Planetary Atmospheres and Planet Habitability

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The Astrophysics of Planetary Habitability

Vienna, Feb. 10th, 2016

Thanks

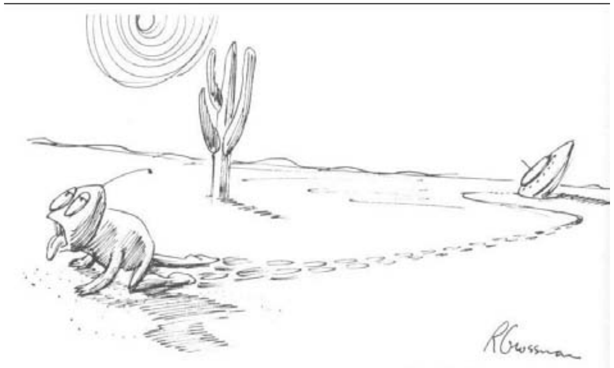
- Organizers
- Kevin France, Shigeru Ida
- Xiaomeng Huang, Tong Li, Wanjing Wan, Yuwei Wang

To build a habitable planet, you need:

- 1) elements important to life as we know it: CHONPS + metals (Fe, Cu, Ni, Mo, Mn, etc.)
  - Seems to be readily available

- 2) sunlight
  - Underground life is not well understood and hard to find around other stars
  - Seems to be readily available except for rogue planets

- 3) liquid water (universal solvent)



"Ammonia! Ammonia!"

Drawing by R. Grossman; © 1962.
The New Yorker Magazine, Inc.

Quiz

- What spheres have we talked about regarding planet habitability?

Setting the stage...

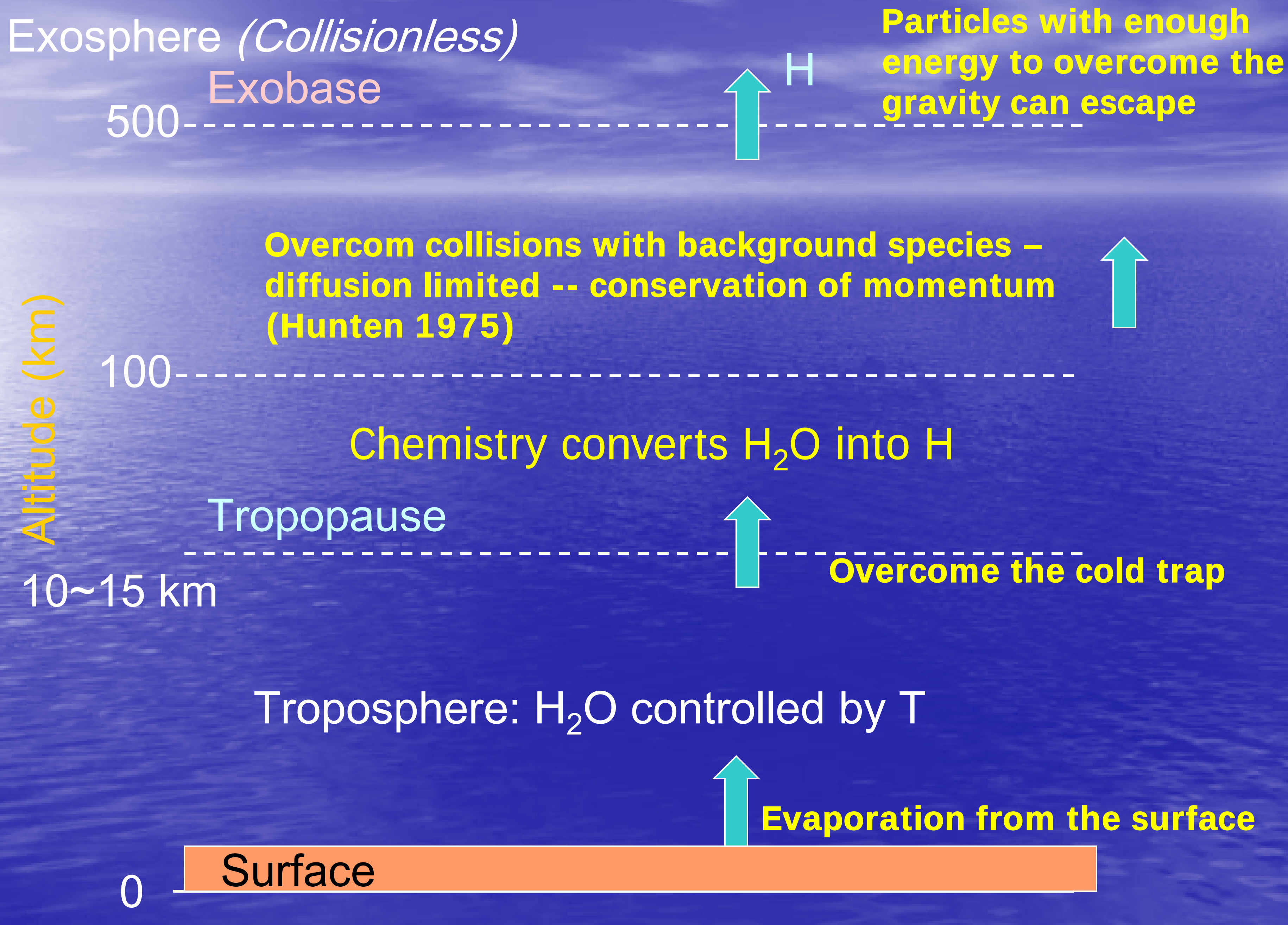
- Processes important for planetary atmospheres (Talks by Meadows, Luftinger, Alibert, Johnstone, Vidotto, and Many Others):
  - Formation: volatiles in the cores, nebula gas capture
  - Degassing: magma ocean phase followed by volcanic/MOR
  - **Escape:** hydrodynamic vs. nonthermal (stellar wind erosion, charge exchange, polar wind, etc. B field)
  - Weathering (climate stability, Abbot+ 2012, Kitzman+ 2015, but also nutrients...)
  - Chemistry (UV, protons, gamma-ray, etc.) and Life

Contents of This Presentation

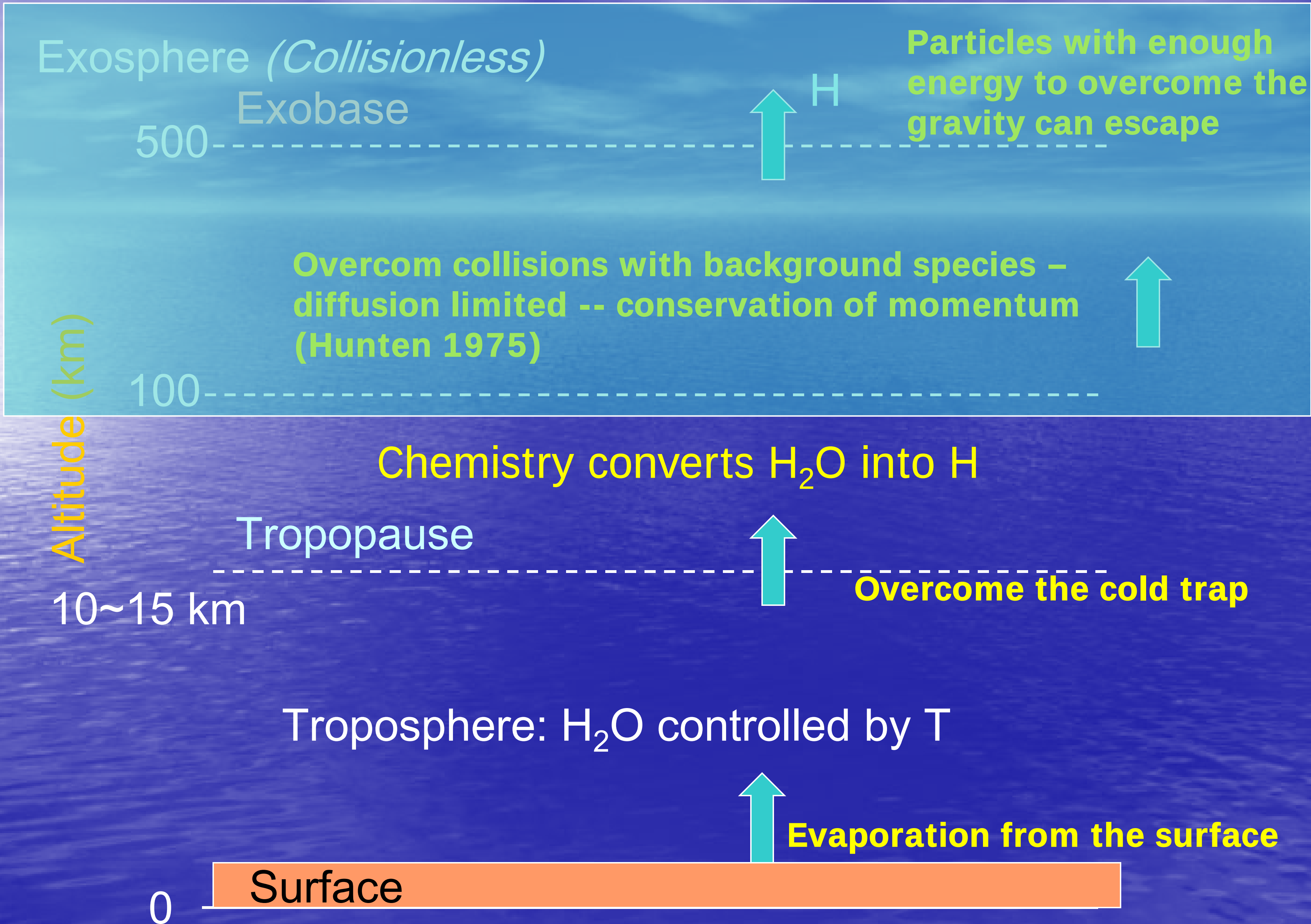
- 1) What's Controlling the Loss of Oceans? – inner edge of the HZ
- 2) The distribution of water amount on HZ rocky planets around M dwarfs is bimodal.
- 3) It is possible to distinguish photochemically produced O2. But O2 buildup as a result of water loss is an open issue.

The Loss of Oceans

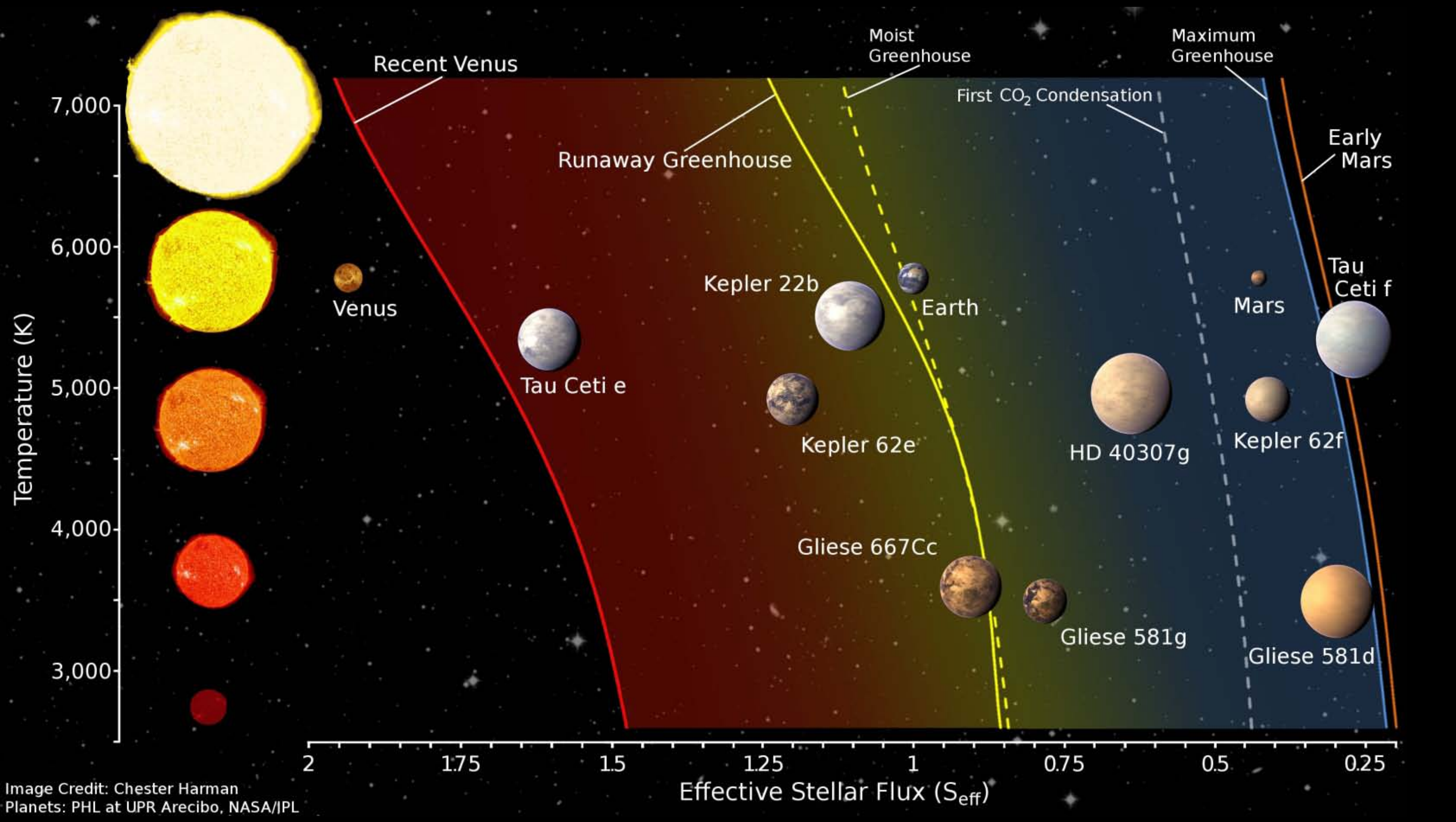
Water loss has 4 bottlenecks



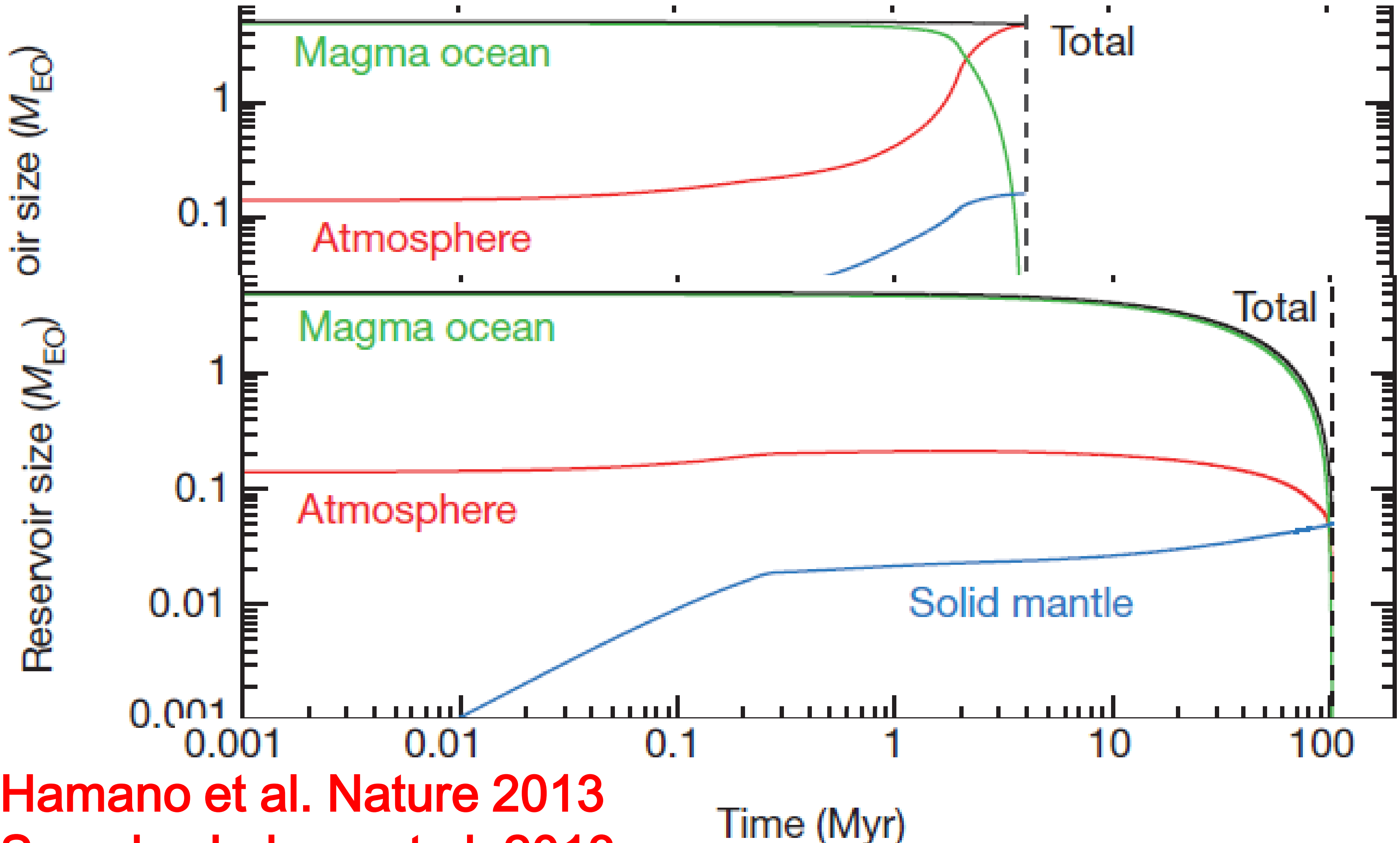
Water loss has 4 bottlenecks



Liquid Water Habitable Zone (Previous Talks)

