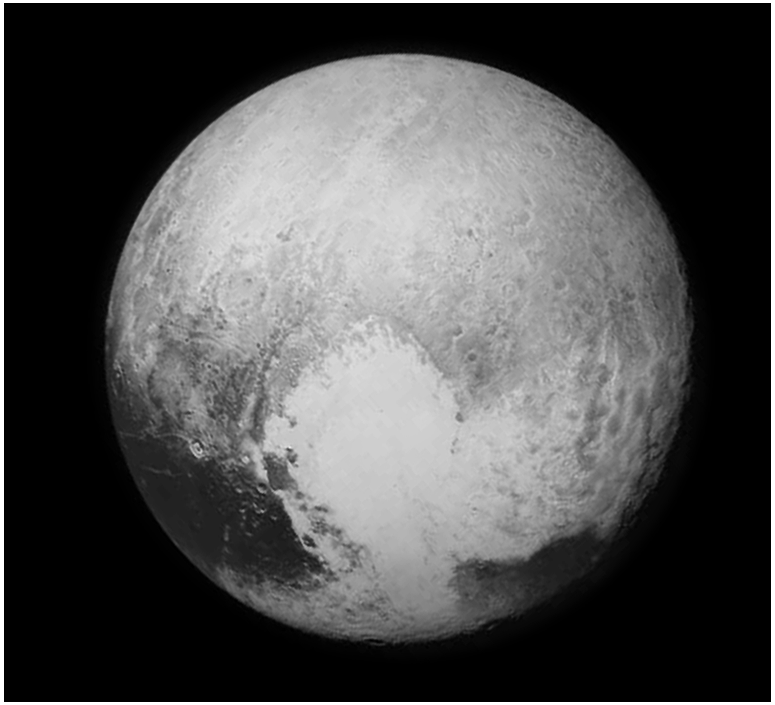
The exploration of exoplanets: What can we learn from solar system synergies?



Pluto,
New Horizons
July 13, 2015

Thérèse Encrenaz

LESIA, Observatoire de Paris

Pathways to Habitable Planets – II

Bern, July 13 – 17, 2015

Outline

- Atmospheric composition: what to expect for exoplanets?
- What are we learning from transit spectroscopy?
- Infrared spectroscopy : reflected starlight and thermal emission
- Characterizing exoplanets' atmospheres: How to optimize the observations -> The ARIEL mission

Atmospheric composition of planets: carbon and nitrogen in the protosolar disk (thermochemical equilibrium)

- LOW T (HIGH P) HIGH T (LOW P)
- CH_4 + H_2O <-> CO + 3 H_2
- 2 NH_3 <-> N_2 + 3 H_2

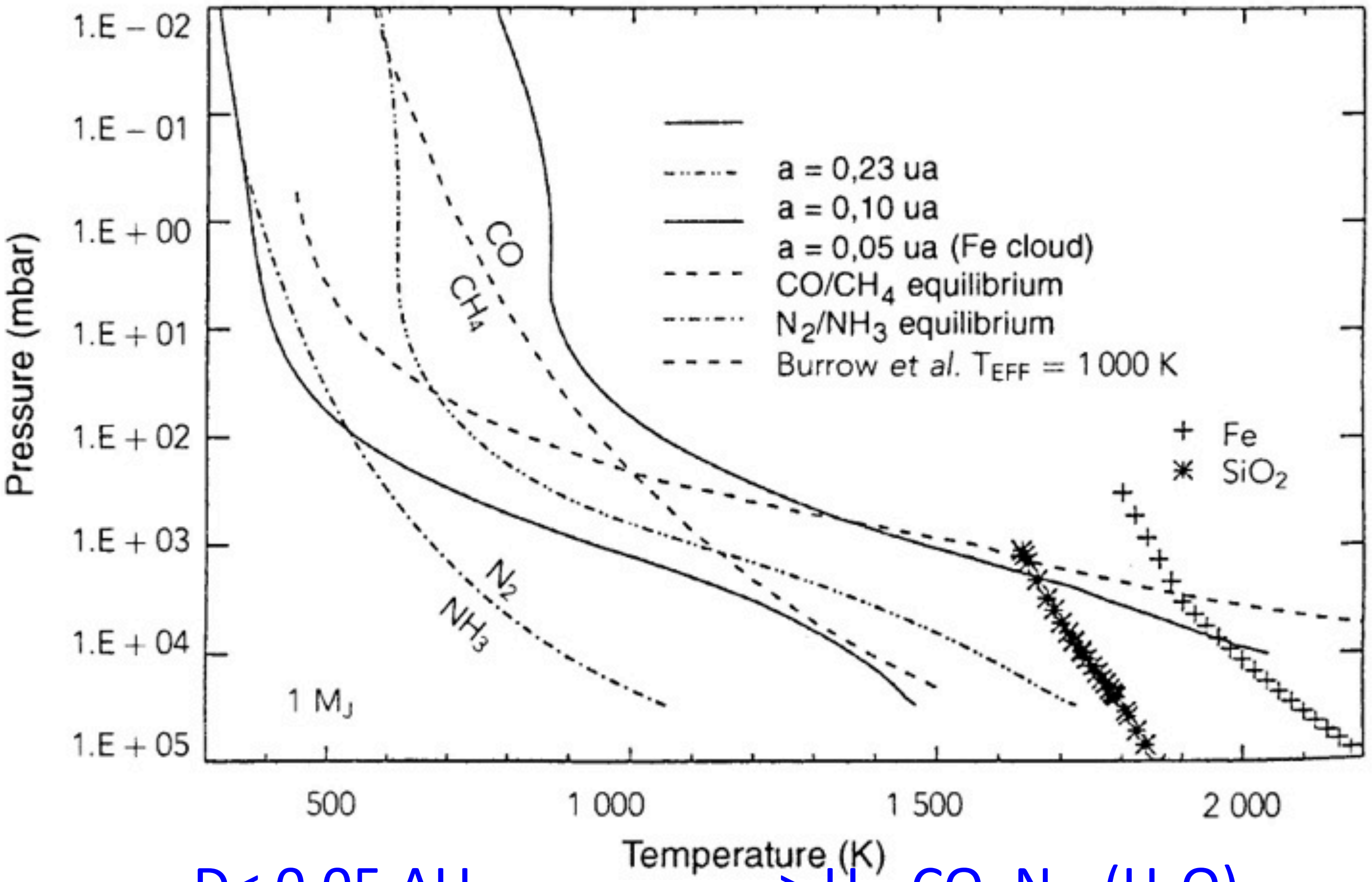
+

- CO + H_2O <-> CO_2 + H_2

Giant planets Rocky planets

-> H_2, CH_4, NH_3, H_2O -> CO_2, N_2, H_2O, CO

Atmospheric composition of giant exoplanets as a function of stellar distance D



D< 0.05 AU -> H_2, CO, N_2, (H_2O)

0.05 < D < 0.10 AU -> H_2, CO, NH_3, H_2O

D > 0.1AU -> H_2, CH_4, NH_3, H_2O

Goukenleuque et al. 1999

The solar system: A planetary inventory

- « Planets » with an atmosphere
- Rocky planets ($M < 10\ M_E$, $D <$ Snow Line)
  - Mars/Venus-type (CO_2, $N_2 + H_2O$)
  - Earth-type (N_2, $O_2 + H_2O$)
- Icy planets ($M < 10\ M_E$, $D >$ Snow Line)
  - Titan/Triton/Pluto-type (N_2, $CH_4 + CO$)
- Giant planets ($M > 10\ M_E$, $D >$ Snow Line)
  - Jupiter-type (H_2, CH_4, $NH_3 + H_2O$)
  - Neptune-type (H_2, CH_4)
- Bare « planets »
- Mercury/asteroid-type (refractories) ($M < M_E$, $D <$ Snow Line)
- TNO-type (ices) ($M < M_E$, $D >$ Snow Line)

Exoplanets: Which atmospheric composition?

- Known parameters: mass, stellar distance, stellar type
- Estimate of the equilibrium temperature:

$$[F^*/D^2](1\text{-}a) = 4\,\sigma\,Te^4$$

- -> Position wrt the snow line (SL)
  - SL: About 180 K at the time of planetary formation (H_2O condensation)
  - >D = 3-4 AU at the time of solar system formation (T about 130 K today)
- -> Estimate of the atmospheric composition

What kind of atmosphere can we expect?
(Solar-type star)

Te (K) 1200 850 460 220 | 120 50

Stellar dist. 0.050.1 0.3 1.5 | 5.0 20.0

(AU)

Small Exoplanet < ROCKY PLANETS > | <ICY PLANETS >

(0.1 - 10 M_E) Mars/Venus-type | Titan-type

(CO_2, N_2, CO, H_2O) | (N_2, CH_4, CO)

Earth-type |

(N_2,O_2+H_2O ocean) |

Giant Exoplanet <HOT JUPITERS> | < GASEOUS > <ICY GIANTS>

(10 - 1000 M_E) | GIANTS

| Jupiter-type Neptune-type

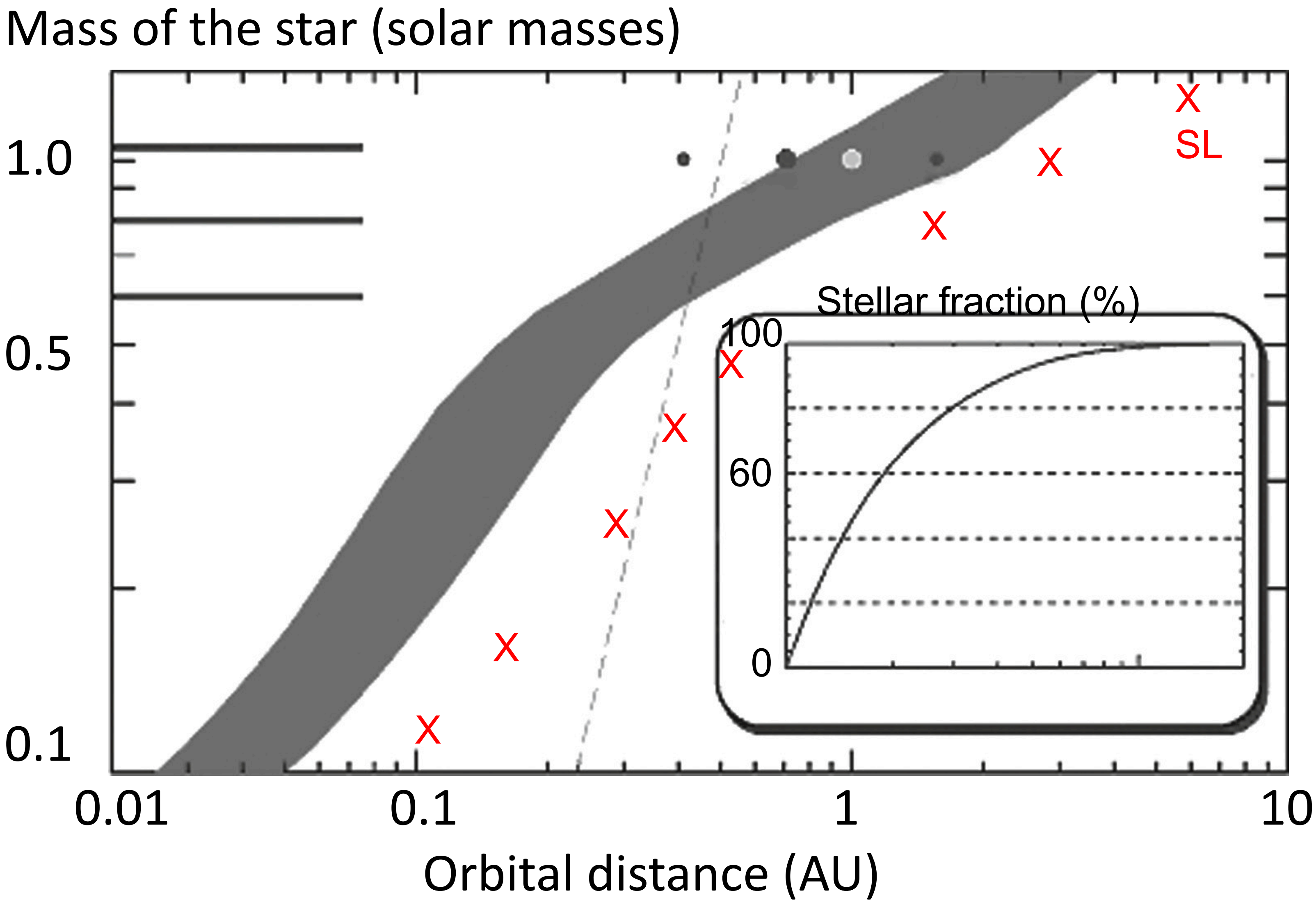
H_2,CO,N_2,H_2O | H_2,CH_4,NH_3,H_2O H_2,CH_4

