Water, Habitability, and Detectability

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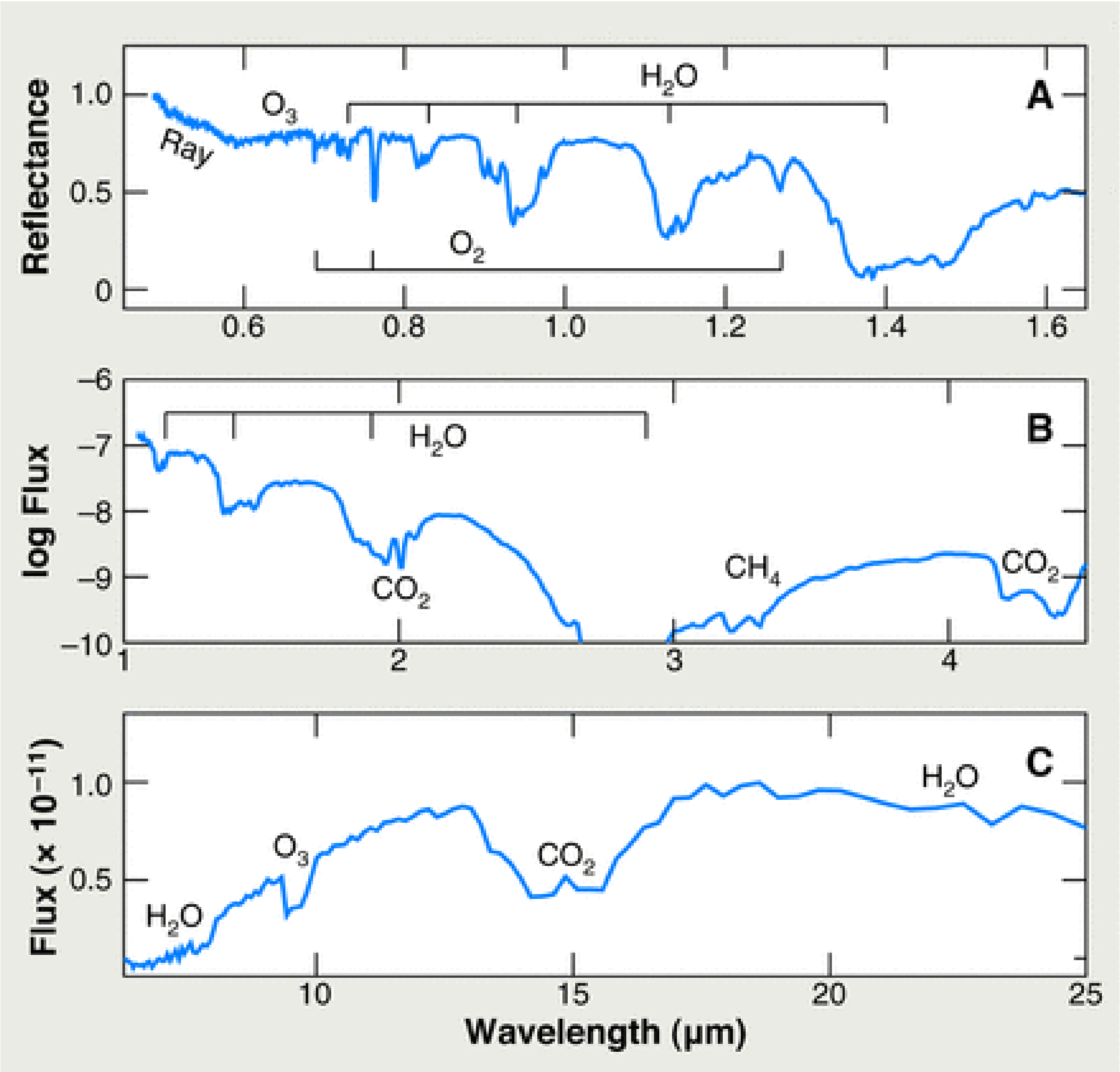
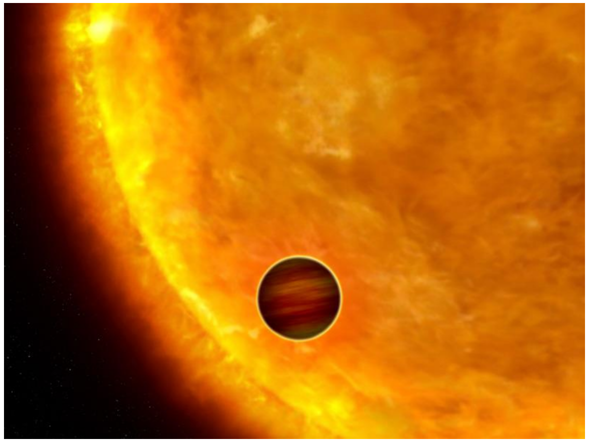
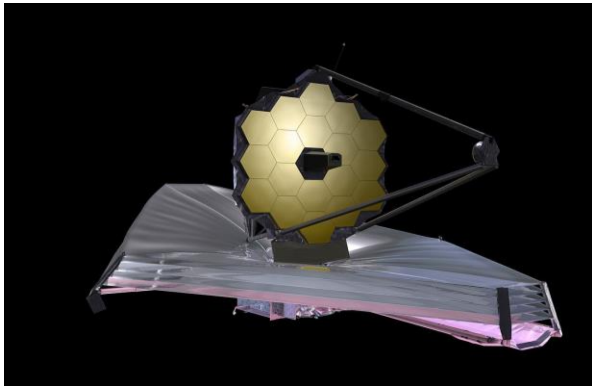
Astrobiology Science Strategy NAS Committee,
Beckmann Center, Irvine, CA (remotely), January 17, 2018

How to look for life on (Earth-like) exoplanets: find oxygen in their atmospheres







How Earth-like must an exoplanet be for this to work?

Seager et al. (2013)

How to look for life on (Earth-like) exoplanets: find oxygen in their atmospheres

Oxygen on Earth overwhelmingly produced by photosynthesizing life, which taps Sun's energy and yields large disequilibrium signature.

Caveats:

Earth had life for billions of years without O_2 in its atmosphere.

First photosynthesis to evolve on Earth was anoxygenic.

Many 'false positives' recognized because O_2 has abiotic sources, esp. photolysis (Luger & Barnes 2014; Harman et al. 2015; Meadows 2017).

These caveats seem like exceptions to the 'rule' that 'oxygen = life'.

How non-Earth-like can an exoplanet be (especially with respect to water content) before oxygen is no longer a biosignature?

Part 1: How much water can terrestrial planets form with?

Part 2: Are Aqua Planets or Water Worlds habitable?
Can we detect life on them?

Part 3: How should we look for life on exoplanets?

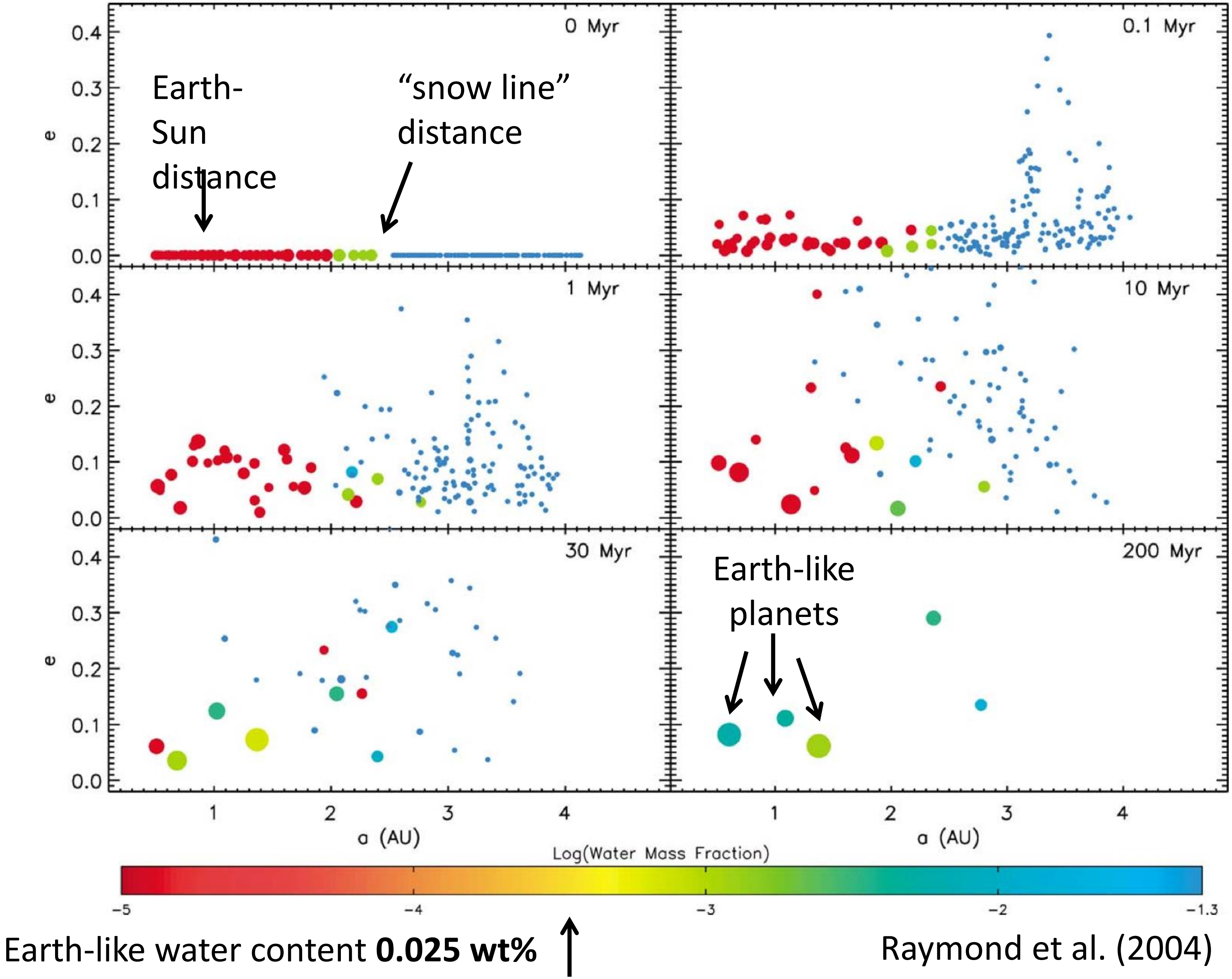
Part 1: How much water can terrestrial planets form with?

Theory says: up to hundreds of oceans’ worth of water
Trappist-1 system suggests hundreds of oceans, especially around M stars

Many (most?) planets may be Aqua Planets or Water Worlds

How much water can terrestrial planets form with?

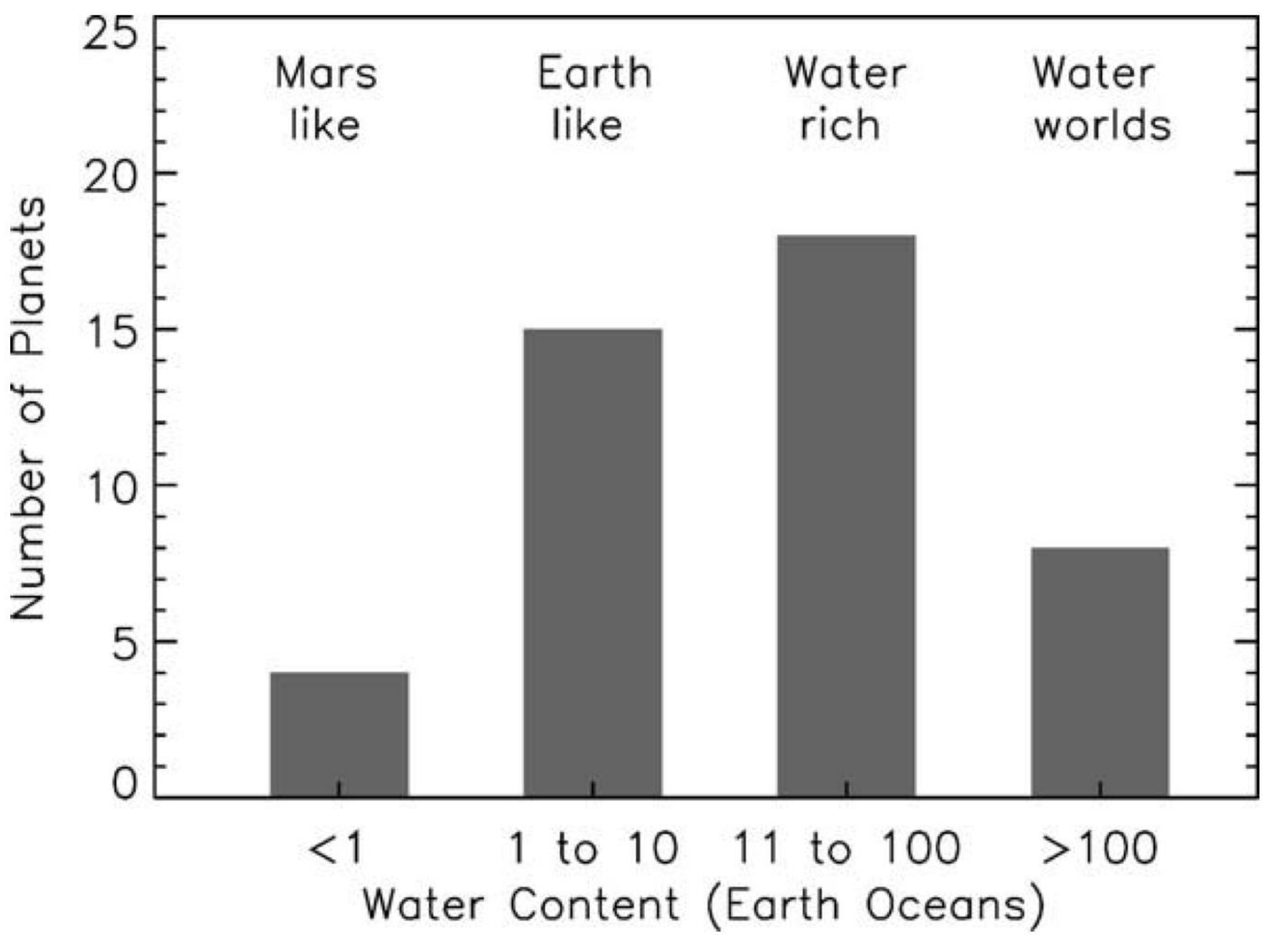
Standard models of accretion suggest abundant water.



Raymond et al. (2004)

How much water can terrestrial planets form with?

"Aqua Planets" (6 - 35 oceans, enough to submerge continents) and "Water Worlds" (> 35 oceans, enough for high-pressure ice layer) might be most likely.

