Introduction to exoplanetology

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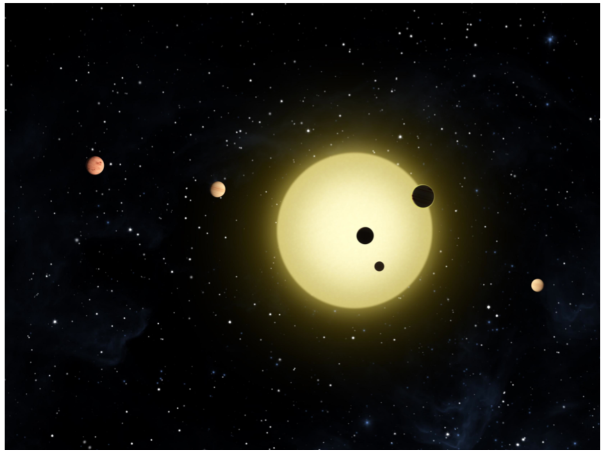
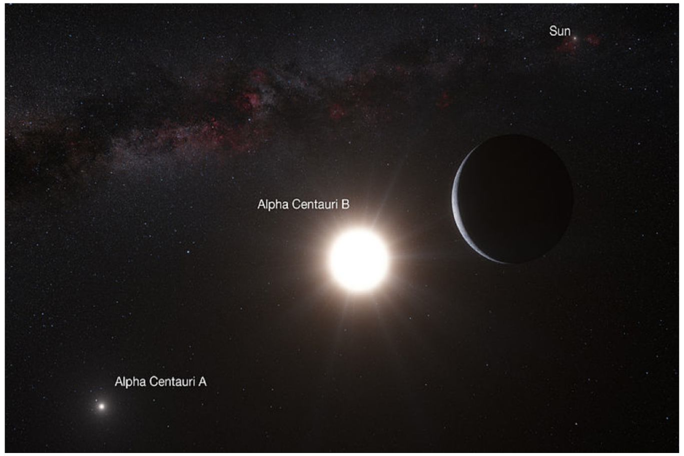
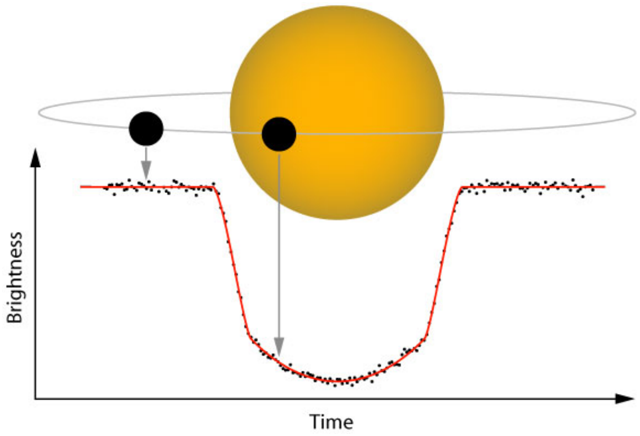
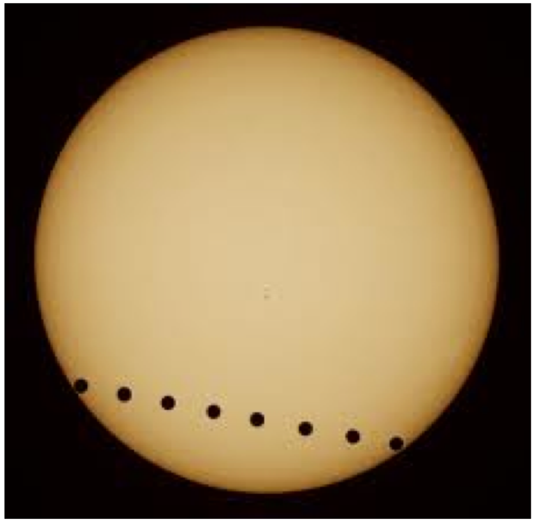


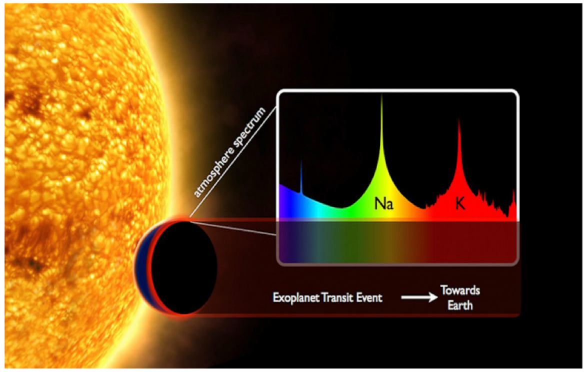


I. IV/V. Introduction to exoplanetology

Transiting exoplanets







Michaël Gillon

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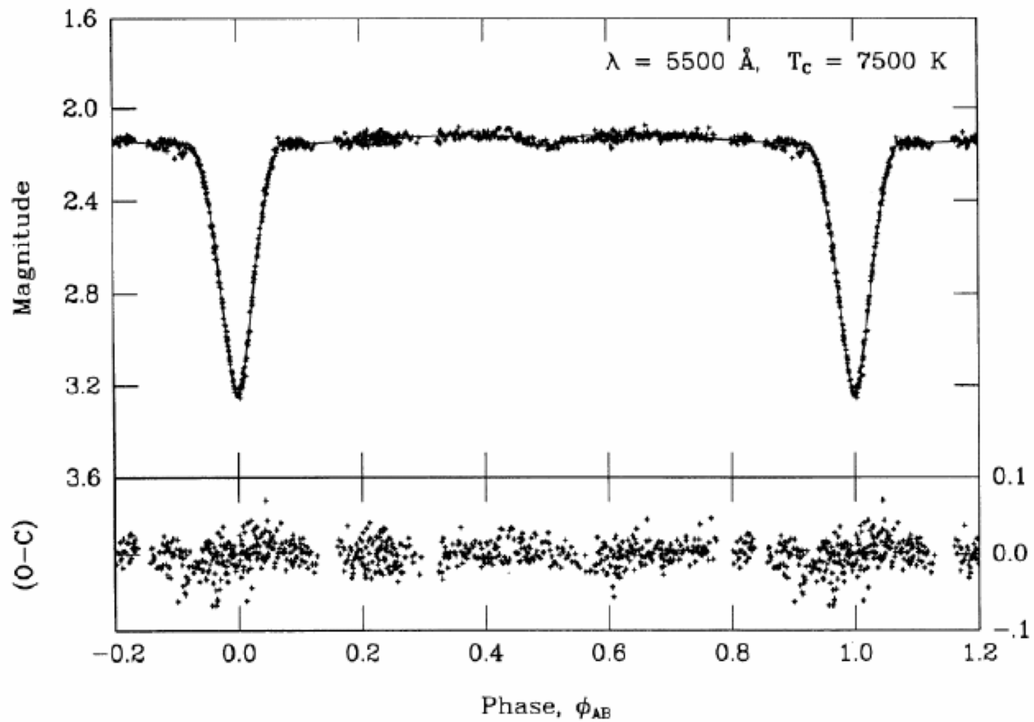
Algol: the Devil's star

Perseus constellation - V=2.1- 92 light-years
Beta Per A (B8V)+ B (K0IV) in mutual orbit with P = 2.85 days (0.06 au)
Beta Per C (A5V) at 2.7 au (680 days)

Its variability could have been known by the Egyptians more than 3000 years ago.
1783: John Goodricke proposed that it is due to eclipses.
End of 19th century: radial velocities show the multiple nature of the star.



On the importance of eclipsing binaries. I

Recall L3 : $$K_{1,2} = M_{2,1}\sin i\left(M_2+M_1\right)^{-2/3}P^{-1/3}(1-e^2)^{-1/2}C$$

with C = constant

If RVs are measured for both stars (SB2), K_1 and K_2 are known.

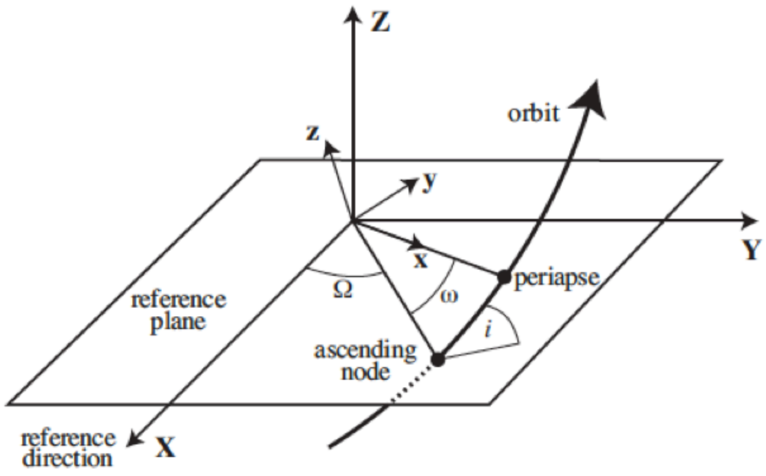
➔ $$\frac{K_1}{K_2}=\frac{M_1}{M_2},$$

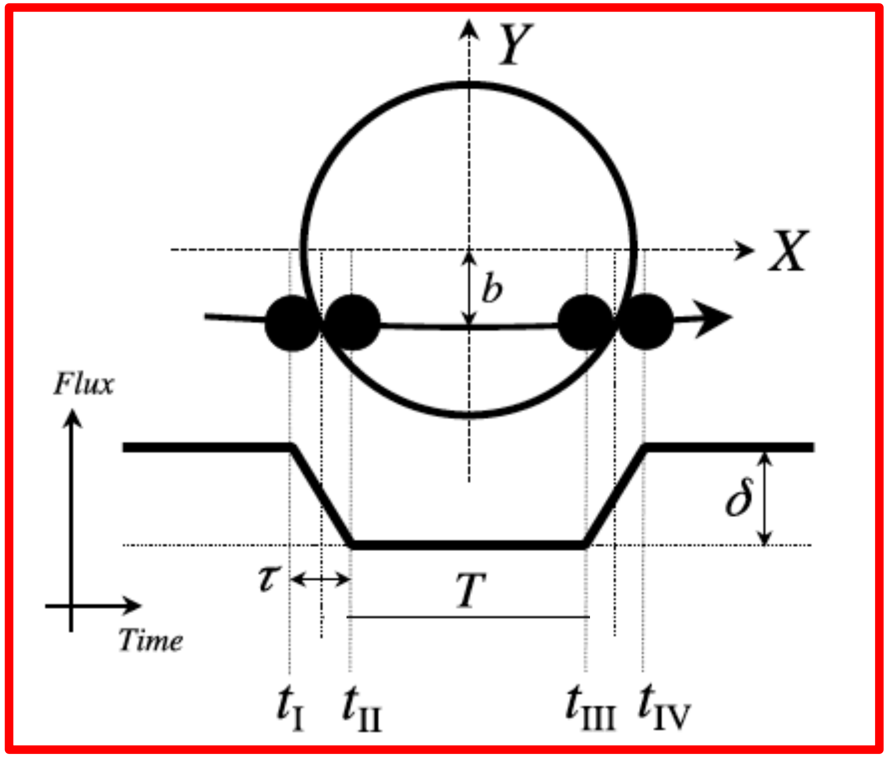
$$\frac{(M_1\sin i)^3}{\left[M_1\left(1+\frac{K_2}{K_1}\right)\right]^2}=\left(\frac{K_2}{C}\right)^3 P(1-e^2)^{3/2}$$

➔ We have $M_1\sin i^3$ and $M_2\sin i^3$

If *i* is known, the stellar masses can be directly measured!

Eclipses





Assumption: 2 spherical bodies

Longitude of ascending node Ω unknown

➔ we assume Ω=180 deg

➔ X-axis is the reference axis.

$$r = \frac{a(1-e^2)}{1+e\cos f}$$

$$X = -r\cos(\omega + f)$$

$$Y = -r\sin(\omega + f)\cos i$$

$$Z = r\sin(\omega + f)\sin i$$

$$r_{sky} = r\sqrt{1-\sin^2(\omega + f)\sin^2 i}$$

Eclipses

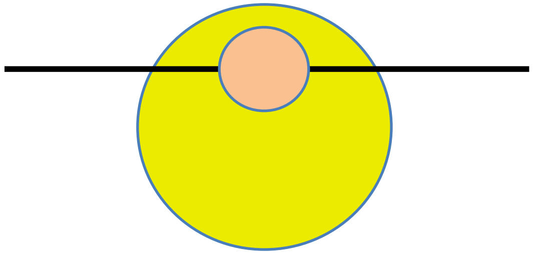
r_{sky} minimal when X=0, at the inferior (**transit**) and superior (**occultation**) conjunctions

$$f_{\rm tra} = +\frac{\pi}{2} - \omega, \quad f_{\rm occ} = -\frac{\pi}{2} - \omega.$$

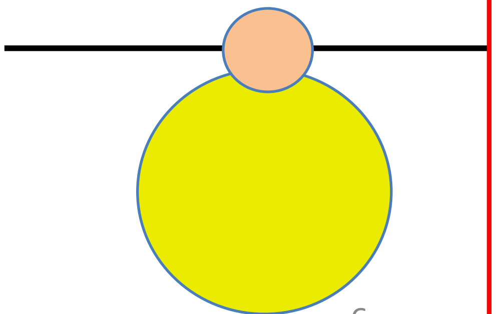
The eclipses **impact parameters** = r_{sky}/R_1 are

$$\boxed{b_{\rm tra} = \frac{a\cos i}{R_\star}\left(\frac{1-e^2}{1+e\sin\omega}\right)} \qquad b_{\rm occ} = \frac{a\cos i}{R_\star}\left(\frac{1-e^2}{1-e\sin\omega}\right)$$

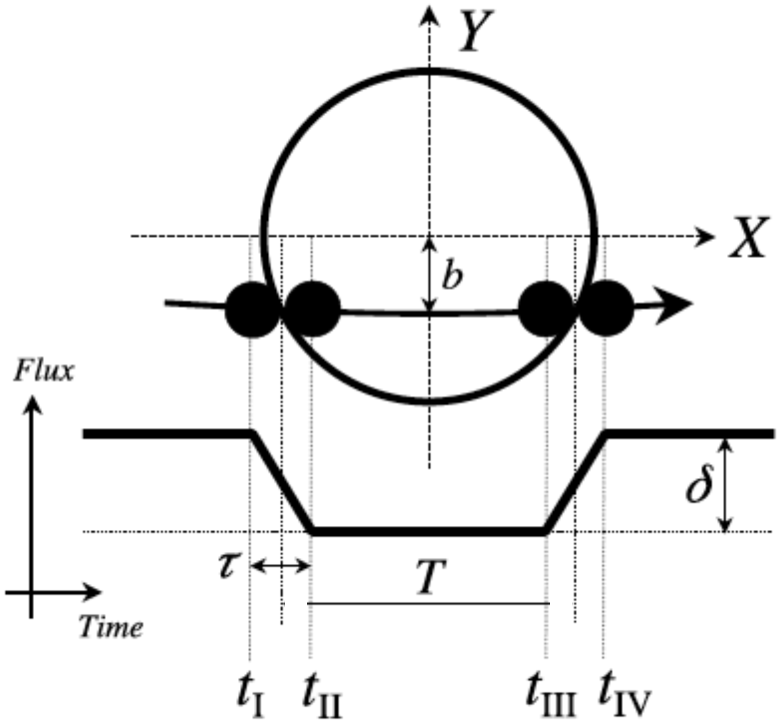
If $b \leq 1-(R_2/R_1)$: full eclipse



If $1-(R_2/R_1) < b < (1+R_2/R_1)$: grazing eclipse



Eclipses



Duration estimate: $\frac{2R_*}{2\pi a/_P} = \frac{PR_*}{\pi a}$

Total duration: T_{IV}-T_I

$$\frac{P}{\pi}\sin^{-1}\left[\boxed{\frac{R_\star}{a}}\frac{\sqrt{(1+k)^2-b^2}}{\sin i}\right]\frac{\sqrt{1-e^2}}{1\pm e\sin\omega}$$

$k=R_2/R_1$

+ : transit
- : occultation

Full eclipse duration: T_{III}-T_{II}

$$\frac{P}{\pi}\sin^{-1}\left[\frac{R_\star}{a}\frac{\sqrt{(1-k)^2-b^2}}{\sin i}\right]\frac{\sqrt{1-e^2}}{1\pm e\sin\omega}$$

+ : transit
- : occultation

Amplitudes (uniform disks) :

Transit : $\delta = \frac{F_{S,1}R_1^2}{F_{S,1}R_1^2 + F_{S,2}R_2^2}\left(\frac{R_2}{R_1}\right)^2$

Occultation : $\delta = \frac{F_{S,2}R_2^2}{F_{S,1}R_1^2 + F_{S,2}R_2^2}$

Eclipses

Amplitudes (uniform disks) :

Transit: $\delta = \dfrac{F_{S,1}R_1^2}{F_{S,1}R_1^2 + F_{S,2}R_2^2}\left(\dfrac{R_2}{R_1}\right)^2$

If $F_{S,2}R_2^2 << F_{S,1}R_1^2 \longrightarrow \boxed{\delta_{tr} = \left(\dfrac{R_2}{R_1}\right)^2}$ Exoplanet + star

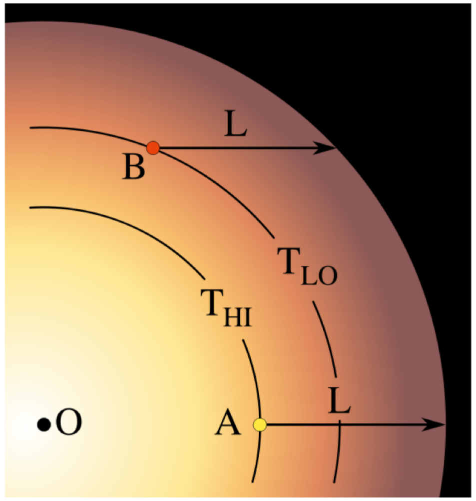
Occultation: $\delta = \dfrac{F_{S,2}R_2^2}{F_{S,1}R_1^2 + F_{S,2}R_2^2}$

If $F_{S,2}R_2^2 << F_{S,1}R_1^2 \longrightarrow \boxed{\delta_{oc} = \dfrac{F_{S,2}}{F_{S,1}}\left(\dfrac{R_2}{R_1}\right)^2}$ Exoplanet + star

Transiting planet: if δ_{tr} and δ_{oc} measured, and $F_{S,1}$ known ➔ $\mathbf{F_{S,2}}$

Emission spectrum of an exoplanet without having to spatially resolve it

Limb darkening



Optical depth $$\tau_\nu(x) = -\int_{\infty}^{x} \rho(s)\kappa_\nu ds$$

Emission surface: optical depth τ = 1
(τ > 1 ➔ opaque)

Disk center: emission of deeper hotter layers than for the limb➔I_s is larger

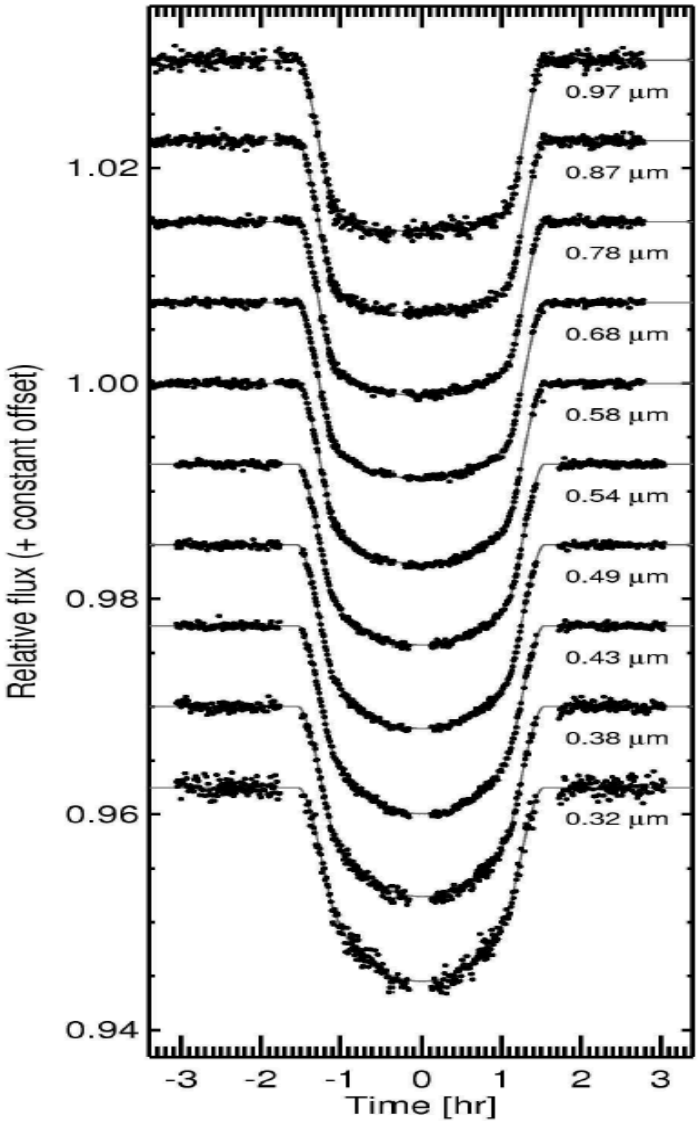
Surface intensity I_S depends on the angle of incidence

Analytical model: $$\frac{I(\psi)}{I(0)} = 1 + \sum_{k=1}^{N} A_k \left(1 - \cos(\psi)\right)^k$$

Limb-darkening decreases with λ because $$\frac{dB_\lambda}{dT} \approx \frac{2ck}{\lambda^4}$$

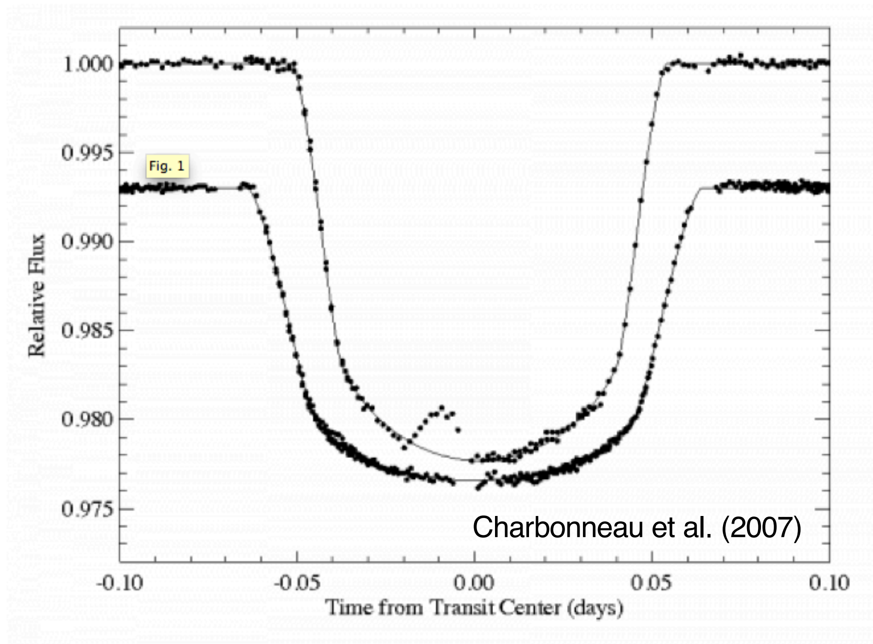
Limb darkening

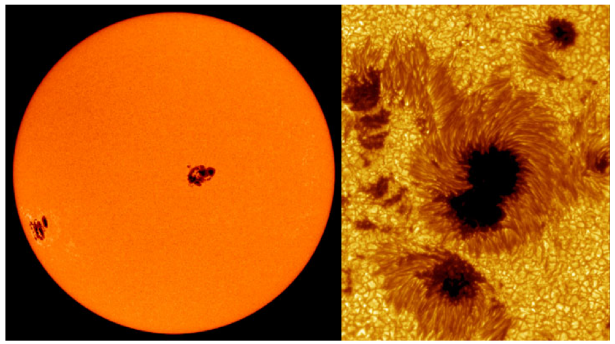
Consequence for transits: the drop of brightness varies with λ.
δ_{tr} is larger than k^2 near the center, smaller near the limb



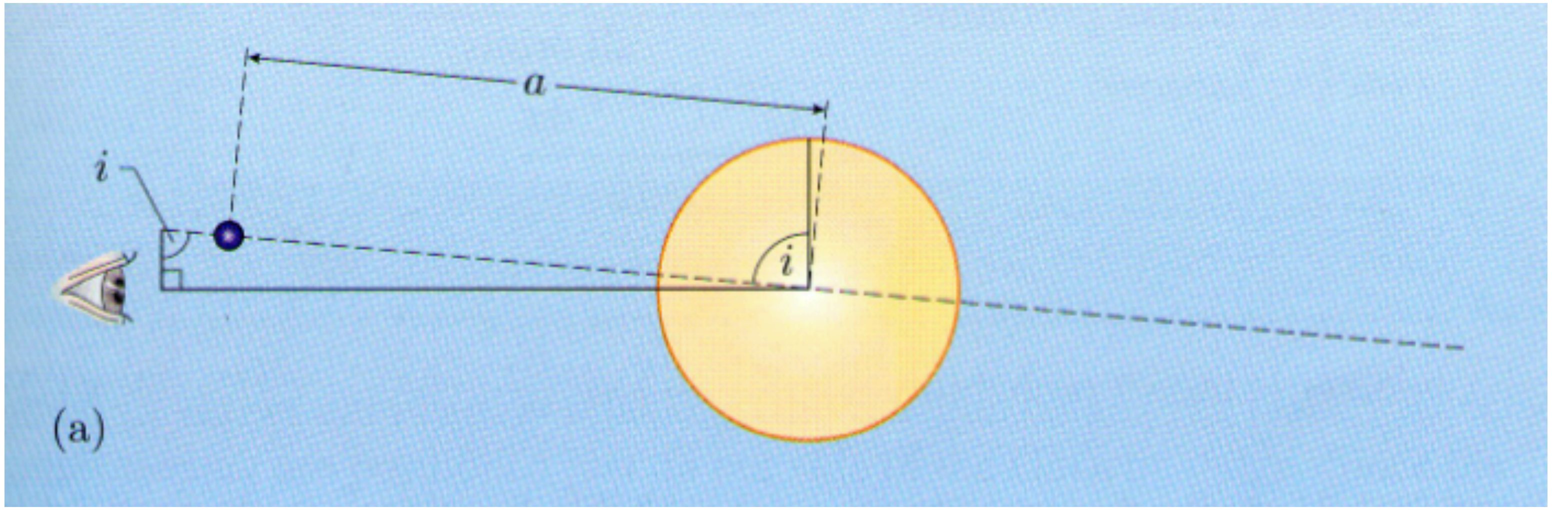
Knutson et al. (2007)

Transit = 1D cartography of the stellar disk





Geometric probability of eclipse



$$p_{\rm tra} = \left(\frac{R_\star \pm R_p}{a}\right)\left(\frac{1+e\sin\omega}{1-e^2}\right)$$

$$p_{\rm occ} = \left(\frac{R_\star \pm R_p}{a}\right)\left(\frac{1-e\sin\omega}{1-e^2}\right)$$

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

On the importance of eclipsing binaries. II

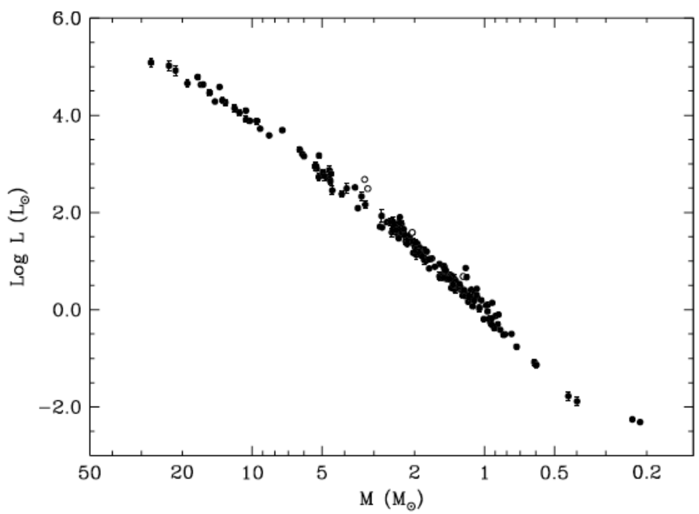
If we have the RVs of both stars (SB2), we know K_1 and K_2

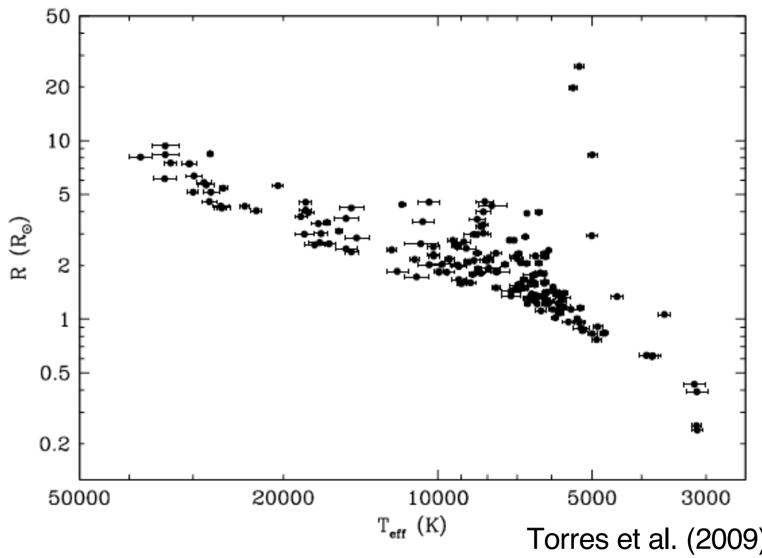
➔ We know $M_1 \sin i^3$ and $M_2 \sin i^3$

If eclipses, *i* is known ➔ the mass is determined for both stars

If a measurement or an estimate of T_{eff} is available for both stars, the light curves analysis will provide also R_1/a and R_2/a
a can be computed from P and $M_1 + M_2$, so R_1 and R_2 can be determined

Model-independent determination of stellar masses and radii!





Torres et al. (2009)

Searching for exoplanet transits?

Otto Struve
[1952]

F. Rossenblatt
[1971]

William J. Borucki
[1984]

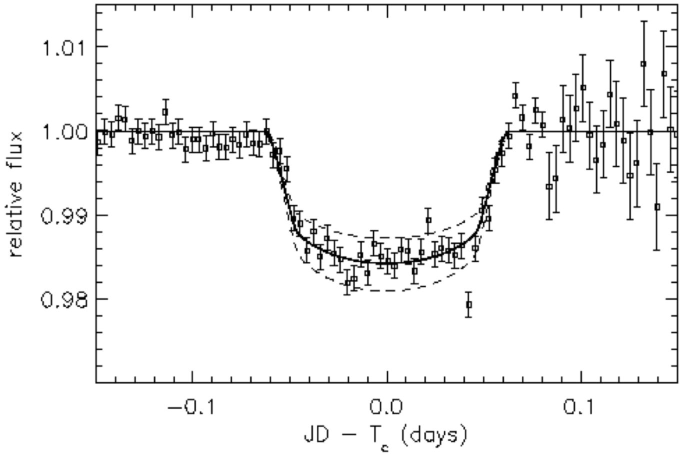
Probability? 0.5% for an Earth analog, 0.1% for Jupiter, ~10% for a hot Jupiter

Amplitude? ~1% for a gas giant planet
~0.01% for a terrestrial planet

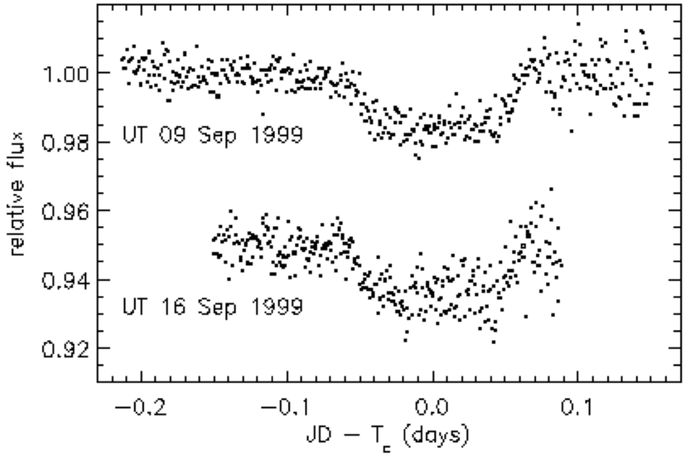
Requires measuring the evolution of the brightness of thousands of stars (*time-series photometry*) with a precision of 0.1% (0.001%) to detect Jupiter-sized (Earth-sized) planets.

Other possible strategy: search for the transits of RV planets

2000: first detection

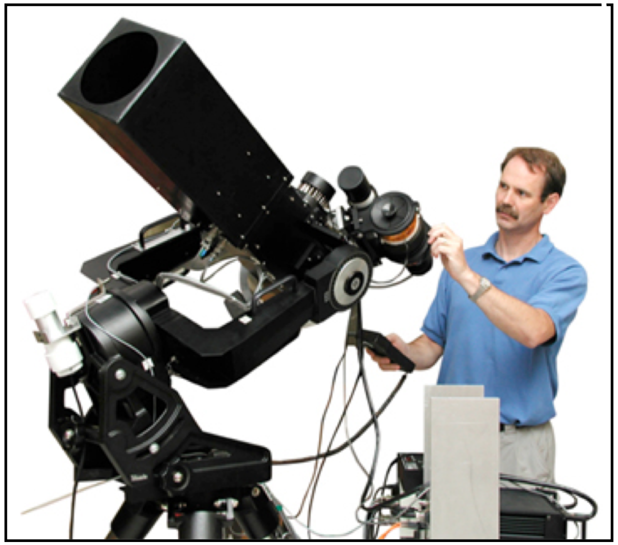


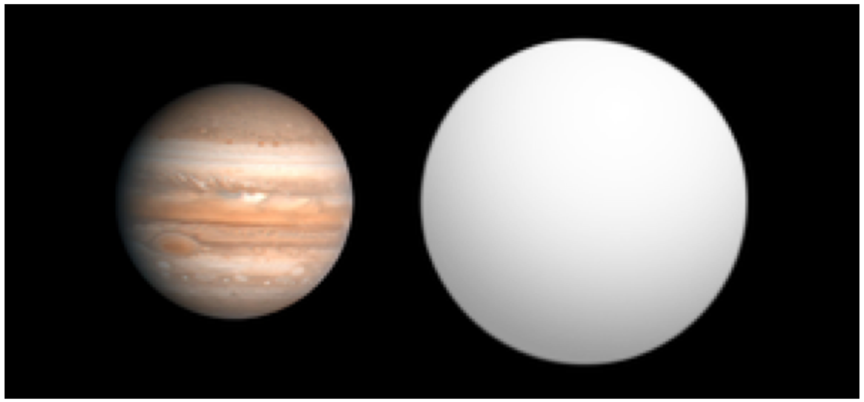
Charbonneau et al. (2000)



Henry et al. (2000)

Planet HD209458b first detected by radial velocity





0.7 $M_{Jupiter}$, 1.35 $R_{Jupiter}$

The years 2000: first transit surveys

OGLE-III
From 2001
Varsaw 1.3m telescope 1.3m
First exoplanet discovered by transit in 2003

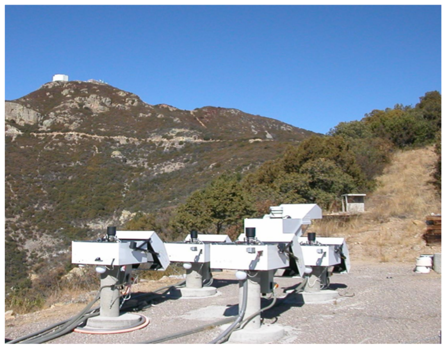
8

TrES
3 telescopes of 10cm. Field of view of 5.7° x5.7°
Multi-longitudes: California, Arizona, Canary Islands
First detection in 2004

5

XO
2 x 11cm lenses. Field of view of 7.2° x7.2°
Hawaii
First detection in 2006

5



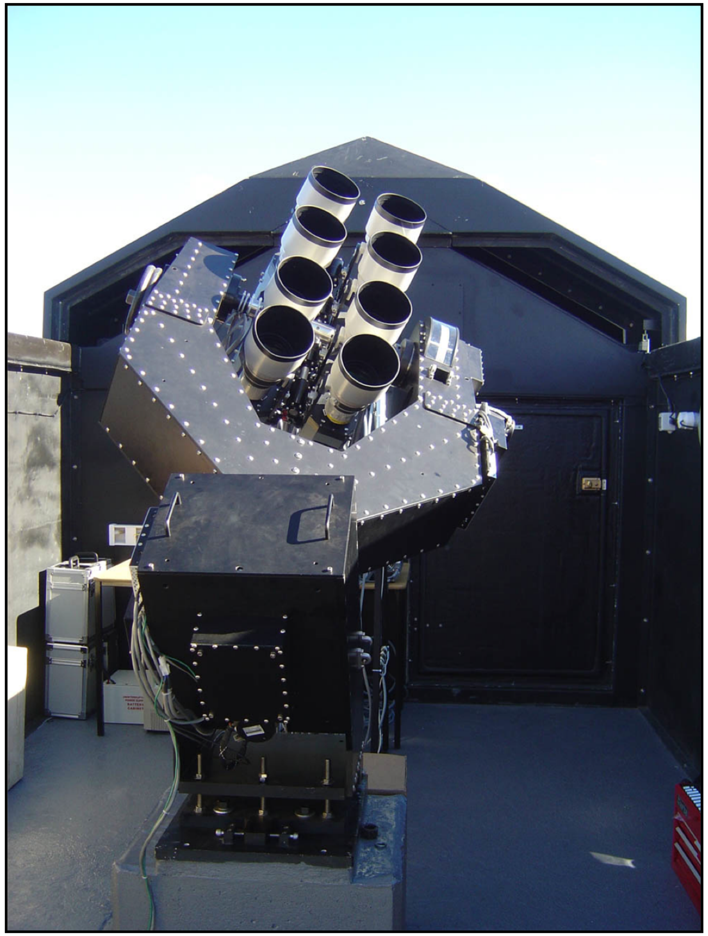
HATNet
6 x 11cm lenses. Field of view 8°x8°
Multi-longitudes : Hawaii, Arizona
First detection in 2006
Now in Southern hemisphere too

>100

WASP: Wide-Angle Search for Planets

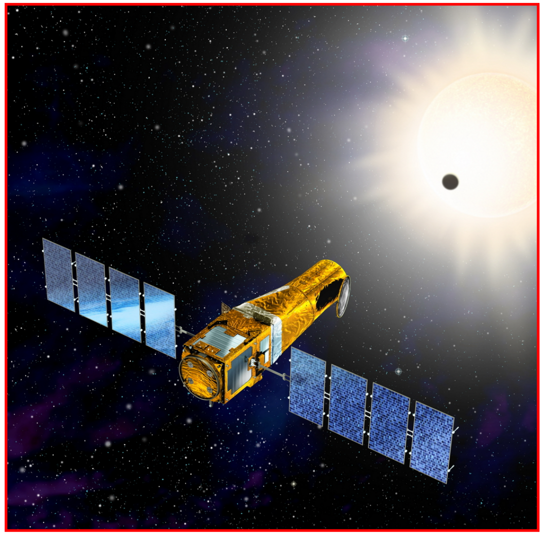
UK universities + foreign collaborators (including ULiege)
First detection in 2007. Lenses of 11cm + CCD
8 lenses per station. Field of view 7.8° x7.8 per lens
Stations: Canary Islands + South Africa

>200



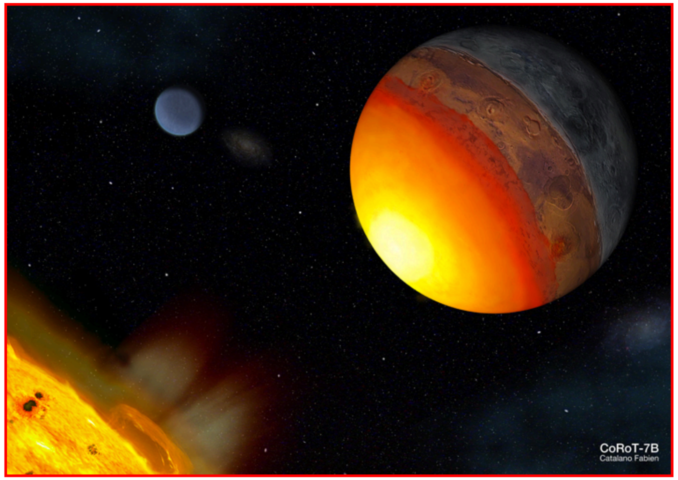
2007 : CoRoT, first space transit survey

- France (CNES) + ESA + several countries (inc. Belgium)
- Objectives: study of stars (asteroseismology) and transit search
- Telescope of 27 cm – Field of view of 3.5 deg^2
- Geocentric orbit
- Launch on 27 December 2006
- Fatal breakdown on 2 November 2012
- More than 20 detected planets, including

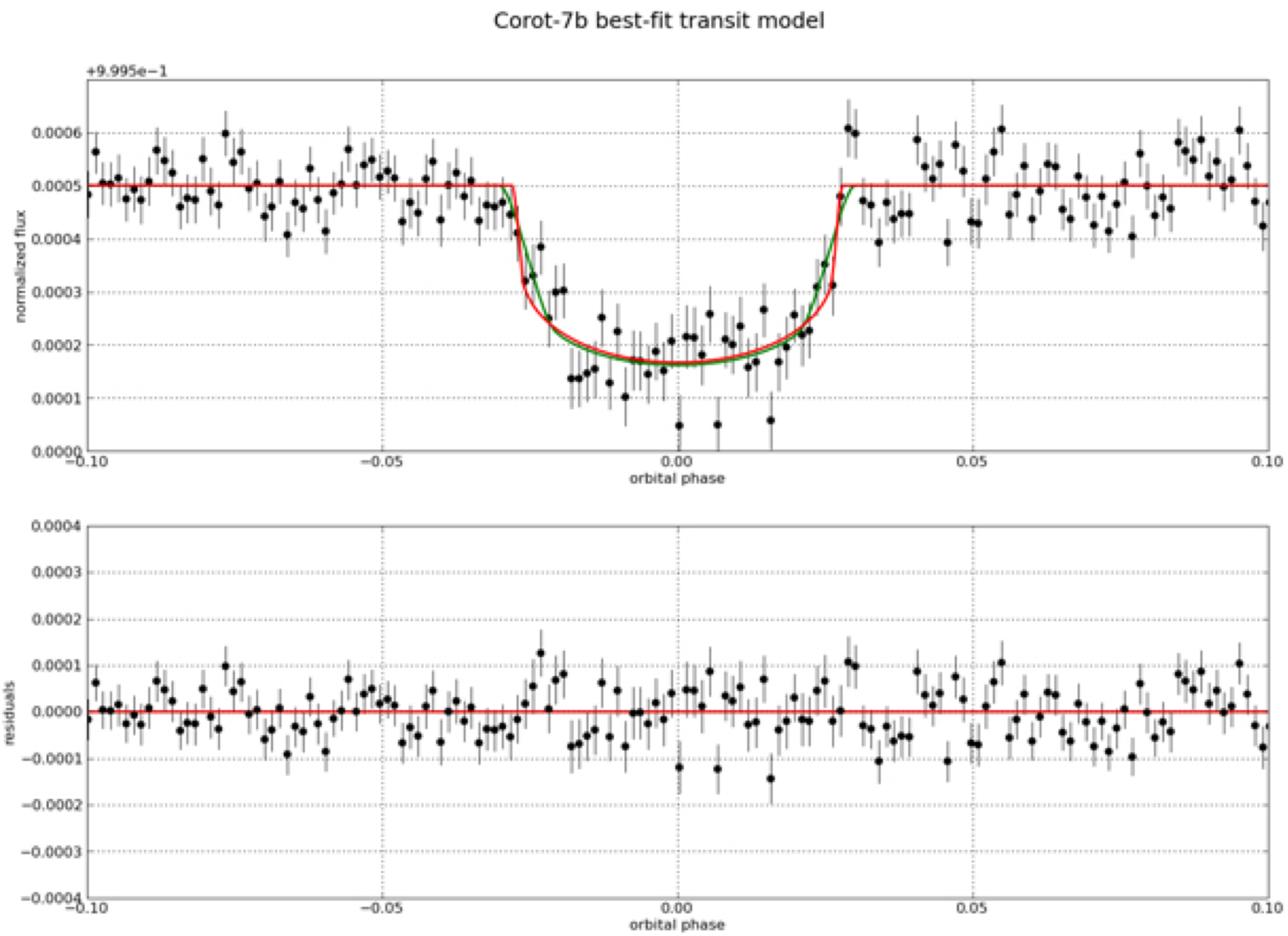


CoRoT-7b, the first transiting super-Earth

- Unicorn constellation
- ~5M_{Earth}, ~1.7 R_{Earth}
- Orbital period of 20.5 hrs!



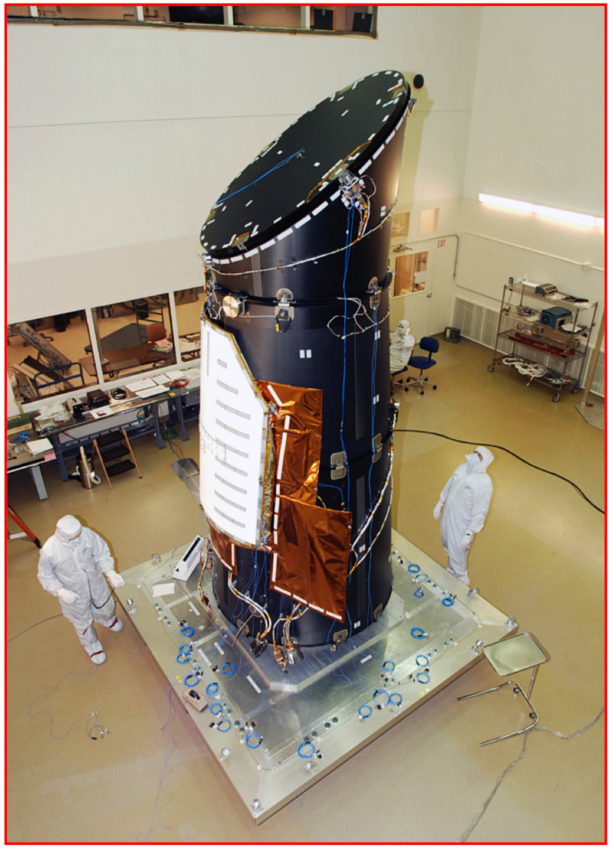
The first transiting super-Earth

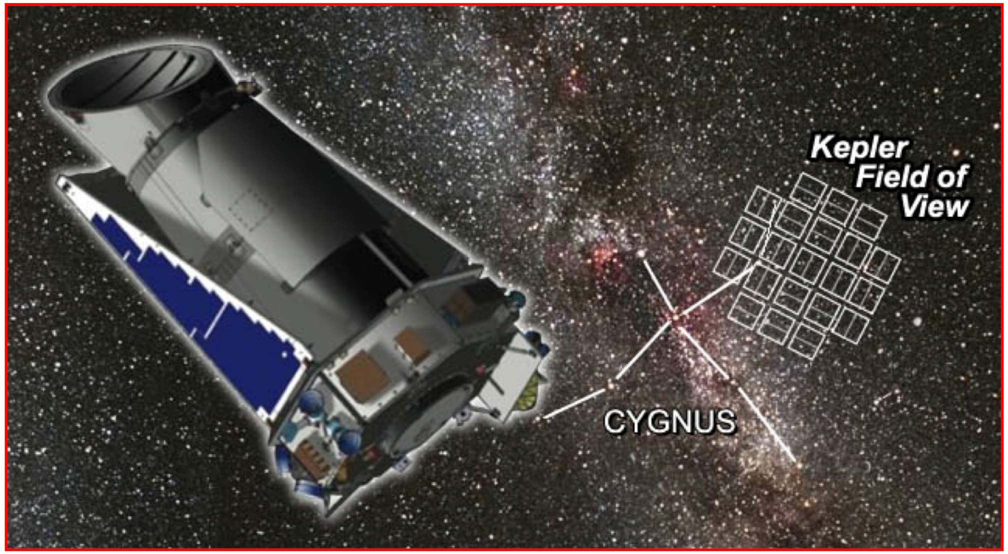


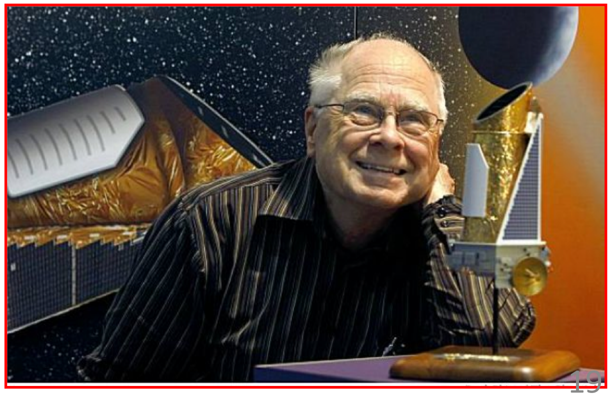
Léger et al. (2009)

The NASA Kepler mission

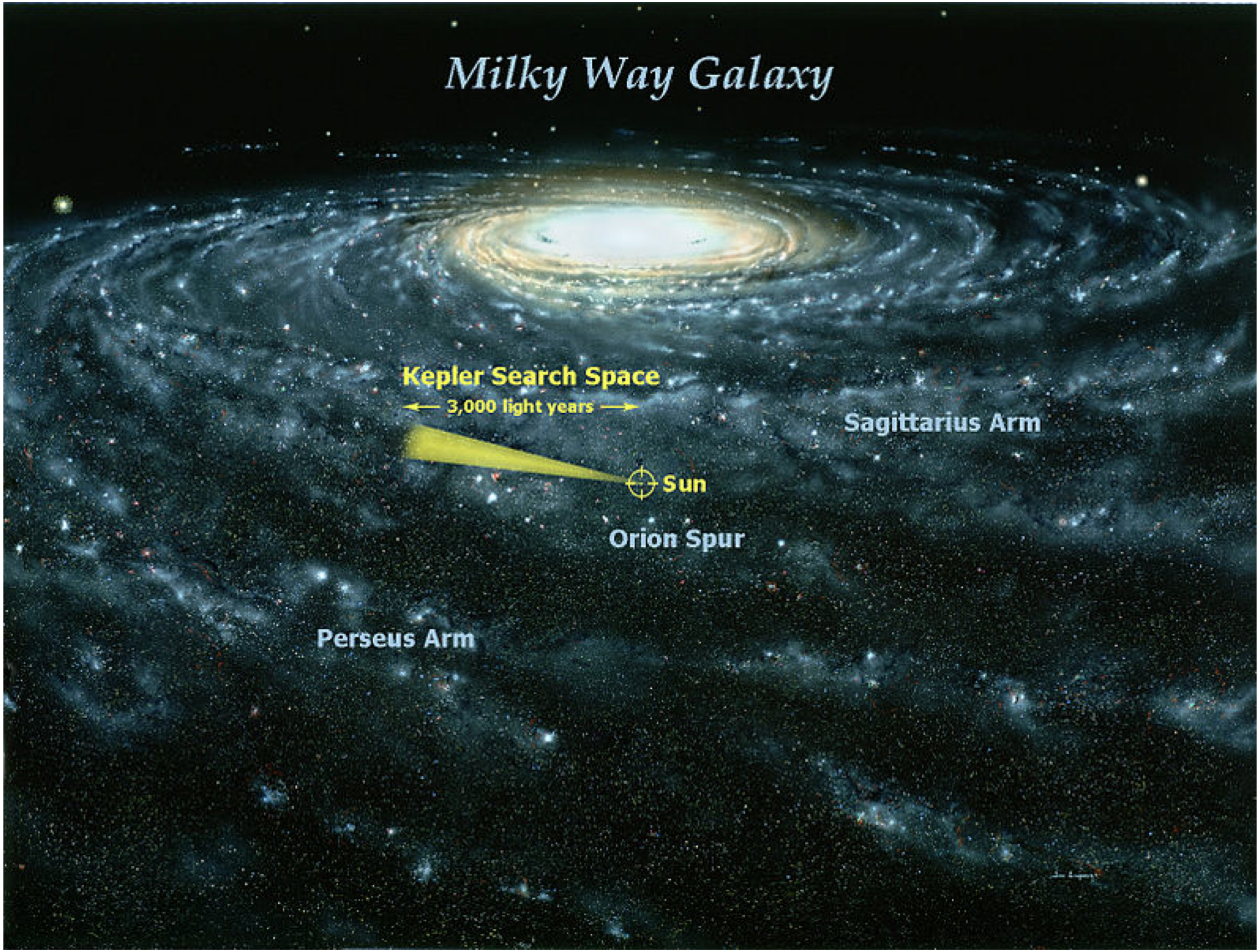
- USA (NASA)
- Objective: search for terrestrial exoplanets
- Telescope of 95cm – Field of view of 115 deg^2
- Heliocentric orbit
- Launch on 7 March 2009.
- End of nominal mission on 15 August 2013.
- More than 2500 detected planets
- More than 3000 candidates still to be confirmed



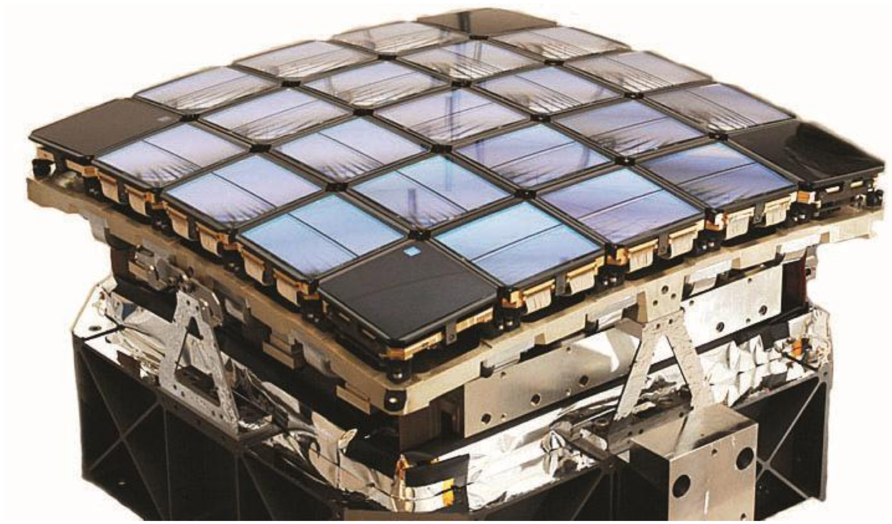




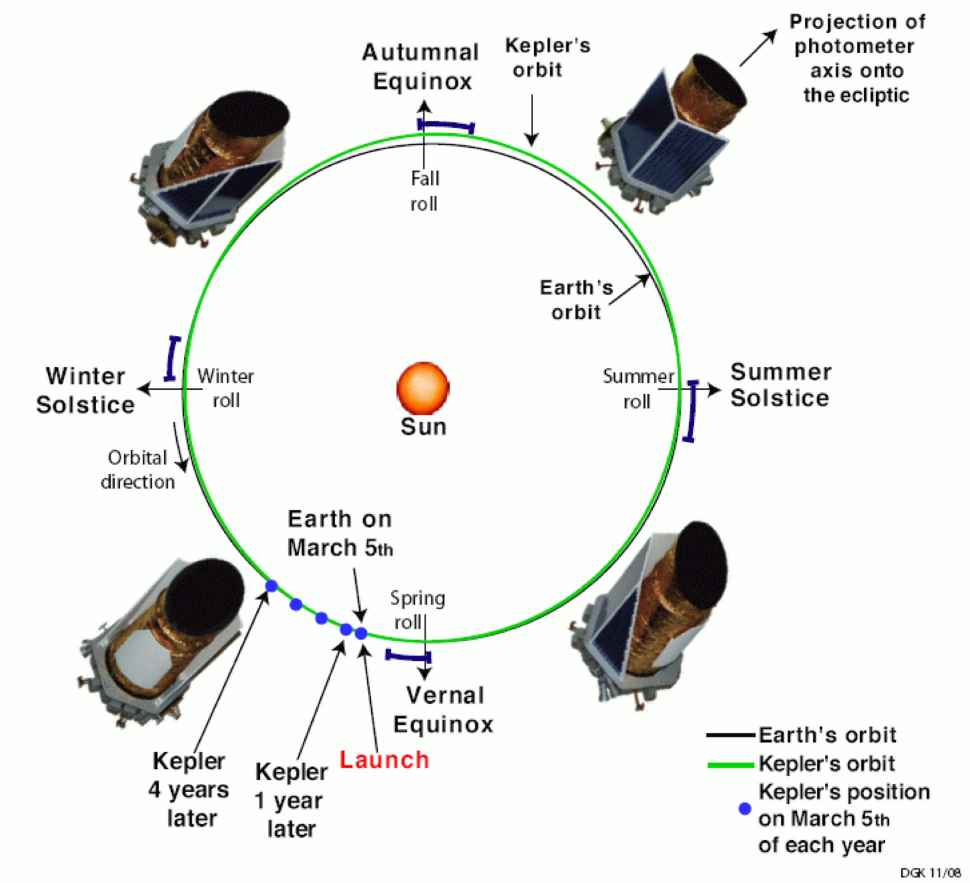
The NASA Kepler mission



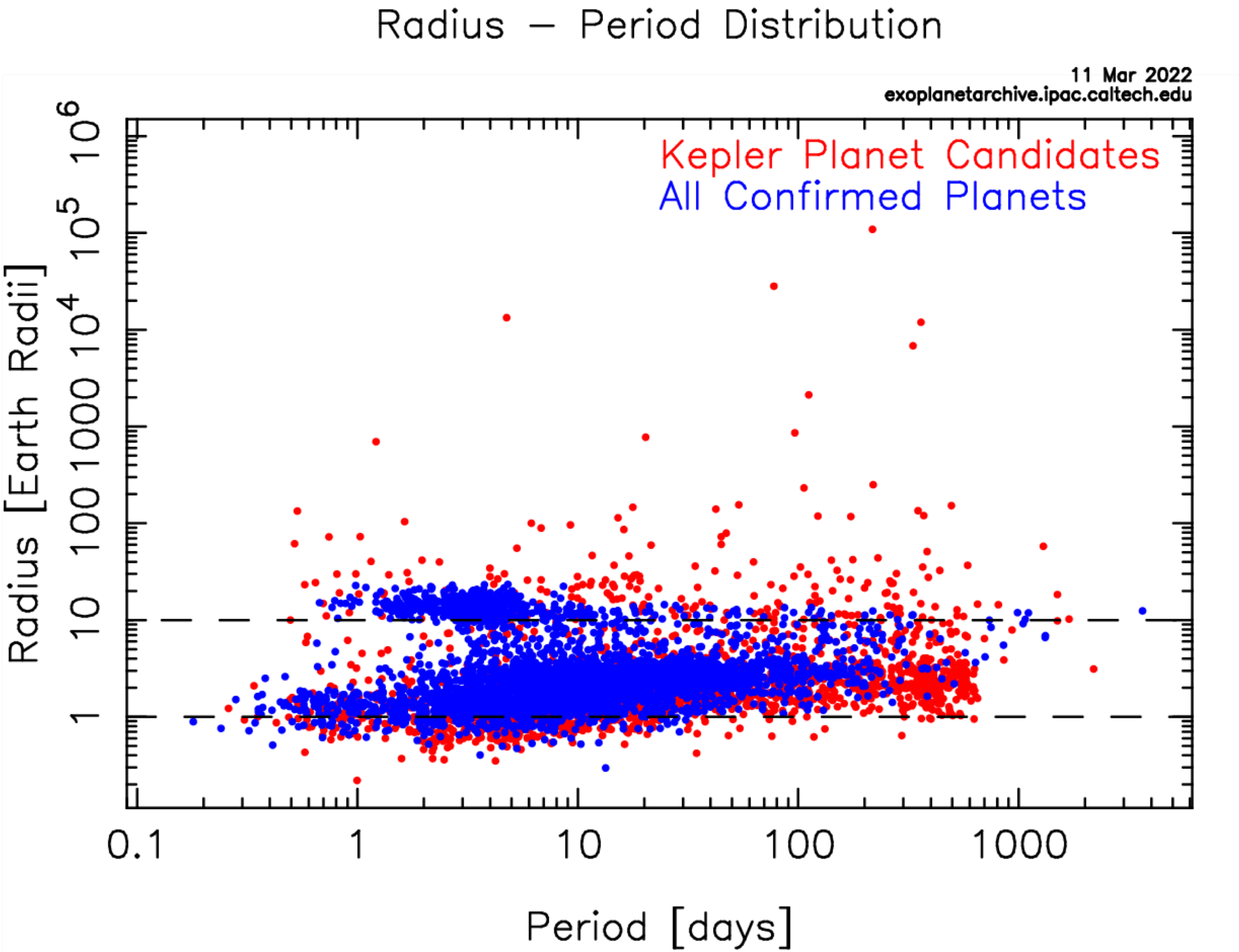
The NASA Kepler mission



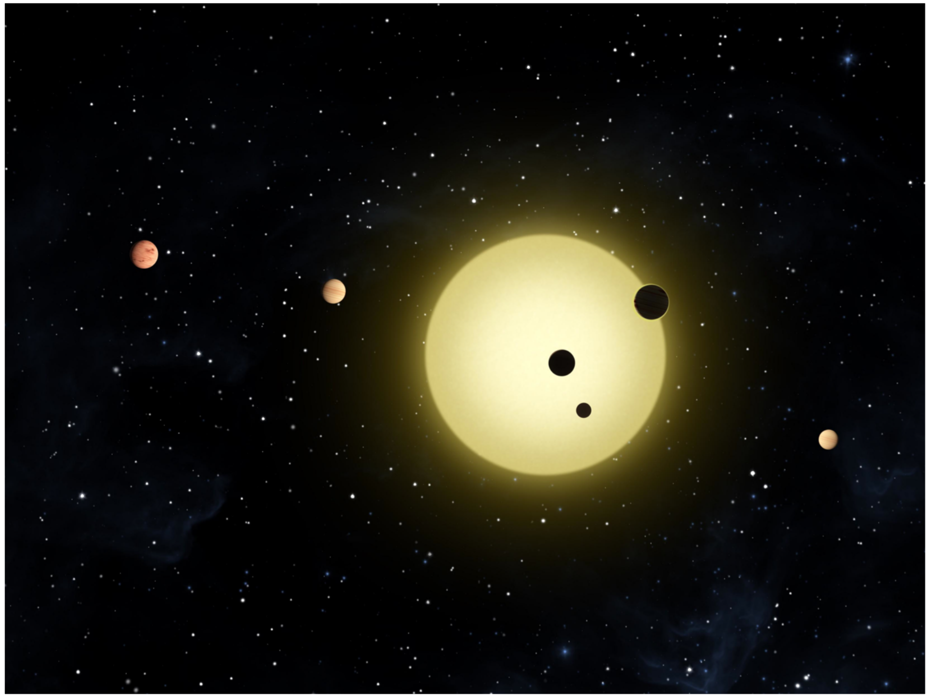
42 CCDs of 2200x1024 pixels
Observation of 0.28% of the sky
Heliocentric *Earth-trailing* orbit



