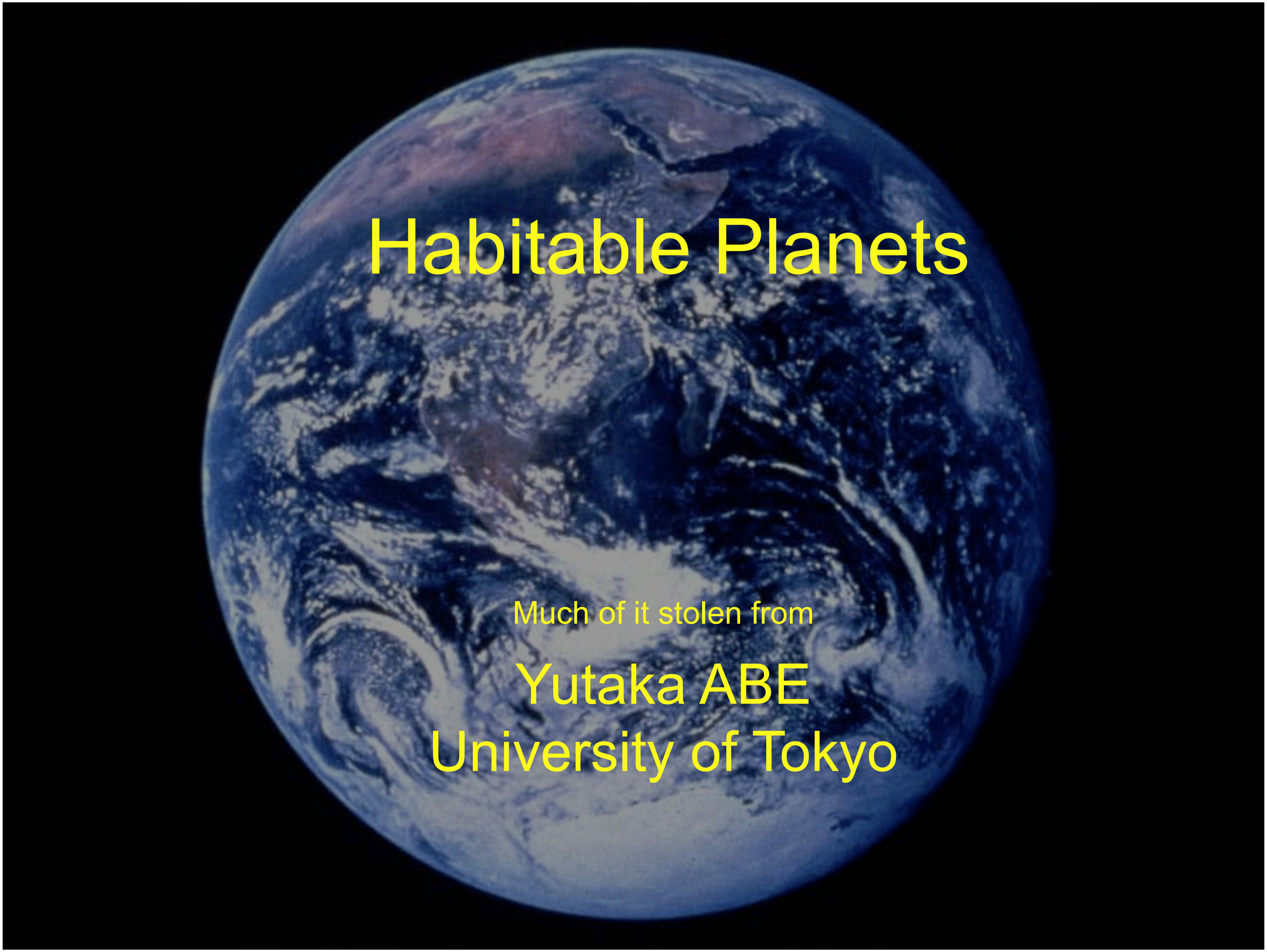
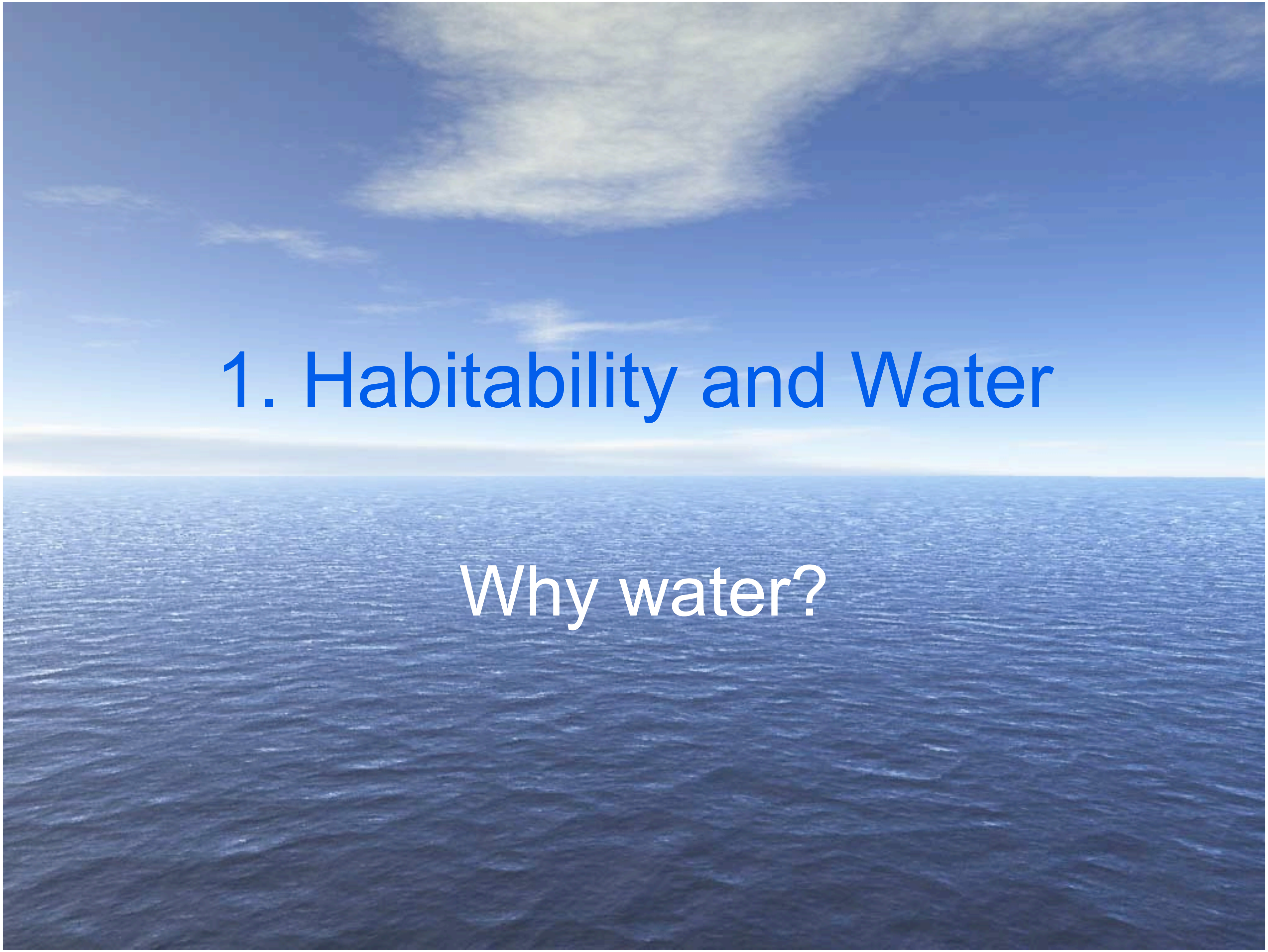

Habitable Planets
Much of it stolen from
Yutaka ABE
University of Tokyo


1. Habitability and Water
Why water?

Importance of Liquid

Gas: highly mobile, but low material density.

Solid: high density but very low mobility.

Liquid: high density and high mobility

Habitable environments likely use a liquid.

H_2O is the most abundant condensible substance in the cosmos

2. Water (Ocean) planets

One kind of Habitable planet
i.e., Generalized Earth

Caladan

An ocean planet where Paul Atreides was born

This image is from a video game

In this image, Caladan appears to be deep in a moist greenhouse

Water (Ocean) planets

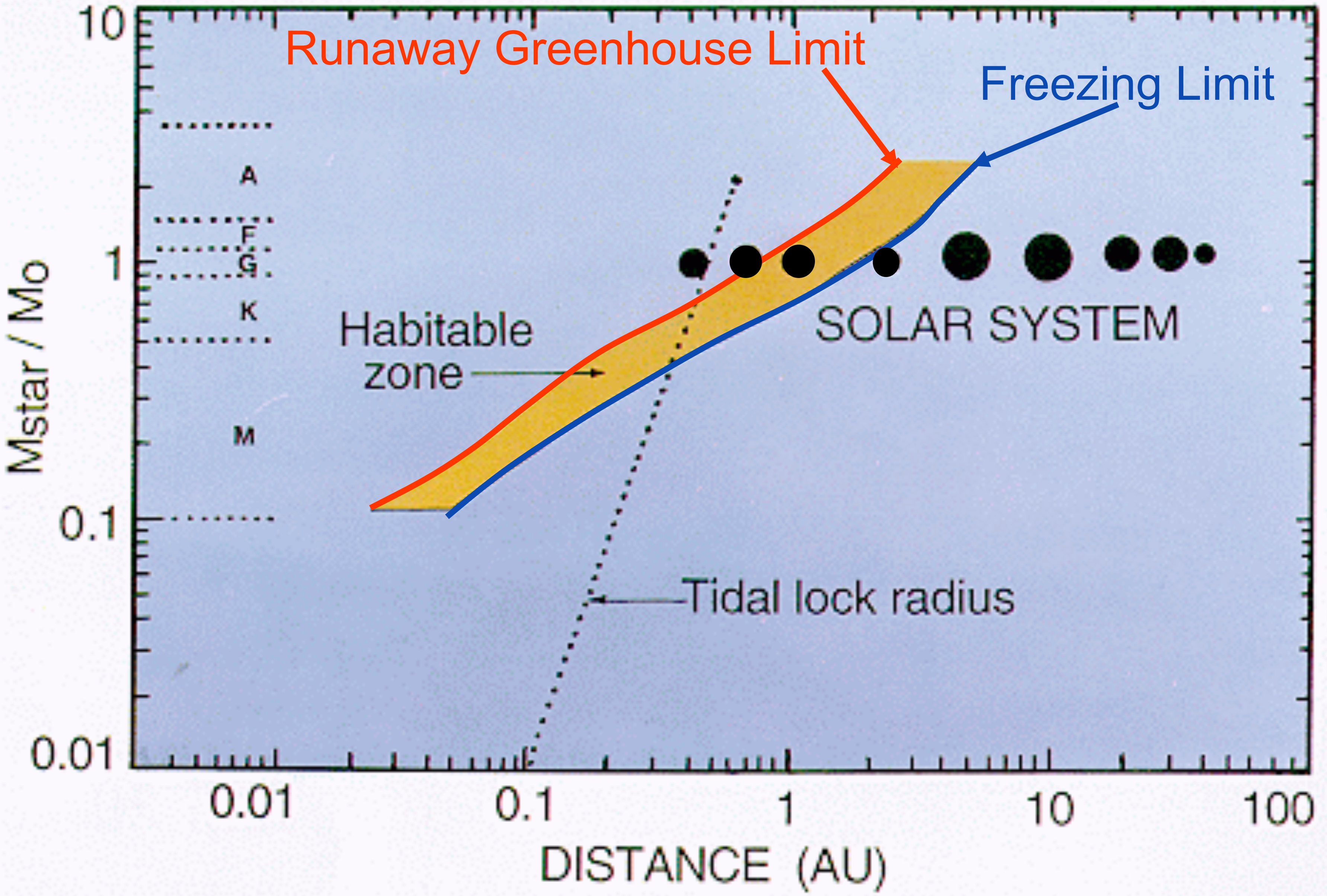
In zero dimensions

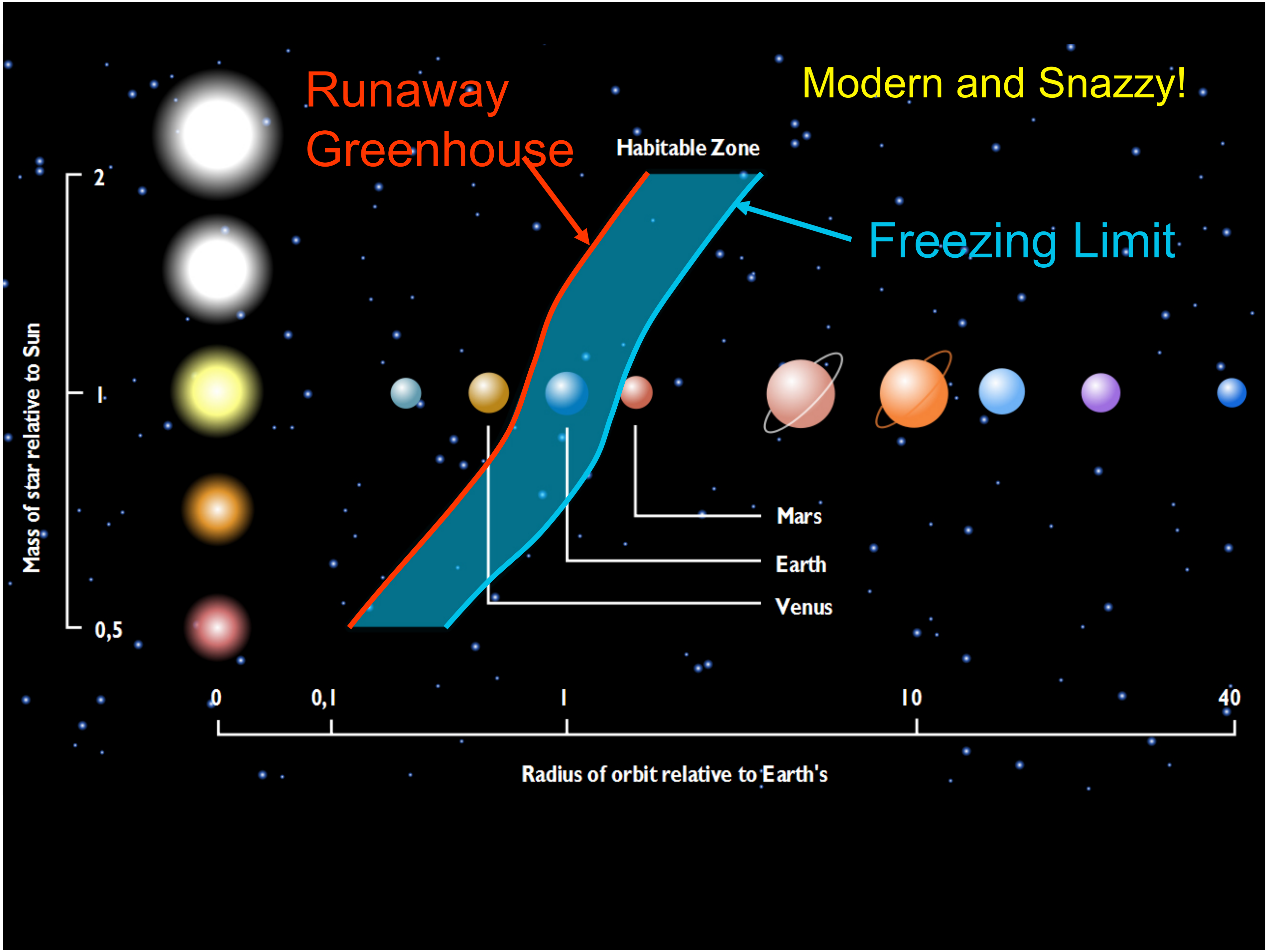
= globally averaged consideration

Bounded thermally by

- complete vaporization
    = runaway greenhouse
- global freezing

The Traditional Habitable Zone Plot (Kasting Whitmire Reynolds 1993





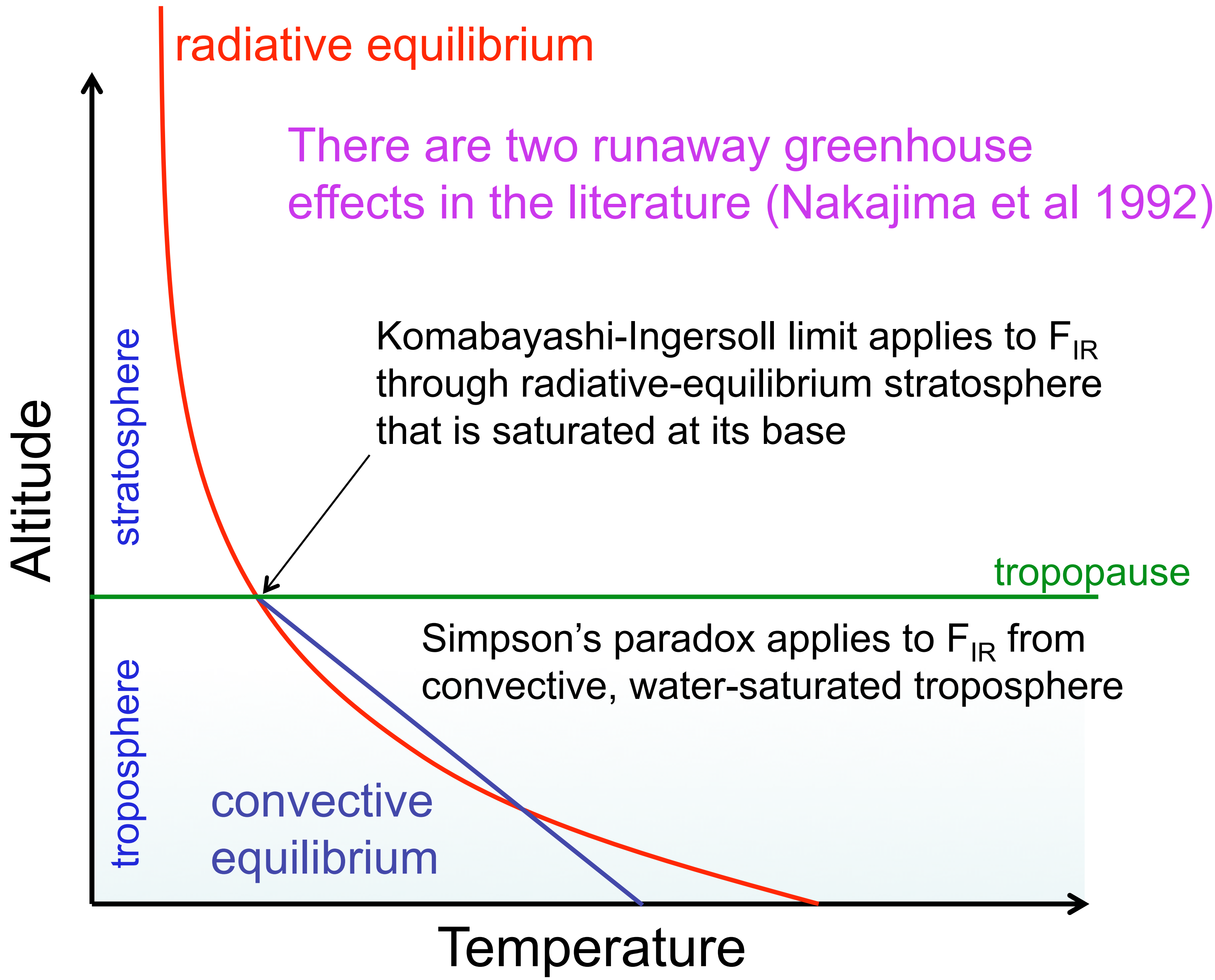
Runaway Greenhouse
Modern and Snazzy!
Habitable Zone
Freezing Limit
Mass of star relative to Sun
2
1
0,5
Mars
Earth
Venus
0
0,1
1
10
40
Radius of orbit relative to Earth's

2.1 Runaway greenhouse

- A moist atmosphere (saturated by water vapor) has an upper limit of the outgoing infrared flux that can be emitted:

- If insolation exceeds this limit, temperature increases until complete evaporation of liquid water from the surface.

