Exoplanets

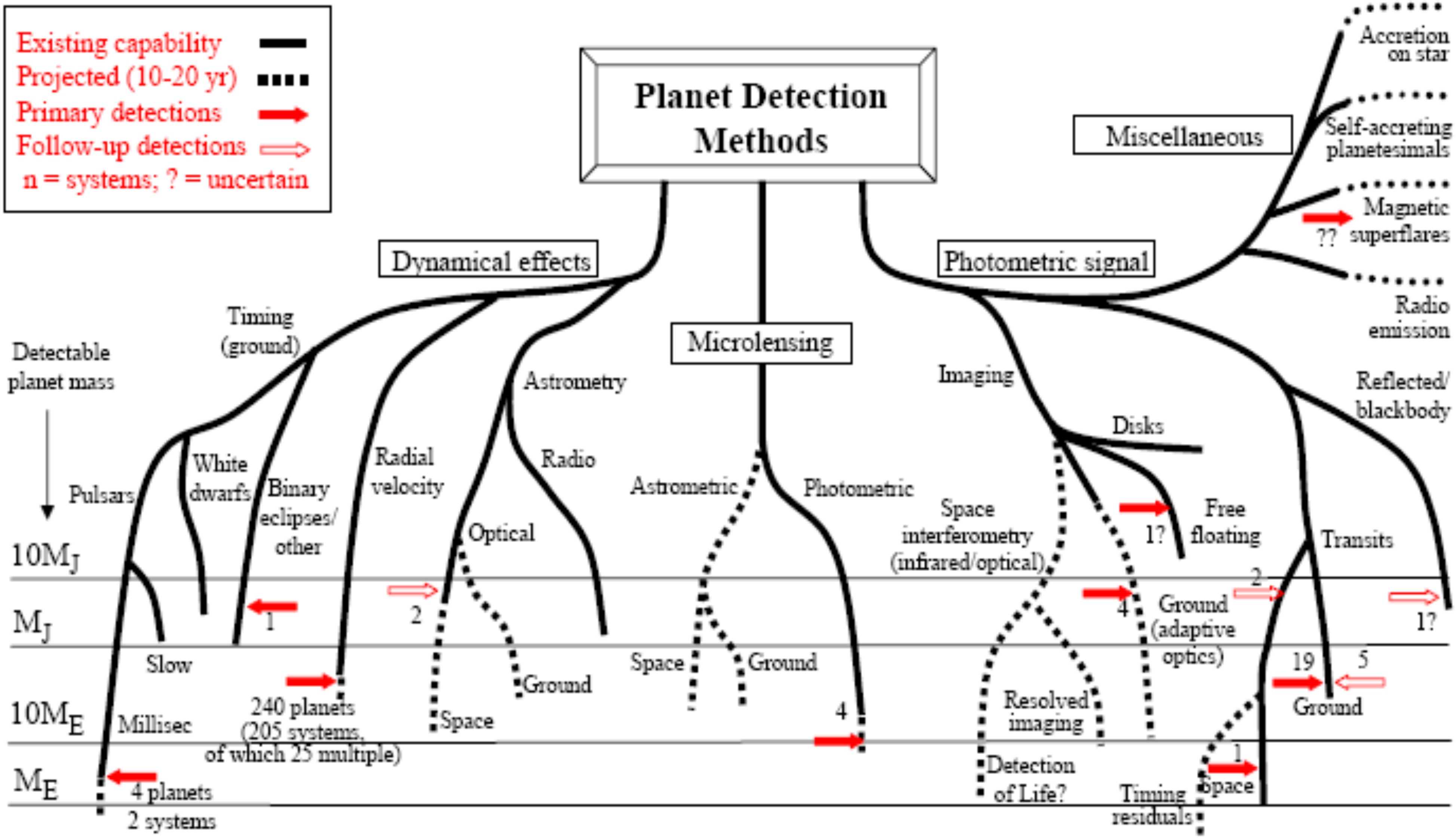
Fall/Winter 2021/2022
Lecture 2
8.10.2021

Outline

- Introduction of detection methods
- Radial velocities
- Transit detection
- Other methods
- The story of the first exoplanet

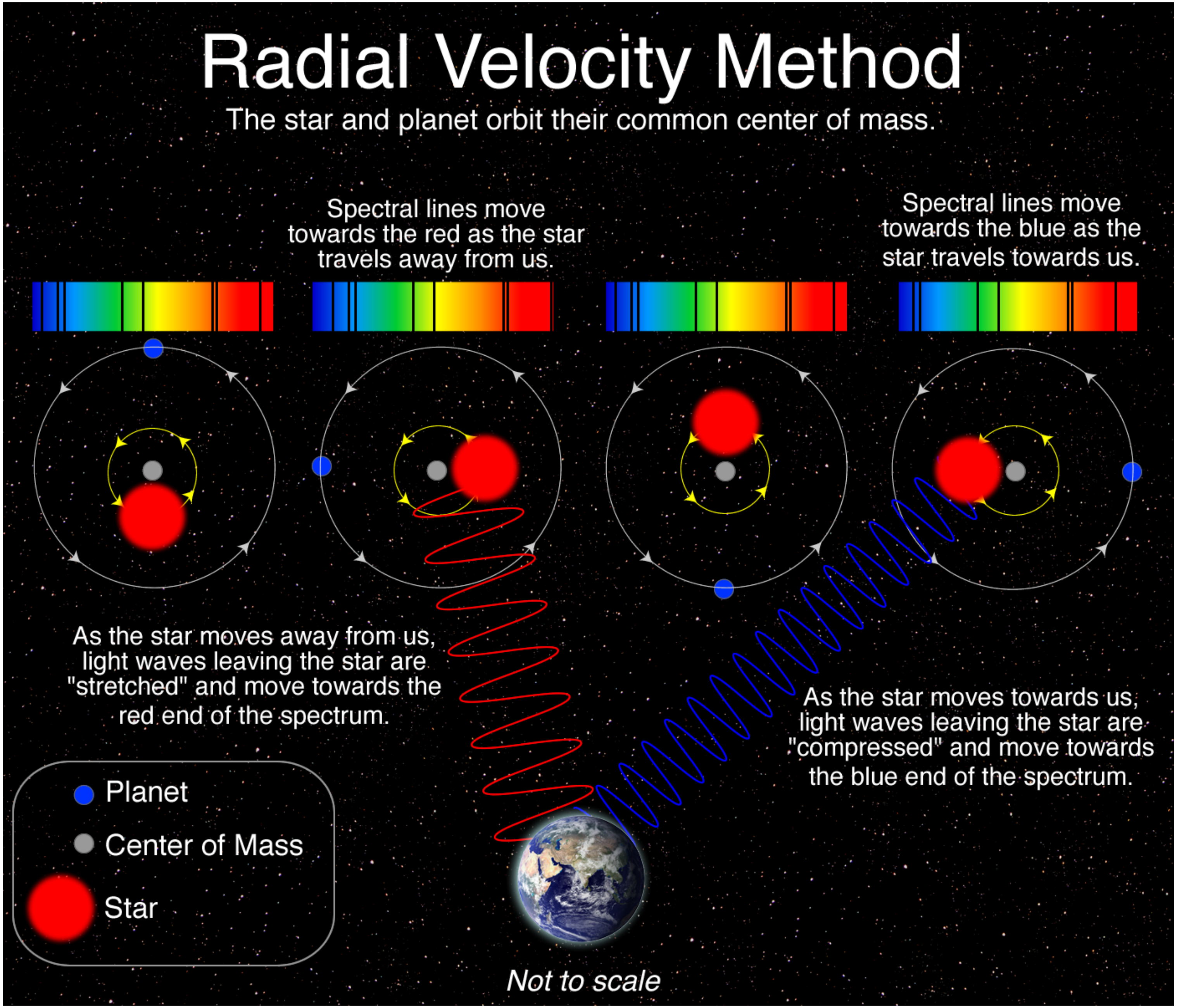
Planet Detection Methods

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



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

Principle of the RV method



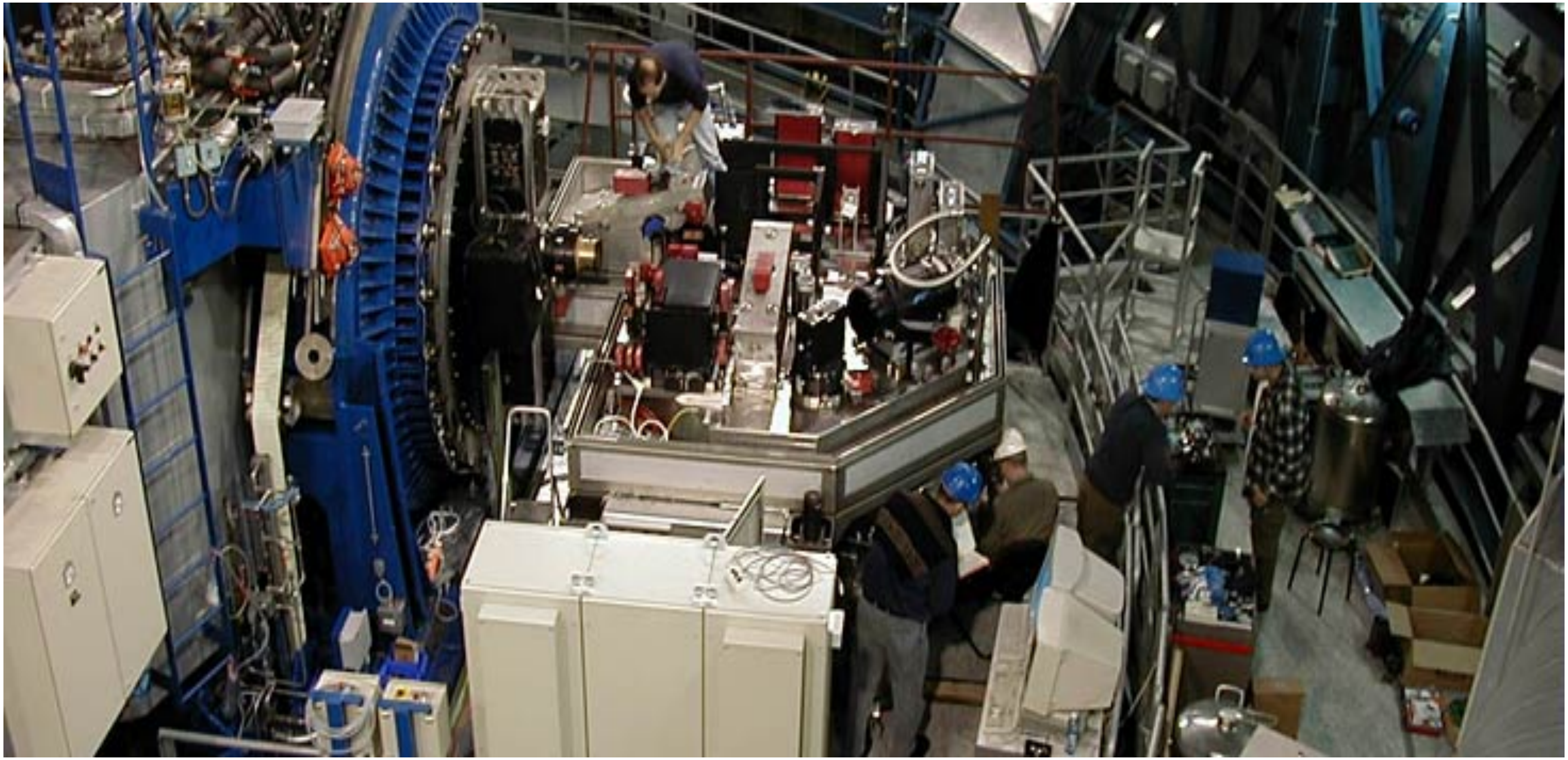
Credit: Las Cumbres Observatory

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

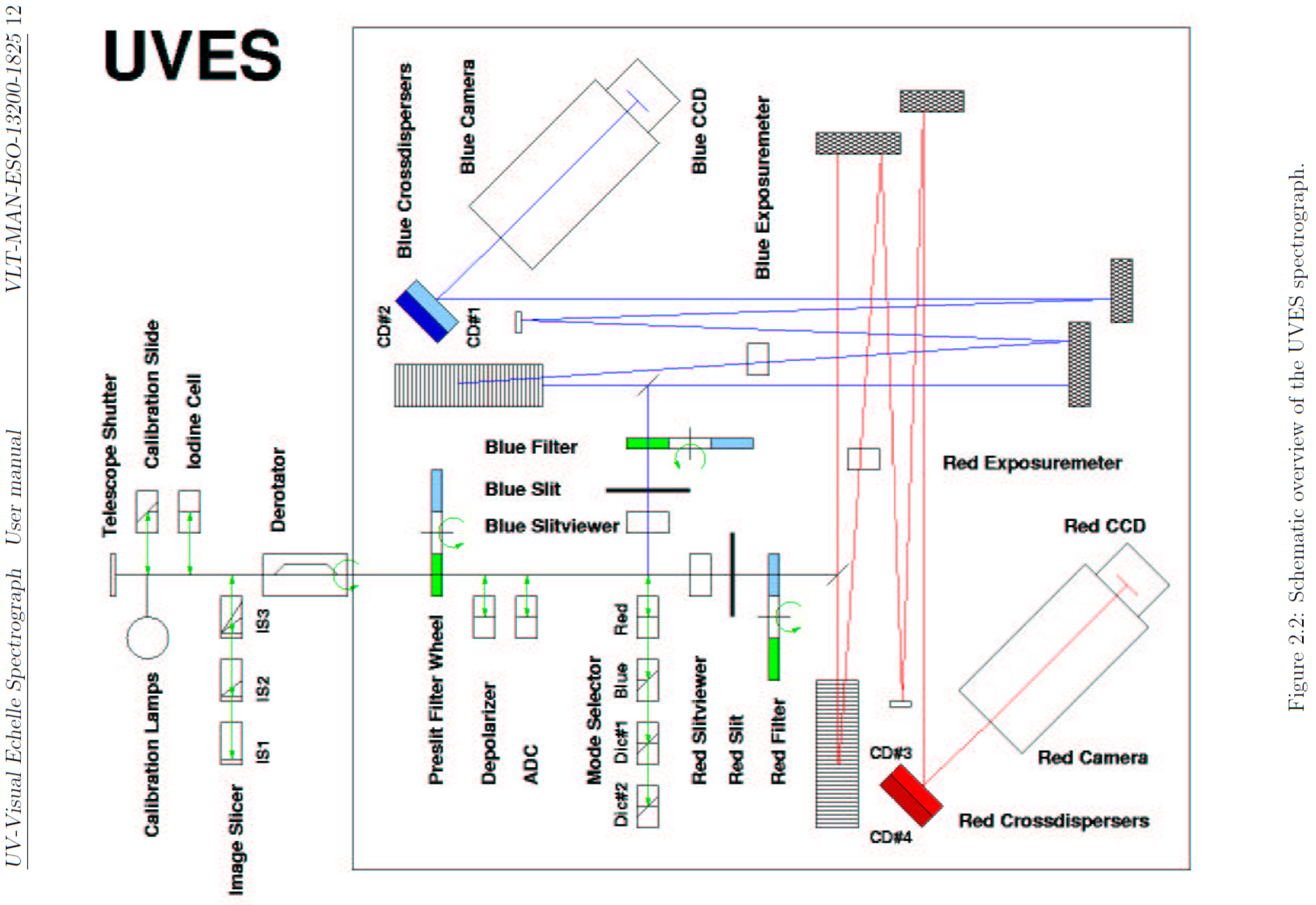
UVES – ESO Paranal

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



Credit ESO

Spectrograph UVES



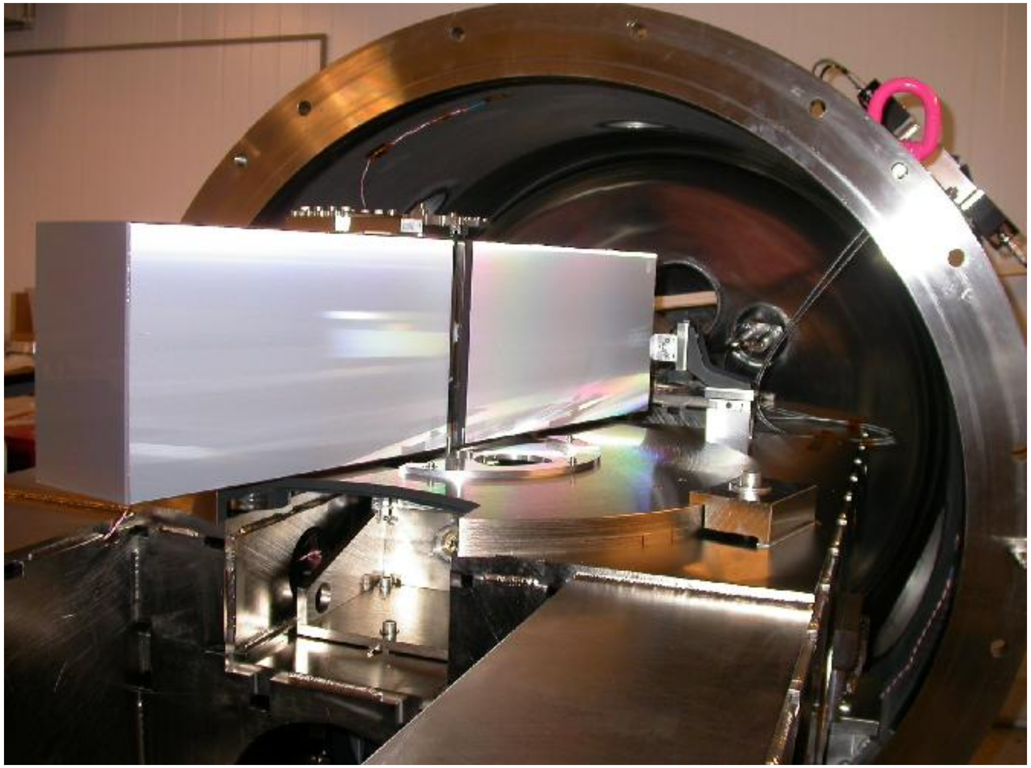
UV-Visual Echelle Spectrograph User manual *VLT-MAN-ESO-13200-1825* 12

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

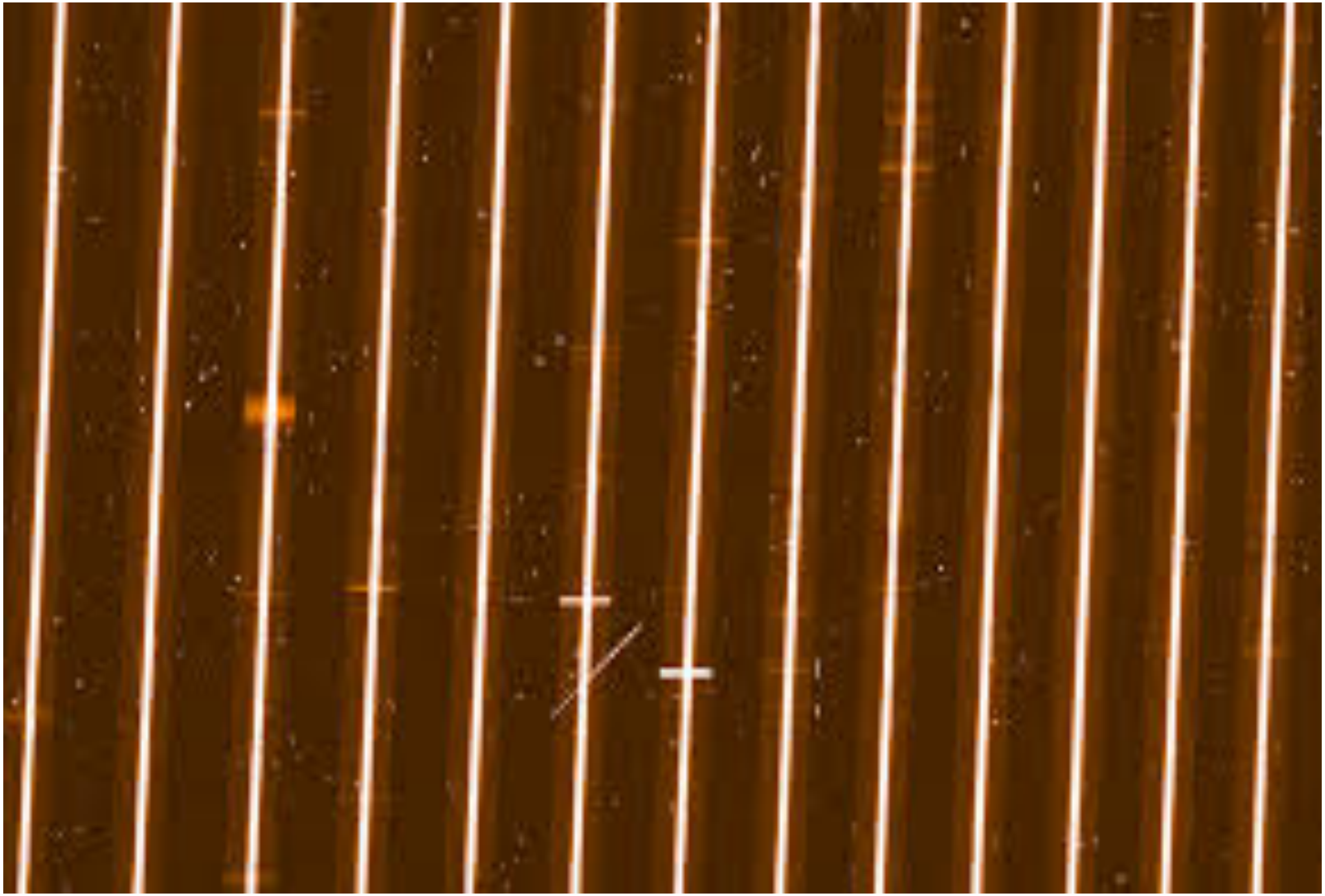
First step

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

(R 40000 plus)

