GEOS 22060/ GEOS 32060 / ASTR 45900

What makes a planet (unin)habitable?

Runaway greenhouse

Lecture 8

Tuesday 30 April 2019

Logistics

- Homework 1 and Homework 2 are graded
- Homework 3 will be issued on Wed or Thu and due on Fri 10
- Total number of homeworks will be 6 (hopefully 7)
- Midterm feedback form results:

# responses = 9	Mean	Median	Max	Min	Outcome (looking at full dist'n)
Frequency of student presentations? 7= more	4.11111111	4	5	4	No change
Pace? 7 = too fast	4.88888889	5	7	3	Slow down
Concepts vs. detail/derivations? (7 = more detail)	4.44444444	4	6	3	No change
Planet-specific examples vs. basic principles (7 = more principles)	4	4	7	2	No change
Blackboard vs. slides? (7 = blackboard)	4.55555556	5	6	3	A bit more blackboard
Accessibility? (7 = adequately accessible)	4.25	4.5	6	3	Remind on extra office hours
Add computer lab(s)? (7 = loads, 4 = one or two)	2.22222222	2	4	1	No labs ...
Other (qualitative)					
Lots of assumed geo knowledge					
Homeworks are scary					
More small coding exercises in Hw would be nice					
State expectations for project component of class					

Course outline

Foundations (1-2 weeks)

- Earth history
- HZ concept, atmospheric science essentials
- Post-Hadean Earth system

Principles – how are habitable planets initiated and sustained? (4-5 weeks)

- Volatile supply, volatile escape **TODAY**
- Runaway greenhouse, moist greenhouse
- Long-term climate evolution
- **Specifics (2.5 weeks)**
- Hyperthermals on Earth
- Early Mars
- Oceans within ice-covered moons
- Exoplanetary systems e.g. TRAPPIST-1 system

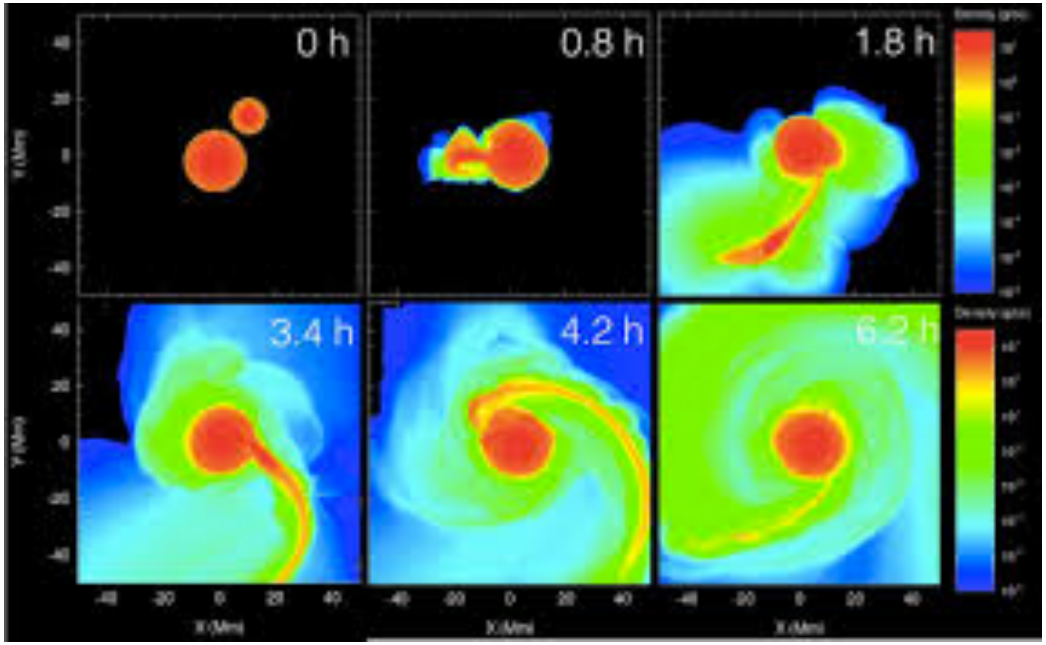
Earth science

planetary science

Lecture 7 wrap-up

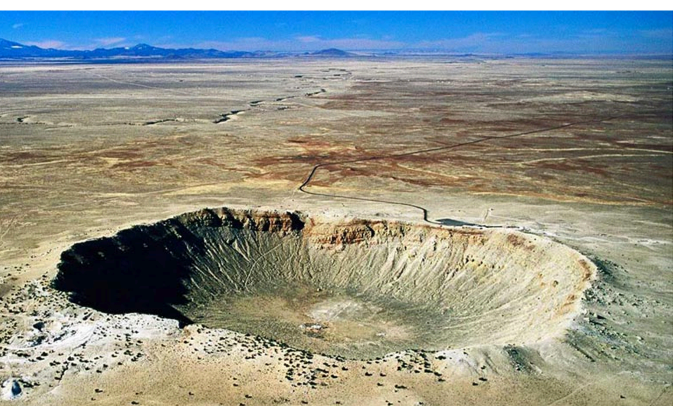
- Energy-limit: XUV driven escape more-likely-than-not sculpts the exoplanet radius-period distribution (‘photo-evaporation valley’)
- Diffusion limit: what regulates H loss from Venus, Earth and Mars today
- Impact erosion – giant impacts and planetesimal impacts

Wrap-up: impact erosion

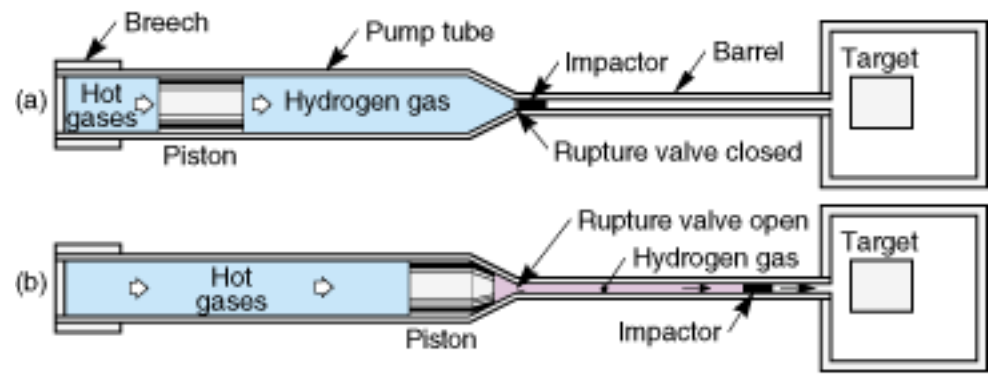


Hydrocode

Nuclear tests



Terrestrial impact craters

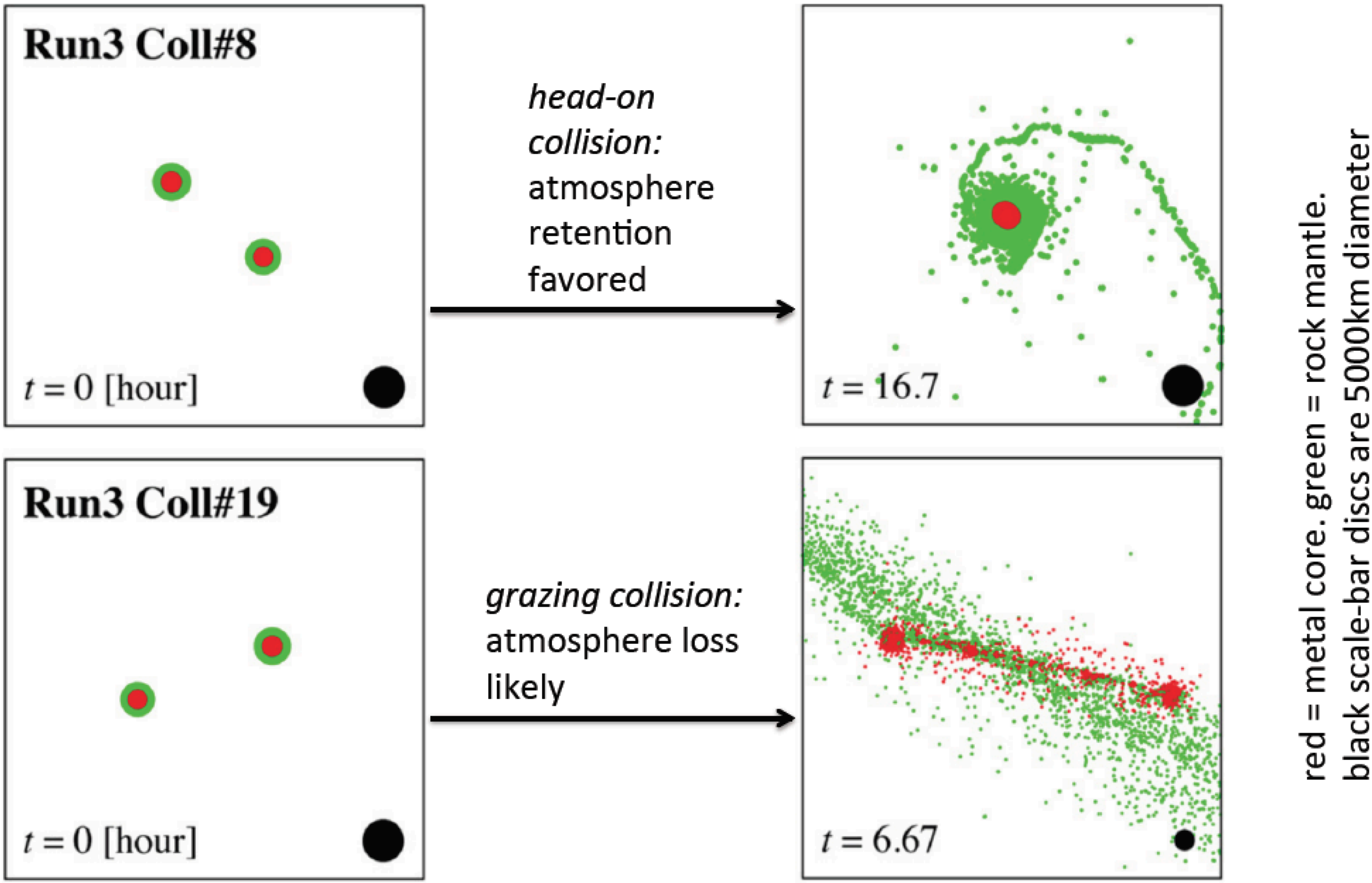


(a) In the first stage of the gas gun (blue shading), hot-burning gases from gunpowder drive a piston, which in turn compresses hydrogen gas. (b) In the second stage (pink shading), the high-pressure gas eventually ruptures a second-stage valve, accelerating the impactor down the barrel toward its target.

Two-stage gas gun

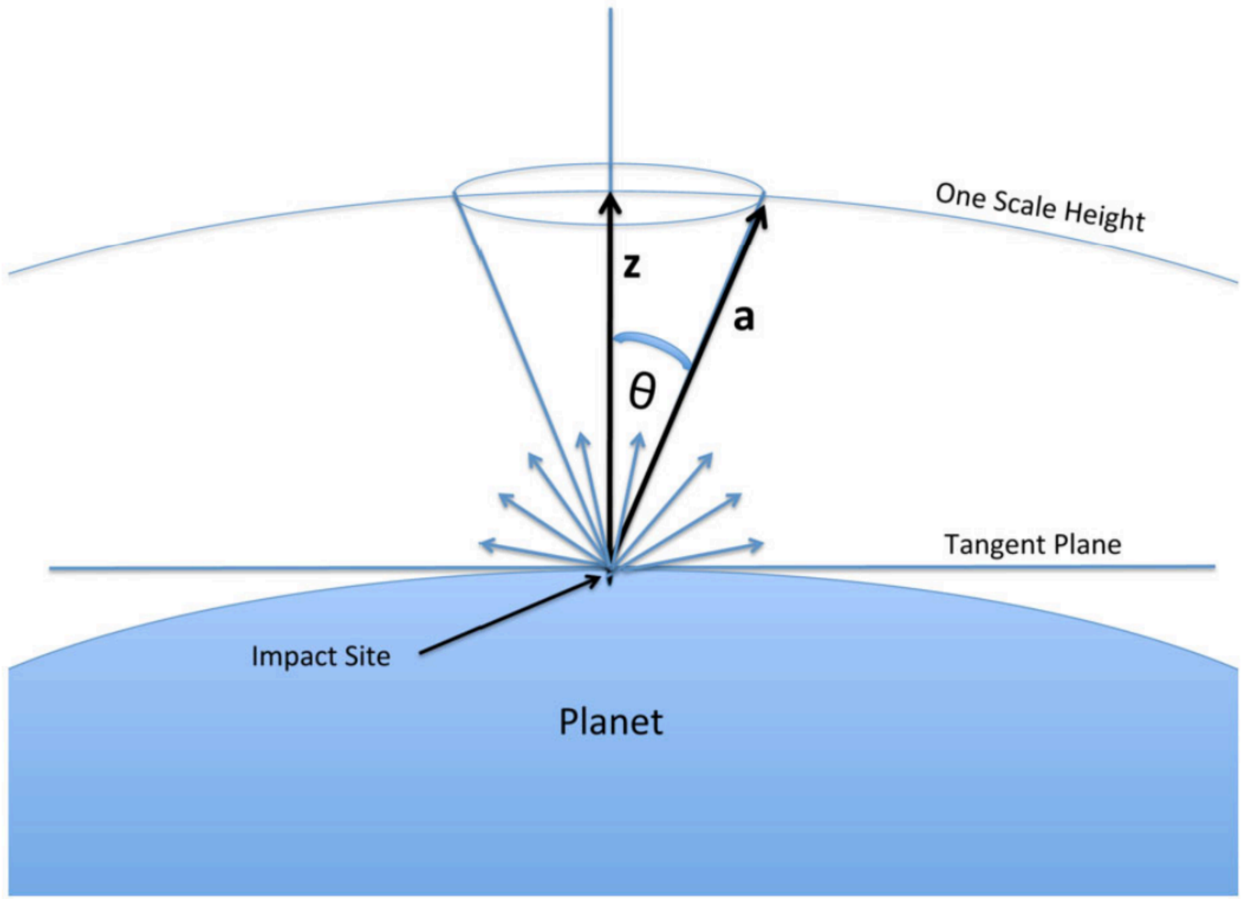
Rocky planets are built by a handful of giant impacts.

Giant impacts can remove atmospheres and oceans. Giant impacts are stochastic.