SNOW LINE, T = 180 K

NB: Very simple model

(Static model at thermochemical equilibrium, no migration)

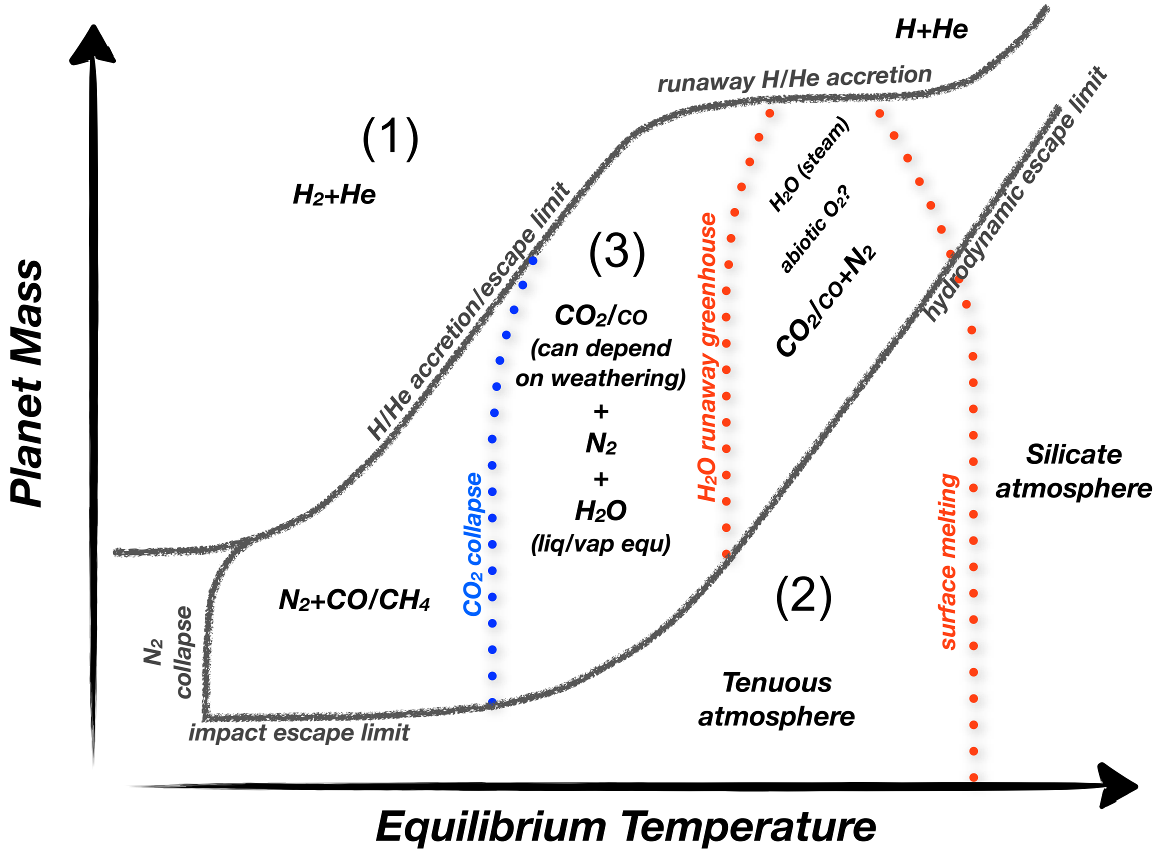
Position of the snow line for various stellar types
T(SL) = 180 K



Exoplanets: Which atmospheric composition?

Three main classes of atmospheres:

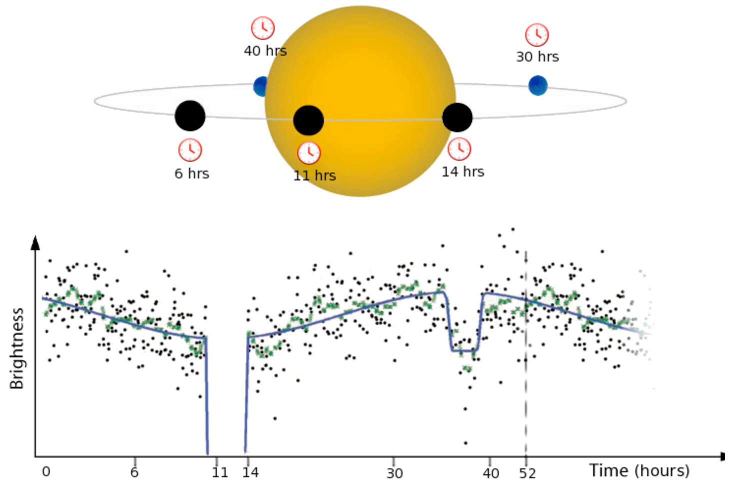
- (1) H/He dominated (massive planets)
- (2) Thin silicate atmospheres(rocky planets)
- (3) $H_2O/CO_2/N_2$ atmospheres (formation close to the snow line)



Forget & Leconte 2014
Leconte et al 2014
Tinetti et al 2014

Transit spectroscopy of an exoplanet: An emerging field

- Primary transits
  - Transmission spectroscopy
  - Probes the upper atmosphere at terminator
- Secondary transits
  - Direct emission (reflected or thermal)
  - Probes the dayside of the atmosphere



Primary Transit

Secondary Transit

- Present observational means: mostly space (HST, Spitzer) + ground-based observations
- 2 main targets HD209458b and HD189733 b + others

Primary transits

Amplitude of the absorption:

$A \sim 5 \times [2R_pH/R*^2]$

$H = RT_e/\mu g$

$g = GM_P/R_P^2$

$= 25\ M_J/R_P^2$ (Jovian units)

$T_e = (1-a)^{0.25} \times 331.0 \times [T*/5770.] \times R*^{0.5}/D^{0.5}$

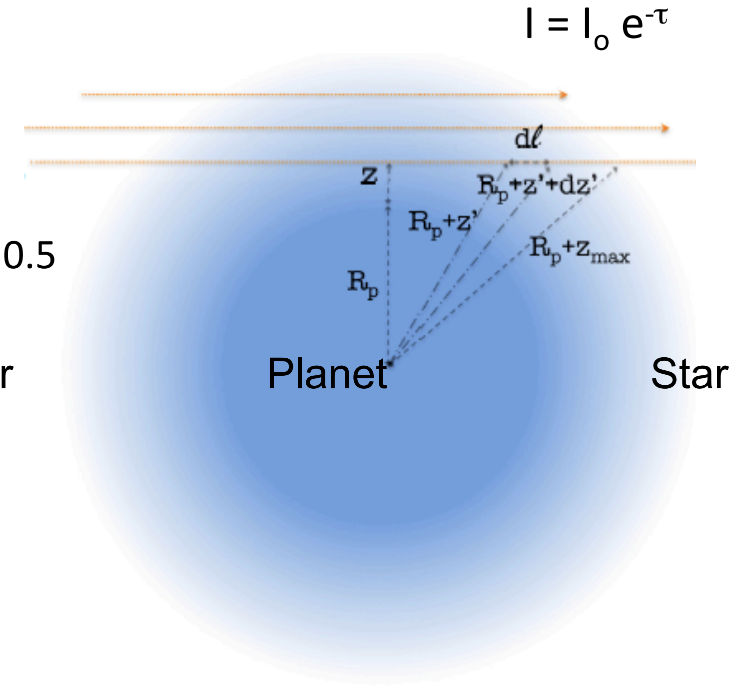
$\mu = 2.4$ (for a H_2-He atm.)

-> $A = 1.4 \times 10^{-6} \times R_P \times H/R*^2$

-> Favourable for **hot, inflated Jupiters** (typically a few 10^{-4})

<- Observer

->



Detection of atmospheric species (always in absorption):

Na, K, H, Cs, haze (visible, HST)

H_2O, CO, CO_2, CH_4 (IR, HST + Spitzer)