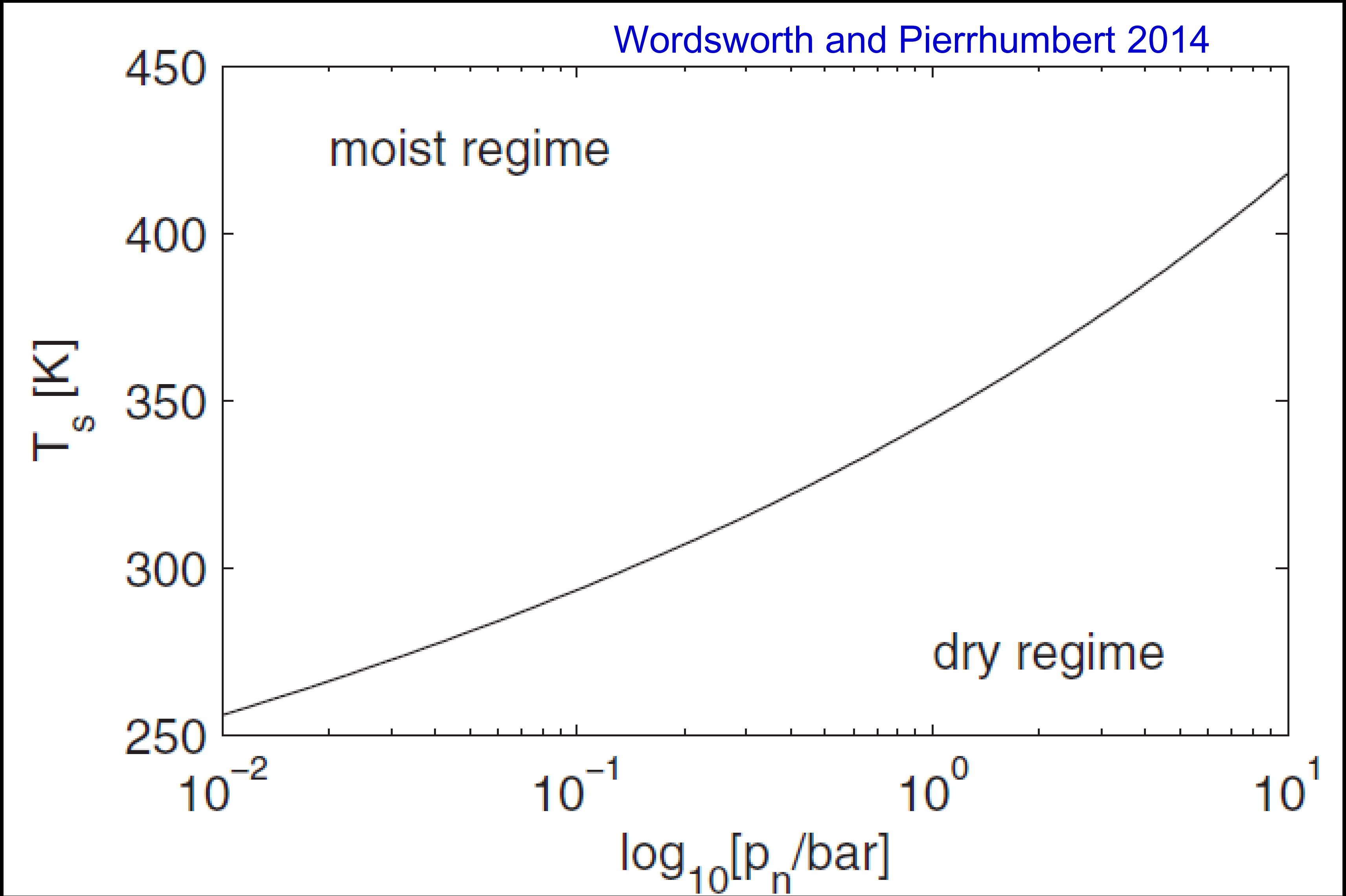


The Early Evolution of Type I and II Planets – Venus became Dry Early

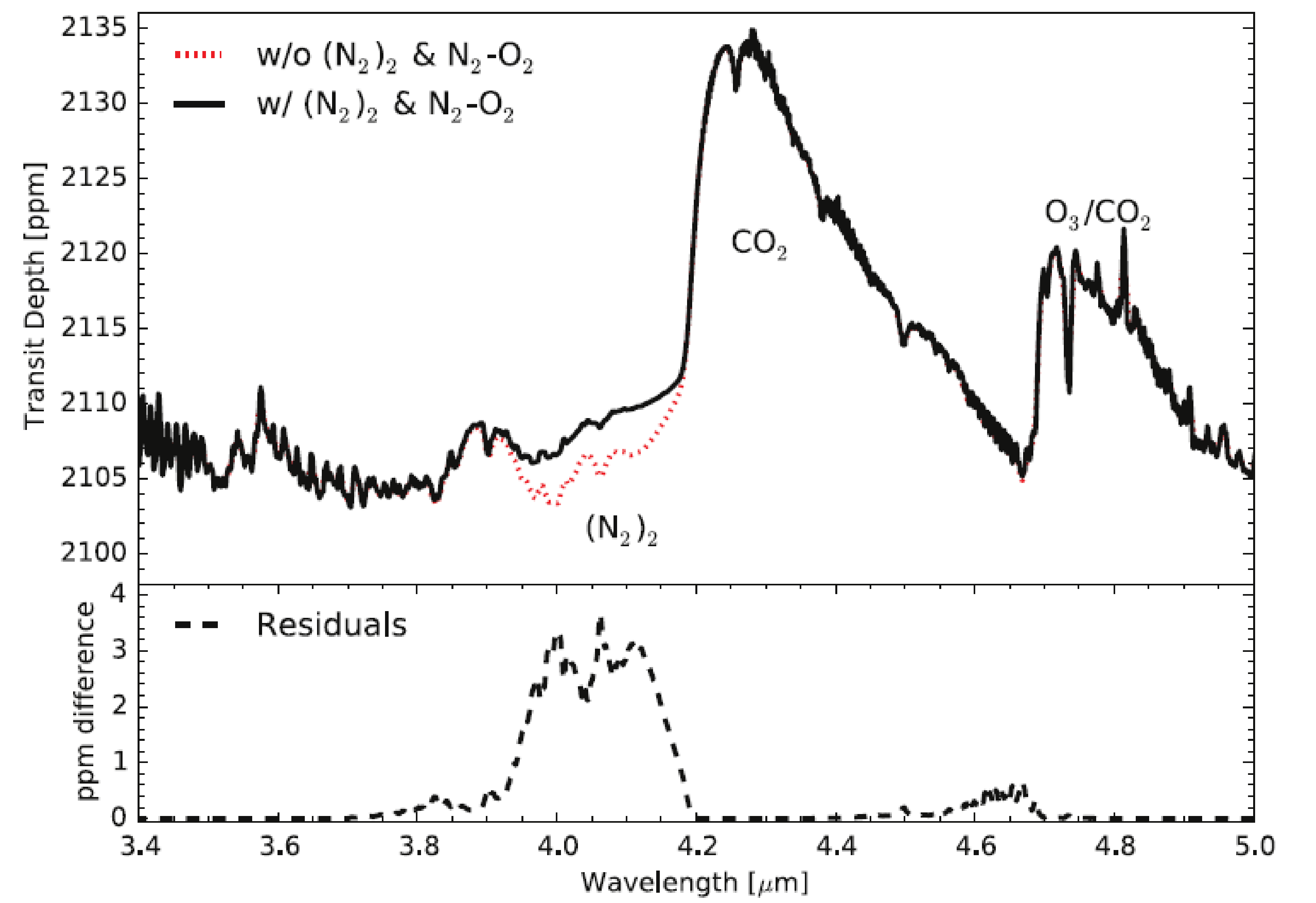


Hamano et al. Nature 2013
See also Lebrun et al. 2013

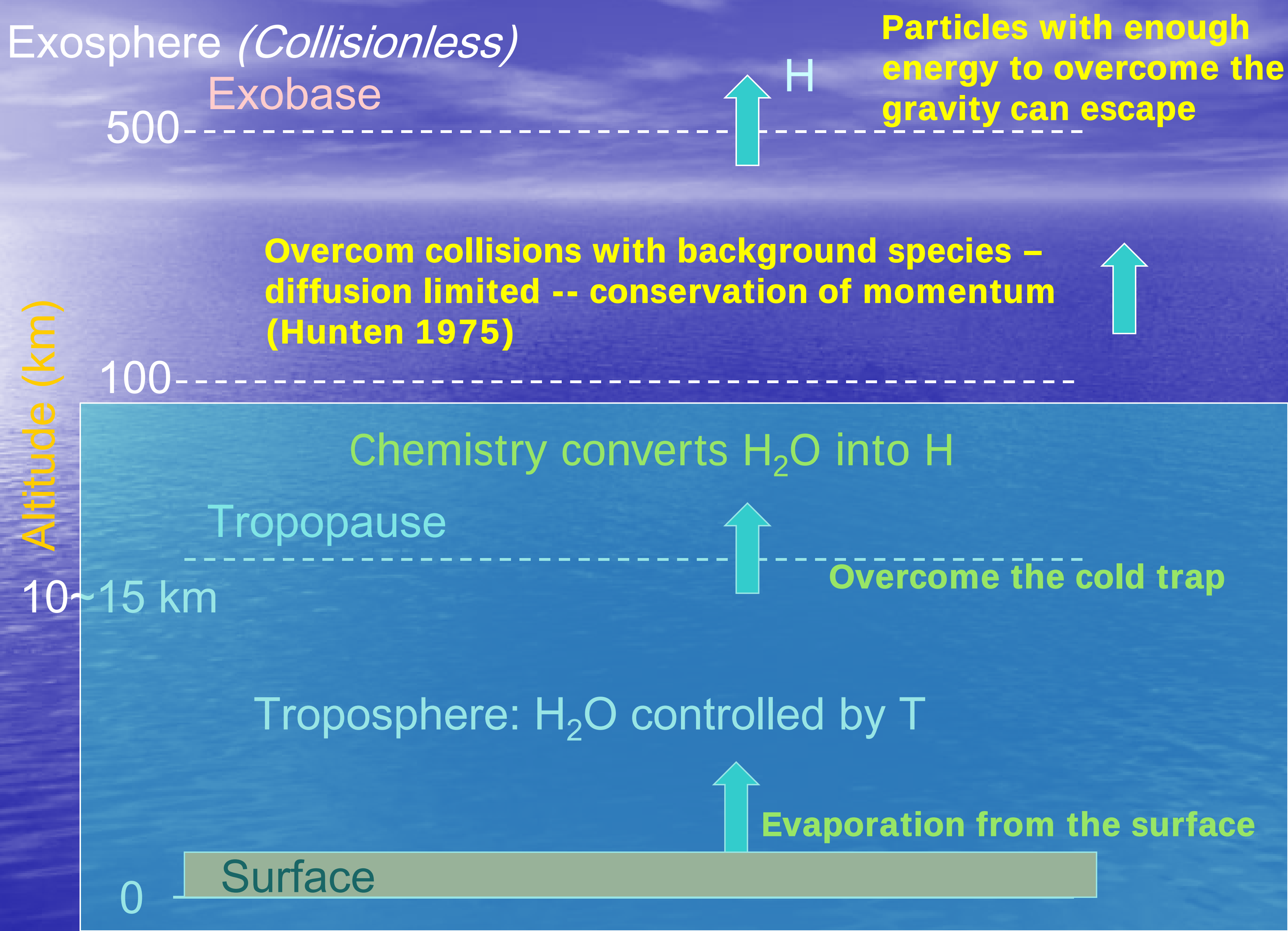
Importance of Atmospheric N_2 Pressure on Ocean Stability



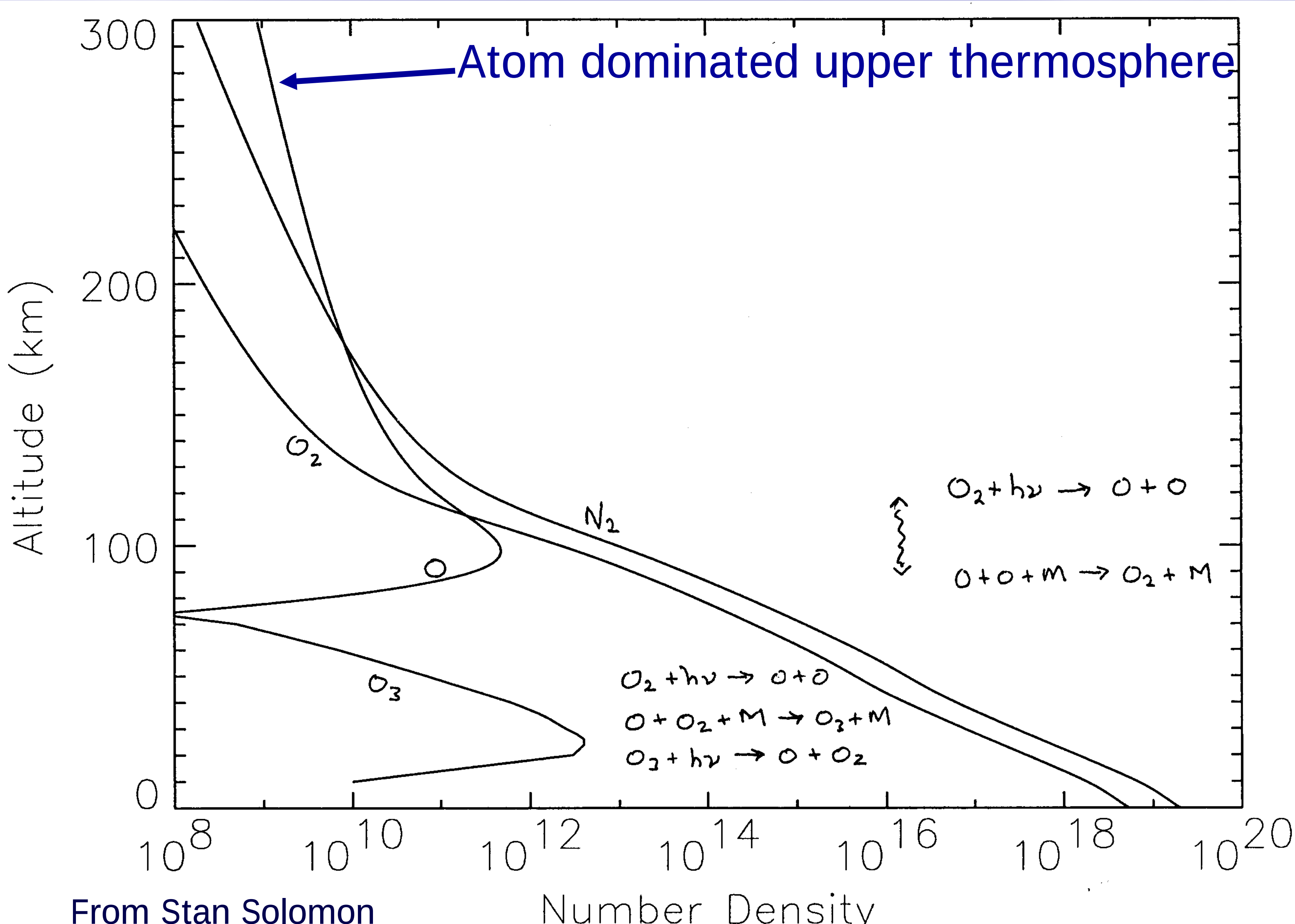
It is possible to find out the N_2 concentration in an exoplanetary atmosphere (Schwieterman+ 2015)



