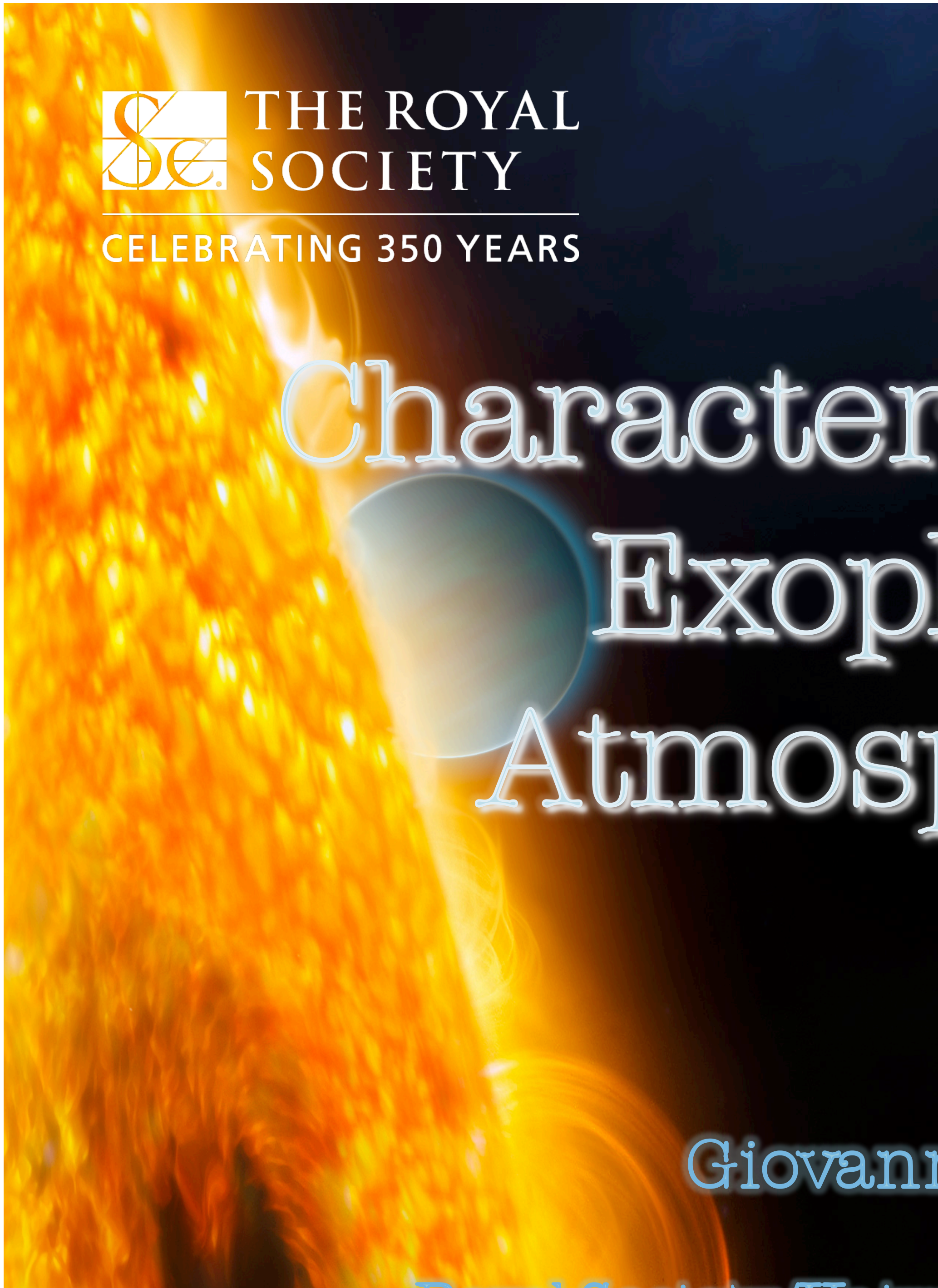
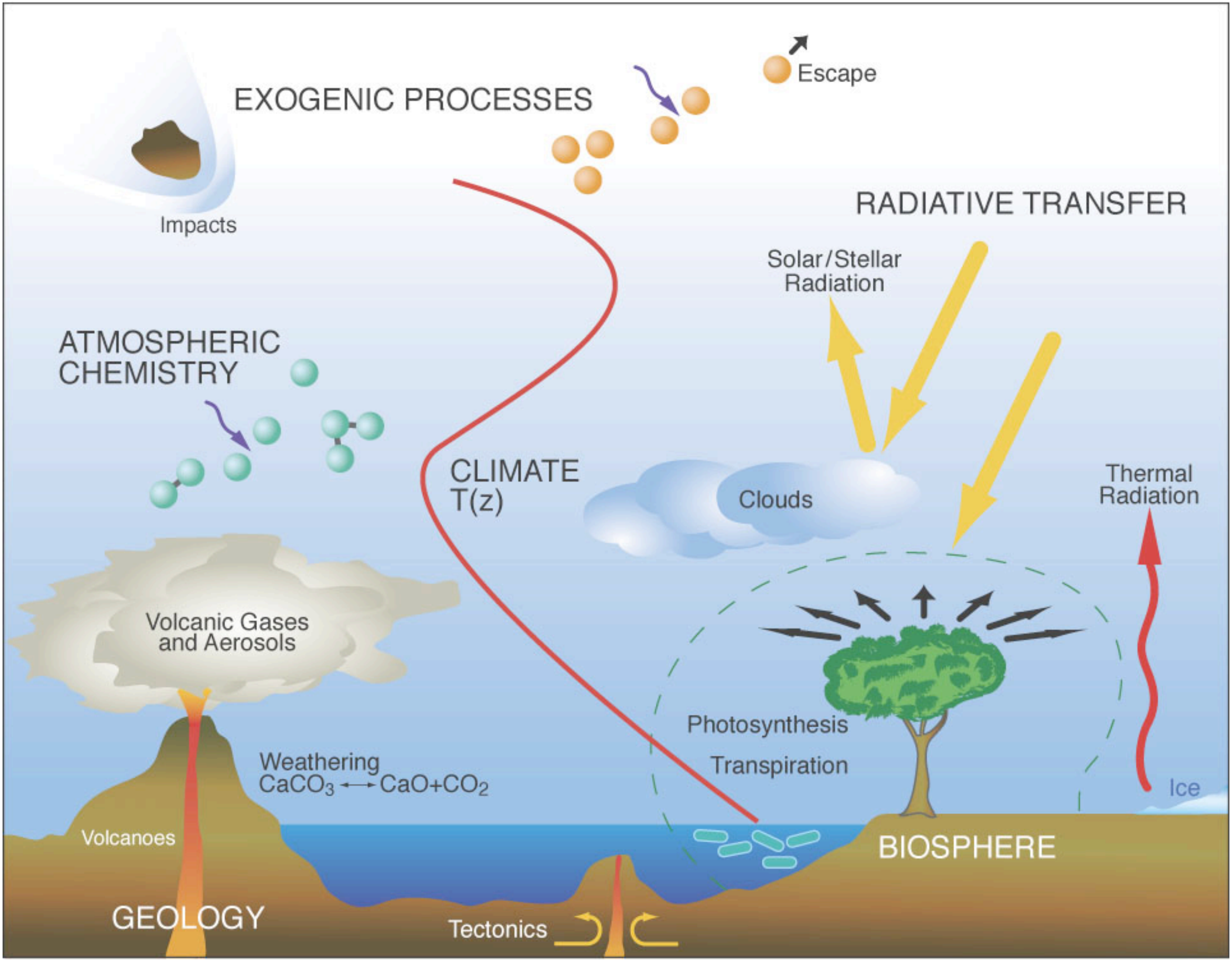


THE ROYAL SOCIETY
CELEBRATING 350 YEARS

Characterisation of Exoplanet Atmospheres

Giovanna Tinetti

Royal Society/University College London



EXOGENIC PROCESSES
Escape
Impacts
RADIATIVE TRANSFER
Solar/Stellar Radiation
ATMOSPHERIC CHEMISTRY
CLIMATE T(z)
Clouds
Thermal Radiation
Volcanic Gases and Aerosols
Photosynthesis
Transpiration
Weathering
$CaCO_3 \leftrightarrow CaO+CO_2$
Ice
Volcanoes
BIOSPHERE
GEOLOGY
Tectonics

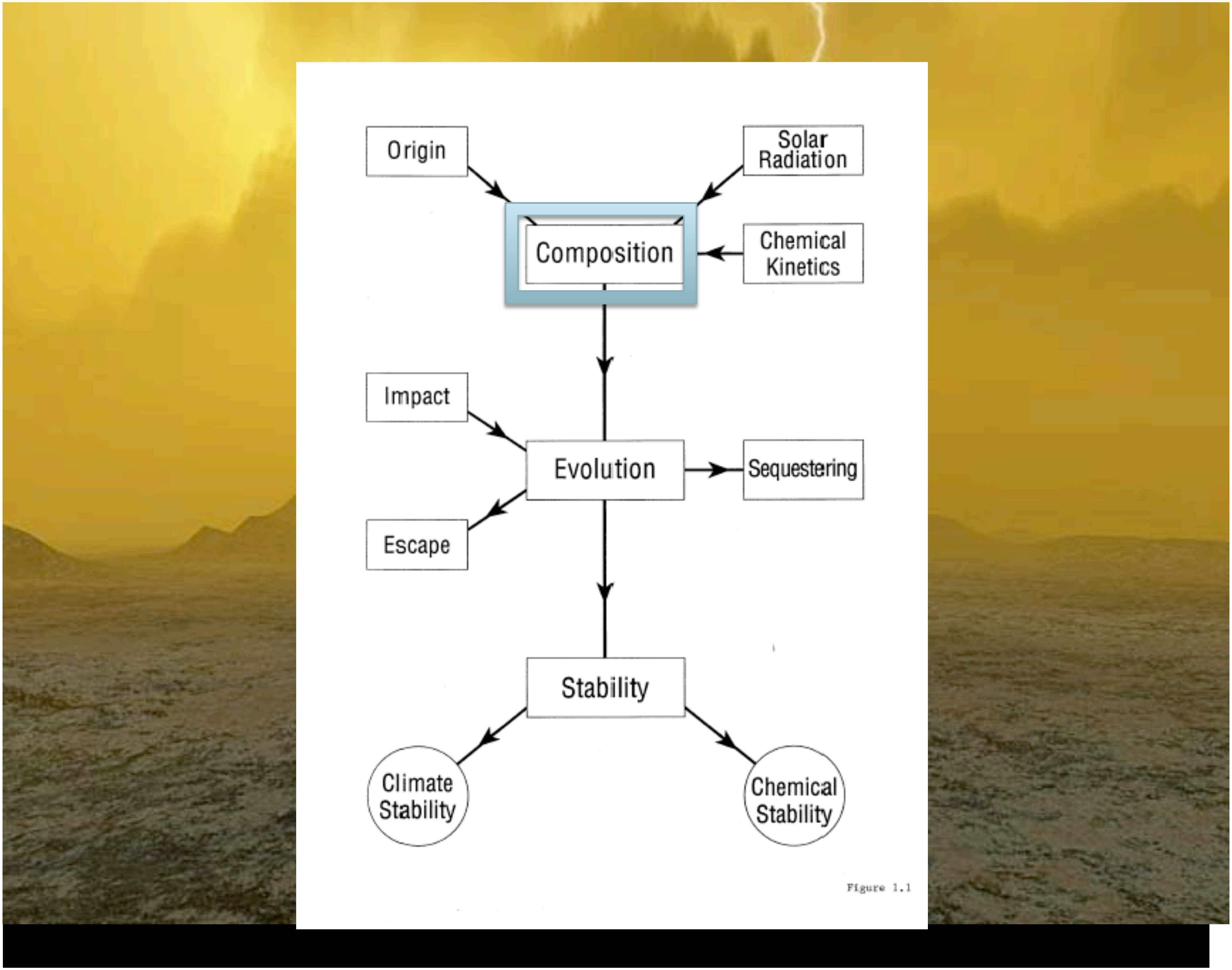

Origin
Solar Radiation
Composition
Chemical Kinetics
Impact
Evolution
Sequestering
Escape
Stability
Climate Stability
Chemical Stability

Figure 1.1

Planets in our solar system

small rocky planets close to the Sun
gas-giant planets more distant from the star

Atmospheres of 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

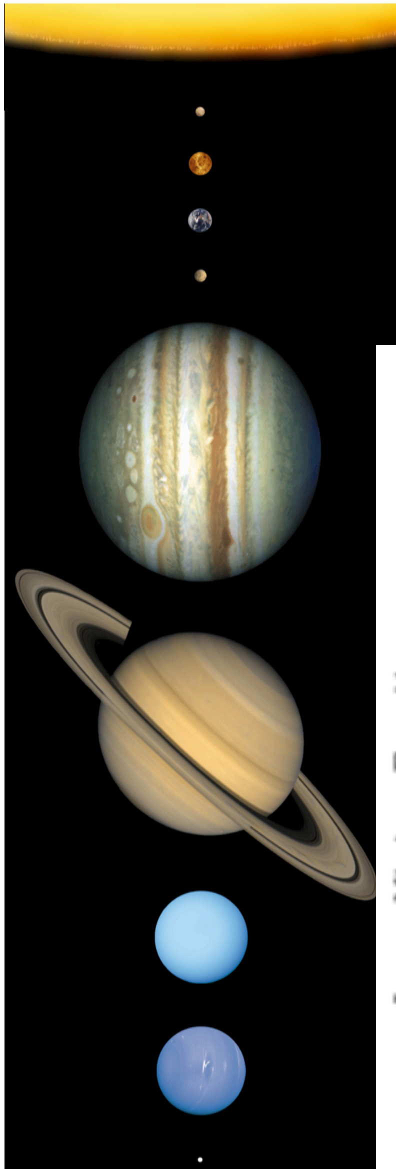
- Exospheres (Mercury, Moon, other Galilean satellites)
  - Solar flux or solar wind action on surfaces

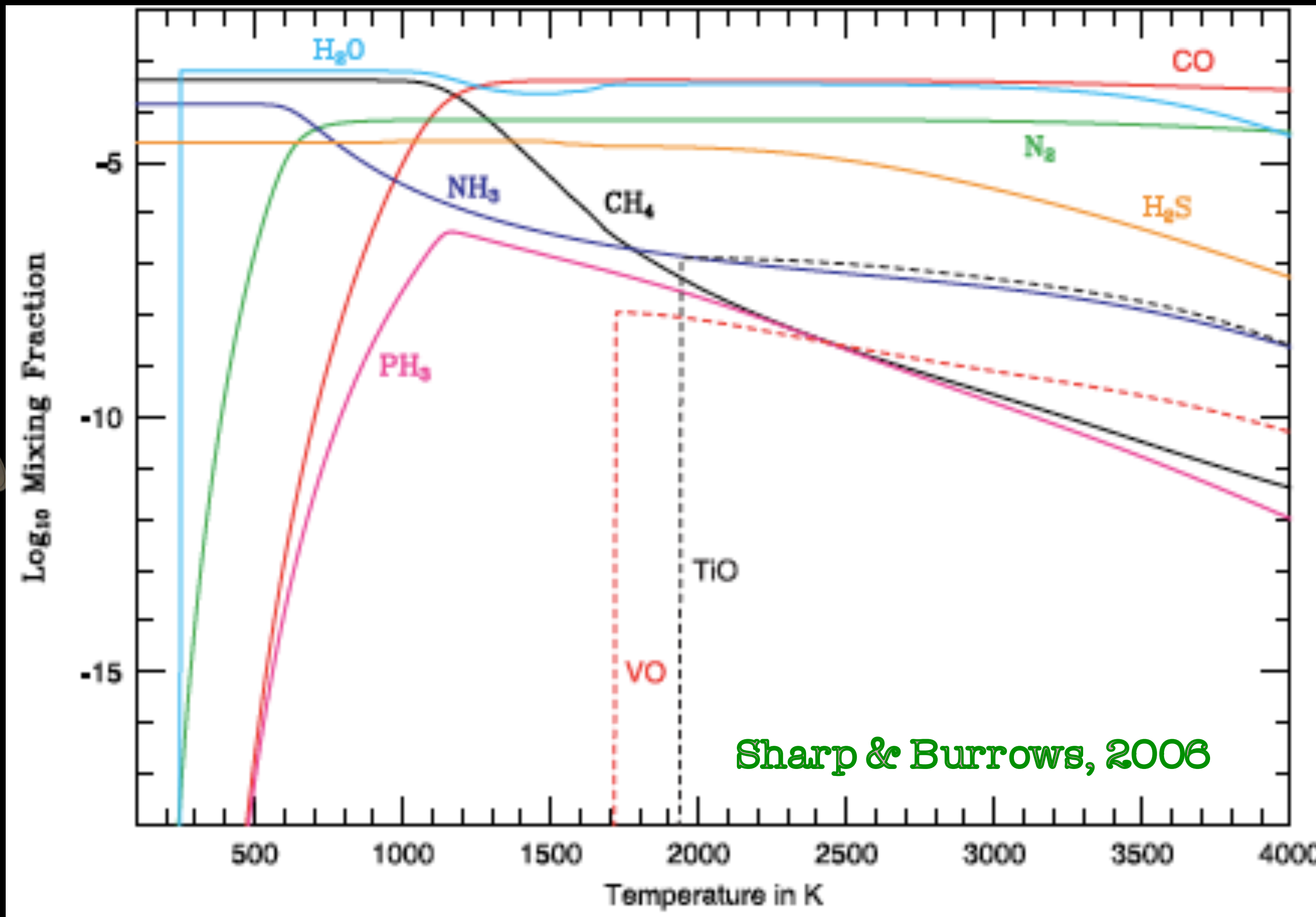
Table 1.3 List of three most abundant gases in planetary atmospheres. Mixing ratios are given in parenthesis. All compositions refer to the surface or 1 bar.

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})

Atmospheric Chemistry

Equilibrium Chemistry

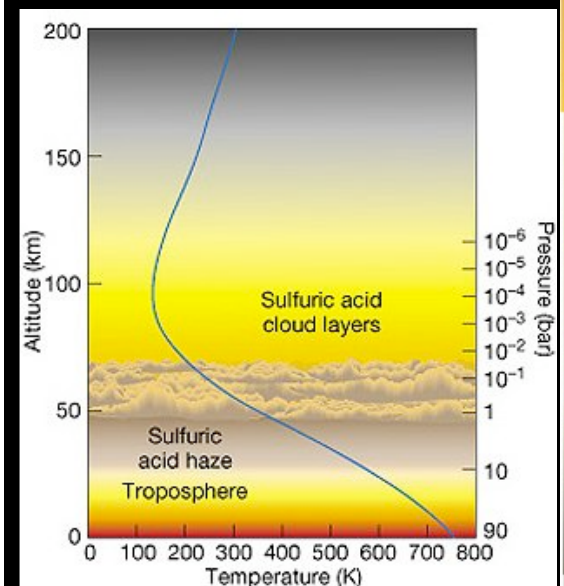


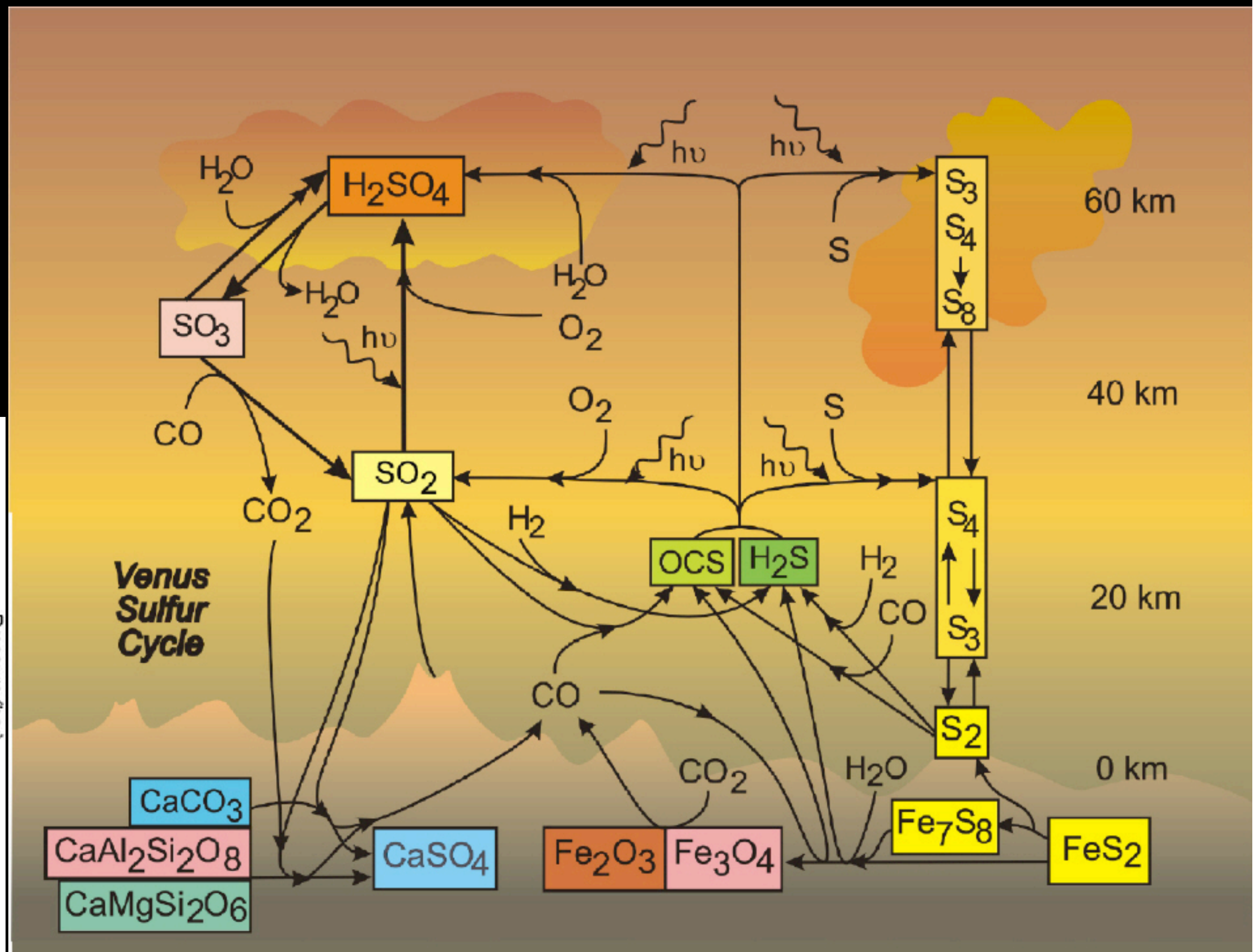


One-dimensional photochemical model

- Solving mass continuity equation
  - $$\frac{\partial n_i}{\partial t} + \frac{\partial \varphi_i}{\partial z} = P_i - L_i$$
  - $$\varphi_i = -\frac{\partial n_i}{\partial z}(D_i + K_{zz}) - n_i\left(\frac{D_i}{H_i} + \frac{K_{zz}}{H_{atm}}\right) - n_i \frac{\partial T}{\partial z}\left[\frac{(1+\alpha_i)D_i + K_{zz}}{T}\right] + n_i w_i$$
  - $K_{zz} = K_0 \times n^{-\gamma}$, $\gamma \approx 0.5$
- Temperature profile from thermochemical calculation
- Chemical reactions from, for example, Yung and DeMore (1999)

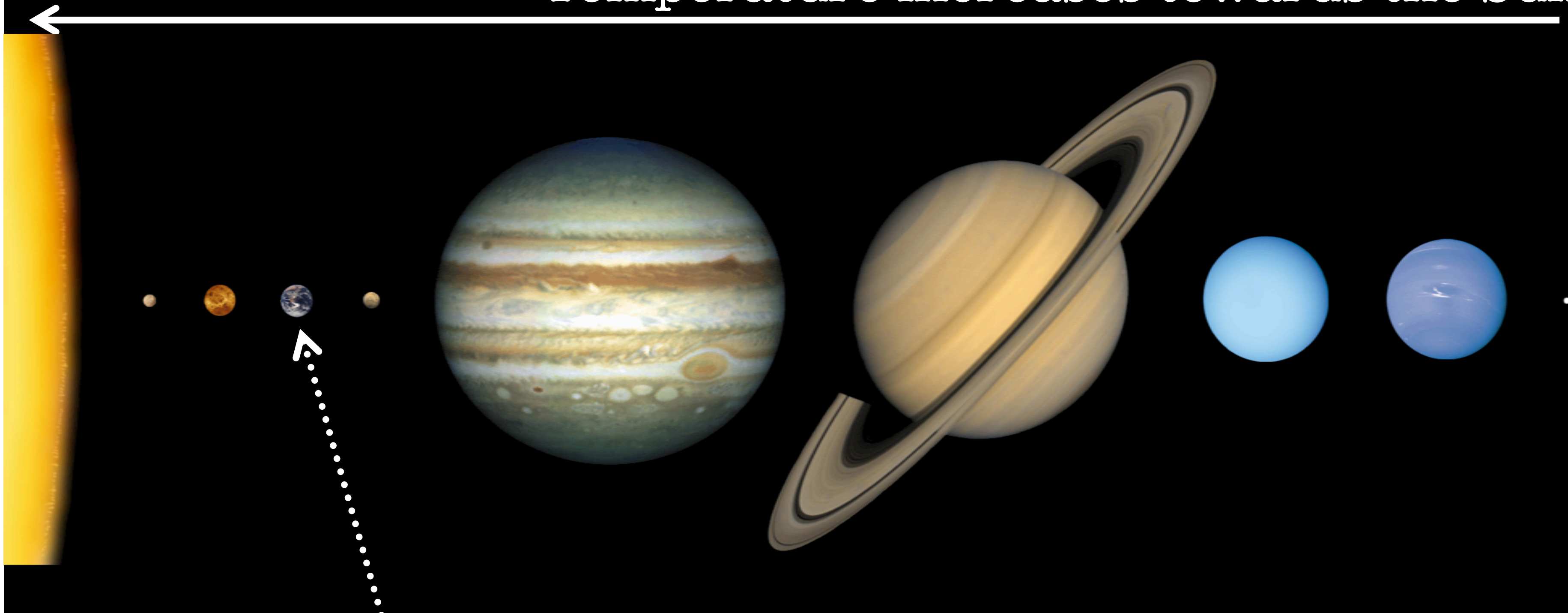
Venus: Photochemical clouds





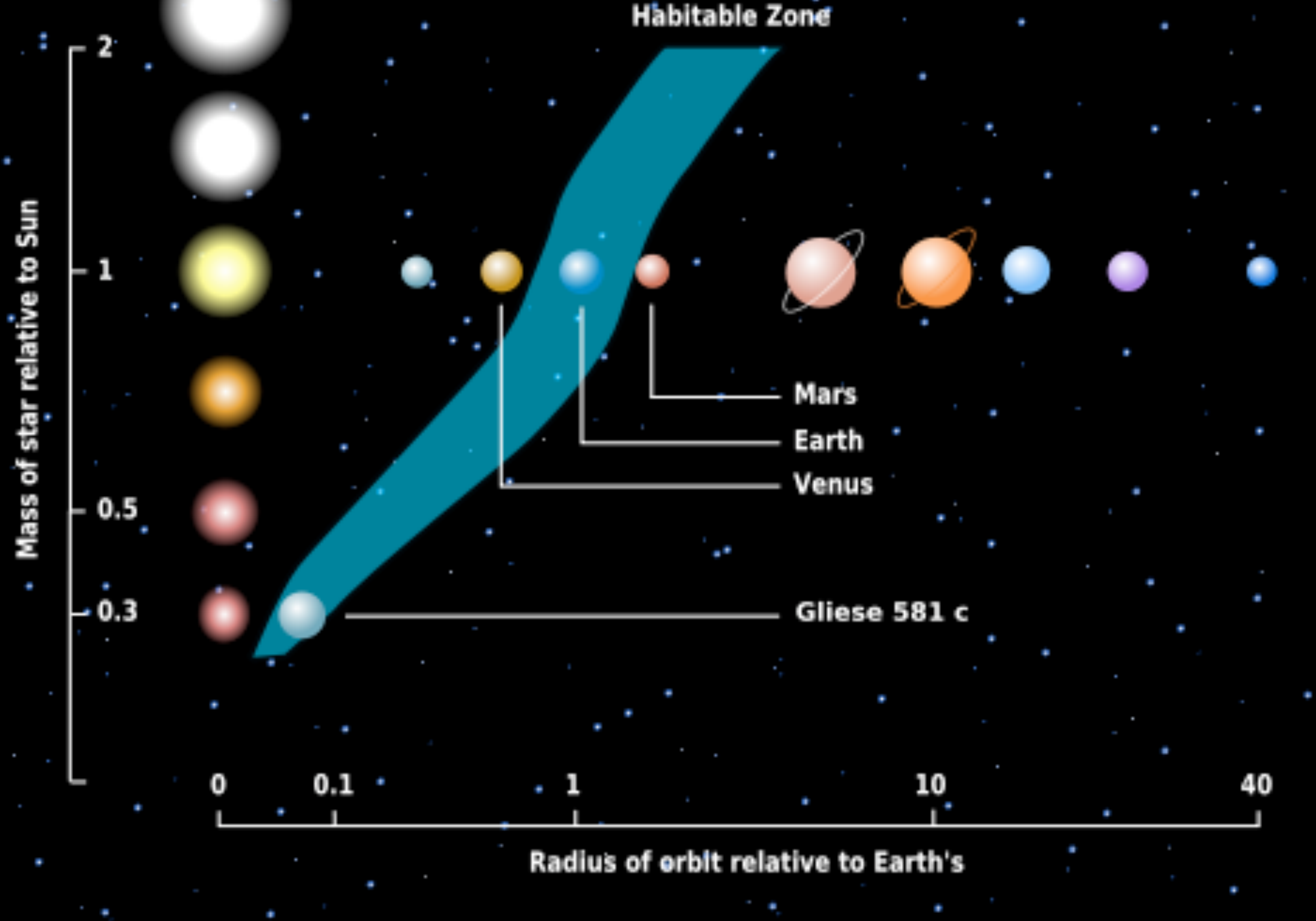
Habitable zone

Temperature increases towards the Sun



Habitable zone= presence of water in the liquid phase

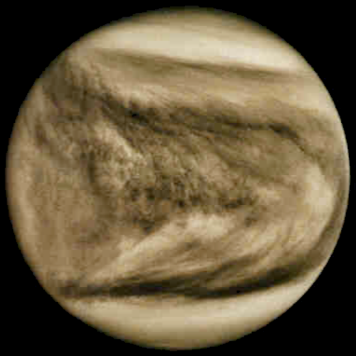
Habitable zone for different stars



Greenhouse effect

Planetary Energy balance is given by:

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

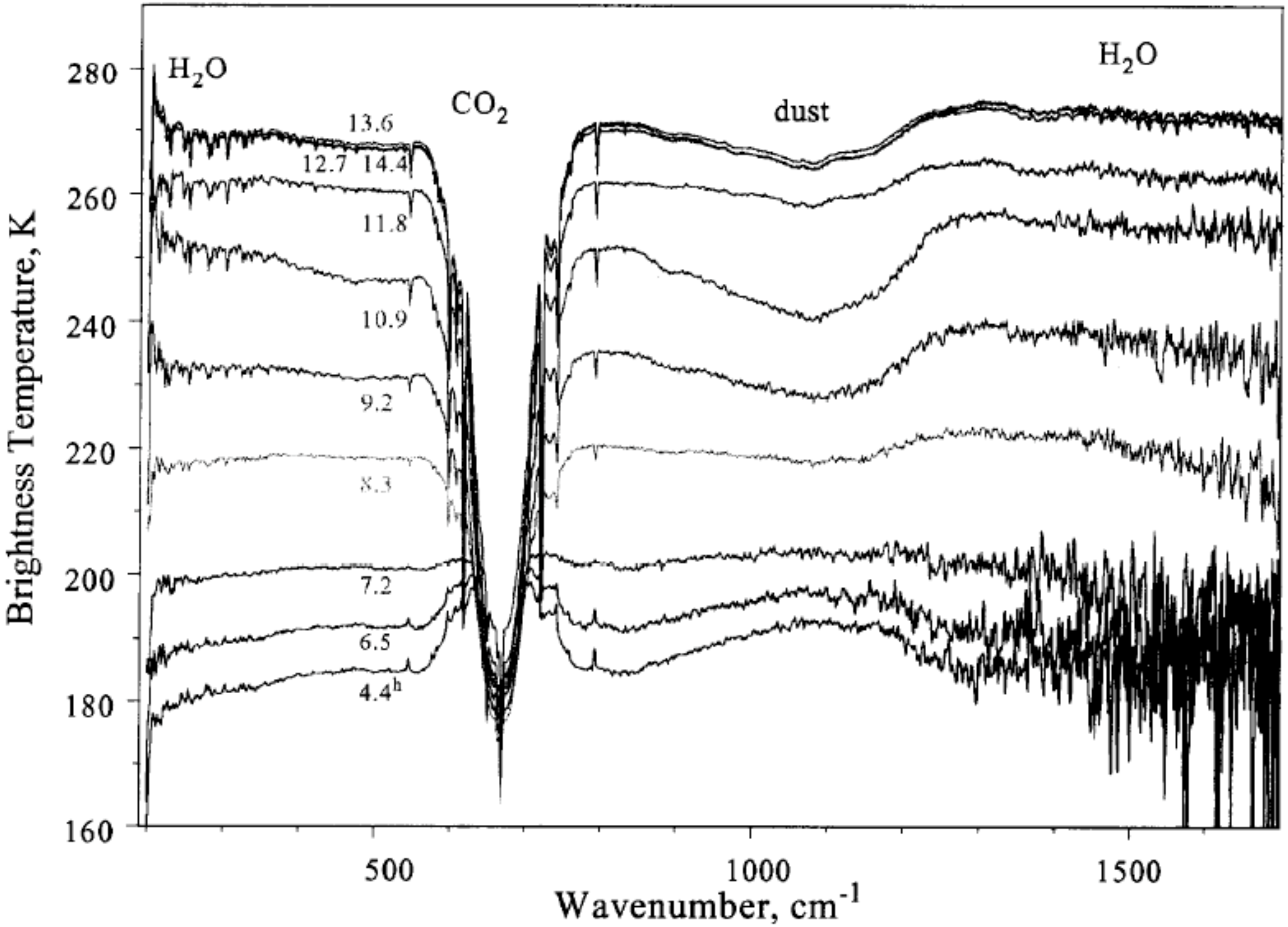


	$T_{effective}$	$T_{surface}$	Greenhouse
Venus	-43C	470C	513C
Earth	-17C	15C	32C
Mars	-55C	-50C	5C

