ASTRO 5: LIFE IN THE UNIVERSE

THE BEGINNINGS AND EVOLUTION OF LIFE ON EARTH

RICHARD NOLTHENIUS, PHD

CABRILLO COLLEGE ASTRONOMY

ALL DUE CREDIT TO DR. JOE LAMANNA AND ALSO TO DR NICK LANE

- I've borrowed heavily from Lamanna's excellent 2016 Presentation on the origin of life and their energy-production via mitochondria in Earth's evolutionary history.
- And from Nick Lane's great presentations (e.g. **here**) on the arrival of eukaryotic life on Earth.
- Mitochondria are the energy producing structures that power all cells on all multi-cellular life (eukaryotes) from the simplest to the most complex. These appear to have a complex and perhaps unlikely evolving relationship with the cells they populate.
- This relates, therefore, to the likeliness of finding life elsewhere in the Universe.
- We'll summarize modern ideas of the origin of life on Earth, so that we're better prepared to understand searches for life elsewhere in the universe.

THE BASICS NECESSARY FOR LIFE

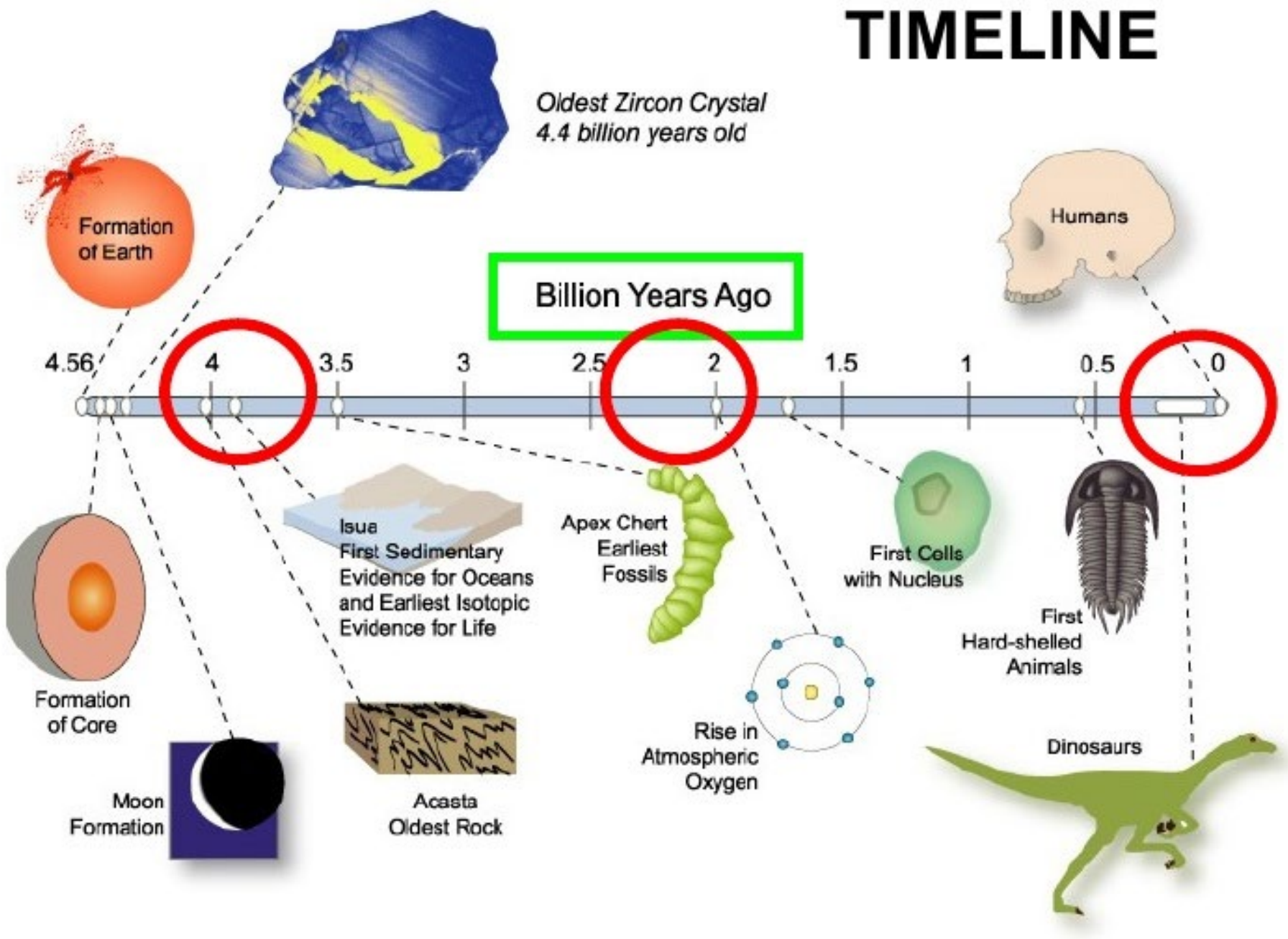
- Energy! – Chemical

--- heat (geothermal for example)

--- photons of light, e.g. sunlight

--- fermentation or oxidation

- The underlying chemicals – amino acids from meteorites, carbon, oxygen, etc.
- Water – very common in the universe, from meteorites and planetesimals

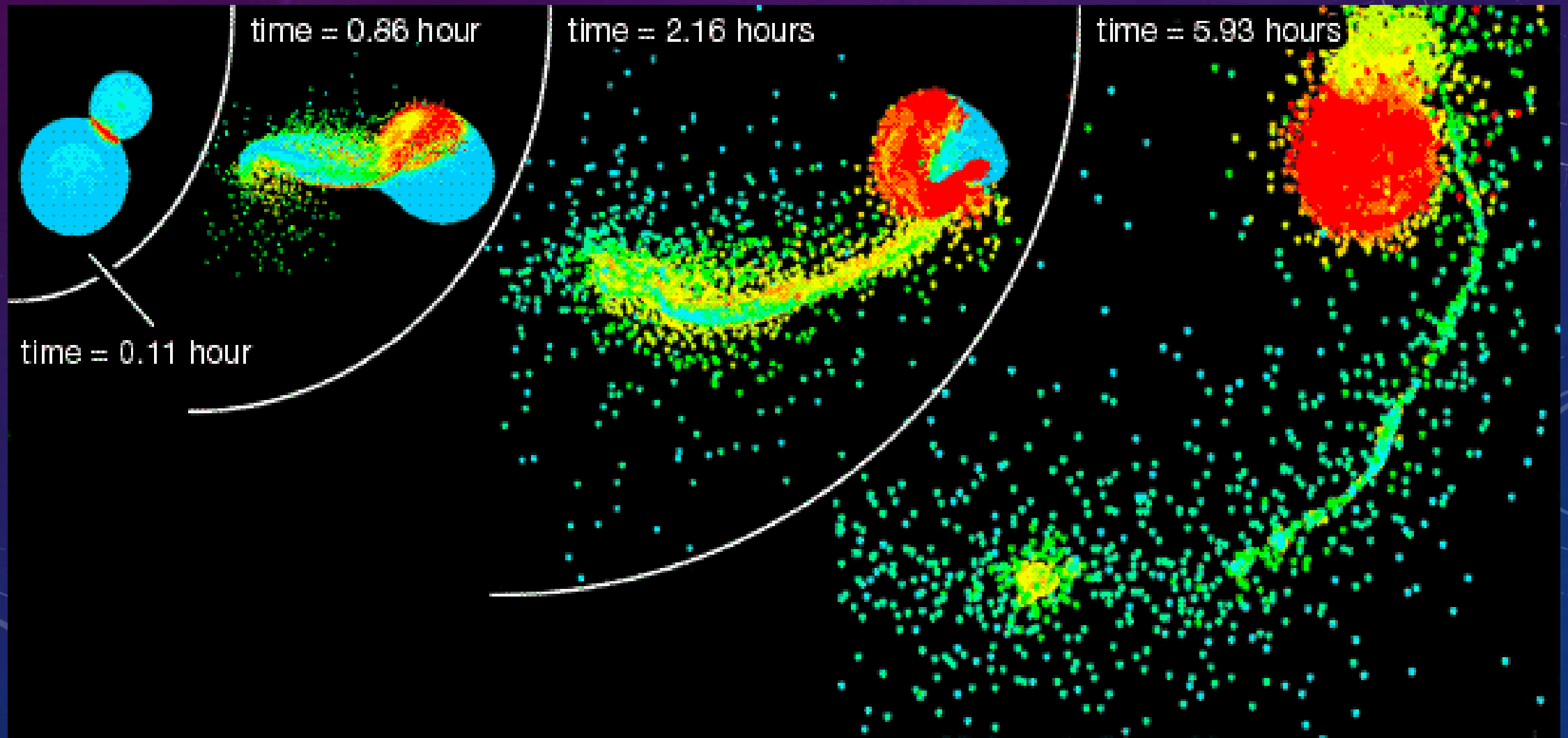


MORE RECENT EVIDENCE SAYS THE OCEANS AND THICK CRUST DATE BACK TO AT LEAST 4.2 BILLION YEARS AGO, SAYS ROCKS ON HUDSON BAY, CANADA.