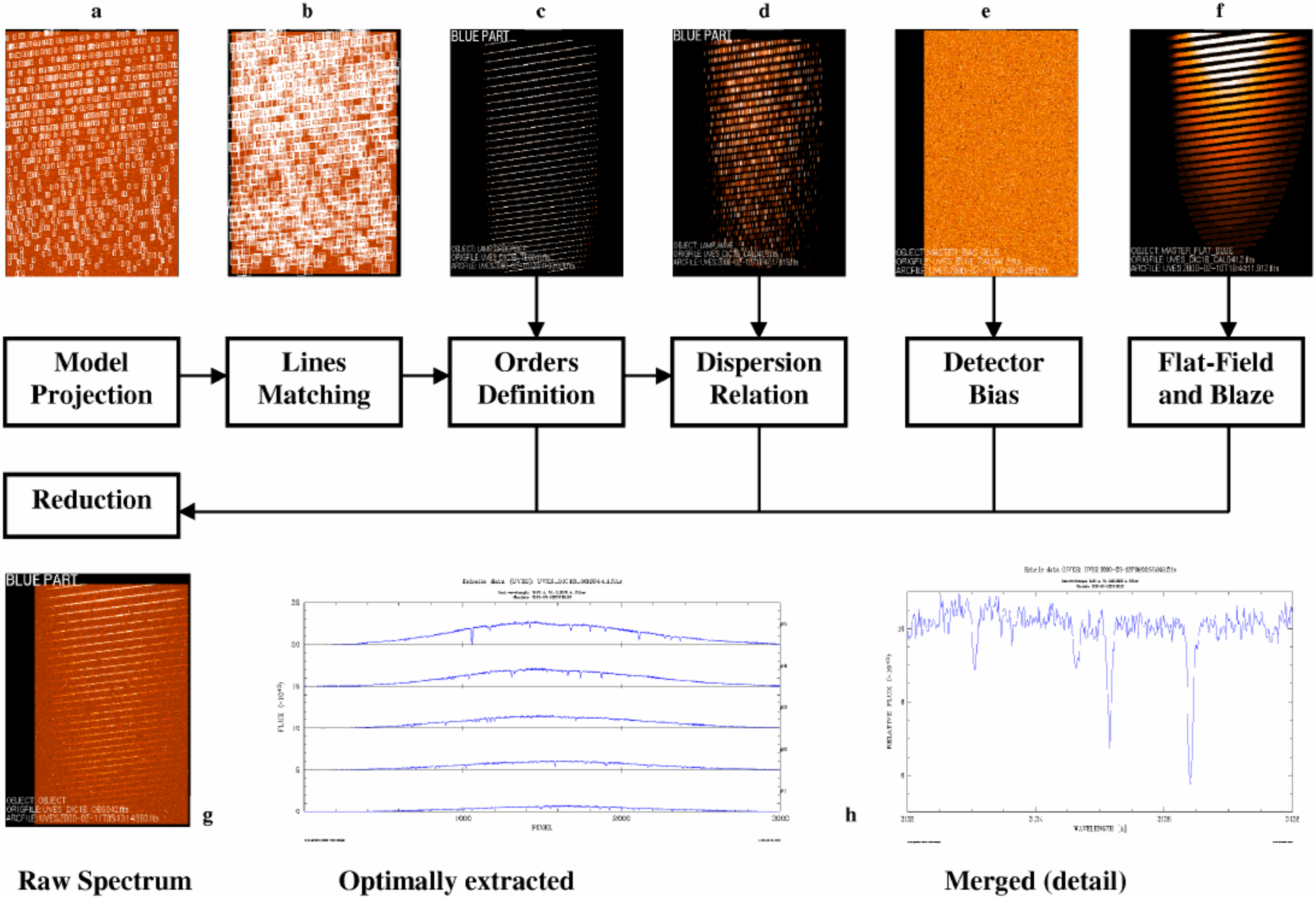
- Basic spectroscopic reduction, bias, correction of instrument effects, merging the echelle sp.
- Identification of lines and determination of the profile (by using calibration spectra – e.g. Iodine cell)

UVES frame example



Credit: ESO

ESO UVES data reduction process



Model Projection → Lines Matching → Orders Definition → Dispersion Relation

Detector Bias

Flat-Field and Blaze

Reduction

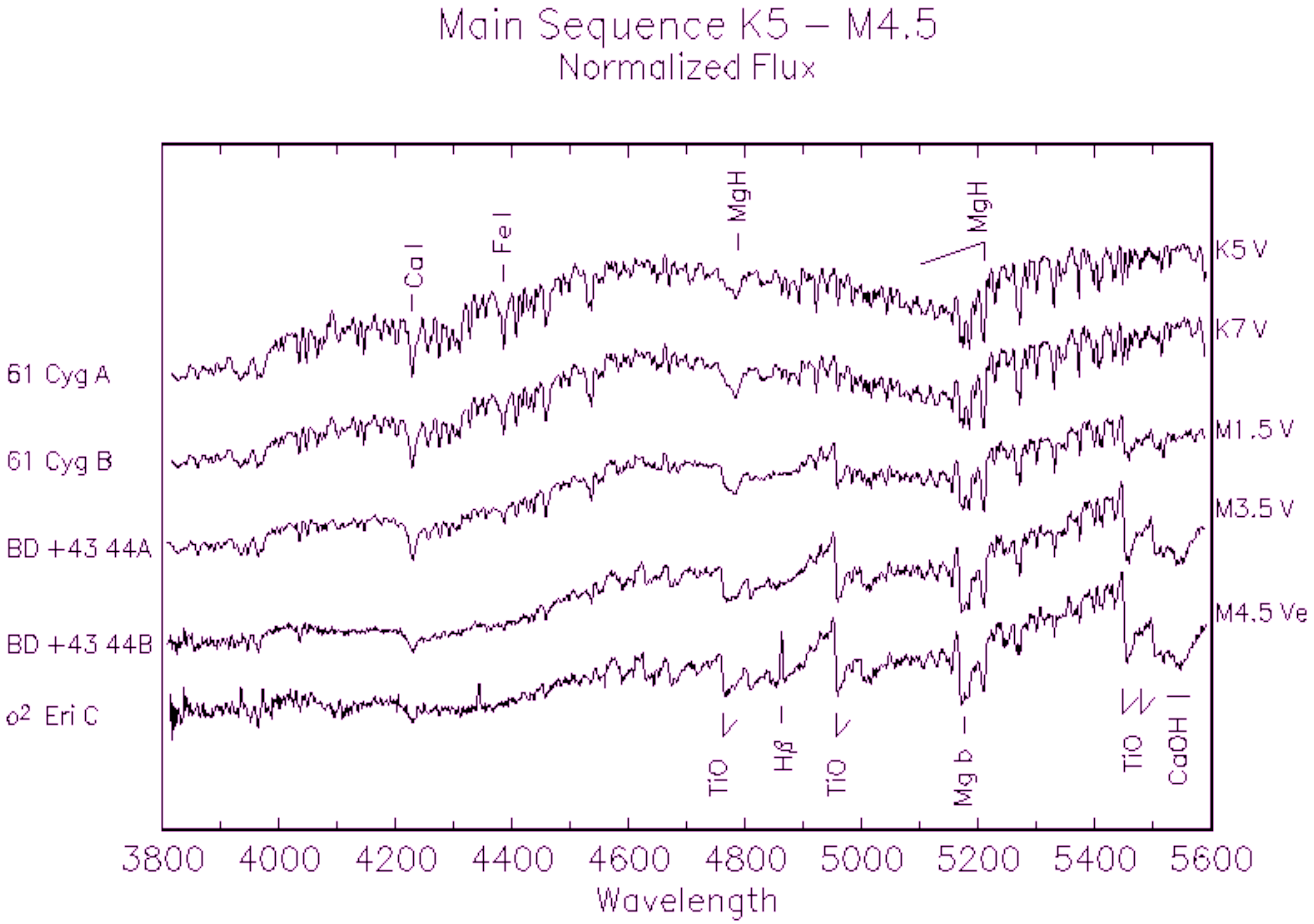
Raw Spectrum

Optimally extracted

Merged (detail)

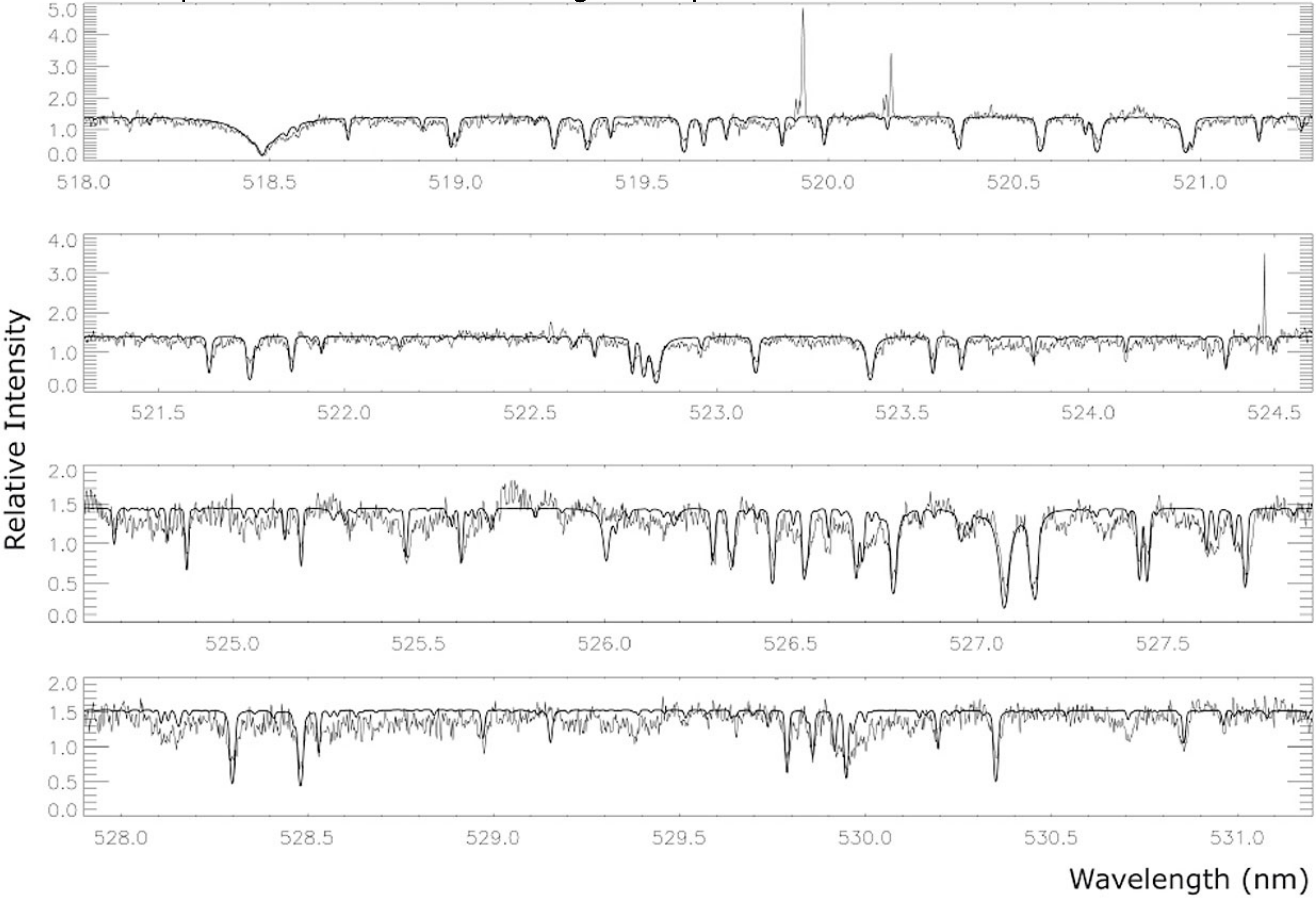
Ballester, et al. https://www.eso.org/observing/dfo/quality/publ/Messenger/UVES_Messenger_101.html

Example of main sequence spectra



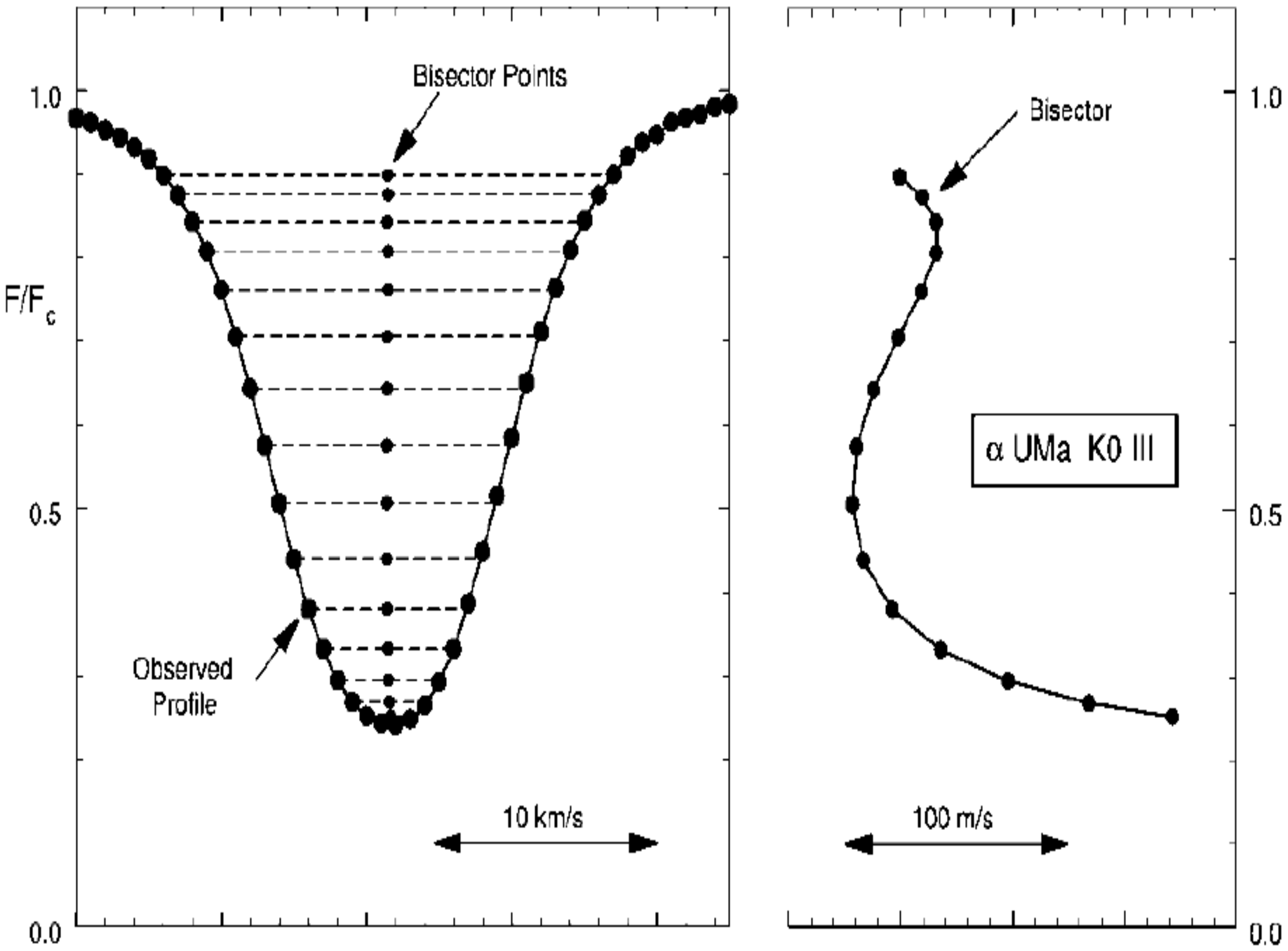
https://ned.ipac.caltech.edu/level5/Gray/frames.html

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)

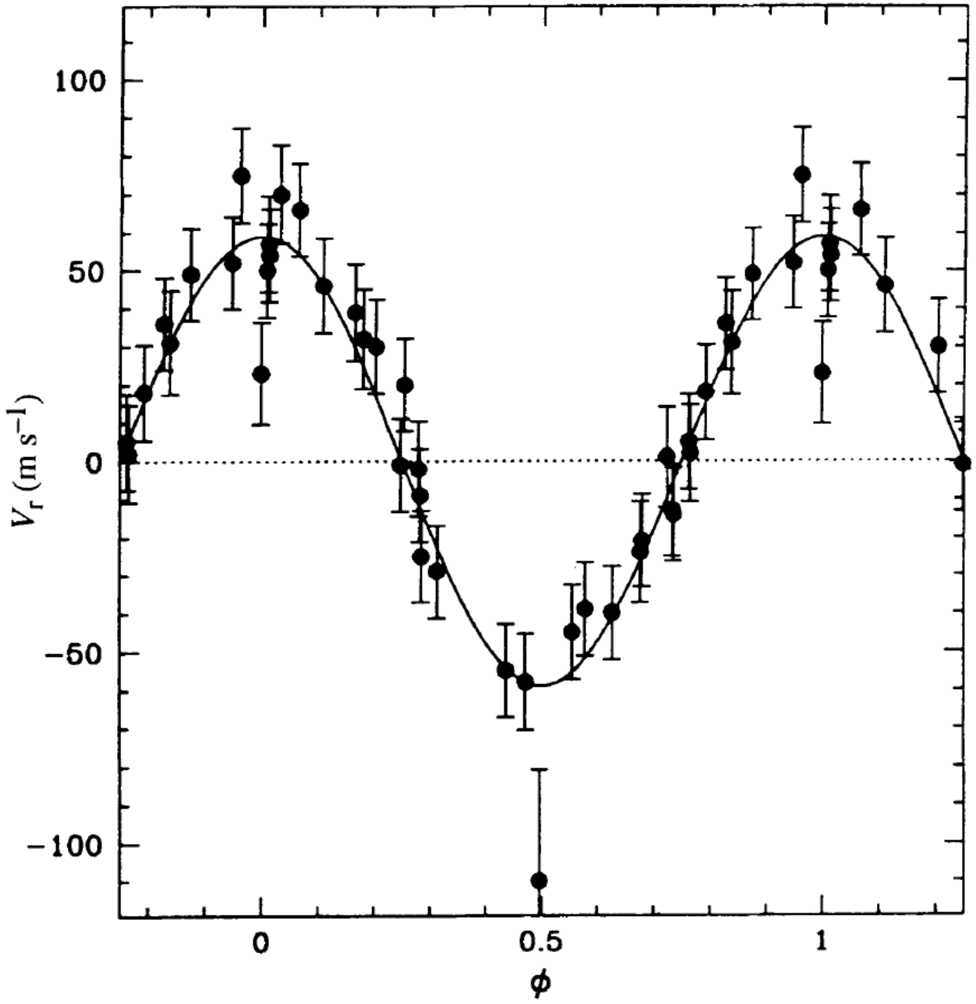


FIG. 4 Orbital motion of 51 Peg corrected from the long-term variation of the γ-velocity. The solid line represents the orbital motion computed from the parameters of Table 1.

Mayor and Queloz, 1995, Nature

Some equations

- Observable semi-amplitude of RV curve K:

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

- Using Kepler law and Newton's law, angular momentum conservation
- For details see:

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

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

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

Semi amplitude K

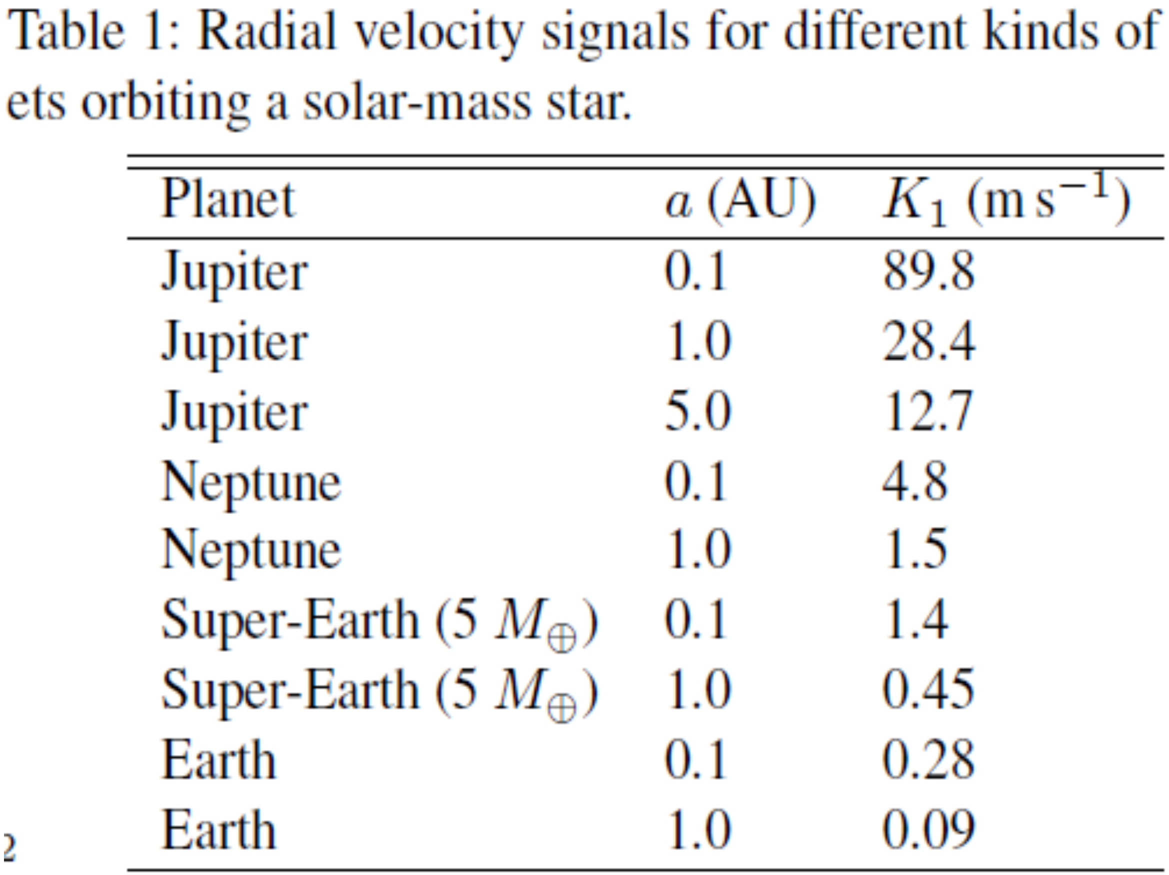


Table 1: Radial velocity signals for different kinds of planets orbiting a solar-mass star.