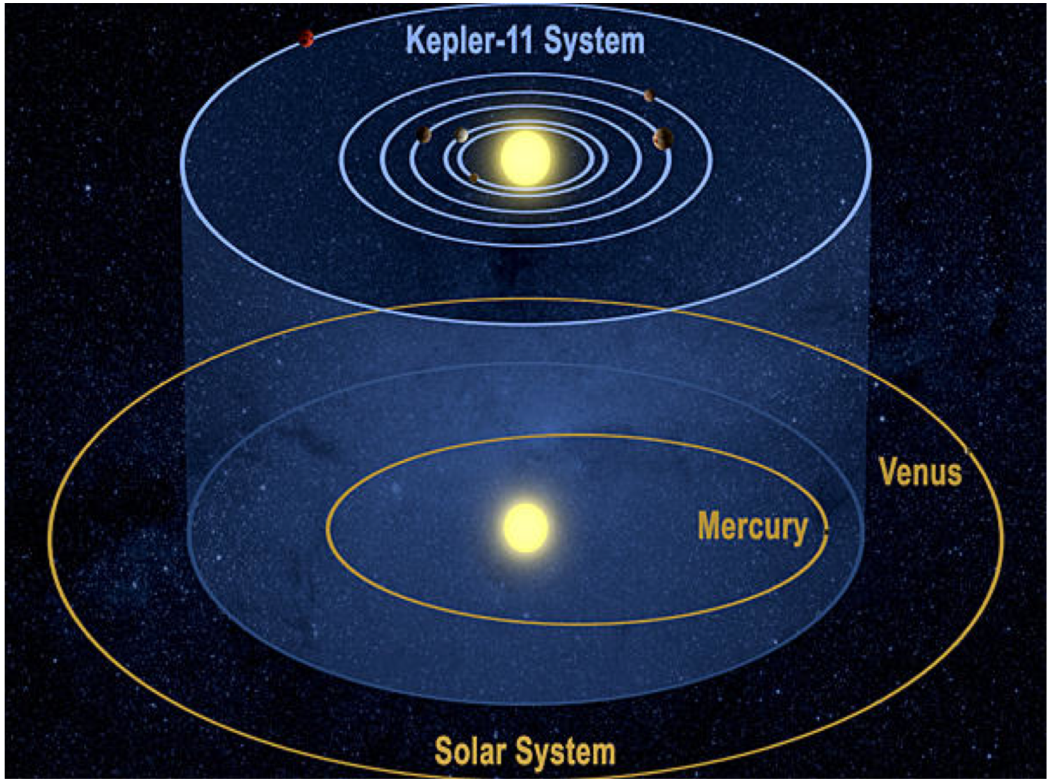
Kepler: more than 4000 candidates

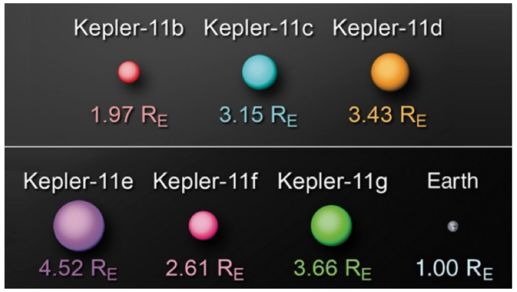


Kepler: multiple transiting systems



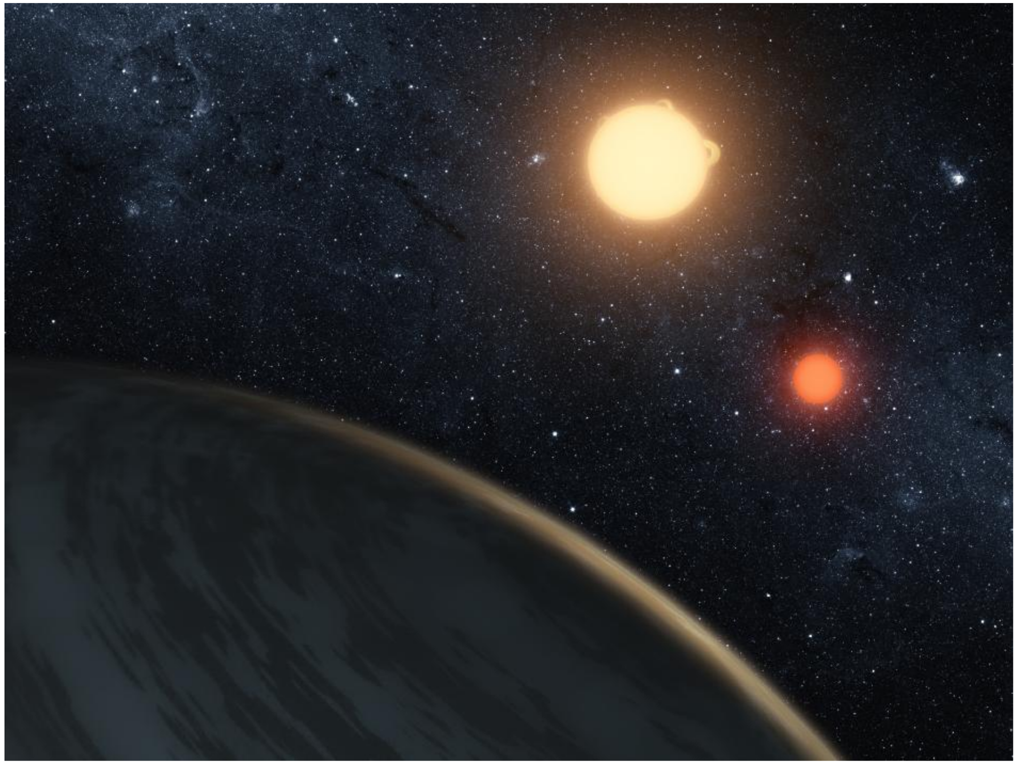
Lissauer et al. (2011)



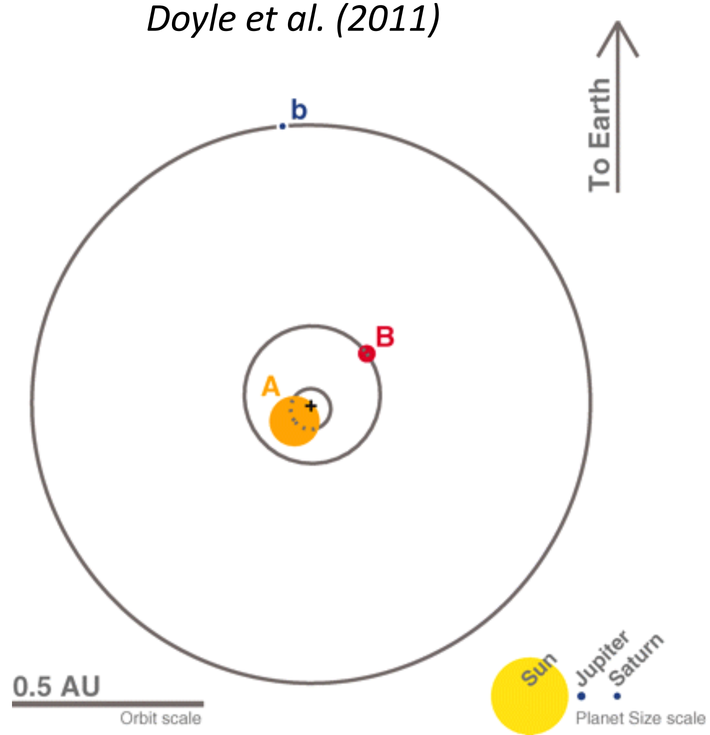


Example : Kepler-11, solar-type star 2000 light-years away
6 transiting planets, from 2 to 4.5 R_{Earth} and from 10 to 120 days period
Mass measurements from their gravitational interactions (TTVs).

Kepler-16b: first circumbinary planet



Doyle et al. (2011)



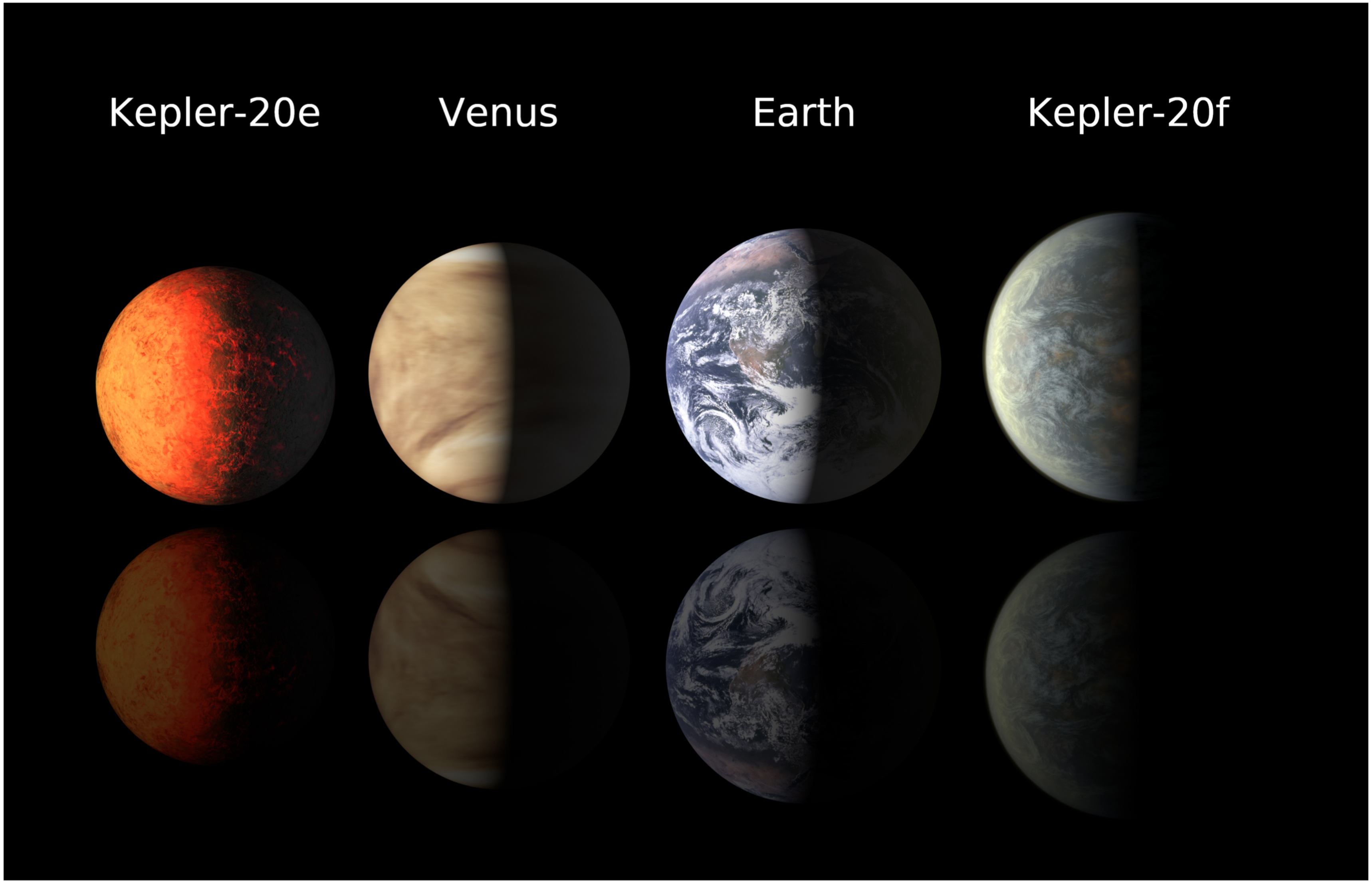
Binary period = 41 days

Planet's period = 230 days

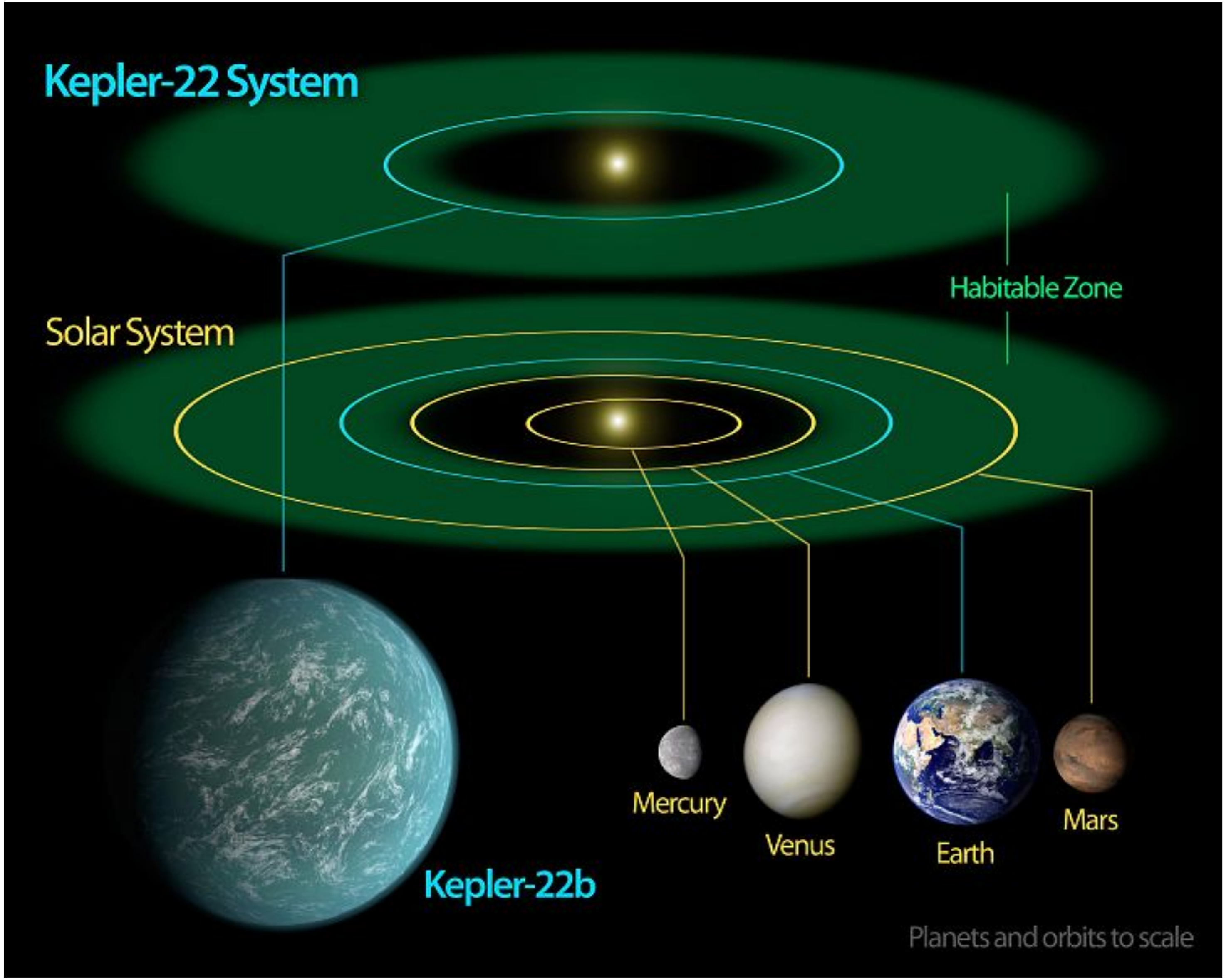
1.1 M_{Saturn}, 0.9 R_{Saturn}

Kepler: Earths

Fressin et al. (2012)



Kepler-22b: first transiting super-Earth in the habitable zone of its host star



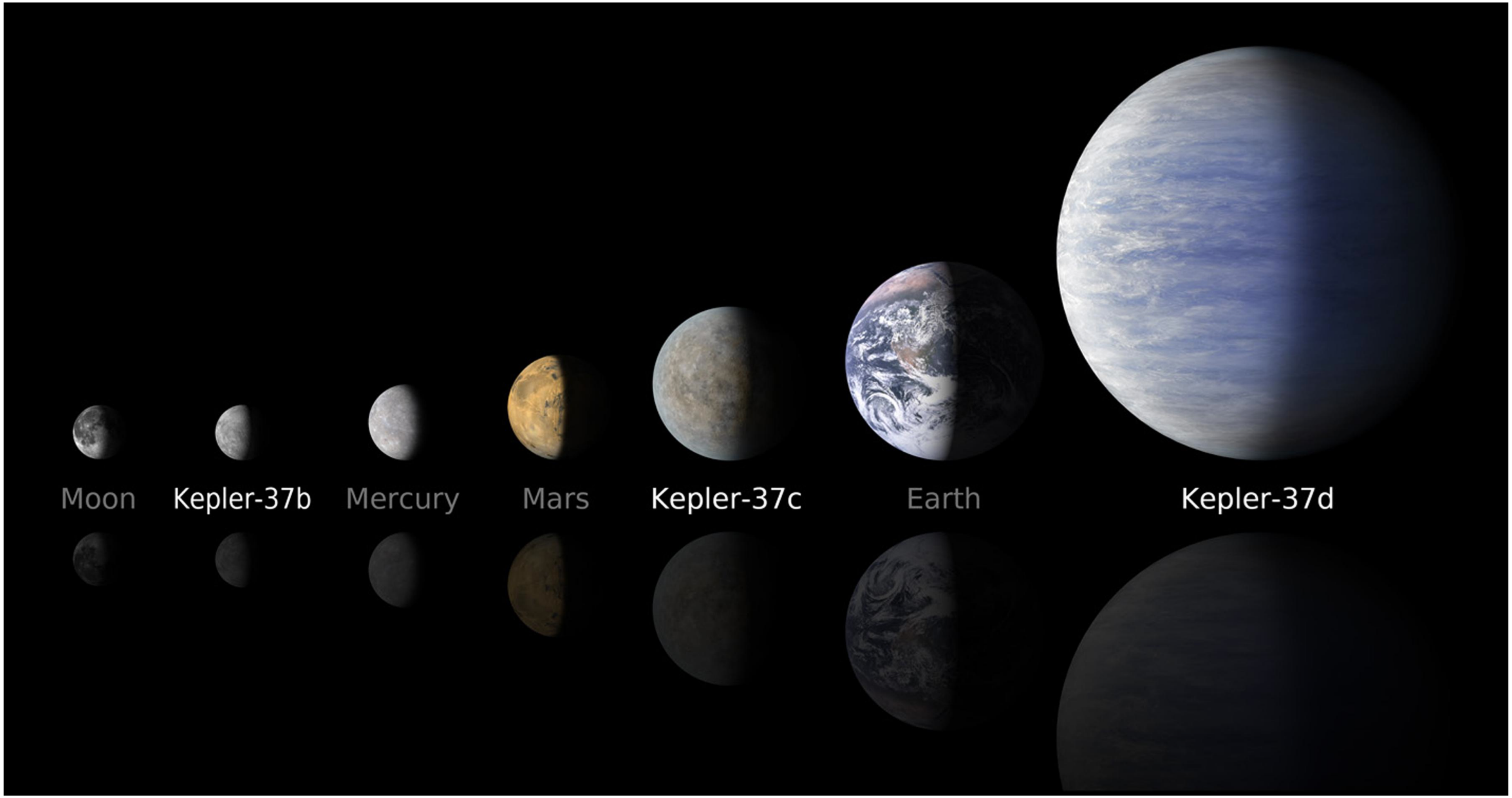
Borucki et al. (2012)

$<125\ M_{Earth}$

$2.4\ R_{Earth}$

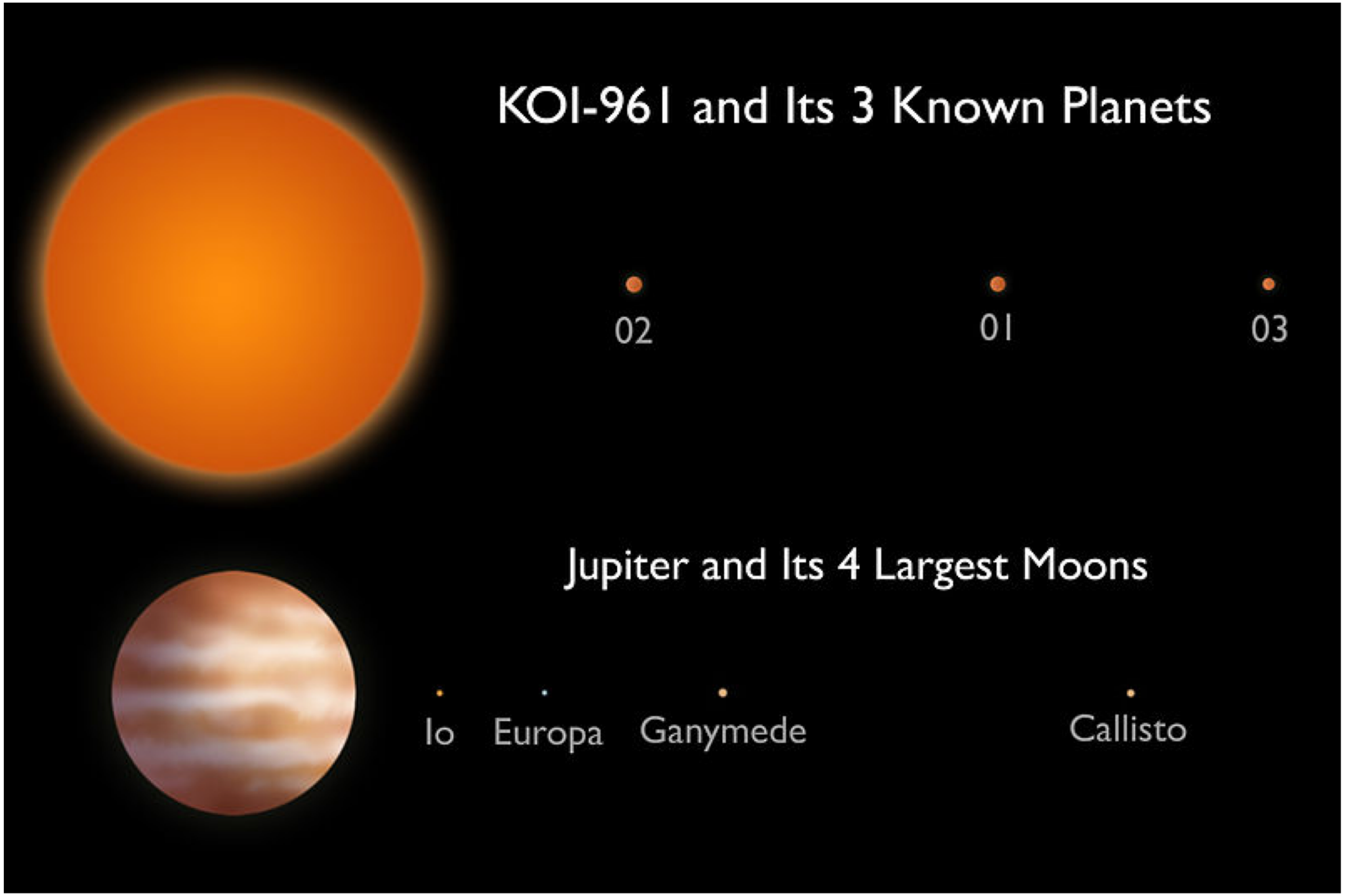
Kepler: Mercuries!

Barclay et al. (2013)



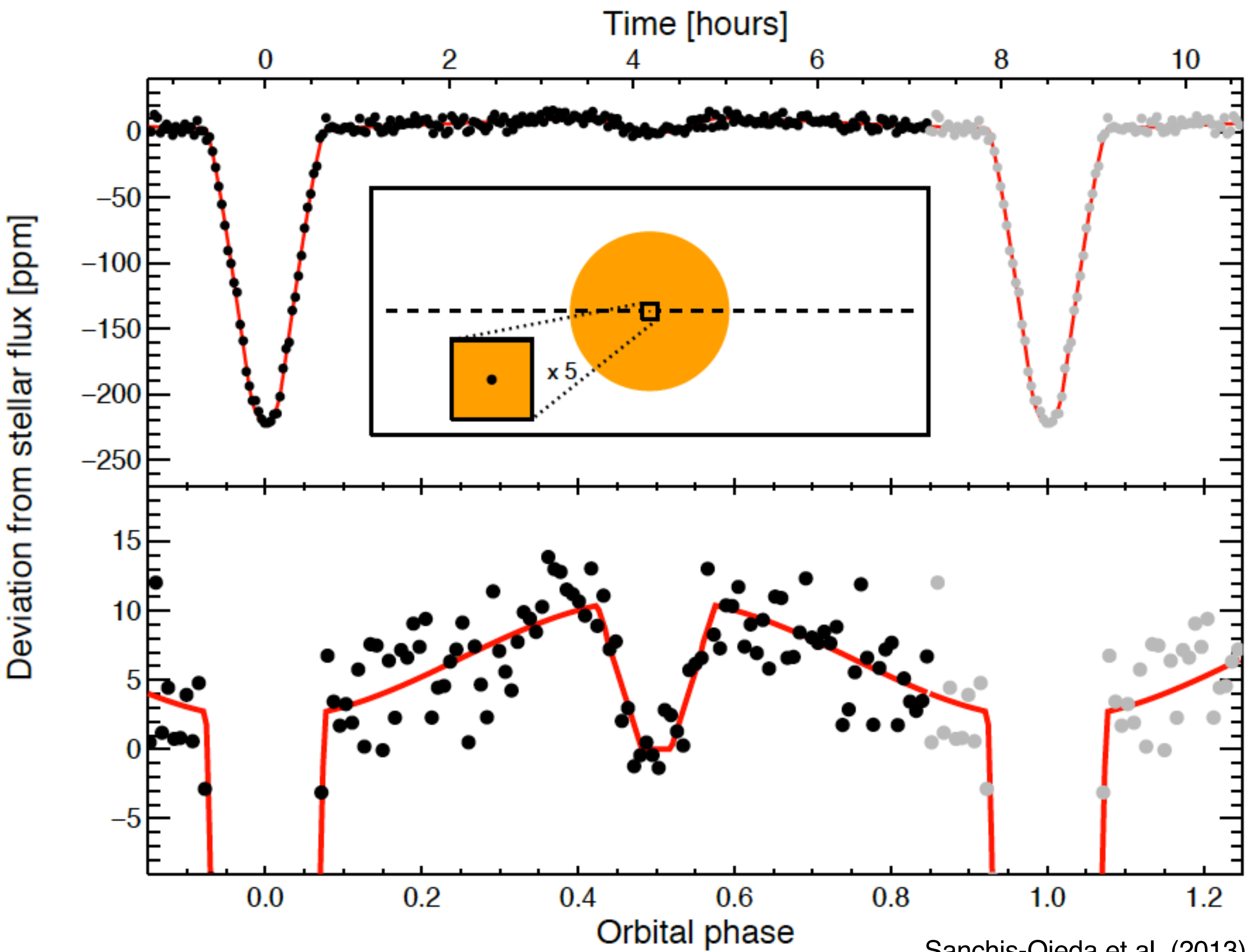
The intriguing Kepler-42 multiple system

Muirhead et al. (2012)



Star of <0.2 R_{sun} 125 light-years away

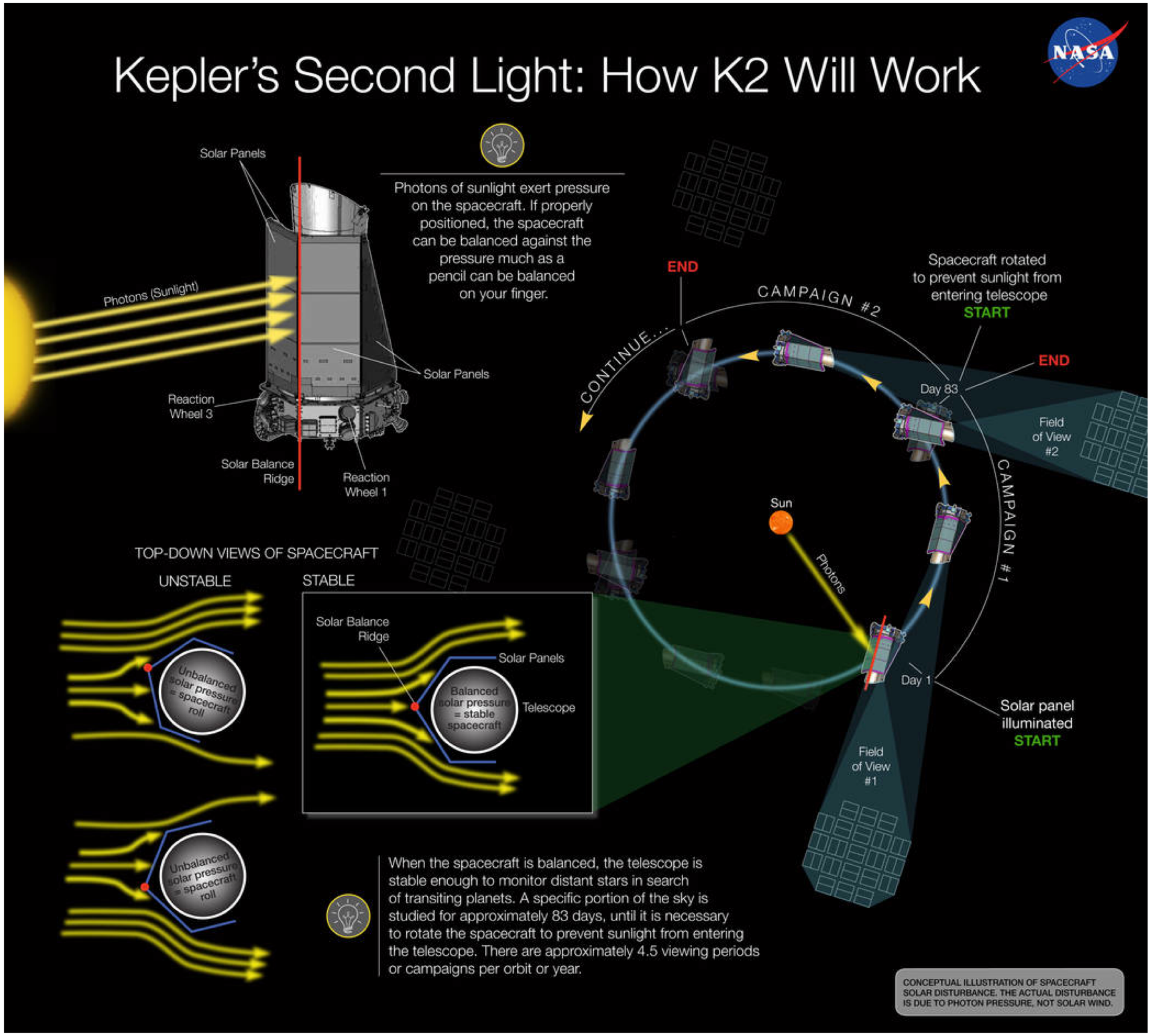
Kepler: ultra-high precision photometry



Sanchis-Ojeda et al. (2013)

Kepler reloaded: the K2 mission

In May 2013, *Kepler* lost the second of four gyroscope-like reaction wheels…



Kepler: summary of results (03/2021)

- 2820 confirmed planets (by RV or TTV ou dynamical+statistics)
- Smaller planet= Kepler-37b, 0.3 R_{Earth} *(Barclay et al. 2013)*
- 10 circumbinary planets
- 5 potentially habitable planets (http://phl.upr.edu/projects/habitable-exoplanets-catalog)
- Thorough characterization of several ‘hot Jupiters’
- 3255 candidates still to be confirmed. Statistical analysis suggests that 90% = planets *(Fressin et al. 2013)*

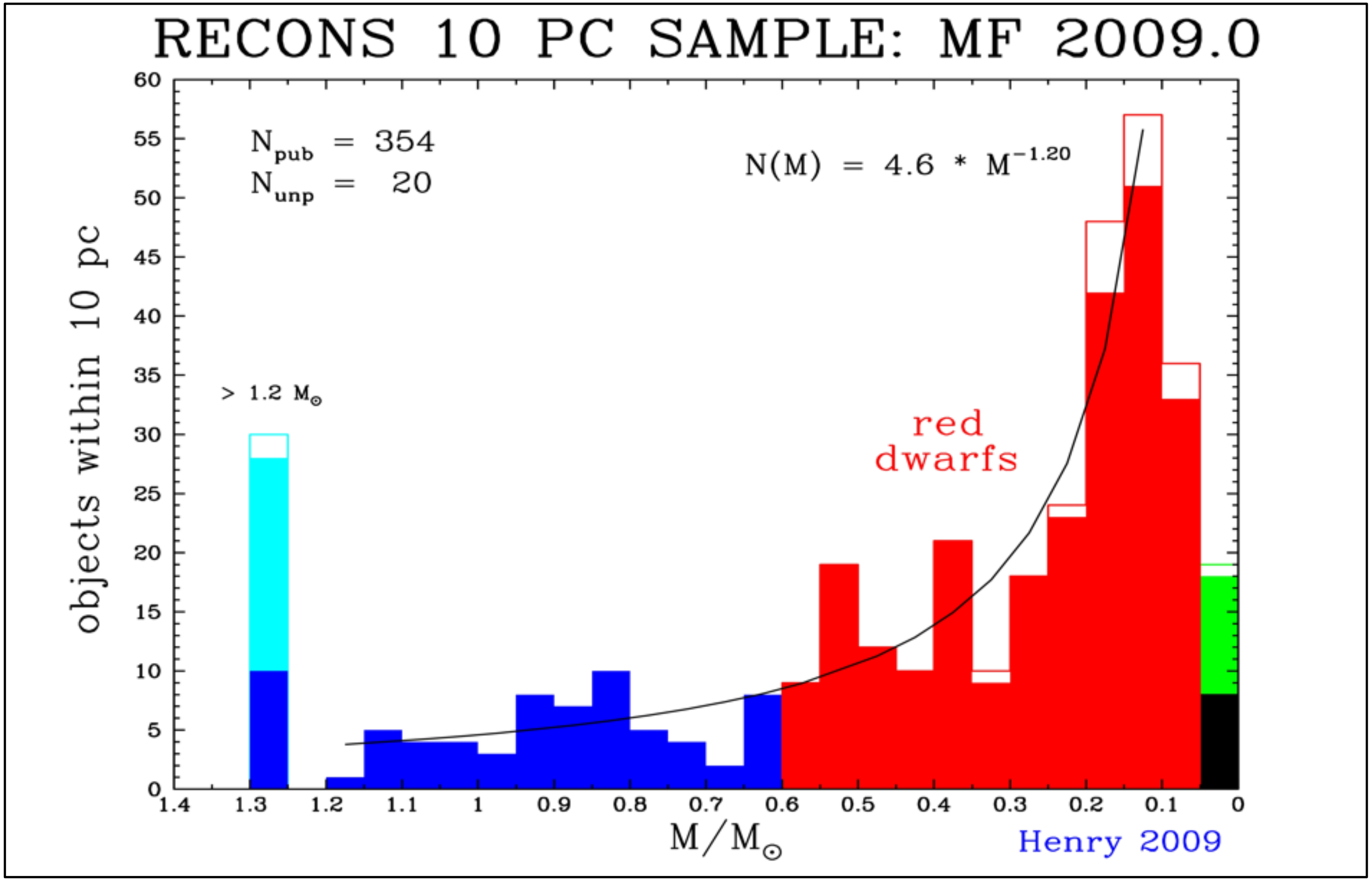
~50% of solar-type stars have a planet with P<88 days (Mercury)

« Earths » (<1.25 R_{earth}):	17%
« Super-Earths » (between 1.25 and 2 R_{earth}):	20%
« Mini-Neptunes » (between 2 and 4 R_{earth}):	20%
« Big Neptunes » and larger (>4 R_{earths}):	4%

Kepler: summary of results (03/2018)

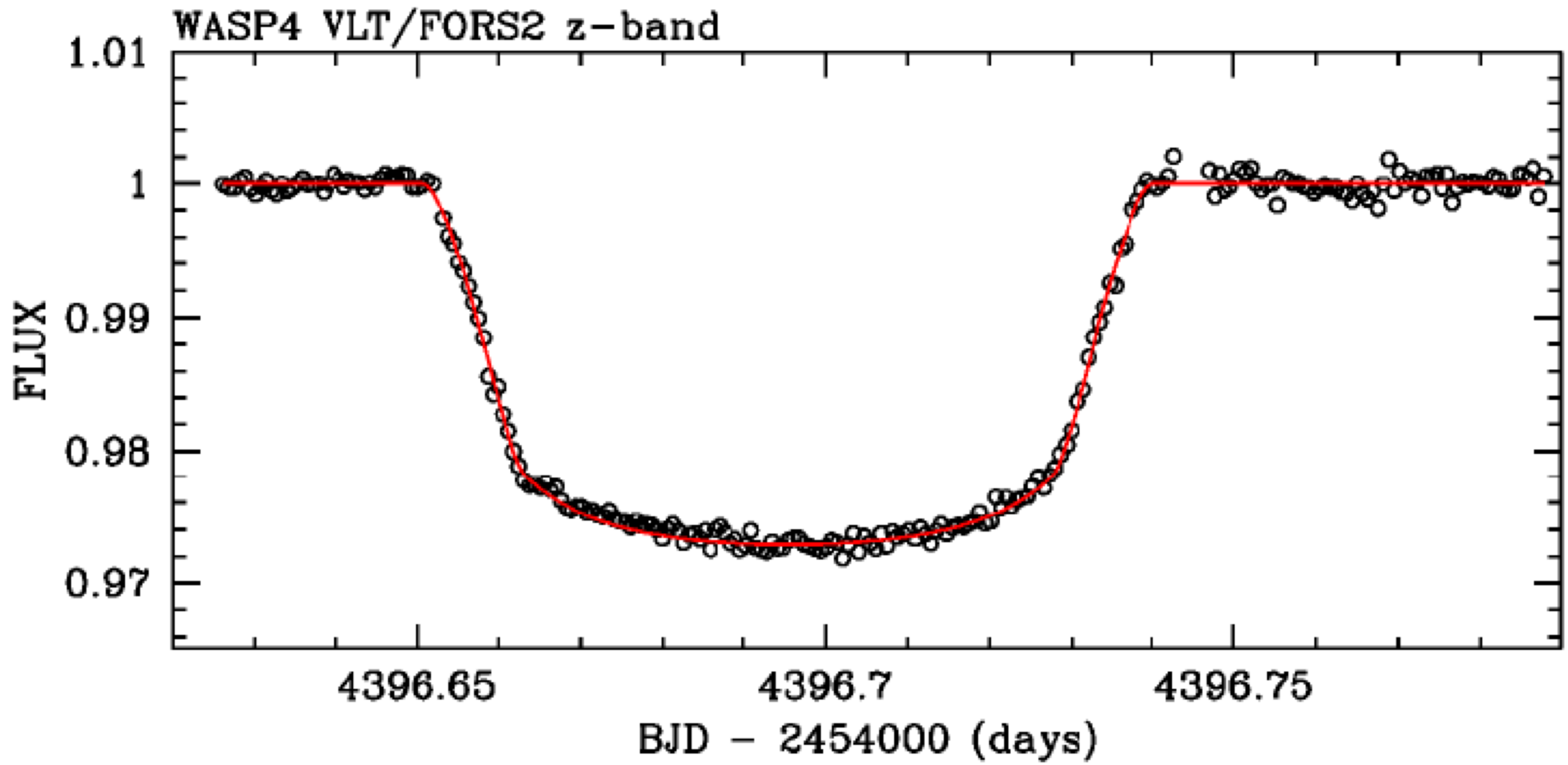
- **Red dwarfs (Teff < 4000K)**: 0.9 planet / star with P<50 days et R < 4 R_{Earth}.

0.15 Earth-sized planet in the habitable zone per star (*Dressing et al. 2013*)



>20 billions of potentially habitable planets in the Galaxy

Modeling of transit light curve



Modeling of a transit light curve

1. **A set of initial values is assumed for (e.g.)**

   P = orbital period (fixed if only one transit)

   e = eccentricity

   ω = argument of periastron

   T_{tr} = time of inferior conjunction (mid-transit)

   b = a cosi/R_* = impact parameter (if circular orbit)

   W = transit duration T_{IV}-T_I

   k = R_p/R_* = square root of transit depth

Modeling of a transit light curve

2. **The scale parameter a/R$_*$ is computed** via

$$W = \frac{P}{\pi} \boxed{\sin^{-1}\left[\frac{R_\star}{a}\frac{\sqrt{(1+k)^2 - b^2}}{\sin i}\right]} \frac{\sqrt{1-e^2}}{1+e\sin\omega}$$

$$\underbrace{\boxed{\frac{W\pi}{P}\frac{1+e\sin\omega}{\sqrt{1-e^2}}}}_{X} = \sin^{-1}\left[\frac{R_*}{a}\frac{\sqrt{(1+k)^2-b^2}}{\sin i}\right]$$

$$\frac{\sqrt{(1+k)^2-b^2}}{\sin X} = \frac{a}{R_*}\sqrt{1-\cos^2 i}$$

$$\frac{(1+k)^2-b^2}{\sin^2 X} + b^2 = \left(\frac{a}{R_*}\right)^2$$

Modeling of a transit light curve

3. The **stellar density** is inferred from Kepler's third law (assuming $M_p << M_*$)

$$a^3 = \left(\frac{P^2 G M_*}{4\pi^2}\right) \quad \rightarrow \quad \frac{a^3}{R^3} = \left(\frac{P^2 G M_*}{4\pi^2}\right)\frac{1}{R_*^3} = \left(\frac{P^2 G}{3\pi}\right)\frac{\rho_*}{\rho_{sun}}$$

High-precision transit light curve
–> strong constraint on stellar properties

Modeling of a transit light curve

4. For each photometric measurement, the position of the planet relative to the star is computed, and from that the fraction of stellar disk occulted by the planetary disk (assuming spherical shapes for both bodies)

$f_{tr} = \pi/2 - \omega$ $E_{tr} = 2\tan^{-1}\left(\sqrt{\frac{1-e}{1+e}}\tan\left(\frac{f_{tr}}{2}\right)\right)$ $M_{tr} = E_{tr} - e \sin E_{tr}$

$$T_{periastron} = T_{tr} - M_{tr} * P$$

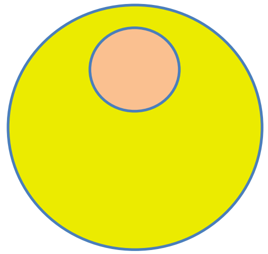
t ➔ M ➔ E ➔ f ➔ $\frac{r}{R_*} = \frac{a}{R_*}\frac{(1-e^2)}{1+e\cos f}$

➔ $\frac{r_{sky}}{R_*} = \frac{r}{R_*}\sqrt{1-\sin^2(\omega+f)\sin^2 i}$

Modeling of a transit light curve

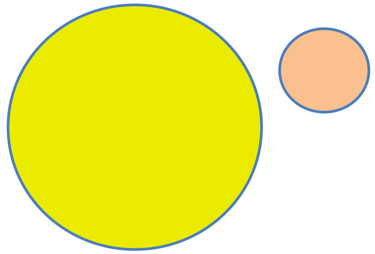
$$\frac{r_{sky}}{R_*} < 1 - \frac{R_p}{R_*}$$

Full superposition



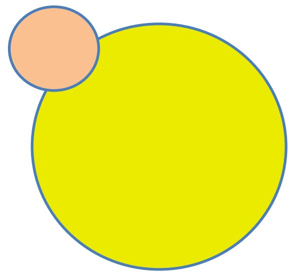
$$\frac{r_{sky}}{R_*} > 1 + \frac{R_p}{R_*}$$

Zero superposition



$$1 - \frac{R_p}{R_*} \leq \frac{r_{sky}}{R_*} \leq 1 + \frac{R_p}{R_*}$$

Partial superposition



Computation of the drop of brightness with an algorithm adapted to the selected limb-darkening law (e.g. Mandel et Agol 2002).

Physical parameters

Transit provide R_p/R_*, a/R_*, and ρ_*. How to obtain R_*, R_p and a?

Option 1: independent spectroscopic analysis provides T_{eff}, [Fe/H], and log g. Analysis based on stellar evolution models gives M_*, and R_* is computed from M_* + ρ_* from transits.

Option 2: after (or during) the analysis of the transits, ρ_* is added as input in the determination of M_* from stellar evolution models.

Option 3: same as option 1 and 2, except that the stellar evolution models are replaced by empirical laws M_*(Teff, [Fe/H], logg) or M_*(Teff, [Fe/H], ρ_*) calibrated on eclipsing binaries (Torres et al. 2009, Enoch et al. 2012).

Option 4: determination of R_* by interferometry or with luminosity + parallax + T_{eff} (nearby star) ➔ ρ_* from the transits is then used to determine M_*

Option 5: if ρ_* is poorly constrained by transits (low SNR, small planet), *a priori* values are assumed for M_* **and** R_*, or a measurement of ρ_* obtained by asteroseismology is used.

Global Bayesian analysis

Practically, it is always preferable to use all the available information and data to maximize the constraints and to identify the most consistent solutions … or to reveal a consistency problem.

Radial velocities

Light curves

Luminosity

Parallax

Atmospheric parameters ([Fe/H], log g, T_{eff})

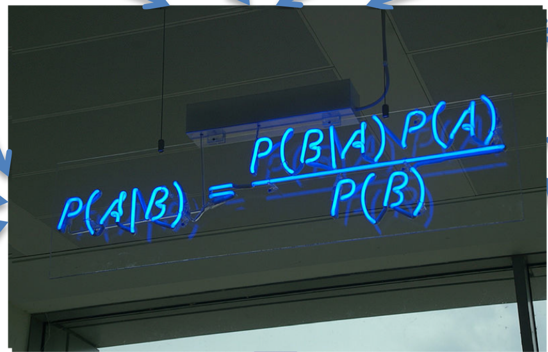
Interferometric measurement of R_*

Stellar evolution models

ρ_* and after from asteroseismology

Eclipsing binaries data

Limb-darkening models

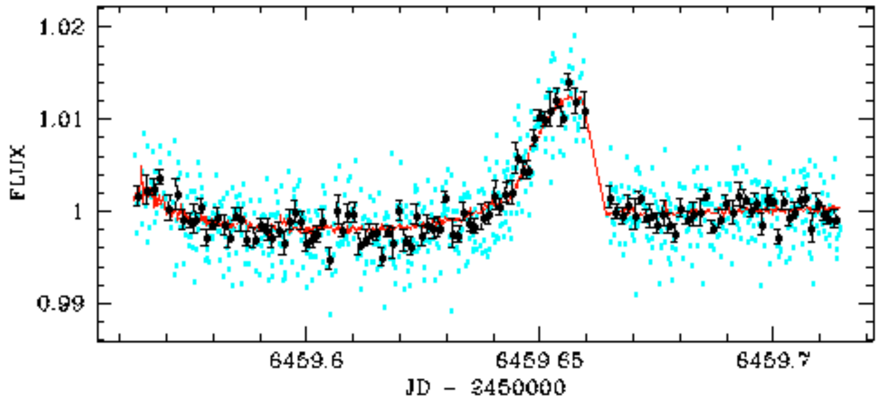


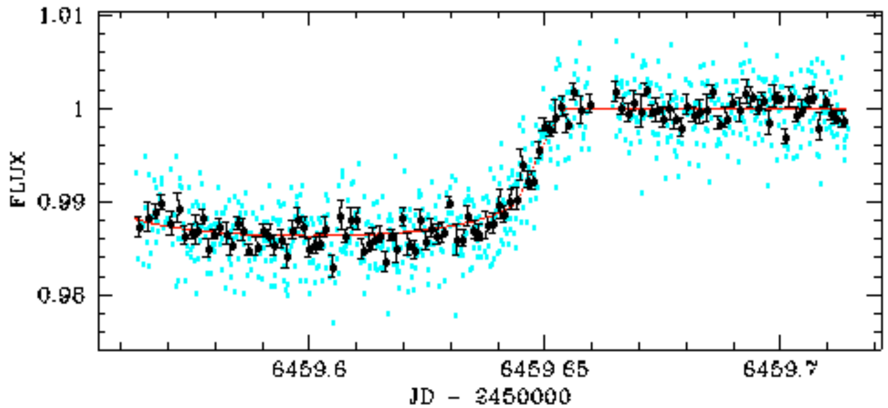
A posteriori probability distributions for M_*, R_*, M_p, R_p, *i*, *a*, *e*, etc…

Example: Markov Chains Monte Carlo (MCMC) method

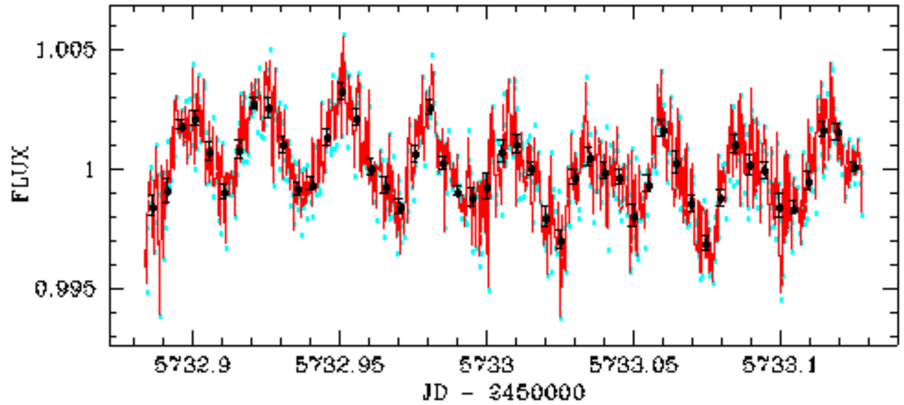
Other effects affecting the data

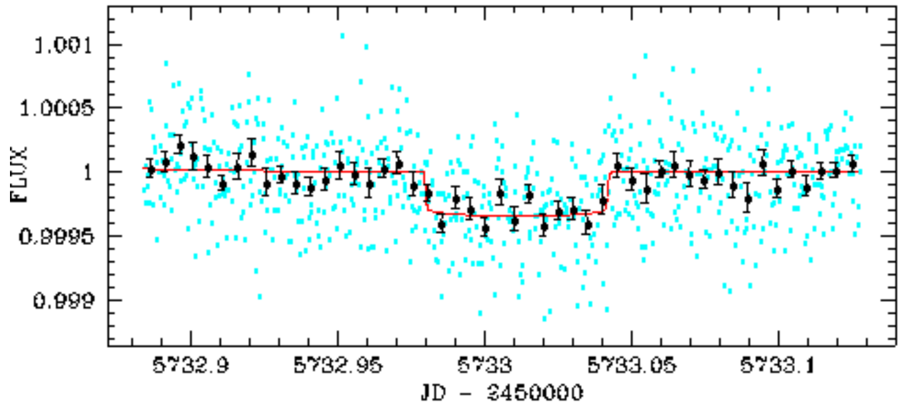
Ground-based photometry





Space-based photometry

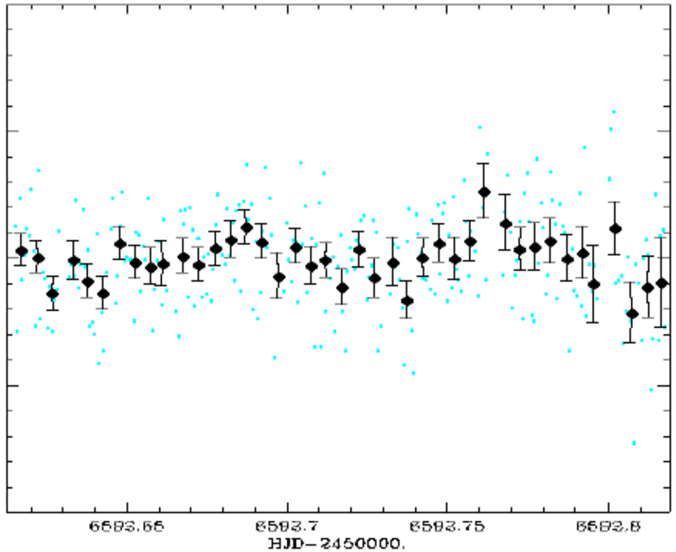


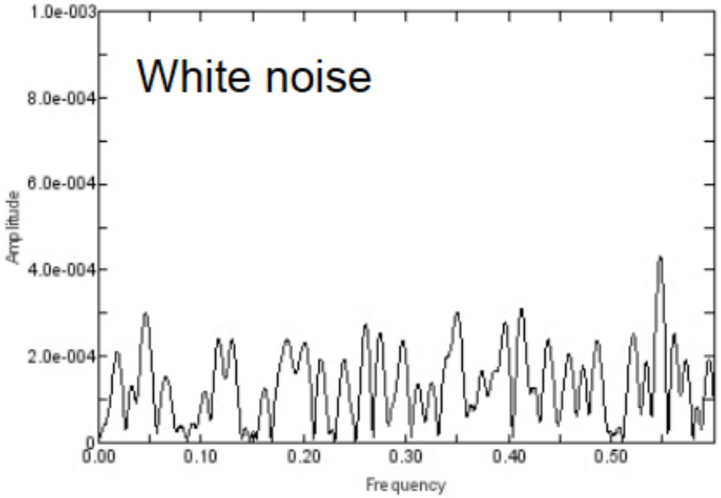


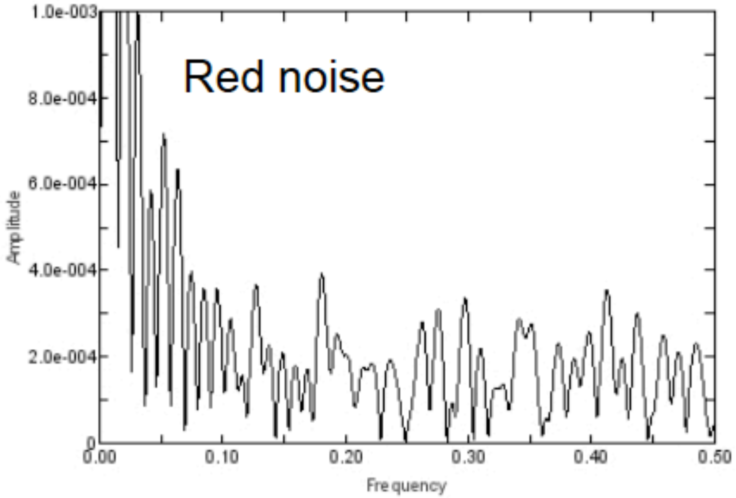
Correlation of the flux with airmass (differential extinction), position on the chip, PSF geometry, background, chip temperature and gain, stellar variability, etc ➔ **global modeling of systematic effects and eclipses**

Red noise

A part of the systematics can't be modeled.
It creates correlated noise (structures) in the light curves







Low-frequency (<< lower than the sampling frequency) noise = RED NOISE

Taking into account the red noise

<u>Several possible approachs.</u>

1. Aggressive filtering of the light curves before analysis until reaching a fully white noise

Ex: SYSREM (Tamuz et al. 2005)

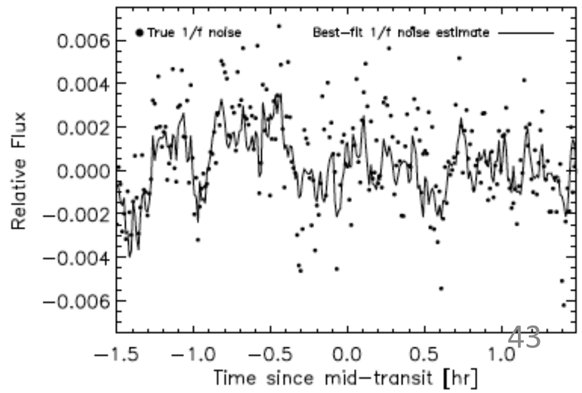
Problem: « cleaning » the light curves = modify the signal ☹

2. **« Prayer bead » method = residual permutation** (Jenkins et al. 2002)

3. **Rescaling of the photometric errors** (Winn et al. 2007)

   Binning of the data to several time bins
   Computation of the standard deviation of the residuals
   Comparaison with the deviation expected in case of white noise ($N^{-1/2}$)
   The largest ratio gives the corrective factor to apply to the errors

4. Modeling of the red noise: wavelets (Carter & Winn 2009)**, gaussian processes** (Danielski et al. 2013)**, etc.**

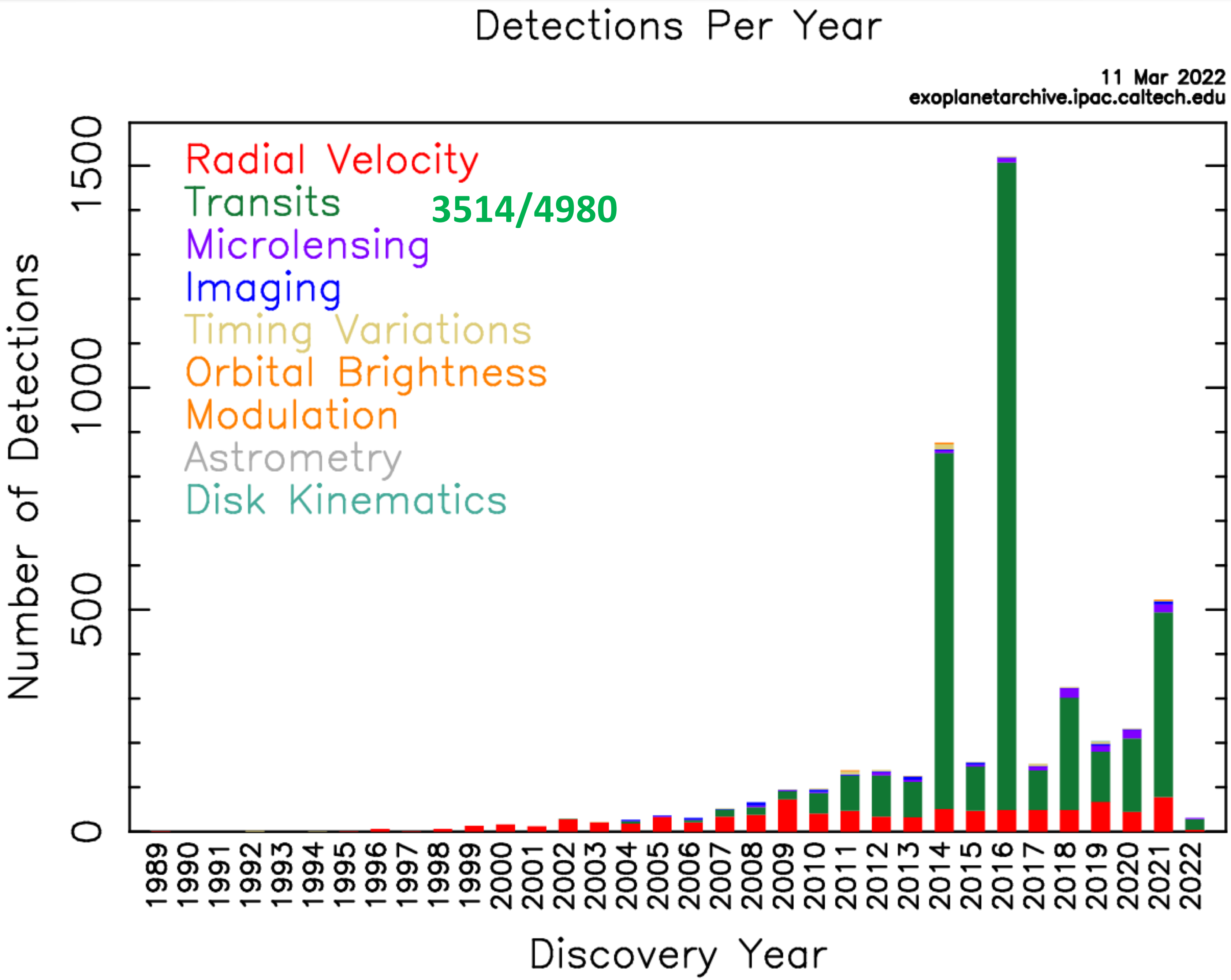


Open source transit analysis programs

- Transit Analysis Package – *Gazack et al. 2012*
- PyTransit – *Parviainem 2015*
- ExoFAST – *Eastman 2013, 2019*
- AstroImageJ – *Collins et al. 2017*
- Exoplanet – *Foreman-Mc Key 2021*
- Transit Light Curve Modeller – *Smith et al. 2017*
- Allesfitter – *Gunther & Daylan 2018*
- Juliet – *Espinoza et al 2018, 2019*
- Pyaneti – *Barragan et al. 2019*

etc…

Transits: a success story



The challenges of transit surveys

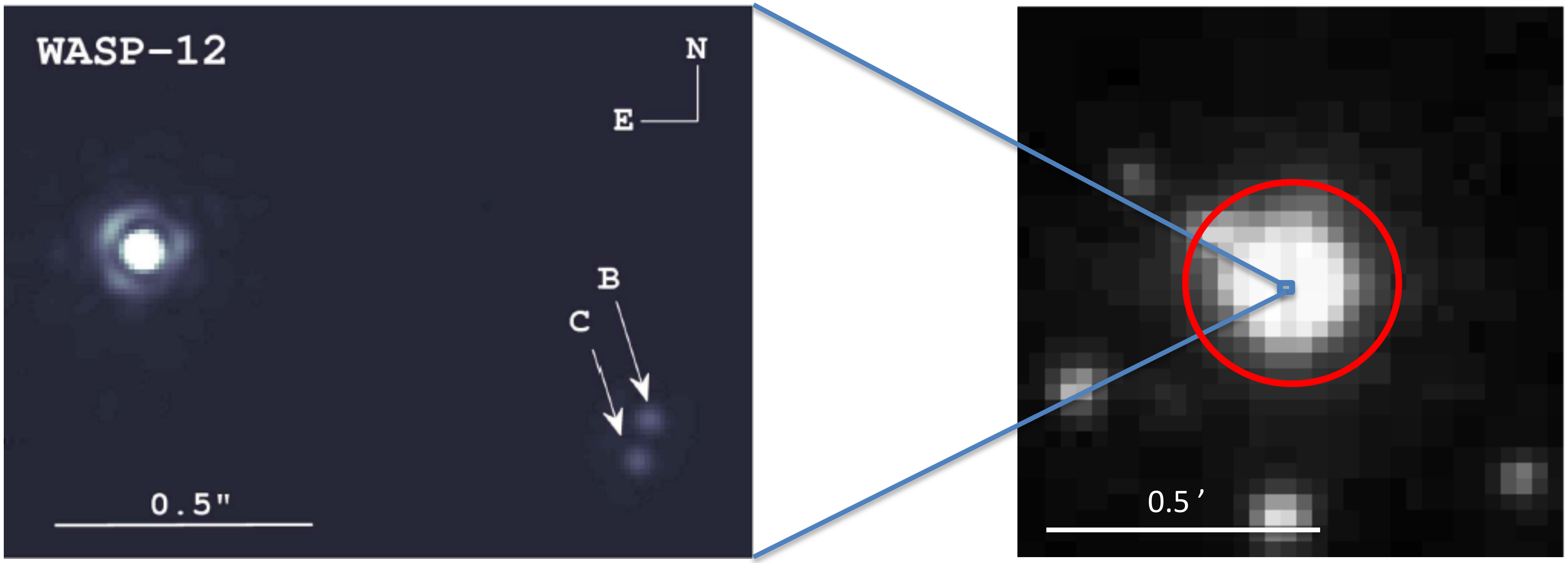
Basic strategy:

1. Light curves for hundreds of thousands of stars
2. Search for periodic box-shape signals consistent with transits
3. Follow-up of the selected candidates to confirm/reject the planetary hypothesis
4. Statistical analysis of ambiguous candidates (Kepler)

Main problem: transit-like signals can have other causes than planets!