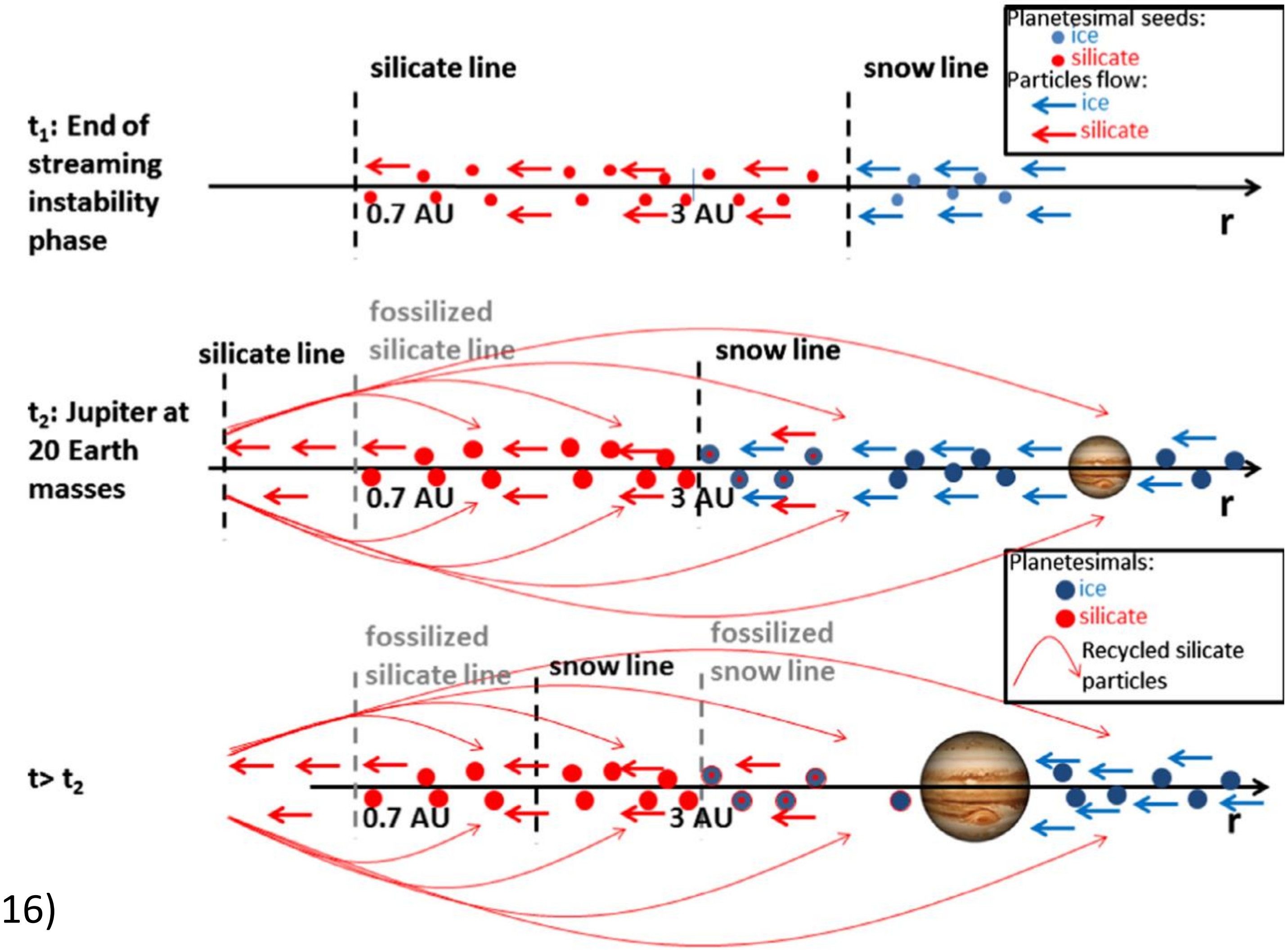


Raymond et al. (2004)

How much water can terrestrial planets form with?

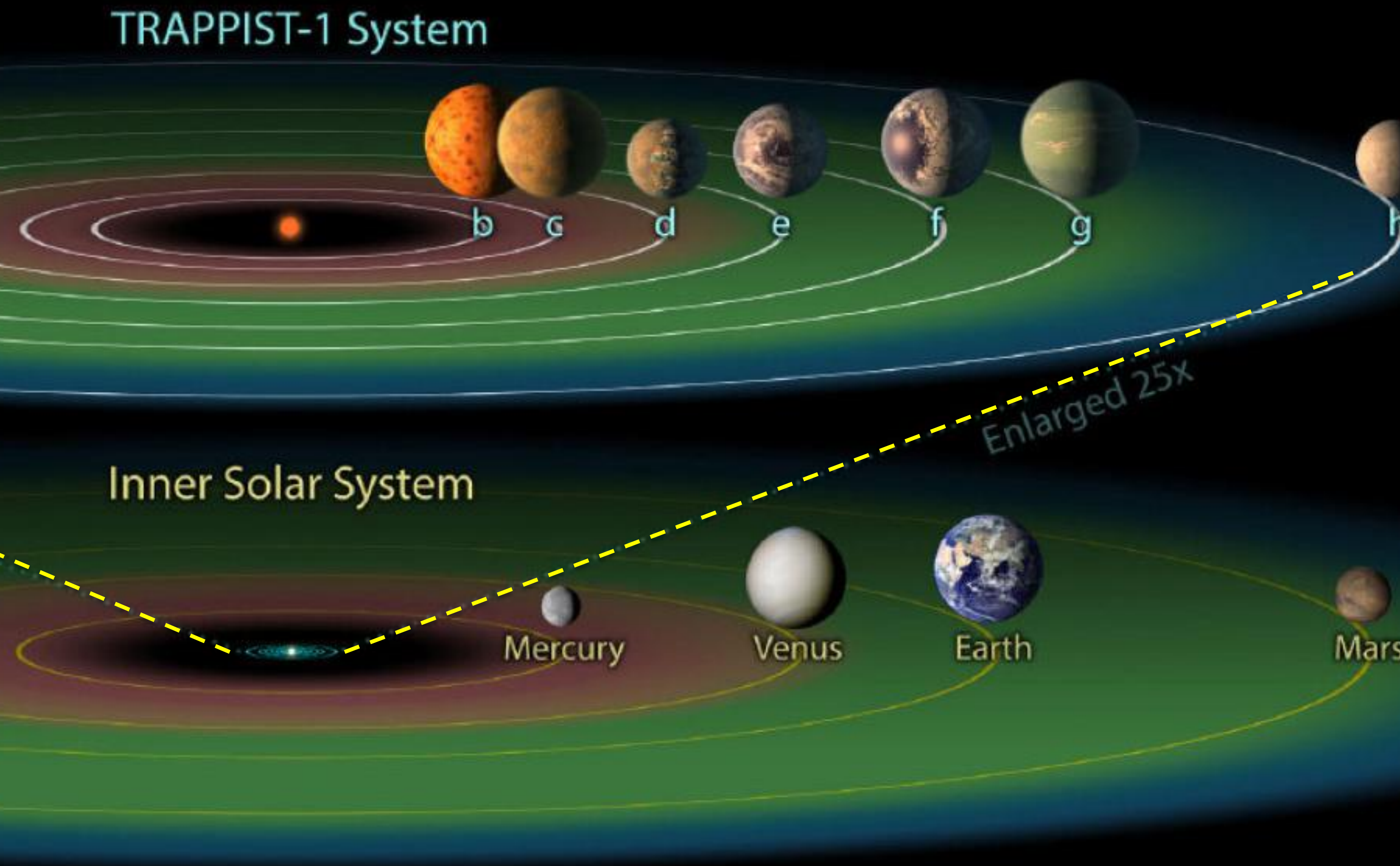
Newer theories of 'fossil snow lines' (Morbidelli et al. 2016) suggest Jupiter's formation deprived the inner solar system of H_2O ice.

Systems without Jupiters would still have water-rich inner planets.



Morbidelli et al. (2016)

How much water did the Trappist-1 planets form with?



NASA

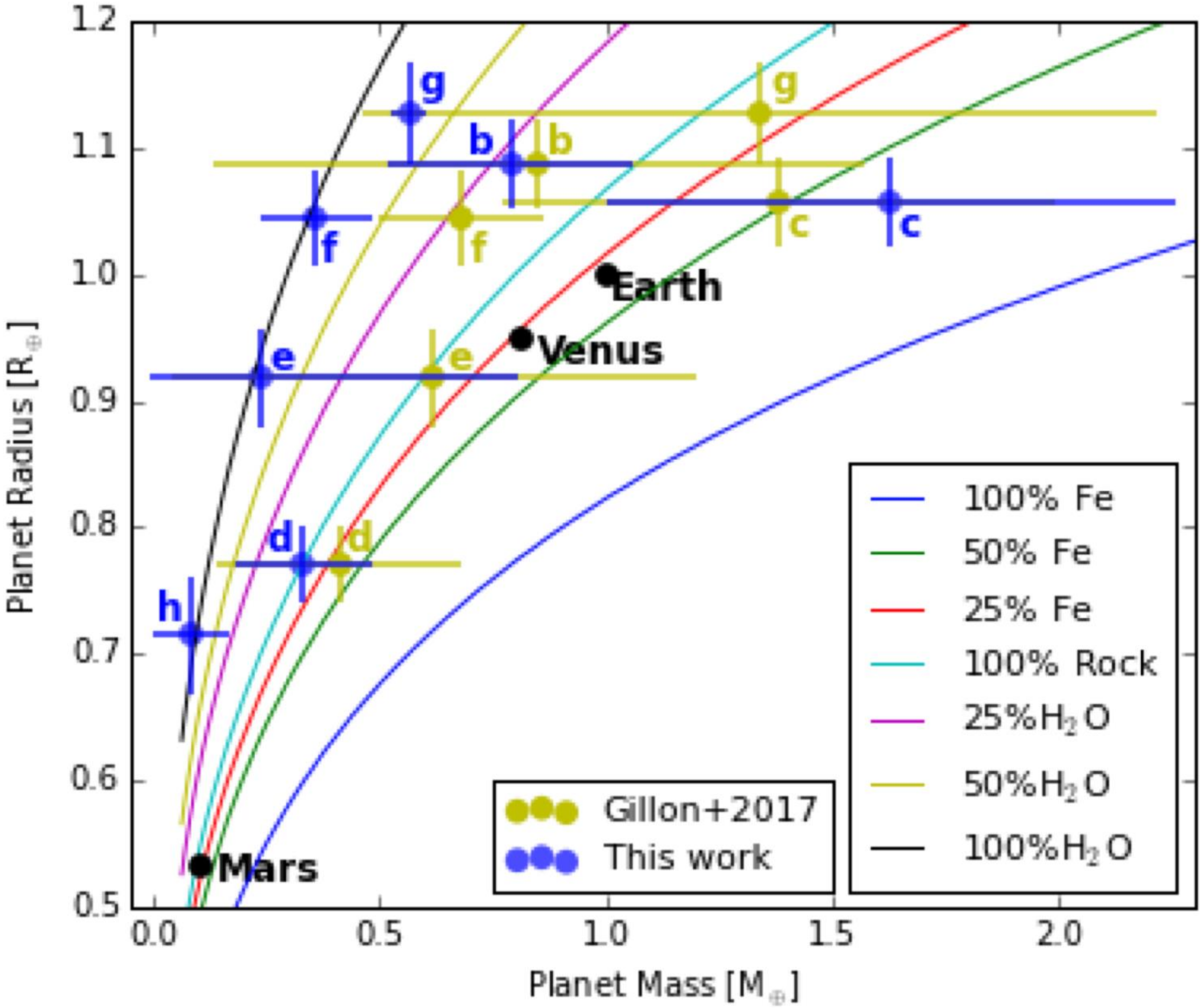
Gillon et al. (2016, 2017)

How much water did the Trappist-1 planets form with?

	Period	Semi-major axis	Mass (TTVs)	Radius (transit)
b	1.5109 d	0.01111 AU	0.79 +/- 0.27 M_E	1.086 +/- 0.035 R_E
c	2.4218 d	0.01522 AU	1.63 +/- 0.63 M_E	1.056 +/- 0.035 R_E
d	4.0498 d	0.02145 AU	0.33 +/- 0.15 M_E	0.772 +/- 0.030 R_E
e	6.0996 d	0.02818 AU	0.24 +/- 0.56 M_E	0.918 +/- 0.039 R_E
f	9.2065 d	0.0371 AU	0.36 +/- 0.12 M_E	1.045 +/- 0.038 R_E
g	12.3528 d	0.0451 AU	0.566 +/- 0.038 M_E	1.127 +/- 0.041 R_E
h	18.7663 d	0.0596 AU	0.086 +/- 0.084 M_E	0.715 +/- 0.047 R_E

Wang et al. (2017)

How much water did the Trappist-1 planets form with?



b, c = rocky, not a lot of ice?

d, e, = less well constrained

f, g, h = appear water-rich, > 50%

Can we better constrain the ice content?

Can we include a realistic Fe/Mg?

Wang et al. (2017), using their data and Gillon et al. (2017) data and Zeng et al. (2016) mass-radius relationships

How much water did the Trappist-1 planets form with?

We **assume** no H_2/He atmospheres in mass-radius relationships

Even a small (~ $10^{-6}\ M_E$) H_2/He atmosphere would inflate planet, and is hard to rule out, but thick H_2/He atmospheres don't seem to inflate planets with $R < 1.6\ R_E$ (Weiss & Marcy 2014; Rogers 2015).

Unlikely to accrete more than ~$10^{-4}\ M_E$ of H_2/He gas (Stokl et al. 2015).

Trappist-1 planets easily lose 0.003 – 0.03 M_E of H_2/He gas (following Wheatley et al. 2017: updated XMM X-ray fluxes, 10% efficient energy-limited mass loss).

Bolmont et al. (2017) also concluded b and c cannot retain atmospheres

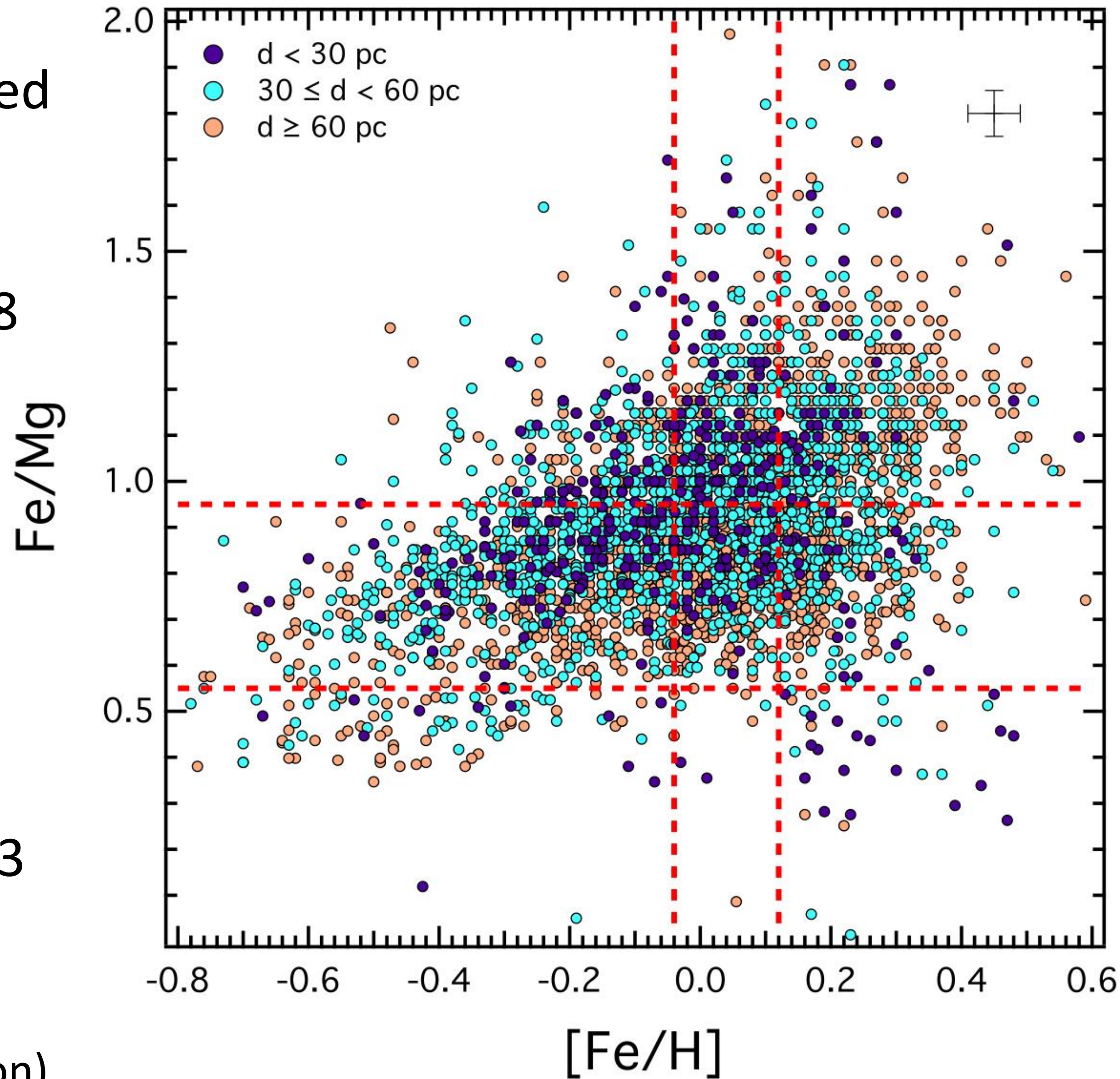
ΔM / 5 Gyr	
b	0.031 M_E
c	0.008 M_E
d	0.014 M_E
e	0.013 M_E
f	0.006 M_E
g	0.003 M_E
h	0.007 M_E

How much water did the Trappist-1 planets form with?

