Characterising Exoplanet atmospheres *today & tomorrow*

Giovanna Tinetti

Royal Society/University College London

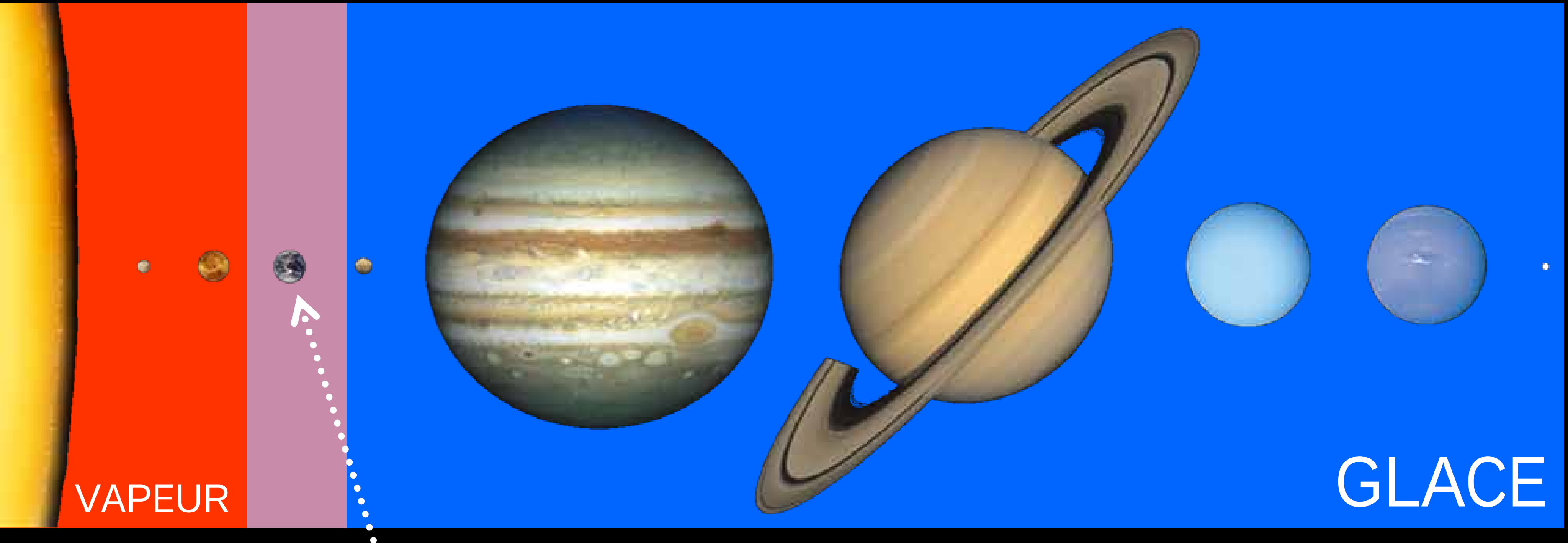
Planets in our solar system

small rocky planets close to the Sun

gas-giant planets more distant from the star

Habitable zone

Temperature increases towards the Sun



Habitable zone= presence of water in the liquid phase

Gauging the Greenhouse

Planetary Energy balance is given by:

$$\sigma T_e^4 = S(1-A)/4$$

	$T_{effective}$	$T_{surface}$	Greenhouse
Venus	-43C	470C	513C
Earth	-17C	15C	32C
Mars	-55C	-50C	5C
	Δ 37 C	Δ 520 C	

A planet's greenhouse effect is as important in determining that planet's surface temperature as is its distance from the star!

After Table 9.1, Bennet, Shostak, Jakosky, 2003

Planetary Atmospheres in the Solar System

- Giant Planets
  - Primary atmospheres (H_2, He, CH_4…)
  - Little evolution (no surface, little escape)

- « Terrestrial » planets (Earth, Venus, Mars, Titan)
  - Secondary atmospheres (CO_2 / N_2, N_2 / O_2, N_2 / CH_4)
  - Outgassed and strongly evolved (escape, surface interaction)

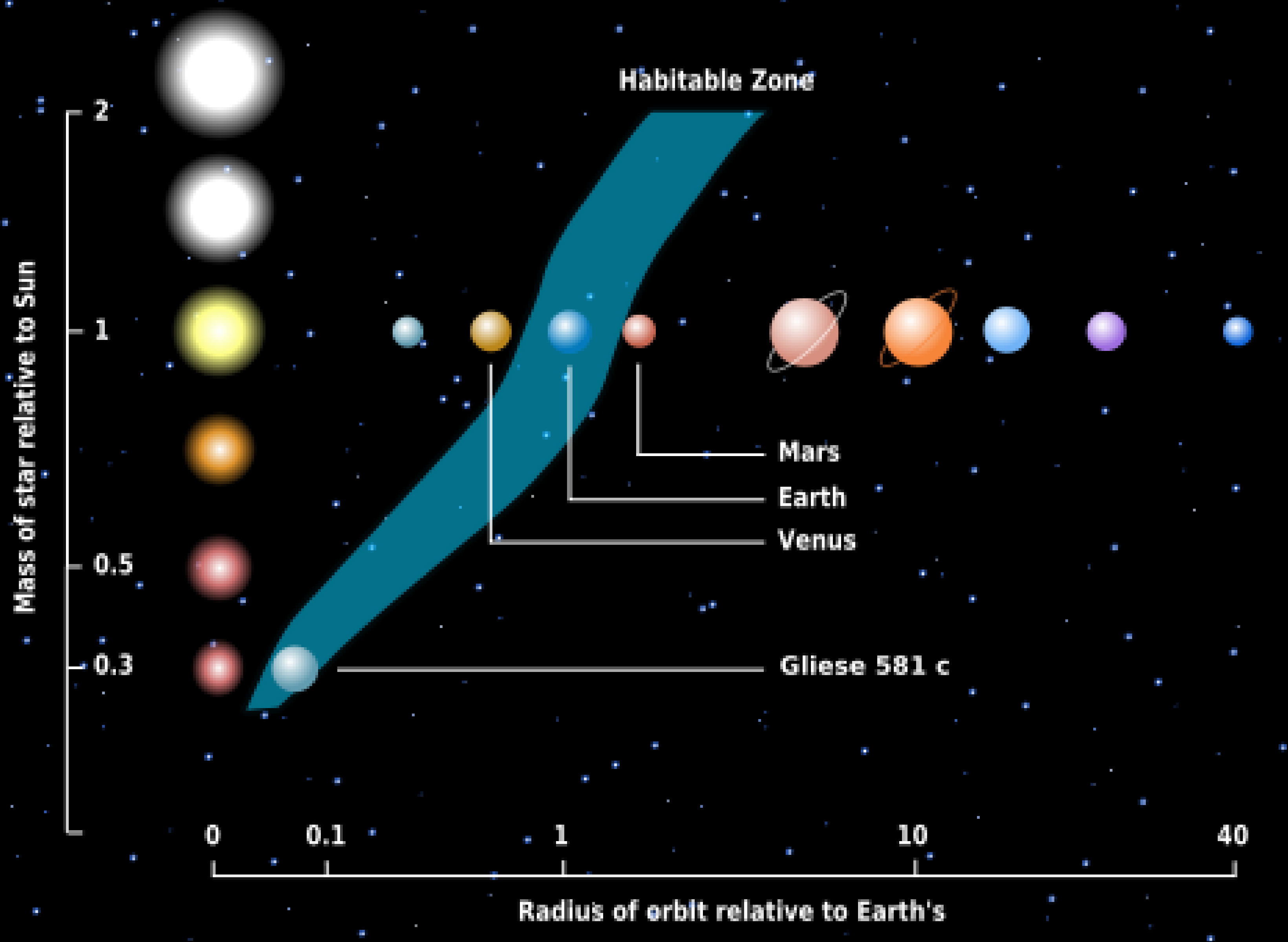
- Tenuous atmospheres (Pluto, Triton, Io, Enceladus)
  - In equilibrium with surface ices or internal sources

- Exospheres (Mercury, Moon, other Galilean satellites)
  - Solar flux or solar wind action on surfaces

Table 1.3 List of three most abundant gases in planetary atmospheres. Mixing ratios are given in parenthesis. All compositions refer to the surface or 1 bar.

Jupiter	H_2 (0.93)	He (0.07)	CH_4 (3×10^{-3})
Saturn	H_2 (0.96)	He (0.03)	CH_4 (4.5×10^{-3})
Uranus	H_2 (0.82)	He (0.15)	CH_4 (2.3×10^{-2})
Neptune	H_2 (0.80)	He (0.19)	CH_4 ($1 - 2 \times 10^{-2}$)
Titan	N_2 (0.95 – 0.97)	CH_4 (3.0×10^{-2})	H_2 (2×10^{-3})
Triton	N_2 (0.99)	CH_4 (2.0×10^{-4})	CO (< 0.01)
Pluto	N_2 (?)	CH_4 (?)	CO (?)
Io	SO_2 (0.98)	SO (0.05)	O (0.01)
Mars	CO_2 (0.95)	N_2 (2.7×10^{-2})	Ar (1.6×10^{-2})
Venus	CO_2 (0.96)	N_2 (3.5×10^{-2})	SO_2 (1.5×10^{-4})
Earth	N_2 (0.78)	O_2 (0.21)	Ar (9.3×10^{-3})

Habitable zone for different stars



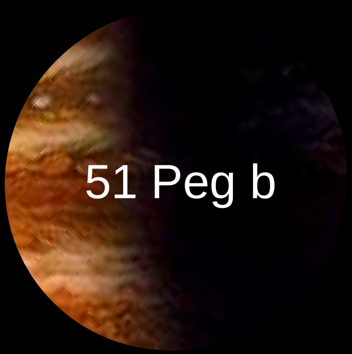
The first extrasolar planet

Mercury Venus Earth

Solar system:

small rocky planets close to the Sun

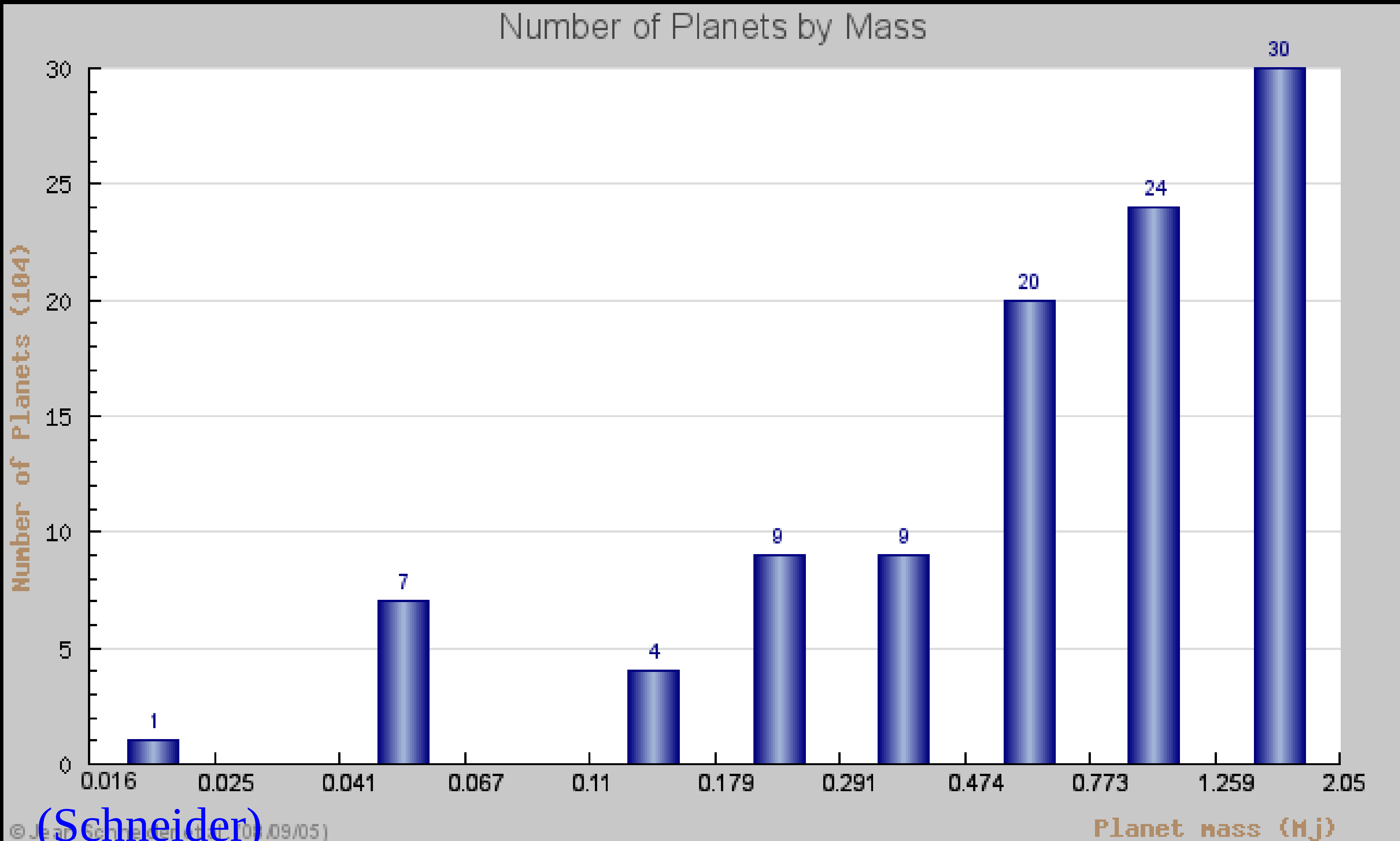
gas-giant planets more distant from the star à à



51 Pegas: a gas-giant very close to its parent star (hot-Jupiter)

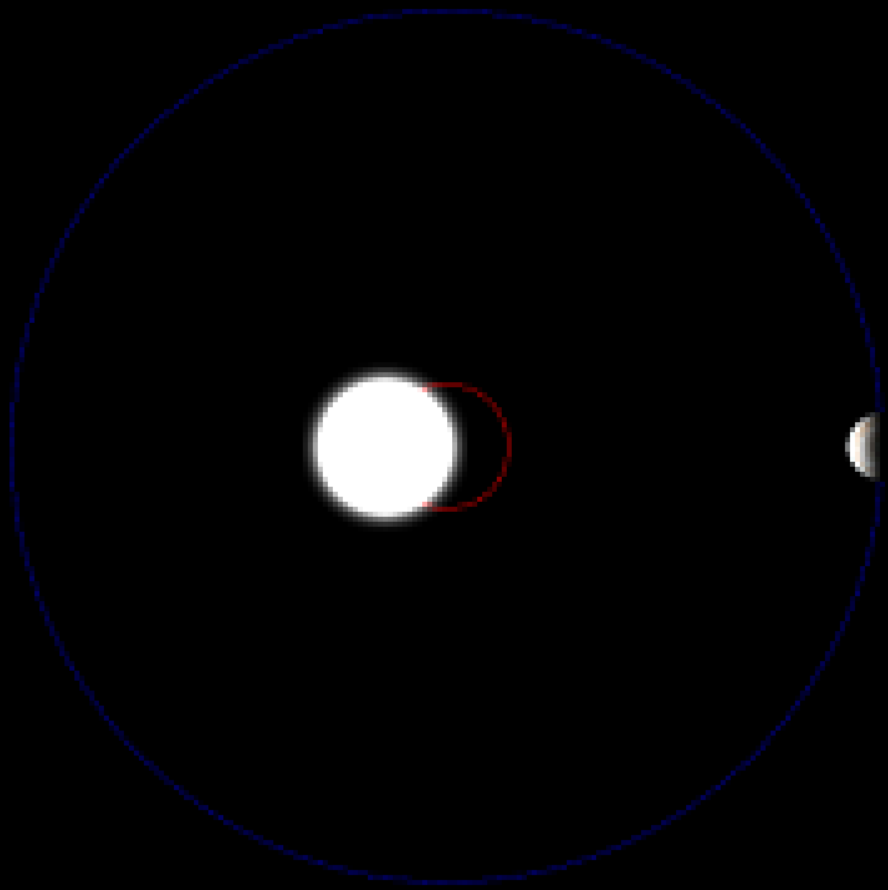
(ß) M. Mayor & D. Queloz, 1995, *Nature* **378** p. 355

450 Extrasolar planets



(Schneider)

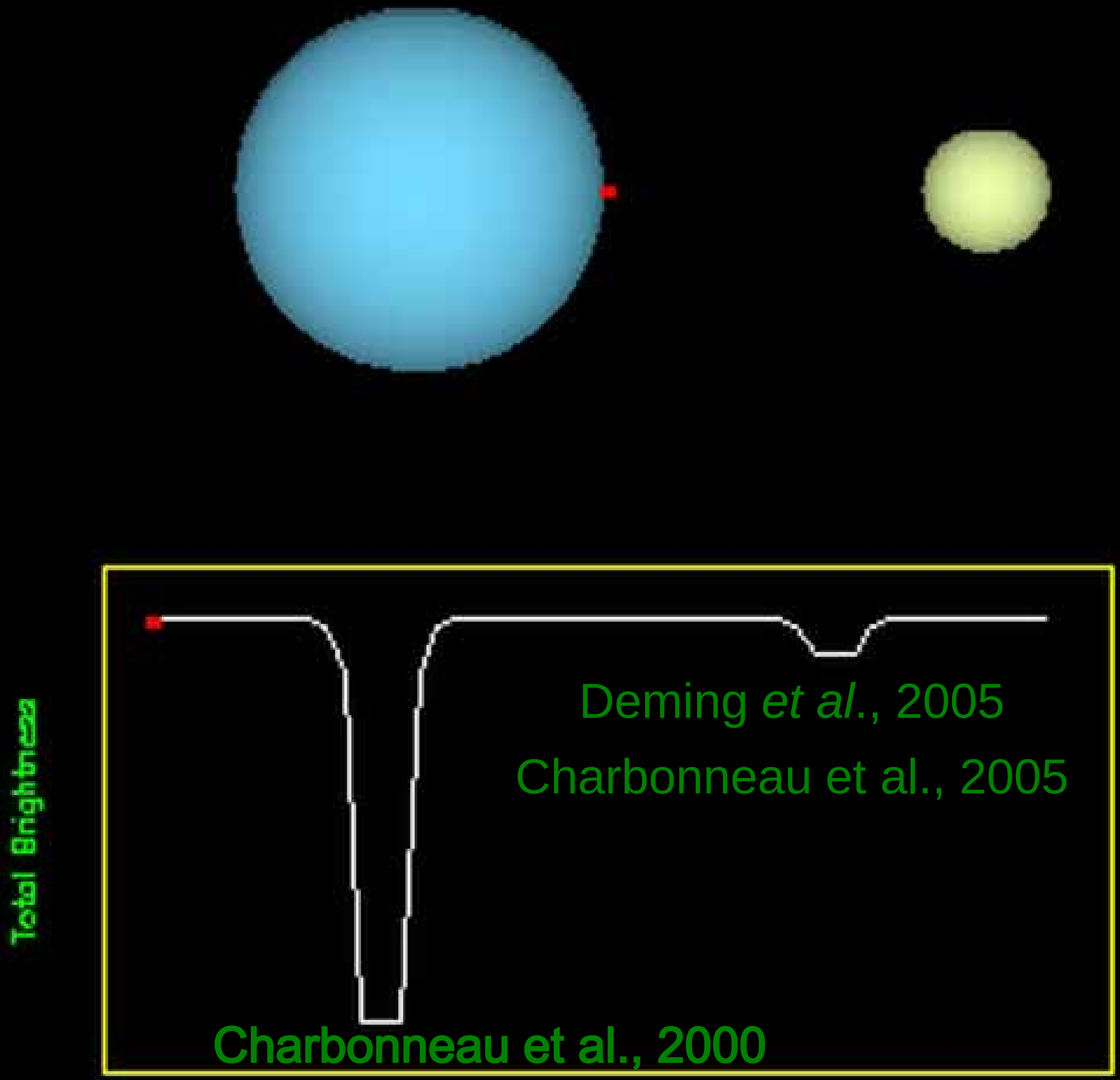
Radial velocity & astrometry



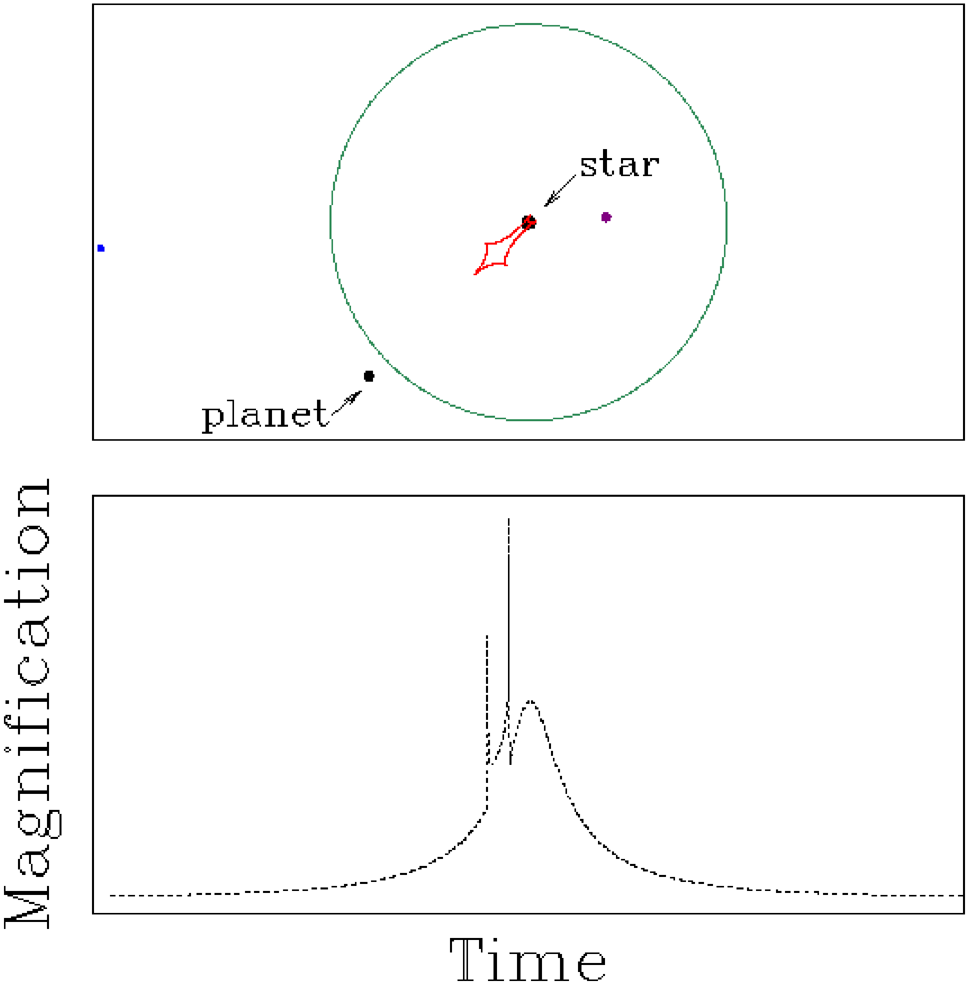
Mayor & Queloz, 1995

Pravdo & Shaklan, 2009

Transit

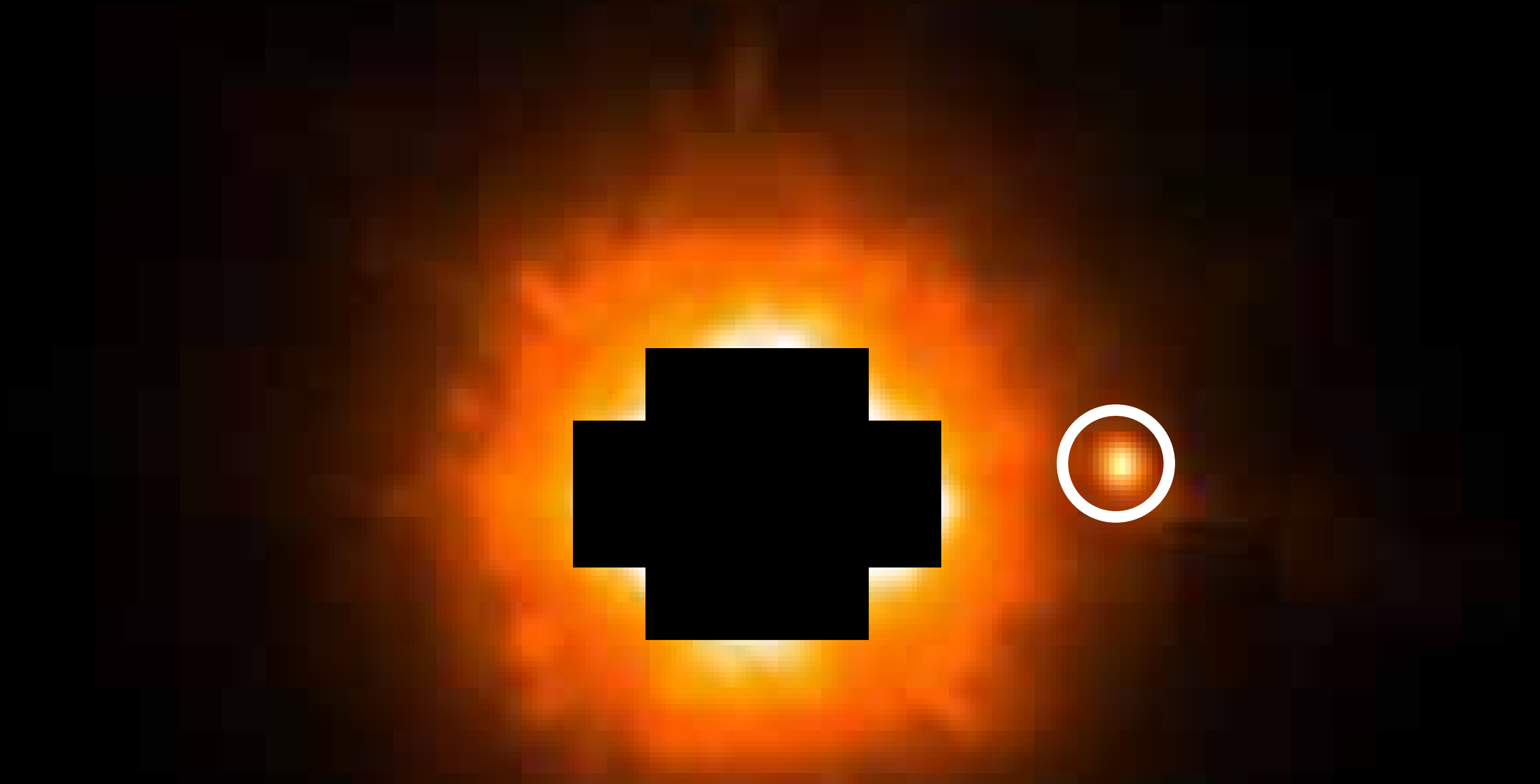

Deming *et al*., 2005
Charbonneau et al., 2005
Total Brightness
Charbonneau et al., 2000

Microlensing



Beaulieu et al., 2005

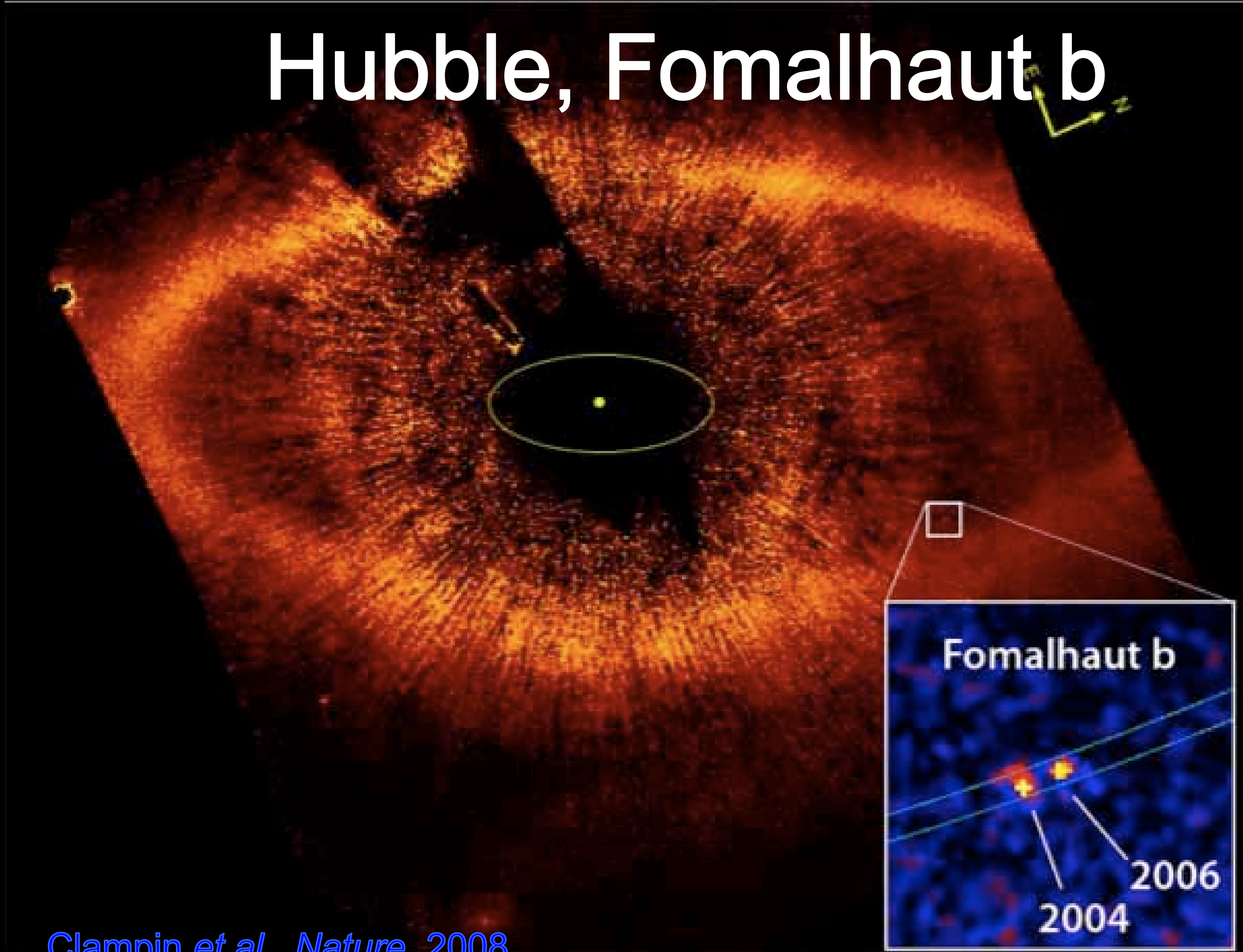
Direct detection



10^9 photons in the visible

10^6 photons in the infrared

Direct detection: Hubble, Fomalhaut b



Clampin *et al.*, *Nature*, 2008

Where are those planets?

