Exoplanets

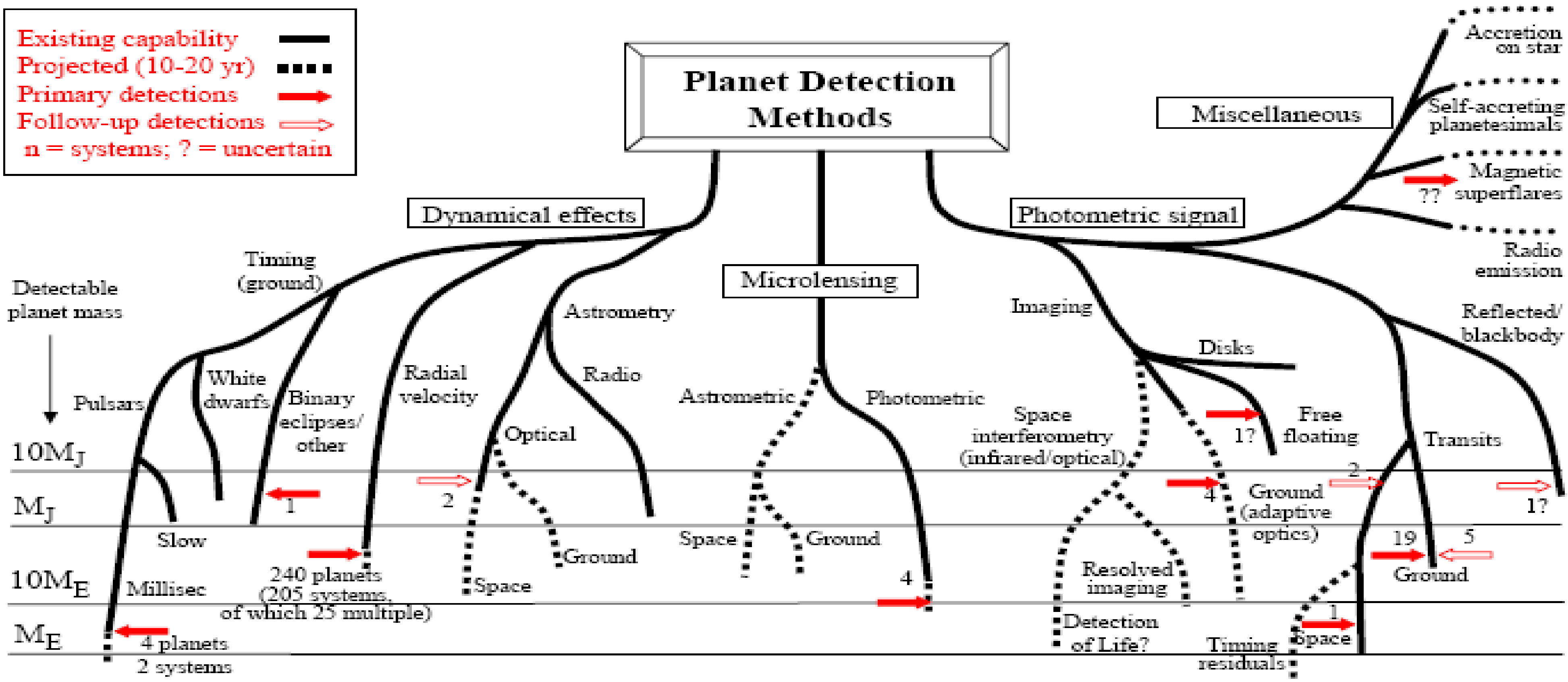
Fall/Winter 2023/2024
Lecture 2
13.10.2023

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)

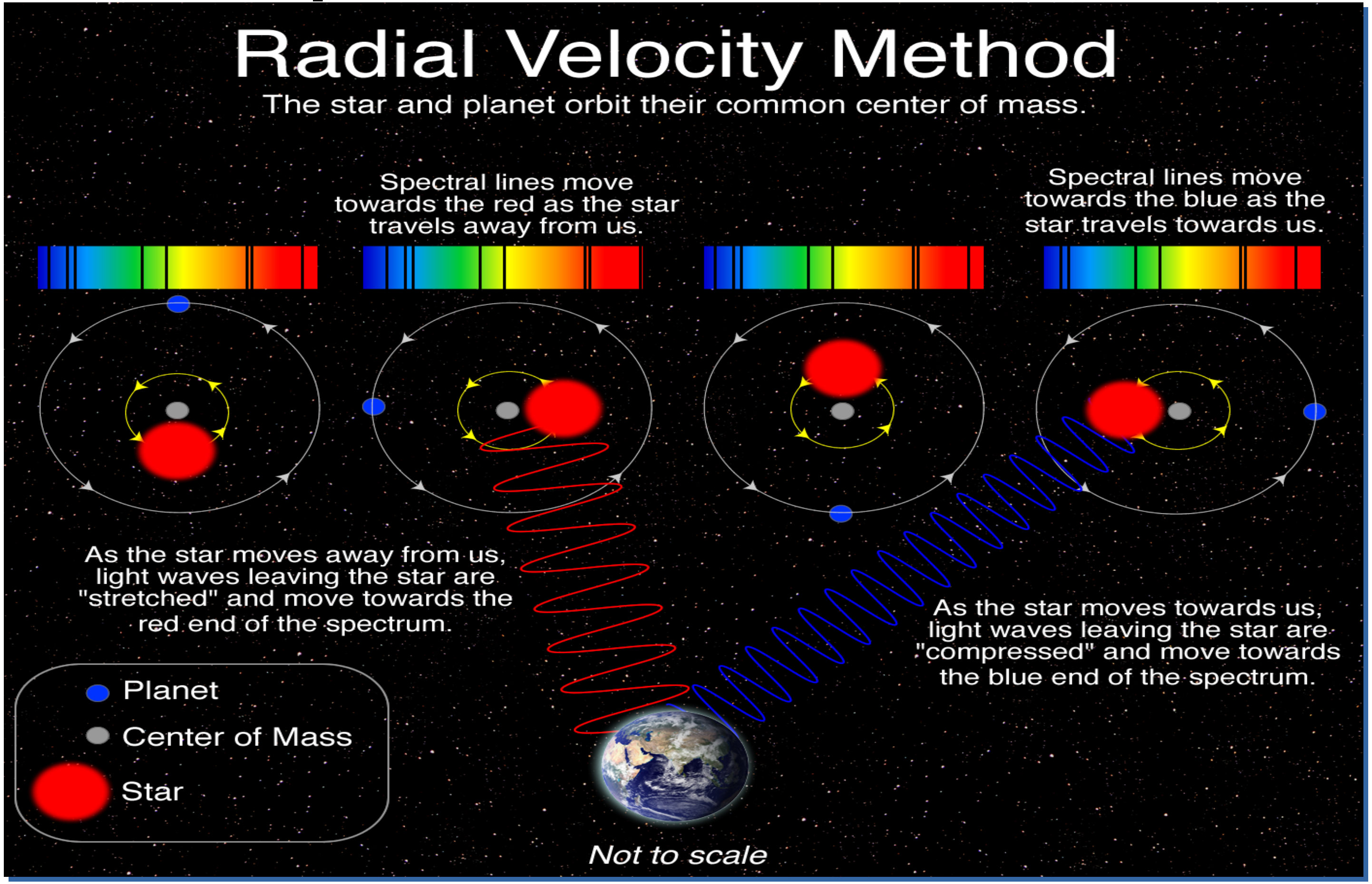
Radial velocities method (RV)

- 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 systém)
- 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

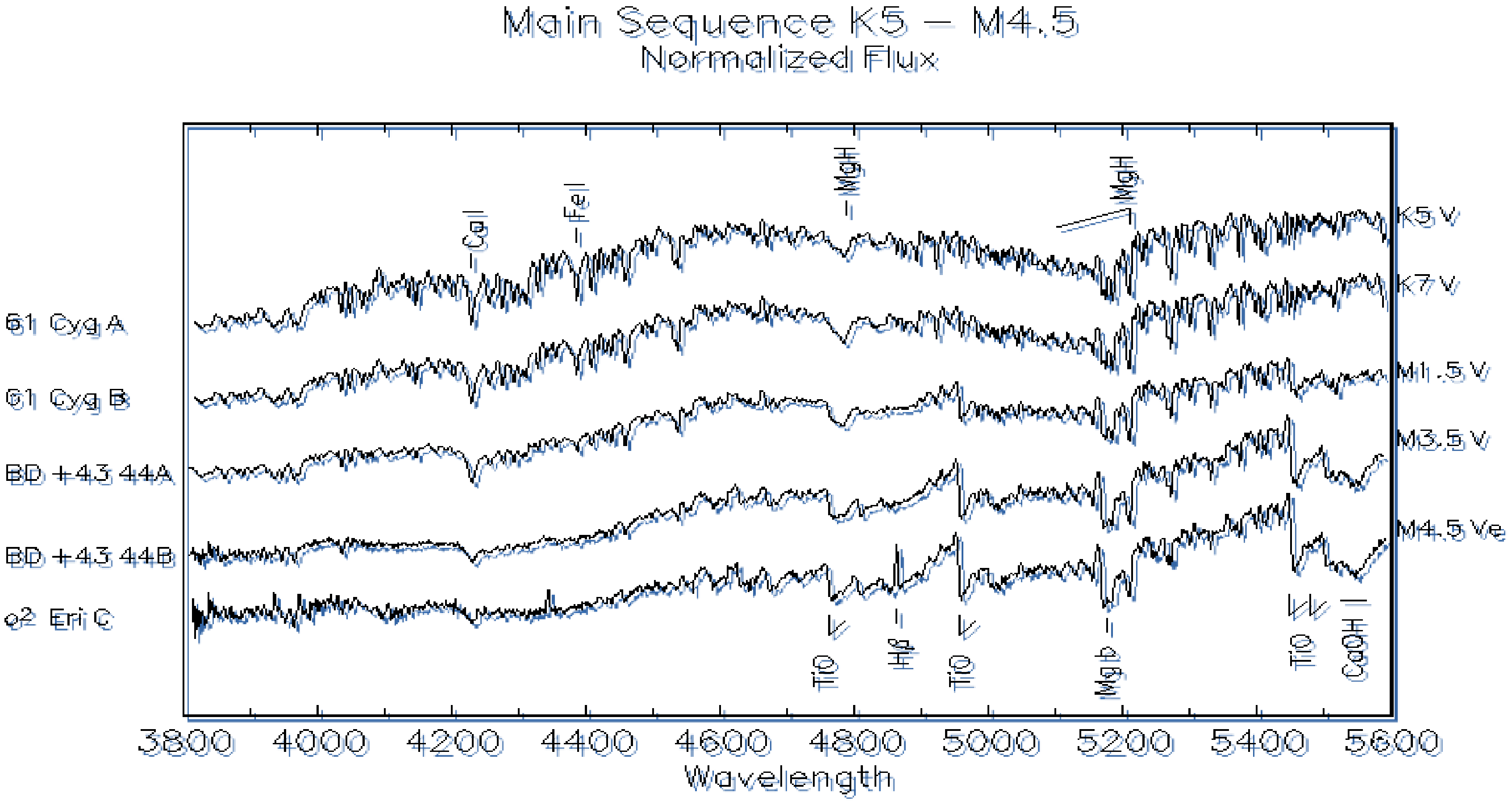
First step

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

(R 40000 plus)

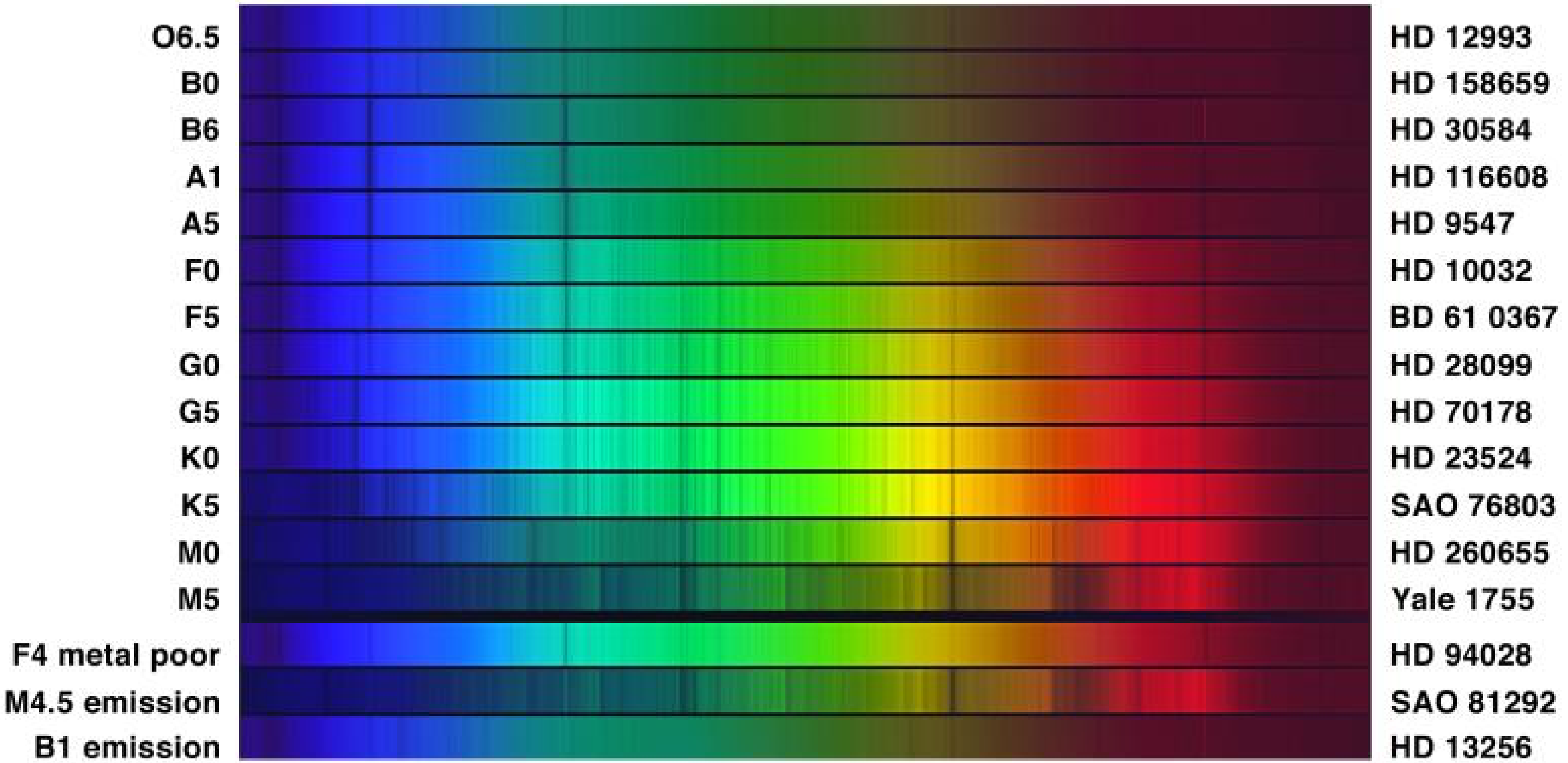
- Basic spectroscopic reduction, bias, correction of instrument effects, merging the echelle sp.
- Identification of lines and determination of the profile (by using calibration spectra – e.g. Iodine cell)

Example of a main sequence spectra



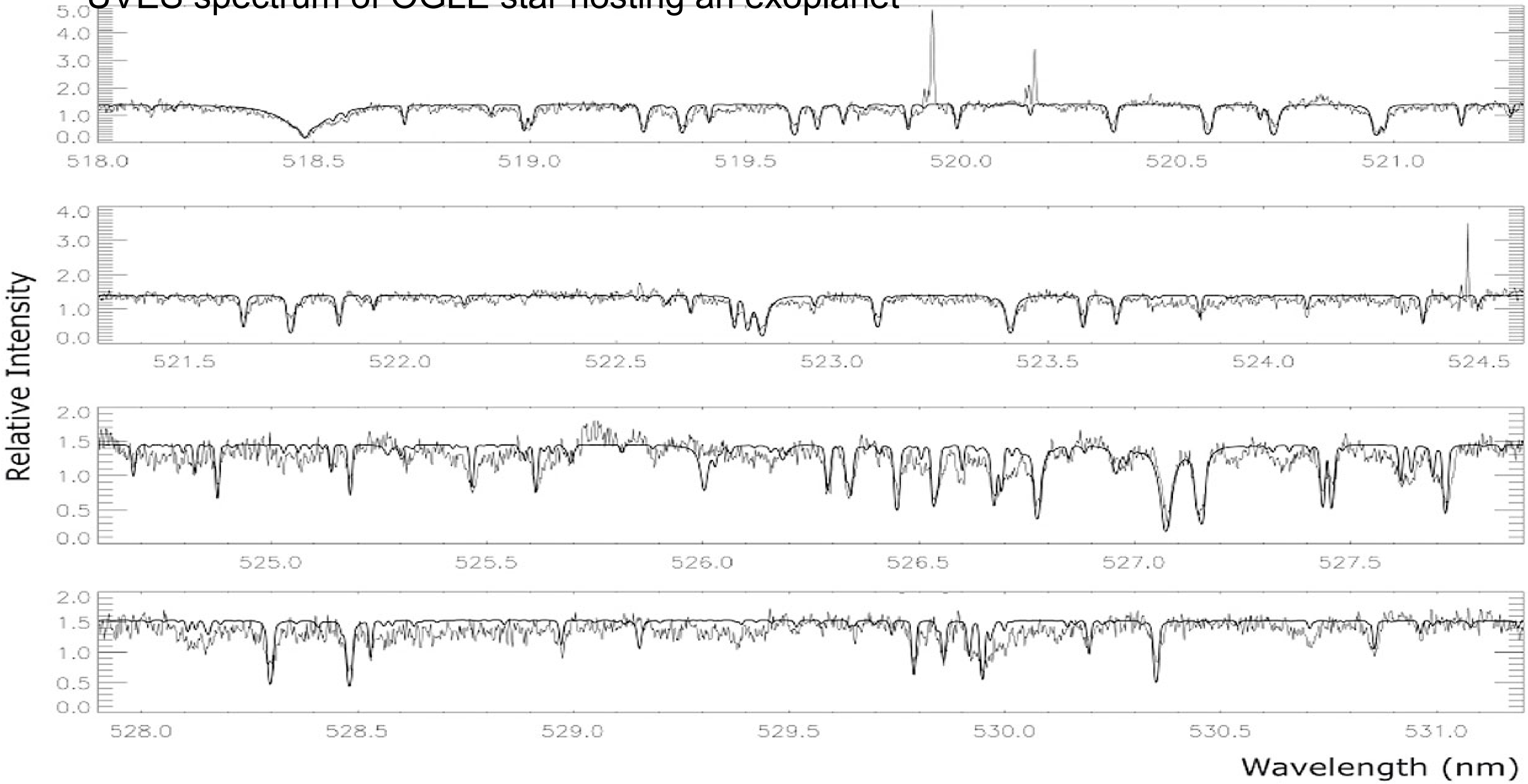
https://ned.ipac.caltech.edu/level5/Gray/frames.html

Various spectral types



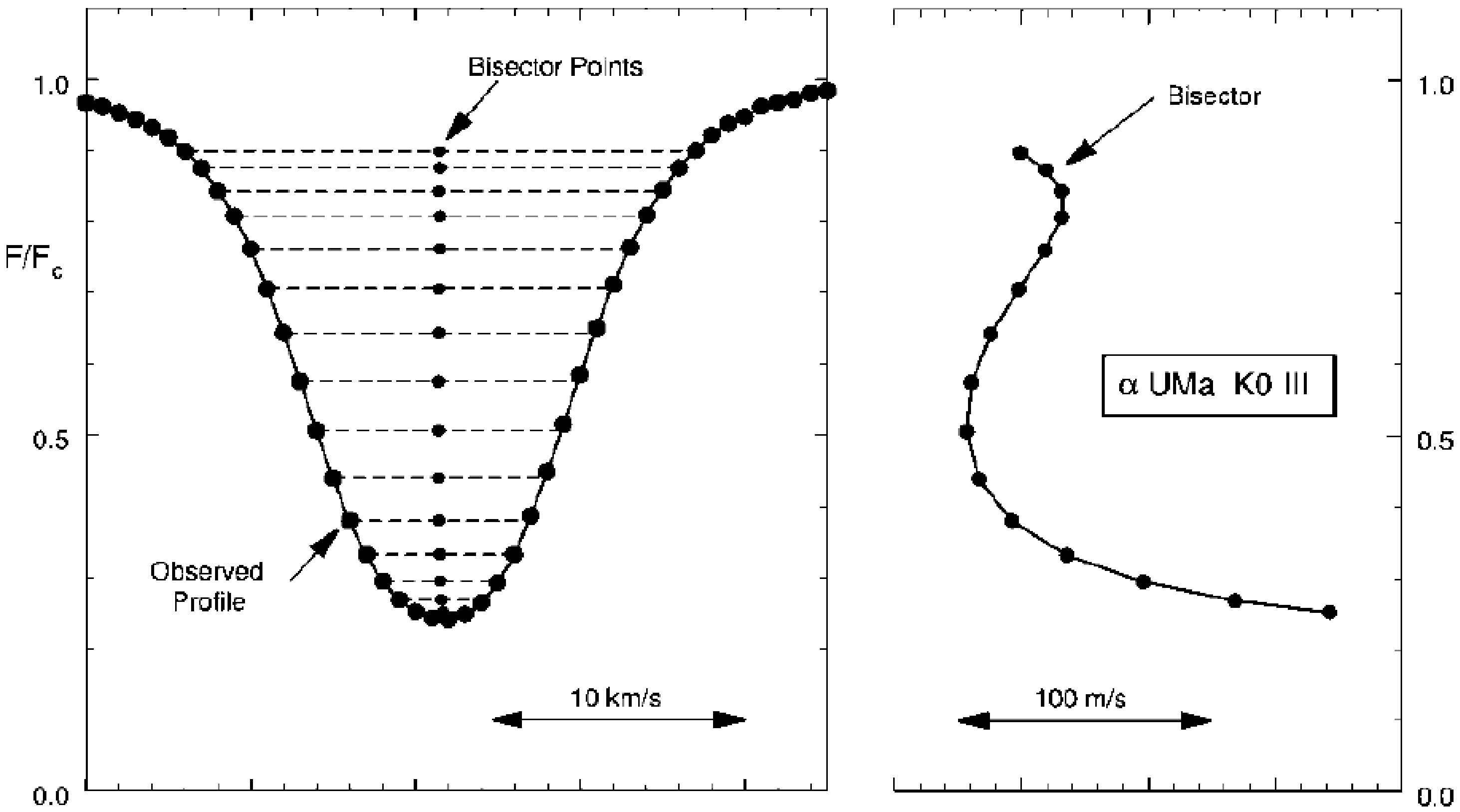
https://apod.nasa.gov/apod/ap010530.html
APOD NASA

UVES spectrum of OGLE star hosting an exoplanet



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

Shapes of lines unveil physics



Gray, 2005, PASP, 117, 711

Results (51 Peg)