Fe/Mg ratio constrained using metallicity

[Fe/H] = +0.04 +/- 0.08
(Gillon et al. 2017)

From Hypatia catalog
(Hinkel et al. 2014):
stars with this [Fe/H] have Fe/Mg = 0.5 – 1.3
1σ = 0.55 – 0.95



Unterborn et al. (in revision)

How much water did the Trappist-1 planets form with?

ExoPlex code written by my group (Lorenzo et al., in prep: Alejandro Lorenzo, Cayman Unterborn, Byeongkwan Ko, Steve Desch)

Computes internal structure and mass-radius relationships of rock/ice planets (no atmospheres)

Iteratively calculates both hydrostatic equilibrium and equilibrium mineralogy, using **PerpleX** Gibbs free energy minimization routine (Connolly 2009) that uses mineral thermodynamic data (Stixrude & Lithgow-Bertelloni 2011).

Similar to code of Dorn et al. (2015).
We can include impurities in core.
We added EOS for ice I, VI, VII.

How much water did the Trappist-1 planets form with?

ExoPlex algorithm:

Stoichiometry, mass set in each zone.
ρ, r(M) initialized.

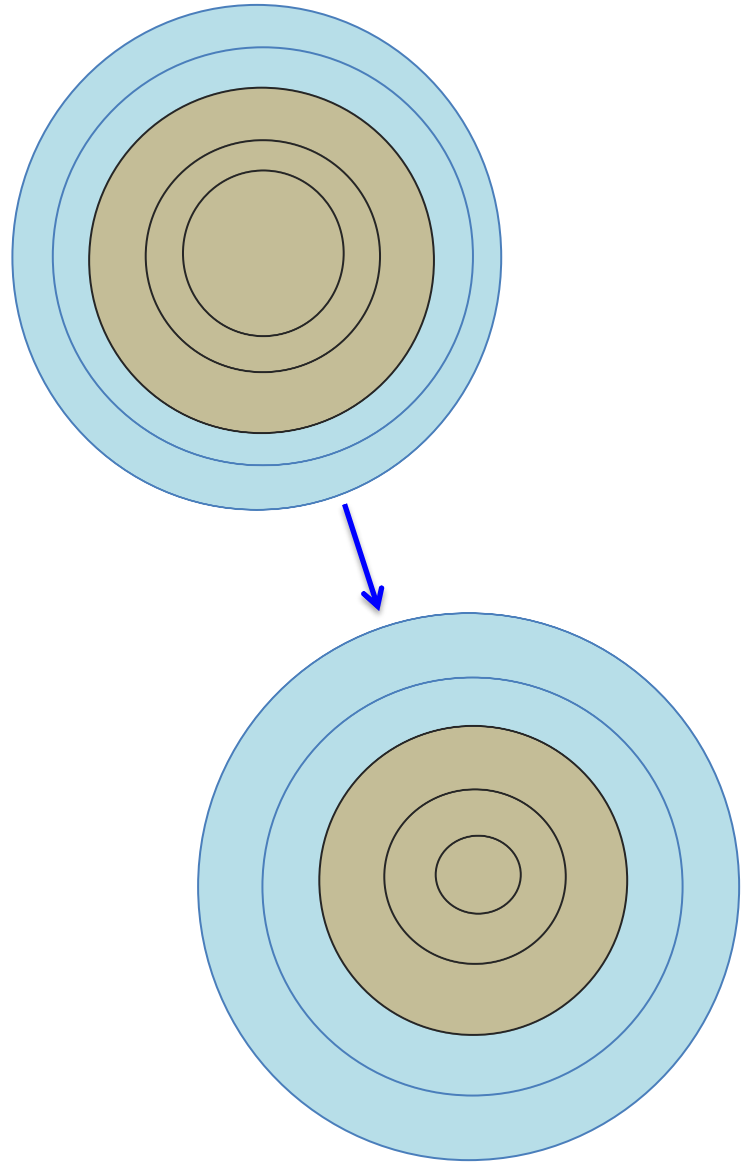
$g(r) = -G\, M(r) / r^2$

α, Cp found

$dP/dr = -\rho(r)\, g(r)$
$dT/dr = T(r)\, \alpha\, g(r) / C_p$

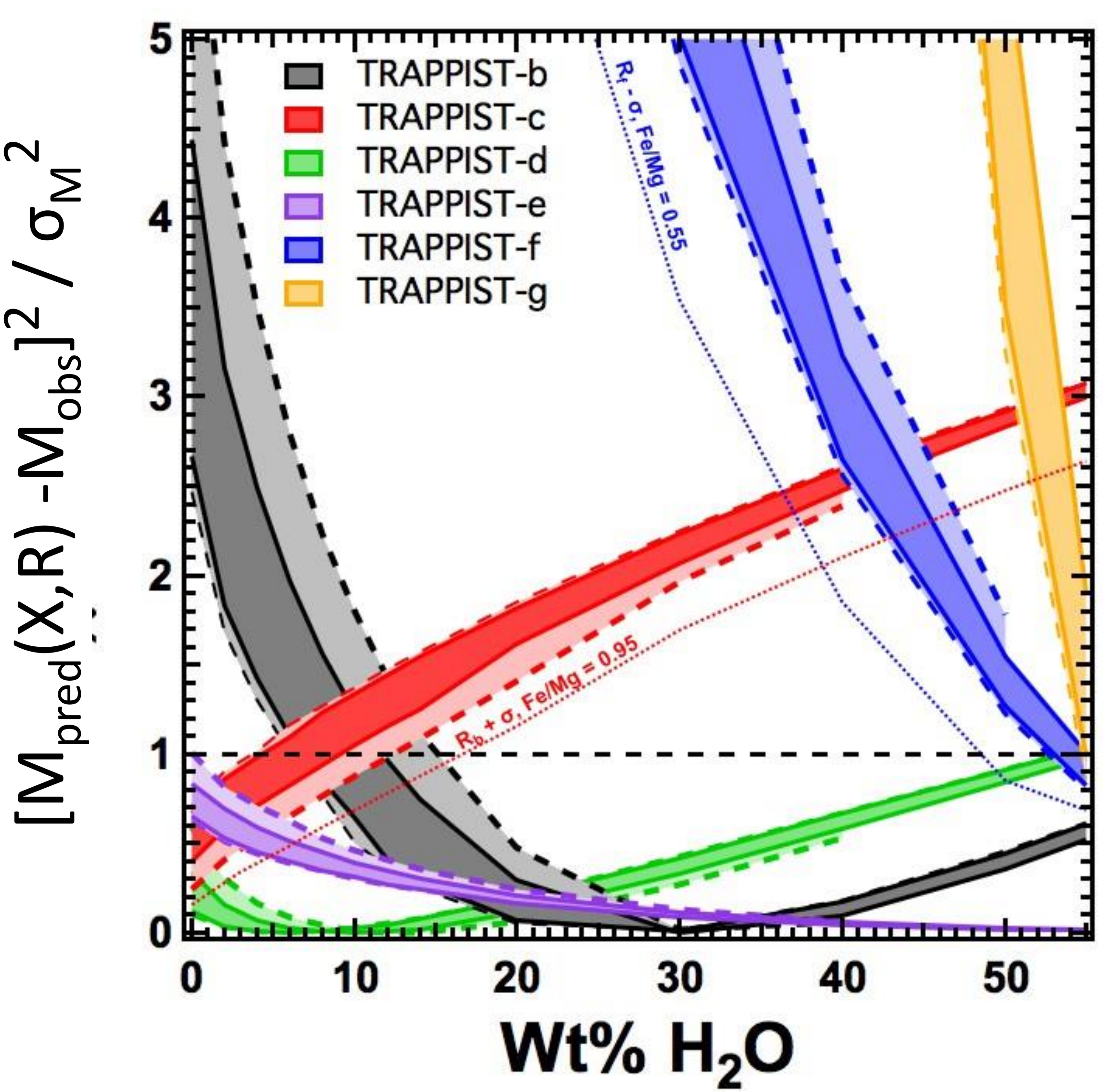
ρ(P,T) found in each zone using PerpleX

Updated ρ = updated r(M)



How much water did the Trappist-1 planets form with?

Now possible to measure H_2O on terrestrial planets to ~ 10 wt%



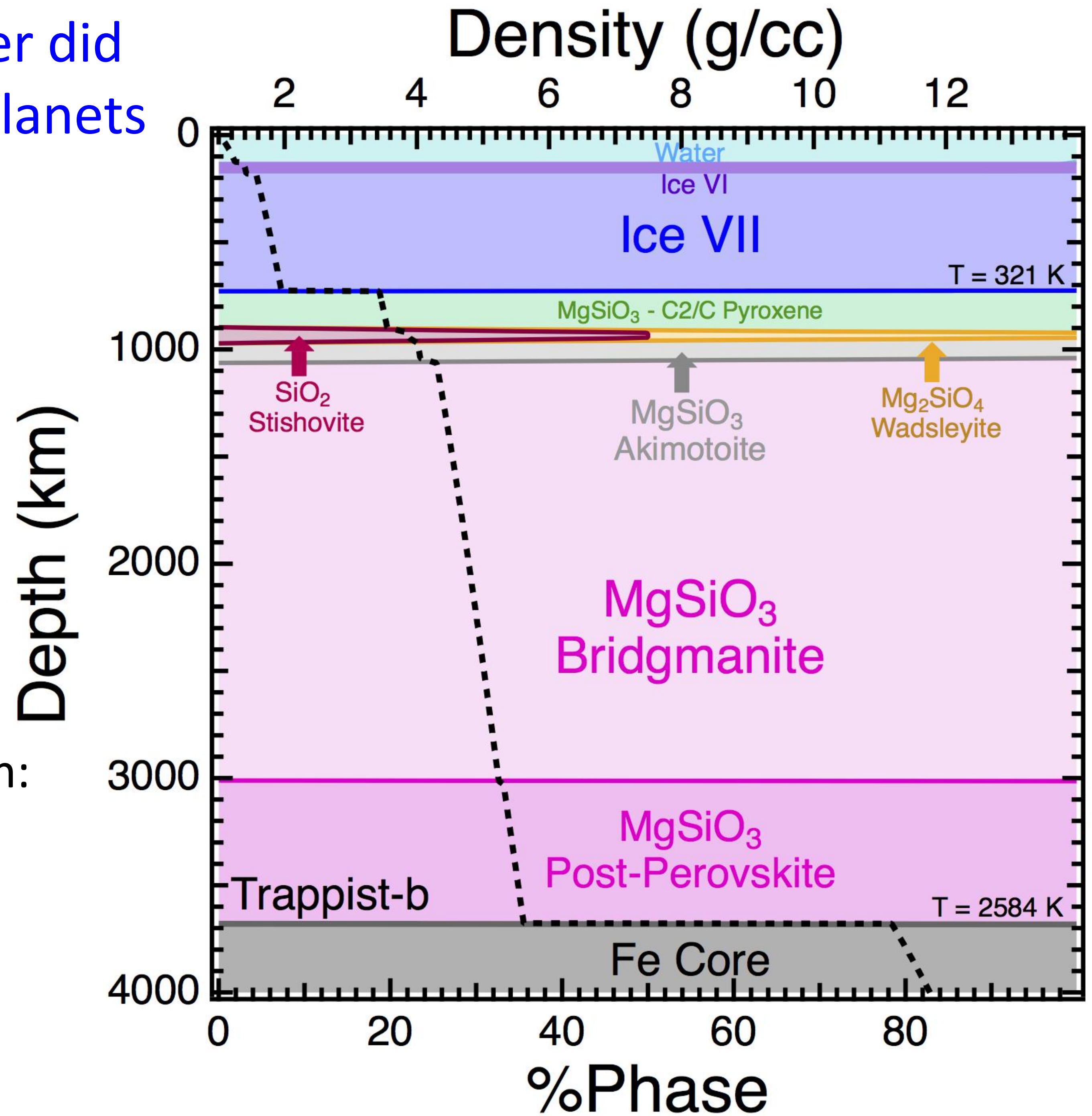
-1b > 7-15wt% H_2O,
-1c < 5-12wt% H_2O
Probably both 7-12wt%

-1f > 52wt% H_2O
-1g > 54wt% H_2O

Fe-Mg-Si-O only, no Ca,Al
Solar Mg/Si = 1.0
Fe/Mg = 0.55 – 0.95

Unterborn, Desch, Hinkel & Lorenzo, in revision at *Nature Astronomy*

How much water did the Trappist-1 planets form with?



Internal structure of Trappist-1b (Rp=6918 km), with:

Fe-Mg-Si-O only

Fe/Mg=0.8

Mg/Si=1.0

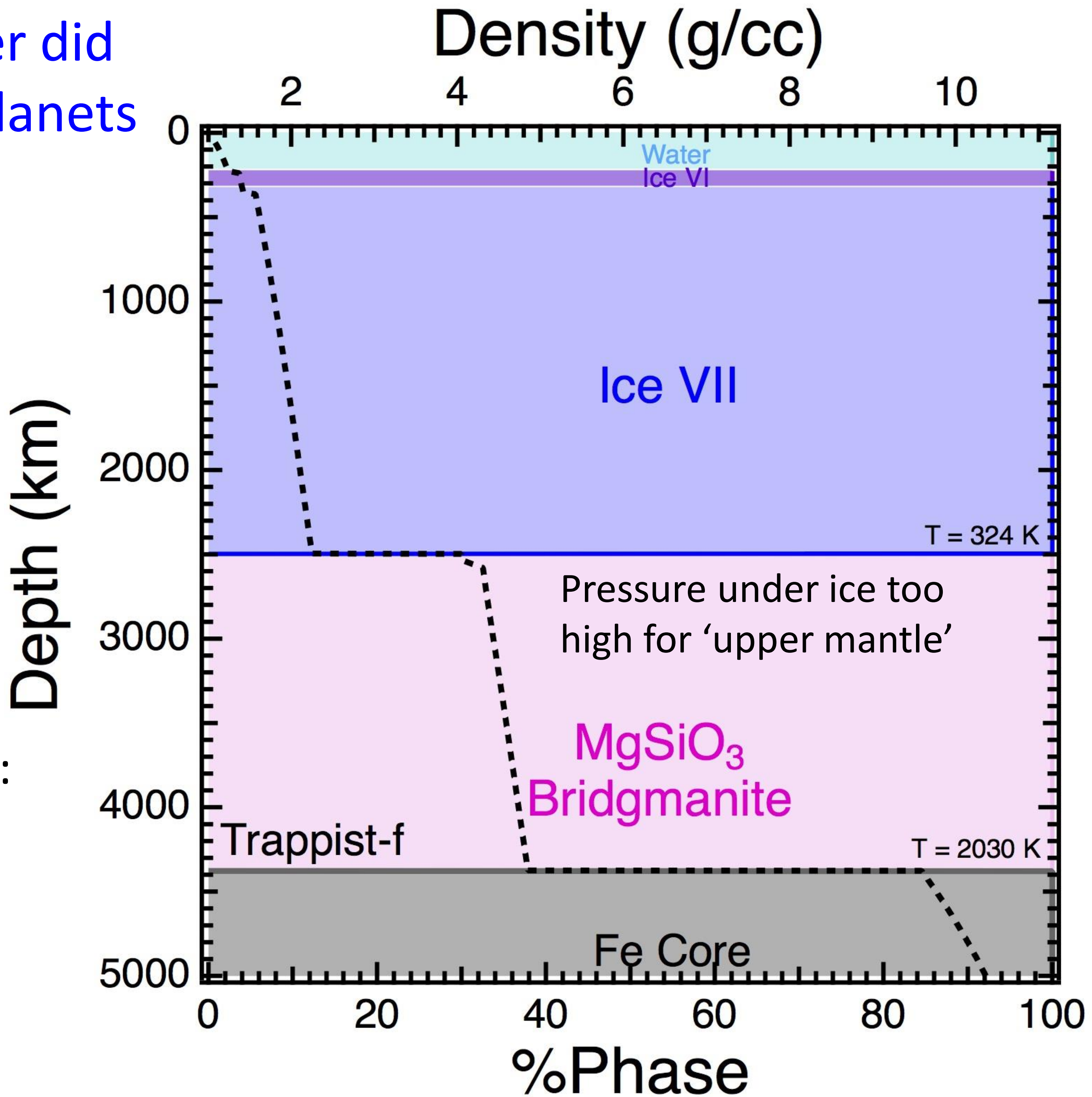
10 wt% water

(400 oceans)

How much water did the Trappist-1 planets form with?

