
Ariel
FRANCE
ARES II: Ariel School
Exoplanetary Atmospheres: From 1D to 3D Models
October 2-11 2021, Biarritz

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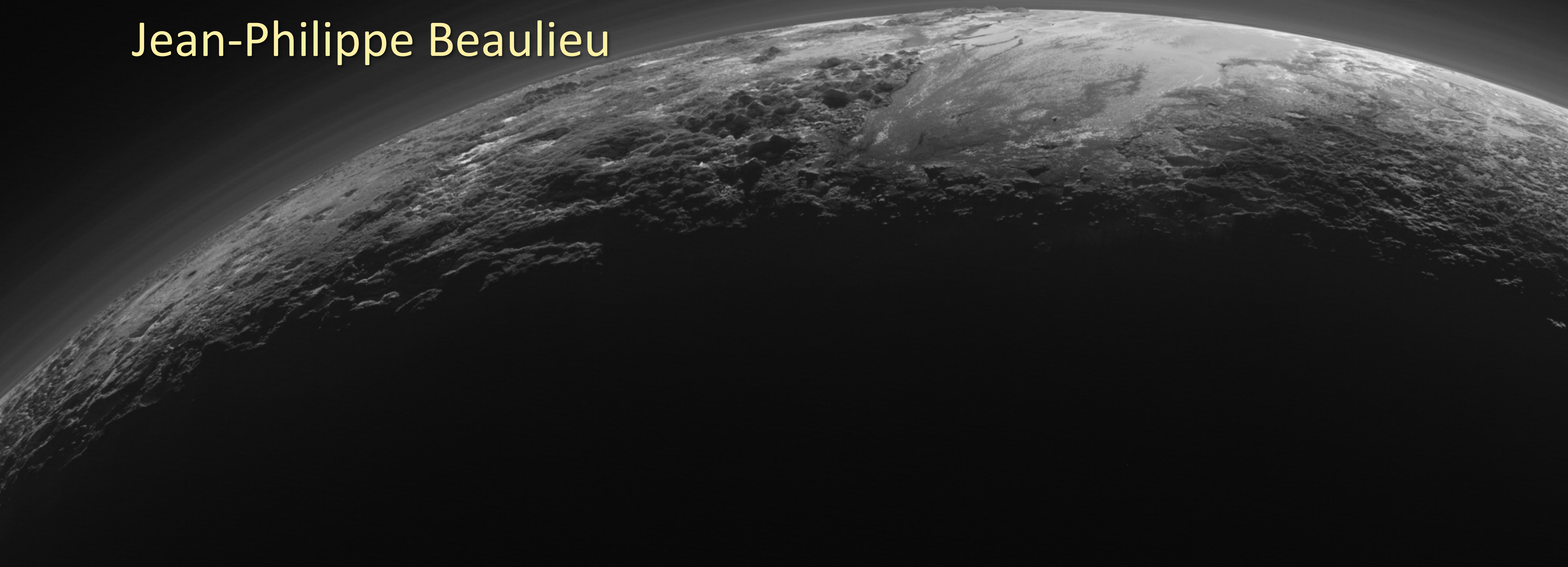
Detection of Exoplanets

Methods, spectral observations

Jean-Philippe Beaulieu



What is a planet, historical view

According to the greeks:

any moving object in the sky is a planet.

The Sun, the moon, Mercury, Venus, Mars, Jupiter, Saturn.

Comets ?

Copernician revolution:

Sun and moons are no more « planets », but the Earth is.

Planets discovered after:

Uranus (William Herschel 1781)

Neptune (Leverrier 1846)

Pluto (Clyde Tombaugh, 1930)

Planet, dwarf planet, and the case of Pluto in 2006

What is a planet, according to IAU resolution B5, 2006

A planet is a celestial body that

1. is in orbit around the Sun,
2. has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and
3. has cleared the neighborhood around its orbit.

A dwarf planet is a celestial body that

1. is in orbit around the Sun,
2. has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape
3. has not cleared the neighborhood around its orbit,
4. is not a satellite.

The zoo is complemented by

- « moons » orbiting planets, 19 are massive enough to be round.
- small bodies, irregular shapes orbiting the sun (asteroids, comets)

Inventory of the solar system

The sun:

- A ball of plasma powered by nuclear fusion in its core.
- 99.8 % in mass of the solar system
- Luminosity of 4 10^8 times total luminosity of Jupiter (emitted + reflected)

Giant planets : mostly H, He, and few-10 % of other elements

Rocky planets : mostly heavy elements

Dwarf planets : mostly heavy elements, rocks, ices

Small bodies : composed of molecular material, some in solid state

→ **A rich diversity !**

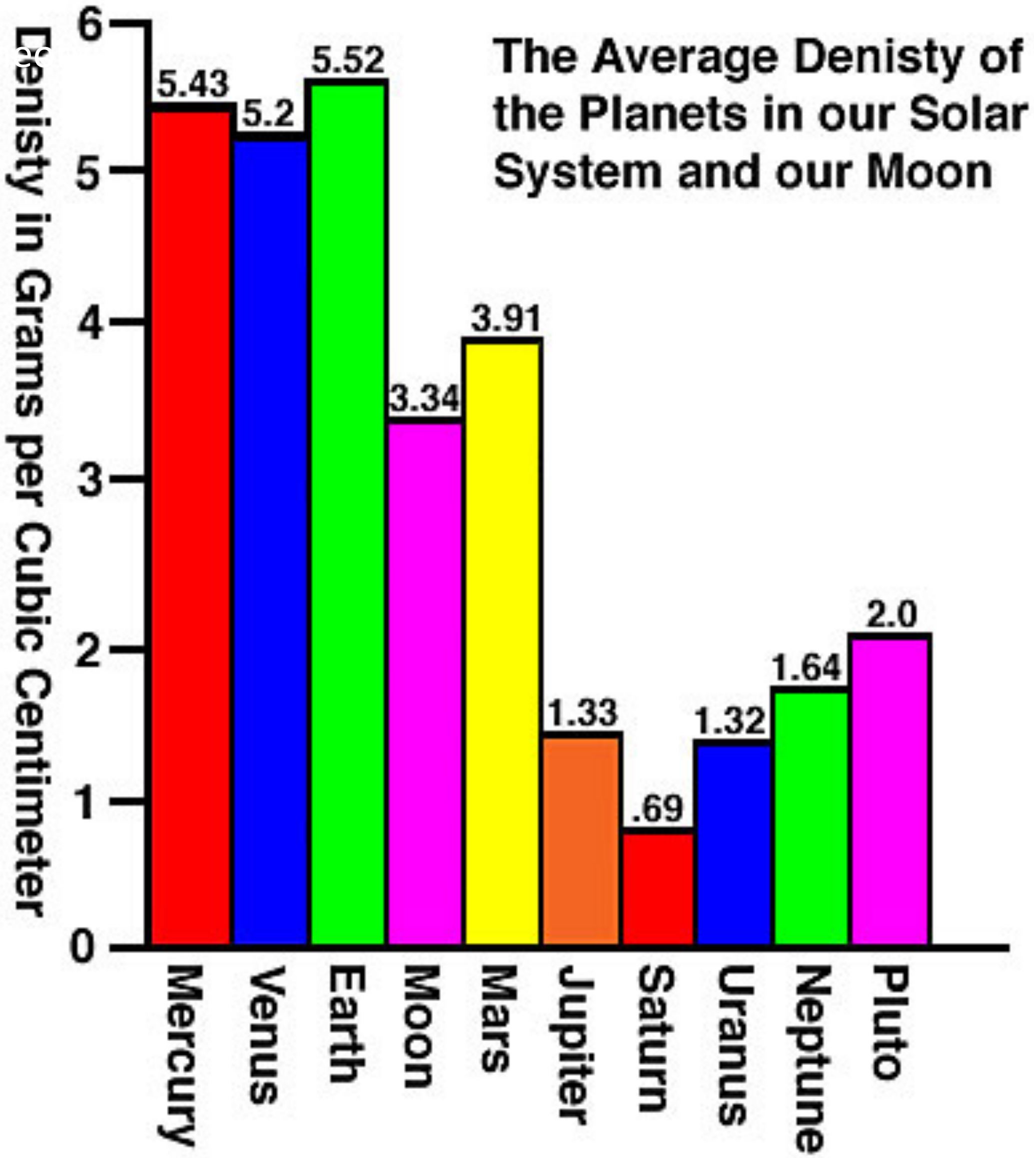
About composition and density

- Rocky planets : 3-6 *g cm*$^{-3}$
  => mostly rocks and metals.

- Gazeous planets: 1-2 *g cm*$^{-3}$
  => Rocky-core, ices and gazes

- Inner belt asteroids: contains metals and rocks

- Outer main belt, KBOs: less metals, more ices



Extrasolar planet detection

Oct 1 2021, 4843 planets / 3579 planetary systems / 797 multiple planet systems

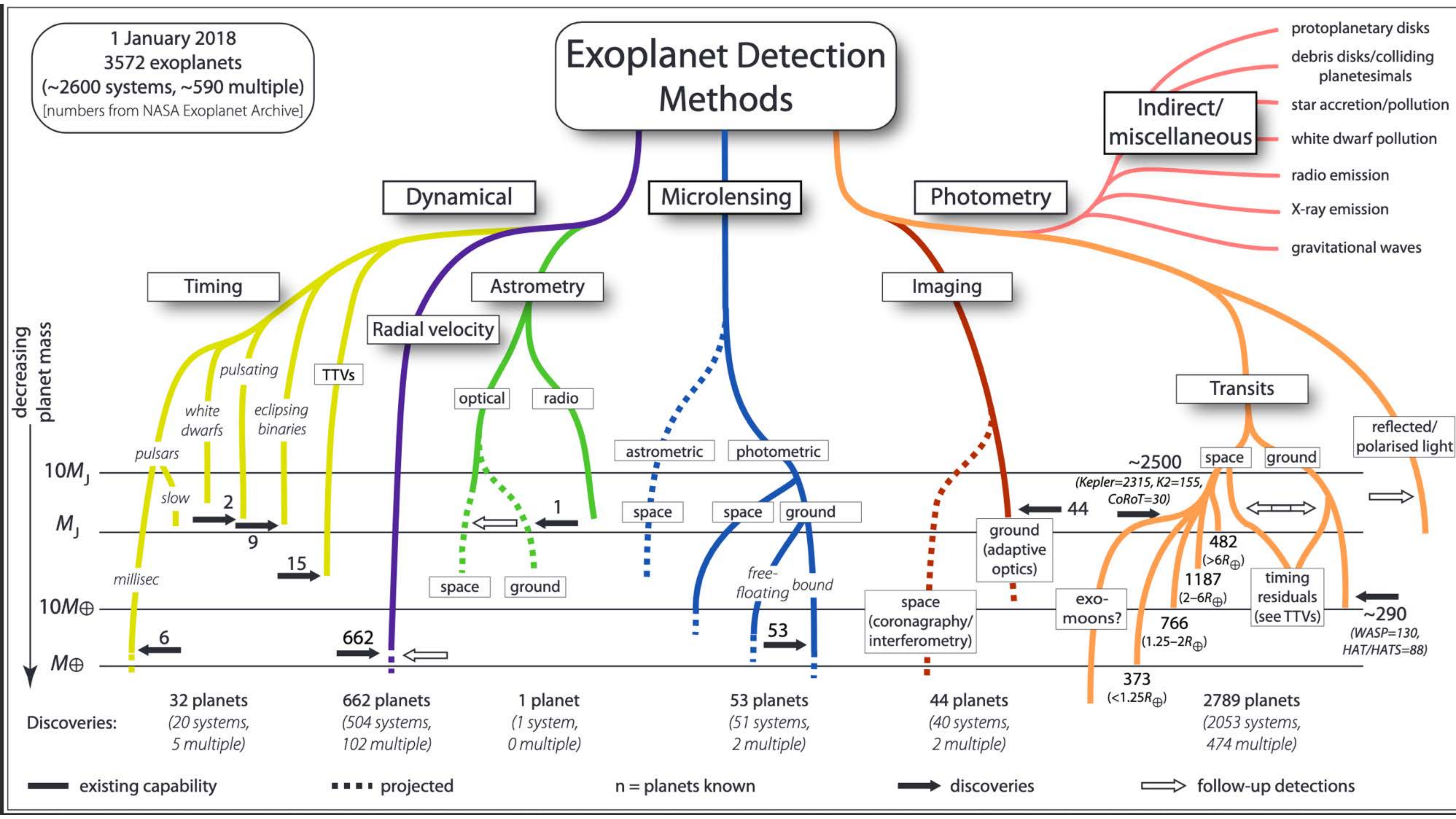
Astrometry (16 objects, 2 planets ??)

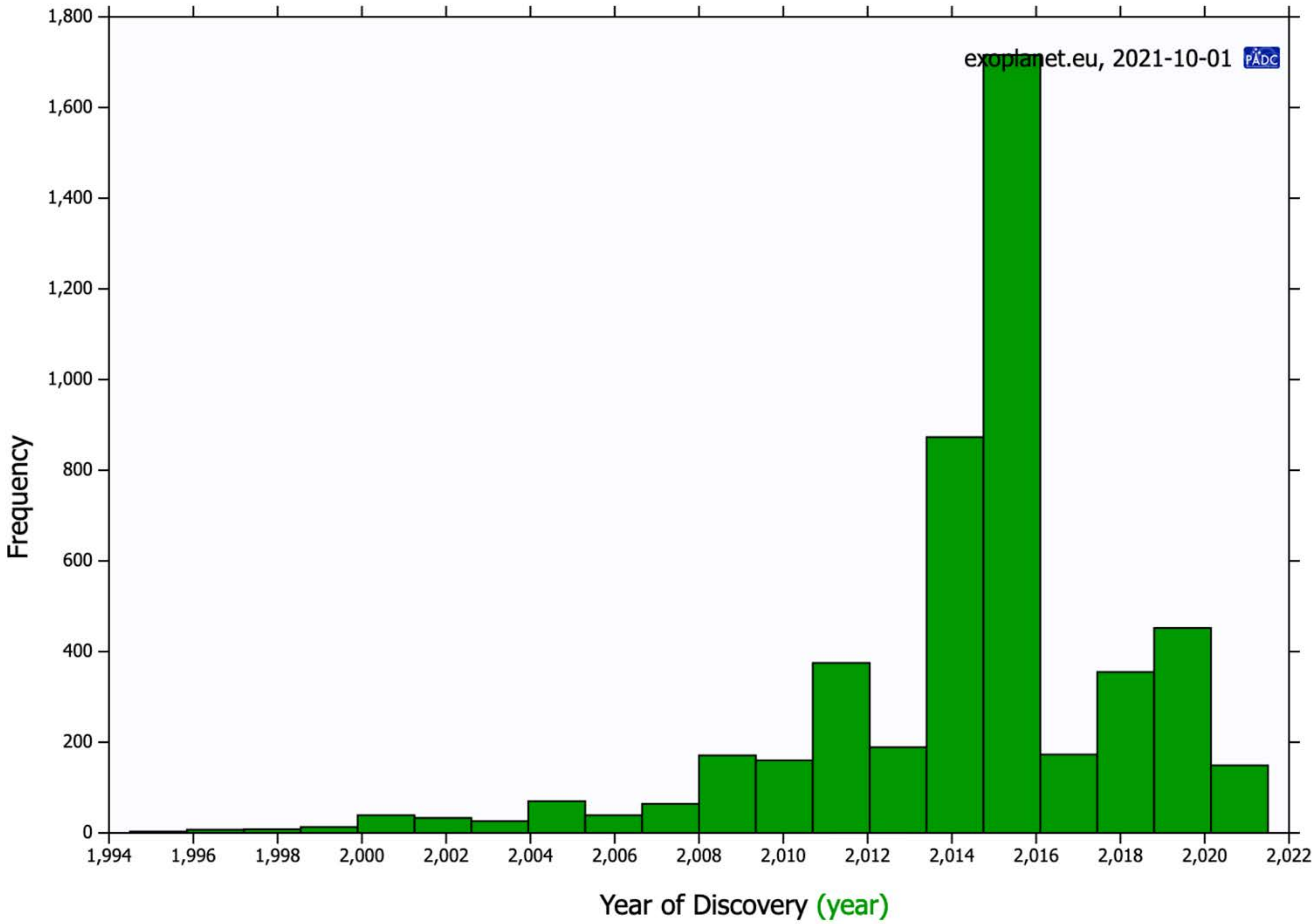
Radial Velocity (966 planets in 712 systems, 173 multiple planet systems)

Transit (3454 planets in 2597 systems, 557 multiple planet systems)

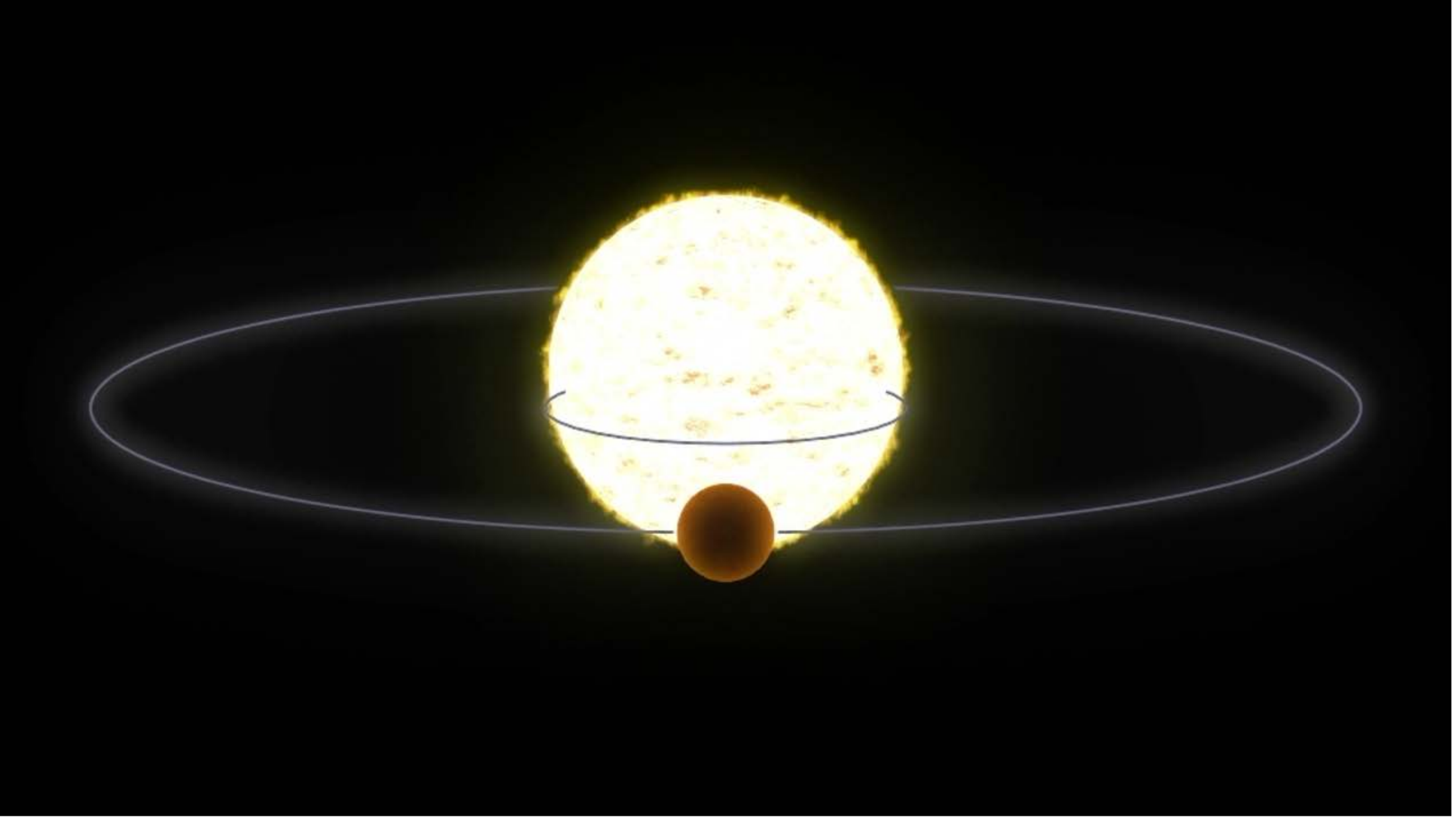
Microlensing (160 planets in 143 systems, 7 multiple planet systems)

Direct detection (154 planets in 111 systems, 7 multiple planet systems)


1 January 2018
3572 exoplanets
(~2600 systems, ~590 multiple)
[numbers from NASA Exoplanet Archive]
Exoplanet Detection Methods
Dynamical
Microlensing
Photometry
Indirect/ miscellaneous
protoplanetary disks
debris disks/colliding planetesimals
star accretion/pollution
white dwarf pollution
radio emission
X-ray emission
gravitational waves
Timing
Astrometry
Imaging
Radial velocity
pulsating
TTVs
white dwarfs
eclipsing binaries
pulsars
optical
radio
Transits
astrometric
photometric
reflected/ polarised light
~2500
(Kepler=2315, K2=155, CoRoT=30)
space
ground
10M_J
slow
2
1
44
9
M_J
space
space
ground
ground (adaptive optics)
482 (>6$R_\oplus$)
15
millisec
space
ground
free-floating
bound
1187 (2–6$R_\oplus$)
timing residuals (see TTVs)
exo-moons?
10$M_\oplus$
space (coronagraphy/ interferometry)
~290
(WASP=130, HAT/HATS=88)
766 (1.25–2$R_\oplus$)
6
662
53
$M_\oplus$
373 (<1.25$R_\oplus$)
decreasing planet mass
Discoveries:
32 planets (20 systems, 5 multiple)
662 planets (504 systems, 102 multiple)
1 planet (1 system, 0 multiple)
53 planets (51 systems, 2 multiple)
44 planets (40 systems, 2 multiple)
2789 planets (2053 systems, 474 multiple)
existing capability
projected
n = planets known
discoveries
follow-up detections



exoplanet.eu, 2021-10-01
PADC
Frequency
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
1,994
1,996
1,998
2,000
2,002
2,004
2,006
2,008
2,010
2,012
2,014
2,016
2,018
2,020
2,022
Year of Discovery (year)



Orders of magnitude with looking at the moon example

1 arcsec = 1.86 km

1 micro arcsec = 1.8 mm
not easy…

TABLE 1
PARALLAX, PROPER MOTION, AND ASTROMETRIC SIGNATURES INDUCED BY PLANETS OF VARIOUS MASSES AND ORBITAL RADII

Source	α
Jupiter at 1 AU (μas)	100
Jupiter at 5 AU (μas)	500
Jupiter at 0.05 AU (μas)	5
Neptune at 1 AU (μas)	6
Earth at 1 AU (μas)	0.33
Parallax (μas)	1×10^5
Proper motion (μas yr^{-1})	5×10^5

NOTE.—A 1 $M_{\odot}$ star at 10 pc is assumed.

Semi amplitude, for star M* and planet Mp on a a (AU) orbit at distance D (in pc)

$$\alpha = 0.3 \, \frac{M_{sun}}{M_*} \, \frac{M_p}{M_{Earth}} \frac{a}{(1\,AU)} \frac{(10\,pc)}{D} \text{ microarcsec}$$

Astrometric wooble

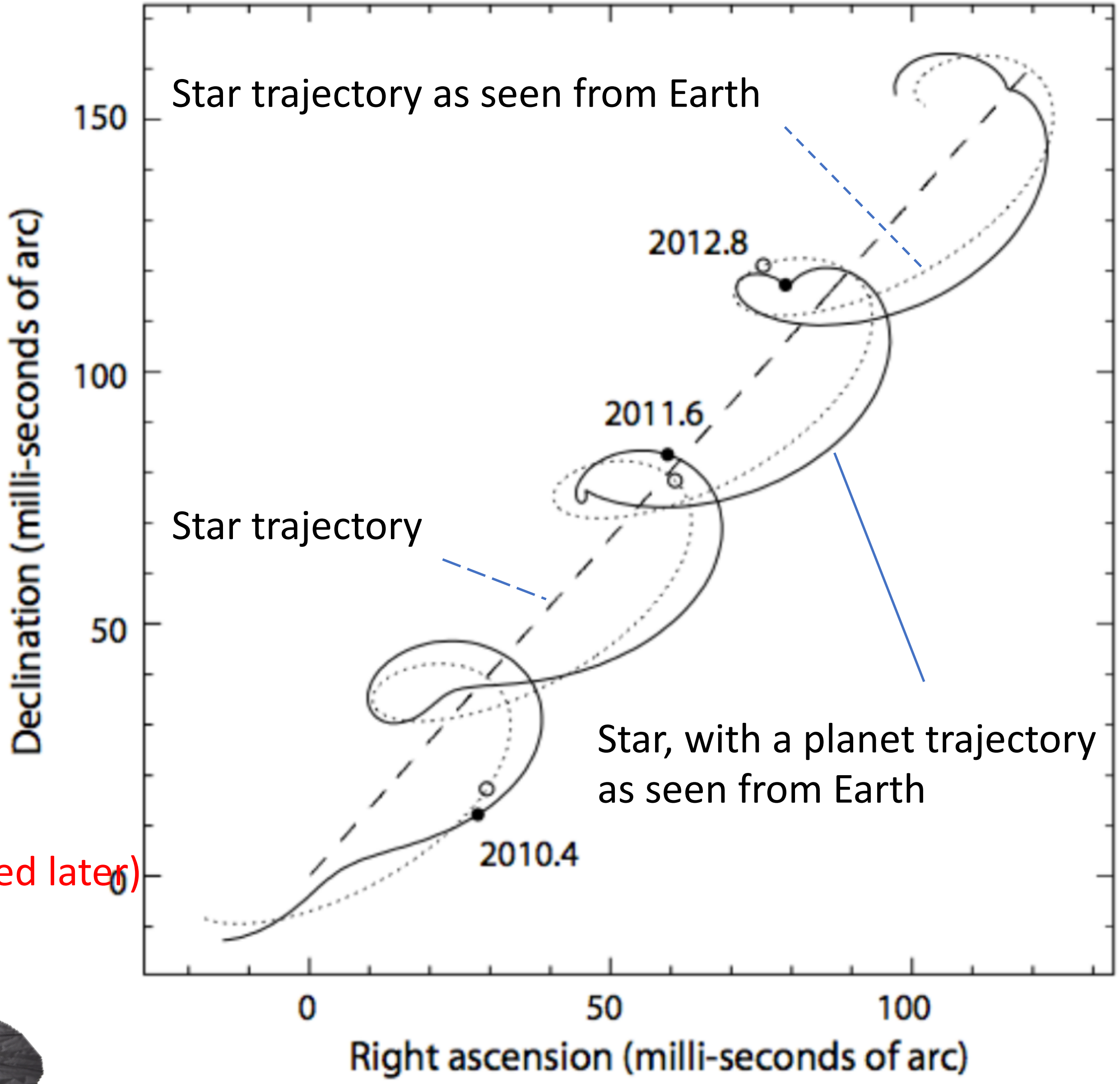
- Sensitivity

Angle variation =

semi major axis / distance

Nearby planets, on wide orbits

Sirius B found this way in XIXth cent.
Barnard star and Epsilon Eridani planets in the 1970s (refuted later)



Planet around the Barnard's star, the « dark, lifeless giant » (1963)

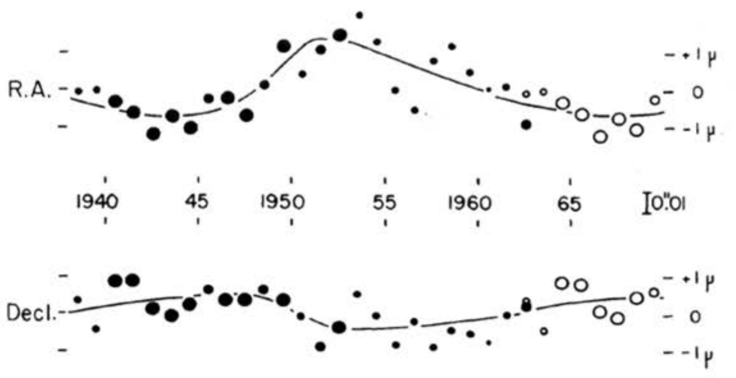


FIG. 5. Barnard's star—yearly means, averaging 96 plates and weight 64. Time displacement curves for $P=24$ yr, $e=0.6$, $T=1950$. Circles are early means transferred 24 yr forward. The scale of the displacements is shown both in terms of 0."01 and of 1μ (.001 mm) on the Sproul plates.

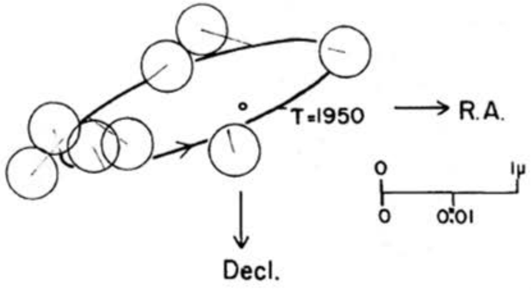
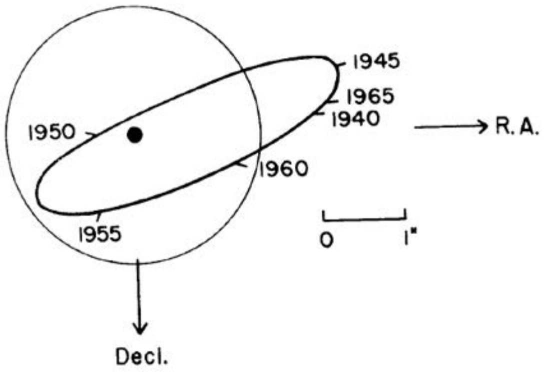
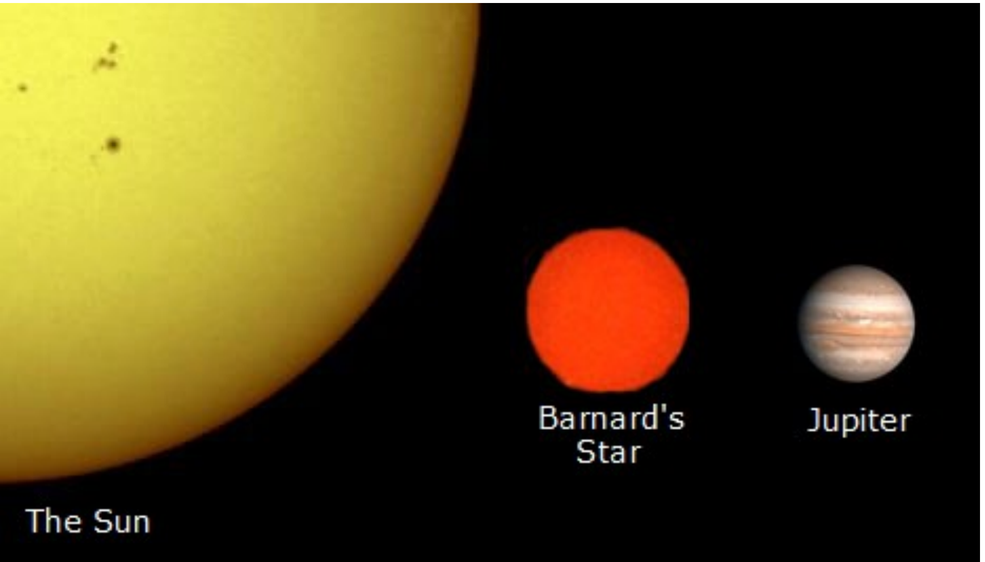
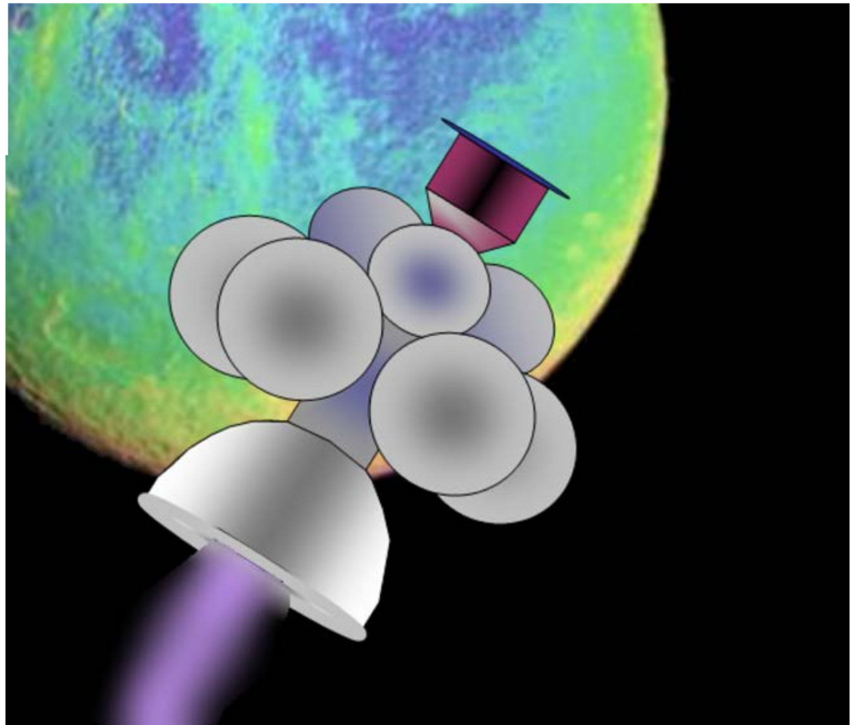


FIG. 7. Barnard's star—apparent orbit. Eight normal points of average weight 203. ○ center of mass. Radii of circles indicate probable errors. $\alpha=1.30\mu=0."0245$, $i=\pm77°$.

FIG. 8. Barnard's star and companion—Apparent relative orbit. Circle represents extreme size of image of Barnard's star.

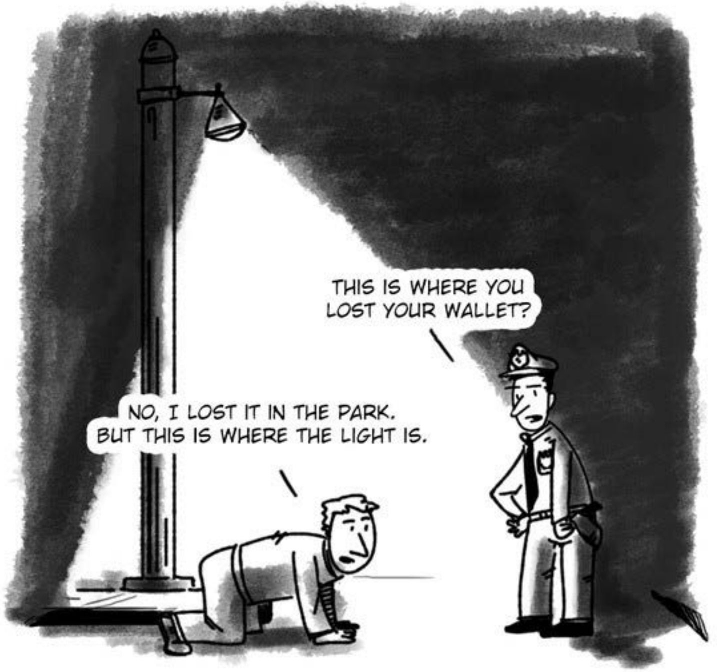




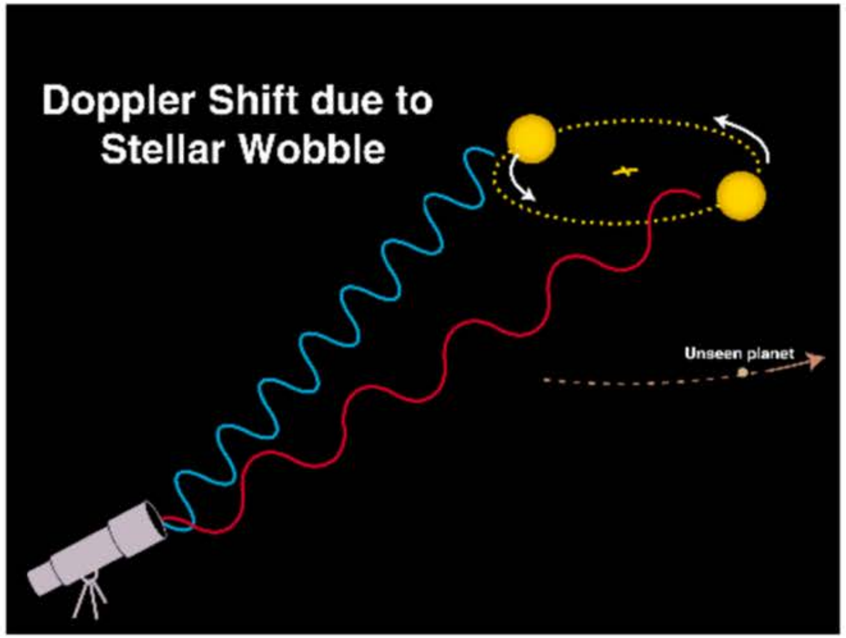


The drunkard search principle

A policeman sees a drunk man searching for something under a streetlight and asks what the drunk has lost. He says he lost his keys and they both look under the streetlight together. After a few minutes the policeman asks if he is sure he lost them here, and the drunk replies, no, and that he lost them in the park. The policeman asks why he is searching here, and the drunk replies, "this is where the light is"



Radial velocity techniques



Doppler-Fizeau

$$\frac{\Delta\lambda}{\lambda} = -\frac{v}{c}$$

Measuring radial velocity of the star oscillating around the center of gravity of the system

$$\dot{\mathbf{r}}_\star = -\dot{\mathbf{r}} M_p/(M_\star + M_p)$$

$$V_{rad} = V_0 + K \cdot [\sin(\nu(t) + \omega) + e \sin\omega]$$

$$r = \frac{p}{1 + e\cos\nu}$$

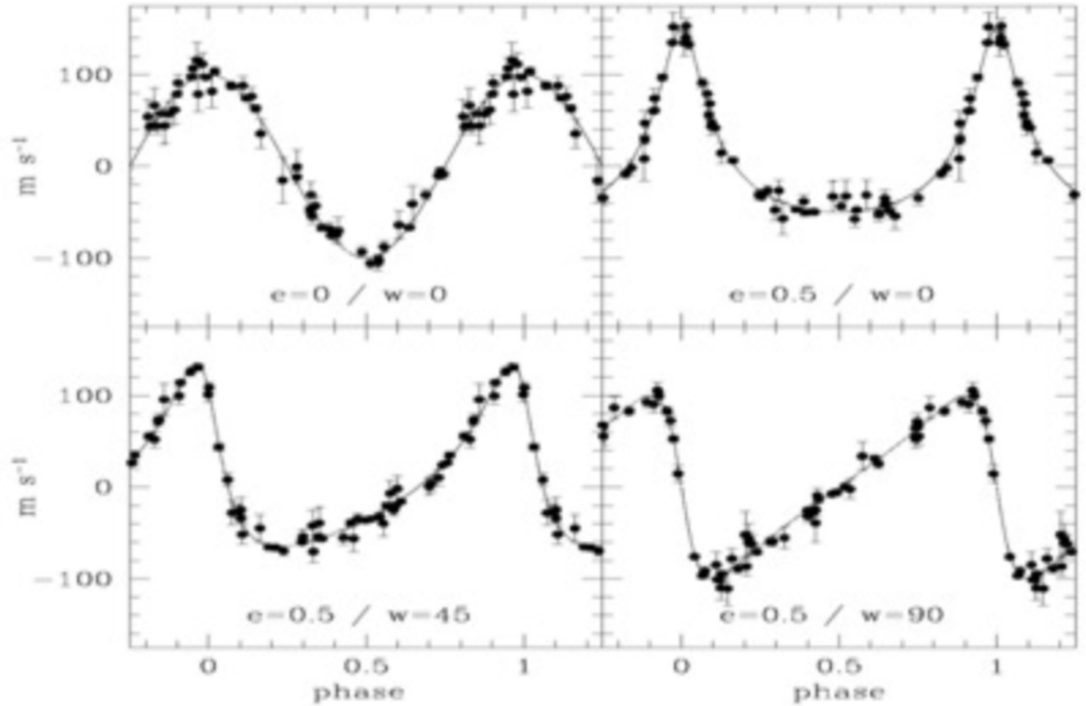
$$p = \frac{M_p}{M_* + M_p} a\,(1 - e^2)$$

Amplitude of the star radial velocity

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

Measuring radial velocities

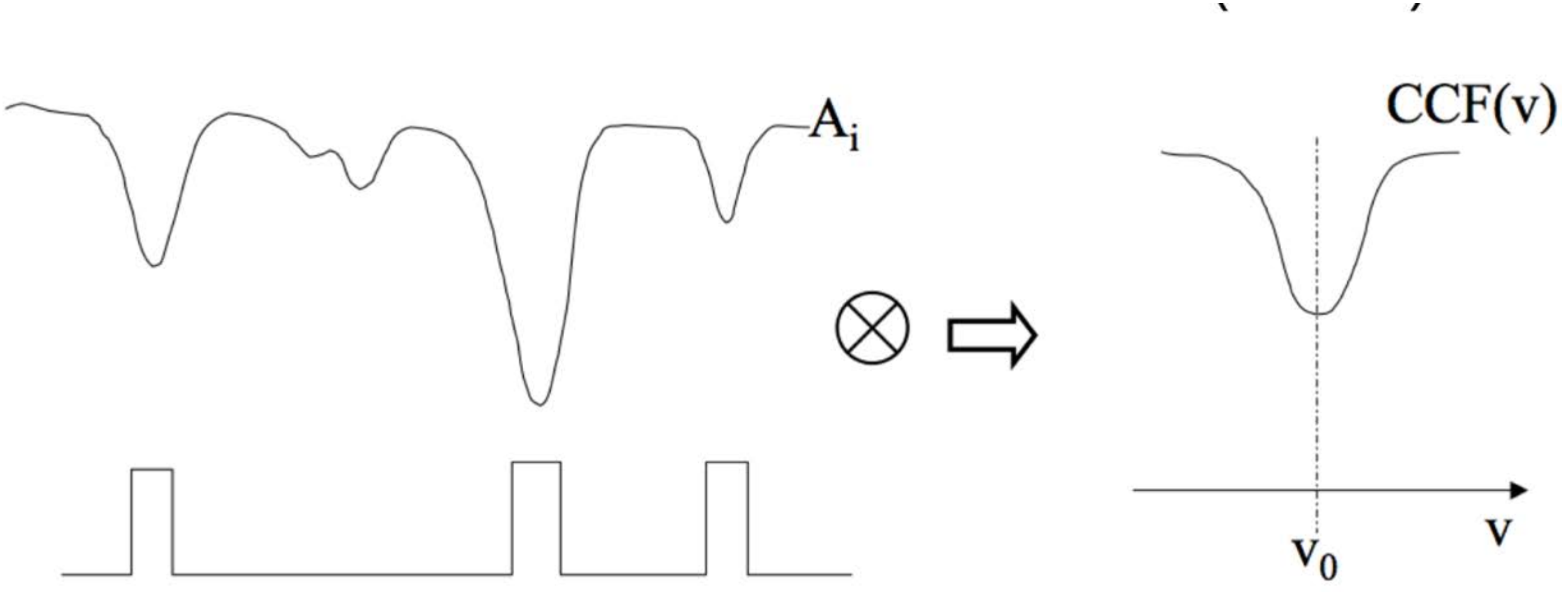
- Jupiter, 11 ms^{-1}, 11 years
- Earth, 0.1 ms^{-1}, 1 year



$$K_\star = 28.45 \left(\frac{1\ \mathrm{an}}{P}\right)^{1/3} \left(\frac{M_\mathrm{p} \sin i}{\mathrm{M_J}}\right) \left(\frac{M_\odot}{M_* + M_\mathrm{p}}\right)^{2/3} \mathrm{m\,s^{-1}}$$

Cross-correlation of observed spectra with reference spectra

Using the global information from the spectra



$$(s*t)(\delta)=\int_{-\infty}^{+\infty} s(\lambda)t(\lambda+\delta)\,d\lambda$$

Search for the first exoplanet…. (1990s)

Solar system

Close rocky planets, Jupiter on 11 yrs orbit.

Let's get Jupiter on ~ 10 years orbit !

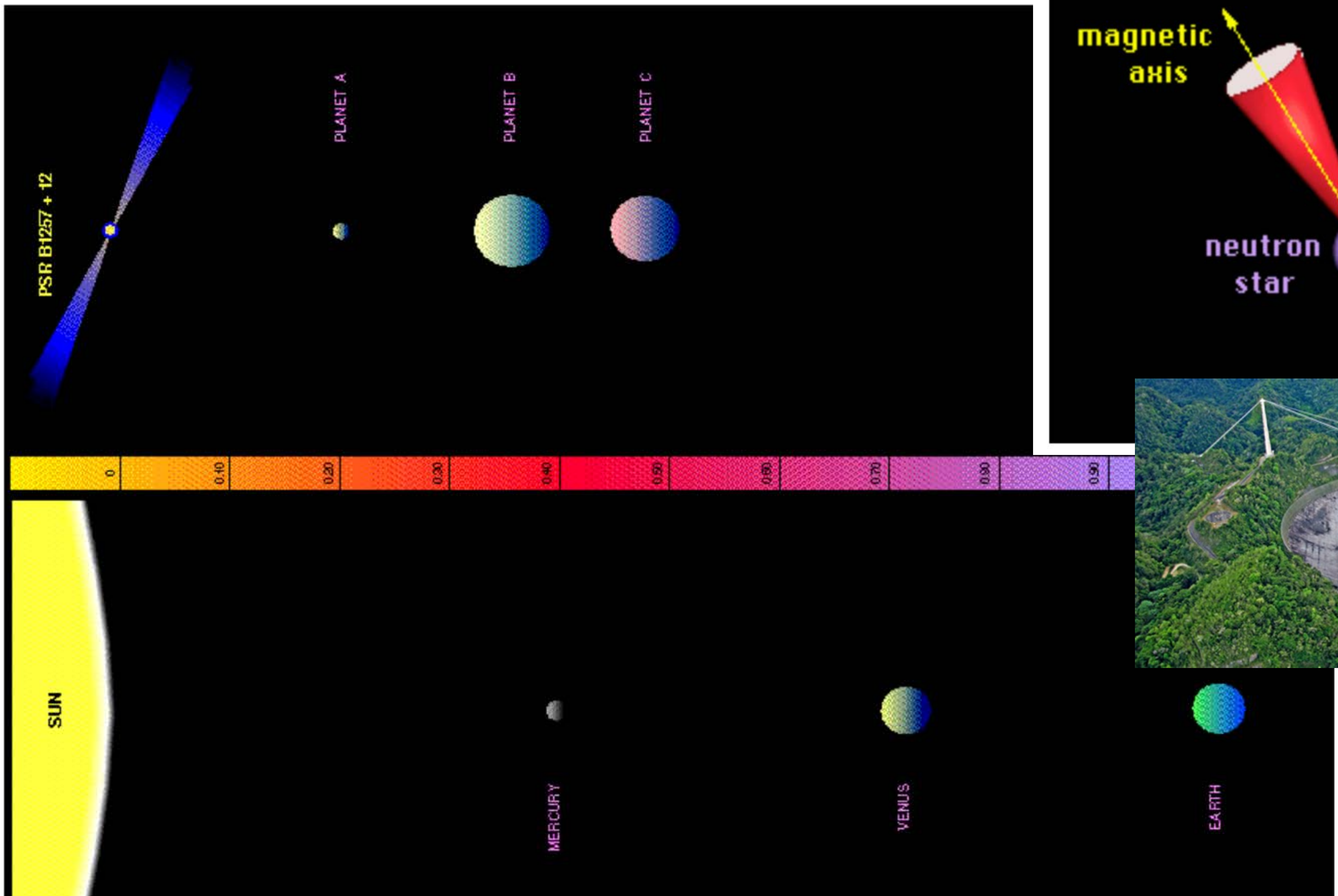
Meanwhile… monitoring Pulsar, because they are cool objects and because they are there

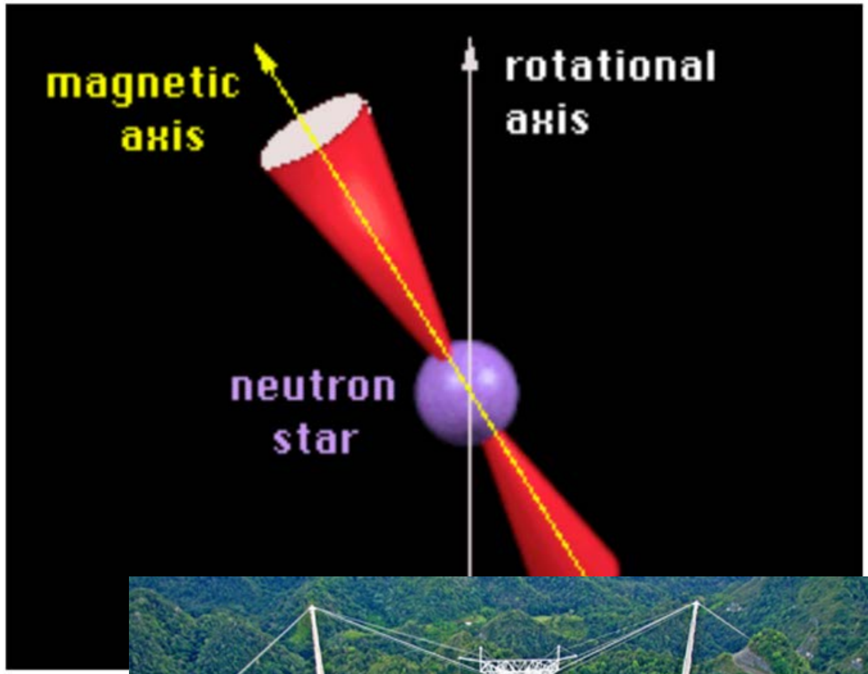
- Drunkard approach…

first planets in 1992 !

Planets around Pulsars in 2012.

PSR 1257+12





Ok, I need 11 years to get a Jupiter mass planet, but I am going to test the stability of my instrument and do repeated observations…

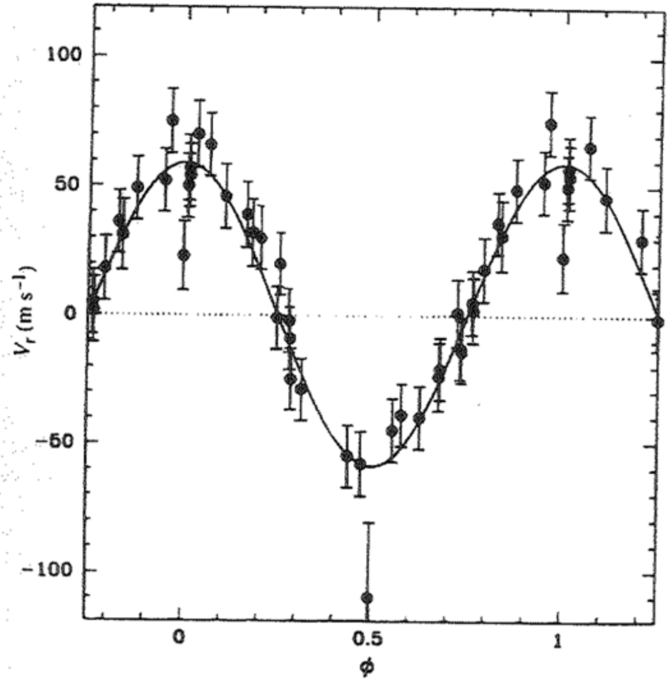
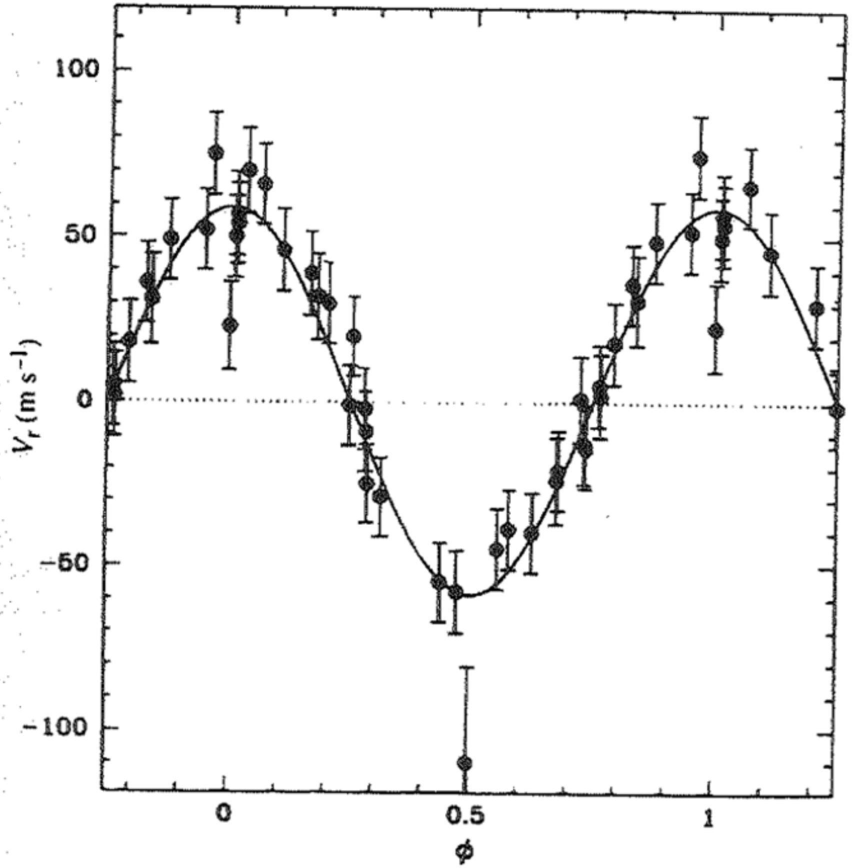


Fig. 1.8 The velocity curve of the star 51 Pegasi, measured by the team led by M. Mayor at the Haute Provence Observatory (After Mayor & Queloz, 1995)

- Drunkard approach… first planet orbiting a star in 1995, P= 4 days ! (Mayor & Queloz)

- Marcy & Butler woke up after 51 Peg, confirmed it, and announced 2 other planets within a month. Data were sleeping on their computers… waiting for long periods.

51 Pegasi, hot Jupiter orbiting a star



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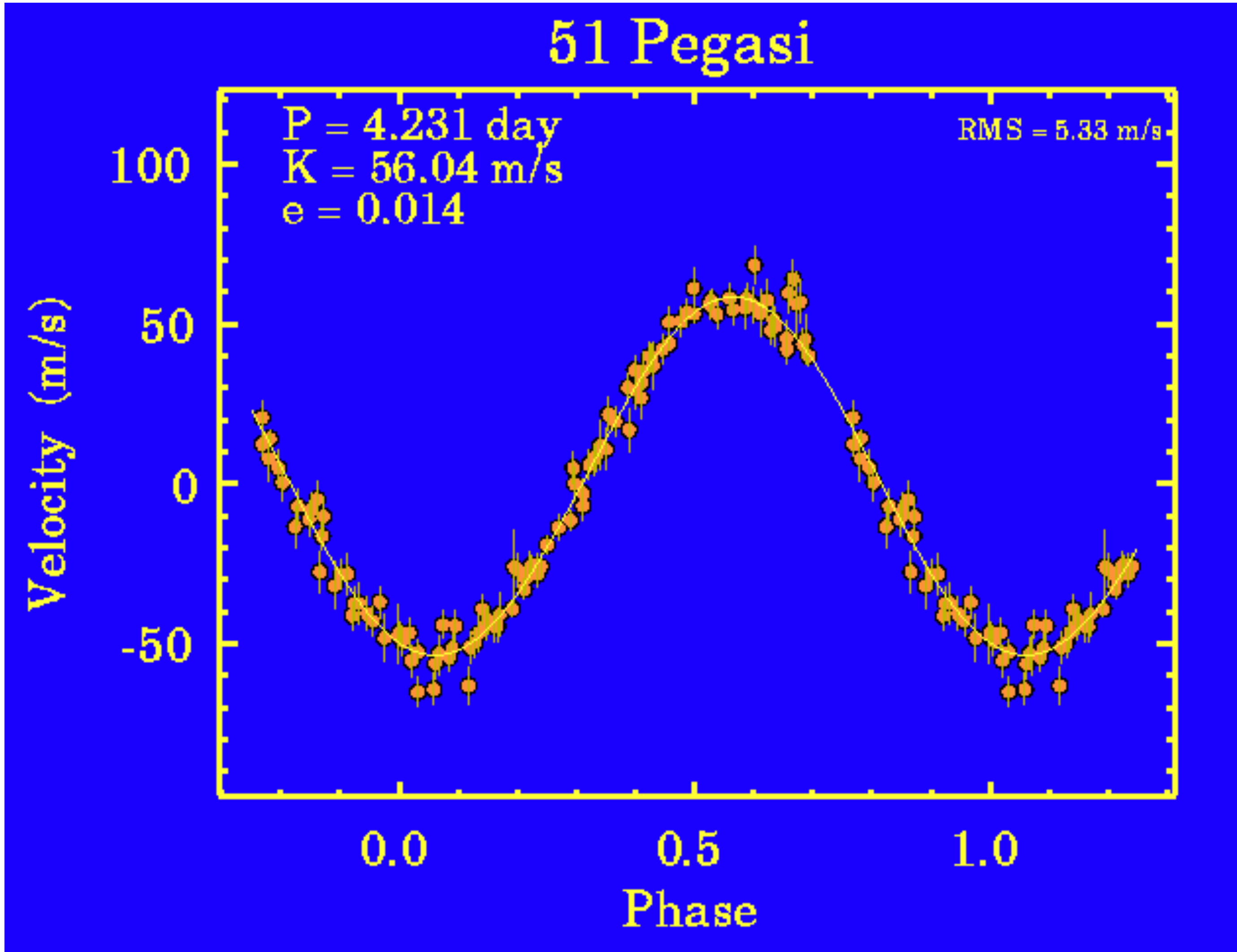
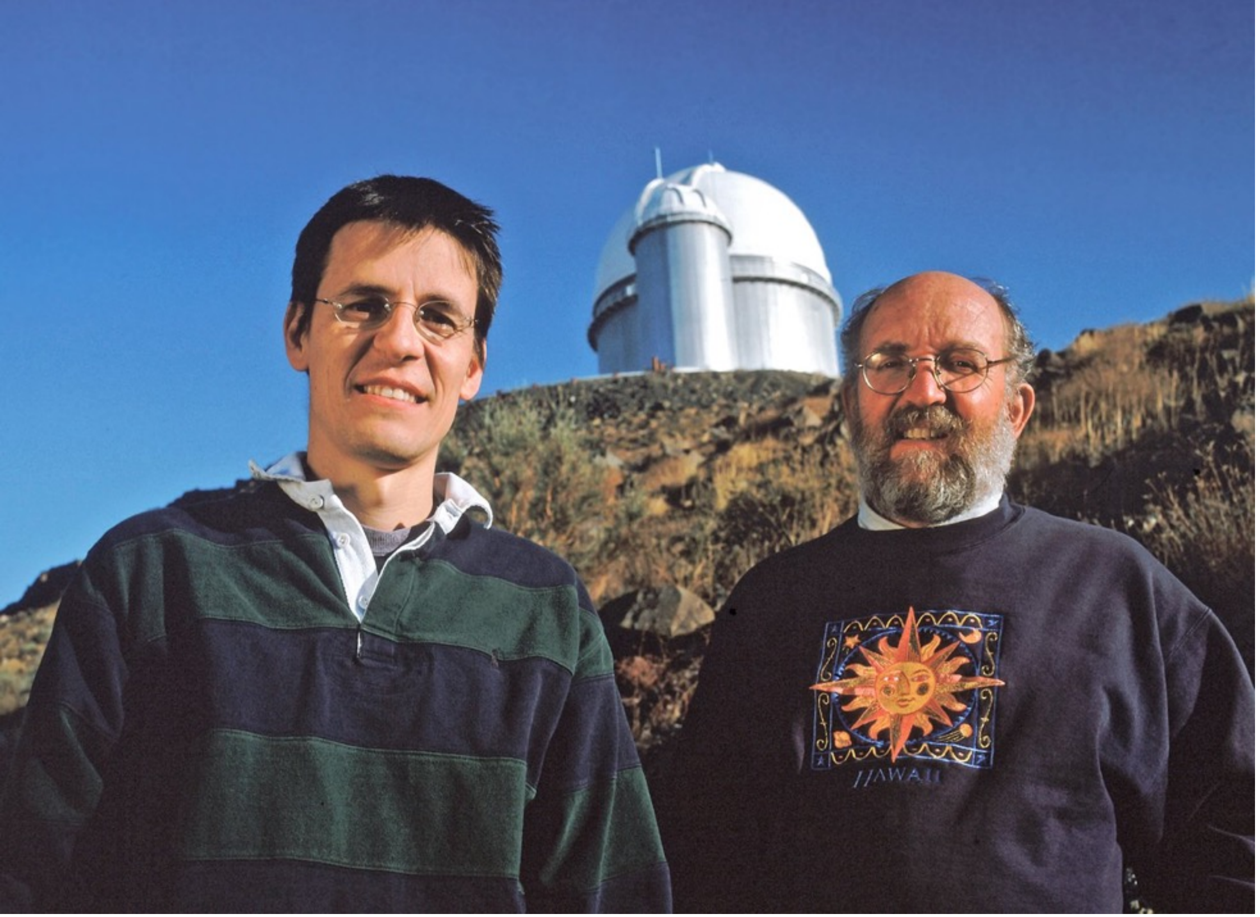
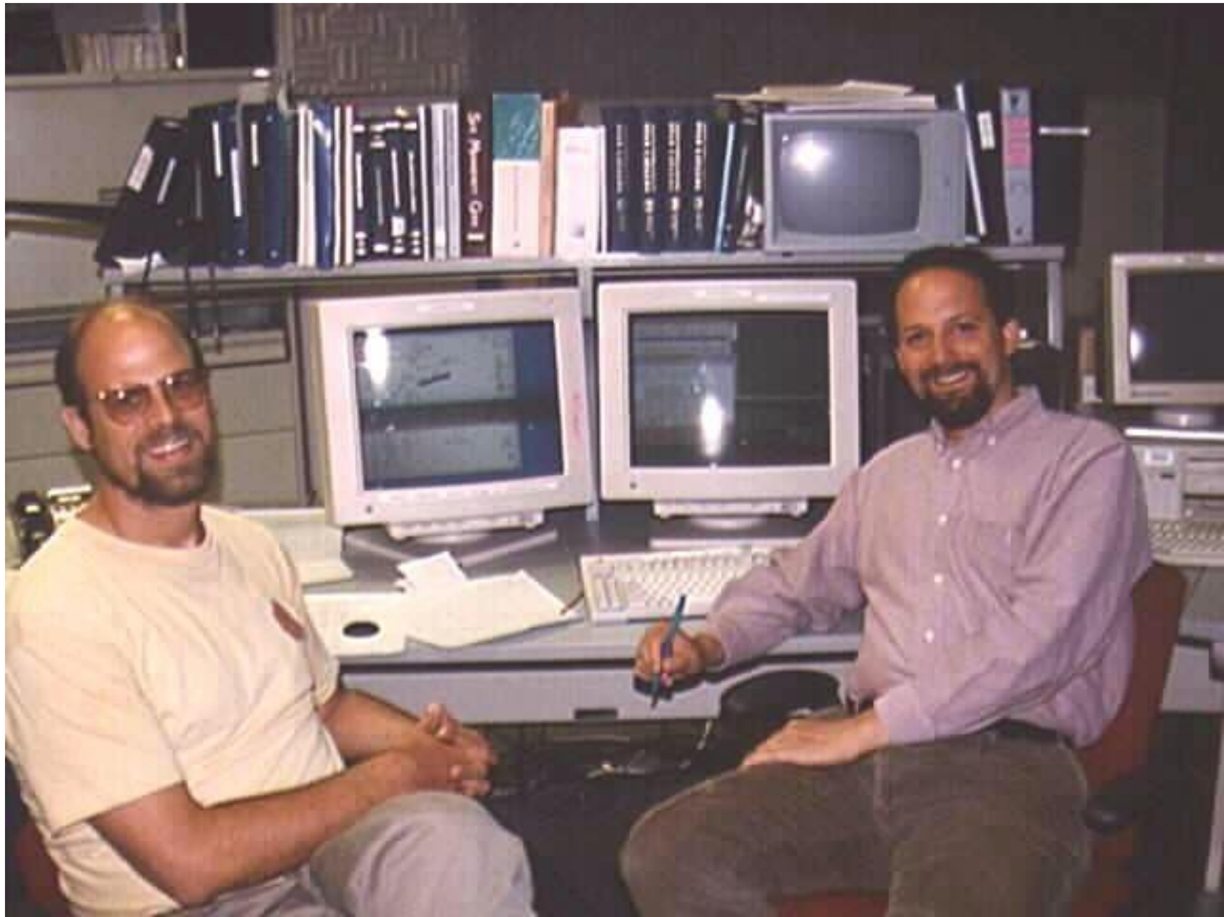




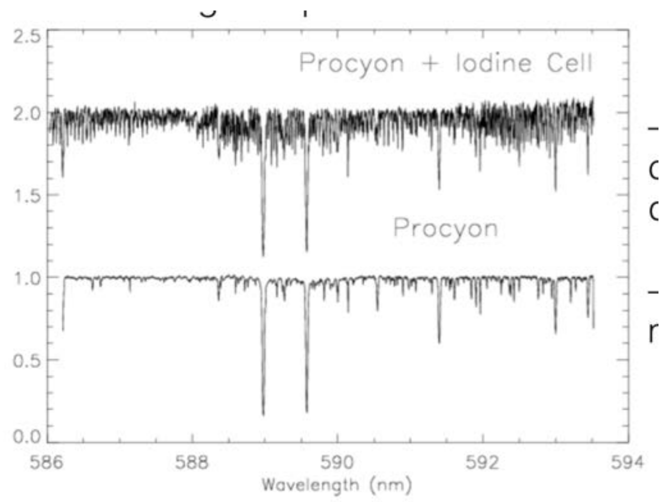
Mayo & Queloz, Swiss

Marcy & Butler, USA



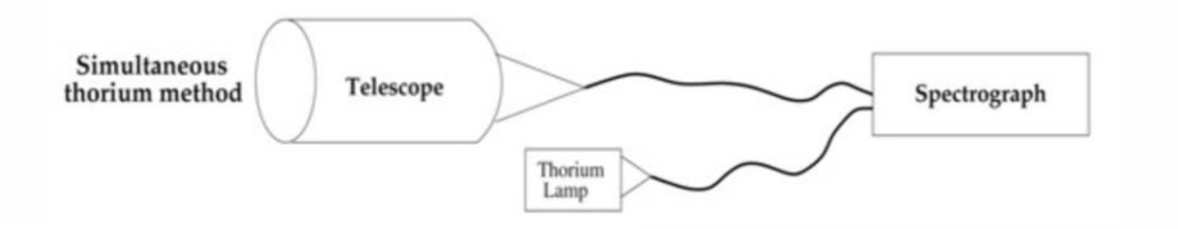
Iodine cell approach (Marcy/Butler)

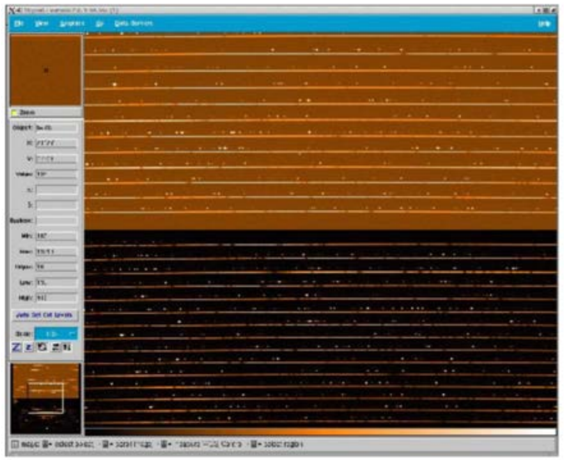
- Superimposing the radial velocity reference on the observed spectra



Down to 3 ms-1, and lot of flux lost

Simultaneous Thorium calibration (Mayor et al.)