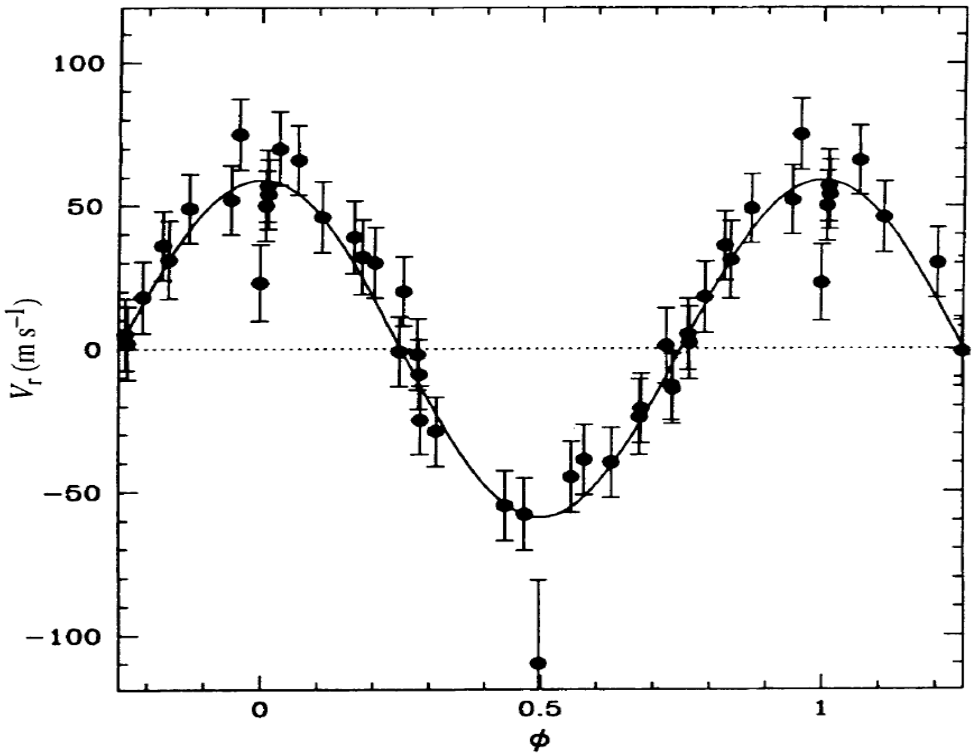
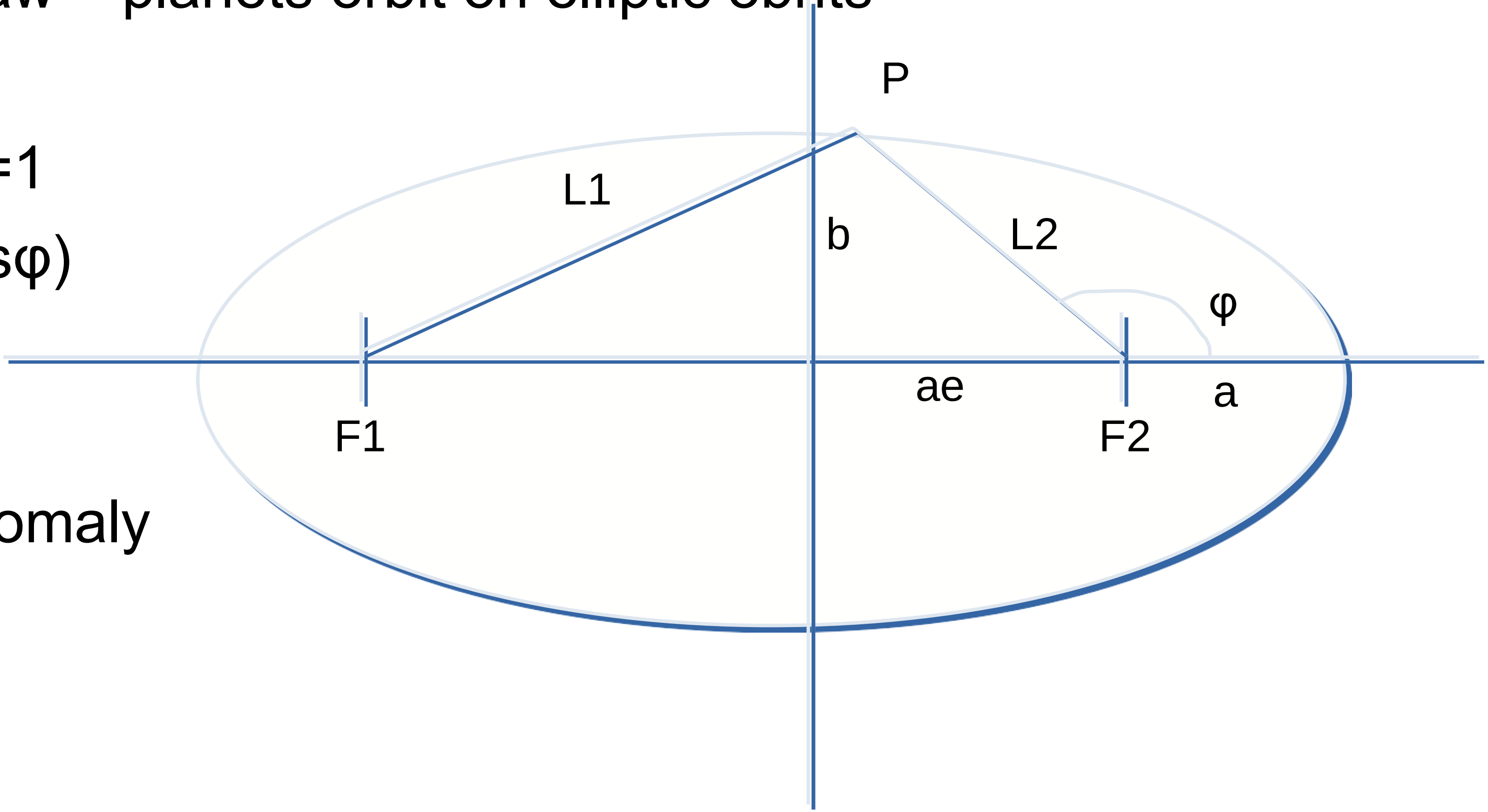


FIG. 4 Orbital motion of 51 Peg corrected from the long-term variation of the γ-velocity. The solid line represents the orbital motion computed from the parameters of Table 1.

Mayor and Queloz, 1995, Nature

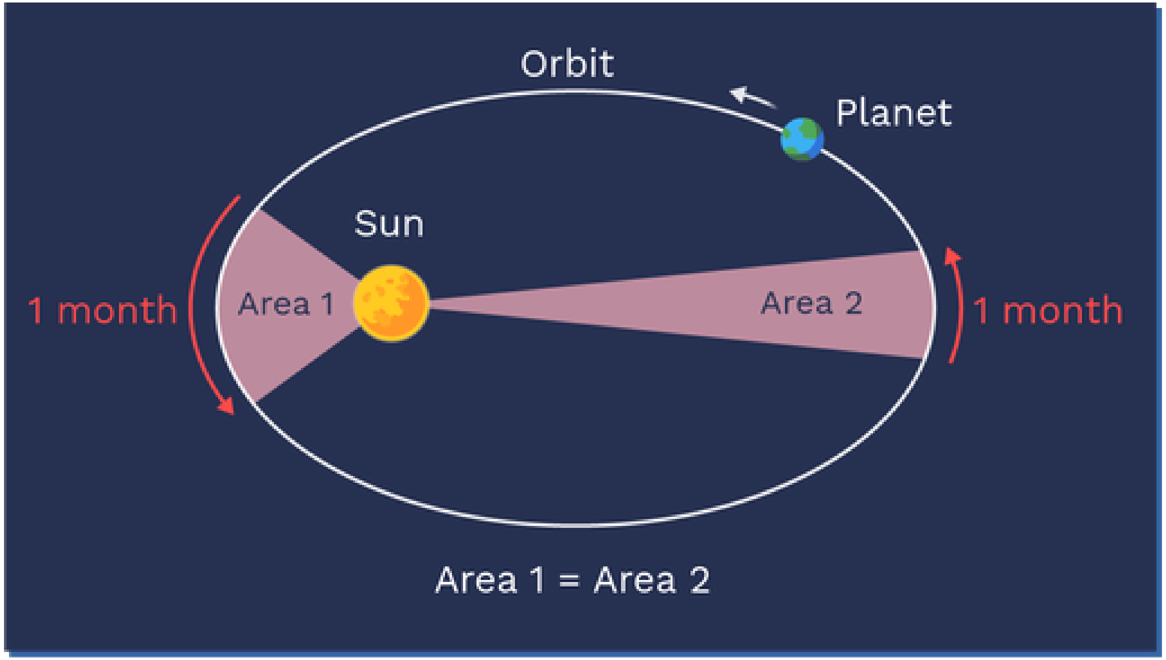
Kepler`s laws

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



Kepler`s laws

- 2nd Kepler`s law



https://theory.labster.com/keplers_second_law

Kepler`s laws

- 3^{rd} 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

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

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

Semi-amplitude K

- 3rd Kepler law

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

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

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

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

Simplification – masses difference

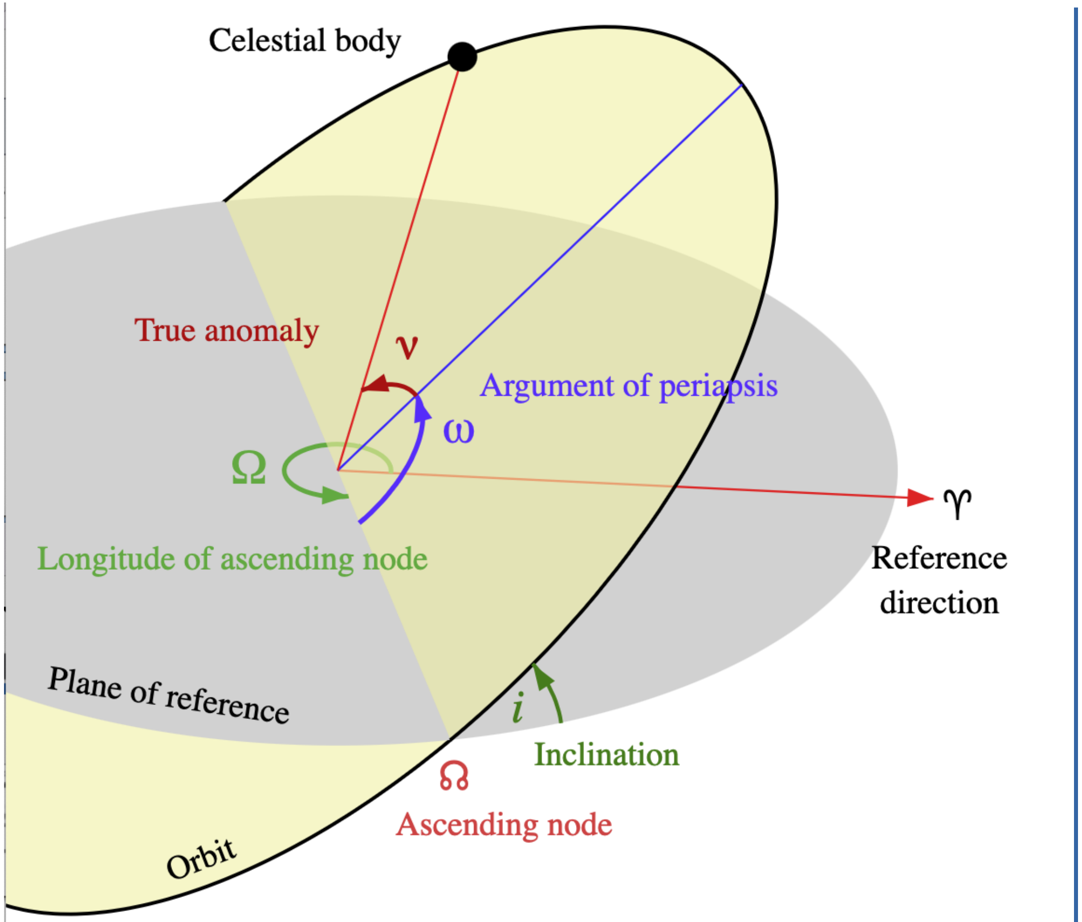
- m1+m2 is approx m1

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

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

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



Wikipedia

Some equations

- Observable semi-amplitude of RV curve K:

$$K_1 = \sqrt{\frac{G}{(1-e^2)}}\, m_2 \sin i\, (m_1+m_2)^{-1/2}\, a^{-1/2}$$

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

- Using Kepler law 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

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

Solar type stars and RVs

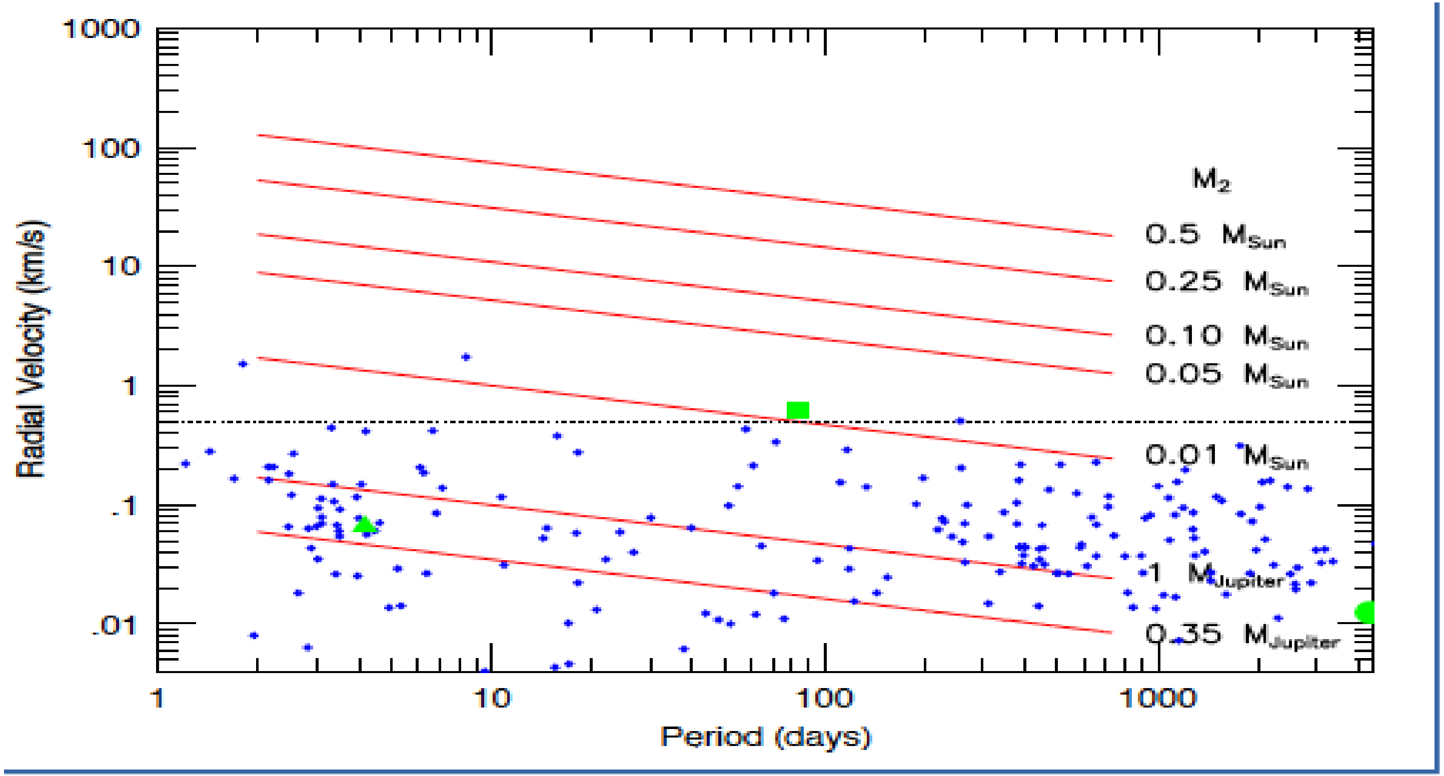


Figure from Hatzes, Cochran, Endl - : Radial velocity of a Solar type star due to a companion

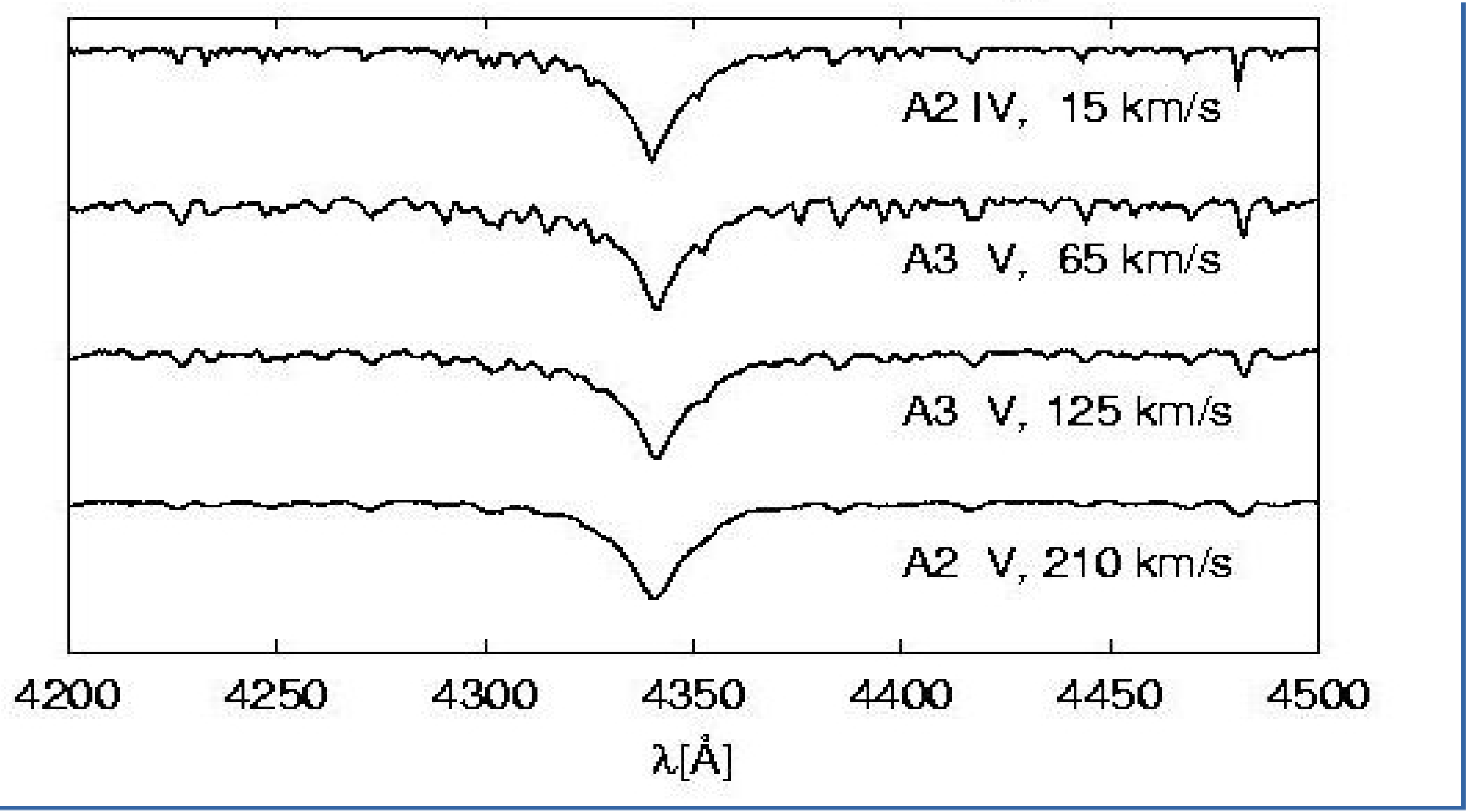
Problems

- 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

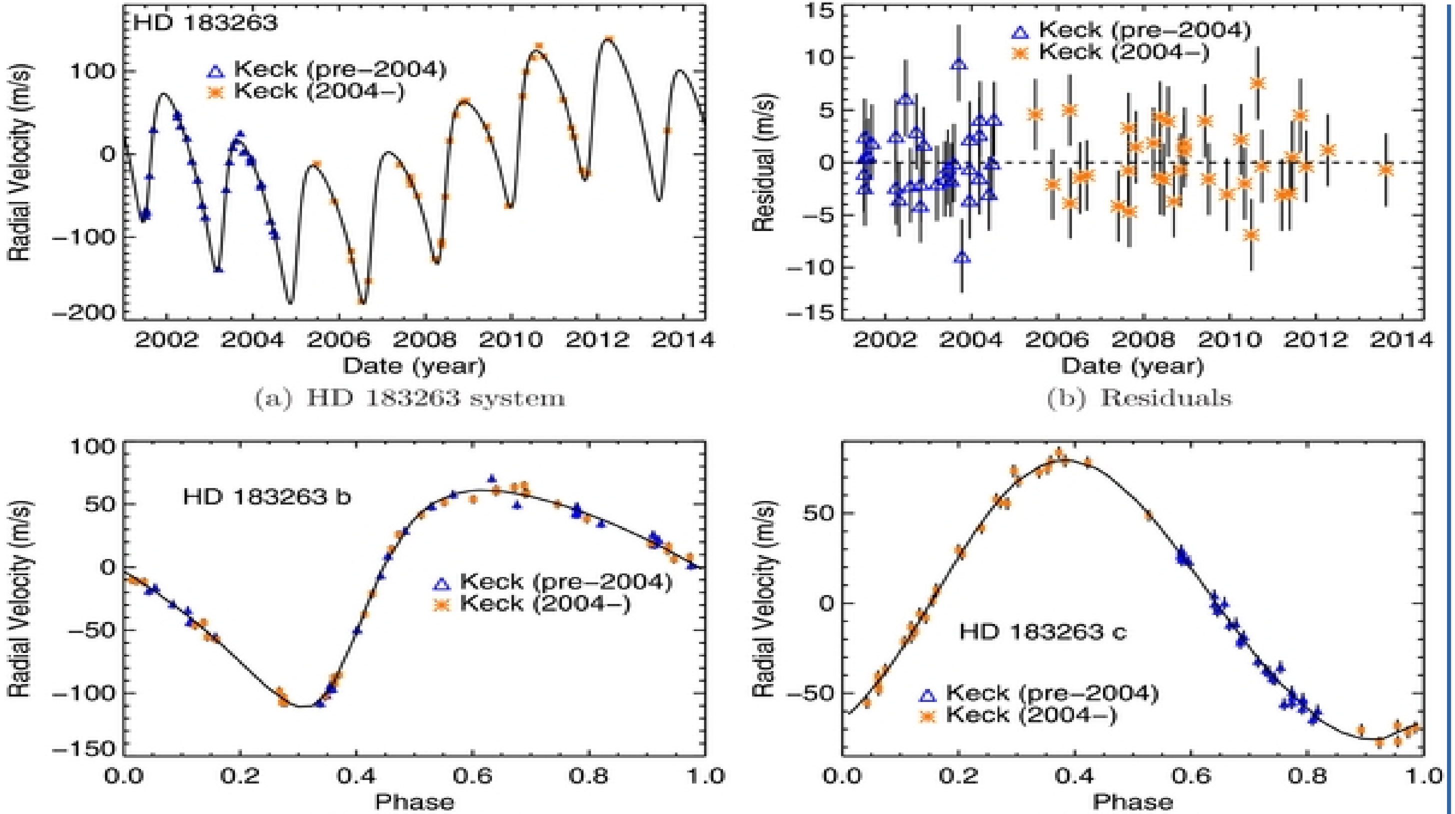
  - mimicking planet effect
- Long periodic planets are difficult to detect – due to coverage of the RV curve

