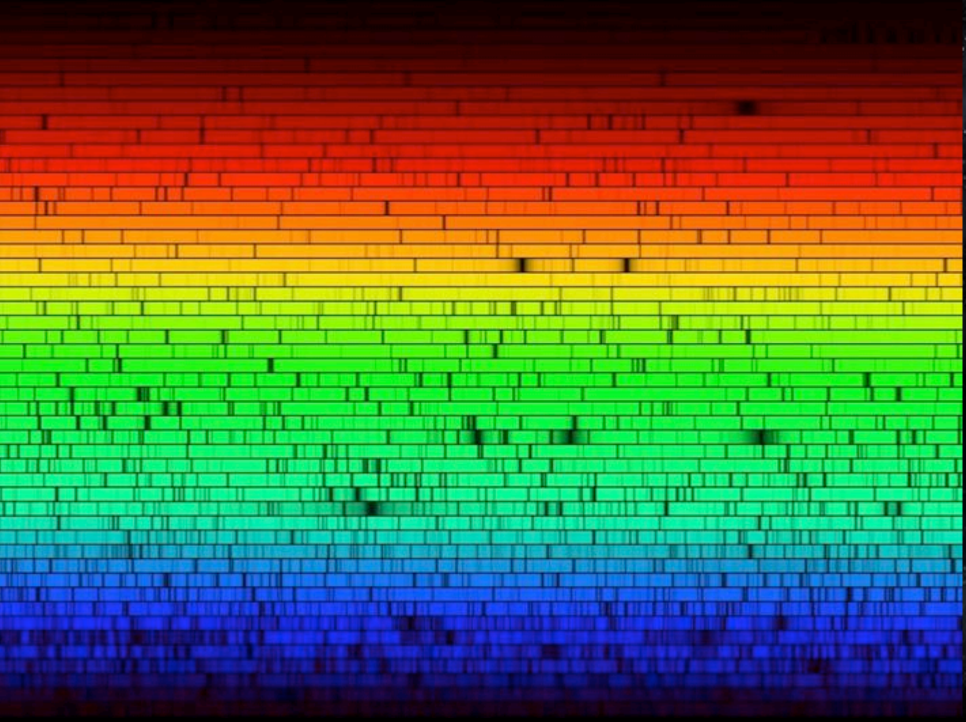
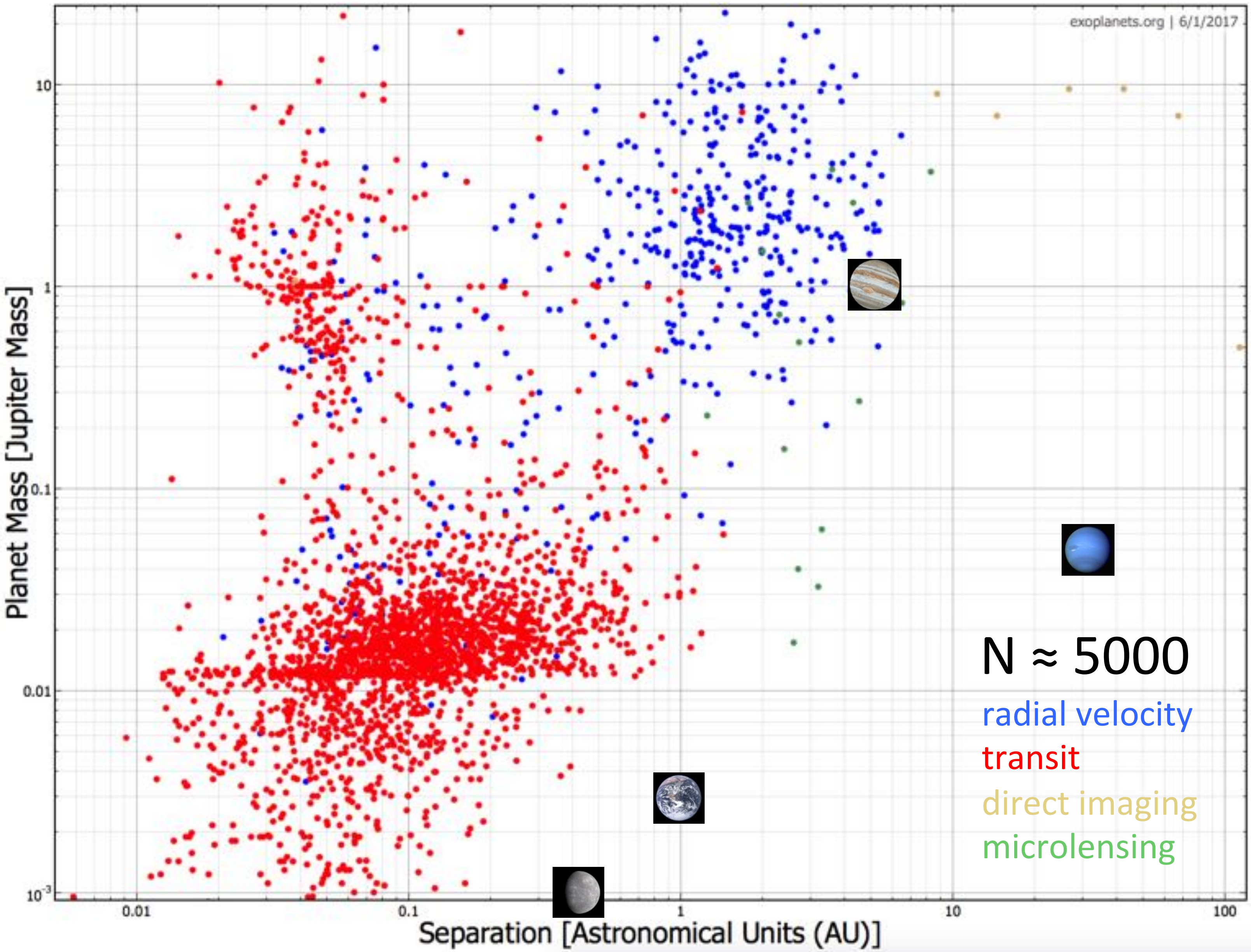


The Role of Precision Spectroscopy in the Search for Earth 2.0

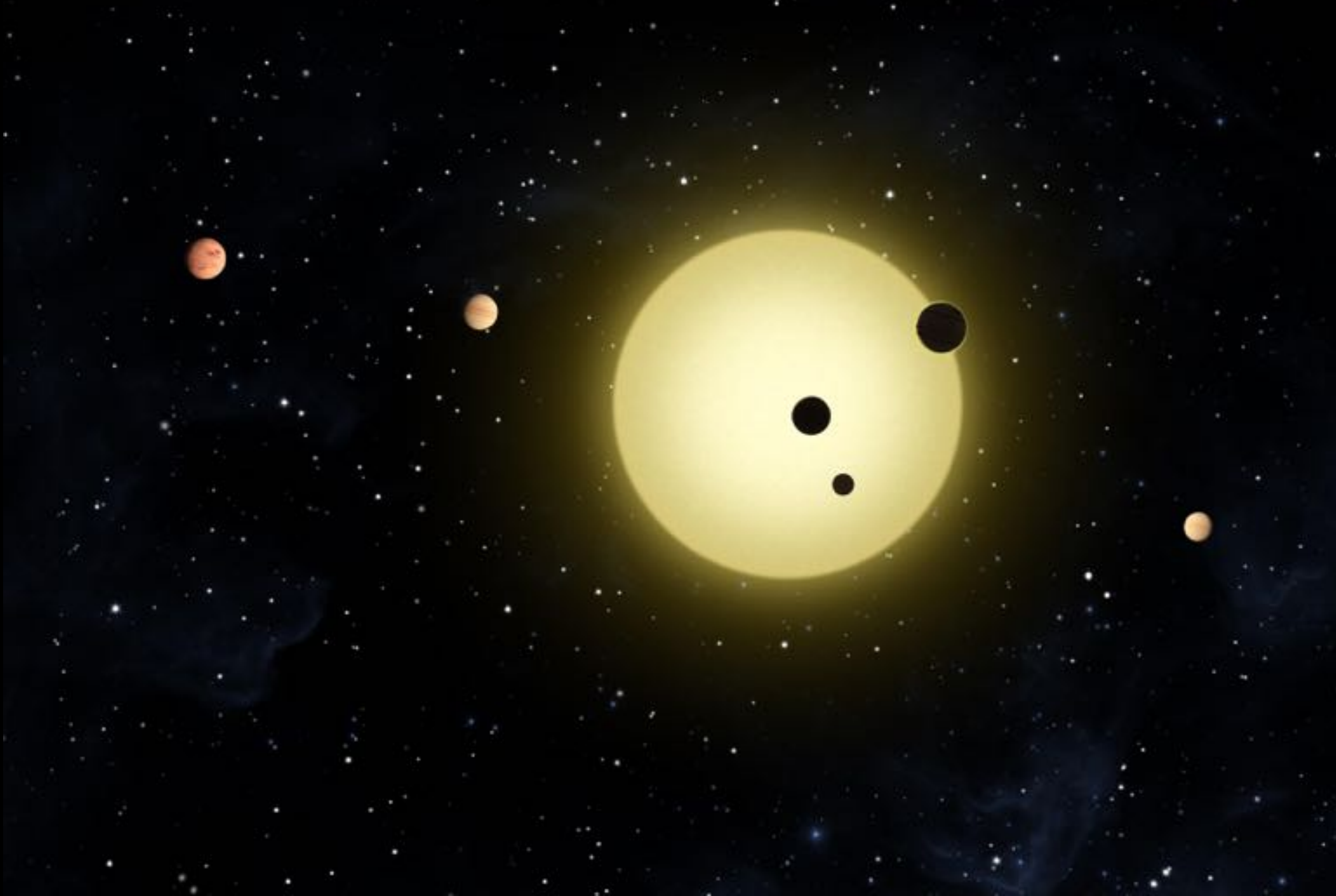
Jacob Bean

University of Chicago

Known exoplanets



The role of precision spectroscopy…



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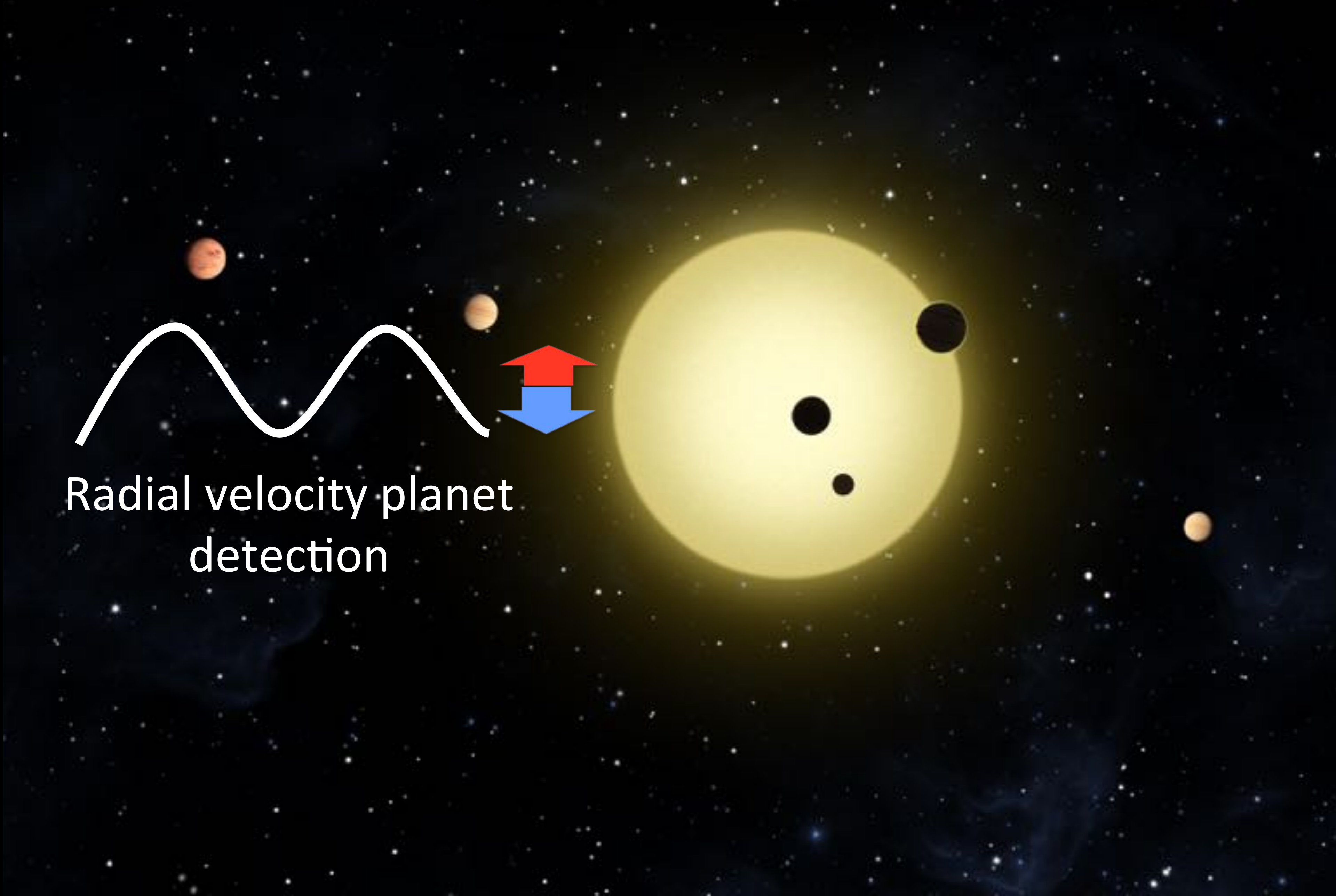

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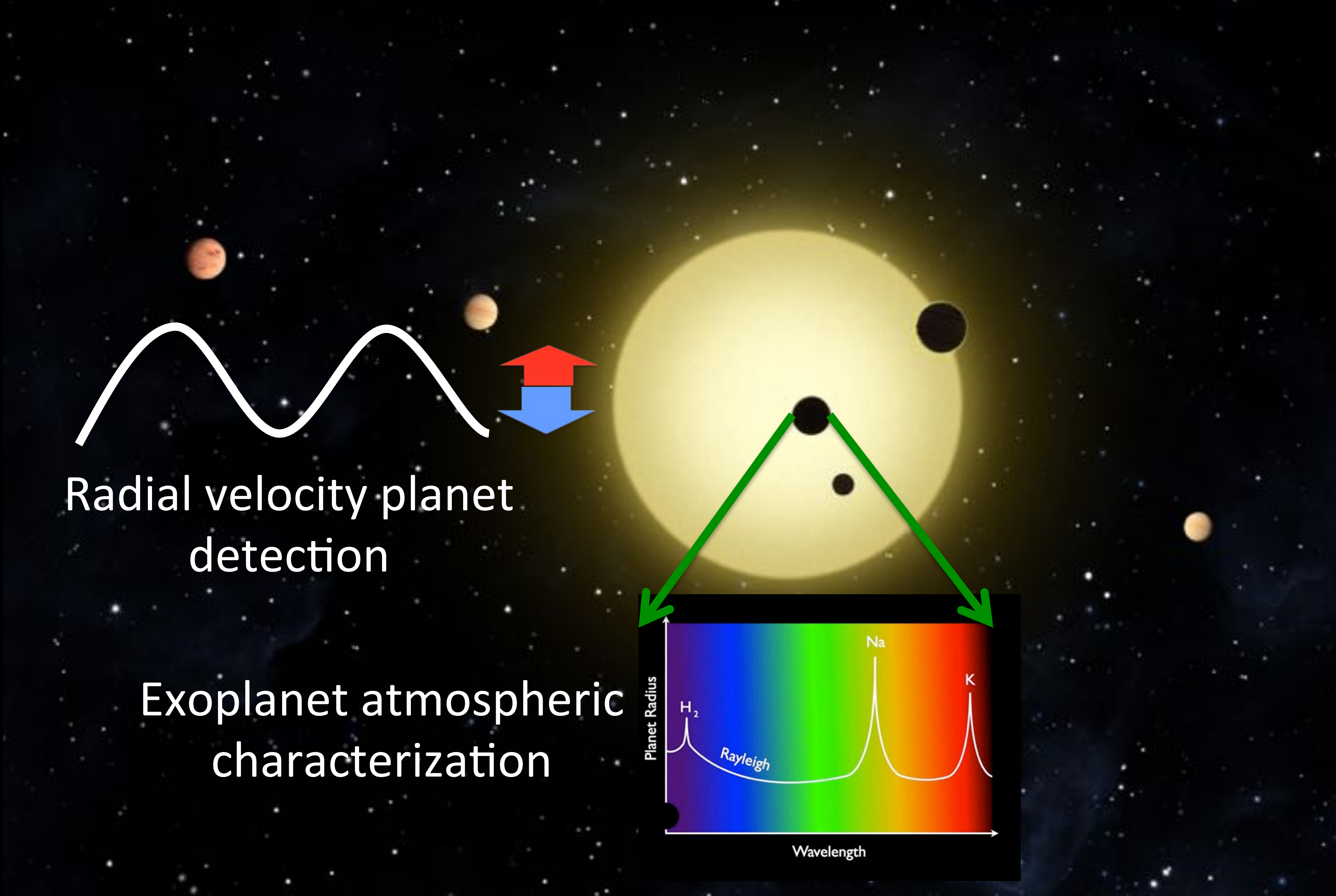

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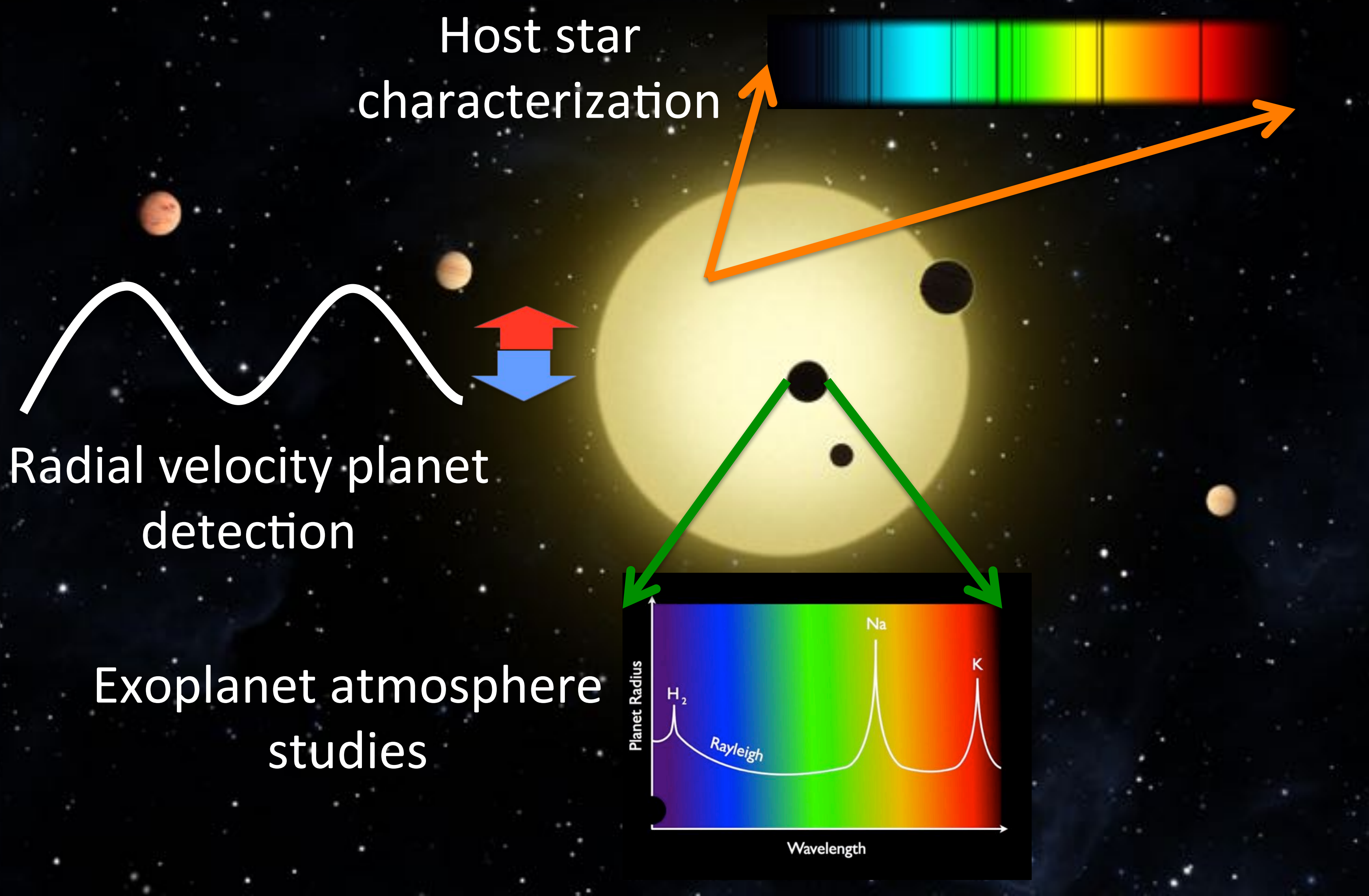

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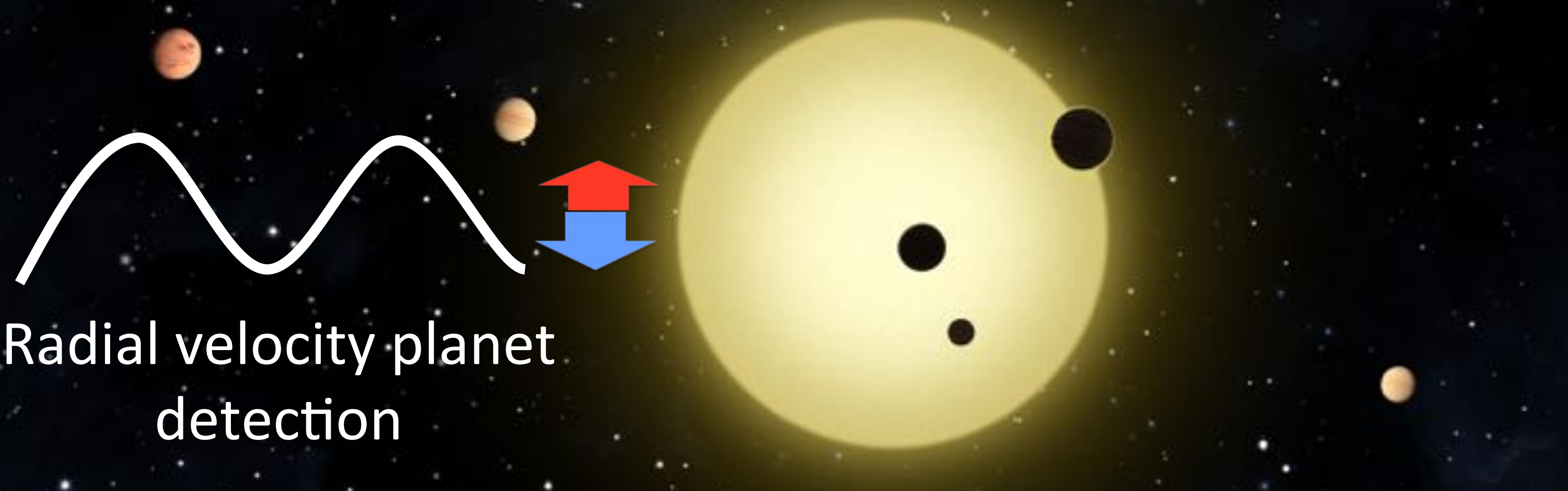
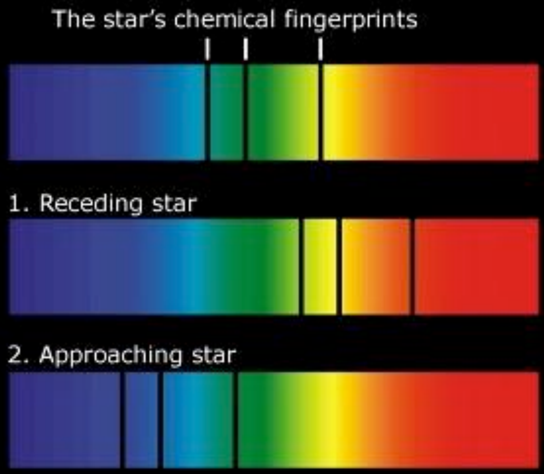
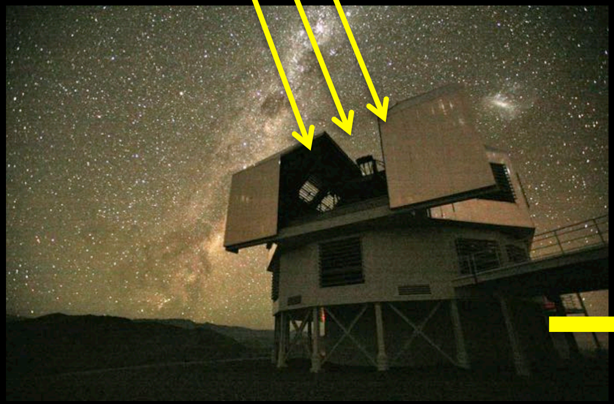
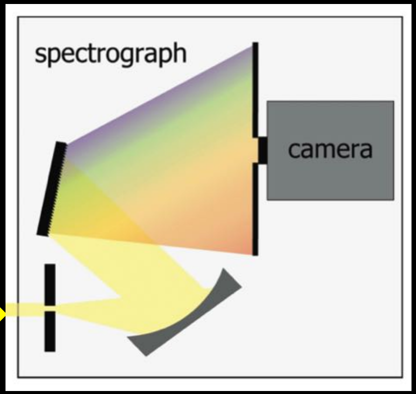