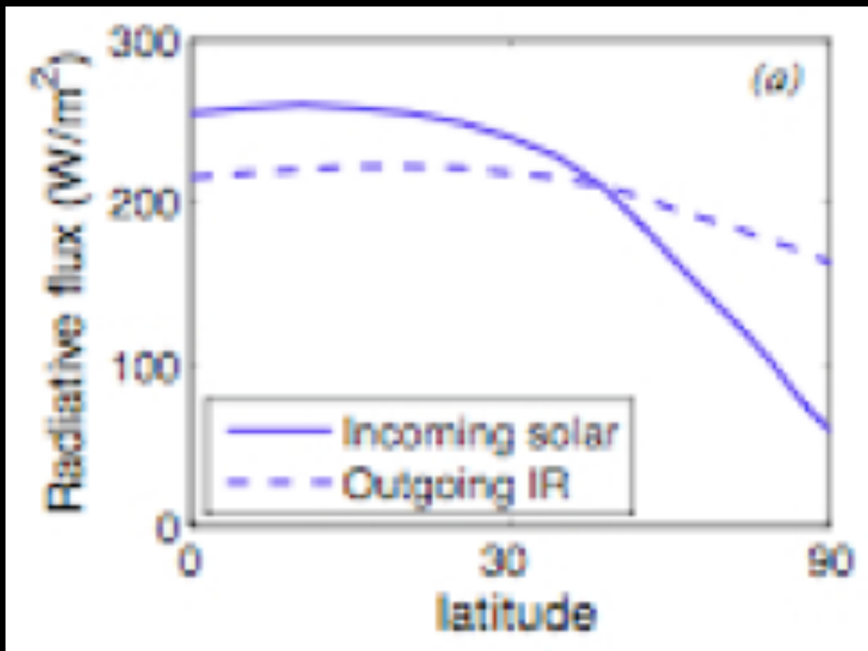
After Table 9.1, Bennet, Shostak, Jakosky, 2005

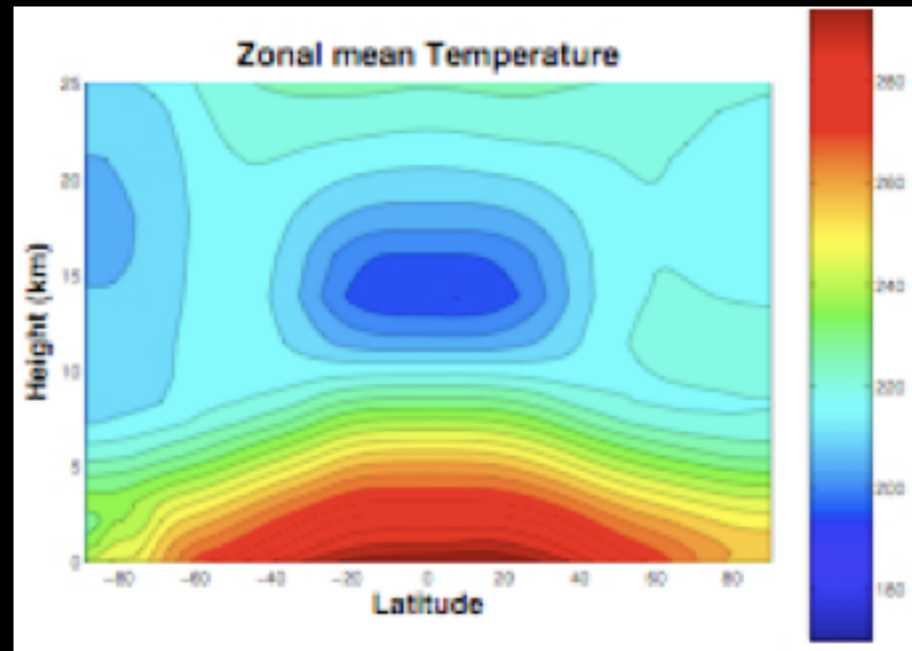
Greenhouse effect

MARS-Mariner 9 / IRIS (1973)



Dynamics





➢Incoming (SW) and outgoing (LW) radiation is NOT homogeneous over the planet

➢The gradient of the difference between radiative equilibrium temperature and effective emitted temperature drives the flow, BUT the flow changes both

➢Most of the transport is not direct: eddies and waves do most of the work

Equations of fluid-dynamics

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v} + w\frac{\partial \mathbf{v}}{\partial z} = -\frac{1}{\rho}\nabla p - f\hat{\mathbf{k}}\times\mathbf{v} + F_{\mathrm{v}} + D_{\mathrm{v}}$$

$$\frac{\partial p}{\partial z} = -\rho g$$

$$\frac{\partial \rho}{\partial t} + \mathbf{v}\cdot\nabla\rho + w\frac{\partial \rho}{\partial z} = -\rho\left(\nabla\cdot\mathbf{v} + \frac{\partial w}{\partial z}\right)$$

$$\frac{\partial \theta}{\partial t} + \mathbf{v}\cdot\nabla\theta + w\frac{\partial \theta}{\partial z} = F_\theta + D_\theta$$

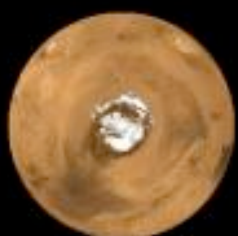
$$p = \rho R T$$

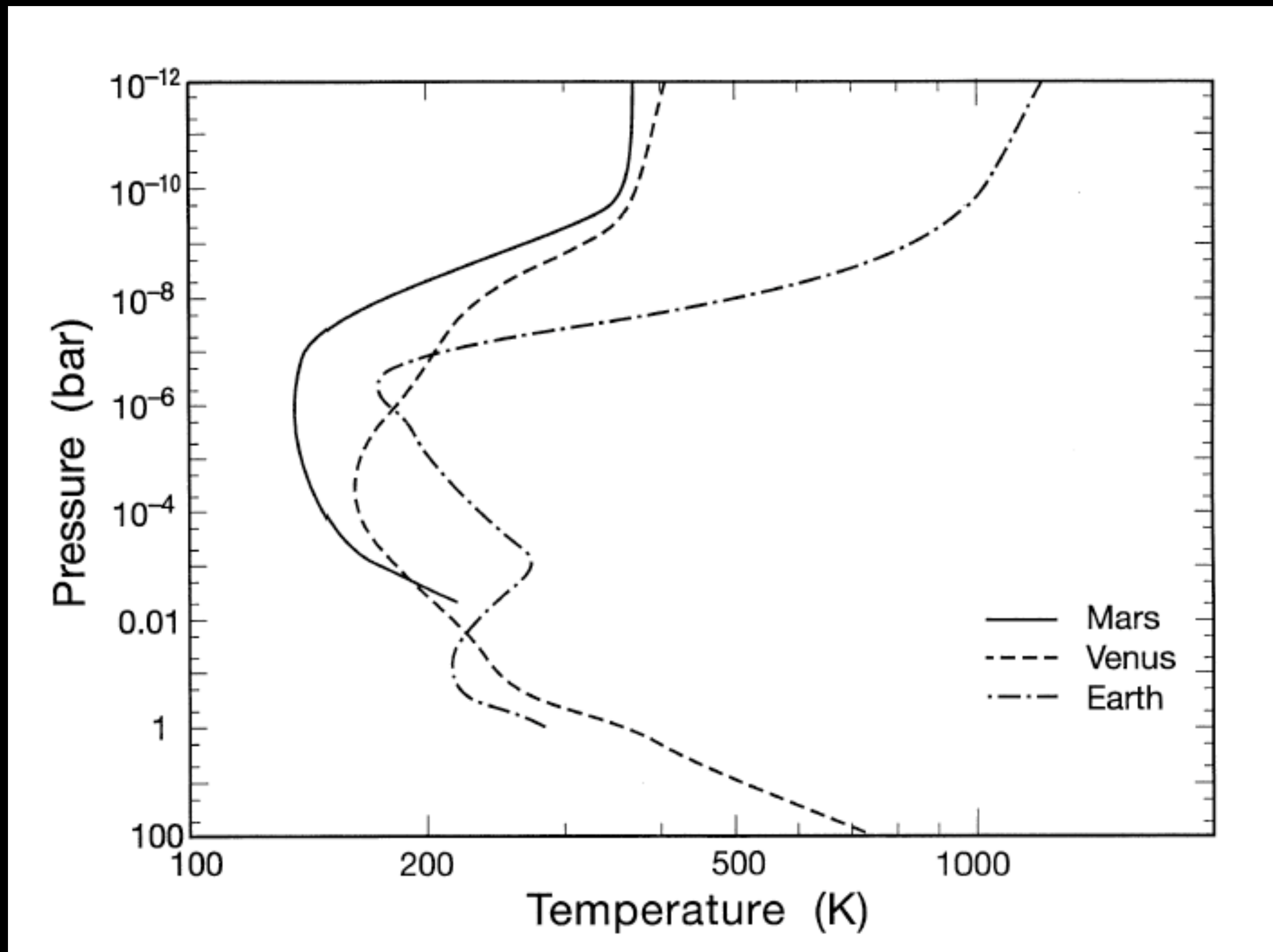
- $\mathbf{v}$ = lateral winds
- w = vertical wind
- p = pressure
- ρ = density
- F = sources
- D = sinks
- f = Coriolis param.
- g = gravity
- θ = potential temp.
- T = temperature
- R = gas constant

➢ Currently equations only approximately solved:

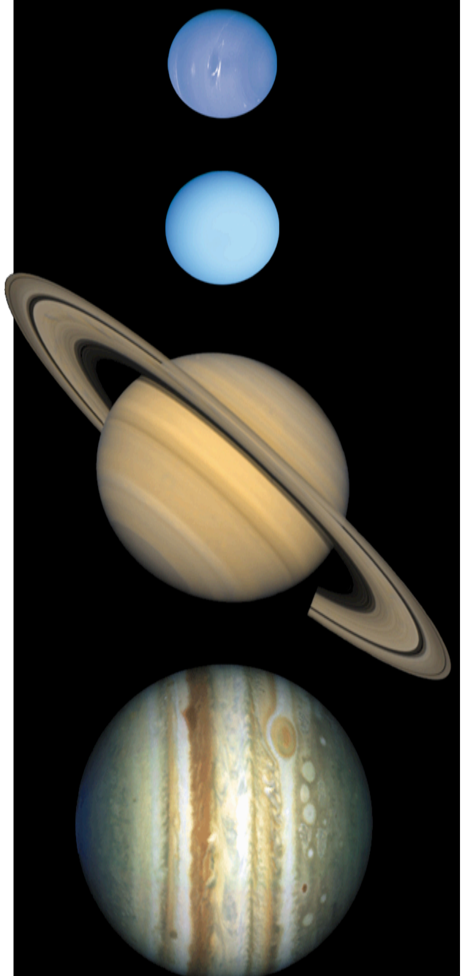
➢ Use them to gain physical insights and study mechanisms, and not make hard predictions

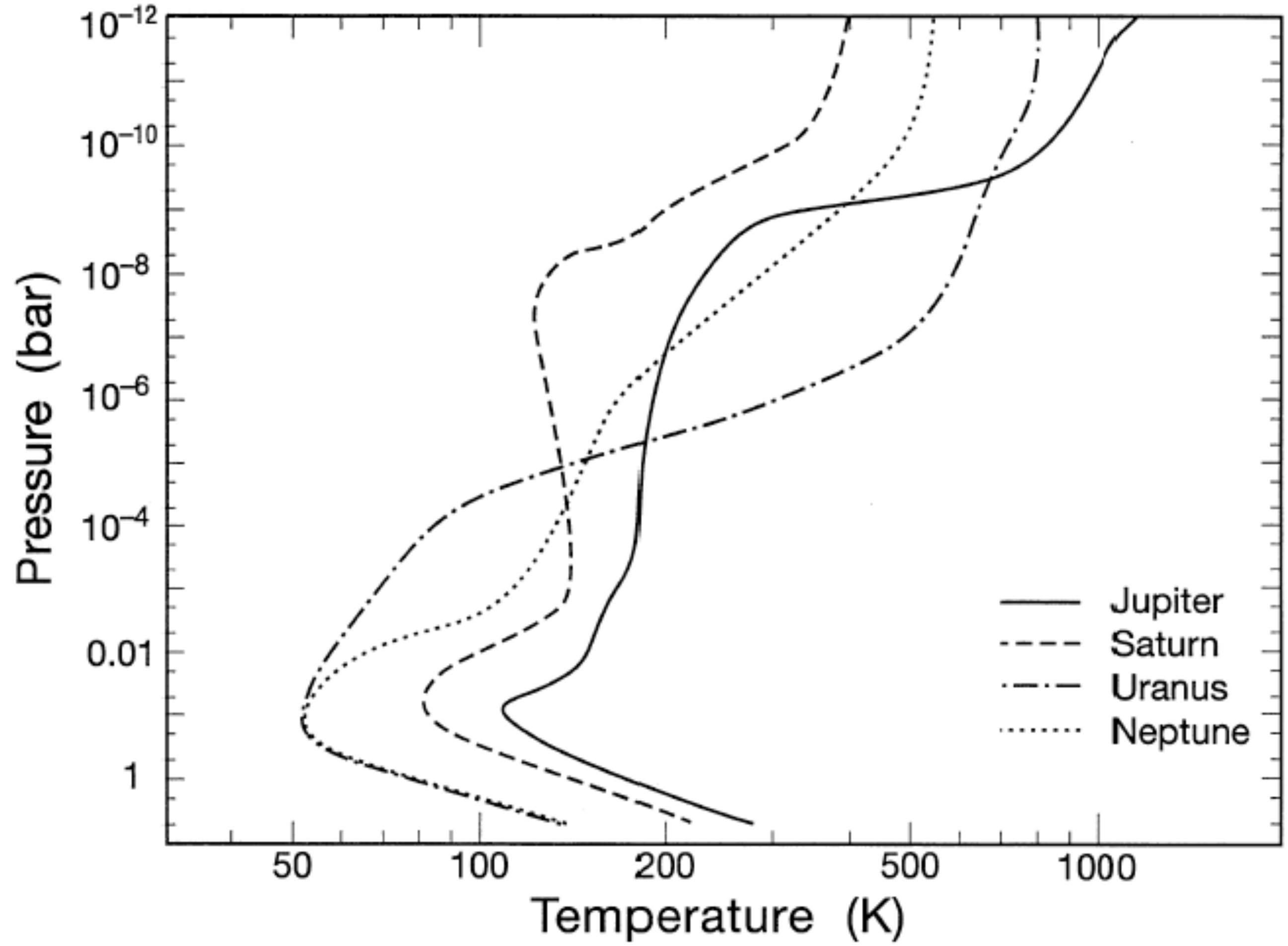
T-P for terrestrial planets in our Solar System



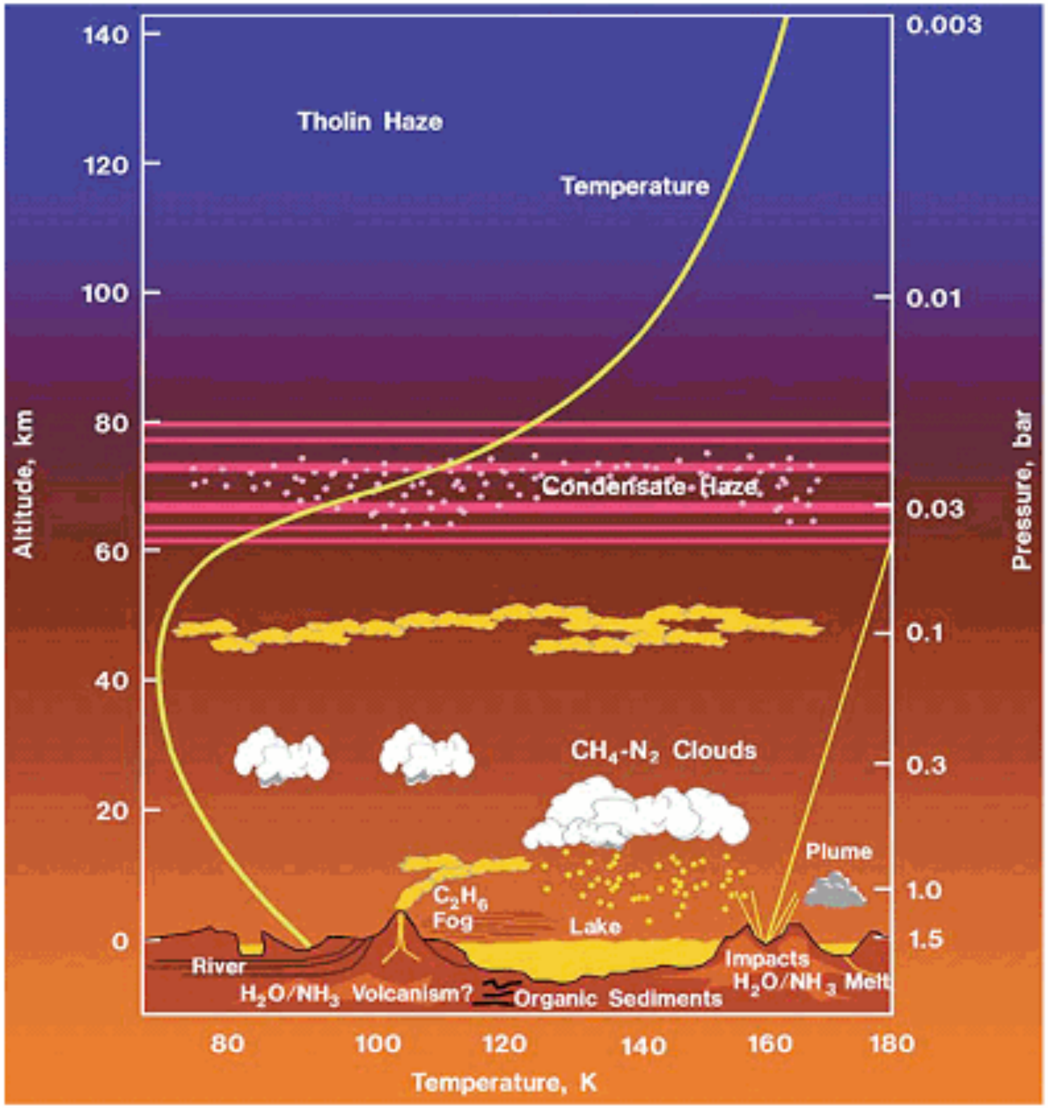


T-P for Giant planets in our Solar System





Titan: Photochemical hazes



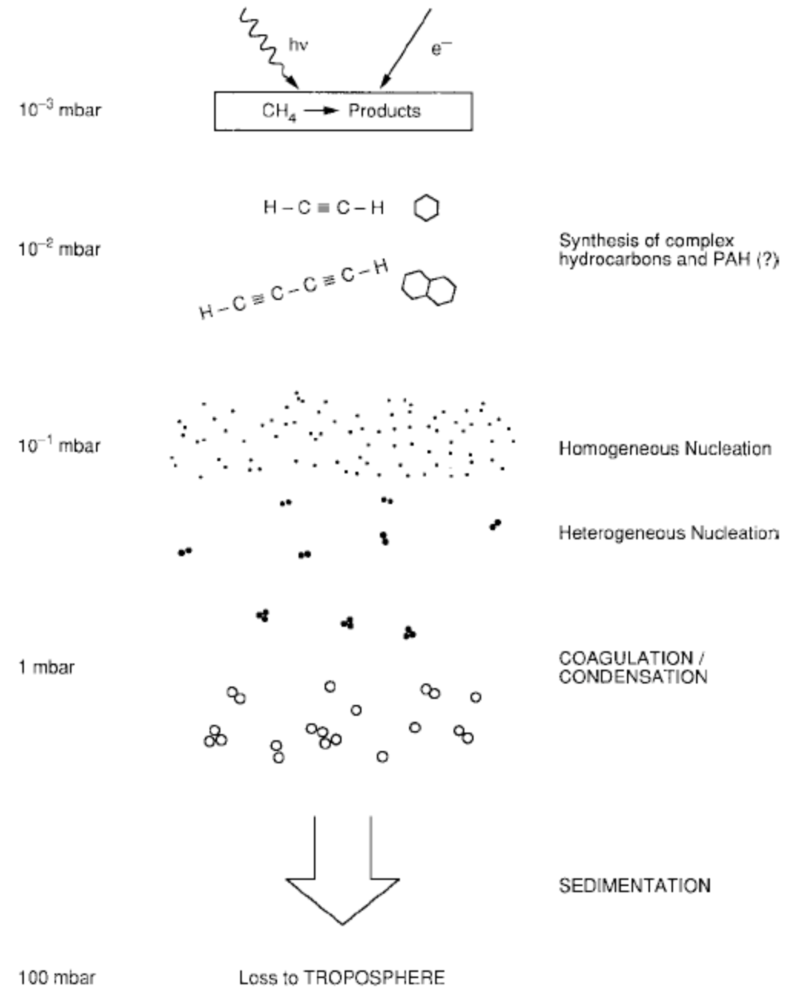


FIG. 1. Schematic diagram of physical processes included in the coupled chemical–aerosol microphysical model.

Upper Atmosphere

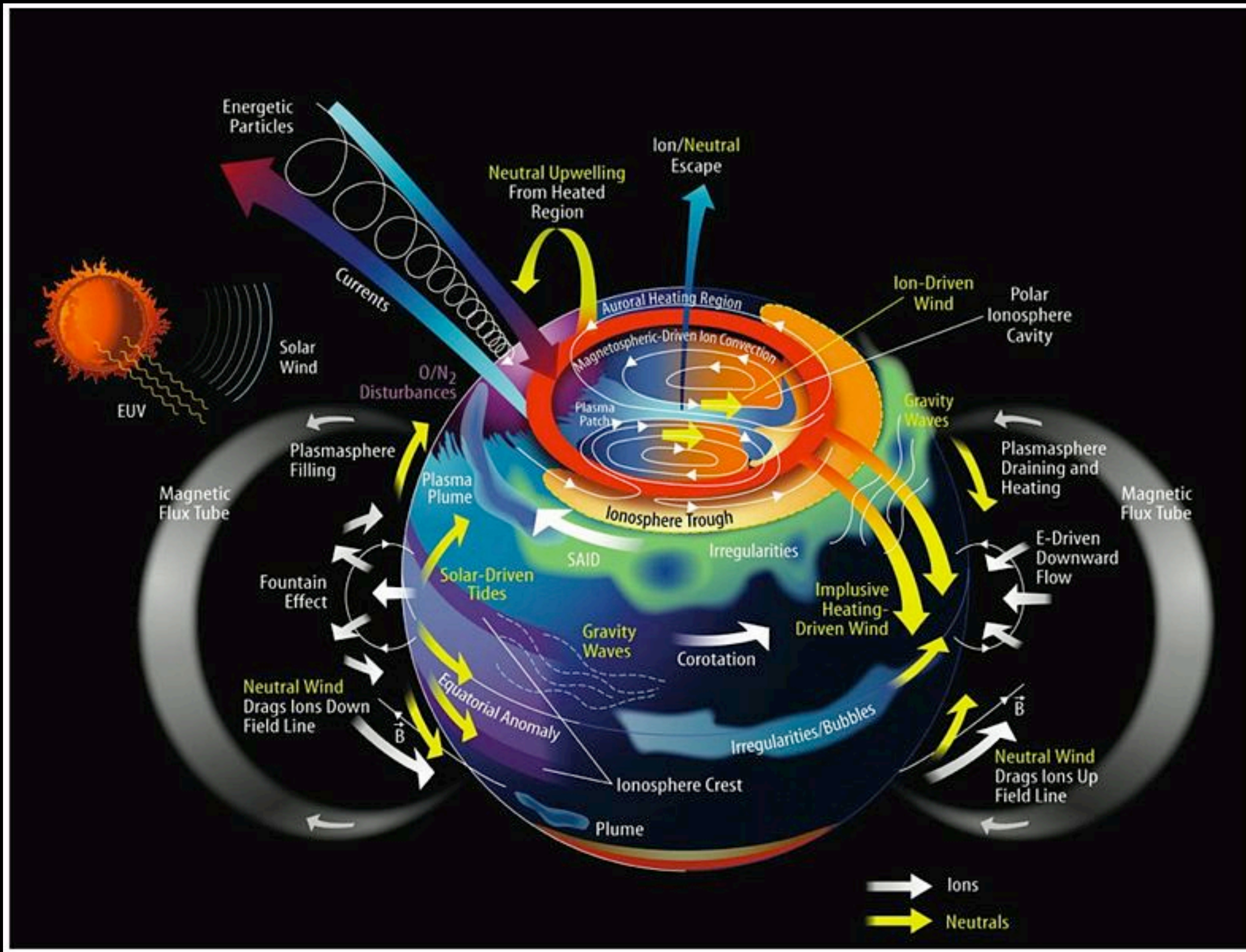
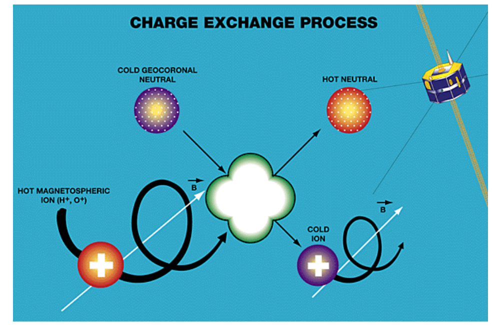
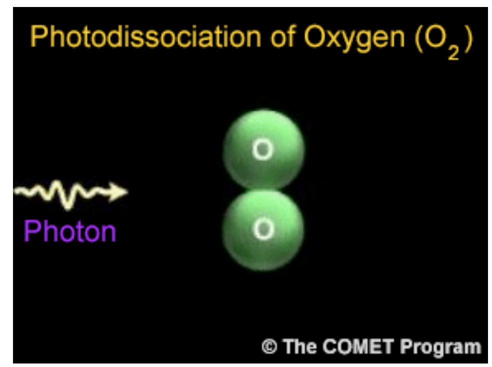


TABLE 1. Nonthermal Processes Leading to Escape*

PROCESS	EXAMPLES	PRODUCT†
1. Charge exchange	$H + H^{+*} \rightarrow H^+ + H^*$	N
	$O + H^{+*} \rightarrow O^+ + H^*$	N
2. Dissociative recombination	$O_2{}^+ + e \rightarrow O^* + O^*$	N
	$OH^+ + e \rightarrow O + H^*$	N
3. Impact dissociation	$N_2 + e^* \rightarrow N^* + N^*$	N
Photodissociation	$O_2 + h\nu \rightarrow O^* + O^*$	N
4. Ion-neutral reaction	$O^* + H_2 \rightarrow OH^+ + H^*$	N
5. Sputtering or Knock-on	$O + O^{+*} \rightarrow O^* + O^{+*}$	N
	$O^* + H \rightarrow O^* + H^*$	N
6. Solar-wind pickup	$O + h\nu \rightarrow O^+ + e$	I
	O^+ picked up	I
7. Ion escape	H^{+*} escapes	I
8. Electric field	$X^+ + eV \rightarrow X^{+*}$	I





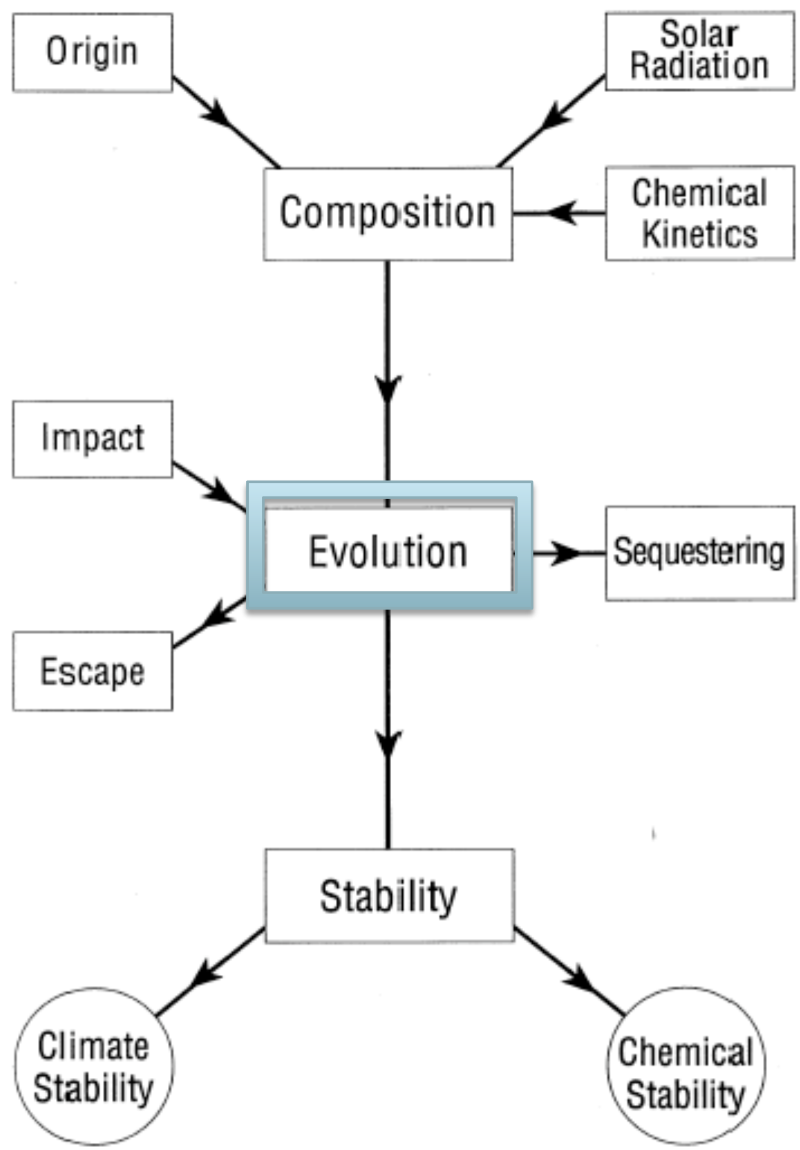

Origin
Solar Radiation
Composition
Chemical Kinetics
Impact
Evolution
Sequestering
Escape
Stability
Climate Stability
Chemical Stability

