Planetary atmospheres:
Solar system and Exoplanets
Spectroscopic characterization of exoplanets’ atmospheres

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Outline

- Planetary atmospheres: an introduction
- Atmospheric composition: what to expect for exoplanets?
- Infrared spectroscopy : reflected starlight and thermal emission
- Characterizing exoplanets' atmospheres: which spectral range and resolving power?
- The EChO project

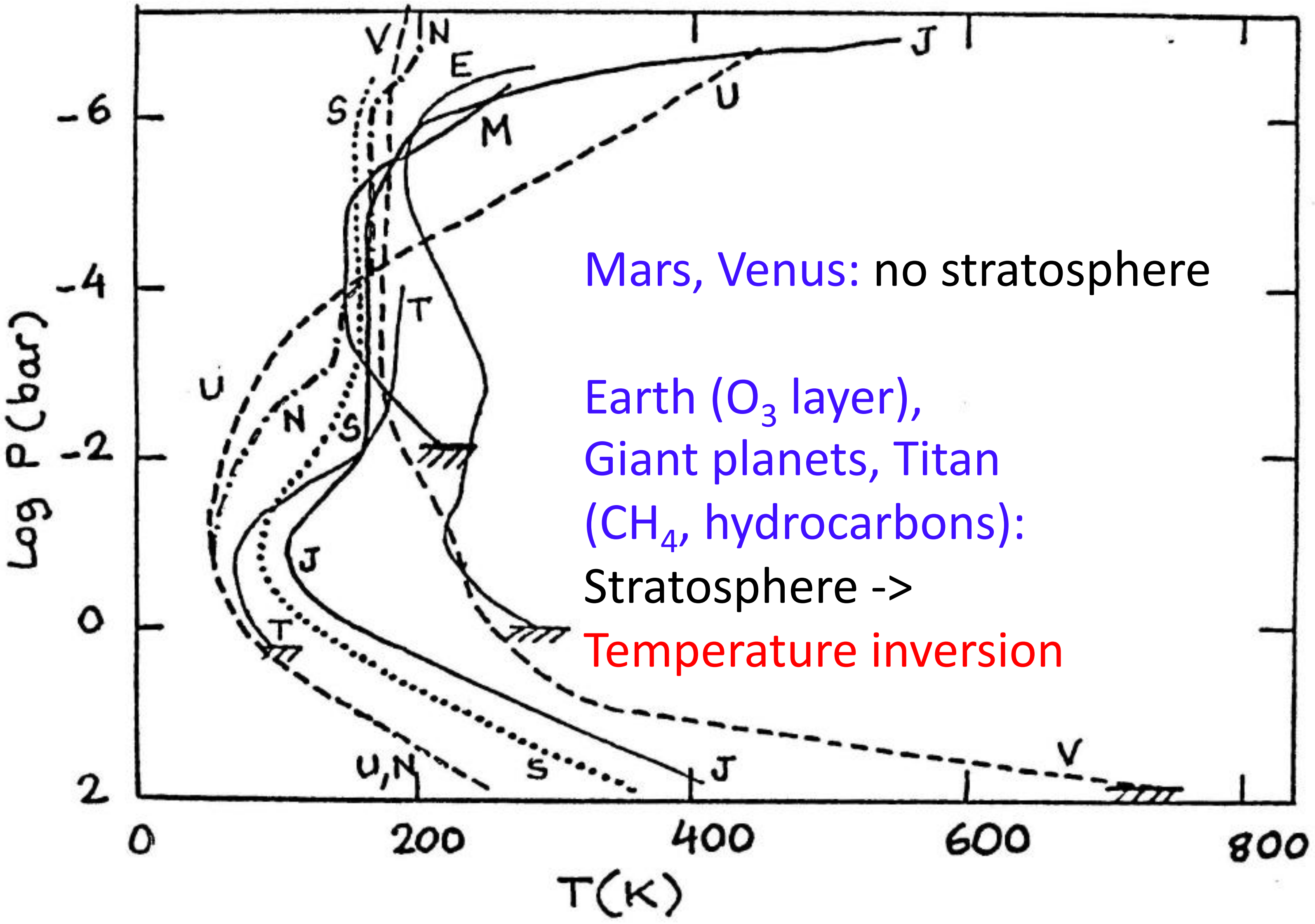
Planetary formation:
Lessons from the solar system

- Planets formed from solid particles in the protosolar disk, following the condensation sequence
  - Close to the Sun (< 3 AU): accretion of silicates and minerals -> rocky planets (small and dense)
  - At larger distances (> 5 UA): accretion of icy cores with masses > 10 M_E -> capture of surrounding gas -> giant planets
  - Between the two: the snow line (T = 180 K)
    - At 4-5 AU at the time of planet's formation

What is an atmosphere?

- Atmos(vapor)+sphaira (ballon): gaseous envelope around a celestial body
- Equilibrium between gravity and pressure: hydrostatic law
  $(P = P_o e^{-z/H}, H=\mathcal{R}T/\mu g)$
- Energy sources:
  - The main factor: the solar (stellar) radiation
  - Internal energy
    - rocky planets: radioactive decay (-> volcanism, plate tectonics)
    - gaseous planets: gravitational contraction, internal processes
- Temperature structure:
  - Troposphere (convective regime, $dT/dz < 0$)
  - Stratosphere (radiative regime, $dT/dz > 0$)
  - Mesosphere, thermosphere