Line broadening, rotation



http://www.astro.uu.se/~ulrike/Spectroscopy.html

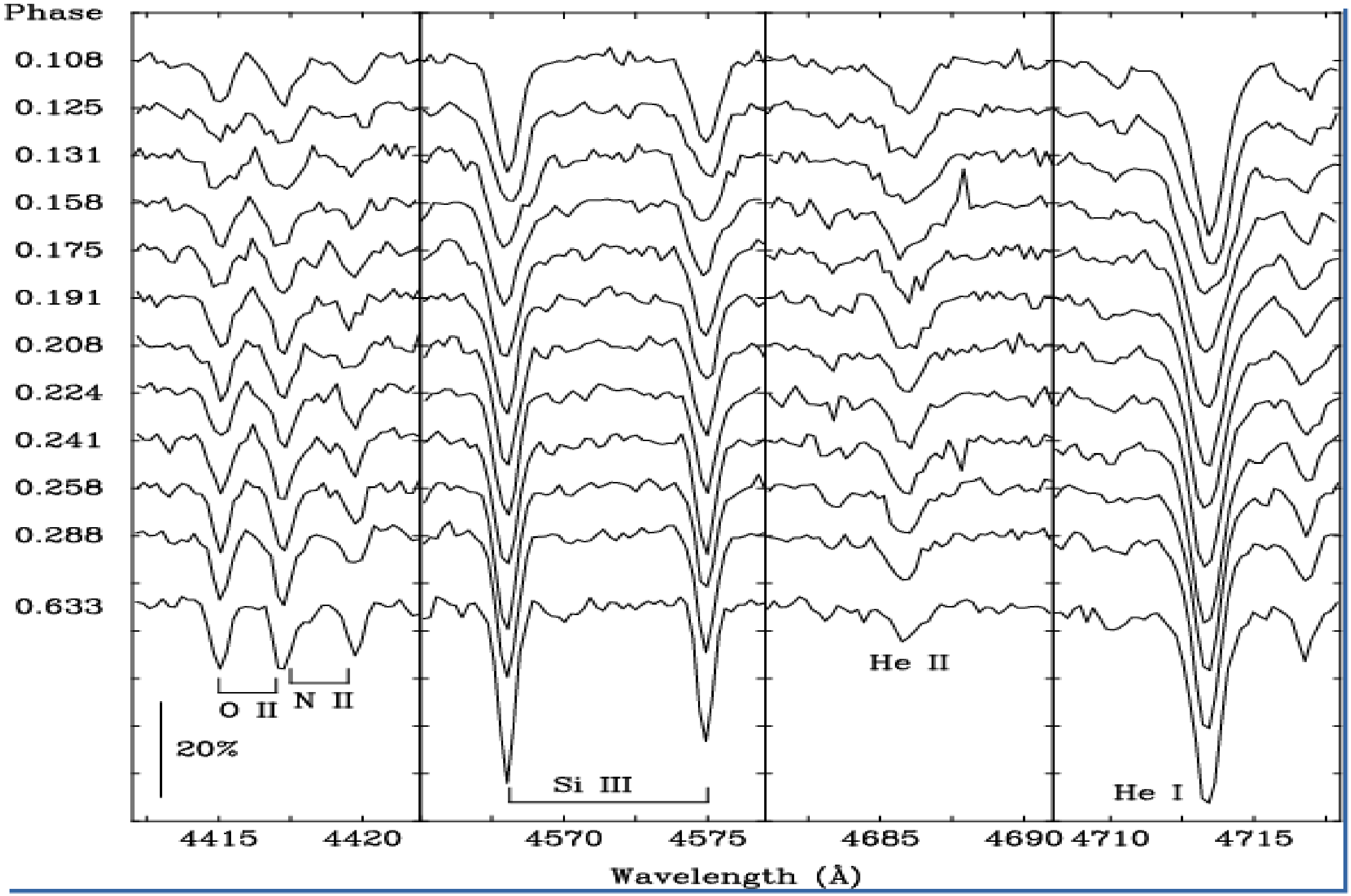
Multiple system



(a) HD 183263 system (b) Residuals (c) HD 183263 *b* (d) HD 183263 *c*

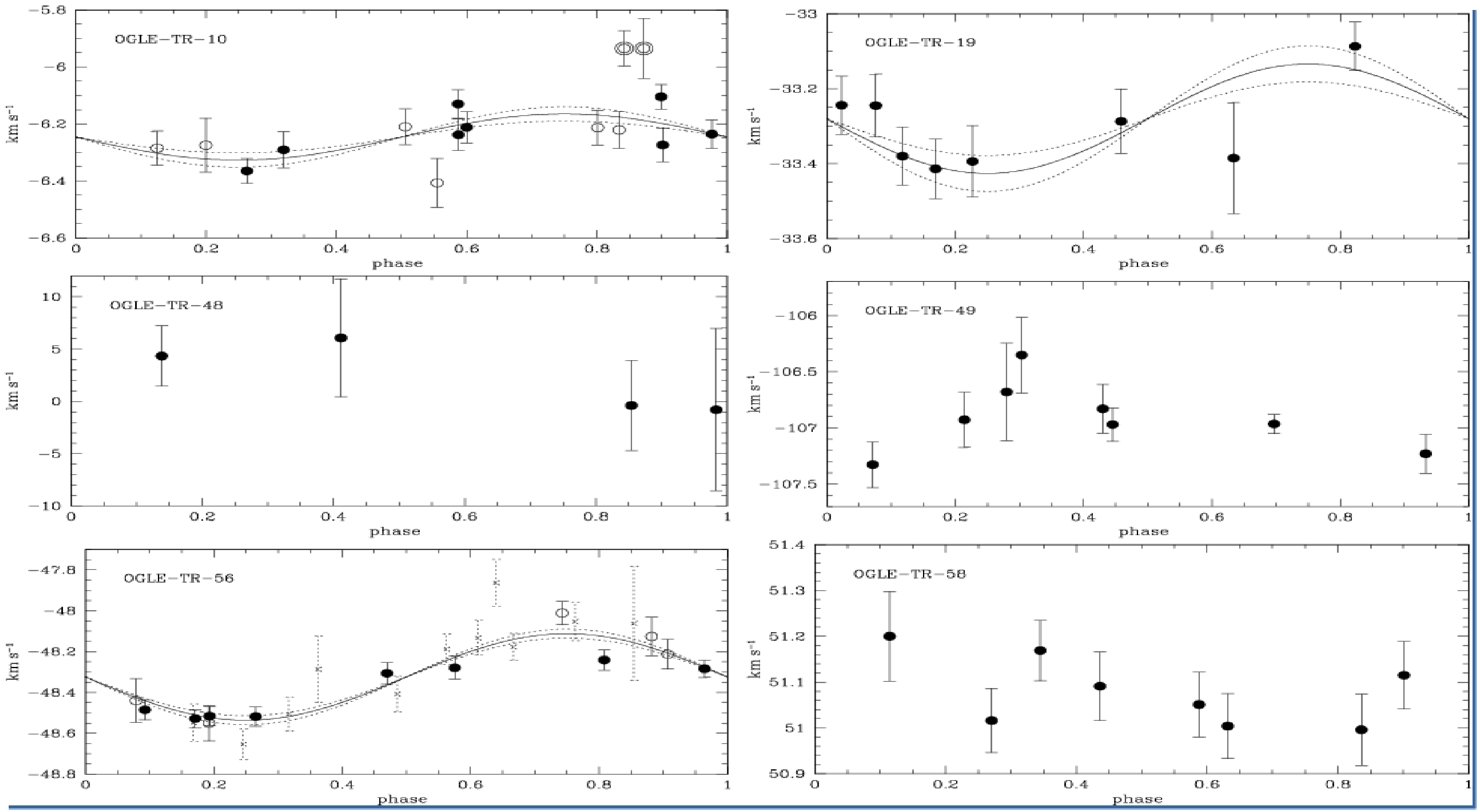
Feng et al. 2015, http://iopscience.iop.org/article/10.1088/0004-637X/800/1/22/pdf

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

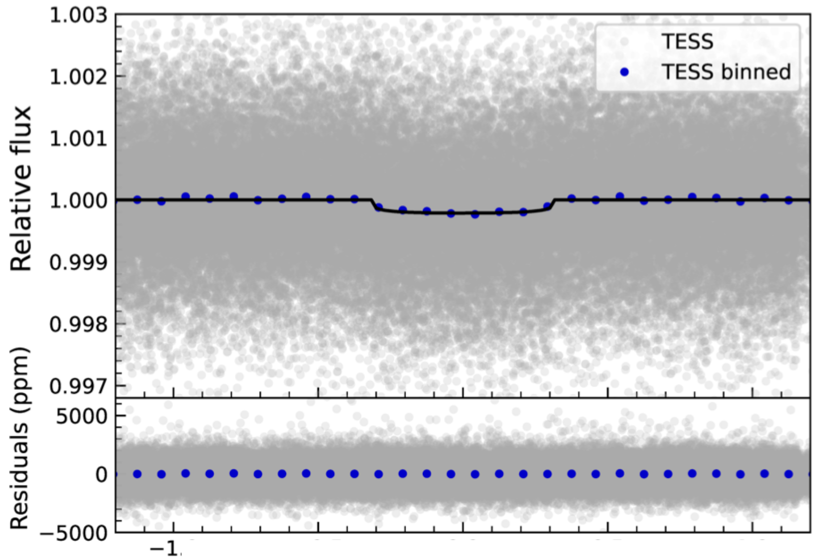


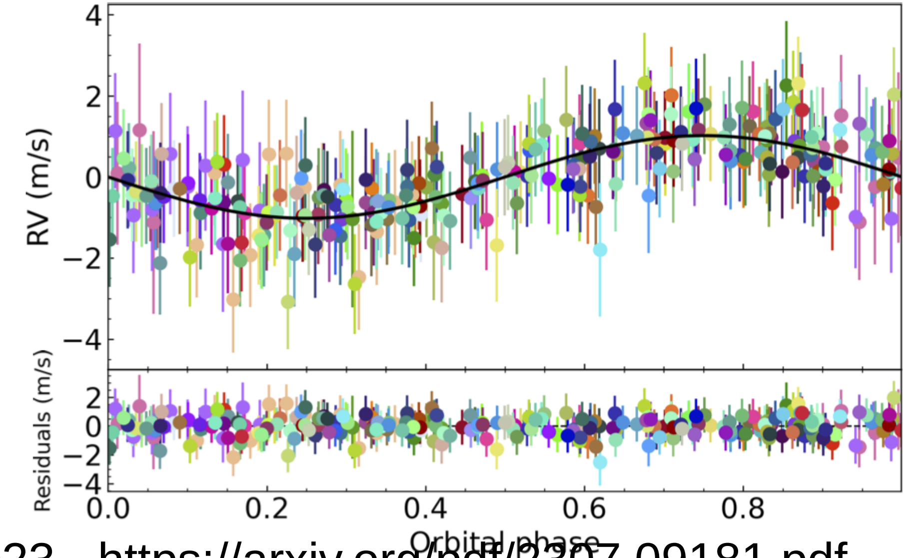
Bouchy et al. 2004, http://www.aanda.org/articles/aa/full/2005/09/aa1723/img38.gif

GJ 367 b - example

Table 1. Fundamental parameters of GJ 367.

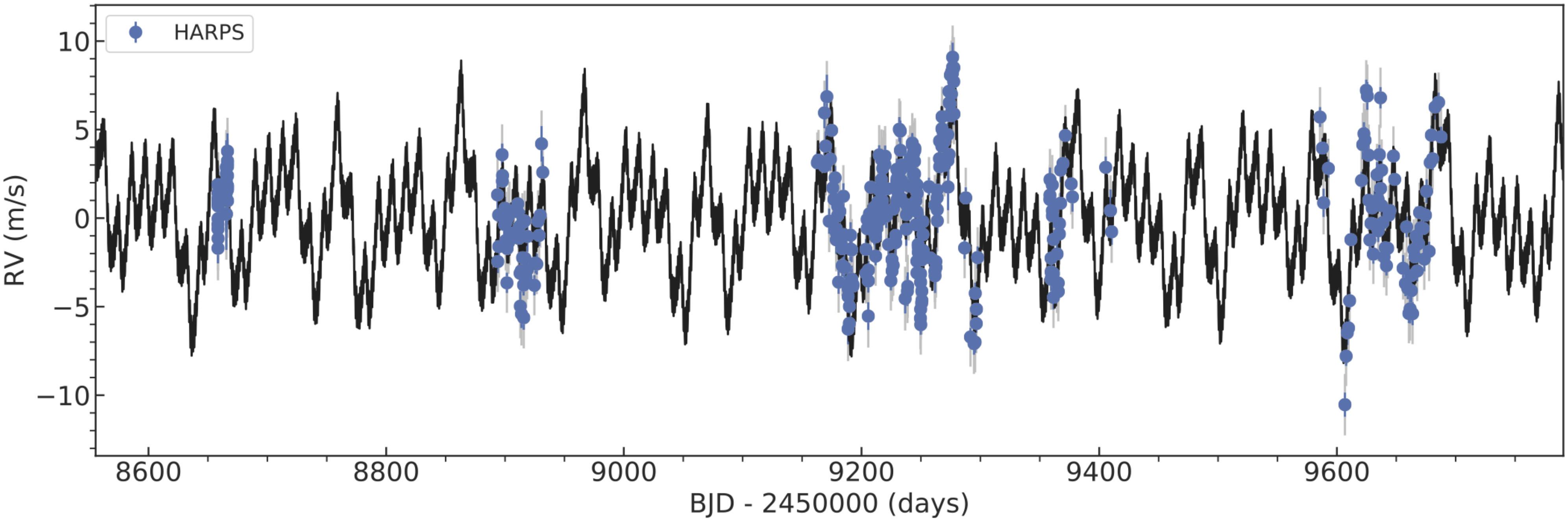
Parameter	Value	Reference
Name	GJ 367	
	TOI-731	
	TIC 34068865	
R.A. (J2000)	09:44:29.15	[1]
Decl. (J2000)	−45:46:44.46	[1]
TESS-band magnitude	8.032 ± 0.007	[2]
V-band magnitude	10.153 ± 0.044	[3]
Parallax (mas)	106.173 ± 0.014	[1]
Distance (pc)	9.413 ± 0.003	[1]
Star mass M_* ($M_\odot$)	0.455 ± 0.011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



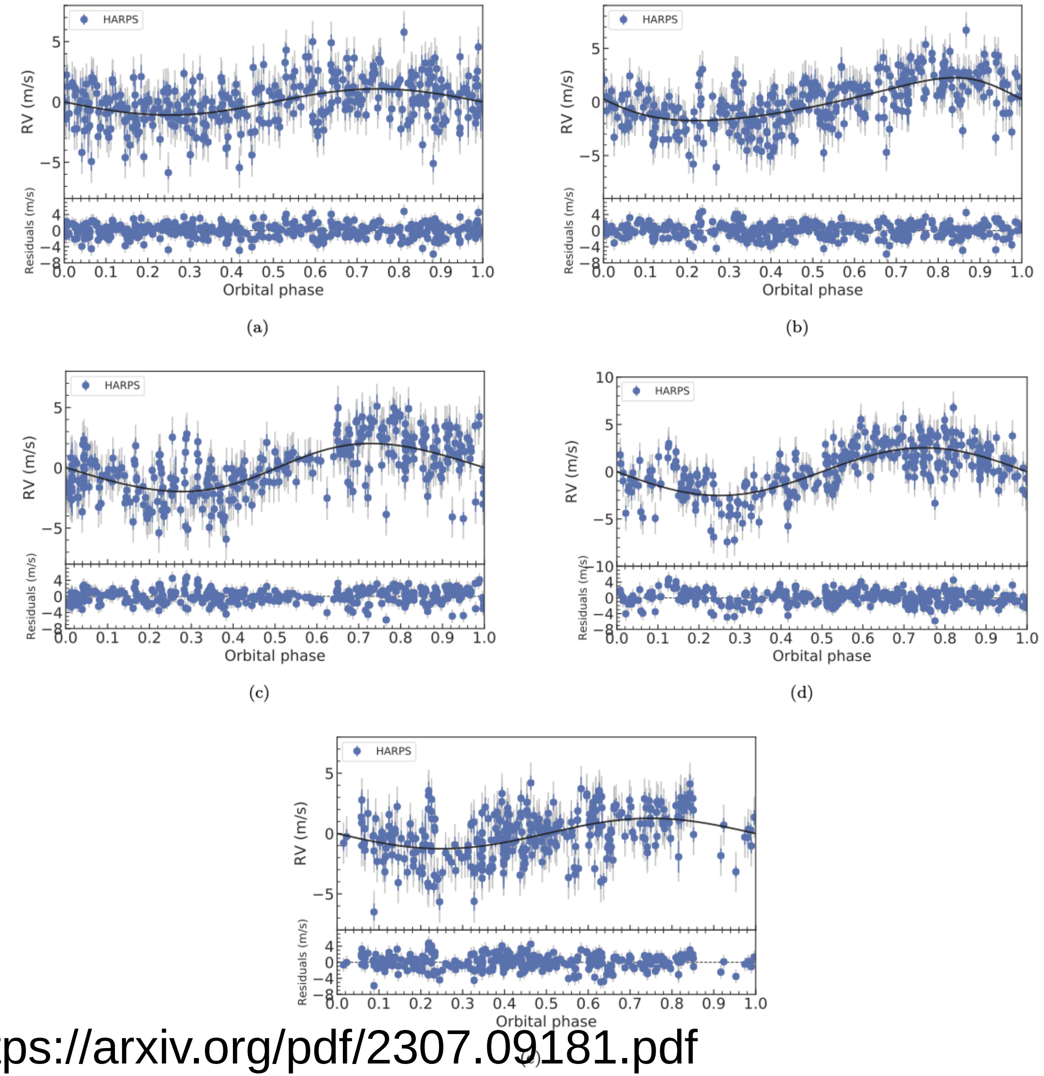


Goffo et al. 2023 - https://arxiv.org/pdf/2307.09181.pdf

But there are roe planets …..



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



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

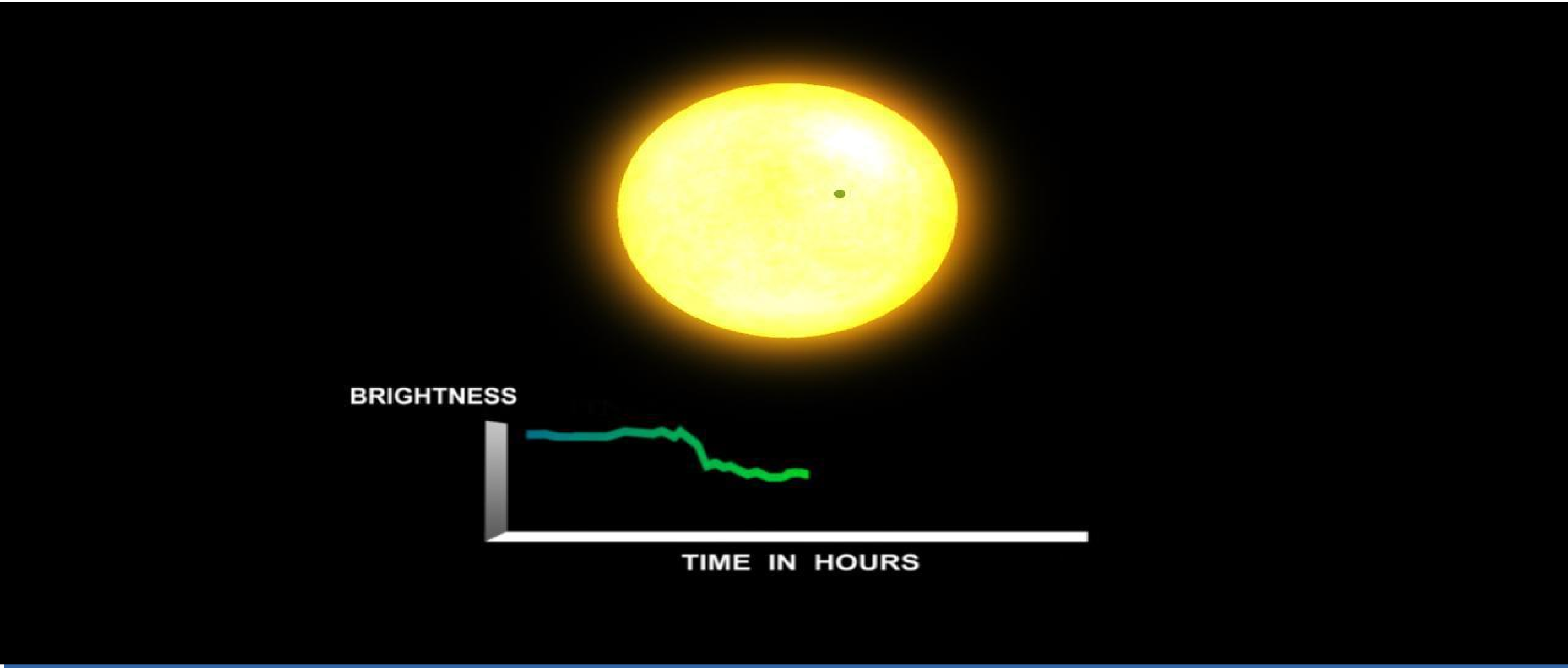
System parameters

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.