Radial velocity planet detection

Radial Velocity Technique







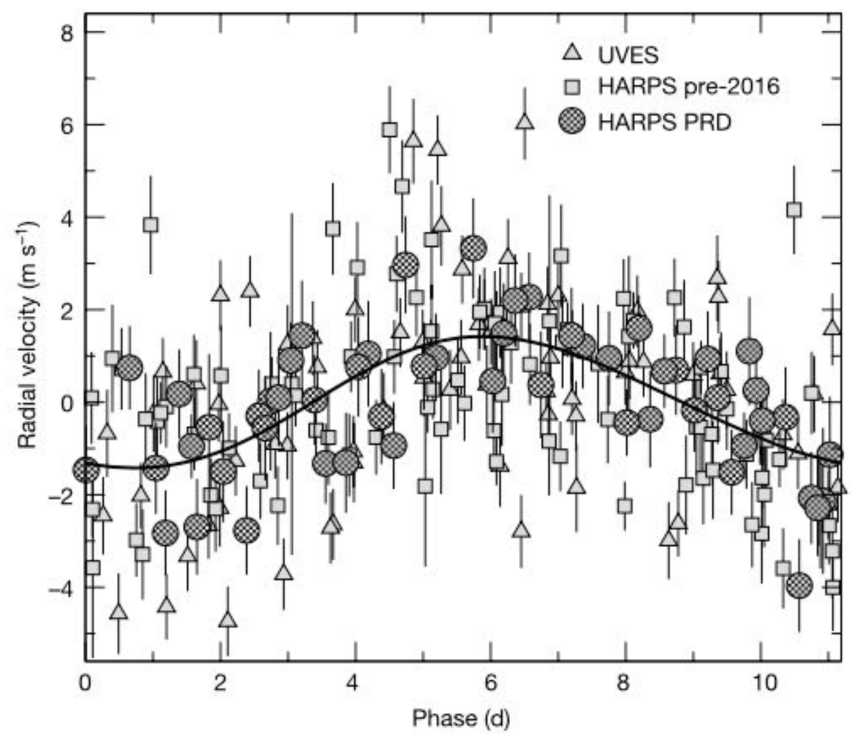
What can you determine?

Table 1 | Stellar properties, Keplerian parameters, and derived quantities

Stellar properties	Value	Reference
Spectral type	M5.5V	2
$M_*/M_\odot$	0.120 (0.105–0.135)	30
$R_*/R_\odot$	0.141 (0.120–0.162)	2
$L_*/L_\odot$	0.00155 (0.00149–0.00161)	2
Effective temperature (K)	3,050 (2,950–3,150)	2
Rotation period (d)	about 83	3
Habitable zone range (AU)	about 0.0423–0.0816	30
Habitable zone periods (d)	about 9.1–24.5	30
Keplerian fit	**Proxima b**	
Period (d)	11.186 (11.184–11.187)	
Doppler amplitude (m s^{-1})	1.38 (1.17–1.59)	
Eccentricity, e	<0.35	
Mean longitude, $\lambda = \omega + M_0$ (°)	110 (102–118)	
Argument of periastron, ω_0 (°)	310 (0–360)	
Statistics summary		
Frequentist FAP	7×10^{-8}	
Bayesian odds in favour, B_1/B_0	2.1×10^7	
UVES jitter (m s^{-1})	1.69 (1.22–2.33)	
HARPS pre-2016 jitter (m s^{-1})	1.76 (1.22–2.36)	
HARPS PRD jitter (m s^{-1})	1.14 (0.57–1.84)	
Derived quantities		
Orbital semi-major axis, a (AU)	0.0485 (0.0434–0.0526)	
Minimum mass, $m_p \sin i$ ($M_\oplus$)	1.27 (1.10–1.46)	
Equilibrium black body temperature (K)	234 (220–240)	
Irradiance compared with Earth	65%	
Geometric probability of transit	about 1.5%	
Transit depth (Earth-like density)	about 0.5%	

The estimates are the maximum *a posteriori* values and the uncertainties of the parameters are expressed as 68% credibility intervals. We provide only an upper limit for the eccentricity (95% confidence level). Extended Data Table 1 contains the list of all of the model parameters.

A small planet in the habitable zone around our nearest neighbor, Proxima Centauri



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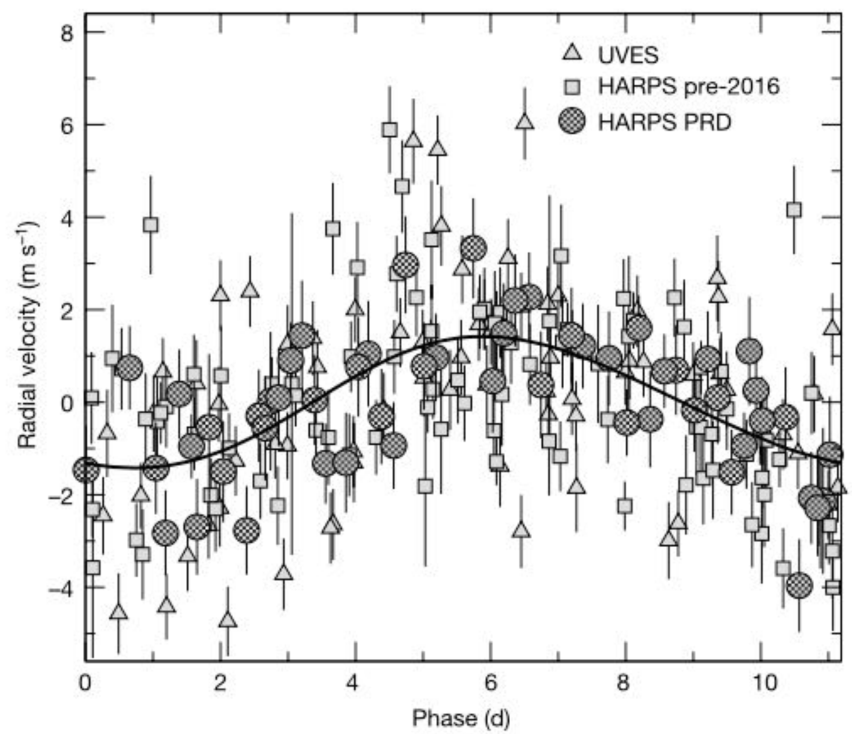

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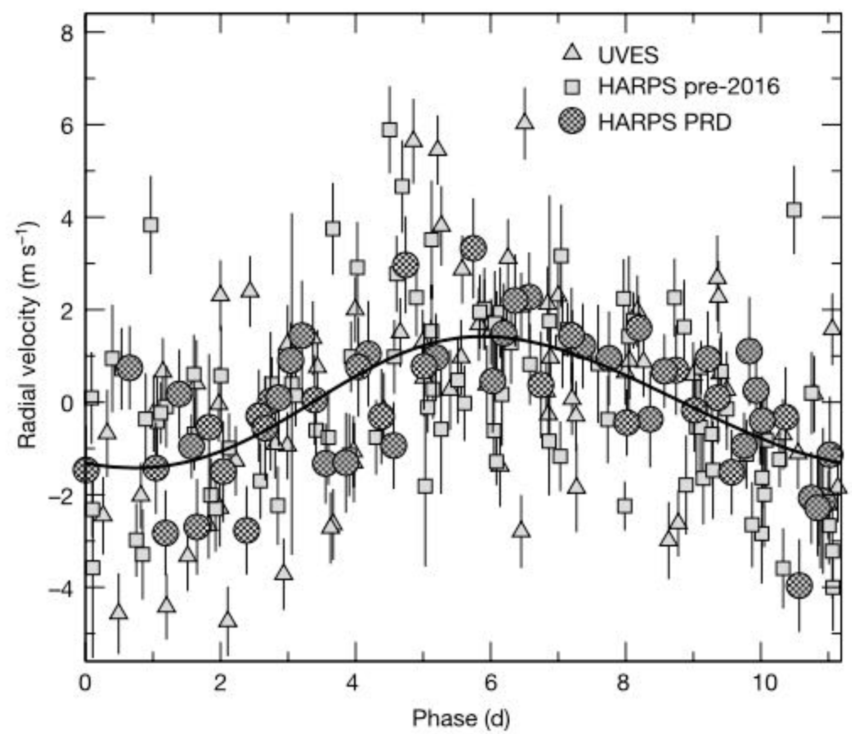
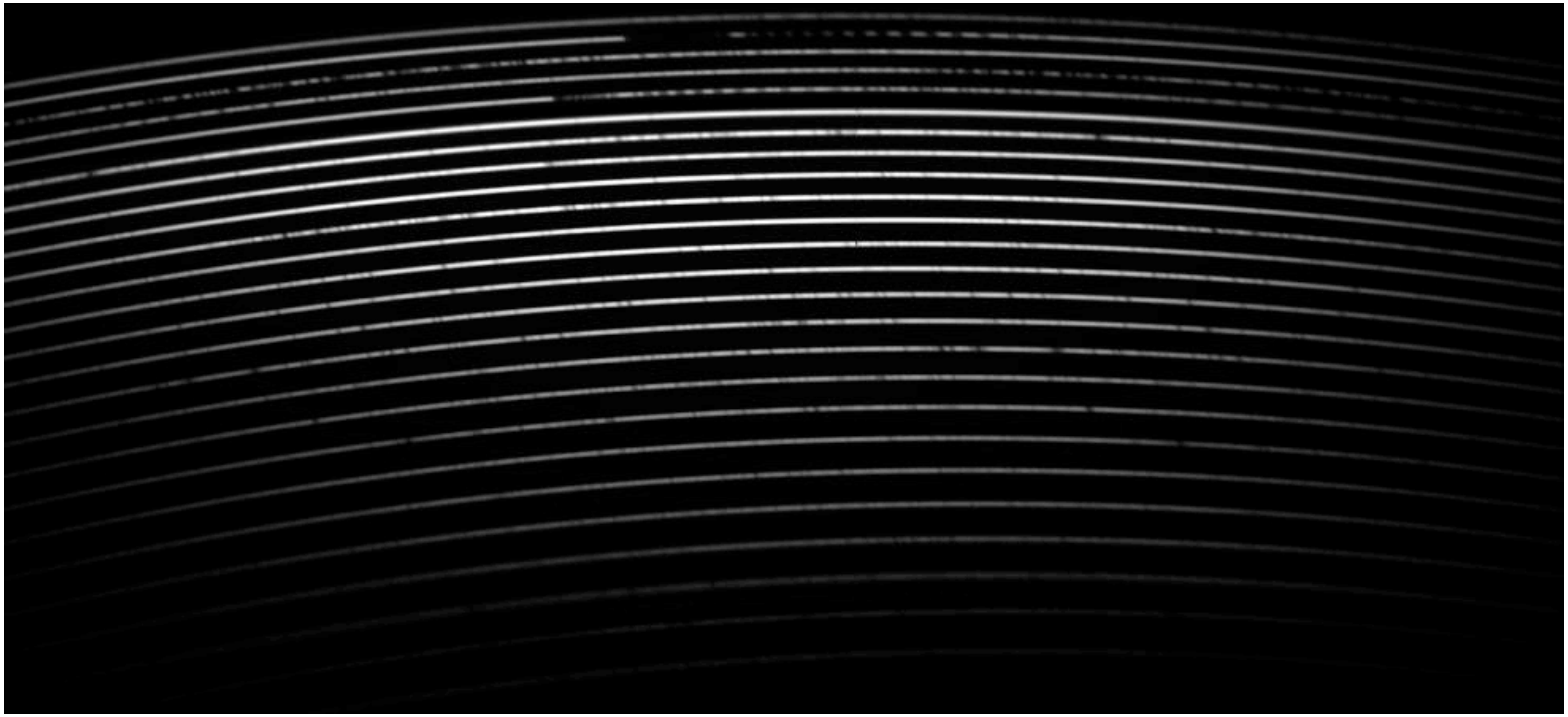


“Cross-Dispersed Echelle” Spectrogrpah



Limitations to instrument stability

- **Changes in the spectrograph response.**

(e.g., mechanical motion of the spectrograph or detector, changes in the refractive index of air inside the spectrograph)

- **Changes in the light injection.**

Strategies for instrument stability

- **Stabilize the instrument with extensive engineering.**
- **Calibrate for (small or large) changes.**

Very stabilized instruments: HARPS @ 3.6m at ESO/Chile

Spectrograph on a rigid bench, which is housed in a vacuum tank.

Very stabilized instruments: HARPS @ 3.6m at ESO/Chile

Spectrograph on a rigid bench, which is housed in a vacuum tank.

The tank itself is housed in a climate controlled room that is never opened.

- Pressure controlled to 10^{-3} mbar
- Optical bench controlled to 1 mK

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Spectrograph on a rigid bench, which is housed in a vacuum tank.

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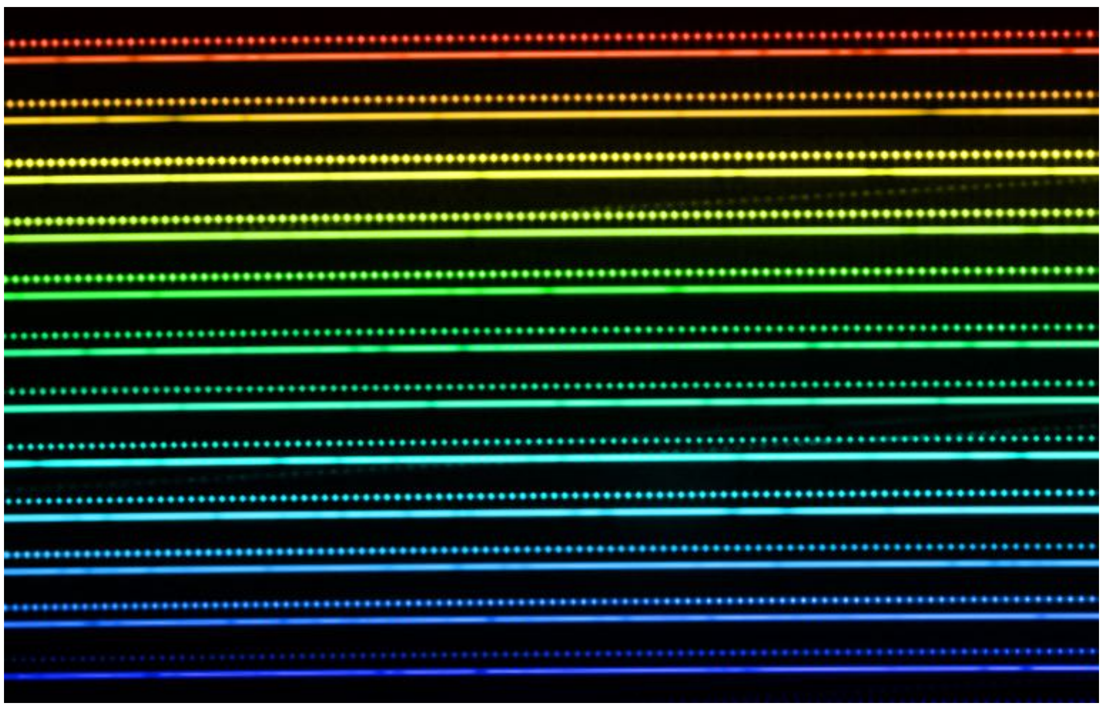
Light is coupled from the telescope with fiber optics that “scramble” the light.

Very stabilized instruments: HARPS @ 3.6m at ESO/Chile



Spectrograph on a rigid bench, which is housed in a vacuum tank.

The tank itself is housed in a climate controlled room that is never opened.

Light is coupled from the telescope with fiber optics that "scramble" the light.

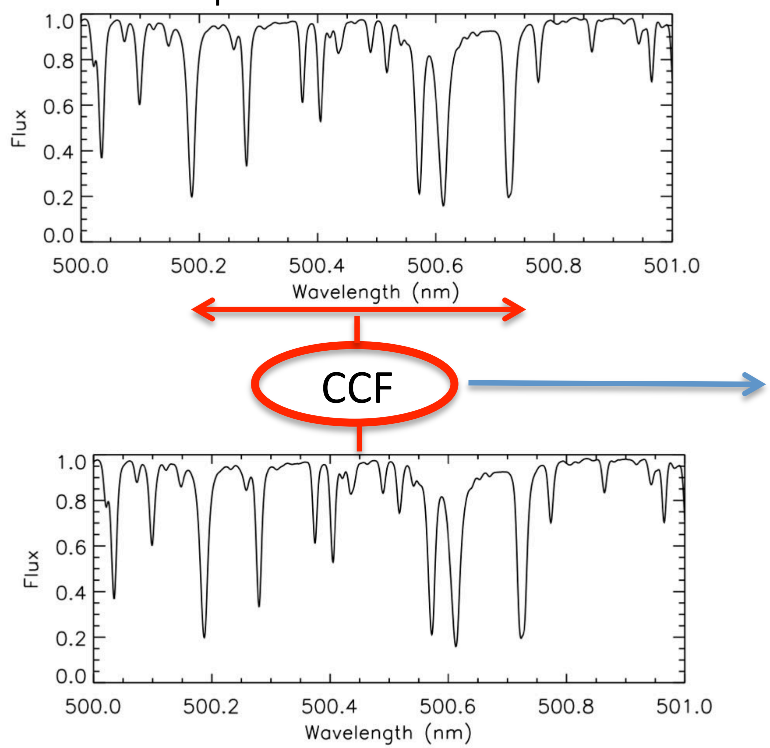
A second fiber feed a simultaneous calibration source.

Very stabilized instruments: HARPS @ 3.6m at ESO/Chile

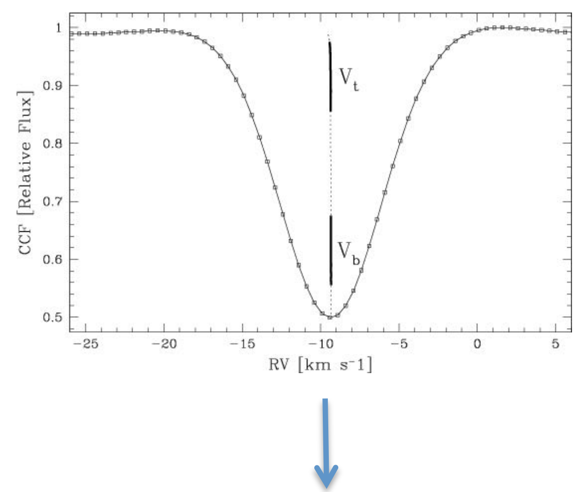
Cross-Correlation Technique

Original reference:
Tonry & Davis 1979, AJ, 84, 10

observed spectrum



template spectrum

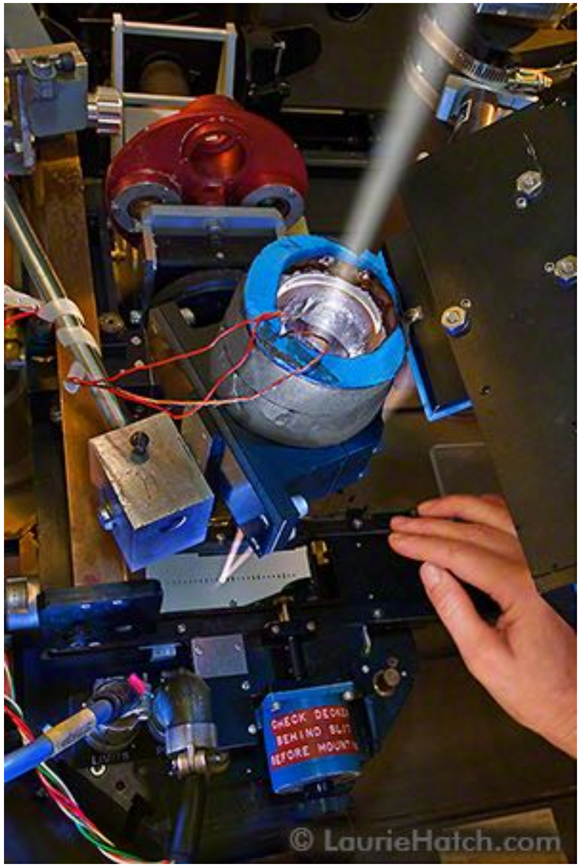


radial velocity

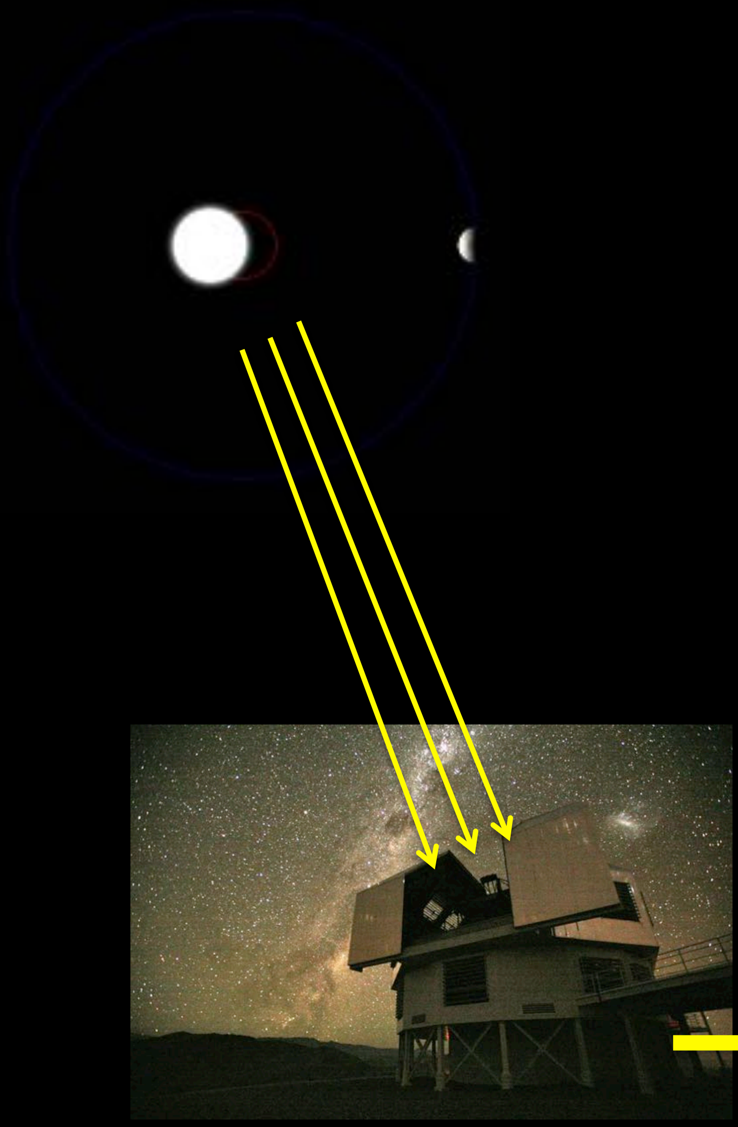
Strategies for instrument stability

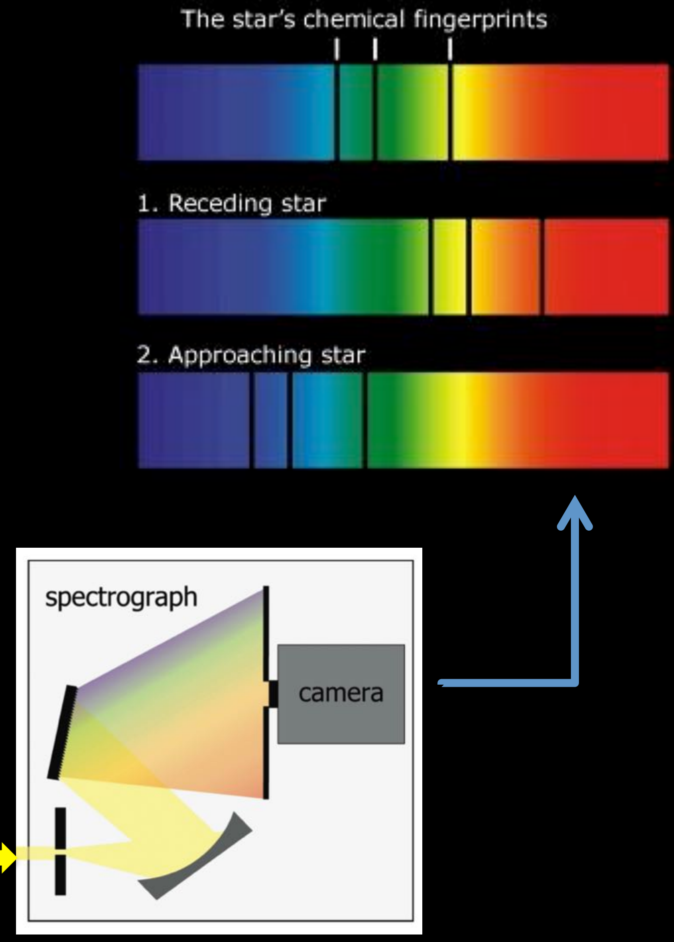
- **Stabilize the instrument with extensive engineering.**
- **Calibrate for (small or large) changes.**

