Introduction to Astrobiology

Chapter 4

Search for habitable environments, biomarkers and life outside the Earth

Search for habitable environments and life in the Solar System

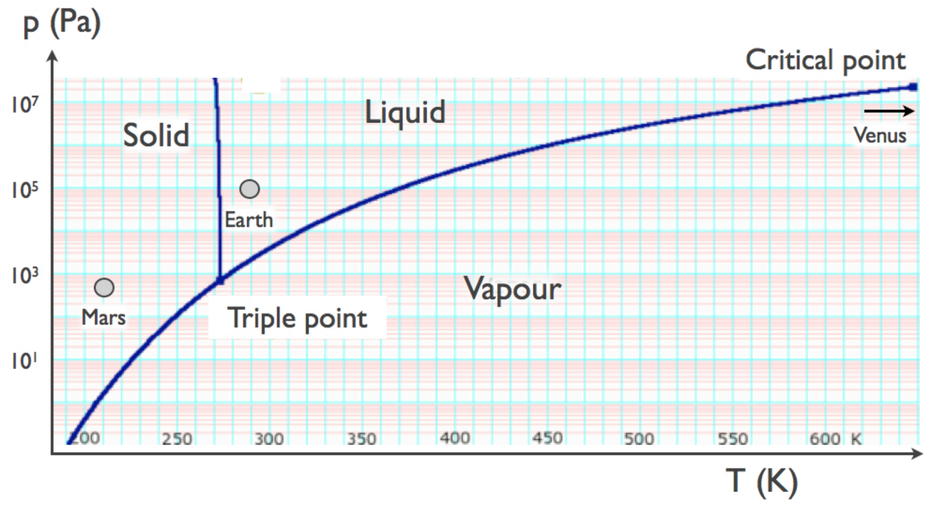
Examples of non-habitable planets

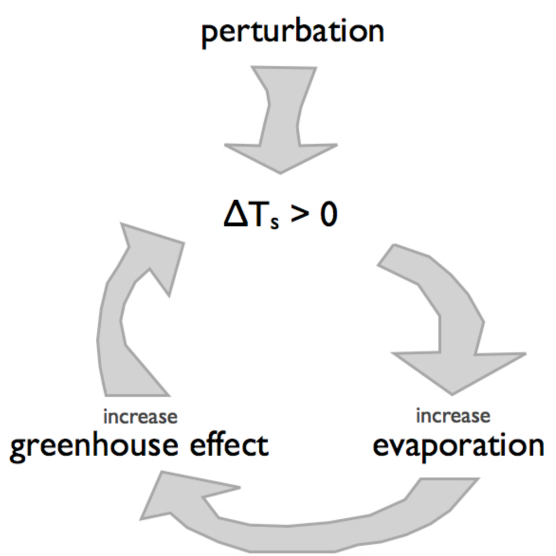
- Venus

  T_s=735 K

  p_s=92 x 10^5 Pa

  Venus has probably undergone a "runaway greenhouse effect" in the early stages of its history





Non-habitable planets

- Jupiter

  Some of the atmospheric layers have pressure and temperature in the intervals
  10^5 Pa < p < 10^7 Pa and 300 < T < 500 K

  In principle, these ranges allow for the presence of liquid water in such atmospheric layers

  - The conditions for life to adapt in such environment are very restrictive
  - Hypothetical forms of life should stay suspended in those layers

  Even if some authors did investigate the potential habitability of such atmospheric layers (Sagan & Salpeter 1976), giant planets are never considered among acndidate habitable planets

Mars

- Surface habitability
- At present time the Mars surface is not habitable
  - Le surface is slightly below the triple point of water
  - $T_s = 210$ K
  - $P_s \sim 600$ Pa (~ 6 mbar)

- In layers below the surface we expect a gradient of pressure and temperature
  - At some proper depth, this could yield conditions suitable for liquid water to exist

Search for water in Mars

- Evidence of water in present-day Mars

  Even if the bulk of the polar caps is constitued by CO_2 ice, the North polar cap must also contain a fraction H_2O

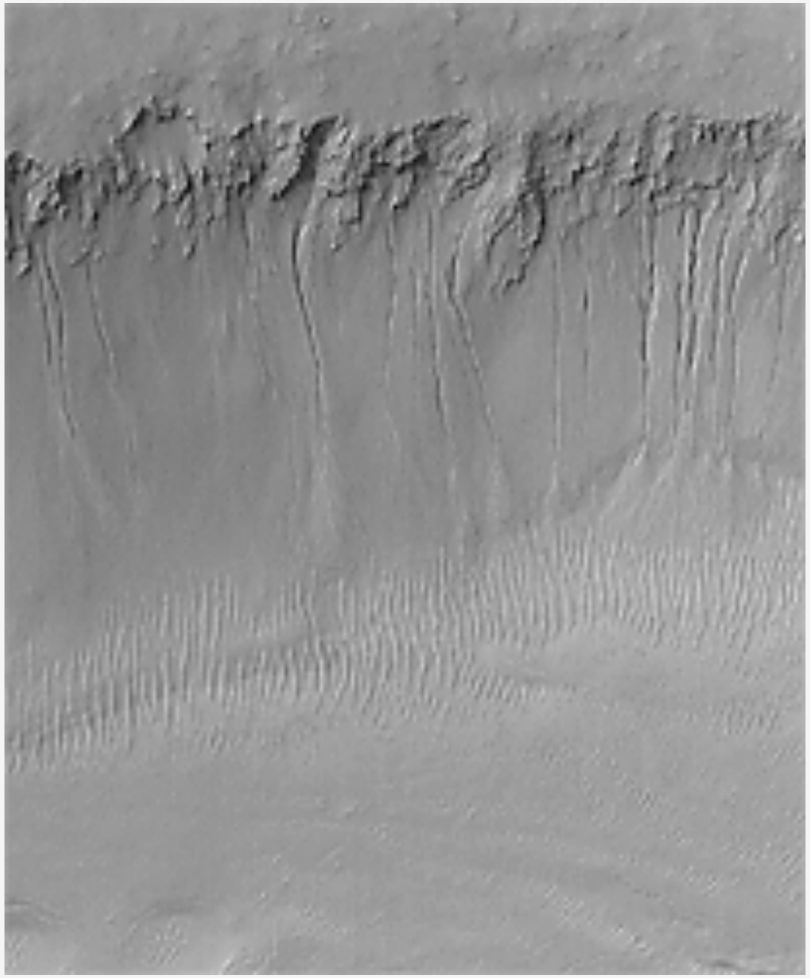
  in order to explain why such polar cap is able to persist, to some extent, during the Mars summer, when CO_2 sublimates into the atmosphere

Search for water in Mars

- Evidence of water in present-day Mars

  Traces of recent erosion at the border of craters

  Interpreted as transient outflows of water in liquid phase (“gullies”)



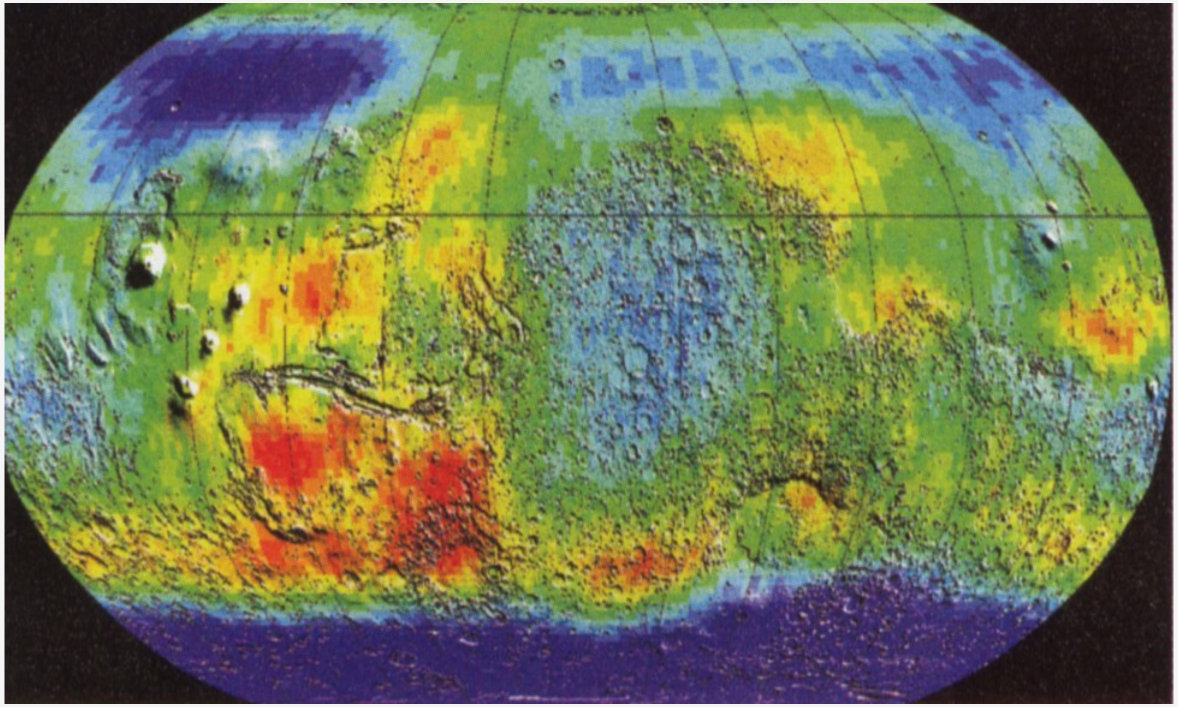
Search for water in Mars

➢ Evidence of water in present-day Mars

Space probes are collecting evidence on the presence of underground water ice

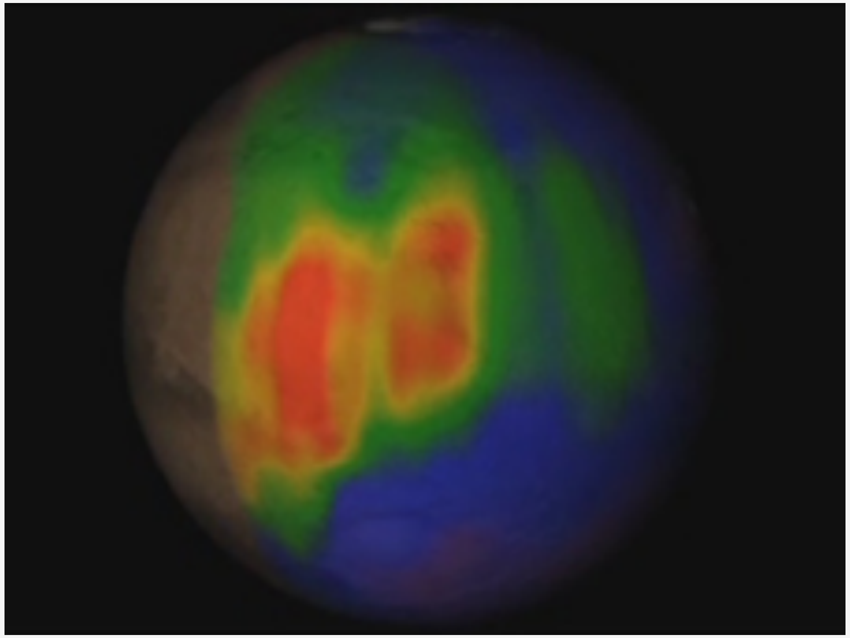
The distribution of hydrogen below the ground, inferred from the data collected from the probe "Mars Odyssey", suggests the existence of layer of water ice at a depth of about one meter

Blue areas: maximum concentration



Tentative evidence of methane in present-day Mars

- Recent claims of detection of CH_4 outgassing on Mars
  - By means of high resolution infrared spectroscopy from Earth
  - Methane emissions seem to have a local and seasonal character
    - Villanueva et al. (2009)
- If confirmed, these observations would suggest the presence of some form of underground chemical activity
  - possibly of geochemical origin, but methane-producing biochemical processes are well-known on Earth



Mars habitability in the past

- Several independent evidence suggests that Mars was habitable in the past

  These evidences are particularly important in astrobiology, because of the possibility that life might have developped on Mars

- Among the different evidences we mention:

  Statistics of impact craters

  Geomorfological evidence

  Martian meteorites collected on Earth

Mars habitability in the past

- Evidence for the presence of a thick atmosphere in the past

  Statistics of the diameters of impact craters

  Deficit of small size ancient craters with respect to recent craters

  The presence of a past atmosphere may have caused this deficit by means of:

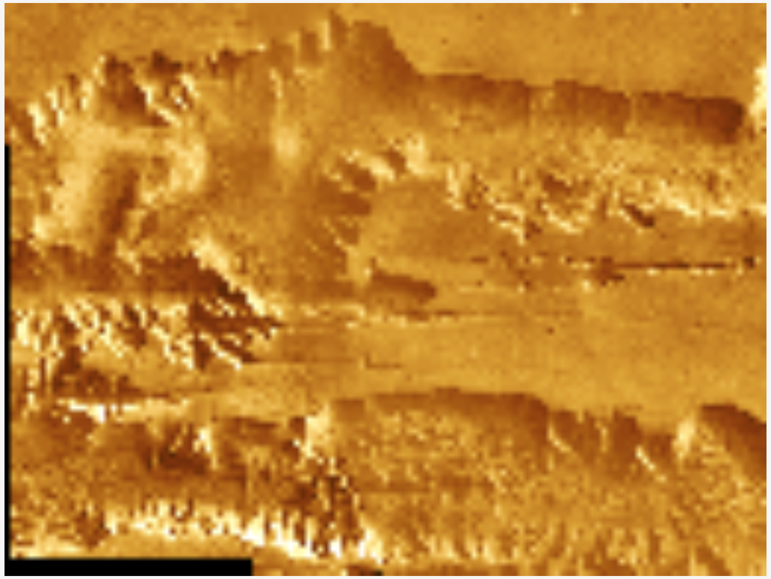
  - Fusion of small size meteoroids due to friction during the crossing of the atmosphere
  - Erosion of the shallowest craters by means of atmospheric weathering

Mars habitability in the past

- Evidence for the presence of liquid water in the past

  Geomorphological evidence

  For instance, network of valleys similar to those excavated by terrestrial rivers

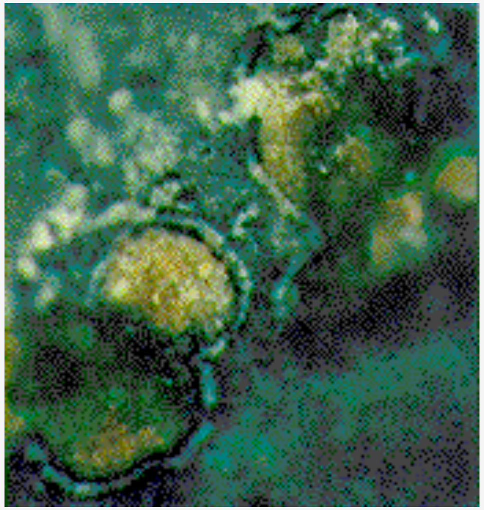


Mars habitability in the past

- Evidence for the presence of liquid water in the past

  Some meteorites, classified as SNC, of martian origin, recovered in Antarctica, suggest that liquid water was present on Mars in past epochs