Exoplanet today

The lightest
1.9 Earth masses (Gliese581d)

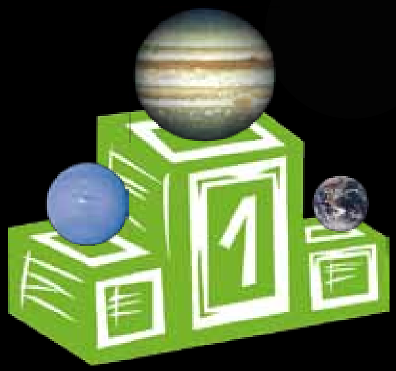
The heaviest
+5000 Earth masses (HD 202206 b)

The shortest year
1 day + 5 hours (OGLE-TR-56 b)

The longest year
100 years (PSR B1620-26 b)

The closest to the Earth
10 light years (Epsilon Eridani)

The farest to the Earth
22000 light years (OGLE-390 b)

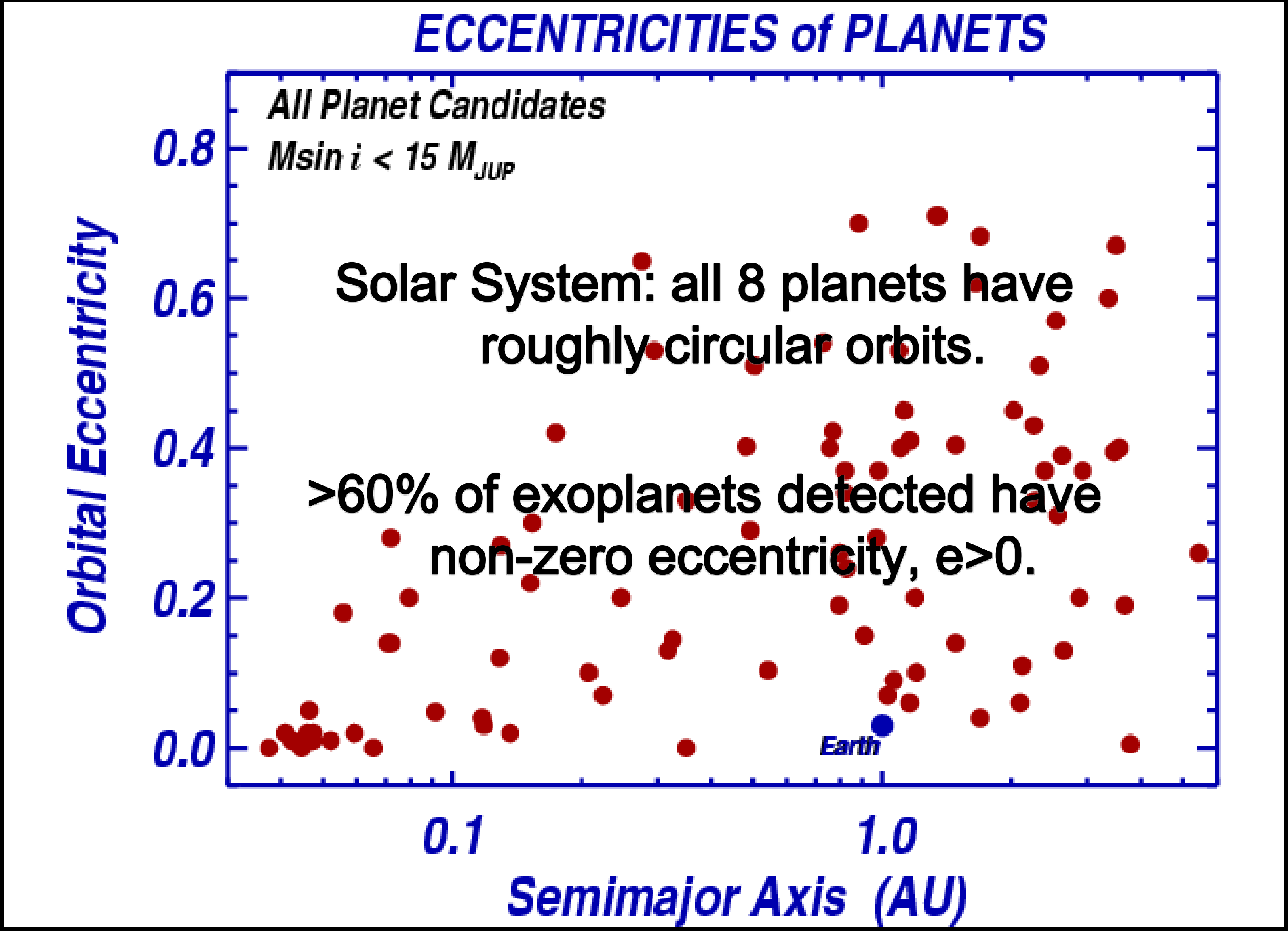


1 light-year = 10 000 billion km

What's wrong with being "fat"?

Equal opportunity for Super-Earths

What's wrong with being eccentric?



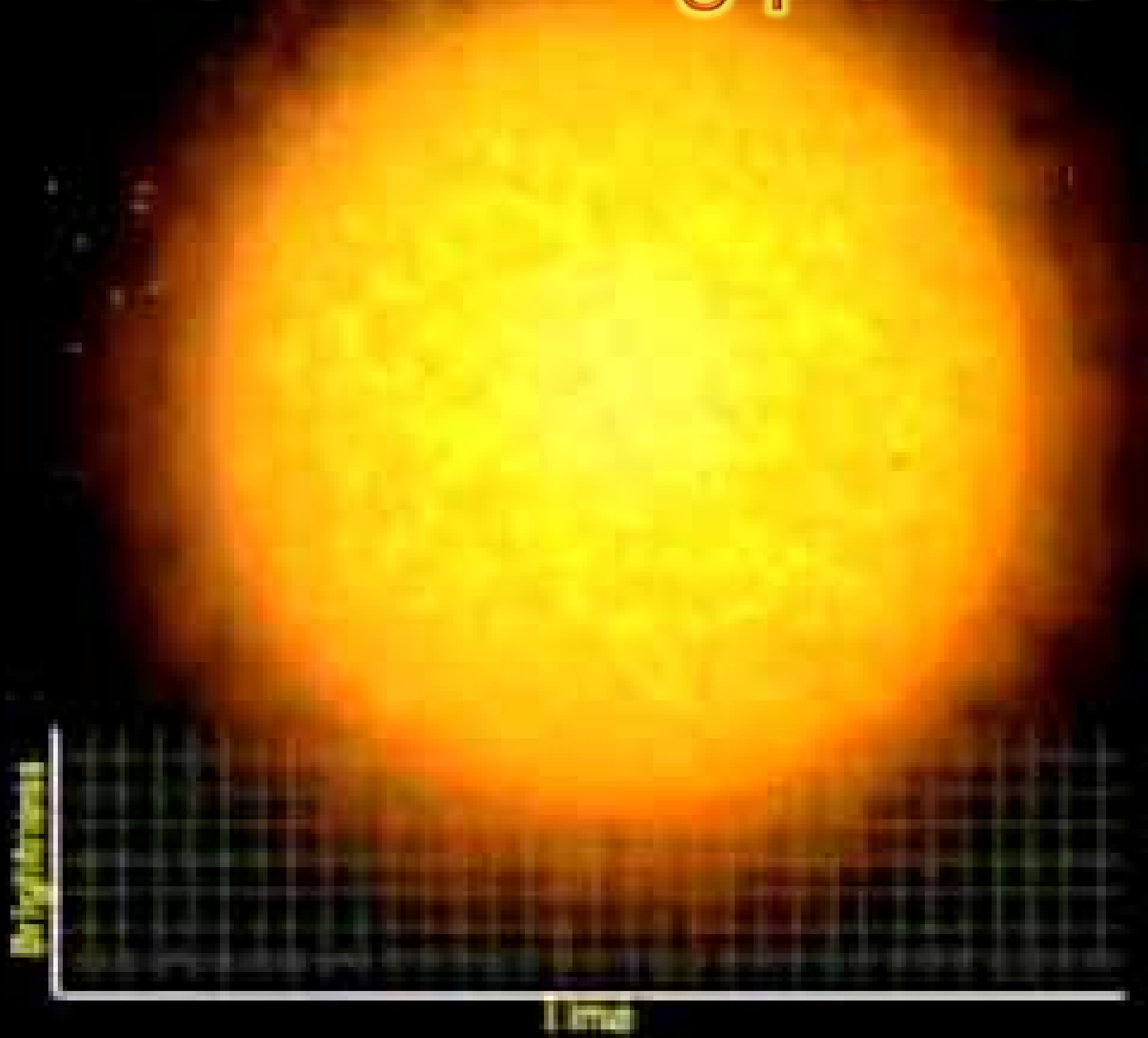
Solar System: all 8 planets have roughly circular orbits.

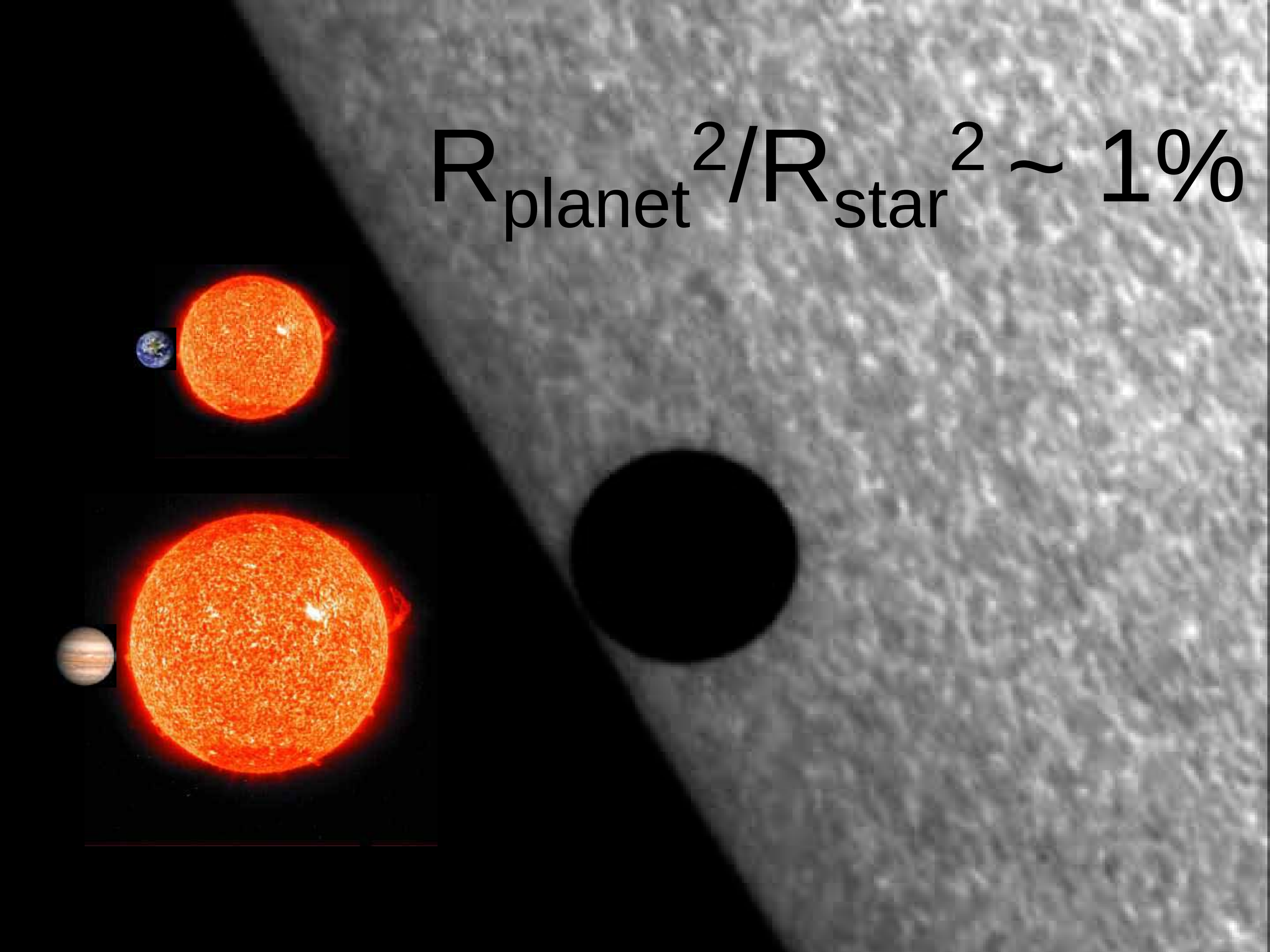
>60% of exoplanets detected have non-zero eccentricity, e>0.

Combining eccentricity and tilt

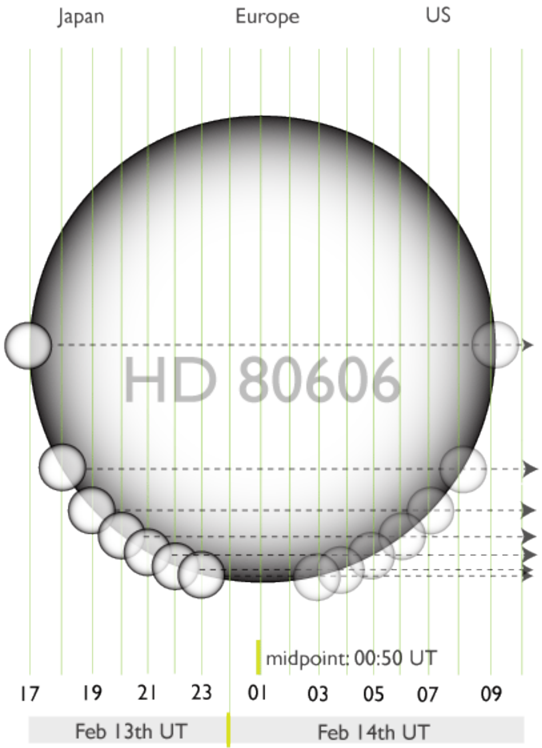
Sertorio & Tinetti, 2002
Williams et al., 2002
Duffy, Tinetti, Liang, in prep

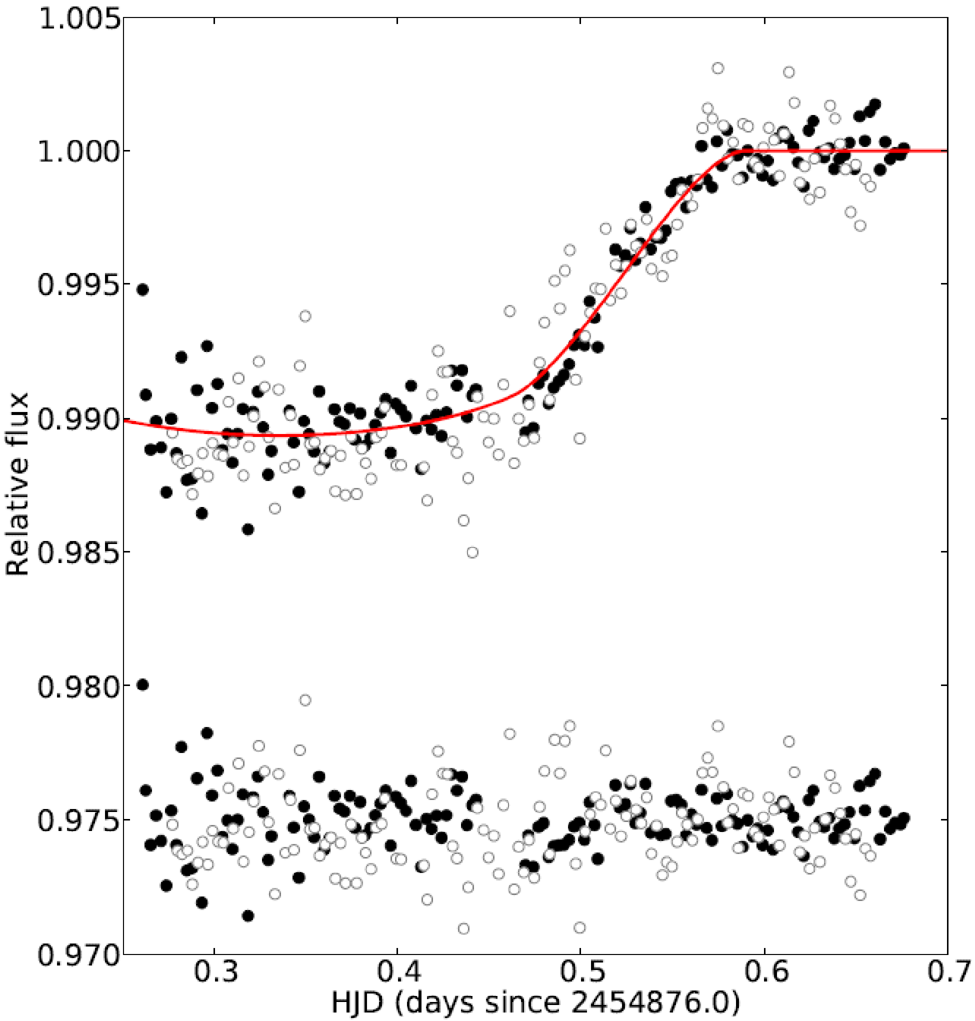
70 Transiting planets




$R_{planet}^2/R_{star}^2 \sim 1\%$

You can do it from London, with 35 cm telescope…

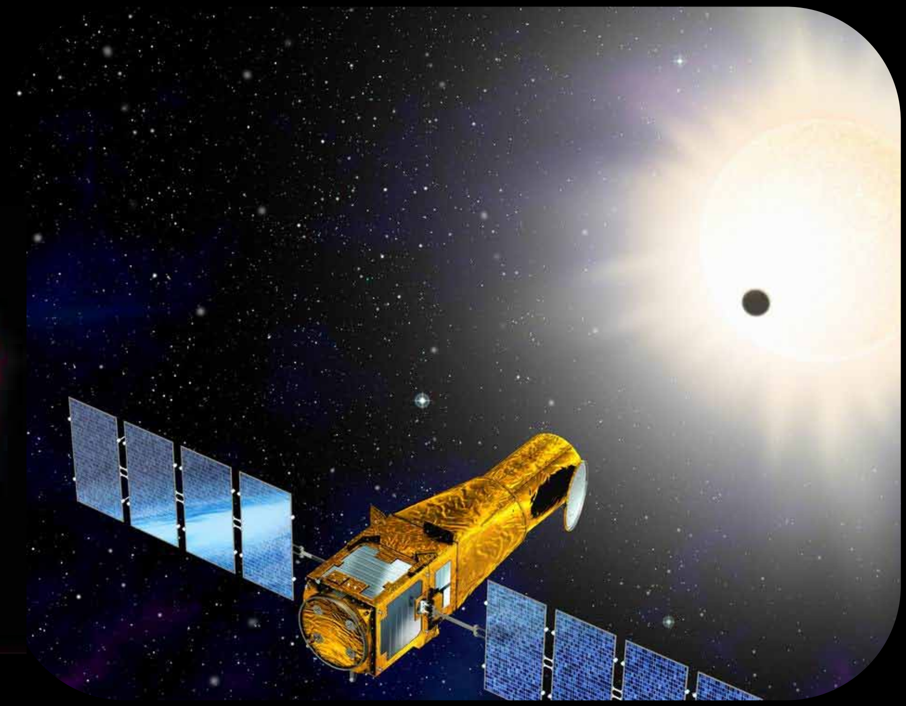




Fossey, Waldmann, Kipping, *MNRAS*, 2009

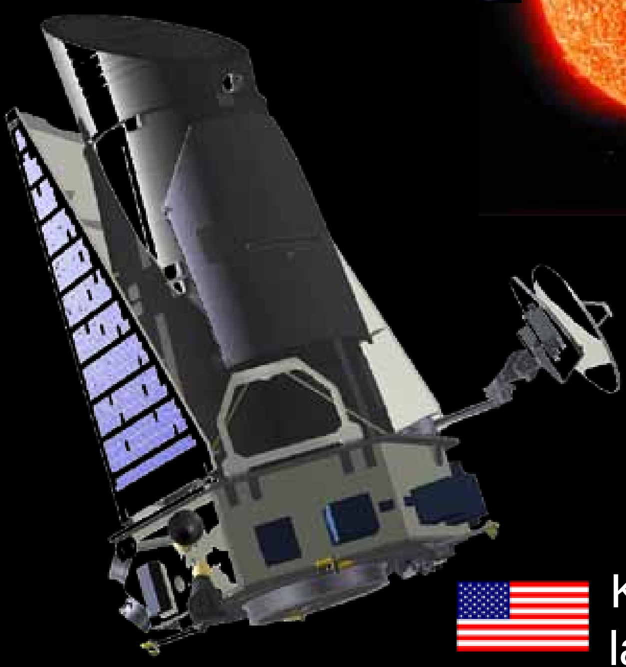
Transit hunters

Earth-size planet transiting Sun-type star ~ 0.01 %



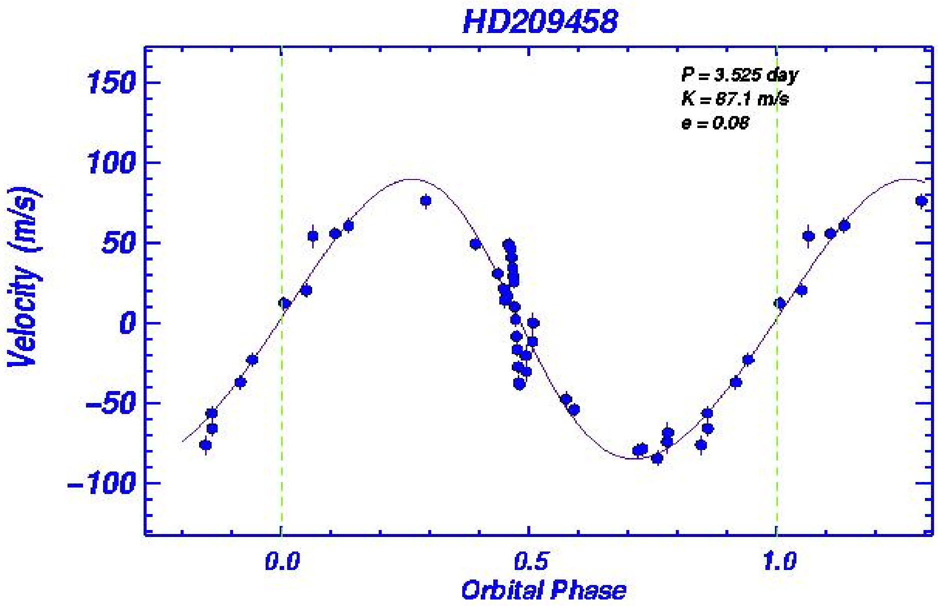
COROT (CNES/ESA)
launch Dec. 2006

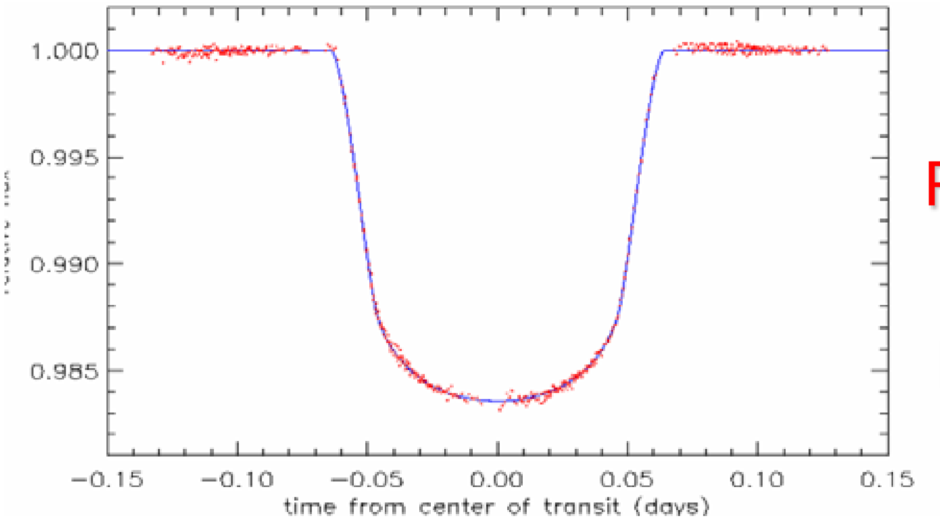
COROT 7B, FIRST TRANSITING SUPER E



KEPLER (NASA)
launch 2009

Radial velocity & Occultation





HD 209458b

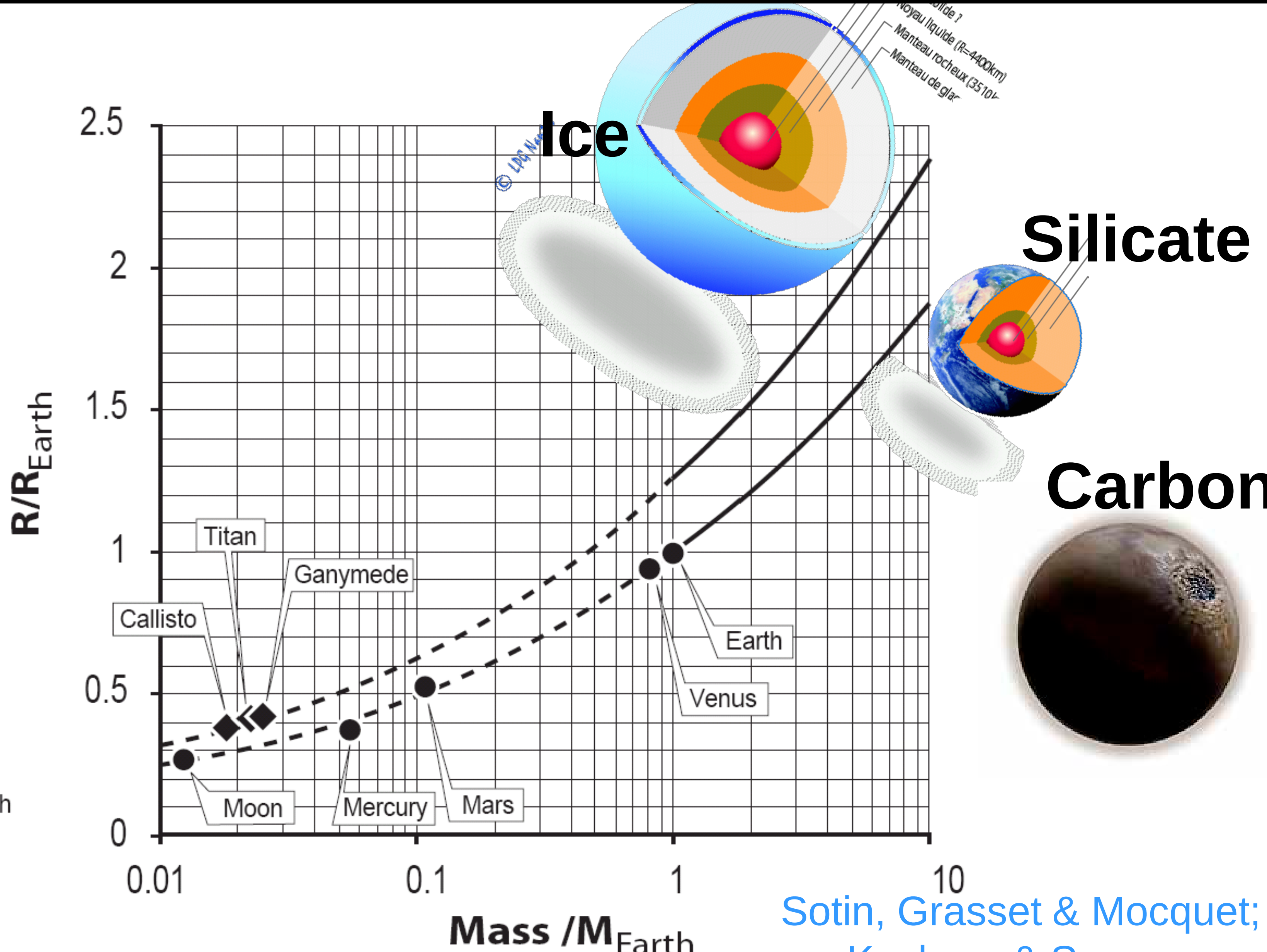
Period = 3.524738 days

Mass = 0.69 ±0.05 $M_{Jupiter}$

Radius = 1.35 ±0.04 $R_{Jupiter}$

Density = 0.35 ±0.05 g/cm^3

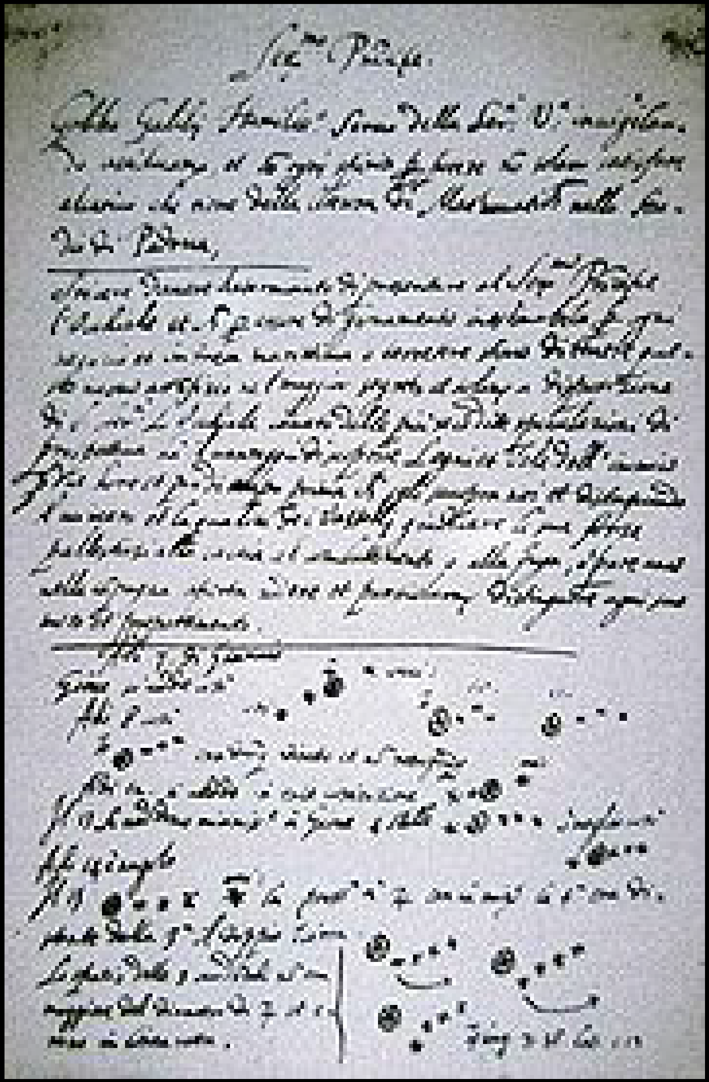
Radius/mass ratio



Sotin, Grasset & Mocquet;
Kuchner & Seager;