Gas cell technique



Radial Velocity Technique





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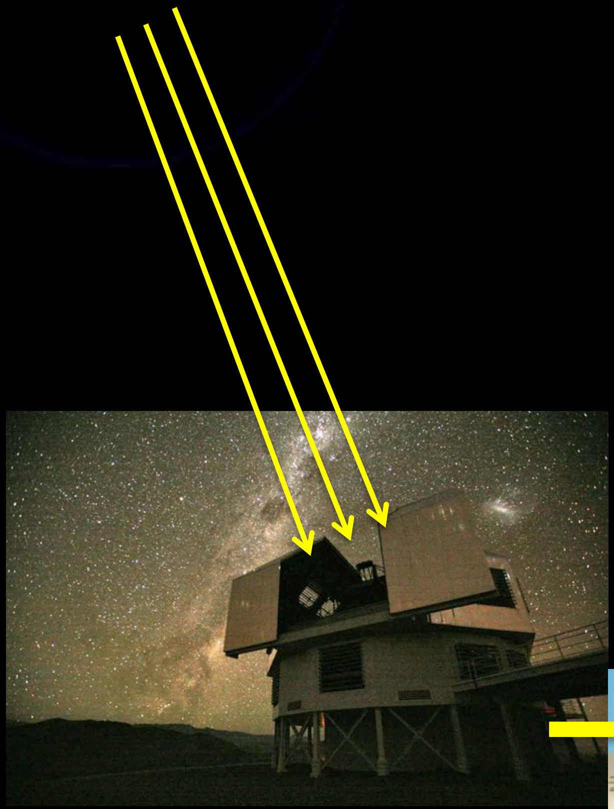

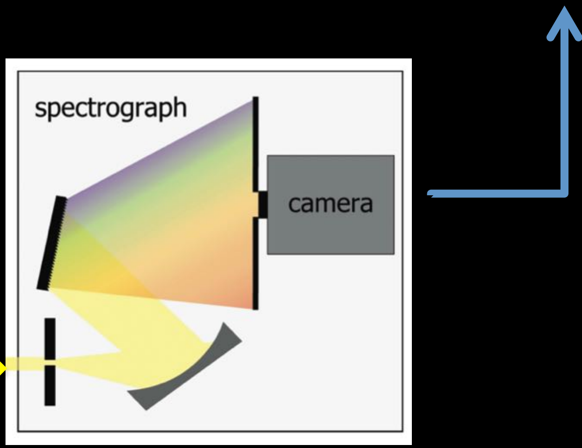

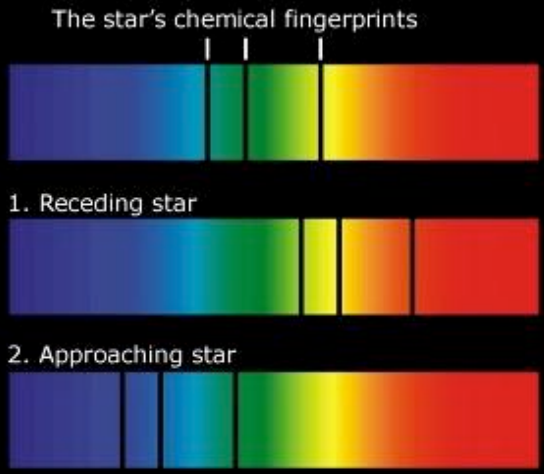

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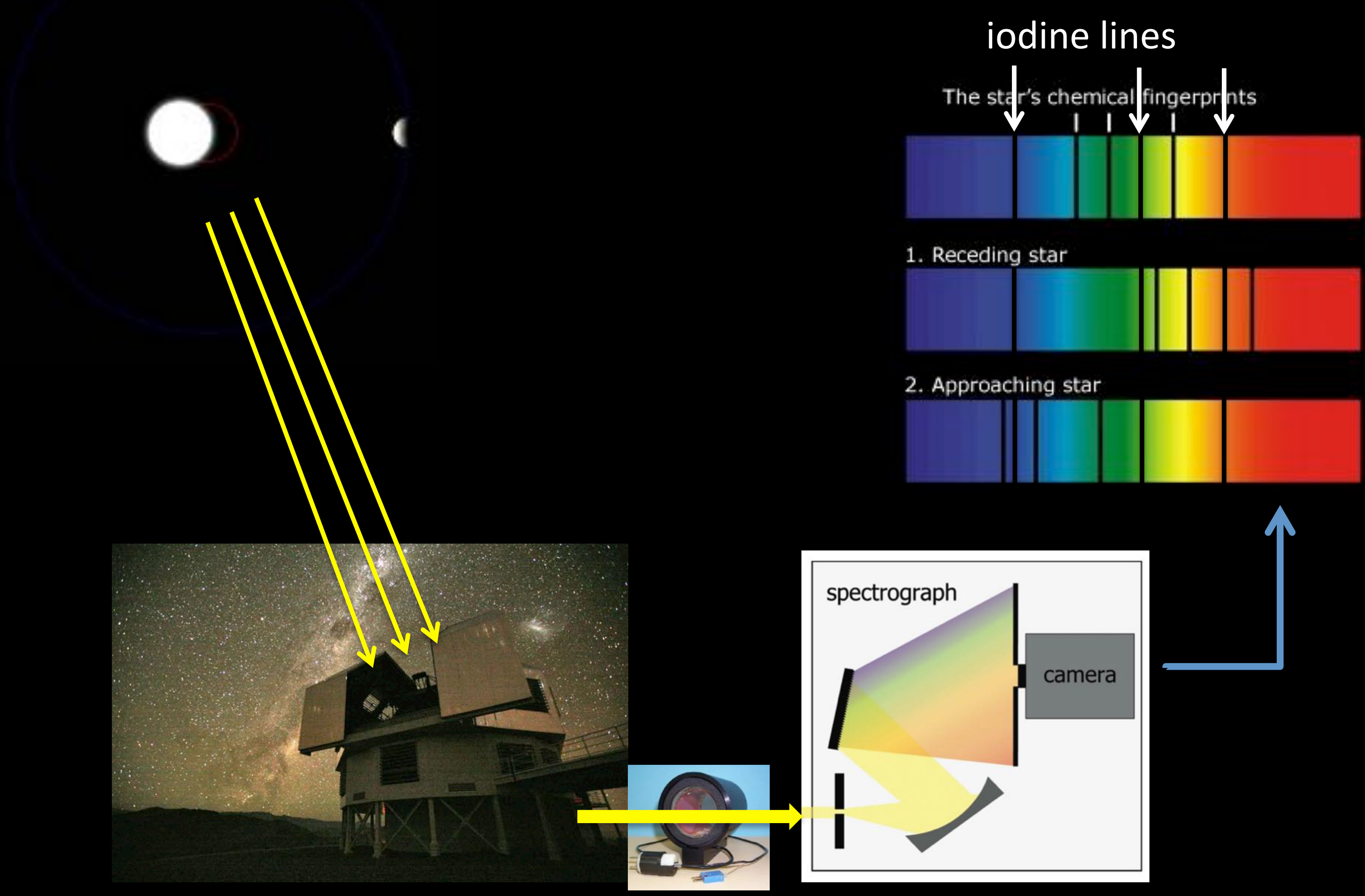
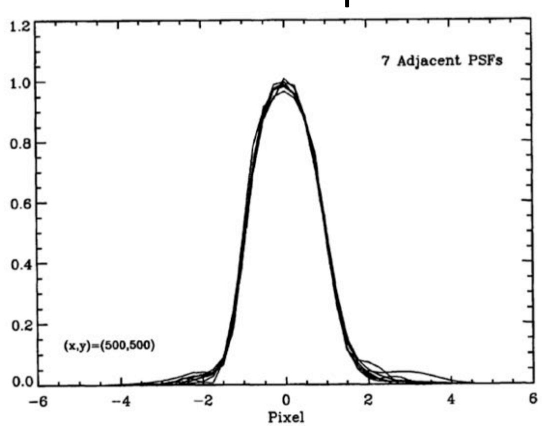
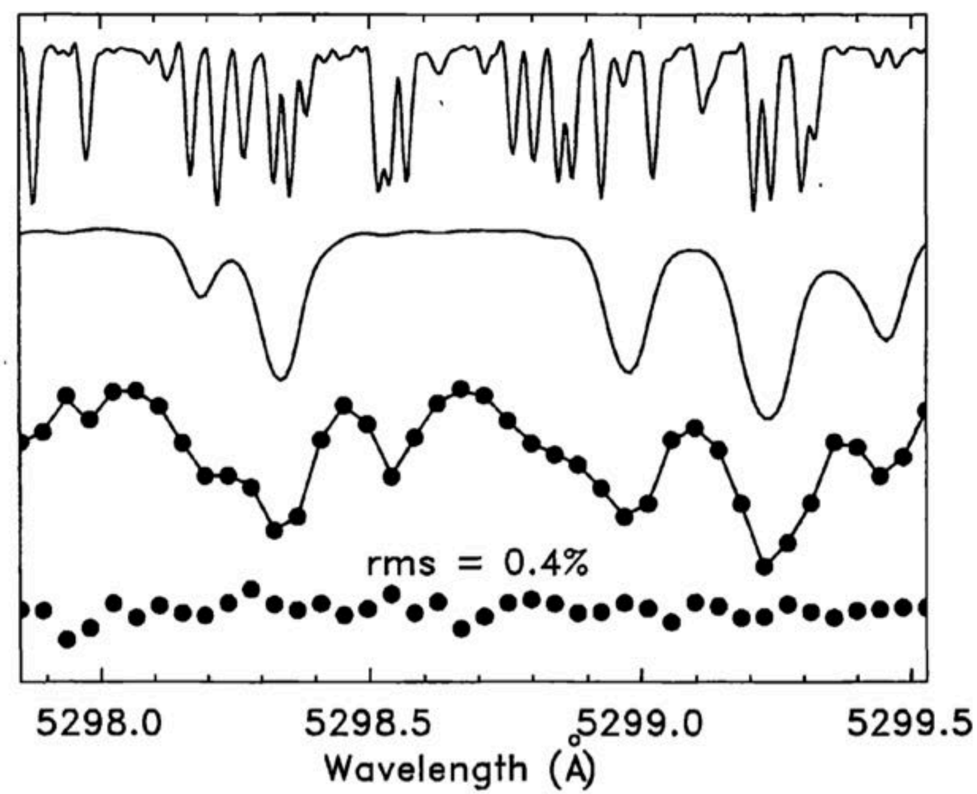


Gas cell technique:
It is a little more complicated

$$I_{obs}(\lambda) = k[T_{I2}(\lambda) I_s(\lambda + \Delta\lambda)] * PSF,$$

instrumental profile



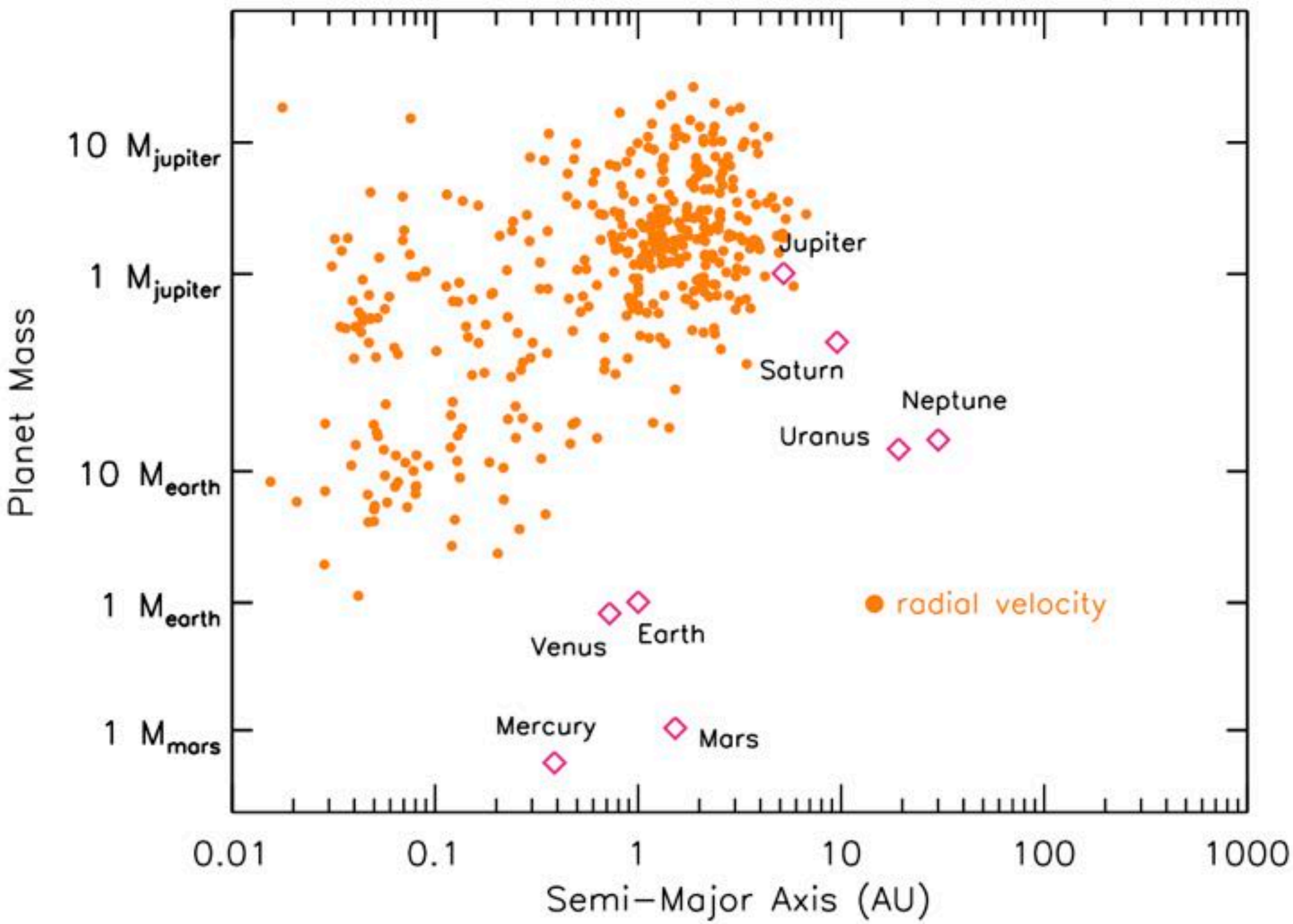


Butler et al. 1996, PASP, 108, 500

Calibrated instruments: HIRES@ 10m Keck telescope in Hawaii

Spectrograph not particularly stabilized.

Known planets from RV



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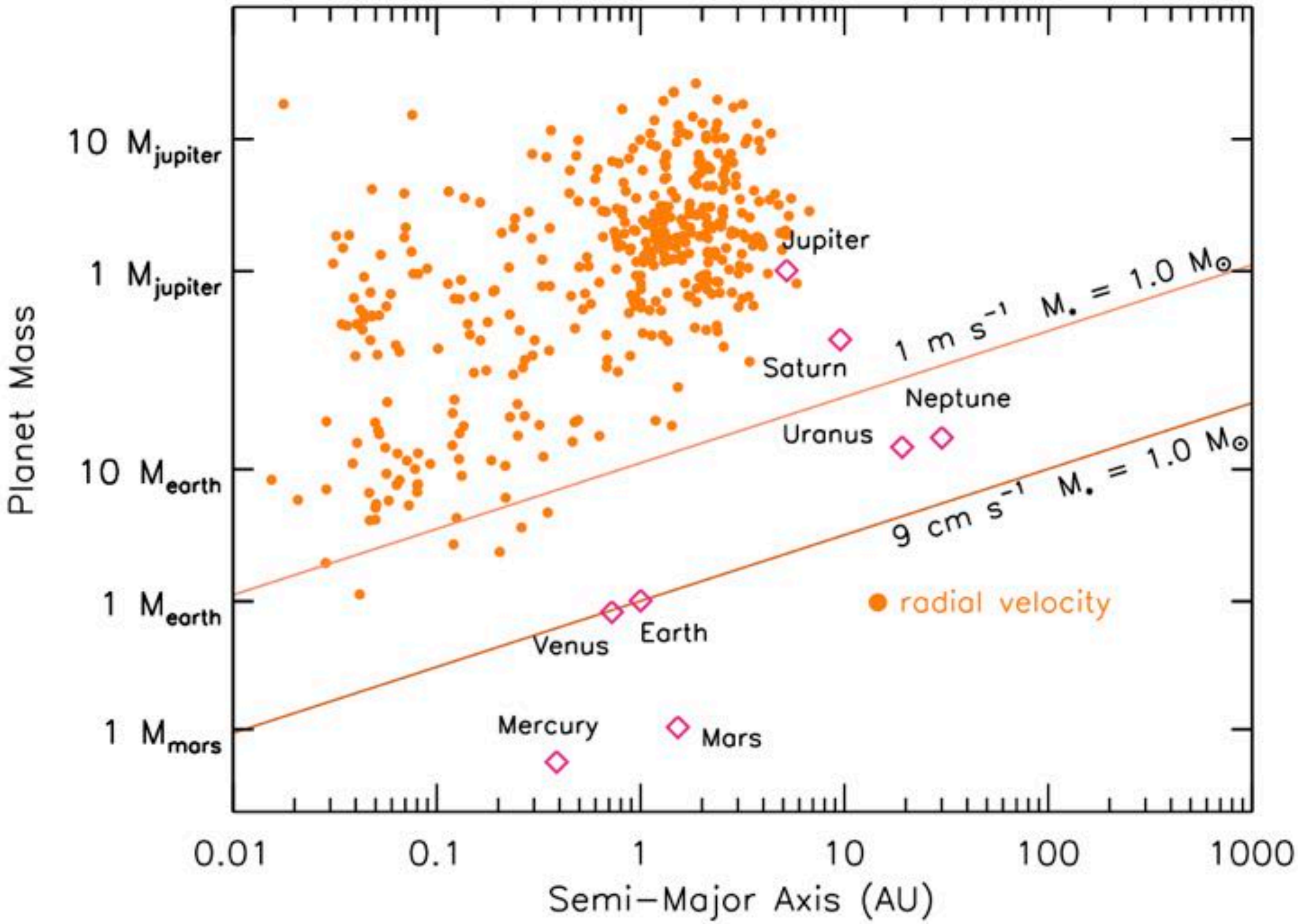
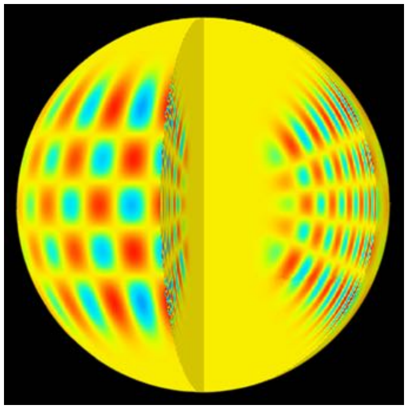
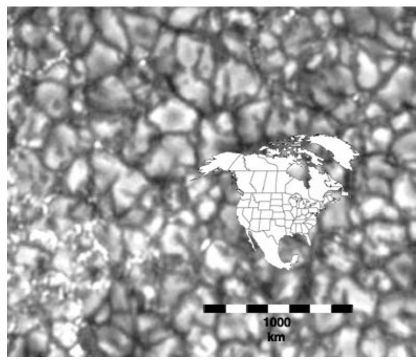
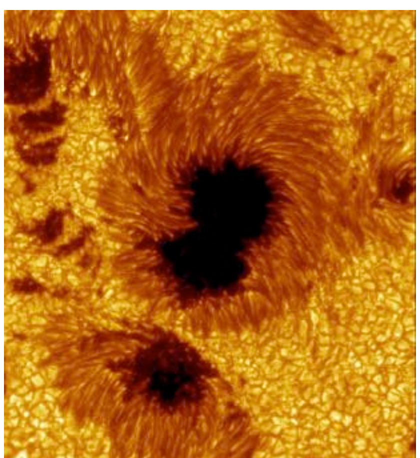


Stellar Limitations to Measuring RVs (Jitter)