- The runaway greenhouse limit is also called the “critical flux”


radiative equilibrium
There are two runaway greenhouse effects in the literature (Nakajima et al 1992)
Komabayashi-Ingersoll limit applies to F_{IR} through radiative-equilibrium stratosphere that is saturated at its base
stratosphere
Altitude
tropopause
Simpson's paradox applies to F_{IR} from convective, water-saturated troposphere
troposphere
convective equilibrium
Temperature

Ingersoll-Komabayashi limit

(1) Radiative equilibrium in the stratosphere

(2) Condensation at the tropopause

(3) Optical depth at the tropopause

Gray Approximation:

(1) $$\sigma T_t^4 = \frac{1}{2} F_{IR}^{\uparrow}\left(\frac{3}{2}\tau_t + 1\right)$$

(2) $$p^*(T) = p_0^* e^{-L/RT}$$

(3) $$\tau_t = \kappa_\nu h p^*(T)\frac{m_\nu}{g\overline{m}}$$

$$\tau_t = \frac{2}{3}\left(\frac{2\sigma T_t^4}{F_{IR}^{\uparrow}} - 1\right)$$

$$\tau_t = \frac{\kappa_\nu h p_0^* m_\nu}{g\overline{m}} e^{-L/RT_t}$$

F_{IR} = planetary thermal radiation

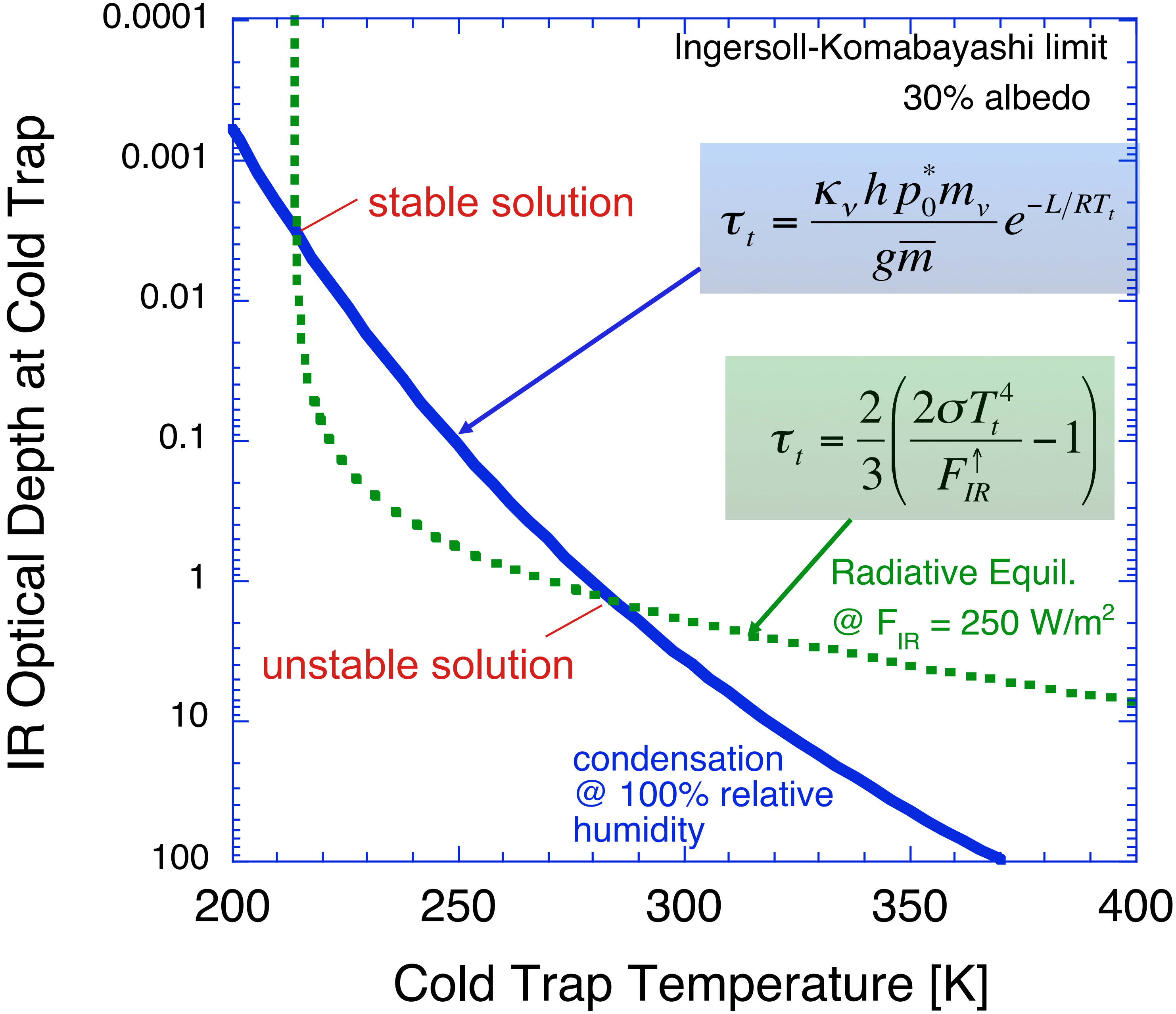
L = latent heat condensation

κ_v = absorption [cm^2/g]

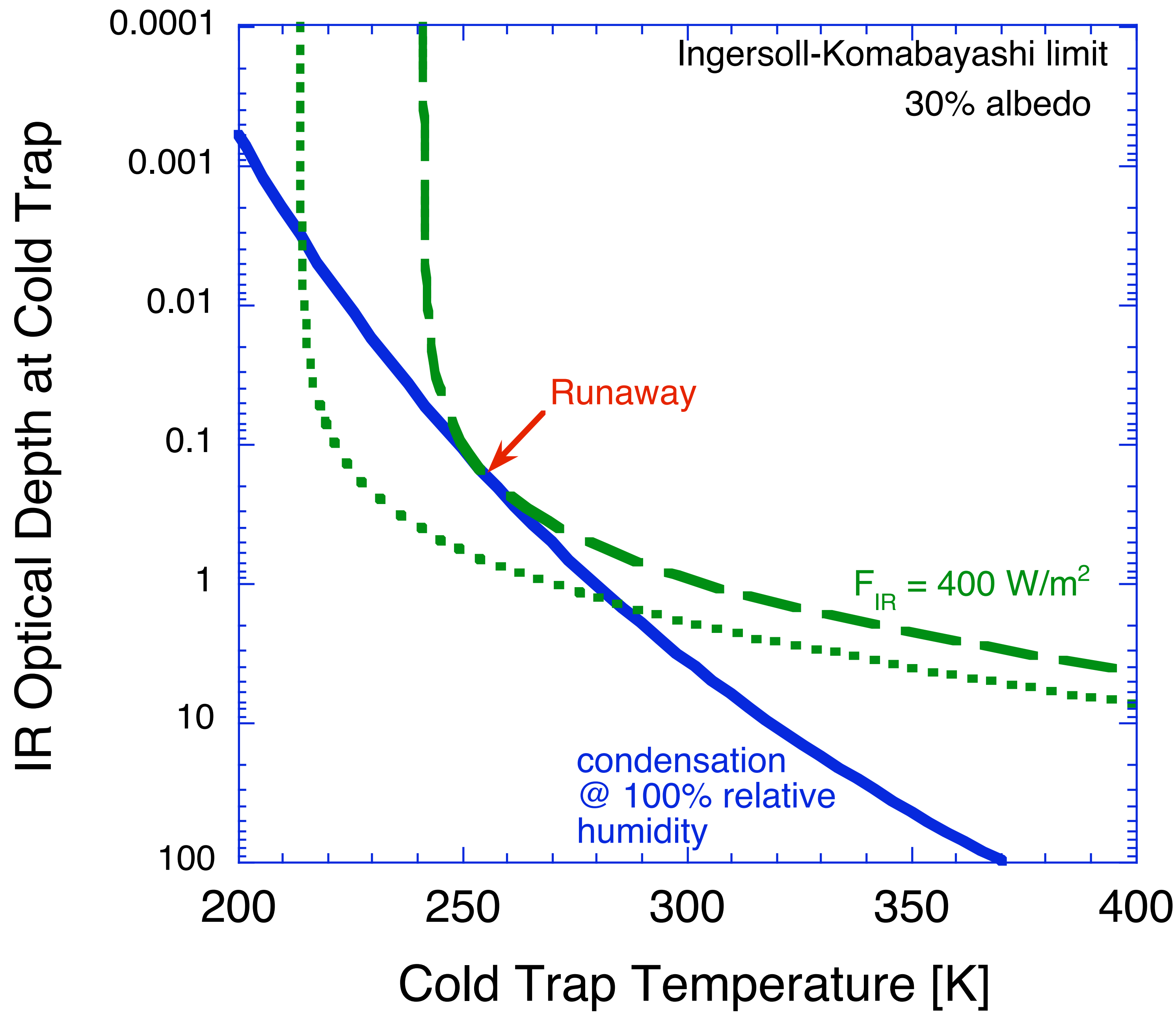
T_t=Tropopause Temperature

h = relative humidity

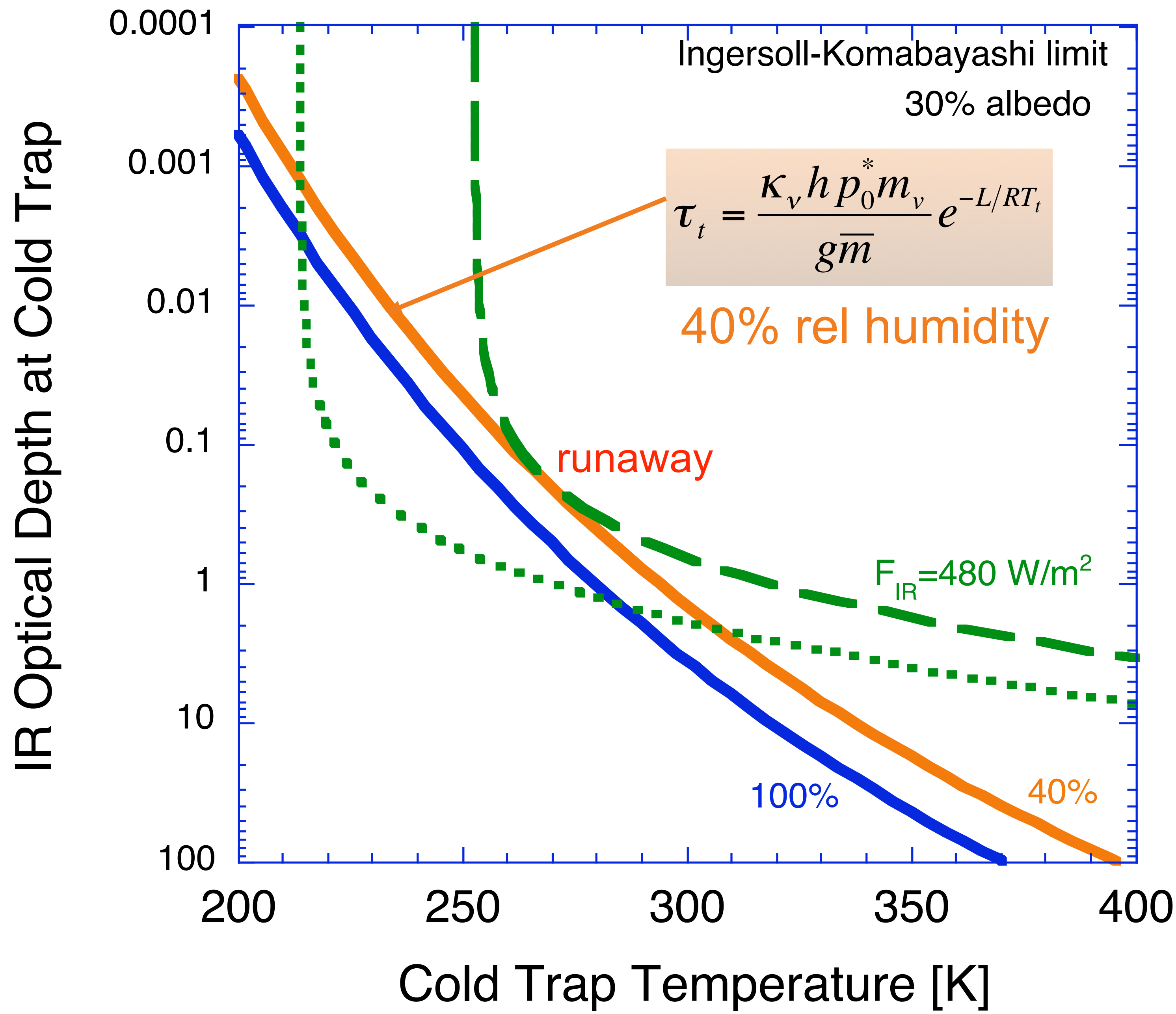
m_v,m = mol weights of vapor, atm



Ingersoll-Komabayashi limit
30% albedo
$$\tau_t = \frac{\kappa_v h p_0^* m_v}{g\overline{m}} e^{-L/RT_t}$$
$$\tau_t = \frac{2}{3}\left(\frac{2\sigma T_t^4}{F_{IR}^{\uparrow}} - 1\right)$$
stable solution
unstable solution
Radiative Equil.
@ F_{IR} = 250 W/m^2
condensation
@ 100% relative
humidity
0.0001
0.001
0.01
0.1
1
10
100
200
250
300
350
400
IR Optical Depth at Cold Trap
Cold Trap Temperature [K]



Ingersoll-Komabayashi limit
30% albedo
Runaway
F_{IR} = 400 W/m^2
condensation
@ 100% relative
humidity
0.0001
0.001
0.01
0.1
1
10
100
IR Optical Depth at Cold Trap
200
250
300
350
400
Cold Trap Temperature [K]



Ingersoll-Komabayashi limit
30% albedo
$$\tau_t = \frac{\kappa_\nu h p_0^* m_\nu}{g\overline{m}} e^{-L/RT_t}$$
40% rel humidity
runaway
F_{IR}=480 W/m^2
100%
40%
0.0001
0.001
0.01
0.1
1
10
100
200
250
300
350
400
IR Optical Depth at Cold Trap
Cold Trap Temperature [K]

Simpson's Paradox (runaway in radiative-convective equilibrium)

Saturation vapor pressure p^* relates the optical depth τ to the radiating temperature T of the moist troposphere.

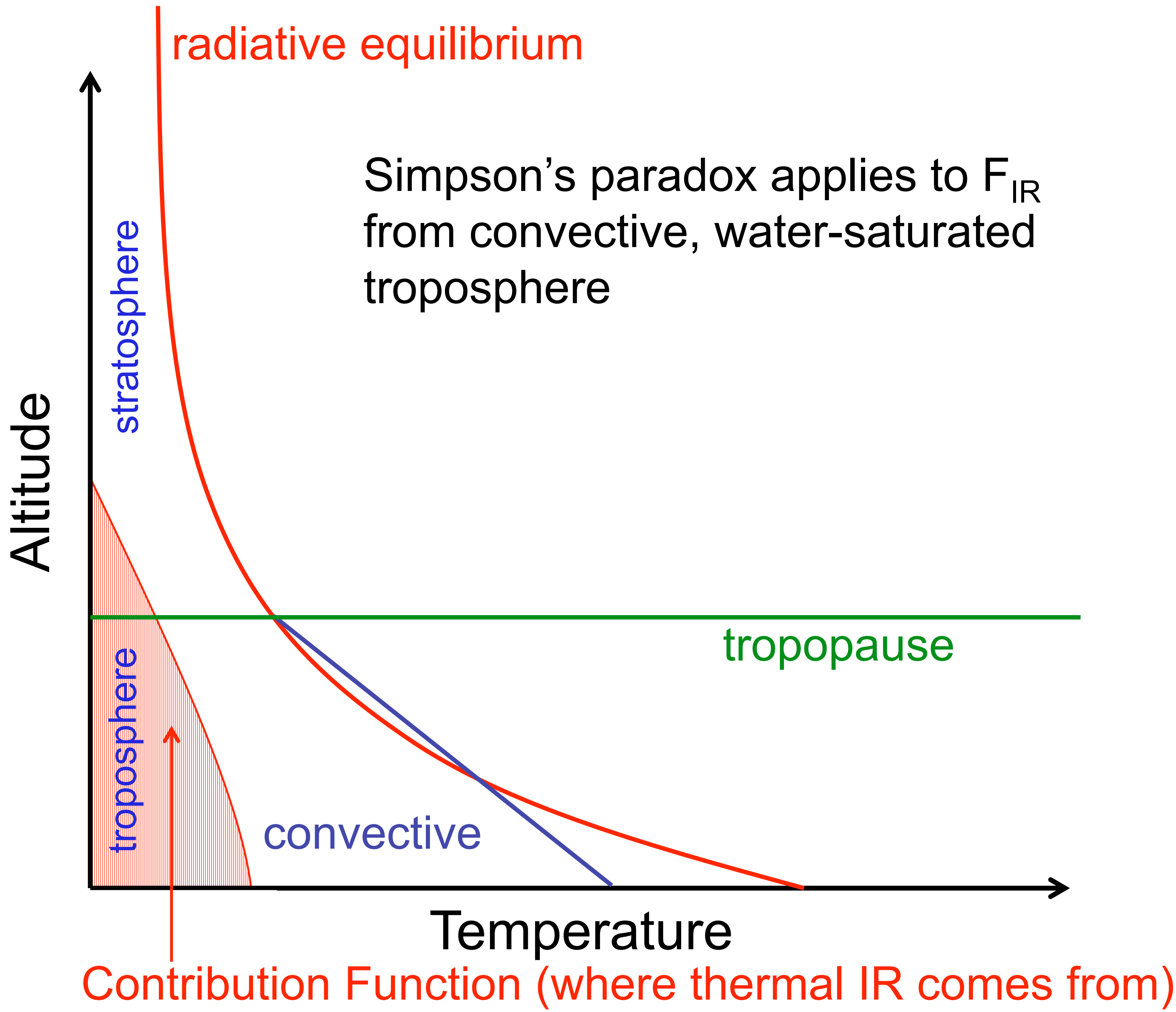
This is illustrated for a gray atmosphere:

$$F_{\mathrm{IR}}^{\uparrow}(\tau=0) \approx \int_0^{\infty} \sigma T^4 e^{-3\tau/2} \, \frac{3}{2} \, d\tau$$ (≈ 310 W/m^2 for Earth)

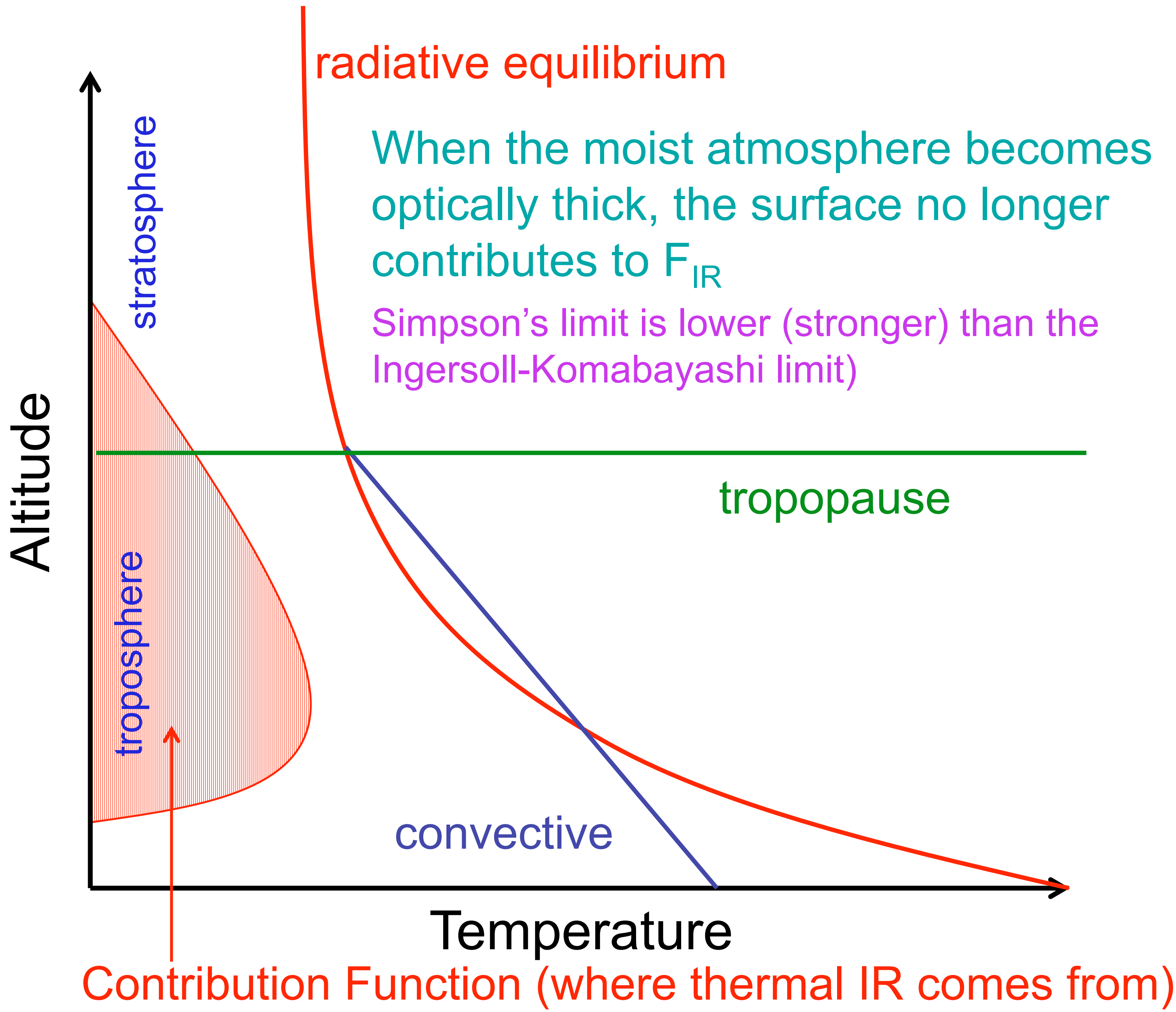
where optical depth depends on the relative humidity h and the saturated column of water vapor

$$\tau(T) \propto \int_z h \, p^*\left(T(z)\right) dz$$

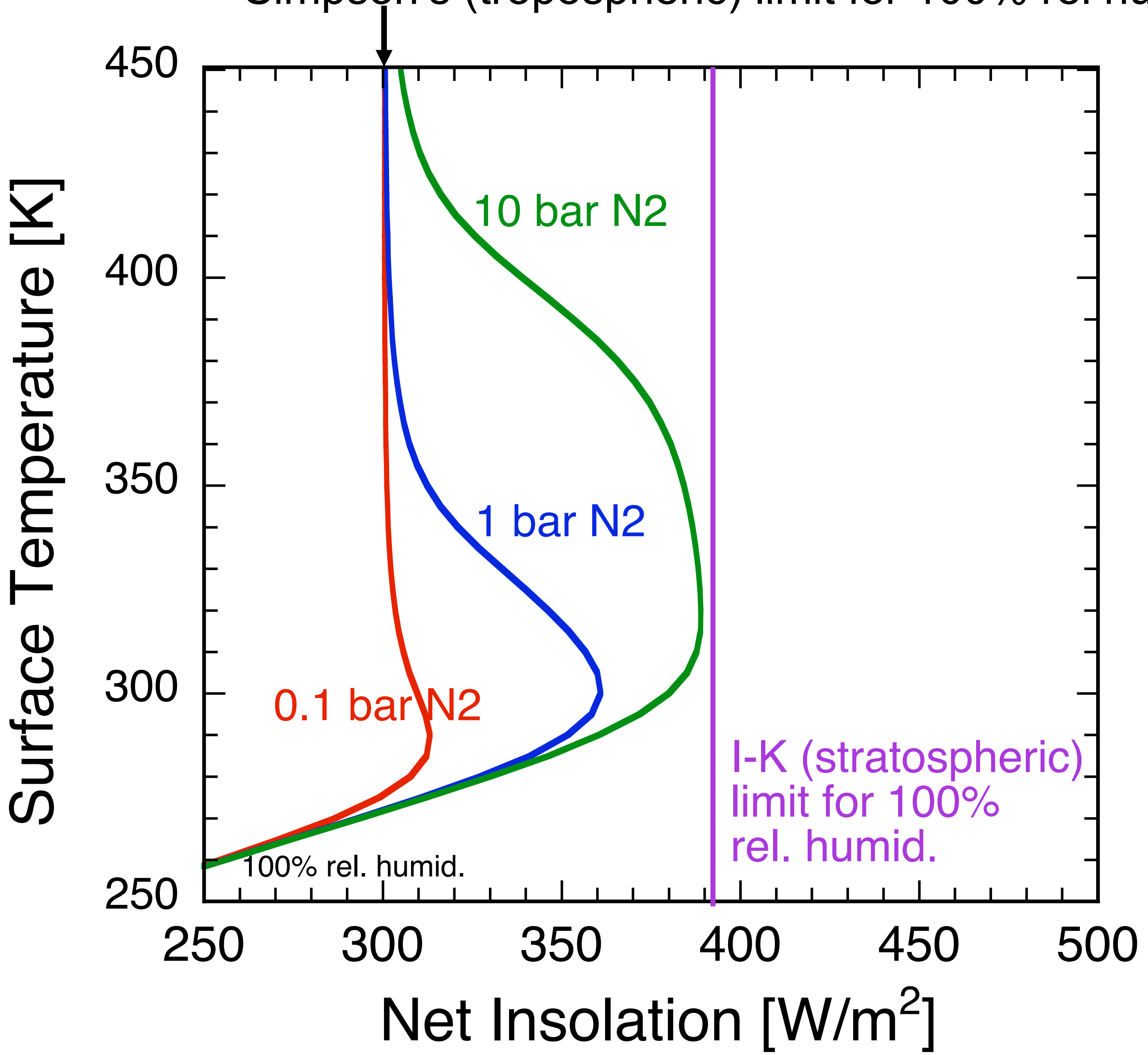
The critical flux depends weakly on g (roughly as $g^{0.25}$)