Figure 1.1

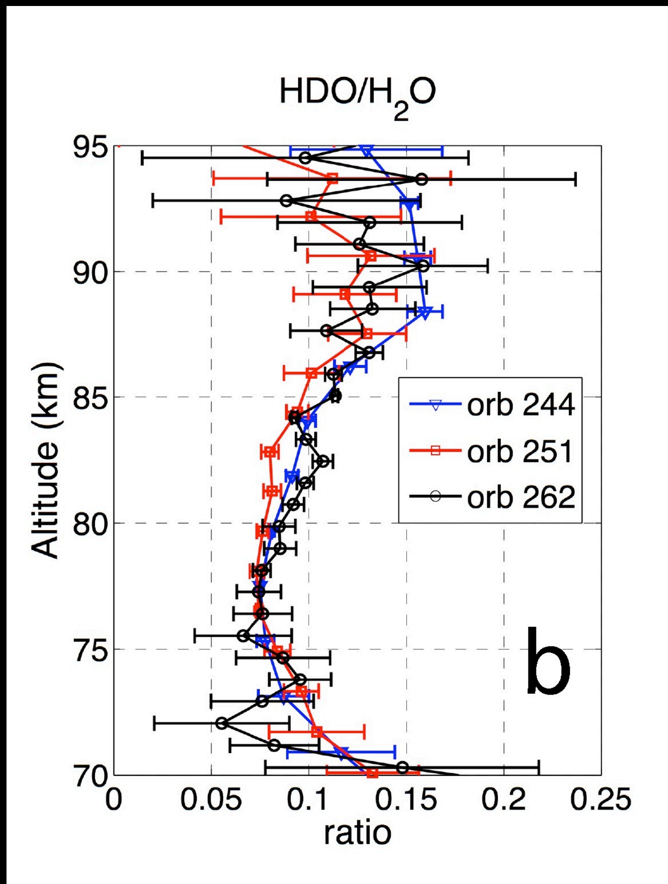
Mars: Gone with the (Solar) Wind

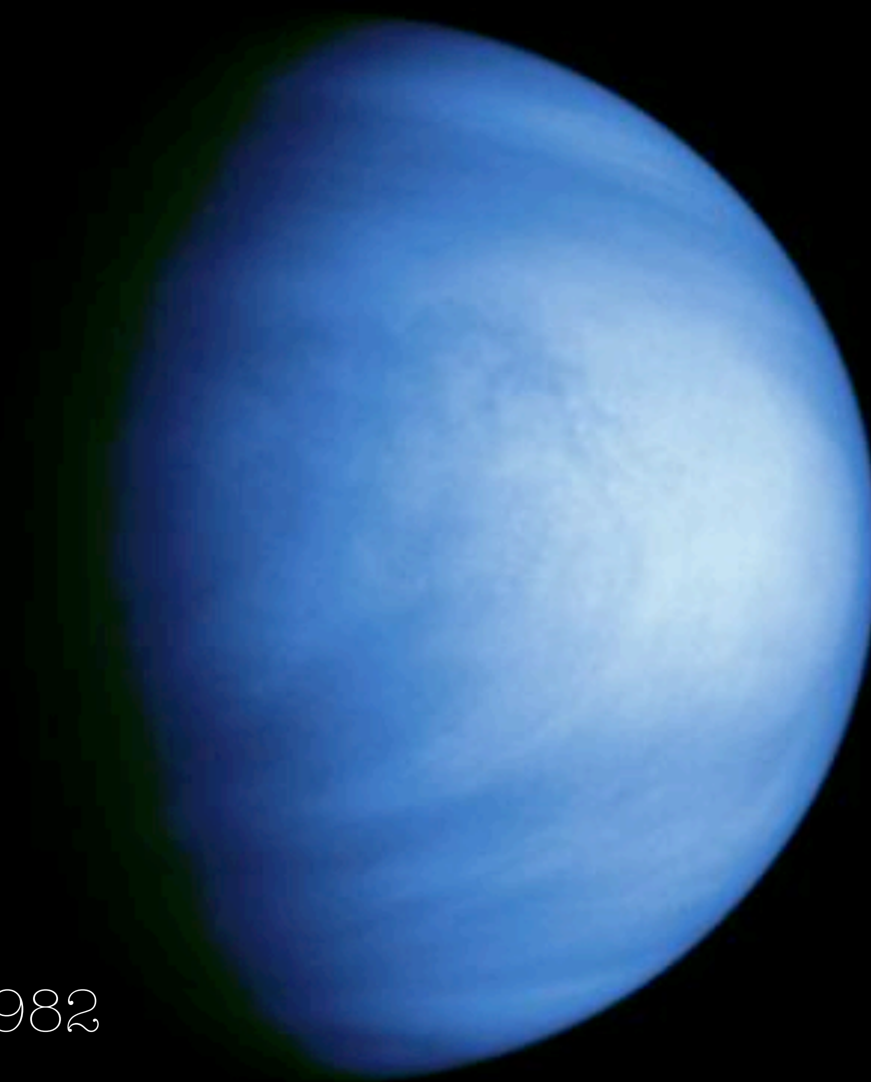
$$\left(\frac{D}{H}\right)_{Mars} = 5 \times \left(\frac{D}{H}\right)_{Earth}$$

$$\frac{D}{H}(t) = \frac{D}{H}(0)\left[\frac{H(0)}{H(t)}\right]^{1-f}$$

Kass and Yung Science 1995

Venus: Loss of Ocean and Sulfur

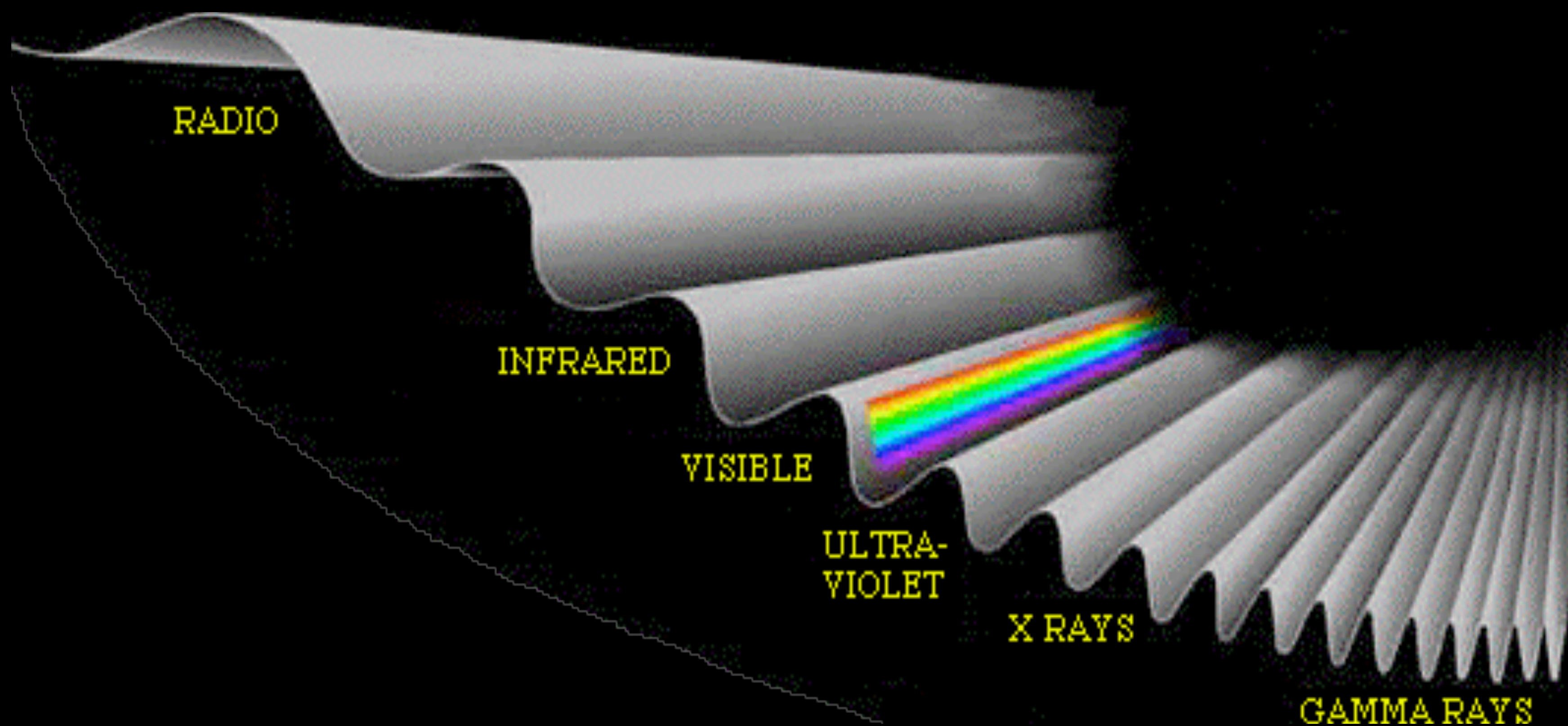


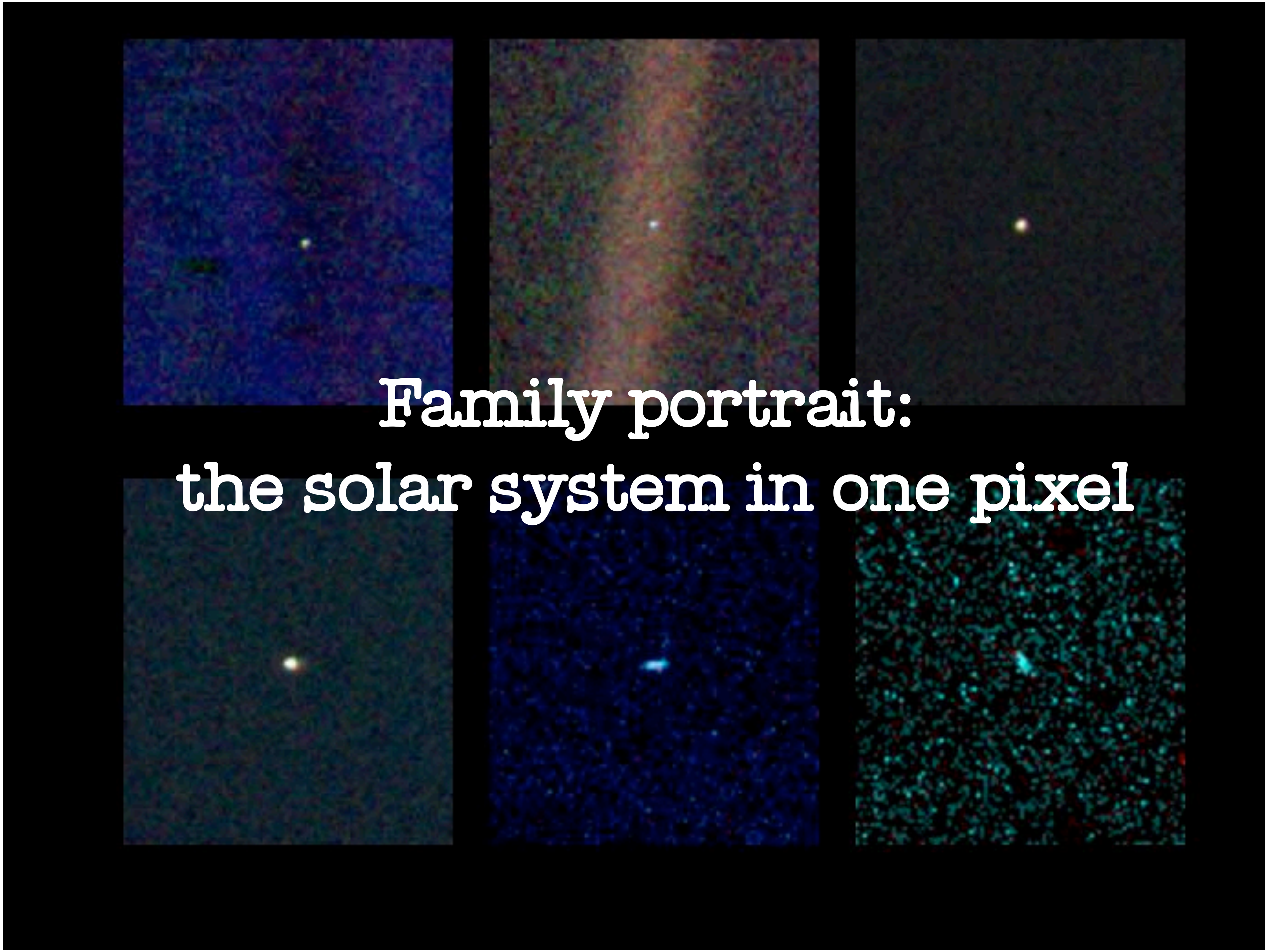


Yung and DeMore Icarus 1982

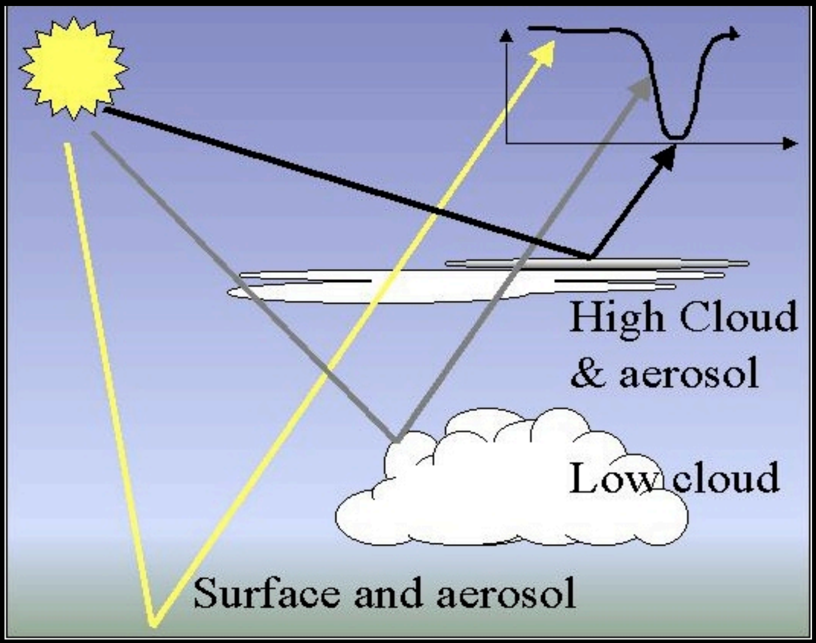
Yung et al. JGR 2008

Learning about distant worlds by analysing their light



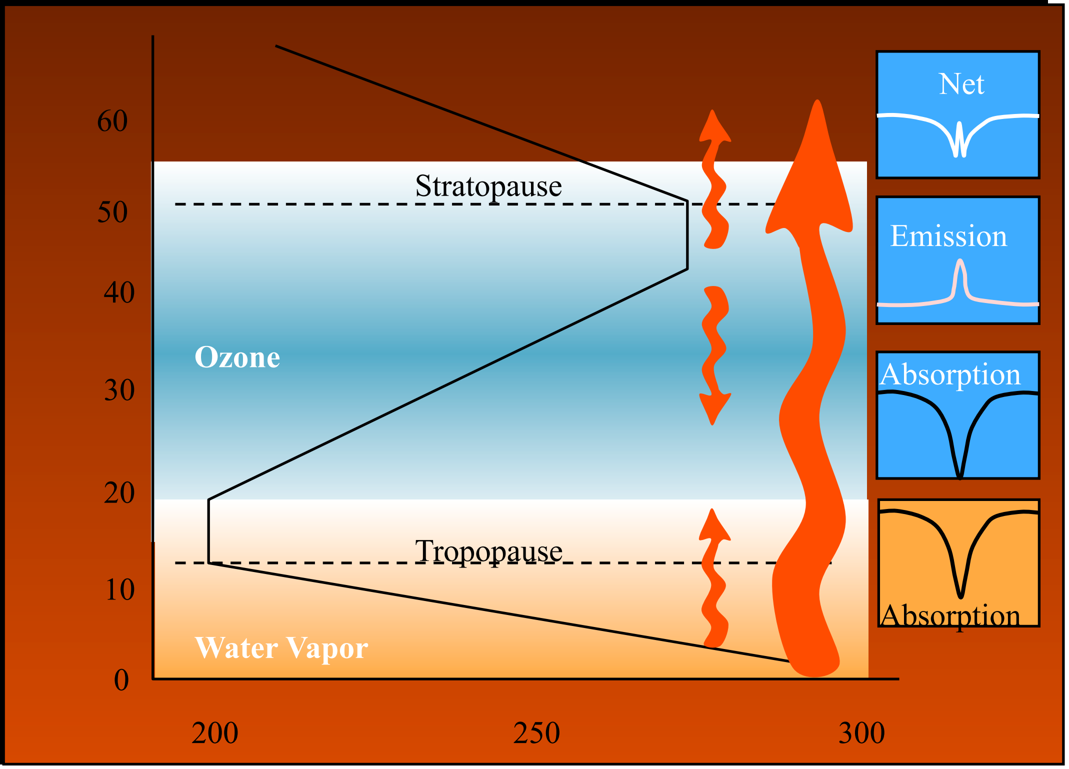

Family portrait:
the solar system in one pixel

Remote-Sensing

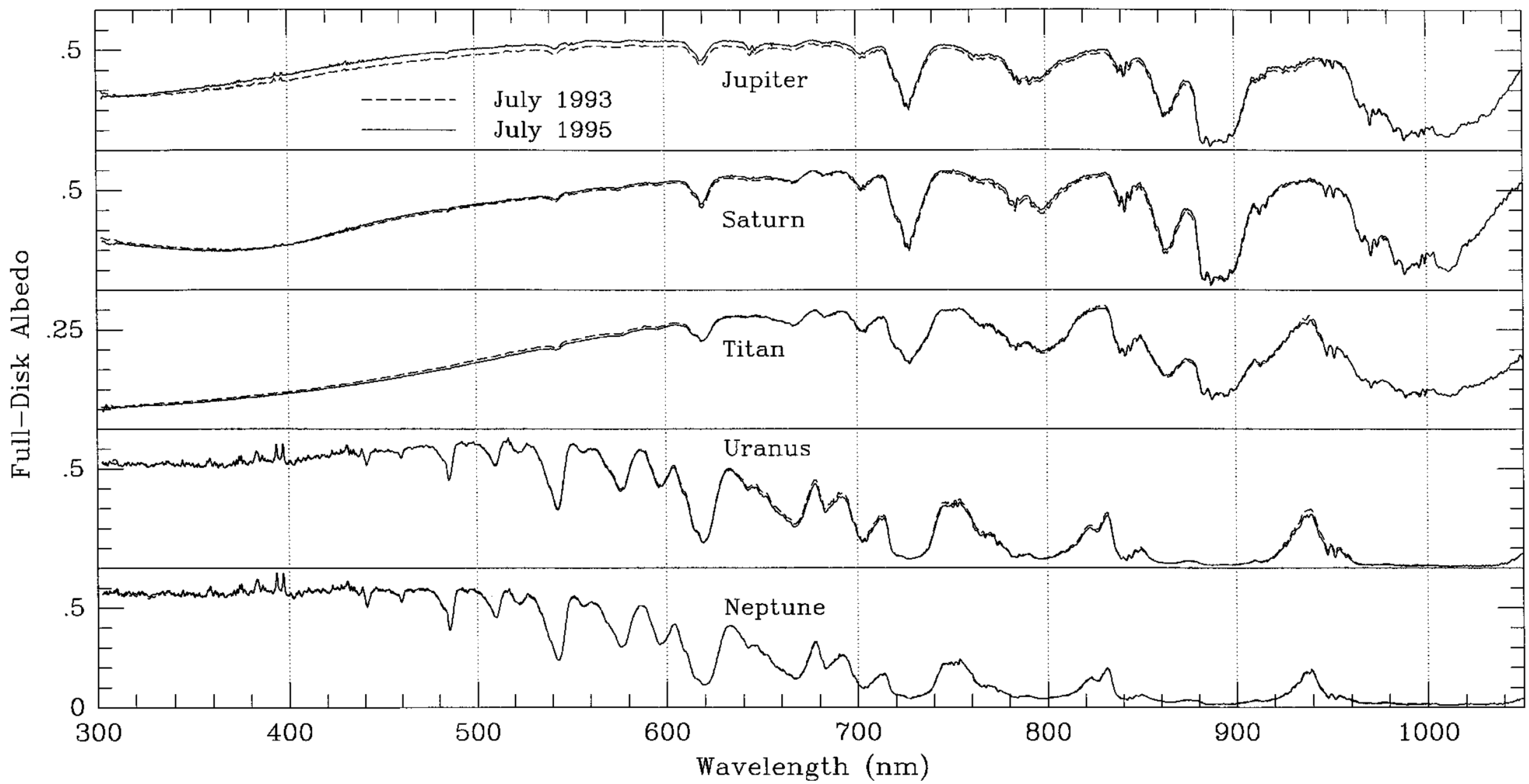


Multiple scattering of reflected photons: Rayleigh scattering/clouds/ surface types. Molecules with electronic transitions