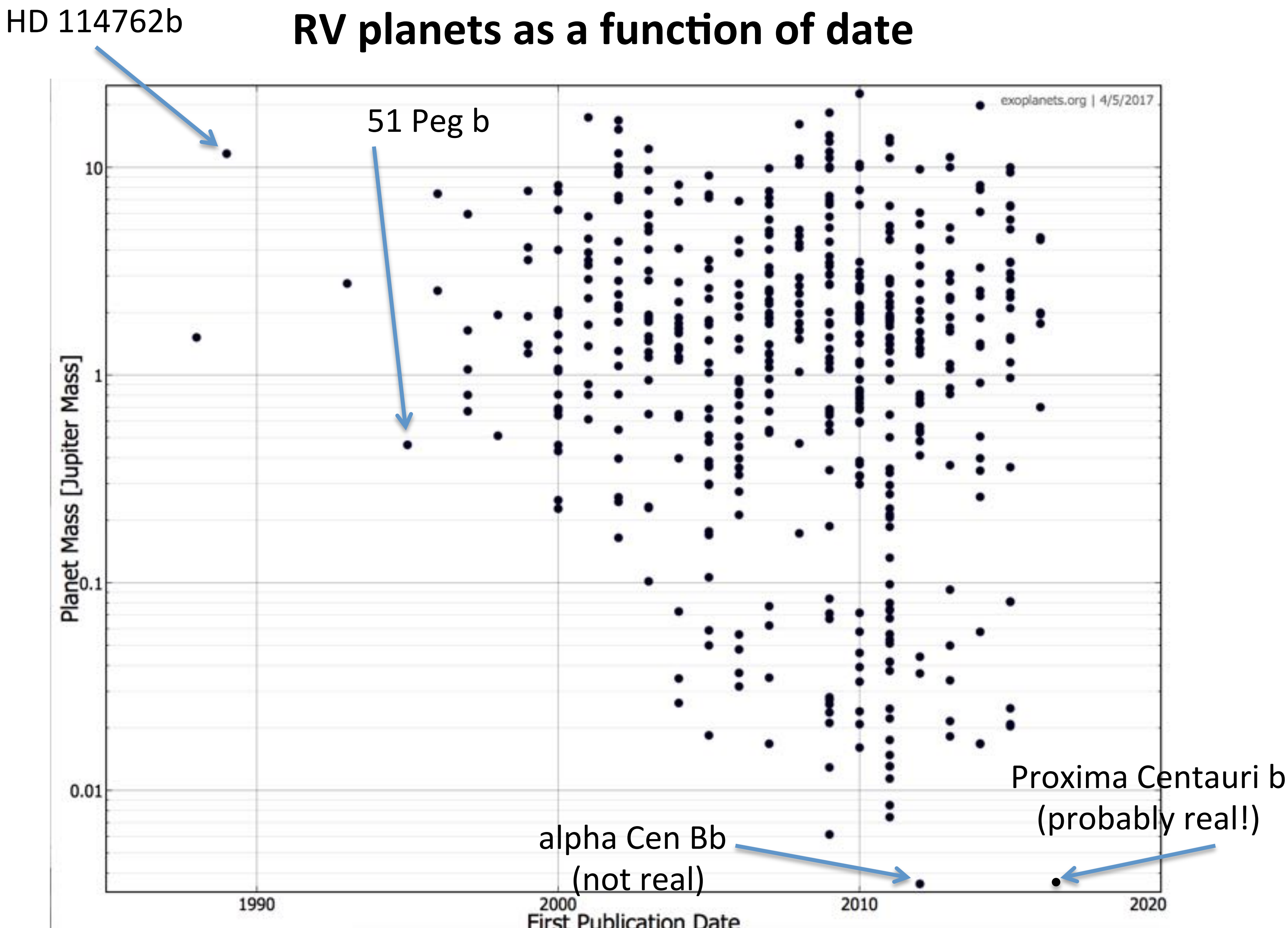


Jitter is caused by non uniformity of the stellar disk as a function of time.

Examples:

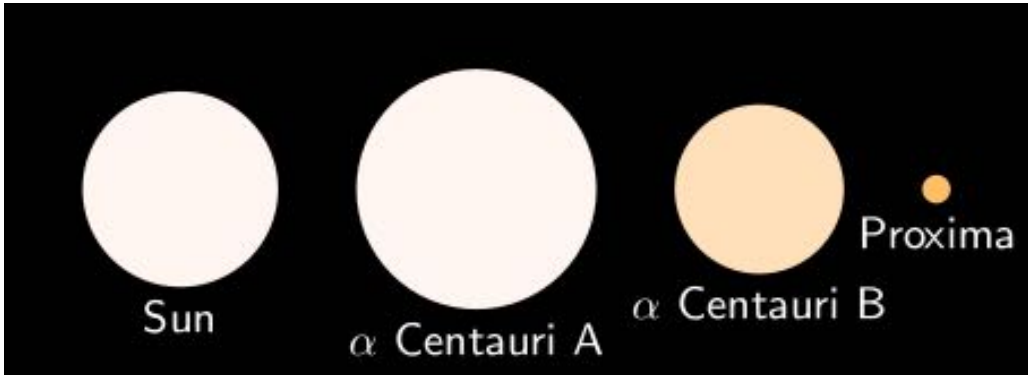
- Acoustic pressure modes (P-modes)
- Granulation
- Spots, plage, faculae

RV planets as a function of date



The Alpha and Proxima Centauri System

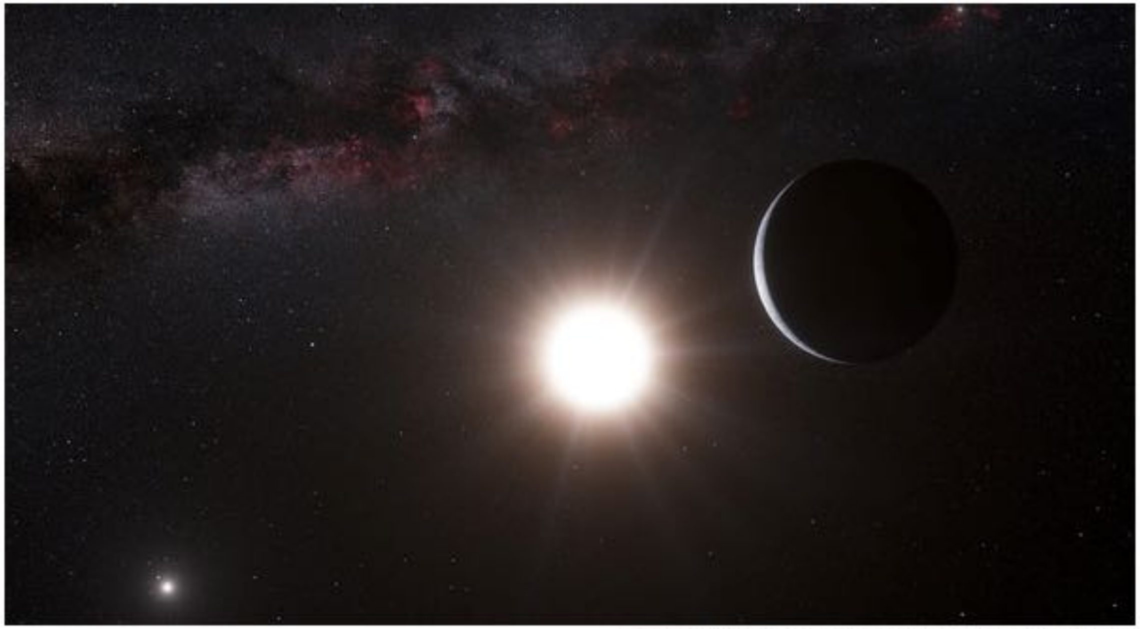
- Alpha and Proxima Centauri system is a triple star system with two Sun-like stars (A and B) and a low-mass star (Proxima, $M=0.1\ M_{sun}$).
- A and B orbit each other in 80 years. Periastron distance is 11 AU.
- Proxima is much further away and has a very long period ($P > 100{,}000$ years).
- This is the closest star system to us ($d = 4.4$ ly).



A small planet around alpha Centauri B

The New York Times

New Planet in Neighborhood, Astronomically Speaking



L. Calcada/European Southern Observatory, via Associated Press

An artist's rendering of a planet astronomers have found in Alpha Centauri, a star system that is the Sun's closest neighbor.

By DENNIS OVERBYE

Published: October 16, 2012

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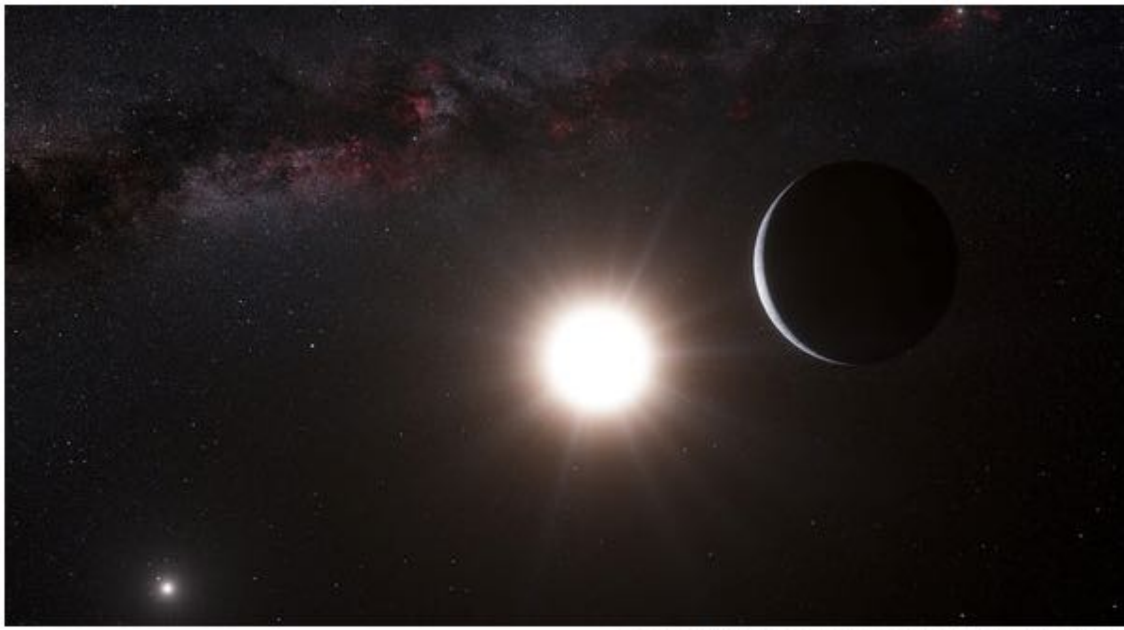

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FAKE NEWS!

Donald J. Trump @realDonaldTrump · 18h

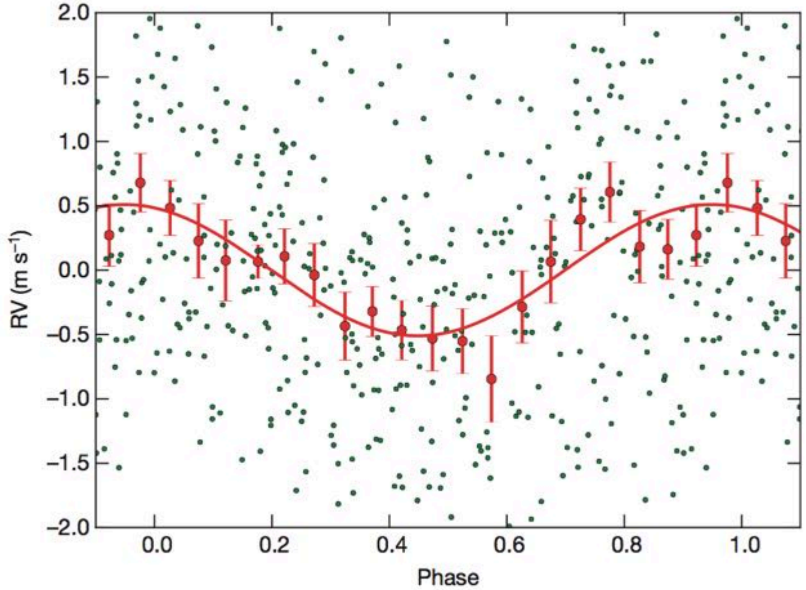
alpha Centauri doesn't even have planets. WEAK! Of course we have the best planets in the solar system – THE BEST!

A small plane around alpha Centauri B

Table 1 | Orbital parameters of the planet orbiting α Centauri B

Parameter	Value
Orbital period (d)	3.2357 ± 0.0008
Time of maximum velocity (BJD)	2455280.17 ± 0.17
Eccentricity	0.0 (fixed)
Velocity semi-amplitude ($m\,s^{-1}$)	0.51 ± 0.04
Minimum mass (Earth masses)	1.13 ± 0.09
Number of data points	459
O − C residuals ($m\,s^{-1}$)	1.20
Reduced χ^2 value	1.51

BJD, barycentric Julian date; O − C, observed minus calculated.



Dumusque et al. 2012, Nature, 491, 207

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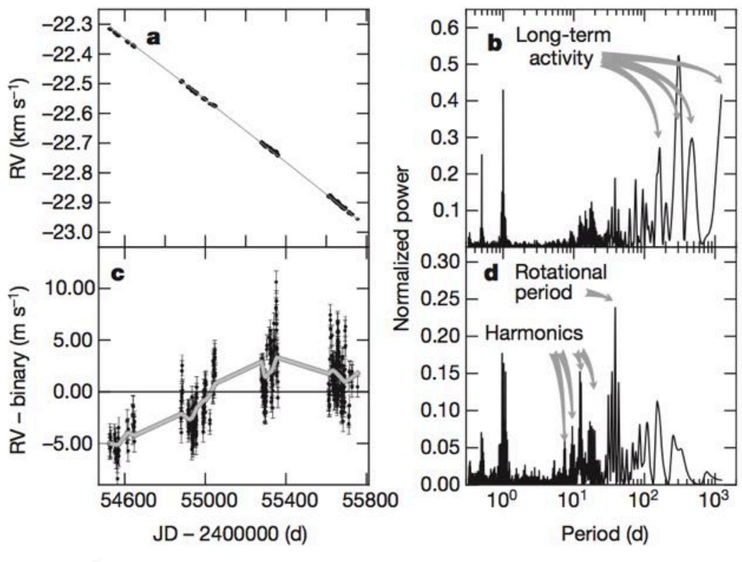

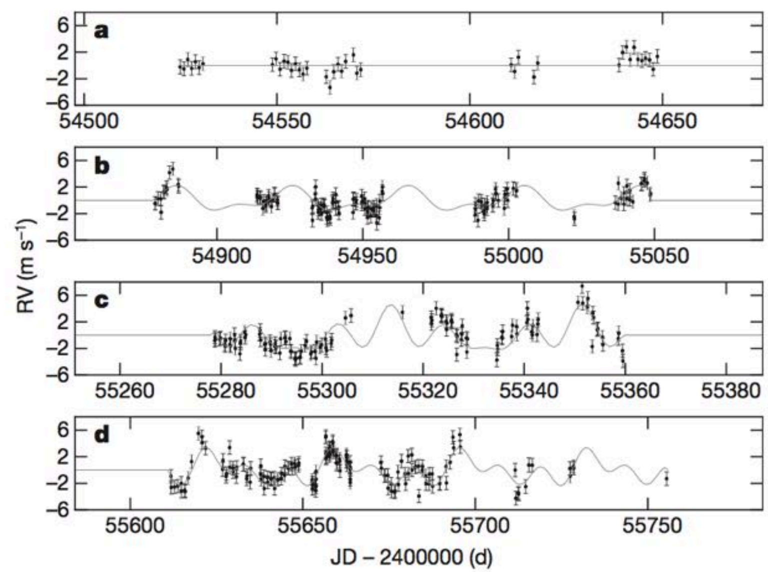

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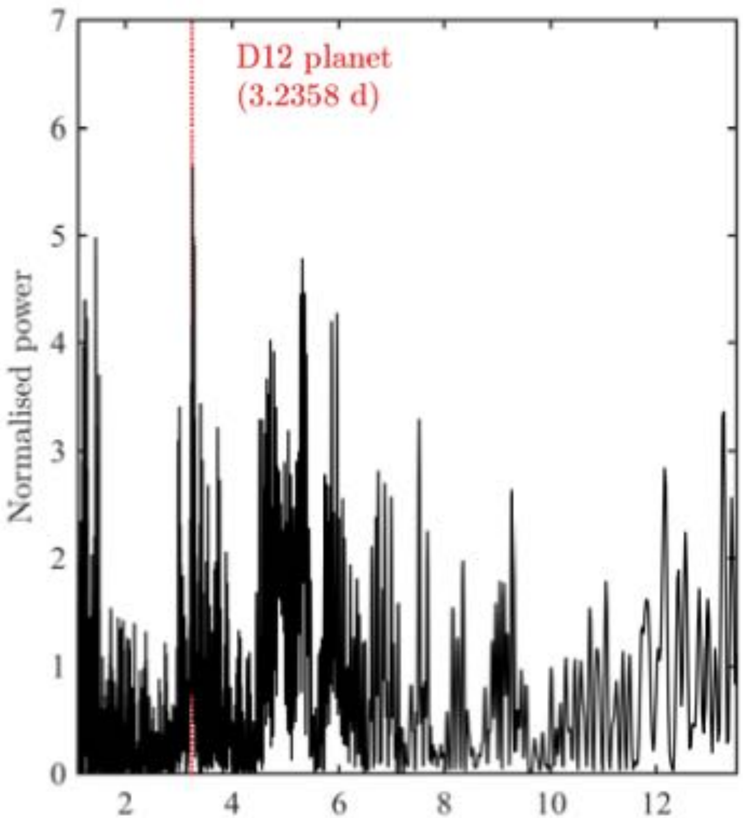
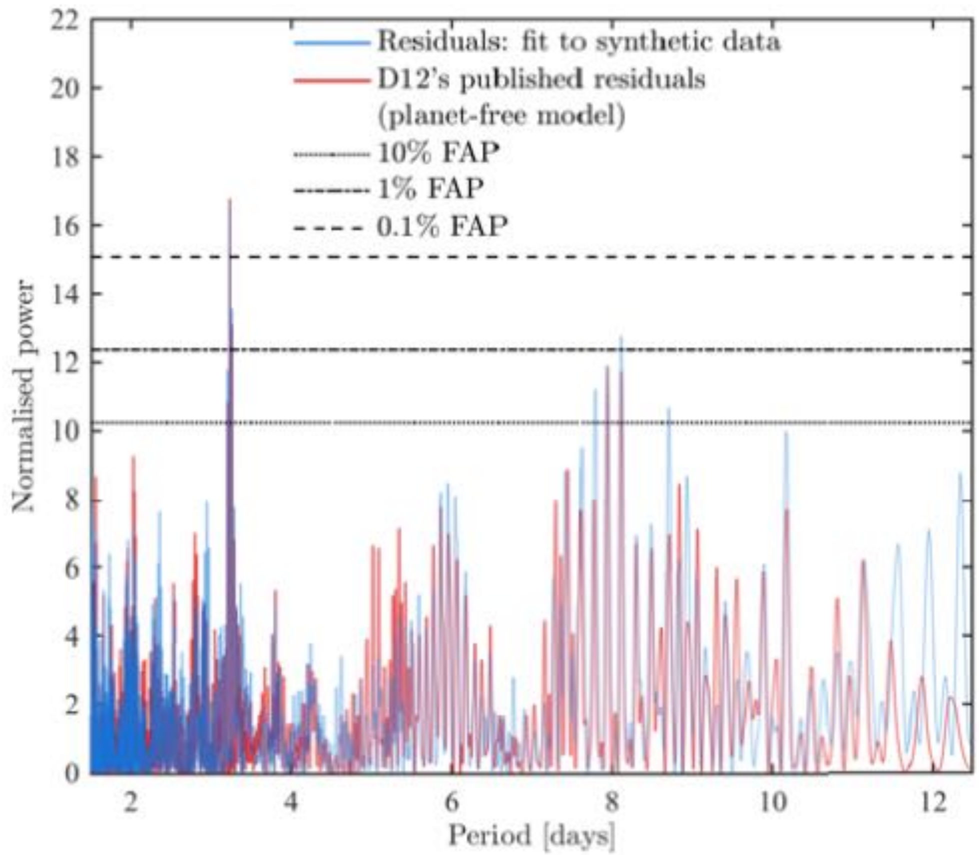
A small planet around alpha Centauri B – Probably not!

