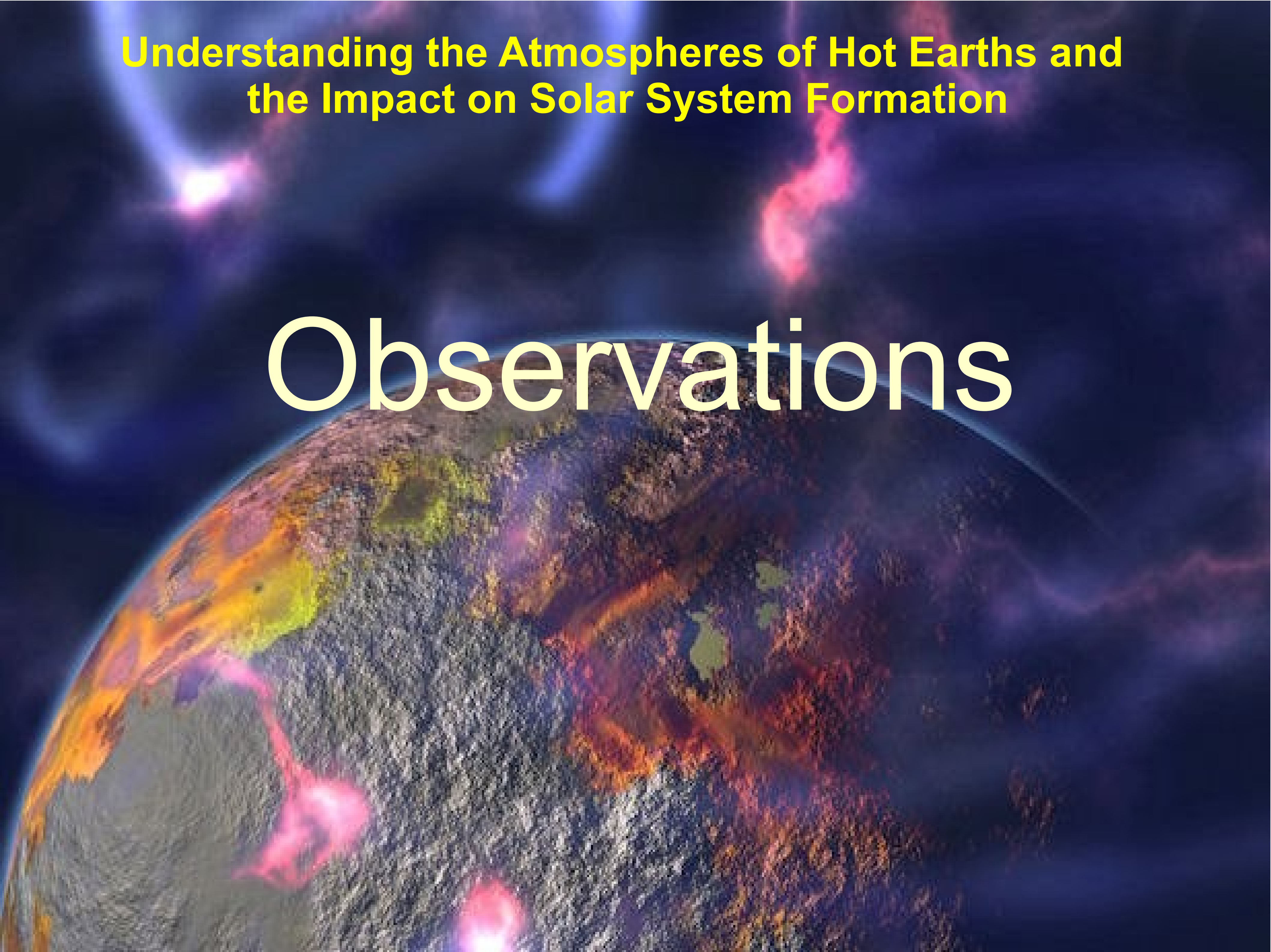


Understanding the Atmospheres of Hot Earths and the Impact on Solar System Formation

Observations

Outline:

1) What has been found-
   - i) Planets
   - ii) Characterization Techniques
   - iii) Properties of planets.

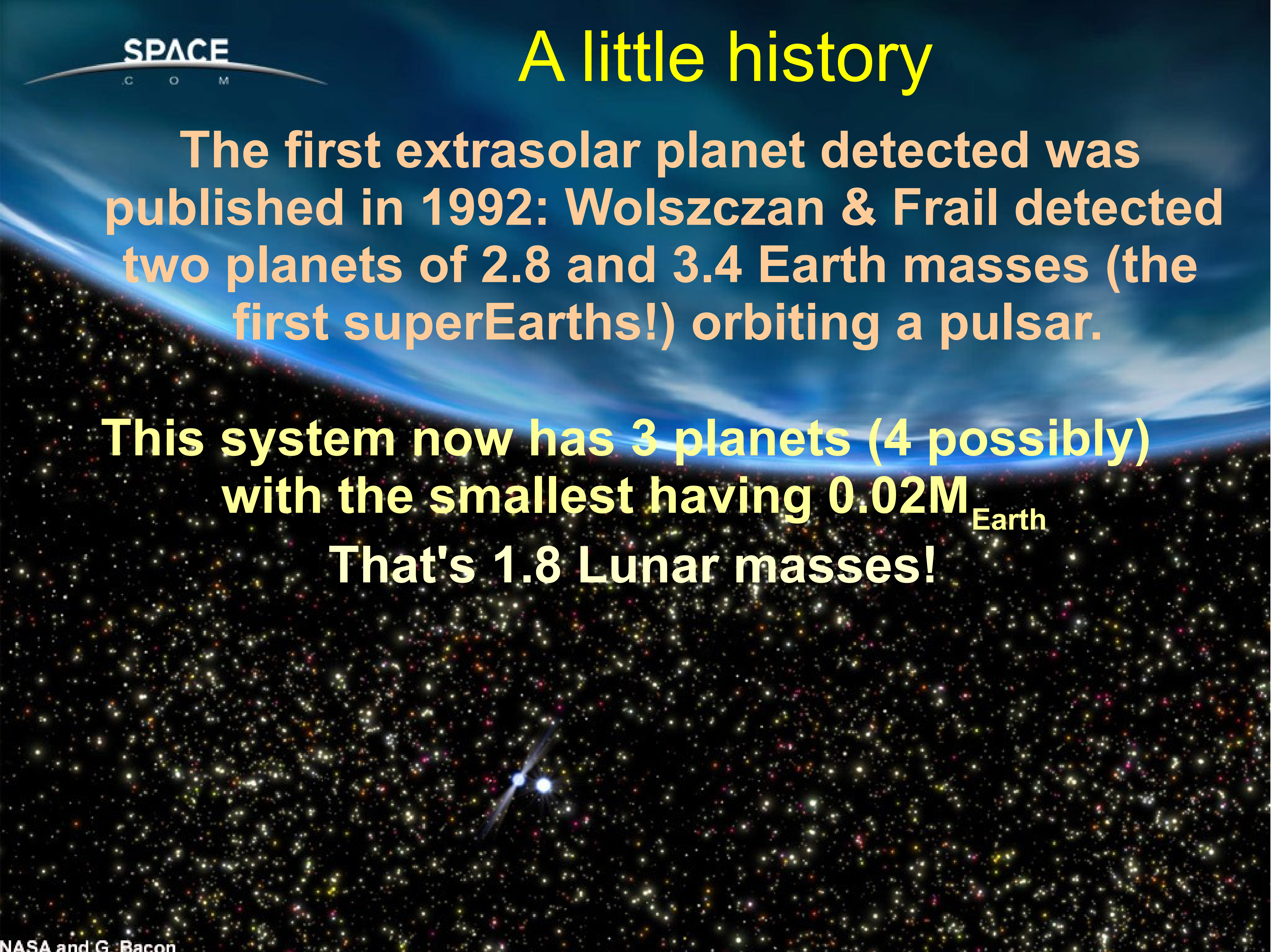
2) What our strategy is-
   - i) Observing
   - ii) Image processing

A little history

The first extrasolar planet detected was published in 1992: Wolszczan & Frail detected two planets of 2.8 and 3.4 Earth masses (the first superEarths!) orbiting a pulsar.

This system now has 3 planets (4 possibly) with the smallest having $0.02M_{Earth}$

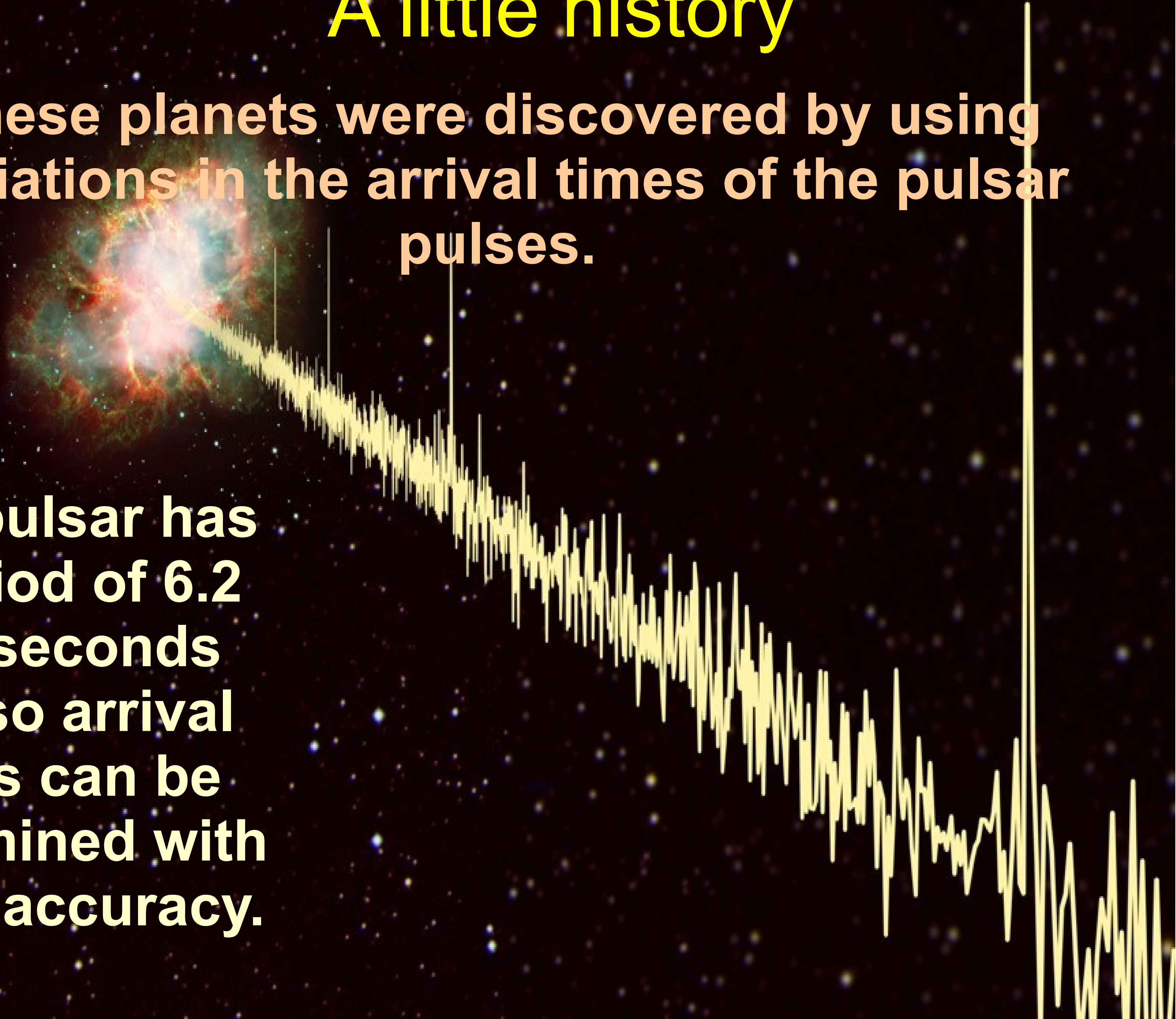
That's 1.8 Lunar masses!



NASA and G. Bacon

A little history

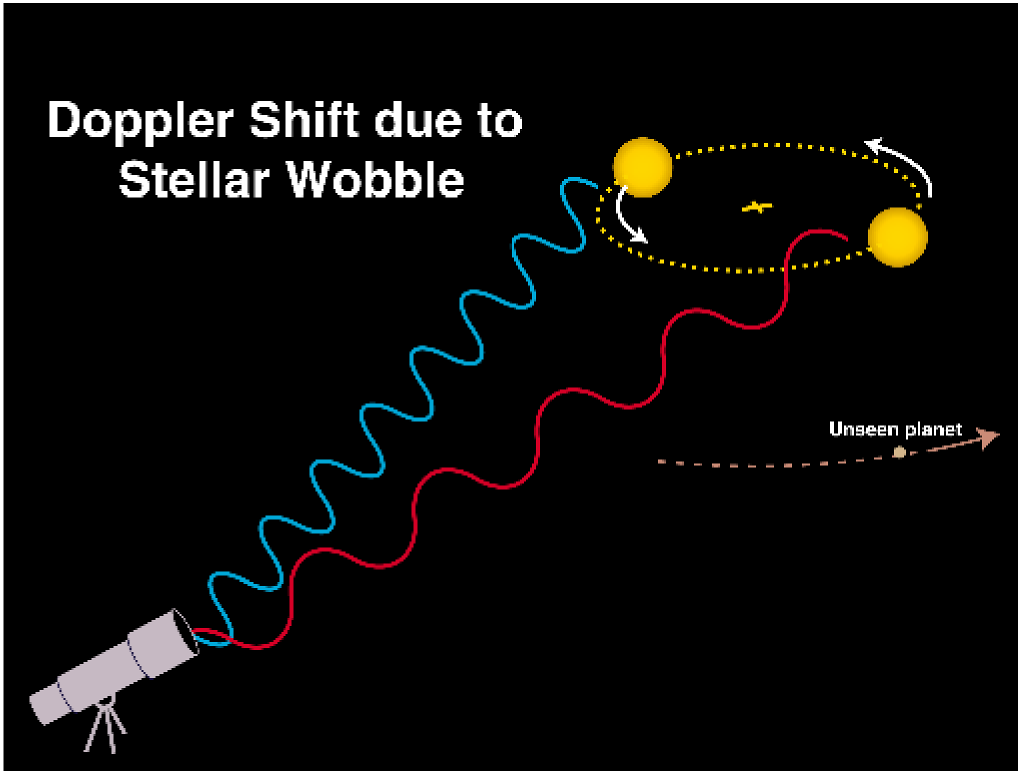
These planets were discovered by using variations in the arrival times of the pulsar pulses.

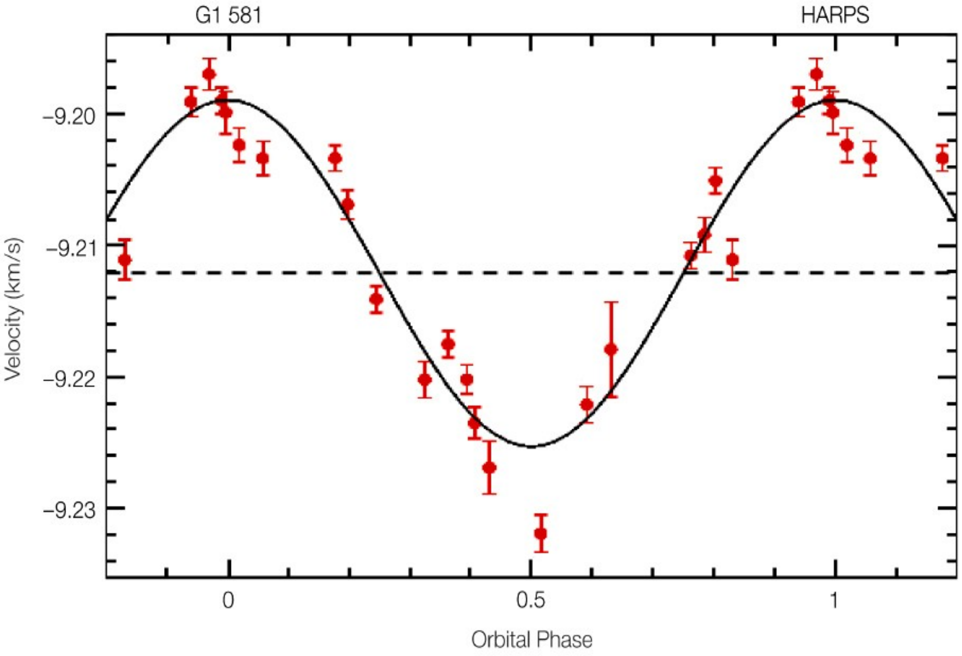


This pulsar has a period of 6.2 milliseconds and so arrival times can be determined with great accuracy.

The first extrasolar planet around a 'normal' (main-sequence) star was discovered in 1995 by Swiss astronomers.

The planet has $M=0.5M_{Jupiter}$ and orbits in 4.2 days. It was discovered via Doppler shifts in the host star's spectrum- the RV method





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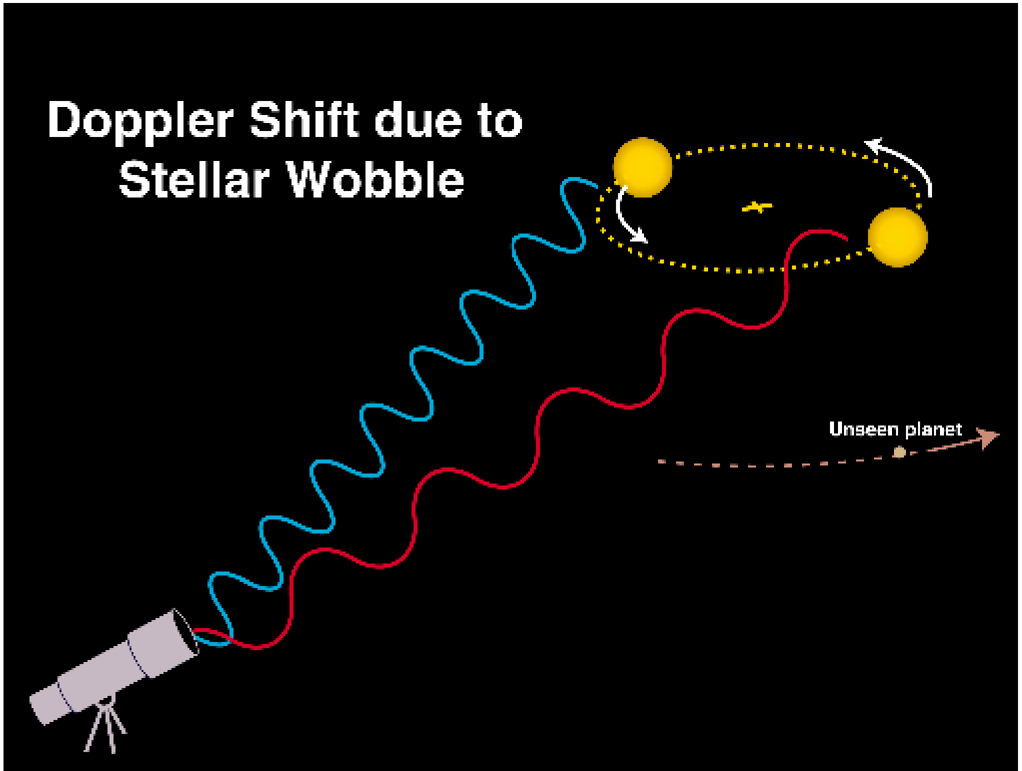
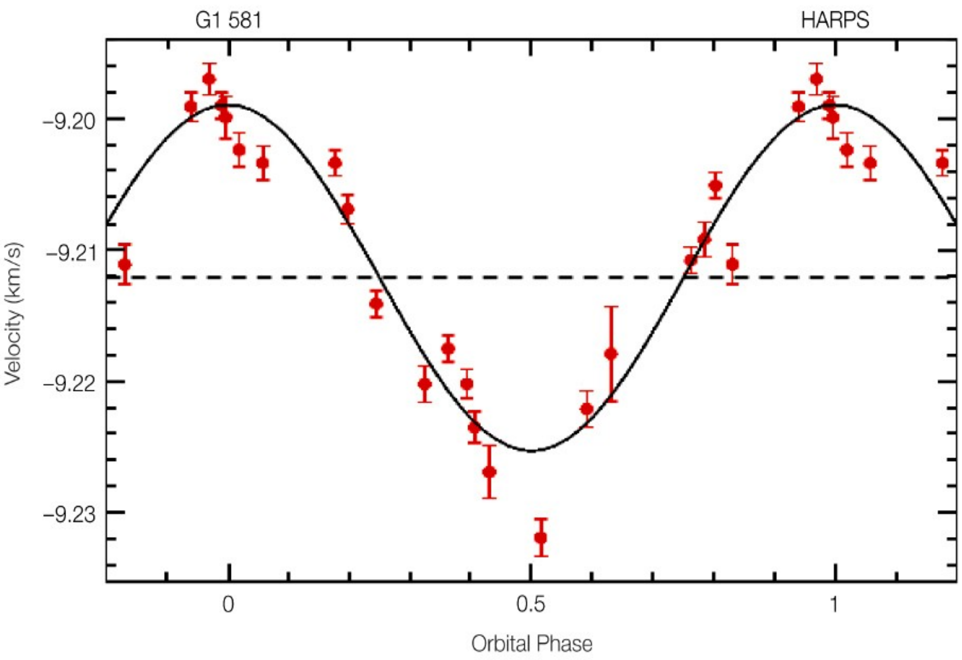




The RV method used a new technique of observing through an iodine cell.

BUT... this method only works for bright stars and is biased towards massive planets in short orbits at low inclinations, which produce the highest velocities.

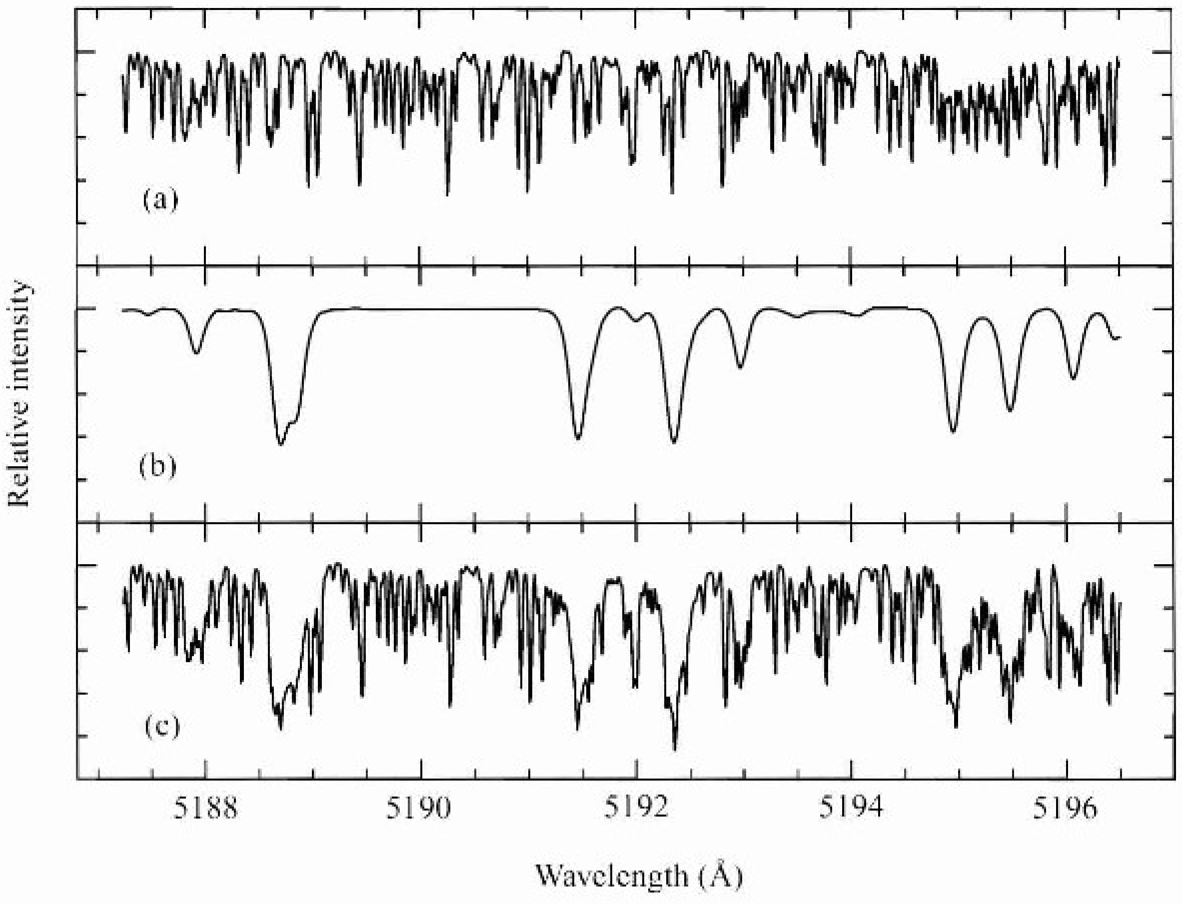


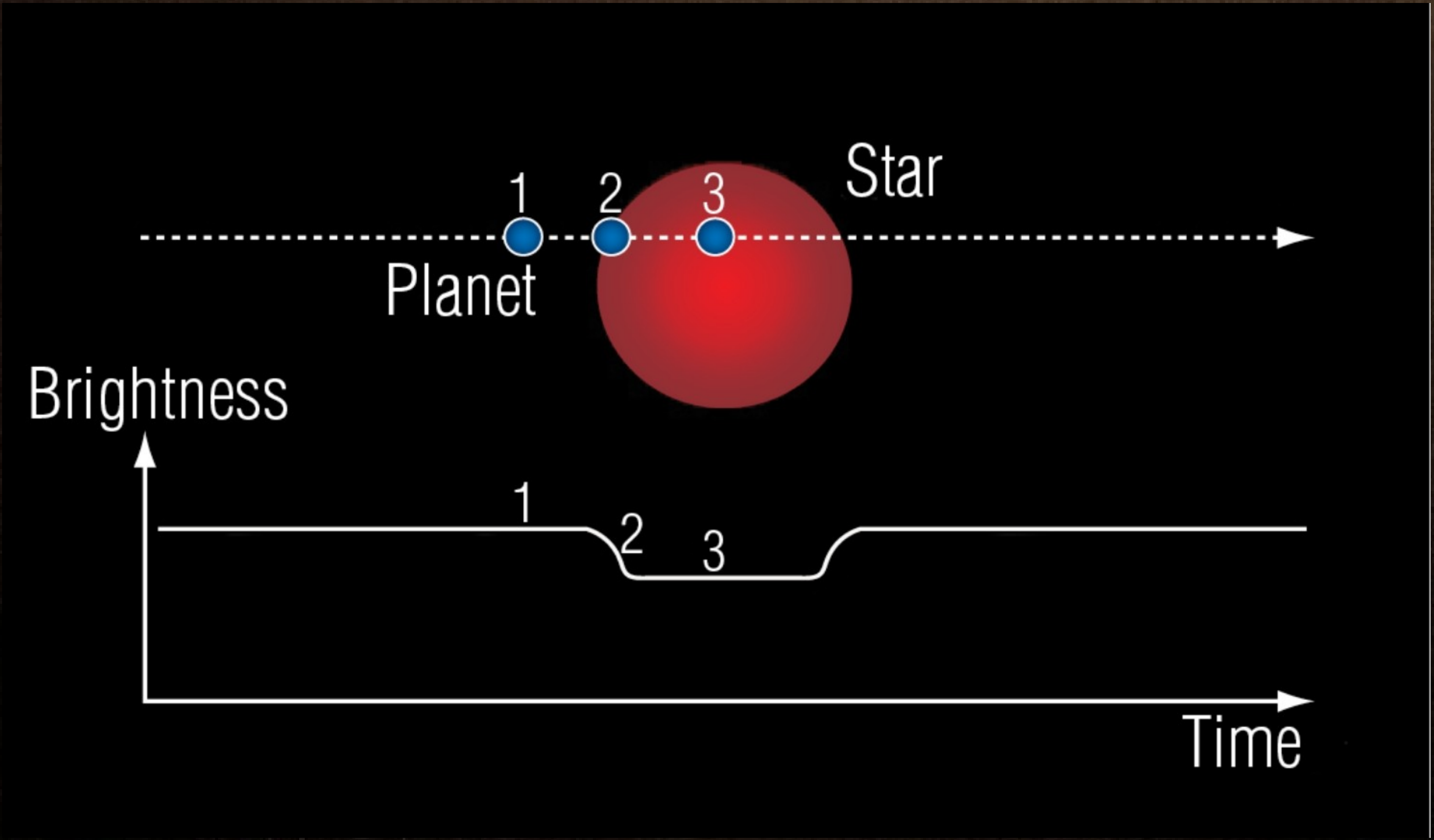
Figure 13.3. Illustration of high-precision Doppler measurements with an iodine cell. (a) Iodine cell absorption spectrum. (b) Spectrum of Procyon. (c) Spectrum of Procyon with the iodine cell in front of the spectrograph slit. The relative Doppler shift between the iodine and star spectra is determined by fitting the spectra from (a) and (b) to the combined spectrum. Figure courtesy William D. Cochran.

And this was largely the state of things for the next 15 years.

About 300 planets were discovered.