A LOT.

Internal structure of Trappist-1f (Rp=6658km), with:
Fe-Mg-Si-O only
Fe/Mg=0.8
Mg/Si=1.0
50 wt% water
(2000 oceans)



How much water can terrestrial planets form with?

Our solar system (planets around a G star):

Kuiper Belt Objects, icy moons ~ 50 wt% H_2O

Earth ~ 0.025 wt% H_2O

Dryness of inner solar system planets attributed to Jupiter trapping icy grains in pressure maximum beyond it (Morbidelli et al. 2016).

Trappist-1 system (planets around an M star):

Trappist-1f,-1g ~ 50 wt% H_2O

Trappist-1b,-1c ~ 7-12 wt% H_2O

Trapping of ice in pressure maxima may not work in M dwarf disks (Desch, Kalyaan, White, in preparation)

Perhaps all planets around M stars have at least several wt% H_2O.

Part 2: Are Aqua Planets or Water Worlds habitable?
Can we detect life on them?

Water-rich planets can be perfectly habitable.

Water-rich planets generally are not good places to look for life (at least using O_2)

Should *Habitability* be our Main Guiding Principle?

habitable

[**hab**-i-t*uh*-b*uh* l]

Spell Syllables

Word Origin

adjective

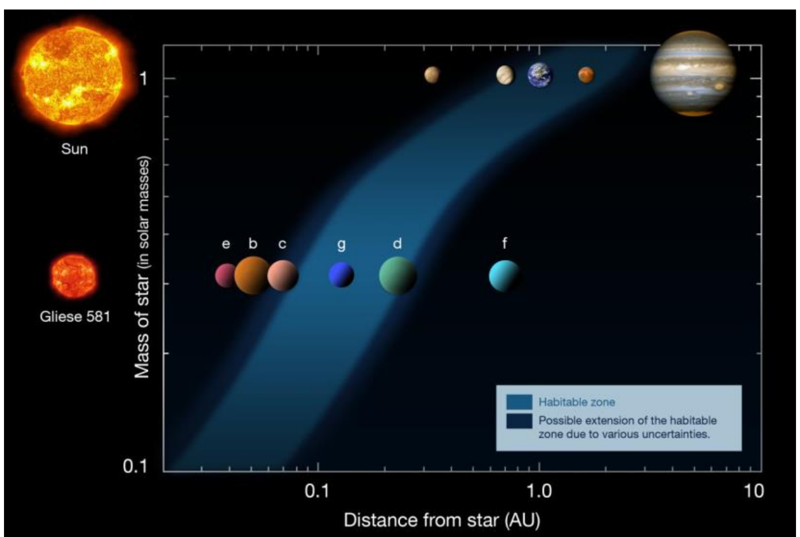
1. capable of being inhabited.

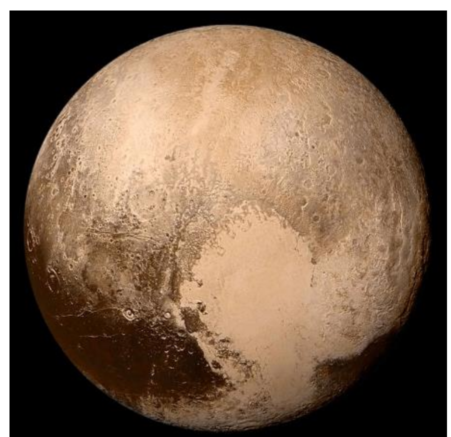
Are water-rich planets habitable?

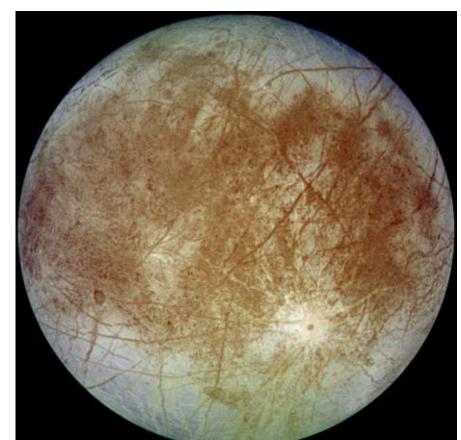
Why is a “habitable world” one with liquid water on the surface?

Why do we try so hard to define “habitability”?

What we really want to do is measure something about an exoplanet that tells us there is life on it.







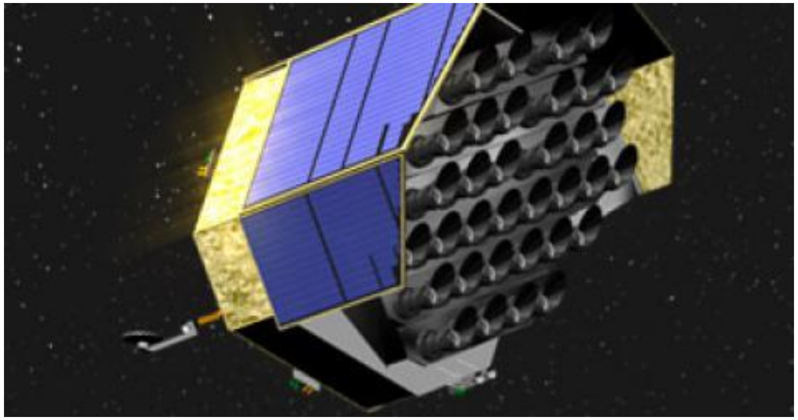
Should *Habitability* be our Main Guiding Principle?

Habitability is not restrictive enough to prioritize observations.
There are already more habitable planets than JWST can characterize.

Low mass (< 4 M_E) transiting exoplanets in their stars' habitable zones

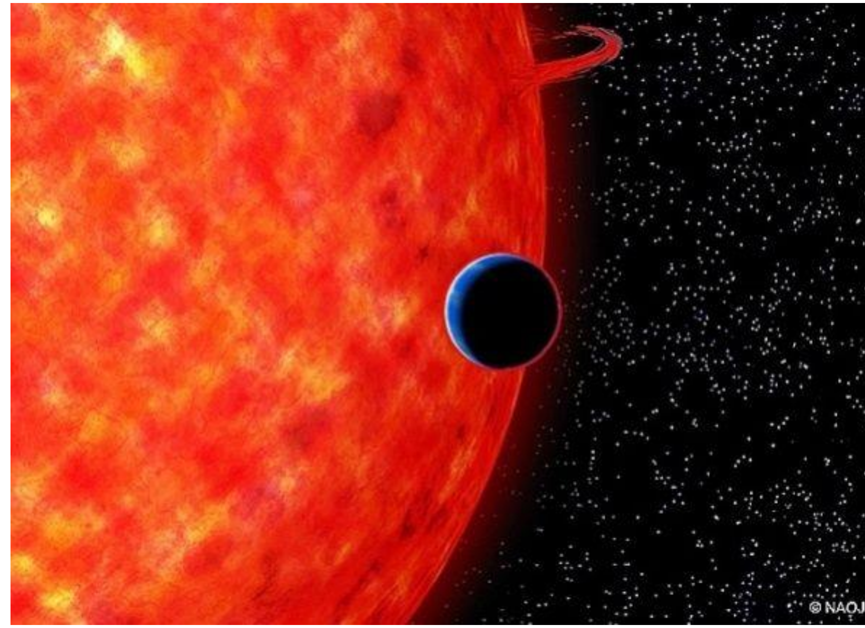
Exoplanet	Host Sp Type	Host [Fe/H]	M_p / M_E	R_p / R_E	Teq (K)
Kepler 62f	K2	-0.37	$2.8_{-1.6}^{+7.4}$	$1.41_{-0.07}^{+0.07}$	244
Kepler 442b	K5	-0.37	$2.3_{-1.3}^{+5.9}$	$1.34_{-0.18}^{+0.11}$	233
Kepler 186f	M1	-0.26	$1.5_{-0.9}^{+3.2}$	1.17	188
TRAPPIST-1e	M8	+0.04	~ 0.6	~ 0.6	230
TRAPPIST-1f	M8	+0.04	~ 0.7	~ 0.7	200
TRAPPIST-1g	M8	+0.04	~ 1.3	~ 1.3	182
Kepler 1229b	M?	-0.06	> 3.8	> 3.8	213

TESS (2018) and PLATO (2026) will soon *greatly* expand this list



Should *Habitability* be our Main Guiding Principle?

POP QUIZ: You have just enough JWST time for IR transmission spectroscopy to measure the abundance of oxygen [O_3 or O_2-O_2] in the atmosphere of **one** exoplanet.



On which exoplanet is the discovery of oxygen most *diagnostic* of life?

Your choices:

A. 1 M_E planet in the Habitable Zone of a G star, with ~1% H_2O	**C.** 1 M_E planet in the Habitable Zone of an M star, with ~ 1% H_2O
B. 1 M_E planet in the Habitable Zone of a G star, with "no" (< 0.1%) H_2O	**D.** 1 M_E planet in the Habitable Zone of an M star, with "no" (< 0.1%) H_2O

Detectability of Life as a Guiding Principle

We must move beyond defining habitability, and start figuring out on which exoplanets is life ***detectable***.

“Detectability” means if life exists, it *can* be identified, because it dominates the geochemical cycle over abiotic processes.

Excess water changes the geochemical cycles of a planet:
6 oceans will submerge the continents....
35 oceans will create a high-pressure ice layer...
100 oceans suppress silicate melting....

Planets with more water than Earth can be habitable ---
even have measureable biogenic oxygen in their atmospheres ---
but are lousy places to be sure you’ve seen the signs of life.

“Earth-like”

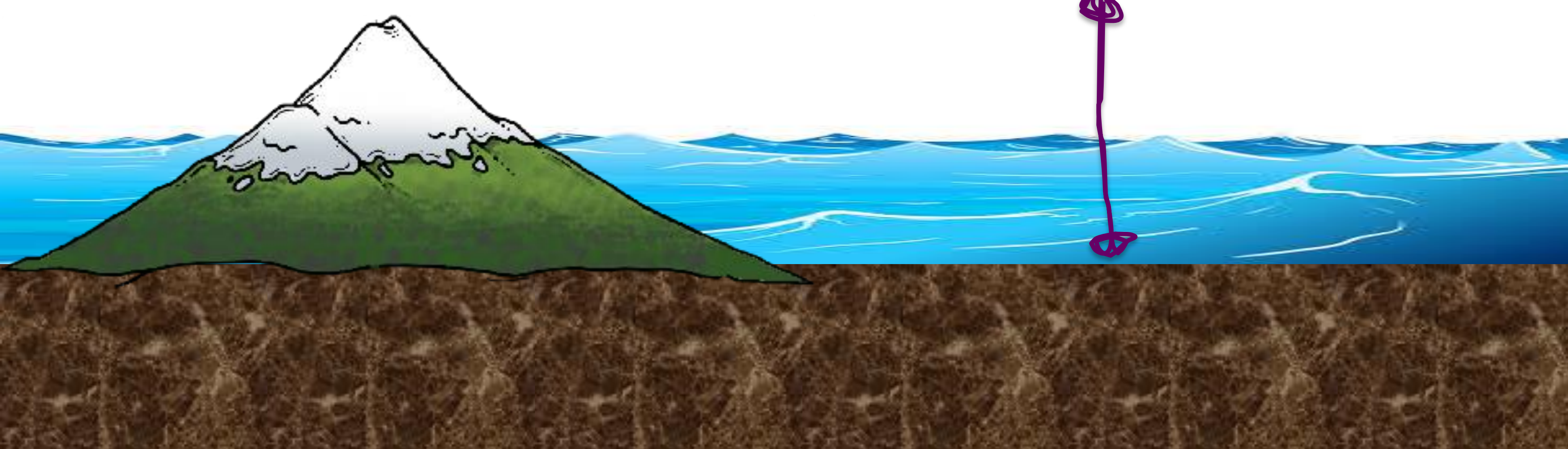
1 Ocean = 1.5×10^{21} kg = 0.025% M_E

abiotic

biotic

Average depth = 3-4 km
(Earth radius = 6371 km)

Seafloor to top of Mauna Loa = 9 km.



Carbon Cycle on Earth

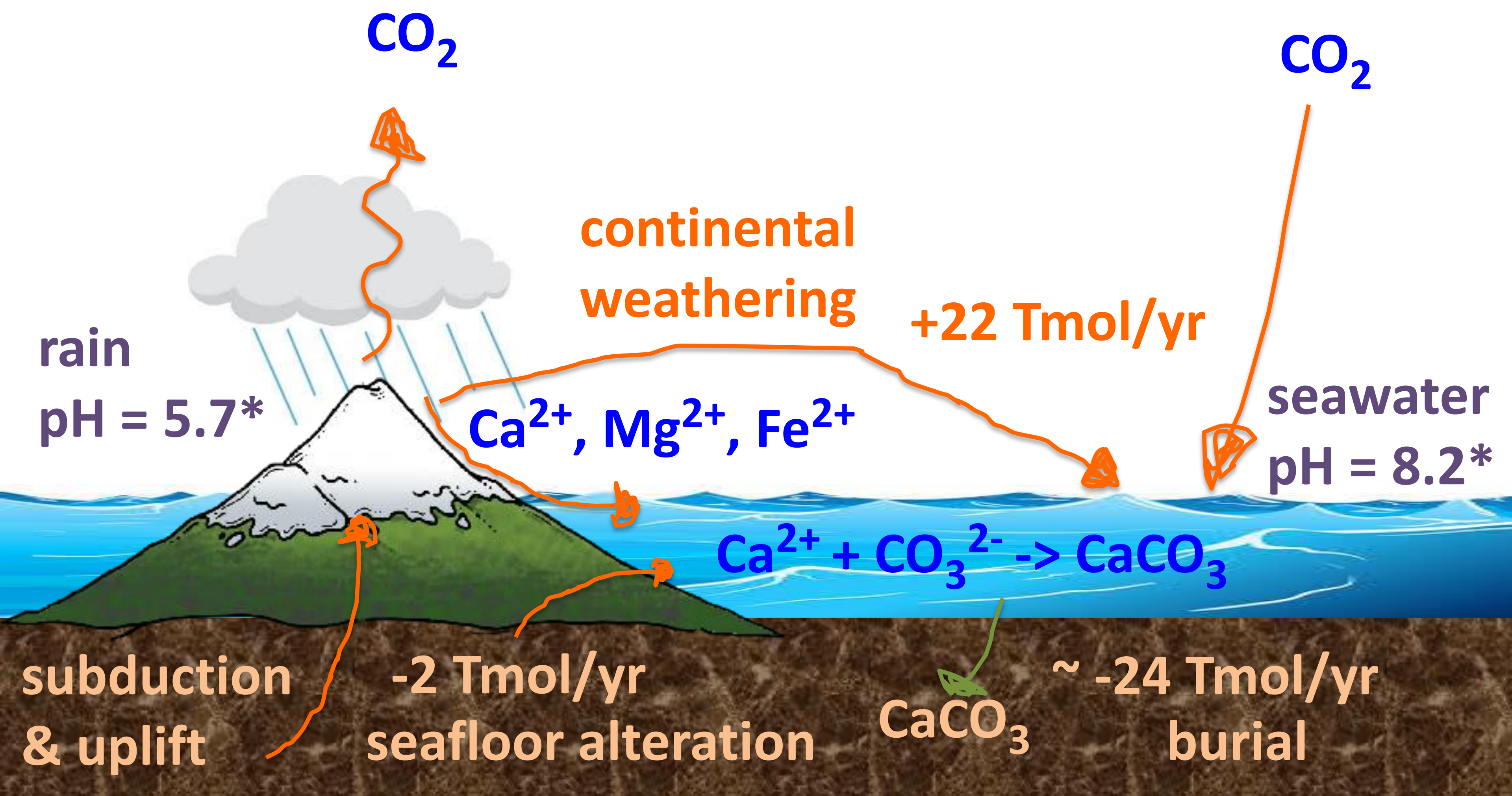
Sleep & Zahnle (2001), Fig. 1;
Wallmann & Aloisi (2012)