The challenges of transit surveys

Next to a star, there are often other stars…

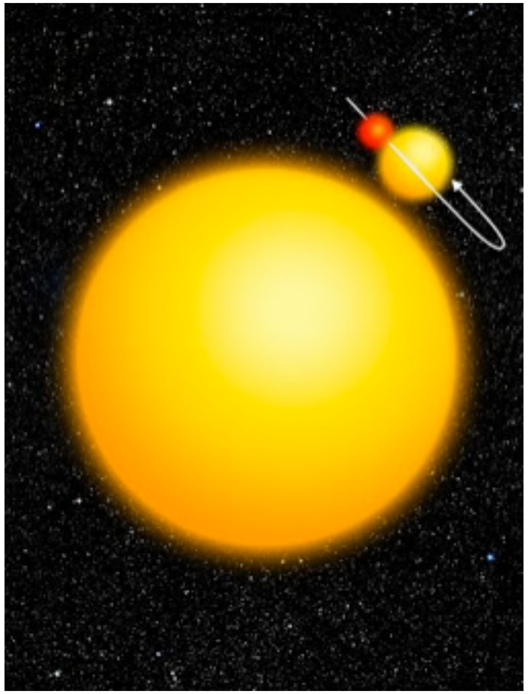


AO image

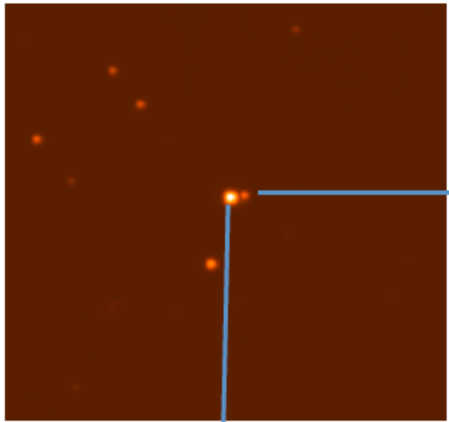
Bechter et al. (2013)

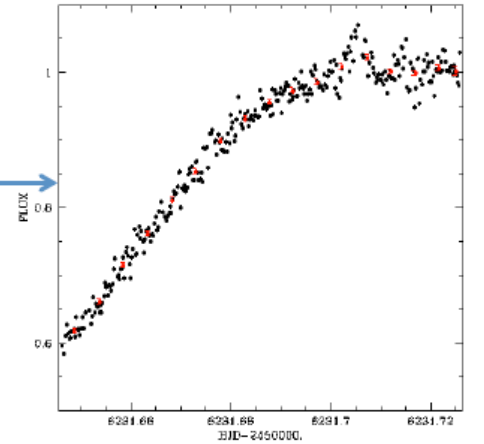
Measured fluxes = integration on several stars
High-resolution imaging is always important

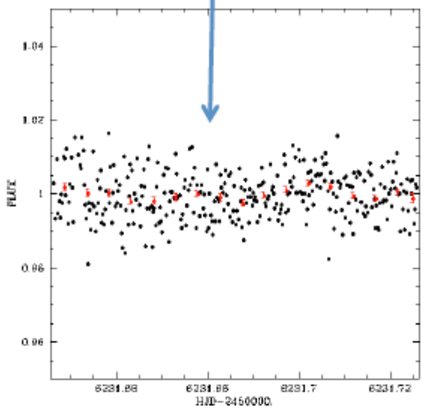
The challenges of transit surveys



Background eclipsing binary blended with the target





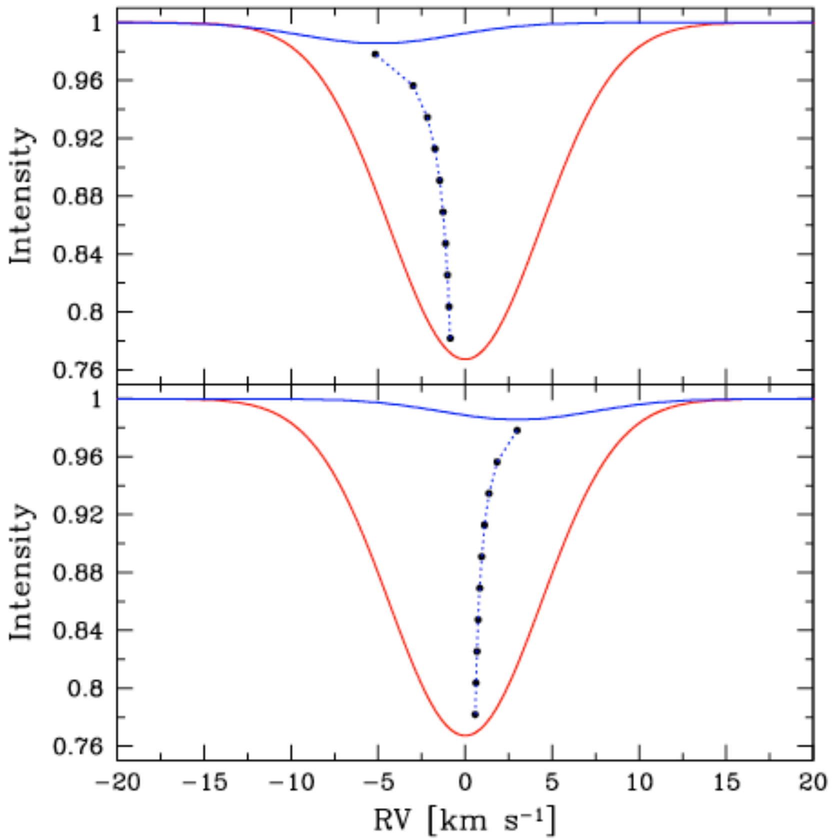


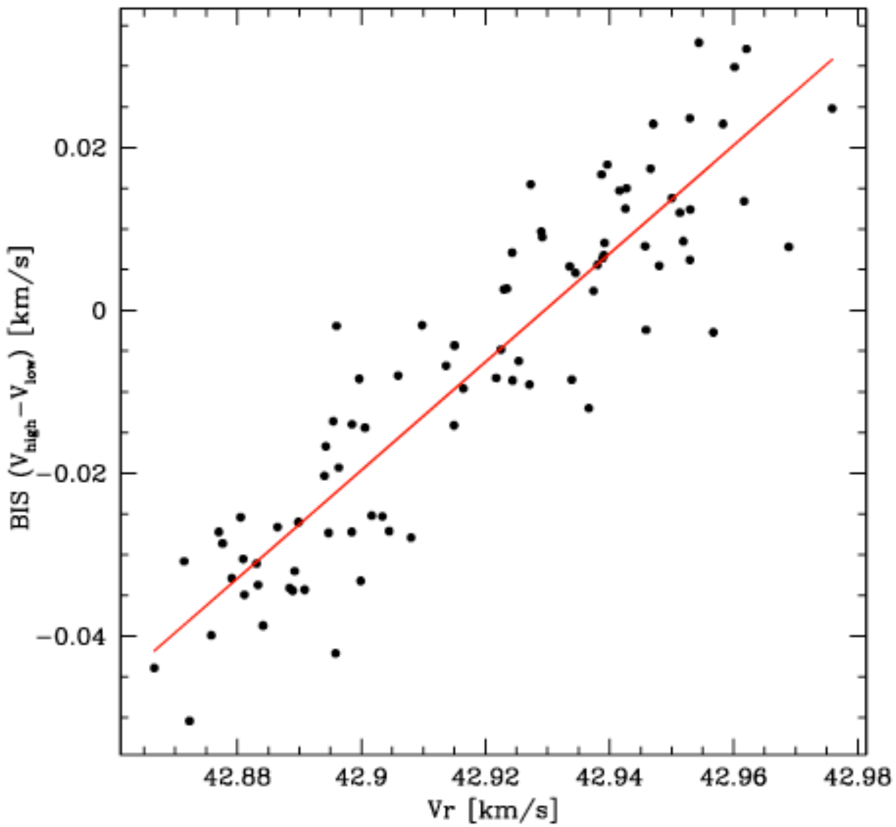
1SWASP J050510.88-111619.6

Discrimination: higher-resolution photometry

The challenges of transit surveys

What if nearly-perfect superposition (ex. triple system)?

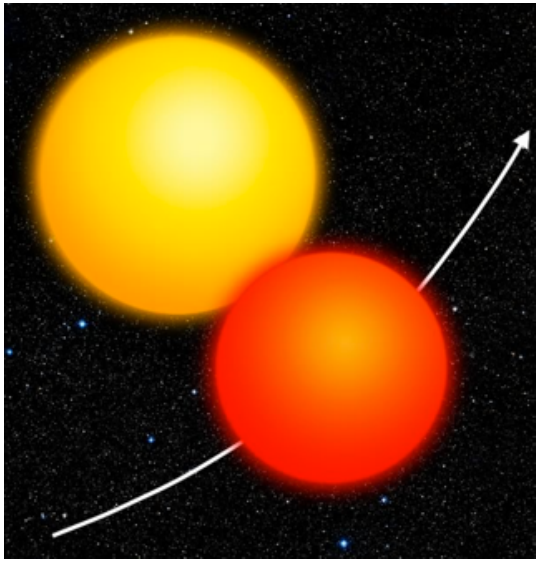




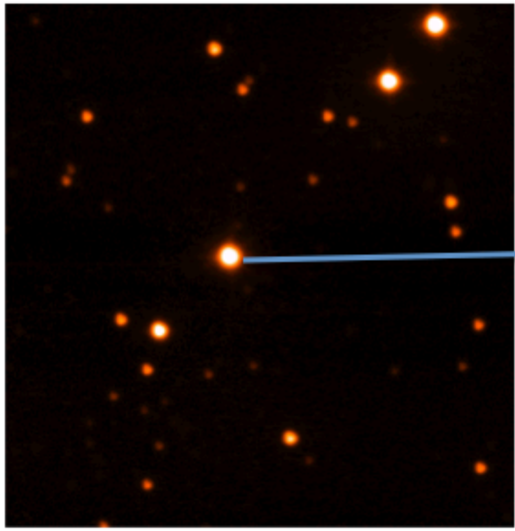
Santos et al. (2004)

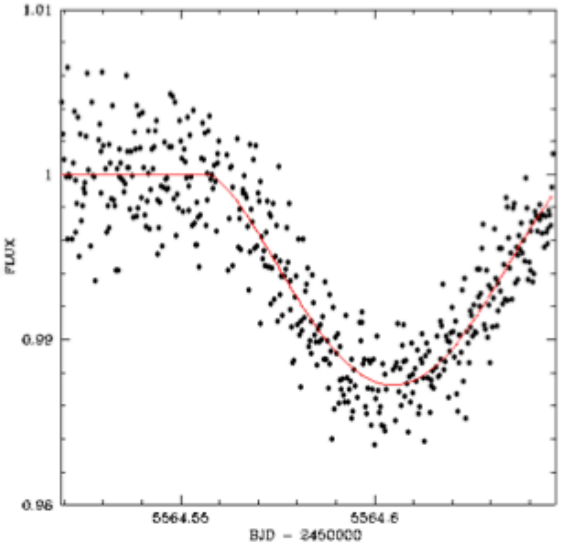
Discrimination: Doppler spectroscopy - bisector

The challenges of transit surveys



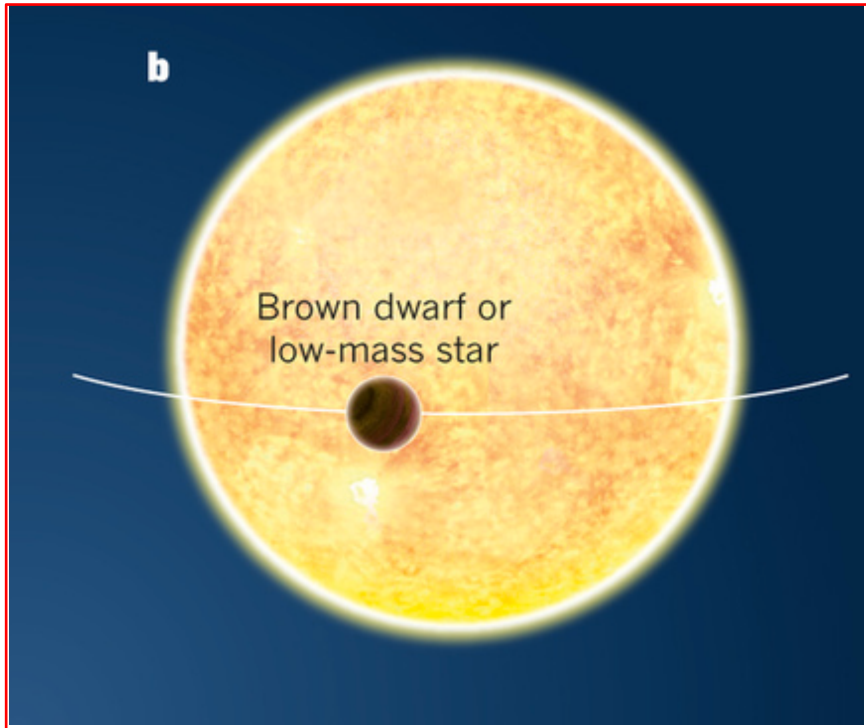
Grazing eclipsing binary



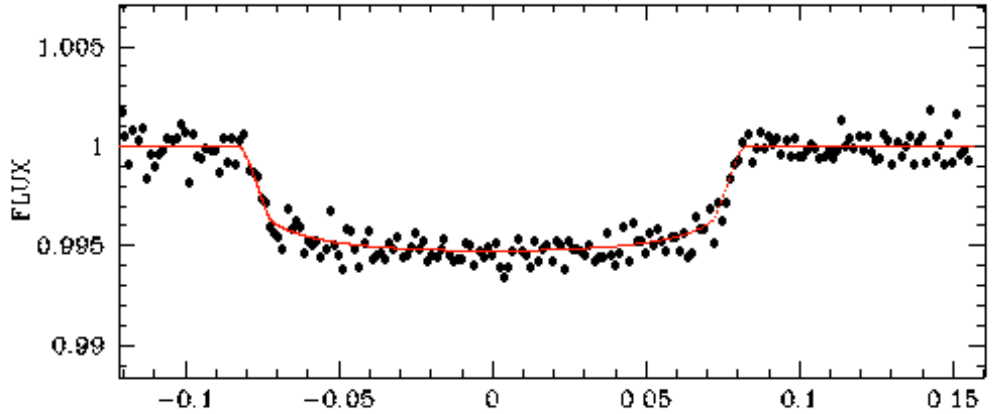


Discrimination: high-precision photometry and/or Doppler spectroscopy

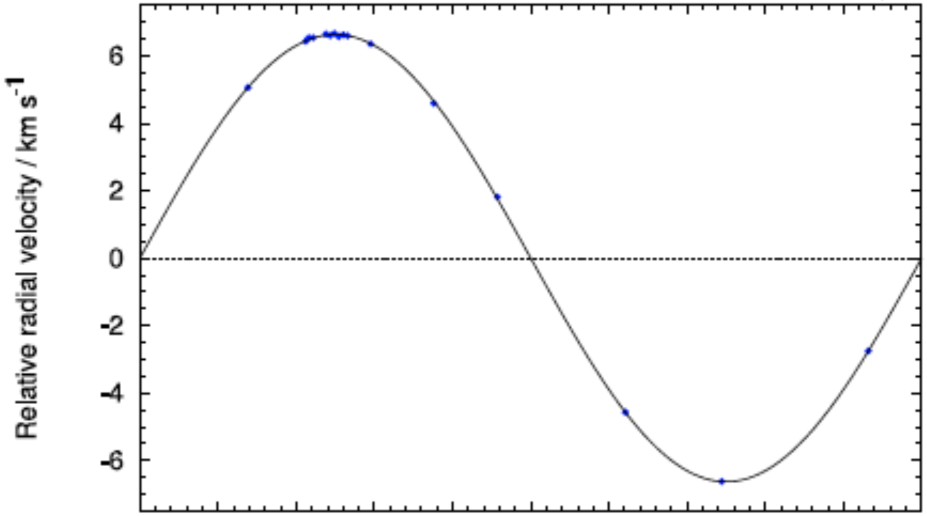
The challenges of transit surveys



Transit of a planetary size object: ultracool dwarf (very-low-mass star or brown dwarf)



Anderson et al. (2011)



e.g. WASP-30b : a brown dwarf of 61 M_{Jup}

Discrimination: Doppler spectroscopy + (occultation photometry)

The challenges of transit surveys

What if no RV detection?

1/ Hot and/or fast-rotating star

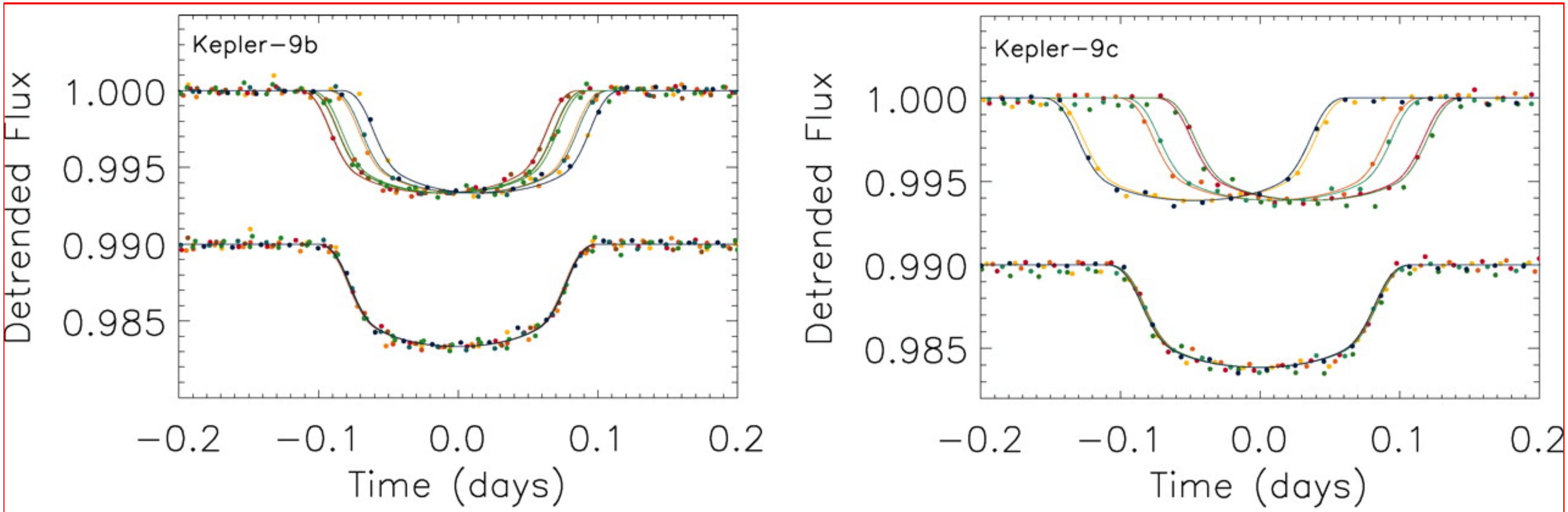
Upper limit on the planet's mass from RVs
e.g. WASP-33b: $M_p < 4.1\ M_{jup}$ on a 1.2d orbit around an A5-type star
(Collier-Cameron et al. 2010)

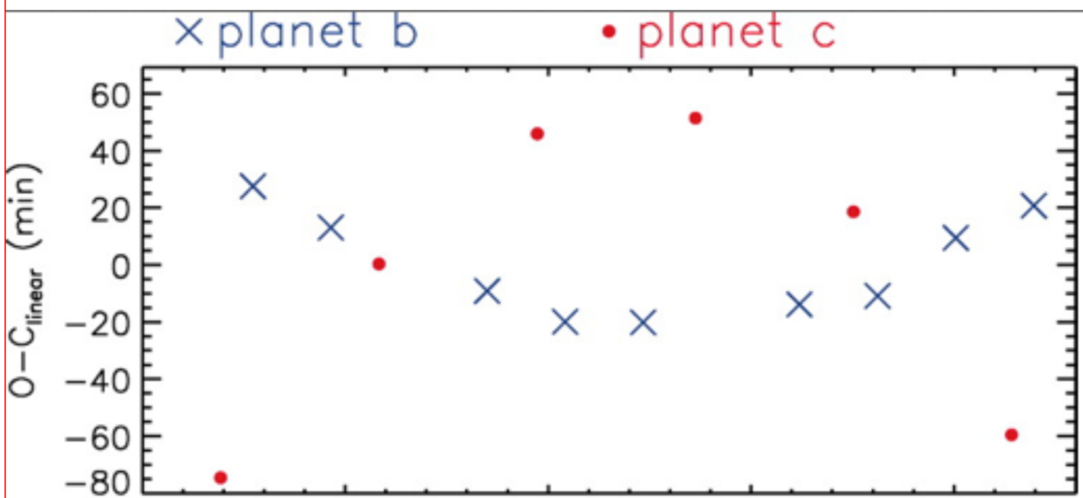
2/ Very-low-mass planets (e.g. Kepler, TRAPPIST-1)

Multiple transiting system: constraints on the masses from the transit timing variations (**TTVs**) due to planet-planet interactions *(Holman & Murray 2005; Agol et al. 2005)*

Modeling of the light curves with planet and eclipsing binary models, and statistical inferences from models comparison.
e.g. **Blender** *(Torres et al. 2010)*, **TRICERATOPS** *(Giacalone et al. 2020)*

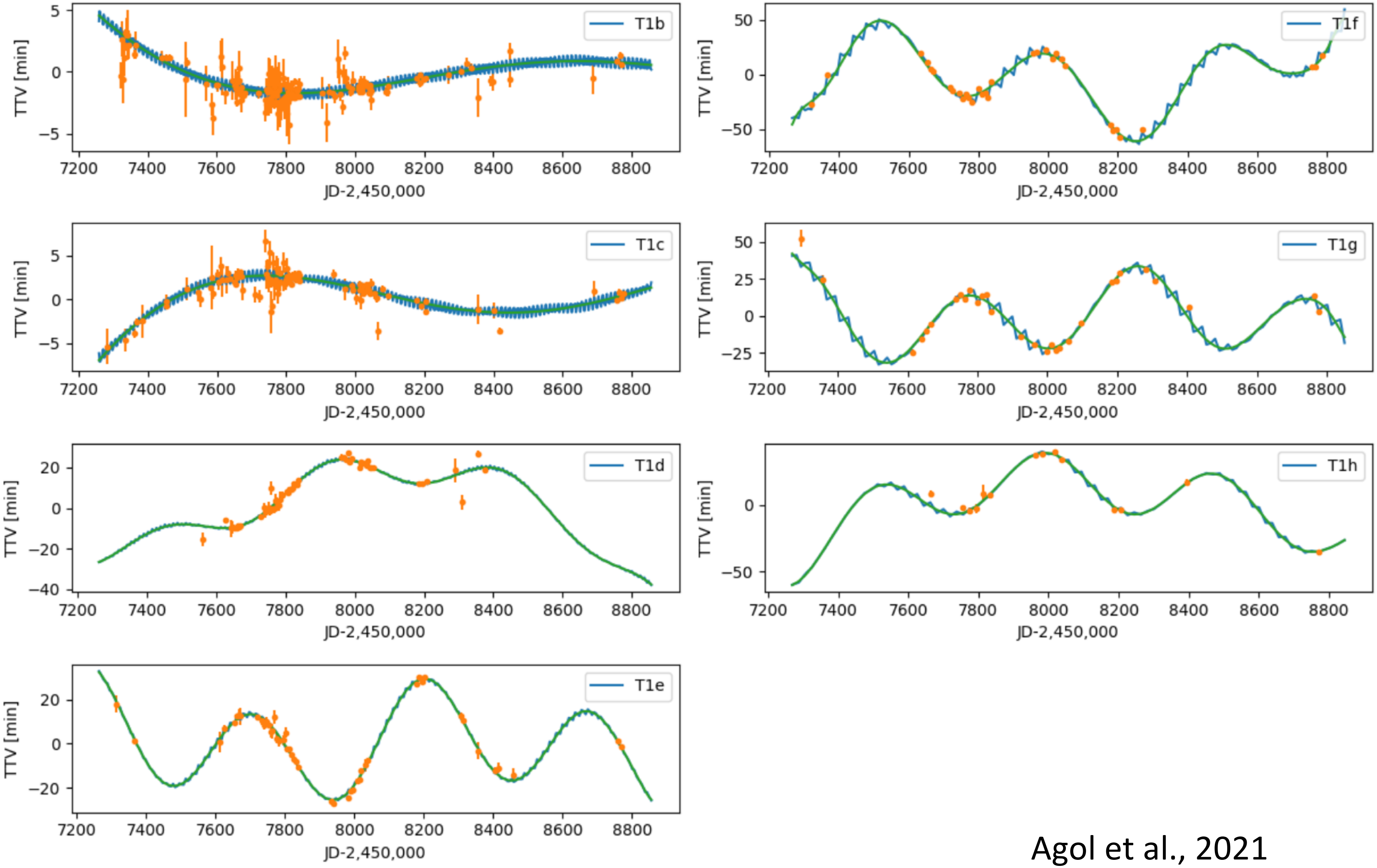
The TTV method





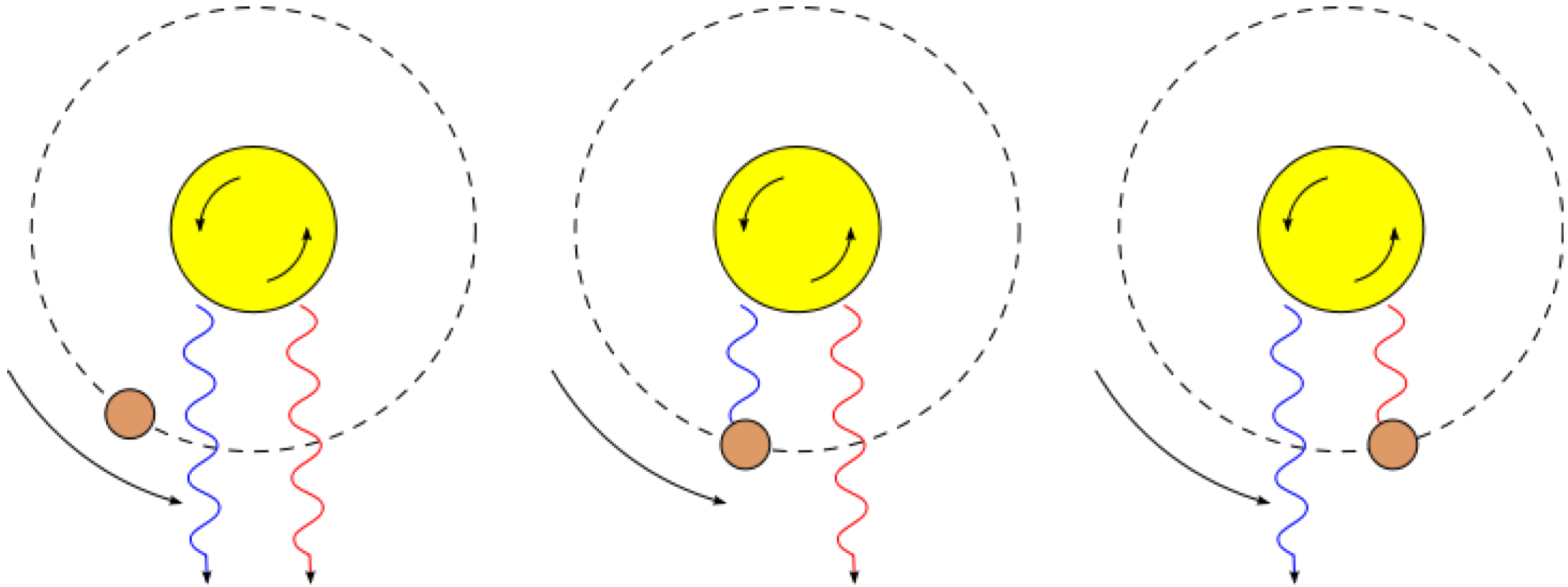
Masses for multiple transiting system.
Detection of new planets.
Possible detection of moons and Trojans.

The TTV method: TRAPPIST-1



Agol et al., 2021

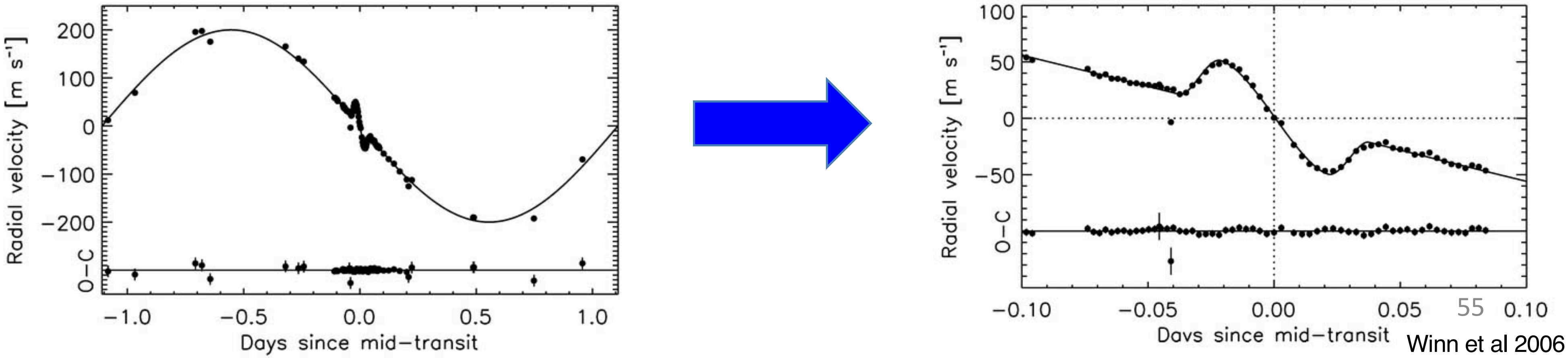
The Rossiter-Mc Laughlin effect



Rotating star + opaque transiting object

High-cadence RV monitoring shows an « anomaly » during the transit.

1st observation: 1911 (eclipsing binary) by Forbes & Schesinger



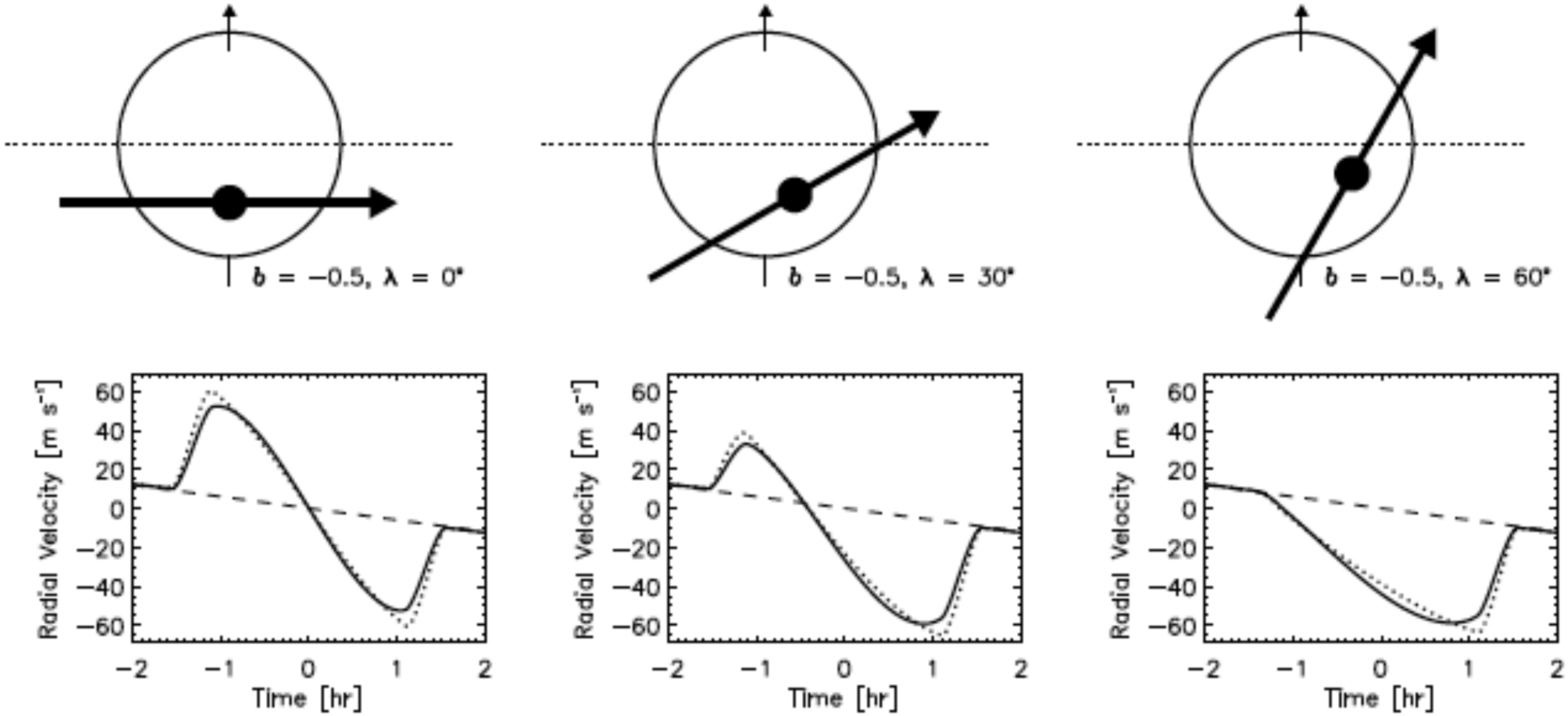
Winn et al 2006

The Rossiter-Mc Laughlin effect

Amplitude:

$$\Delta RV \approx \frac{R_p^2}{R_*^2}\sqrt{1-b^2}\,V_* \sin I_*$$

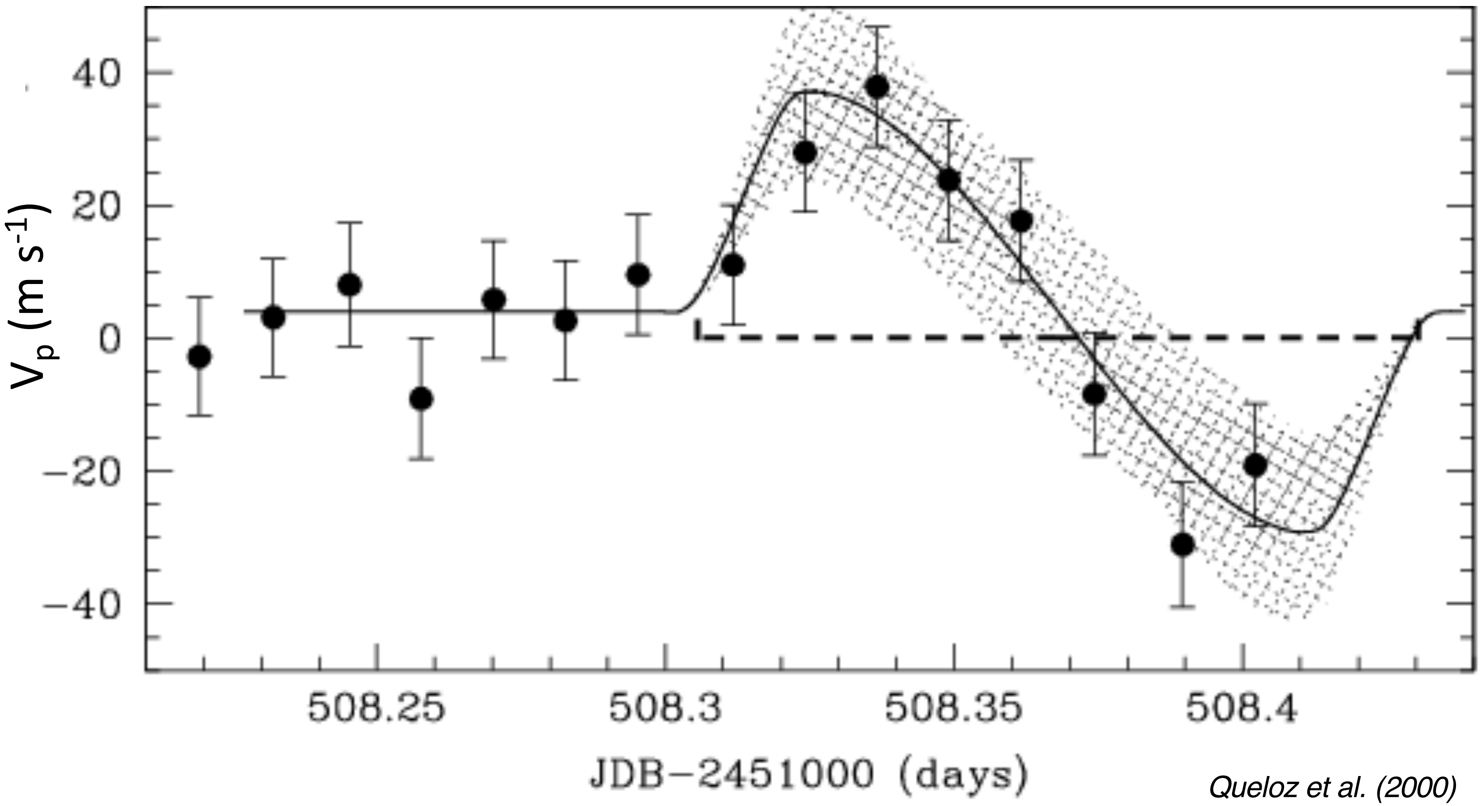
Geometry: depends on the angle λ between the projections on the sky plane of the stellar spin axis and the planet's orbital axis.



Gaudi & Winn (2006)

The Rossiter-Mc Laughlin effect

First detection for an exoplanet: HD209458b in 2000



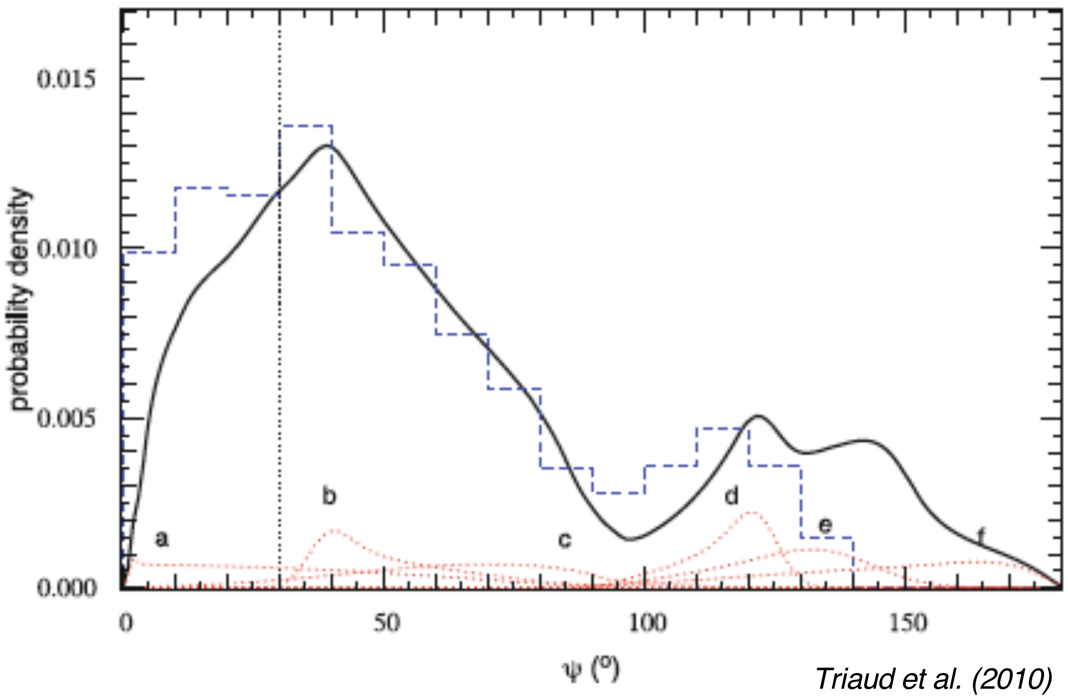
Queloz et al. (2000)

The Rossiter-Mc Laughlin effect

λ teaches us about the dynamical history of the system (migration)

Disk-driven migration mechanisms predict circular well-aligned orbits.

3-body migration mechanisms (planet-planet scattering or Kozai) predict eccentric misaligned orbits.



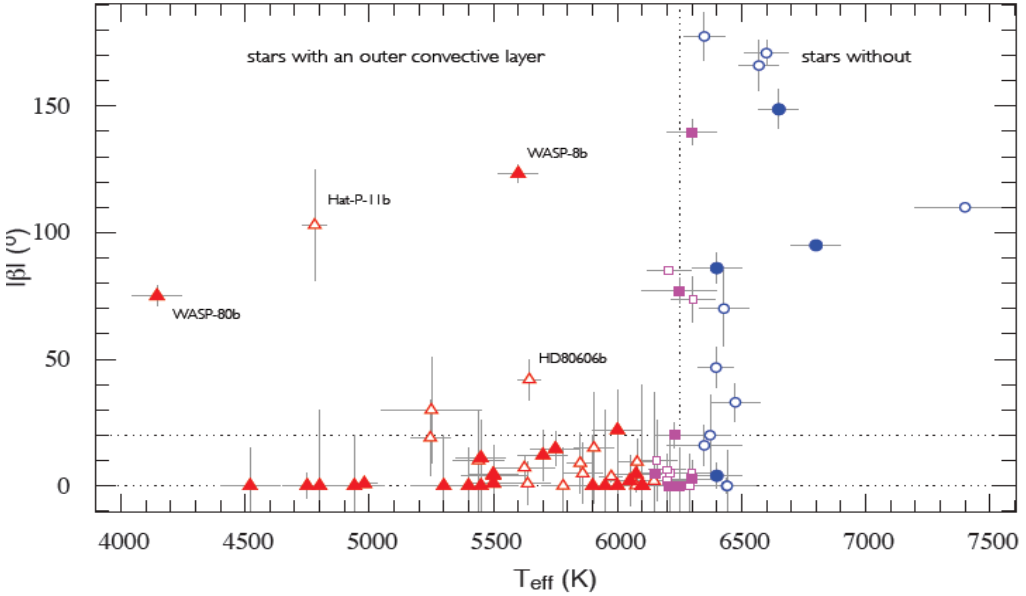
Triaud et al. (2010)

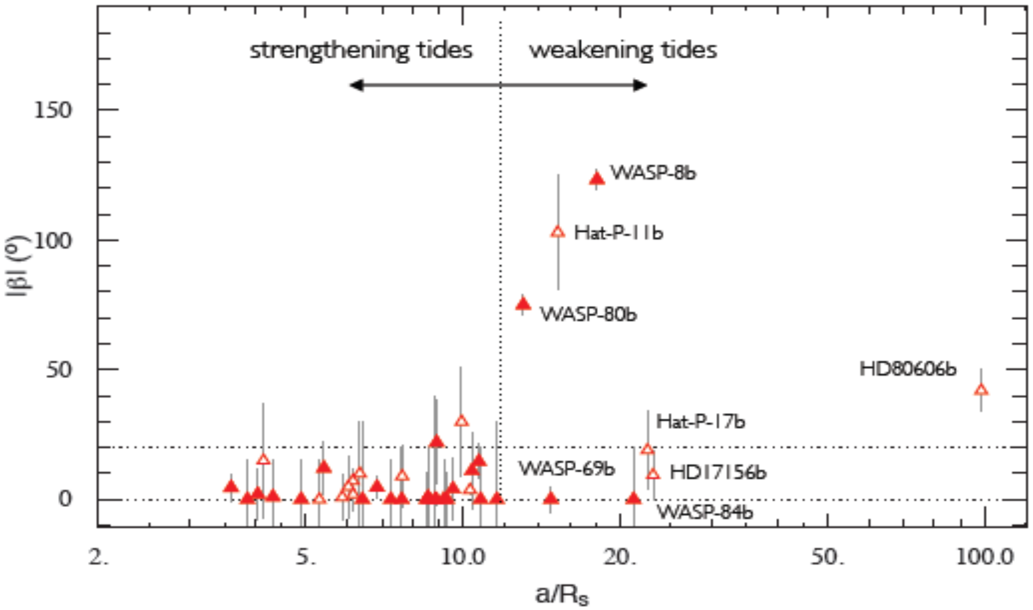
Observations: many hot Jupiters on misaligned, and even retrograde, orbits

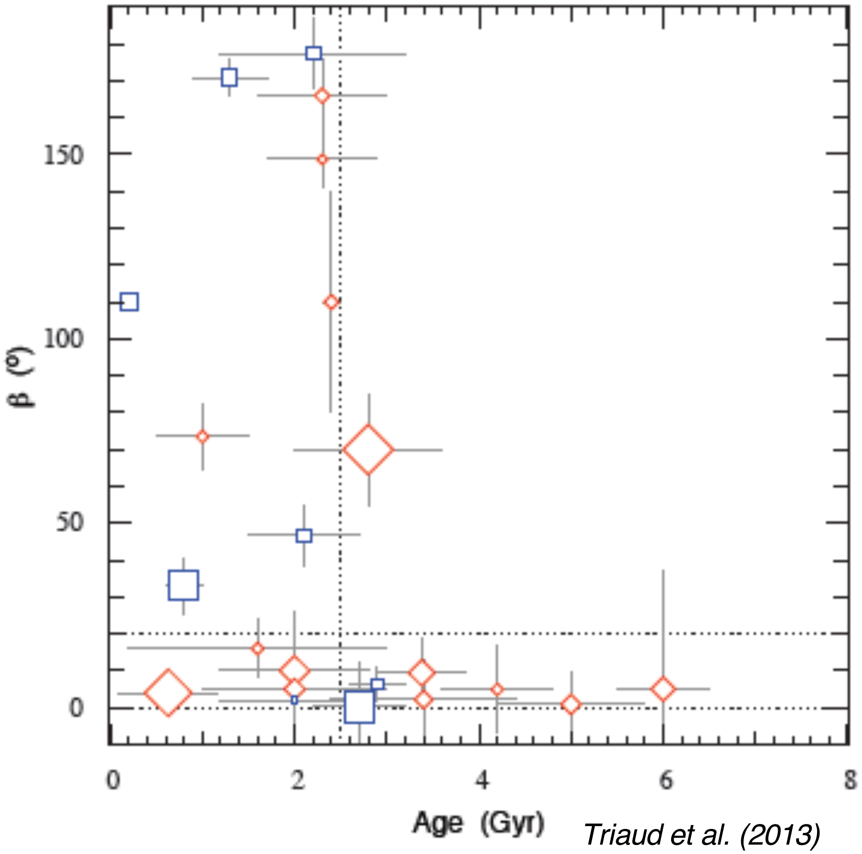
Good agreement with predictions of 3-body migration models

The Rossiter-Mc Laughlin effect

Traces of orbital realignement by tidal effects?