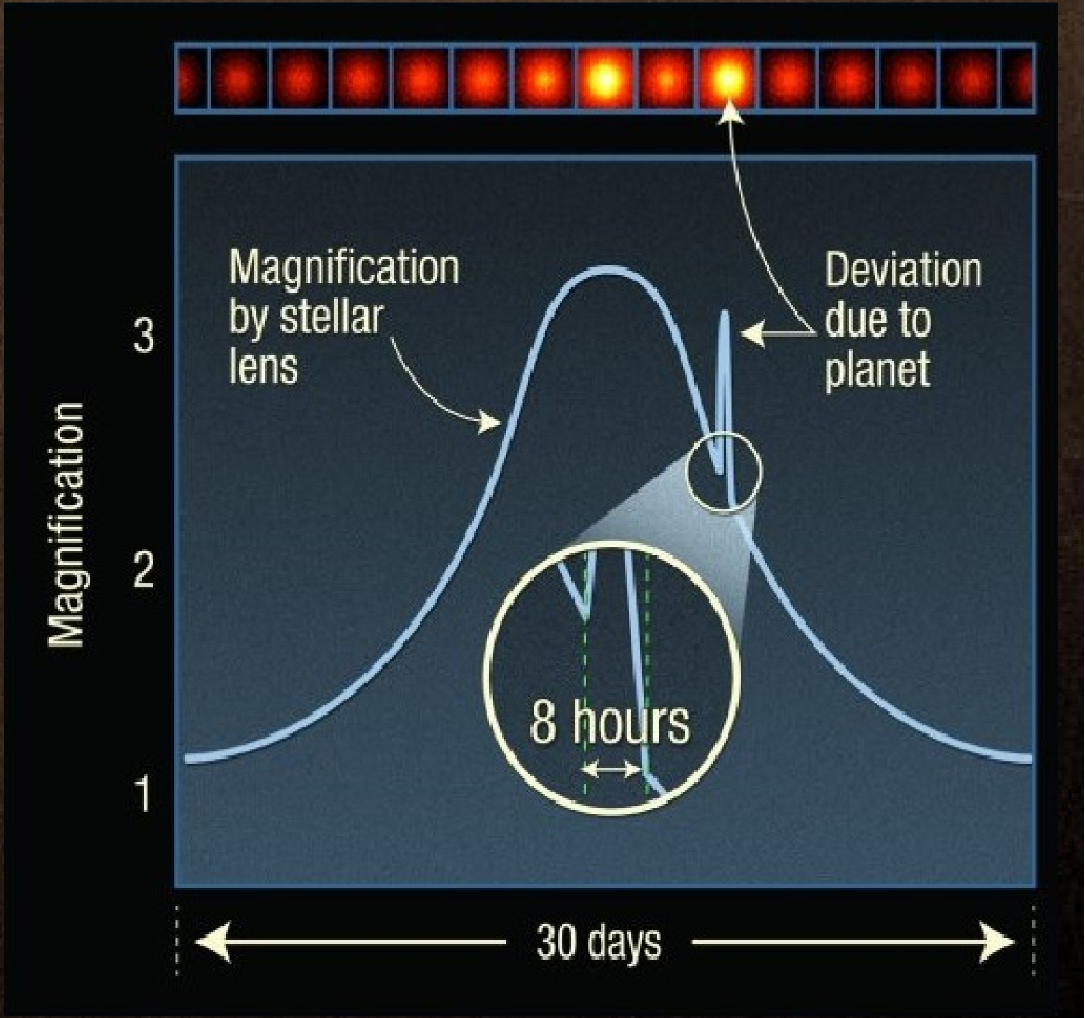
Improvements in the RV method detected planets down to about 8 Earth masses in very short orbits.

Transits of a few (already known) planets were detected from Earth.

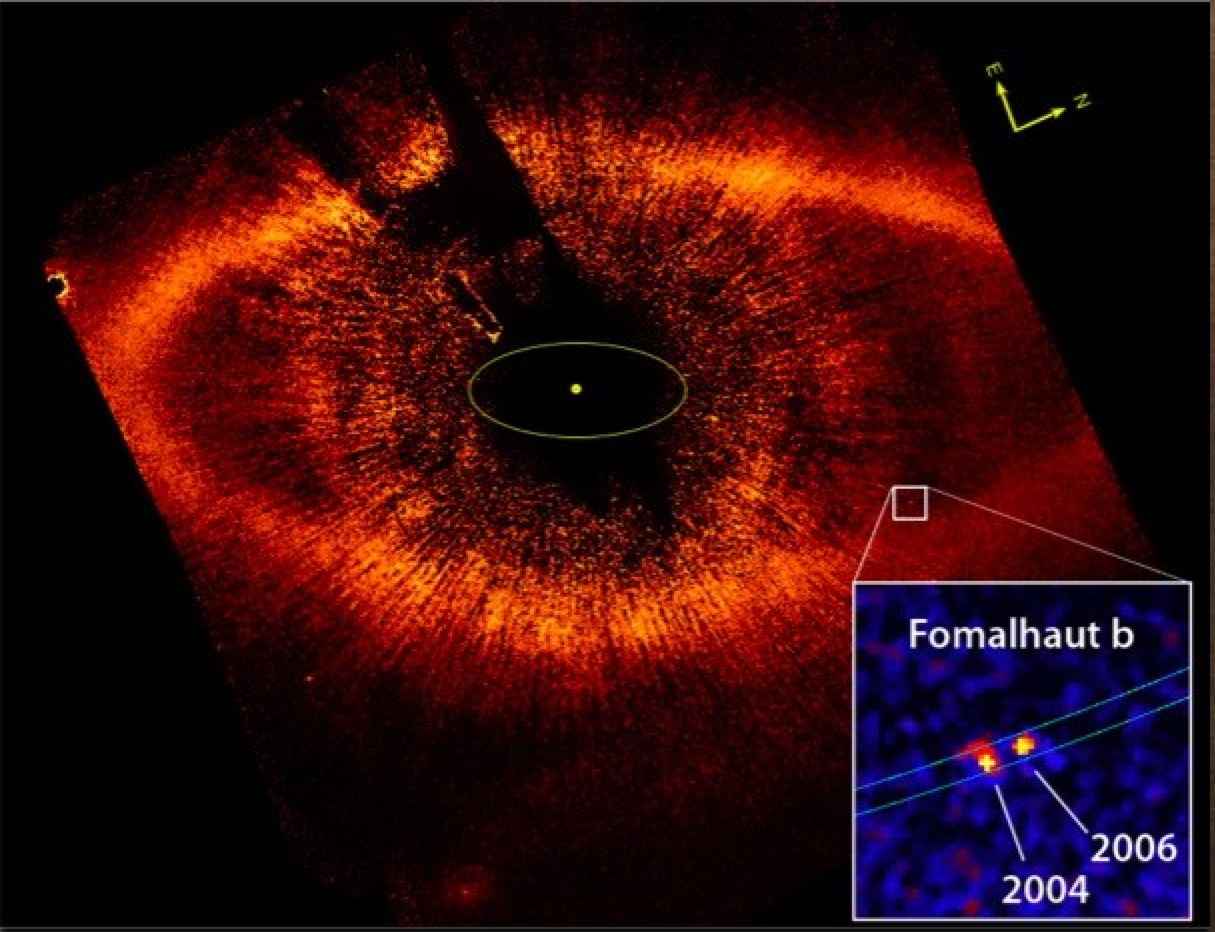


A few planets were detected using microlensing.

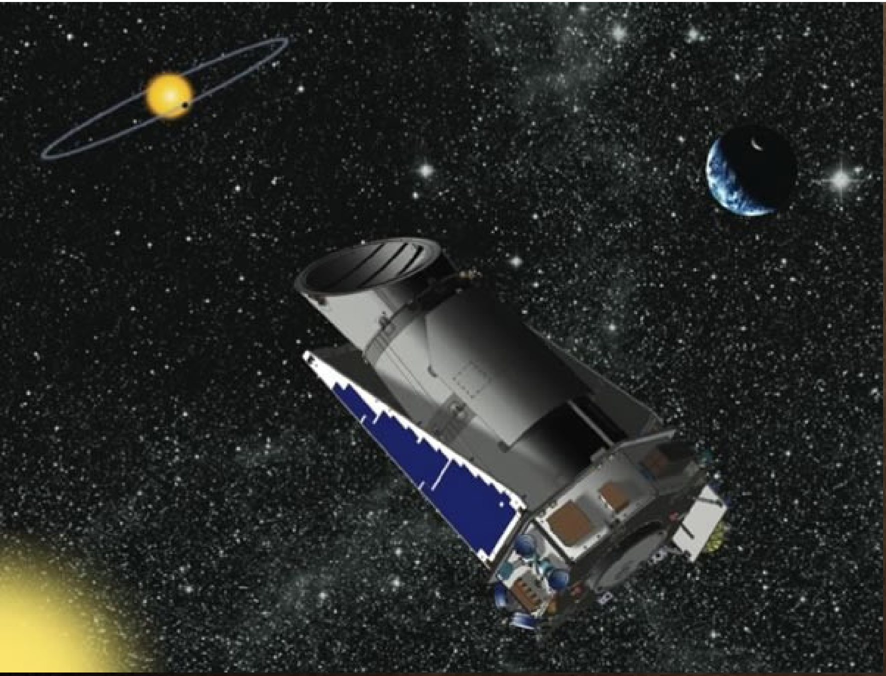
These events do not repeat.



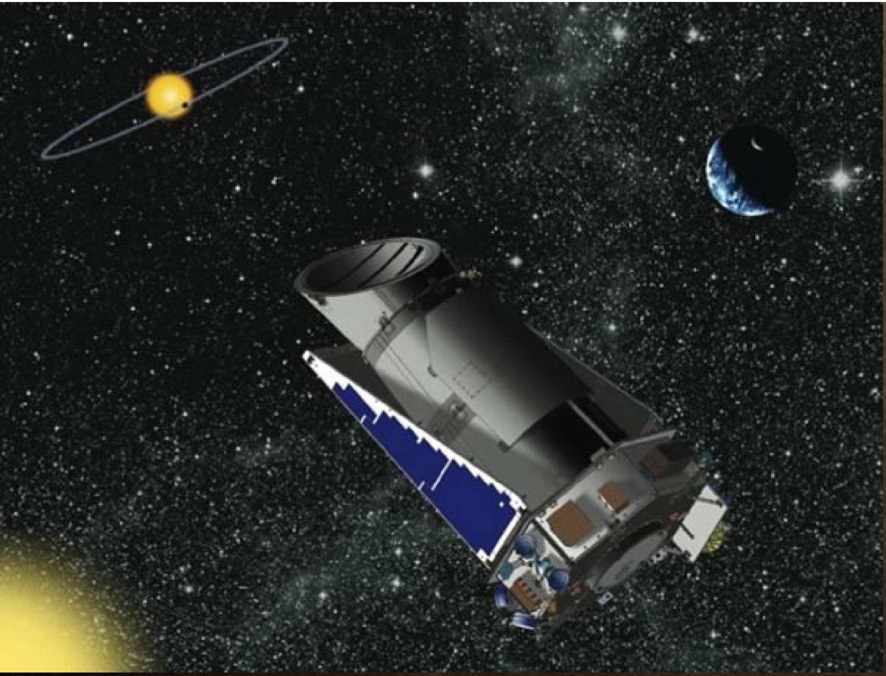
These are all indirect methods! The planet itself is not measured, only its effect on the host star.



Direct imaging: currently works for big planets far from their host stars. Fomalhaut b is $2M_J$, 115 AU from its host star.



Kepler began taking data in March 2009, and now there are nearly 3,900 planet candidates! Kepler has used the transit method, while staring at 150,000+ stars.

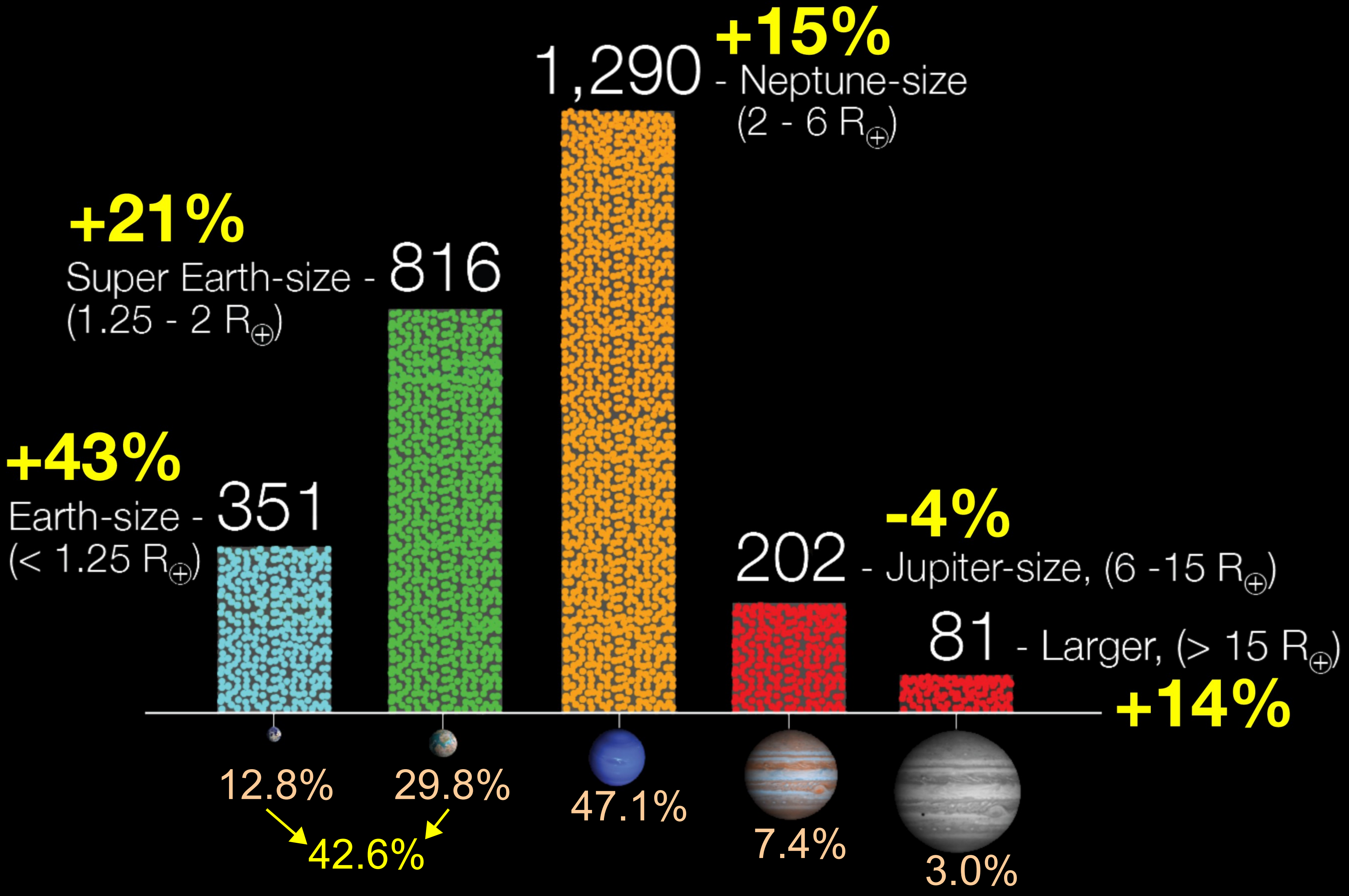


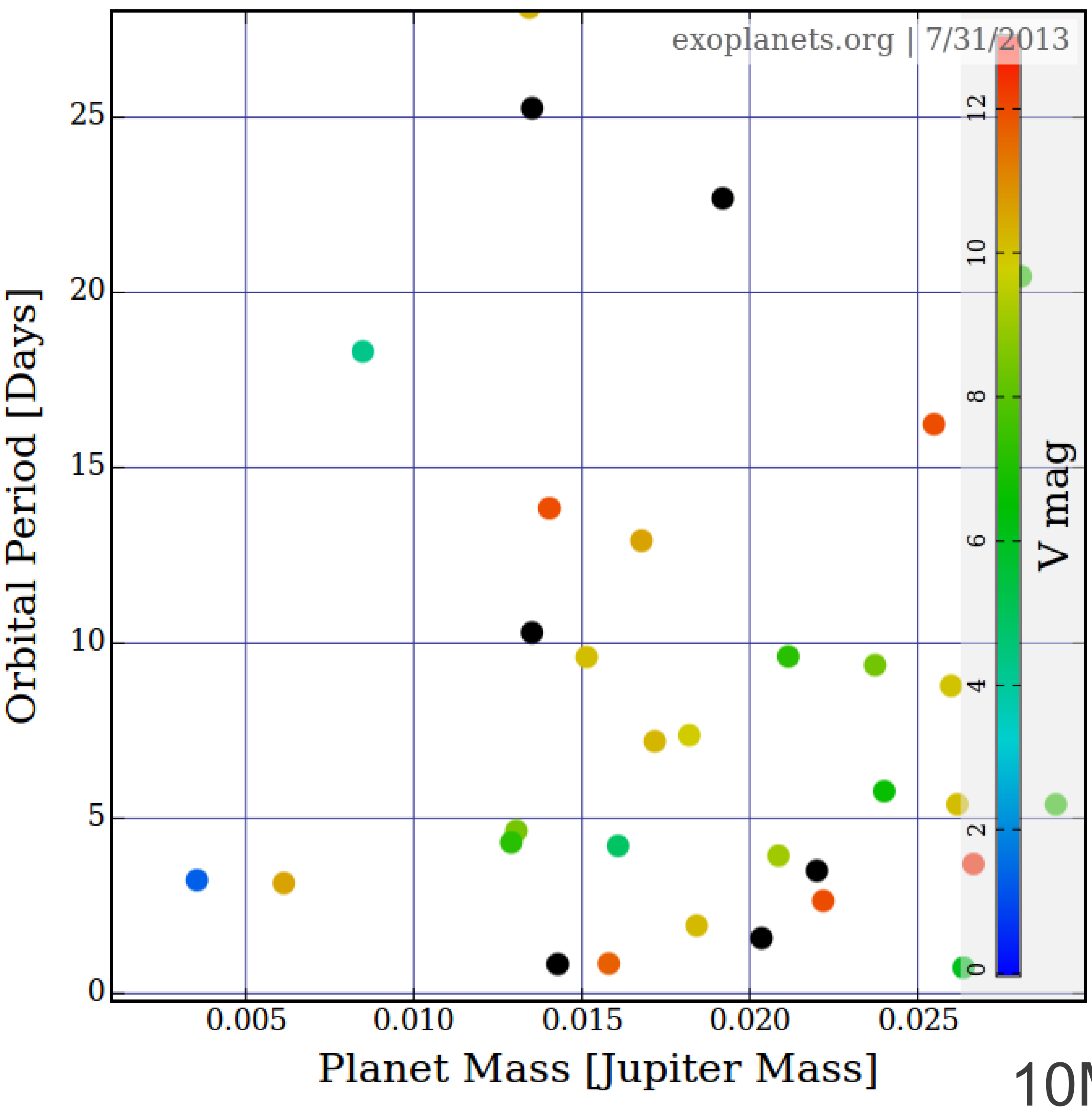
This has been the tipping point.

There are now so many planets that we can do some statistics.

Sizes of Planet Candidates

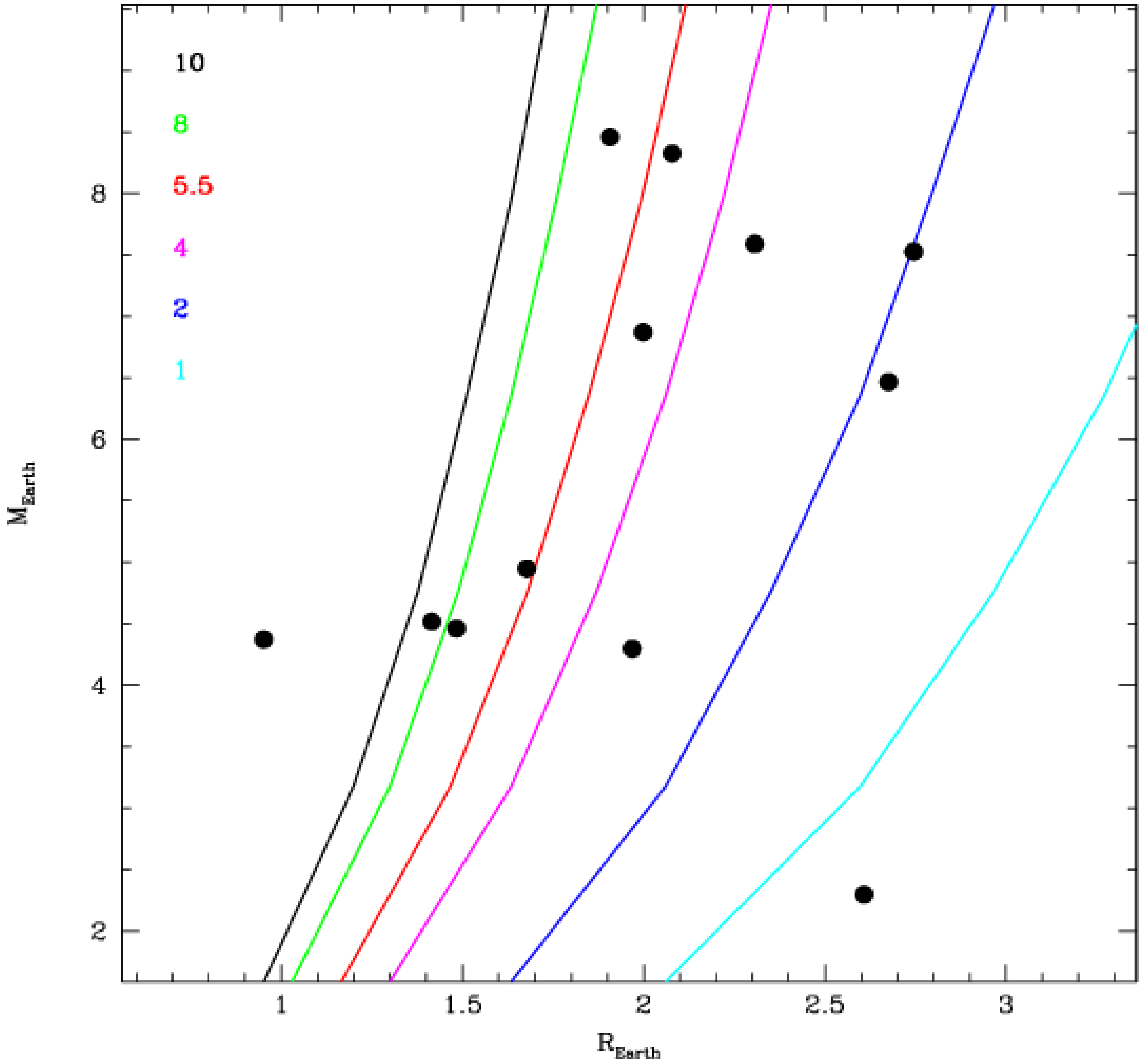
As of January 7, 2013





Planets we may be interested in.

$10M_{Earth}$

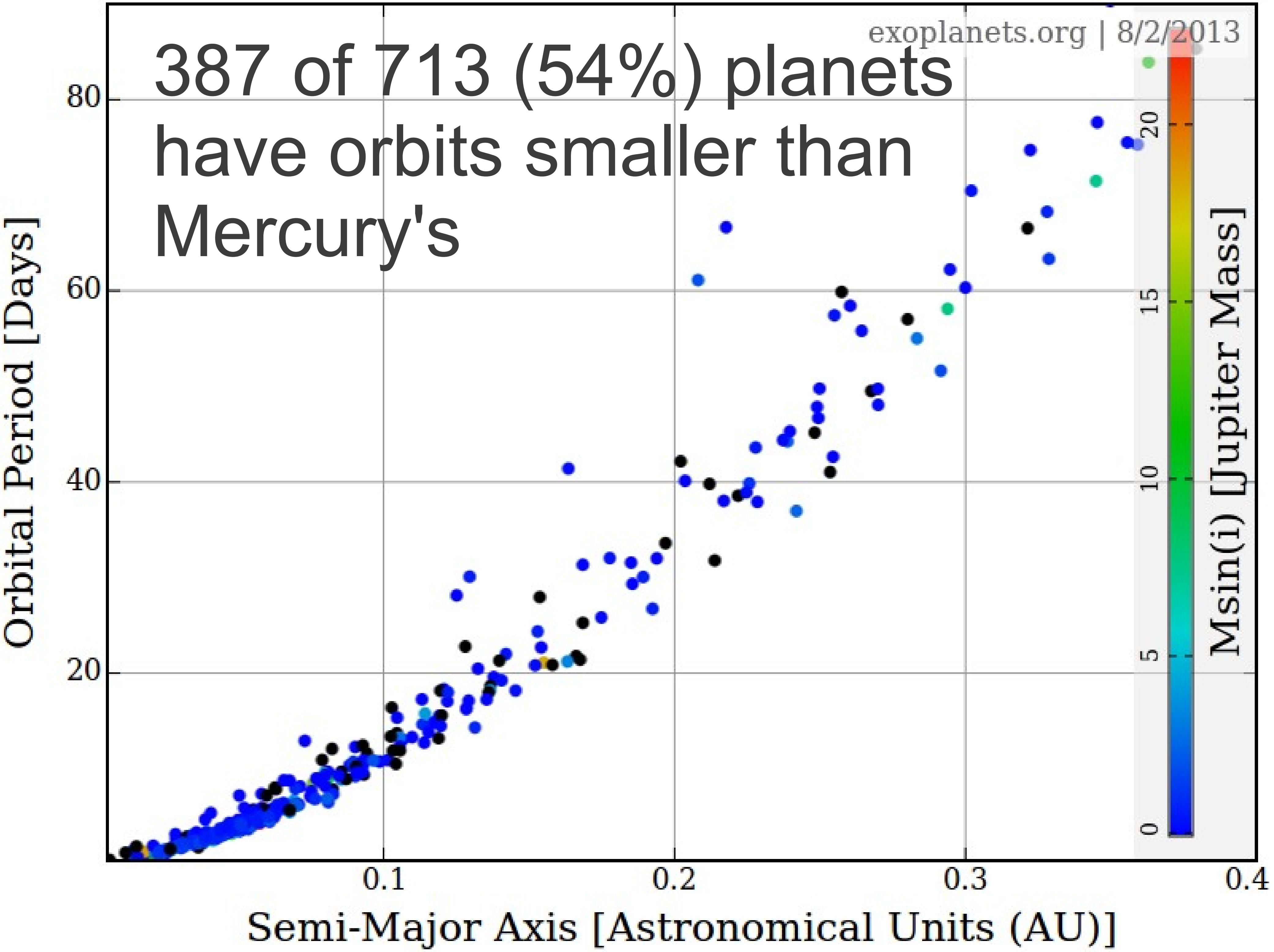

10
8
5.5
4
2
1
8
6
4
2
M_{Earth}
1
1.5
2
2.5
3
R_{Earth}

Not in the previous graphs (no mass estimates)

P_{Orb}=	13	21	40 days
a_{AU}=	0.10	0.14	0.21 AU

Mercury's orbit is 88 days at 0.39 AU.

387 of 713 (54%) planets have orbits smaller than Mercury's



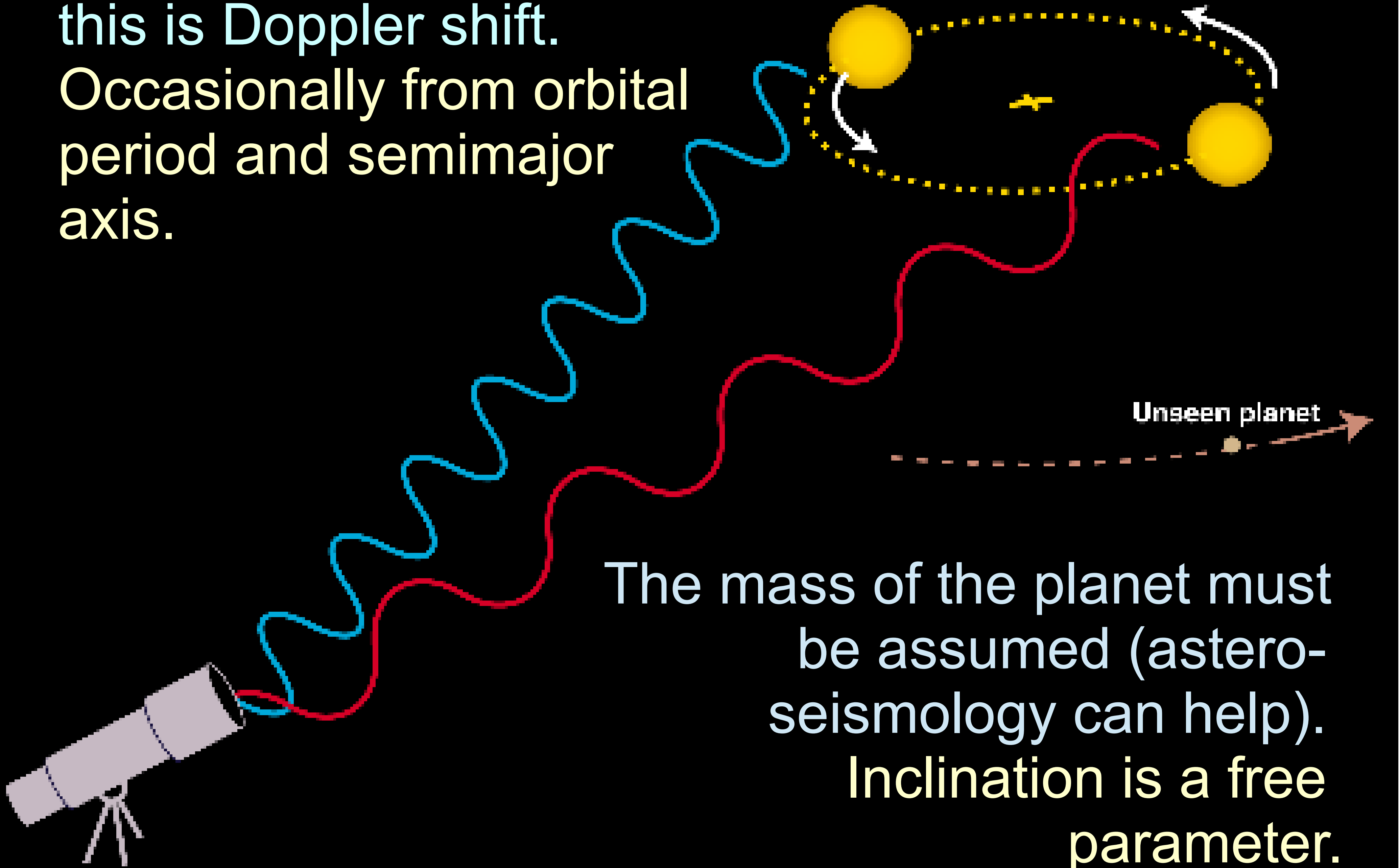
Characterization Techniques

Orbit: Mass and Radius

Transmission Spectroscopy

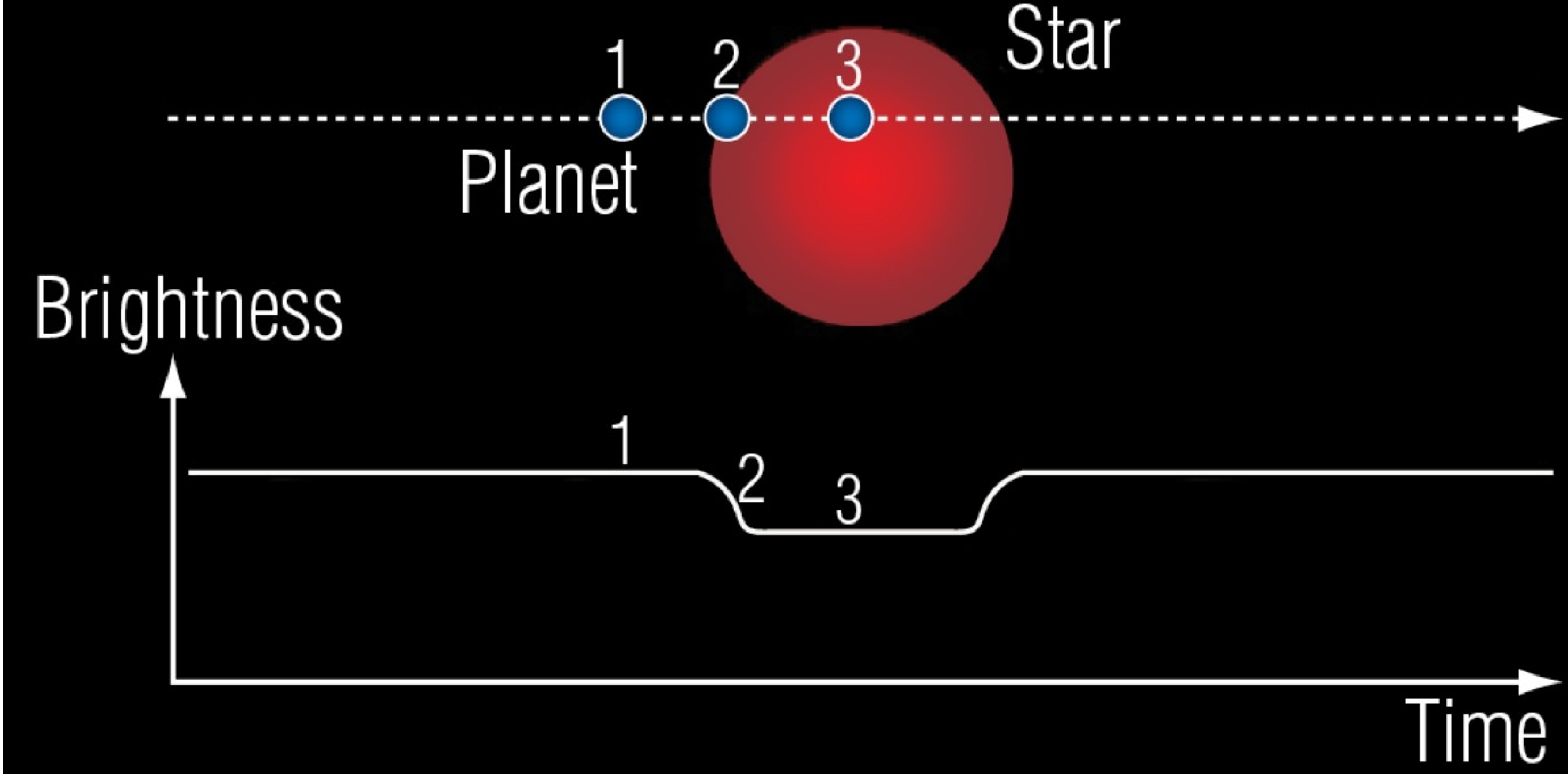
Reflection Spectroscopy (including broadband photometry)

Masses come from orbital mechanics only. Typically this is Doppler shift. Occasionally from orbital period and semimajor axis.