outgassing

+4 Tmol/yr

pCO_2 = 0.27 mbar*

* = pre-industrial

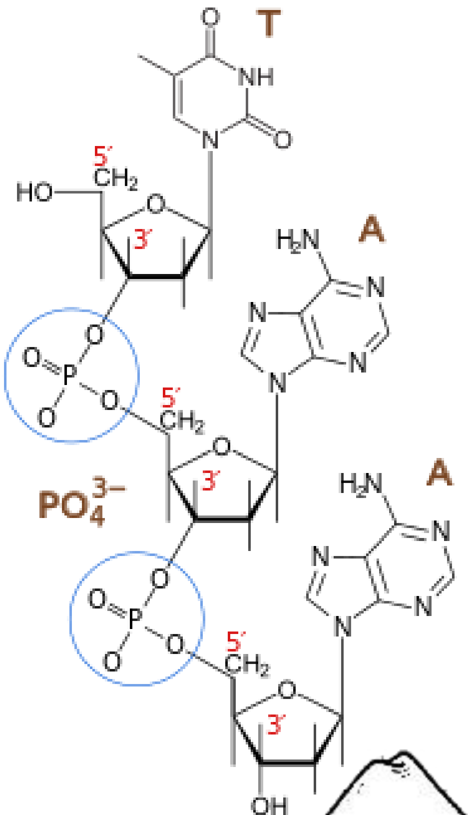


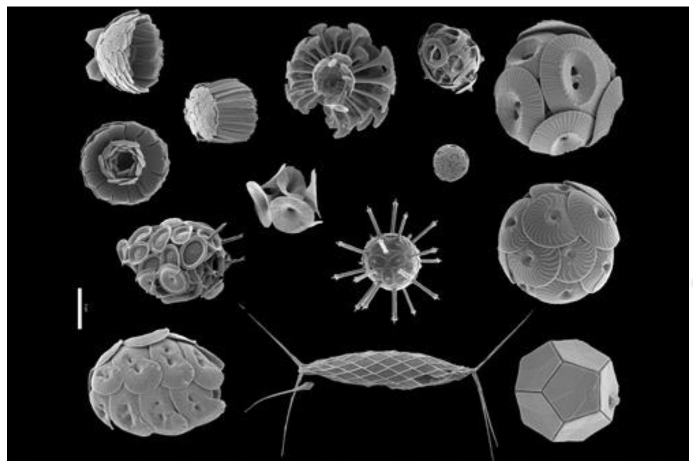
Organic Burial

Organisms remove C from the ocean when they sink to seafloor and are buried.

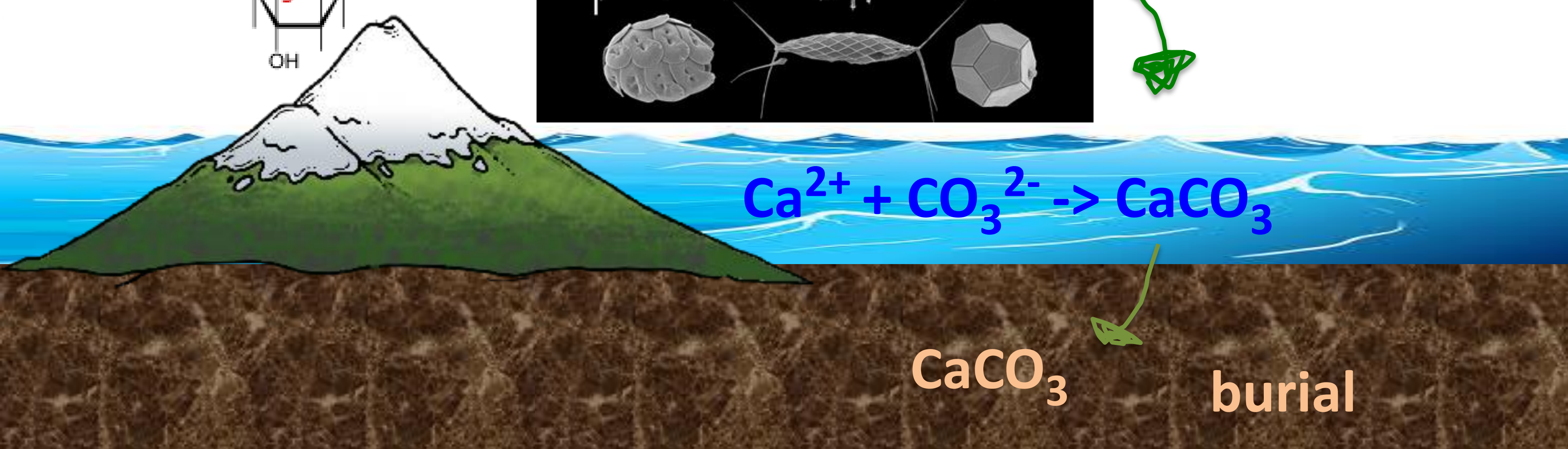
Most organisms have C:N:P = 106:16:1 (*Redfield ratio*). P needed in DNA and ATP.

1 P atom buried for every 106 – 170 C atoms buried (Colman & Holland 2000)



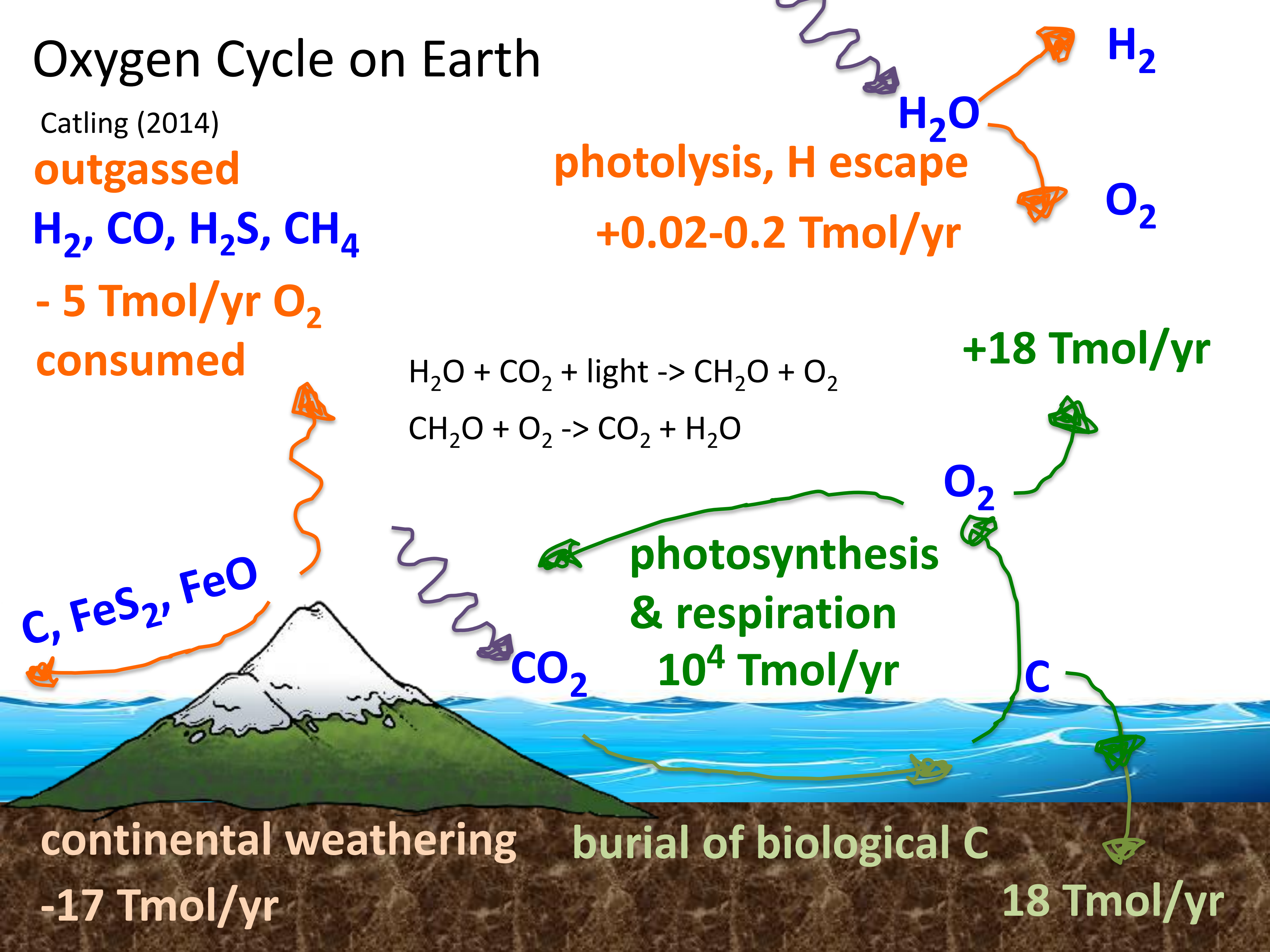


Coccolithophores



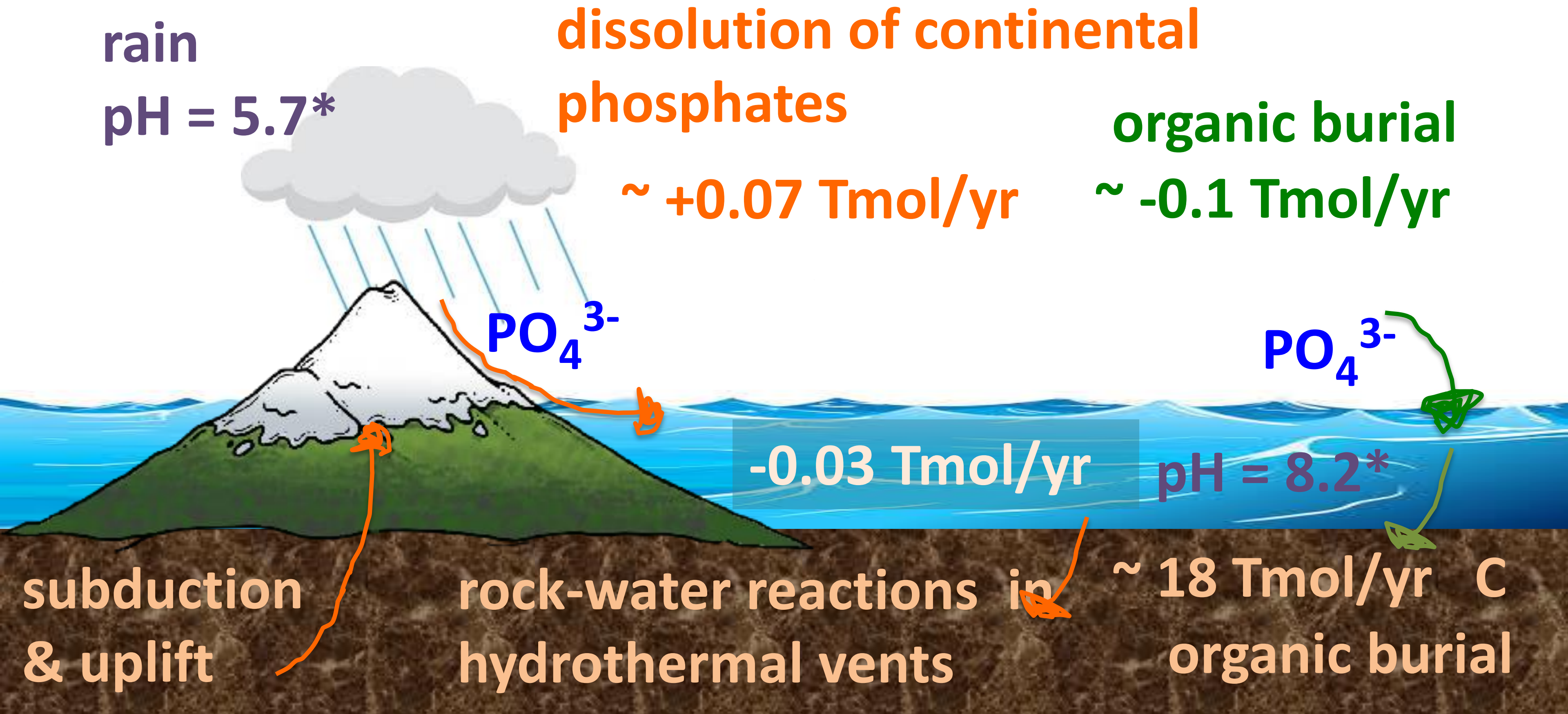
Oxygen Cycle on Earth

Catling (2014)



Phosphorus Cycle on Earth

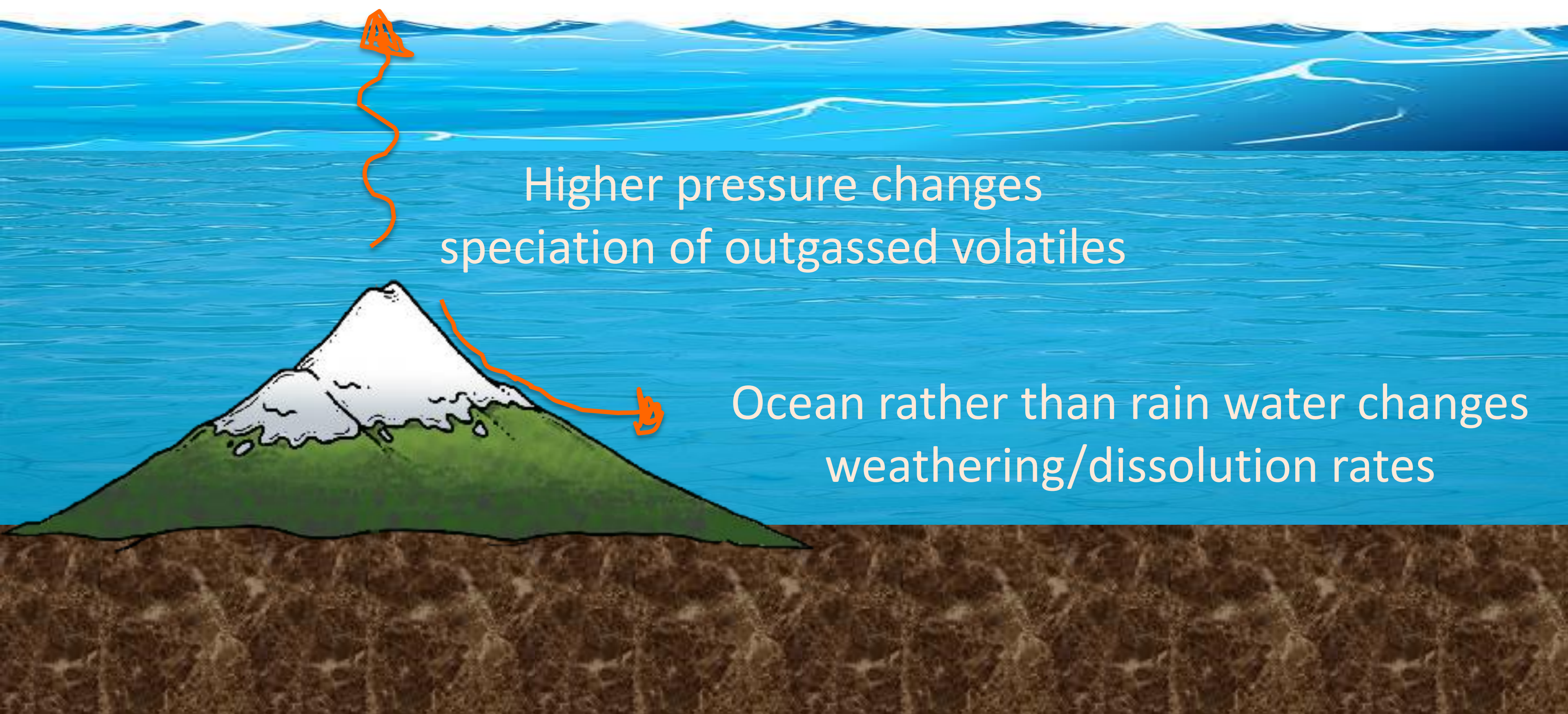
The seafloor is a net sink for phosphorus.