Thermal structure of planetary atmospheres



Mars, Venus: no stratosphere

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

Exoplanets' atmospheres:
The important parameters

- Orbital parameters:
  - The distance to the star -> effective temperature

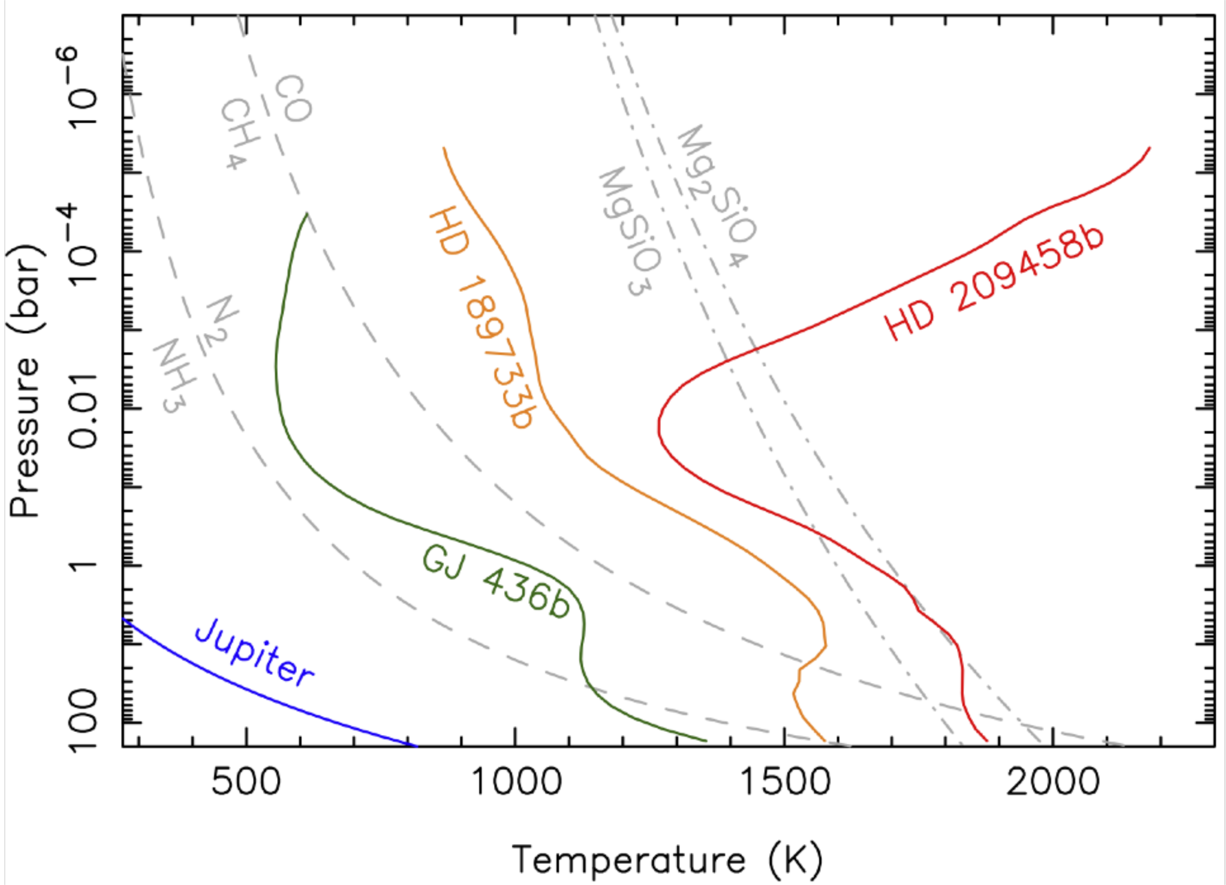
    $[F^*/D^2](1-a) = 4\,\sigma\,Te^4$
  - The obliquity -> seasonal effects (cf. Earth, Mars)
- Physical parameters:
  - The mass
    - $<10\ M_E$: rocky (icy) bodies expected (cf. Mars, Titan)
    - $>10\ M_E$: giant planets expected (cf. Jupiter, Neptune)
  - The albedo -> fraction of reflected/absorbed stellar energy
  - The rotation period -> effect on atmospheric circulation
  - The magnetic field -> existence of a magnetosphere

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

Comparison with thermochemical models



Jupiter: NH_3, CH_4 expected and observed

GJ 436b: N_2, CH_4 expected

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

-> Life is different from expectations!

EChO Proposal, Fig. 14

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 temperature: $[F^*/D^2](1-a) = 4\,\sigma\,Te^4$
- -> Position wrt the snow line (SL)
  - SL: About 180 K at the time of planetary formation (H_2O condensation)
  - >D = 4-5 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)

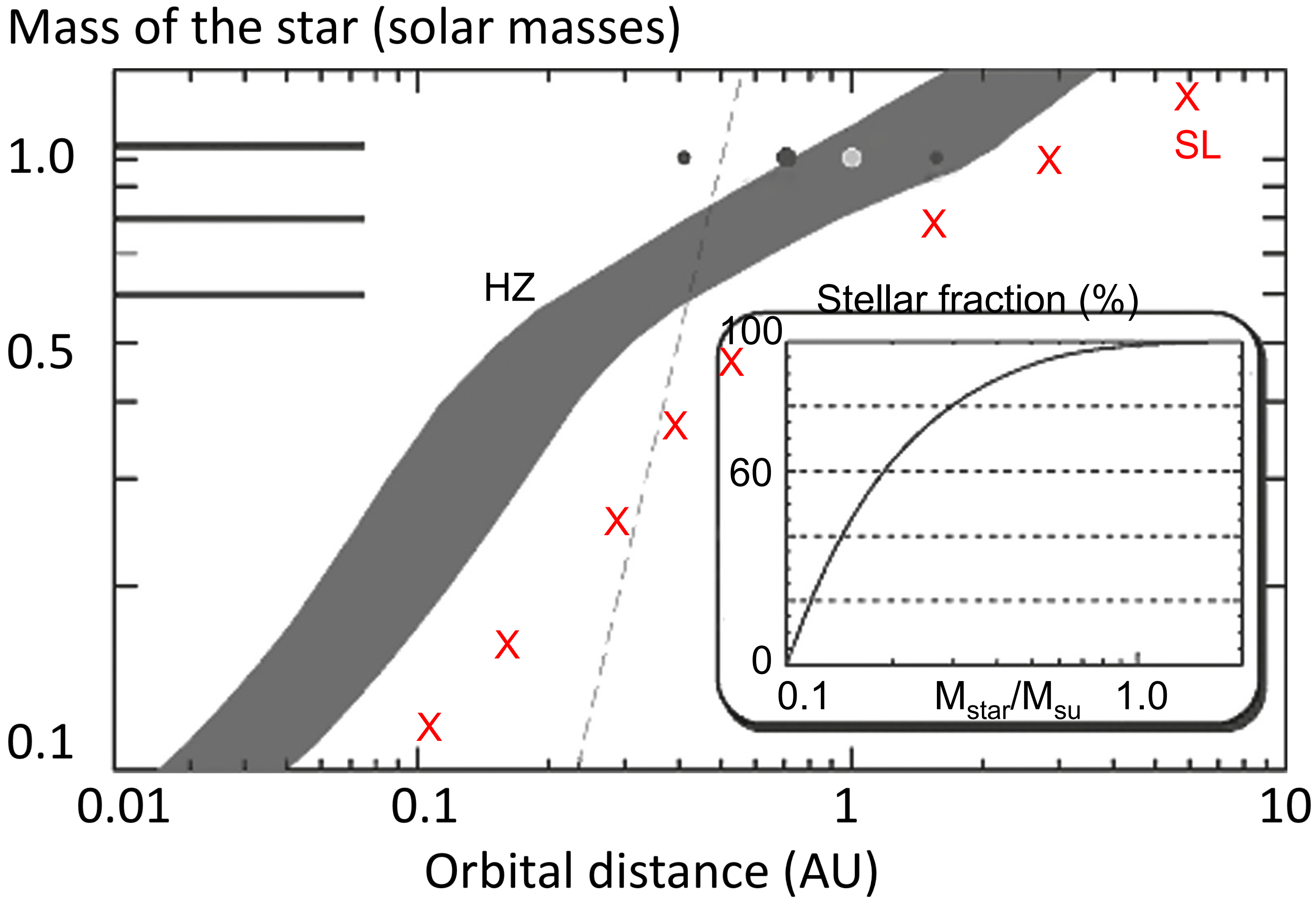
Te (K)	1200	850	460	220	120	50
Stellar dist. (AU)	0.05	0.1	0.3	1.5	5.0	20.0