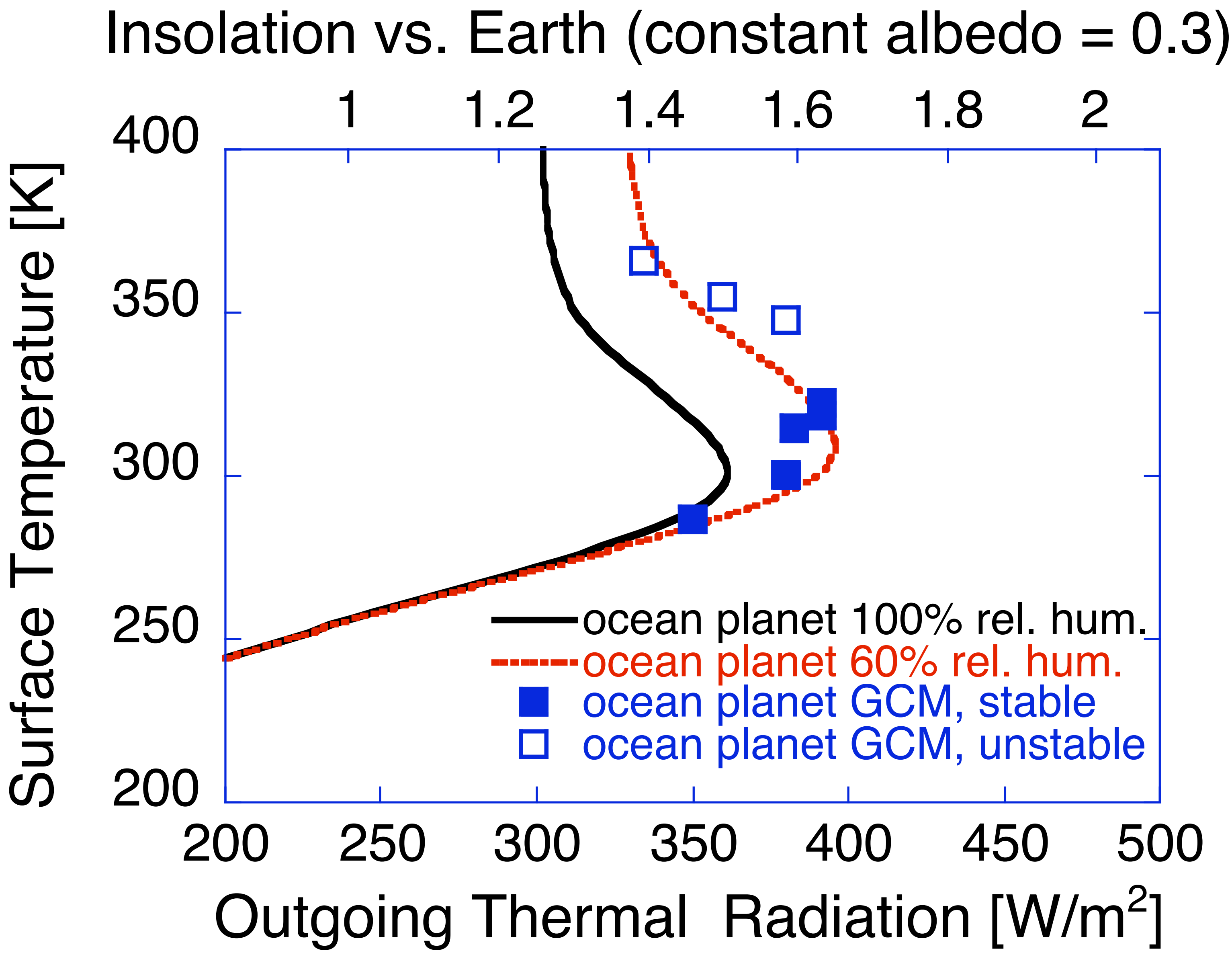
radiative equilibrium
Simpson's paradox applies to F_{IR} from convective, water-saturated troposphere
stratosphere
Altitude
tropopause
troposphere
convective
Temperature
Contribution Function (where thermal IR comes from)


radiative equilibrium
When the moist atmosphere becomes optically thick, the surface no longer contributes to F_{IR}
Simpson's limit is lower (stronger) than the Ingersoll-Komabayashi limit)
stratosphere
Altitude
tropopause
troposphere
convective
Temperature
Contribution Function (where thermal IR comes from)

Simpson's (tropospheric) limit for 100% rel humid



1-D follows Nakajima et al J. Atmos. Sci. (1992)



1-D follows Nakajima et al J. Atmos. Sci. (1992)

GCM expts by Ishiwatari et al J. Atmos. Sci. (2002)

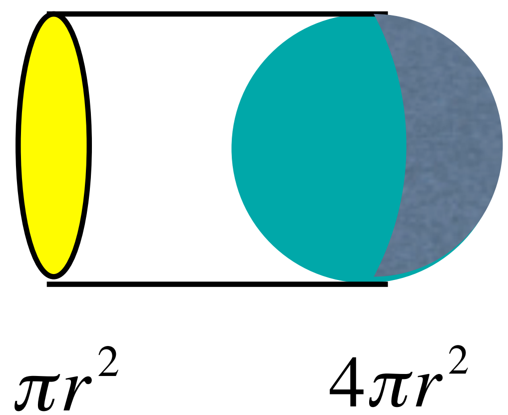
2.2 freezing limit

A simple global energy balance model with ice albedo feedback.

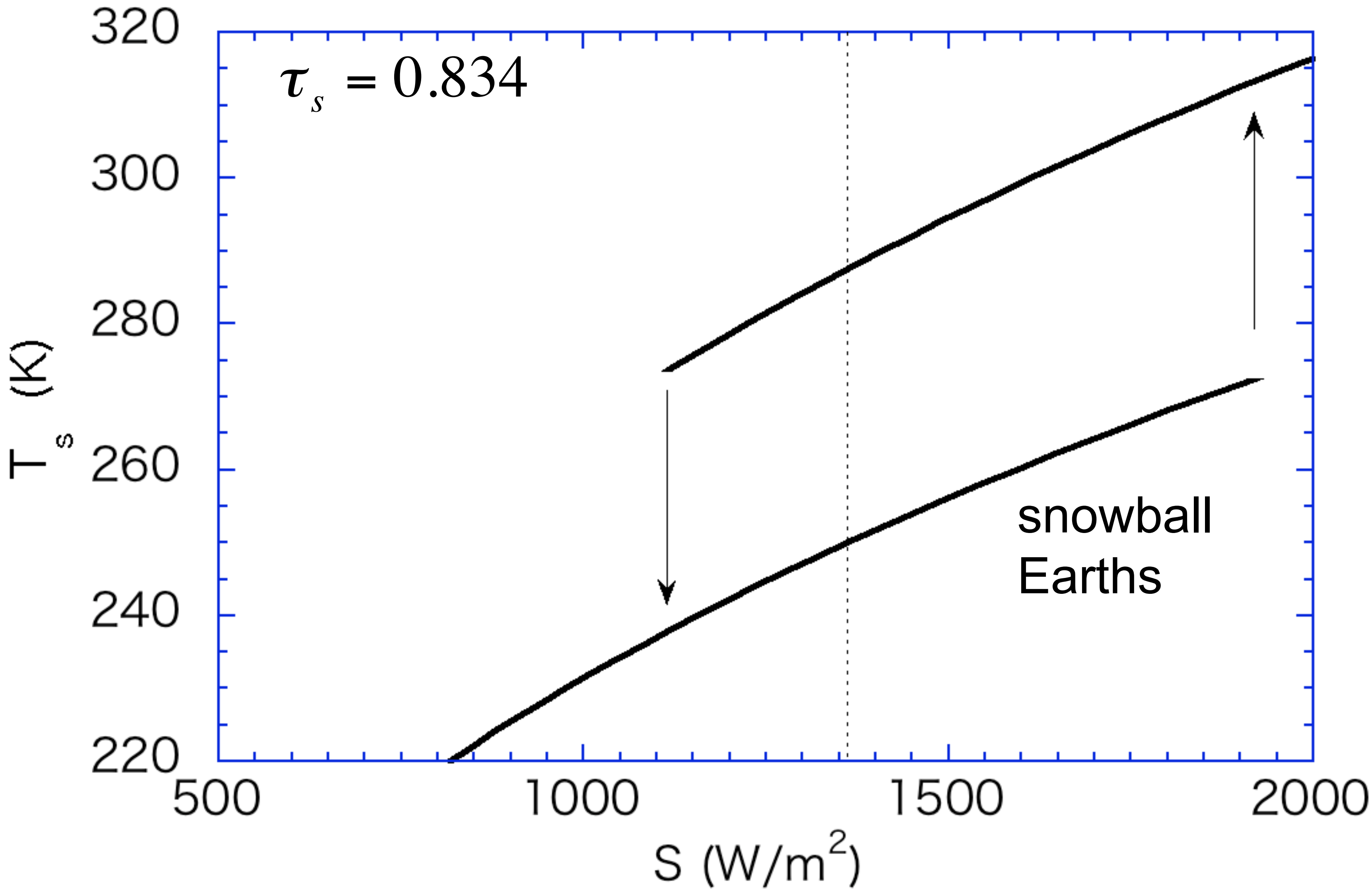
$$\pi r^2 S(1 - A) = 4\pi r^2 F$$

$$F = \frac{2\sigma T_s^4}{\frac{3}{2}\tau_s + 2}$$

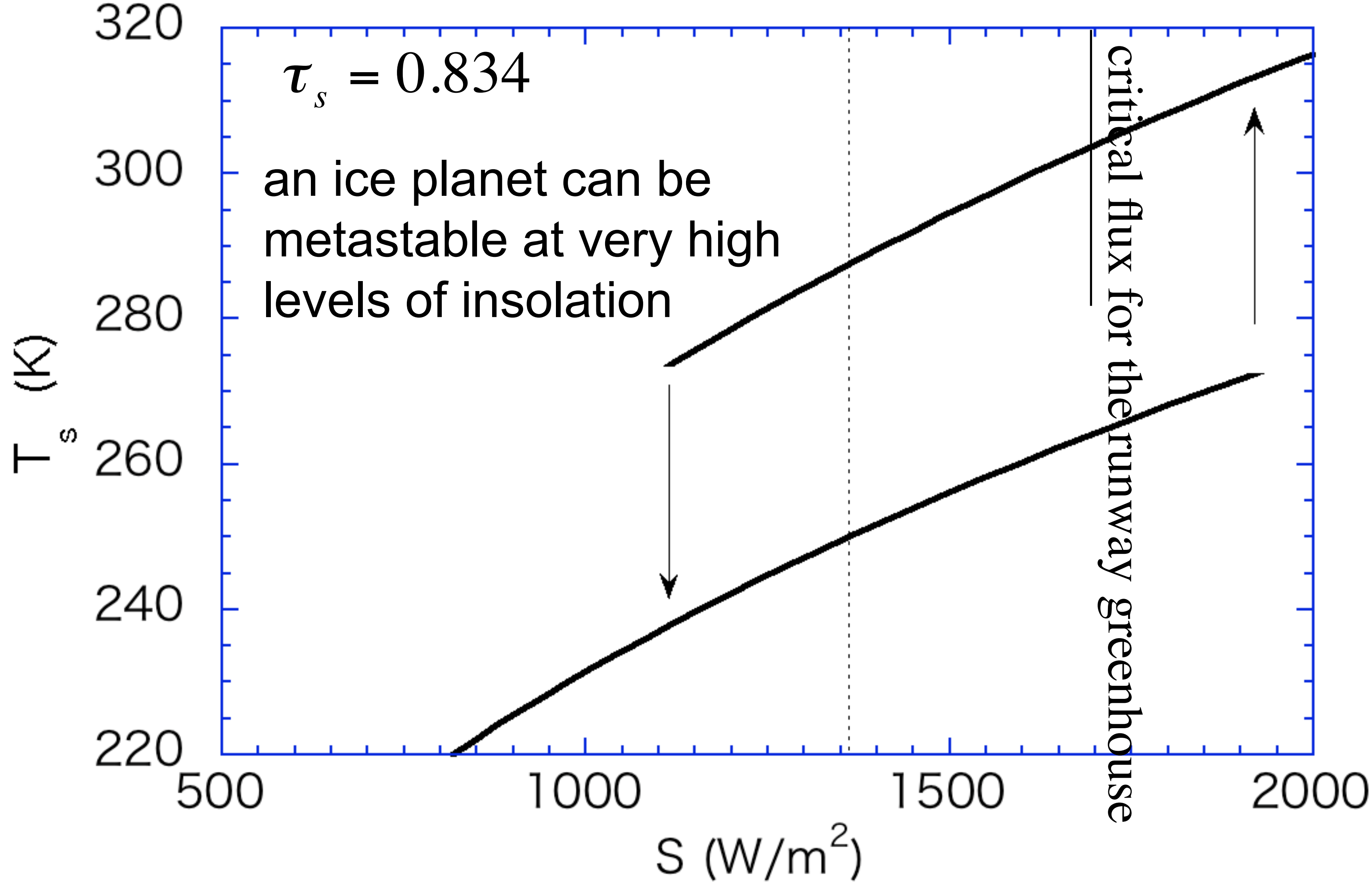
$$A = \begin{cases} 0.3 & (T_s \geq 273) \\ 0.6 & (T_s < 273) \end{cases}$$



Multiple equilibria - snowball Earth



Multiple equilibria

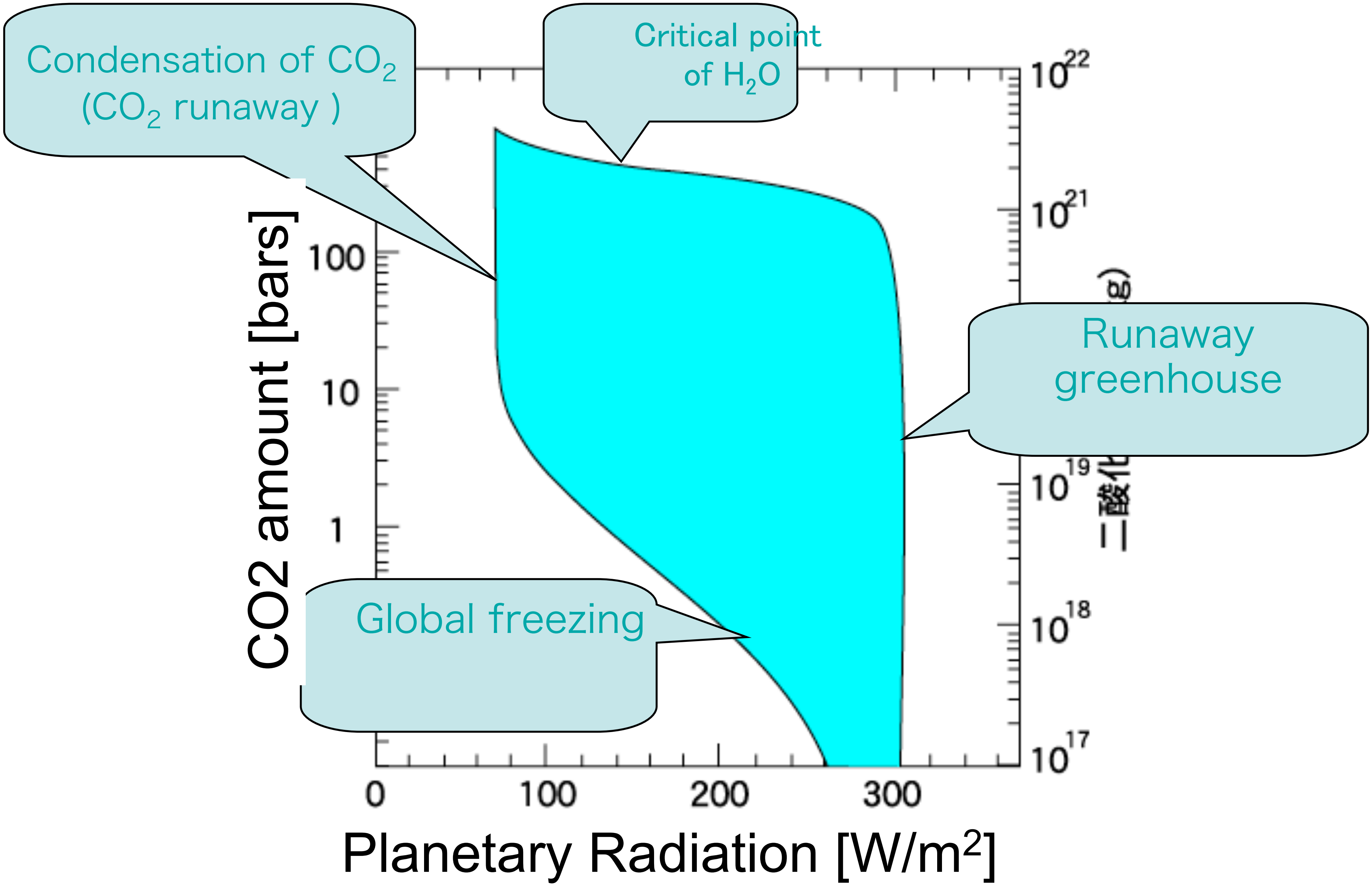


2.3 H_2O-CO_2 Planets

The HZ in 2D!