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

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

Solar type stars and RVs

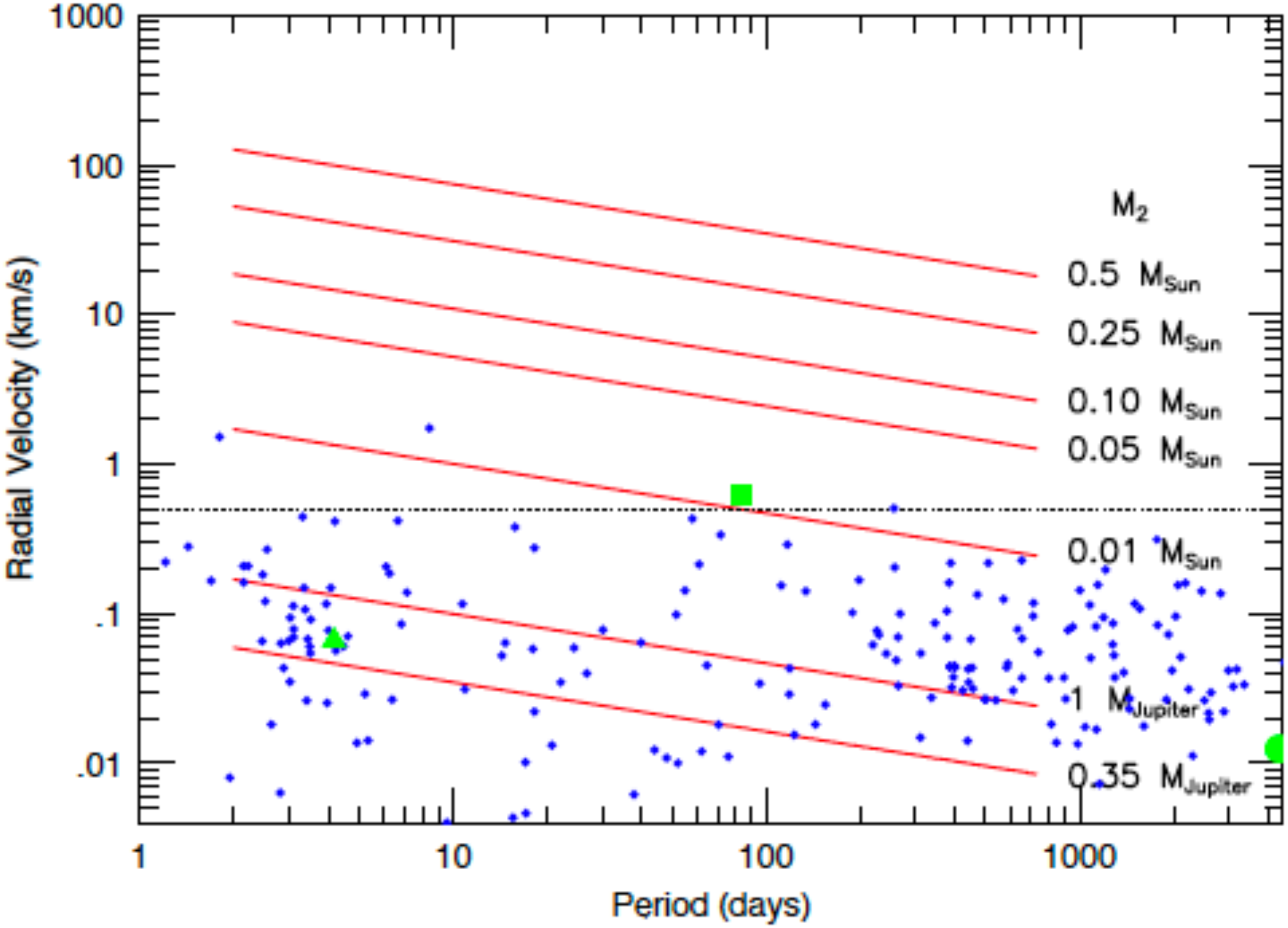
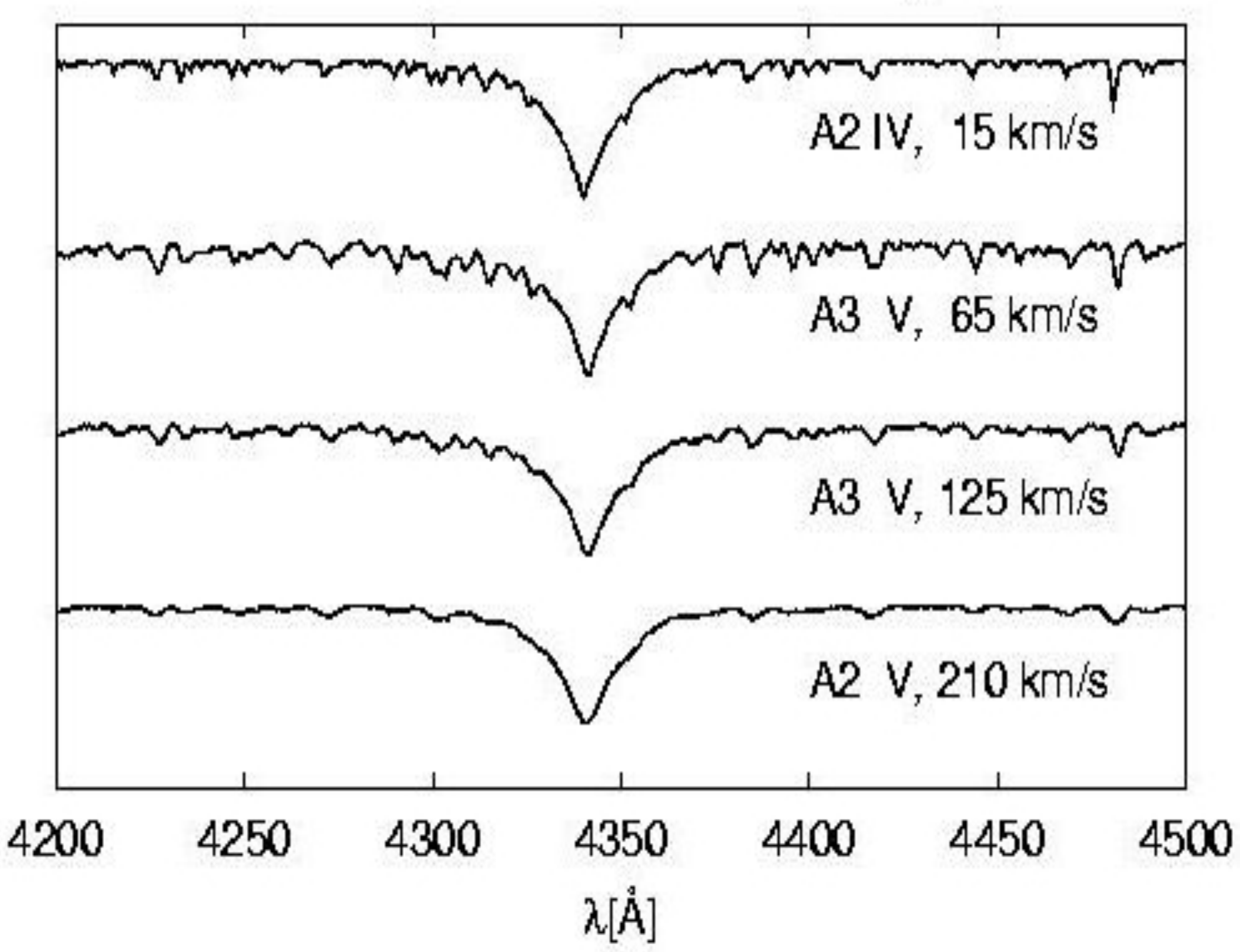


Figure from Hatzes, Cochran, Endl - : Radial velocity of a Solar type star due to a companion

Problems

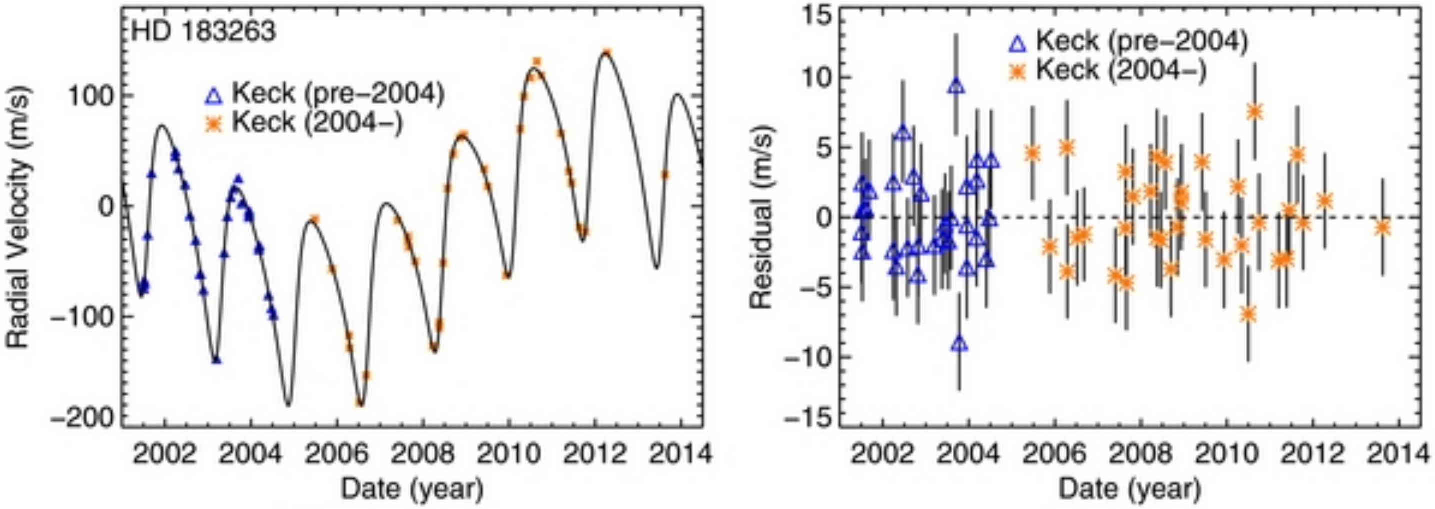
- Mass is a lower limit (unless inclination is known)
- Stellar variability – pulsations (cm/s accuracies)
- Multiplicity of stars – shape of the RV curve
  - difficult RV curves
- Fast rotation of stars – broadening of the lines
  - mimicking planet effect
- Long periodic planets are difficult to detect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

Line broadening, rotation

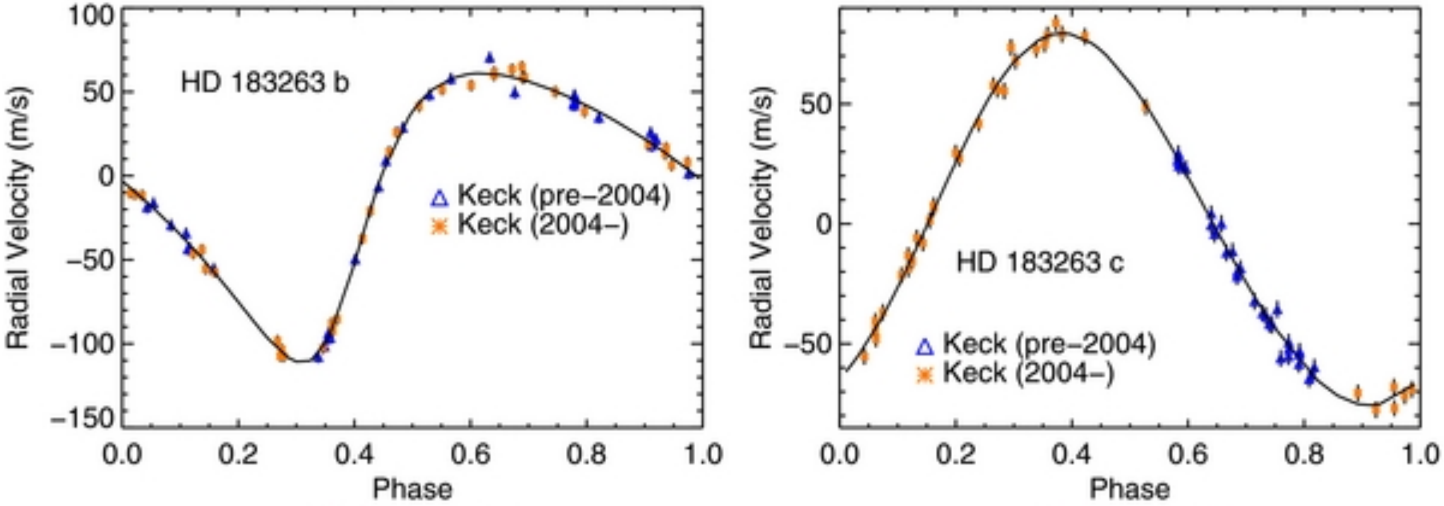


http://www.astro.uu.se/~ulrike/Spectroscopy.html

Multiple system



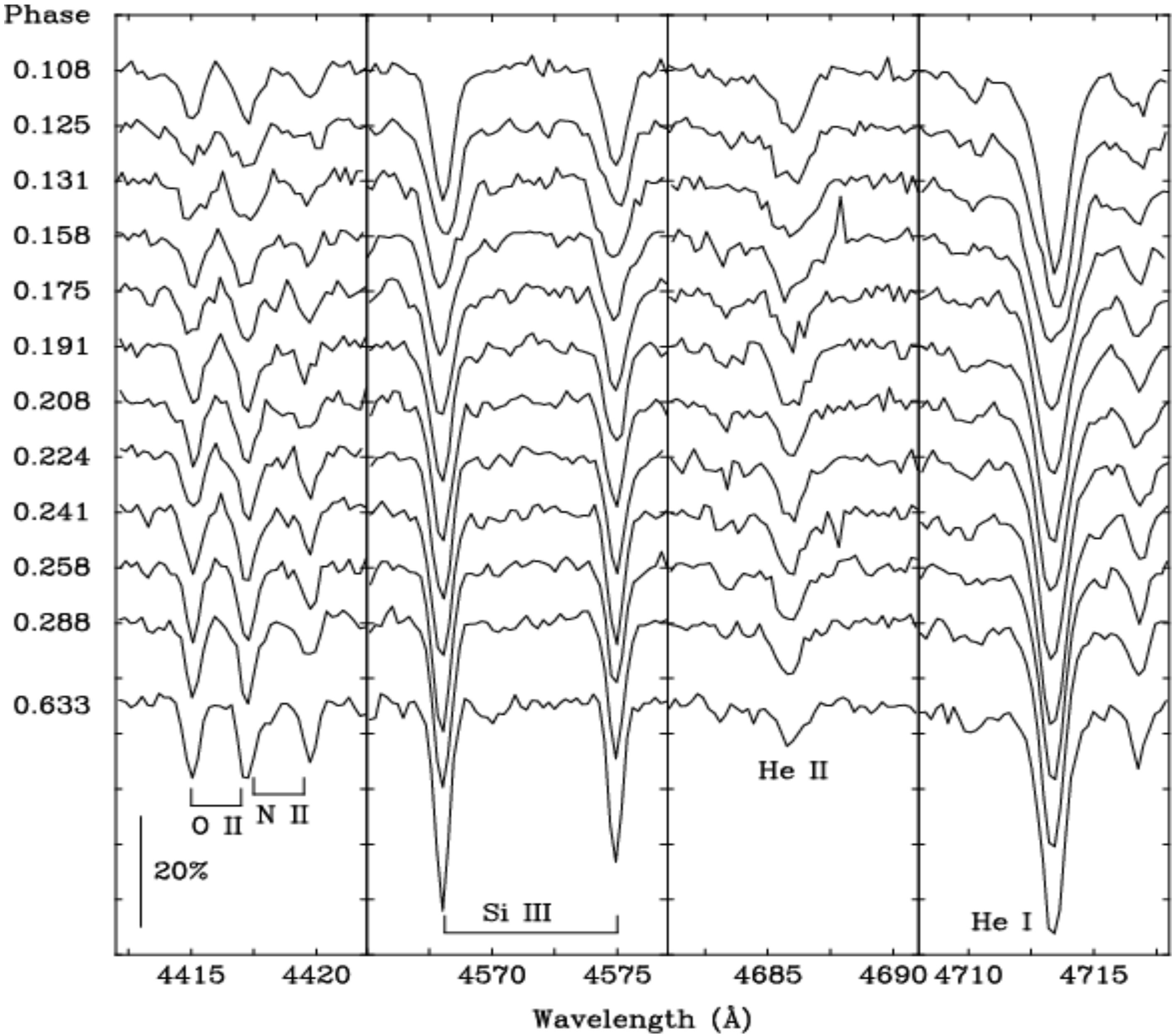
(a) HD 183263 system (b) Residuals



(c) HD 183263 *b* (d) HD 183263 *c*

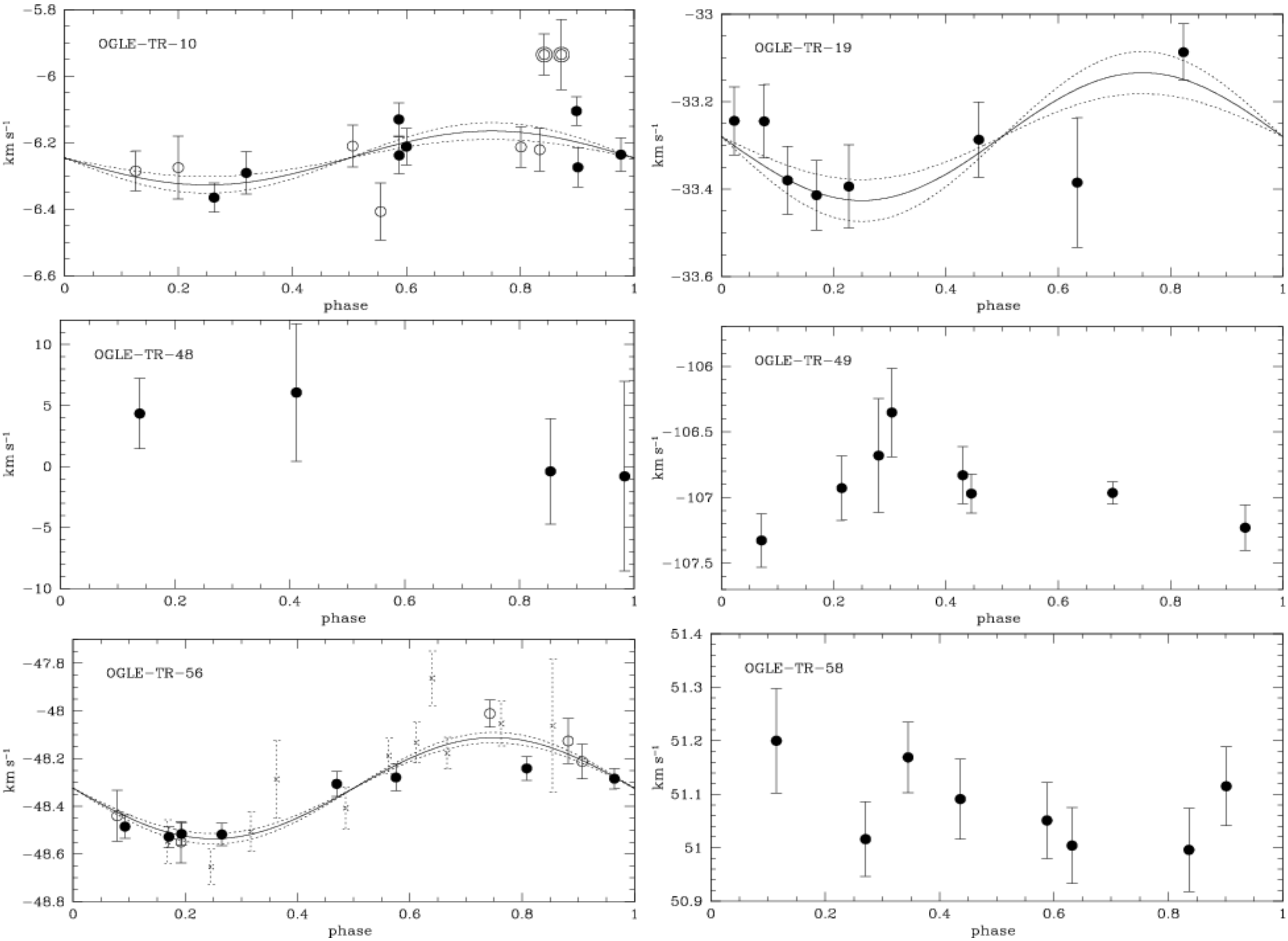
Feng et al. 2015, http://iopscience.iop.org/article/10.1088/0004-637X/800/1/22/pdf

Pulsations



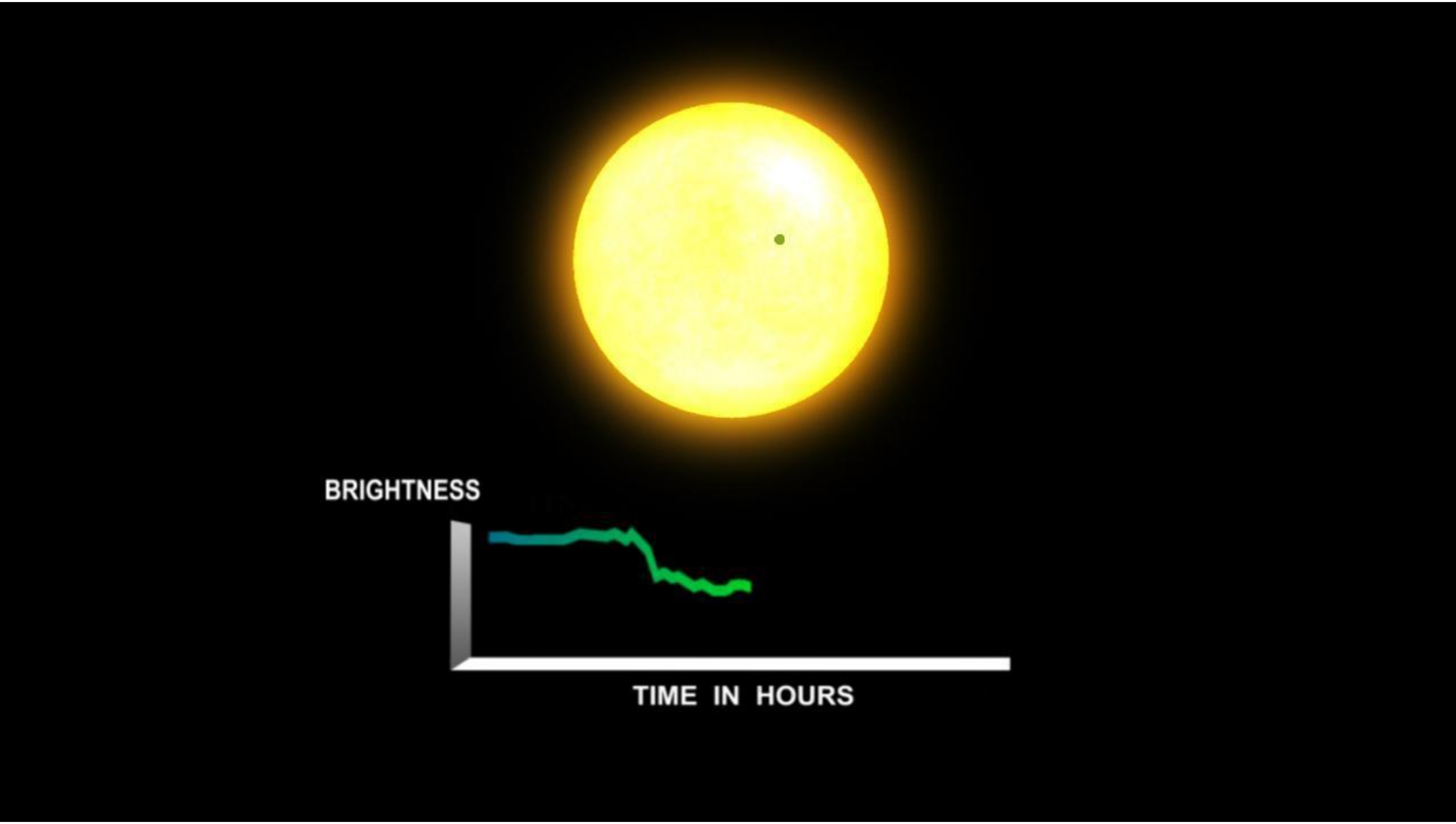
Jeffery et al., A&A 376, 497-517 (2001)
http://www.aanda.org/articles/aa/full/2001/35/aah2647/aah2647.right.html