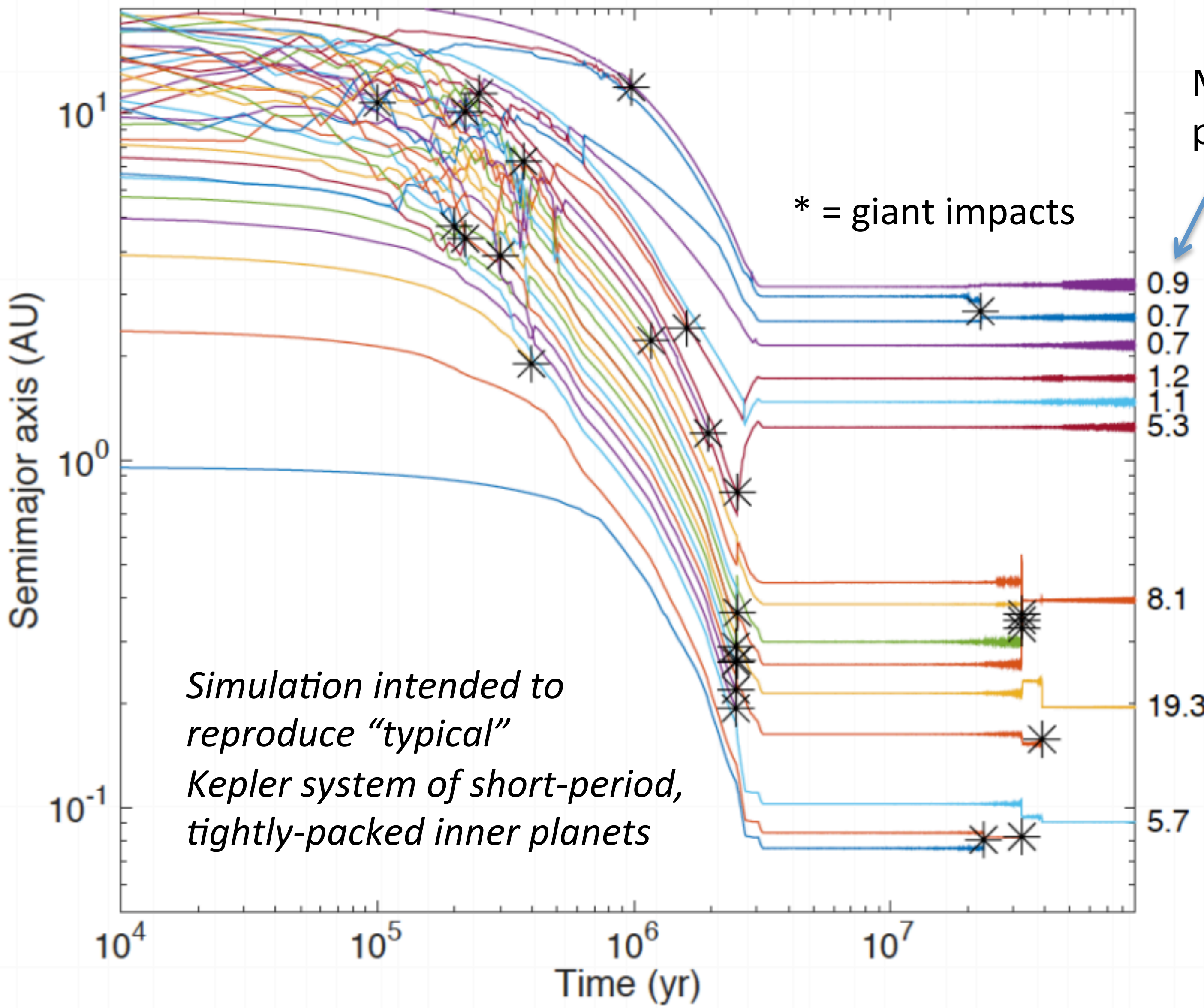


Genda et al., *"Ejection of iron-bearing giant-impact fragments and the dynamical and geochemical influence of the fragment re-accretion,"* Earth and Planetary Science Letters 2017

Fig. 6 Illustration of the impact geometry. Planetesimal impacts can only eject atmosphere locally. Treating their impact as a point-like explosion leading to an isotropic shock at the impact site, the maximum atmospheric mass that they can eject in a single impact is given by all the mass above the tangent plane, which is a fraction given by $h/2R$ of the total atmospheric mass. Figure after Schlichting et al. (2015)



Formation of Earth-sized planets involves giant (oligarchic) impacts.



Masses of resulting planets (Earths)

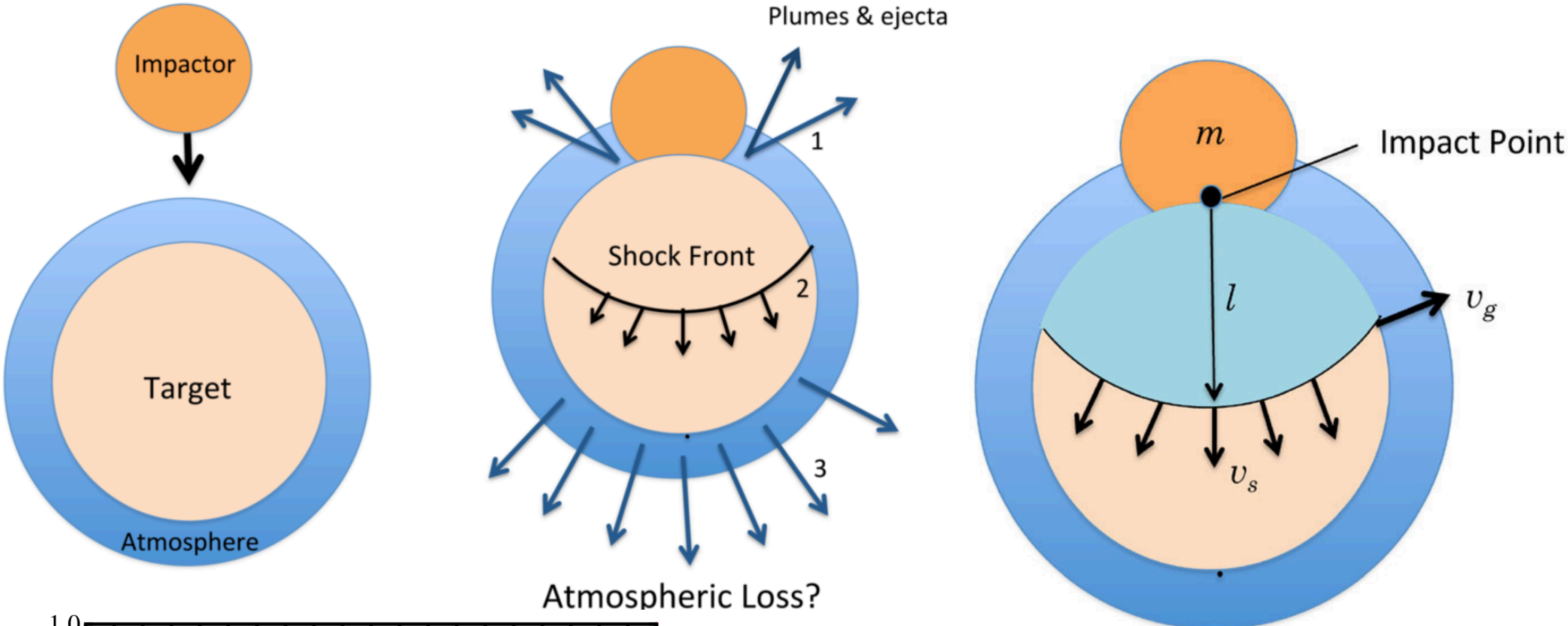
* = giant impacts

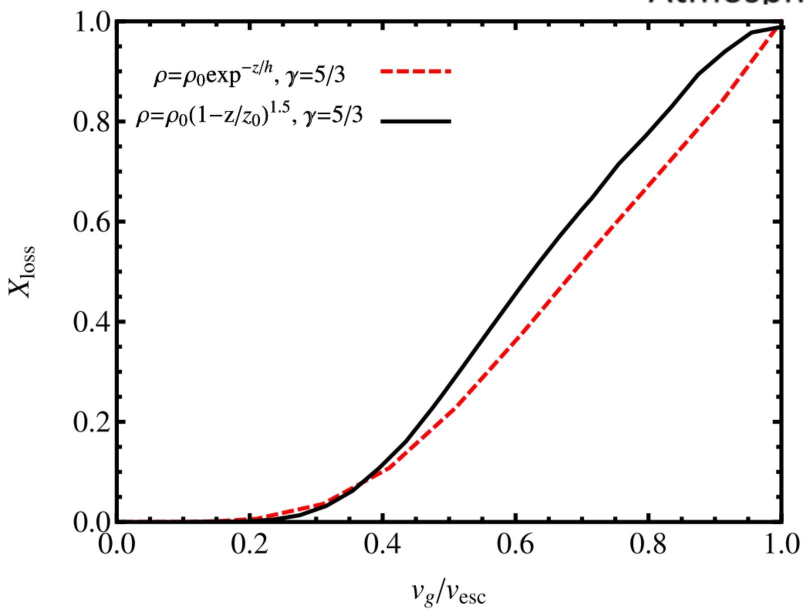
The output underlying this plot was generated by C. Cossou.

Simulation intended to reproduce "typical" Kepler system of short-period, tightly-packed inner planets

The Moon-forming impact was not the last big impact on Earth, but it was the last time that Earth hit another planet.

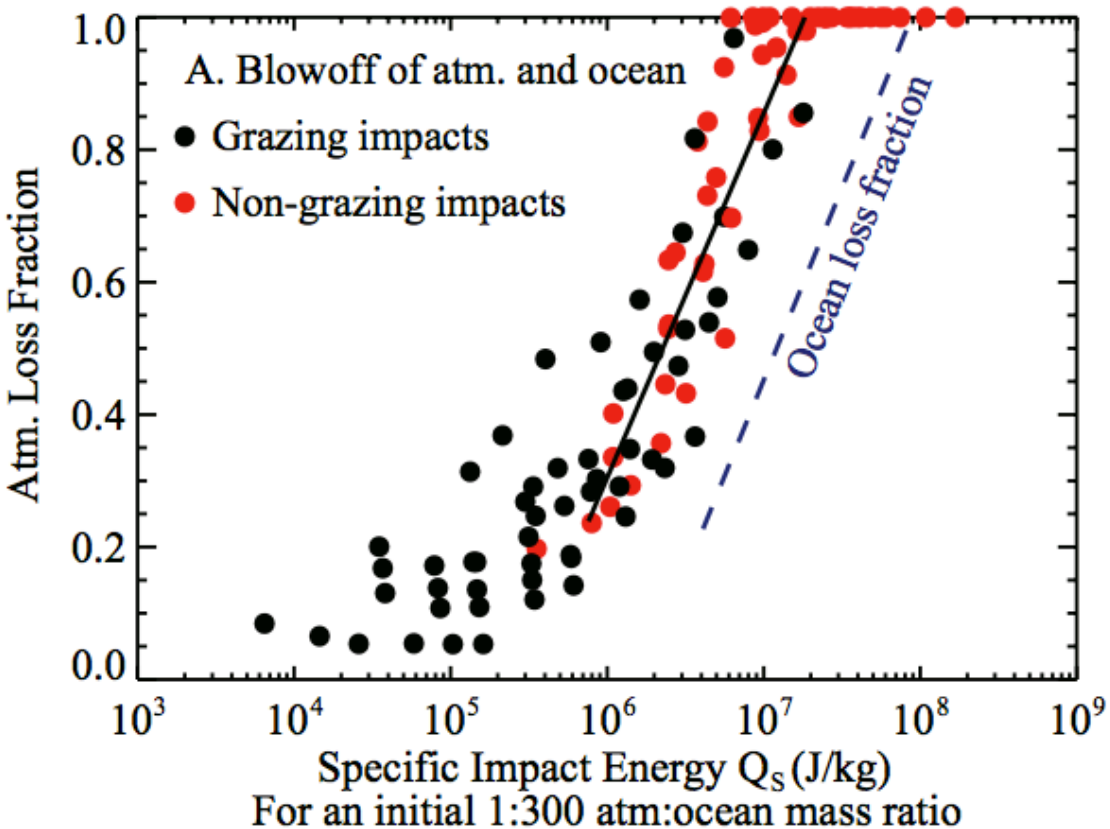
The atmosphere-loss escape efficiency of giant impacts is set by the ground-motion speed





Schlichting & Mukhopadhay 2018

Ocean removal by giant impacts? (Ocean vaporization != ocean removal)



Stewart et al. LPSC 2014

Simulations suggest that the Moon-forming impact was marginally able to remove any pre-existing Earth ocean

$Q_s \sim v_e^2$ for oligarchic impact

$$v_e = \sqrt{\frac{2GM}{r}}$$

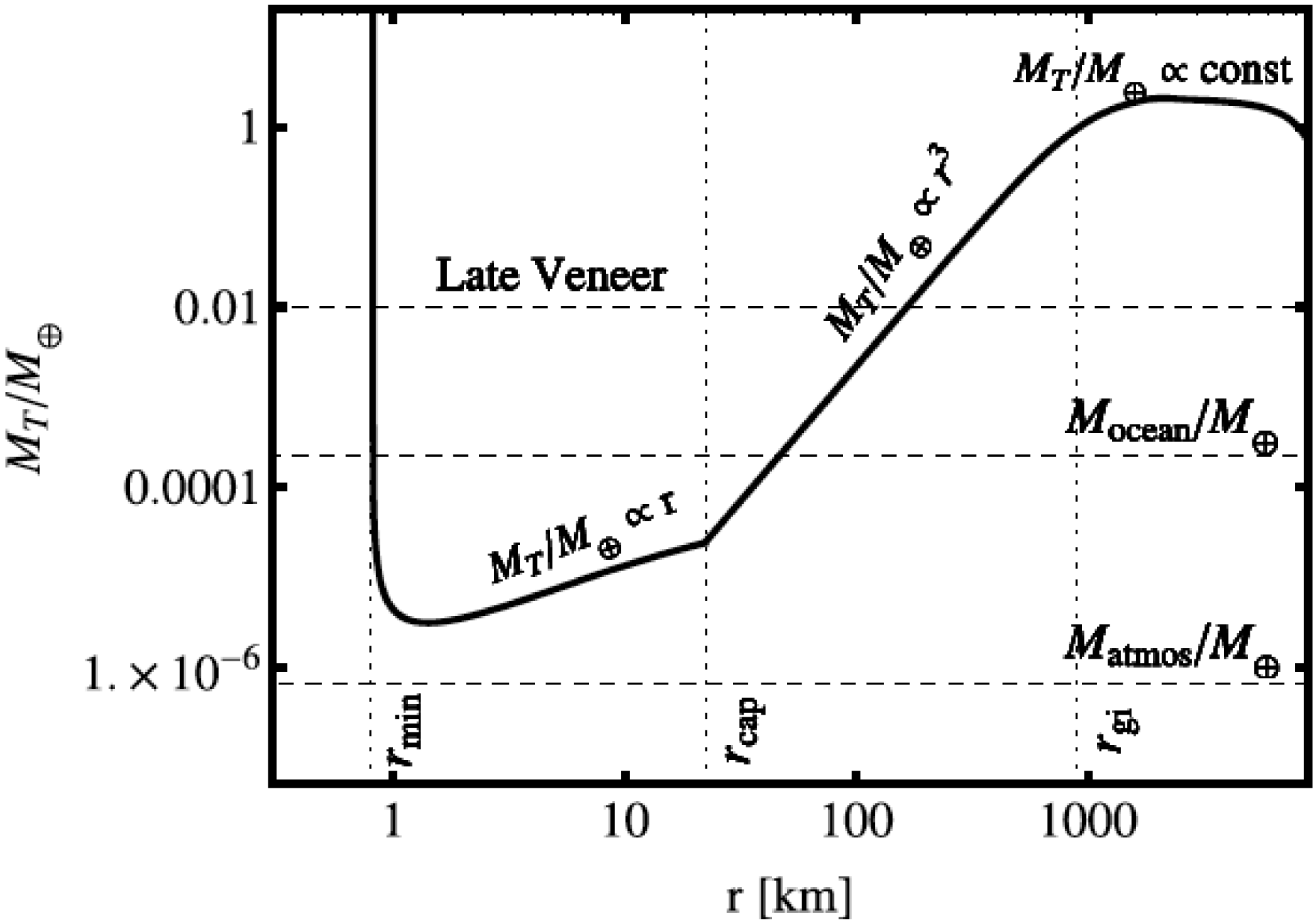
escape velocity

There have also been major recent developments in our understanding of Moon formation, the Moon's orbital evolution, and Moon-induced tidal heating, but orbital/tidal effects are not part of this course.