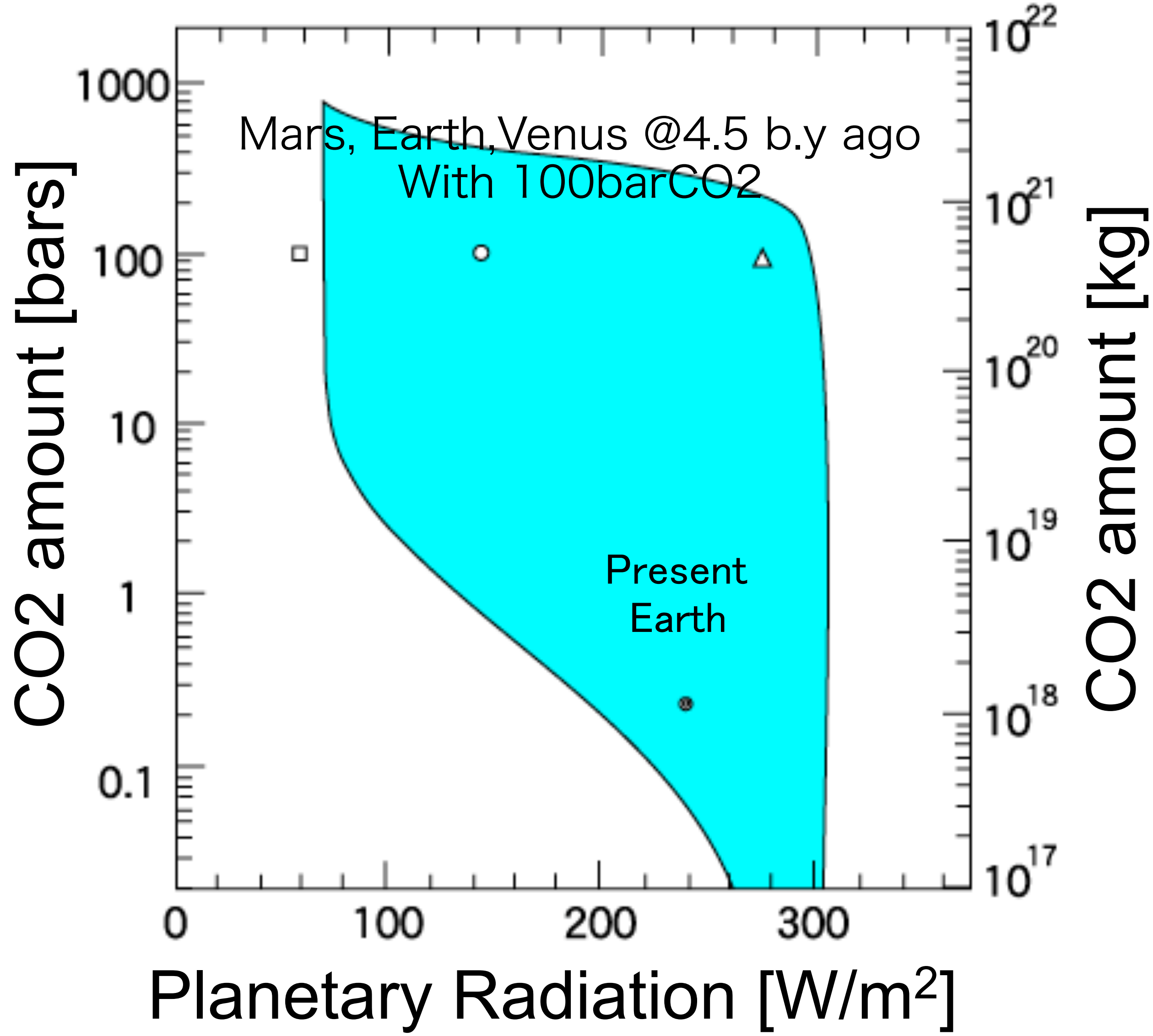
Earth is an example of an H_2O-CO_2 Planet, to first approximation

Stability regime of liquid water



Yutaka Abe (1993)

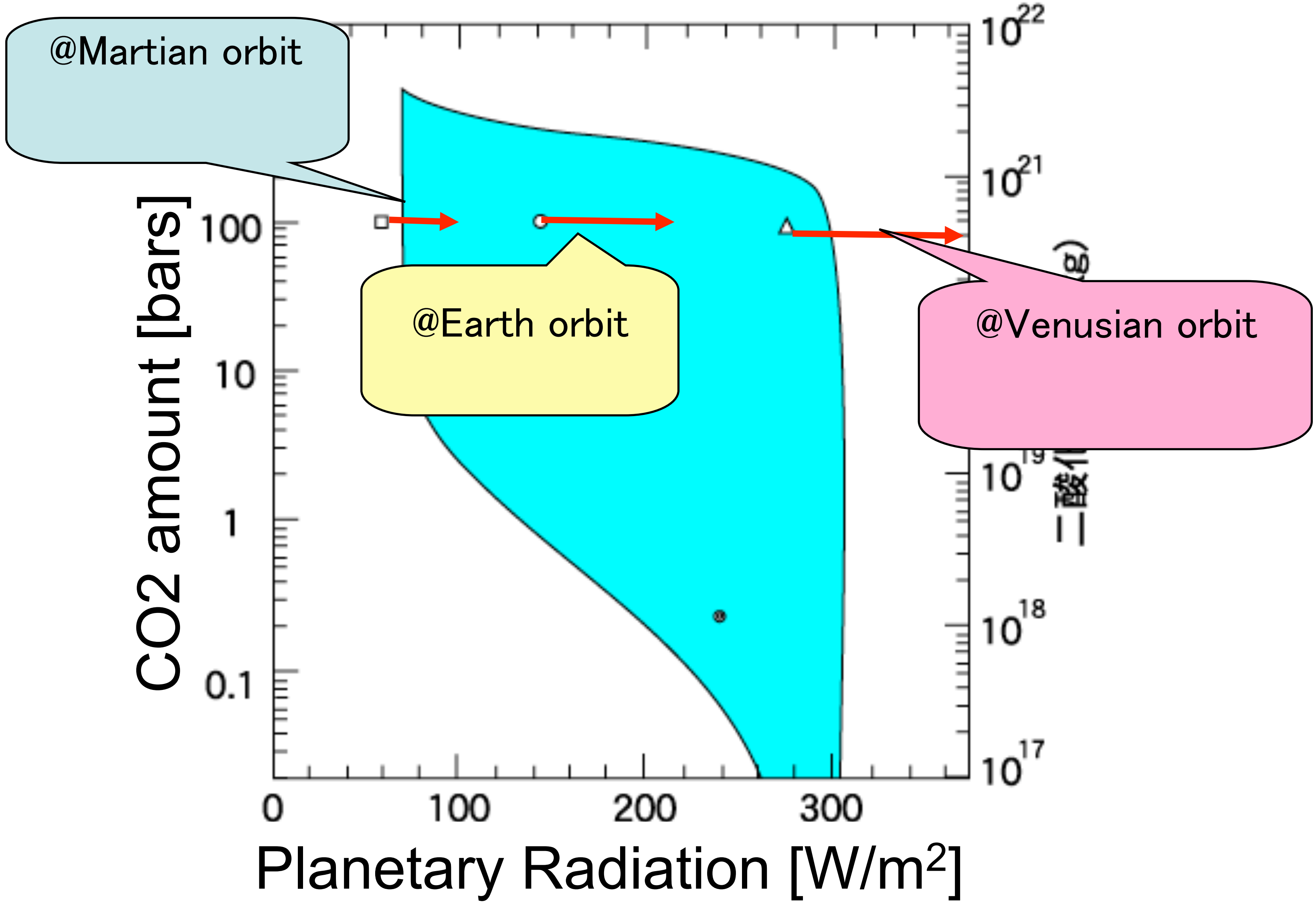
Earth-sized planet @Mars, Venus ,Earth orbit



Yutaka Abe (1993)

Evolution of the central star

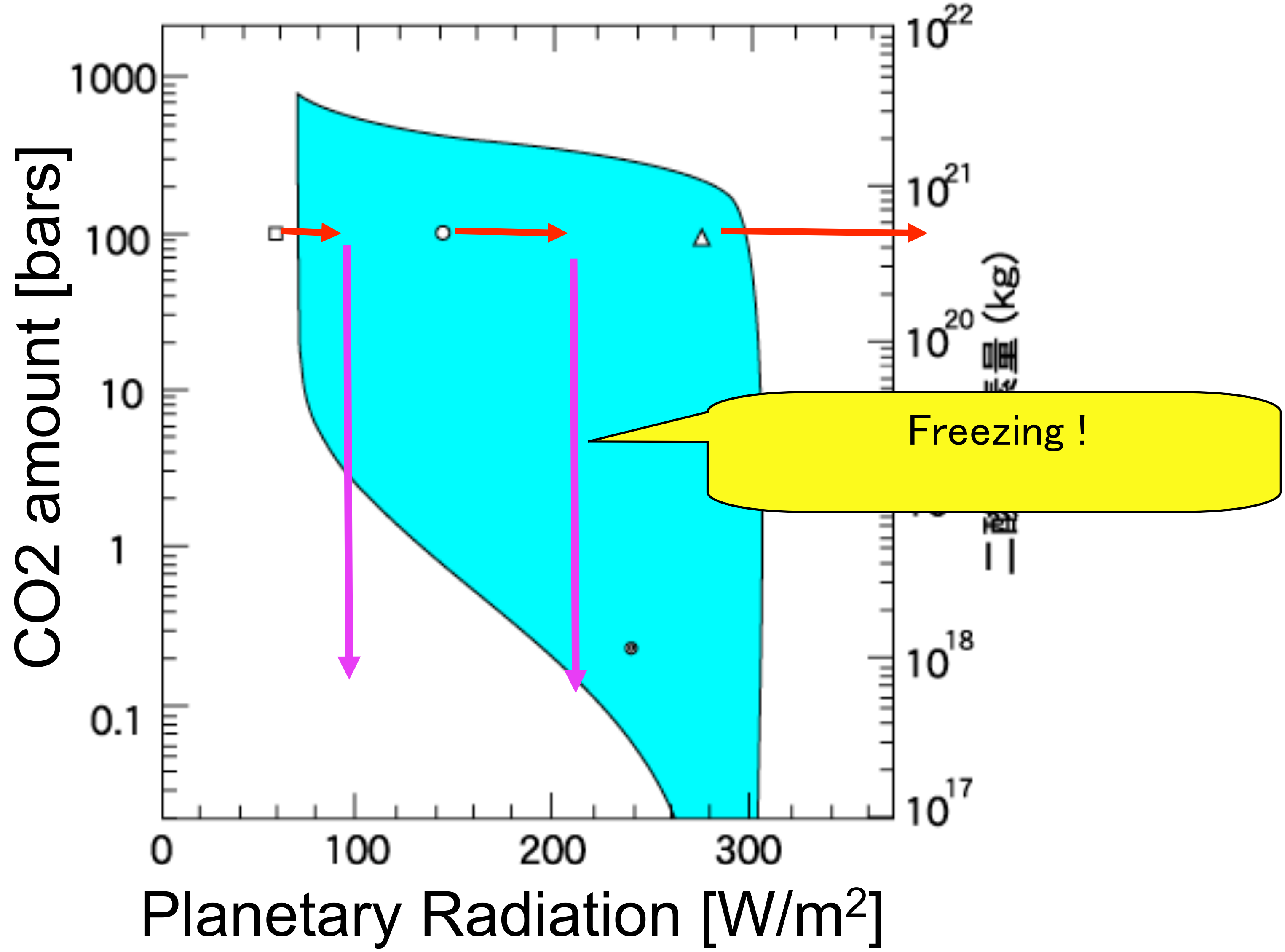
Increase of insolation: Planets move right on this diagram.



Yutaka Abe (1993)

Effect of carbonate formation

Decrease of CO2: Planets move downward on this diagram.



Yutaka Abe (1993)

3. Land Planets

Dune (Herbert 1965) is a fictional example

Titan is an example in our Solar System

“Facts” of Dune

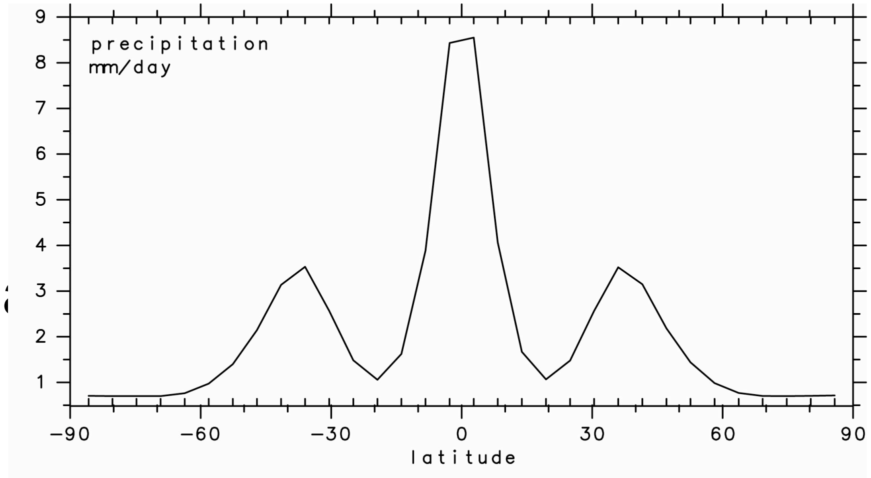
• Dune is dry!

- Dune has powerful dust storms
- There are some evaporite deposits
- Nitrogen-oxygen atmosphere
- It is sparsely habitable near the poles

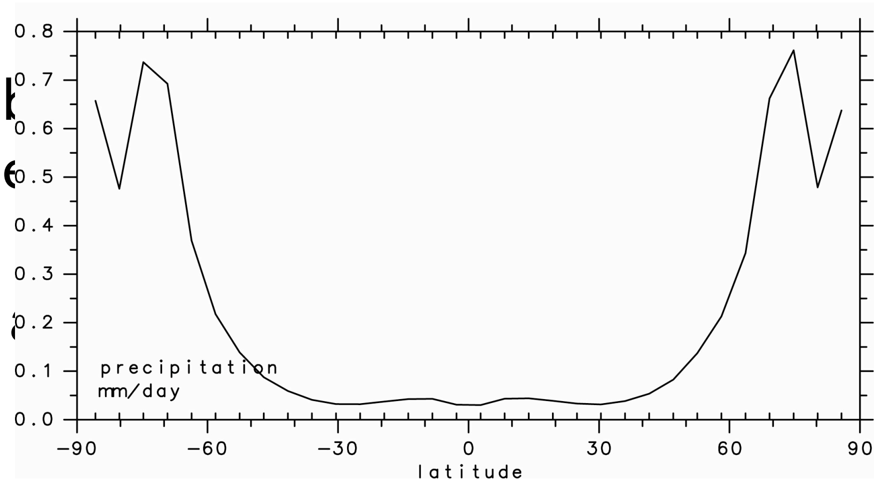
- the tropics are extremely dry
- small polar ice caps
- extensive polar aquifers
- there are polar dews

Ocean planet and Land planet

- Water Planet (ocean planet):
- A planet with a globally wet surface.
- Precipitation and evaporation are not in balance

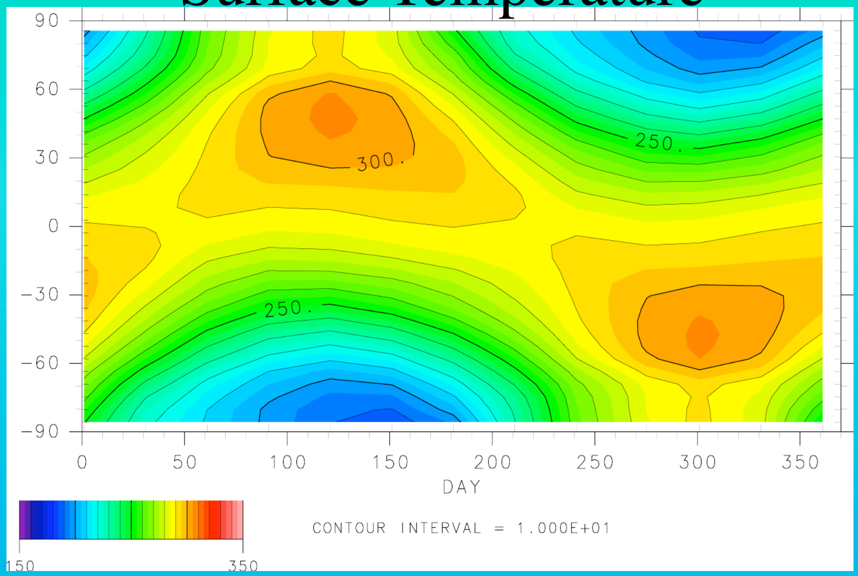


- Land Planet:
- A planet on which the surface water distribution is dominated by the atmospheric circulation (Abe et al., 2005).
- Precipitation and evaporation are in balance

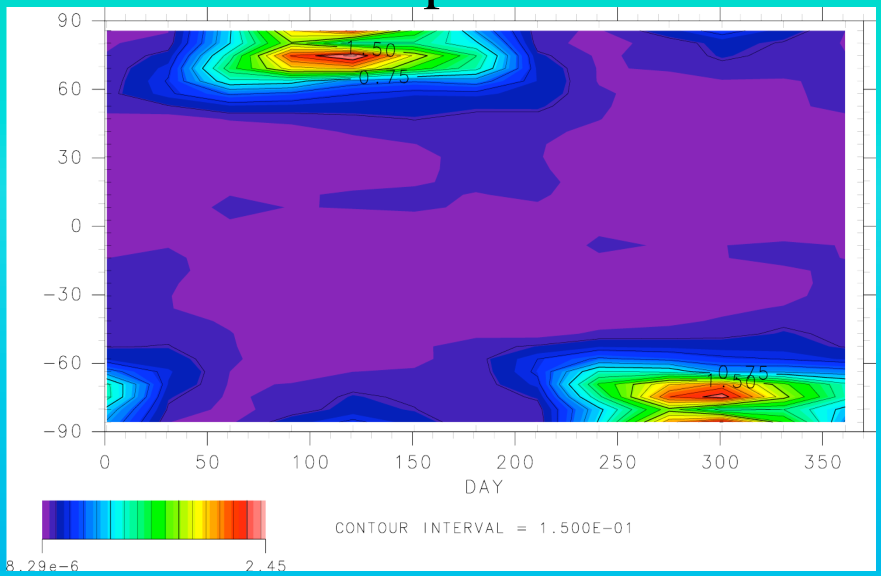


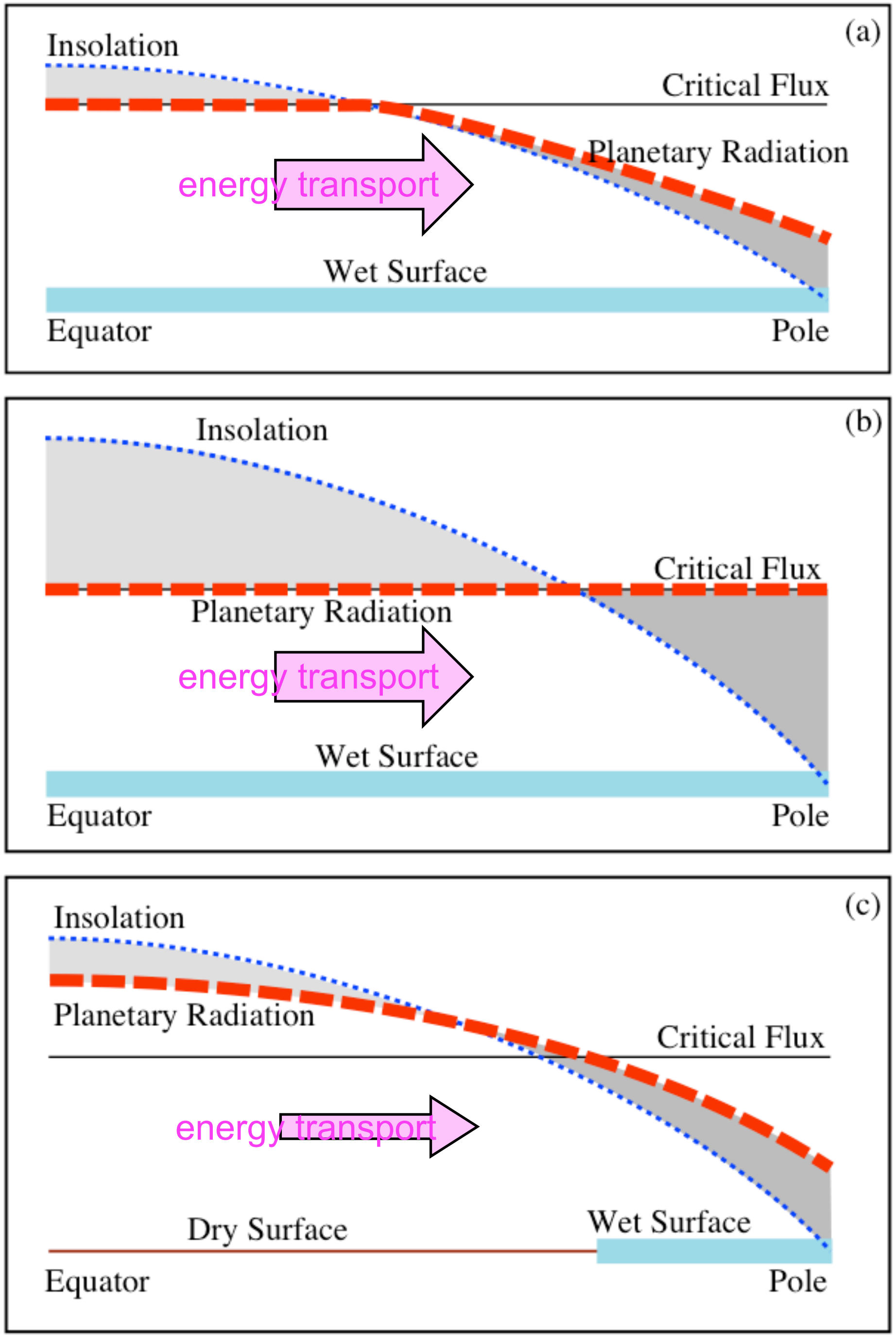
Example of A Land Planet

Surface Temperature



Precipitation





Earth: tropics are stabilized by heat transport to the poles

Ocean planet: runs away when poles cannot radiate all the heat that comes from the tropics

Land planet can radiate more efficiently from dry tropics - poles stay habitable

Abe & Abe-Ouchi 2005

Some idealized GCM experiments by Professor Abe

Model

A general circulation model, CCSR/NIES AGCM 5.4g (T21L11 and T21L20) (Numaguti, 1999)

An Earth-sized planet with 1 bar air atmosphere on a circular orbit.