Unresolved cases RV



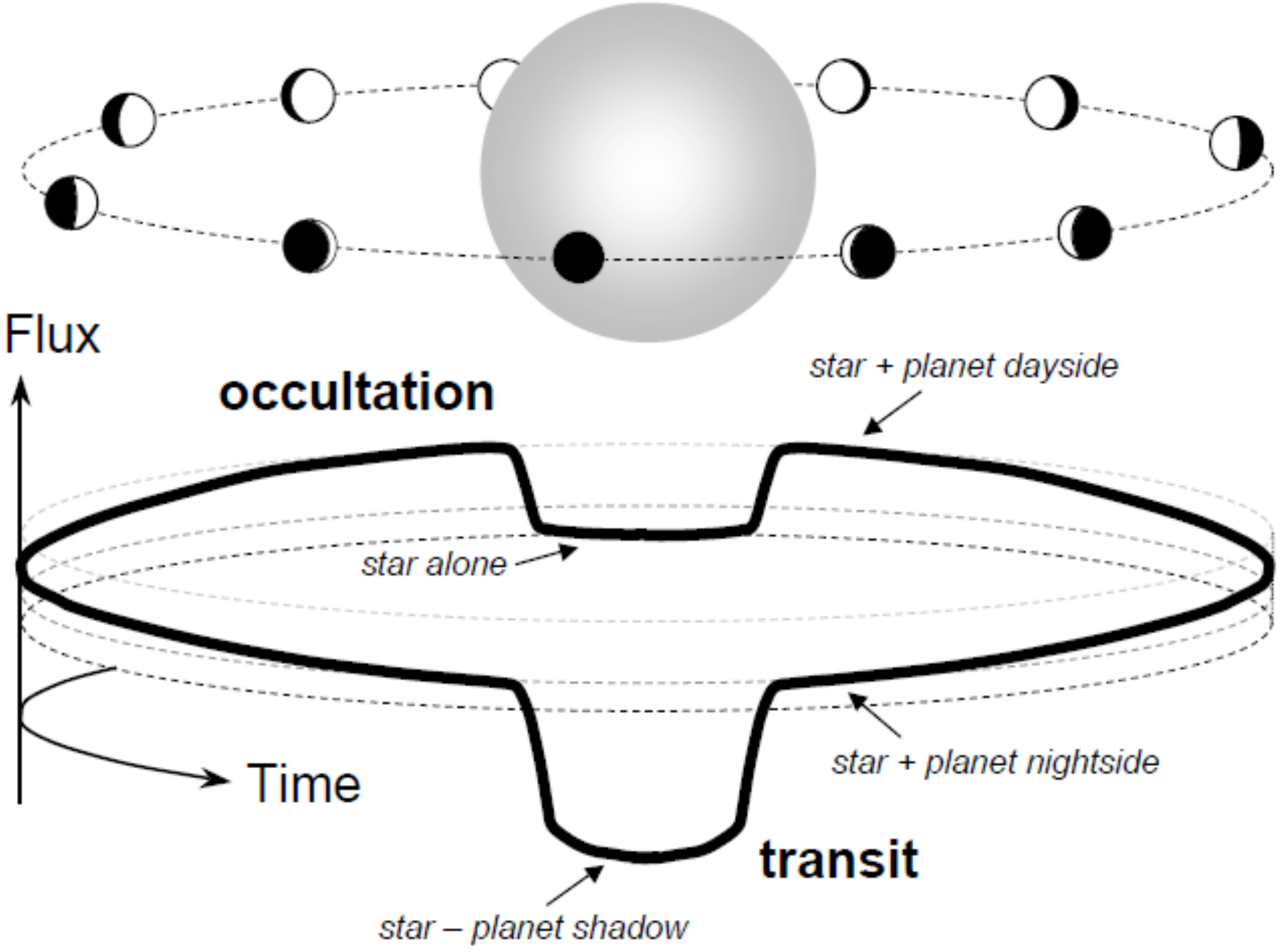
Bouchy et al. 2004, http://www.aanda.org/articles/aa/full/2005/09/aa1723/img38.gif

Transit method



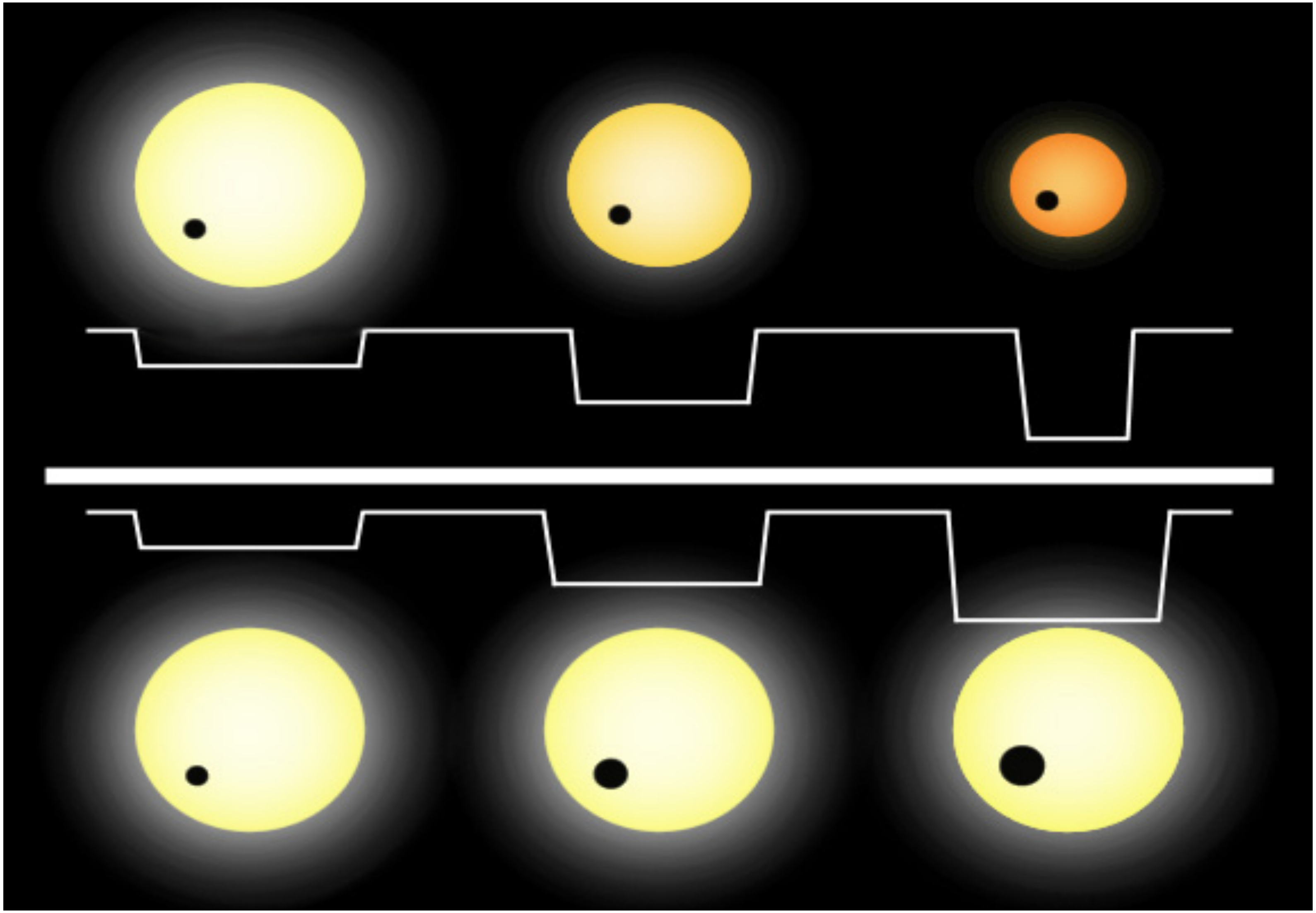
http://www.nasa.gov/mission_pages/kepler/multimedia/images/kepler-transit-graph.html

Eclipses/transits



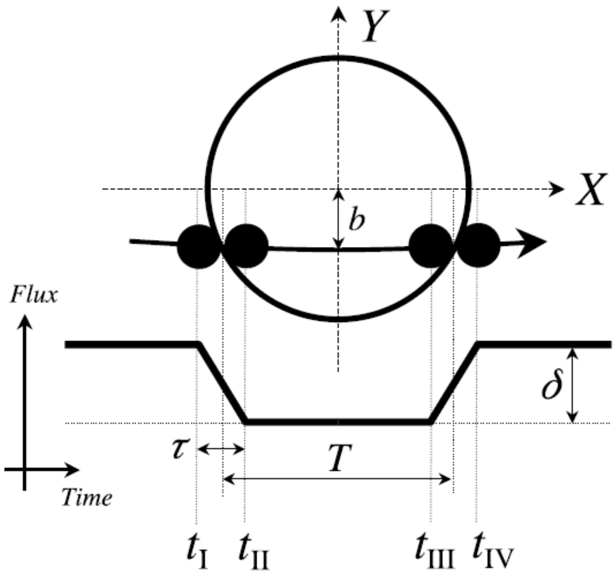
From Winn, 2010, http://arxiv.org/pdf/1001.2010v5.pdf

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:

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

- 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

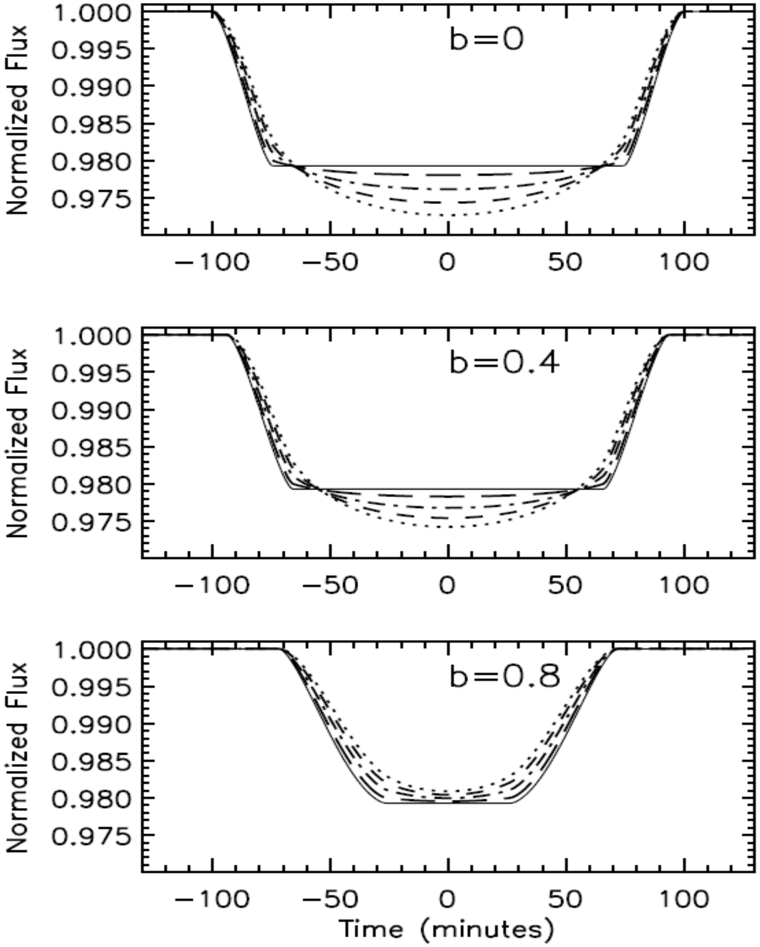


Fig. 3.— Solar limb darkening dependence of a planet transit light curve. In these theoretical light curves the planet has $R_p = 1.4R_J$ and $a = 0.05$ AU and the star has $R_* = R_\odot$ and $M_* = M_\odot$. The solid curve shows a transit light curve with limb darkening neglected. The other planet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

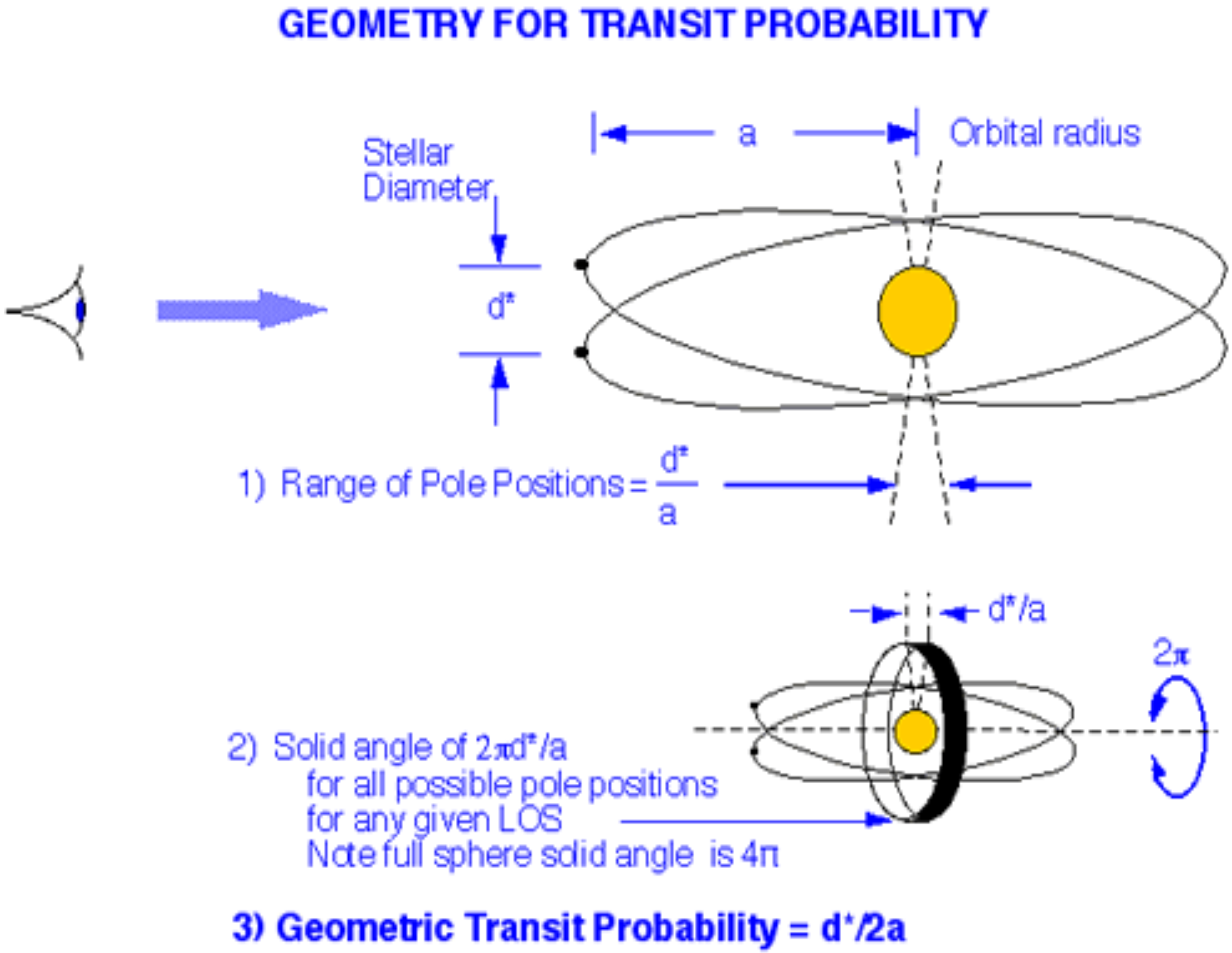
Problems

- 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 eclipse, mid-time of transit, duration of transit and durations of ingress and egress

Geometrical probability



GEOMETRY FOR TRANSIT PROBABILITY

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

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

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

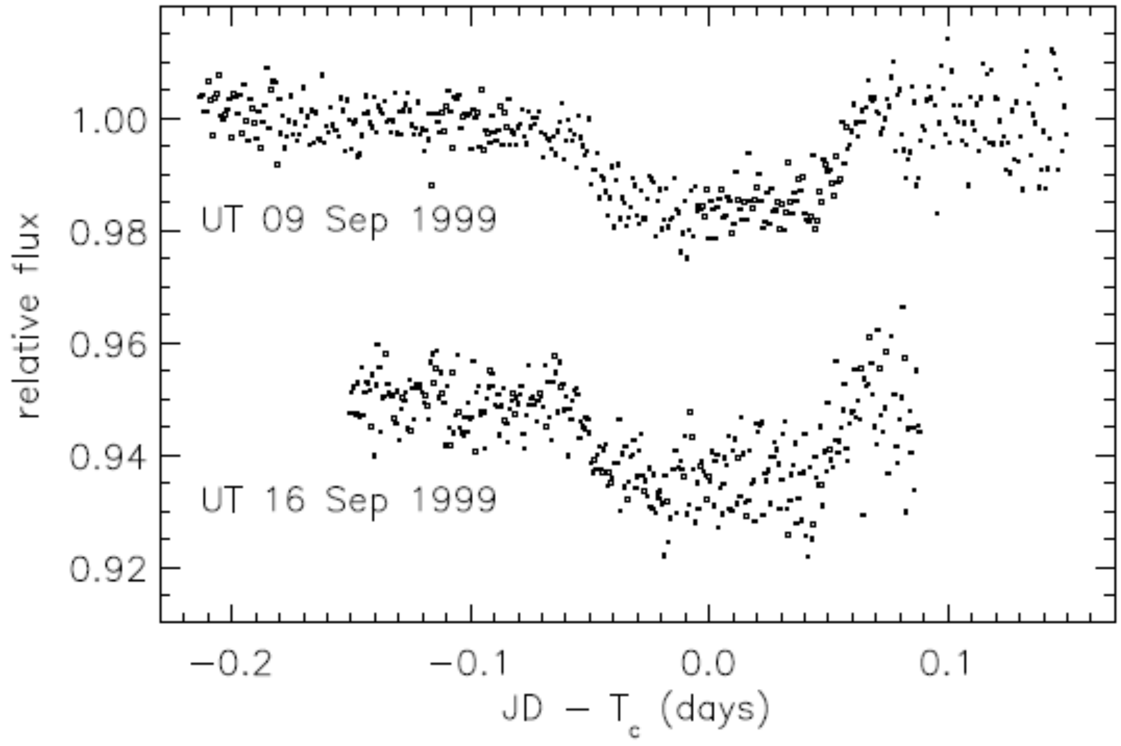
Credit: NASA Kepler

Transit Properties of Solar System Objects

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

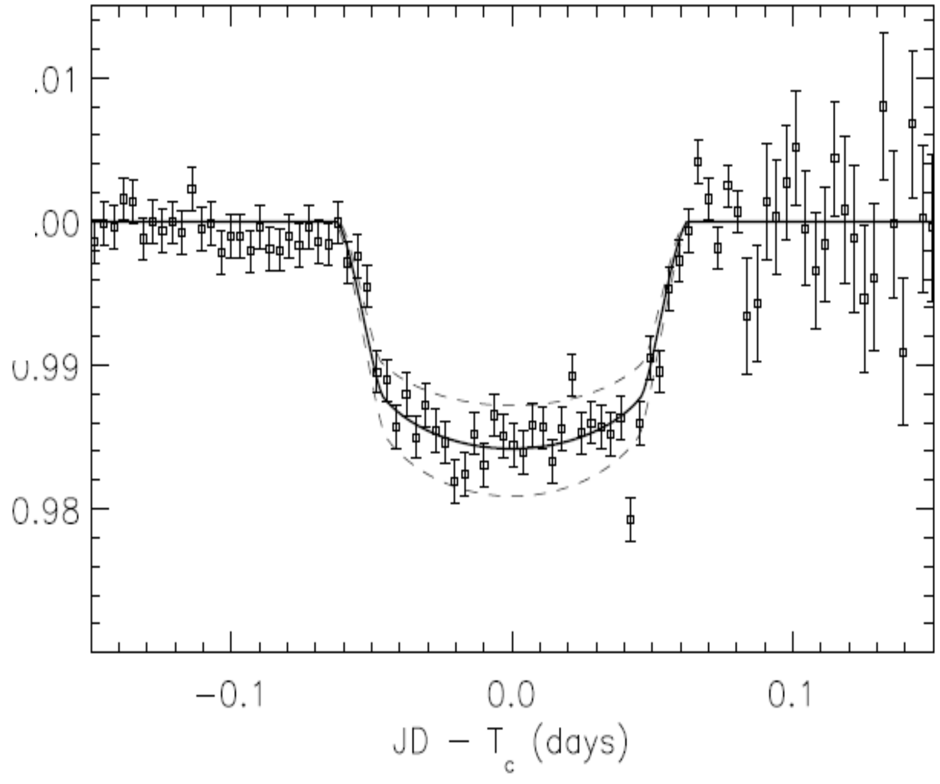
https://web.njit.edu/~gary/320/Lecture10.html

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)