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	<PEGASIDES>	< GASEOUS > GIANTS	<ICY GIANTS>
(10 - 1000 M_E)		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

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



A few important caveats

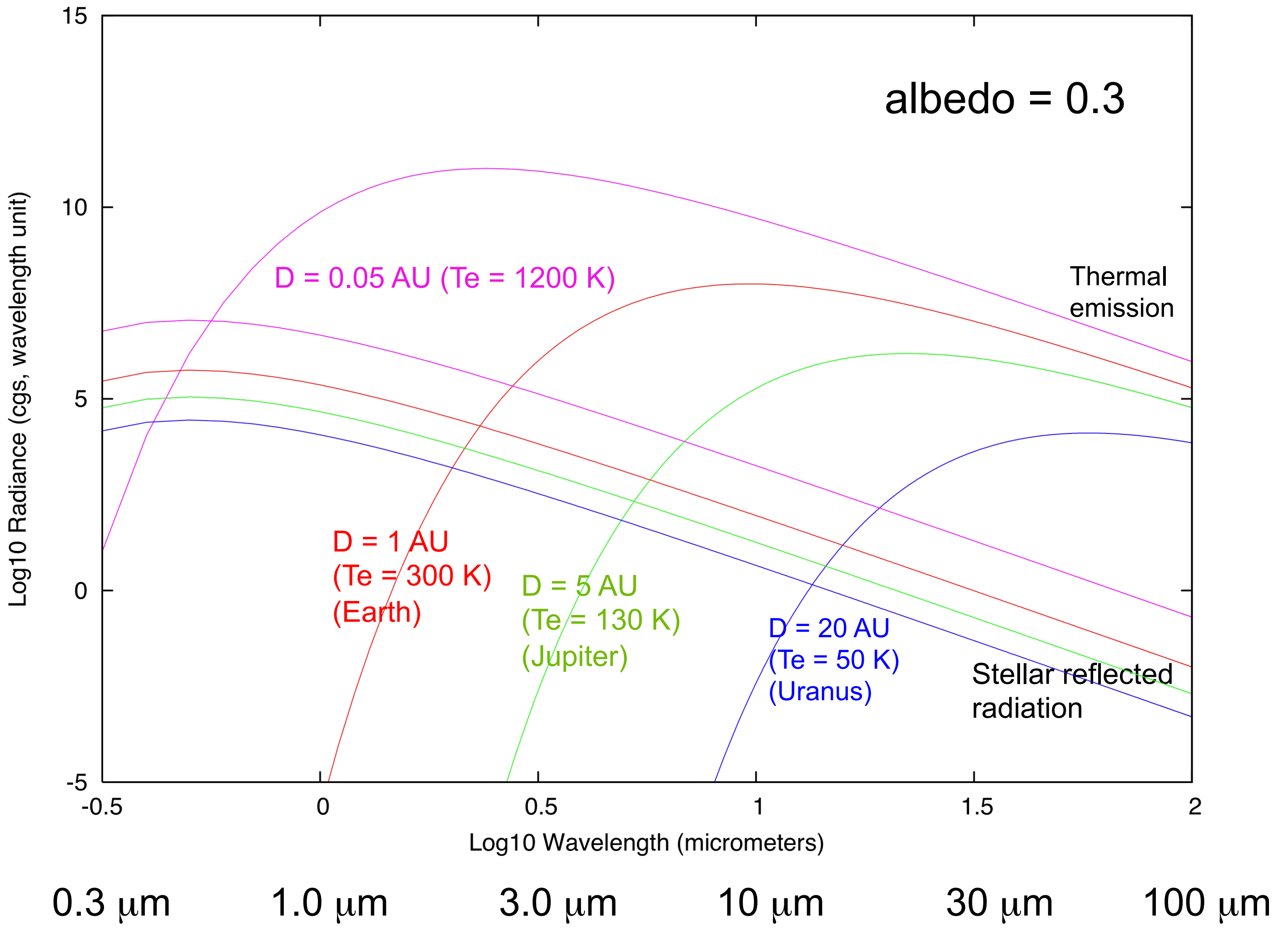
- This is a static model: no migration is assumed
    - Migration is common in exoplanetary systems
    - Migration was moderate in the case of the solar system
- Other parameters are involved:
    - Albedo -> effect on Te
    - Rotation period -> effect on Te
        - Phase-locked planets -> strong day/night contrasts
    - Possible greenhouse effect -> may increase Ts vs Te
        - Earth: 15 K; Venus: over 200 K
    - Obliquity
        - Atmospheric dynamics -> may change day/night contrasts
    - Magnetic field -> may prevent atmospheric escape

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))
- Fluorescence emission (UV, visible, near-IR)
  - Emission lines in the upper atmospheres (H, H_2, N_2, radicals; NIR: CH_4, CO)

