Habitable exoplanets: modeling & characterization

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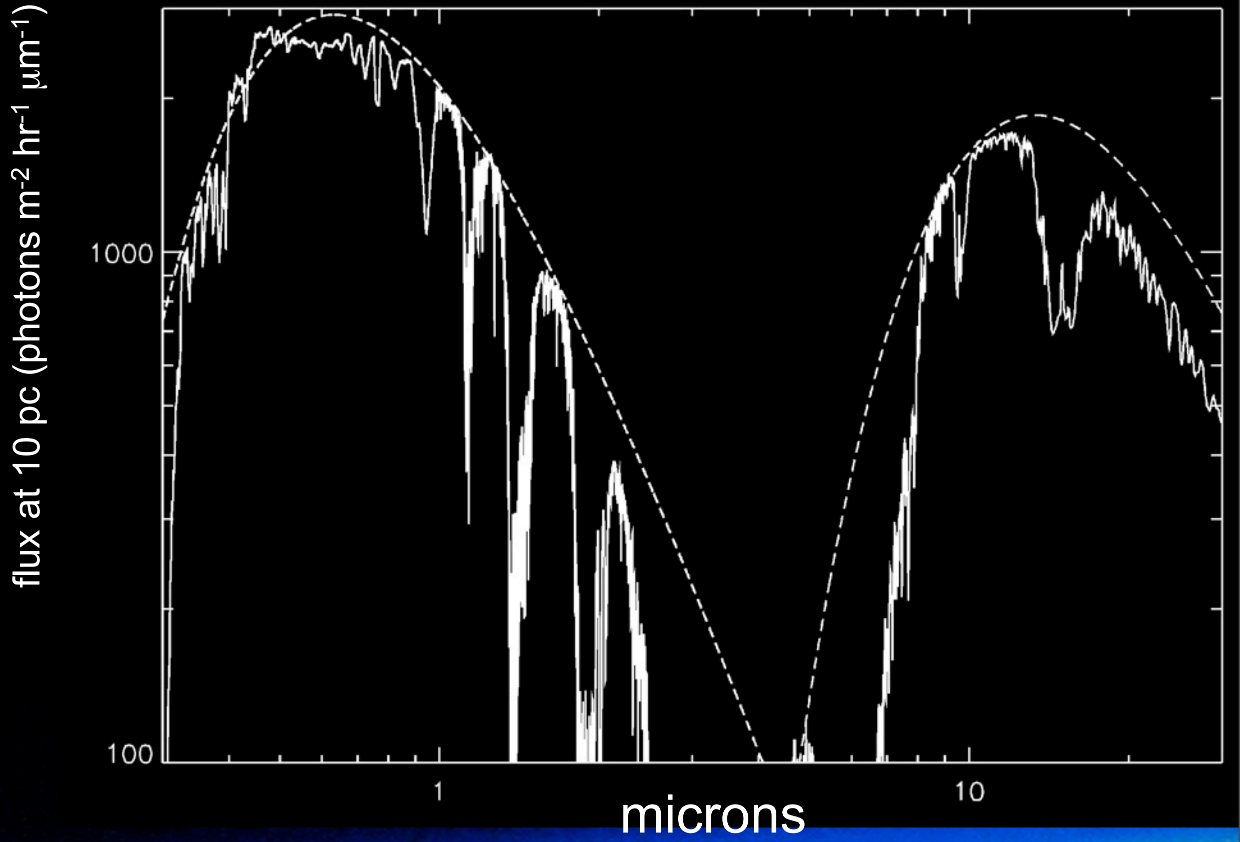
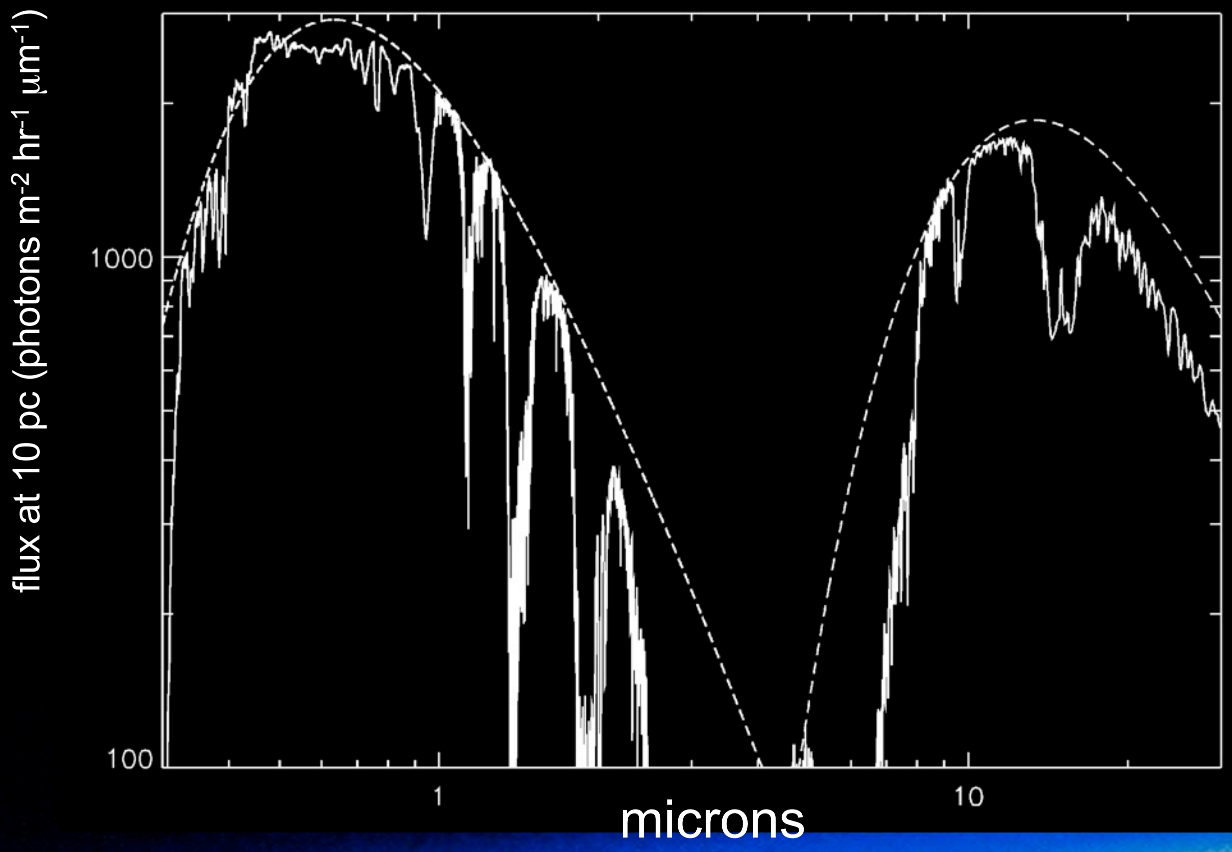


atmosphere: $9\times10^{-7}\ M_\oplus$

water: $3\text{-}5\times10^{-4}\ M_\oplus$

water vapor $< 1\times10^{-8}\ M_\oplus$



CO_2 :

$4\times10^{-10}\ M_\oplus$ (atmosphere)

$5\times10^{-5}\ M_\oplus$ (crust)

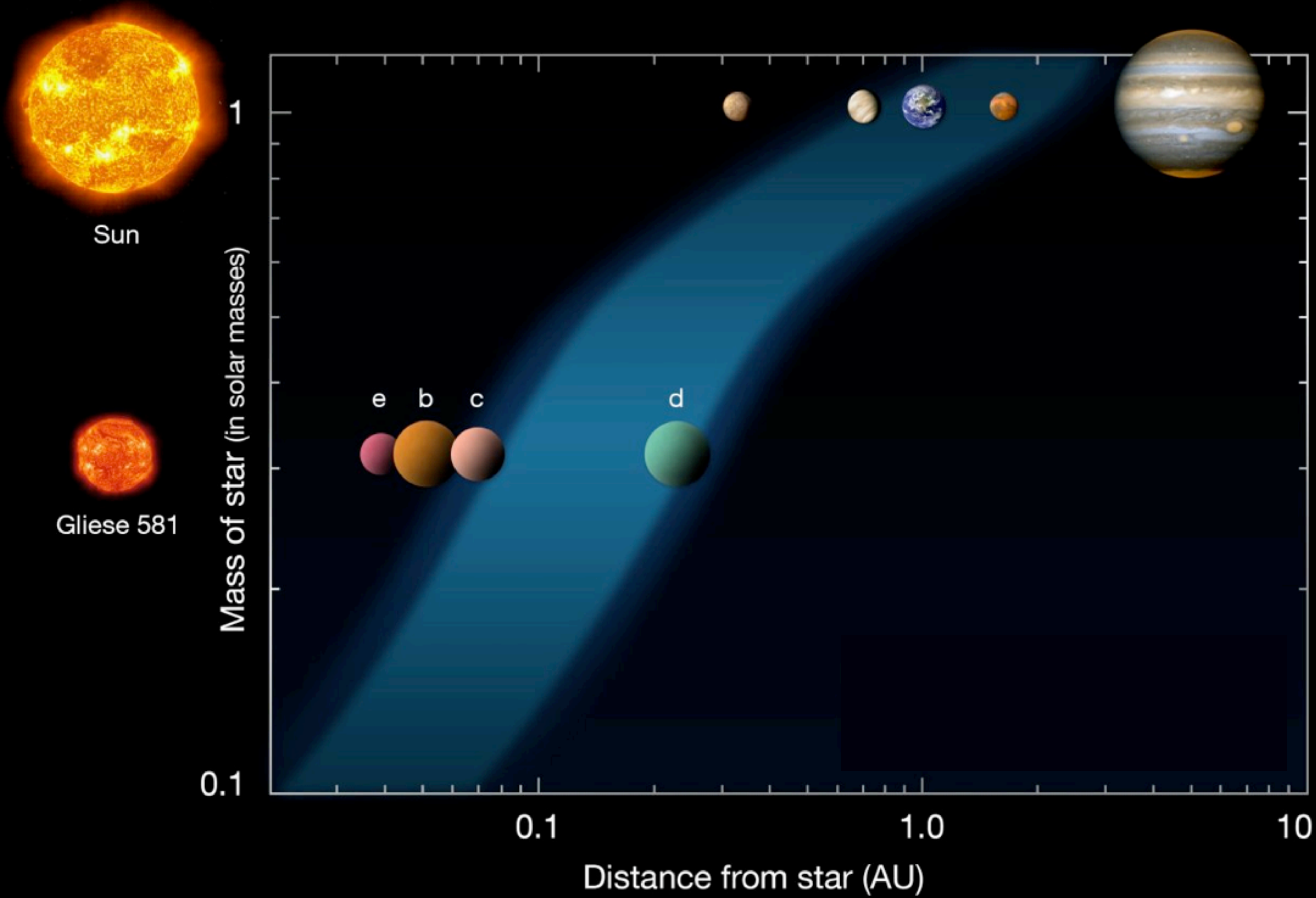
$2\times10^{-4}\ M_\oplus$ (mantle)

What does *habitable* mean ?

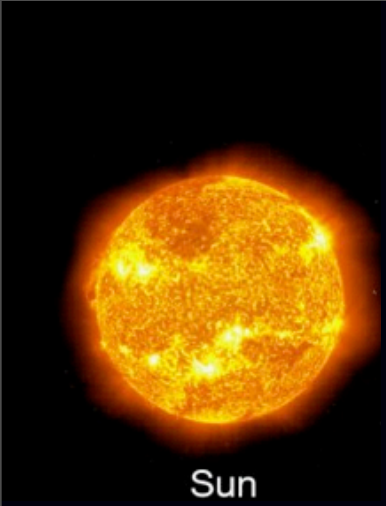
in this talk:
habitable = able to have surface liquid water

why is <u>surface</u> liquid water interesting ?

*** photosynthesis ***



Selsis et al. 2007 (HZ), Mayor et al. 2009 (Gl581 planets)

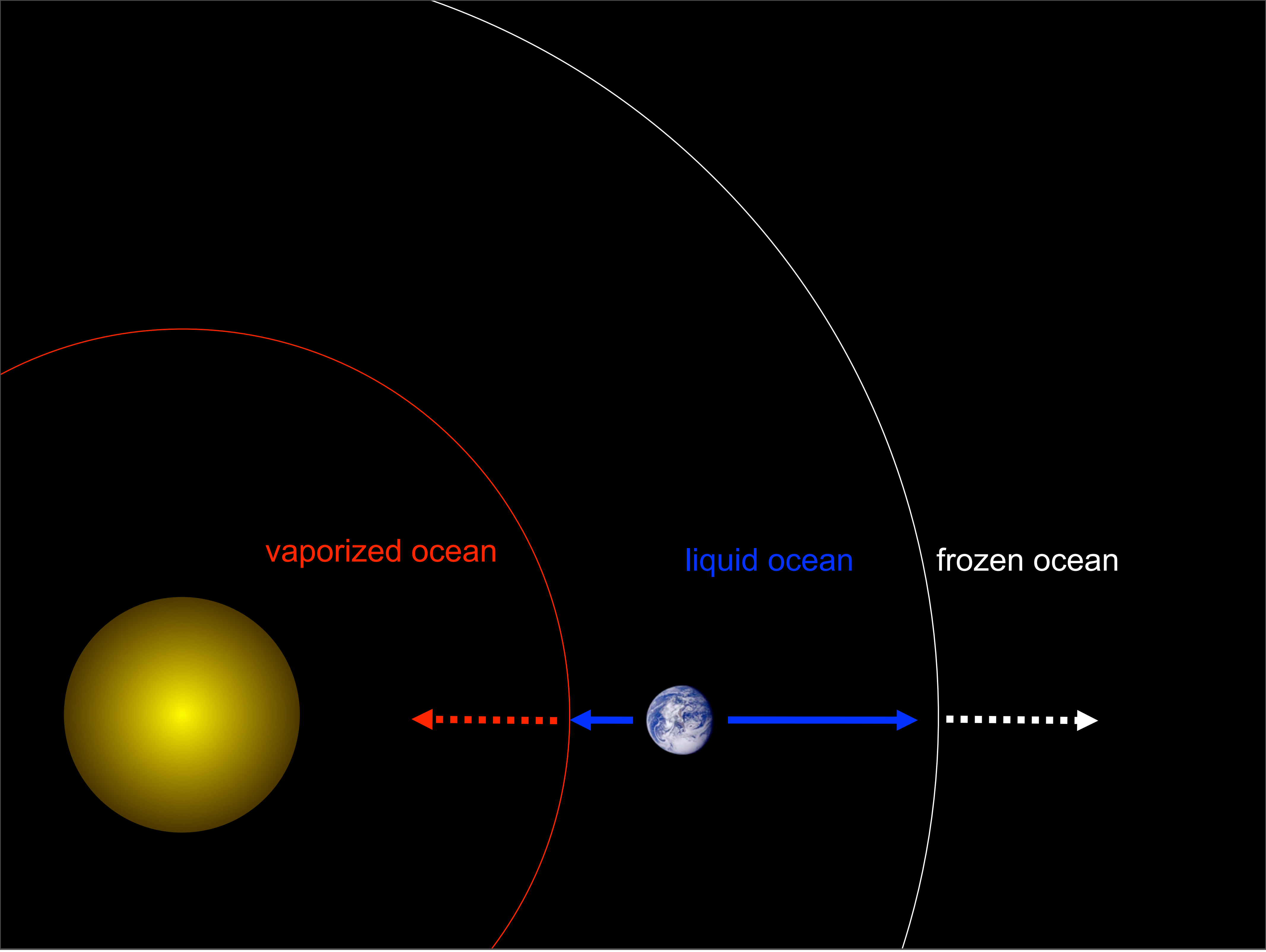


Solar HZ planets

- at least one known case !

- transiting HZ planets around G-stars will be statistically far and will offer low planet-to-star contrast ratios