Water loss has 4 bottlenecks

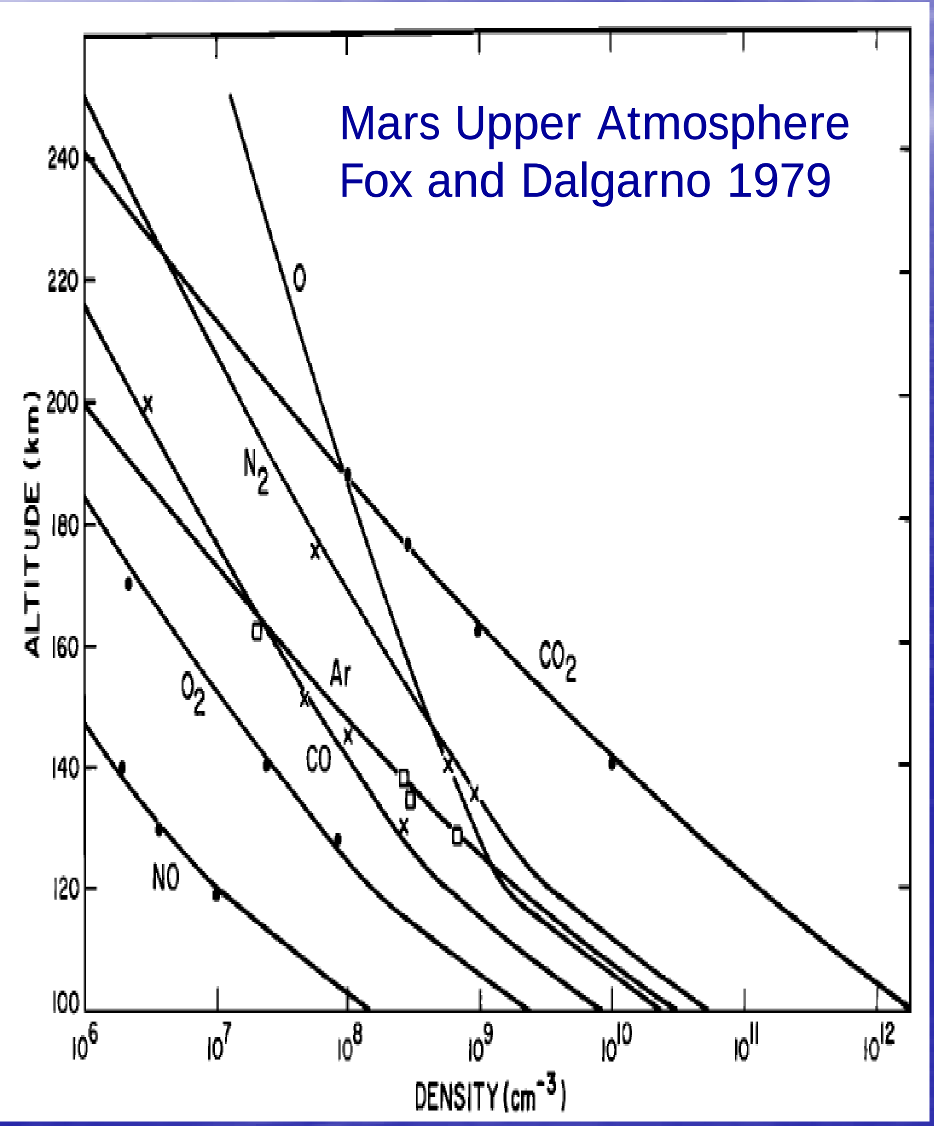


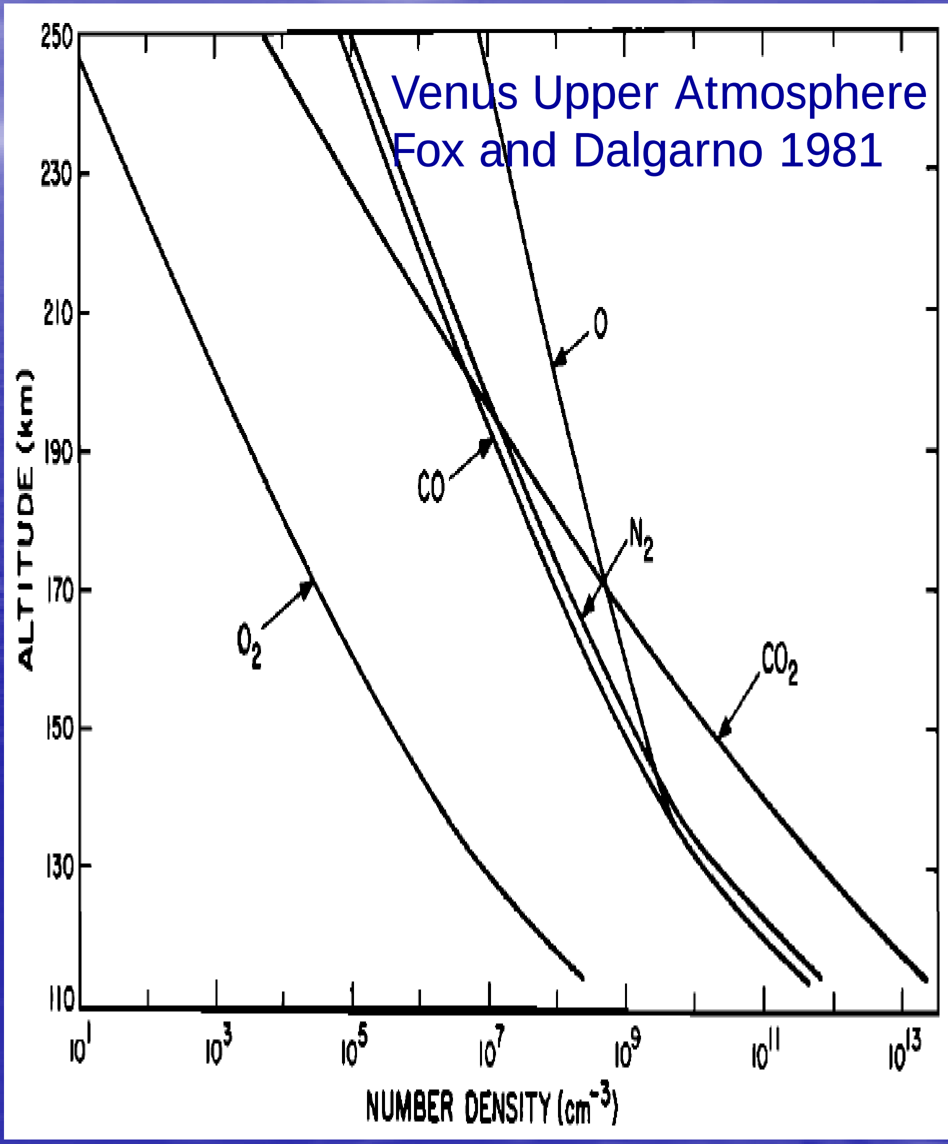
Density Structure of the Earth's Atmosphere



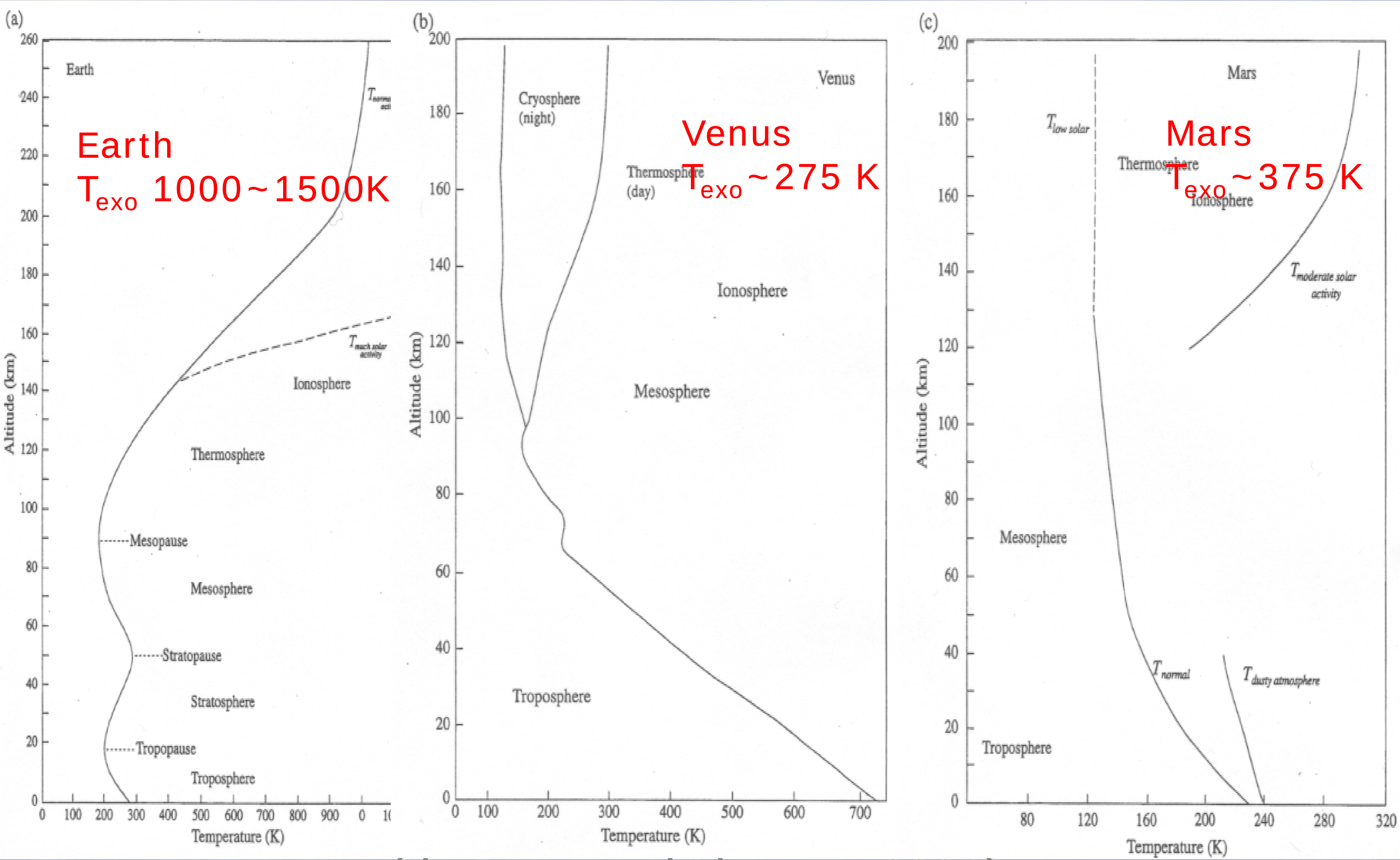
From Stan Solomon

Upper Atmosphere Structures of Venus and Mars



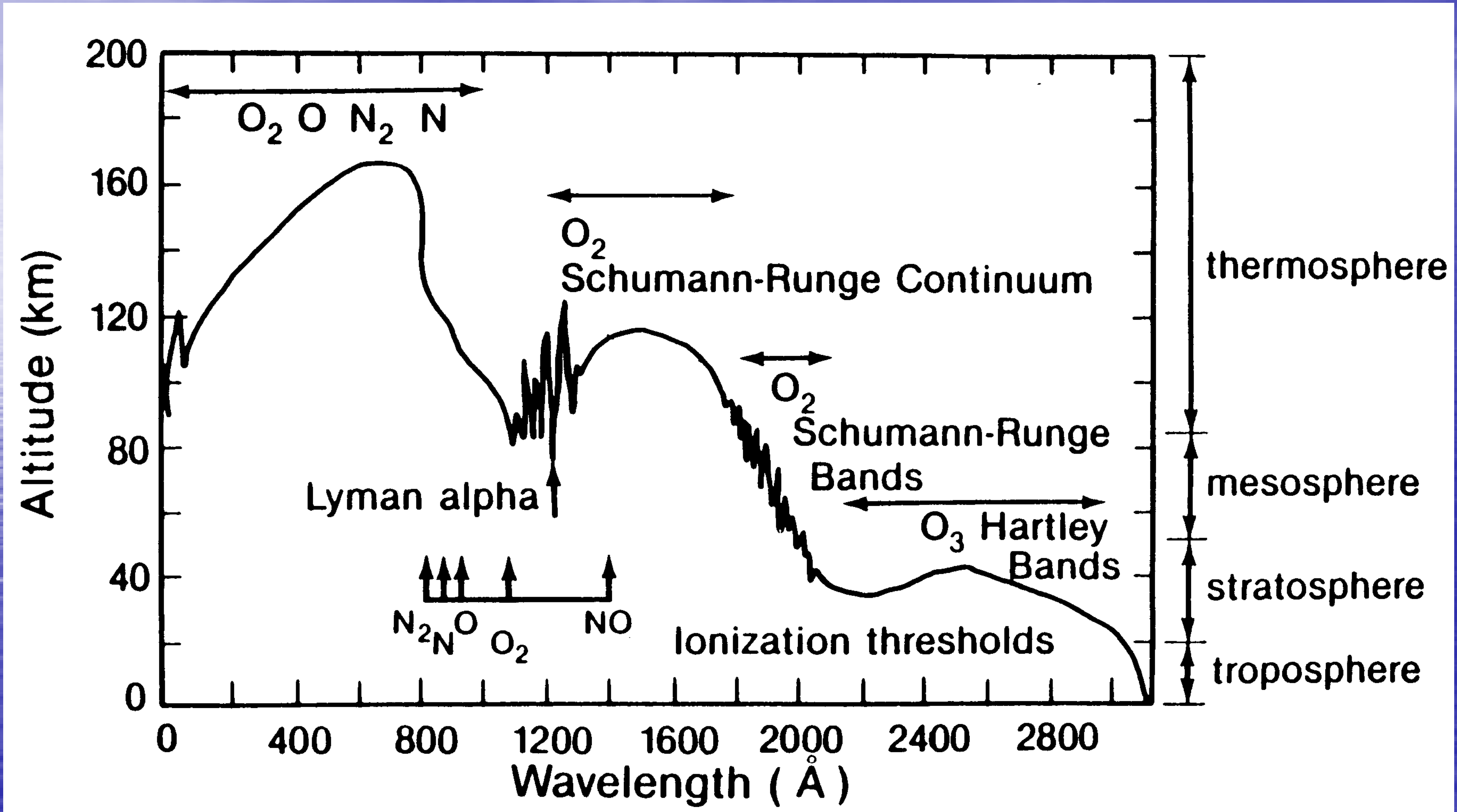


Temperature Structures in the Thermospheres of Terrestrial Planets in the Solar System Today