The IR range is best suited for probing exoplanets’ neutral atmospheres

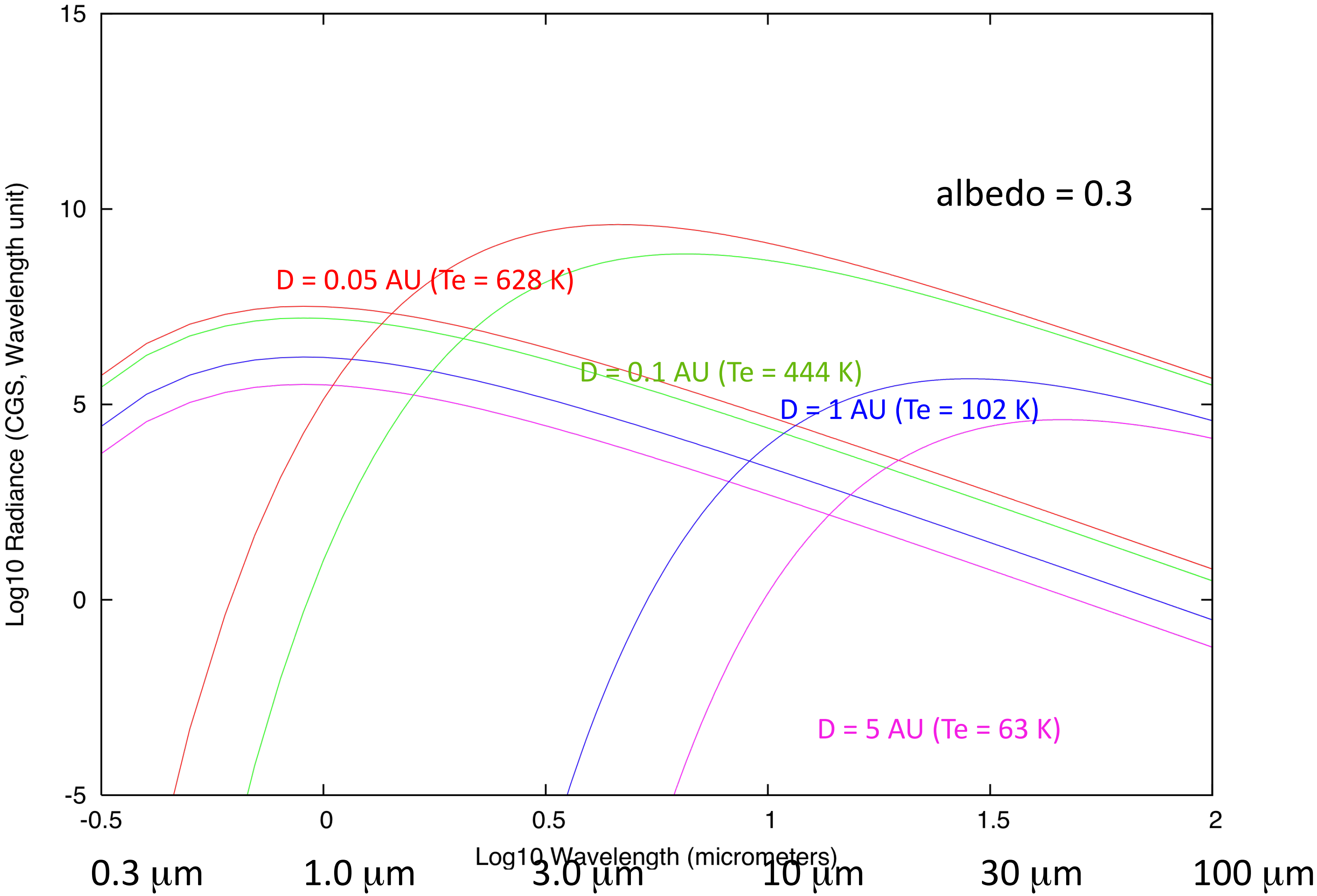
Reflected stellar light and thermal emission –Solar-type stars



Solar-type stars: At 0.05 AU, the thermal radiation dominates at $\lambda > 0.5$ µm

At 1 AU, both radiations are equal at 3 µm

Reflected stellar light and thermal emission: M-type stars



At 0.1 AU (T = 444 K)), both components are equal at 2 µm

Reflected/scattered emission vs thermal emission for different types of exoplanets

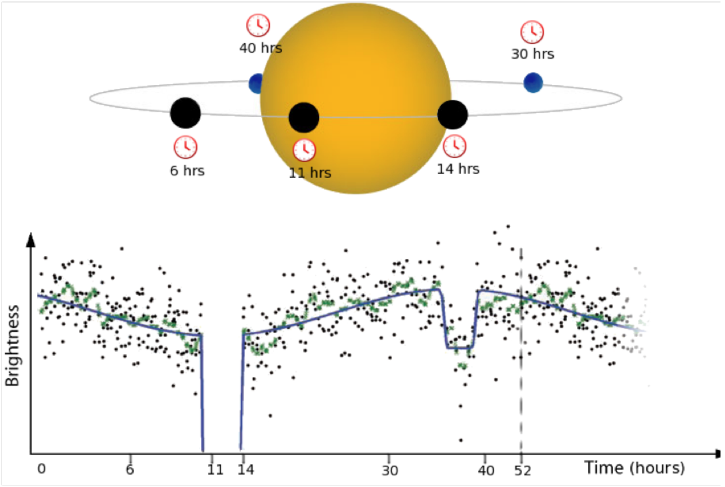
$\lambda_0 = \lambda$ (Reflected = Thermal)

Type of exoplanet	**Jupiter (M > 20 ME)** **a = 0.03 (hot, warm)** **a =0.3 (temperate)**	**Neptune (M = 10-20 ME)** **a= 0.03 (hot, warm)** **a = 0.3 (temperate)**	**Super-Earth (M < 10ME)** **a = 0.3 (hot, warm)** **a = 0.3 (temperate)**
Hot (> 700 K)	< 1 μm F: D < 0.25 AU G: D < 0.1 AU M: D < 0.025 AU	< 1 μm F: D < 0.25 AU G: D < 0.1 AU M: D < 0.025 AU	< 1.6 μm F: D < 0.5 AU G: D < 0.2 AU M: D < 0.05 AU
Warm (400 K < T < 700 K)	1 – 1.6 μm F: D = 0.25 – 0.5 AU G: D = 0.1 – 0.3 AU M: D = 0.025 – 0.05 AU	1 – 1.6 μm F: D = 0.25 – 0.5 AU G: D = 0.1 – 0.3 AU M: D = 0.025 – 0.05 AU	1.4 - 2.0 μm F: D = 0.5 – 1 AU G: D = 0.2 – 0.6 AU M: 0.05 – 0.1 AU
Temperate (250 K < T < 350 K)	1.2 – 2.5 μm F: D = 1 – 2 AU G: D = 0.7 – 1.5 AU M: D = 0.07 -0.1 AU	1.2 – 2.5 μm F: D = 1 – 2 AU G: D = 0.7 – 1.5 AU M: D = 0.07 -0.1 AU	3 – 5 μm F: D = 1 -2 AU G: D = 0.7 -1.5 AU M: D = 0.07 – 0.1 AU

Transit spectroscopy of an exoplanet

- Primary transits
  - Transmission spectroscopy
  - Probes the upper atmosphere at terminator

    Unknown: scale height (T, μ)
  - Well adapted to hot gaseous exoplanets
- Secondary transits
  - Mostly thermal emission
  - Well adapted to all kinds of exoplanets
  - \> How to raise the degeneracy between Temperature profile and abundances of atmospheric species?