- characterization requires Darwin/TPF/NWO class observatories

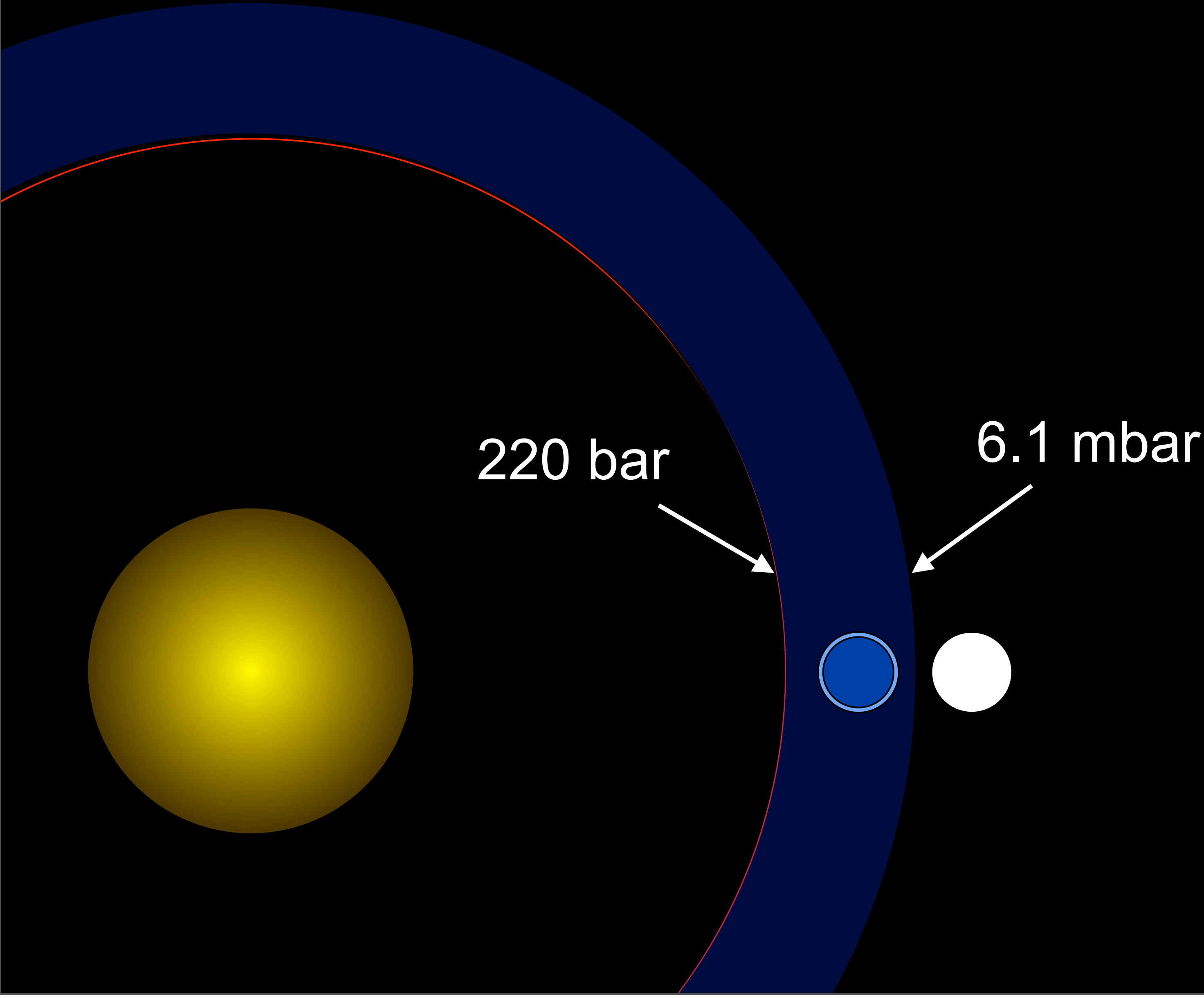


vaporized ocean

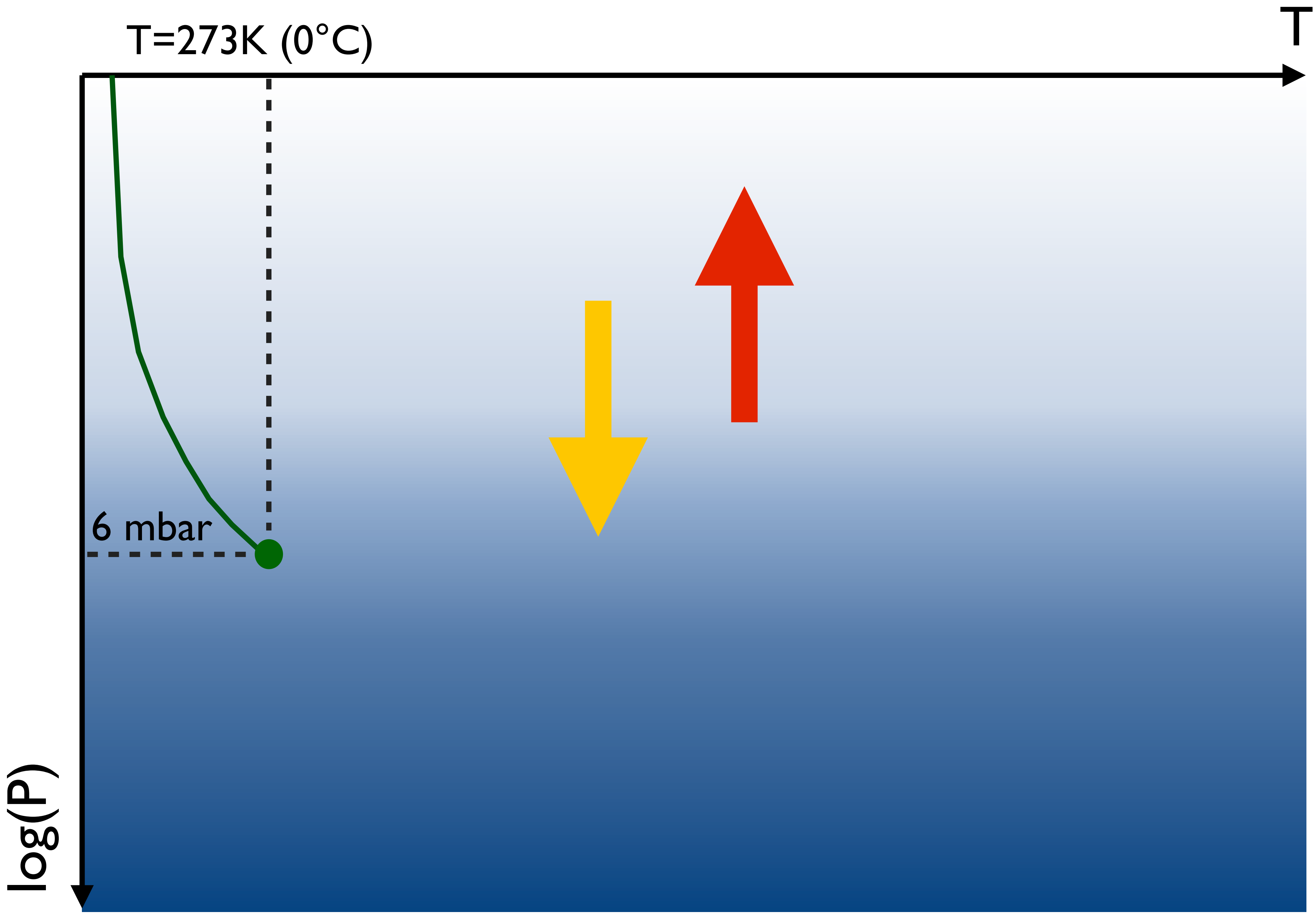
liquid ocean

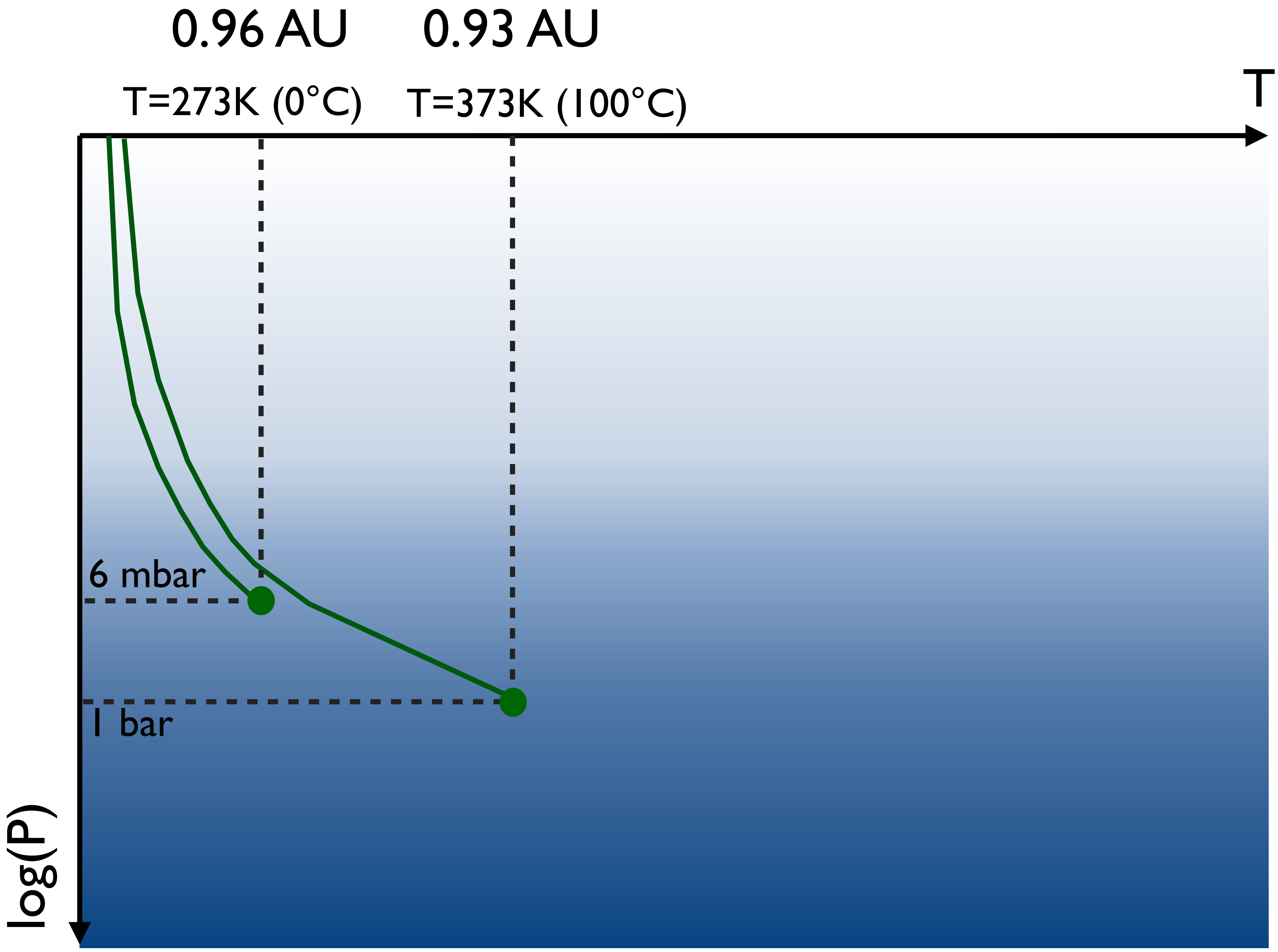
frozen ocean

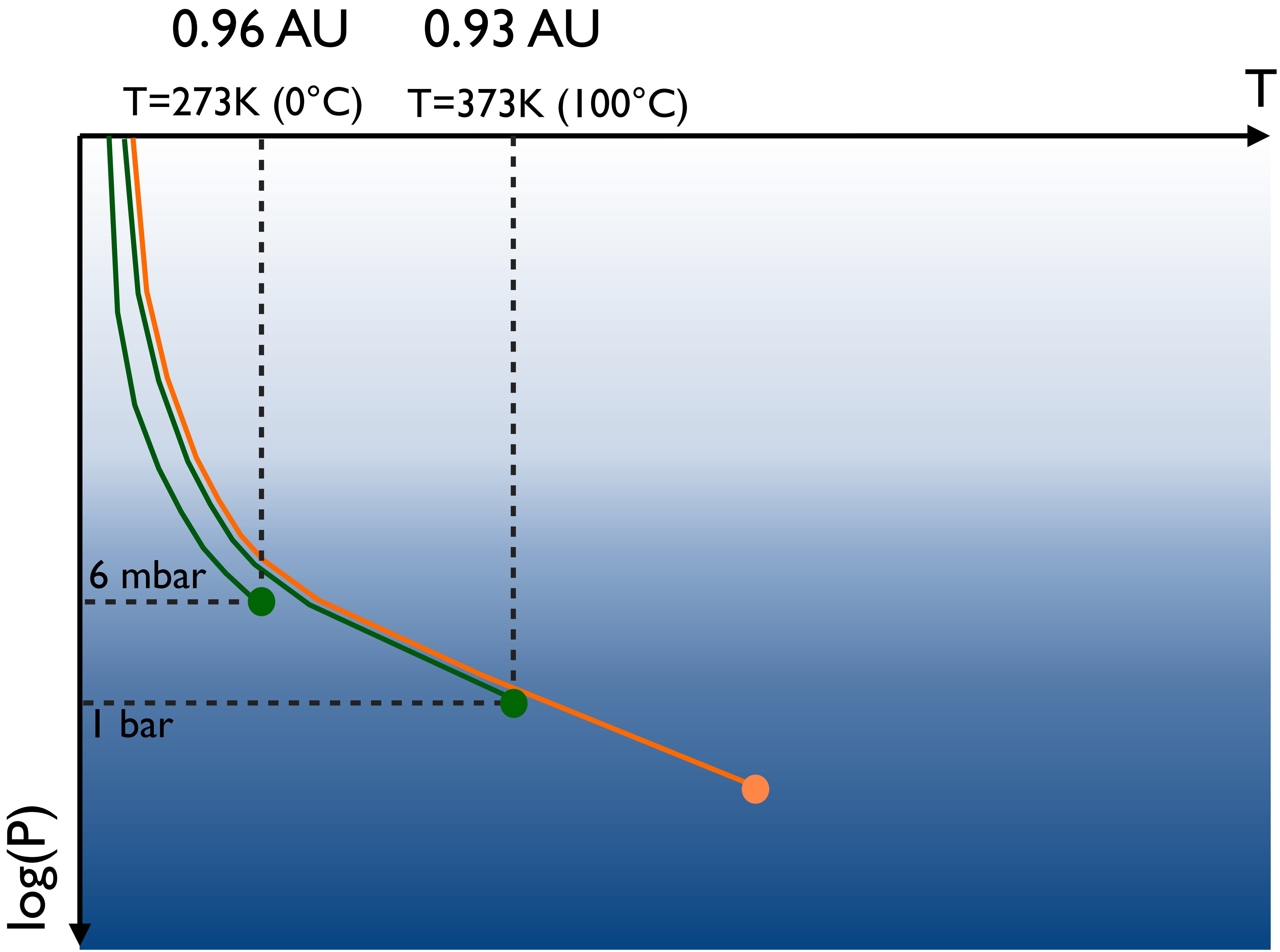
Inner HZ:
Water is *self-sufficient:*

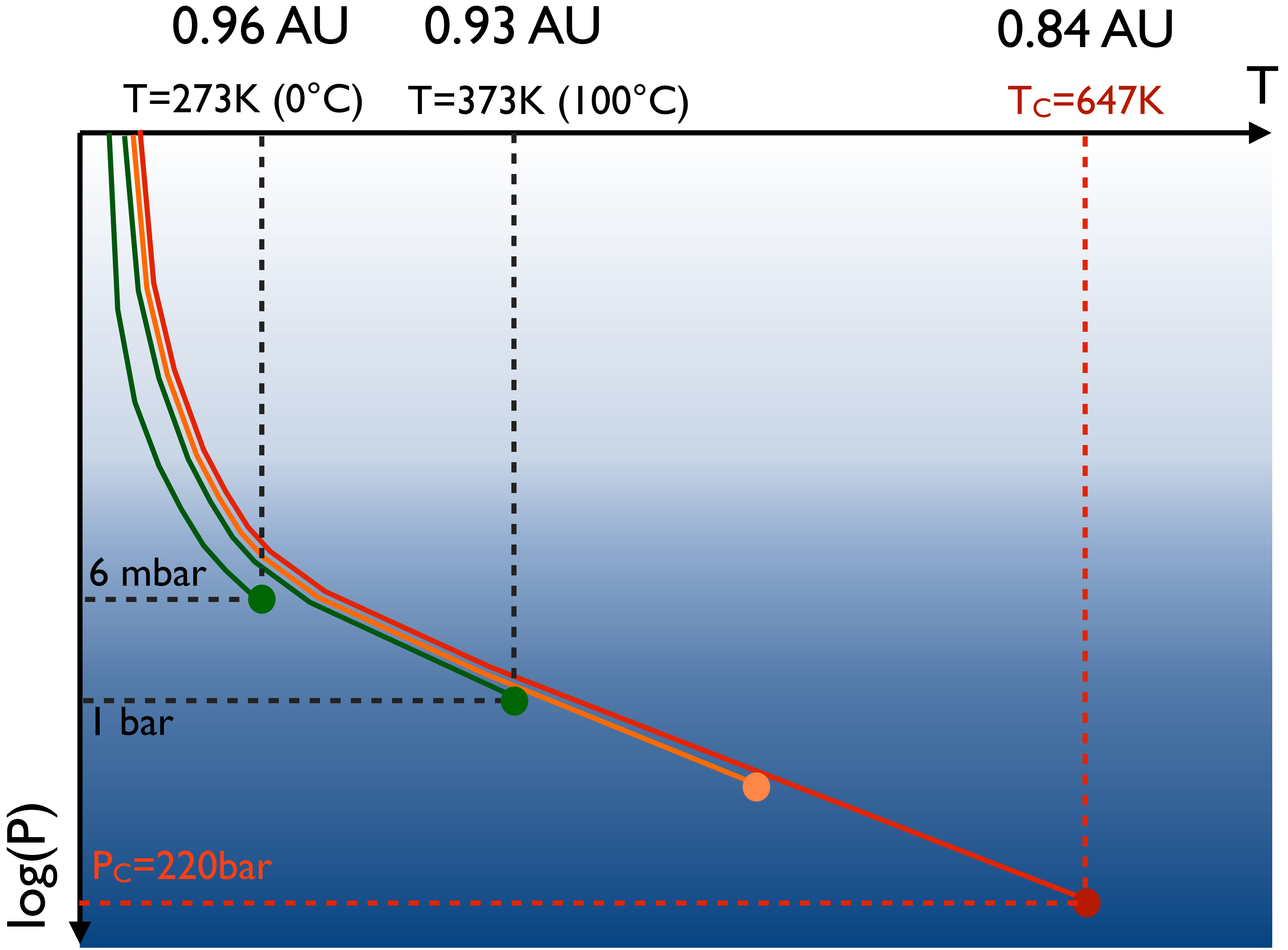


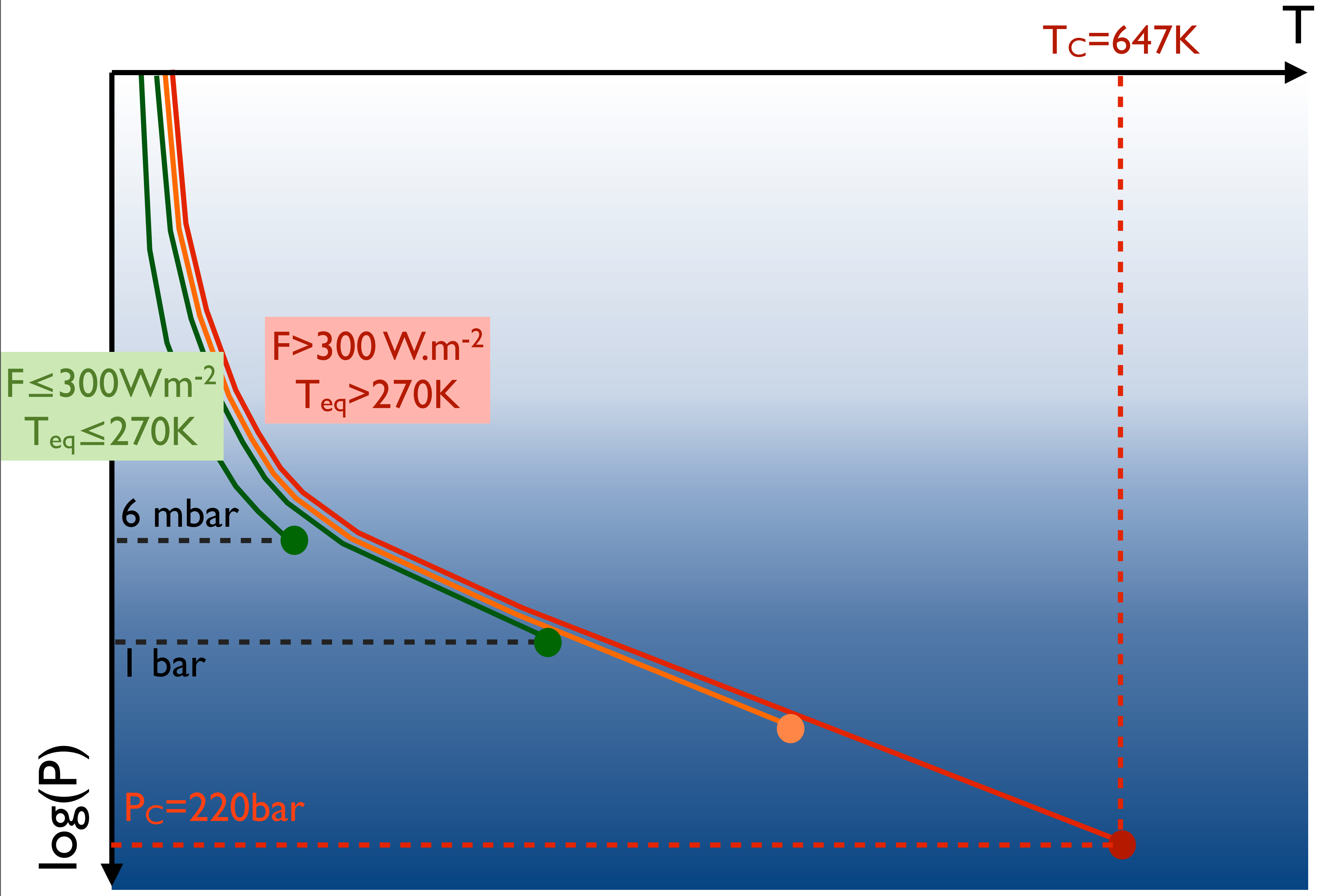
0.96 AU

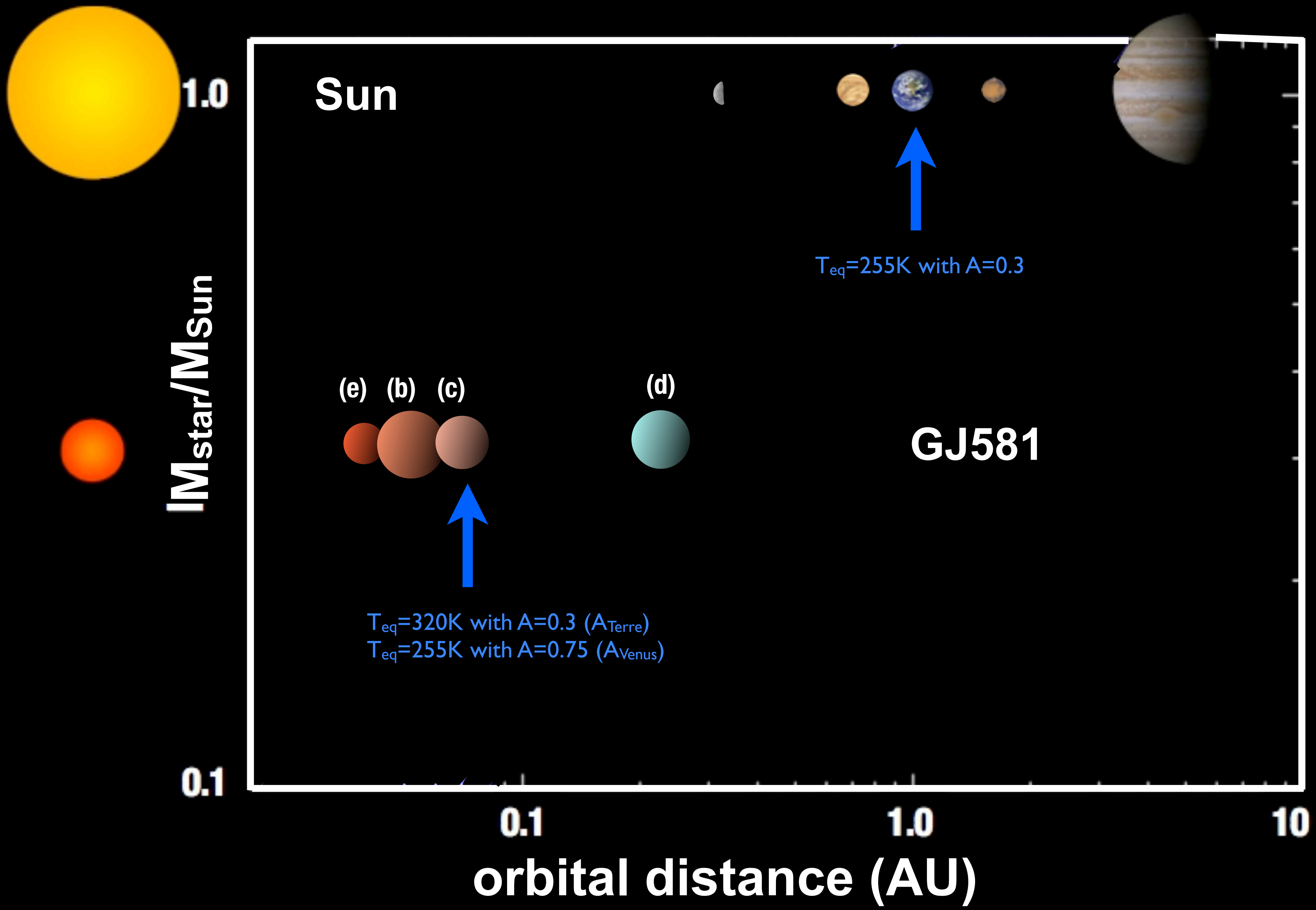



0.96 AU
0.93 AU
T=273K (0°C)
T=373K (100°C)
T
6 mbar
1 bar
log(P)


0.96 AU
0.93 AU
T=273K (0°C)
T=373K (100°C)
T
6 mbar
1 bar
log(P)


0.96 AU
0.93 AU
0.84 AU
T=273K (0°C)
T=373K (100°C)
Tc=647K
T
6 mbar
1 bar
Pc=220bar
log(P)


T
T_C=647K
F>300 W.m^-2
T_eq>270K
F≤300Wm^-2
T_eq≤270K
6 mbar
1 bar
log(P)
P_C=220bar