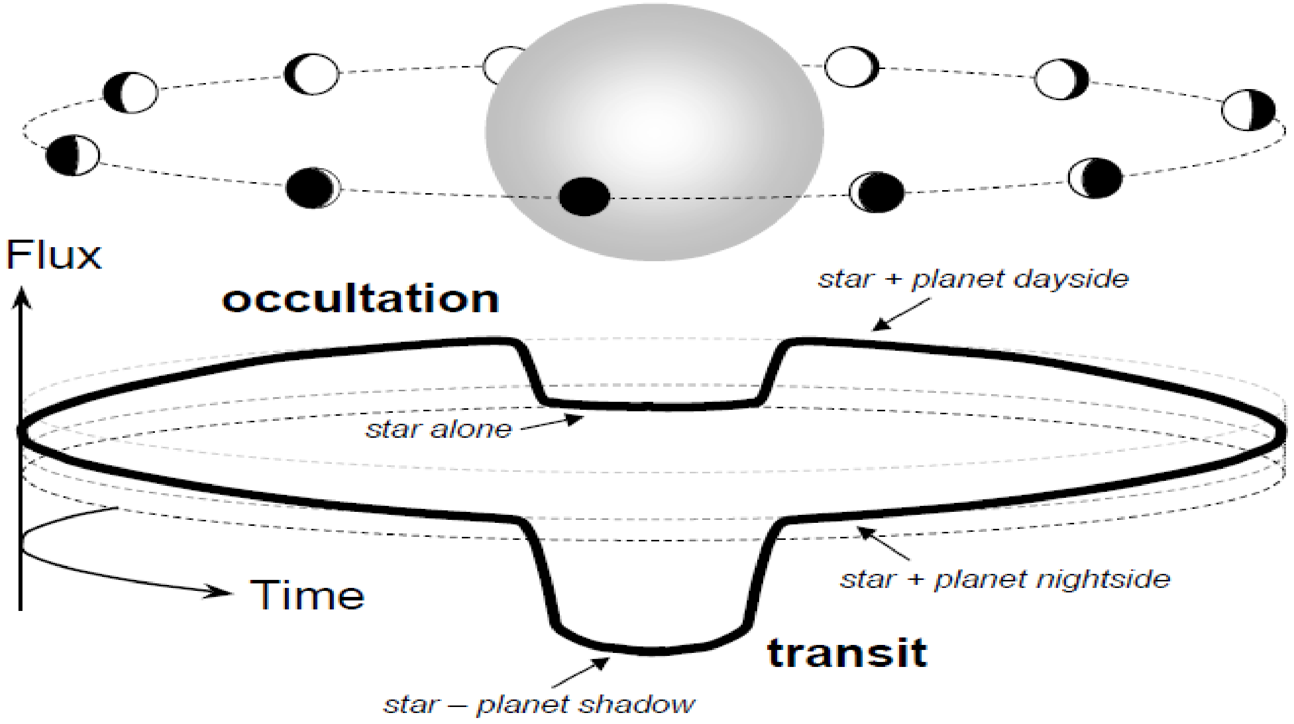
Parameter	Prior	Derived value
GJ 367 b		
Model parameters		
Orbital period $P_{\rm orb,b}$ [days]	$\mathcal{N}$[0.3219225, 0.0000002]	0.3219225 ± 0.0000002
Transit epoch $T_{0,\rm b}$ [BJD$_{\rm TDB}$-2,450,000]	$\mathcal{N}$[8544.1364,0.0004]	8544.13632 ± 0.00040
$\sqrt{e_{\rm b}}\sin\omega_{\star,\rm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

The transit method



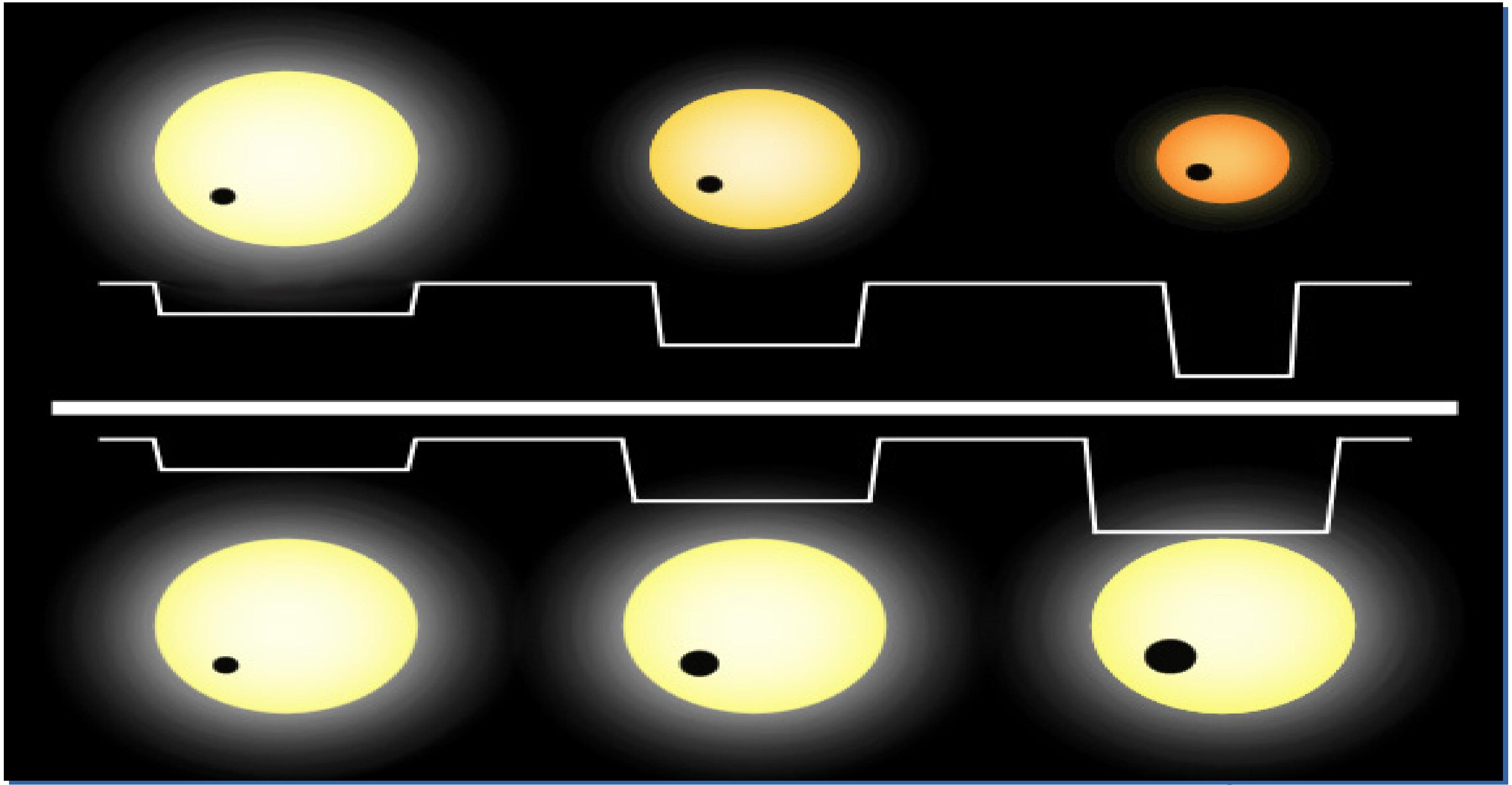
http://www.nasa.gov/mission_pages/kepler/multimedia/images/kepler-transit-graph.html

Eclipses/transits



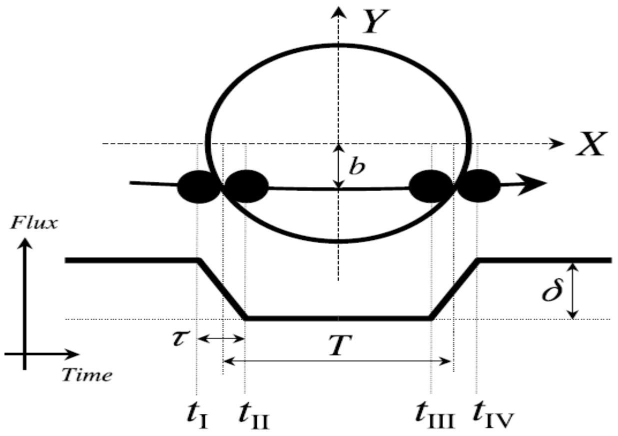
From Winn, 2010, http://arxiv.org/pdf/1001.2010v5.pdf

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:

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

- Transit shape:

$$I(p,z) = 1 - L(p,z)$$

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

- 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

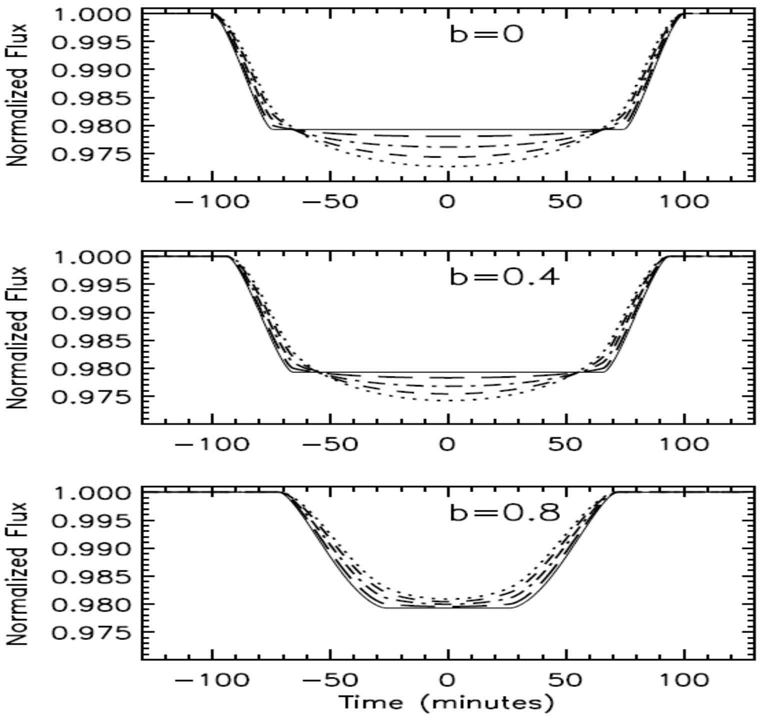


Fig. 3.— Solar limb darkening dependence of a planet transit light curve. In these theoretical light curves the planet has $R_p = 1.4R_J$ and $a = 0.05$ AU and the star has $R_* = R_\odot$ and $M_* = M_\odot$. The solid curve shows a transit light curve with limb darkening neglected. The other planet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

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

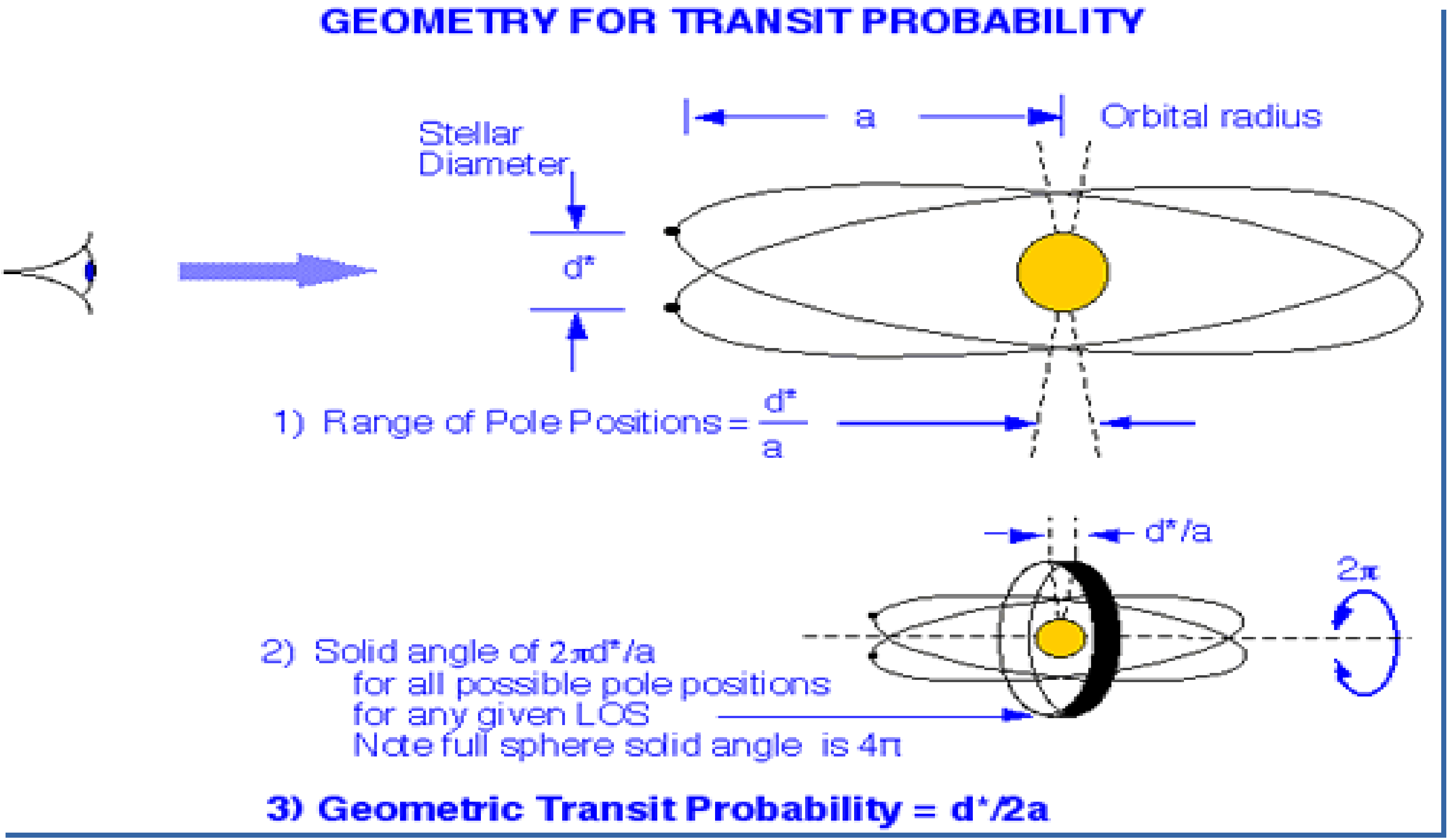
Problems

- 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

Geometrical probability



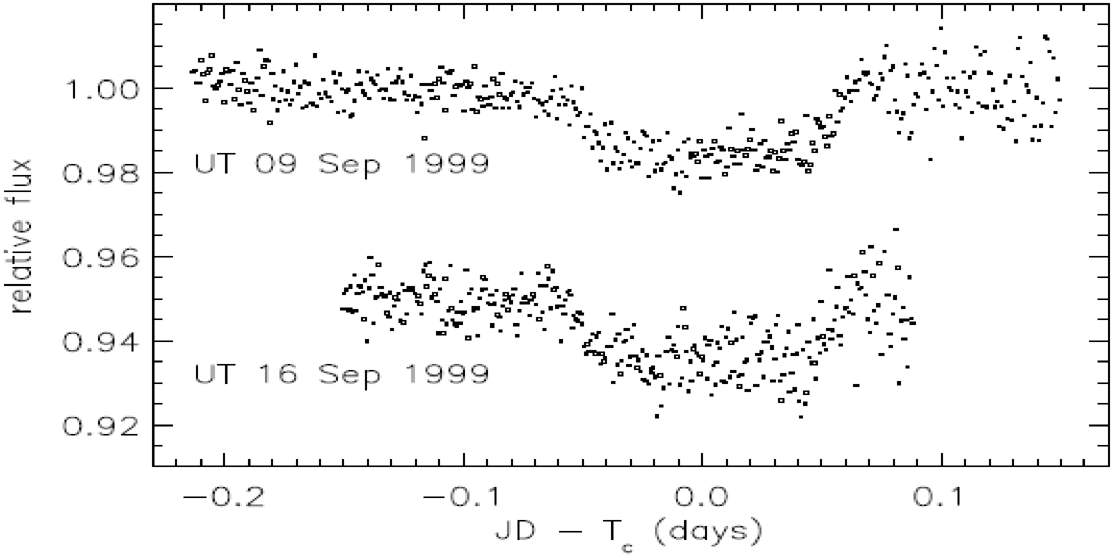
Credit: NASA Kepler

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
	$P^2M^* = a^3$		13sqrt(a)	$\% = (d_p/d^*)^2$	d*/D	phi

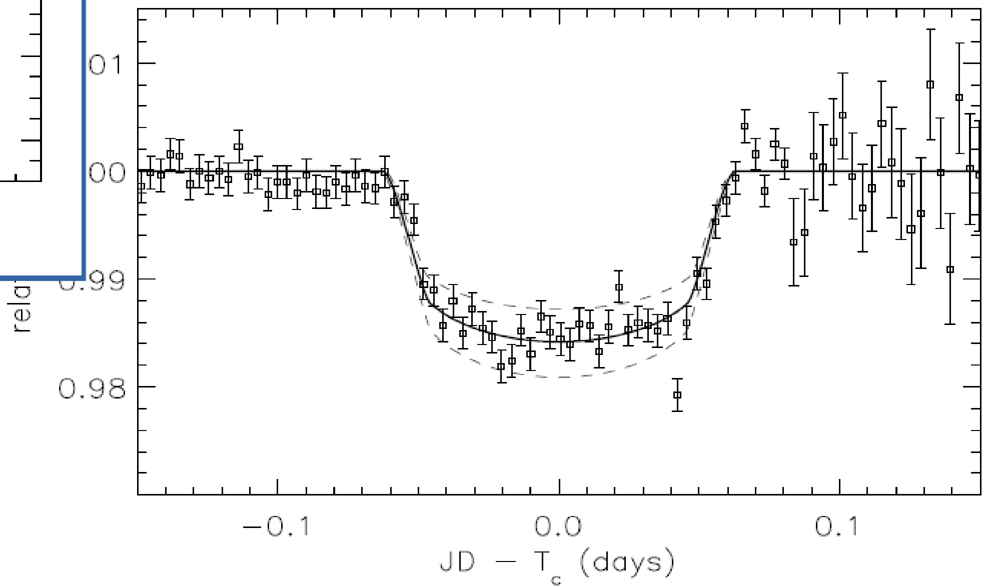
https://web.njit.edu/~gary/320/Lecture10.html

First transiting exoplanet



HD209458b

Charbonneau et al. 2000



HD209458b

- Parameters

  - Mass : 0.69Mj
  - Radius : 1.38 Rj
  - O. period : 3.5 days

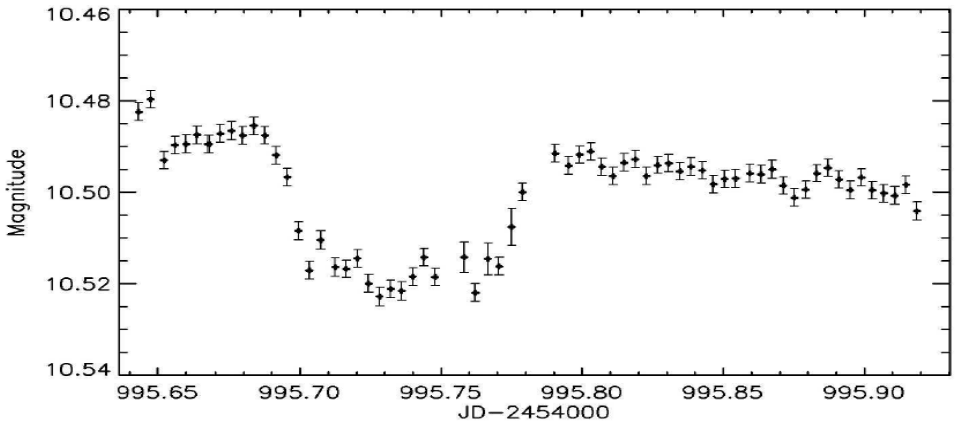
- Star: G0V

  brightness: 7 mag (V)

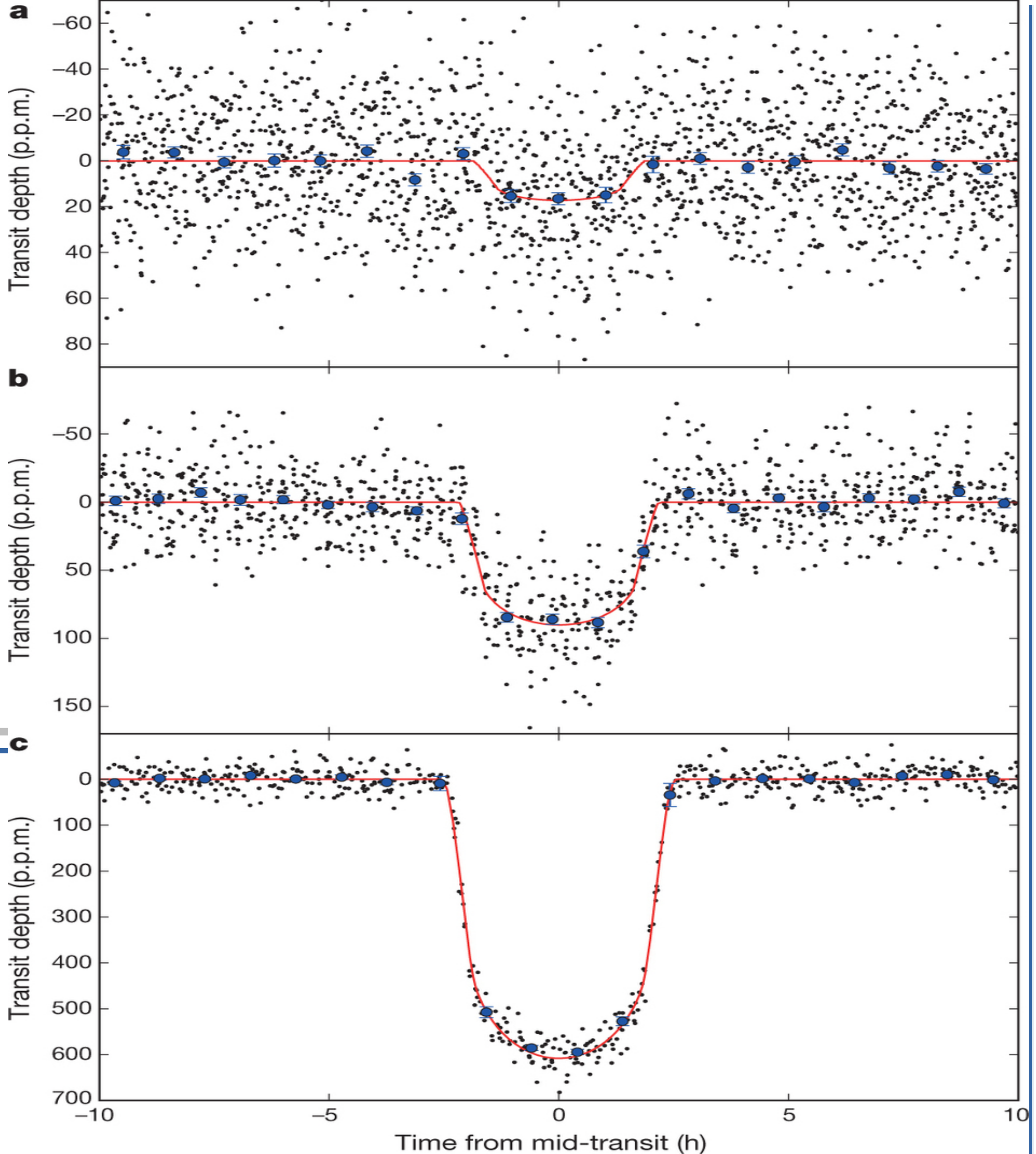
http://mnras.oxfordjournals.org/content/418/3/1822