- Fixed CO_2 concentration. (345 ppm)
- Spin period (= a "day") is 24 hours
- Revolution period around the Sun (= a "year") is 360 days.
- Obliquity =0 °

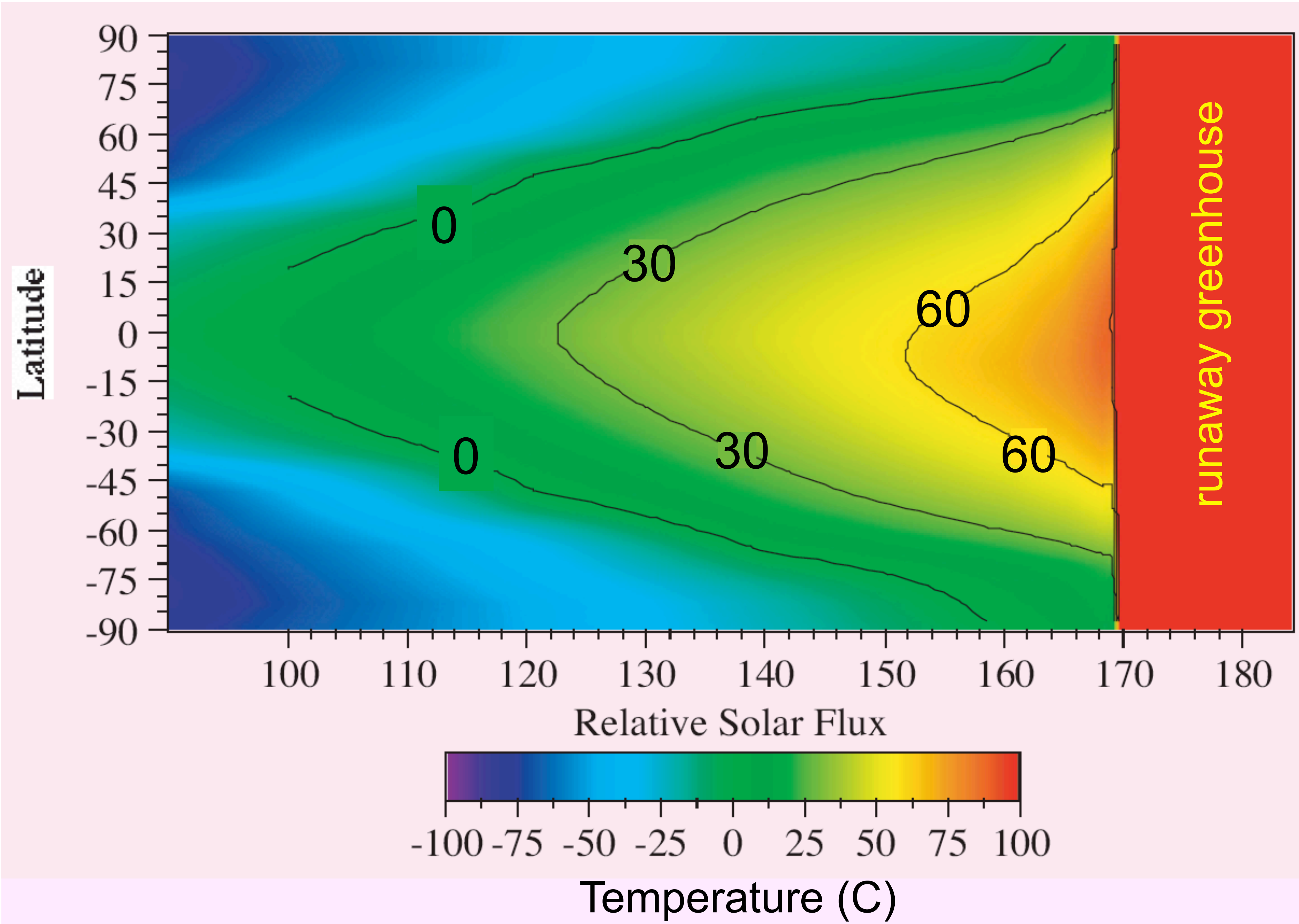
Land Planet:

- Surface paremters of desert (ground albedo 0.3), No topography.
- A bucket model with the saturation depth of 10 cm
- No ground water transport: atmospheric controll of water distribution

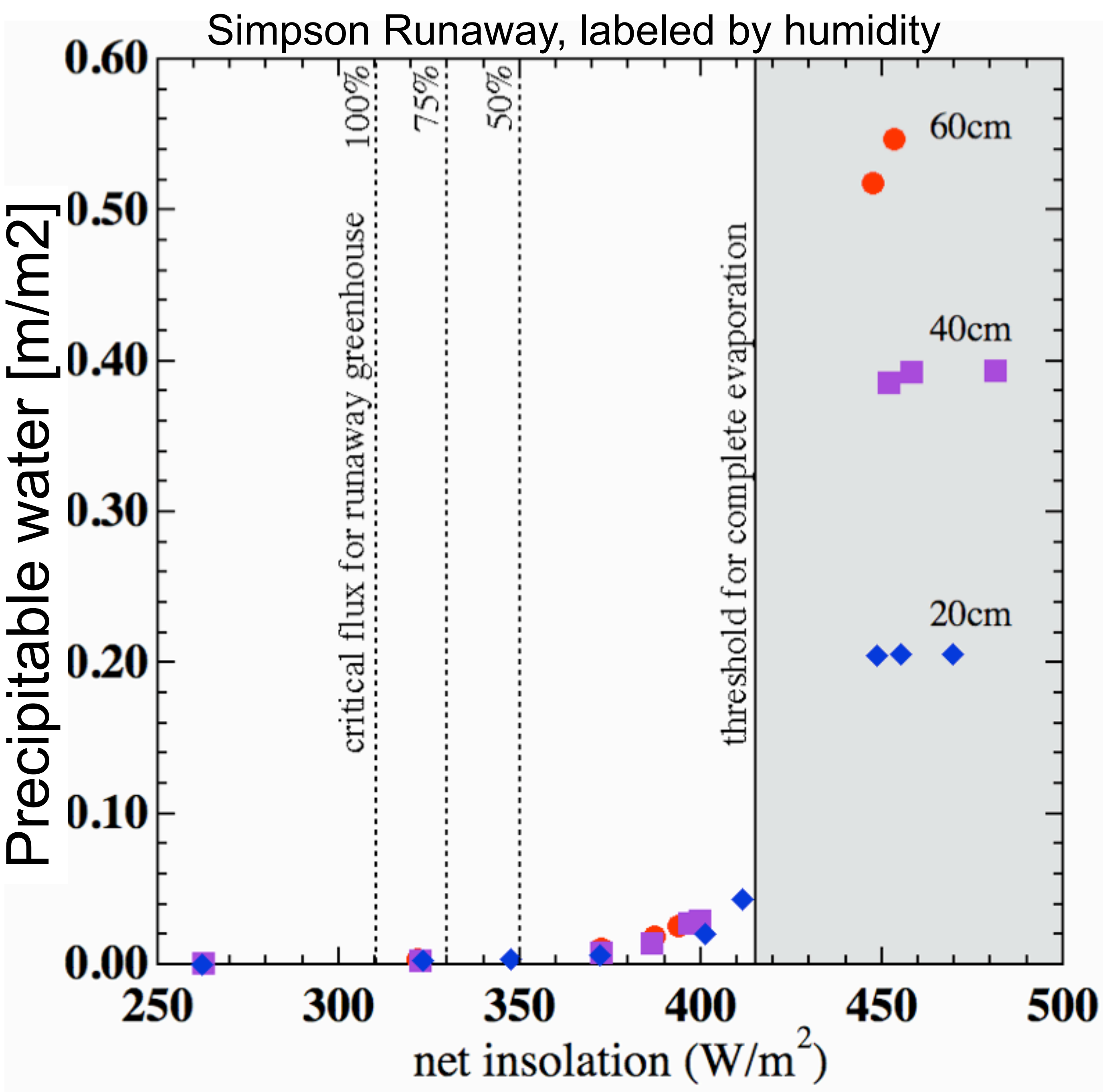
Ocean Planet:

- 50m slab ocean

More than 100 cases are examined with various solar flux.

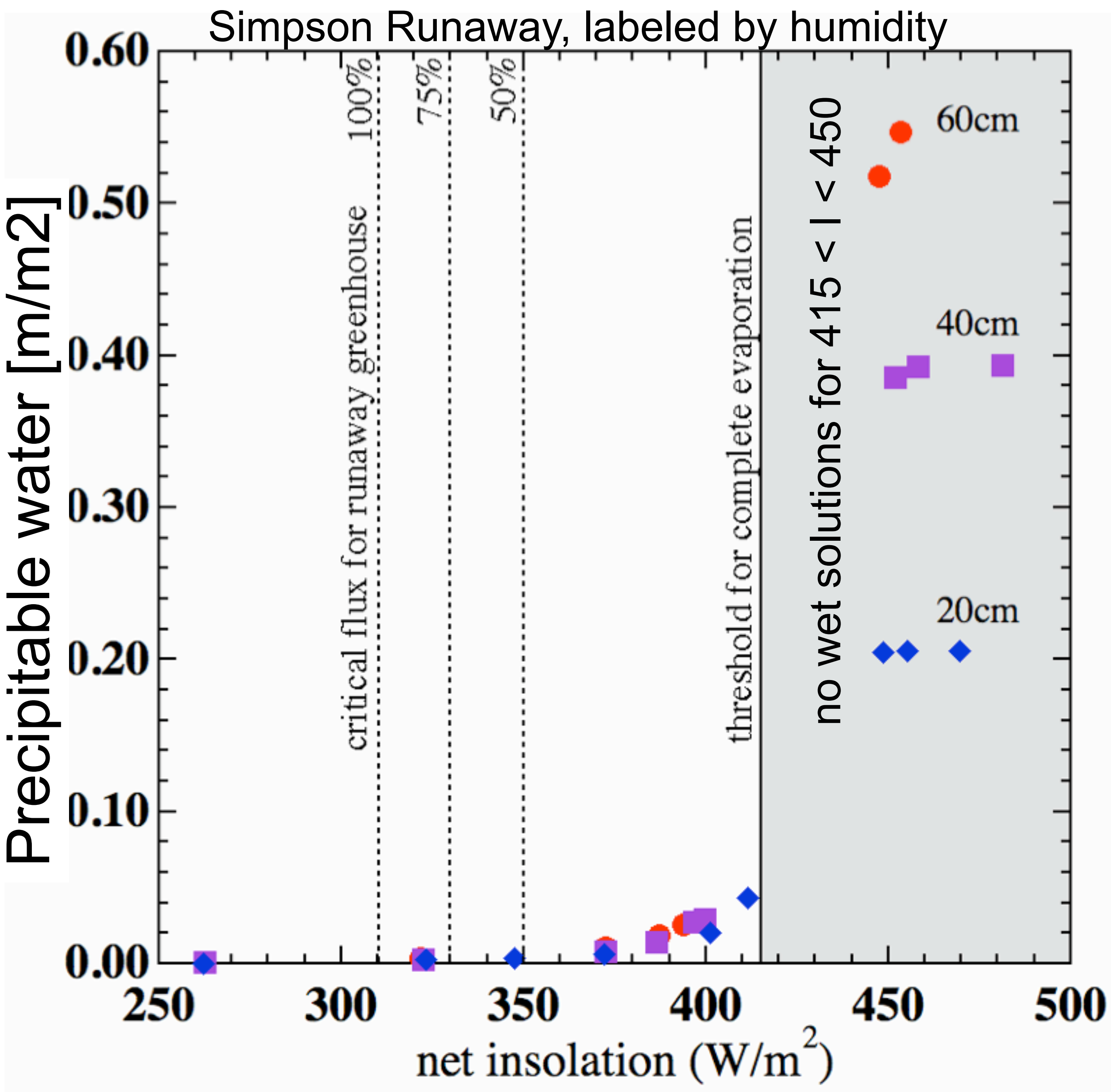


90
75
60
45
30
15
0
-15
-30
-45
-60
-75
-90
Latitude
0
30
60
0
30
60
runaway greenhouse
100
110
120
130
140
150
160
170
180
Relative Solar Flux
-100
-75
-50
-25
0
25
50
75
100
Temperature (C)



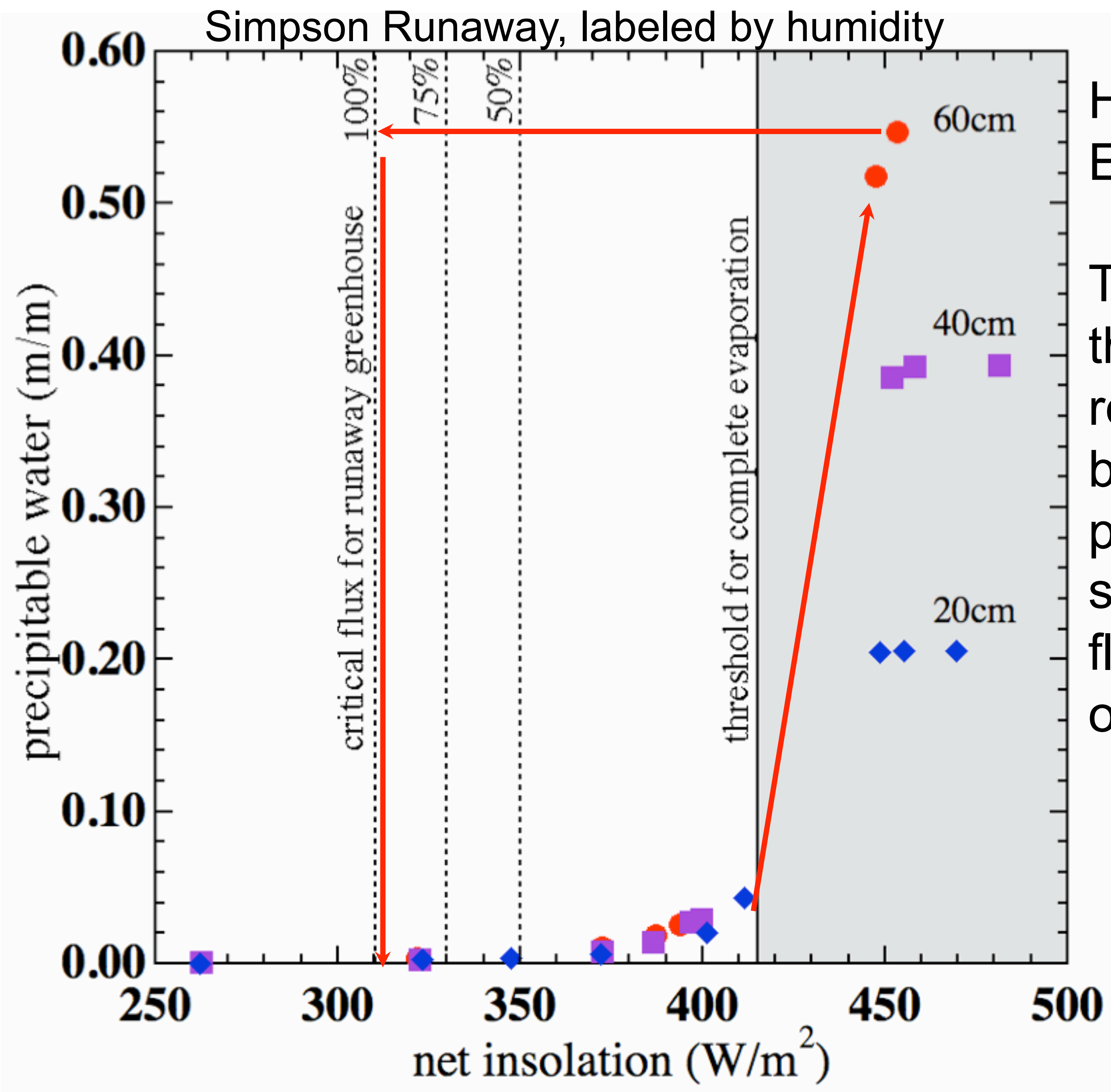
Land planet is more stable at high insolation than ocean planet

Abe & Abe-Ouchi 2005



The discontinuity from 415 W/m² to 450 W/m² is caused by an albedo jump: clouds and polar caps disappear

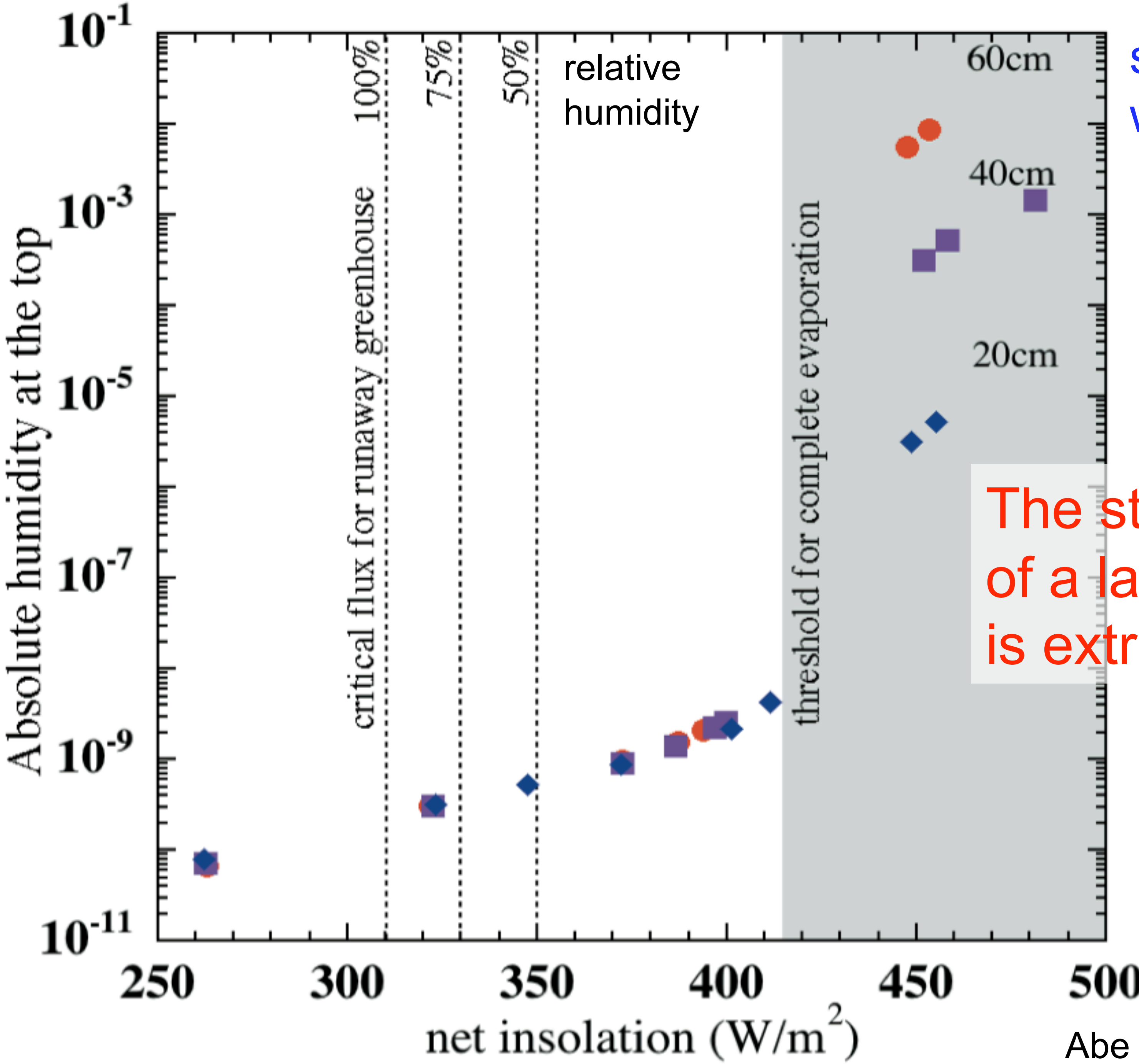
Abe & Abe-Ouchi 2005



Hysteresis Effect:

To condense the water requires bringing the planet to the same critical flux as an ocean planet