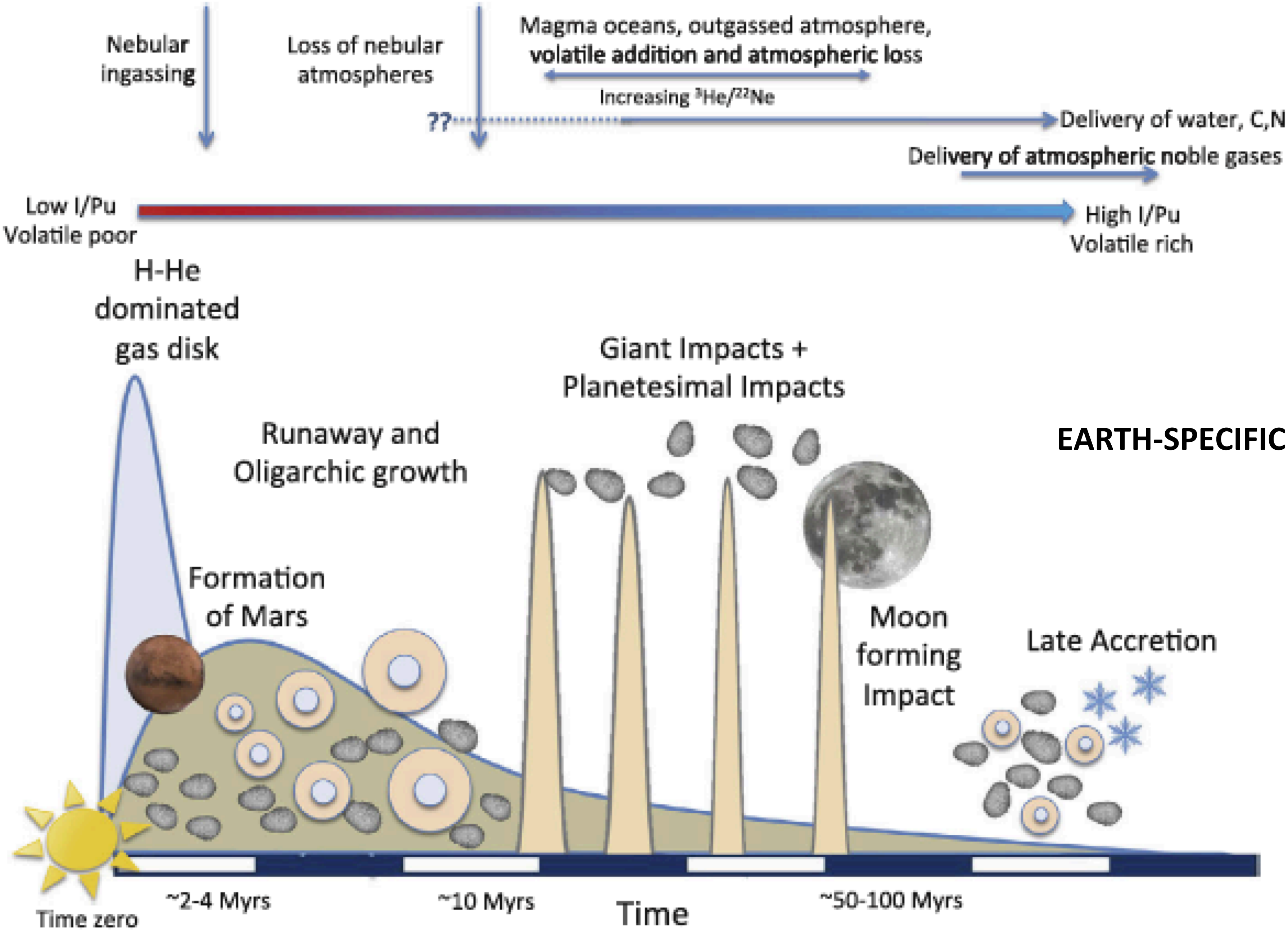
Total impactor mass needed to eject the atmosphere as a function of impactor radius

Impacts by small asteroids/comets efficiently eject ~1 bar atmospheres

The peak would move to larger *r* if the initial atmospheric pressure were greater

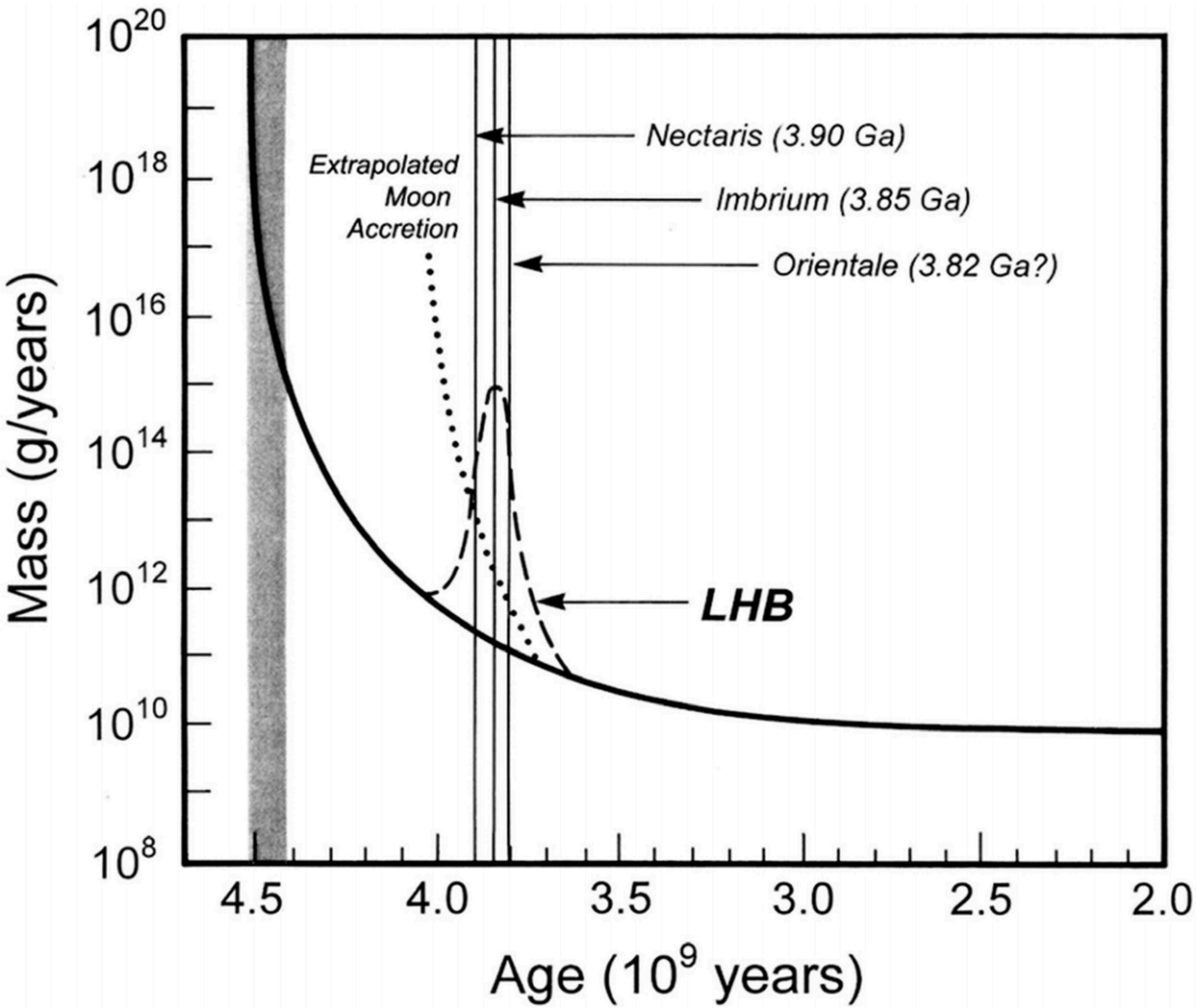


Schlichting & Mukhopadhay 2018



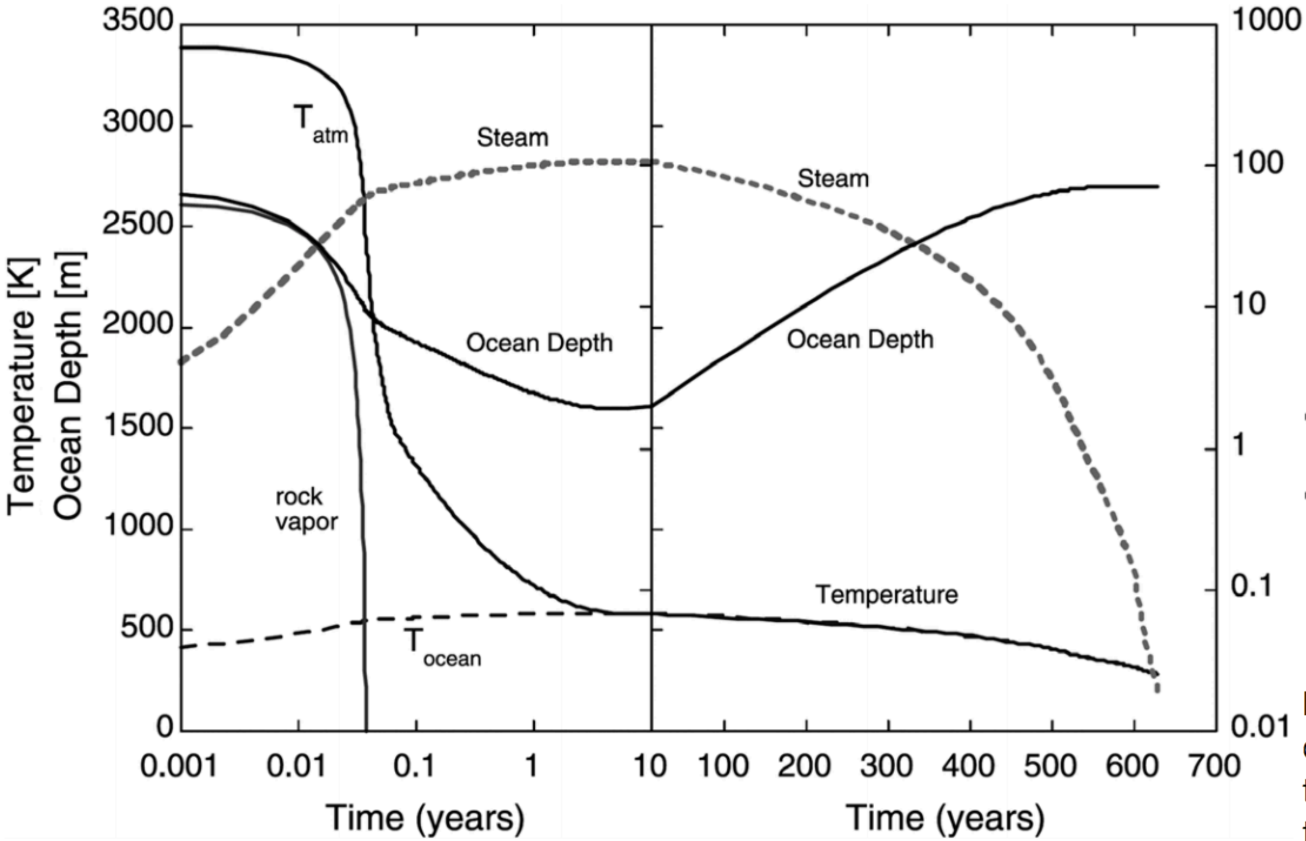
Schlichting & Mukhopadhay 2018

An uptick in bombardment ~3.9 Ga?



Catling & Kasting ch. 6 (Fig. 6.18)

Effect of basin-forming impacts on habitability: impact frustration of life establishing itself on Earth?



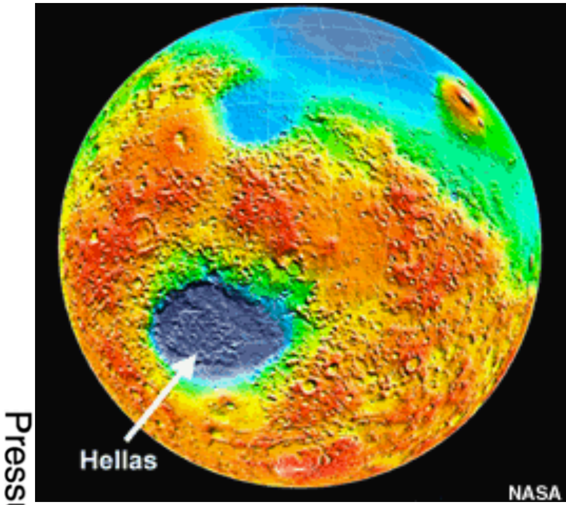


Figure 6.19 The environmental consequences on the early Earth of an impactor that released 10^{27} J, comparable to that that caused the 2100 km-wide Hellas basin on Mars. Ocean depth, ocean temperature, and atmospheric temperature are shown as a function of time, along with the pressure of rock vapor and steam. (From Nisbet *et al.* (2007a). Reproduced with permission of Springer. Copyright 2007, Springer Science + Business Media, Inc.)