“Aqua Planet”

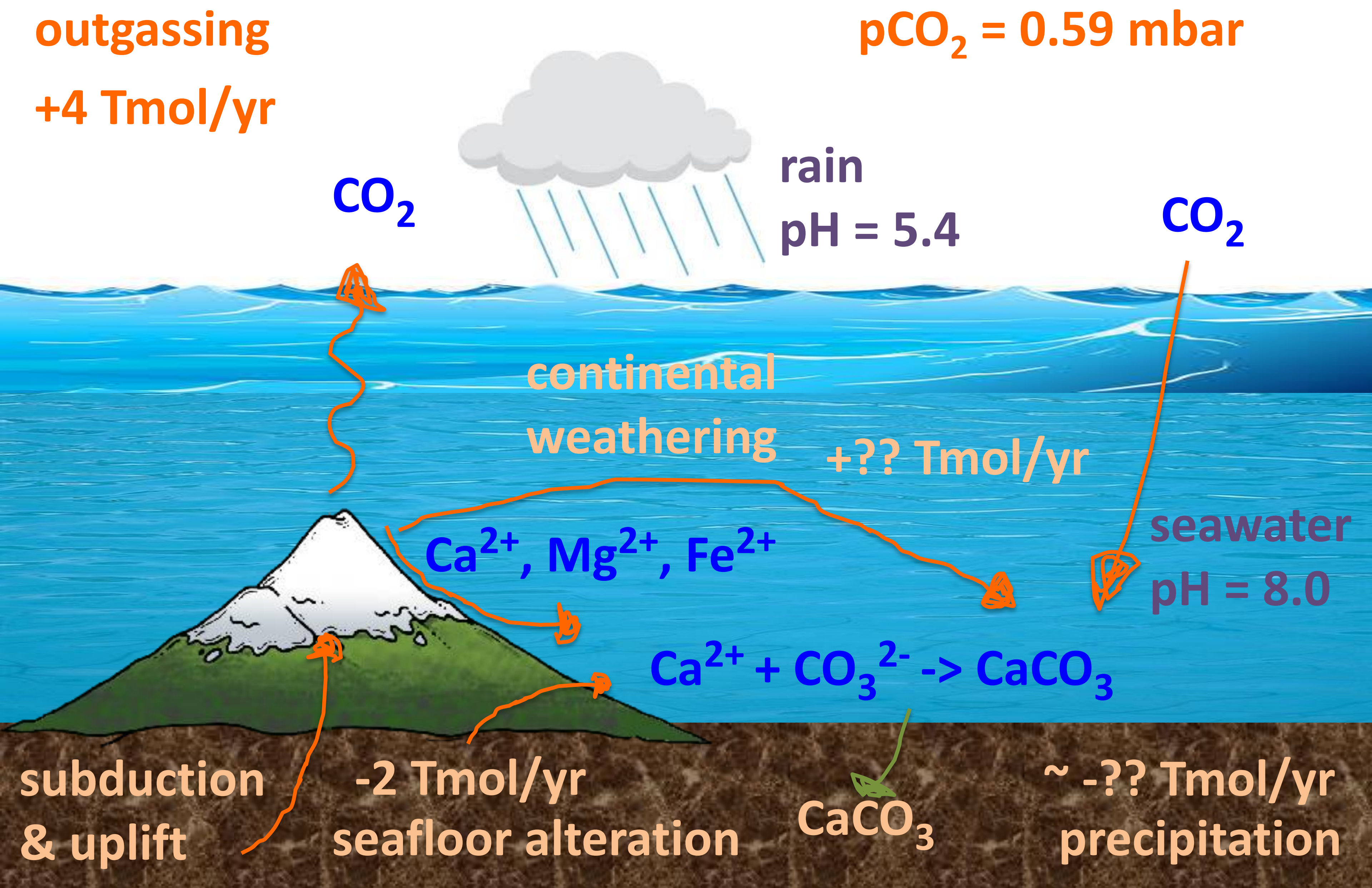
6 Oceans = 0.15% M_E

Average depth = 18 km

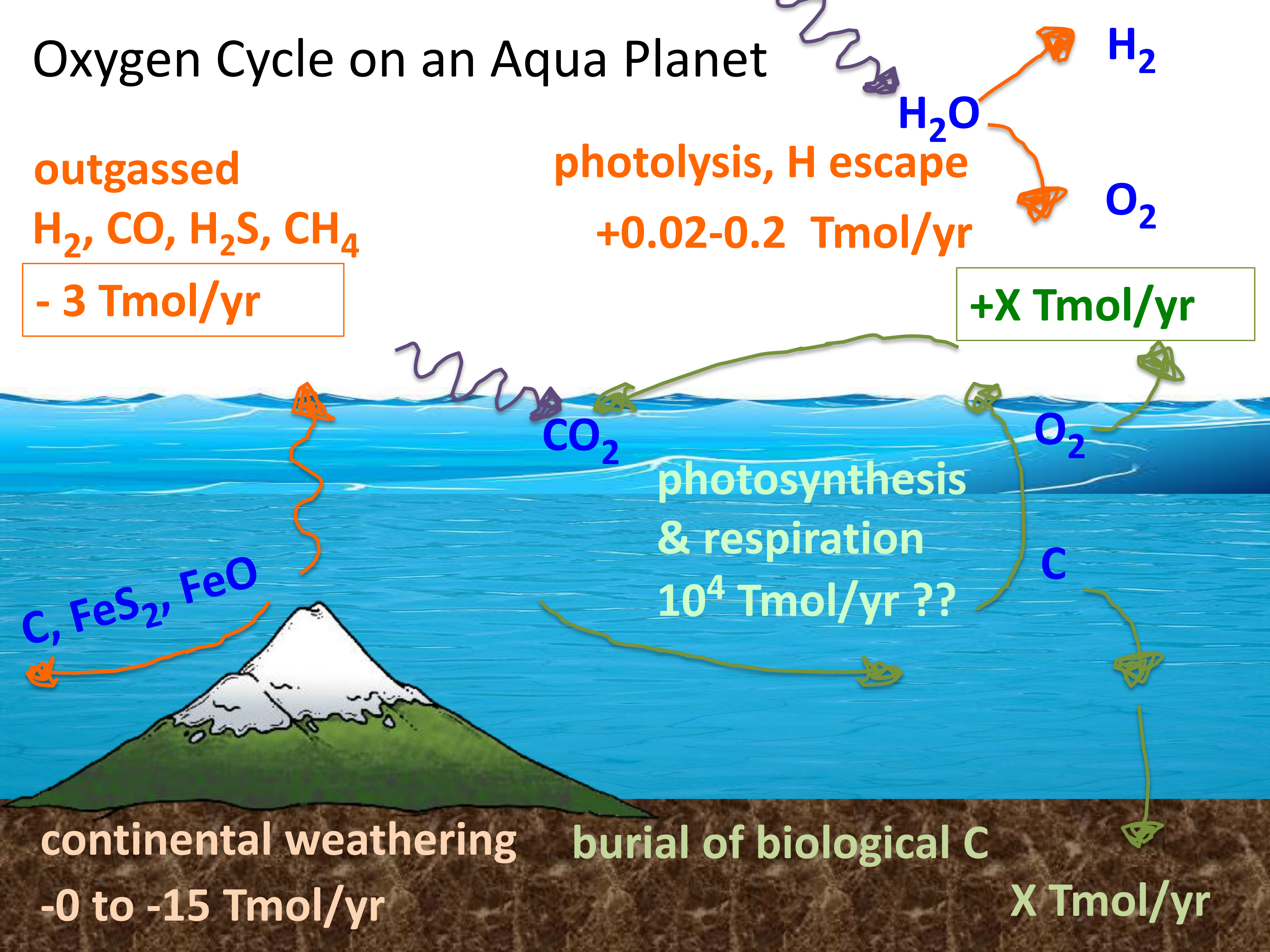


Carbon Cycle on an Aqua Planet

Sleep & Zahnle (2001), Fig. 4;
Wallmann & Aloisi (2012)



Oxygen Cycle on an Aqua Planet



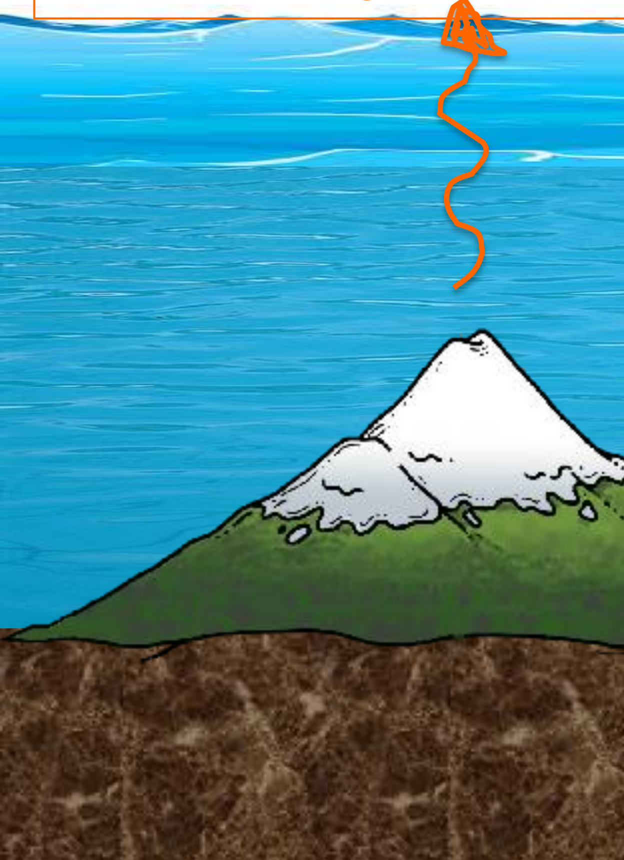
Oxygen Cycle on an Aqua Planet

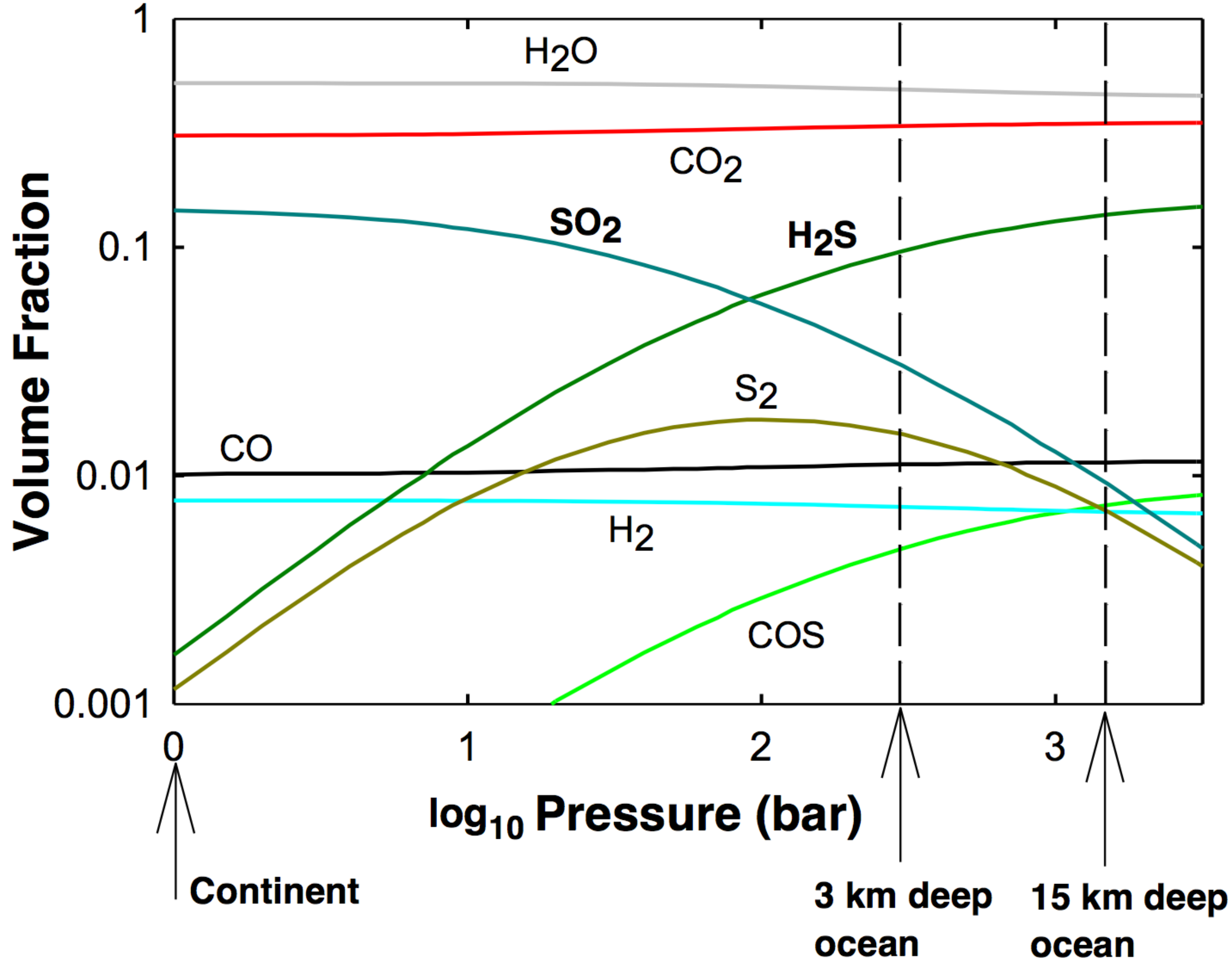
outgassed

H_2, CO, H_2S, CH_4

-3 Tmol/yr ?

-30 Tmol/yr ?