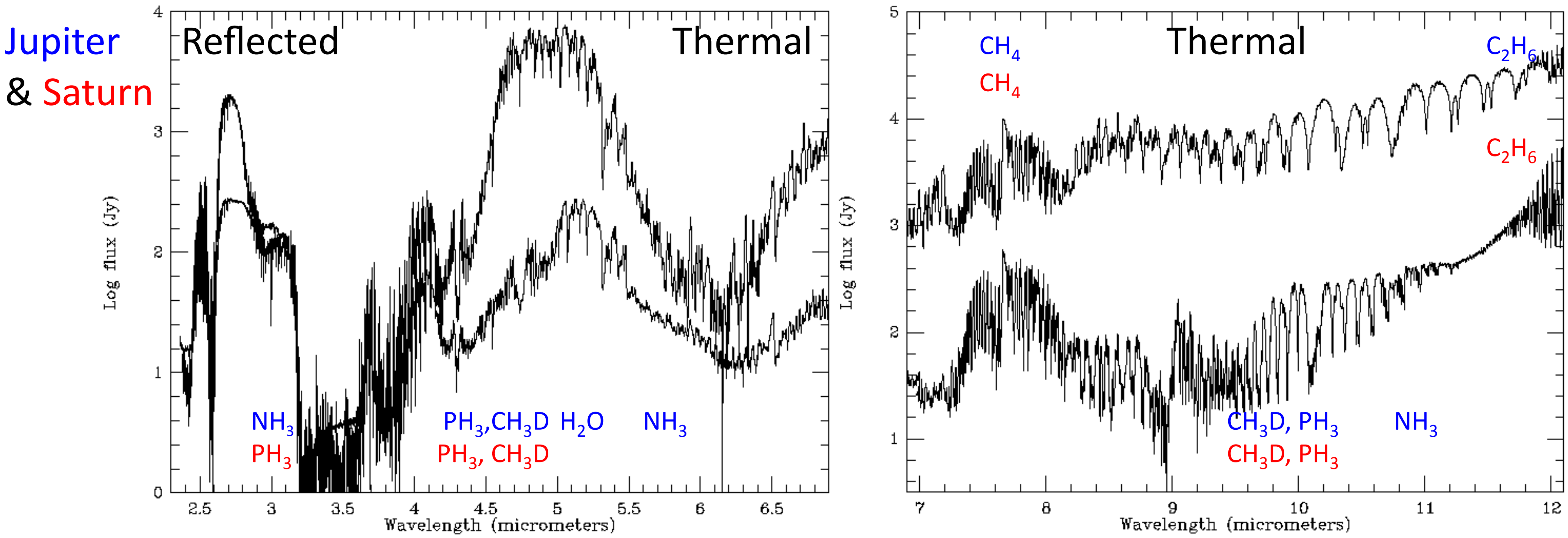
Primary Transit

Secondary Transit

EChO Proposal, Fig. 5

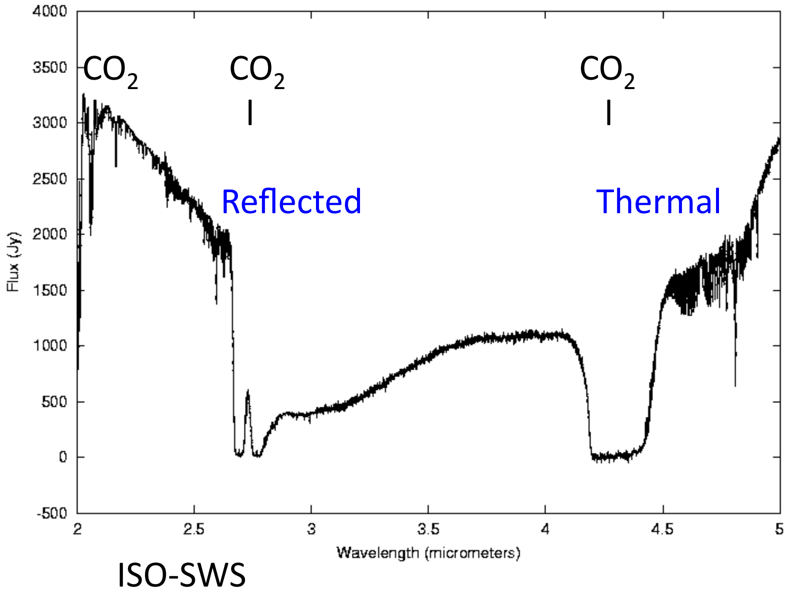
Constraints on the spectral range (1)

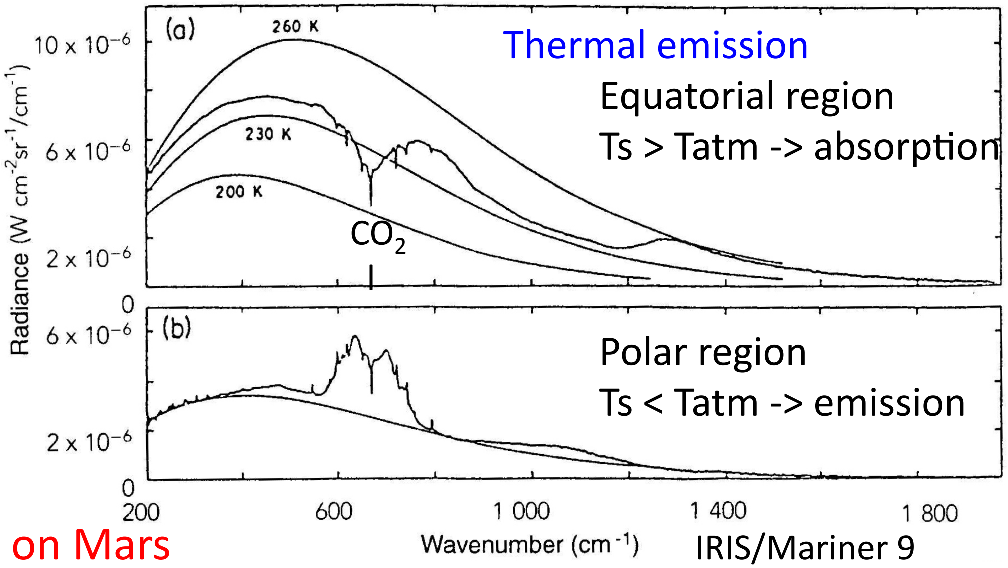
- The need for measuring both reflected/scattered and thermal emissions
  - Possible for Warm & Temperate Jupiters and Neptunes, and for all super-Earths (secondary transits)
  - Advantage: Helps to separate the identification of molecules from the thermal profile
    - Reflected/scattered stellar light -> absorption features



Constraints on the spectral range (2)

- The need for several bands of a given species
  - Different atmospheric levels are probed
  - Using bands of different intensities allows to better resolve the temperature/composition ambiguity in a thermal emission spectrum