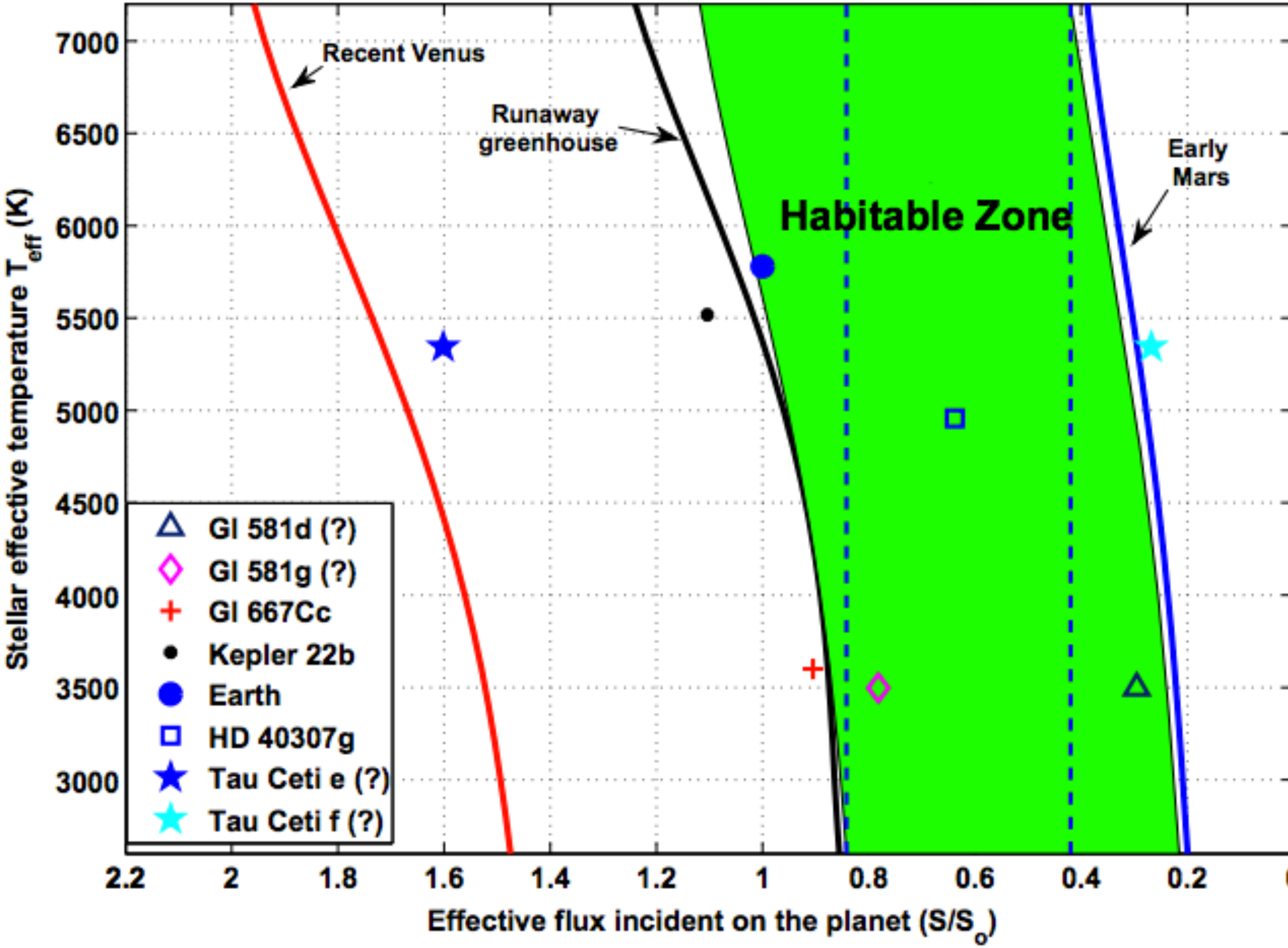
e.g. Maher & Stevenson 1987

Lecture 8
Runaway greenhouse – key points

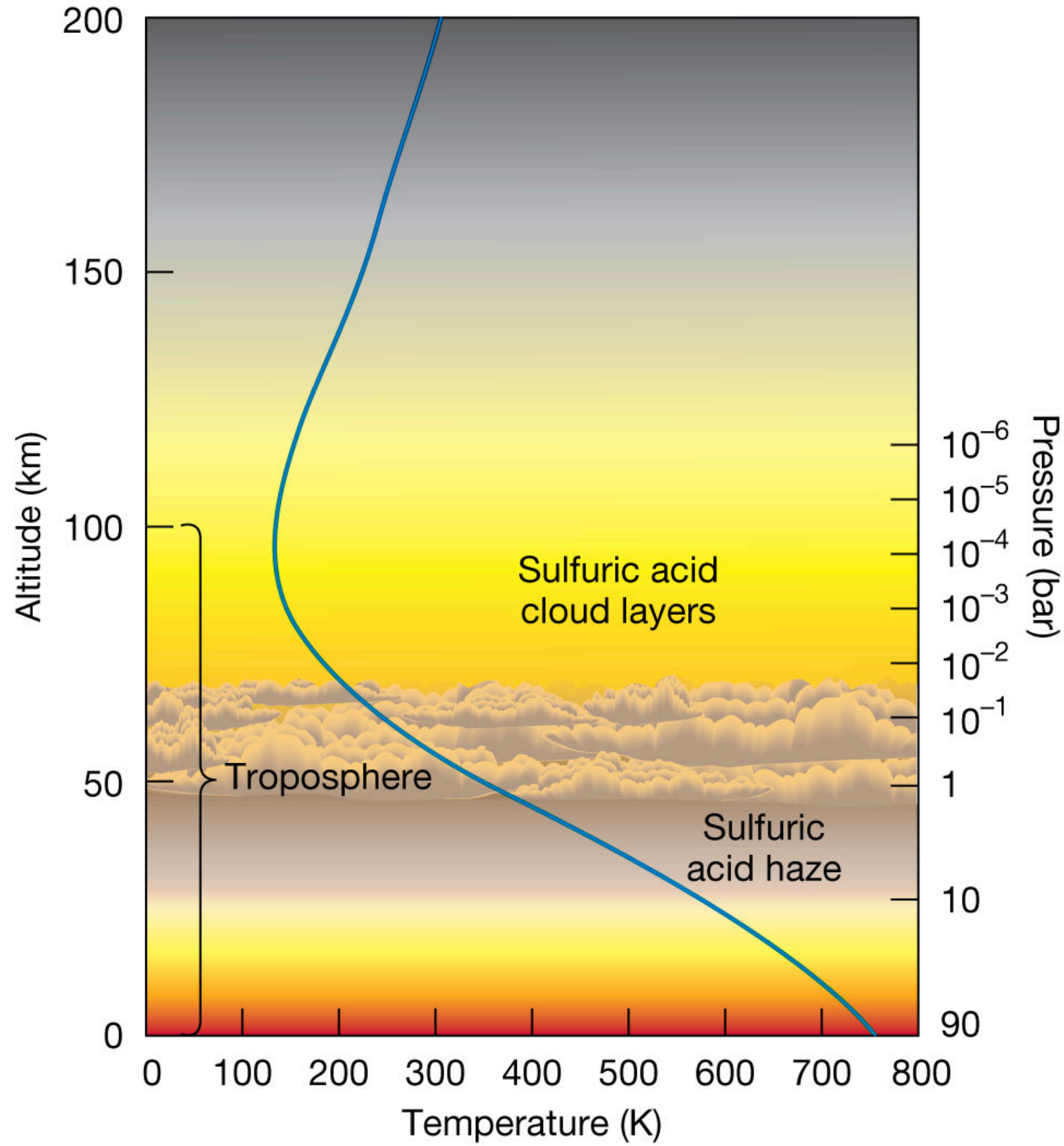
- The (H2O-)runaway greenhouse is a geologically rapid increase in planet surface temperature from <500K to >1000K caused by a positive feedback between the saturation vapor pressure of water vapor and the planet surface temperature
- Be able to explain the mechanism of the runaway greenhouse
- It is almost certain that release of CO_2 by humans cannot cause a runaway greenhouse
- The exact threshold for the runaway greenhouse depends on cloud cover, land fraction, and planet rotation rate

Chalkboard

Energy balance ←→ Planck feedback
Effect of fixed-T-offset high-altitude optically thick IR absorber on Planck feedback
Runaway GH represents failure of the Planck feedback


Recent Venus
Runaway greenhouse
Habitable Zone
Early Mars
Gl 581d (?)
Gl 581g (?)
Gl 667Cc
Kepler 22b
Earth
HD 40307g
Tau Ceti e (?)
Tau Ceti f (?)
Stellar effective temperature T_{eff} (K)
7000
6500
6000
5500
5000
4500
4000
3500
3000
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Effective flux incident on the planet (S/S_o)

Venus is dry today



The inner edge of the habitable zone is defined by the runaway greenhouse limit

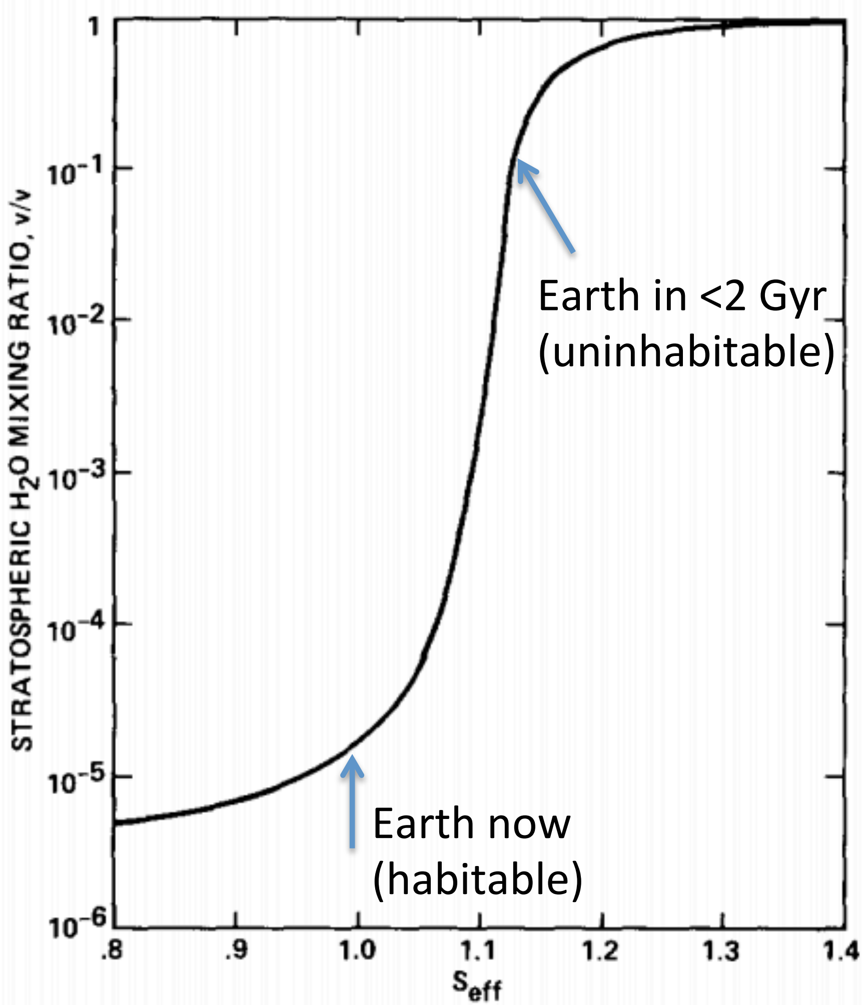


FIG. 14. H_2O volume mixing ratio in the stratosphere versus effective solar constant S_{eff}.

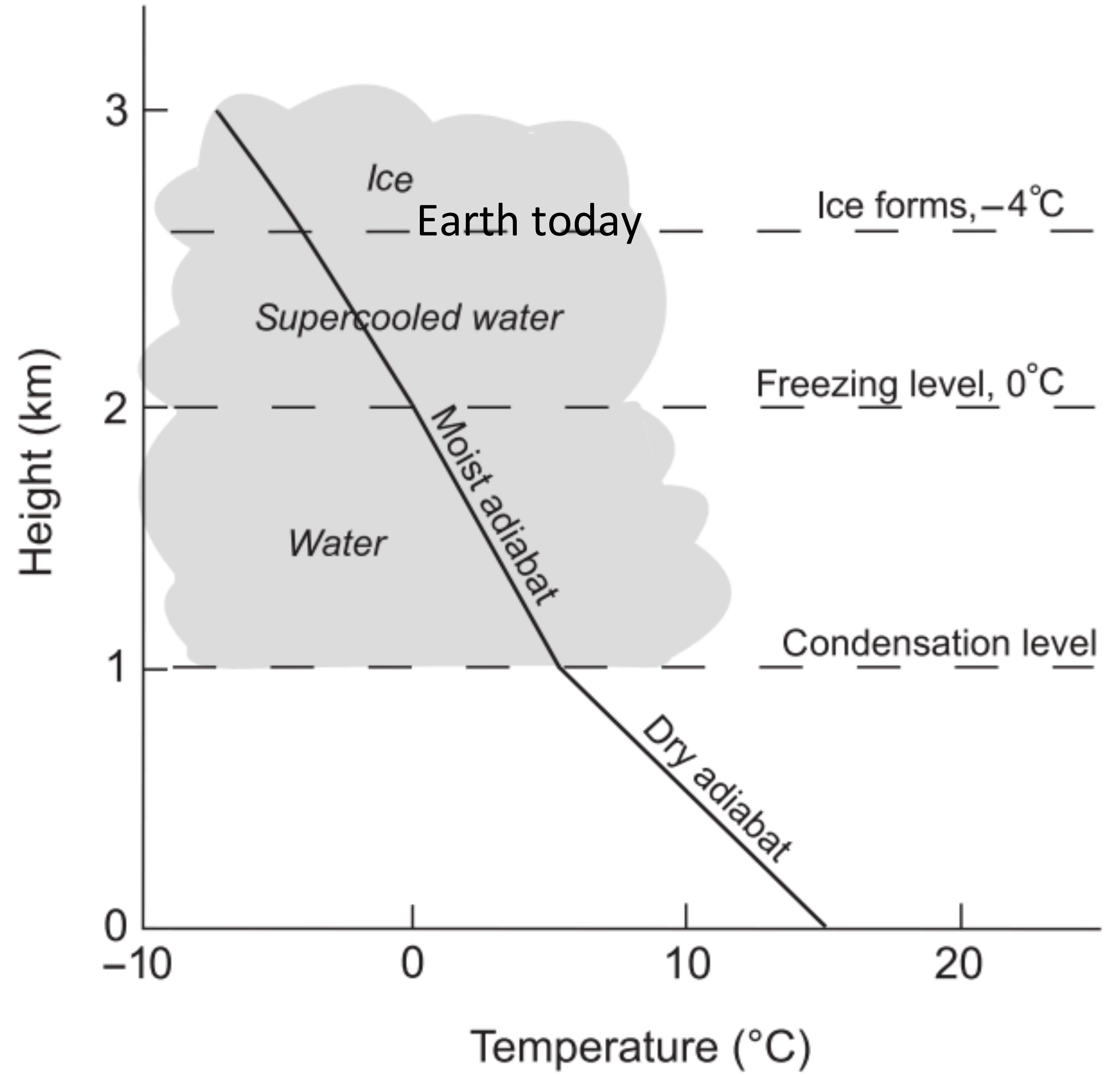
Clasius-Clapeyron relation:
exponential increase in water vapor partial pressure with increasing T (7% per degree K, linearizing around modern Earth T)

$$\frac{de_s}{dT} = \frac{l_c e_s}{R_c T^2}, \qquad \text{or} \qquad \frac{\mathrm{d}(\ln e_s)}{dT} = \frac{l_c}{R_c T^2}$$

$$e_s(T) = e_s(T_0)\exp\left(\int_{T_0}^{T} \frac{l_c}{R_c}\frac{dT}{T^2}\right) \approx e_s(T_0)\exp\left[\frac{l_c}{R_c}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right] \tag{1.49}$$

section 1.1.3.5 of Catling & Kasting, ch. 1

Definitions: adiabat and moist adiabat (1/2)



Definitions: adiabat and moist adiabat (2/2)

Condensible "c" (e.g. water) and noncondensible "a" (e.g. O_2/N_2)
Assume instant precipitation of condensate

$$(m_a + m_c)\delta Q = m_a c_{pa} dT - \frac{m_a}{\rho_a} dp_a + m_c c_{pc} dT - \frac{m_c}{\rho_c} dp_c + L dm_c$$

zero by definition
of adiabat

Assuming saturation (relative humidity = 1),

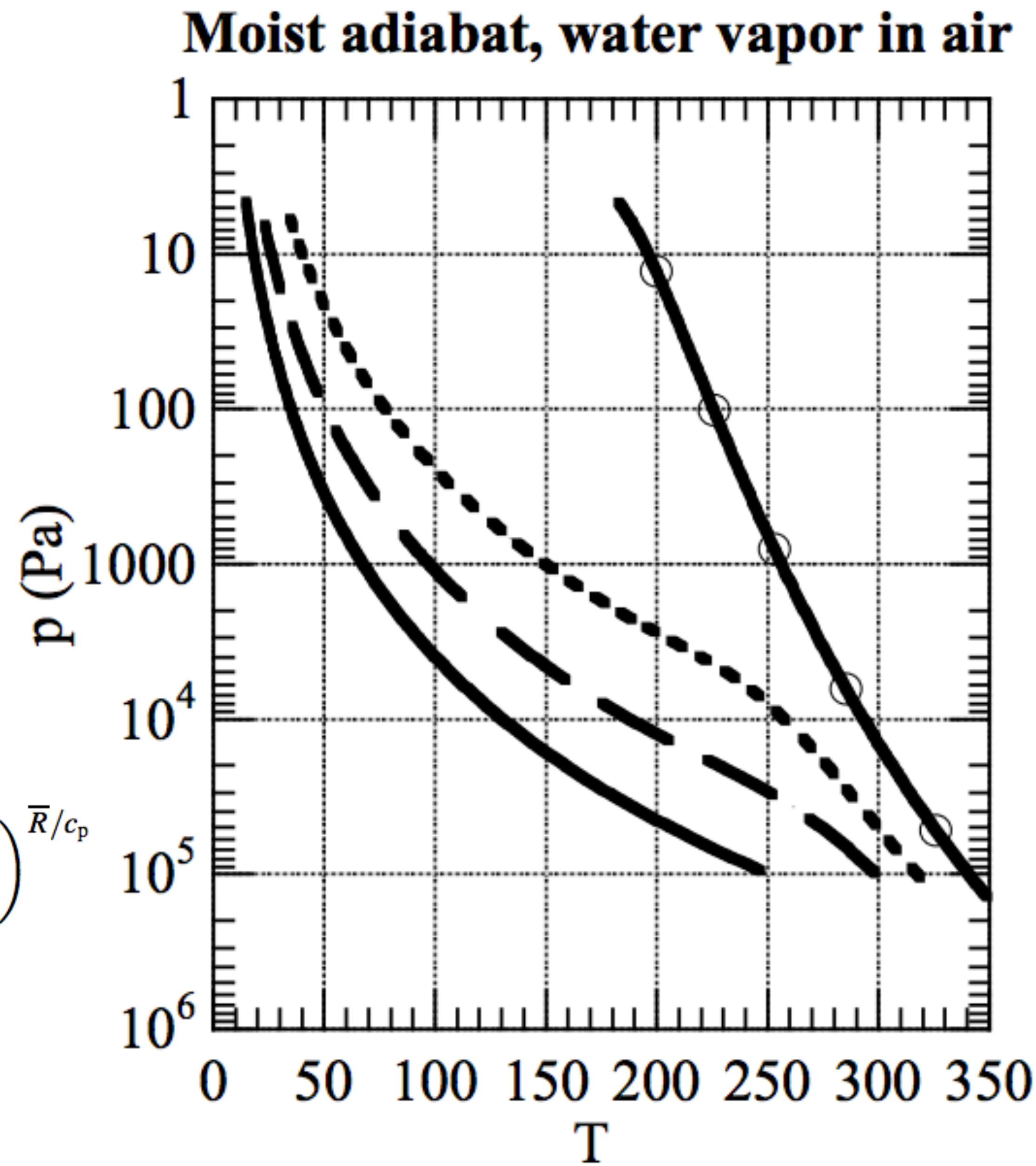
$$\frac{d \ln T}{d \ln p_a} = \frac{R_a}{c_{pa}} \frac{1 + \frac{L}{R_a T} r_{sat}}{1 + \left(\frac{c_{pc}}{c_{pa}} + \left(\frac{L}{R_c T} - 1\right) \frac{L}{c_{pa} T}\right) r_{sat}}$$

In the limit $r_{sat} = 0$ (dry atmosphere), this equation
gives the dry adiabat

Mixing ratio at
saturation

In the limit where water vapor is the dominant constituent
of the atmosphere, this tends to the saturation vapor pressure curve.