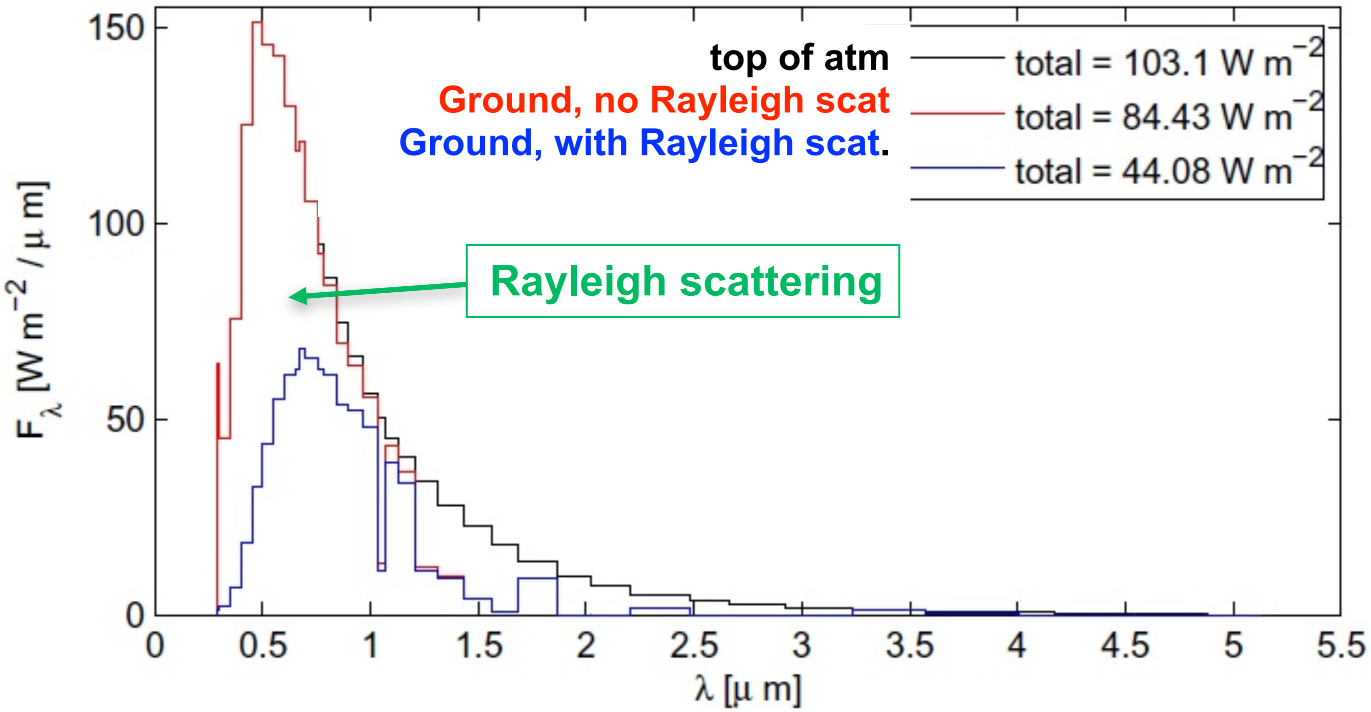


T_{eq}=255K with A=0.3

T_{eq}=320K with A=0.3 (A_{Terre})
T_{eq}=255K with A=0.75 (A_{Venus})

Vitesse Radiale GJ581: Udry et al., 2007; Mayor et al., 2009 - HZ: Selsis et al., 2007

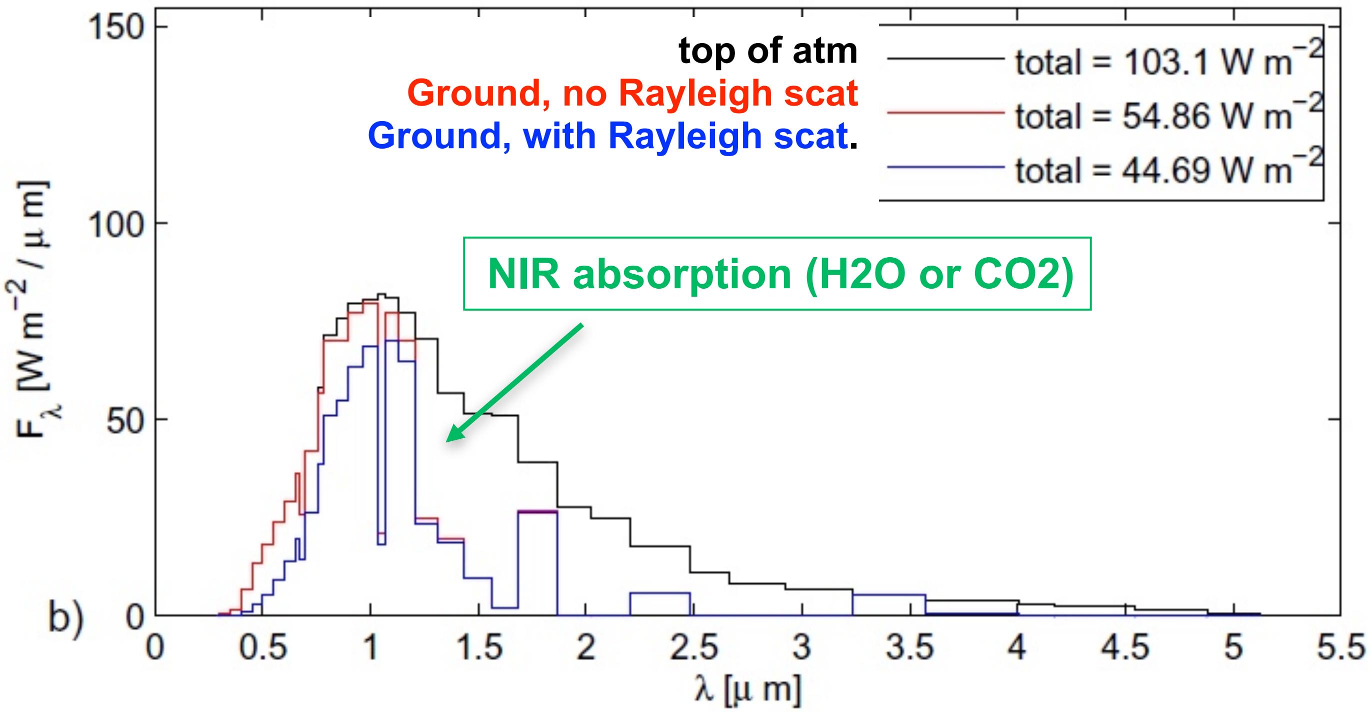
G star



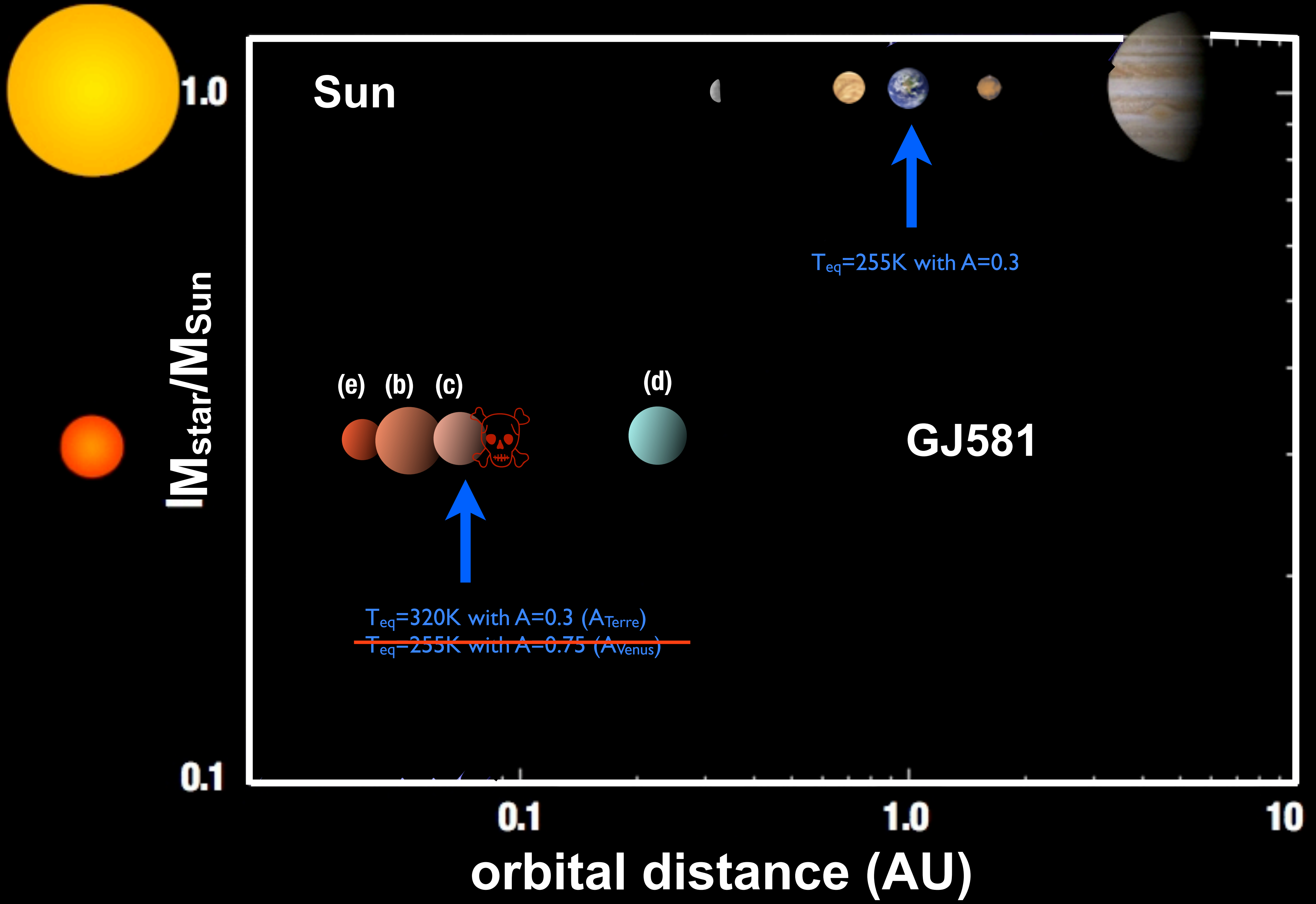
Rayleigh scattering

CO_2 atmosphere

M star



NIR absorption (H2O or CO2)



T_{eq}=255K with A=0.3

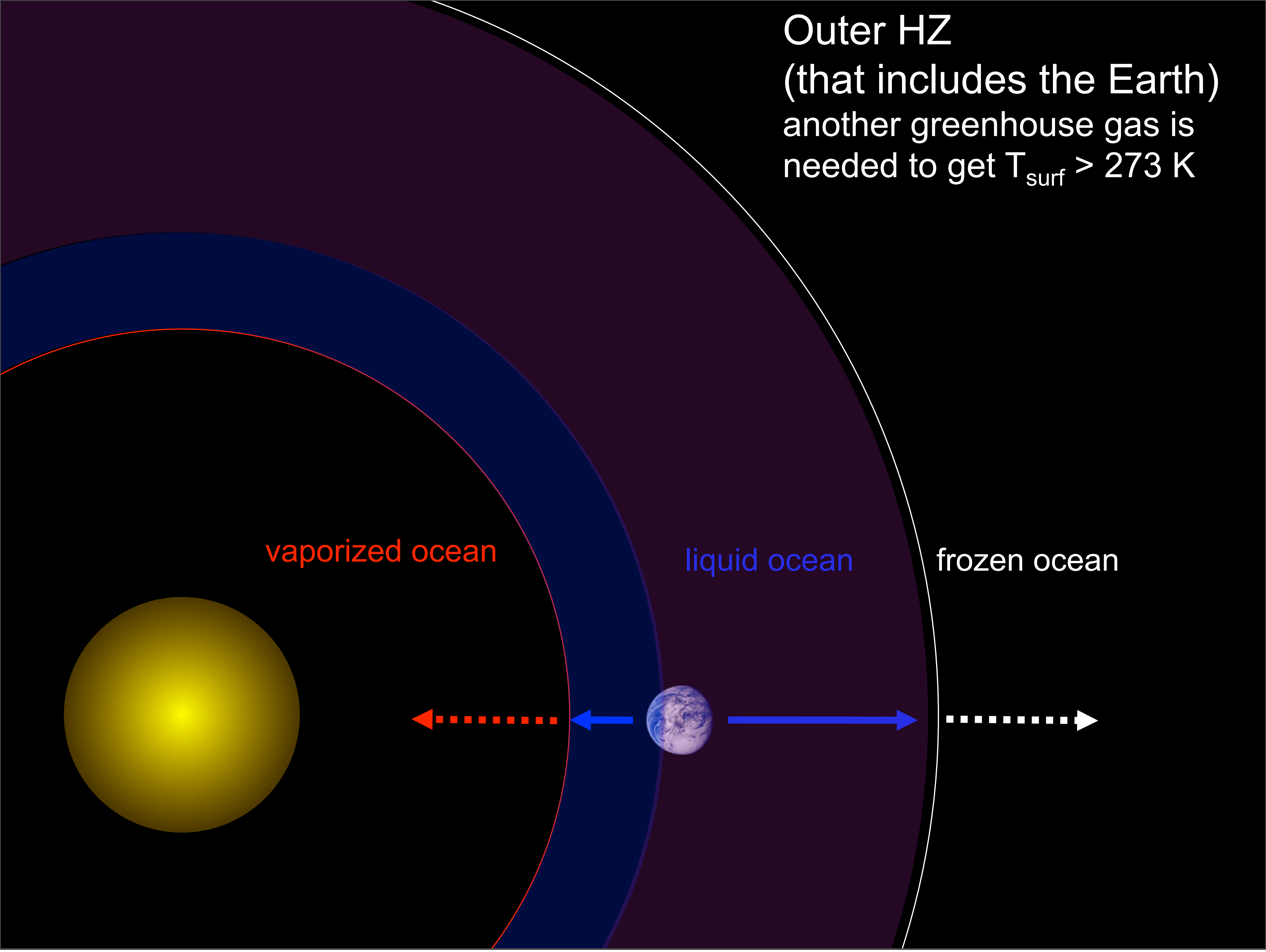
T_{eq}=320K with A=0.3 (A_{Terre})

~~T_{eq}=255K with A=0.75 (A_{Venus})~~

Vitesse Radiale GJ581: Udry et al., 2007; Mayor et al., 2009 - HZ: Selsis et al., 2007

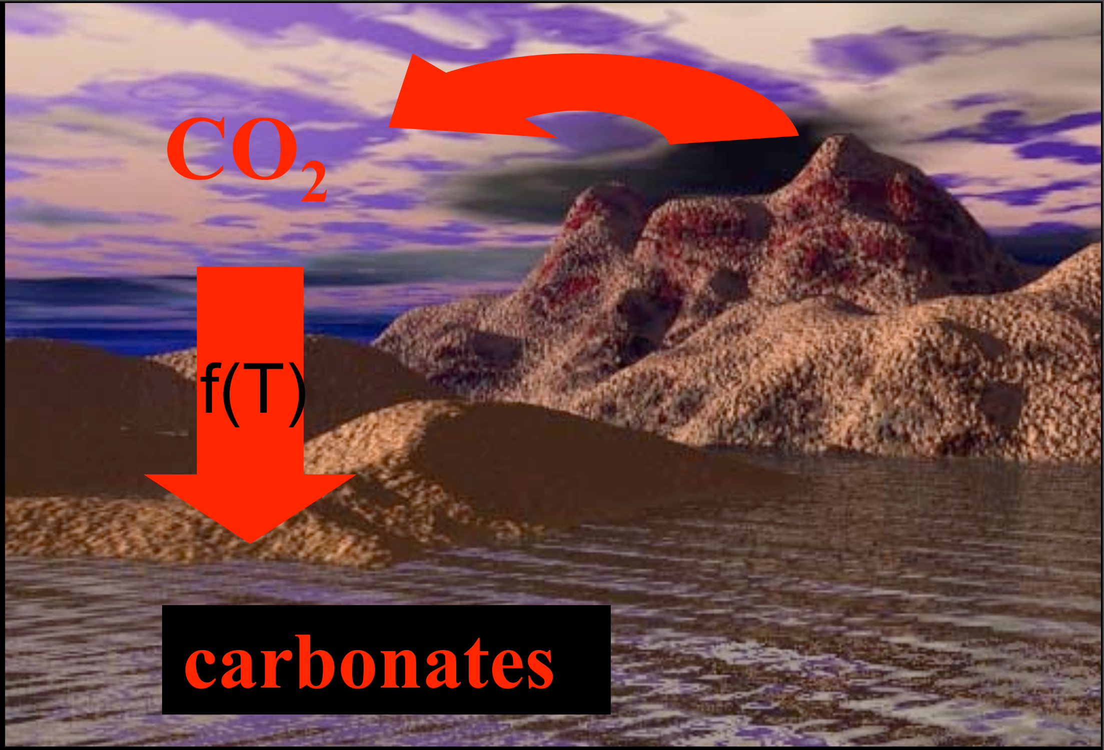
Outer HZ
(that includes the Earth)

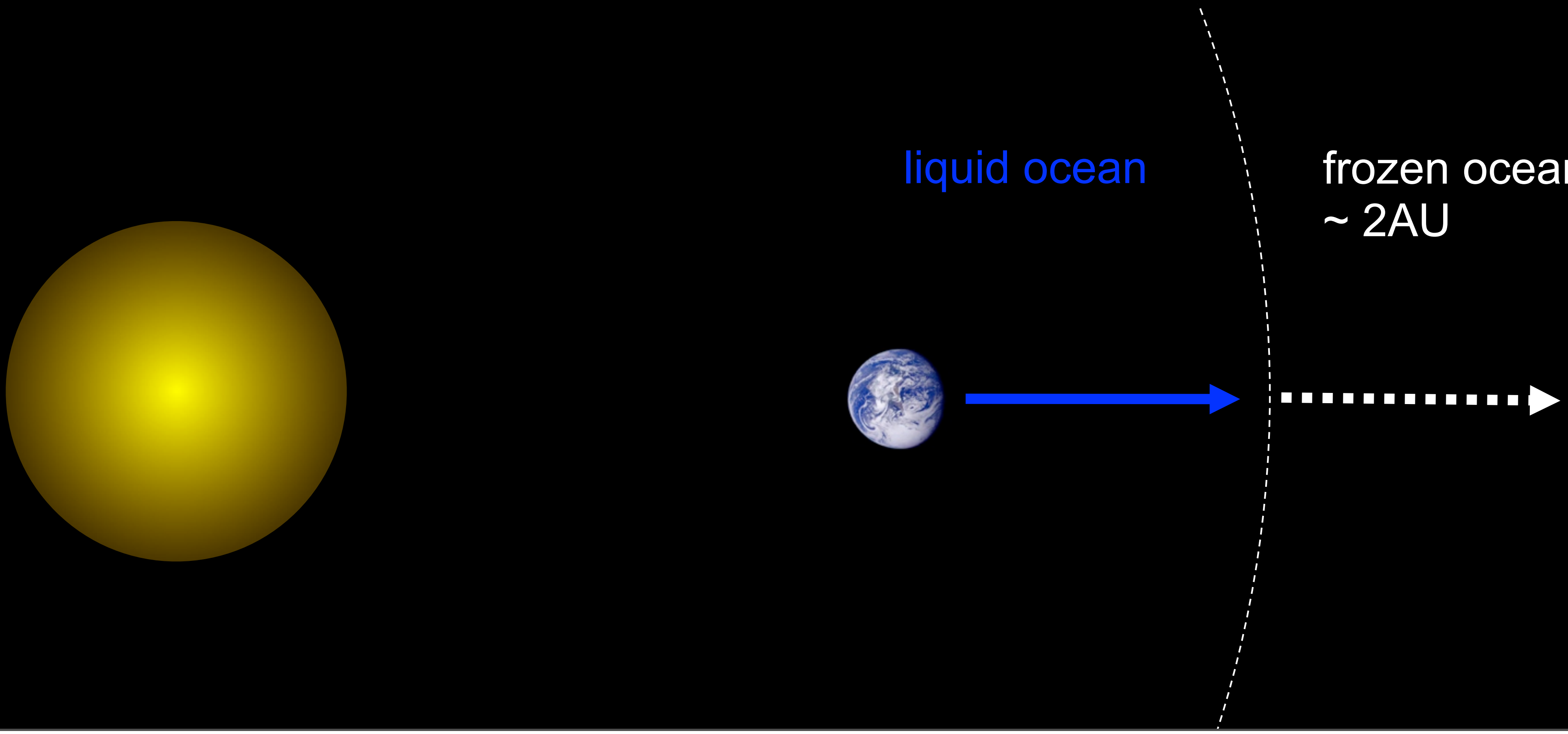
another greenhouse gas is needed to get T_{surf} > 273 K