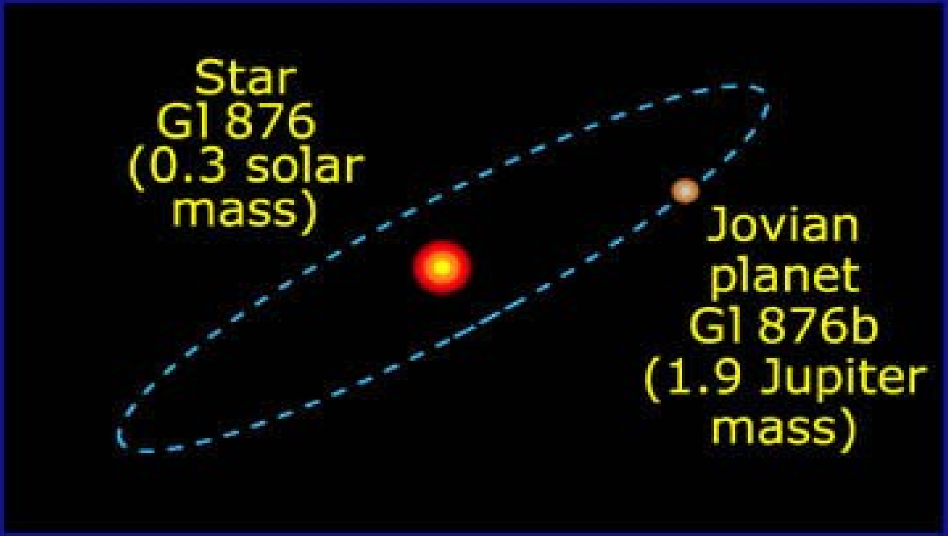


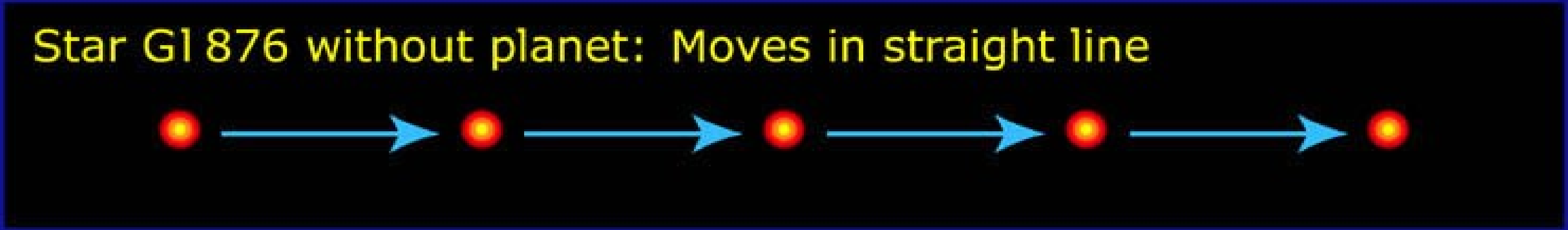
The mass of the planet must be assumed (astero-seismology can help). Inclination is a free parameter.

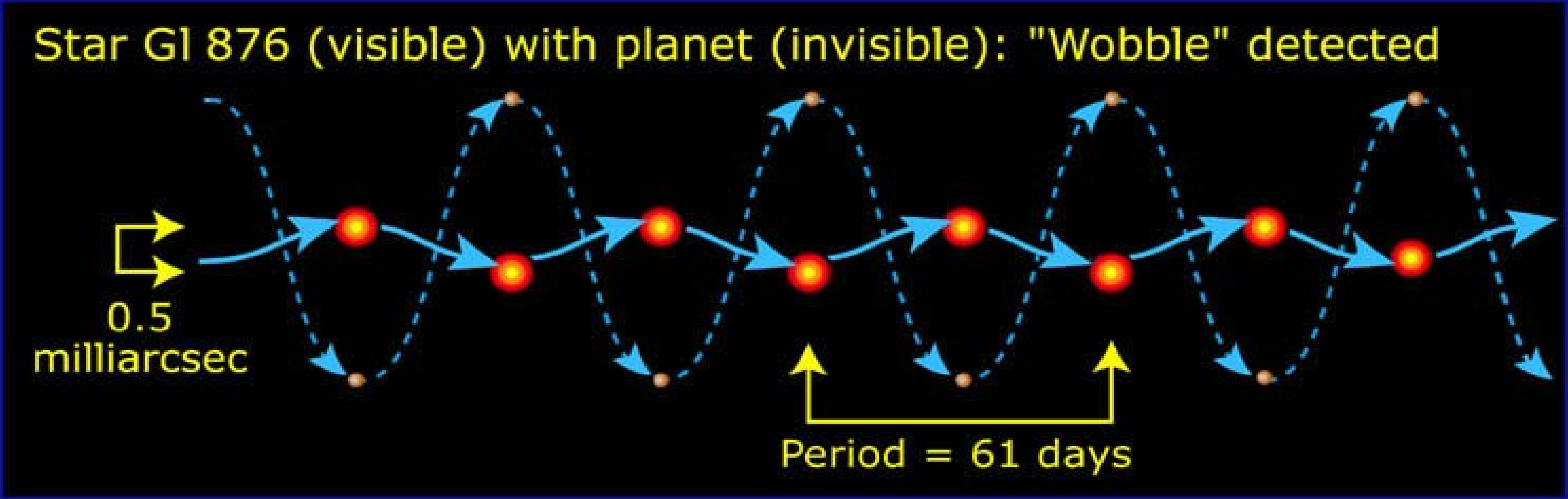
Transits also constrain the inclination: but for *very* short period planets, the constraints are lessened.



Doppler plus astrometry can constrain the inclination.

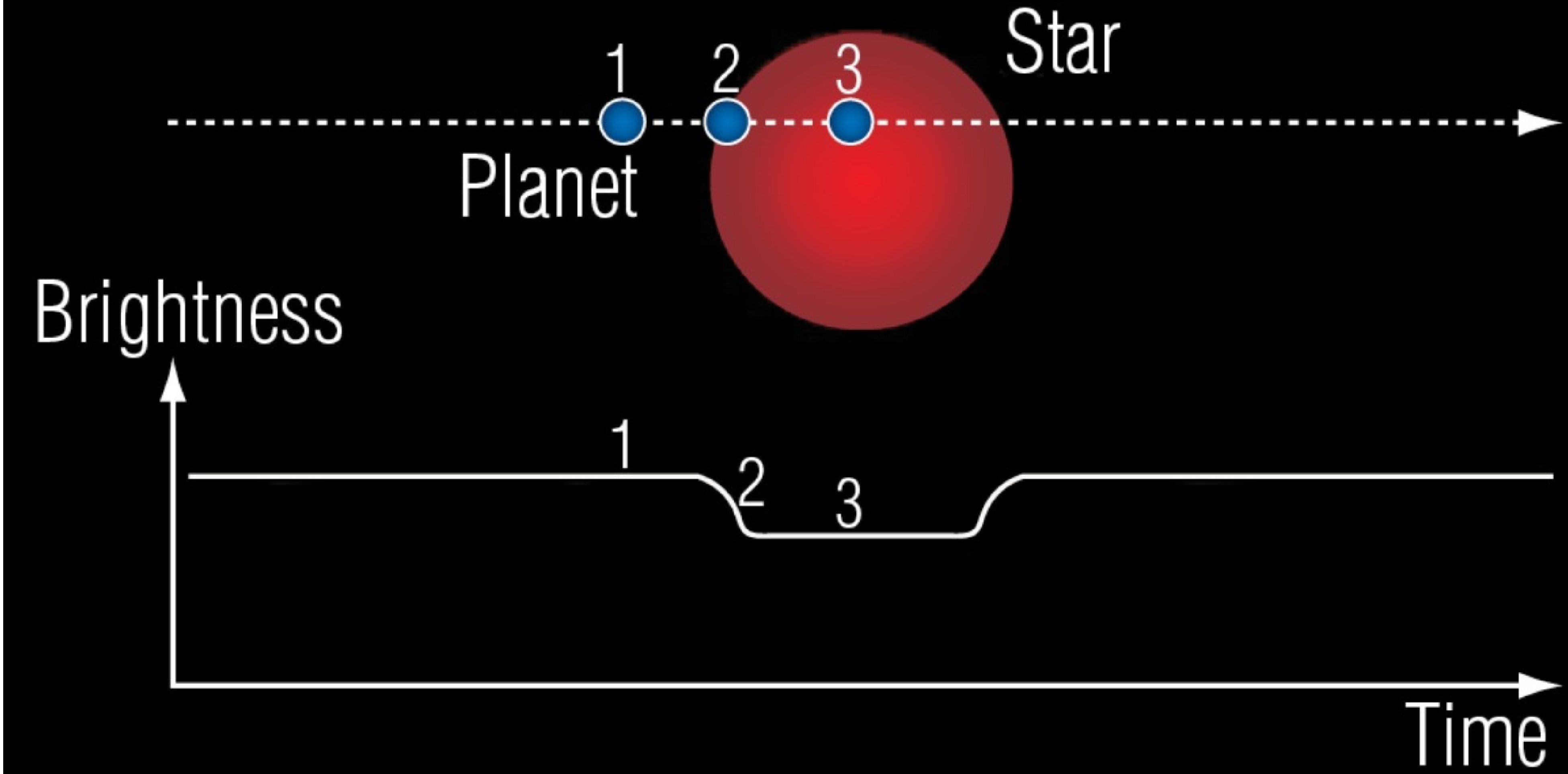




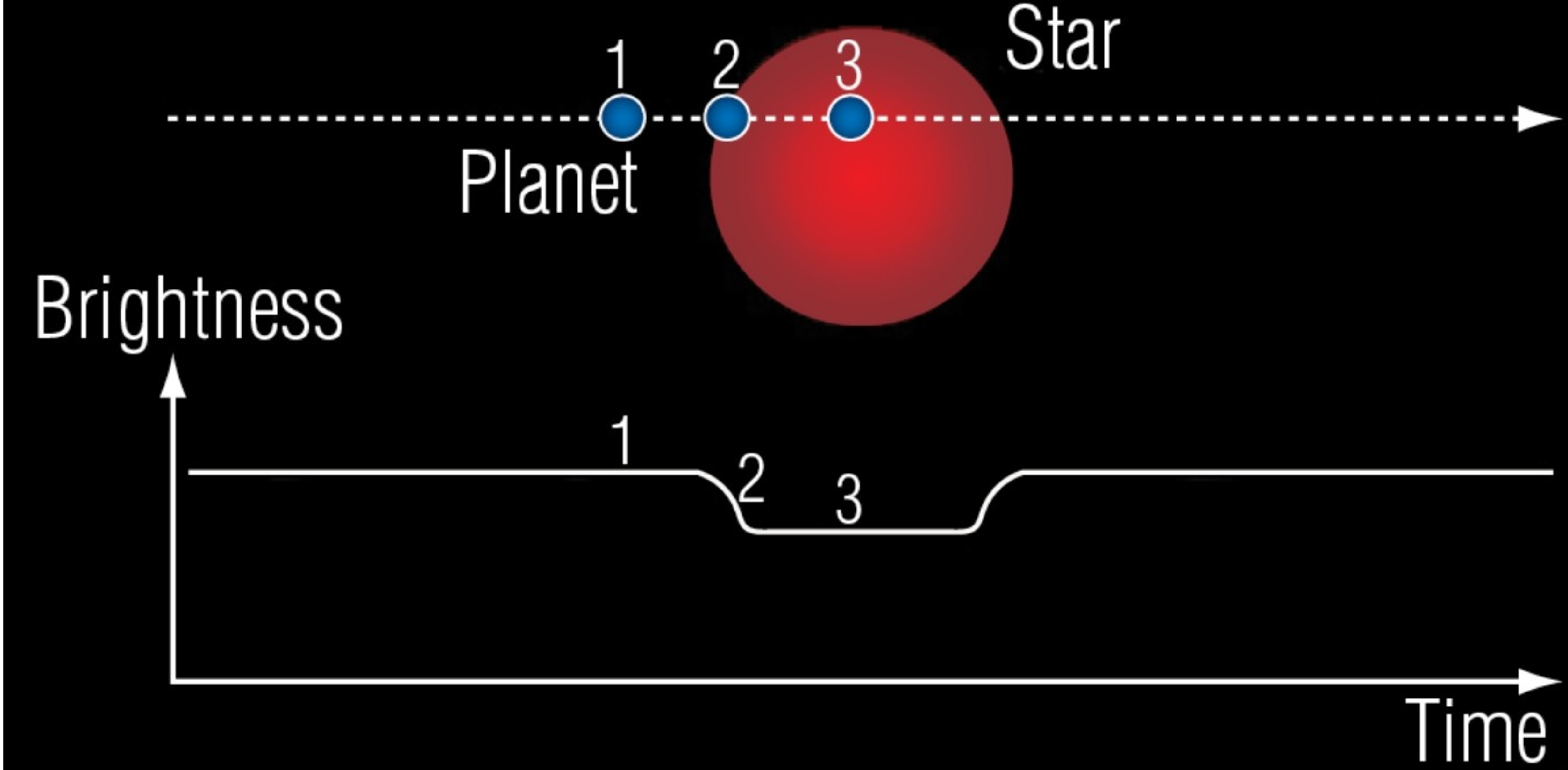


Transits also give the planet's radius.

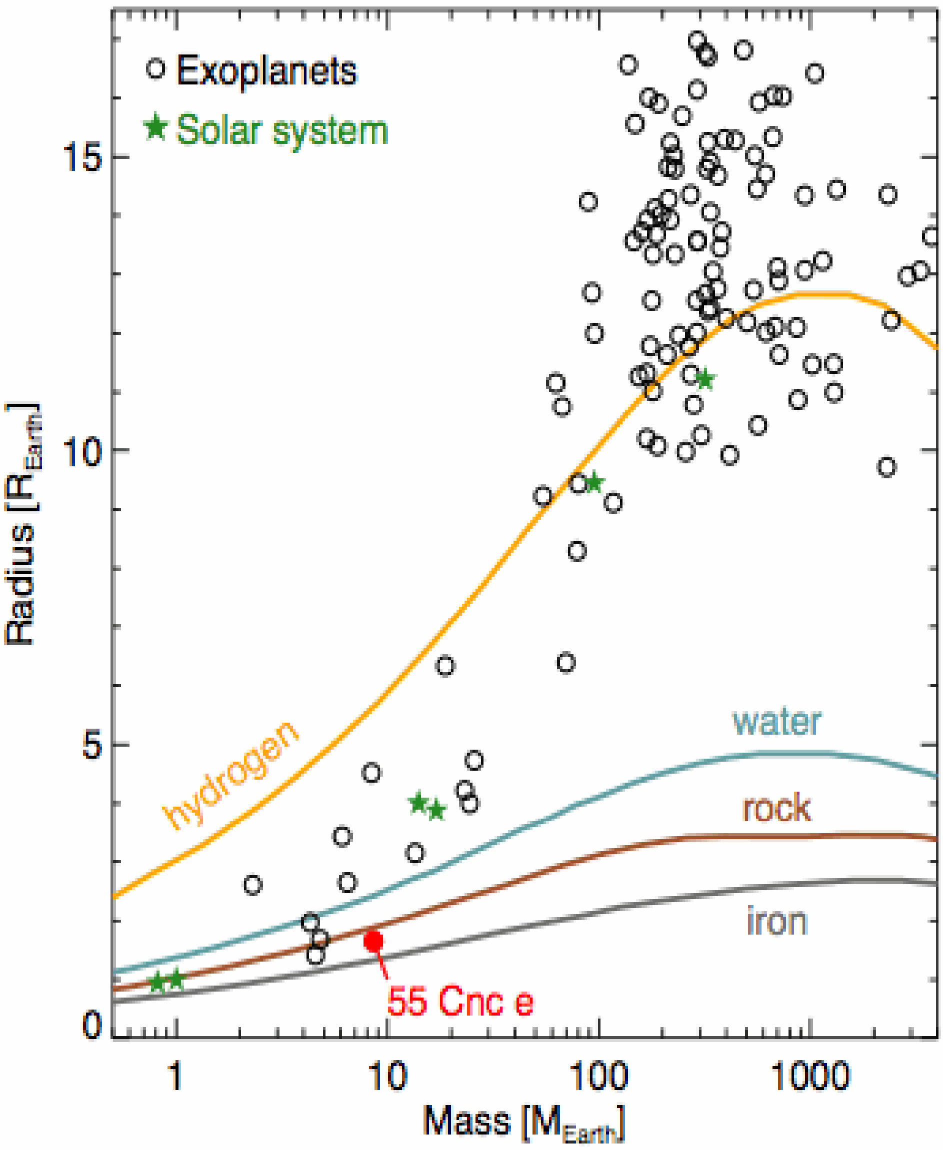
Again asteroseismology can help.

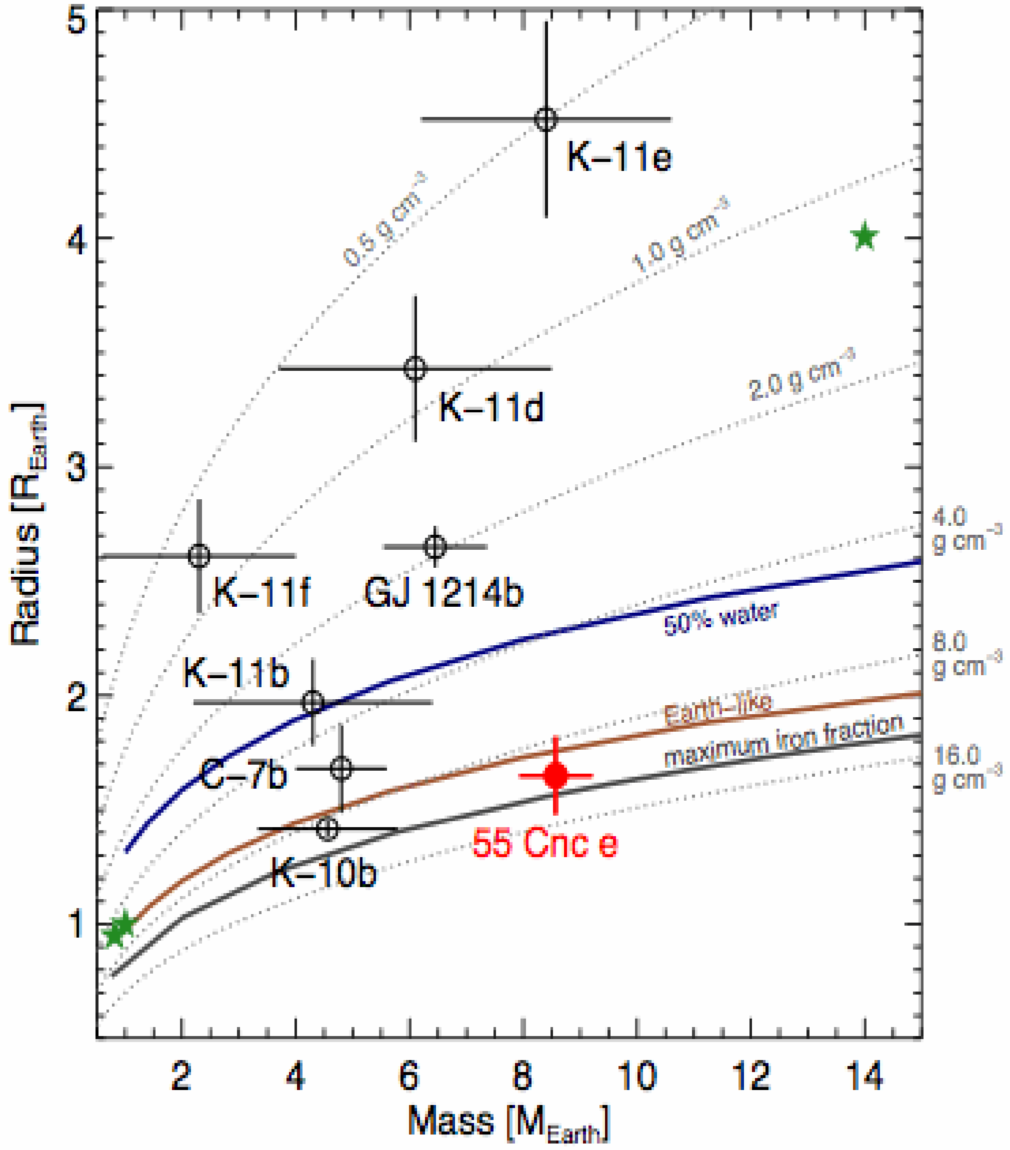


With sufficient transit precision (ingress/egress timings), inclination can be determined too (and more precise radii).

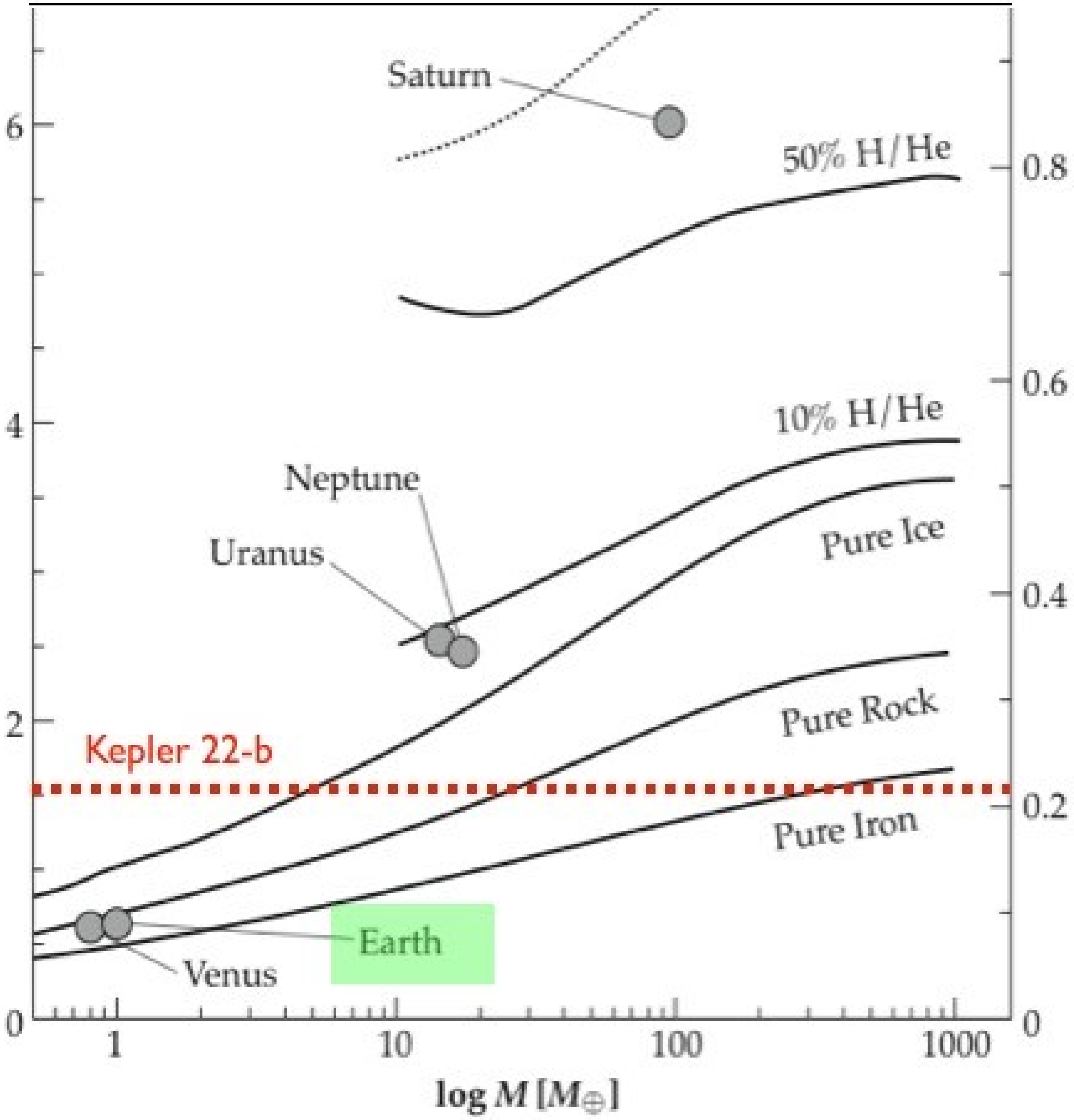


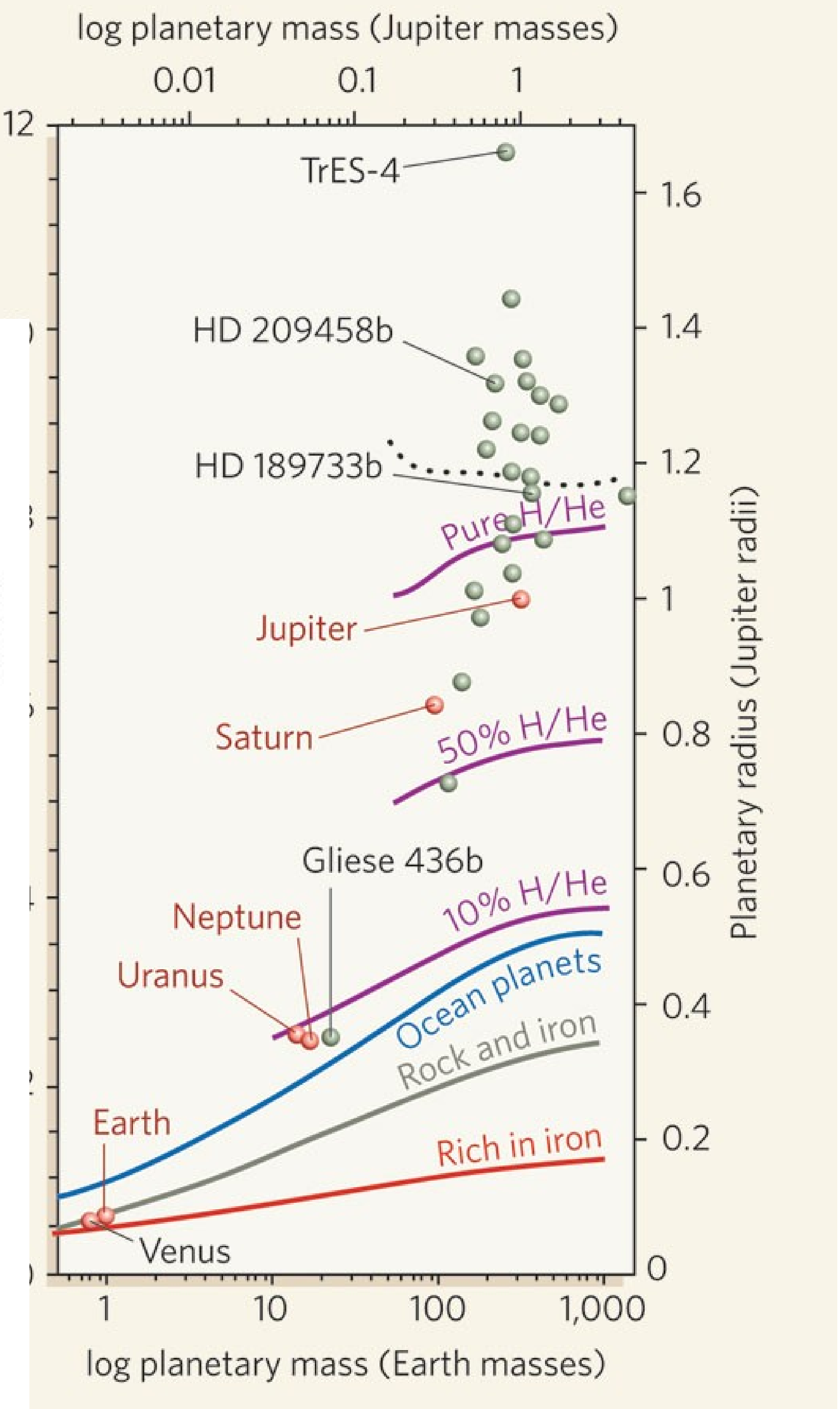
With mass and radius come density. Model comparisons can be used to infer bulk composition.