As temperature increases, the moist adiabat increasingly diverges from the dry adiabat



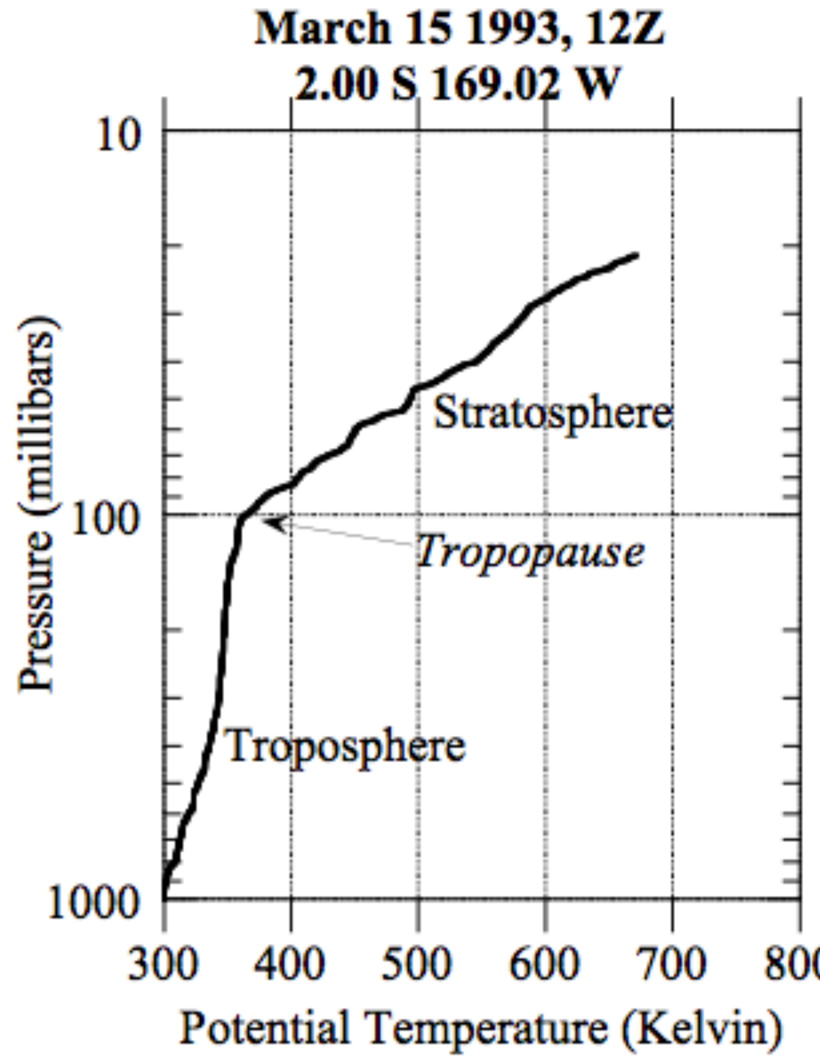
dry adiabat:

$$T = T_{\text{ref}}\left(\frac{p}{\text{p}_{\text{ref}}}\right)^{\overline{R}/c_{\text{p}}}$$

RELATIVE HUMIDITY=1
EARTH AIR, 1 BAR (DRY)
Pierrehumbert 2010

Stratospheric cold-trap

potential temperature: $\vartheta = T\left(\frac{p_{\mathrm{ref}}}{p}\right)^{\kappa}$



The runaway greenhouse leads to the end of habitability

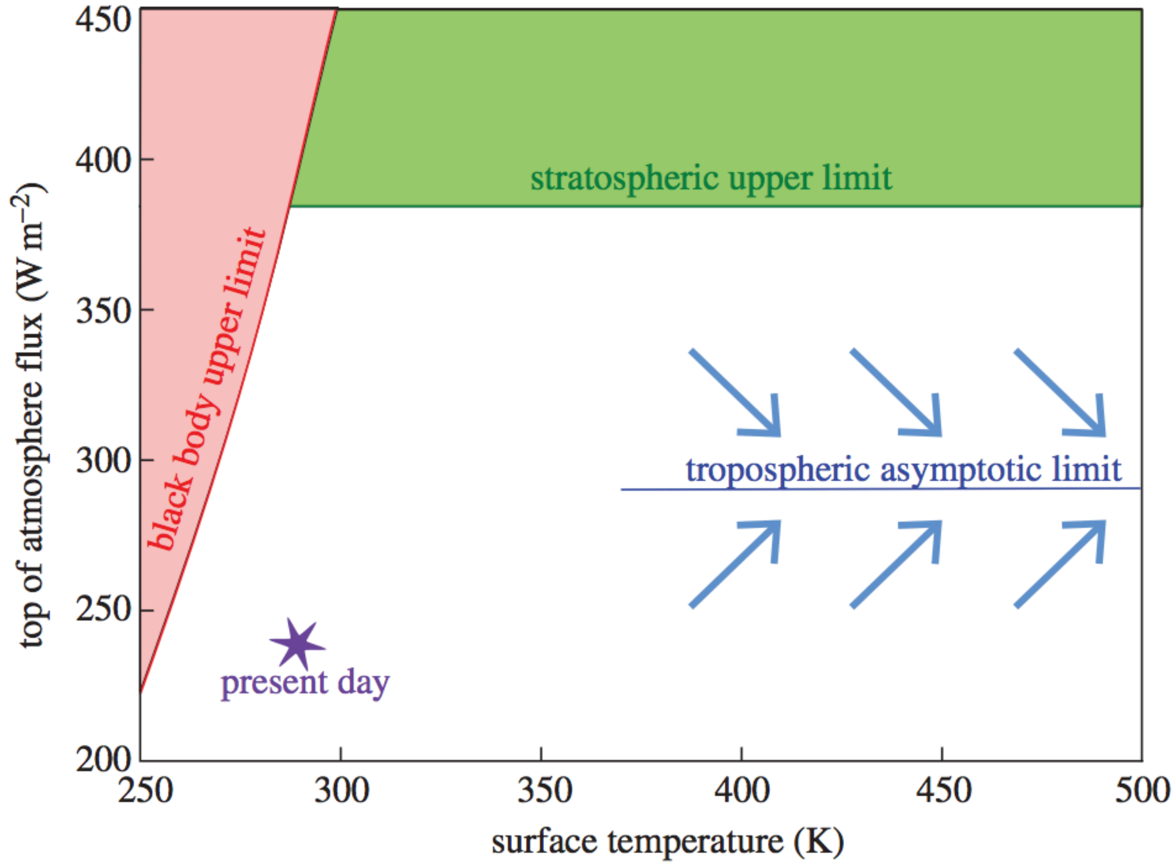
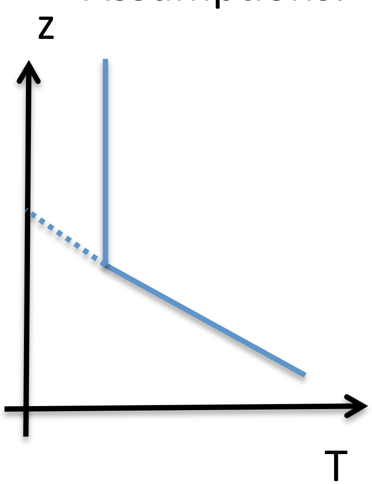


Figure 1. Radiation limits (solid lines) as a function of surface temperature, after Nakajima *et al.* [13]. Inaccessible regions are shaded. All of the white area can, in theory be occupied depending on the amount of non-condensible greenhouse gas (e.g. carbon dioxide) present, but at higher temperatures, outgoing flux will tend towards the tropospheric limit, as indicated by the arrows. Present day mean surface temperature is 289 K with an outgoing thermal flux of 239 W m^{-2}. Note that the change in temperature with flux is equivalent to the climate sensitivity, so the horizontal lines of the radiation limits imply infinite climate sensitivity, hence a runaway greenhouse.

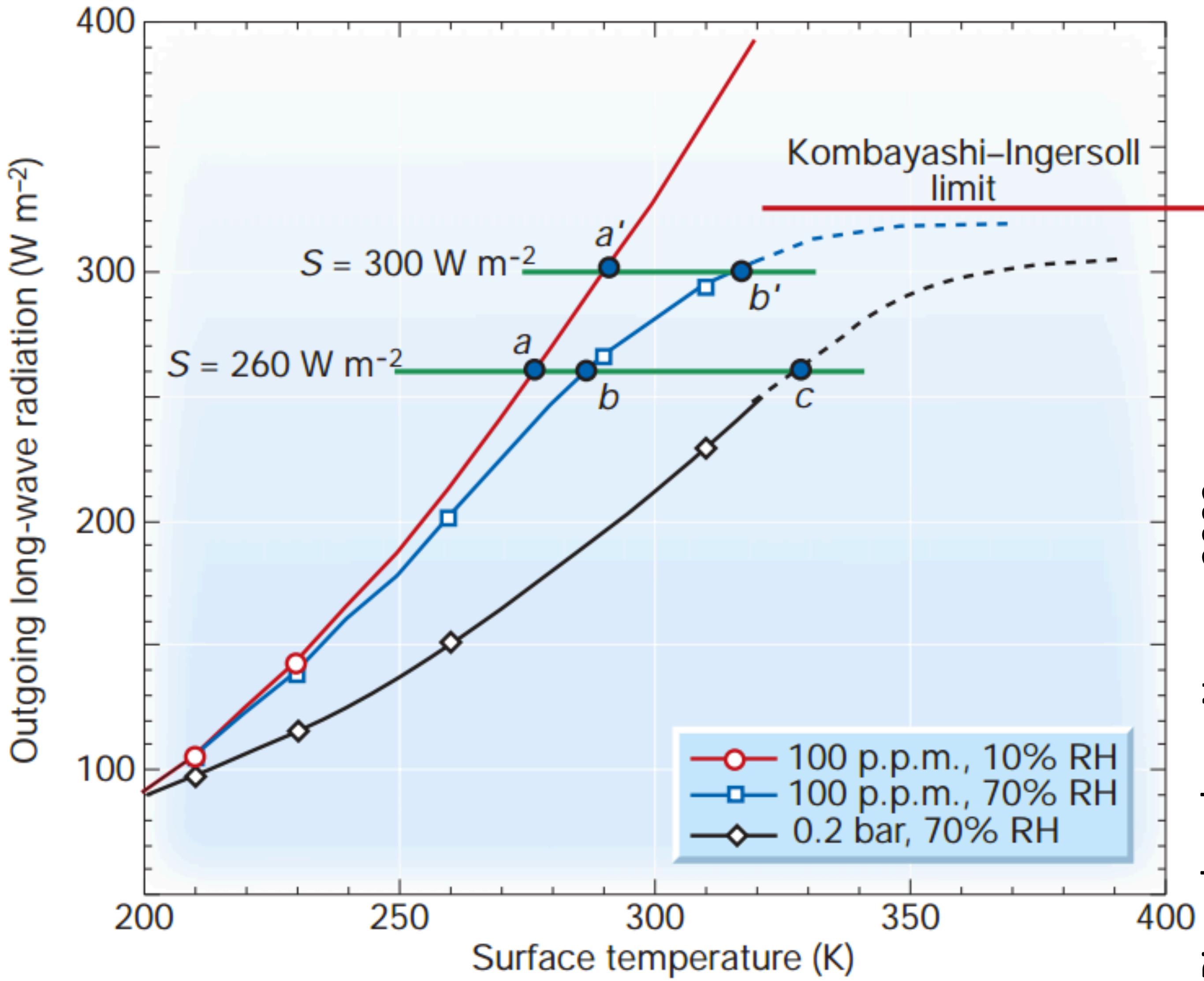
Goldblatt & Watson 2012, following Nakajima 1992

Condensable greenhouse gases lead to climate instability (Kombayashi-Ingersoll limit)

Assumptions:



Constant RH (RH = relative humidity)



Pierrehumbert, Nature, 2002

Consequences:
(all are important)
H_2O dissociation
VNIR window
Surface magma
All water lost to space
Carbonates decompose

The switch from a dry to a moist stratosphere happens over a narrow range of Tsurf – because of the exponential dependence of s .v.p. on T, combined with the lapse rate feedback

