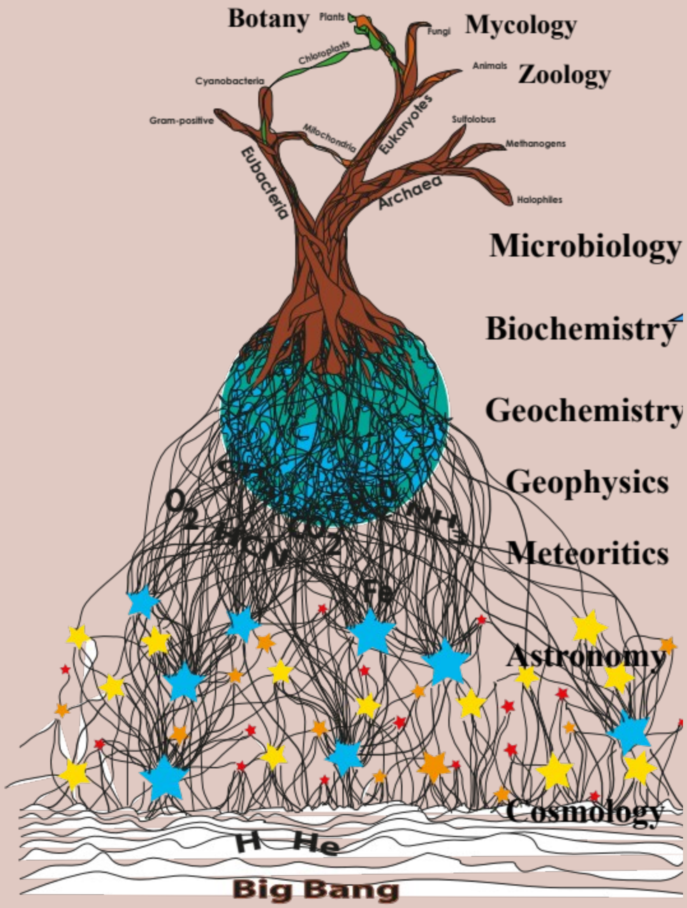
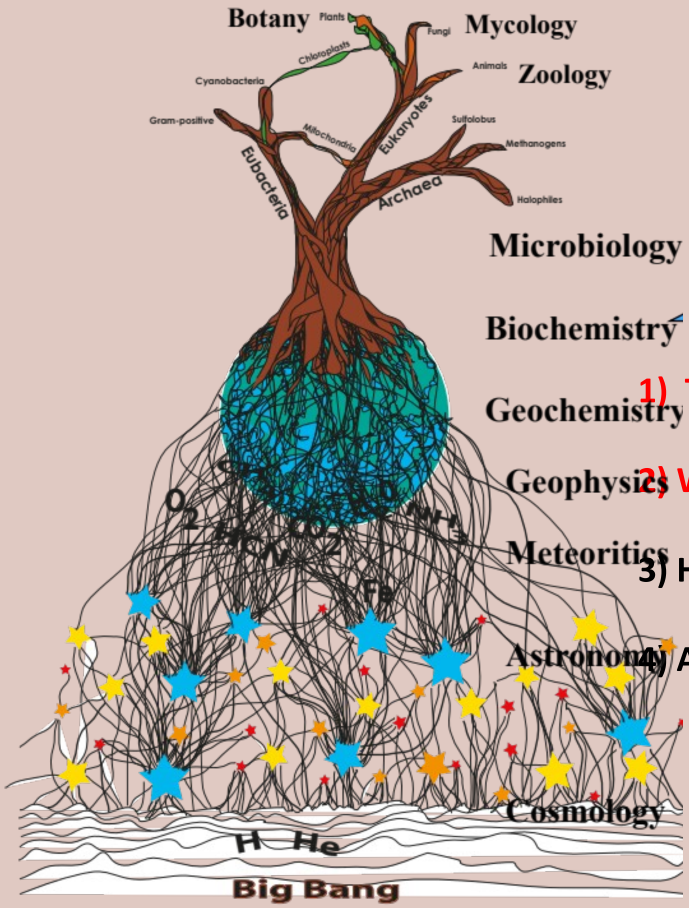


Habitability and the Search for Life Elsewhere

Charley Lineweaver
Australian National University



Habitability and the Search for Life Elsewhere

1) The origin of life: WHAT, WHEN, WHERE, HOW, WHY ?

2) What kind of planets are in the universe?

3) Habitable Zones: Terrestrial, Circumstellar, Galactic, Universal

4) Are we Alone? What can life on Earth tell us about life elsewhere?

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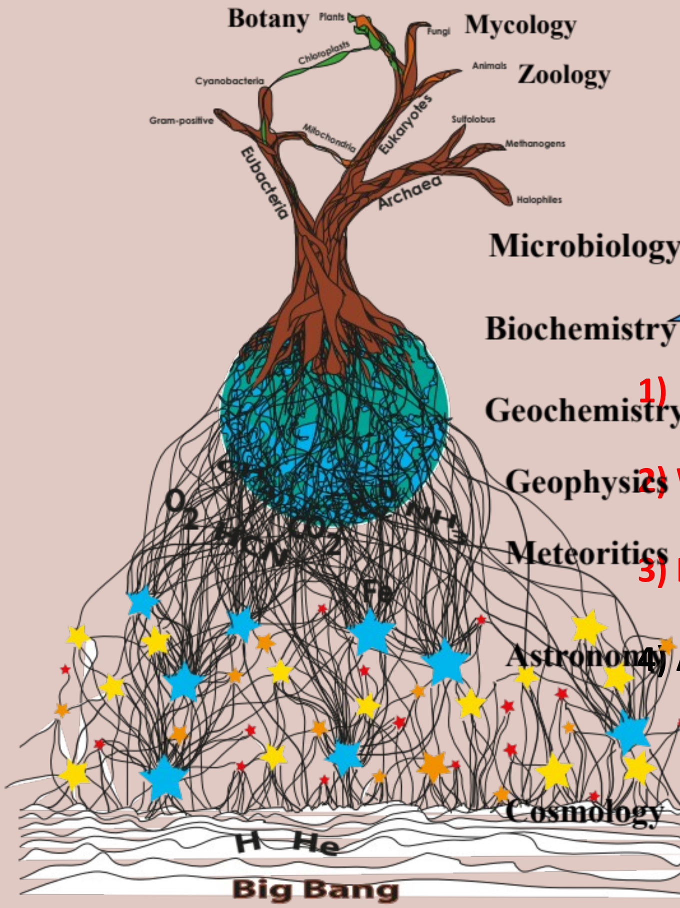
Habitability and the Search for Life Elsewhere



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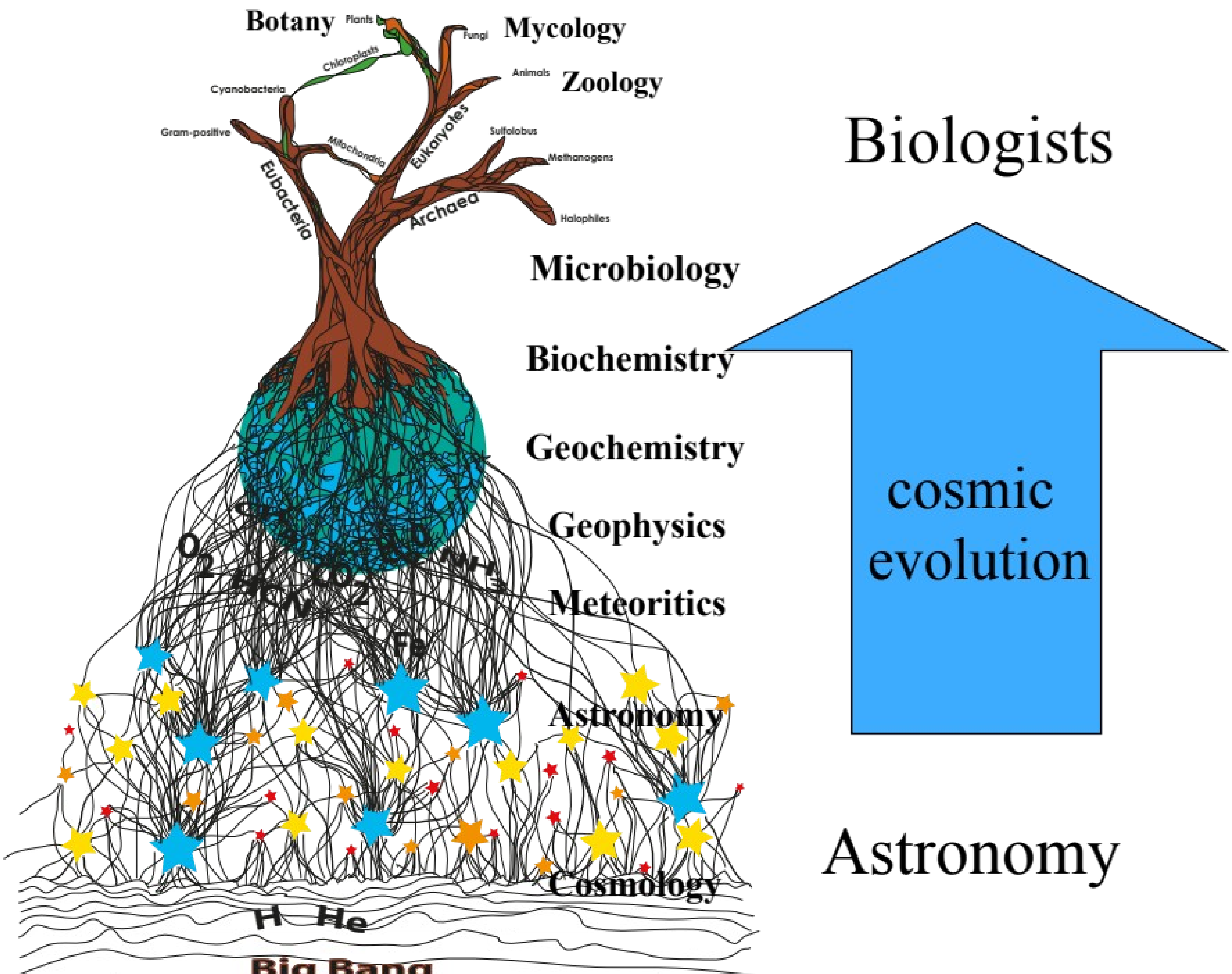
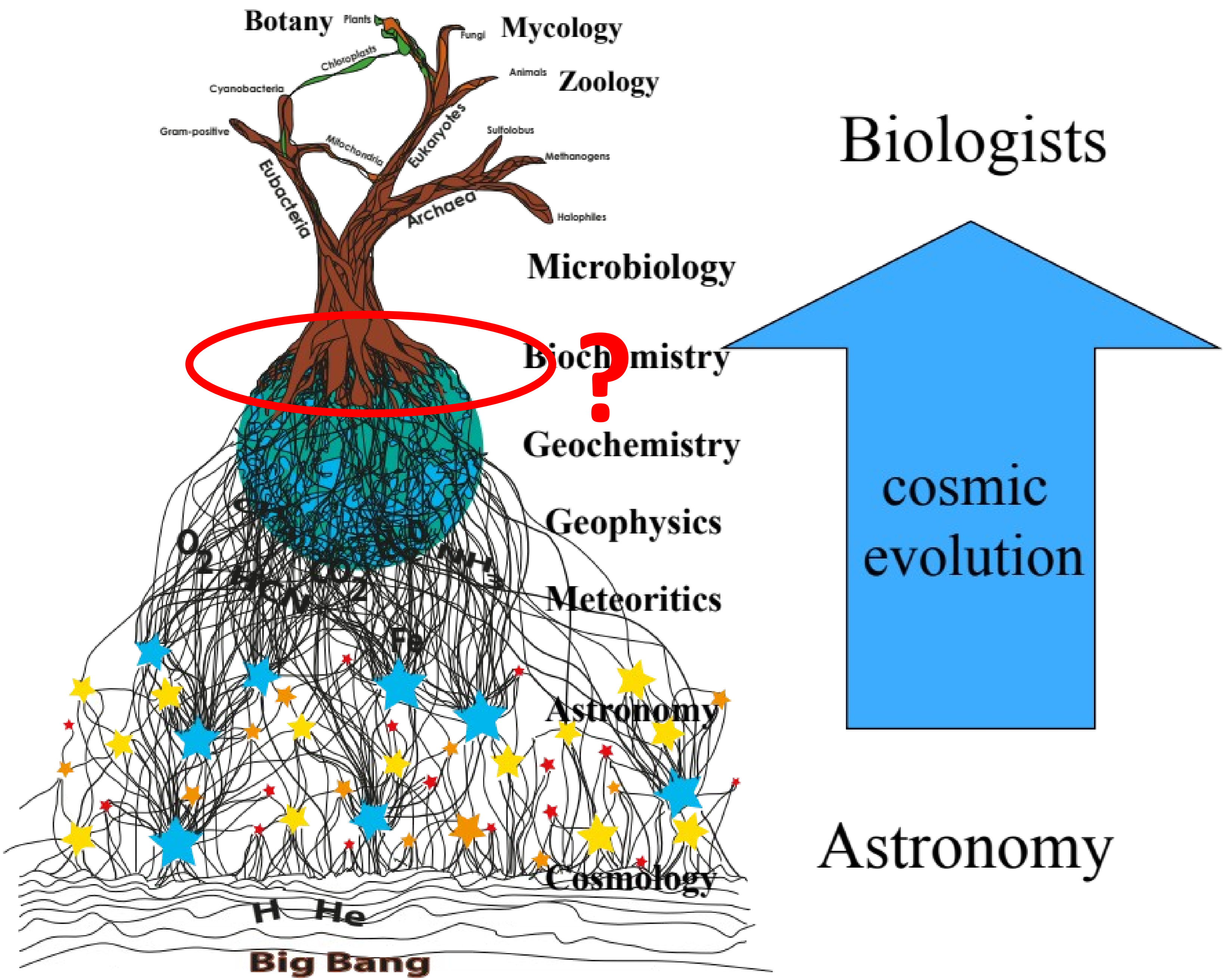
Charley Lineweaver
Australian National University

Habitability of Planets
Galaxies and Universes



Lineweaver & Chopra 2012



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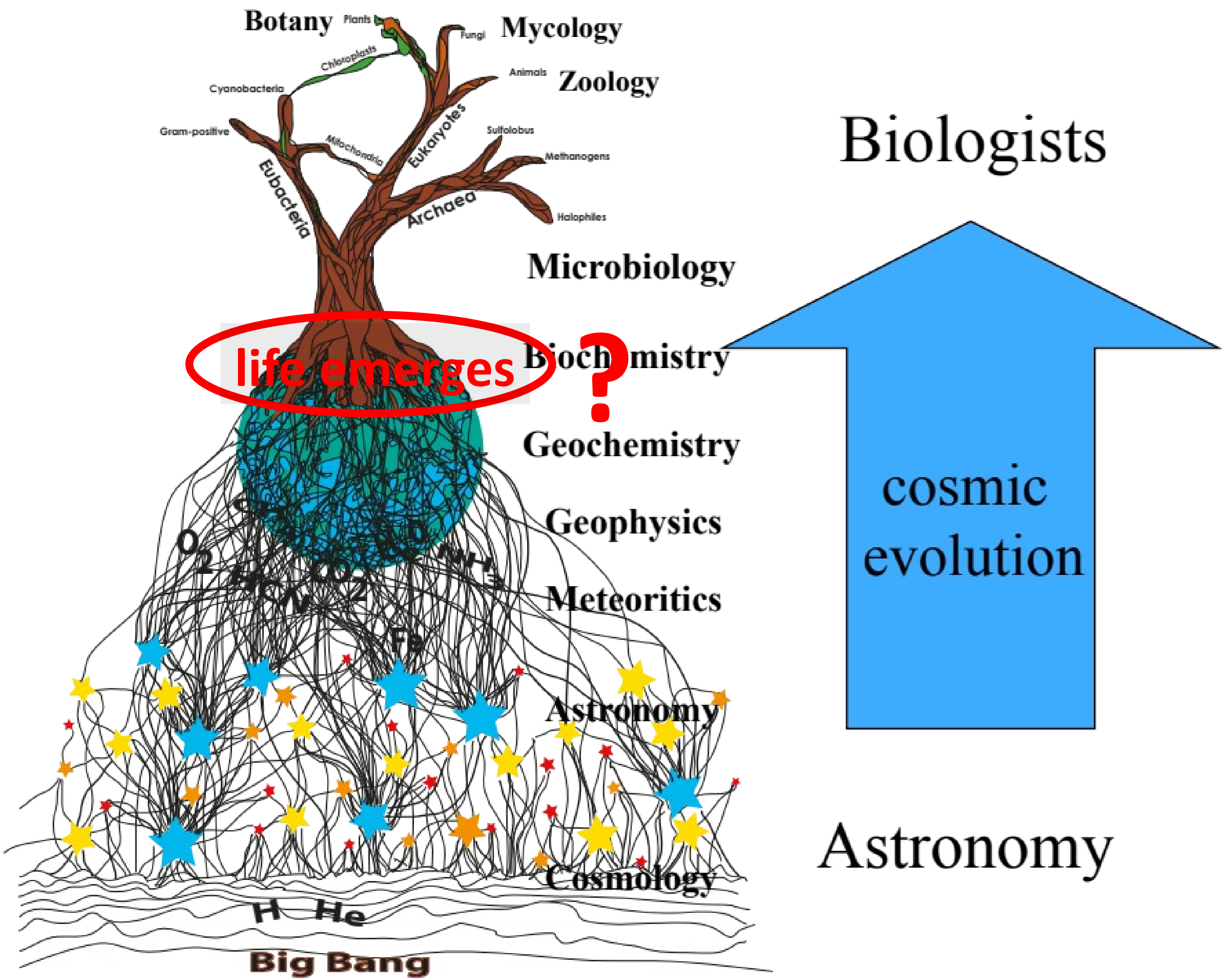

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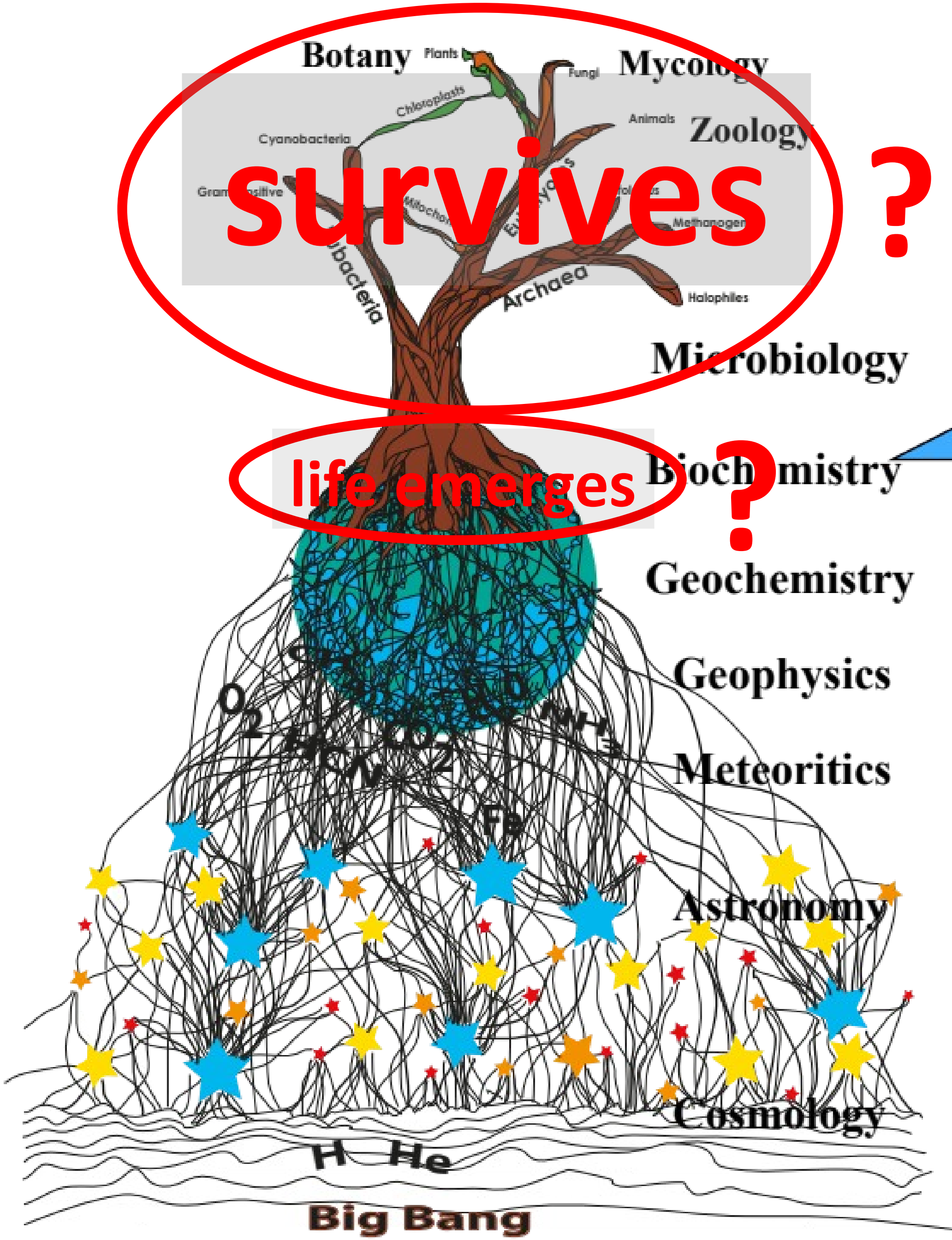
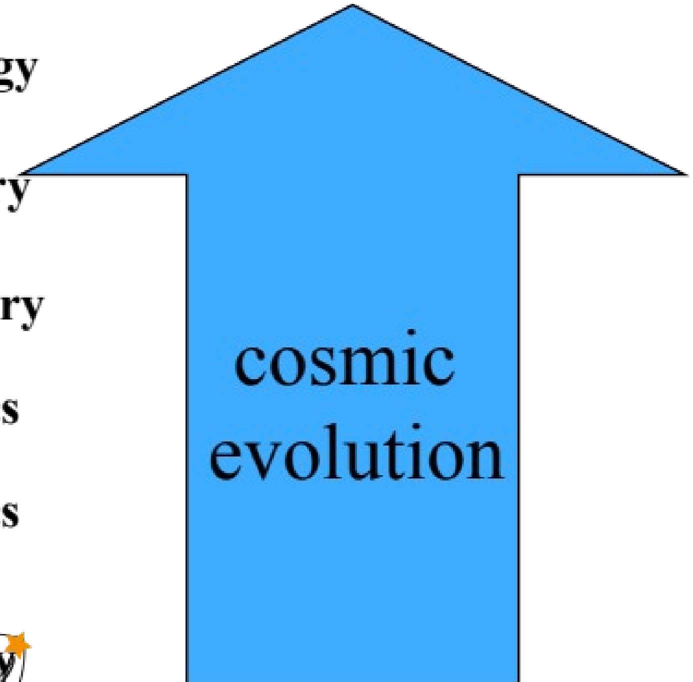


Biologists



Astronomy

Lineweaver & Chopra 2012

2 parts to habitability

1) suitable for the origin of life

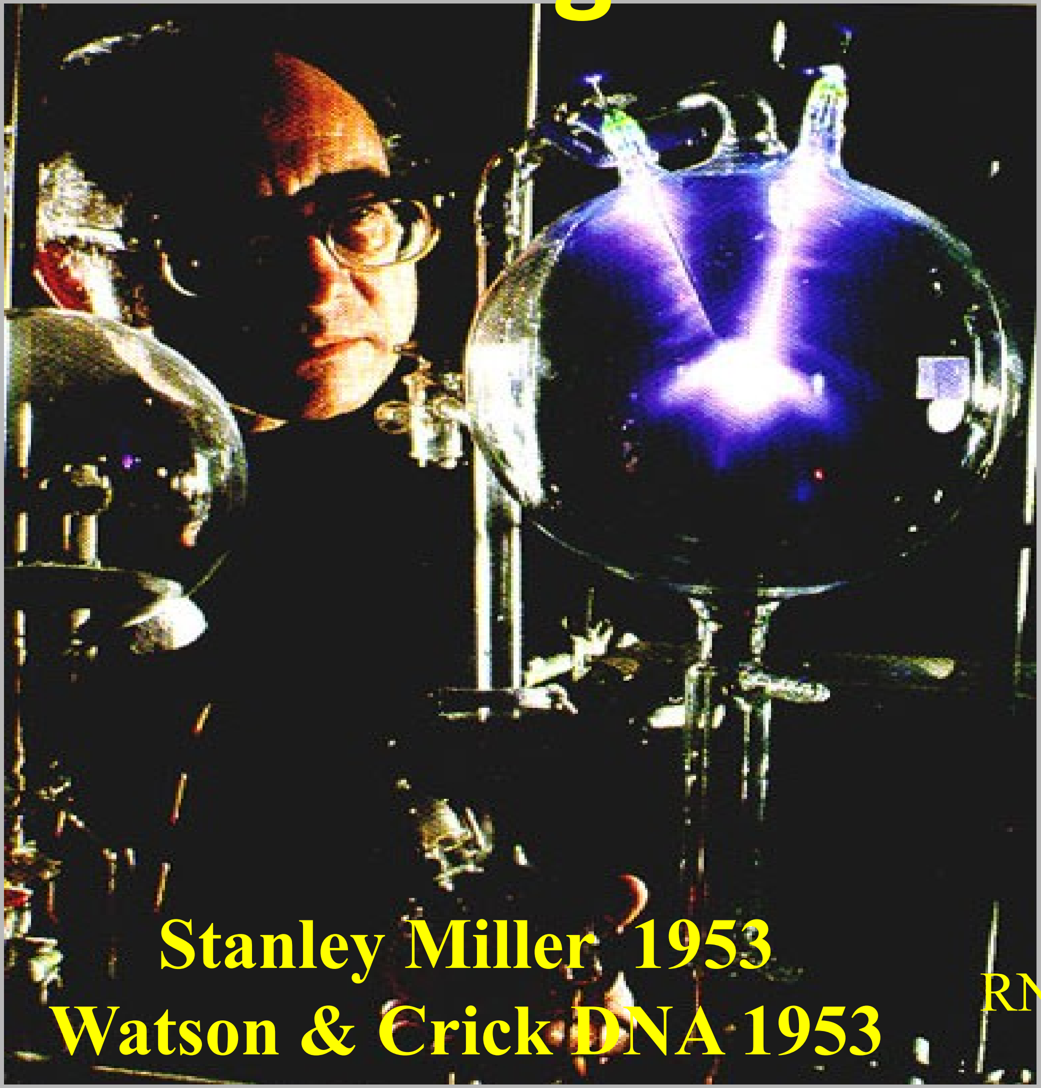
planet or moon, surface or hydrothermal vent, chemical disequilibrium, redox reactions, auto-catalytic cycles, hydration/dehydration, UV photons, large impacts, lipids, amino acids, liquid solvent (H_2O, CO_2, CH_4)