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

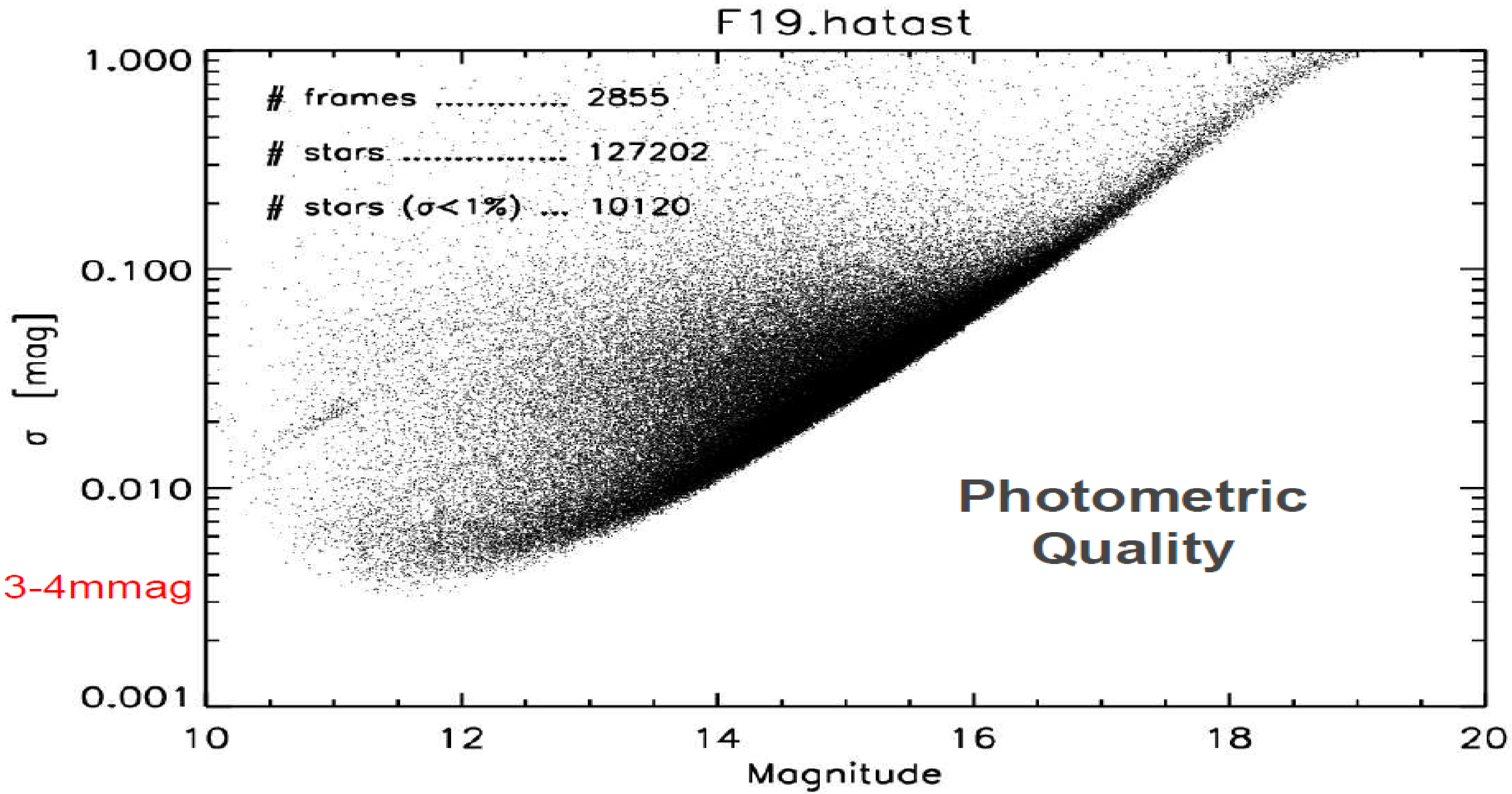
BEST II

Observatorio Cerro Armazones, Chile

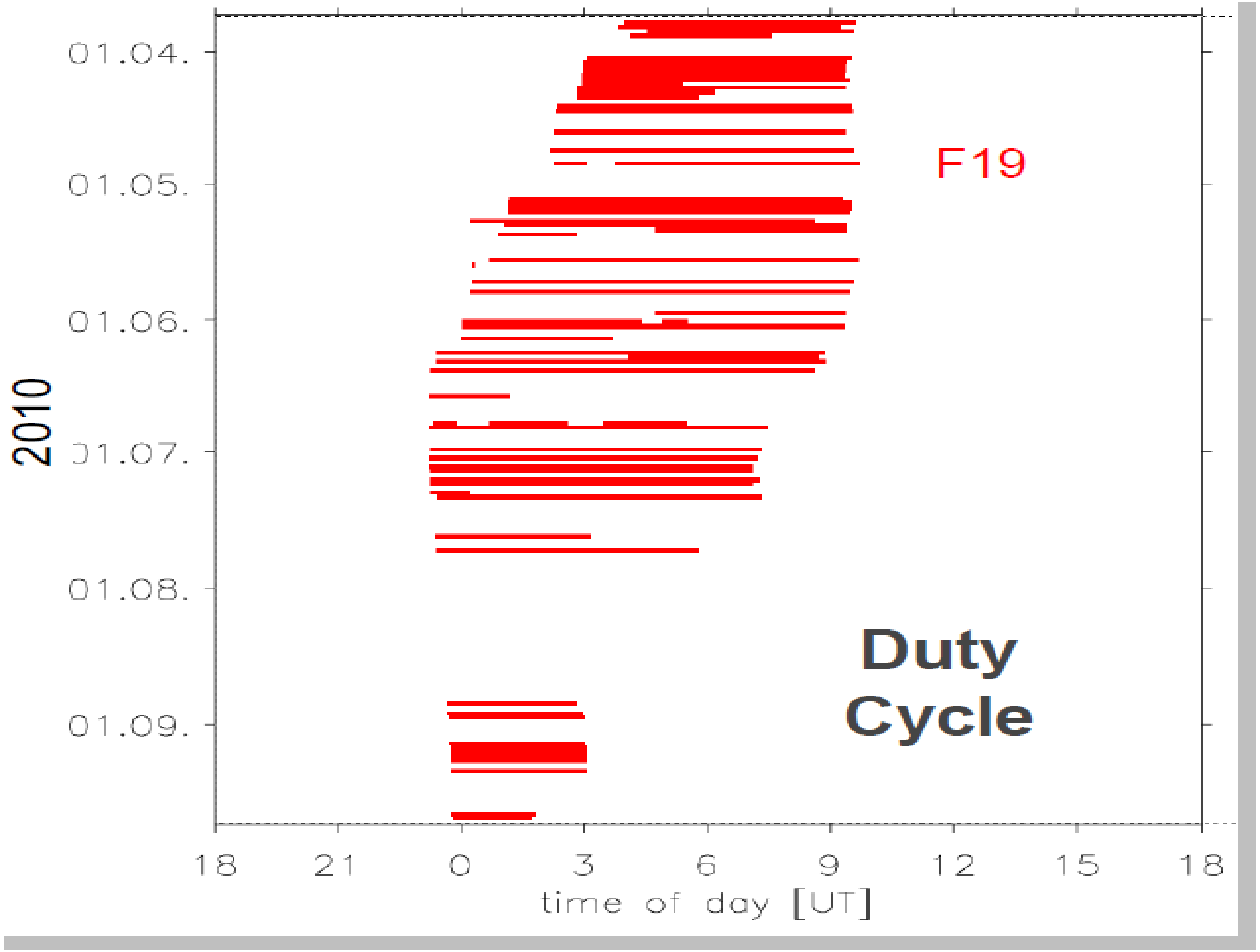
<u>Specifications:</u>

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



Duty cycle



01.04.
01.05.
01.06.
01.07.
01.08.
01.09.
2010
F19
Duty Cycle
18 21 0 3 6 9 12 15 18
time of day [UT]

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

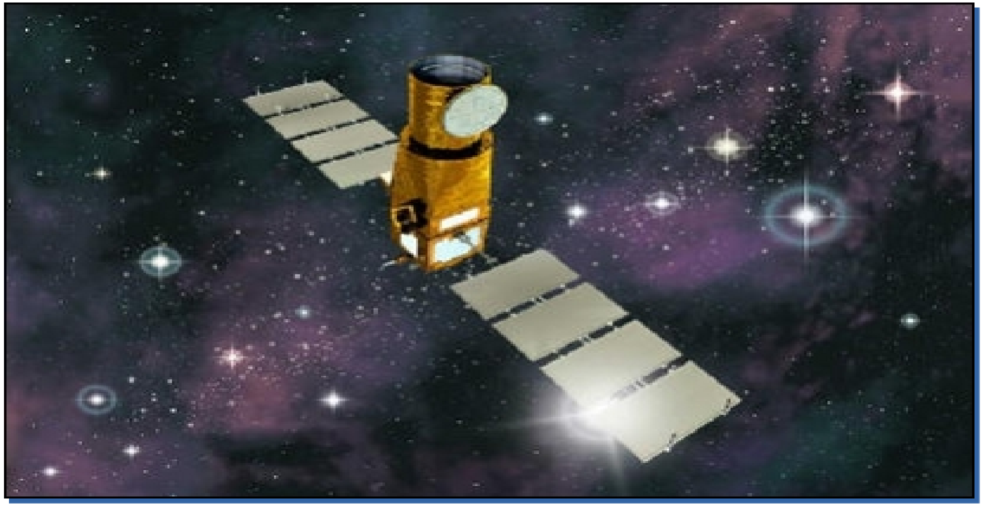
http://www.mpia.de/homes/mancini/hat-south.html

CoRoT

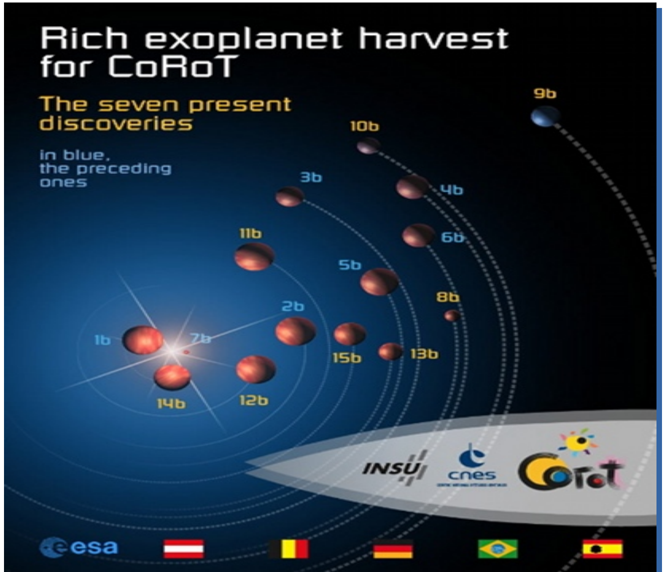
Convection, Rotation and planetary Transits

Launched 2006 – mission end 2013

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

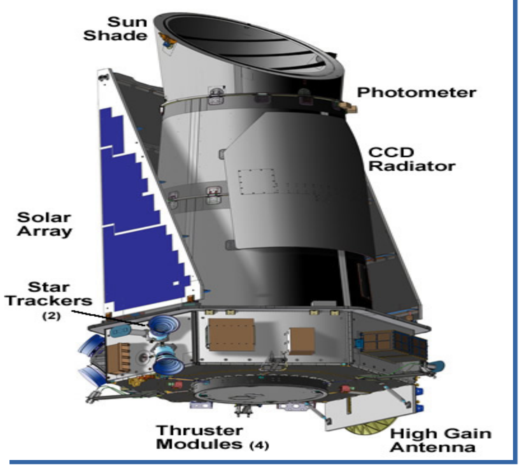


ESA webpages



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

Microlensing

The lense/Earth configuration does not repeat (usually)

It is difficult to confirm such planets

OGLE – Optical gravitational lensing experiment

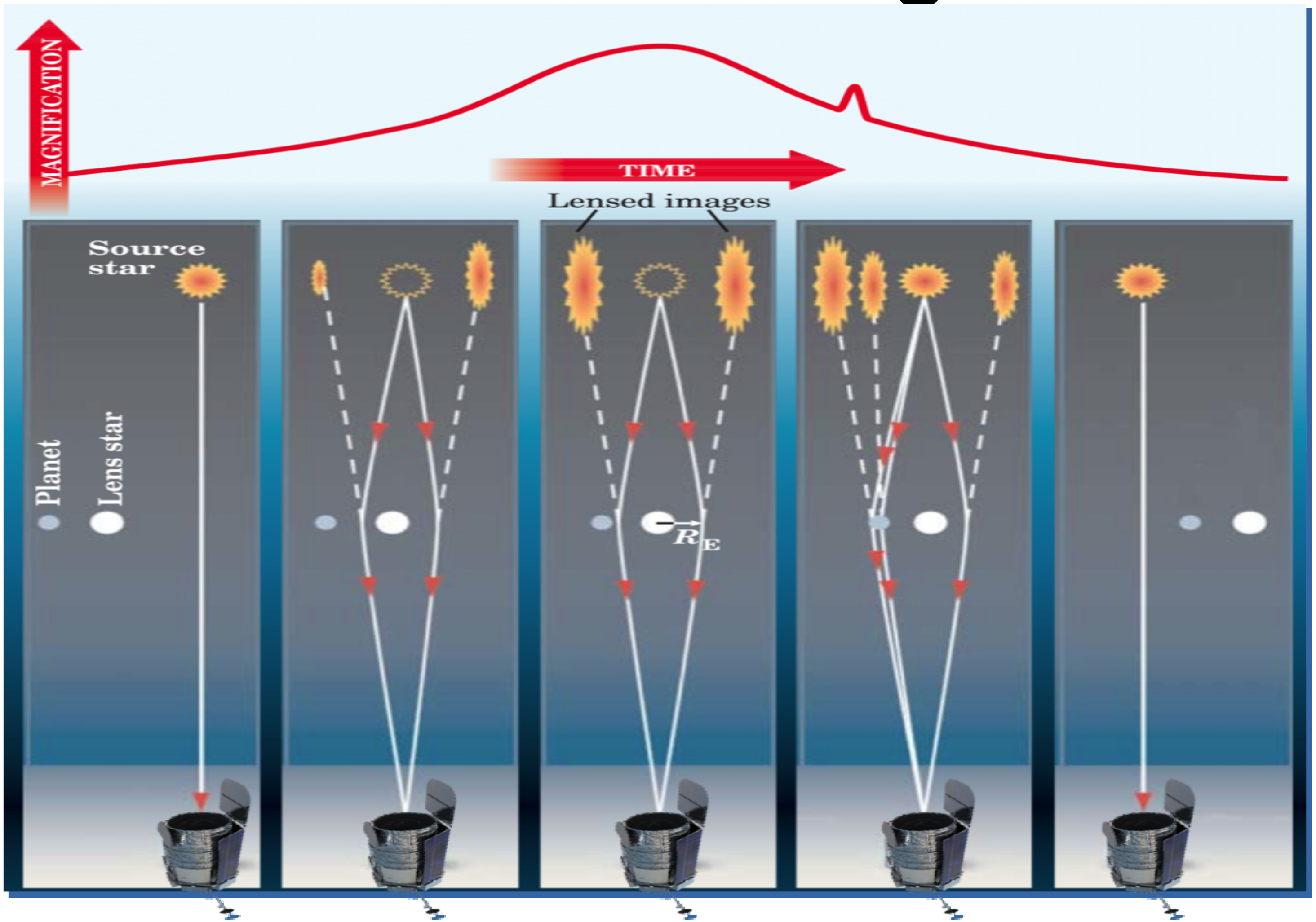
- 1.3m Las Campanas, Warsaw Univ.

- discovered planets by transit and microlensing (about 20)

- typically fainter stars

http://www.astrouw.edu.pl/index.php/ogle-article

Microlensing



http://wfirst.gsfc.nasa.gov/learn/exoplanets/

Astrometry

- Astrometric signature on sky measurable:

$$\alpha = \left(\frac{M_{\rm p}}{M_\star}\right)\left(\frac{a_{\rm p}}{1\ {\rm AU}}\right)\left(\frac{d}{1\ {\rm pc}}\right)^{-1} {\rm arcsec}$$

- Astrometric signature of planets usually 10 µas and less
- For some planets (Jupiters), detectable by Gaia

Astrometry

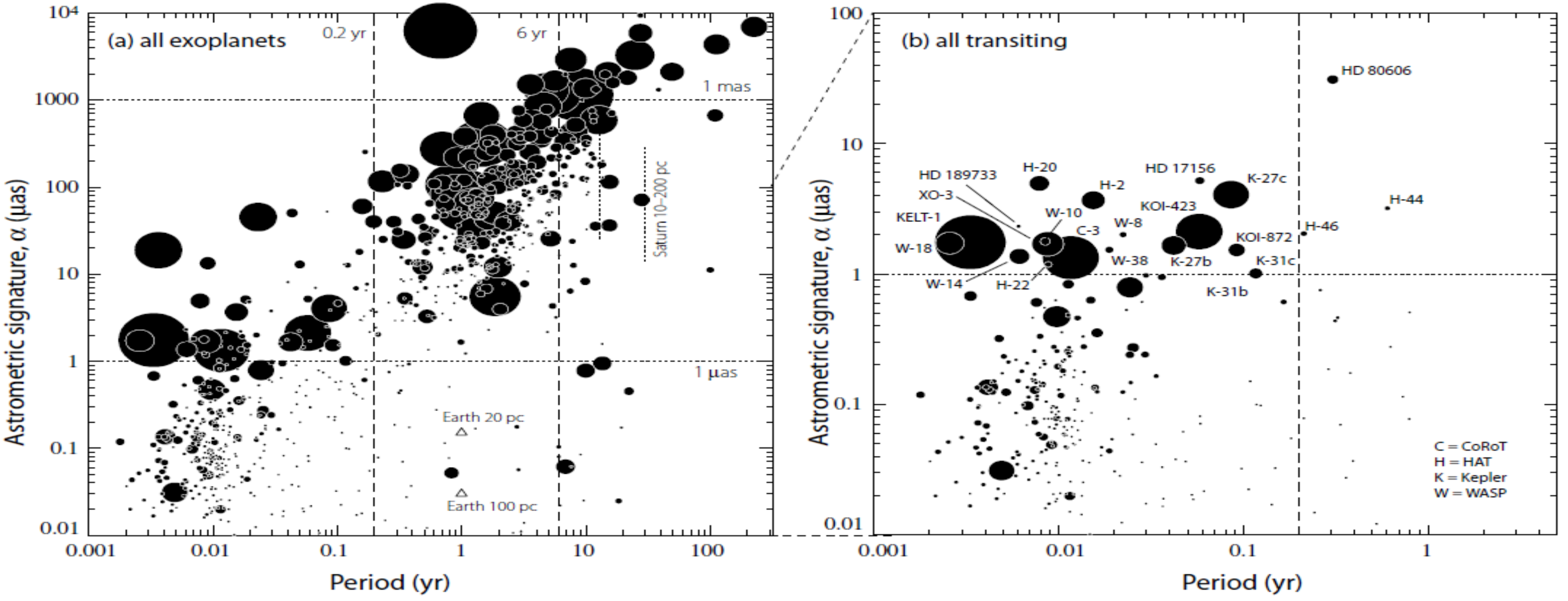
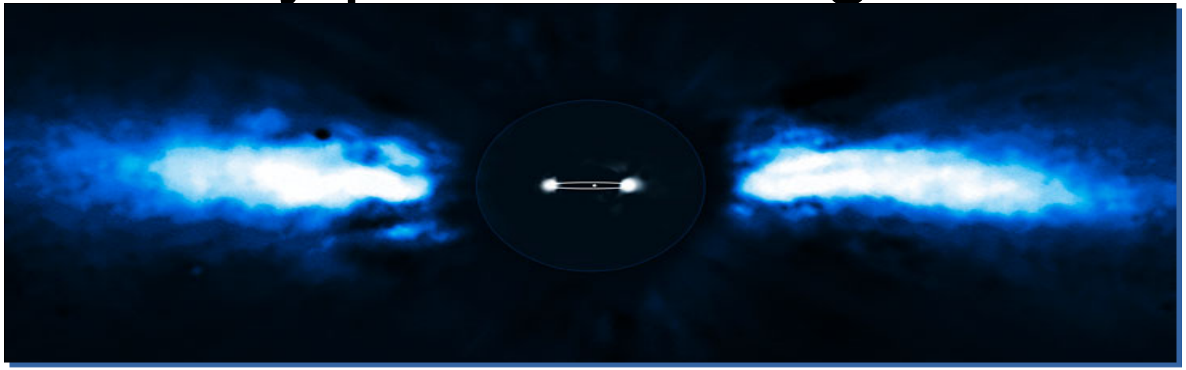


Fig. 1.— Astrometric signature versus period calculated for the objects listed in **exoplanet.eu** at 2014 September 1 for all 1821 confirmed planets (left), and for the subset of 1129 transiting planets with appropriately known data (right). Note the different scales in abscissa and ordinate. Circle sizes are proportional to planet mass; the prominent object (left) at $P = 0.7$ yr, $\alpha = 6300\,\mu$as, is the $28.5 M_{\rm J}$ astrometric detection DE0823–49 b. Unknown distances are set to $d = 1000$ pc. Transiting planets with $\alpha > 1\,\mu$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.

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

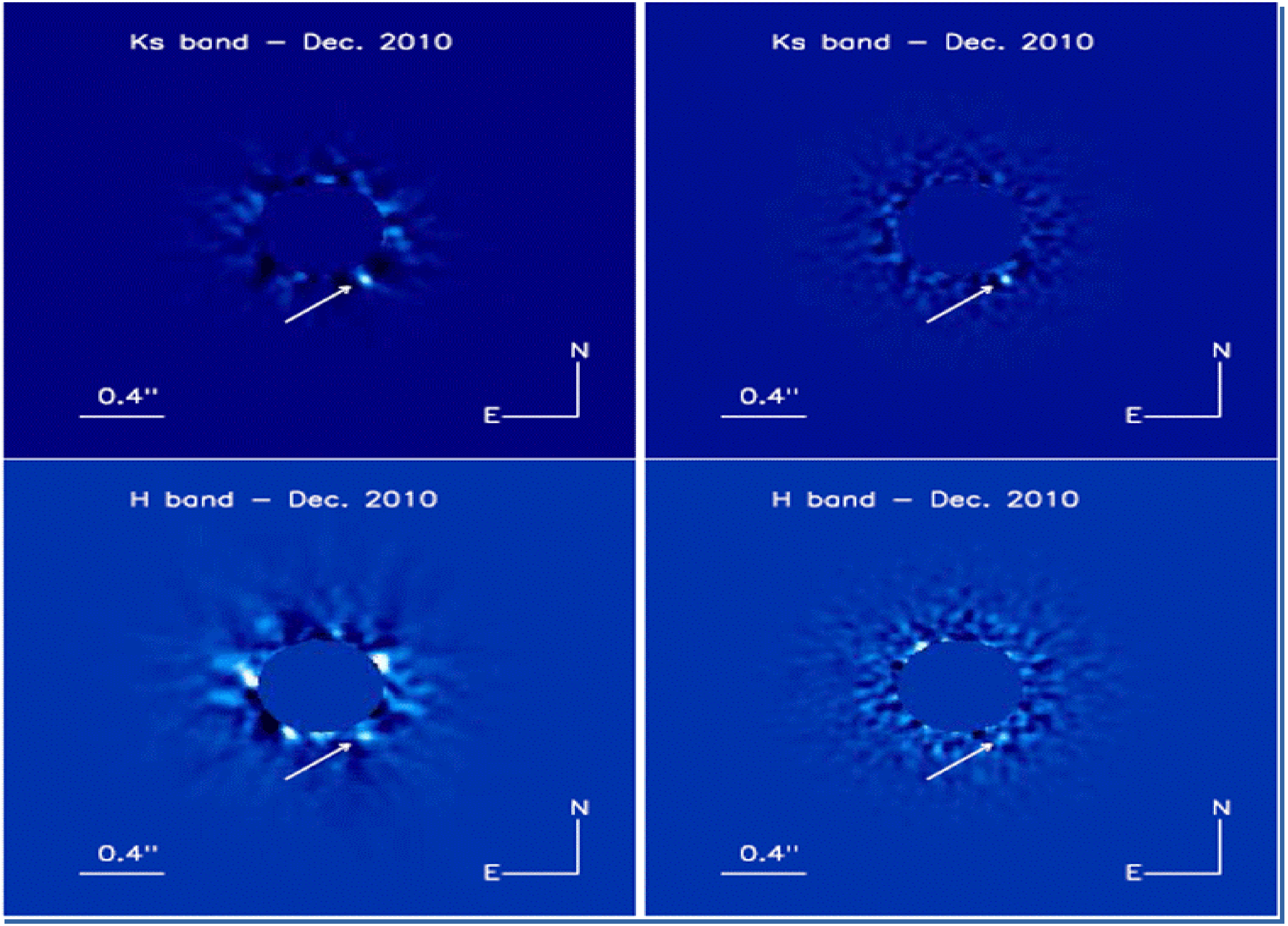
Direct imaging

- 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



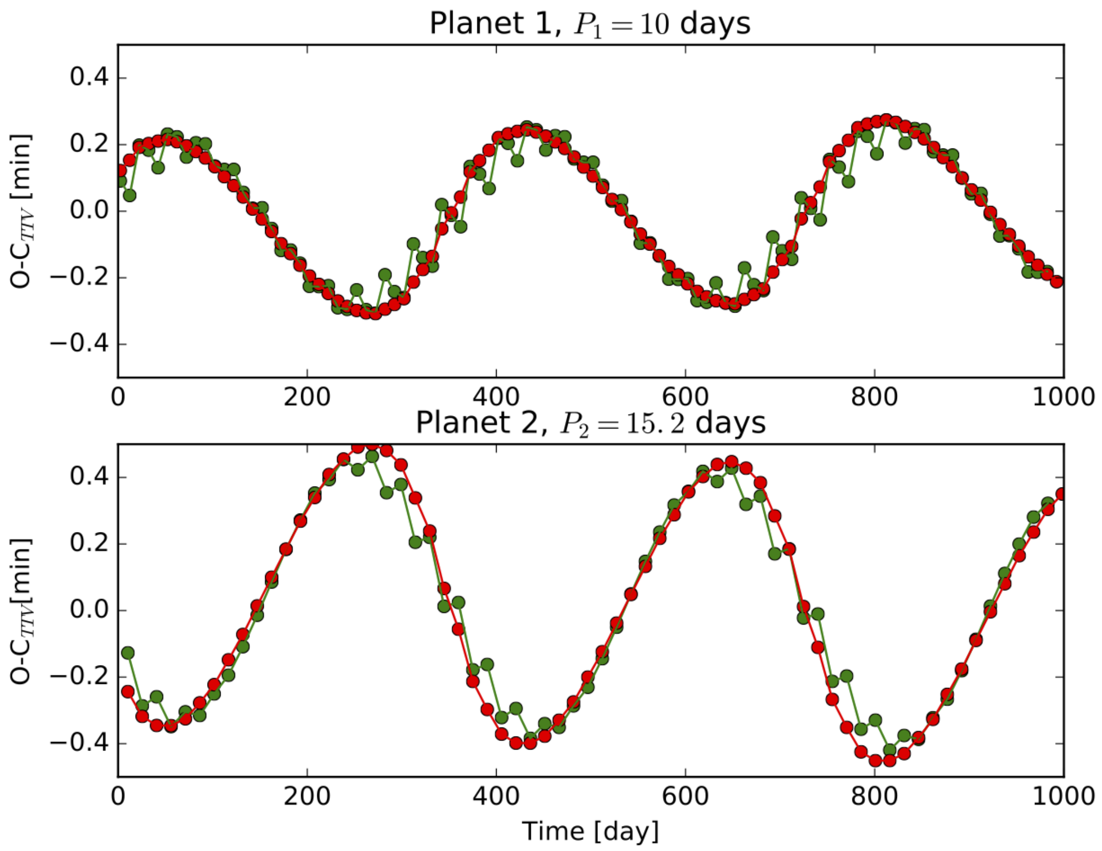
Credit : ESO press release (Beta Pic, A. Lagrange)