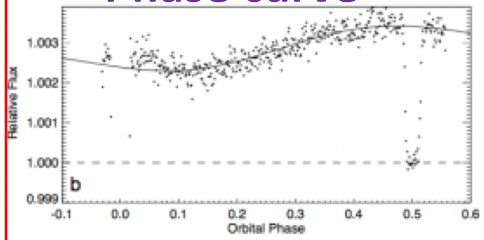


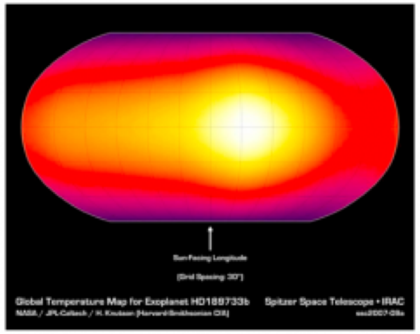


Triaud et al. (2013)

Studying the atmospheres of transiting planets

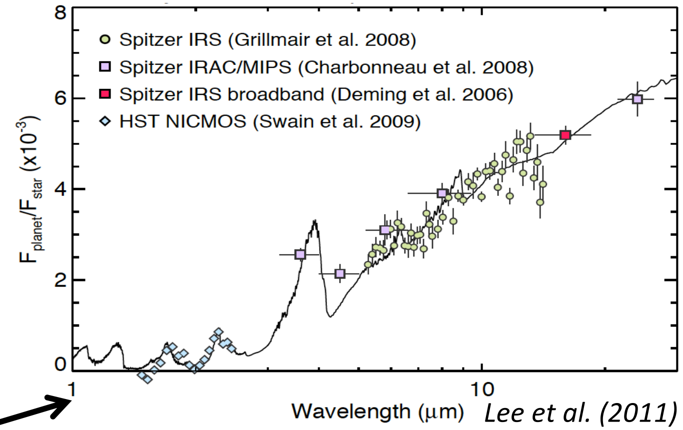
Phase curve



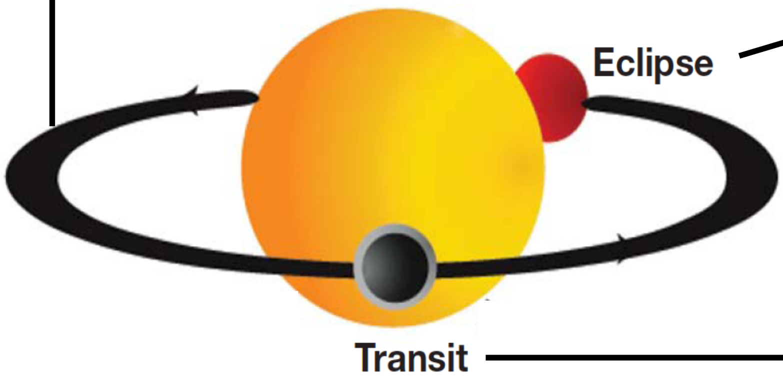


Knutson et al. (2008)

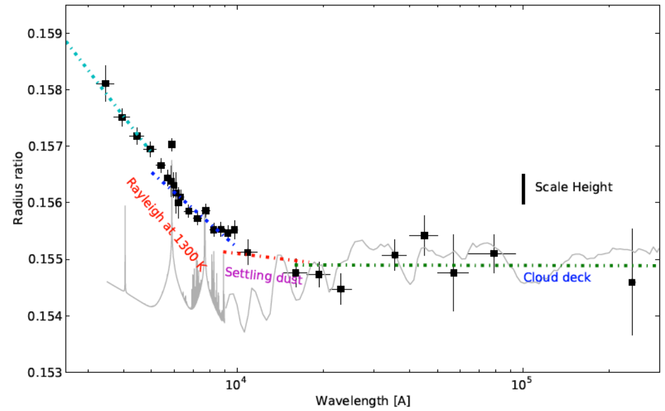
Emission spectrophotometry (dayside)



Lee et al. (2011)



Transmission spectrophotometry (limb)



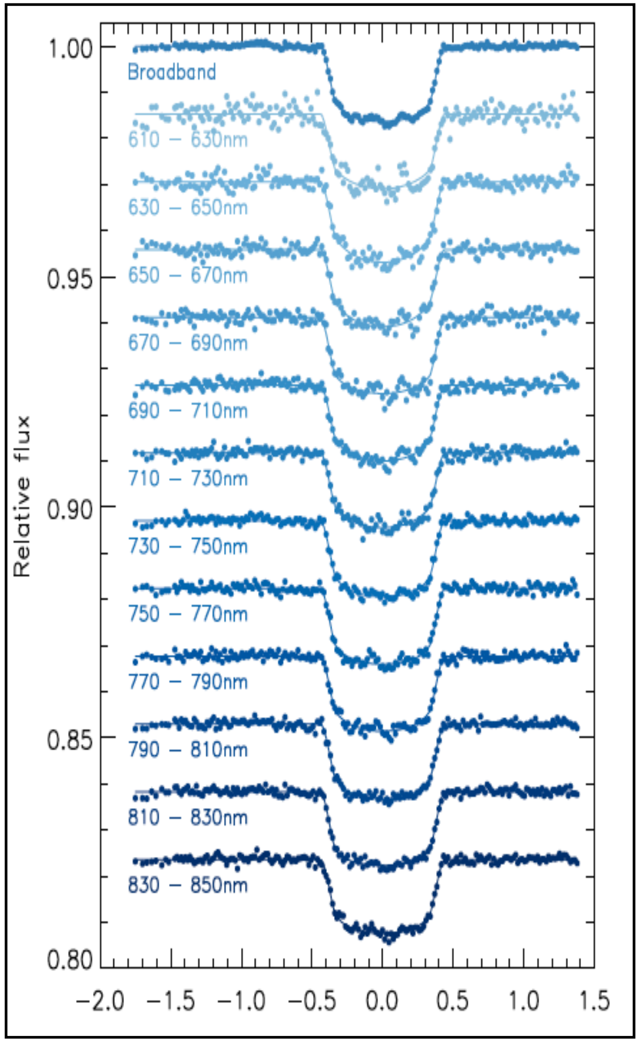
Deming & Seager (2009)

Pont et al. (2013)

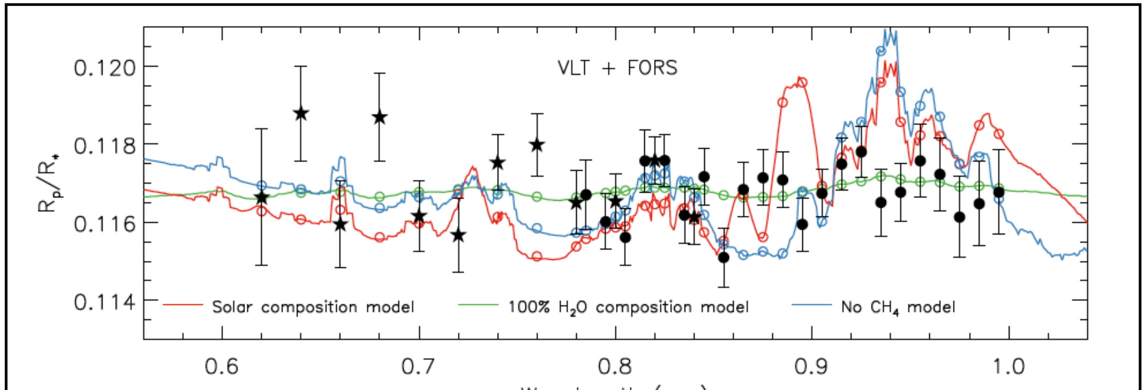
Planet's spectra without the need for ultra-high spatial resolution

Bonus: mass, radius, orbit, obliquity, etc…

Transit transmission spectrophotometry



Bean et al. (2011)



Bean et al. (2011)

Signal amplitude? *(Seager & Sasselov 2000)*
At the λ of a strong atomic or molecular transition, the effective radius of the planets increases of some (N_H~5) **scale heights H = kT/μg**

$$\Delta\delta = \frac{\pi(R_p + N_H H)^2}{\pi R_\star^2} - \frac{\pi R_p^2}{\pi R_\star^2} \approx 2N_H\delta\left(\frac{H}{R_p}\right)$$

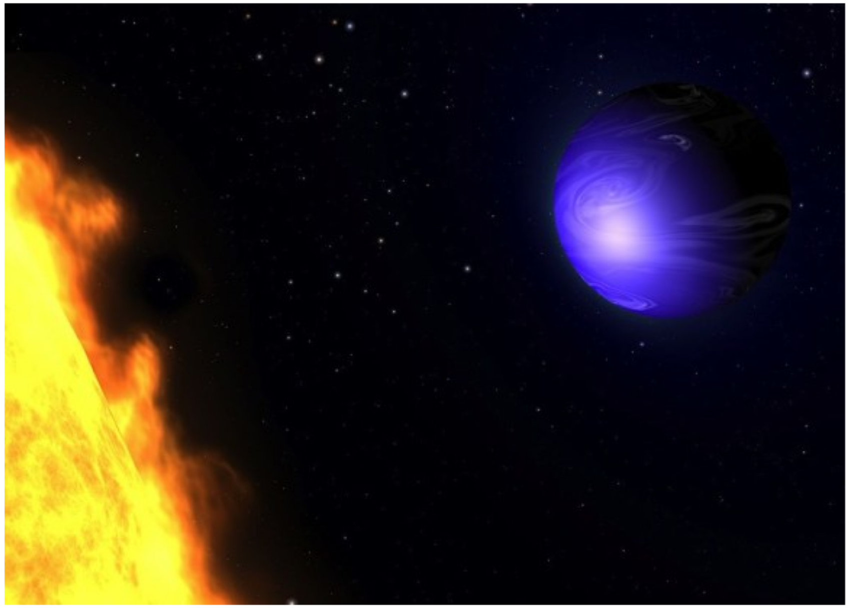
Hot Jupiter: ~100ppm, Earth+Sun: ~1ppm

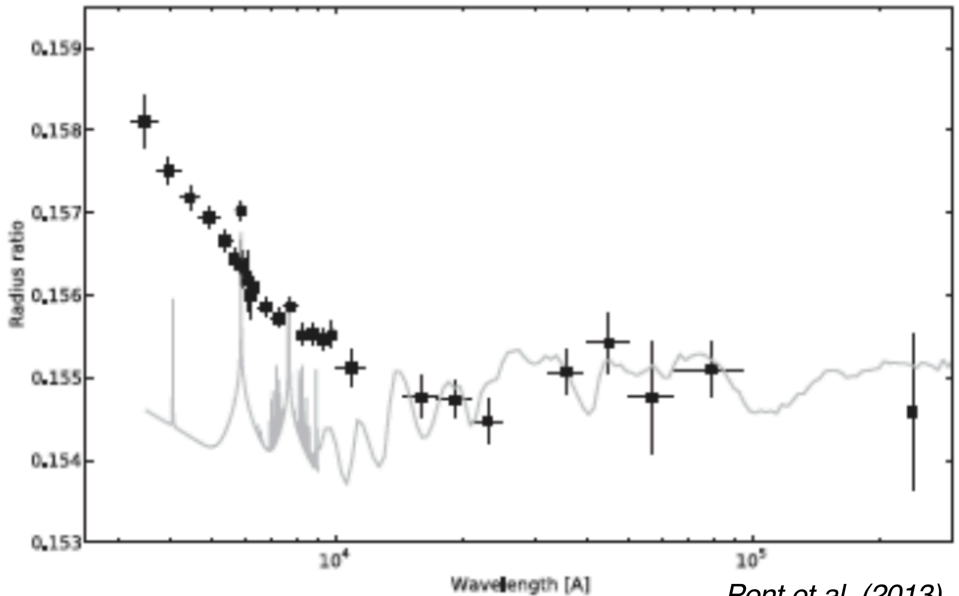
Transit transmission spectrophotometry

Rayleigh scattering is λ-dependent and stronger at shorter wavelengths. It concerns the molecules and condensates that are small compared to λ.

For bigger particules (compared to λ) ➔ **Mie scattering**, less λ-dependent.

Depending on the atmosphere composition, the extent of the cloud cover, and the composition and altitude of the clouds, these two kinds of scattering impact more or less strongly the transmission spectra.





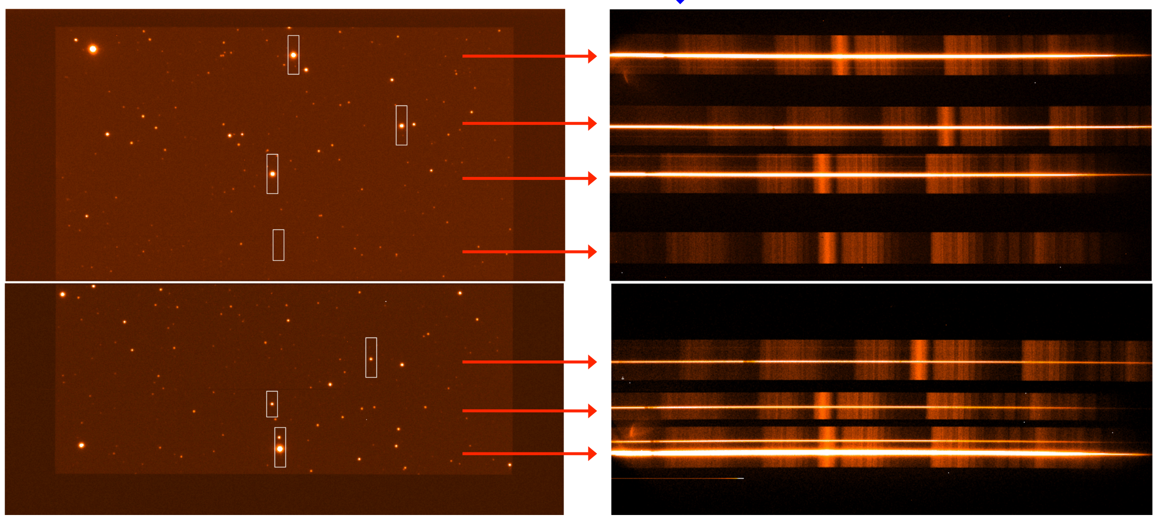
Pont et al. (2013)

Transit transmission spectrophotometry

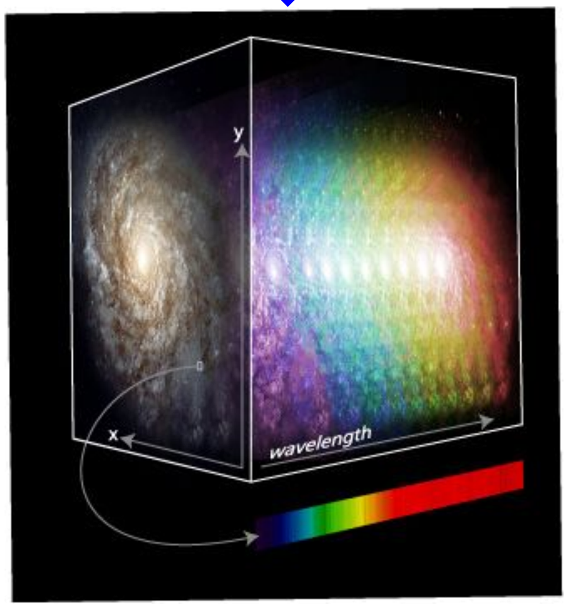
Practically:

Broadband observation of several transits at different wavelengths
BUT: impact of stellar variability; low spectral resolution

Mono- (space) or multi-object (ground) time-series spectroscopy,
➔ wide-slit spectroscopy or Integral Field Unit (IFU)



Delrez et al. (2013)

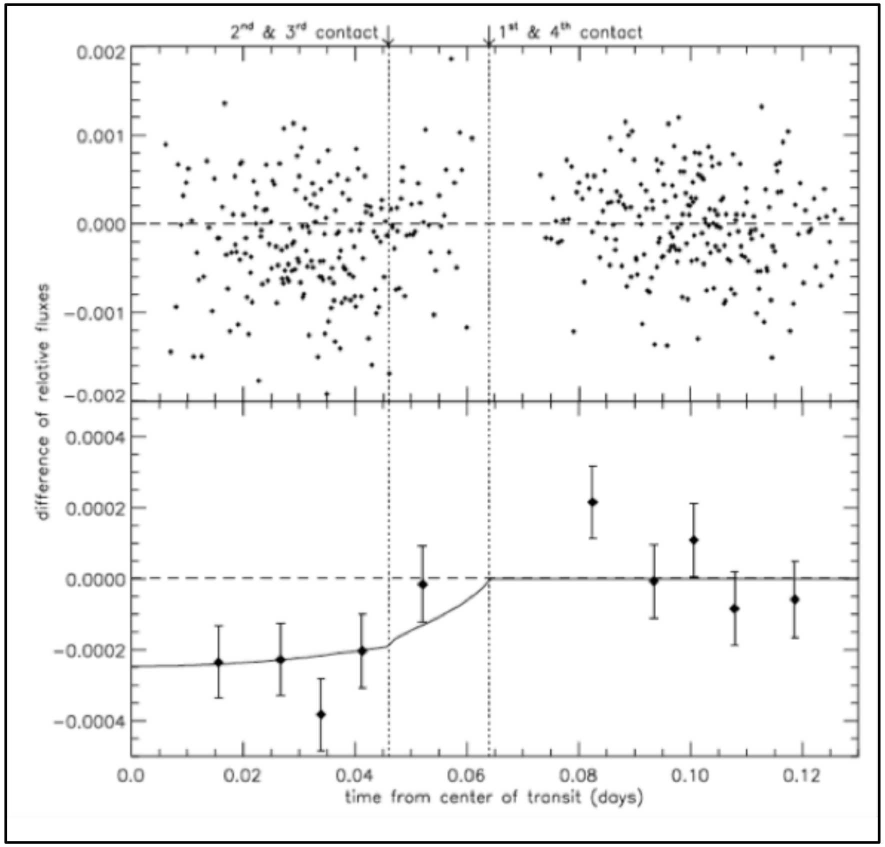


Transit transmission spectroscopy: results

Atomic sodium in the atmosphere of HD209458b

Instrument: STIS spectrograph aboard HST

Objective: to detect the Na I (5890,5986Å) resonance doublet signal, basing on theoretical predictions of Seager & Sasselov (2000)



~4 sigmas detection

Signal 3 times fainter than expected

Depletion of Na I? Competition between Na and Na_2S? Then only 1% of Na should be in atomic form…

High-altitude clouds?

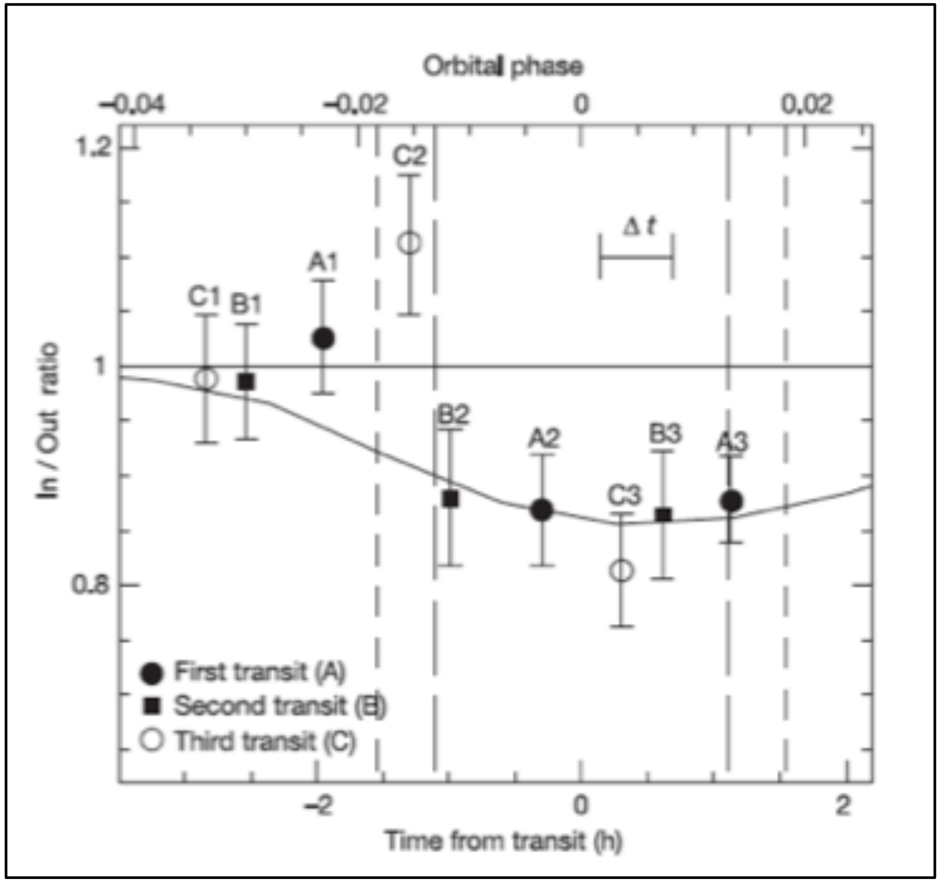
Charbonneau et al. (2002)

Transit transmission spectroscopy: results

Atmospheric escape for HD209458b

Instrument: STIS spectrograph aboard HST

Objective: To detect the H Lyman-α (121.6 nm) line.



~4 sigmas detection

Effective radius of 4.3 R_{jup}!

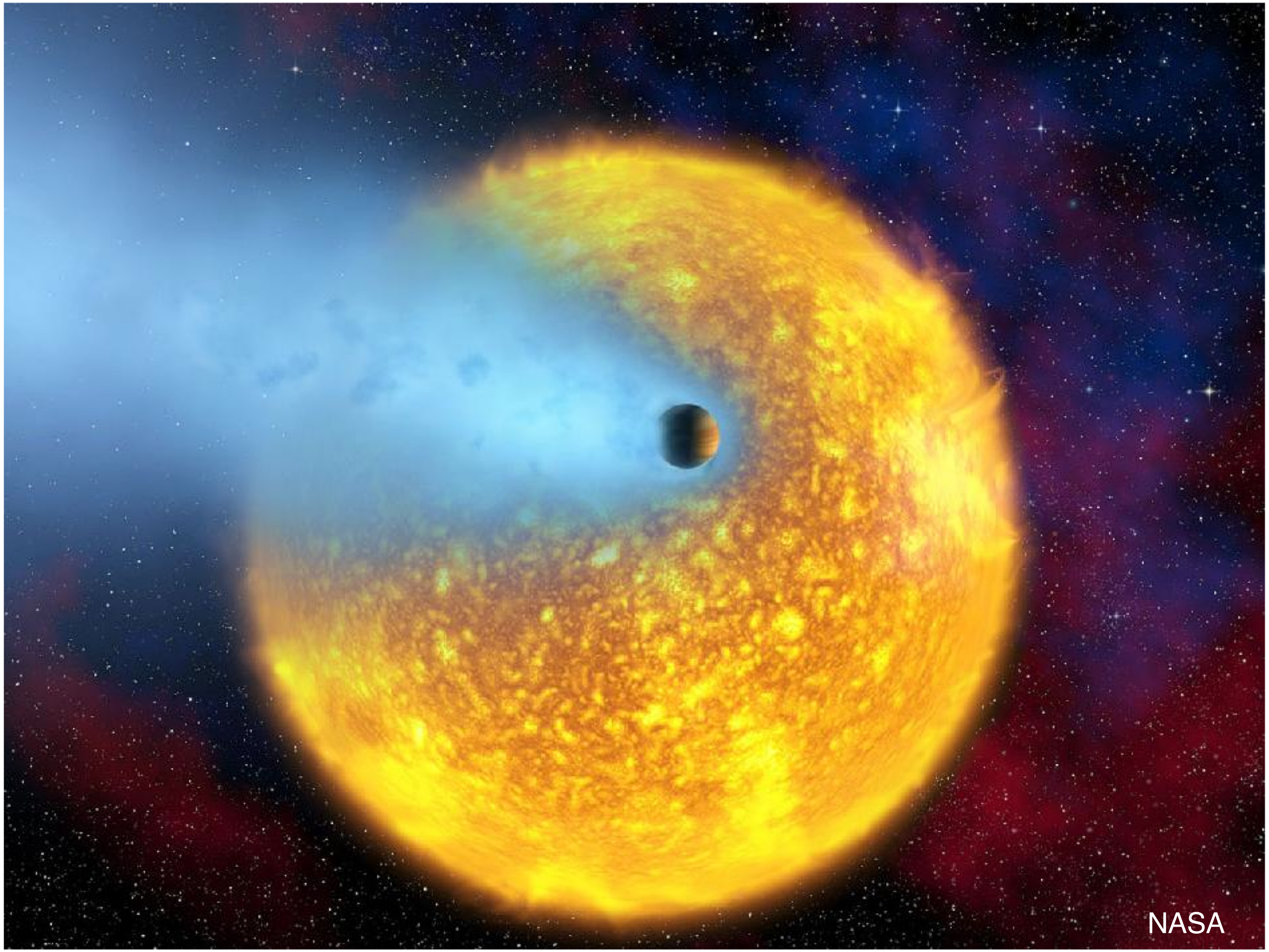
Exosphere forming a comet-like coma around the planet

Mass loss is negligible (~0.1% over the life of the star)

Vidal-Majar et al. (2003)

Transit transmission spectroscopy: results

Atmospheric escape for HD209458b

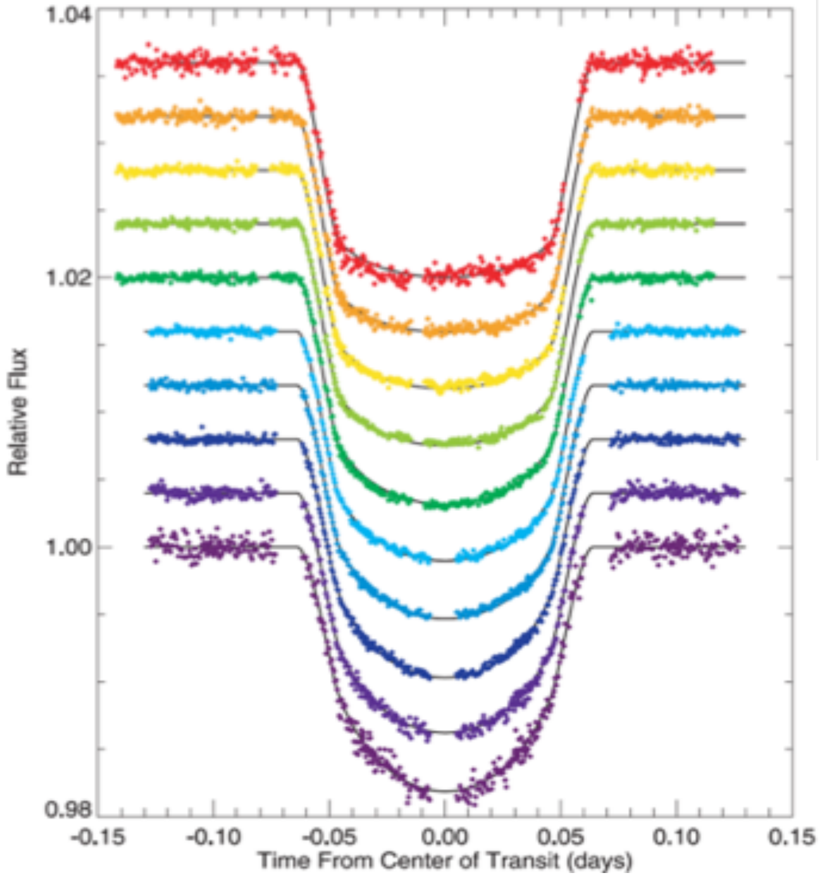


Transit transmission spectroscopy: results

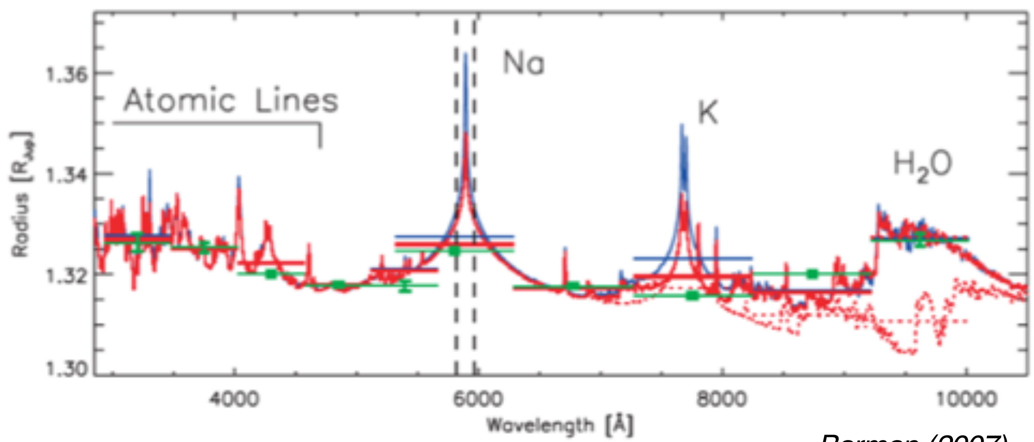
Water in the atmosphere of HD209458b ?

Instrument: STIS spectrograph aboard HST

Objective: low-resolution spectrum between 300 and 1000nm



Knutson et al. (2007)



Barman (2007)

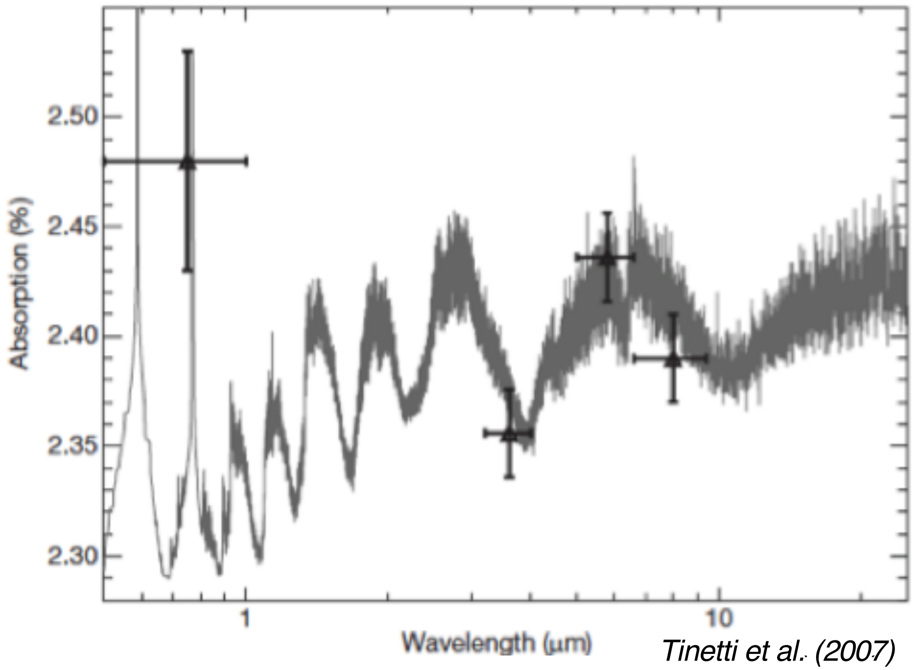
Instrumental effects
➔ low-significance detection

Transit transmission spectroscopy: results

Water in the atmosphere of HD189733b ?

Instrument: IRAC camera aboard Spitzer

Objective: detection of H_20 that should produce $\Delta(dF_{5.8\mu m} - dF_{3.6\mu m})$ between 150 and 400ppm

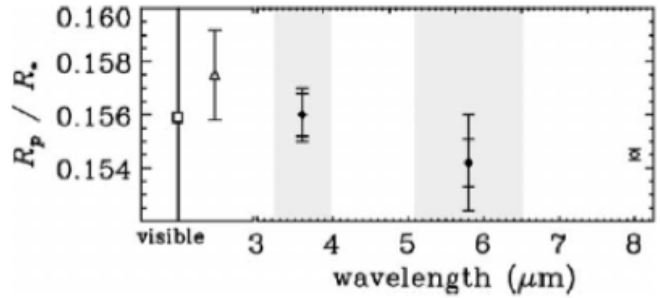


Tinetti et al. (2007)

Only H_2O explains the measurements

R_p larger in the optical?
If so: clouds? Aerosols?
Effect of spots?

But independent analysis of the same data did not confirm the results…



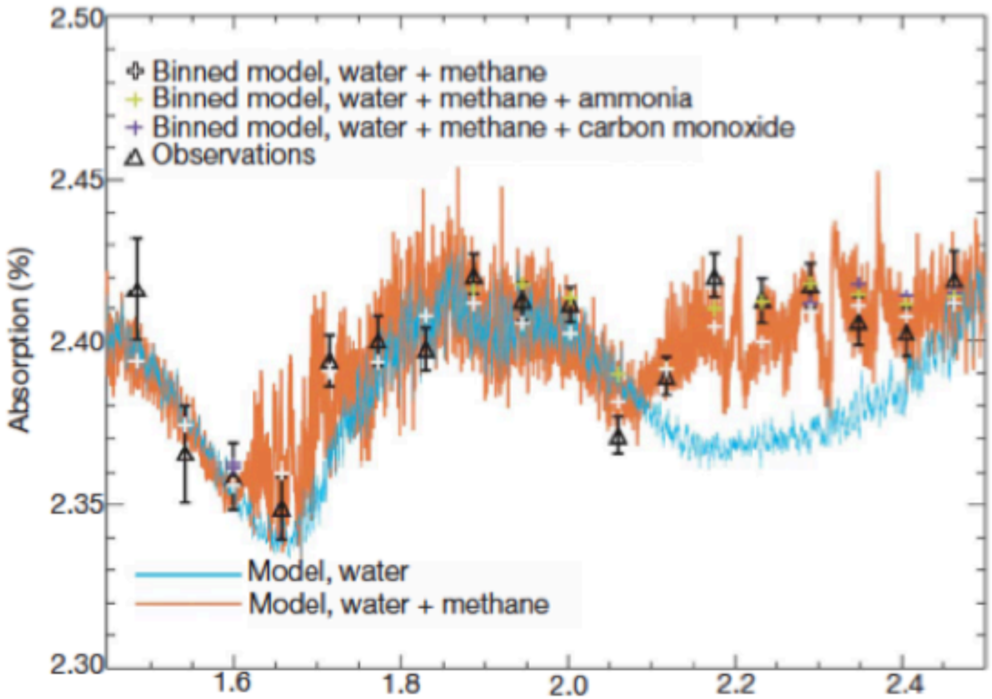
Ehrenreich et al. (2007)

Transit transmission spectroscopy: results

Methane in the atmosphere of HD189733b ?

Instrument: NICMOS spectrograph aboard HST

Objective: low-resolution spectrum in the near-IR



Detection of H_2O and CH_4

CO should be the main carbon molecule when T>1200K

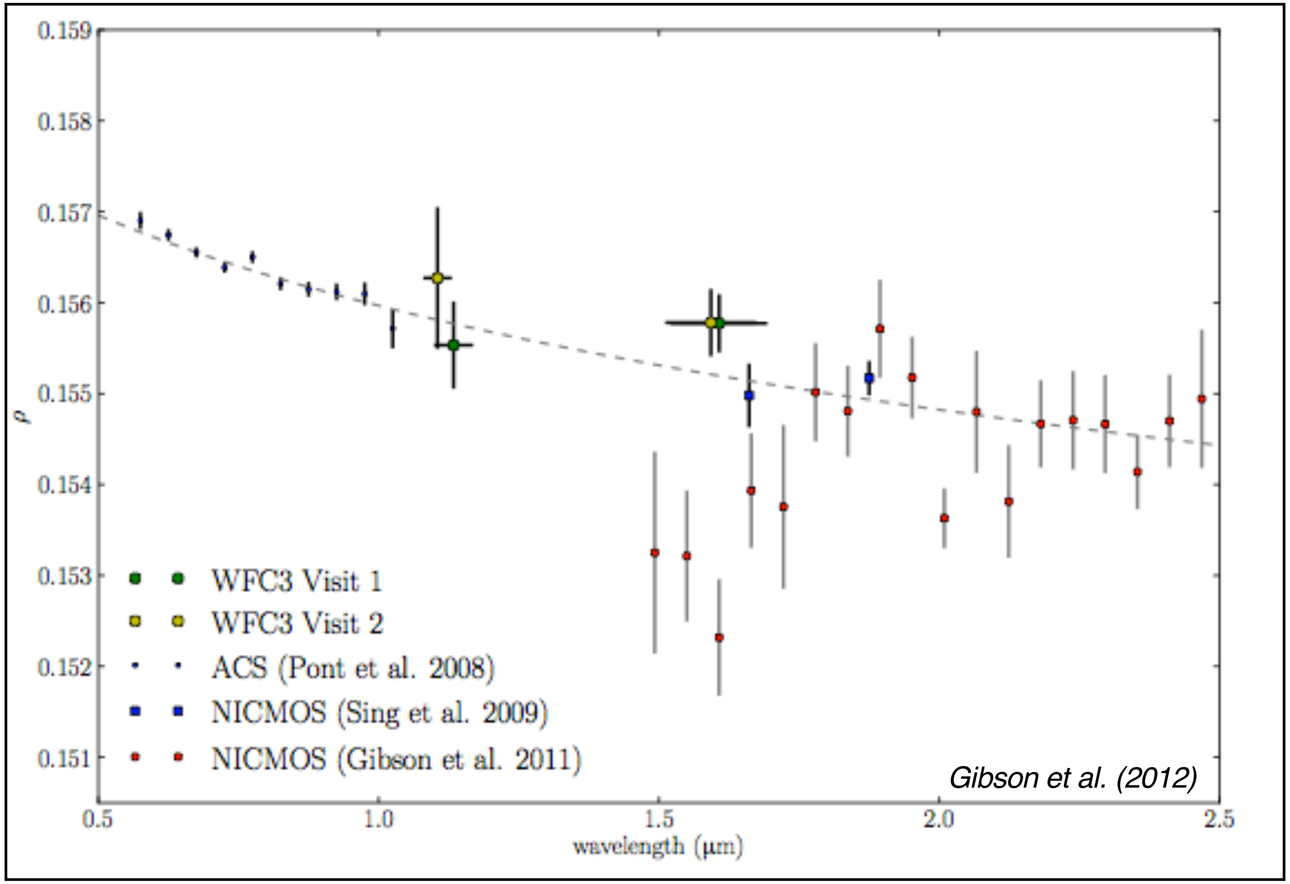
➔ Chemical gradient?

➔ Photochemical mechanism?

Light curves are « detrended » using out-of-transit data and an arbitrary function of 5 external parameters.

➔ **Errors ~50ppm. Realistic?**

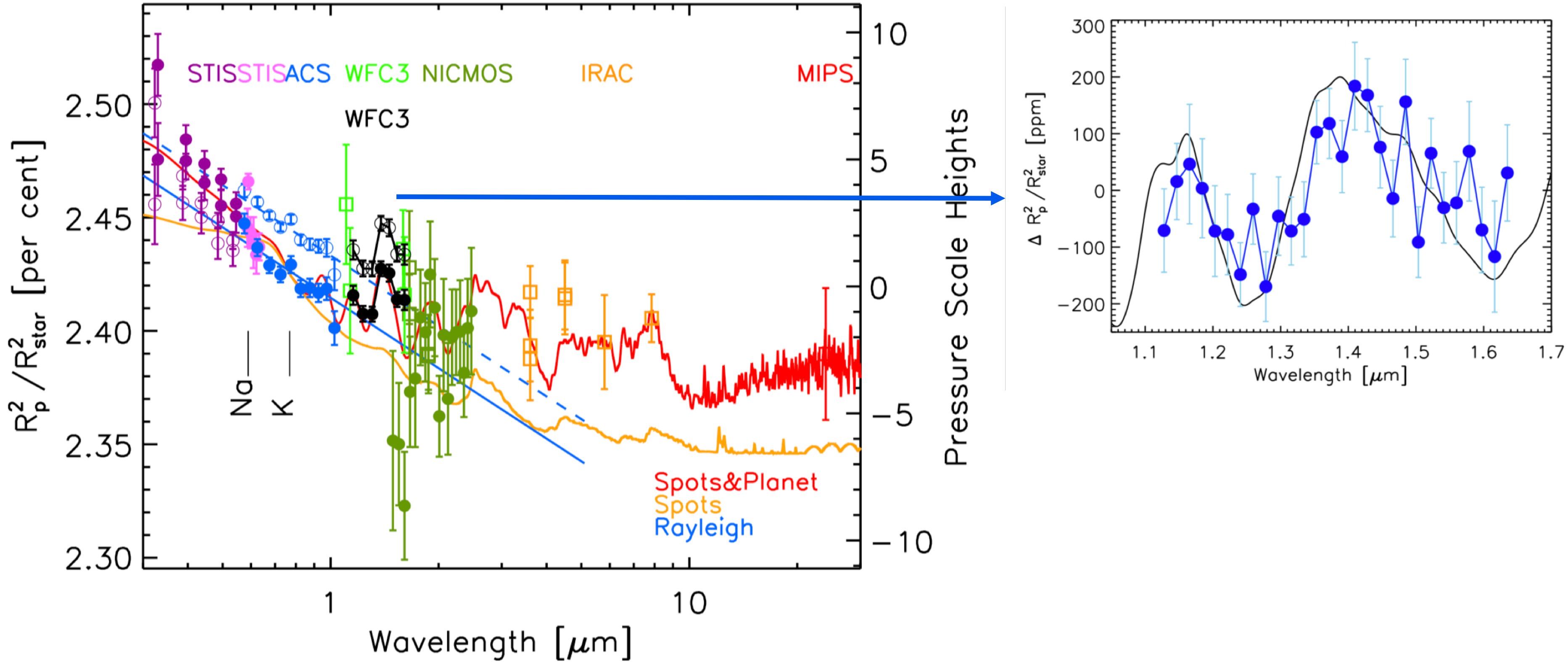
Transit transmission spectroscopy: results



Spectrum dominated by Rayleigh scattering (dust)
Spots complicate the interpretation
NICMOS systematic effects were strongly underestimated.

Transit transmission spectroscopy: results

The actual transmission spectrum of HD189733b

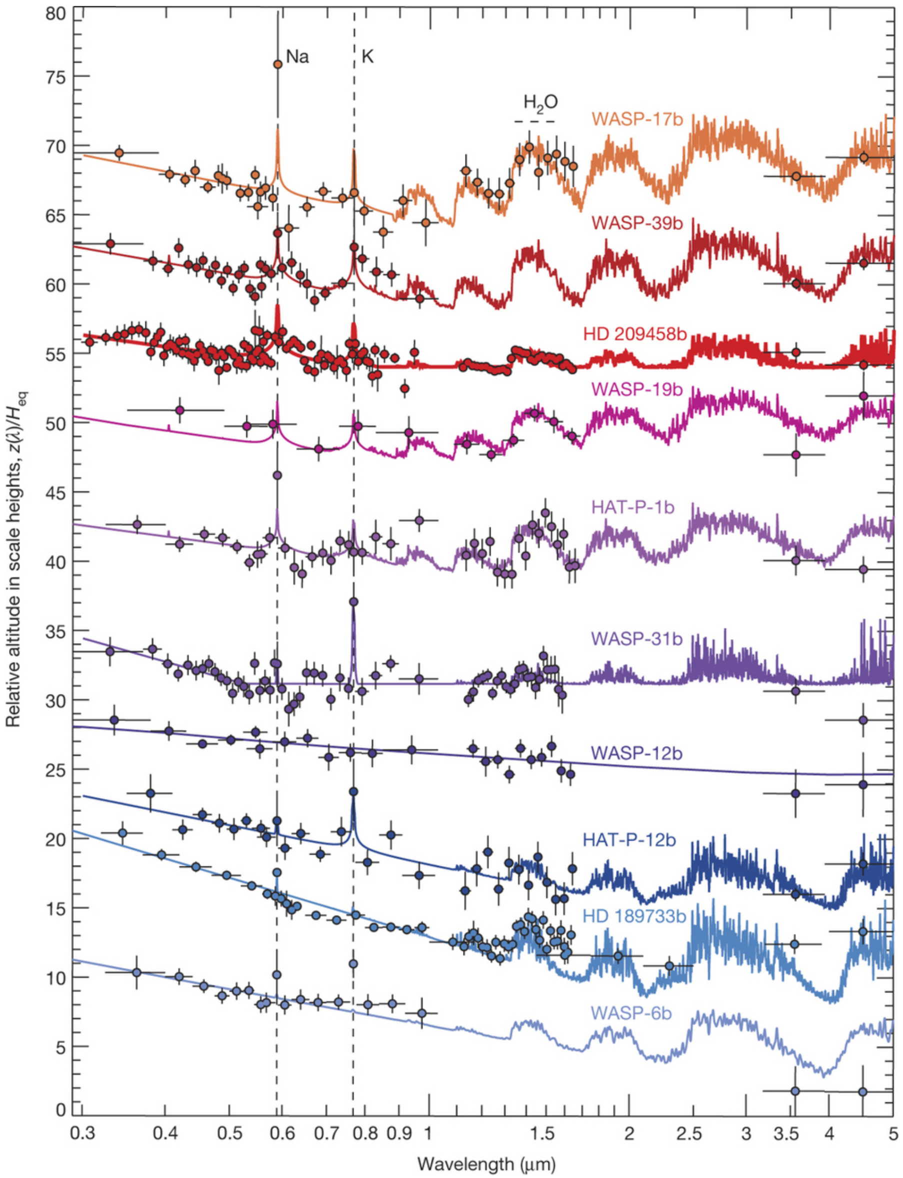


Mc Cullough et al. (2014)

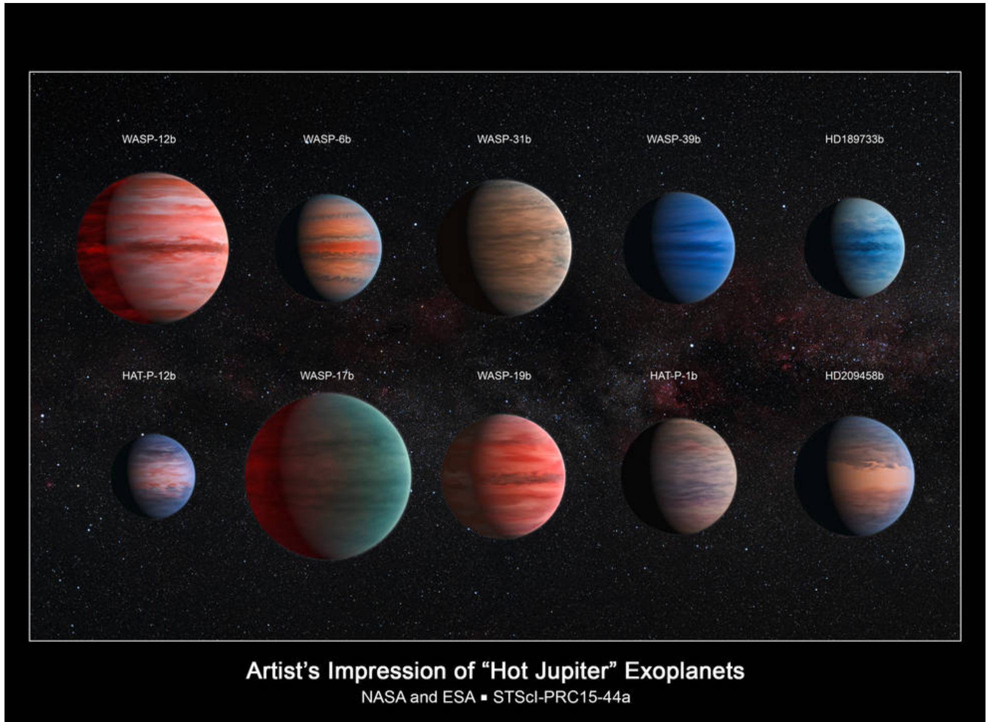
Spectrum dominated by Rayleigh scattering (high-altitude haze)
and/or by unocculted star spots
Na, K, and water signatures are detected

Transit transmission spectroscopy: results

Some more recent results…



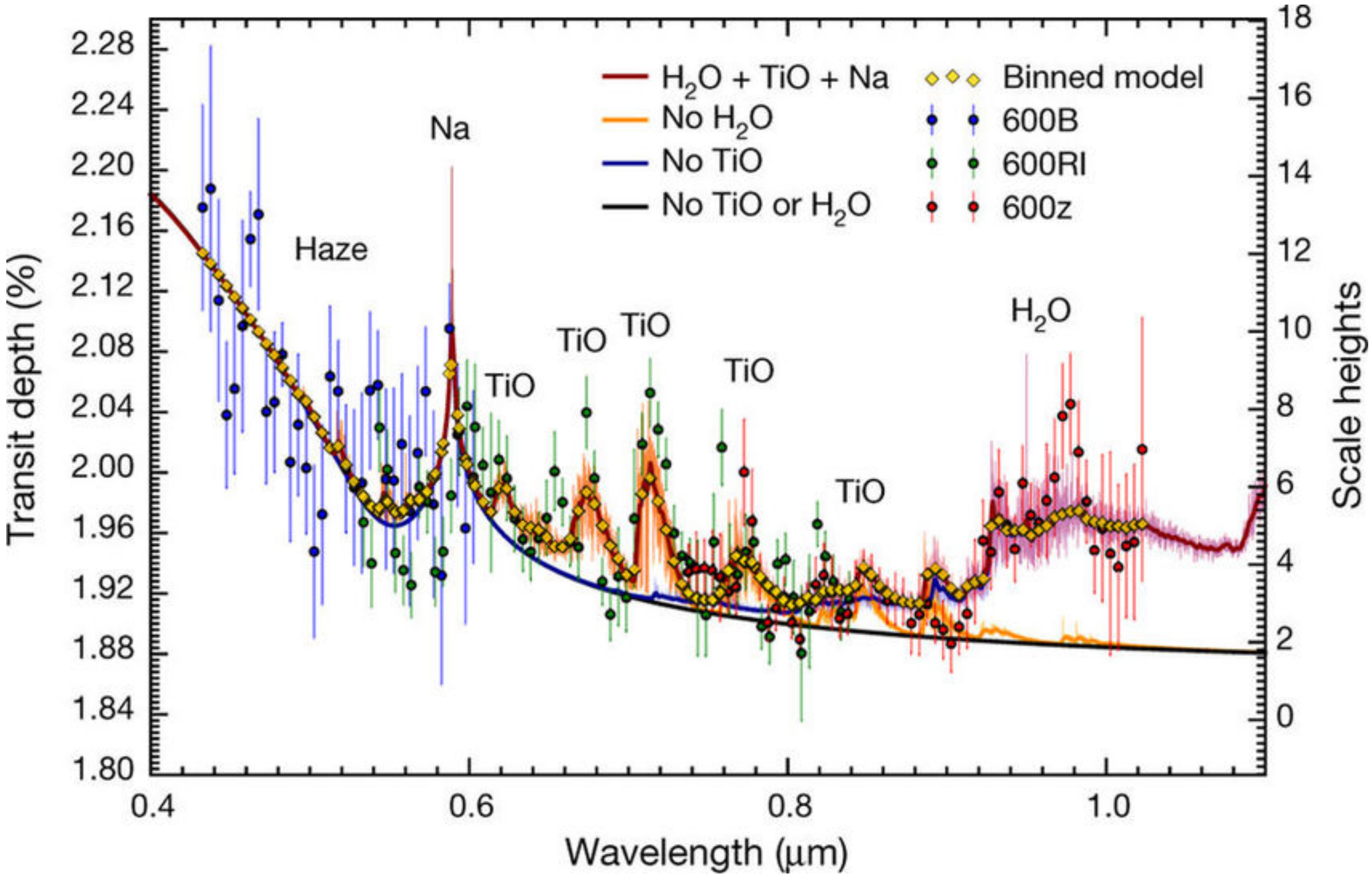
Comprehensive survey of ten planets shows a continuum of clear to cloudy atmospheres on hot Jupiters…



Sing et al. (2016)

Transit transmission spectroscopy: results

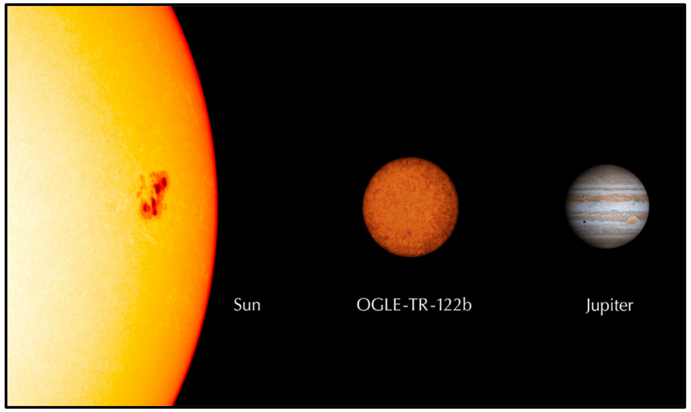
TiO and H_2O in the very hot (T_{eq} ~ 1900K) giant planet WASP-19b



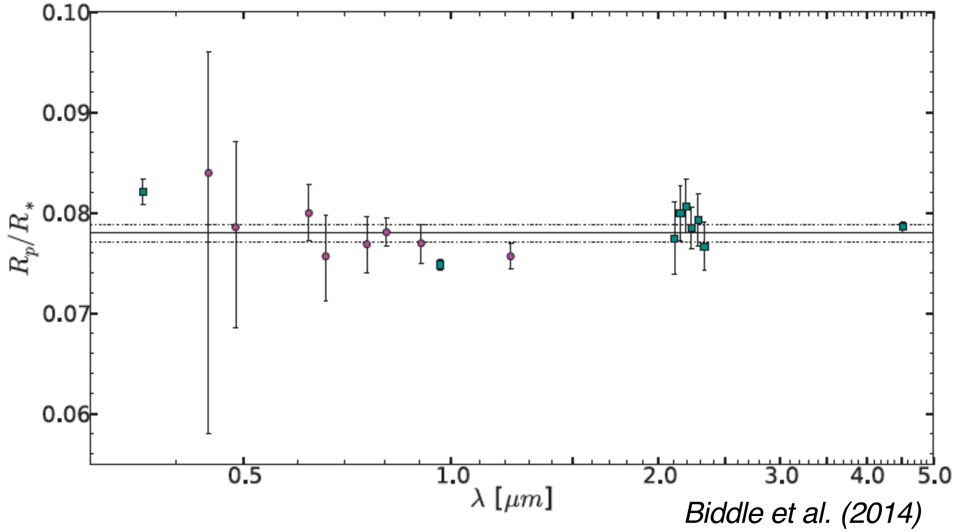
Sedagahti et al. 2017

Transit transmission spectroscopy: results

Studying small planets?
Targetting small stars!

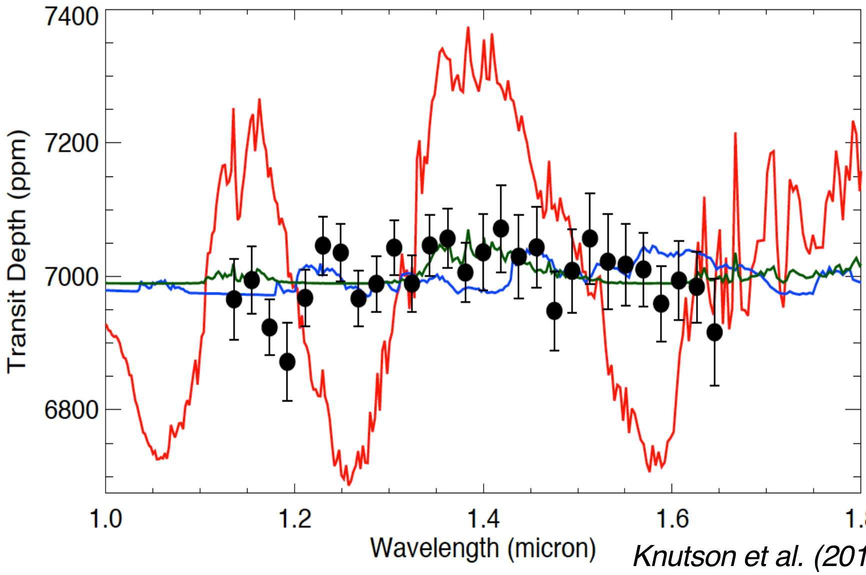


GJ3470b: 4.4 R_{earth} + 0.53 R_{sun}



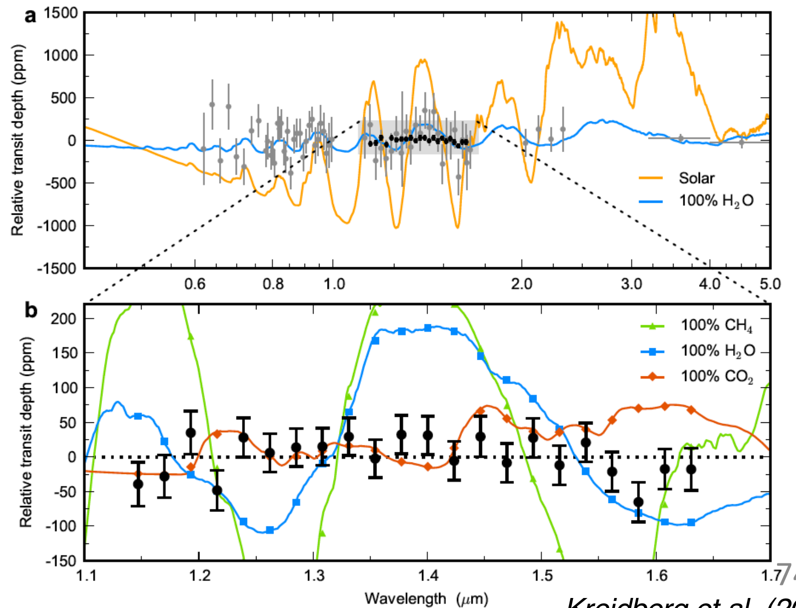
Biddle et al. (2014)

GJ436b: 4.1 R_{earth} + 0.46 R_{sun}



Knutson et al. (2014)

GJ1214b: 2.8 R_{earth} + 0.22 R_{sun}

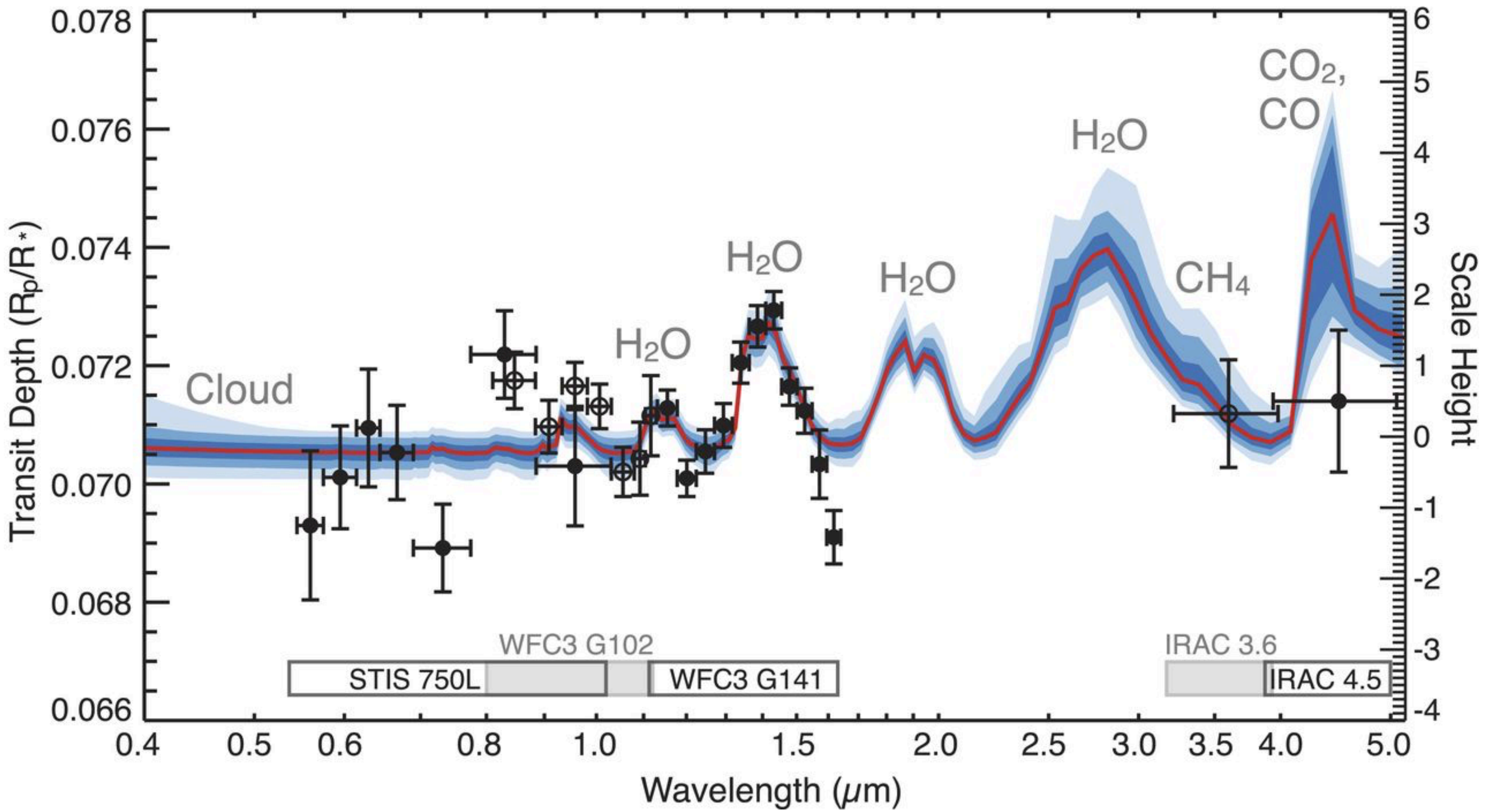


Kreidberg et al. (2014)

Transit transmission spectroscopy: results

Water in the atmosphere of the bloated hot Neptune HAT-P-26b

18.6 M_{earth}, 6.3 R_{earth} + 0.8 R_{sun} K-dwarf

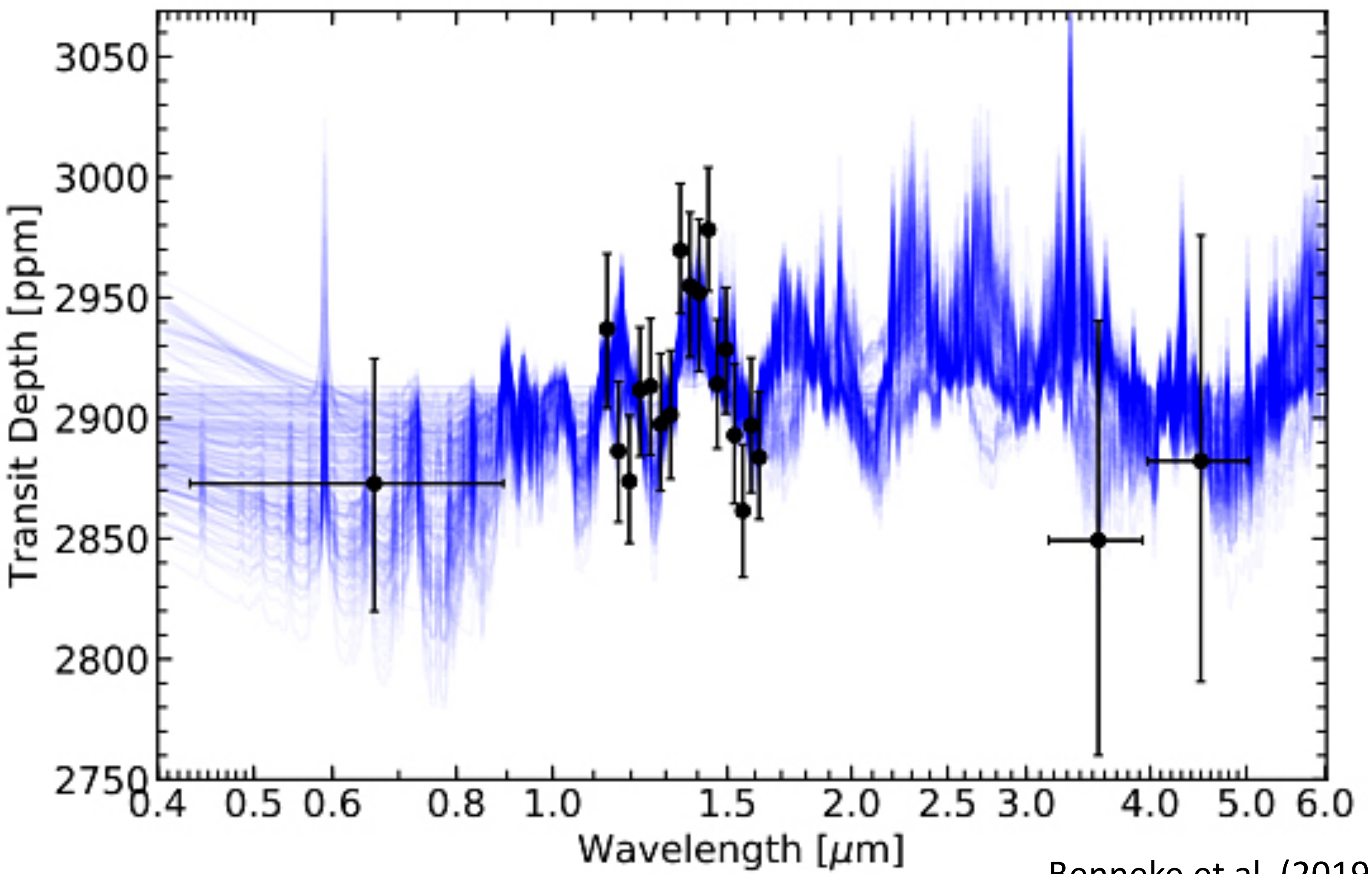


Wakeford et al. (2016)

Transit transmission spectroscopy: results

Water in the atmosphere of the habitable zone super-Earth K2-18b

8.5 M_{earth}, 2.3 R_{earth} + 0.5 R_{sun} M-dwarf



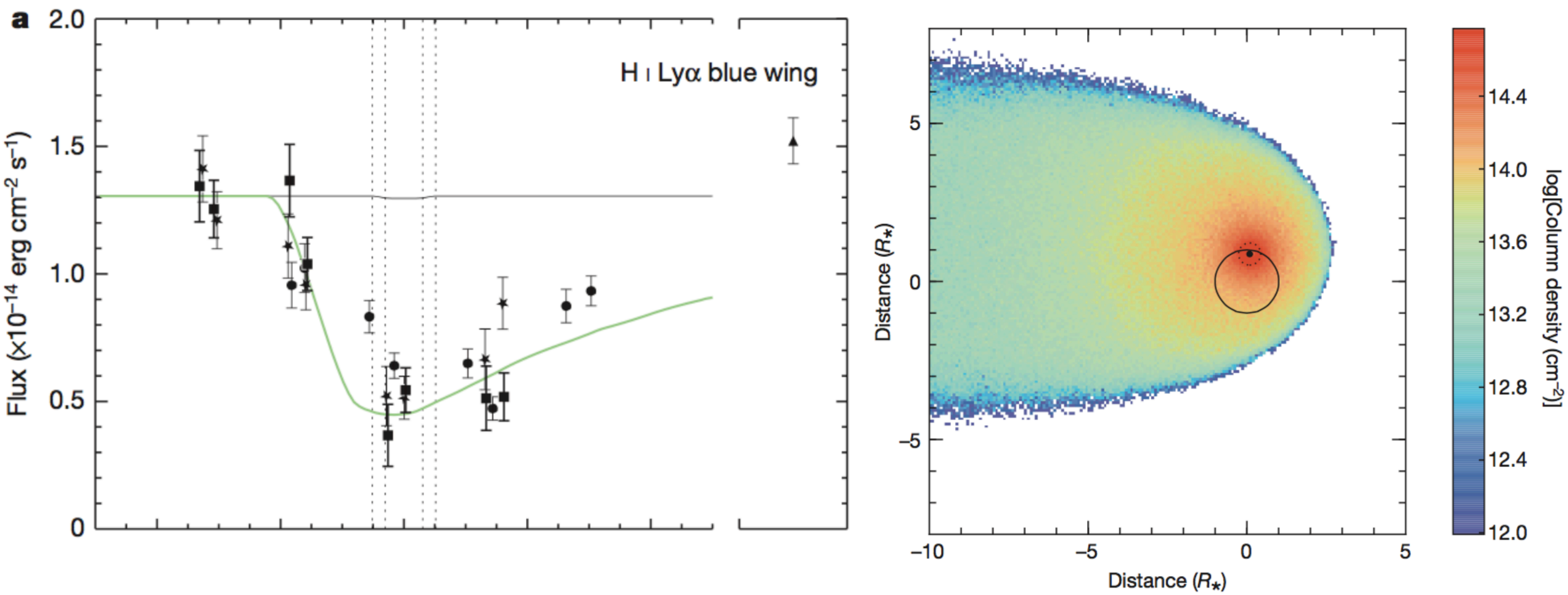
Benneke et al. (2019)

Transit transmission spectroscopy: results

A giant comet-like cloud of hydrogen escaping a hot Neptune

Instrument: STIS spectrograph aboard HST

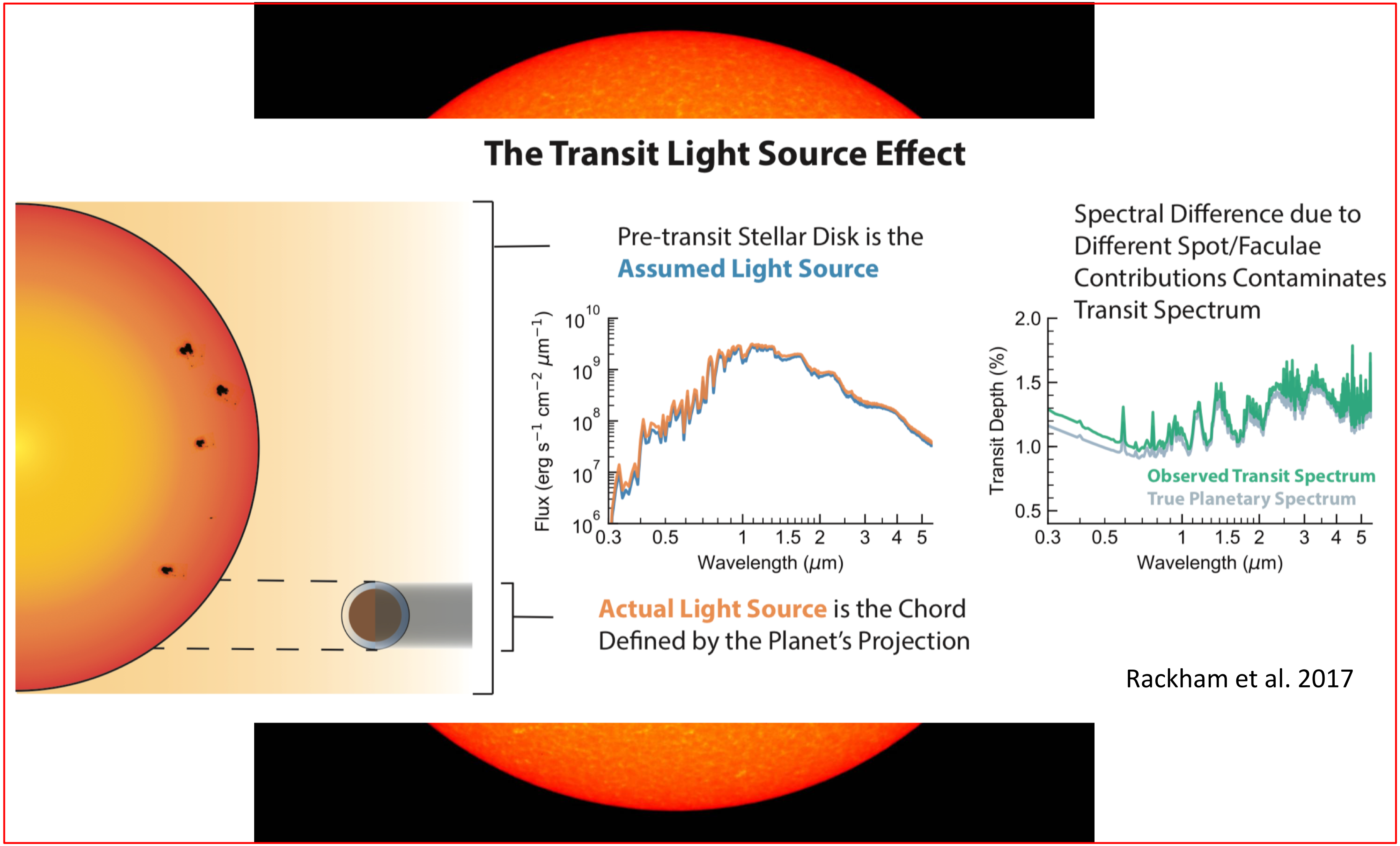
Objective: measure the transit in H I Ly-α line (121.6nm)



Ehrenreich et al. (2016)

Transit depth: 56% instead of 0.7%!