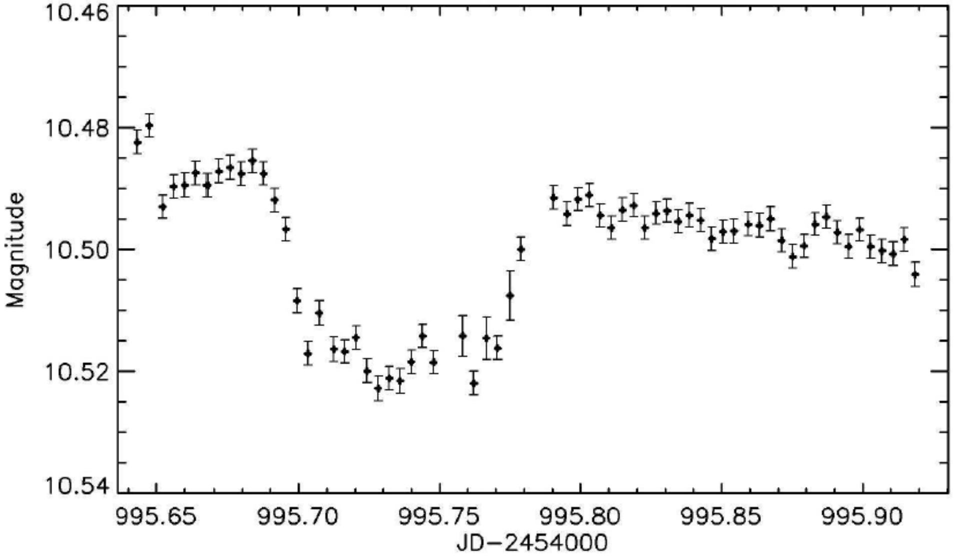
  Teff: 6092 K

  Metallicity: 0.02

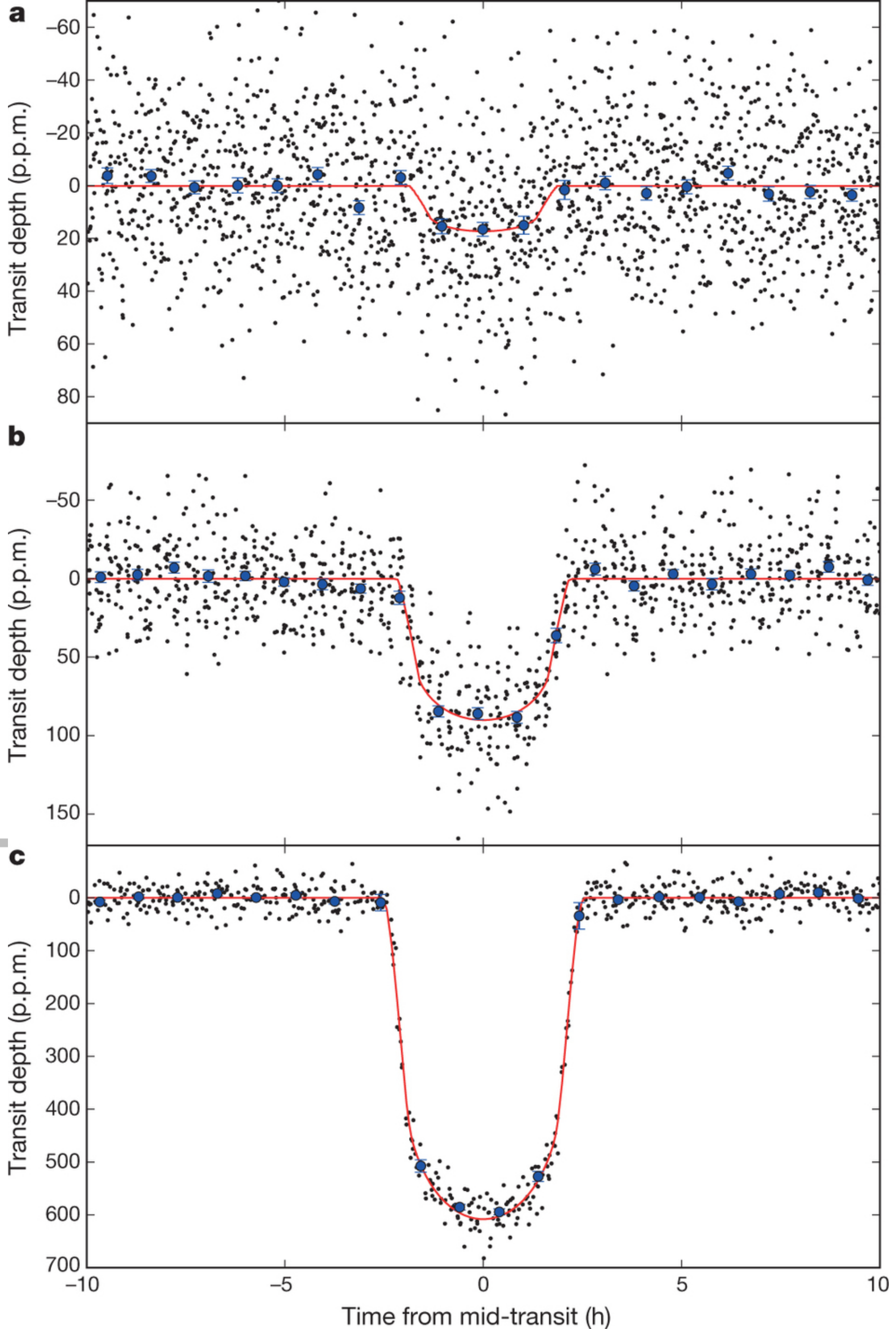
http://mnras.oxfordjournals.org/content/418/3/1822

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

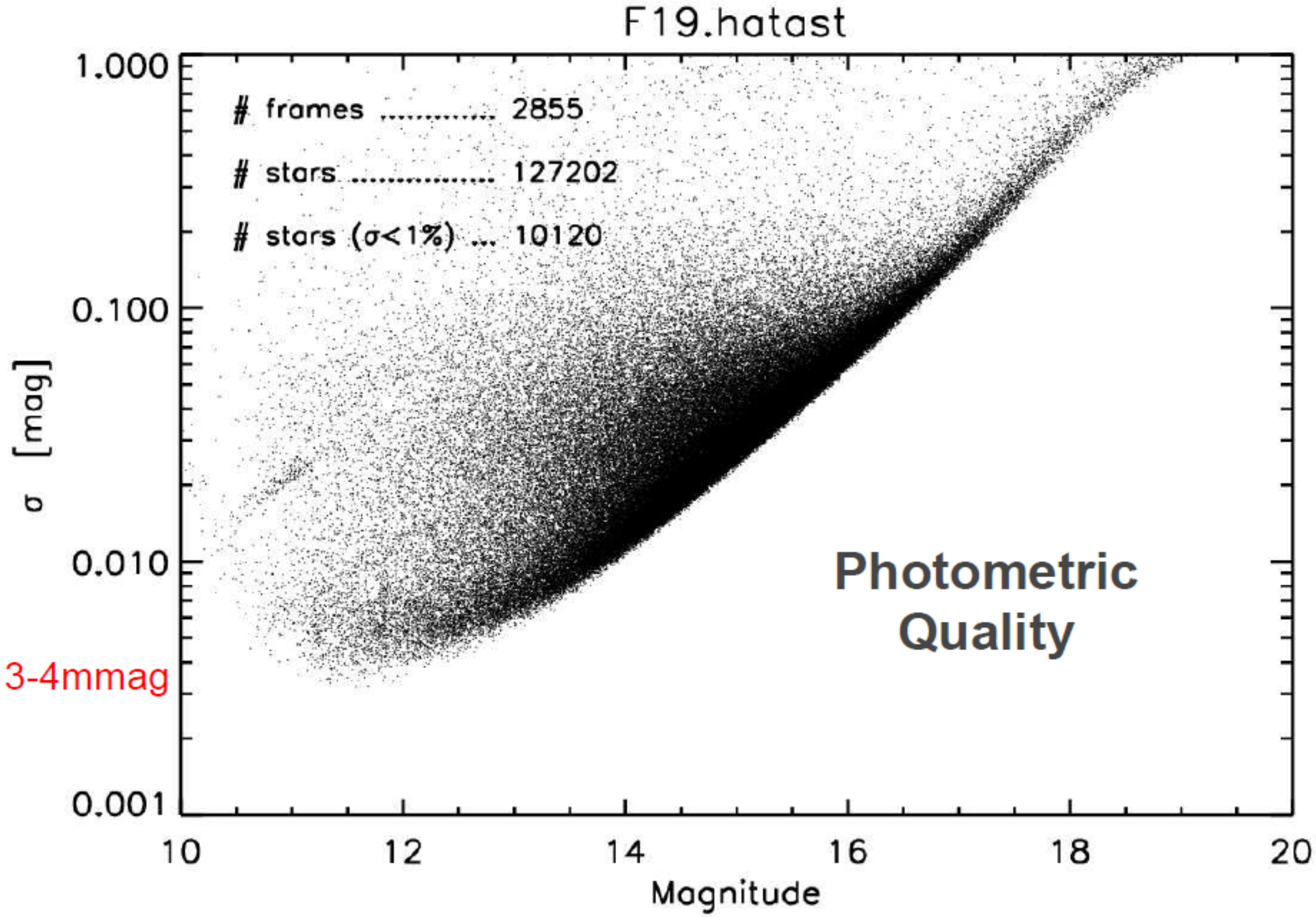
BEST II

Observatorio Cerro Armazones, Chile

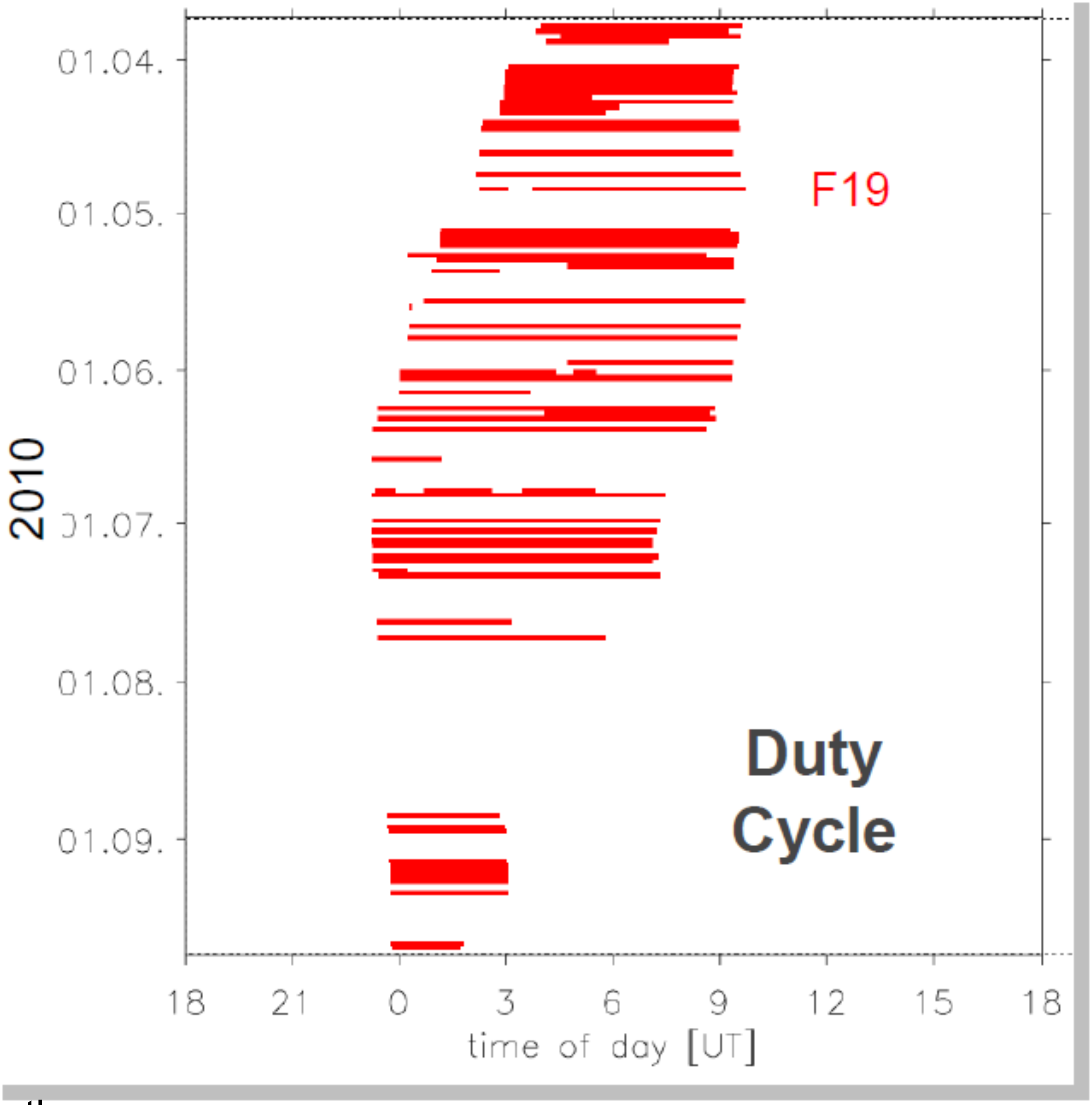
<u>Specifications:</u>

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



DLR-Thomas Fruth

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

exoplanets around

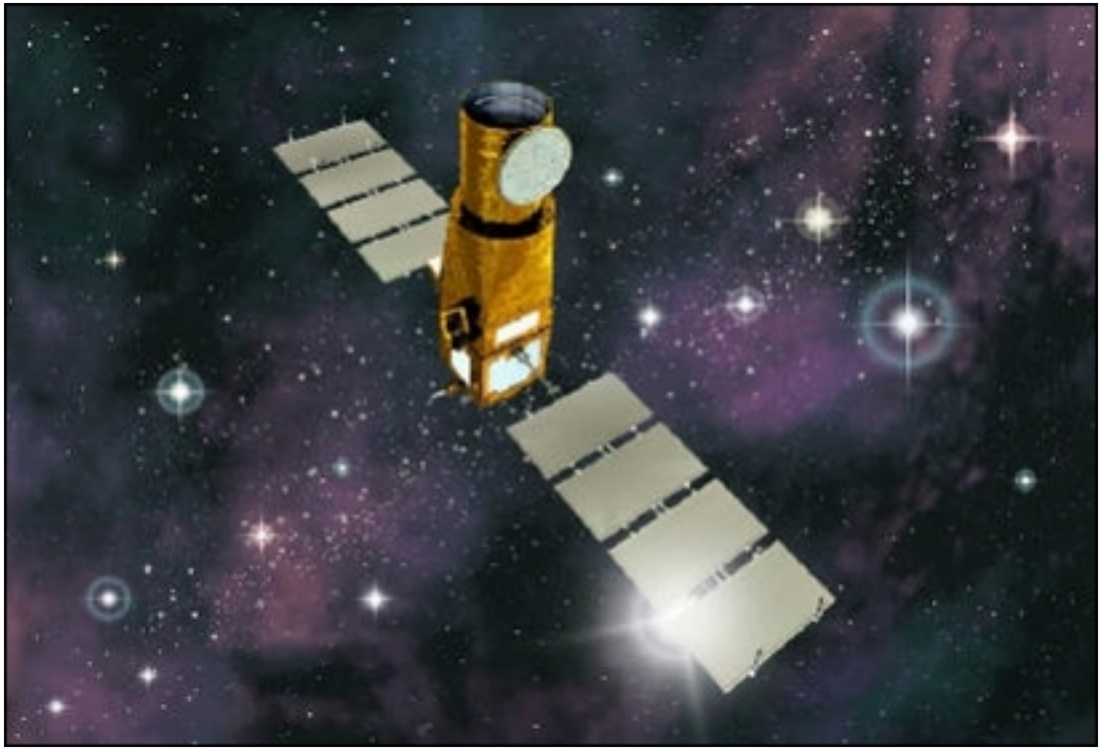
http://www.mpia.de/homes/mancini/hat-south.html

CoRoT

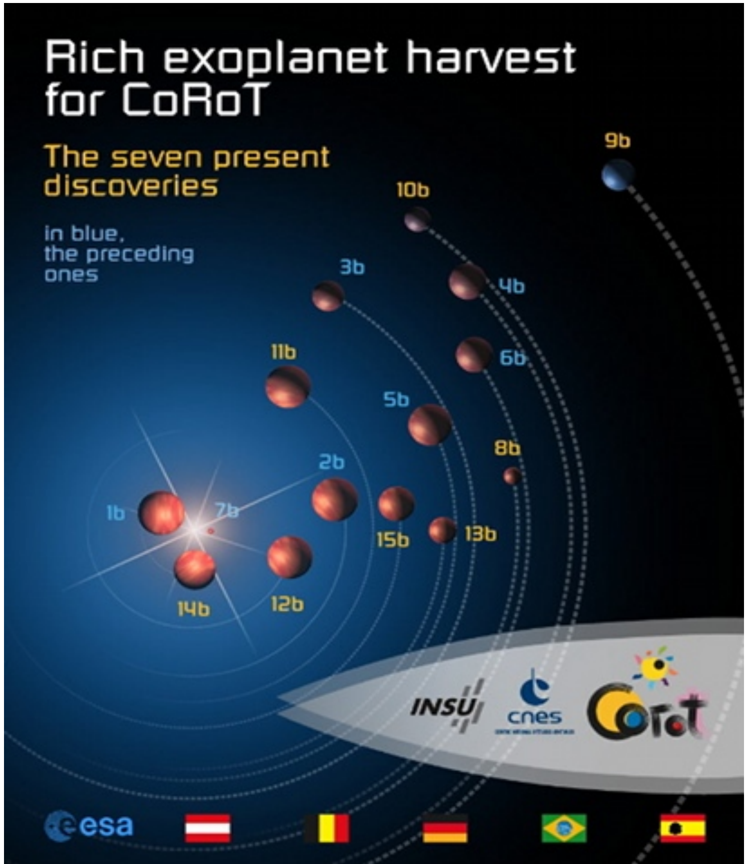
Convection, Rotation and planetary Transits

Launched 2006 – mission end 2013

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

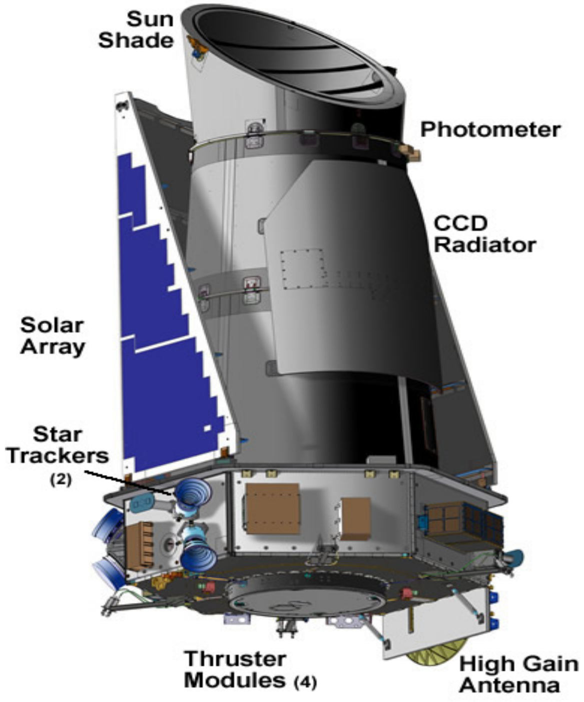


ESA webpages



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

Detected 2000+ confirmed planets

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

Microlensing

The lense/Earth configuration does not repeat (usually)

It is difficult to confirm such planets

OGLE – Optical gravitational lensing experiment

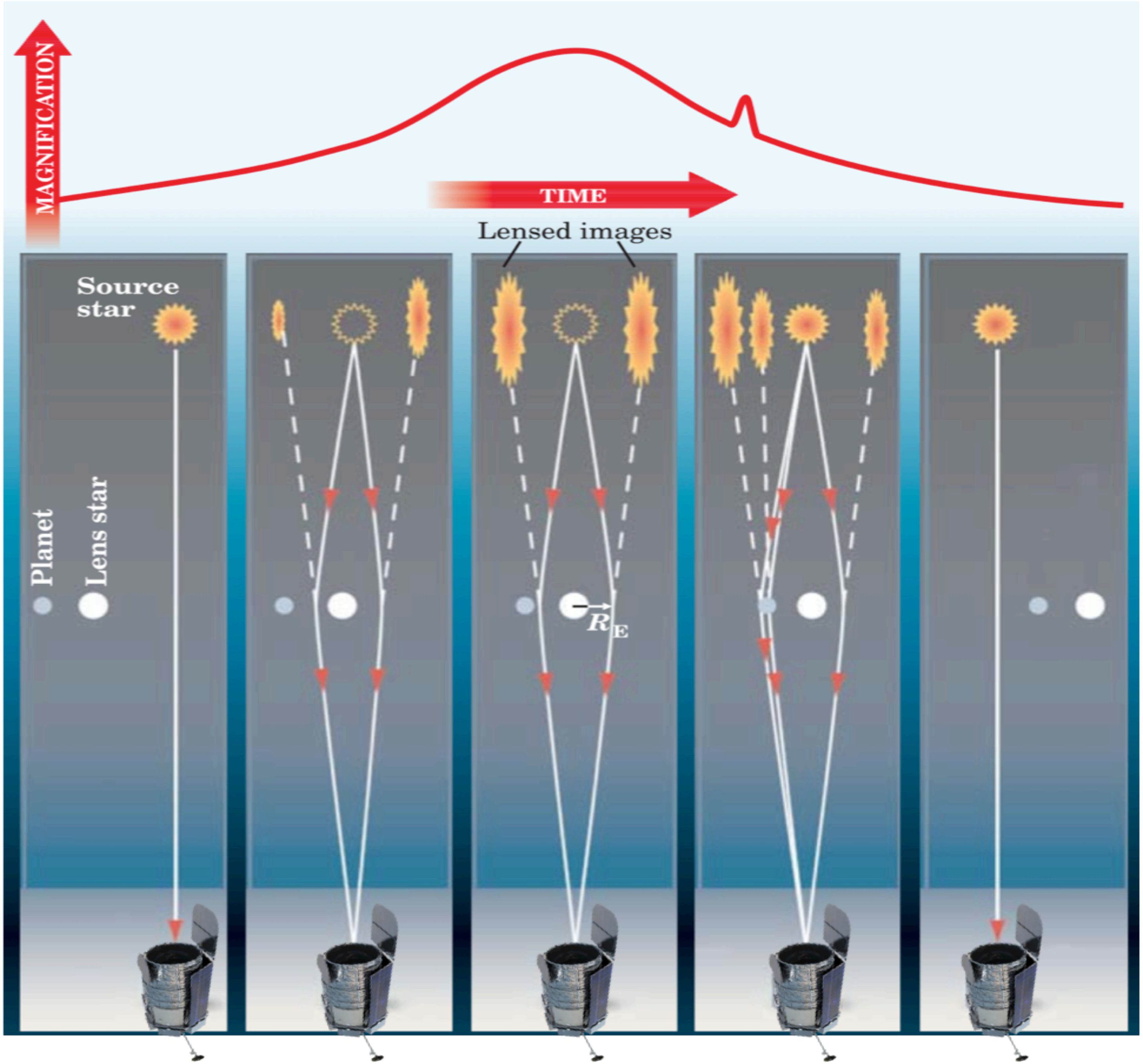
- 1.3m Las Campanas, Warsaw Univ.