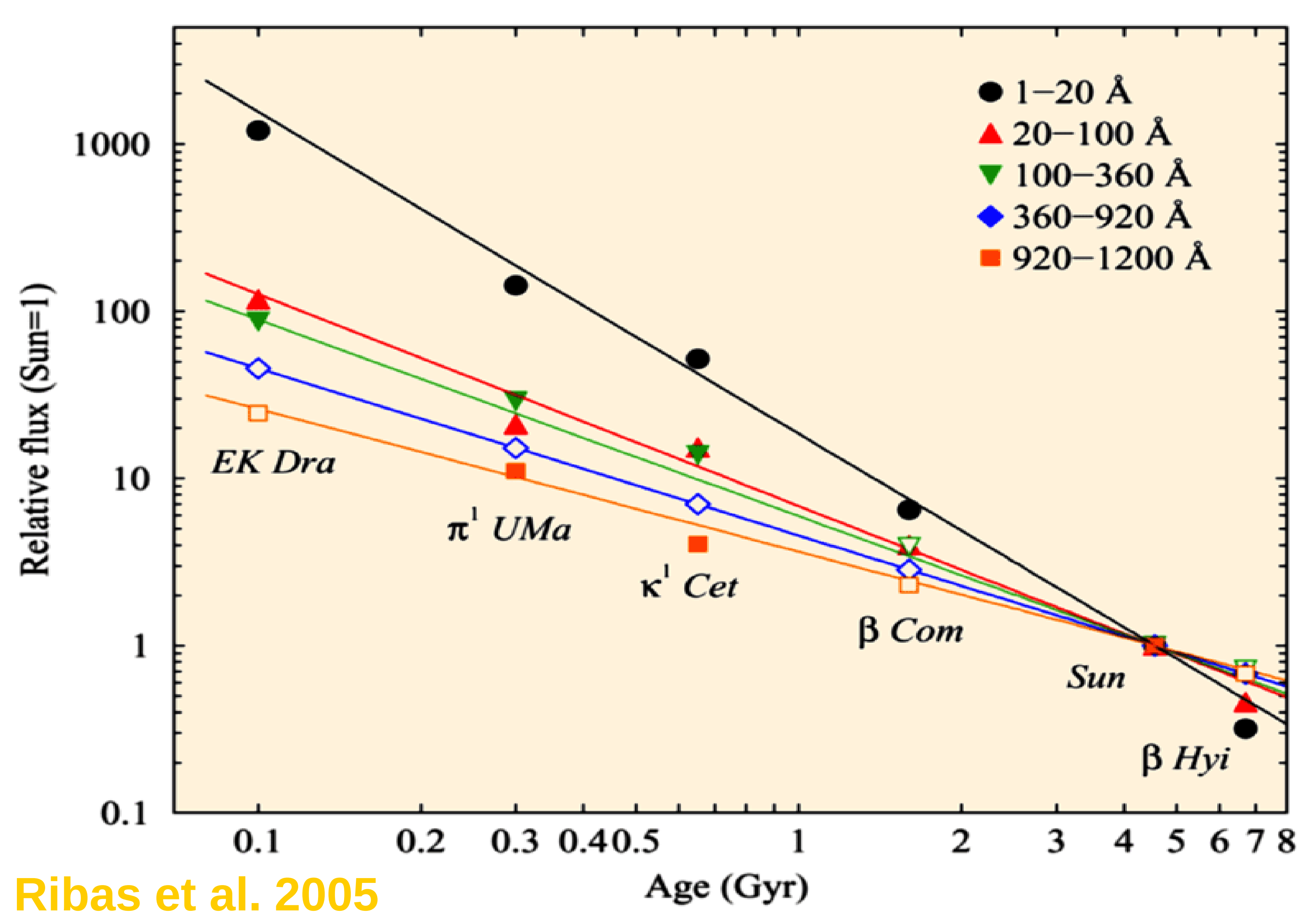


(de Pater and Lissauer 2001)

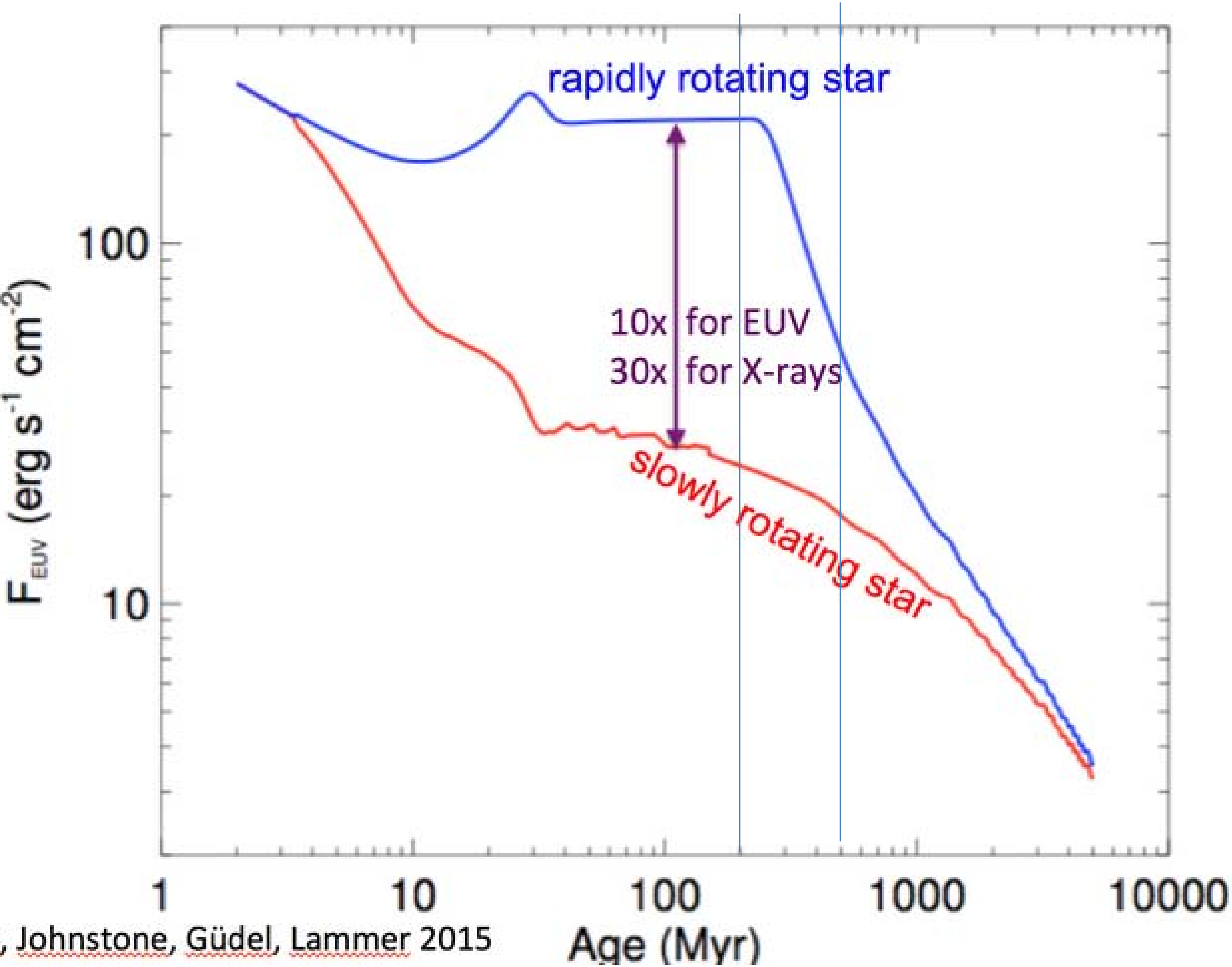
Penetration Depth ($\tau = 1$)



The young Sun emitted stronger XUV



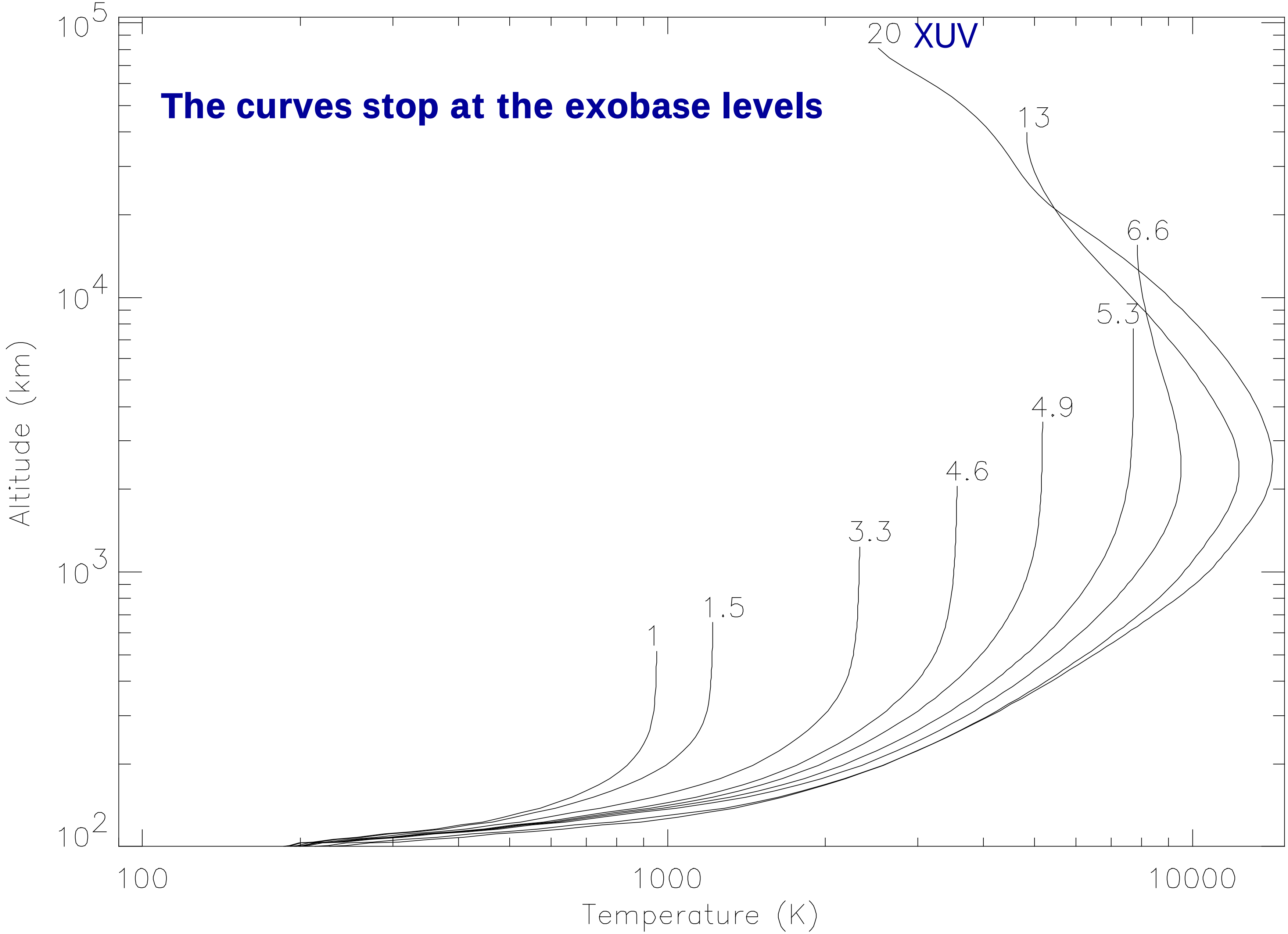
Ribas et al. 2005



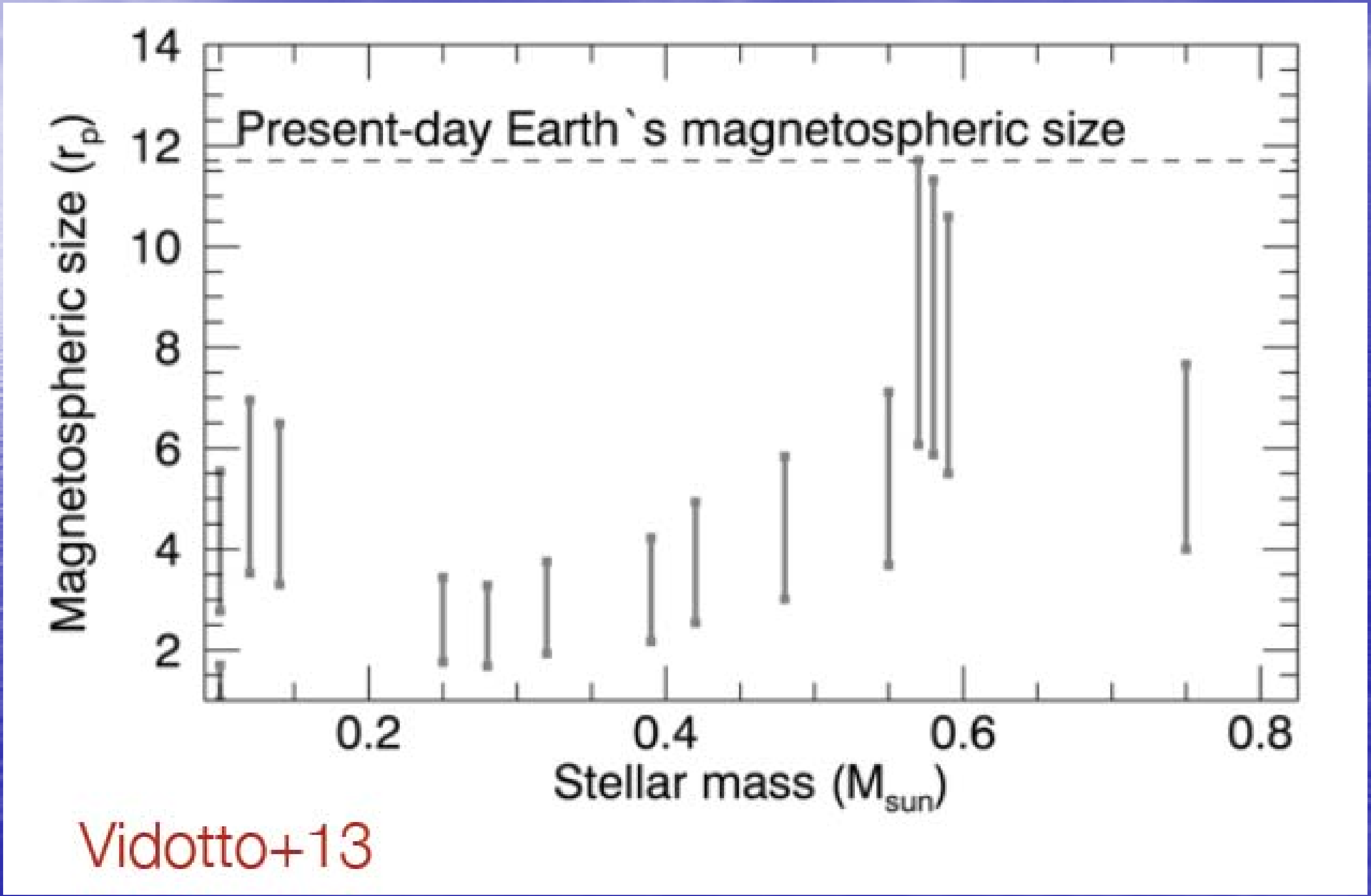
Tu, Johnstone, Güdel, Lammer 2015

Responses of N_2-O_2-rich atmosphere to strong XUV

(Tian et al. 2008a)



Under Strong XUV Radiation, the magnetosphere, thermosphere, and ionosphere could all occupy the same space! B field protection may be incomplete.