From Jupiter's moons…

Galileo (the mission), 1989



Galileo « *Sidereus Nuncius* » 1610

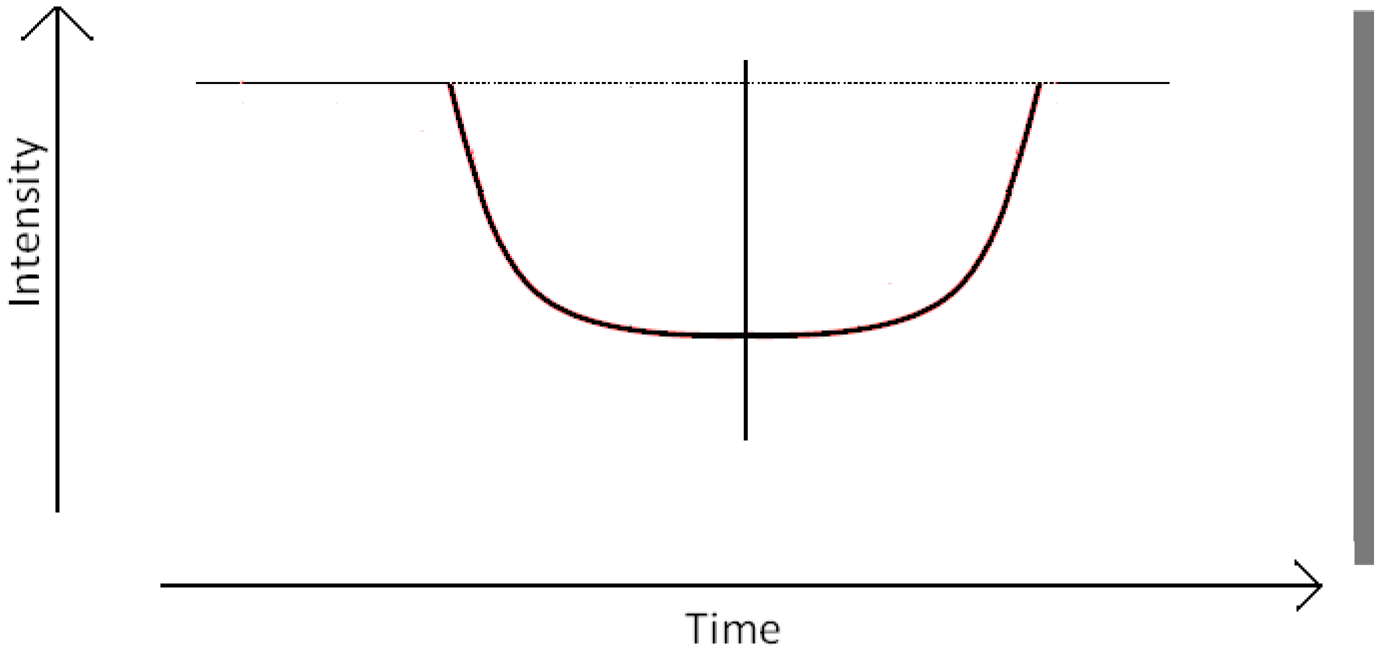
...to Exo-Jupiters' moons

The Jupiter-planet's wobble can be detected with Kepler

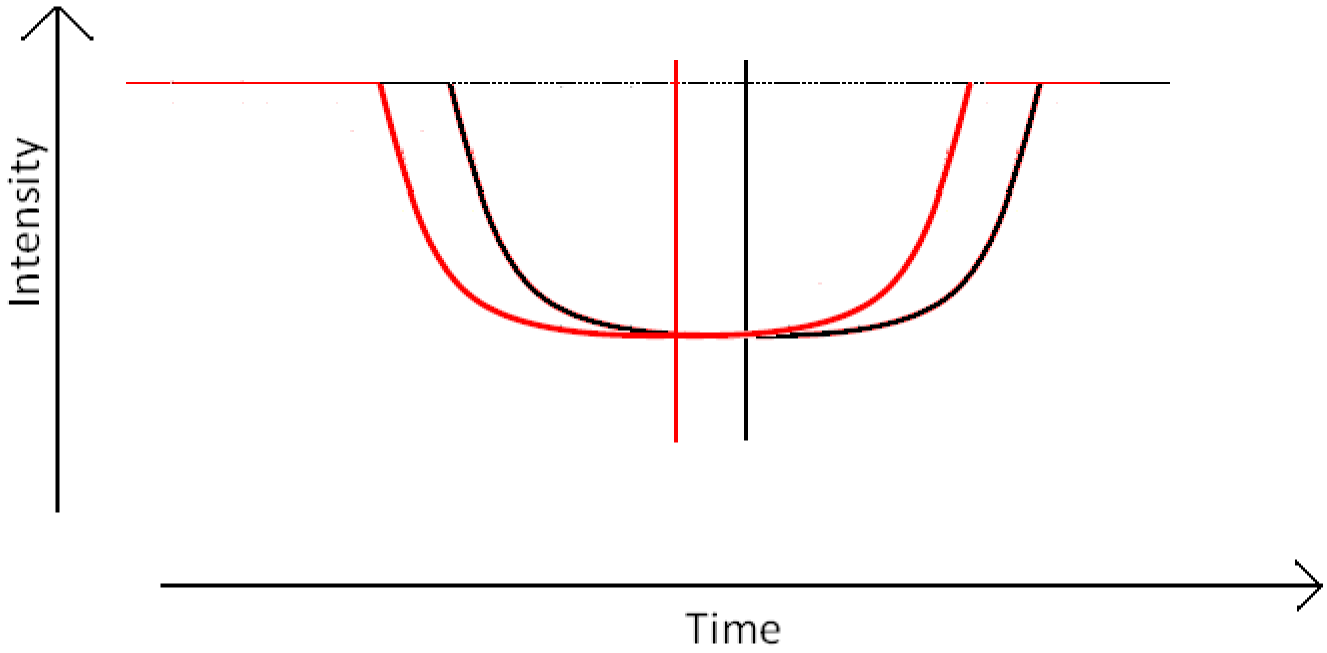
(Combination of TTV-TDV)

Kipping, 2008, 2009;
Kipping et al., 2009

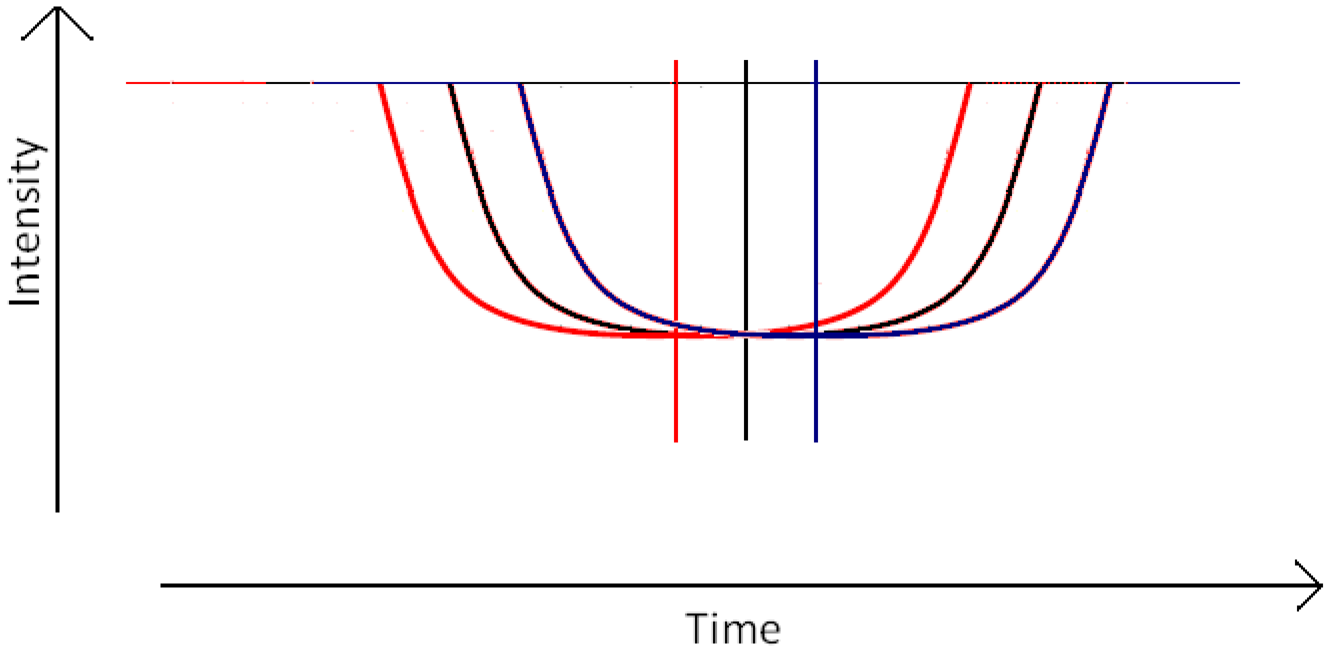
Transit Time Variation (TTV)



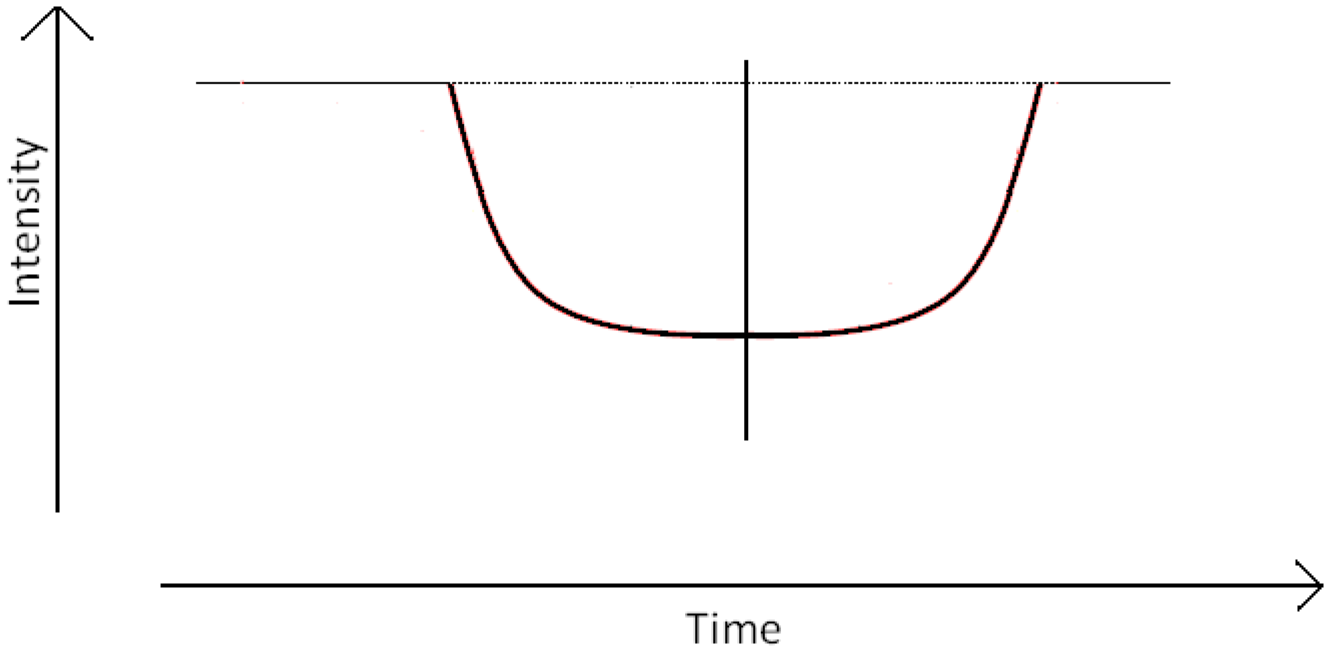
Transit Time Variation (TTV)



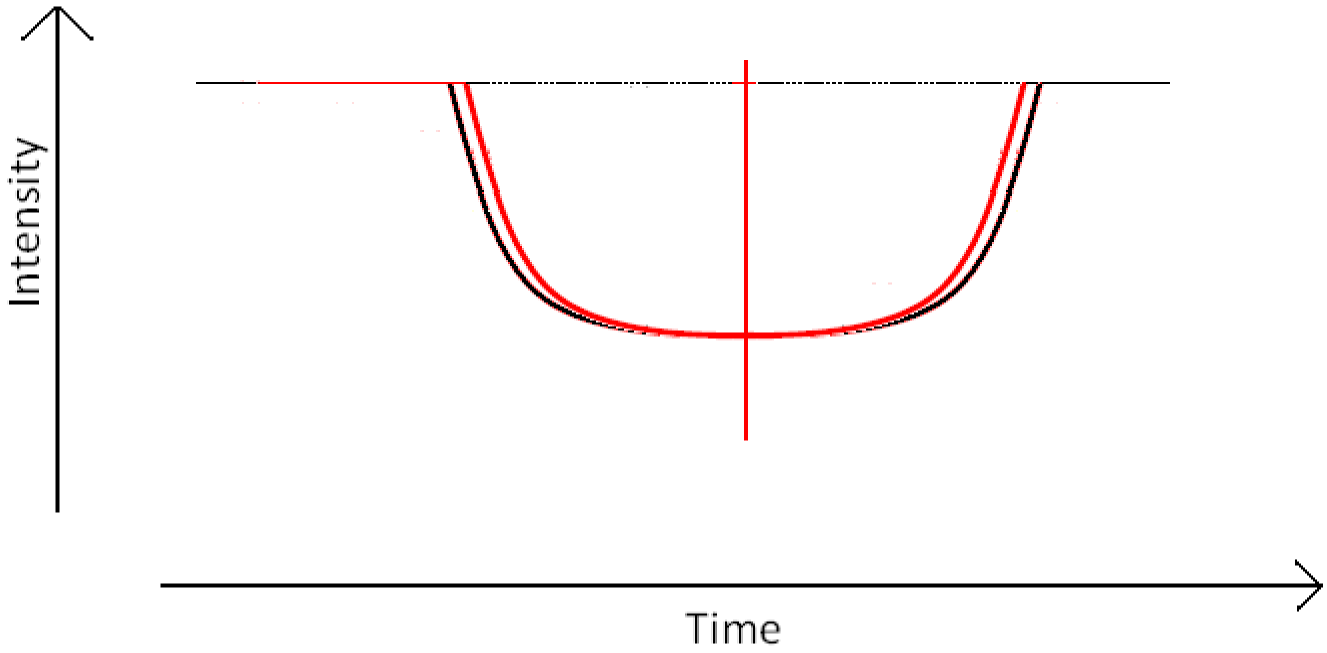
Transit Time Variation (TTV)



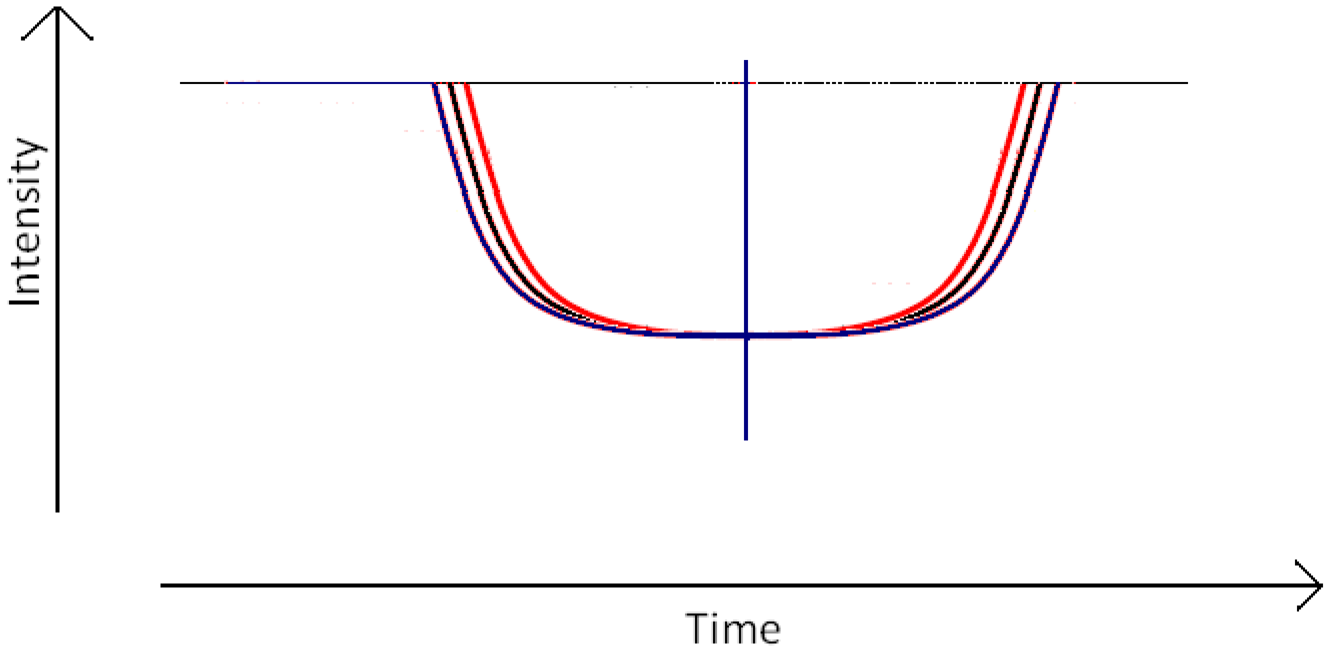
Transit Duration Variation (TDV)



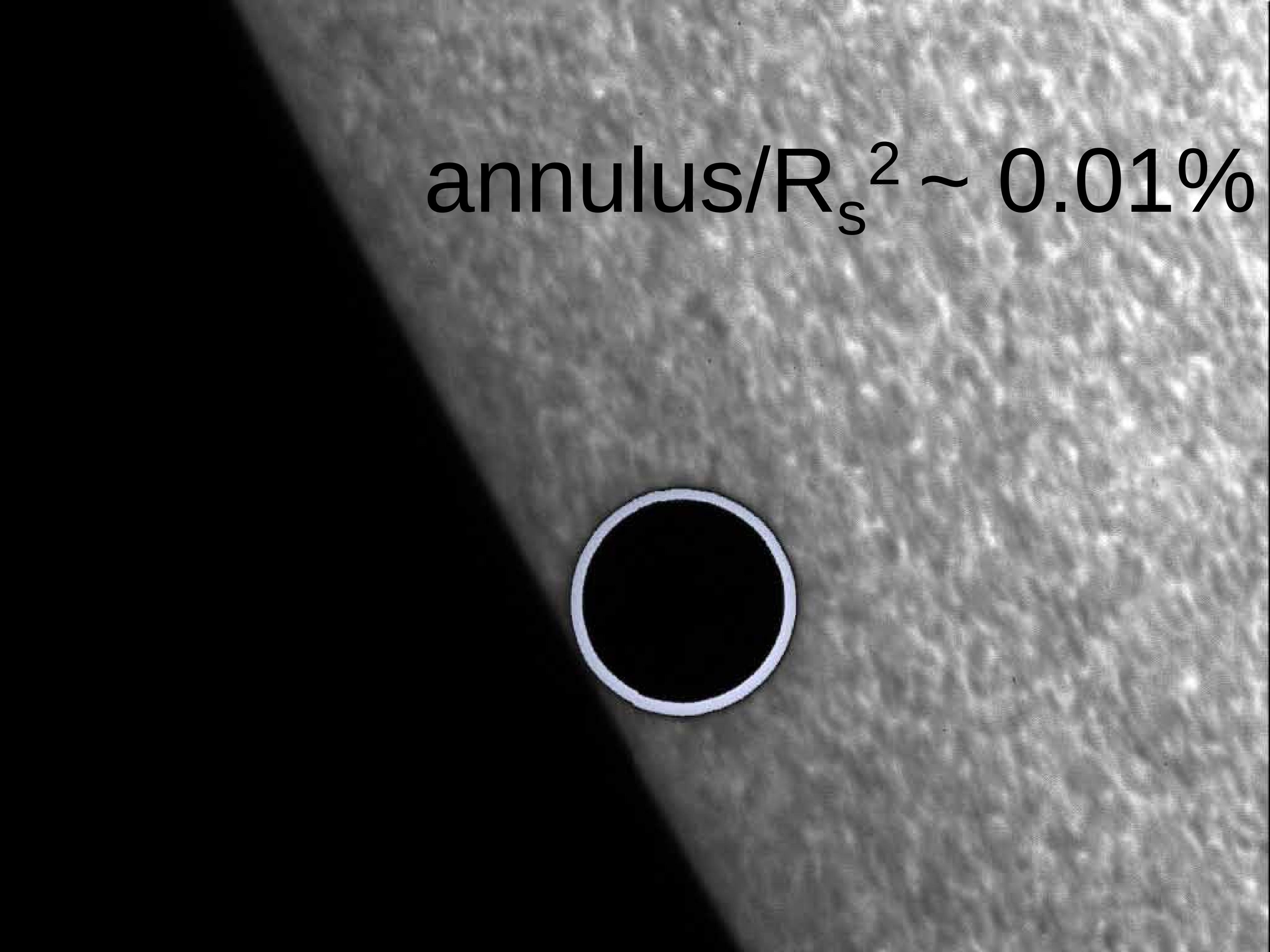
Transit Duration Variation (TDV)



Transit Duration Variation (TDV)



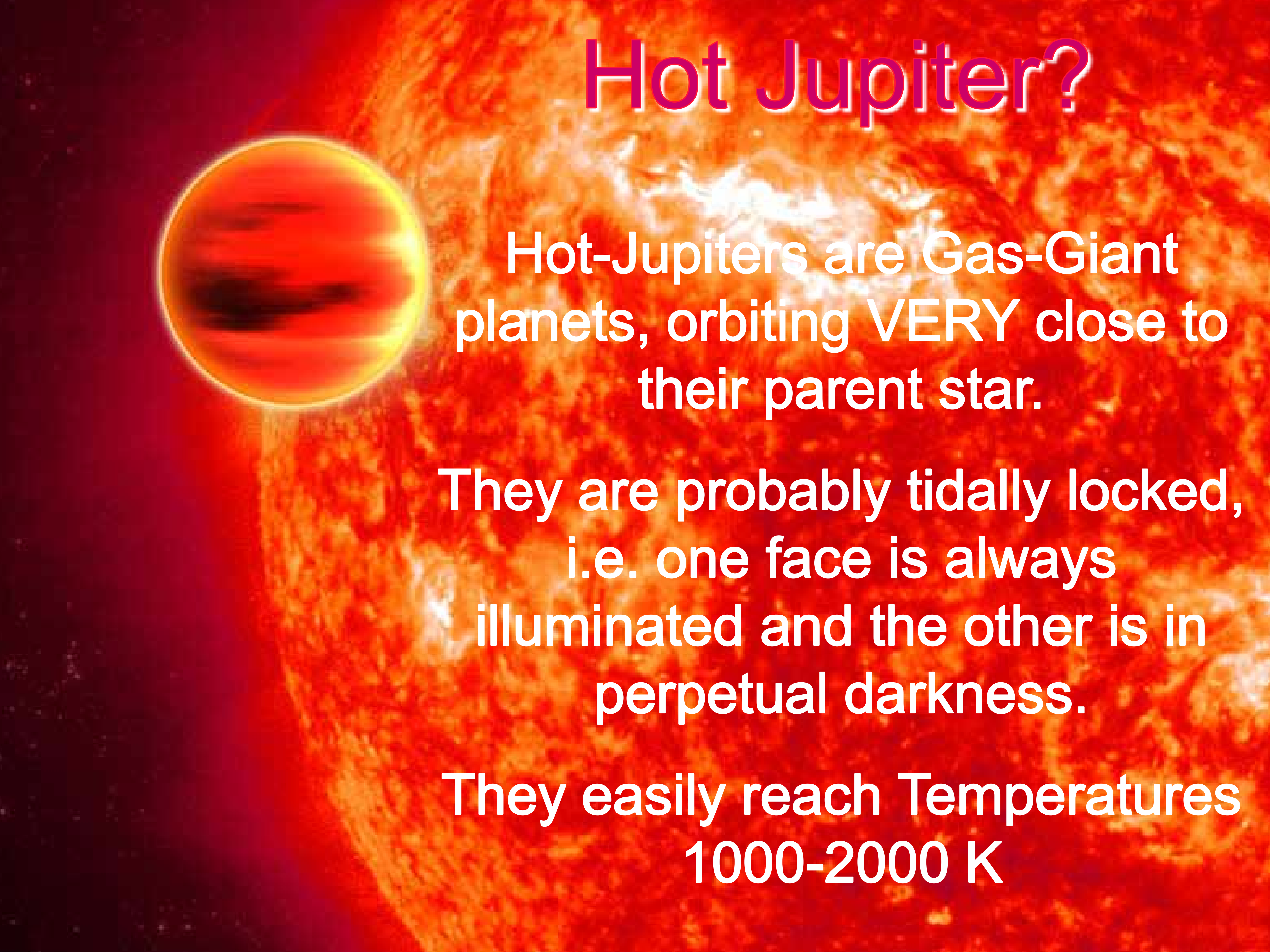

Seager & Sasselov, ApJL, 2000;
UV-VIS
Brown, ApJ, 2001;
VIS-NIR
Tinetti et al., ApJL, 2007;
Mid-IR



$annulus/R_s^2 \sim 0.01\%$

Select your target, instrument & spectral region

You want it hot, fluffy and big!



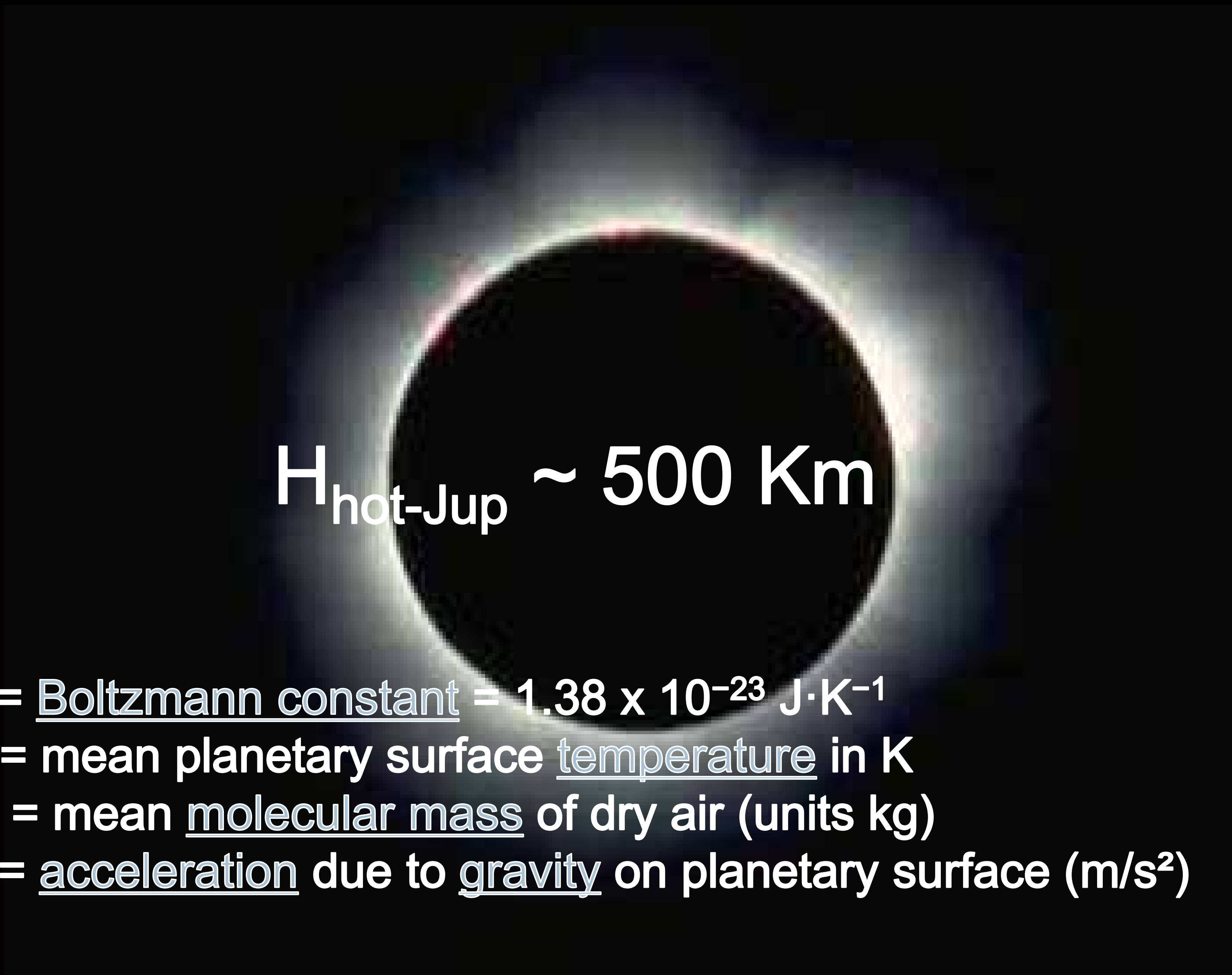
Hot Jupiter?

Hot-Jupiters are Gas-Giant planets, orbiting VERY close to their parent star.

They are probably tidally locked, i.e. one face is always illuminated and the other is in perpetual darkness.