2) suitable to support life

continuous source of free energy, water, starlight,

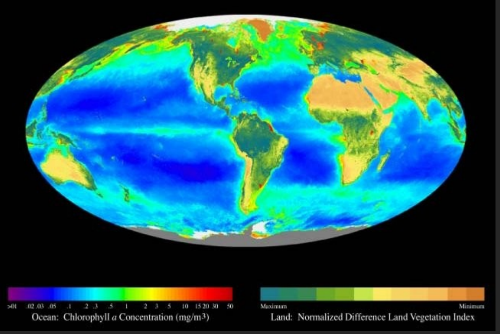
no giant impacts, no nearby supernova

origin of life

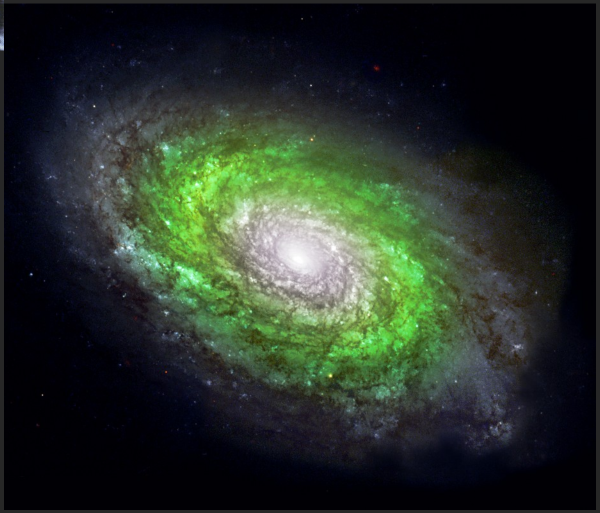


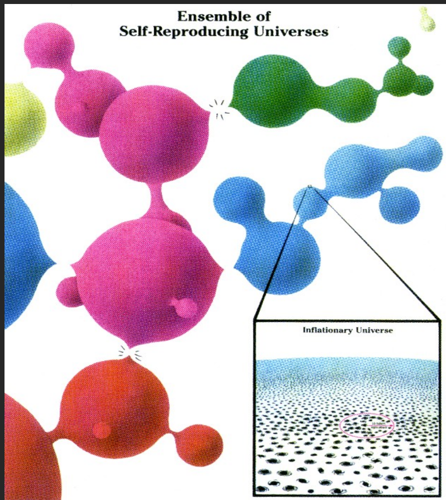
amino acids
polypeptides
proteinoids
lipids
carbonaceous
chondrites
water
sugars
alcohols
auto-catalytic
cycles
RNA coder +enzyme

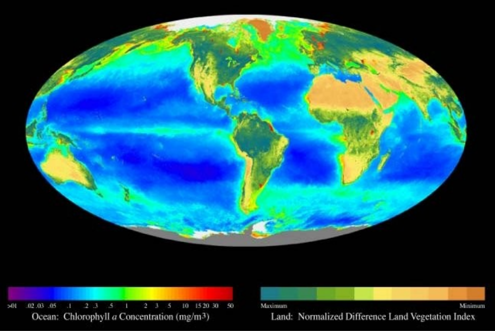
suitable to
support life



Are there specific places and times
on Earth or in our Solar System,
on planets orbiting other stars,
in our galaxy or other galaxies
or even in other universes
where we are more likely to find life?







Terrestrial HZ

regions of the earth fit for life
temperature/water, nutrients

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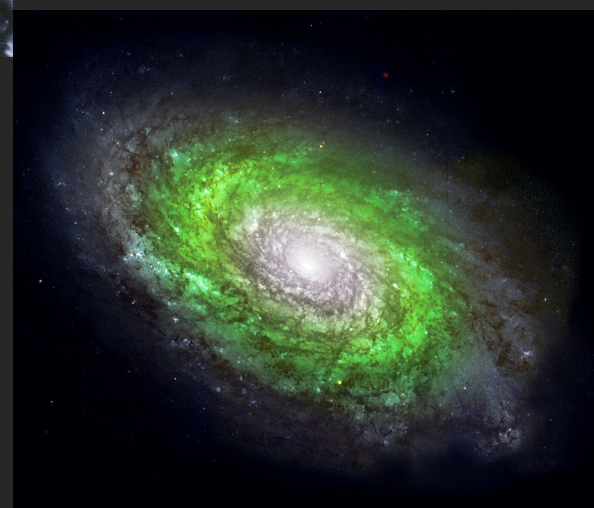

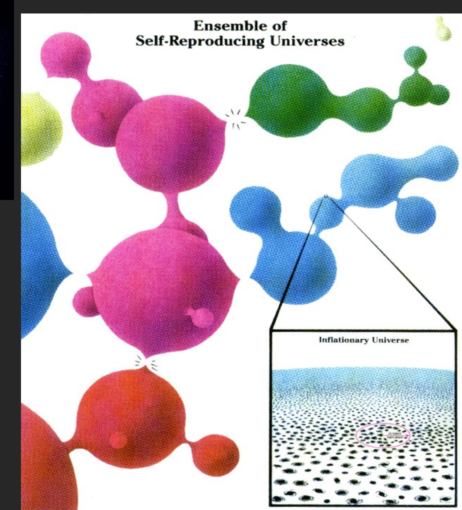

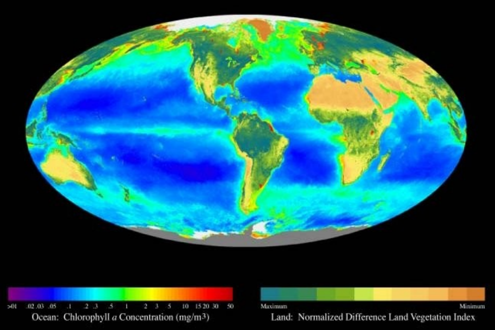

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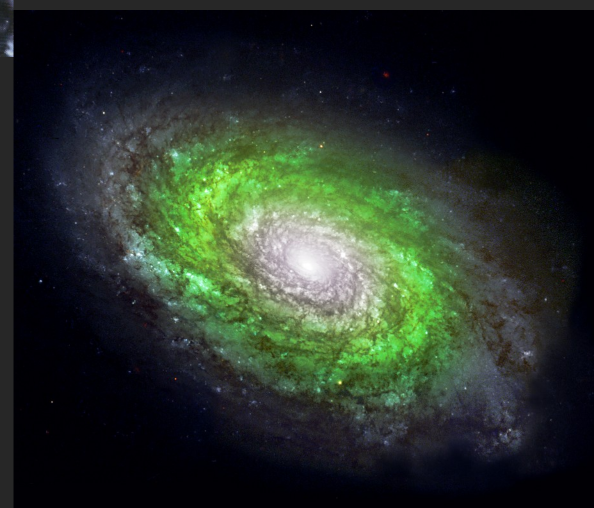
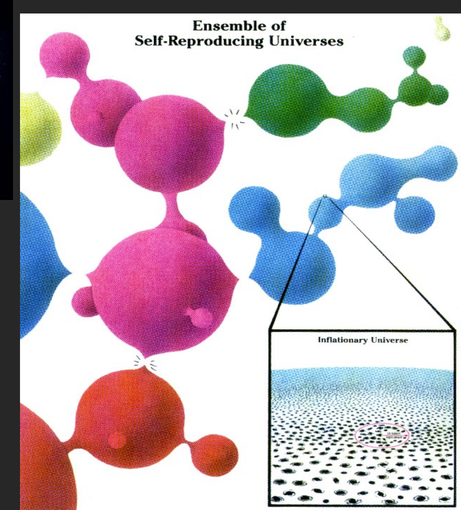
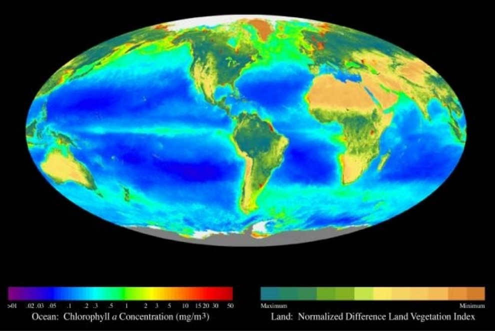
Circumstellar HZ

regions of the Solar System or other
planetary systems fit for life
wet rocky surface or hydrothermal vents







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regions of the earth fit for life
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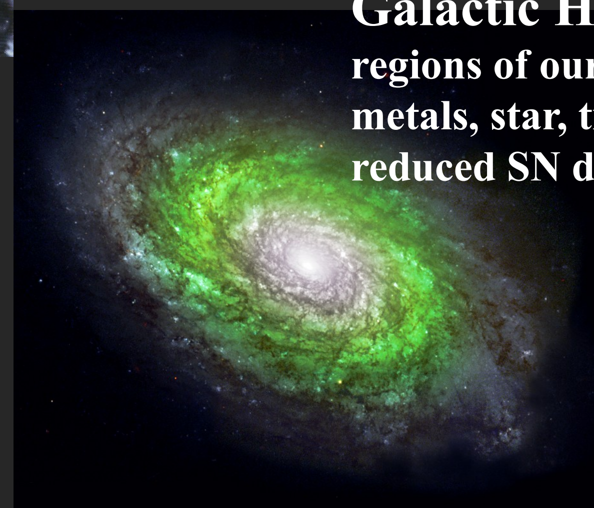
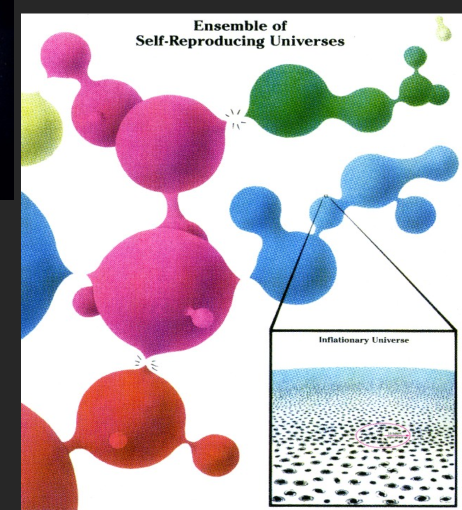
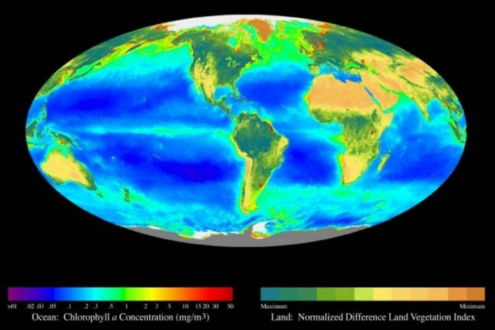


Galactic HZ

regions of our galaxy fit for life
metals, star, time,
reduced SN danger





Terrestrial HZ

regions of the earth fit for life
temperature/water, nutrients

Are there specific places and times
on Earth or in our Solar System,
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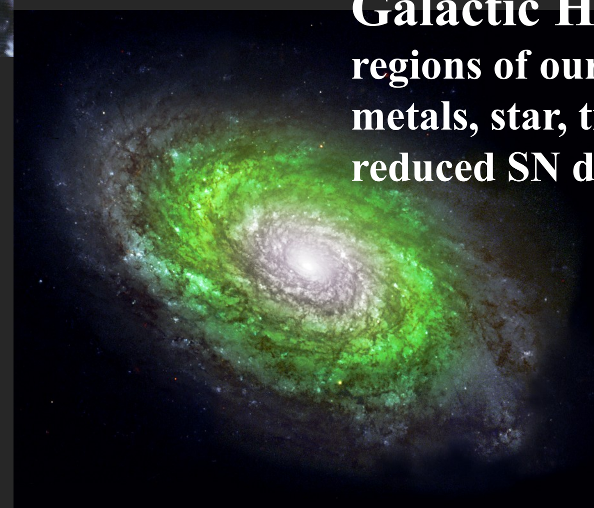
Circumstellar HZ

regions of the Solar System or other planetary systems fit for life
wet rocky surface or hydrothermal vents

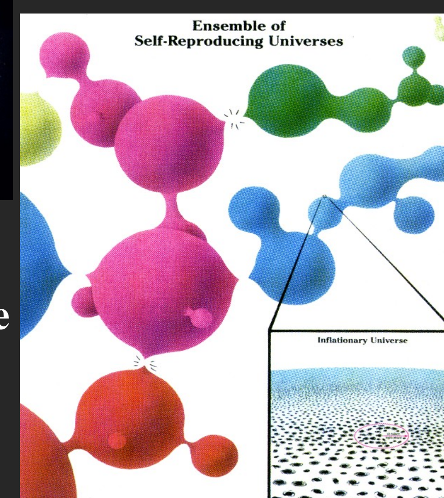


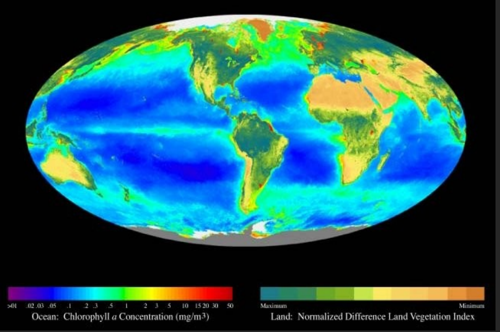
Galactic HZ

regions of our galaxy fit for life
metals, star, time,
reduced SN danger

Multiverse HZ

regions of the multiverse fit for life
stars/galaxies, time,
laws, constants, □,
baryogenesis, inflation





Terrestrial HZ
regions of the earth fit for life
temperature/water, nutrients

Are there specific places and times
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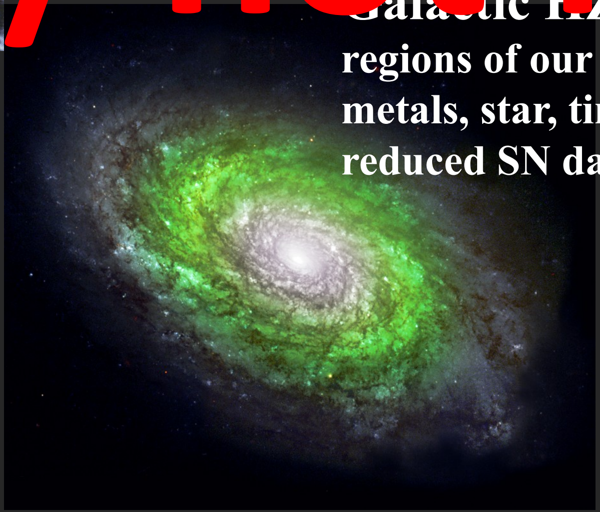
in our galaxy or other galaxies
or even in other universes

where we are more likely to find life?

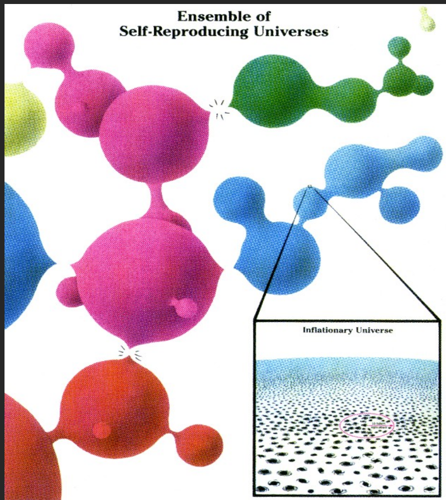
0-D

fit / not fit

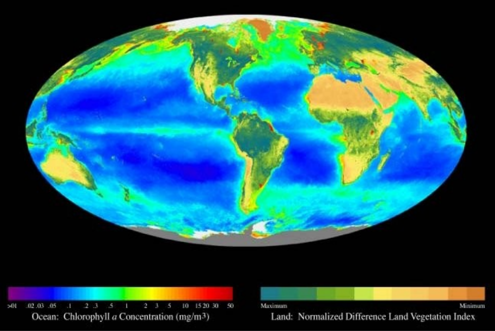
Circumstellar HZ
regions of the Solar System or other planetary systems fit for life
wet rocky surface or hydrothermal vents



Galactic HZ
regions of our galaxy fit for life
metals, star, time,
reduced SN danger



Multiverse HZ
regions of the multiverse fit for life
stars/galaxies, time,
laws, constants, □,
baryogenesis, inflation



Terrestrial HZ

regions of the earth fit for life
temperature/water, nutrients

Are there specific places and times
on Earth or in our Solar System,
on planets orbiting other stars,
in our galaxy or other galaxies
or even in other universes

where we are more likely to find life?

0-D

fit / not fit

Circumstellar HZ

regions of the Solar System or other
planetary systems fit for life
wet rocky surface or hydrothermal vents

Galactic HZ

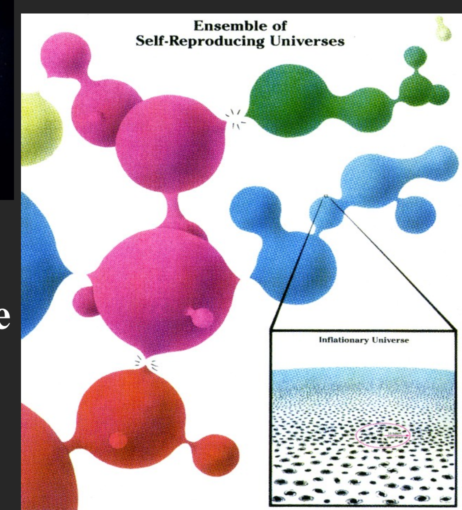
regions of our galaxy fit for life
metals, star, time,
reduced SN danger

very fit/kinda fit/ ehh / less fit / not fit

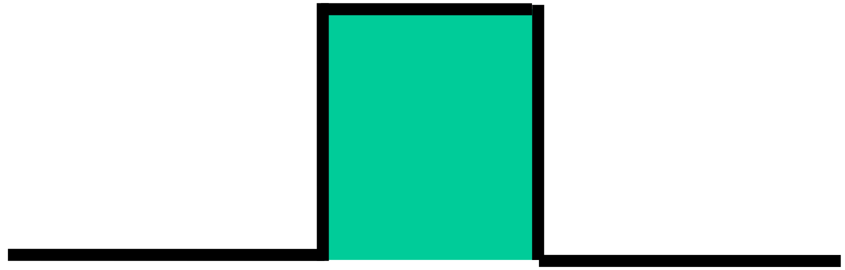
1-D

Multiverse HZ

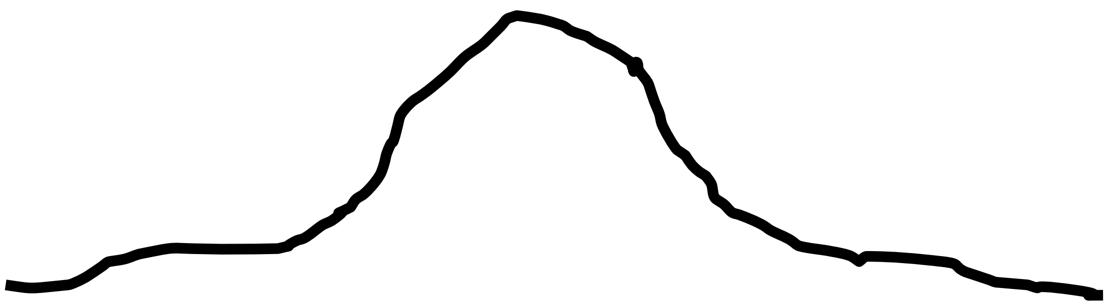
regions of the multiverse fit for life
stars/galaxies, time,
laws, constants, □,
baryogenesis, inflation