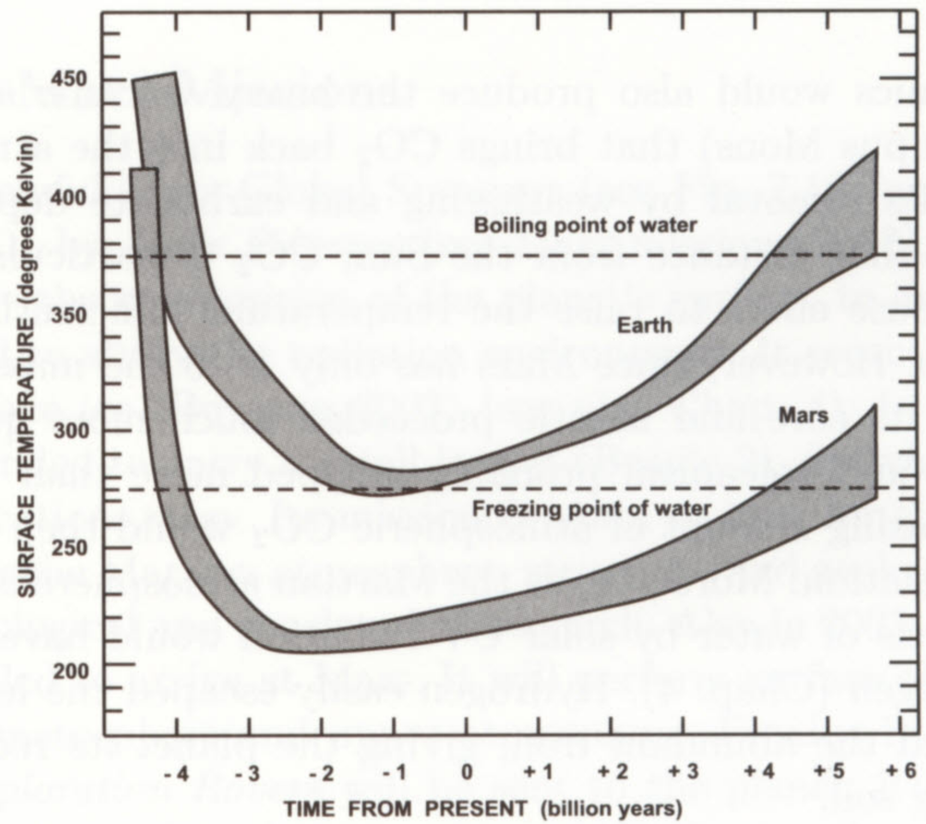
  ALH 84001, found in 1984



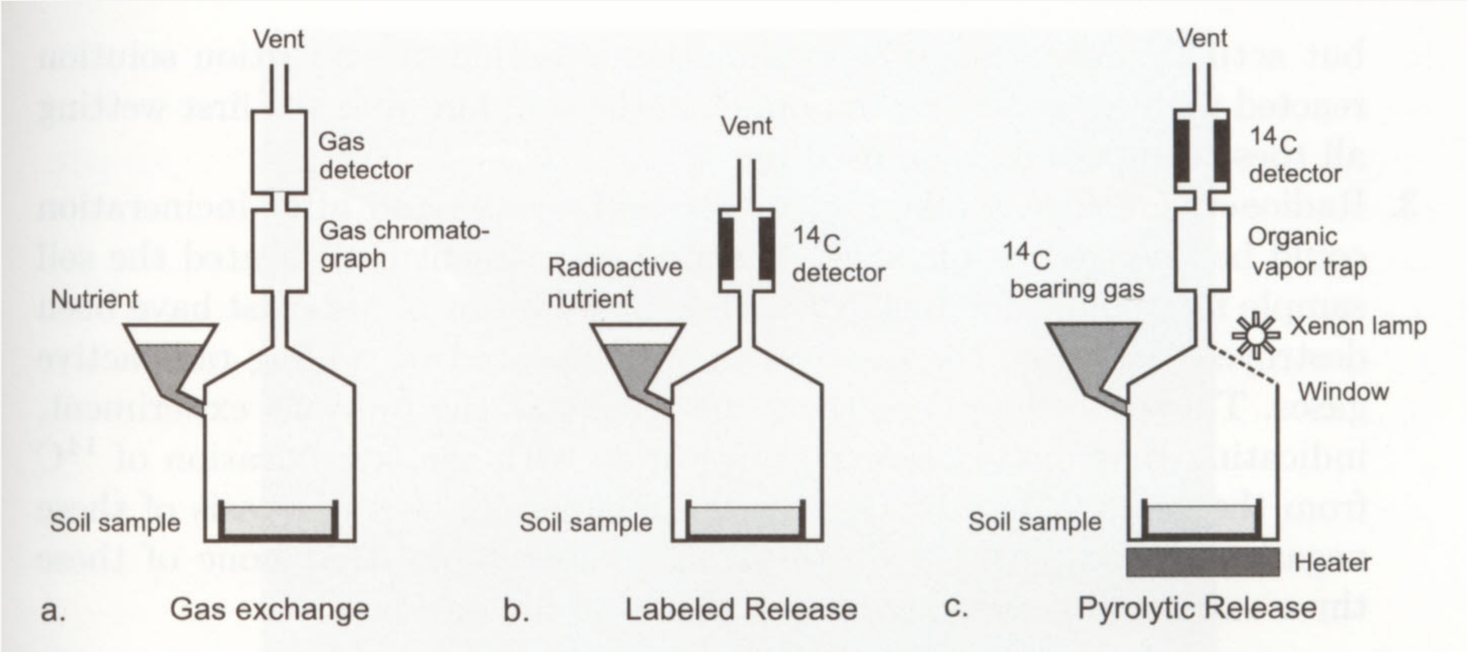
Mars habitability in the past

- In light of the “faint young sun paradox”, the requirement for a primordial CO_2-rich atmosphere is more compelling for Mars than the Earth
- An intense, early vulcanic activity may have generated large amounts of atmospheric CO_2

  The greenhouse effect would have provided a temperature sufficiently high for water being in the liquid phase in an atmosphere of higher pressure than today



Early searches for life on Mars



Viking experiments (1976) searched for traces of biological activity from the analysis of samples collected in a few martian landing sites

Three different experiments were carried out and analysed *in situ*, searching for evidence of biochemical processes

The results of one of the three experiments were consistent with the presence of biochemical activity; however, this signal is believed to be a "false positive" since it was not confirmed by the other two experiments

Searches for life on Mars

The ambiguous results of the Viking experiments teach us how difficult is to reveal the presence of life, even when we can analyse samples

The analysis of samples <u>in situ</u> is less accurate than the analysis that could be performed in laboratories on Earth, but bringing the sample back to Earth would increase dramatically the cost of the mission

The results of the Viking experiments do not exclude that life might exist in other locations on Mars

Active biological processes might take place in underground layers at a proper depth, where the temperature and pressure gradients would allow liquid water to be present

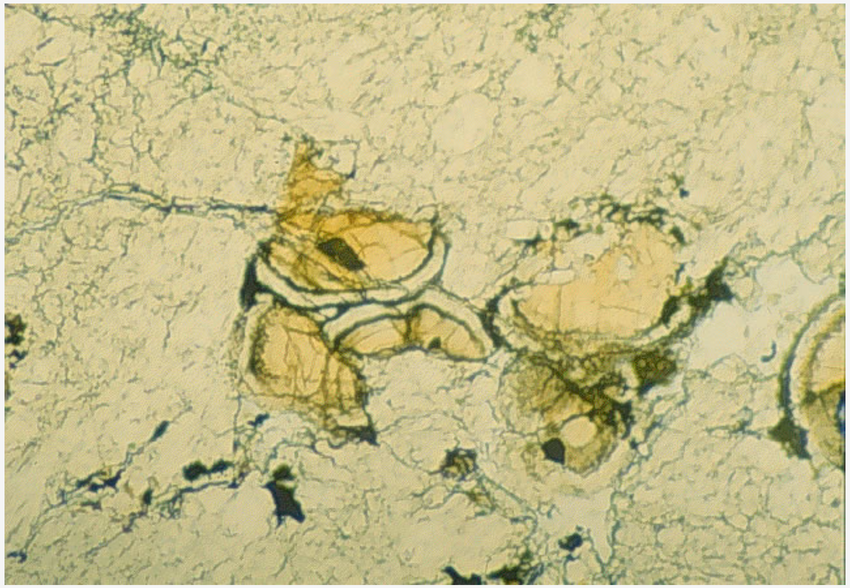
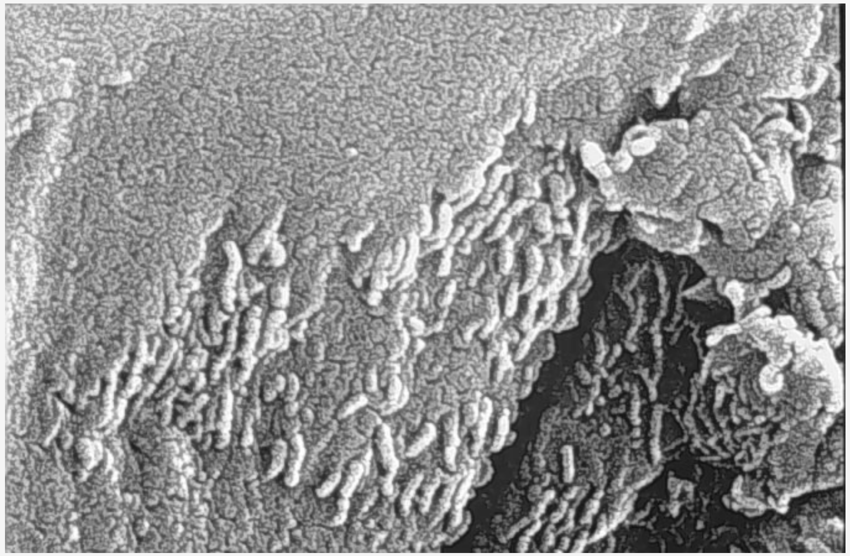
Searches for life on Mars

- Searches for life in the past history of Mars

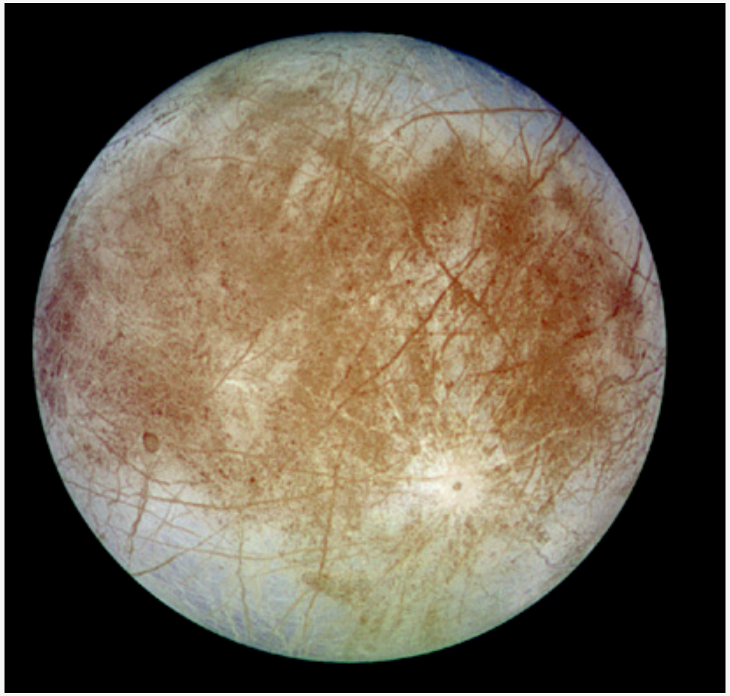
The analysis of the meteorite ALH 84001 revealed microstructures with morphology suggestive of a biological origin

Carbonate globules with an age of 3.9 Ga have been found in the interior

However, the sizes of those structures, between 20 and 100 nm, are too small with respect the smallest sizes of the living cells that we know

Europe



- One of the 4 major moons of Jupiter
  - The second one in order of distance
- Europes' surface is not habitable

  $\langle T_s \rangle = 103$ K, $p_s=10^{-6}$ Pa
- In spite of this fact, Europe is one of the most interesting astronomical bodies in the Solar System from the point of view of astrobiology

Europe

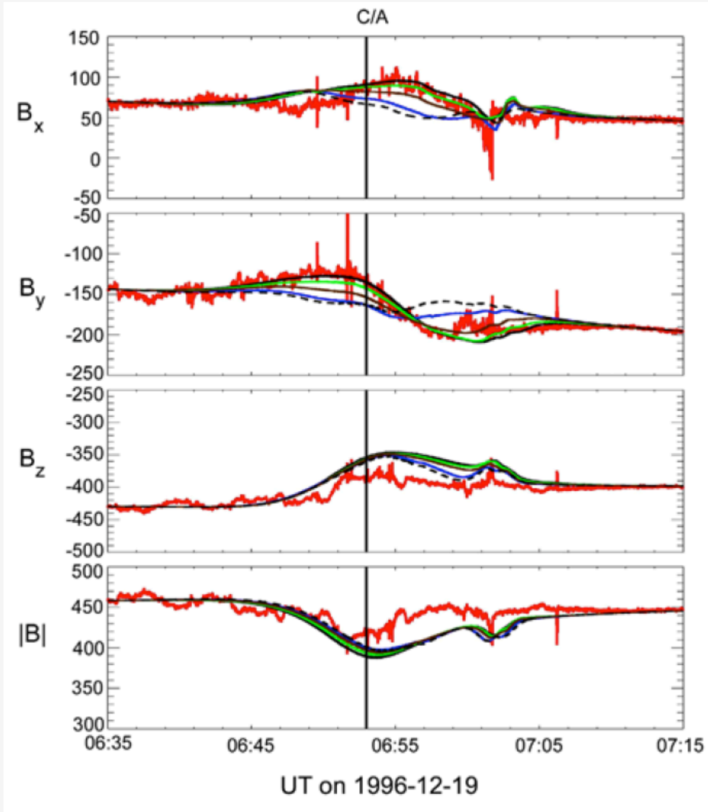
- Europe has been the target of several space missions
- The most detailed observations have been obtained by the "Galileo" probe
  - Launched in 1989, the probe made several "flybyes" around Europe in 1997
- The surface of Europe is made of H_2O ice
  - The surface morphology, with relatively few impact craters, suggests that the surface is constantly being reshaped
  - Different types of shallow structures can be seen on the surface
    - Their presence is emphasized by differences in albedo

Europe

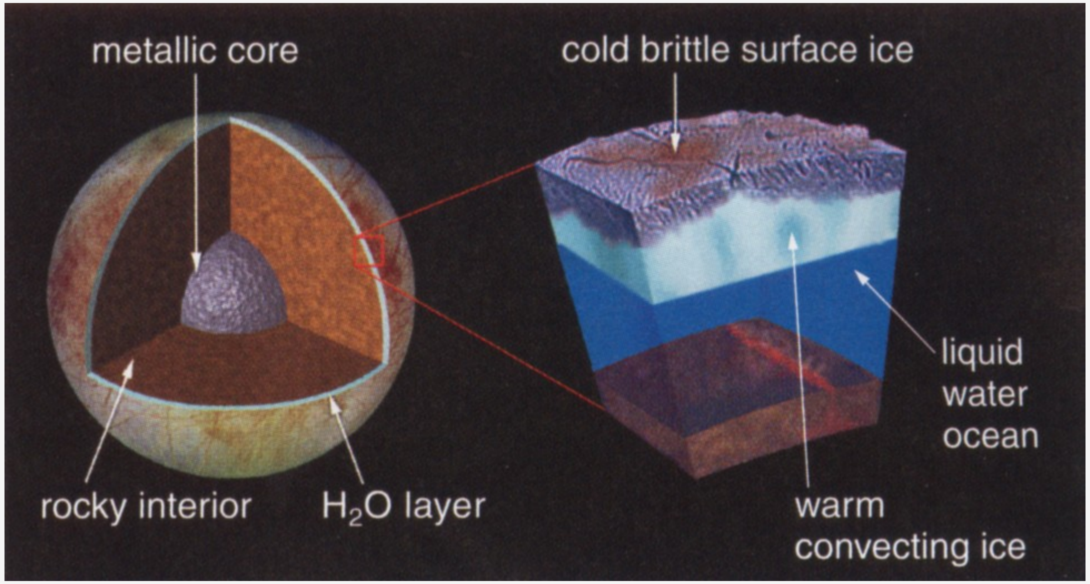
- A water ocean is believed to exist below the external ice layer