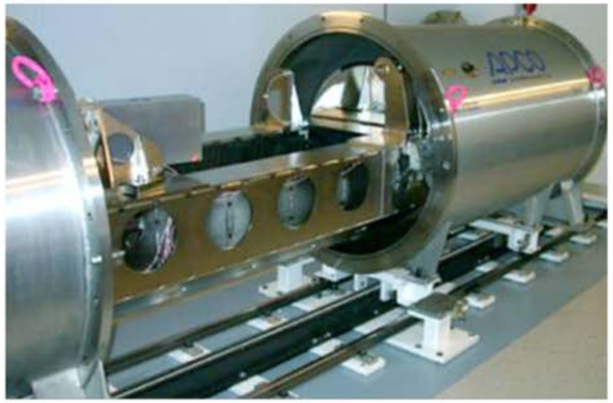
Down to 1 ms-1, and below

HARPS, the best of the best spectrograph

1ms^{-1} routinely, and even better…

Grand father of ESPRESSO (VLT), 10 cms^{-1}

Codex (ELT) 2 cms^{-1}



➔ **Temperature and pressure** in the spectrograph must be regulated very precisely.
1m/s = 0.01K = 0.01 mbar

➔ **Mechanical stability**: flexures can lead to RV drifts > 10m/s

➔ **Stability of the illumination** of the spectrograph' slit: internal calibration or use of optical fibers that minimize the illumination effects

➔ **Wavelength calibration**: Iodine cell, Thorium-Argon lamp, laser comb, Fabry-Perot

➔ **Homogeneity and electronical performances of the detector**: ultra-high quality + very thorough calibration are required

➔ **Avoiding the spectral areas rich in telluric lines** (especially in the red and IR) that can be variable

➔ **Minimizing contamination** by the light of the **Moon**

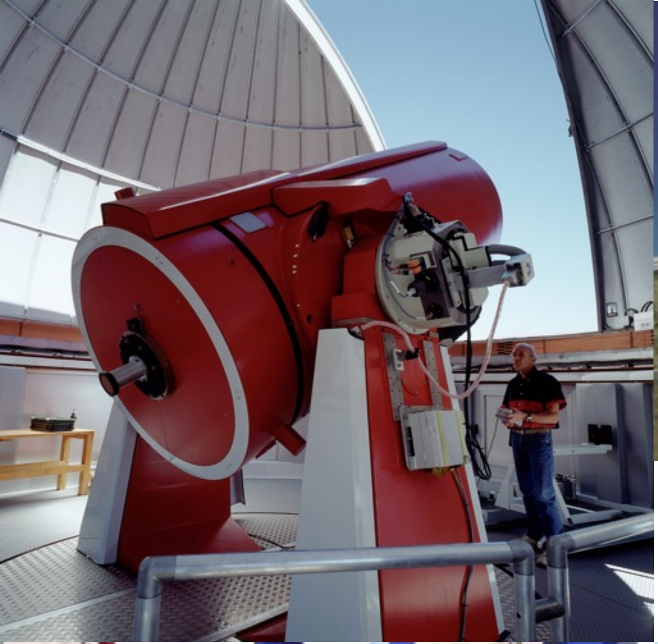
Stellar noises

Oscillations (p-modes) : star having a convective envelope. Period of a few minutes, increases if stellar density decreases. Amplitude of a few m/s for each mode.
Solution: averaging with exposures of at least 15 min.

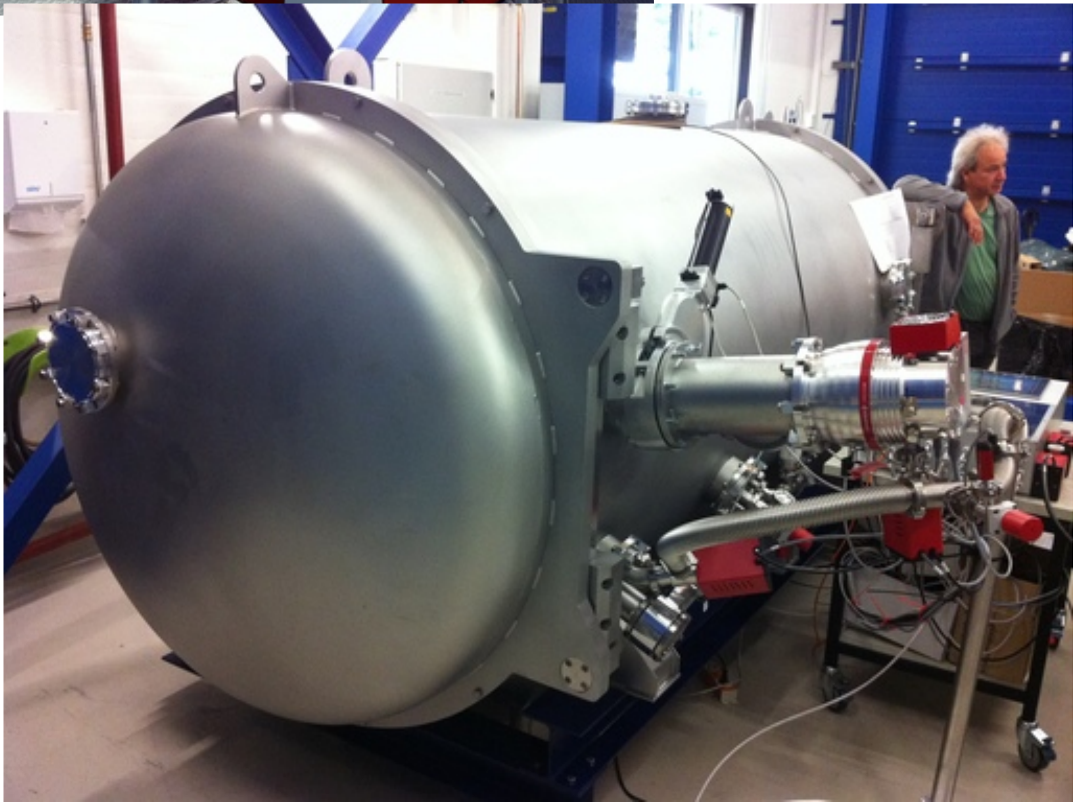
Granulation: stars with convective envelope. Amplitude integrated on the stellar disk of the order of m/s. Characteristic timescale ~ 10 min, or more (meso and super-granulation).
Solution: several exposures per night.

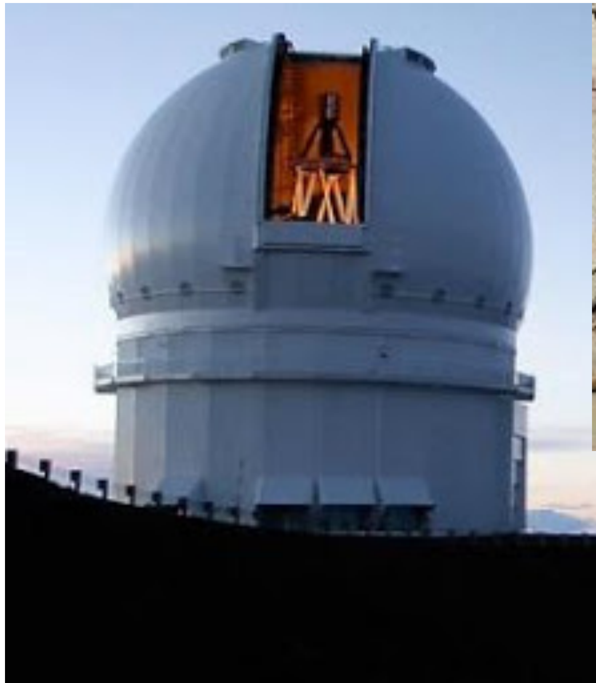
Magnetic activity: rotating spots on the photosphere. Amplitude decreases and period increases with age. Amplitude can exceed 100m/s for a young star.
Solution: targeting old stars– observing in the IR – modeling the effect of spots using activity indicators, simultaneous time-series photometry, and/or a priori knowledge of the rotation of the star - strategy adapted to the star to average at best the effects of the activity

Magnetic cycles: 11 years for the Sun. Not only the RV precision varies with the magnetic phase, but possibly the RV itself too.
Solution: targeting old stars?




MINERVA
AUSTRALIS





Native Apps

Executables (64-bit and 32-bit) for Windows and (64-bit) for Macintosh computers are available for all of our older projects (NAAP, ClassAction, & Ranking Tasks). The appropriate package for your (or your student's) computer system must be downloaded and installed locally. Note that these are actual applications that run in your native OS and their longevity depends only upon your OS. There is no similar viable solution for Chromebooks.

https://astro.unl.edu/nativeapps/

Note that every simulation available in the past on this site is contained in either the ClassAction or NAAP Labs native app. (In ClassAction look under the Animations tab.) The following guide to content is provided to assist you in navigating. Student guides and demonstration guides can be found on the NAAP Resources page.

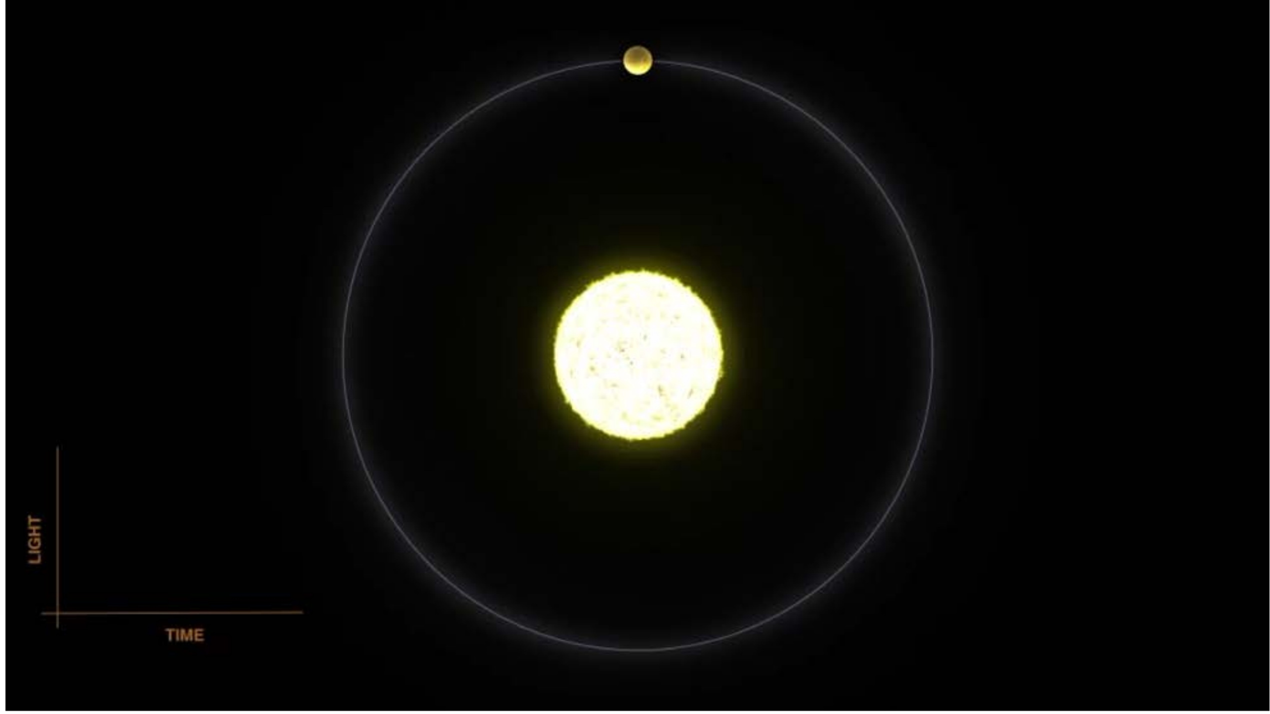
Windows Executables (for 64-bit machines, what most people want)

ClassAction - v2.3.msi	97.4 MB	January 30, 2020
NAAP Labs - v1.1.msi	22.4 MB	January 30, 2020
Interactives - v1.1.msi	46.7 MB	January 30, 2020

MacOS Executables

ClassAction - v2.3.pkg	97.1 MB	January 30, 2020
NAAP Labs - v1.1.pkg	22.4 MB	January 30, 2020
Interactives - v1.1.pkg	46.2 MB	January 30, 2020

The transit technique



Only planets closed to ~ 90 deg inclinaison

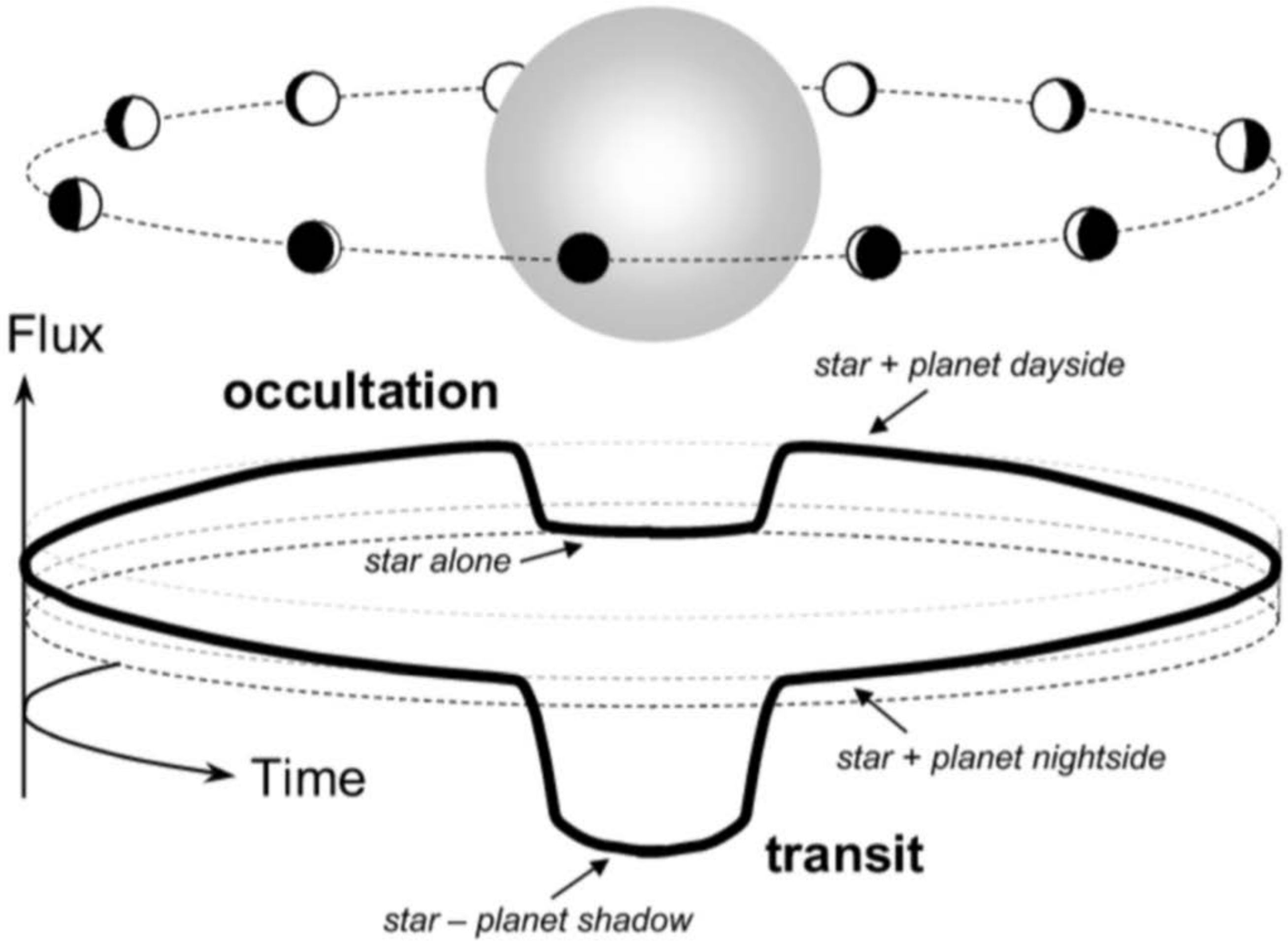
Transit probability $\mathcal{P}_{\mathrm{tr}} = \frac{R_* + R_{\mathrm{p}}}{a\,(1 - e^2)} \simeq R_*/a$

10 % probability for a planet at 0.05 AU around a solar like star

Transit depth $\Delta F/F \simeq R_p^2/R_*^2$

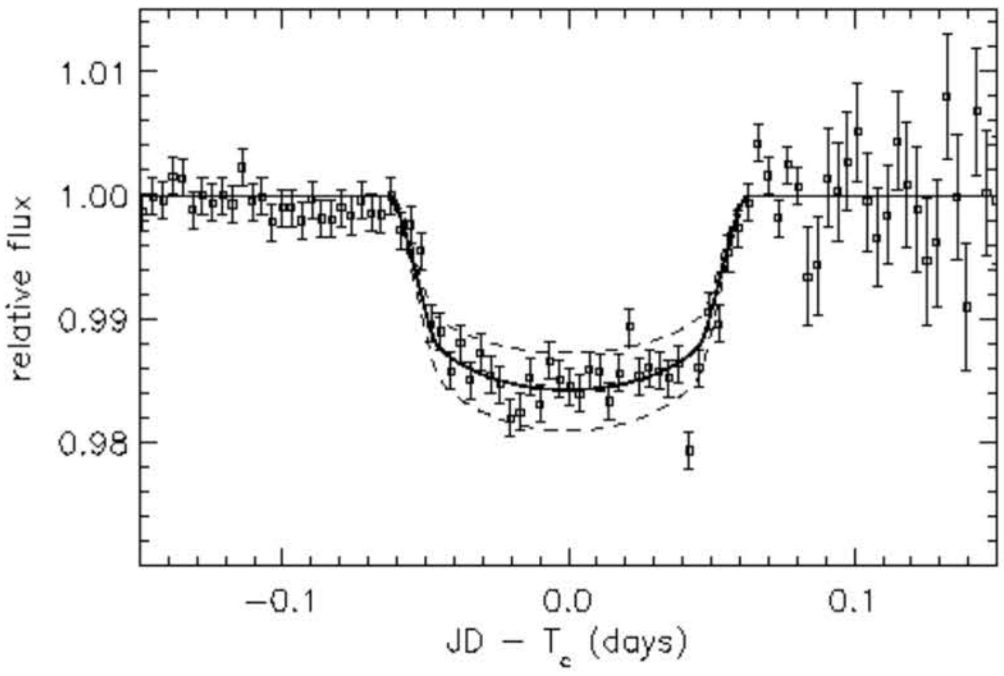
Jupiter : 1 % depth Earth: 0.01 % depth

transit and occultations



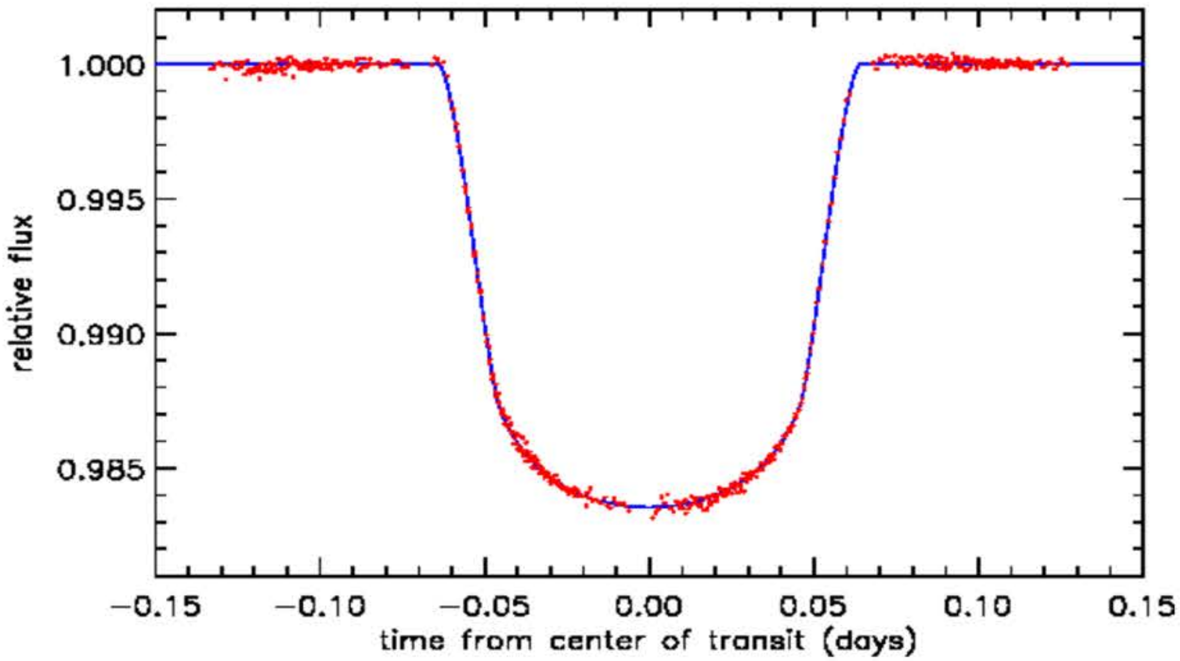
HD209458b transiting hot Jupiter in 1999

Observations du sol



Charbonneau et al. (1999)

Observations spatiale HST



Charbonneau et al. (2000)

Ground-based transit searches – 2002

Transit Search Programmes

	Programme	D (cm)	focal ratio	$\Omega^{0.5}$ (deg)	N_x (kpix)	N_y (kpix)	no. of CCDs	pixel (arcsec)	sky mag	star mag	d (pc)	stars ($x10^3$)	planets /month
1	PASS	2.5	2.0	127.25	2.0	2.0	15	57.75	6.8	9.4	83	18	6.3
2	WASP0	6.4	2.8	8.84	2.0	2.0	1	15.54	9.6	11.8	246	2	0.8
3	ASAS-3	7.1	2.8	11.21	2.0	2.0	2	13.93	9.9	12.0	272	5	1.7
4	RAPTOR	7.0	1.2	55.32	2.0	2.0	8	34.38	7.9	11.1	179	33	11.7
5	TrES	10.0	2.9	10.51	2.0	2.0	3	10.67	10.5	12.7	362	10	3.5
6	XO	11.0	1.8	10.06	1.0	1.0	2	25.00	8.6	11.9	258	3	1.2
7	HATnet	11.1	1.8	19.42	2.0	2.0	6	13.94	9.9	12.5	338	28	9.7
8	SWASP	11.1	1.8	31.71	2.0	2.0	16	13.94	9.9	12.5	338	74	26.0
9	Vulcan	12.0	2.5	7.04	4.0	4.0	1	6.19	11.6	13.4	497	12	4.1
10	RAPTOR-F	14.0	2.8	5.93	2.0	2.0	2	7.37	11.3	13.4	498	8	2.9
11	BEST	19.5	2.7	3.01	2.0	2.0	1	5.29	12.0	14.2	668	5	1.8
12	Vulcan-S	20.3	1.5	6.94	4.0	4.0	1	6.10	11.7	14.1	642	24	8.5
13	SSO/APT	50.0	1.0	5.05	2.9	3.1	2	4.20	12.5	15.5	1103	65	22.8
14	RATS	67.0	3.0	1.31	2.0	2.0	1	2.30	13.8	16.4	1548	12	4.2
15	TeMPEST	76.0	3.0	0.77	2.0	2.0	1	1.35	15.0	17.1	1944	8	2.9
16	EXPLORE-OC	101.6	7.0	0.32	2.0	3.3	1	0.44	17.1	18.4	2881	5	1.6
17	PISCES	120.0	7.7	0.38	2.0	2.0	4	0.33	17.1	18.6	3045	8	2.7
18	ASP	130.0	13.5	0.17	2.0	2.0	1	0.30	17.1	18.7	3125	2	0.6
19	OGLE-III	130.0	9.2	0.59	2.0	4.0	8	0.26	17.1	18.7	3125	20	7.1
20	STEPSS	240.0	0.0	0.41	4.0	2.0	8	0.18	17.1	19.5	3757	17	5.9
21	INT	250.0	3.0	0.60	2.0	4.0	4	0.37	17.1	19.5	3800	37	13.1
22	ONC	254.0	3.3	0.53	2.0	4.0	4	0.33	17.1	19.5	3817	30	10.5
23	EXPLORE-N	360.0	4.2	0.57	2.0	4.0	12	0.21	17.1	19.9	4196	46	16.2
24	EXPLORE-S	400.0	2.9	0.61	2.0	4.0	8	0.27	17.1	20.0	4313	58	20.1

Ground-based transit searches – 2002

Transit Search Programmes

	Programme	D (cm)	focal ratio	$\Omega^{0.5}$ (deg)	N_x (kpix)	N_y (kpix)	no. of CCDs	pixel (arcsec)	sky mag	star mag	d (pc)	stars ($x10^3$)	planets /month
~~1~~	~~PASS~~	2.5	2.0	127.25	2.0	2.0	15	57.75	6.8	9.4	83	18	6.3
~~2~~	~~WASP0~~	6.4	2.8	8.84	2.0	2.0	1	15.54	9.6	11.8	246	2	0.8
• 3	ASAS-3	7.1	2.8	11.21	2.0	2.0	2	13.93	9.9	12.0	272	5	1.7
• 4	RAPTOR	7.0	1.2	55.32	2.0	2.0	8	34.38	7.9	11.1	179	33	11.7
~~5~~	~~TEP~~	10.0	2.9	10.51	2.0	2.0	3	10.67	10.5	12.7	362	10	3.5
6	XO	11.0	1.8	10.06	1.0	1.0	2	25.00	8.6	11.9	258	3	1.2
7	HATnet	11.1	1.8	19.42	2.0	2.0	6	13.94	9.9	12.5	338	28	9.7
8	SWASP	11.1	1.8	31.71	2.0	2.0	16	13.94	9.9	12.5	338	74	26.0
~~9~~	~~Vulcan~~	12.0	2.5	7.04	4.0	4.0	1	6.19	11.6	13.4	497	12	4.1
• 10	RAPTOR-F	14.0	2.8	5.93	2.0	2.0	2	7.37	11.3	13.4	498	8	2.9
• 11	BEST	19.5	2.7	3.01	2.0	2.0	1	5.29	12.0	14.2	668	5	1.8
~~12~~	~~Vulcan-S~~	20.3	1.5	6.94	4.0	4.0	1	6.10	11.7	14.1	642	24	8.5
~~13~~	~~SSO/APT~~	50.0	1.0	5.05	2.9	3.1	2	4.20	12.5	15.5	1103	65	22.8
~~14~~	~~RATS~~	67.0	3.0	1.31	2.0	2.0	1	2.30	13.8	16.4	1548	12	4.2
~~15~~	~~TeMPEST~~	76.0	3.0	0.77	2.0	2.0	1	1.35	15.0	17.1	1944	8	2.9
~~16~~	~~EXPLORE-OC~~	101.6	7.0	0.32	2.0	3.3	1	0.44	17.1	18.4	2881	5	1.6
~~17~~	~~PISCES~~	120.0	7.7	0.38	2.0	2.0	4	0.33	17.1	18.6	3045	8	2.7
~~18~~	~~ASP~~	130.0	13.5	0.17	2.0	2.0	1	0.30	17.1	18.7	3125	2	0.6
19	OGLE-III	130.0	9.2	0.59	2.0	4.0	8	0.26	17.1	18.7	3125	20	7.1
~~20~~	~~STEPSS~~	240.0	0.0	0.41	4.0	2.0	8	0.18	17.1	19.5	3757	17	5.9
~~21~~	~~INT~~	250.0	3.0	0.60	2.0	4.0	4	0.37	17.1	19.5	3800	37	13.1
~~22~~	~~ONC~~	254.0	3.3	0.53	2.0	4.0	4	0.33	17.1	19.5	3817	30	10.5
~~23~~	~~EXPLORE-N~~	360.0	4.2	0.57	2.0	4.0	12	0.21	17.1	19.9	4196	46	16.2
~~24~~	~~EXPLORE-S~~	400.0	2.9	0.61	2.0	4.0	8	0.27	17.1	20.0	4313	58	20.1

Ground-based transit searches – 2002

Transit Search Programmes

Programme		D (cm)	focal ratio	$\Omega^{0.5}$ (deg)	N_x (kpix)	N_y (kpix)	no. of CCDs	pixel (arcsec)	sky mag	star mag	d (pc)	stars ($x10^3$)	planets /month
[illegible]	[illegible]	2.5	2.0	127.25	2.0	2.0	15	57.75	6.8	9.4	83	18	6.3
[illegible]	[illegible]	6.4	2.8	8.84	2.0	2.0	1	15.54	9.6	11.8	246	2	0.8
[illegible]	[illegible]	7.1	2.8	11.21	2.0	2.0	2	13.93	9.9	12.0	272	5	1.7
[illegible]	[illegible]	7.0	1.2	55.32	2.0	2.0	8	34.38	7.9	11.1	179	33	11.7
[illegible]	[illegible]	10.0	2.9	10.51	2.0	2.0	3	10.67	10.5	12.7	362	10	3.5
6	XO	11.0	1.8	10.06	1.0	1.0	2	25.00	8.6	11.9	258	3	1.2
7	HATnet	11.1	1.8	19.42	2.0	2.0	6	13.94	9.9	12.5	338	28	9.7
8	SWASP	11.1	1.8	31.71	2.0	2.0	16	13.94	9.9	12.5	338	74	26.0
[illegible]	[illegible]	12.0	2.5	7.04	4.0	4.0	1	6.19	11.6	13.4	497	12	4.1
[illegible]	[illegible]	14.0	2.8	5.93	2.0	2.0	2	7.37	11.3	13.4	498	8	2.9
• 11	BEST	19.5	2.7	3.01	2.0	2.0	1	5.29	12.0	14.2	668	5	1.8
[illegible]	[illegible]	20.3	1.5	6.94	4.0	4.0	1	6.10	11.7	14.1	642	24	8.5
[illegible]	[illegible]	50.0	1.0	5.05	2.9	3.1	2	4.20	12.5	15.5	1103	65	22.8
[illegible]	[illegible]	[illegible]	[illegible]	1.31	2.0	2.0	1	2.30	13.8	16.4	1548	12	4.2
[illegible]	[illegible]	76.0	3.0	0.77	2.0	2.0	1	1.35	15.0	17.1	1944	8	2.9
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.0	3.3	1	0.44	17.1	18.4	2881	5	1.6
[illegible]	[illegible]	120.0	7.7	0.38	2.0	2.0	4	0.33	17.1	18.6	3045	8	2.7
[illegible]	[illegible]	130.0	13.5	0.17	2.0	2.0	1	0.30	17.1	18.7	3125	2	0.6
[illegible]	[illegible]	130.0	9.2	0.59	2.0	4.0	8	0.26	17.1	18.7	3125	20	7.1
[illegible]	[illegible]	240.0	0.0	0.41	4.0	2.0	8	0.18	17.1	19.5	3757	17	5.9
[illegible]	[illegible]	[illegible]	[illegible]	0.60	2.0	4.0	4	0.37	17.1	19.5	3800	37	13.1
[illegible]	[illegible]	[illegible]	3.3	0.53	[illegible]	[illegible]	4	0.33	17.1	19.5	3817	30	10.5
[illegible]	[illegible]	360.0	4.2	0.57	2.0	4.0	12	0.21	17.1	19.9	4196	46	16.2
[illegible]	[illegible]	400.0	2.9	0.61	2.0	4.0	8	0.27	17.1	20.0	4313	58	20.1

QATAR
KELT
Mearth
HATSouth
CSTAR, ASTAR, ASTEP,
Solaris, PTF, APACHE, Dunlap

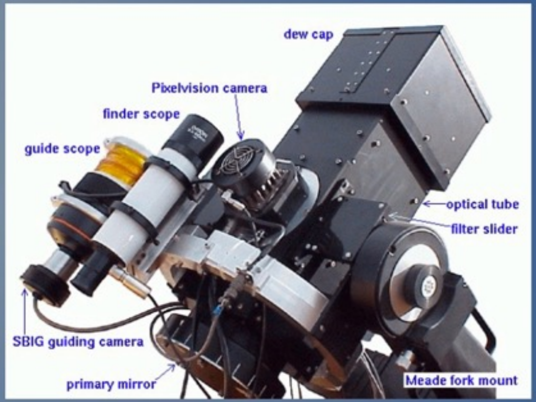
The previous slides shows how being overoptimistic could lead to severe disillusion

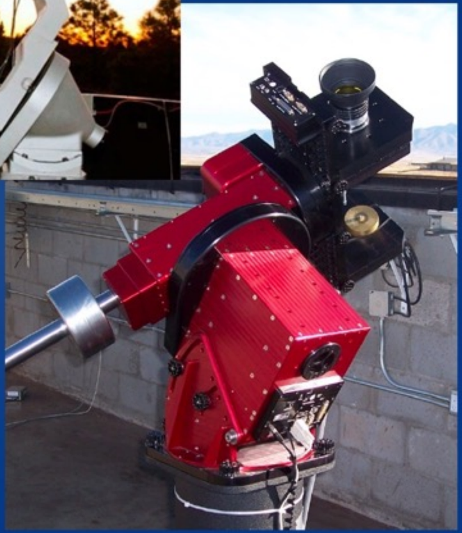
Handwaving calculations with naive assumptions such as:

- CCD camera are perfect
- There is no differential refraction
- Ignoring correlated noise in the data
- Scintillation noise

It is not easy as one might think… but now, it is working fine !

Ground-based transit searches



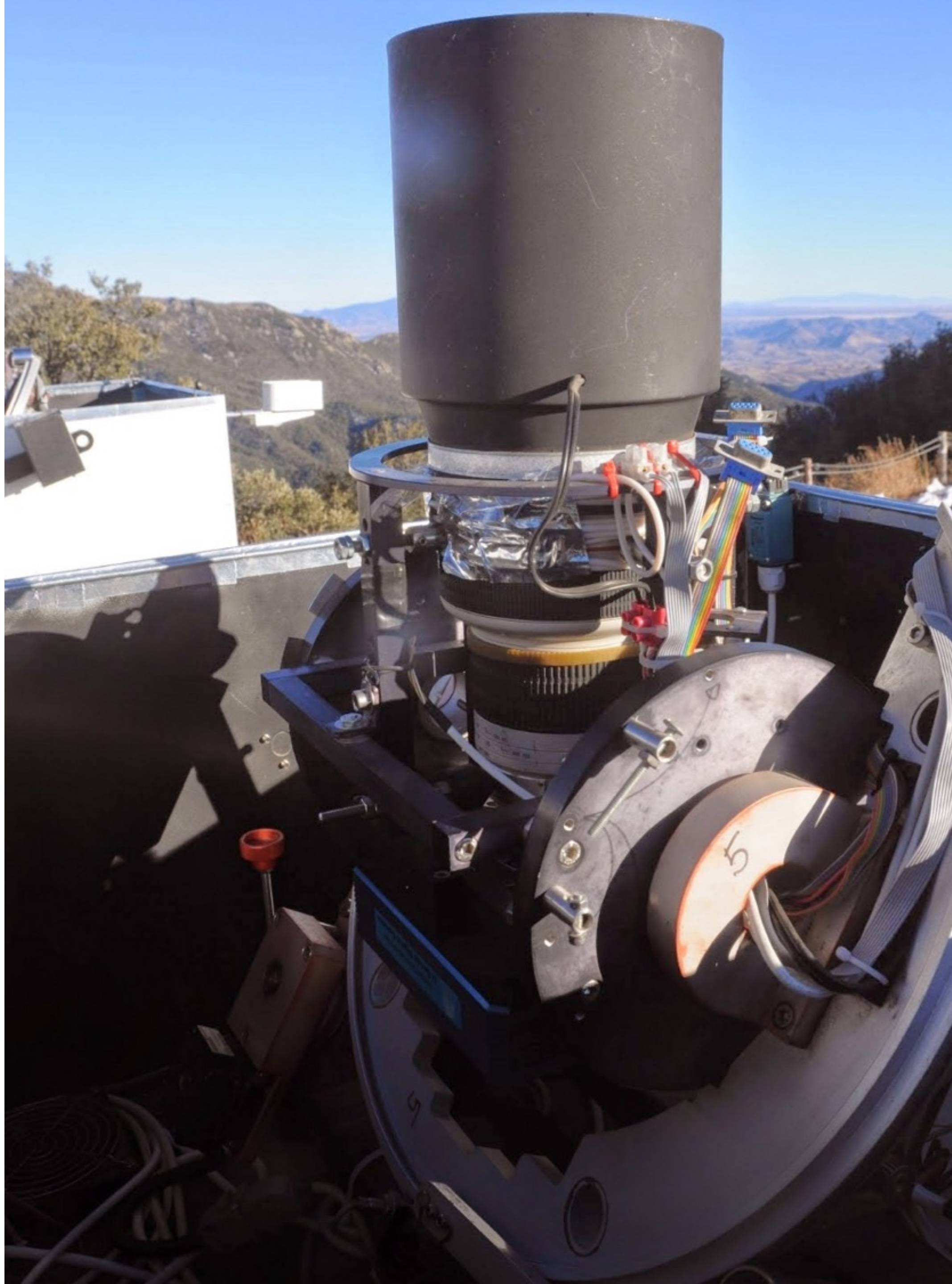


HATNet

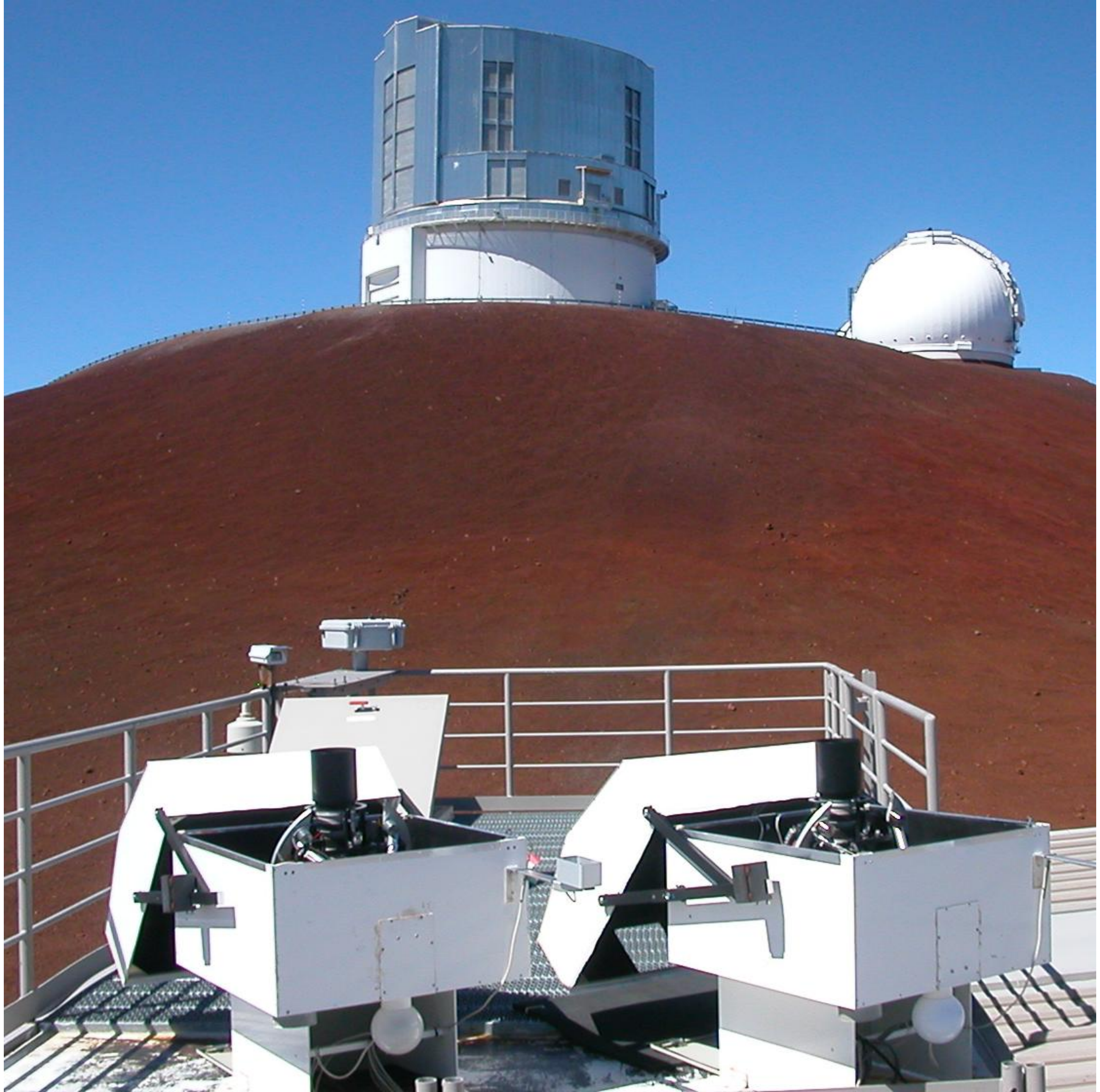
- 200 mm lens, F/1.8
- CCD camera
- Custom mount

- Gaspar Bakos et al.

- 70 planets (Hat North)
- 73 planets (Hat South)

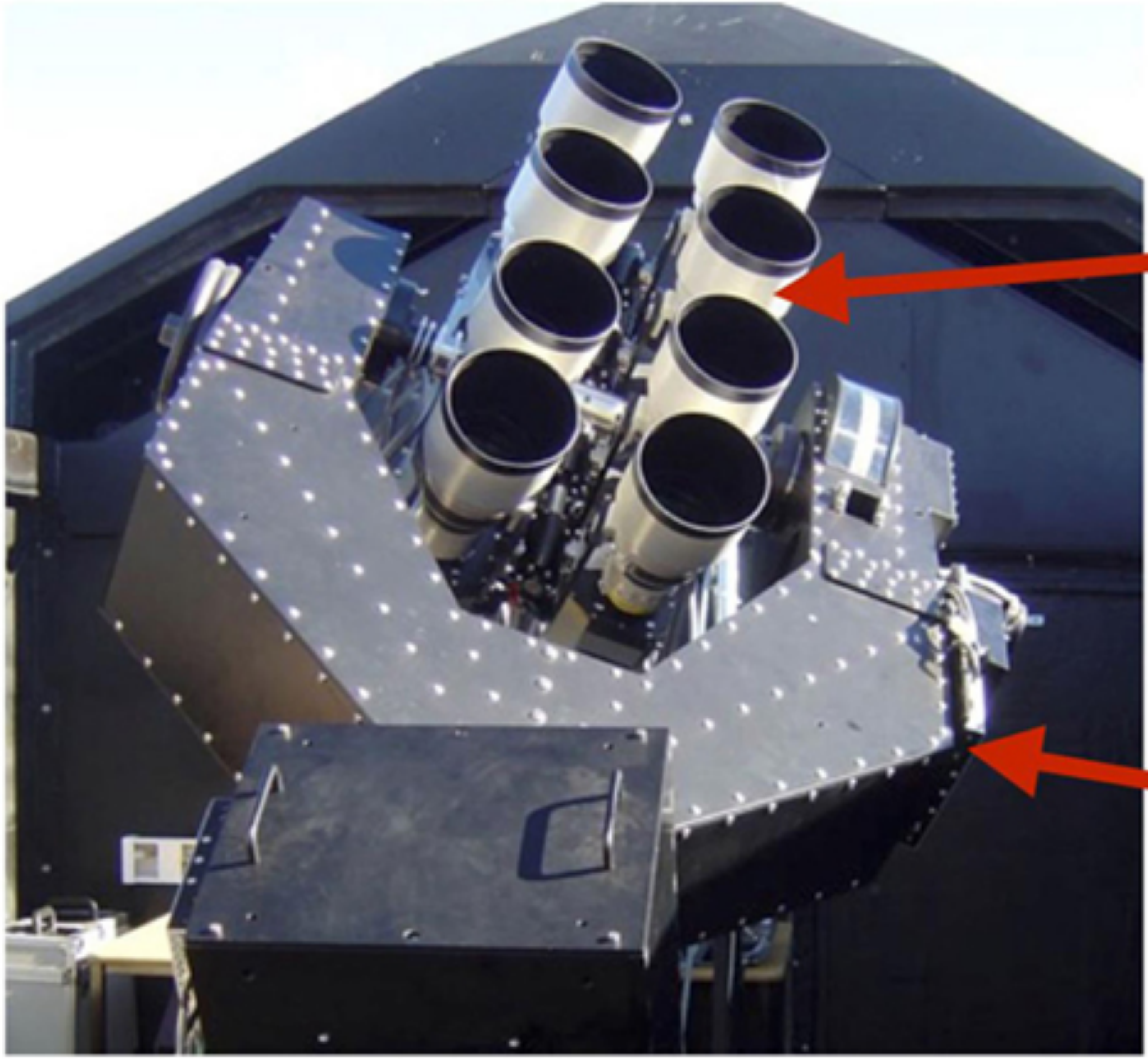



HAT5
HAT 10



The SuperWASP Camera array

Exoplanets to date : 192 since 2000



Eight lenses look at different parts of the sky

The big 'U' shape moves during the night to follow the stars

NGTS at Paranal

- 12 telescopes

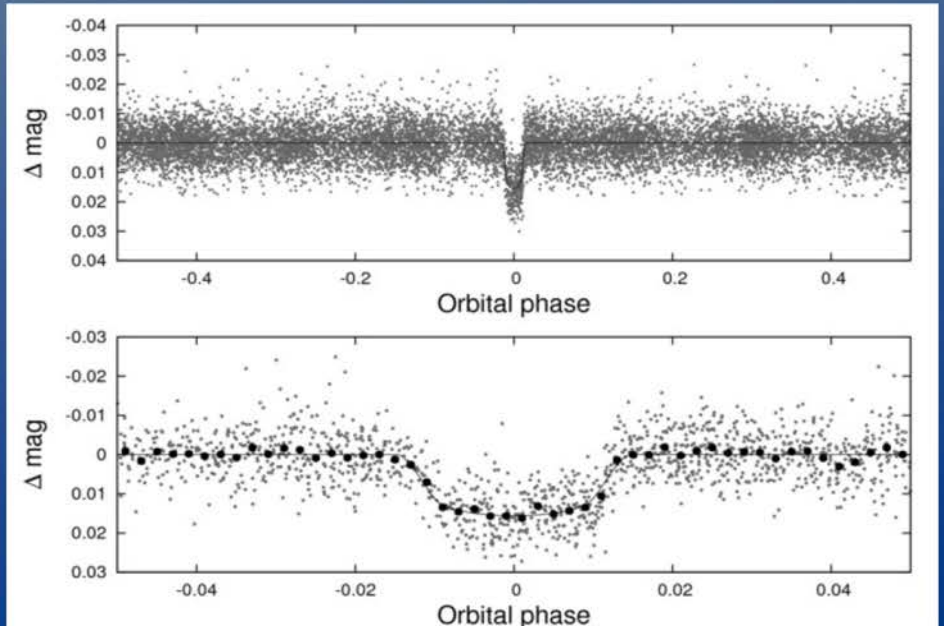
20 cm aperture, f/2.8

Andor cameras

Fov 3 x 3 deg each

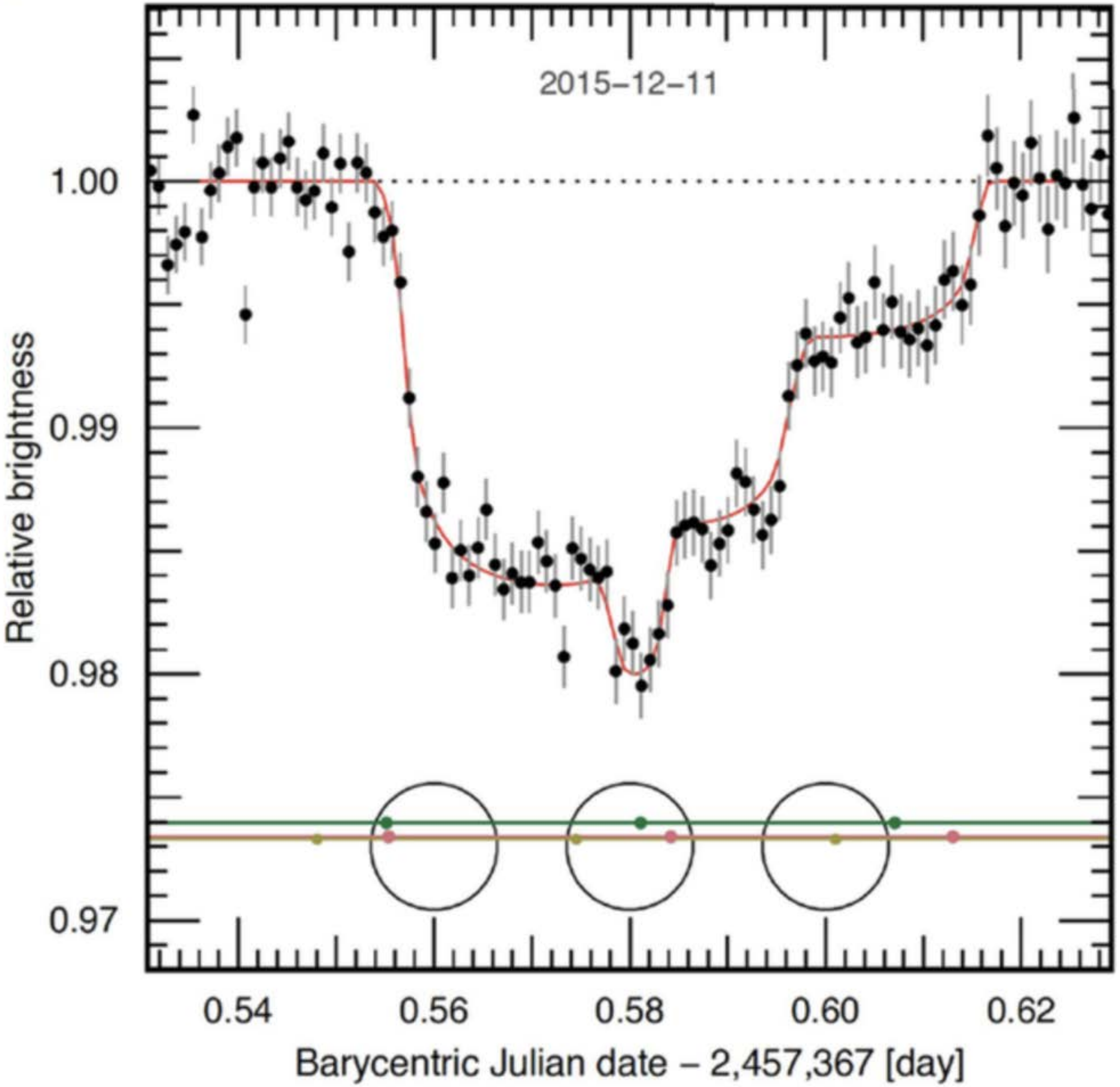
100 sq deg

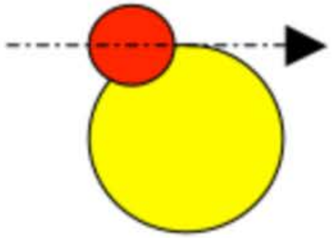
Ground-based surveys – HATSouth



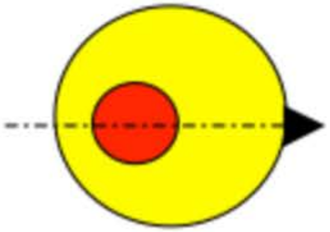
- 3 stations: LCO (Chile), HESS (Namibia), SSO (Australia).
- Operational: 2010 – present.
- 6 x (4 x 0.2m) telescopes, each with 8° x 8° FOV, 8K x 8K pix FI CCD, sloan r filter.
- "Home-made" dome, mount, electronics, software.
- Off-the-shelf (Apogee) CCD, (Takahashi) optics, filters.
- 1 planet (HATS-1b) with P=3.44d.
- V < 14.5 targets. K and M dwarfs. Follow-up with extended team using multiple resources.
- Sensitive to long period and shallow transits.
- Princeton, MPIA, ANU, PUC collaboration.
- See Bakos et al. 2012, Penev et al 2012, astroph

triple transit of TRAPPIST-1c, 1e, and 1f.

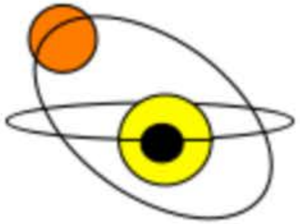




Grazing binary



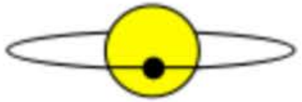
Small star (same radius as Jupiter planet)



Binaries on excentric orbit

Eclipsing binary with bright blend

Variable star, correlated noise, alien spaceship, other ?