Habitable Zones



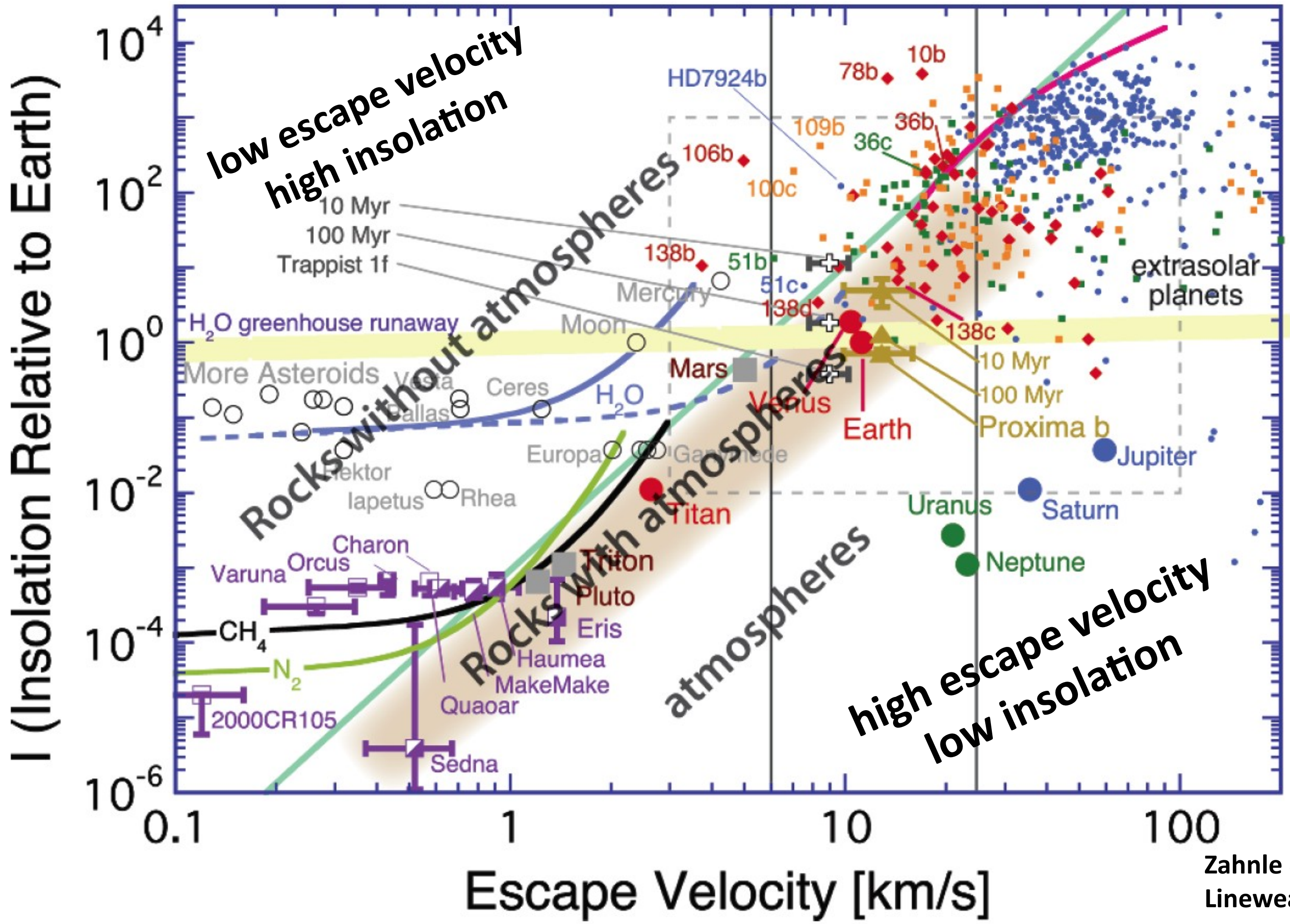
0-D



1-D

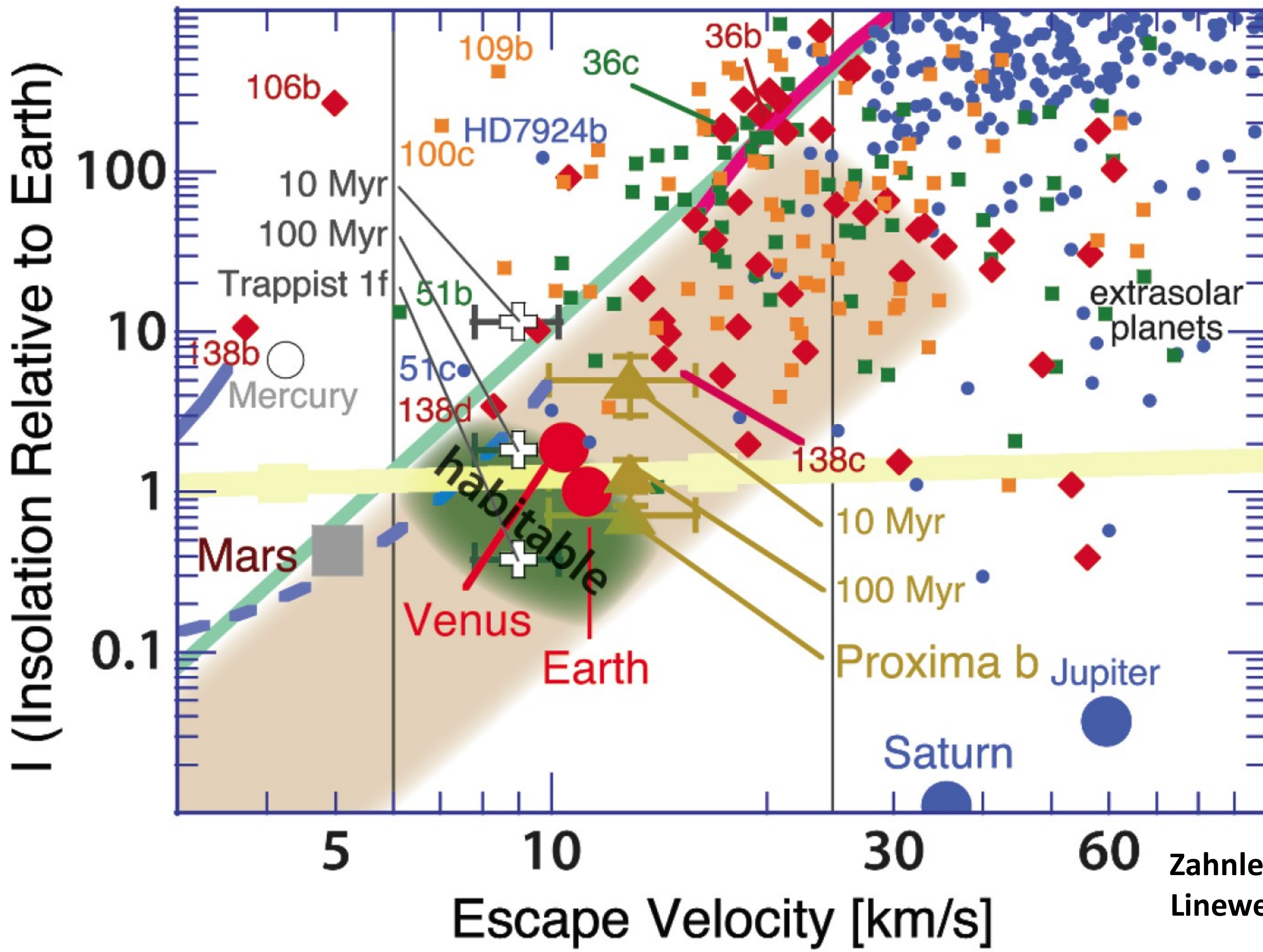

shoreline

Cosmic Shoreline



Zahnle & Catling 2017
Lineweaver et al 2019

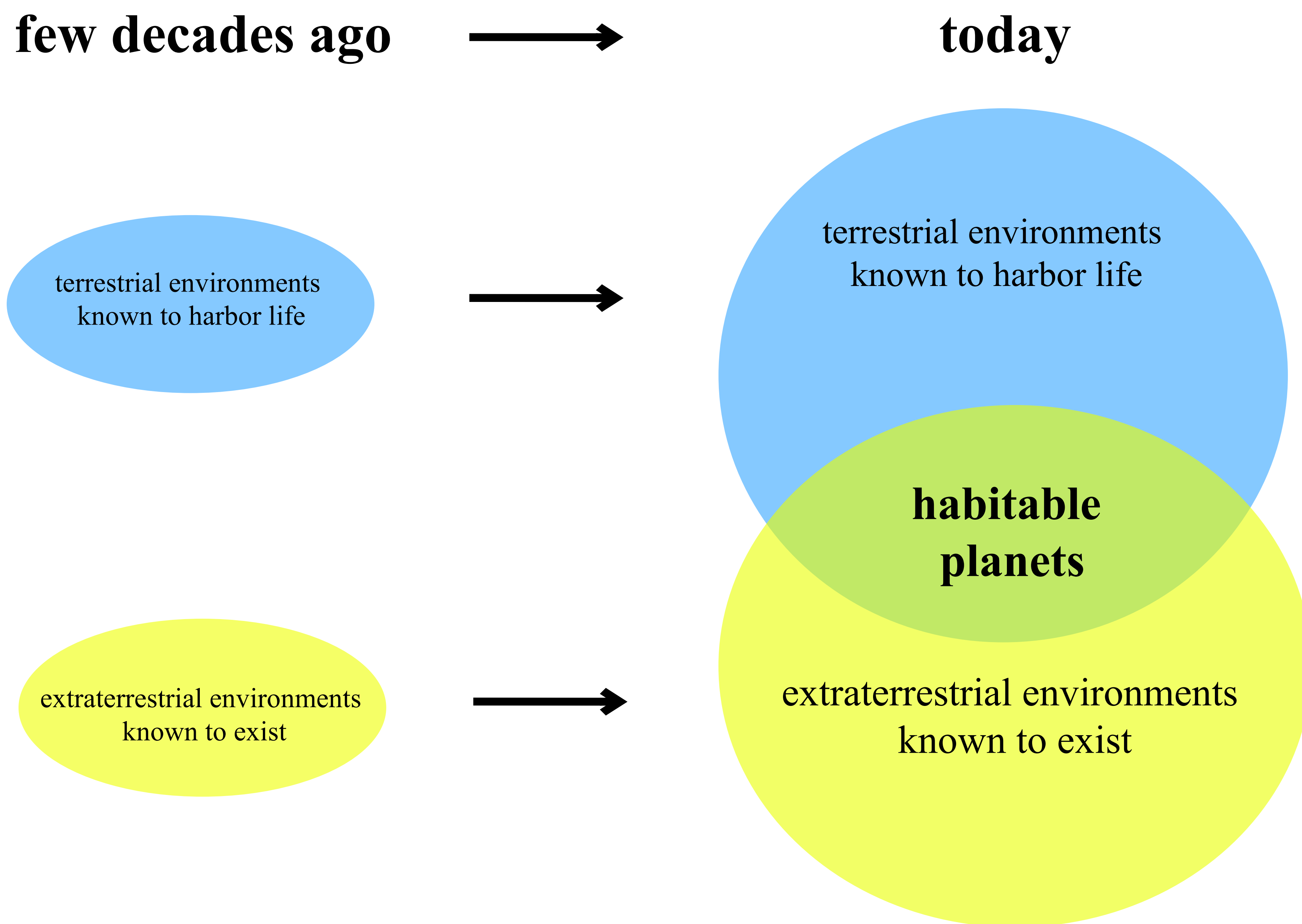
Cosmic Shoreline



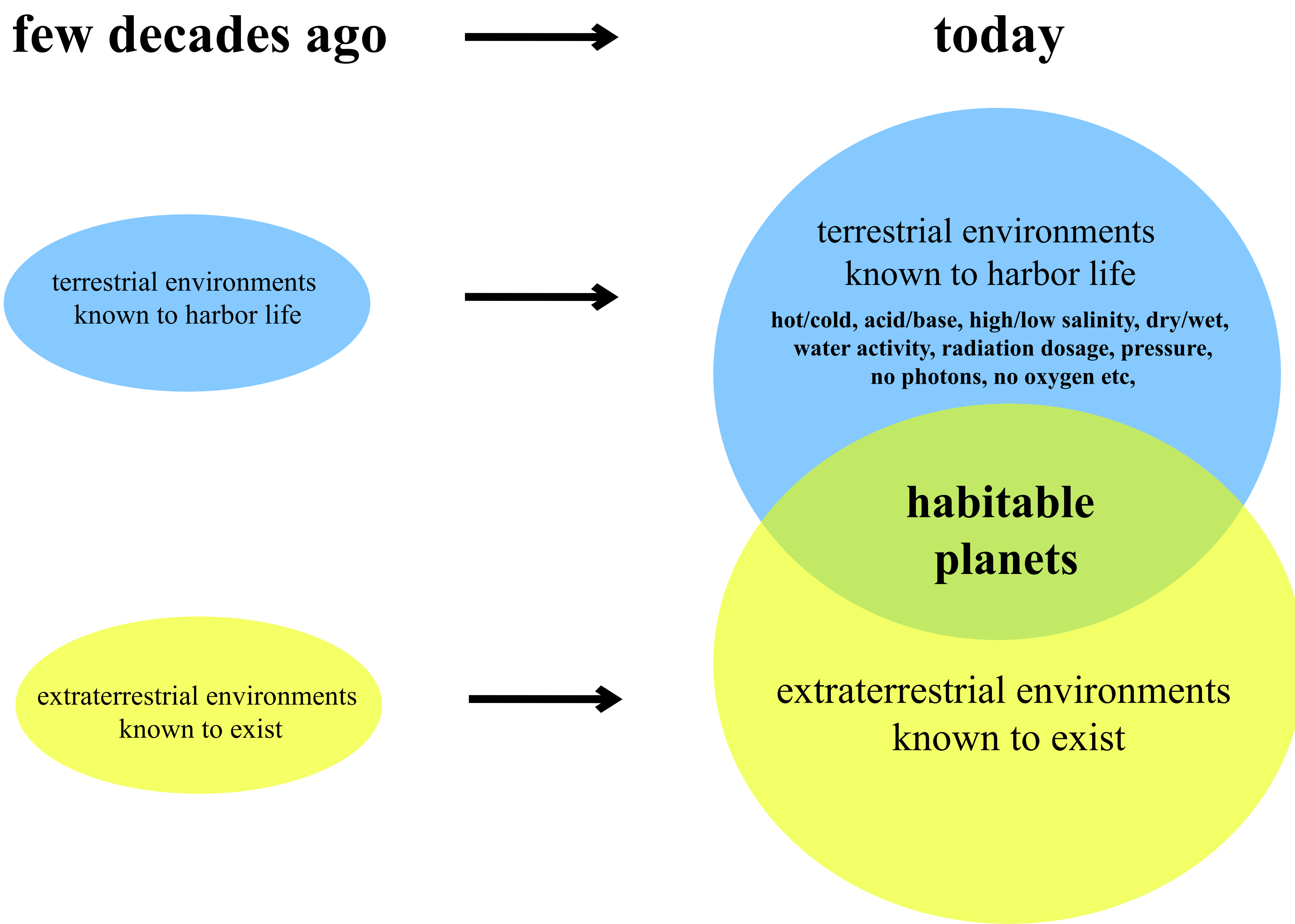
Zahnle & Catling 2017
Lineweaver et al 2019

Finding other Earths and potentially other life forms is a major, increasingly reasonable scientific goal.

Our search for habitable planets and inhabited planets is now in high gear.

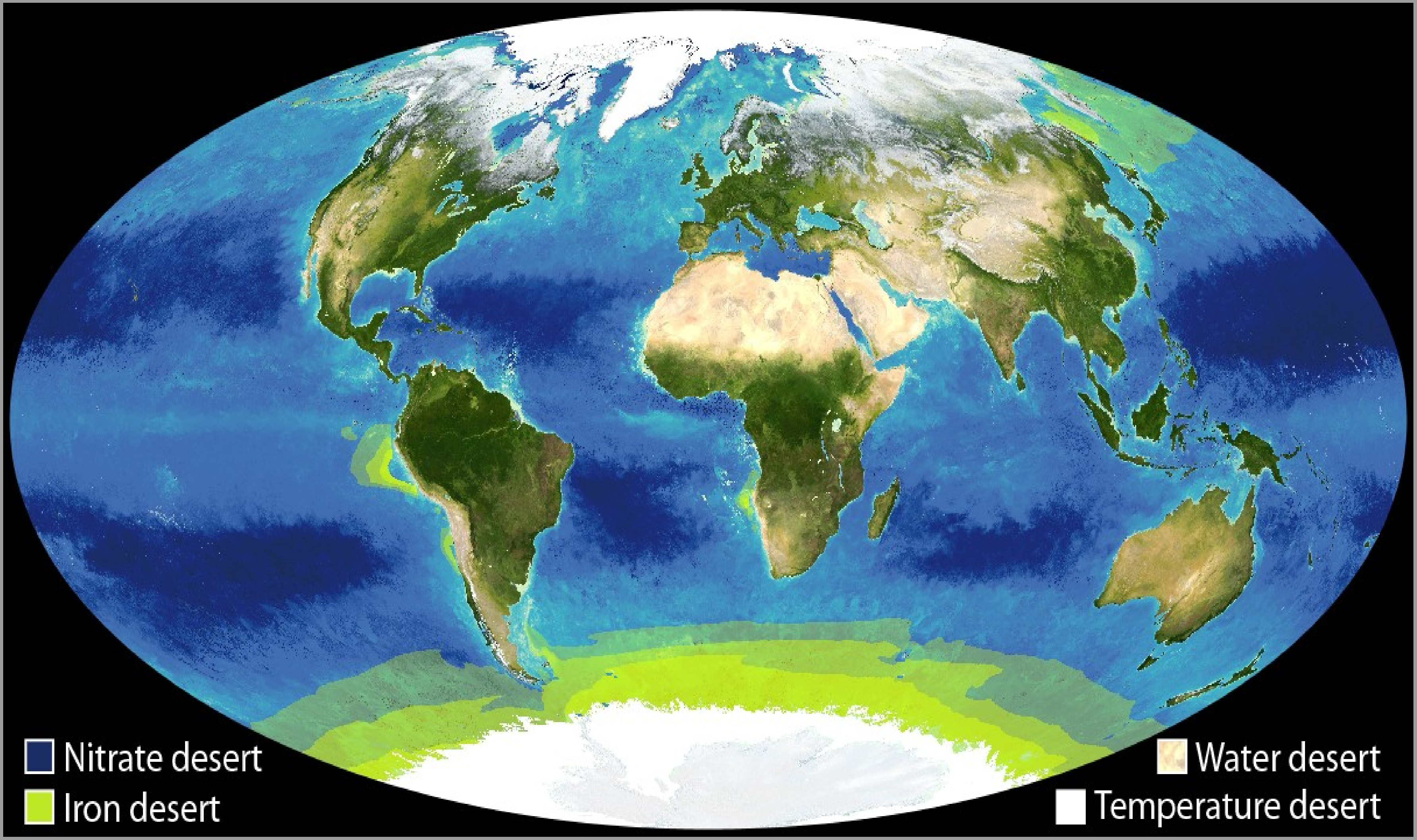


Lineweaver & Chopra 2012



Lineweaver & Chopra 2012

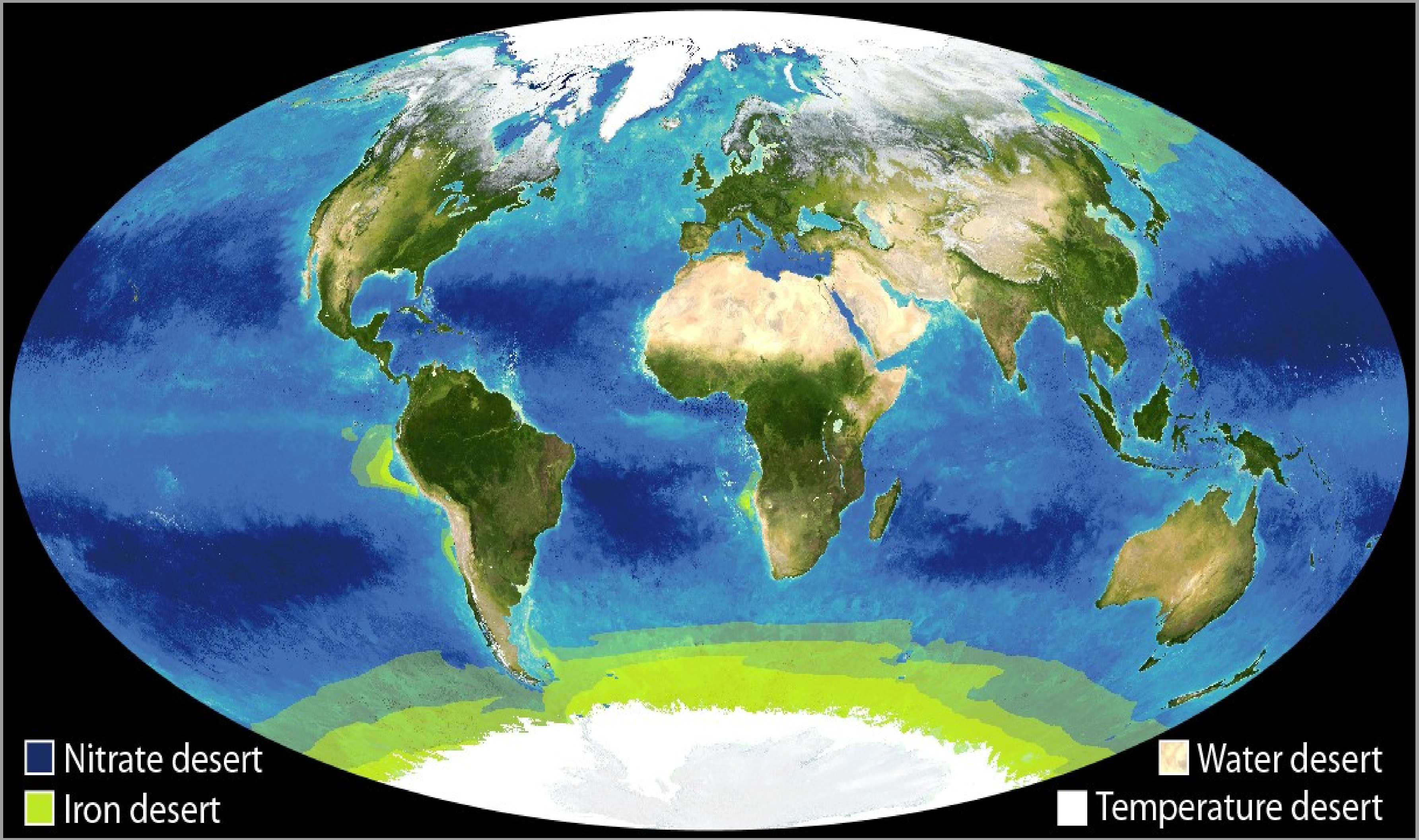
Terrestrial Habitable Zones



Lineweaver & Chopra 2012

Terrestrial Habitable Zones

Life is not evenly distributed over the surface of the Earth



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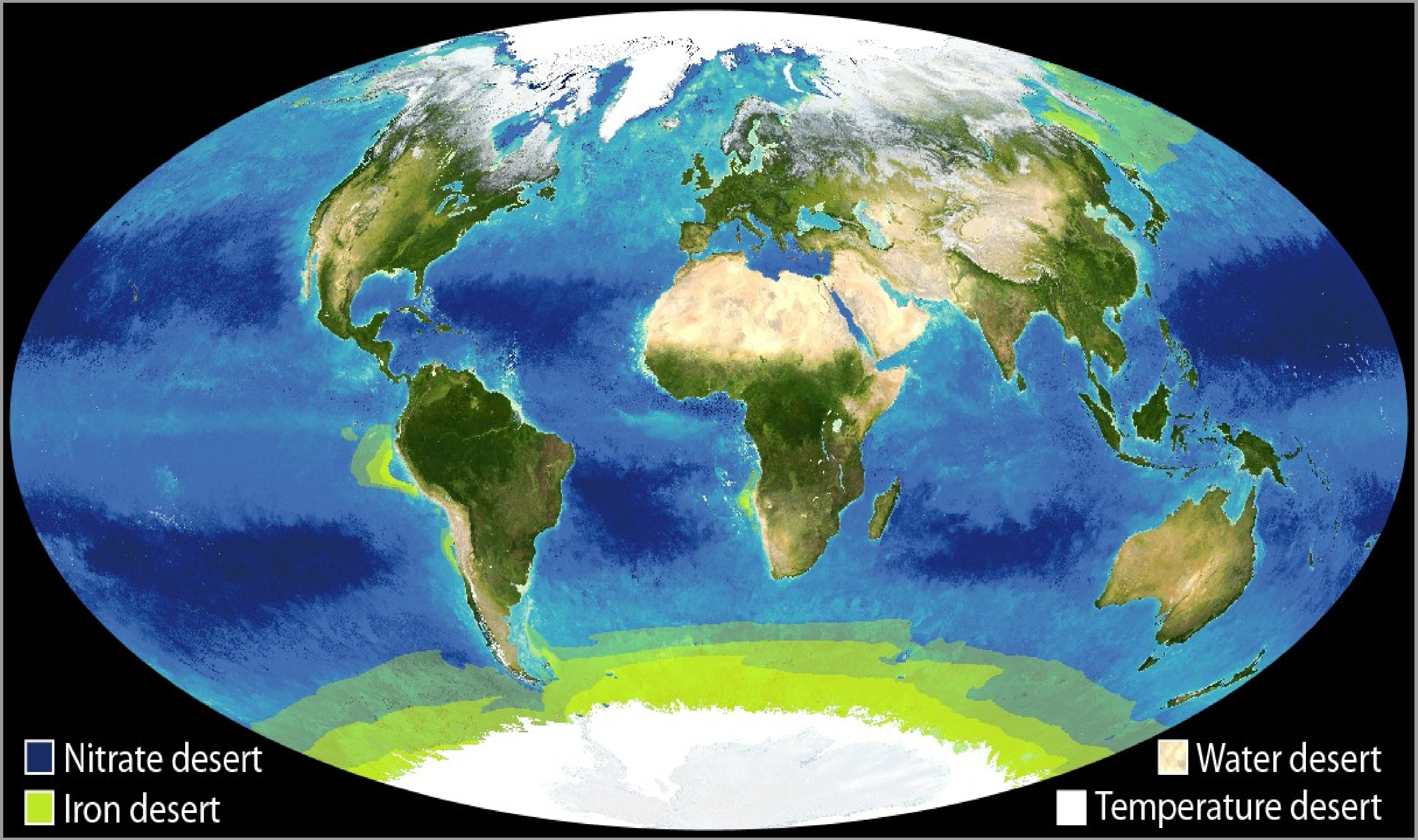
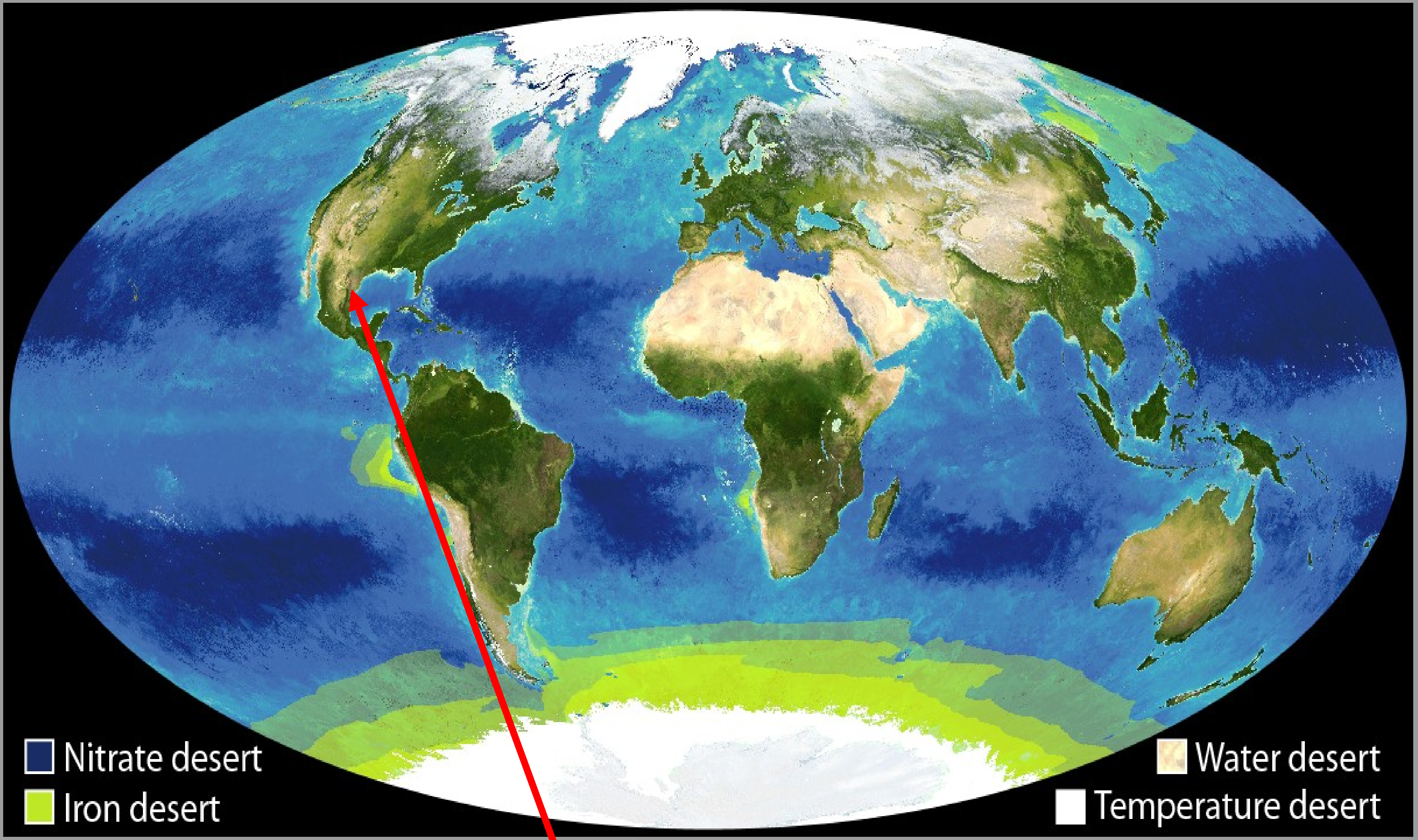


Carbon desert ?
Phosphorus desert ?
Sulfur desert ?