- discovered planets by transit and nsing (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:

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

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

Astrometry

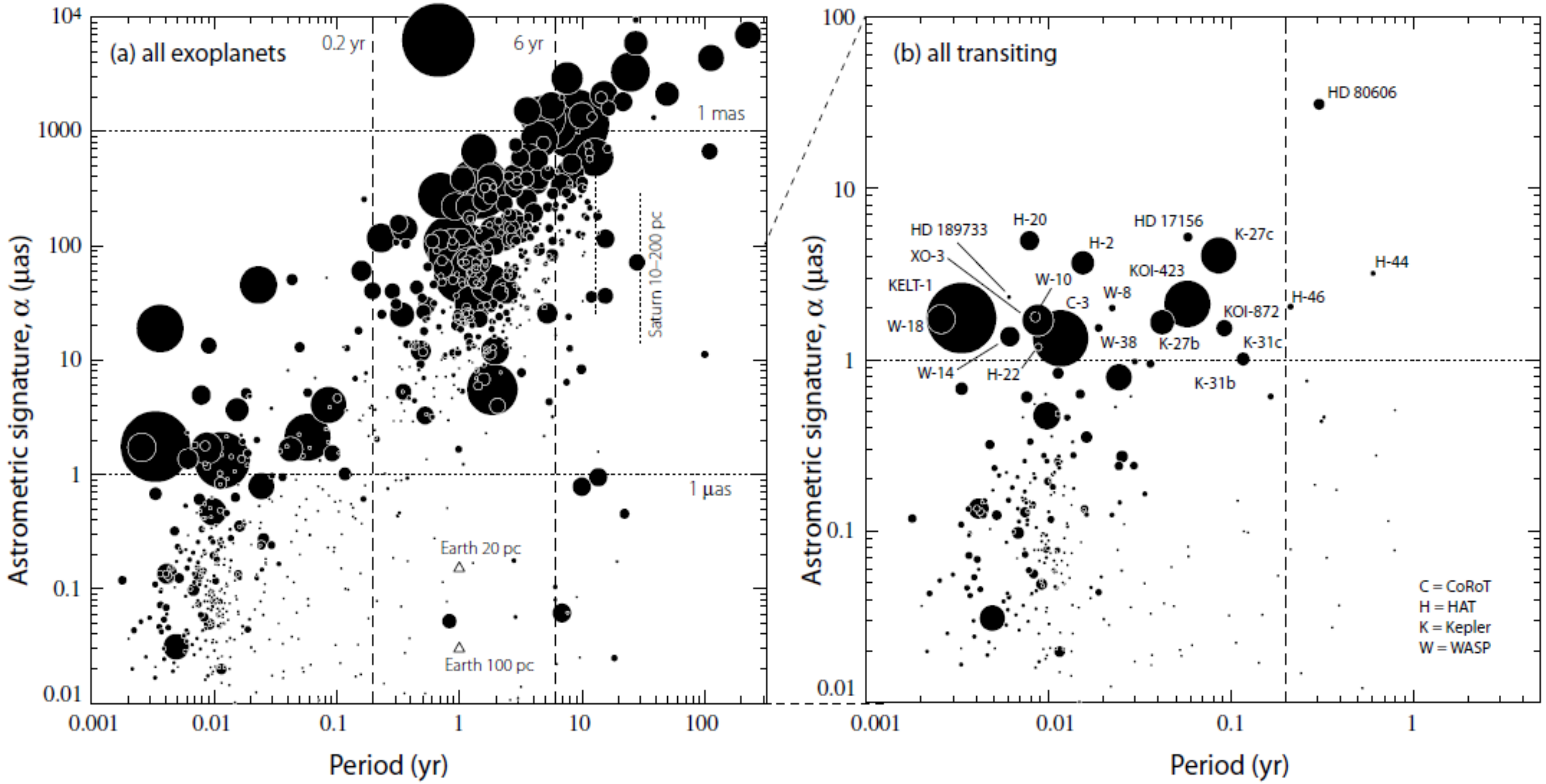
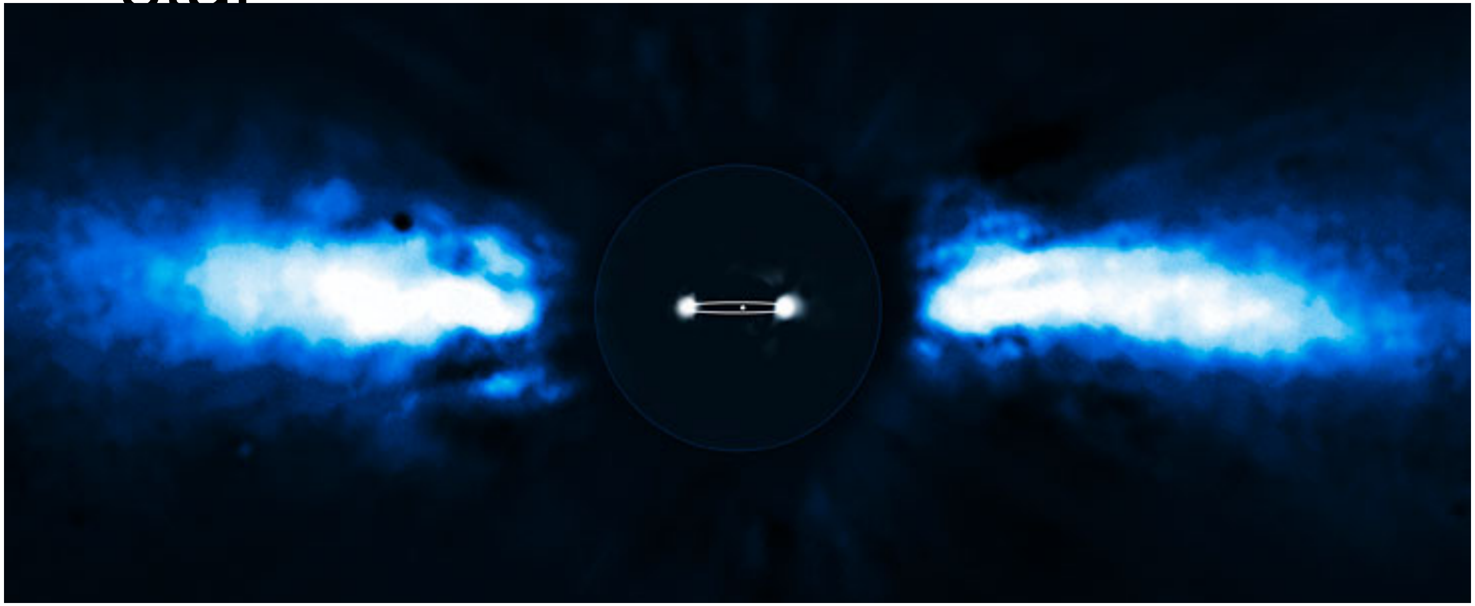


Fig. 1.— Astrometric signature versus period calculated for the objects listed in `exoplanet.eu` at 2014 September 1 for all 1821 confirmed planets (left), and for the subset of 1129 transiting planets with appropriately known data (right). Note the different scales in abscissa and ordinate. Circle sizes are proportional to planet mass; the prominent object (left) at $P = 0.7$ yr, $\alpha = 6300\,\mu$as, is the $28.5 M_\mathrm{J}$ 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

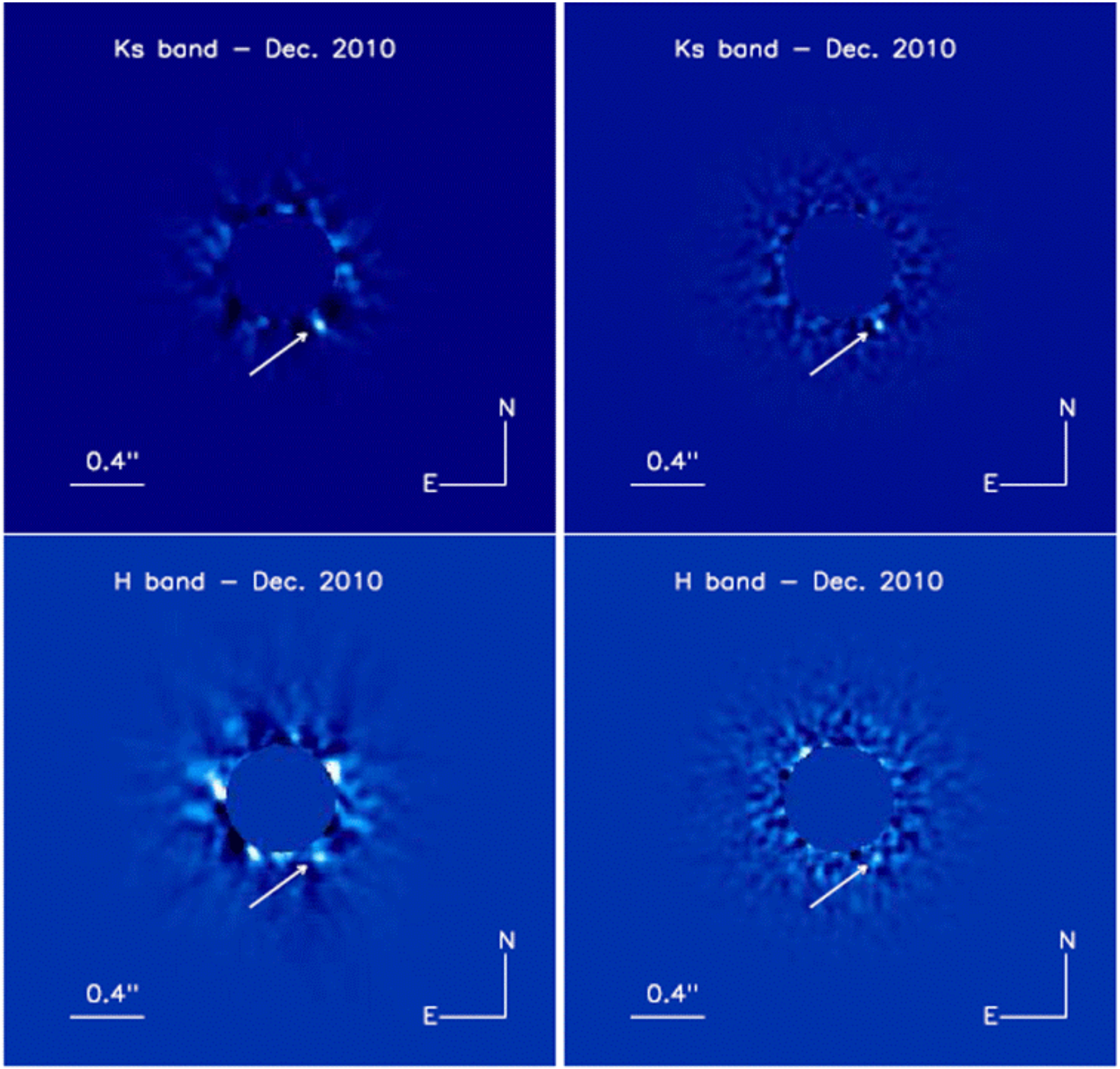
Direct imaging

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



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

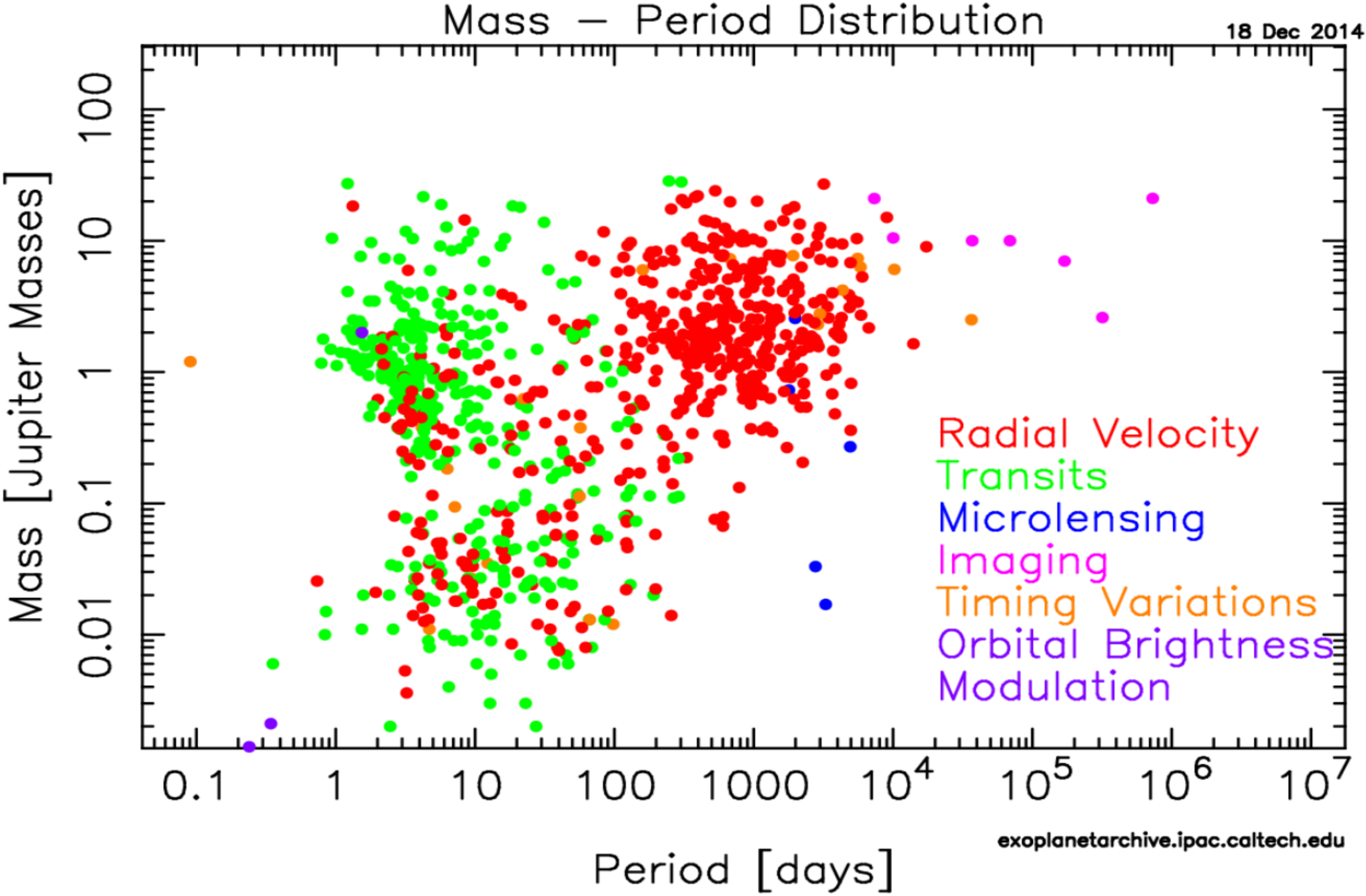
And here is a detail



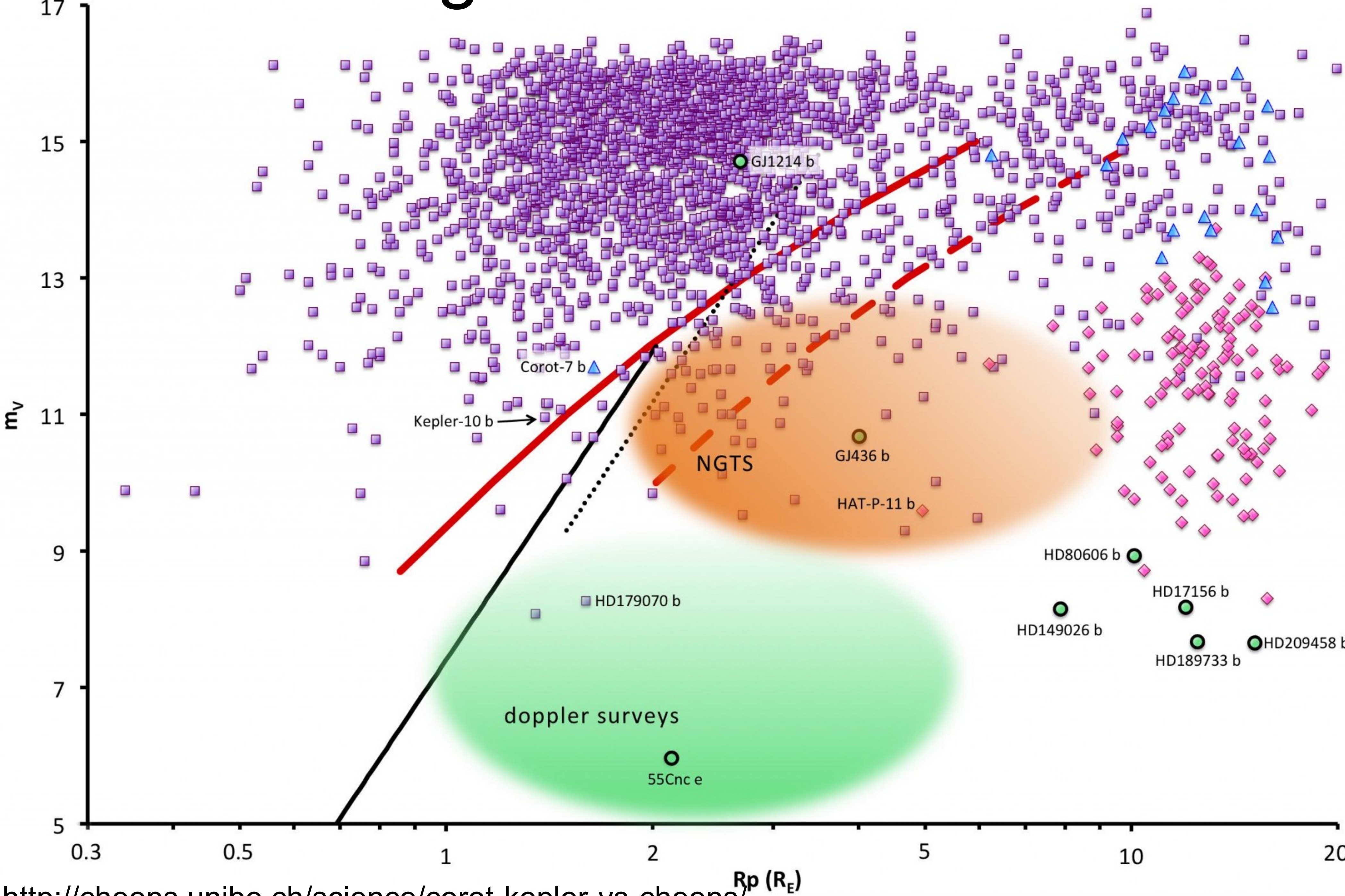
http://www.aanda.org/component/content/article?id=908