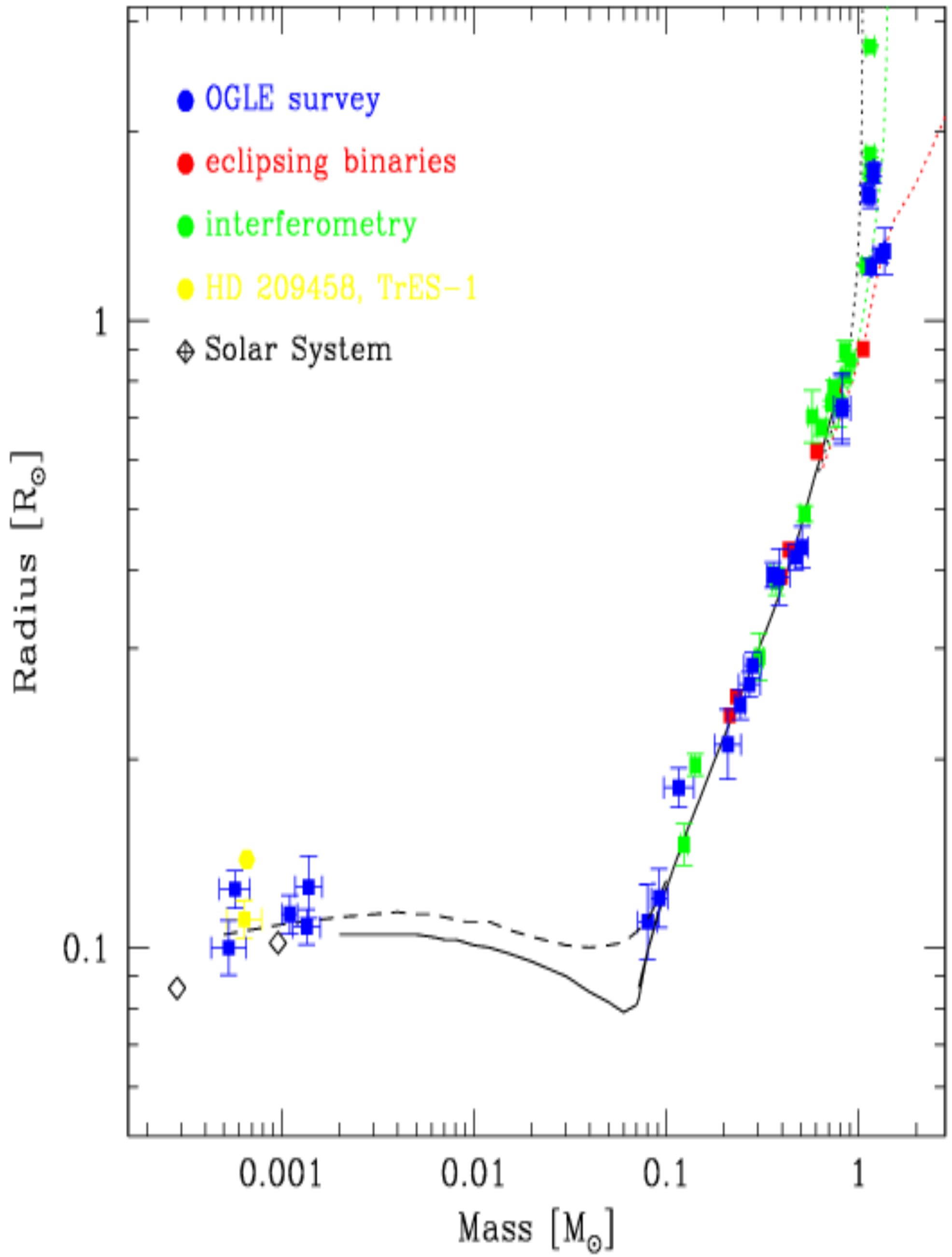


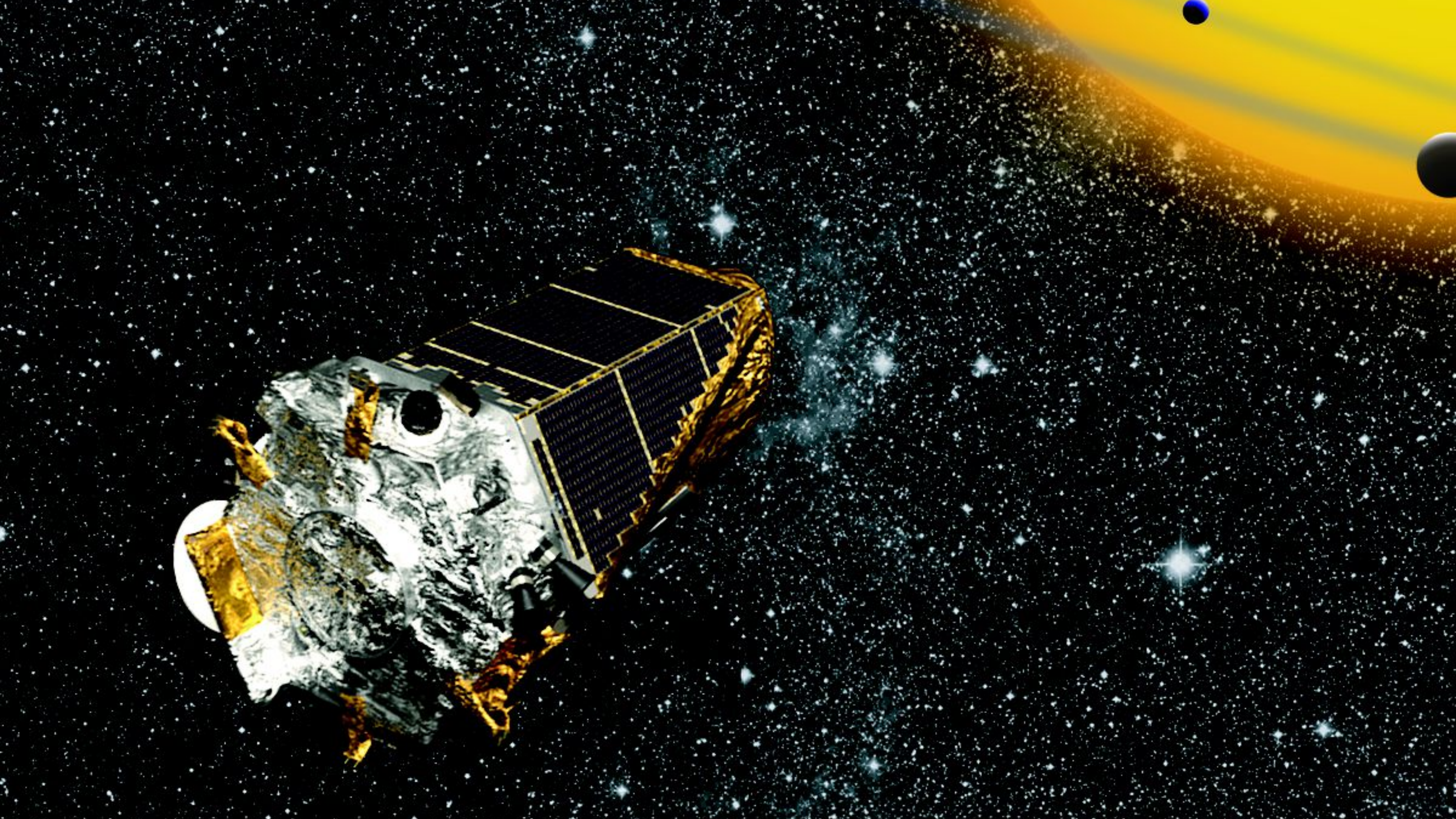
Genuine transiting planet

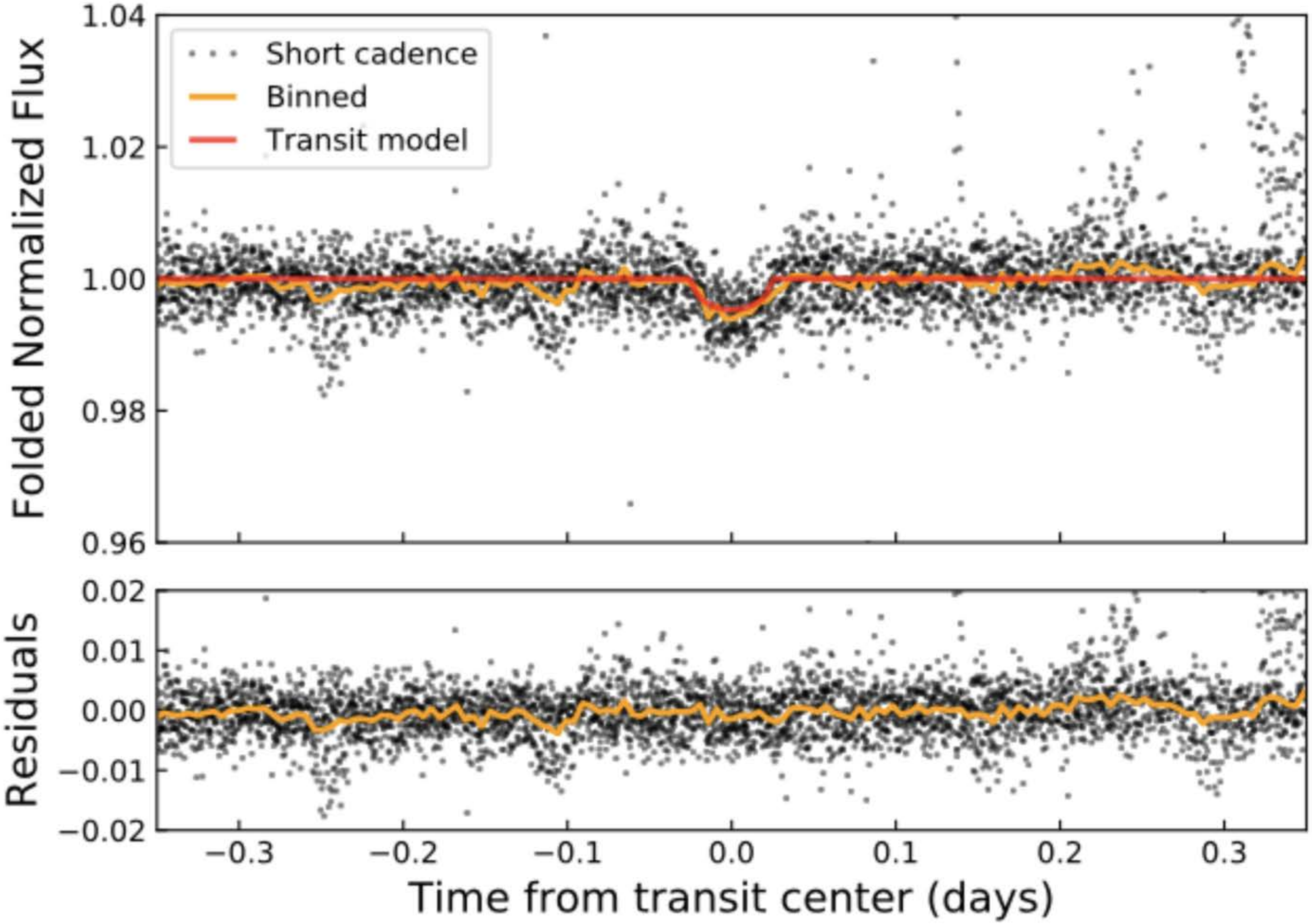
Mass-radius relation

A 0.1 Mo star and a Jupiter can have similar radius

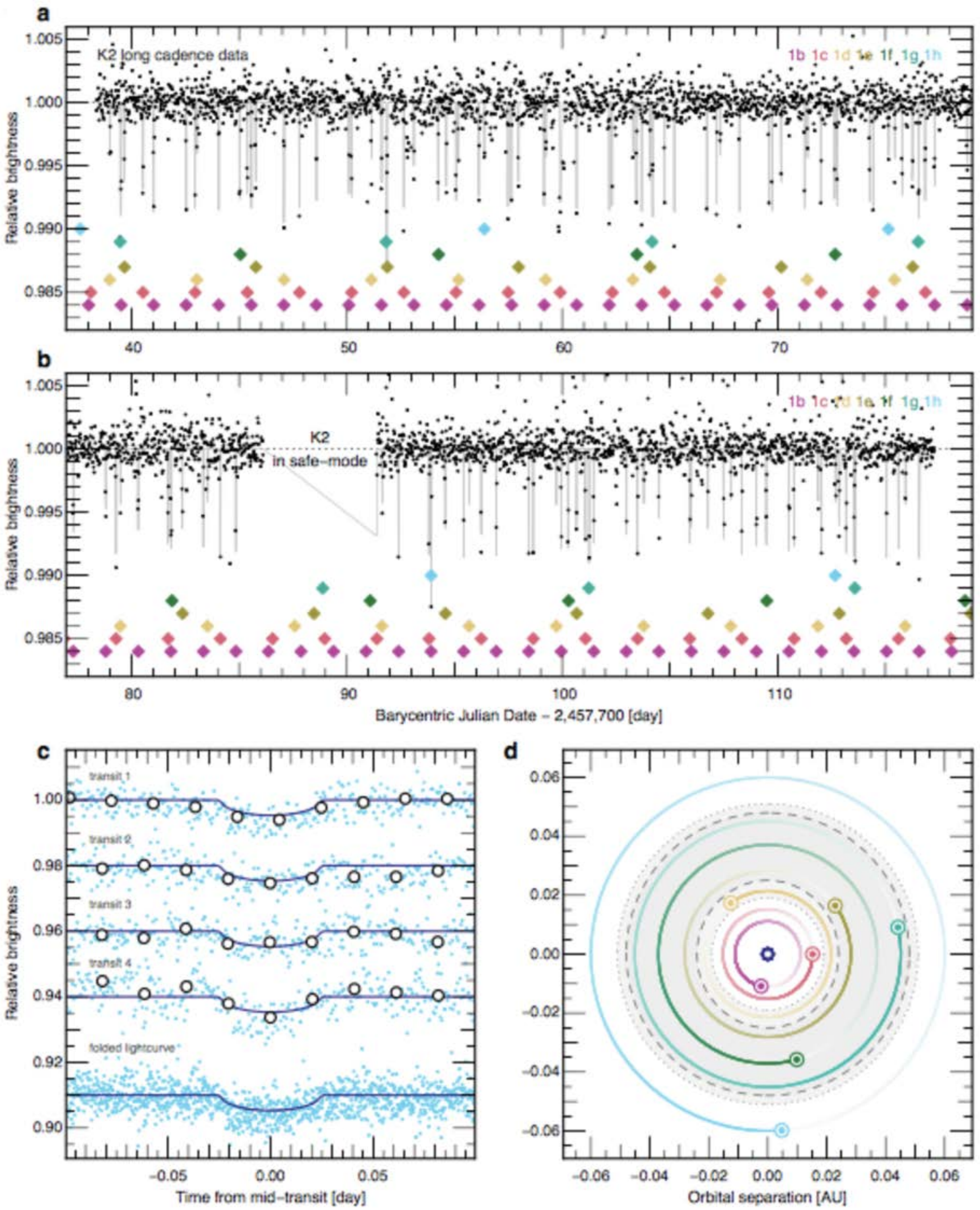
Need to combine with radial velocities

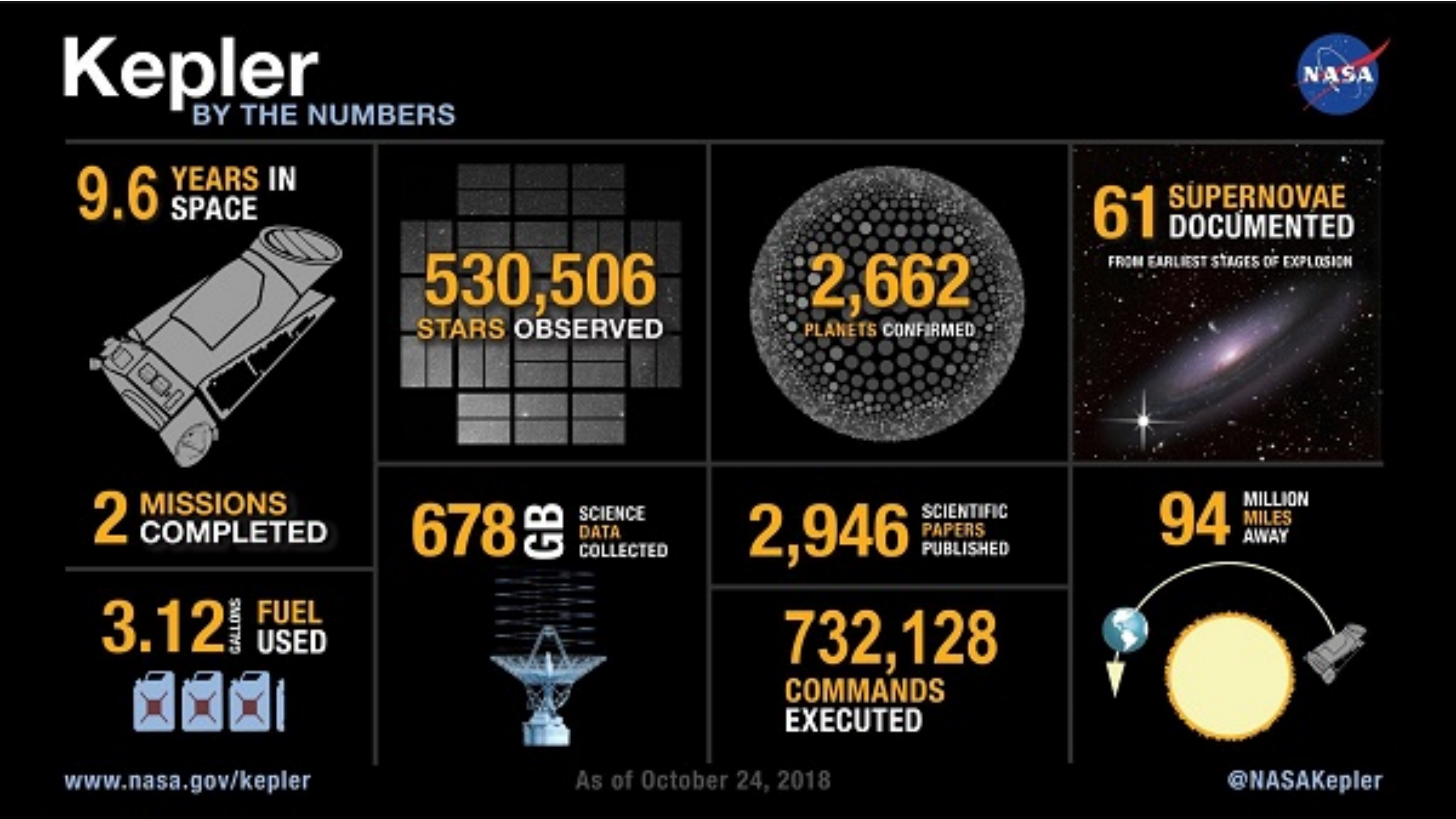




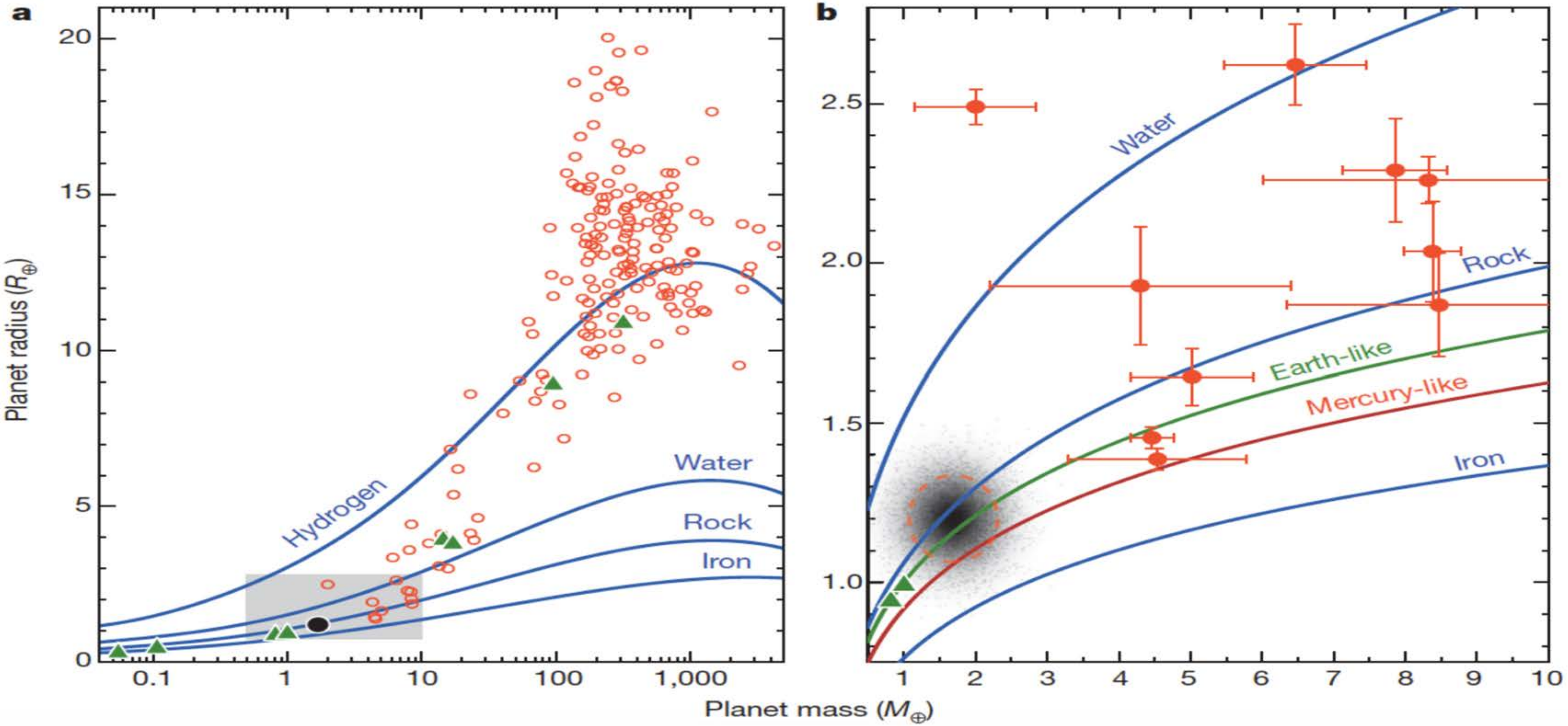


Short cadence
Binned
Transit model
Folded Normalized Flux
1.04
1.02
1.00
0.98
0.96
Residuals
0.02
0.01
0.00
−0.01
−0.02
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
Time from transit center (days)


a
K2 long cadence data
1b 1c 1d 1e 1f 1g 1h
Relative brightness
b
K2
in safe-mode
Barycentric Julian Date − 2,457,700 [day]
c
transit 1
transit 2
transit 3
transit 4
folded lightcurve
Relative brightness
Time from mid-transit [day]
d
Orbital separation [AU]

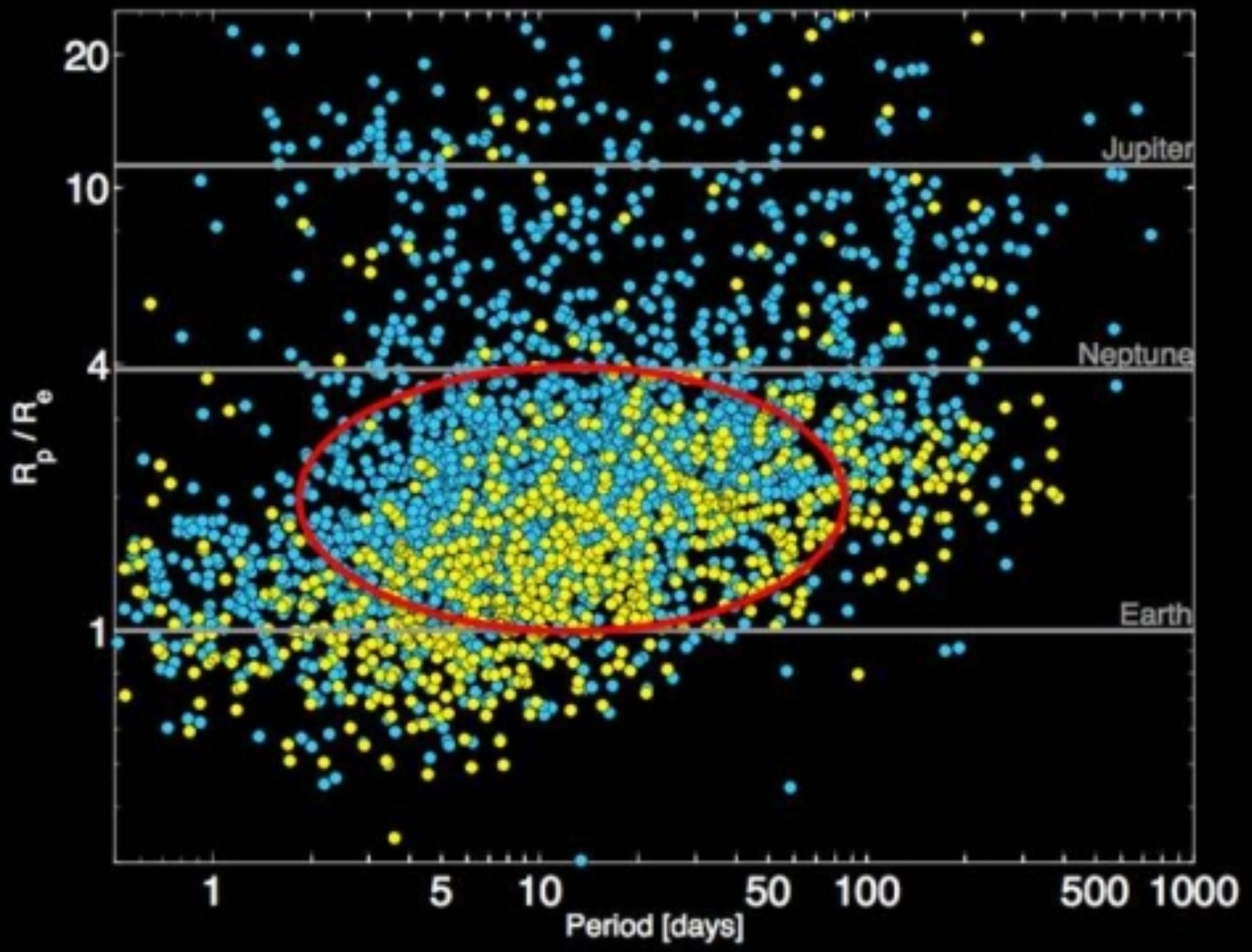

Kepler
BY THE NUMBERS
NASA
9.6 YEARS IN SPACE
530,506 STARS OBSERVED
2,662 PLANETS CONFIRMED
61 SUPERNOVAE DOCUMENTED
FROM EARLIEST STAGES OF EXPLOSION
2 MISSIONS COMPLETED
678 GB SCIENCE DATA COLLECTED
2,946 SCIENTIFIC PAPERS PUBLISHED
94 MILLION MILES AWAY
3.12 GALLONS FUEL USED
732,128 COMMANDS EXECUTED
www.nasa.gov/kepler
As of October 24, 2018
@NASAKepler

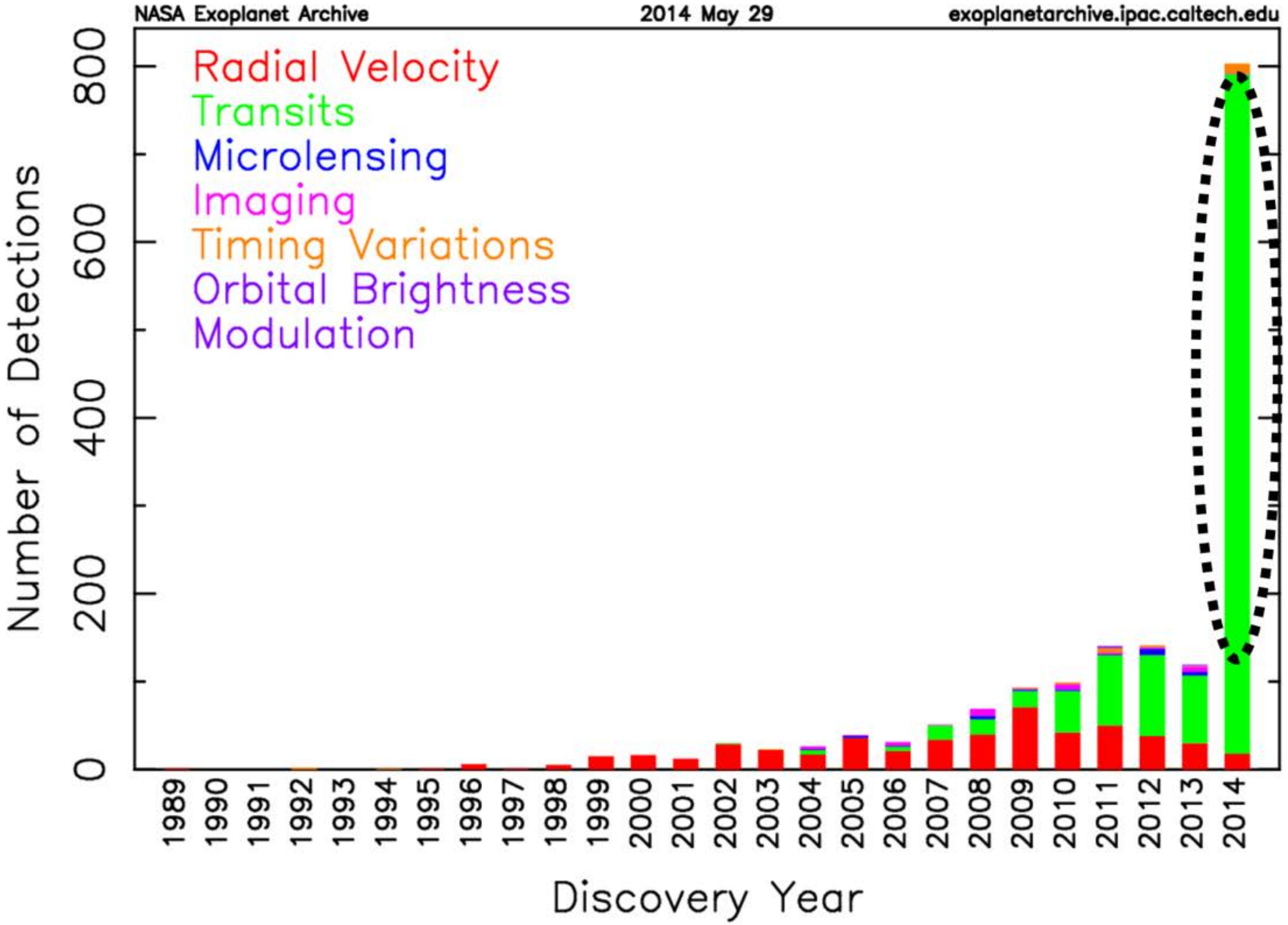
Mass-radius of gazeous planets and small ones in 2013…

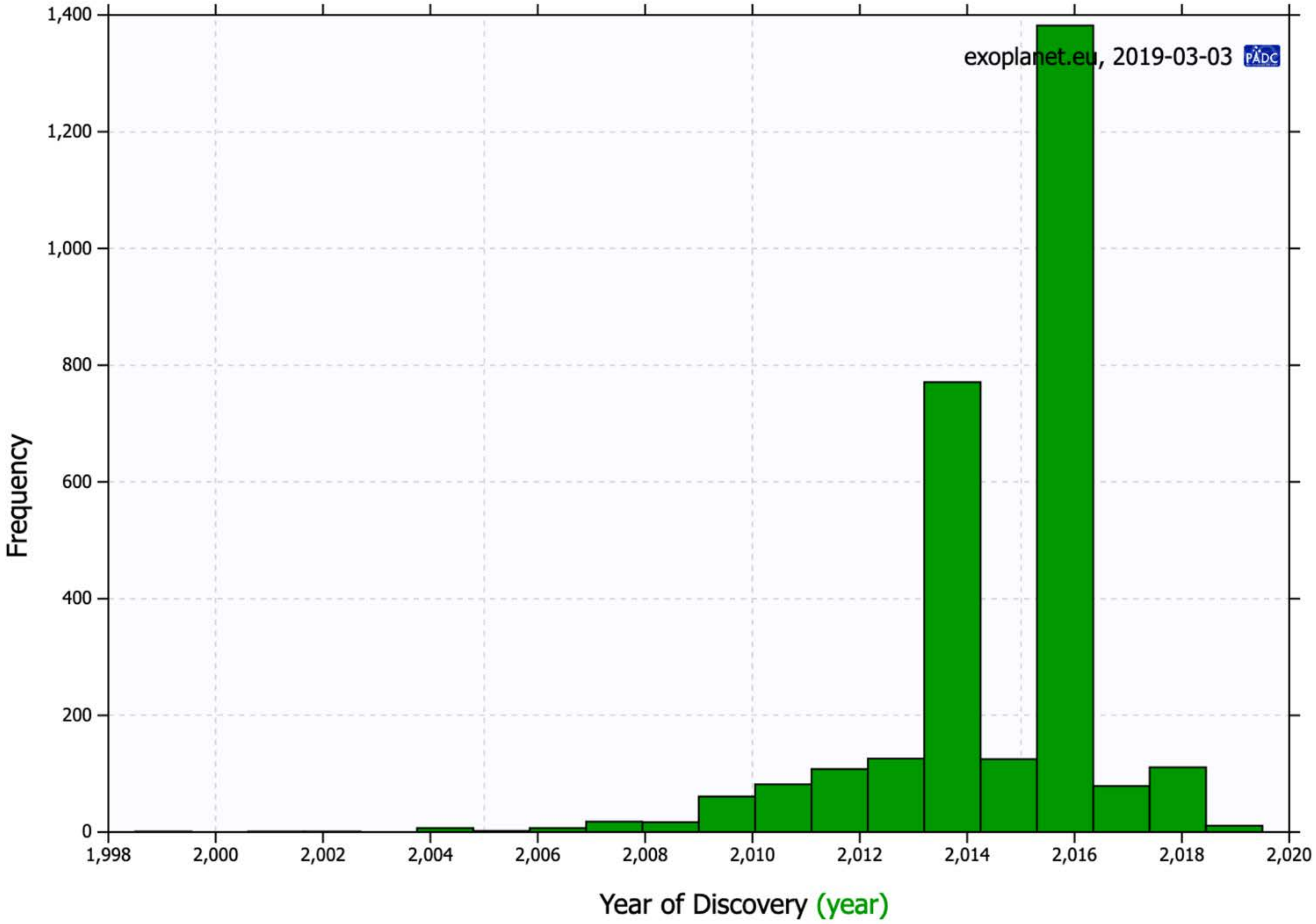


Kepler Planet Candidates

January 2014

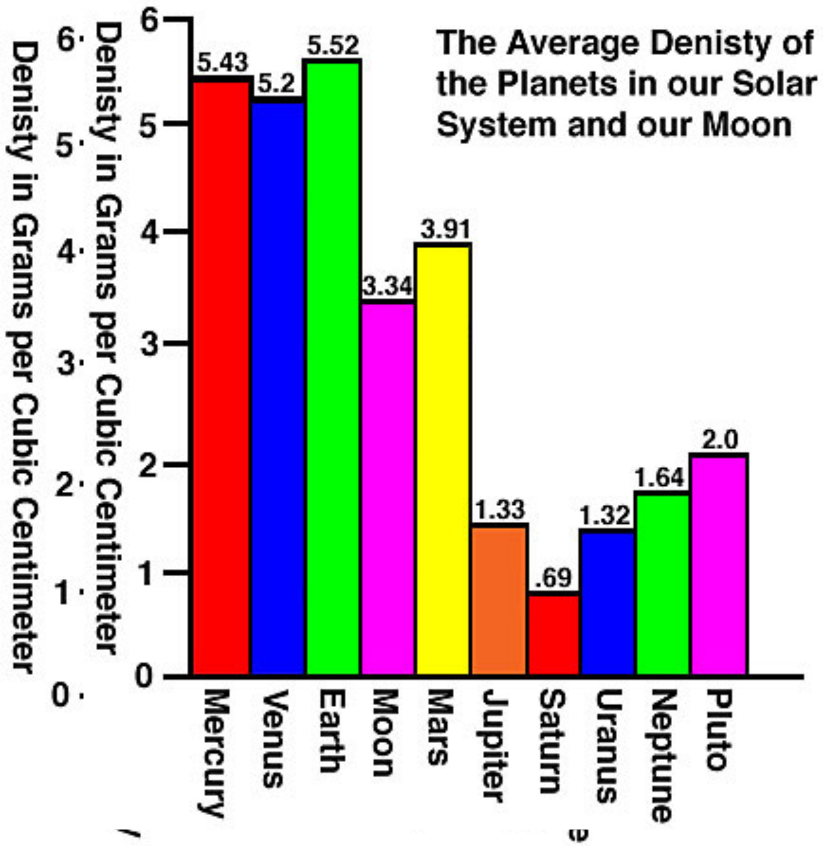


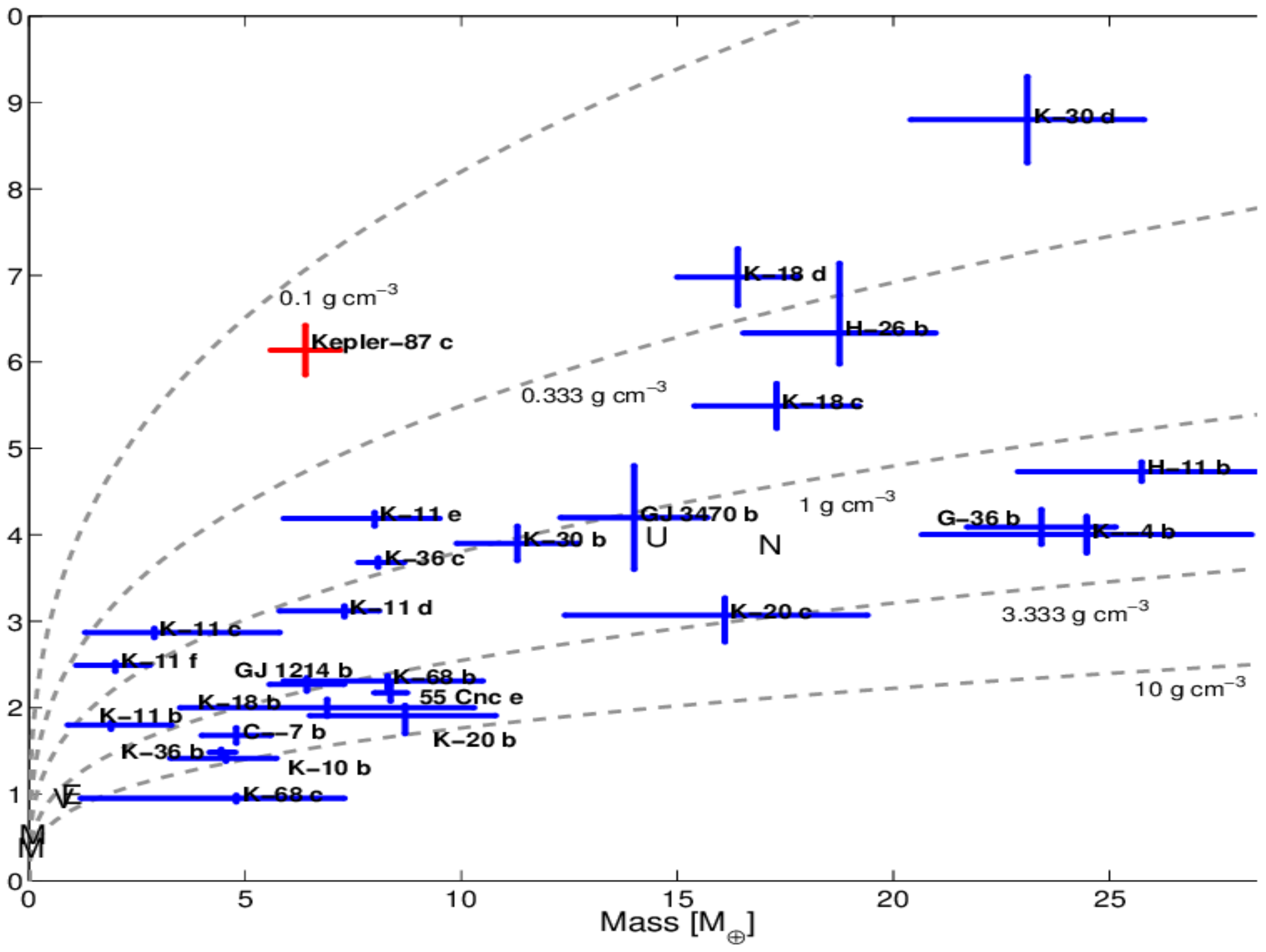

NASA Exoplanet Archive
2014 May 29
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
Number of Detections
0
200
400
600
800
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Discovery Year



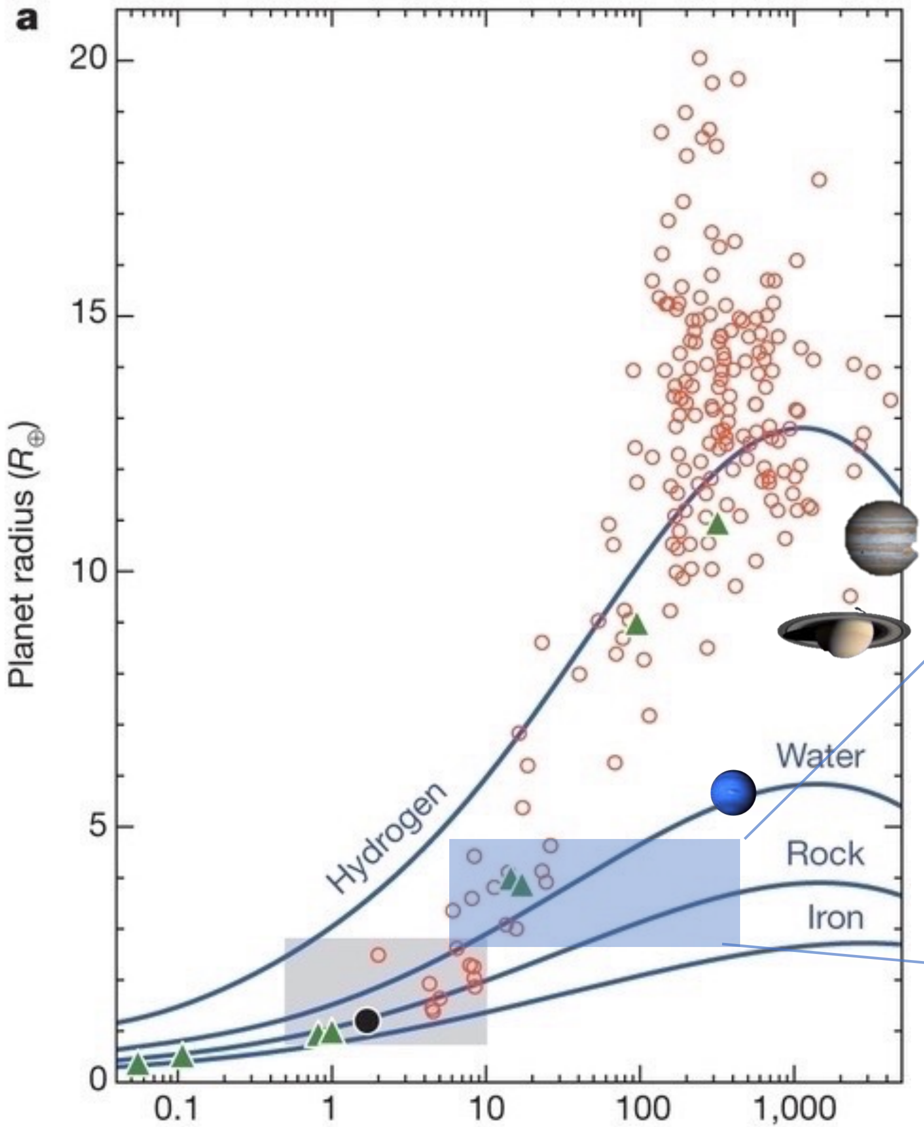
exoplanet.eu, 2019-03-03
Frequency
1,400
1,200
1,000
800
600
400
200
0
1,998
2,000
2,002
2,004
2,006
2,008
2,010
2,012
2,014
2,016
2,018
2,020
Year of Discovery (year)

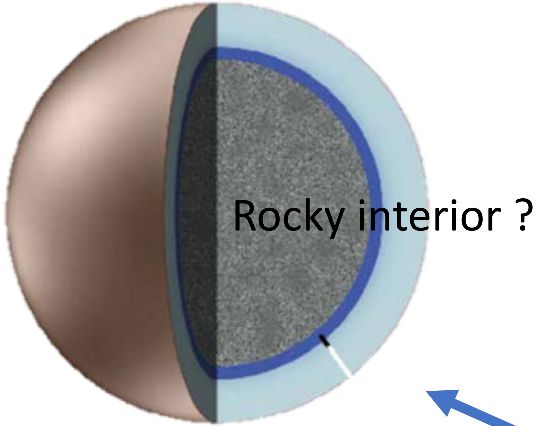
Mass radius relations and isodensity curves



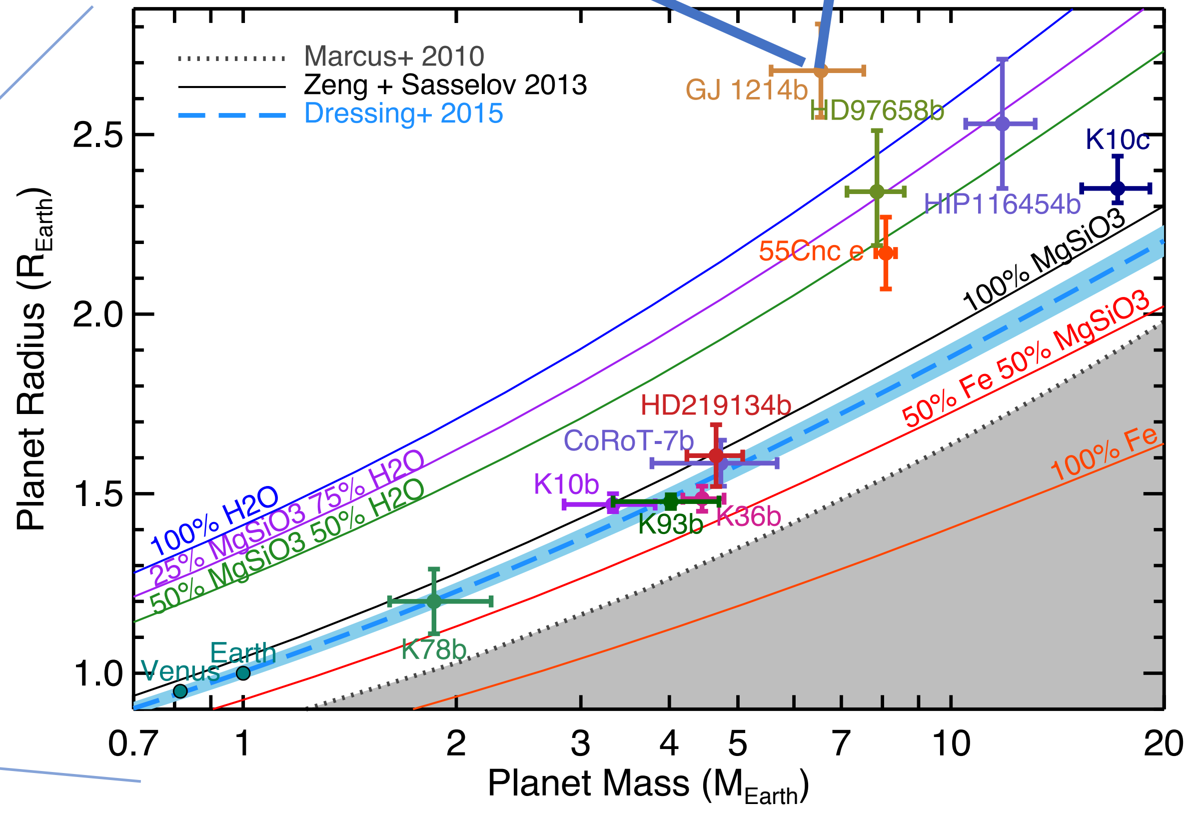


Classification according to density





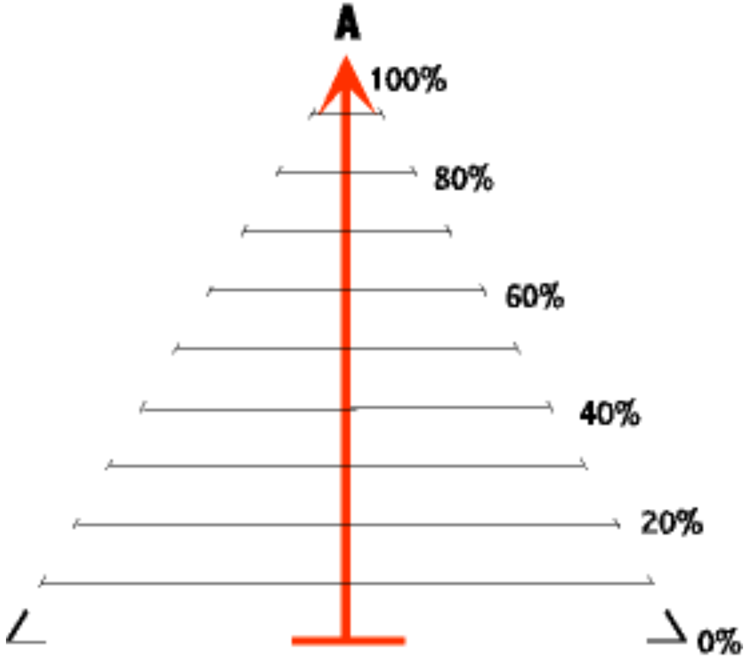
Or ?

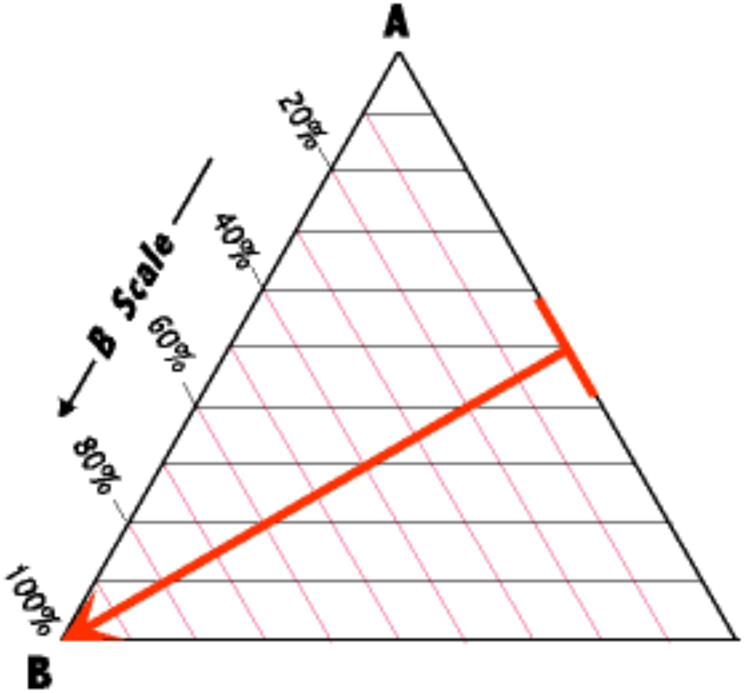


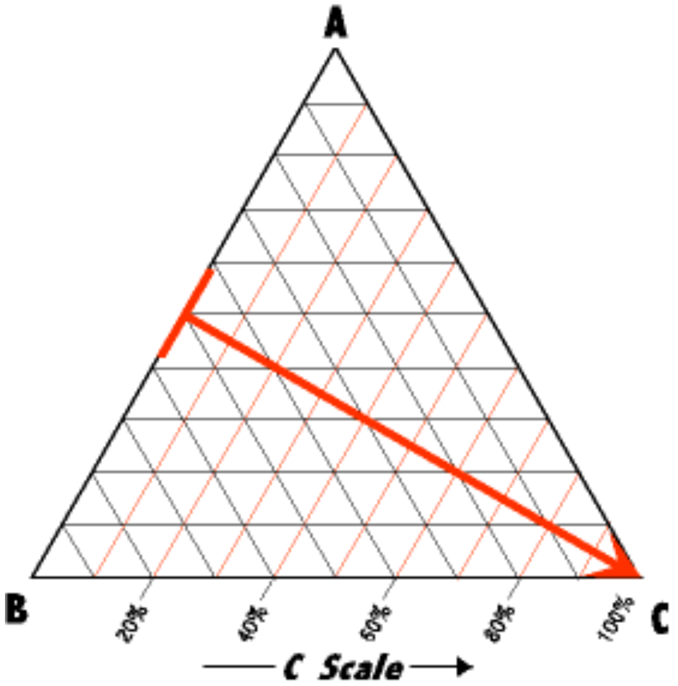
Howard et al., 2013; Motalebi et al., 2015

Ternary diagrams

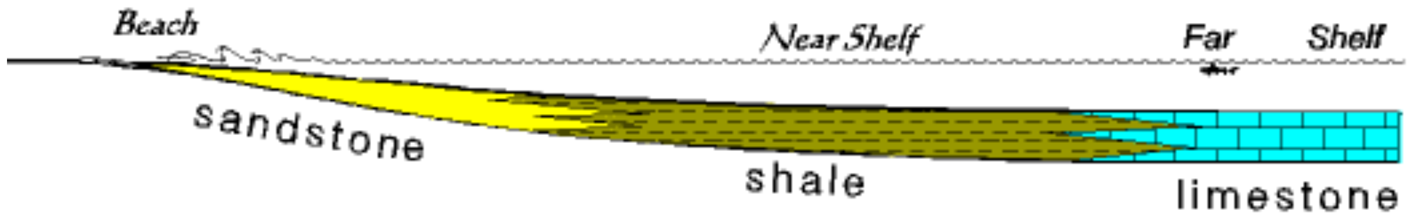
- A+B+C=100 %
- How to plot the 3 variables together

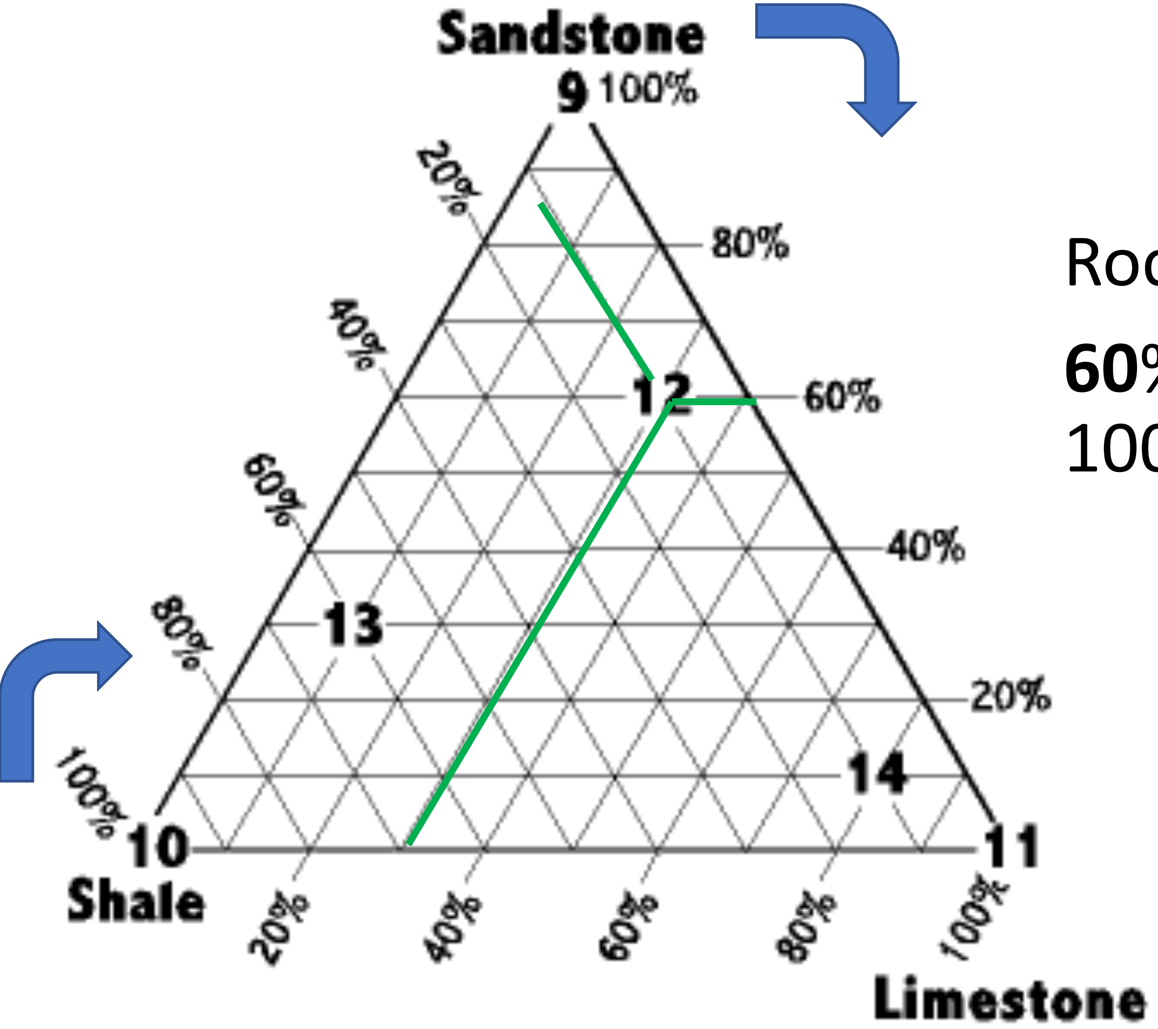






Example of reading the figure

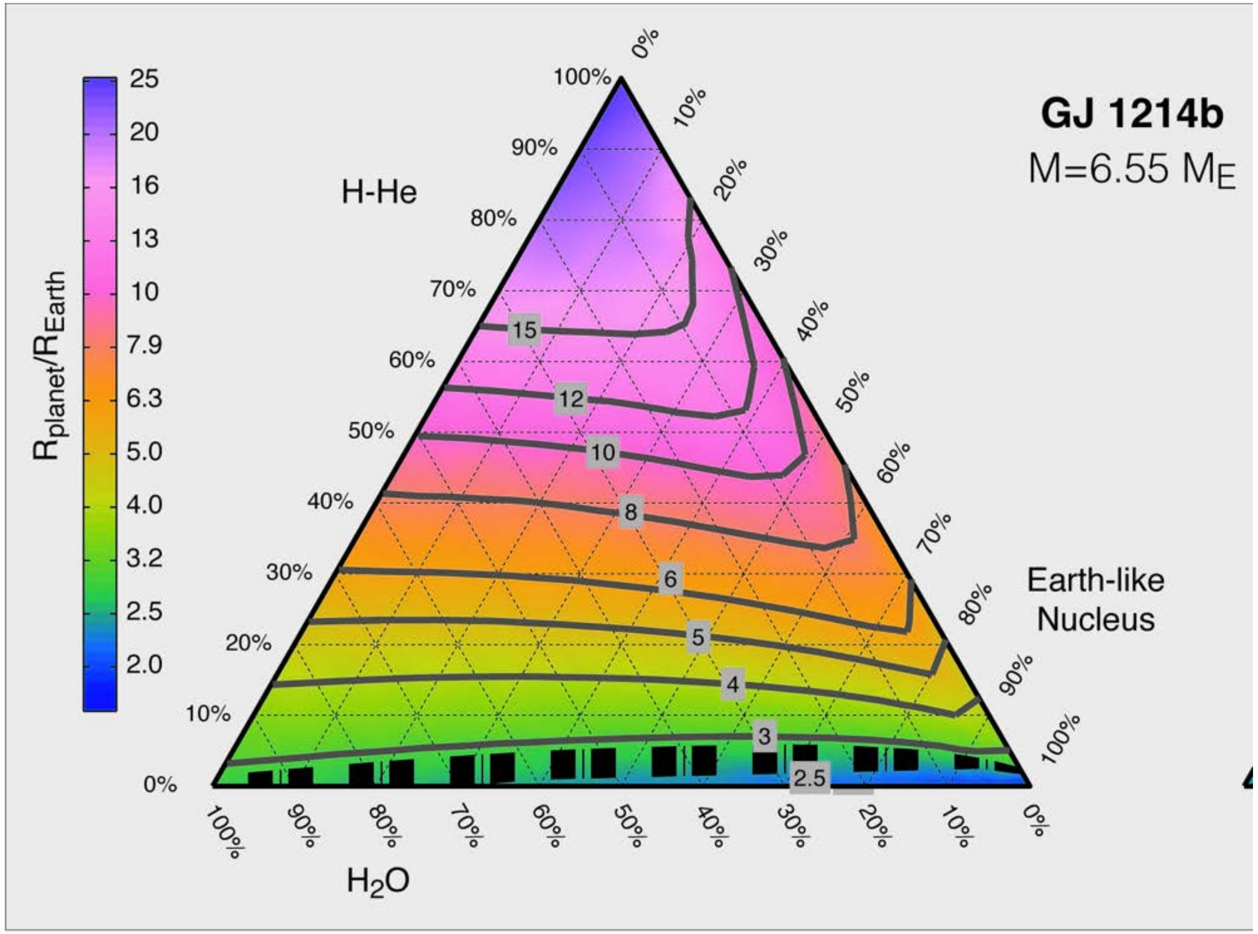


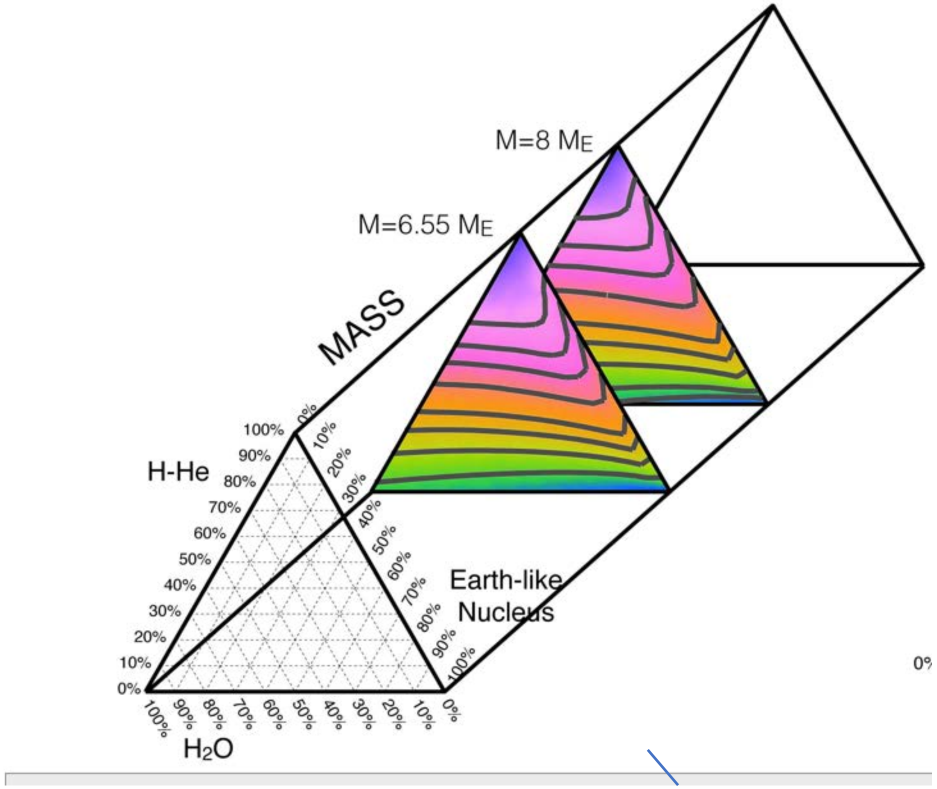


Rock 12:

60% Sandstone | **10**% Shale | **30**% Limestone = 100%

GJ1214b, 6.55 Mearth
Calculating different models   H-He, H2O, Earth like nucleus fractions.
Isocurves for Radiu 2.5, 3, ..., 10, 12, 15 Rearth



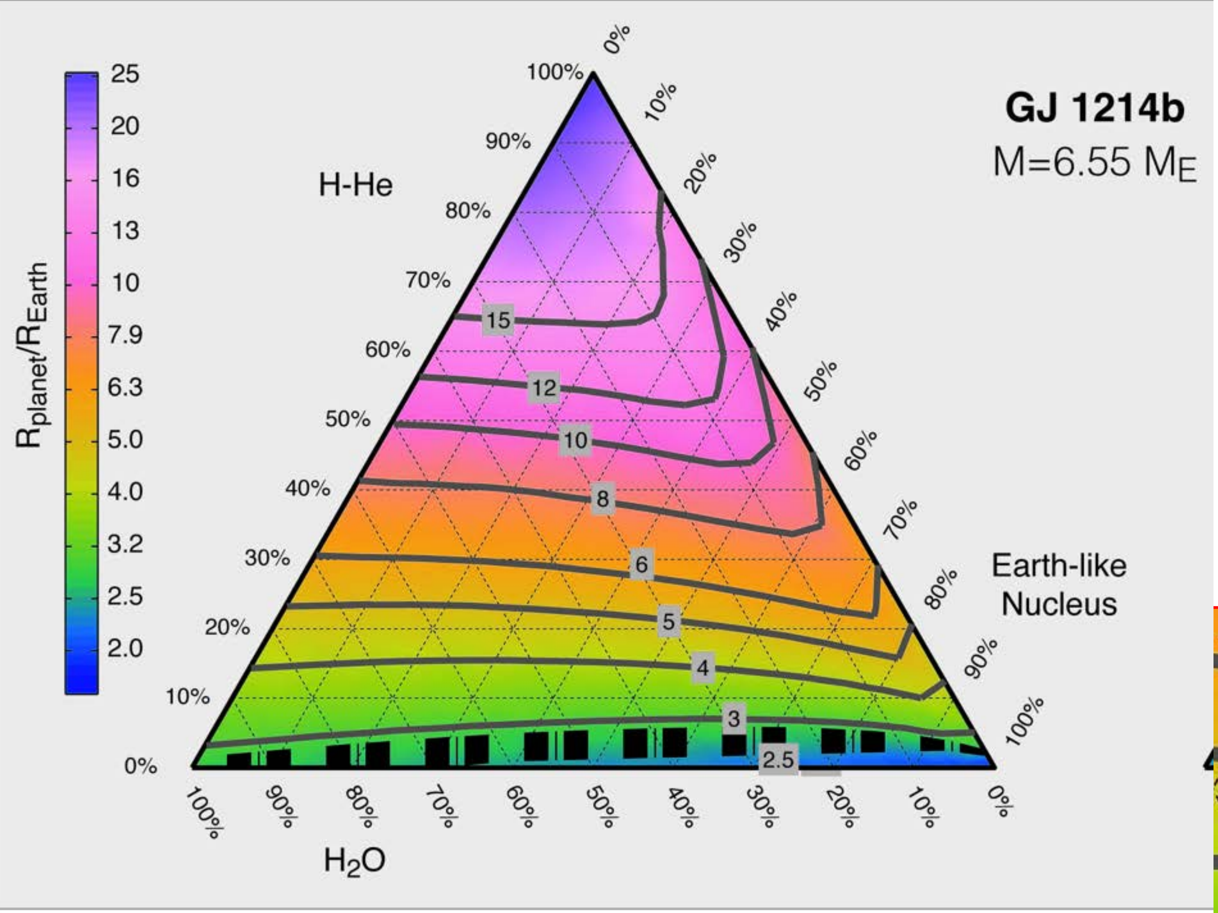


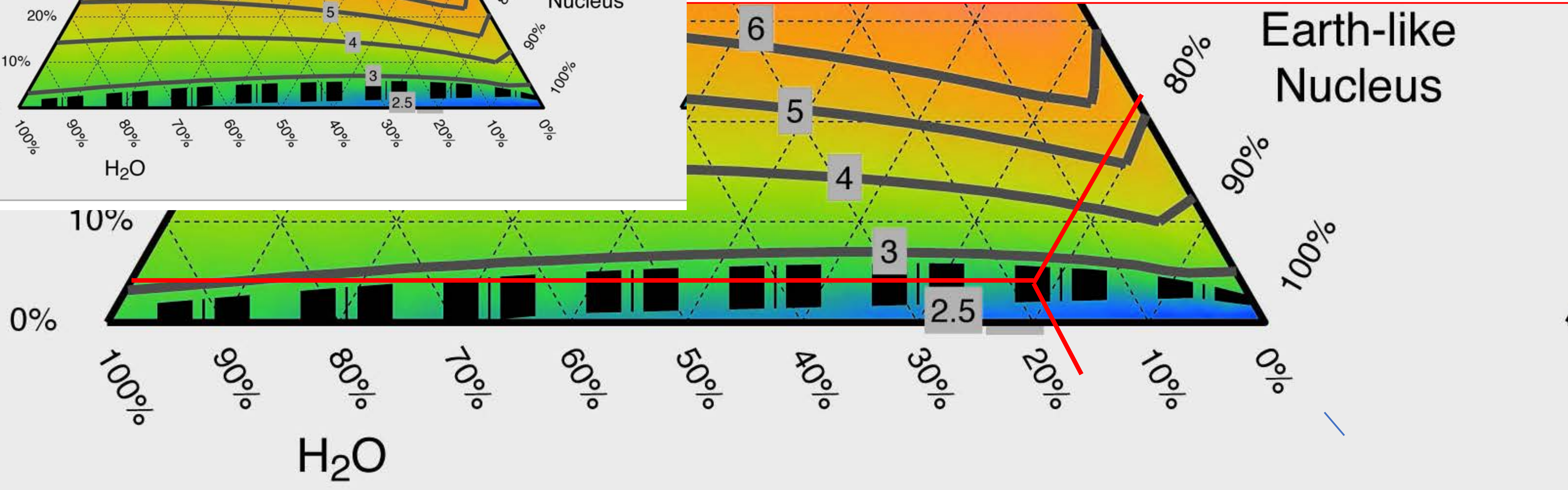
Valencia, 2013

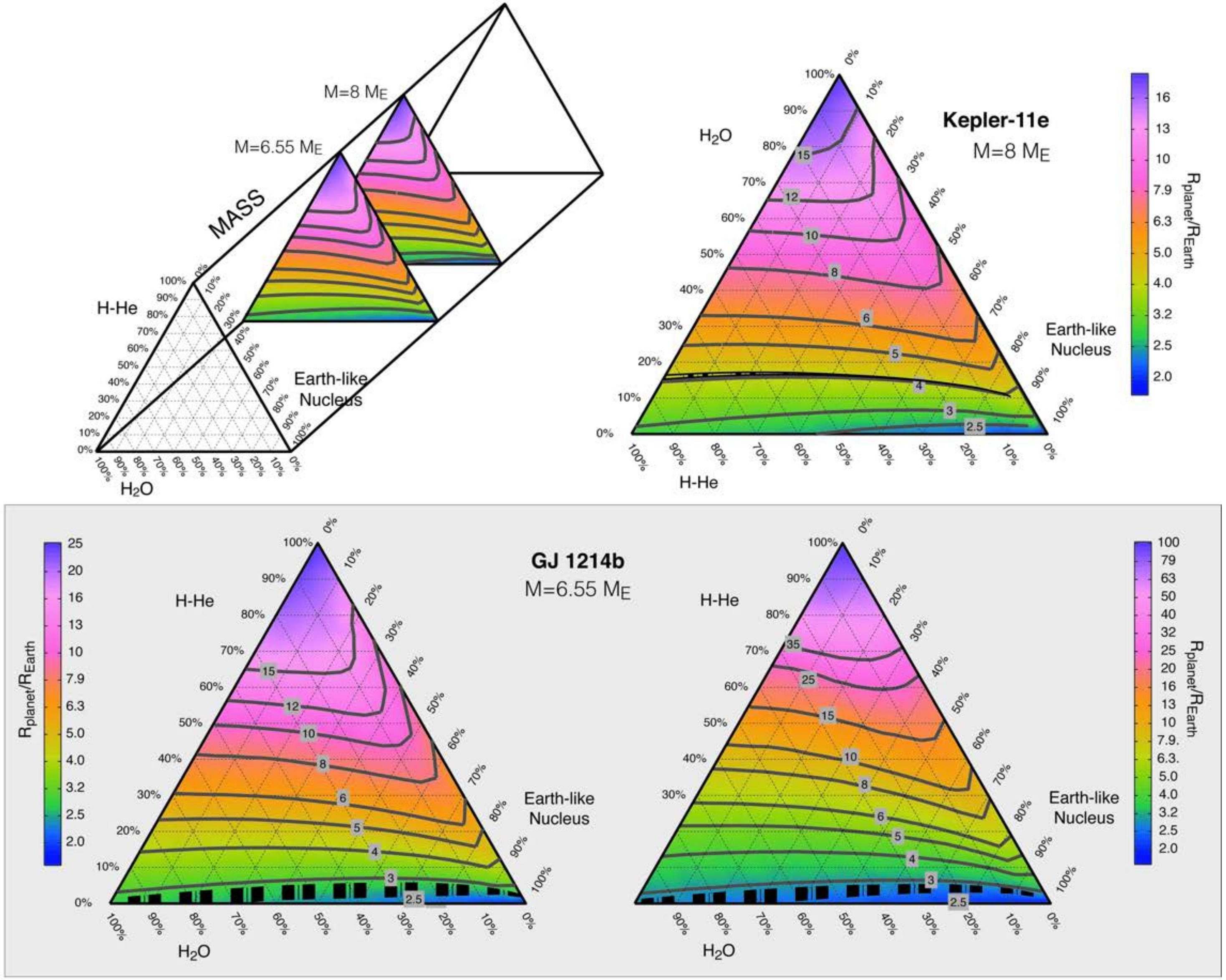
GJ1214b, radius ~2.6 Earth radii

18% H_2O + 5% H-He +77 % Earth like

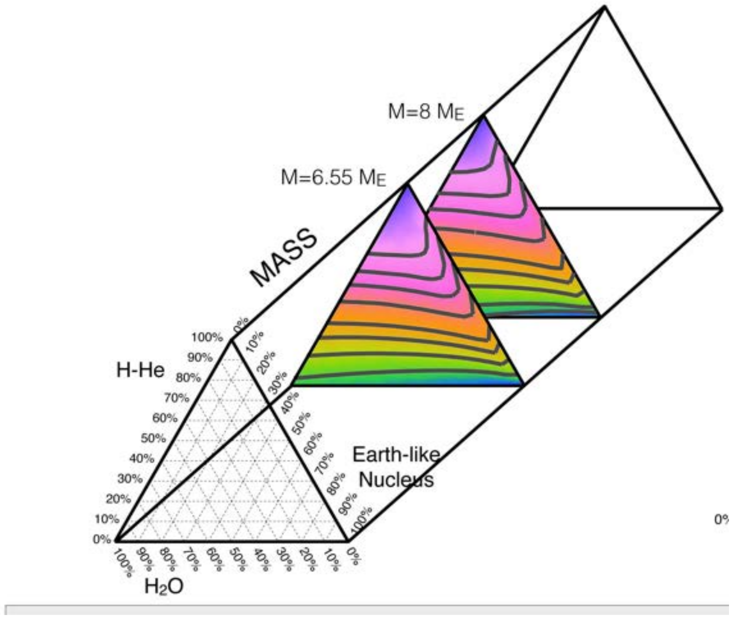
Or 100 % water ?