Terrestrial Habitable Zones

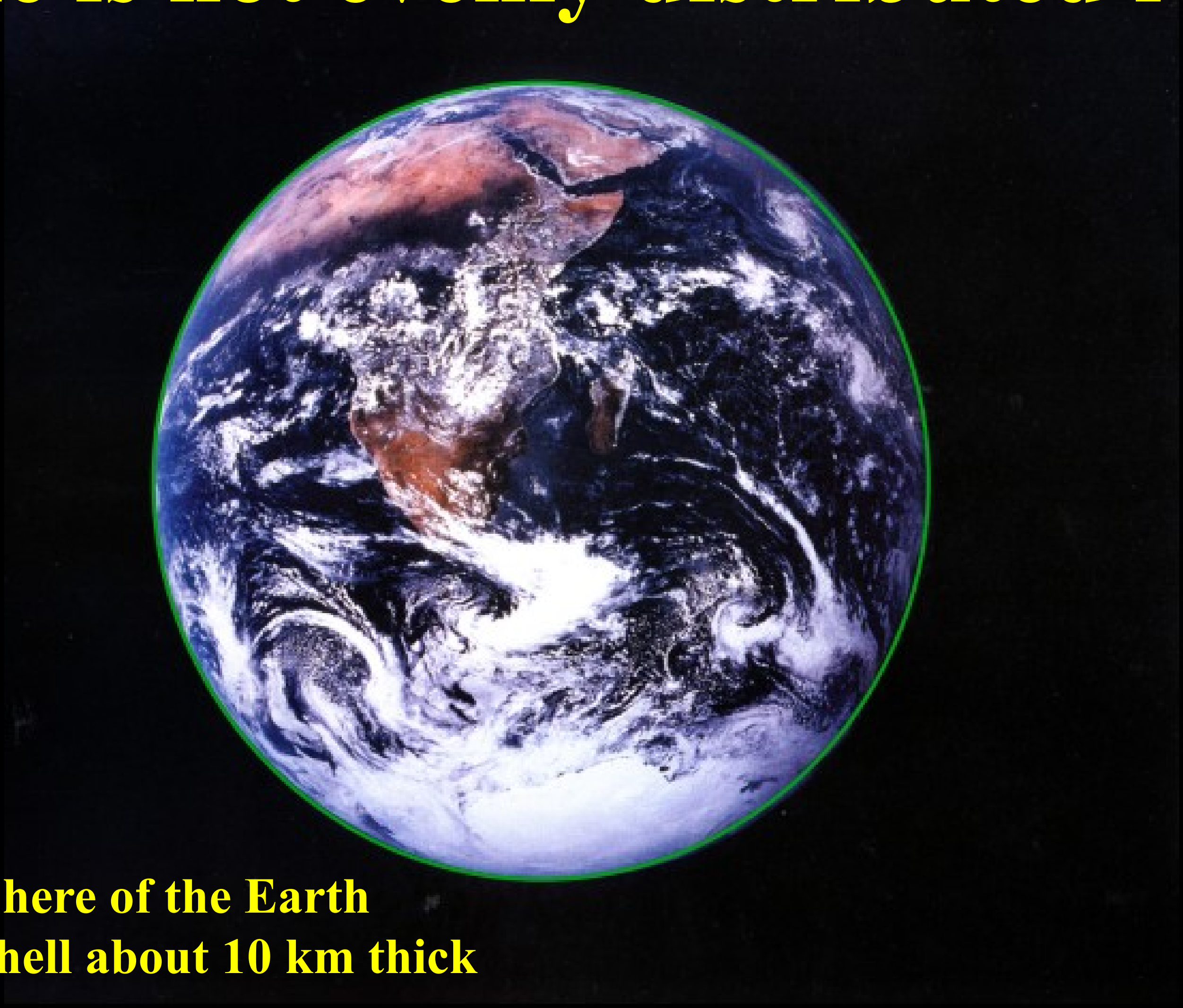
Life is not evenly distributed over the surface of the Earth



Carbon desert ?
Phosphorus desert ?
Sulfur desert ?

Life is not evenly distributed radially

Life is not evenly distributed radially



The biosphere of the Earth
is a thin shell about 10 km thick

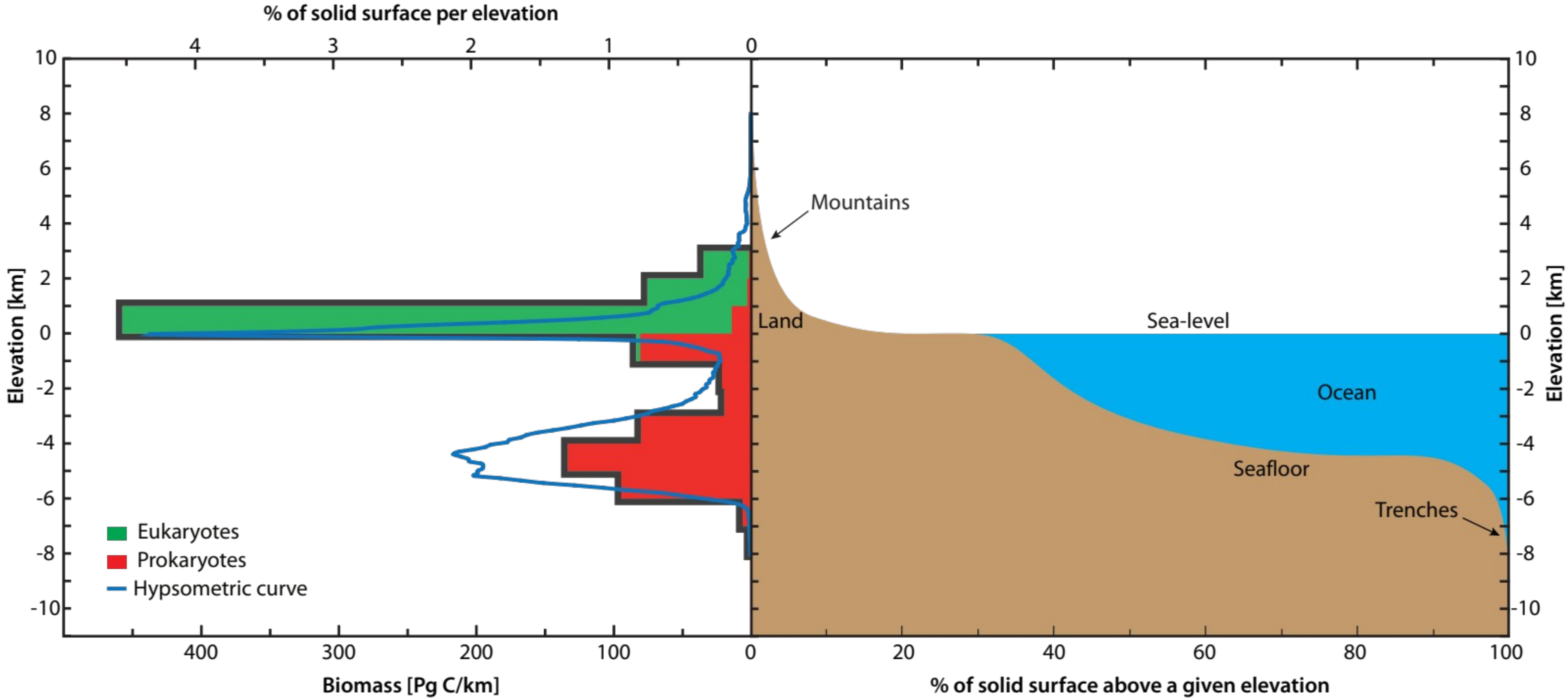
Life is not evenly distributed radially

The biosphere of the Earth
is a thin shell about 10 km thick

If the radius of the Earth were one meter
the thickness of the biosphere would be 1 mm.

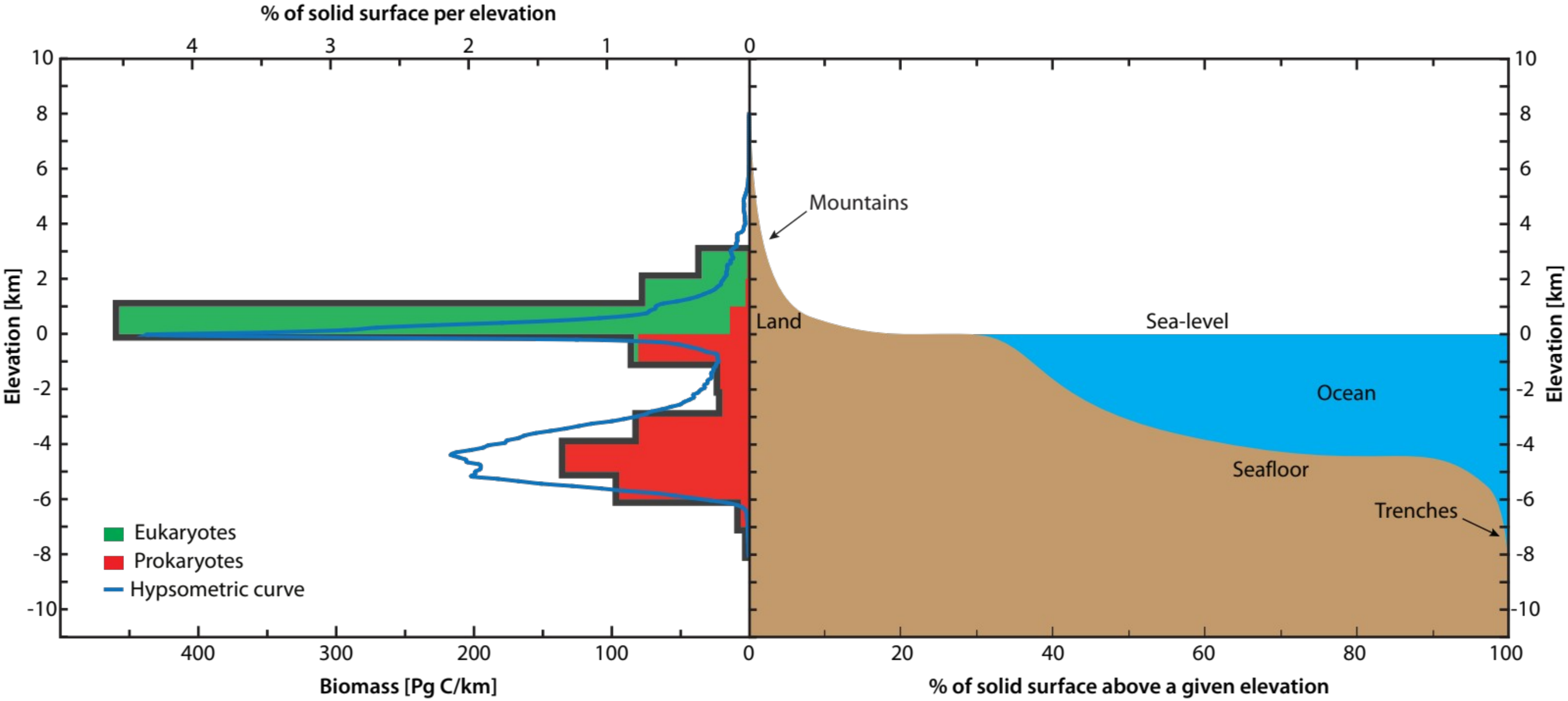

biosphere

Vertical profile of life on Earth



Lineweaver & Chopra 2012

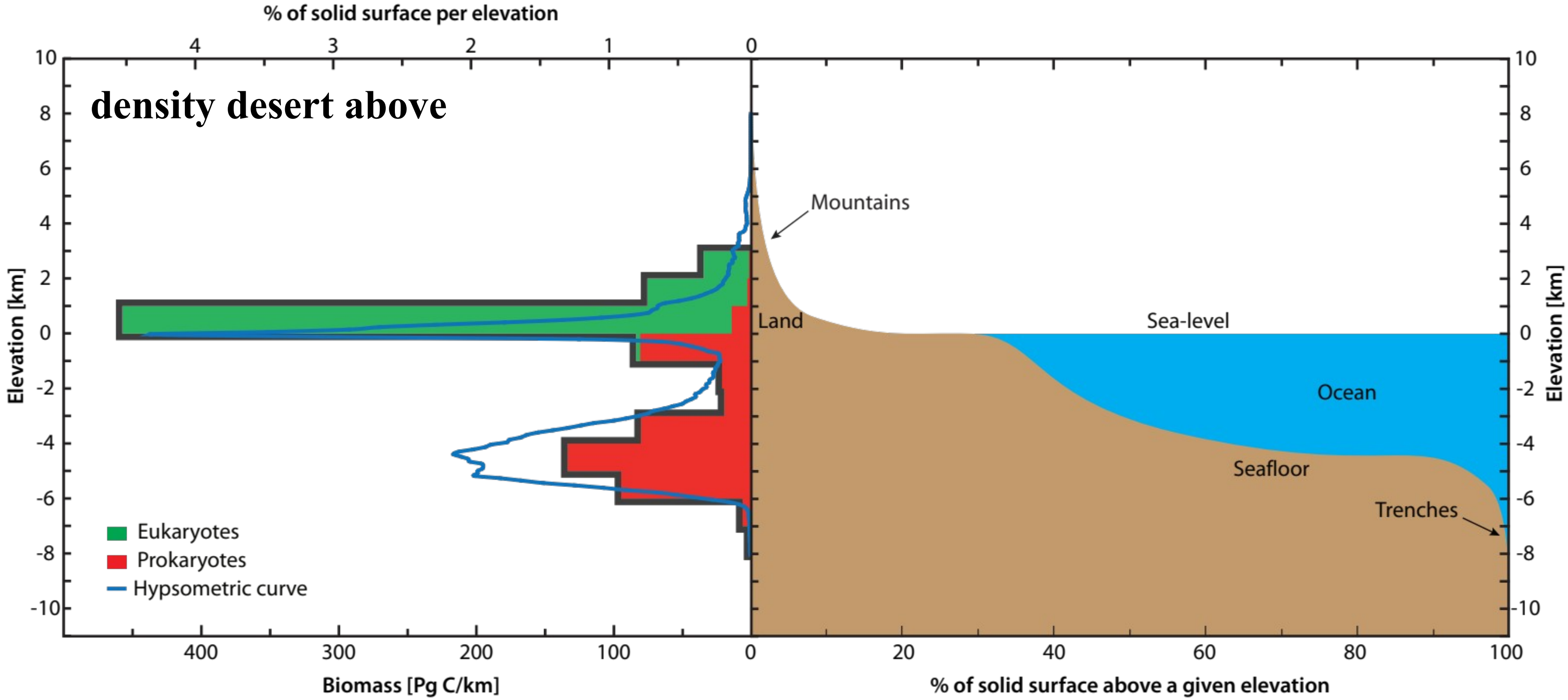
Vertical profile of life on Earth



heat desert below

Lineweaver & Chopra 2012

Vertical profile of life on Earth

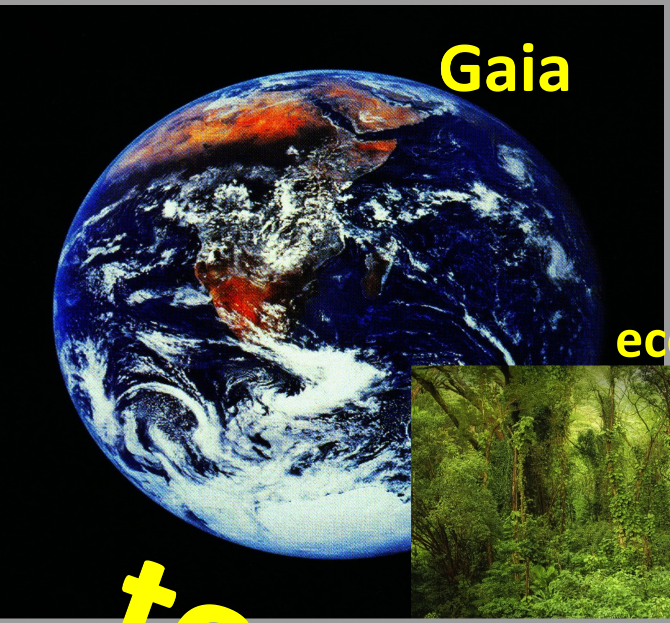


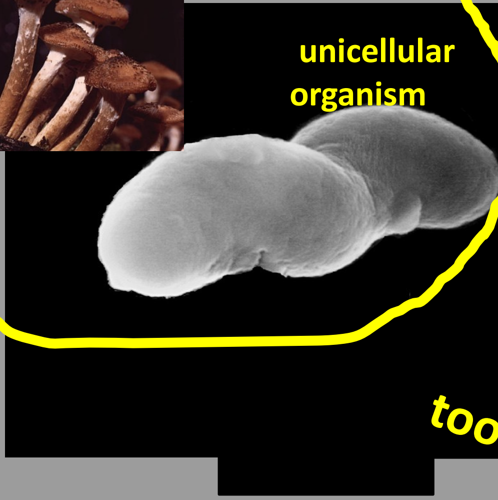
heat desert below

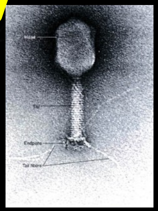
Lineweaver & Chopra 2012

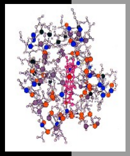
Habitable for whom?

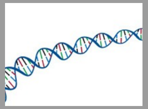
Are there size boundaries to life ?





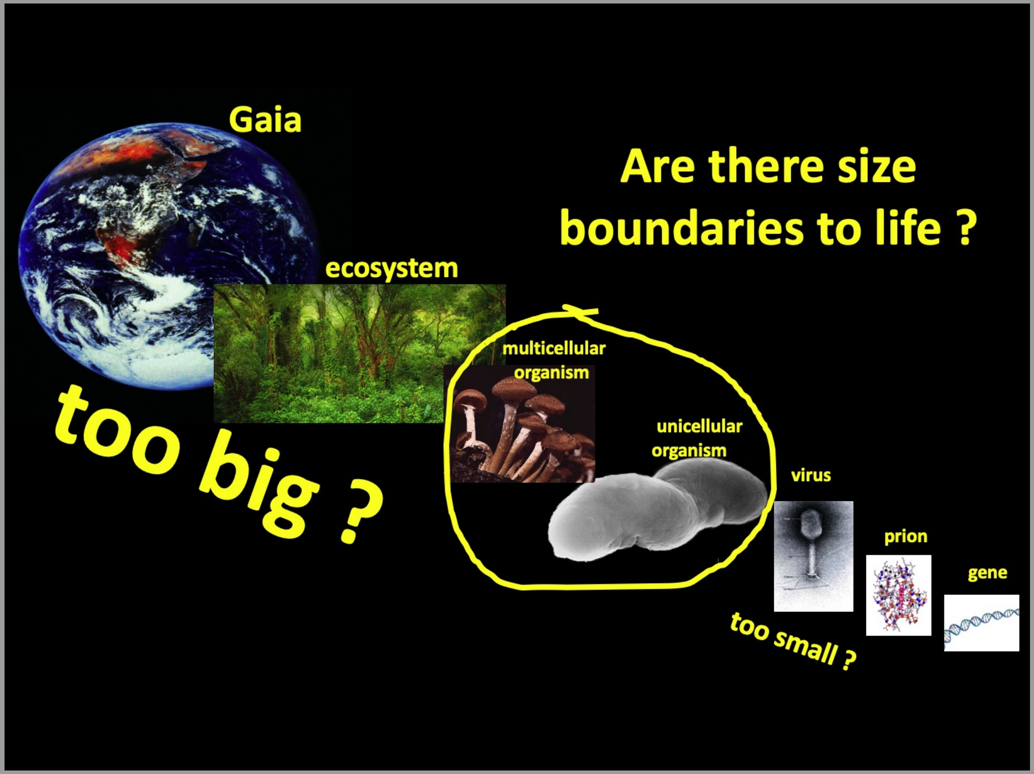


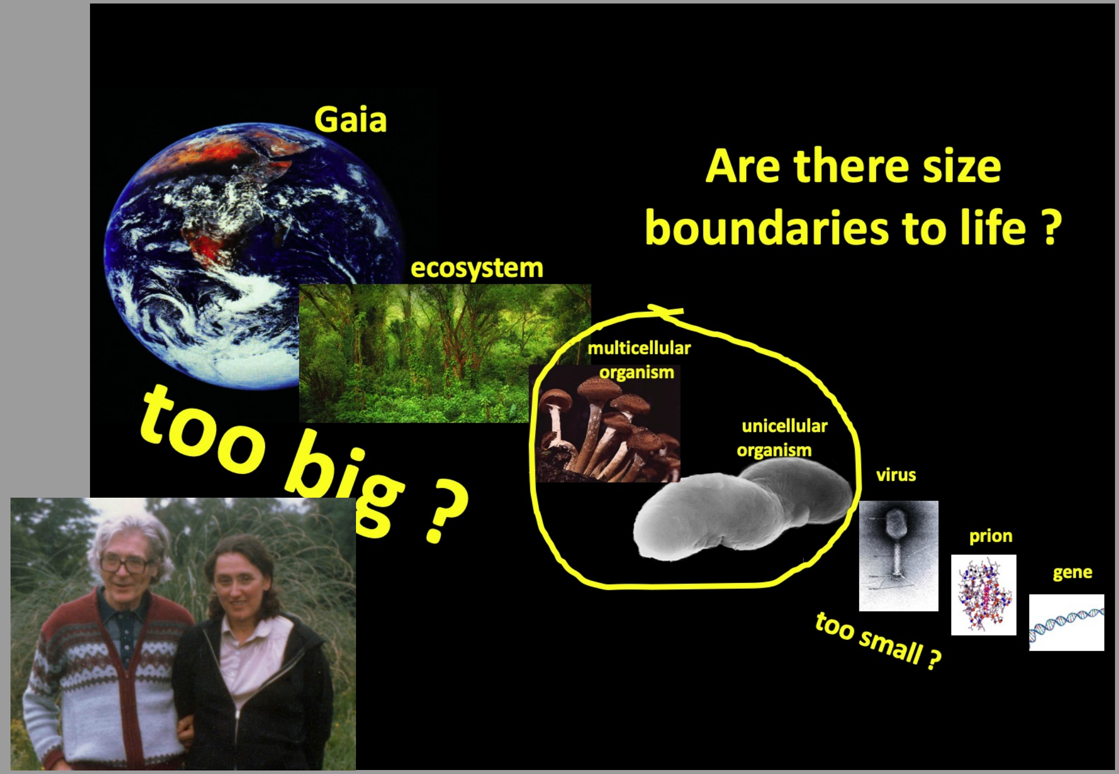




too big ?

too small ?


Gaia
Are there size
boundaries to life ?
ecosystem
multicellular
organism
unicellular
organism
too big ?
virus
prion
gene
too small ?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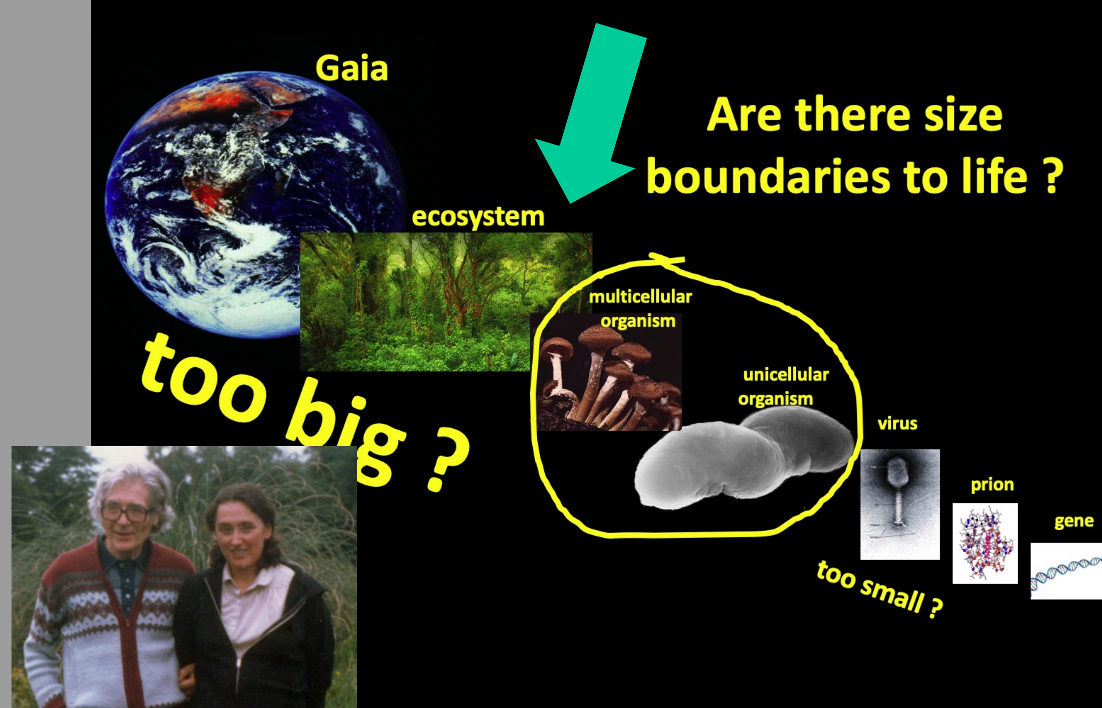
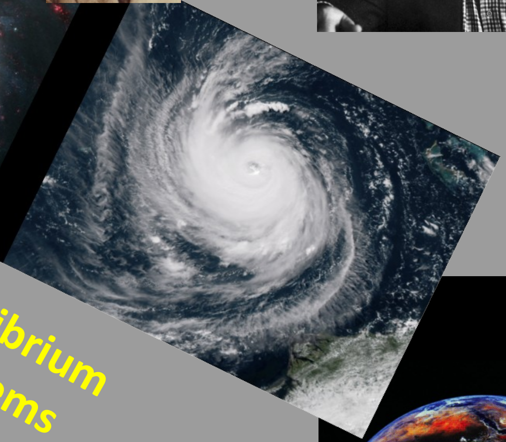
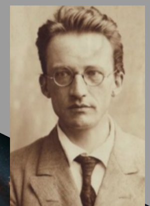
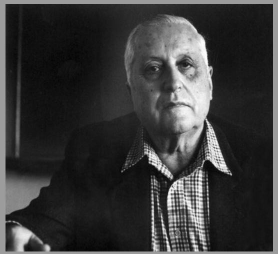
David
Sloan
Wilson