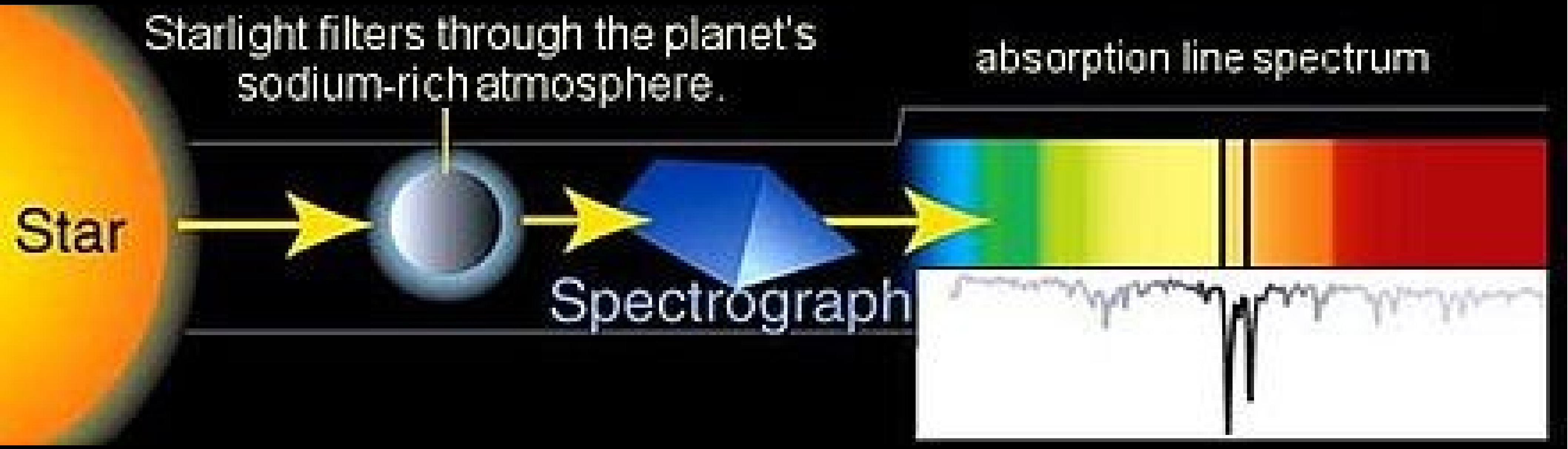


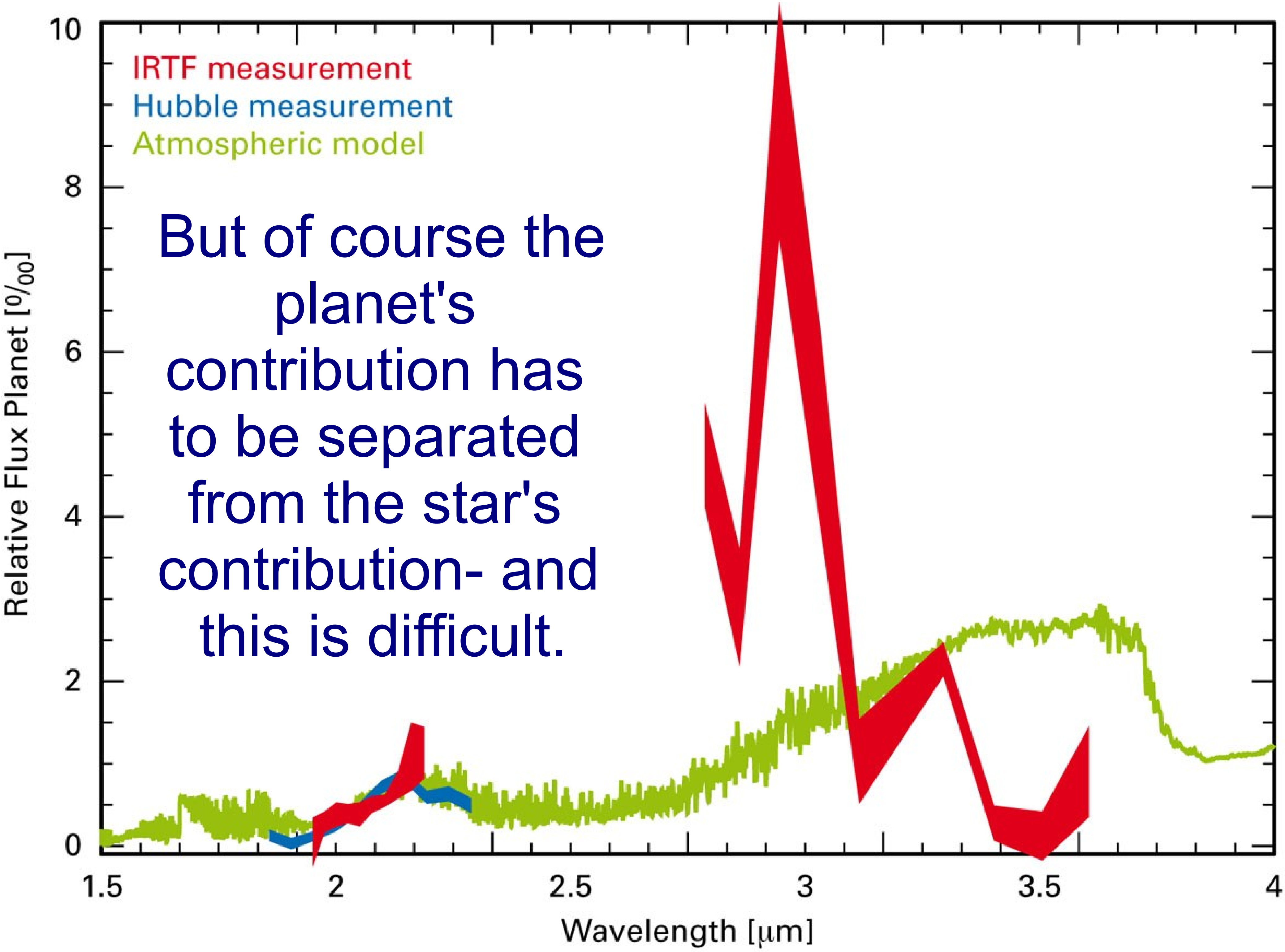
But the model dependence is large and open to some interpretation.



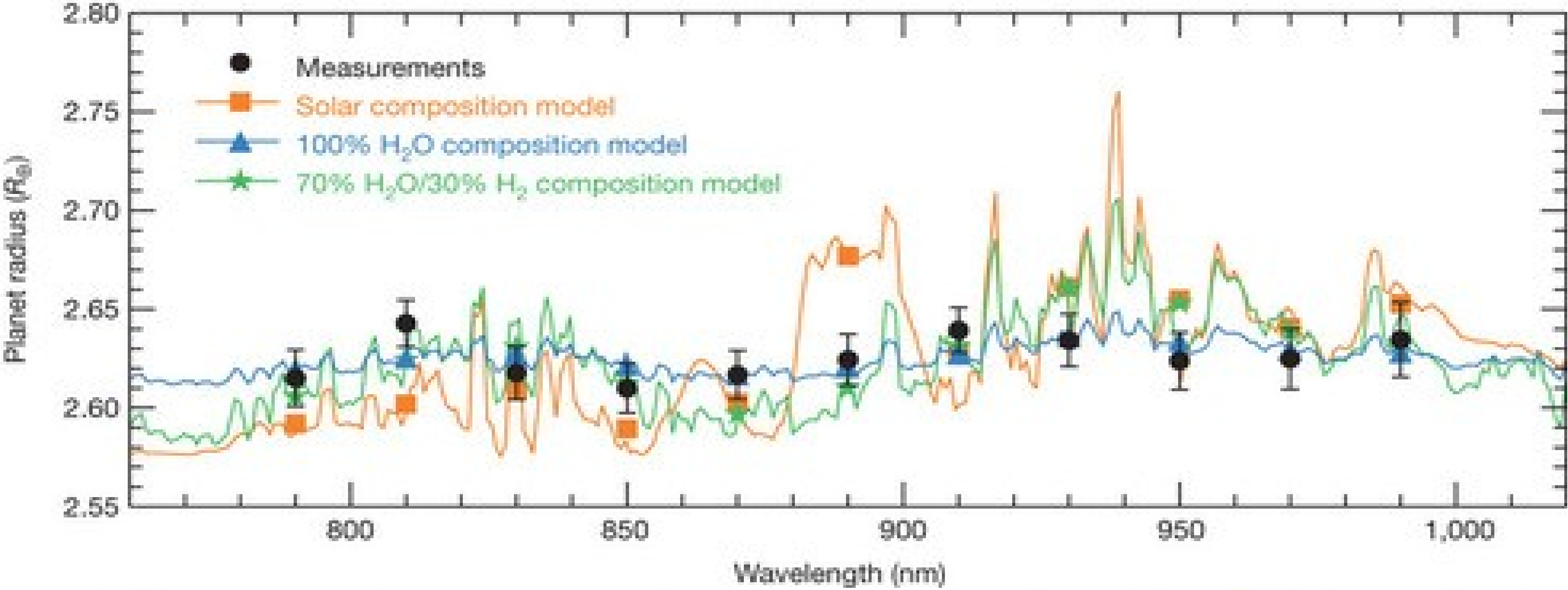


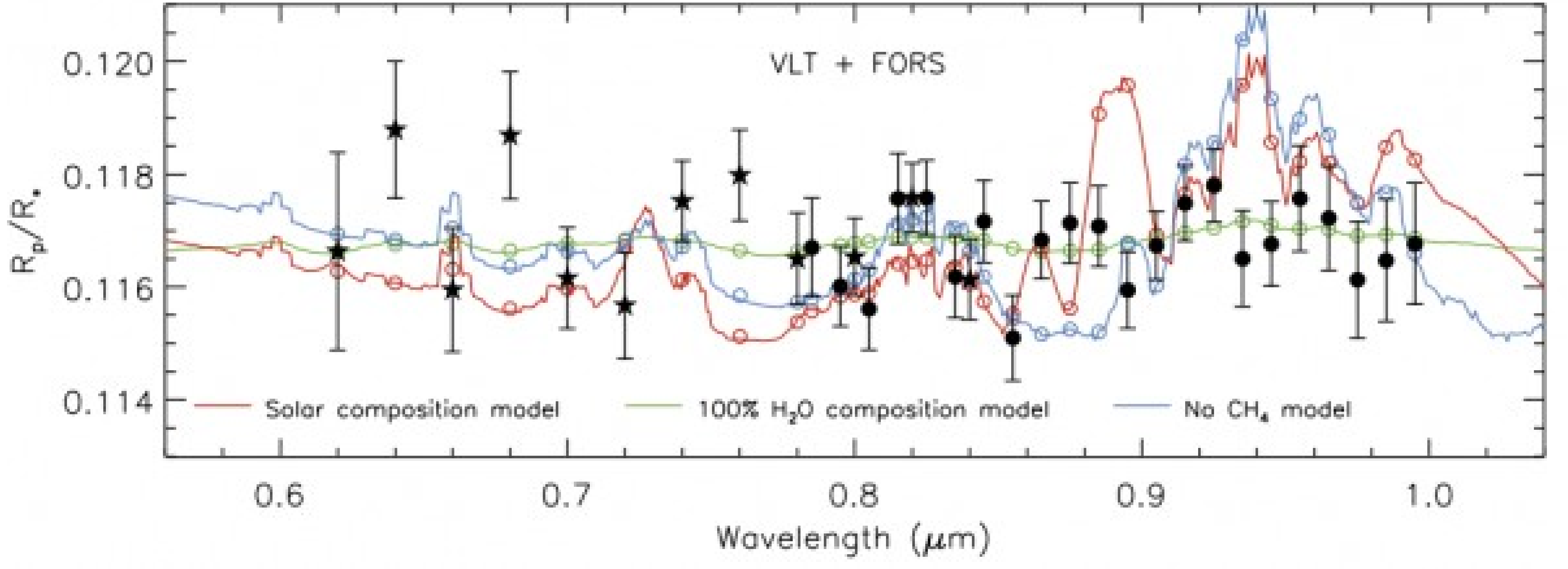
Transmission spectroscopy is a more direct means of detecting the planet- but only the atmosphere.

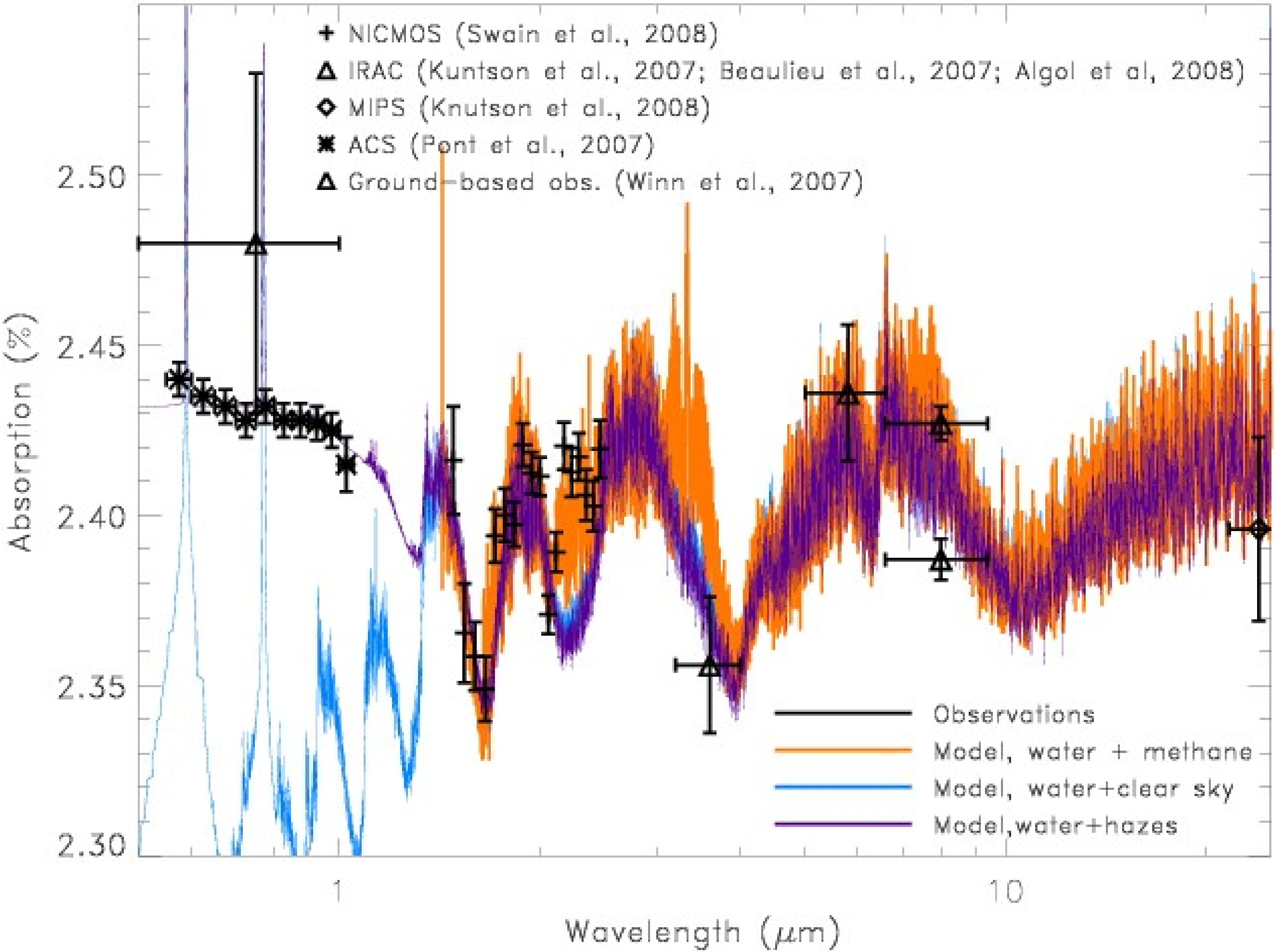




But of course the planet's contribution has to be separated from the star's contribution- and this is difficult.


Measurements
Solar composition model
100% H_2O composition model
70% H_2O/30% H_2 composition model
Planet radius ($R_⊕$)
2.80
2.75
2.70
2.65
2.60
2.55
800
850
900
950
1,000
Wavelength (nm)


VLT + FORS
R_p/R_*
0.120
0.118
0.116
0.114
Solar composition model
100% H_2O composition model
No CH_4 model
0.6
0.7
0.8
0.9
1.0
Wavelength (μm)

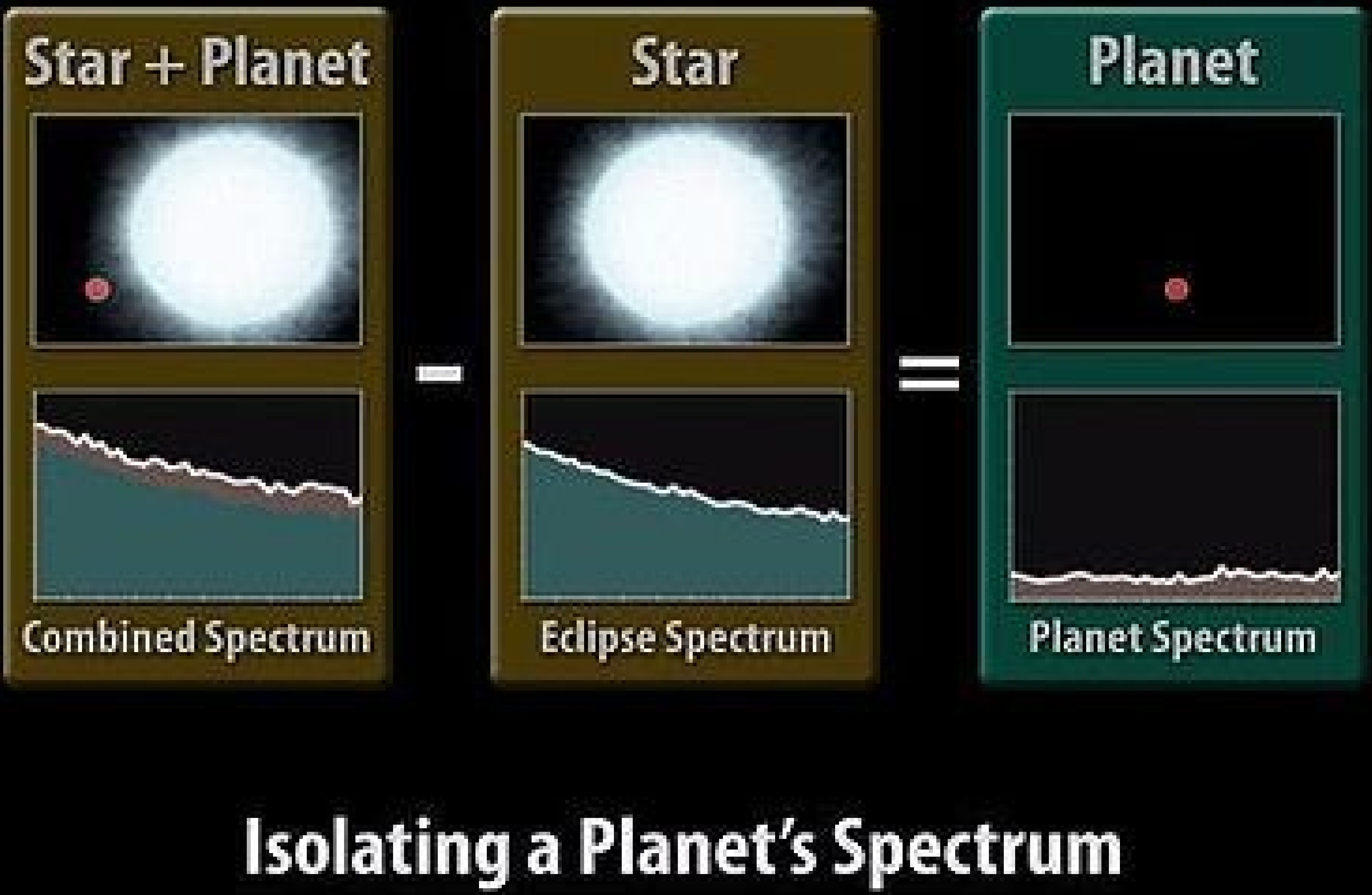


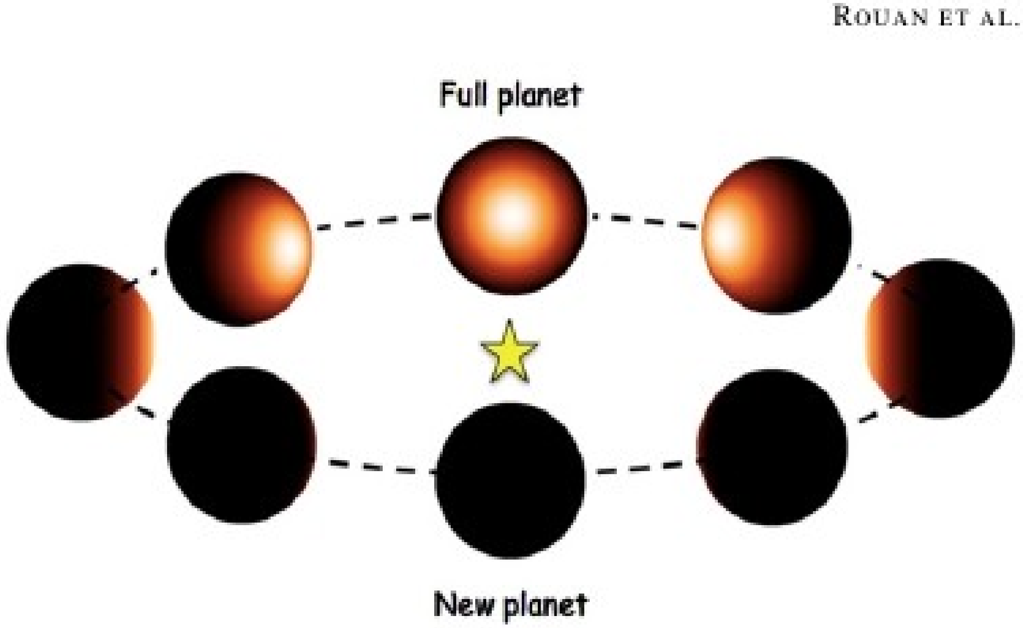
NICMOS (Swain et al., 2008)
IRAC (Kuntson et al., 2007; Beaulieu et al., 2007; Algol et al, 2008)
MIPS (Knutson et al., 2008)
ACS (Pont et al., 2007)
Ground-based obs. (Winn et al., 2007)
Observations
Model, water + methane
Model, water+clear sky
Model,water+hazes
Absorption (%)
2.50
2.45
2.40
2.35
2.30
1
10
Wavelength (μm)

Note that mostly these are not true spectra.

They are multi-filtered data compared to synthetic, or lab, spectra.

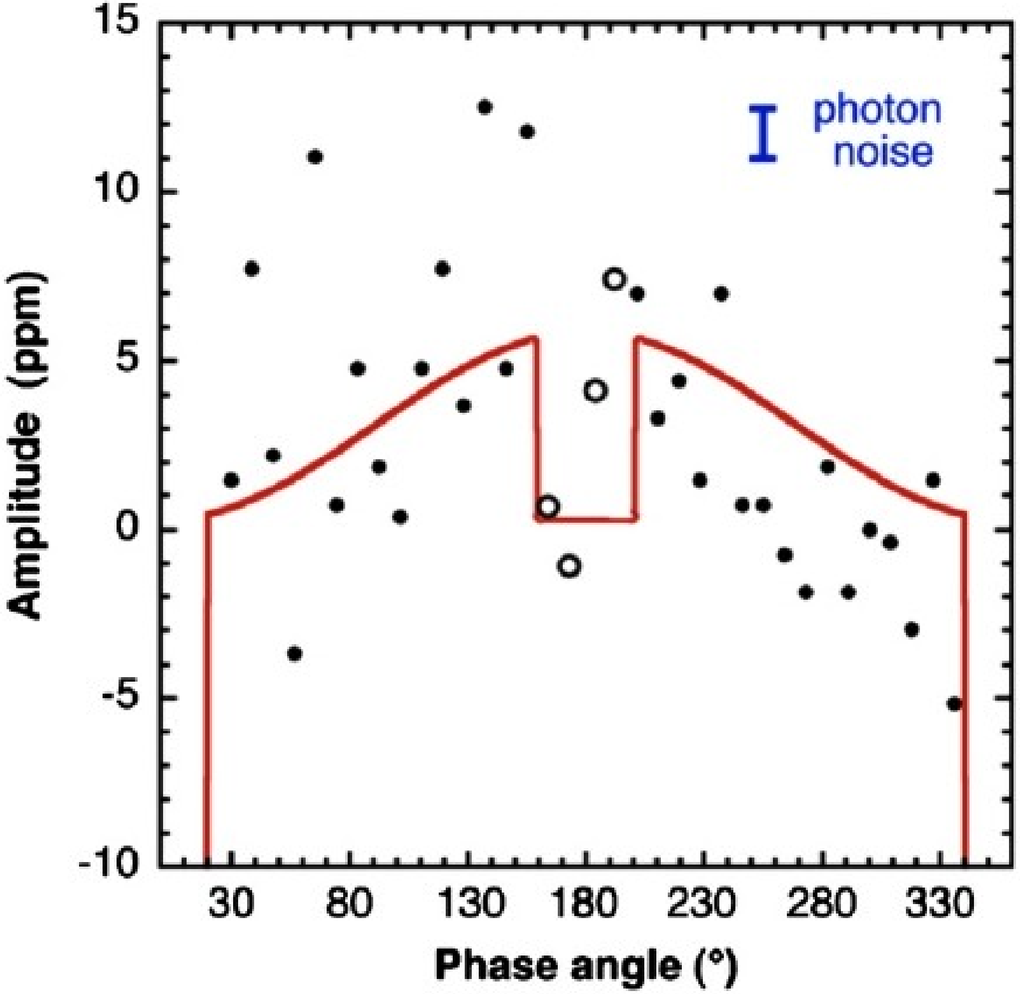
Reflection Spectrum: Differenced from the star.



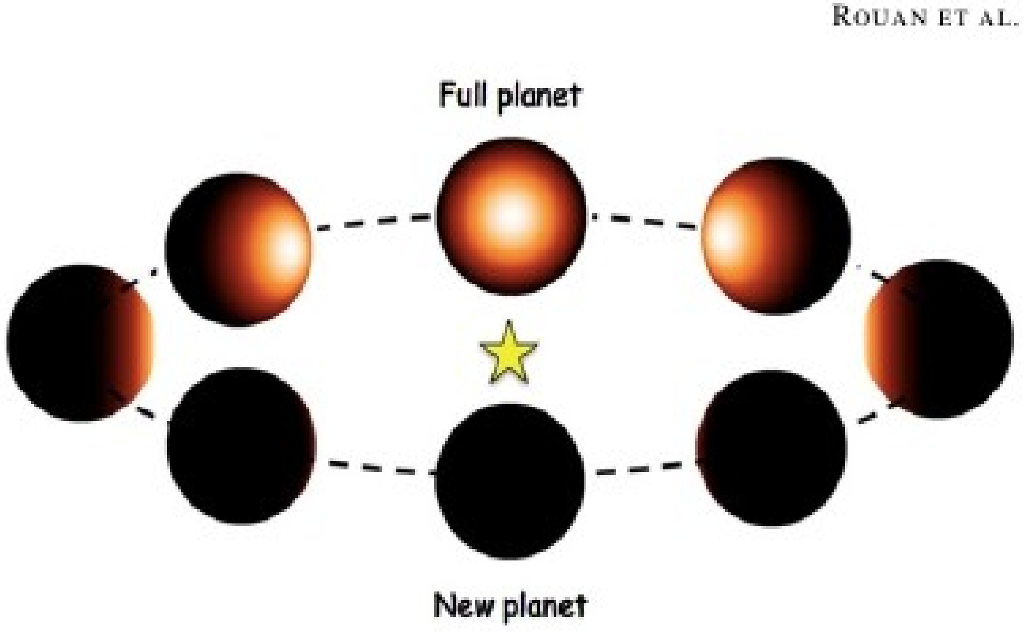


At different orbital phases, the amount of light received from the planet changes.

Each *filter*, which is a summed portion of the spectrum, will depend on the amount of reflected starlight (albedo) and the planetary contribution (blackbody + emission).