Outer boundary of the HZ

Walker et al., 1981 (carbonate-silicate cycle)
Kasting et al., 1993





Outer boundary of the HZ

Walker et al., 1981 (carbonate-silicate cycle)
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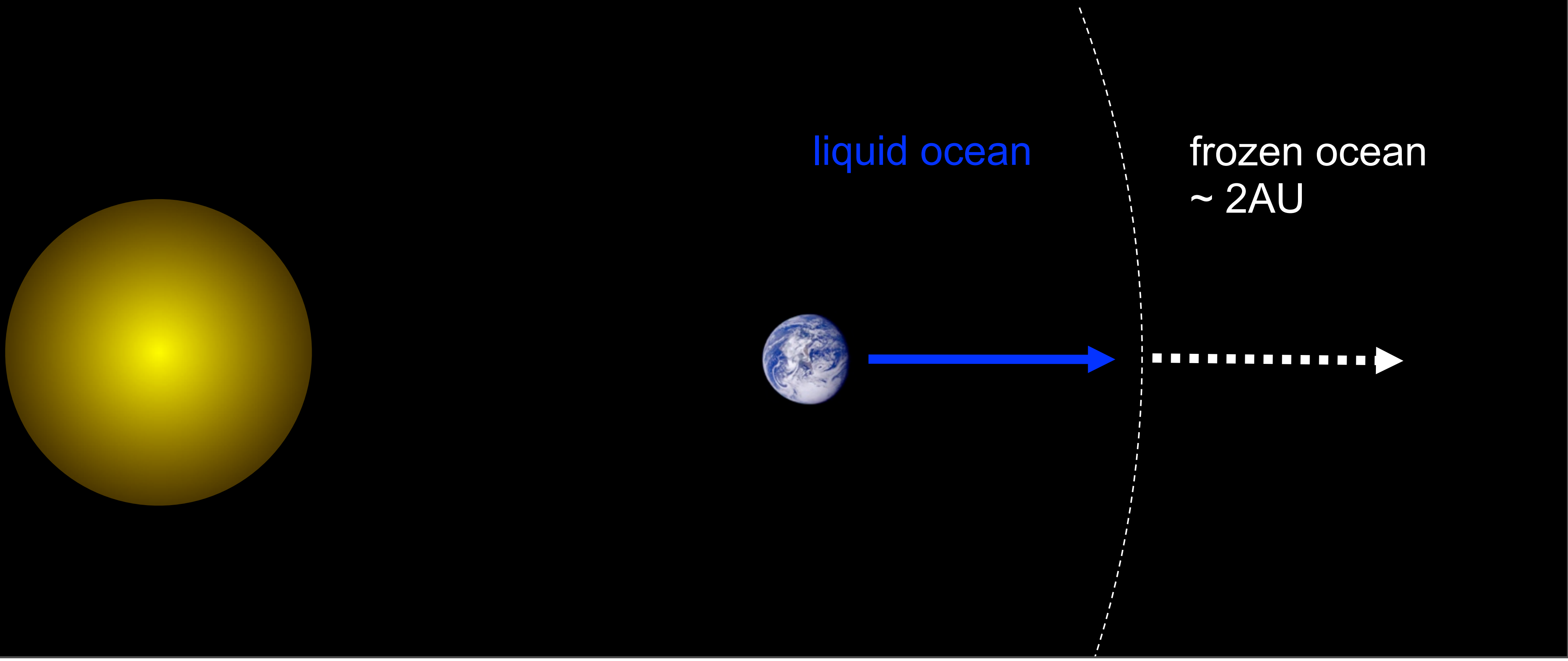
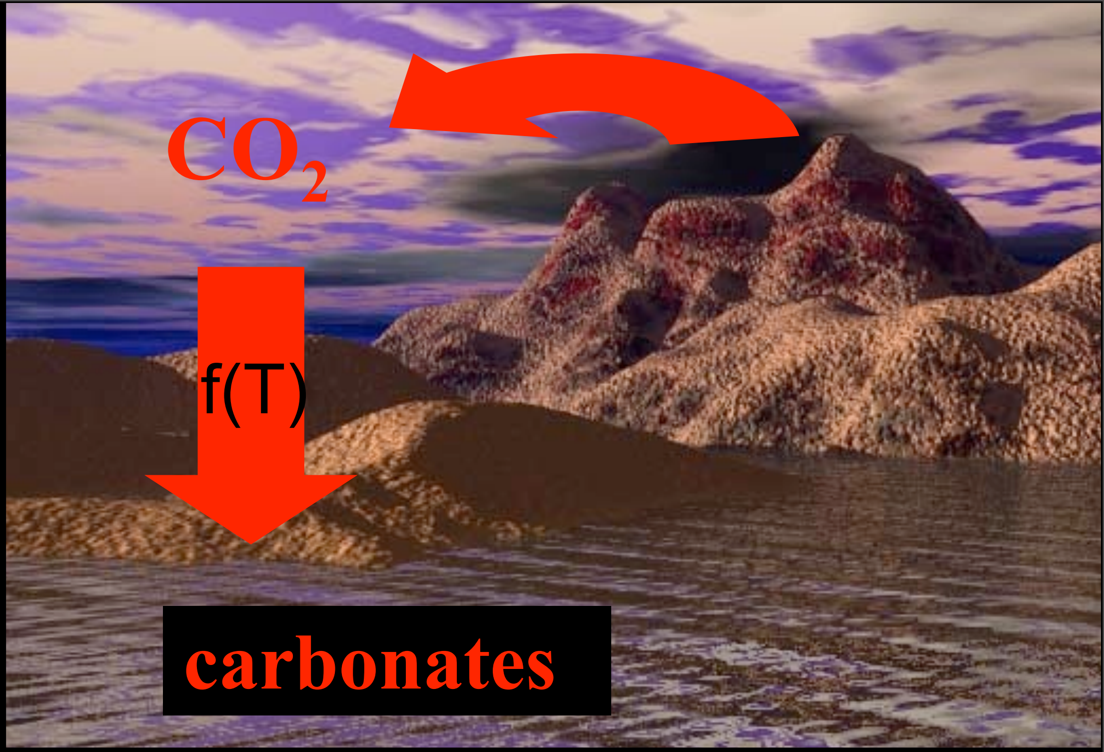
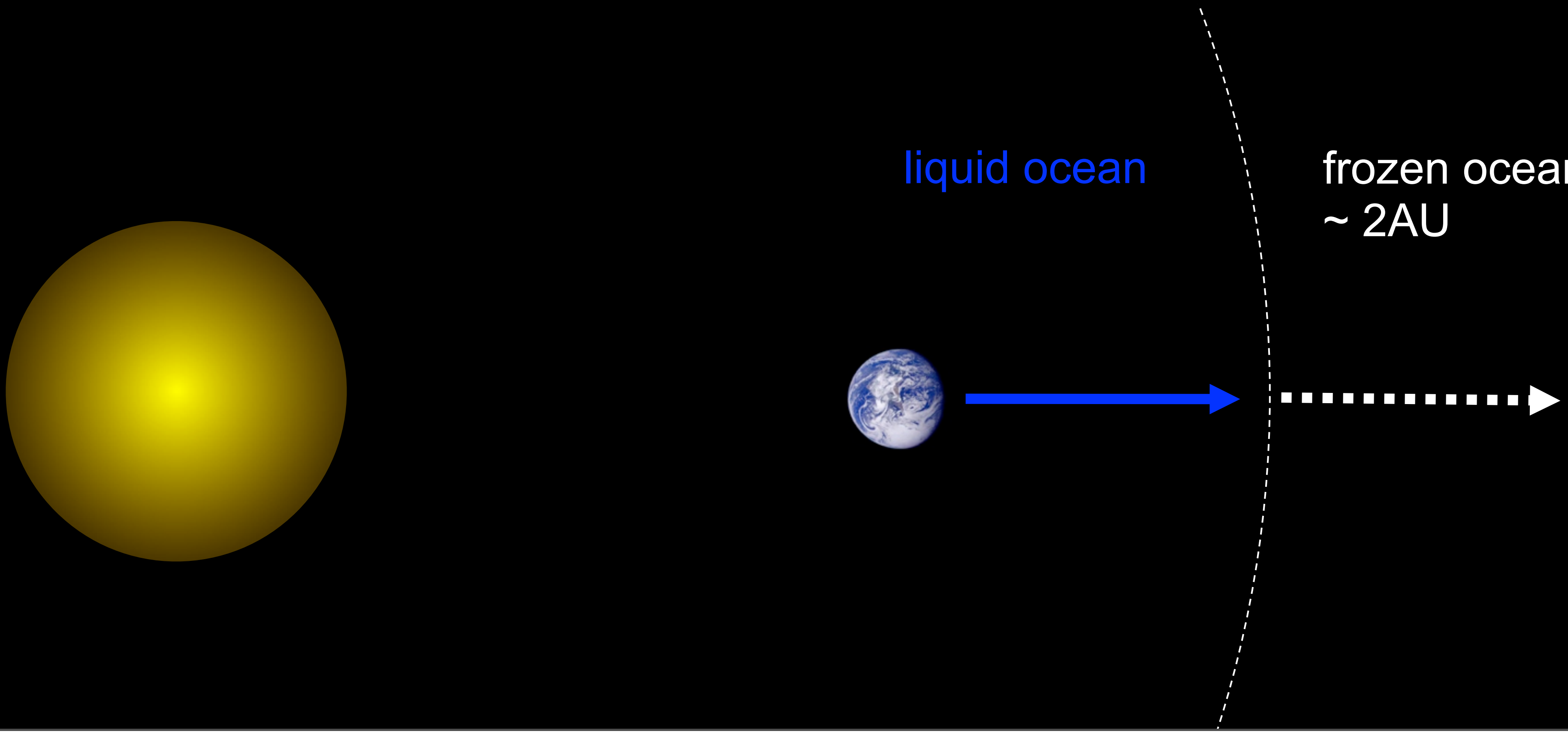
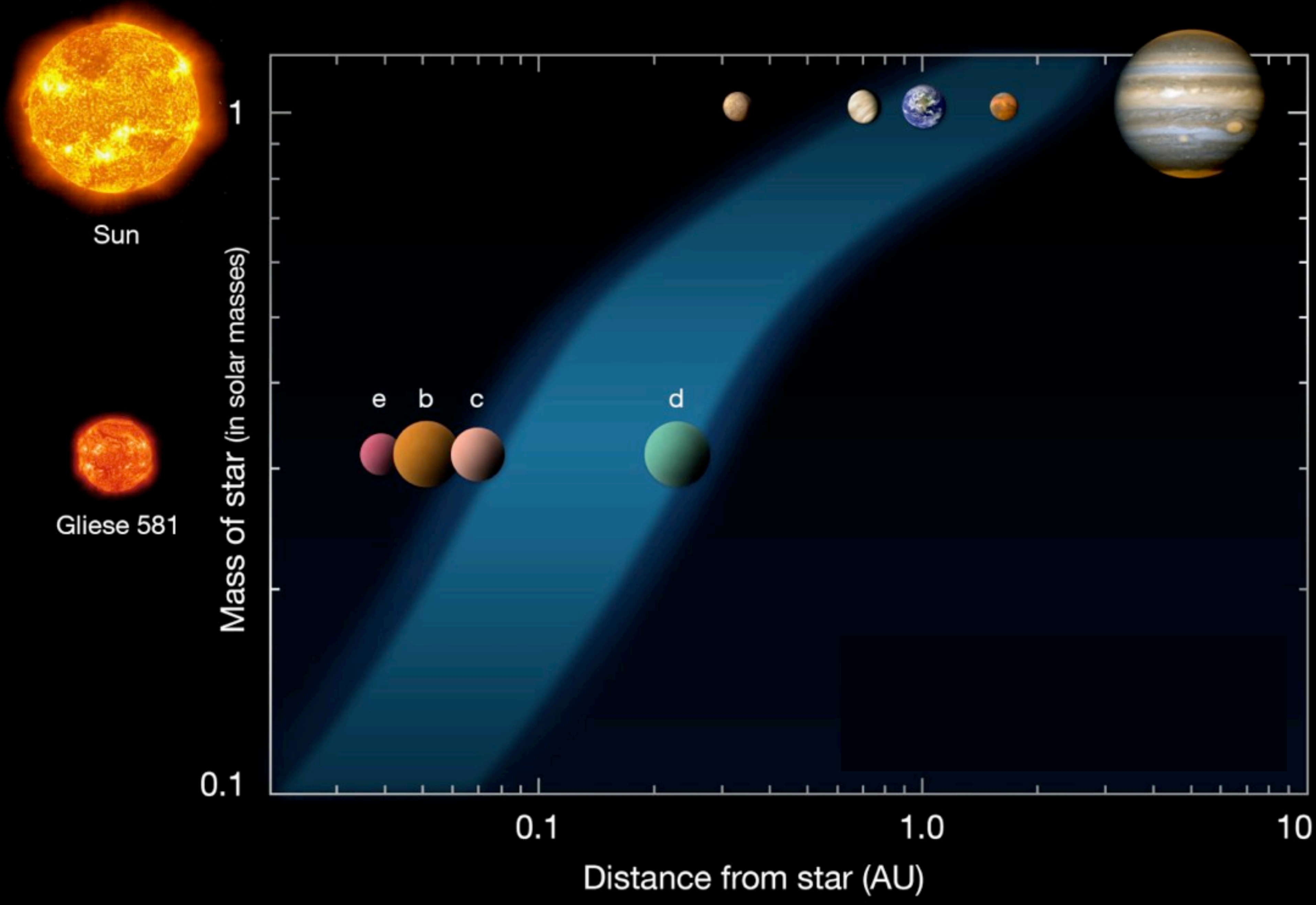


Outer boundary of the HZ

Walker et al., 1981 (carbonate-silicate cycle)
Kasting et al., 1993







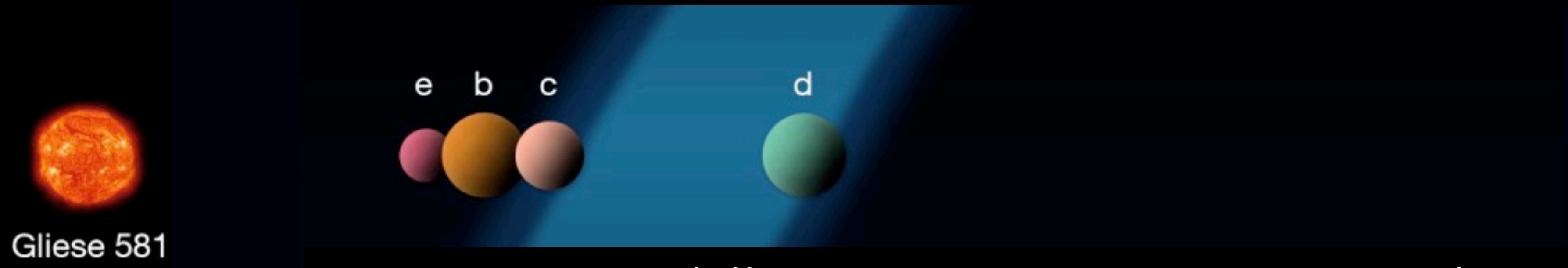
Selsis et al. 2007 (HZ), Mayor et al. 2009 (Gl581 planets)

M-stars HZ planets

- most stars are M stars

- HZ planets are detectable by RV

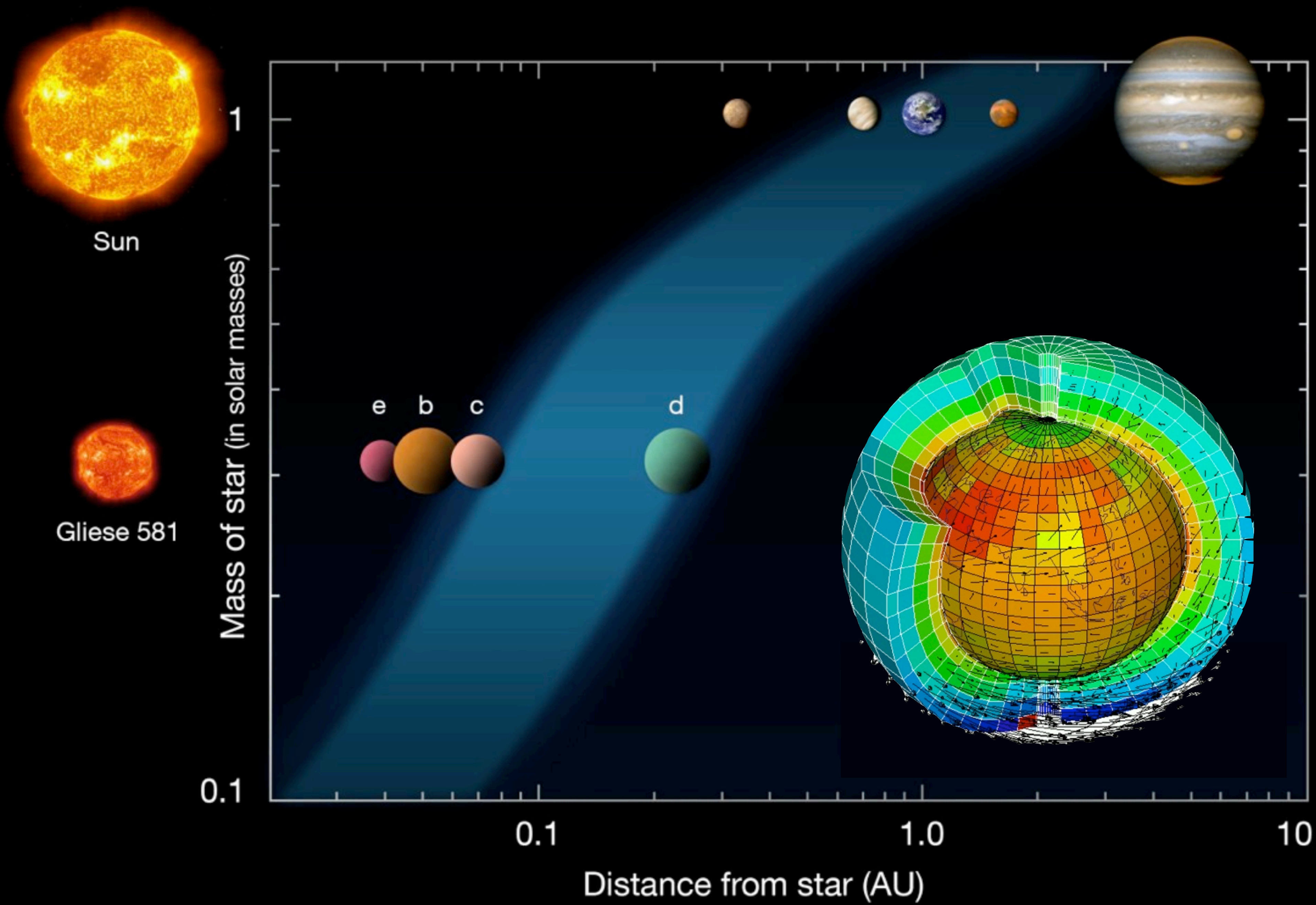
- if transiting, the planet-to-star contrast ratio can make eclipse spectroscopy (marginally) possible



- tidally evolved (affects rotation rate and obliquity)

- different spectrum (cannot scale modeling done with solar irradiation)

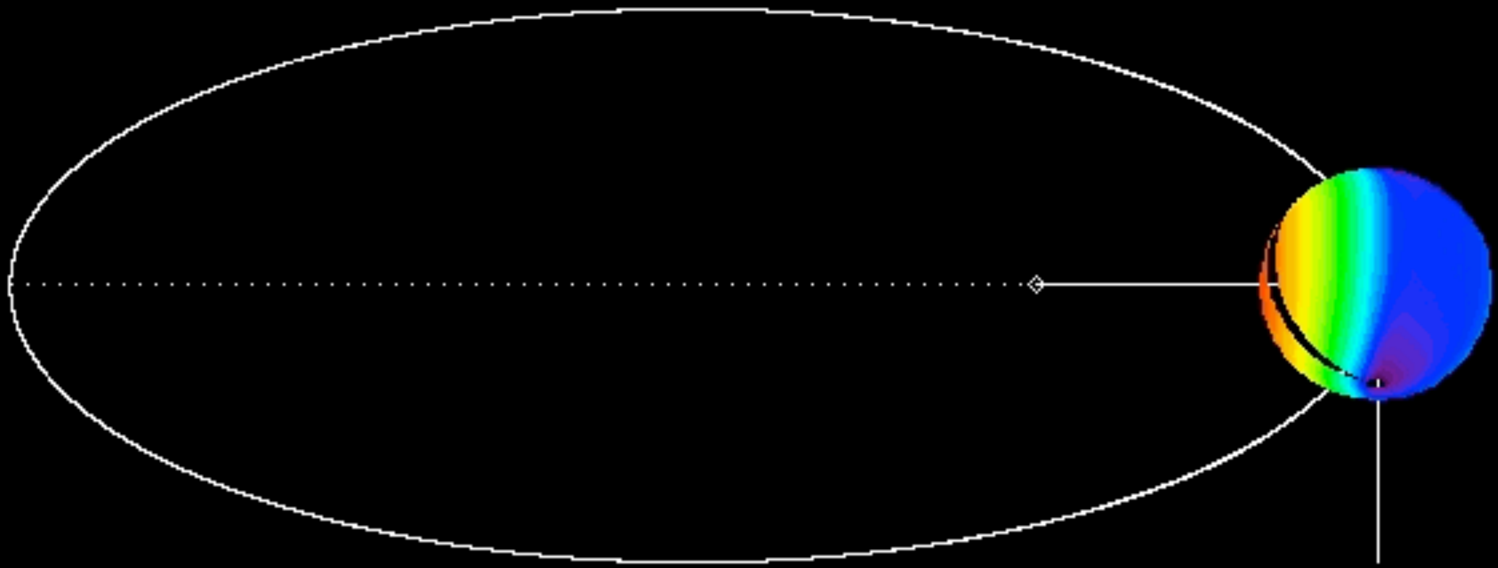
- M stars remain active for a long time: strong X, EUV, stellar winds and associated atmospheric erosion



