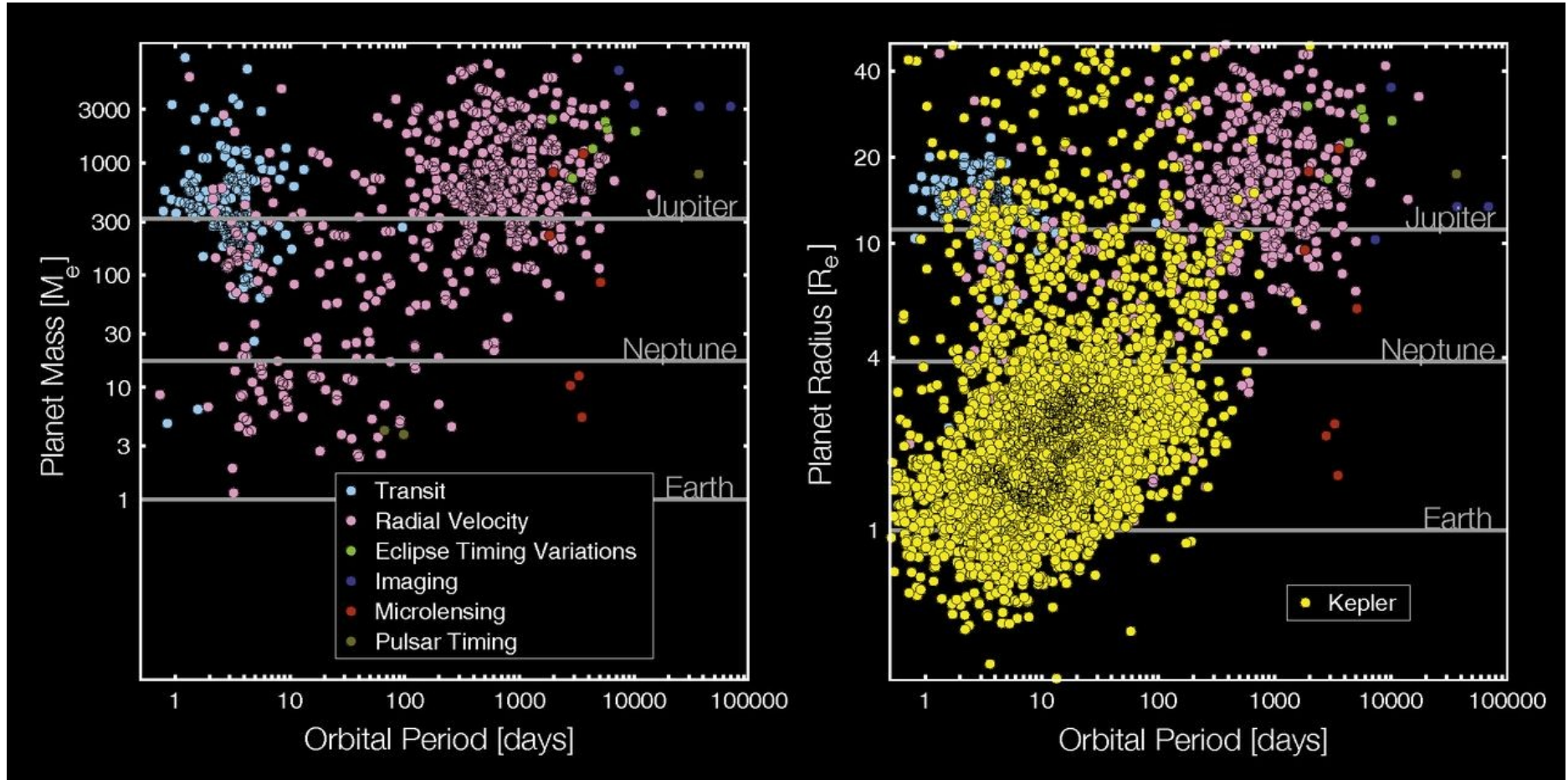




# Magnitude vs. radius



# And similar with Kepler



# Mass. vs. distance to star