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

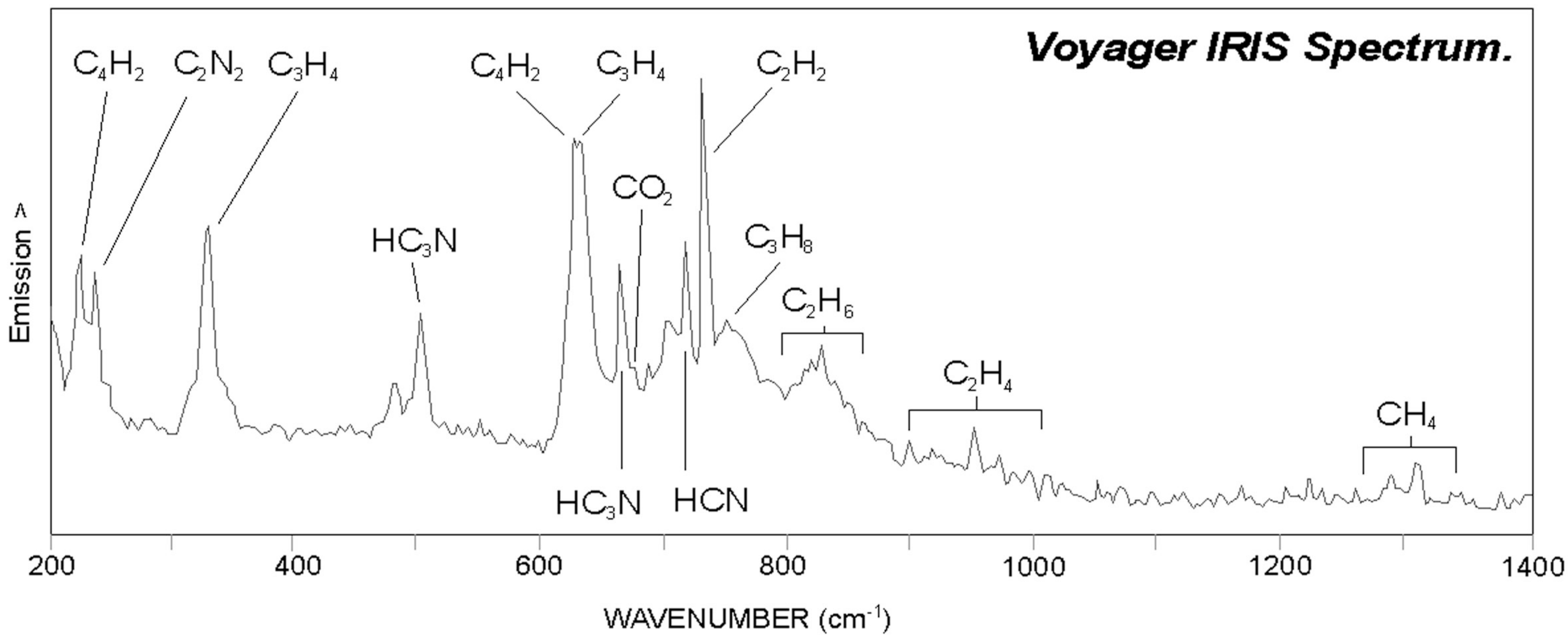


Planetary spectra in the VIS



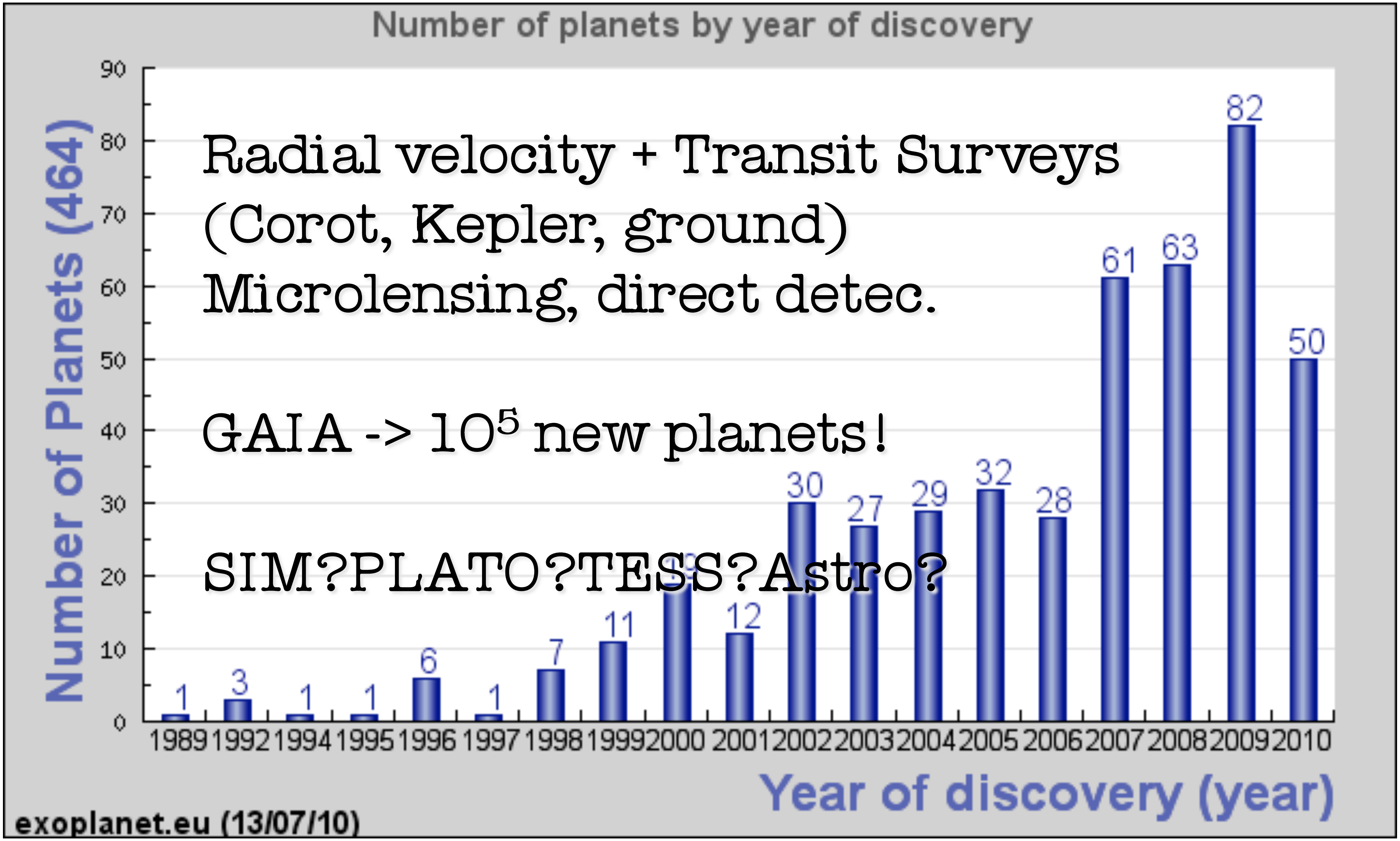
Karkoschka, Icarus, 1998

Titan

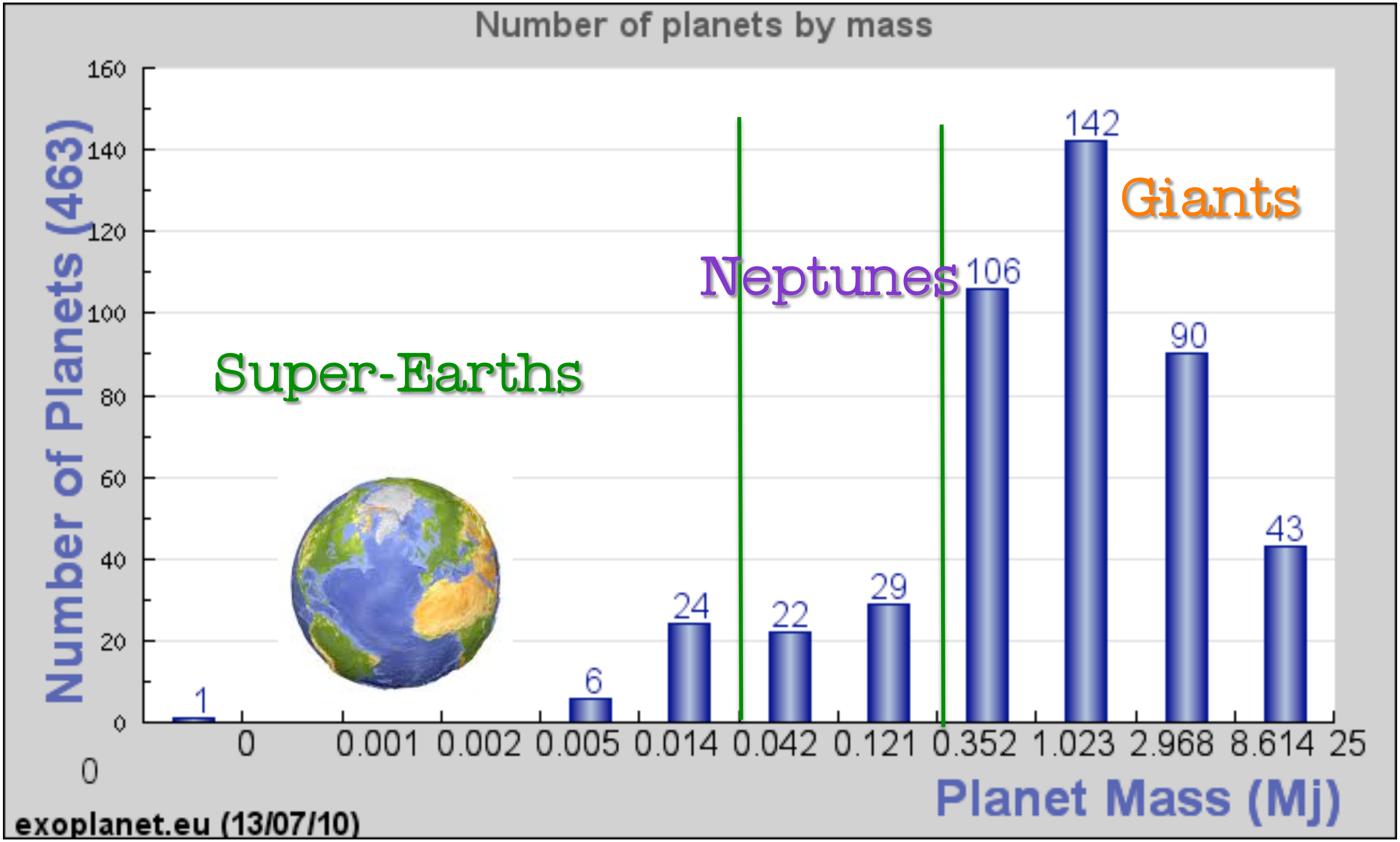


Samuelson *et al. (1983)*

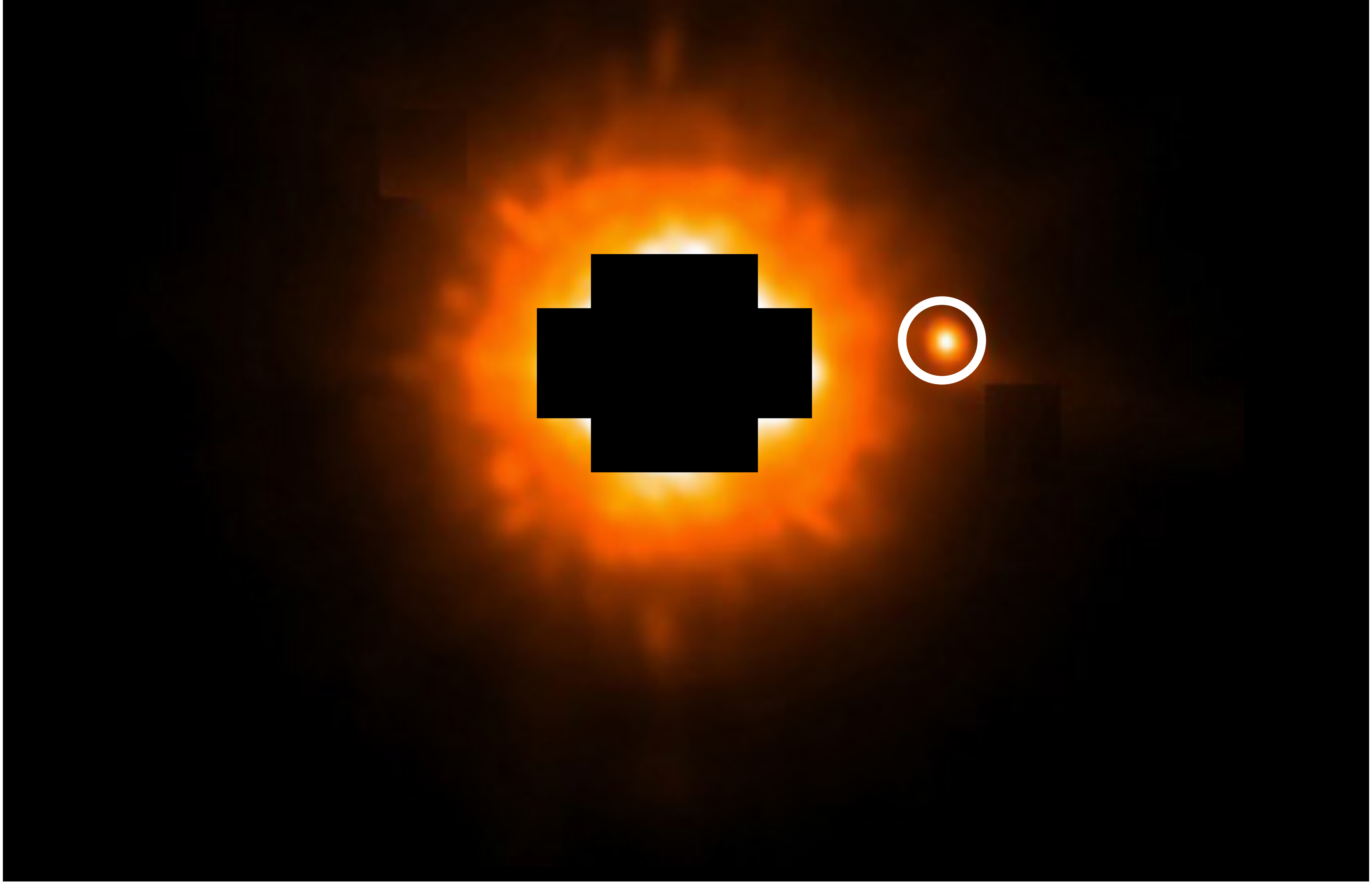
463 Exoplanets



463 Exoplanets

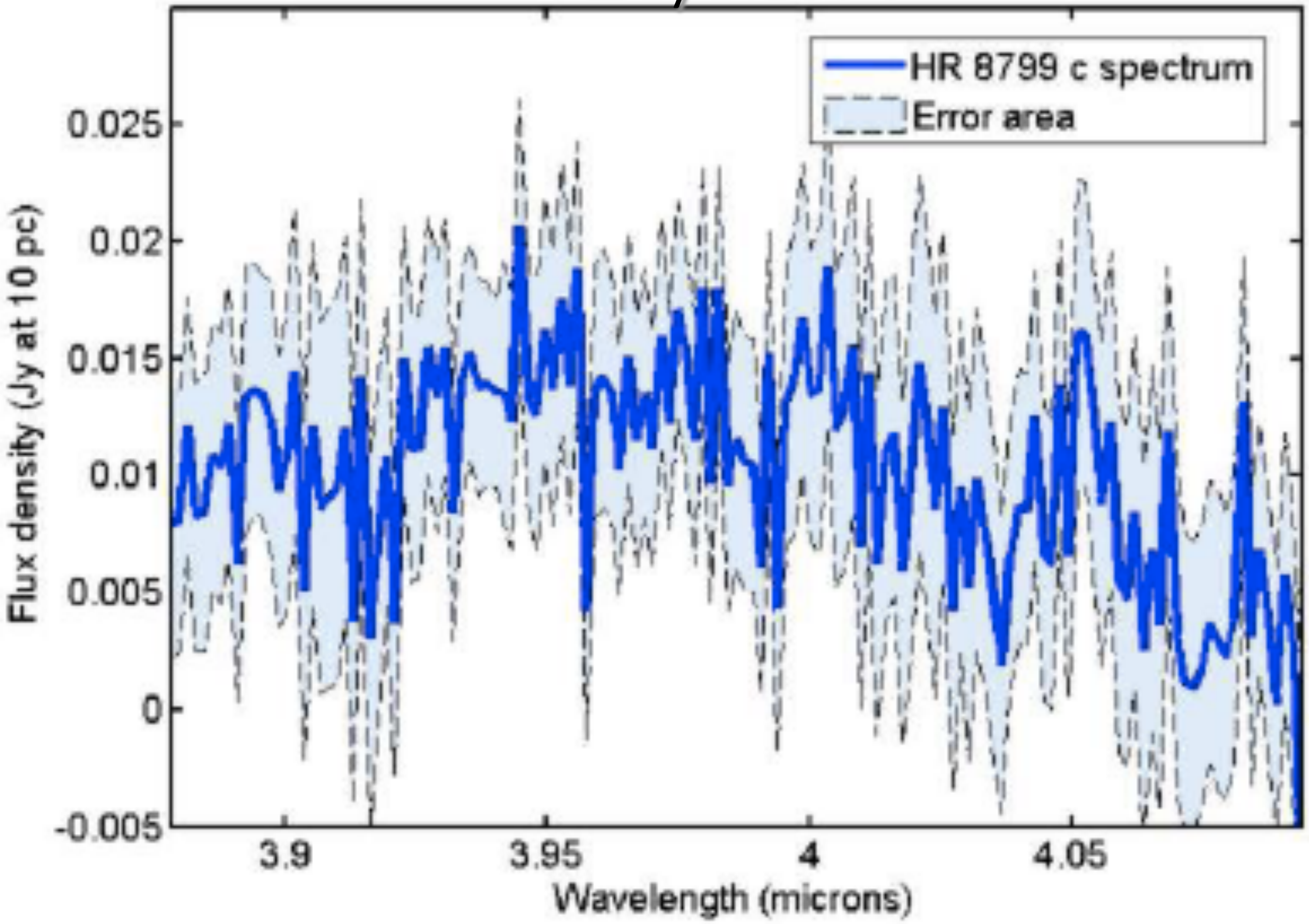


Direct detection



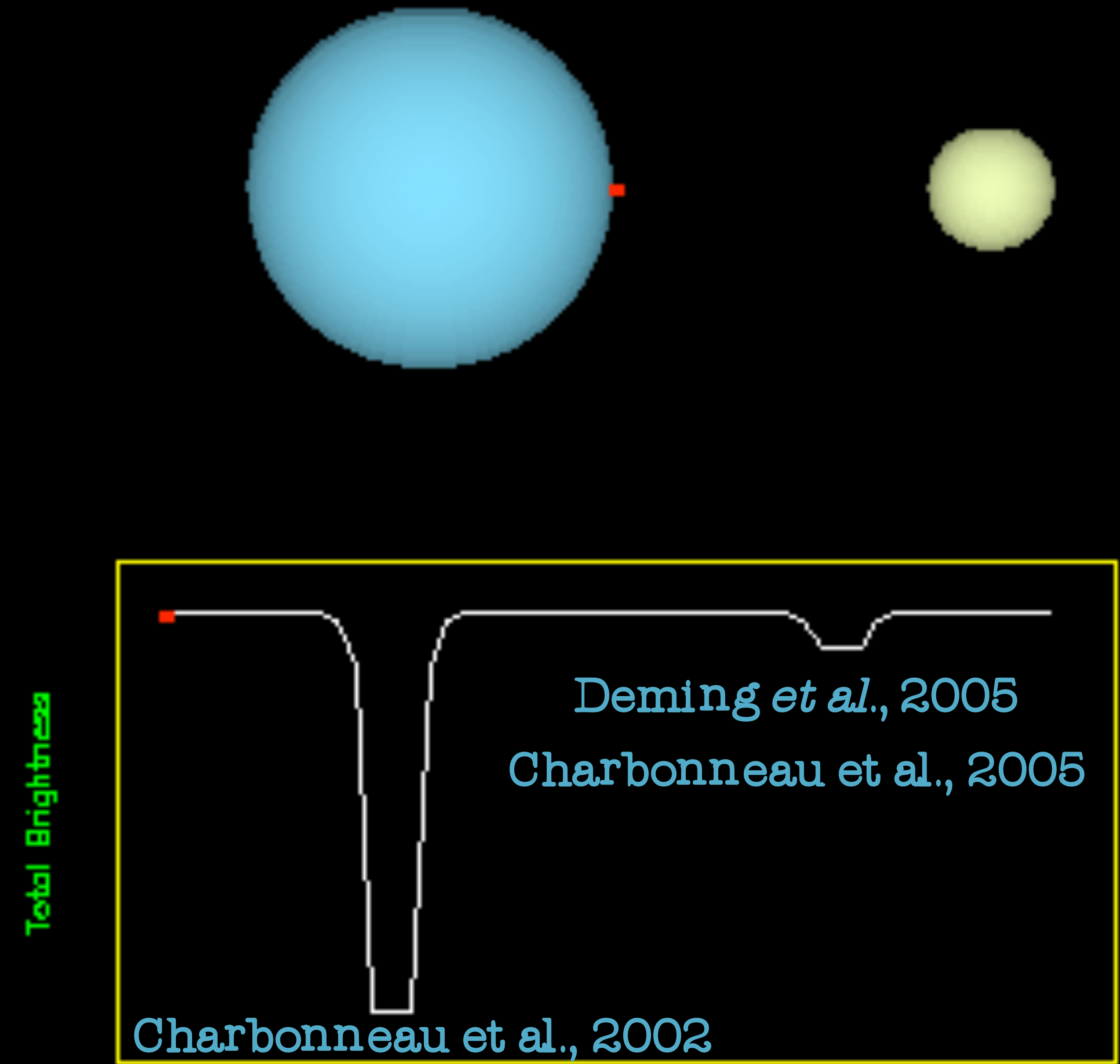
Spectrum of HR 8799 c*

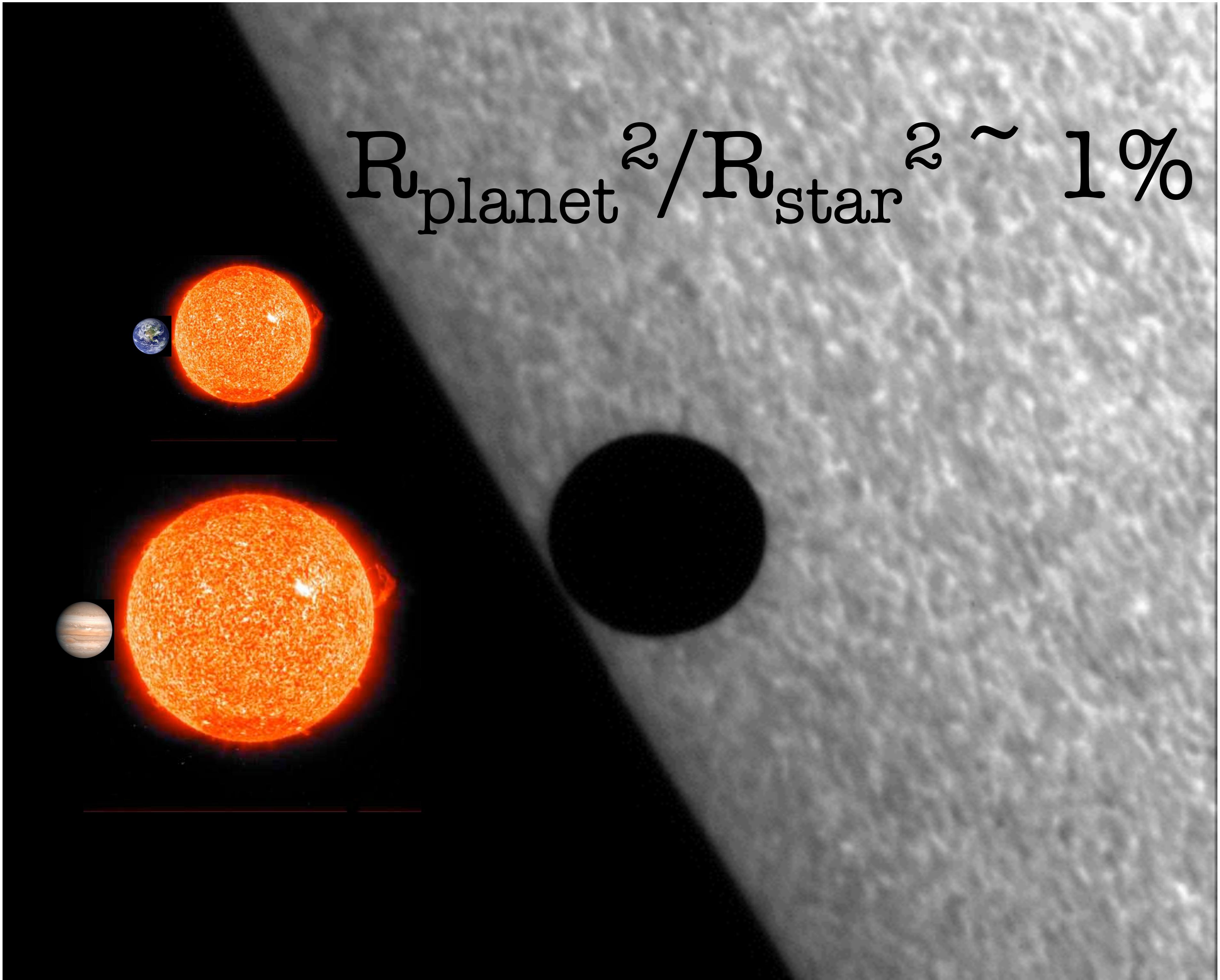
VLT/NACO

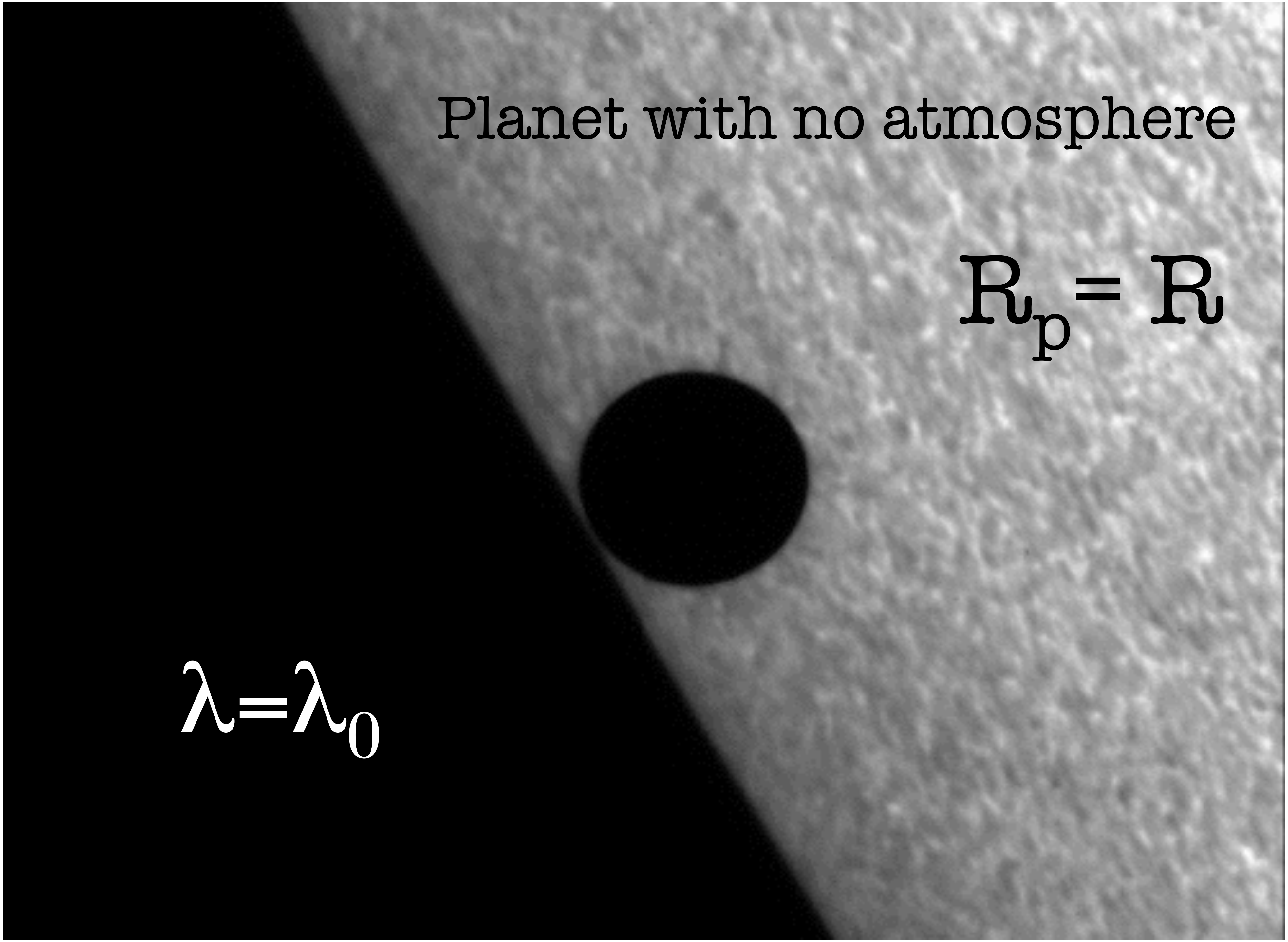


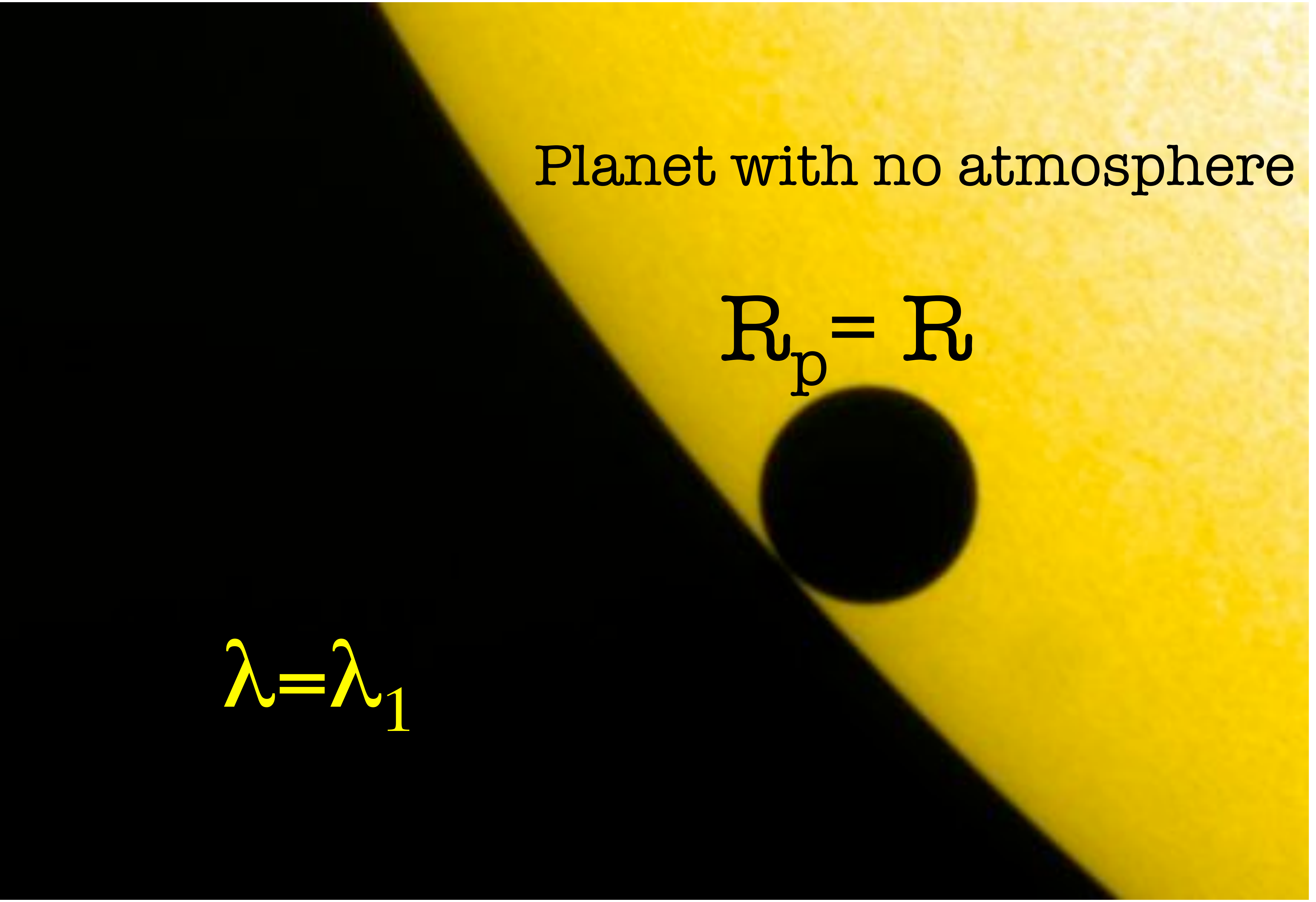
Janson *et al.*, 2010

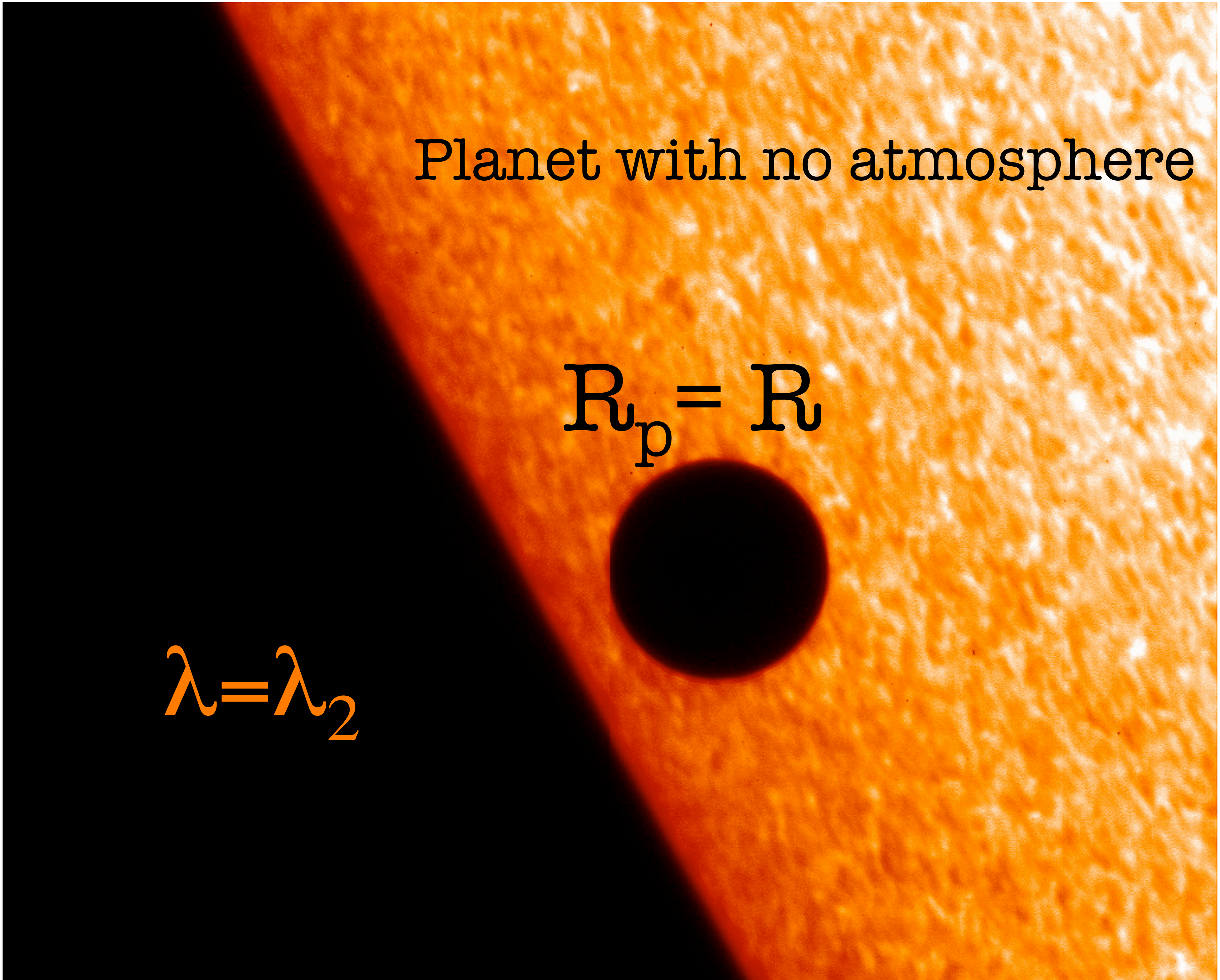
Transiting planets



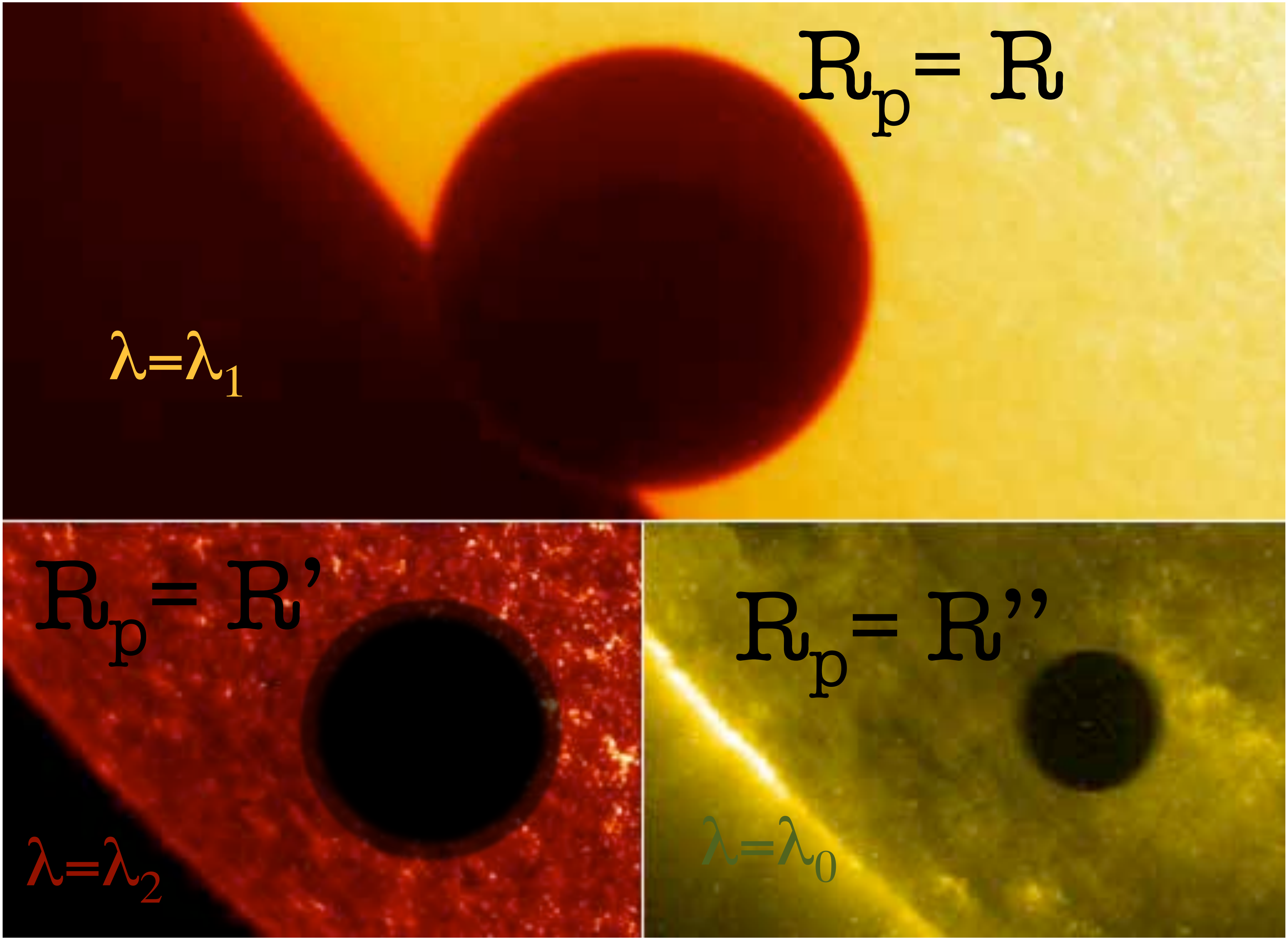

$R_{planet}^2/R_{star}^2 \sim 1\%$


Planet with no atmosphere
$R_p = R$
$\lambda=\lambda_0$


Planet with no atmosphere
$R_p = R$
$\lambda = \lambda_1$

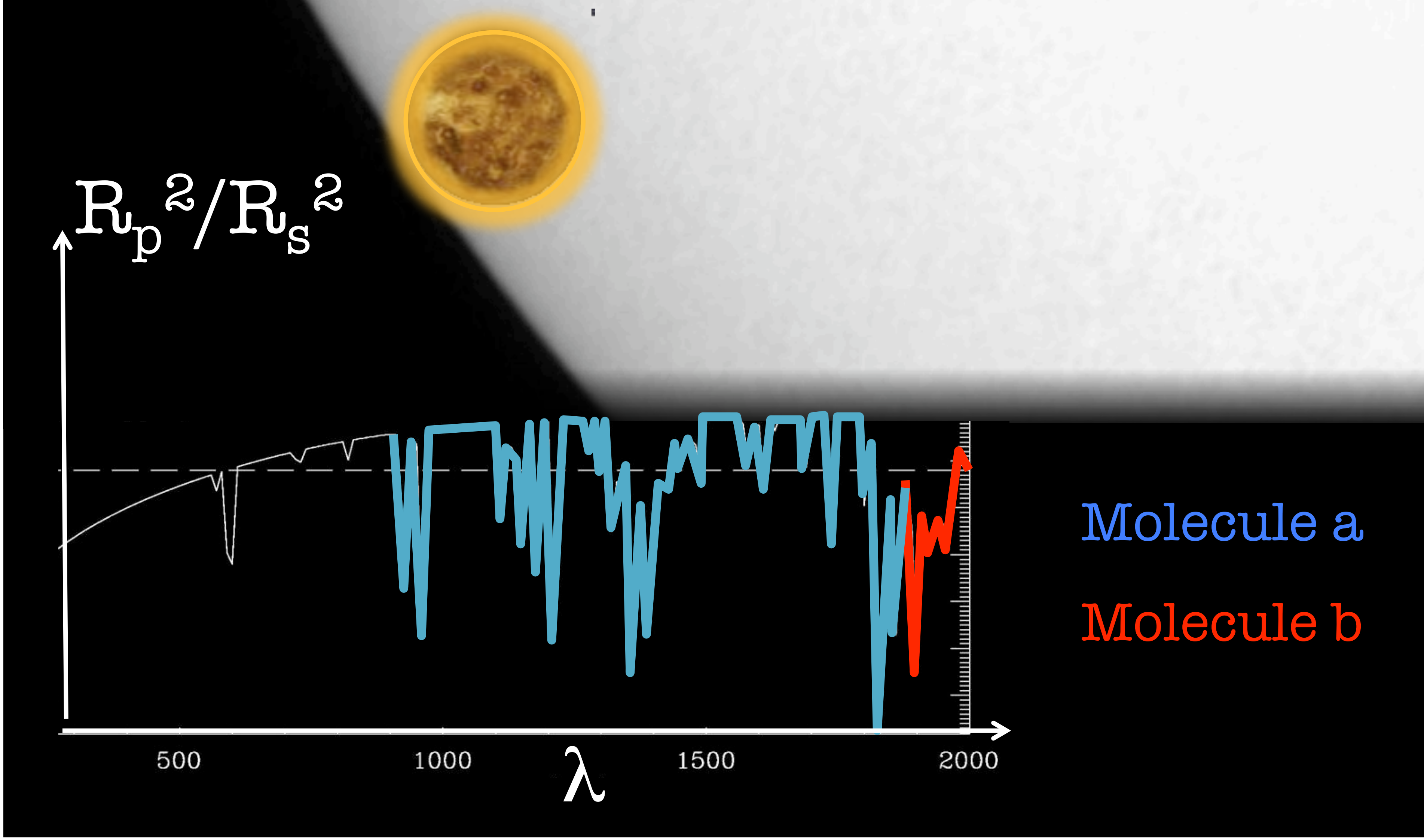


Planet with no atmosphere
R_p = R
λ=λ_2



$R_p = R$
$\lambda=\lambda_1$
$R_p = R'$
$\lambda=\lambda_2$
$R_p = R''$
$\lambda=\lambda_0$