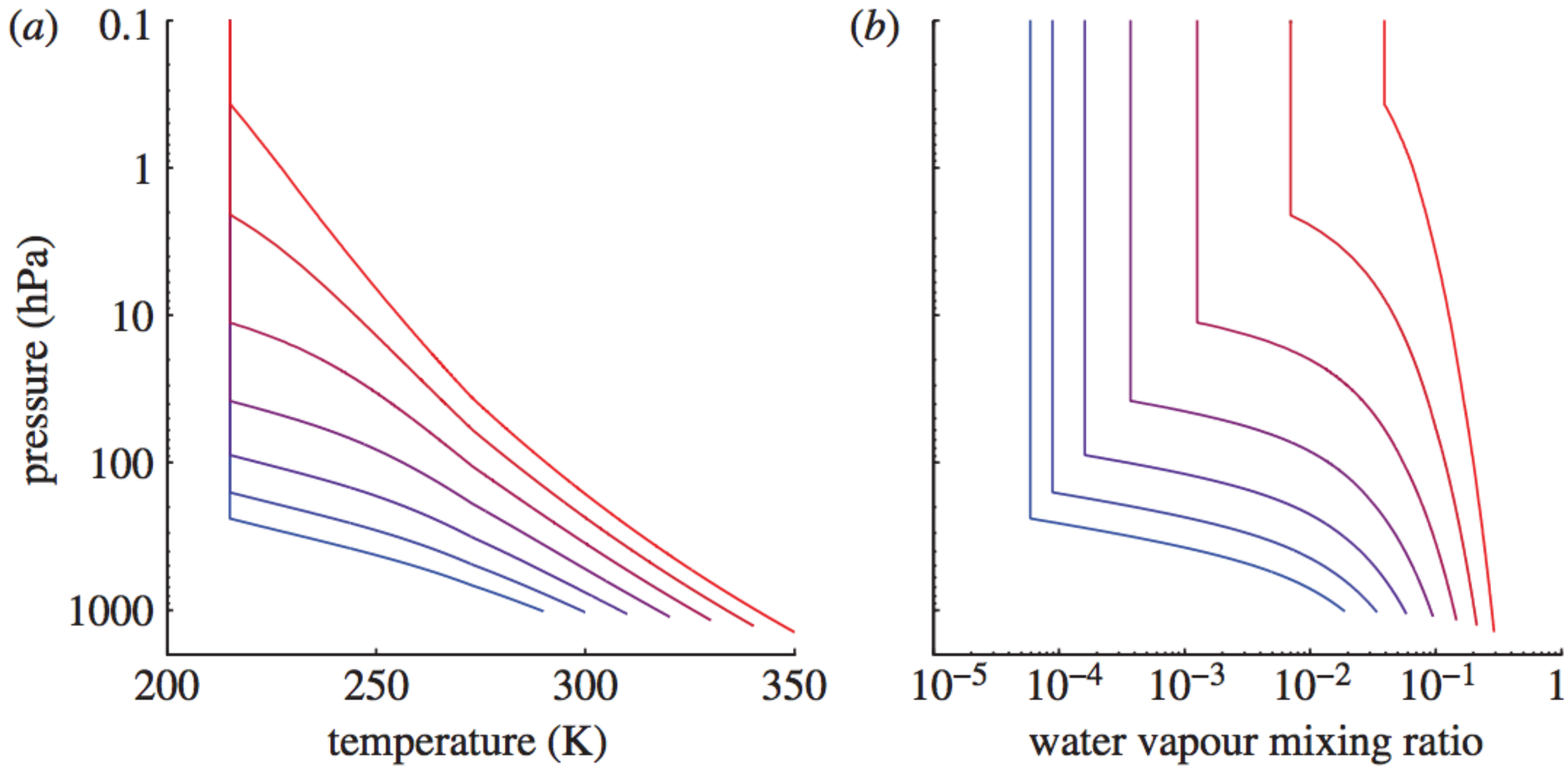
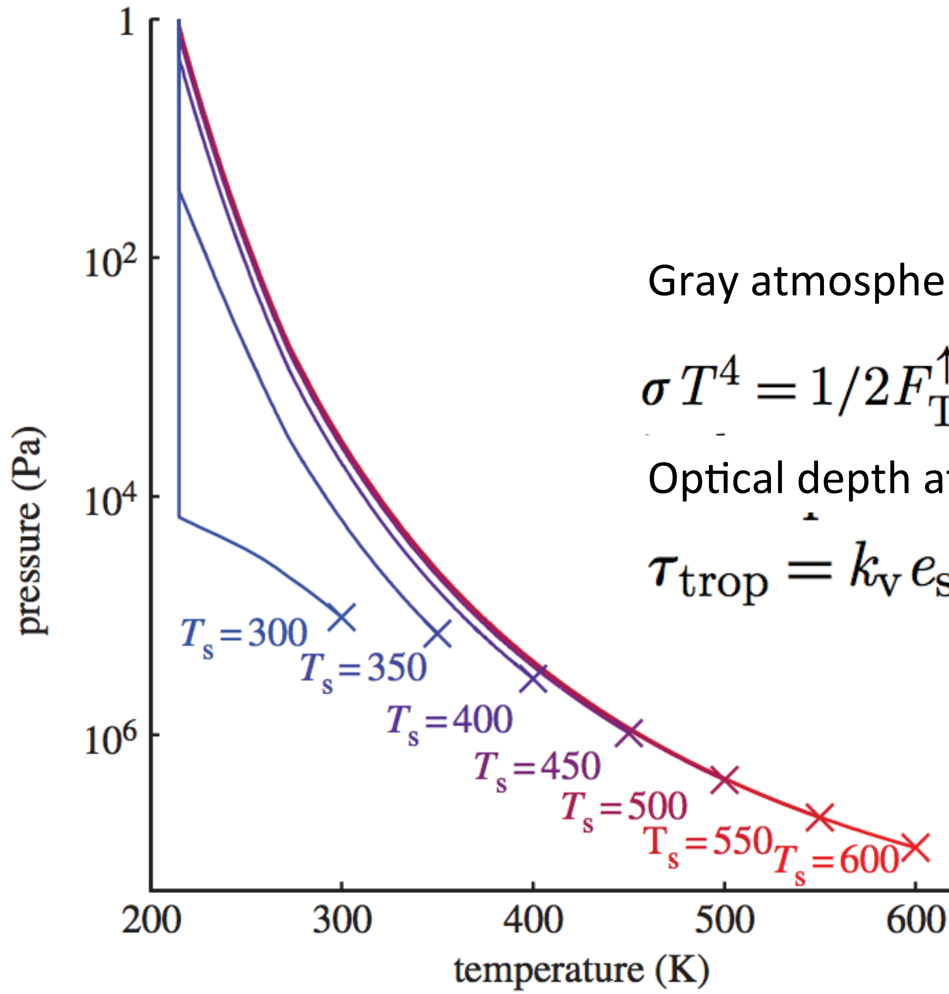


Figure 3. (*a*) Change in temperature structure and (*b*) moisture structure for warming atmospheres. A background pressure of 10^5 Pa is assumed, equal to that of Earth's atmosphere.

Goldblatt & Watson 2012



Gray atmosphere:

$$\sigma T^4 = 1/2 F^{\uparrow}_{\mathrm{TOA}} (3/2\tau + 1)$$

Optical depth at tropopause:

$$\tau_{\mathrm{trop}} = k_{\mathrm{v}}\, e_{\mathrm{s}}(T_{\mathrm{trop}}) \underline{1/g} M_{\mathrm{v}} / \bar{M}$$

(1/g) in brackets

Figure 4. Temperature structure of the atmosphere with increasing surface temperature. A background pressure of 10^5 Pa is assumed, equal to that of Earth's atmosphere.

Goldblatt & Watson 2012

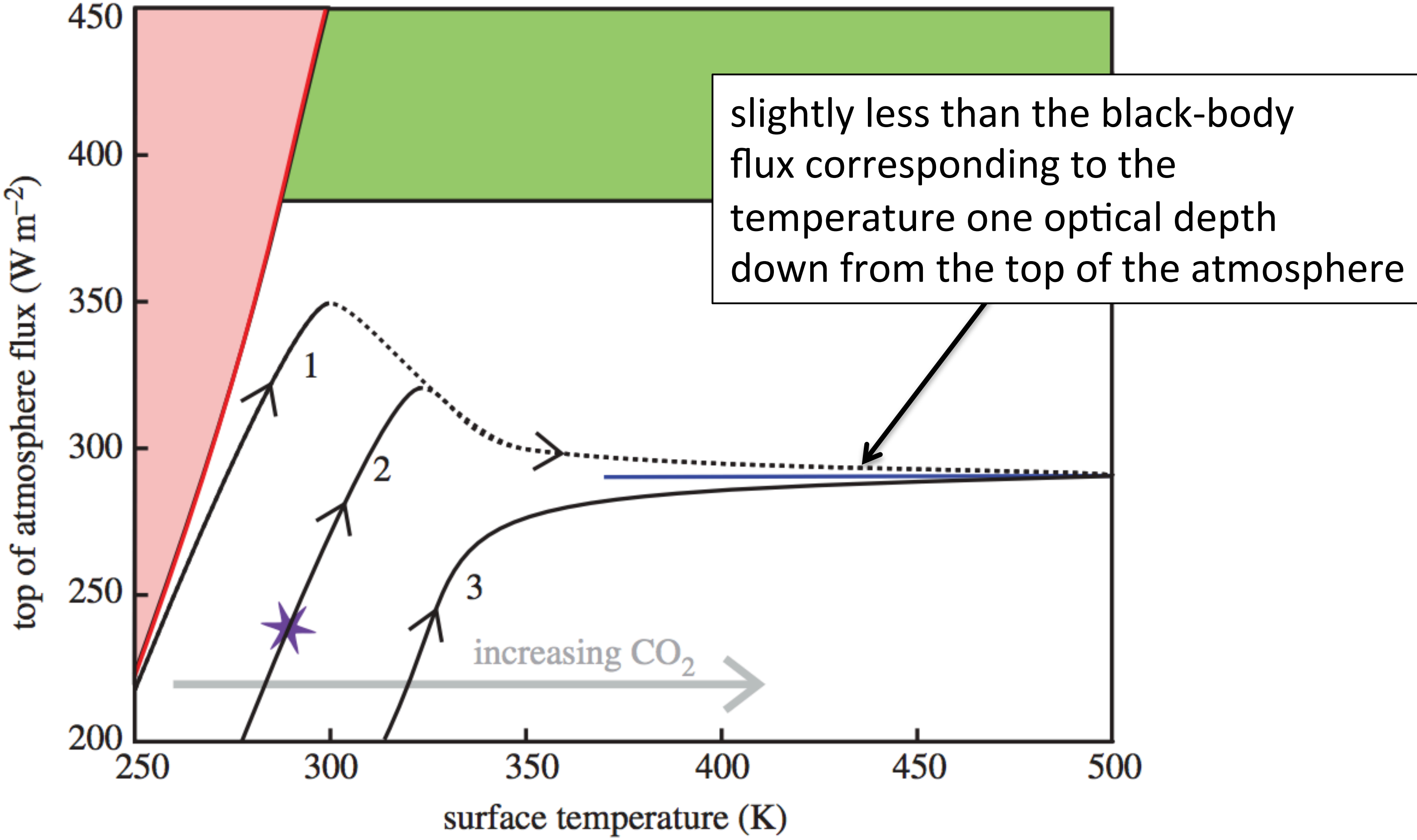
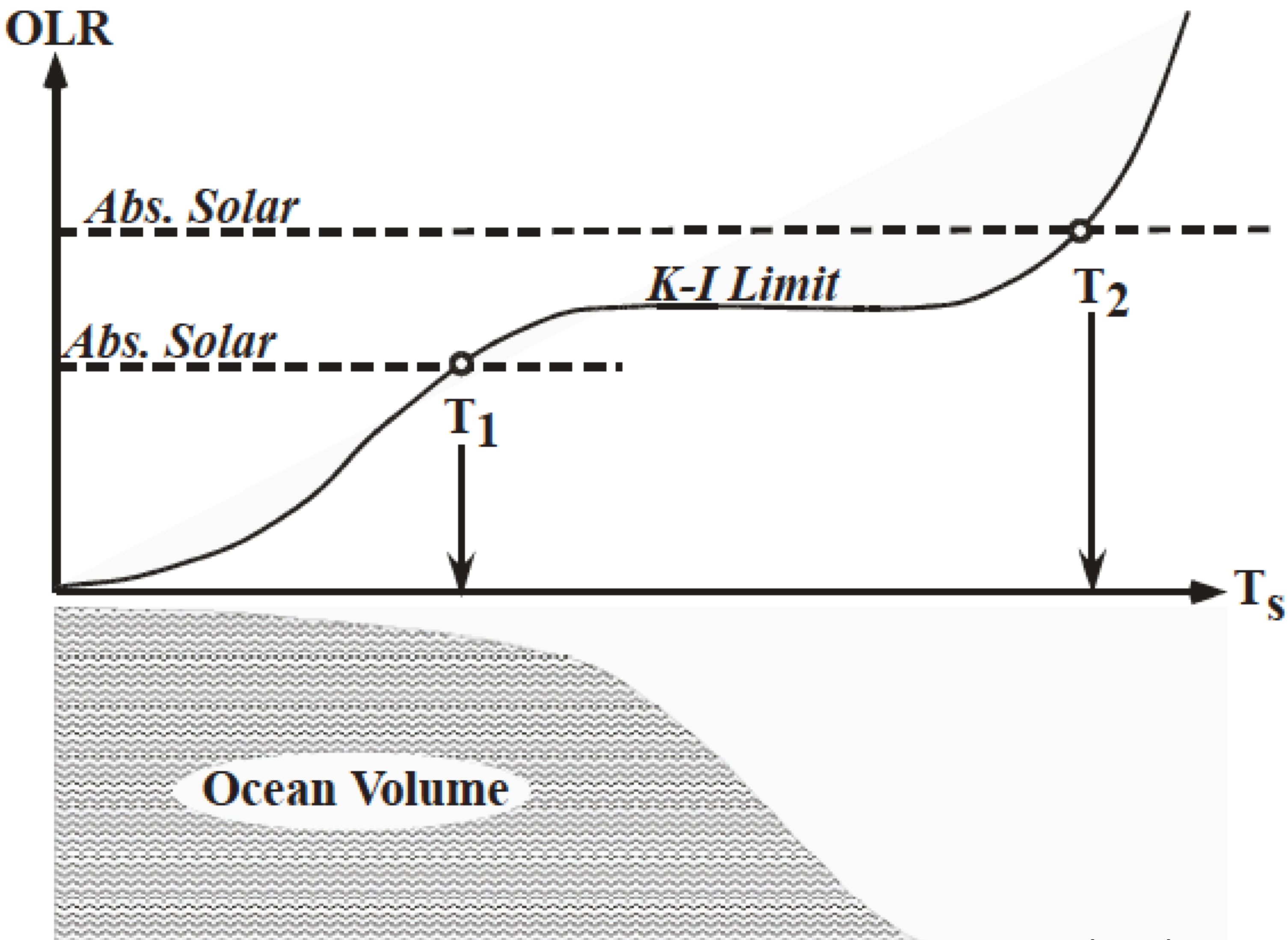


Figure 5. Increase in outgoing thermal flux as a function of surface temperature, after Nakajima *et al.* [13]. Black lines marked from 1 to 3 show how the top of atmosphere flux changes with increasing surface temperature for successively higher concentrations of a non-condensible greenhouse gas (e.g. carbon dioxide). Line 2 corresponds to Earth's present amount of non-condensible greenhouse gases and lines 1 and 3 are illustrative of lower and higher concentrations, respectively. All lines are for an amount of background, non-condensible and non-radiatively active gas similar to Earth's (see fig. 6 of Nakajima *et al.* [13] for other background gas inventories). Radiation limits are shown in colour (see figure 1 for labels). Fig. 9 of Kasting [12], derived from a spectrally resolved model, has similar features.

Goldblatt & Watson 2012

The runaway greenhouse leads to the loss of surface liquid water
(However, a supercritical H2O-rich C-poor phase may persist)



Pierrehumbert 2010 figure 4.4

What stops the temperature from going up indefinitely? (Why is it limited to ~1500K?)
(It's not the latent heat of magma melting – it's coincidence that the runaway GH stops around the dry-rock solidus).
Two key windows in the water vapor absorption spectrum: 8-12 microns and <~4 microns