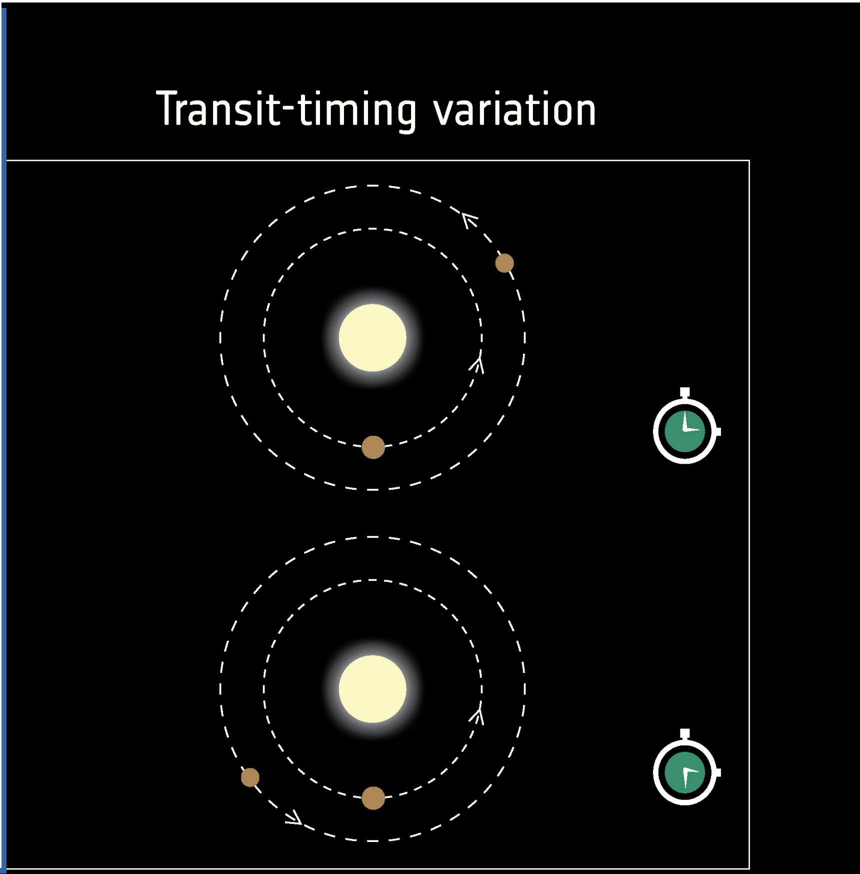
And here is a detail



http://www.aanda.org/component/content/article?id=908

Transit timing variations - TTV

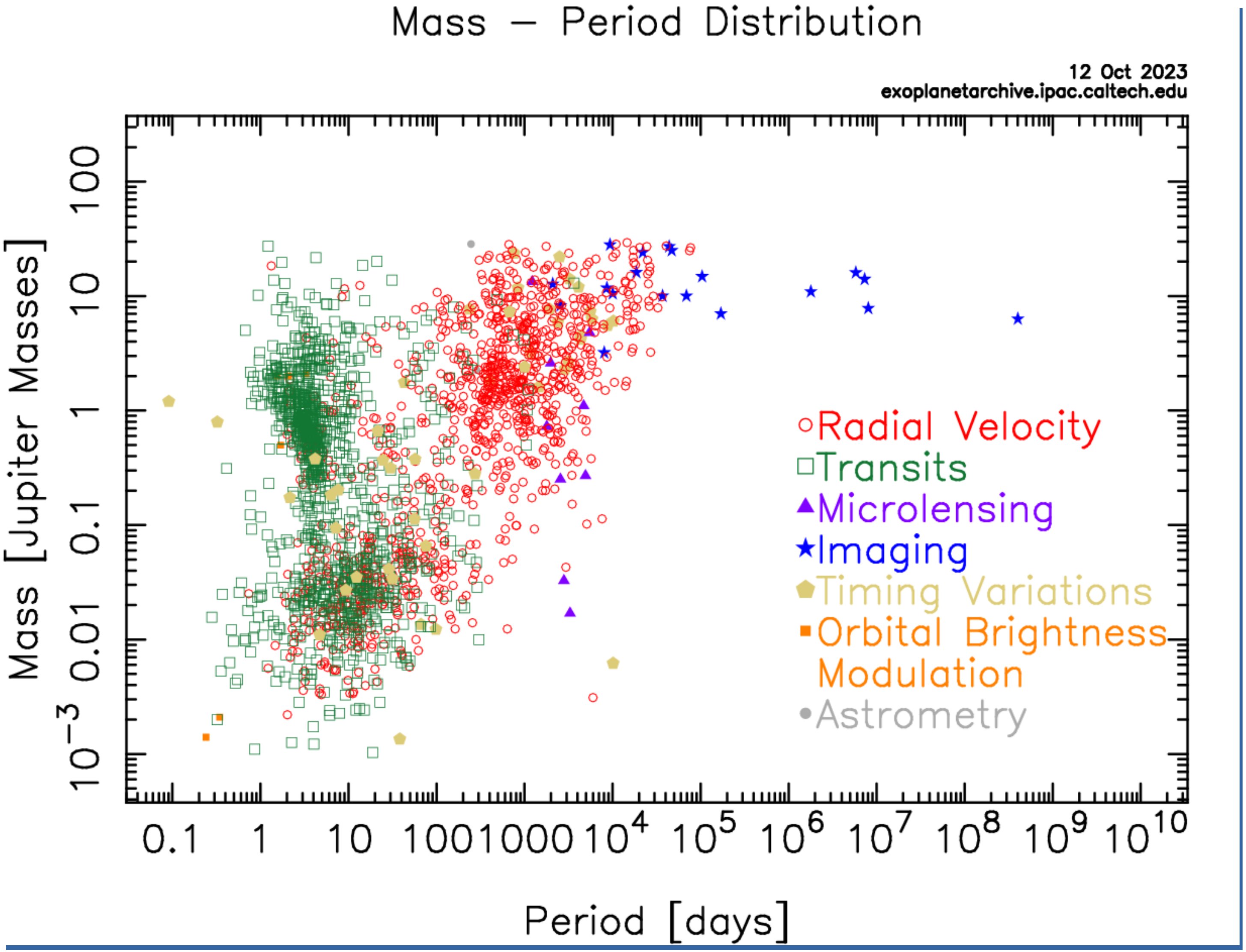




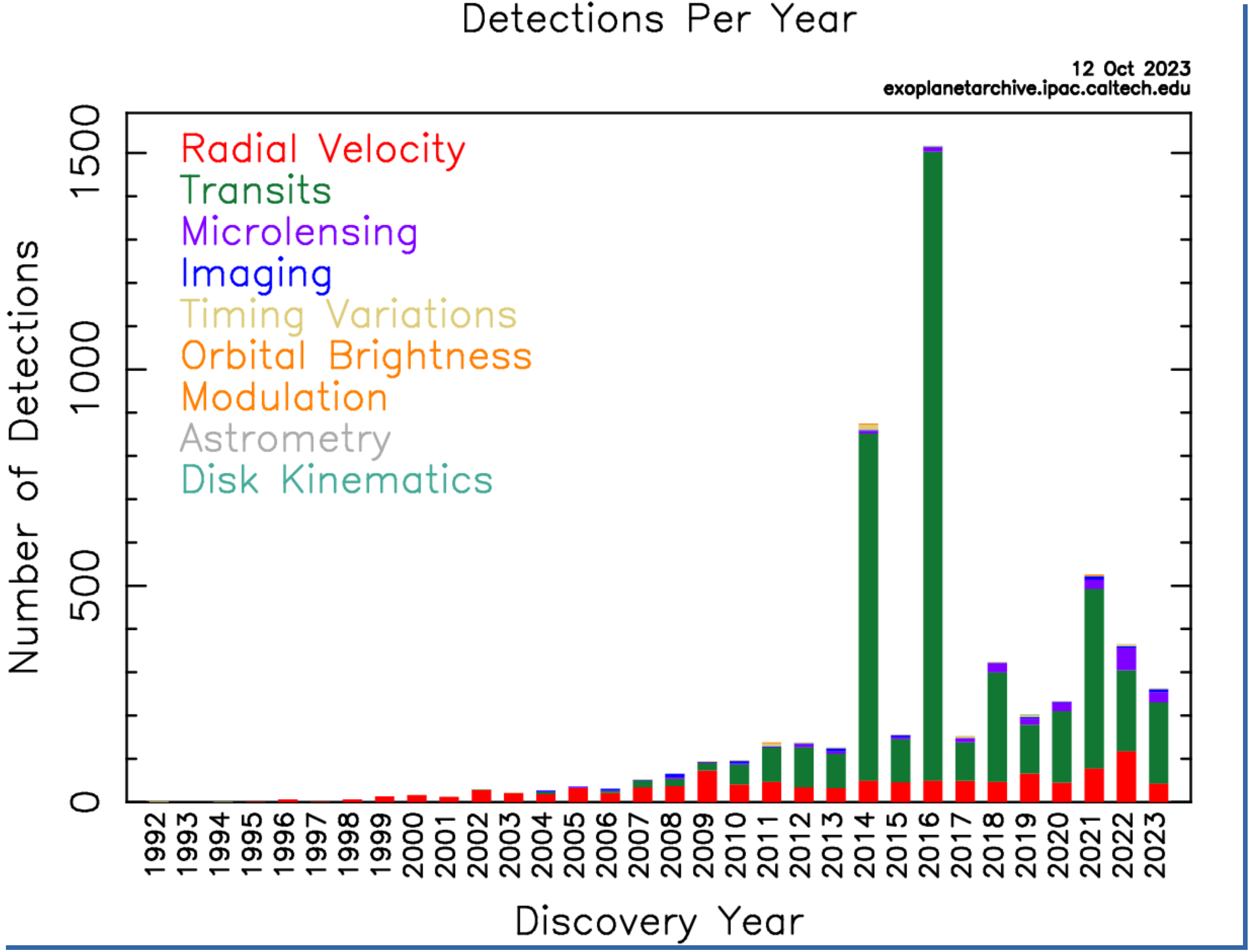
https://arxiv.org/pdf/1706.09849.pdf

ESA

Some statistics
Completeness of surveys

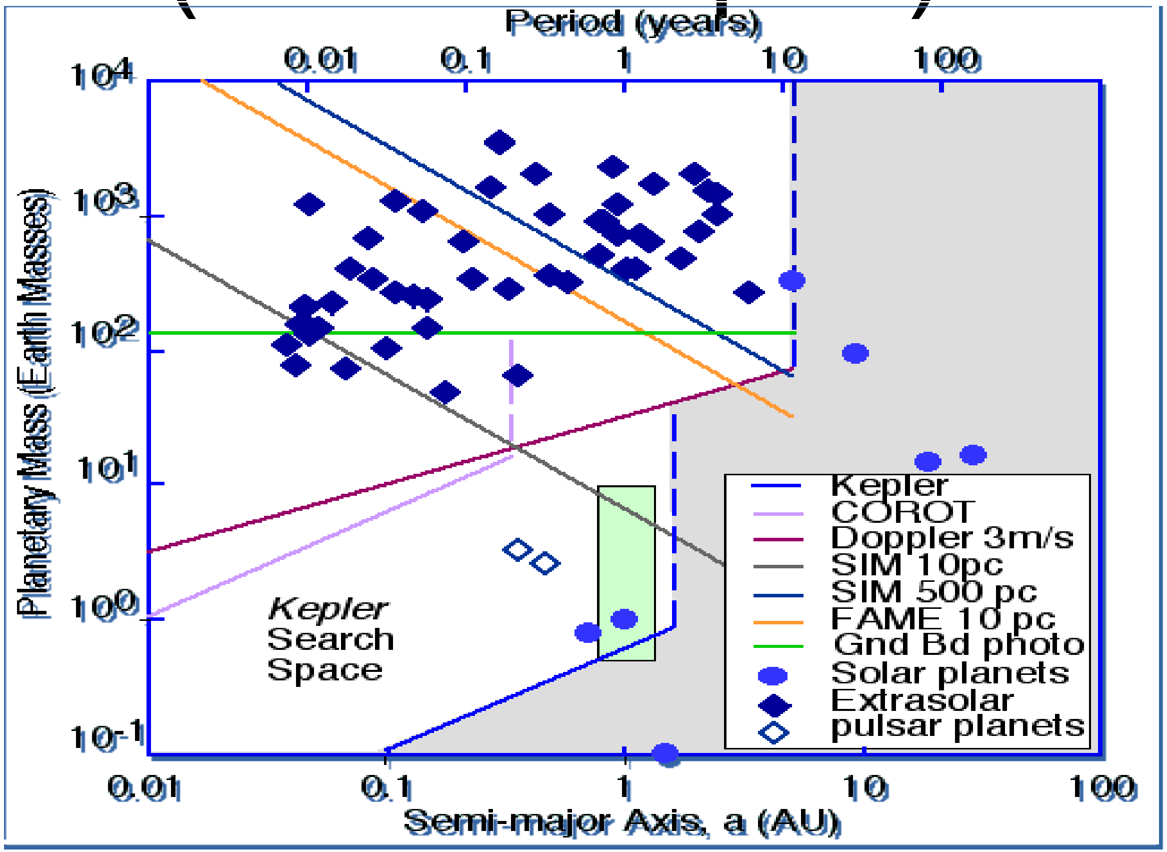


https://exoplanetarchive.ipac.caltech.edu/exoplanetplots/exo_massperiod.png



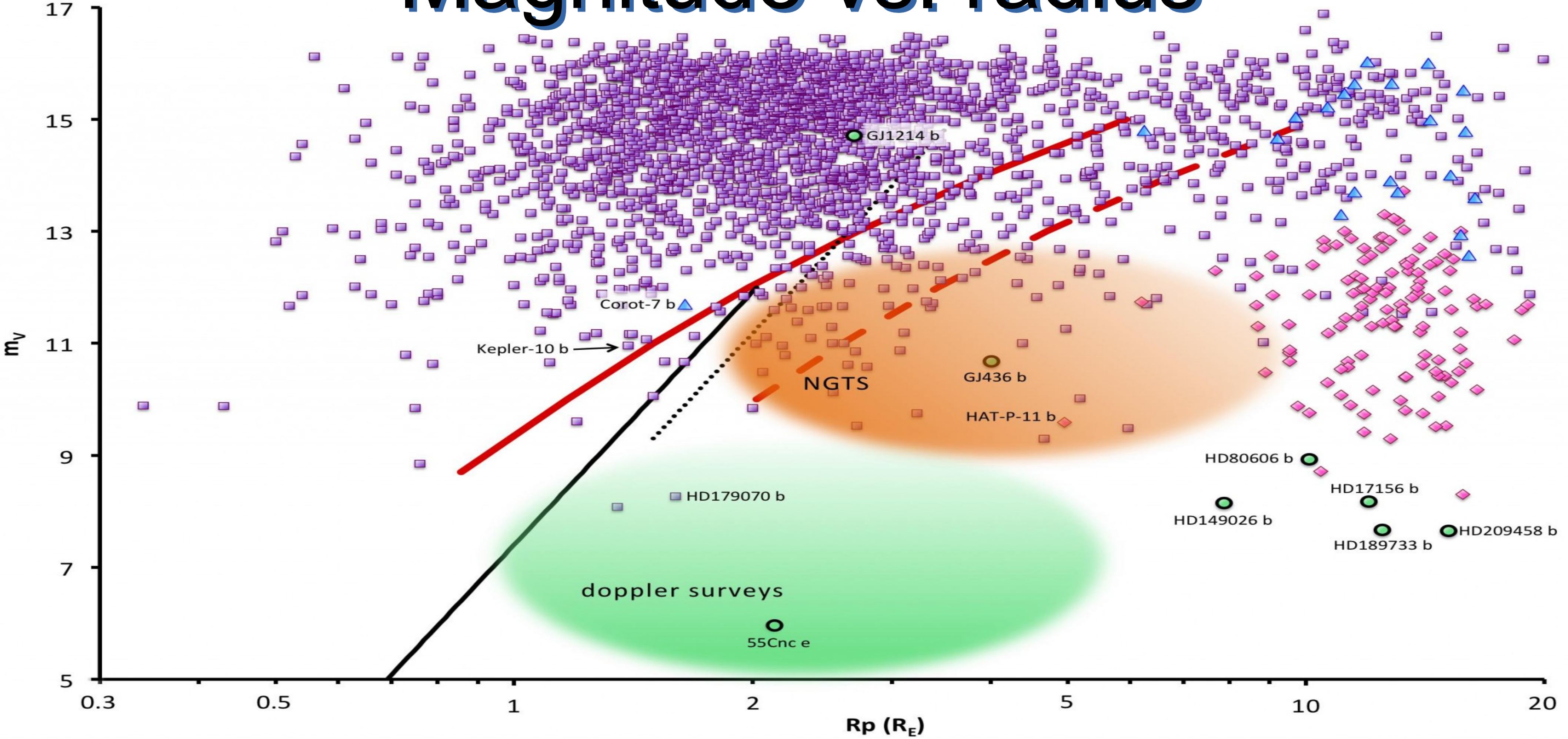
https://exoplanetarchive.ipac.caltech.edu/exoplanetplots/exo_dischist.png

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



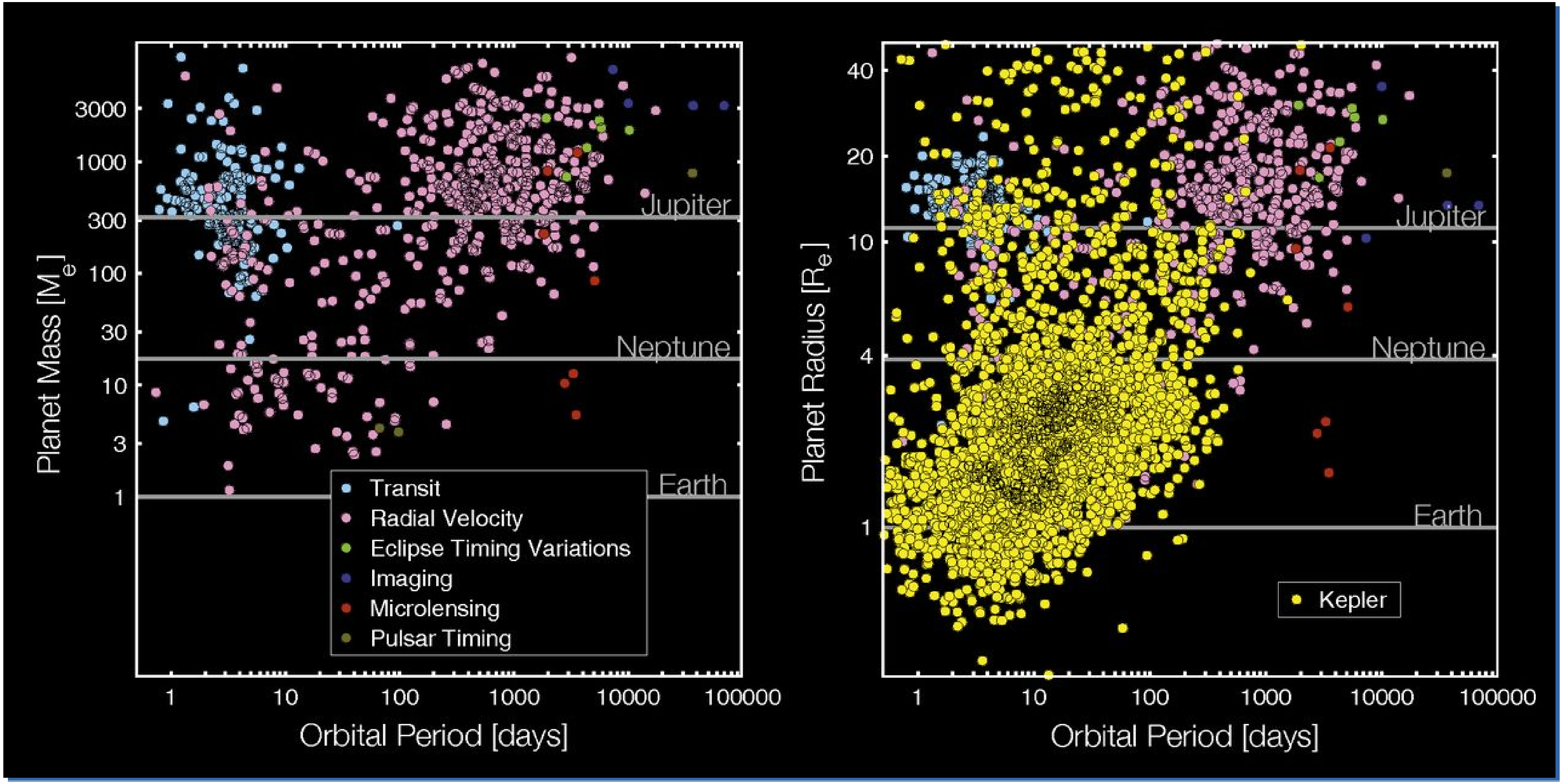
Credit: NASA

Magnitude vs. radius



http://cheops.unibe.ch/science/corot-kepler-vs-cheops/

And similar with Kepler



http://kepler.nasa.gov/news/nasakeplernews/index.cfm?FuseAction=ShowNews&NewsID=356