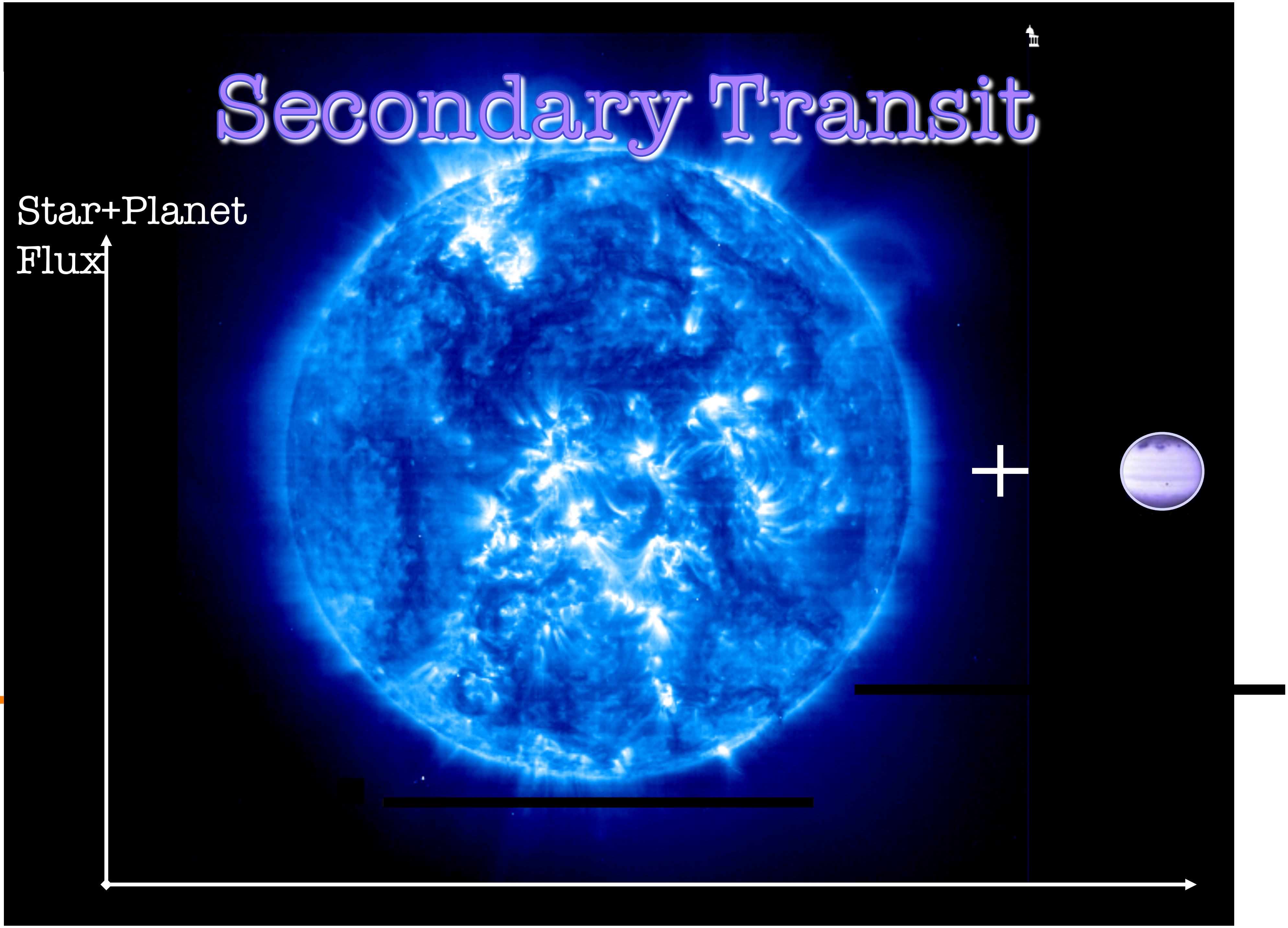
Spectral signature of a transiting planet



$H= kT /(M\,g)$

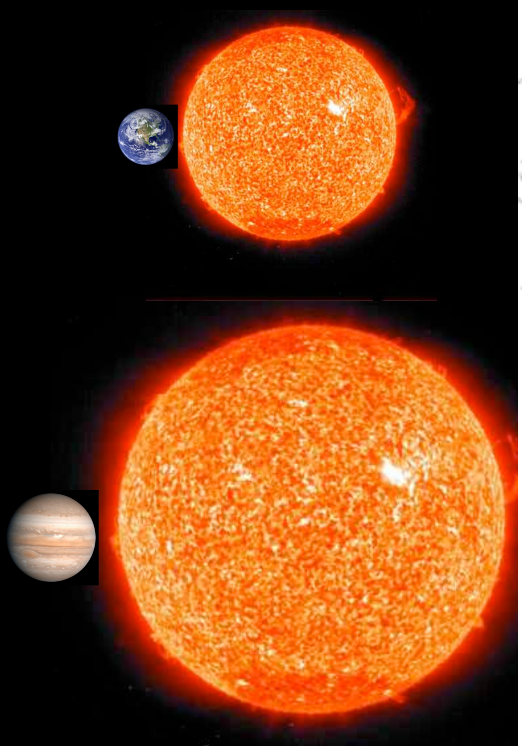
$H_{hot\text{-}Jup} \sim 500$ Km

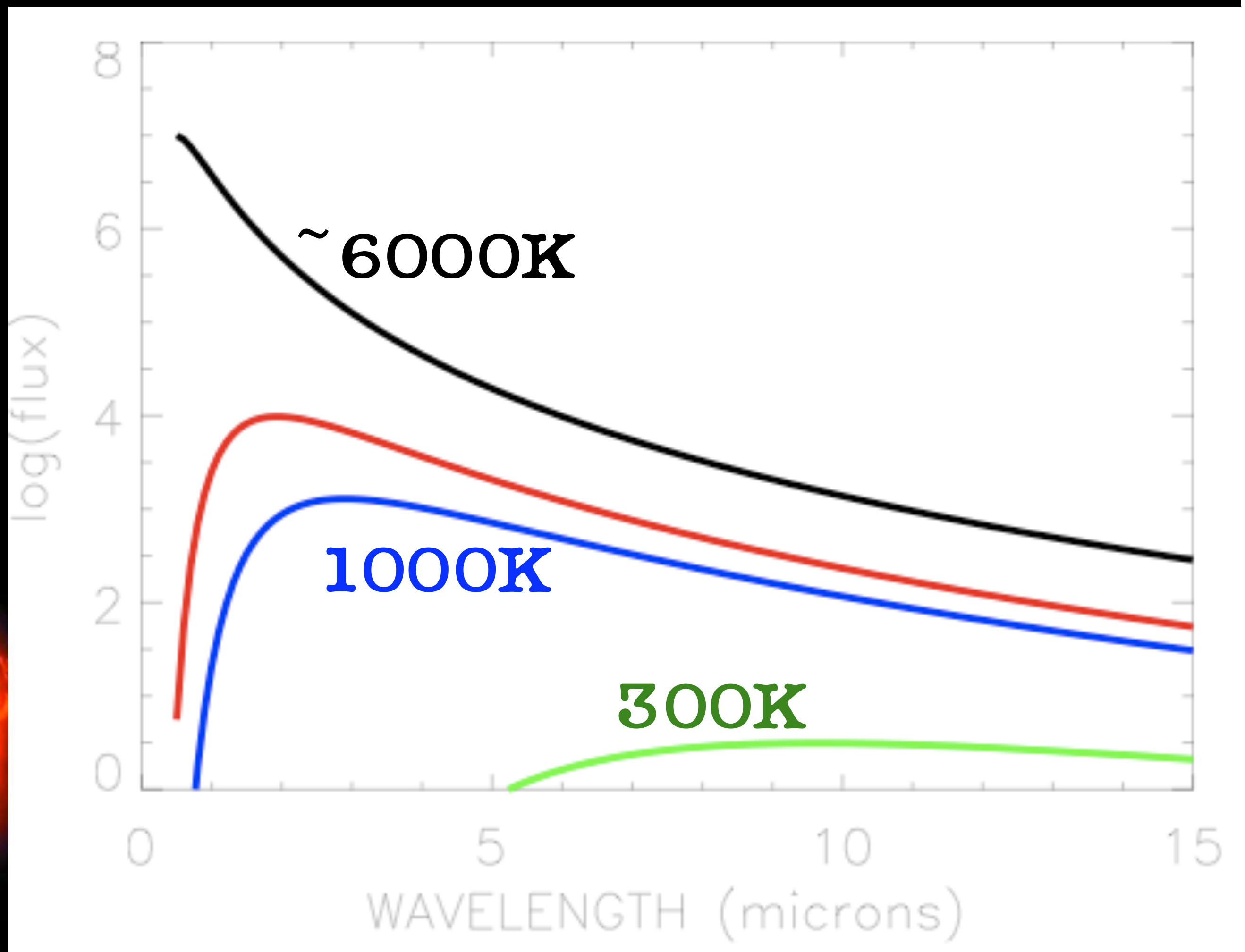
k = Boltzmann constant = 1.38×10^{-23} J·K^{-1}
T = mean planetary surface temperature in K
M = mean molecular mass of dry air (units kg)
g = acceleration due to gravity on planetary surface (m/s^2)


Secondary Transit
Star+Planet
Flux
+

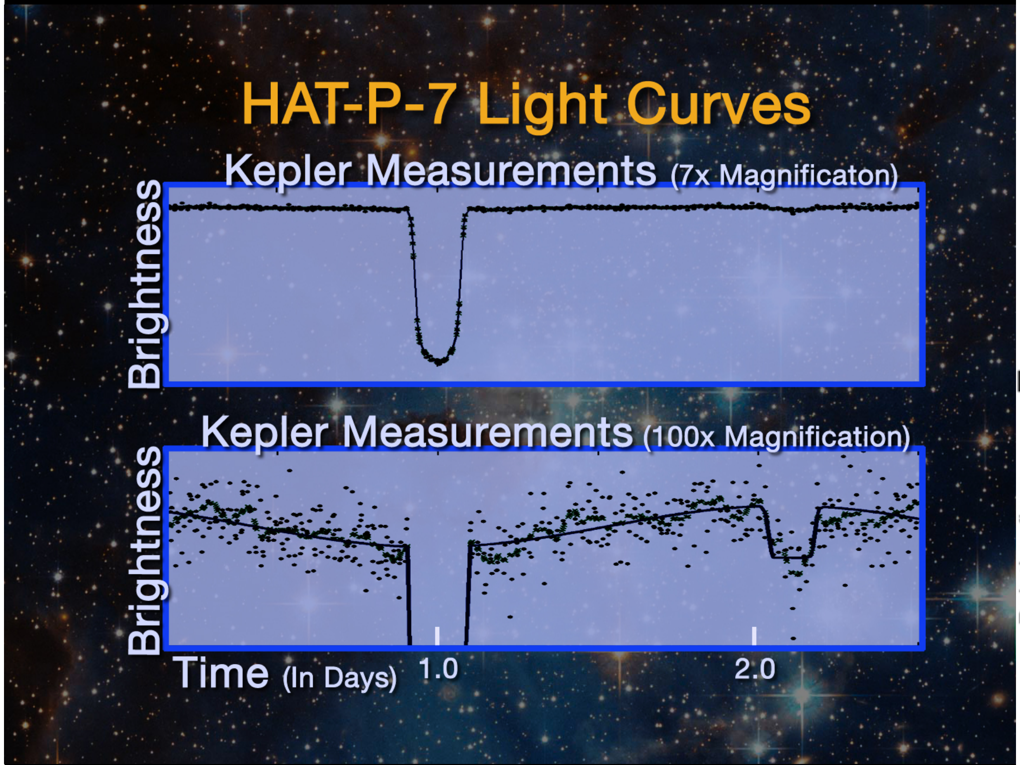
$(R_p/R_*)^2 F_p(\lambda)/F_*(\lambda)$ ~0.1%

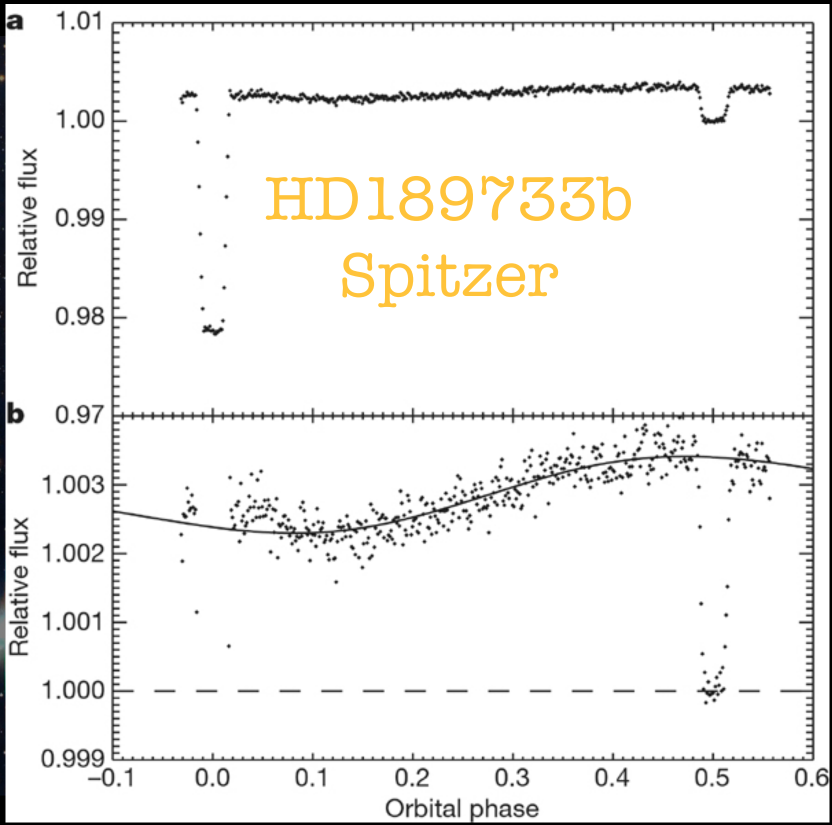
~1%





Light curve of a transiting exoplanet





Borucki et al., *Science*, 2009

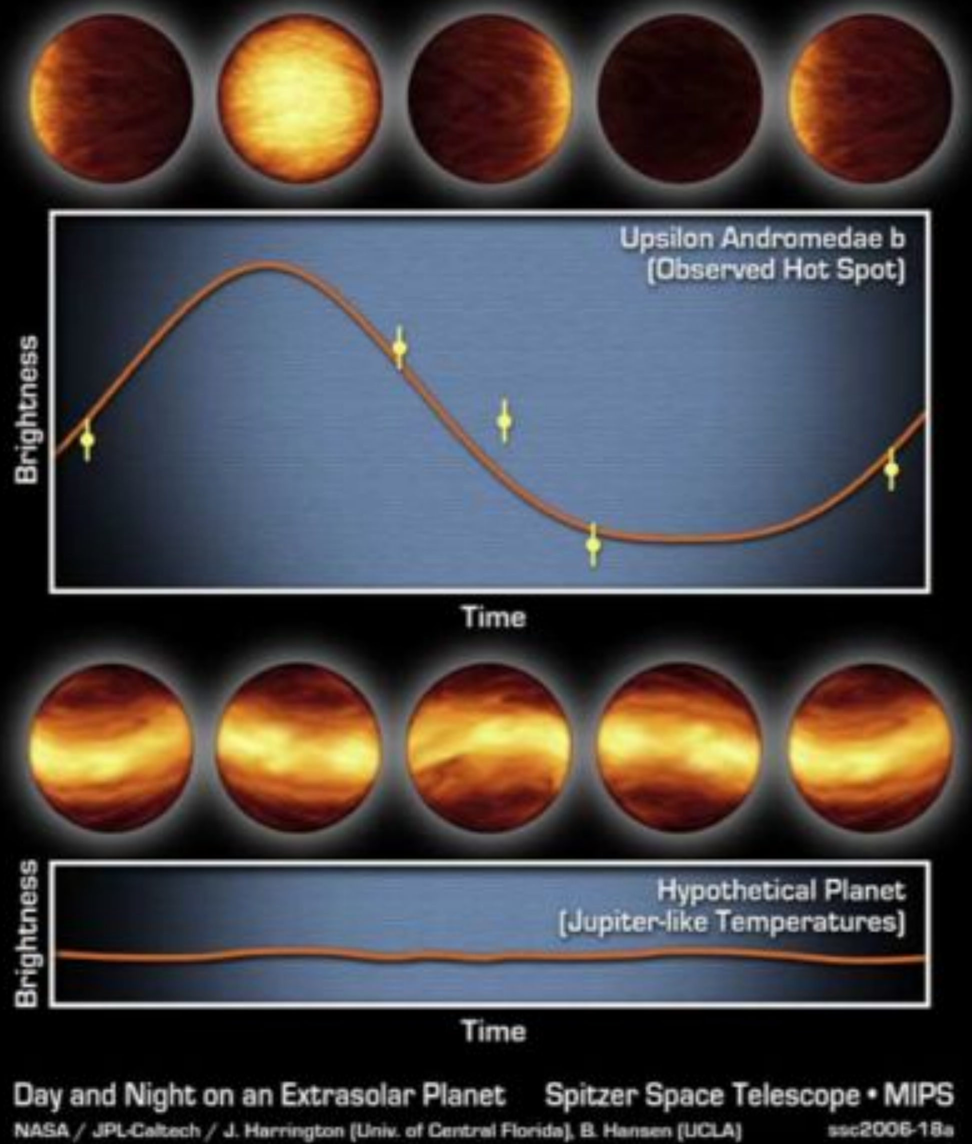
Knutson et al., *Nature*, 2007

Combined light star-planet

Light curves of a non-transtiting exoplanet

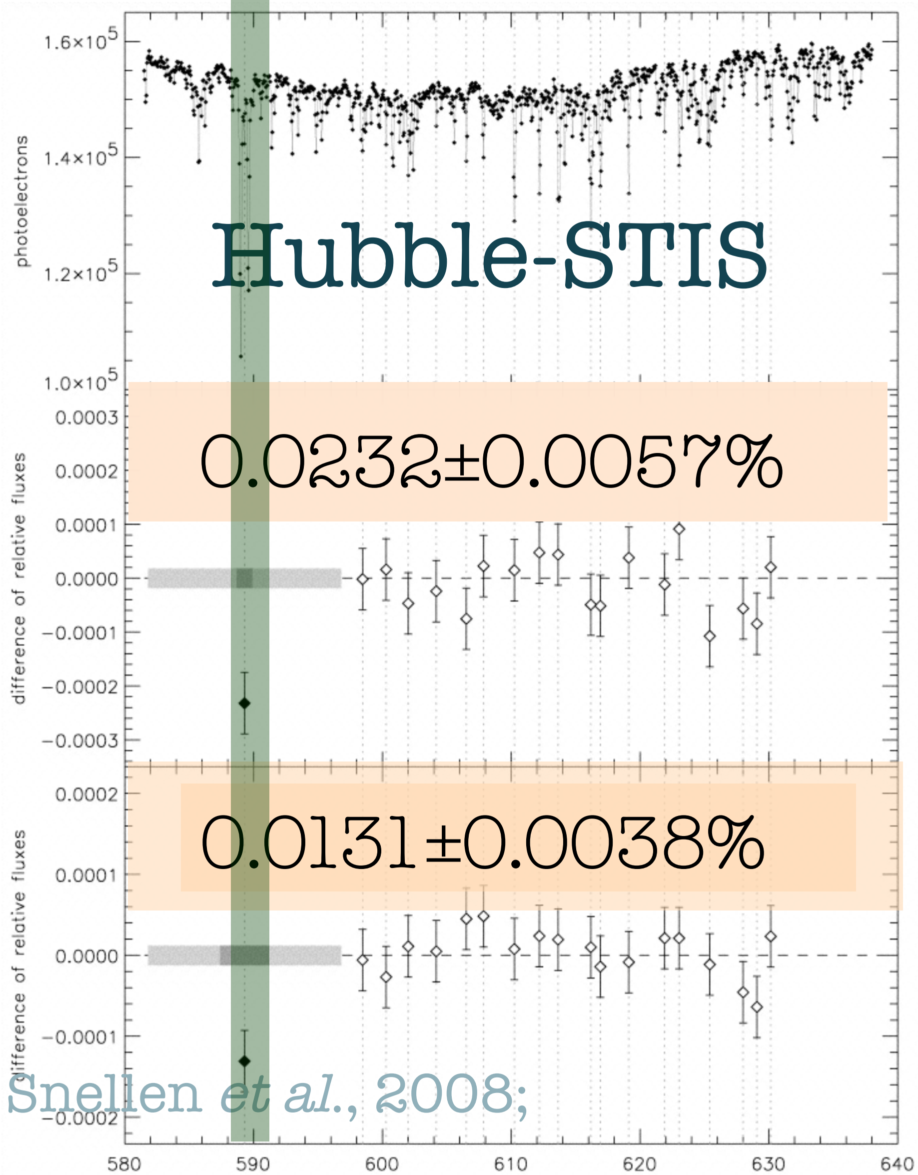
υ Andromeda

contribution from the planet: ~0.1%



Harrington et al., Science, 2006

Na in the atmosphere of Hot-Jupiters

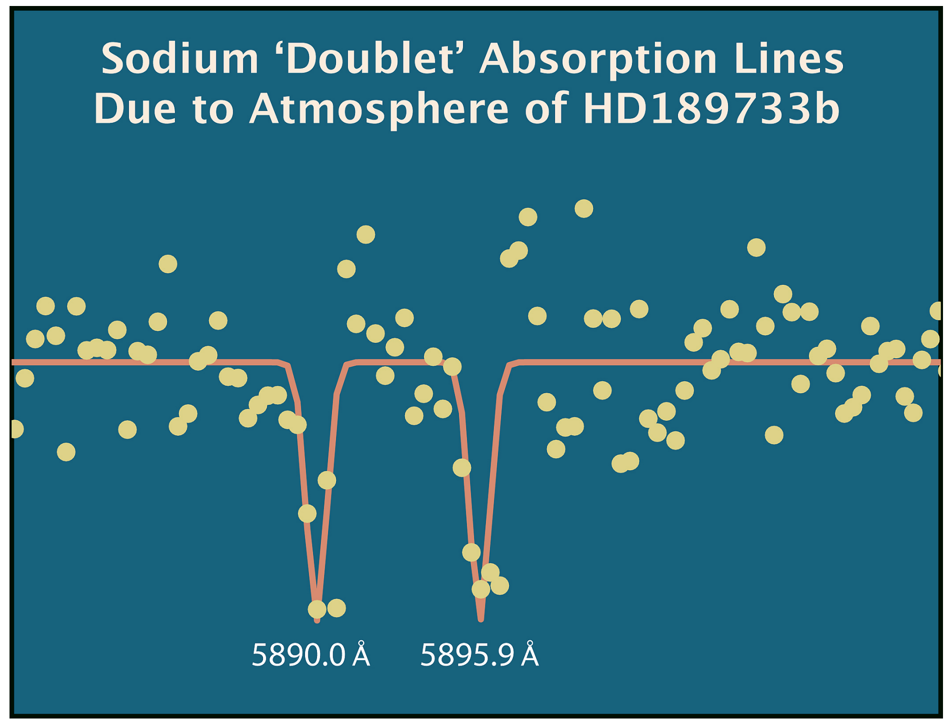


Snellen *et al.*, 2008;

589. nm Wavelength (nm)