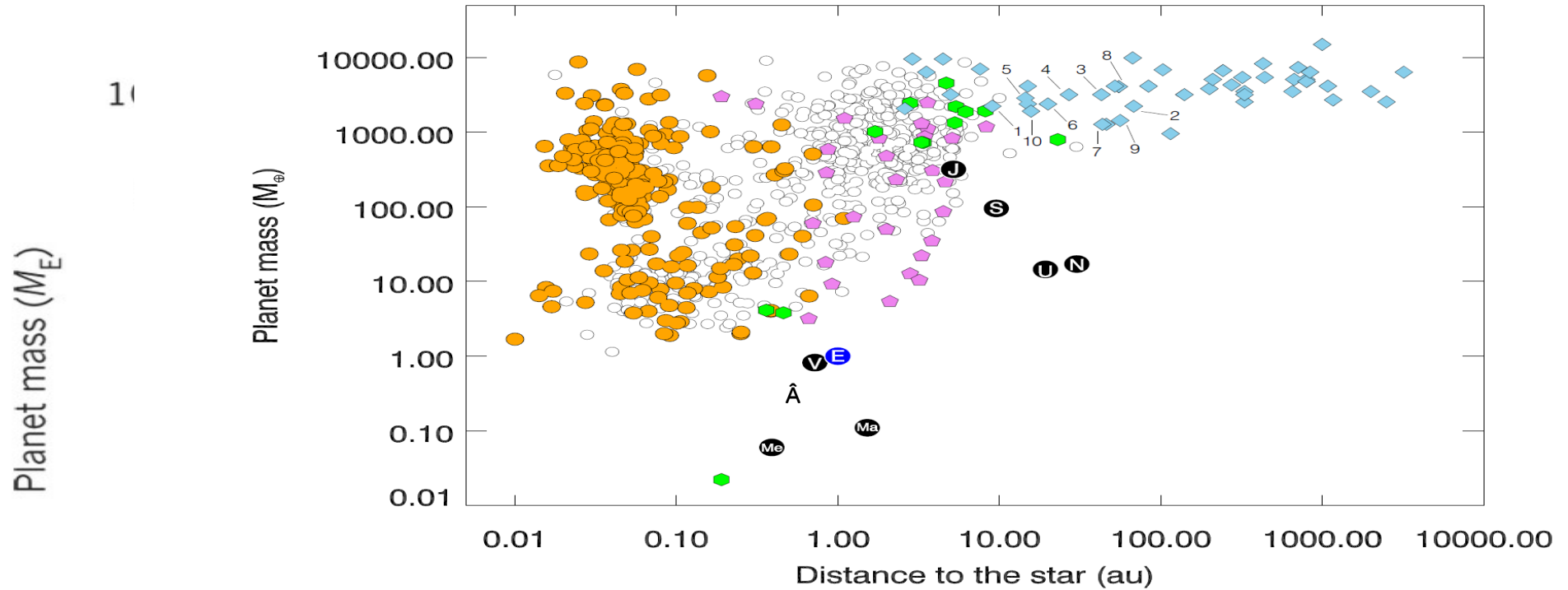
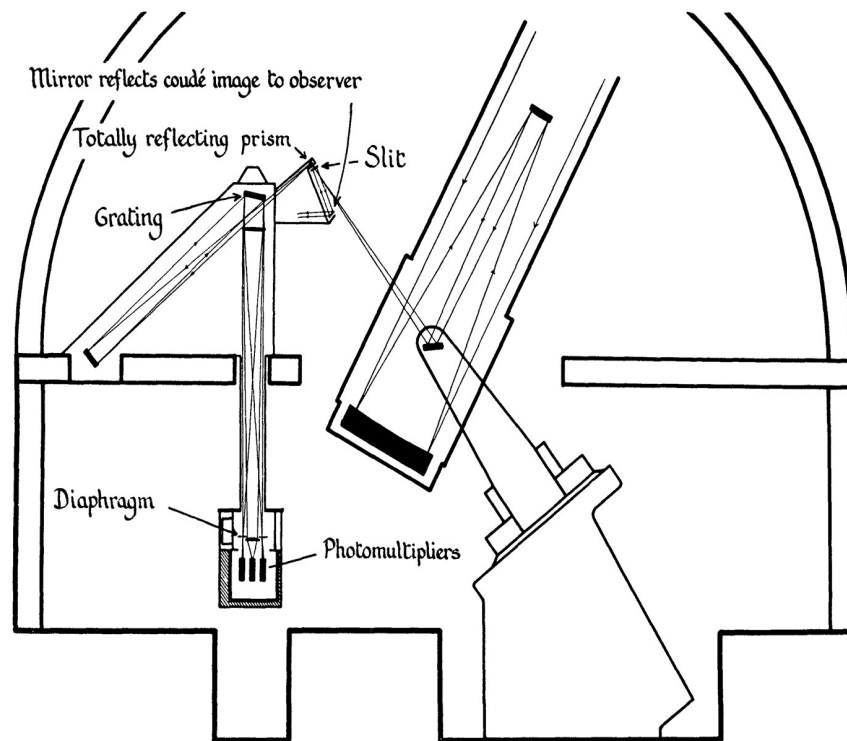
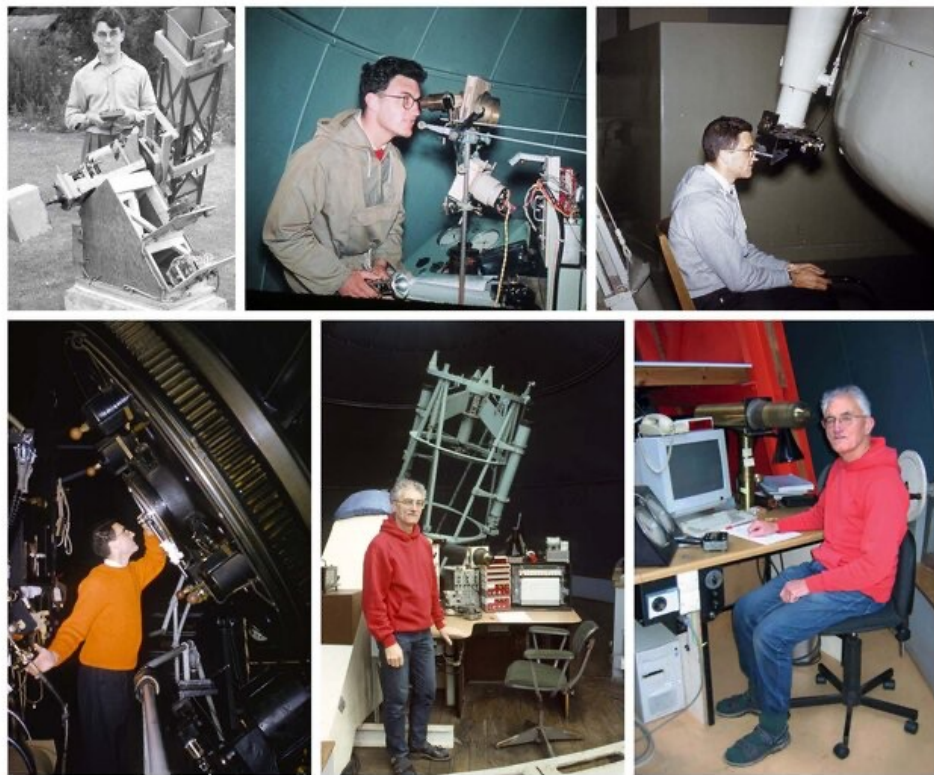