  The thickness of the layer is not known; likely to be between a few km and some tens of km

- The evidence for liquid water is indirect, but quite convincing
  - The fractures in the ice shield hint at presence of liquid water under the surface
  - Magnetometric measurements performed by the Galileo probe indicate the presence of an internal layer with electrical conductivity similar to that of salty water (Khurana et al. 1998)
  - Internal sources of energy are expected to exist at large depths; the heating would melt the ice from below



Europe



➢ Internal heating

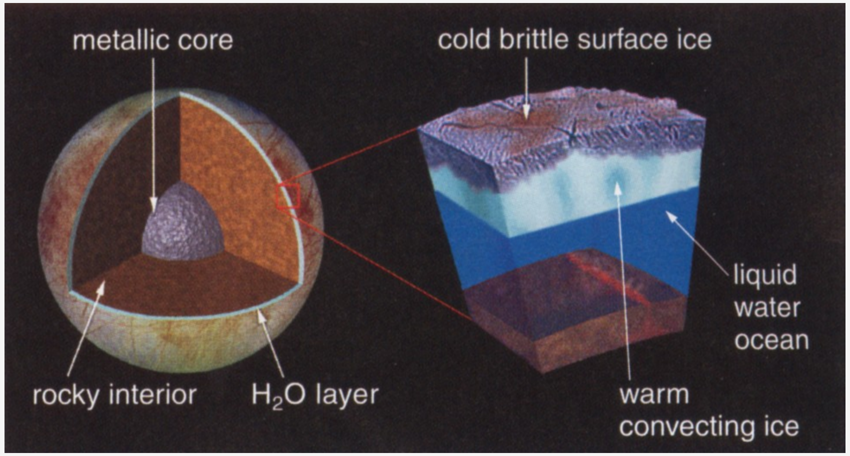
– The heat would be produced by tidal interactions with Jupiter; the strong effects of vulcanism found in the first moon of Jupiter (Io), indicate that also on Europe tidal effects could produce internal heating

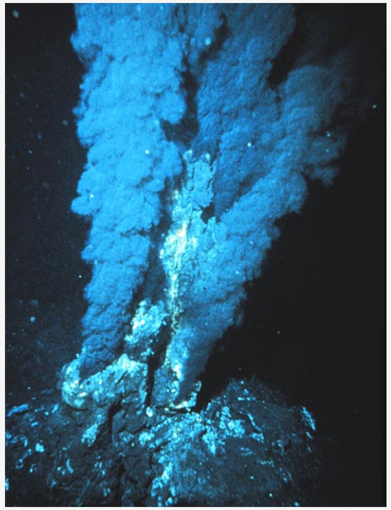
➢ Internal structure

The mean density, ρ=3.0 g cm^{-3}, is similar to the value typical of silicates

Below the layers of solid and liquid water, the interior must be rocky

Habitability of Europe's interior



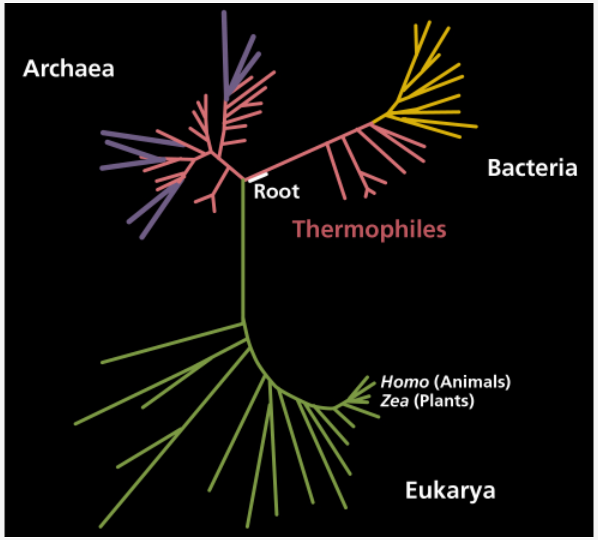


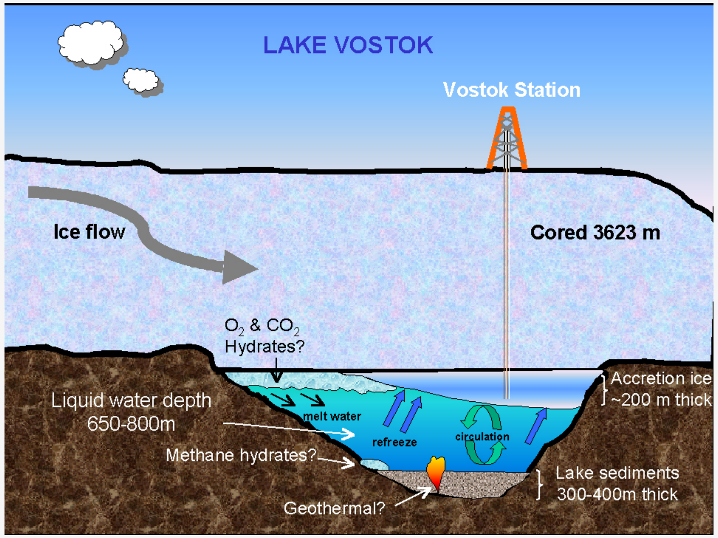
?

- The presence of liquid water <u>below the surface</u> makes Europe the main candidate for studies of habitability outside the "circumstellar habitable zone" (which is instead referred to the <u>surface habitability</u>)
- It is plausible that "hydrothermal vents", similar to those found at the bottom of the Earths oceans, may exist at the bottom of Europe's ocean
- In this case, all the main ingredients of habitability would be present:

  Liquid water, energy sources, protection from ionizing radiations

Motivations to search for life on Europe
Connection with studies in Antarctica





The fact that Earth's termophilic organisms found around hydrothermal vents are close to the root of the phylogenetic tree (relatively close to the origin of life), adds an additional element of interest to the search for life in Europe

The existence of terrestrial cryophilic organisms and the searches for life in Anctartic subglacial lakes are motivated by the similarity with Europe's conditions; the scientific results that might be found in Antarctica and the technological development required to carry out this type of research are all relevant for Europes' astrobiological studies

Searches for biomarkers on Europe’s surface

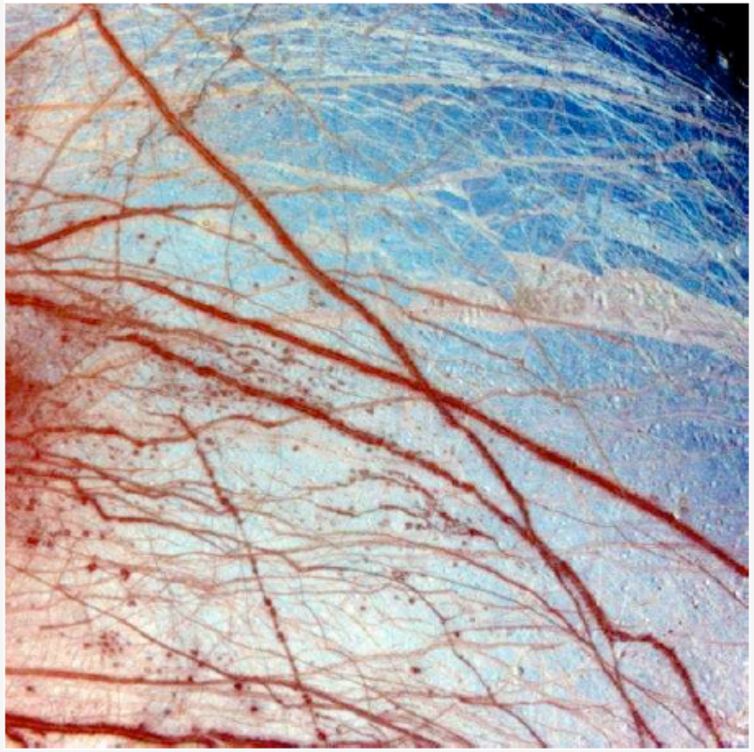
- The icy surface of Europe shows reddish streakes due to different compounds, such as sulfate salts and sulfuric acid

  Their presence may be related to outgassing from Io, but also to an exchange of material between the surface and the subsurface layers, down to the liquid layers

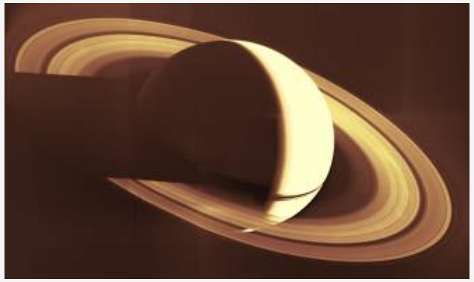
- The chemical pathways able to lead to the formation of such chemical compounds are currently investigated to search for evidence of biochemical activity, if any

  In terrestrial life, sulfur can be produced biologically, in which case the isotopic ratio $^{32}S/^{34}S$ tends to be higher than the corresponding non-biological ratio

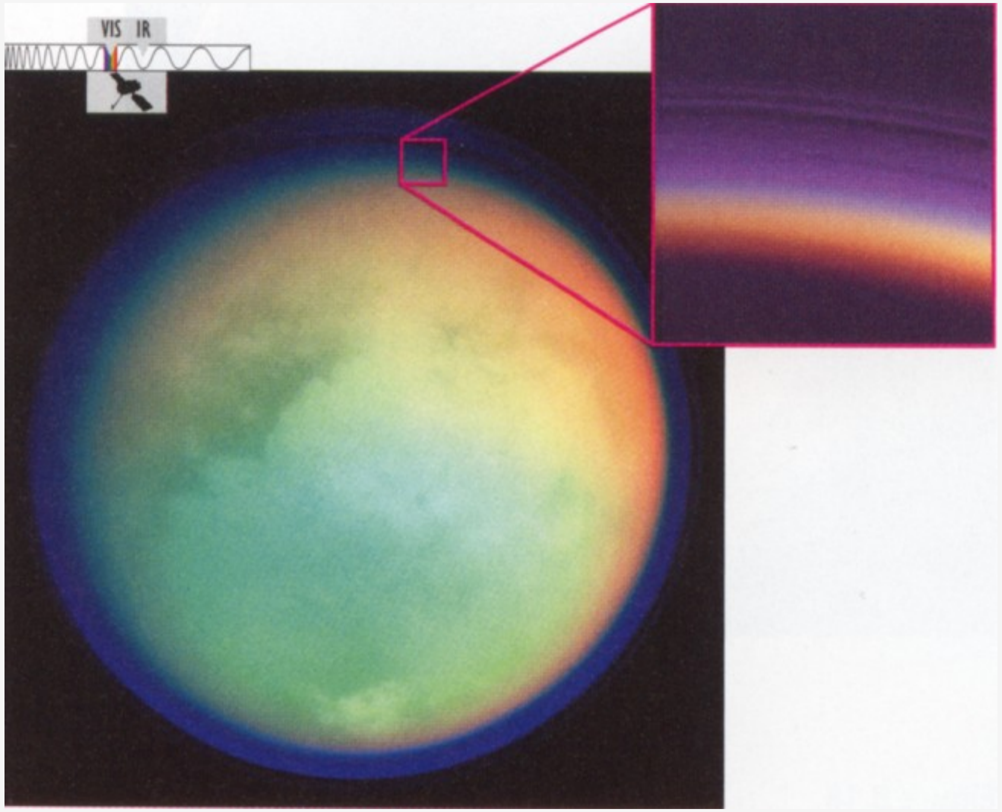
- Future space missions on Europe are considering the possibility of measuring the sulfur isotopic ratio on Europe’s surface, searching for evidence of a biological origin



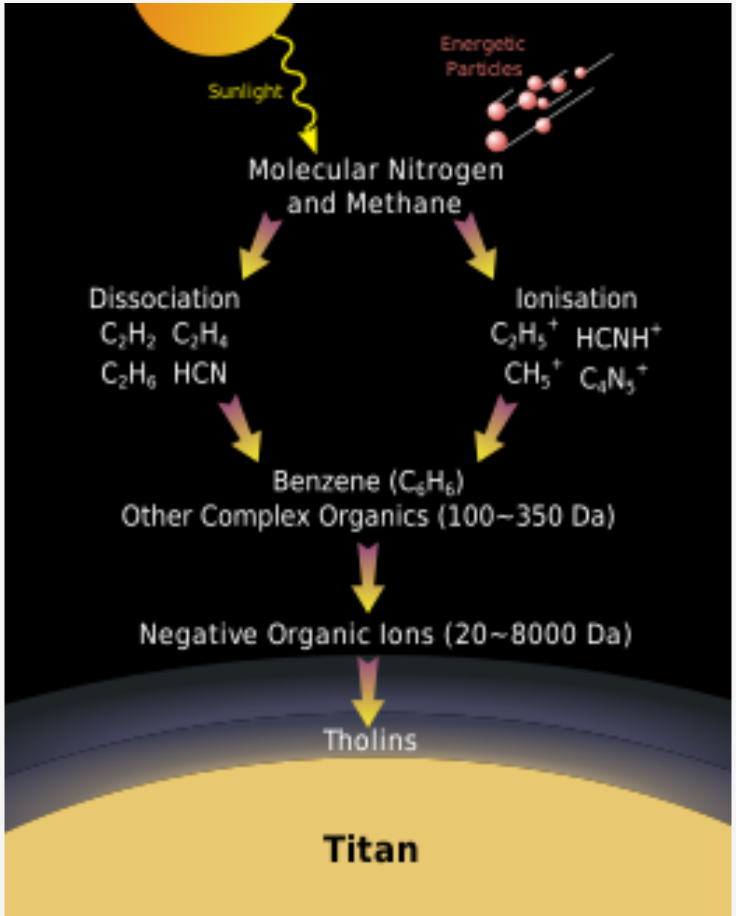
Titan



- Largest satellite of Saturn
  - Radius 40% of Earth's radius
  - Non habitable surface:
  - $<T_s>=94$ K $p_s=1.47\ 10^5$ Pa
- Main observations from space missions
  - NASA Pioneer 11, Voyager 1 and 2 between 1979 and 1982
  - Mission NASA/ESA Cassini-Huygens, since 2004
    - Close up maps obtained by Cassini
    - Landing of the Huygens probe in 2005



Titan's atmosphere



The most abundant molecule is N_2, as in the Earth's atmosphere

The highest atmospheric layers are characterized by a *haze* of *tholin*

- Organic compounds obtained from the processing of simple organic molecules photo-dissociated and photo-ionized