Real data



Simulated data with no planet



Rajpaul+ (2016)

A small planet around Proxima Centauri

The New York Times

One Star Over, a Planet That Might Be Another Earth

By KENNETH CHANG AUG. 24, 2016

An artist's impression of the planet Proxima b orbiting Proxima Centauri, the closest star to Earth's sun.
M. Kornmesser/European Southern Observatory

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M. Kornmesser/European Southern Observatory

Donald J. Trump @realDonaldTrump · 18h

FINALLY another solar system delivers. Just like Obamacare, a day late and a dollar short though. Best taco bowl still at Trump Tower

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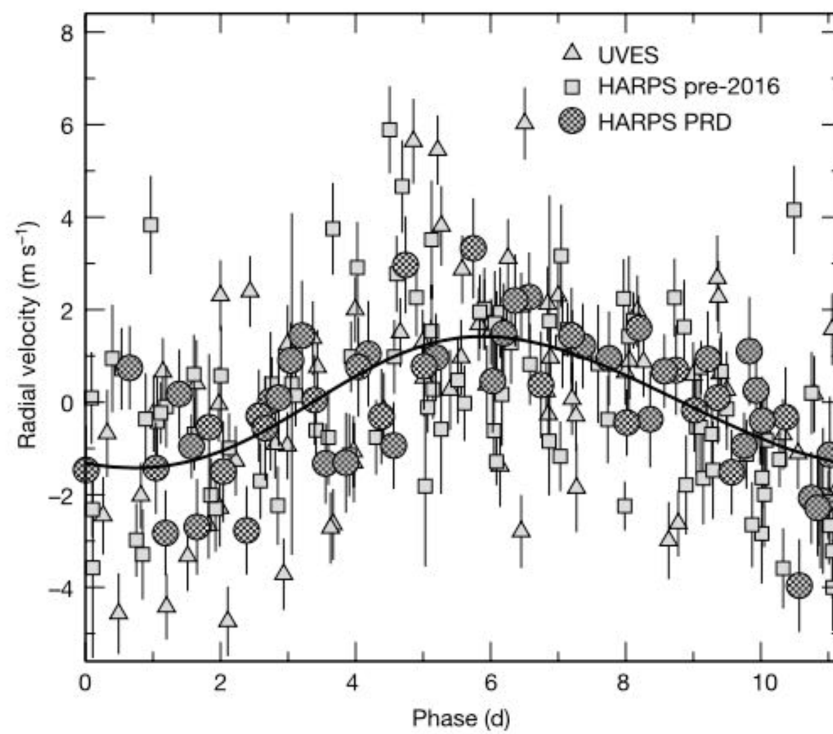
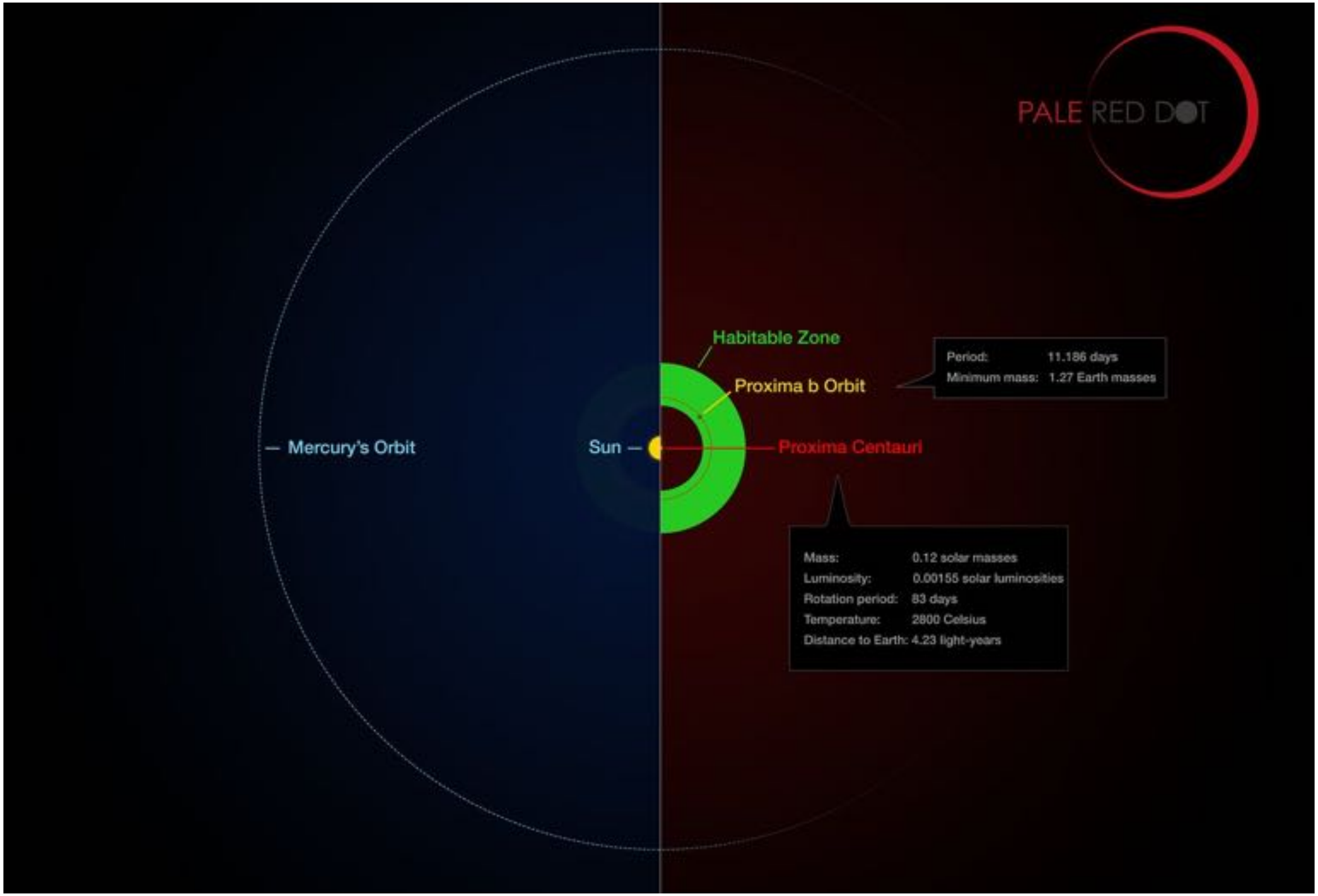
HARPS pre-2016 jitter (m s^{-1})	1.76 (1.22–2.36)	
HARPS PRD jitter (m s^{-1})	1.14 (0.57–1.84)	
Derived quantities		
Orbital semi-major axis, a (AU)	0.0485 (0.0434–0.0526)	
Minimum mass, $m_p \sin i$ ($M_\oplus$)	1.27 (1.10–1.46)	
Equilibrium black body temperature (K)	234 (220–240)	
Irradiance compared with Earth	65%	
Geometric probability of transit	about 1.5%	
Transit depth (Earth-like density)	about 0.5%	

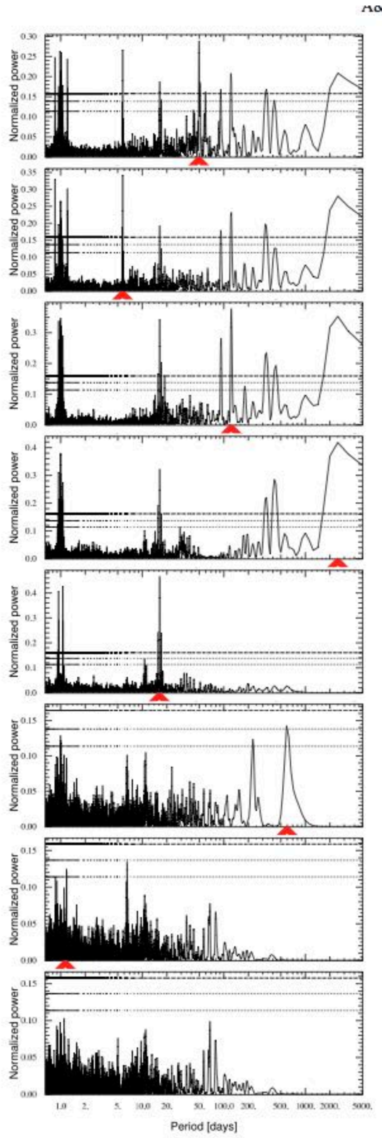
The estimates are the maximum *a posteriori* values and the uncertainties of the parameters are expressed as 68% credibility intervals. We provide only an upper limit for the eccentricity (95% confidence level). Extended Data Table 1 contains the list of all of the model parameters.



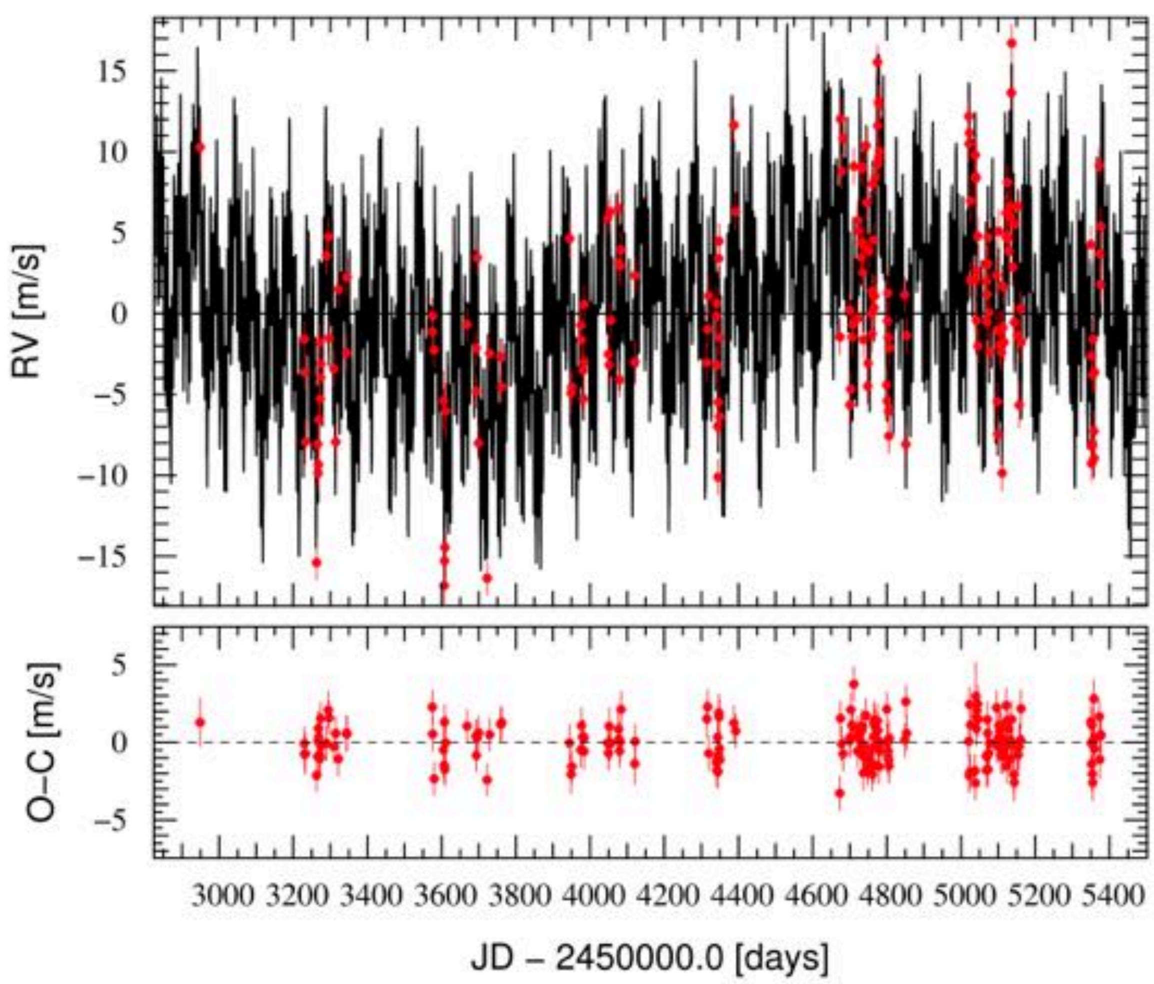
A small planet around Proxima Centauri



Seven planets around a single star?

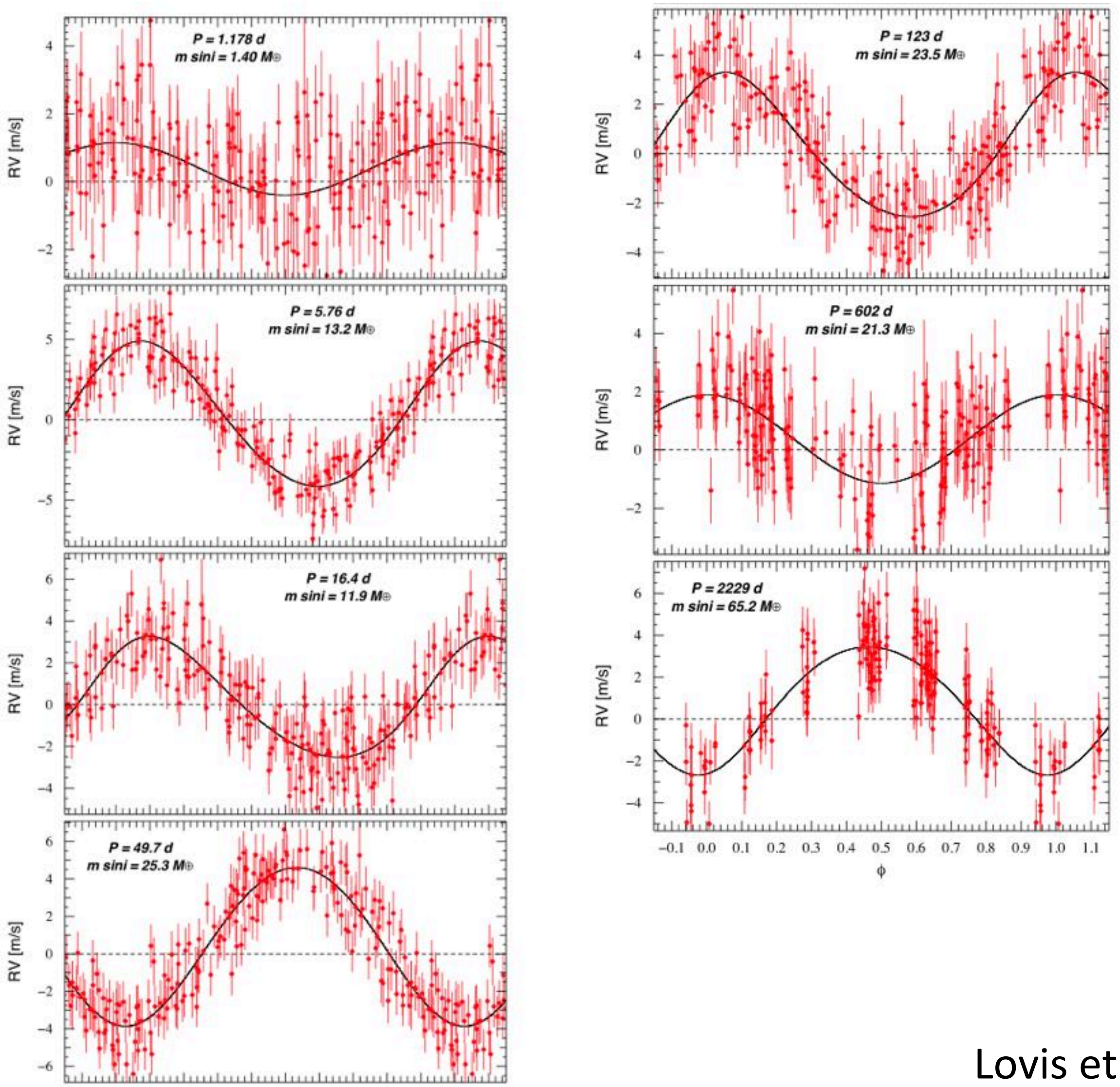


HD 10180



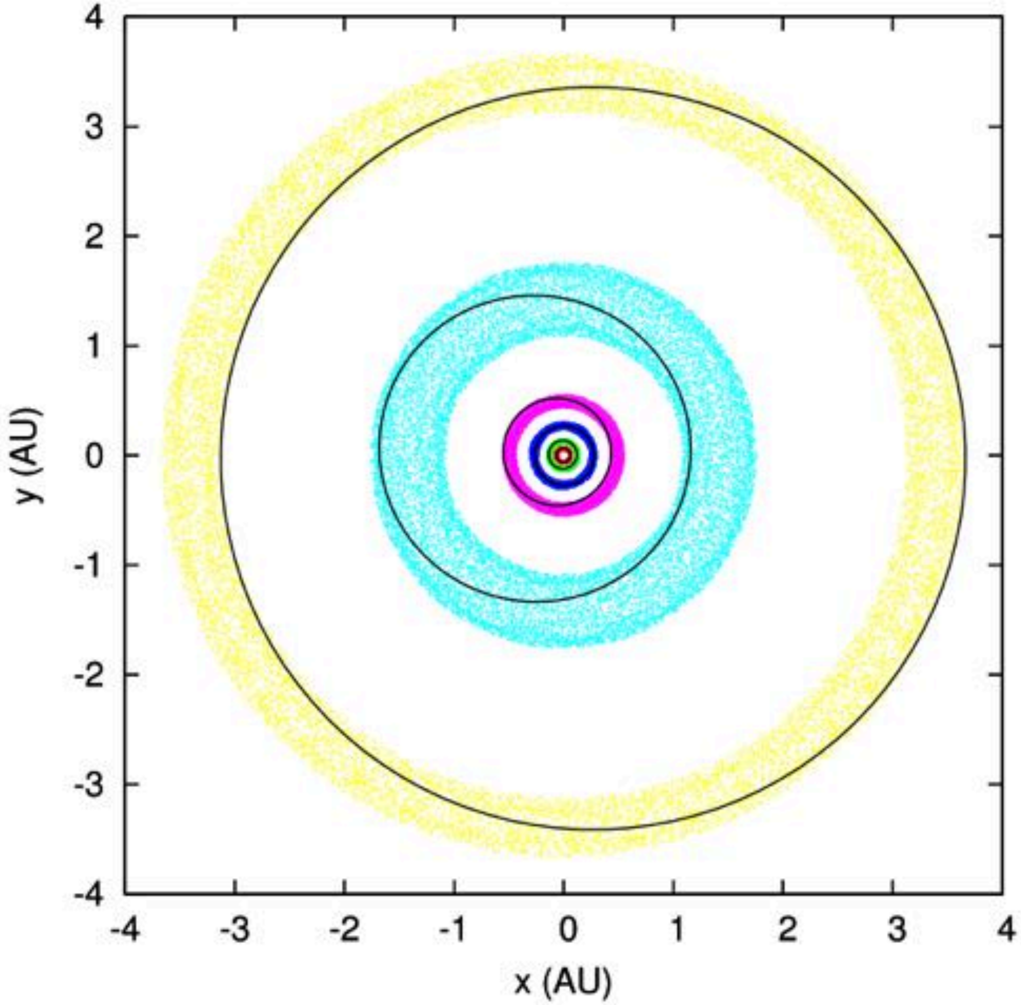
Lovis et al. 2011, A&A, 528, 112

Seven planets around a single star?



Lovis et al. 2011, A&A, 528, 112

Seven planets around a single star?



Lovis et al. 2011, A&A, 528, 112

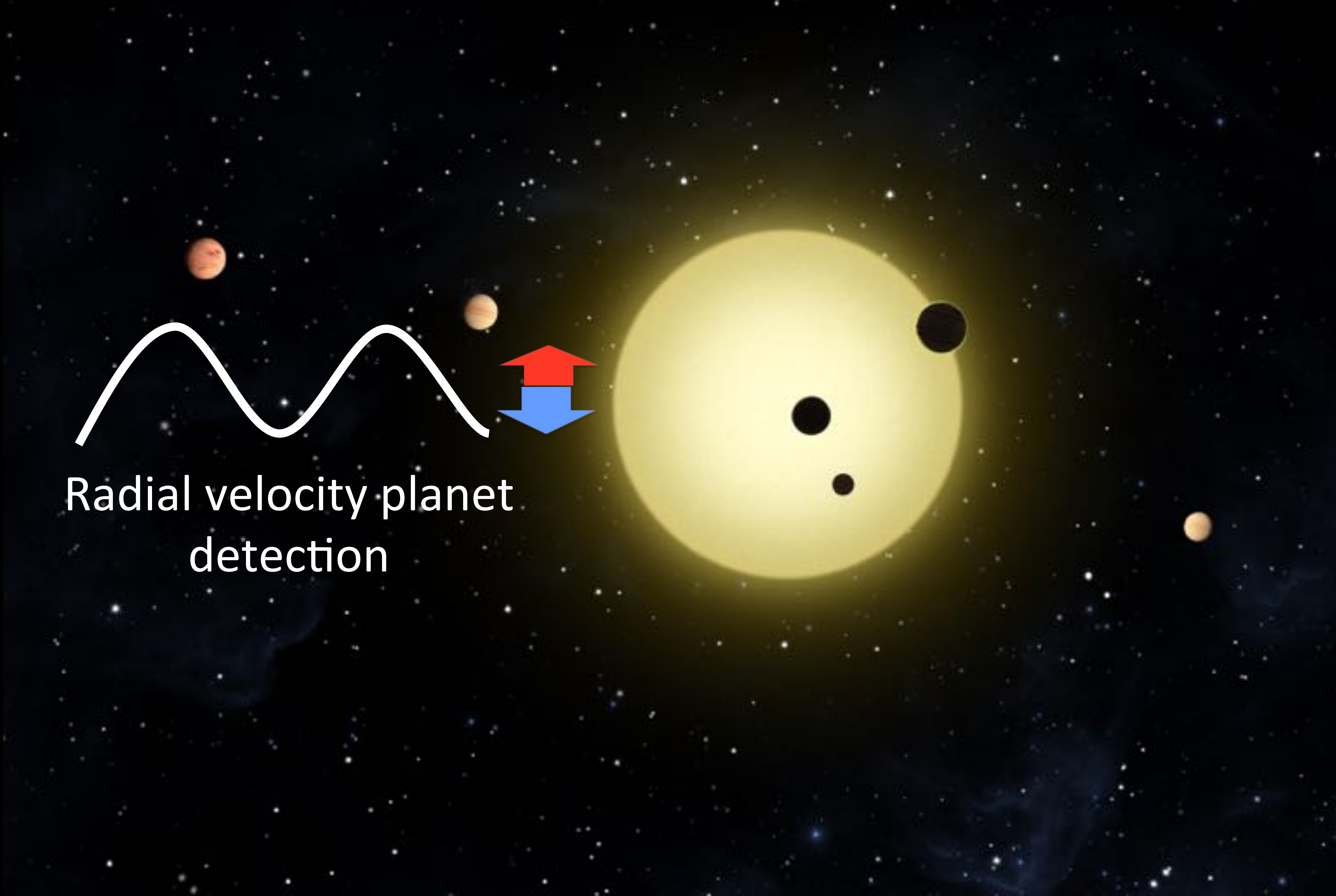
New radial velocity spectrographs

Instrument	Telescope	Measurement precision, Spectral Grasp, Resolution	PI; (relevant publications) / First Light
APF	Lick 2.4 m	1 m/s, 374-970 nm, R=120k / 490-600 with iodine cell	Vogt; (Vogt et al. 2014, Radovan et al. 2010) / 2013
CHIRON	Chile	0.5 m/s over 10 days, 2 m/s over 2 years, R~90k,130k	Debra Fischer; Commissioned 2012; Tokovinin et al (2013)
CODEX	E-ELT	2 cm/s, 370-710 nm, R=120k	Pasquini; (Delabre & Manescau 2010; Pasquini et al. 2010a,b, 2008) / ~2025
Coralie	Euler Swiss Telescope	2 m/s, 391-681 nm, R=50k	(Queloz et al. 1999) / 1998
ESPRESSO	VLT	10 cm/s (5 cm/s), 380-686 nm, R=120k (220k)	Pepe; (Spanò et al. 2012, 2008; Pepe et al. 2010) / 2016
EXPRES	DCT	10 cm/s, 380-700 nm, R~200k	Fischer; 2016-2017
G-CLEF	GMT	20 cm/s, 350-950 nm, R=120k / also MOS mode	Szentgyorgyi; (Szentgyorgyi et al. 2012) / 2021
Hamilton Echelle	Lick: Shane 3m CAT 0.6m	3 m/s, 340-900 nm, R=60-100k, 490-600 with iodine cell	Vogt; (Vogt 1987) / 1986
HARPS-N	TNG 3.6 m	1 m/s, 380-680 nm, R=110,000k	Pepe; (Cosentino et al., 2012, 2014; Langellier et al. 2014) / 2012
HARPS	ESO 3.6 m	1 m/s , 380-680 nm, R=110,000k	Pepe; (Pepe et al. 2000, 2003; Rupprecht et al. 2004, Lovis et al. 2006) / 2002
HIRES	Keck 10 m	2 m/s, 360-1000 nm, R=85k / 490-600 with iodine cell	Vogt; (Vogt et al. 1994) / 1996
HRS	HET	2.5 m/s, 390-1100 nm, R=120k	MacQueen; (Tull et al. 1998) / 2001
LCOGT NRES	Global network of 6 spectrometers	~1-3 m/s, 390-860 nm; R~53k	(Eastman et al. 2014) / 2015-2016
MINERVA	Mt Hopkins 4x0.7 m	~1 m/s, 500-650 nm, R~50k	John Johnson (Swift et al. 2015) / 2015
SHREK	Keck 10 m	1 m/s, 440-590 nm, R=85k / red channel later	Howard & Marcy; (http://nexsci.caltech.edu/keck_strategic_planning_Sep2014.pdf)
Sophie	1.93 m Haute-Provence	3 m/s, 387-694 nm, R=75k	(Perruchot et al. 2008) / 2006
TRES	Whipple Obs 1.5 m	15 m/s, 380-900 nm, R=44k	Szentgyorgyi; (Szentgyorgyi & Furesz 2007) / 2007
Tull Echelle	2.7 m Harlan J. Smith	340-1090 nm, R=60k, 240k	Phillip MacQueen;