THE EARLIEST ATMOSPHERE WAS KNOCKED AWAY BY THE IMPACT THAT CREATED THE MOON

- A Mars sized planet hit Earth just a few millions of years after it had formed, a glancing blow that created the moon.
- Evidence: moon's orbit is ~plane of the solar system, not the equator of the Earth. And, the moon is very poor in iron. The planet that hit us, it's iron sank to the center of the Earth.

ONLY 6 HRS AFTER IMPACT, THE MOON HAS ALREADY FORMED AT THE END OF THE TIDAL TAIL OF BLASTED-OFF MATERIAL. MOST MATERIAL IMPACTS BACK ONTO EARTH, CREATING GREAT HEAT AND LIBERATING MUCH INTERNAL VOLATILES. MOON CONDENSES QUICKLY ENOUGH TO ESCAPE THIS FATE.



WE BELIEVE ALL LIFE BEGINS AS CARBON-BASED. CARBON IS THE ONLY ATOM CAPABLE OF BUILDING COMPLEX STRUCTURES AT PLANETARY TEMPERATURES BY NATURAL PROCESSES *(LIFE IS COMPLEXITY, IF ANYTHING!)*

- It might progress to silicon-based, as the invention of carbon-based life. More on that later, not here!

WHEN DID LIFE BEGIN?

- Microbial mats 3.5 billion years ago, evidence very strong
- 3.85 billion years ago, C13/C12 ratios in some rocks and zircons suggest organic origin for the carbon contained in these rocks. Life prefers C12 so a lower C13/C12 ratio than exists in the atmosphere suggests the carbon was isotopically altered by life.
- In theory, hydrothermal deep sea vents could have had life even earlier, perhaps 4.1 billion years ago.
- The oldest rocks known are 4.2 billion years old, found on the shore of Hudson Bay, Canada, with amphibolite formations showing they must have formed in water and nearby similar age rocks at high pressure, indicating a thick solid crust had already formed.

EARLIEST LIFE WAS SINGLE-CELLED (I.E. "PROKARYOTES"

- They date back to about 3.8 billion years ago
- They formed in an environment without free oxygen. All oxygen was bound up in minerals or in water
- They had no nucleus, much of the machinery we see in the cells of multi-cellular life today was not yet evolved. They had a cell membrane, however, and we call them 'cells'.

SLEEP *ET AL.* (2014) MODEL THE POST-IMPACT EARTH AND FIND:

- The impact liberates trapped volatiles of water vapor and CO2 at high density (more than 200 bar?), blocking outgoing IR, raising Runaway Greenhouse at temps > 500K on the surface, for ~10 million years
- Then cooling, ocean formed from H_2O, leaving ~100 bar of CO_2, Lesser amounts of SO_2 (sulfate), HF (hydrogen flouride), and HCl (Hydro-chloride).
- To explain life by 3.8 billion years ago, requires rapid weathering/subduction to sequester CO_2
- How rapid is not certain, but that's a lot of CO_2 in the earliest atmosphere…

LIFE AS EARLY AS 4.1 BILLION YRS AGO?

- UCLA researchers studying zircon crystals find good evidence for organic carbon (C13/C12 ratio) graphite in zircons 4.1 B yrs old, suggesting oceans and life this far back (Bell *et al*. 2015).
- This is during the hypothesized "late heavy bombardment" period which would seem to make life pretty hard to maintain, although evidence "late bombardment" period was much milder than once thought.
- Not clear the resolution of this data into a consistent and well-accepted picture.
- Other evidence of life 3.8-4.3B yrs ago around hydrothermal vents (Dodd *et al.* 2017)

OUR LATER ATMOSPHERE…

- Probably delivered by comets and outgas'ed from our own volcanoes - water, carbon, nitrogen, oxygen, sulfur, and smaller amounts of neon, argon, and other elements
- Volcanoes likely very active in early Earth as crust was still hot and thin, and these light elements were still rising by bouyancy from the the deeper parts of Earth
- Ammonia = NH_3, likely common and emitted by volcanoes. Ammonia common in Jupiter's atmosphere. Would dissociate over time… it is a greenhouse gas

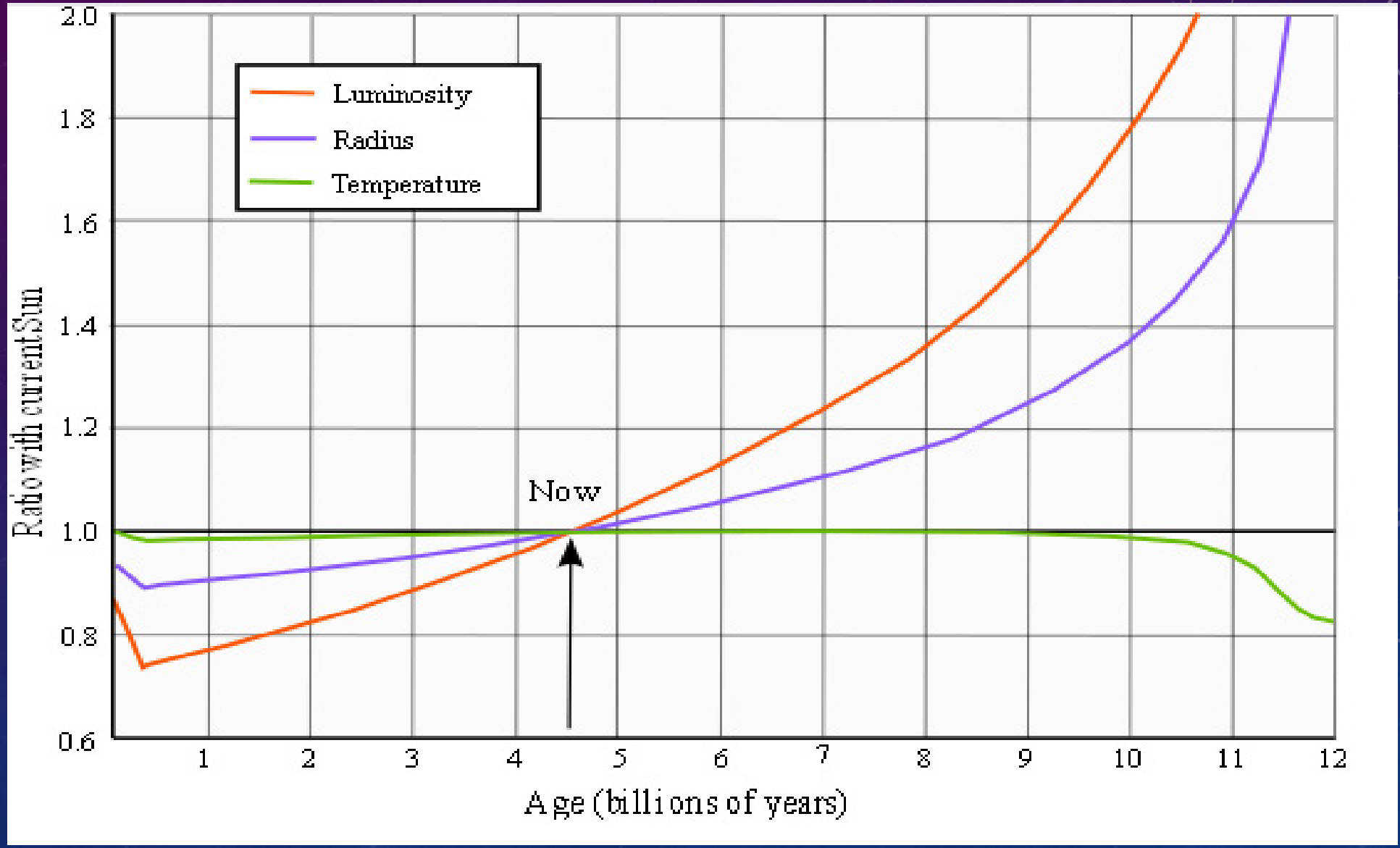
WHENCE OUR N_2 ATMOSPHERE? IT'S 78% OF TODAY'S ATMOSPHERE

- Solar UV broke Ammonia into free N and H, and the H was mostly lost to outer space, **and the N combined to make N2 and enriched the atmosphere**. Also possible volcanoes contributed, giving back nitrogen trapped in the initial condensation of the planet.
- CO2 also richer than today; heavy and most easily retained by gravity.
- Probably NOT enough CO2 to fully account for the weaker sunlight of that era and keep Earth from being frozen, as it was NOT frozen. So need a mix of greenhouse gases it seems.