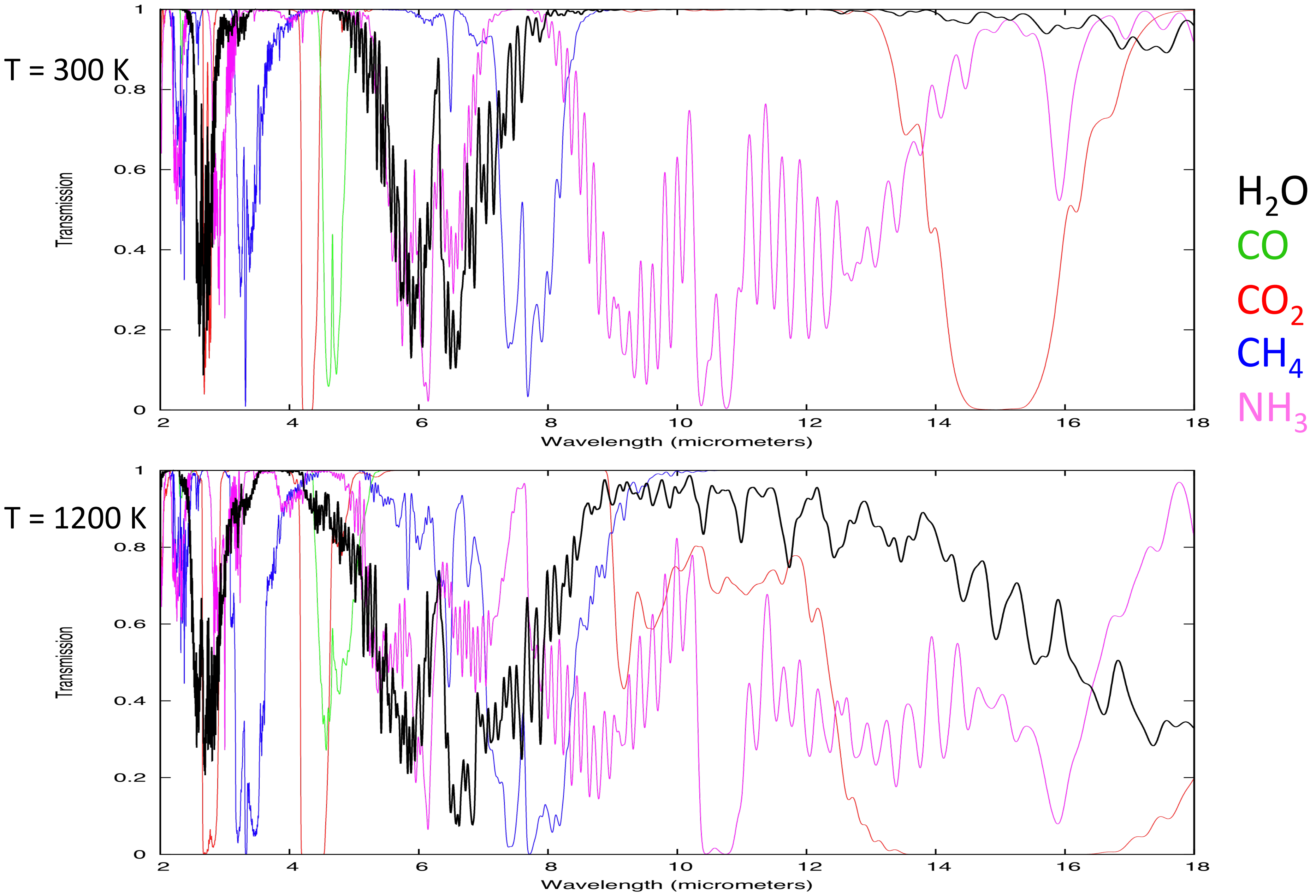


CO$_2$ on Mars

An inventory of expected molecular signatures in the 1 – 20 μm spectral range

Molecule	1-5 μm	> 5 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	

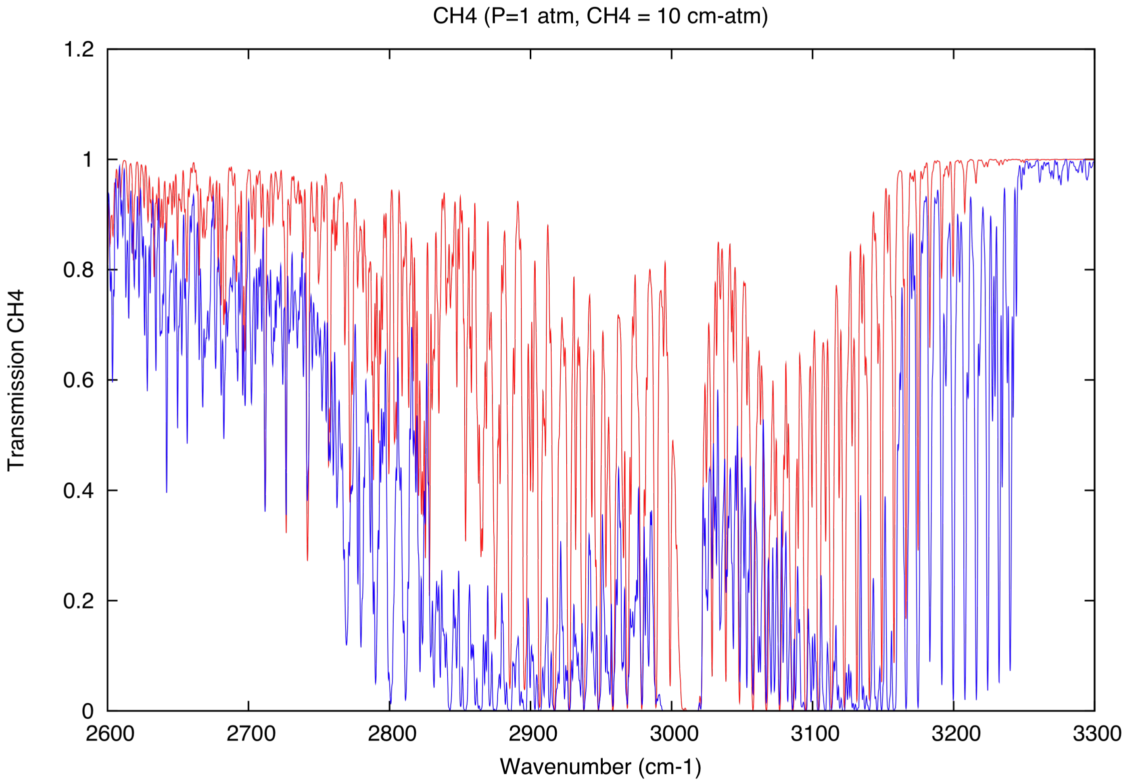
Spectral signatures of a few important molecules (10 cm-am, P = 1bar)



Constraint on the spectral resolving power (1)

- 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 $2B_0 > 10\ \mathrm{cm}^{-1}$ (excludes CO and CO_2)

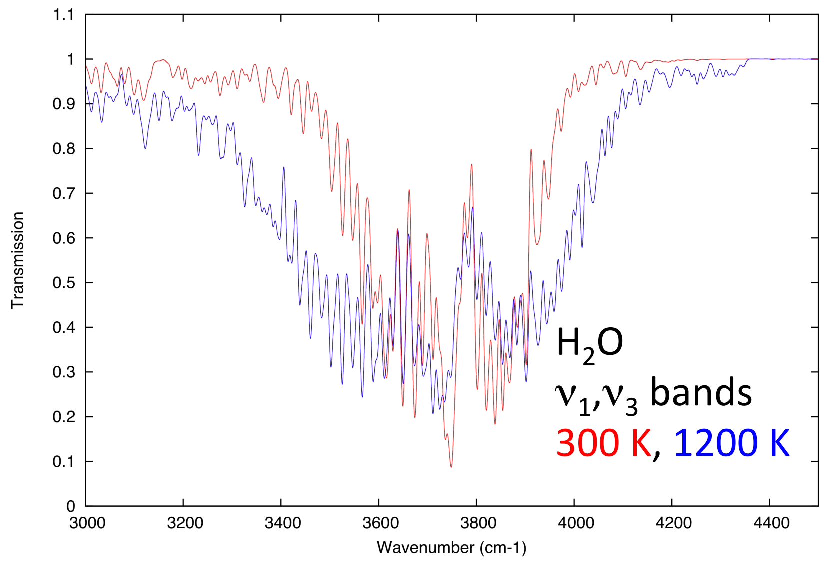
Molecule	**$\Delta\nu = 2B_0$ (cm^{-1})**	**R**
CH_4	10	300 (3.3 µm)
CO	3.8	565 (4.7 µm)
CO_2	1.6	420 (15 µm)
H_2O	29	130 (2.7 µm)
NH_3	20	165 (3.0 µm)
HCN	3	250 (13.7 µm)
O_3	0.9	1200 (9.7 µm)