They easily reach Temperatures 1000-2000 K

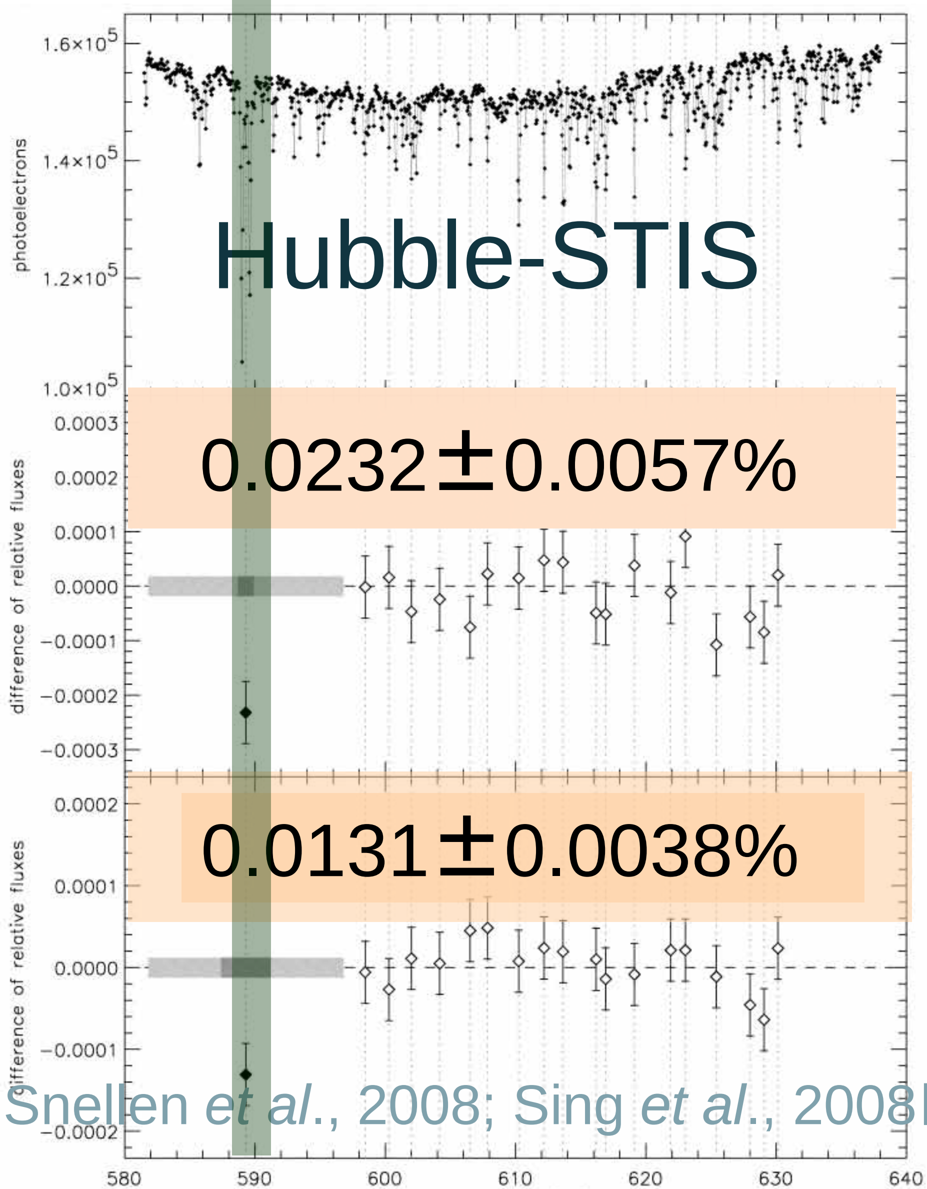
$H = kT/(M g)$



$H_{hot\text{-}Jup} \sim 500$ Km

k = Boltzmann constant = 1.38×10^{-23} J·K^{-1}
T = mean planetary surface temperature in K
M = mean molecular mass of dry air (units kg)
g = acceleration due to gravity on planetary surface (m/s^2)

Na in the atmosphere of Hot-Jupiters



Hubble-STIS

0.0232±0.0057%

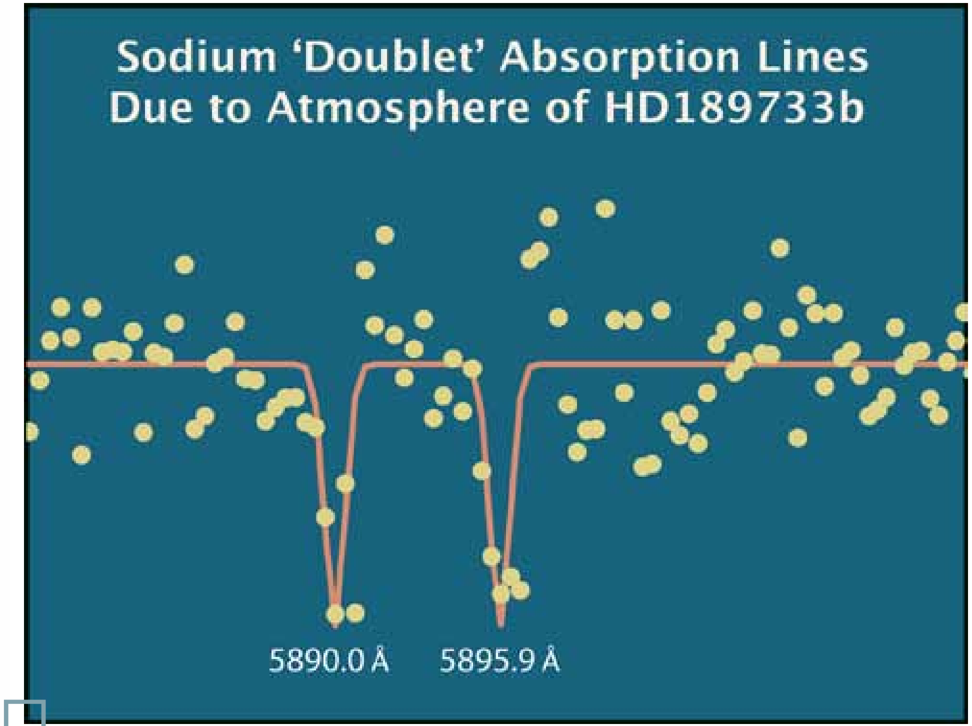
0.0131±0.0038%

Snellen *et al*., 2008; Sing *et al*., 2008

589. nm Wavelength (nm)

Charbonneau *et al*., 2002

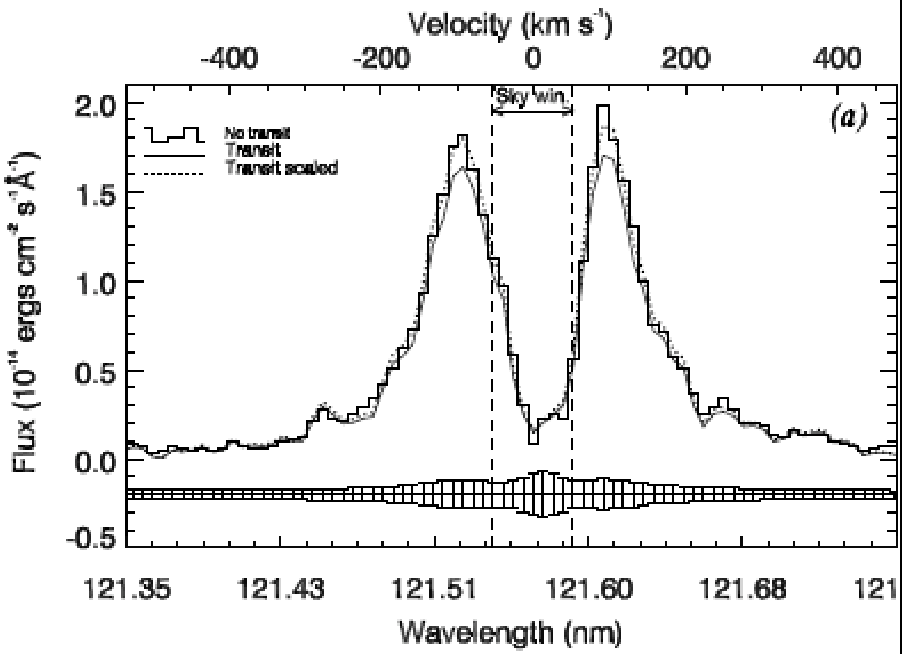
Ground-based observations



Redfield *et al*., 2007

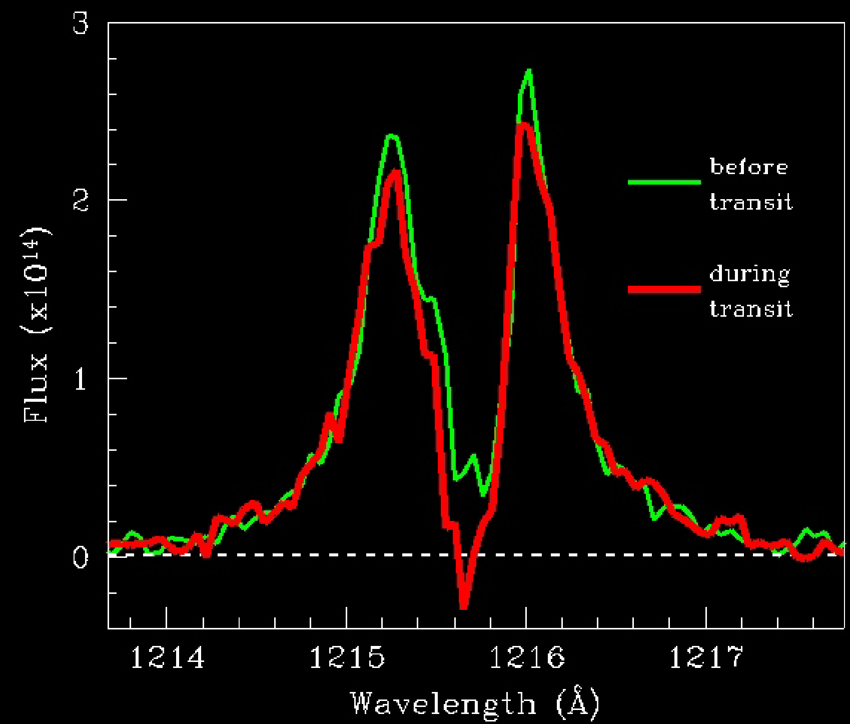
STIS: Lya HD 209458b

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



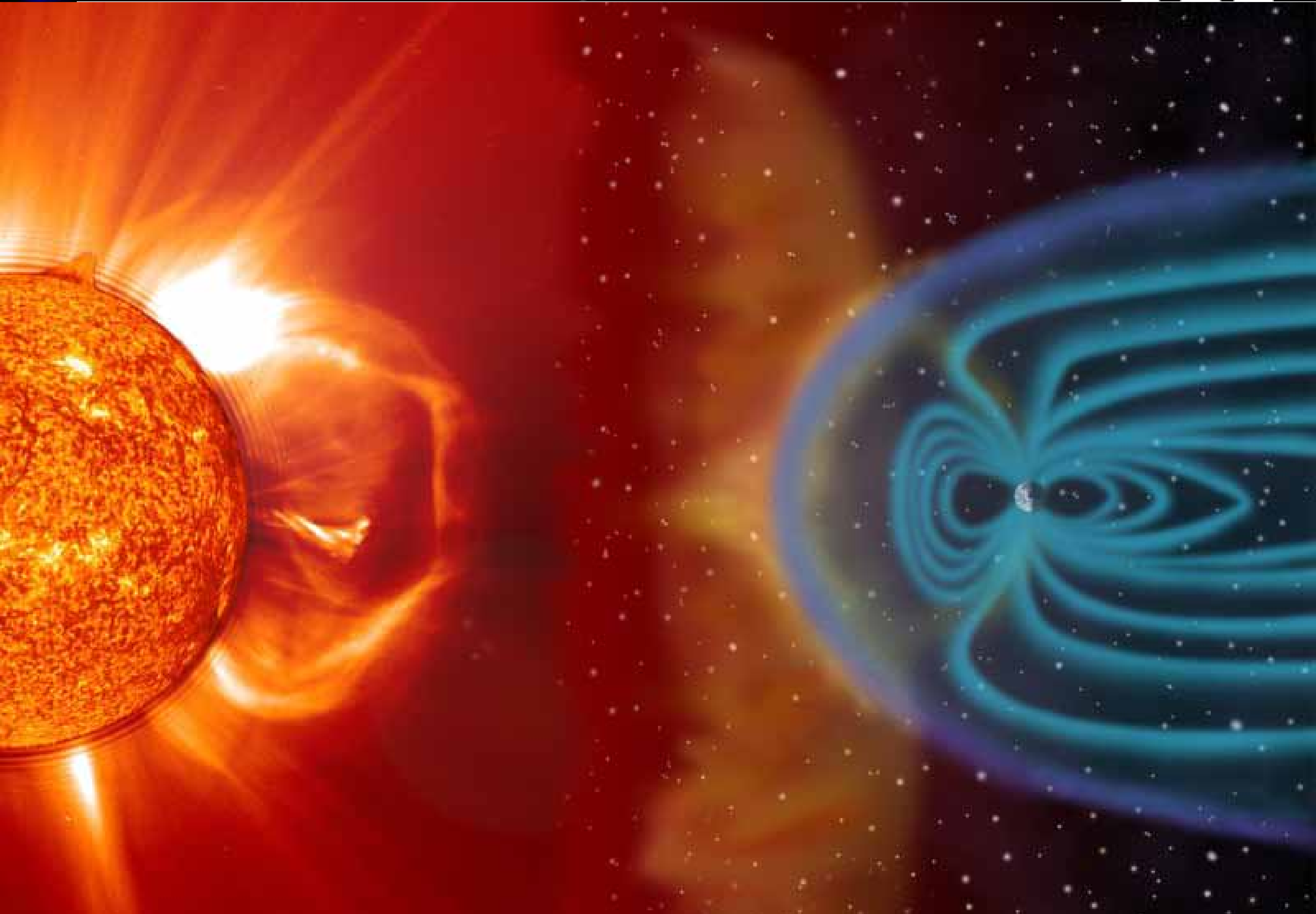
Ben-Jaffel, ApJL, 2008

15% absorption in the Lya line



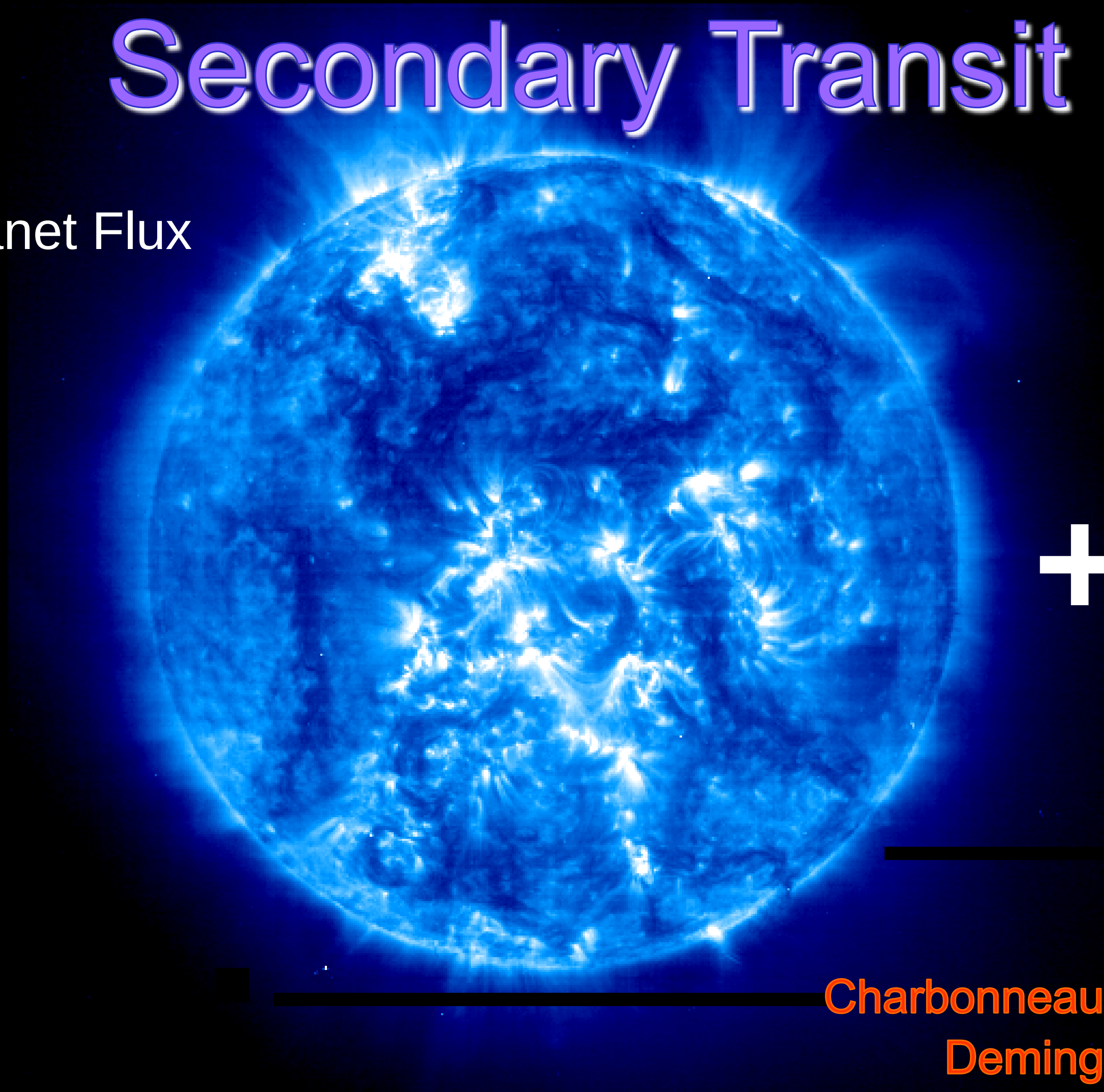
Vidal-Madjar et al., *Nature*, 2003
Ballester, Sing, Herbert, *Nature*, 2007

STIS: Lya HD 209458b

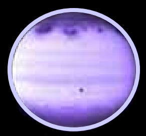


Secondary Transit

Star+Planet Flux



+

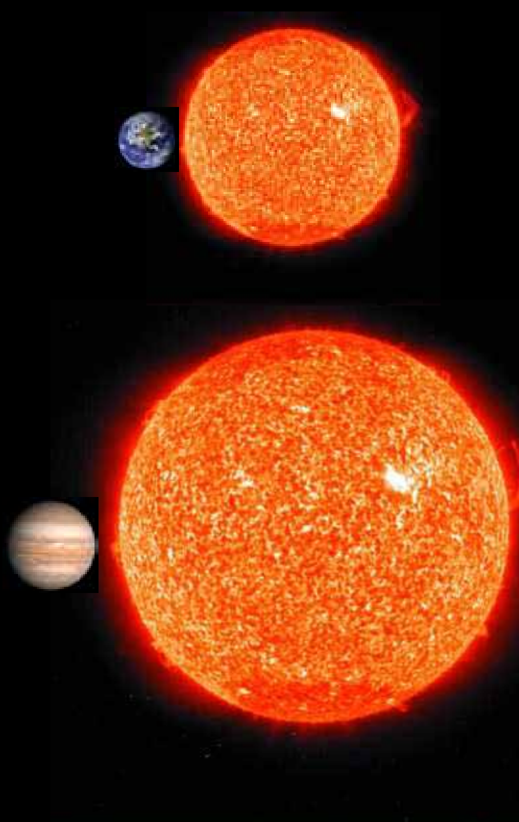


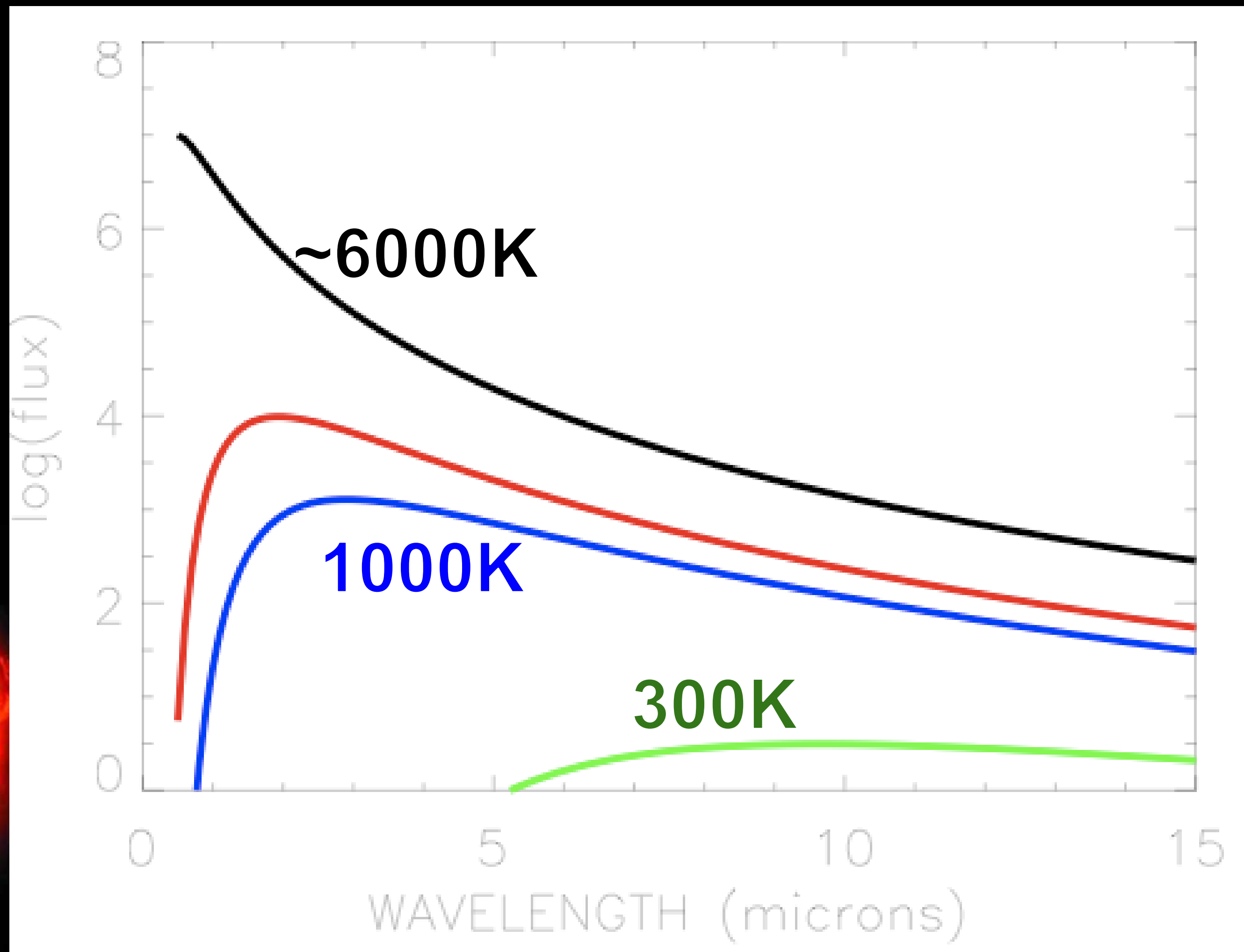
Charbonneau *et al.*, 2005

Deming *et al.*, 2005

$(R_p/R_*)^2 \; F_p(\lambda)/F_*(\lambda)$ ~0.1%

~1%





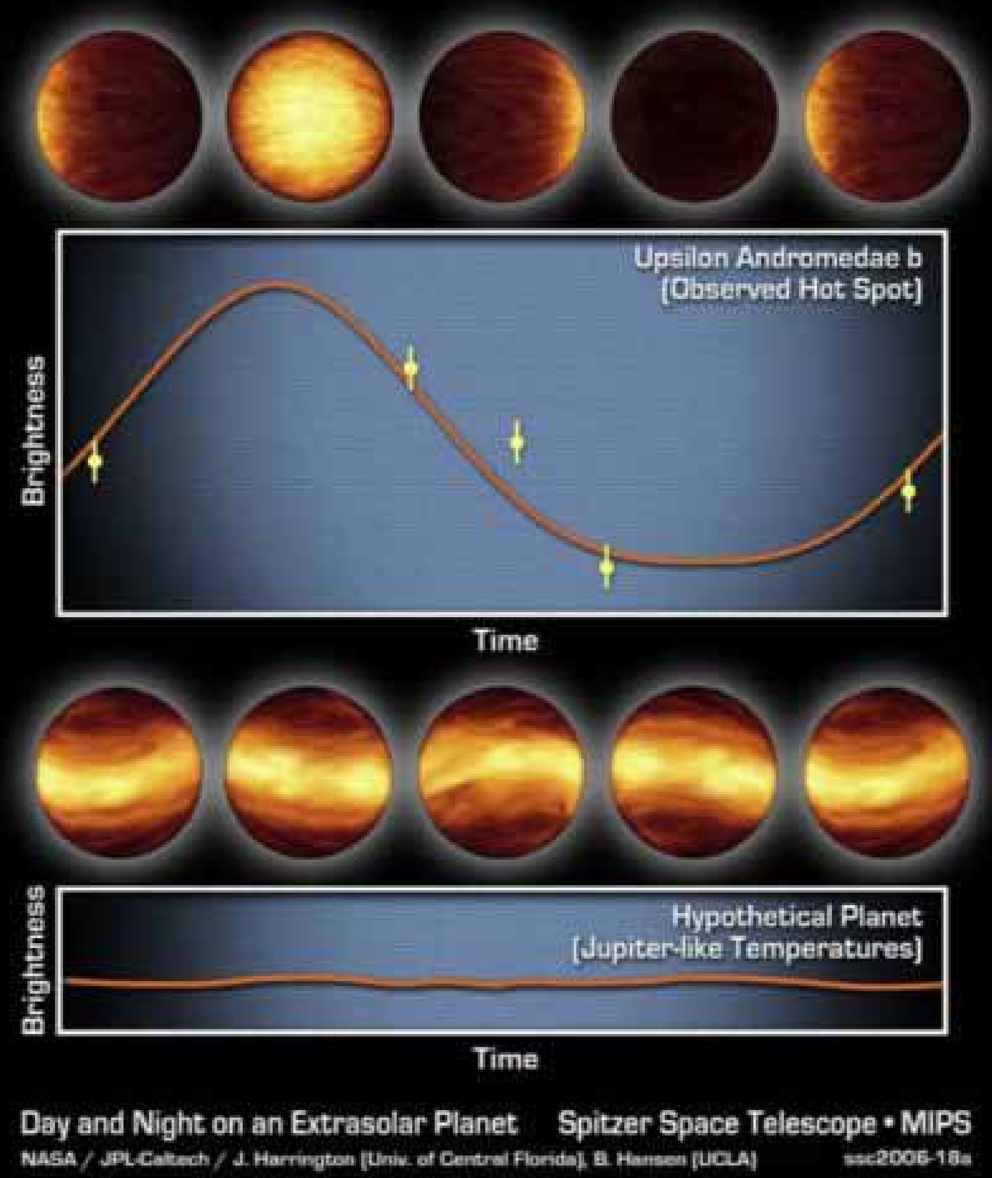
Combined light star-planet

Harrington *et al*., 2006

Light curves of a non-transtiting exoplanet

 Andromeda

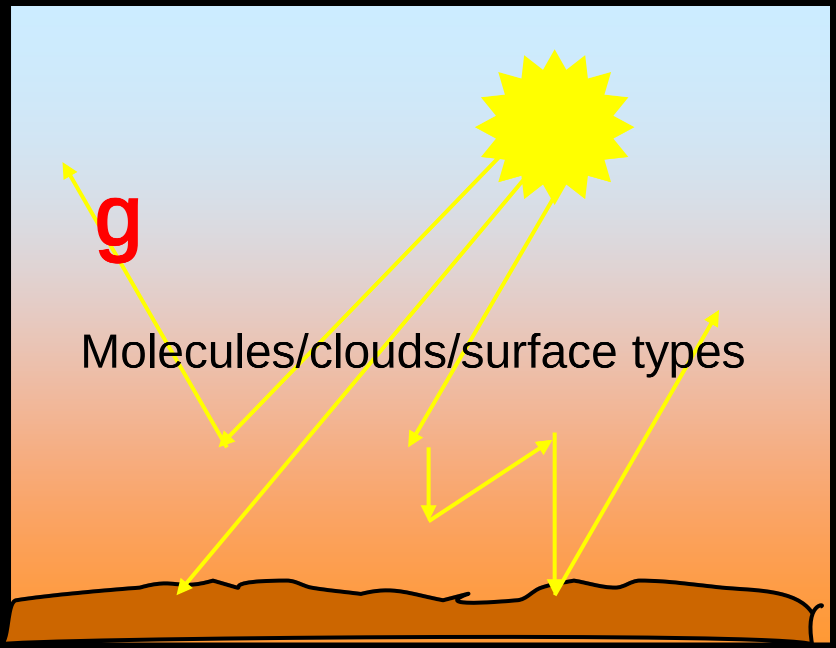
contribution from the planet:
~0.1%

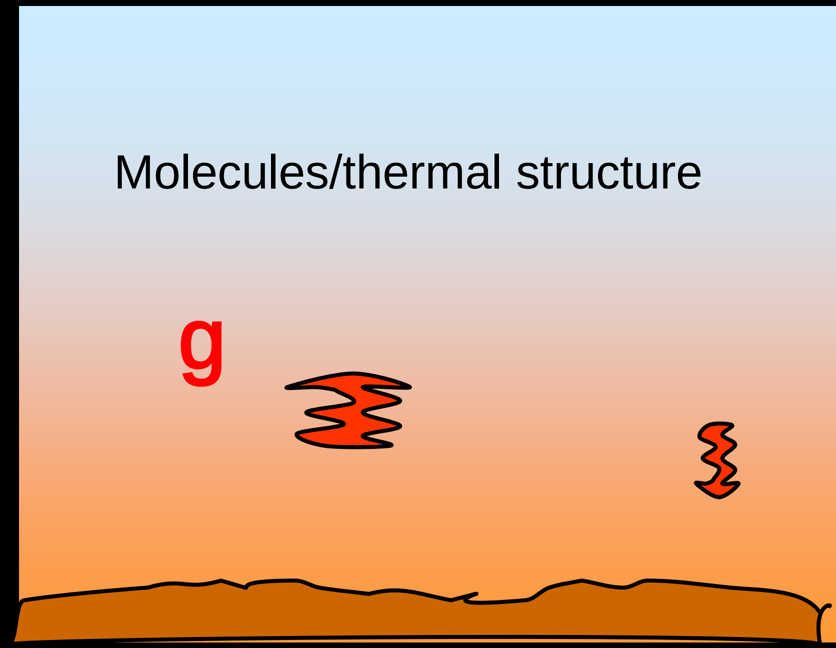


Harrington et al., Science, 2006

Stellar light reflected by the planet (UV/visible)

Photons emitted by the planet (IR)

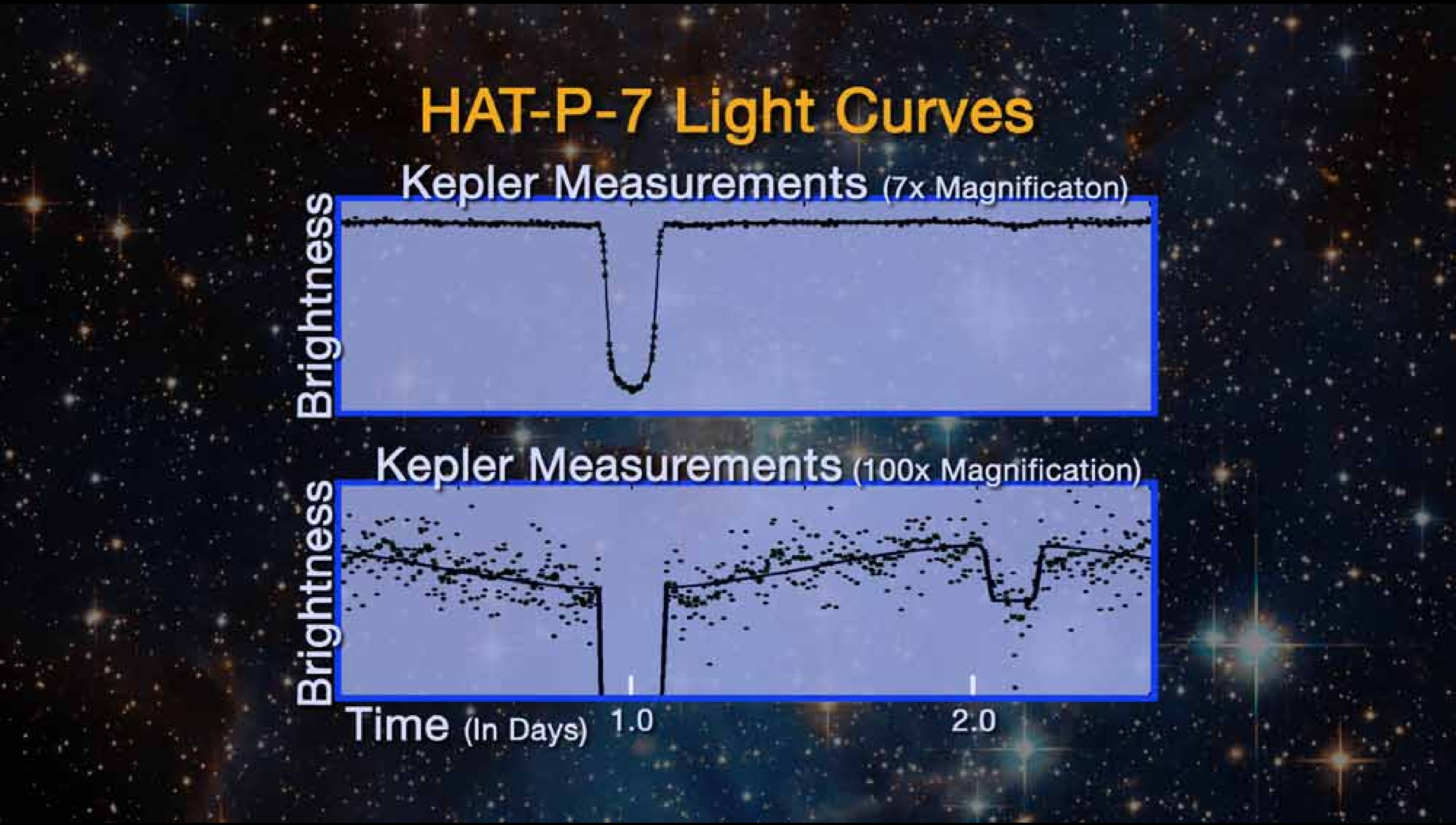




Multiple scattering of **reflected** photons:
Rayleigh scattering/clouds/surface types
Molecules with electronic transitions