A hydrostatic atmosphere vs. a hydrodynamic atmosphere

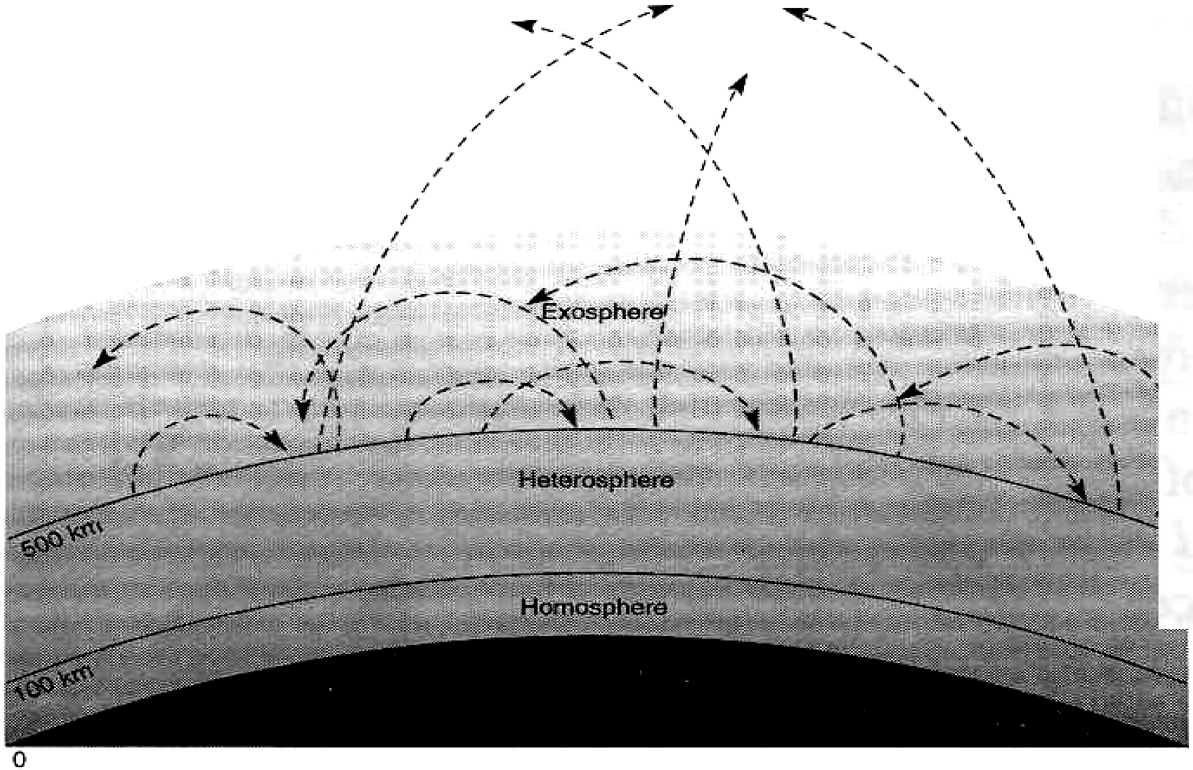
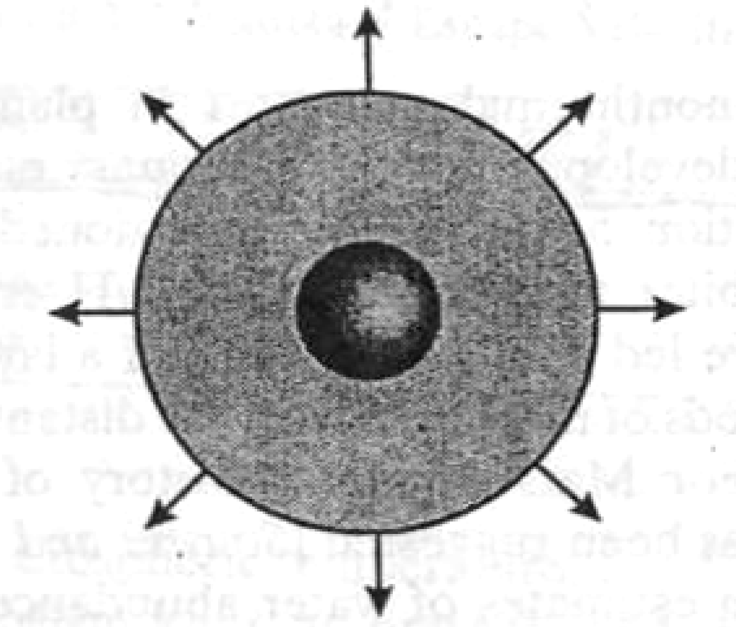
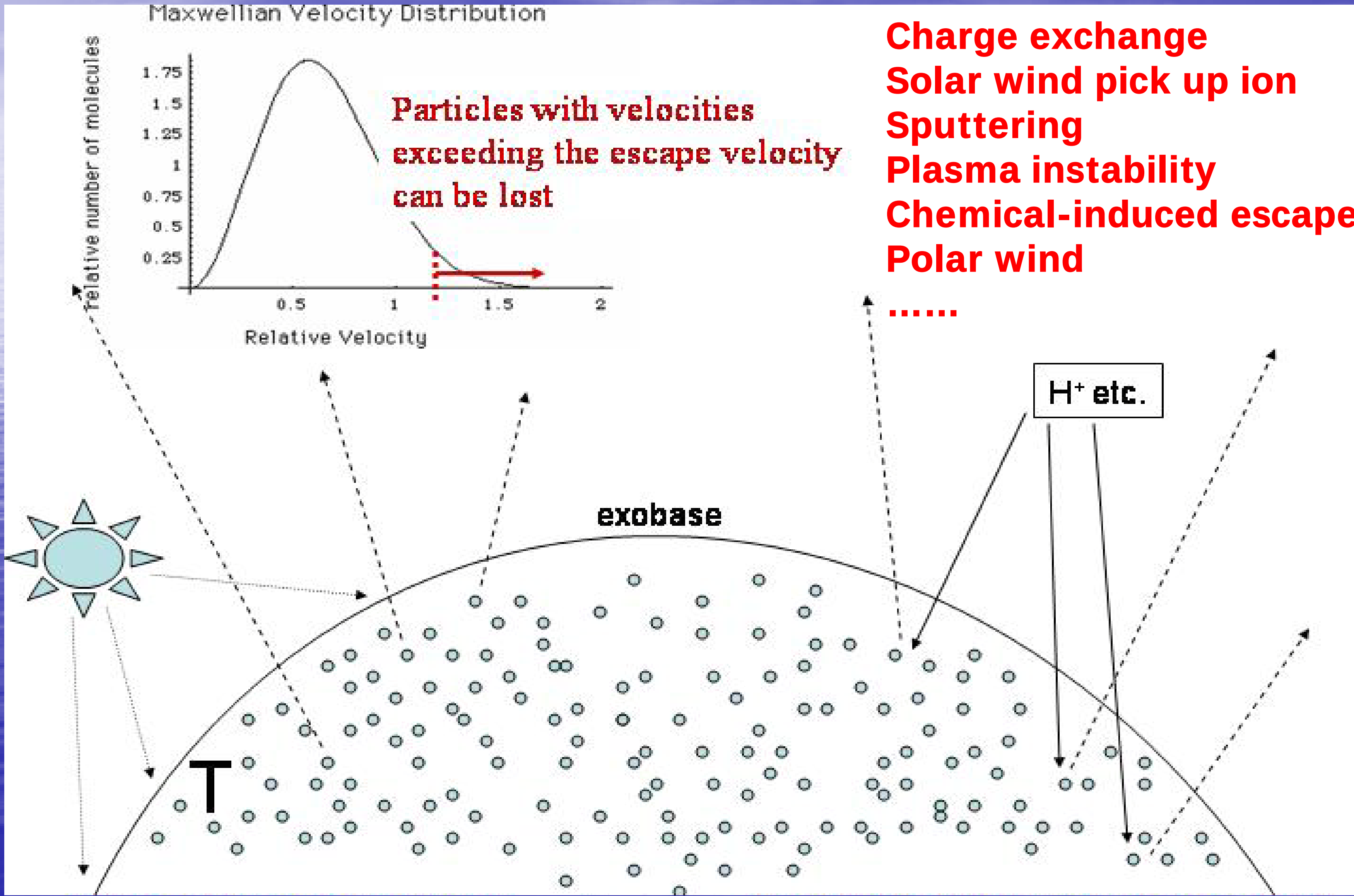


Figure 1.5 Schematic cross section of the atmosphere illustrating the homosphere, heterosphere, and the exosphere, in which molecular trajectories are shown.

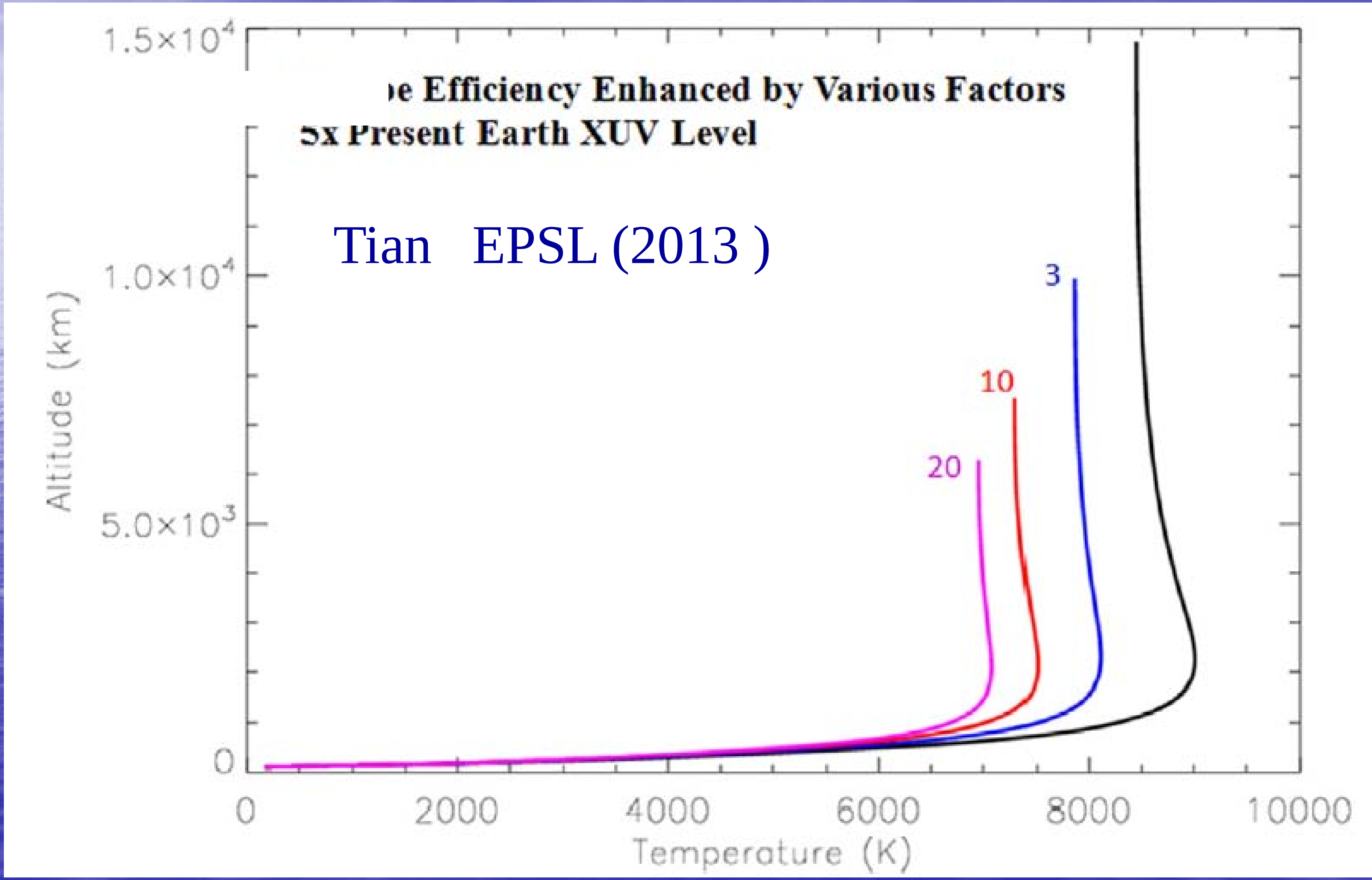


Atmosphere Escape Processes

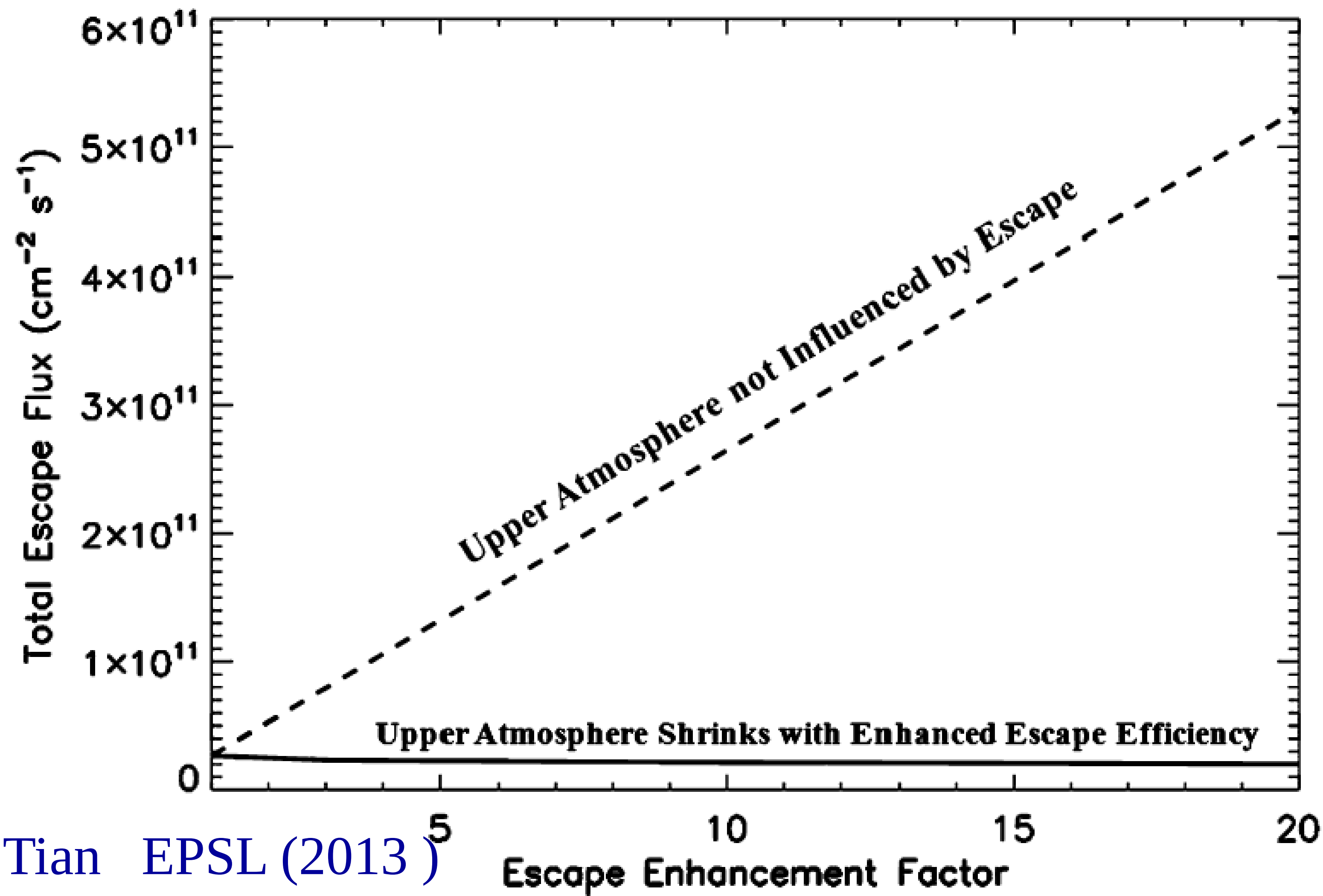
Charge exchange
Solar wind pick up ion
Sputtering
Plasma instability
Chemical-induced escape
Polar wind
……



Planetary upper atmosphere in the hydrodynamic regime would shrink IF more efficient escape processes were at work near the exobase – *conservation of energy*



Conservation of total escape rate in the hydrodynamic regime



Tian EPSL (2013)

Are there processes which can deposit energy efficiently into the upper atmosphere?