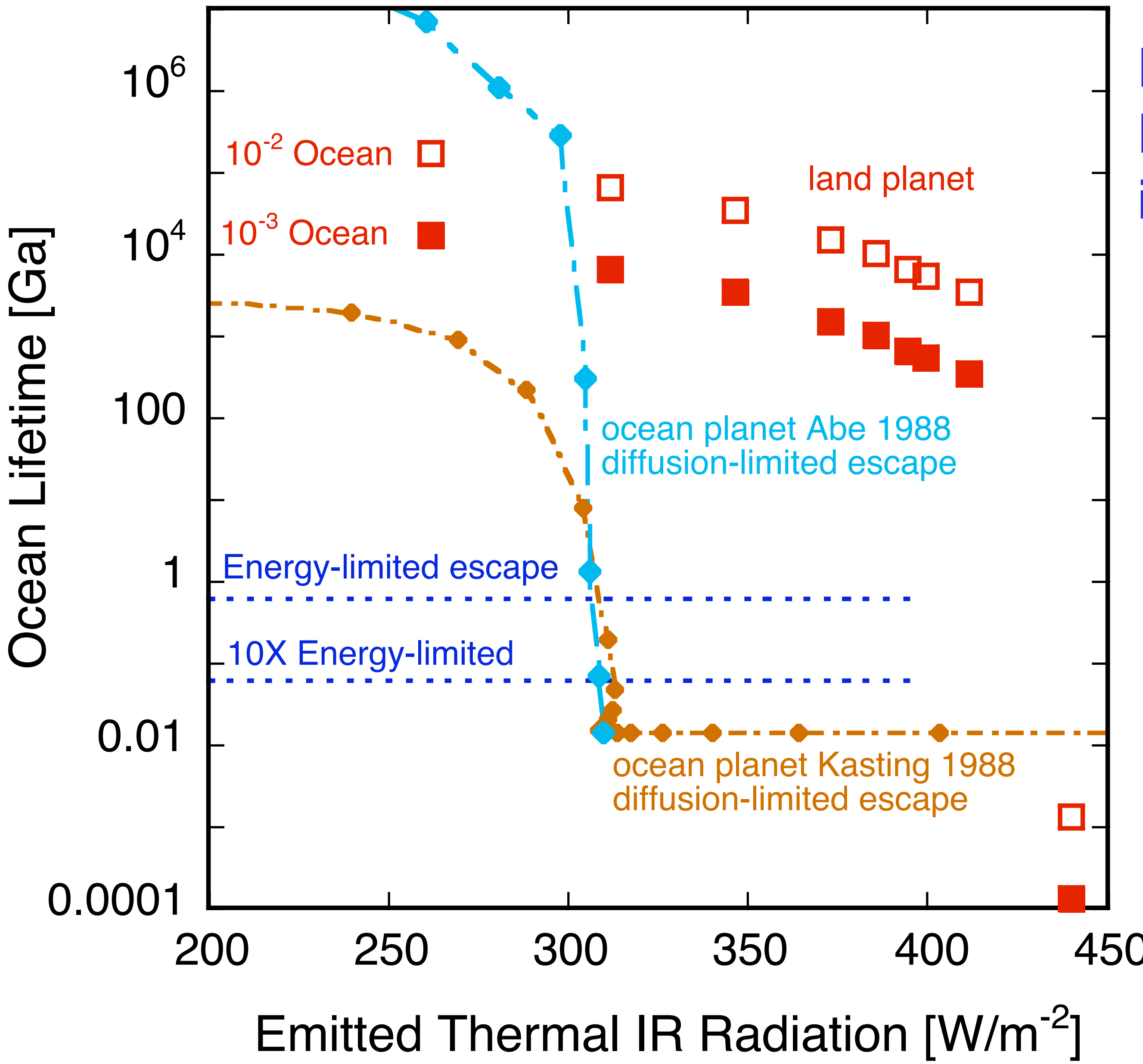
Abe & Abe-Ouchi 2005



stratospheric water vapor

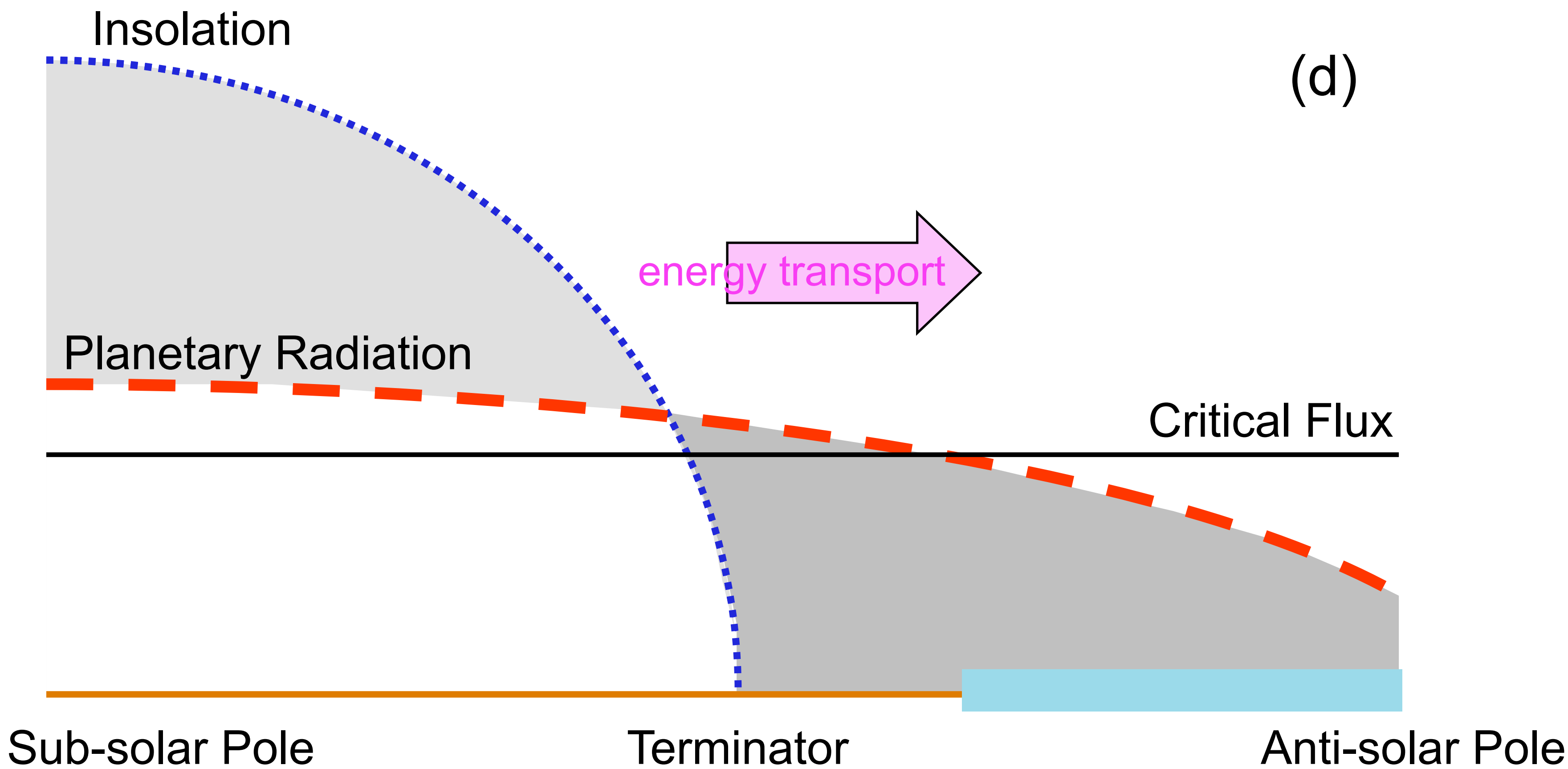
The stratosphere of a land planet is extremely dry

Abe & Abe-Ouchi 2005



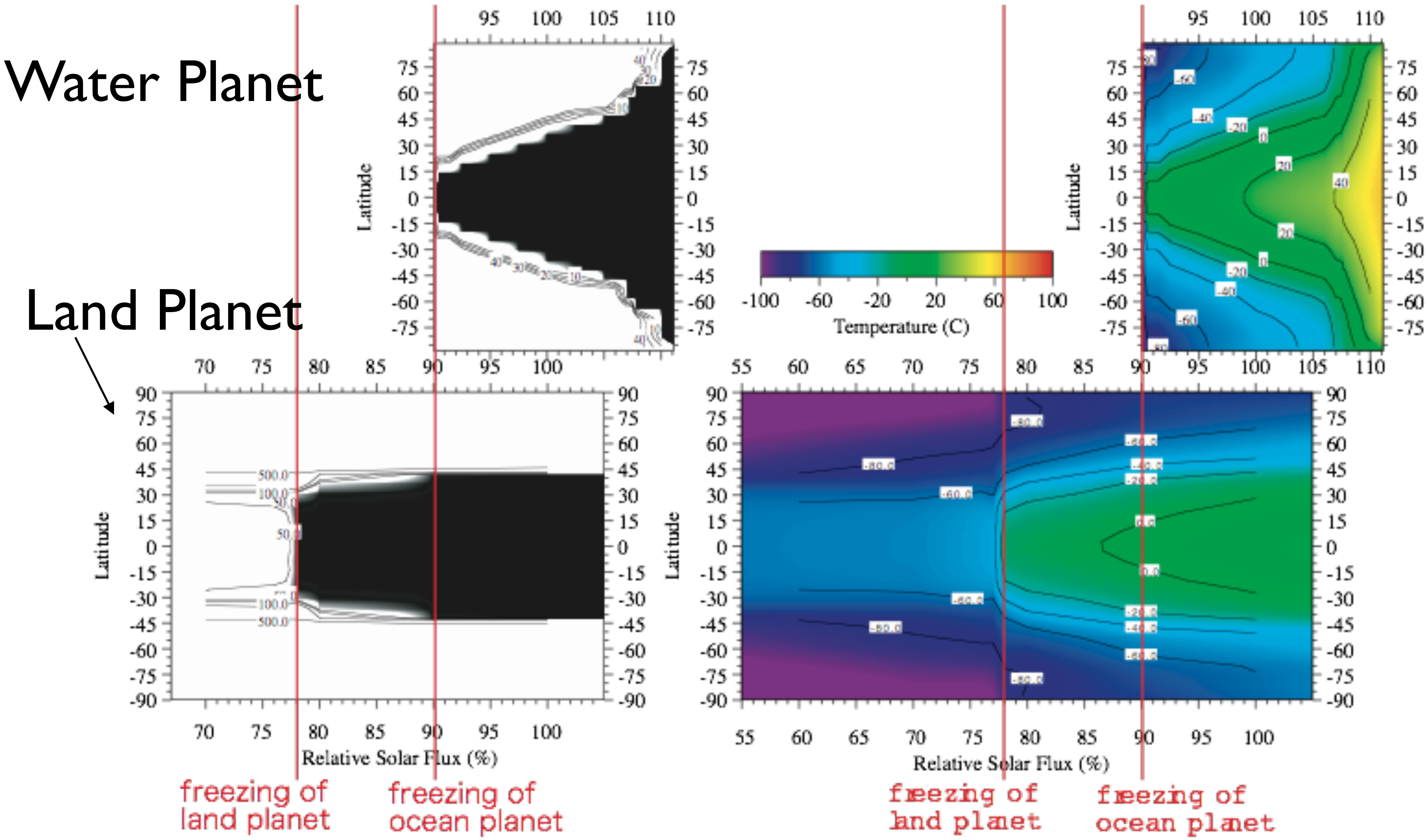
Hydrogen Escape is inhibited

Land planets are stable against H escape



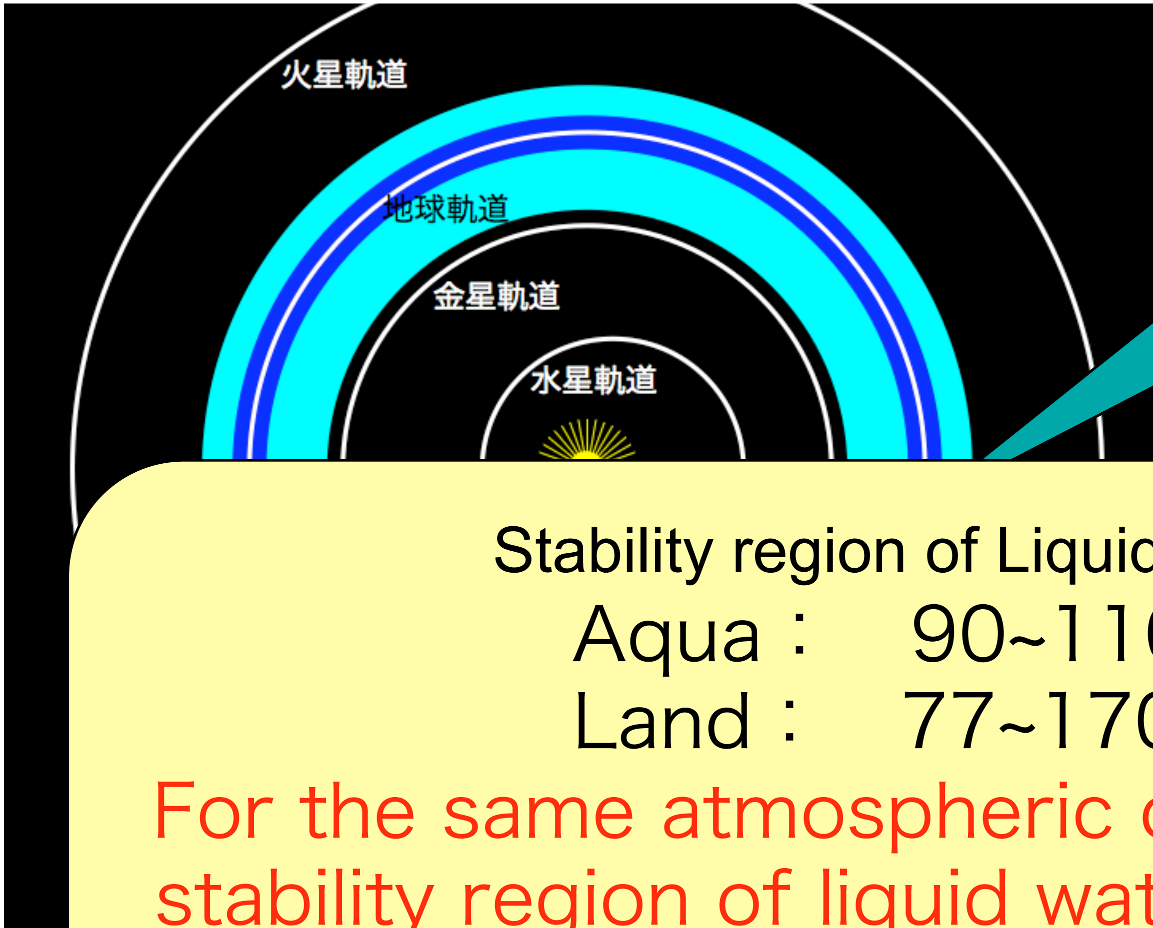
A dry synchronous M-dwarf planet is another form of land planet: the dry hemisphere radiates away most of the sunlight

3.2 Different Freezing limits, too



Land planets are harder to freeze than water planets.

3.3 Land Planet vs Water Planet



Stability region of Liquid water

Aqua Planet

Land Planet

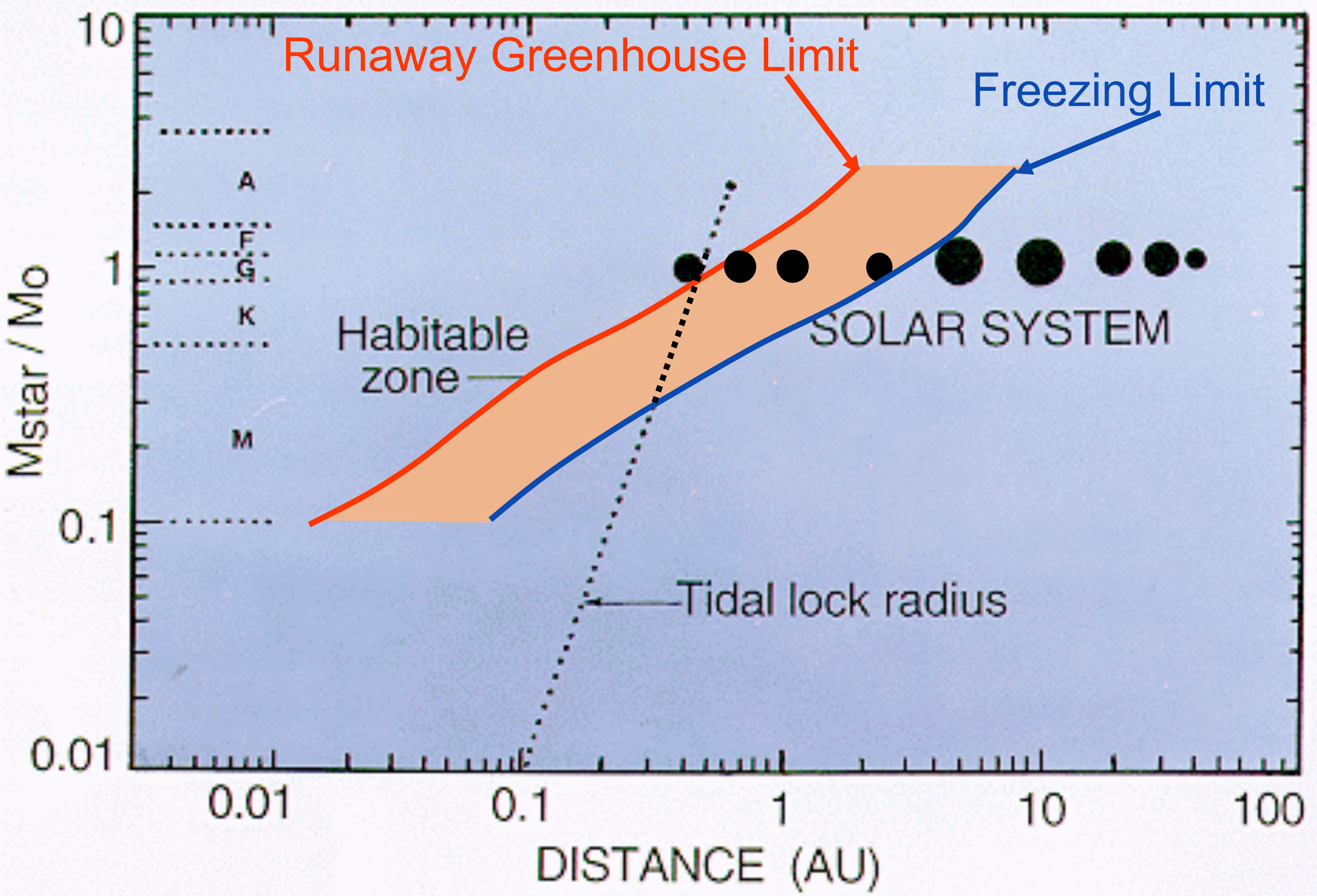
Stability region of Liquid water

Aqua： 90~110%

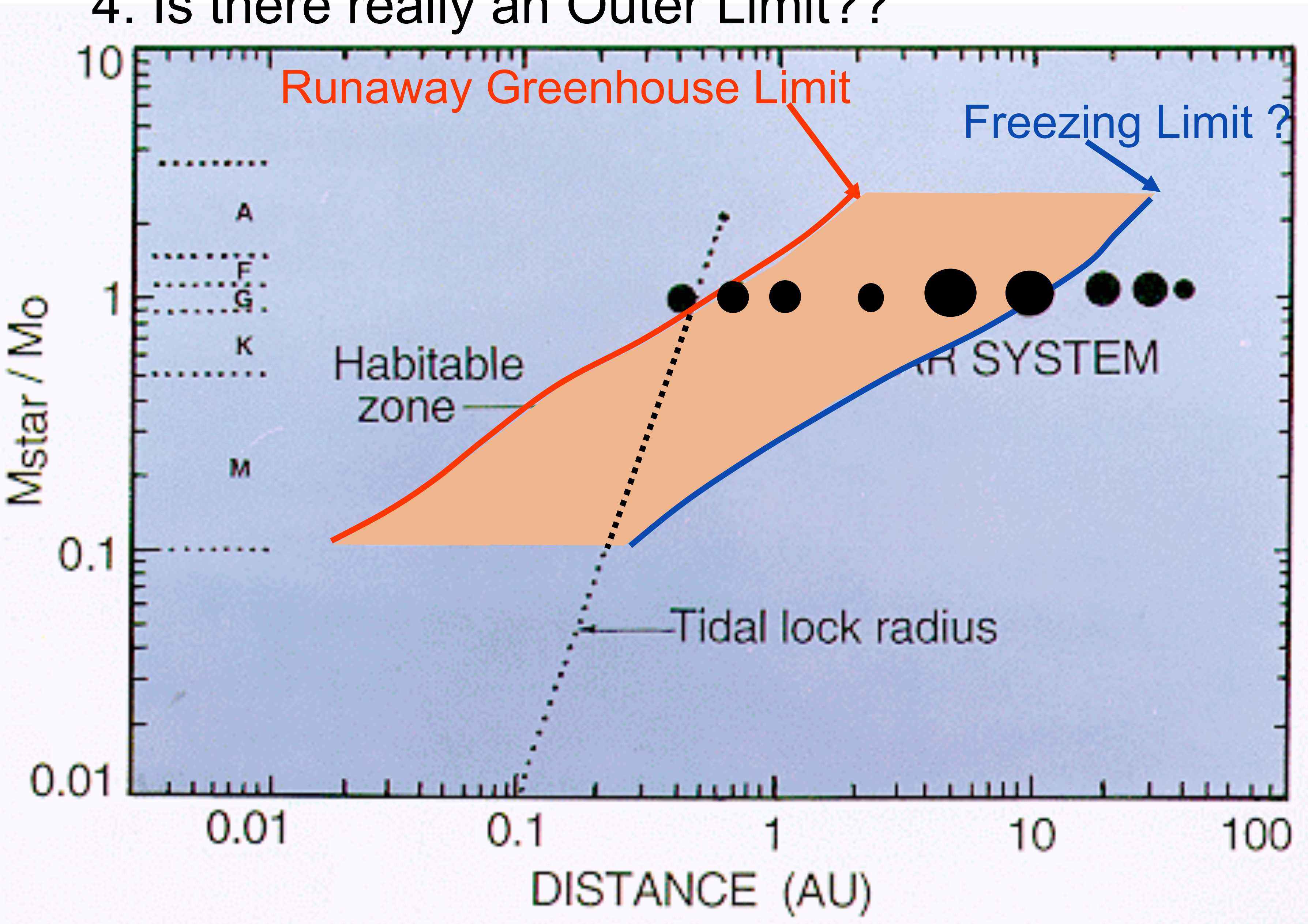
Land： 77~170%

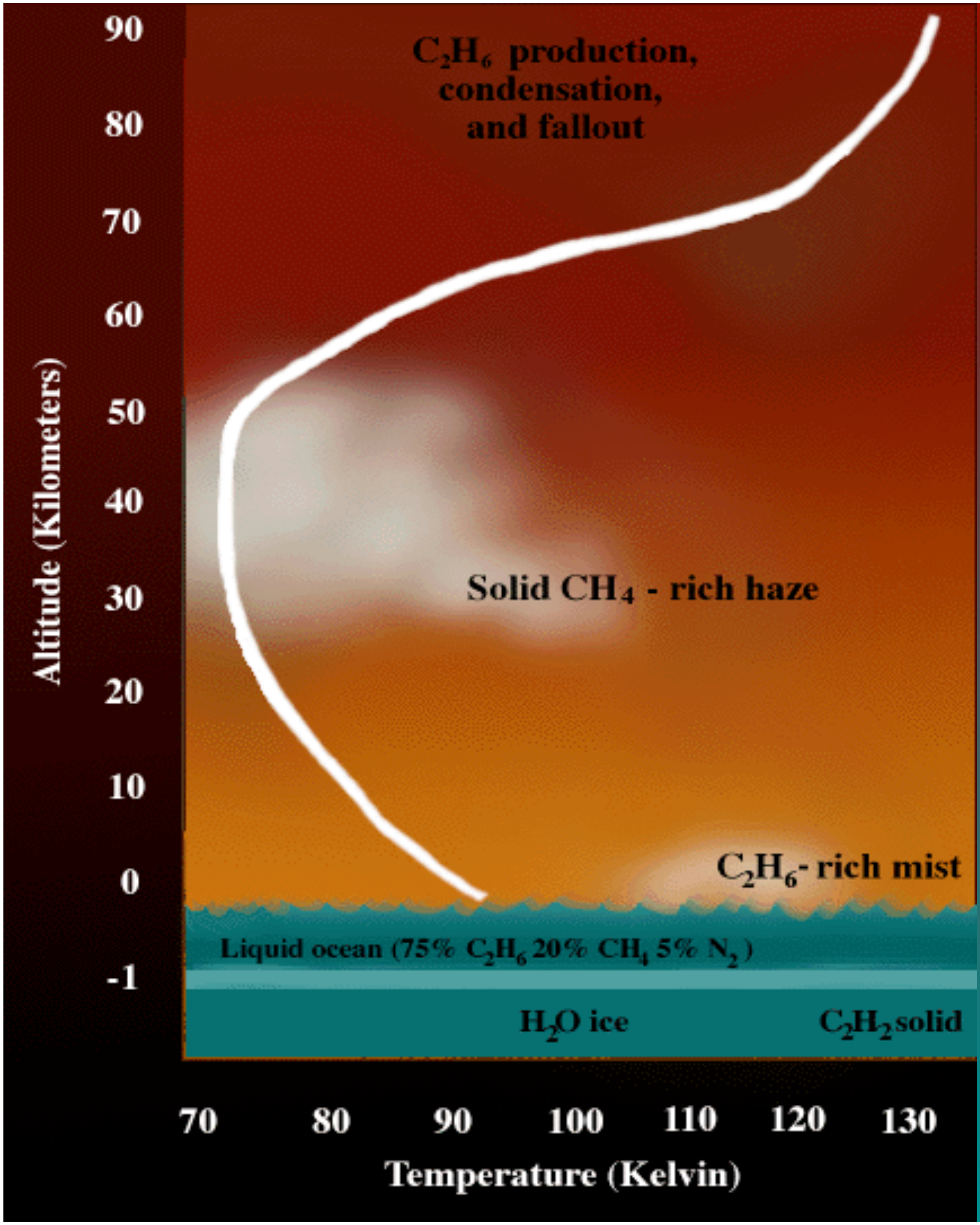
For the same atmospheric conditions, the stability region of liquid water is narrower for Aqua planet than Land planet ~ by factor 3 !!