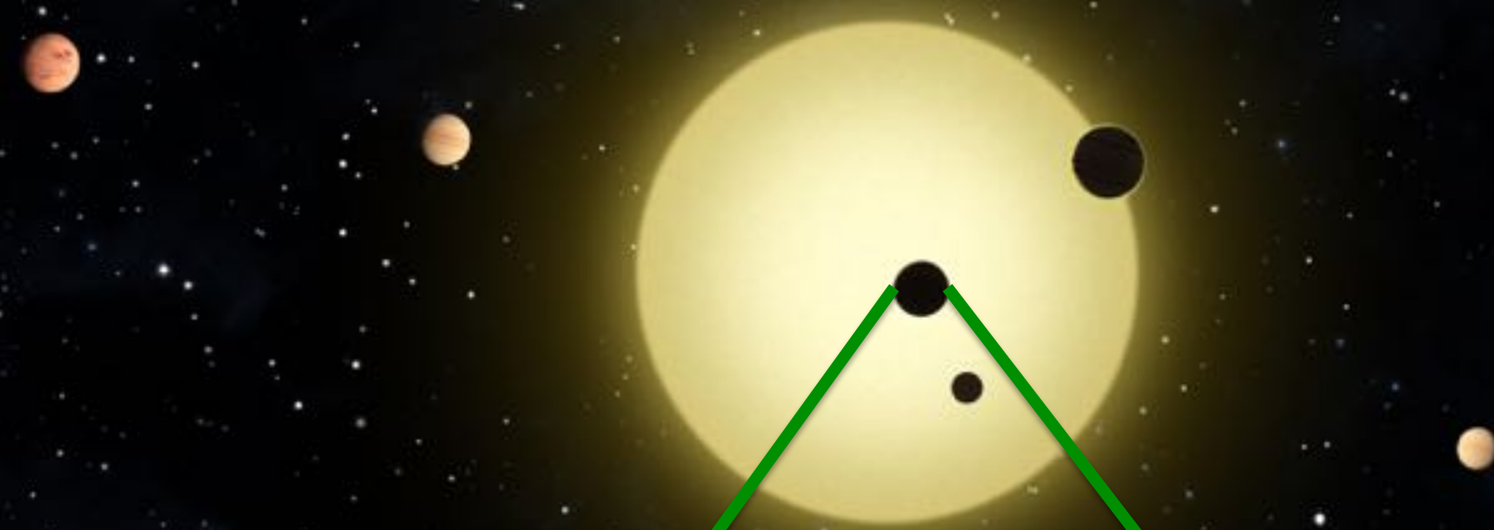
Instrument	Telescope	Measurement precision, Spectral Grasp, Resolution	PI or relevant publication, First Light
APOGEE	2.5-m Sloan Foundation Telescope	~10 m/s, MOS, 1.51-1.70 microns, R=22.5k	Deshpande et al. (2013)
CARMENES	Calar Alto	~3 m/s; 0.5-1.8, microns, R~80k	Quirrenbach et al. (2012), 2016
CRIRES	VLT	5 m/s, K-band, R~100k	Bean et al. (2010)
CSHELL	IRTF	5 m/s short term, 35 m/s long term, K-band R=46k	Anglada-Escude et al. (2012b), Plavchan et al. (2013a,b)
ESPaDOnS	CFHT	0.3-1 microns, R~70k	Jean-Francois Donati
HPF	HET	~3 m/s, YJ bands R~50k	Mahadevan et al. (2012)
iSHELL	IRTF	~2-3 m/s, HK bands R~75k	Rayner et al. (2012), 2016
iGRINS	Harlan Smith @ McDonald	HK bands, R~40k	Dan Jaffe, (Yuk et al. 2010)
iLocater	LBT	20 cm/s, 0.95-1.10 microns, R=150k	Justin R. Crepp, in design study phase
MINERVA-RED	Mt Hopkins 2x0.7 m	< 1 m/s, 0.8-1.0 microns	Cullen Blake, spectrometer in lab testing phase
NIRSPEC2	Keck	J,H,K,L or M band, R~50k	Ian McLean, in design study phase
SPIRou	CFHT	0.98-2.35 microns, R~70k	Thibault et al. (2012), 2017

See reviews: Plavchan+ (2015, arXiv:1503.01770)
Fischer+ (2016, arXiv:1602.07939)
Wright (2017, arXiv:1707.07983)

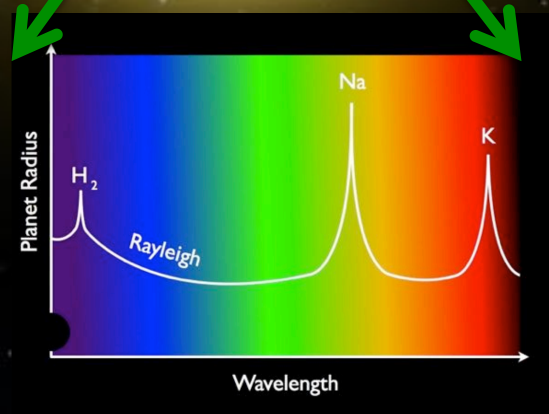
The role of precision spectroscopy…

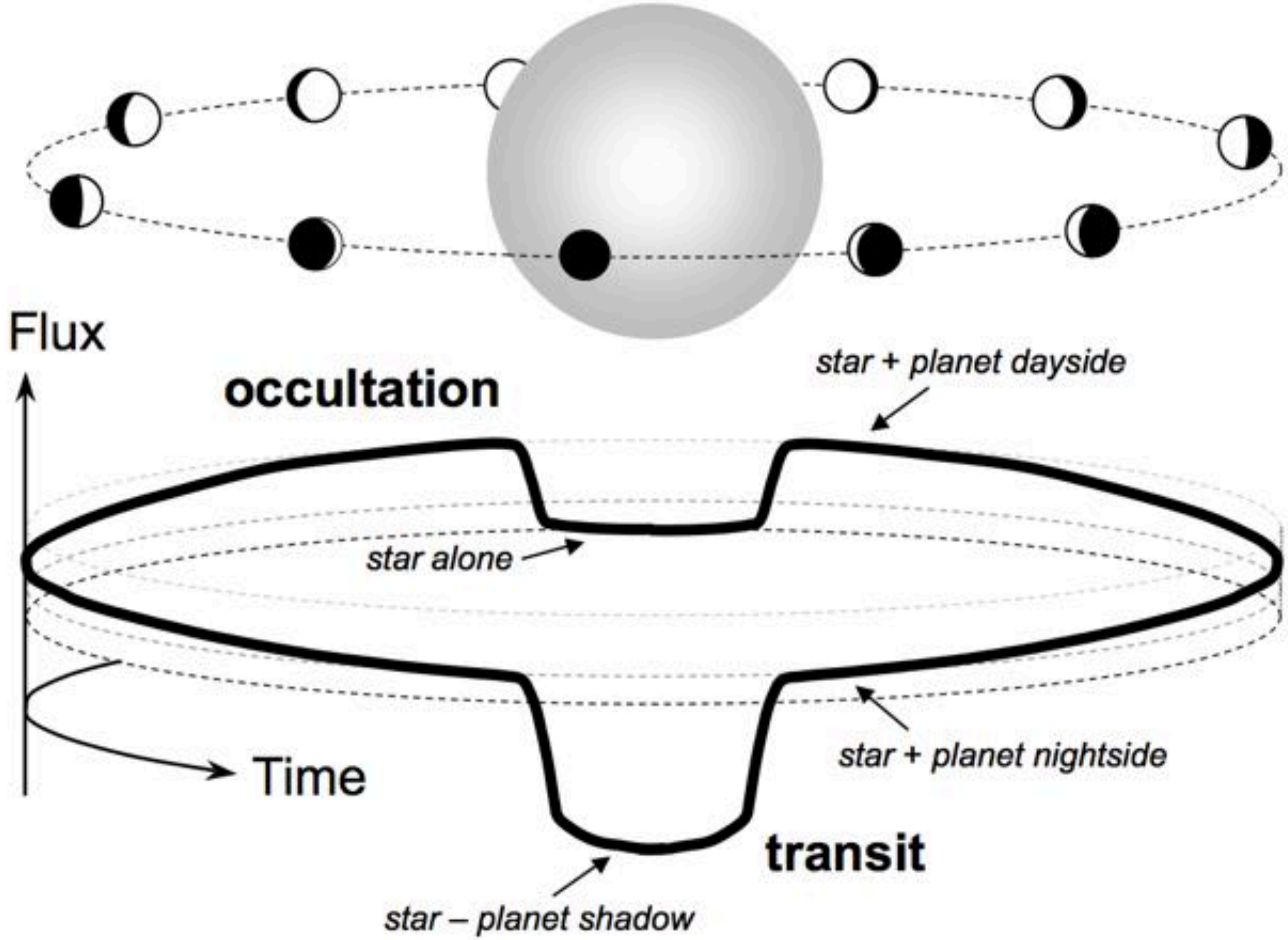


The role of precision spectroscopy…



Exoplanet atmospheric characterization





Textbook chapter: Winn (arXiv:1001:2010)

The things that you can directly measure:

- Transit duration
- Ingress/egress time
- Transit depth
- Mid-transit time
- Time between successive transits

Things that you can derive from these observables:

- Orbital period
- Orbital ephemerides
- Ratio of the size of the planet to the size of the host star (R_p/R_s)
- Impact parameter, $b = a \cos i / R_s$ for $e = 0$

Things that you can use these values to determine with K and e from RV, and estimate of M_s:

- Ratio of the size of the semi-major axis to the size of the host star (a/R_s)
- Orbital inclination
- Planet mass
- a for the orbit using Newton's version of Kepler's third law
- Radius of the star
- Radius of the planet
- Density of the star
- Surface gravity of the planet

Finding transiting planets

Two ways:

- Look for the transits with no prior knowledge
- Look for transits of planets found with the radial velocity method

Transit Searches: the bad news

Recall the transit probability:

$$p_{\rm tra} = p_{\rm occ} = \frac{R_\star}{a} \approx 0.005 \left(\frac{R_\star}{R_\odot}\right)\left(\frac{a}{1\ {\rm AU}}\right)^{-1}$$

For a Hot Jupiter, $p \approx 10\%$

But these planets have a frequency, $\eta \approx 1\%$

Therefore on order of a thousand stars have to be searched for find just a single planet this way.

Transit Searches: the bad news

Recall the transit duration:

$$T_{\rm tot} \equiv t_{\rm IV} - t_{\rm I} = \frac{P}{\pi} \sin^{-1}\left[\frac{R_\star}{a}\frac{\sqrt{(1+k)^2 - b^2}}{\sin i}\right]$$

For a Hot Jupiter around a Sun-like star, $T_{\rm tot} \approx 3$ hours

Which is ≈ 5% of the orbital period (e.g., 3 days).

So, one has to search many thousands of stars continuously for days at a time.

Transit Searches: some good news

Recall the transit depth: $\delta = (R_p/R_s)^2$ (neglecting limb darkening)

For a Hot Jupiter around a Sun-like star, $\delta \approx 1\%$

Say you want to detect this signal at 10σ confidence…

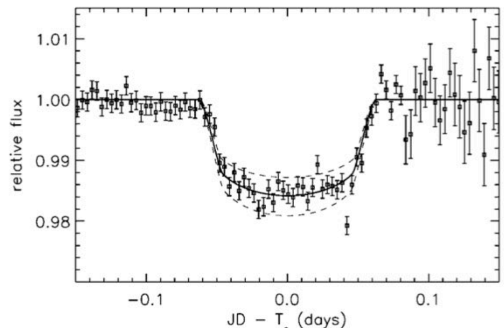
$S/N = \mathrm{sqrt}(N_{photons})$

How many photons do you need to collect to get S/N = 10?

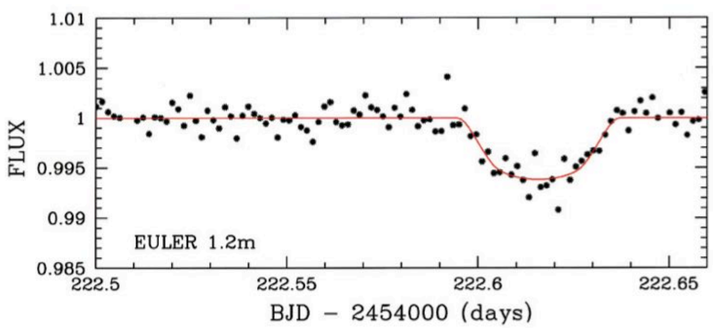
A measly 1×10^6 photons!

This can be done with amateur equipment!

Remember the transit depth: $(R_p/R_s)^2$!!!

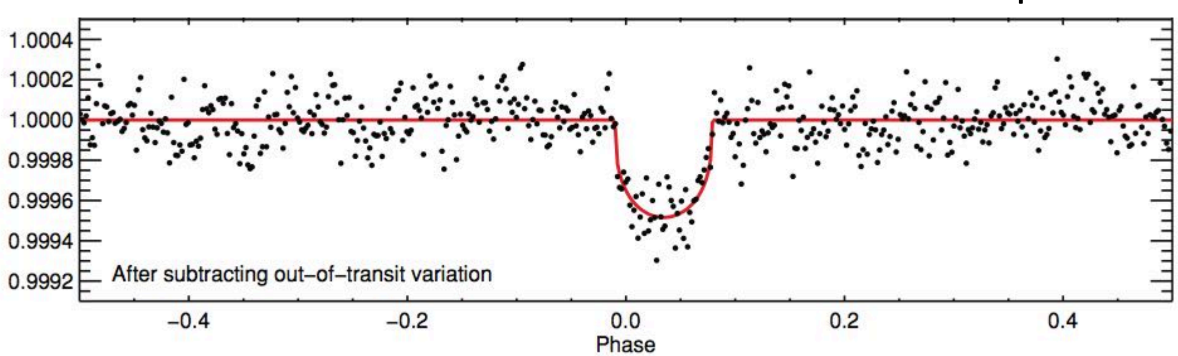


Jupiter: 1.5% transit depth
HD 209458b − from the ground

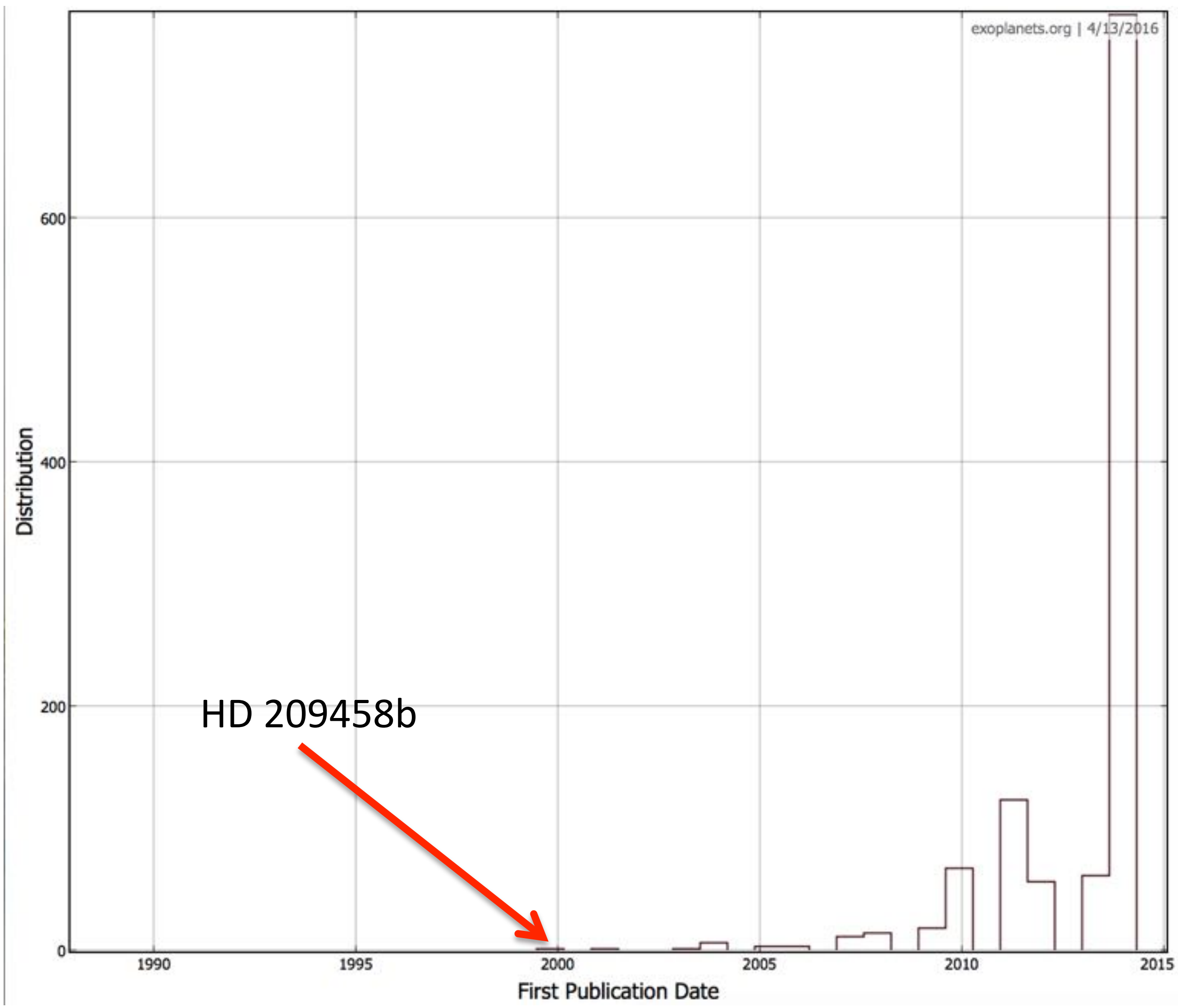


Neptune: 0.5% transit depth
GJ 436b − from the ground, but an M dwarf host

Super-Earth: 0.05% transit depth
55 Cnc e − from space



Transit Searches: timeline

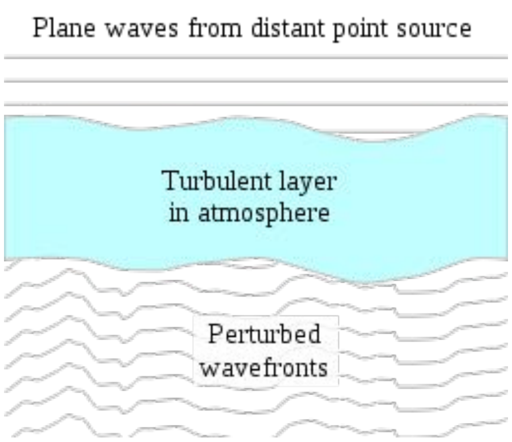


Transit Searches: why the drought?

1. More noise than expected from the Earth's atmosphere

Scintillation: $$\sigma_{\text{scin}} = \sigma_0 \frac{(\text{Airmass})^{7/4}}{D^{2/3}(\Delta t)^{1/2}} \exp\left(-\frac{h}{8000\ \text{m}}\right)$$

The variations in intensity component of atmospheric 'seeing'.



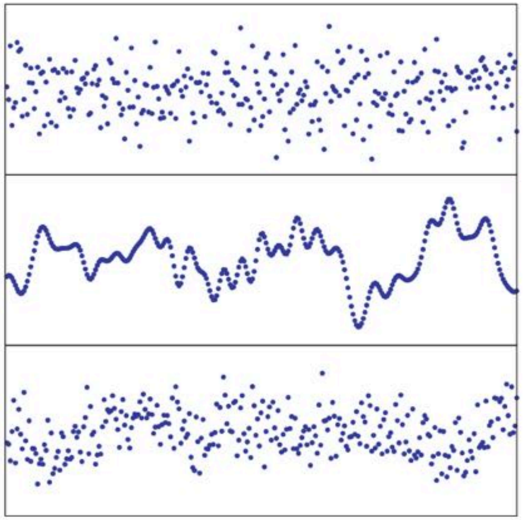
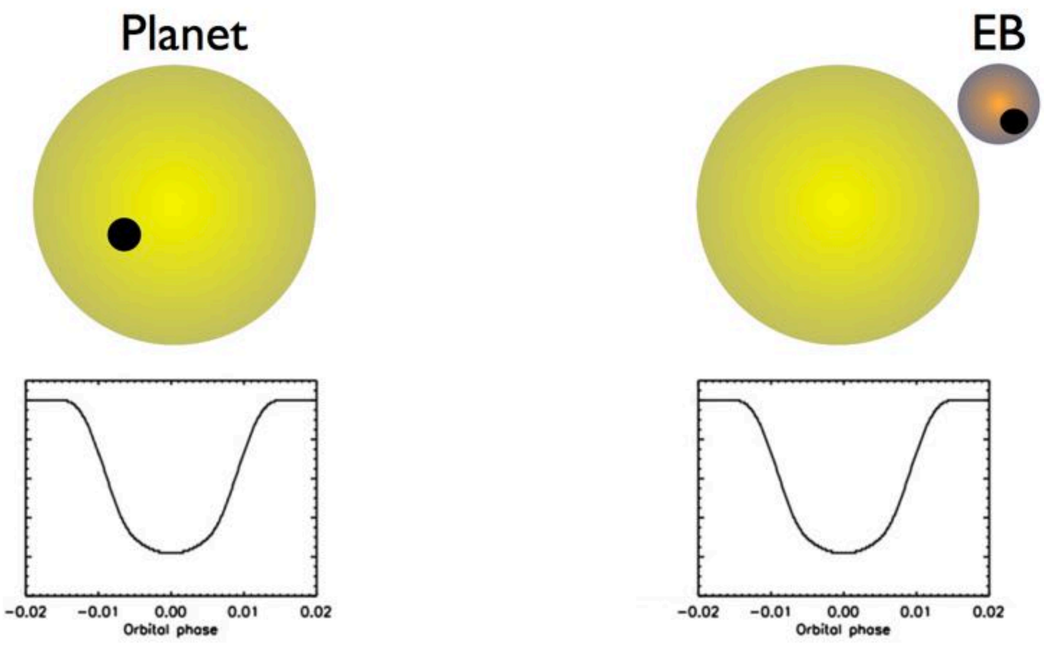


Figure 2. Light curves with white noise only (top panel), red noise only (middle panel) and white and red noise (bottom panel). Typical light curves from a high-precision rapid time-series photometry for bright targets in transit surveys resemble portions of the bottom-panel curve.

Transit Searches: why the drought?

2. A high rate of astrophysics false positives

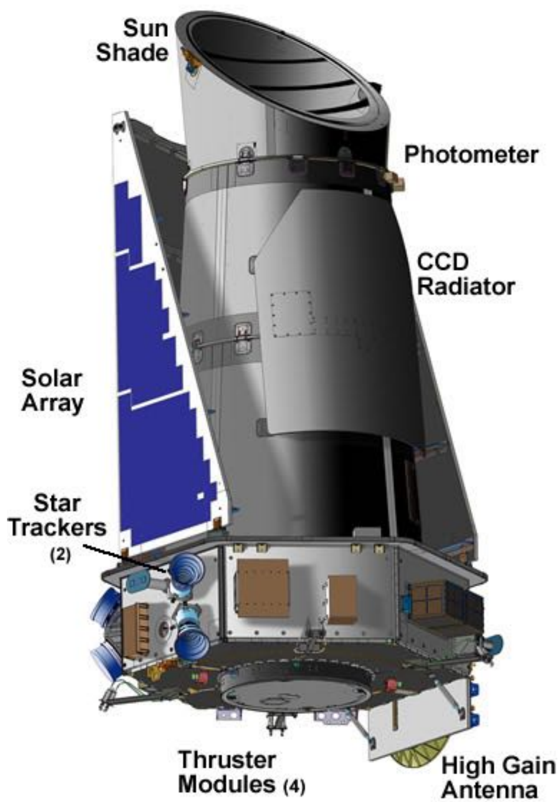


Transit Searches: why the drought?