Photons **emitted** by the planet,
Molecules (roto-vibrational modes),
thermal structure, clouds

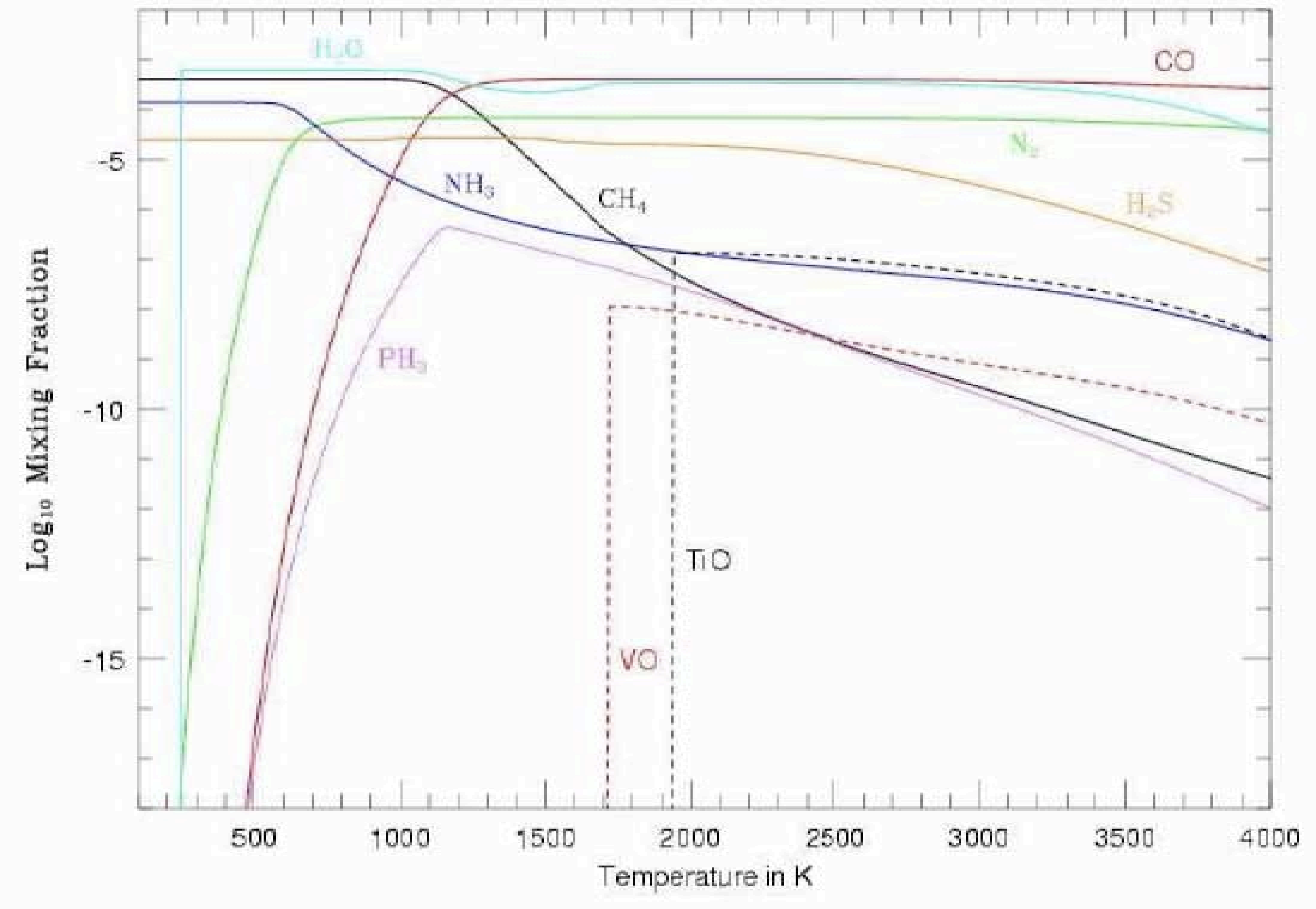
Light curve of a transtiting exoplanet



Borucki et al., Science, 2009

Atmospheric Chemistry

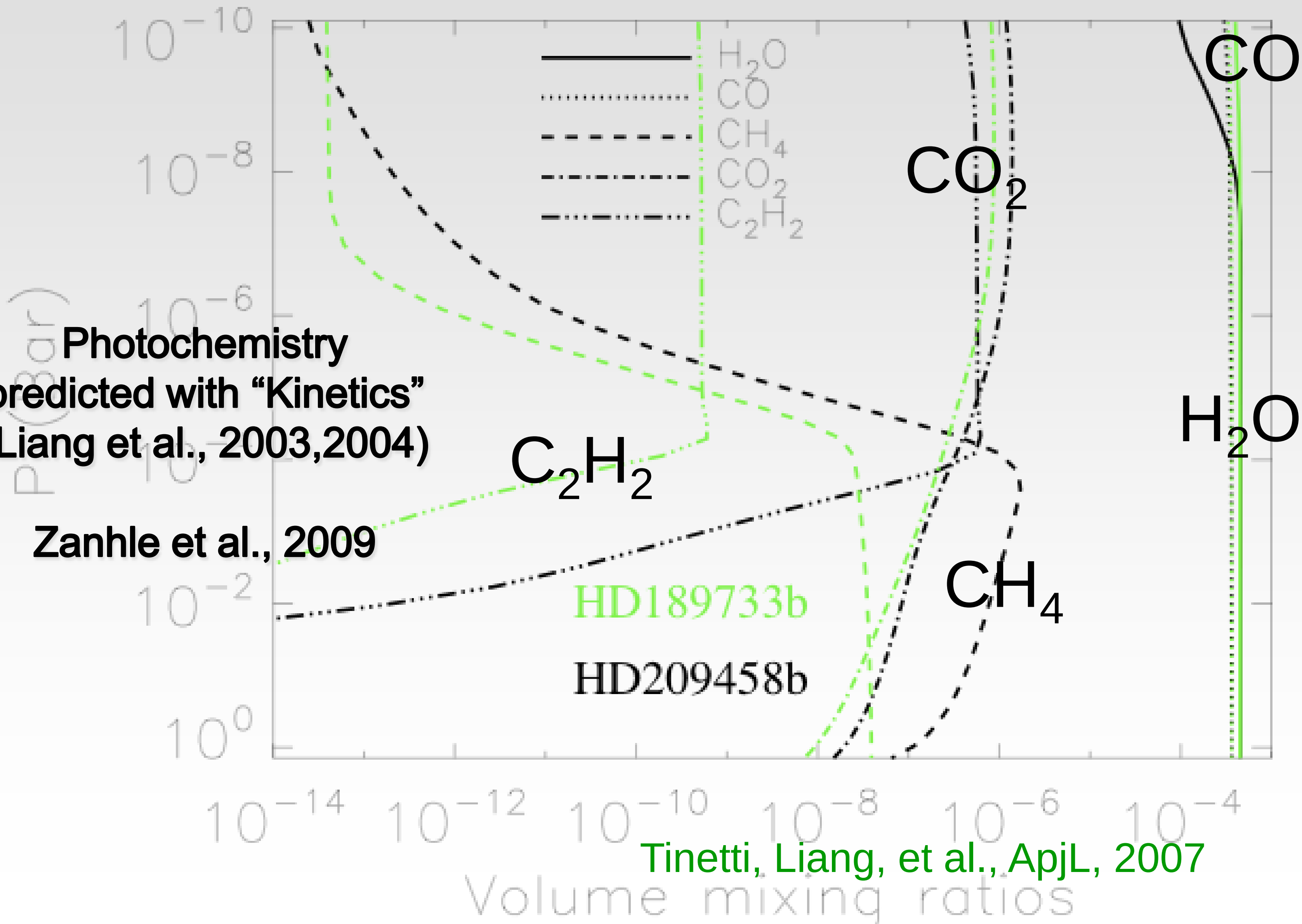
Equilibrium Chemistry



The chemistry of Hot-Jupiters

UCL

C/O ratio = solar?

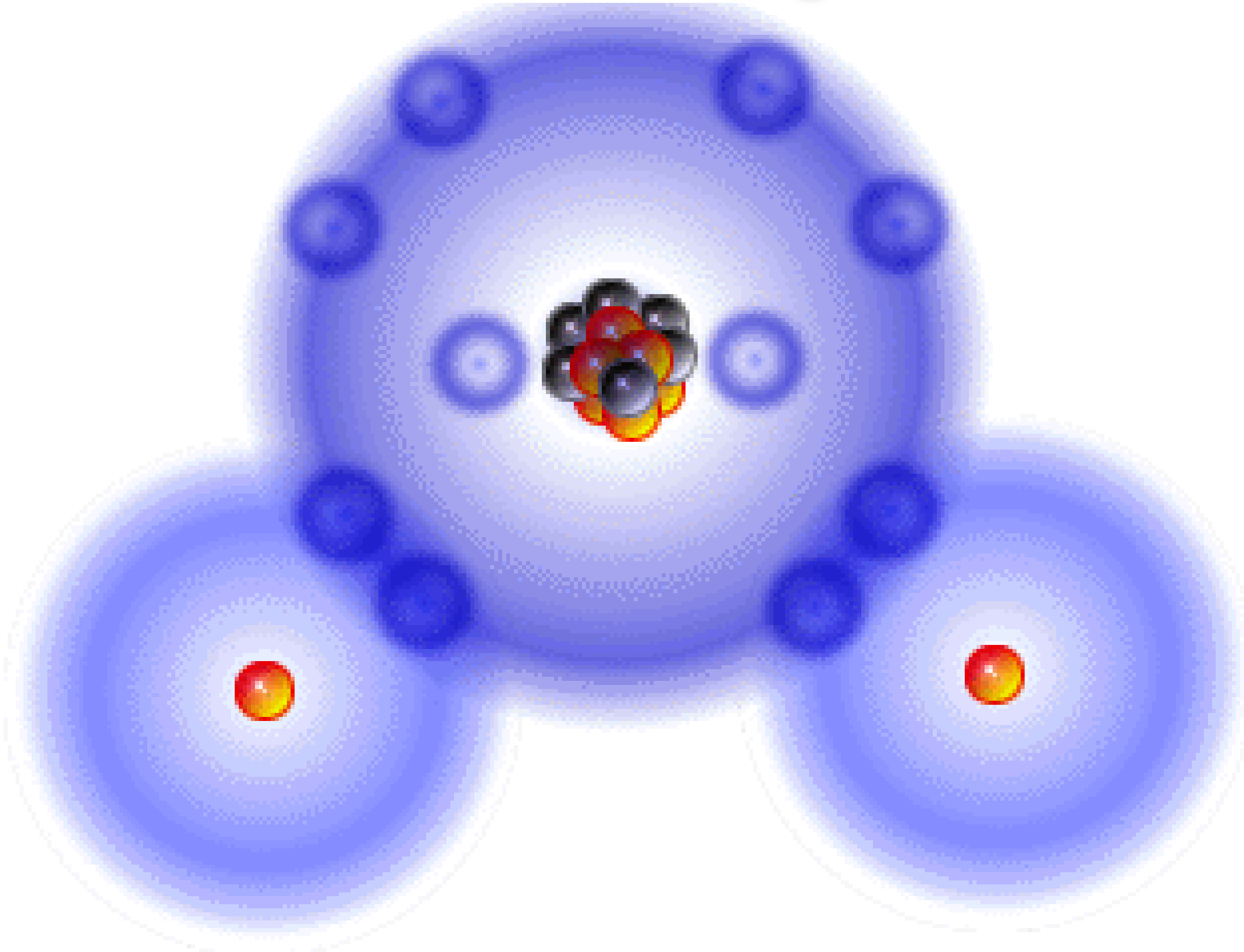


Photochemistry predicted with "Kinetics" (Liang et al., 2003,2004)

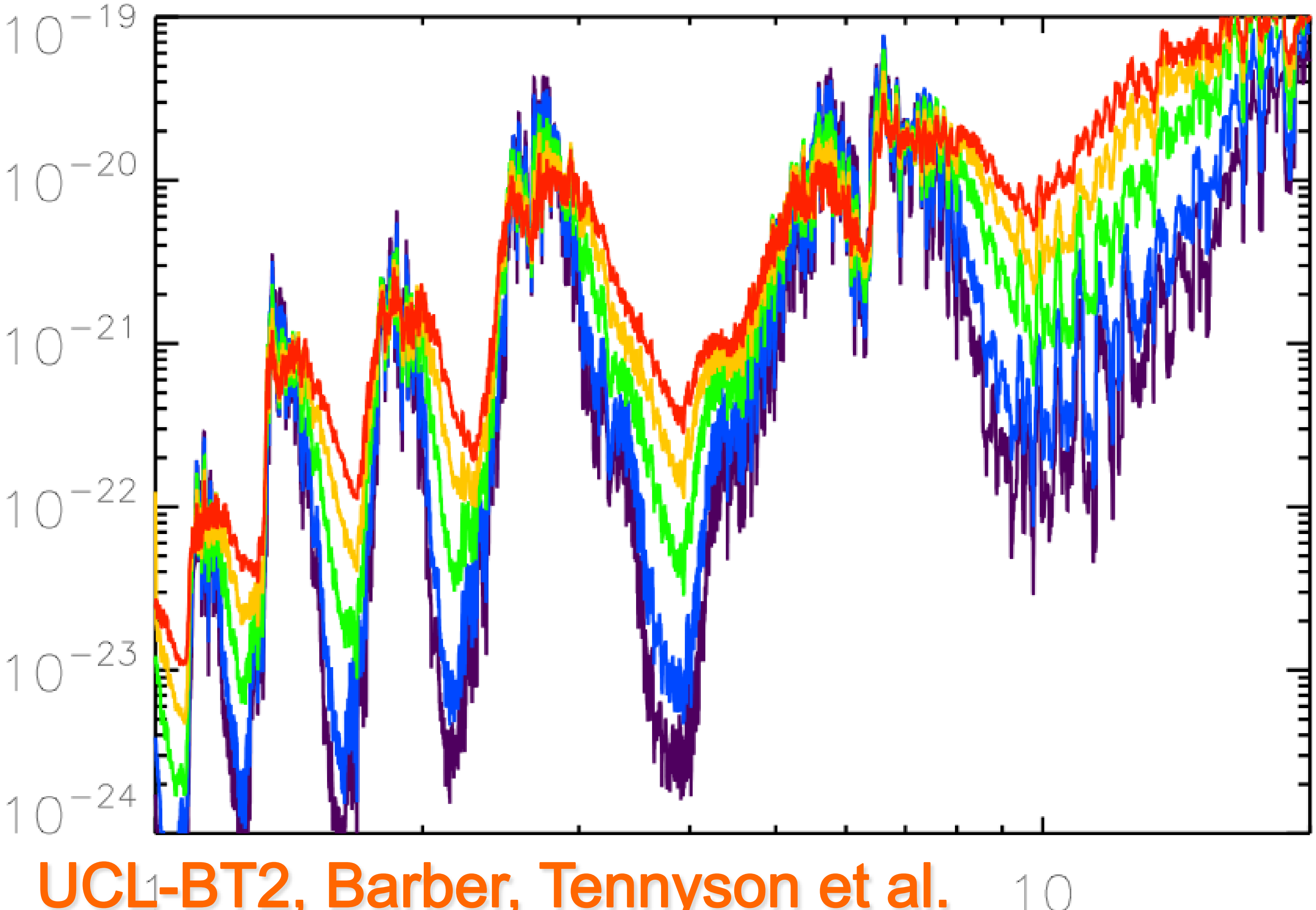
Zanhle et al., 2009

Tinetti, Liang, et al., ApjL, 2007

Water vapour

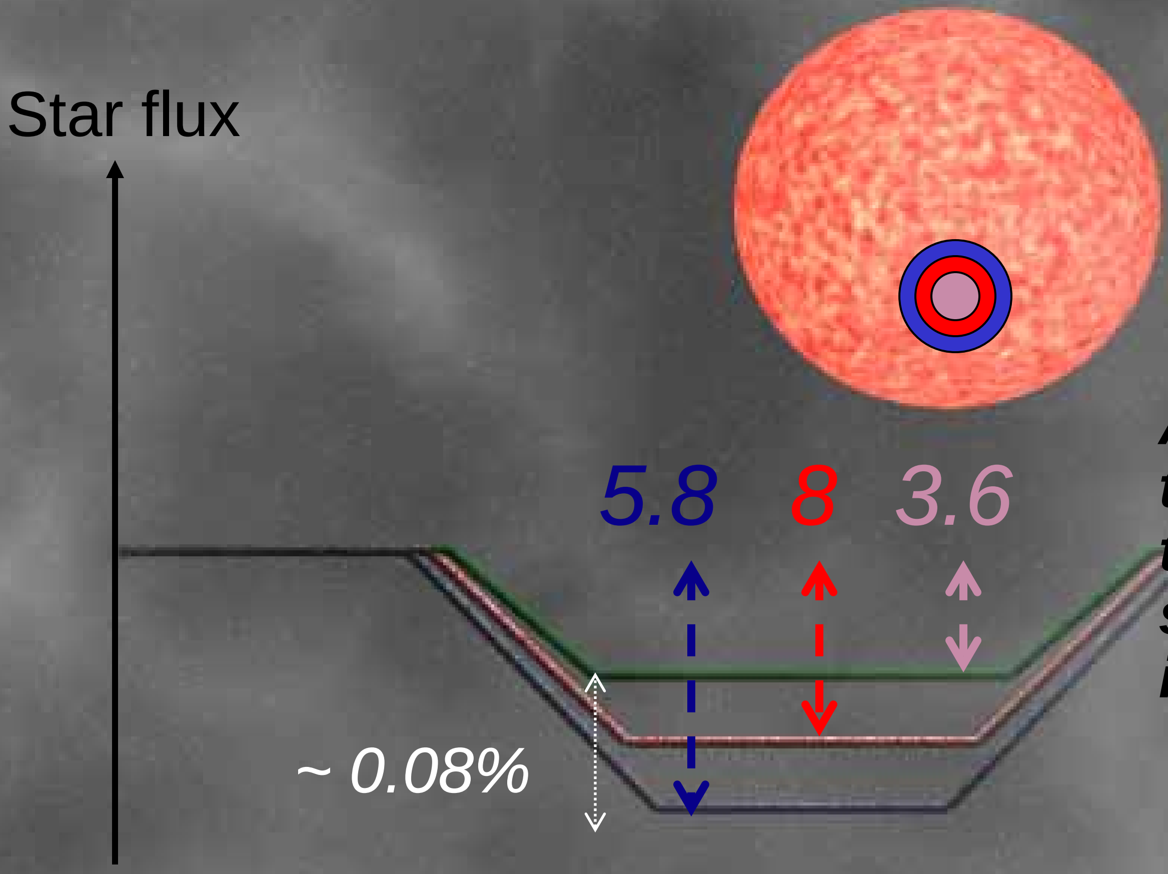


Water, between 800K and 2500K



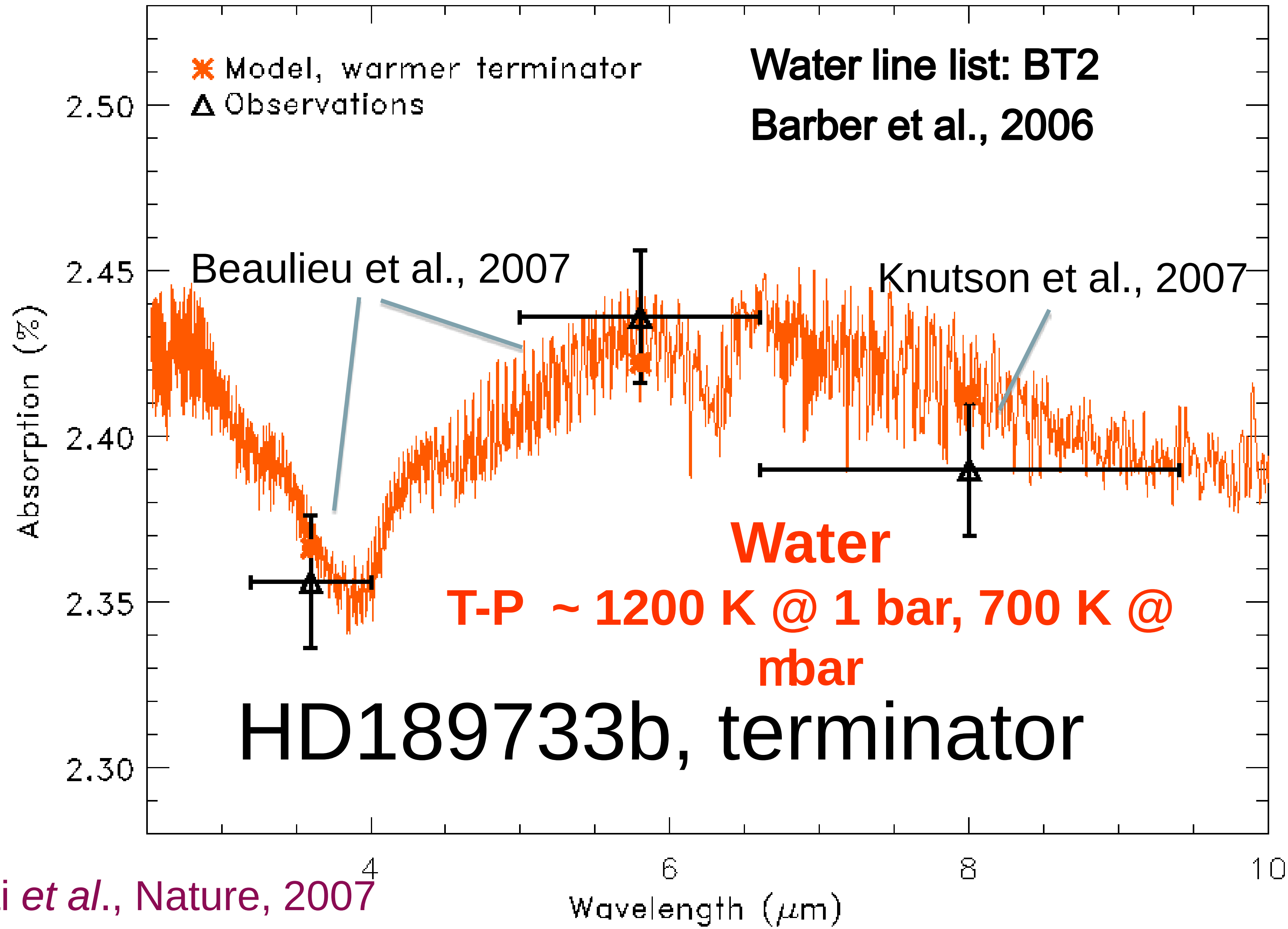
UCL-BT2, Barber, Tennyson et al.

Spitzer observations in the InfraRed for planet HD 189733b



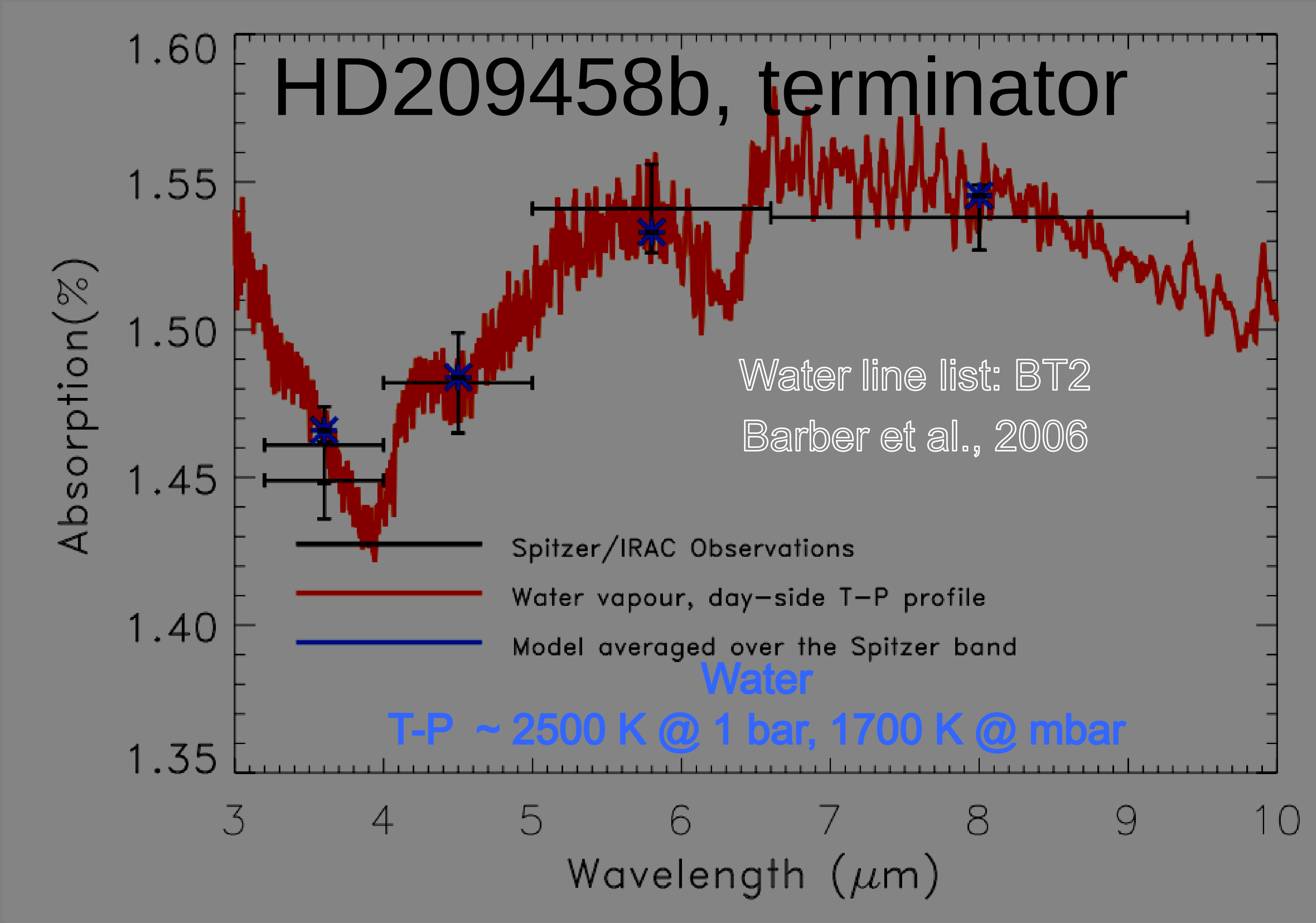
At 3.6, 5.8 and 8 mm, the planet shows different transit depths: something is absorbing in its atmosphere!