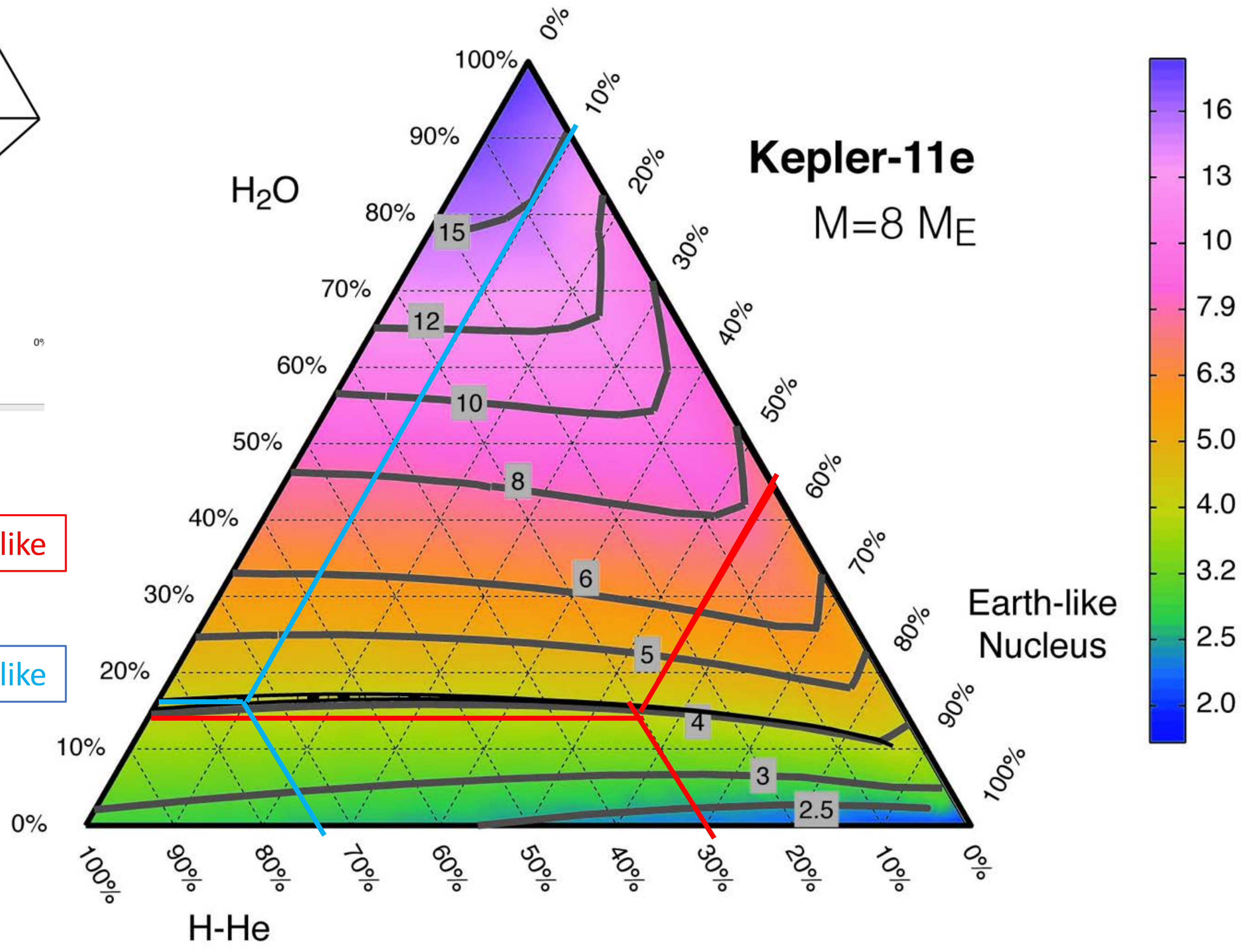


Ternary Diagrams for GJ 1214b and Kepler-11e. These triangular diagrams relate the composition in terms of earth-like nucleus fraction, water+ices fraction, and H/He fraction to total mass, to the radius for a specific planetary mass. Each vertex corresponds to 100%, and the opposite side to 0% of a particular component. The color bar shows the radius in terms of Earth-radii, and the grey lines are the isoradius curves labeled in terms of Earth-radii. The collection of ternary diagrams for a range of planetary masses forms a triangular prism. The black band shows the compositions constrained by data for GJ 1214b for a grain-free envelope (top left), and a grainy envelope (bottom right), and Kepler-11e for a grain free envelope (top right) as projected onto the planetary mass MMM from the ternary diagrams at M+ΔMM+Delta MM+ΔM and M−ΔMM-Delta MM−ΔM (where ΔM Delta MΔM are the uncertainty values taken from the observational data).

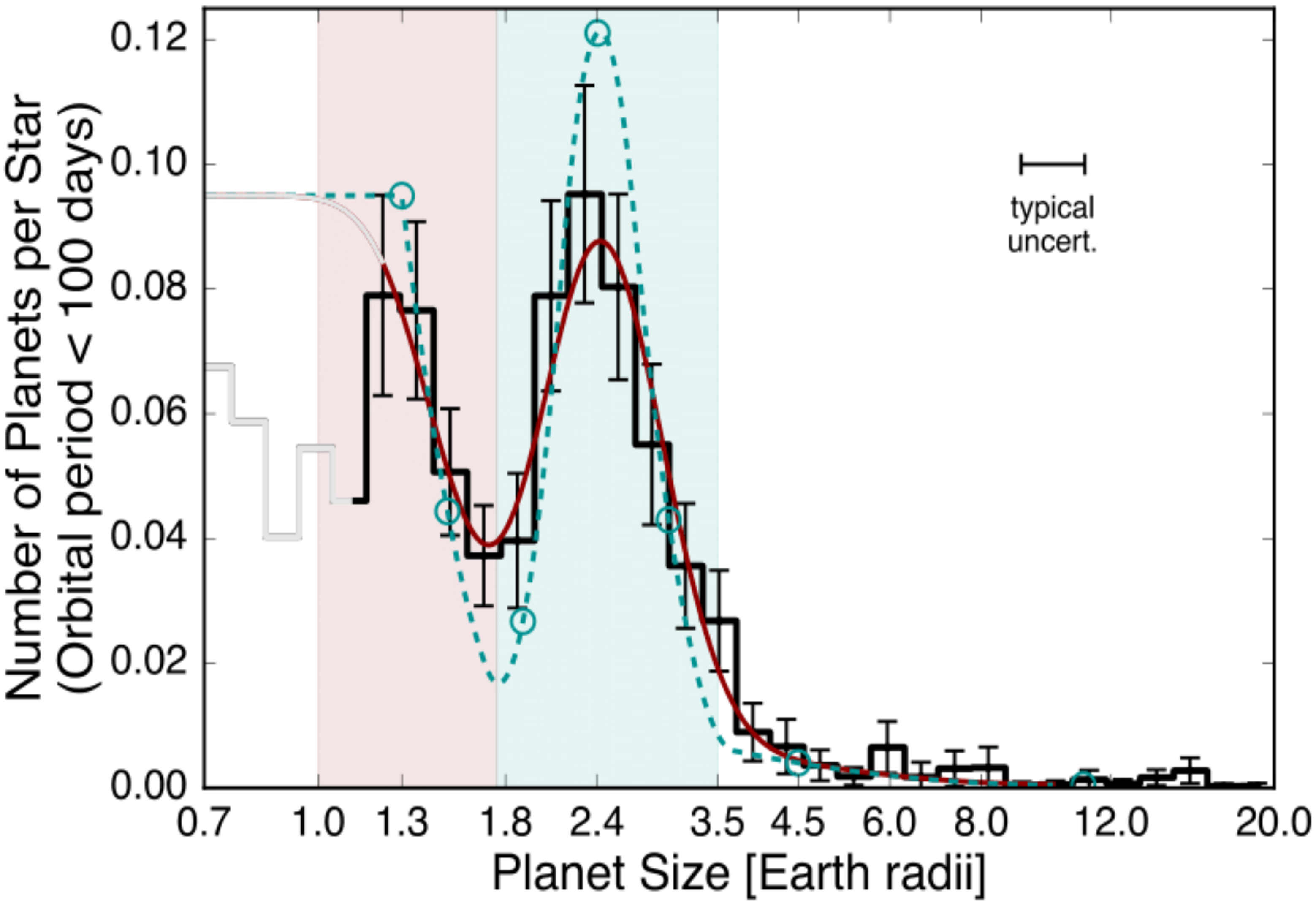


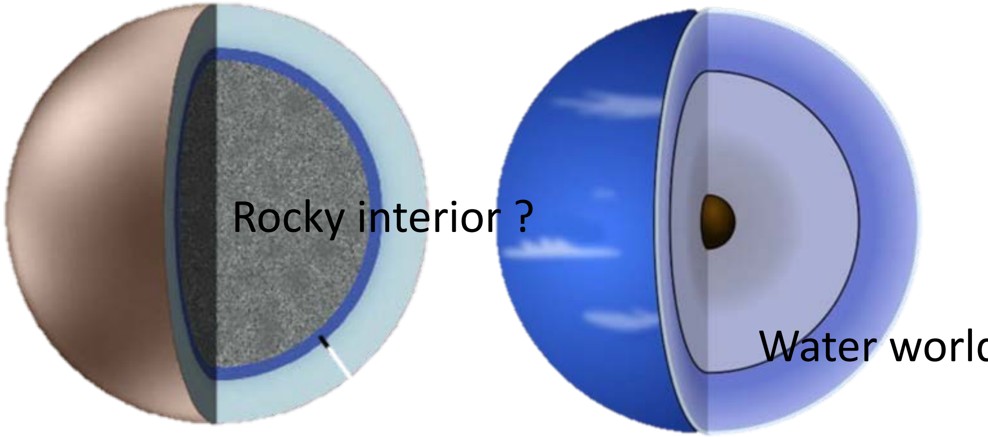
15% H2O + 30% H-He +55 % Earth like

18% H2O + 72% H-He +10 % Earth like



Histogram of planet radii, 2 peaks, super-Earth and Mini-Neptune



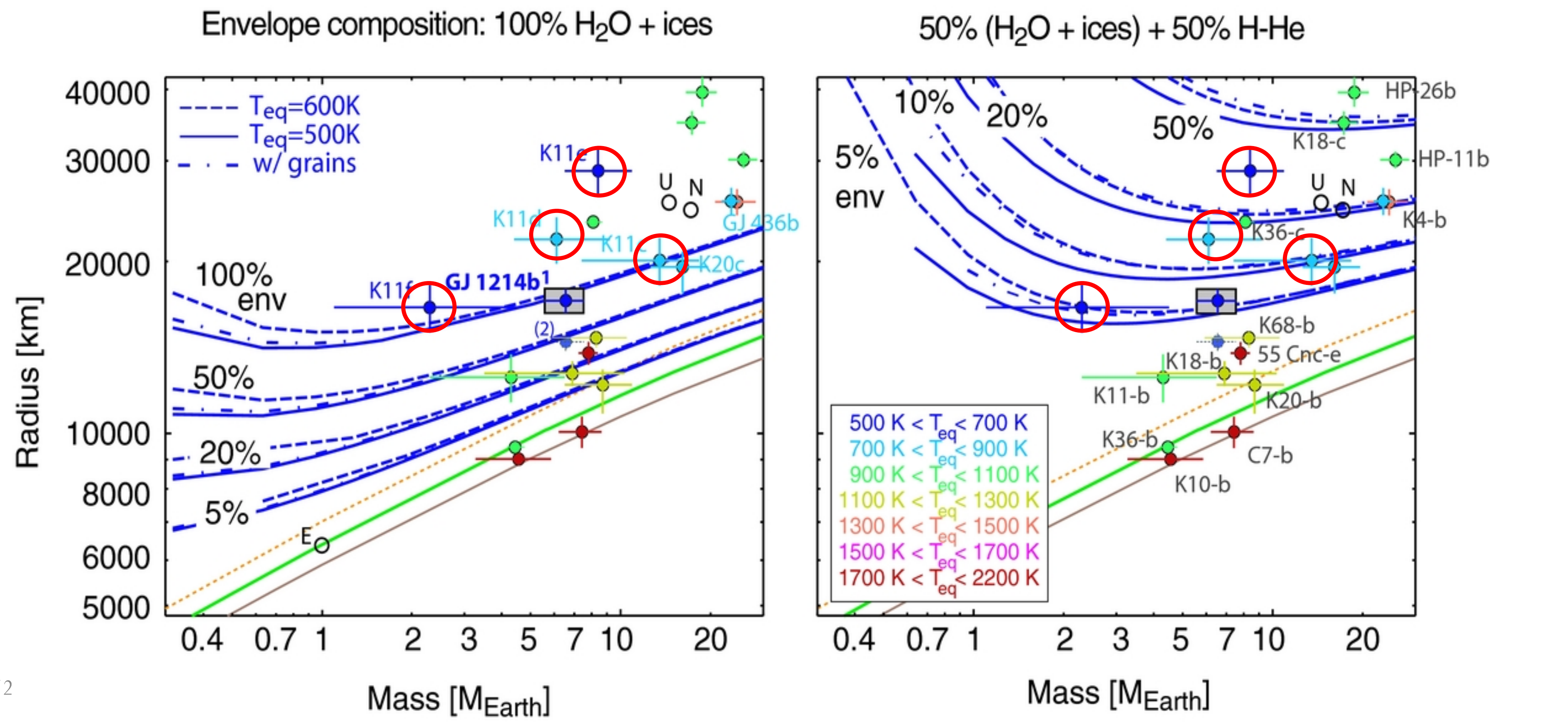


Completeness-corrected histogram of planet radii for planets with orbital periods shorter than 100 days.

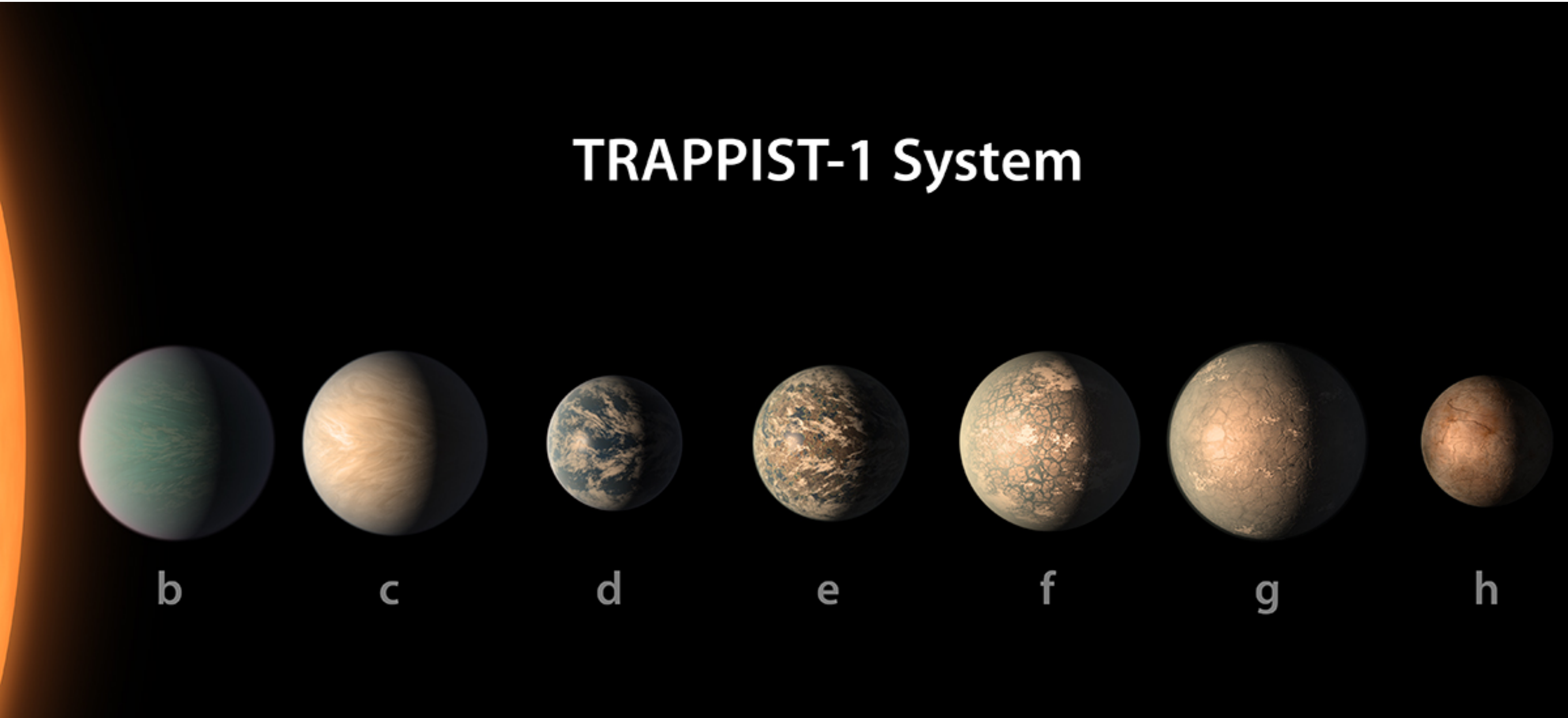
Lightly shaded regions encompass our definitions of "super-Earths" (light red) and "sub-Neptunes" (light cyan). The dashed cyan line is a plausible model for the underlying occurrence distribution after removing the smearing caused by uncertainties on the planet radii measurements.

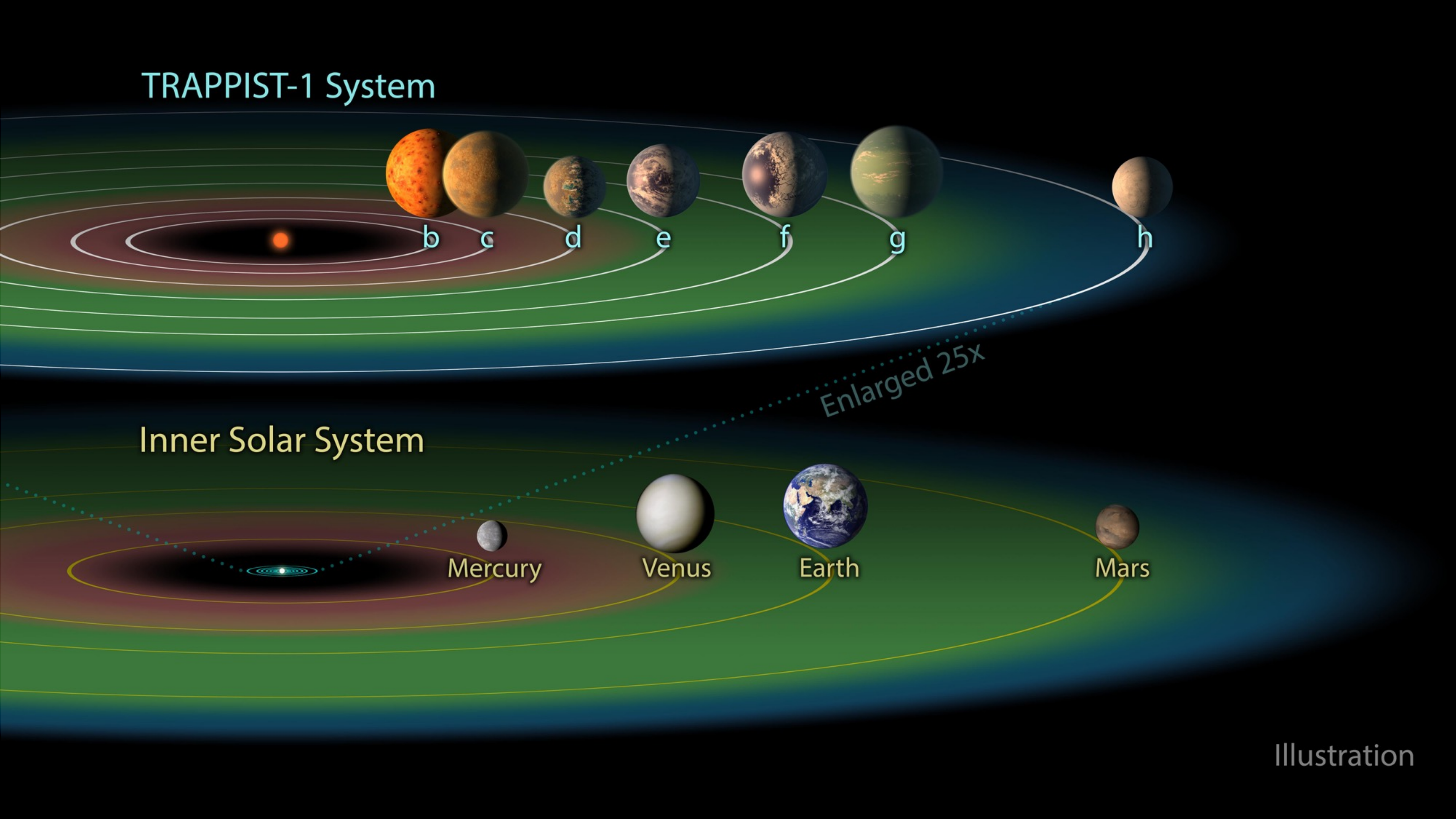
A fabulous diversity in the exoplanet zoo
Mass and Radius are not enough

5 Super Earth / Mini Neptunes in Kepler 11. Very different atmospheres !
(Lissauer et al. 2011, Valencia et al., 2013)



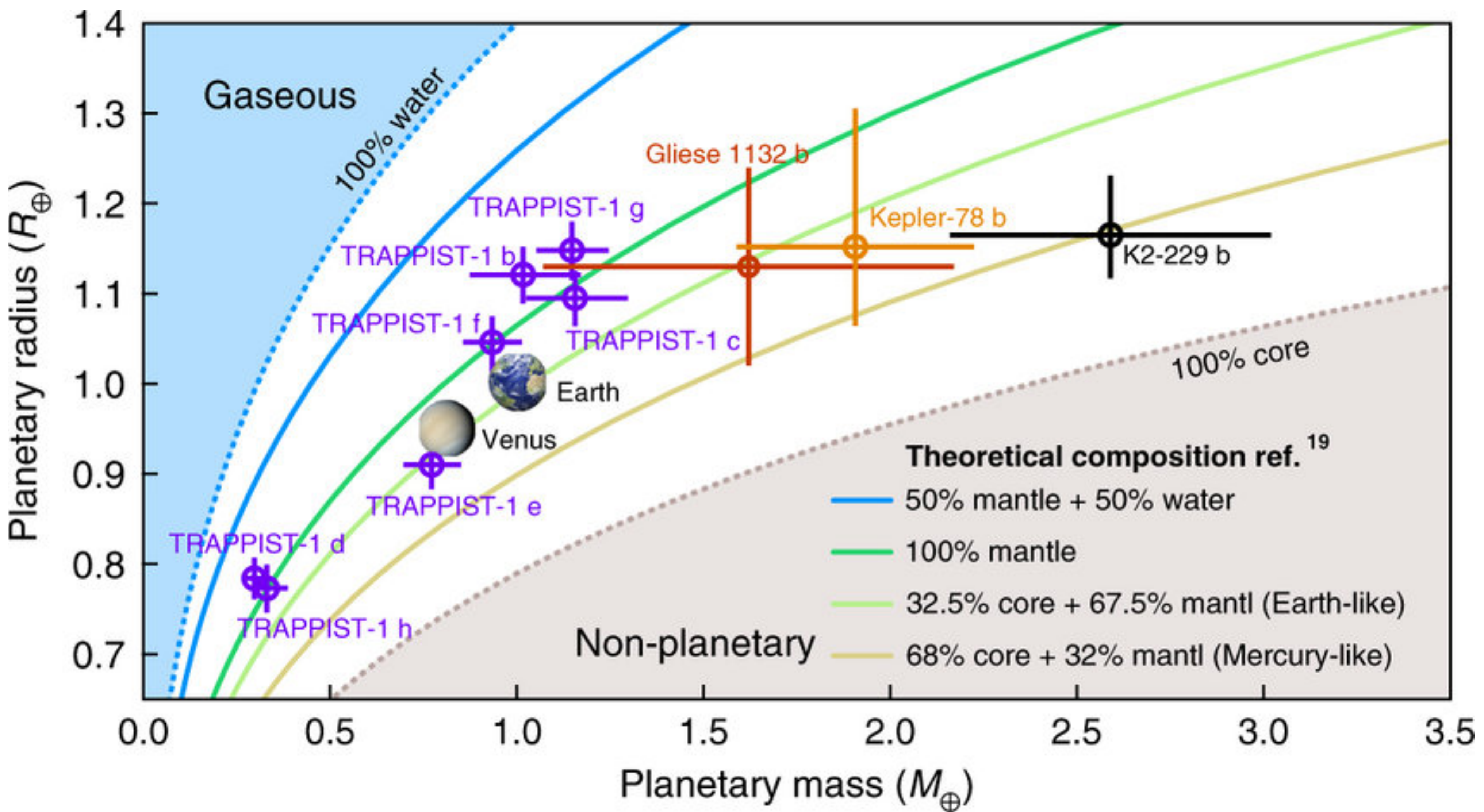

Trappist projet, hunting for transiting planets
60 cm telescope, Chile, Marocco
Led by M. Gillon


TRAPPIST-1 System
b
c
d
e
f
g
h

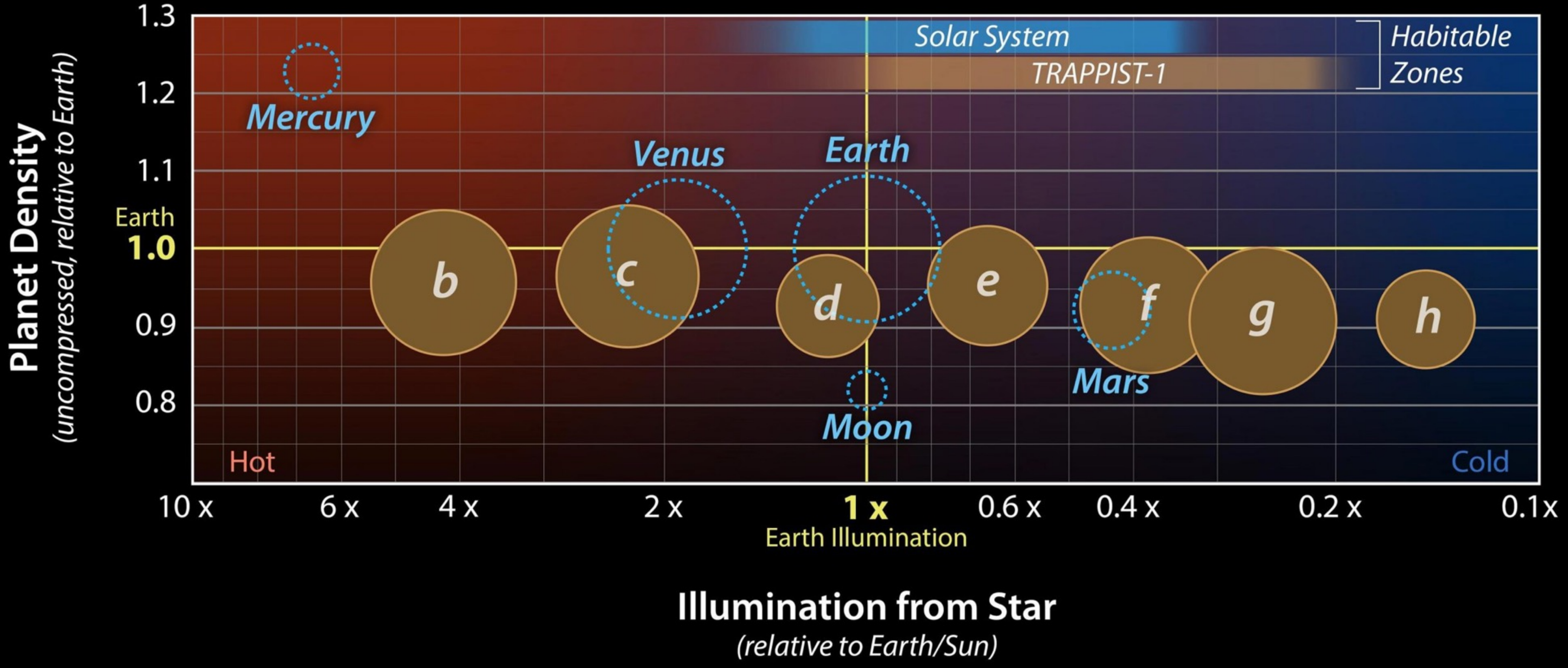


TRAPPIST-1 System
b
c
d
e
f
g
h
Enlarged 25x
Inner Solar System
Mercury
Venus
Earth
Mars
Illustration

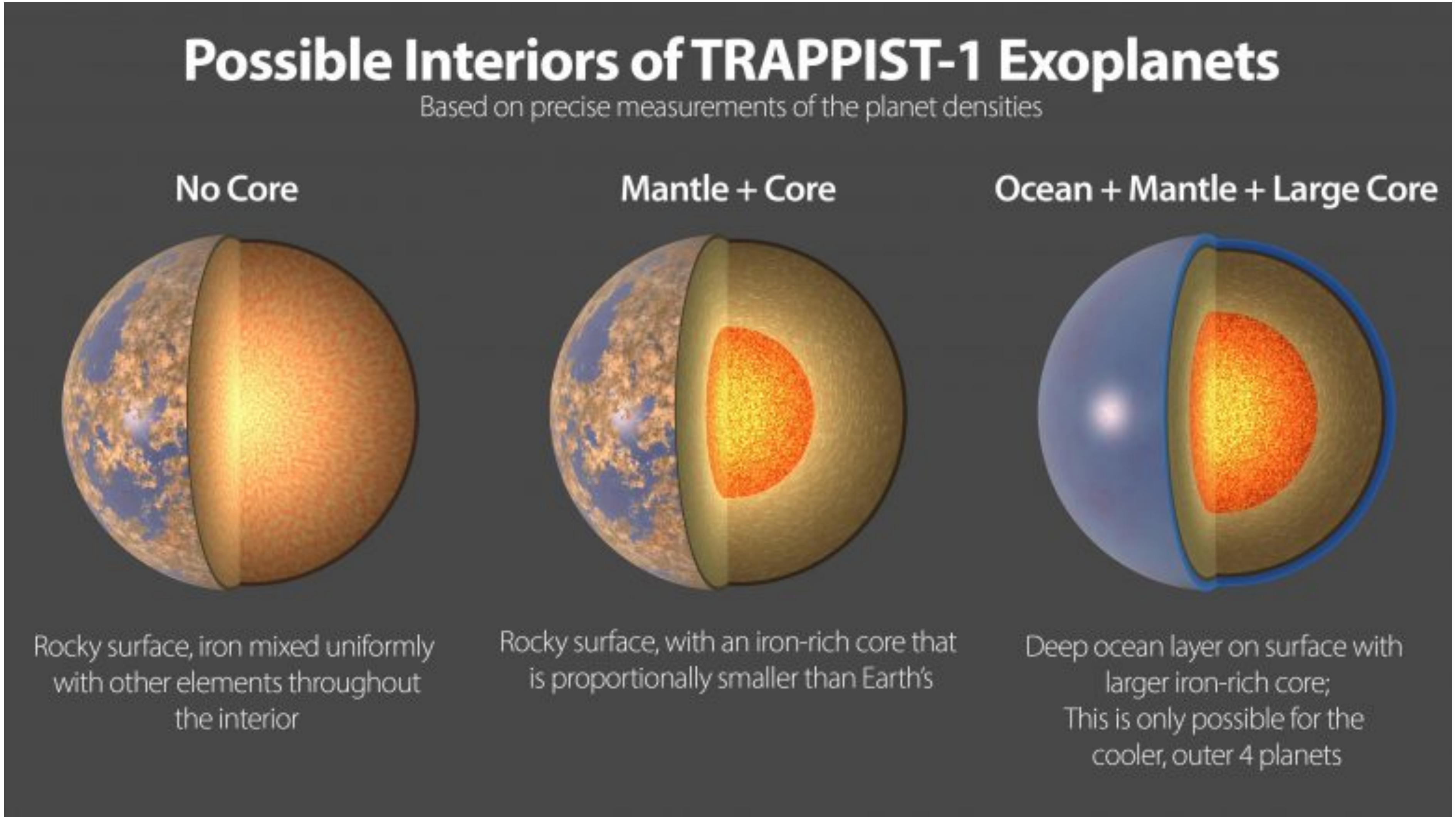
The Trappist-1 system



TRAPPIST-1/Solar System Comparison



All seven planets have similar densities, but we do not how they are composed

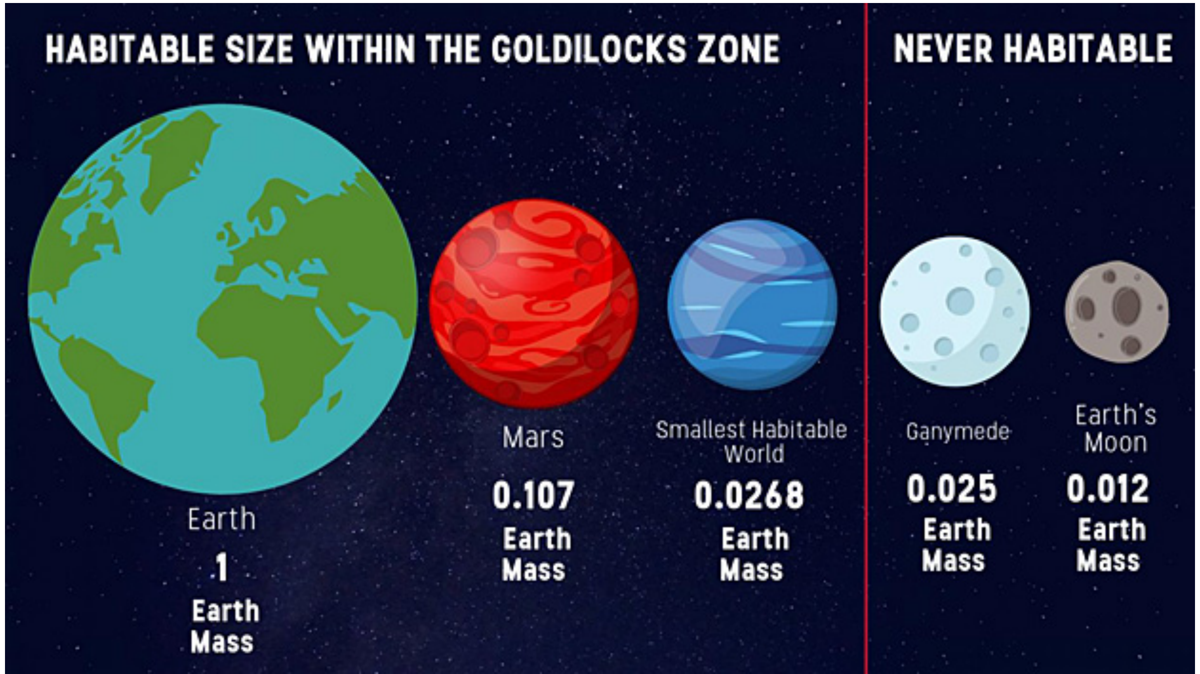


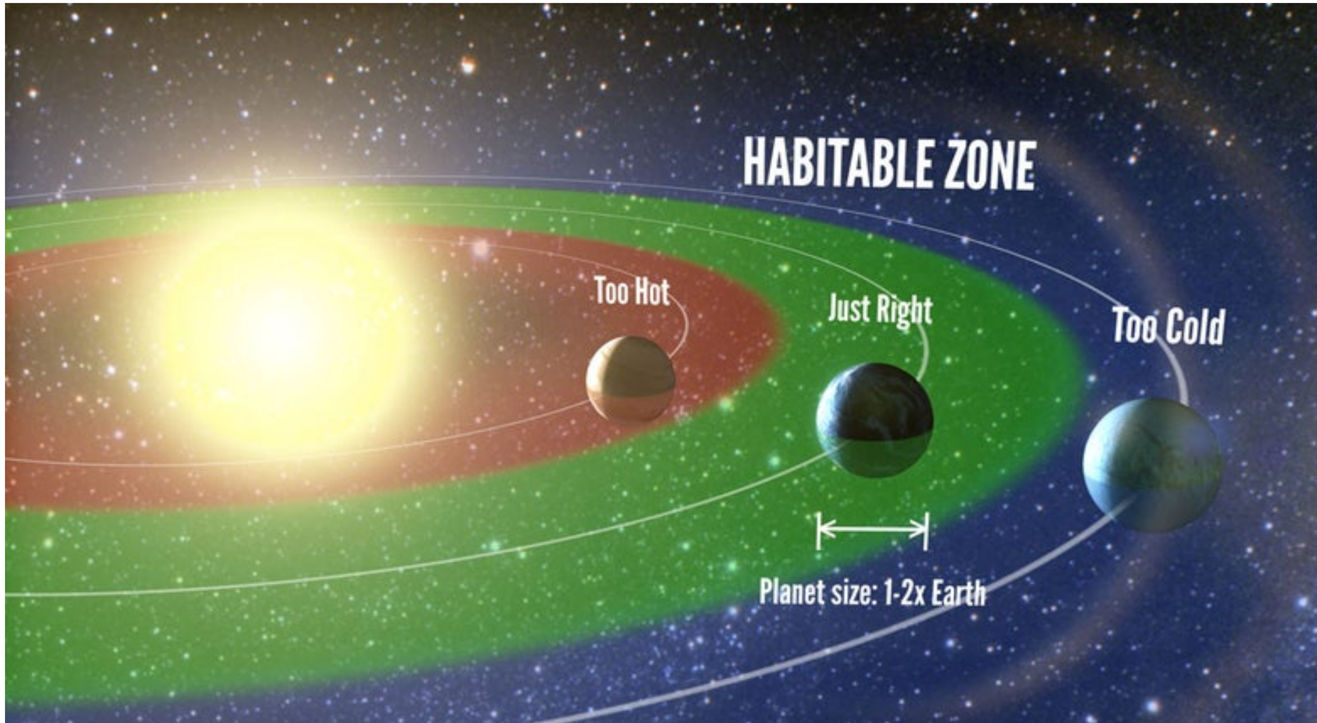
And habitable planets ?

Level 0: water liquid on the surface, big enough to keep its atmosphere, not gaz giant

But… what about greenhouse effects from atmosphere? UV & X Ray flux from star ? nature of the atmosphere ?   No guaranty it is like the Earth !

So, be careful when using the word « habitable » ☺

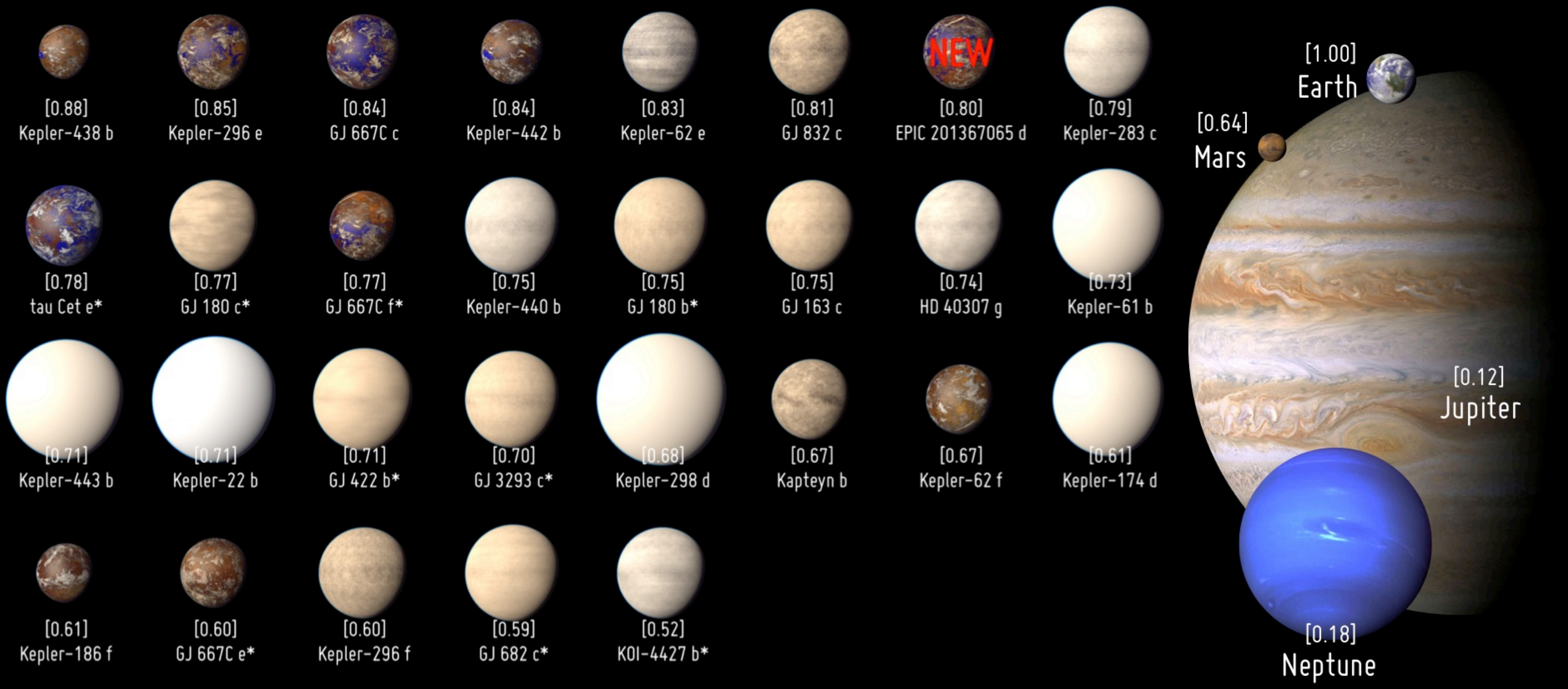




Potentially Habitable Exoplanets

Ranked by the Earth Similarity Index (ESI)

PHL
MAPPING THE HABITABLE UNIVERSE



Artistic representations. Earth, Mars, Jupiter, and Neptune for scale. ESI value is between brackets. Planet candidates indicated with asterisks.

CREDIT: PHL @ UPR Arecibo (phl.upr.edu) January 16, 2015

Take away points.

- Lots of transiting planets, hot or warm
- Measured transit depth gives ~ $(R_{planet} / R^*)^2$ and fit of light curve inclination i.
- If radial velocity is measured-> i is known, hence Mass of planet is known

- Gazeous planets with wide range of mean densities, inflated hot jupiters
- Large numbers of planets with Radius < 4 Rearth
- Super-Earth (2- 8 Mo, R < 1.6Rearth)
- Ocean planets (large amount of H20)
- Mini Neptunes (down to ~5 Mearth, and 3-4 Rearth)
- Between 1.3-2.3 Rearth radius, overlap of populations of super Earth and mini-Neptunes

Native Apps

Executables (64-bit and 32-bit) for Windows and (64-bit) for Macintosh computers are available for all of our older projects (NAAP, ClassAction, & Ranking Tasks). The appropriate package for your (or your student's) computer system must be downloaded and installed locally. Note that these are actual applications that run in your native OS and their longevity depends only upon your OS. There is no similar viable solution for Chromebooks.

Note that every simulation available in the past on this site is contained in either the ClassAction or NAAP Labs native app. (In ClassAction look under the Animations tab.) The following guide to content is provided to assist you in navigating. Student guides and demonstration guides can be found on the NAAP Resources page.

https://astro.unl.edu/nativeapps/

Windows Executables (for 64-bit machines, what most people want)

ClassAction - v2.3.msi	97.4 MB	January 30, 2020
NAAP Labs - v1.1.msi	22.4 MB	January 30, 2020
Interactives - v1.1.msi	46.7 MB	January 30, 2020

MacOS Executables

ClassAction - v2.3.pkg	97.1 MB	January 30, 2020
NAAP Labs - v1.1.pkg	22.4 MB	January 30, 2020
Interactives - v1.1.pkg	46.2 MB	January 30, 2020

Choose a planet, plot radial velocity, transit curve

- GJ 436b, hot Neptune, 22 Mearth, 3.95 Rearth, star 0.4 Mo
- GJ1214b Mini-Neptune, 6.5 Mearth, 2.6 Rearth, star 0.15 Mo

Radial velocity at 10 ms-1 and 1ms-1

Transit photometry at 0.5 millimag or 3 millimags.

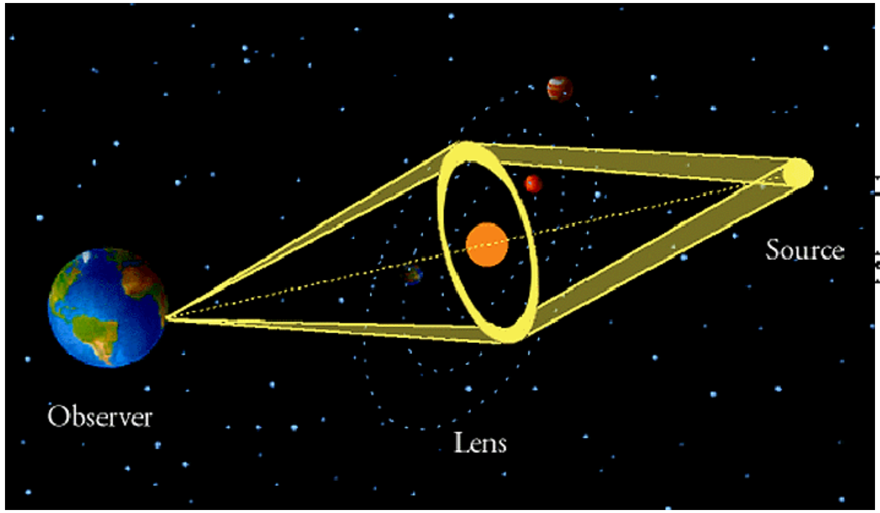
If the star is a star like the sun, how does it look ?

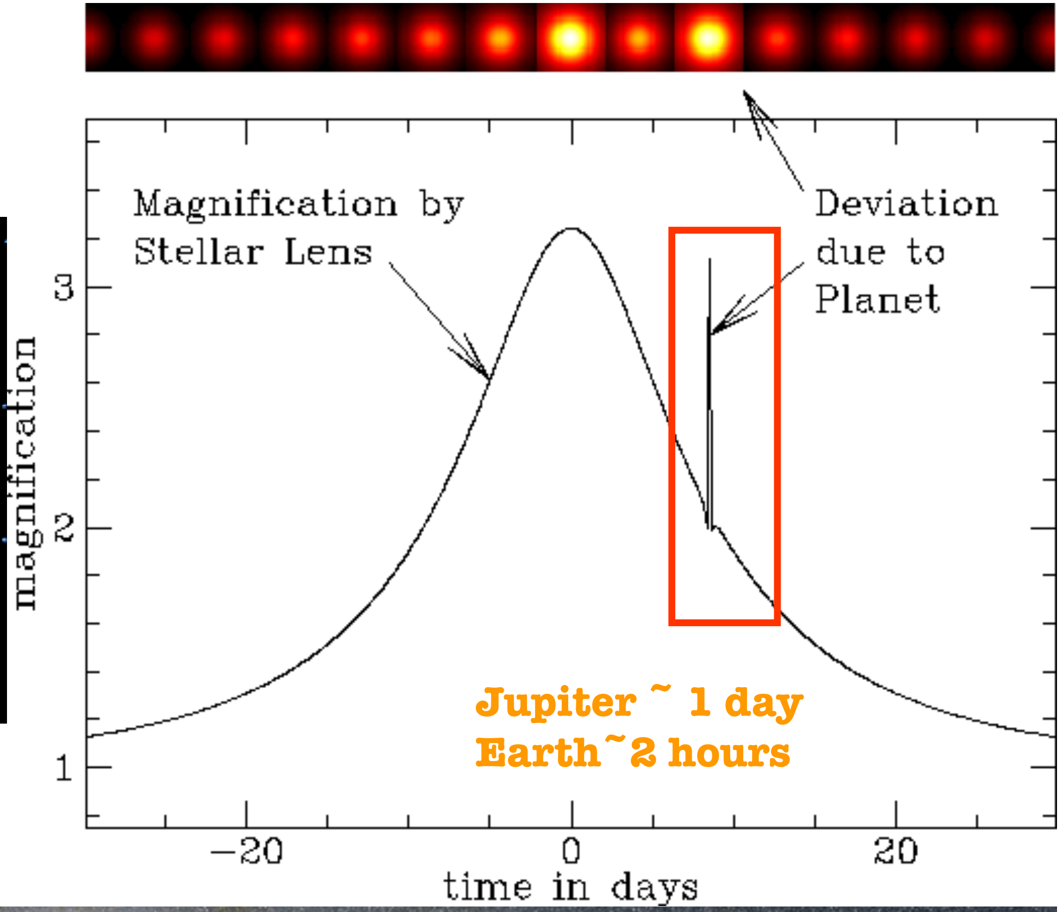
Not that easy to get the planet…

It is easier with smaller stars (more RV amplitude and larger transit), but the smaller stars are colder, more active, so RV and photometry can be tricky.

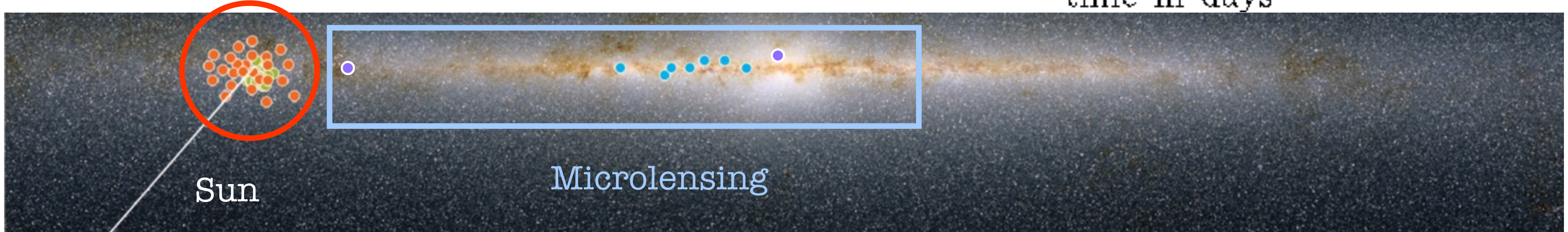
Searching for planet via microlensing

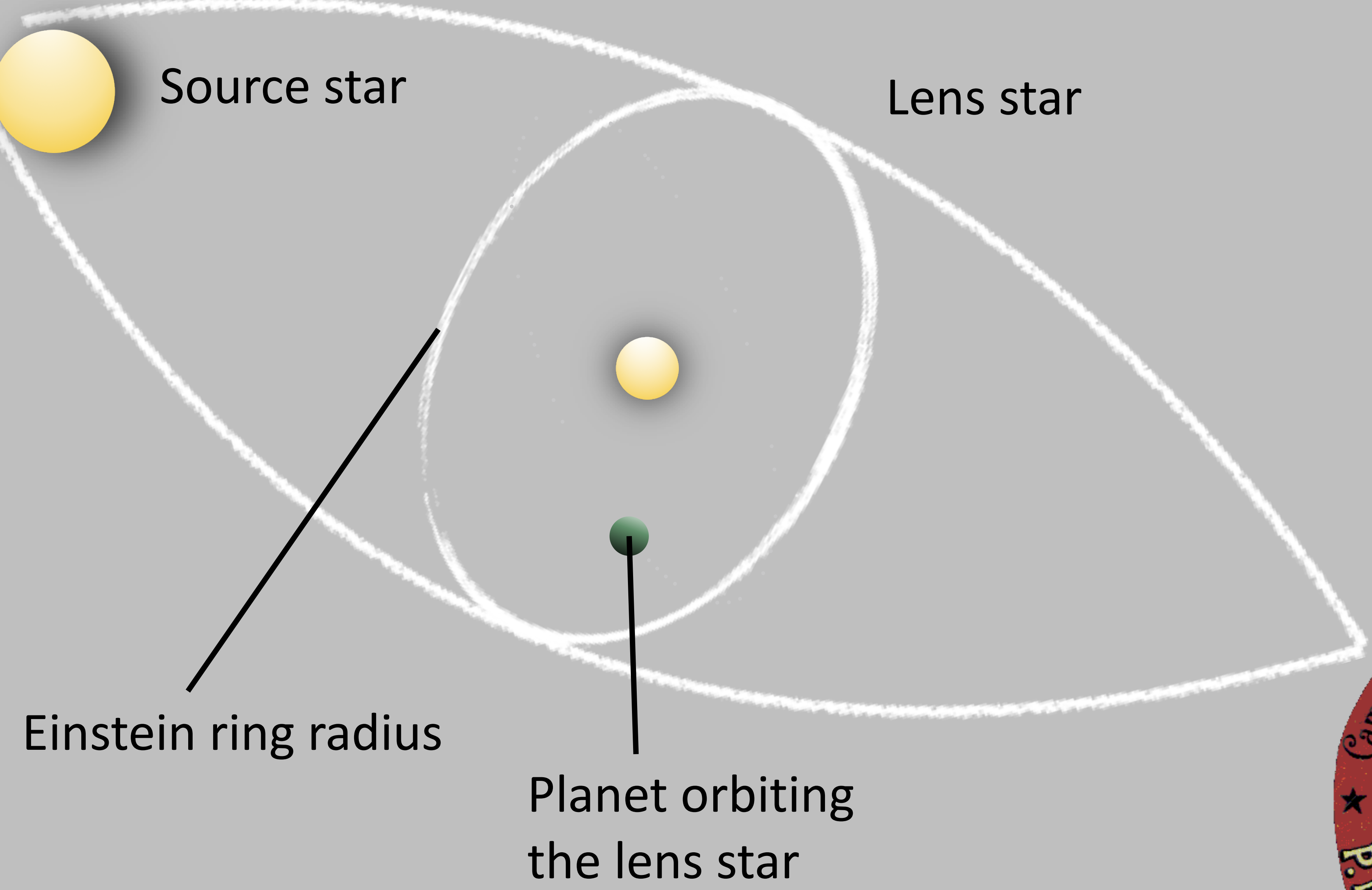
$t_E = 70\sqrt{M/Mo}$ days



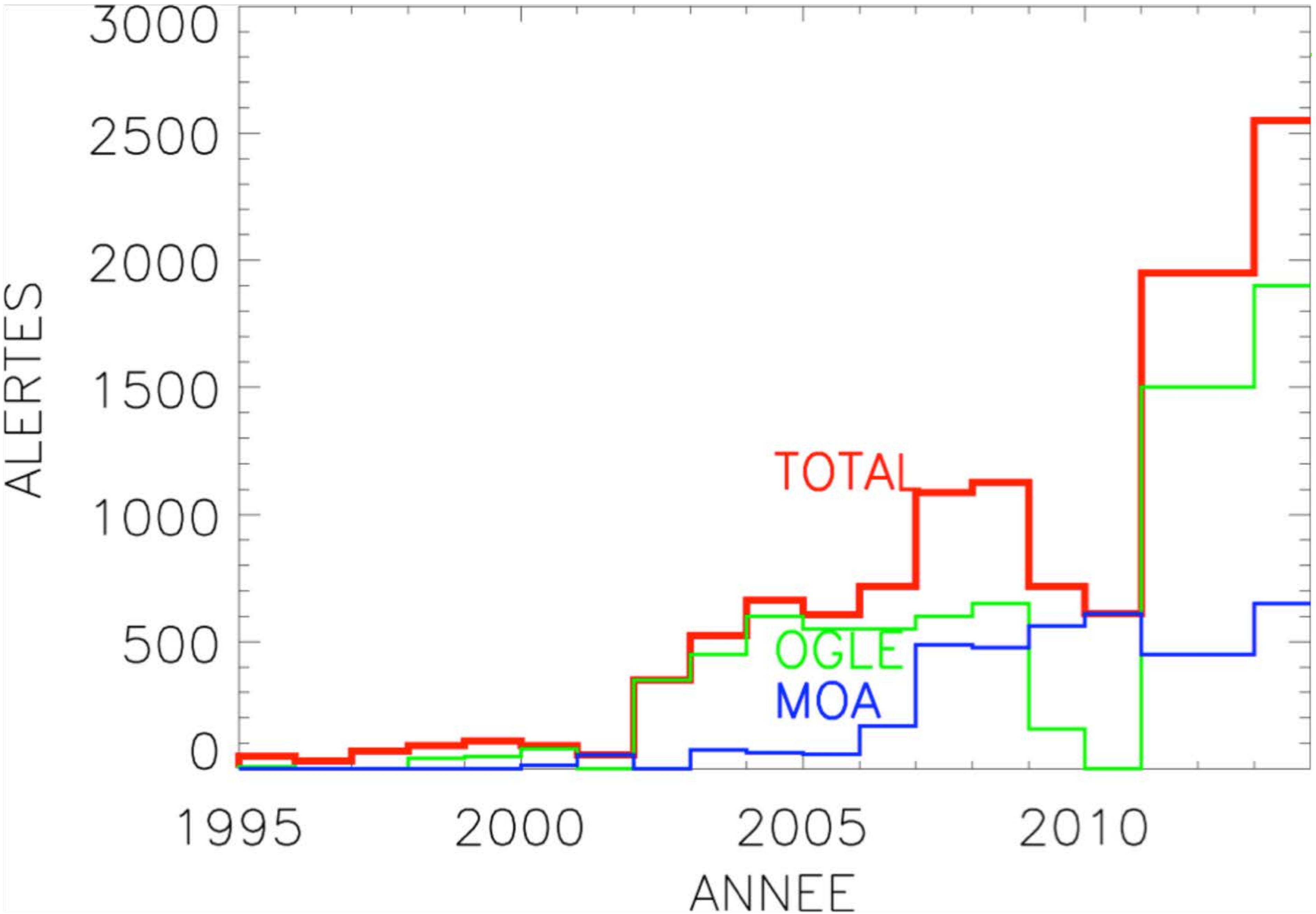


Radial velocities & transits



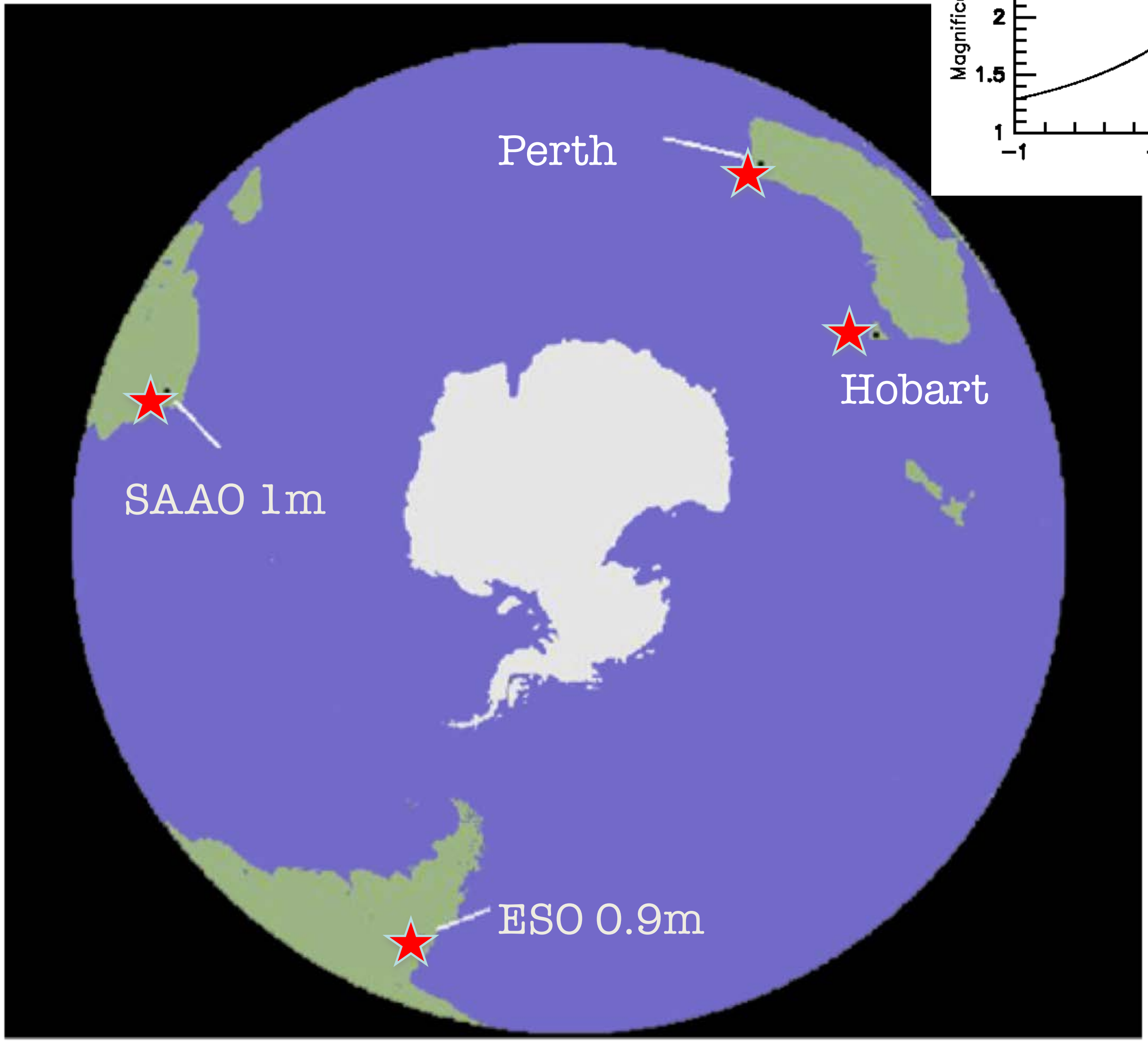

Source star
Lens star
Observer
Einstein ring radius
Planet orbiting the lens star

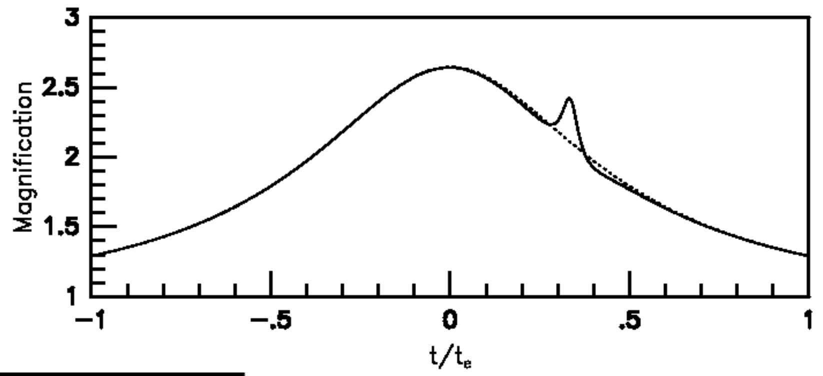
Camembert "LA PLANÈTE" Extra fin
DÉPOSÉ
Seul dépôt
P. MALAUZAT. 61, Rue Ramey, PARIS



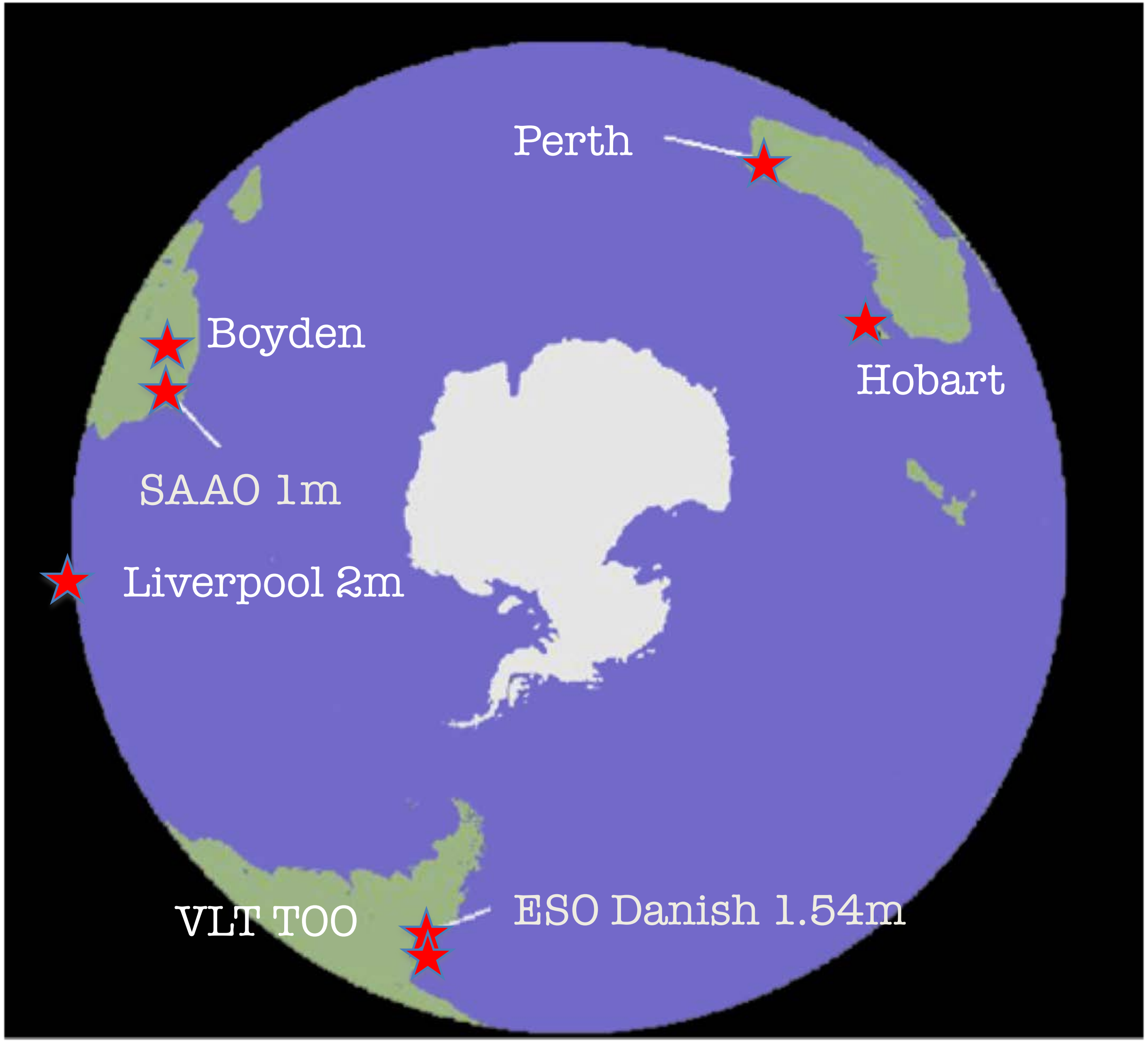
3000
2500
2000
1500
1000
500
0
ALERTES
1995
2000
2005
2010
ANNEE
TOTAL
OGLE
MOA