YOUNG FAINT SUN PARADOX

- The sun, like all stars, increases in luminosity all during its life, until the very late moments before death.
- The sun has increased in luminosity by 30% since shortly after Earth formed, (as the solar core becomes increasingly enriched in denser helium, creating stronger core density and gravity and hence raising the fusion rate.
- All stars do this, converting their potential energy into kinetic, and then into fusion energy, and outgoing luminosity)

THE LUMINOSITY OF THE SUN WAS ALMOST 30% LOWER 4.2 BILLION YEARS AGO, DIM ENOUGH TO FREEZE EARTH



YET WE HAVE GOOD EVIDENCE OF A LIQUID OCEAN GOING BACK TO 4.2 BILLION YEARS AGO

- – almost all the way back to our 4.56 Billion year ago birth, and life almost as far back
- Oceans should have been frozen solid if atmosphere then was like today's, yet weren't.
- **Resolution: Must have had much more greenhouse gas heat trapping in early atmosphere. Can we make this much additional greenhouse effect and be consistent with the evidence?**

HOW DO WE KNOW WHEN THE OCEANS FORMED?

- Banded iron amphibolite formations in **Greenland and Northern Canada which formed 3.8 billion years ago** - can only form in oceans.
- **Pillow Lava formations** date back to 3.8 billion years, only form underwater.
- Even older - Zircon crystals found in Jack Hills, Australia record O18/O16 ratios, which indicate the onset of weathering (e.g. rain and oceans) at **4.2 billion years ago.**
- **So – a liquid ocean! But…**
- …this is a weak constraint on temperature then because we could have had higher atmospheric pressure, and at pressure = 10 bars (10 times the pressure you feel around you now), liquid water can exist up to ~177C = 450K.

MODERN UNDERSEA PILLOW LAVA; PILLOW LAVA DATING FAR BACK ARGUE FOR AN EARL OCEAN

BOULDER FROM A BANDED IRON FORMATION. THESE ONLY FORM IN OCEANS

COULD THE GREENHOUSE WARMING ALL BE FROM CO2? THIS STUDY SAYS - WELL, NOT IMPOSSIBLE. BUT ONLY IF ATMOSPHERIC DENSITY IS MUCH HIGHER TOO. WAS IT? WE'LL SEE…

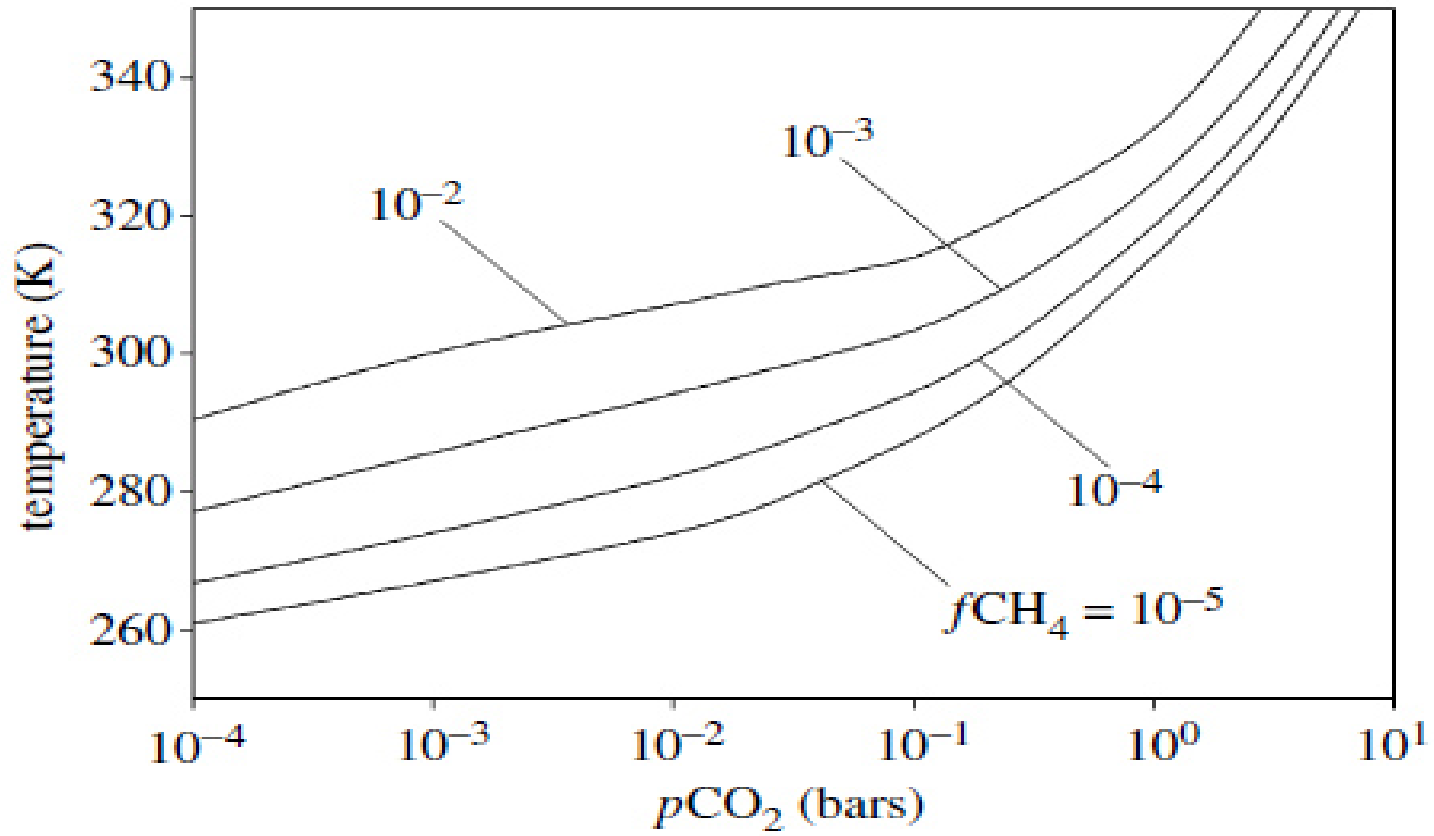


Figure 3. Surface temperature as a function of CO_2 partial pressure and CH_4 mixing ratio. The assumed solar constant was 77% of the present value, which is appropriate for 3.3 Ga. The climate model is from Pavlov *et al.* (2000), with modifications described in the text.

EARLY GREENHOUSE CLUES…

- If we had as high as ~10 bar of CO2 (10x current atmosphere's pressure, and all of it as CO2), this would warm Earth enough to compensate for the low solar luminosity.
- But, this implies rainwater would have a very acidic pH of 3.7, and this high level acidity would cause extremely high rates of chemical weathering, which we do **not** see in ancient rock
- Glaciation ~3 Byrs ago suggests temperatures were more moderate by then.
- Conclusion – temperatures probably much cooler than a "hot house" ~70C