Charbonneau *et al.*, 2002

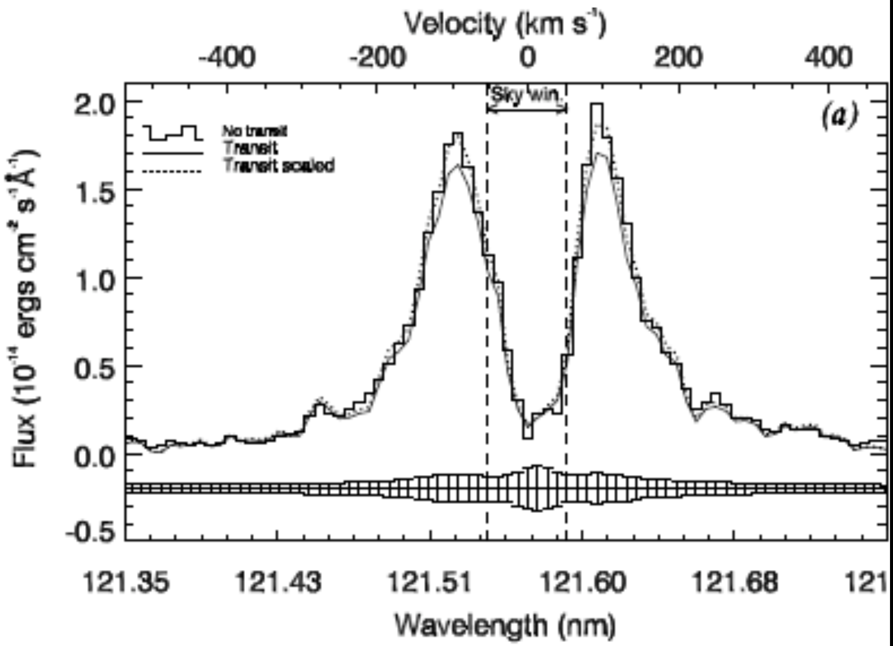
Ground-based observations



Redfield *et al.*, 2007

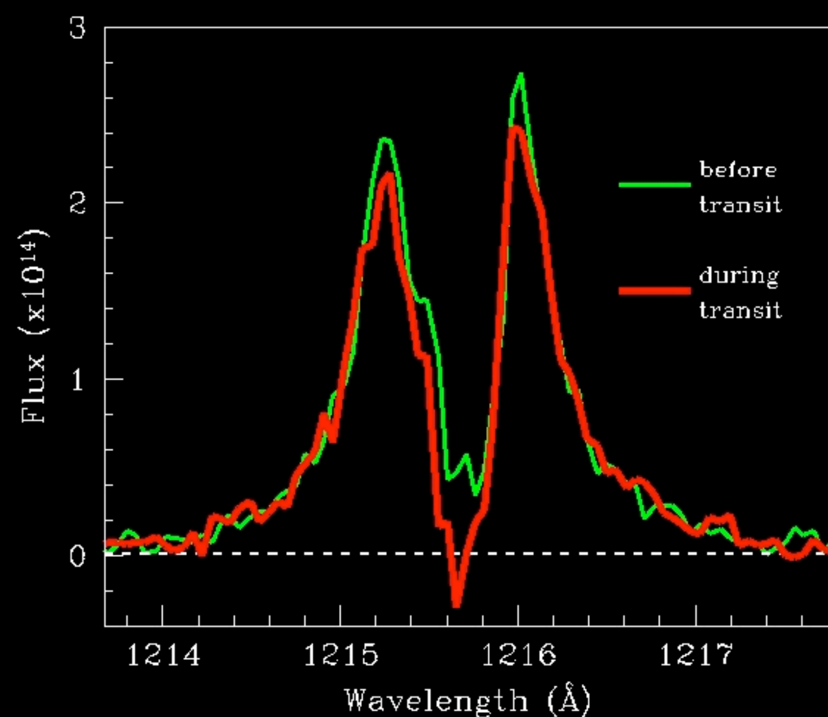
STIS: Lyα HD 209458b

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



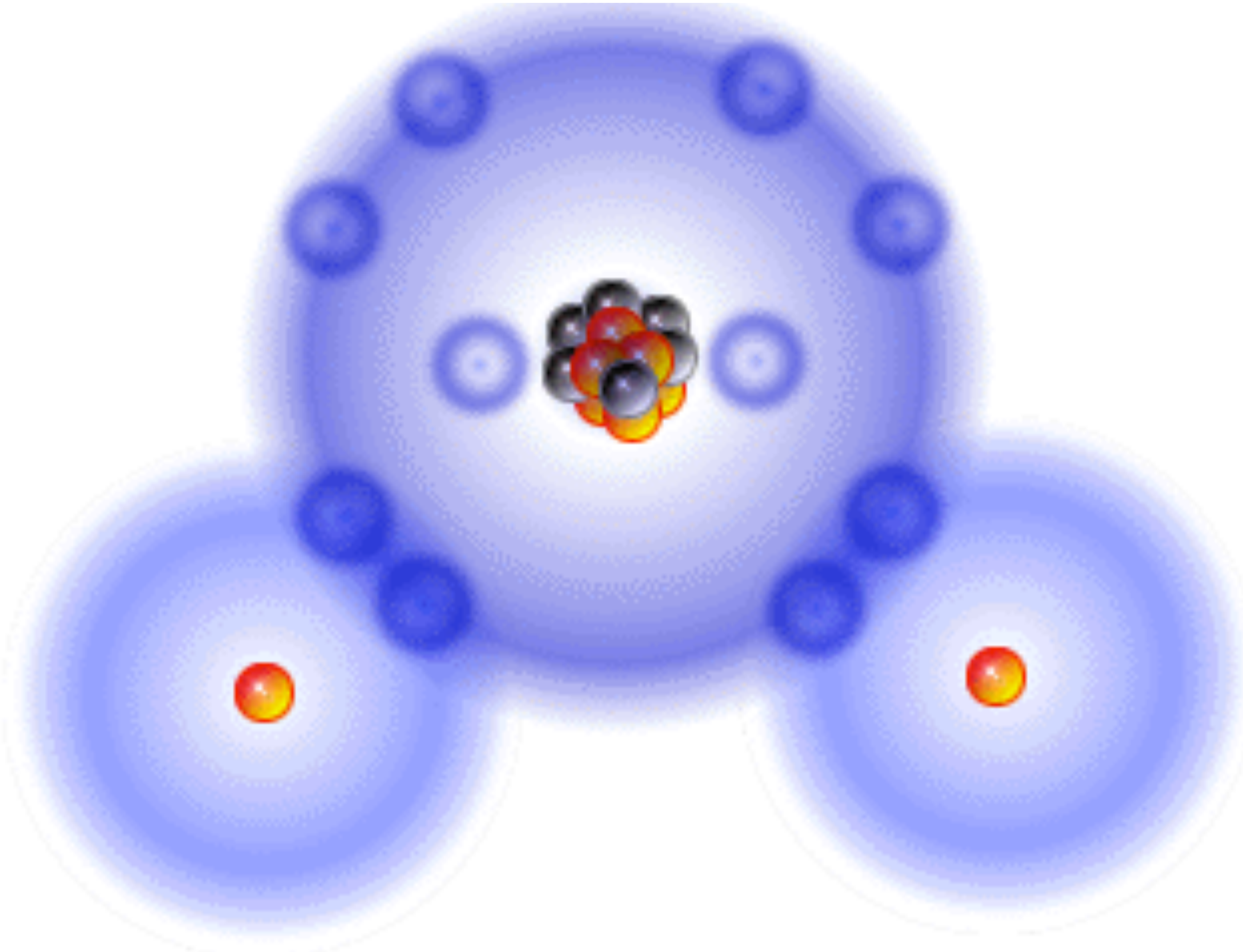
Ben-Jaffel, ApJL, 2008

15% absorption in the Lyα line

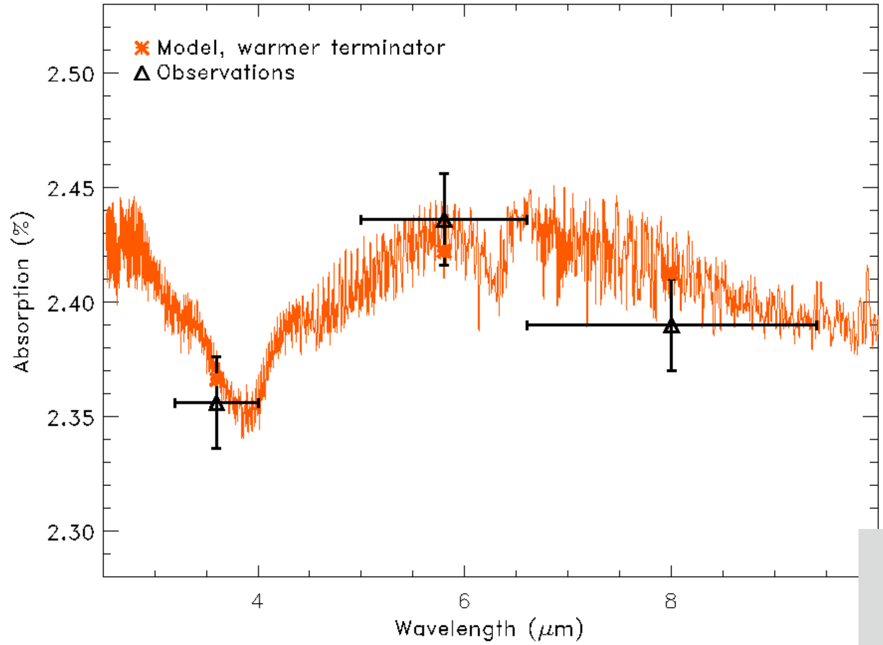


Vidal-Madjar et al., *Nature*, 2003
Ballester, Sing, Herbert, *Nature*, 2007

Water

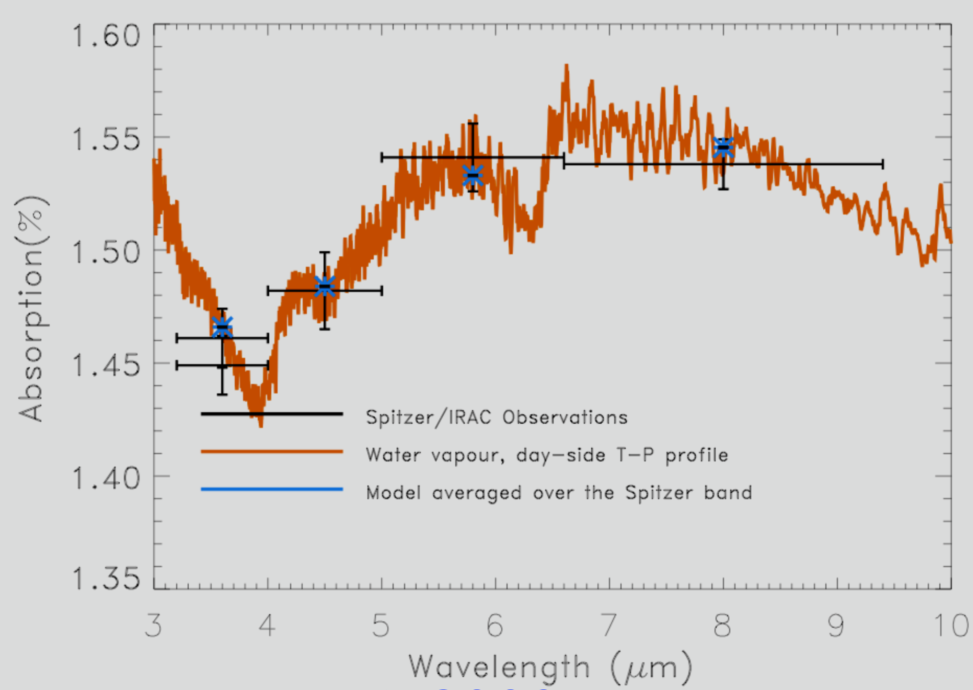


IRAC: transmission band-photometry



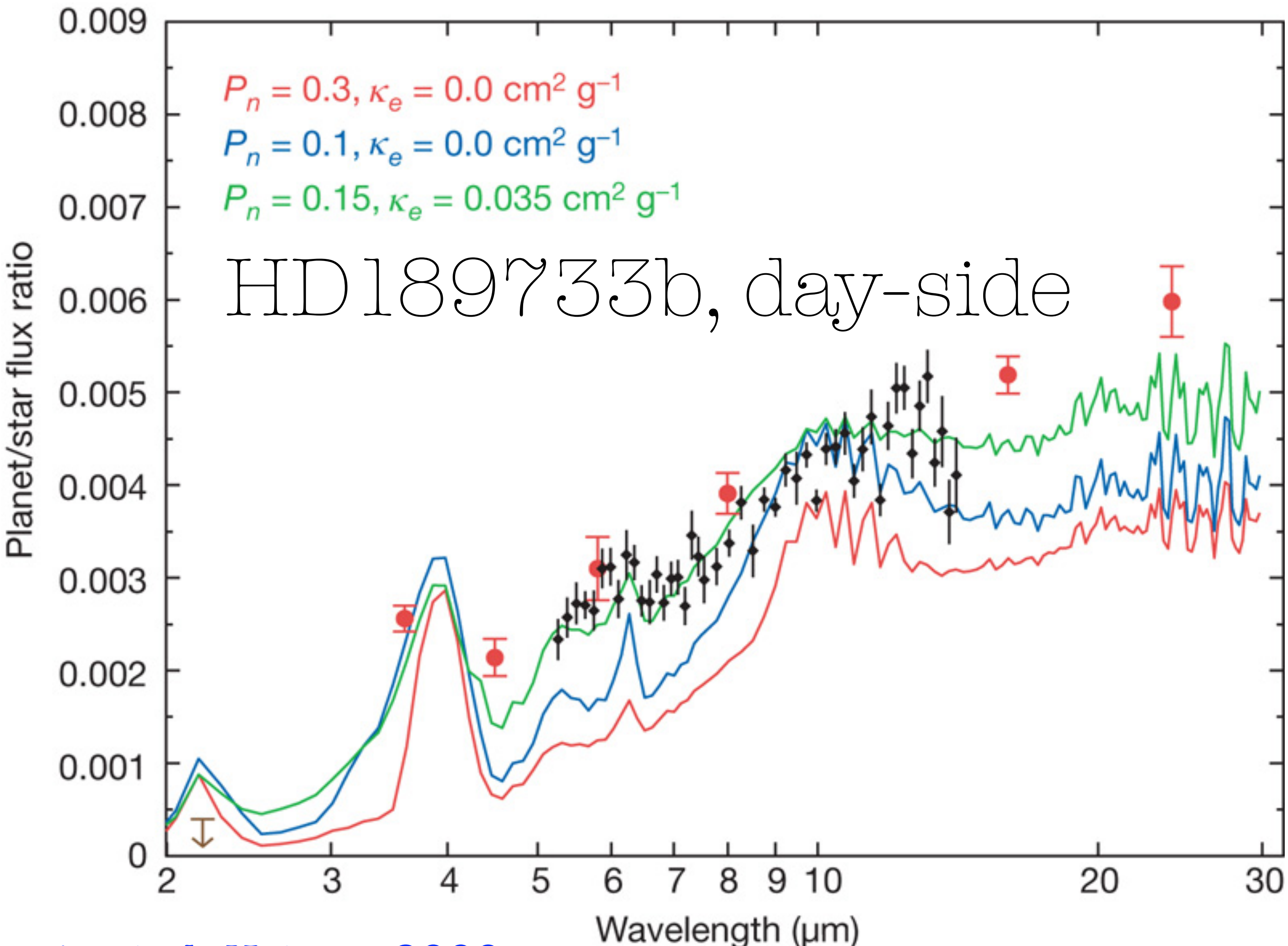
Terminator of
HD189733b & HD209458b

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

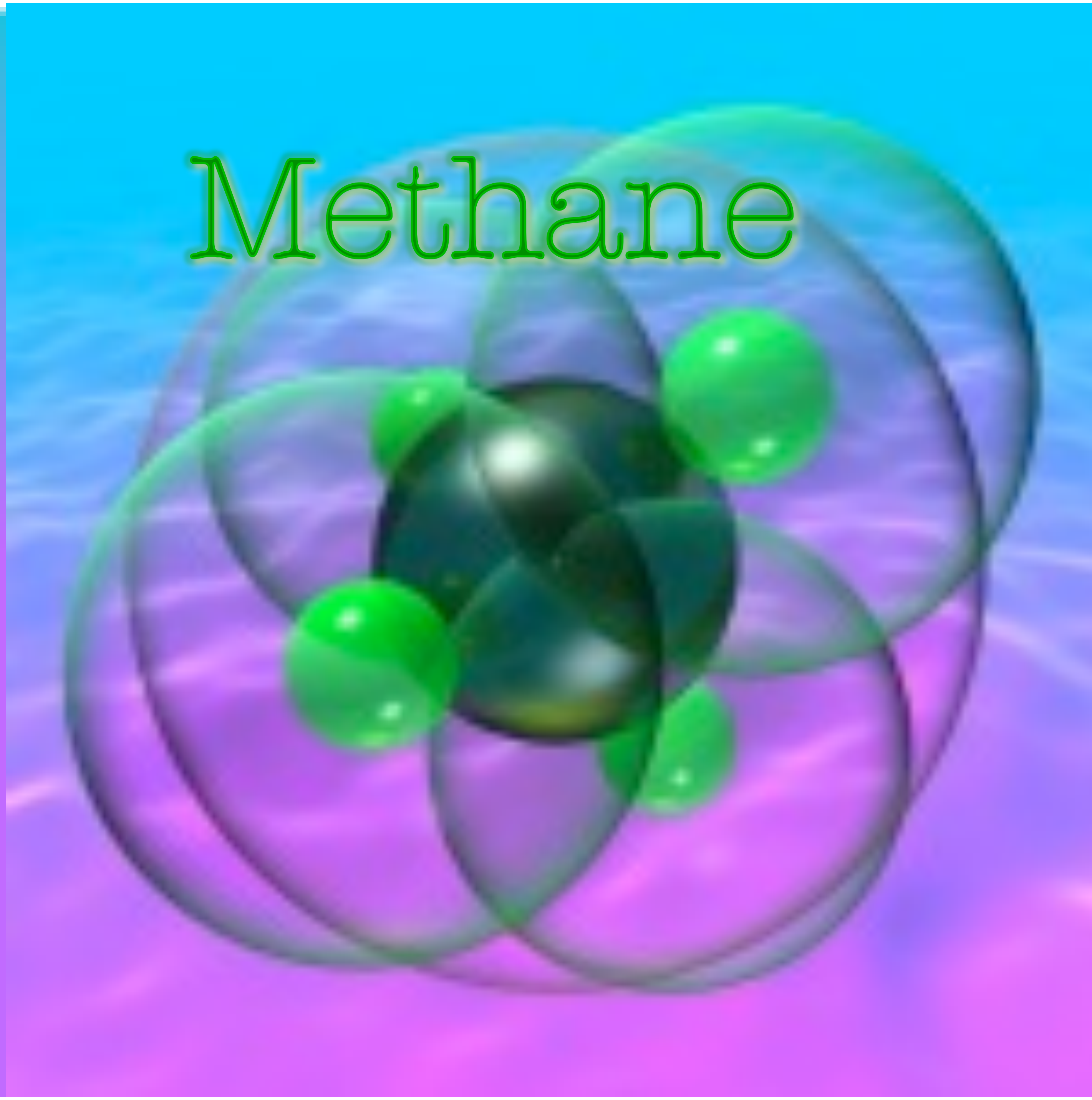


Beaulieu *et al.*, 2009

IRS: emission spectroscopy

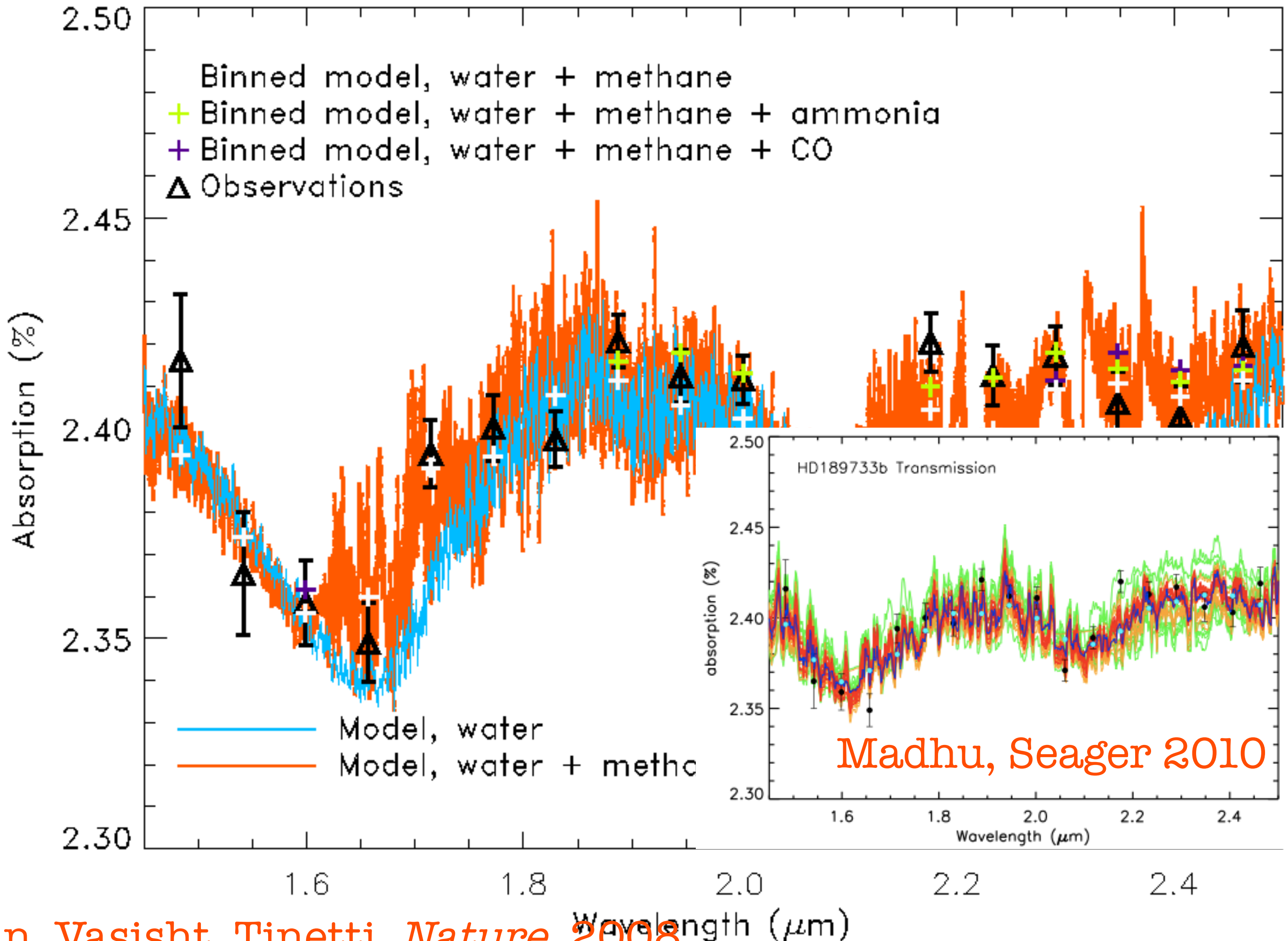


Grillmair *et al.*, Nature, 2008


Methane

NICMOS: transmission spectroscopy

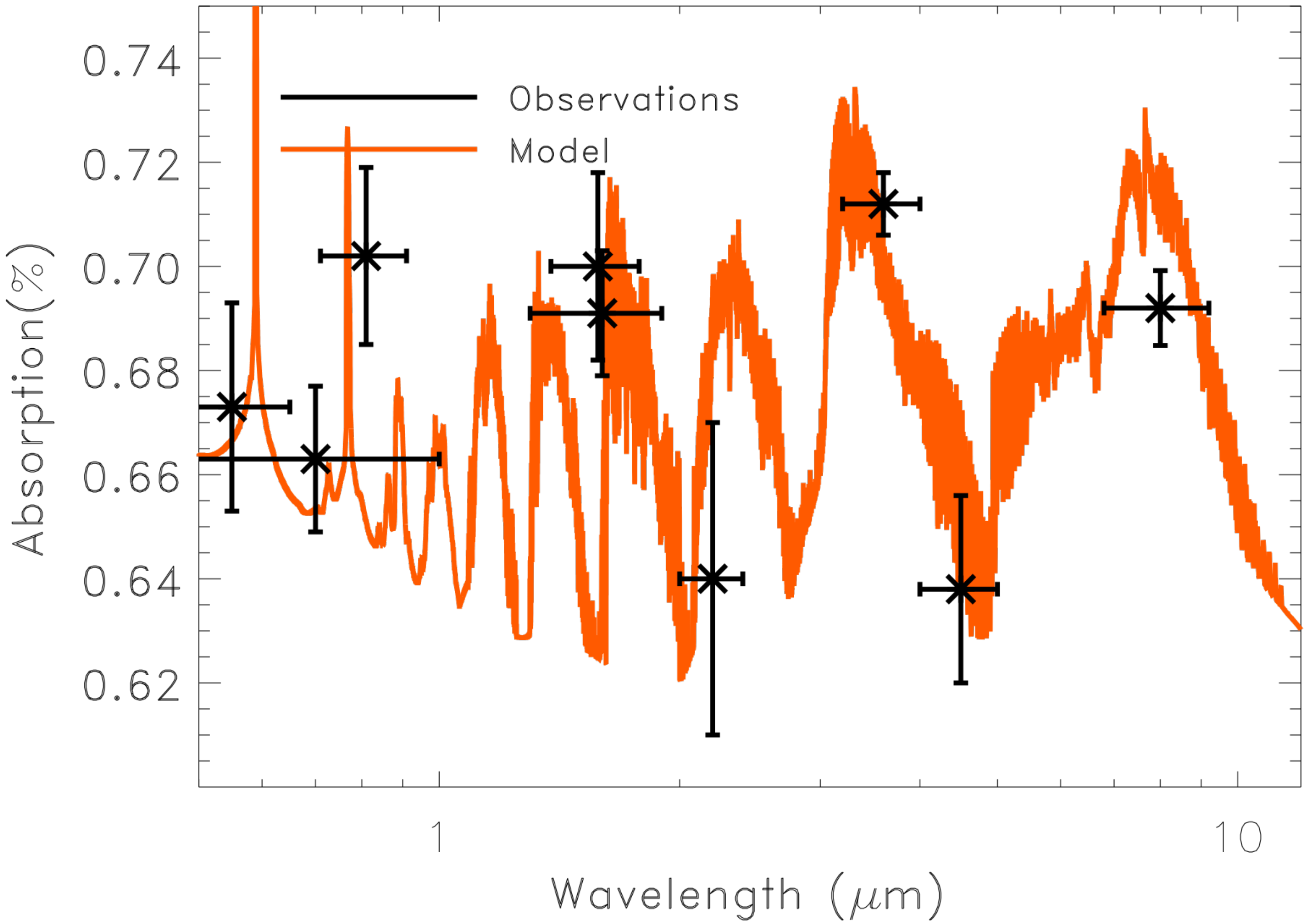
HD189733b, terminator



Swain, Vasisht, Tinetti, *Nature*, 2008

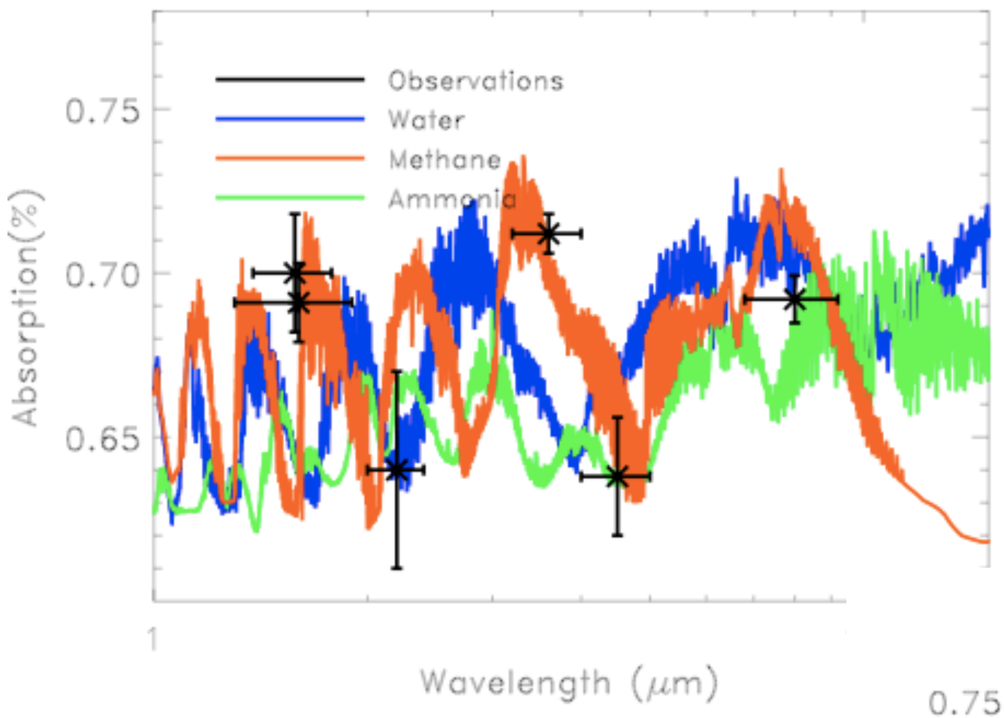
GJ436b: transmission band-photometry

Methane-rich atmosphere?

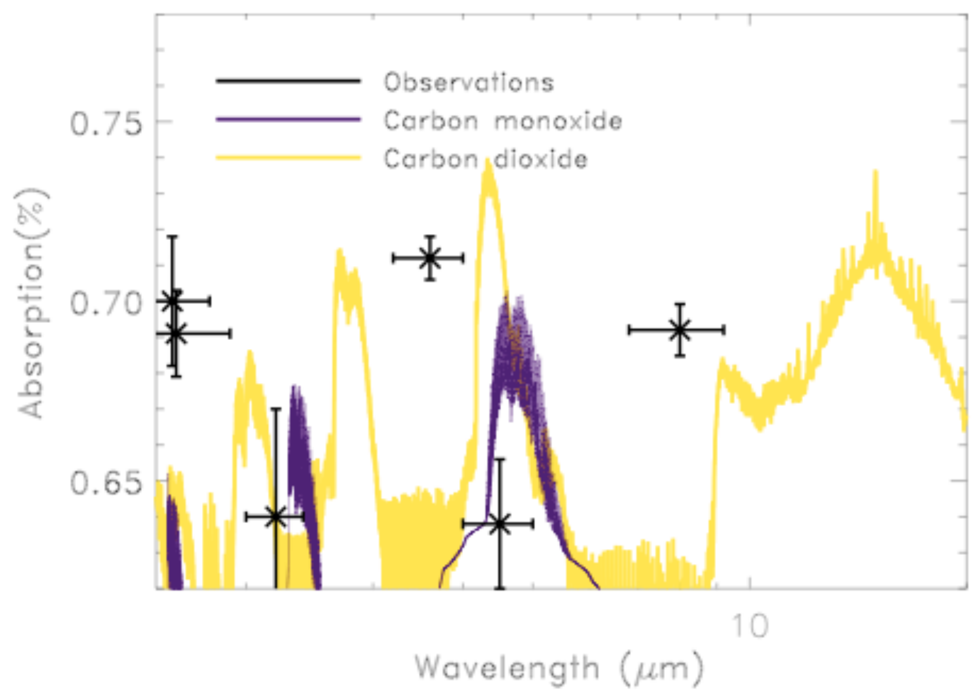


Beaulieu *et al.*, 2010

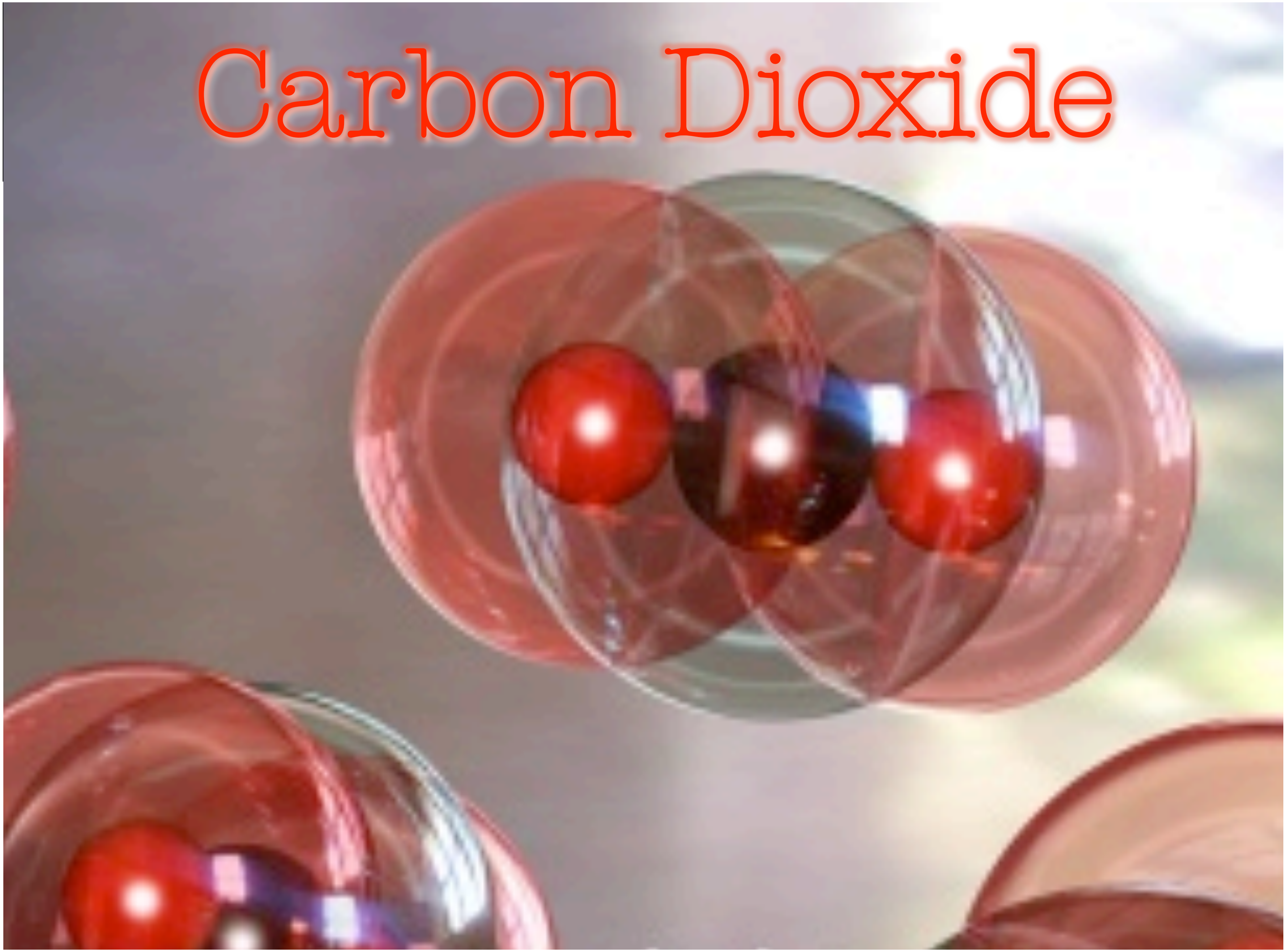
GJ436b: transmission band-photometry



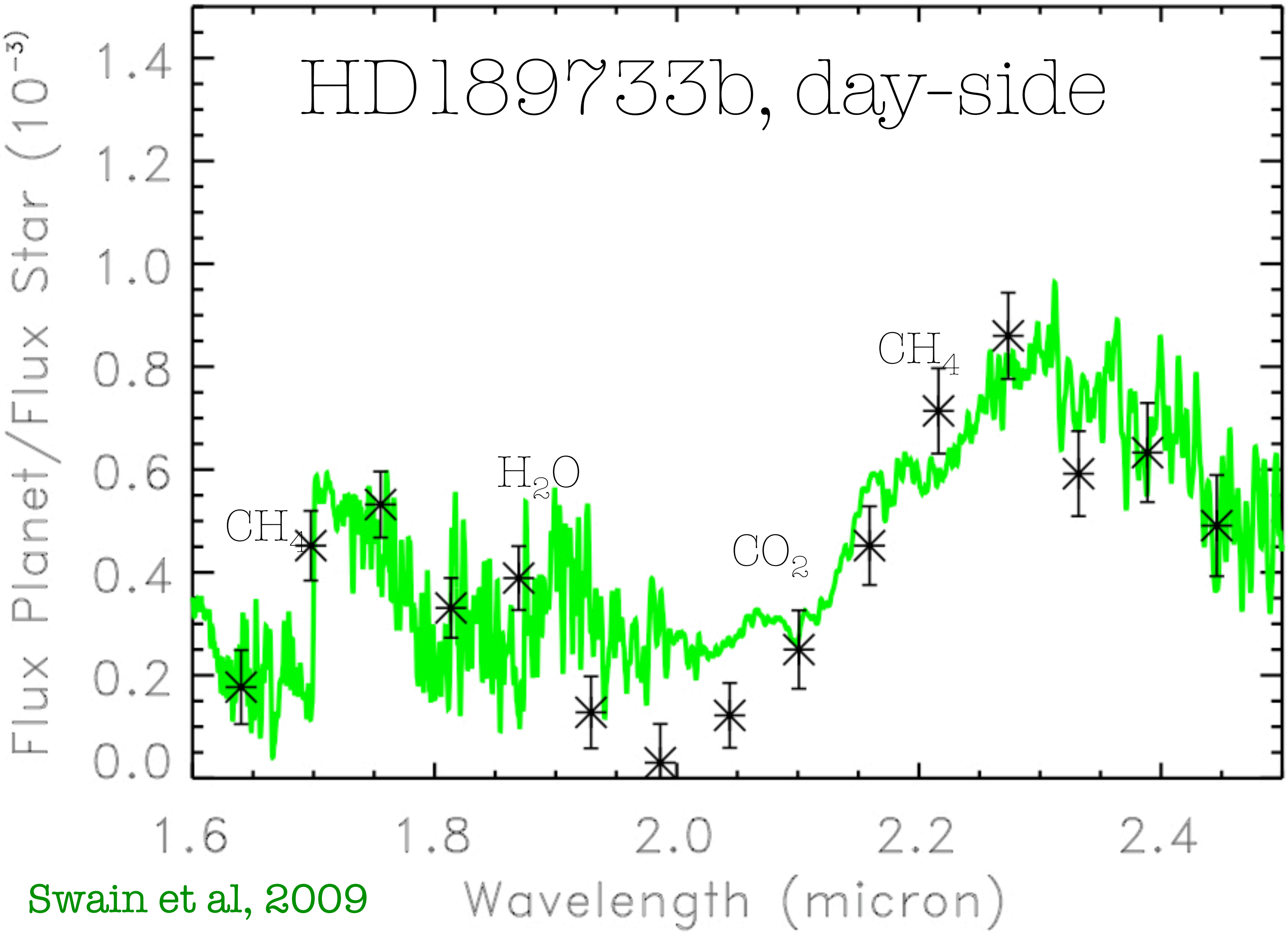
Methane-rich atmosphere?
No evidence of CO/CO_2