PLANET 1997

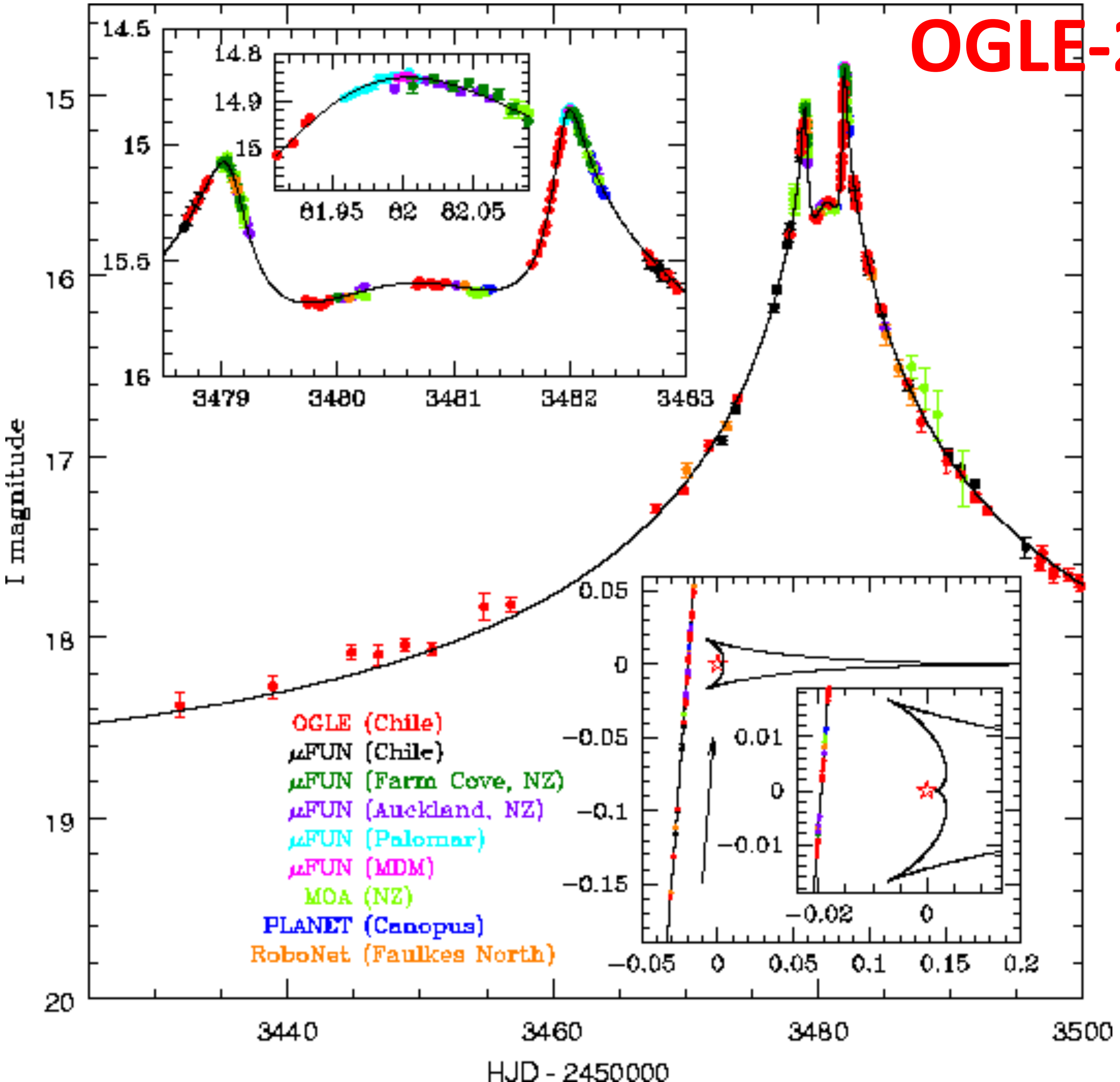

Perth
Hobart
SAAO 1m
ESO 0.9m


Magnification
3
2.5
2
1.5
1
−1
−.5
0
.5
1
t/tₑ

PLANET 2005


Perth
Boyden
Hobart
SAAO 1m
Liverpool 2m
VLT TOO
ESO Danish 1.54m

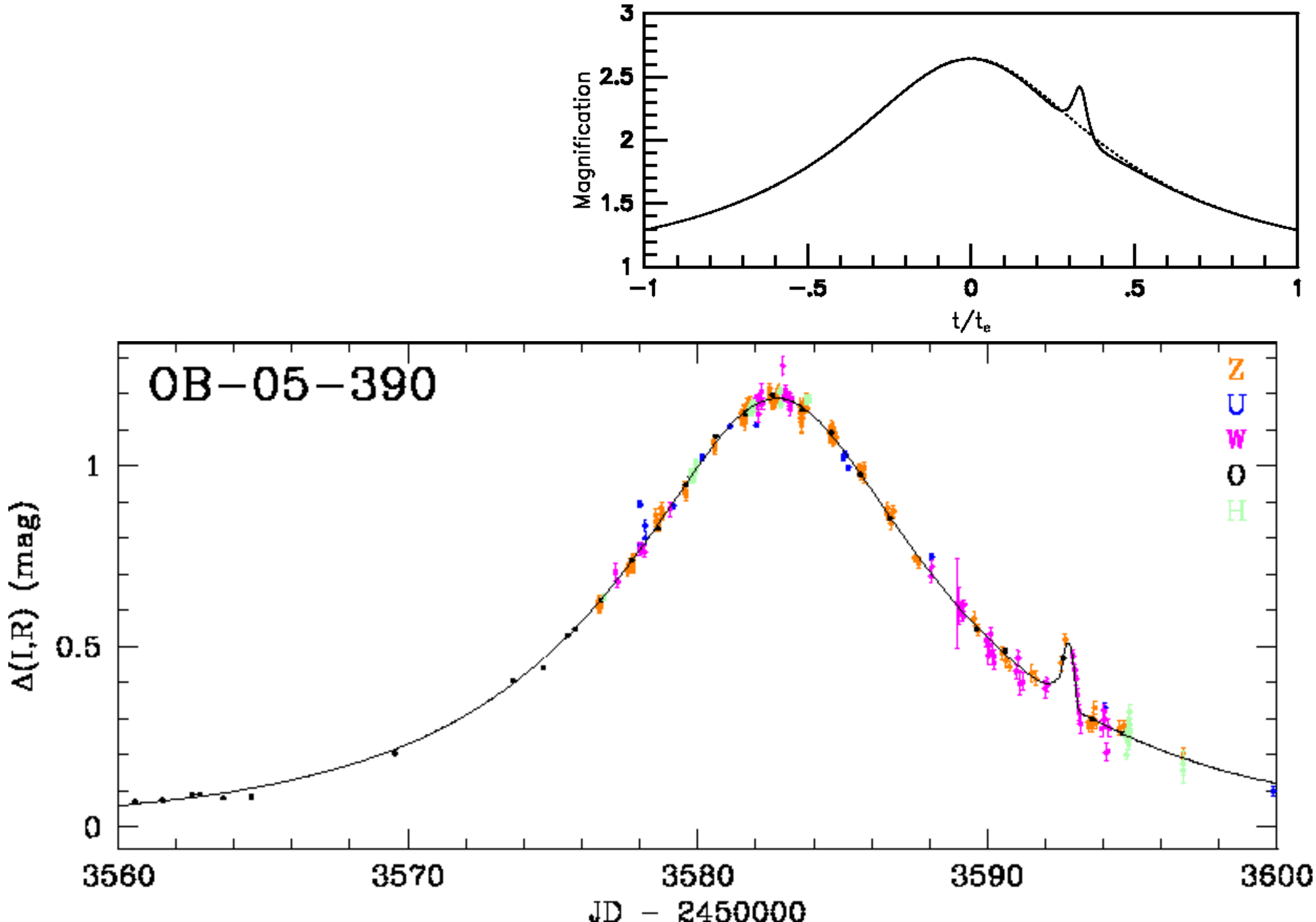
OGLE-2005-BLG-071



Close binary :
d=0.758
$q=6.7\ 10^{-3}$

Wide binary :
d=1.294
$q=7.1\ 10^{-3}$

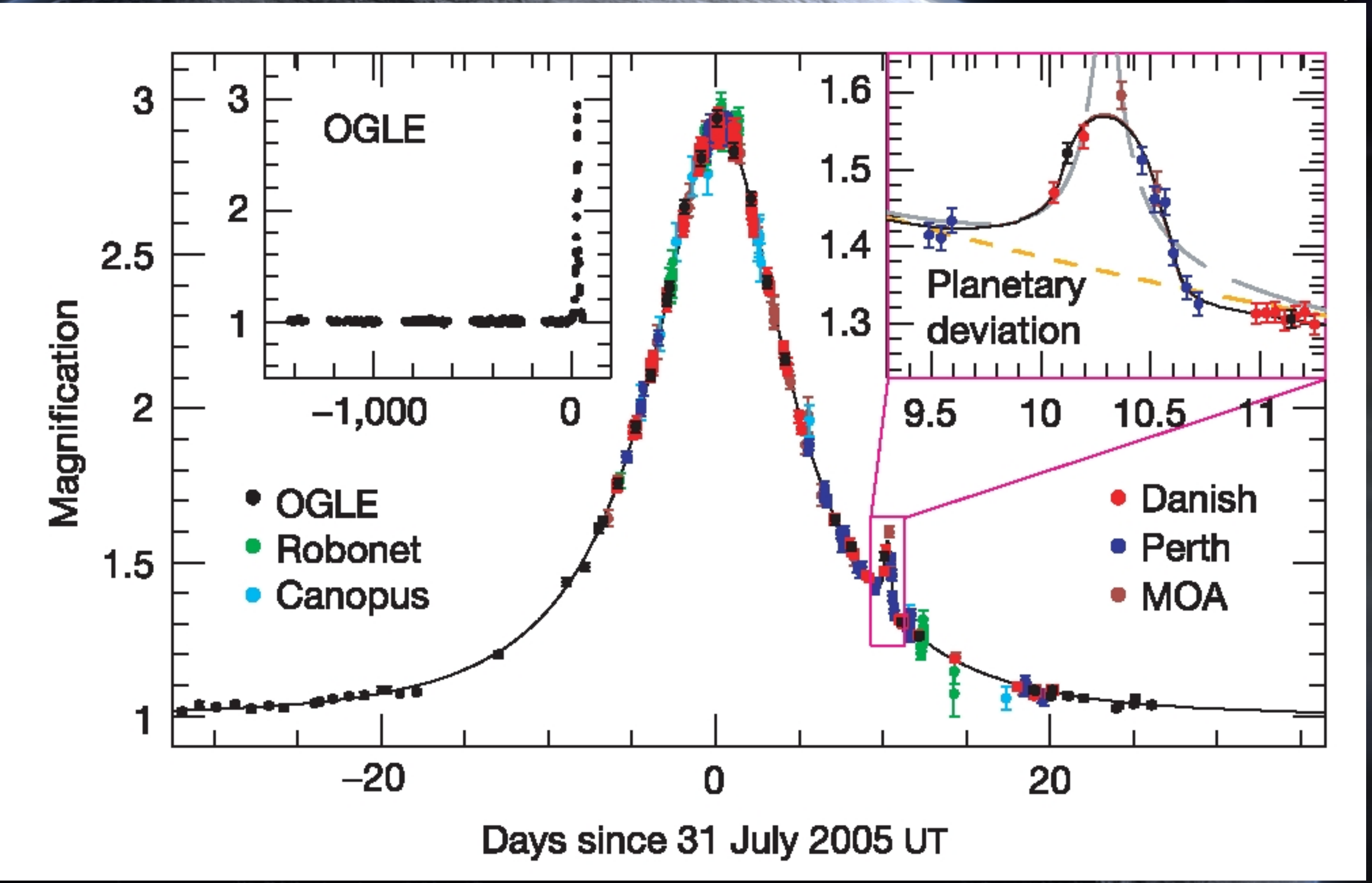
M* ~ 0.45 Mo
5.2 ± 1.8 kpc
2.7 MJupiter
a ~ 2.2 AU or3.7 AU



Magnification
t/t_e
OB-05-390
Z
U
W
O
H
Δ(I,R) (mag)
JD - 2450000

A first frozen super Earth

Gas giants are are, super Earth-Neptunes are common
Same direction as the core accretion model predictions



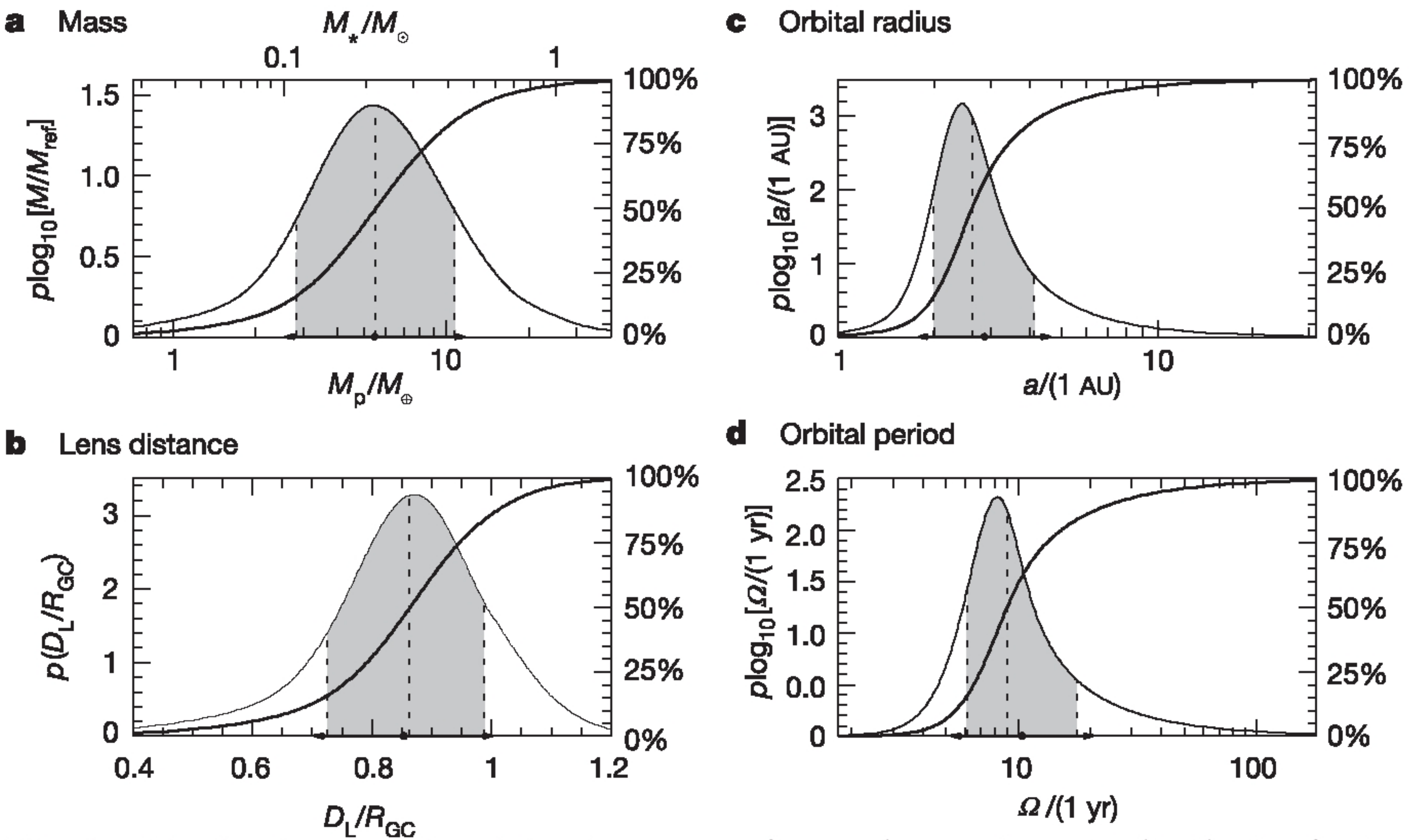
$$M_* = 0.22^{+0.21}_{-0.11}\ M_{\text{SUN}}$$

$$M_{\text{p}} = 5.5^{+5.5}_{-2.7}\ M_{\text{EARTH}}$$

$$a = 2.6^{+1.5}_{-0.6}\ \text{AU}$$

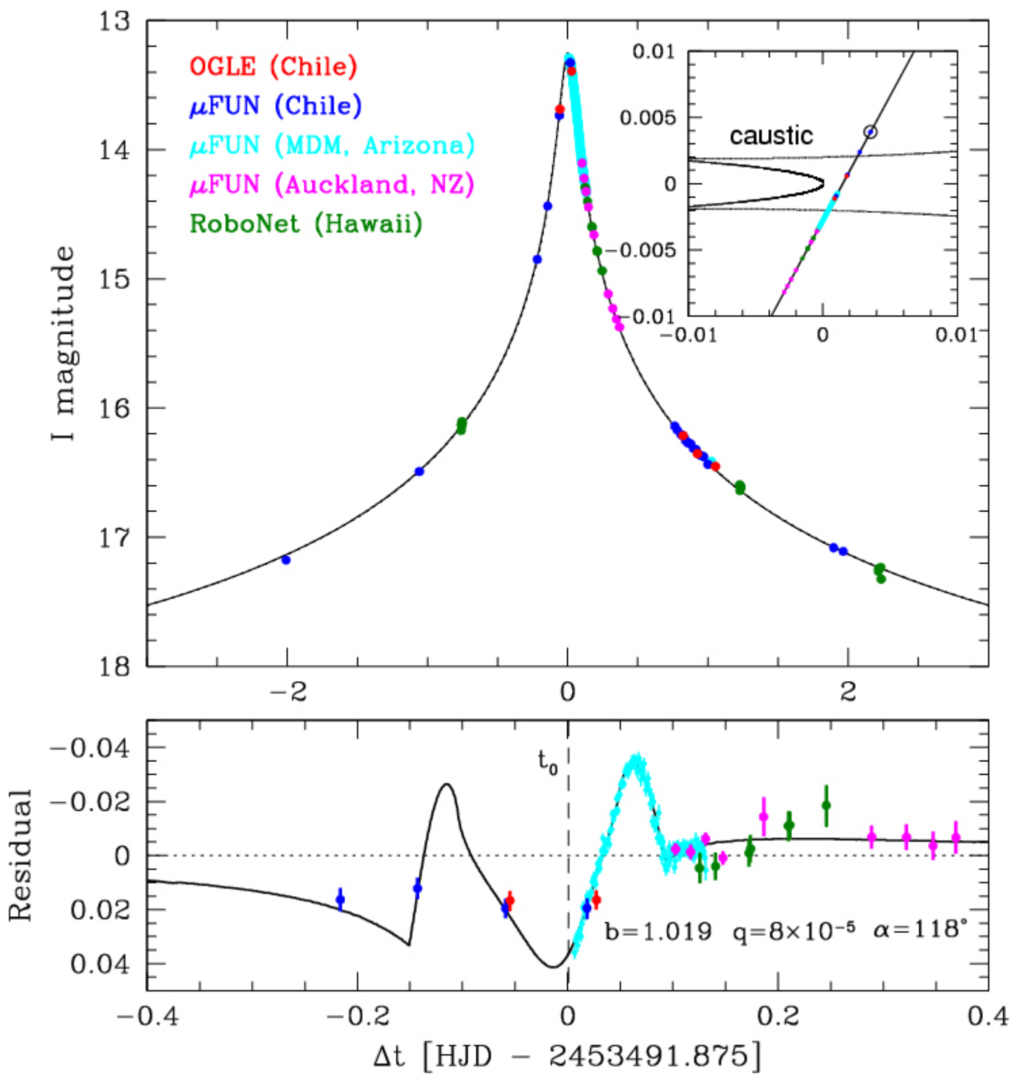
Beaulieu et al., 2006, Nature (PLANET, OGLE, MOA)

Properties of the star & the planet



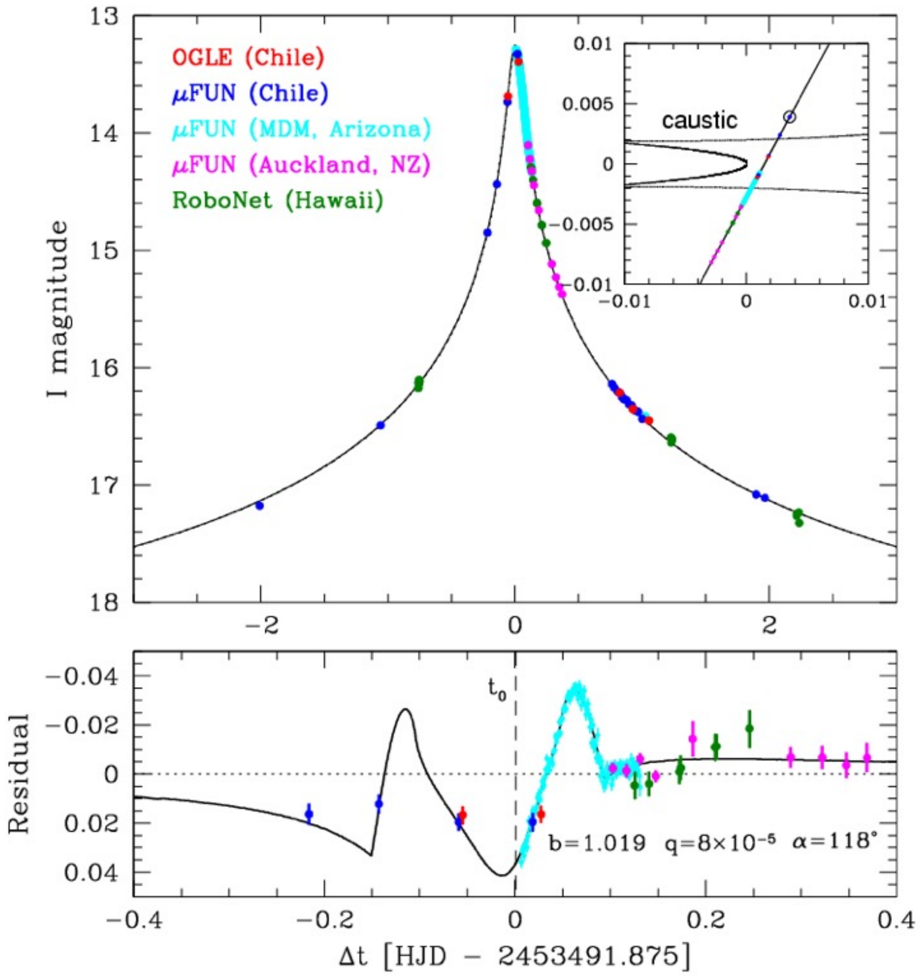
Like Hoth planet from star wars

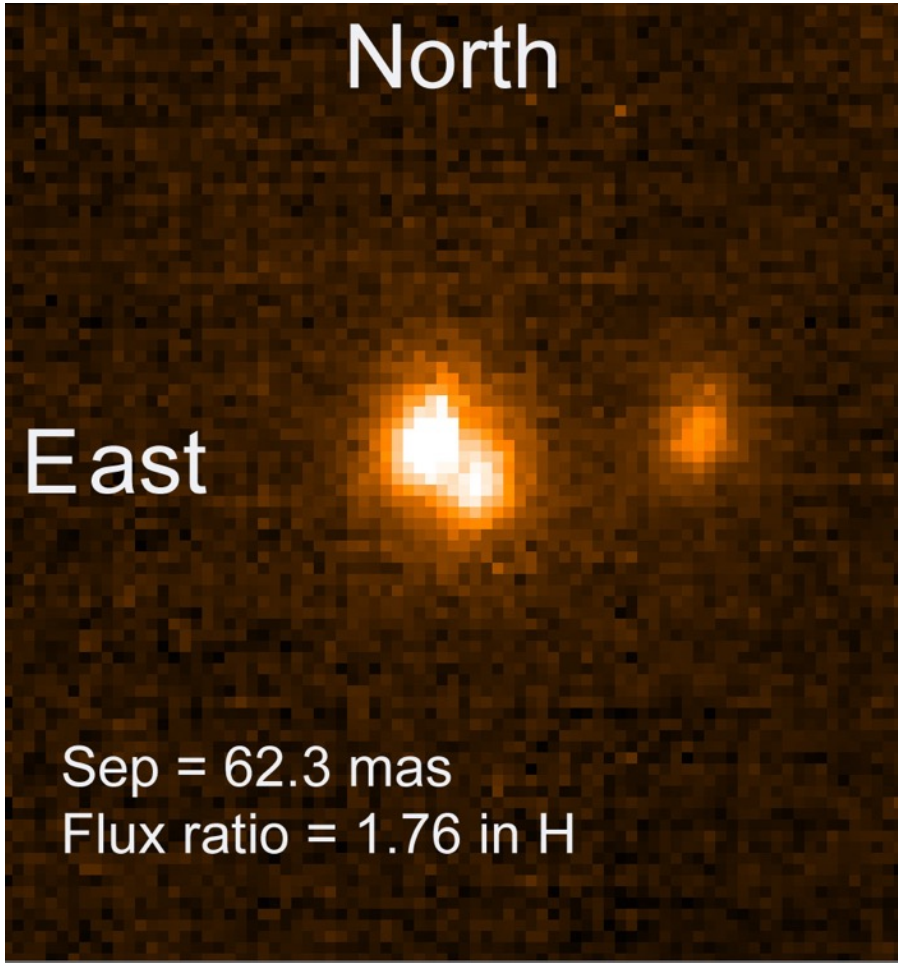
OGLE-2005-BLG-169Lb : a ~13 $M_\oplus$ planet



Gould et al. 2006, MicroFUN, OGLE, RoboNet

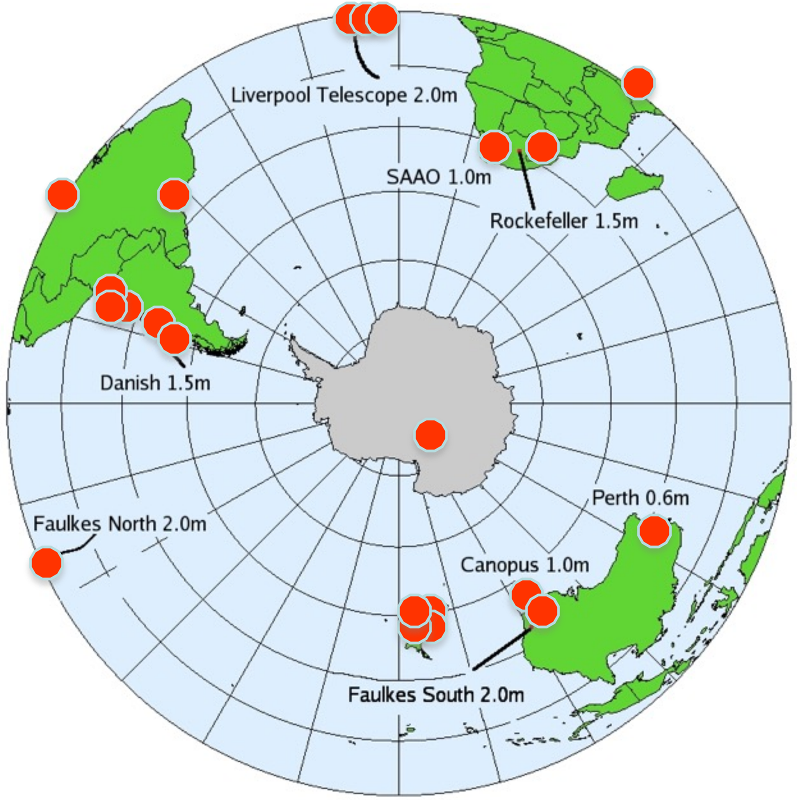
With KECK, detecting the lens in 2013 Measuring proper motion





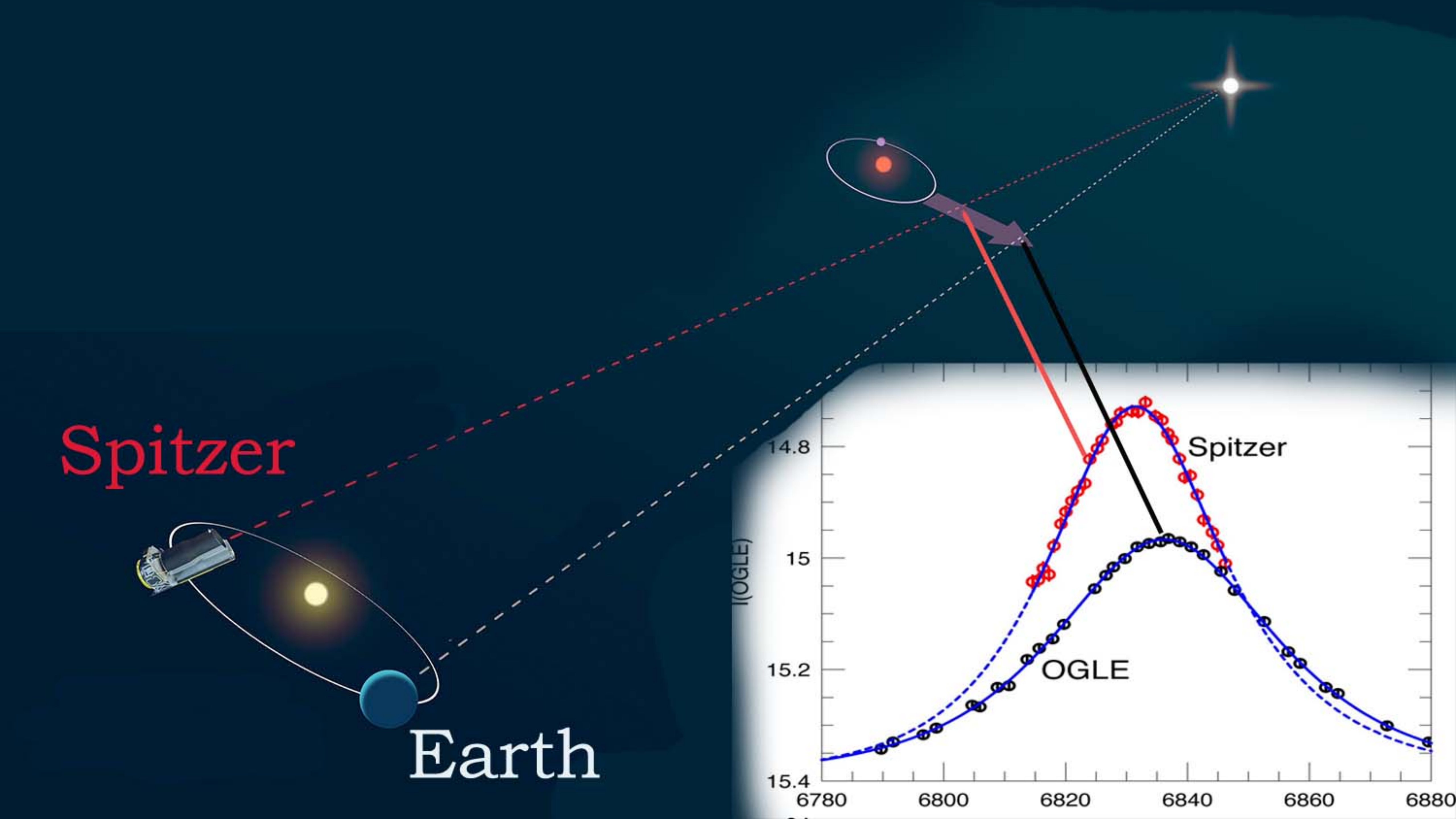
Planet hunting in 2013

- Network of telescopes, round the clock observations, online analysis.

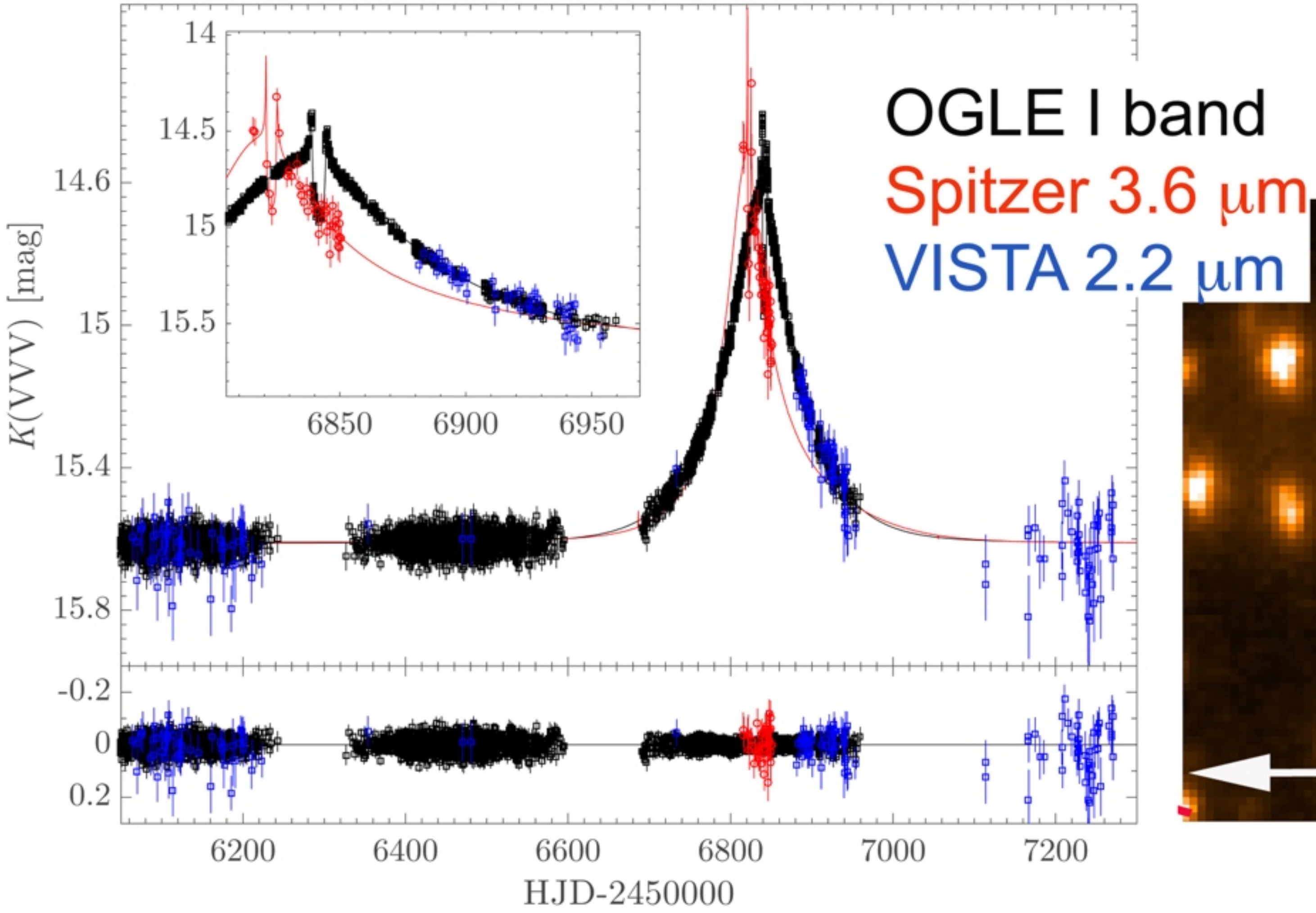


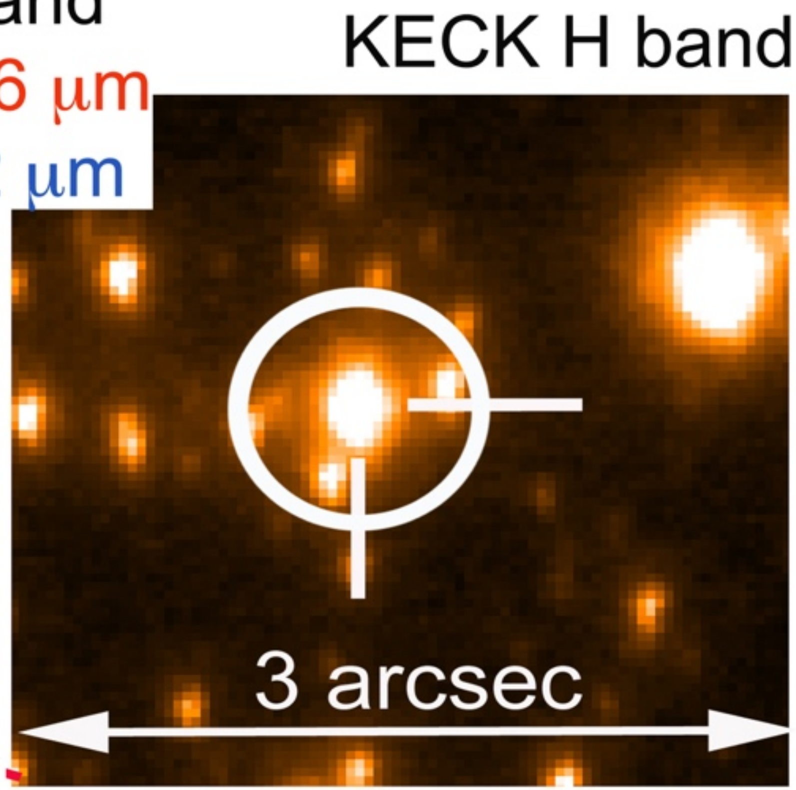
From 4 telescopes, to a fleet of 45+ telescopes on alert
Including DOME C

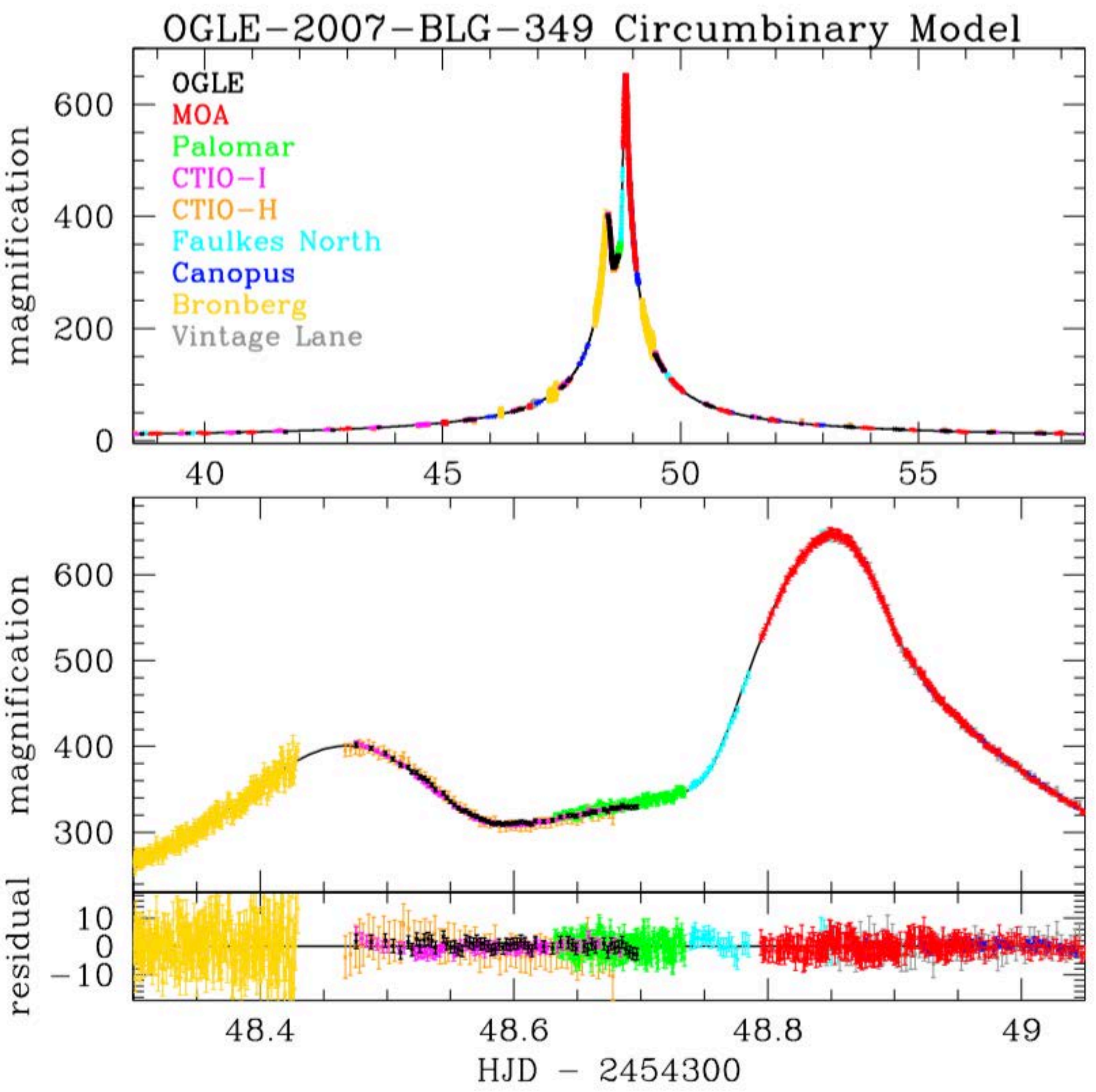
2007-2011: 4-7 planets/year
2012 = 22 planets.
2013-2019 = 10-15 planets/year


Spitzer
Earth
Spitzer
OGLE
I(OGLE)
14.8
15
15.2
15.4
6780
6800
6820
6840
6860
6880

Ground-space parallax to measure masses



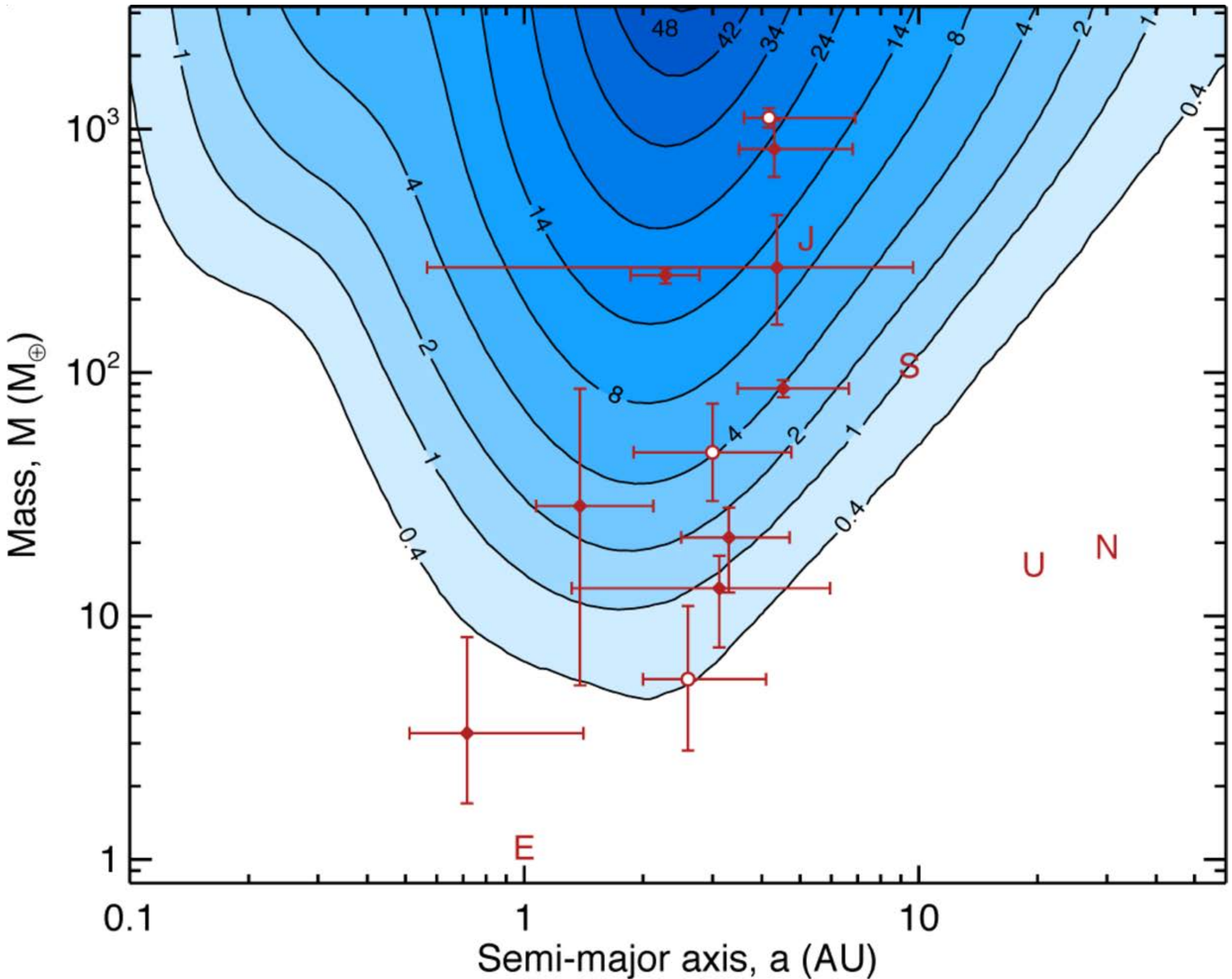


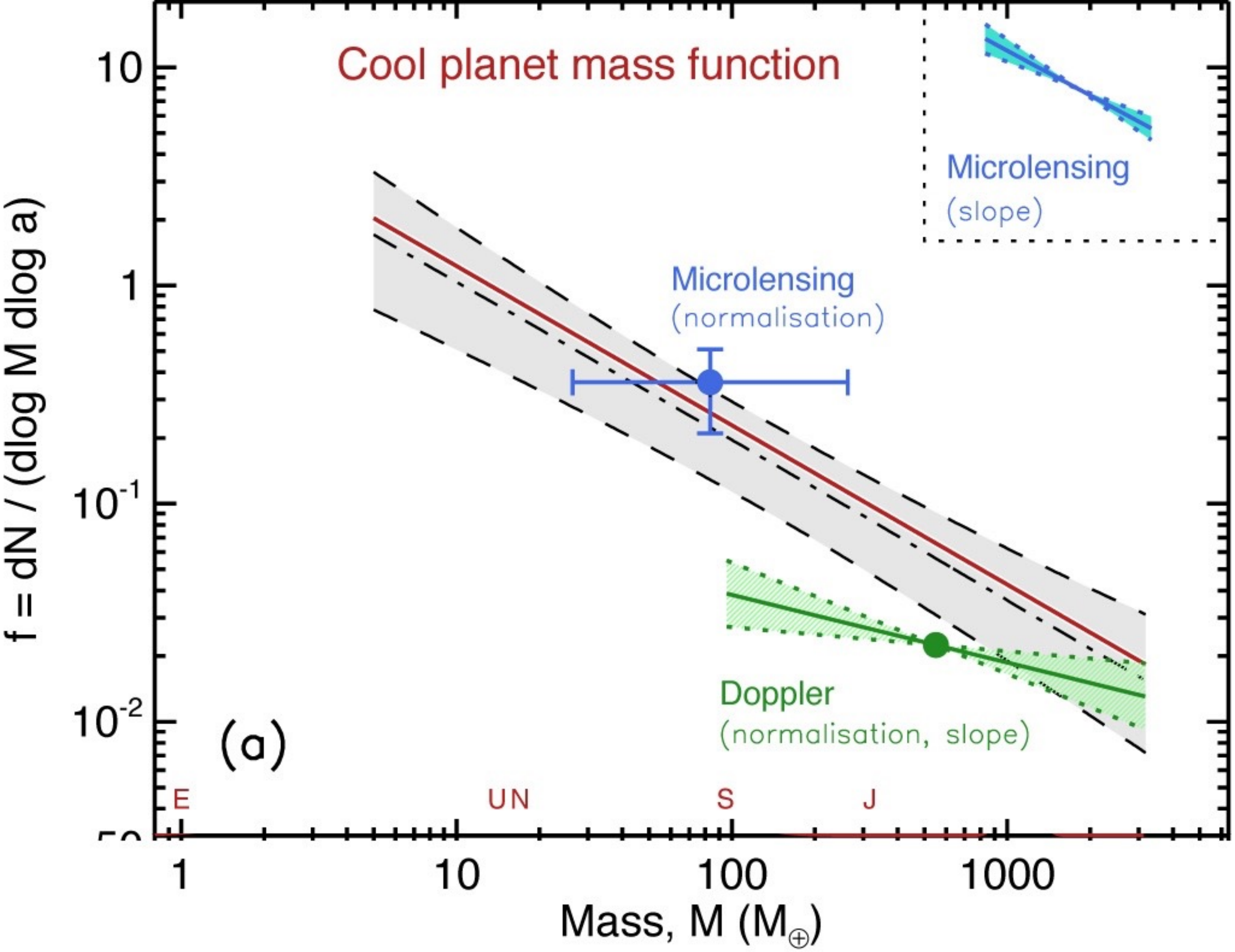


OGLE-2007-BLG-349 Circumbinary Model
OGLE
MOA
Palomar
CTIO-I
CTIO-H
Faulkes North
Canopus
Bronberg
Vintage Lane
magnification
residual
HJD − 2454300

Tatooine

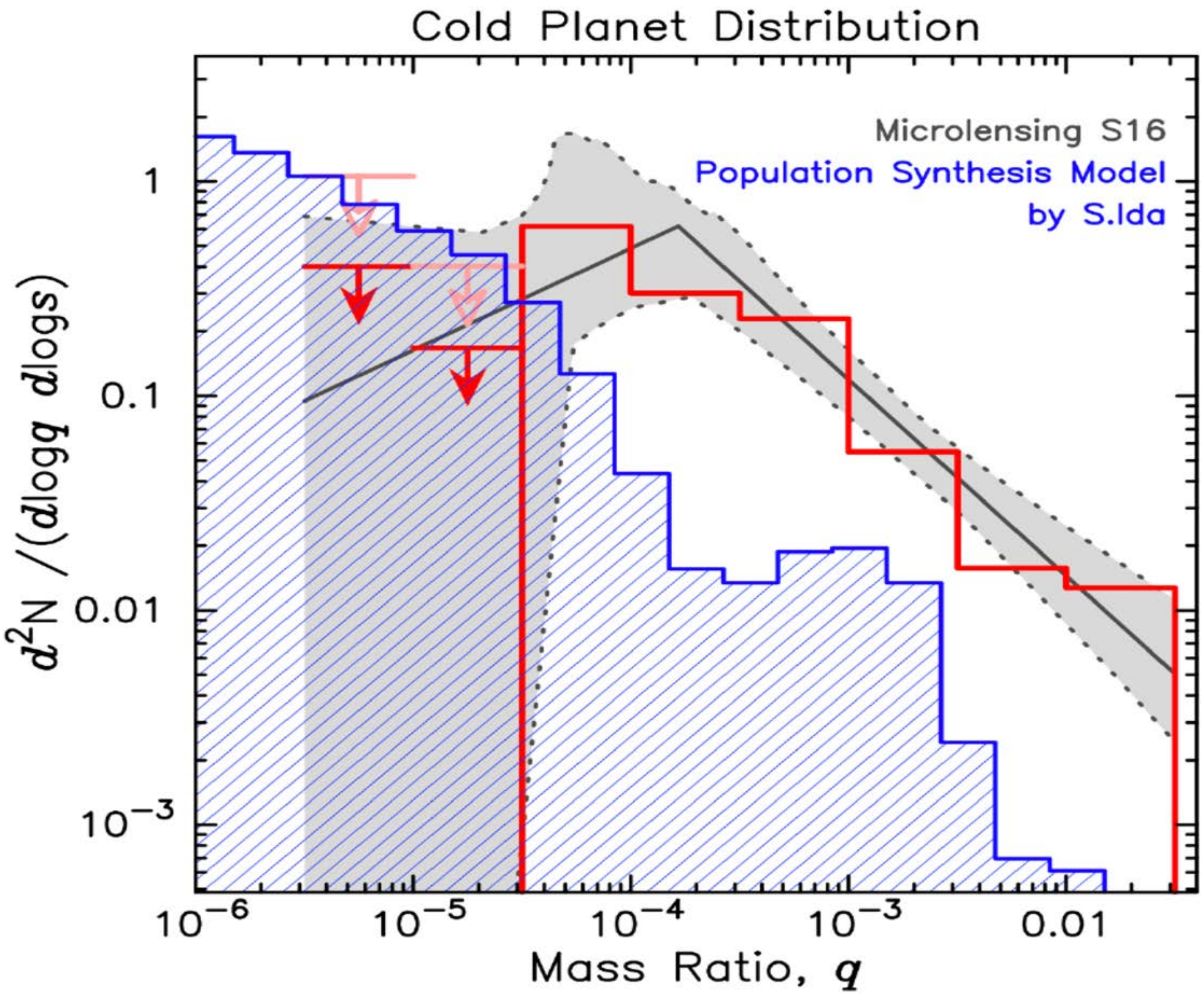
Detection efficiencies 2002-2007

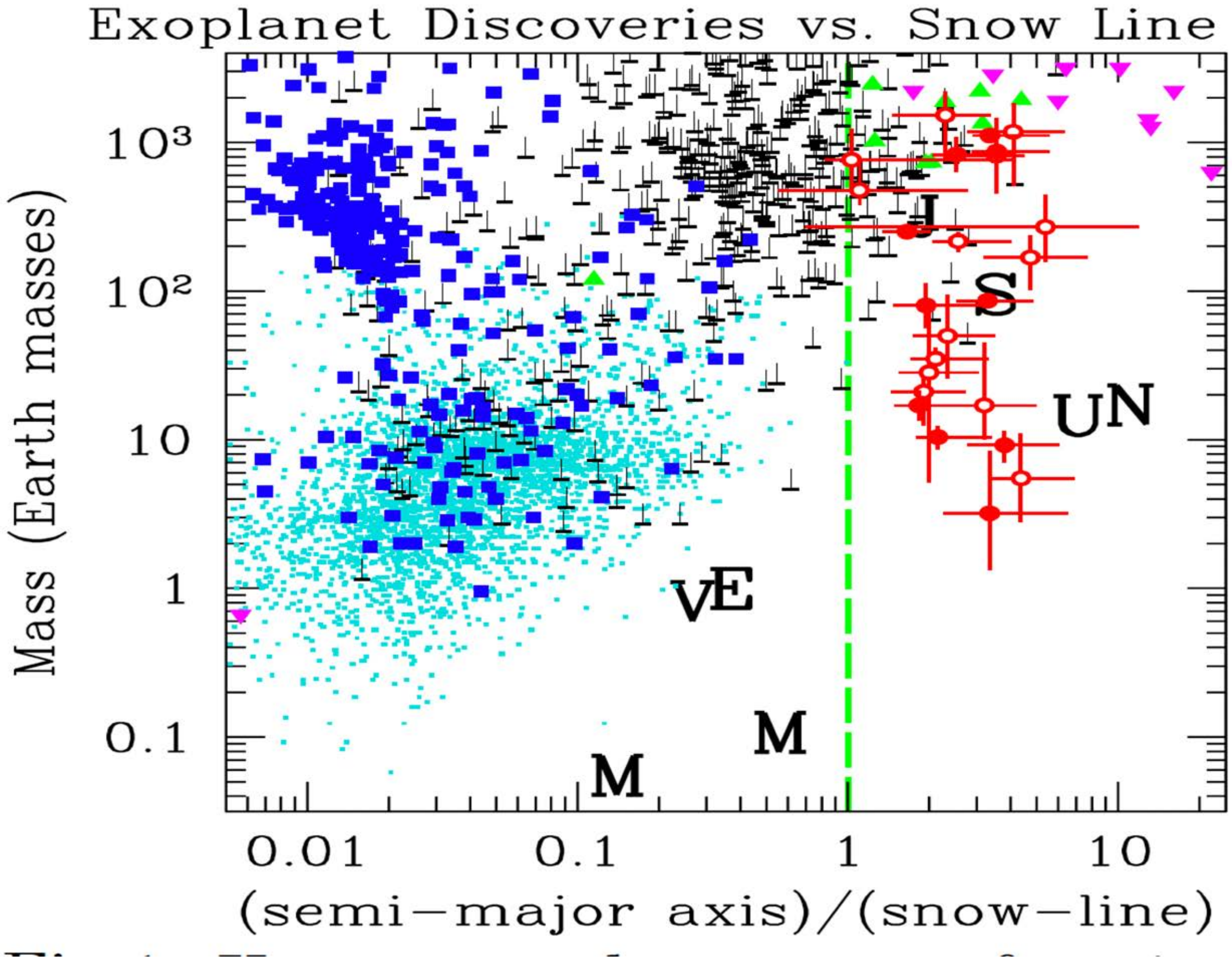




Cassan et al. 2012, Nature

Cold planets, mass-ratio function, suzuki et al. 2016

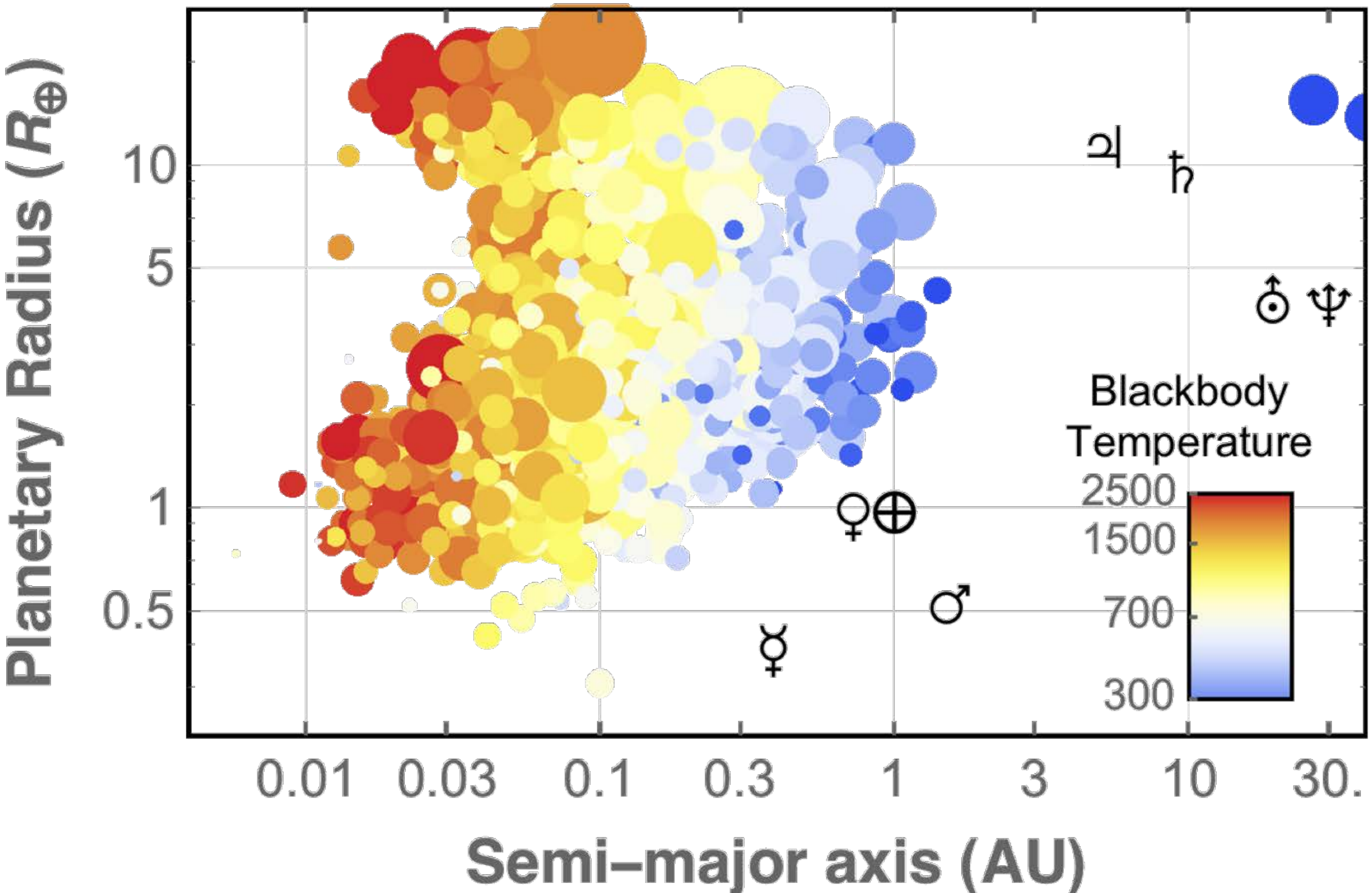




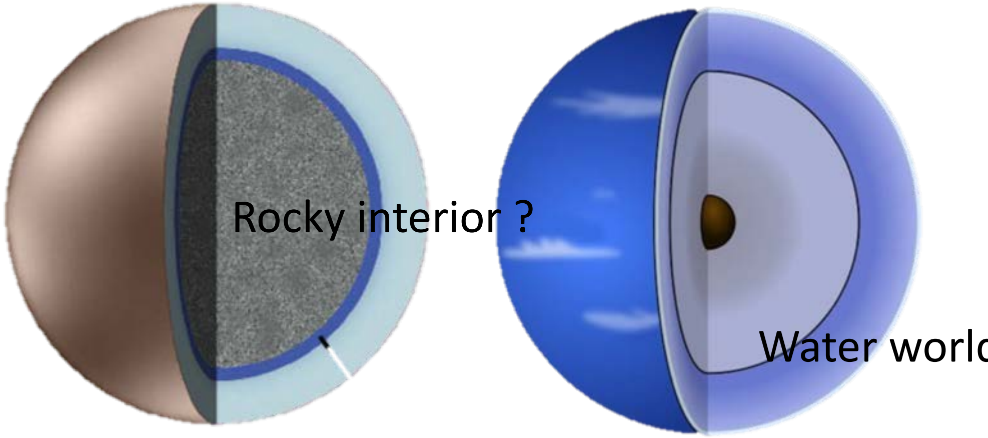
Snow line approximated as 2.7 x M / Mo (AU)

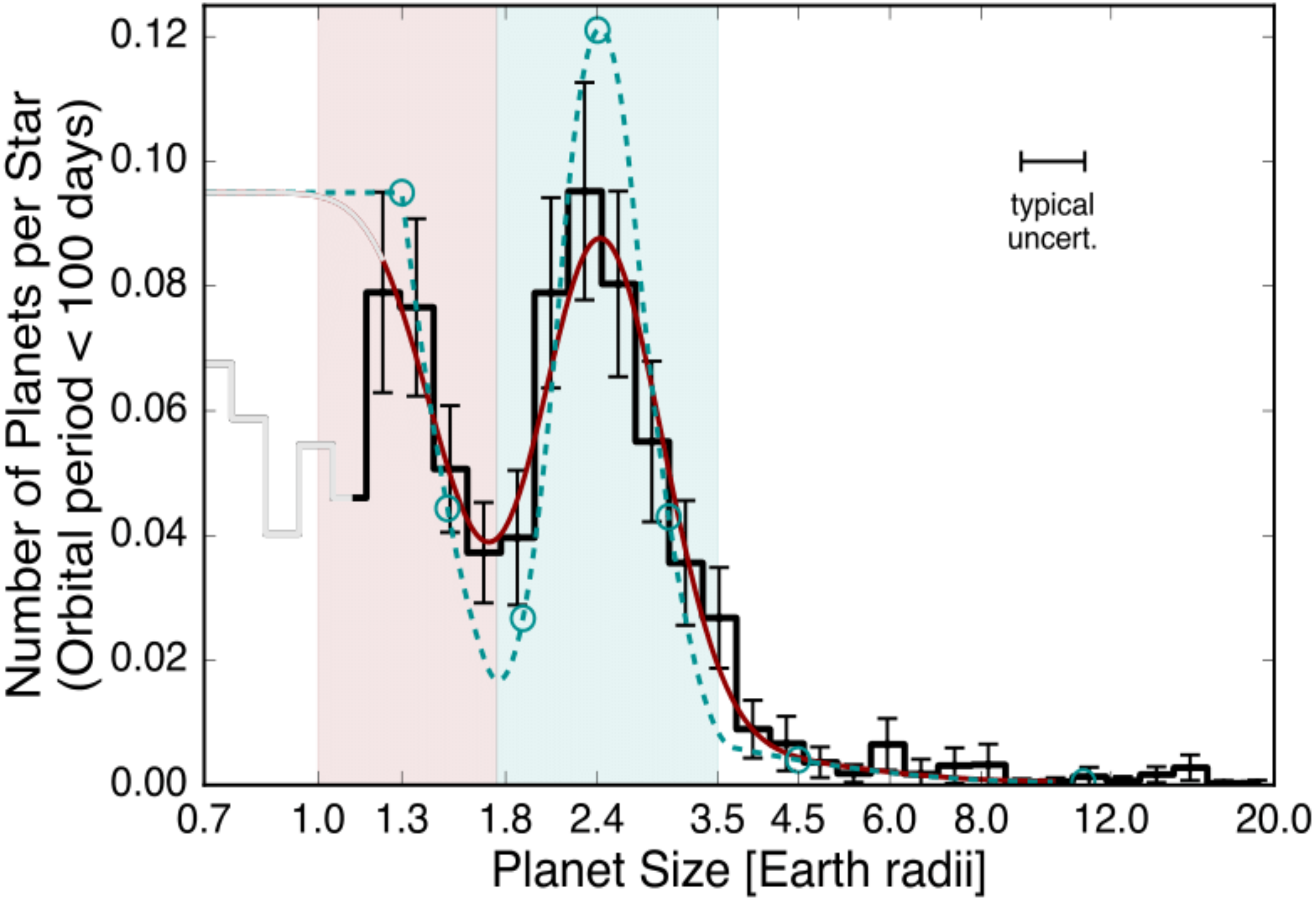
Exoplanets today: huge diversity

3800+ PLANETS, 2700 PLANETARY SYSTEMS KNOWN IN OUR GALAXY



Histogram of planet radii, 2 peaks, super-Earth and Mini-Neptune





Completeness-corrected histogram of planet radii for planets with orbital periods shorter than 100 days.