Titan's surface

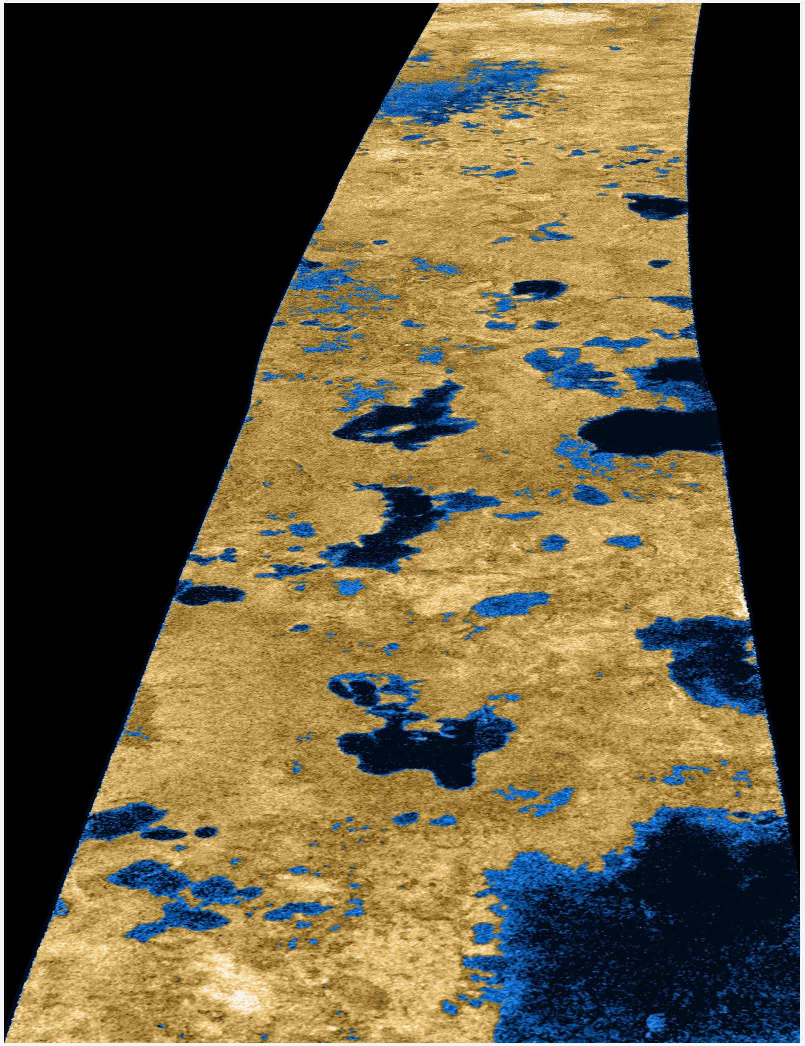
- The surface pressure is comparable to that of the Earth (50% larger)

  p_s=1.47 x 10^5 Pa

- What makes particularly interesting Titan is the presence of large amounts of organic molecules in liquid phase, forming surface lakes of hydrocarbons

  Mainly methane (CH_4) ed ethane (C_2H_6)

  The lakes have been discovered by the *Cassini* probe and, with higher detail, in the landing site of the *Huygens* module



Titan as a laboratory of astrobiology

- The presence of large quantities of organic material makes it possible the formation of complex organic molecules on Titan
  - Laboratory simulations of Titan's atmosphere have shown the possibility of formation of prebiotic material, including aminoacids and nucleic acids
    - Horst et al. (2010)
- Titan is an ideal laboratory to understand whether a biochemsitry based on a liquid different from water, such as methane and ethane, can be possible
  - However, methane and ethane molecules are not polar
  - Some authors have considered the possibility that non polar liquids may give rise to some type of alternative biochemistry, but this possibility is controversial
    - Schulze-Makuch & Irwin (2004)
- Liquid water might exist in undergound layers in Titan
  - There are no direct evidences, but the expert agree that this possibility is plausible; in this case, the exchanges between the organic material and the liquid water may yield extremely interesting astrobiological conditions in the subsurface layers

Enceladus

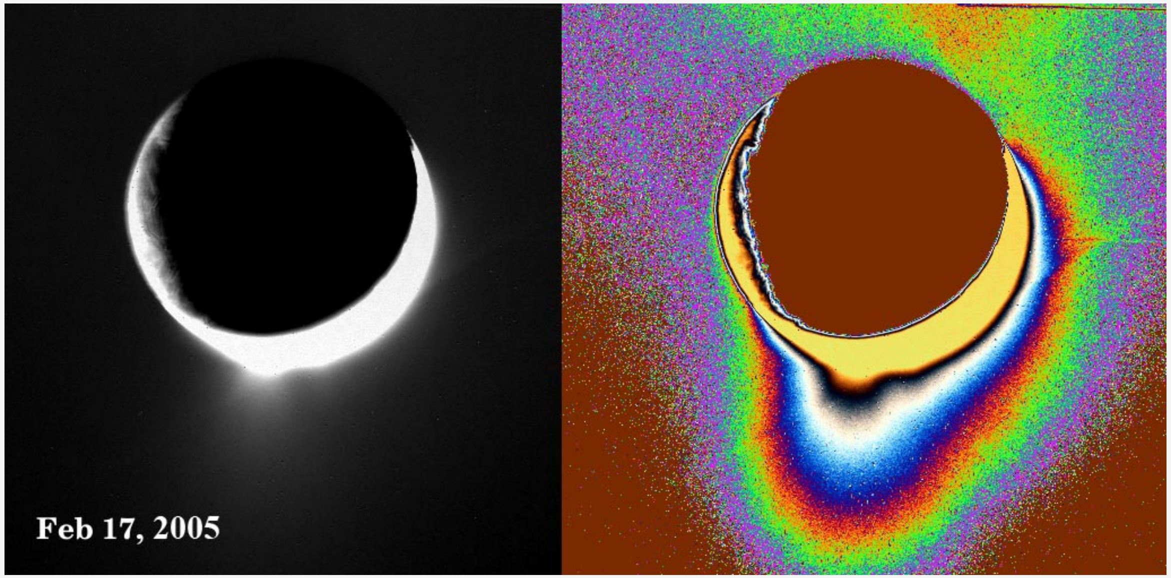
- Small satellite of Saturn

  The surface is icy

  Some of its features are interesting in astrobiology: jets of icy particles and water vapour are being ejected from the South pole

  This activity suggests the presence of an internal energy source of geophysical character; the water vapour shows evidence of simple organic compounds

  McKay et al. (2008, AsBio, 8, 909)



Future missions of astrobiological interest towards Jupiter and Saturn

For reasons of budget, missions to Jupiter/Europe are preferred over missions to Saturn/Titan

Different projects have been considered, in collaboration between NASA and ESA, but some have been discontinued due to the high costs

The ESA project currently under consideration is called

Jupiter Icy Moon Explorer (JUICE)

and it is mostly motivated by astrobiological research on Europe

Search for habitable environments and biomarkers in extrasolar planets (exoplanets)

Exoplanets and astrobiology

- In exoplanets we cannot apply the detailed techniques of astrobiological research used in the Solar System (e.g. sample analysis)
  - In this case we focus on studies of habitability and search for biomarkers

- Habitability

  The habitability of exoplanets can be assessed from the study of the orbits, of the central star and of the planetary properties

  Here we focus on surface habitability

- Search for biomarkers

  Biomarkers can be searched in the spectra of exoplanet atmospheres

Search for <u>habitable</u> exoplanets

In spite of the large number of exoplanets discovered so far
(http://exoplanet.eu - http://exoplanets.org),
the number of habitable exoplanets is still quite small

We briefly review the observational limitations of this type of search

Relation between stellar parameters and distance of the habitable zone (HZ)

$$\sigma T_p{}^4 = \tfrac{1}{4}\, S_* \, (1-A)$$

$$S_* \equiv L_*/(4\pi d^2)$$

$$S_* = \frac{R_*^2}{d^2}\sigma T_*^4$$

$$(1-A)\,\frac{R_*^2}{4\,d^2}\,T_*^4 = T_\mathrm{p}^4$$

Assuming
$A \sim$ const
$d = a$

$$T_\mathrm{p} \propto \left(\frac{R_*}{a}\right)^{\frac{1}{2}} T_*$$

Assuming T_p constant, optimal for life, the distance a of the habitable zone increases linearly with the stellar radius and quadratically with the effective temperature

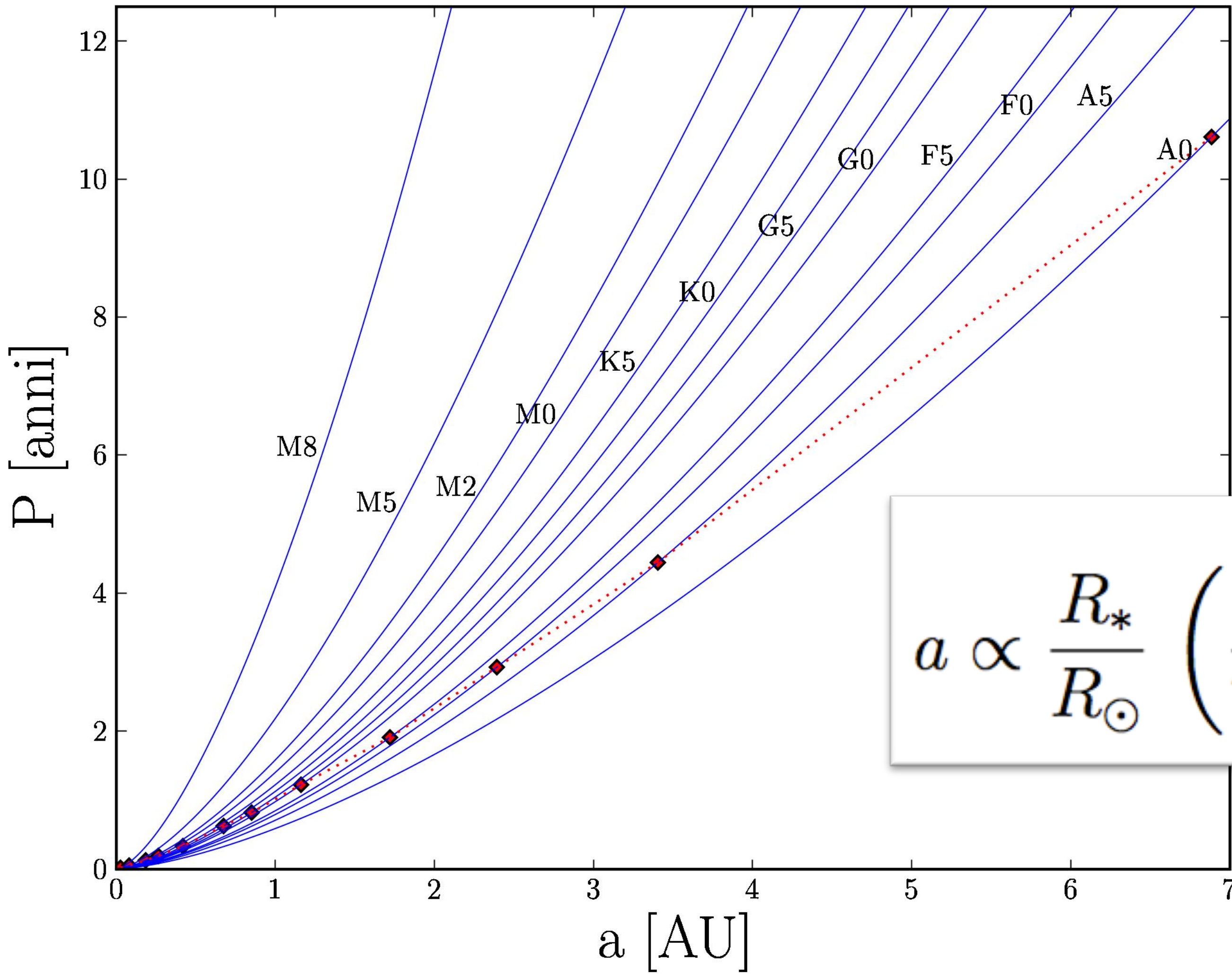
$$\frac{a}{1\,\mathrm{AU}} = \frac{R_*}{R_\odot}\left(\frac{T_*}{T_\odot}\right)^2$$

Detection of habitable planets: observational issues

The habitable zone becomes more distant in early type stars

Because of the III Kepler law, the orbital periods will become larger

The temporal baseline for detecting habitable planets will become longer for early type stars



$$a \propto \frac{R_*}{R_\odot} \left(\frac{T_*}{T_\odot} \right)^2$$

Detection of habitable planets: observational issues

- The temporal baseline of observations for detecting habitable exoplanets does not represent a serious problem

  Planets in the HZ of late-type stars can be detected in short time scales

  Planets in the HZ of early-type stars require several years of observations, but these planets are less interesting from the point of view of astrobiology, because of the relatively fast evolution of the stellar luminosity, which limits the continuous habitability (required for life to evolve into complex forms)

  Planets in the HZ of early-type stars can be detected with the "direct imaging" on observational time scales much shorter than the orbital period

- There are several types of observational bias that affect the detection of habitable planets

  The bias depend on the observational technique used to detect the planet

Detection of habitable exoplanets with the “direct imaging” method

The direct imaging technique favours the discovery of planets with large angular separation from their central star

$$\theta = \arctan(a/D)$$

Planets at large semi-major axis, a, and small distances from the observer, D, will be detected more easily

The bias of the semimajor axis, a, favours the detection of planets that tend to be too distant from the HZ; less critical for early-type stars

The bias of the stellar distance, D, favours nearby stars and, in practice, low-mass stars because they are more numerous in a distance-limited volume;

as a result, detection of planets around M-type stars will be favoured

Detection of habitable exoplanets with the "direct imaging" method

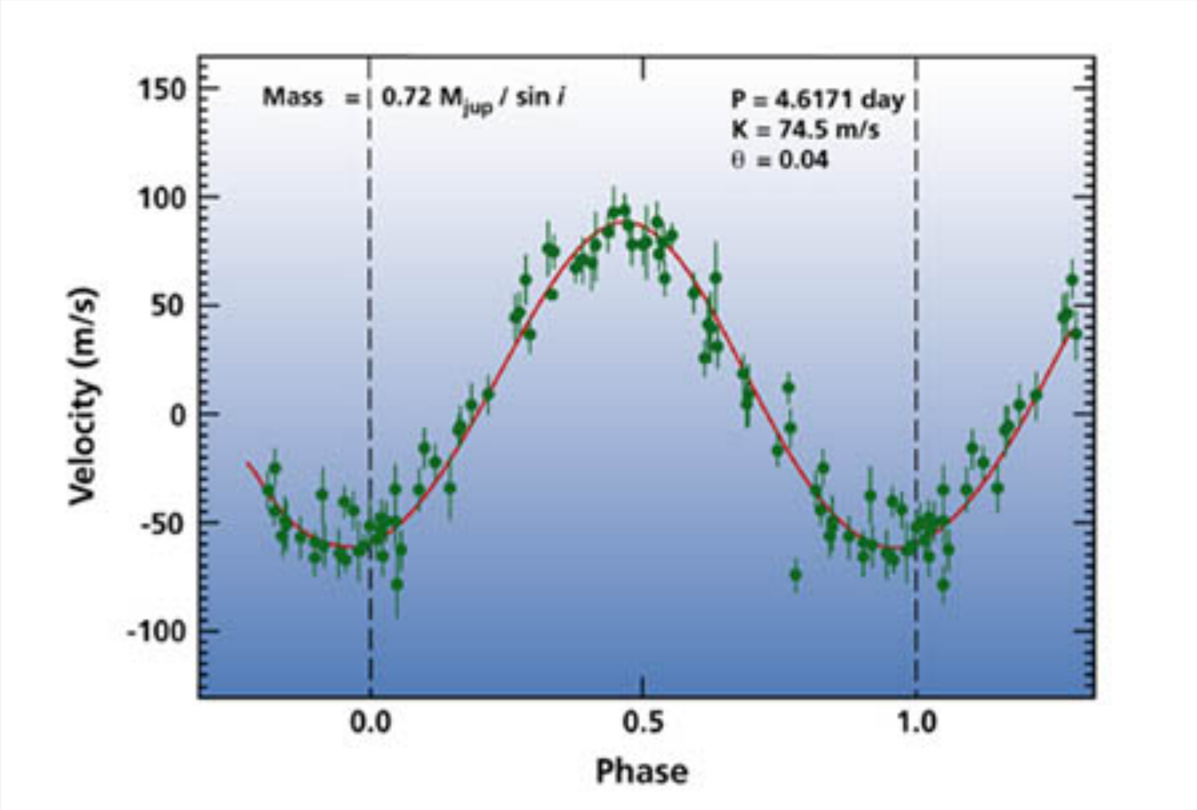
In order of increasing difficulty,
the roadmap for detection of exoplanets with the "direct imaging" method is:

young giant planets (strongest IR emission), old giant planets, neptunes, rocky planets far from the HZ and, eventually, rocky planets in the HZ