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

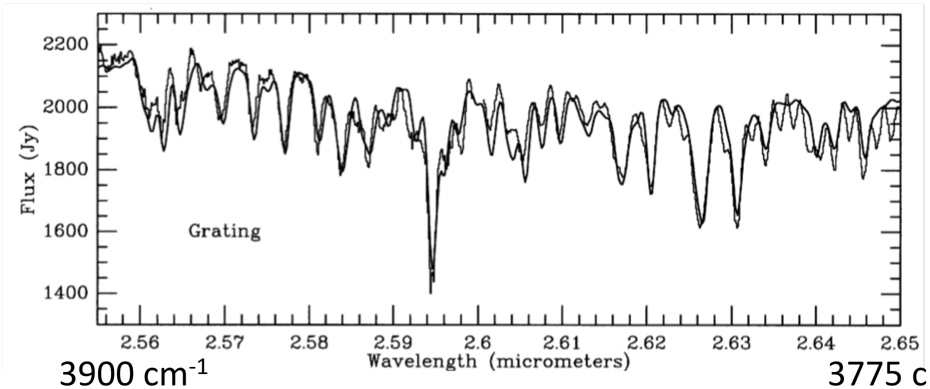
Constraint on the spectral resolving power (2)

H_2O
ν_1, ν_3-bands (2.66 μm)
and ν_2-band (6.27 μm)



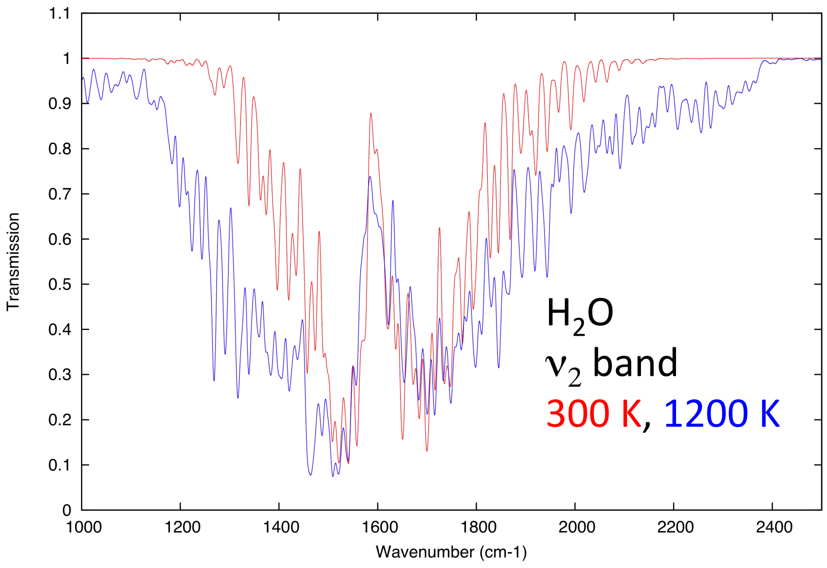
Line separation ($2B_0$): $\Delta\nu = 29$ cm^{-1}
Required resolving power:
130 @ 2.7 μm (ν_1, ν_3)
60 @ 6.2 μm (ν_2)-> possible with EChO

NB: Gaps at 2.63 μm (detectable with R=75)
and 6.25 μm (detectable with R = 30)



3900 cm^{-1} 3775 cm^{-1}

Mars ISO-SWS (Lellouch et al. 2000)

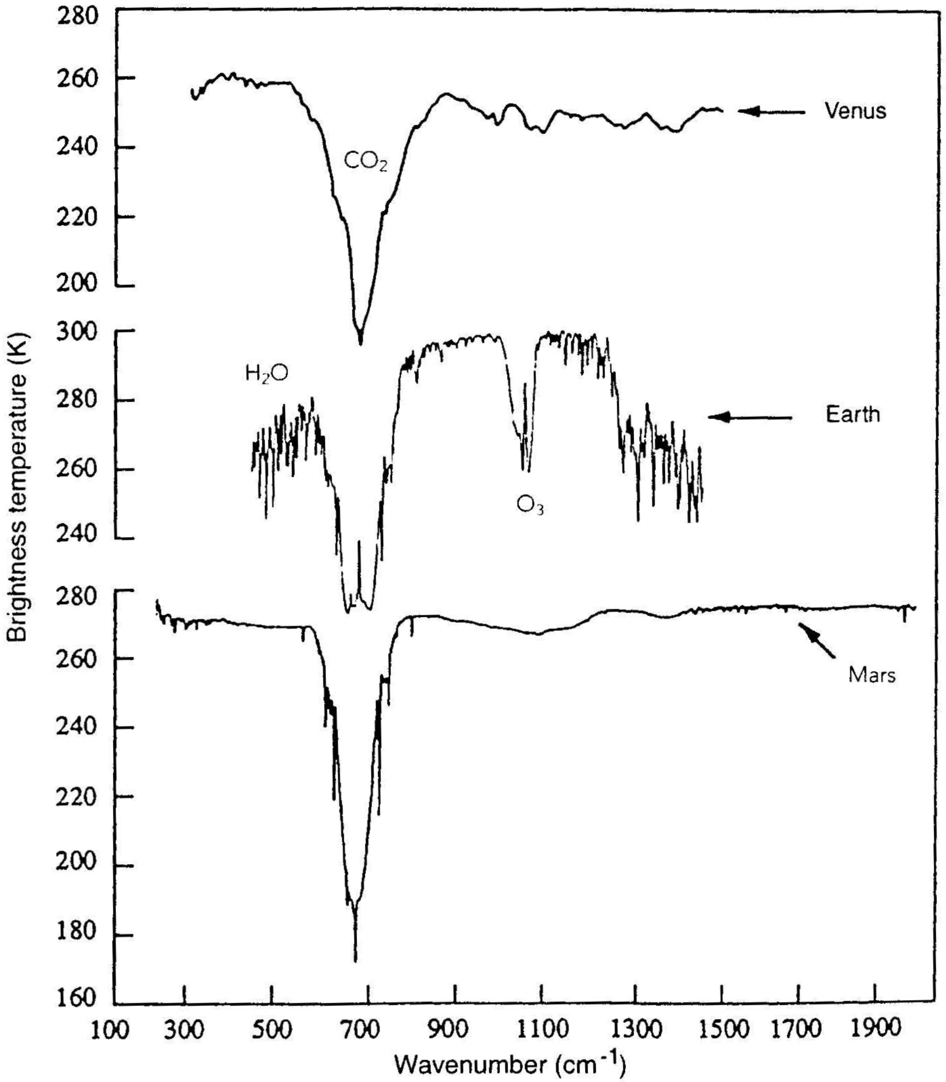


Constraint on the spectral resolving power (3)