Figure 3: *Mass and semi-major axis of known planets.* Planetary mass is plotted as a function of semi-major axis (the distance to the host star). Solar-system planets are shown by black circles, the Earth in blue. Exoplanets detected with different techniques and instrumentation are represented by different 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<sup>196</sup>.



# First high dispersing spectrograph



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

# 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

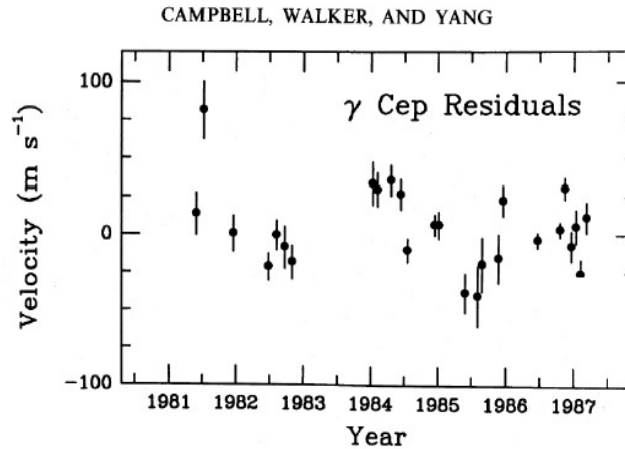
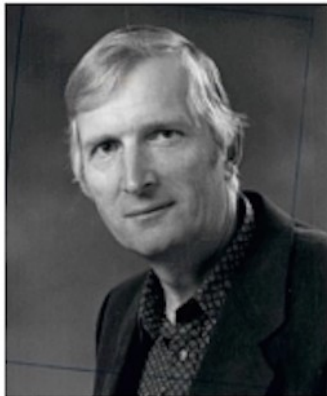
# Bruce Campbell and Gordon Walker