Transit transmission spectroscopy: stellar issue?



High-resolution transit spectroscopy

Principles:

transit ➔ absorption of the stellar light by the atmosphere's molecular lines (e.g. CO).

During the transit, the lines of the star and of the planet move quickly in opposite direction

Method: cross-correlation with a synthetic transmission spectrum of CO (or other molecules)

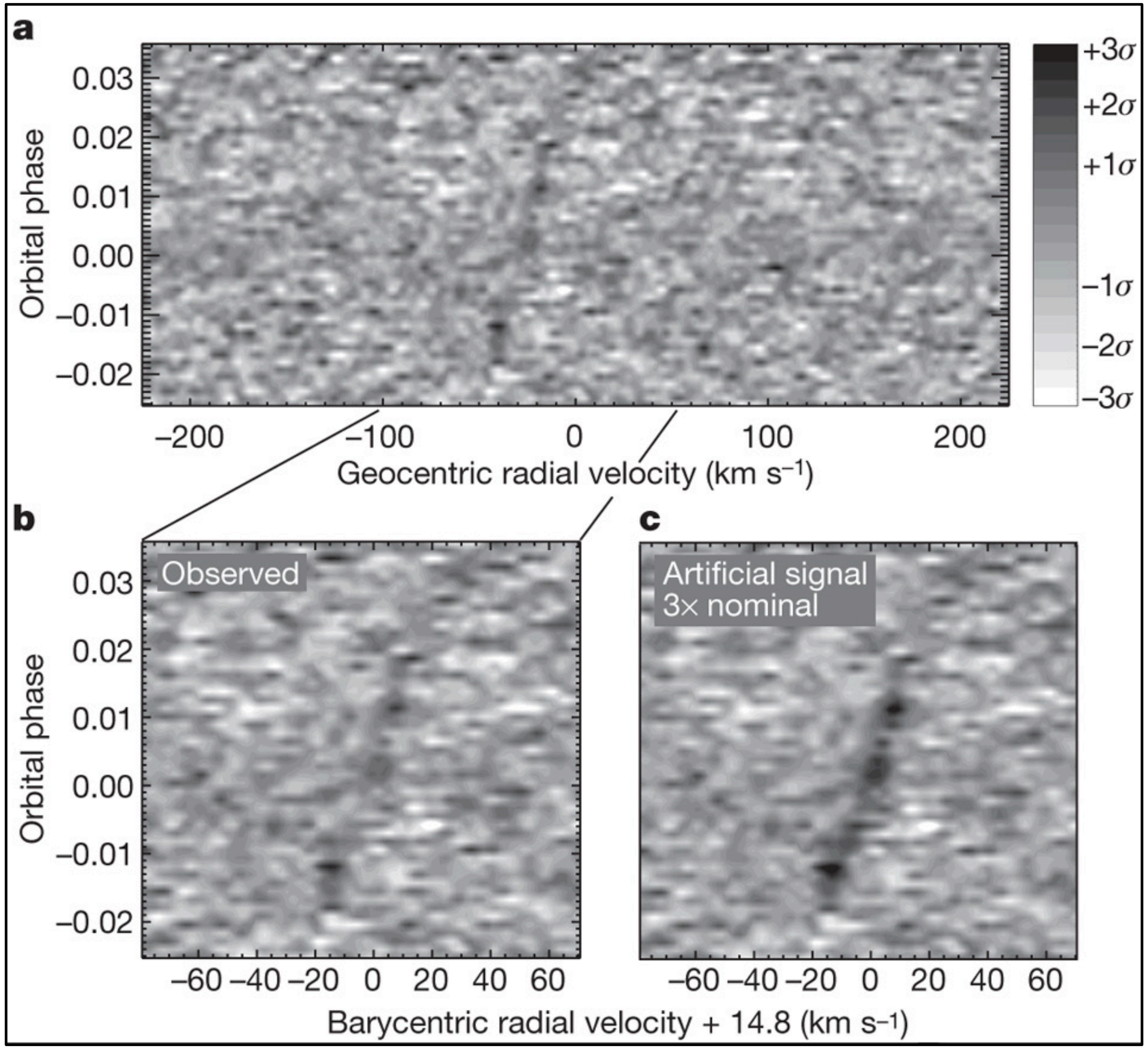
Requires very high signal-to-noise ratio and resolution in the IR.
(e.g. CRIRES spectrograph on the VLT, R~100,000)

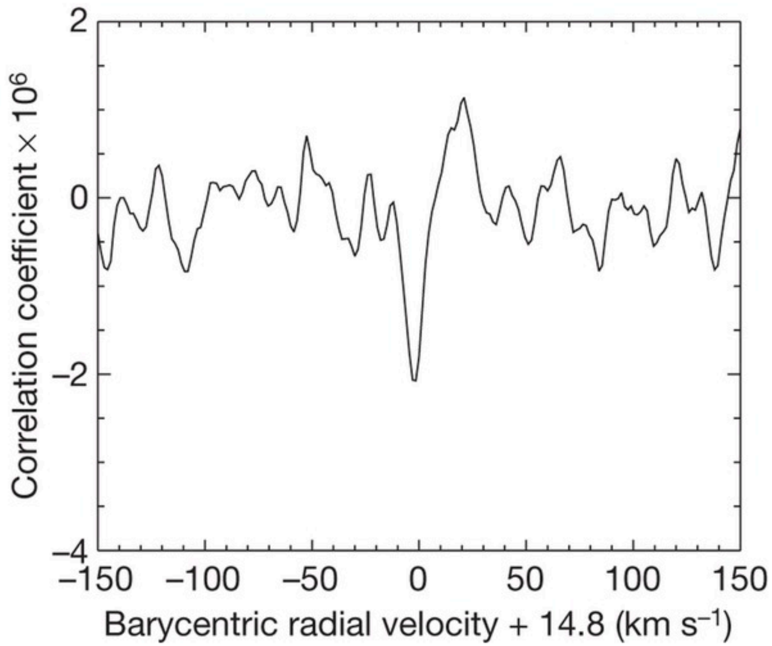
Method's outcomes:

Orbital speed of the planet -> stellar mass (SB2).
Abundance of CO in the limb of the planet
Shift in RV relative to the star: wind

High-resolution transit spectroscopy

HD209548b with VLT/CRIRES

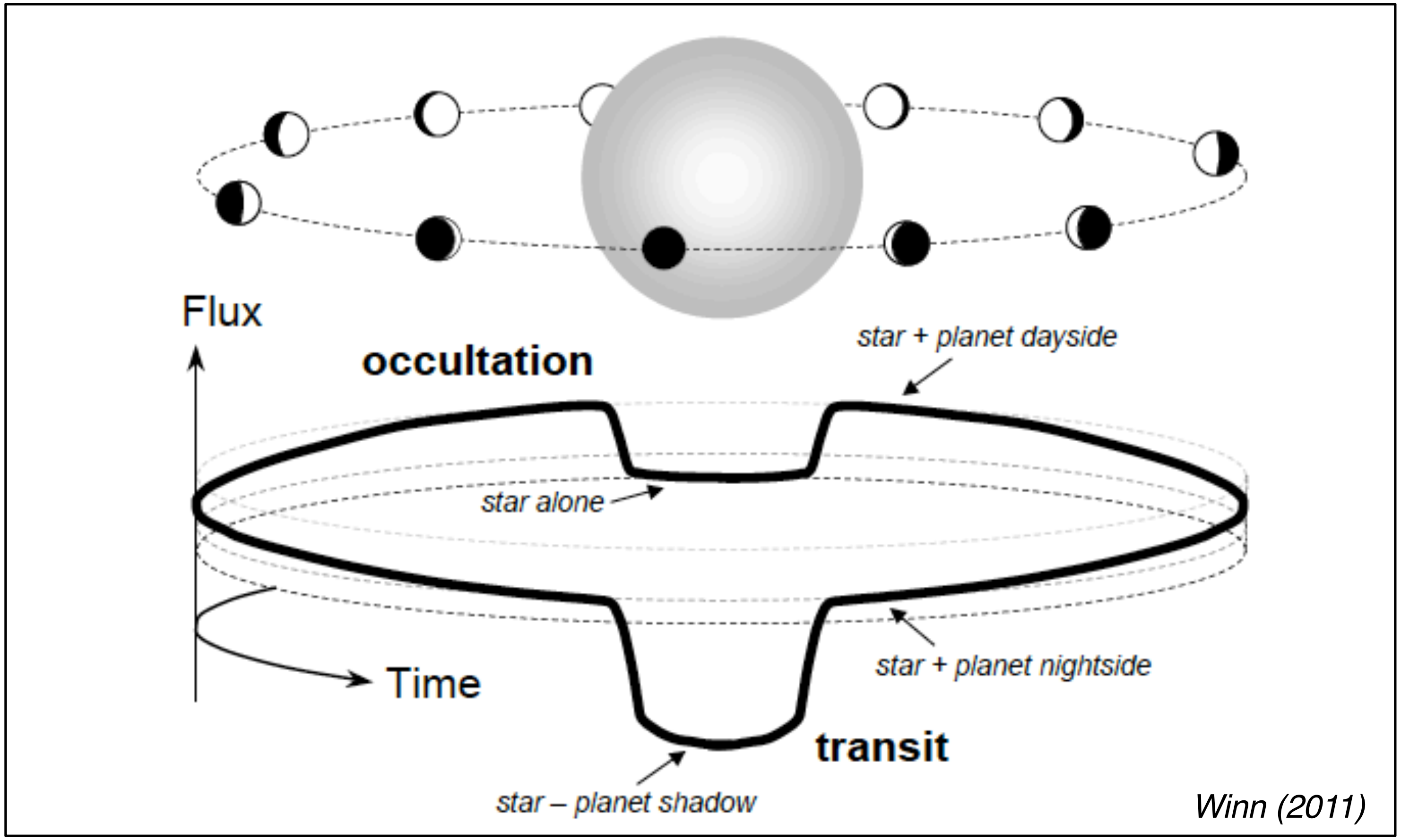




Detection significance: 5.6 σ

Snellen et al. (2010)

Occultation emission spectrophotometry



IR :

$$\delta_{occ}(\lambda) = k^2 \frac{B_\lambda(T_p)}{B_\lambda(T_\star)}$$

Measurement of the brightness temperature $T_b(\lambda)$ of the dayside hemisphere.

Optical:

$$\delta_{occ}(\lambda) = A_{g\lambda} \left(\frac{R_p}{a}\right)^2$$

Measurement of the geometrical albedo A_λ of the dayside hemisphere.

Occultation emission spectrophotometry

Thermal emission measurement: measurement of the brightness temperature of the planet's dayside

Constraint on the day-night heat distribution and on the albedo

$$T_{eq,\,day} = T_* \left(\frac{R_*}{a}\right)^{1/2} [f(1 - A_B)]^{1/4},$$

f = redistribution factor
= 1/4 if incident energy is distributed uniformly by the atmosphere
= 2/3 if it is directly reemitted by the dayside

A_B = Bond albedo

$T_{eq,day}$ can reach 3000K for a hot Jupiter!

Corresponding occultation depth in the near-IR: ~1/1000th

Occultation emission spectrophotometry

Bond albedo A_B = fraction of incident energy reflected back to space. A_B between 0 and 1

Geometrical albedo $A_g(\lambda)$ = ratio between the flux of the light reflected by a planet seen at phase angle α=0 and the flux of the light reflected by a Lambertian disk of same angular size.

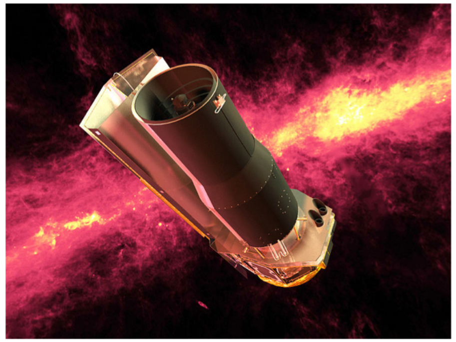
Lambertian surface = fully reflecting surface, with an isotropic emission surface intensity (e.g. a white sheet).

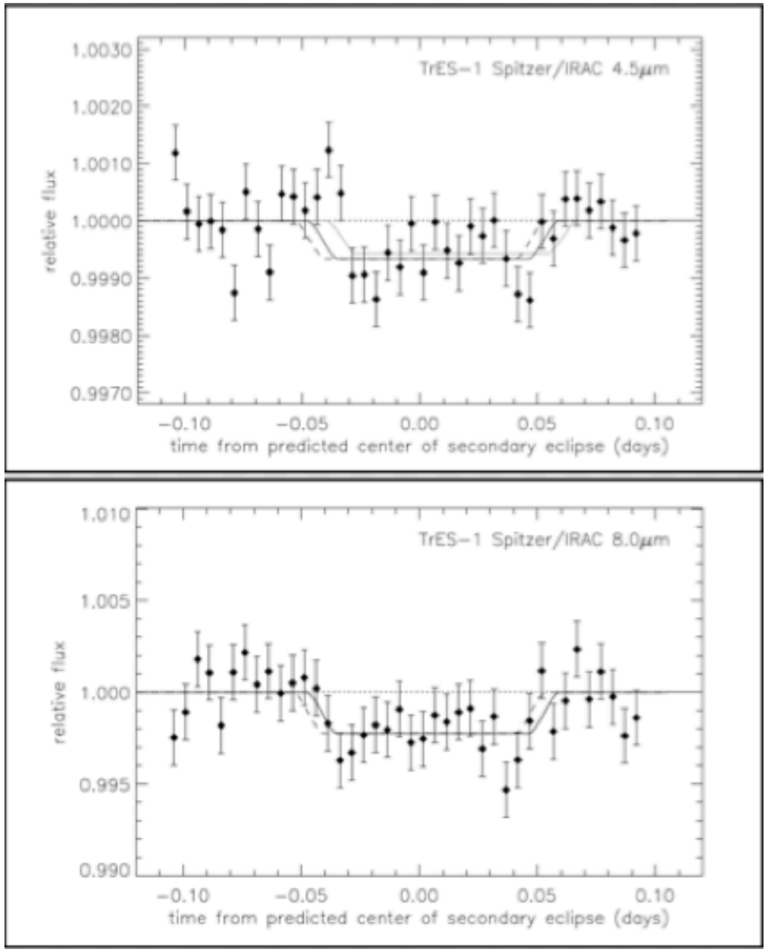
$A_g(\lambda)$ can be > 1 ! e.g. A_g(optical) for Enceladus = 1.38
Depends on the scattering properties of the surface material.

Brightness temperature $T_b(\lambda)$ = temperature of a black body for which the flux at the wavelength λ would match the measured flux.

Occultation emission spectrophotometry

First detection: 2005 – TrES-1b – *Charbonneau et al. (2005)*
Instrument : Spitzer/IRAC at 4.5 and 8 microns





$dF_{4.5\mu m} = 660 \pm 130$ ppm
$dF_{8\mu m} = 2250 \pm 360$ ppm

$T_{b,4.5\mu m} = 1010 \pm 60$ K
$T_{b,8\mu m} = 1230 \pm 110$ K

↓

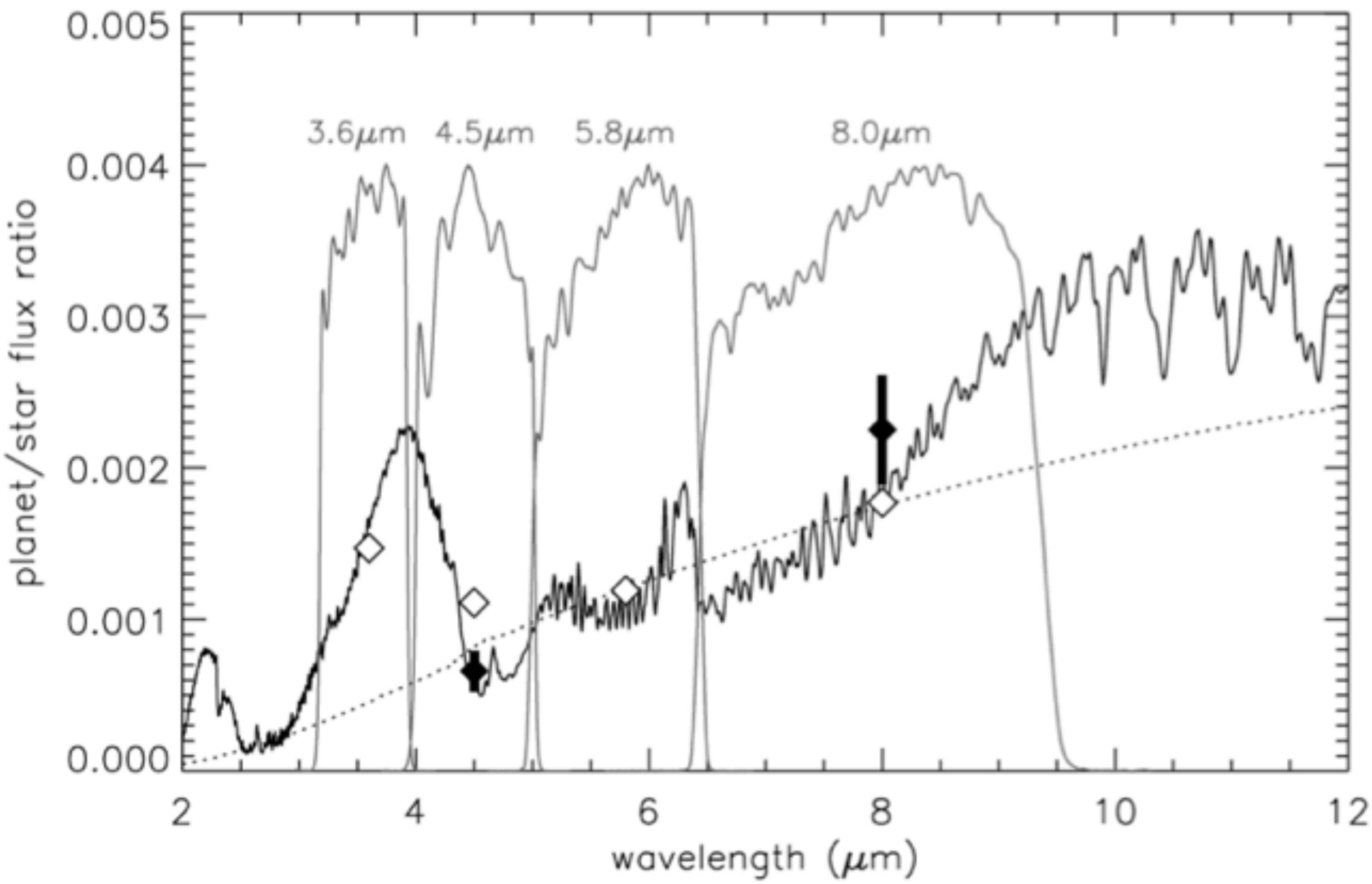
$T_{eq,jour} = 1060 \pm 50$ K

➔ **$A_B = 0.31 \pm 0.14$ for $f=1/4$**

Of course, a planet is not a black body, and f is unknown…

Occultation emission spectrophotometry: results

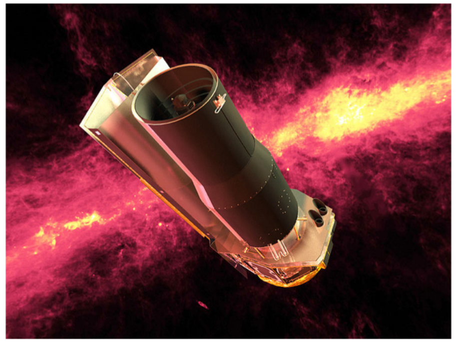
First detection: 2005 – TrES-1b – *Charbonneau et al. (2005)*
Instrumen : Spitzer/IRAC at 4.5 and 8 microns

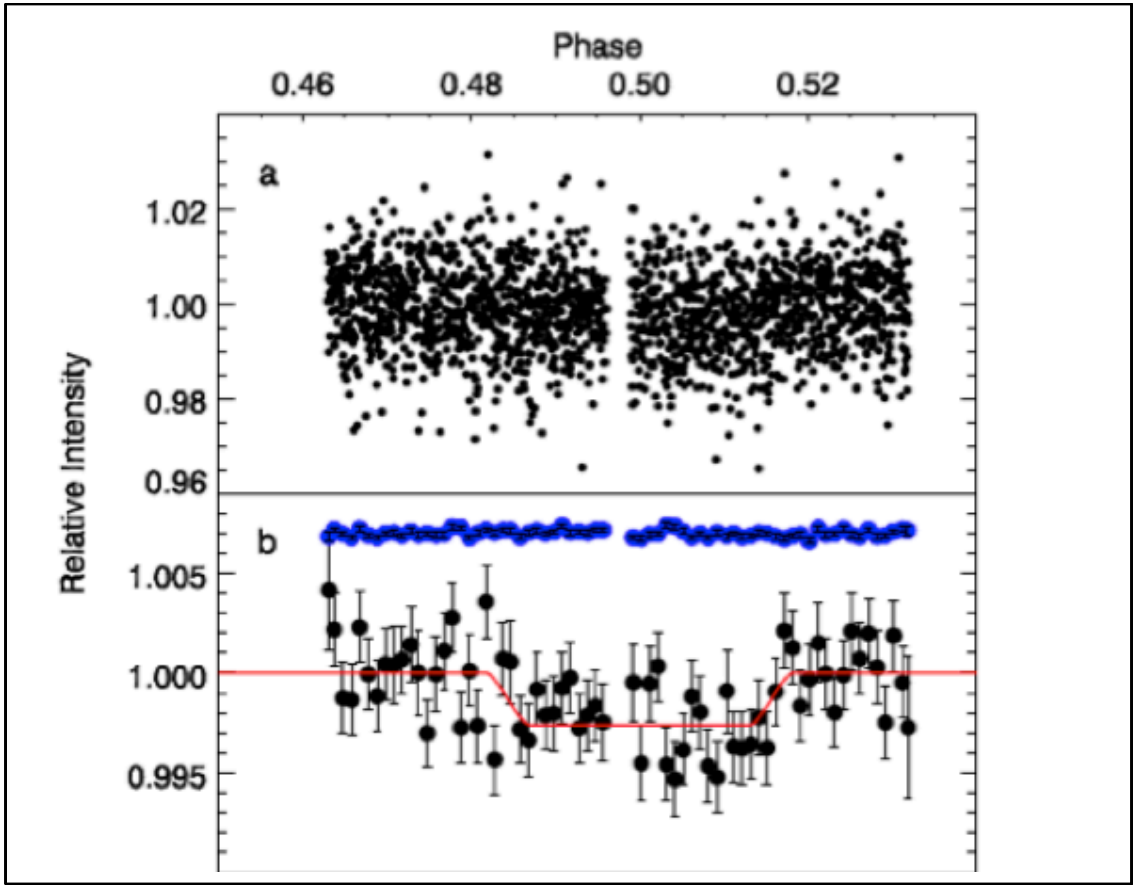


Model for 51 Peg b *(Sudarsky et al. 2003)* adapted to TrES-1b

Occultation emission spectrophotometry

First detection: 2005 - HD209458b – *Deming et al. (2005)*
Instrument: Spitzer/MIPS at 24 microns





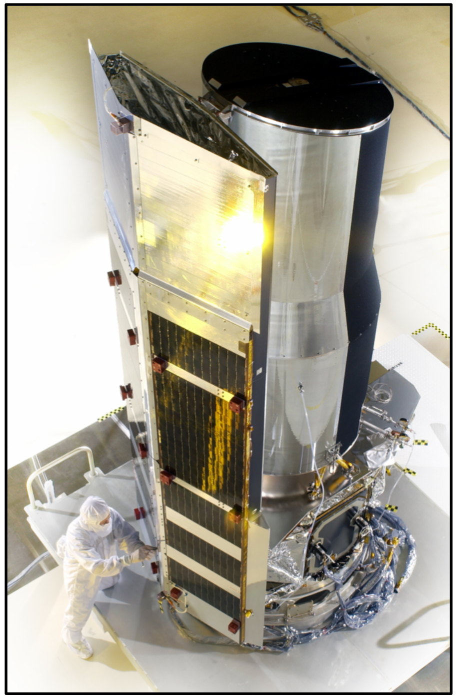
$dF_{24\mu m}$ = 260 ± 50 ppm

$T_{b,24\mu m}$ = 1130 ± 150 K

Occultation emission spectrophotometry

The important contribution of the Spitzer Space Telescope

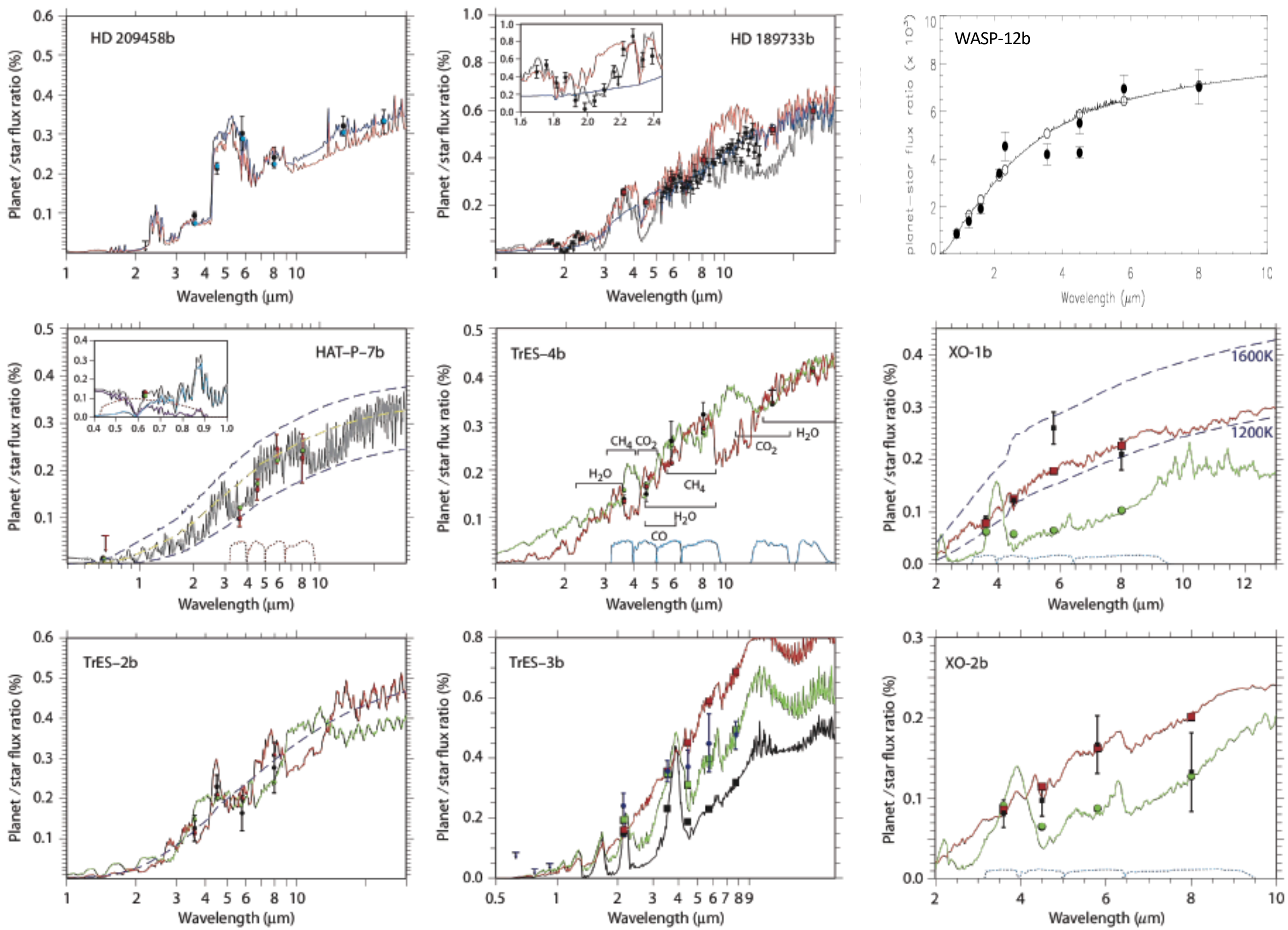
- Launch in 2003
- Cryogenized to 5.5K (Beryllium mirror) by liquid He until May 2009
- 85 cm aperture
- Heliocentric orbit, receding from Earth (0.1 au/yr)
- 3 instruments:
  - ◆ IRAC camera (3.6, 4.5, 5.8, and 8µm)
  - ◆ IRS spectrograph (5 & 40 µm), low (R~60-130) and medium (R~600) resolution
  - ◆ MIPS camera (24, 70, 160 µm)



Occultation emission spectrophotometry: results

The large contribution of Spitzer

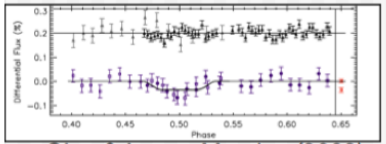
Deming & Seager (2010); Crossfield et al. (2012)



Occultation emission spectrophotometry: results

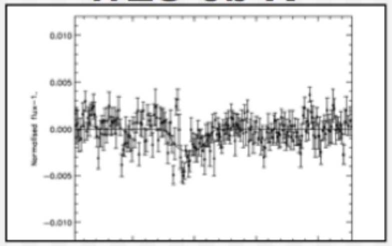
The complementary contribution of ground-based telescopes: the near-IR (JHK)

OGLE-TR-56b z'



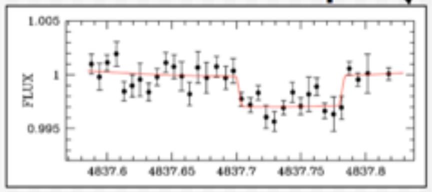
Sing & Lopez-Morales (2009)

TrES-3b K



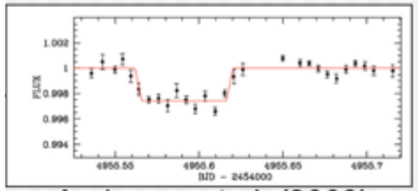
De Mooij & Snellen (2009)

CoRoT-1b 2.09 µm



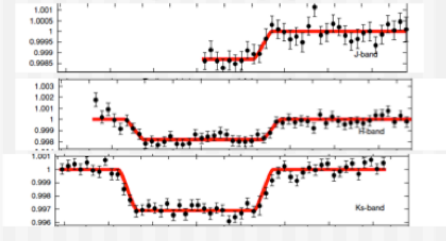
Gillon et al. (2009)

WASP-19b H



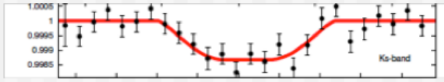
Anderson et al. (2009)

WASP-12b J H K



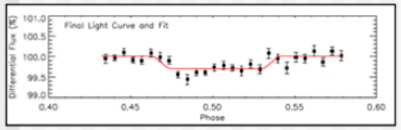
Croll et al. (2011)

TrES-3b K



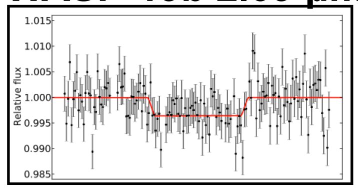
Croll et al. (2010b)

CoRoT-1b K



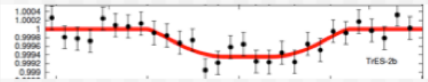
Rogers et al. (2010)

WASP-19b 2.09 µm



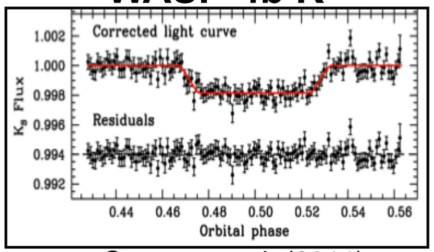
Gibson et al. (2010)

TrES-2b K



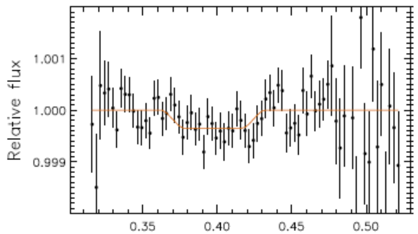
Croll et al. (2010a)

WASP-4b K



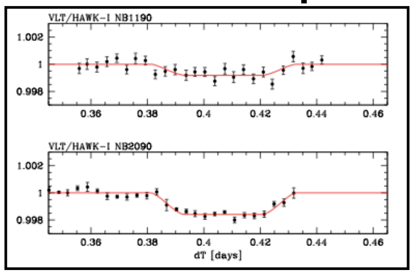
Caceres et al. (2011)

WASP-19b z'



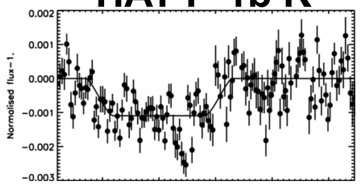
Lend et al. (2013)

WASP-43b
1.19 & 2.09 µm



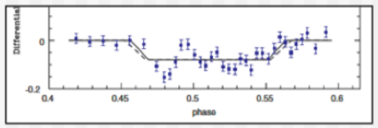
Gillon et al. (2012)

HAT-P-1b K



De Mooij et al. (2011)

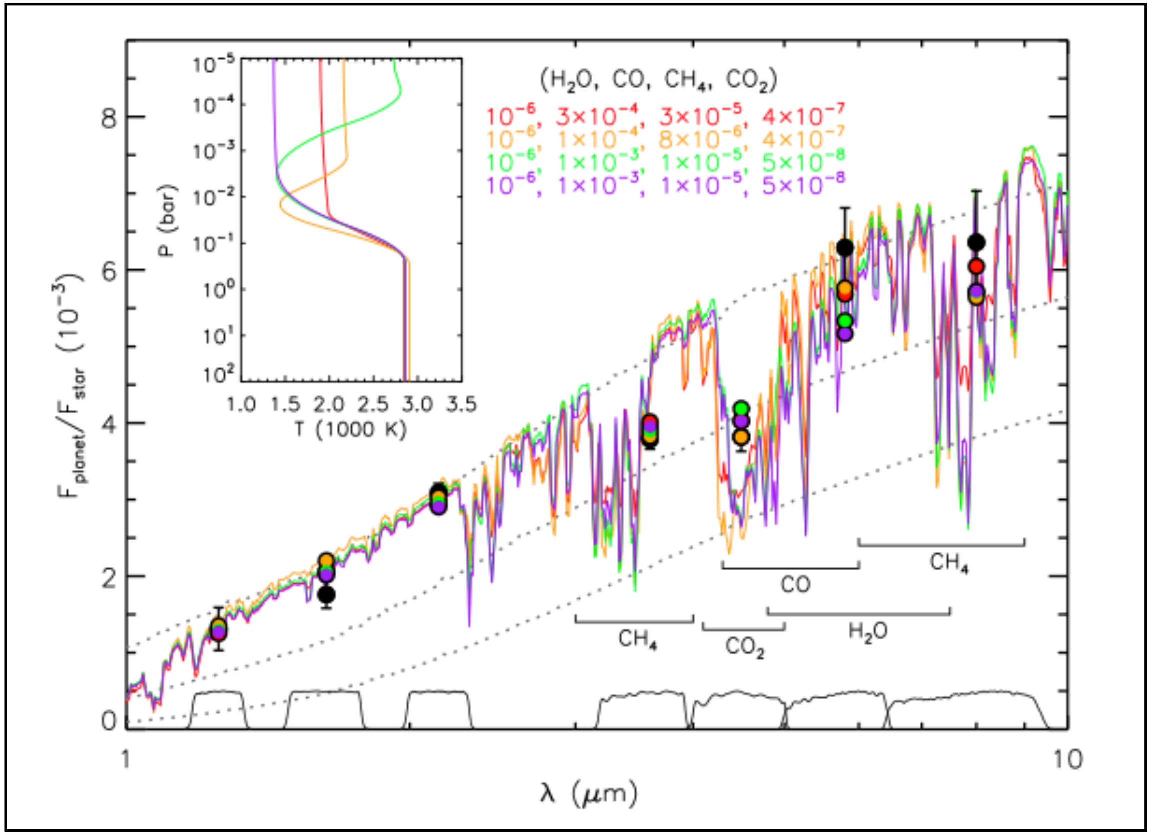
WASP-12b z'



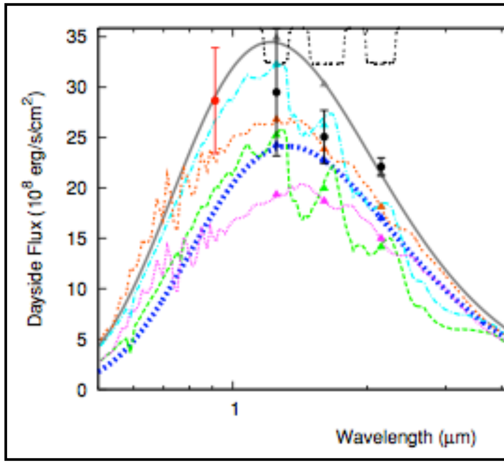
Lopez-Morales et al. (2010)

Occultation emission spectrophotometry: results

The complementary contribution of ground-based telescopes the near-IR (JHK) = SED peak of hot Jupiters



Madhusudhan et al. (2011)



Croll et al. (2011)

WASP-12b: a planet without stratosphere and with a large C/O ratio?

Not so sure… *(Crossfield et al. 2013)*

Occultation emission spectrophotometry: results

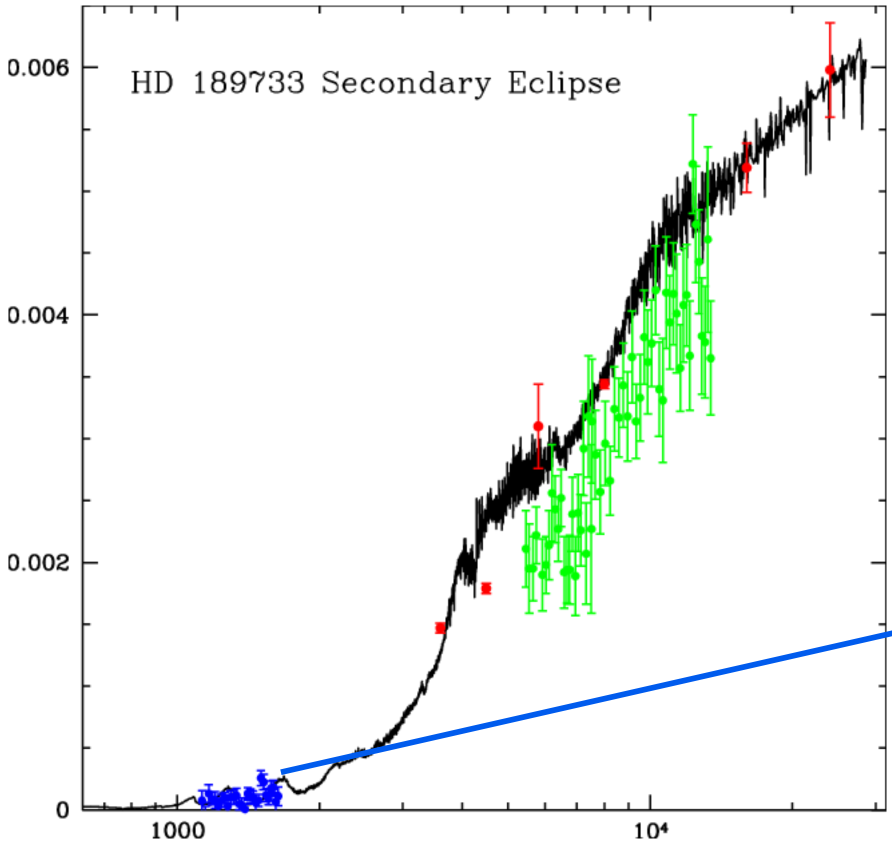
HD 189733b

Spitzer/MIPS 24µm
Spitzer/IRS 16µm
Spitzer/IRS spectrum from 5 to 15 µm
Spitzer/IRAC 3.6, 4.5, 5.8, 8 µm
HST/NICMOS spectrum from 1.7 to 2.5 µm

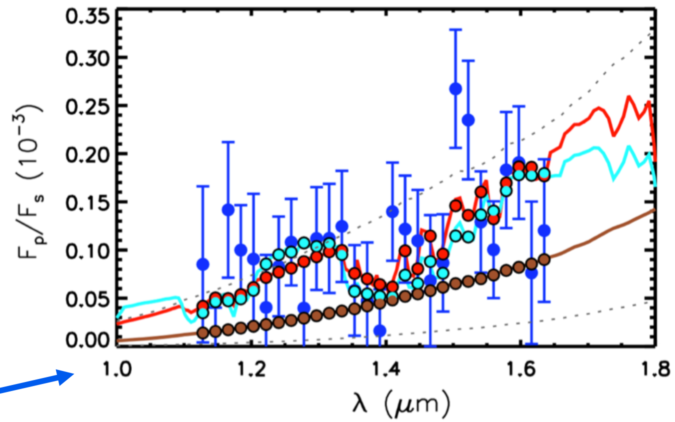
Marginal water detection
(Crouzet et al. 2014)

Thermal profile: monotone, no stratosphere detected *(Madhusudhan & Seager 2009)*

Spectrum dominated by condensates? *(Pont et al. 2013)*



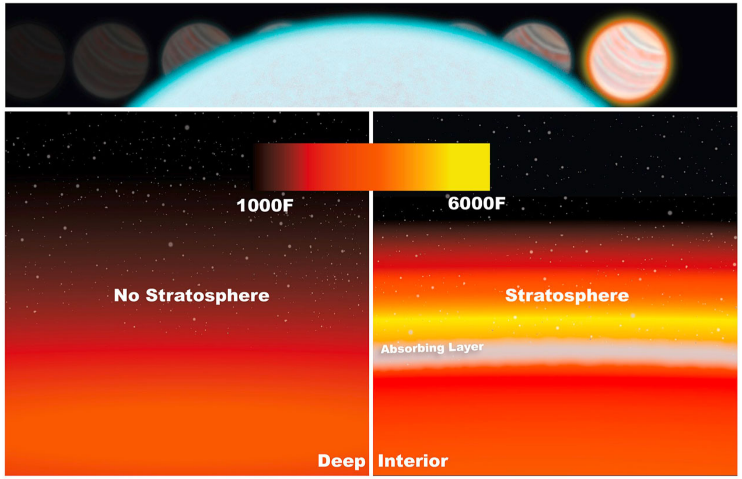
Bailey et al. (2018)



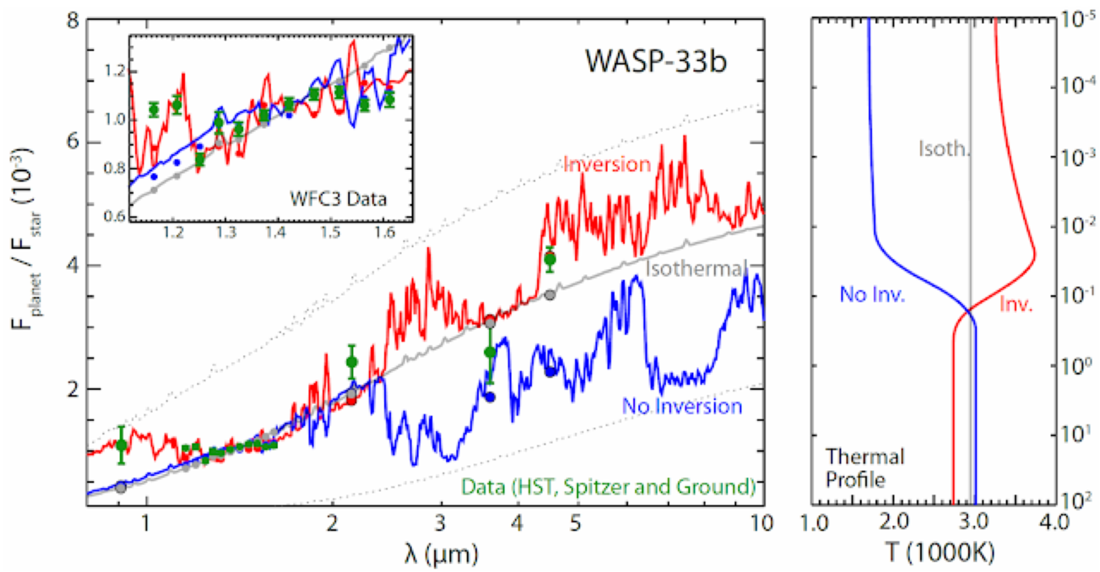
Crouzet et al. (2014)

Occultation emission spectrophotometry: results

Some hot Jupiters have a stratosphere

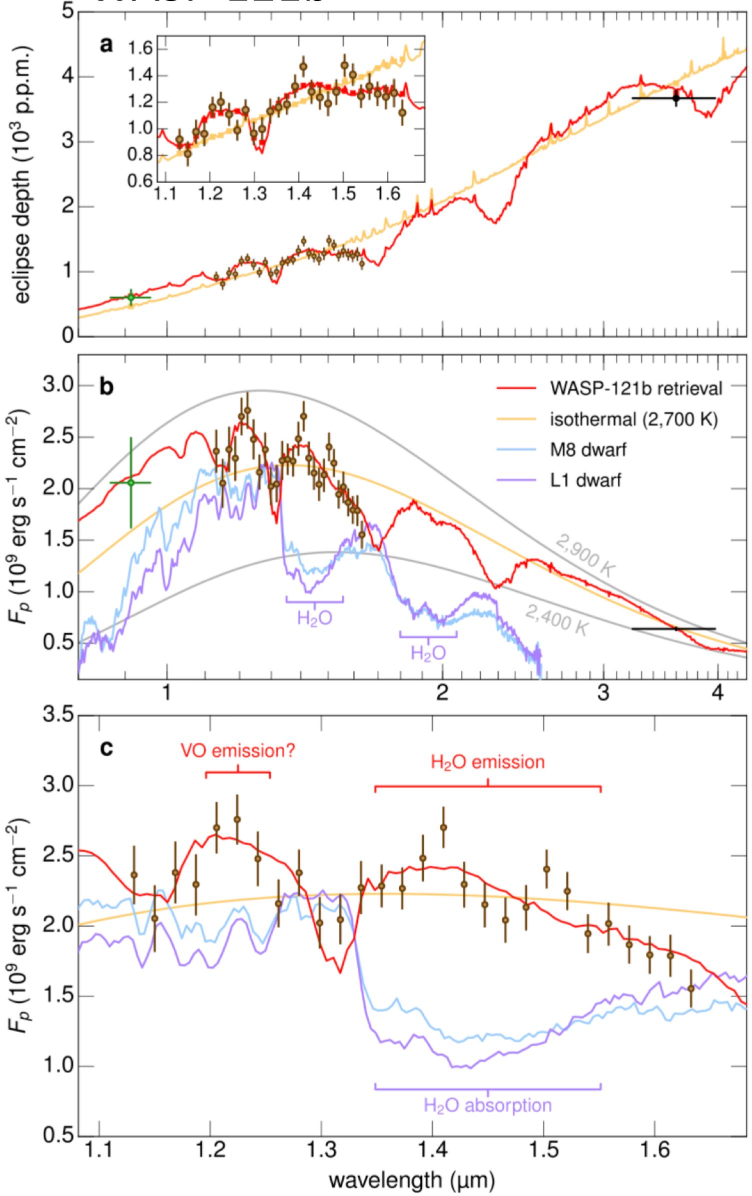


WASP-33b



Mandel et al. (2015)

WASP-121b

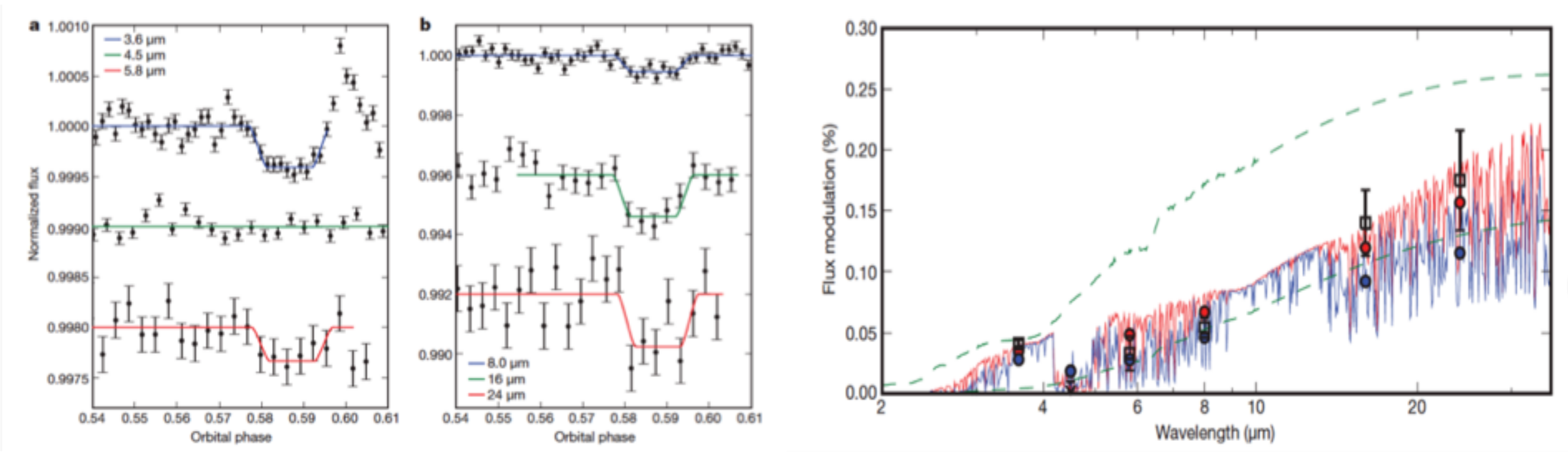


Evans et al. (2017)

Occultation emission spectrophotometry: results

The first emission spectrum of a 'hot Neptune'

Stevenson et al. (2010)



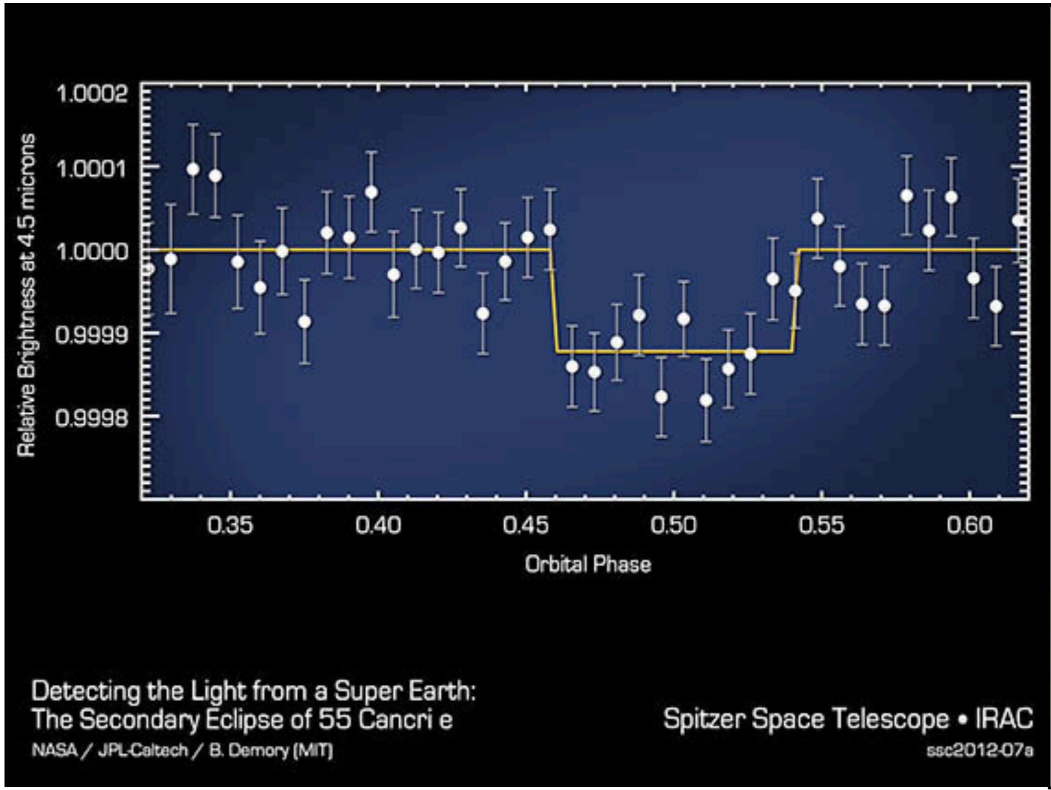
High CO abundance, deficiency in CH_4

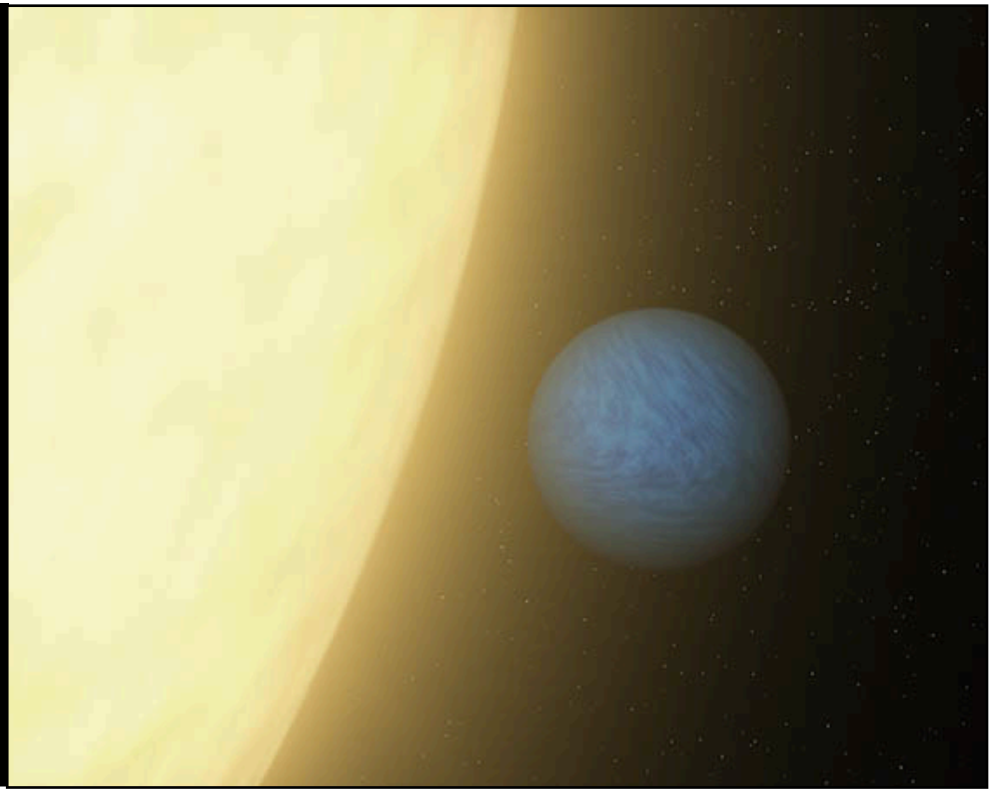
CH_4/CO ratio at least 10^5 times smaller than expected…

Chemical disequilibrium? (vertical mixing? methane polymerisation?)