group
selection

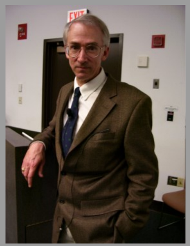






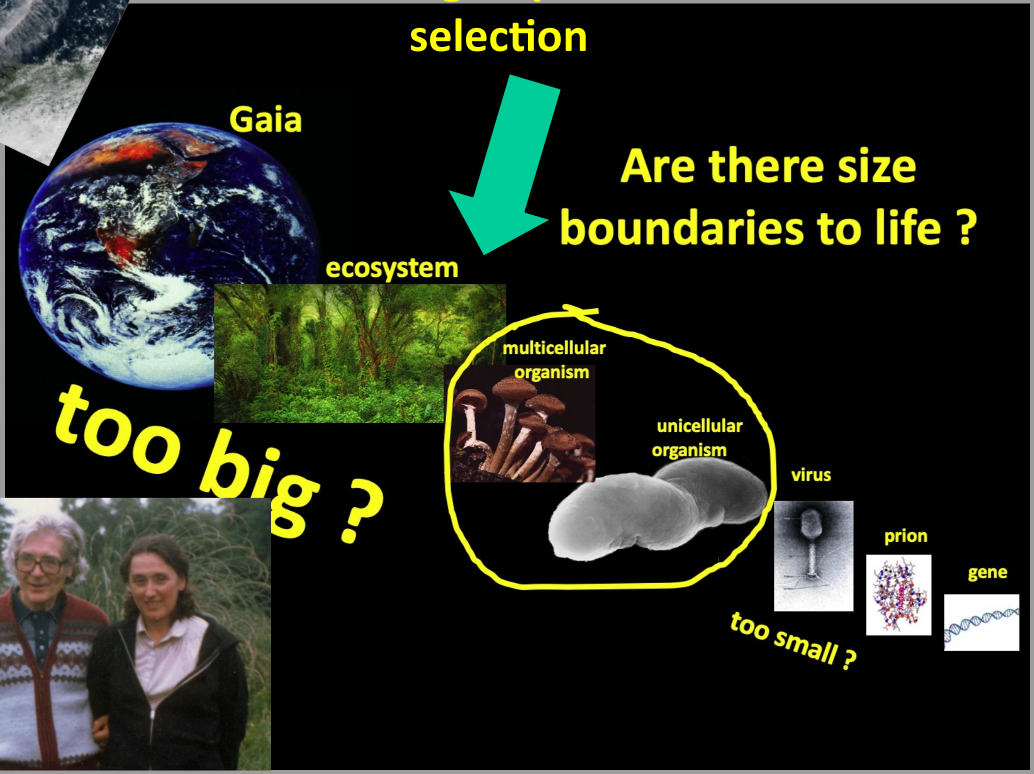


Far From Equilibrium
Dissipative Systems



David
Sloan
Wilson

group
selection




Far From Equilibrium
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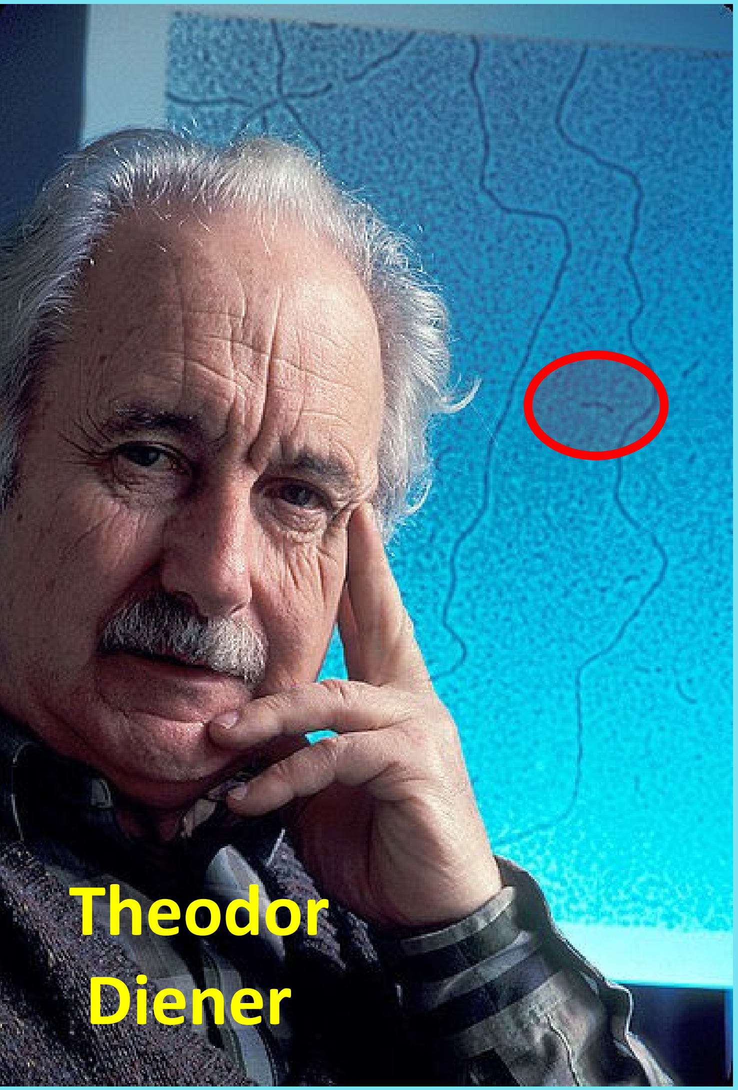
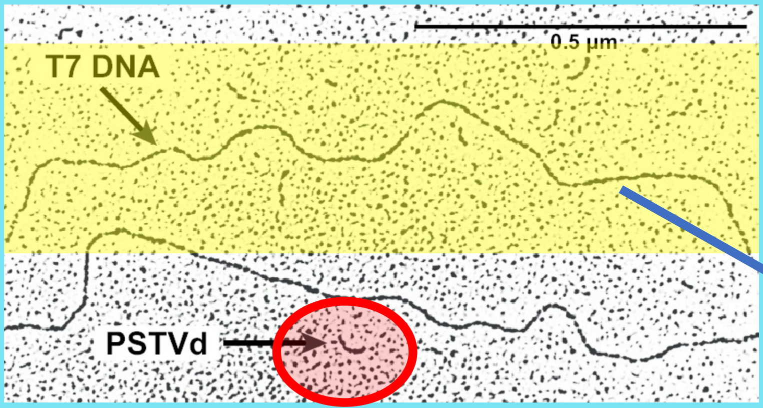
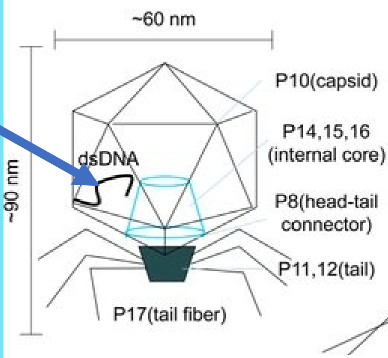


PSTV: Potato Spindle Tuber Viroid

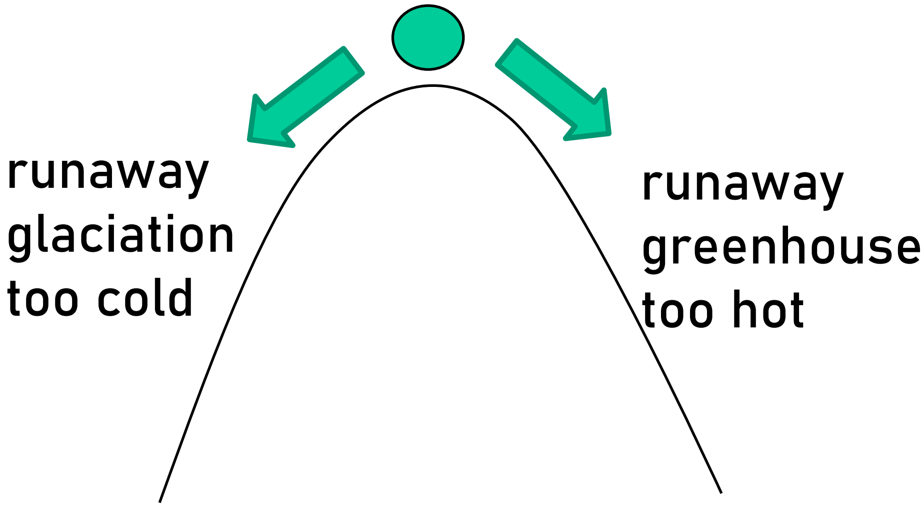




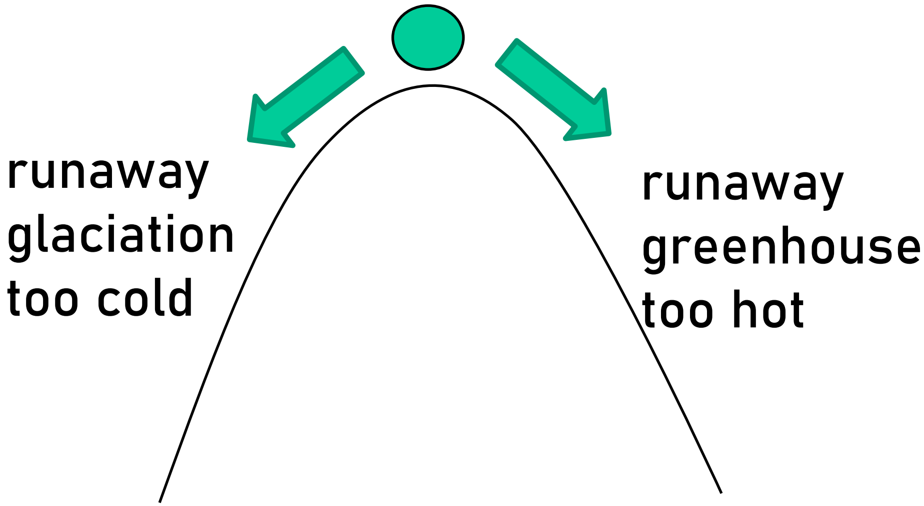
coliphage T7 DNA

viroids are plausible “living fossils” of the hypothetical RNA World

Diener 1989, 2016



no silicate weathering
in the first ~ billion years
no negative feedback



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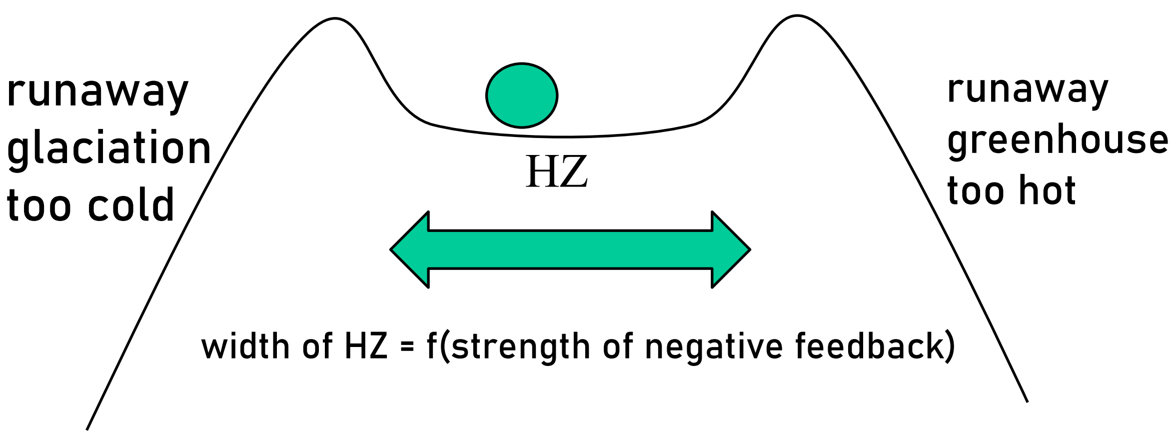
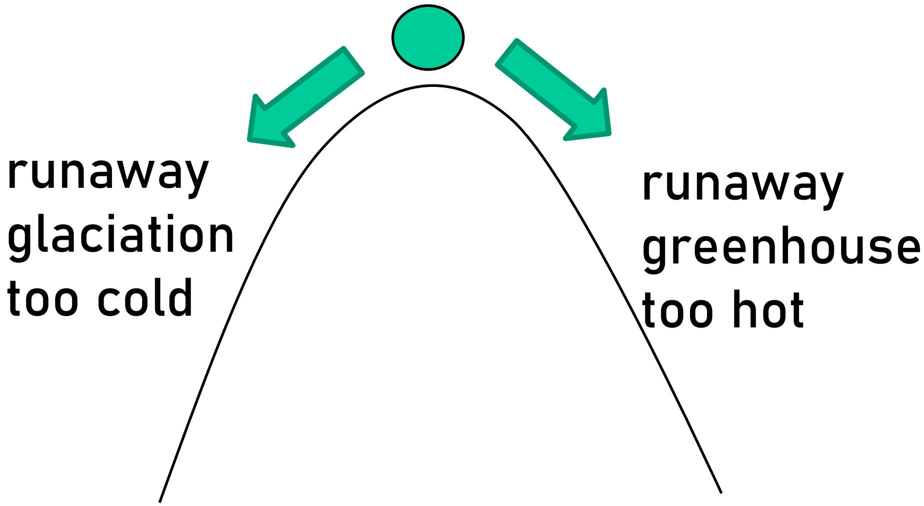


silicate weathering
negative feedback

37 degrees C
Gaian regulation



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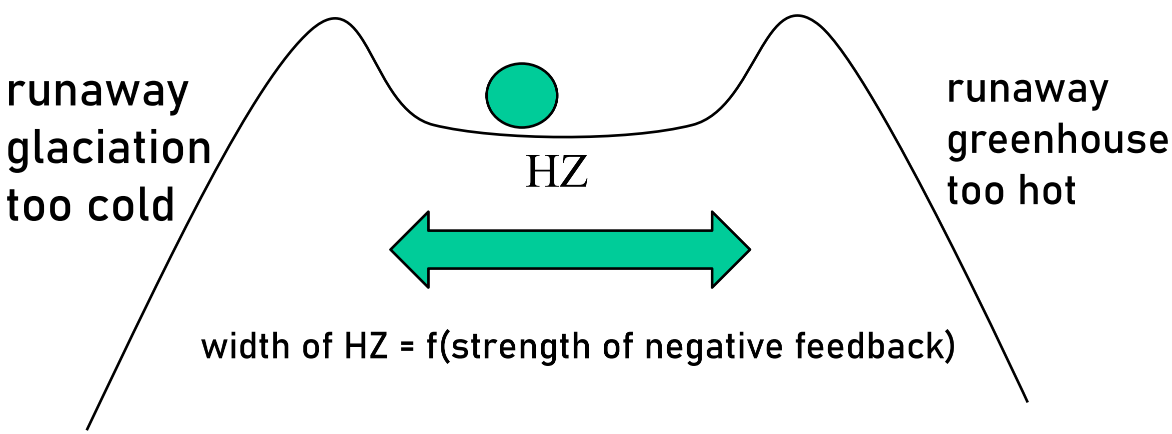


silicate weathering
negative feedback

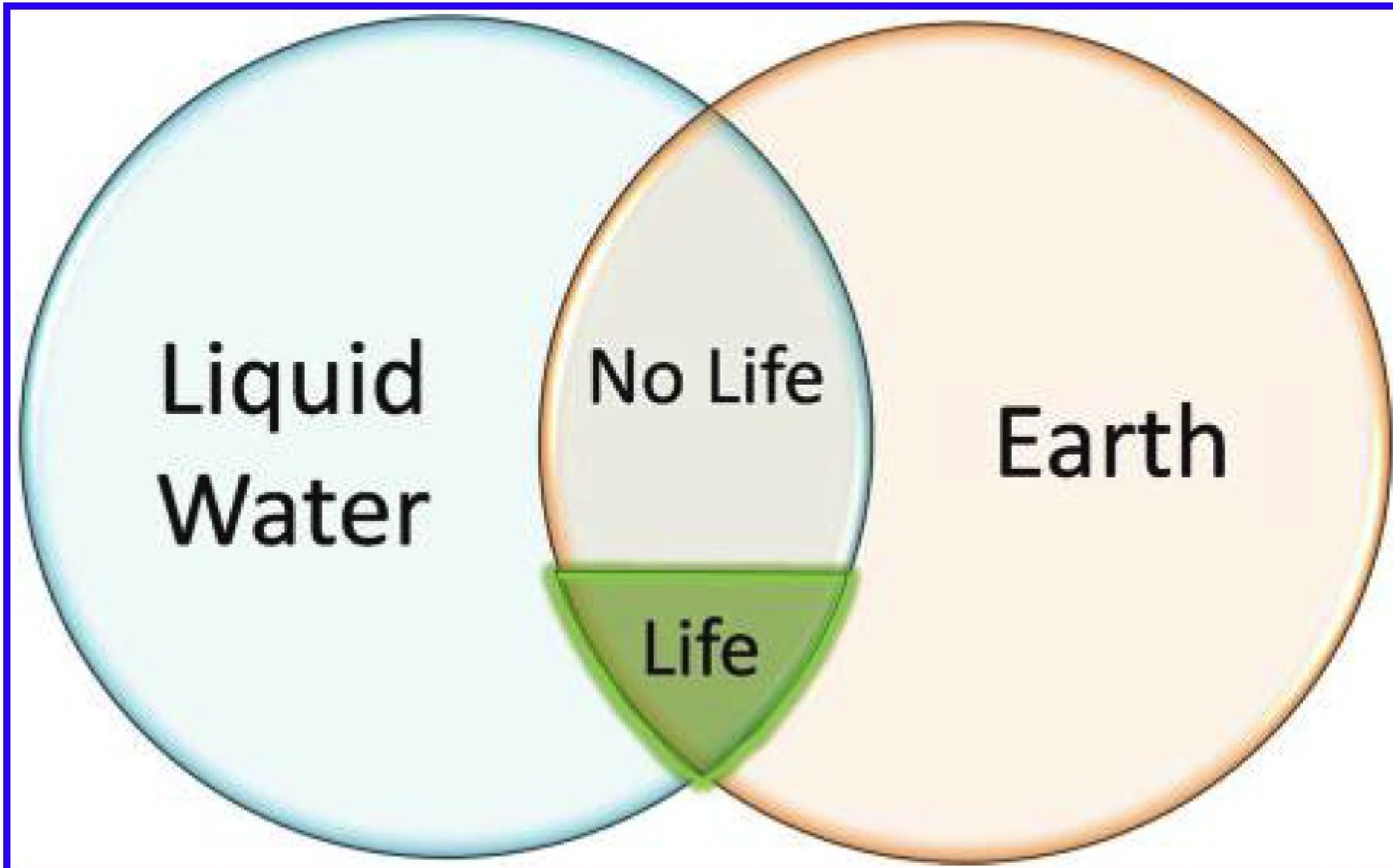
37 degrees C
Gaian regulation

cars don't stay on the road without a driver
planets don't remain habitable without life