Selsis et al. 2007 (HZ), Mayor et al. 2009 (Gl581 planets)

Eccentric planets

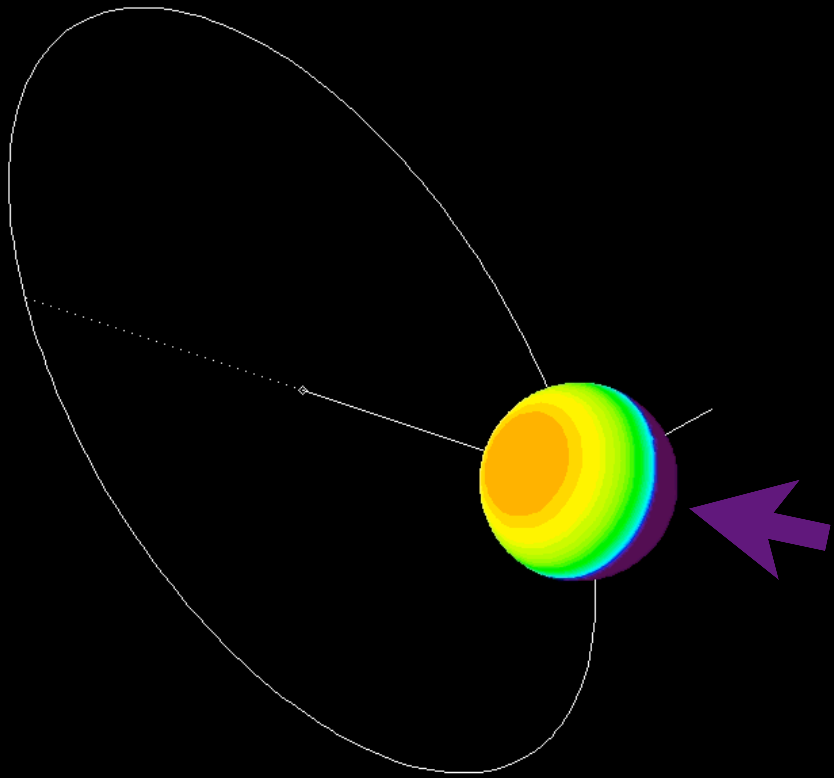
- mean insolation = $F(a)(1-e^2)^{-½}$
- variation of insolation
- rotation (equilibrium or resonance)
- tidal dissipation



slowly-rotating or synchronous planets

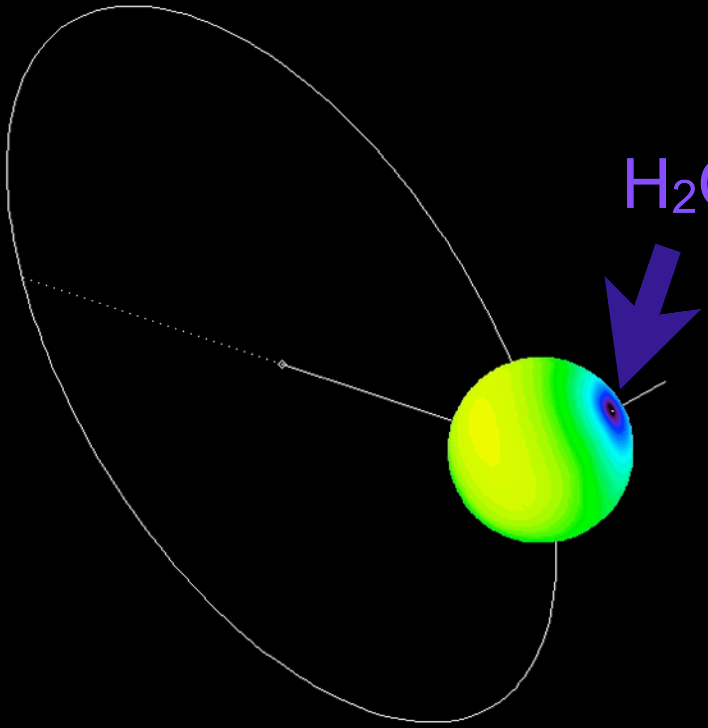
Tidally-evolved planets should be found either in their equilibrium rotation state (f(e)) or in a spin-orbit resonance (which could be 1:1)

For GJ581d: $P_{ROT}=0.4P_{ORB}$ if e=0.38
$P_{ROT}=0.55P_{ORB}$ if e=03
Leconte et al., 2010, Heller et al., 2011



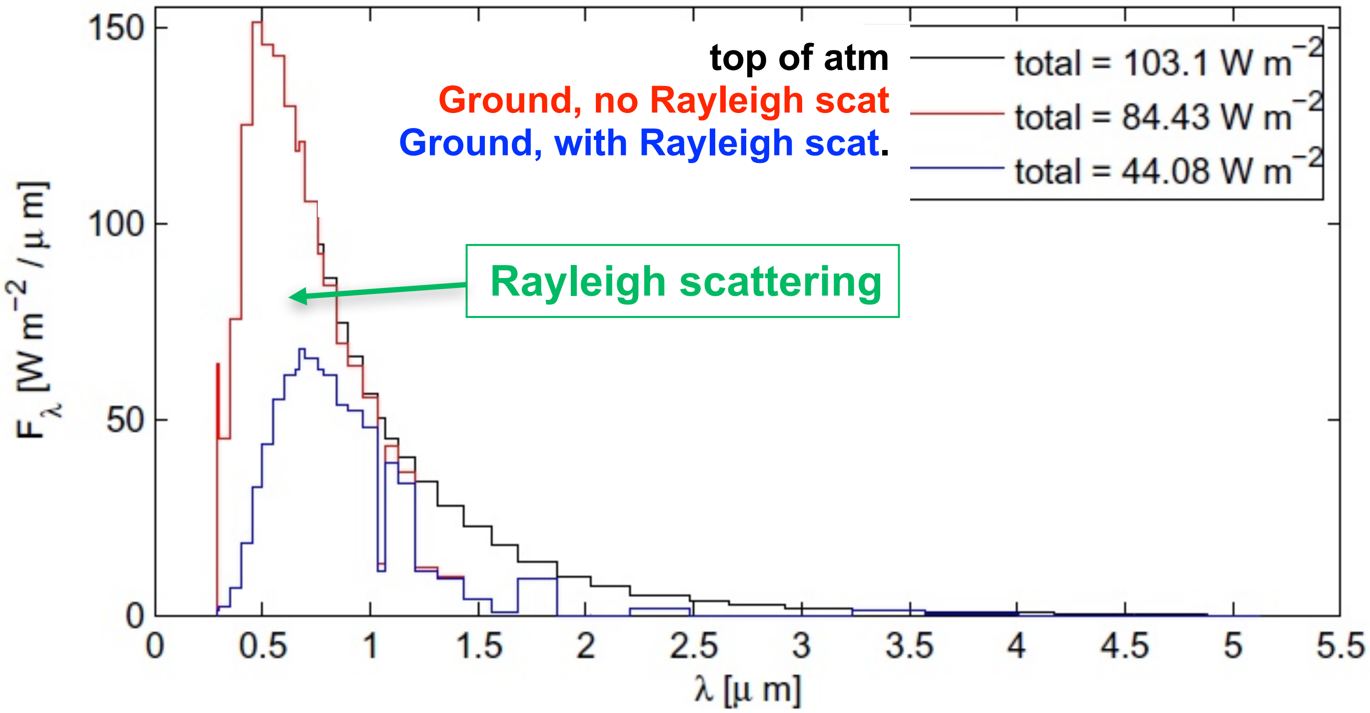
H_2O, CO_2 trap ?

0° obliquity



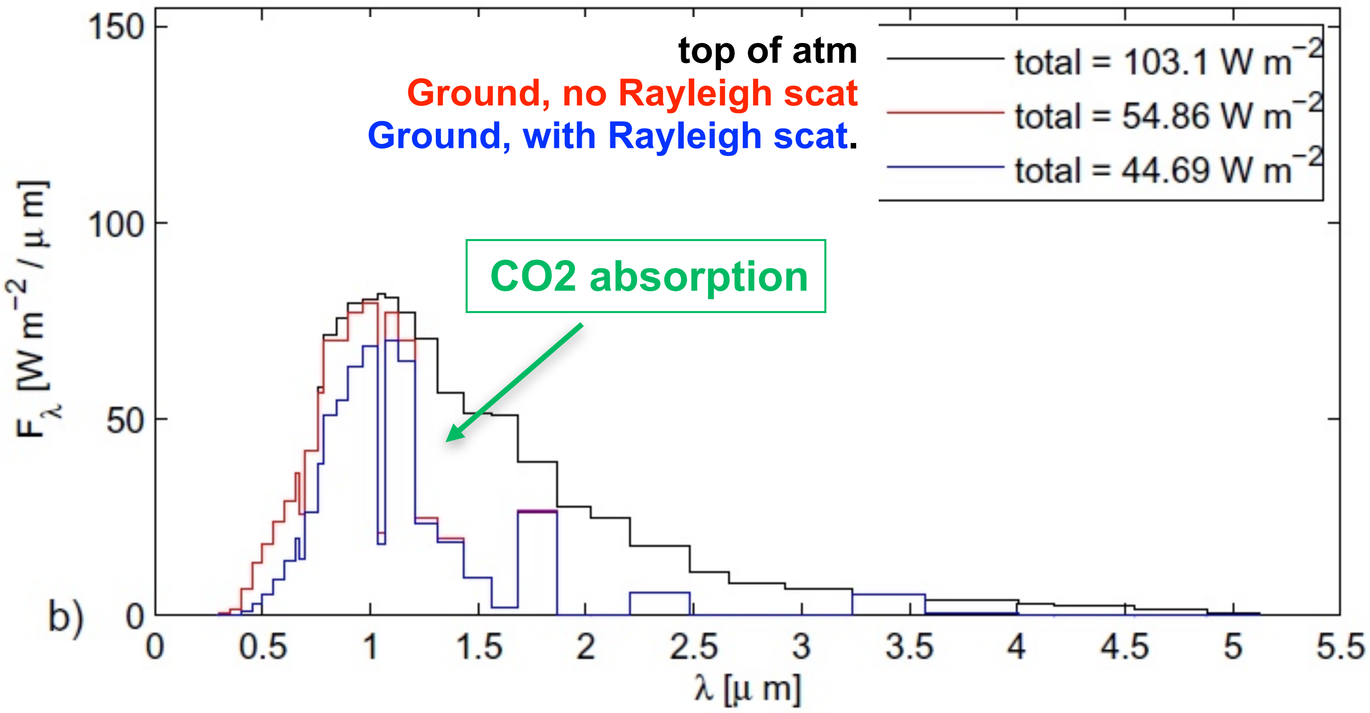
H_2O, CO_2 trap ?

G star

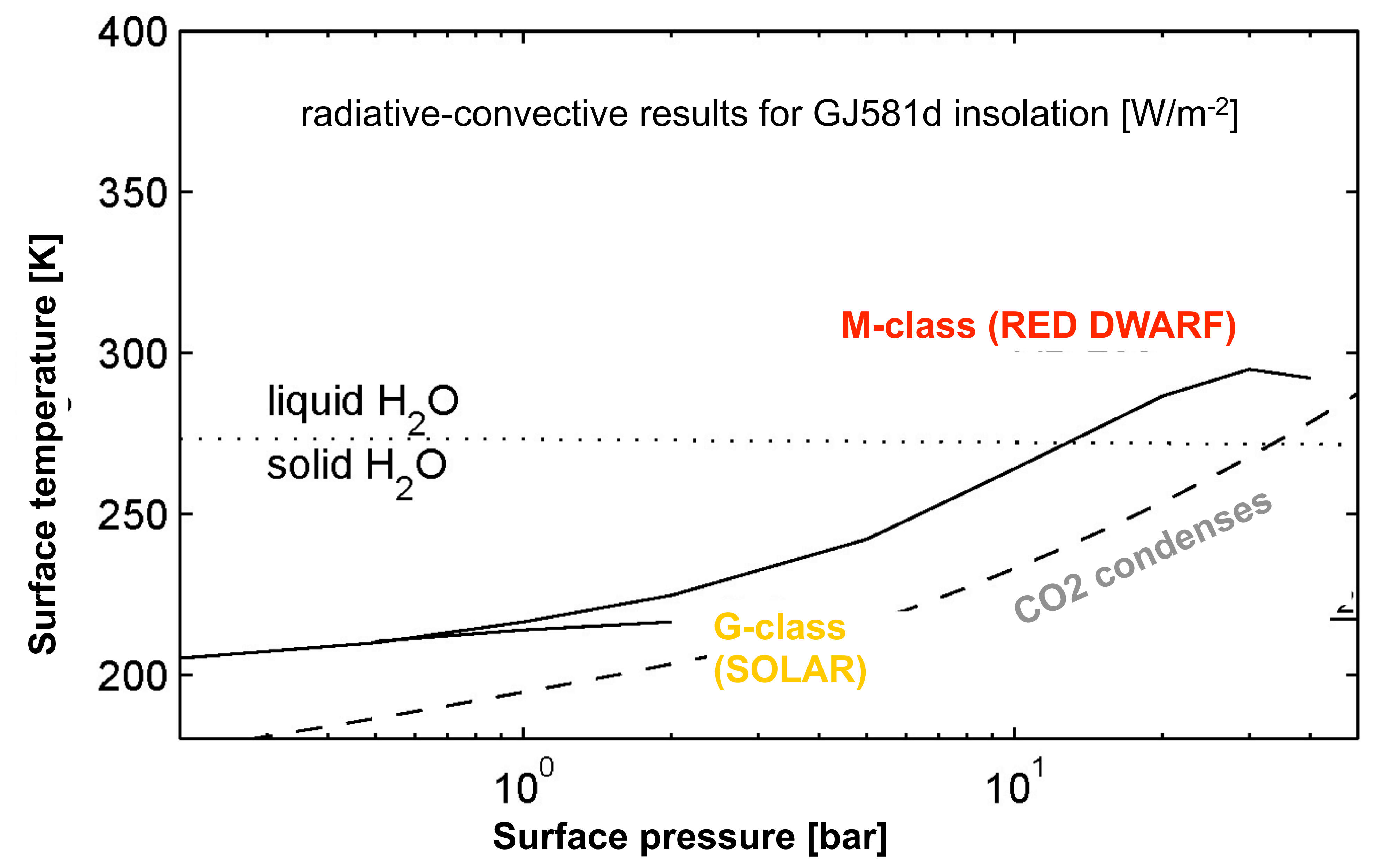


CO_2 atmosphere

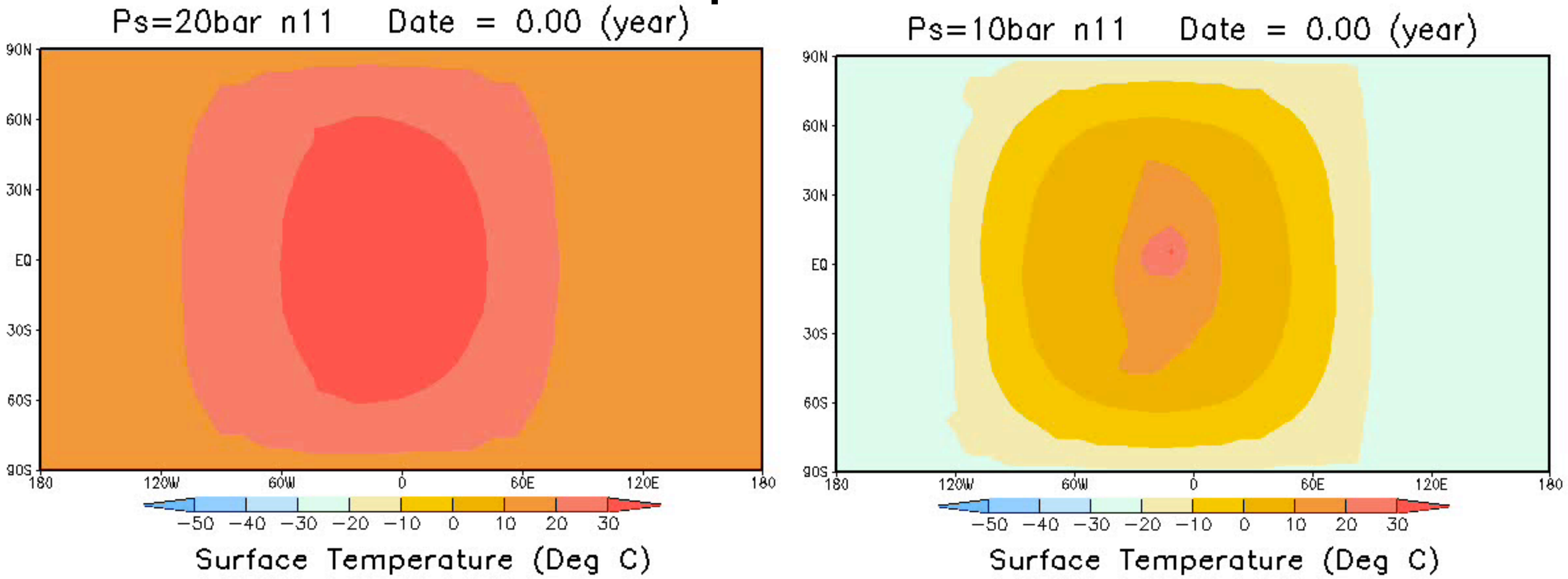
M star

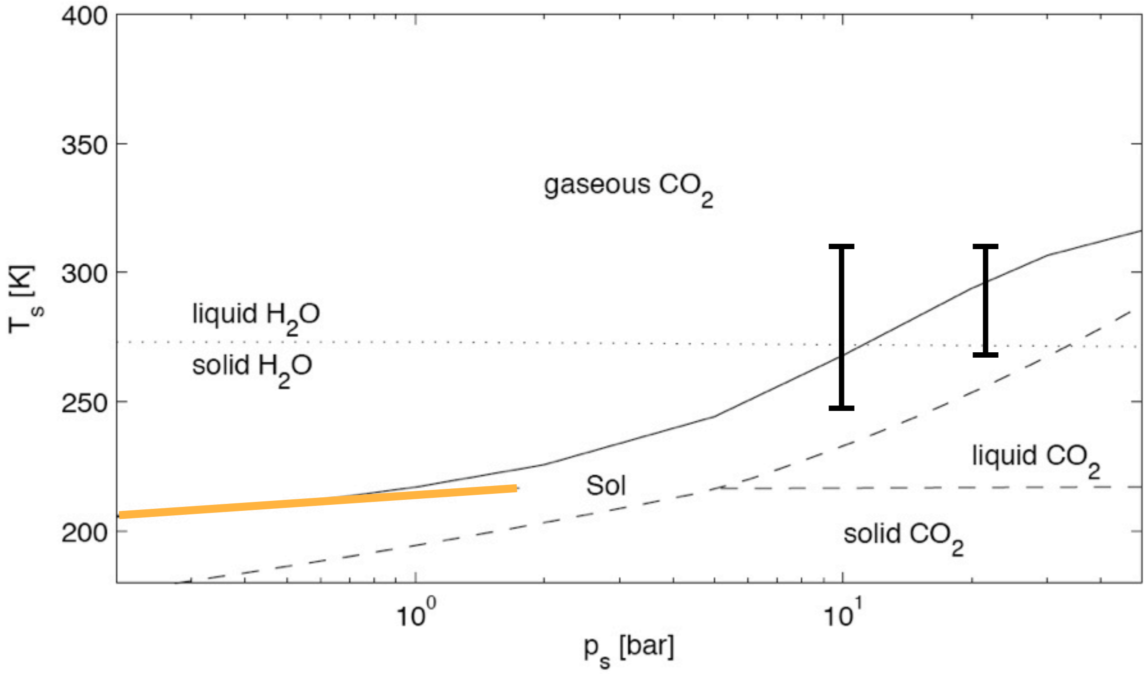


Pure CO_2 atmospheres (no CO2 clouds)



pure CO_2



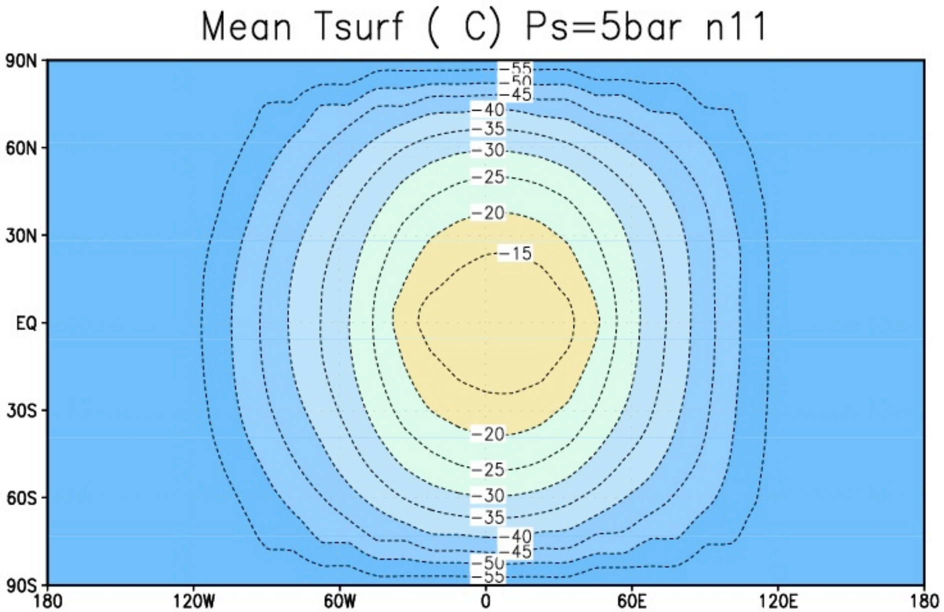


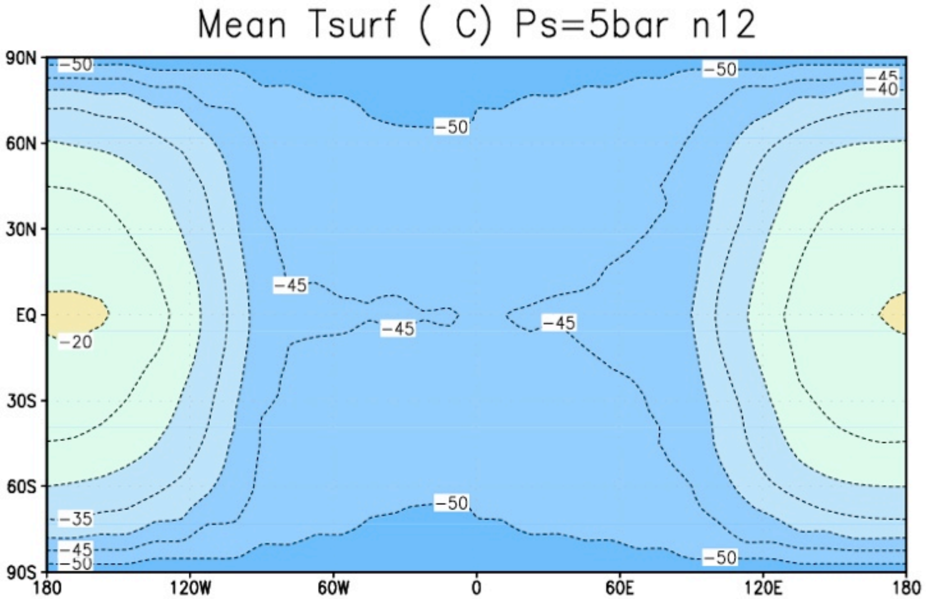
No CO_2 collapse but cold trap for H_2O in the 10 bar case