3. Hot Jupiters are not very common

Frequency is a little less than 1%

The Kepler Mission



A custom-built, 0.95m diameter space telescope dedicated to finding transiting planets

Cost: $600M

Launched in 2009

Observing strategy is to stare at the same field for 3+ years

1000s of transiting planets found

Recently passed the 2000 paper mark

Spacecraft failure in May 2013

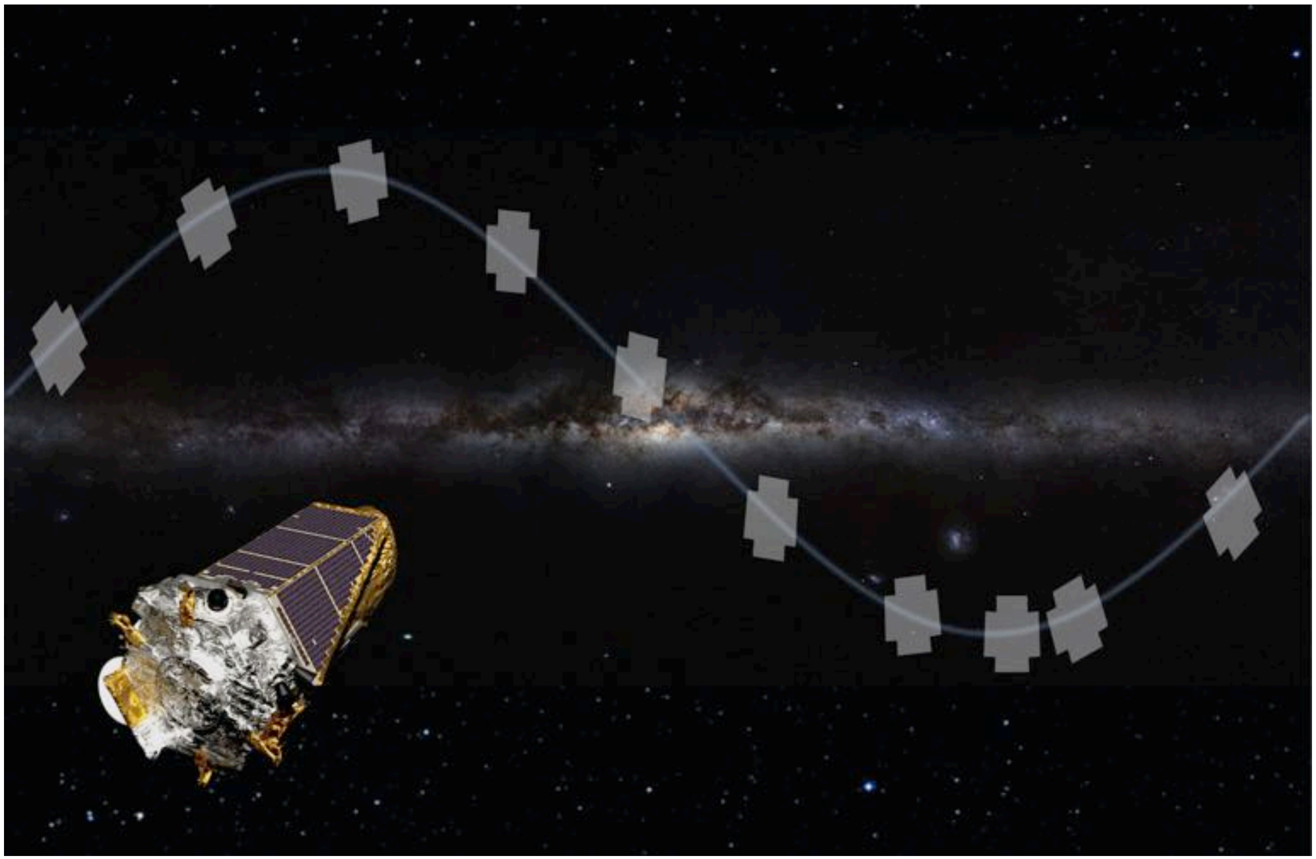
Kepler-62: a five planet system with two super-Earths in the habitable zone

The New York Times

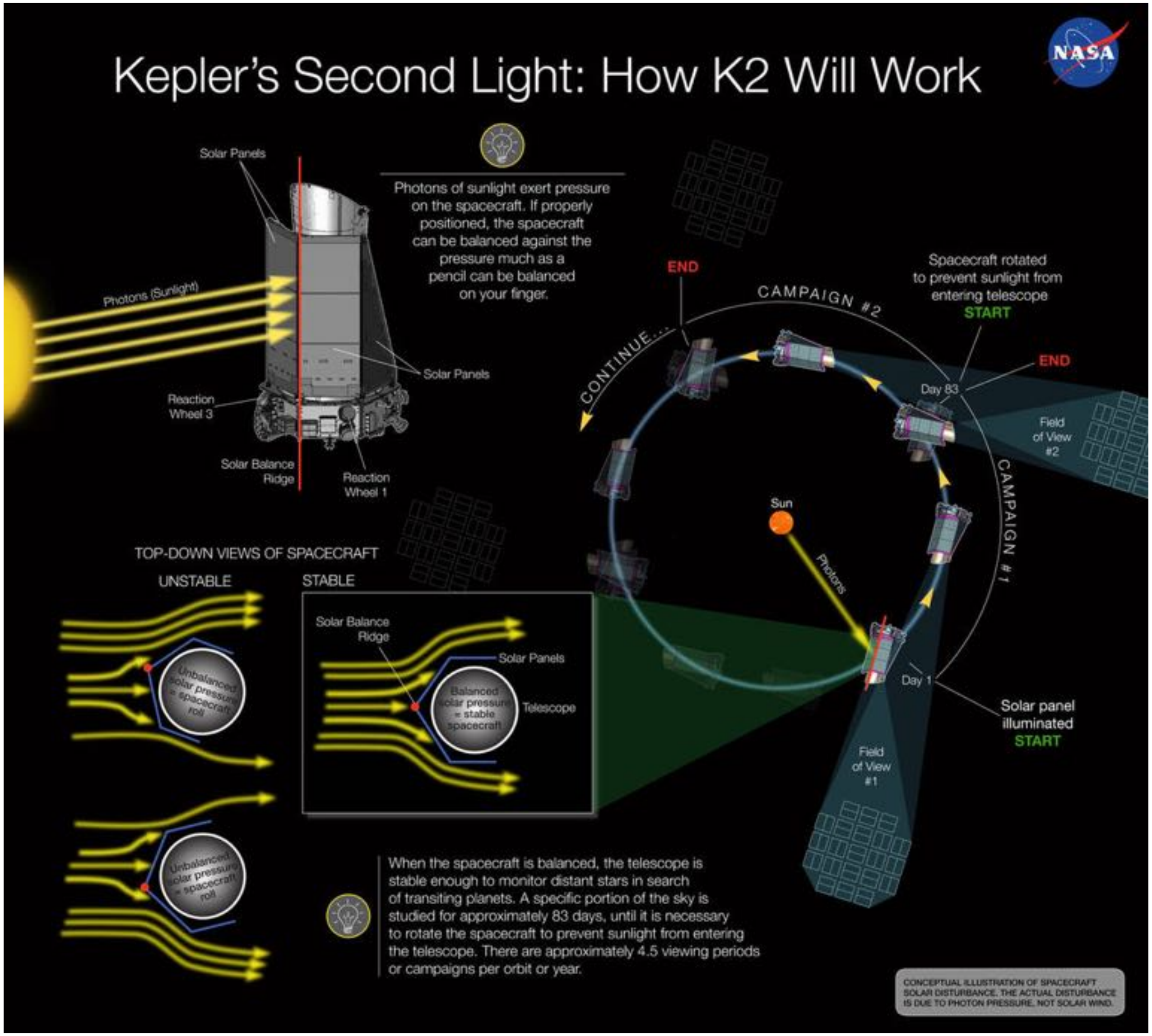
Two Promising Places to Live, 1,200 Light-Years From Earth

Announced April 19, 2013

Kepler → K2

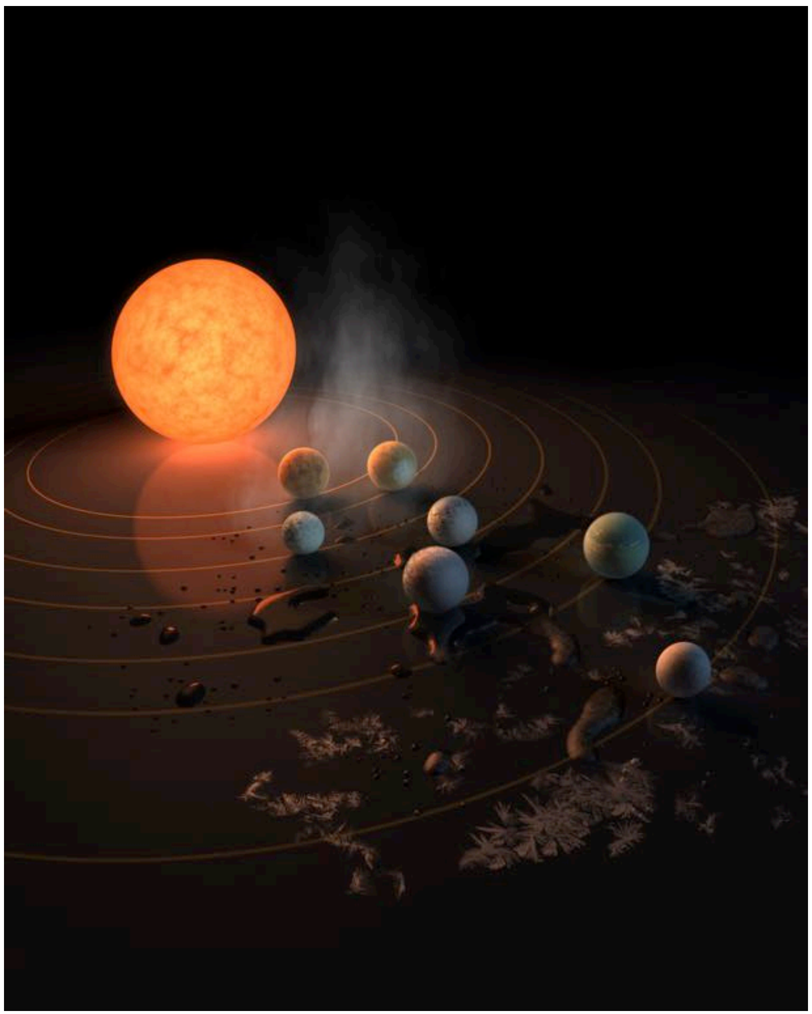


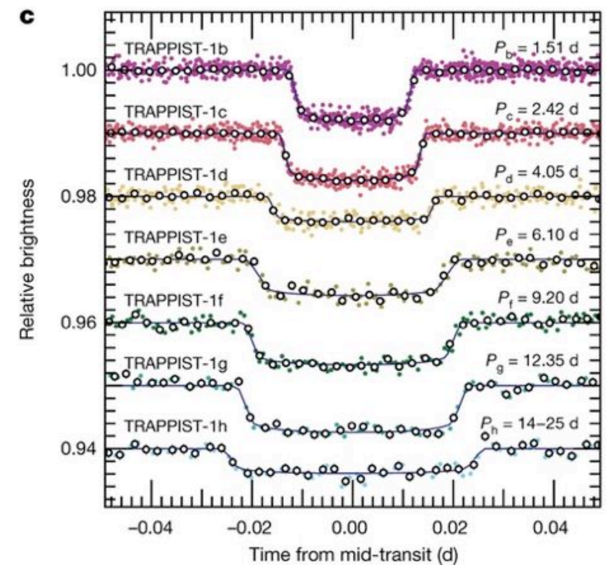
Kepler → K2

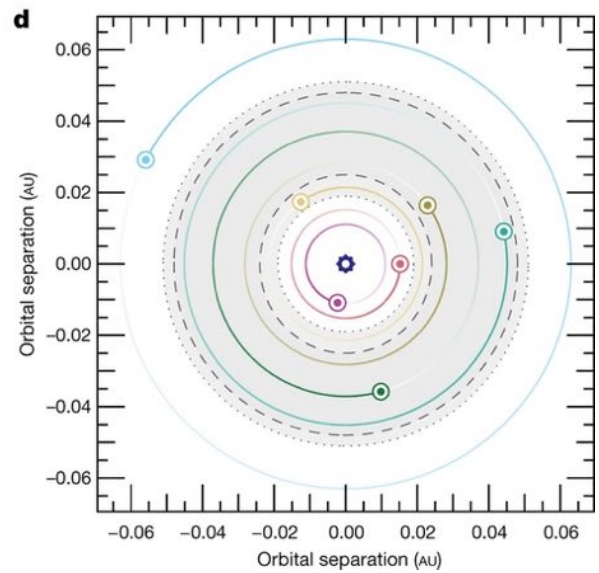


Kepler's Second Light: How K2 Will Work
NASA
Solar Panels
Photons of sunlight exert pressure on the spacecraft. If properly positioned, the spacecraft can be balanced against the pressure much as a pencil can be balanced on your finger.
Photons (Sunlight)
Solar Panels
Reaction Wheel 3
Solar Balance Ridge
Reaction Wheel 1
END
CAMPAIGN #2
CONTINUE...
Spacecraft rotated to prevent sunlight from entering telescope
START
END
Day 83
Field of View #2
Sun
Photons
CAMPAIGN #1
Day 1
Solar panel illuminated
START
Field of View #1
TOP-DOWN VIEWS OF SPACECRAFT
UNSTABLE
STABLE
Solar Balance Ridge
Solar Panels
Telescope
Unbalanced solar pressure = spacecraft roll
Balanced solar pressure = stable spacecraft
Unbalanced solar pressure = spacecraft roll
When the spacecraft is balanced, the telescope is stable enough to monitor distant stars in search of transiting planets. A specific portion of the sky is studied for approximately 83 days, until it is necessary to rotate the spacecraft to prevent sunlight from entering the telescope. There are approximately 4.5 viewing periods or campaigns per orbit or year.
CONCEPTUAL ILLUSTRATION OF SPACECRAFT SOLAR DISTURBANCE. THE ACTUAL DISTURBANCE IS DUE TO PHOTON PRESSURE, NOT SOLAR WIND.

Seven Earth-size planets around the brown dwarf TRAPPIST-1

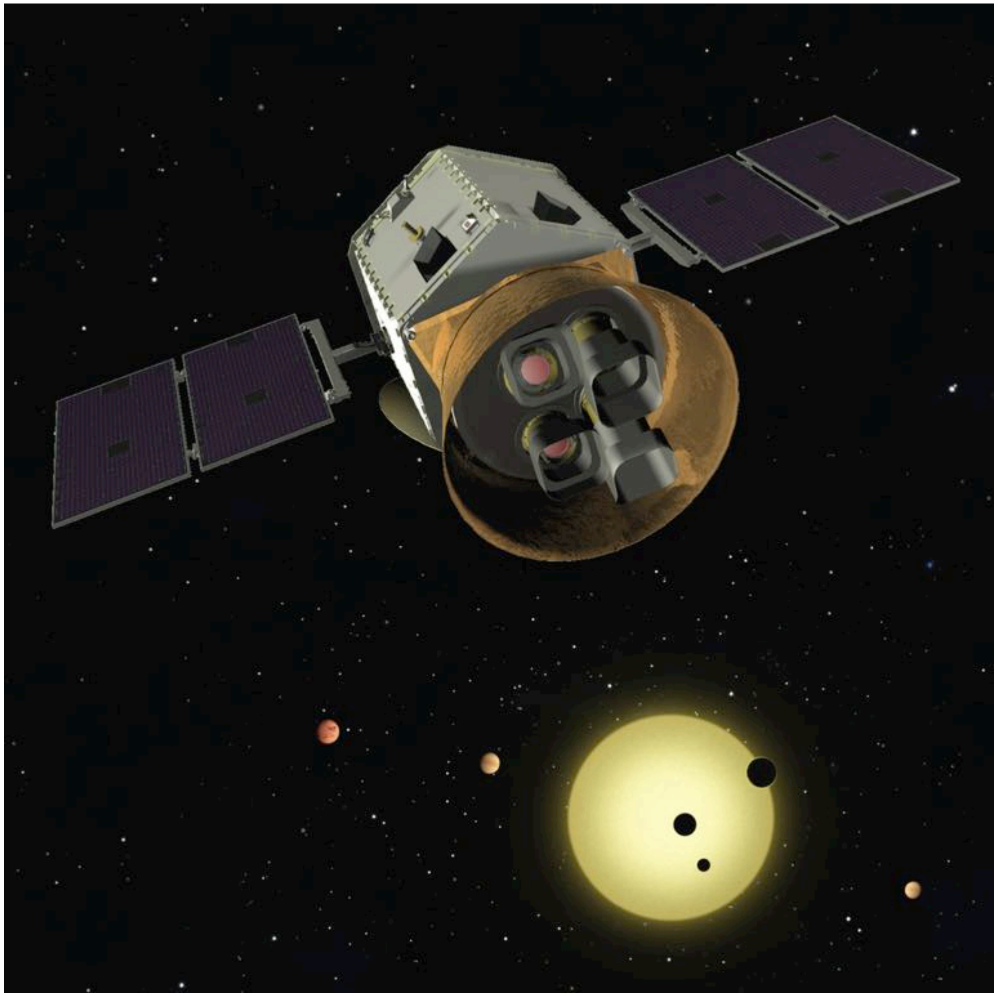






Gillon+ 2016, 2017

TESS: Transiting Exoplanet Survey Satellite



A new space telescope to find small transiting planets around bright stars – these are the planets that we could study in more detail.

NASA mission

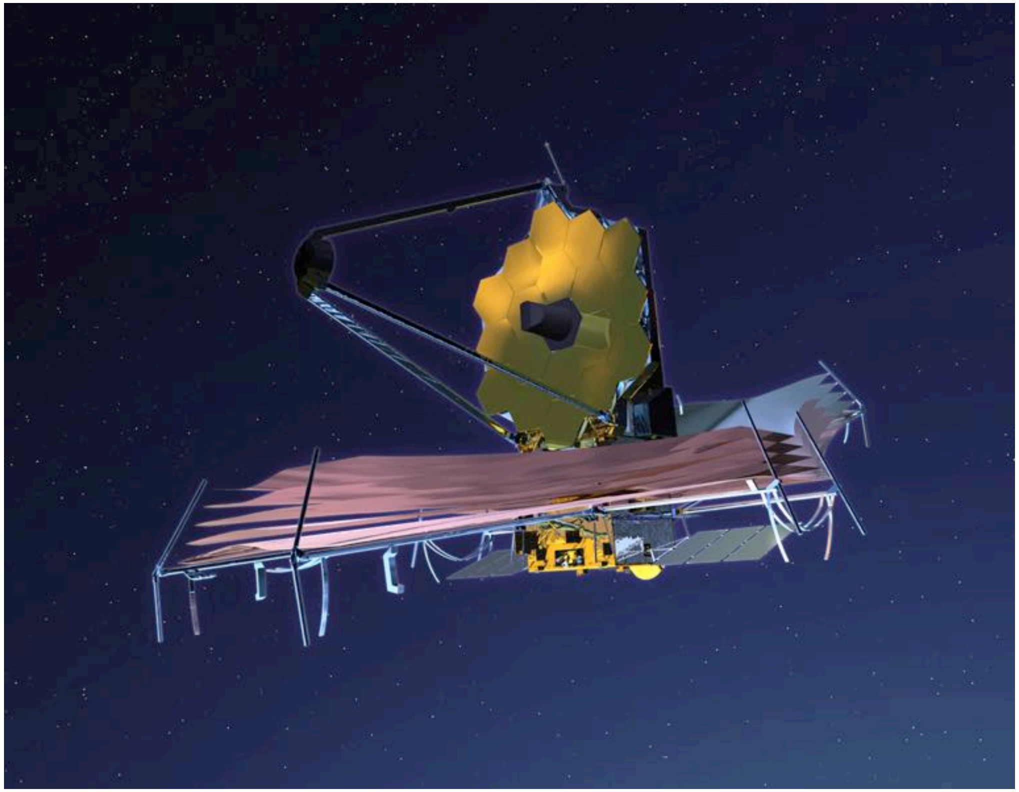
$200M cost

4 x 10cm lenses

Scheduled for launch in 2018

Mostly planets in short-period orbits, but may find habitable-zone planets around small stars

The James Webb Space Telescope



The JWST is the intellectual successor to Hubble.

It will have a 6.5m mirror that is optimized for infrared observations.

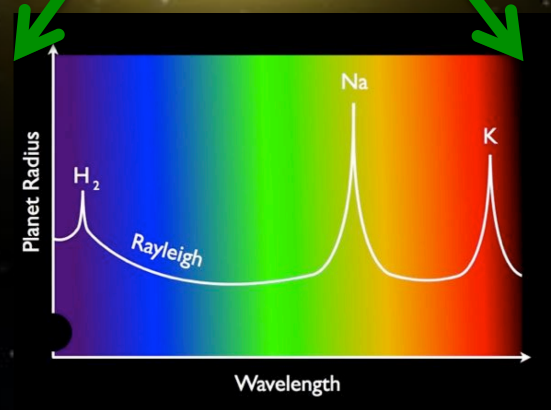
It is scheduled for launch in 2018.

The estimated cost of the project is $8B.