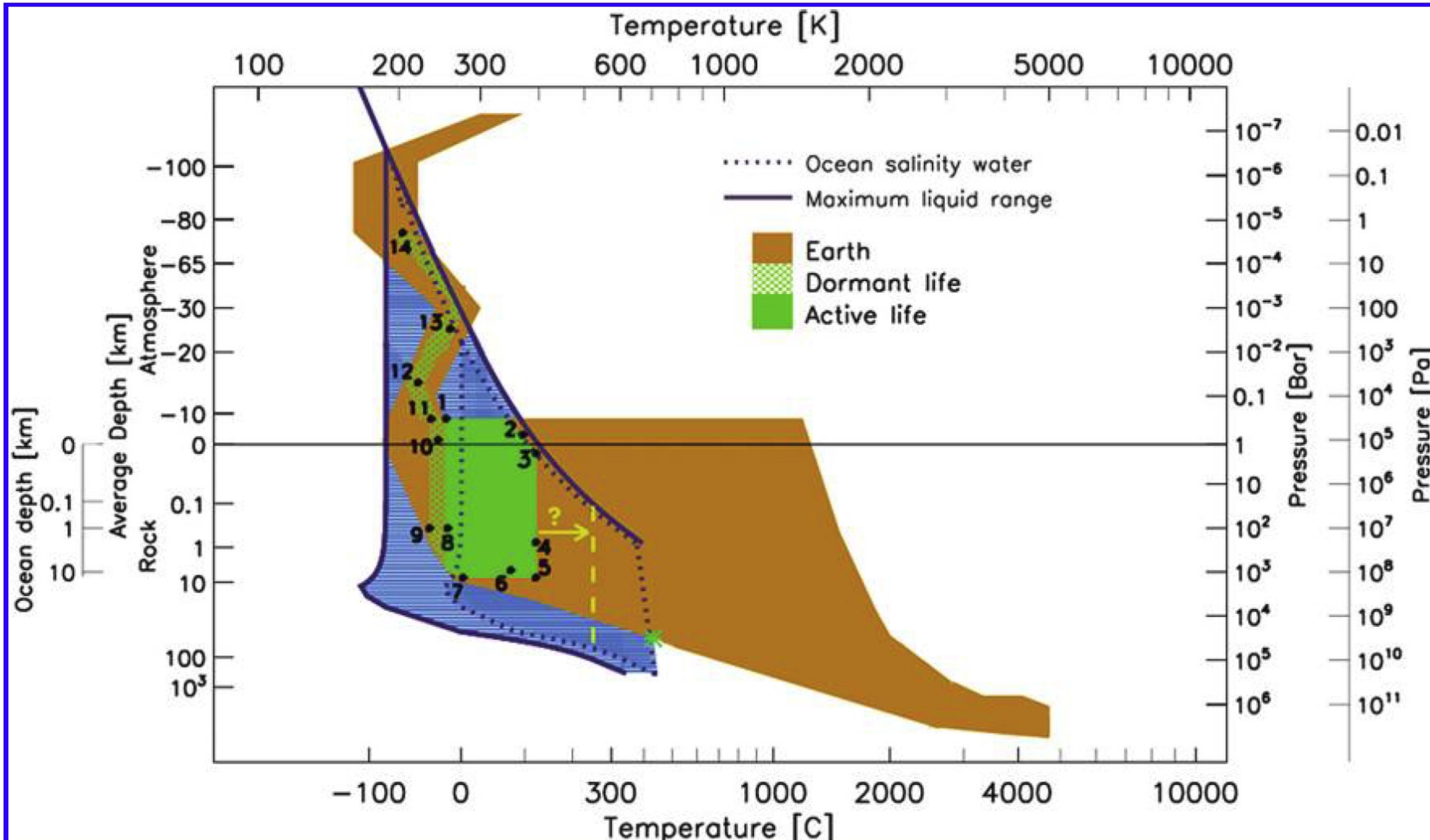
Follow

the

water

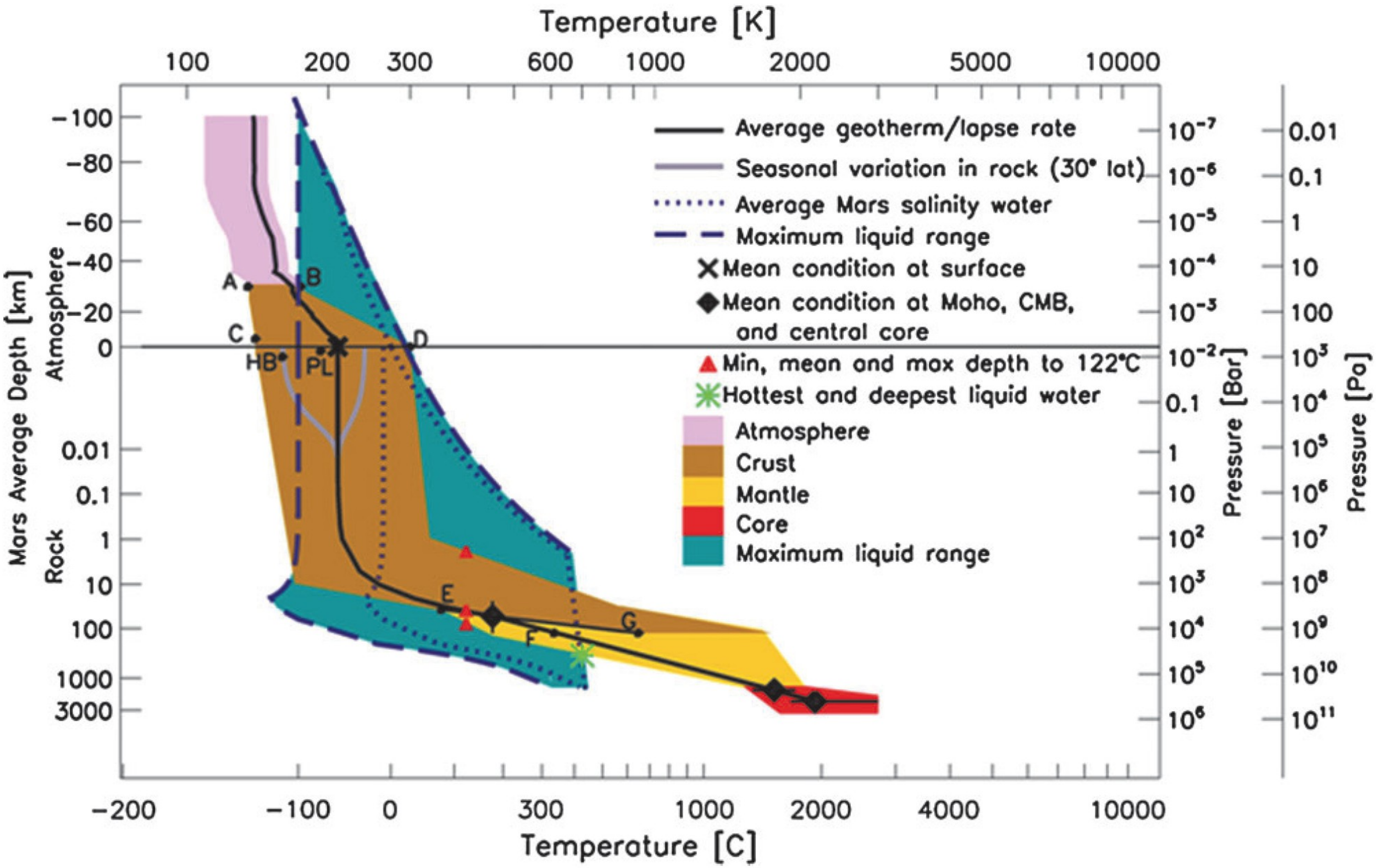


Jones and Lineweaver 2010

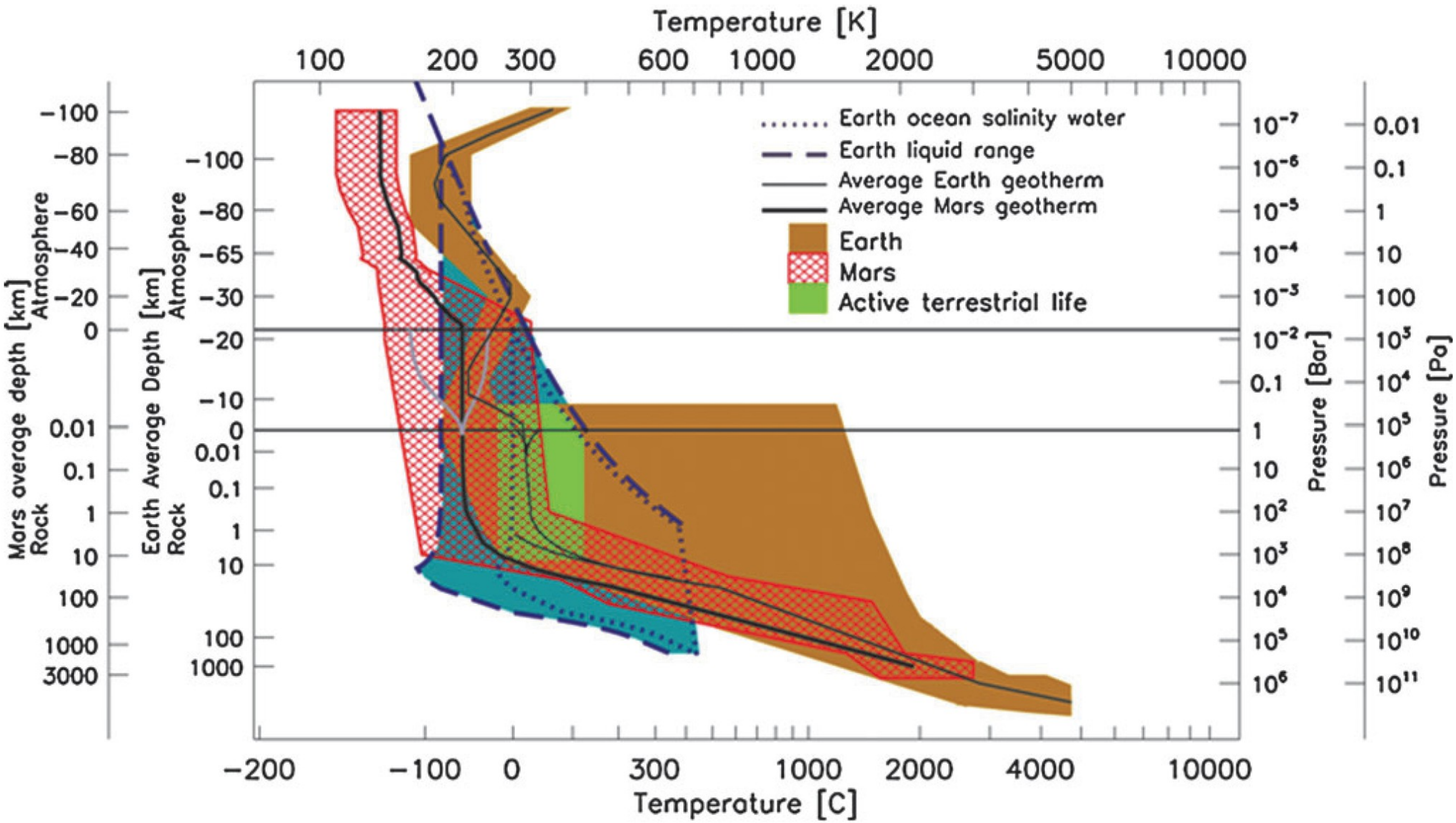


Jones and Lineweaver 2010

MARS

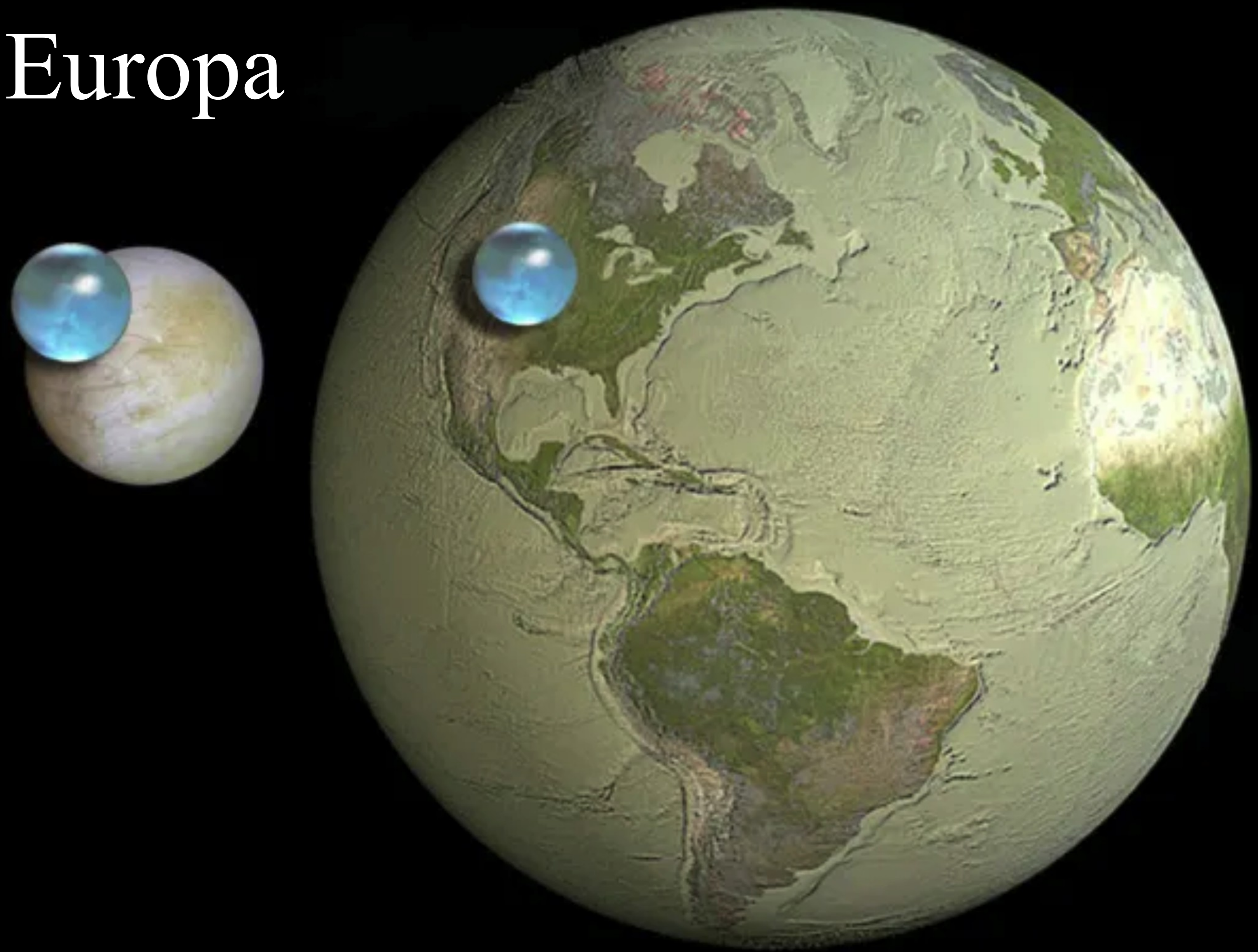


Jones and Lineweaver 2011



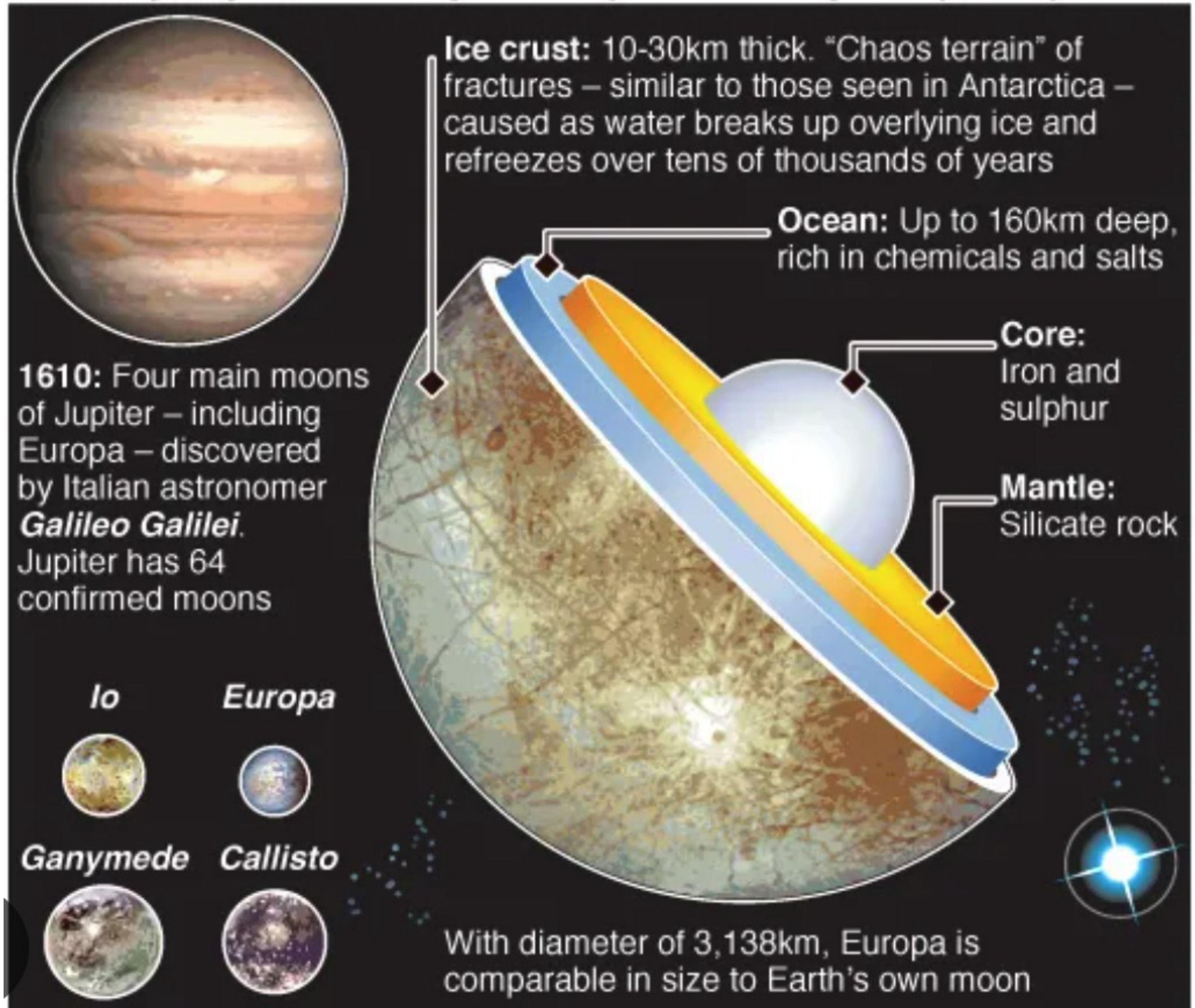
Jones and Lineweaver 2011

Europa



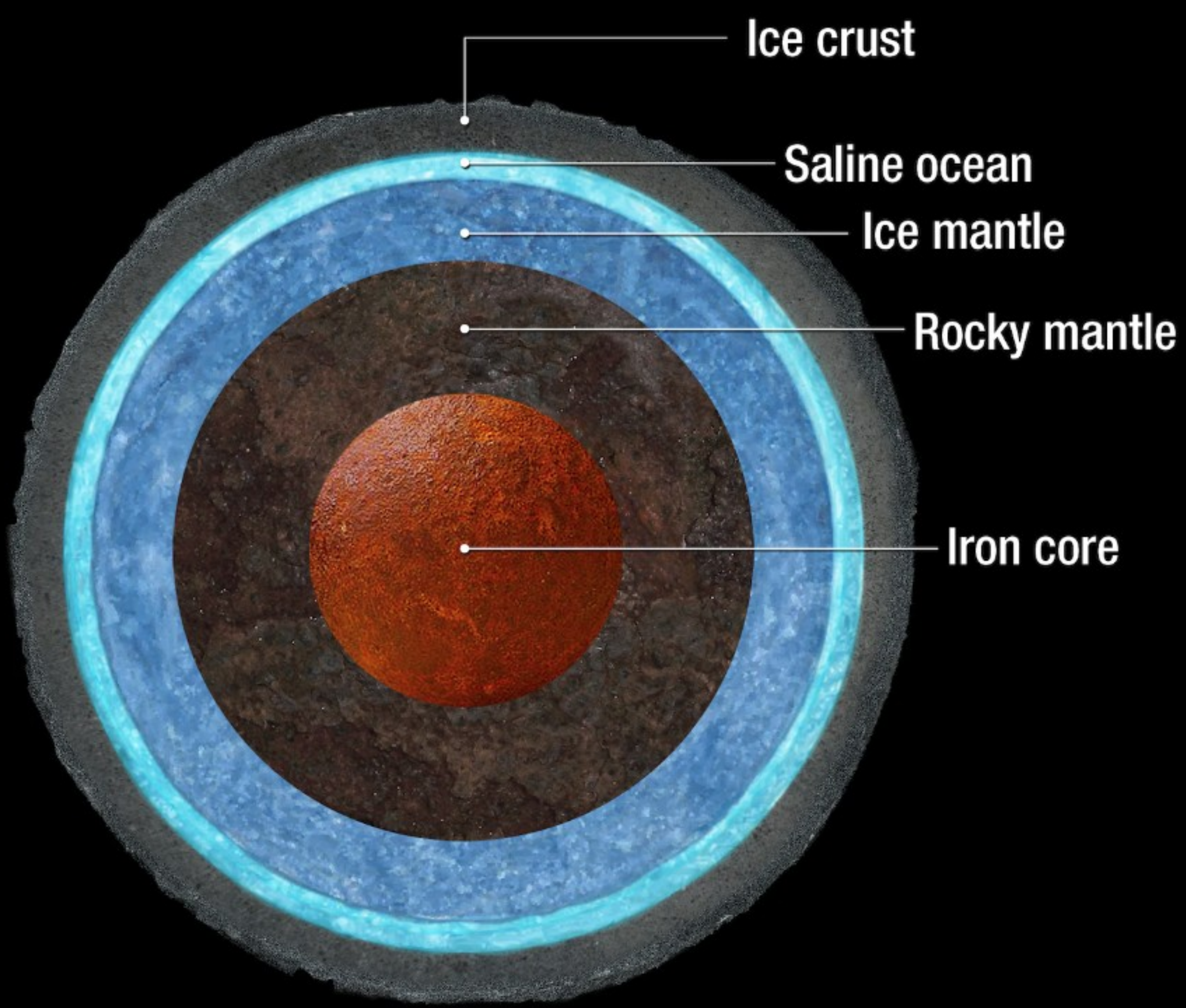
Jupiter's moon Europa could foster life

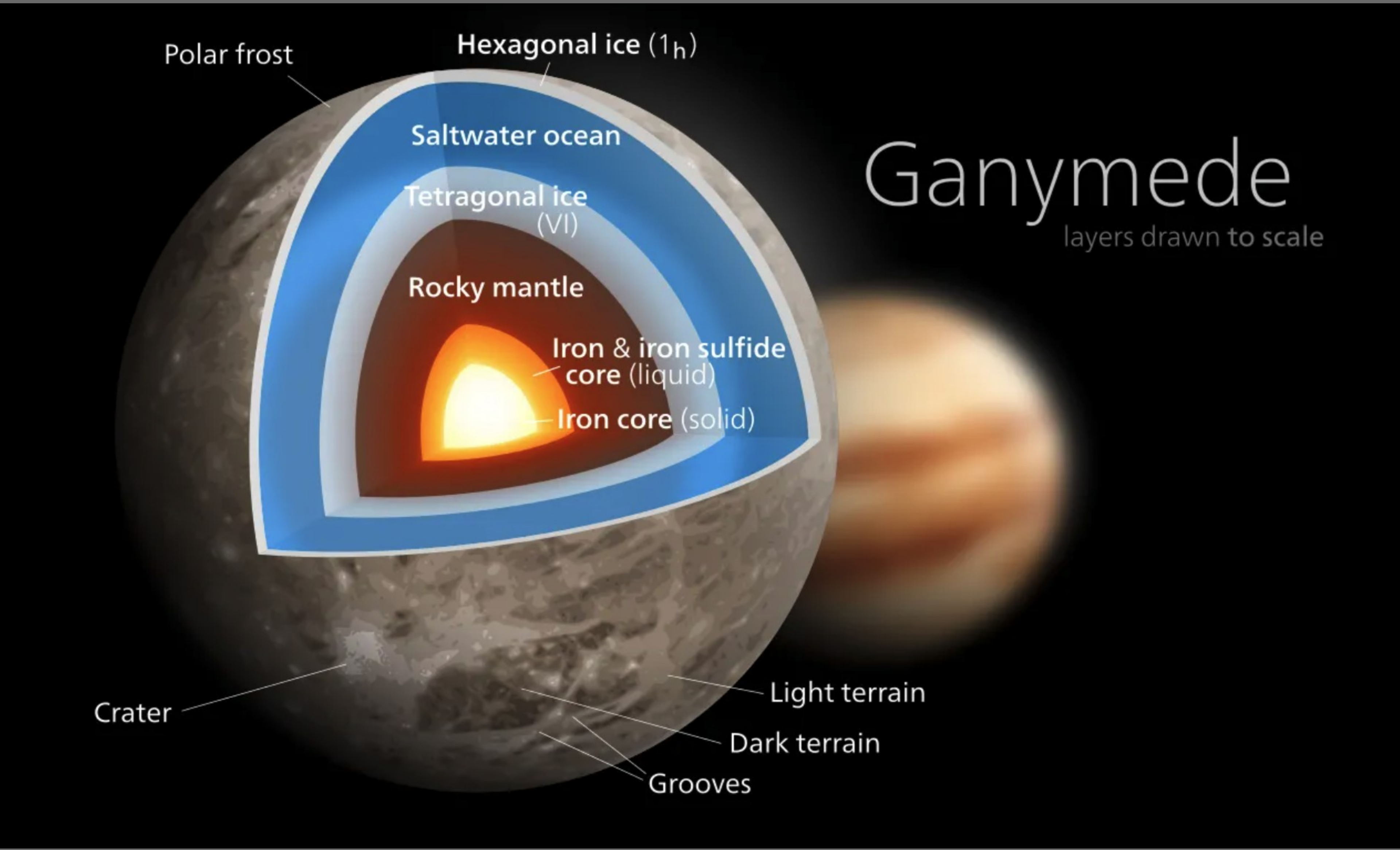
New research suggests that an ocean of water just beneath the icy shell of Europa might support life, with plumes of warmer water fracturing the surface giving access to organic compounds and light for photosynthesis