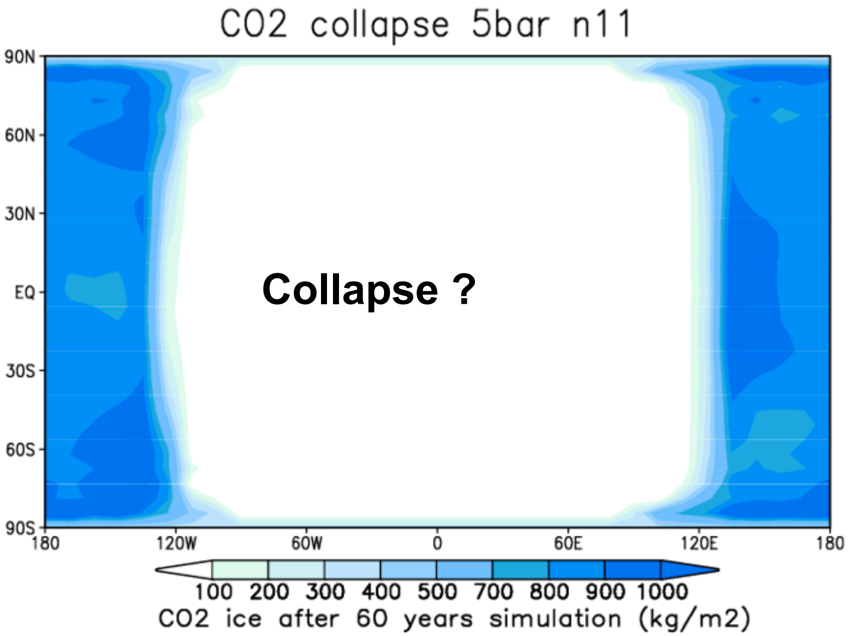
Wordsworth et al., 2011

Annual mean temperatures, rotation and CO_2 collapse

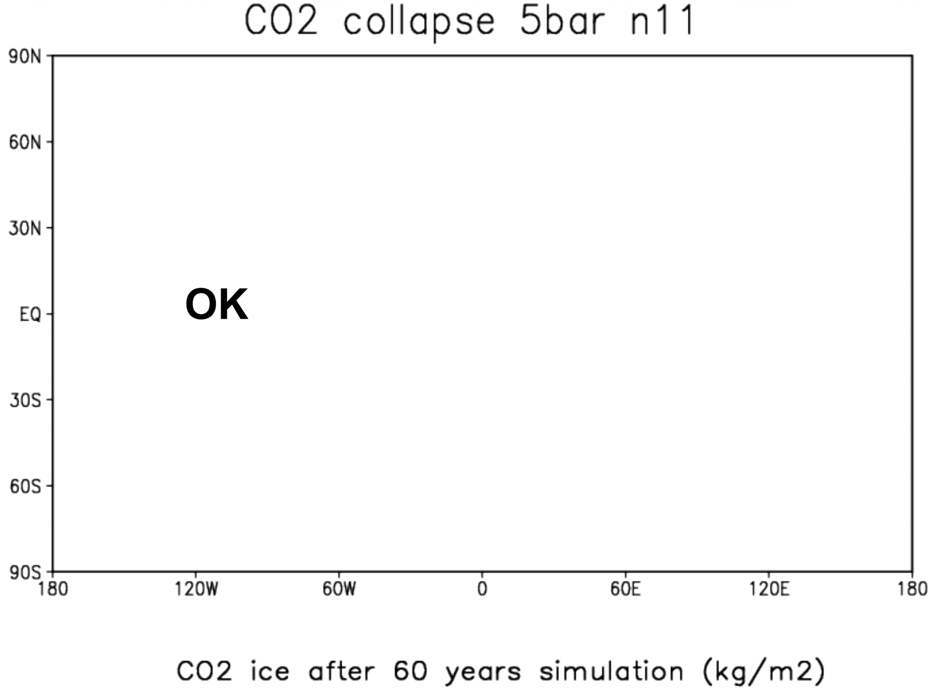
5 bars


Mean Tsurf (C) Ps=5bar n11


Mean Tsurf (C) Ps=5bar n12

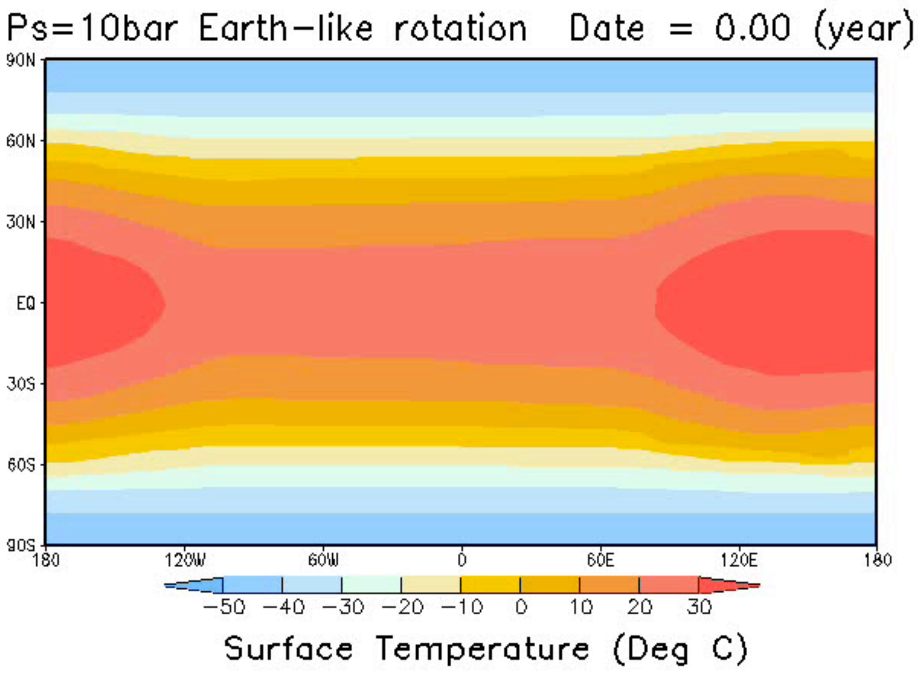

CO2 collapse 5bar n11

Collapse ?

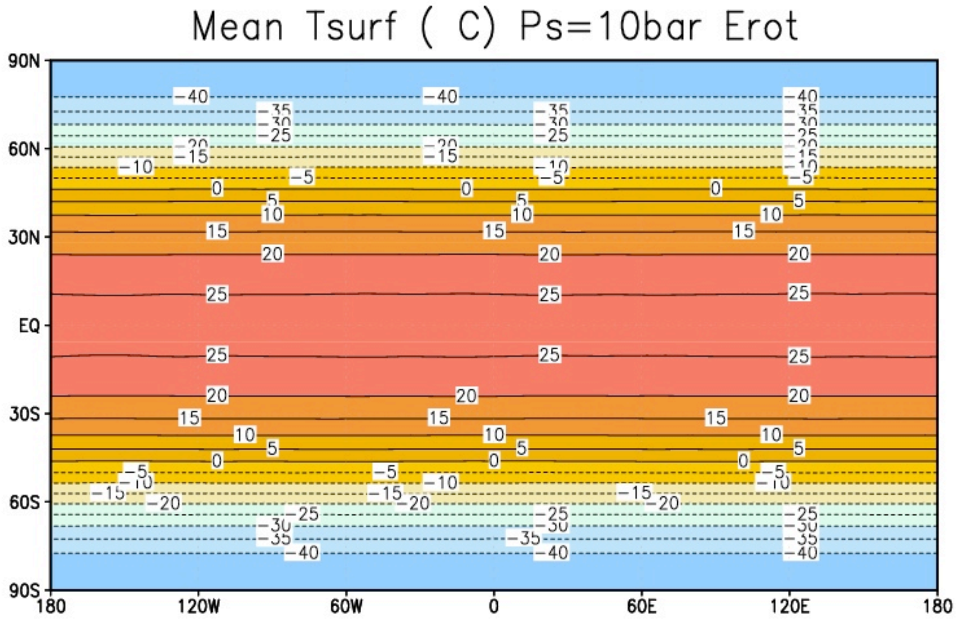

CO2 collapse 5bar n11

OK

Wordsworth et al., 2011



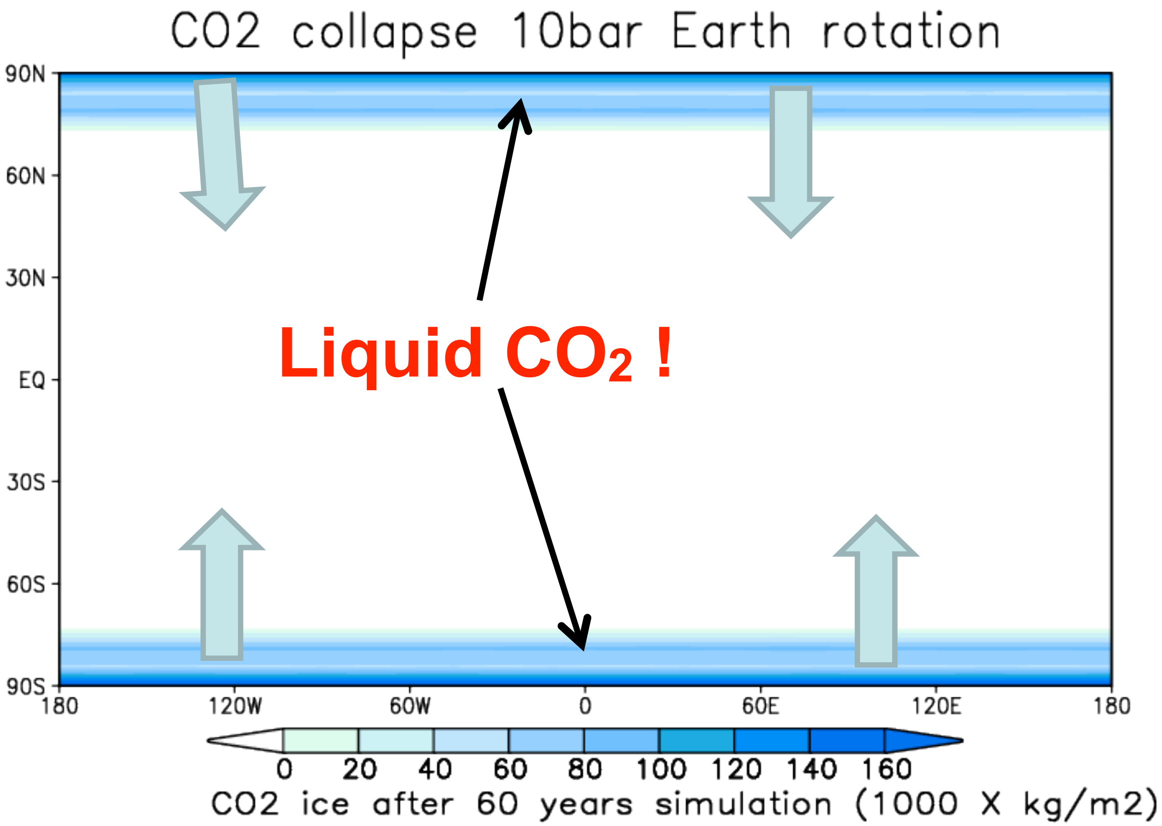
Ps=10bar Earth−like rotation Date = 0.00 (year)



Mean Tsurf (C) Ps=10bar Erot

annual mean temperatures, rotation and CO_2 collapse

10 bars

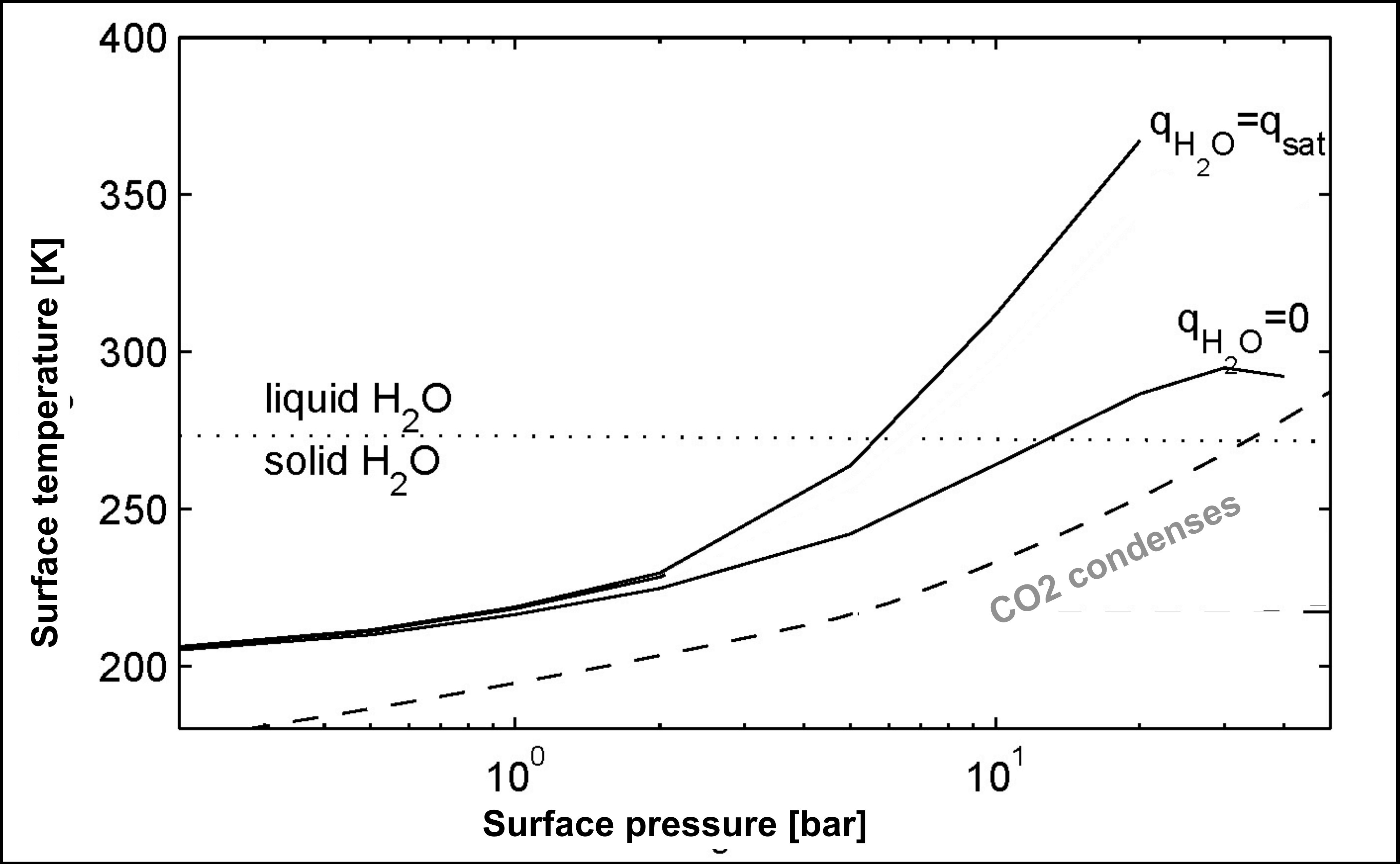


CO2 collapse 10bar Earth rotation

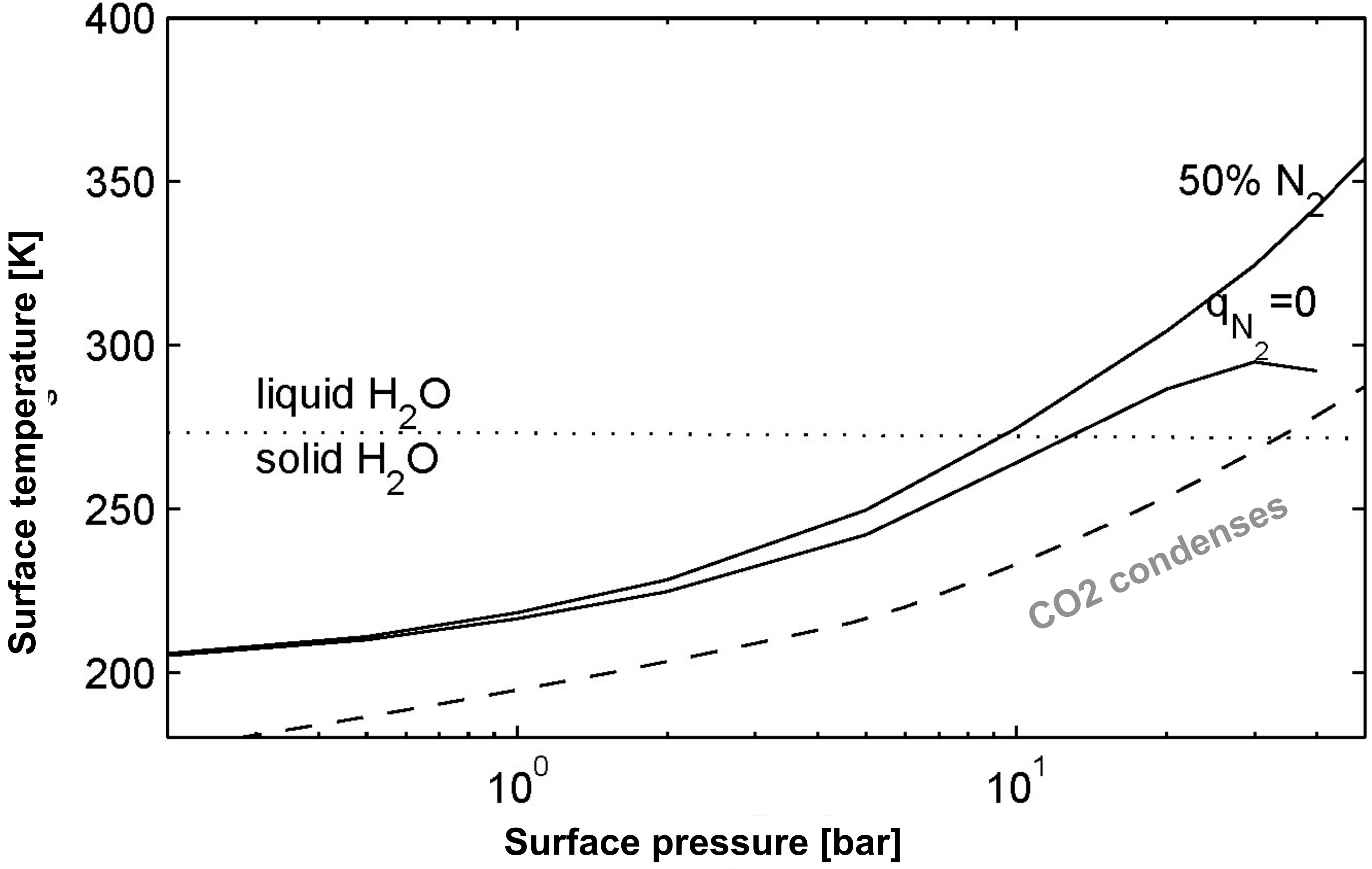
Liquid CO_2 !