Mass. vs. distance to star

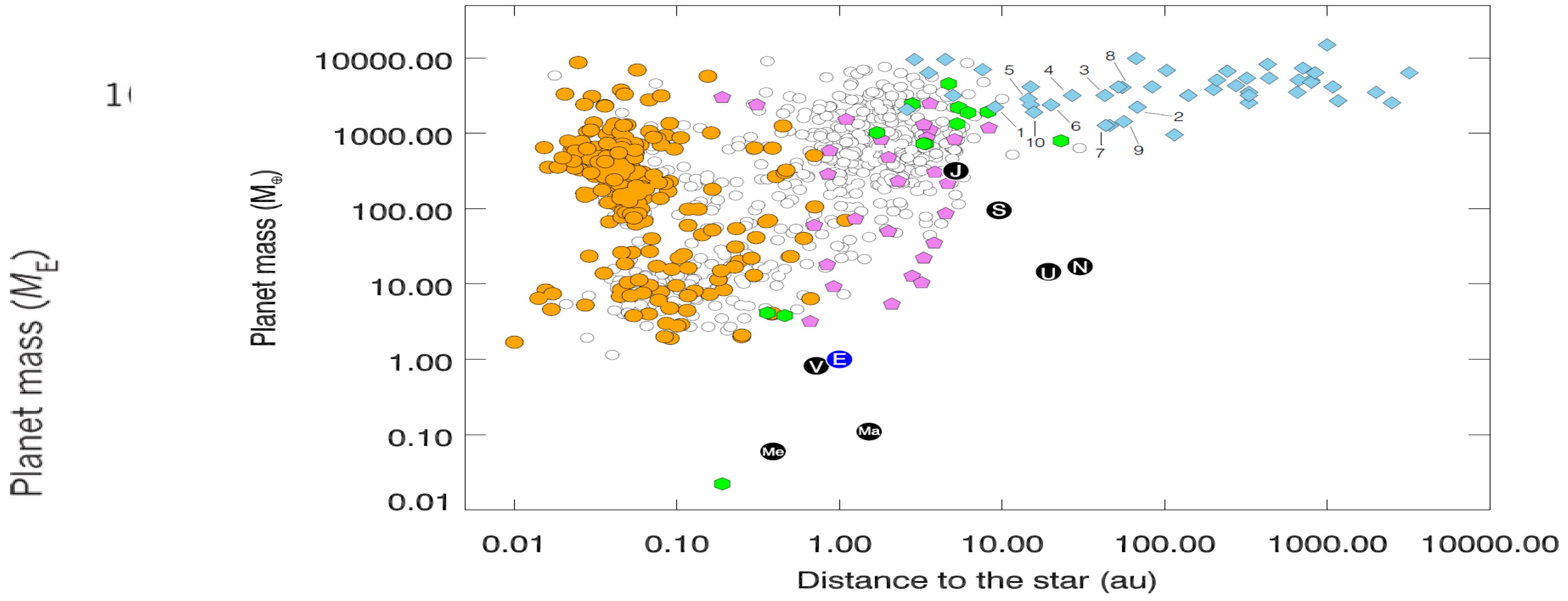
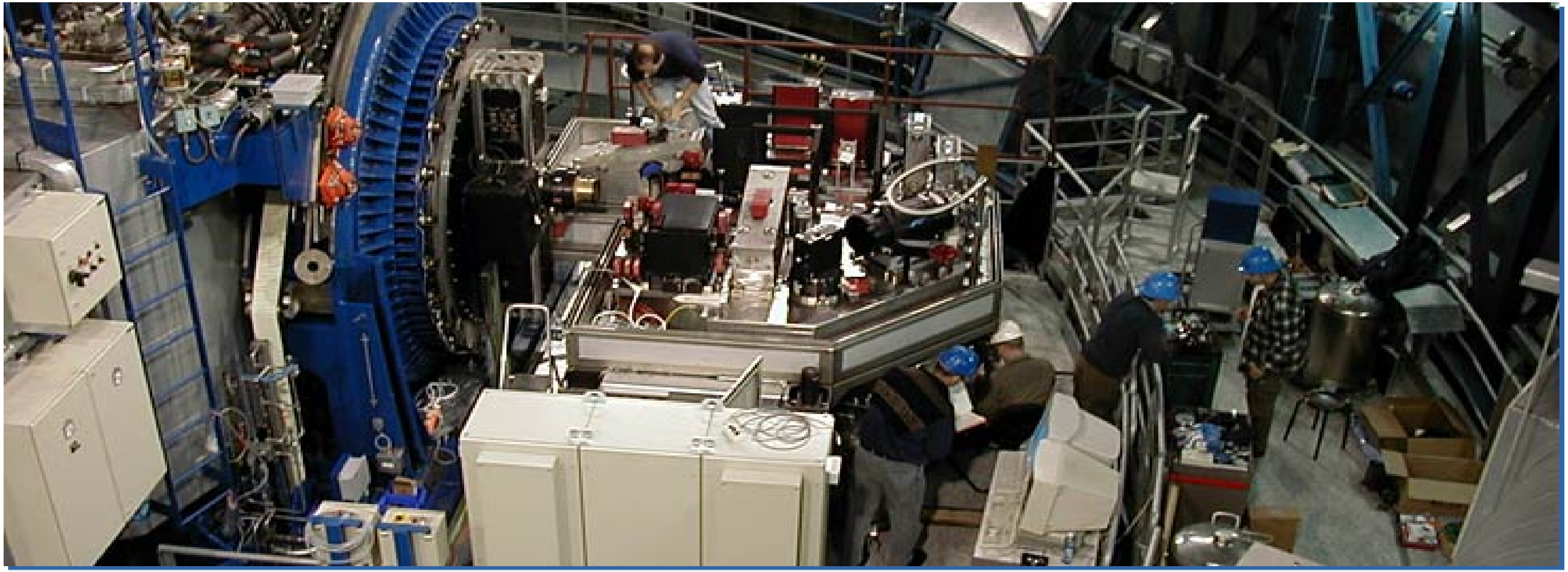


Figure 3: *Mass and semi-major axis of known planets.* Planetary mass is plotted as a function of semi-major axis (the distance to the host star). Solar-system planets are shown by black circles, the Earth in blue. Exoplanets detected with different techniques and instrumentation are represented by different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

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

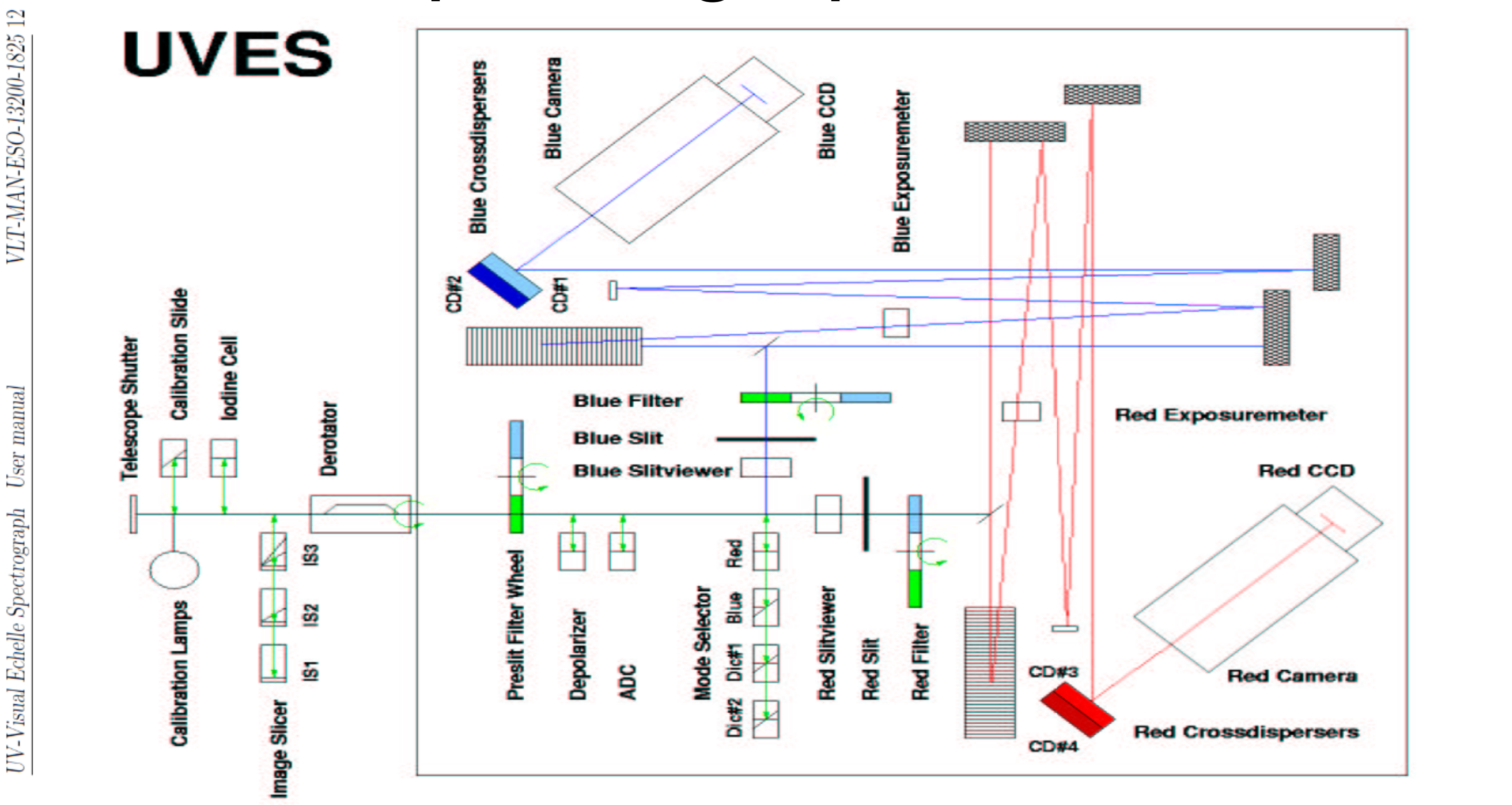
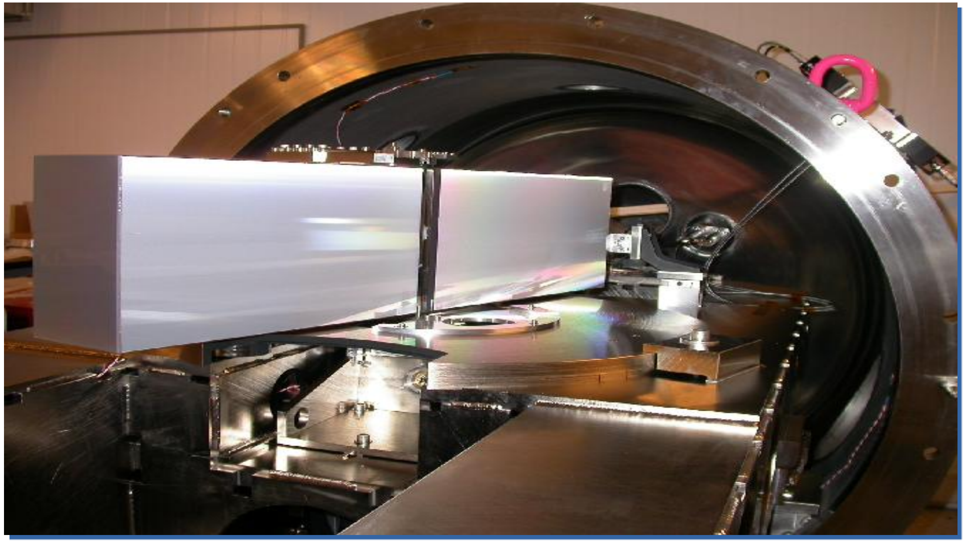


Figure 2.2: Schematic overview of the UVES spectrograph.

https://www.eso.org/sci/facilities/paranal/instruments/uves/doc/VLT-MAN-ESO-13200-1825_v93.pdf

HARPS- ESO La Silla

- High res. Echelle spectrograph (115000), slit, visual light 378-691nm
- RV accuracies to cm/s – extremely stable



http://www.eso.org/sci/facilities/lasilla/instruments/harps/overview.html

Long way towards exoplanets

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

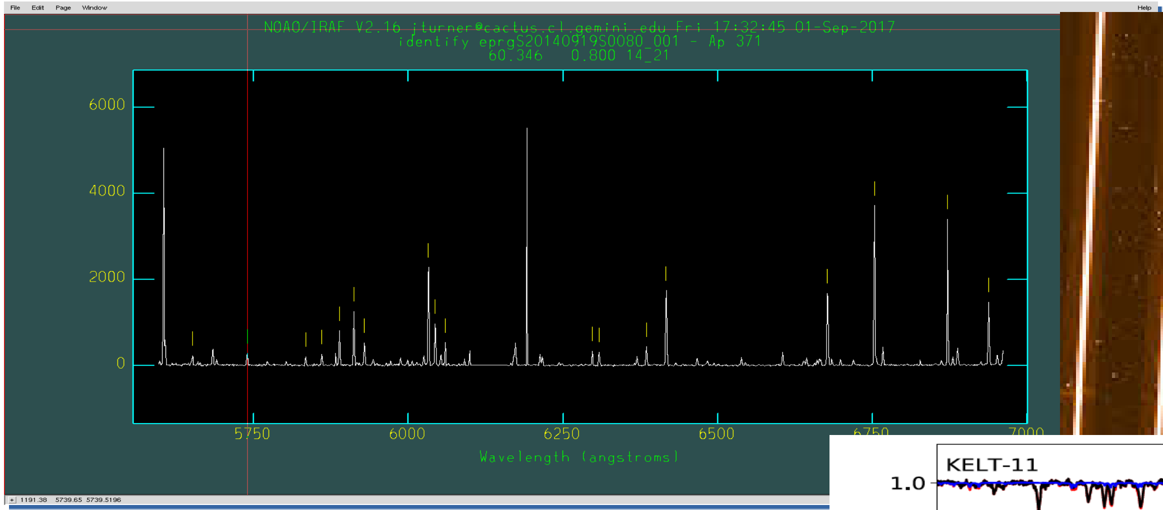
Image: ESO

Bruce Campbell and Gordon Walker

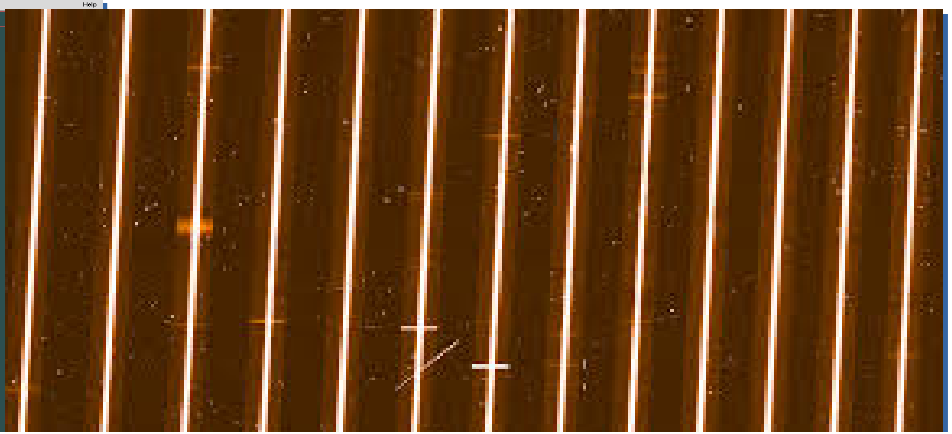
- First spectroscopic exoplanet survey 1971
- Hydrogen Fluoride cell for calibration
- The goal is to convert pixel scale (detector) into wavelength as accurately as possible
- http://articles.adsabs.harvard.edu/pdf/1979PASP...91..540C

https://dtm.carnegiescience.edu/news/brief-personal-history-exoplanets

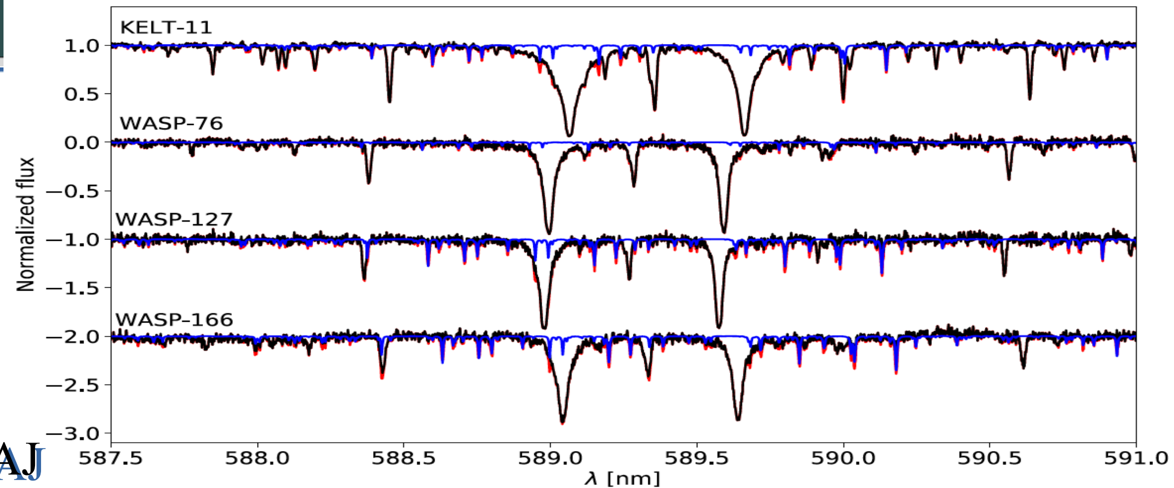
Importance of the wavelength calibration



GMOS tutorial

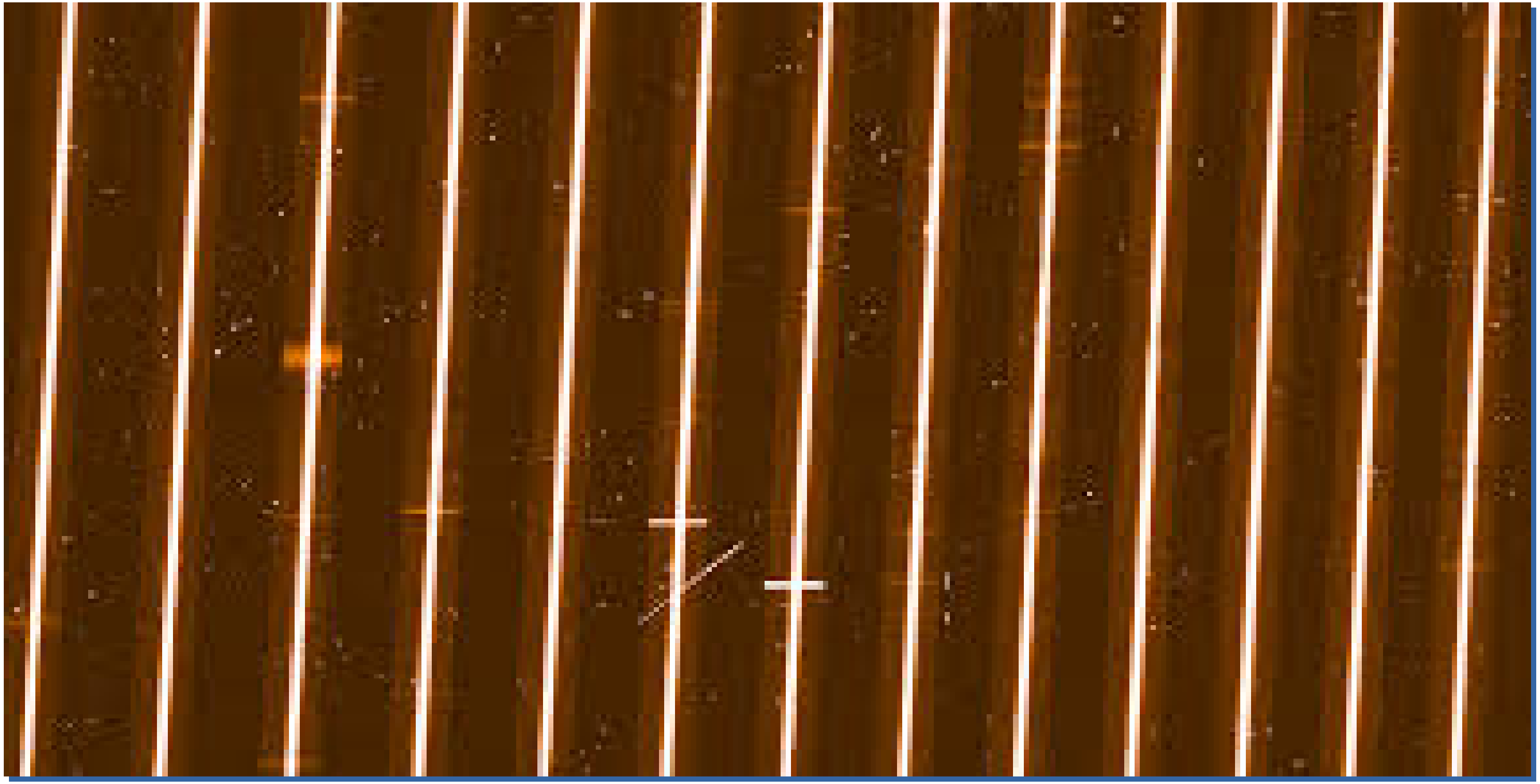


Getting from raw spectra to calibrated spectra



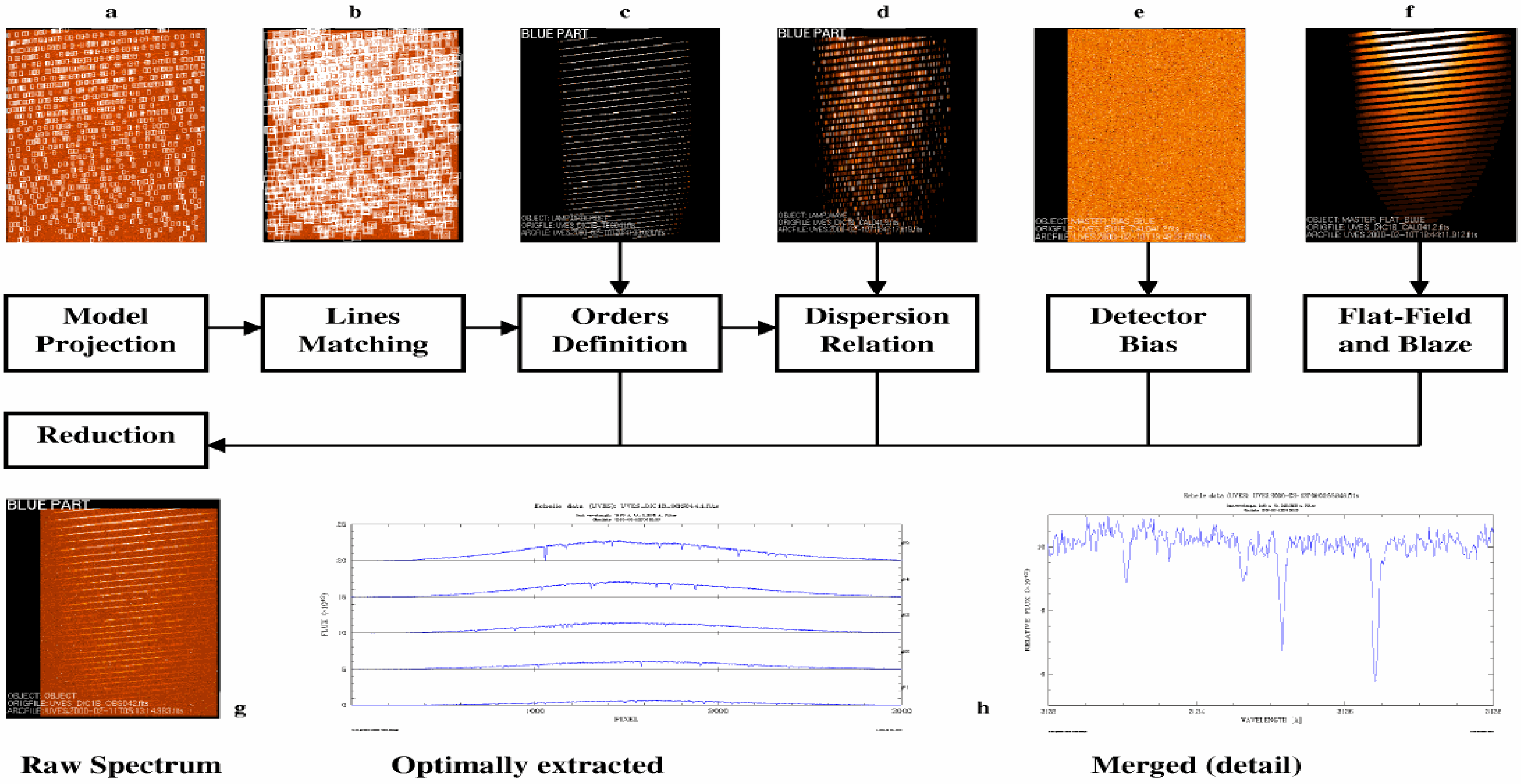
Zak et al. 2020, AJ

UVES frame example



Credit: ESO

ESO UVES data reduction process



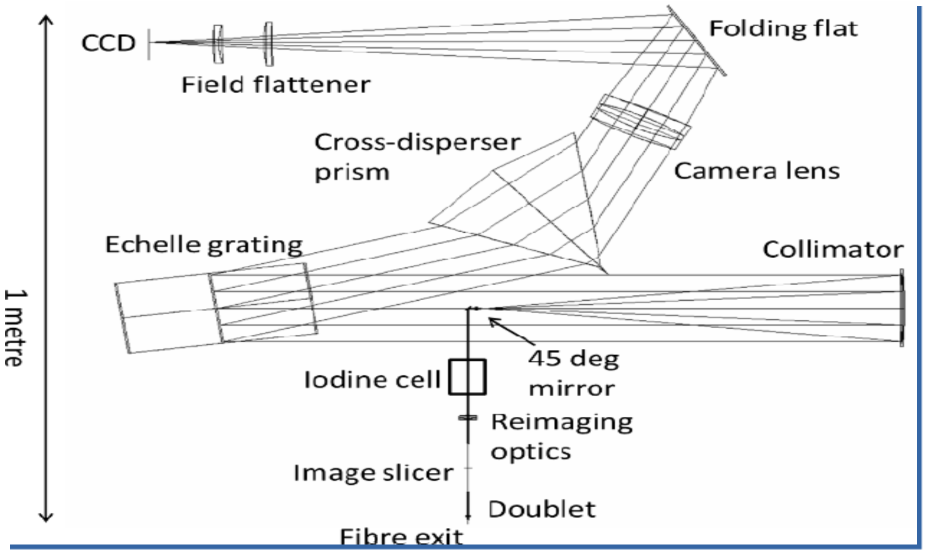
Ballester, et al.