The last category is the most interesting one for astrobiology, but the most difficult to achieve: none of the observational projects currently foreseen will be able to detected rocky planets in the HZ with imaging

Space interferometry in the infrared spectral band, with coronagraphic instruments, will be required to achieve this goal in the future

Detecting habitable planets with the *Doppler method*



For circular orbits, the semi-amplitude K is given by

$$K = (2\pi G/P)^{1/3}\, M_P \sin i \,/\, (M_* + M_P)^{2/3}$$

Table I
Radial Velocity Signals of the Planets

Planet	M_p (M_J)	R (AU)	P (years)	$\Theta_\star$ at 10 pc (mas)	$V_\star$ ($\mathrm{m\,s^{-1}}$)
Mercury	1.74E-4	0.387	0.241	6.4E-6	0.008
Venus	2.56E-3	0.723	0.615	1.8E-4	0.086
Earth	3.15E-3	1.000	1.000	3.0E-4	0.089
Mars	3.38E-4	1.524	1.881	4.9E-5	0.008
Jupiter	1.0	5.203	11.86	0.497	12.4
Saturn	0.299	9.54	29.46	0.273	2.75
Uranus	0.046	19.18	84.01	0.084	0.297
Neptune	0.054	30.06	164.8	0.156	0.281
Pluto	6.3E-6	39.44	247.7	2.4E-5	3E-5

Detecting habitable planets with the *Doppler method*

- Advantages of M-type stars with the Doppler method

  The semi-amplitude of the radial velocity curves scales as

  $$K \sim (a\, M_{*})^{-1/2}$$

  where a is the semi-major axis, M_{*} the stellar mass

  The advantage of a smaller stellar mass combines with the advantage of the smaller distance of the habitable zone

  For a given planetary mass, the Doppler signal of a planet in the HZ of an M-type star is ~ 3-30 times stronger than the signal of planet in the HZ of a solar-type star

Detecting habitable planets with the *Doppler method*

Also the Doppler method is sensititive to the distance from the observer, D

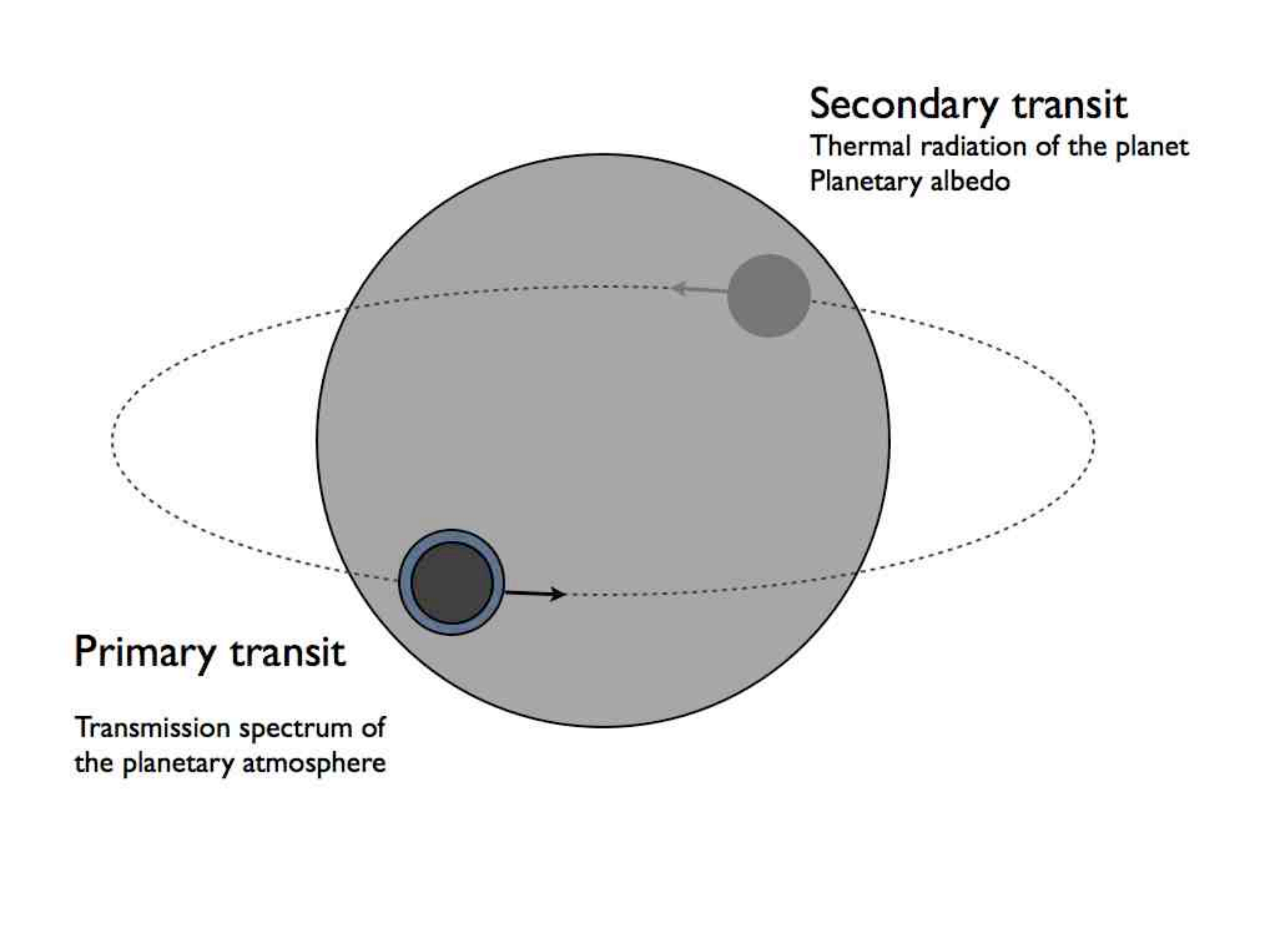
The flux of stellar photons scales as D^{-2}

The signal-to-noise ratio of the spectrum scales with the square root of the number of photons, and therefore scales as D^{-1}

For a given observing time and stellar type, the measurements of stellar radial velocities will be more accurate in nearby stars

Also in this case, the high density of low-mass stars favours the detection of planets around M-type stars (however, one should also take into account that early-type stars are brighter)

Detection of habitable planets with the *transit method*



Detection of habitable planets with the *transit method*

- Transit depth of the minimum of the light curve

$$\Delta F = \frac{F - F_{\rm tr}}{F} = \left(\frac{R_{\rm p}}{R_*}\right)^2$$

The strongest signal is given by giant planets around stars of small radii

For a given planet size, the detection will be easier, in terms of signal-to-noise ratio, in front of stars of small size

Since late-type stars on the main sequence have smaller radii than early-type stars, the transit signal will be more intense in late-type stars

However, at a given stellar distance, the signal-to-noise ratio of the spectrum will be higher for early-type stars

Detection of habitable planets with the *transit method*

- Geometrical probability of detecting a planet with the transit method

$$\mathcal{P}_{\rm tr} \simeq 4.65 \times 10^{-3} \, \frac{R_* \, [R_\odot]}{a \, [\mathrm{AU}]}$$

The probability is low and requires surveys of many thousands of stars to discover transits

The geometrical probability increases with the inverse of the semi-major axis

Since habitable planets around late-type stars are located at small semi-major axis, also the geometrical probability will become higher in late-type stars

This can be seen combining the above relation with the relation previously derived, between planetary and stellar parameters

$$T_{\rm p} \propto \left(\frac{R_*}{a}\right)^{\frac{1}{2}} T_*$$

$$\mathcal{P}_{\rm tr} \sim (T_{\rm p}/T_*)^2$$

Potential problems of habitable planets around M-type stars

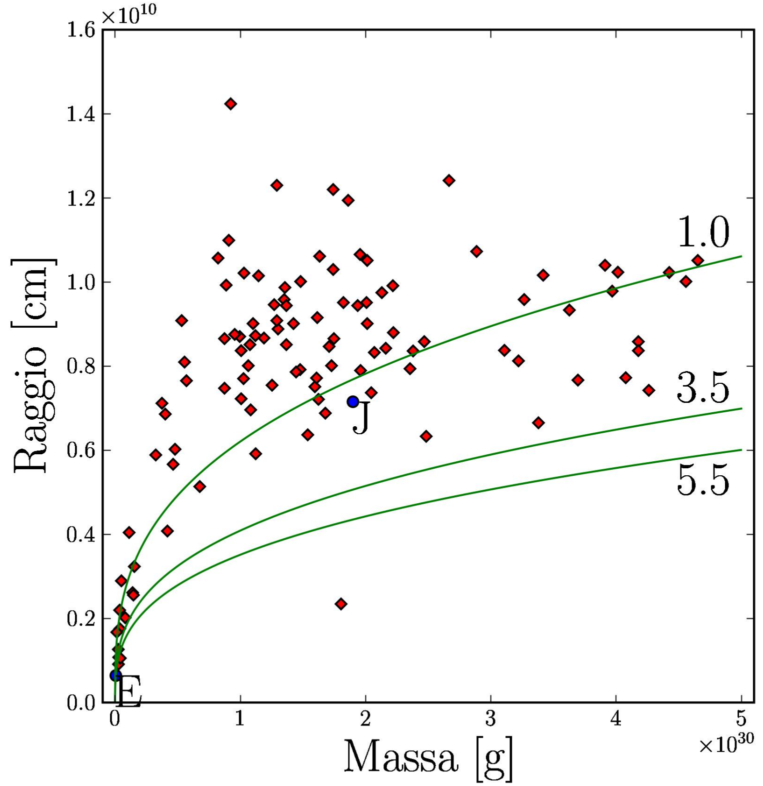
- M-type stars are strongly favoured for detection of exoplanets in the HZ

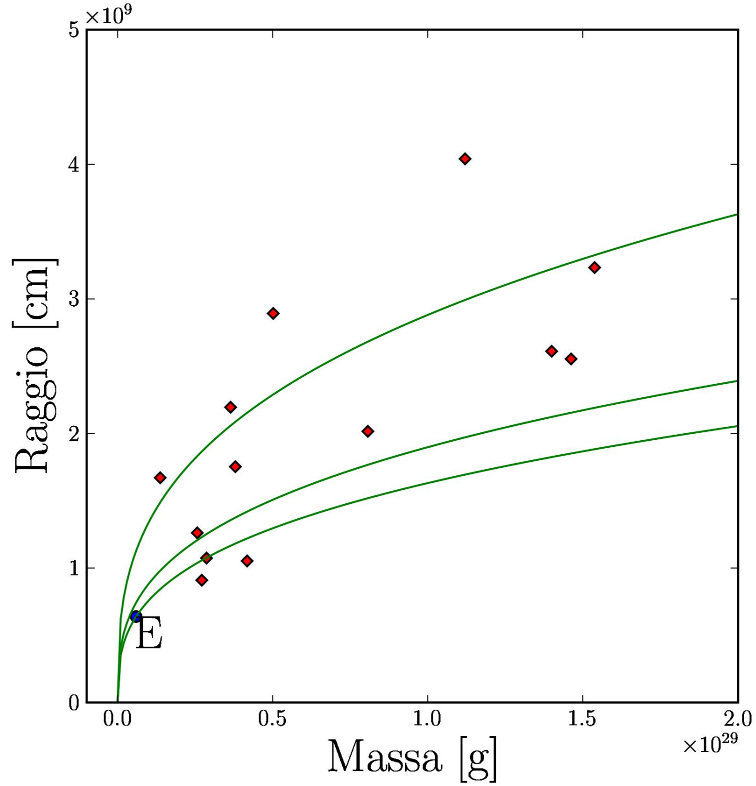
- However, the effective habitability around these type of stars is under debate, because of the following potential problems:
  - The intense stellar activity, characteristic of late-type stars, may give problems of "space weather"
    - e.g., effects on the planet of high-energy particles emitted by the star
  - The vicinity to the star may lead to a synchronization of the planet orbital period with the planet rotation period ("tidal locking")
    - this has heavy implications on the planetary climate
  - The different spectral distribution of M-type stars with respect to solar-type stars may give a lower efficiency of photosynthesis

- Probably, none of these problems completely prevent the habitability

Search for rocky habitable planets

By combining the observational data obtained with the Doppler and transit methods, we can measure masses and radii of exoplanets.
In this way we can study their mean density and internal composition.





Most exoplanets discovered so far are gaseous ($\rho < 1$ g cm^{-3}), but we are starting to discover rocky ones ($\rho > 3$ g cm^{-3})

List of “super-Earths” (May 2012)

HD 1461 b	a=0.0635 AU	M=7.63 M(earth)
HD 7924 b	a=0.0566 AU	M=9.26 M(earth)
HD 20794 b	a=0.1207 AU	M=2.70 M(earth)
HD 20794 c	a=0.2036 AU	M=2.36 M(earth)
HD 20794 d	a=0.3498 AU	M=4.70 M(earth)
GJ 176 b	a=0.0657 AU	M=8.27 M(earth)
HD 40307 c	a=0.0801 AU	M=6.72 M(earth)
HD 40307 b	a=0.0469 AU	M=4.10 M(earth)
HD 40307 d	a=0.1324 AU	M=8.93 M(earth)
CoRoT-7 b	a=0.0172 AU	M=4.95 M(earth)
55 Cnc e	a=0.0154 AU	M=7.81 M(earth)
HD 85512 b	a=0.2604 AU	M=3.62 M(earth)
GJ 3634 b	a=0.0287 AU	M=7.06 M(earth)
HD 97658 b	a=0.0797 AU	M=6.40 M(earth)
61 Vir b	a=0.0501 AU	M=5.11 M(earth)
GJ 581 c	a=0.0729 AU	M=5.33 M(earth)
GJ 581 d	a=0.2177 AU	M=6.08 M(earth)
GJ 581 e	a=0.0285 AU	M=1.95 M(earth)
GJ 1214 b	a=0.0143 AU	M=6.47 M(earth)
HD 156668 b	a=0.0500 AU	M=4.15 M(earth)
Kepler-10 b	a=0.0168 AU	M=4.52 M(earth)
Kepler-20 b	a=0.0454 AU	M=8.46 M(earth)
Kepler-20 d	a=0.3453 AU	M=7.53 M(earth)
HD 181433 b	a=0.0801 AU	M=7.55 M(earth)
Kepler-11 b	a=0.0911 AU	M=4.30 M(earth)
Kepler-11 d	a=0.1542 AU	M=6.10 M(earth)
Kepler-11 f	a=0.2495 AU	M=2.30 M(earth)
Kepler-11 e	a=0.1939 AU	M=8.40 M(earth)
Kepler-18 b	a=0.0447 AU	M=6.88 M(earth)
HD 215497 b	a=0.0466 AU	M=6.63 M(earth)
GJ 876 d	a=0.0208 AU	M=5.86 M(earth)

“Super-Earths” : M < 10 M(earth)