Sources: Nature, NASA, University of Arizona

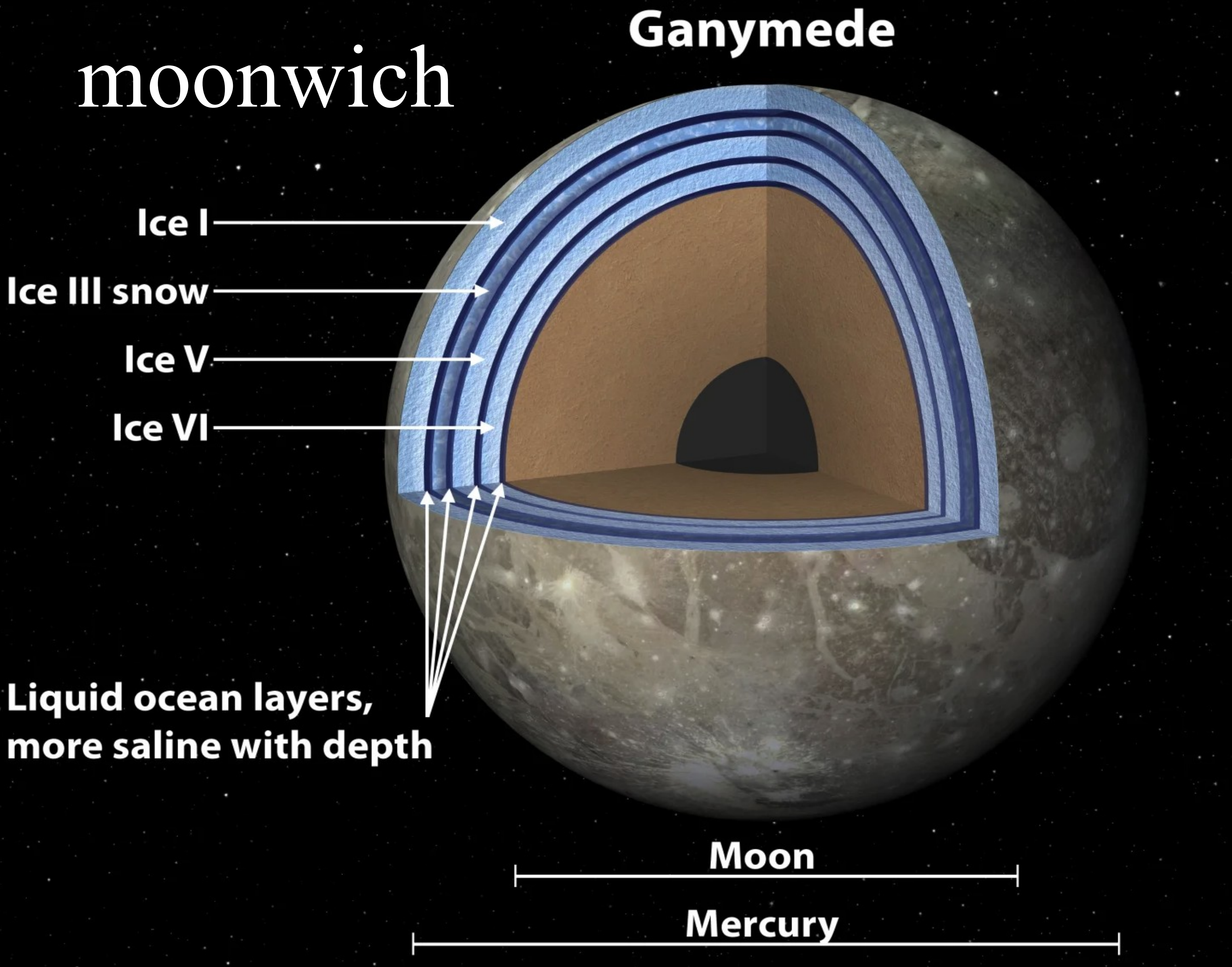
Ganymede Interior

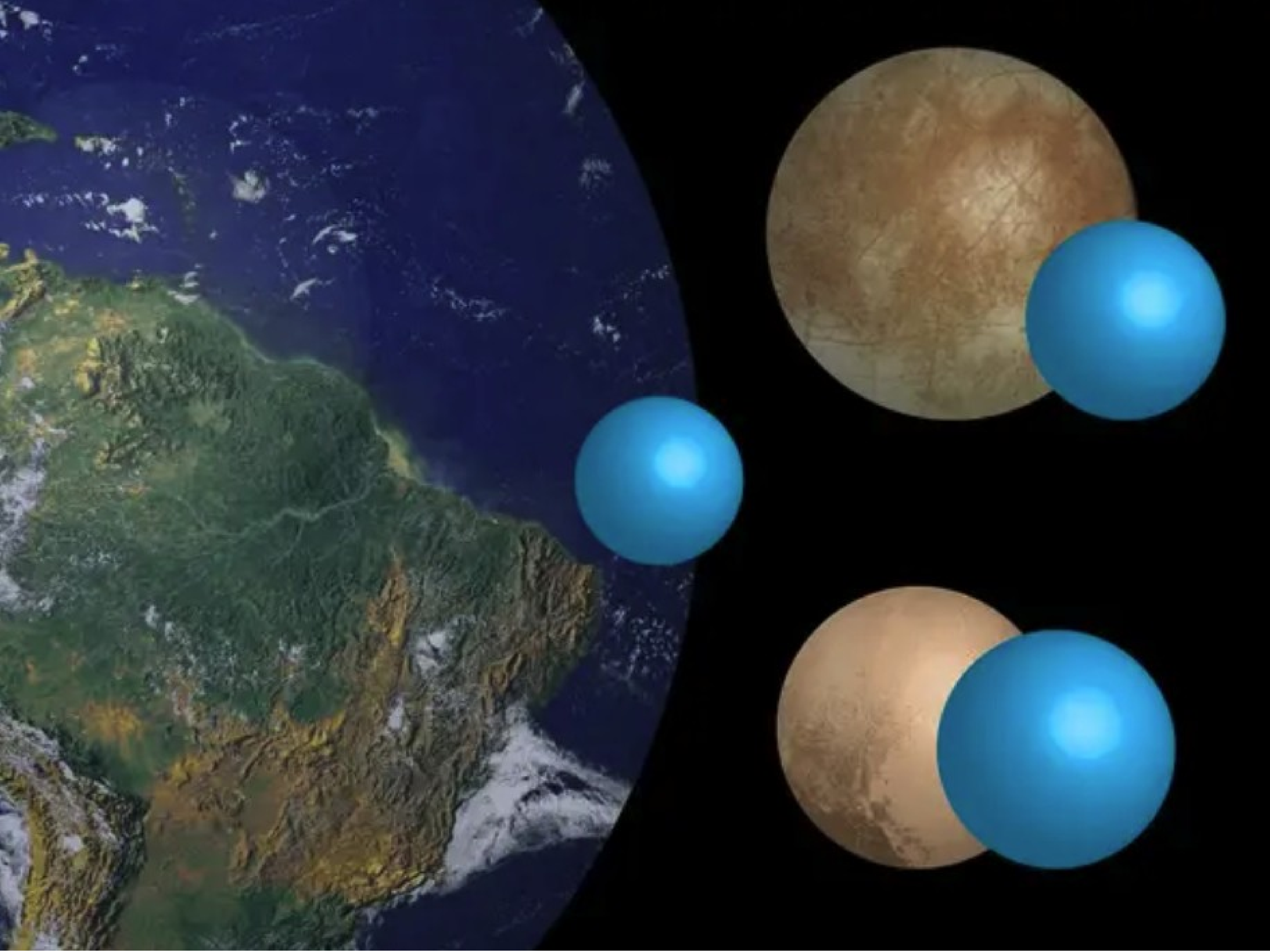


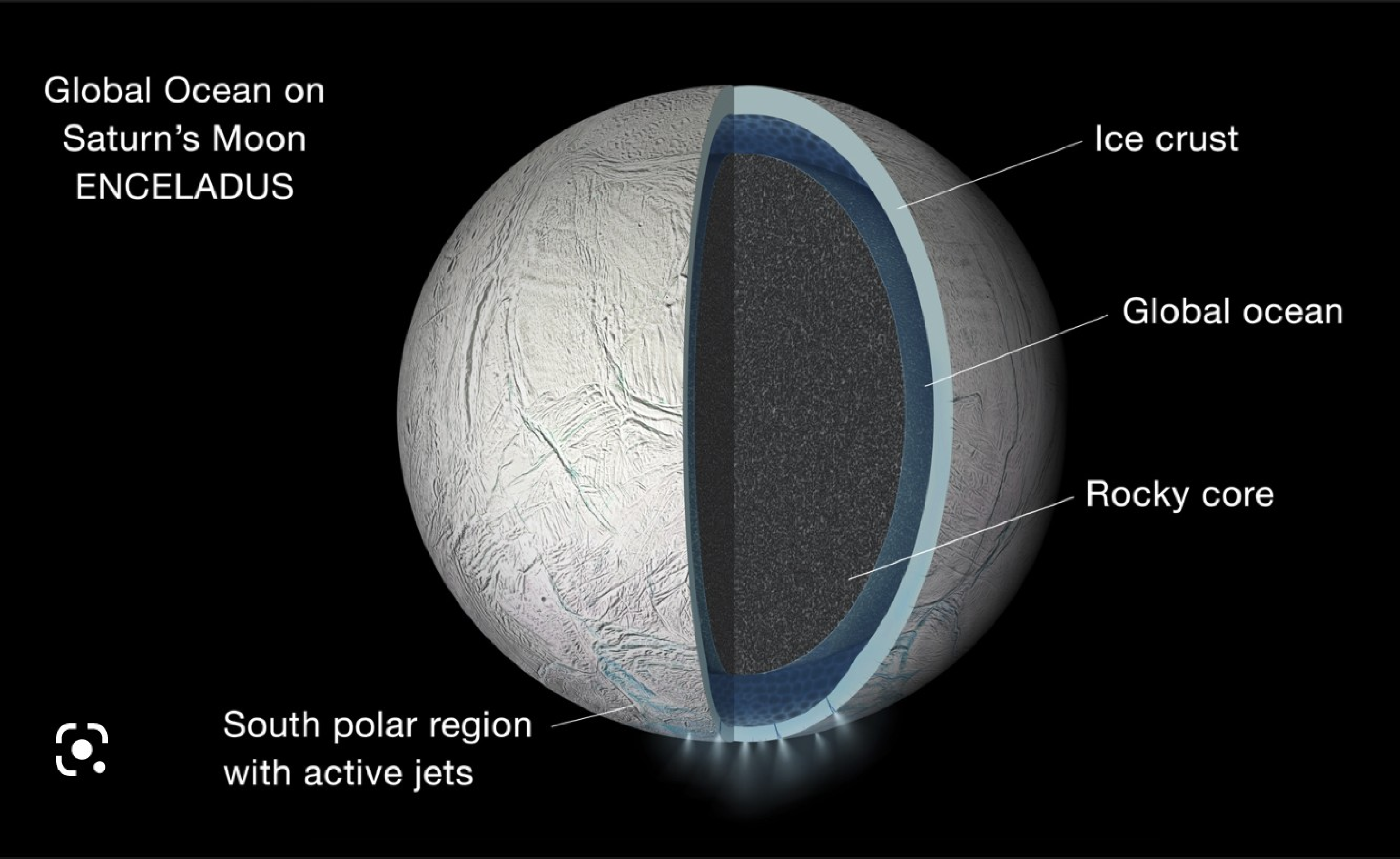


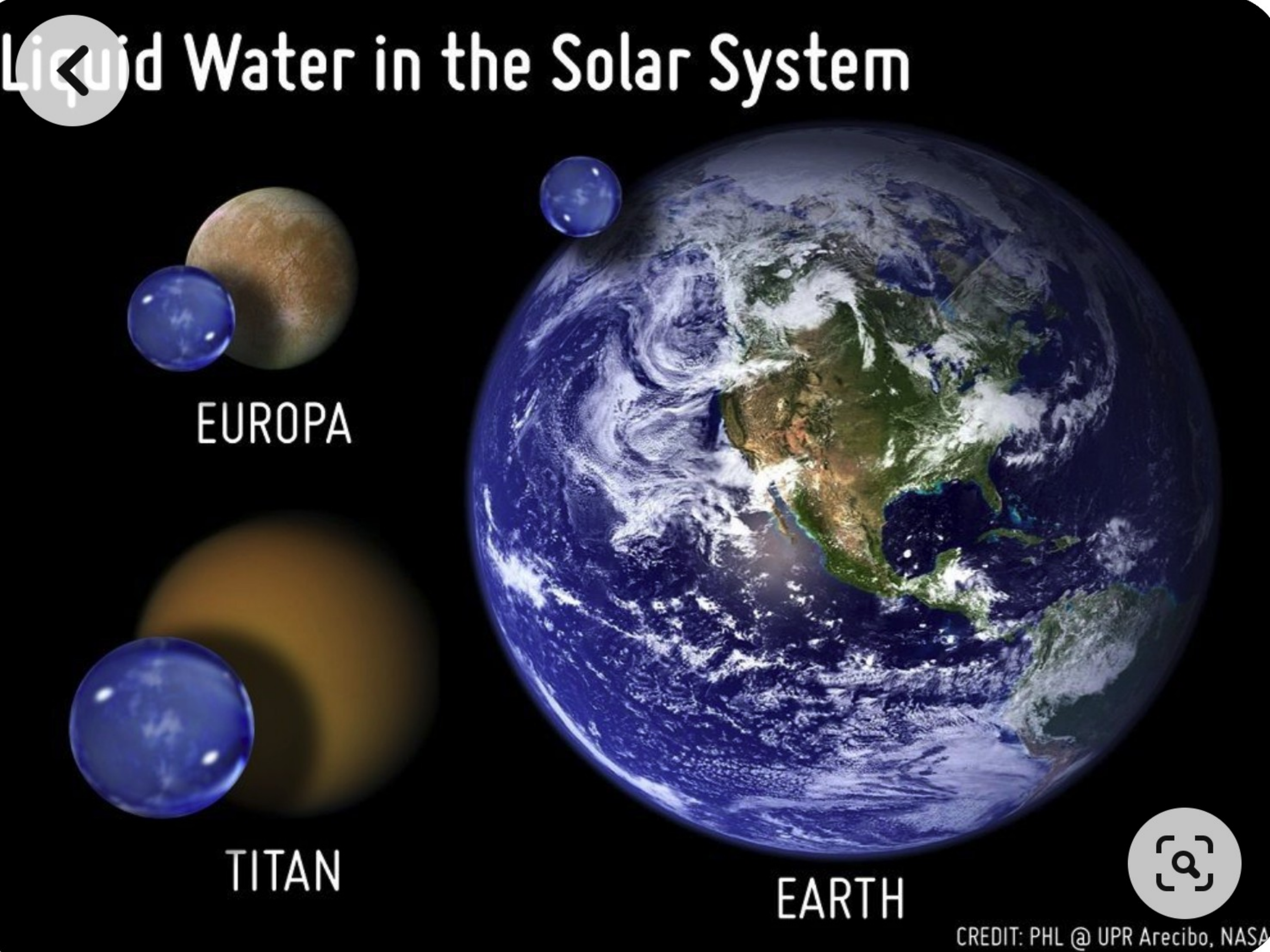
Polar frost
Hexagonal ice (1h)
Saltwater ocean
Tetragonal ice (VI)
Rocky mantle
Iron & iron sulfide core (liquid)
Iron core (solid)
Ganymede
layers drawn to scale
Crater
Light terrain
Dark terrain
Grooves

moonwich


Ganymede
Ice I
Ice III snow
Ice V
Ice VI
Liquid ocean layers,
more saline with depth
Moon
Mercury

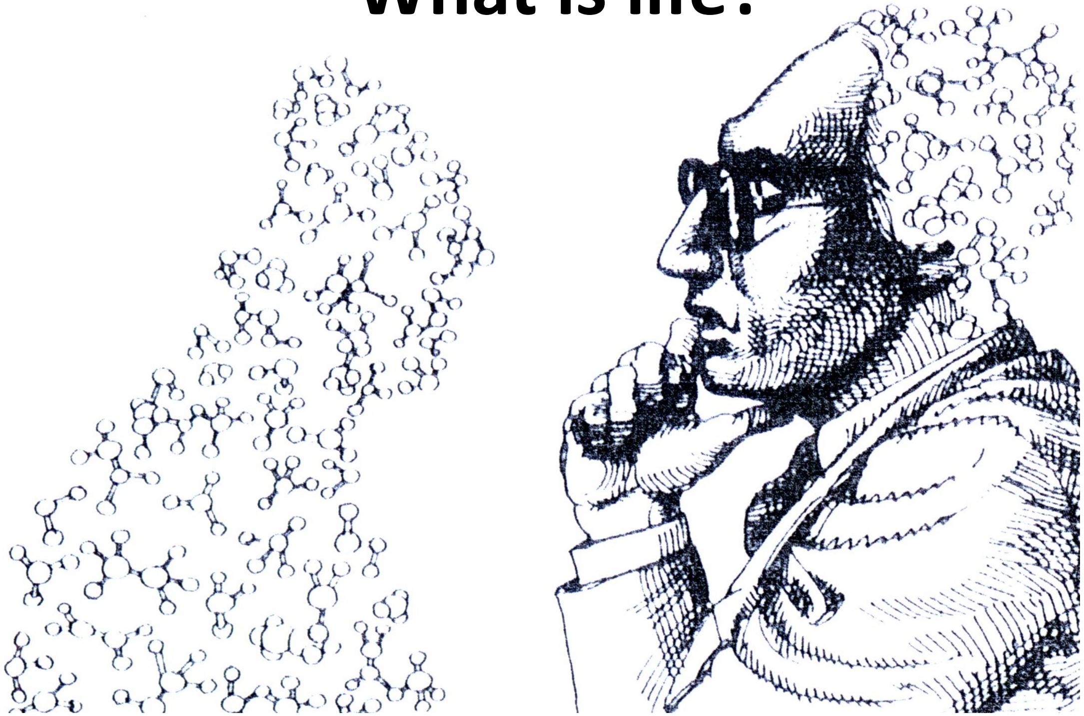



Global Ocean on
Saturn's Moon
ENCELADUS
Ice crust
Global ocean
Rocky core
South polar region
with active jets


Liquid Water in the Solar System
EUROPA
TITAN
EARTH
CREDIT: PHL @ UPR Arecibo, NASA

It's hard (maybe even impossible) to talk about habitability unless we know what life is

What is life?



Victor Juhasz

EXOPLANETS

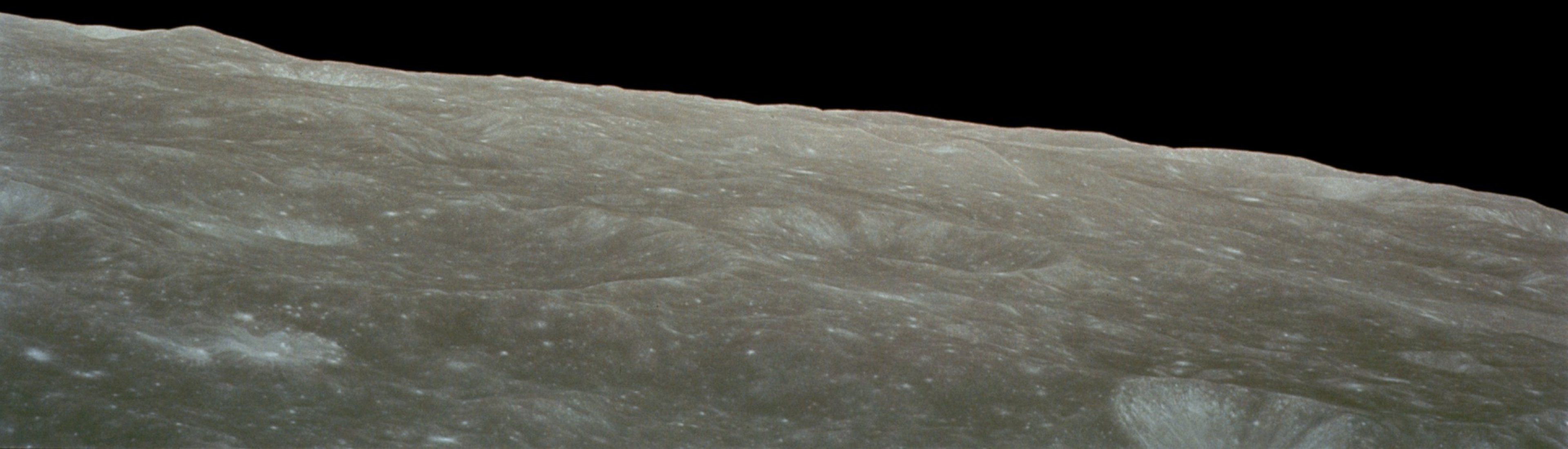

What does
"earth-like"
mean?
What are the relevant features of our Earth that made
it possible for life to emerge and survive for 4 billion years?

What does "earth-like" mean?

wet and rocky

$0.5 < M < 2\ M_{Earth}$	gravity, atmosphere
$0.5 < l < 2\ l_{Earth}$	temperature, atmosphere
large Moon	tidal cycling hydration/dehydration
30% continents	fresh water, 3 phases: solid/liquid/gas
30% cloud cover	albedo control, temperature
high mass star (UV)	emergence of life
$0.5 < age < 2\ age_{Earth}$	time to evolve

What are the relevant features of our Earth that made it possible for life to emerge and survive for 4 billion years?



The Galactic Habitable Zone and the Age Distribution of Complex Life in the Milky Way

Charles H. Lineweaver,[1,2]* Yeshe Fenner,[3]* Brad K. Gibson[3]*

We modeled the evolution of the Milky Way Galaxy to trace the distribution in space and time of four prerequisites for complex life: the presence of a host star, enough heavy elements to form terrestrial planets, sufficient time for biological evolution, and an environment free of life-extinguishing supernovae. We identified the Galactic habitable zone (GHZ) as an annular region between 7 and 9 kiloparsecs from the Galactic center that widens with time and is composed of stars that formed between 8 and 4 billion years ago. This GHZ yields an age distribution for the complex life that may inhabit our Galaxy. We found that 75% of the stars in the GHZ are older than the Sun.

As we learn more about the Milky Way Galaxy, extrasolar planets, and the evolution of life on Earth, qualitative discussions of the prerequisites for life in a Galactic context can become more quantitative (*1–3*). The Galactic habitable zone (GHZ) (*4*), analogous to the concept of the circumstellar habitable zone (*5*), is an annular region lying in the plane of the Galactic disk possessing the heavy elements necessary to form terrestrial planets and a sufficiently clement environment over several billion years to allow the biological evolution of complex multicellular life. In order to more quantitatively estimate the position, size, and time evolution of the GHZ, we combined an updated model of the evolution of the Galaxy (*6*) with metallicity constraints derived from extrasolar planet data (*7*).

Of the factors that determine the location of the GHZ, the abundance of elements heavier than hydrogen and helium (metallicity) is particularly crucial because these elements are what terrestrial planets are composed of. The current metallicity of the Galaxy can be directly measured. However, modeling is needed to identify the metallicity distribution throughout the history of the Milky Way.

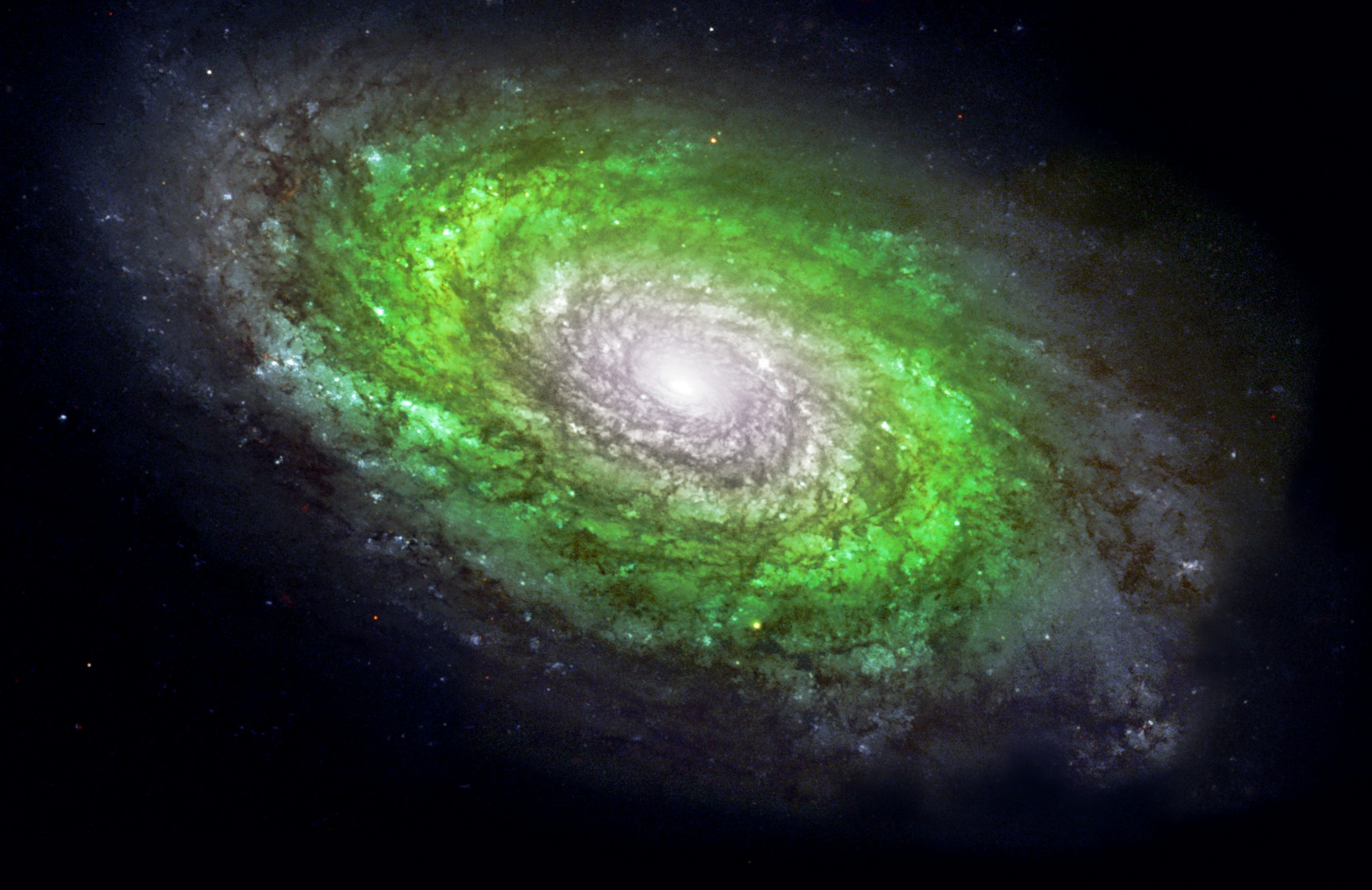
We simulated the formation of the Galaxy with the use of two overlapping episodes of accretion that correspond to the buildup of the halo and disk. The gas accretion rate falls off exponentially on a small [~1 Gyear (Gy)] time scale for the first phase and a longer time scale (~7 Gy) for the second phase. Although there is a 1-Gy delay between the onset of halo formation and the onset of thin disk formation, the formation of these two components overlaps in time. In our model, we monitor the creation of heavy elements and the exchange of matter between stars and gas. Model parameters have been chosen to reproduce the key observational constraints, namely, the radial distribution of stars, gases, and metals; the metallicity

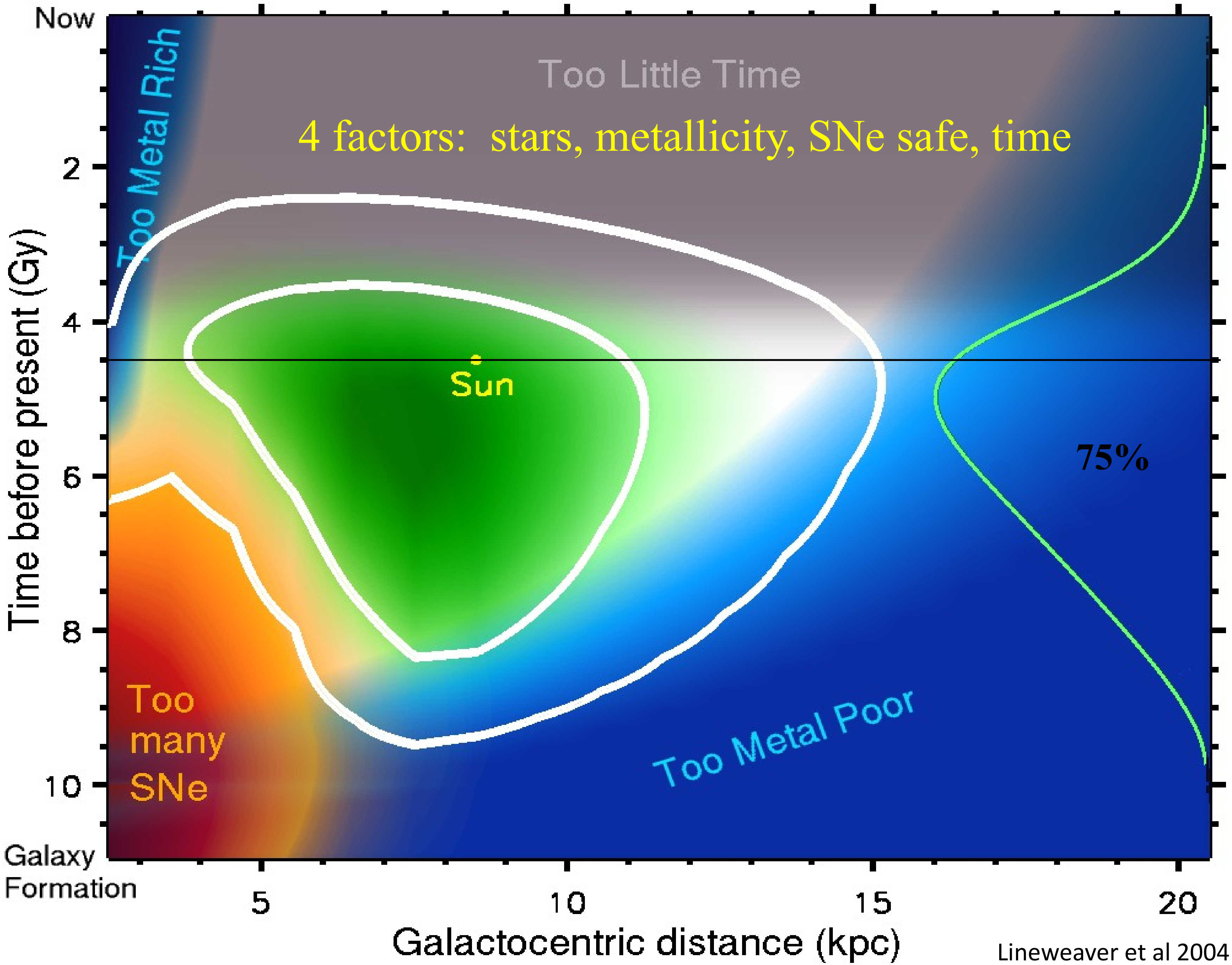
[1]Department of Astrophysics, University of New South Wales (NSW), Sydney, NSW 2052, Australia. [2]Australian Centre for Astrobiology, Macquarie University, NSW 2109, Australia. [3]Centre for Astrophysics and Supercomputing, Swinburne University, Hawthorn, VIC 3122, Australia.

*To whom correspondence should be addressed. E-mail: charley@bat.phys.unsw.edu.au (C.H.L.); yfenner@astro.swin.edu.au (Y.F.)