P5.3, 5.14, *Kislyakova Talk*

Temporal Variations and Impact of Stellar Wind on Atmosphere and Habitability: P5.4, 5.7-8, 5.10, 5.13, 5.15-16

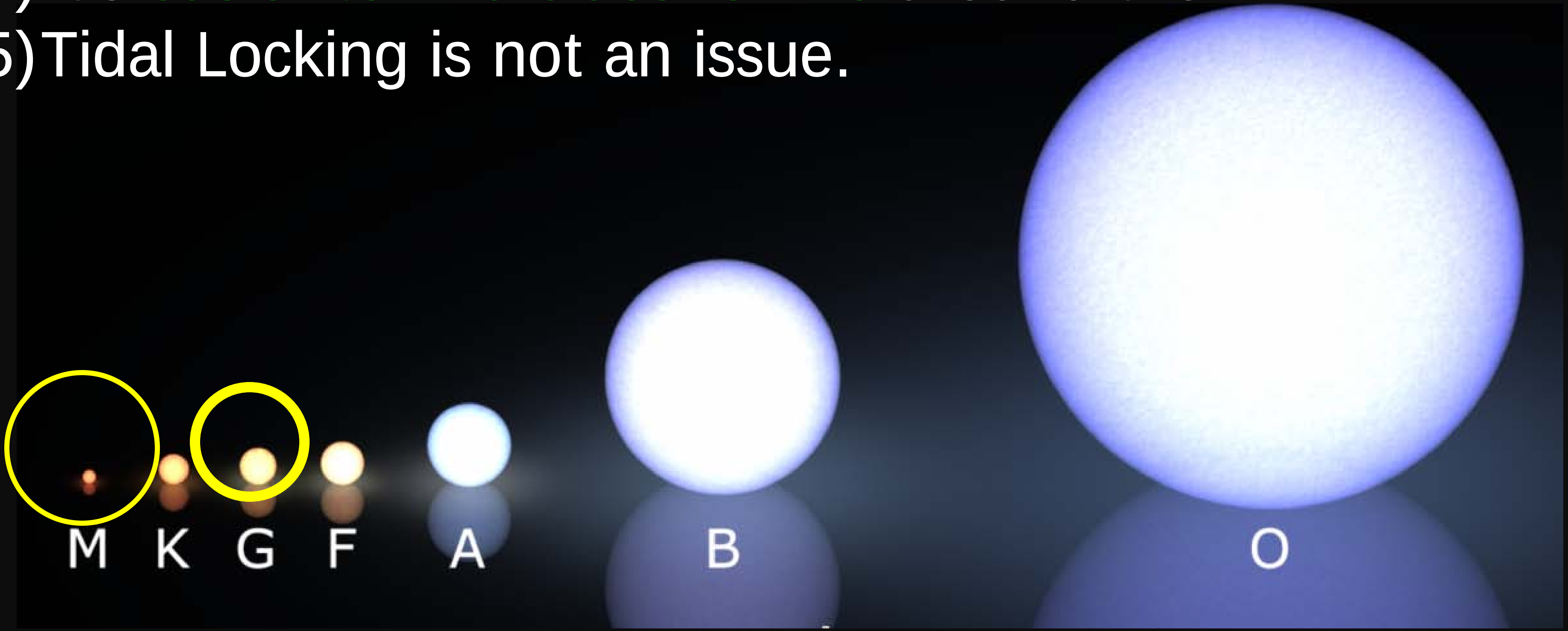
Now we know more about the HZ -- Planets in the HZ of Sun-like stars should be habitable.

K-452 is probably still habitable today!

What about M dwarfs?

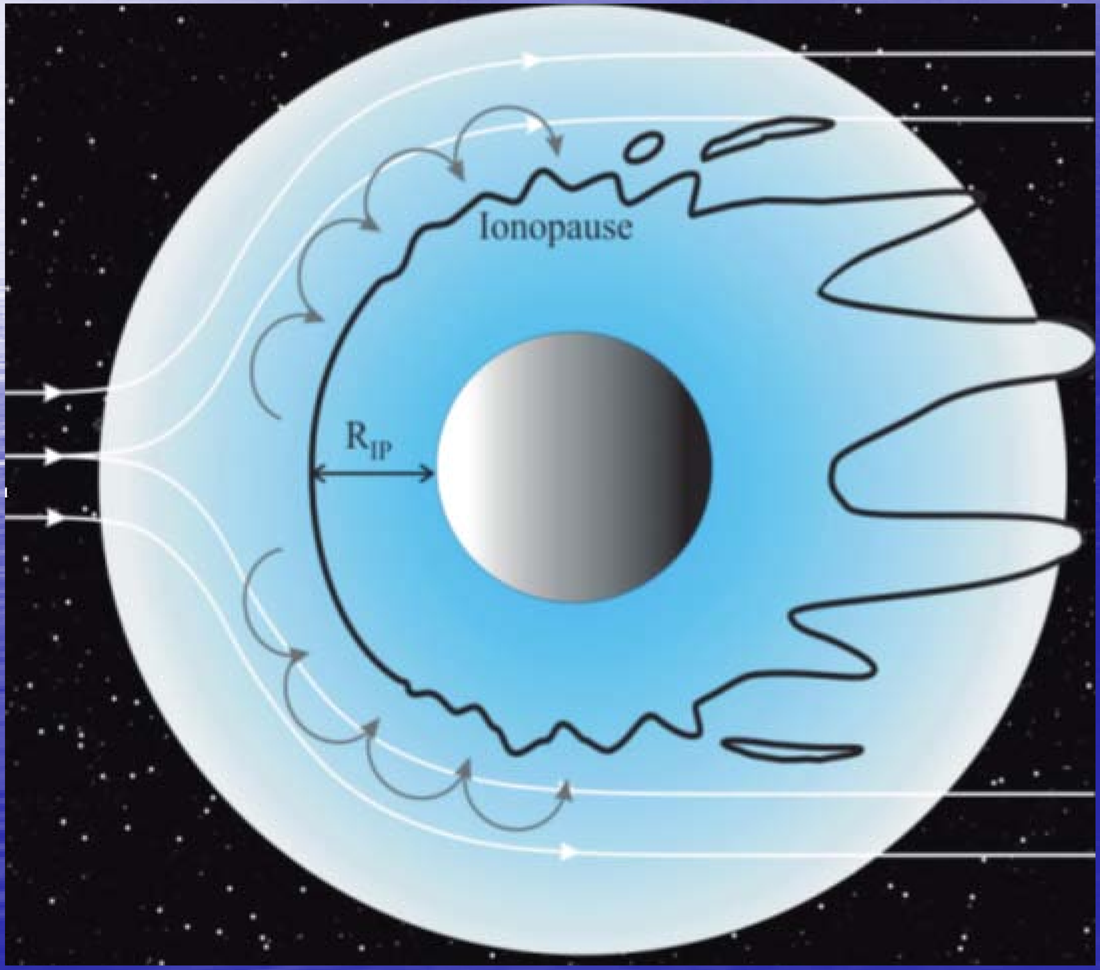
M dwarfs as the fast track to find exoplanet life:

1) There are many of them;
2) They live very long time;
3) It's easier to detect habitable planets around them;
4) It's easier to find clues for life around them.
5) Tidal Locking is not an issue.



http://en.wikipedia.org/wiki/File:Morgan-Keenan_spectral_classification.png

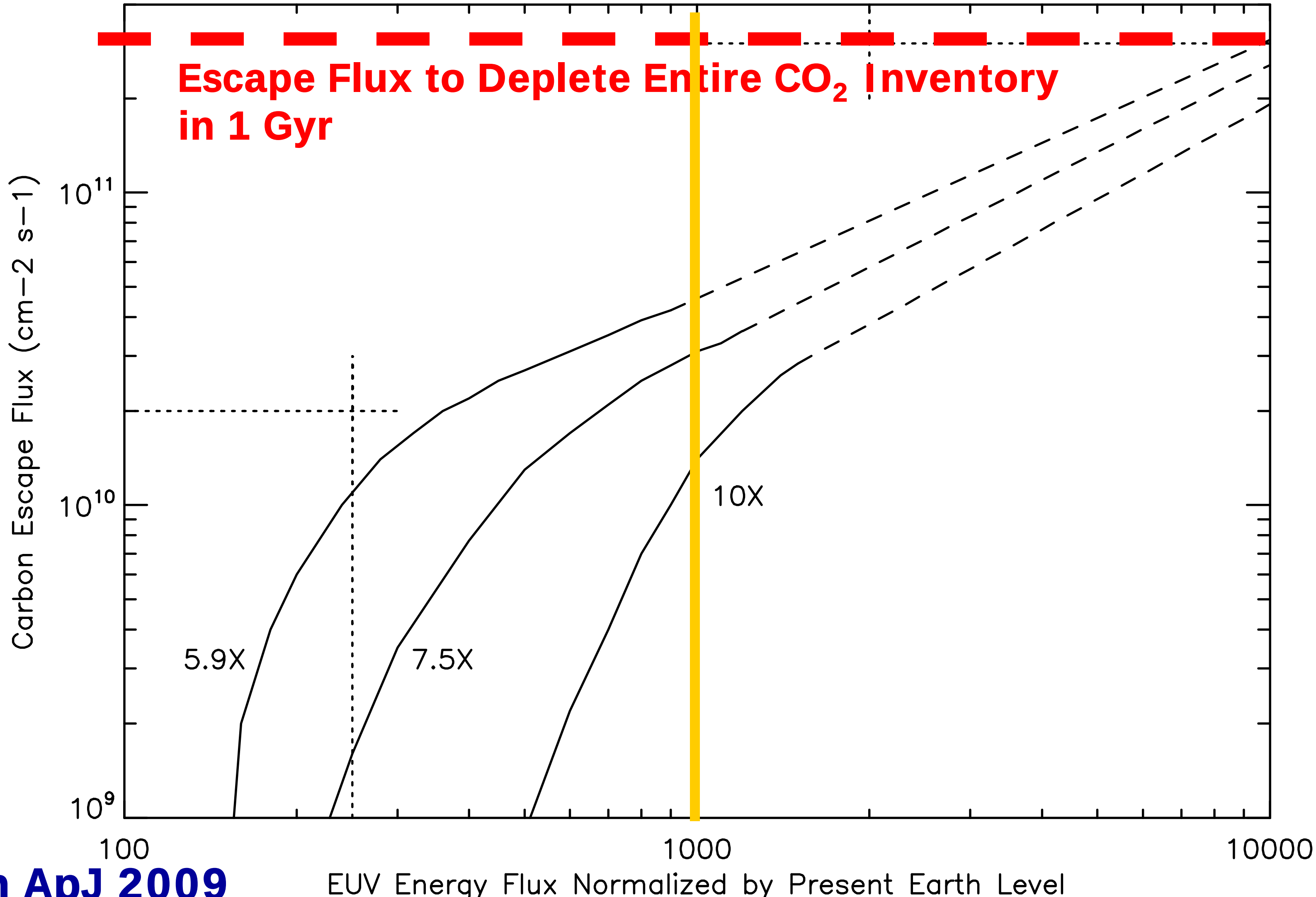
Stellar wind erosion can get rid of hundreds of bars of CO_2 from Earth-mass planets in 1 Gyr!! (Lammer et al. 2007)



Can the atmospheres of super Earths' survive?

CO_2 Atmospheres of Most Super Earths are Safe

But other compositions ....?



Tian ApJ 2009

Pre-Main Sequence M dwarfs were Brighter!

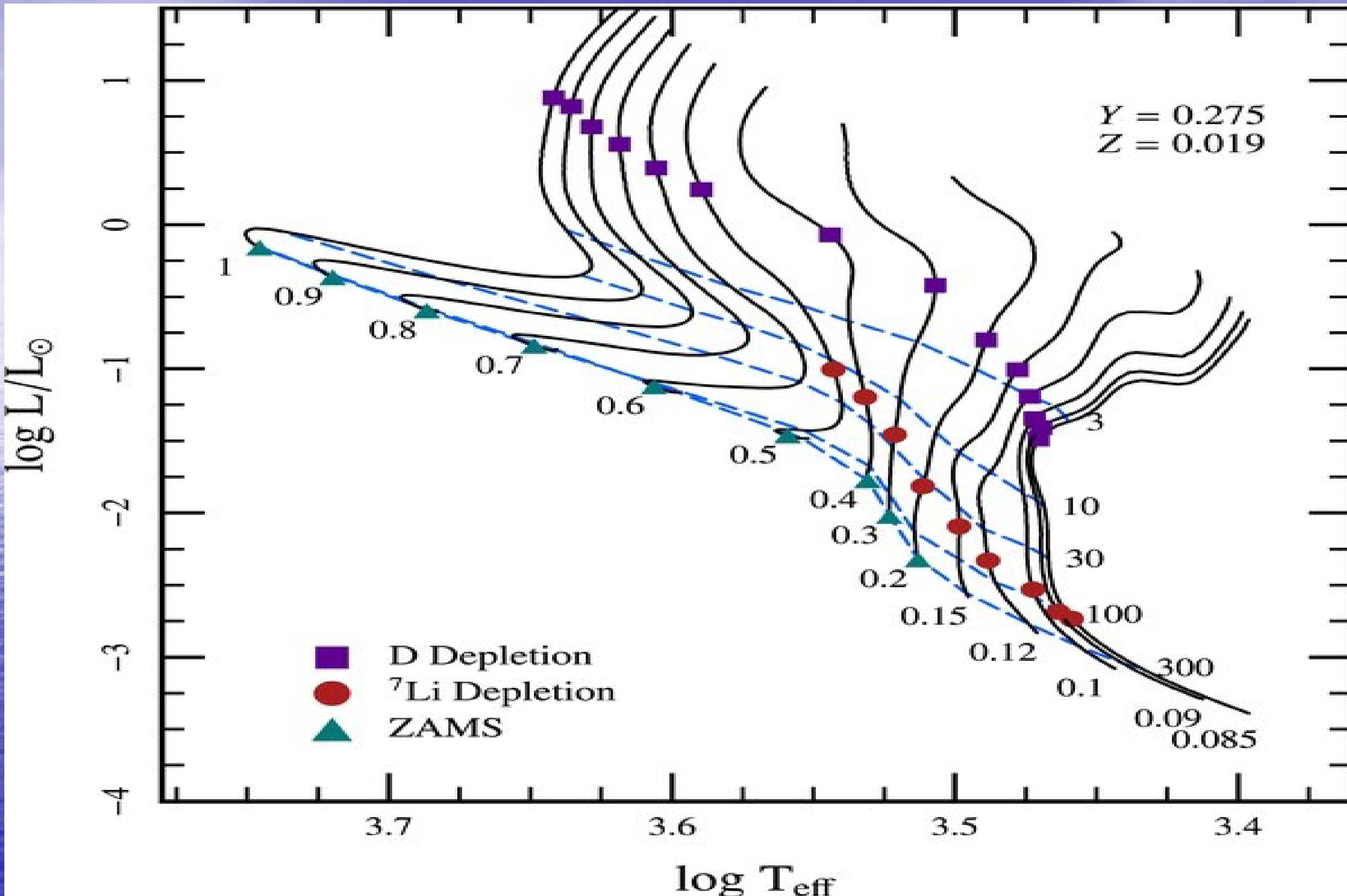


Figure 15 from Modules for Experiments in Stellar Astrophysics (MESA)
Bill Paxton et al. 2011 ApJS 192 3 doi:10.1088/0067-0049/192/1/3