The Land Planet HZ



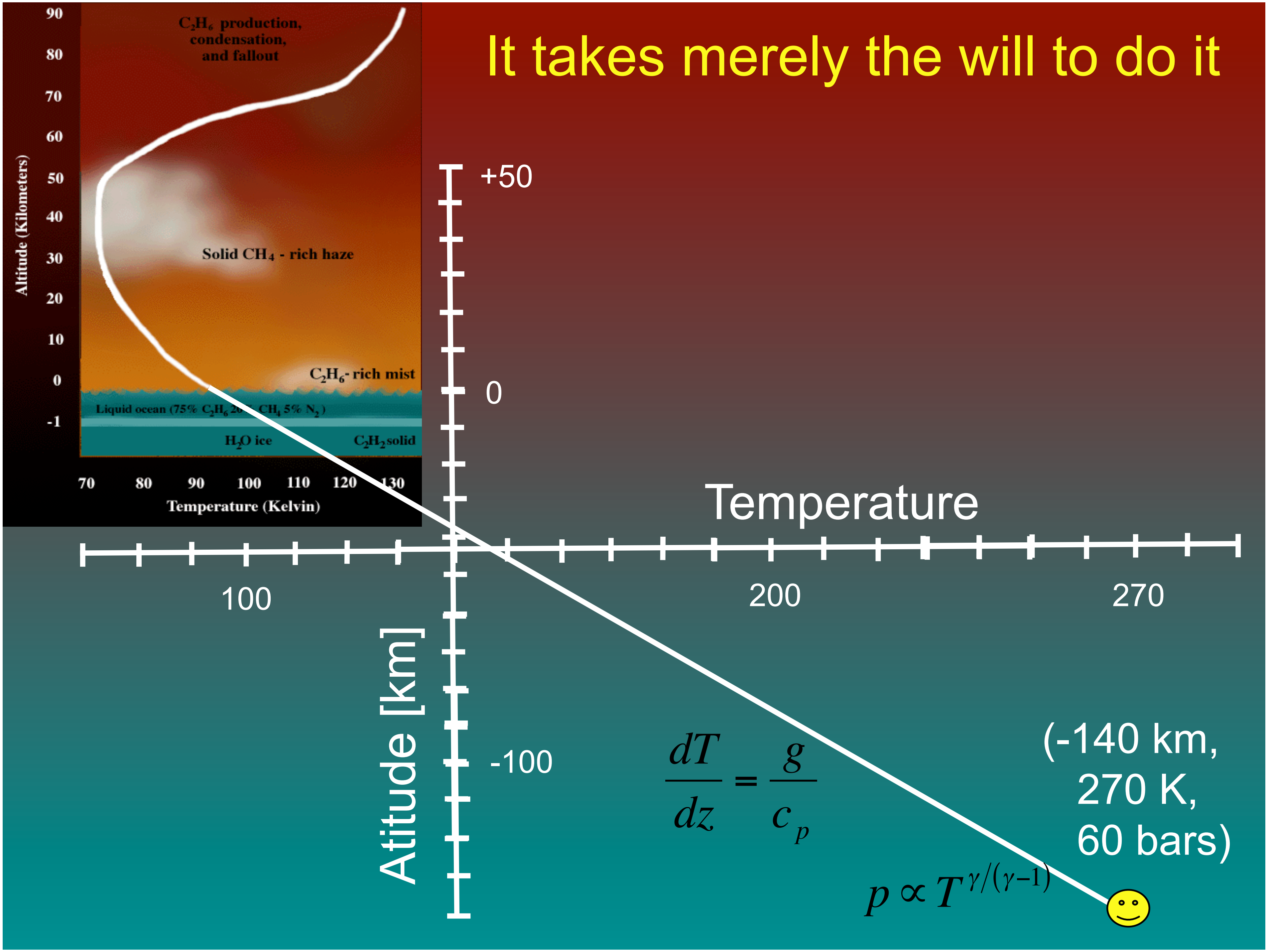
4. Is there really an Outer Limit??





Titan

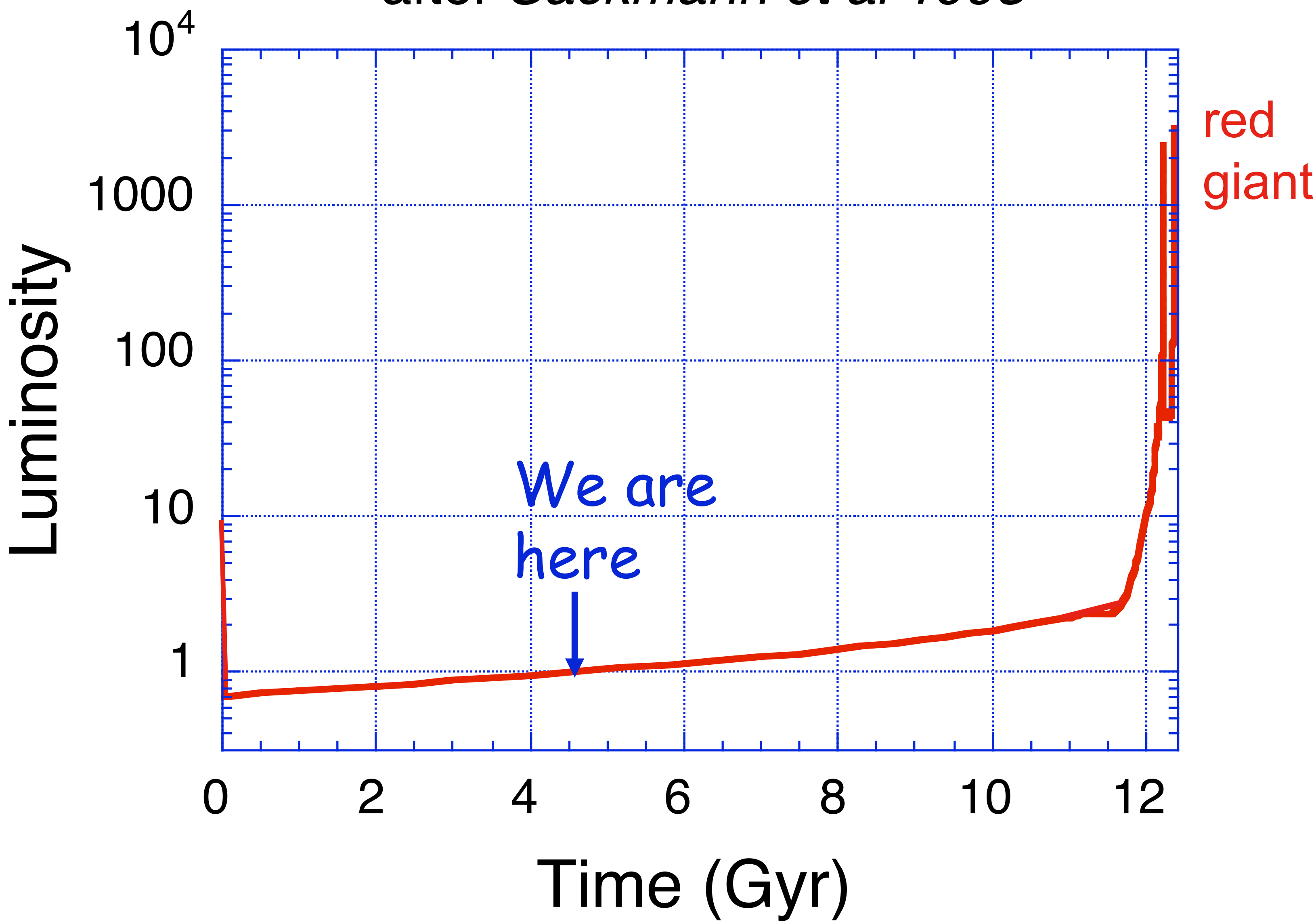
Temperature profile

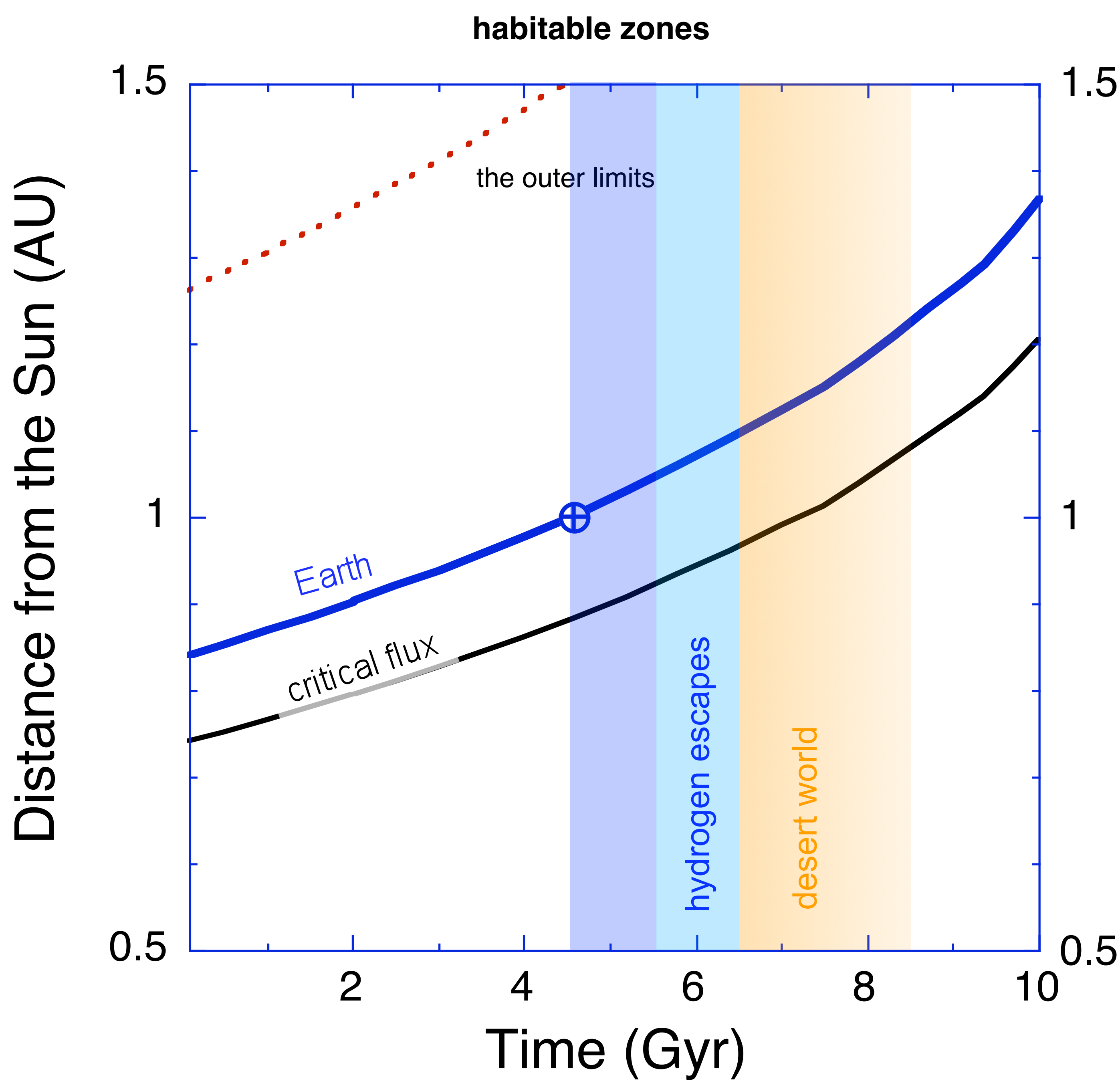


It takes merely the will to do it
C2H6 production, condensation, and fallout
Solid CH4 - rich haze
C2H6- rich mist
Liquid ocean (75% C2H6 20% CH4 5% N2)
H2O ice
C2H2 solid
Altitude (Kilometers)
90
80
70
60
50
40
30
20
10
0
-1
70 80 90 100 110 120 130
Temperature (Kelvin)
+50
0
-100
Temperature
100
200
270
Atitude [km]
$\frac{dT}{dz} = \frac{g}{c_p}$
$p \propto T^{\gamma/(\gamma-1)}$
(-140 km, 270 K, 60 bars)

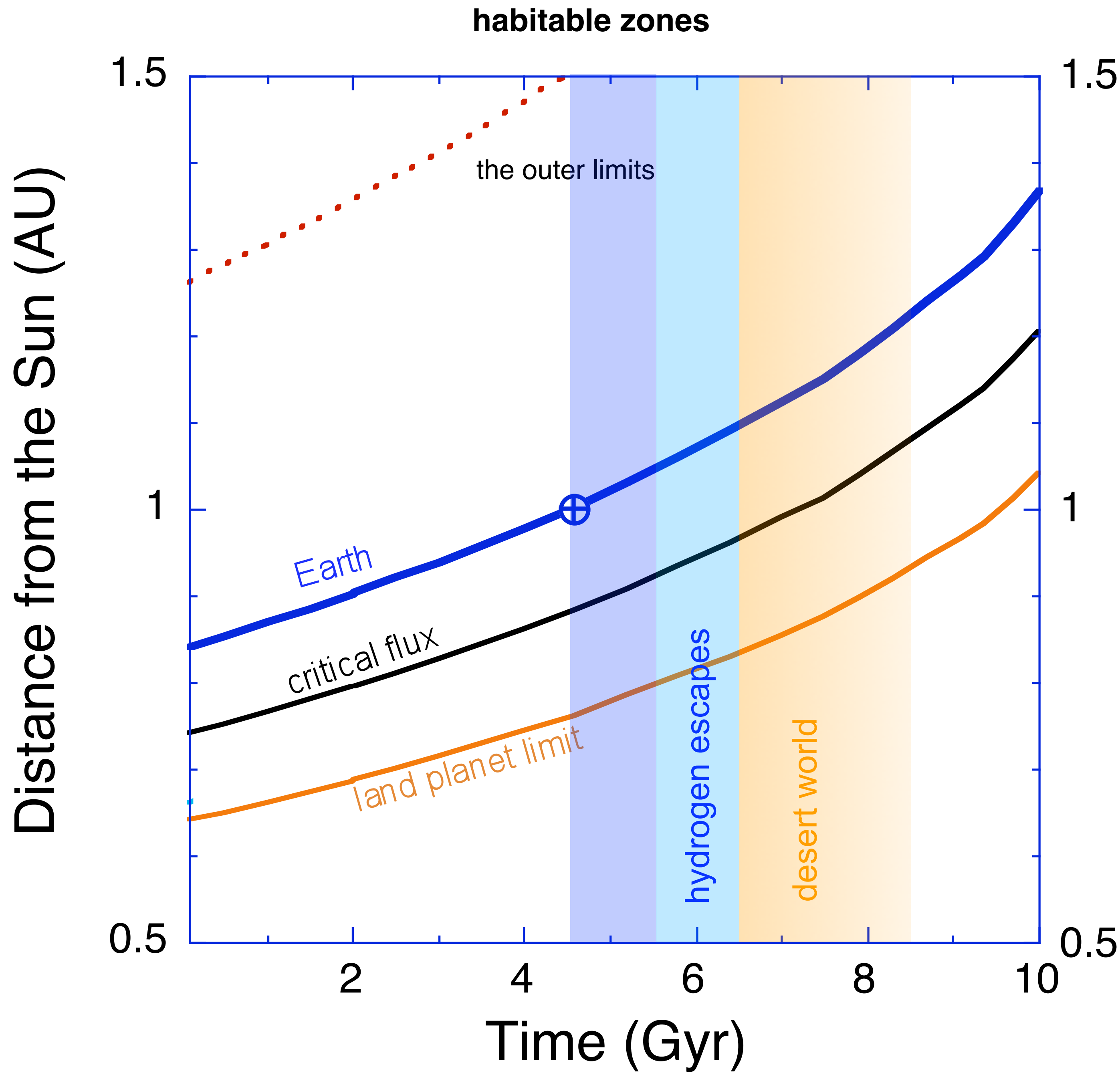
5. The Evolving Sun

after *Sackmann et al 1993*



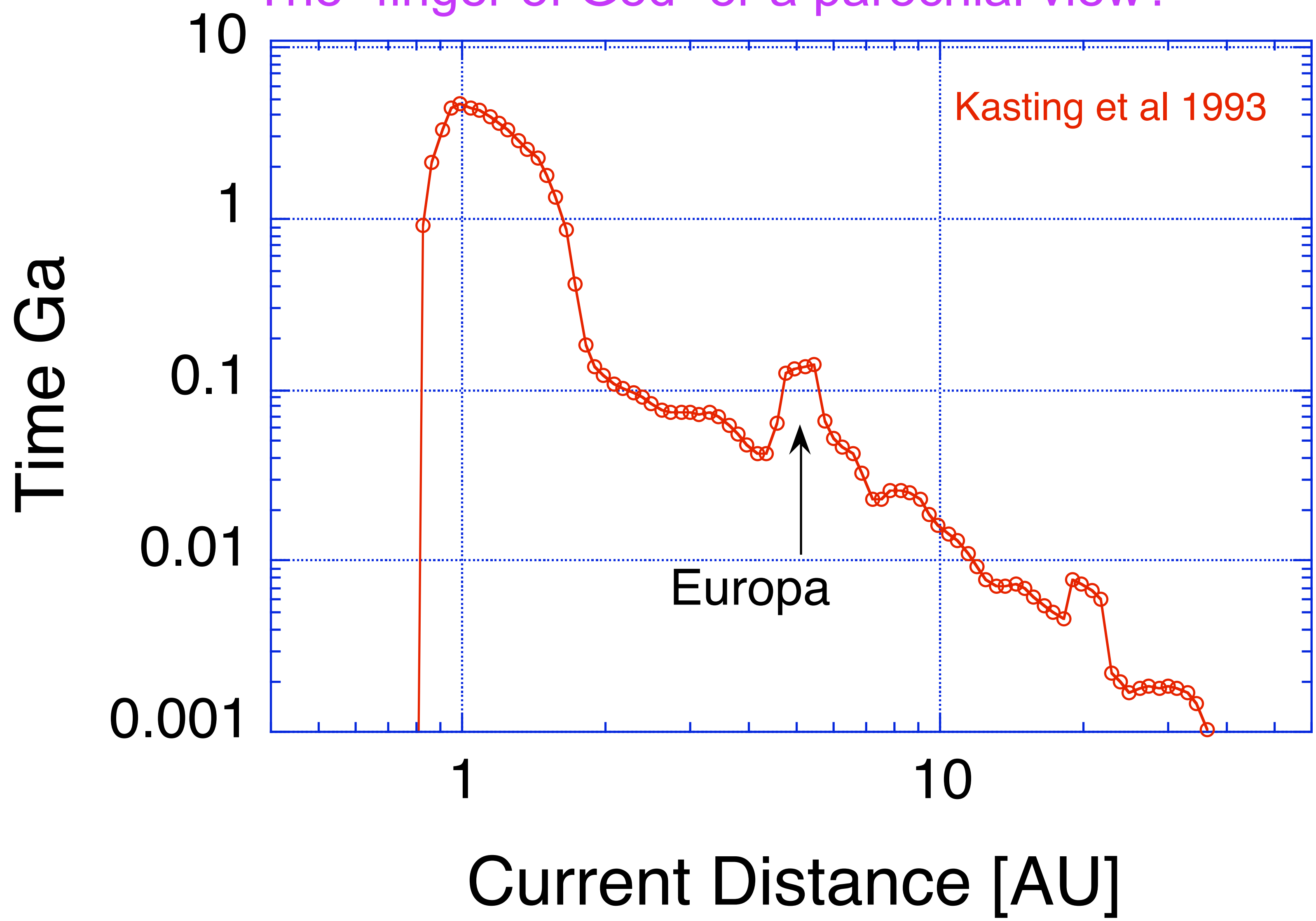


habitable zones
1.5
1
0.5
1.5
1
0.5
2
4
6
8
10
Time (Gyr)
Distance from the Sun (AU)
the outer limits
Earth
critical flux
hydrogen escapes
desert world