Synthetic transmission spectra of hot Jupiters

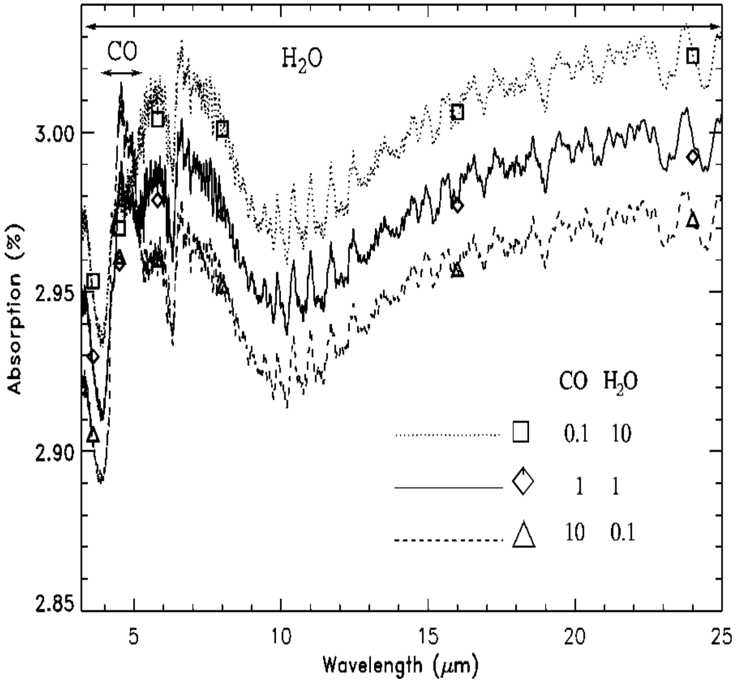


Fig. 2*a*

HD189733b

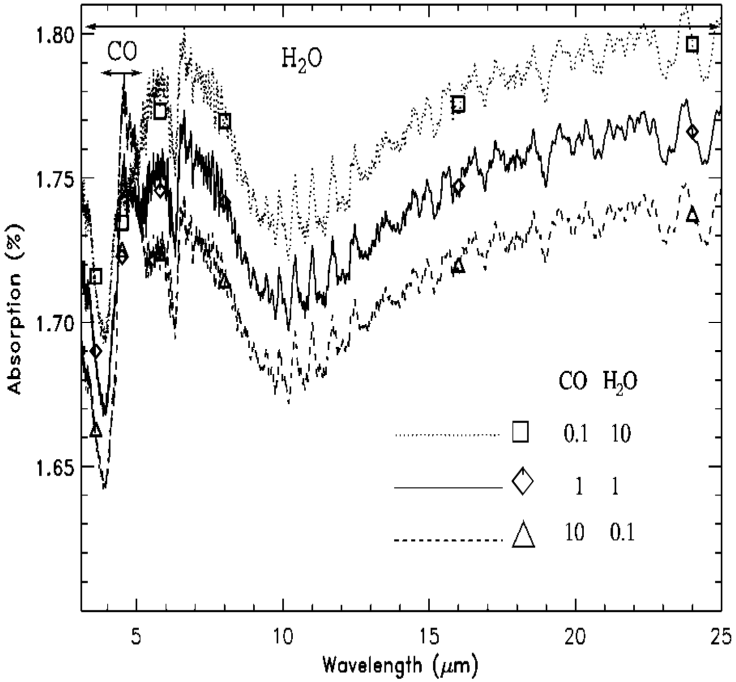
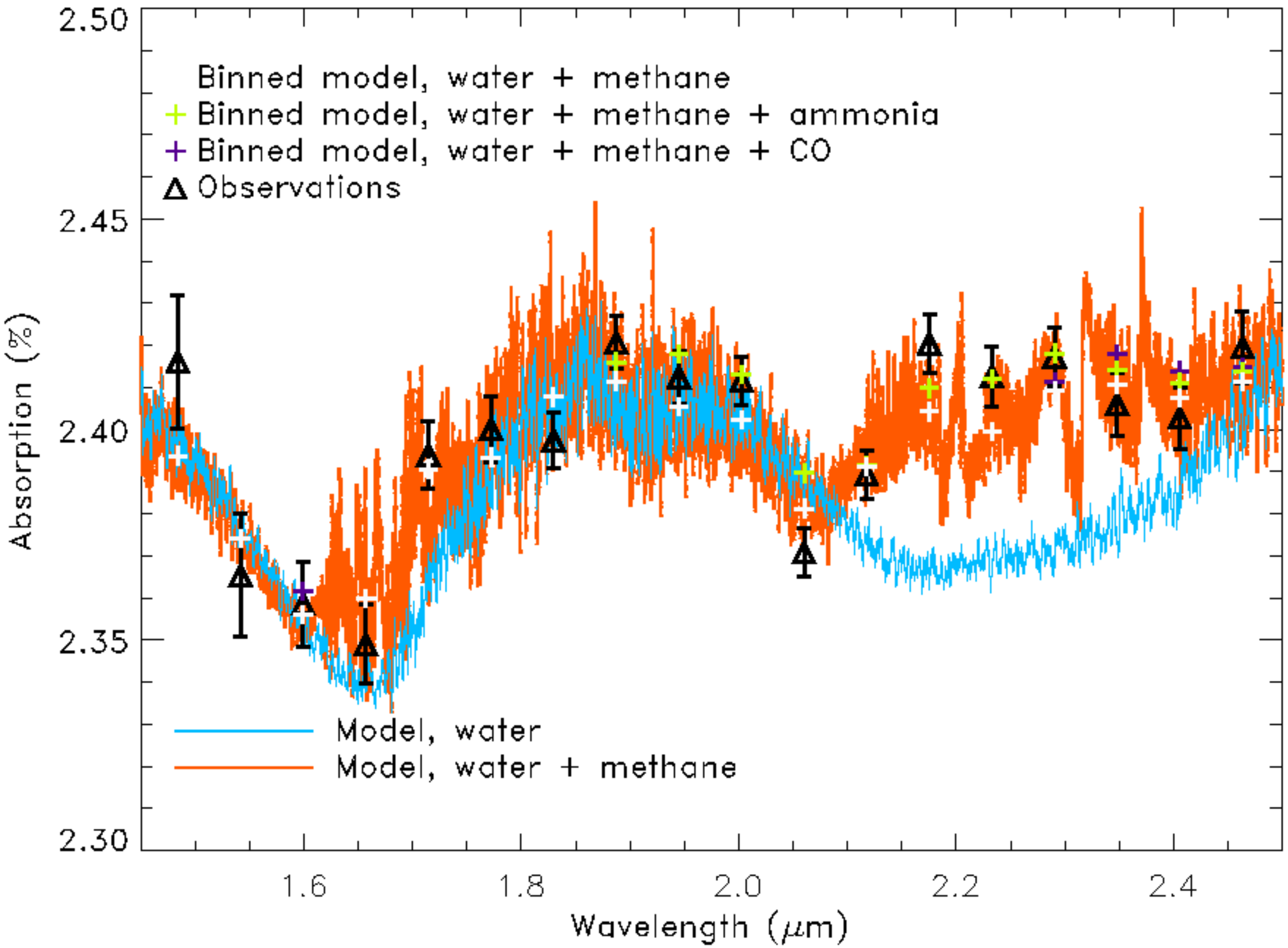


Fig. 2*b*

HD209458b

G. Tinetti et al. ApJ 2007

Primary transit, HD189733b – Data: HST NICMOS



Swain, Vasisht, Tinetti, *Nature*, 2008

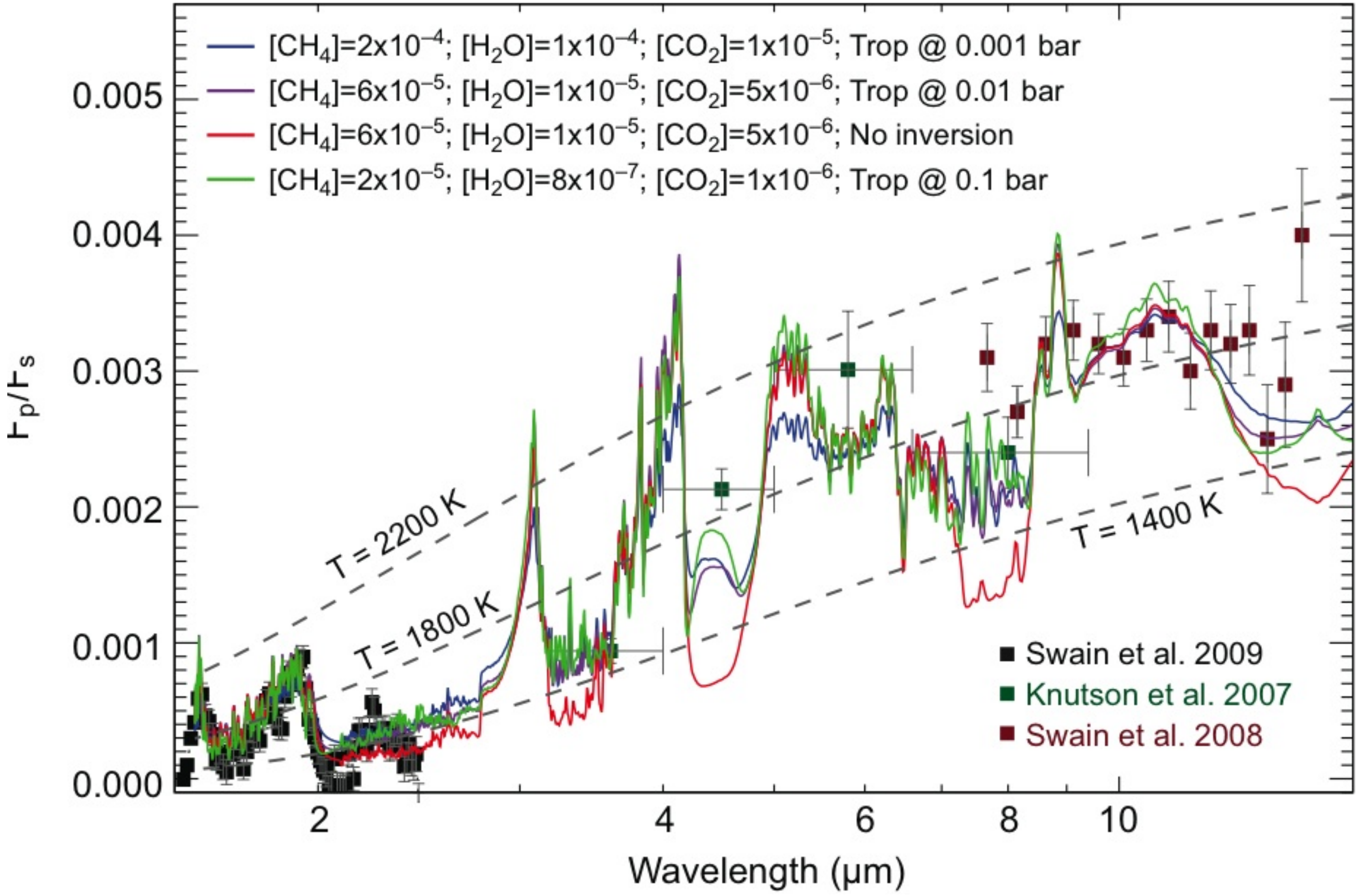
Secondary transits

- The dayside of the planet is observed directly

$$F_{II}(\lambda) = \left(\frac{R_p}{R_\star}\right)^2 \frac{F_p(\lambda)}{F_\star(\lambda)}$$

- In the case of hot exoplanets, the thermal component dominates beyond 1μm
  - > Two possible approximations in the thermal regime:
  - $\rho 1 = [R_P/R^*]^2 \times [T_e/T^*]^4$ (λ = 1-2 μm) (a few 10^{-4})
  - $\rho 2 = [R_P/R^*]^2 \times [T_e/T^*]$ (λ > 20 μm) (a few 10^{-3})
- > Favourable for **hot and massive planets transiting low-mass stars**
- **NB:** For interpreting the thermal emission, the thermal profile must be known

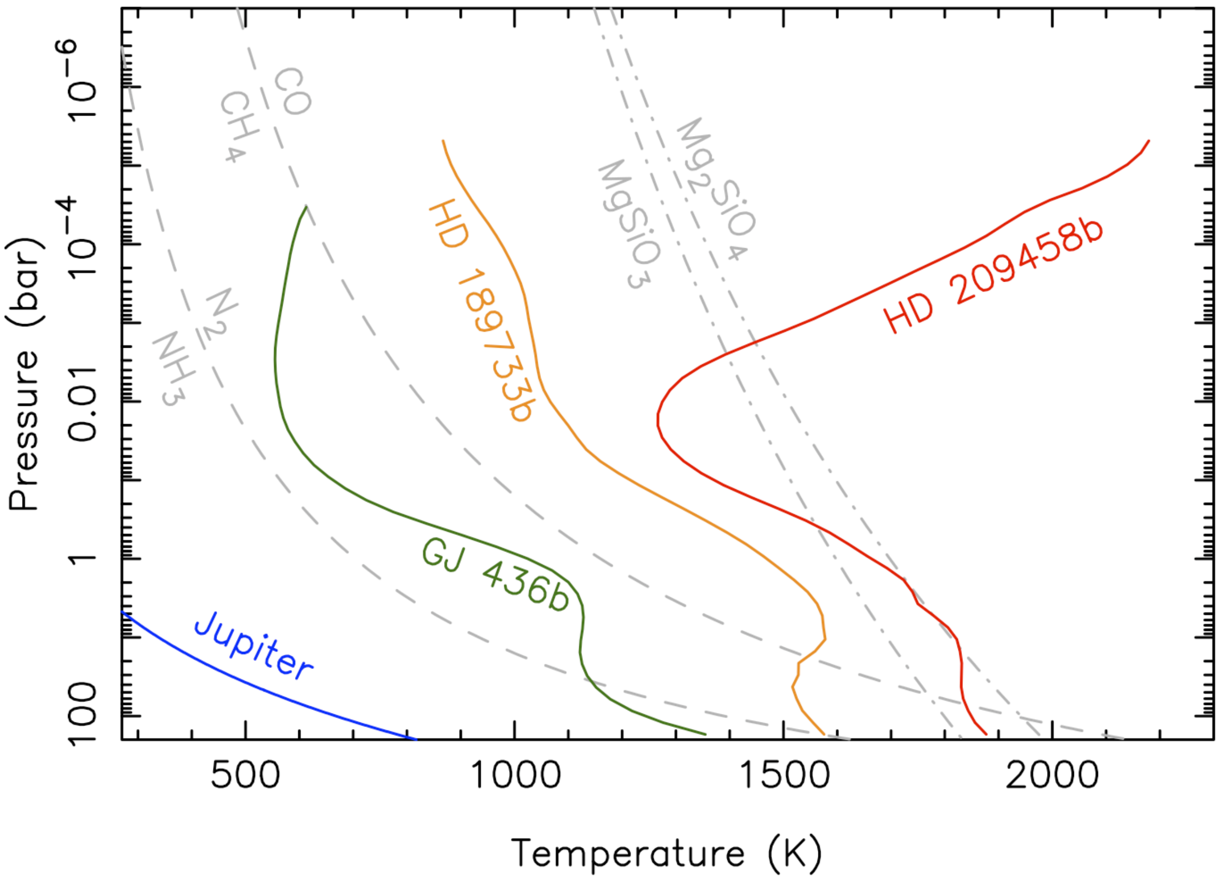
Secondary transit, HD189733b – Data: HST/Spitzer