Some statistics
Completeness of surveys

Mass vs. period

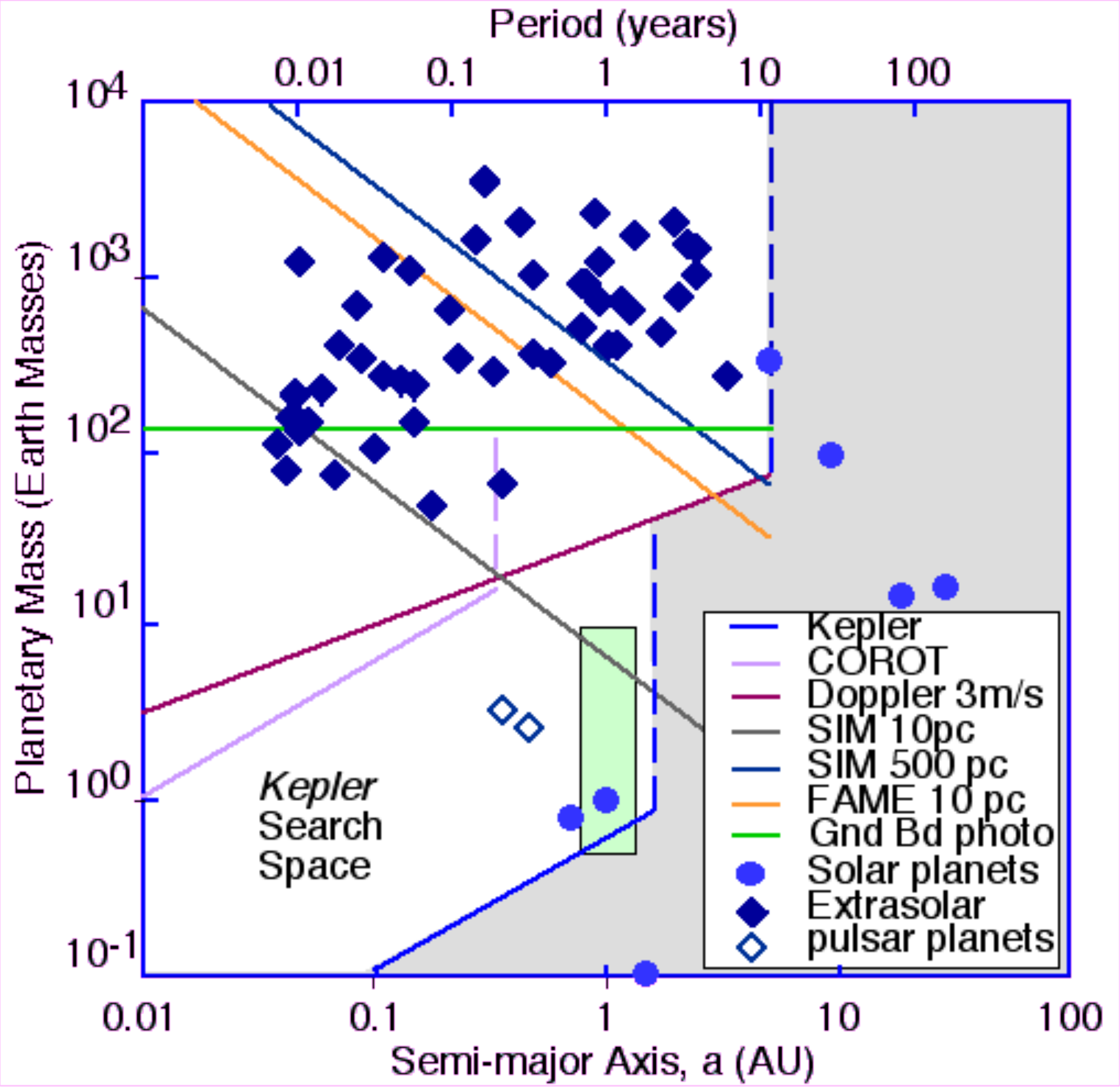


Magnitude vs. radius



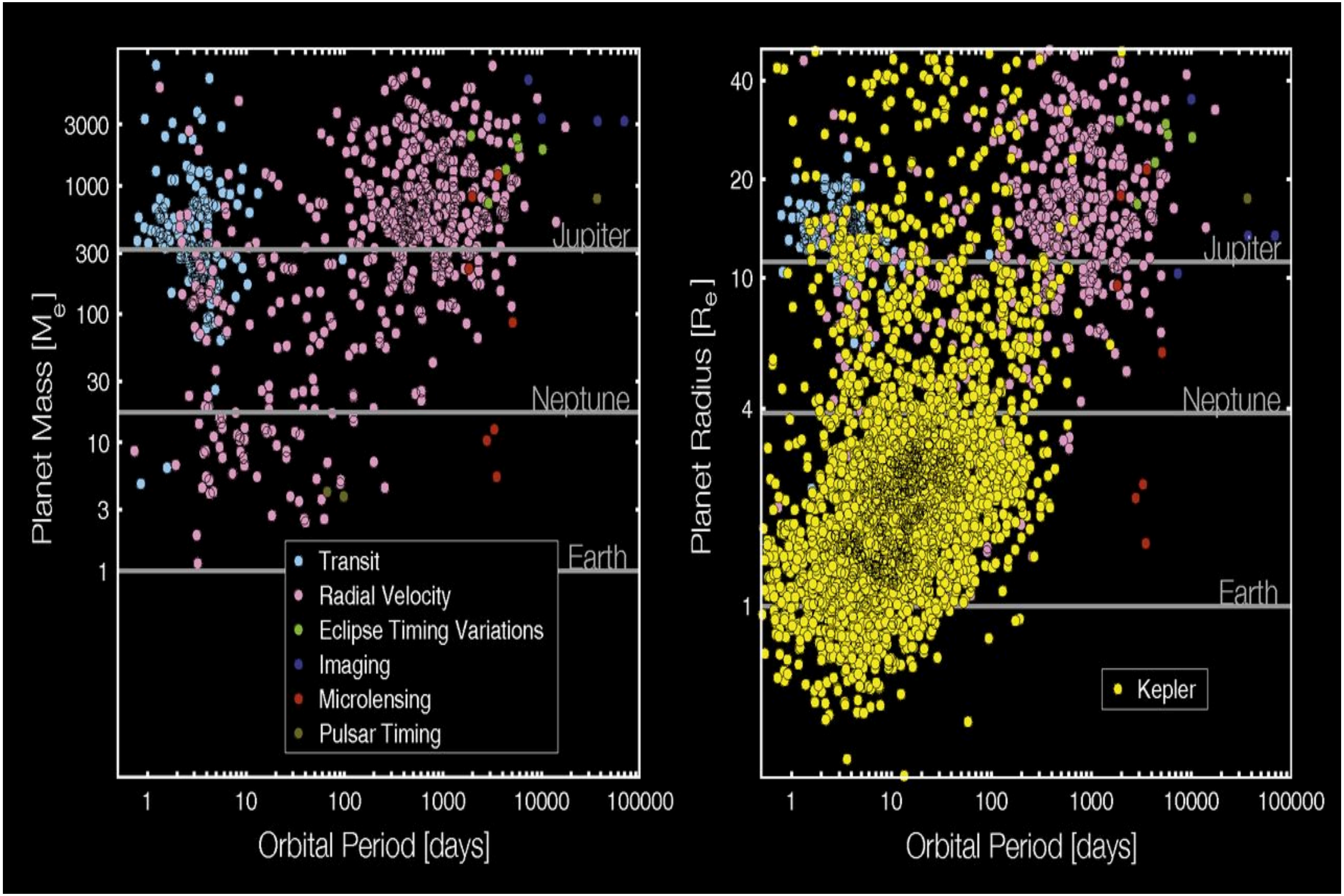
http://cheops.unibe.ch/science/corot-kepler-vs-cheops/

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



Credit: NASA

And similar with Kepler



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

Mass. vs. distance to star

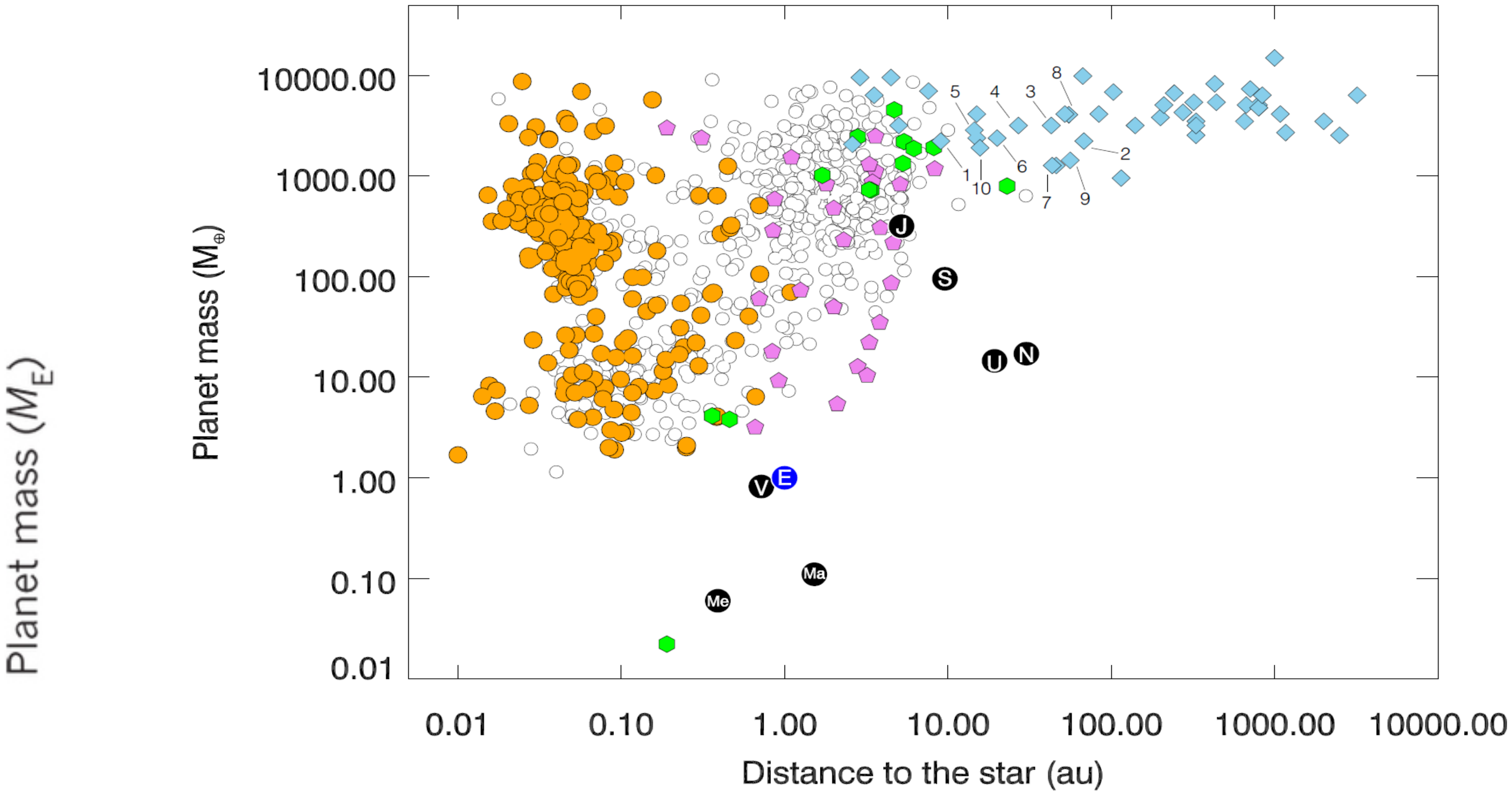


Figure 3: *Mass and semi-major axis of known planets.* **Planetary mass is plotted as a function of semi-major axis (the distance to the host star). Solar-system planets are shown by black circles, the Earth in blue. Exoplanets detected with different techniques and instrumentation are represented by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