Beaulieu *et al.*, 2010


Carbon Dioxide

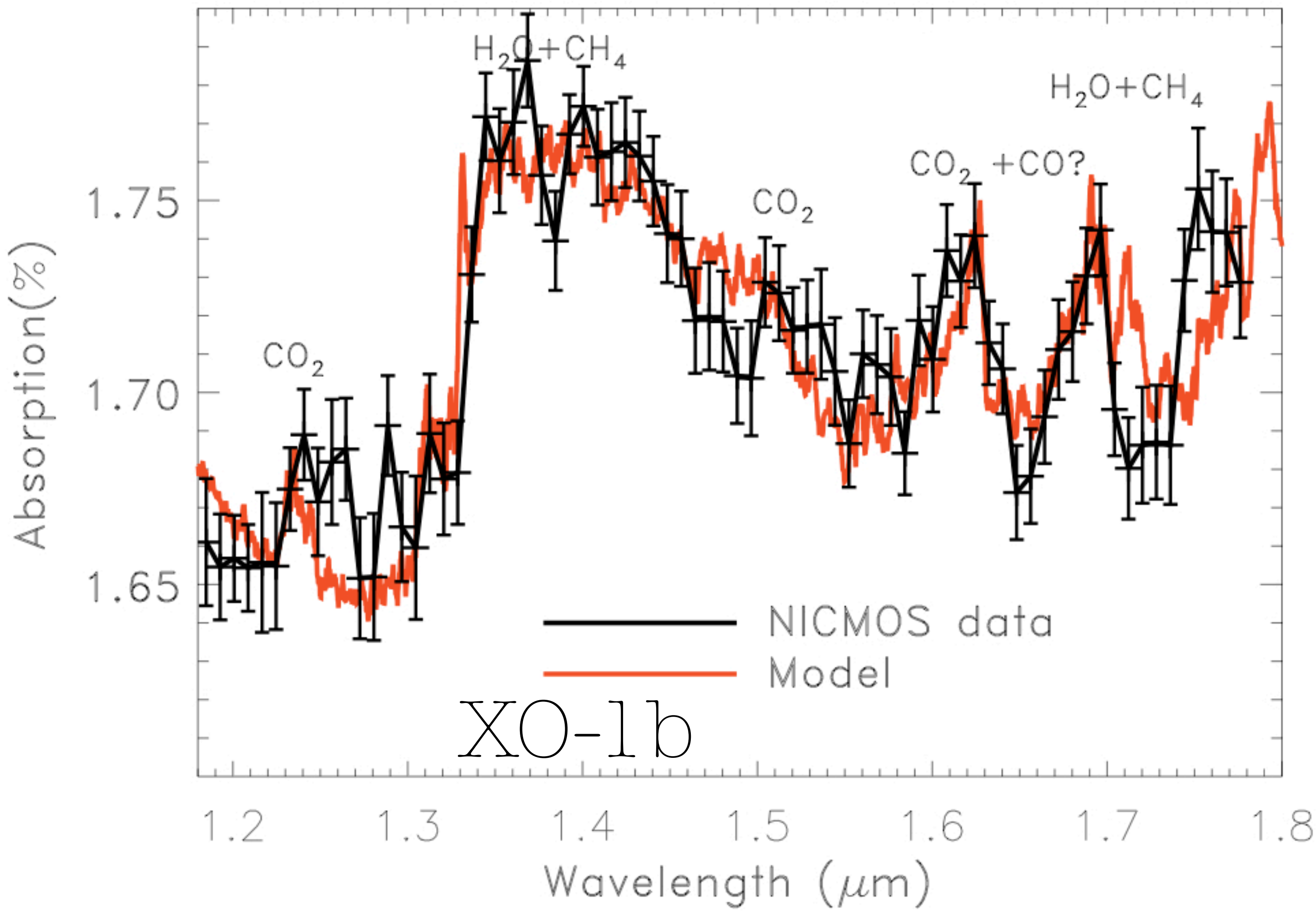
NIR-MIR emission spectroscopy



Swain et al, 2009

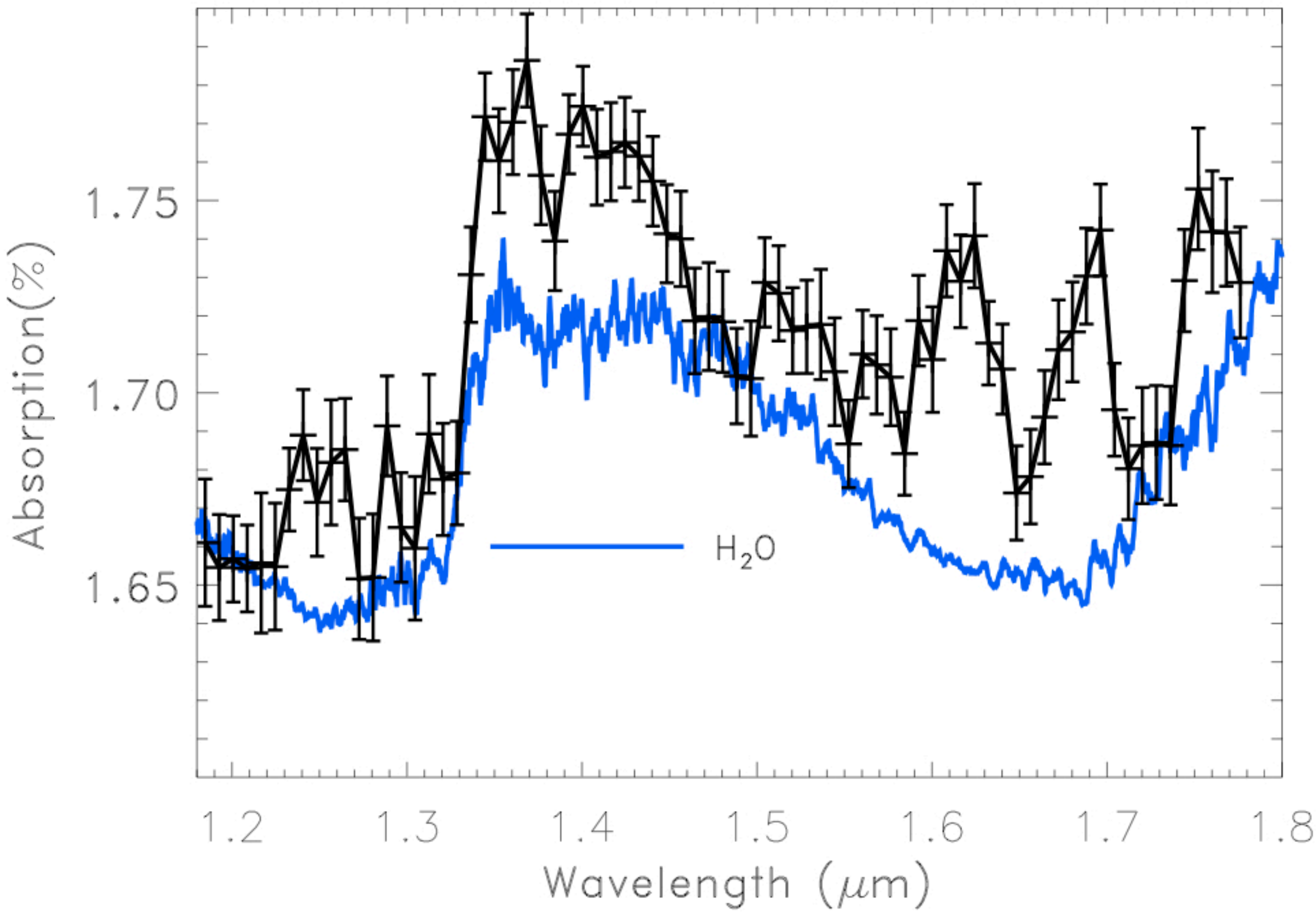
Transit spectroscopy, Hubble

UCL



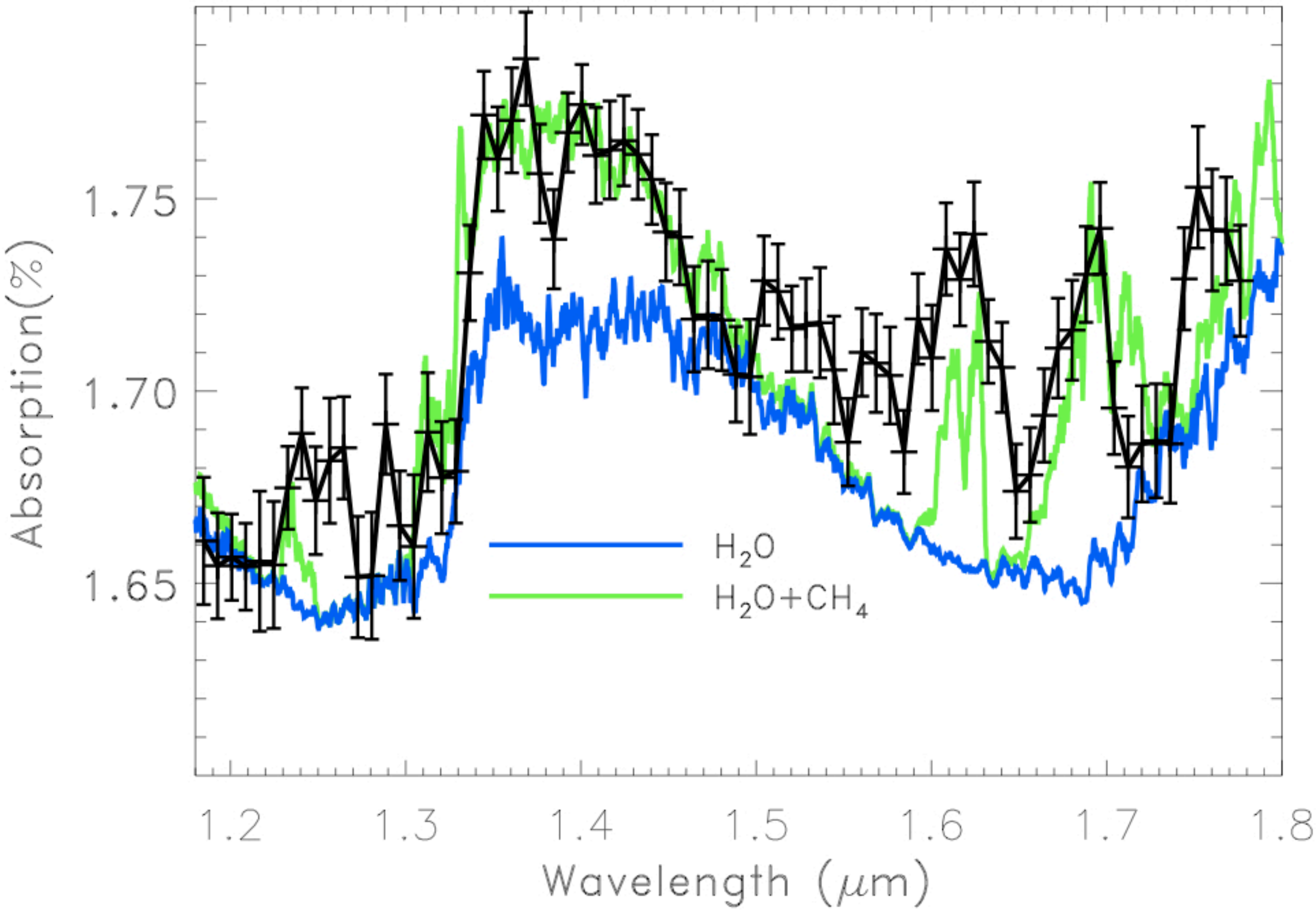
Tinetti, et al., 2010

NICMOS: transmission spectroscopy



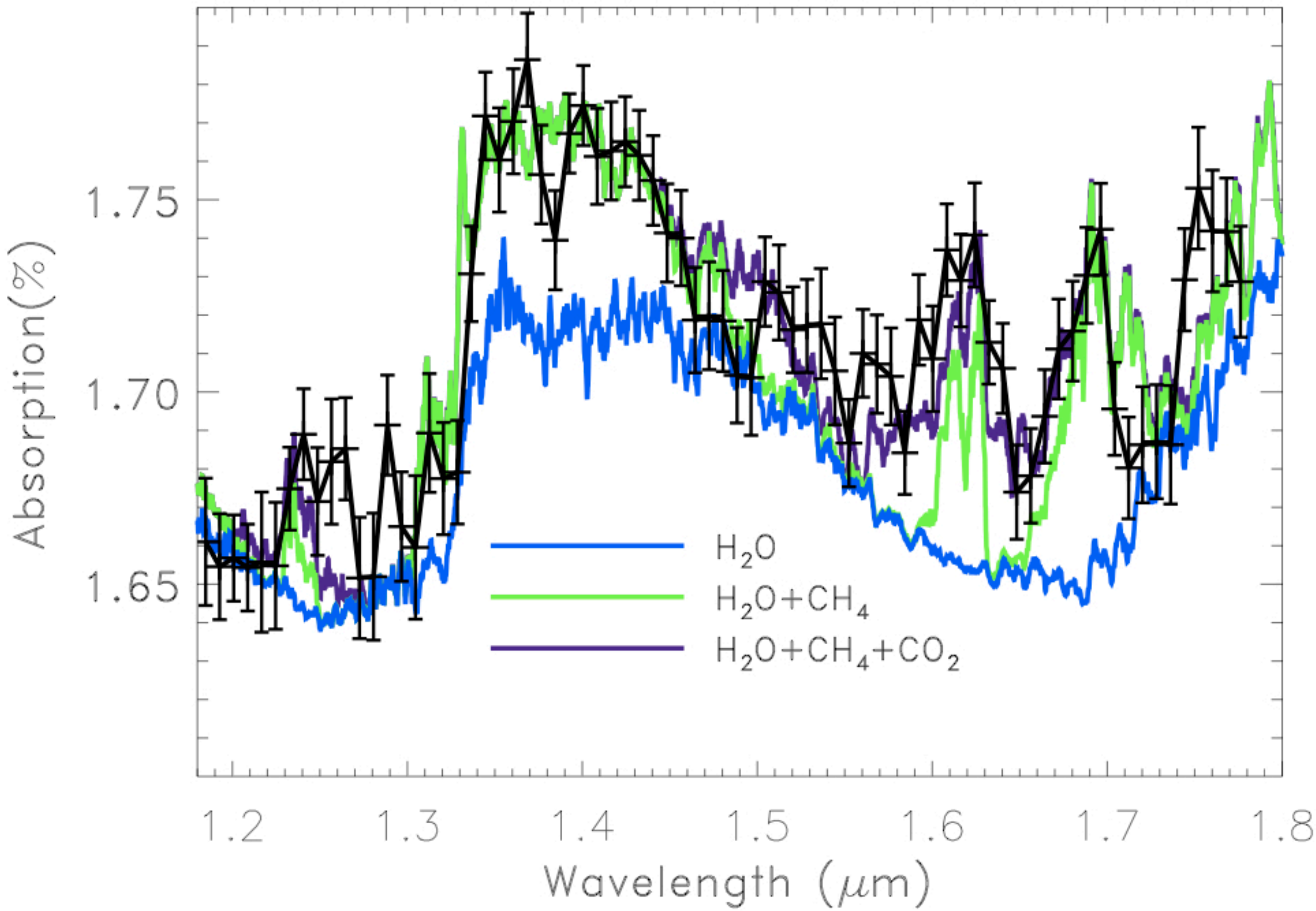
Tinetti, *et al.*, 2010

NICMOS: transmission spectroscopy



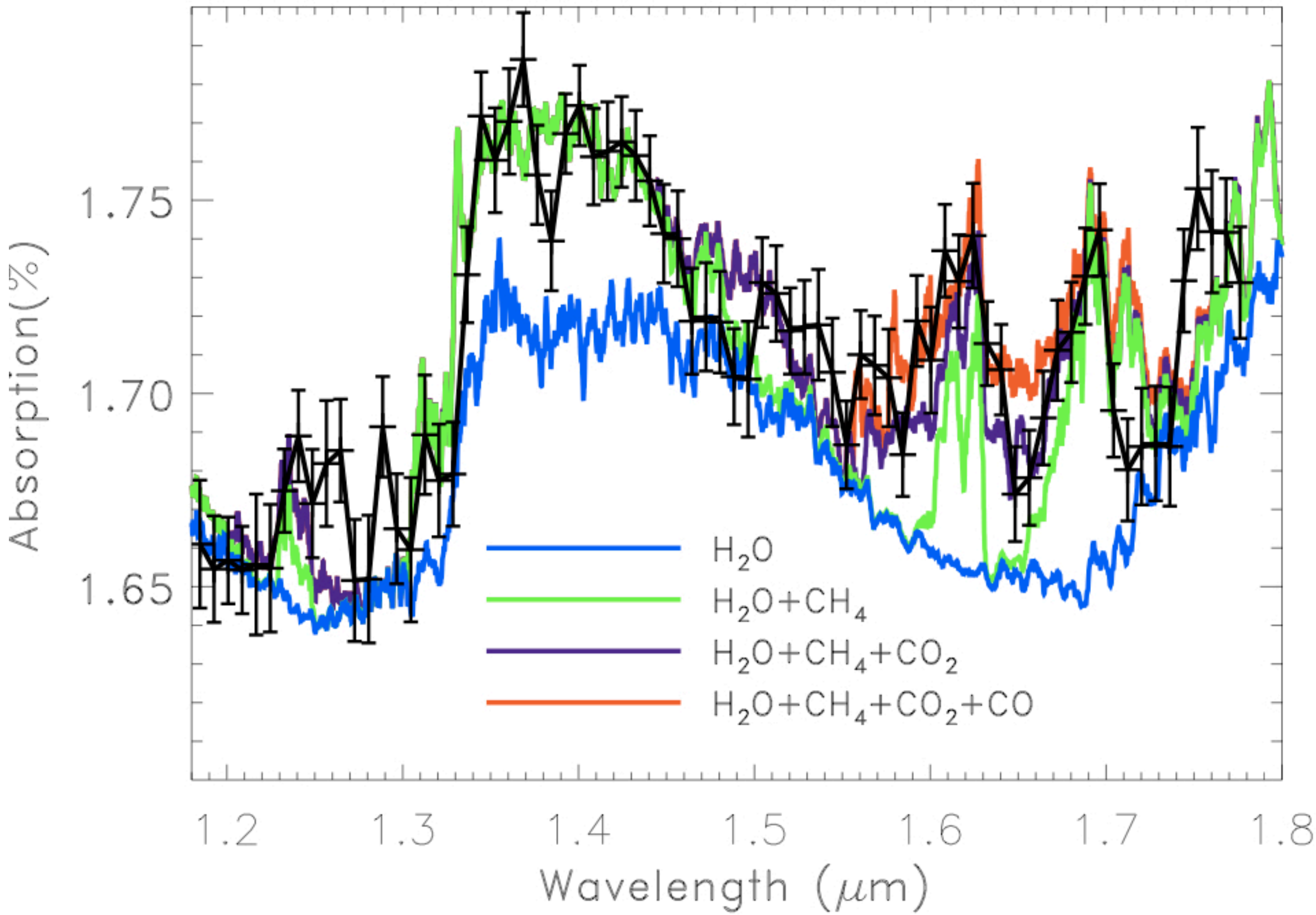
Tinetti, *et al.*, 2010

NICMOS: transmission spectroscopy



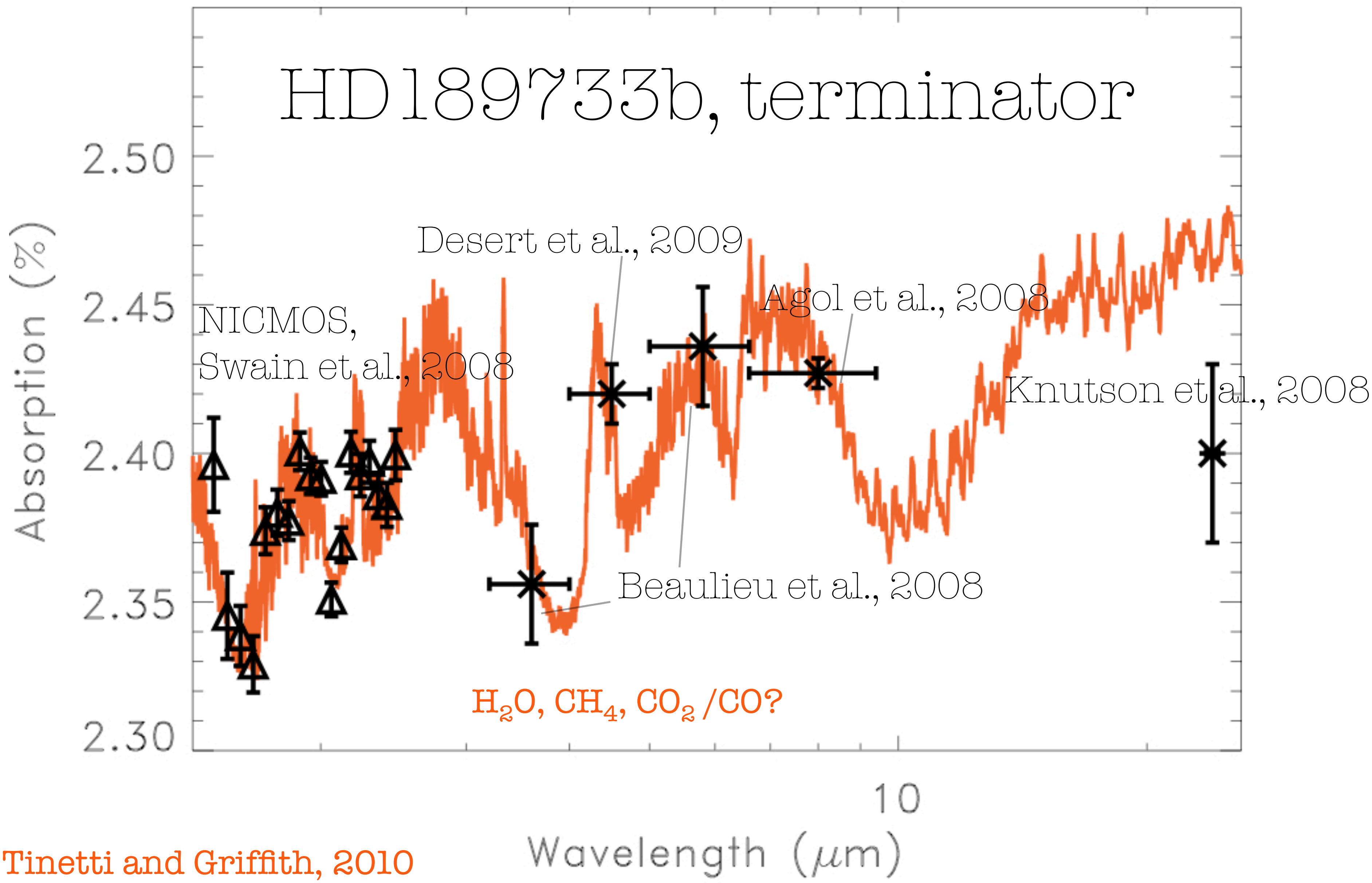
Tinetti, *et al.*, 2010

NICMOS: transmission spectroscopy



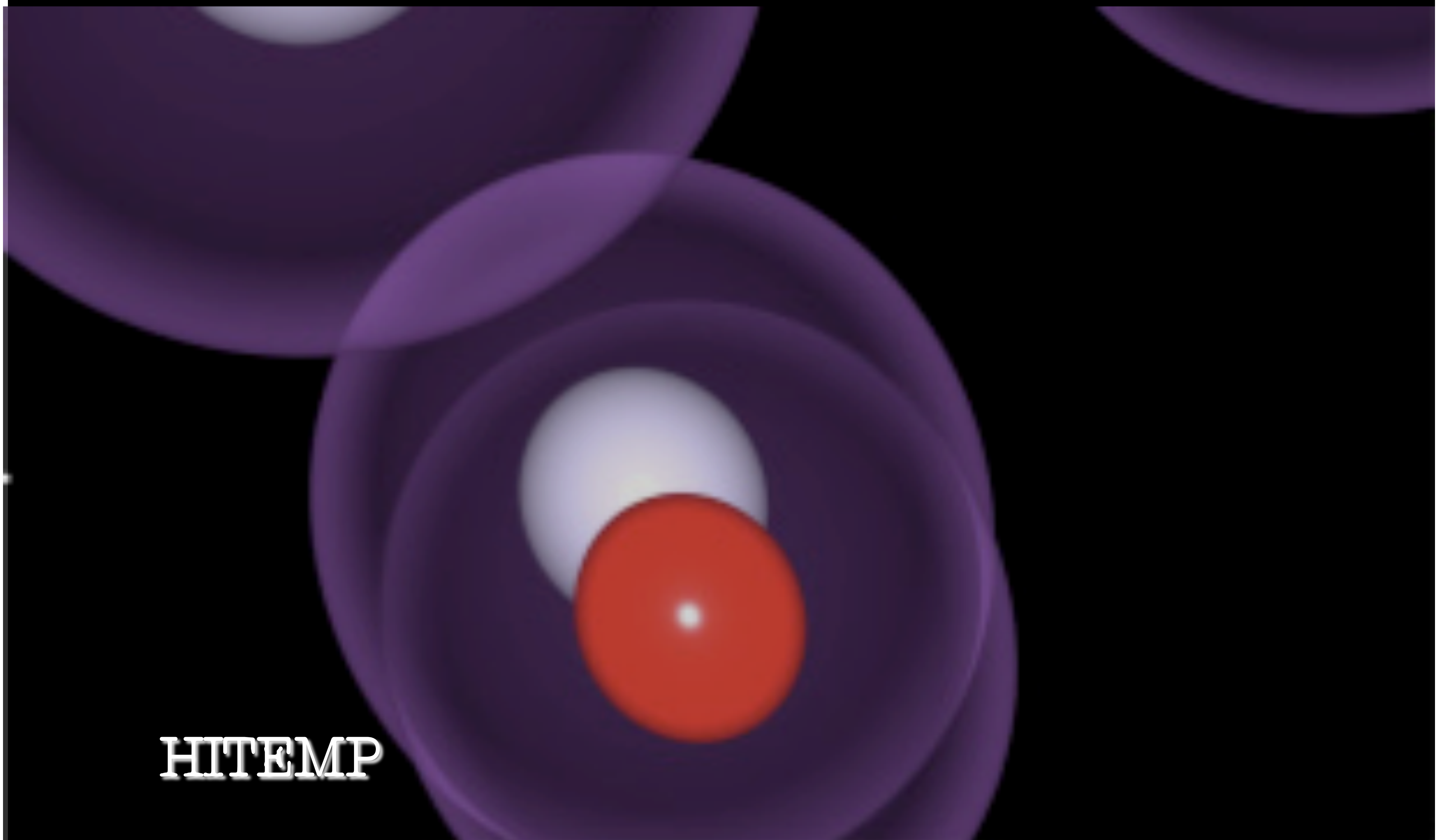
Tinetti, *et al.*, 2010

Non simultaneous observations (risky)

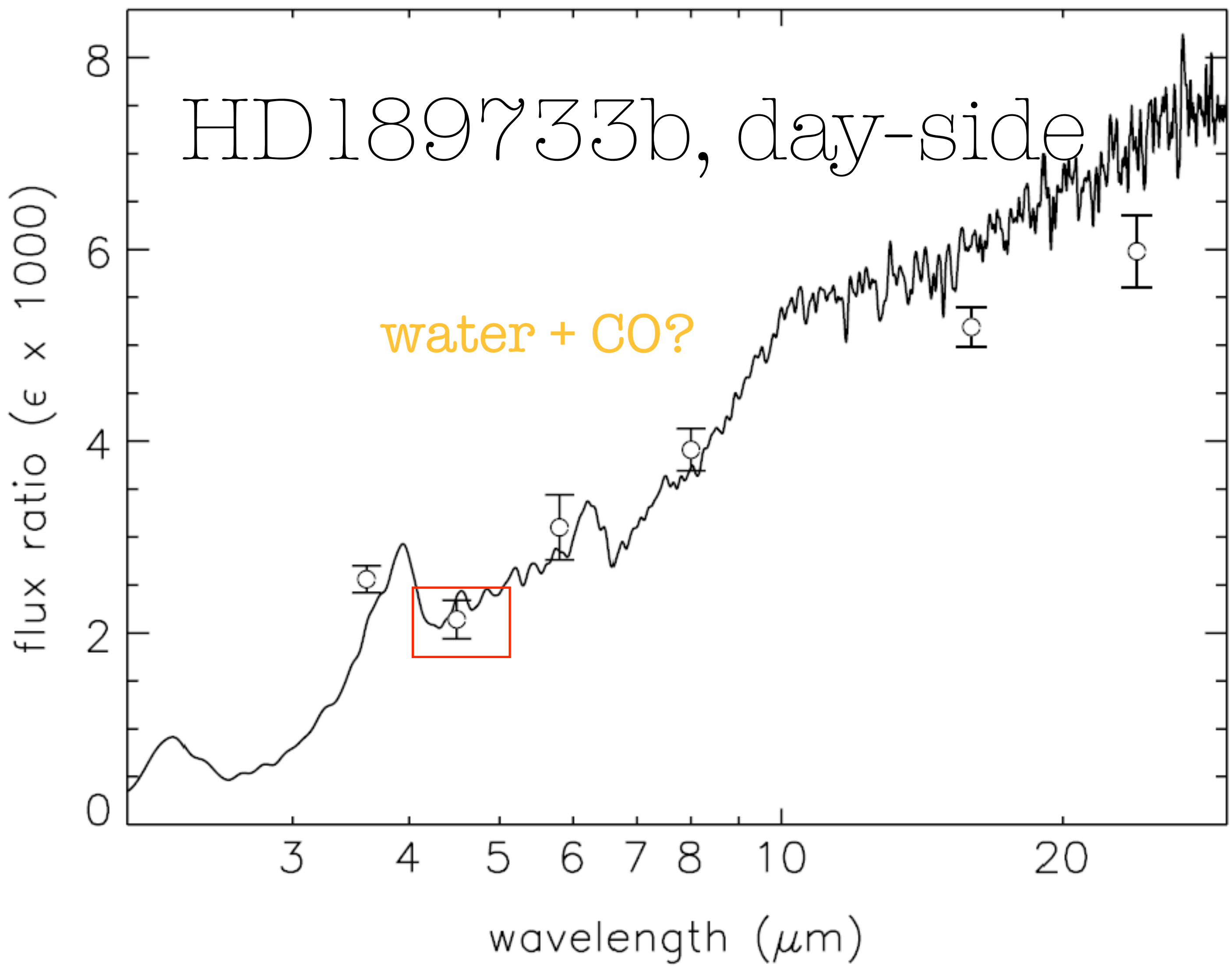


Tinetti and Griffith, 2010

Carbon Monoxide?

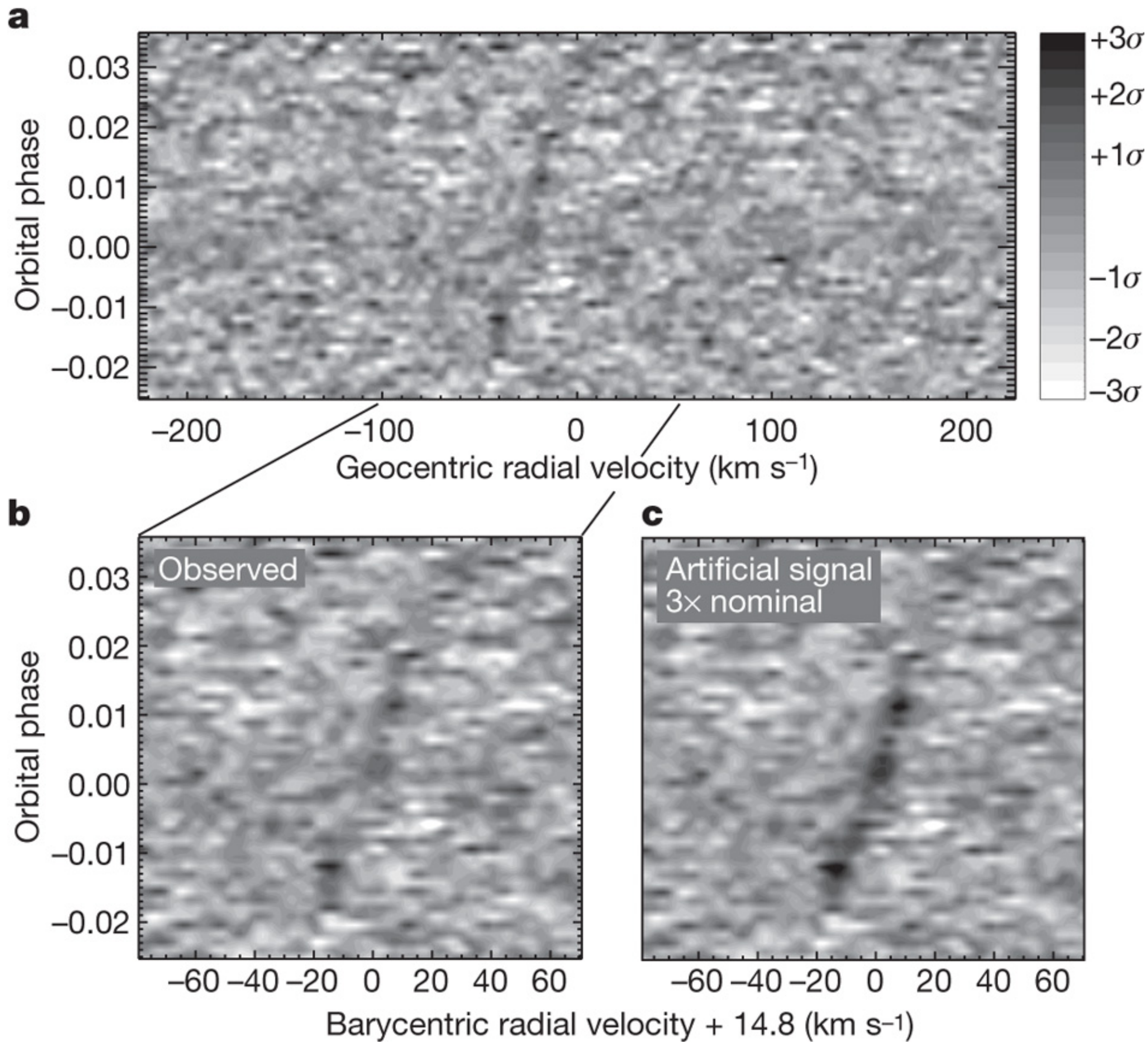


IRAC: Secondary transit photometry



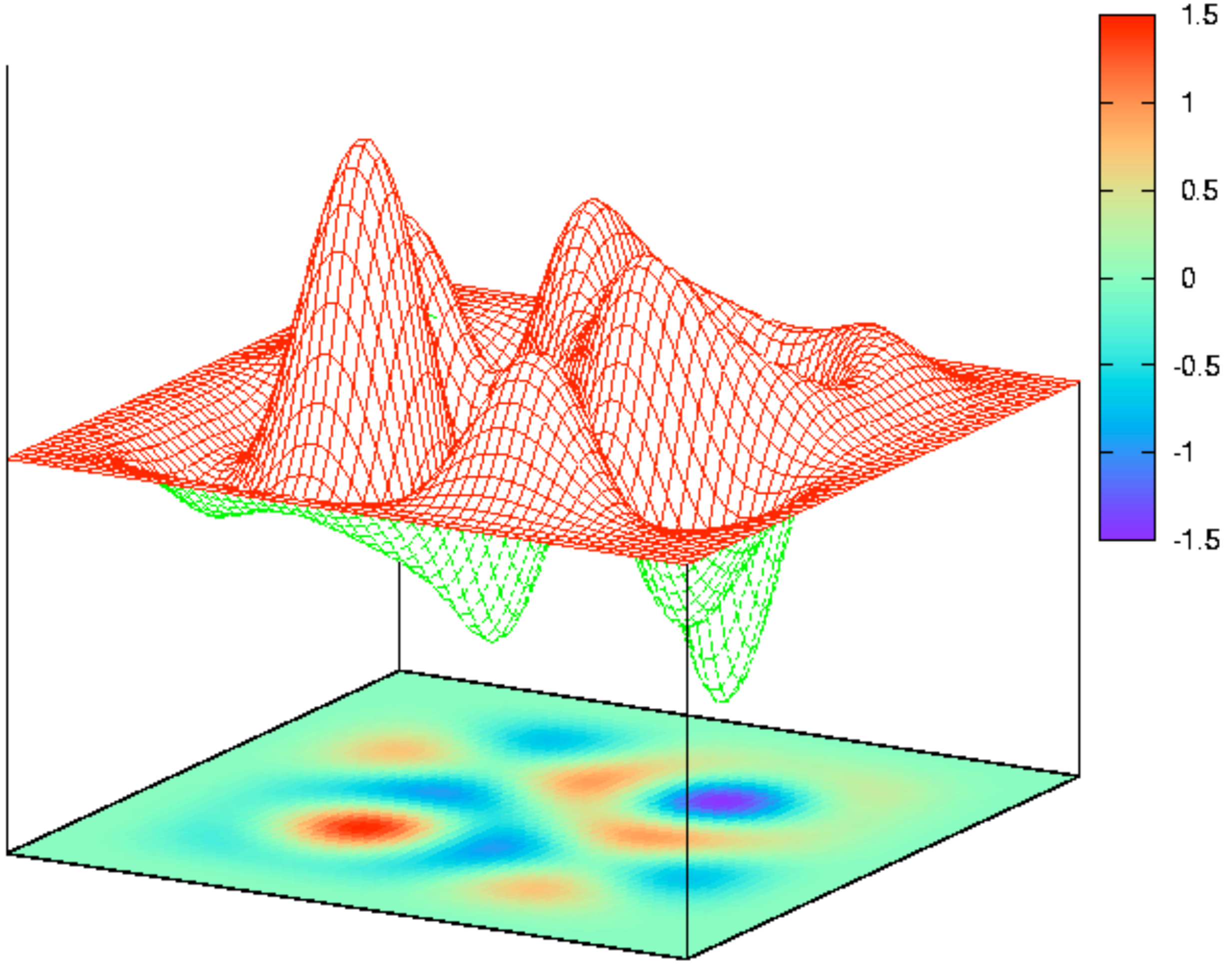
Charbonneau *et al.*, 2008; Barman, 2008;