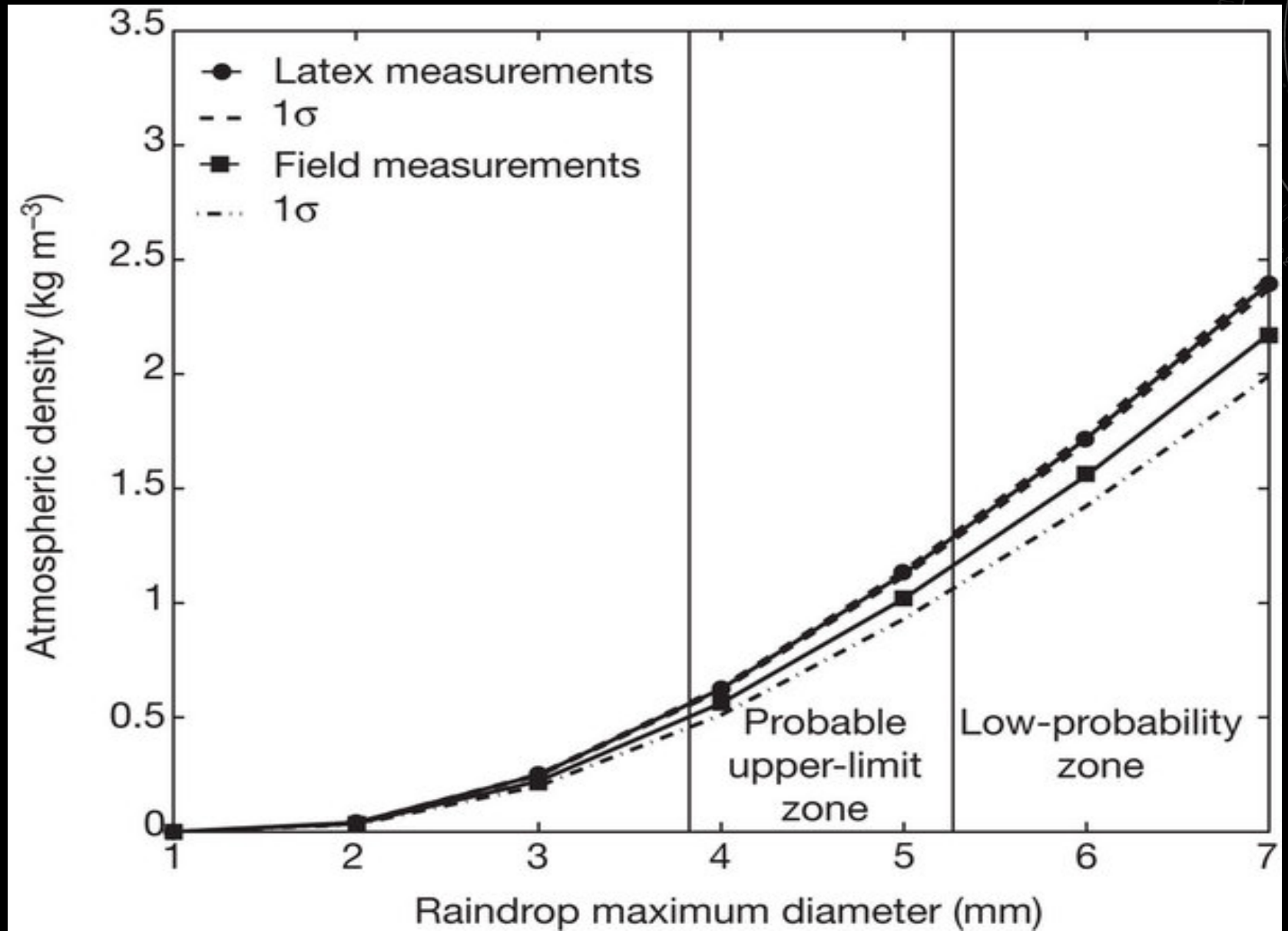
MORE CLUES… CO2 ALONE WON'T WORK AS OUR MAIN GREENHOUSE GAS BACK THEN

- If Earth had same 24hr rotation rate and air pressure, we need an atmosphere of ~28% CO2 to allow the liquid ocean as we know we had.
- But early Earth almost certainly was spinning much faster than this, so soon after planetary collision created the moon, which was much closer to us than today, since subsequent tidal friction has then pushed the moon ¼ million miles away by slowing Earth's rotation.
- The more rapid rotation of Early Earth implies we'd need more like a 100% CO2 atmosphere at today's pressures. Or more. <u>That's way too much to be consistent with evidence…</u>

GEOCHEMICAL ANALYSIS OF WEATHERING SHOWN IN FOSSILIZED ANCIENT SOIL IN MINNESOTA INDICATES WE HAD ONLY ABOUT 1% CO2 ATMOSPHERE DURING THE ARCHEAN ERA, WHICH BEGAN 4.0 BILLION YEARS AGO. NOT 100% CO2!

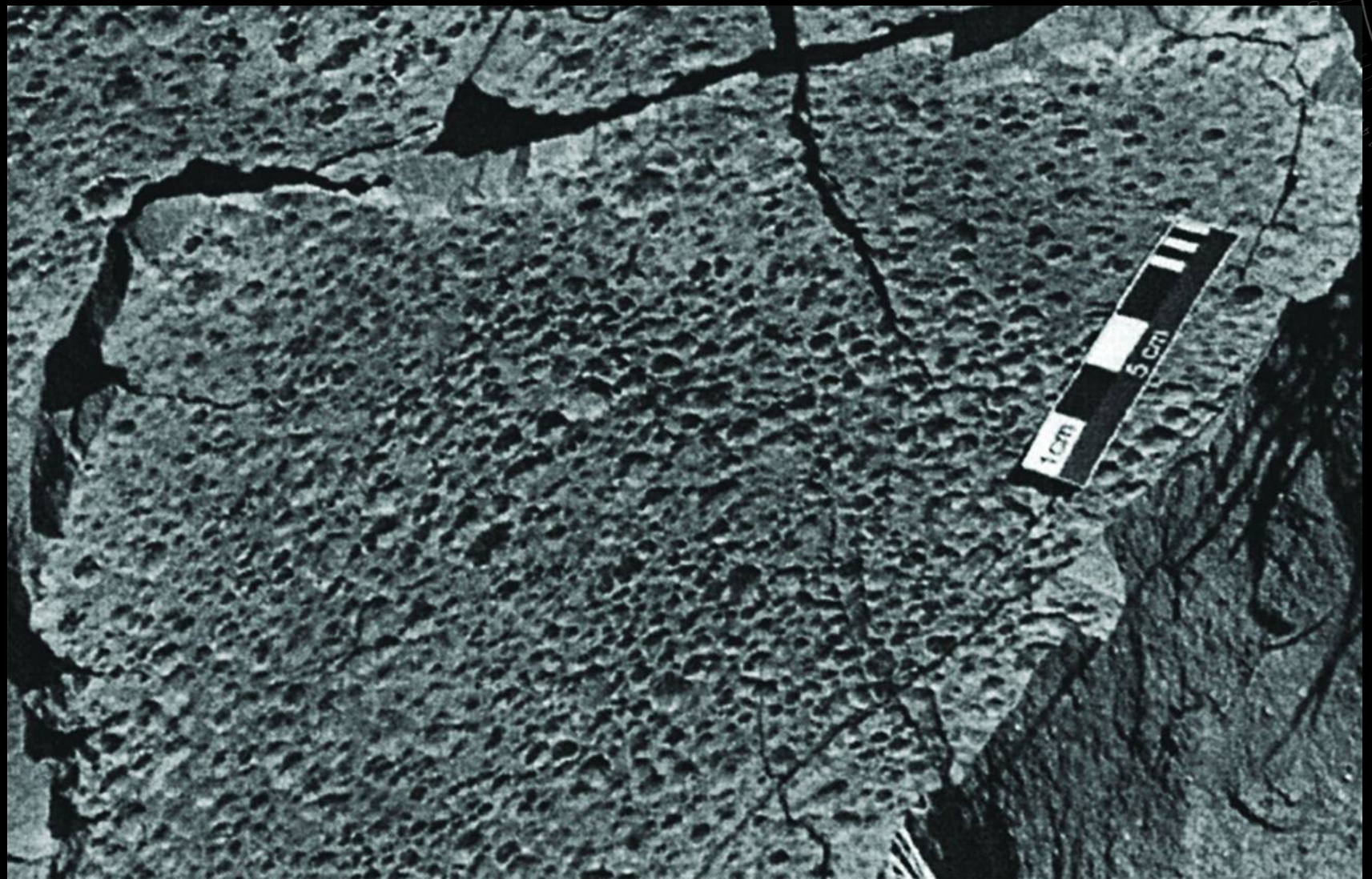
- Weathering pulls CO2 out of the atmosphere.
- So CO2 alone won't work, but methane could – with essentially no oxygen around, methane would be stable and is a ~100x more powerful greenhouse gas than CO2, pound for pound.
- Higher air pressure would help. But here's an ingenious clue - discovery of fossilized raindrops on 2.7 billion year old mud…

RAINDROP IMPRINT DIAMETER *VS.* ATMOSPHERIC DENSITY. DENSER ATMOSPHERE PERMITS BIGGER DROPS, WHICH WILL DROP FASTER UNDER GRAVITY



FOSSILIZED IMPRINTS OF RAINDROPS ON VOLCANIC ASH MUD HELP DETERMINE THE DENSITY OF EARTH'S ATMOSPHERE 2.7 B YEARS AGO: NO MORE THAN 2X TODAY'S (S.M. SOM *ET AL.* NATURE 2012)

FOSSILIZED RAINDROP IMPRINTS: 2.7 BILLION YEARS AGO



LATE CAMBRIAN (0.5 B YRS AGO) FOSSILIZED RAINDROP IMPRINTS, SIMILAR IN SIZE TO 2.7 B YEARS AGO. IMPLIES SIMILAR ATMOSPHERIC DENSITY. BUT WE KNOW THE DENSITY AT 0.5 BILLION YEARS AGO WAS SIMILAR TO TODAY. SO HIGH ATMOSPHERE PRESSURE LOOKS UNLIKELY

WORKING SOME PHYSICS ON THE RAINDROPS IMPLIES AIR PRESSURE, DENSITY BACK THEN WAS SIMILAR TO TODAY'S

The Mechanism: Higher density atmosphere permits bigger raindrops due to surface tension considerations, and bigger drops fall faster under gravity, making bigger imprints, which we don't see.