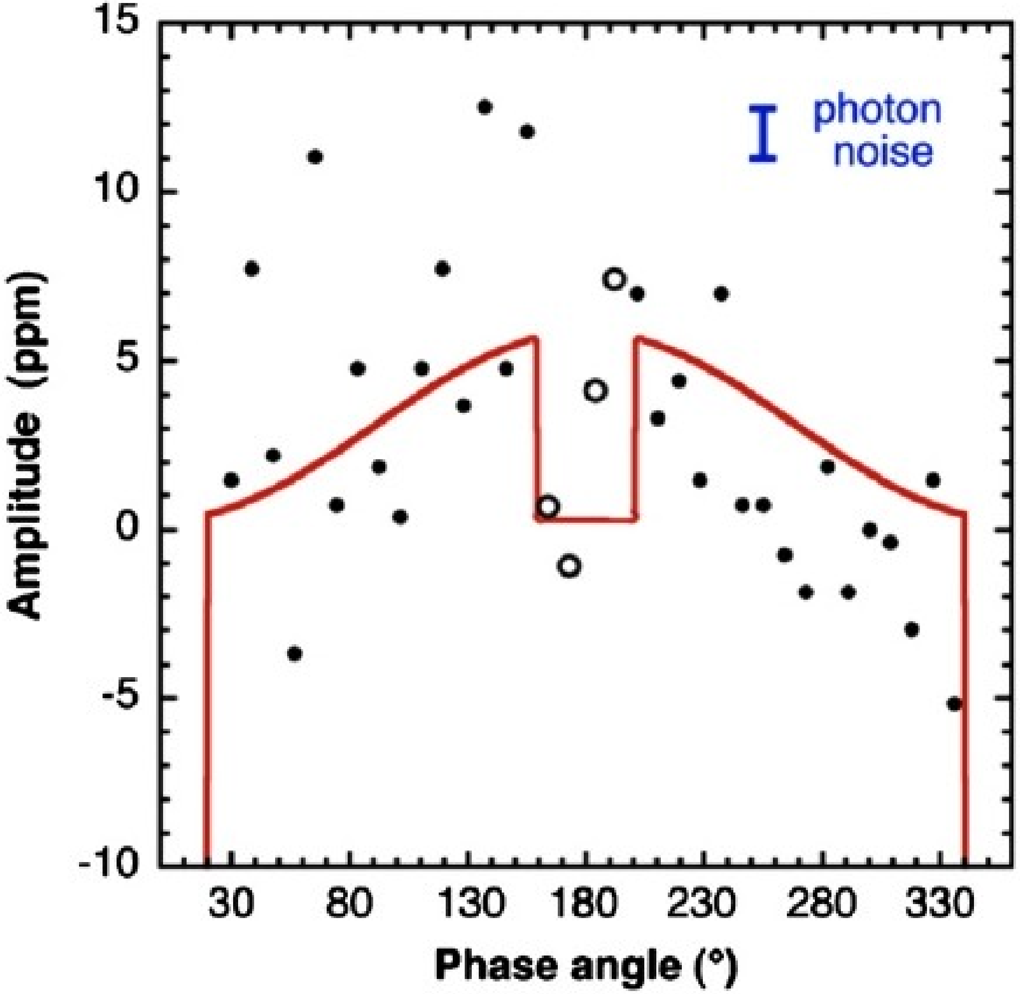


Rouan et al. 2011



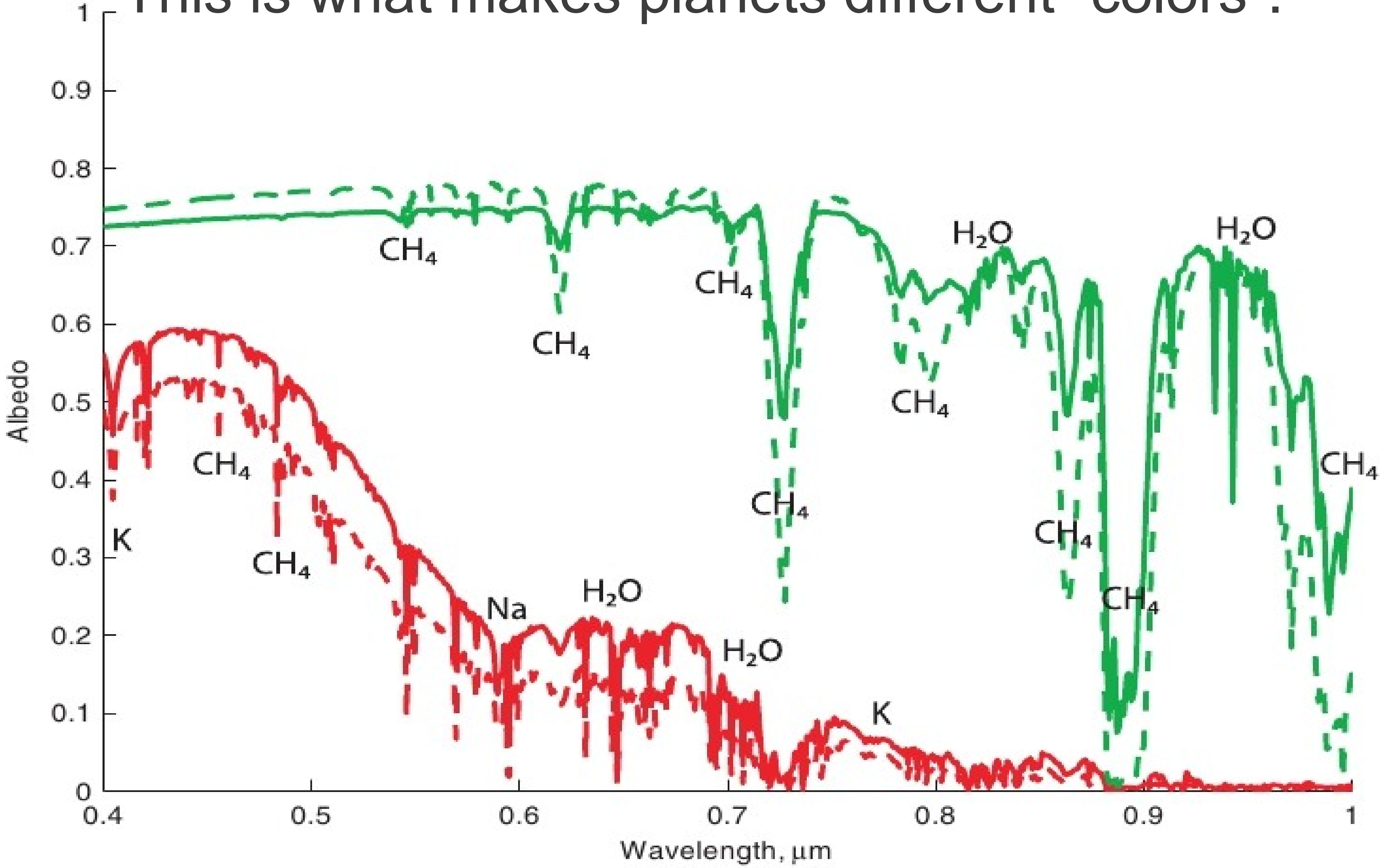
At different orbital phases, the amount of light received from the planet changes.

In transiting systems, at some phases (secondary eclipse), there is starlight only (the planet is behind the star), which can be compared to other phases, where the planet contributes.

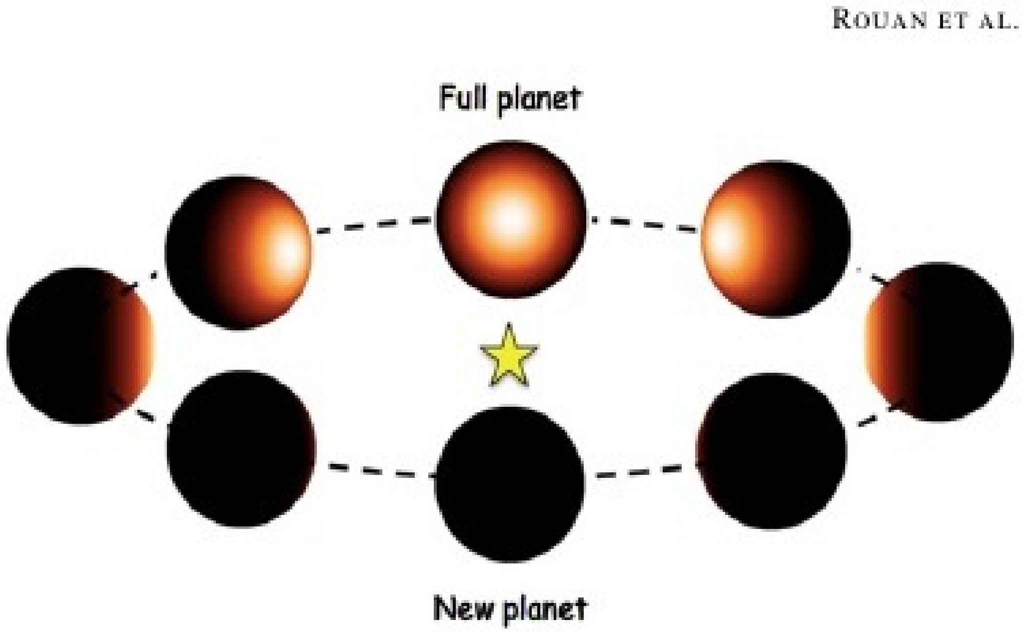


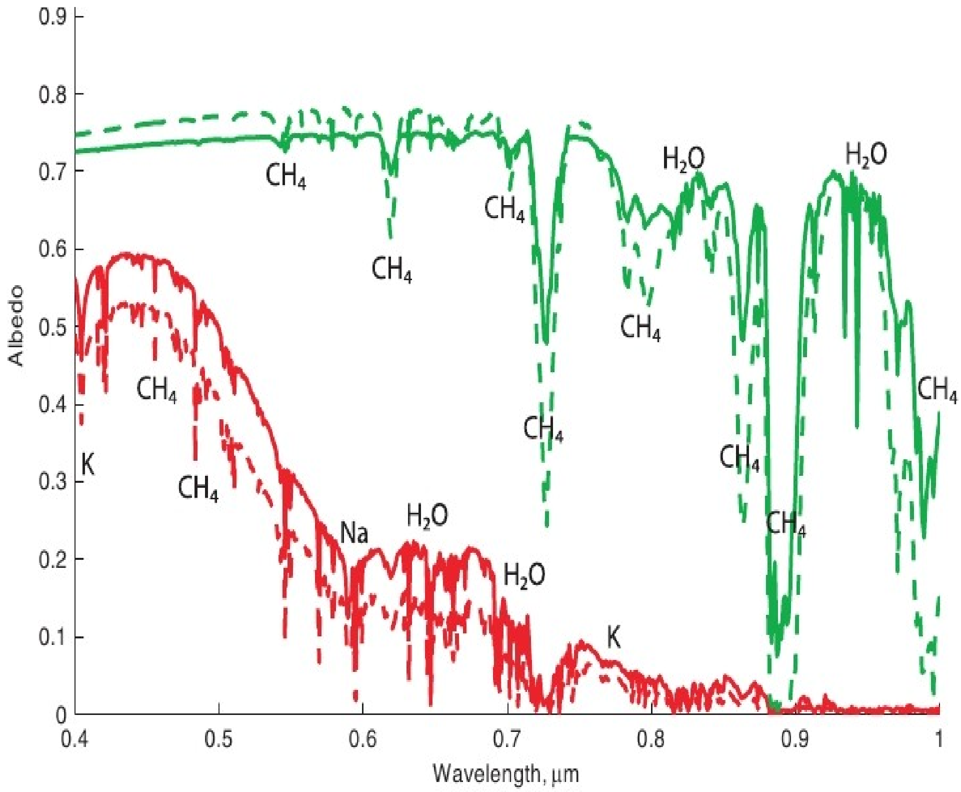
Rouan et al. 2011

Then there is wavelength-dependent albedo. This is what makes planets different "colors".

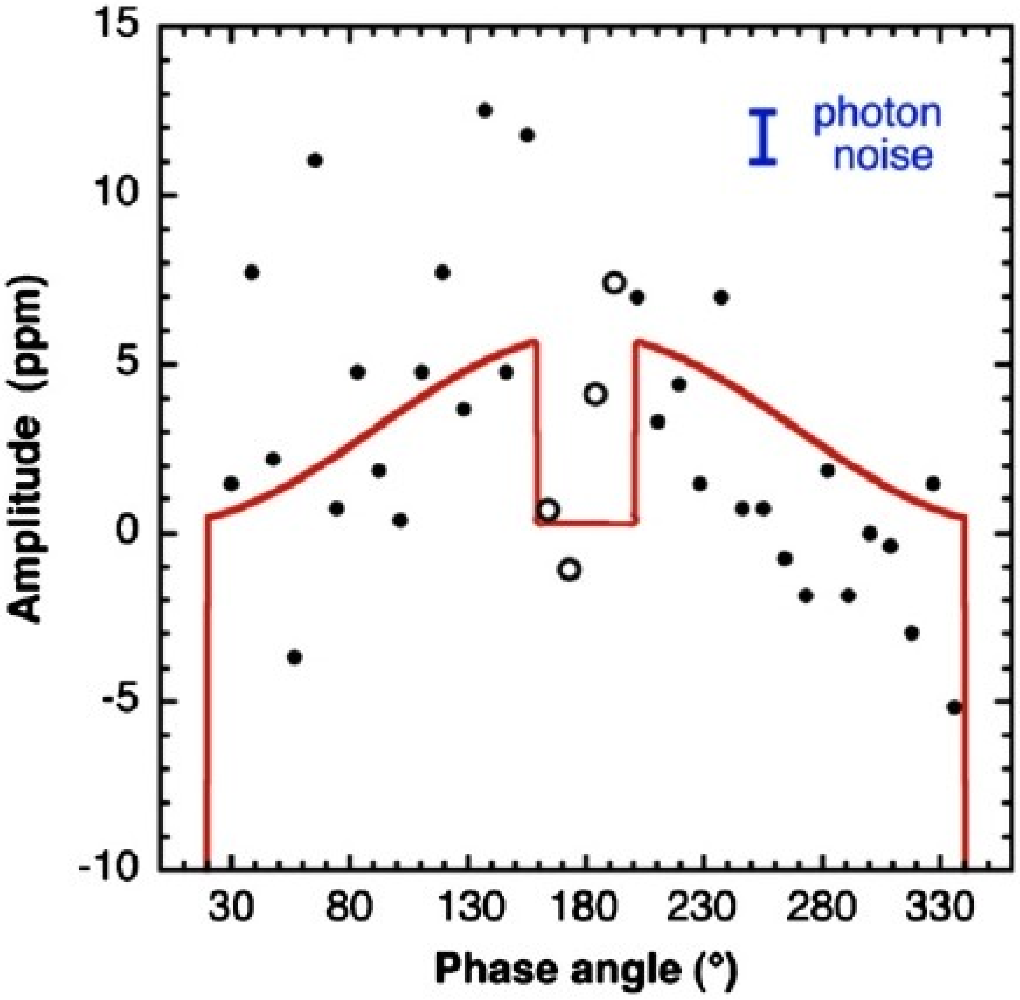


Combined, you get color and phase dependent reflection





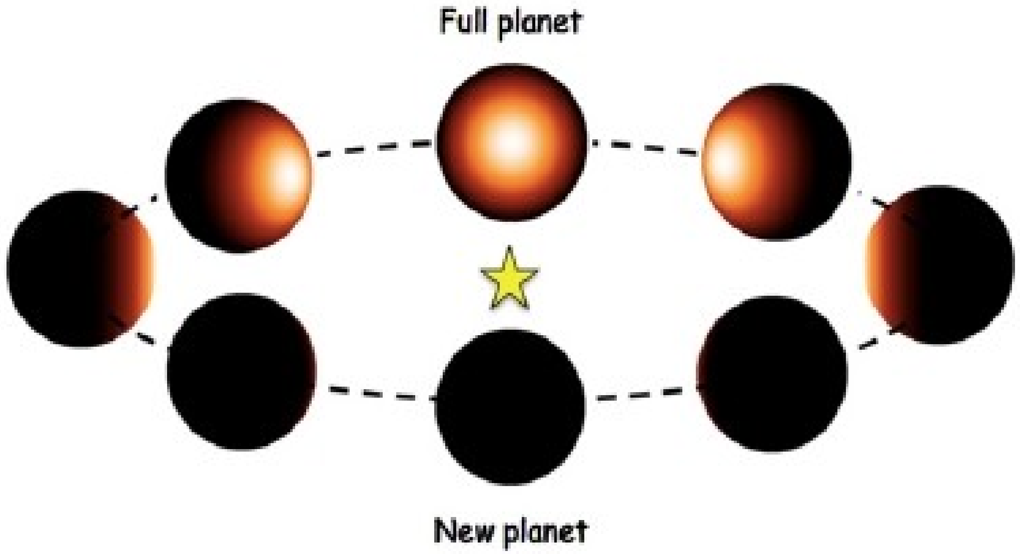
hot-vs-cold Jupiter

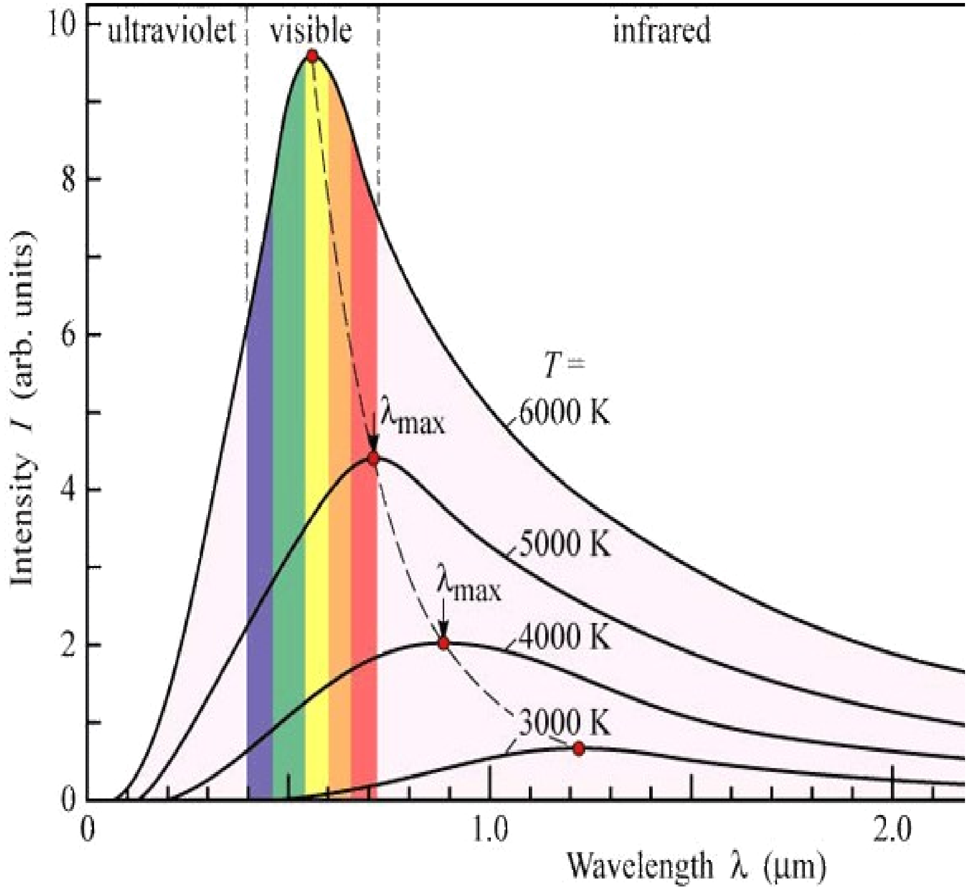


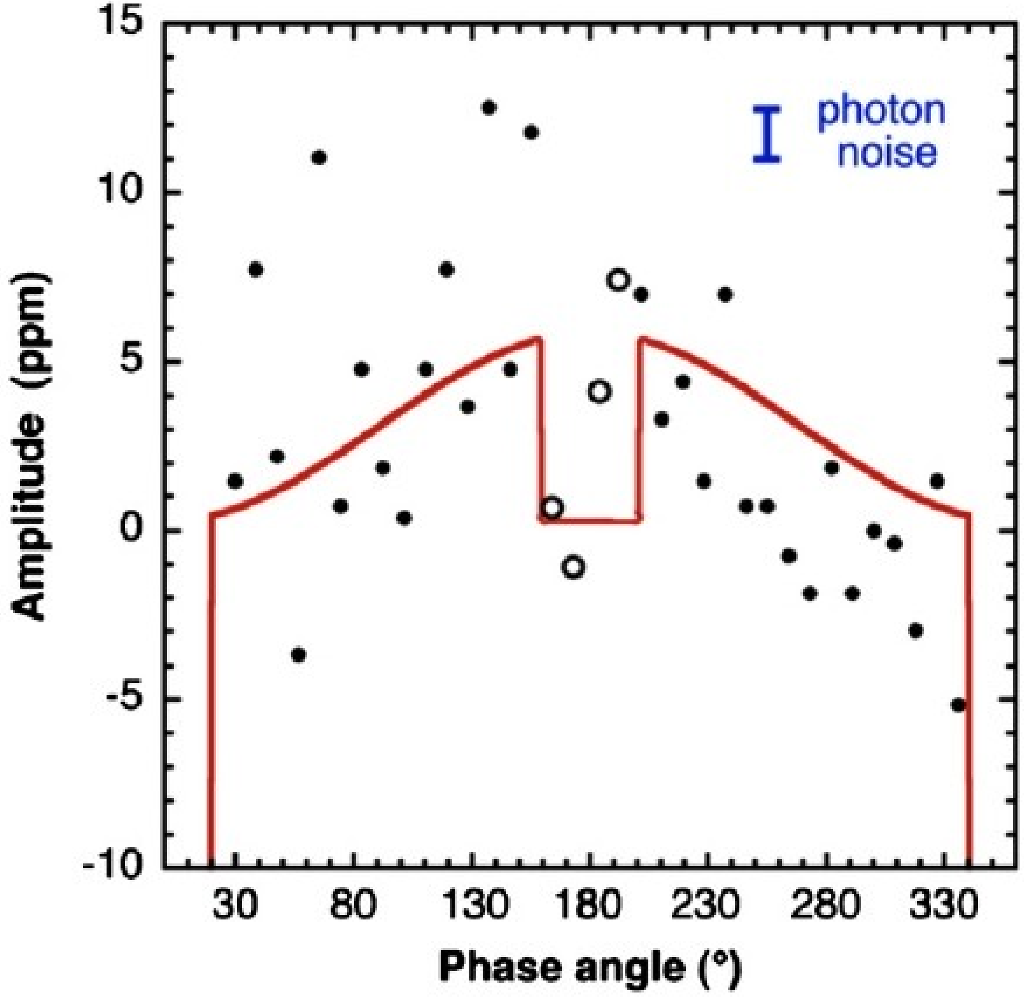
Rouan et al. 2011

You can also get phase dependent thermal emission.

ROUAN ET AL.



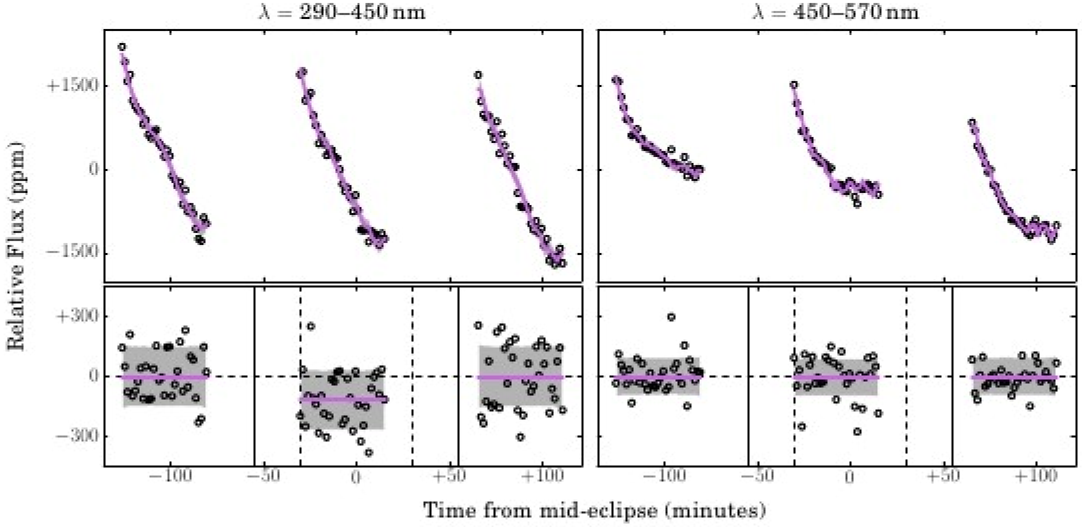




3.0

Rouan et al. 2011

This is how the 'blue' planet was found(?)



Actual measurements

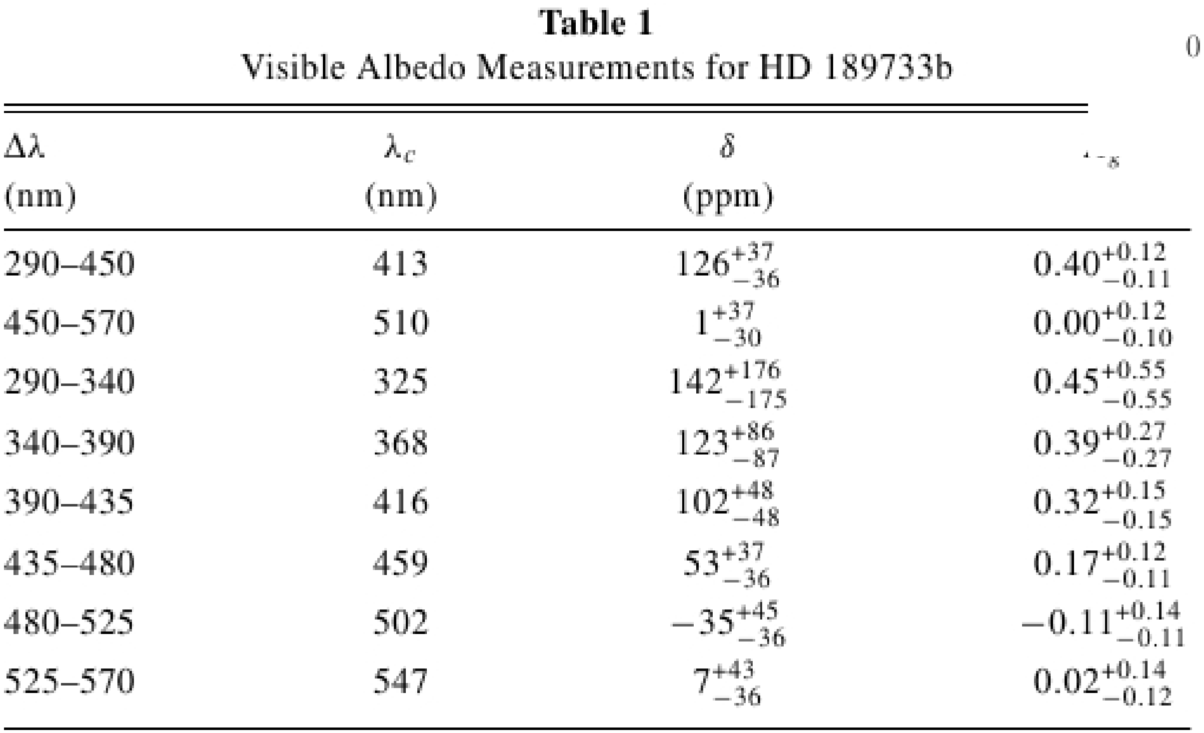
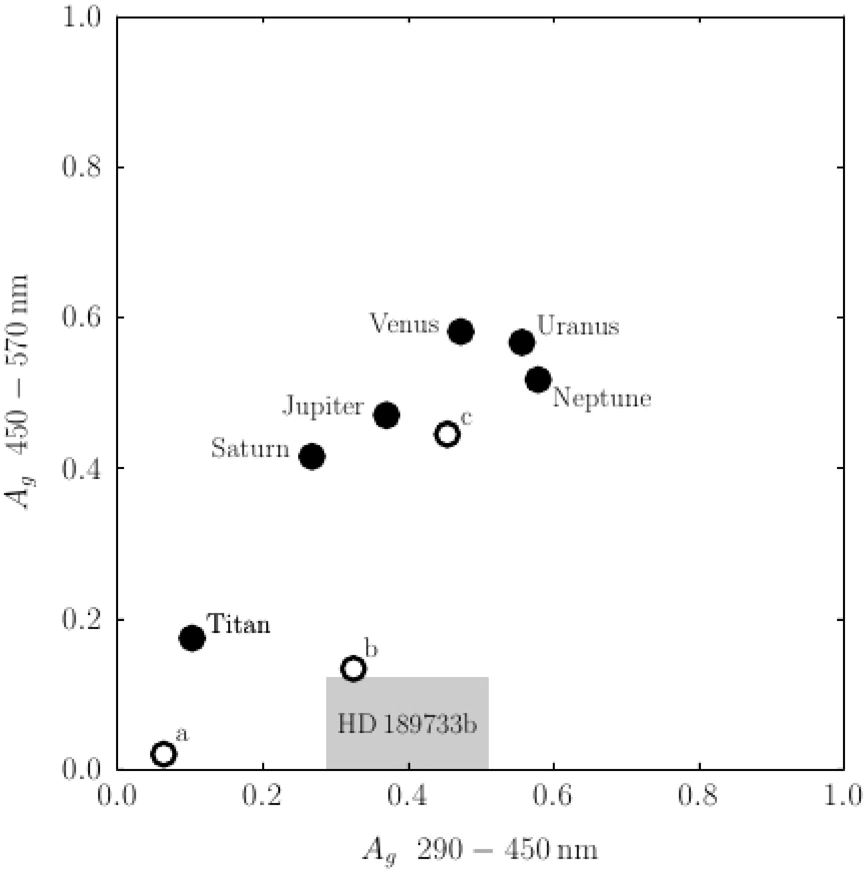


Table 1
Visible Albedo Measurements for HD 189733b

$\Delta\lambda$ (nm)	λ_c (nm)	δ (ppm)	
290–450	413	126^{+37}_{-36}	$0.40^{+0.12}_{-0.11}$
450–570	510	1^{+37}_{-30}	$0.00^{+0.12}_{-0.10}$
290–340	325	142^{+176}_{-175}	$0.45^{+0.55}_{-0.55}$
340–390	368	123^{+86}_{-87}	$0.39^{+0.27}_{-0.27}$
390–435	416	102^{+48}_{-48}	$0.32^{+0.15}_{-0.15}$
435–480	459	53^{+37}_{-36}	$0.17^{+0.12}_{-0.11}$
480–525	502	-35^{+45}_{-36}	$-0.11^{+0.14}_{-0.11}$
525–570	547	7^{+43}_{-36}	$0.02^{+0.14}_{-0.12}$



Conclusions

from
Evans et al. 2013

I'll come back to this in the context of lava planets and magma oceans.