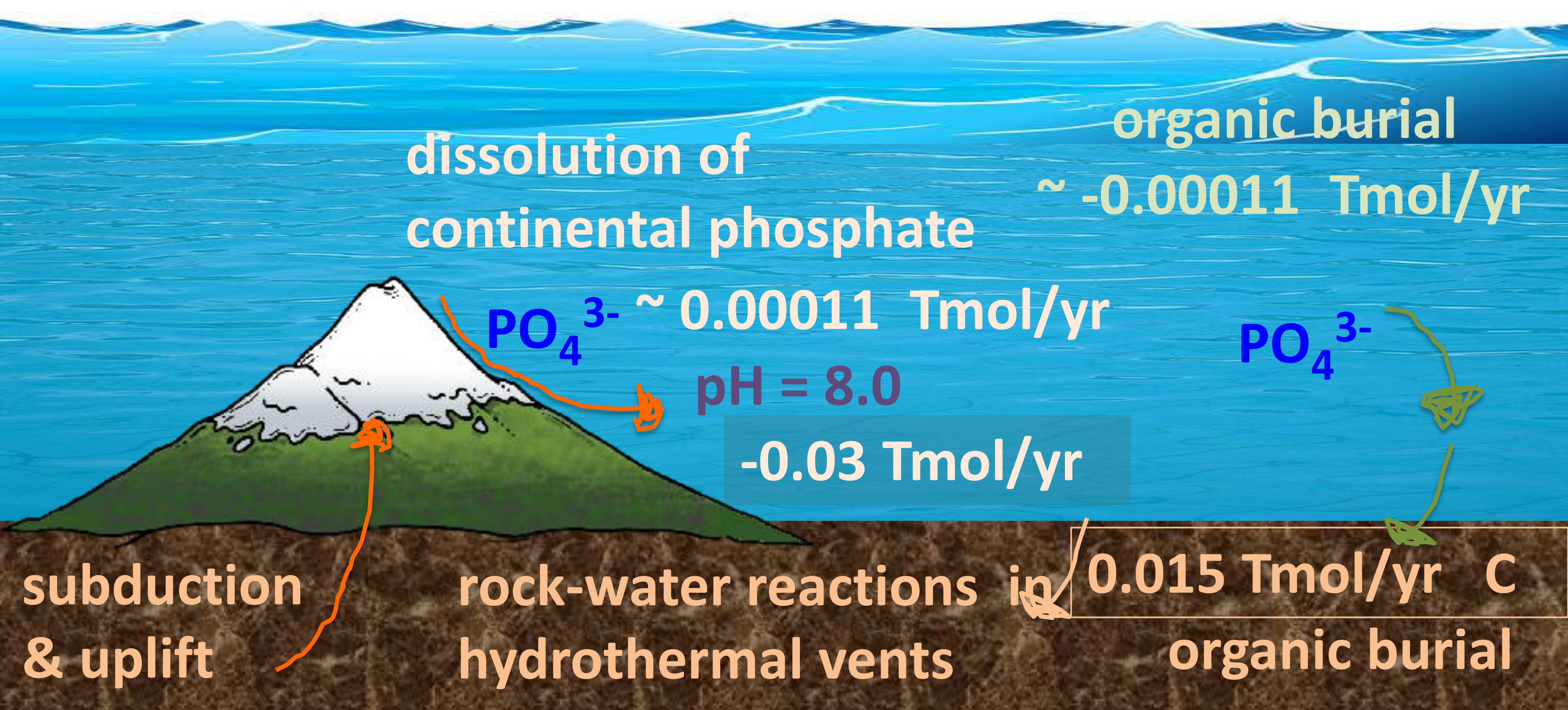
As ocean depths increase, outgassed species more reducing (H_2S / SO_2 increases). Reductant flux sensitive to pressure and redox of mantle.

Phosphorus Cycle on on Aqua Planet

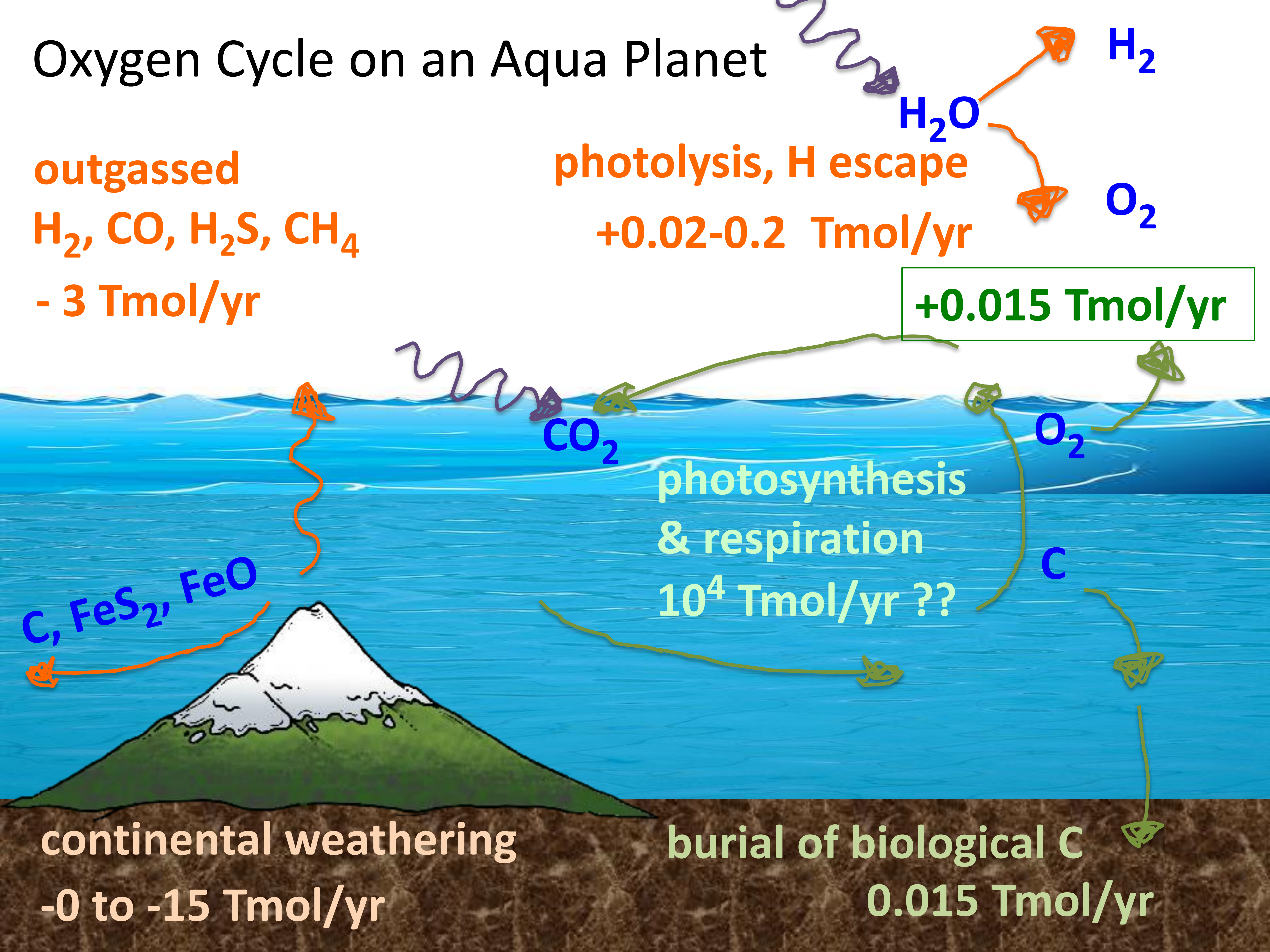
Phosphate dissolution sensitive to ~8x slower weathering, and higher pH: ~ 80 times slower at pH = 8.0 than at pH = 5.7 (Adcock et al. 2013)

Dissolved phosphate is *the* limiting nutrient.

Lower P flux = lower C burial flux



Oxygen Cycle on an Aqua Planet



"Water World"

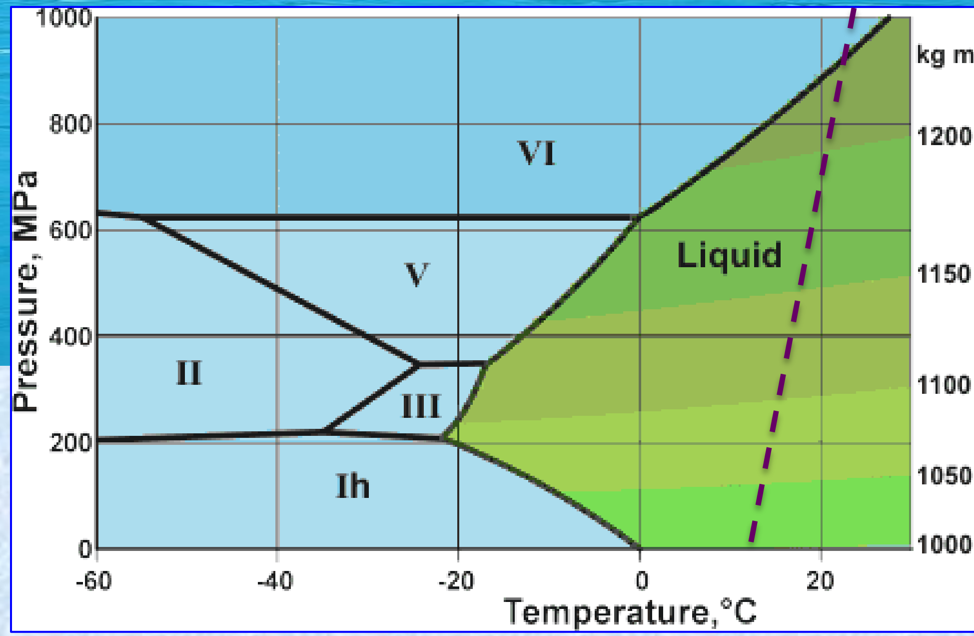
Kuchner (2003); Leger et al. (2004); Fu et al. (2010)

50 Oceans = 1.0% M_E

Average depth of water+ice ~ 150 km

P > 1 GPa, depth > 100 km

Ice VI

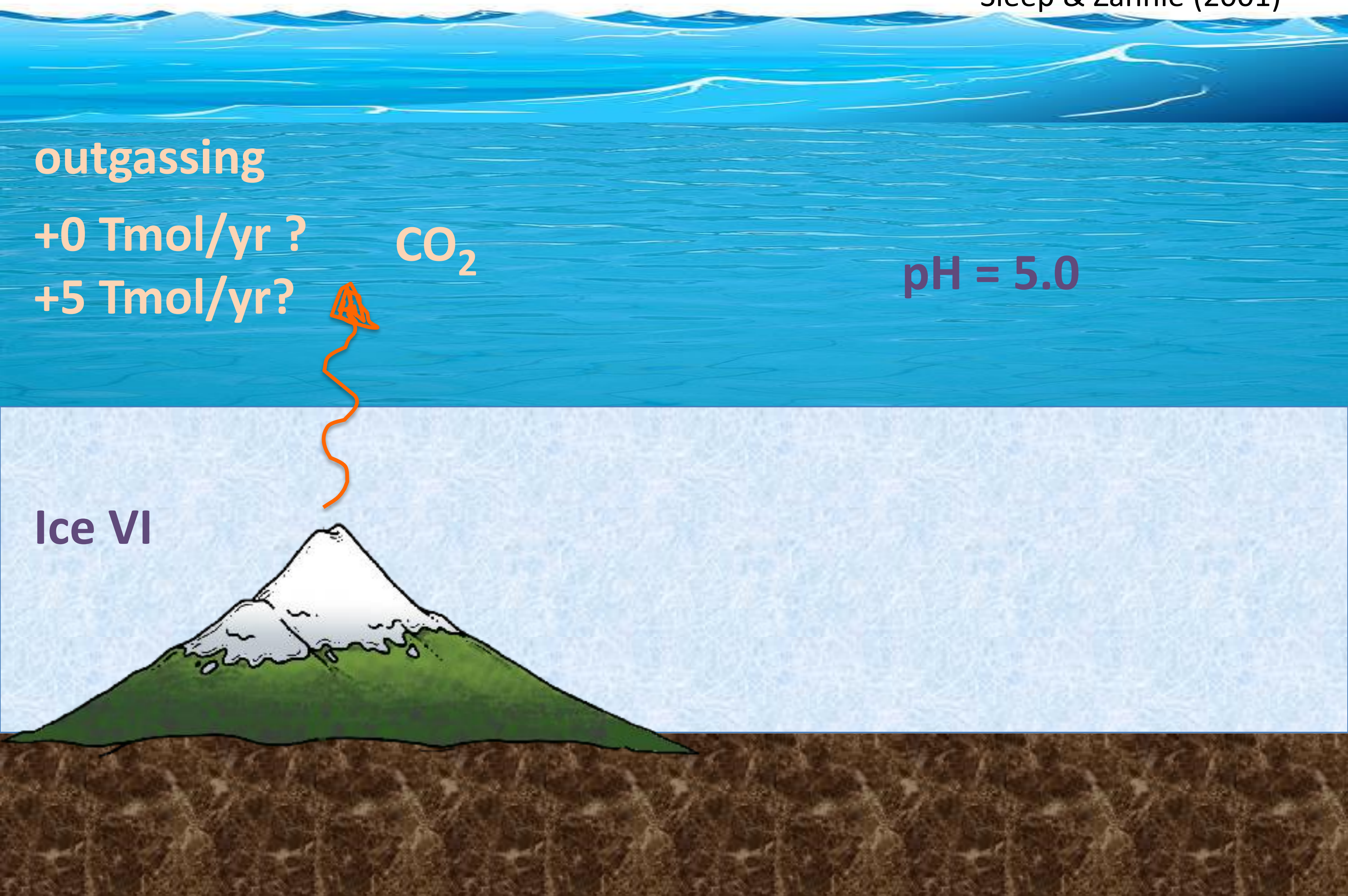


Noack et al. 2016

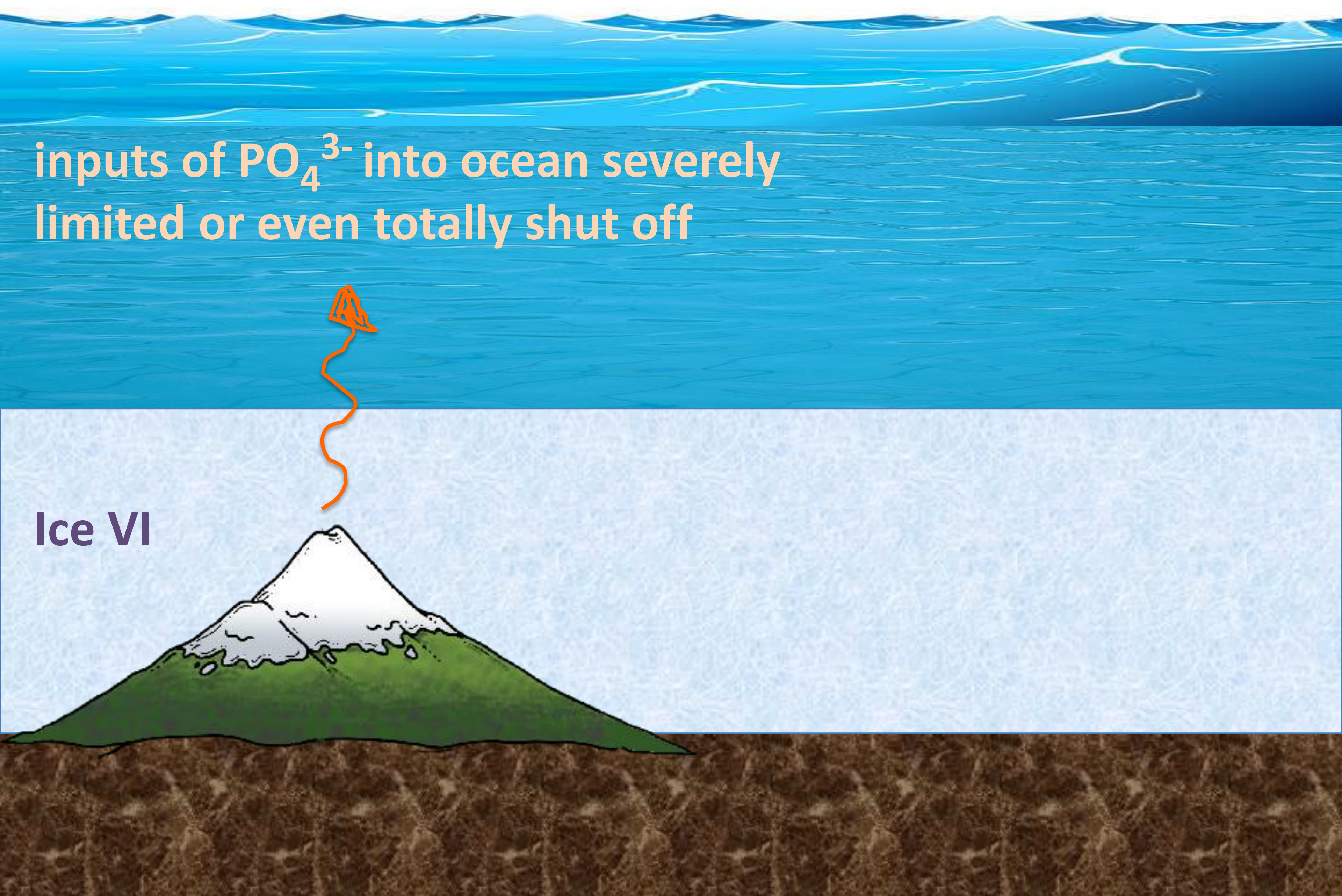
Carbon Cycle on a Water World

pCO_2 = 20 bars?