Occultation emission spectrophotometry: results

The first detection of the light of a 'super-Earth' *Demory et al. (2012)*

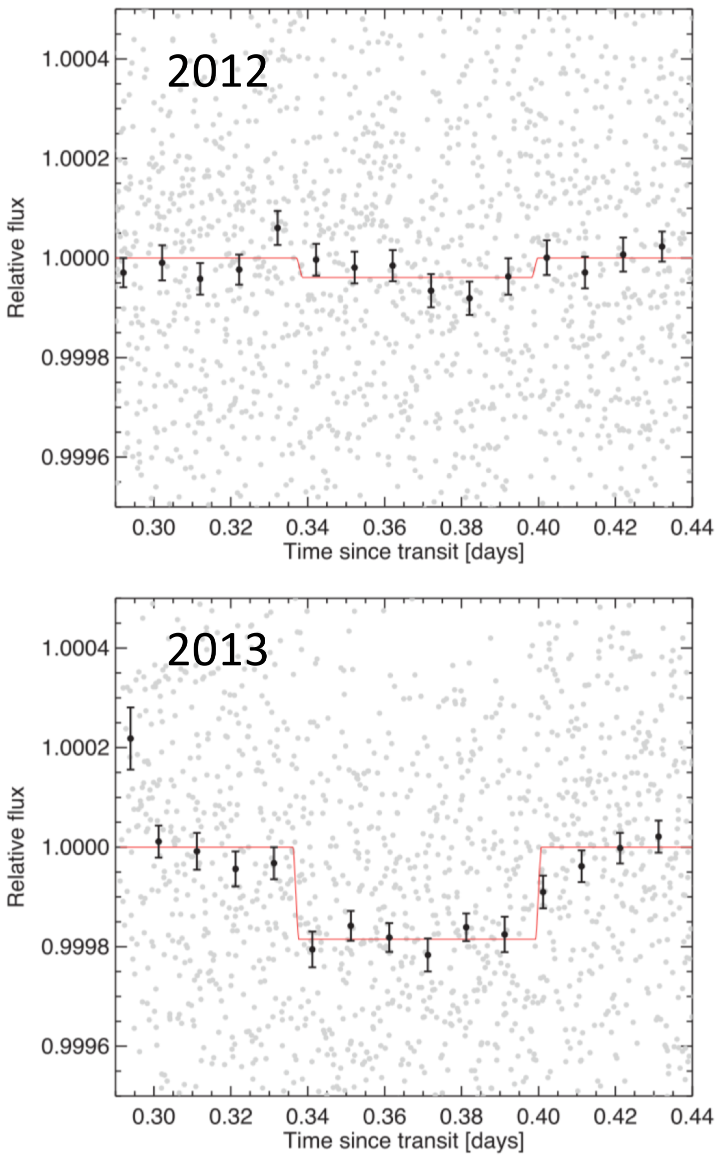


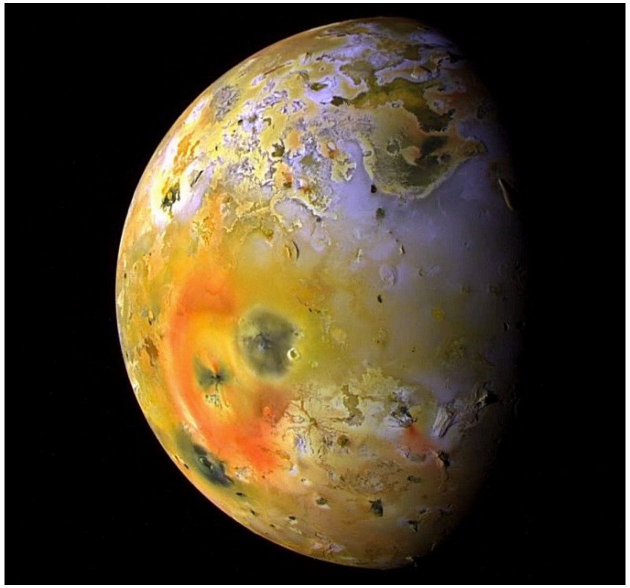


131±28 ppm – $T_{brightness}$ = 2350±300 K
Spitzer IRAC - 4.5μm – 4 observed occultations
2 R_{earth} + G8-type star at 12pc – V=6, K=4
P < 18hrs!

Occultation emission spectrophotometry: results

The variable emission of the super-Earth 55 Cnc e





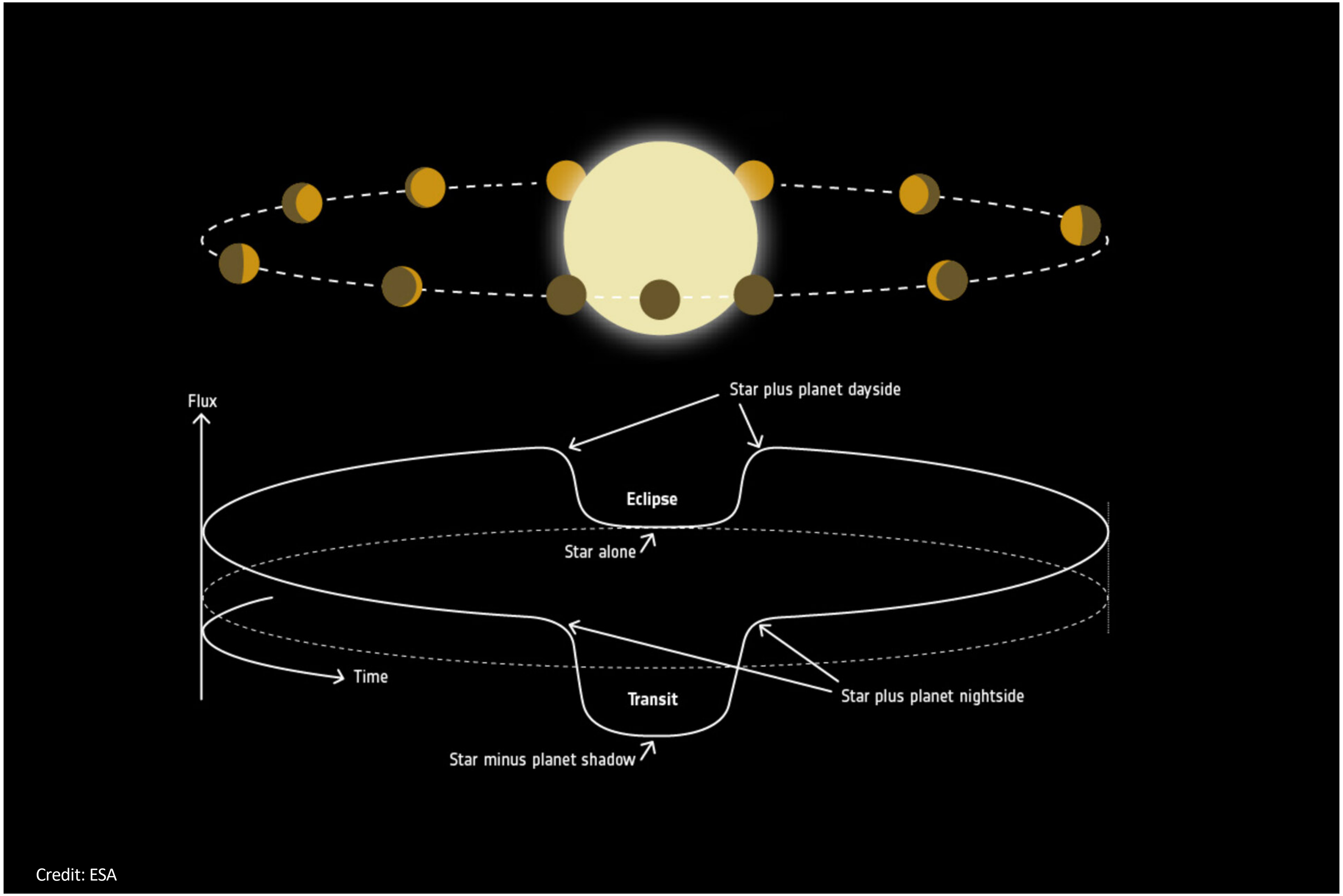
Io-like volcanism?

Tore of circumstellar material?

Demory et al. (2016)

Phase curve

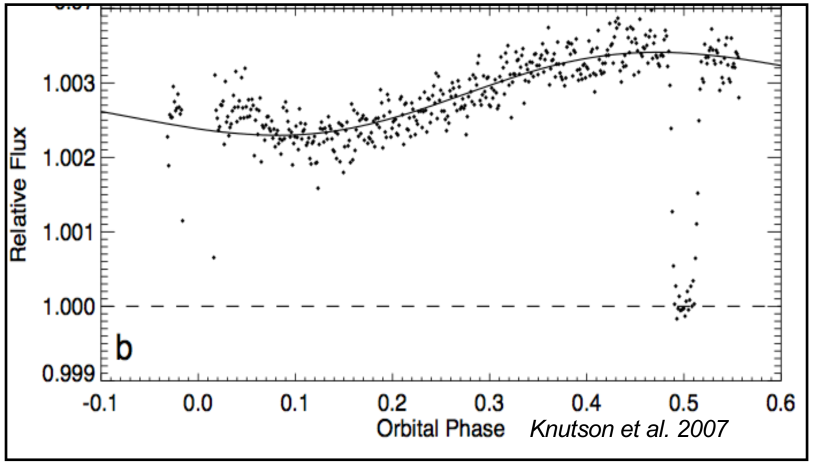
Longitudinal map = constraint on the heat transfert and albedo



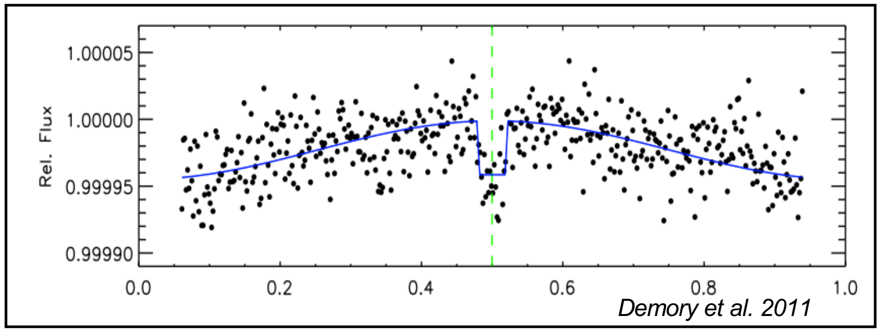
Phase curve

Longitudinal map = constraint on the heat transfert and albedo

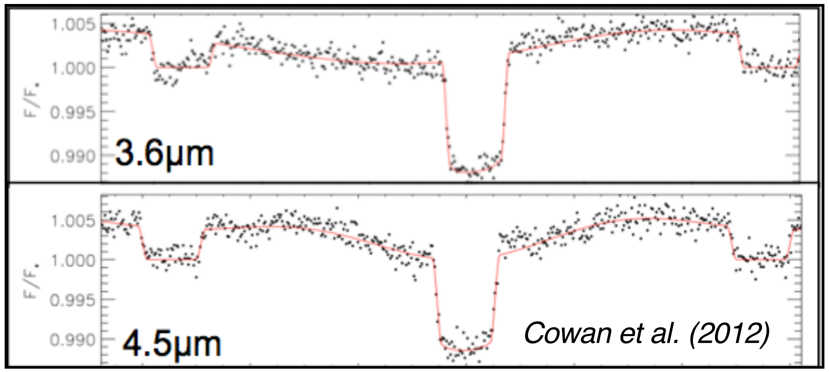
Degeneracy heat transfert/albedo raised by phase curve in the optical (albedo) & IR (heat transfert).



HD189733b – Spitzer photometry at 8µm
Efficient distribution & hot spot shifted to the East

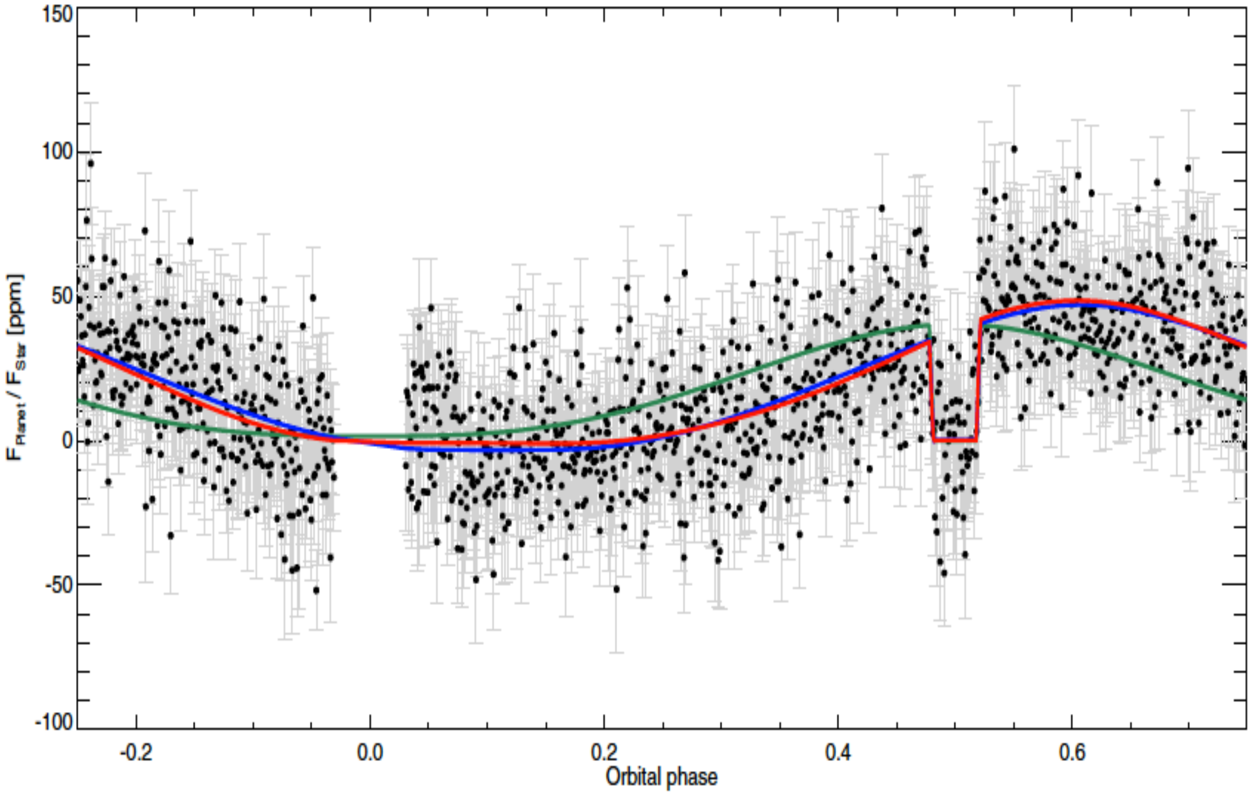


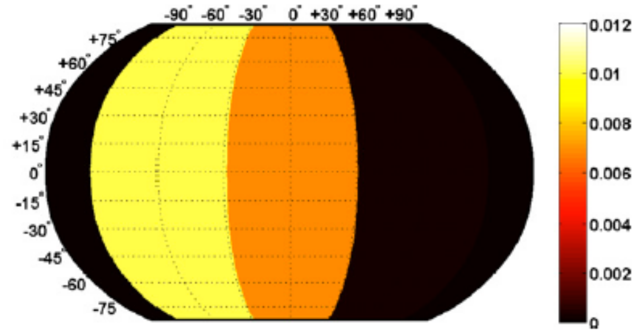
Kepler-7b – Kepler photometry in the optical
High albedo for a hot Jupiter (A_g~0.3)



WASP-12b – Spitzer photometry at 3.6/4.5µm
Inefficient distribution and non-zero albedo

Phase curve and 1D map: example





Demory et al. (2013)

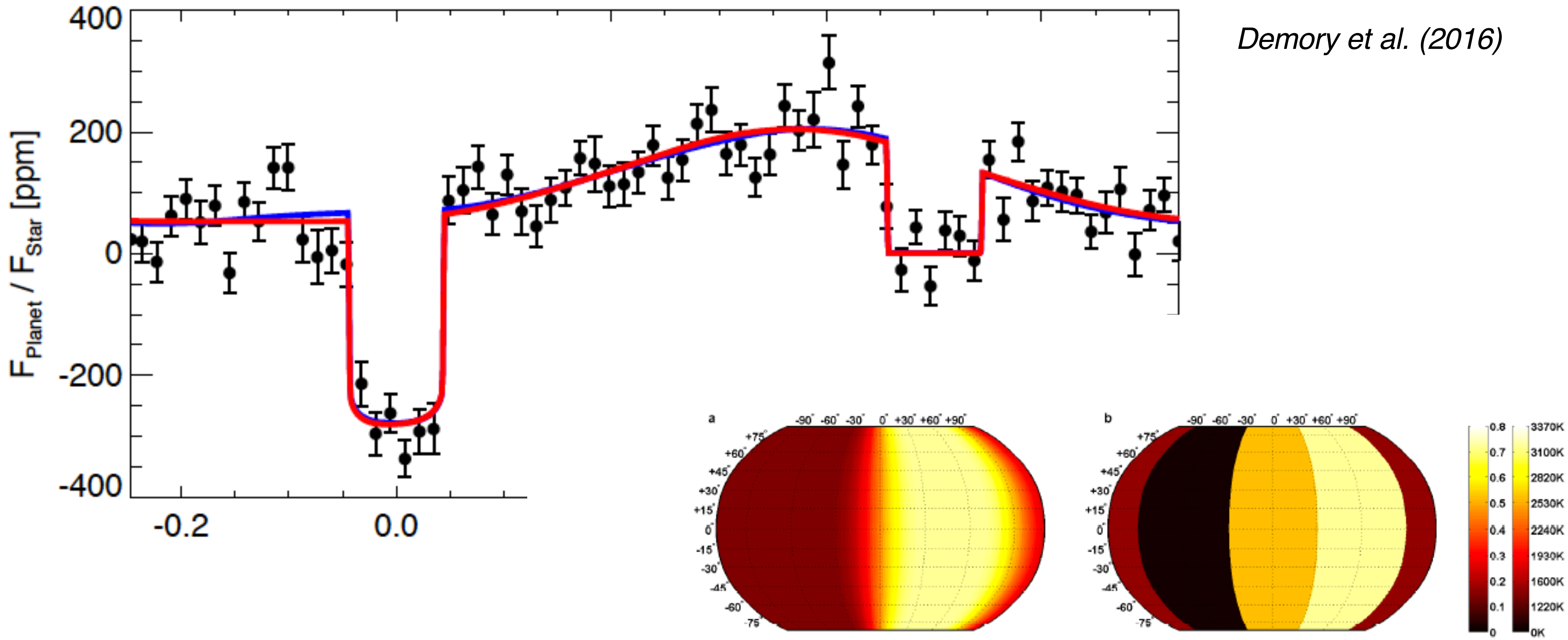
Hot Jupiter Kepler-7 : 0.45 M_J, 1.6 R_J, T_{eq} = 1600K

Occultation not detected by Spitzer ➔ **reflected light**

$A_g = 0.35 \pm 0.02$

Shape of the phase curve indicates a variation of the reflecting surface with longitude ➔ **clouds** (silicates?)

Phase curve and 1D map: super-Earth!

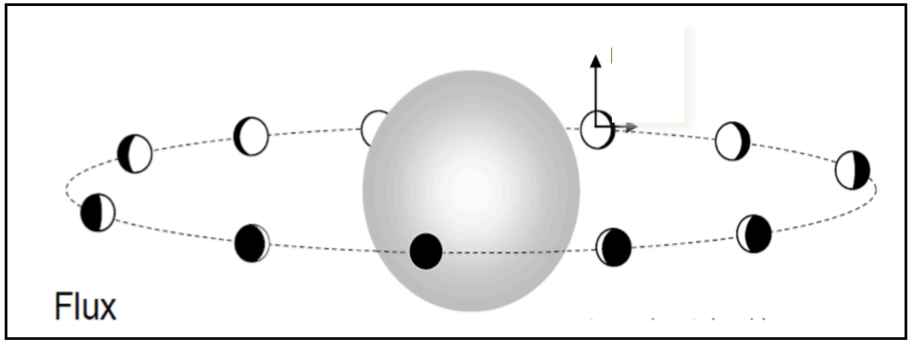


Demory et al. (2016)

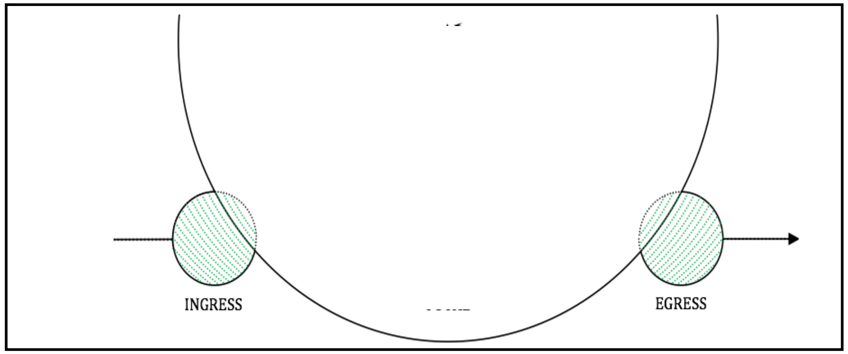
55 Cancri e: 8 M_{Earth}, 2 R_{Earth}, on a 18hr orbit around a nearby solar-type star
Day side is heated up to 3000K!
Night side is 1300K cooler
This large thermal gradient is consistent with an atmosphereless rocky planet
Phase shift: lava flows on the dayside?

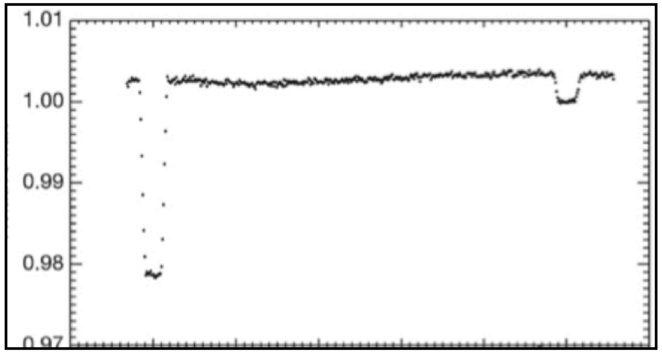
Phase curve + eclipse scanning

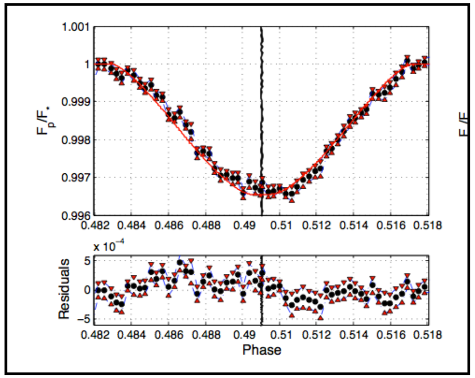
2D-map of exoplanets!

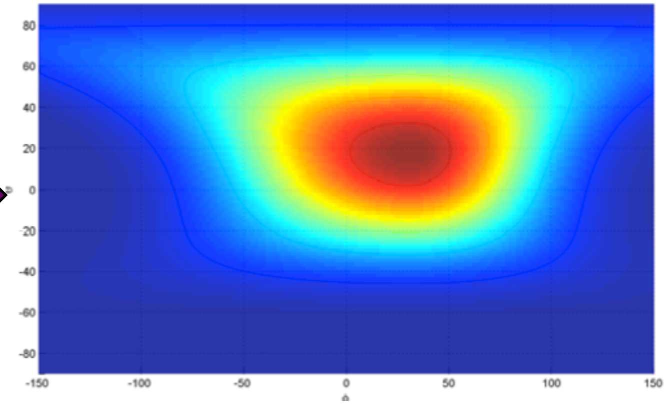


+









HD189733b

Global analysis of Spitzer data

e < 0.0081 (at 2-σ)

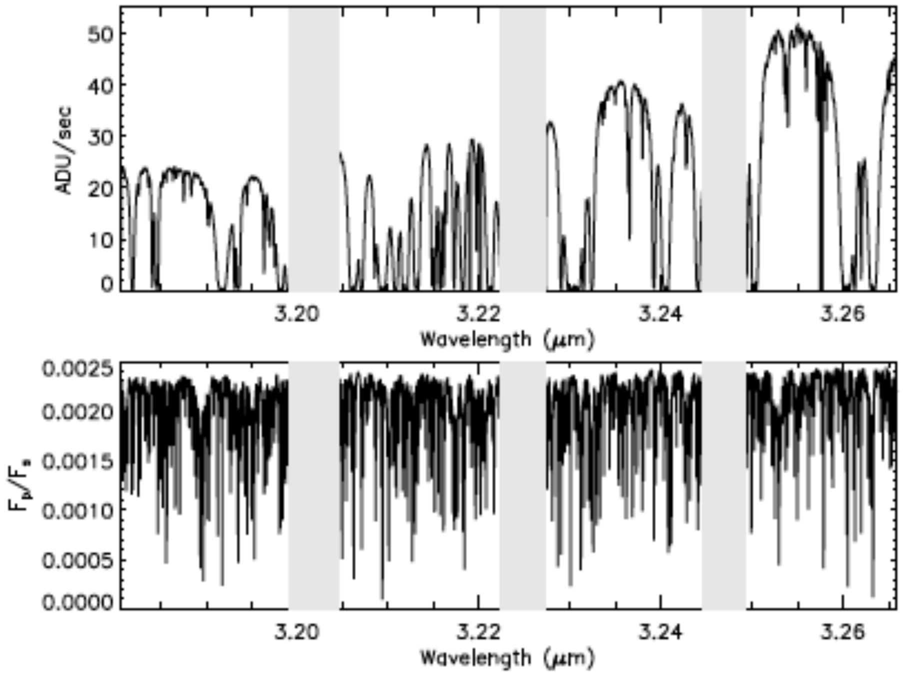
Hot spot at 24±11° E, 17±10° N

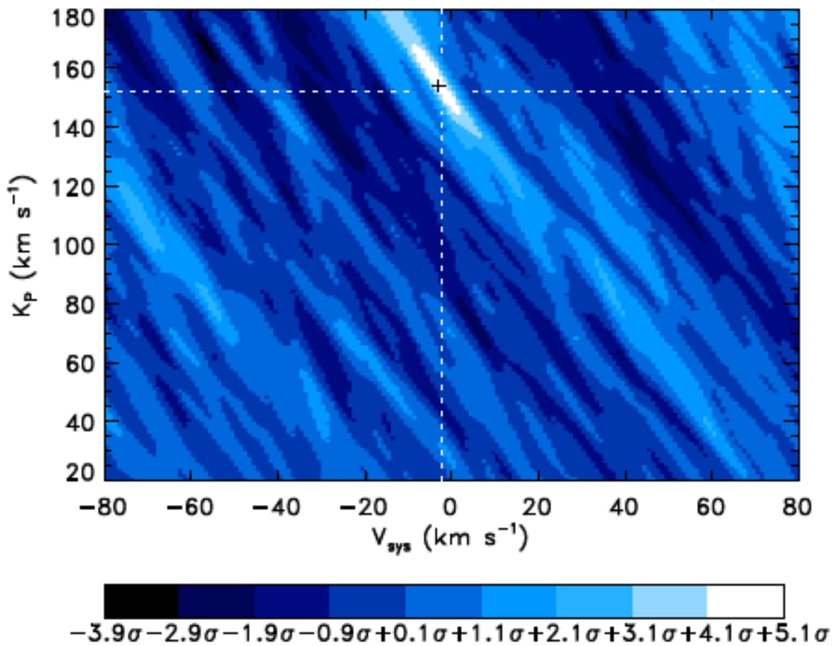
de Witt et al. (2012)

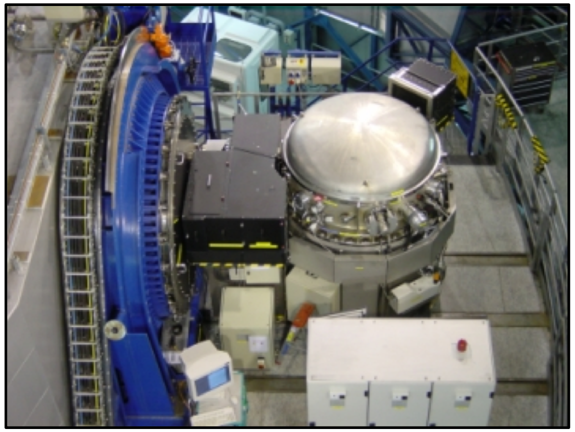
See also Majeau et al. (2012)

High-resolution phase spectroscopy

Birkby et al. (2013)







VLT/CRIRES, R=100000, 3.2µm

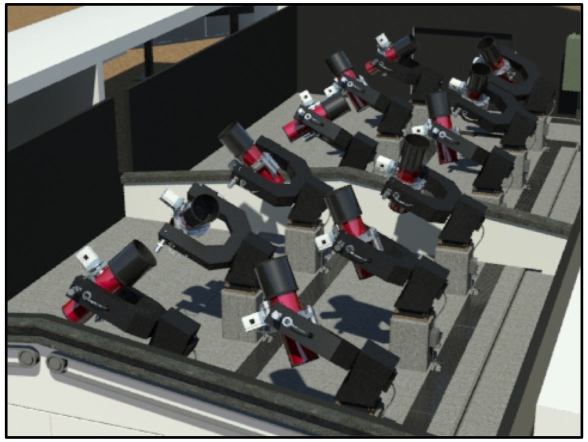
Detection of H_2O at 5-σ

Phase from 0.38 to 0.48, dVR_p ~75 km/s

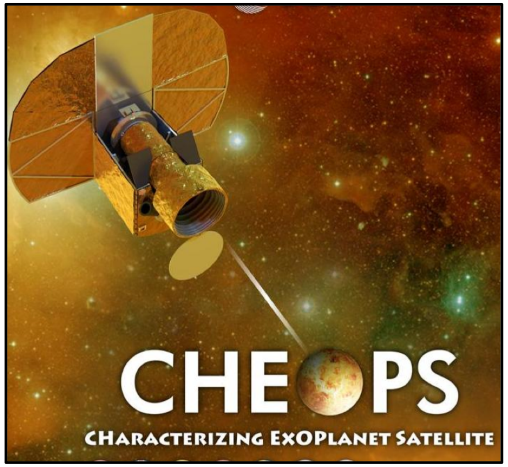
Transiting planets: present & future

1. Detections

Next-**G**eneration **T**ransit **S**urvey (**NGTS**)
ESO Paranal – since 2016
Search for Neptunes around K- and early-M-type stars with V<13
12 telescopes of 20cm
Field of view of 3°x3° by telescope, 108 deg^2 in total



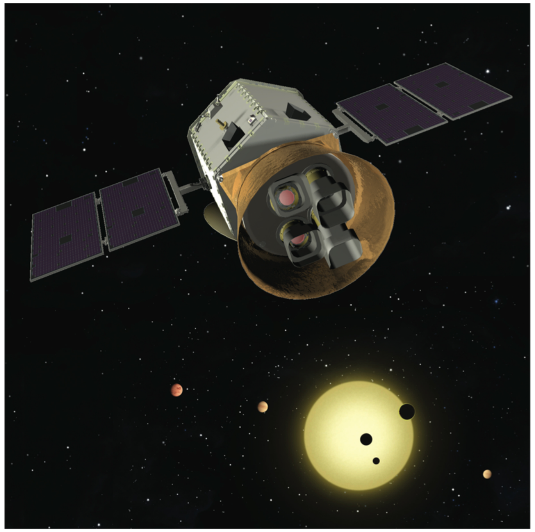
CHaracterising **ExOP**lanets **S**atellite (**CHEOPS**)
Switzerland/ESA and several countries (Belgium)
Telescope of 30cm in low geocentric orbit
Launched in 2019, operations ongoing.
Search for transits of RV planets
Caracterisation of planets transiting nearby stars



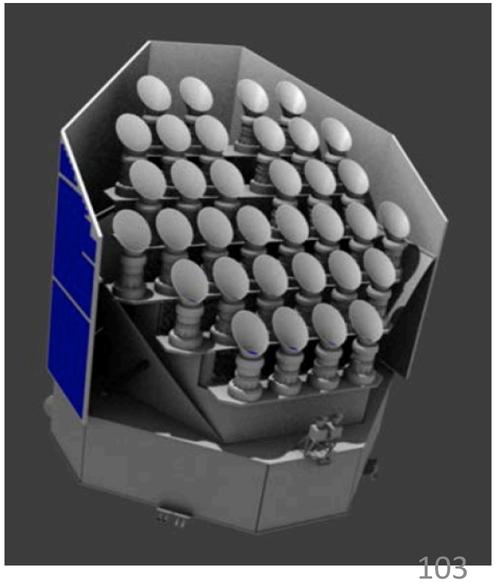
Transiting planets: present & future

1. Detections

Transiting **E**xoplanet **S**urvey **S**atellite (**TESS**)
MIT/NASA – launched in 2018
Orbit in 1:2 resonance with the Moon
Survey of 2 years on all stars with V<12
~27 days per target, more for ecliptic poles
Several lenses of ~13cm
Detection of super-Earths and Neptunes around nearby FGKM-types stars.

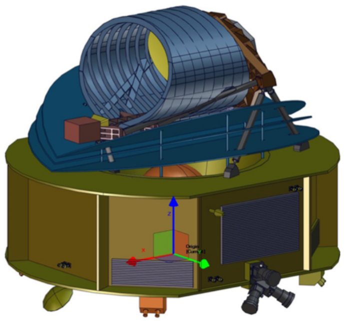


PLAnetary **T**ransits and **O**scillations (**PLATO**)
ESA – ~2025
L2 orbit
Survey of 6 ans covering ~50% of the sky
V magnitude from 4 to 16
85000 stars with V<11
34 telescopes – field of 2250 deg^2
Detection of pot. habitable Earths in front of nearby solar-type stars

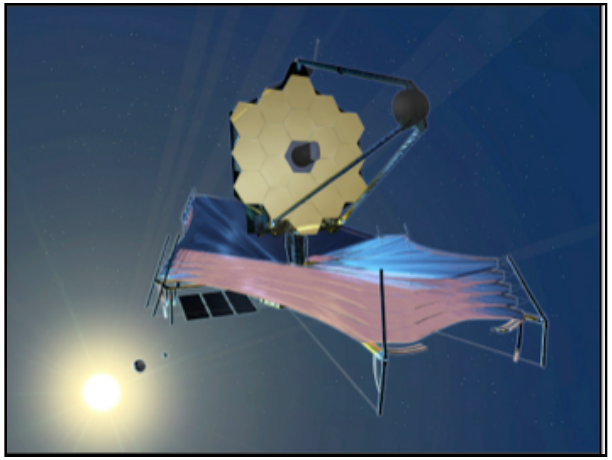


Transiting planets: the future

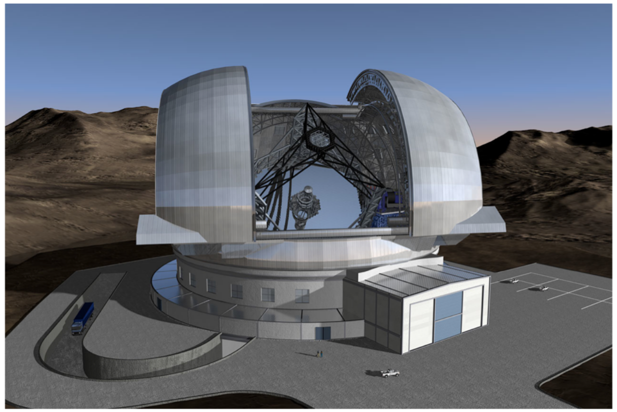
2. Atmospheric study



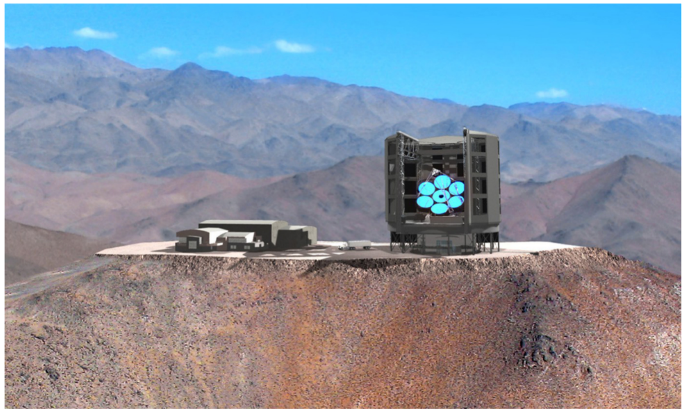
ARIEL
ESA
1.1x0.7m
0.5 to 7.8μm
2028



JWST
NASA+ESA/CSA
6.5m
0.6 to 23μm
2021

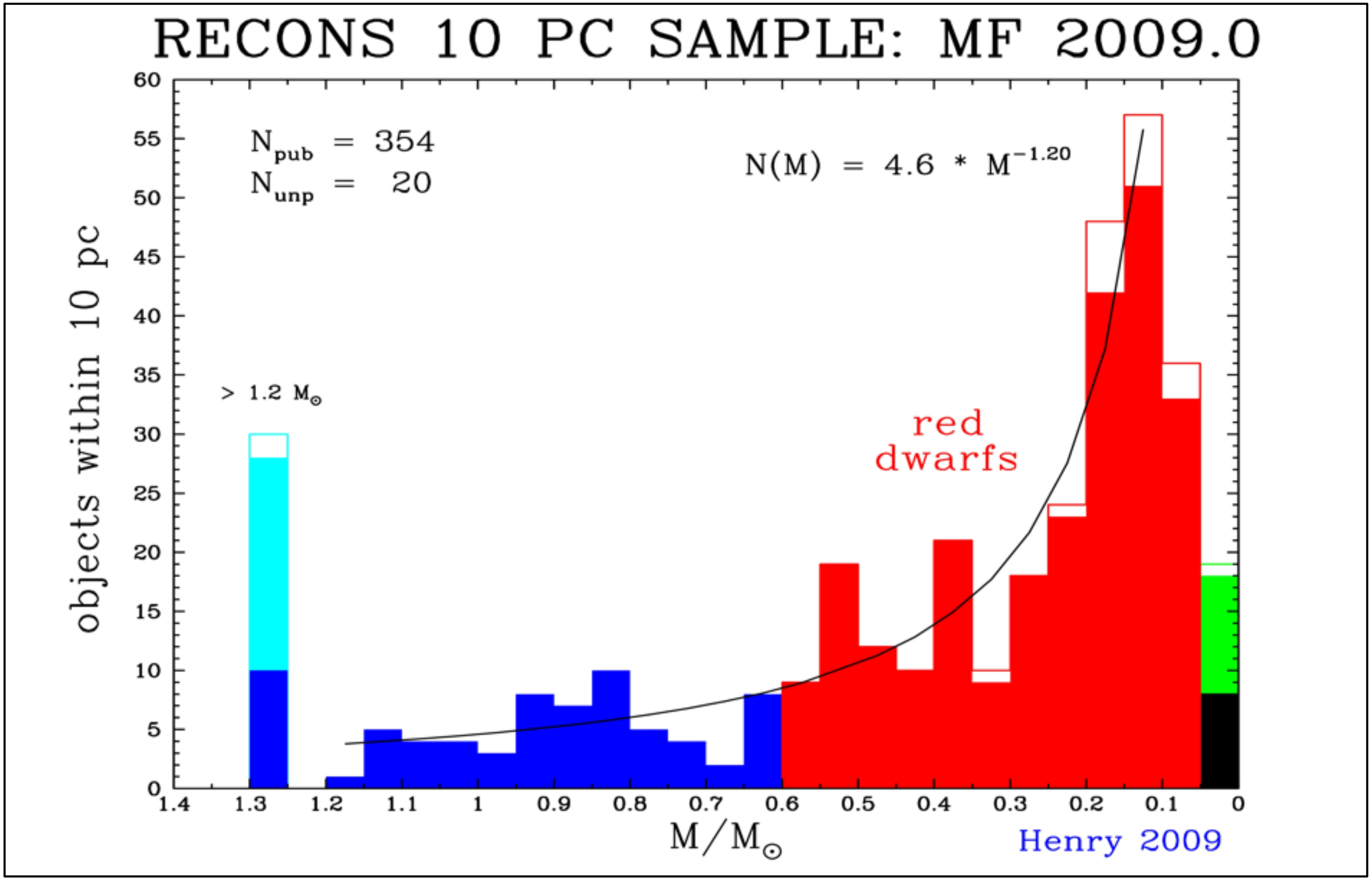


E-ELT
ESO – 39m
Visible + IR
~2025

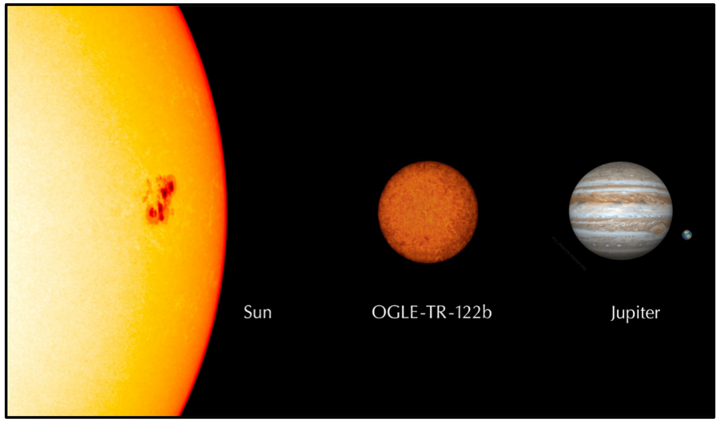


GMT
USA – 25m
Visible + IR
~2025

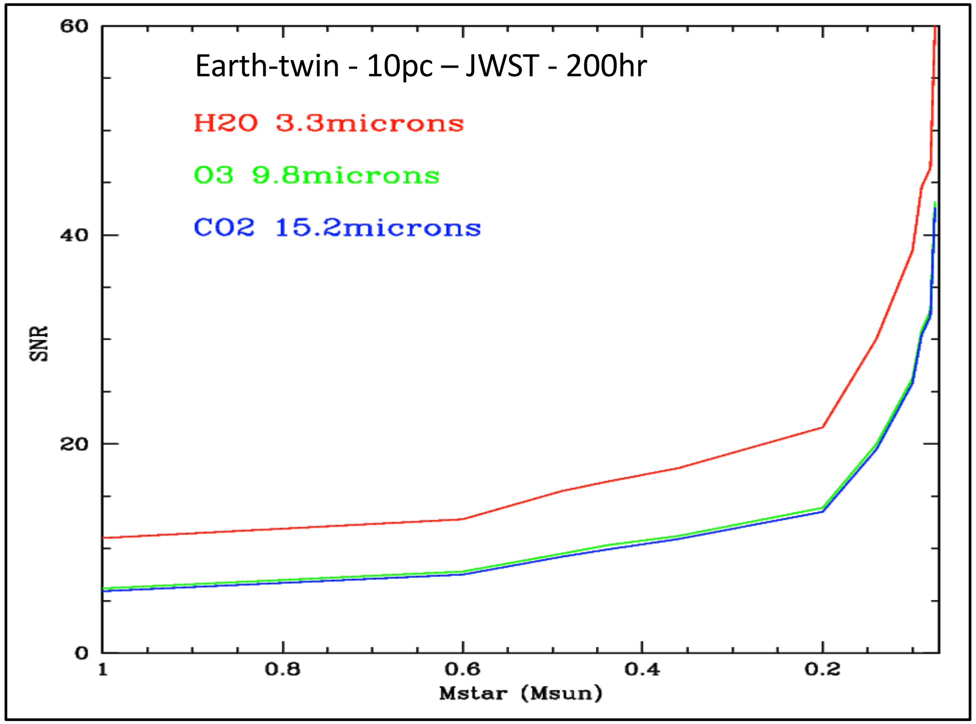
The importance of M-dwarfs



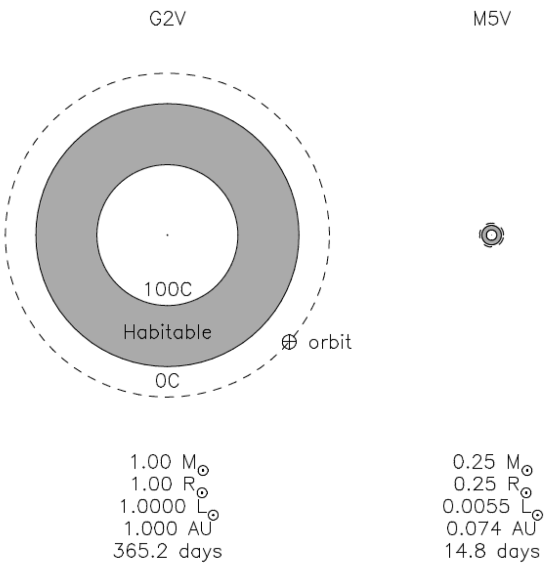
The importance of M-dwarfs



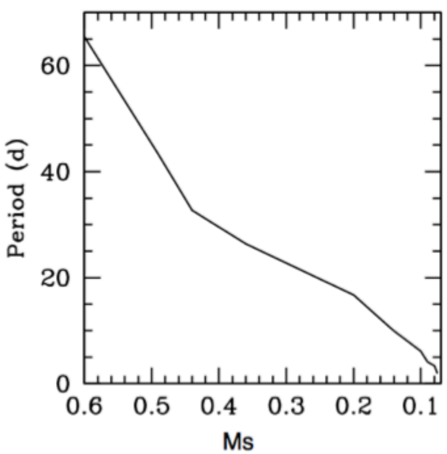
ESO

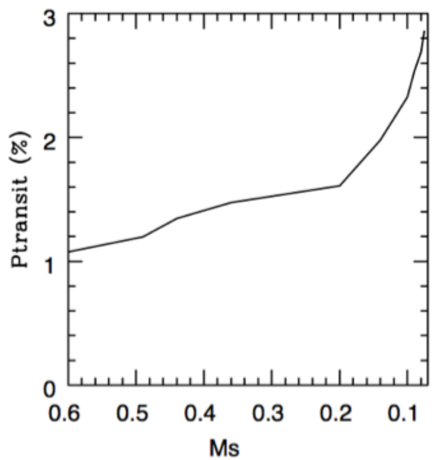


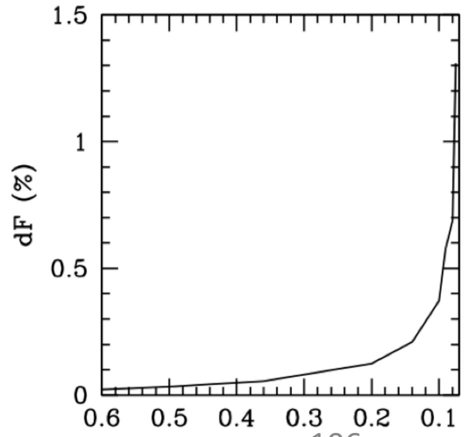
Based on Kaltenegger & Traub (2009)



Charbonneau (2009)

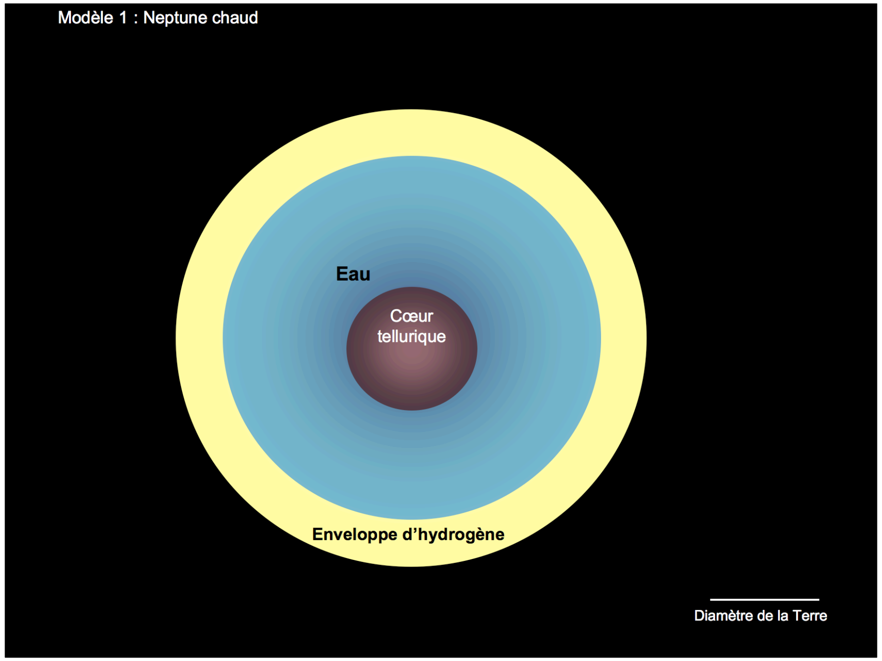


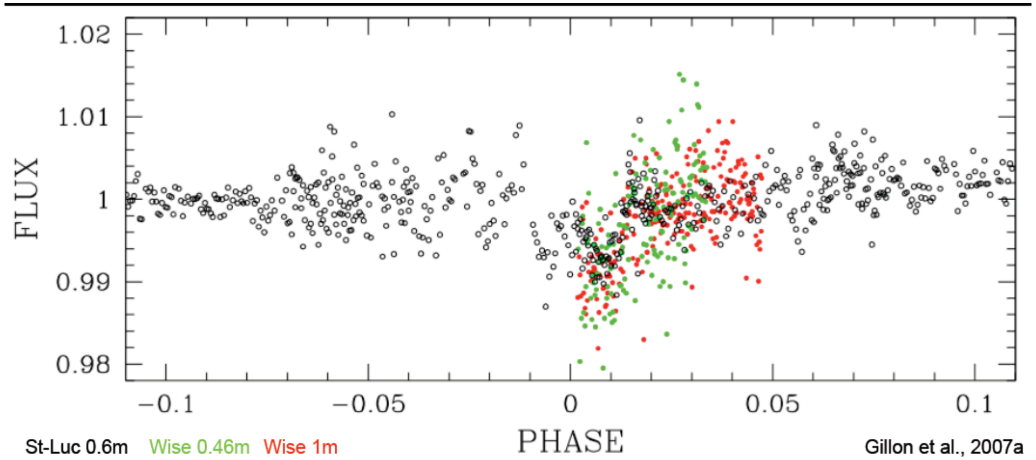


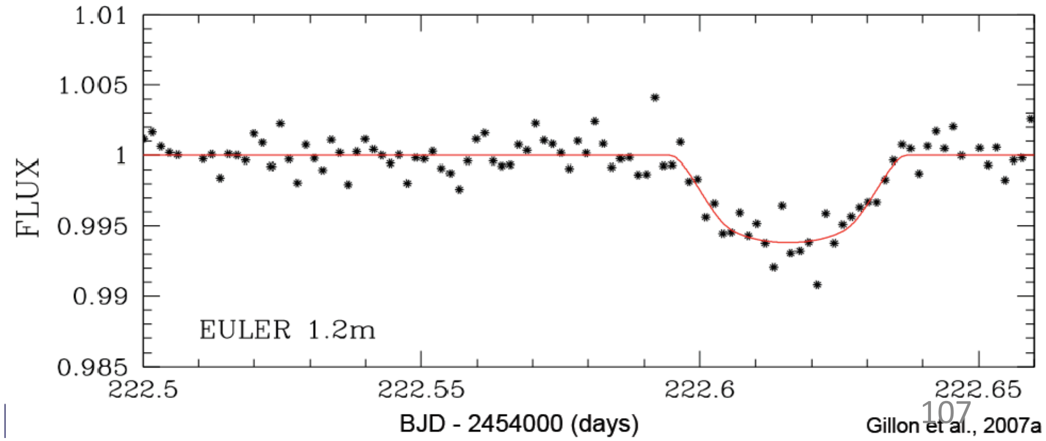


The importance of M-dwarfs

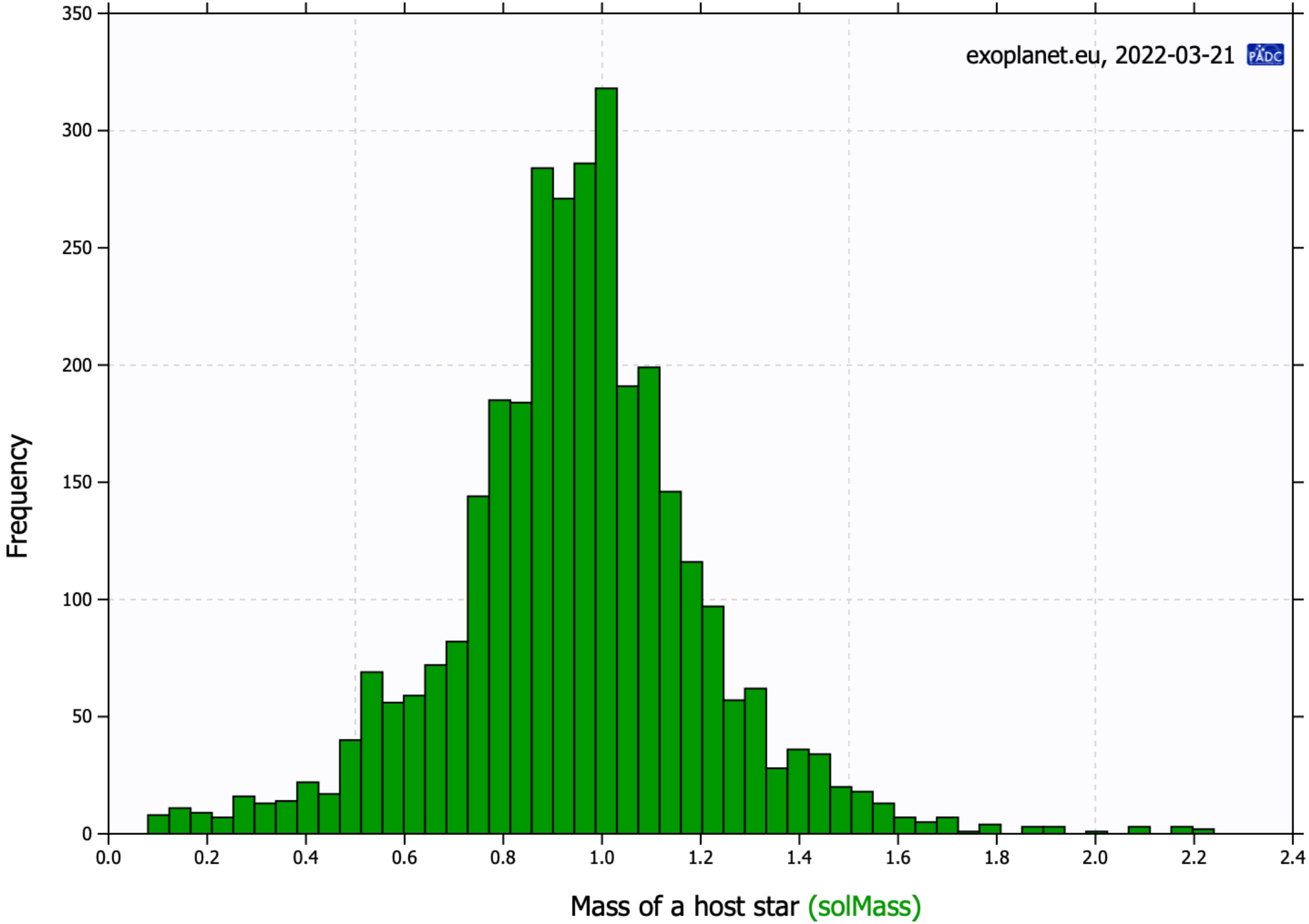
GJ436b : first transiting « Neptune »
Transit detected en 2007 with an amateur 60cm telescope in the Swiss mountains (St-Luc)