IRAC: transmission band-photometry



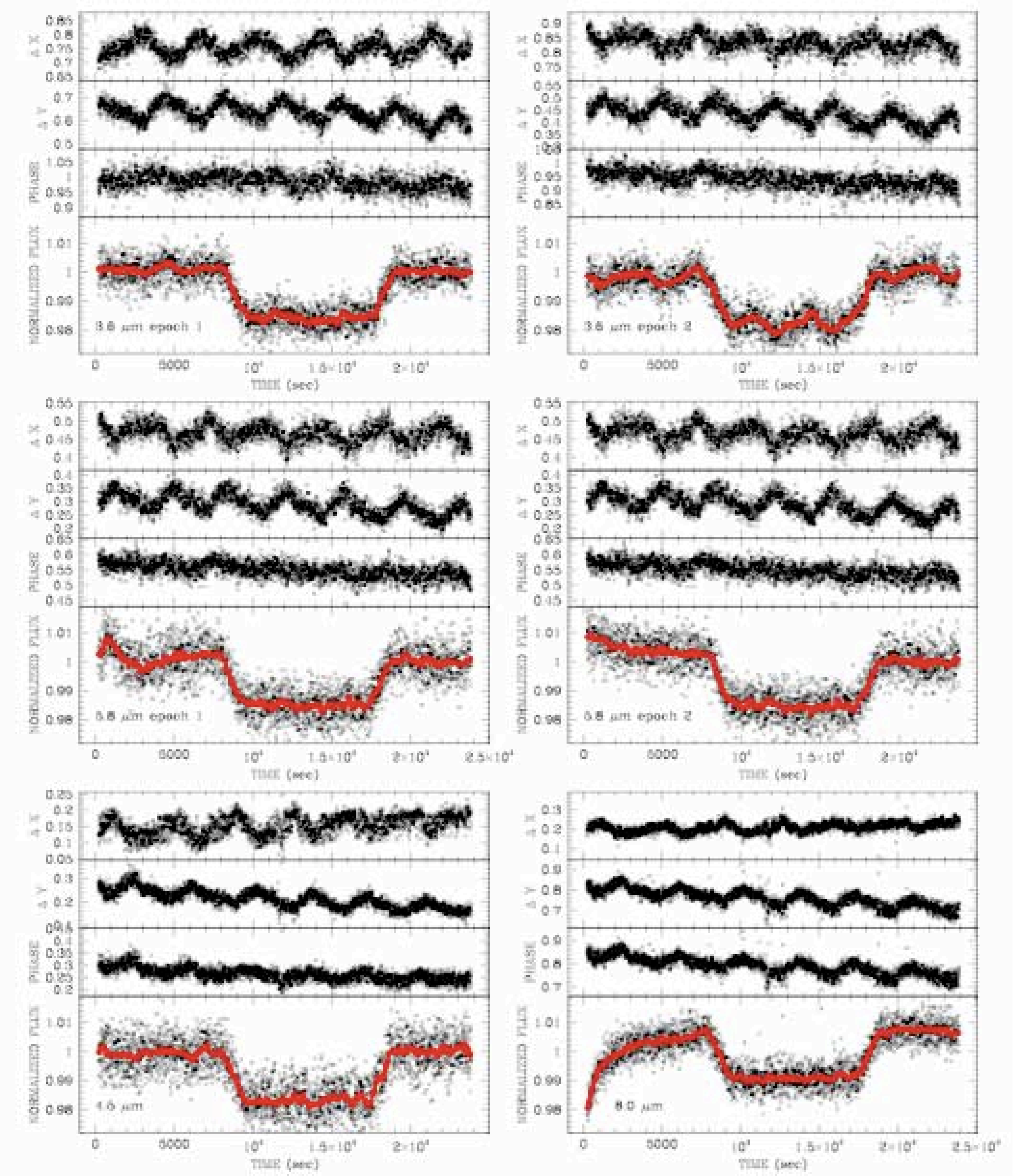
Tinetti *et al*., Nature, 2007

IRAC: transmission band-photometry



Beaulieu, Kipping, Batista, Tinetti, Ribas *et al.*, submitted

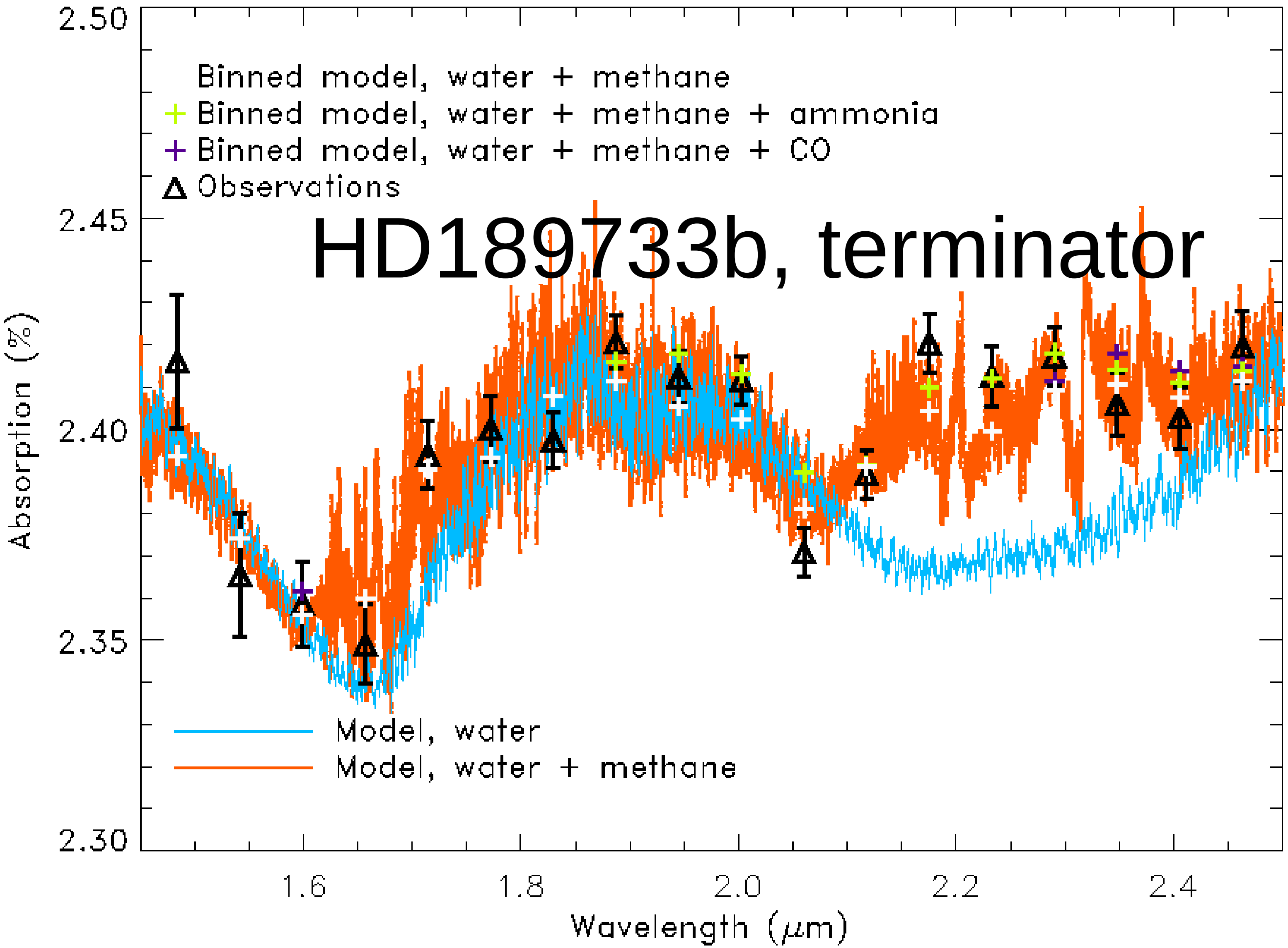
IRAC: transmission band-photometry



Beaulieu, Kipping, Batista, Tinetti, Ribas *et al.*, submitted

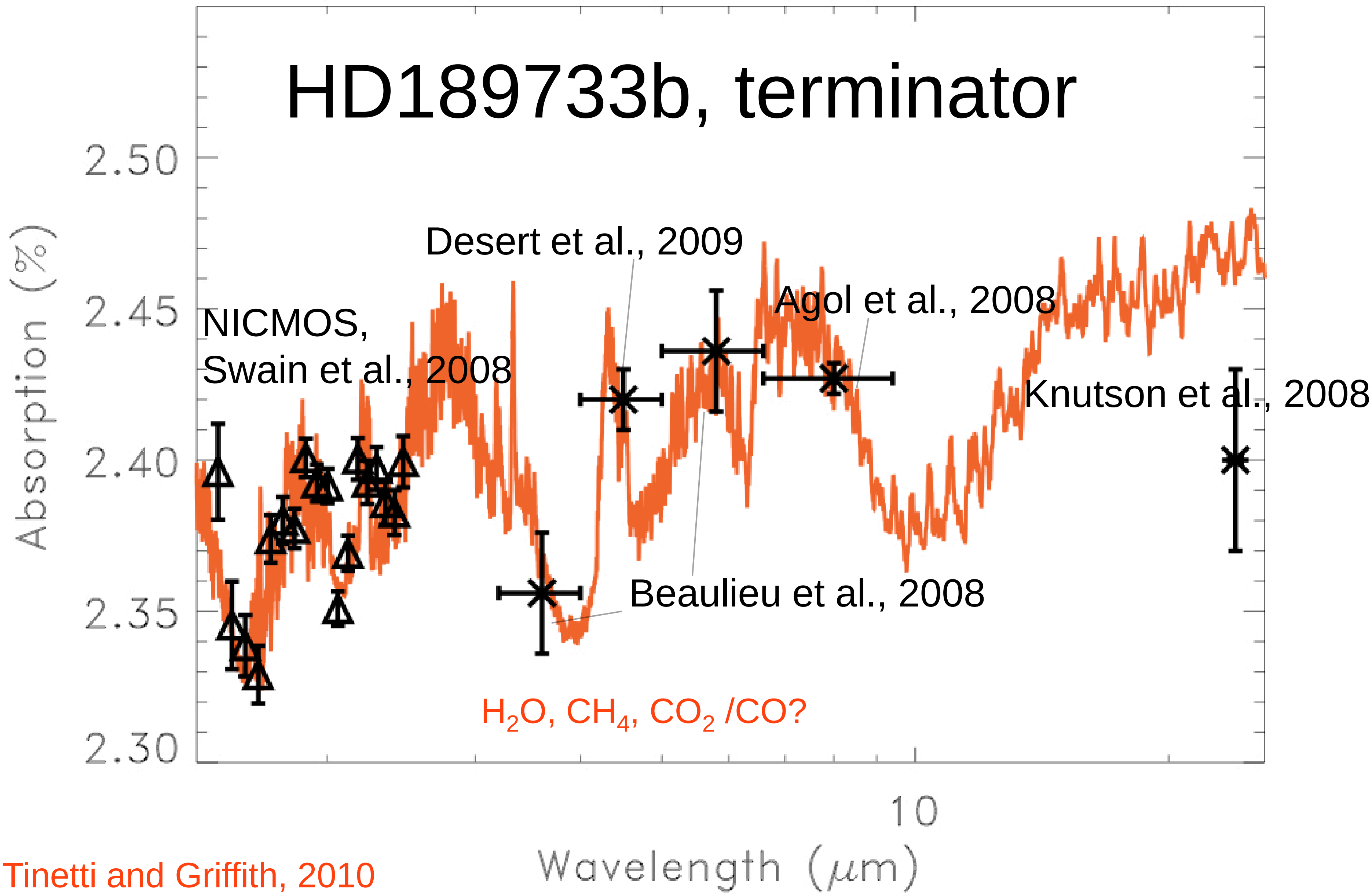
Methane

NICMOS: transmission spectroscopy



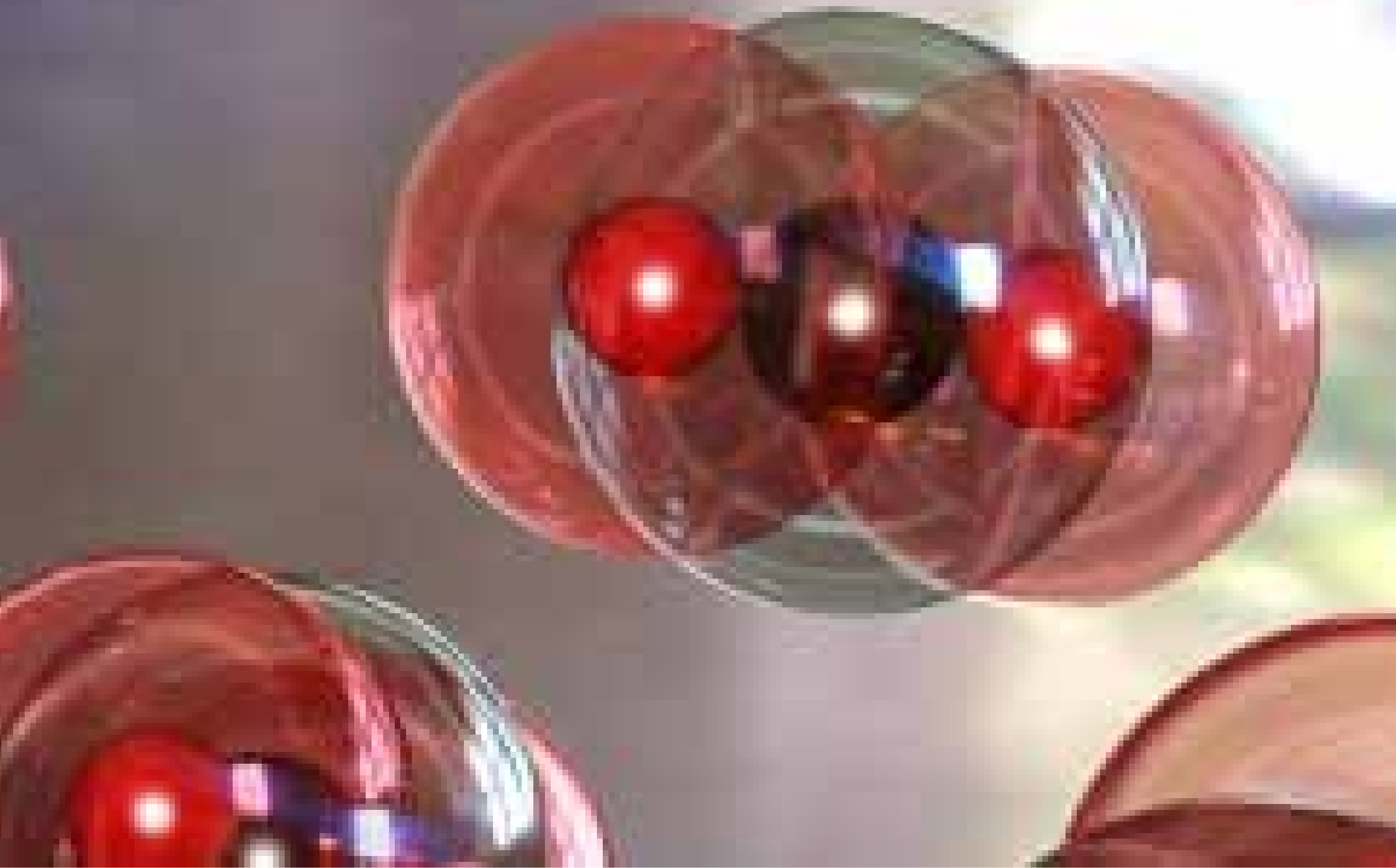
Swain, Vasisht, Tinetti, *Nature*, 2008

Transmission spectroscopy/photometry



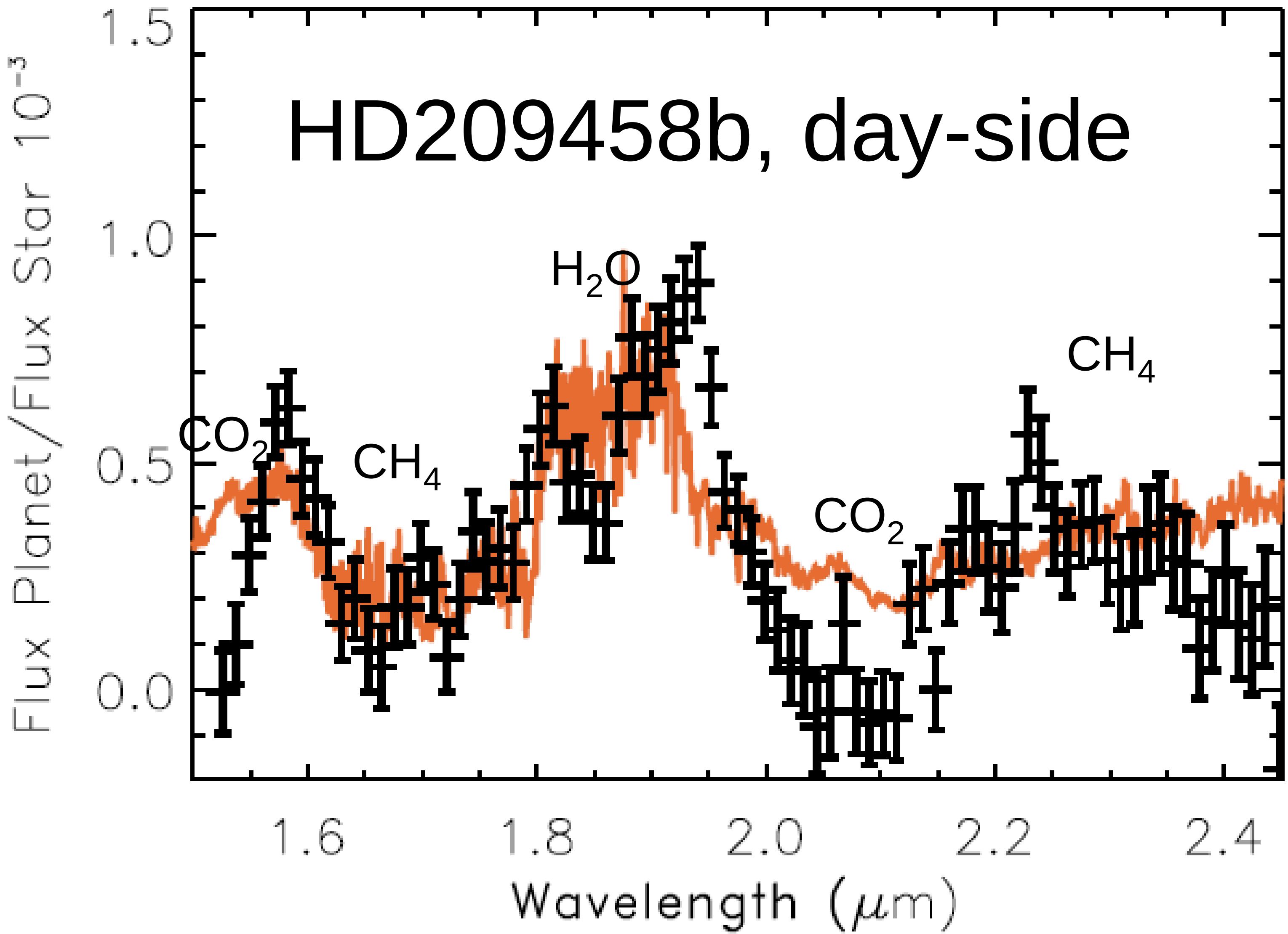
Tinetti and Griffith, 2010

Carbon Dioxide



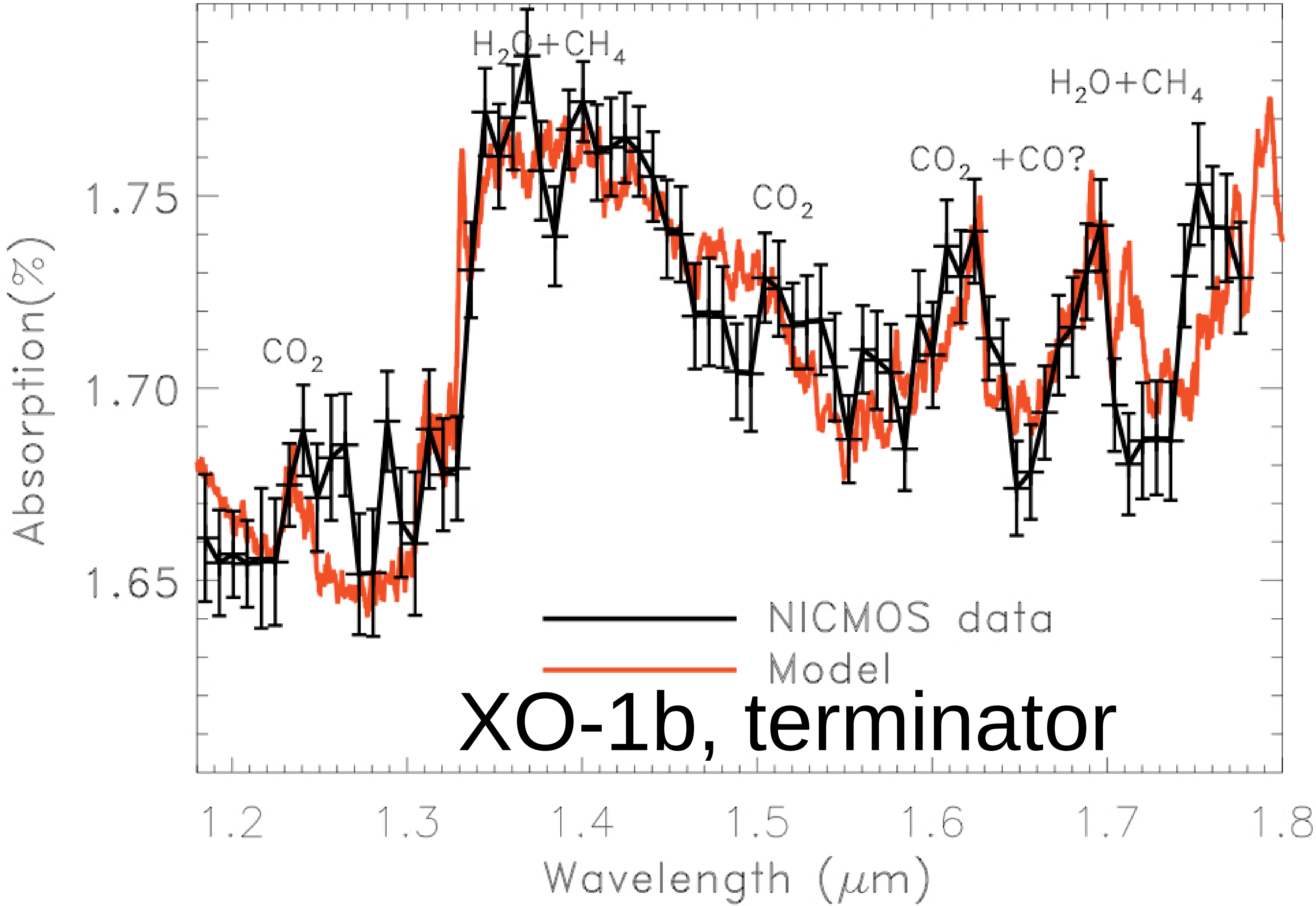
NIR emission spectroscopy

UCL



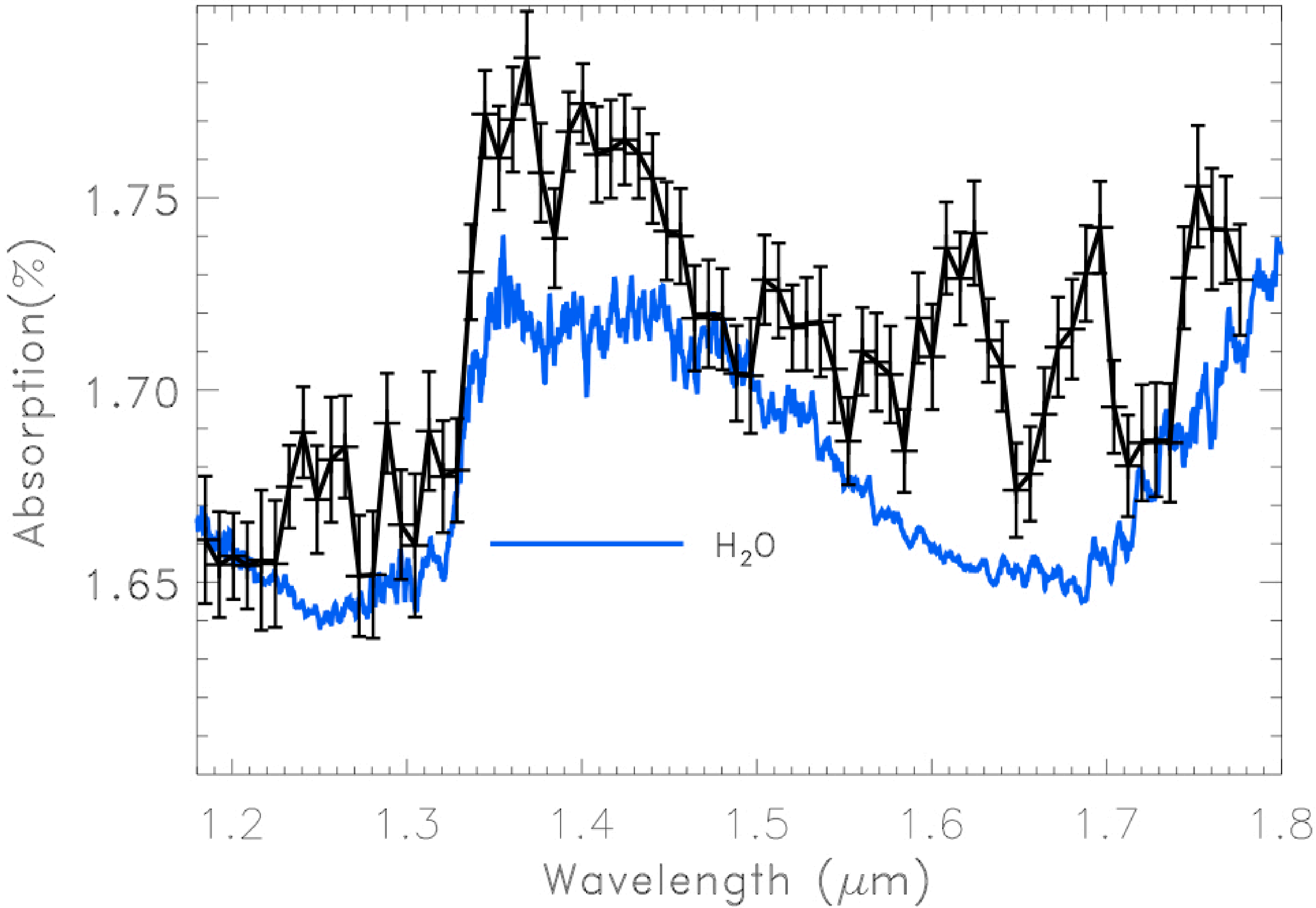
Swain, Tinetti, Vasisht, Deroo, Griffith, et al., 2009