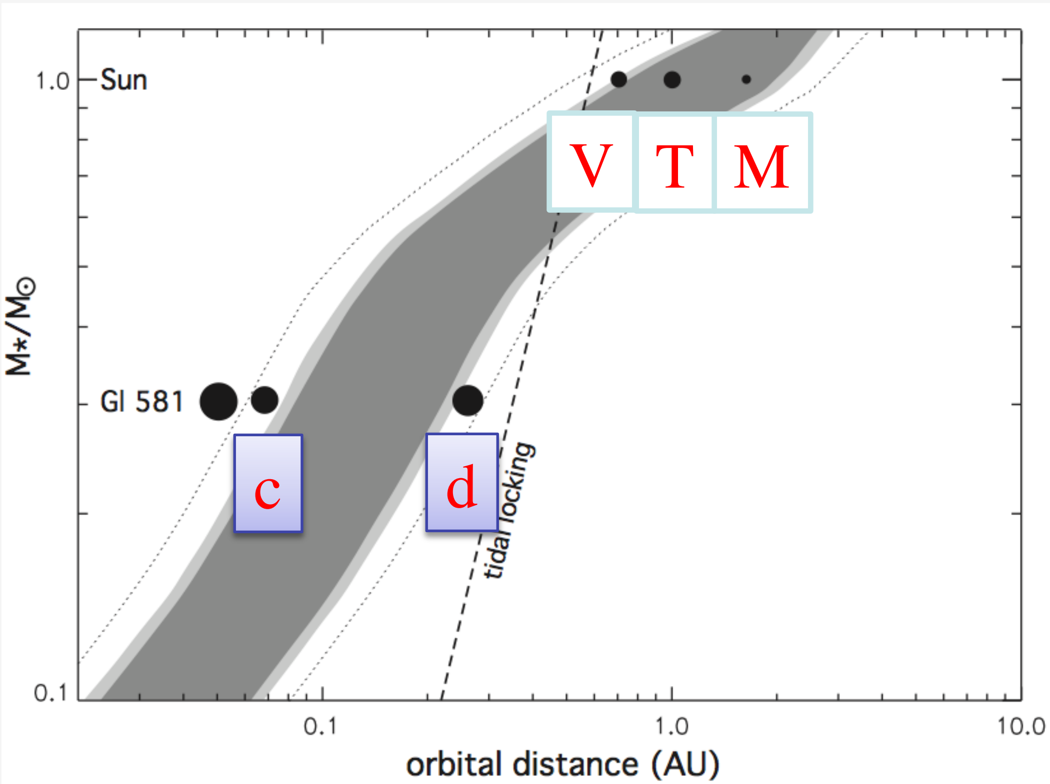
Best candidates habitable planets, in lack of Earth-mass planets

At largers masses, the planet could become a gaseous giant in the course of planetary formation

However, super-Earths could also have an icy core

One of the most interesting planetary systems discovered in the past years, as far as the habitability is concerned, is the system around the star Gl581, with a few planets close to the habitable zone (HZ)

By applying models of planetary climate one can understand the limits of habitability of such planets for different sets of planetary conditions

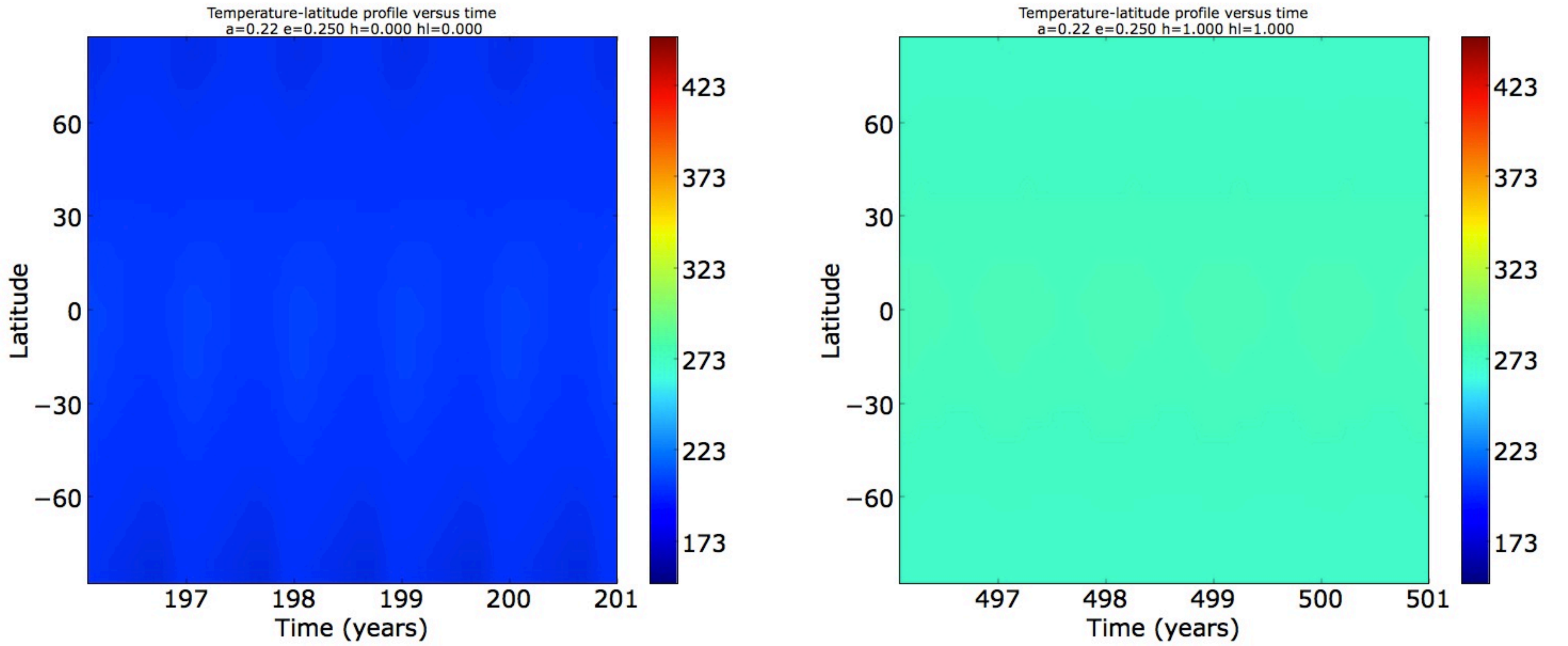


Habitability of Gl 581d

By using an Earth-like climate model, the planet is completely frozen

To make the planet habitable we need a very strong greenhouse atmosphere
Our calculations suggest that a pressure of CO_2 of at least 8 bar is required
More than three orders of magnitude than the the Earth's $p(CO_2)$

If the pressure is so high, the model predicts a very uniform surface temperature, not affected by seasonal and latitudinal variations



Kepler-22b (Borucki et al. 2012)

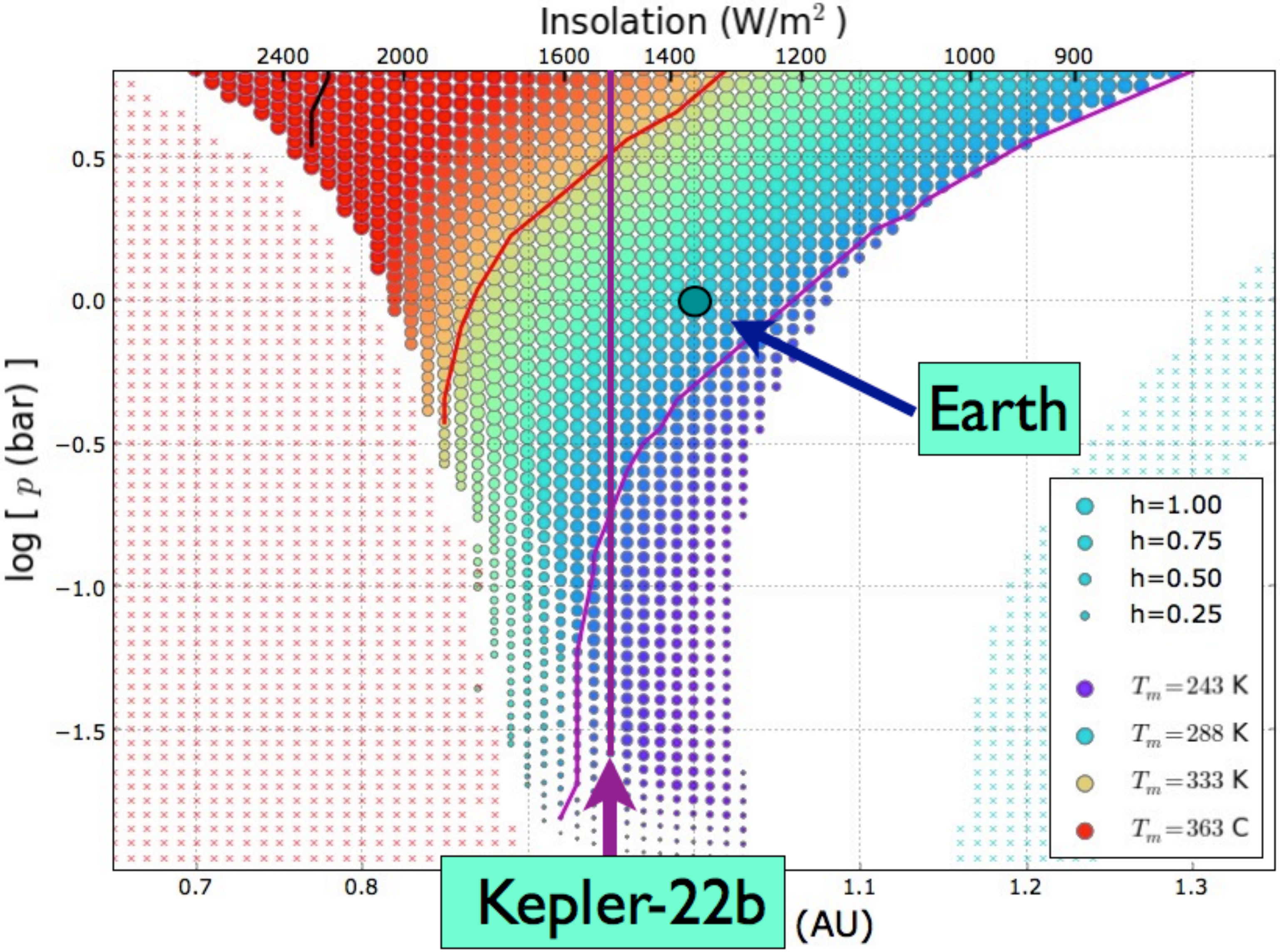
Characteristics of Kepler-22 and 22b

Parameter	Value
Effective temperature, $T_{\rm eff}$ (K)	5518 ± 44
Surface gravity, log g (cgs)	4.44 ± 0.06
Metallicity, [Fe/H]	-0.29 ± 0.06
Projected rotation $v \sin i$ (km s^{-1})	0.6 ± 1.0
Density, g cm^{-3}	1.458 ± 0.030
Mass, $M_\odot$	0.970 ± 0.060
Radius, $R_\odot$	0.979 ± 0.020
Luminosity, $L_\odot$	0.79 ± 0.04
Kepler magnitude (mag)	11.664
Age (Gyr)	Not determined
Distance (pc)	190
Orbital period, P (days)	$289.8623 + 0.0016/-0.0020$
Epoch, T0 (BJD-2,454,900)	66.6983 ± 0.0023
Scaled semimajor axis, a/R_*	$186.4 + 1.1/-1.6$
Scaled planet radius, $R_{\rm p}/R_*$	$0.0222 + 0.0012/-0.0011$
Impact parameter, b (eccentric orbit)	$0.768 + 0.132/-0.078$
Orbital inclination, i (deg)	$89.764 + 0.025/-0.042$
Transit duration, Δ (hr)	$7.415 + 0.067/-0.078$
Radius, $R_\oplus$	2.38 ± 0.13
Mass, $M_\oplus$, (1σ, 2σ, and 3σ upper limits)	36, 82, 124
Orbital semimajor axis, a (AU)	$0.849 + 0.018/-0.017$
Equilibrium temperature, $T_{\rm eq}$ (K)	262

Stellar spectral distribution not too different from solar

Planet lies beyond tidal lock distance and has R=2.38 $R_\oplus$

... but the mass is still not "weighted" with accuracy...

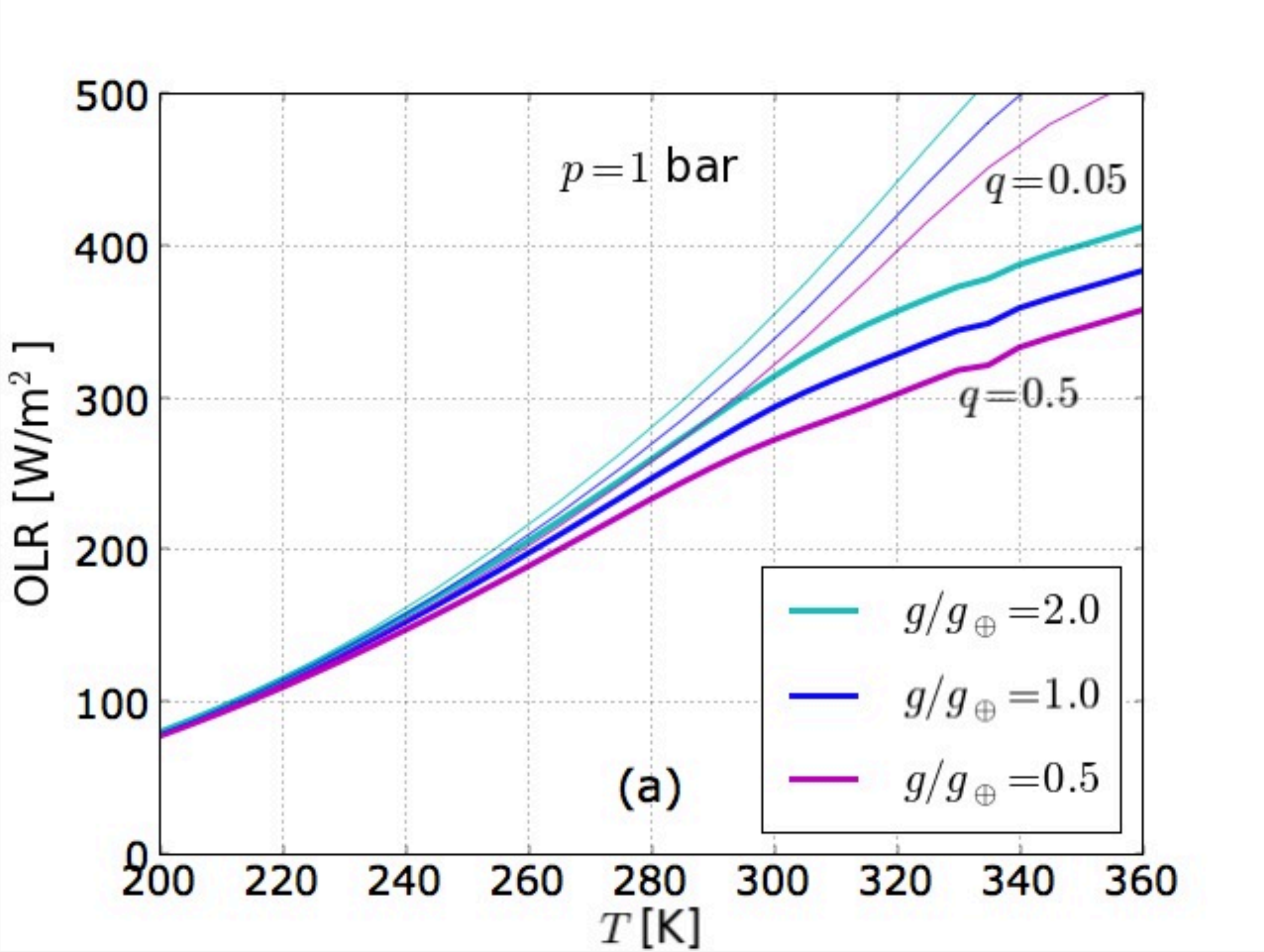


Insolation (W/m^2)
2400
2000
1600
1400
1200
1000
900
log [p (bar)]
0.5
0.0
−0.5
−1.0
−1.5
0.7
0.8
1.1
1.2
1.3
(AU)
Earth
Kepler-22b
h=1.00
h=0.75
h=0.50
h=0.25
$T_m = 243$ K
$T_m = 288$ K
$T_m = 333$ K
$T_m = 363$ C