Tinetti & Griffith, 2010

First results from transit spectroscopy on hot Jupiters:

1. Temperature inversion in some hot Jupiters
2. Departure from thermochemical equilibrium



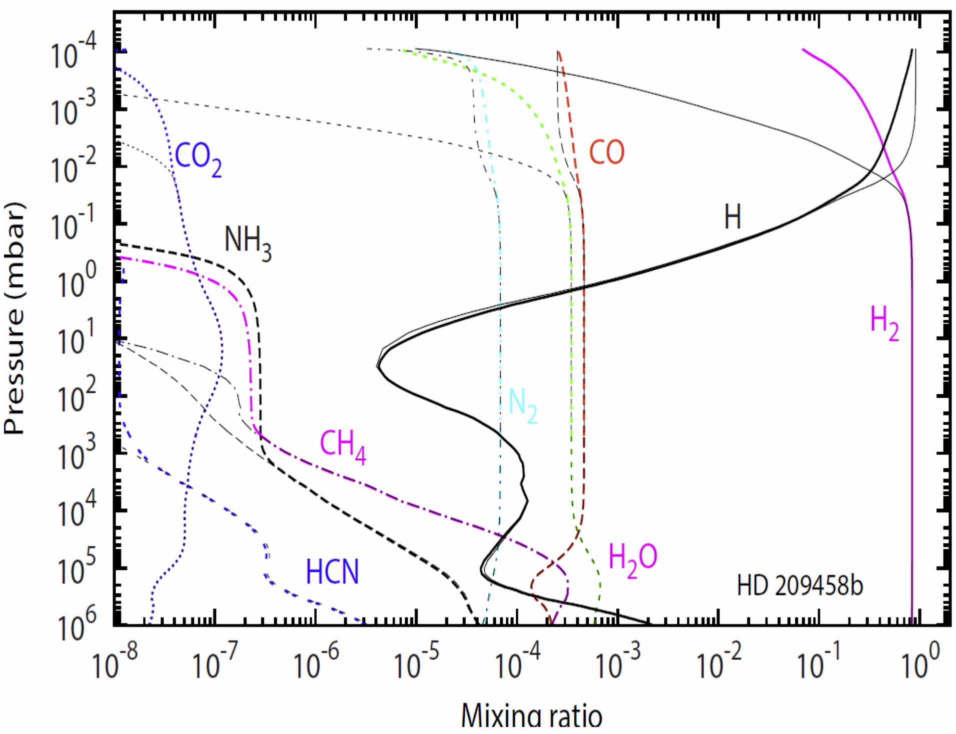
HD 189733b: CO, N_2 expected… but CH_4, H_2O, NH_3 observed

HD 209458b: CO, N_2 expected… but CH_4, CO_2 observed

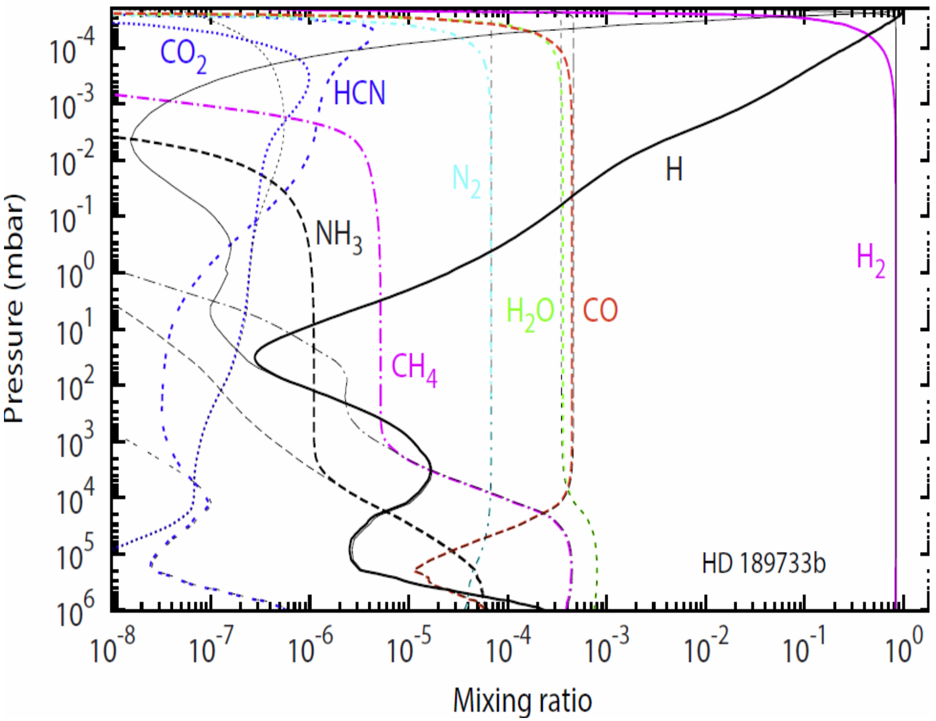
EChO Proposal, Fig. 14

Departure from thermochemical equilibrium:

1. Photolysis
2. Vertical mixing



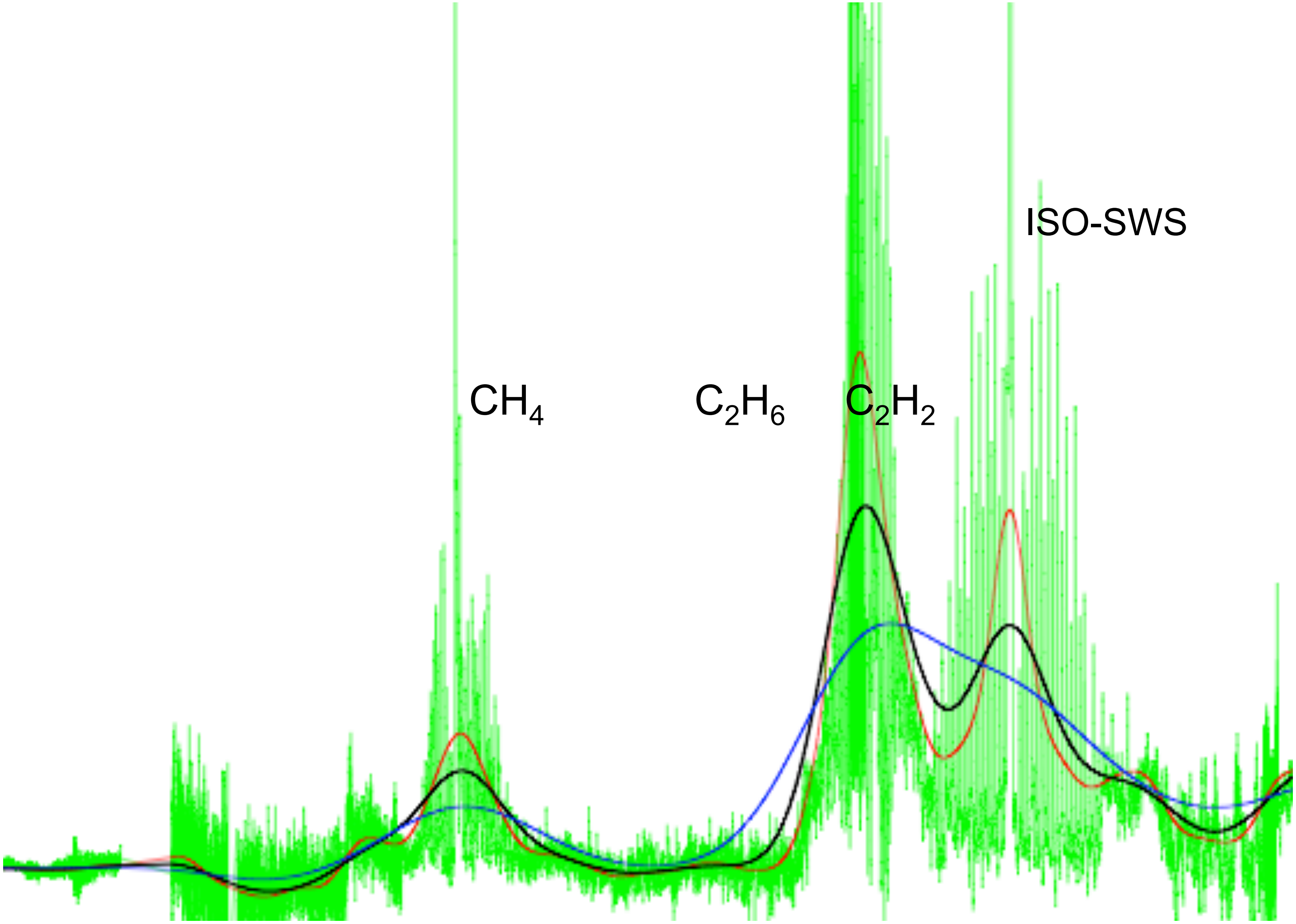
HD209458B



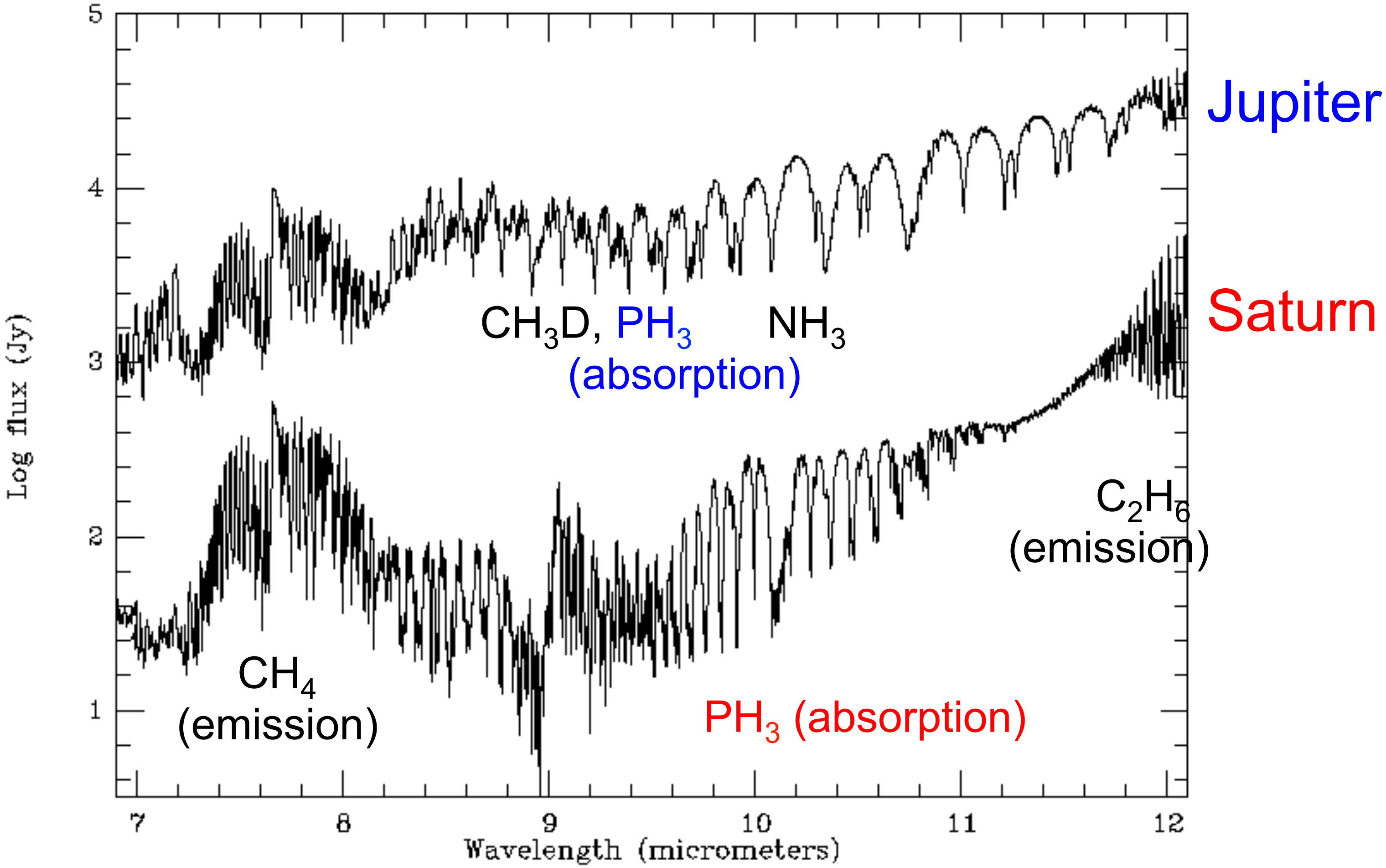
HD189733b

Venot et al. 2012

An example of photochemistry in the giant planets: Hydrocarbons in Neptune



An example of vertical mixing in the giant planets: PH_3 in Jupiter and Saturn

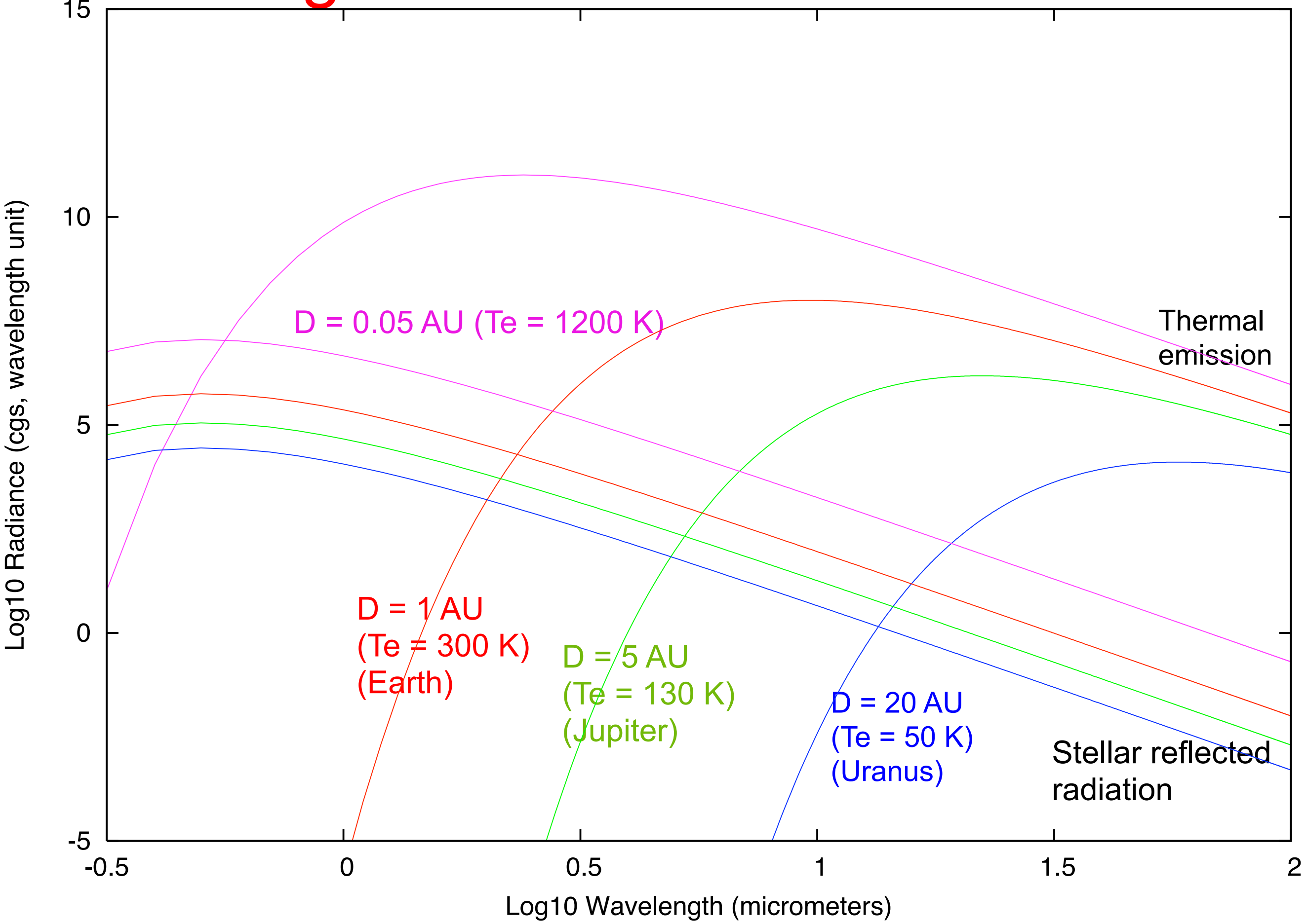


PH_3 is stronger in Saturn because the vertical mixing is stronger

Spectroscopy of an exoplanet

- Reflected starlight component (UV, visible, near-IR)
  - Albedo is about 0.3 for most of solar-system planets
  - Absorption lines or bands in front of stellar blackbody
- Thermal component (IR, submm & mm)
  - Mostly depends upon the temperature of the emitting region
  - Emission lines in the stratosphere, absorption lines in the troposphere (function of T(P))

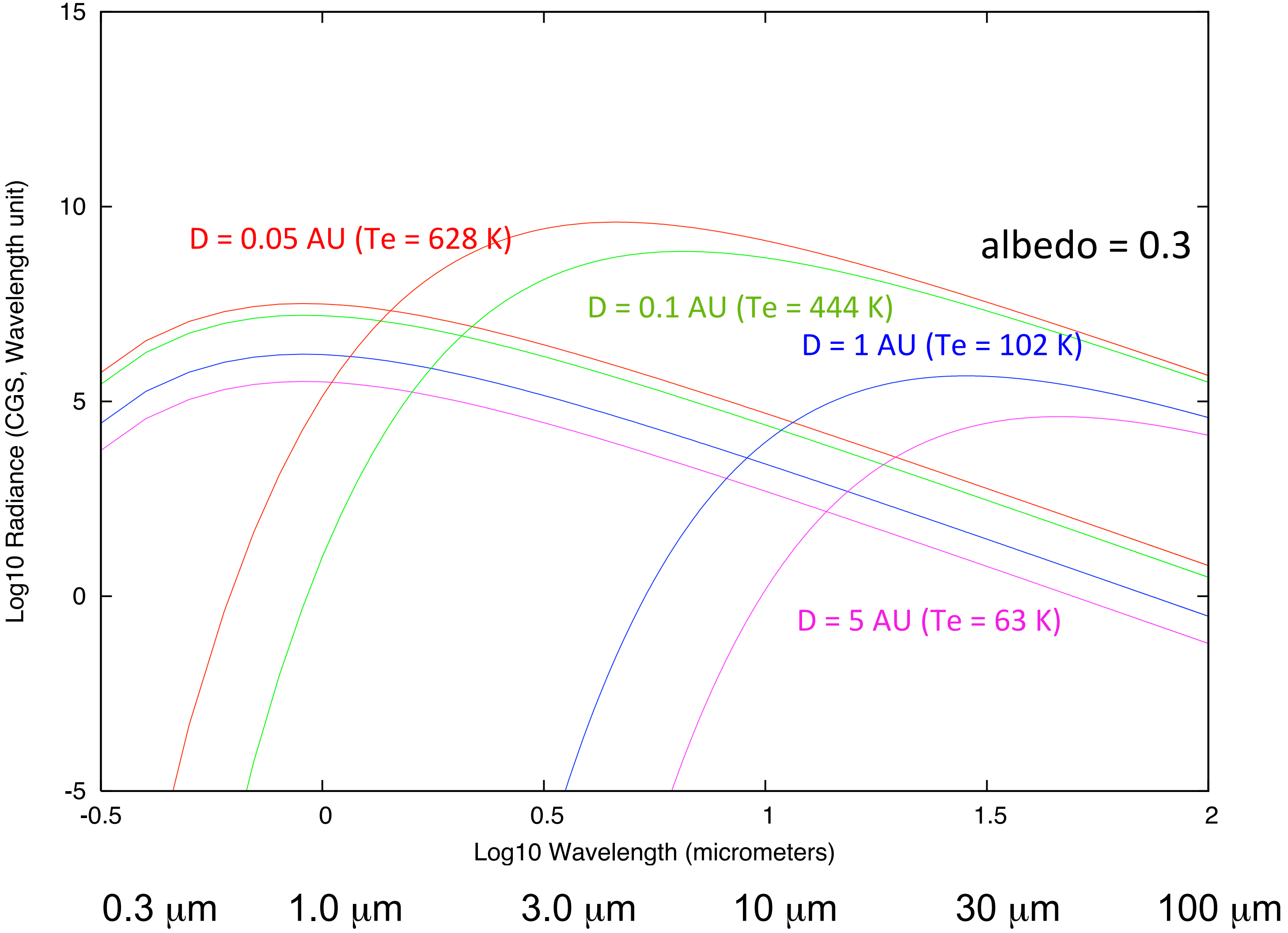
Reflected stellar light vs thermal emission - Solar-type stars



0.3 μm 1.0 μm 3.0 μm 10 μm 30 μm 100 μm

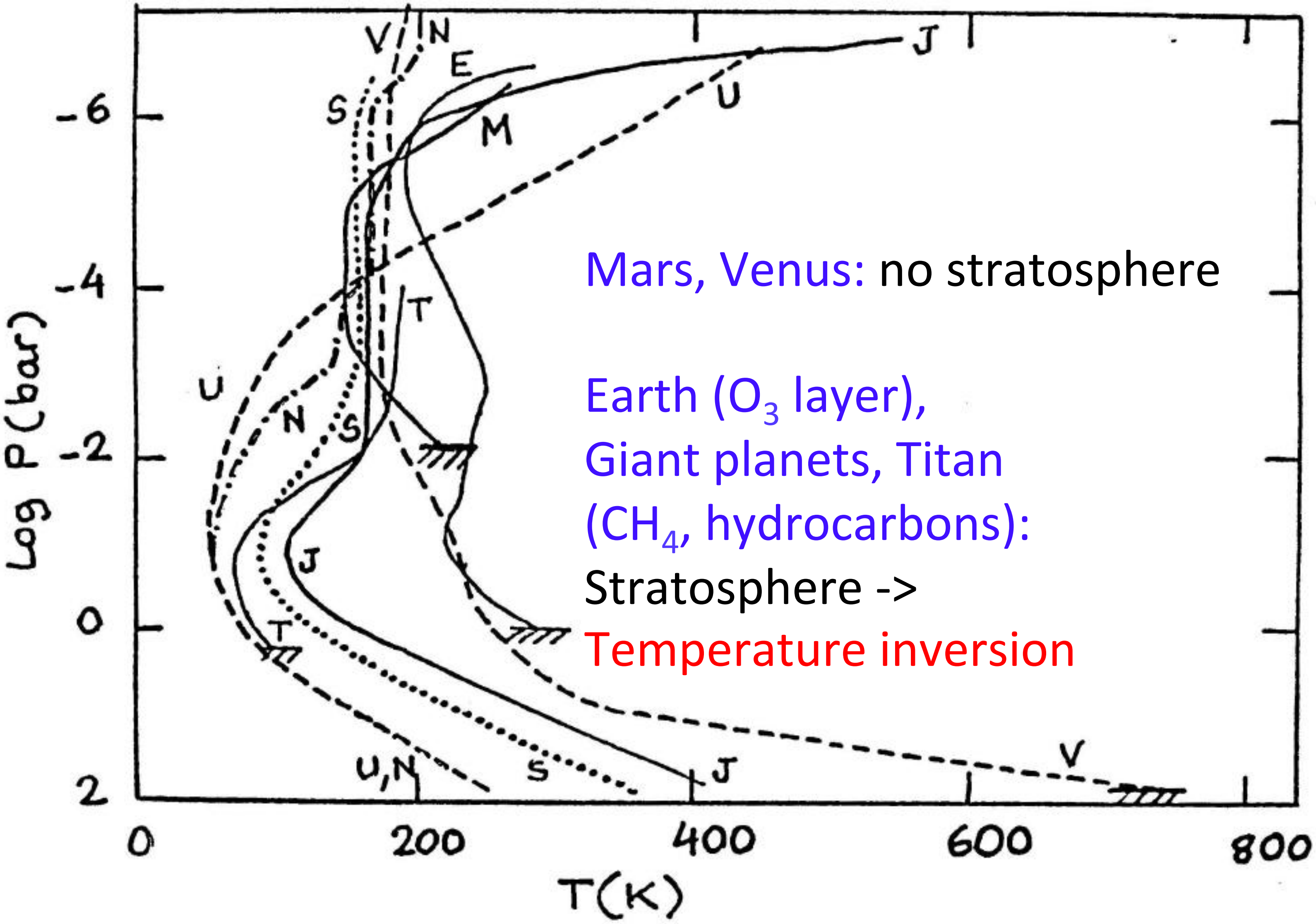
Solar-type stars: At 0.05 AU, the thermal radiation dominates even at 1 μm
At 1 AU, both radiations are equal around 3 μm