Long way towards exoplanets

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

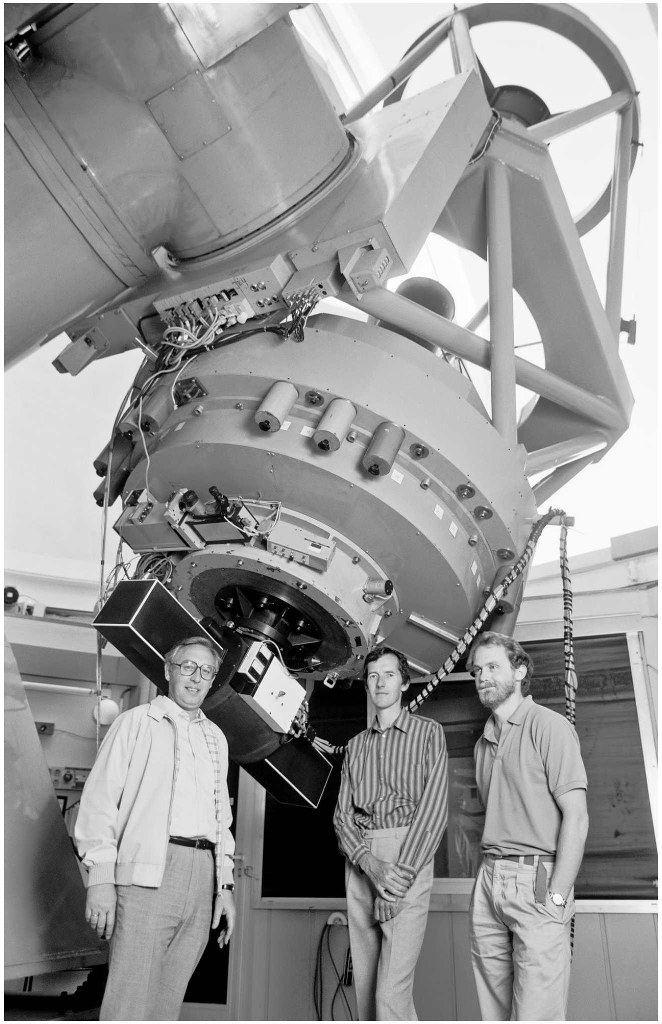


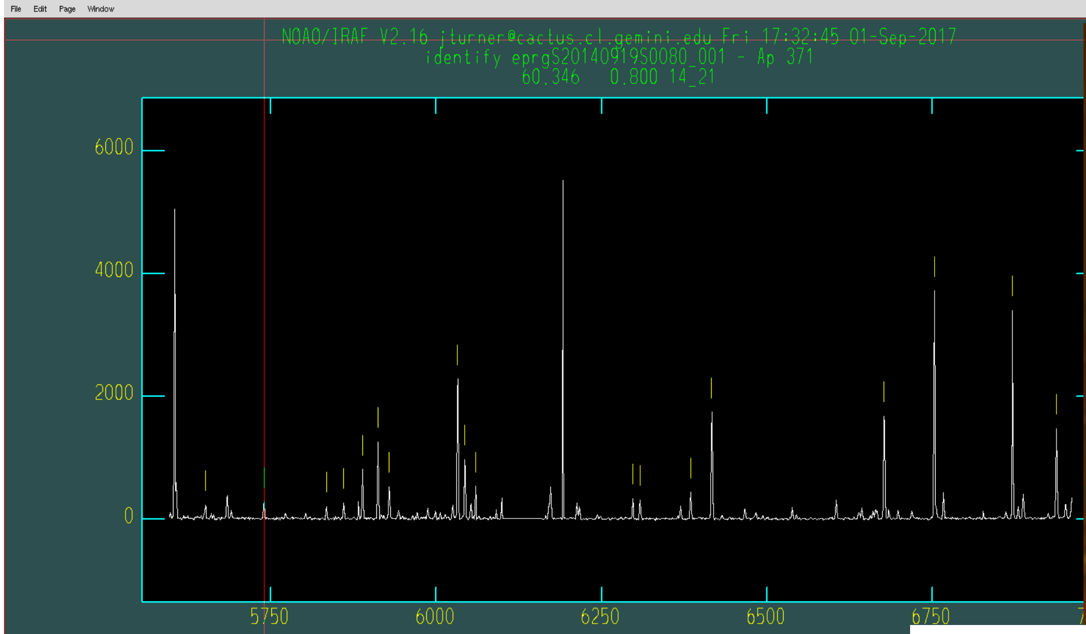
Image: ESO

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.har 1979PASP...91..540C

https://dtm.carnegiescience.edu/news/brief-personal-histo

Importance of the wavelength calibration



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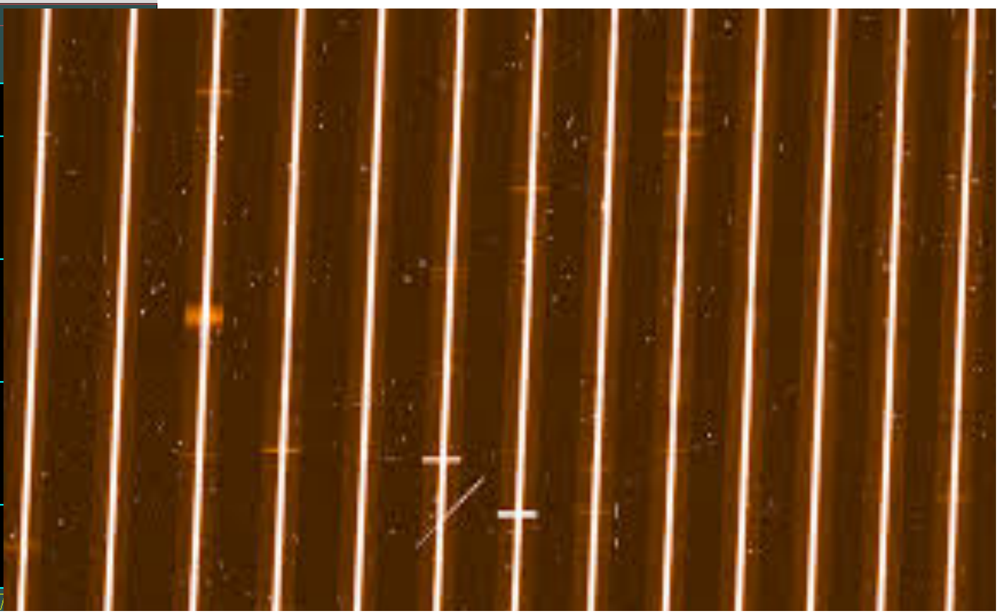
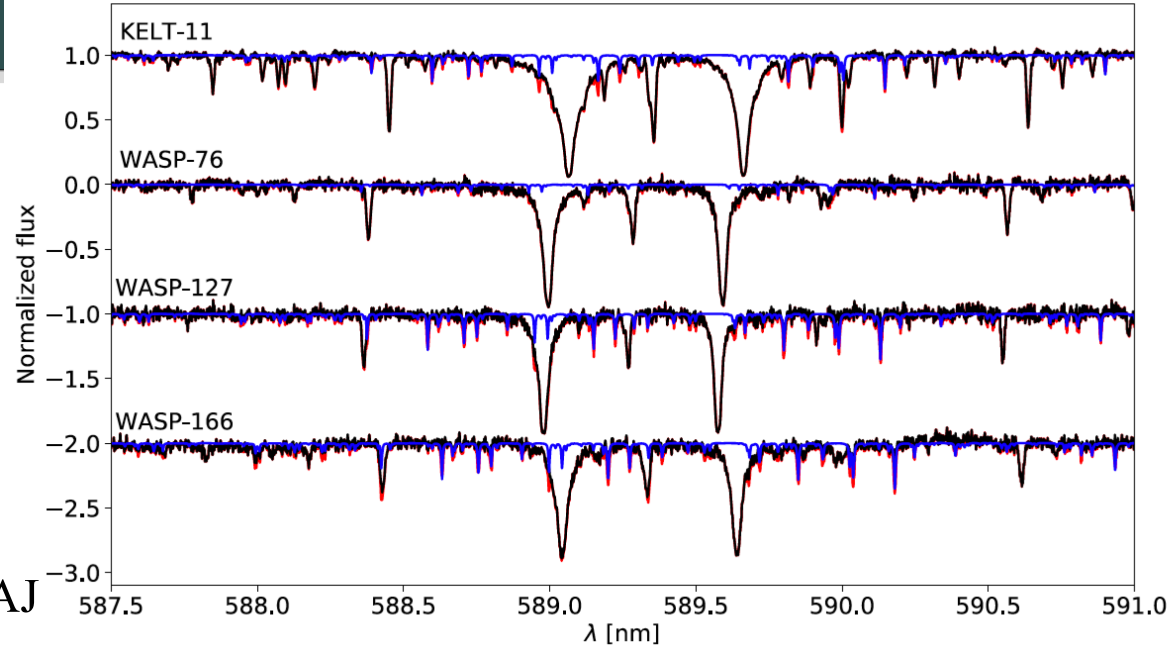
NOAO/IRAF V2.16 jturner@cactus.cl.gemini.edu Fri 17:32:45 01-Sep-2017
identify eprgS20140919S0080_001 - Ap 371
60.346   0.800 14_21
```



GMOS tutorial

Getting from raw spectra to calibrated spectra

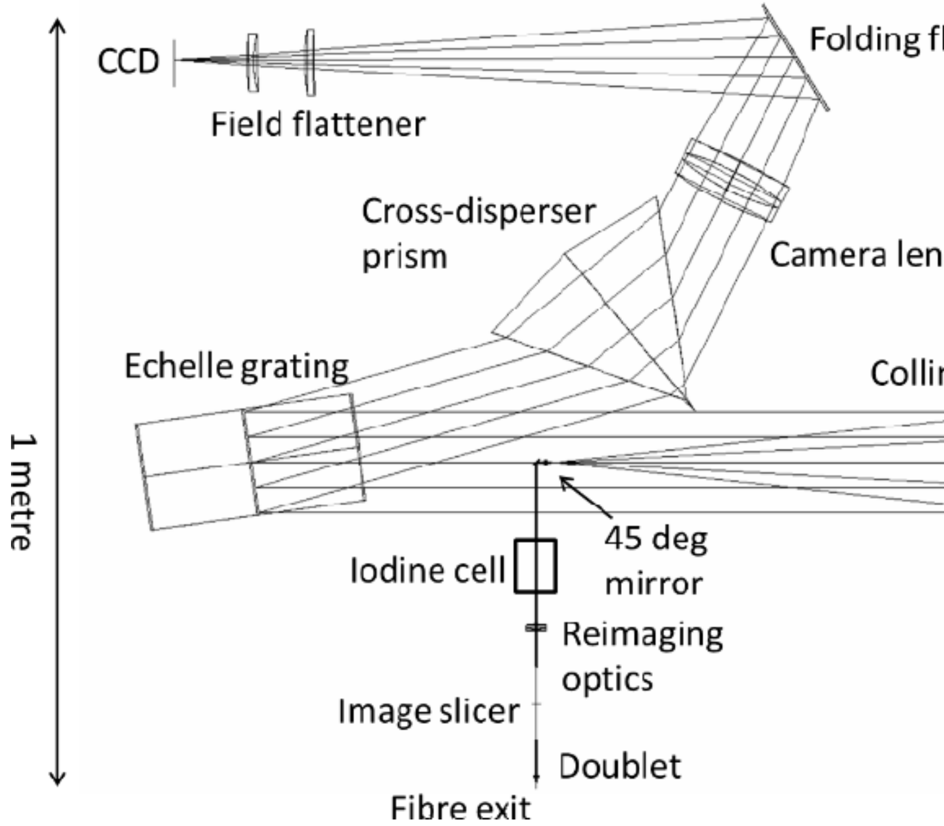


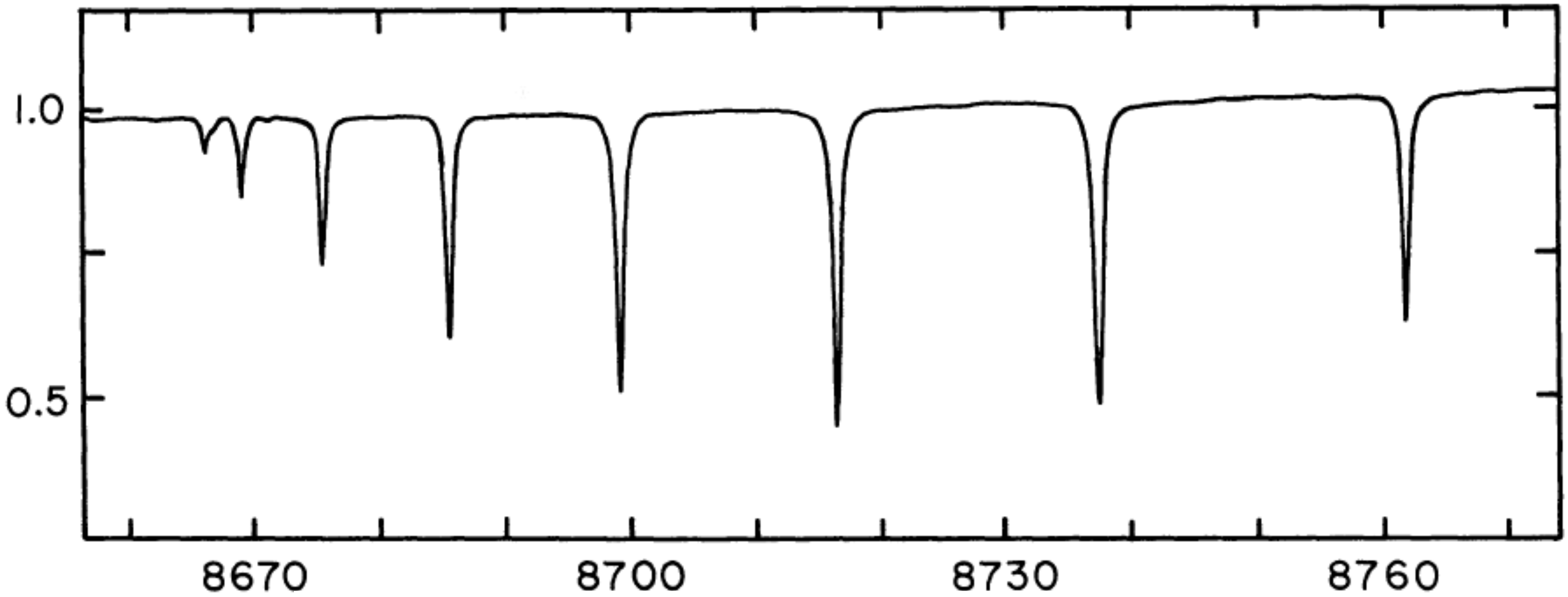
Zak et al. 2020, AJ

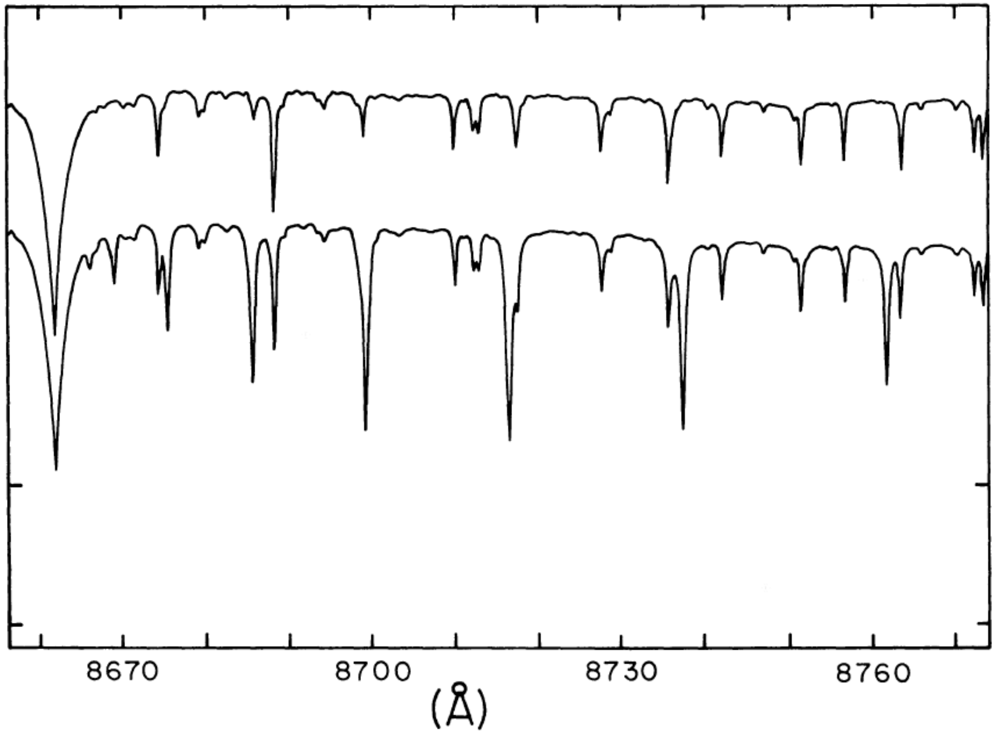
Why an absorption cell?

- 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, SP

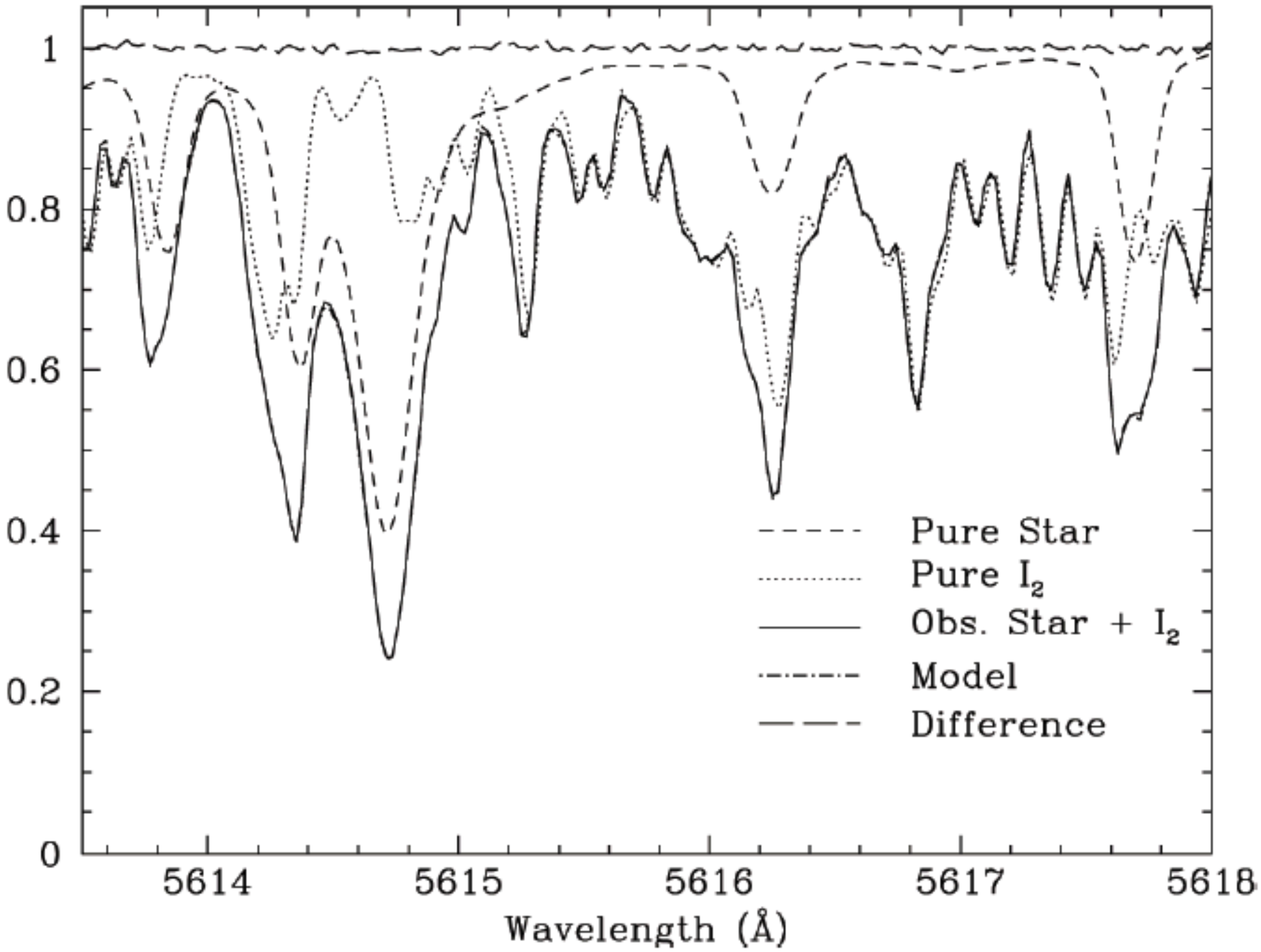






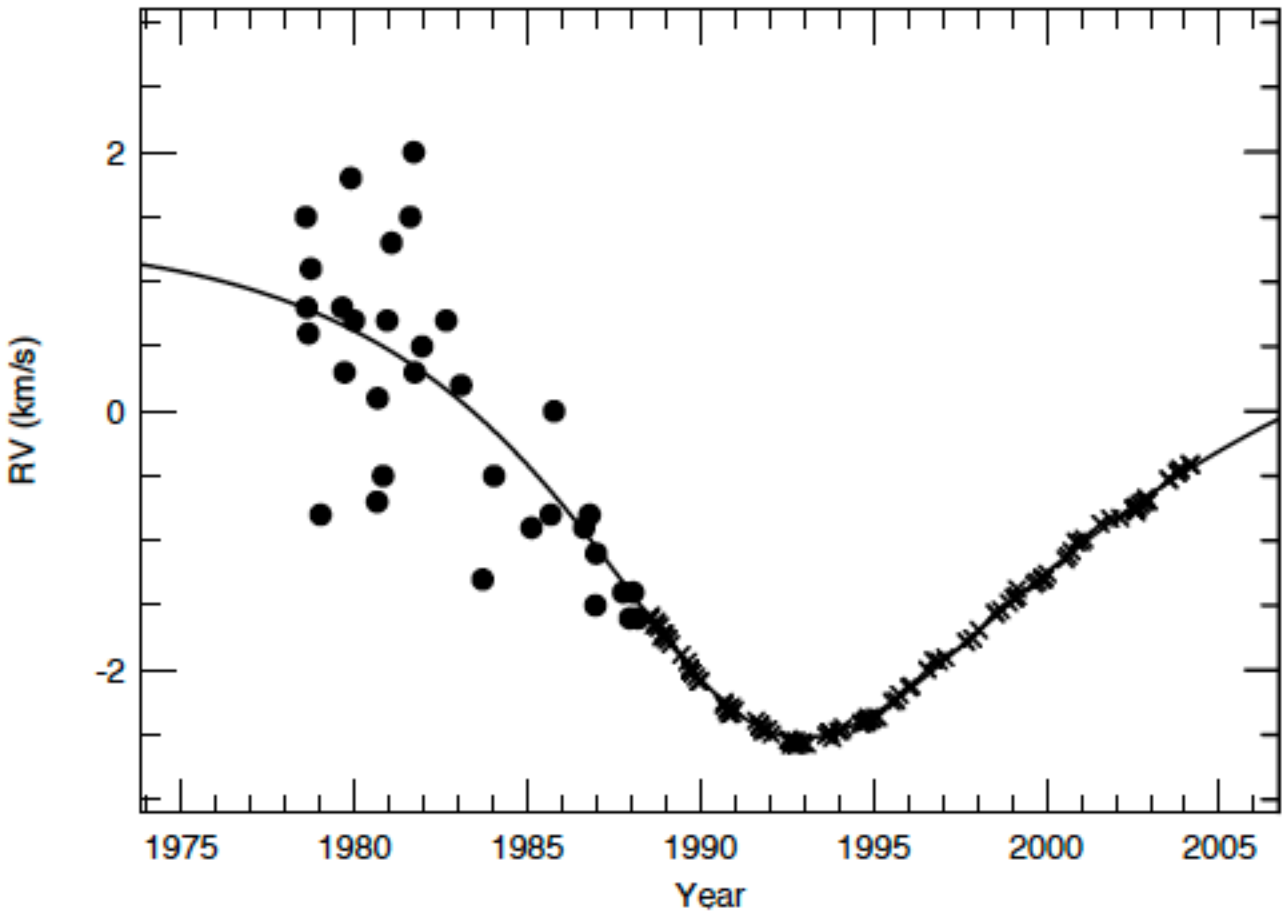
http://articles.adsabs.harvard.edu/pdf/1979PASP...91..540C

Iodine



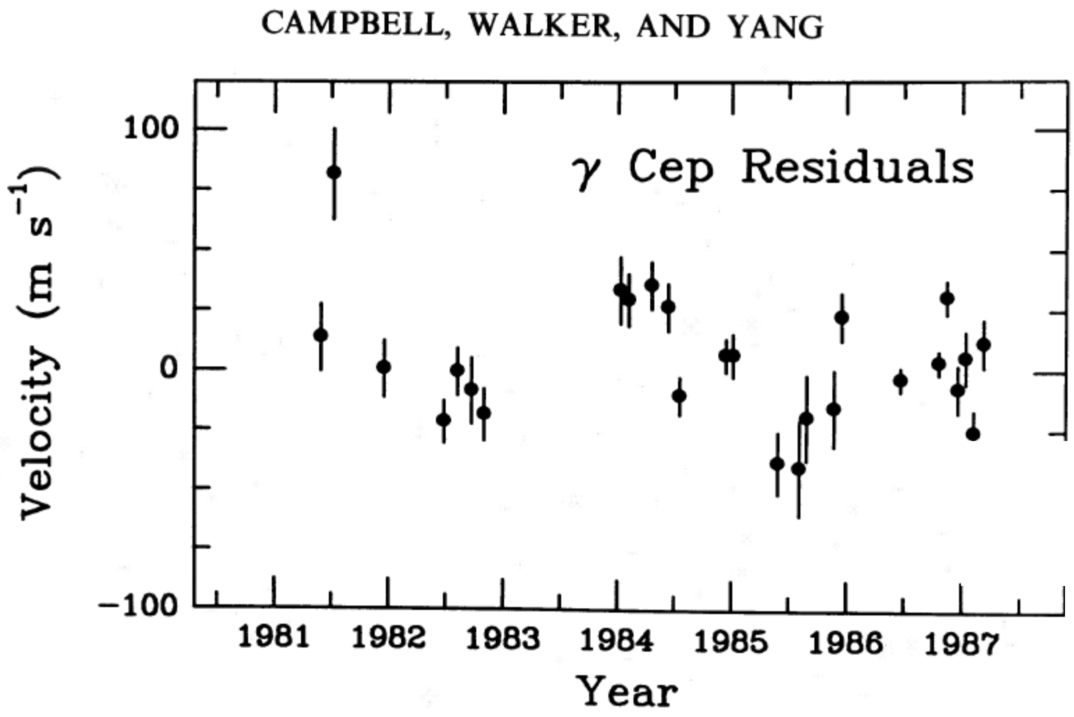
From Hatzes, Cochran and Endl - The Detection of Extrasolar Planets using Precise Stellar Radial Velocities

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

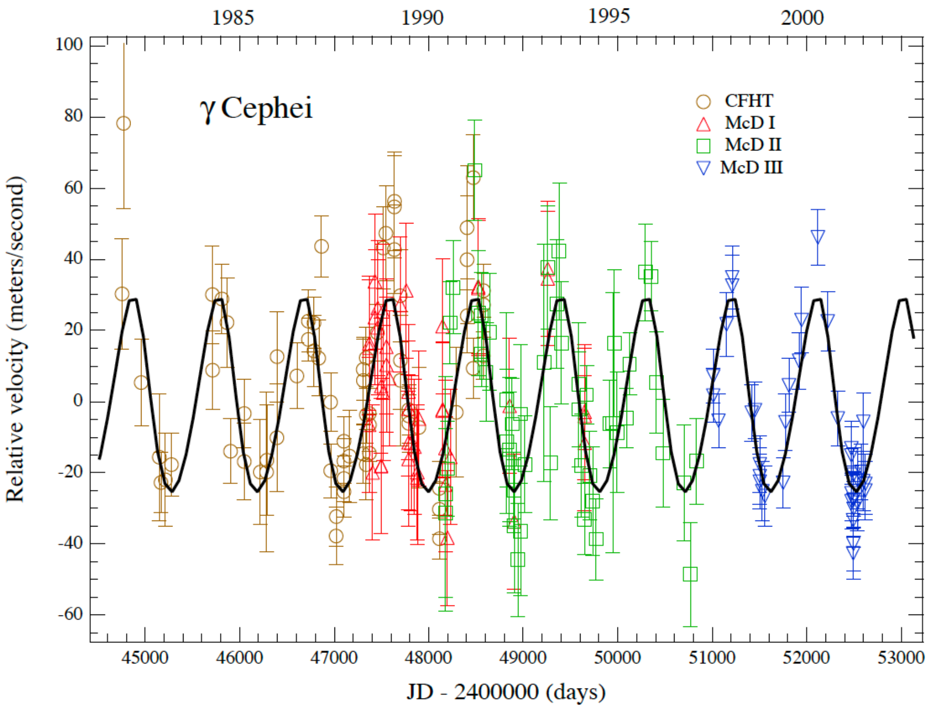
Case of gamma Cep (it is a planet!)



Campbell, Walker and Yang, 1988, ApJ

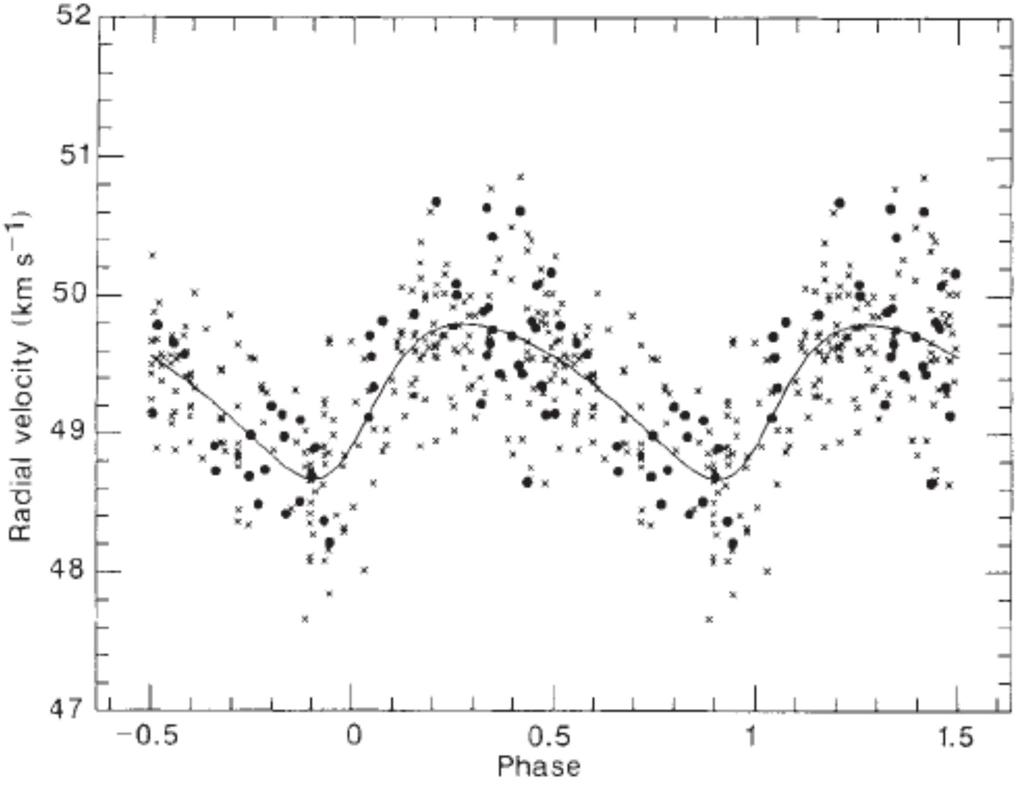
P = 903 days
Mass = 1.85 Mjupiter

Hatzes et al. 2003, ApJ

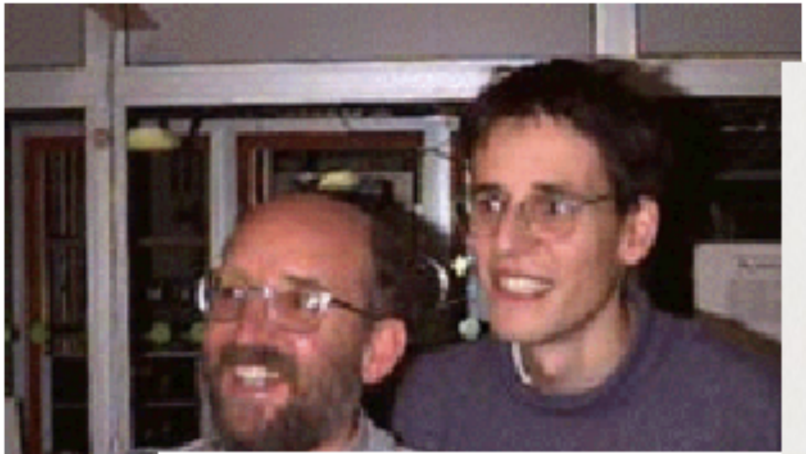


The Case of Dave Lathams planet

- HD114762
- A BD? A planet?
- 11- 65 Jupiter Masses?
- Or more or less?
- Mass of 107 Jup. confirmed
- very low inclination
- Flavien, A&A
- https://arxiv.org/abs/1910.07



From Latham et al. 1989, Nature



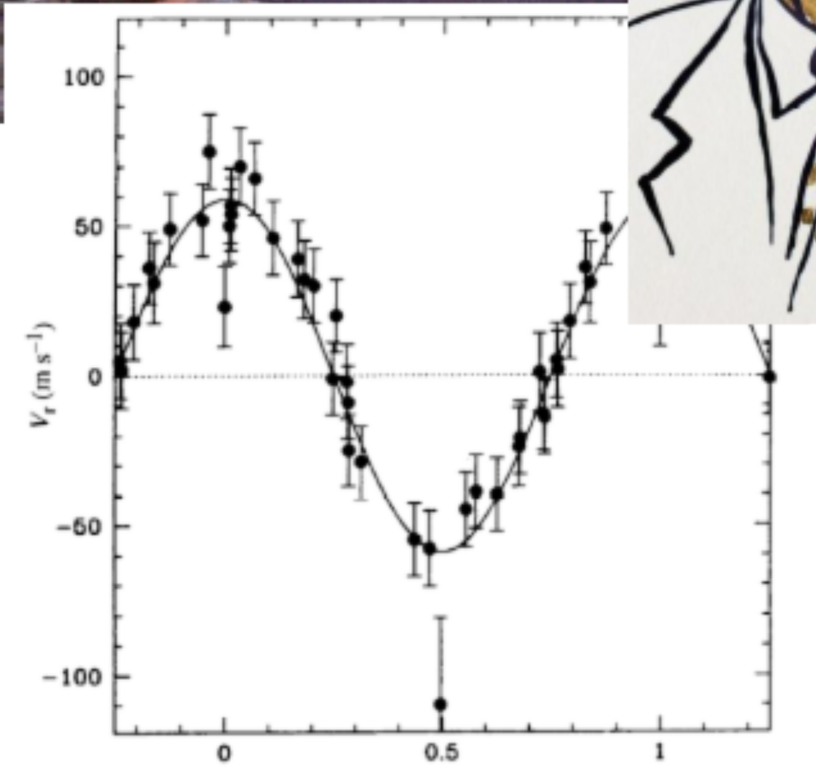


Image from Mayor and Queloz, 1995, Nature

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

Some equations

- Conservation of angular momentum **L** in the central field force
- **torque**=**r** x **F** , **r** and **F** are parallel vectors therefore **torque=0**
- d**L/**dt**=torque** but torque is 0 thus **L** is constant
- **L=r** x m**v=const** L=rmvsin(alpha)=const
- dA/dt=rv sin(alpha)/2=const/(2m) (Second Kepler Law)
- Polar equation of an ellipse:

$$r = \frac{p}{1+\varepsilon\cos(\varphi-k)}$$

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

- Using Kepler law and Newton's law, angular momentum
- For details see:

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

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