A Hot Jupiter

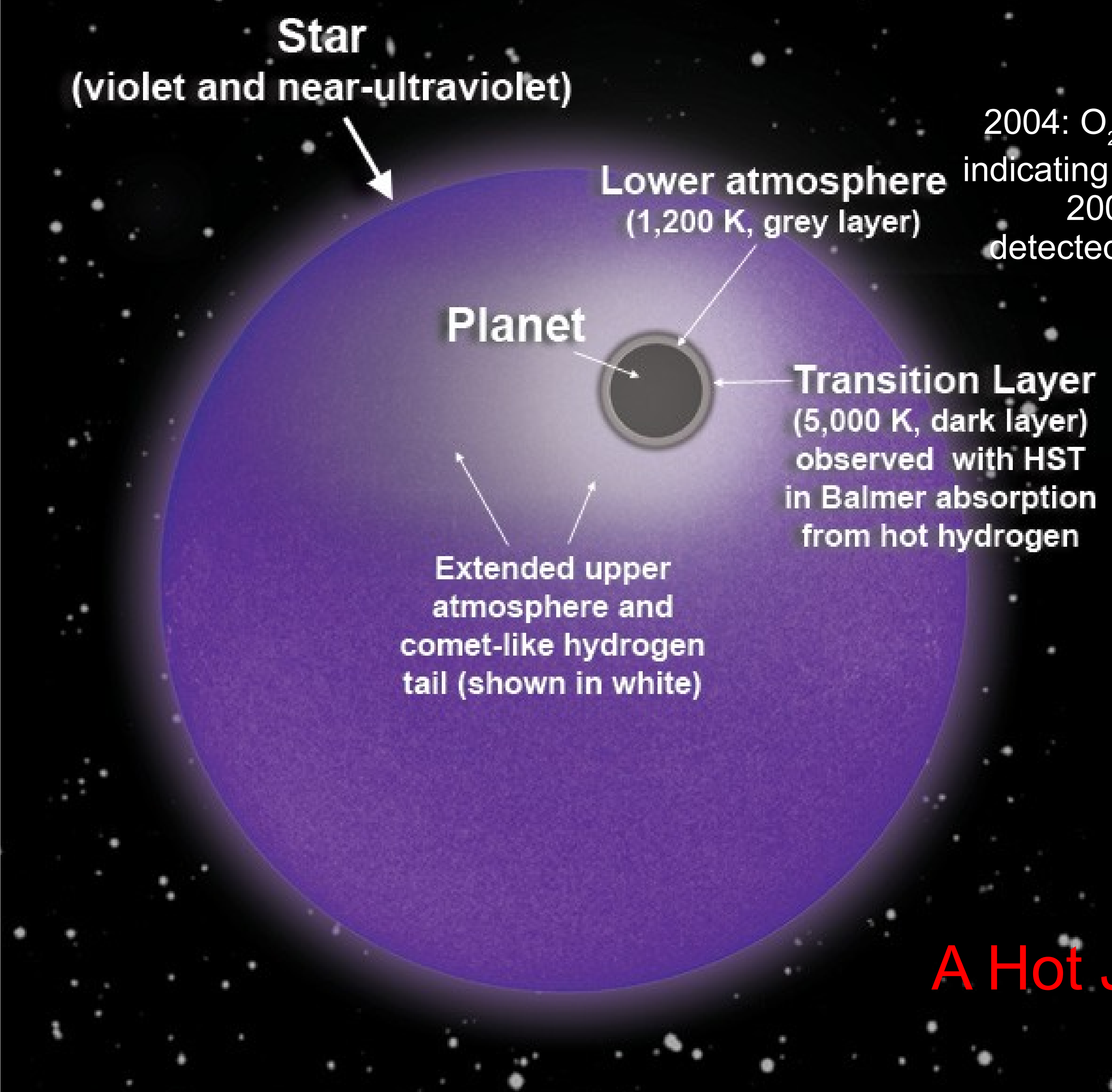


Image Credit: L. McKibben and G.E. Ballester (UA-LPL)

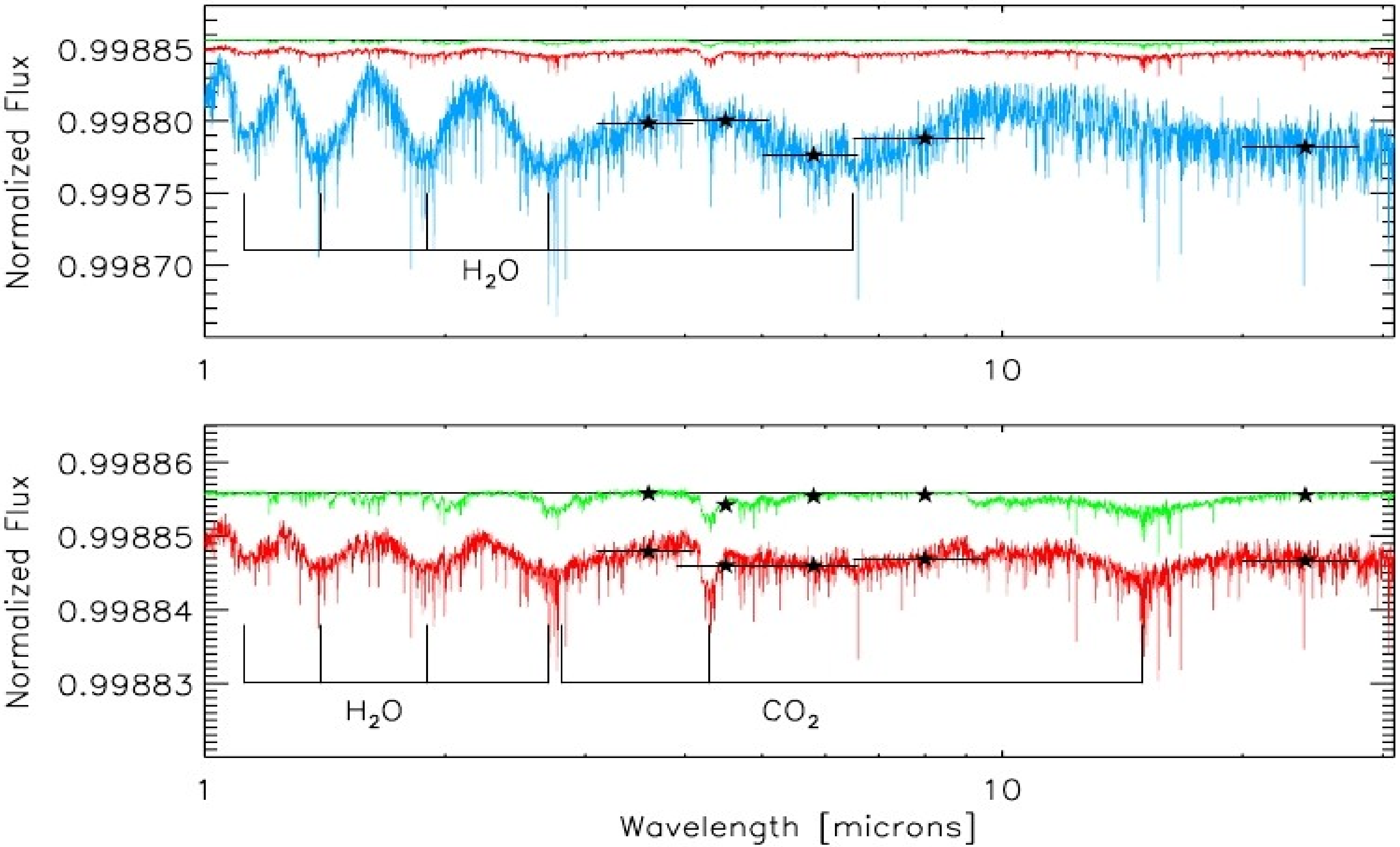
2002: Sodium detected
2003: H_2 detected
2004: O_2 & C & $3R_p$ atmo and tail indicating evaporating atmosphere.
2007: Balmer series & jump detected, providing the picture at left.

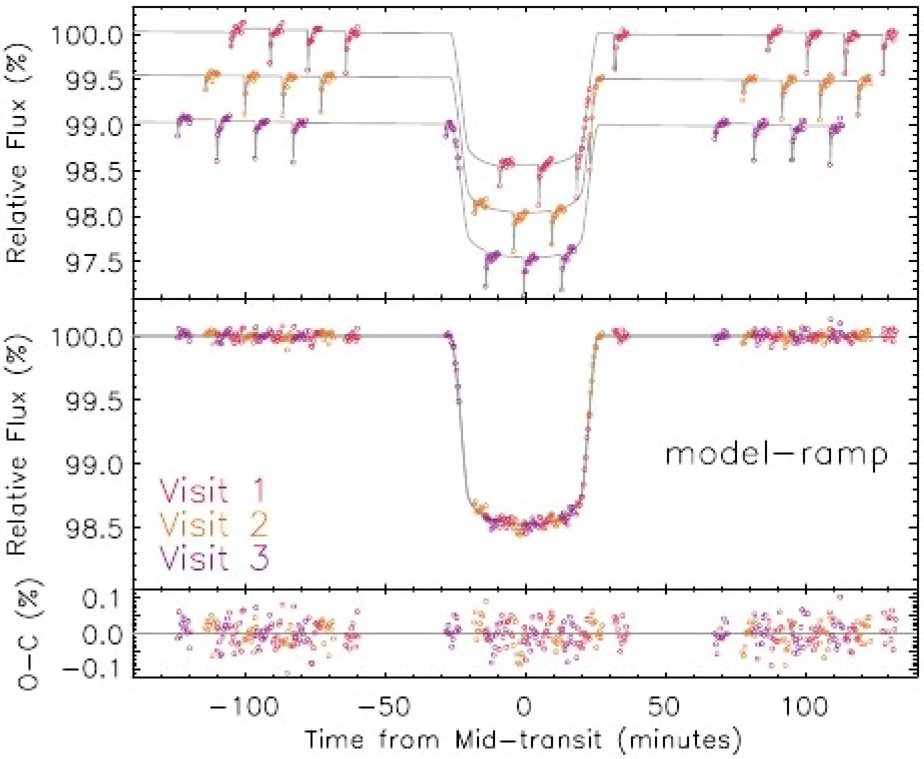
All HST UV/nUV transmission spectroscopy.

Findings and speculations for hot (super)Earths that we're interested in.

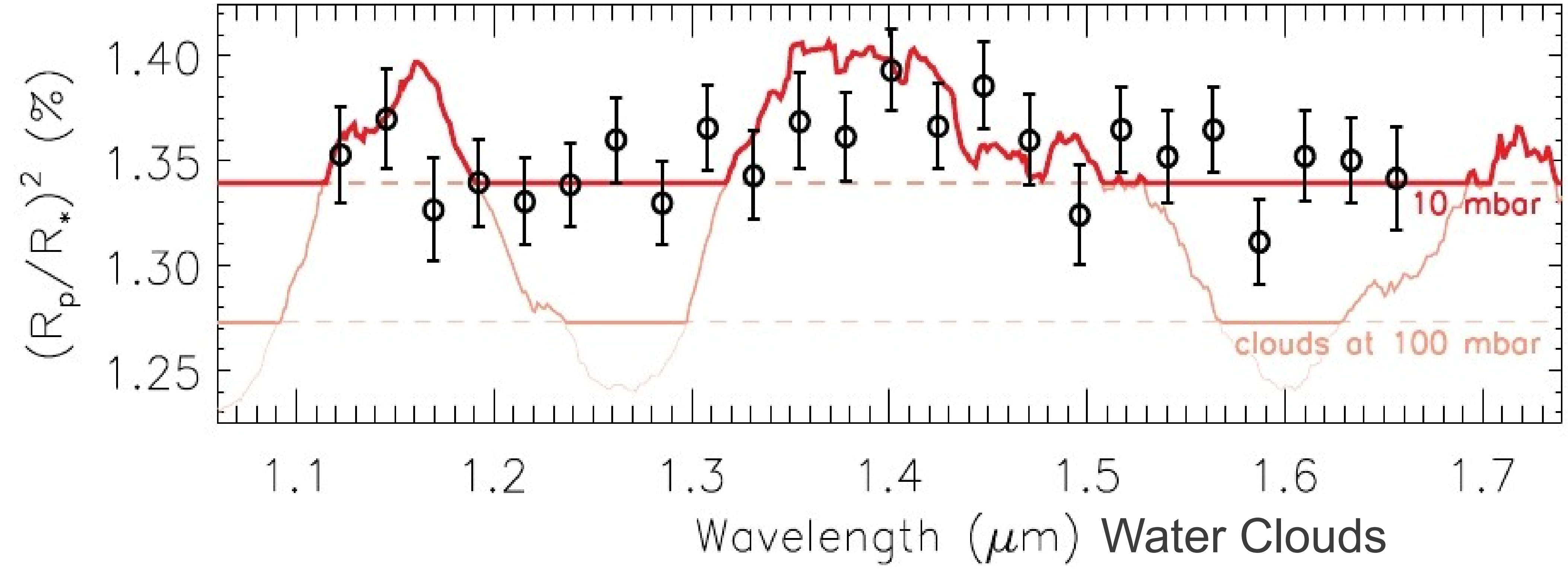
Model transmission spectra for H-rich (blue), H-poor (green) and intermediate H (red) atmospheres for a hot SuperEarth.

Spitzer bands shown as points.

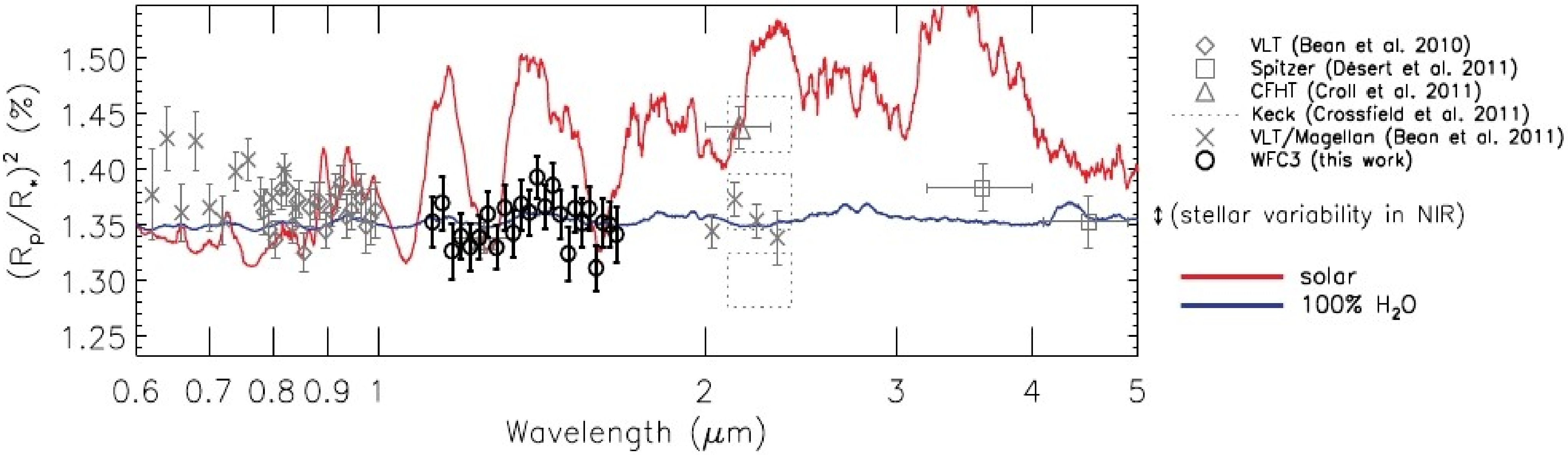




HST transmission spectroscopy determined that the atmosphere is optically thick for GJ1214b ($R=2.7R_{Earth}$ Berta et al. 2011)



Water Clouds



Overall, GJ1214b's IR transmission spectrum is consistent with H_2O.

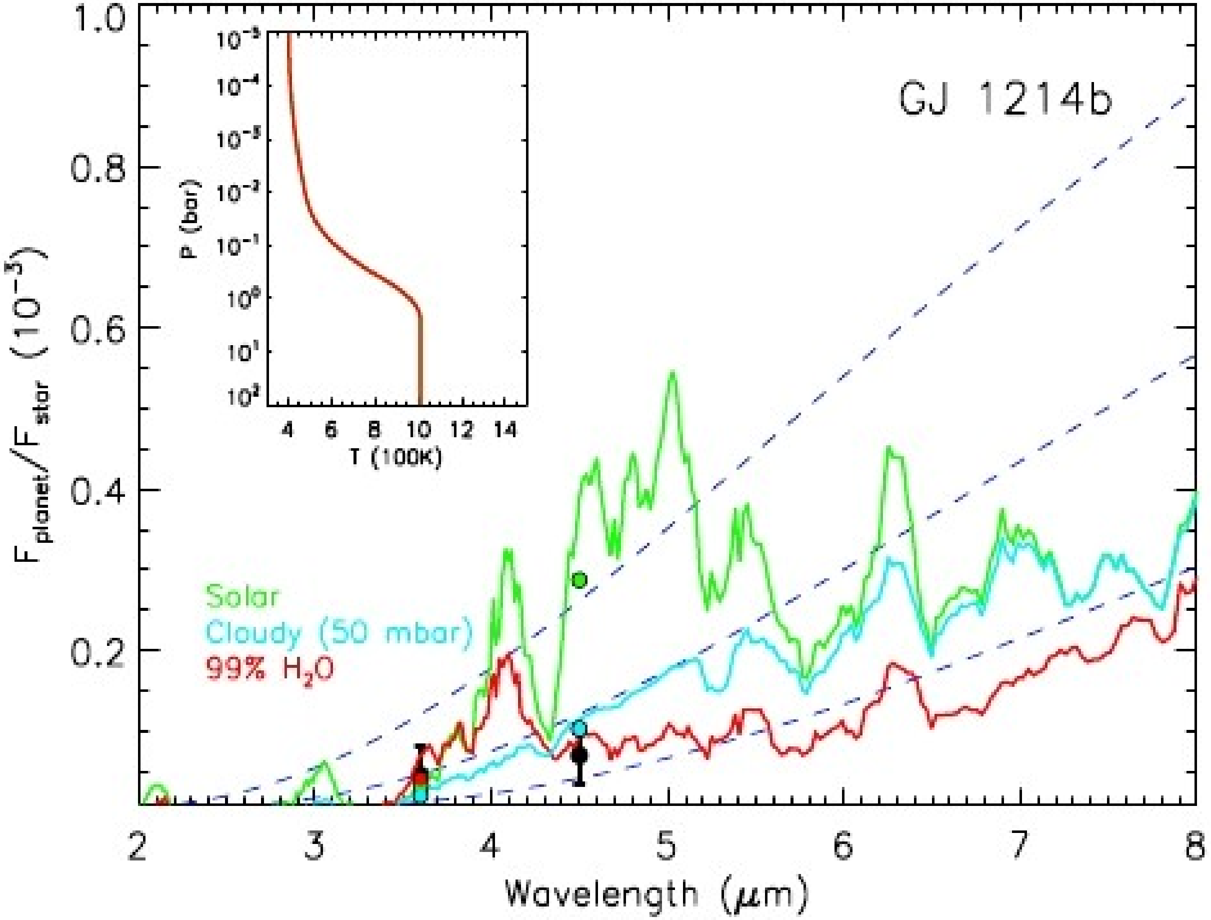
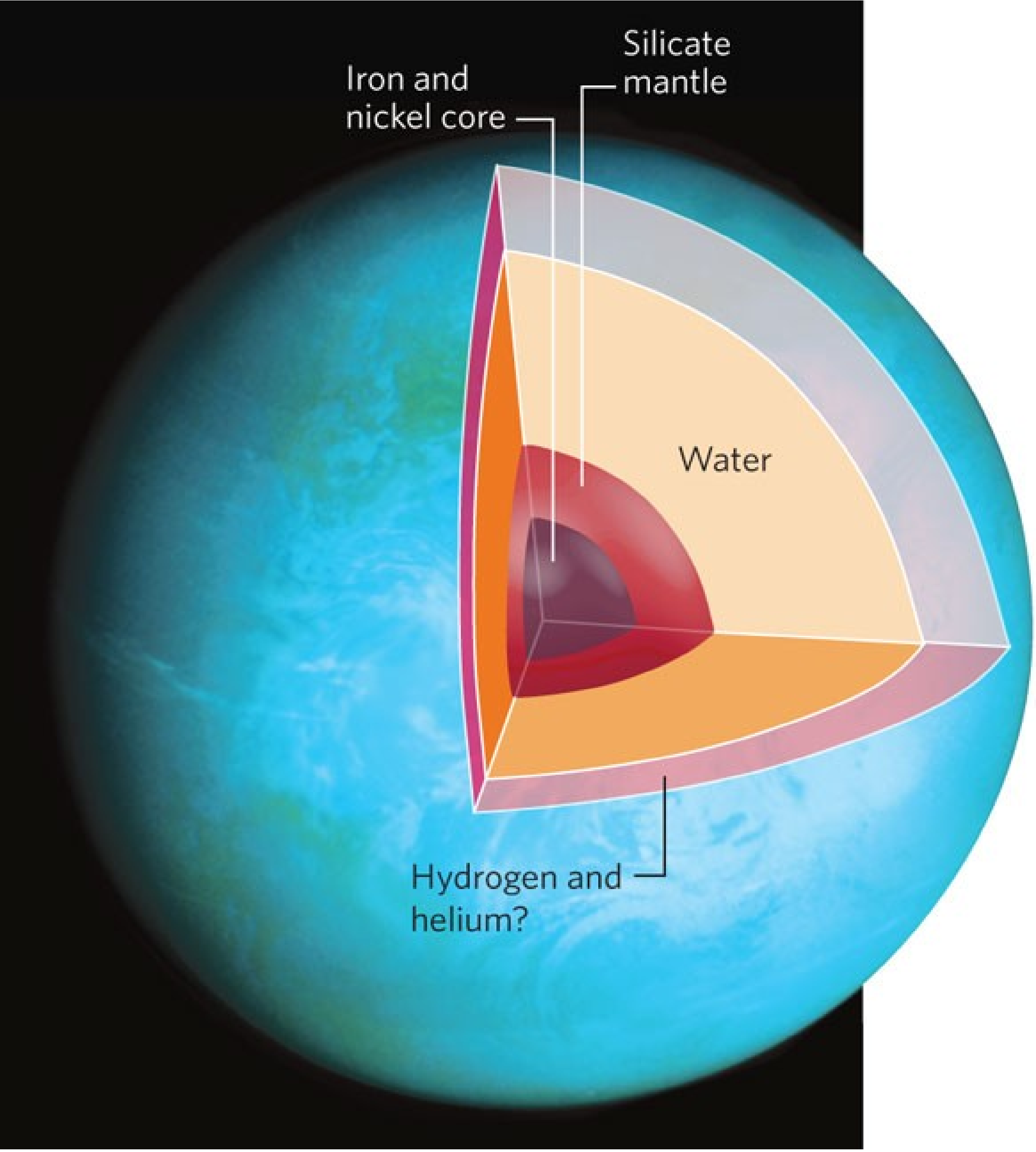


Fig. 10. Observations and model spectra of thermal emission from GJ 1214b. The black circles with error bars show the planet-star flux ratios observed in the *Spitzer* IRAC bandpasses at 3.6 and 4.5 μm. The green and red solid curves in the main panel show model spectra of an atmosphere with a solar abundance H_2-rich composition and one with a water-rich composition, respectively. The inset shows the temperature profile for both models. The blue dashed curves show blackbody spectra of the planet with temperatures of 500 K, 600 K, and 700 K.

As is the reflection spectrum. From Spitzer: Gillon et al. 2013

Note that there are 2 data points!

At 3.6 and 4.5 microns.



GJ1214b is a hot Super-Earth:

Mass = 6.5 M_{Earth}

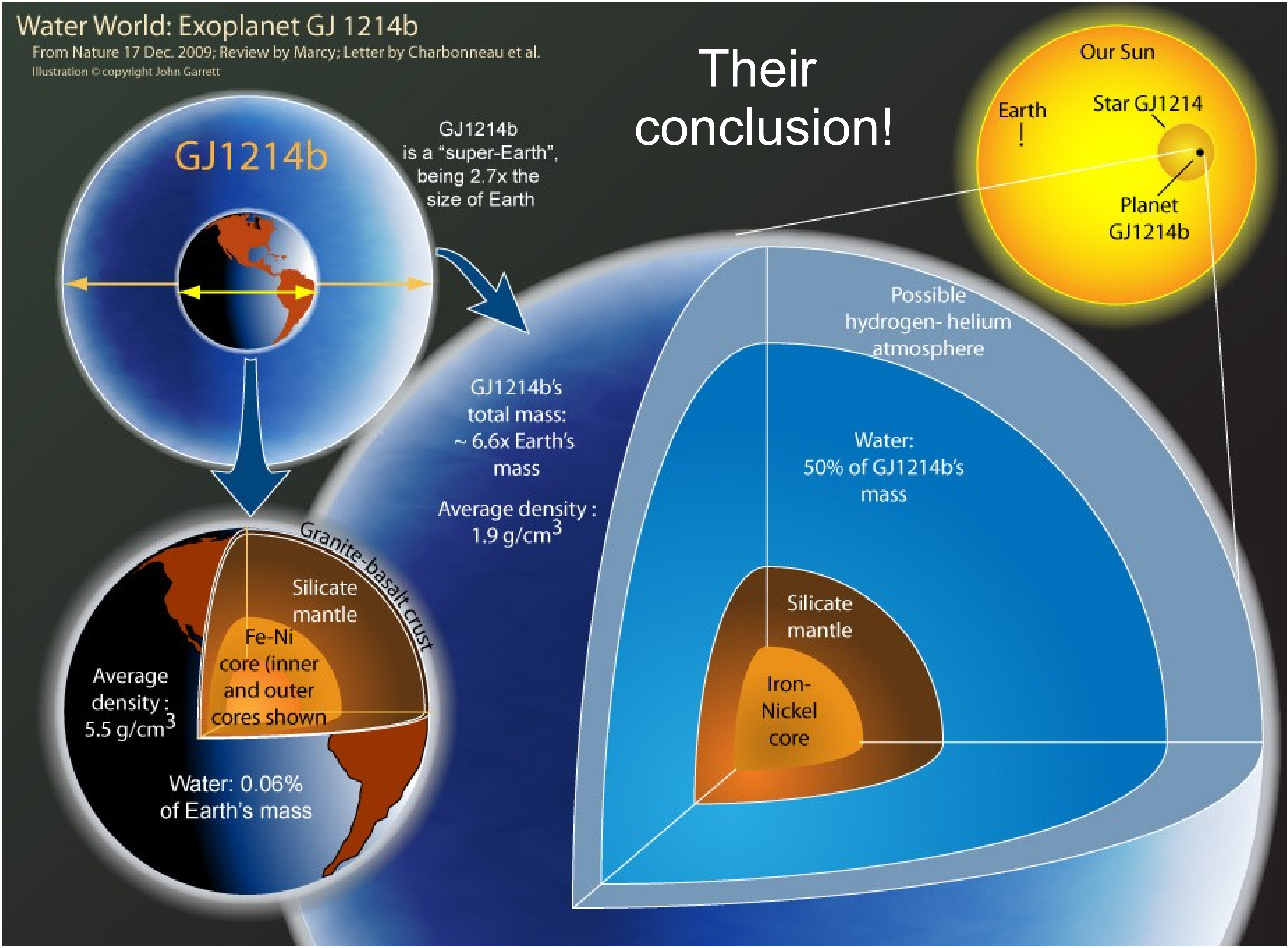
Radius = 2.7 R_{Earth}

ρ = 1.6 +/- 0.6 g/cc

(Anglada-Escude et al. 2013)

BUT... a side note that CFHT WIRCam observations indicate a H/He atmosphere inconsistent with a water world. (Croll et al. 2011; transmission spectra)

Their conclusion!



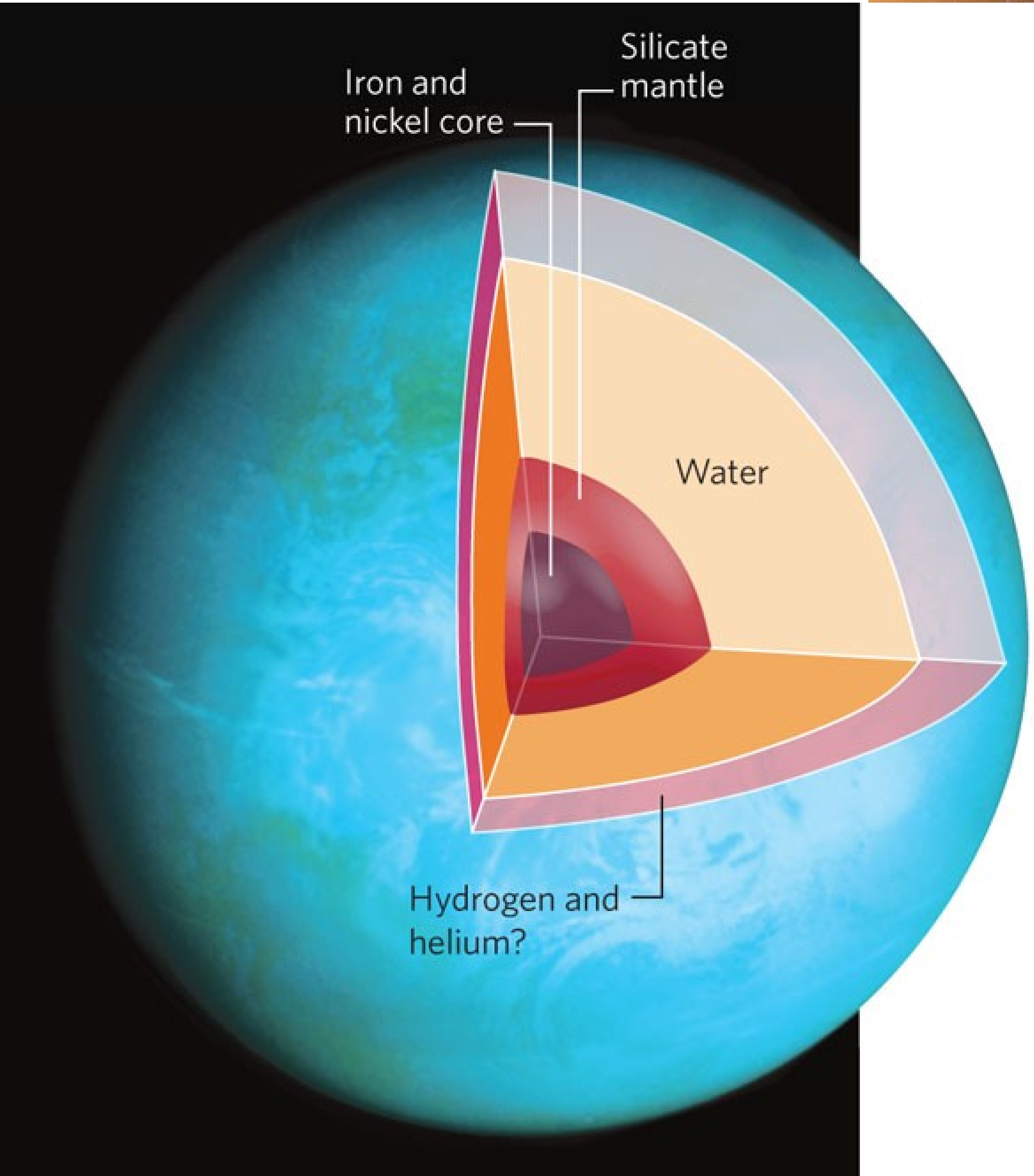
Water World: Exoplanet GJ 1214b

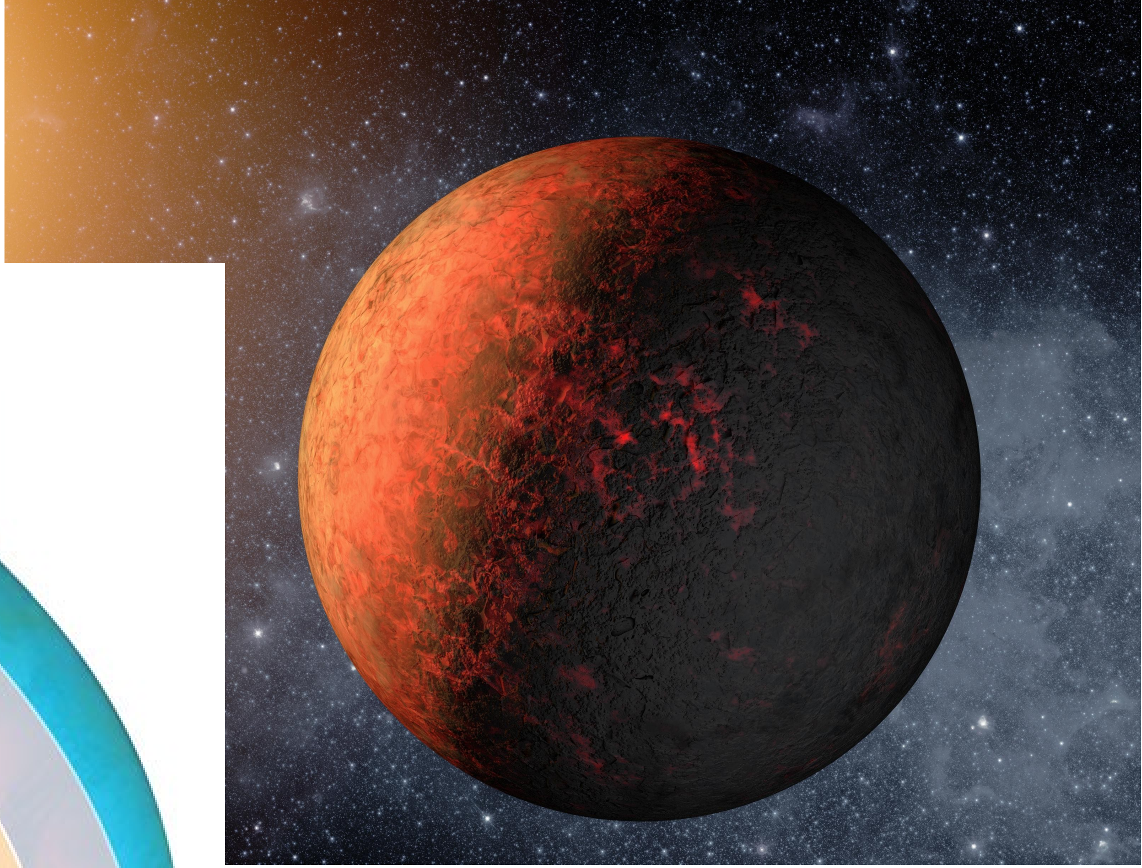
From Nature 17 Dec. 2009; Review by Marcy; Letter by Charbonneau et al.