Reflected stellar light vs thermal emission: M-type stars



M-type stars: At 0.05 AU, the thermal radiation dominates above 1.5 μm
At 1 AU, both radiations are equal at 8 μm

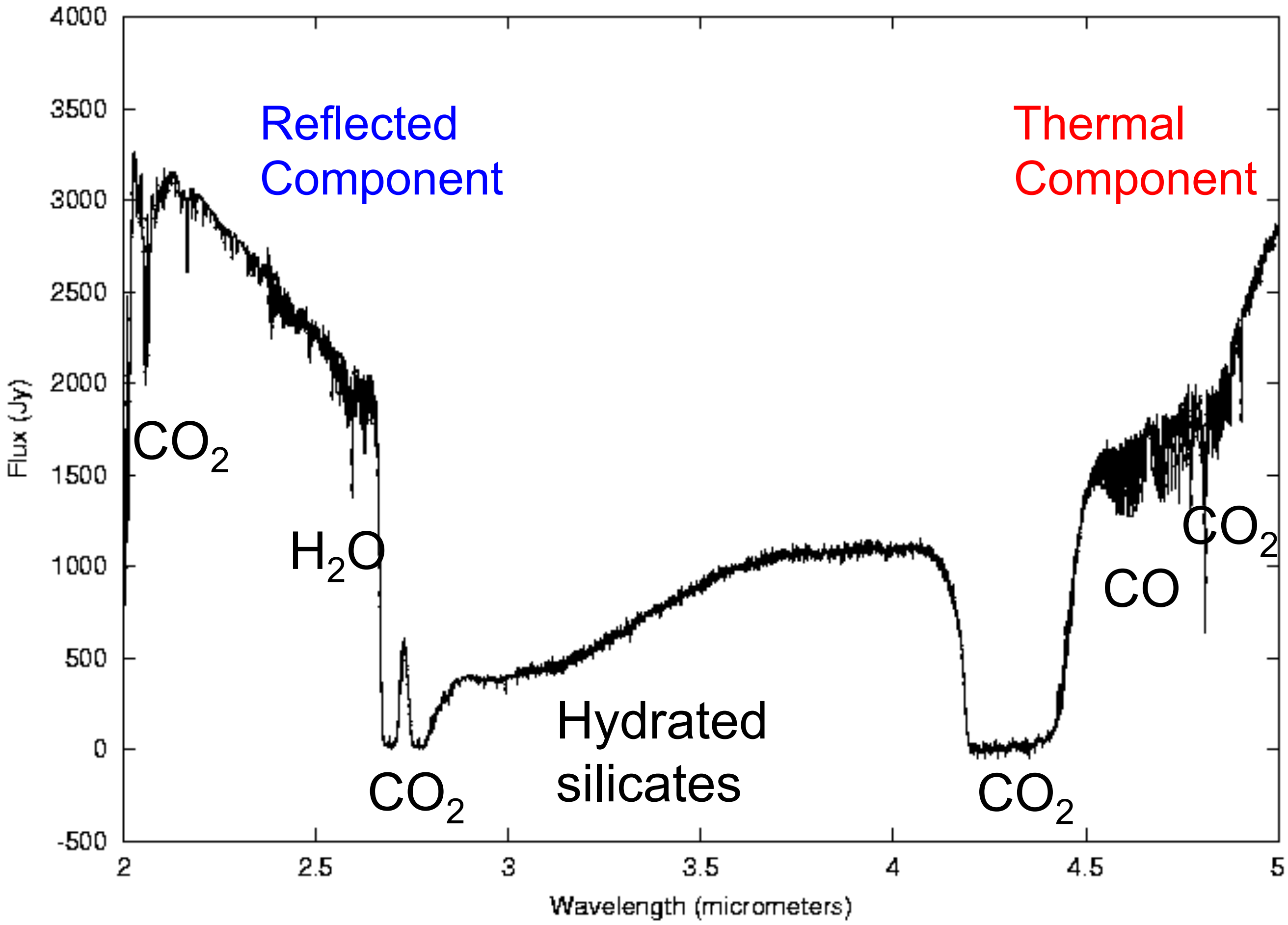
Thermal structure of planetary atmospheres



Mars, Venus: no stratosphere

Earth (O_3 layer),
Giant planets, Titan
(CH_4, hydrocarbons):
Stratosphere ->
Temperature inversion

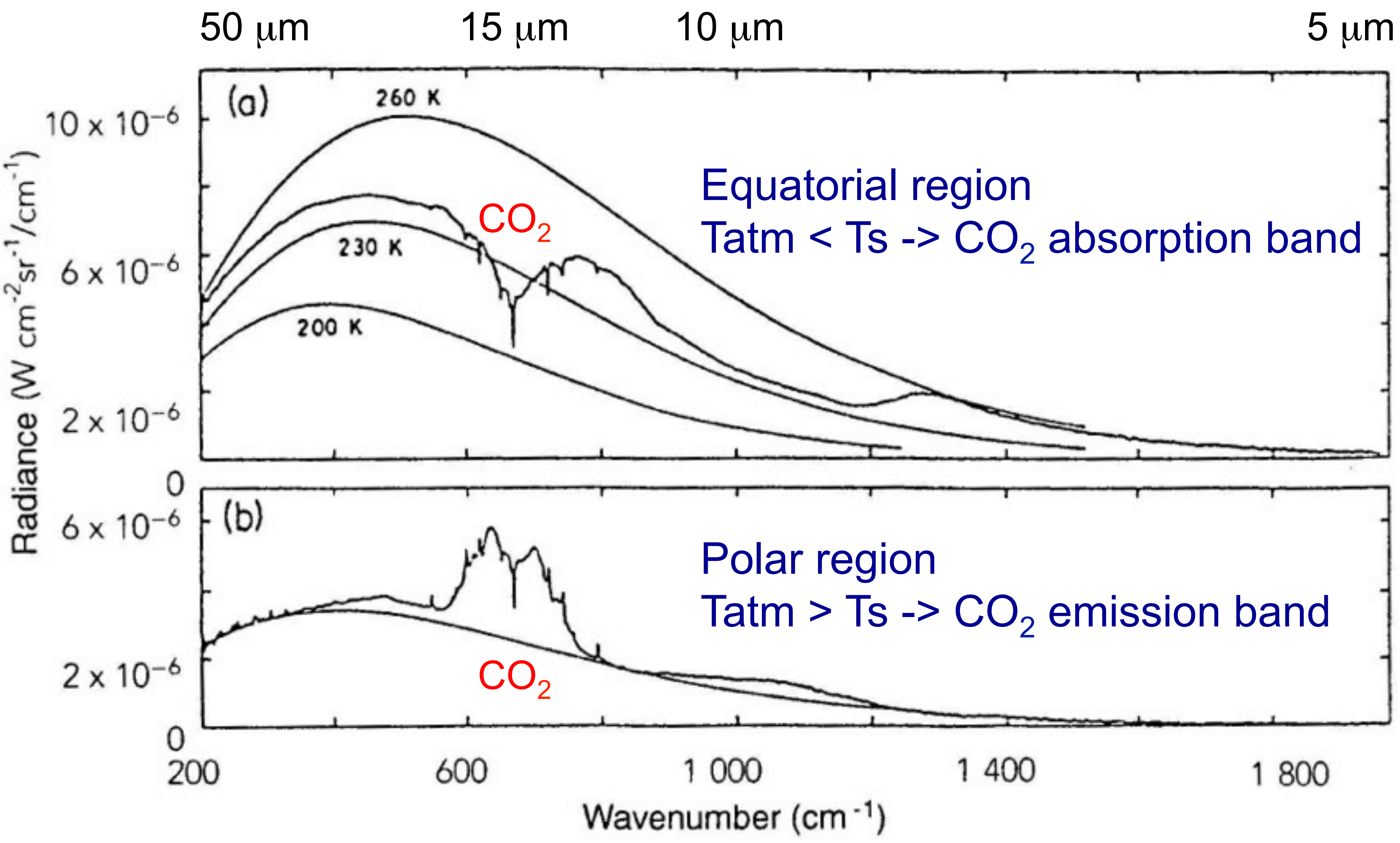
The IR spectrum of Mars (ISO-SWS)



Spectral signatures: CO_2, H_2O, CO

Lellouch et al., 2000

Thermal emission: the case of Mars



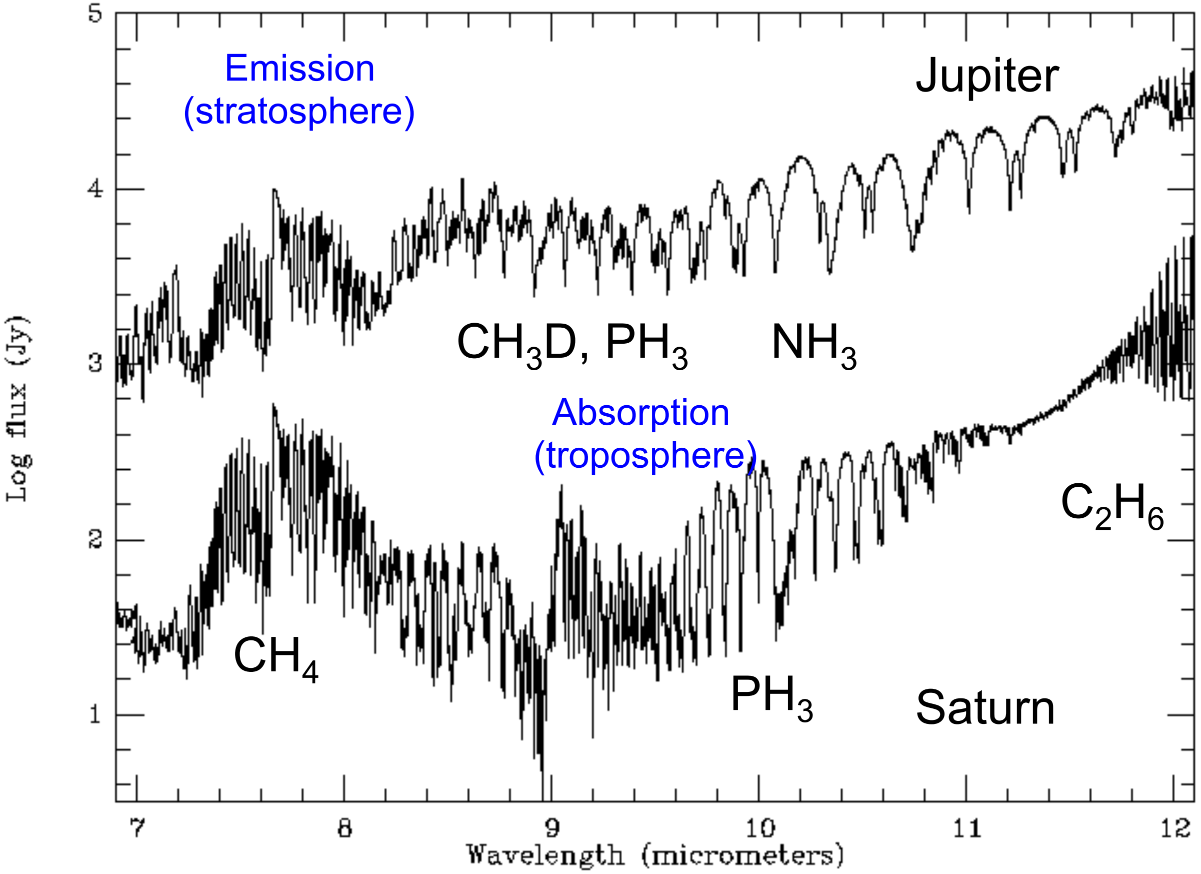
Equatorial region
Tatm < Ts -> CO_2 absorption band