NICMOS: transmission spectroscopy



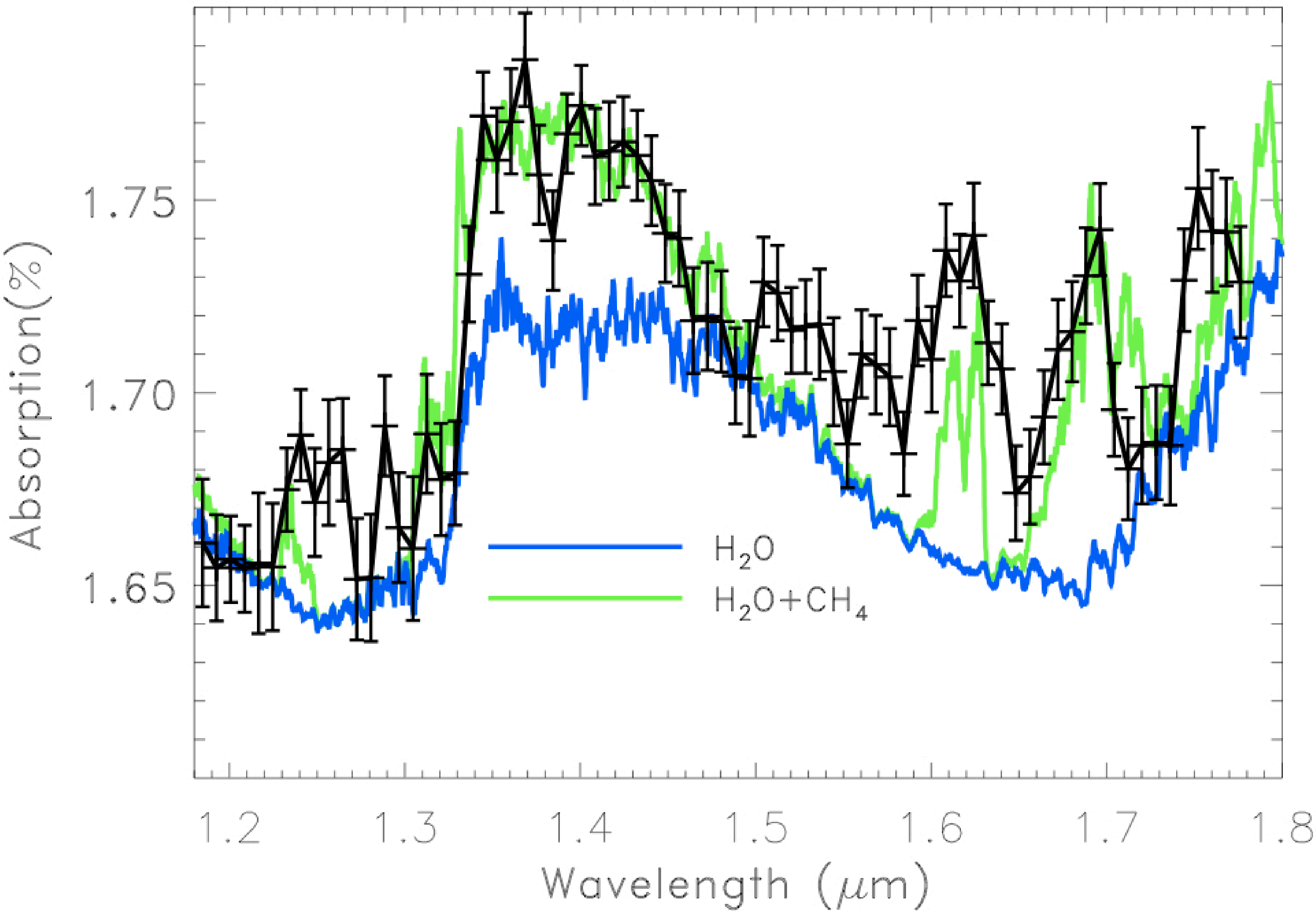
Tinetti, et al., ApJ, 2010

NICMOS: transmission spectroscopy



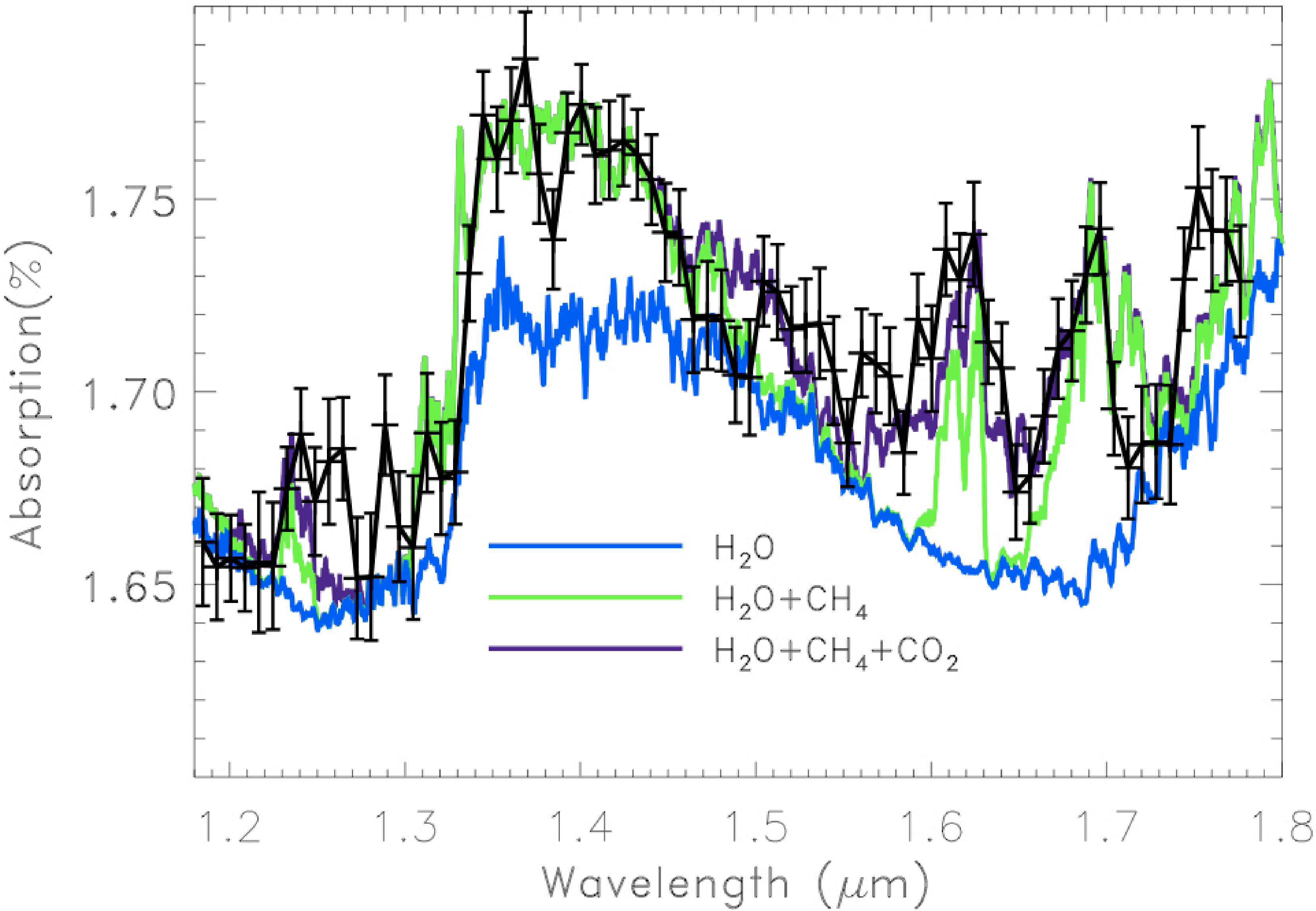
Tinetti, *et al*., ApJ, 2010

NICMOS: transmission spectroscopy



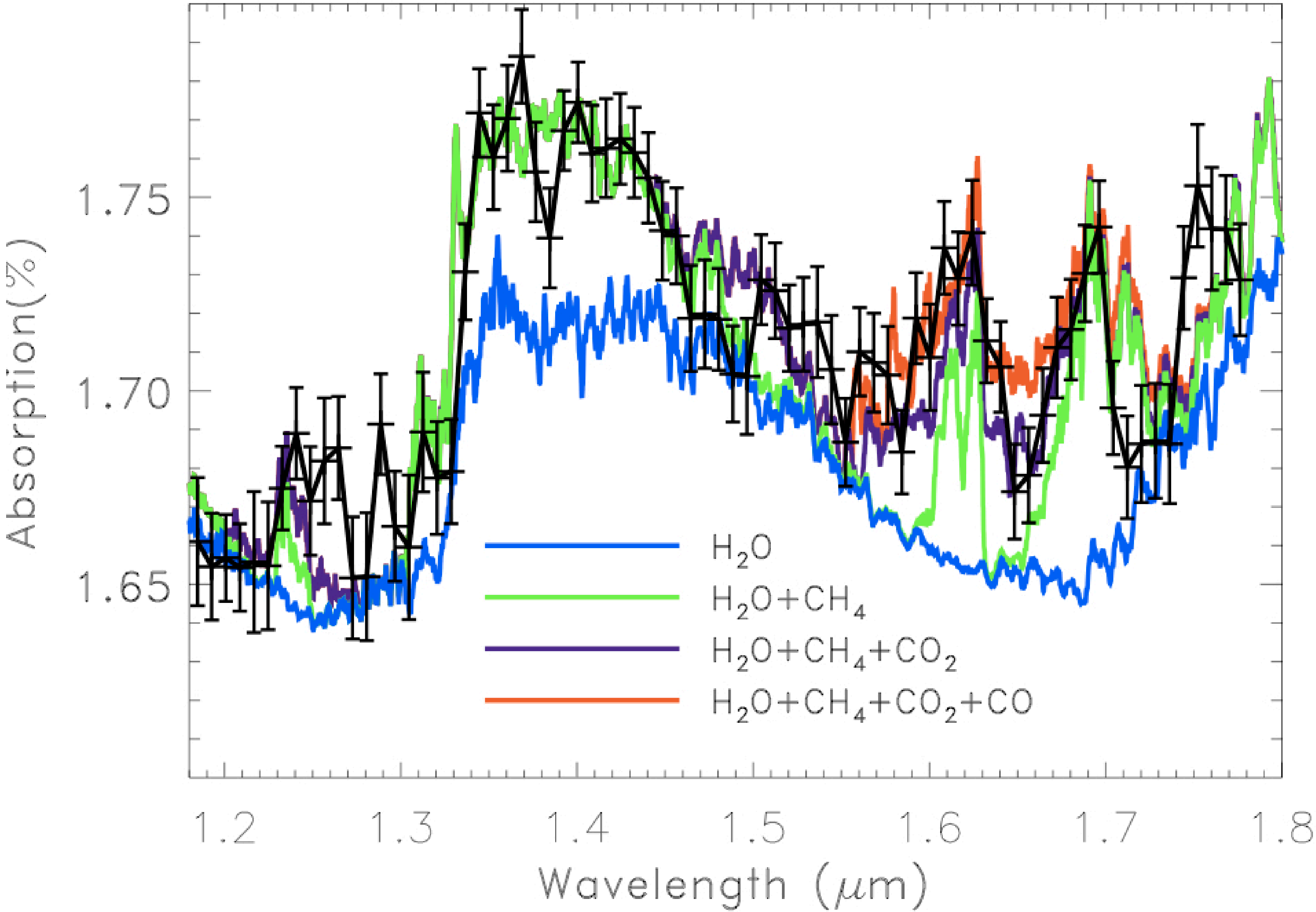
Tinetti, *et al*., ApJ, 2010

NICMOS: transmission spectroscopy



Tinetti, *et al*., ApJ, 2010

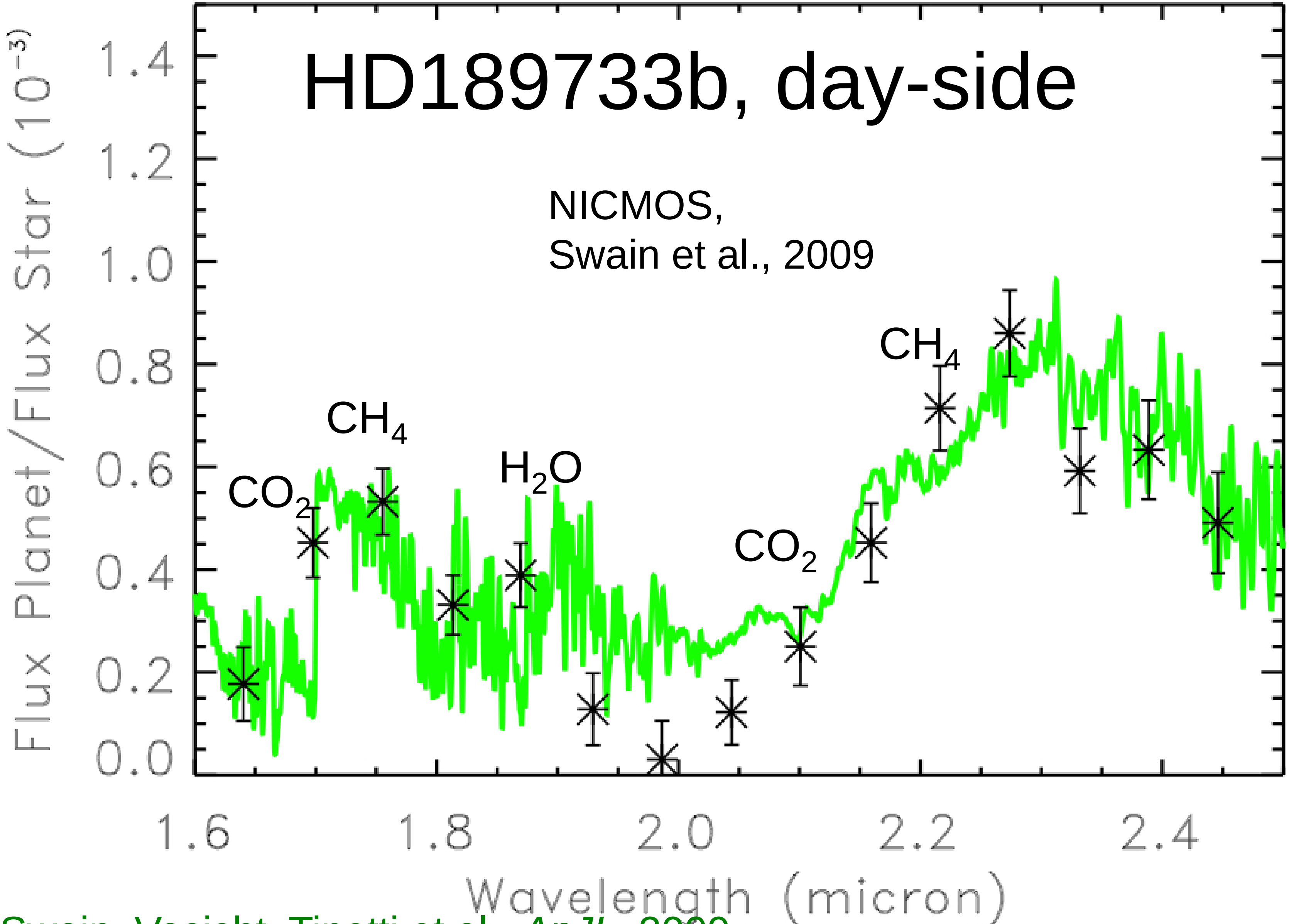
NICMOS: transmission spectroscopy



Tinetti, *et al*., ApJ, 2010

NIR-MIR emission spectroscopy

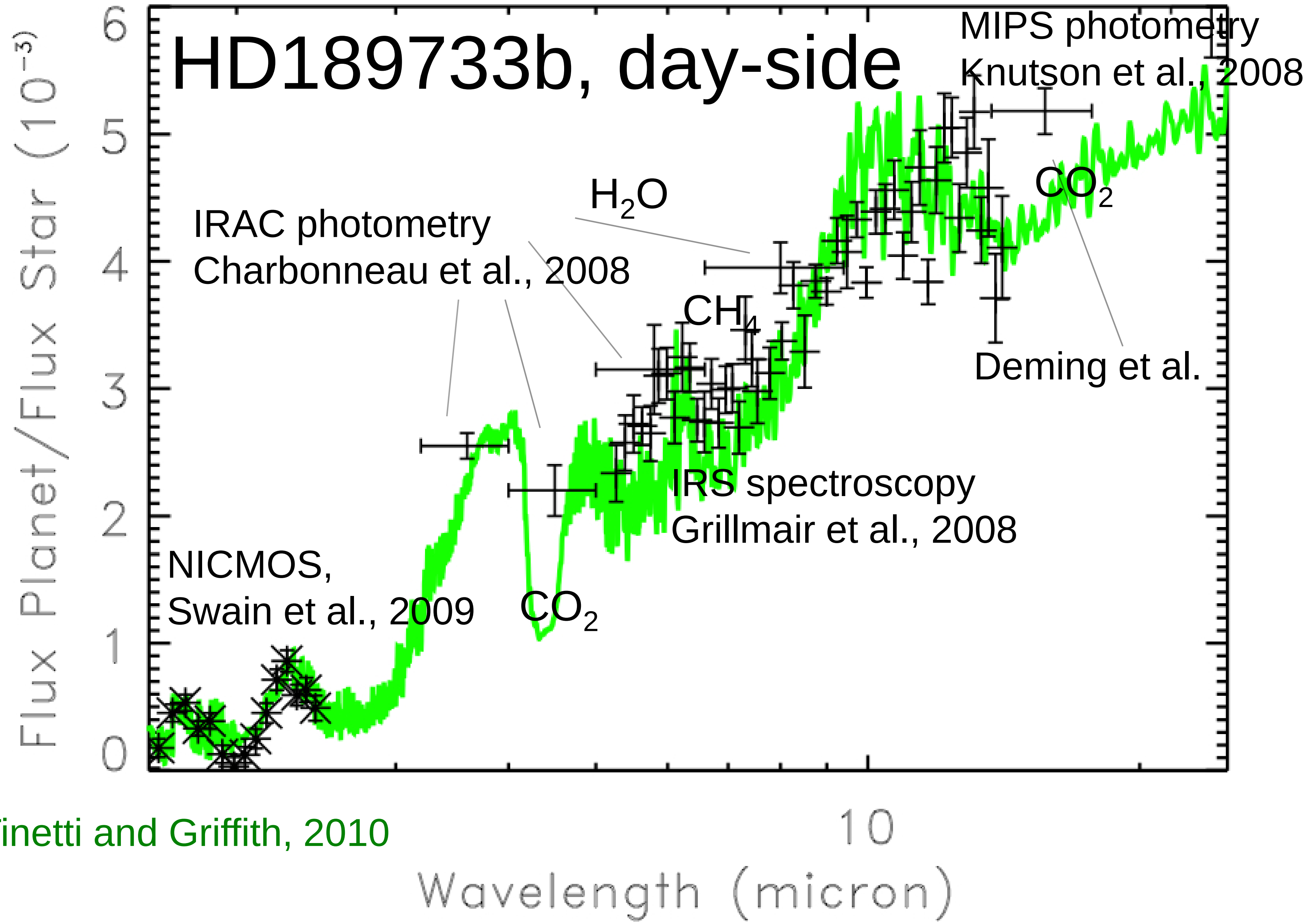
UCL



Swain, Vasisht, Tinetti et al., *ApJL,* 2009

NIR-MIR emission spectroscopy

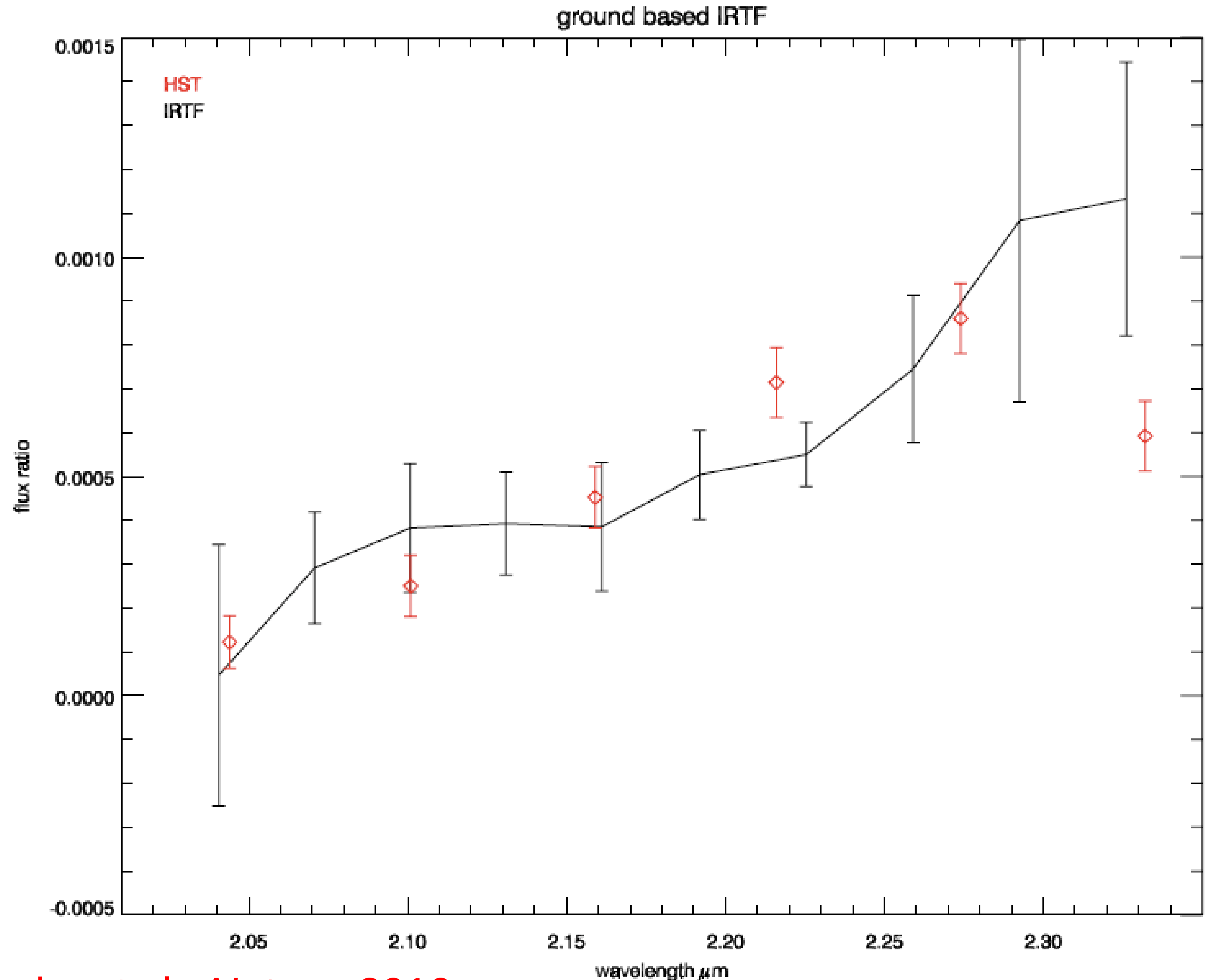
UCL



Tinetti and Griffith, 2010

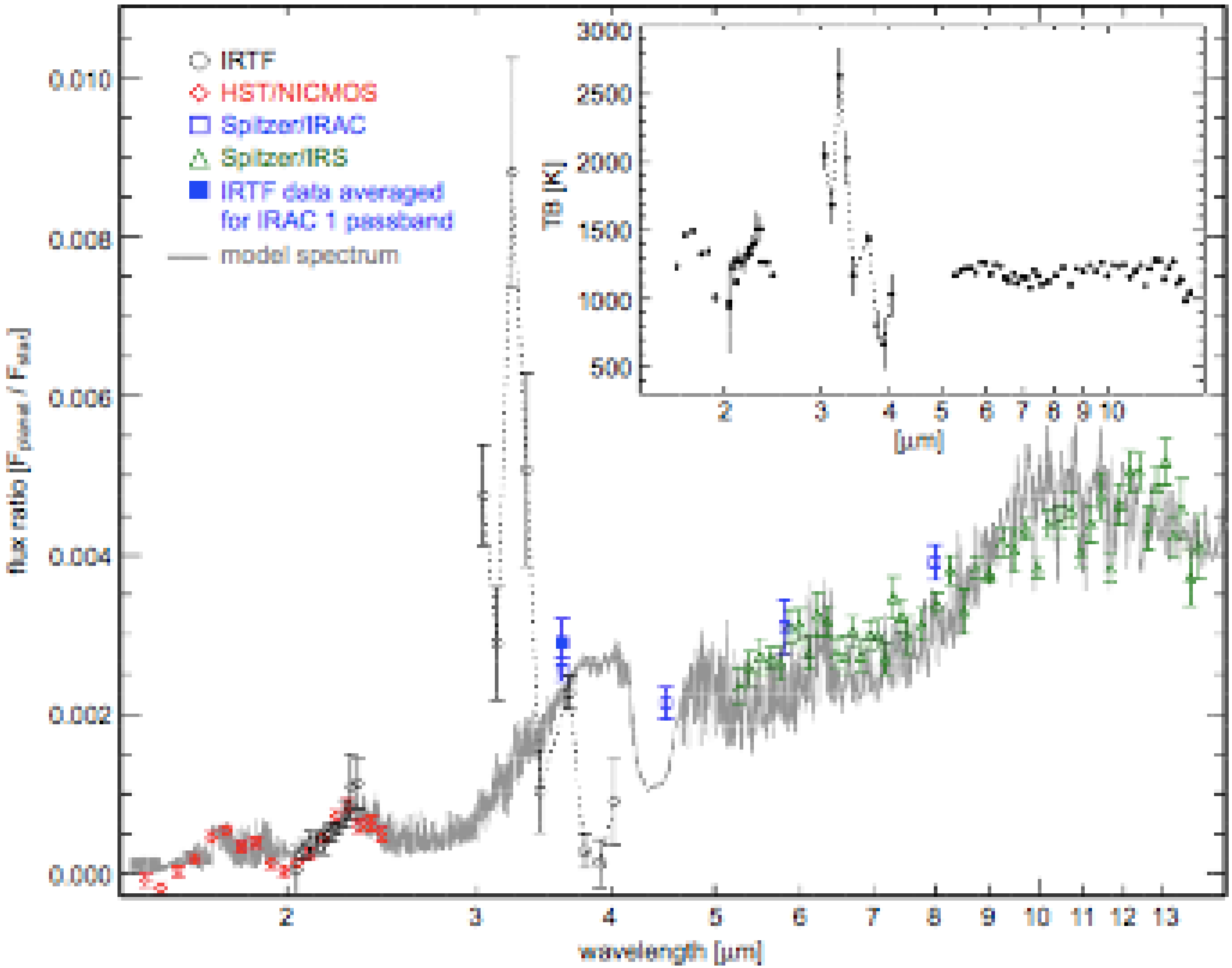
Now

NIR-MIR emission spectroscopy



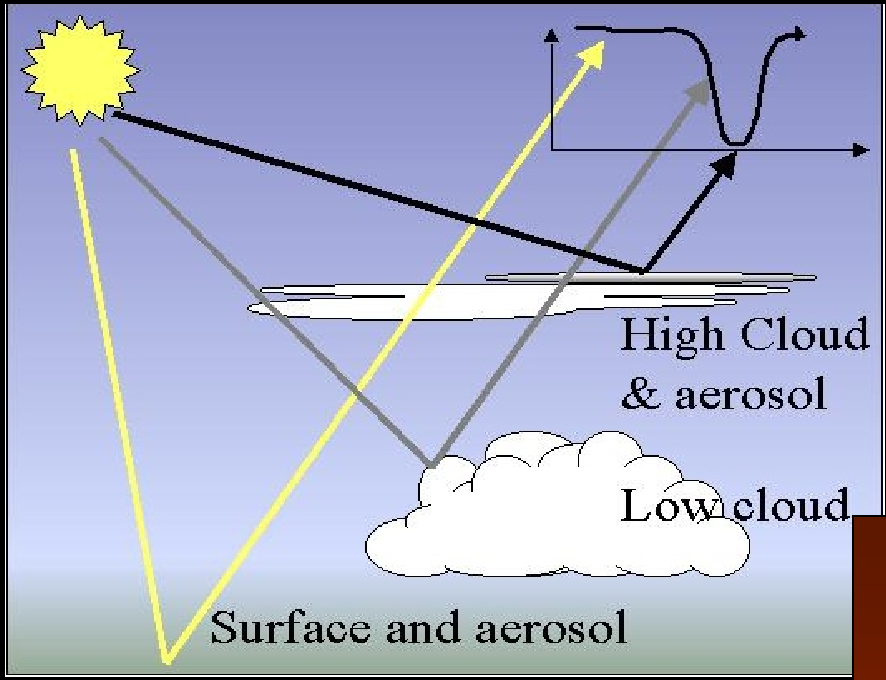
Swain, et al., *Nature,* 2010

NIR-MIR emission spectroscopy



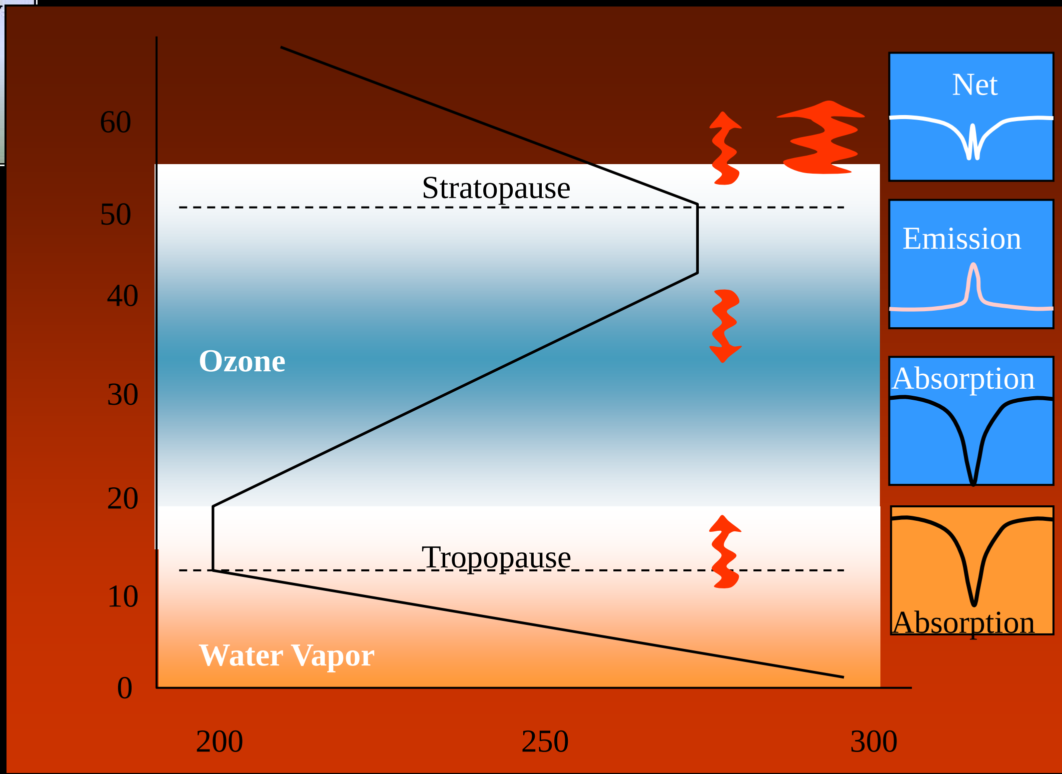
Swain, et al., *Nature*, 2010

Spectral retrieval

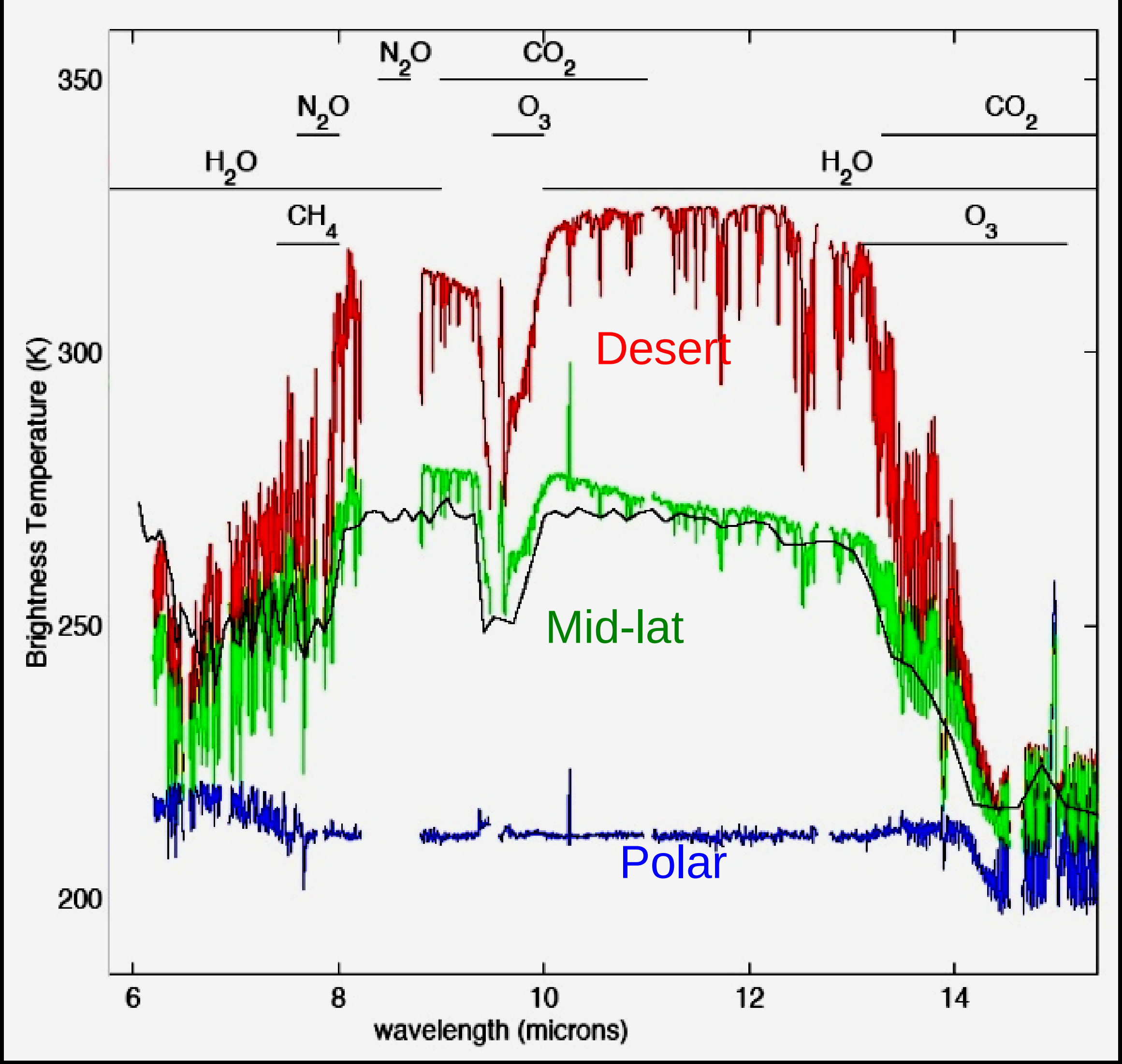


In the visible, sunlight is reflected and scattered back to the observer, and is absorbed by materials on the planet's surface and in its atmosphere.

The planet is warm and gives off its own infrared radiation. As this radiation escapes to space, materials in the atmosphere absorb it and produce spectral features.