The importance of M-dwarfs



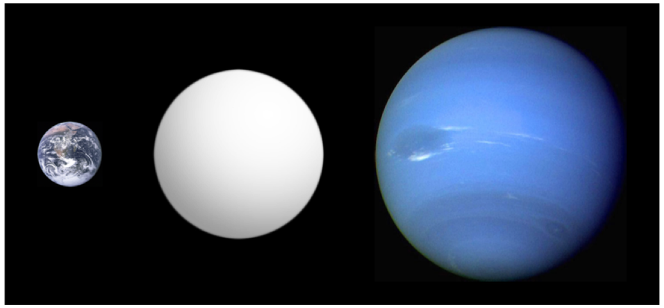
The importance of M-dwarfs

MEarth: 2x8 telescopes of 40cm – Arizona + Chile – individual observations of nearby (<33pc) M-dwarfs smaller than 0.3 Rsun

MEarth-like survey: Apache (Italy)

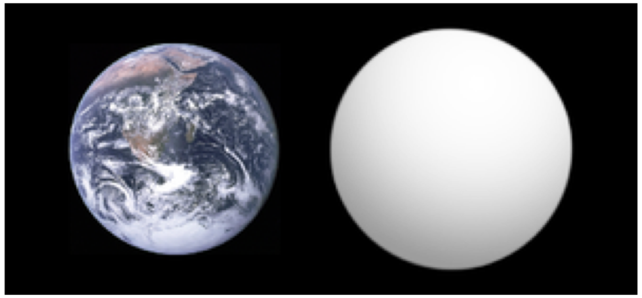
GJ1214b

Charbonneau et al. 2009



The importance of M-dwarfs

MEarth 2nd discovery: GJ1132b



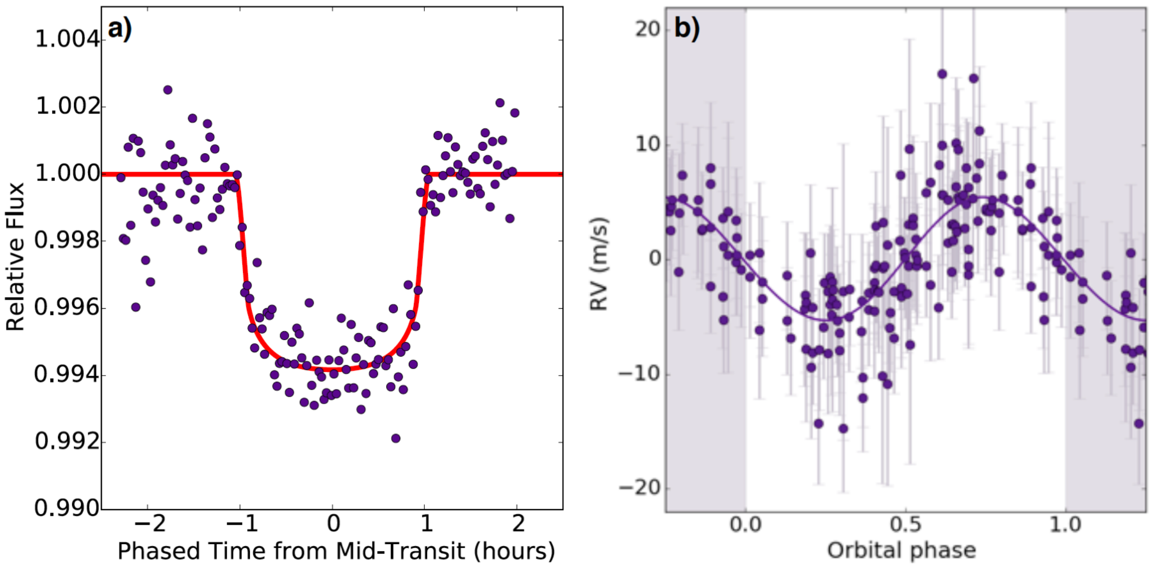
1.6 Mearth
1.2 Rearth
Teq ~500K
P=1.6d
Mstar = 0.18 Msun
Rstar = 0.21 Rsun

Berta et al. (2015)

The importance of M-dwarfs

MEarth 3rd discovery: LHS1140b

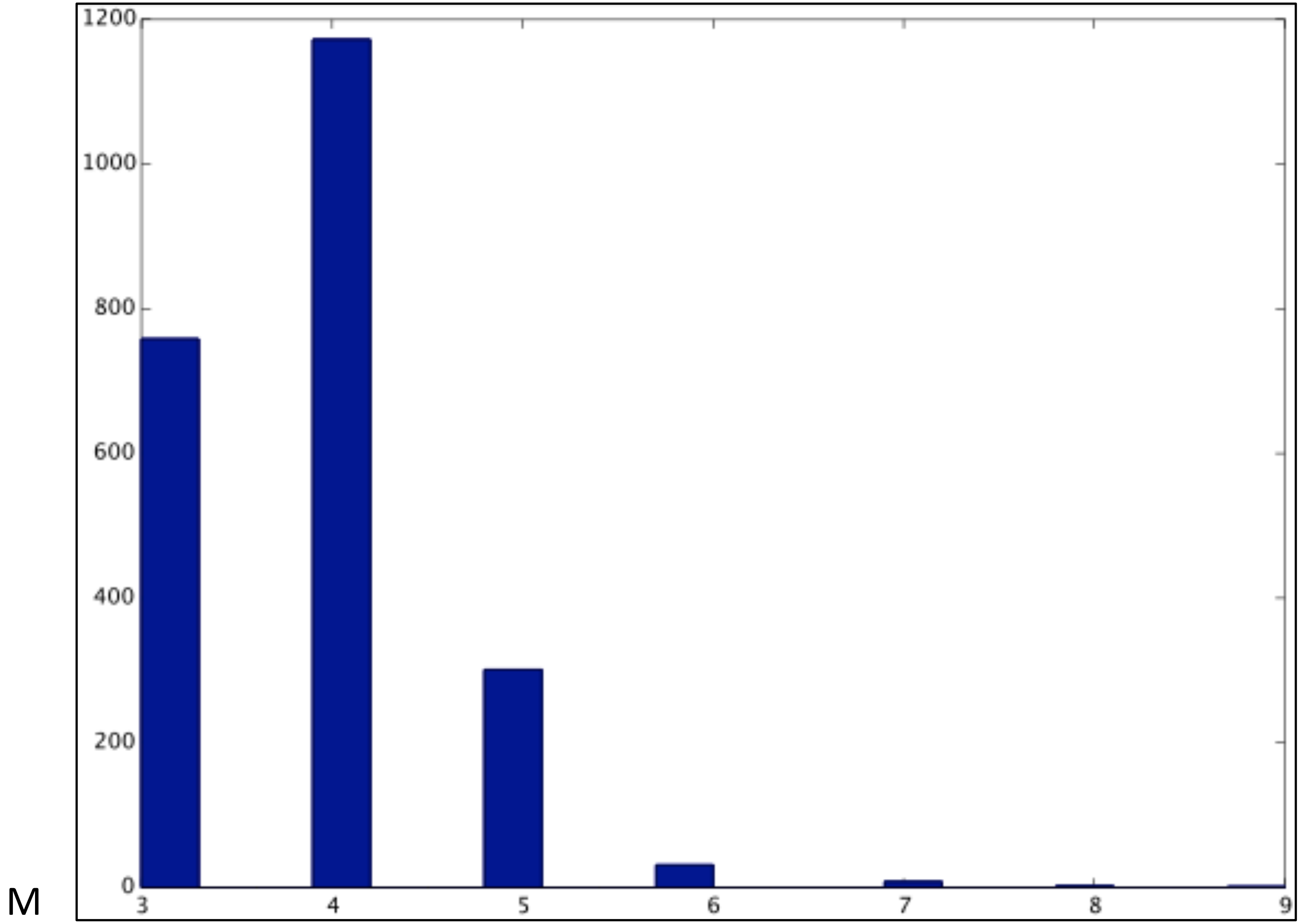
6.7 Mearth
1.4 Rearth
Teq ~230K
P=24.7d
Mstar = 0.15 Msun
Rstar = 0.19 Rsun



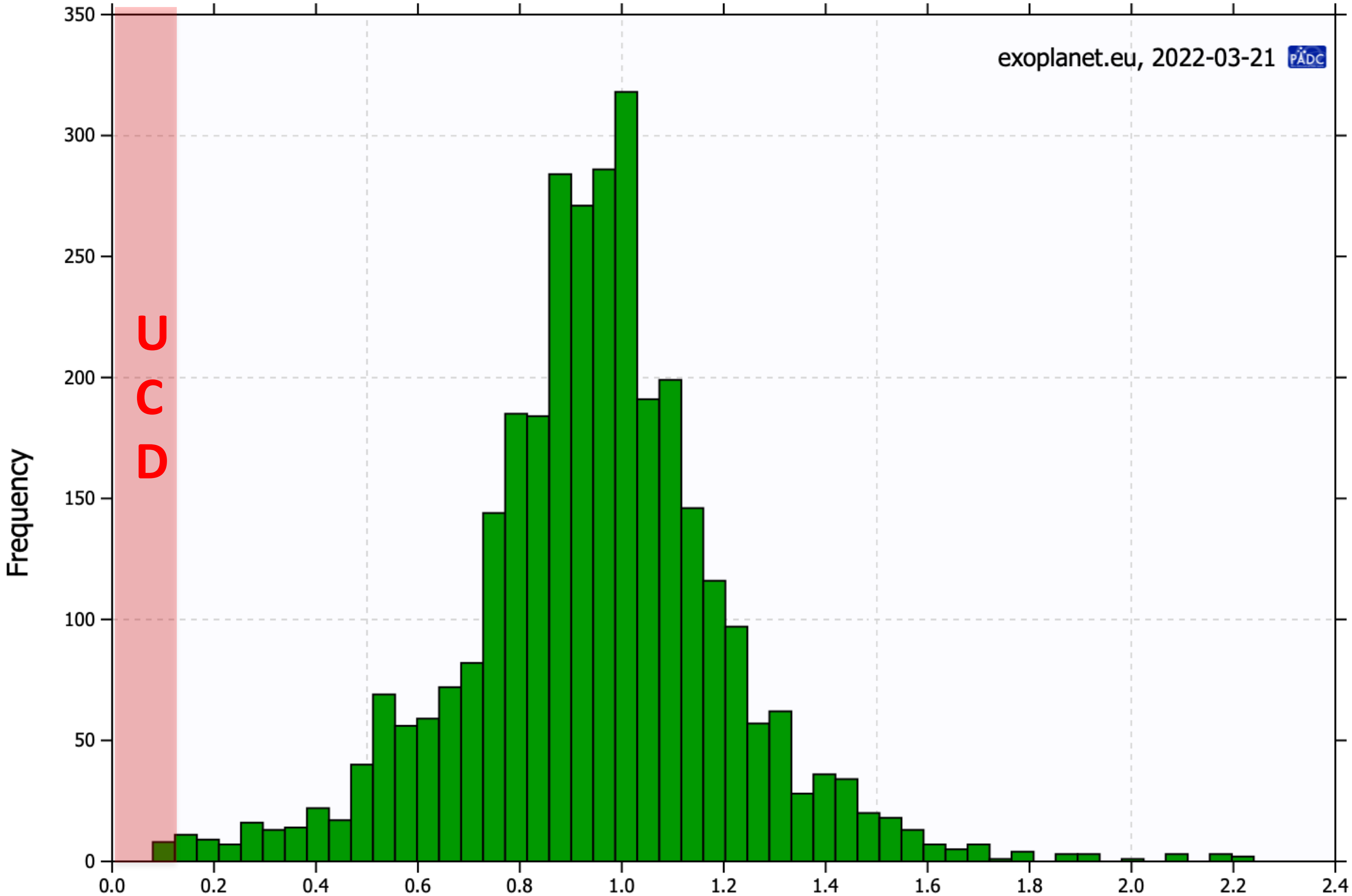
Dittmann et al. (2017)

The importance of M-dwarfs

MEarth : distribution of targets per spectral type

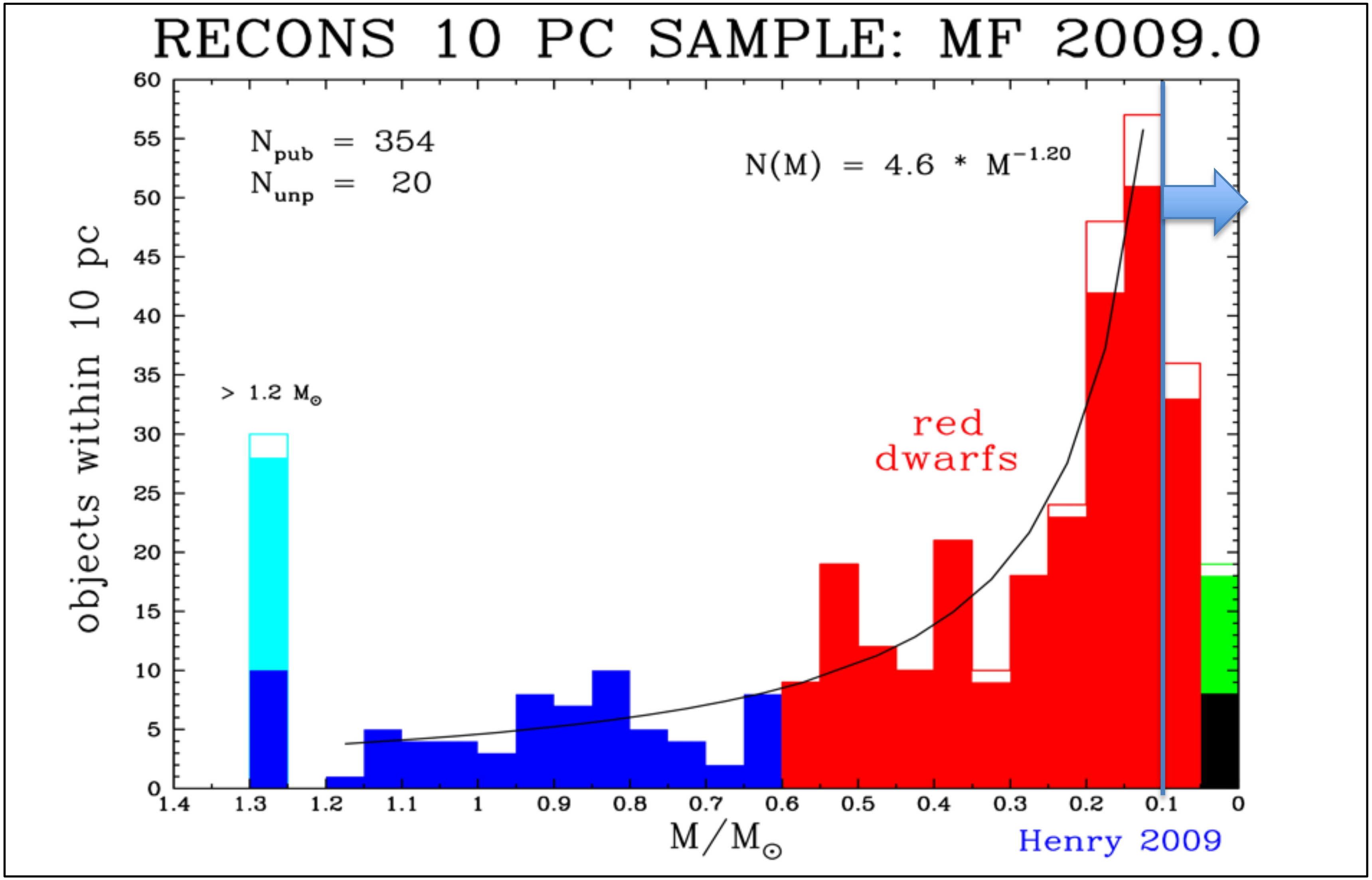


The importance of M-dwarfs

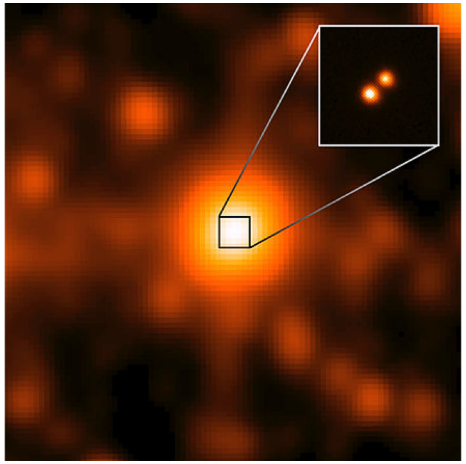


UCD = Ultra-cool dwarfs = smallest lowest-mass stars and brown dwarfs

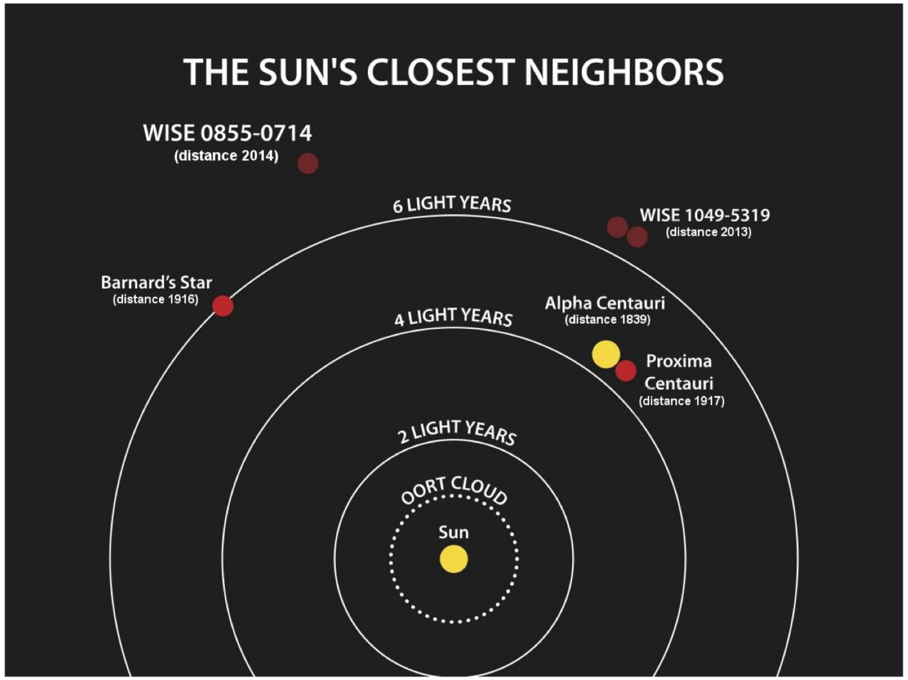
The importance of M-dwarfs



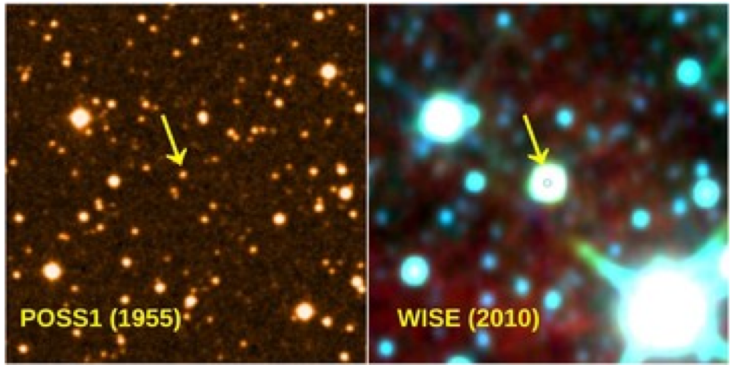
New nearby UCDs are regularly found

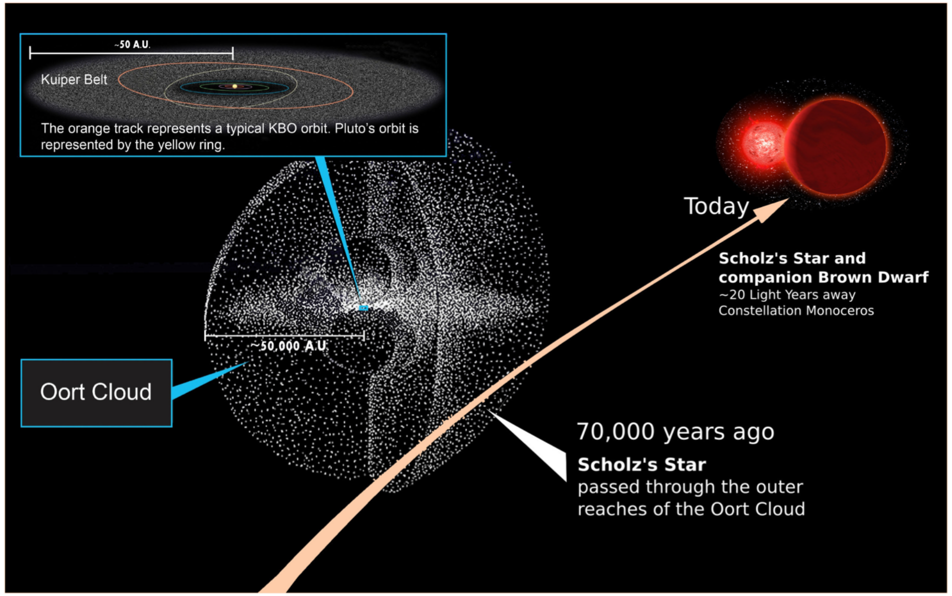


Luhman-16AB
Binary BD L9+T1 at 2pc
(Luhman 2013)



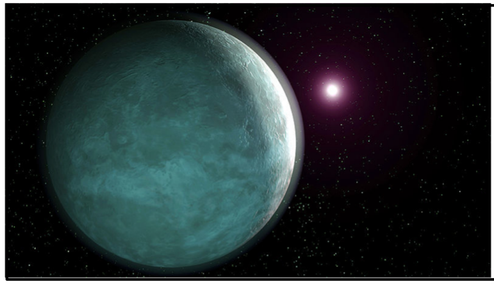
Scholtz's star: M9.5 star + T5 BD at 6pc
(Scholtz 2013)





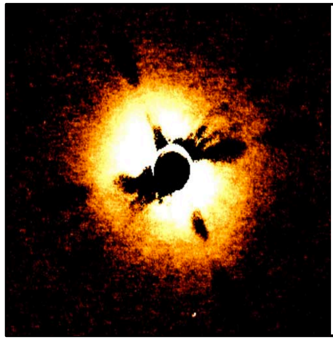
The importance of M-dwarfs

UCDs and planets



MOA-2007-BLG-192Bb *(Bennett et al. 2008, Kubas et al. 2012)*

$3.3M_{earth}$ planet at 0.66 AU away from a star(?) of 0.085 M_{sun}
~660pc

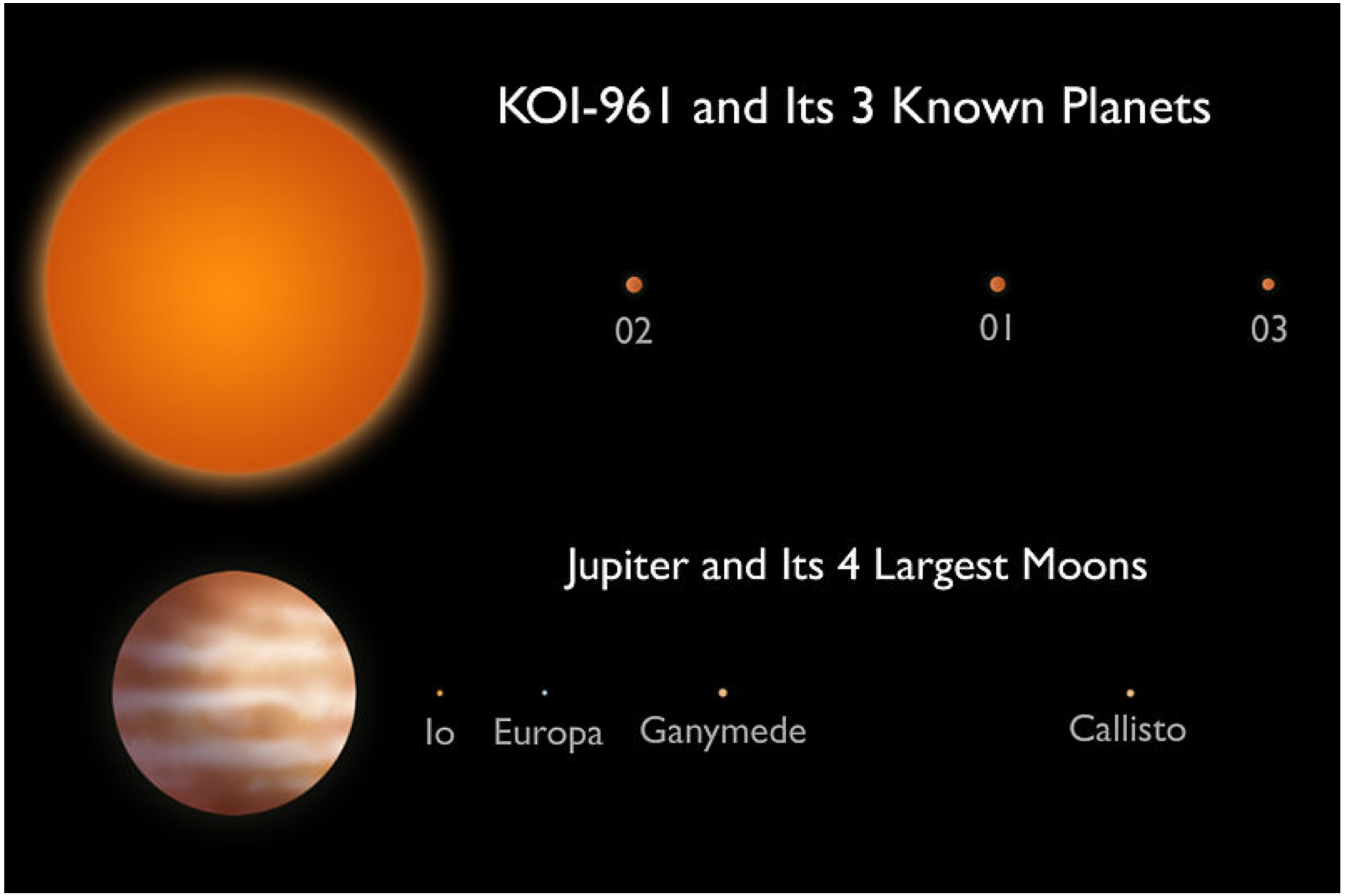


Disks are frequent around young UCDs *(Luhman et al. 2007)*
Mass and size of disk are proportionnal to the mass of the central object *(Klein et al. 2003)*
Planetesimal formation as frequent as for solar-type stars *(Pascussi et al. 2011)*

Models predict systems rich in short-period telluric planets
(Raymond et al. 2007; Montgomery & Laughlin 2009; Masahiro & Ida 2009)
They don't agree on the composition of the planets
For brow dwarfs, tidal evolution could push the planets outward
(Bolmont et al. 2012)

The importance of M-dwarfs

Kepler-42: Jovian-like systems frequent around UCDs?



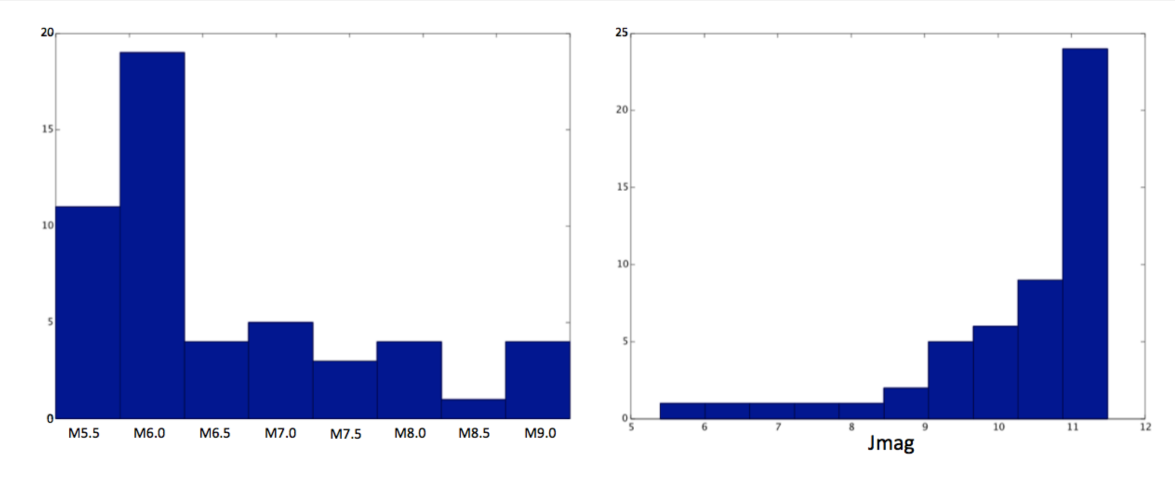
~0.13 $M_\odot$, ~0.17 $R_\odot$
T_{eff} ~3200K
M4V @ 39pc

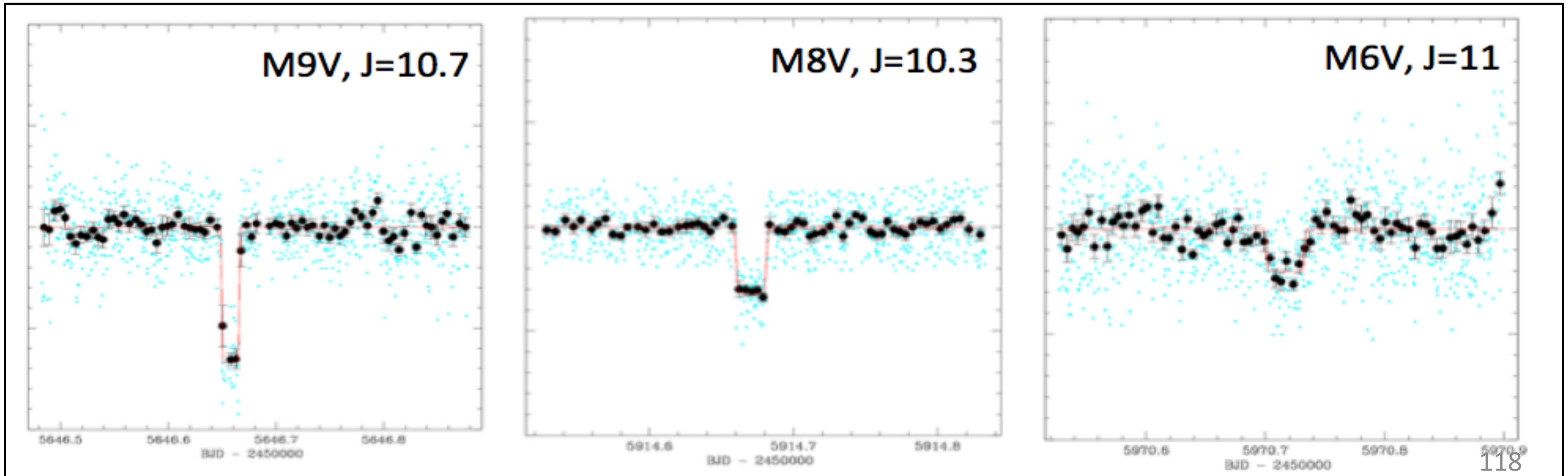
Only 27 redder dwarfs observed by Kepler mission (phase 1)

Muirhead et al. (2012)

TRAPPIST/UCDTS

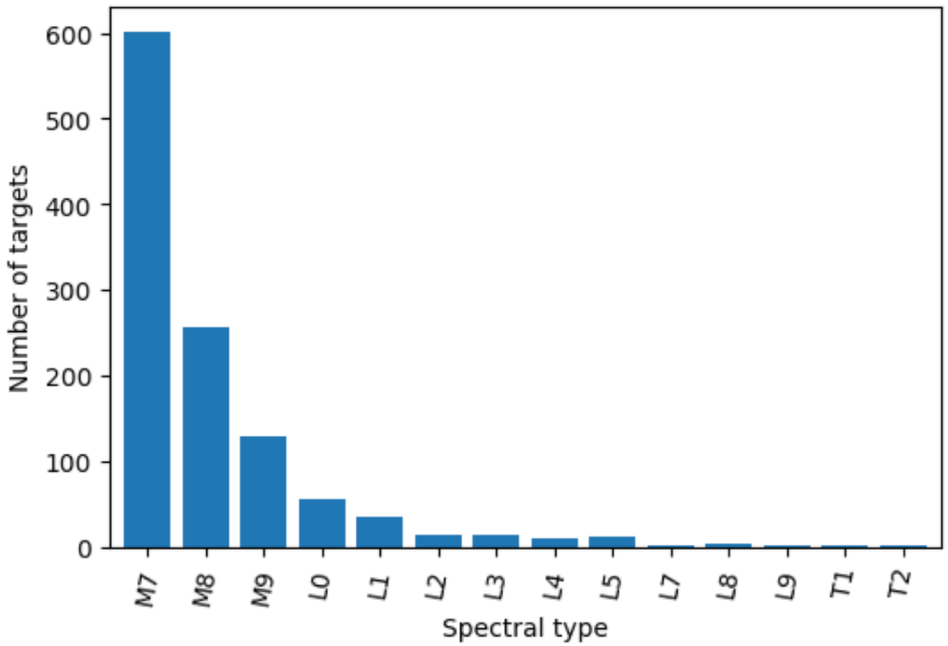
50 targets with J<11.5 (now 12)
100hr per target
Goal: prototype (precision – variability)

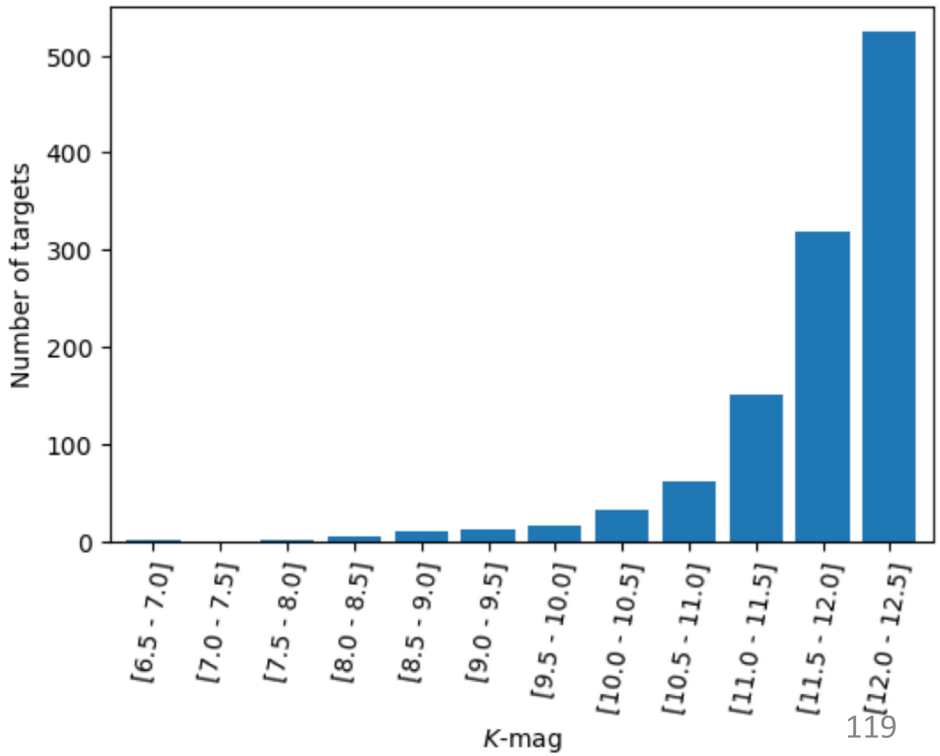




SPECULOOS

Search for **P**lanets **EC**lipsing **UL**tra-c**OO**l Stars
Network of 1m robotic telescopes
~1000 UCDs with K<12.5
Several nights per target to explore >50% of the habitable zone
ULiege + Cambridge + MIT + Birmingham + Bern





The SPECULOOS network

SSO/SNO = SPECULOOS-South/North Observatory
TS/TN = TRAPPIST-South/North

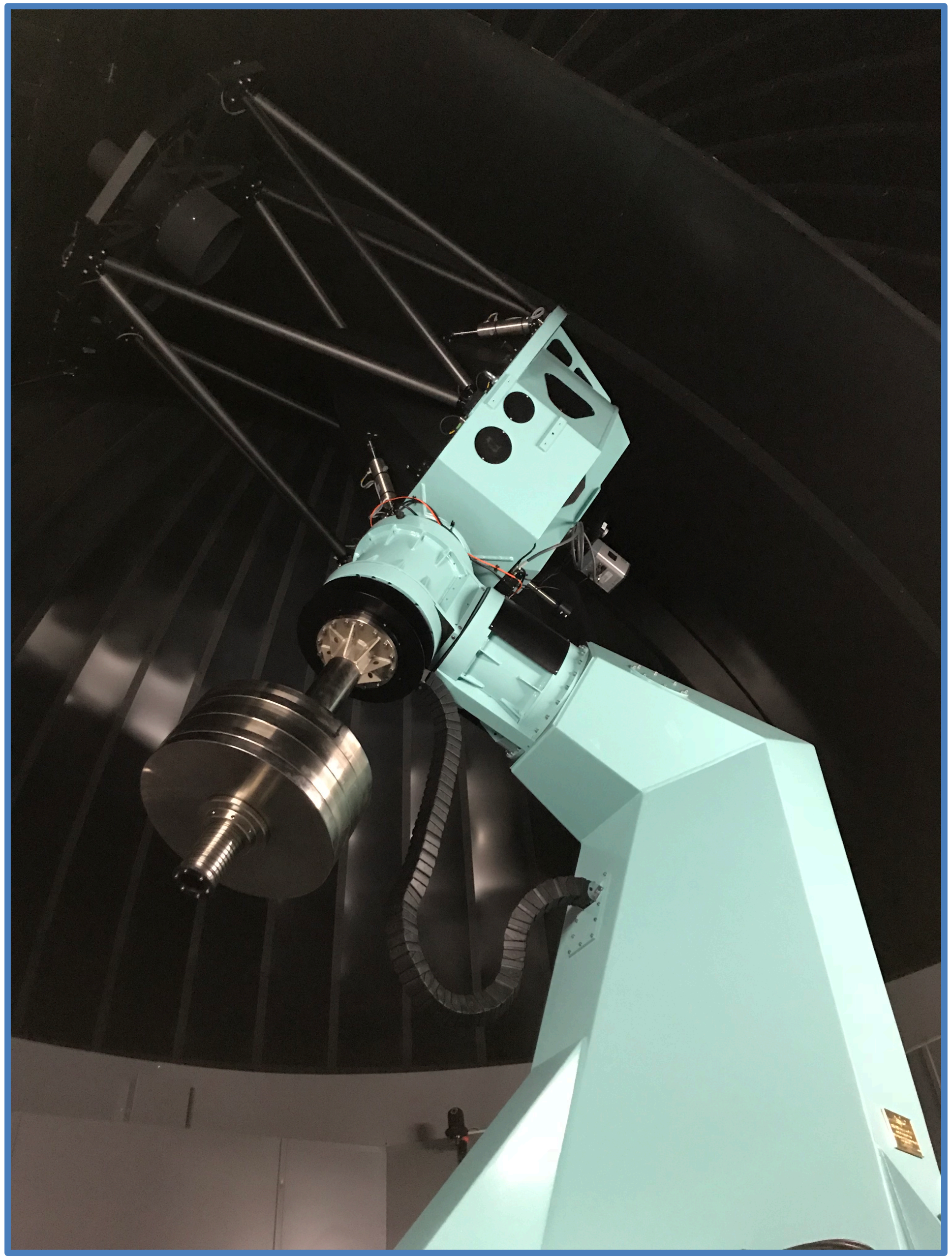
The SPECULOOS-South Observatory

The SPECULOOS-South Observatory

The SPECULOOS-South Observatory

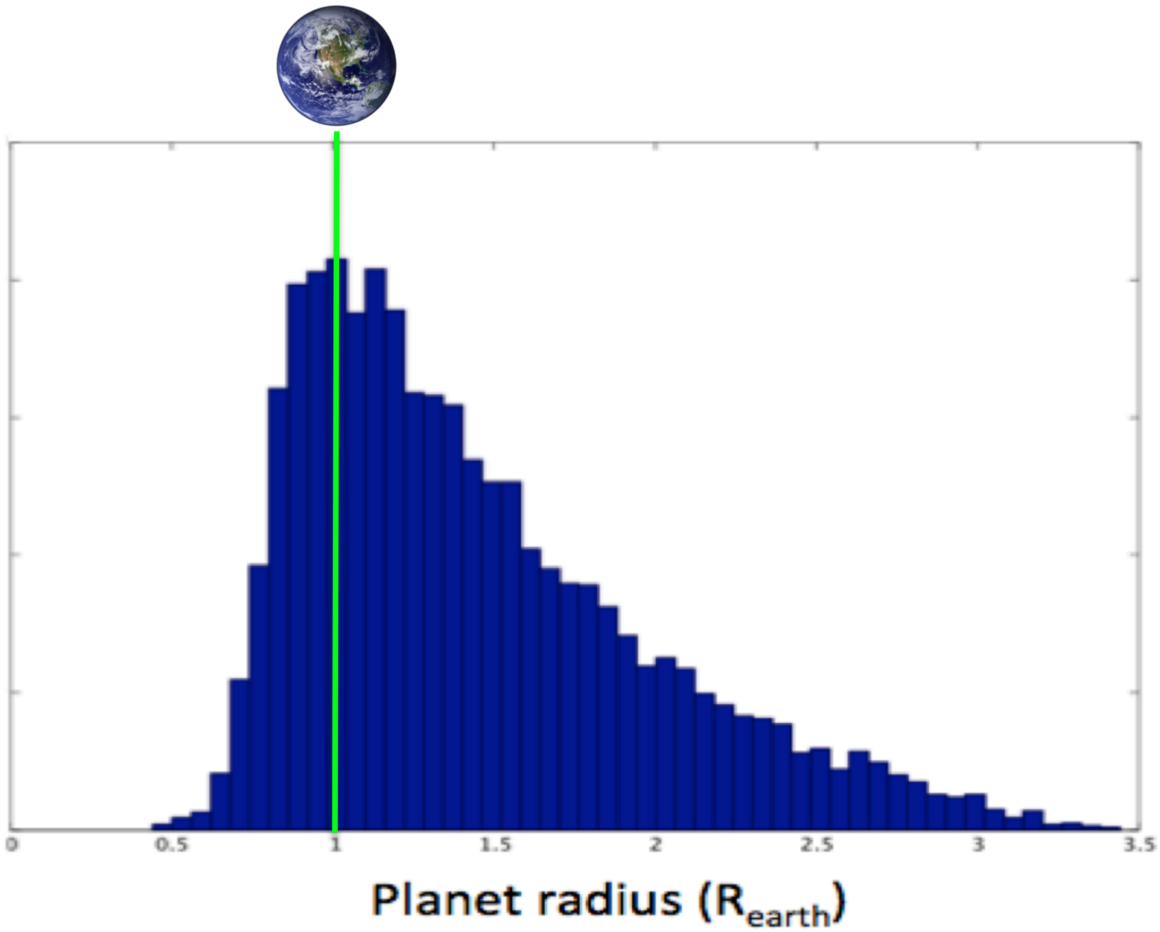
The SPECULOOS-South Observatory

The SPECULOOS-South Observatory



SPECULOOS

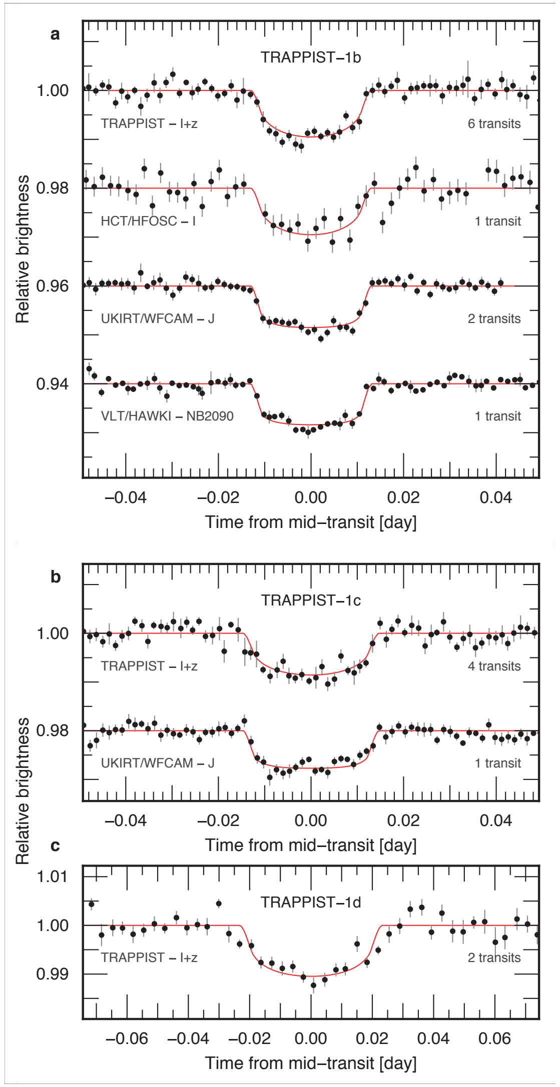
Simulations predict an efficient exploration of the Earth-sized regime



Simulations: 14±6 planets, with 4±2 in the habitable zone

SPECULOOS

Confirmation by the TRAPPIST prototype survey!



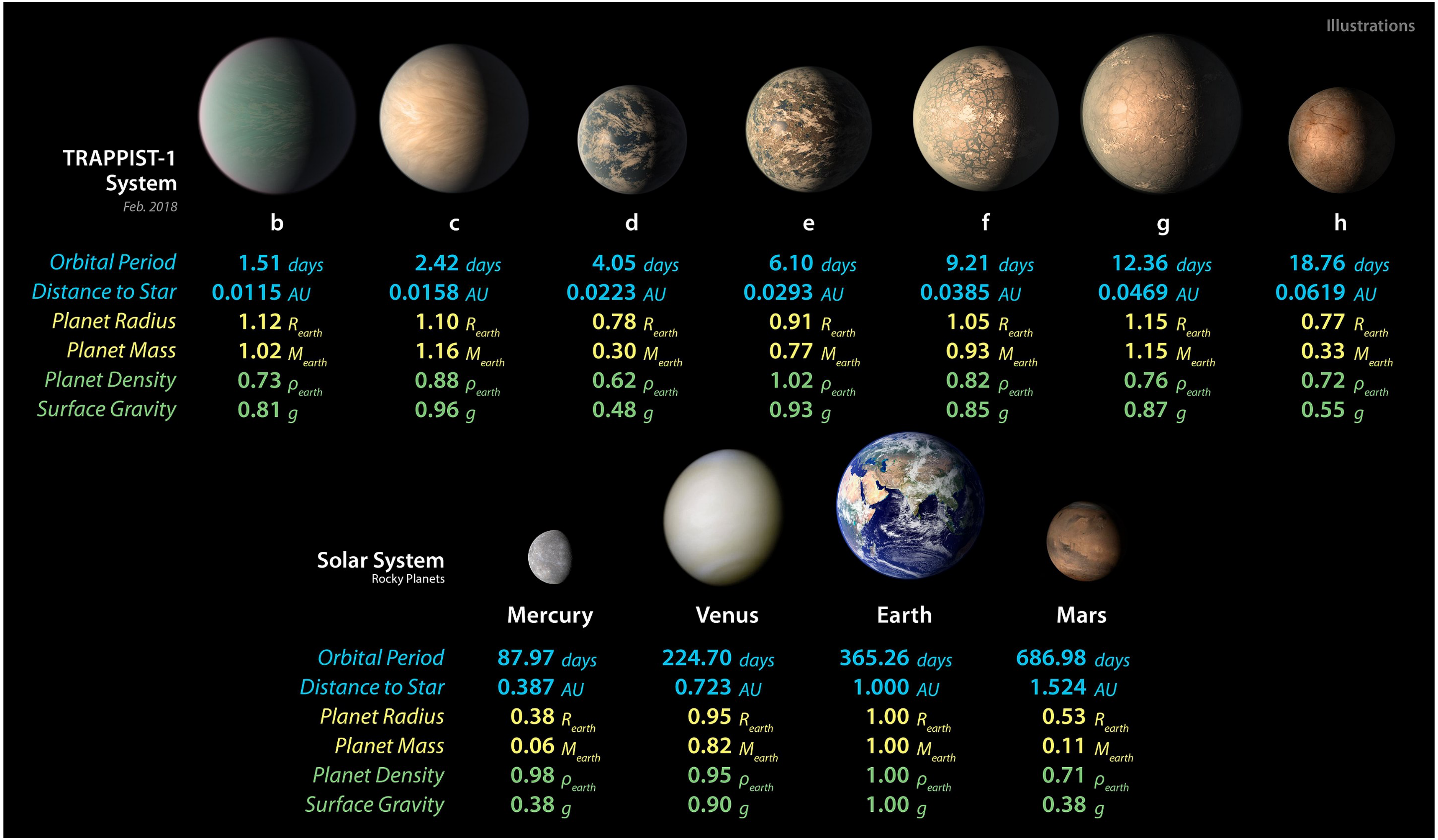
3 Earth-sized planets transiting a nearby M8-type star
Mstar = 0.08 Msun
Rstar = 1.1 Rjup
Teff = 2550K

Equilibrium temperatures of the planets between 200 and 400K

Nearby (12 pc) -> **good targets for atmospheric study with JWST & ELTs**

SPECULOOS

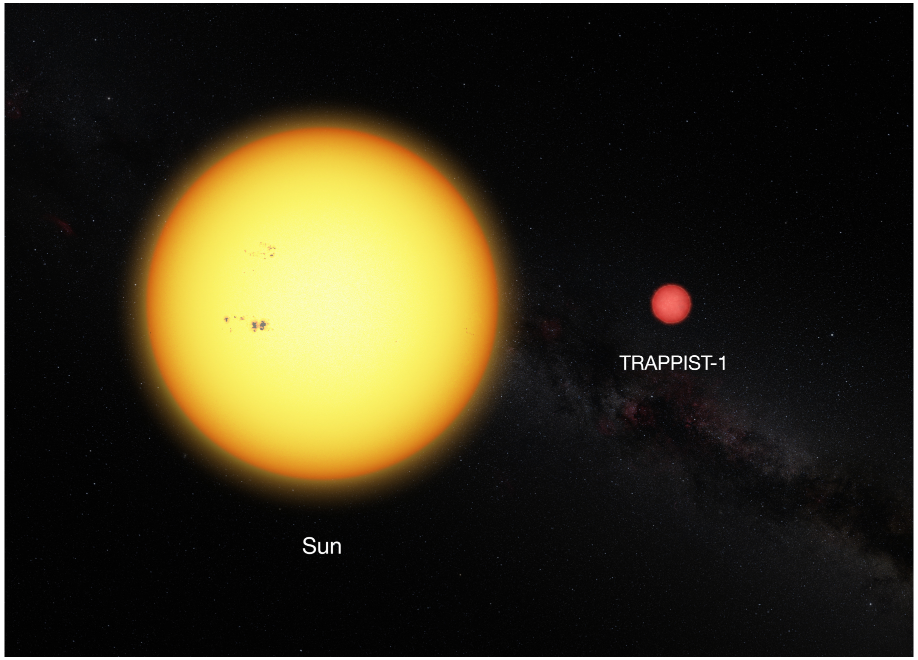
Confirmation by the TRAPPIST prototype survey!