The Astrophysical Journal Letters, 797:L25 (8pp), 2014 December 20

THE HABITABLE ZONES OF PRE-MAIN-SEQUENCE STARS

Ramses M. Ramirez[1,2,3] and Lisa Kaltenegger[1,2]

nature geoscience
LETTERS
PUBLISHED ONLINE: 16 FEBRUARY 2015 | DOI: 10.1038/NGEO2372

Water contents of Earth-mass planets around M dwarfs

Feng Tian[1*] and Shigeru Ida[2]

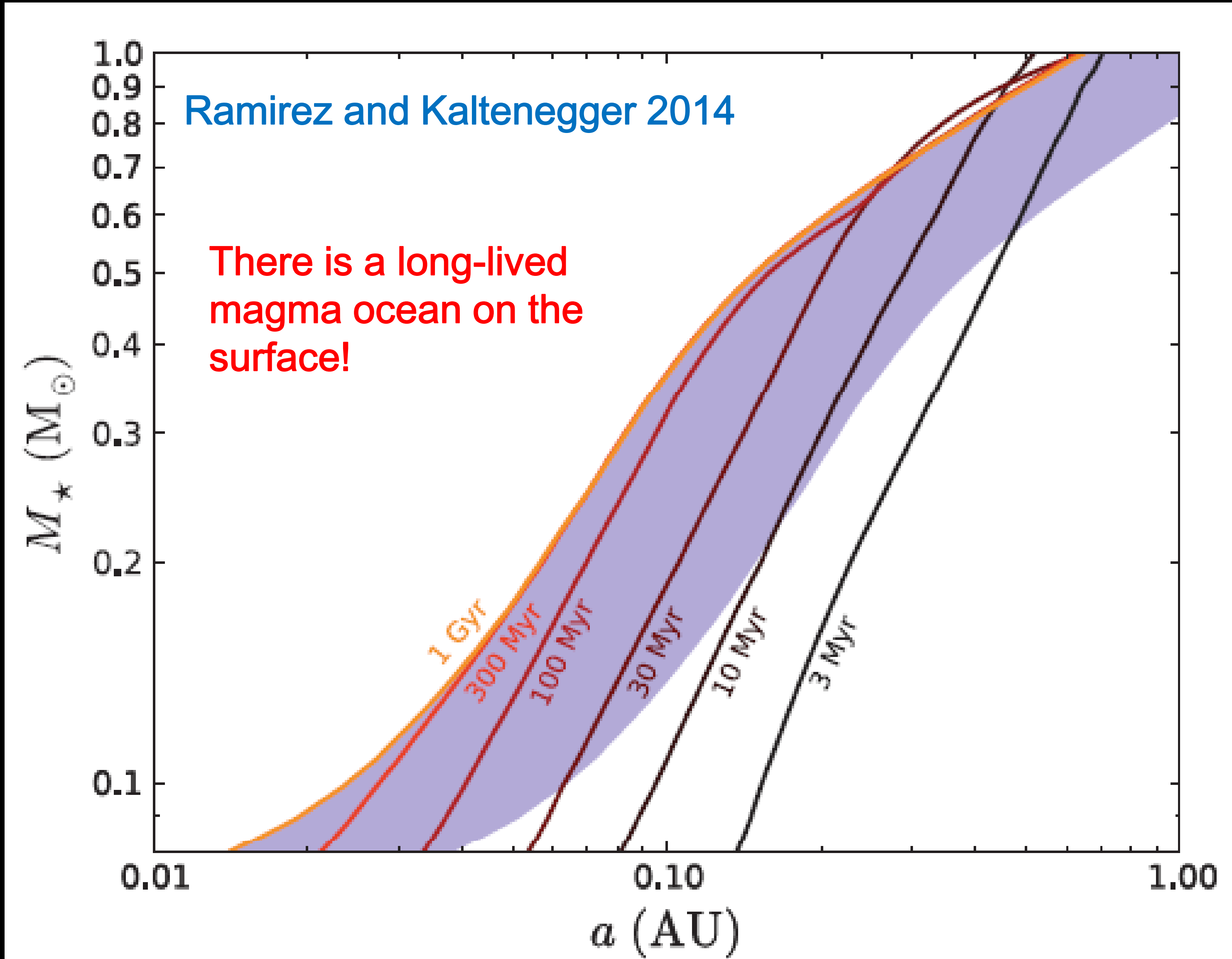
ASTROBIOLOGY
Volume 15, Number 2, 2015

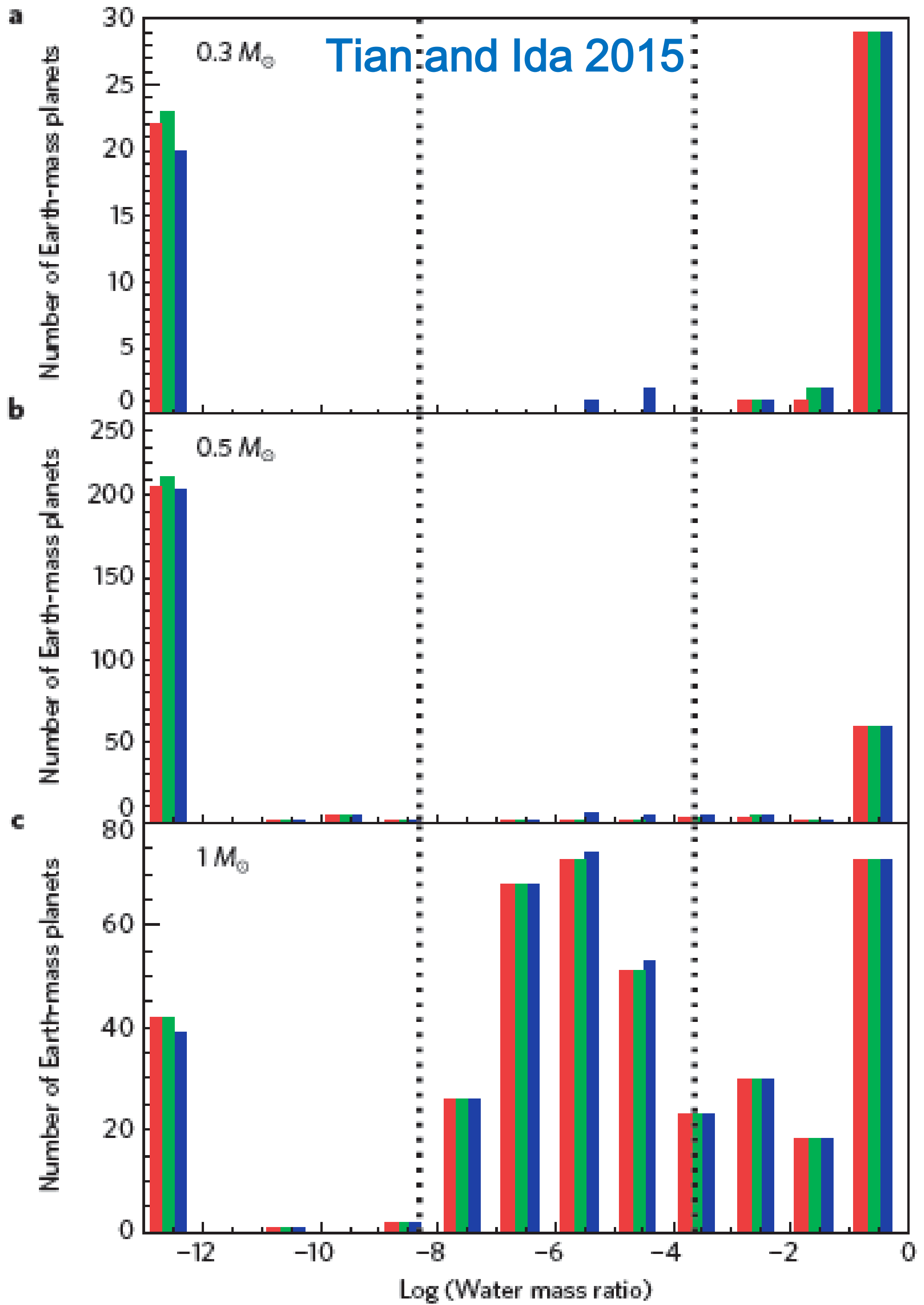
DOI: 10.1089/ast.2014.1231

Extreme Water Loss and Abiotic O_2 Buildup on Planets Throughout the Habitable Zones of M Dwarfs

R. Luger[1,2] and R. Barnes[1,2]

The HZ of M dwarfs migrates inward significantly during PMS phase -- H2O in danger!





Tian and Ida 2015
a
b
c
0.3 $M_\odot$
0.5 $M_\odot$
1 $M_\odot$
Number of Earth-mass planets
Log (Water mass ratio)
30
25
20
15
10
5
0
250
200
150
100
50
0
80
60
40
20
0
−12
−10
−8
−6
−4
−2
0

模式计算的每千颗恒星周围的行星统计

a:类地行星定义为质量在0.1到10地球质量范围的行星

Planet Statistics Around 1000 Stars

Stellar Mass(Solar Mass)	# of All Planets	# of Earth-mass planets	# of HZ Earth-mass planets	# of HZ Ocean Planets	# of HZ Dune Planets	# of Earth-twins
0.3	69000	5000	55	31	23	1
0.5	75000	9000	292	60	220	12
1	38000	8000	407	91	45	271

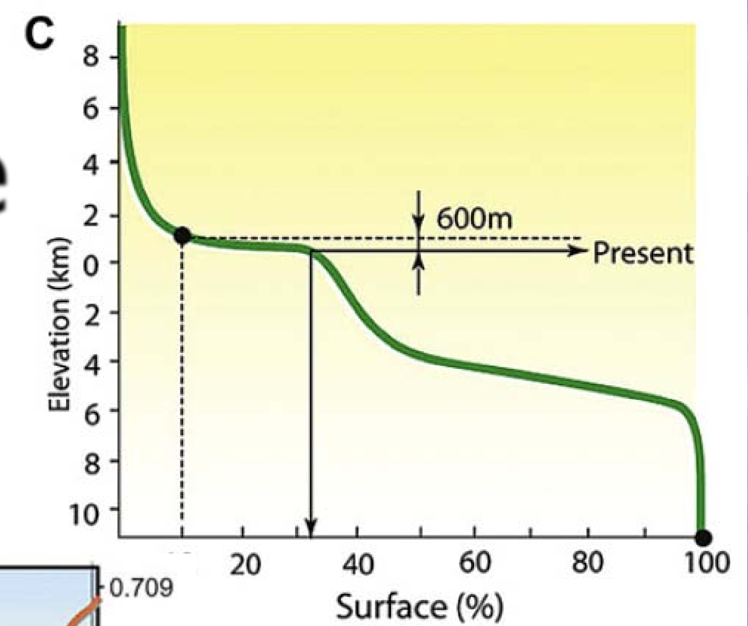
Earth-mass planets are defined to have mass between 0.1 and 10 Earth masses

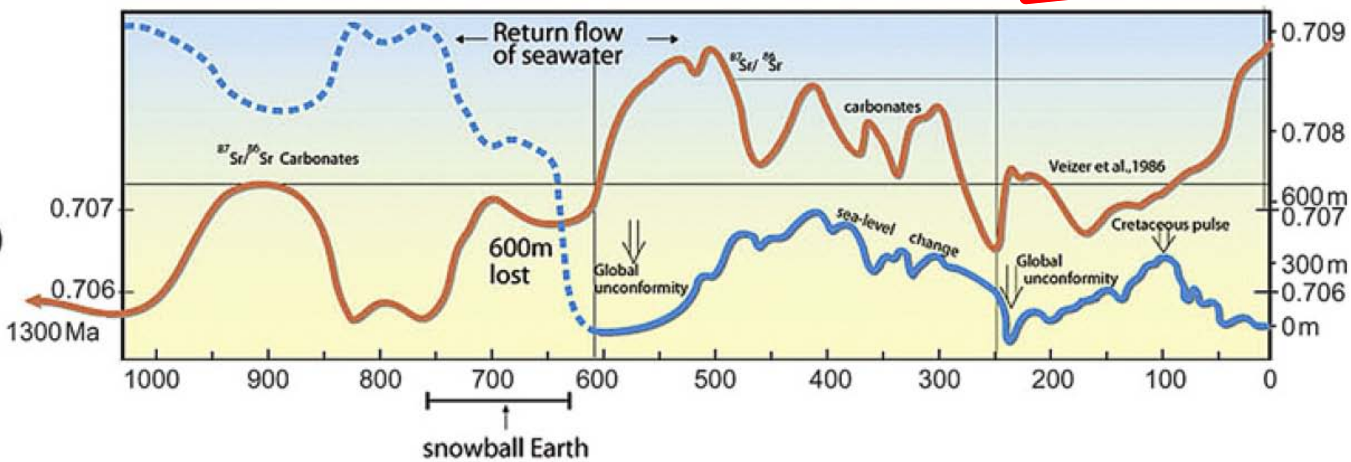
Earth-twins are defined as Earth-mass planets with surface water between Venus water content and 1% mass fraction.

- M dwarfs:
  - 0.1%~1% probability to have Earth-twins (0.1-10 M_{earth} + Water fraction >1e-8 and < 1e-2)
- Sun-like Stars:
  - 10% probability

Ocean planets may have nutrient problems.