 2004

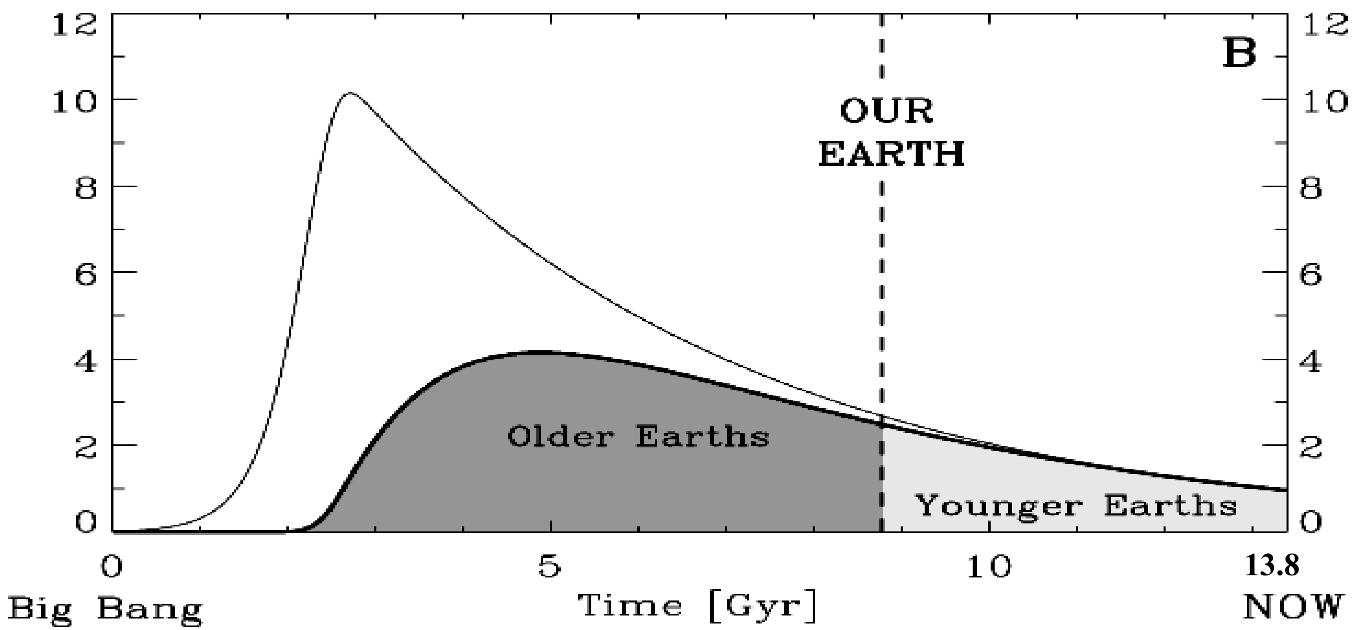
The Galactic Habitable Zone




Now
Too Metal Rich
Too Little Time
4 factors: stars, metallicity, SNe safe, time
Sun
75%
Too many SNe
Too Metal Poor
Time before present (Gy)
2
4
6
8
10
Galaxy Formation
5
10
15
20
Galactocentric distance (kpc)
Lineweaver et al 2004

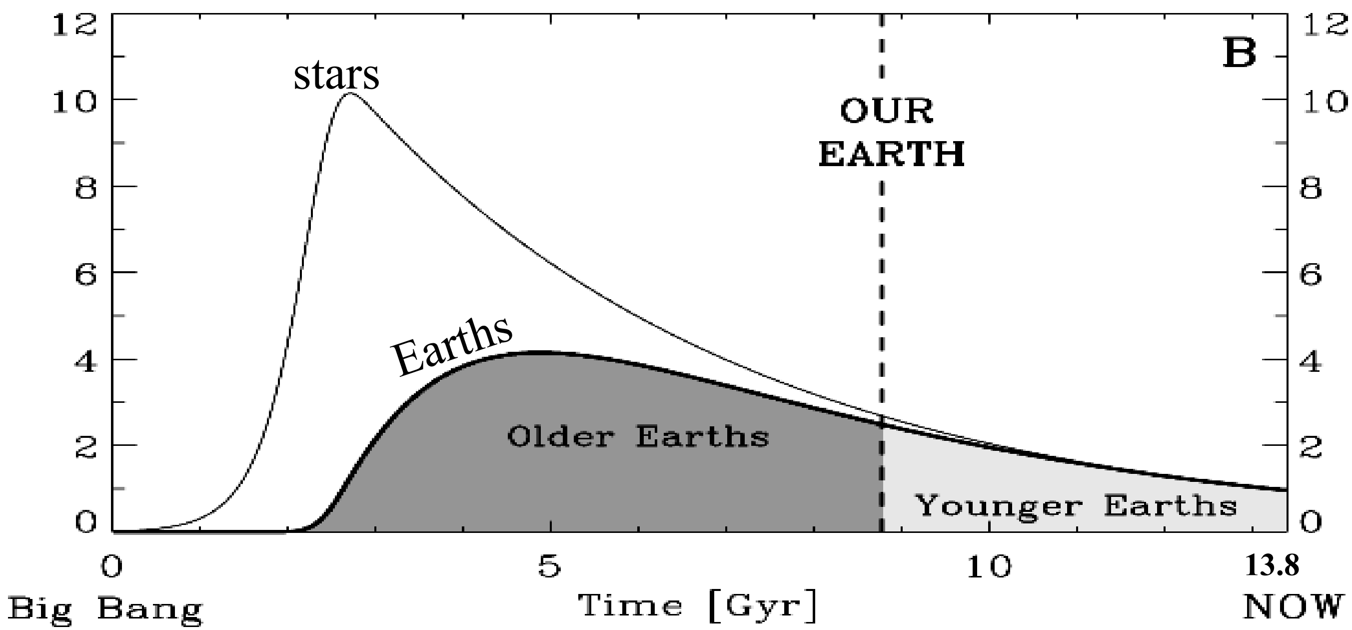
Lineweaver 2000

age distribution of Earths



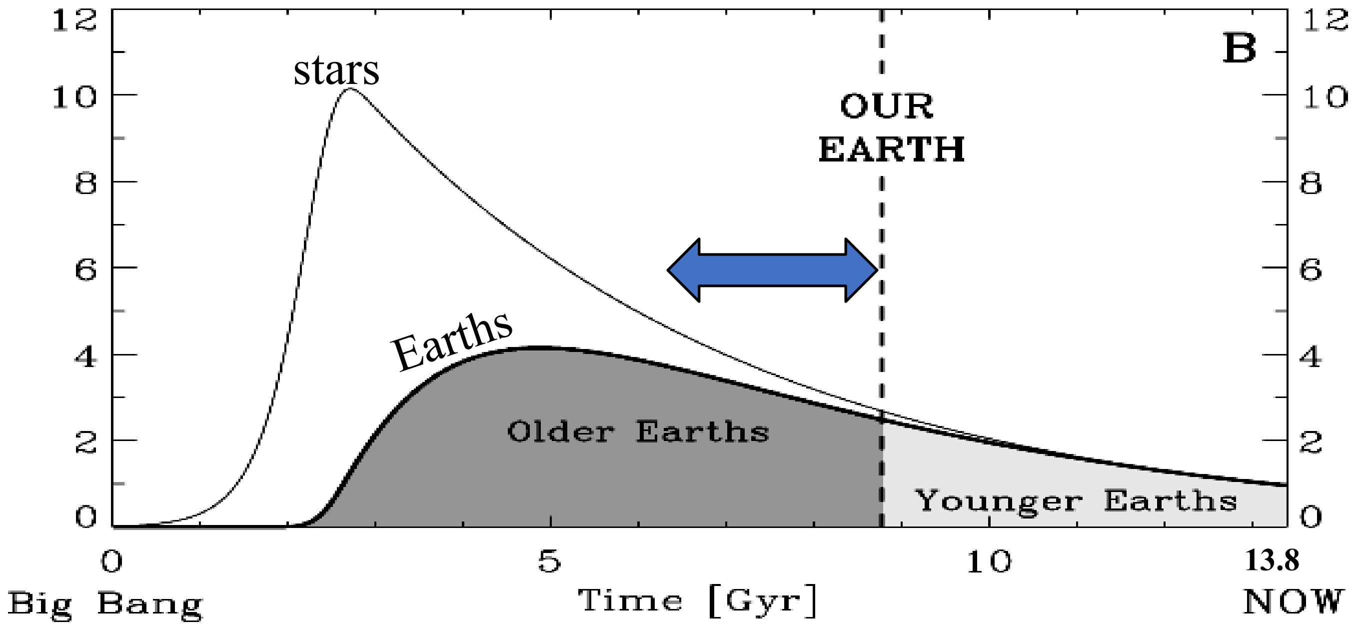
Lineweaver 2000

age distribution of Earths



Lineweaver 2000

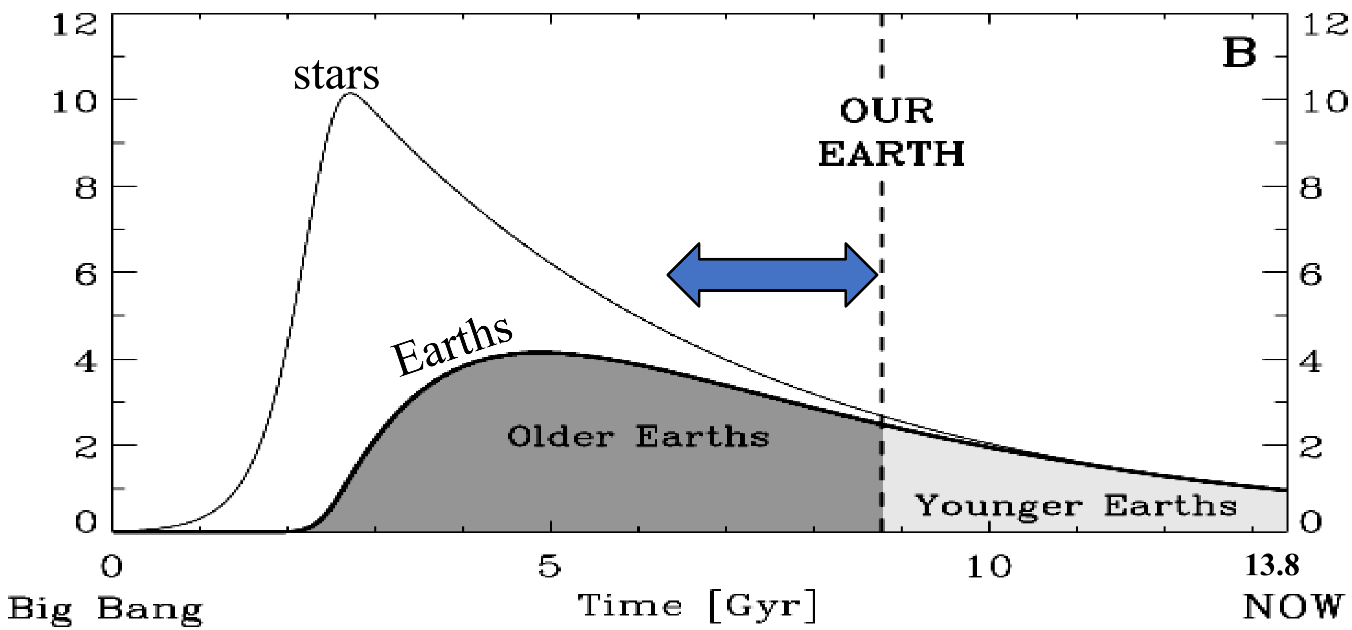
age distribution of Earths



Our Earth is ~ 2 billion years younger than other Earths

Lineweaver 2000

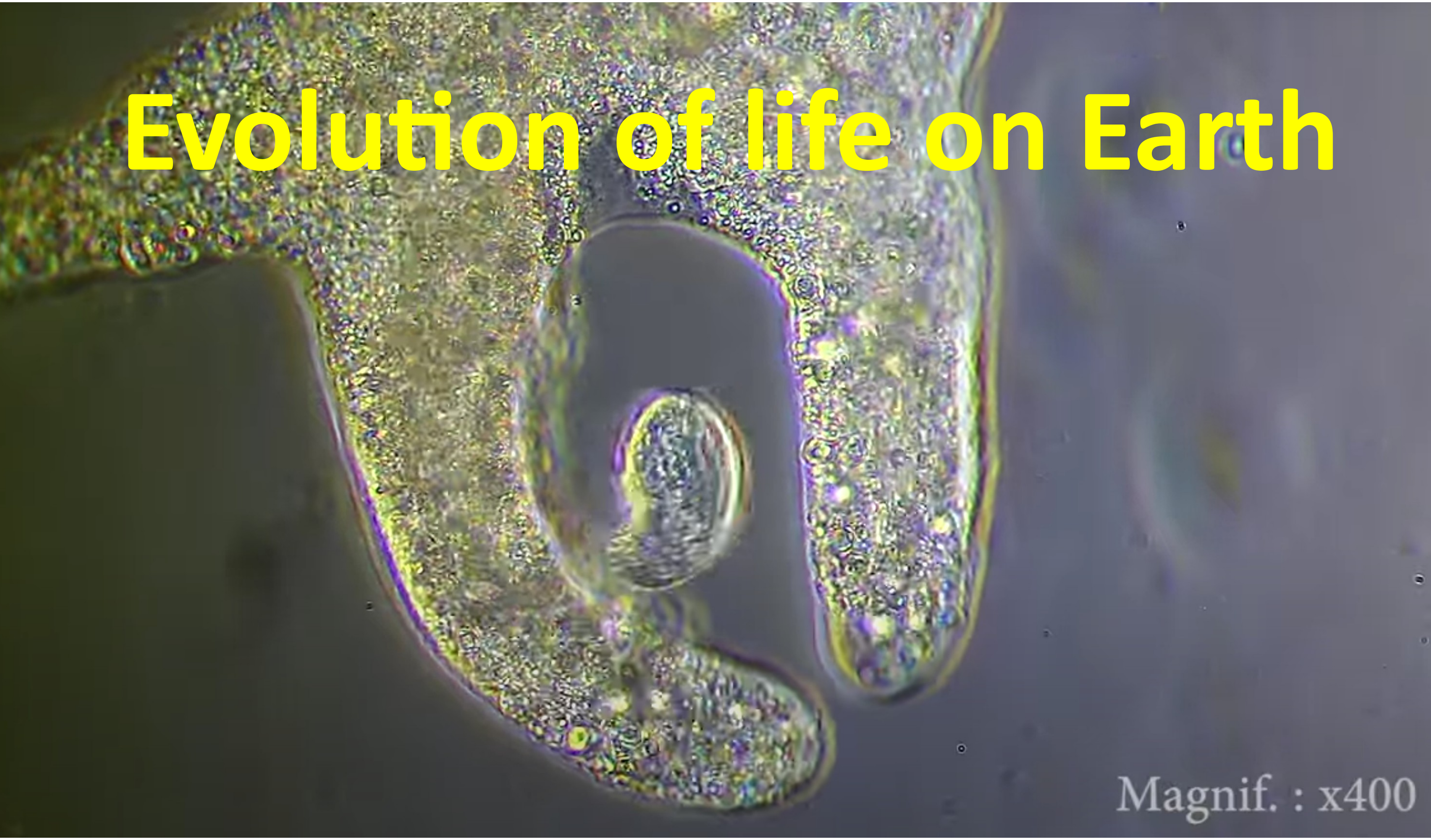
age distribution of Earths



Our Earth is ~ 2 billion years younger than other Earths

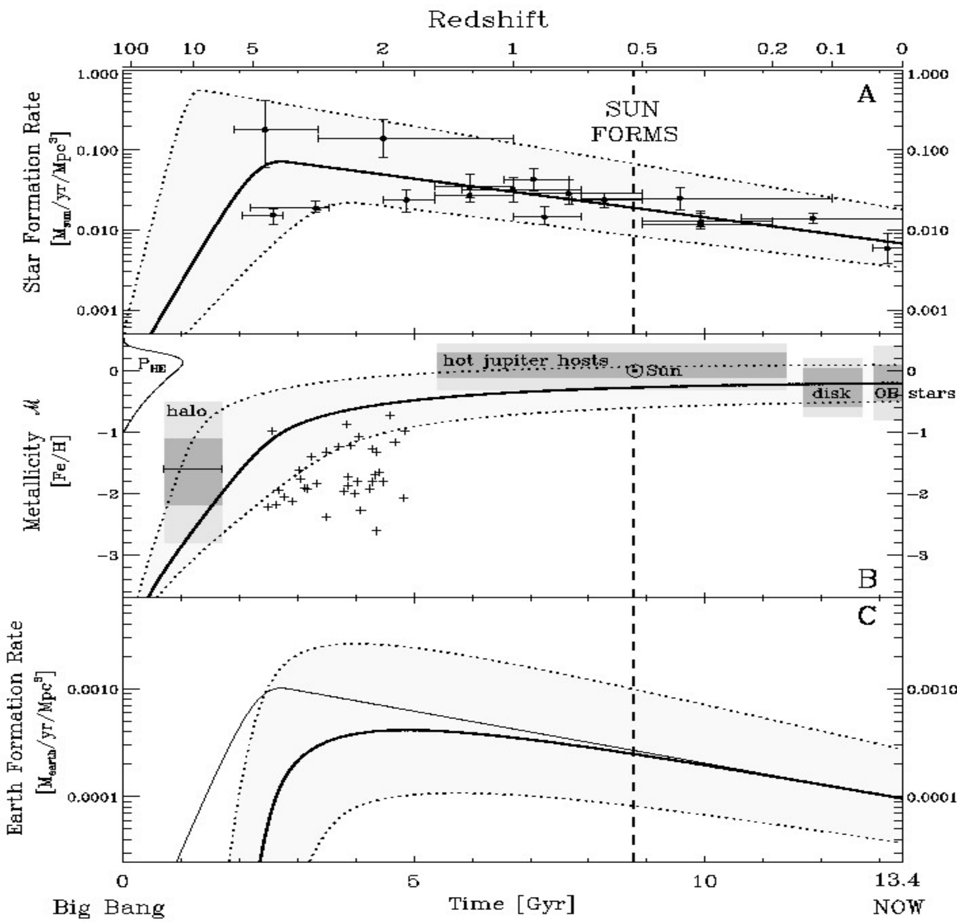
If life has emerged on other Earths, it has had ~ 2 billion years longer to evolve !

Evolution of life on Earth



Evolution of life on Earth

~2 billion years ago
we were amoeba-like

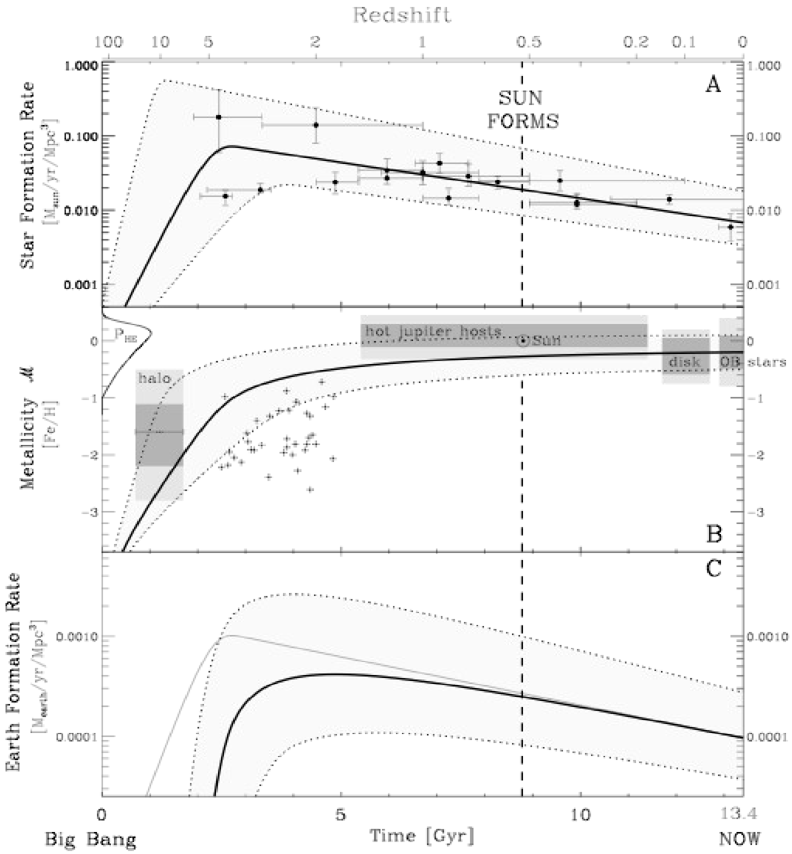


The age distribution of terrestrial planets in the universe.

Lineweaver, Icarus, 2001

There has been plenty of time for life to have evolved elsewhere. Tmean = 1.8 +/- 0.9 Gyr older than Earth.

`If life is common in the universe – as suggested by the rapid appearance of life on Earth--then this age distribution gives us an idea of how we compare to other life that may exist in the universe.' → Lineweaver and Davis Astrobiology 2002



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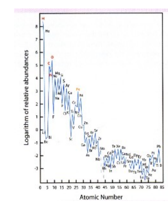
Lineweaver, Icarus, 2001



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Why ET won't return our calls

We're far too immature

Ahead of our time . . . Earth may be too young for contact from intelligent extra-terrestrials.

By MARIA HAWTHORNE and JIM BAYNES

A MAJOR generation gap which put Earth almost two billion years behind similar planets may be the reason extra-terrestrials have not contacted us, Australian research has suggested.

A University of NSW astronomer believes Earthlings are simply too young to attract communication from intelligent life from outer space.

Researcher Dr Charles Lineweaver calculated that Earth-like planets orbiting other stars would be on average about 1.8 billion years older than Earth.

That would put Earthlings on the same evolutionary scale as bacteria to any far more developed neighbours, and such highly developed life would be unlikely to communicate via a primitive medium like radio waves, Dr Lineweaver said.

In a paper submitted to the journal *Icarus*, Dr Lineweaver concluded that three-quarters of all Earth-like planets must have been around longer than the Earth and that the average age was 6.4 billion years, compared with Earth's 4.6 billion years.

"The rare clue is that most of the life-forms in the universe have had two billion years longer to evolve than we have.

"To put this time span in perspective, two billion years ago our ancestors were microscopic single-celled amoebas," Dr Lineweaver said.

Dr Lineweaver looked at a host of factors that determined the formation and destruction of planets, including the presence of heavy atoms, which were not contained in the early universe.

Heavier elements are only released when old stars explode as supernovas and rocky planets cannot form around a star without enough heavy atoms in the dust it is made of.

But too many heavy elements would lead to giant planets orbiting so close to their parent stars that they destroyed newborn earths, theoretically allowing planets to be dated.

What any extra-terrestrials may have developed with their head-start on humans is anyone's guess.

But Dr Lineweaver questions whether they would even want to communicate with a species so much its junior — just as humans don't try to communicate with bacteria.

"People aren't interested in talking to bacteria, trees, dolphins in their own languages — and we have a big brain."

Although the discovery is sure to stir the imagination, Dr Lineweaver hopes rather it will shoot down some romantic assumptions about extra-terrestrials, highlighting how little is actually known.

"We assume that . . . any species worth its salt would adopt or evolve towards human-like intelligence," he said.

"If we're talking about aliens who have two billion years difference then I just don't know what we're talking about."

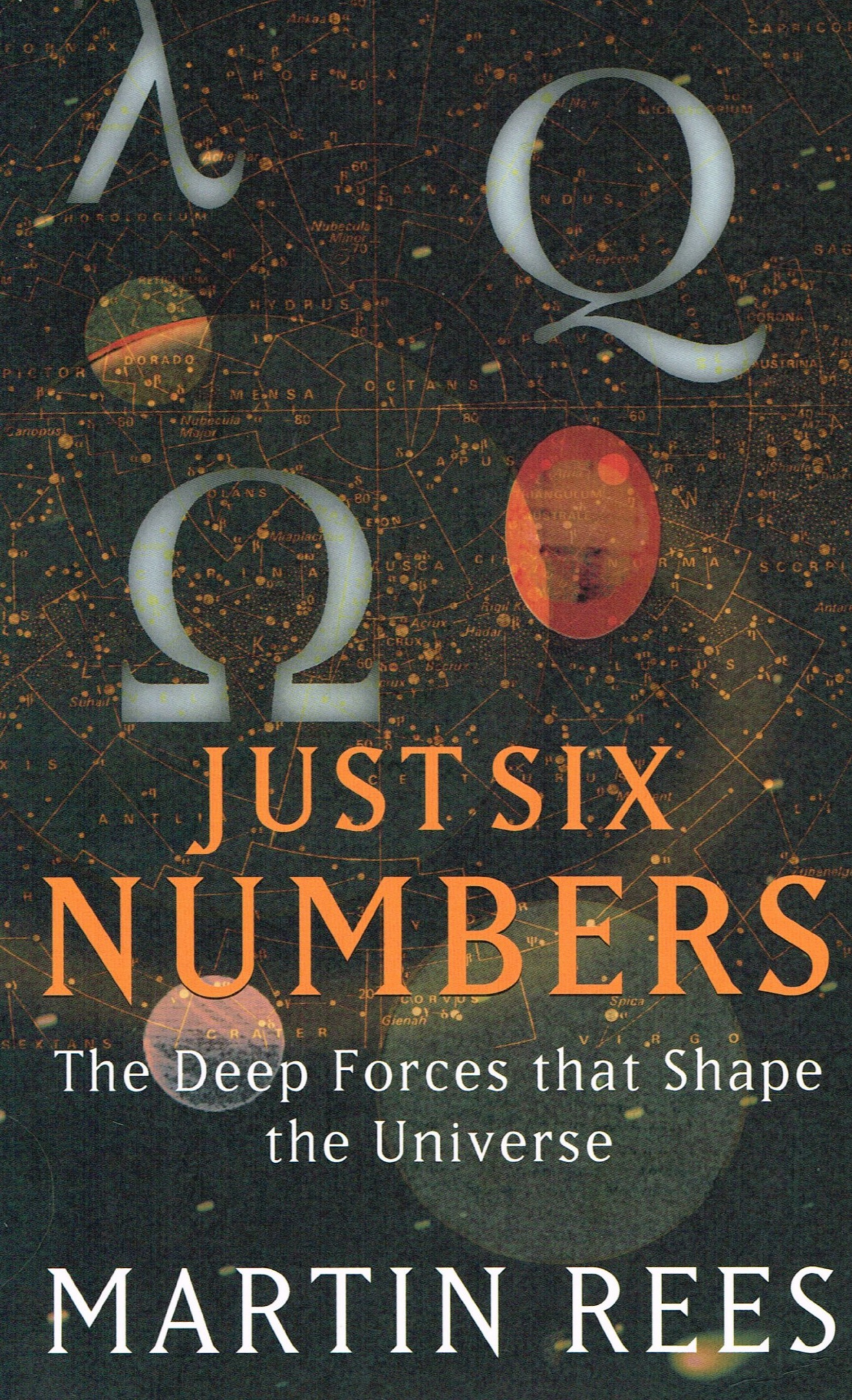
So what life is in the universe?

"I think the universe is filled at least with bacteria and lots of other weird things, and [we're] not going to find any English-speaking colonies or human-like intelligence," Dr Lineweaver said.

The new kids

- **Other** planets capable of sustaining similar life are on average 1.8 billion years older than Earth
- **In** that time humans have climbed up the evolutionary ladder from microscopic single-celled amoebas
- **Extra**-terrestrials may not want to talk to beings so far their evolutionary inferior
- **They** would probably not communicate via relatively primitive radio waves


Milan Cirkovic
(Serbian Astronomer)
Island Universes



number of spatial
dimensions

D=3

nuclear efficiency

□ = 0.007

$N = 10^{36}$

number of protons needed to have their gravity as strong as the nuclear force