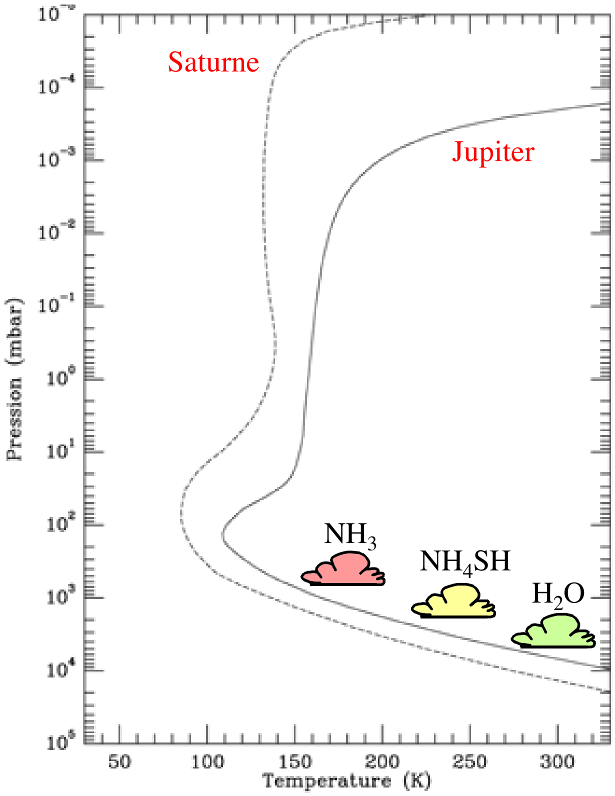
Polar region
Tatm > Ts -> CO_2 emission band

The spectrum of Mars in the thermal IR (5-50 µm)
Hanel et al., 1992

The atmosphere of two giant planets: The thermal component

Jupiter & Saturn - ISO-SWS





Knowing the thermal profile is essential for identifying molecules

How to optimize the spectroscopy of exoplanets?

- The IR range is best suited for analysing neutral species
  - UV, visible -> atoms, ions, radicals
- Include both reflected & thermal regimes
  - > Allows to remove the T(P) degeneracy
  - > In the thermal range: [Planet/Star] flux ratio increases with λ
  - > Best choice : 1 -20 μm
- Observe several bands of the same molecule
  - > Different band strengths probe different atmospheric levels
- Separate adjacent components of a given molecular band
  - > Constraint on the resolving power

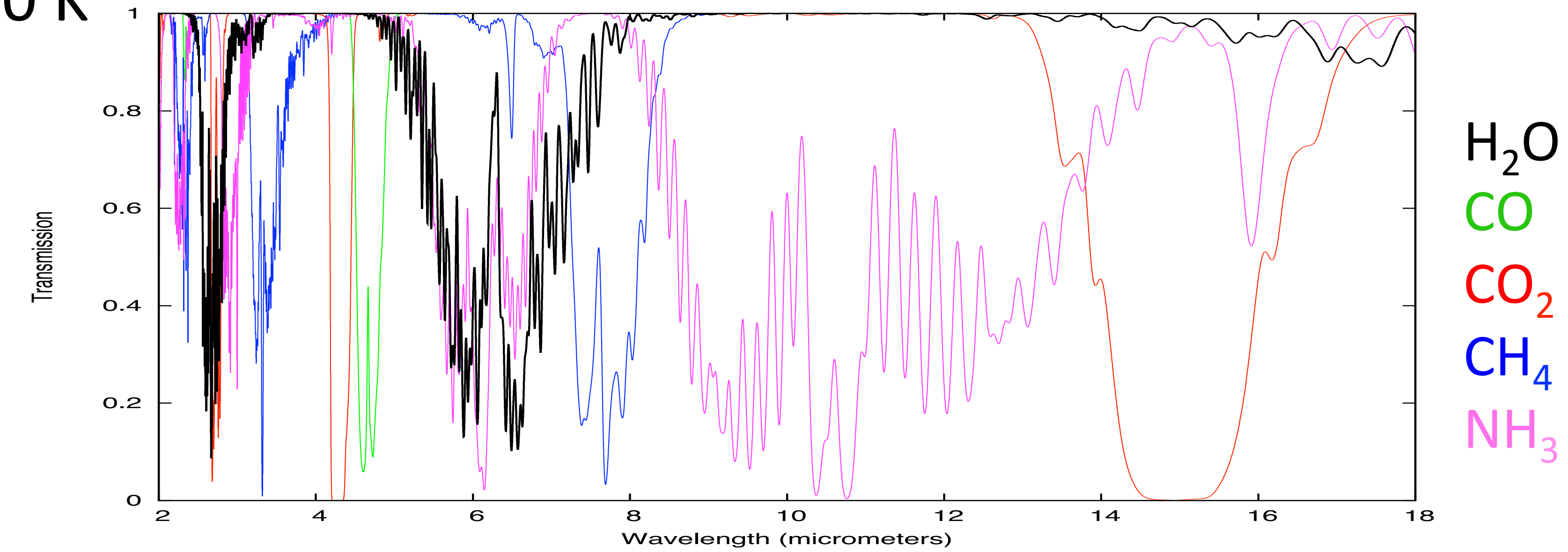
An inventory of expected signatures

	1-5 μm	6-30 μm
• H_2O	1.38, 2.69	6.2, >20
• CO_2	1.44, 2.0, 4.25	15.0
• CO	2.35, 4.7	
• CH_4	1.65, 2.2, 3.3	7.7
• C_2H_2	3.0	13.7
• C_2H_6	3.4	12.1
• NH_3	3.0, 6.1	10.5
• HCN	3.0	14.0
• H_2	2.12, 4.5	17, 28
• H_3^+	2.0, 4.0	

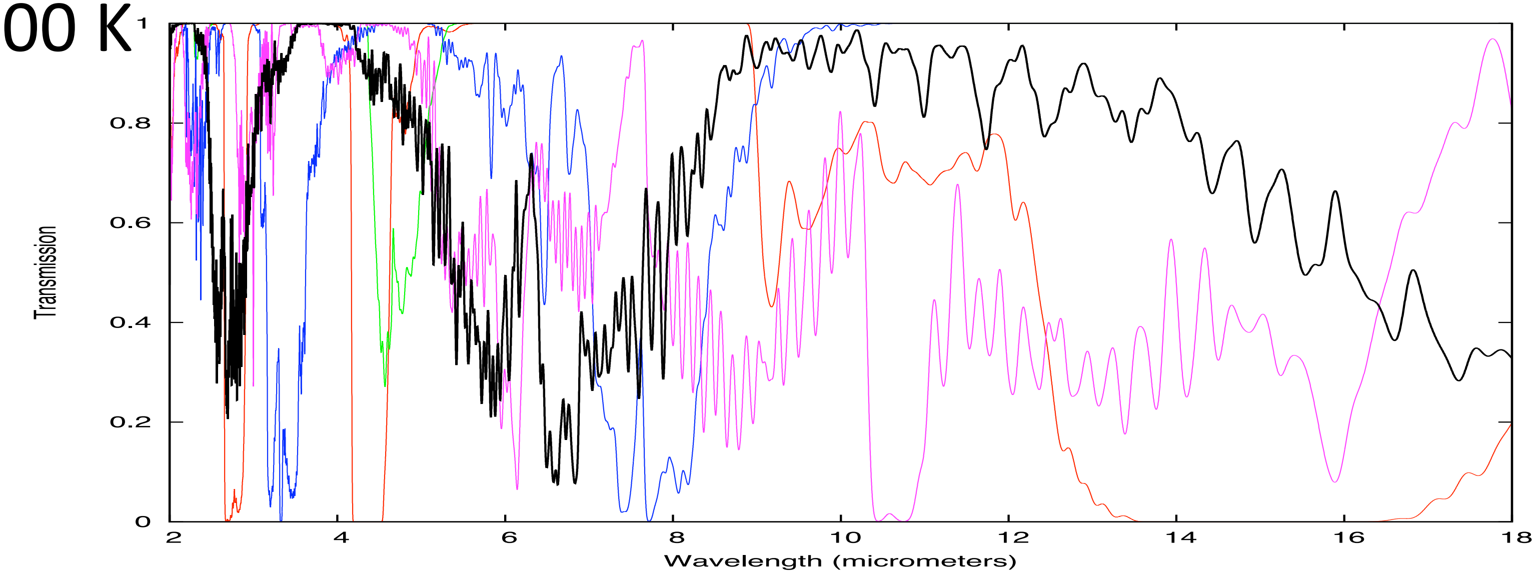
Spectral signatures of a few important molecules

(10 cm-am, P = 1bar)