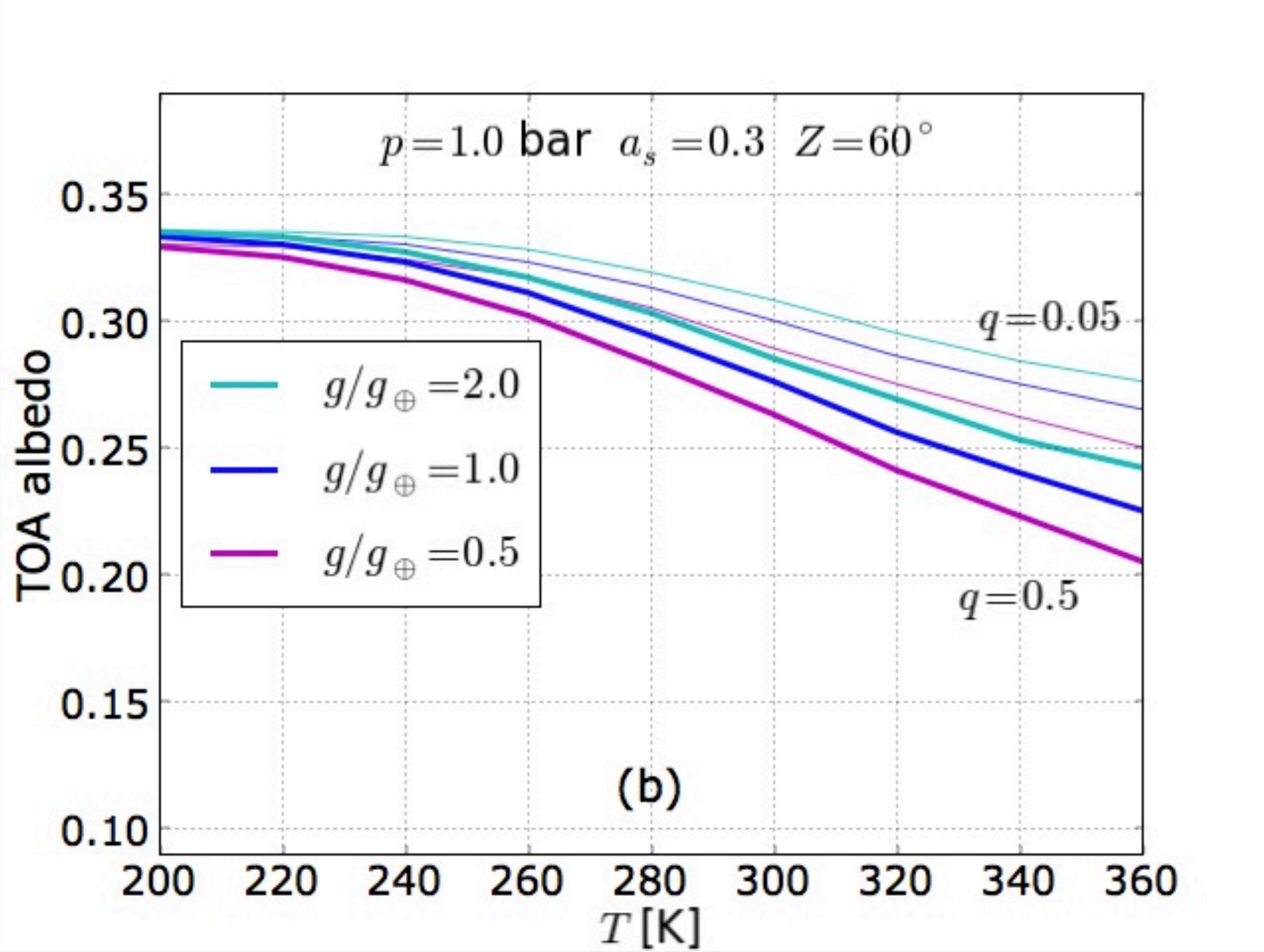
Effects of gravity and pressure
on the climate and habitability of exoplanets

Vertical mass column of the atmosphere: p/g

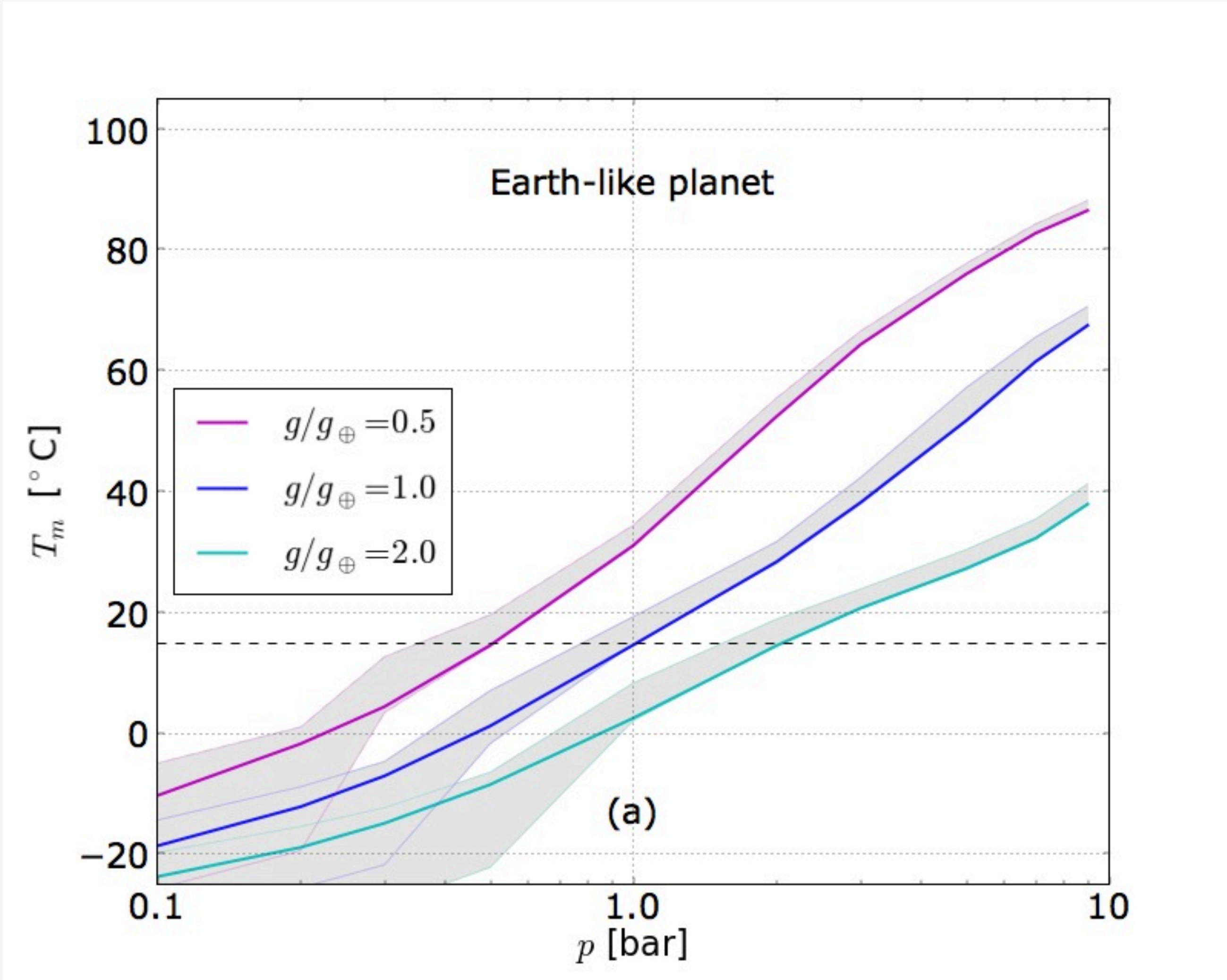
Effects of gravity on the Outgoing Longwave Radiation (OLR)



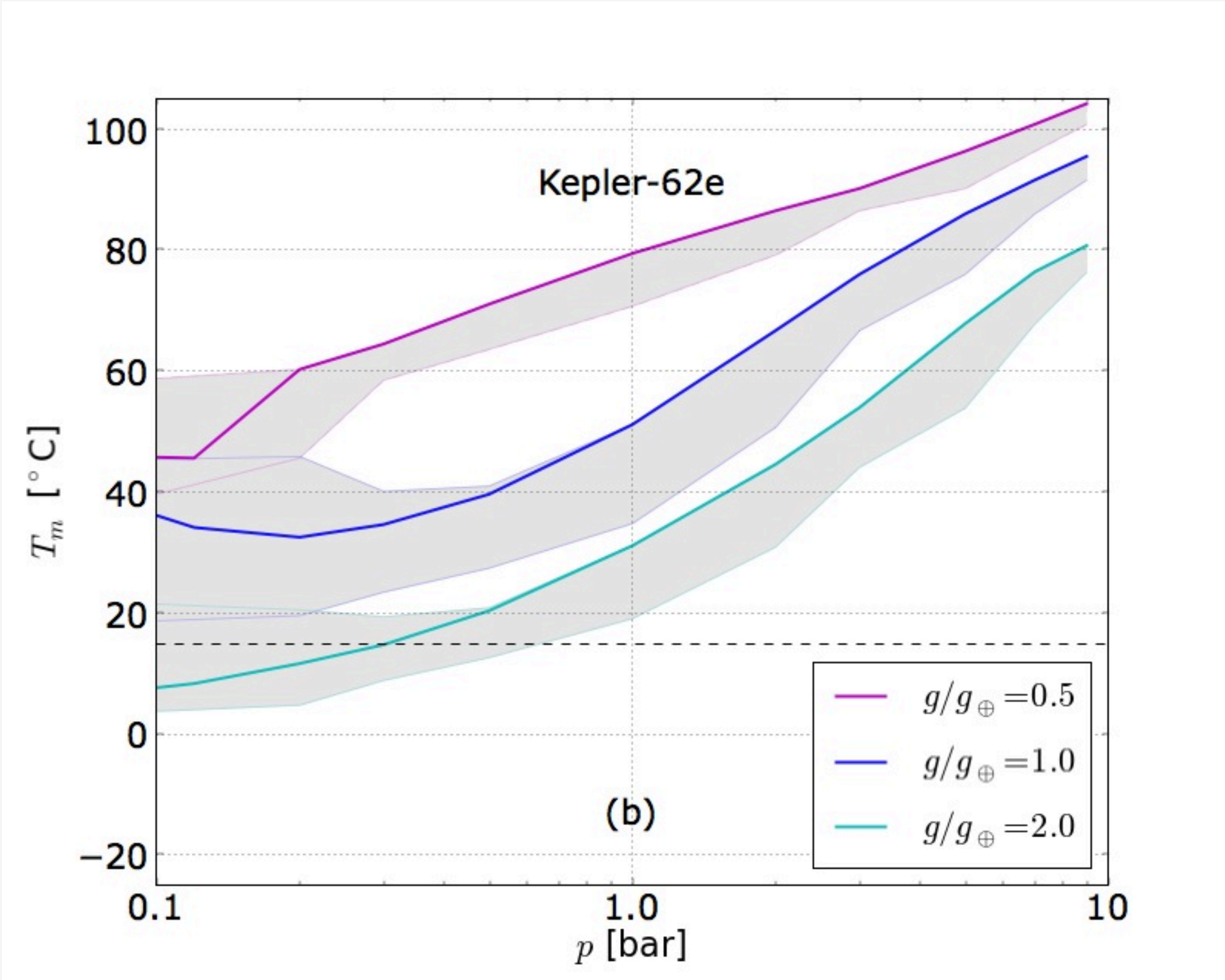
Effects of gravity on the top-of-atmosphere (TOA) albedo



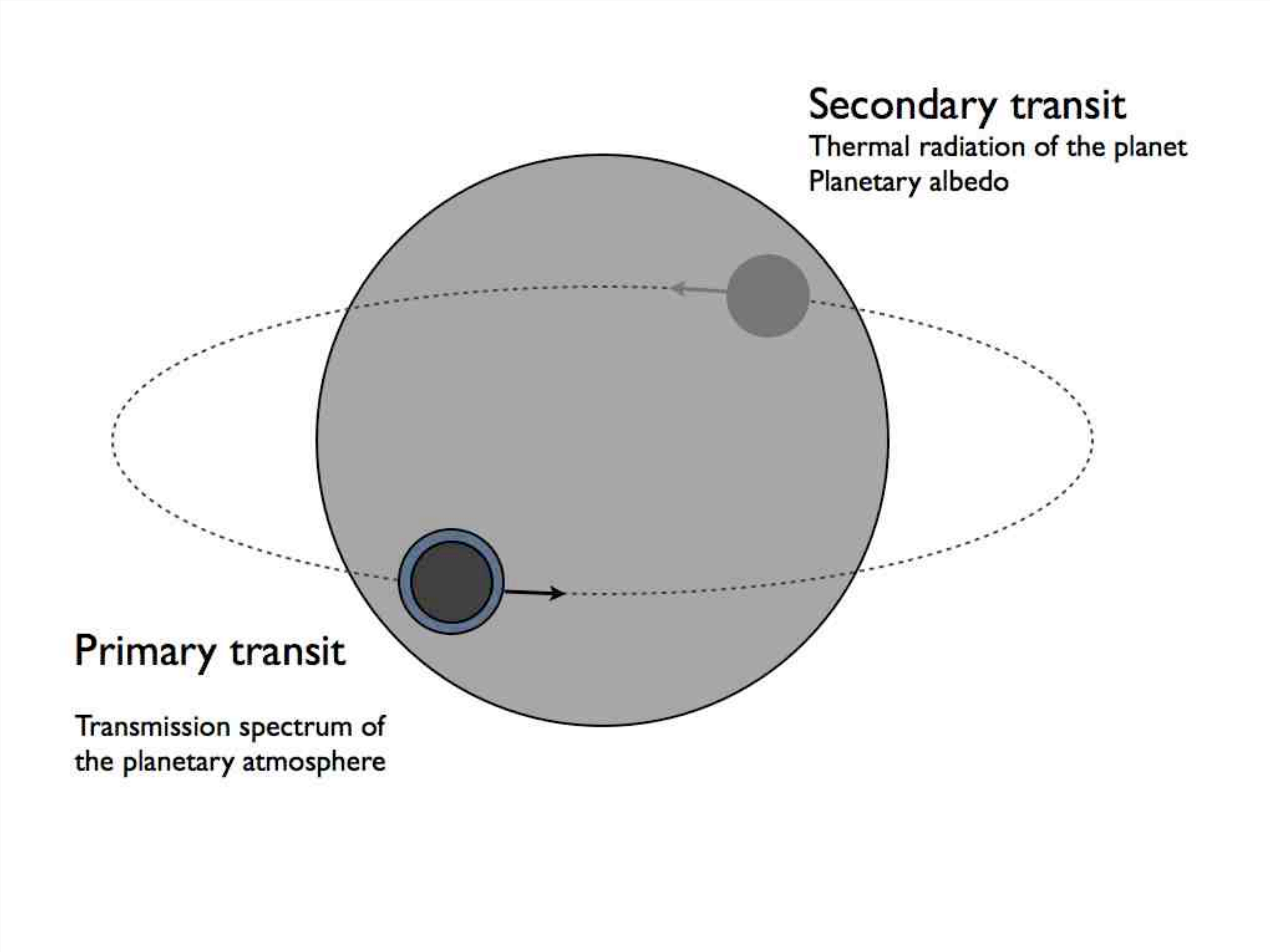
Effects of gravity and pressure on the mean global temperature