- But 2.7 B years ago the sun was 19% less luminous than today's. So if atmosphere is similar density, still need significant greenhouse to explain unfrozen Earth.
- Adding more greenhouse effect from methane and NH molecule might be enough, but we're not sure of the final answer as yet.

BLATTLER *ET AL.* (2016) IMPROVE CONSTRAINTS AND AGREES: ~LOW CO2 2-3 BILLION YRS AGO. ROUGHLY 1% OF OUR ATMOSPHERE

ARTICLES NATURE GEOSCIENCE DOI: 10.1038/NGEO2844

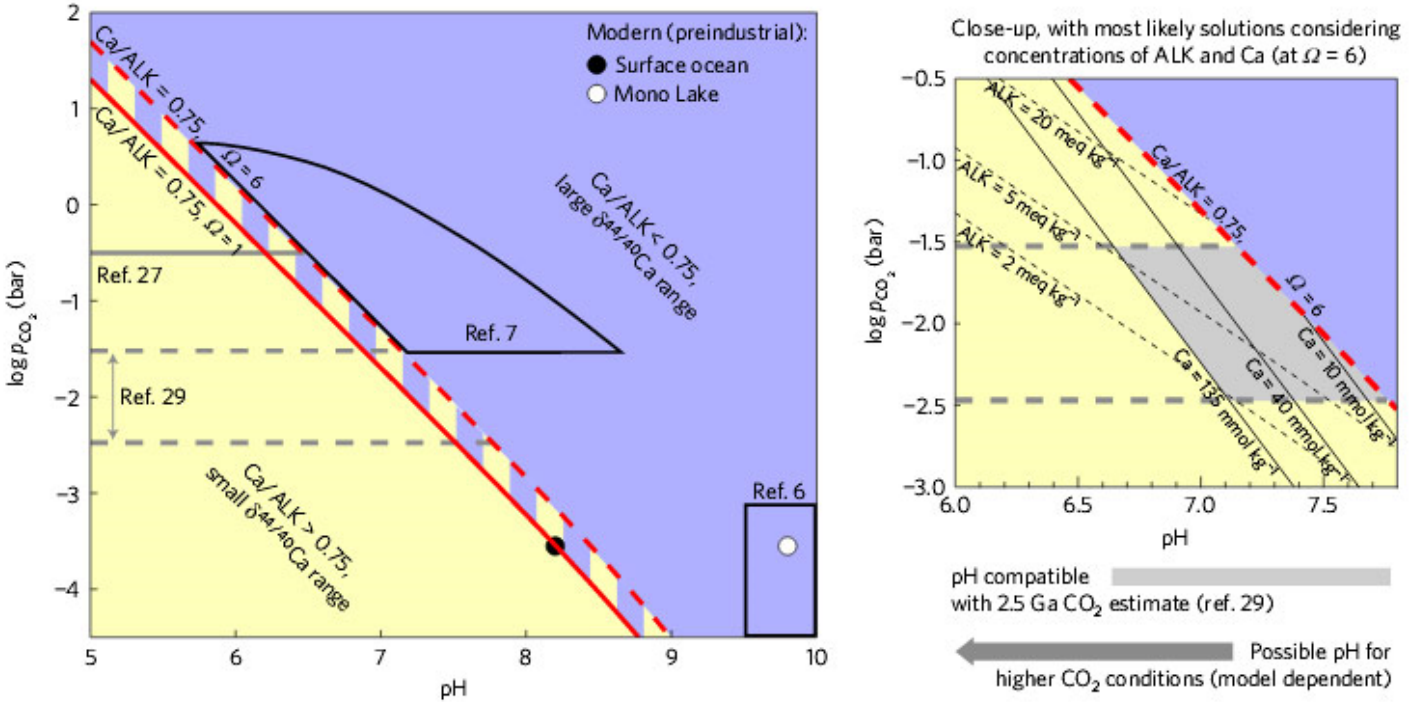


Figure 3 | Equilibrium carbonate chemistry solutions in p_{CO_2}–pH space, divided by the calcium isotope constraint that Ca/ALK > 0.75. Permissible solutions are shown in yellow; the blue region is inconsistent with data from this study. Uncertainty in the boundary between these regions from assuming different calcite saturation states is reflected in the striped zone between the solutions for Ca/ALK = 0.75 at $\Omega = 1$ and $\Omega = 6$. Black outlines indicate preferred solution spaces from previous work. Grey horizontal lines show various estimates for p_{CO_2}: solid line is a model result[27] for obtaining a mean surface temperature of 288 K (compatible with a mostly ice-free Archaean) at 2.5 Ga with increased CO_2 alone; dashed grey lines reflect upper and lower limits on p_{CO_2} estimated from a 2.5-Ga palaeosol[29]. The close-up view shows contours of ALK and Ca concentration at $\Omega = 6$, with a reasonable upper limit on Ca (see Supplemental Methods) used to further define the likely solution space.

CURRENTLY, THE MOST LIKELY EXPLANATION FOR THE WARM TEMPS YET COLDER SUN BACK 4.2 BYRS AGO…

- **Is higher greenhouse warming** due to …

- 1. Lots of primordial **methane (CH4)** which would be stable given lack of free atmospheric oxygen during first ~billion years of Earth. Methane ~100x greenhouse power as CO2, pound for pound. Methane doesn't leave easy "fingerprints" to help us, though, so it's a guess.
- 2. Some **CO2**, which is a tough, stable molecule, about 40x pre-industrial levels (or 1.2% if atmosphere density then is same as today)
- N_2 at ~2x today's level (i.e. atmosphere twice as dense) will help GHG's widen absorption bands and increase GH effect. (pressure broadening of spectral lines)
- All this is comfortably within observational limits, it'll all work to explain. But, **too much** CO_2 will conflict with weathering data, as does too much N_2
- Minor effect: Possible to also allow the Earth to be a little closer to the sun w/o violating astronomical observations, but not a whole lot.
- H_2O and higher ammonia will also add to greenhouse effect, although they can't add a lot *vs.* today because water rains out, and ammonia wouldn't survive long in the early atmosphere.
- No big contradictions here, just sparse data and awaiting better data for the precise greenhouse atmosphere we had.