Wordsworth et al., 2011

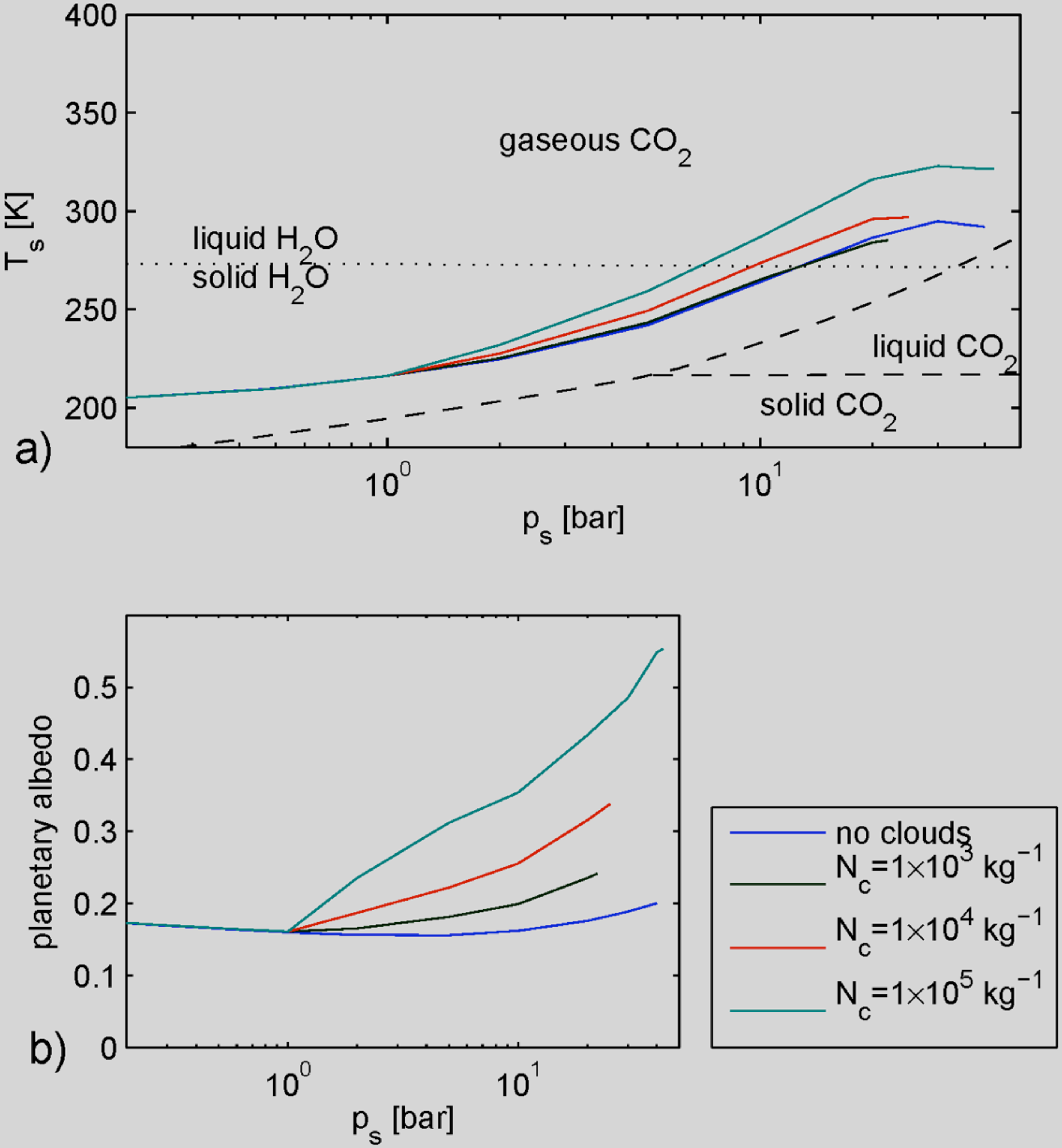
$CO_2 + H_2O$


Surface temperature [K]
400
350
300
250
200
Surface pressure [bar]
10^0
10^1
$q_{H_2O}=q_{sat}$
$q_{H_2O}=0$
liquid H_2O
solid H_2O
CO2 condenses

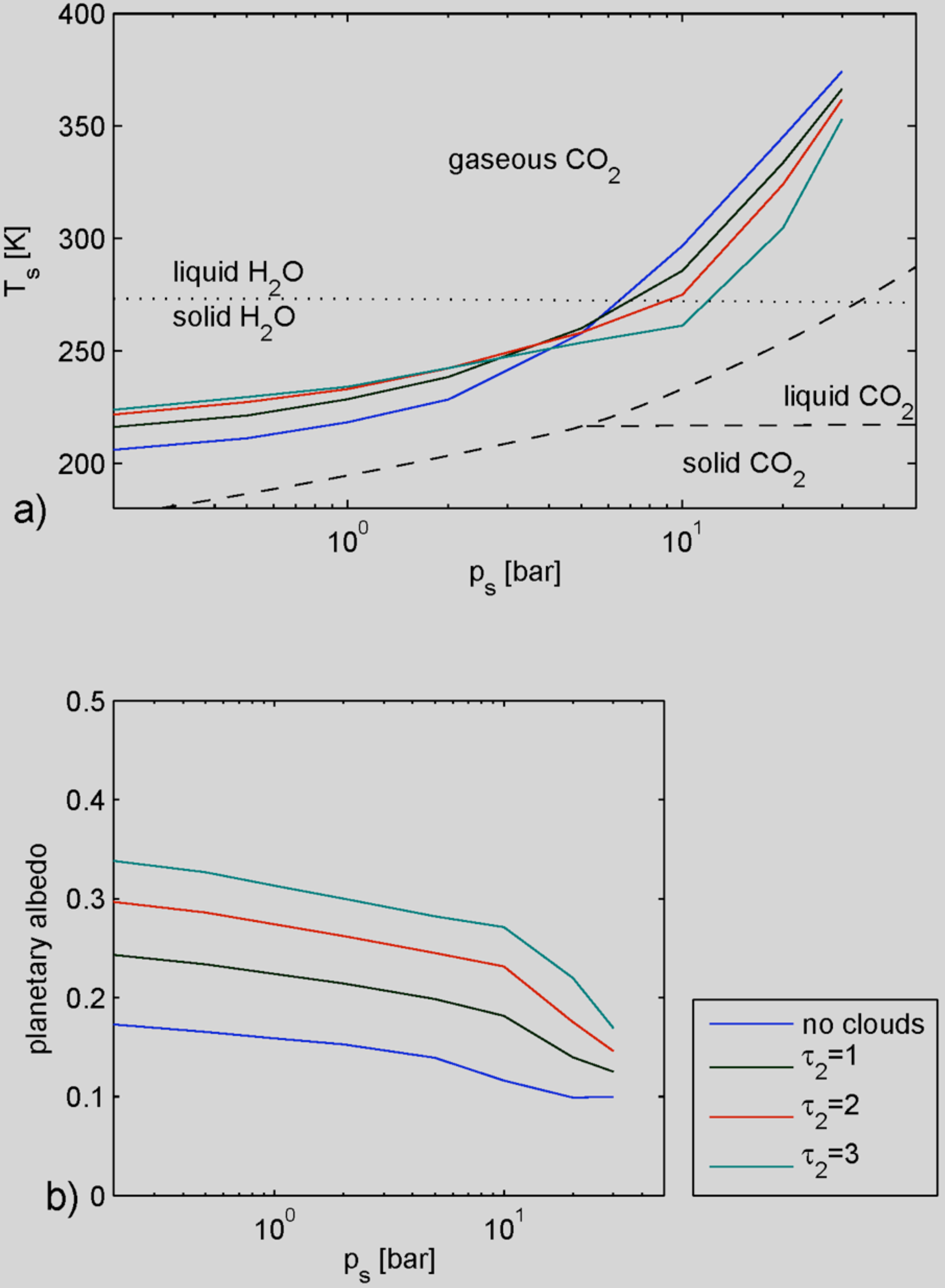
$CO_2 + N_2$


400
350
300
250
200
Surface temperature [K]
10^0
10^1
Surface pressure [bar]
50% N_2
$q_{N_2}=0$
liquid H_2O
solid H_2O
CO2 condenses

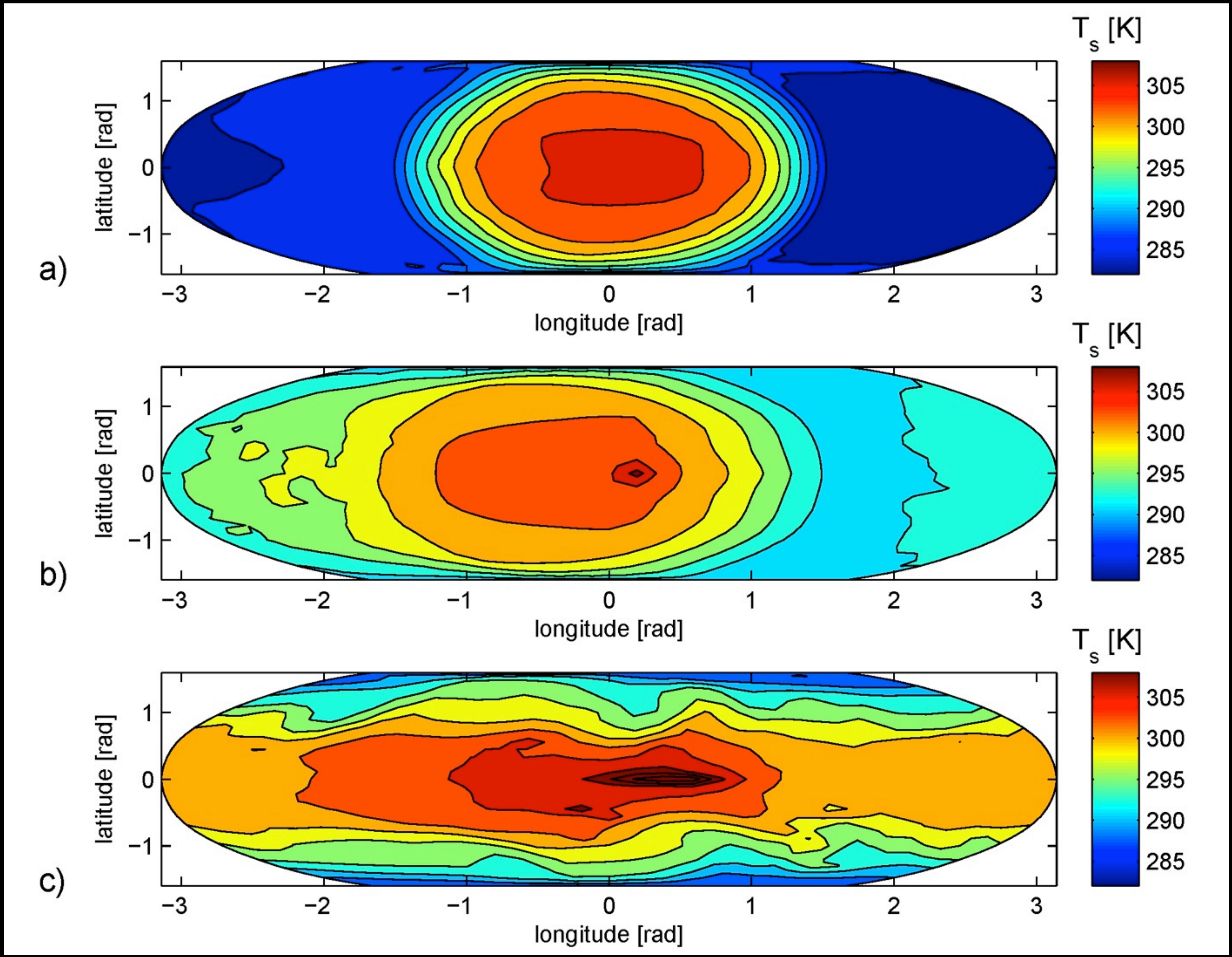
CO_2 clouds

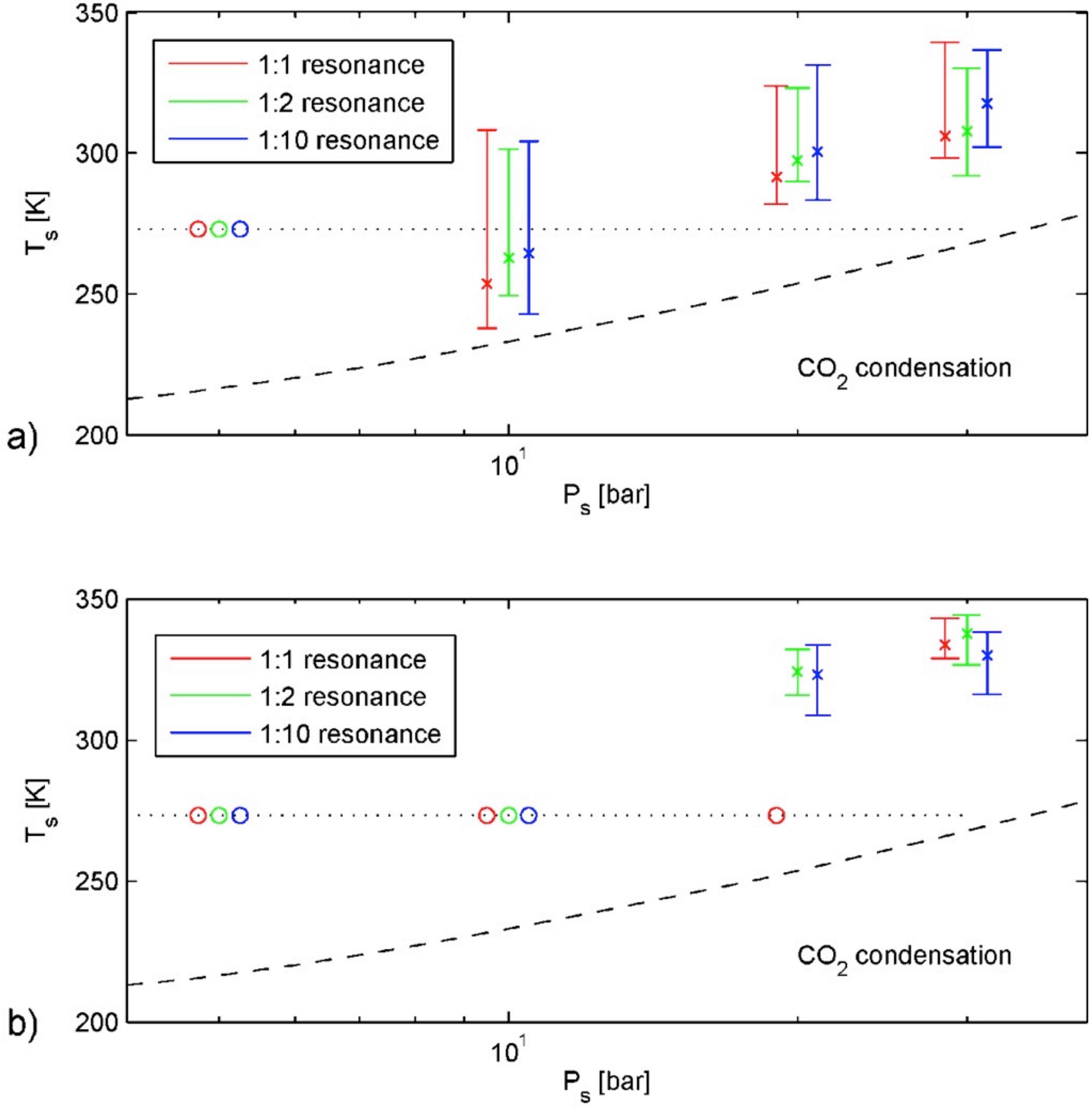

400
350
300
250
200
T_s [K]
gaseous CO_2
liquid H_2O
solid H_2O
liquid CO_2
solid CO_2
a)
10^0
10^1
p_s [bar]
0.5
0.4
0.3
0.2
0.1
0
planetary albedo
b)
10^0
10^1
p_s [bar]
no clouds
$N_c=1\times10^3$ kg^{-1}
$N_c=1\times10^4$ kg^{-1}
$N_c=1\times10^5$ kg^{-1}

H_2O



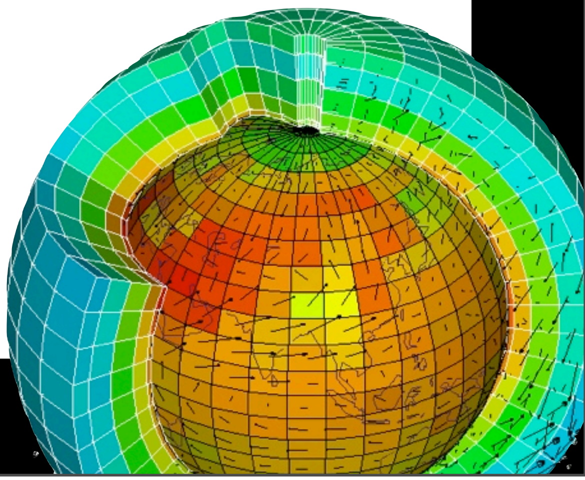
400
350
300
250
200
T_s [K]
gaseous CO_2
liquid H_2O
solid H_2O
liquid CO_2
solid CO_2
a)
10^0
10^1
p_s [bar]
0.5
0.4
0.3
0.2
0.1
0
planetary albedo
b)
10^0
10^1
p_s [bar]
no clouds
τ_2=1
τ_2=2
τ_2=3


a)
b)
c)
T_s [K]
305
300
295
290
285
latitude [rad]
1
0
−1
longitude [rad]
−3
−2
−1
0
1
2
3



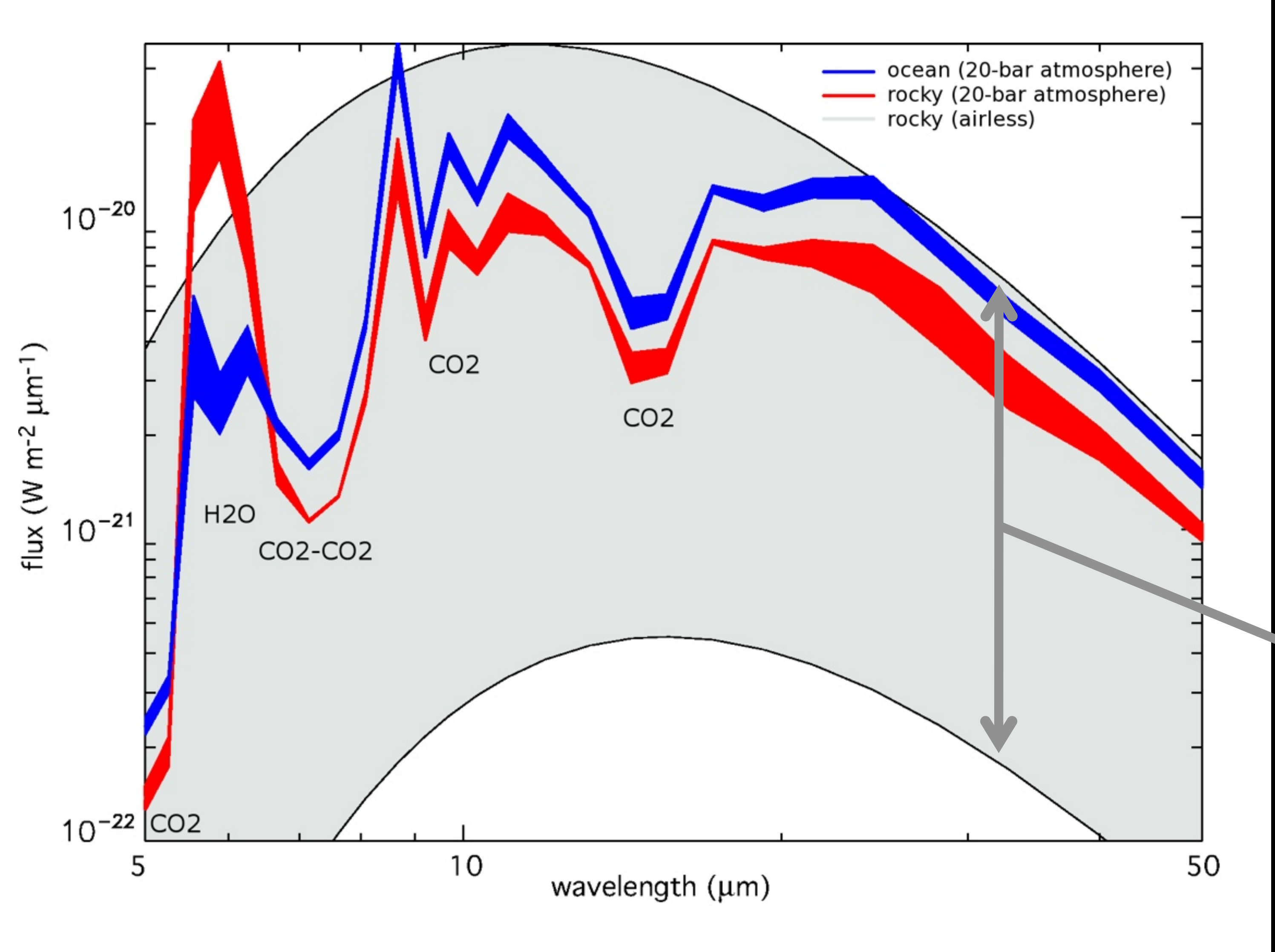
ROCKY

OCEAN



Wordsworth et al. (2011)