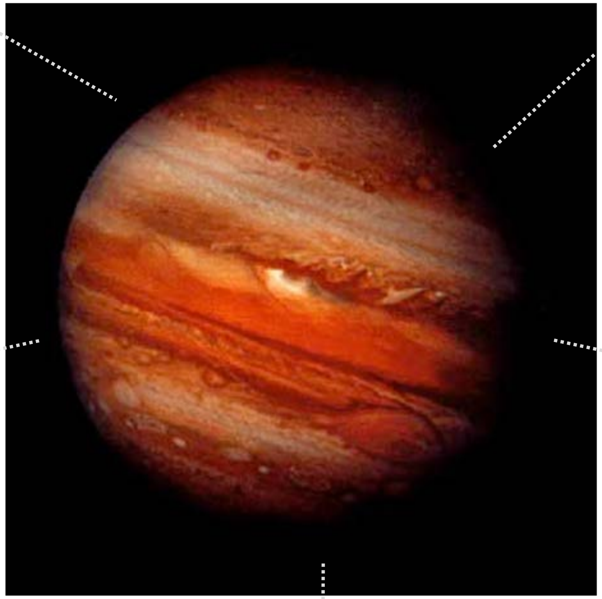
Lightly shaded regions encompass our definitions of “super-Earths” (light red) and “sub-Neptunes” (light cyan). The dashed cyan line is a plausible model for the underlying occurrence distribution after removing the smearing caused by uncertainties on the planet radii measurements.

Gaseous giant planets

Formed elsewhere and migrated

Planet formation
C/O ratio

Energy budget
Albedo/thermal emission



Planet-star interaction
Photochemistry+
Day/night variation

Weather
Temporal variability/
T-P profile

Planet evolution
Escape/H_3^+

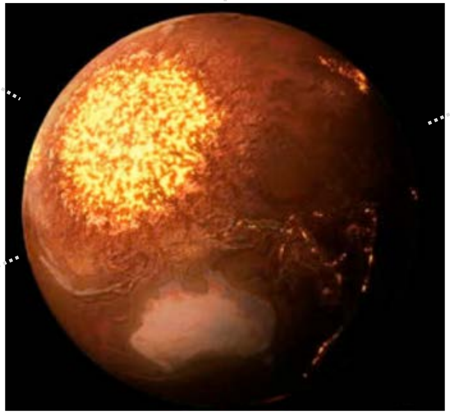
Terrestrial planets,

formed in situ ? Remnant of gaseous giant ?

Primary or secondary atmosphere?
H_2 retained or not

Does the planet have an atmosphere?
Spectral observations

Energy budget
Albedo/thermal emission



Habitable conditions?
Temperature?
H_2O?

Main atmospheric component
Primary transit observations

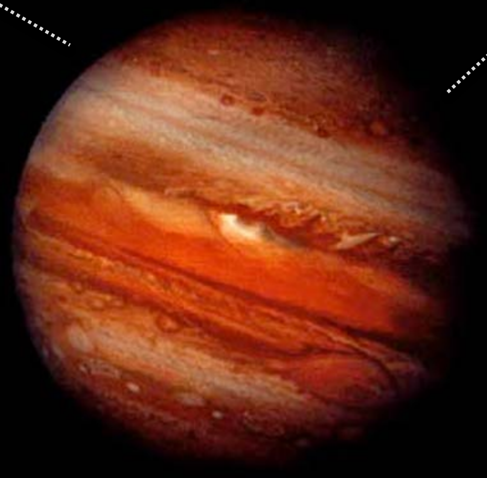
Planet-star interaction
Photochemistry

Gaseous planets

formed elsewhere and migrated

Planet formation
C/O ratio

Energy budget
Albedo/thermal emission



Planet-star interaction
Photochemistry+
Day/night variation

Weather
Temporal variability/
T-P profile

Planet evolution
Escape/H_3^+

Terrestrial planets

formed in situ? Or remnant of gaseous planets' core?

Primary or secondary atmosphere?
H_2 retained or not

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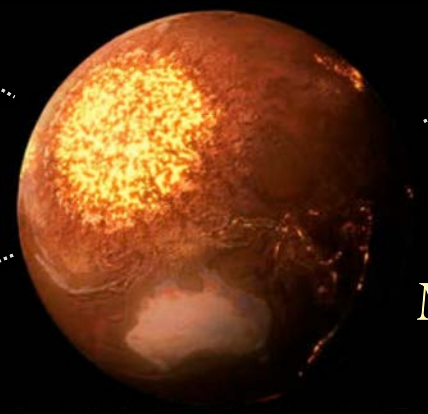
Energy budget
Albedo/thermal emission



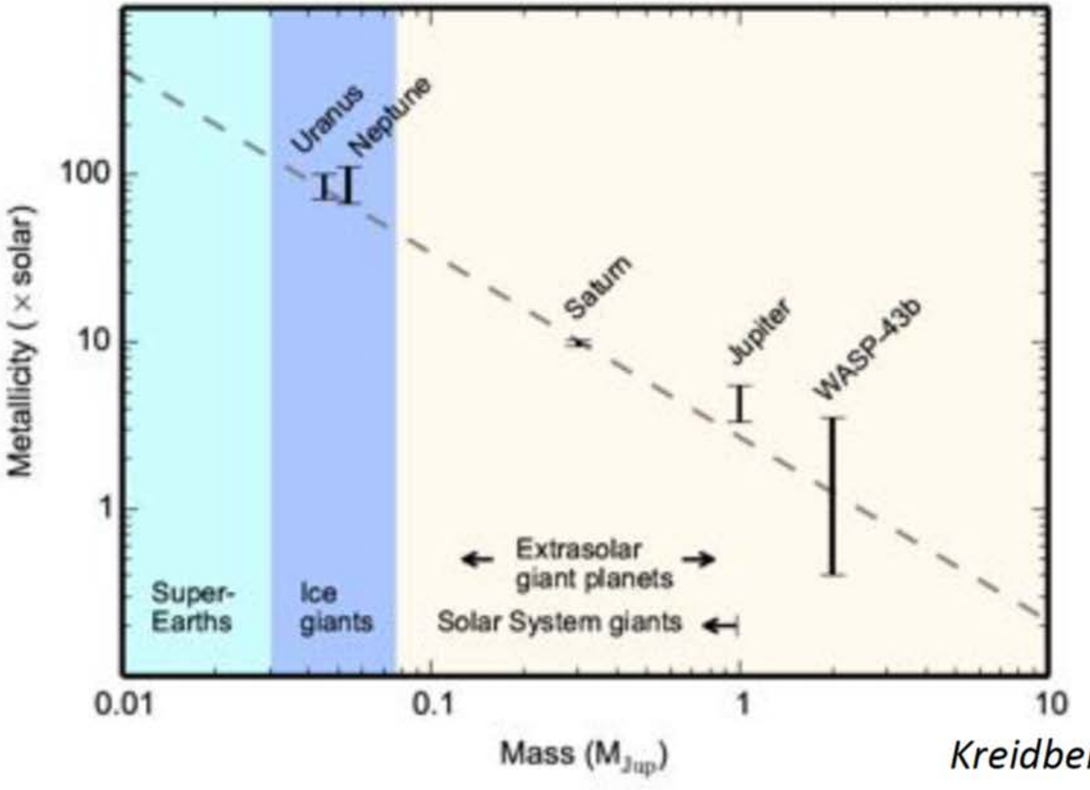
Habitable conditions?
Temperature? H_2O?

Main atmospheric component
Primary transit observations

Planet-star interaction
Photochemistry

Atmospheres as a probe of planetary interior and formation

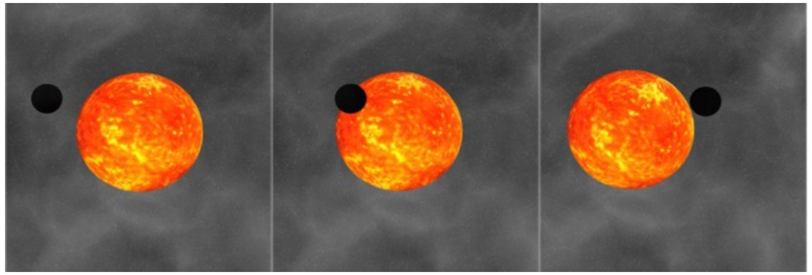
Metallicity = fraction of heavy elements (heavier than H and He)
For Solar System atmospheres, metallicity ≈ $[C]/[C]_{solar}$
For exoplanetary atmospheres, metallicity ≈ $[O]/[O]_{solar}$

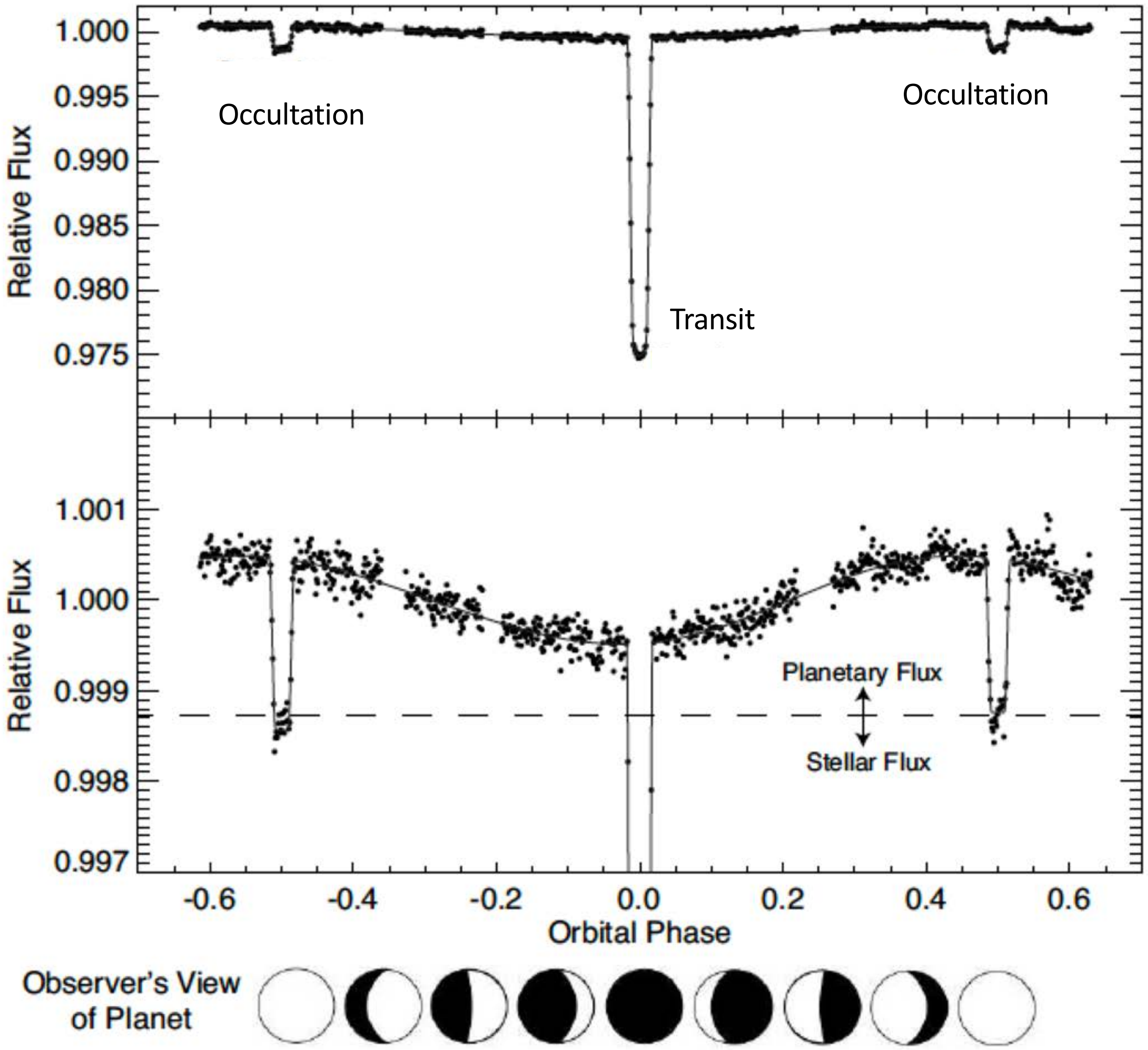


Kreidberg et al. (2015)

- Metallicity decreases with planetary mass in the Solar System
- Sub-Neptunes/Neptunes planets formed in-situ should have a relatively low metallicity

→ Measuring the metallicity allows to test formation and migration mechanisms





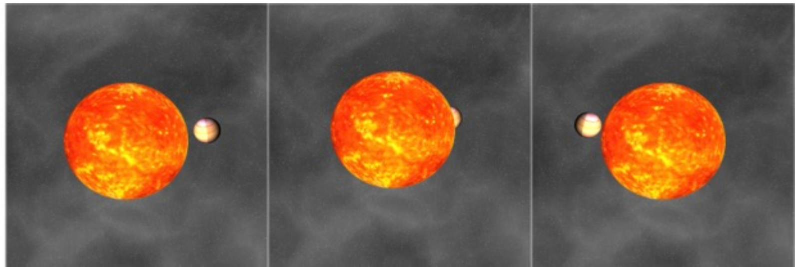
Transit depth:

$$\delta_{tra} = \left(\frac{R_p}{R_\star}\right)^2$$

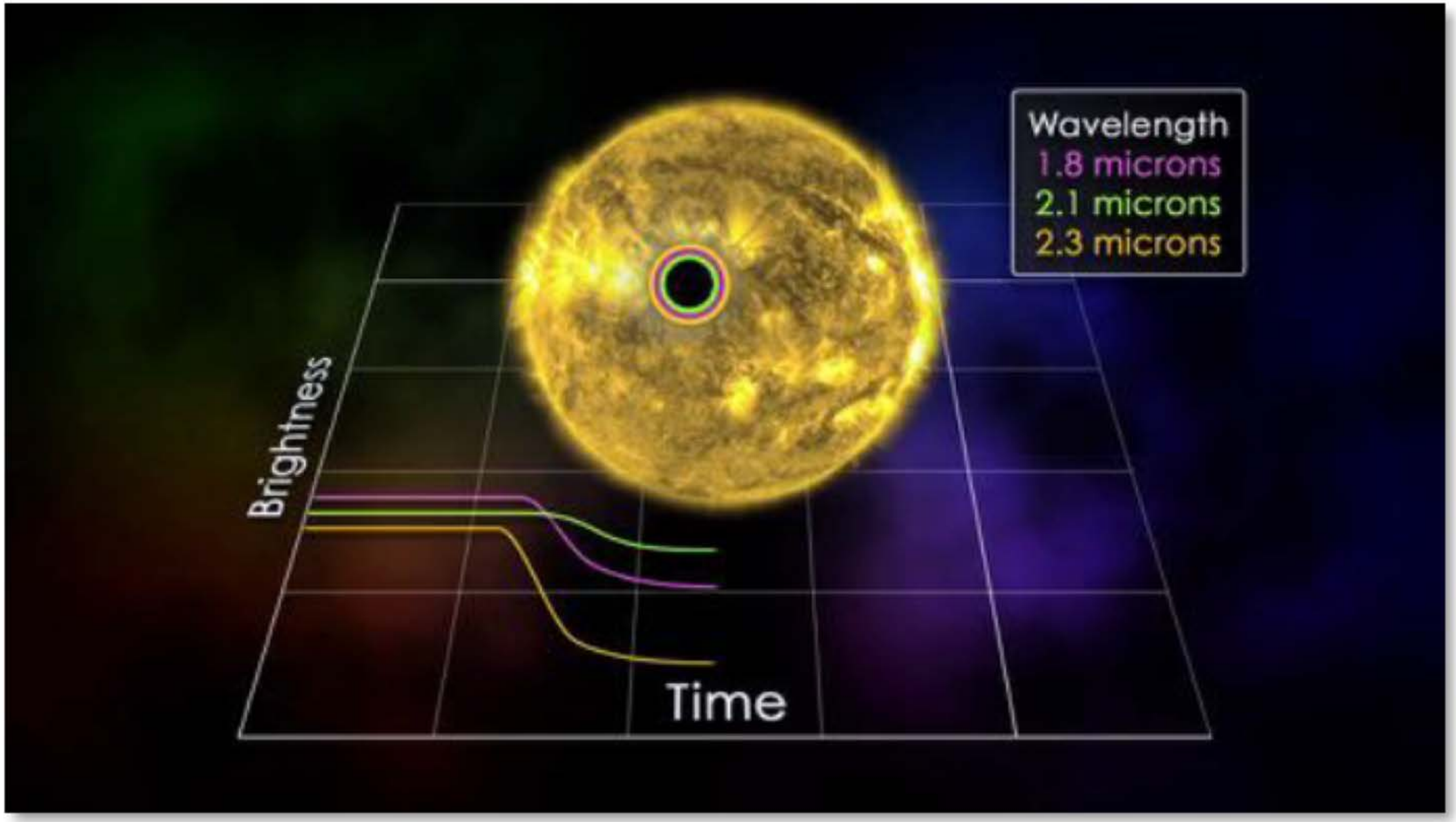
Occultation depth:

$$\delta_{occ} = \frac{I_p}{I_\star}\left(\frac{R_p}{R_\star}\right)^2$$

Flux ratio day side of the planet / star



At different wavelength, because of different absorbing molecules-> different effective radius



Scale height in an atmosphere

$$P(z) = P(z_{0)}\ exp\left(-\frac{Z-Z}{H}\right)$$

Pressure falls off exponentially with height in atmosphere with uniform temperature.

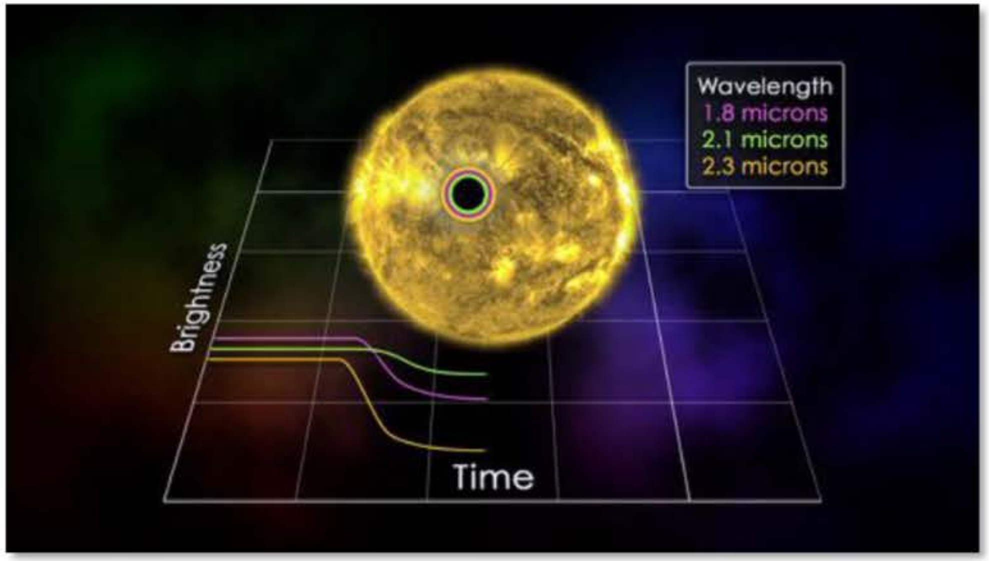
$H = \left(\frac{RT}{Mg}\right)$ has the dimension of distance and is called, the scale height.

M is the mean molecular mass, 2.3 g/MOL for hot Jupiter, 28 g/MOL for Earth

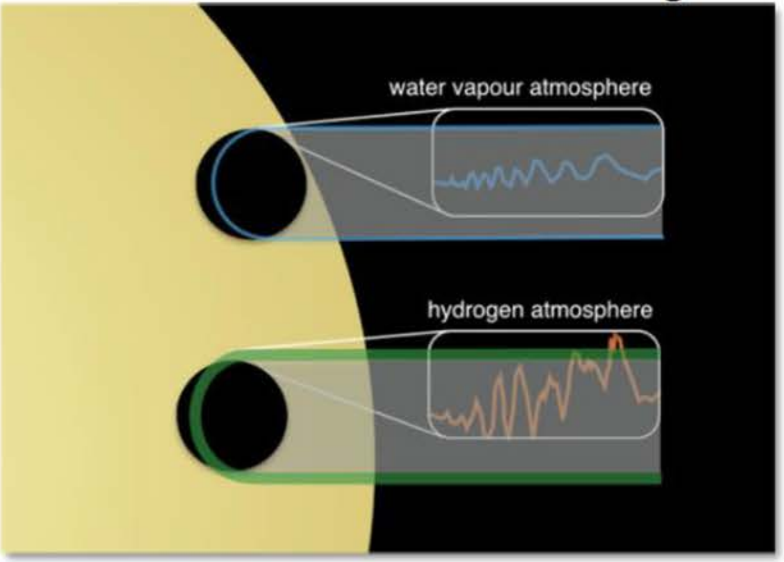
Atmosphere of gazeous planets more extended than Earth like !

I) Transit

Spectroscopy



Effect of mean molecular weight



- The expected depth of the absorption features in a haze-free atmosphere is proportionalto the atmospheric scale height

Variation of transit depth:

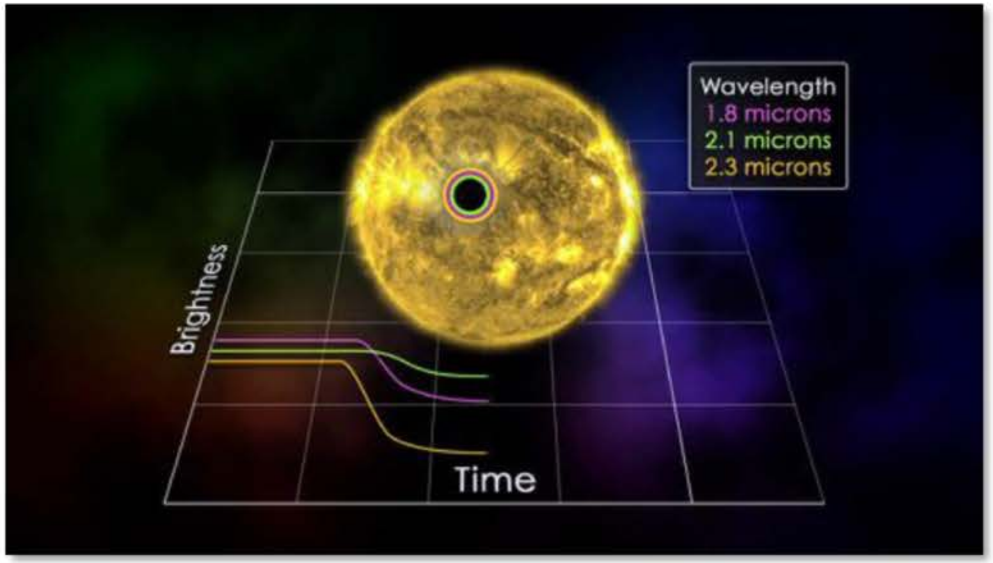
$$\Delta\delta_{tra} = \frac{\pi(R_p + N_H H)^2}{\pi R_\star{}^2} - \frac{\pi R_p{}^2}{\pi R_\star{}^2} \approx 2N_H \delta_{tra}\left(\frac{H}{R_p}\right)$$

Scale height: $H = \frac{RT}{Mg}$; Number of scale heights: $N_H \approx 7$ (for low resolution)

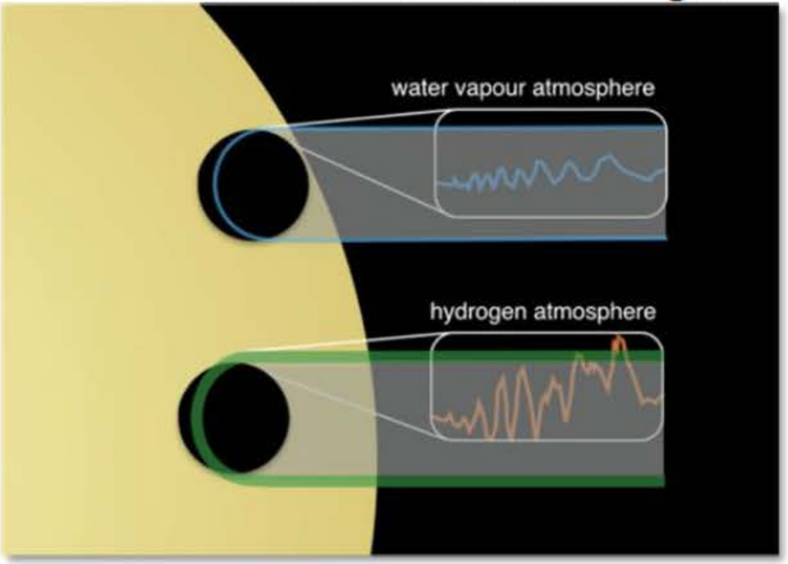
→ Transit spectroscopy easier for high scale height (e.g. hot giant planets)

I) Transit

Spectroscopy



Effect of mean molecular weight



Variation of transit depth:

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

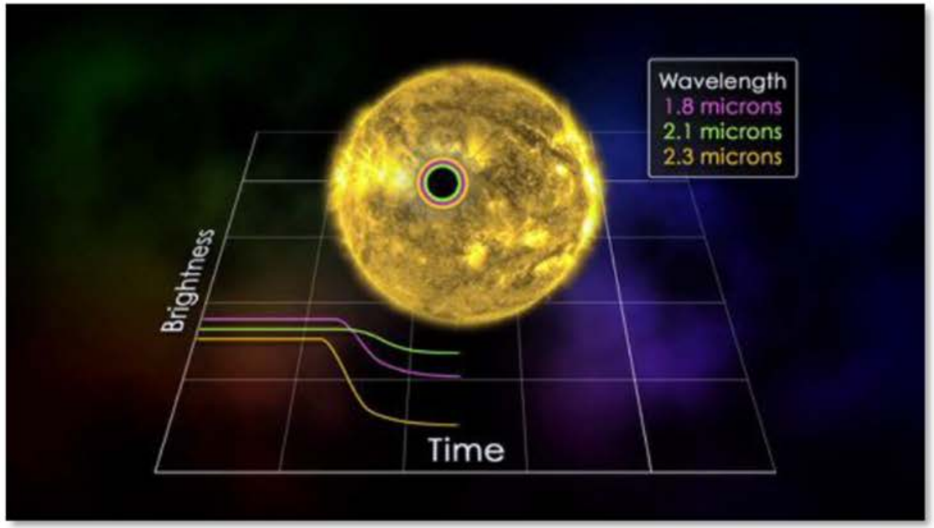
Scale height: $H = \frac{RT}{Mg}$; Number of scale heights: $N_H \approx 7$ (for low resolution)

For an Sun-like star:

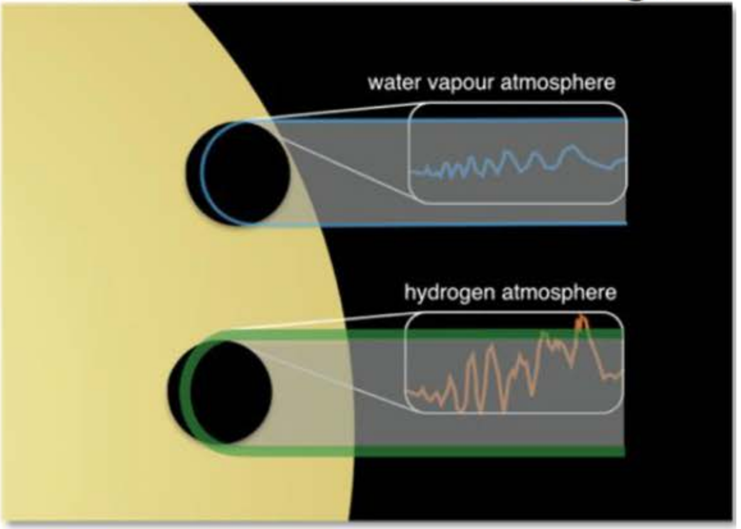
- Hot Jupiter (T=1300 K, g=25 m s^{-2}, M=2.3 g/mol): $\delta_{tra} \approx 0.01$, $\Delta\delta_{tra} \approx 4.10^{-4}$
- Earth-like planet (T=280 K, g=10 m s^{-2}, M=28g/mol): $\delta_{tra} \approx 10^{-4}$, $\Delta\delta_{tra} \approx 2.10^{-6}$

I) Transit

Spectroscopy



Effect of mean molecular weight



Variation of transit depth:

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

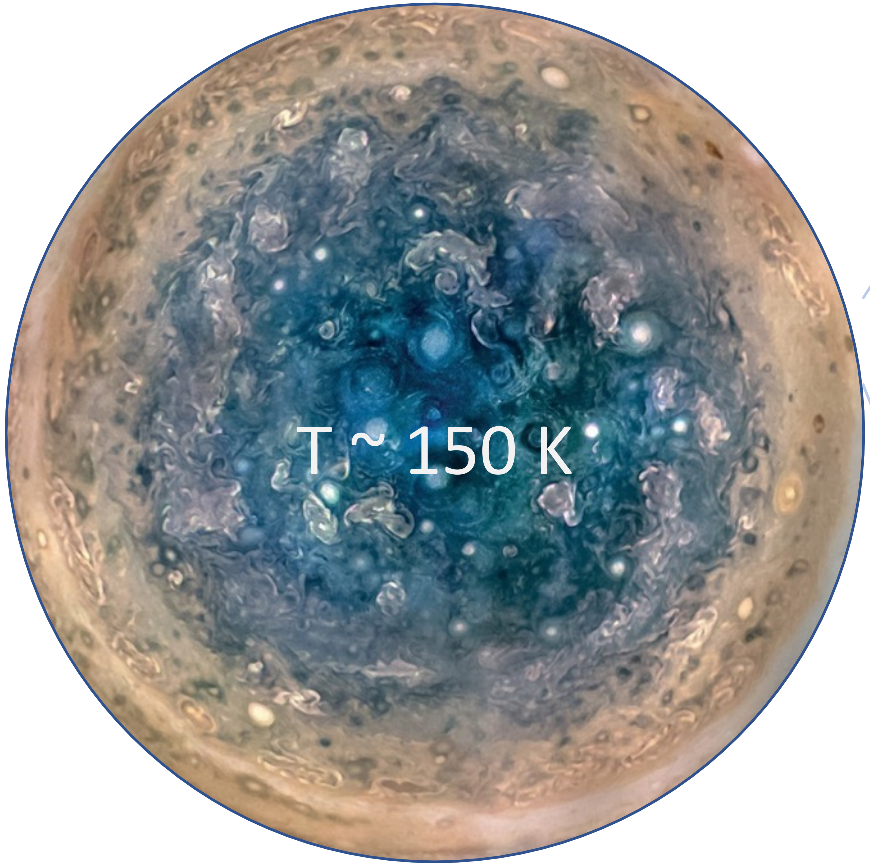
Scale height: $H = \frac{RT}{Mg}$; Number of scale heights: $N_H \approx 7$ (for low resolution)

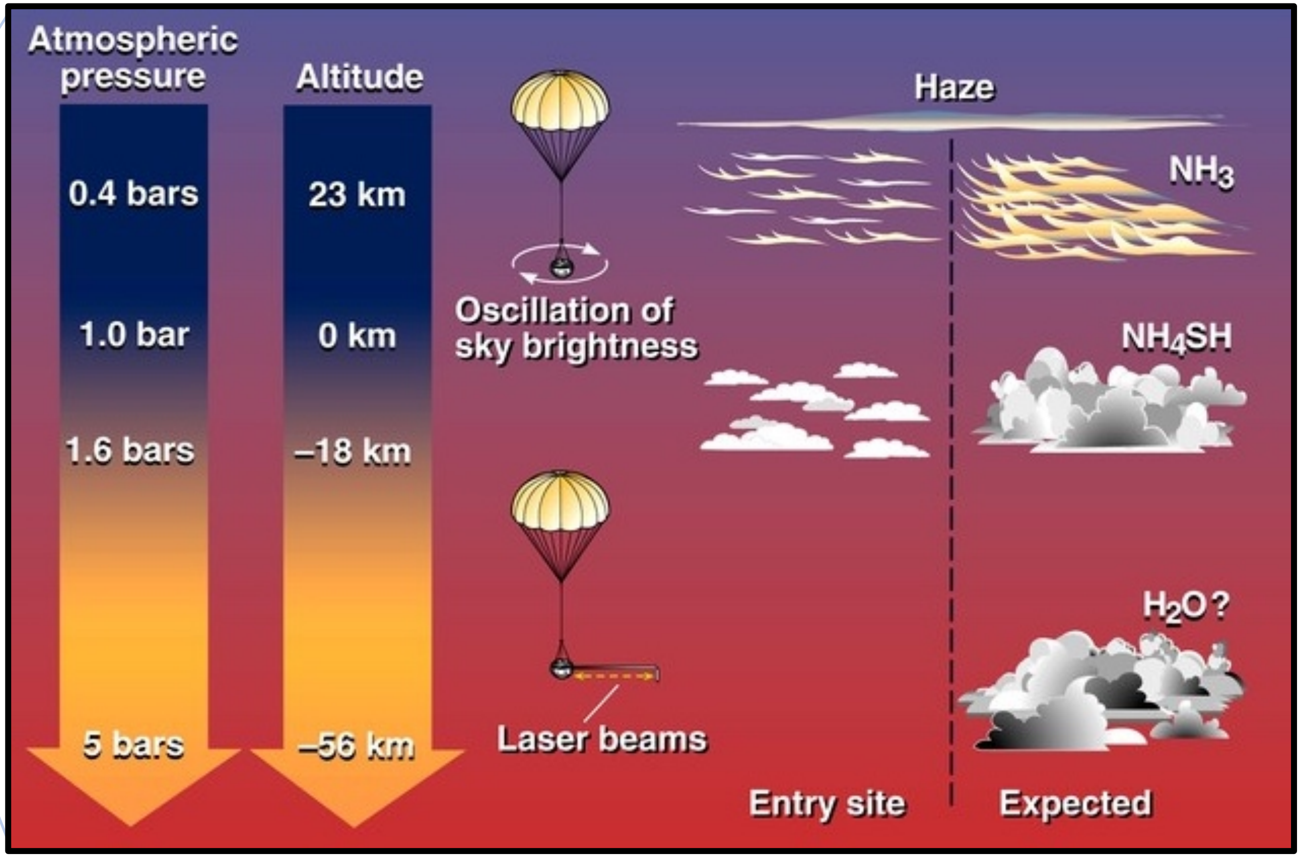
For Trappist-1 (0.015 R_s):

- Hot Jupiter (T=1300 K, g=25 m s^{-2}, M=2.3 g/mol): $\delta_{tra} \approx 0.7$, $\Delta\delta_{tra} \approx 2.10^{-2}$
- Earth-like planet (T=280 K, g=10 m s^{-2}, M=28g/mol): $\delta_{tra} \approx 6.10^{-3}$, $\Delta\delta_{tra} \approx 10^{-4}$

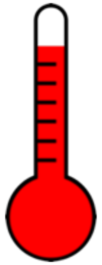
The Sun's planets are cold

SOME KEY O, C, N, S MOLECULES ARE **NOT** IN GAS FORM

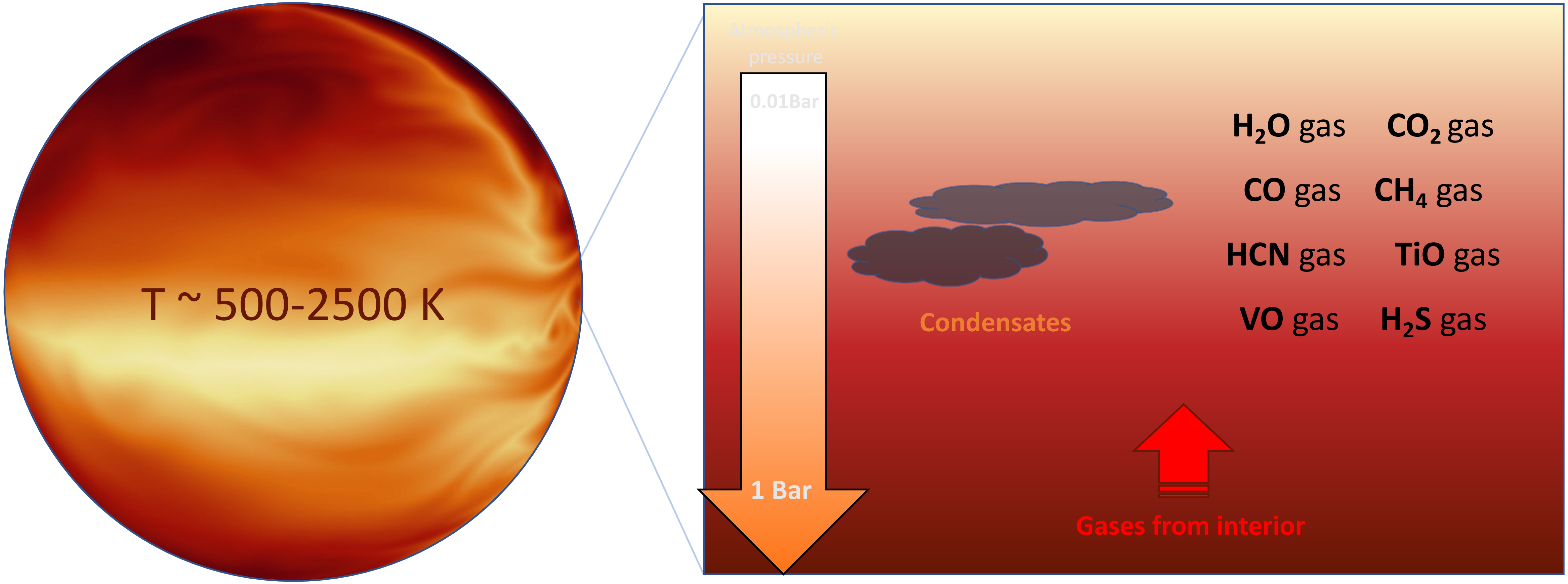




Warm/hot exoplanets



O, C, N, S (Ti, VO, Si) MOLECULES ARE IN GAS FORM



LOWELL OBSERVATORY

BULLETIN No. 103

Vol. IV

FURTHER EVIDENCE OF VEGETATION ON MARS

William M. Sinton

There has long been evidence pointing to the presence of vegetation on Mars. Photographs taken by E. C. Slipher at the Lowell Observatory have for decades shown the seasonal variation of the intensity of the dark regions. Every spring and summer a wave of darkening spreads from the polar regions toward the equator (1). In addition to the seasonal variation there are non-systematic changes; areas that were never dark have become dark, and a few dark areas have become light and blended into the desert regions. A striking case of the appearance of a dark region occurred in 1954 when an area of 580,000 square miles at 240° longitude and 20° latitude was newly dark (2). The region in which it is situated has, however, been undergoing development for many years.

The author using the 61-inch telescope of the Harvard College Observatory during the 1956 opposition made a new test for the presence of organic molecules on Mars (3). Organic molecules possess strong absorption bands at 3.5 μ as a result of the resonance of their carbon-hydrogen bonds. It was found that in the plants tested, this band was double, most likely as a result of interaction between a pair of hydrogen atoms attached to the same carbon atom, as occurs in paraffin molecules.

The results of the 1956 observations indicated the presence of the band in the light reflected from Mars, but they left some doubt as to the reality of the absorption. Furthermore, the regions of Mars which produced the absorption were not ascertained in this work. At the 1958 opposition the test was made again with improved equipment and the reality and distribution of the band were established.

MARS ATTACKS!

Detection of 3 molecular bands in 1956…

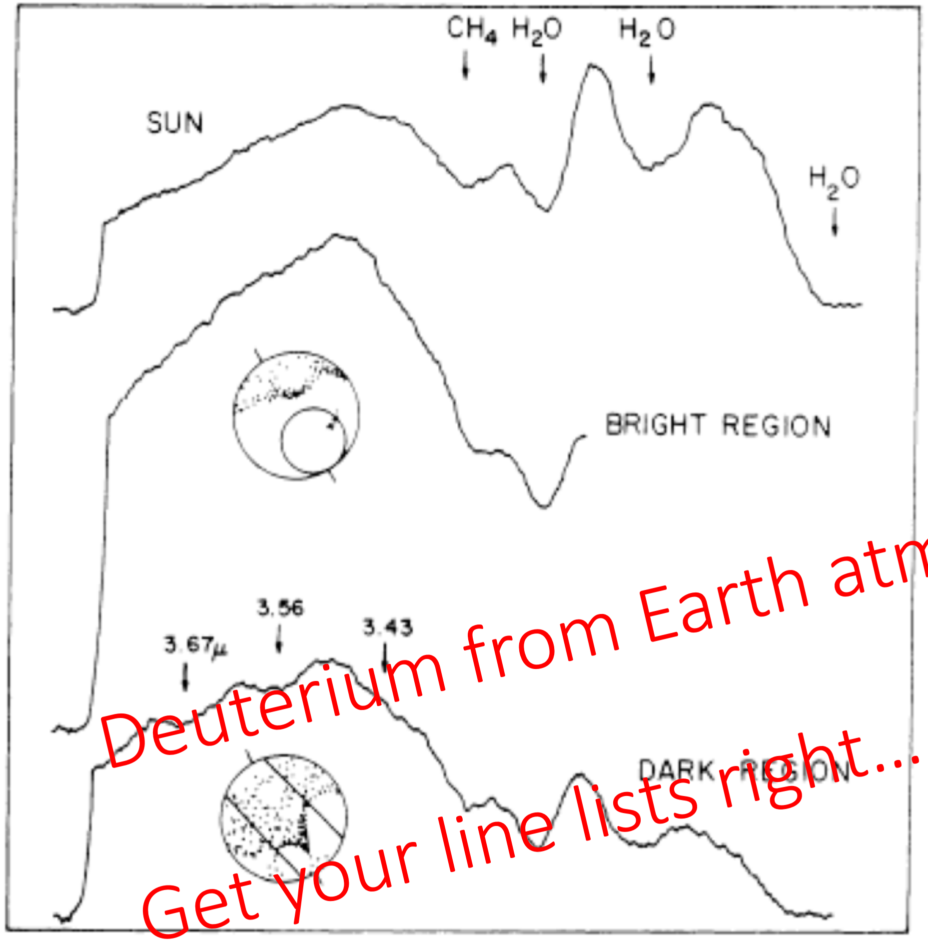


Figure 1. Infrared spectra of Mars and the sun. The upper curve shows the spectrum of the sun with absorptions produced by water and methane in the earth's atmosphere. The middle curve is the spectrum of Amazonis, the desert region within the circle in the sketch. The bottom curve shows the spectrum of a strip across Mars as shown in the sketch and includes Syrtis Major. The last spectrum shows the absorptions supposedly due to organic molecules.

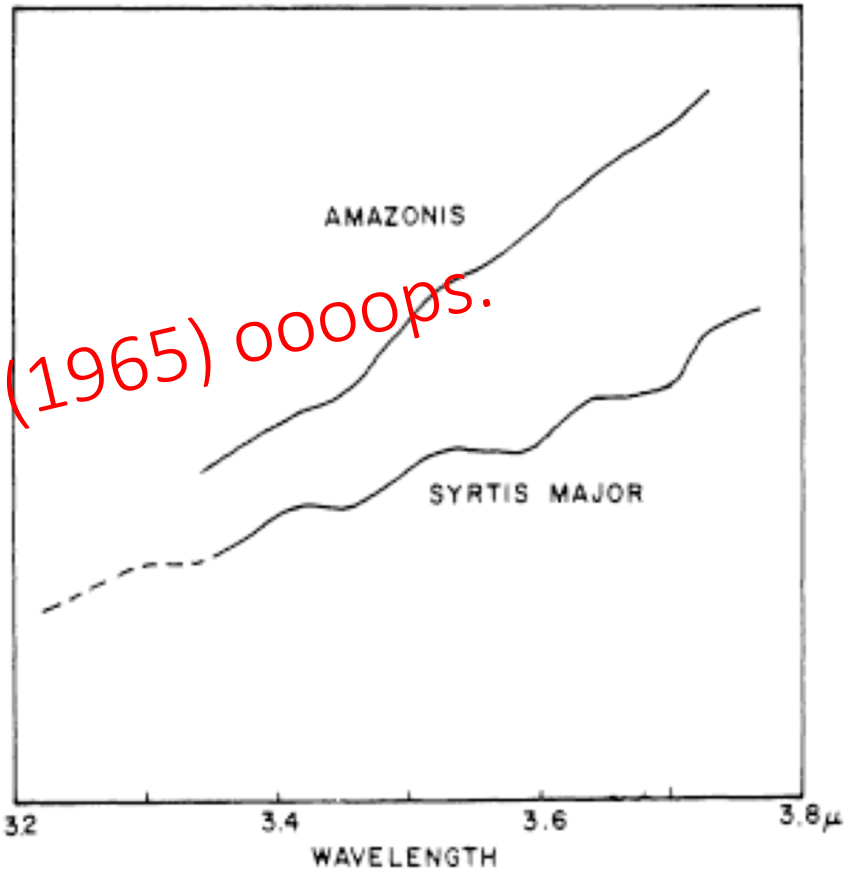


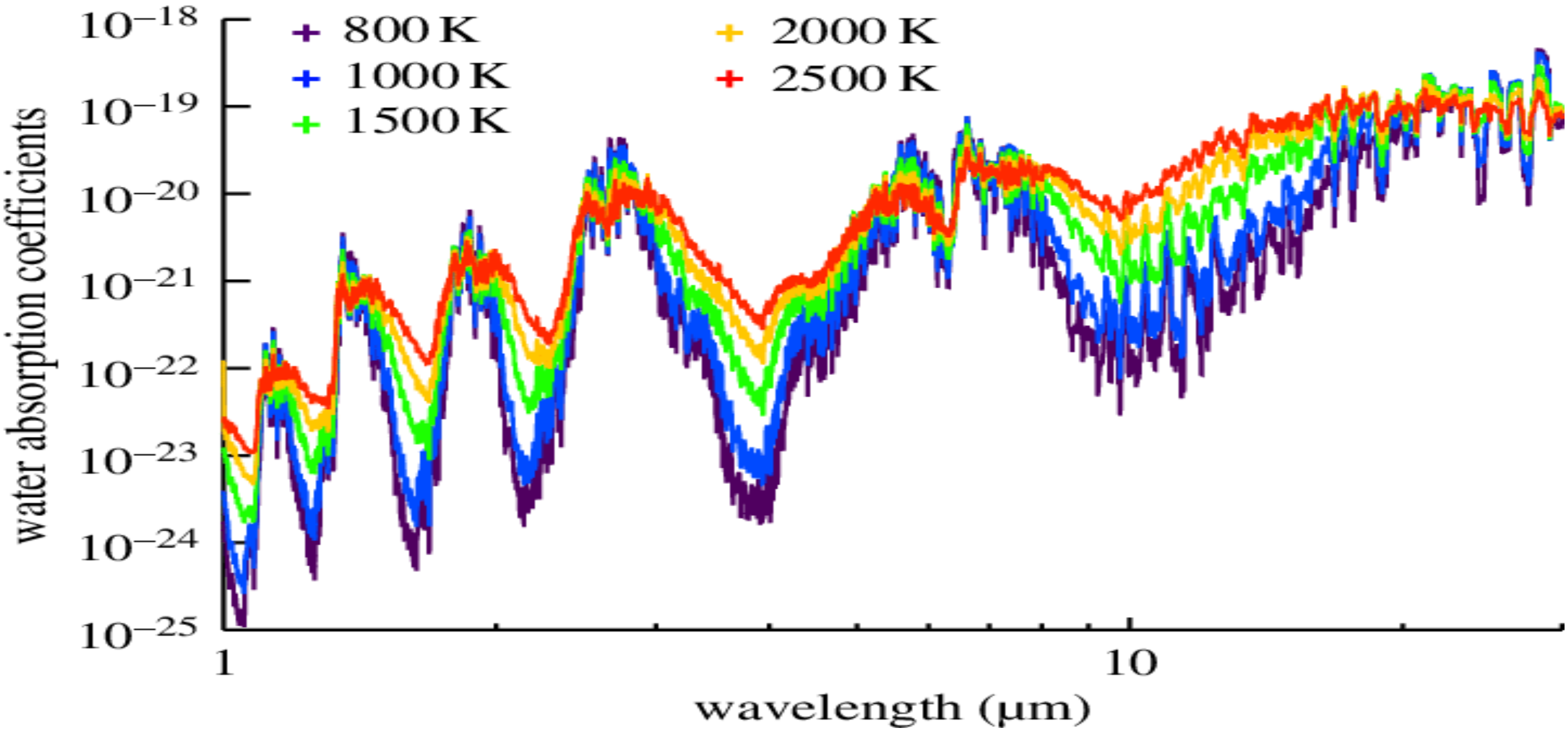
Figure 2. The spectra of Amazonis and Syrtis Major after division by the solar spectrum. The dashed portion of the curve is the region through strong methane and water-vapor absorption and the variations are not believed to be significant.

Deuterium from Earth atmosphere… (1965) oooops.

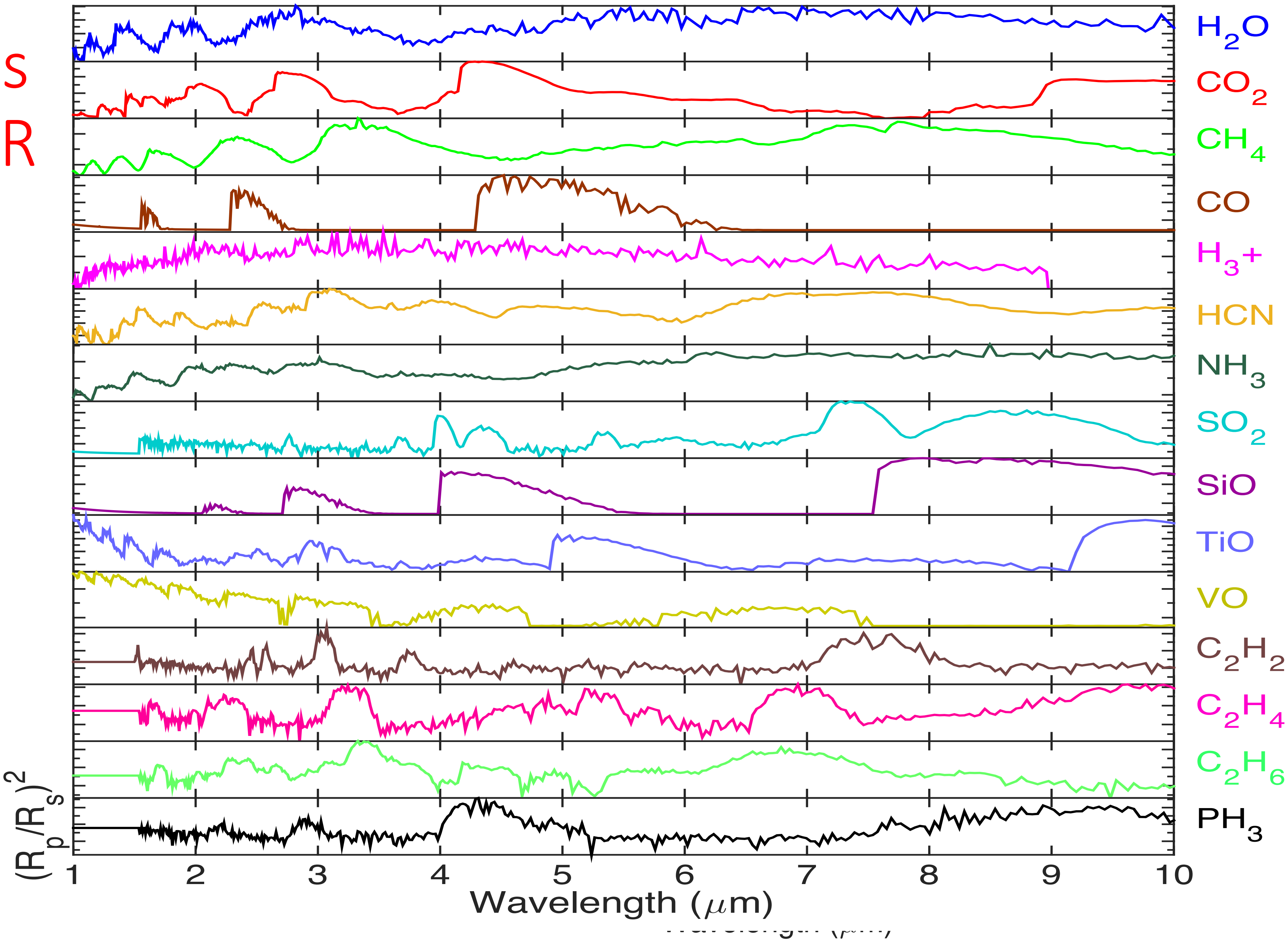
Get your line lists right…

We need good line lists…
Exomol and other groups

Water vapour absorption as a function of temperature and wavelength

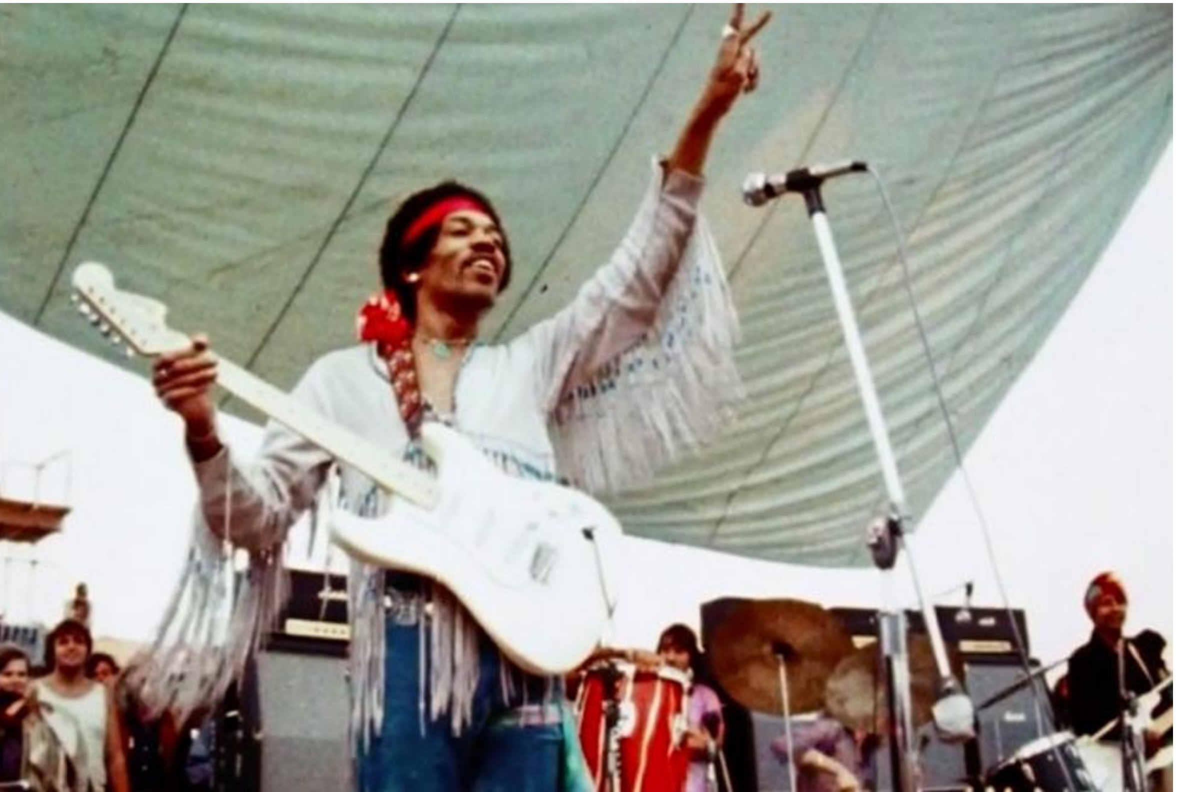


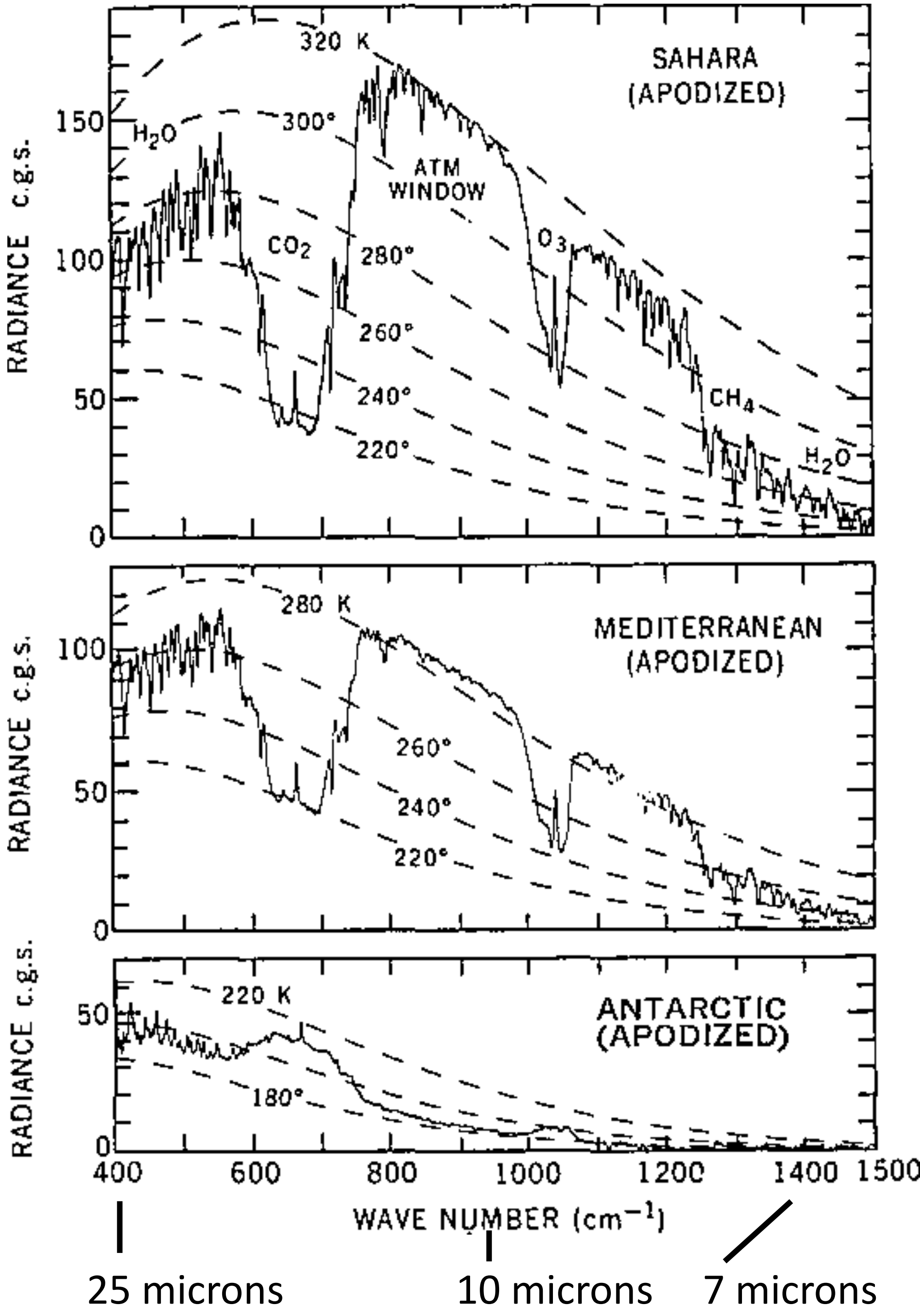
Key molecules absorbing in IR



The Earth, 1970s, Nimbus-4

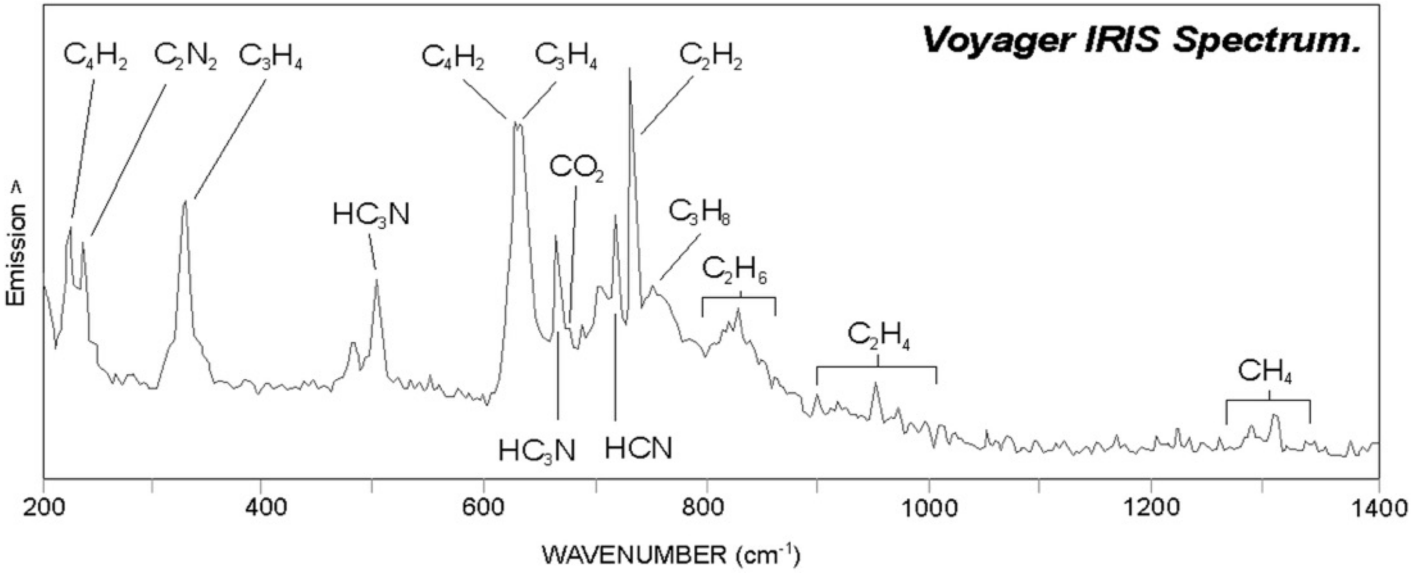
The acquisition of spectroscopic data of the Earth from artificial satellites has changed the old question of whether the phenomenon of terrestrial life is unique or not…