Illustration © copyright John Garrett

55 Cnc e

$M=7.8M_{Earth}$ $R=2.17R_{Earth}$





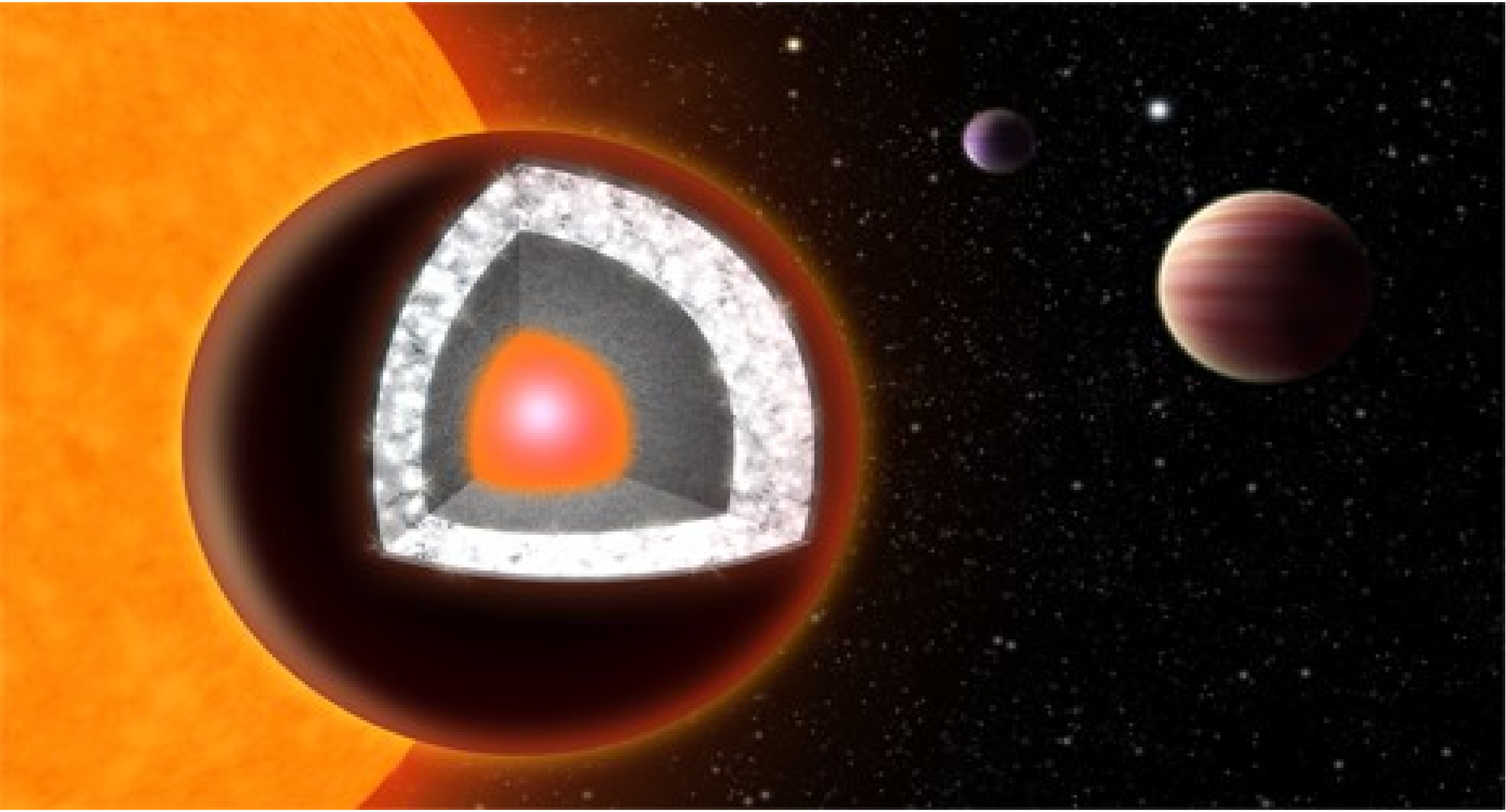
Density downgraded to $4.78^{+1.31}_{-1.20}$g/cc (Demory 2011)

Steamy water atmosphere?

55 Cancri e: Now fortified with Carbon!

$M \sim 8M_{Earth}$, $R \sim 2.2R_{Earth}$, $P_{orb}=18$ hours $T \sim 2,400K$

(Madhusudhan et al. 2012)



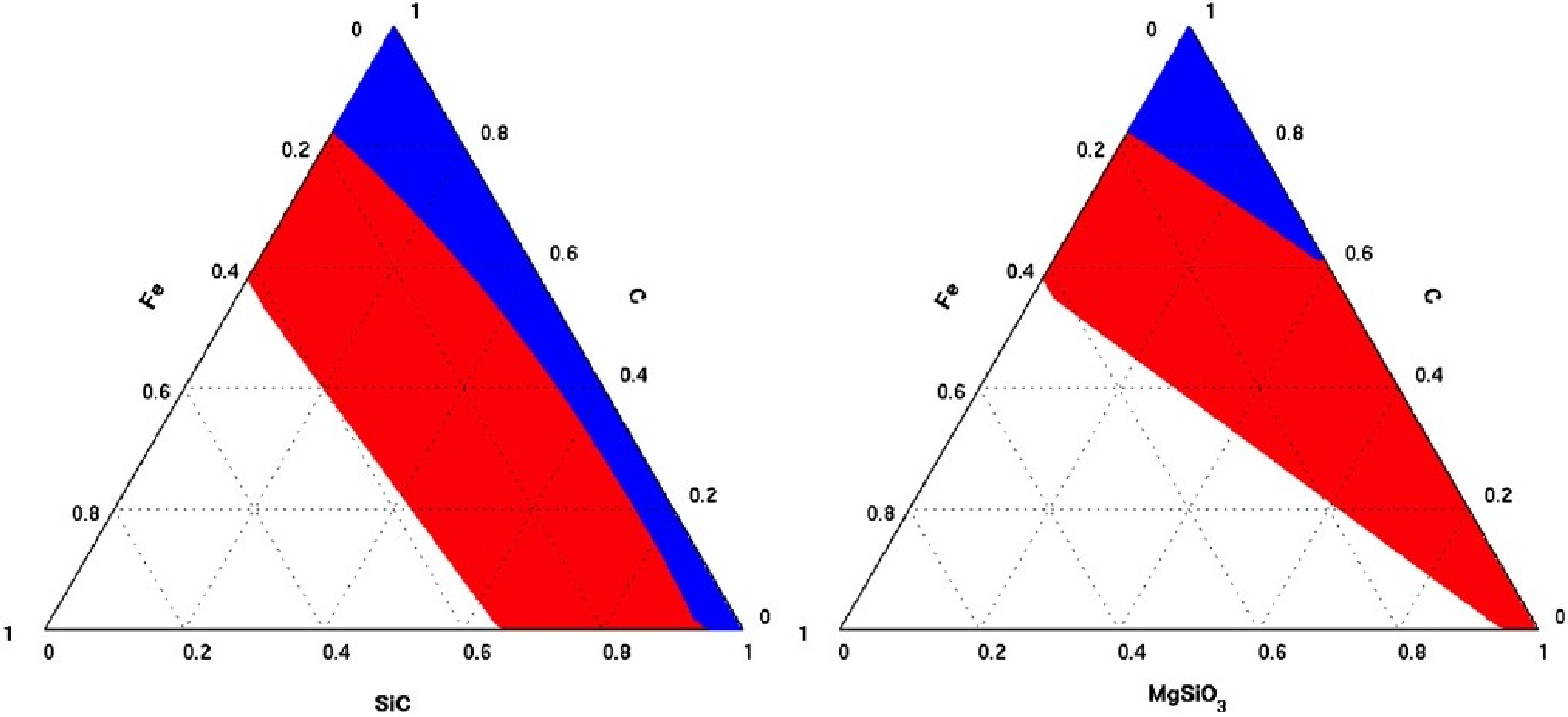
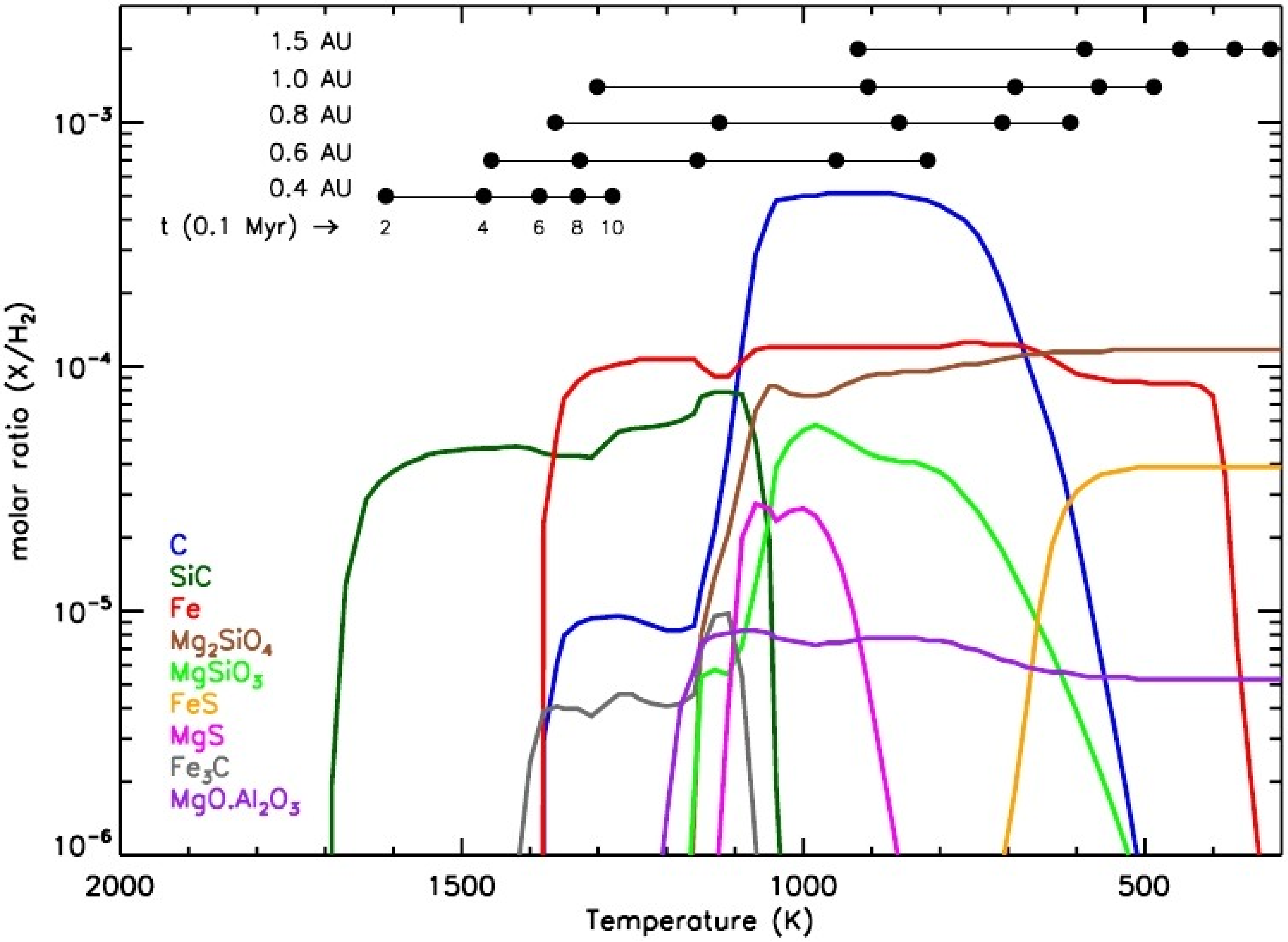


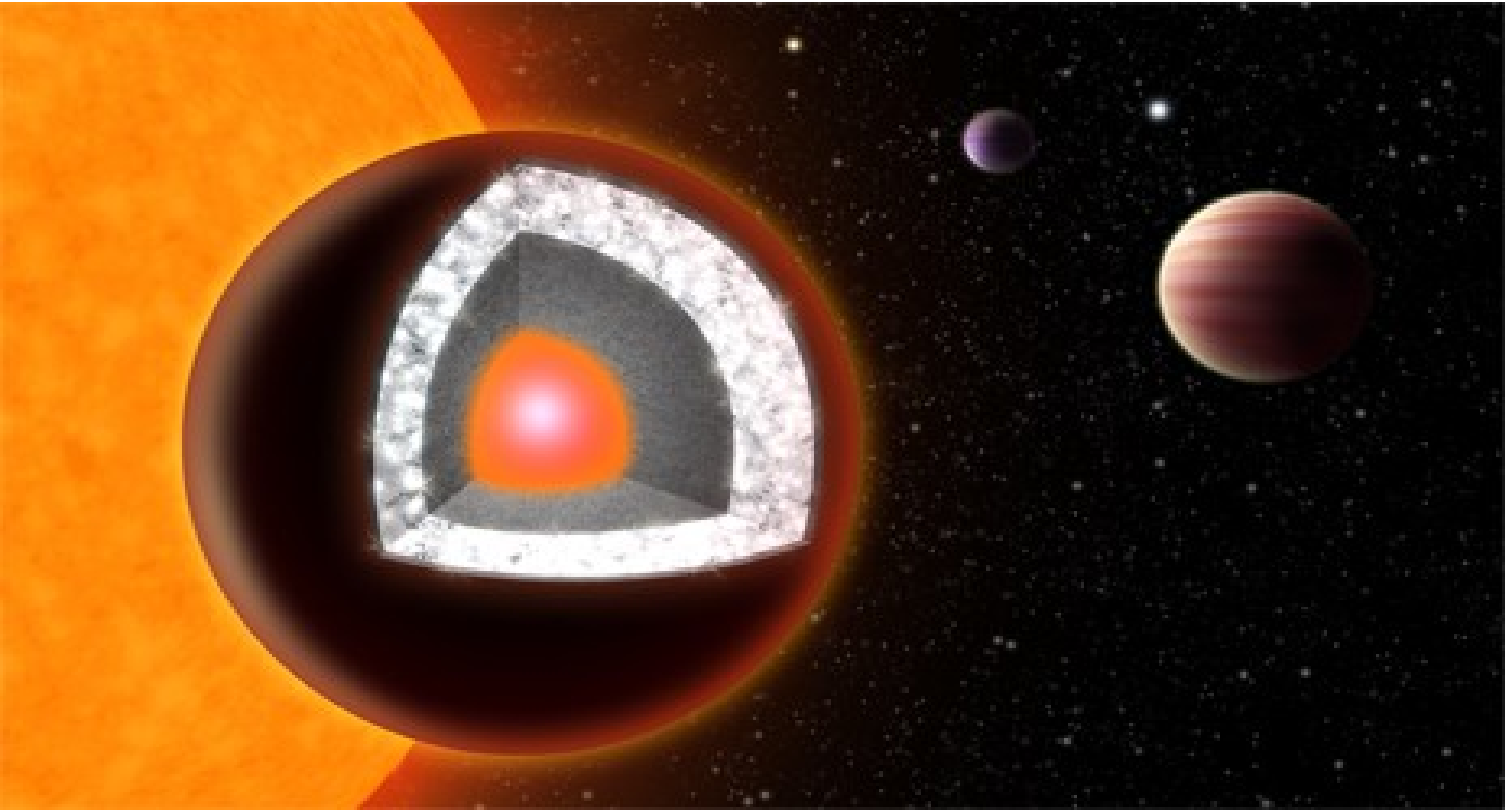
Figure 2. Ternary diagrams showing the range of interior compositions allowed by the mass and radii of 55 Cancri e. Two classes of interior models were considered, based on the planetesimal compositions predicted by the stellar abundances. Left: models composed of Fe, SiC, and C. Right: models composed of Fe, $MgSiO_3$, and C. In each case, the red (blue) contours show the constraints from the visible (gray) radius. The blue contours are subsets of the red contours. The three axes in each case show the mass fractions of the corresponding species.

The planet is primarily composed of carbon as graphite and diamond; iron; silicon carbide; and possibly some silicates

The star is carbon-rich, so the protostellar disk was also likely to be.



Graphite over diamond over silicon-based minerals over iron core. Hot side ~2,400K.



CoRoT-7b

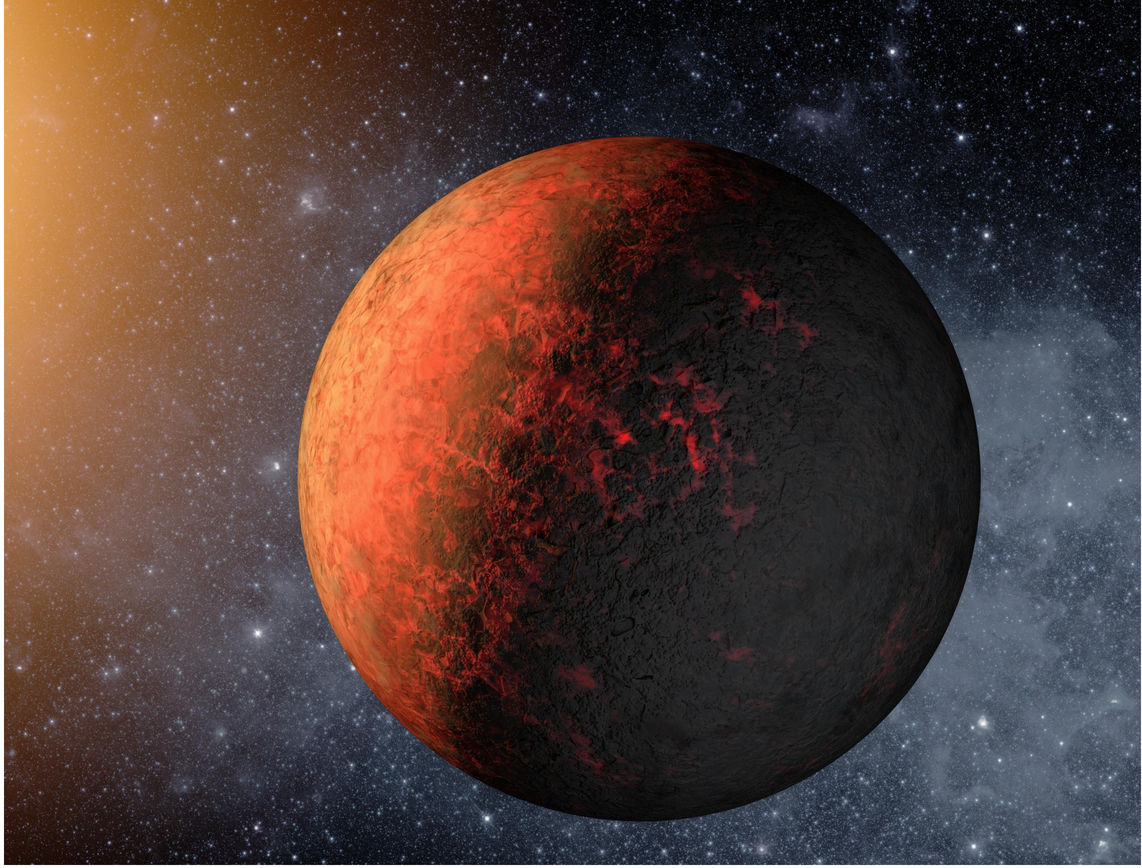
$M=7.42M_{Earth}$ $R=1.58R_{Earth}$

ρ = 10.4 $^{+}/_{-}$ 1.8 g/cc

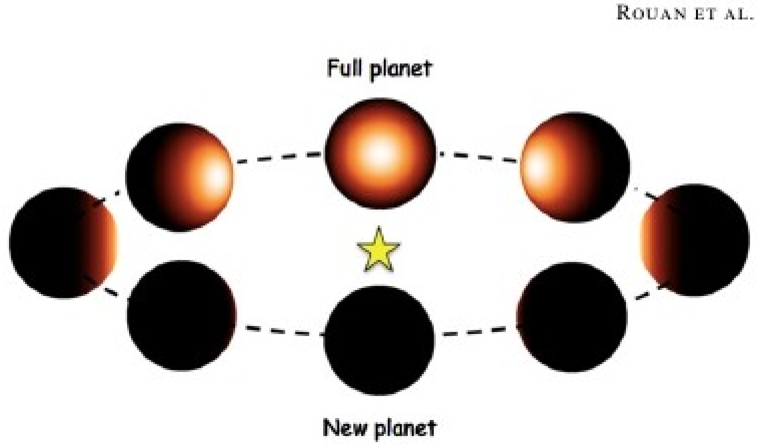
Kepler 10b

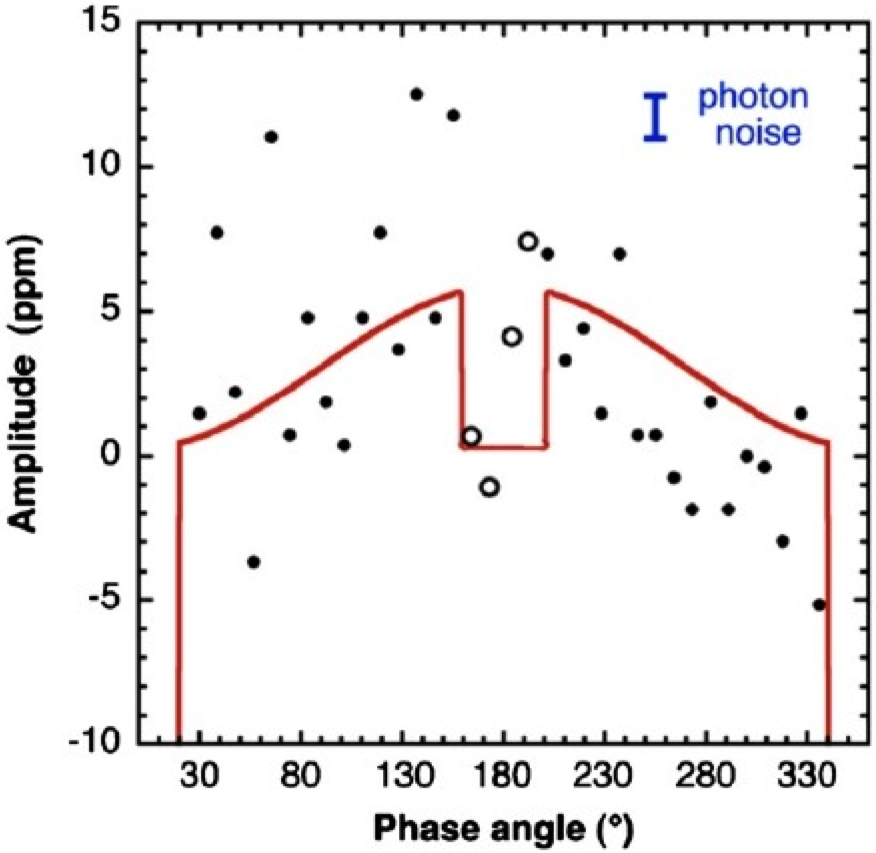
$M=4.5M_{Earth}$ $R=1.4R_{Earth}$

ρ = 8.7 g/cc



Both claimed as Fe-rich Mercury-like from structural models only (Gong & Zhou 2012 and Wagner et al. 2012).



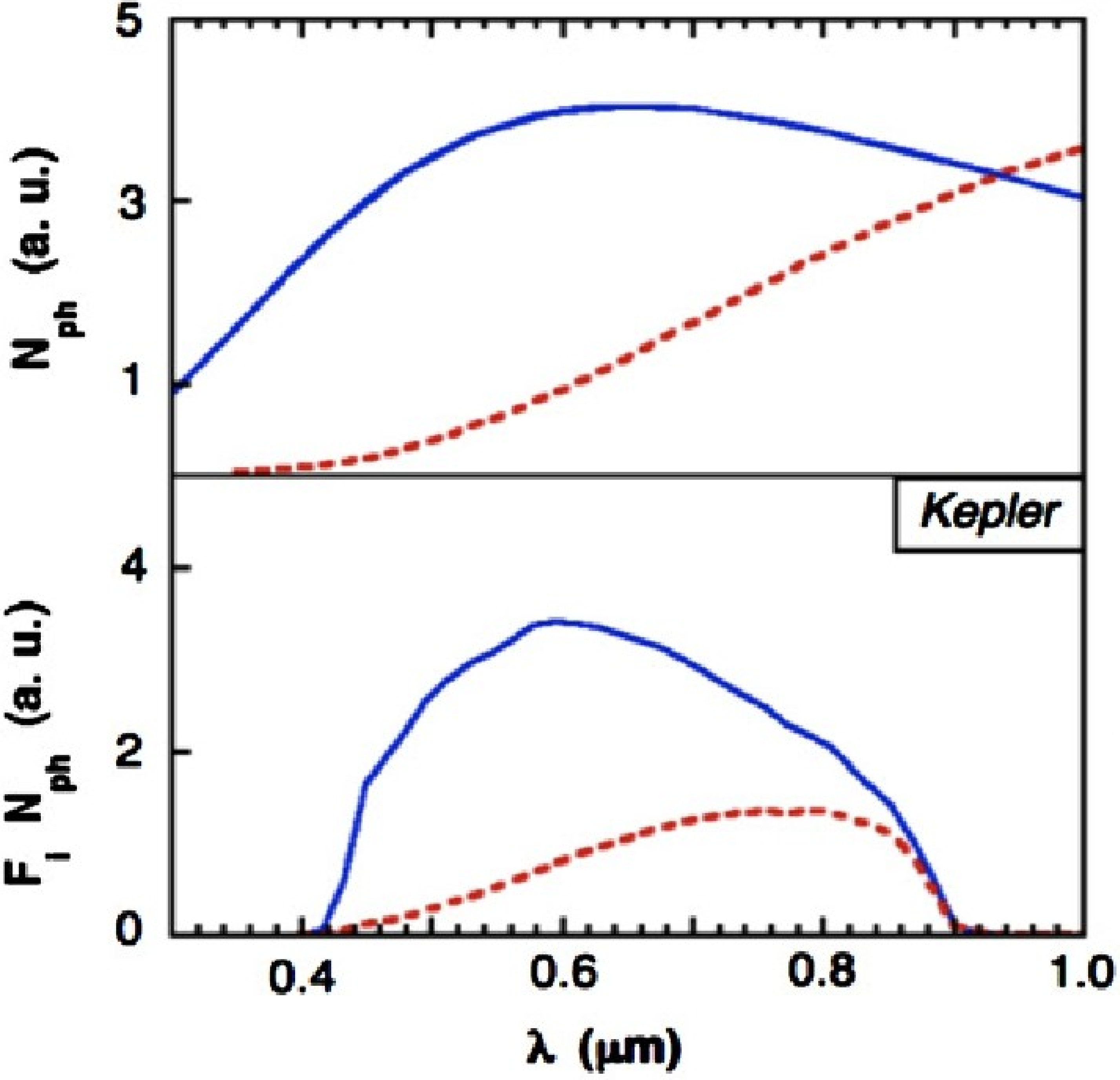


Kepler 10b:
The lightcurve is measured around the orbit (at right) and a model is generated (above)

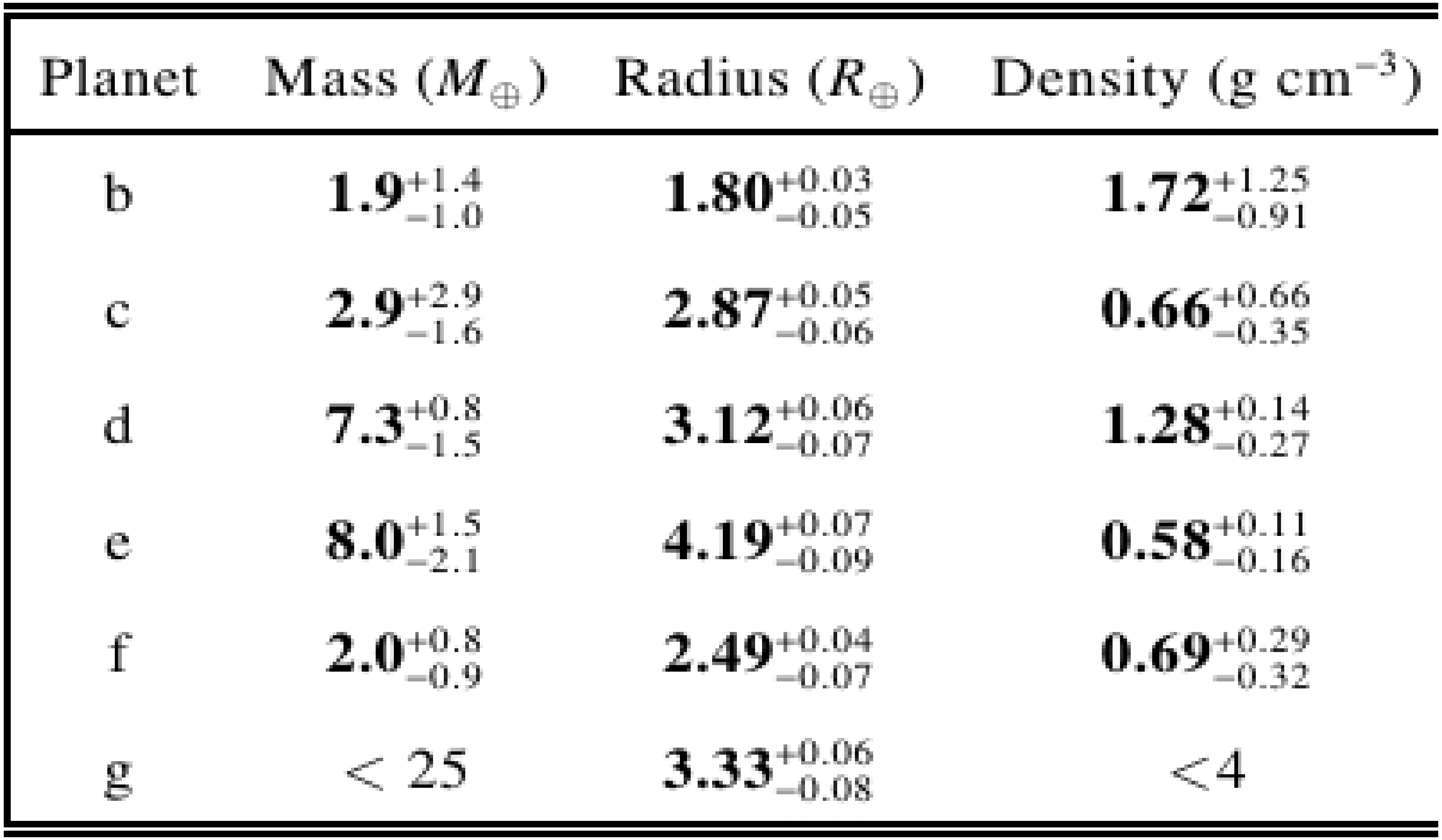
The model is essentially a 2-parameter fit: albedo and thermal radiation; assuming negligible atmosphere, constant albedo, and the emissivity of liquid alumina.
(Rouan et al. 2011)

Reflected (blue) and thermal emission (red) for a=0.5 just outside of secondary transit.