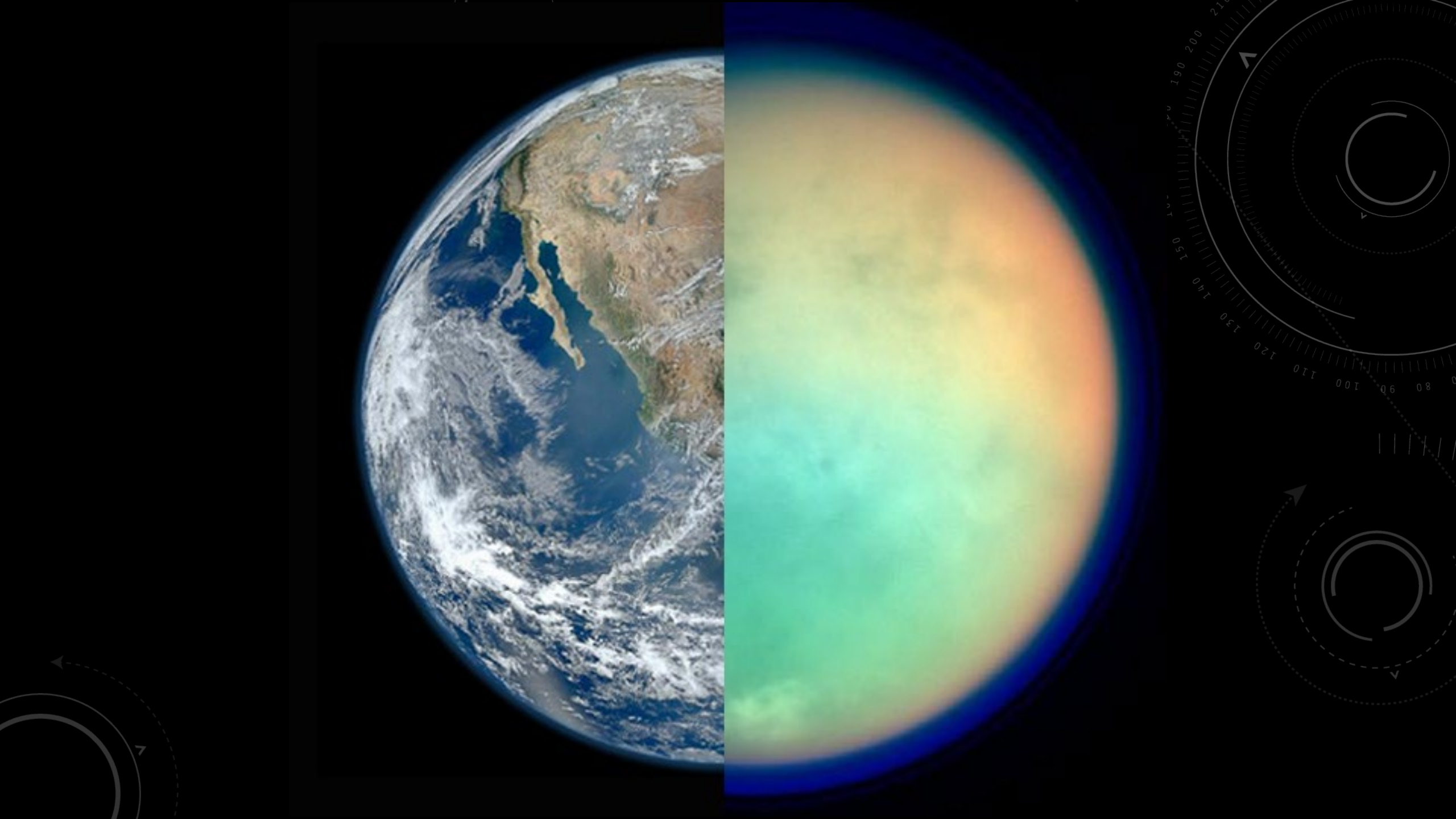
- Nice summary here

2.7-2.9 BILLION YEARS AGO: OLDEST EVIDENCE FOR GLACIERS

- Young *et al.* (1998) and here
- Glaciers push ALL debris regardless of size or mass. So, characteristic glacial deposits are an unsorted mix of all sizes of rocks and sand.
- Such deposits, in a laminated matrix of mudstone is interpreted as ice-rafted glacial debris melted and deposited onto lake/ocean floor sediments.
- We see such deposits 2.9 and 2.75 B yrs ago
- Therefore, Earth temps must have been not too different than today's, with higher greenhouse and dimmer sun to allow it to be this cold

2.6-2.5 BYRS AGO: UNSTABLE SWINGS IN COMPOSITION: METHANE HAZE TO OXYGEN CLEAR

- This is suggested by isotope ratios of sulfur and carbon in rocks in a South African formation, showing microbial mats which produced oxygen.
- Could be why pinning down the composition at this time is hard – it transitioned, depending on methane production by early microbes
- From Titan-like haze, to clean up oxygen-rich skies, and back and forth for 100-200 million years, then permanently to oxygen clear skies thereafter
- See **story, Zerkle *et al.* 2012**
- **Methane, again, is a very powerful greenhouse gas**



FROM NATIONAL GEO ARTICLE ON ZERKLE *ET AL.* 2012 PAPER ON THIS

- “Core samples from these rocks contain microbial mats, which show that some of the tiny creatures in shallow seas were producing oxygen long before the Great Oxygenation of our atmosphere.
- The rocks also contain carbon and sulfur isotopes—chemicals that would have reacted with oxygen. The levels of the different kinds of isotopes present indicate that sometimes oxygen production was happening when the atmosphere was thick with methane—but other times the atmosphere must have been free of methane haze.
- Methane and oxygen won’t co-exist in the atmosphere for long, since methane oxidizes to CO2 and H2O.
- The clarity of the early atmosphere seems to flip flop roughly every few million years, Zerkle *et al.* report, hinting at a push and pull between microbes that generated oxygen and those that belched methane.”

OXYGEN CONCENTRATION WAS LOW, AND RISING THROUGH EARTH'S HISTORY. THE GEOLOGICAL EVIDENCE…

- Iron (Fe) is extremely reactive with oxygen. If we look at the oxidation state of Fe in the rock record, we can infer a great deal about atmospheric oxygen evolution.
- **Archean Period** - Find occurrence of minerals that only form in non-oxidizing environments in Archean sediments: Pyrite (Fools gold; FeS_2), Uraninite (UO_2). These minerals are easily dissolved out of rocks under present (high oxygen) atmospheric conditions.
- ***Banded Iron Formation (BIF)*** - Deep water deposits in which layers of iron-rich minerals alternate with iron-poor layers, primarily chert. Iron minerals include iron oxide, iron carbonate, iron silicate, iron sulfide. BIF's are a major source of iron ore, as they contain magnetite (Fe_3O_4) which has a lower oxygen-to-iron ratio than hematite. These are common in rocks 2.0 - 2.8 B.y. old, but do not form in today's high oxygen environment.
- ***Red beds*** (continental siliciclastic deposits) are never found in rocks older than 2.3 billion years ago, but are common during Phanerozoic (relatively recent) time. Red beds are red because of the highly oxidized mineral hematite (Fe_2O_3), that probably forms secondarily by oxidation of other Fe minerals that have accumulated in the sediment.

MORE EVIDENCE FOR A LOW OXYGEN ATMOSPHERE: BIOLOGICAL

- **Chemical building blocks of life could not have formed in the presence of atmospheric oxygen**. Chemical reactions that yield amino acids **outside of cells** are inhibited by presence of even very small amounts of oxygen – which is extremely reactive (we love anti-oxidants in our food!).
- Oxygen prevents growth of the most primitive living bacteria such as photosynthetic bacteria, methane-producing bacteria and bacteria that derive energy from fermentation.
- Since today's most primitive life forms are anaerobic, the guess is that the first forms of cellular life probably had similar metabolisms.
- Today these *anaerobic* life forms are restricted to anoxic (low oxygen) habitats such as swamps, ponds, and lagoons.