1980s, voyager satellite

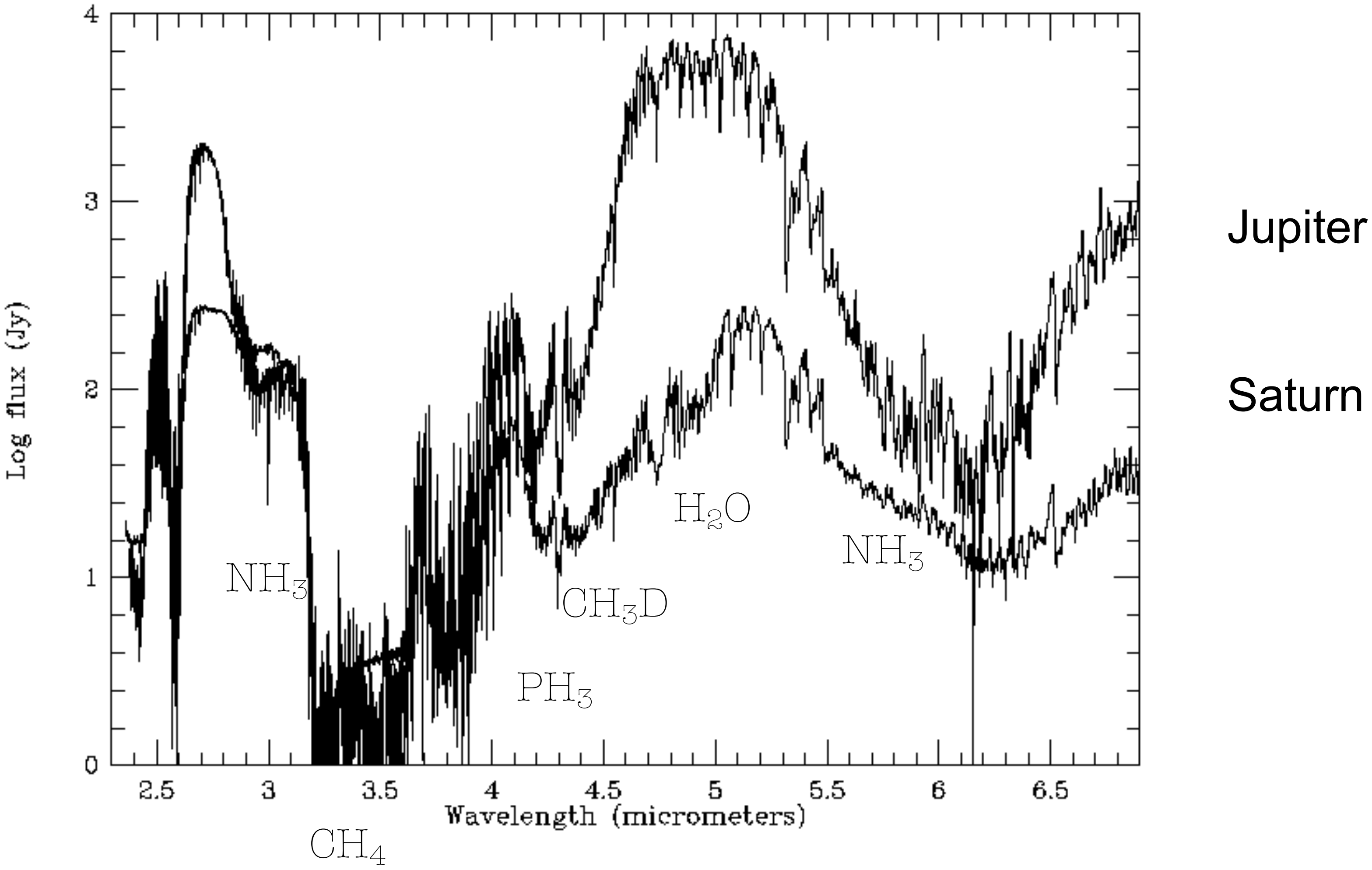
Titan



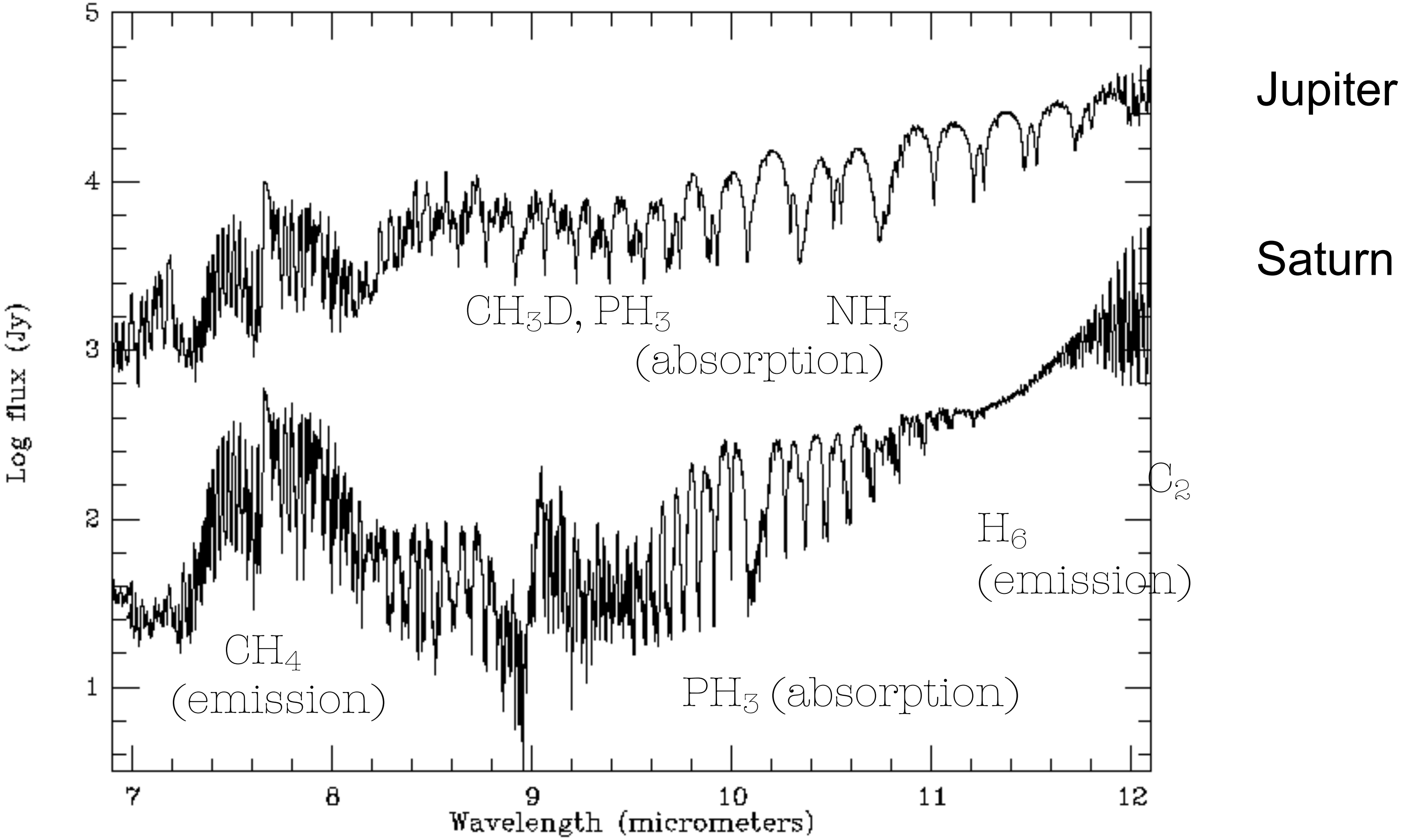
IRIS / Voyager R = 4.3 cm-1

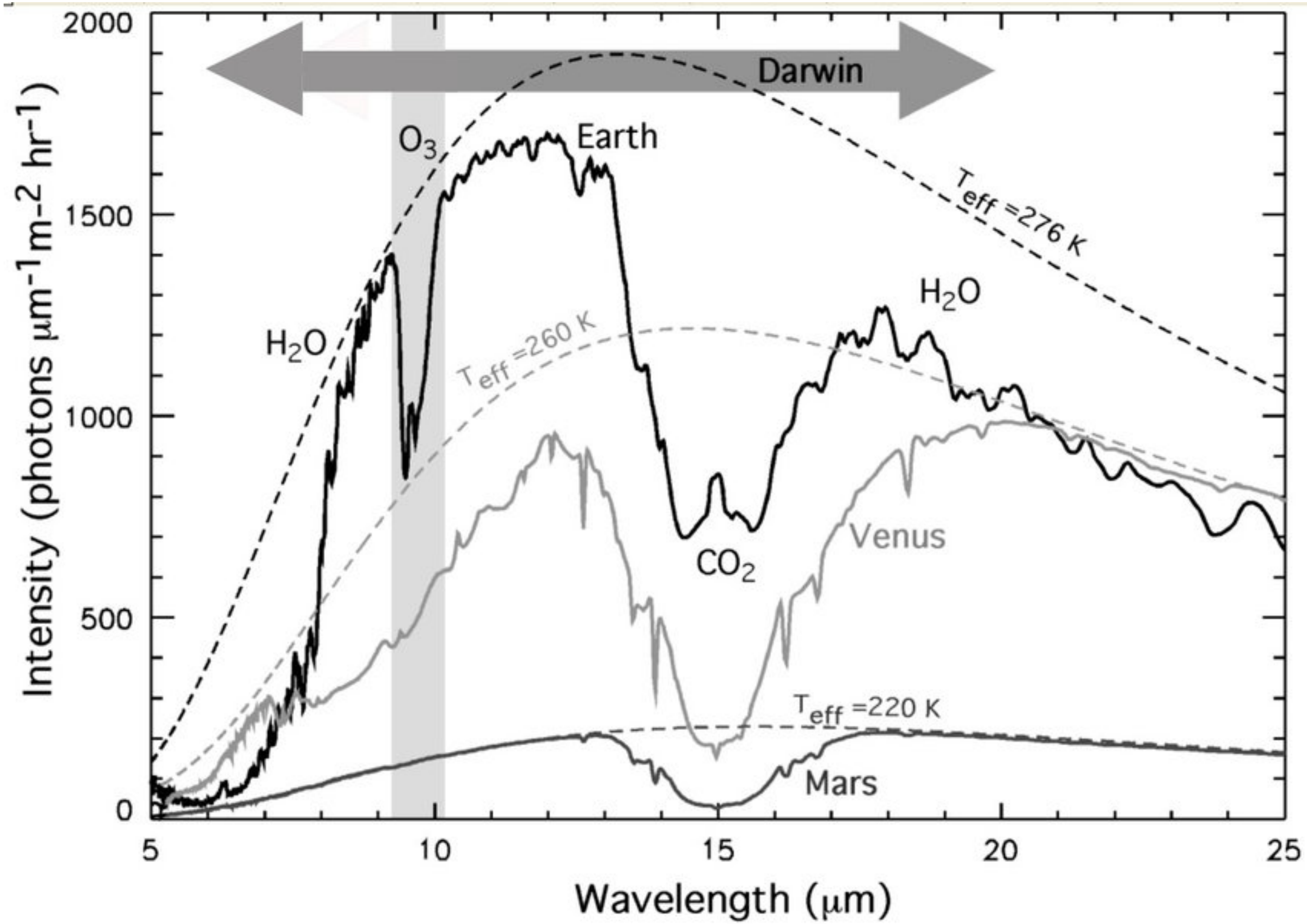
Samuelson *et al. (1983)*

Line identification @ 5 um: R > 200



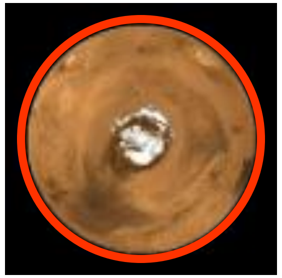
Line identification : R > 100

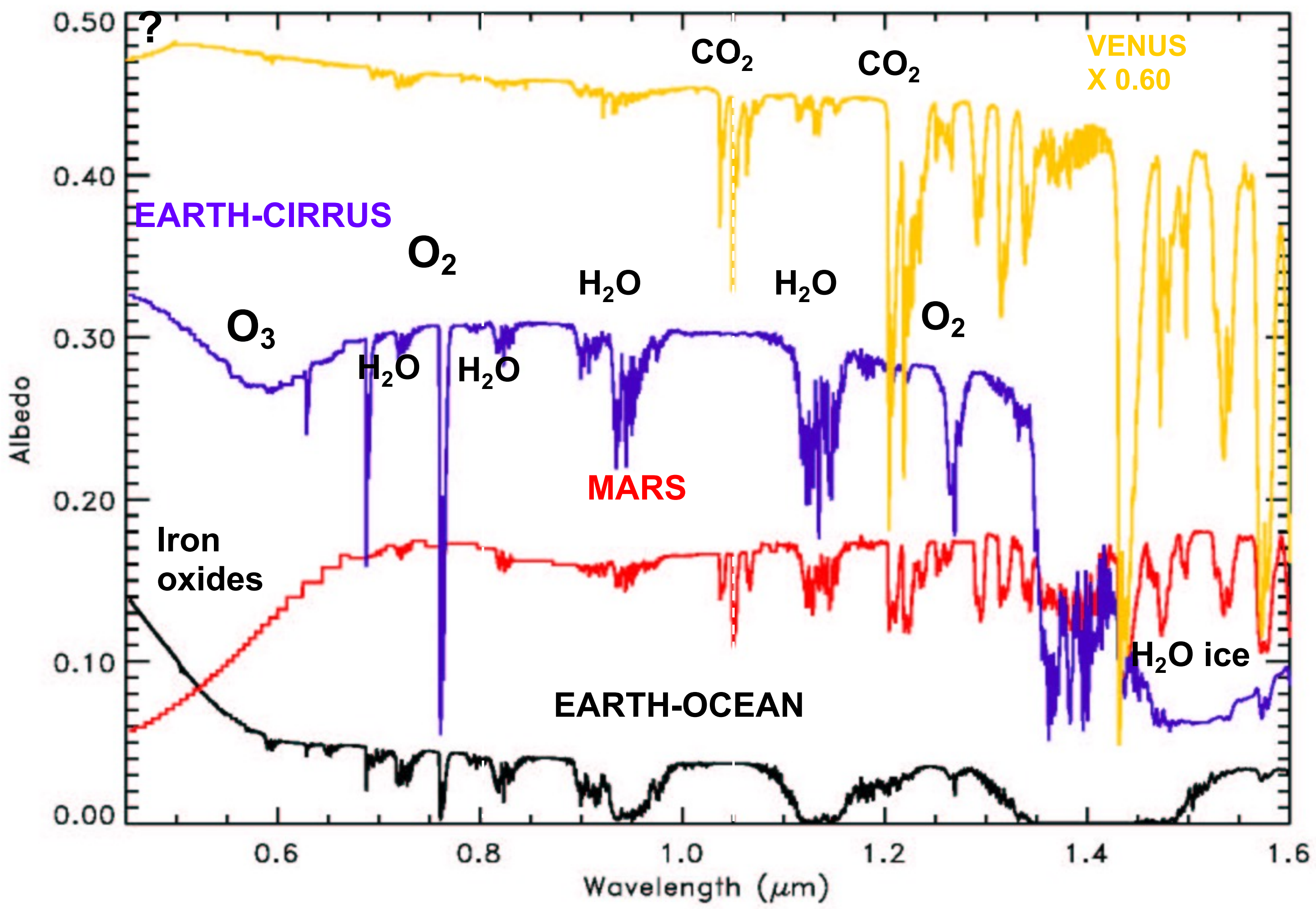




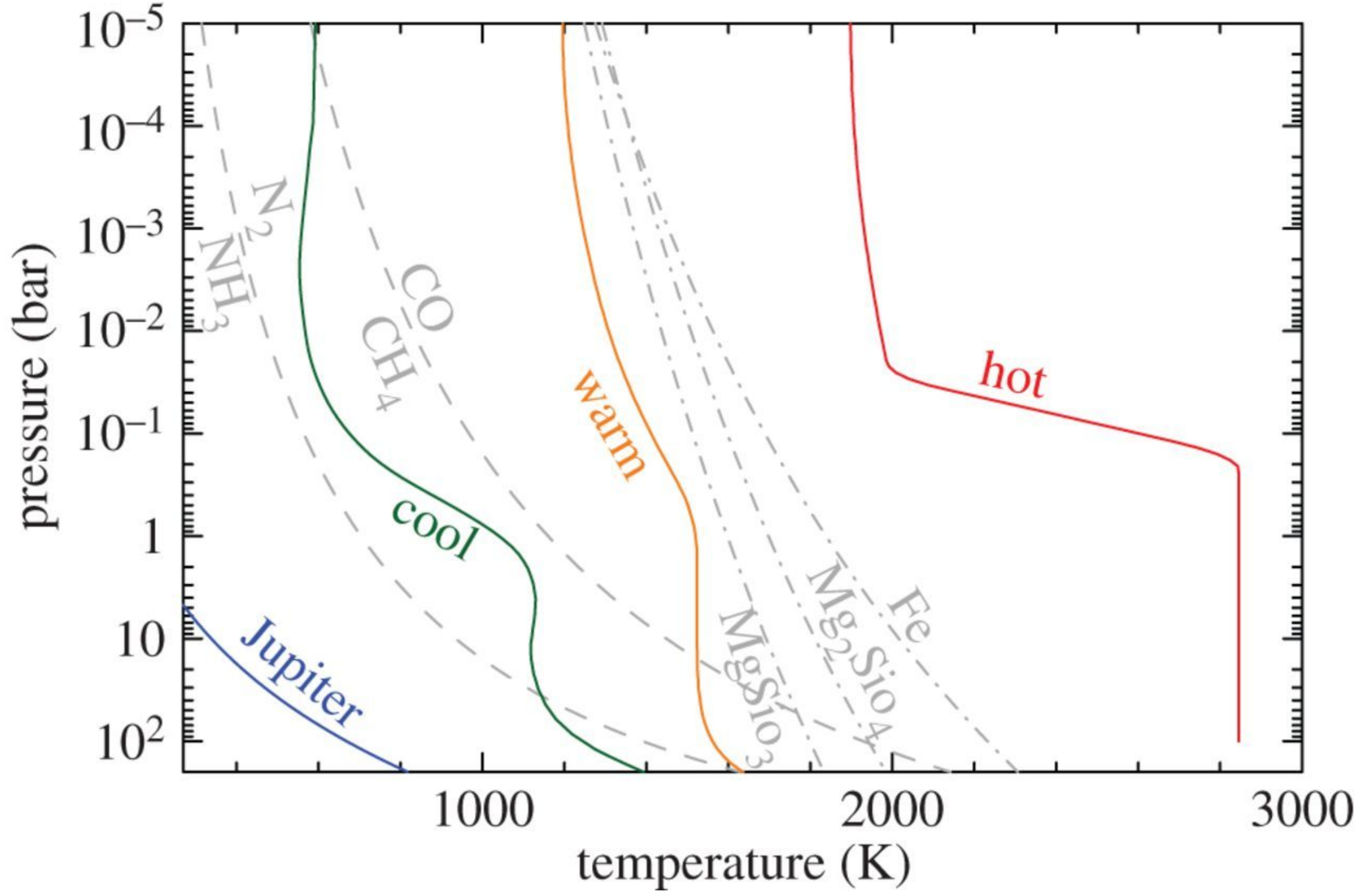
Darwin
O_3
Earth
T_{eff} =276 K
H_2O
H_2O
T_{eff} =260 K
CO_2
Venus
T_{eff} =220 K
Mars
Intensity (photons μm-1m-2 hr-1)
Wavelength (μm)
2000
1500
1000
500
0
5
10
15
20
25

More recent spectra in our solar system

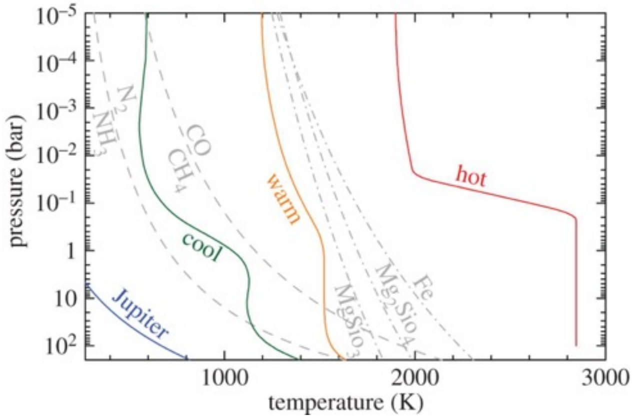




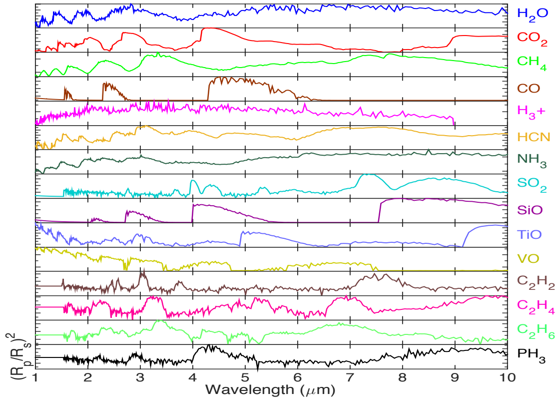
Temperature-Pressure profile in hot Jupiters



Thermal profiles for the hypothetical ‘hot’, ‘warm’ and ‘cool’ exoplanets (as labelled) used in the chemical models shown in figure. The grey dashed lines represent the equal-abundance curves for CH4–CO and NH3–N2. Profiles to the right of these curves are within the N2 and/or CO stability fields. The dot-dashed lines show the condensation curves for MgSiO3, Mg2SiO4 and Fe (solid, liquid). Moses 2014



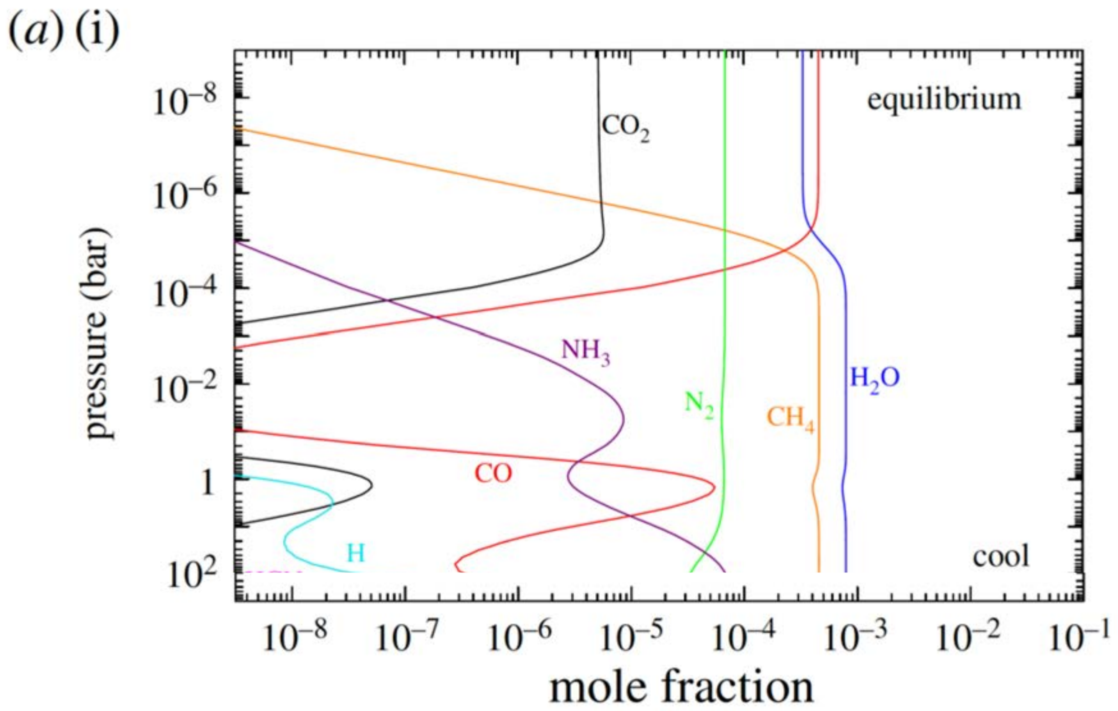
Temperature-pressure Profile

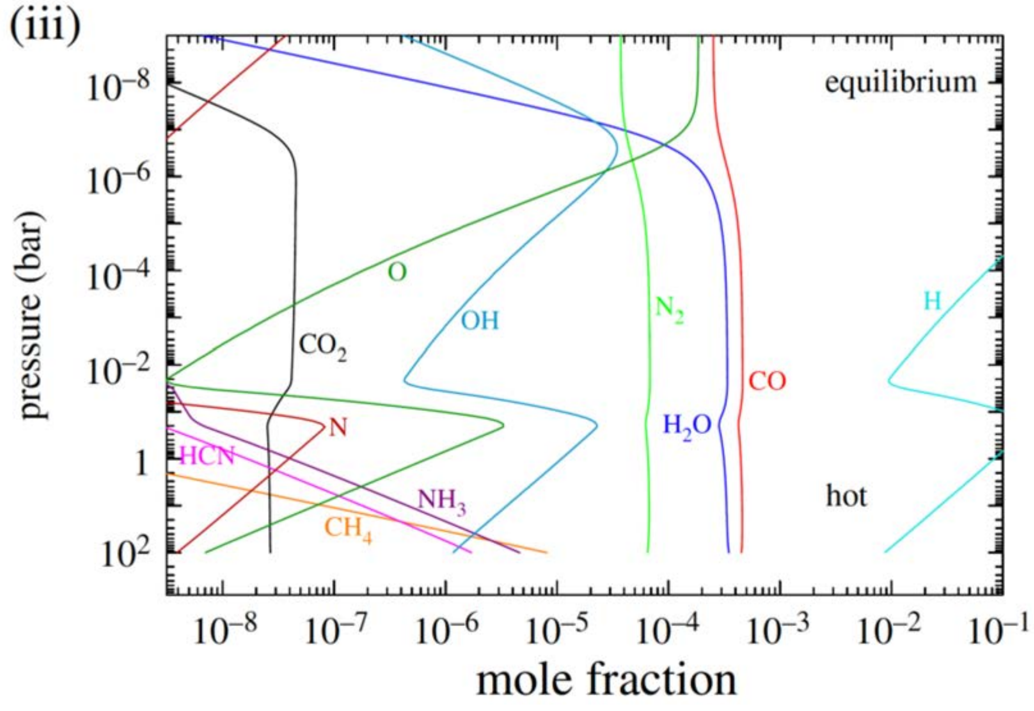


Molecules lines list

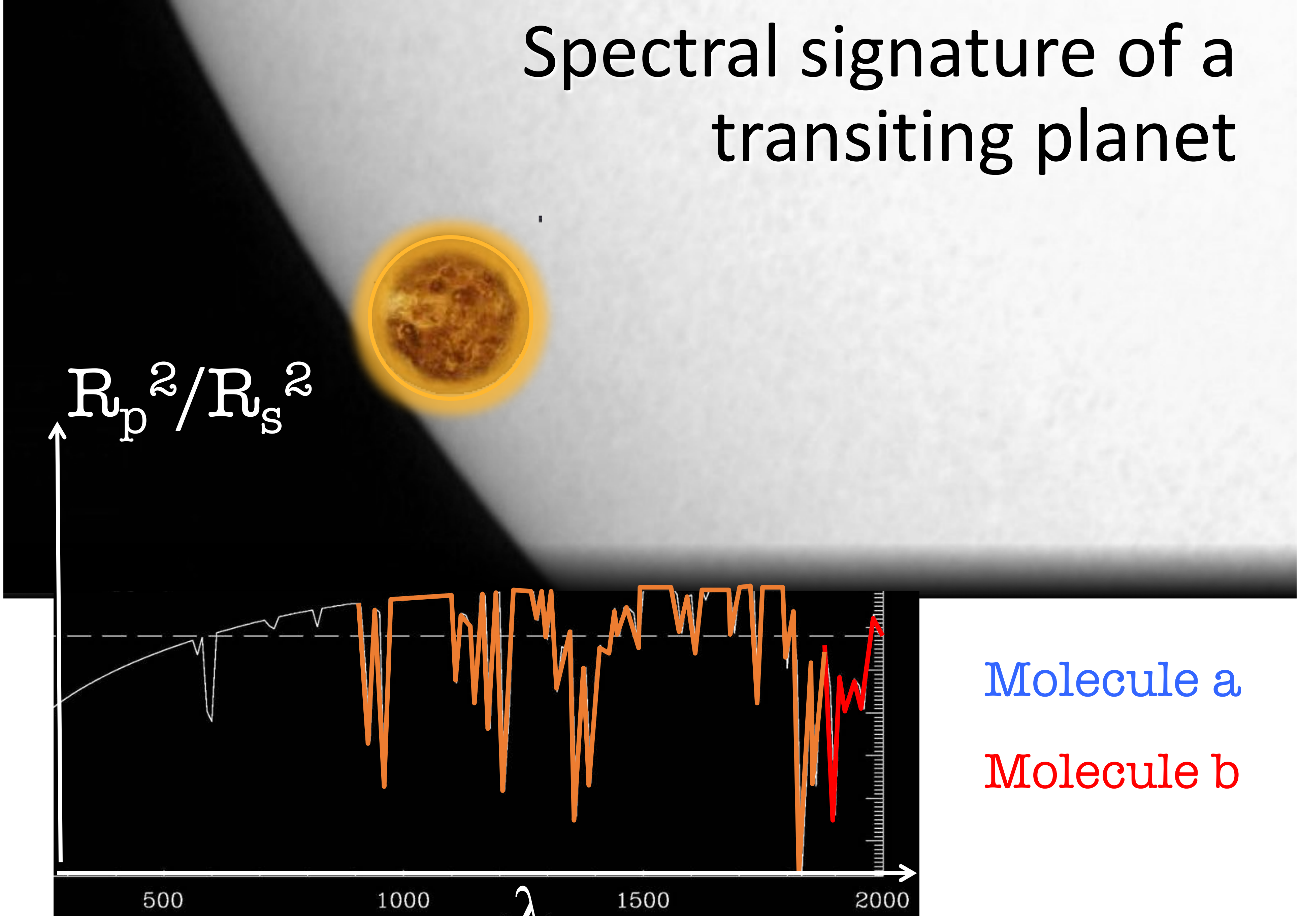
Chemistry in equilibrium

Which molecules are expected to be abundant ?



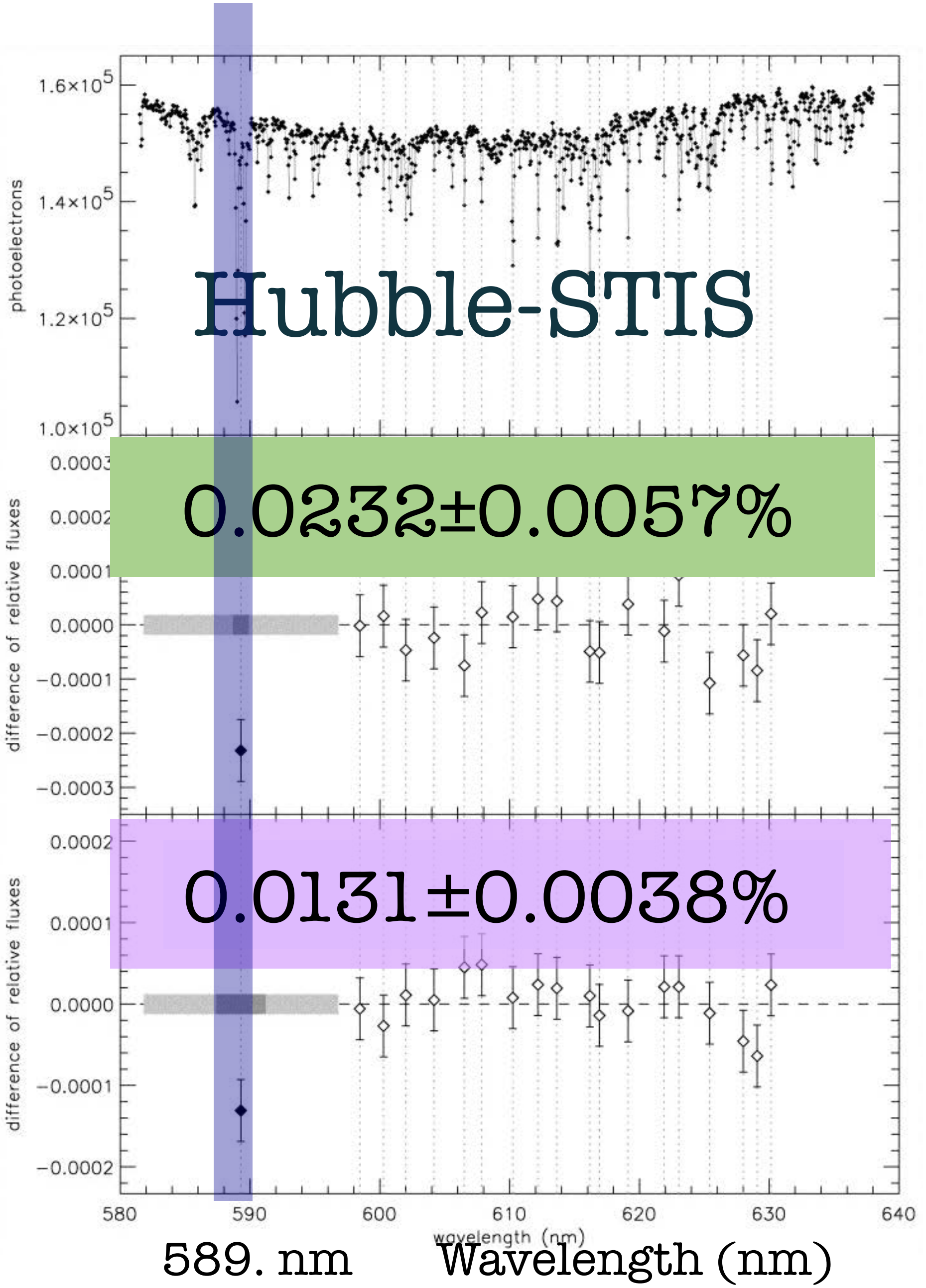


Spectral signature of a transiting planet



Molecule a

Molecule b

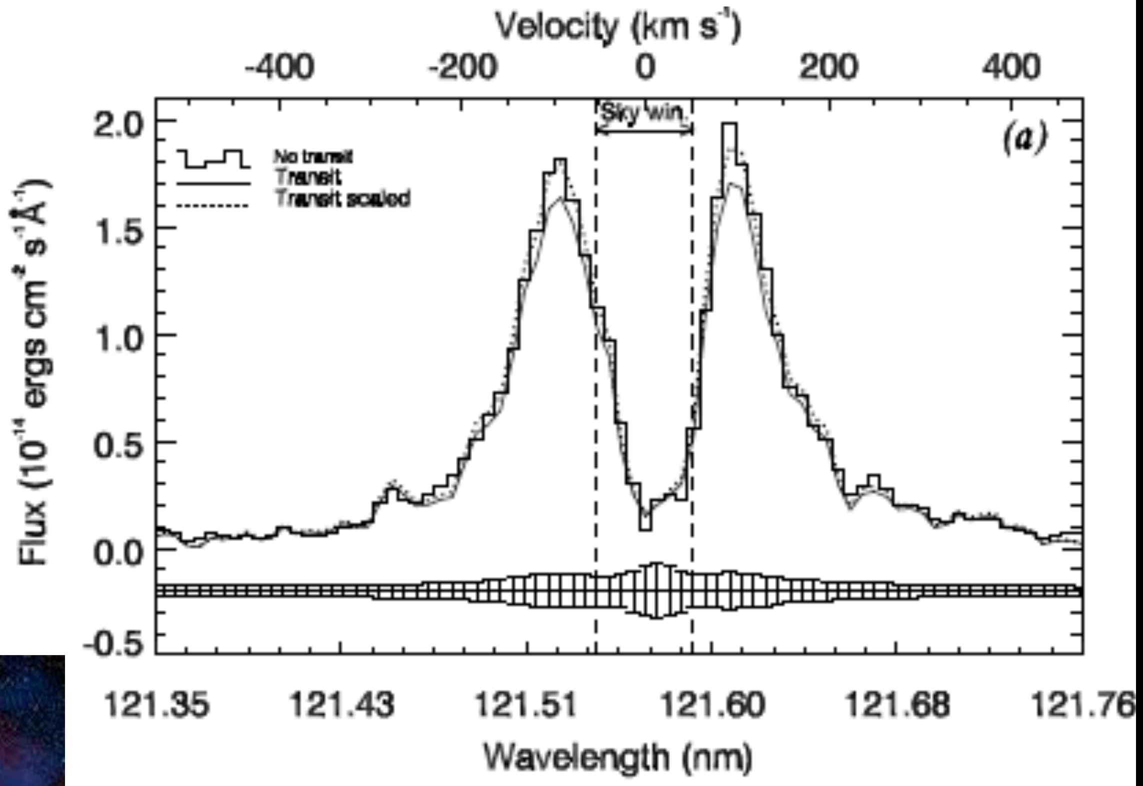


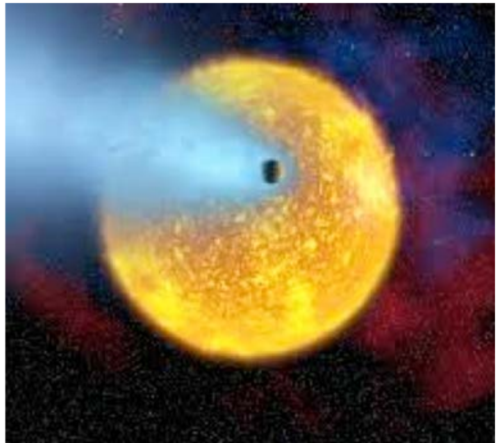
Charbonneau *et al.*, 2002

Let’s chat with Emilie about it !

STIS: Lyα HD 209458b

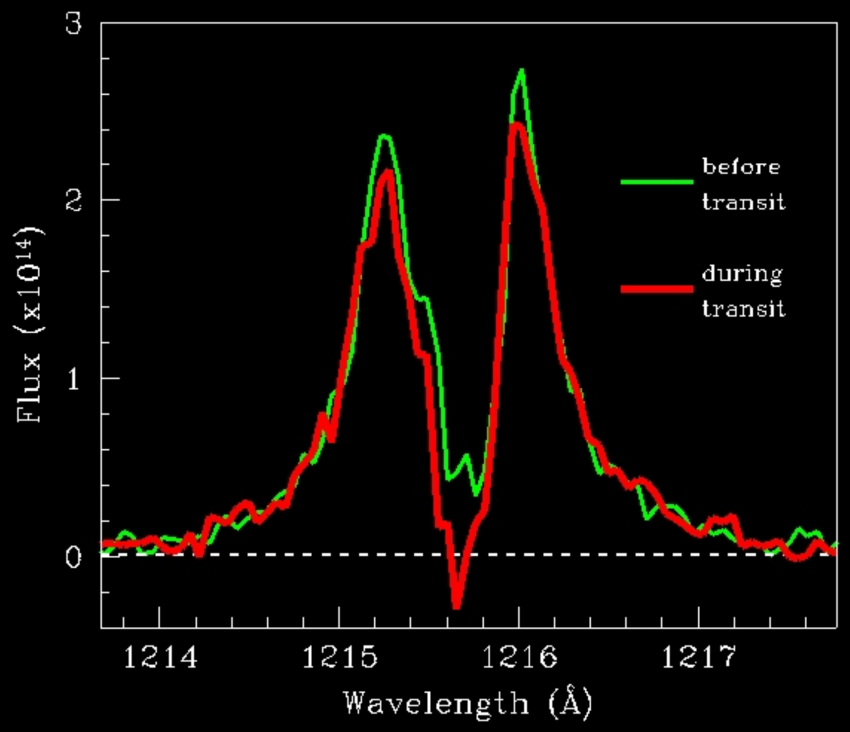
~9% absorption in the Lyα line,
No red/blue shift





Ben-Jaffel, ApJL, 2008

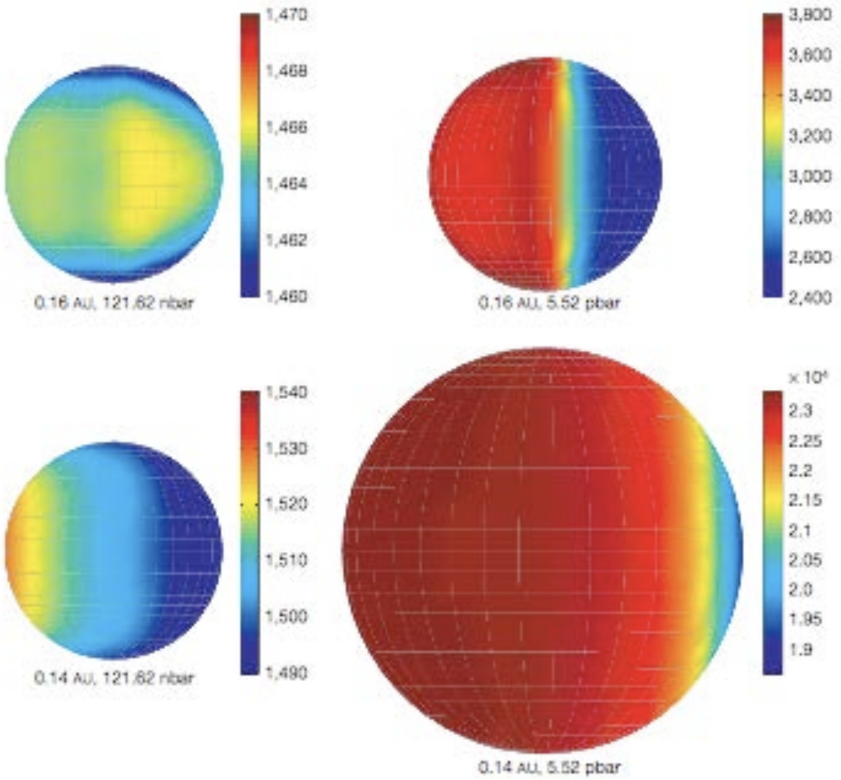
15% absorption in the Lyα line



Vidal-Madjar et al., *Nature*, 2003
Ballester, Sing, Herbert, *Nature*, 2007

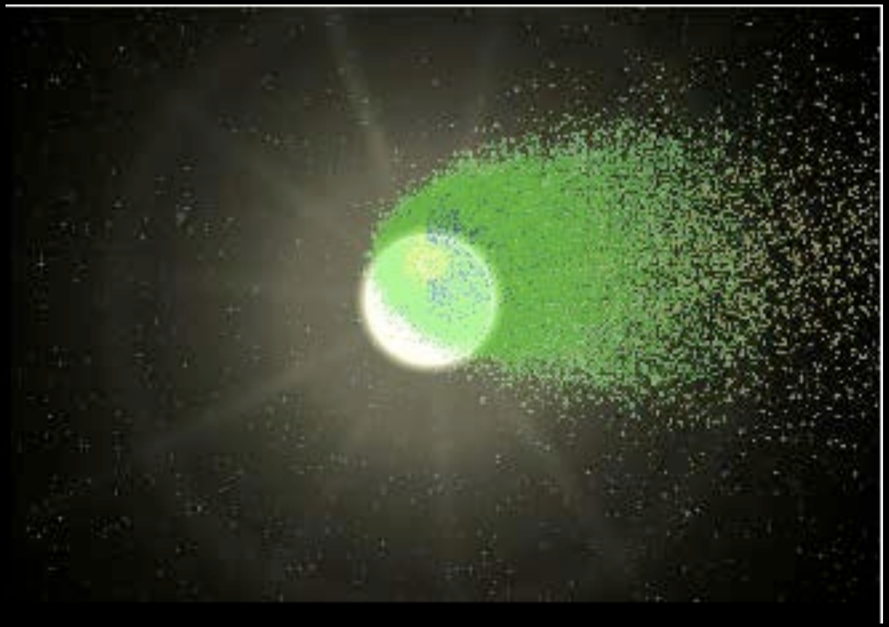
STIS: Lyα HD 209458b

Planetary properties of the upper atmosphere



Koskinen et al., Nature, 2008

Stellar wind

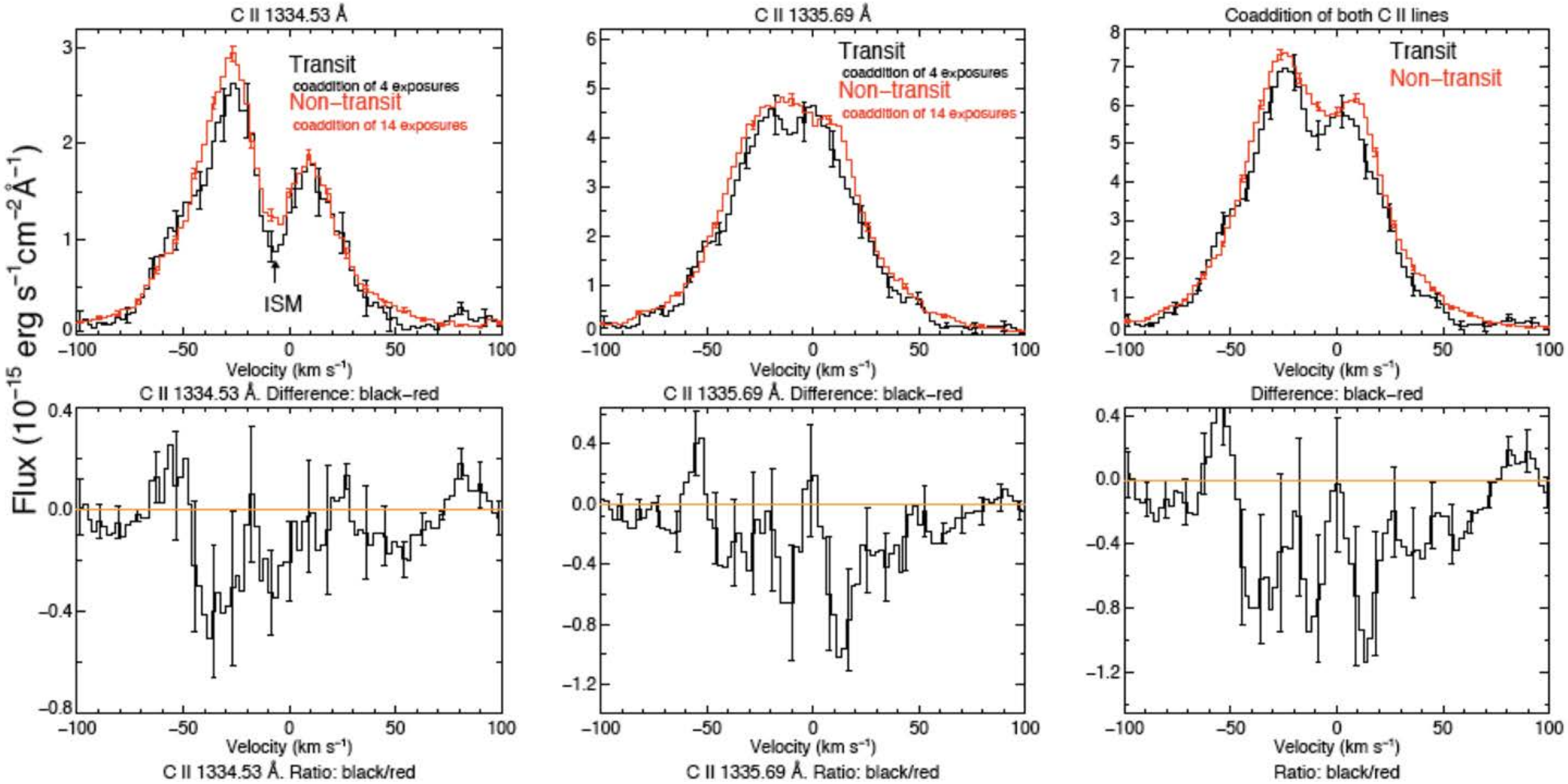


Holmstrom et al., Nature, 2008

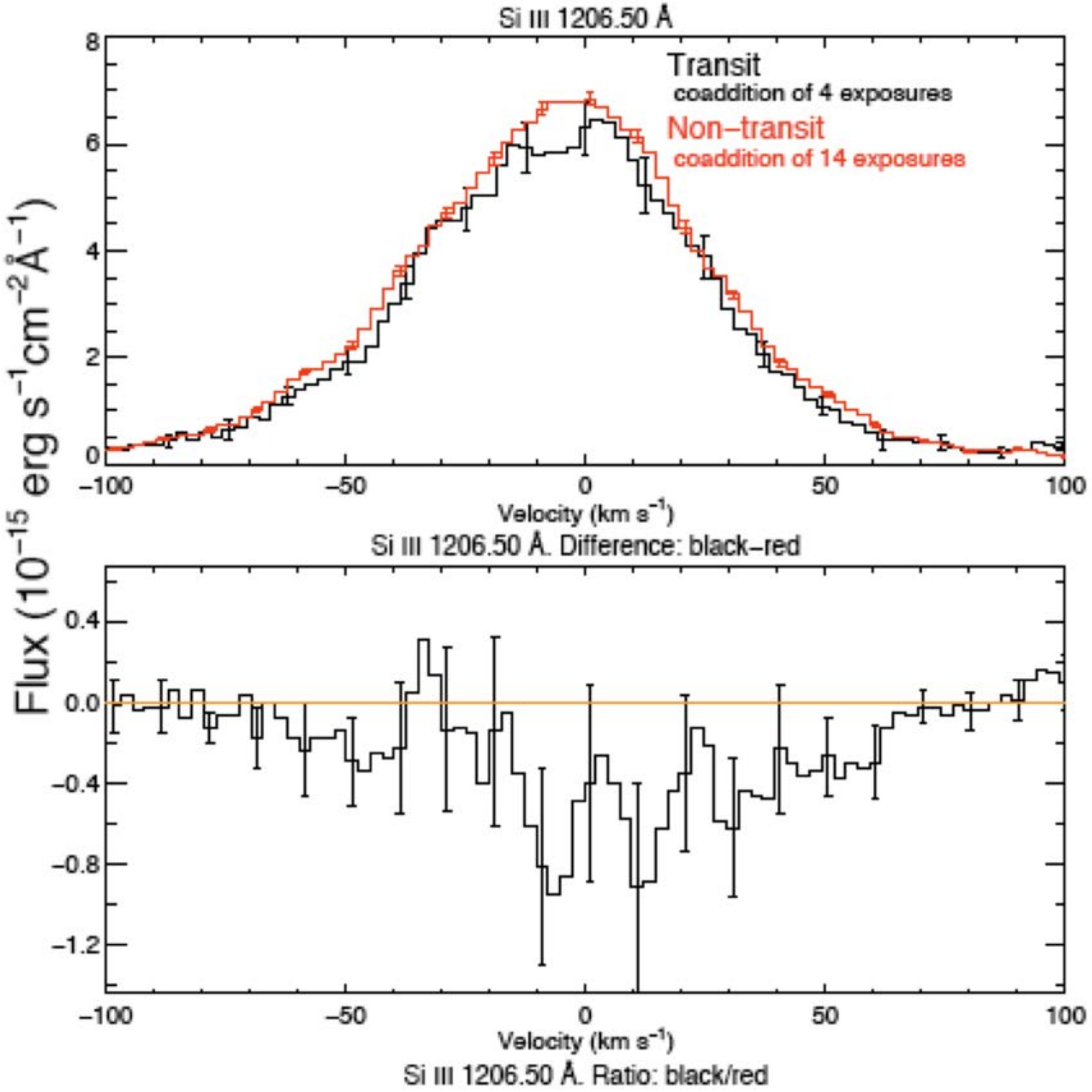
Energetic Neutral Atoms around HD 209458b ?
Evaporation ?

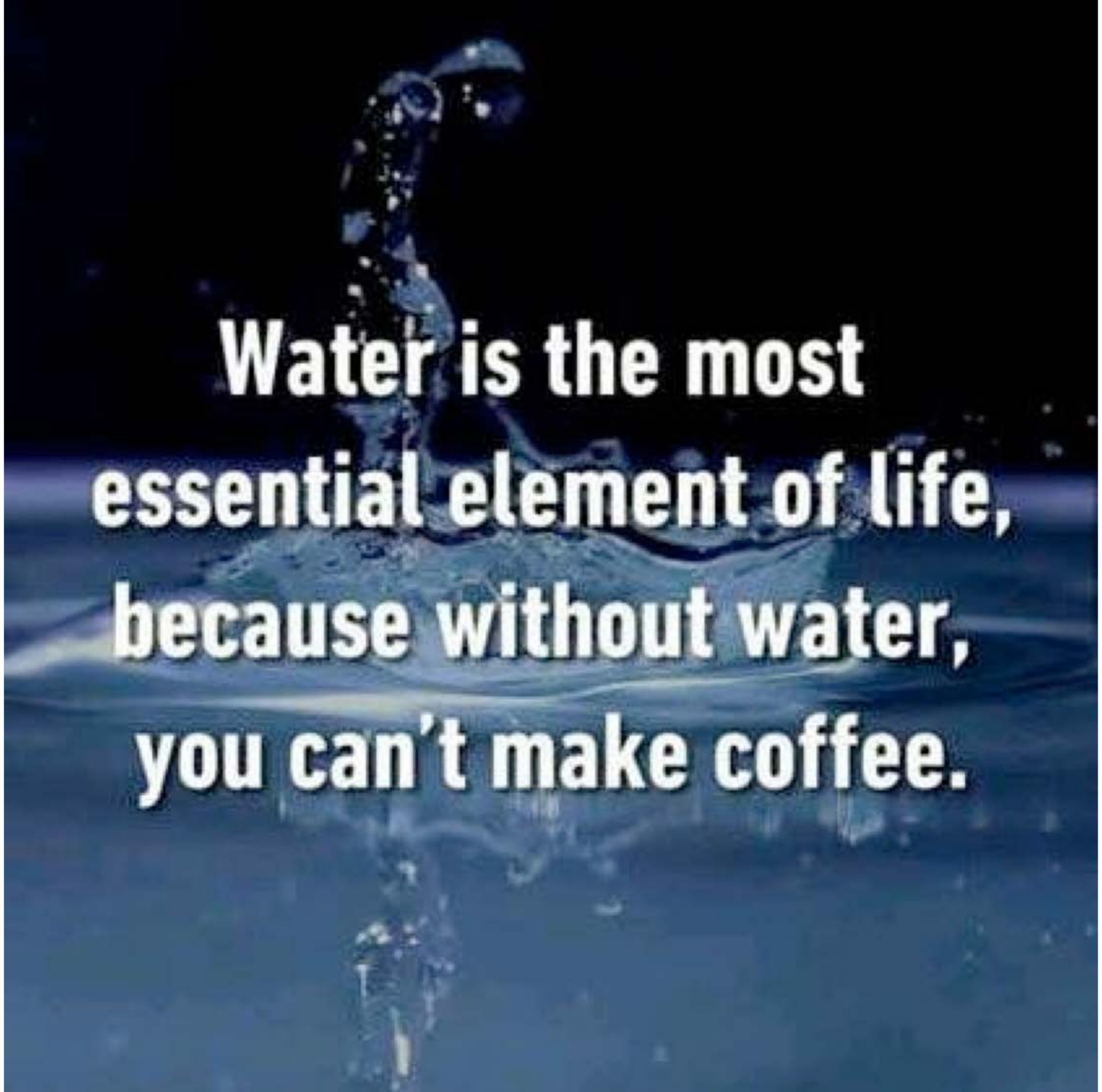
Koskinen et al., 2010; Yelle, 2003; Lecavelier et al., 2003; Lammer..2004, Tian et al. 2005,

CII Transit Measurements (Linsky et al. 2010)

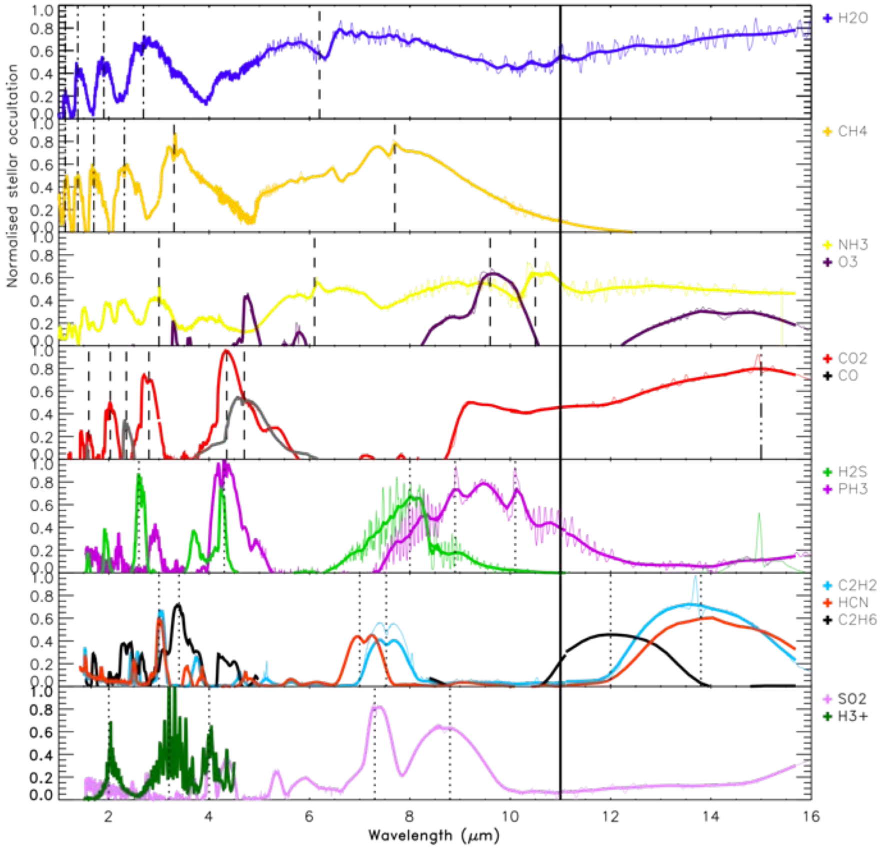


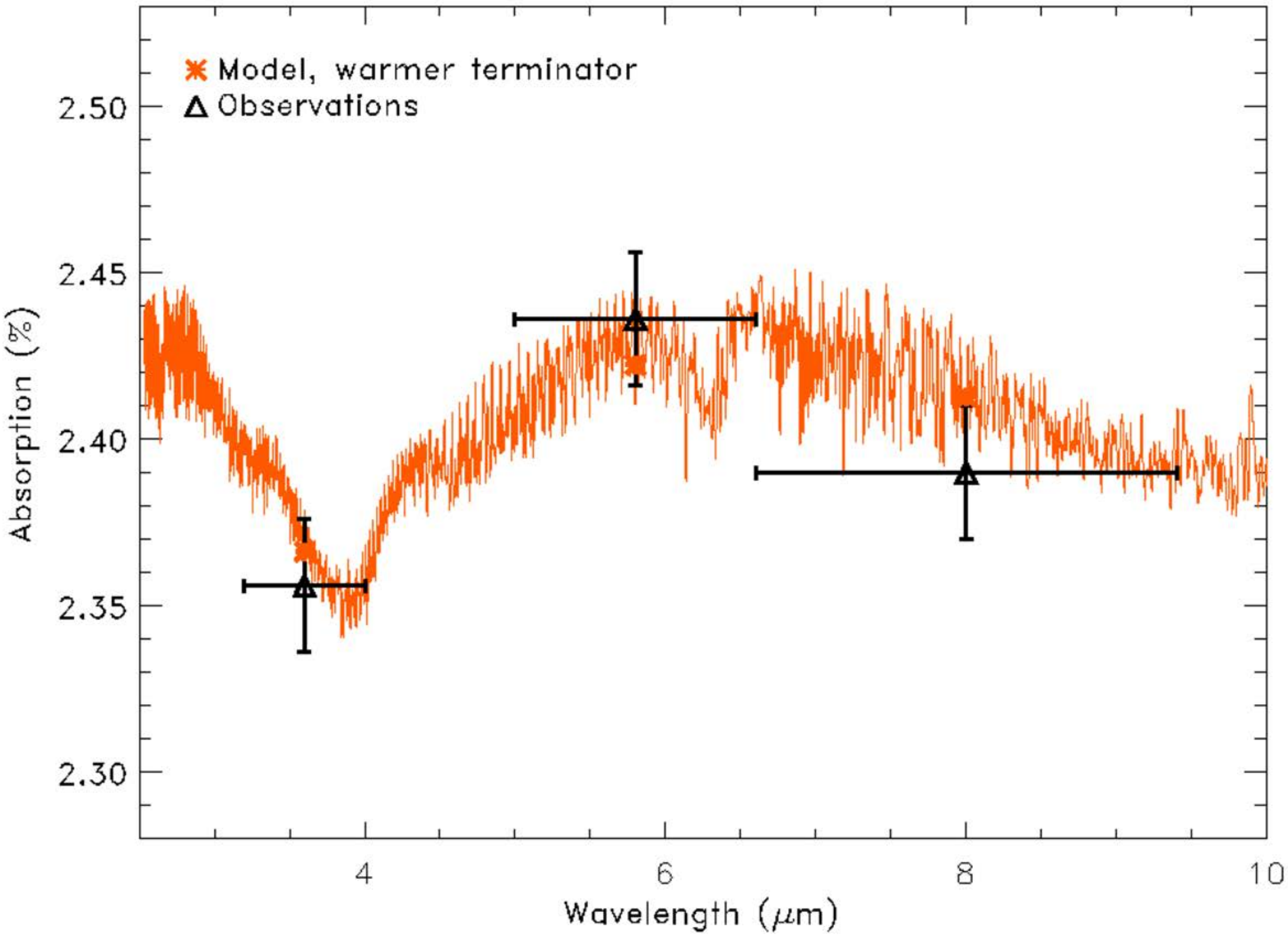
SiIII Transit Measurements (Linsky et al. 2010)




Water is the most
essential element of life,
because without water,
you can't make coffee.

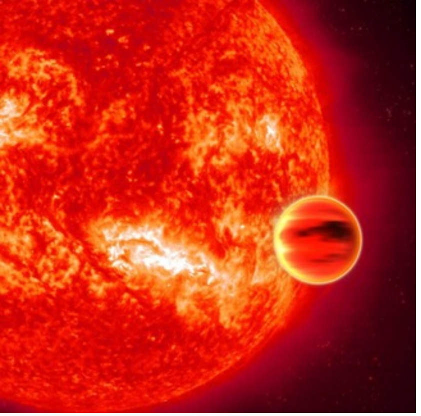
Water vapor in the hot Jupiter HD189733b

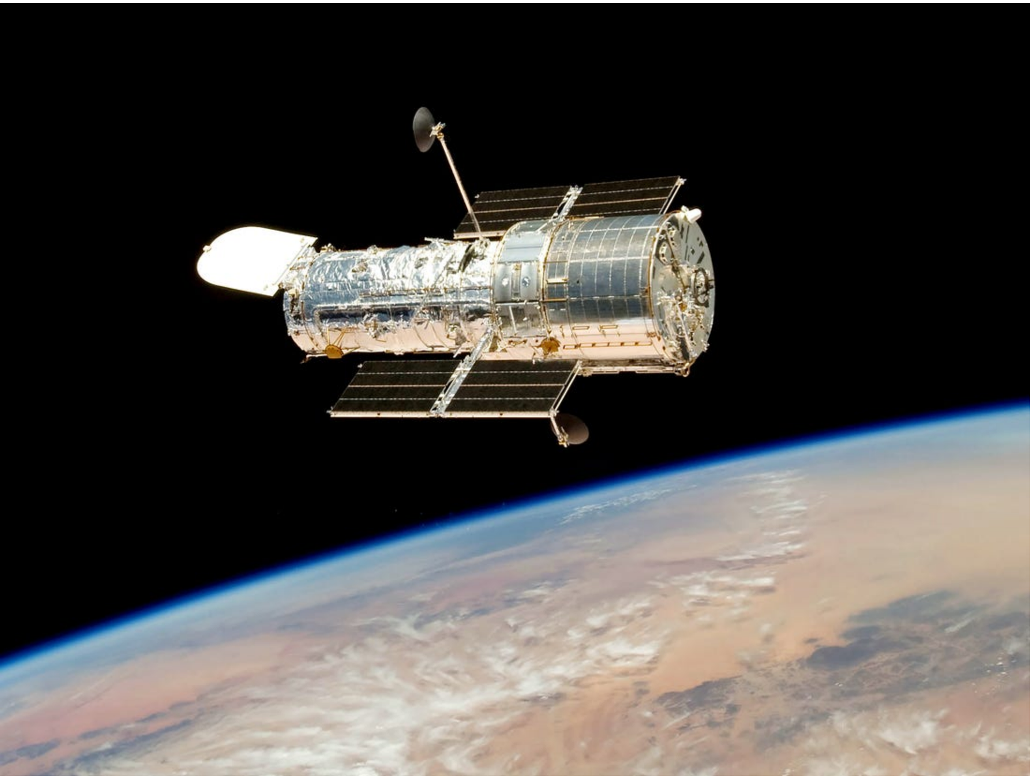


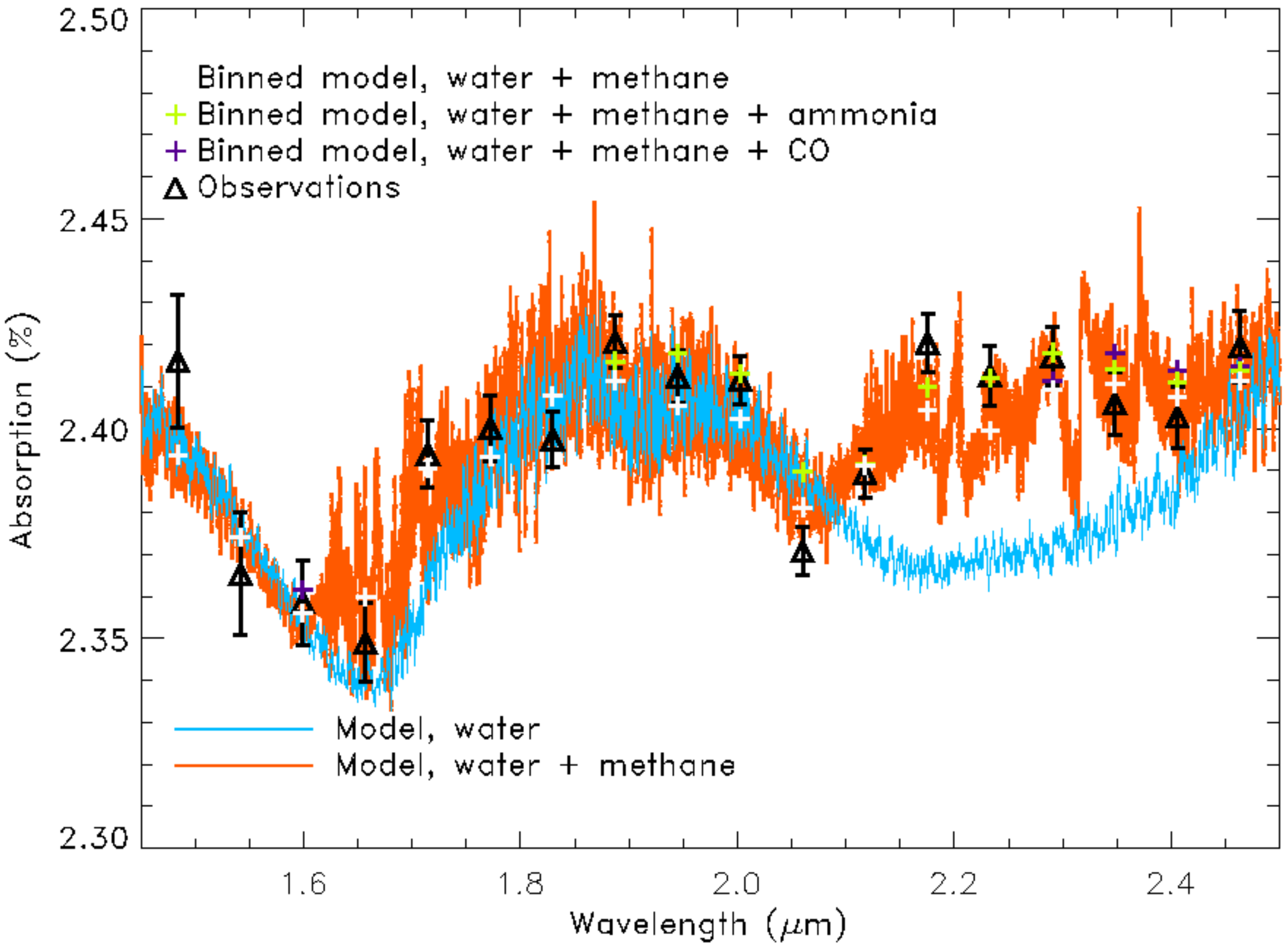


Tinetti *et al.*, Nature, 2007; Beaulieu et al. 2008

HD189733b, Water + Methane



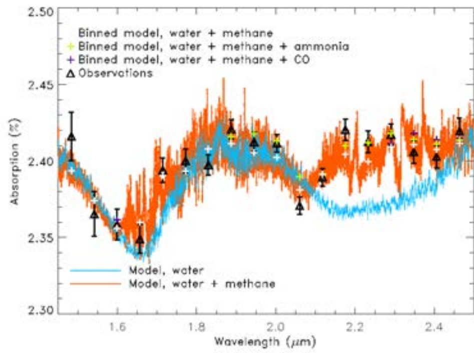




Swain, Vasisht, Tinetti, *Nature*, 2008

HD 189733 b

- Models with $H2O$, $CH4$, clouds and hazes (Emilie)



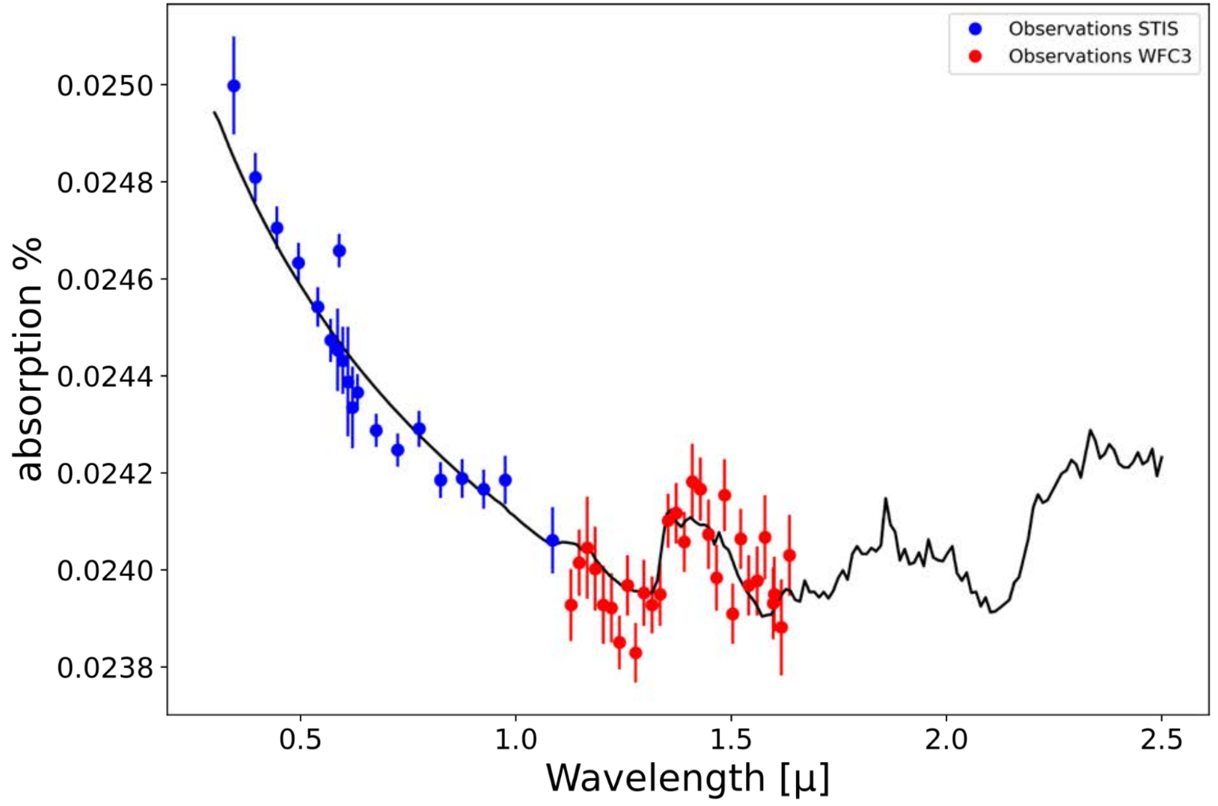


Figure 8 : Transmittance spectrum on HST STIS and WFC3 observations (Sing et al. 2016) of hot Jupiter HD189733b.