- Maruyama+ 2013

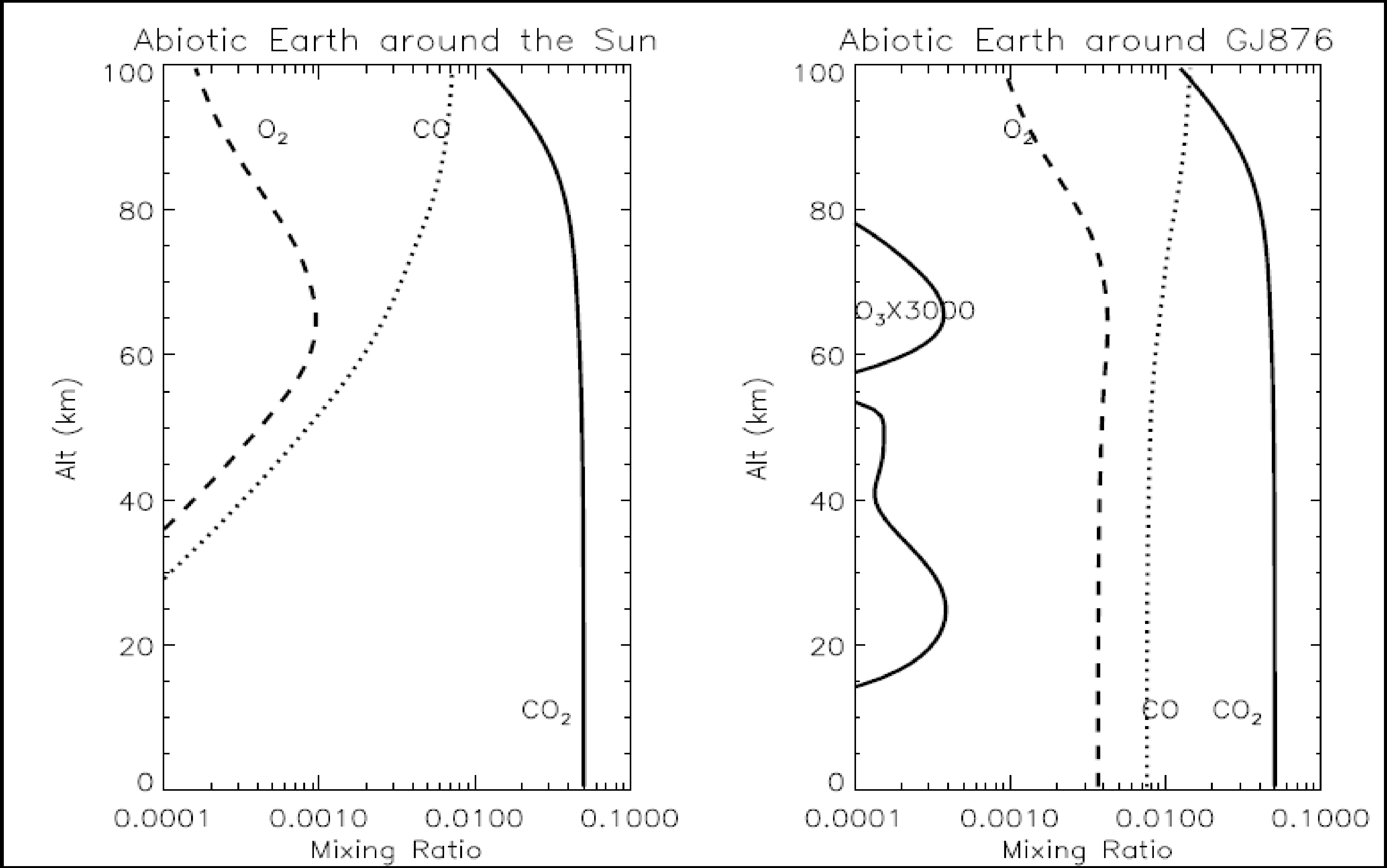




Dohm and Maruyama 2014

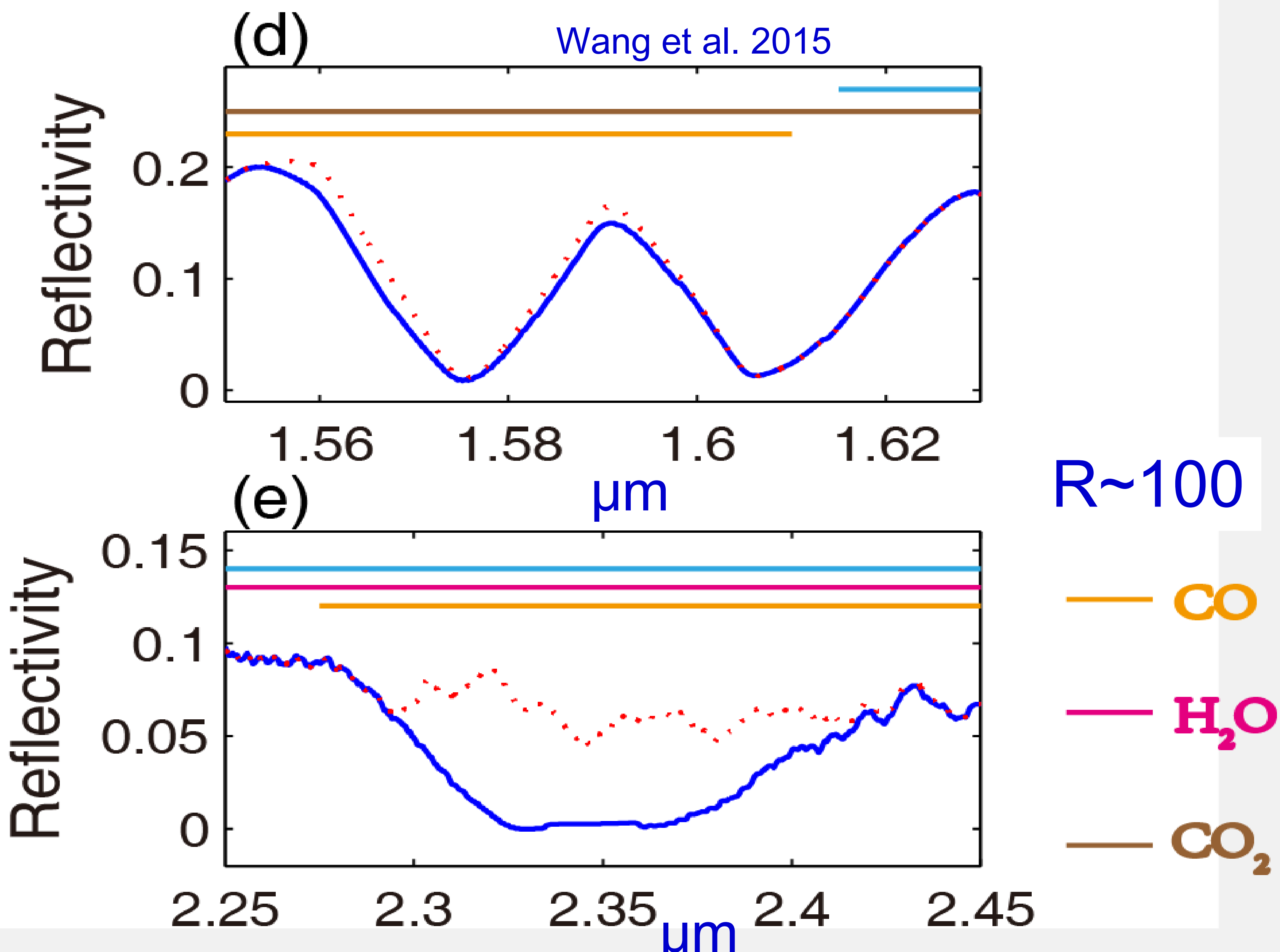
Habitable Trinity is a newly proposed concept of a habitable environment. This concept indicates that the coexistence of an atmosphere (consisting largely of C and N), an ocean (H and O), and a landmass (supplier of nutrients) accompanying continuous material circulation between these three components driven by the Sun is one of the minimum requirements for life to emerge and evolve. The life body consists of C, O, H, N and other various nutrients, and therefore, the presence of water, only, is not a sufficient condition. Habitable Trinity environment must be maintained to supply necessary components for life body. Our Habitable Trinity concept can also be applied to other planets and moons such as Mars, Europa, Titan, and even exoplanets as a useful index in the quest for life-containing planetary bodies.

As a result of high FUV/NUV ratio, abiotically produced O_2 and O_3 could be maintained in the atmosphere.

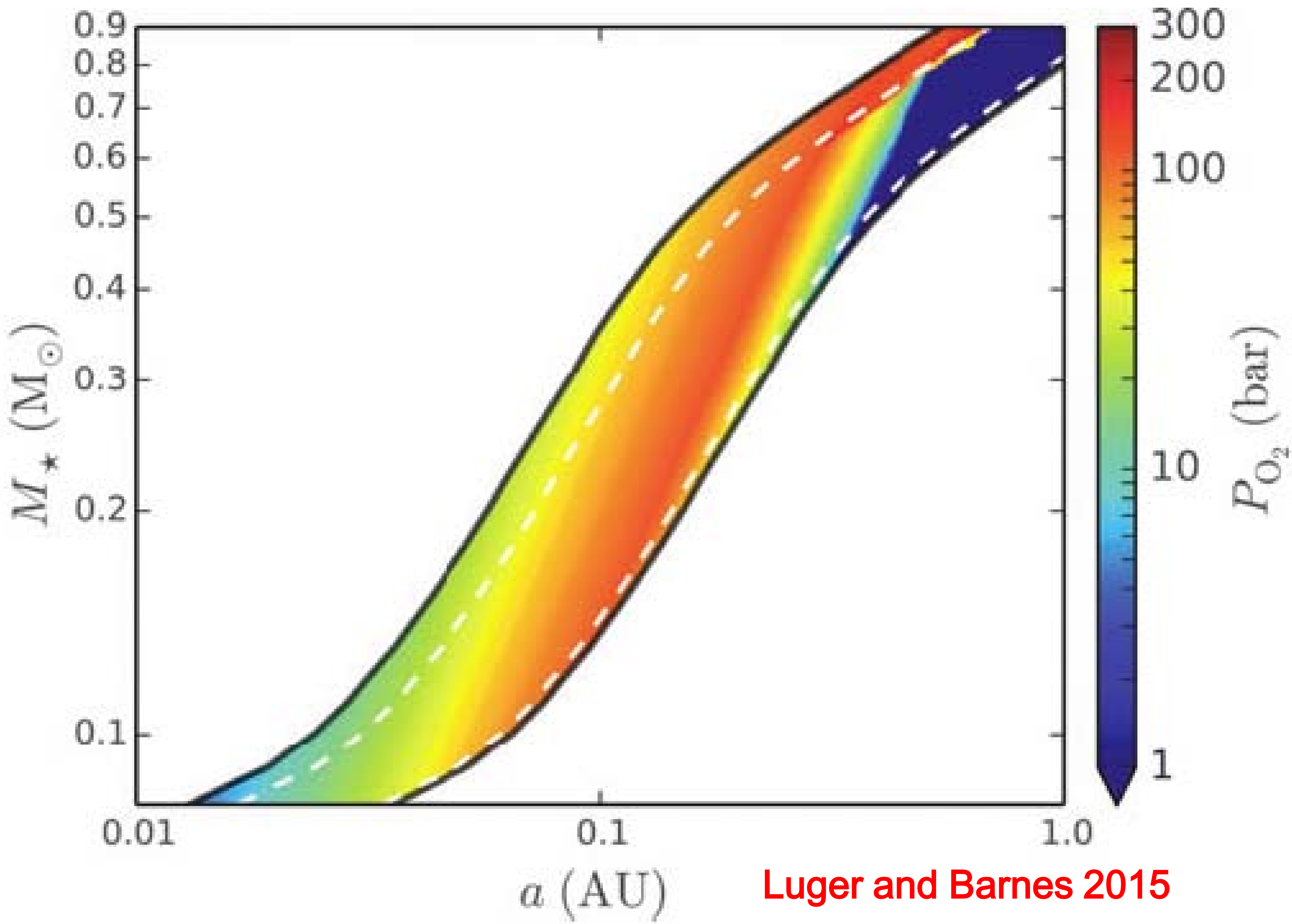


Tian+EPSL 2014; also see Dogmal-Goldman + 2014, Gao+ 2015, Harman+ 2015

But 10^{-3} level of CO is Easy to Detect.

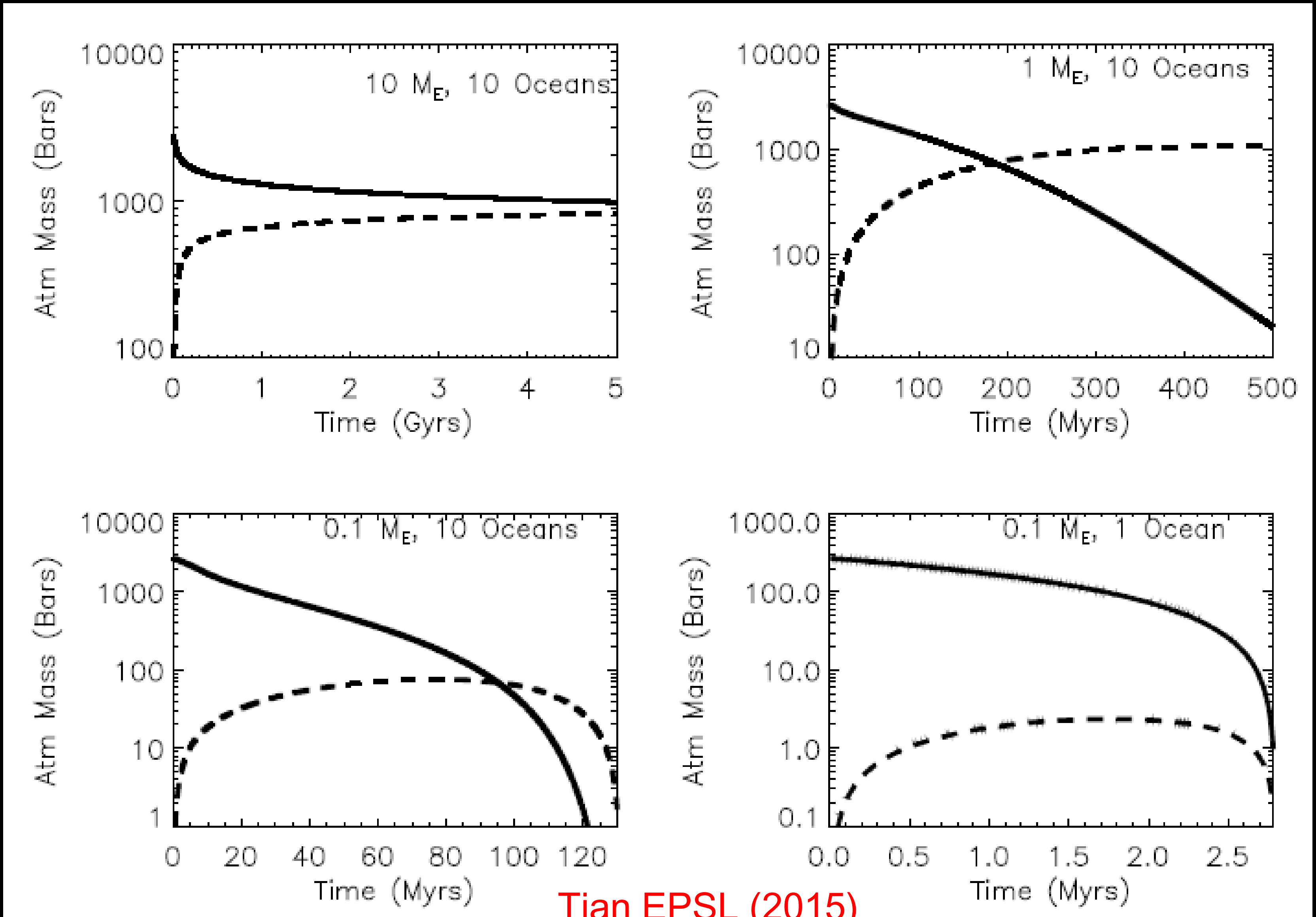


2000 bars of O_2 could build up!



Luger and Barnes 2015

Buildup of Dense O_2 Atmospheres is Sensitive to the Initial Ocean Inventory. And it's hard to keep a low O_2 atmosphere.



Tian EPSL (2015)

M dwarfs as the Fast Track Toward Exoplanet Life Detection?

1) Mid M dwarfs likely have bimodal distribution of water on their HZ planets
   water rich ones from formation (Alibert talk on Tuesday and Lena talk tomorrow);
   Water poor ones from formation (Lugaro Talk, *Haghighipour Talk*) and PMS evolution (Meadows Talk, this talk)
2) Too much water is bad (Abbot+ 2012, Dohm and Maruyama 2014, Kitzman+ 2015, Noack talk tomorrow).
3) Maybe some late processes or unknown physics can help. But how to distinguish a planet with 4-km ocean from one with 100-km ocean?

In addition, it's difficult to determine the mass of a HZ exoplanet around early M dwarfs – mid M dwarfs are better (Newton talk)

Final Thoughts: How to Determine Planet Habitability?

1) For M dwarfs, perhaps this will be achieved by observations of biosignature (a little bit O_2?)!!

2) Alternatively, observing planets around stars at different age, especially PMS M dwarfs -- Understand the evolution of uninhabitable planets (Meadows Talk)