Resolving power required :

CO_2 $\Delta\lambda = 3\ \mu m$ (R = 3)

O_3 $\Delta\lambda = 1\ \mu m$ (R = 10)



Venus

Earth

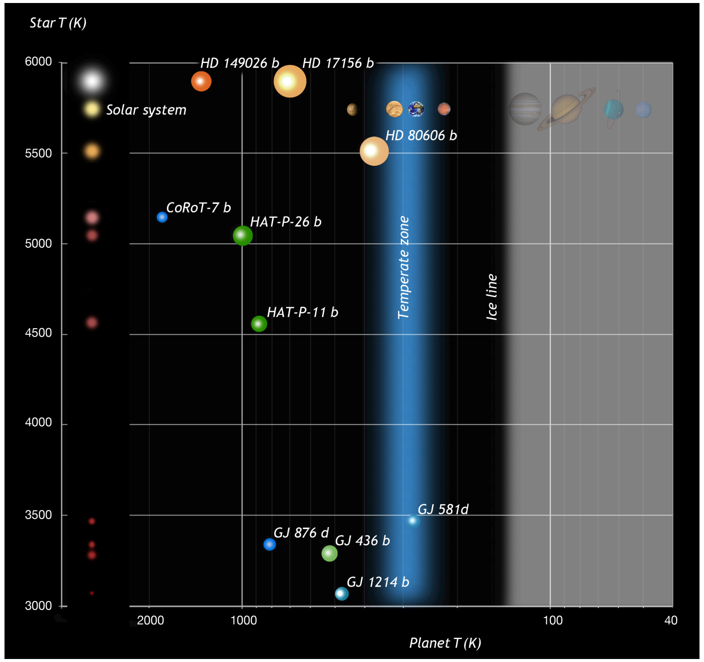
Mars

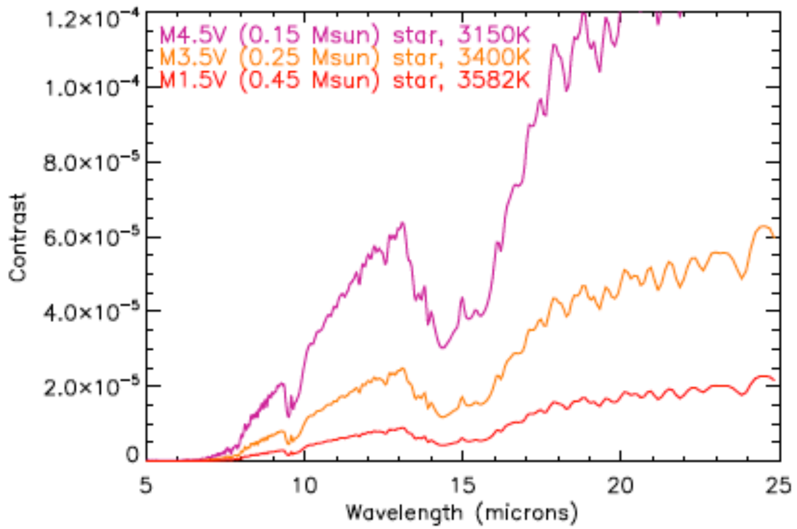
Above 8 μm, R = 20 is sufficient for identifying the shapes of CO_2, O_3 and HCN

Hanel et al., 1992

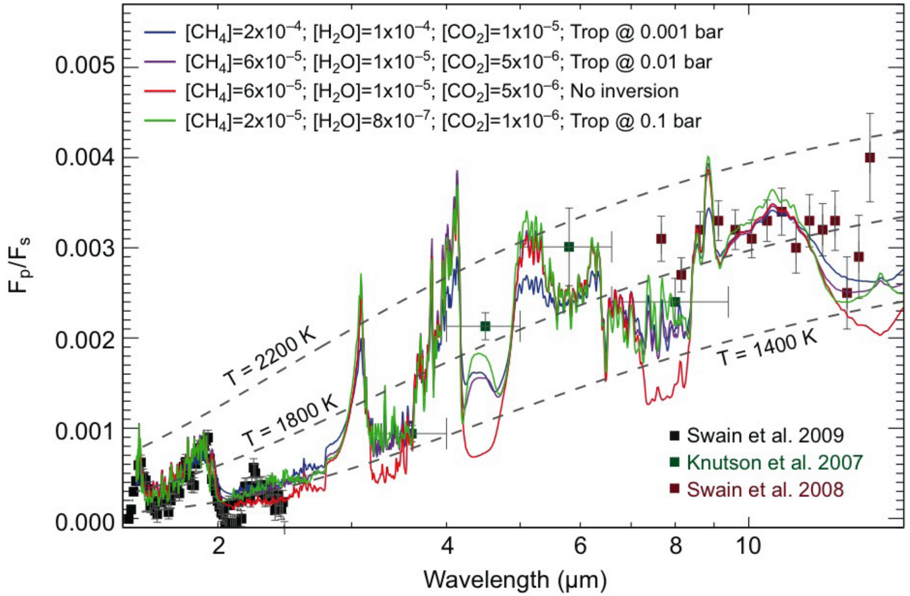
The EChO mission

-European consortium (G. Tinetti et al.)
-Pre-selected for M3/Cosmic Vision (launch around 2022)
-Spectroscopic characterization of exoplanets by transit
-1.2-1.4 m telescope @ L2
-1-16 μm + Visible simultaneous coverage
- R = 300 at λ < 9 μm, 20 at λ > 9 μm
-Target list: Hot Jupiters -> Super Earths
-Super-Earths around M-dwarfs will be priviledged





Super-Earths around M dwarfs (Tessenyi et al. 2011)
The P/S contrast increases from M1.5 to M4.5



HD209458b (secondary transit)
Data: HST, Spitzer, ground-based

Conclusions

- For solar-type stars and exoplanets at $D < 0.05$ AU, thermal emission dominates for $\lambda > 0.5\ \mu m$
- In the thermal regime, determining the thermal profile is essential for identifying atmospheric species
- This is best done by observing both reflected/thermal emissions, and by using several bands of a given species with different intensities
- A simultaneous coverage of the spectral range (ideally 1-16 μm) + visible is important for correcting the stellar variability
- A resolving power of 300 should be sufficient for identifying most of the major species at all temperatures
- Above 8 μm, $R = 20$ is sufficient for identifying the shapes of CO_2, O_3 and HCN
- These are the objectives of the EChO Mission!