Assumes night side is cold and (fitted- Bruce?) day side reaches 3000K

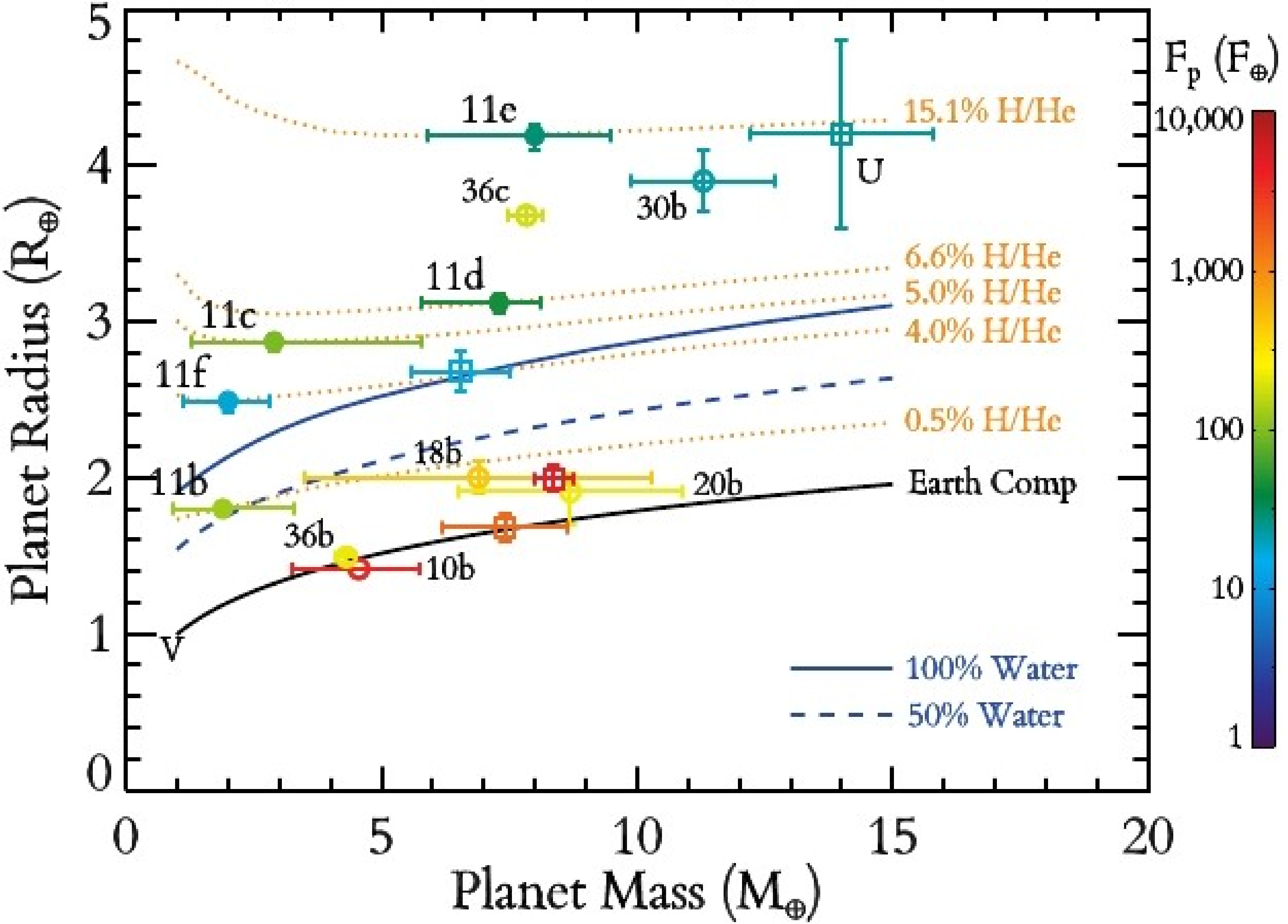


Kepler 11 has 6 planets, 5 with orbital periods under 50 days.

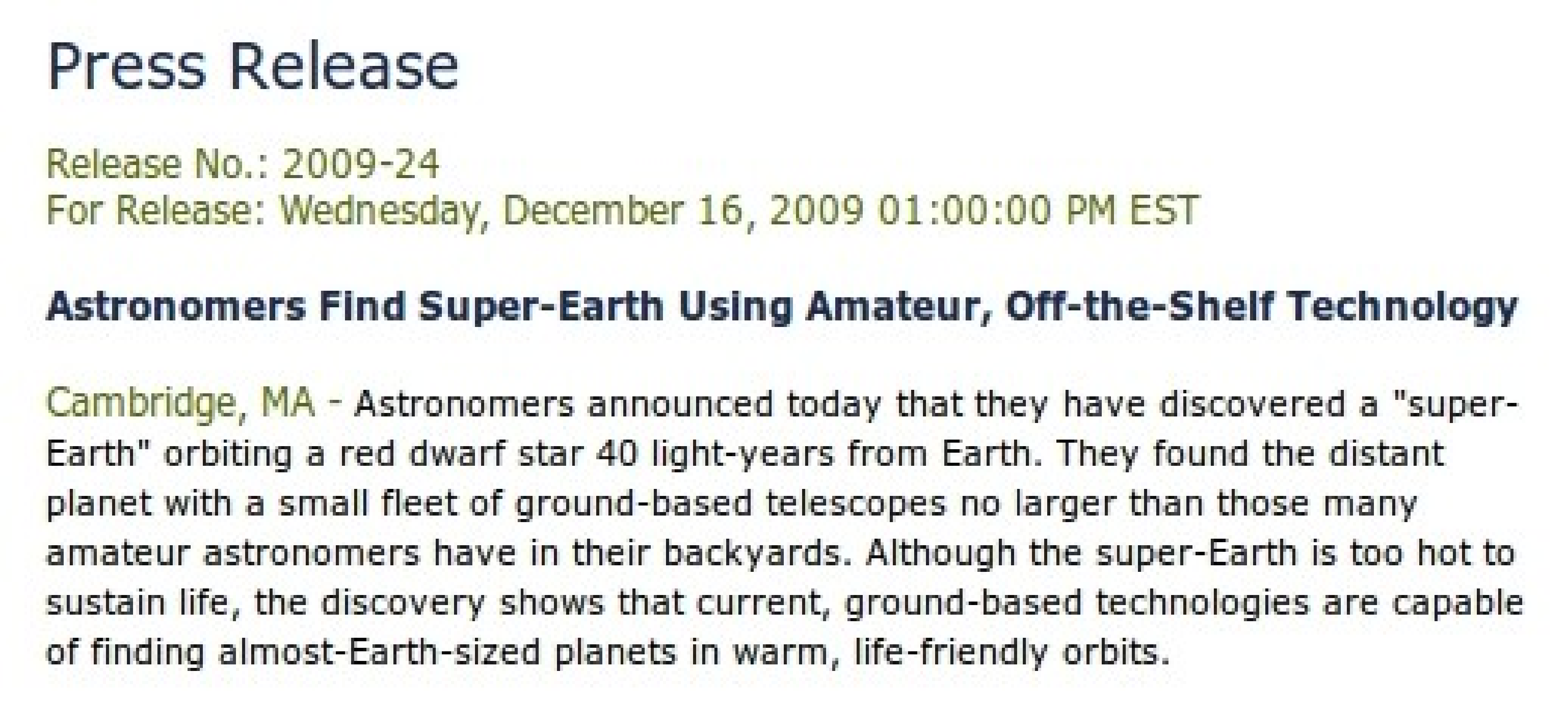


Planet	Mass ($M_\oplus$)	Radius ($R_\oplus$)	Density (g cm^{-3})
b	$\mathbf{1.9}^{+1.4}_{-1.0}$	$\mathbf{1.80}^{+0.03}_{-0.05}$	$\mathbf{1.72}^{+1.25}_{-0.91}$
c	$\mathbf{2.9}^{+2.9}_{-1.6}$	$\mathbf{2.87}^{+0.05}_{-0.06}$	$\mathbf{0.66}^{+0.66}_{-0.35}$
d	$\mathbf{7.3}^{+0.8}_{-1.5}$	$\mathbf{3.12}^{+0.06}_{-0.07}$	$\mathbf{1.28}^{+0.14}_{-0.27}$
e	$\mathbf{8.0}^{+1.5}_{-2.1}$	$\mathbf{4.19}^{+0.07}_{-0.09}$	$\mathbf{0.58}^{+0.11}_{-0.16}$
f	$\mathbf{2.0}^{+0.8}_{-0.9}$	$\mathbf{2.49}^{+0.04}_{-0.07}$	$\mathbf{0.69}^{+0.29}_{-0.32}$
g	< 25	$\mathbf{3.33}^{+0.06}_{-0.08}$	<4

But all with low densities. (Lissauer et al. 2013)


Planet Radius ($R_\oplus$)
Planet Mass ($M_\oplus$)
0
5
10
15
20
1
2
3
4
5
F_p ($F_\oplus$)
10,000
1,000
100
10
1
11e
36c
30b
U
11d
11c
11f
18b
11b
20b
36b
10b
V
15.1% H/He
6.6% H/He
5.0% H/He
4.0% H/He
0.5% H/He
Earth Comp
100% Water
50% Water

Our Strategy (so far)

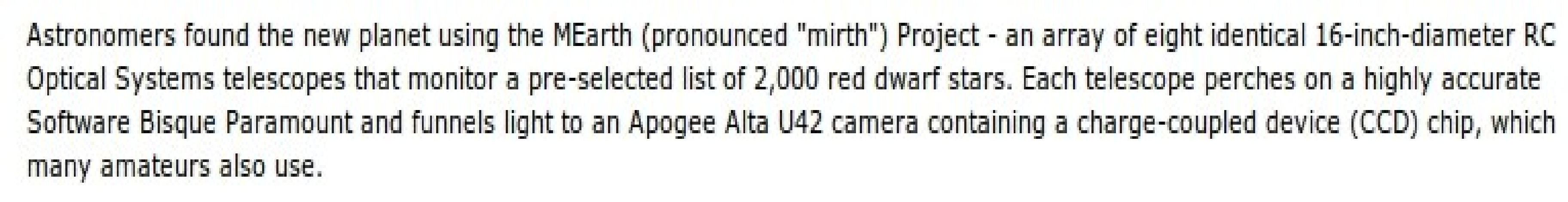


Press Release

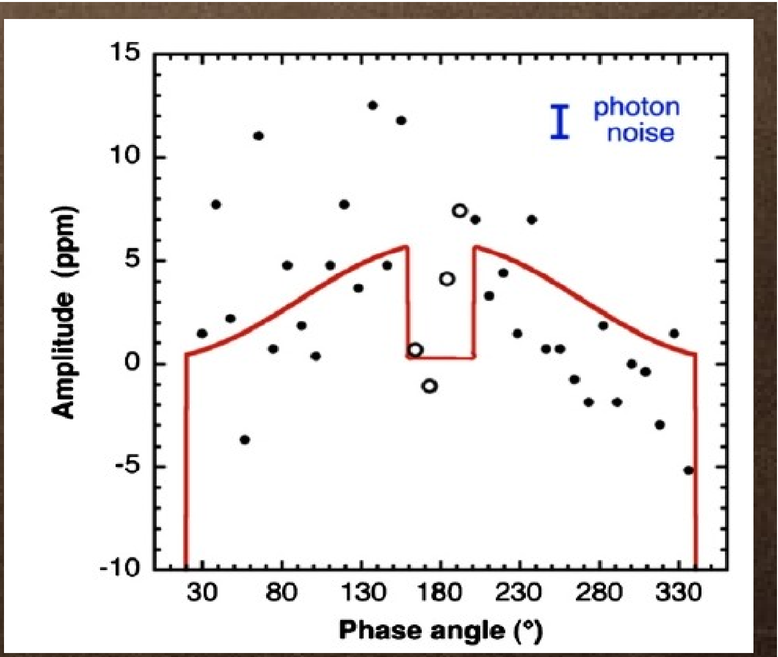
Release No.: 2009-24
For Release: Wednesday, December 16, 2009 01:00:00 PM EST

Astronomers Find Super-Earth Using Amateur, Off-the-Shelf Technology

Cambridge, MA - Astronomers announced today that they have discovered a "super-Earth" orbiting a red dwarf star 40 light-years from Earth. They found the distant planet with a small fleet of ground-based telescopes no larger than those many amateur astronomers have in their backyards. Although the super-Earth is too hot to sustain life, the discovery shows that current, ground-based technologies are capable of finding almost-Earth-sized planets in warm, life-friendly orbits.

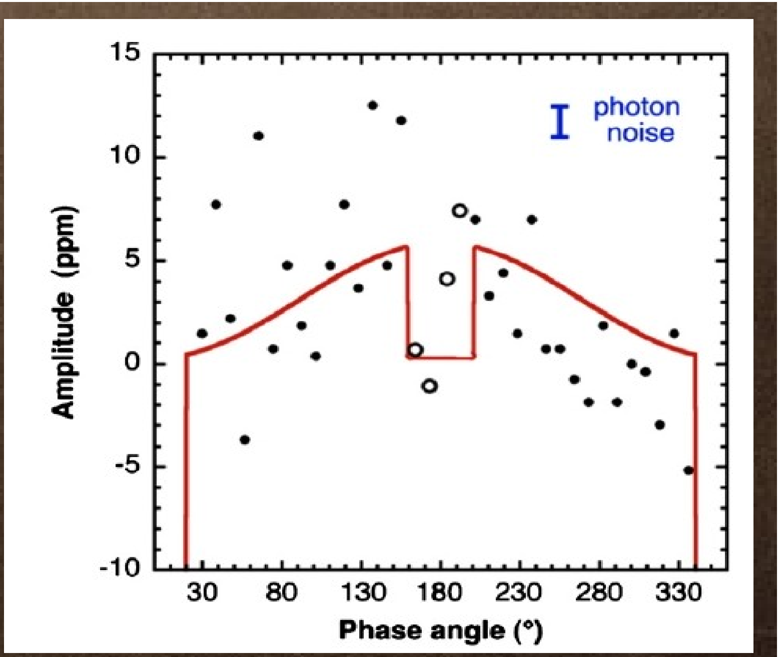


Astronomers found the new planet using the MEarth (pronounced "mirth") Project - an array of eight identical 16-inch-diameter RC Optical Systems telescopes that monitor a pre-selected list of 2,000 red dwarf stars. Each telescope perches on a highly accurate Software Bisque Paramount and funnels light to an Apogee Alta U42 camera containing a charge-coupled device (CCD) chip, which many amateurs also use.



Observe several star/planet systems with varying sized planets (from superJupiters down to superEarths) at several orbital phases. This is done in several filters from Sloan u (where thermal emission from the planet should be zero) to I (where thermal emission may contibute).

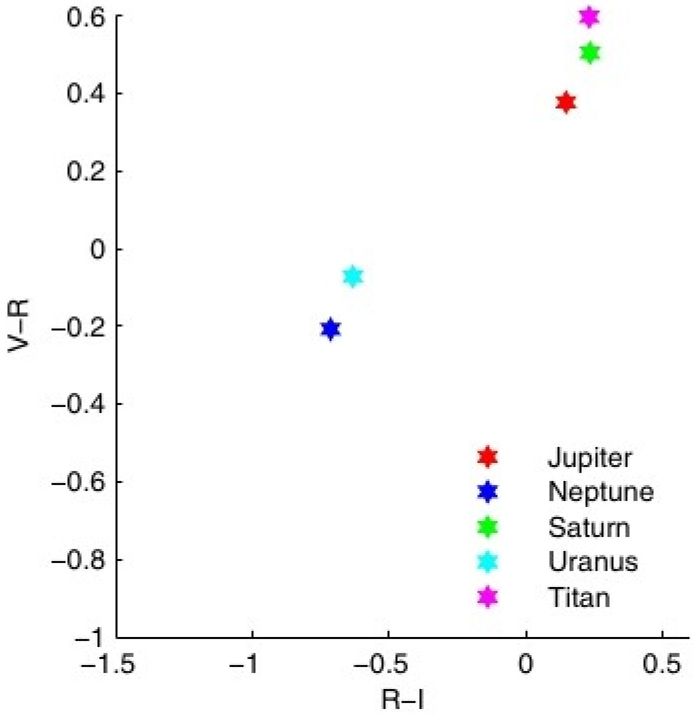
Build up the phase-dependent lightcurve (like at right) and compare with models.

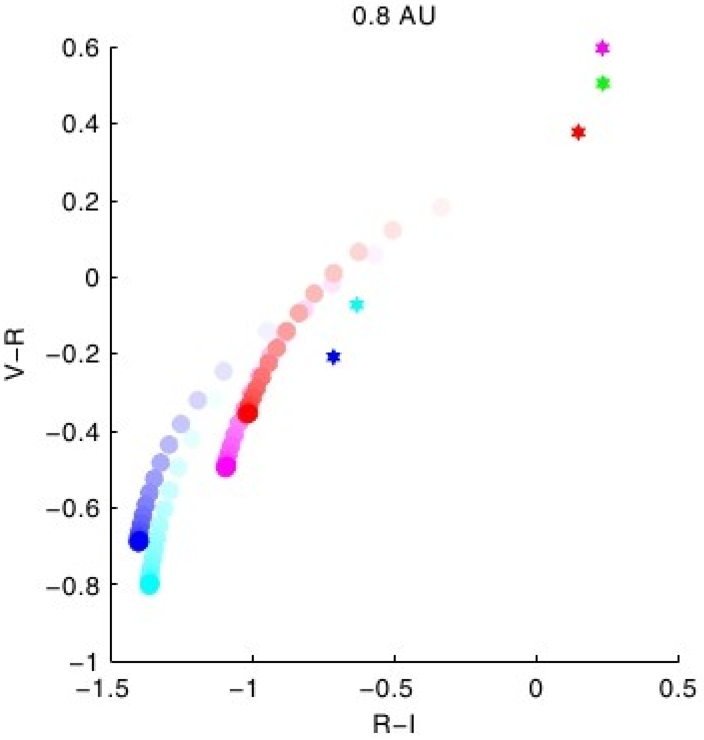


Use color-color diagrams as diagnostics.

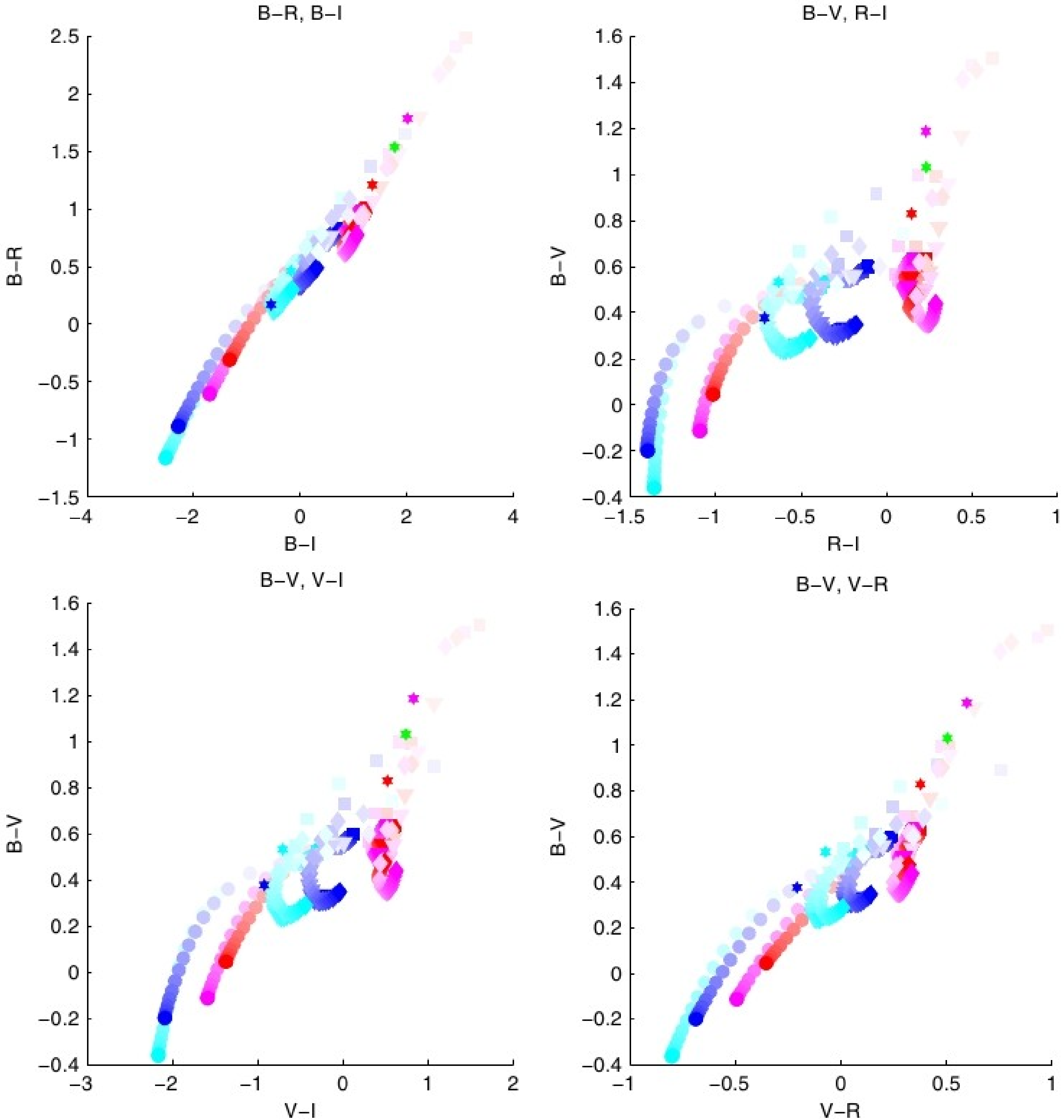
Color-color predictions for Gaseous planets.

(from Cahoy, Marley, & Fortney: NASA Ames)





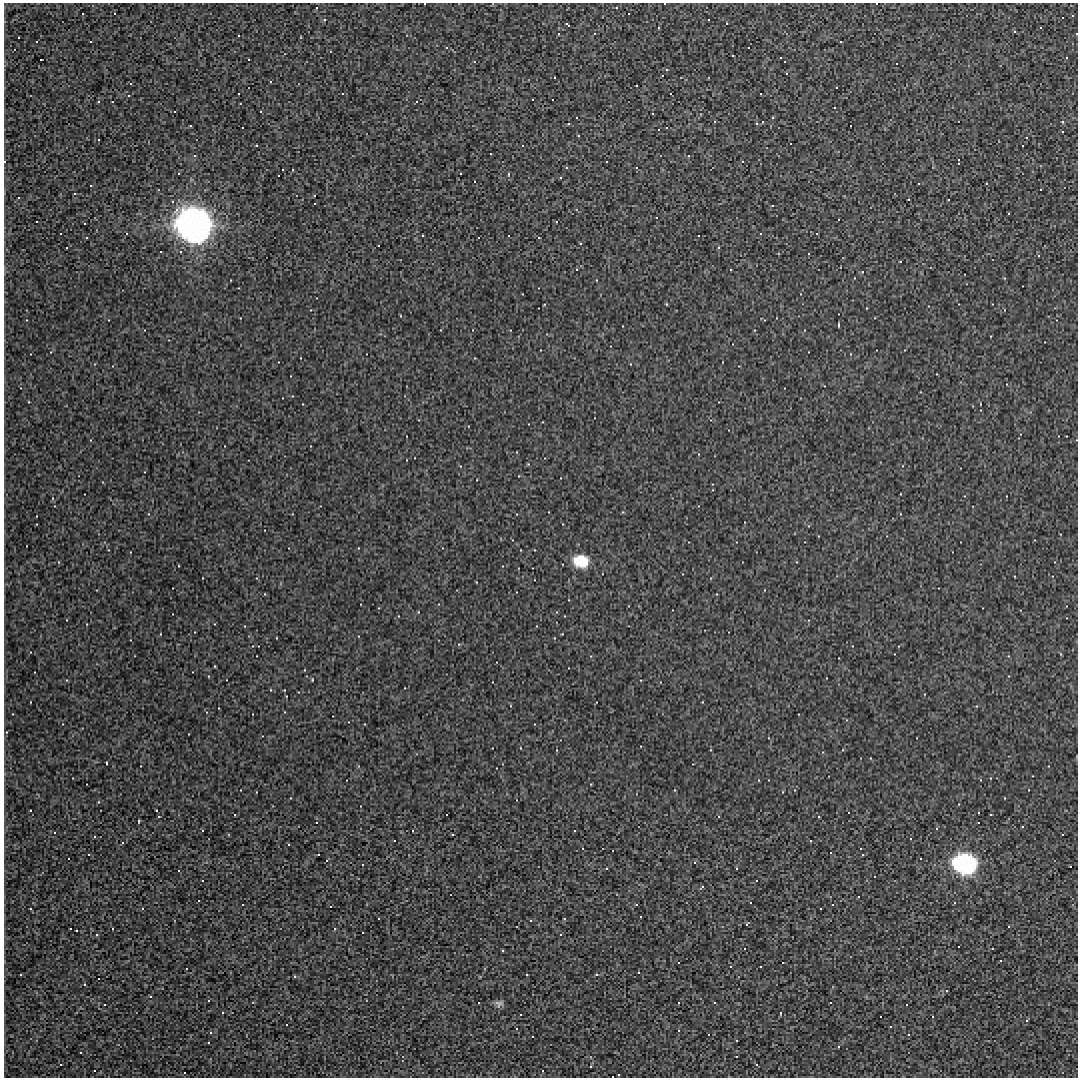
The streaks indicate orbital phase from 0 (behind, but not obscured) to 180 (illuminated side away from observer) as they fade away.



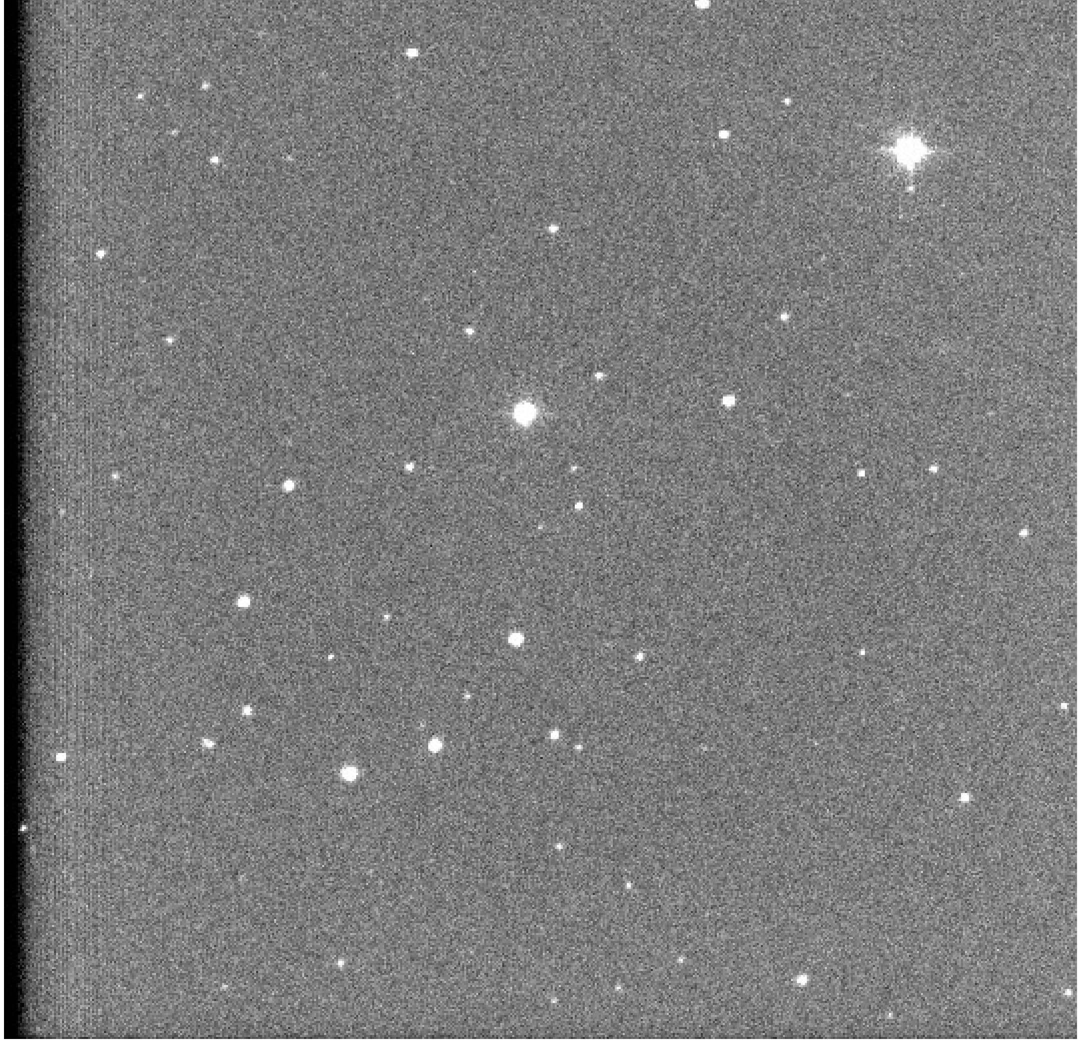
Another one from the same paper but with more filter combinations.

Note that these are all optical. (I is Bessell I, just like we're using and is very near-IR)

Initially, we thought we'd use GTCam2 and simultaneously plug away in 3 colors; taking a ton of images!
However, the lack of comparison stars is an issue.



So we're using our other CCD camera and flipping filters. The FoV is 4 times larger so we get many more comparison stars.



The End