Effects of gravity and pressure on the mean global temperature



Searches for biomarkers
Observations of planetary atmospheres



Absorption spectroscopy of planetary atmospheres

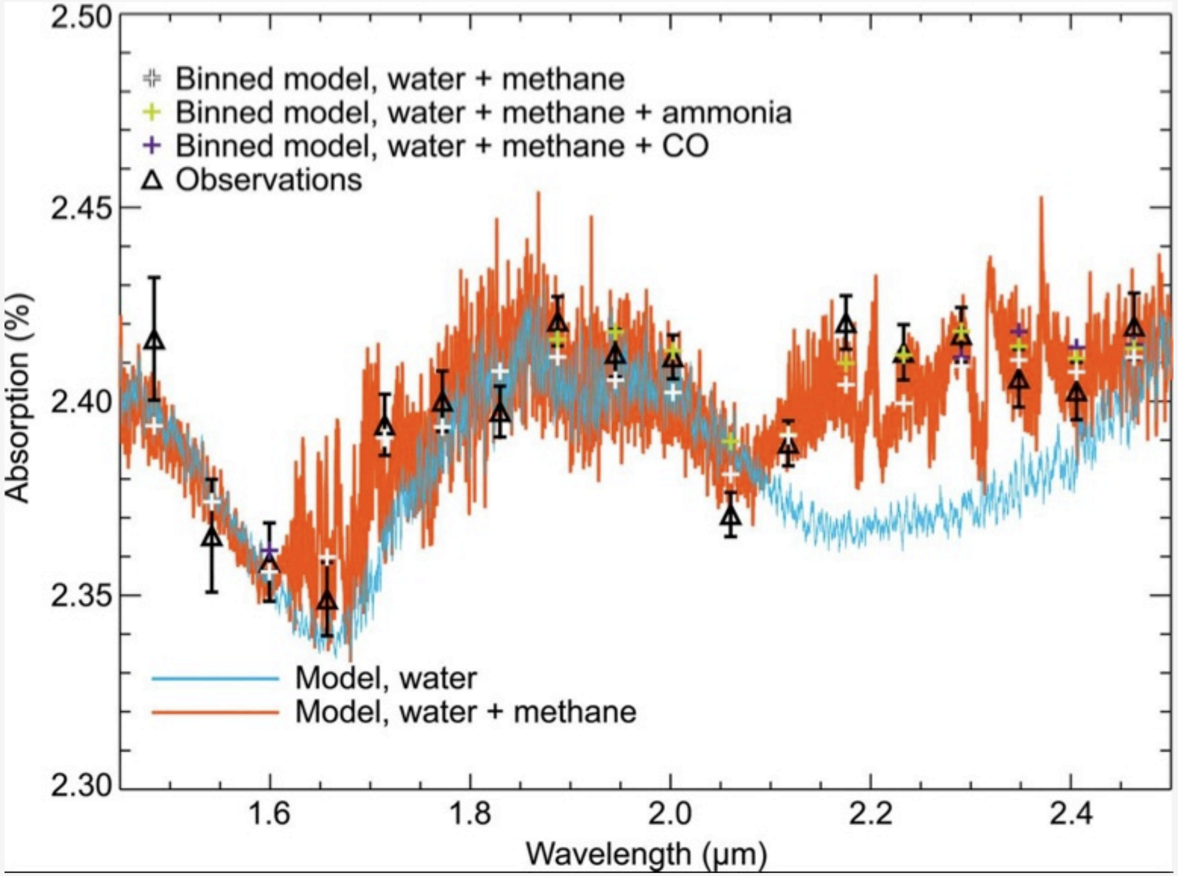
- The atmospheric absorption signal scales with the scale-height of the atmosphere, h, and the planet radius, R_p
- Gaseous giants give the strongest signal; already detected
  - e.g. Tinetti et al. (2007)
- Earth-like atmospheres are beyond detection limit even for the most advanced instrumental projects currently scheduled
- Atmospheres of super-Earths may be feasible with next generation instrumentation
- Detection bias favours stars with smaller radii

$$\delta I \sim \frac{2\,h\,R_\mathrm{p}}{R_*^2}$$

Absorption spectroscopy of planetary atmospheres

- Atmospheric absorption spectroscopy with primary transits: molecular detections in gaseous giant planets

H_2O, CH_4, CO_2, CO

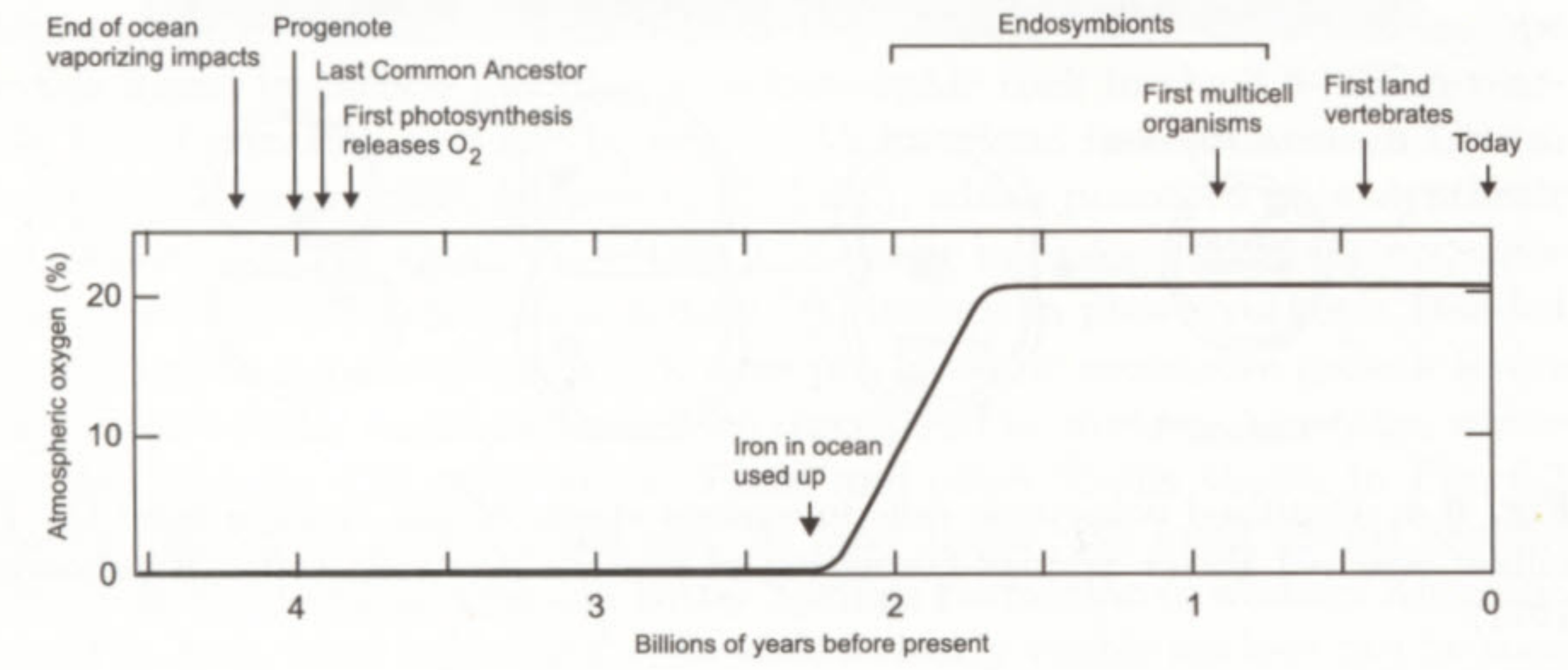


Biomarkers in the spectra of planetary atmospheres

Oxygen is considered one of the most promising biomarkers

In absence of a biosphere, oxygen tends to oxydate rocks and to decrease its atmospheric concentration

The history of Earth's atmospheric oxygen reveals the fundamental role of biology

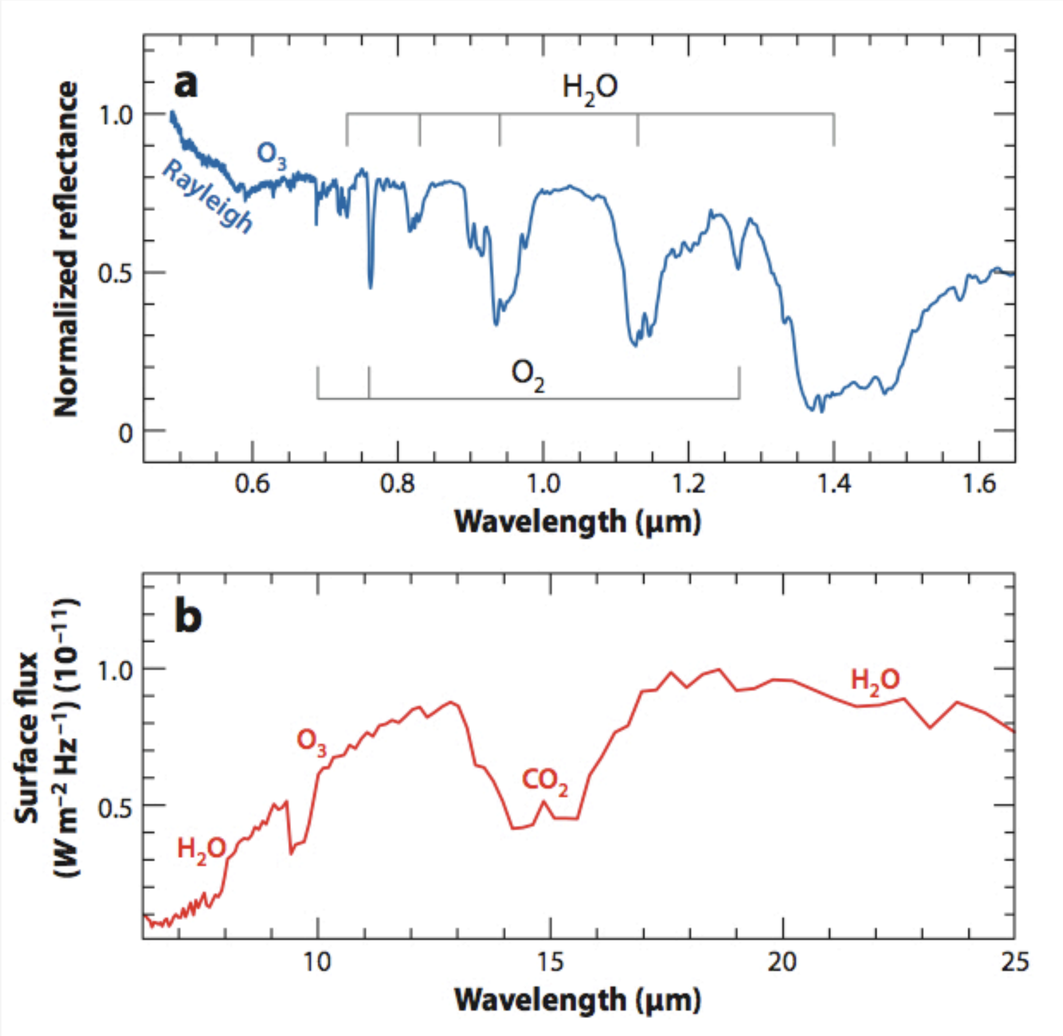


What do we hope to detect in planetary atmospheres?

Examples: spectra of the Earth's atmosphere observed from space

Reflection spectrum
in the visible/near IR

IR emission spectrum



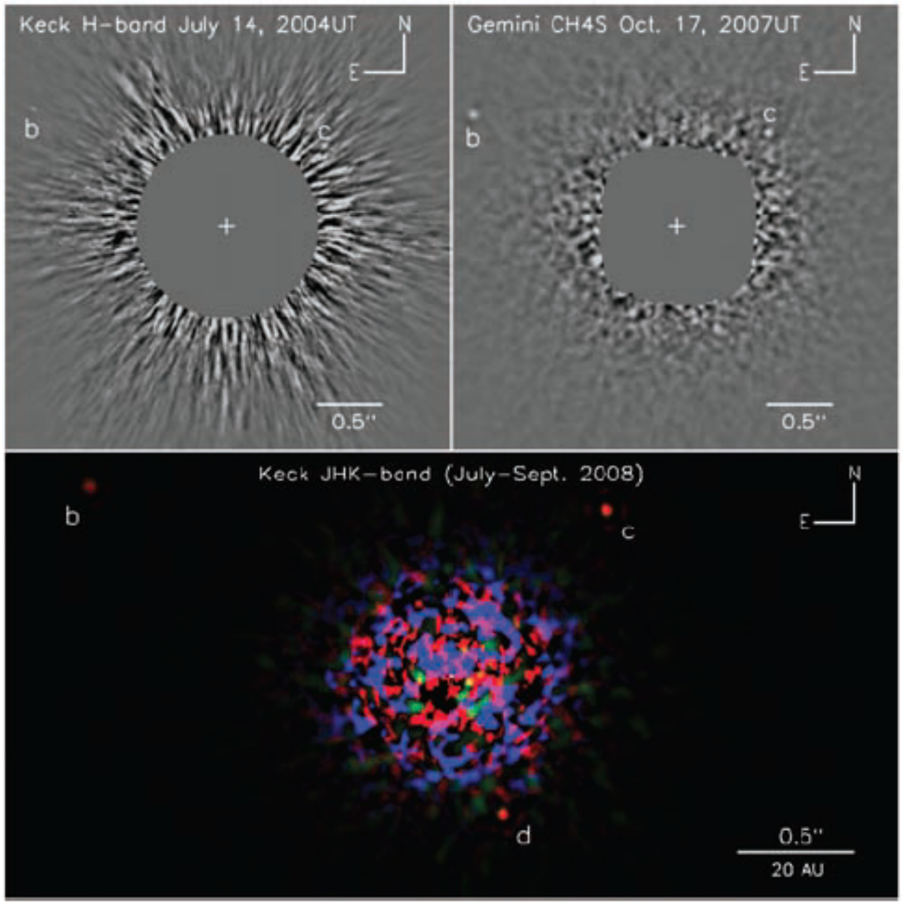
Direct imaging studies of planetary atmospheres

Example of multiple planetary system: HR 8799bcd (Marois et al. 2008)

IR imaging of nearby, young stars

(young stars → young planets → IR emitters)

Fig. 1. HR 8799bcd discovery images after the light from the bright host star has been removed by ADI processing. **(Upper left)** A Keck image acquired in July 2004. **(Upper right)** Gemini discovery ADI image acquired in October 2007. Both b and c are detected at the two epochs. **(Bottom)** A color image of the planetary system produced by combining the J-, H-, and Ks-band images obtained at the Keck telescope in July (H) and September (J and Ks) 2008. The inner part of the H-band image has been rotated by 1° to compensate for the orbital motion of d between July and September. The central region is masked out in the upper images but left unmasked in the lower to clearly show the speckle noise level near d.



Direct imaging studies of planetary atmospheres: detection of molecular absorption

Fig. 2. K-band spectrum of HR 8799c (black) at the full resolution of OSIRIS ($\lambda/\Delta\lambda \sim 4000$). Both lines and continuum are shown, and the spectral features most relevant to objects of this mass are highlighted. For clarity, uncertainties are shown separately in red. The best-fitting model spectrum is shown in green. A clear drop from CO is detected, along with features typical of the CO bandhead at $\lambda >$ 2.29 μm. The slight increase in the spectrum at the red end is attributed to residual speckle effects after the attenuation algorithm. Again, broad features from CH_4 are not easily detected. Spectral data are provided in database S1 (*15*).