Spectral retrieval in the IR



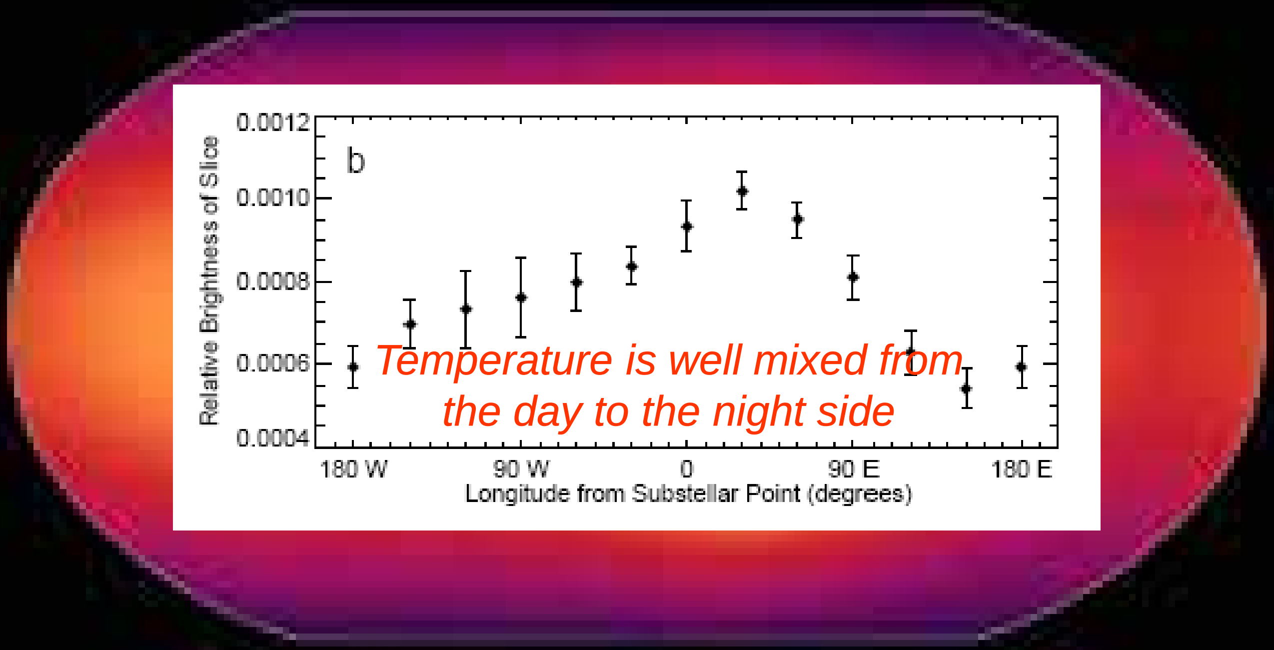
AIRS data

⇒Thermal variations ~50%

(Hearty, et al. 2009)

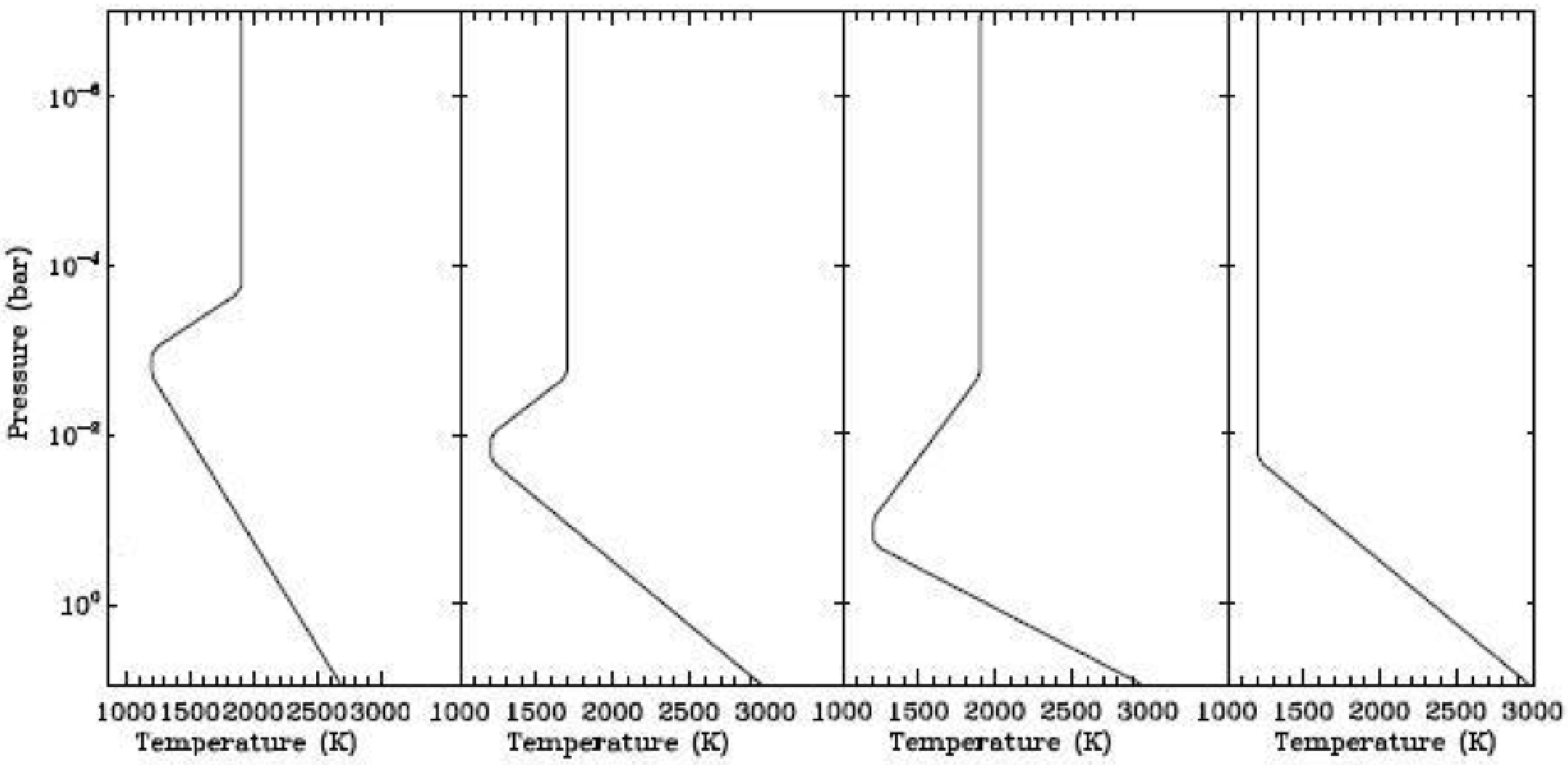
Light curves: thermal horizontal gradients

HD 189733b
primary& secondary transit @ 8 & 24 μm



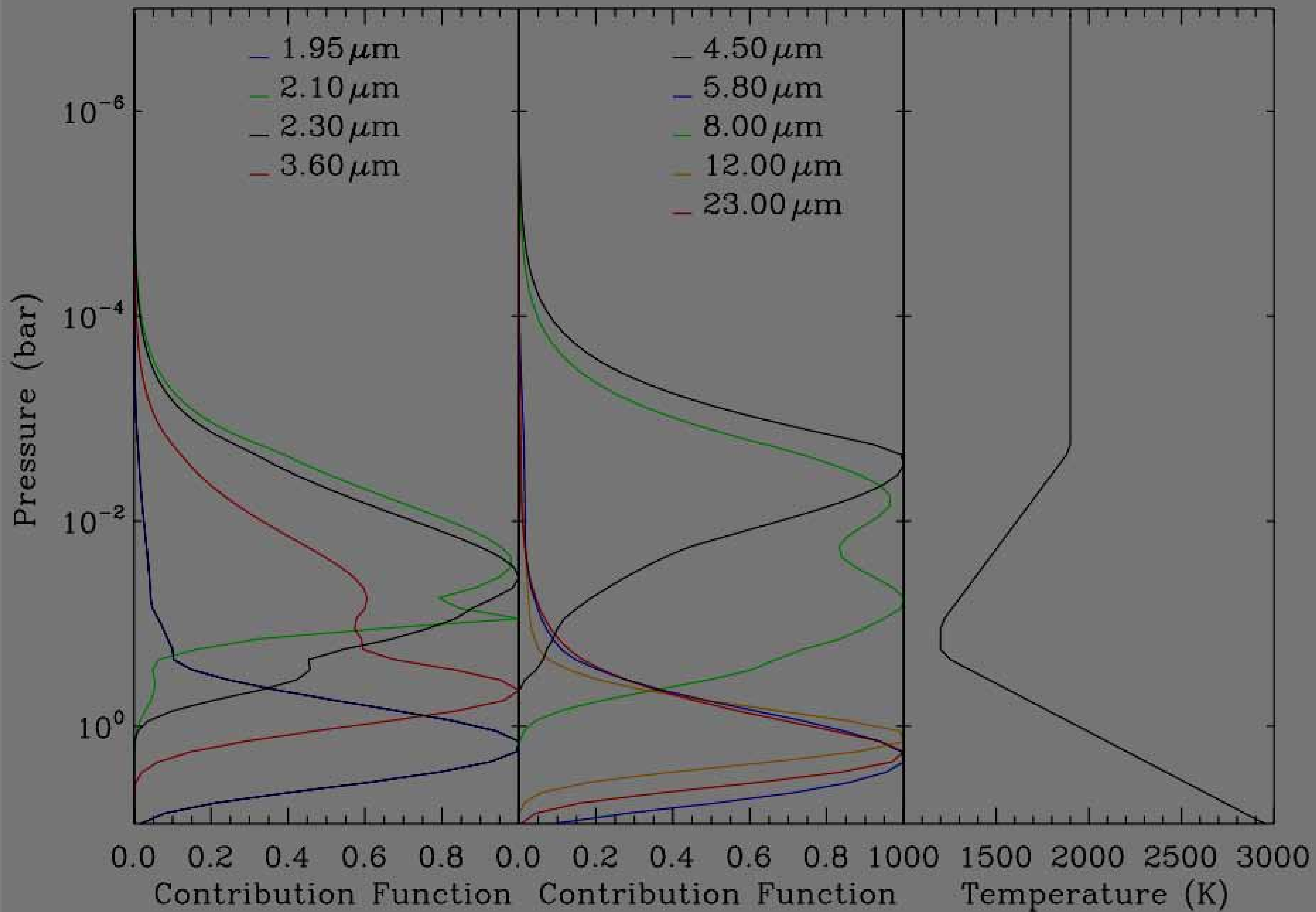
Knutson et al., *Nature*, 2007; ApJ, 2008

HD209458b, day-side



Swain, Tinetti, Vasisht, Deroo, Griffith, et al., 2009

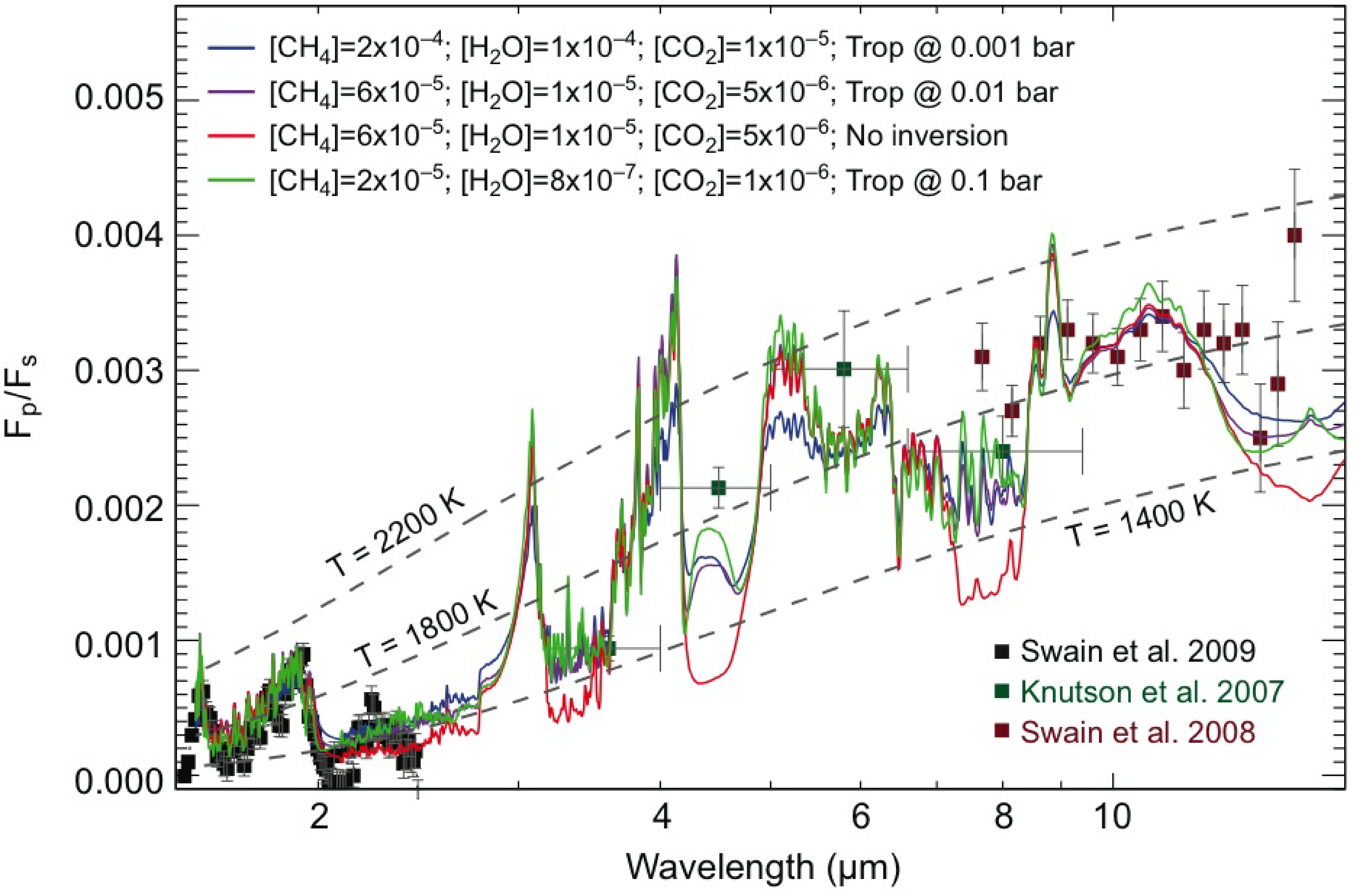
Degeneracy T-P profile, mixing ratios



Swain, Tinetti, Vasisht, Deroo, Griffith, et al., 2009

Degeneracy composition T-P profile

UCL



Swain, Tinetti, Vasisht, Deroo, Griffith, et al., 2009

Hot-Jupiters

- We find water vapour, methane present in all 3 Hot-Jupiters
- CO_2, hazes, CO are also likely to be present
- There is a degeneracy of interpretation mixing ratios/thermal profiles.
- More data at higher resolution are desirable to break the degeneracy,
- and also better line lists for methane, hydrocarbons, H_2S, CO_2, etc. @ 1000-2000K


Next 5 years:
more GJ1214b!

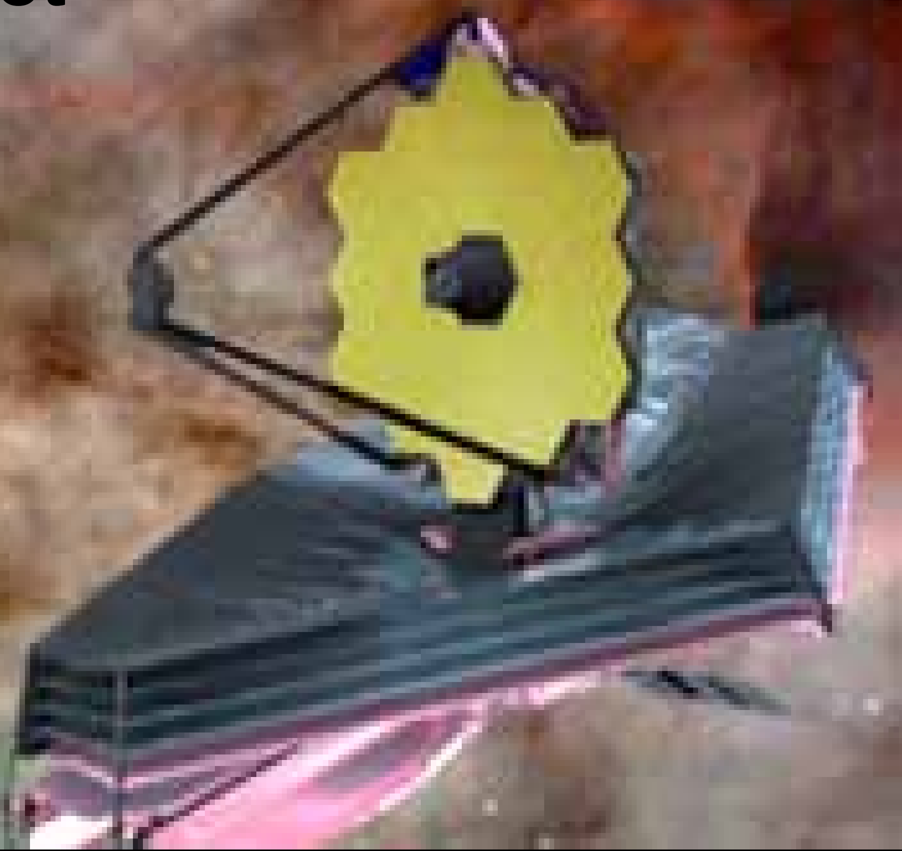
Coming soon...


High-res.
Spectroscopy
from ground,
Super-Earths &
Earth-size
planets

James Webb Space Telescope NASA-ESA (launch ~ 2014)

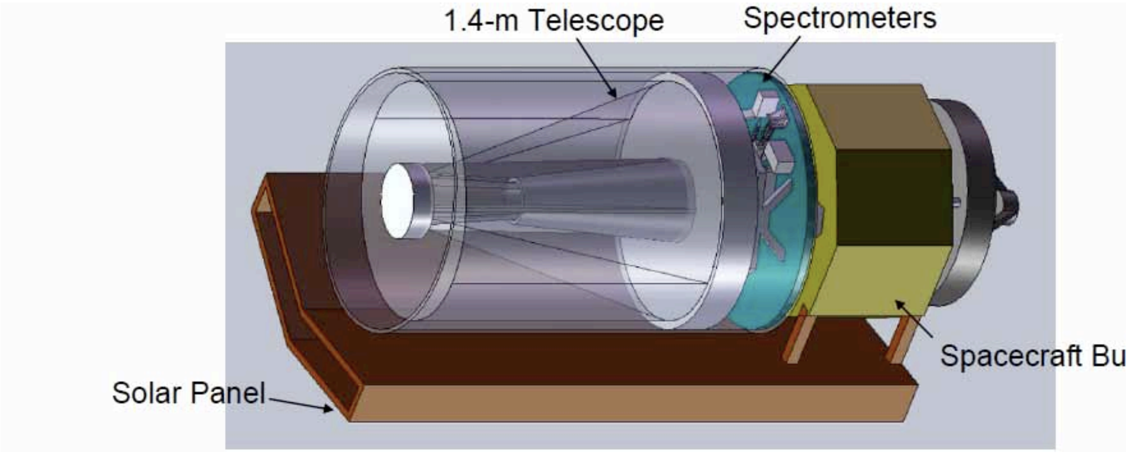
High-res. Spectroscopy for Hot-Jupiters/Neptunes

Super-Earths & Earth-size planets

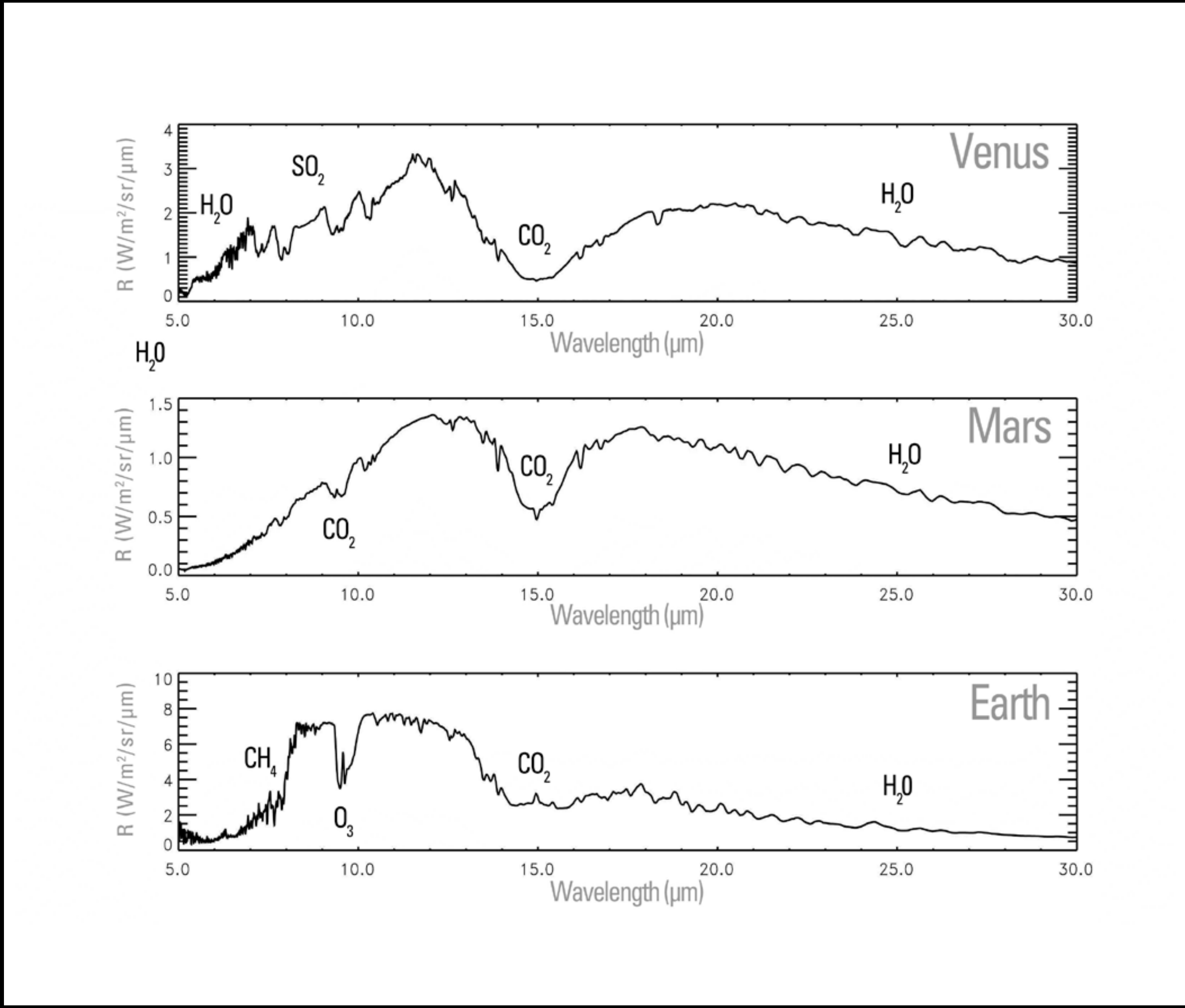


THESIS

- A THESIS-like mission will be able to *characterise the atmospheres of exoplanets down to the Super-Earth size in the habitable zone of later-type stars*,
  - using NIR-MIR transit spectroscopy
- The mission characteristics comply with the criteria of an ESA medium-size mission
- 1.5m telescope + VIS+NIR+MIR spectrographs



Emission spectra for terrestrial planets in our Solar System



Up to 10 Hours	Few days	Up to 2 weeks
Hot Jupiter / G0v star in K, L, N bands	Super Earth (E) / M5V *mag* 9.5v	Super Earth (V) / M5v *mag* 9.5Mv
Hot Neptune / G0v star, in K, L, N bands	Super Earth (WT) / M5v *mag* 11Mv	Super Earth (E) / M3v *mag* 9Mv
Hot SE (500 & 700K) / M5v *mag* 9.5Mv	Super Earth (E) / M5v *mag* 11Mv	
Super Earth (WT) / M5v *mag* 9.5Mv	Super Earth (WT) / M3v *mag* 9Mv	

All Super Earths have **R**=1.6 ***Rearth*** and observed in **N Band**

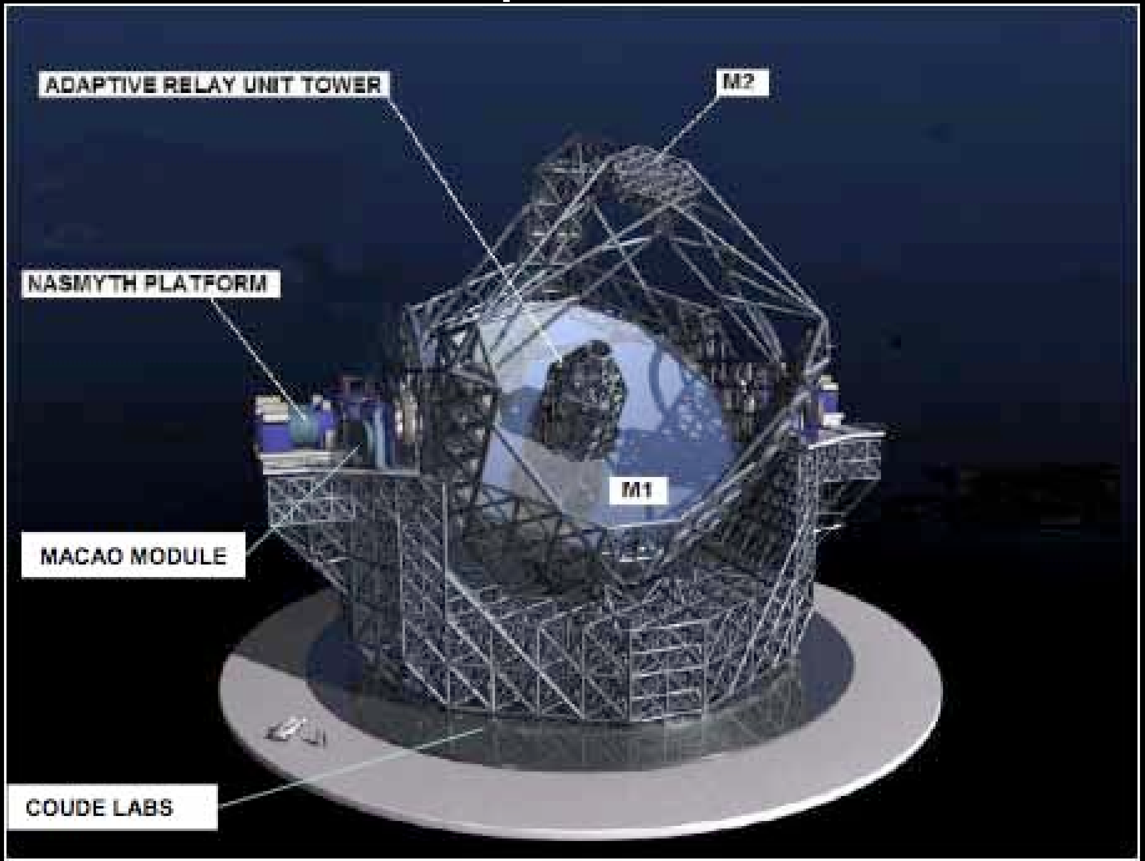
E: Earth-Like, WT: Warm Titan-like, V: Venus-like

S/N = 10, R=10, in each band

Tessenyi, et al., in prep.

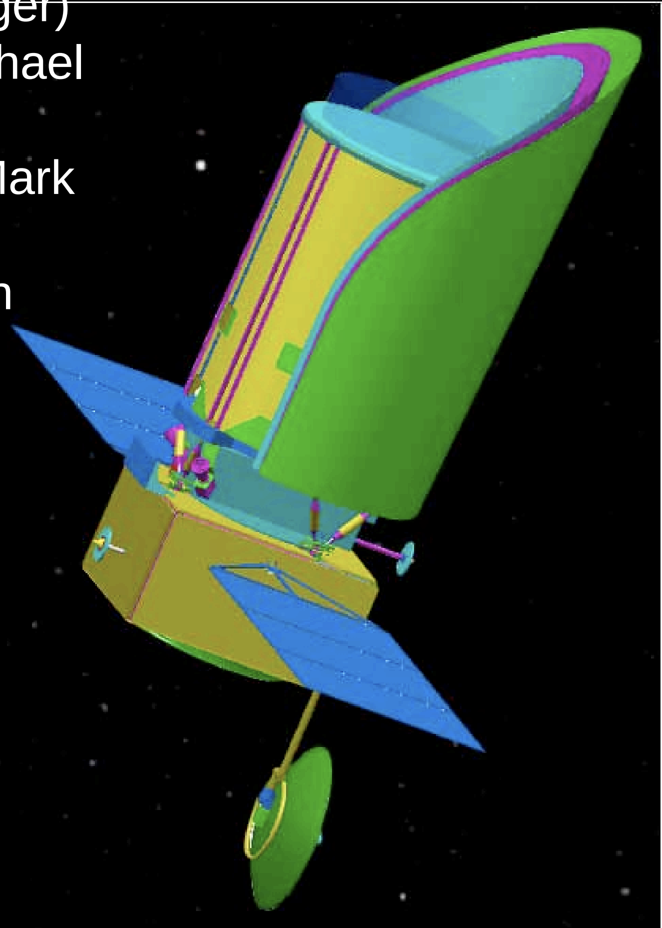
ESO Extremely Large Telescope-EPICS (~2018)

EPICS, instrument for ELT (32 m class ground-telescope) to detect directly exoplanets down to large terrestrial planets

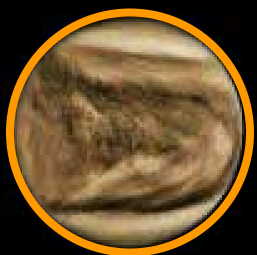


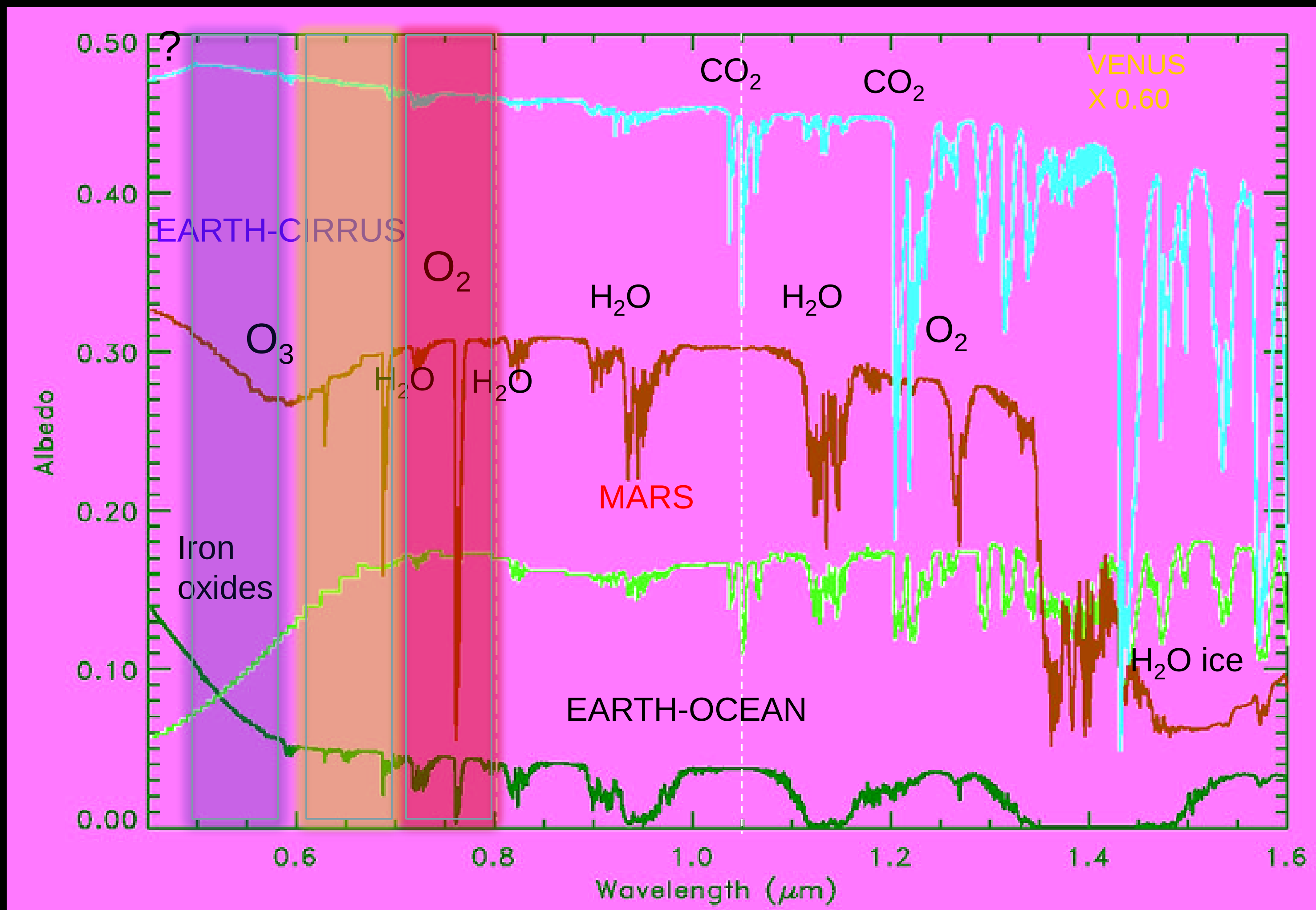
Medium size space telescope + Coronograph

ü Access: coronagraphs for exoplanet missions (John Trauger)
ü Davinci, Dilute Aperture VIsible Nulling Coron. Imager(Michael Shao)
ü EPIC: directly imaging exoplanets orbiting nearby stars (Mark Clampin)
ü PECO: refining a Phase Induced Amplitude Apodization Coronograph (Olivier Guyon)

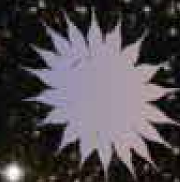


Terrestrial planets in our Solar System in the Visible-NIR





The New World Observer



NWO is a large-class Exoplanet mission that employs two spacecrafts: a “starshade” to suppress starlight before it enters the telescope and a conventional telescope to detect and characterize exo-planets.

Cash, *Nature*, 2006

Back-up