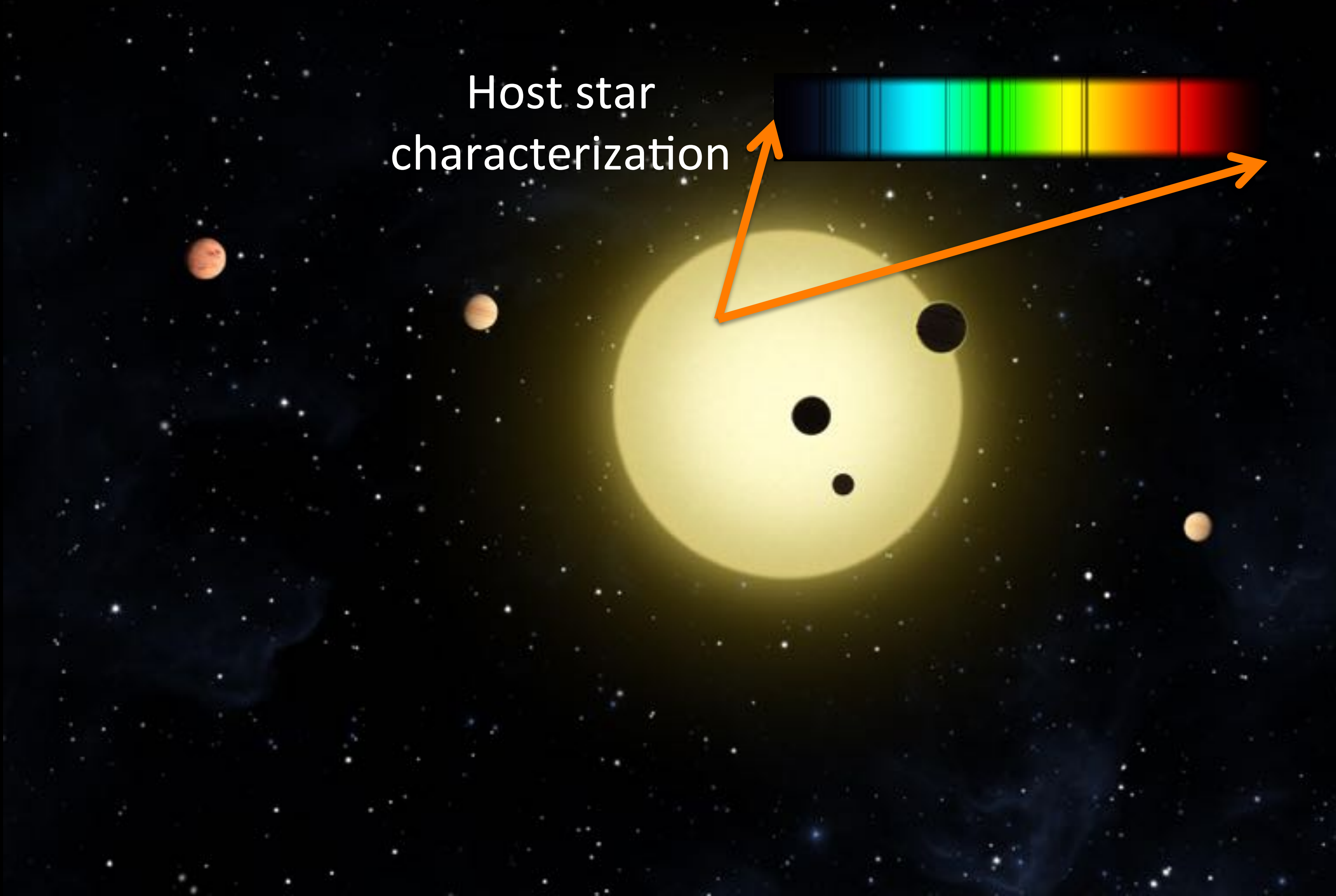
The role of precision spectroscopy…

Radial velocity planet detection

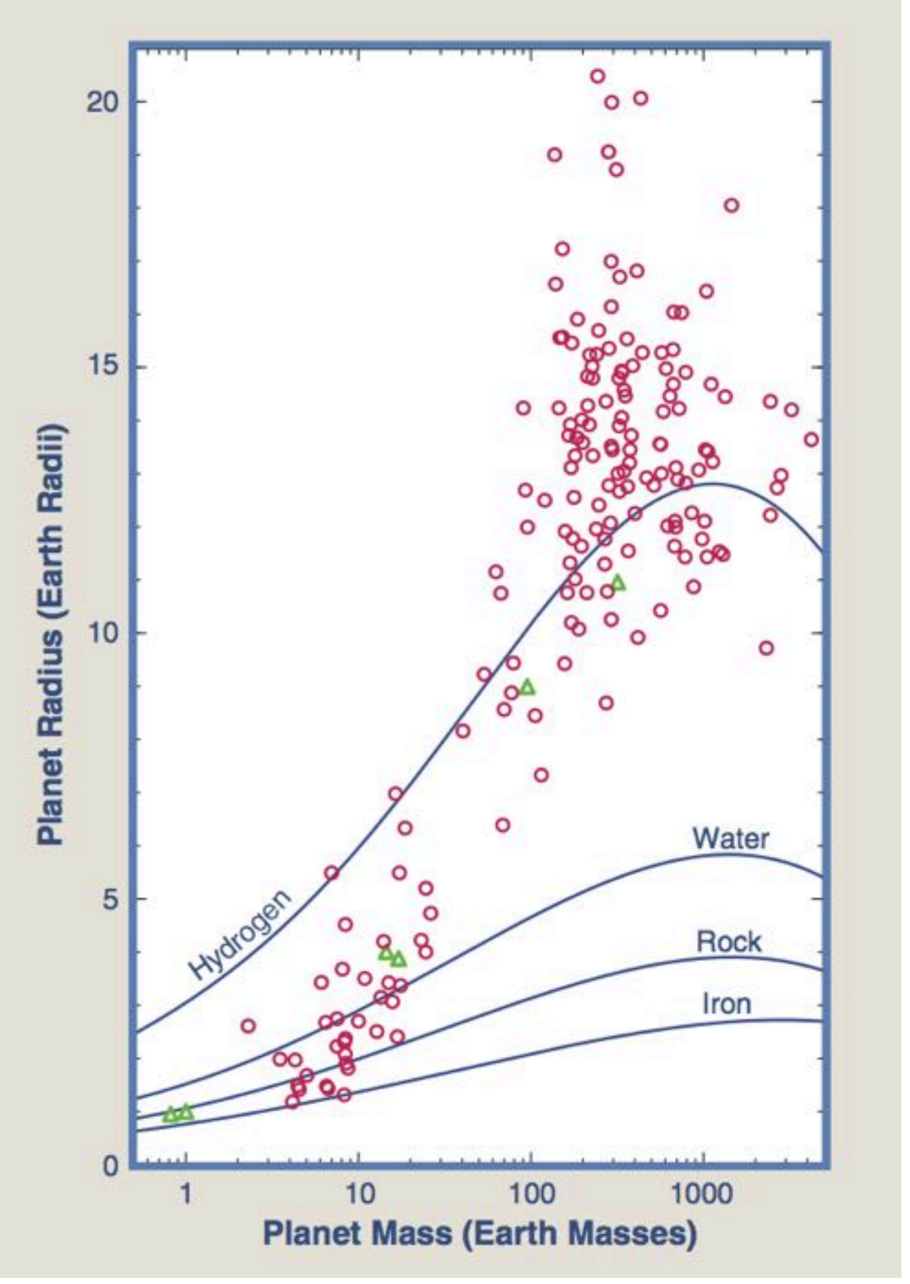
Exoplanet atmosphere studies



The role of precision spectroscopy…

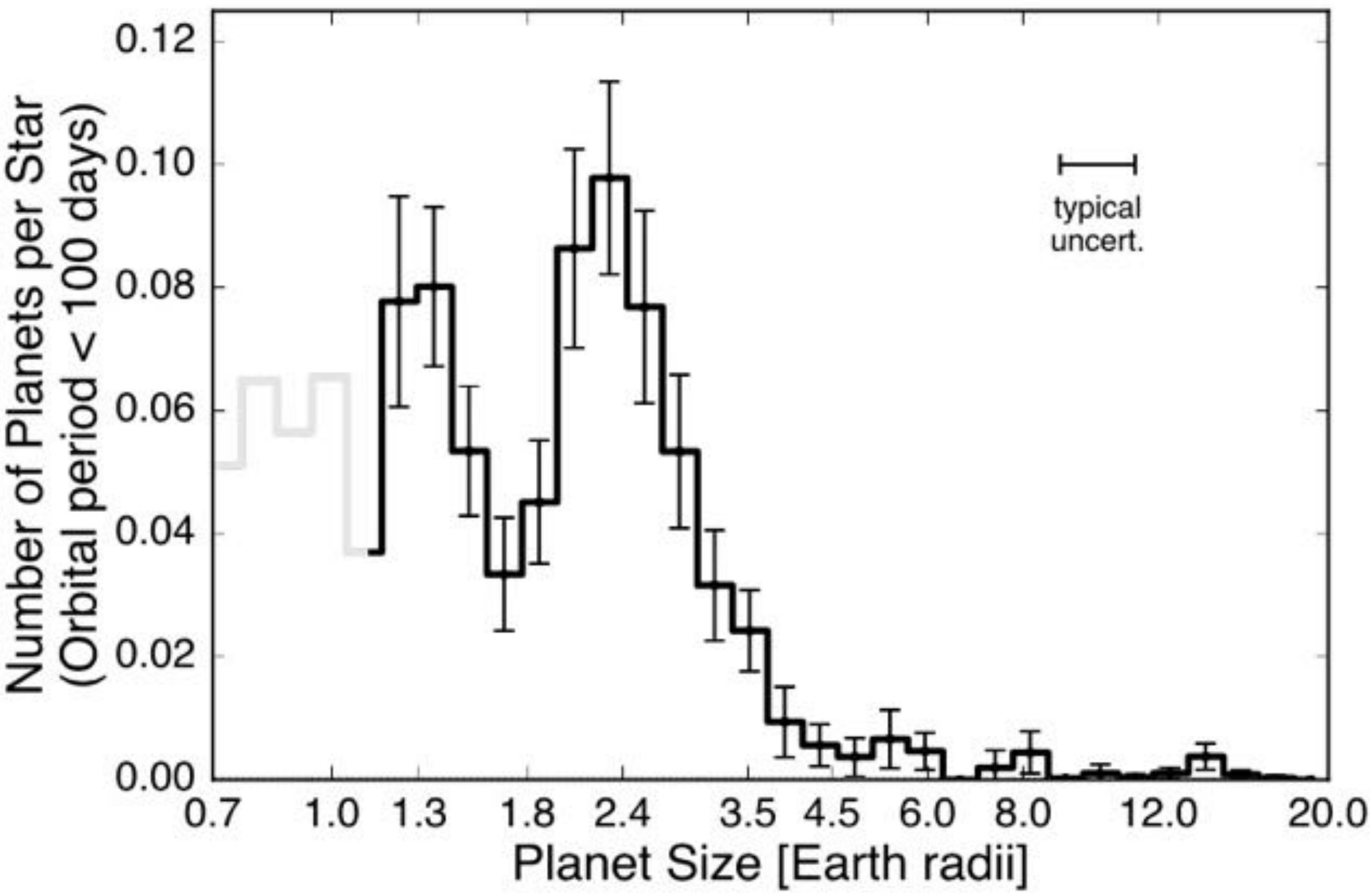


Both radial velocities and transits depend on stellar characterization to derive the absolute planet properties



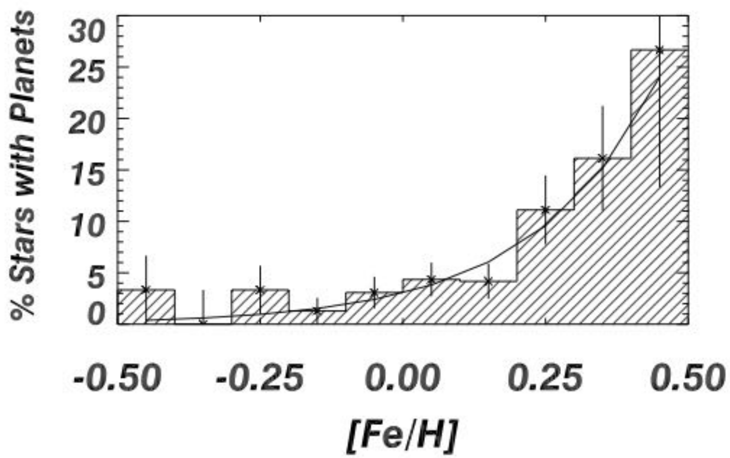
Howard 2013, Science, 340, 572

The importance of precise stellar characterization

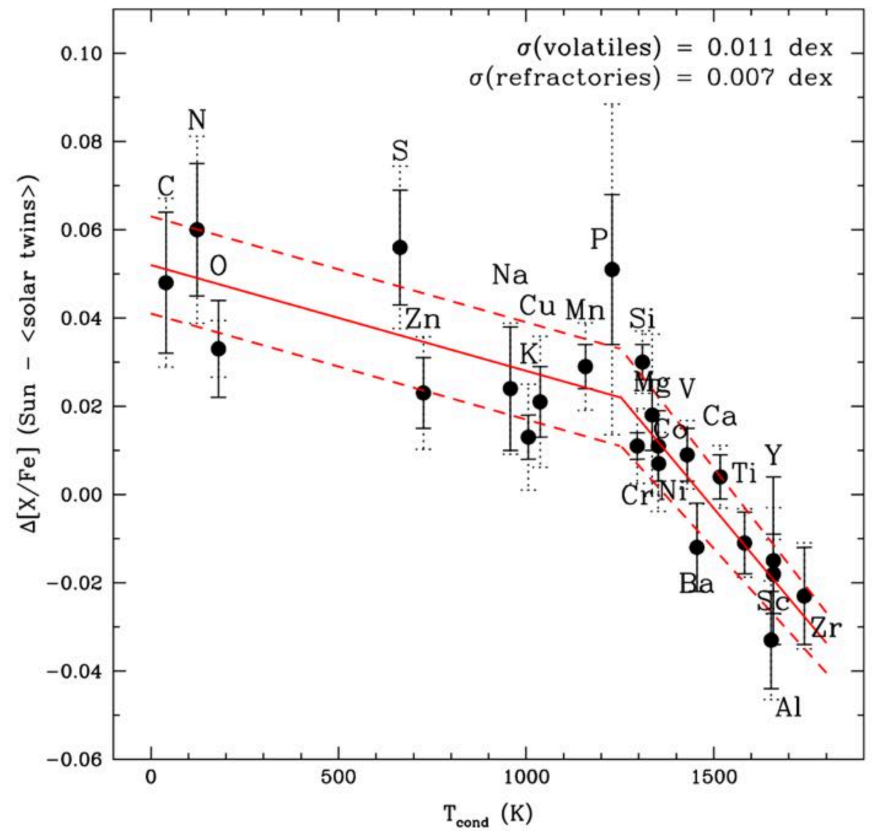


Fulton+ 2017

Host stars are a fossil record of planet formation

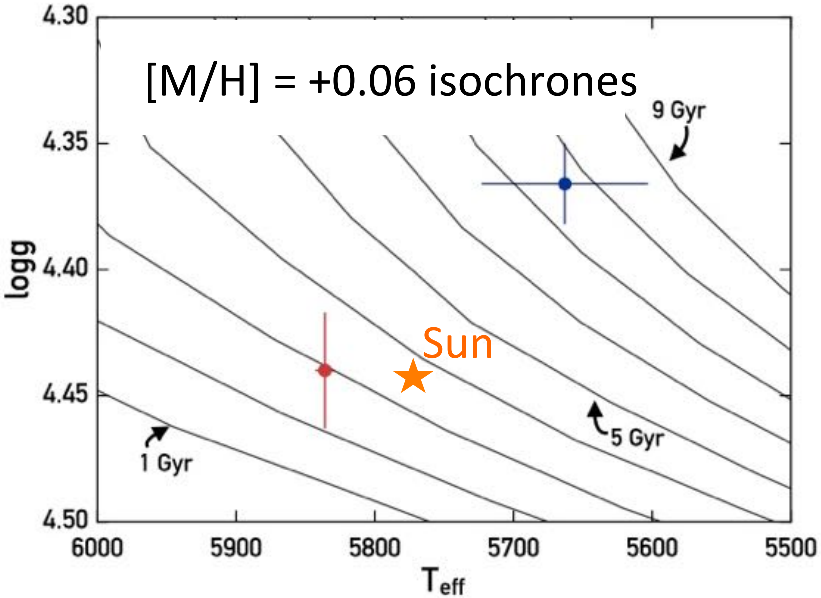


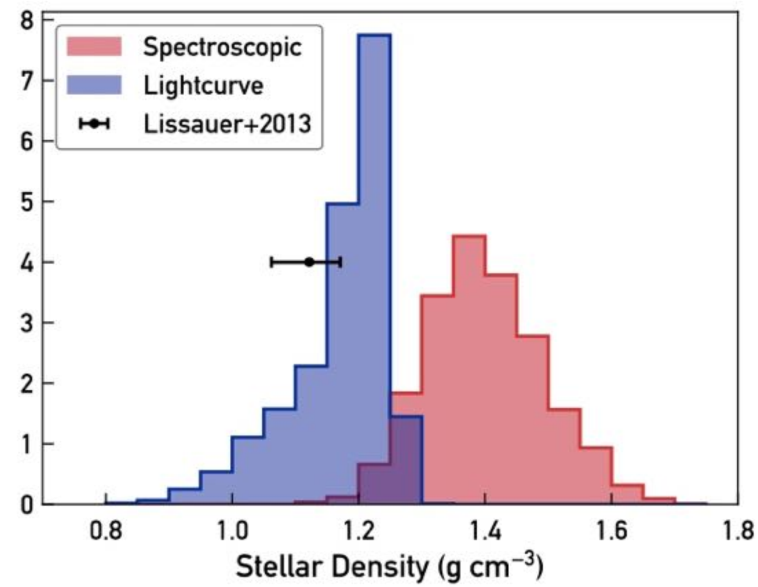
Valenti & Fischer 2005



Melendez+ (2009)

Interpret TTV masses with caution: Re-evaluating the Kepler-11 system



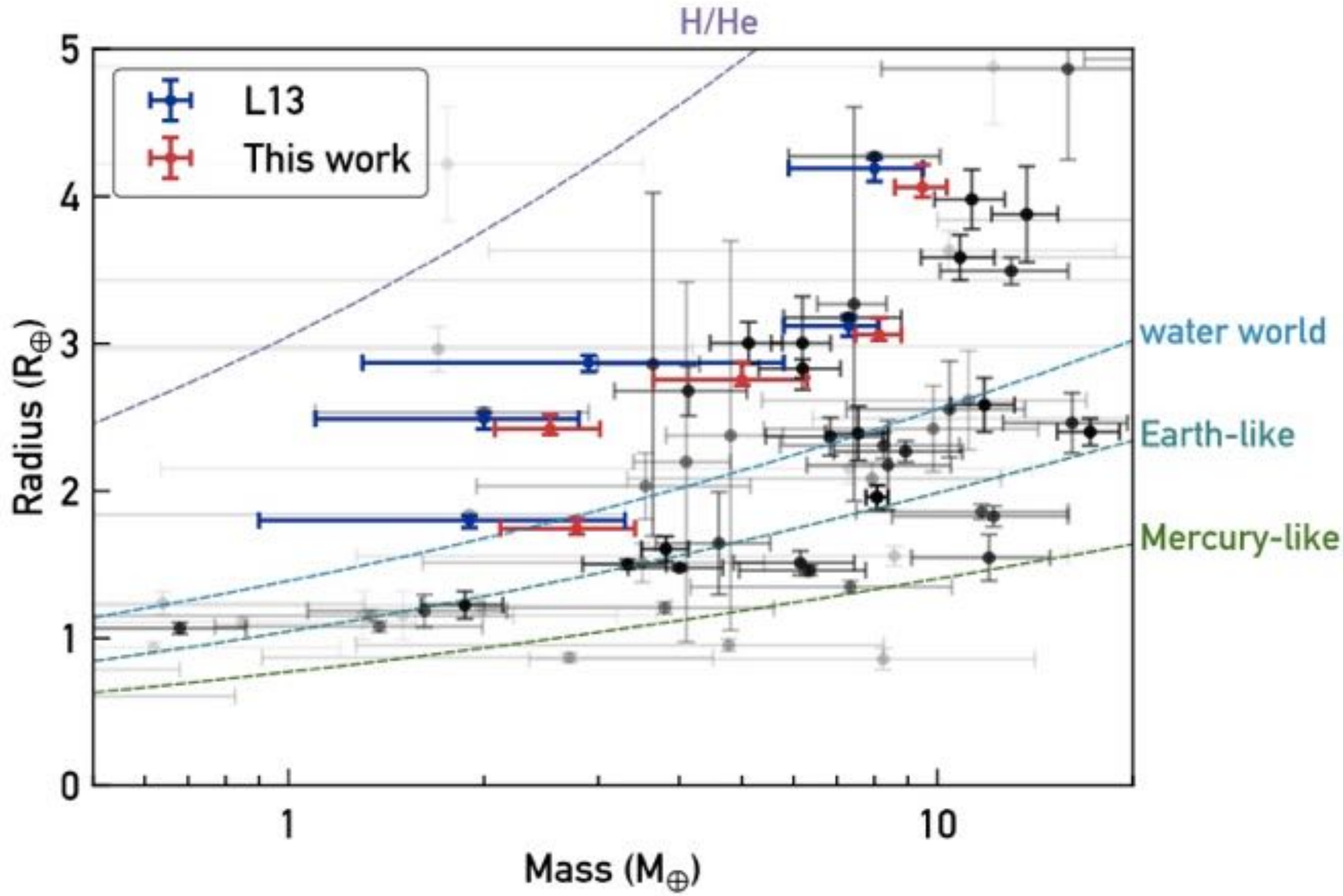


High-precision spectroscopy (S/N = 250) with differential equivalent width technique

Low-precision spectroscopy (S/N= 30) with spectral fitting

Bedell+ 2017

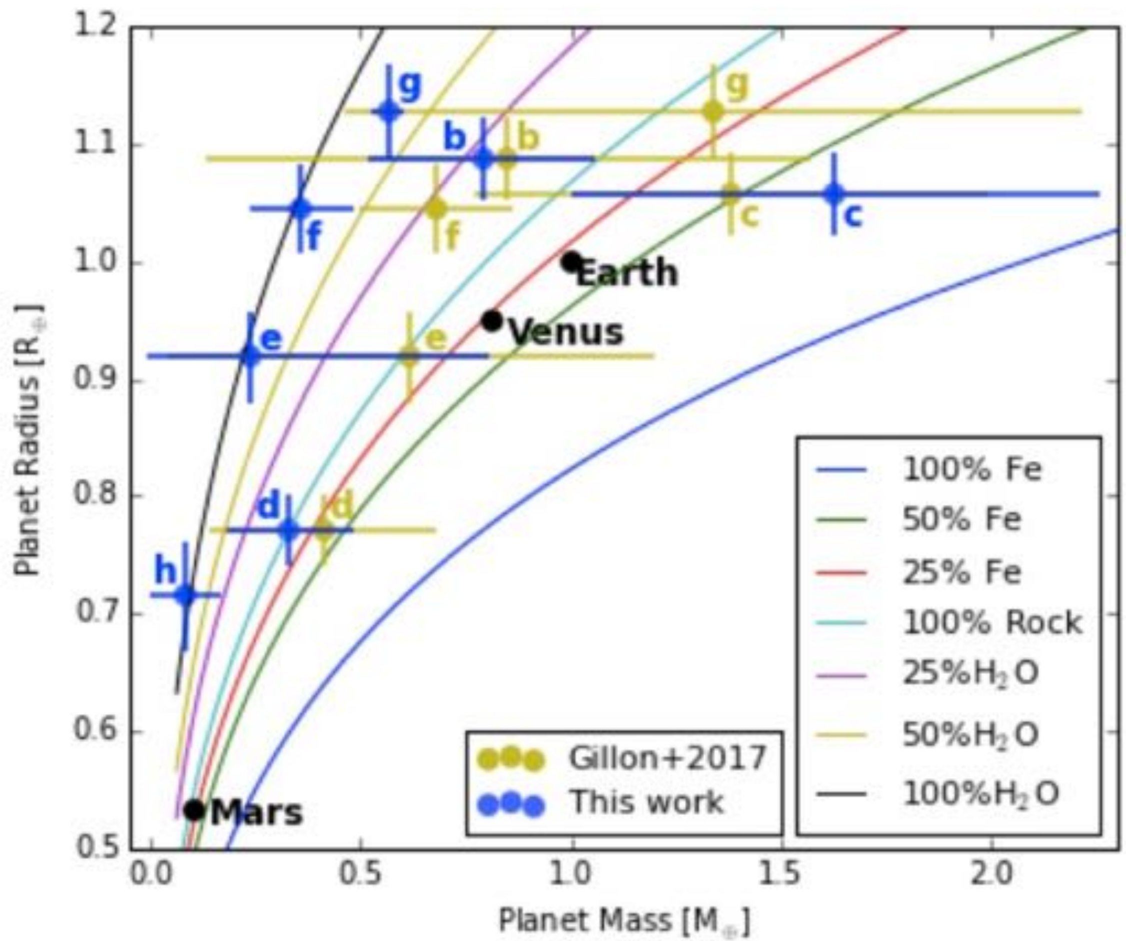
Interpret TTV masses with caution: Re-evaluating the Kepler-11 system



Planet densities change by 20 – 95%!

Bedell+ 2017

Interpret TTV masses with caution: Can we trust the TRAPPIST-1 masses?



Wang+ 2016

Challenges looking forward

- **Radial velocity planet detection:**
  - How do we disentangle stellar jitter and instrumental noise from the signals of Earth twins?
  - How do we best use the next generation of large telescopes?
  - How do we measure the masses of a large sample of TESS planets?
- **Host star characterization:**
  - Can we connect stellar abundances to planet formation beyond the giant planet − metallicity correlation?
  - How do we accurately characterize large numbers of exoplanet host stars in the TESS era?
- **Transit spectroscopy:**
  - How much of JWST's potential power will we be able to use for transit spectroscopy?
  - How do we move beyond one-off studies to the statistical investigation of exoplanet atmospheres?