- 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

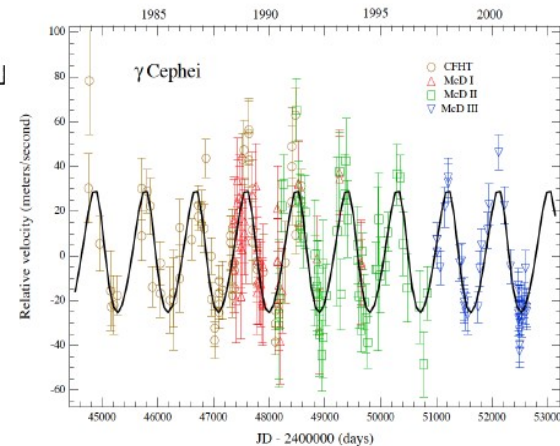
- Started around 1971, calibration with HF lamp
- First real planet but retracted
- RVs down to 3 m/s
- Gamma Cephei story



Campbell, Walker and Yang, 1988, ApJ

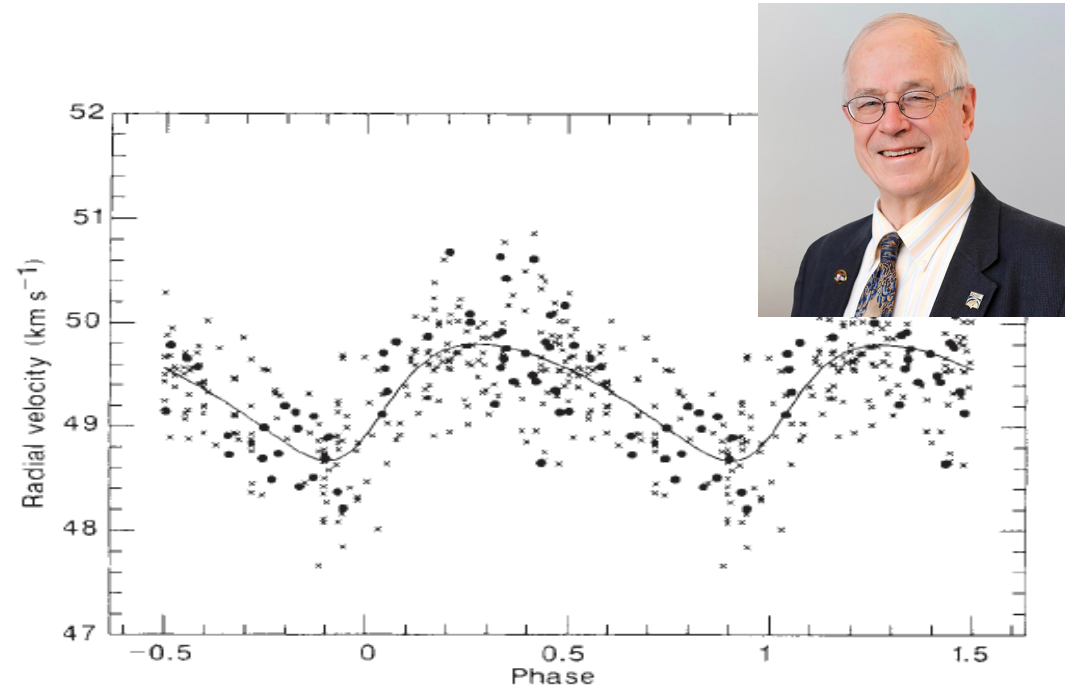
$P = 903$  days  
Mass = 1.85  $M_{\text{Jupiter}}$

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](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>