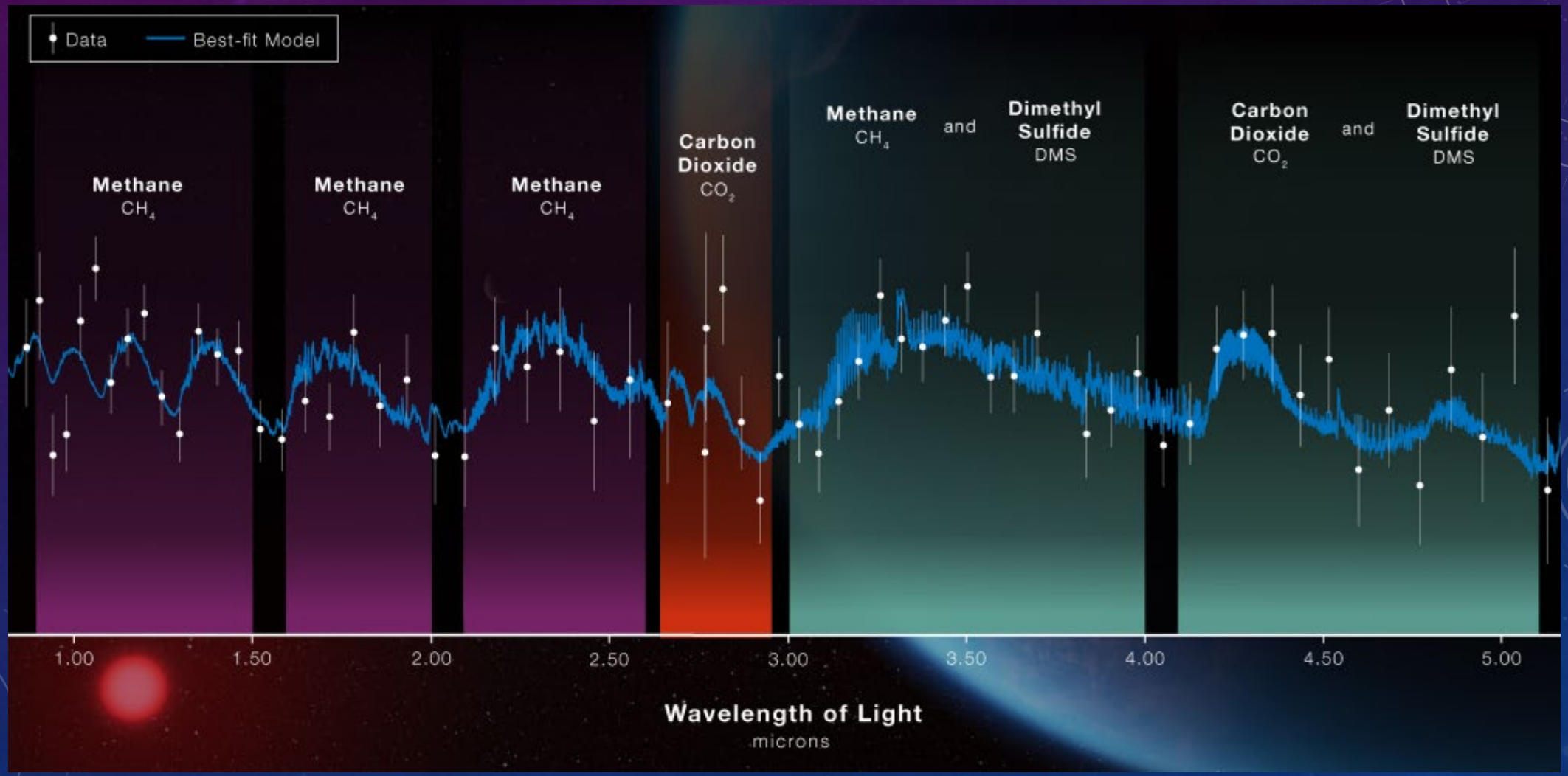
METHANE AS A SIGNATURE OF LIFE

- Primitive organisms on Earth respirate carbon from CO_2 and, w/o oxygen present, instead the respirated C bonds with hydrogen, making CH_4: Methane!
- In 2023, the James Webb Telescope is finding methane and CO_2 on an exoplanet which seems in excess of what can be explained by a-biotic processes….

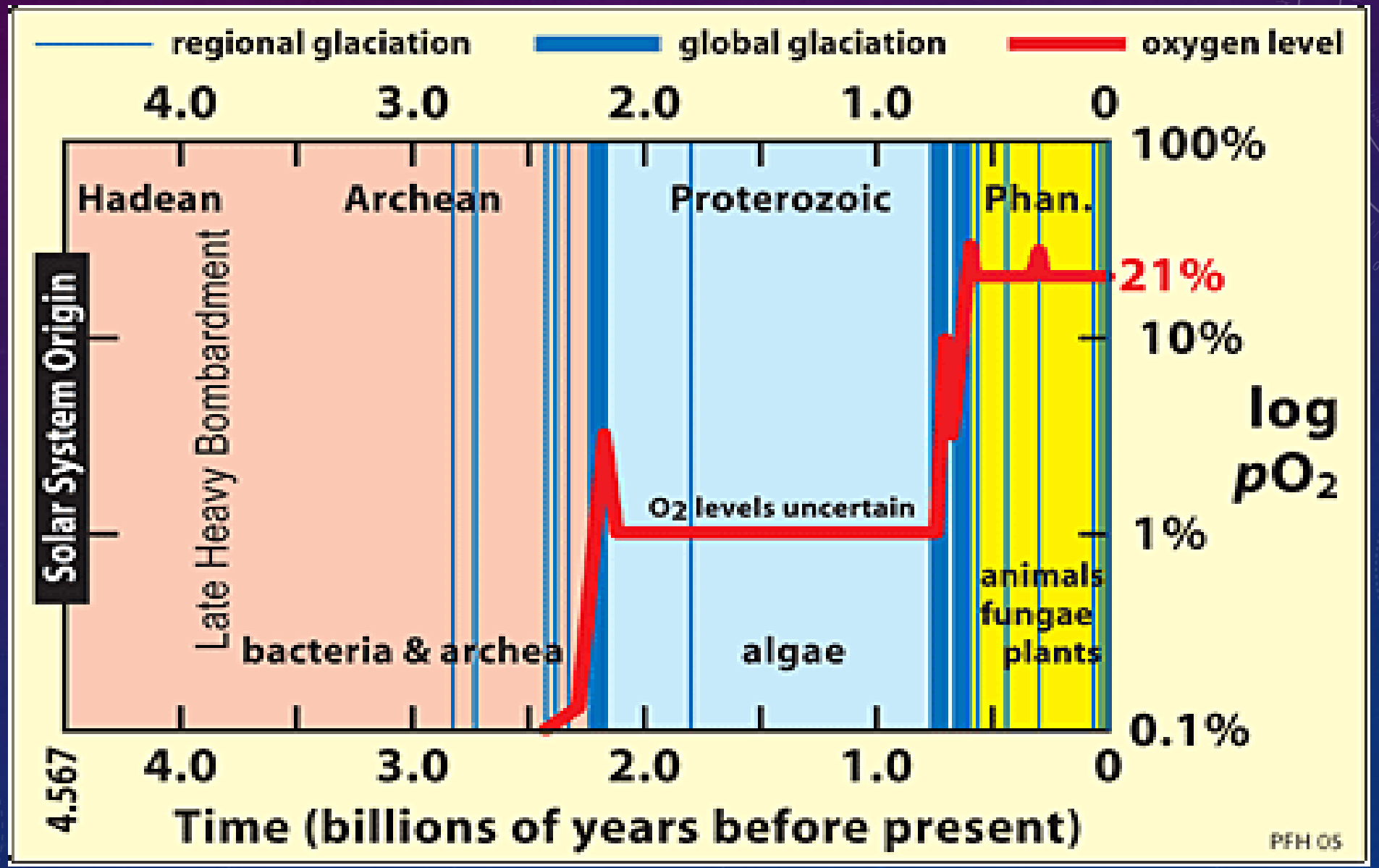
"ASSESSING THE HABITABILITY OF EXOPLANETS WITH JWST" -

- Link : https://physics.aps.org/articles/v16/178
- *"On Earth that something is predominantly life. Nearly all of Earth's methane is biogenic—it was produced either directly by a living thing (mostly as a by-product of animal digestion) or indirectly by the decay of organic matter.*
- *"But methane also belches from volcanoes, outgasses during chemical reactions within rocks, and appears after a comet or asteroid impact. Thus, methane alone is not enough to claim a planet hosts life.*
- *Thompson and her colleagues have, however, investigated mixtures of methane and other gases that might be harder to explain with geochemistry alone.*
- *"They found that a potential biosignature would be an upper atmosphere containing methane and carbon dioxide, but no oxygen or hydrogen, and little or no carbon monoxide [3]. Models indicate that such a gas combination can arise when a planet's methane originates on its surface, where scientists think life will reside.*

THE TRANSMISSION SPECTRUM FOR K2-18b: Shows strong evidence of CO2 and methane, weaker evidence for DMS, though.



STUDIES SUGGEST OXYGEN AT ONLY 1% OF OUR ATMOSPHERE OR LESS, UNTIL ~700M YRS AGO, ALLOWING THE "CAMBRIAN EXPLOSION" OF LIFE TO TRANSFORM EARTH. WE STILL HAVE ONLY SINGLE-CELLED LIFE RIGHT UP TO ONLY ABOUT 600 MILLION YEARS AGO.



WITHOUT AN OZONE LAYER, YOU CANNOT HAVE LIFE ON LAND… SOLAR UV IS TOO DEADLY

- Life remained strictly in the ocean until enough oxygen could be generated by early photosynthetic life to create enough oxygen to high enough density to create ozone, which will absorb most of the sun's UV light while heating the upper stratosphere.
- This new zone for absorbing solar heating also then creates a new layer in the atmosphere – the stratosphere, defined by the fact that air temperatures go UP as you rise through the stratosphere (to where the UV is absorbed).
- This then prevents convection from the lower atmosphere from rising into the stratosphere. Good! This permits water to remain in the lower atmosphere where it's safe from the "runaway greenhouse" or destruction by solar UV.

BY THE WAY, NO LIFE ON LAND? NO INTELLIGENT LIFE!

- We'll argue that later
- This isn't just a put-down on dolphins and whales!

WHY DID IT TAKE SO LONG FOR OXYGEN LEVELS TO RISE?

- The ocean chemistry explanation is complex, but **Scott *et al.* 2013** find that molybdenum, essential for life, was very rare in these ancient ocean sediments, as was oxygen, halting the evolution of complex oxygen-using life for as long as 2 billion additional years.
- Wondering out loud, am I here… being a heavy element, is it far more typical that is not just rare, but unavailable entirely on many otherwise promising planets out there, having sunk into the inner Earth soon after formation

MOLYBDENUM - TURNS OUT IT IS ESSENTIAL FOR LIFE!