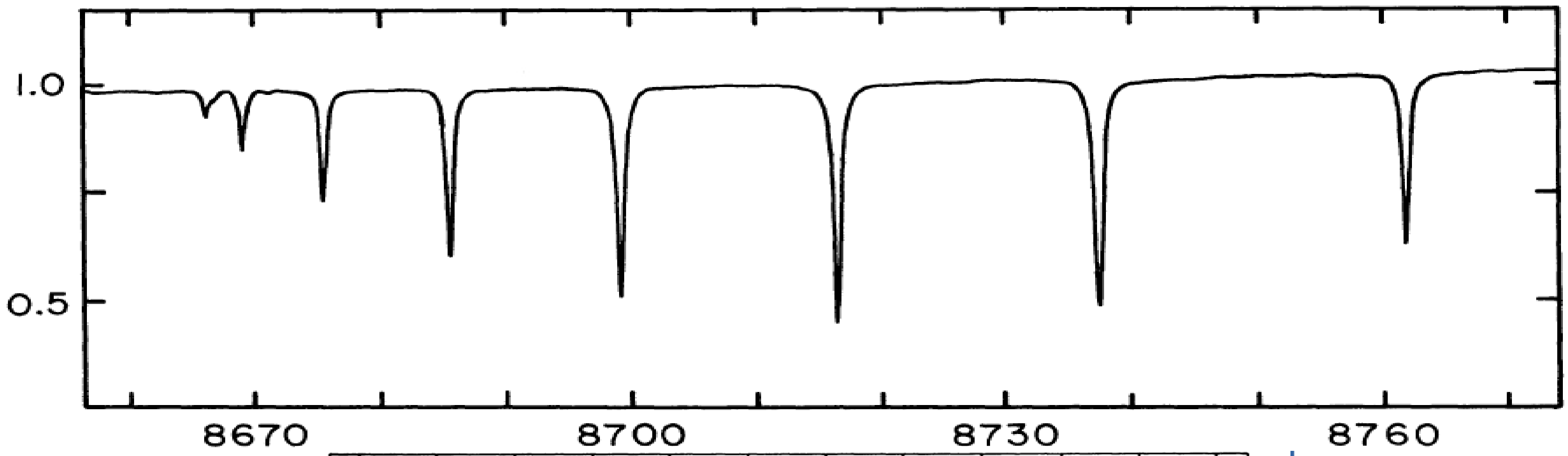
https://www.eso.org/observing/dfo/quality/publ/Messenger/UVES_Messenger_101.html

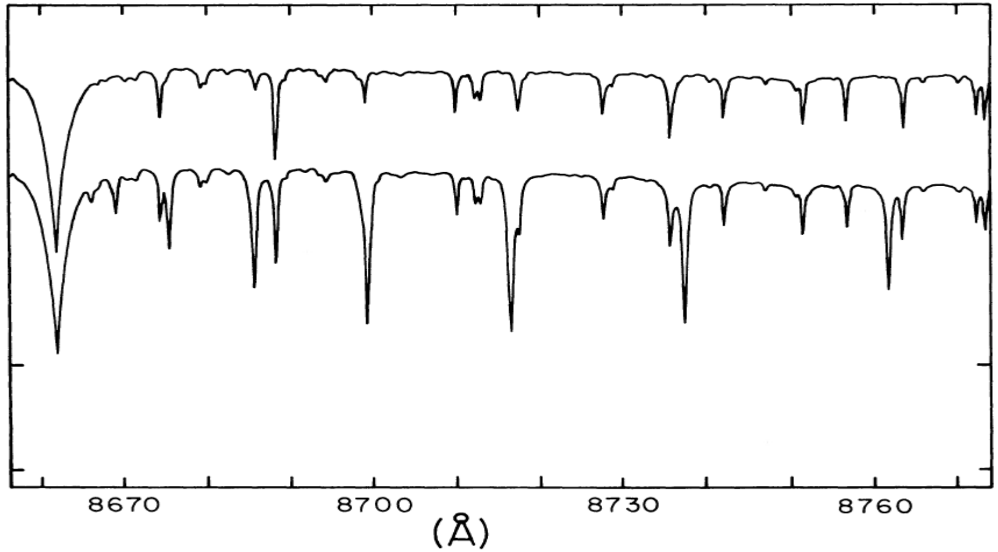
Why an absorption cell?

- HF lines clearly defined
- Increasing the stability
- Precision down to 15 m/s
- However HF is dangerous!
- Needs to be filled for each night
- Lines cover limited wavelengths
- Iodine was another choice
- Iodine is less dangerous

Chiron design CTIO - Schwab et al. 2010, SPIE

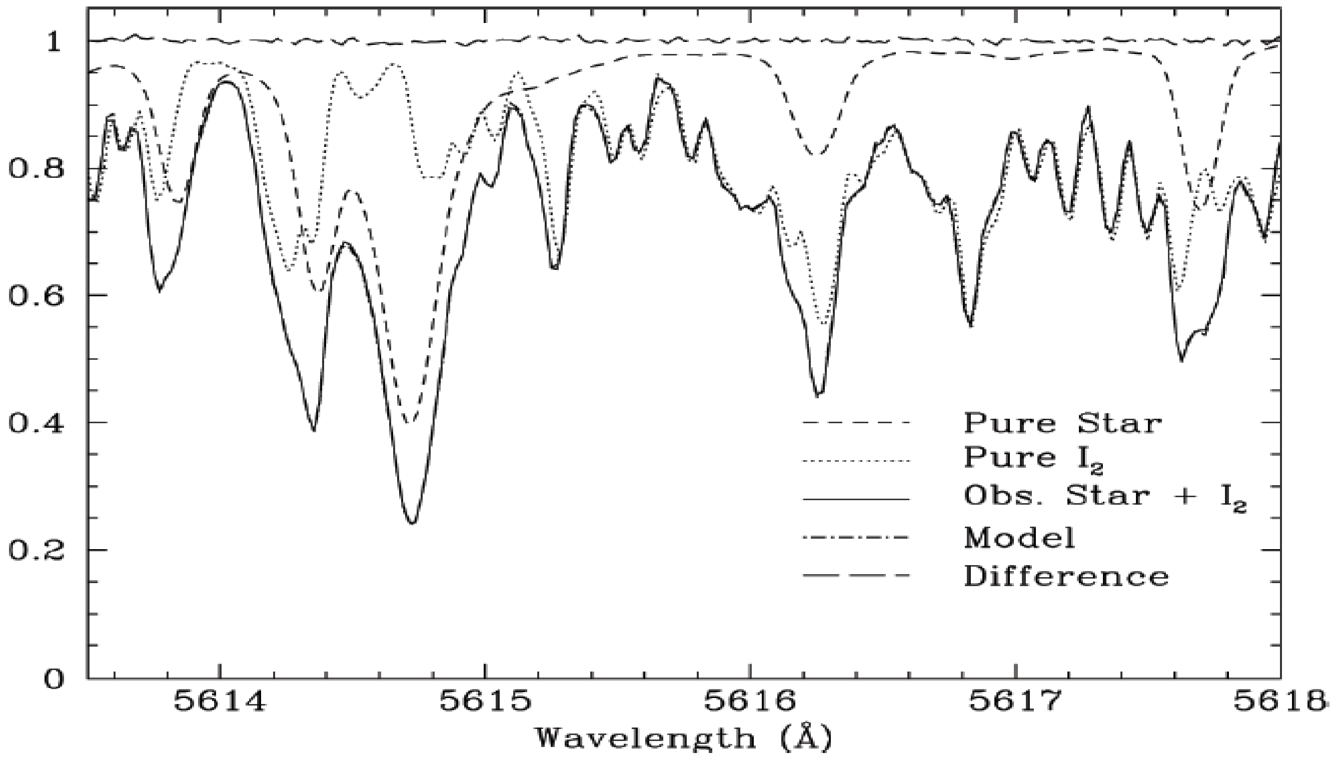






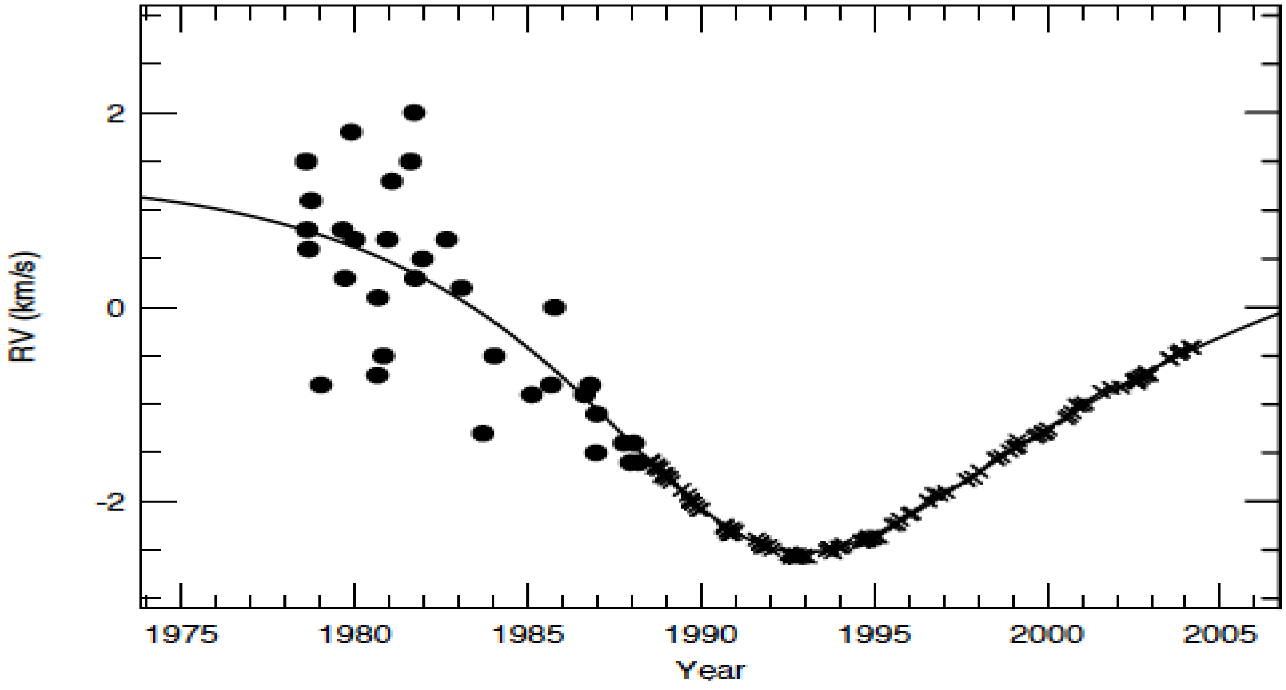
http://articles.adsabs.harvard.edu/pdf/1979PASP...91..540C

Iodine



From Hatzes, Cochran and Endl - The Detection of Extrasolar Planets using Precise Stellar Radial Velocities

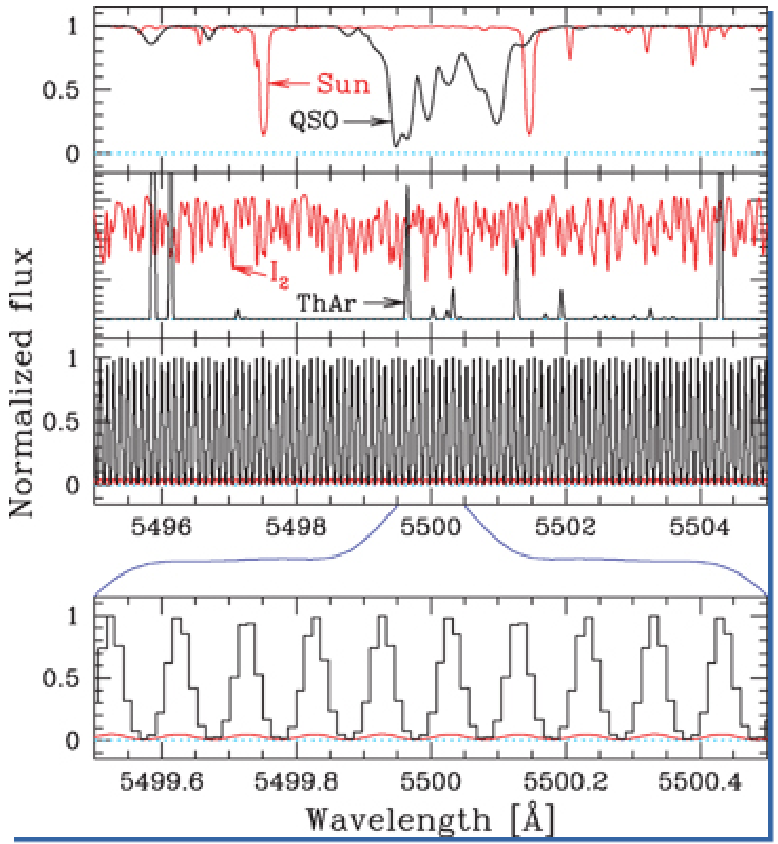
Iodine and no iodine



Gamma Cep with Iodine and without Iodine cell - figure from Hatzes, Cochran and Endl - The Detection of Extrasolar Planets using Precise Stellar Radial Velocities

Laser frequency combs

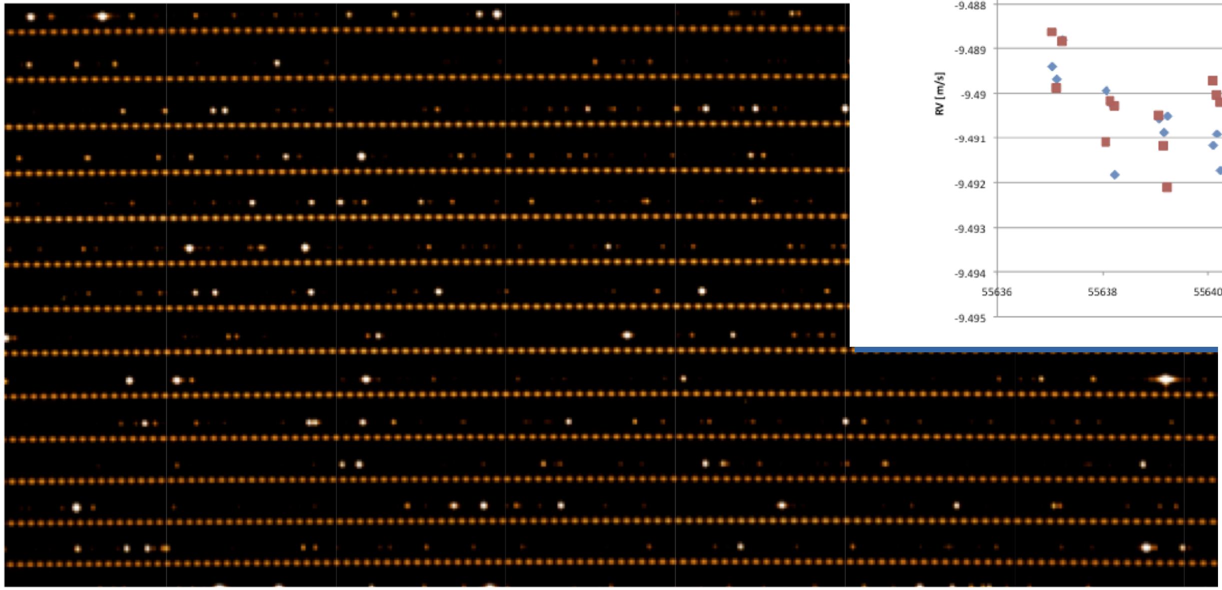
- Femtosecond lasers
- Very precise, laser combs related to atomic clock

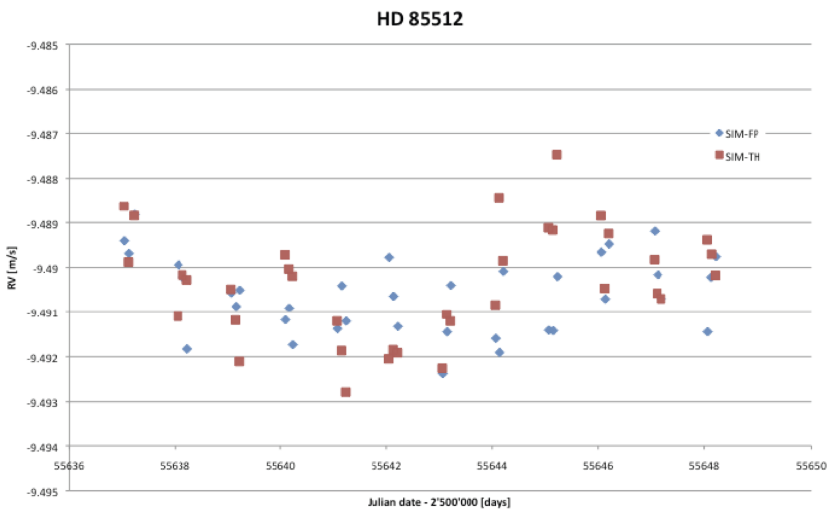


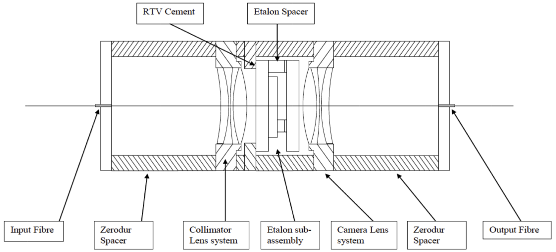
M. T. Murphy, Th. Udem, R. Holzwarth, A. Sizmann, L. Pasquini, C. Araujo-Hauck, H. Dekker, S. D'Odorico, M. Fischer, T. W. HÃ¤nsch, A. Manescau, High-precision wavelength calibration of astronomical spectrographs with laser frequency combs,Â Monthly Notices of the Royal Astronomical Society, Volume 380, Issue 2, August 2007, Pages 839â€“847,Â https://doi.org/10.1111/j.1365-2966.2007.12147.x

Fabry perot etalon

- More stable than ThAr
  cm/s level

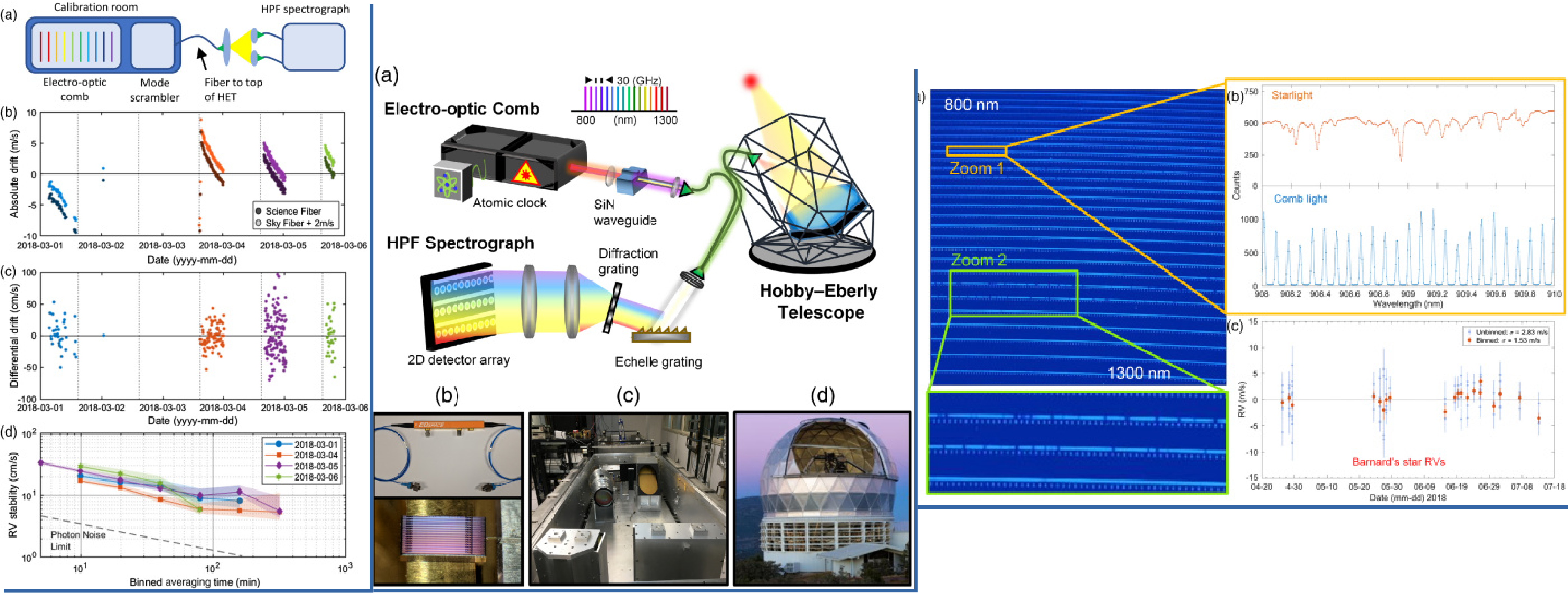






http://obswww.unige.ch/~wildif/publications/2011_8151-51.pdf

Laser frequency combs nowadays



Metcalf et al., 2019, https://opg.optica.org/optica/fulltext.cfm?uri=optica-6-2-233&id=405187

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