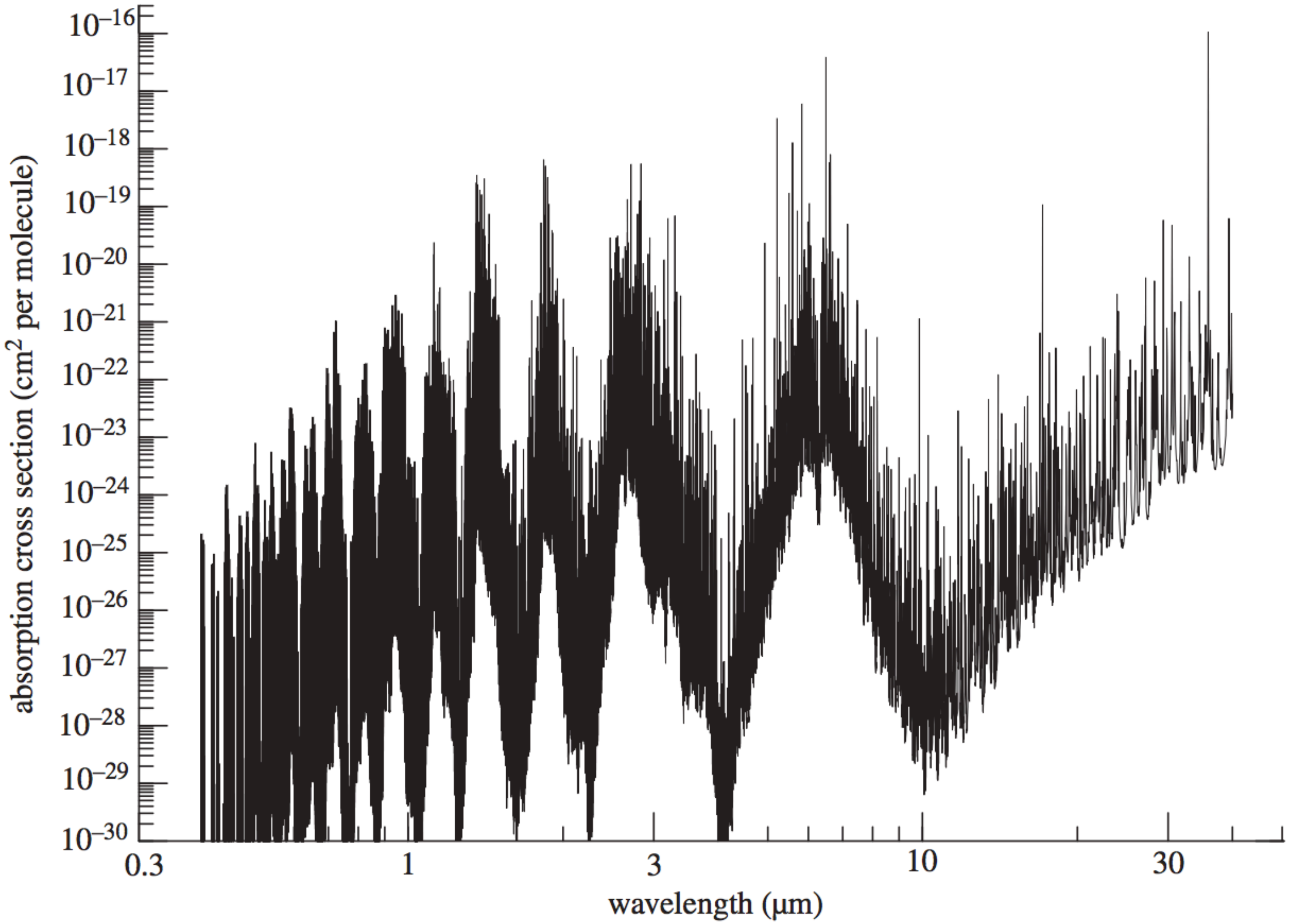
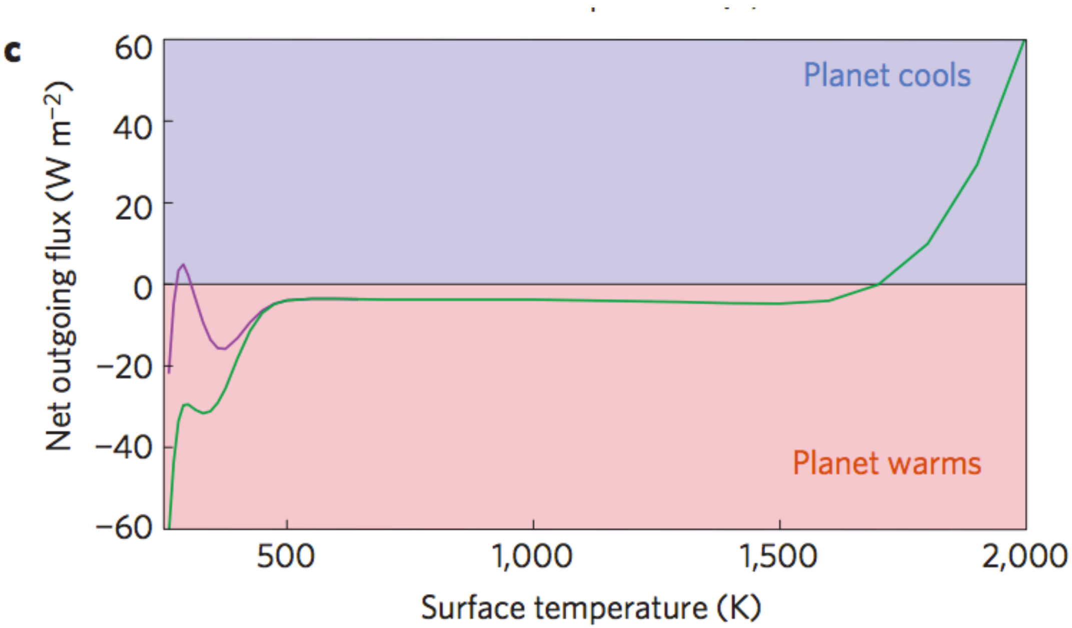


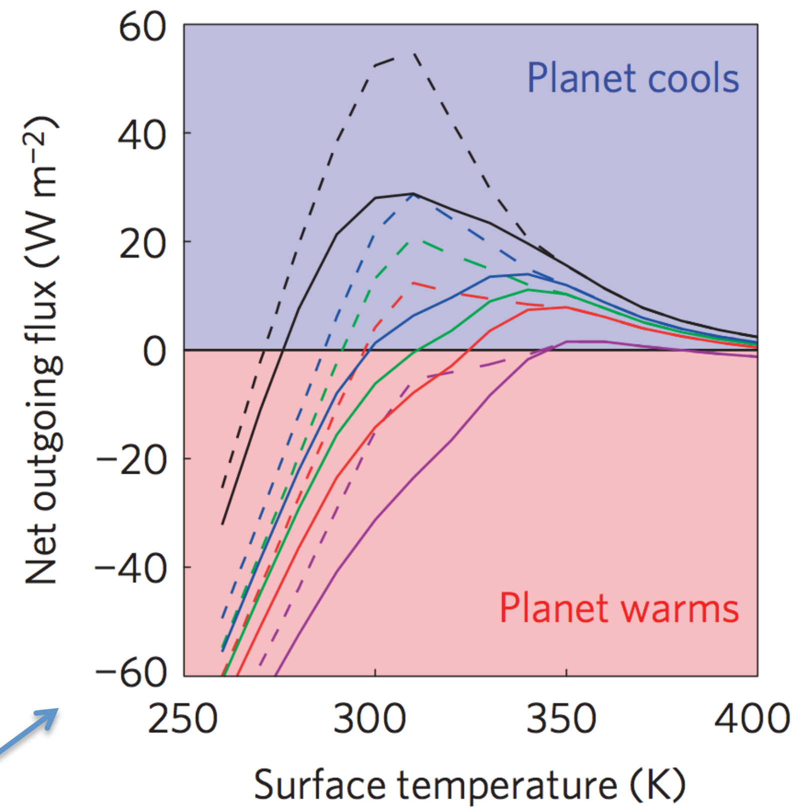
Figure 6. Absorption spectrum of water vapour (0.3–40 μm) shown at 220 Pa and 260 K. Note the 'window' regions where the absorption coefficient is low and the general decline of absorption coefficient at a shorter wavelength.

Anthropogenic greenhouse gases (probably) cannot trigger the runaway greenhouse.

Goldblatt et al. Nature Geoscience 2014



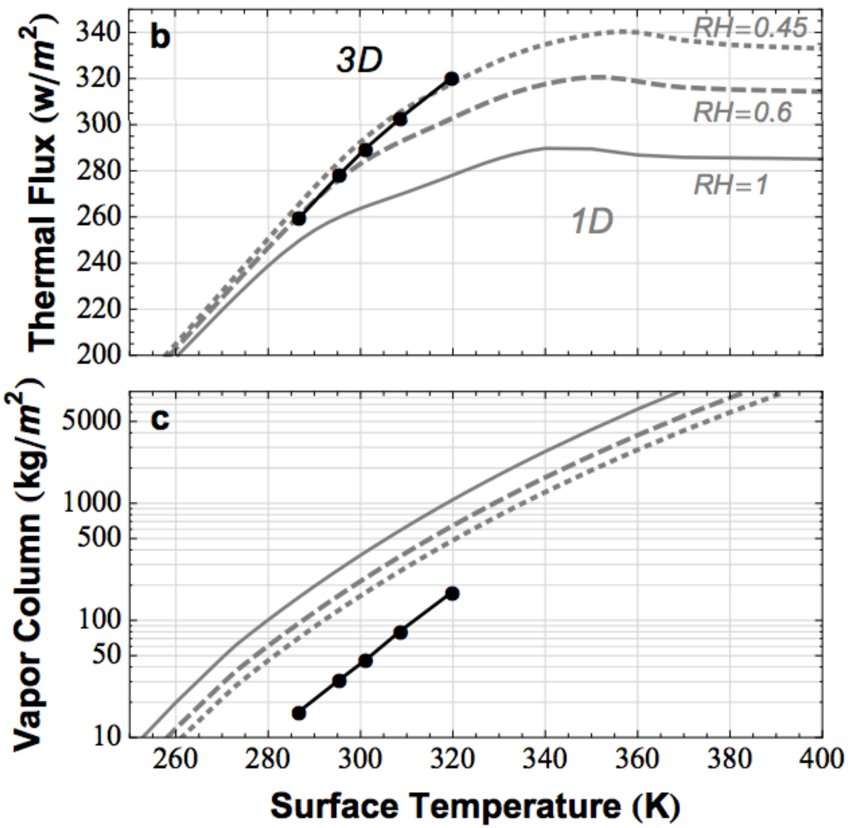
Scenario	CO_2 (ppmv)	
Baseline	0	Black
Pre-industrial	287	Green
RCP 8.5, year 2100	936	Blue
Extreme anthropogenic	3,000	Red
Arbitrarily high	30,000	purple



Dashed lines: RH < 1
Solid lines: RH = 1

Modern albedo

Earth today is close to the runaway greenhouse limit. The runaway greenhouse can be triggered by an increase in solar luminosity



Leconte et al. 2013 Nature

Time for loss (10^9 yr)

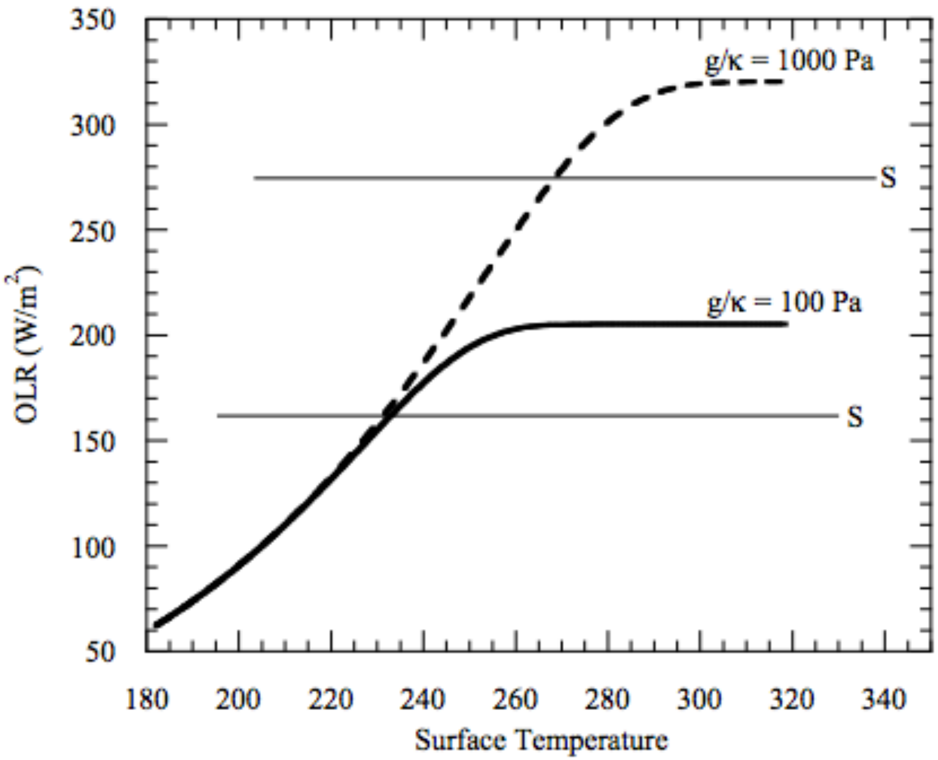
water lost (bars)

$$\Delta t(\mathrm{by}) = 2.4 \times 10^9\ \Delta p(\mathrm{H_2O})/\Phi_{\mathrm{esc}}(\mathrm{H})$$

H loss flux (atoms cm^{-2} s^{-1})

High gravity moves the runaway greenhouse limit closer to the star
e.g. metal-rich planet, larger-radius super-Earth

Temperature → vapor pressure
Vapor pressure x humidity / gravity → column mass of greenhouse gas
Column mass → greenhouse effect.

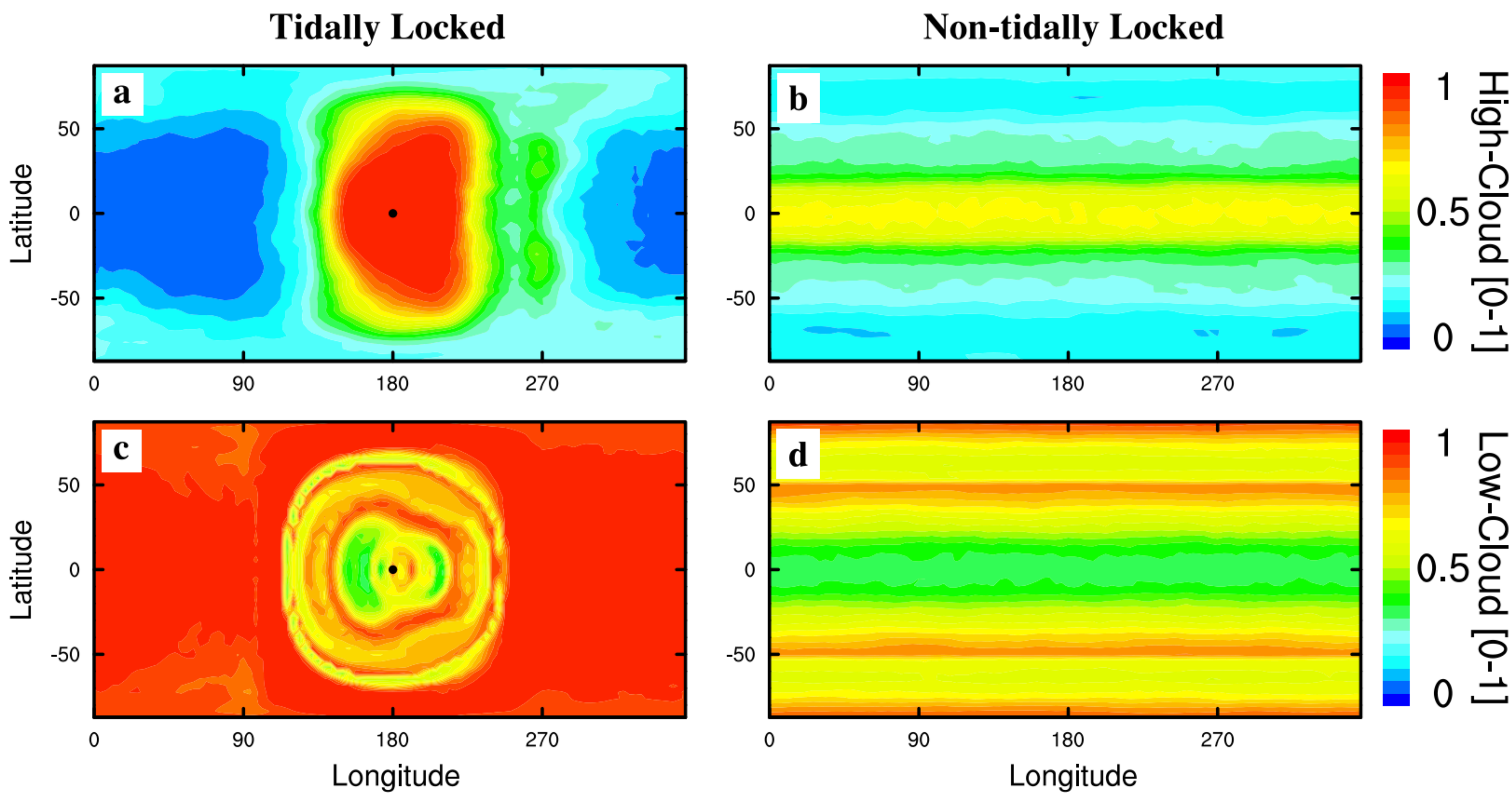


Model	Inner Habitable Zone: Moist greenhouse	Runaway greenhouse
Mars-sized planet*	1.035 AU	1.033 AU
Earth	0.99 AU	0.97 AU
Super-Earth**	0.94 AU	0.92 AU
$p\mathrm{CO}_2 = 5.2 \times 10^{-3}$ bar†	**1.00 AU**	**0.97 AU**
$p\mathrm{CO}_2 = 5.2 \times 10^{-2}$ bar	1.02 AU	0.97 AU
$p\mathrm{CO}_2 = 5.2 \times 10^{-1}$ bar	1.02 AU	0.97 AU
$p\mathrm{CO}_2 = 5.2$ bar	0.99 AU	0.97 AU

* Surface gravity = $3.73\ \mathrm{m.s^{-2}}$
** Surface gravity = $25\ \mathrm{m.s^{-2}}$

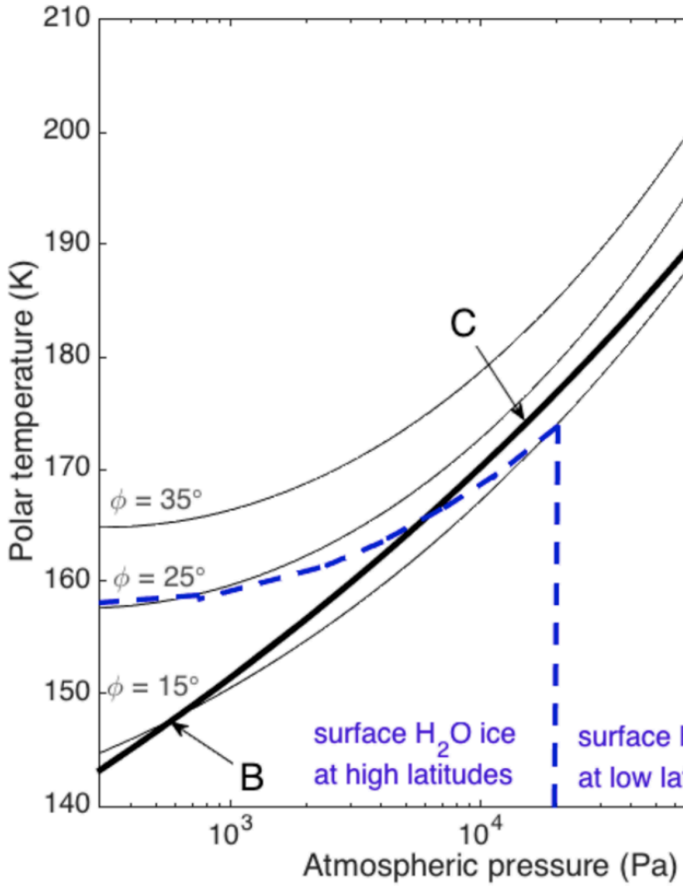
Max OLR ~= slightly less than the blackbody flux corresponding to the temperature one optical depth down from the top of the atmosphere

High-albedo clouds can shift the runaway GH boundary closer to the star. High-albedo clouds are at the substellar point when the planet is slowly rotating (e.g., tidally locked and in the habitable zone).