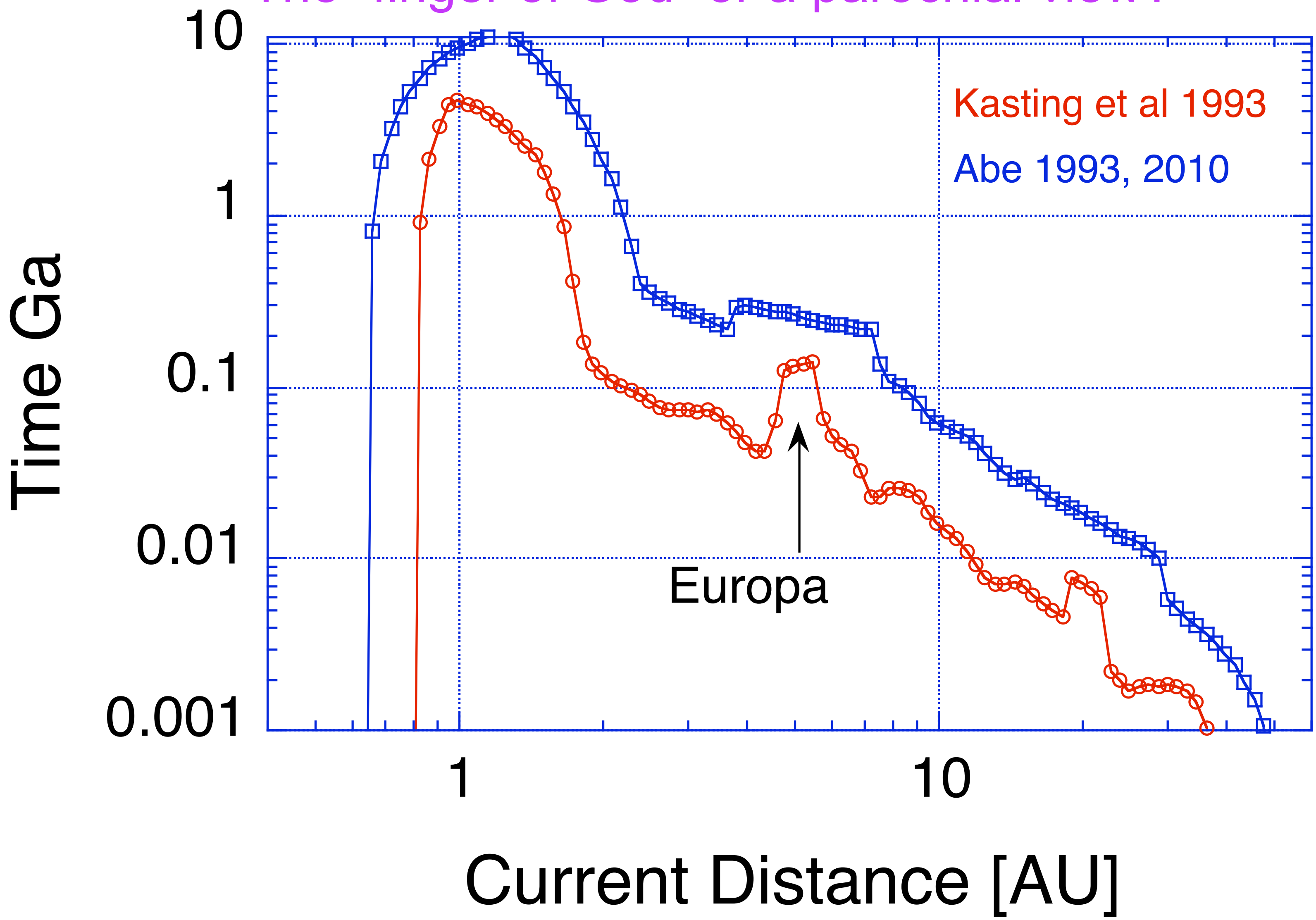
habitable zones
1.5
1
0.5
1.5
1
0.5
2
4
6
8
10
Time (Gyr)
Distance from the Sun (AU)
the outer limits
Earth
critical flux
land planet limit
hydrogen escapes
desert world

The “finger of God” or a parochial view?



How long a planet at a given current distance from the Sun remains "habitable."

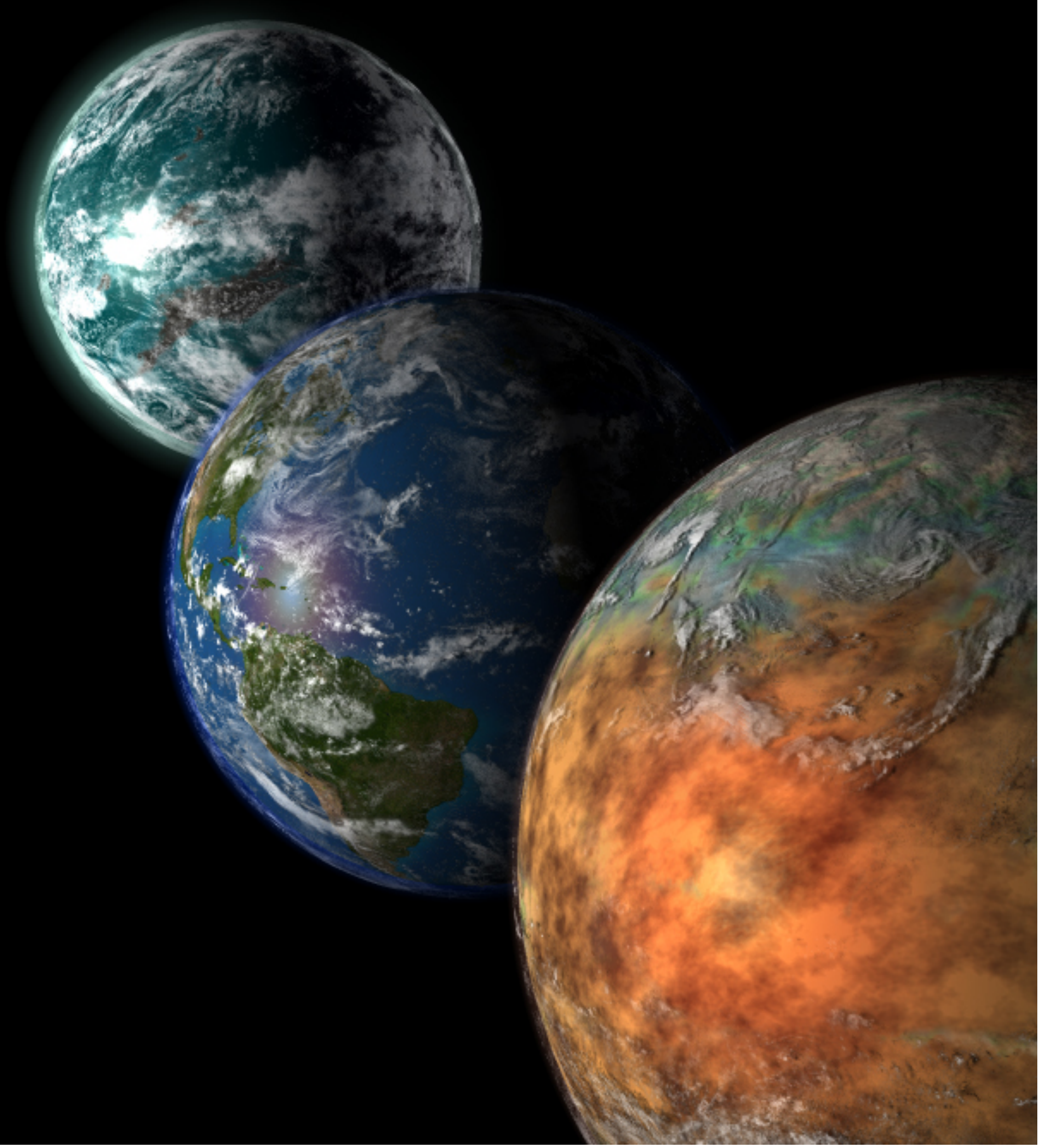
The "finger of God" or a parochial view?



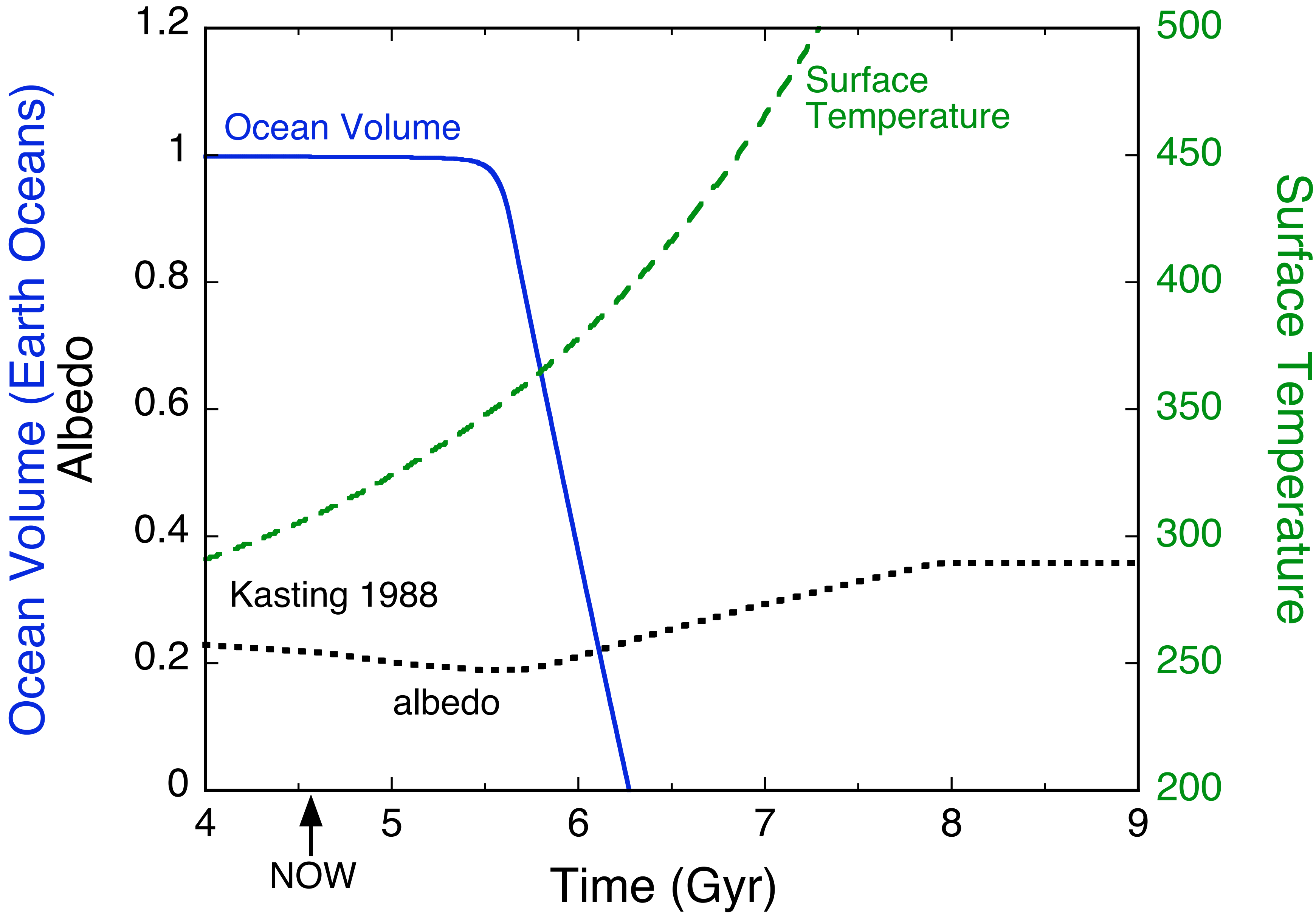
How long a planet at a given current distance from the Sun remains "habitable."


Europa under the HB Sun
(butterfly metaphor)

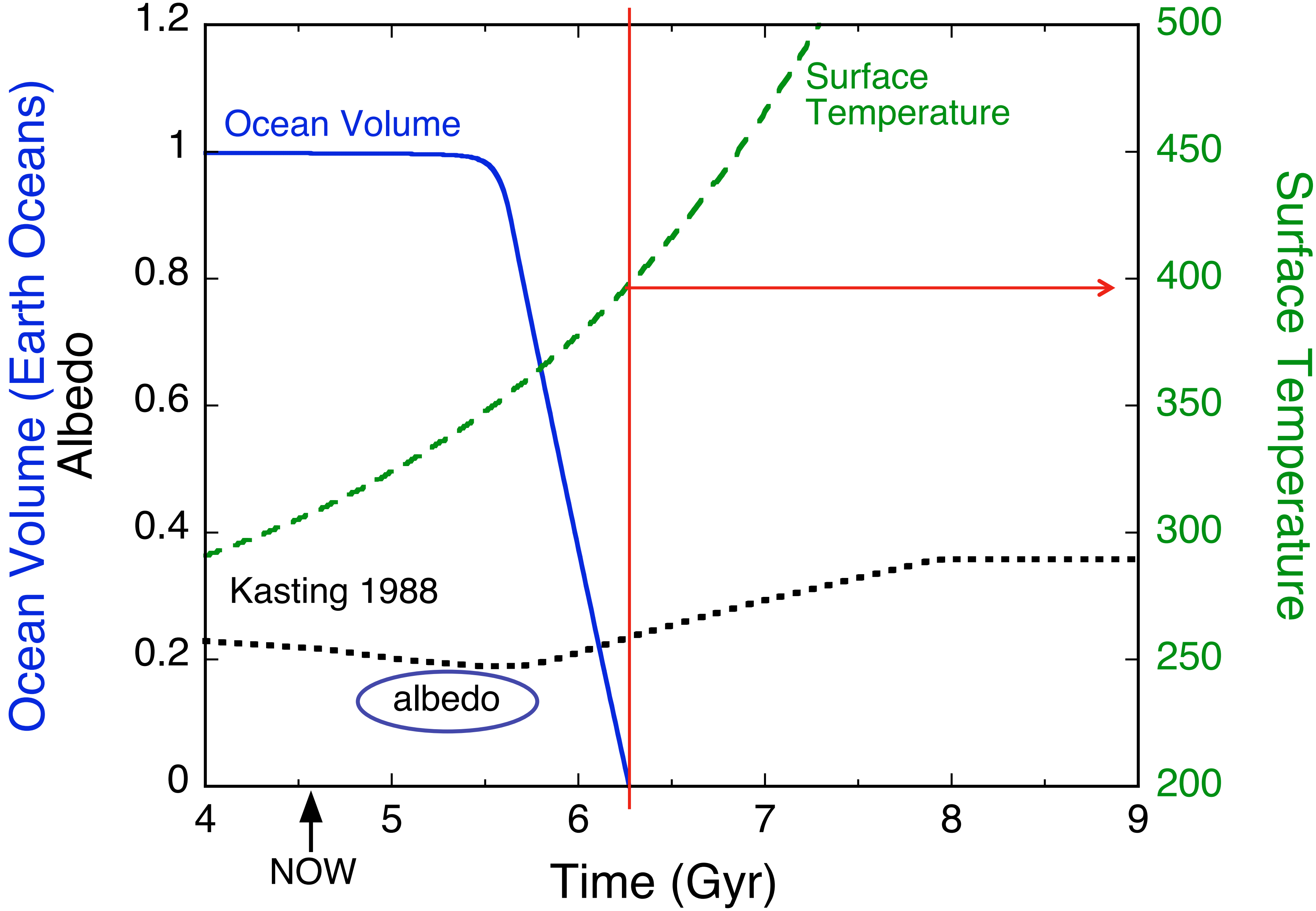
6. Creation myths: how a Dune might evolve

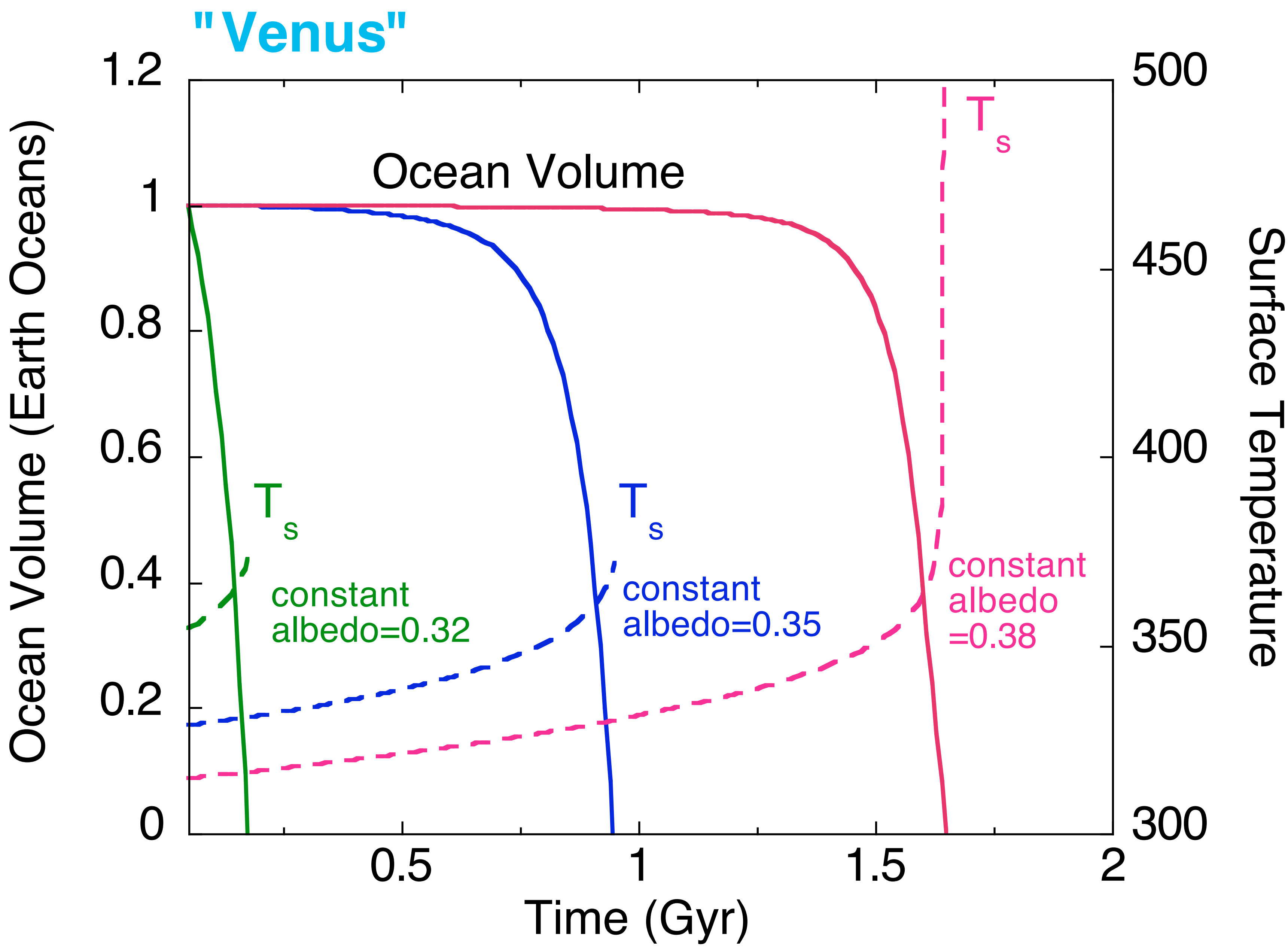


Kasting's (1988) moist greenhouse model (I've added the H escape)



Surface T is ~400 K when the ocean evaporates... Works better with a thin atmosphere




"Venus"
Ocean Volume
Ocean Volume (Earth Oceans)
1.2
1
0.8
0.6
0.4
0.2
0
Surface Temperature
500
450
400
350
300
0.5
1
1.5
2
Time (Gyr)
T_s
T_s
T_s
constant albedo=0.32
constant albedo=0.35
constant albedo =0.38

Some Words

- A habitable land planet appears to be more stable against the runaway greenhouse effect than an ocean planet like Caladan or Earth
- The inner edge of the HZ for land planets was inside of Venus's orbit when the Sun was young
- Land planets are also more stable against ice-albedo runaway
- There is no obvious outer limit to the HZ
  - other greenhouse gases can contribute
  - soluble greenhouse gases work better for land planets
- land planets will be among the first extrasolar habitable planets to be discovered in transit
- tidally-locked planets of M dwarfs have excellent prospects for providing habitable, Dune-like conditions

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