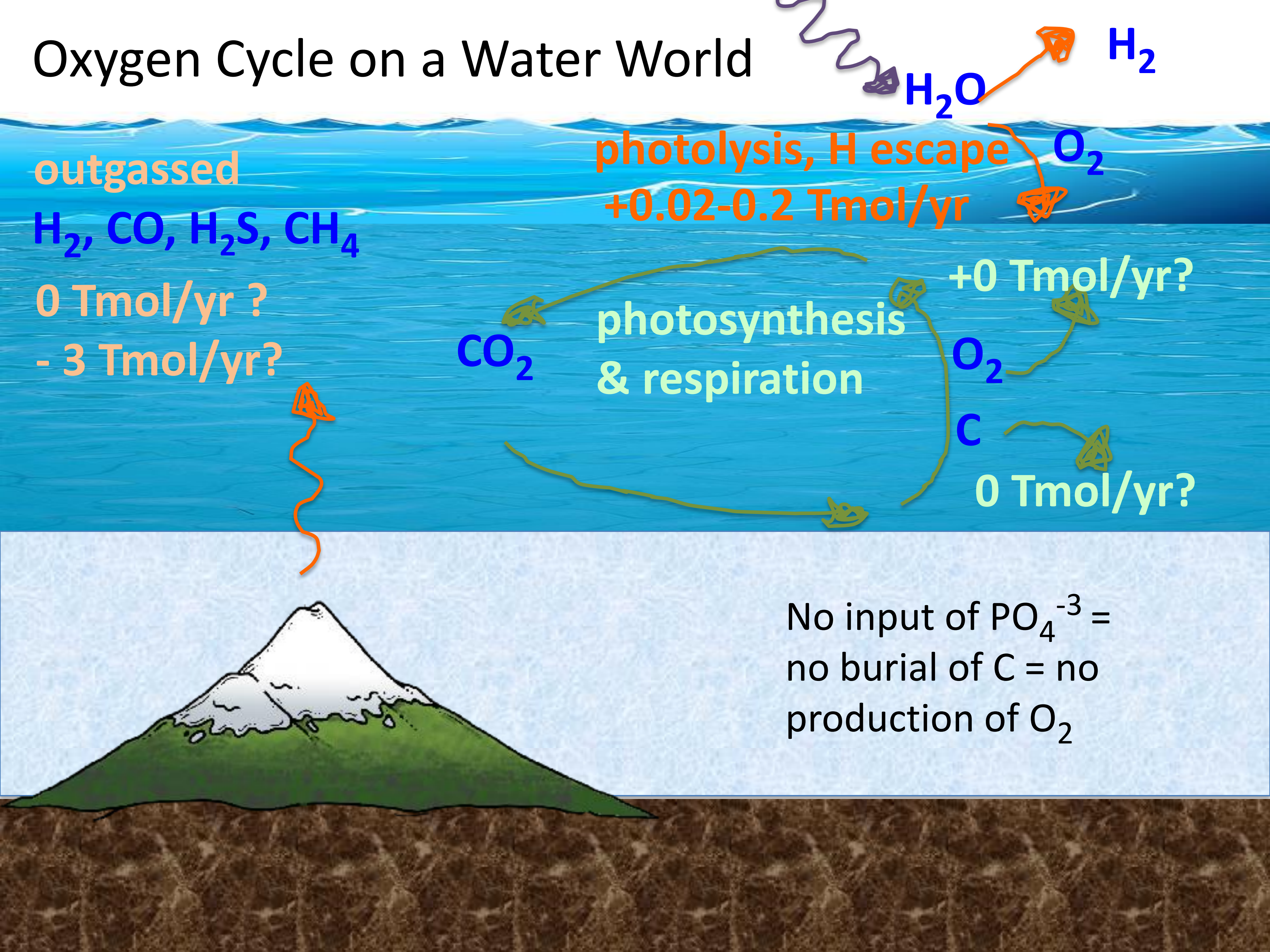
Sleep & Zahnle (2001)



Phosphorus Cycle on a Water World



Oxygen Cycle on a Water World



More Water Just Makes Things Worse

100 Oceans = 2.0% M_E

Average depth of water+ice ~ 300 km

Pressures in rock layer too high for rock to melt. Continents don’t form. No geochemical cycling between mantle and ocean.

Detectability of Life on Aqua Planets, Water Worlds

Earths, Aqua Planets, Water Worlds: All may be habitable.
All may have life producing measureable oxygen.
But Ocean + Land needed to be sure the oxygen signifies life.

On **Earth**, O_2 is overwhelmingly biotic and is a biosignature.

$DI = \log_{10}(20\ \text{Tmol/yr} \ / \ 0.02\ \text{Tmol/yr}) = \mathbf{+3}$

Aqua Planets: Low P input = low C burial = low O_2 production.
O_2 supplied by biology and photolysis at comparable rates.
We can't be sure O_2 is biotic.

$DI = \log_{10}(0.015\ \text{Tmol/yr} \ / \ 0.02\ \text{Tmol/yr}) \approx \mathbf{0}$

Water Worlds: Oceans may have no P inputs: no ability to export C, so no O_2 buildup.

$DI = \log_{10}(0.0\ \text{Tmol/yr} \ / \ 0.02\ \text{Tmol/yr}) = \mathbf{-\infty}$

Detectability Guides Observations

POP QUIZ: On which exoplanet is the detection of oxygen most *diagnostic* of life?

A. 1 M_E planet in the Habitable Zone of a G star, with ~1% H_2O

DI = **-∞**

C. 1 M_E planet in the Habitable Zone of an M star, with ~ 1% H_2O

DI = **-∞**

B. 1 M_E planet in the Habitable Zone of a G star, with "no" (< 0.1%) H_2O

DI = **0** (Aqua Planet) to
DI =**+3** (Earth-like)

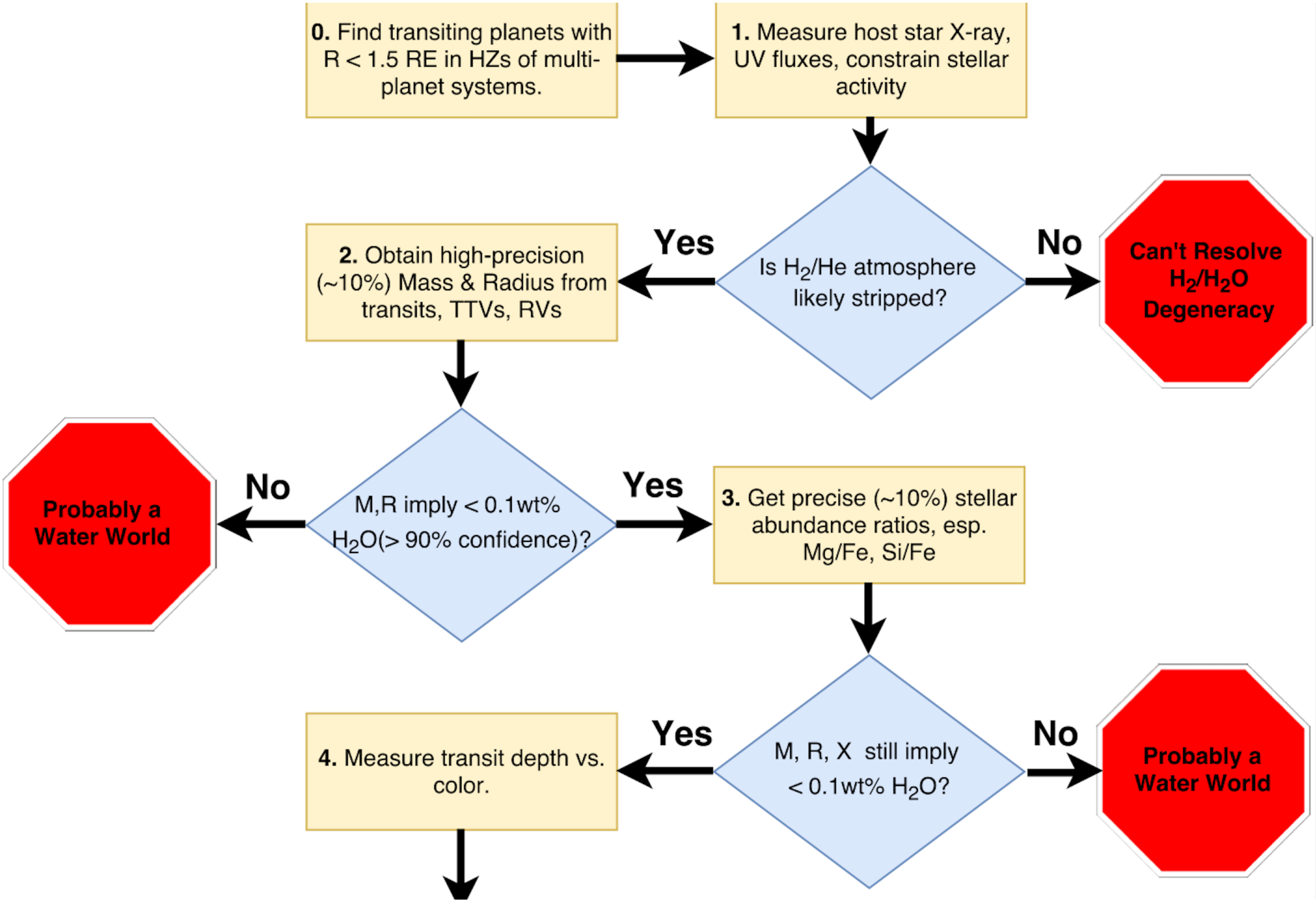
D. 1 M_E planet in the Habitable Zone of an M star, with "no" (< 0.1%) H_2O

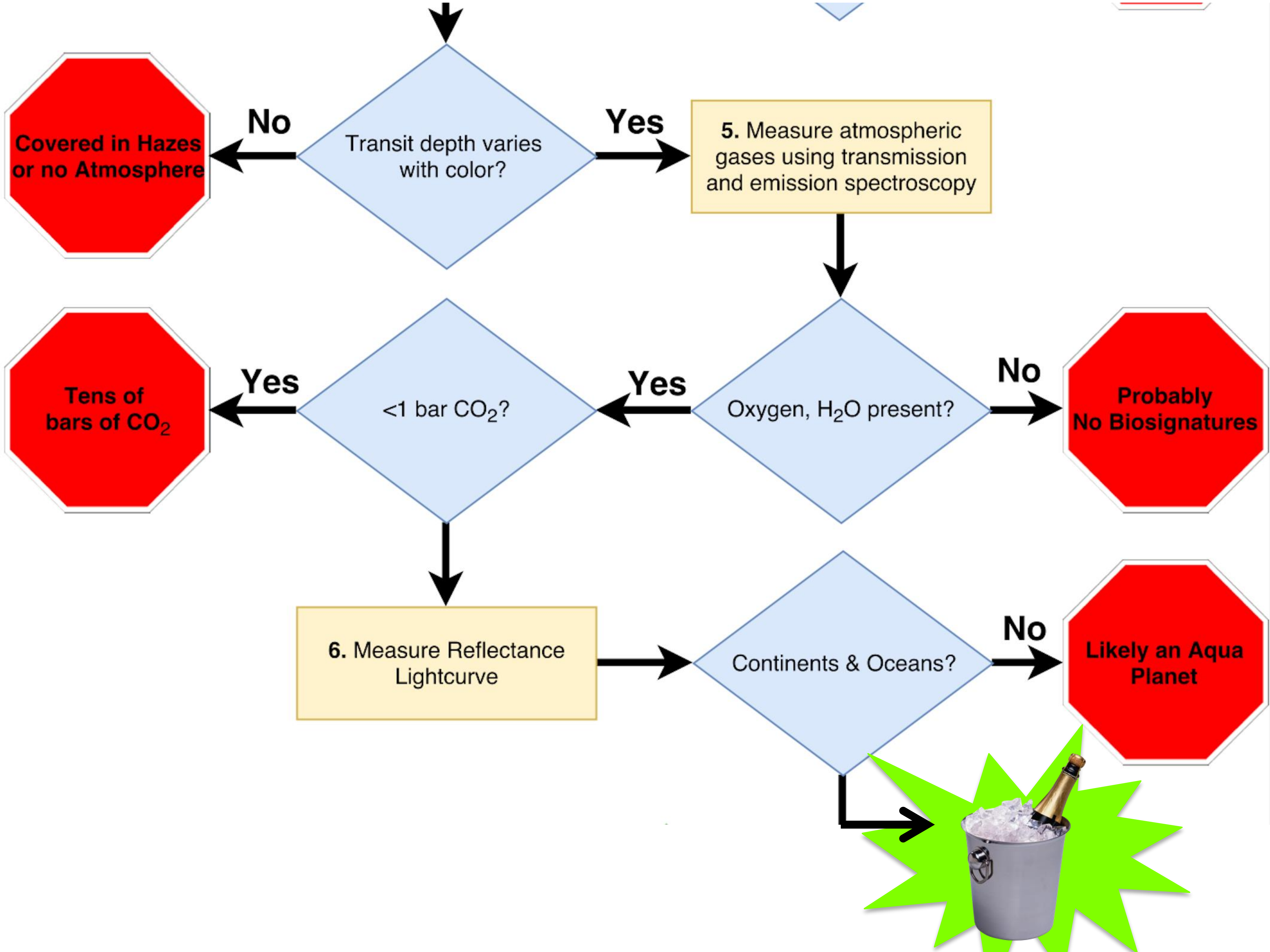
DI = **-1** (Aqua Planet) to
DI =**+2** (Earth-like)

Part 3: How should we look for life on exoplanets?

Oxygen is a biosignature on exoplanets with water AND land.

We must prioritize those rocky exoplanets with less than measureable water content.


0. Find transiting planets with R < 1.5 RE in HZs of multi-planet systems.
1. Measure host star X-ray, UV fluxes, constrain stellar activity
Is H_2/He atmosphere likely stripped?
Yes
No
Can't Resolve H_2/H_2O Degeneracy
2. Obtain high-precision (~10%) Mass & Radius from transits, TTVs, RVs
M,R imply < 0.1wt% H_2O(> 90% confidence)?
No
Probably a Water World
Yes
3. Get precise (~10%) stellar abundance ratios, esp. Mg/Fe, Si/Fe
M, R, X still imply < 0.1wt% H_2O?
Yes
No
Probably a Water World
4. Measure transit depth vs. color.


Covered in Hazes or no Atmosphere
No
Transit depth varies with color?
Yes
5. Measure atmospheric gases using transmission and emission spectroscopy
Tens of bars of CO_2
Yes
<1 bar CO_2?
Yes
Oxygen, H_2O present?
No
Probably No Biosignatures
6. Measure Reflectance Lightcurve
Continents & Oceans?
No
Likely an Aqua Planet

Part 1: How much water can terrestrial planets form with?

Theory says: up to hundreds of oceans' worth of water
Trappist-1 suggests hundreds of oceans, especially around M stars
Many (most?) planets may be Aqua Planets or Water Worlds

Part 2: Are Aqua Planets or Water Worlds habitable?
Can we detect life on them?

Water-rich planets can be perfectly habitable.
Water-rich planets generally are not good places to look for life (at least using O_2)

Part 3: How should we look for life on exoplanets?

Oxygen is a biosignature on exoplanets with water AND land.
We must prioritize those rocky exoplanets with *less than measureable* water content.