Yang et al. 2013

Runaways due to the GH-effect of a condensable apply to non-H2O condensates as well – e.g., CO2 on Mars



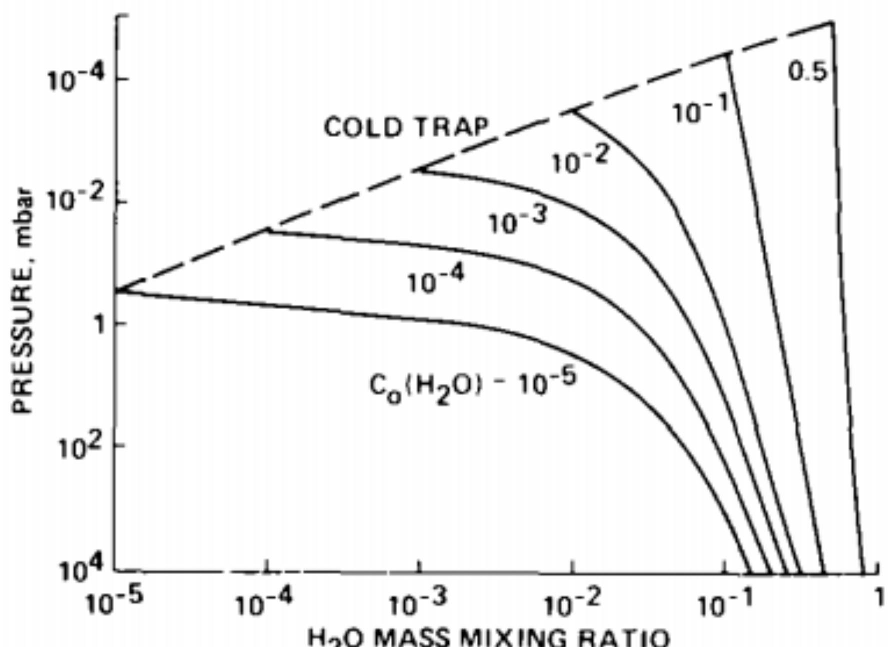
Kite et al. arXiv:1709.08302

Fig. 3. Phase portrait for atmospheric collapse on Mars, showing how atmospheric collapse drives H_2O-ice distribution (this calculation uses the GCM of ref. 17). Thin black lines show annual-mean polar temperature as a function of atmospheric pressure assuming Faint Young Sun luminosity. Thick black line is the condensation curve for CO_2; atmospheres below this line are collapsing onto polar CO_2 ice caps (e.g., **A→B**). Blue dashes outline the approximate pressures and obliquities below which H_2O ice is stable only at Mars' poles [e.g. 17, 29, 54]. Collapse leads to relocation of surface H_2O ice from highlands to poles. In this GCM, for an initial CO_2 inventory of 8×10^{18} kg (= 2 bar), the atmosphere is stable until $\varphi \leq 15$ deg (at **A**). Rapid collapse ($\sim10^3$ yr) moves the system to point **B**. Increasing obliquity (over 10^5-10^7 yr) moves the (ice cap)/atmosphere system along the condensation curve to **C**, (the highest φ consistent with permanent CO_2 ice caps). Further φ rise leads to sublimation of the CO_2 ice cap ($\sim10^3$ yr) and the system returns to **A**.

Also: N2 runaway on Early Titan?

The runaway & moist greenhouses: under the hood

Raising temperature raises the H_2O mixing ratio at the cold trap (assumed isothermal)



Kasting 1988

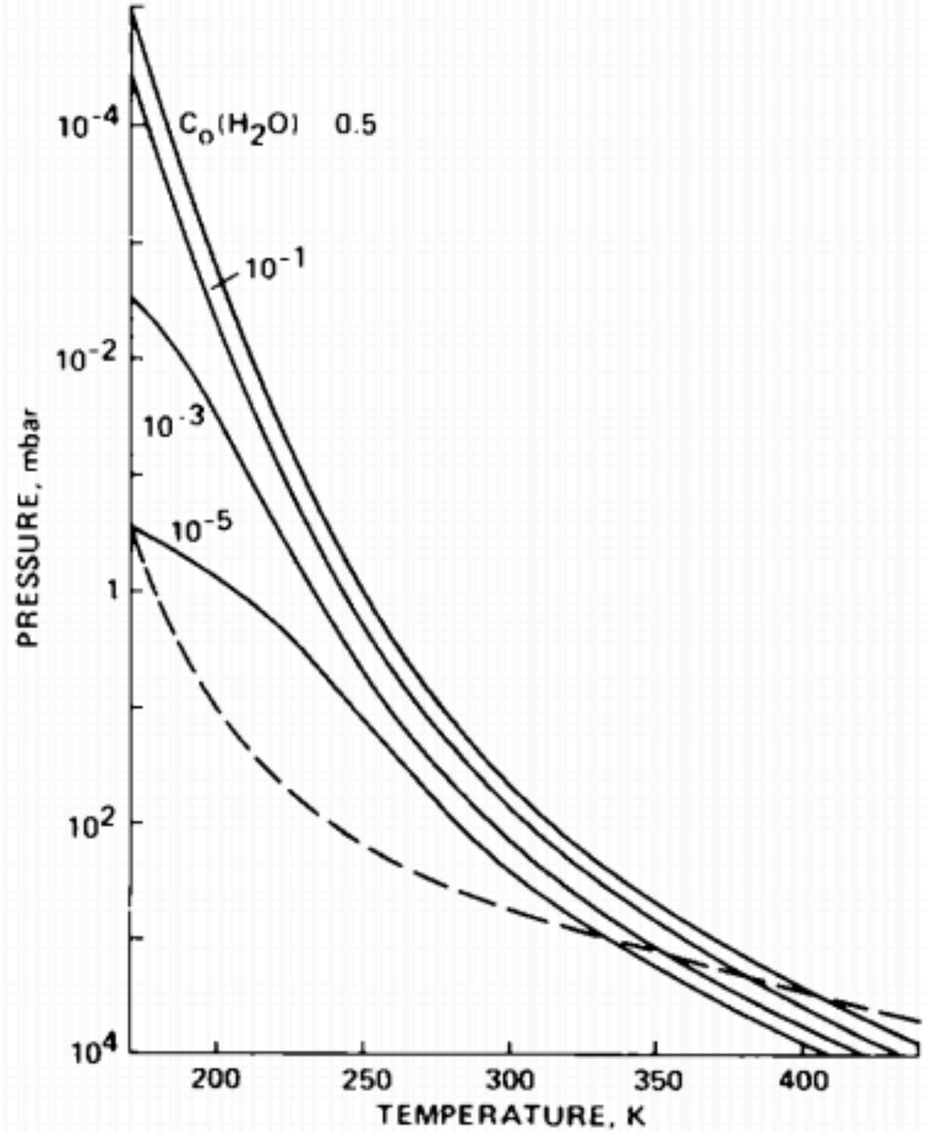


FIG. 15. Calculated pseudoadiabatic temperature profiles for various values of the H_2O mass mixing ratio at the cold trap. The dashed curve represents the dayside temperature profile below 90 km in the present Venus atmosphere.

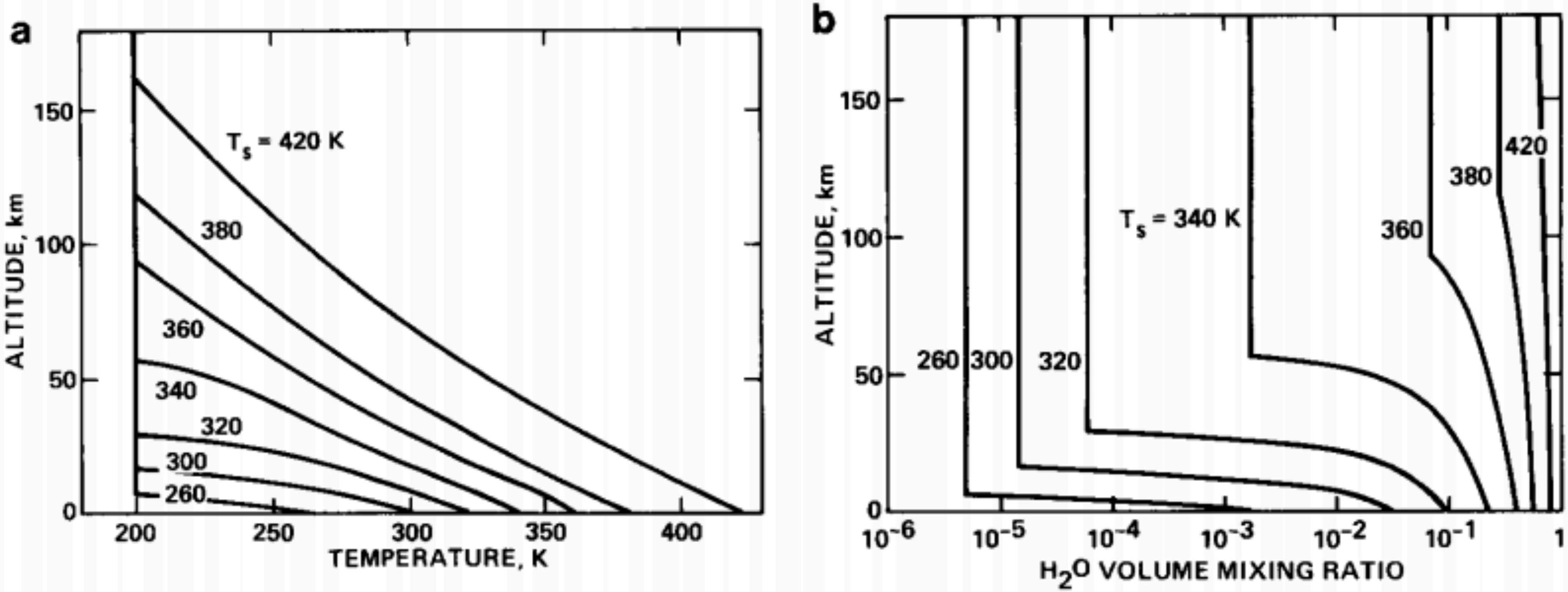


FIG. 5. Temperature (a) and H_2O volume mixing ratio (b) versus altitude for selected moist greenhouse atmospheres. The lower portions of the curves represent moist pseudoadiabats.

Kasting 1988

How was the last 10th of Venus' ocean removed?

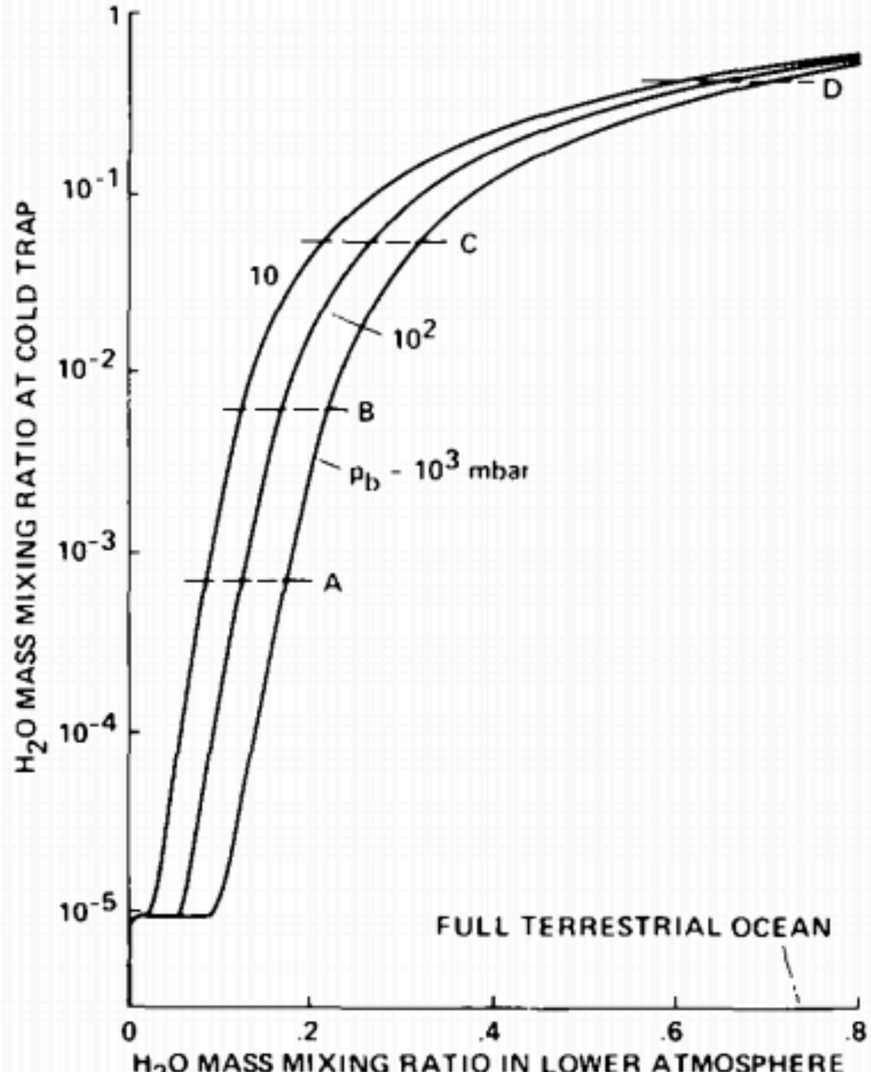


FIG. 17. Relationship between the H_2O mass mixing ratio at the cold trap and in the lower atmosphere for three different values of the pressure p_b at the bottom of the moist convective layer. The horizontal dashed lines labeled A to D correspond to the cases described in the text.

Kasting 1988

Runaway greenhouse – key points

- The (H2O-)runaway greenhouse is a geologically rapid increase in planet surface temperature from <400K to >1000K caused by a positive feedback between the saturation vapor pressure of water vapor and the
- Be able to explain the mechanism of the runaway greenhouse
- It is almost certain that release of CO2 by humans cannot cause a runaway greenhouse
- The exact threshold for the runaway greenhouse depends on cloud cover, land fraction, and planet rotation rate

Backup/additional slides