TRAPPIST-1

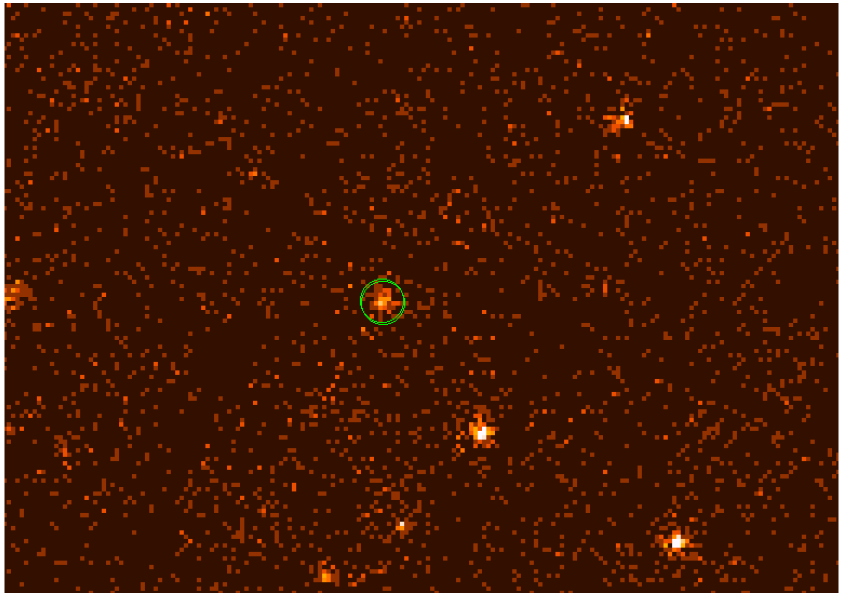
Host star: discovered in 2000 by *Gizis et al*. V=18.8, I=14.0, J=11.3, >500 Myr

$0.089 \pm 0.006\ M_{\odot}$, $T_{eff} = 2516 \pm 41$ K, [Fe/H] = $+0.04 \pm 0.08$



$0.121 \pm 0.003\ R_{\odot}$, $0.00052 \pm 0.00002\ L_{\odot}$

Van Grootel et al. (2018)



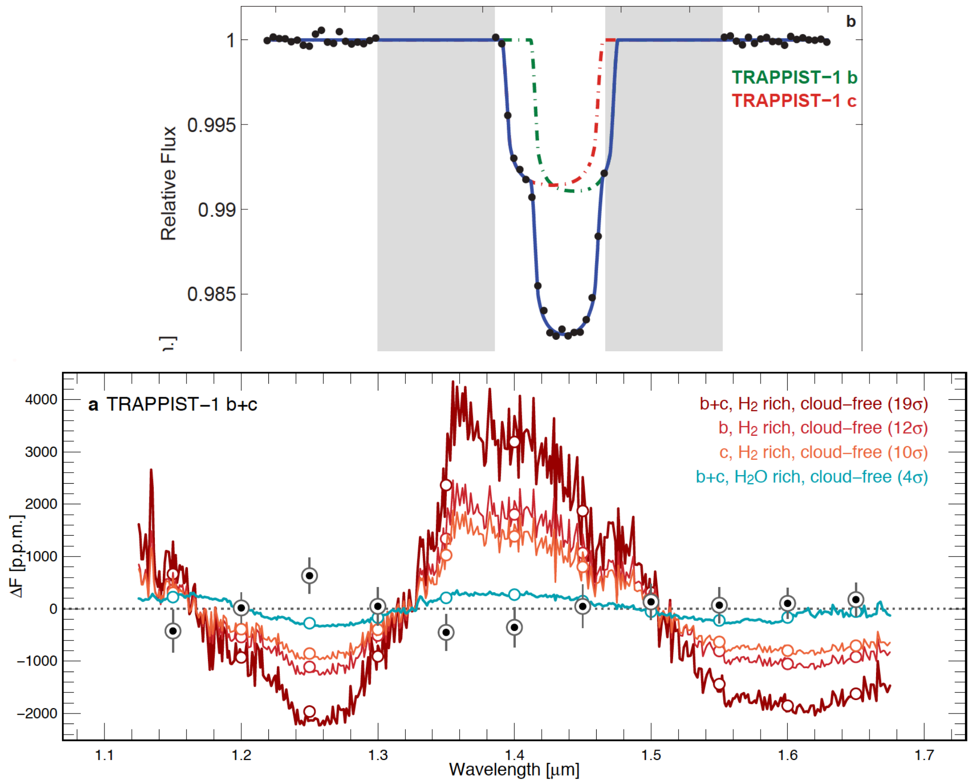
XMM-*Newton*: strong X-ray emission, $L_X / L_{bol} = 2 - 4\ 10^{-4}$

Wheatley et al. (2016)

TRAPPIST-1

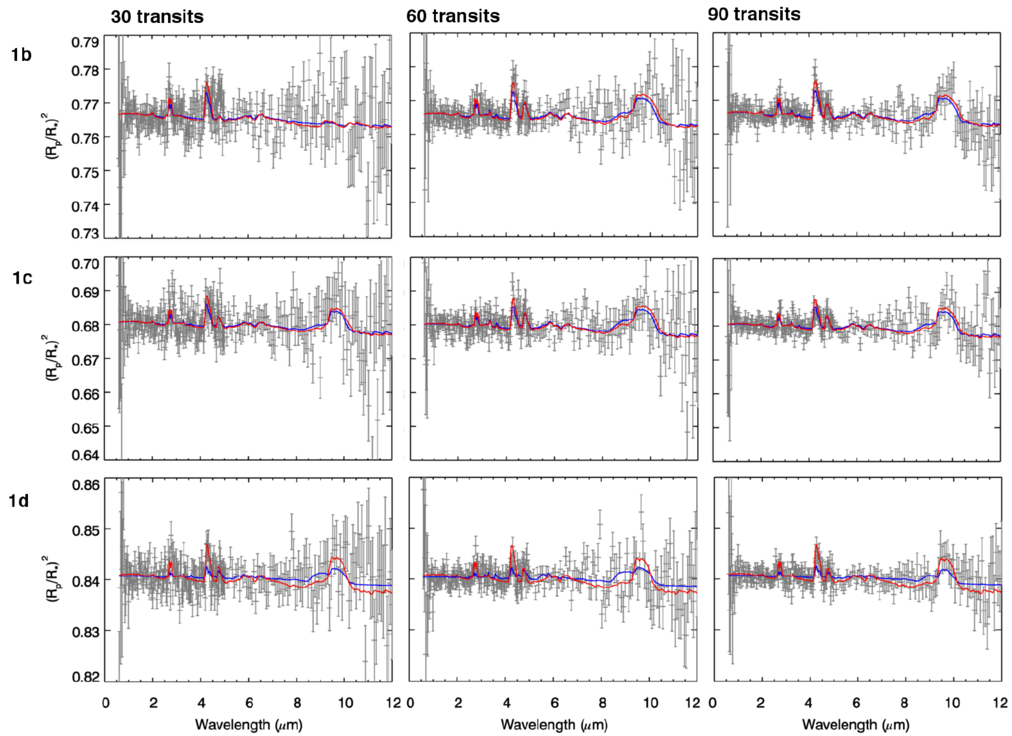
A first opportunity to study the atmosphere of temperate Earth-sized planets

First with HST



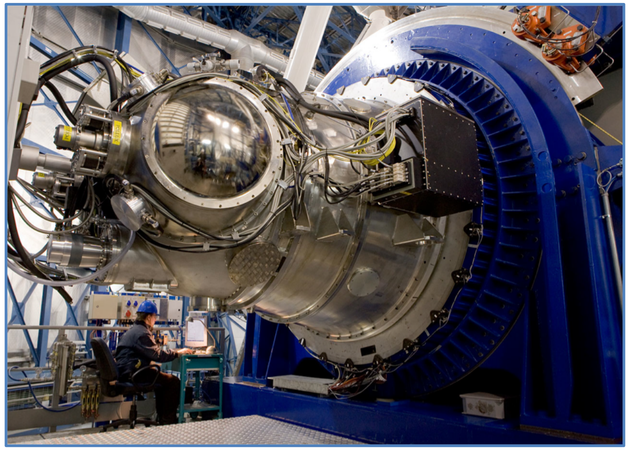
de Wit at al. (2016)

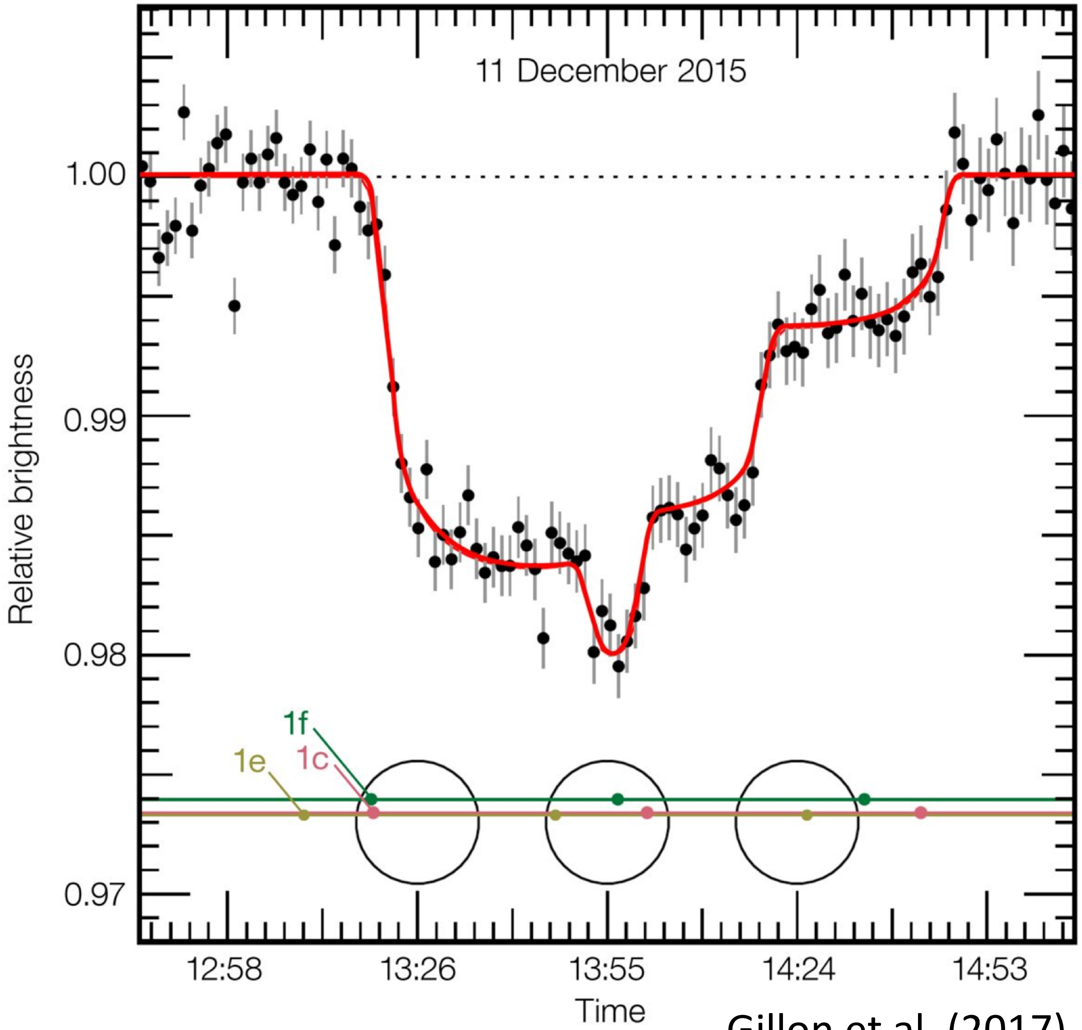
…and then with JWST, ELTs, etc



Barstow & Irwin (2016)

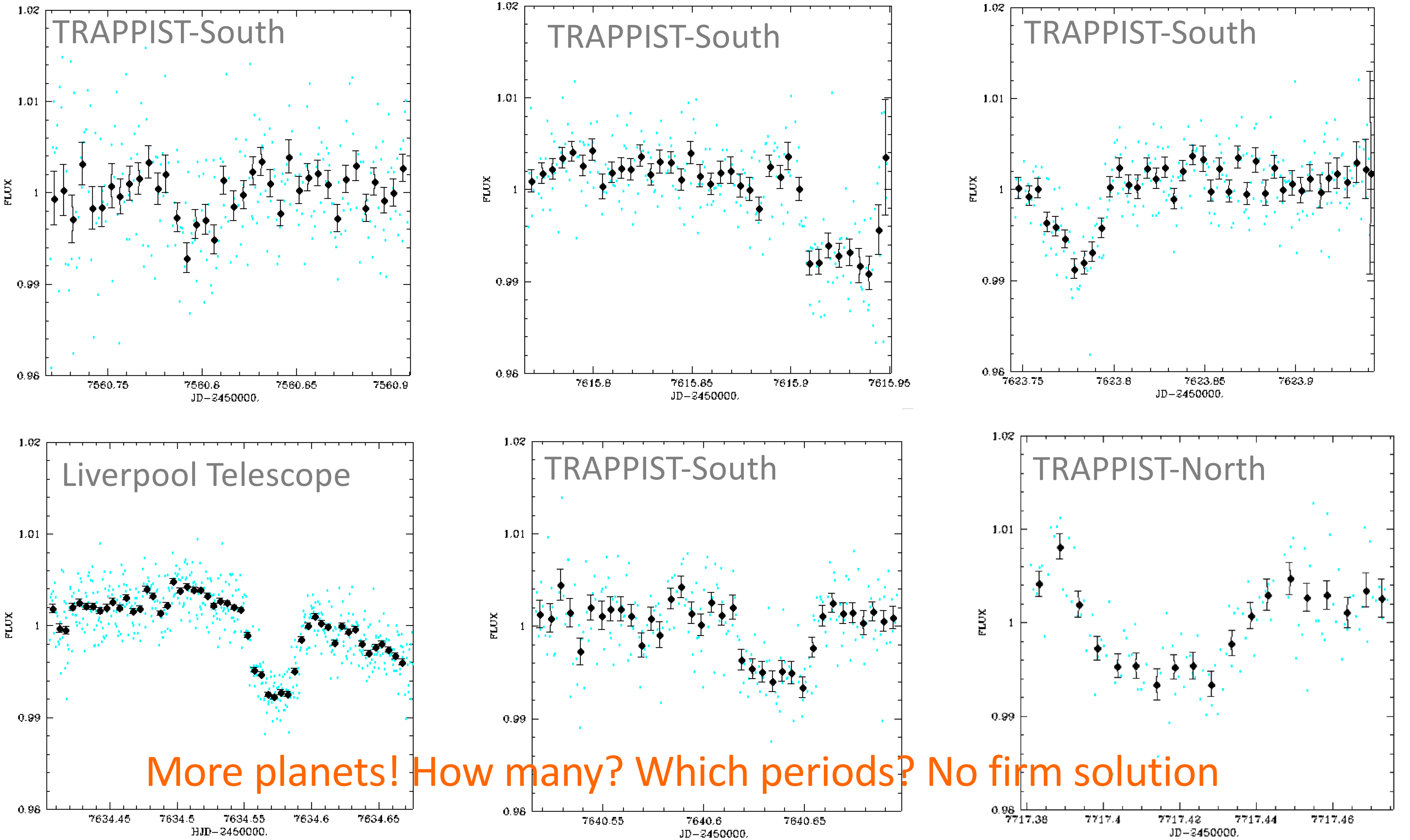
Three Earth-sized planets transiting at the same time





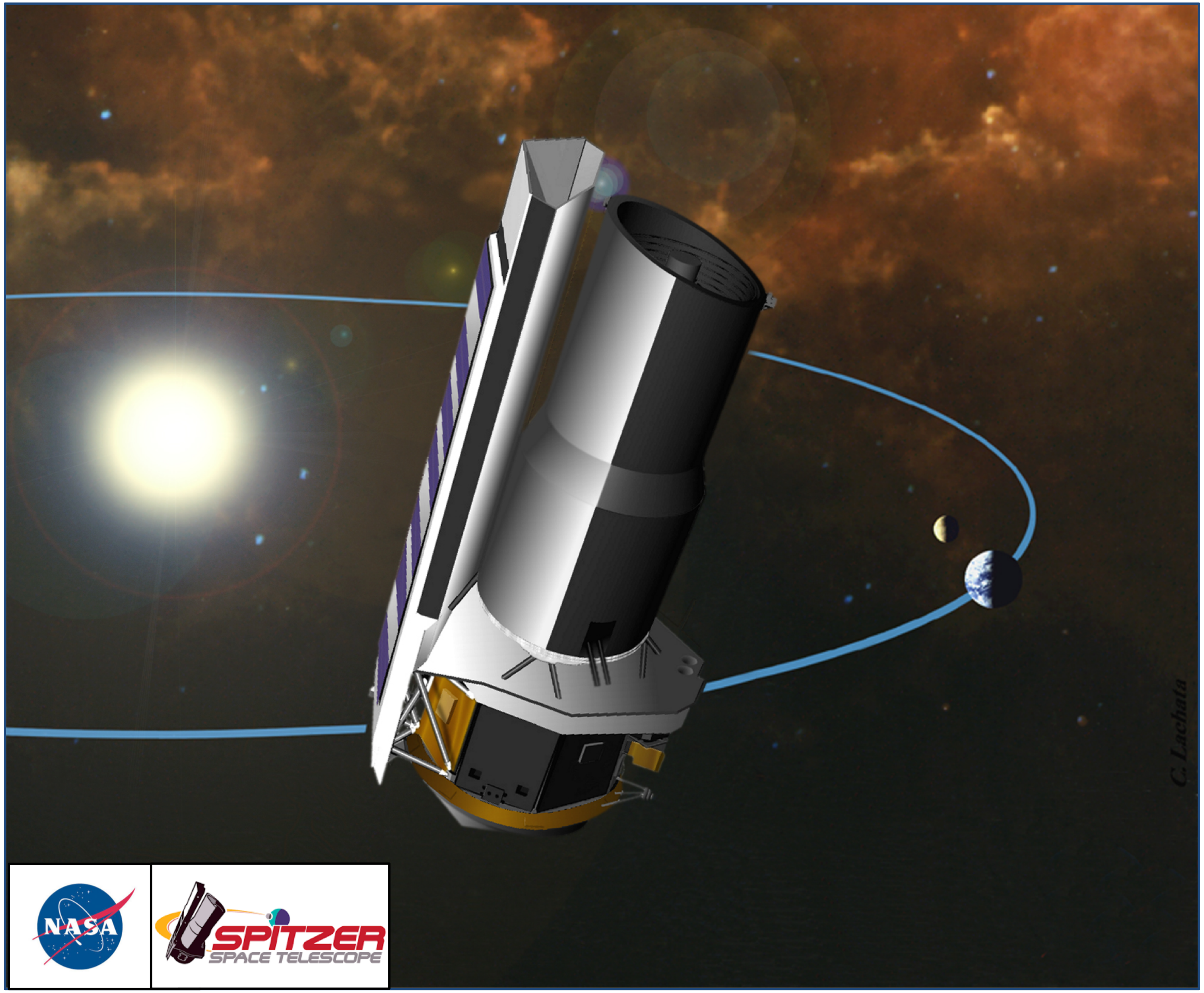
Gillon et al. (2017)

2016: intensive photometric follow-up from the ground

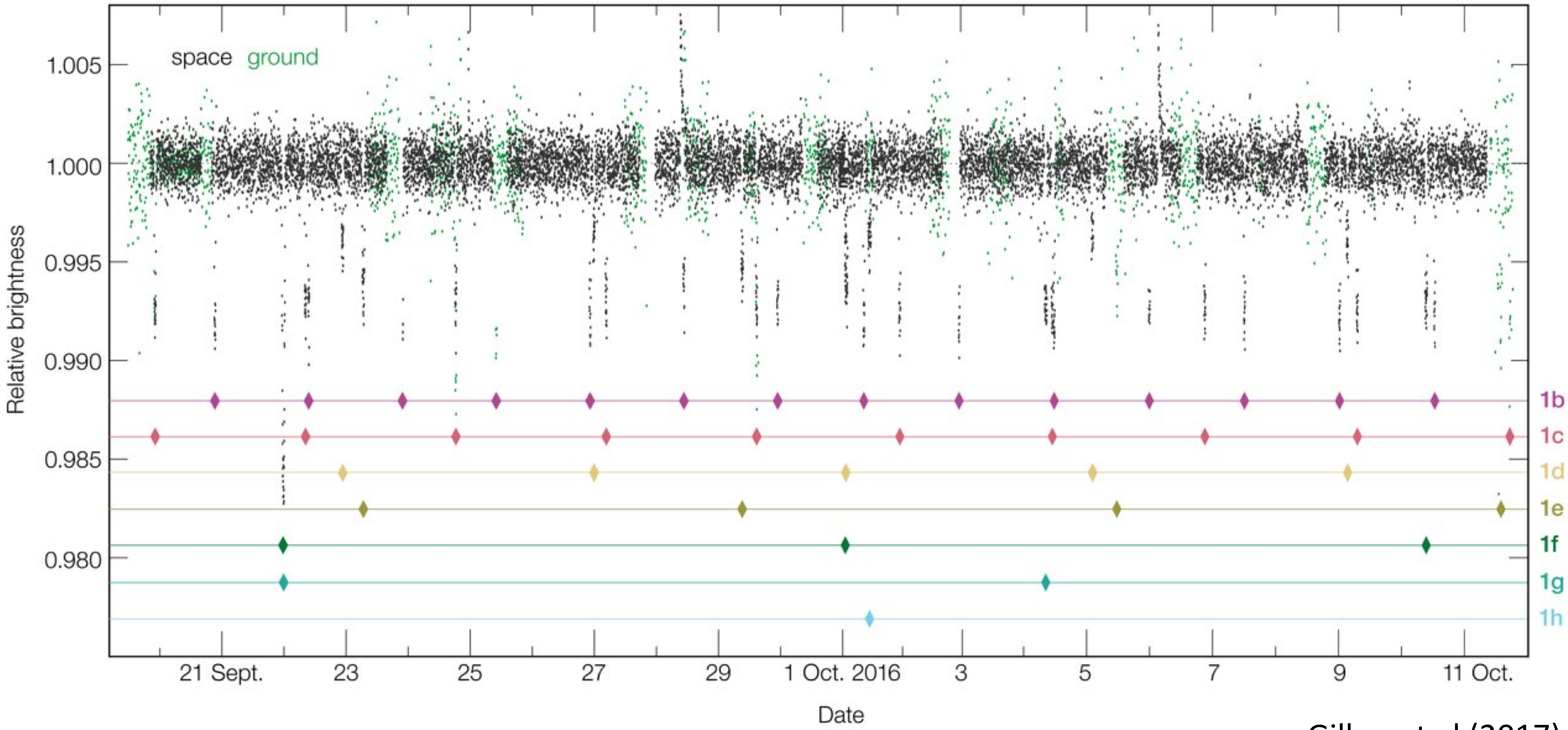


More planets! How many? Which periods? No firm solution

The perfect telescope for the job

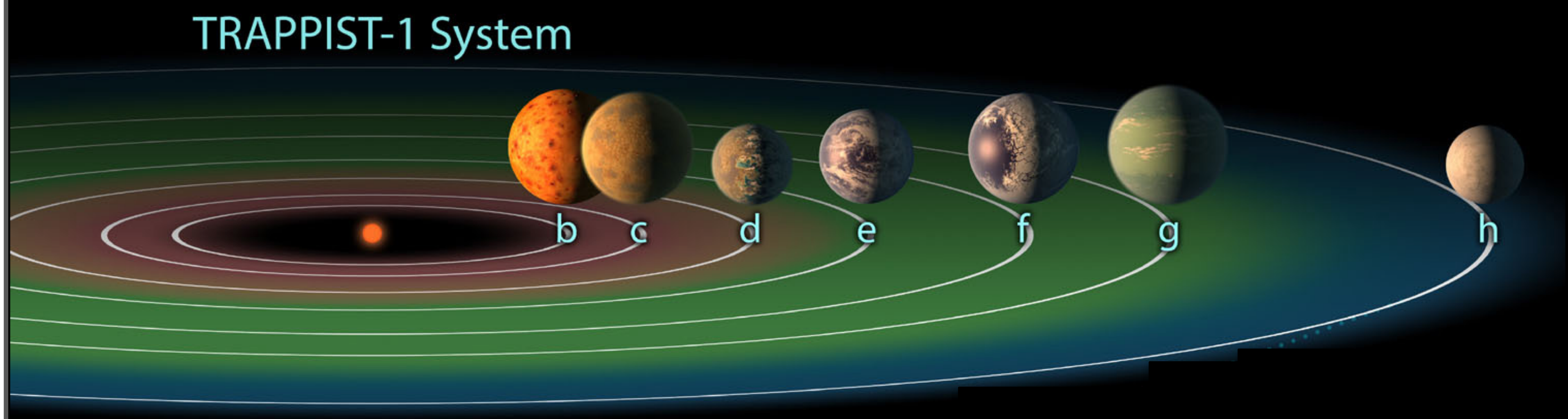


Fall 2016: Spitzer cracks the system

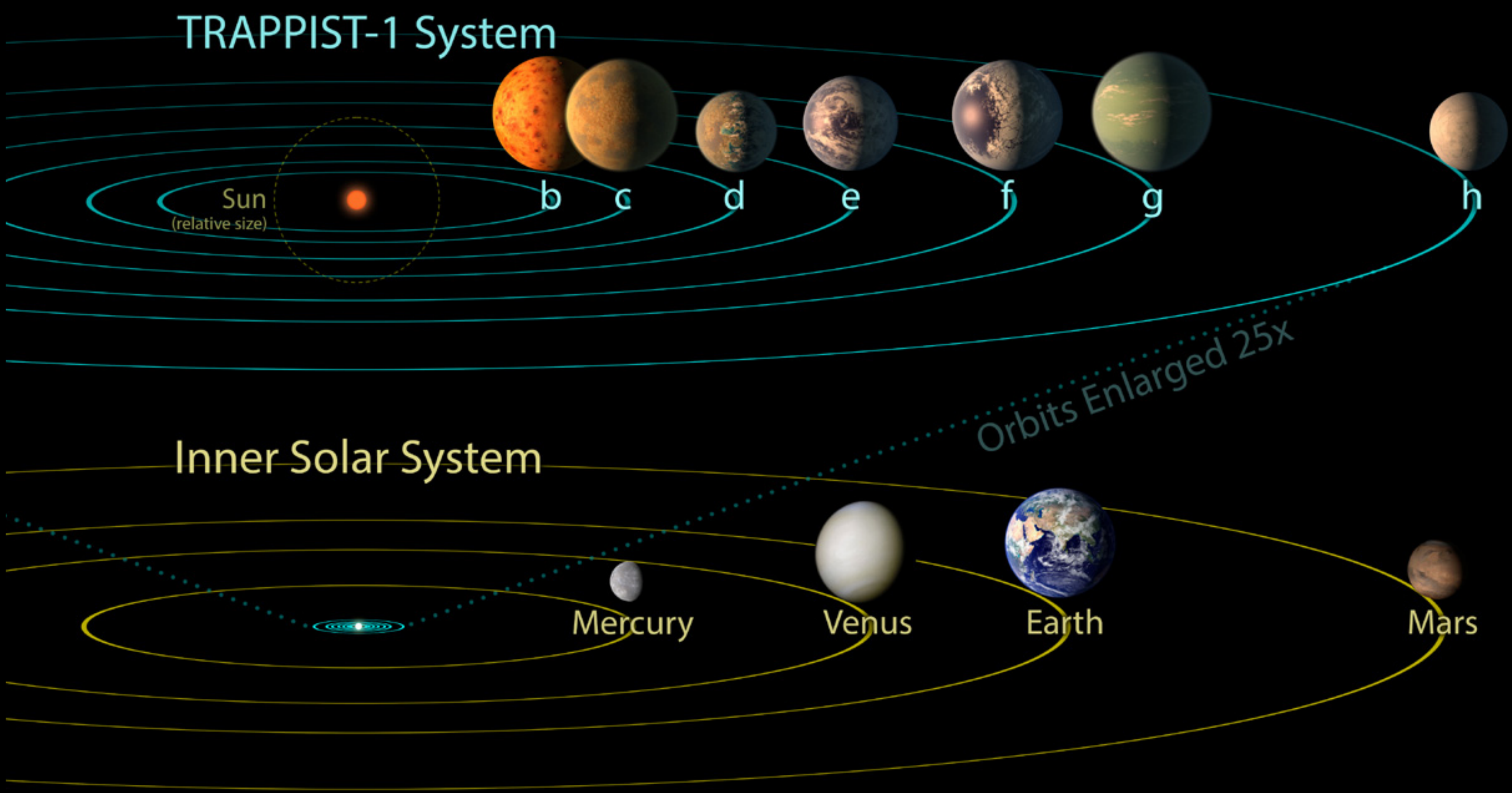


Gillon et al (2017)

20 days of nearly continuous observation… and 34 transits!


TRAPPIST-1 System
b
c
d
e
f
g
h

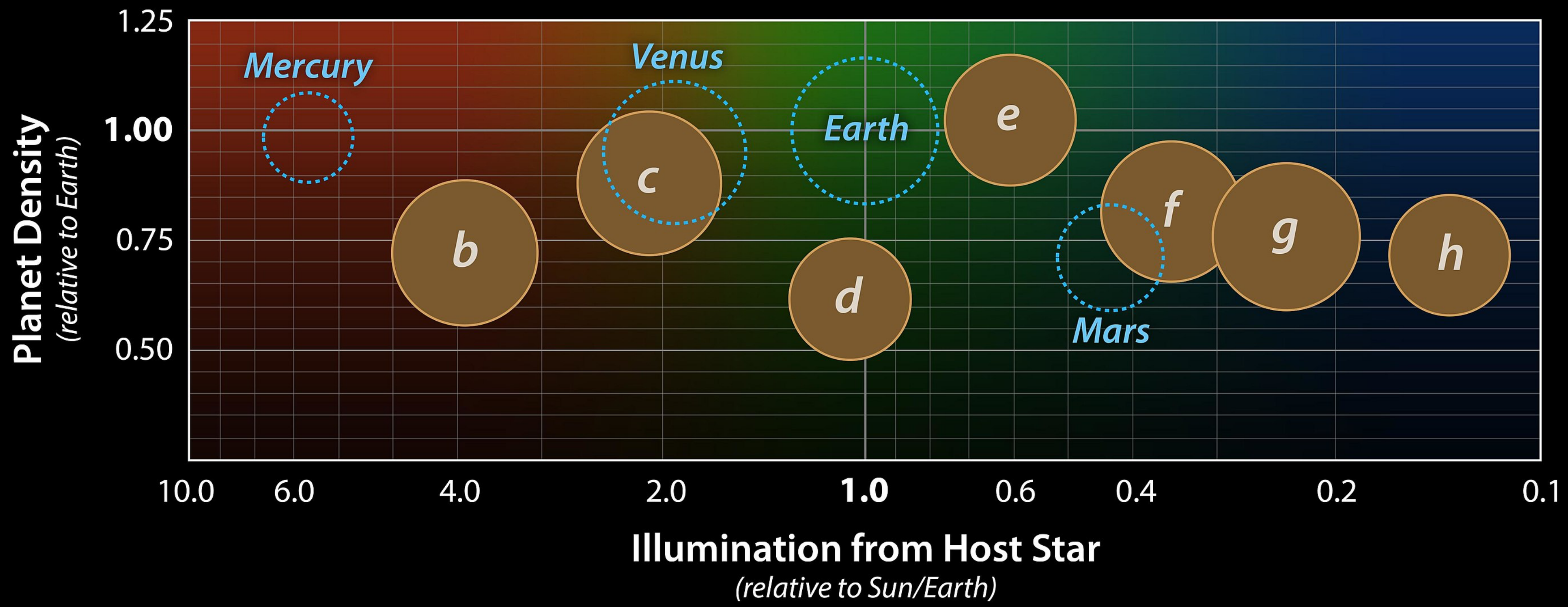
A very compact system



A 7-planets resonant chain

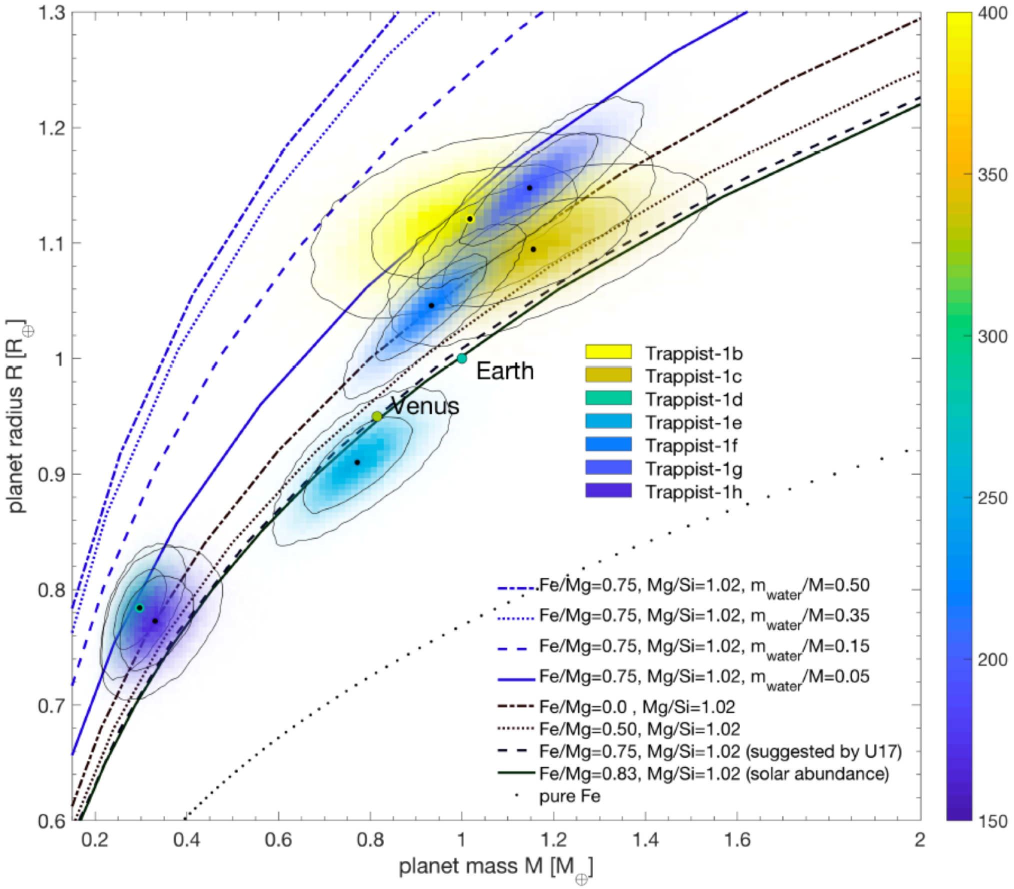
Water worlds?

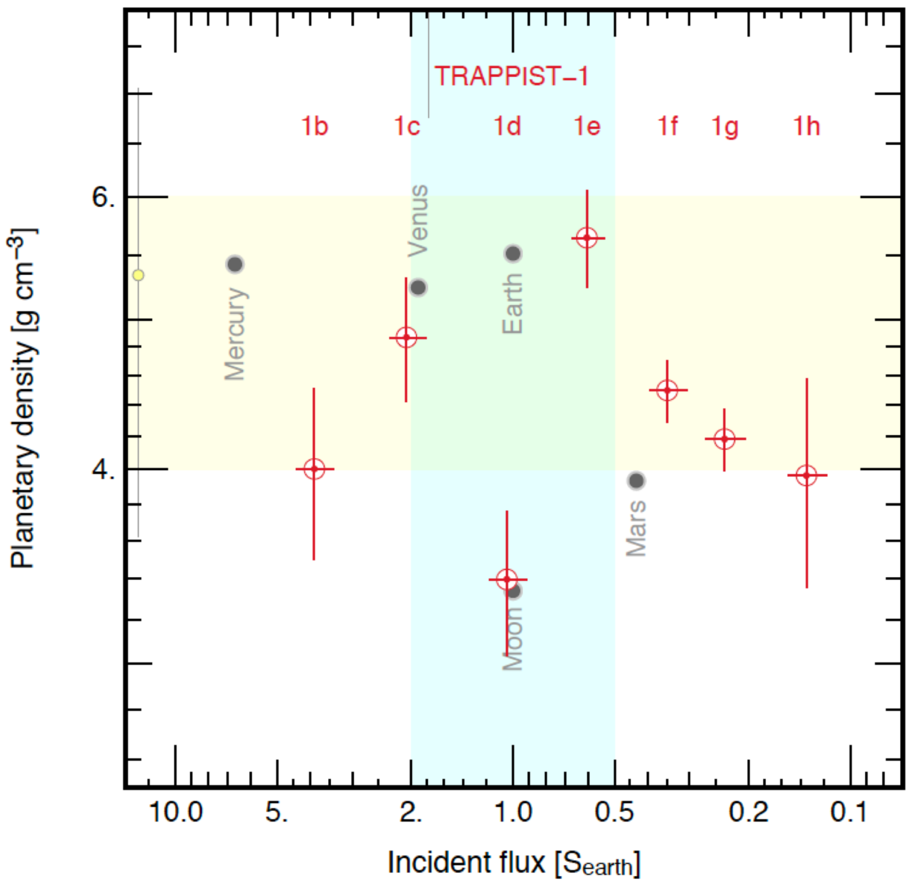
TRAPPIST-1/Solar System Comparison



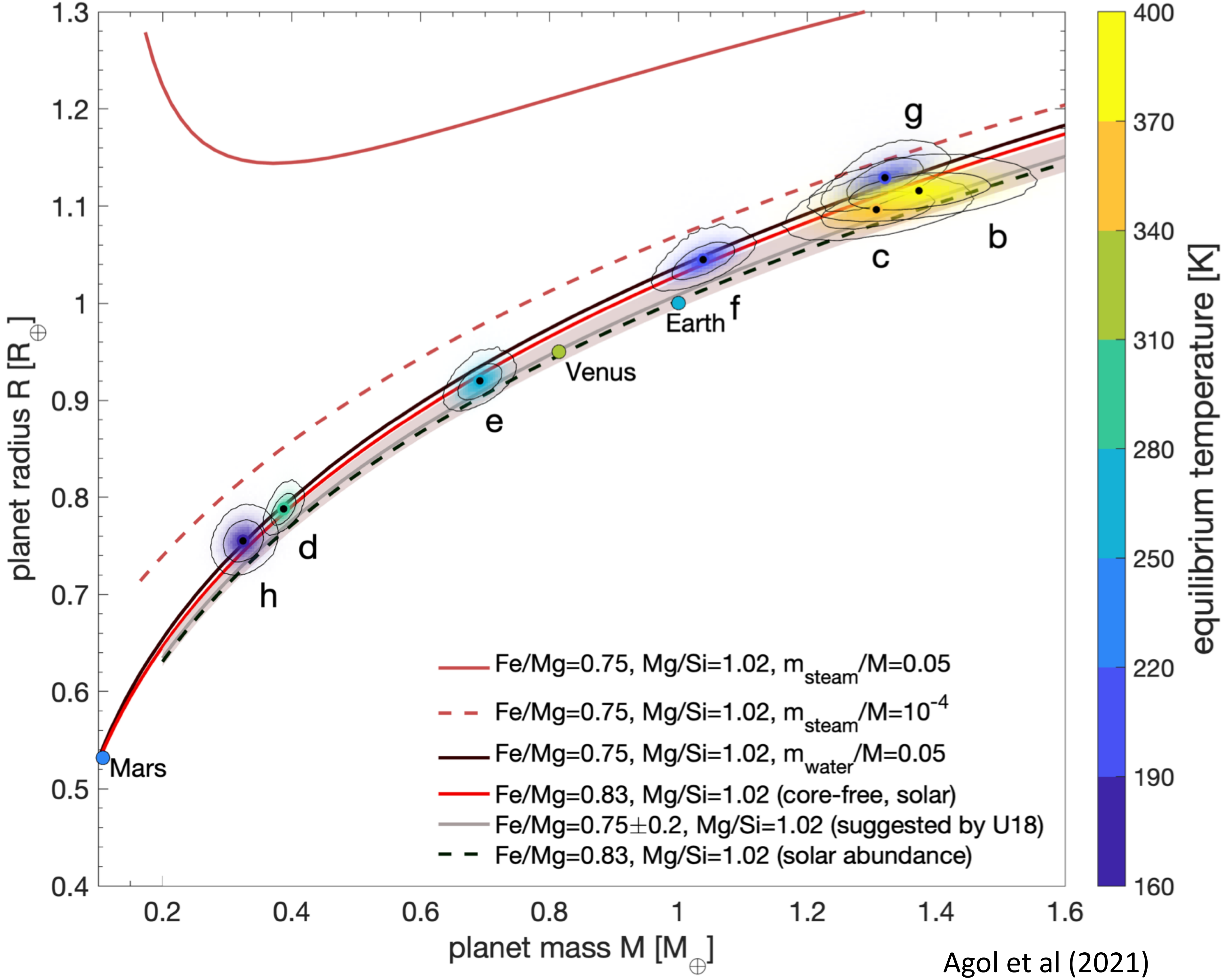
Credits: R. Hurt/JPL/NASA

The composition and irradiation of the TRAPPIST-1 planets





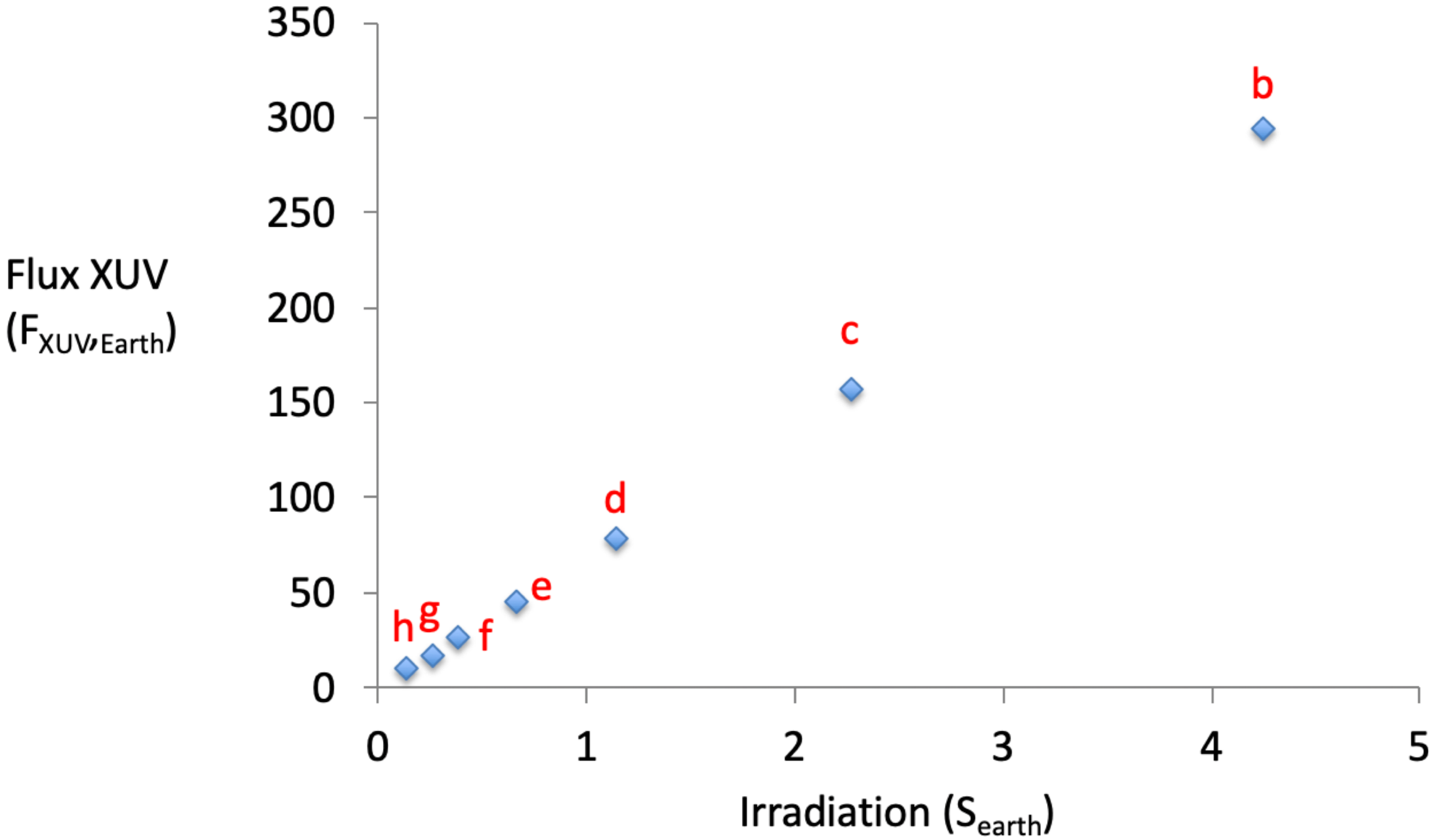
Grimm et al (2018)



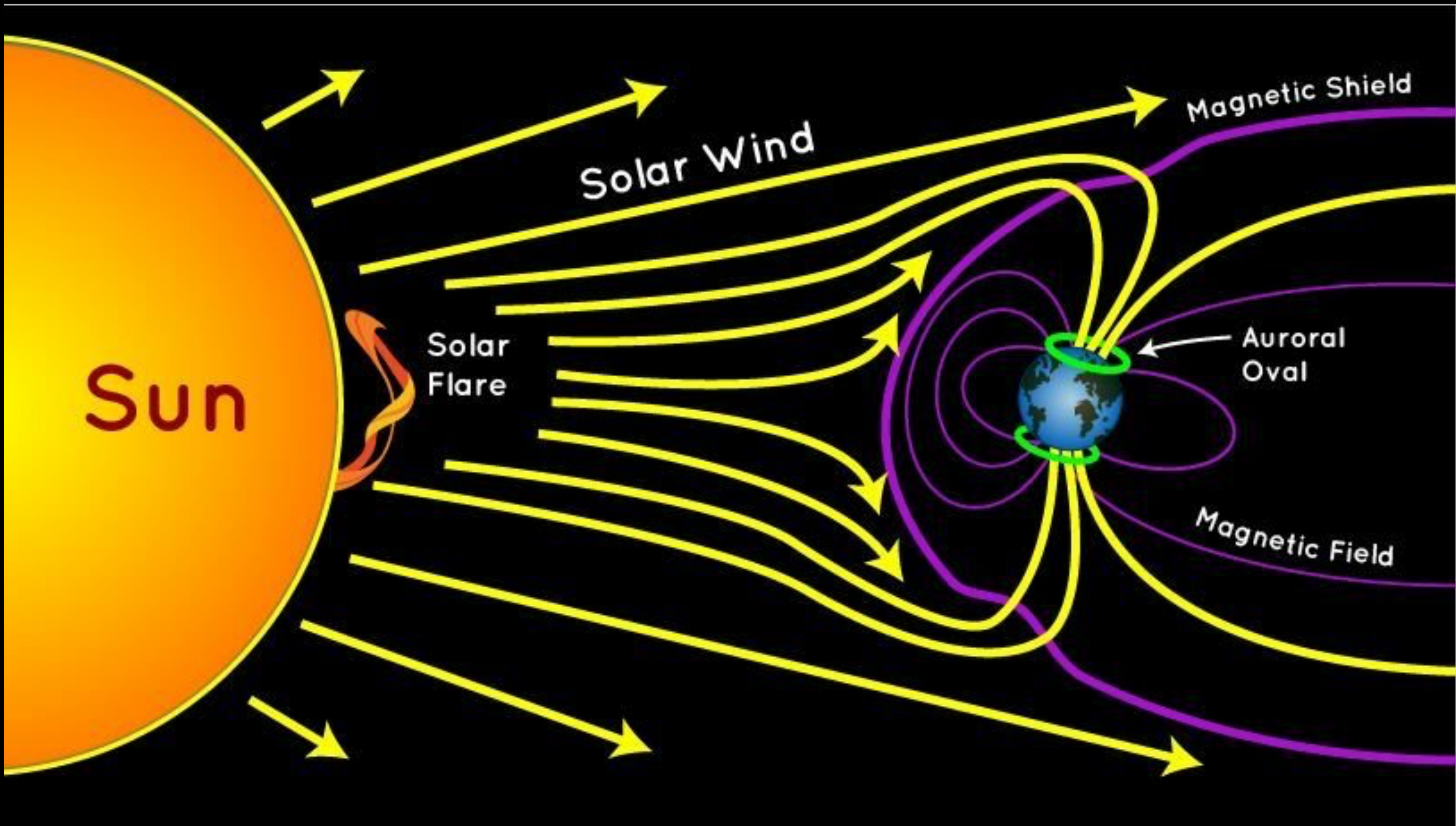
Agol et al (2021)

The harsh environment of TRAPPIST-1

X and UV flux on the planets estimated from XMM-Newton (Wheatley et al. 2016) and HST/STIS (Bourrier et al. 2017) measurements.

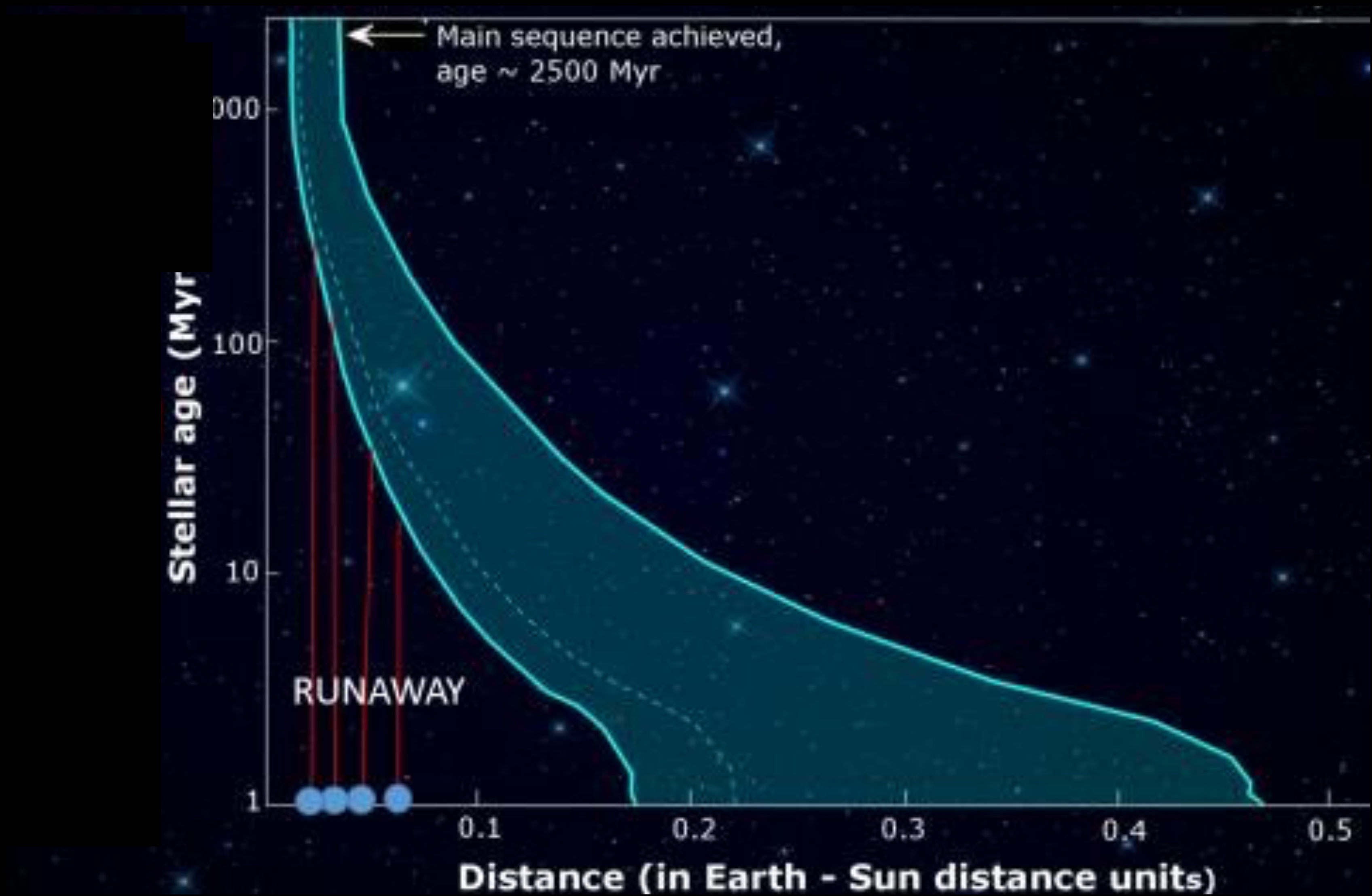


The harsh environment of TRAPPIST-1



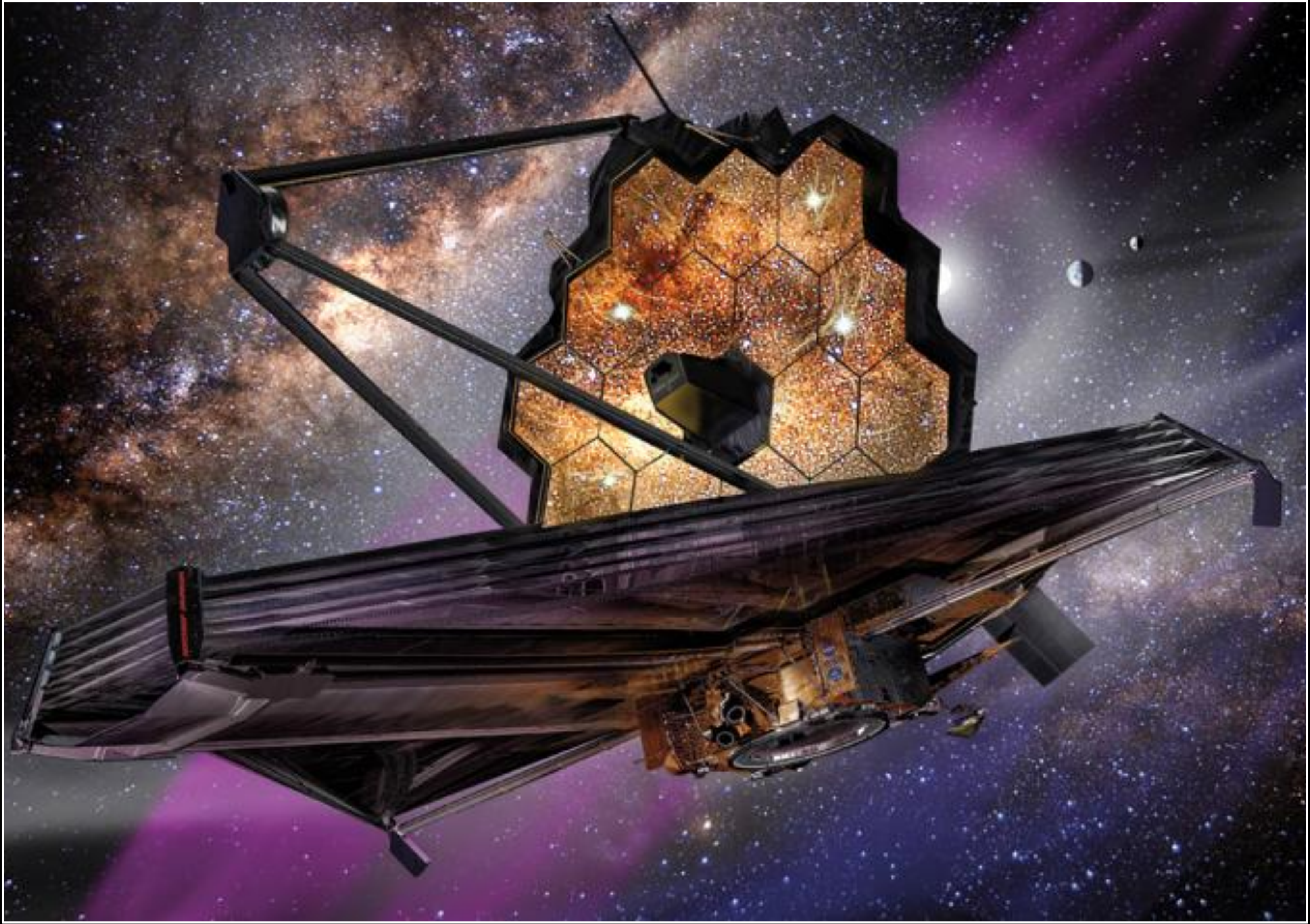
Credits: NASA

TRAPPIST-1 planets: cooked during >1 Gyrs



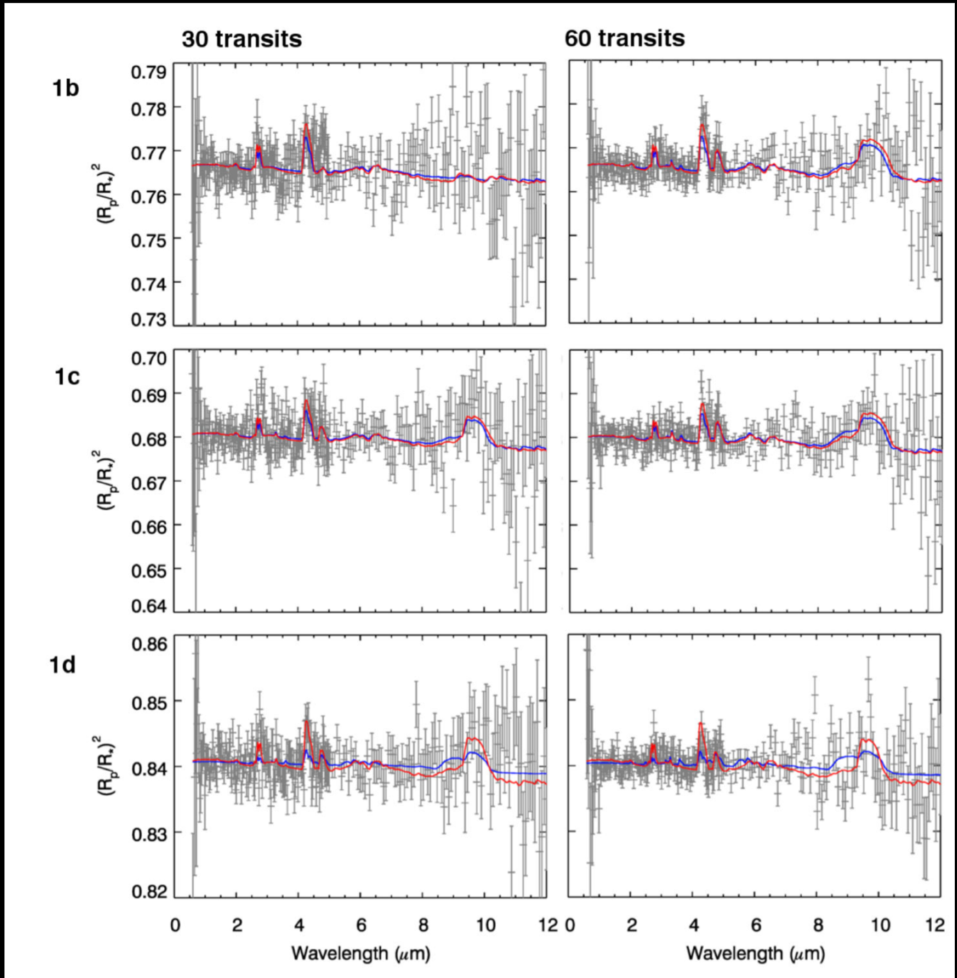
Credits: Mario-Ramirez & Kaltenegger 2017

2021: the James Webb Space Telescope

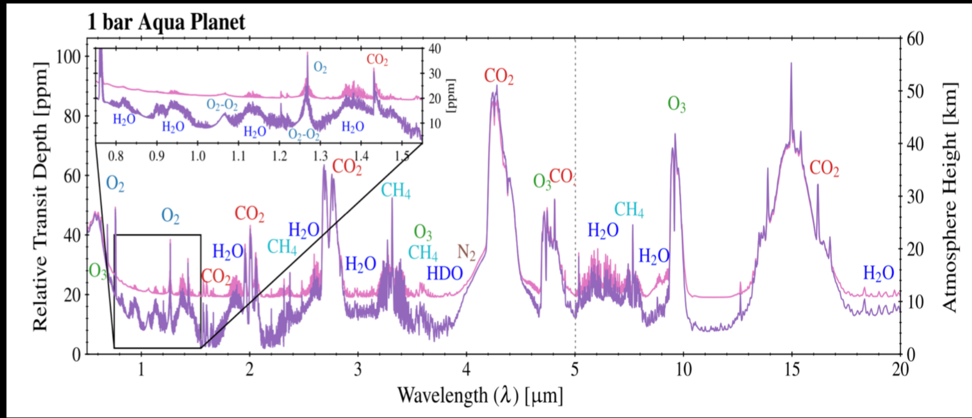


Credits: James Vaughan

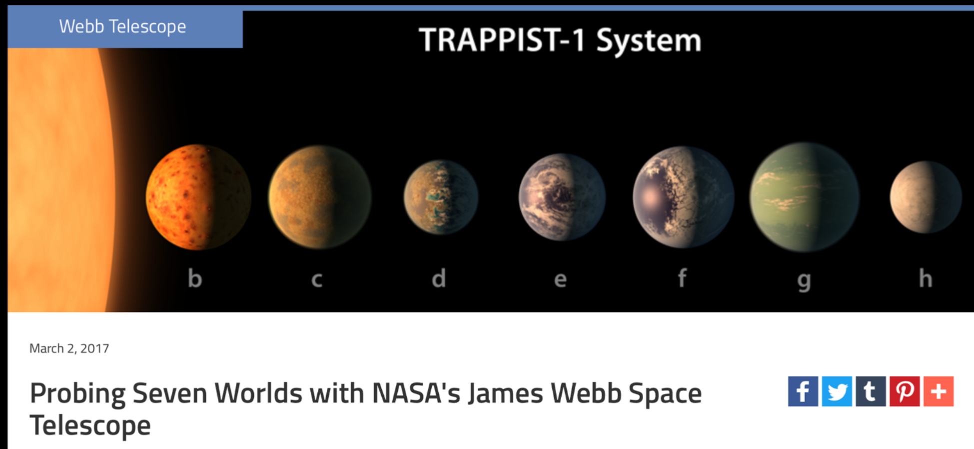
2022: James Webb Space Telescope



Barstow & Irwin 2016



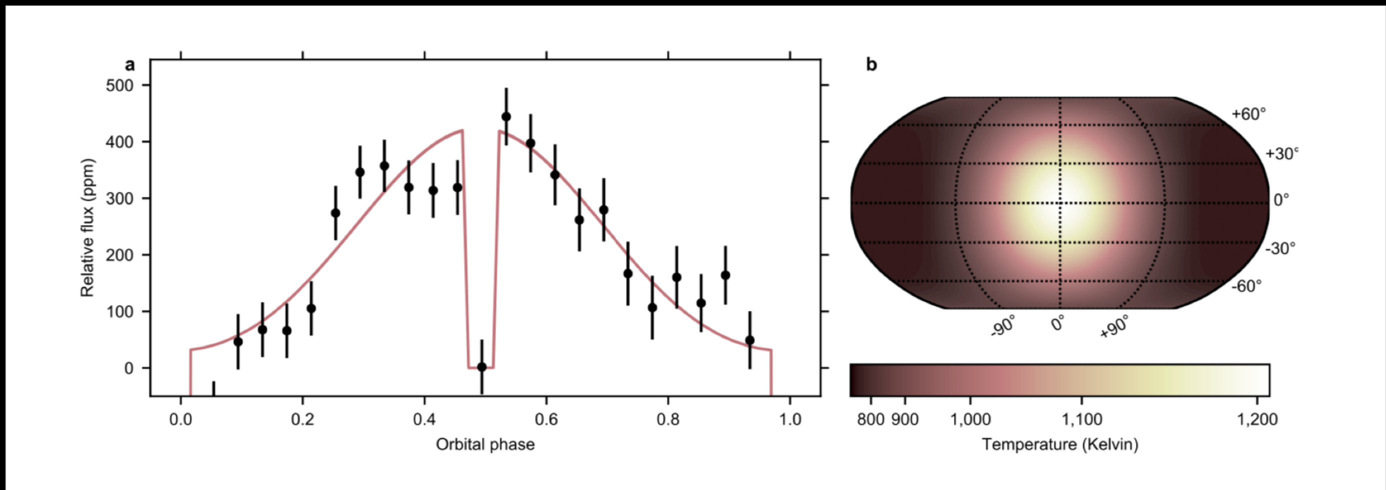
Lincowski et al. 2018



TESS and rocky planets around mid-type M-dwarfs

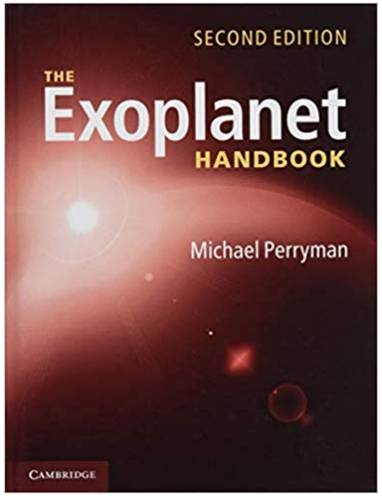
LHS3844: a rocky Earth-mass planet on a 11hr-orbit around a M4-type star at 15pc (Vanderspek et al 2018).

Spitzer phase curve suggests no atmosphere (Kreidberg et al. 2019)

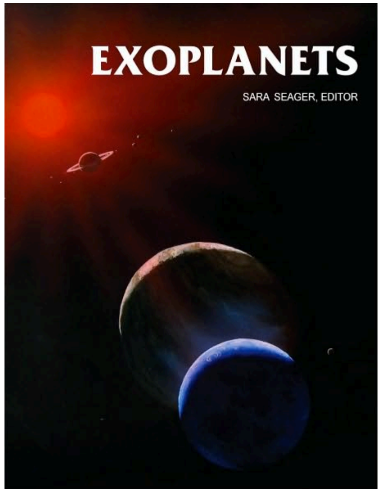


LP791-18: at least 3 planets around a M6-type M-dwarf at 26.5pc, including a super-Earth at the inner edge of the habitable zone (Crossfield et al. 2019)

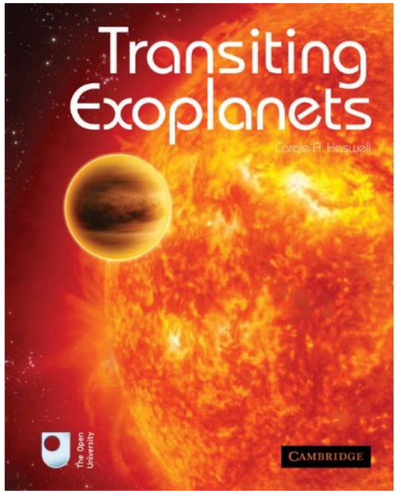
References



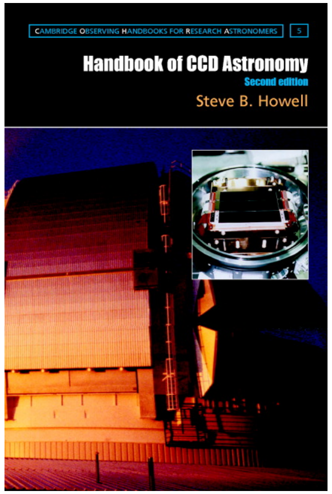
M. Perryman
Cambridge University Press
Chapter 6



S. Seager
University of Arizona Press
Chapter 3 (J. Winn)



C. A. Haswell
Cambridge University Press
Chapters 2 to 7



S. B. Howell
Cambridge University Press
Chapters 1 to 5