CO detection with VLT-Crires

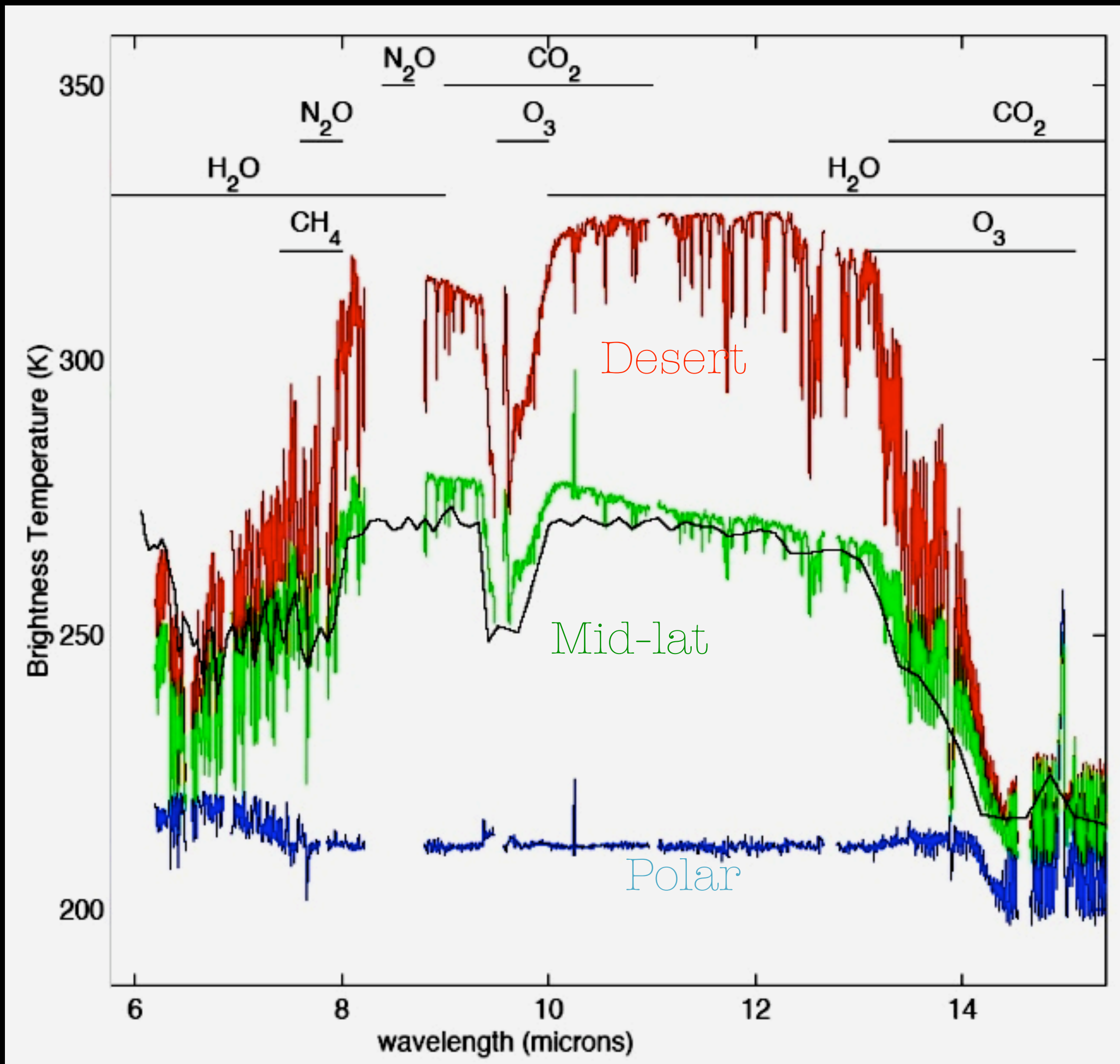


Snellen *et al.*, Nature, 2010

Degeneracy of solutions



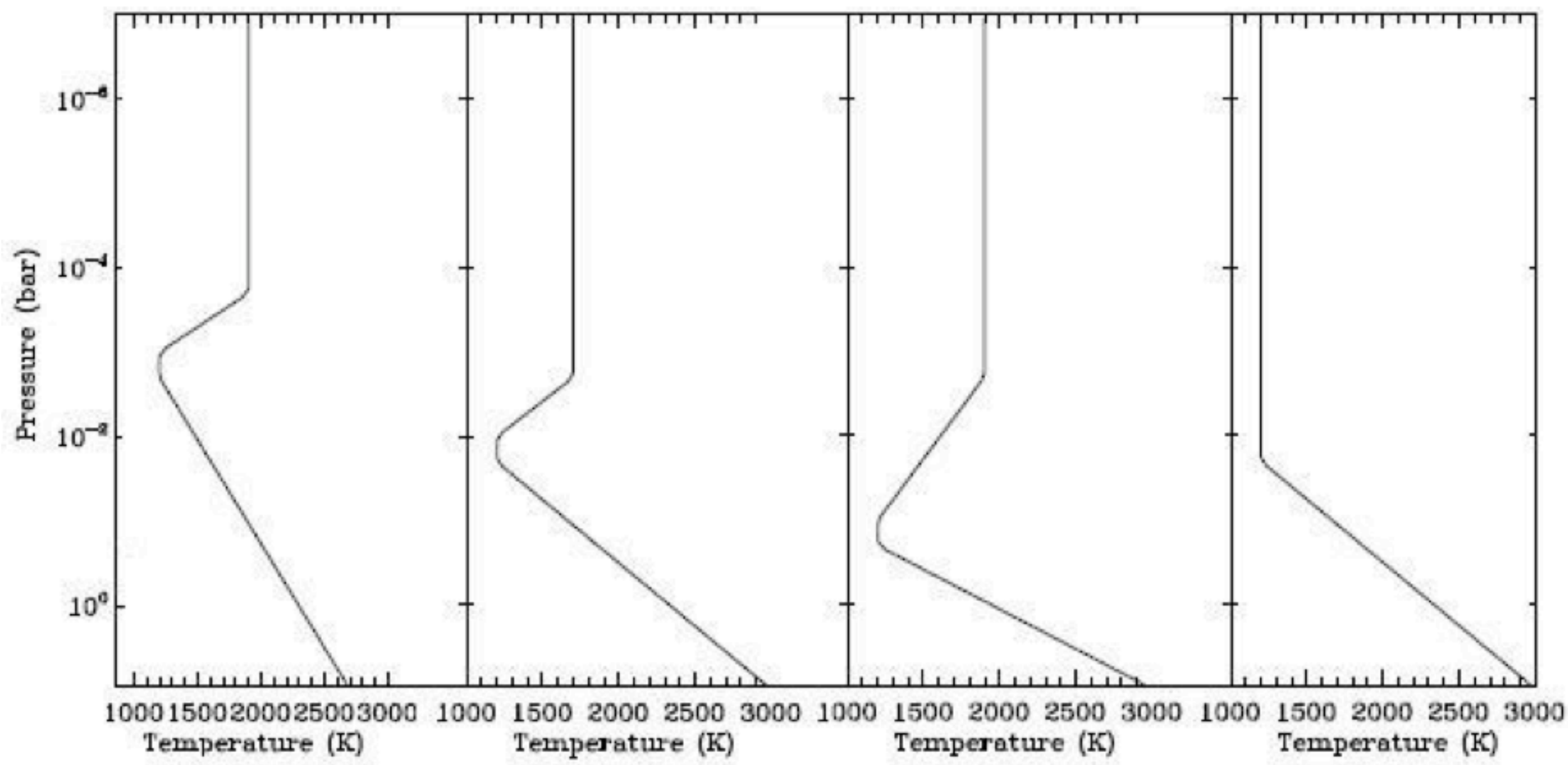
Spectral retrieval in the IR



⇒Thermal variations ~50%

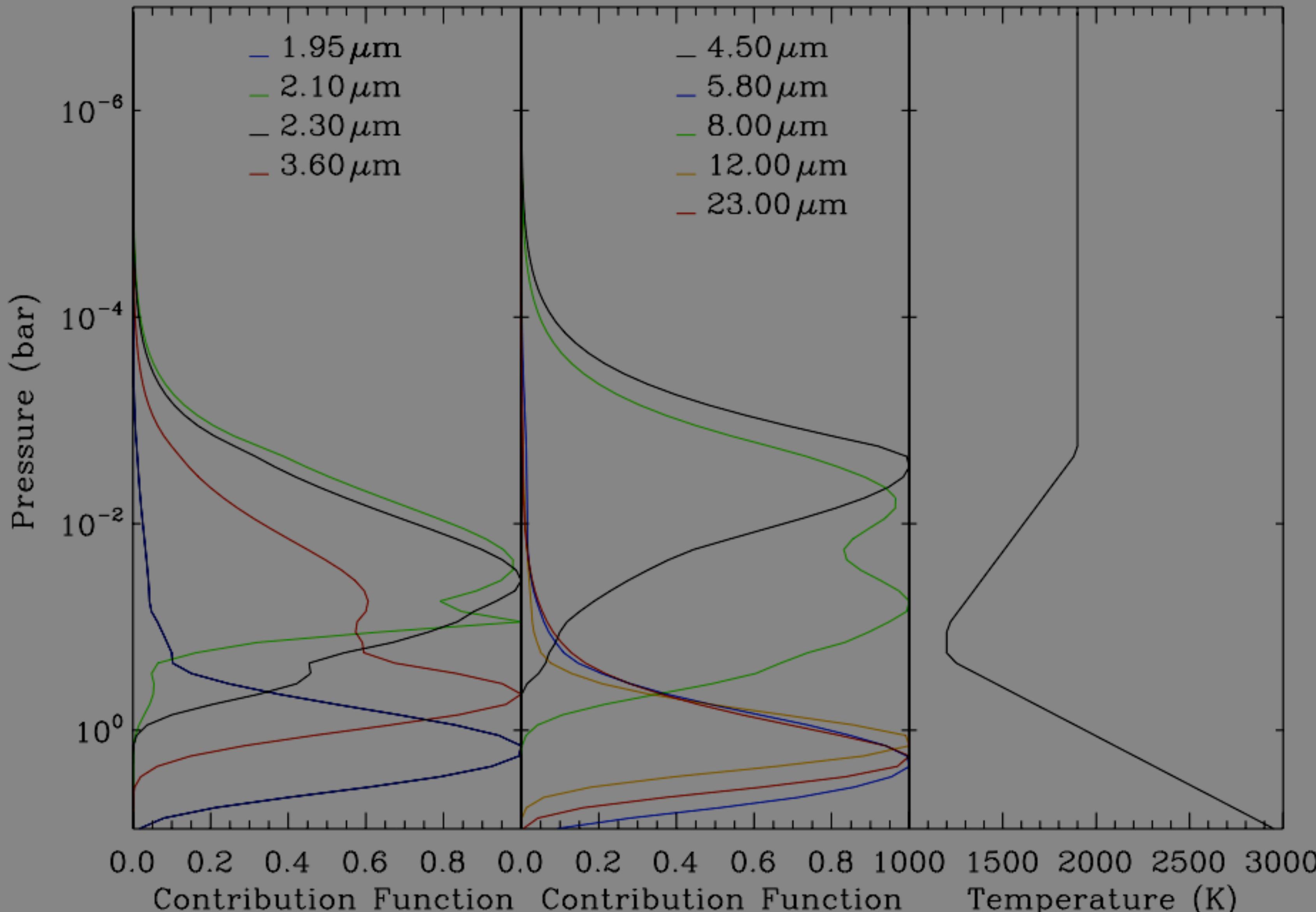
(Hearty et al 2009)

HD209458b, day-side



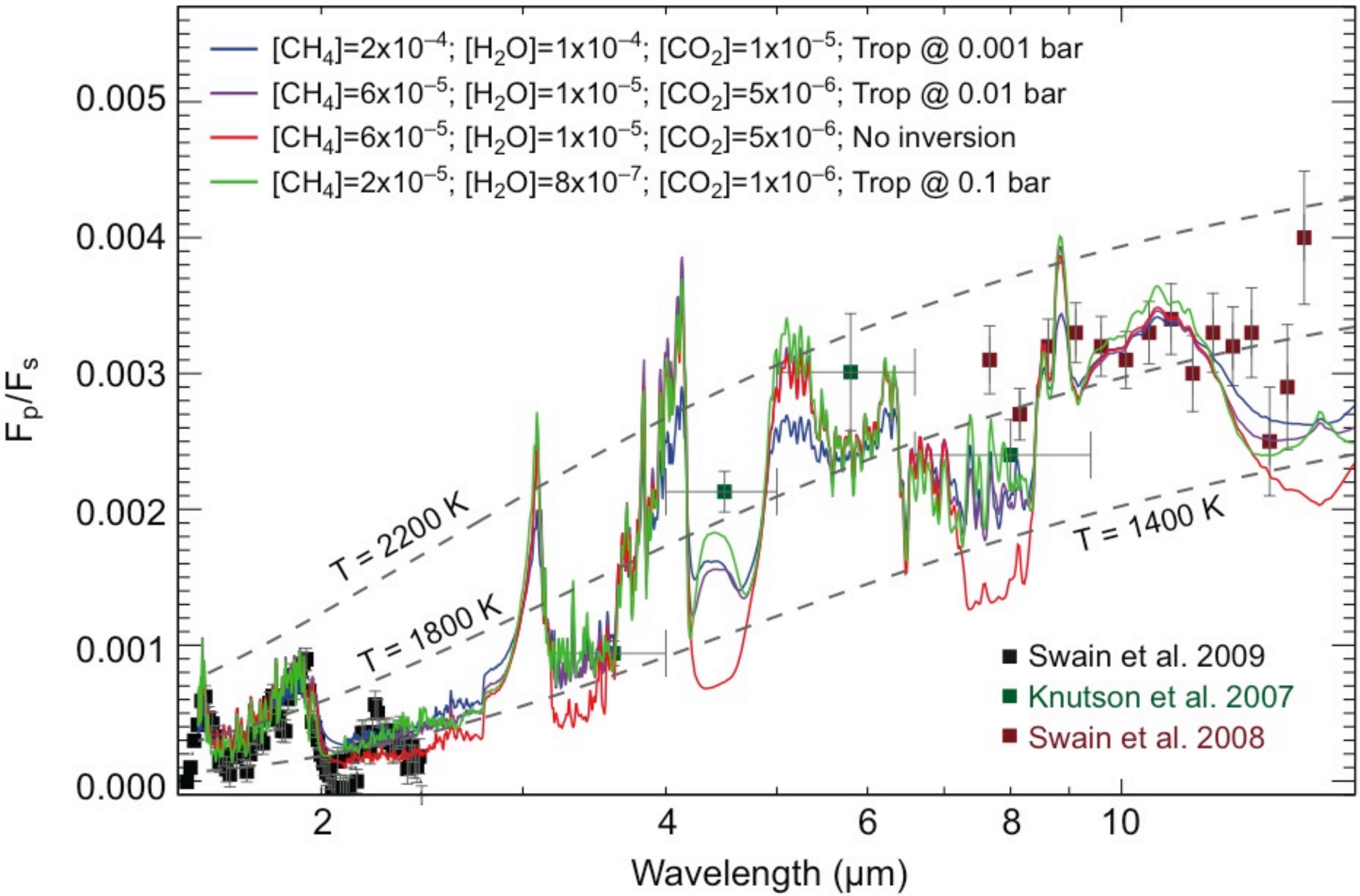
Swain, *et al.*, 2009; Griffith and Tinetti, 2010

Degeneracy T-P profile, mixing ratios



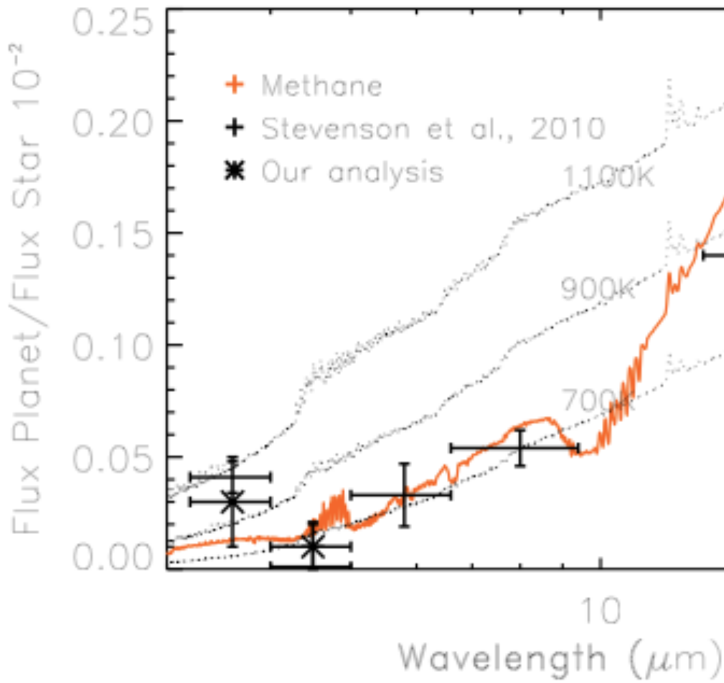
Swain, *et al.*, 2009; Griffith and Tinetti, 2010

Degeneracy composition T-P profile



Swain, *et al.*, 2009

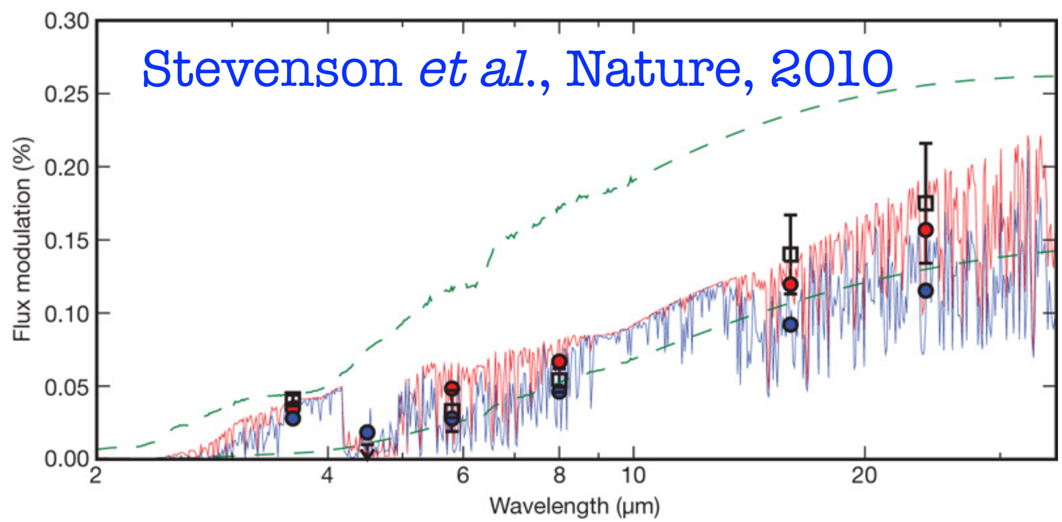
Degeneracy of solutions



Beaulieu *et al.*, 2010

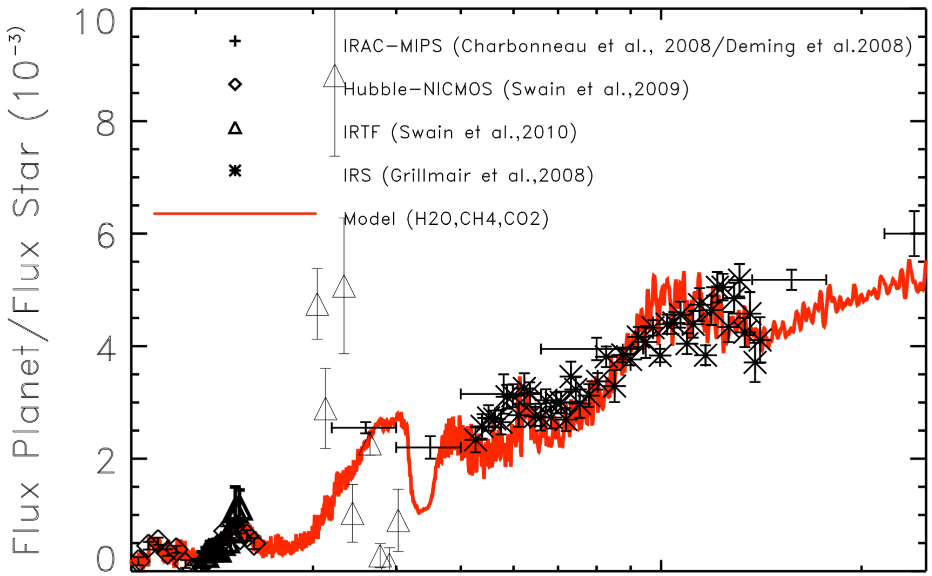
Methane-rich atmosphere or methane poor?

Spectroscopy needed!

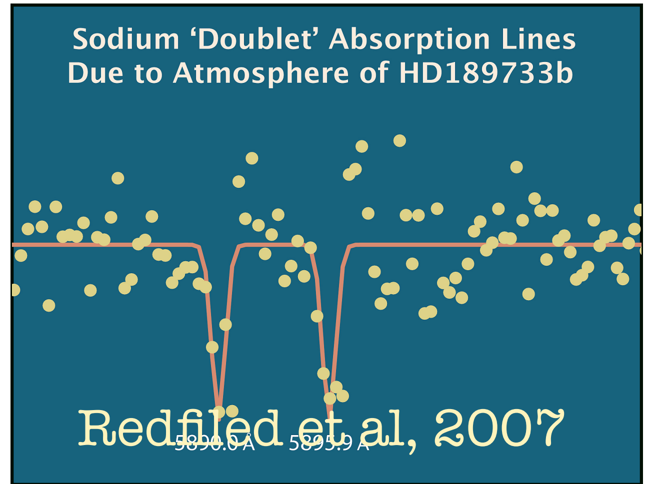



The ground
revolution

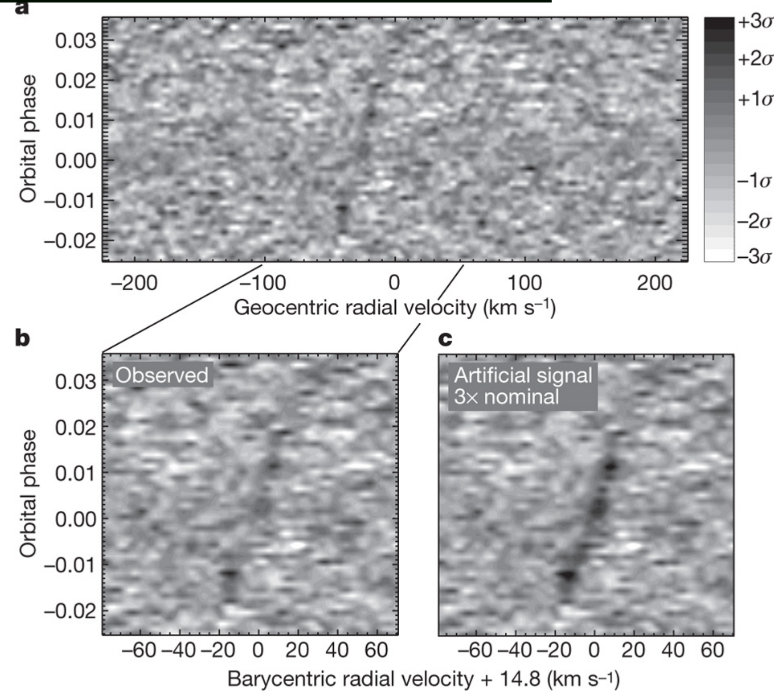
Ground-based spectroscopy



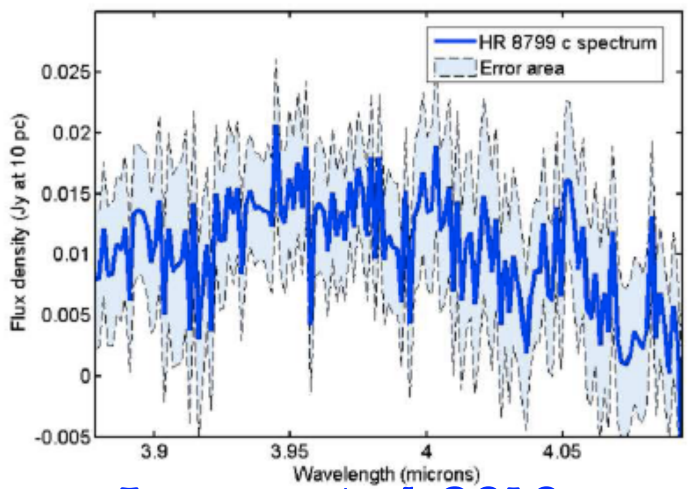
Swain, et al., *Nature*, 2010



Redfiled et al, 2007



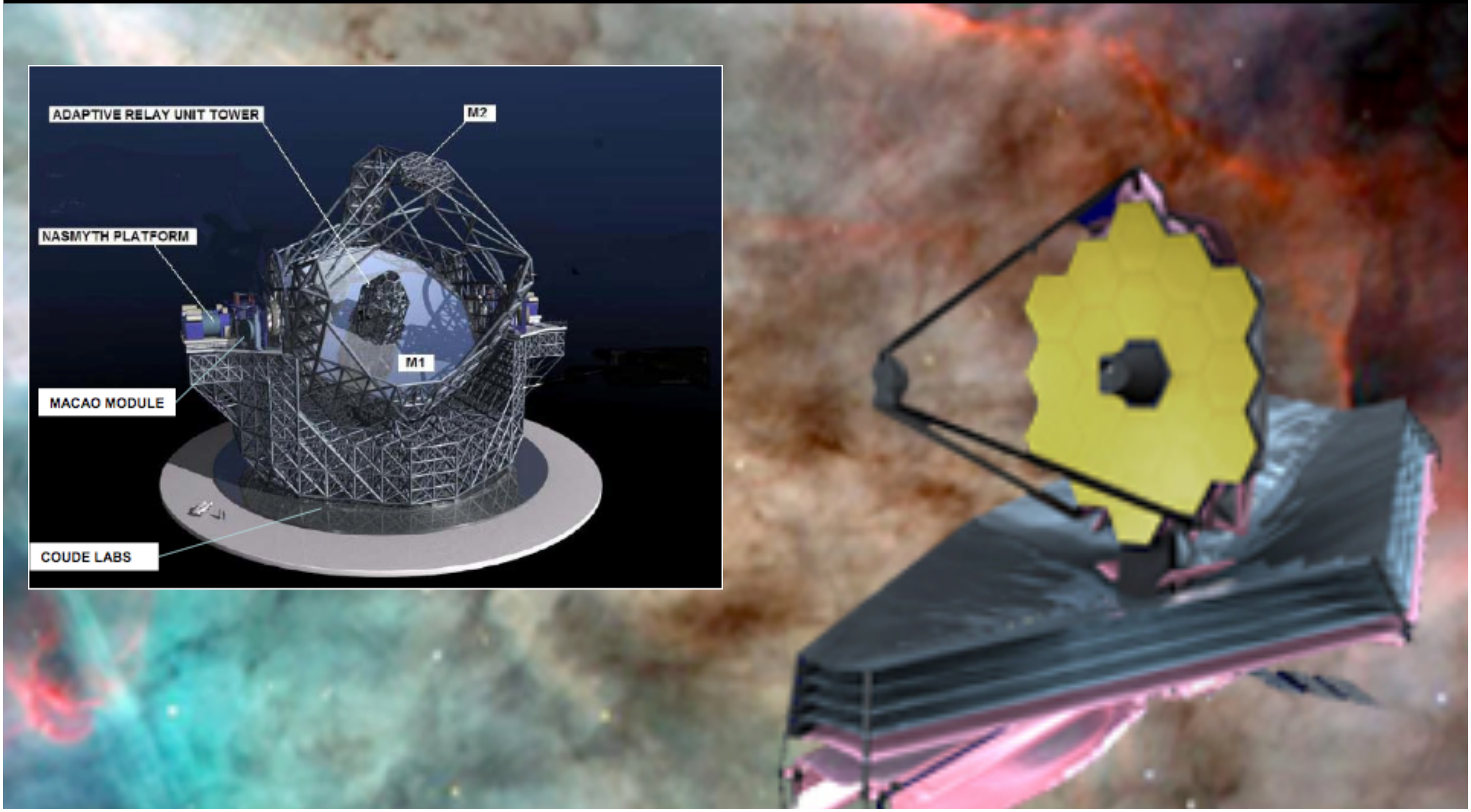
Snellen *et al.*, Nature, 2010



Janson *et al*, 2010


Next decade:
more Super-earths!

Next generation of ground and space-based telescopes



Medium size space telescope + Coronograph

✓Access: coronagraphs for exoplanet missions (John Trauger)

✓Davinci, Dilute Aperture VIsible Nulling Coron. Imager(Michael Shao)

✓EPIC: directly imaging exoplanets orbiting nearby stars (Mark Clampin)

✓PECO: refining a Phase Induced Amplitude Apodization Coronograph (Olivier Guyon)

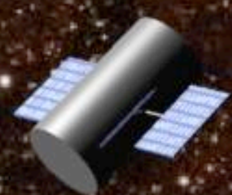
?

SEE

Super Earth Explorer

Occulter

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.

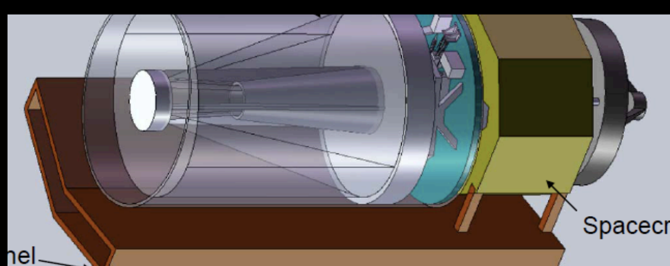


Cash, *Nature*, 2006

Mission for combined light

- European version of THESIS (M-class)

- 0.5-16 (28) micron spectroscopy of planet+star
- Giants, Neptunes, Super-earths in Hab. Zone M-stars



Conclusions

- We find water vapour, methane, CO, CO_2 present in the Hot-Jupiters analysed
- 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
- Favorable Neptunes and Super-Earths can already been studied with transit technique