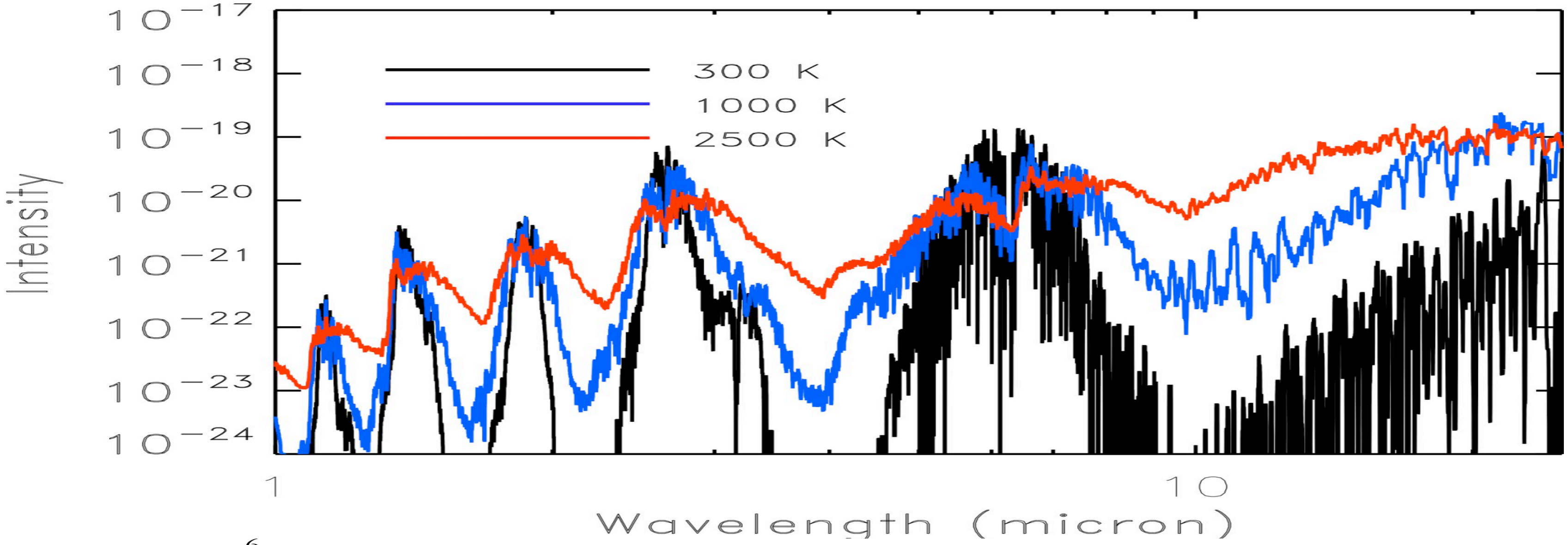
T = 300 K

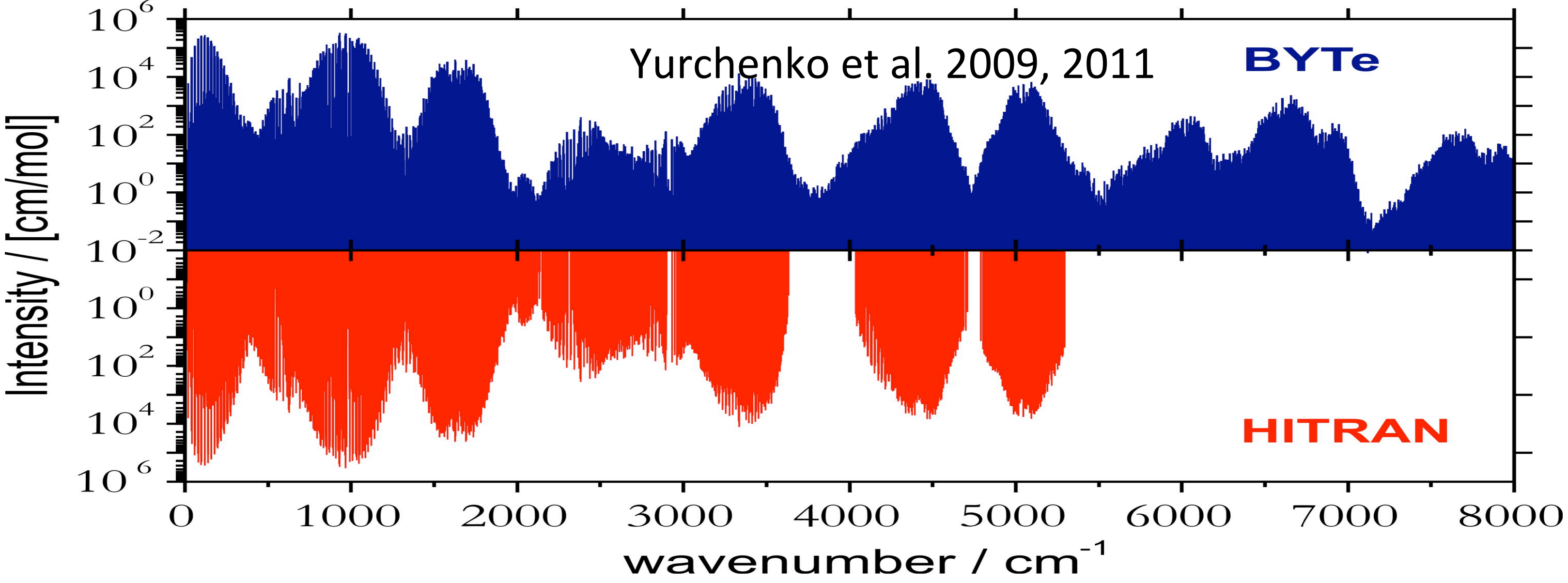


T = 1200 K



The need for a high-temperature molecular database





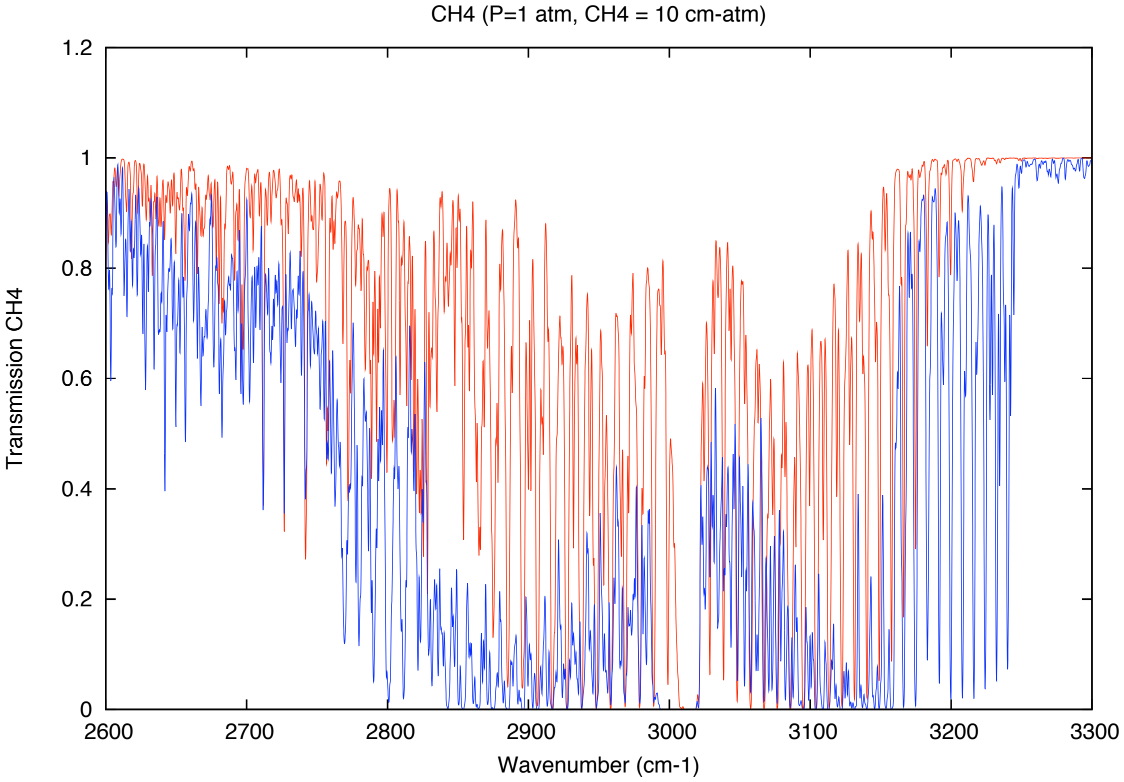
Yurchenko et al. 2009, 2011

Constraint on the spectral resolving power

- At high temperature, the molecular bands are strongly broadened
- The resolving power should allow the separation of two adjacent J-components
- R = 300 is OK for all molecules with $2B_0 > 10$ cm^{-1} (excludes CO and CO_2) (in the case of space observations)

Molecule	**$\Delta\nu = 2B_0$ (cm^{-1})**	**R**
CH_4	10	300 (3.3 μm)
CO	3.8	565 (4.7 μm)
CO_2	1.6	420 (15 μm)
H_2O	29	130 (2.7 μm)
NH_3	20	165 (3.0 μm)
HCN	3	250 (13.7 μm)
O_3	0.9	1200 (9.7 μm)

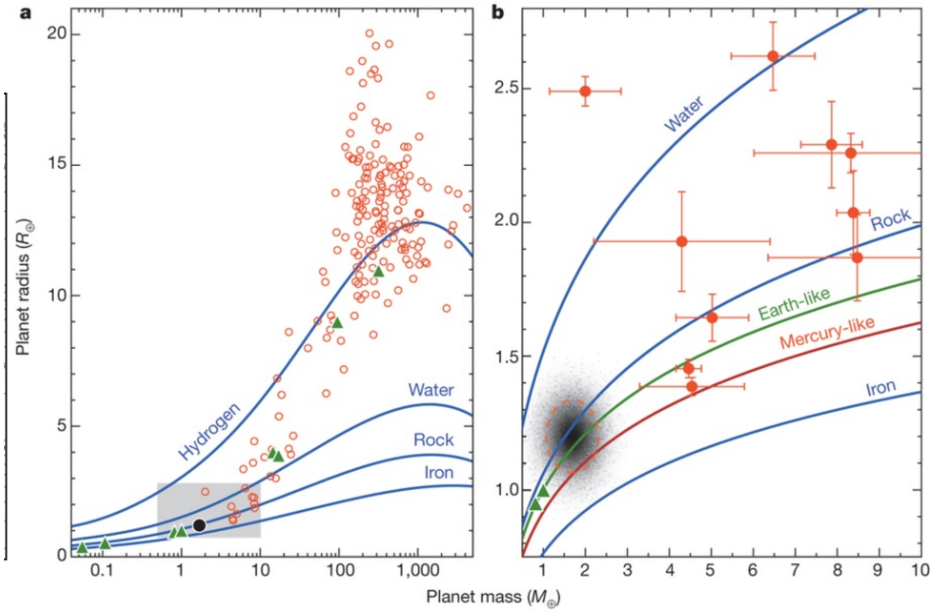
Tinettti et al. 2013



The ν_3 band of CH_4 (3.3 μm)
$\Delta\nu = 10$ cm^{-1}

The ARIEL Mission

- Cosmic Vision M4 candidate, under assessment study
- 1-m effective diameter telescope at L2
- Spectral range: 2-8 μm, R = 180
- Method: Transit spectroscopy of 150-300 exoplanets
- Targets: Gas giants -> super-Earths, hot -> temperate, F-> M stars
- 3-year mission
- **Objective: Atmospheric composition of a large sample of exoplanets**



Talk by Giovanna Tinetti on Thursday July 16

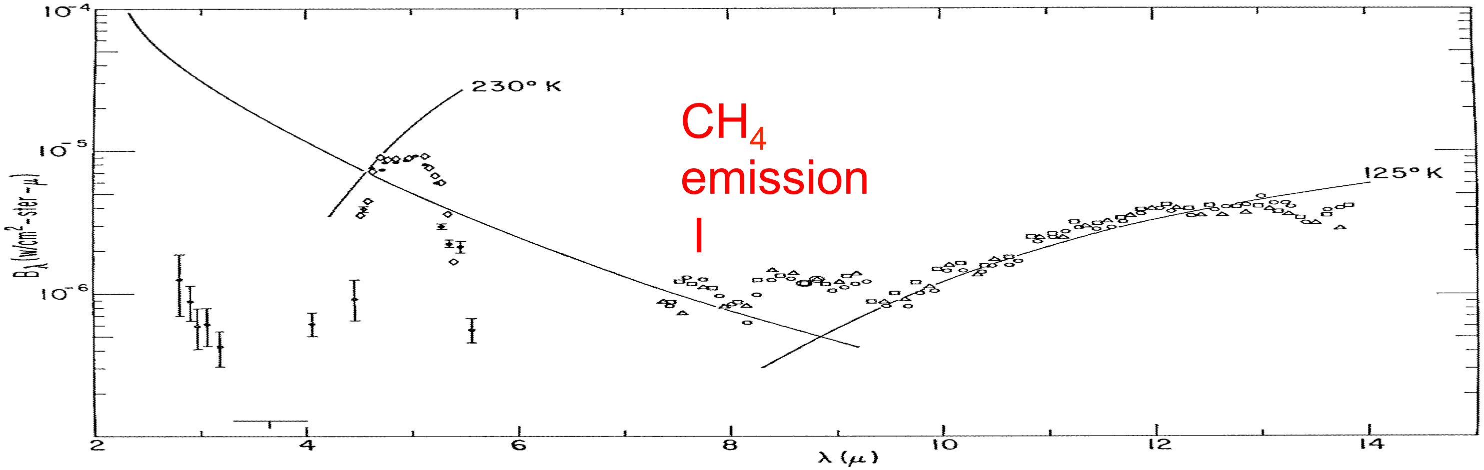
Howard et al. 2013

A last message….

-Let’s go **step by step**: the spectroscopy of exoplanets will improve as in the case of the solar system planets

-Let’s try to understand first the **whole variety** of exoplanets

Gillett et al.
ApJ 1969:
First evidence for a thermal inversion



Jupiter ISO-SWS
1996

(R = 2000)