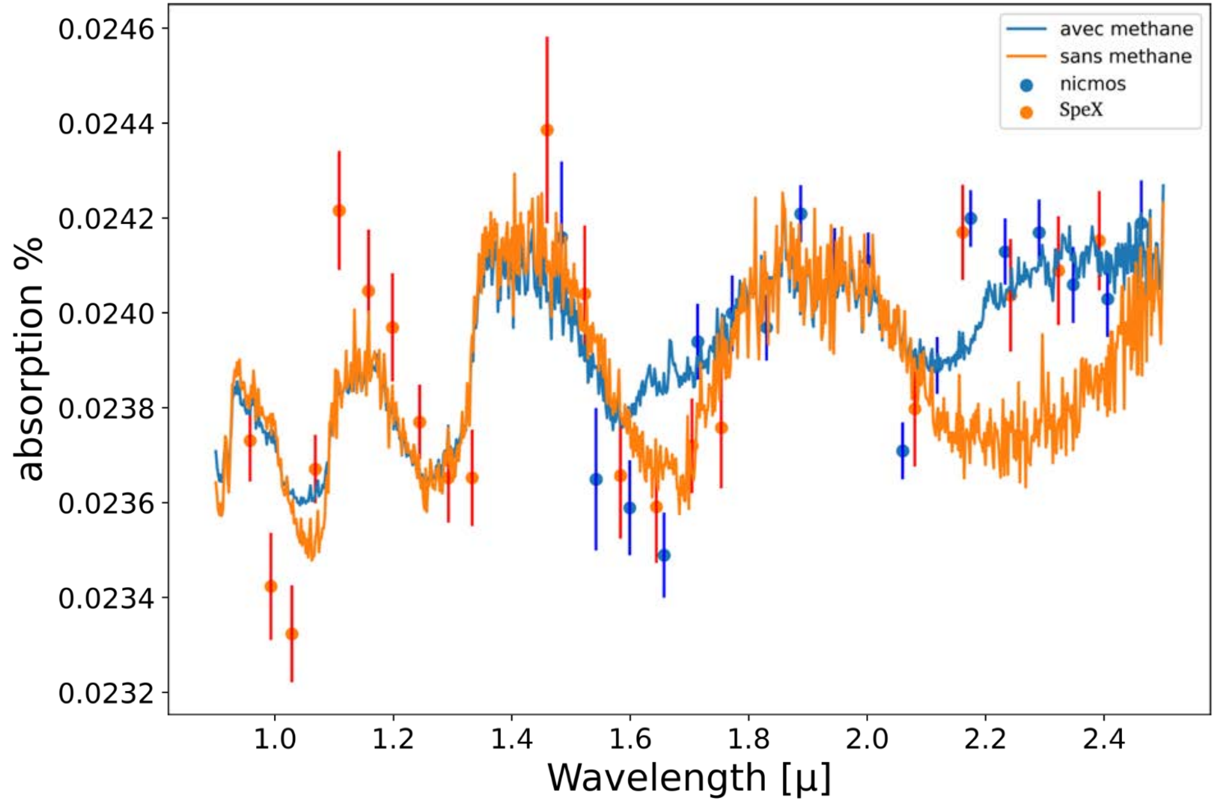
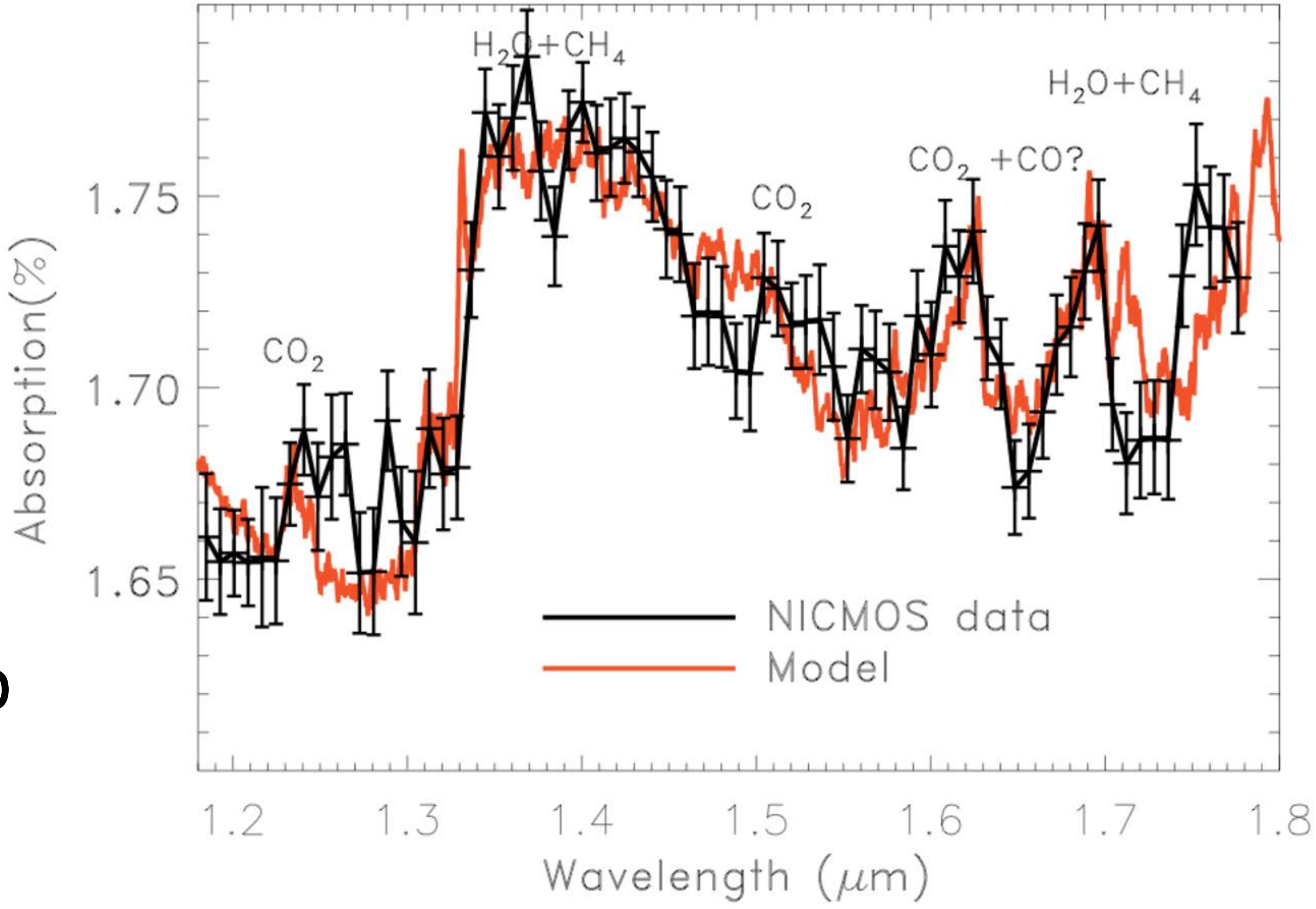


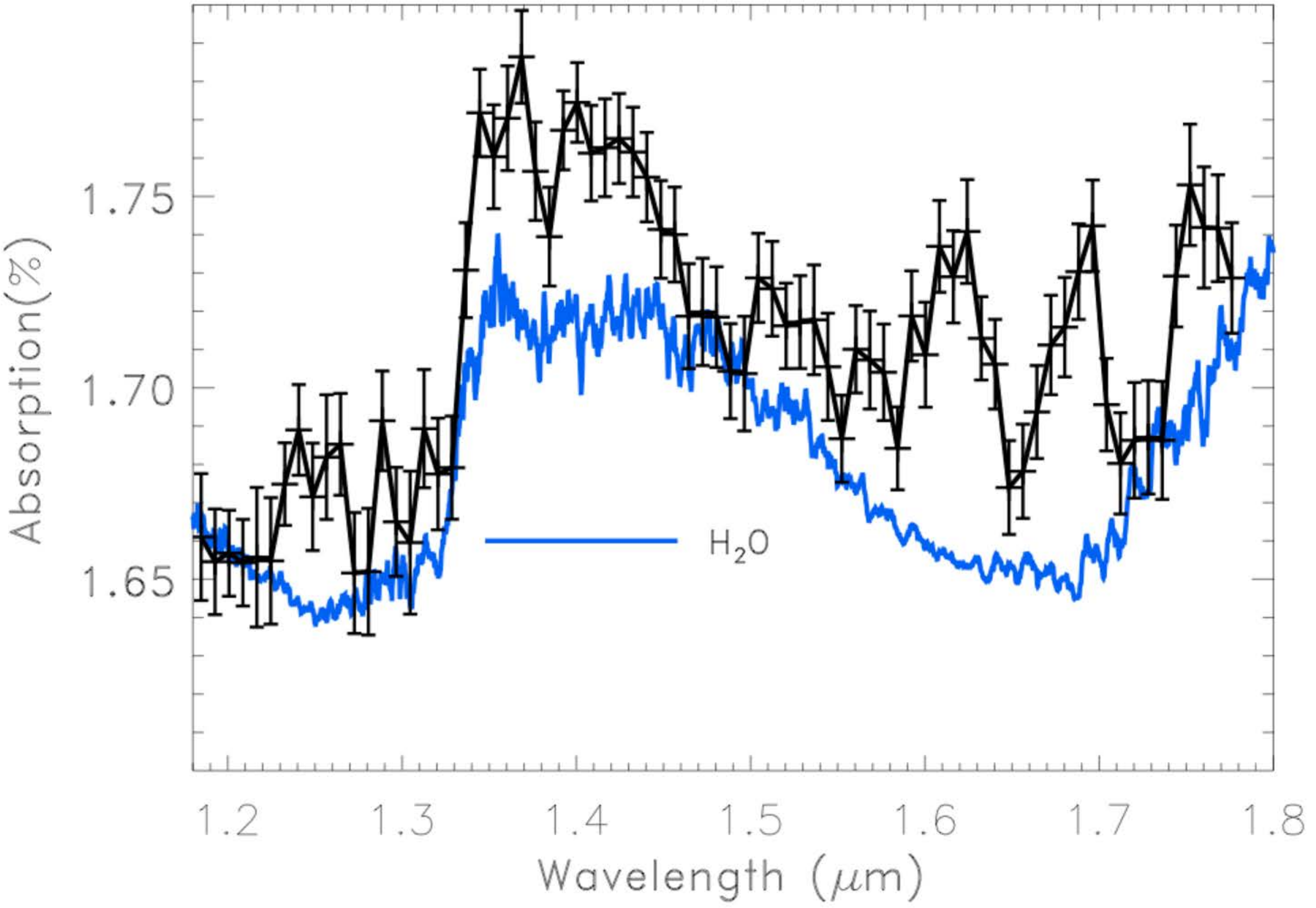
Figure 9 : Transmittance spectrum on SpeX (Danielski et al. 2014) and HST NICMOS (Swain et al. 2008) of hot Jupiter HD189733b.

Hubble: transit spectroscopy

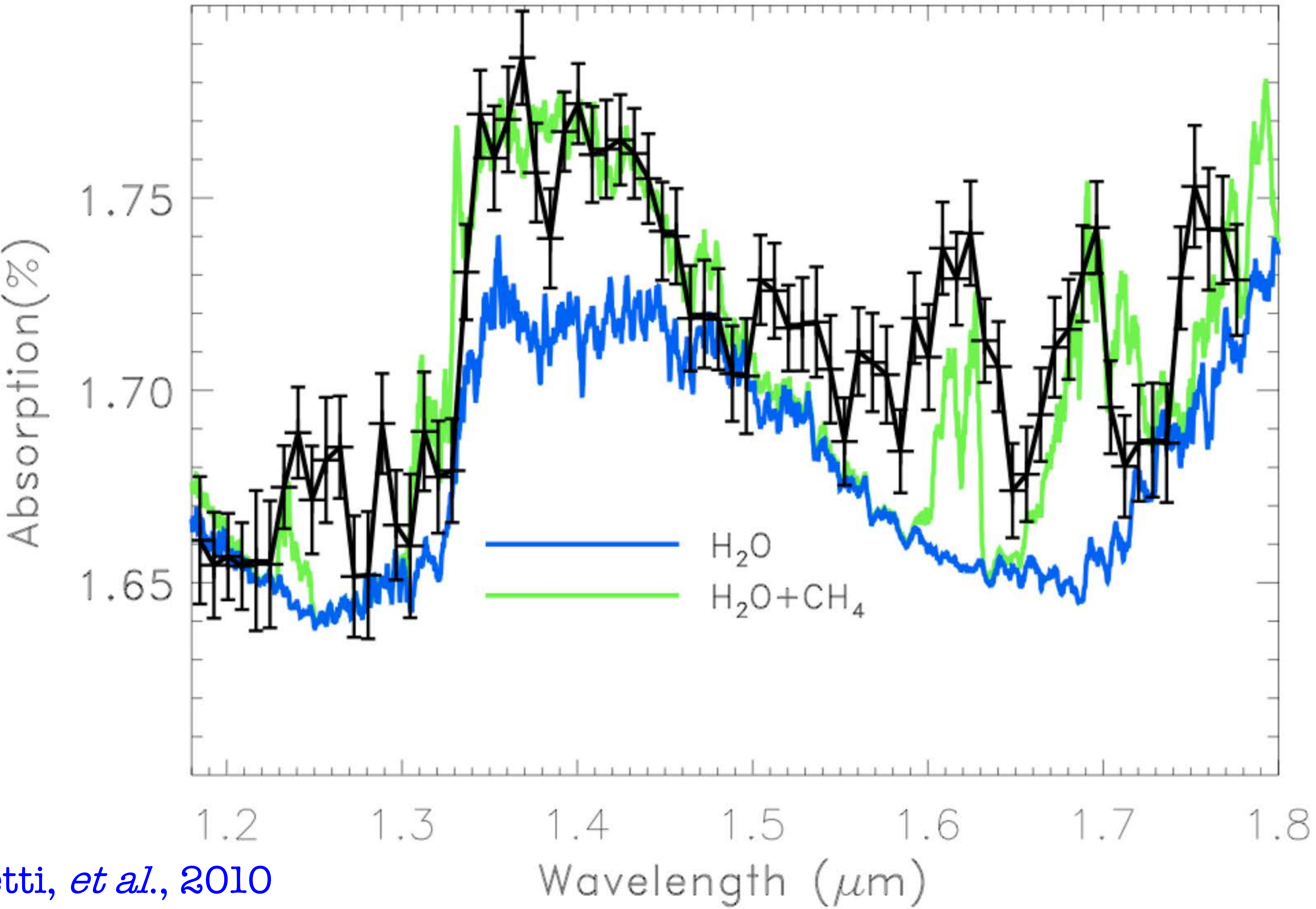


Hot-Jupiter: XO-1b

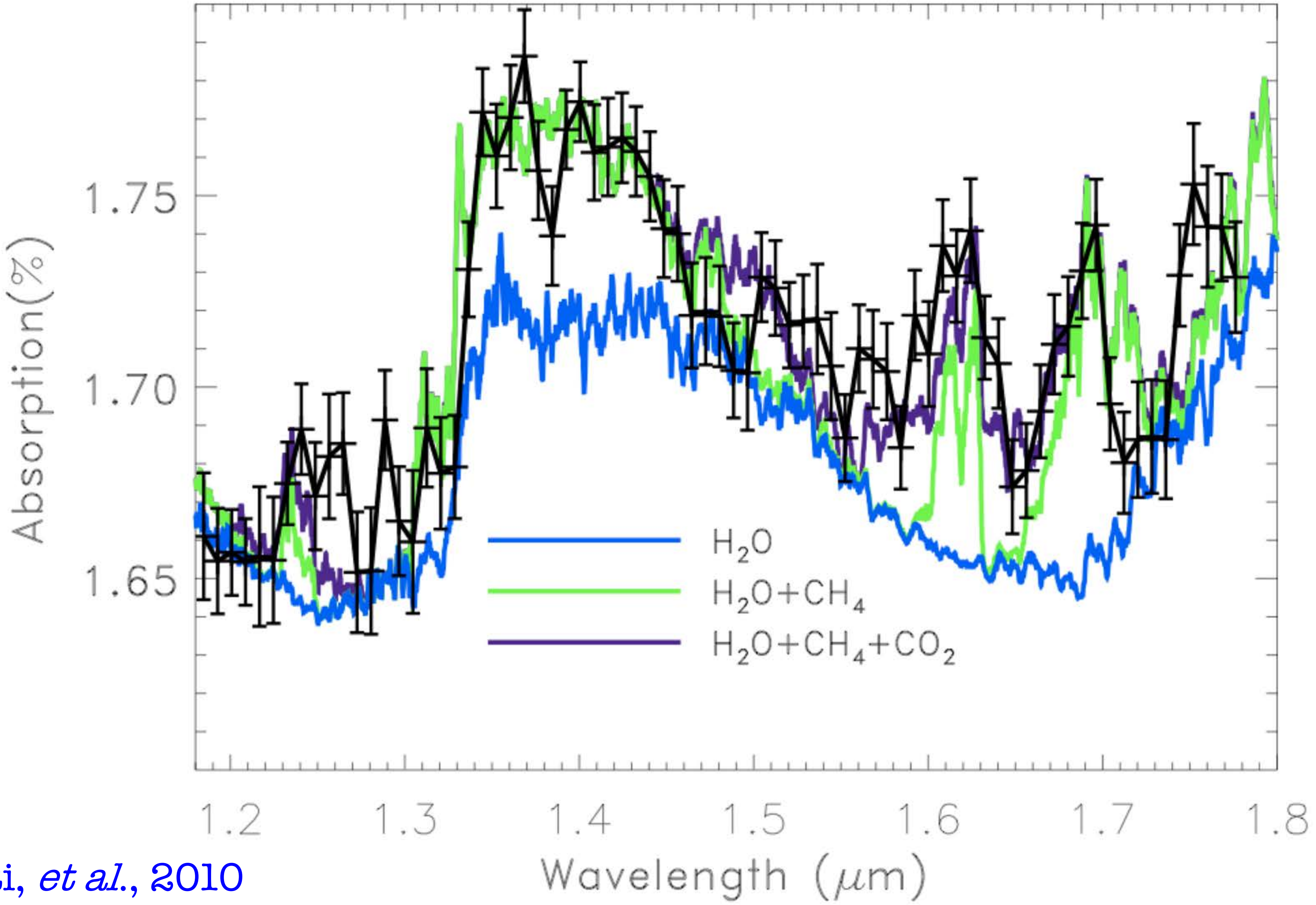
Tinetti, *et al.*, 2010



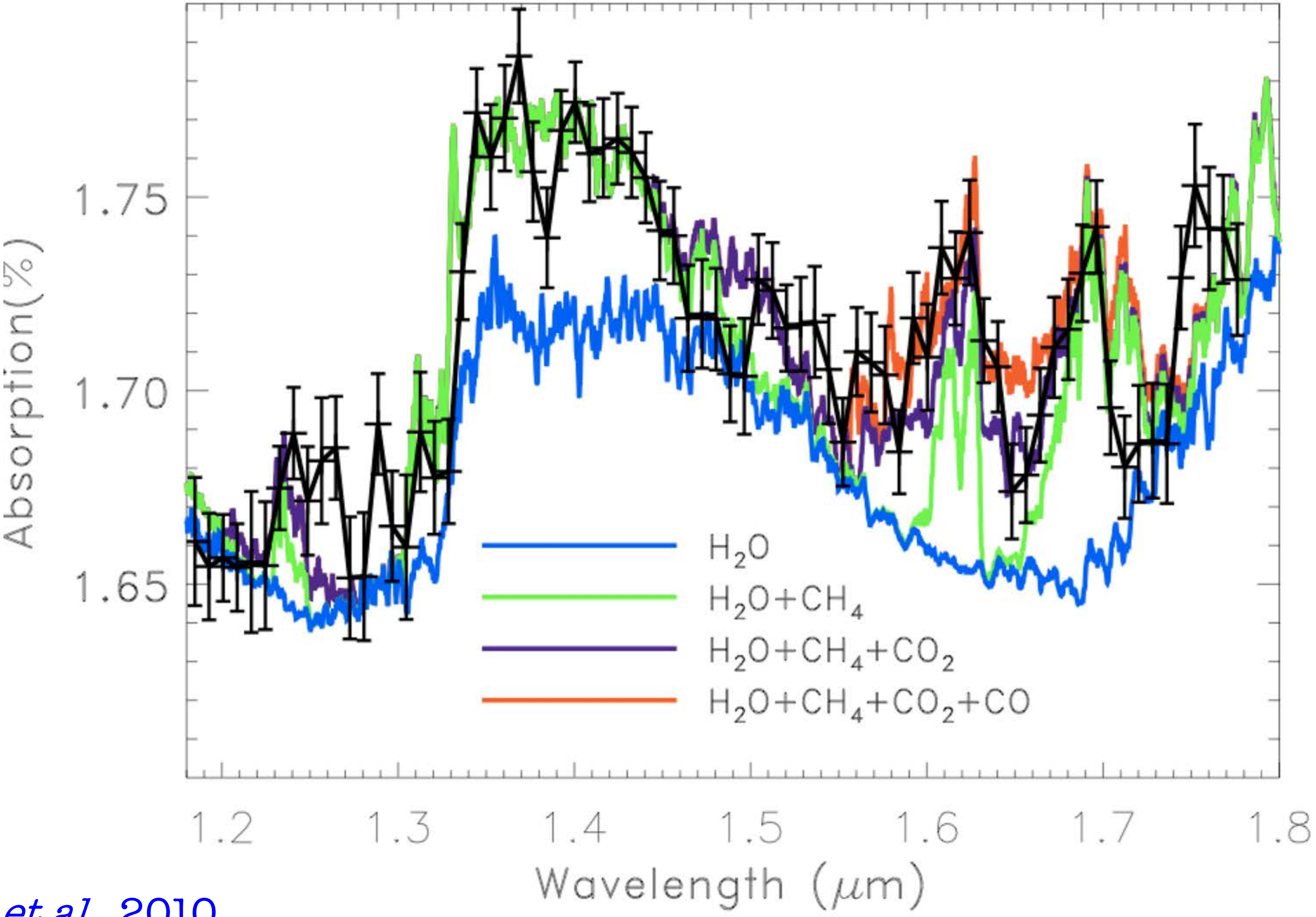
Tinetti, *et al.*, 2010



Tinetti, *et al.*, 2010



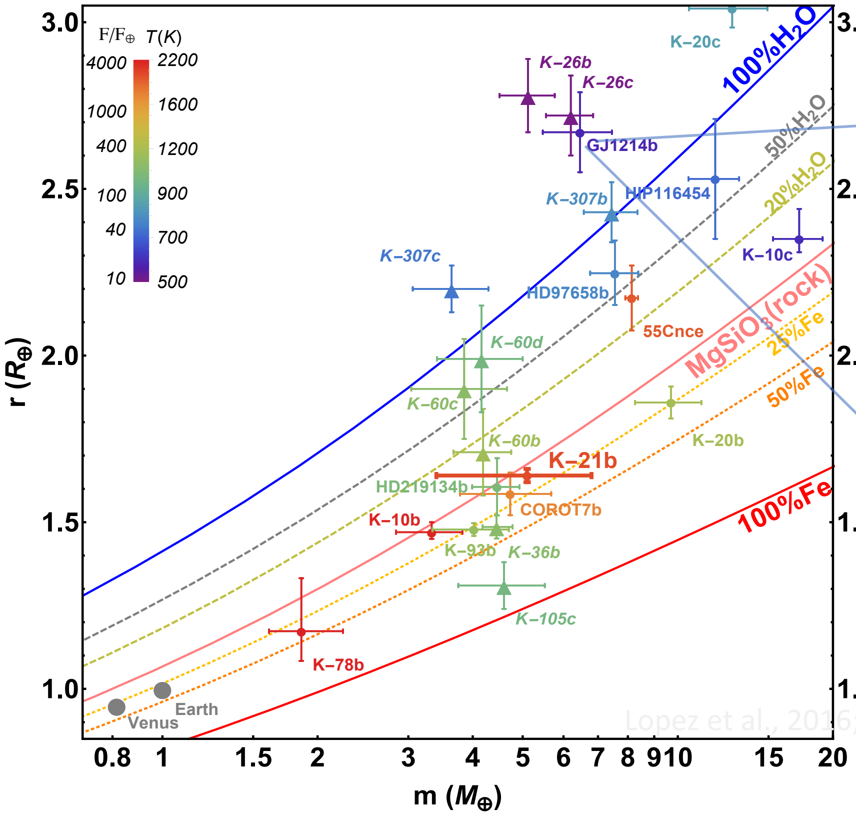
Tinetti, *et al.*, 2010

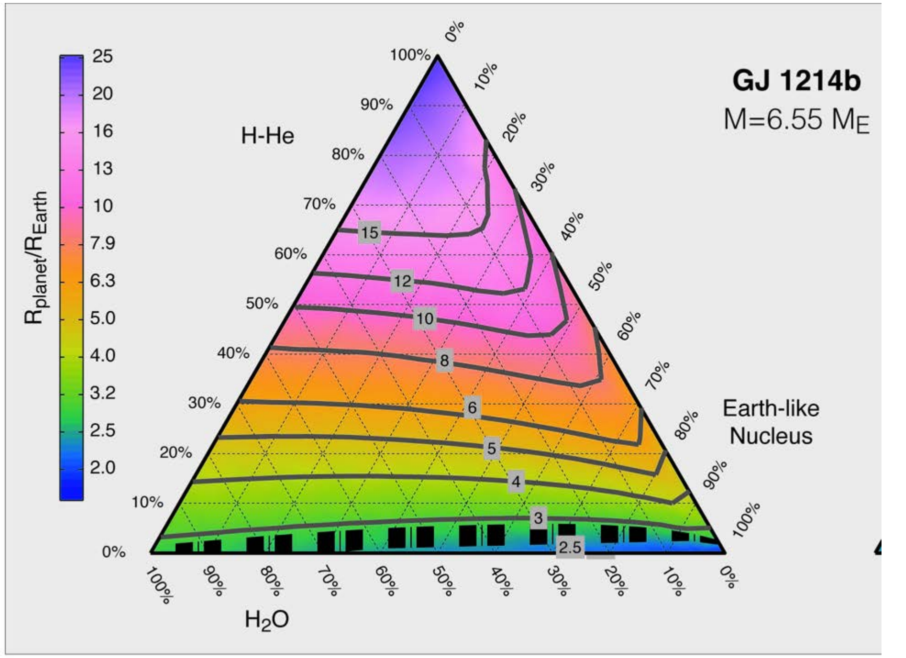


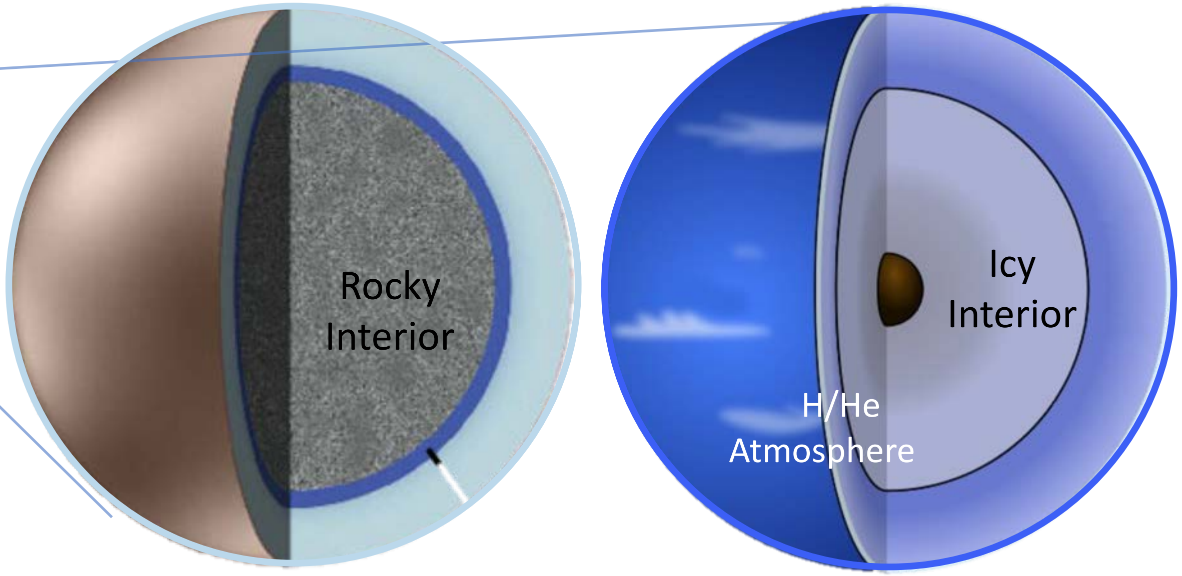
Tinetti, *et al.*, 2010

Spectroscopy to learn the structure of the planet

Density observations



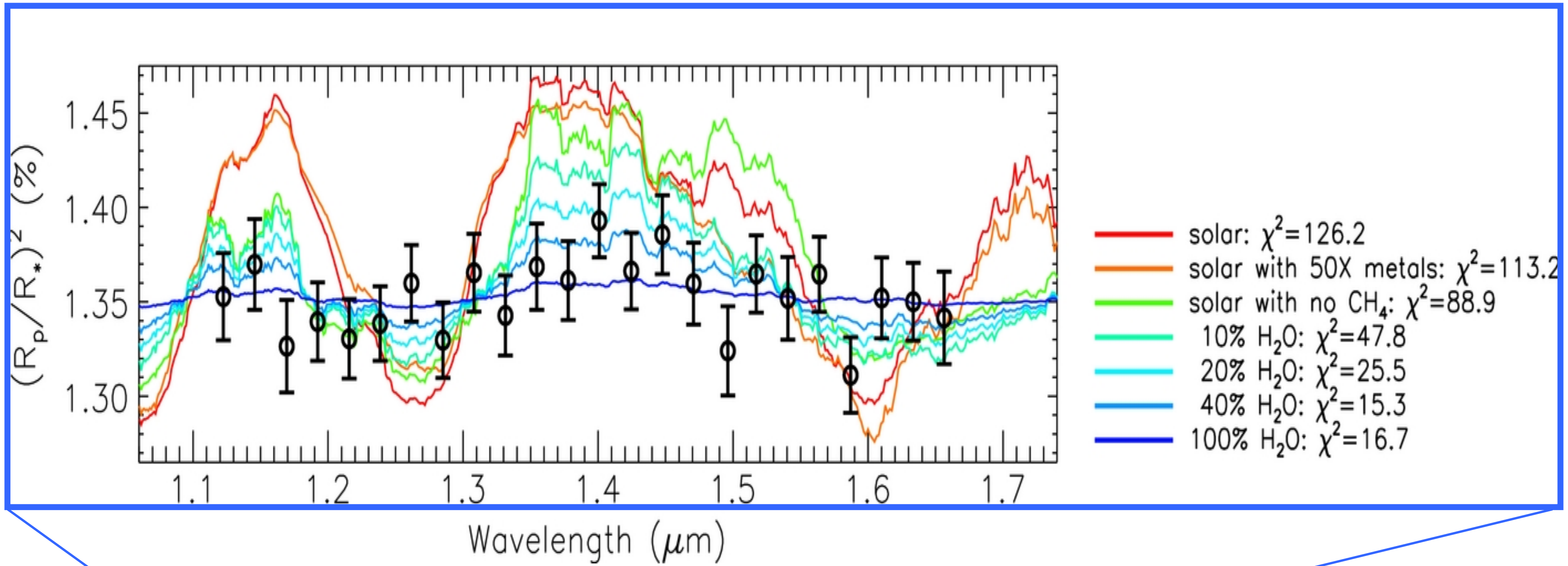


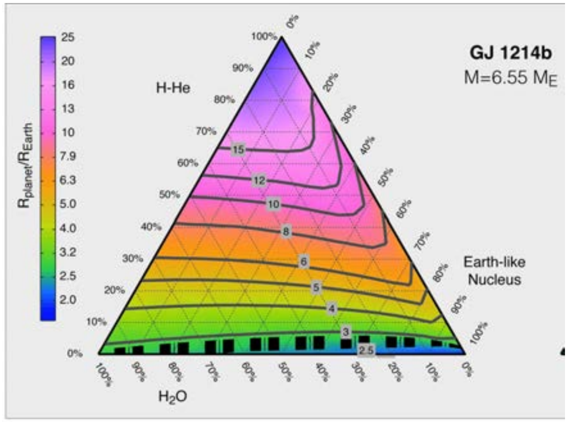


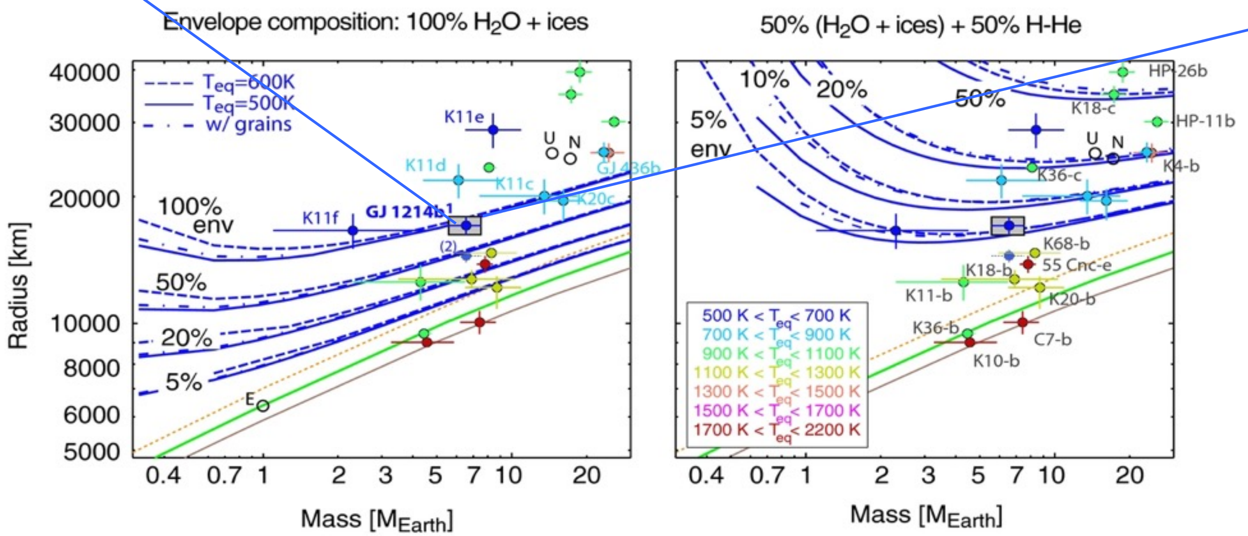
Same mean density – Different atmospheric signatures

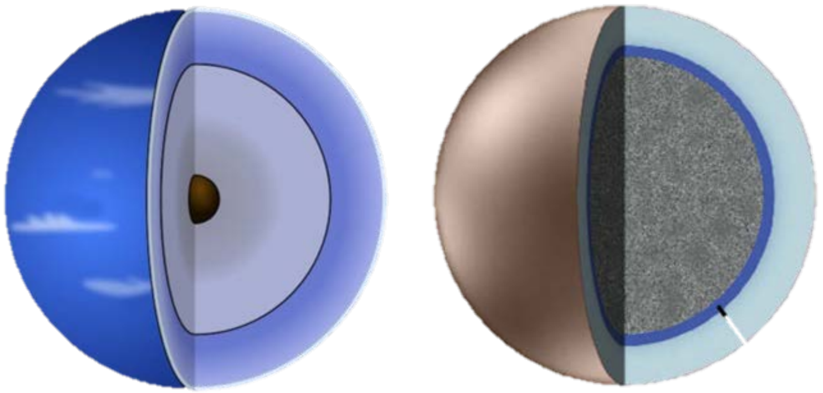
Lopez et al., 2016; Valencia et al., 2013

GJ1214, super Earth ? Mini Neptunes ? With HST clouds are currently hidding molecules
Need to go further to the IR

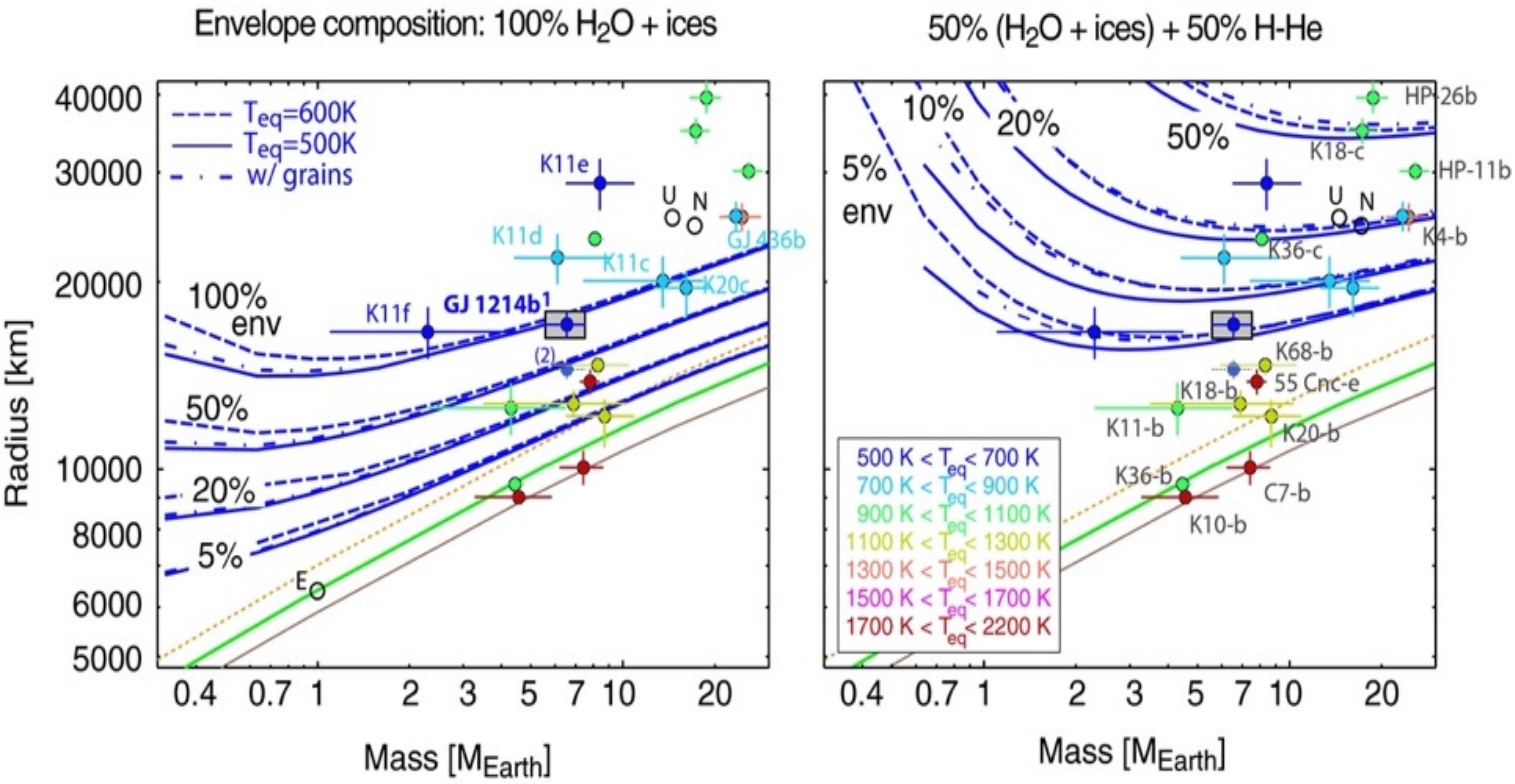








What about Kepler 11 planets ?



Snellen et al., 2010, VLT spectra of HD209458b

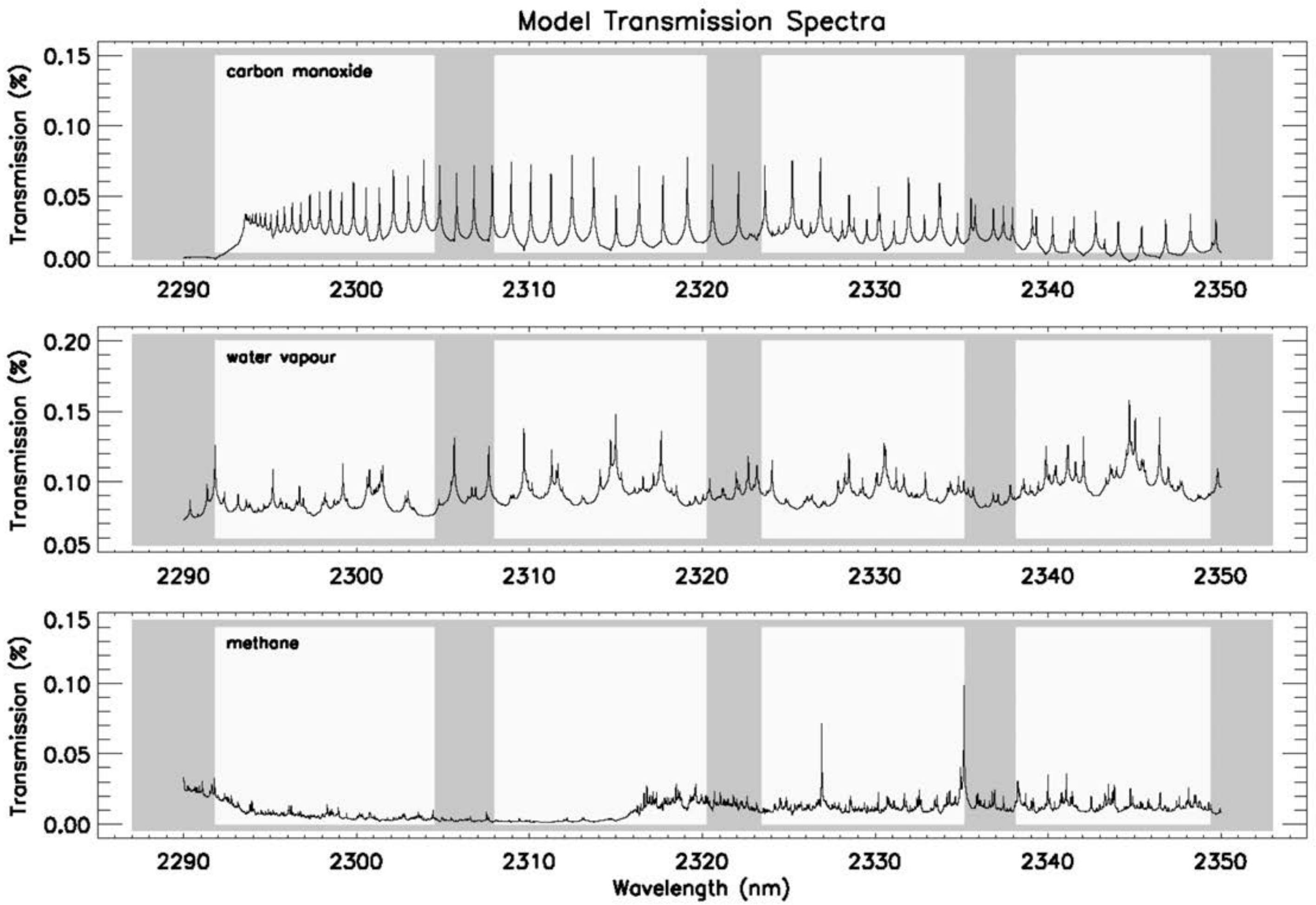
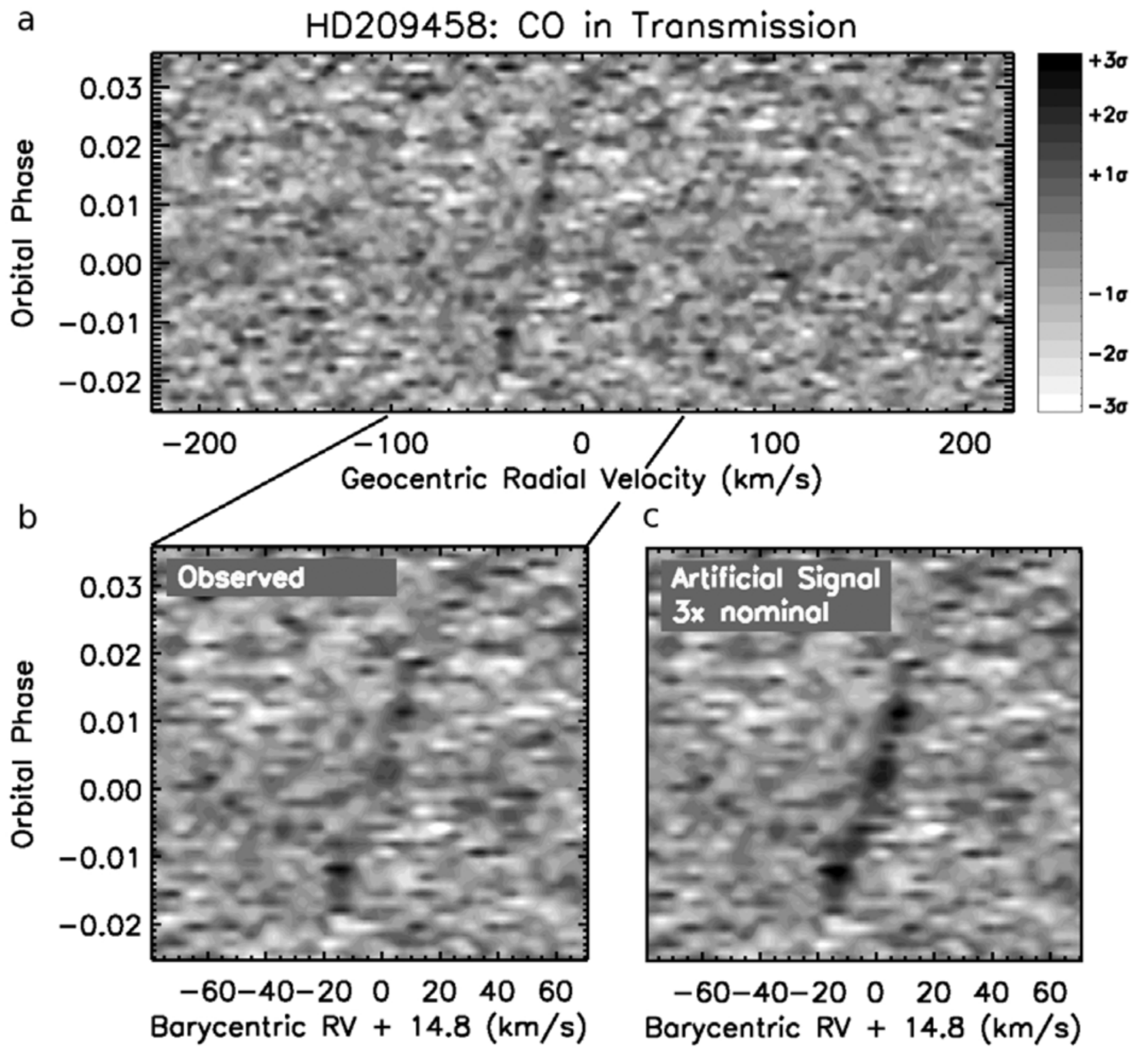


Figure S2: Models used for the transmission of carbon monoxide (top panel), water vapour (middle panel), and methane (lower panel) in the atmosphere of HD209458b.

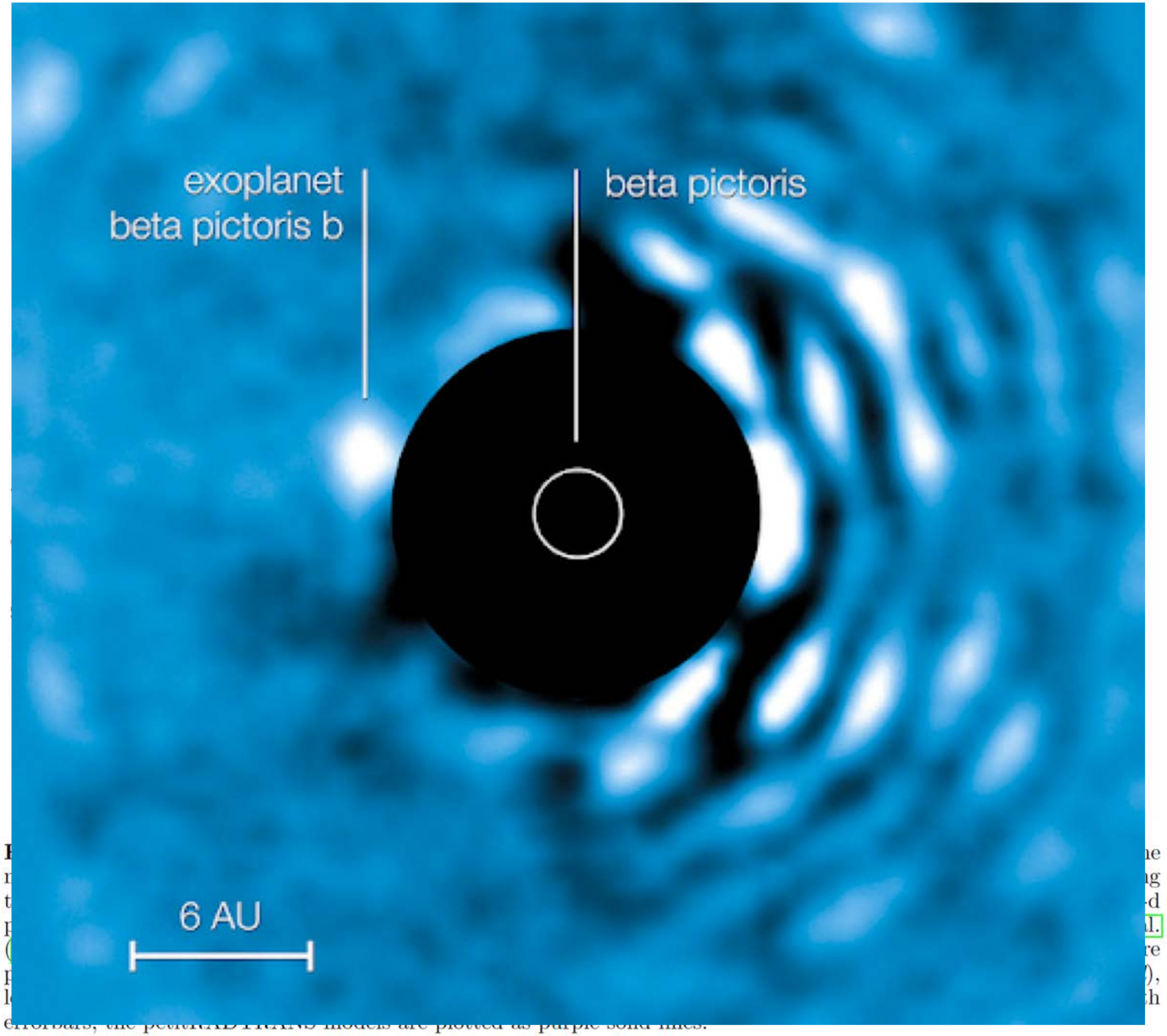
- strong wind flowing from the irradiated dayside to the non-irradiated nightside of the plan within the 0.01-0.1 mbar atmospheric pressure range probed by these observations.

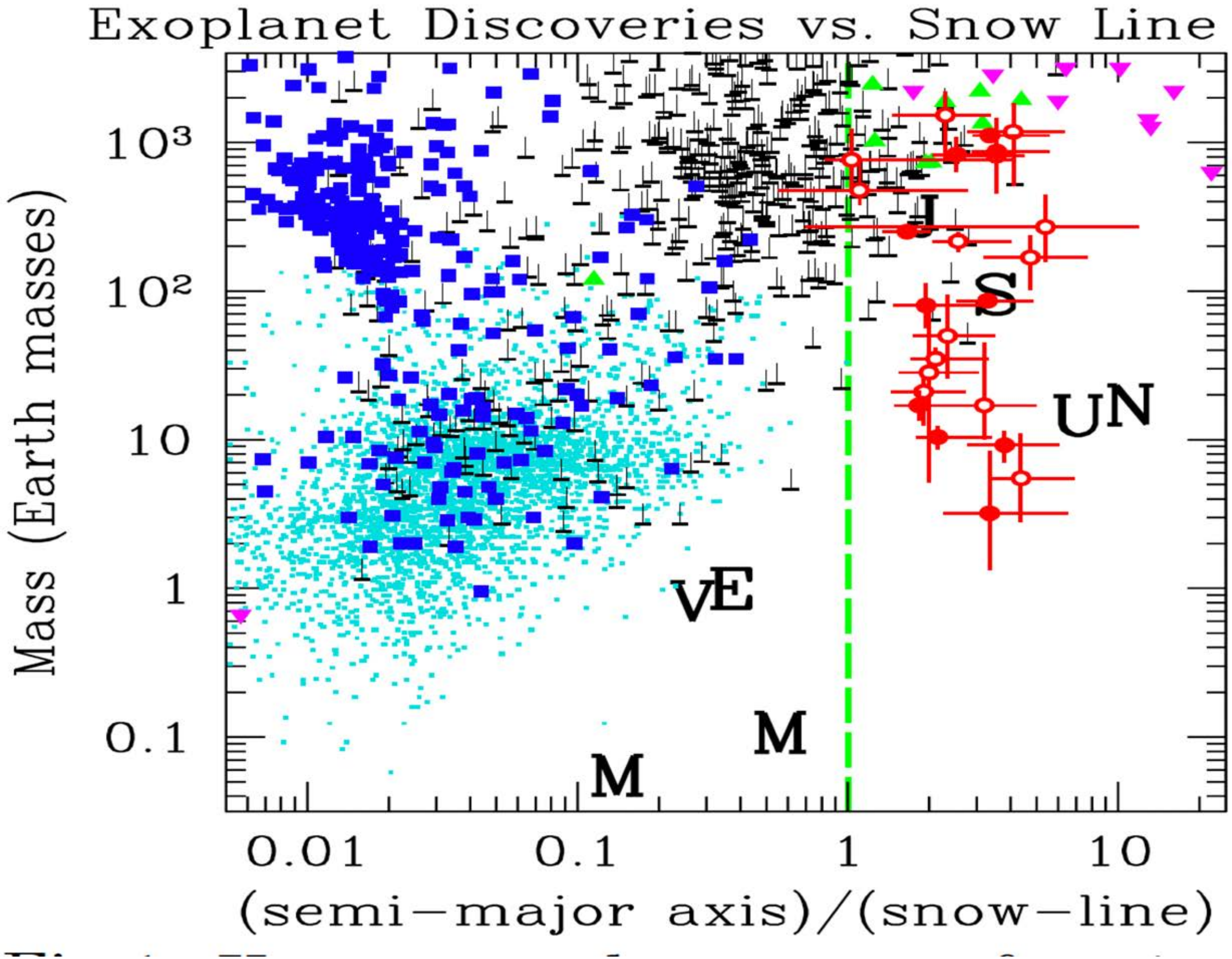
- CO mixing ratio of 1-3x10^{-3} in the upper atmosphere.



Gravity spectra of betapicb, R=500 and R=70

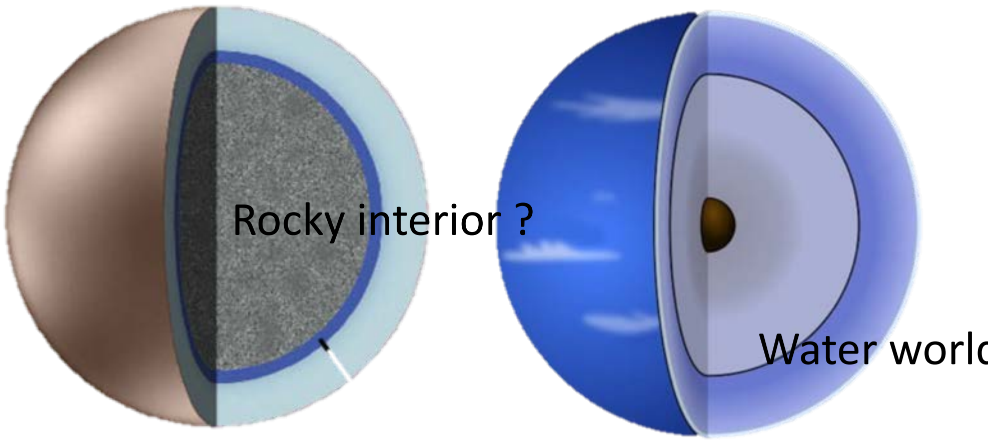
1) mass ~ brown dwarf
2) low C/O ratio for the planet suggests a formation through core-accretion, with strong planetesimal enrichment.

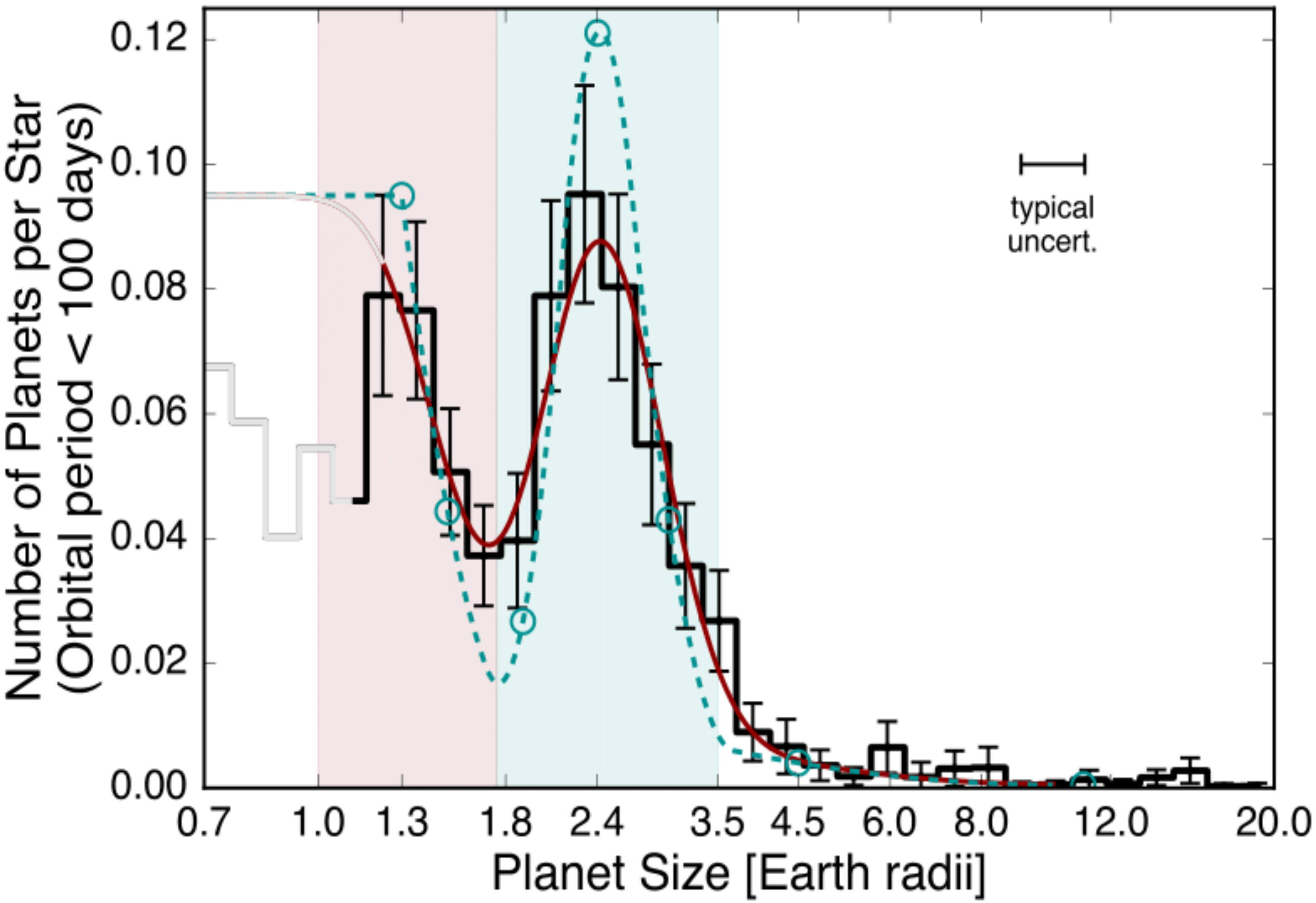




Snow line approximated as 2.7 x M / Mo (AU)

Histogram of planet radii, 2 peaks, super-Earth and Mini-Neptune





Completeness-corrected histogram of planet radii for planets with orbital periods shorter than 100 days.

Lightly shaded regions encompass our definitions of "super-Earths" (light red) and "sub-Neptunes" (light cyan). The dashed cyan line is a plausible model for the underlying occurrence distribution after removing the smearing caused by uncertainties on the planet radii measurements.