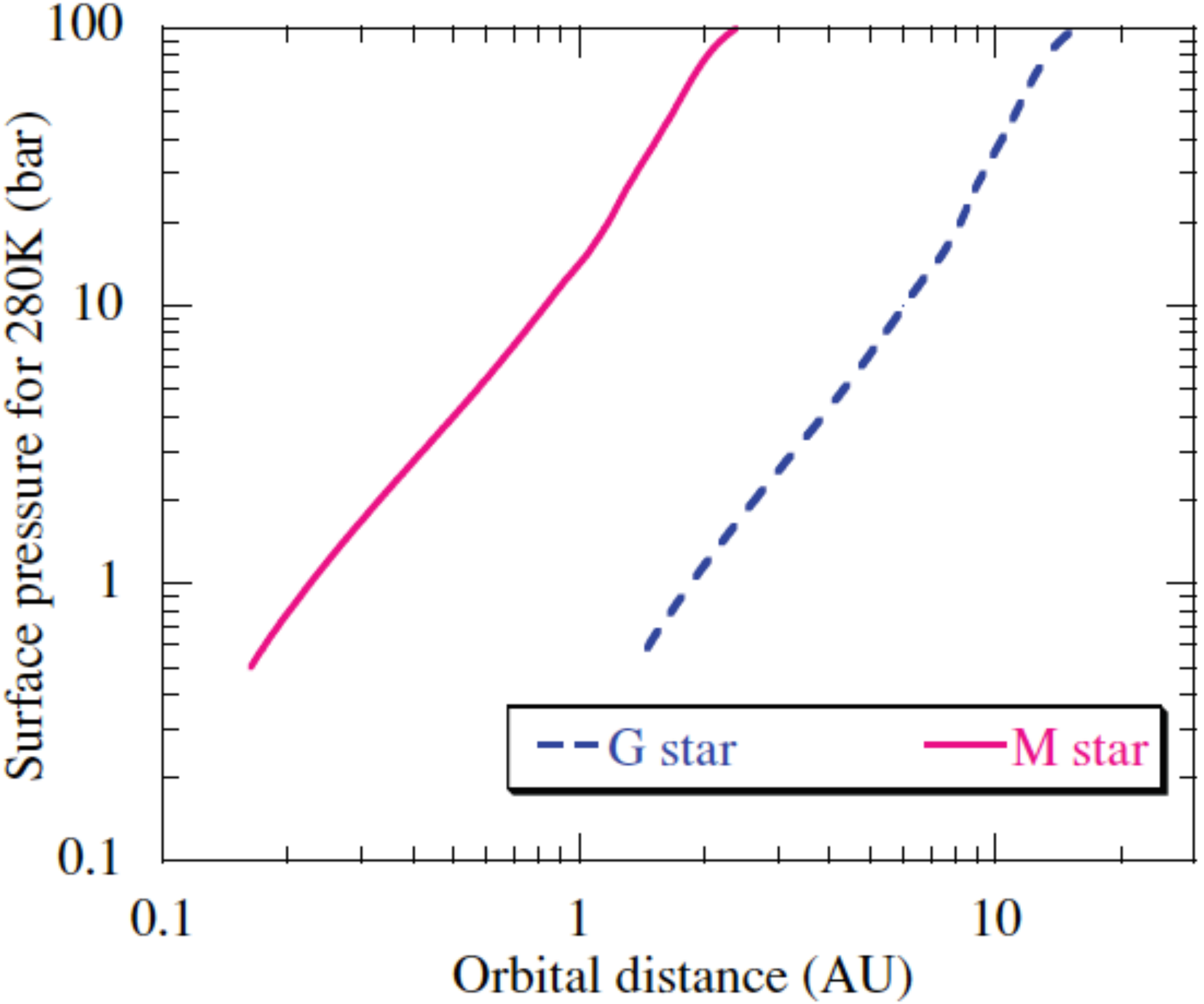
How can we distinguish the various possible cases?



Planet / star contrast ratio of order 10^{-6}
→TPF / Darwin mission required

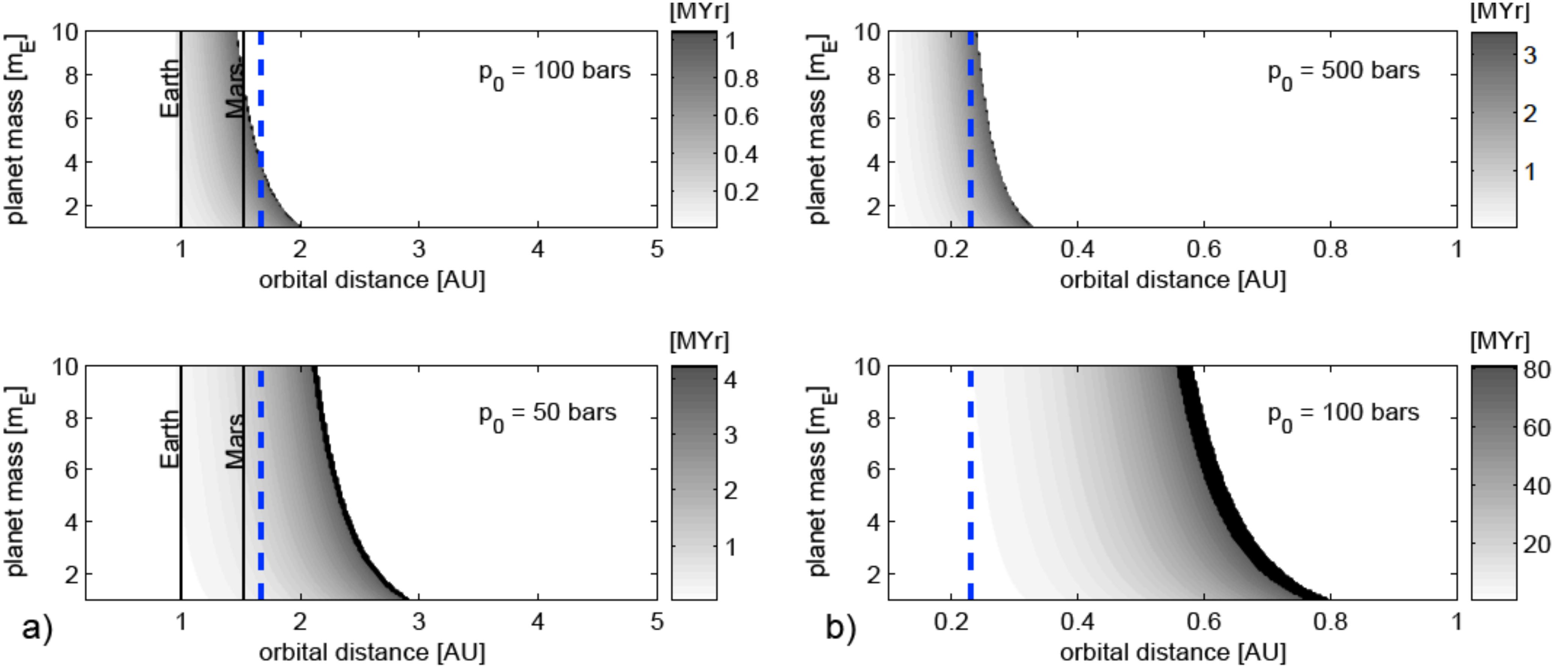
Large orbital flux variations in airless case

Greenhouse warming by H_2 atmospheres

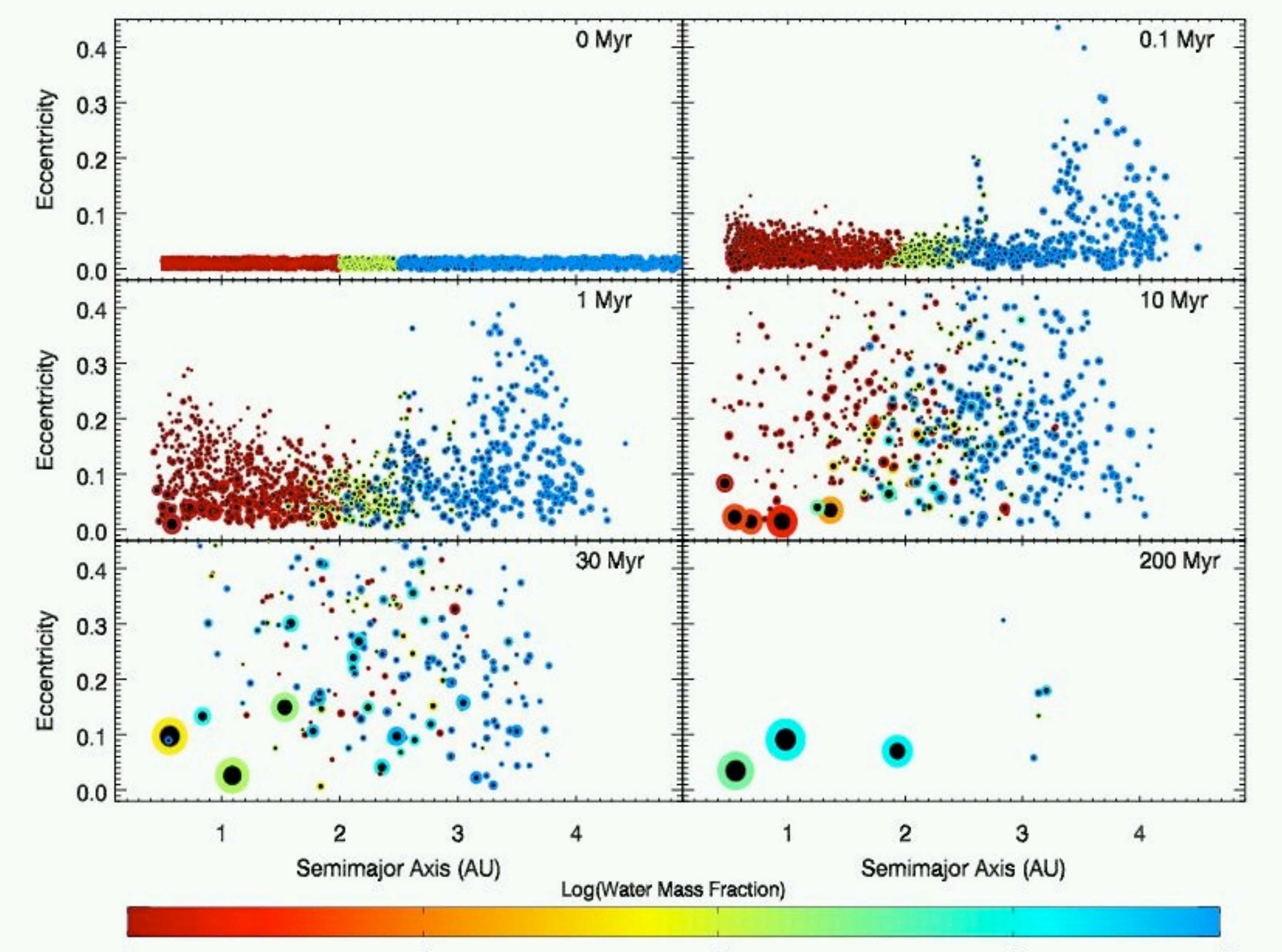


Pierrehumbert and Gaidos, 2011

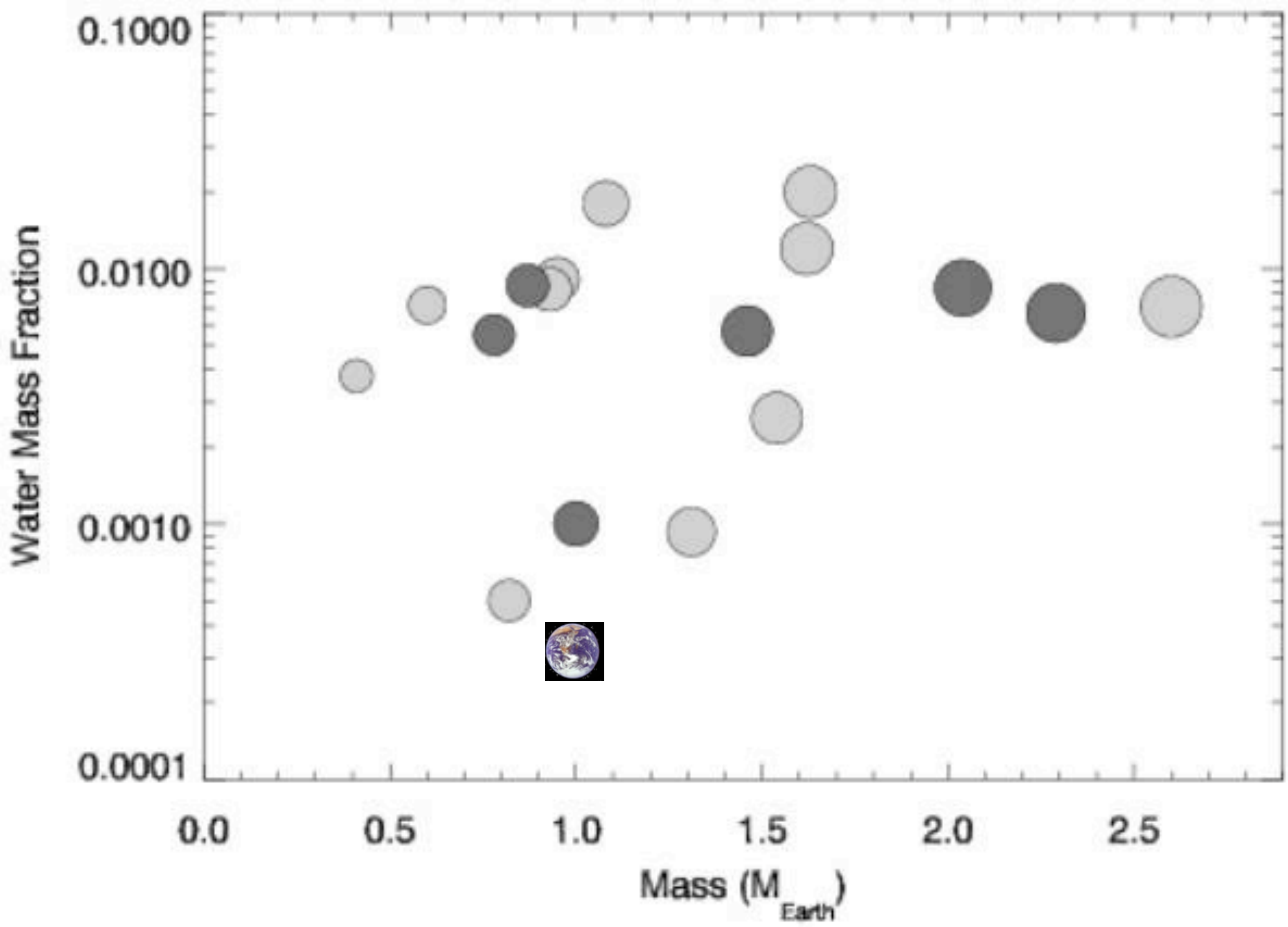
How long does the right H_2 pressure can be sustained ?



Wordsworth, submitted



Raymond et al., 2006



Raymond et al., 2007

Walsh, Morbidelli, Raymond et al., 2011

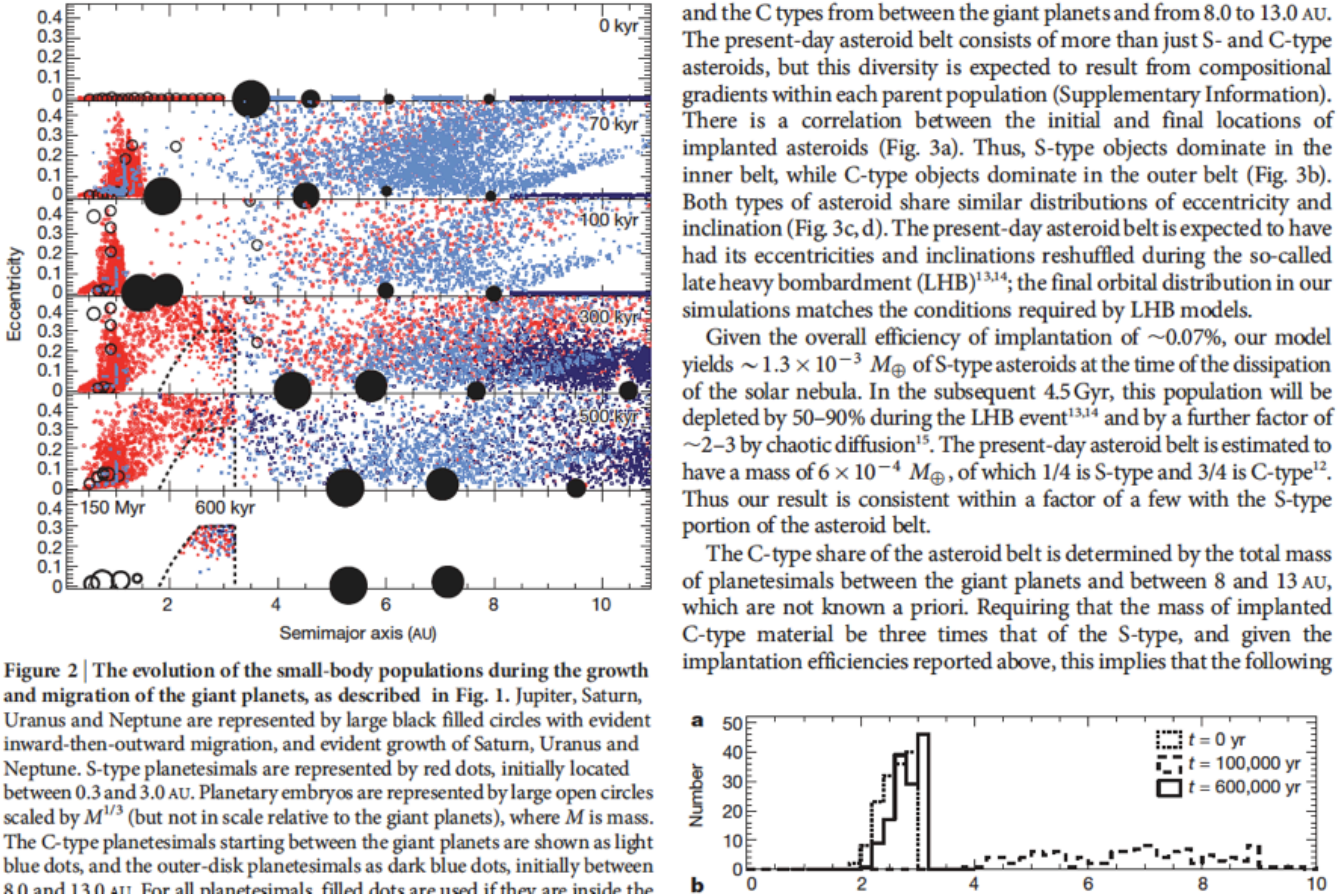


Figure 2 | The evolution of the small-body populations during the growth and migration of the giant planets, as described in Fig. 1. Jupiter, Saturn, Uranus and Neptune are represented by large black filled circles with evident inward-then-outward migration, and evident growth of Saturn, Uranus and Neptune. S-type planetesimals are represented by red dots, initially located between 0.3 and 3.0 AU. Planetary embryos are represented by large open circles scaled by $M^{1/3}$ (but not in scale relative to the giant planets), where M is mass. The C-type planetesimals starting between the giant planets are shown as light blue dots, and the outer-disk planetesimals as dark blue dots, initially between 8.0 and 13.0 AU. For all planetesimals, filled dots are used if they are inside the

and the C types from between the giant planets and from 8.0 to 13.0 AU. The present-day asteroid belt consists of more than just S- and C-type asteroids, but this diversity is expected to result from compositional gradients within each parent population (Supplementary Information). There is a correlation between the initial and final locations of implanted asteroids (Fig. 3a). Thus, S-type objects dominate in the inner belt, while C-type objects dominate in the outer belt (Fig. 3b). Both types of asteroid share similar distributions of eccentricity and inclination (Fig. 3c, d). The present-day asteroid belt is expected to have had its eccentricities and inclinations reshuffled during the so-called late heavy bombardment (LHB)[13,14]; the final orbital distribution in our simulations matches the conditions required by LHB models.

Given the overall efficiency of implantation of ~0.07%, our model yields $\sim 1.3 \times 10^{-3}\ M_{\oplus}$ of S-type asteroids at the time of the dissipation of the solar nebula. In the subsequent 4.5 Gyr, this population will be depleted by 50–90% during the LHB event[13,14] and by a further factor of ~2–3 by chaotic diffusion[15]. The present-day asteroid belt is estimated to have a mass of $6 \times 10^{-4}\ M_{\oplus}$, of which 1/4 is S-type and 3/4 is C-type[12]. Thus our result is consistent within a factor of a few with the S-type portion of the asteroid belt.

The C-type share of the asteroid belt is determined by the total mass of planetesimals between the giant planets and between 8 and 13 AU, which are not known a priori. Requiring that the mass of implanted C-type material be three times that of the S-type, and given the implantation efficiencies reported above, this implies that the following