- *“Quite extraordinarily molybdenum is an essential element in life for the uptake of nitrogen from both nitrogen gas and nitrate, yet it is a relatively rare heavy trace element. It also functions in a few extremely important oxygen-atom transfer reactions at low redox potential. This review poses the question "Why does life depend upon molybdenum?" The answer has to be based upon the availability of the element and on chemical superiority in carrying out the essential tasks. We illustrate here the peculiarities of molybdenum chemistry and how they have become part of certain enzymes. The uptake and incorporation of molybdenum are dependent on its availability, selective pumps, and carriers (chaperones), but 4.5 x 10(9) years ago molybdenum was not available when both tungsten and vanadium or even iron were possibly used in its place. While these possibilities are explored, they leave many unanswered questions concerning the selection today of molybdenum.” (Abstract from Williams and Frausto de Silva 2002)*

YET VANADIUM “PERFORMS POORLY” AS A SUBSTITUTE FOR MOLYBDENUM

- ***Why vanadium complexes perform poorly in comparison to related molybdenum complexes in the catalytic reduction of dinitrogen to ammonia (Schrock cycle): a theoretical study (Guha and Phukan 2012)***

WATER… IT'S PECULIAR AND RARE FLUID PROPERTY OF GETTING LESS DENSE AS IT COOLS AND JUST BEFORE IT FREEZES, IS ESSENTIAL FOR A LIVING PLANET

- **Consider our episodes of "Snowball Earth"!**

“<u>SNOWBALL EARTH</u>” 2.2B YRS AGO. EVIDENCE – GLACIAL DEPOSIT STRATA WHICH WERE ESTIMATED TO BE AT THE EQUATOR THROUGH MAGNETIC FIELD ORIENTATION (AND TECTONIC MOTION STUDIES).

SCHRAG AND HOFFMAN (BOTH HARVARD) IN NAMIBIA, AFRICA. EVIDENCE FOR SNOWBALL EARTH 700 MILLION YEARS AGO; ICE-RAFTED SHALLOW OCEANIC GLACIAL DEPOSIT LAYER POOR IN CARBONATES, FOLLOWED (LAYER ABOVE) OF CARBONATE-RICH GLACIAL-FREE SEDIMENTS, AFTER CO2 RETURNED TO THE ATMOSPHERE

OTHER EVIDENCE FOR WIDESPREAD FROZEN OCEAN AND CONTINENTS…

- …is here
- **My summary of that source**:

-- Glacial deposits show on shallow ocean bottom in these areas, indicating glaciers dumped right into the oceans, and this was again at ~the equator. If it's that cold at sea level at the equator, strongly suggests it is frozen EVERYwhere.

-- Banded iron formations found exclusively in glacial marine strata after 1.9B yrs ago, indicating widespread anoxia (consistent with an ice-covered ocean unable to communicate with the atmosphere) and an increase in the ratio of Fe to S entering the ocean (consistent with ice-covered continents).

-- Deep flooding of previously shallow-water shelves and platforms after the Sturtian and Marinoan meltdowns, sustained after isostatic re-adjustments, reflecting slow tectonic subsidence over millions of years under the ice.

Conclusion: Equatorial ocean glacial deposits say ice existed on the ocean itself; the continental glaciers pushed their moraines and boulder-strewn debris down to sea-level and out onto the ocean as an ice shelf, until it eventually melted (see following slides)

So "SnowBall Earth" Looks Real

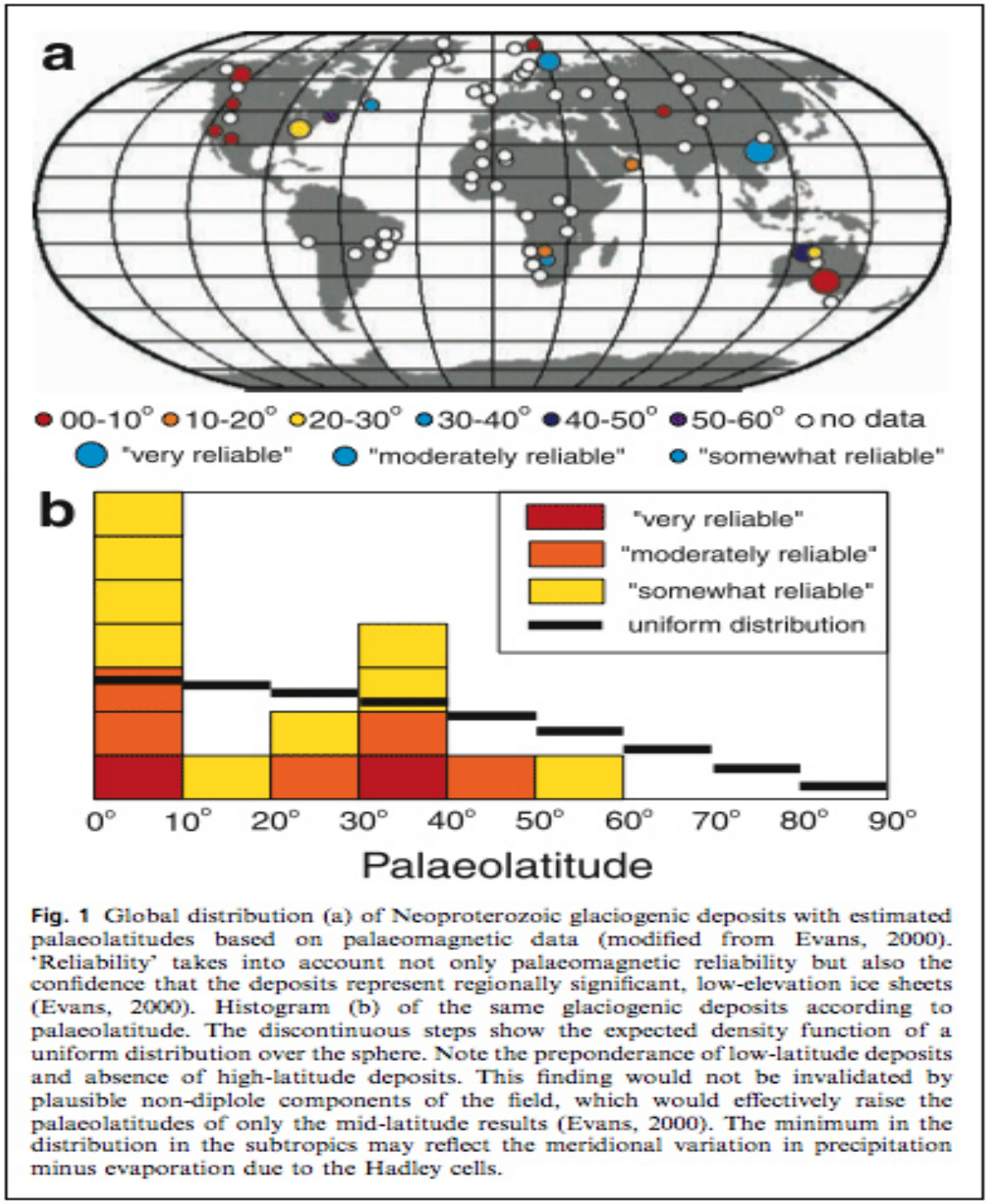


Fig. 1 Global distribution (a) of Neoproterozoic glaciogenic deposits with estimated palaeolatitudes based on palaeomagnetic data (modified from Evans, 2000). 'Reliability' takes into account not only palaeomagnetic reliability but also the confidence that the deposits represent regionally significant, low-elevation ice sheets (Evans, 2000). Histogram (b) of the same glaciogenic deposits according to palaeolatitude. The discontinuous steps show the expected density function of a uniform distribution over the sphere. Note the preponderance of low-latitude deposits and absence of high-latitude deposits. This finding would not be invalidated by plausible non-diplole components of the field, which would effectively raise the palaeolatitudes of only the mid-latitude results (Evans, 2000). The minimum in the distribution in the subtropics may reflect the meridional variation in precipitation minus evaporation due to the Hadley cells.

MANY SITES AROUND EARTH SHOW GLACIAL DEPOSITS WHEN THOSE SITES WERE TROPICAL.

GLACIAL DEPOSITS IN SHALLOW EQUATORIAL OCEAN FLOOR ADJACENT TO CONTINENTS INDICATES GLACIERS AT SEA LEVEL AND ICE-COVERED OCEAN OFF-SHORE.

ALTERNATIVE EXPLANATIONS (WIDELY VARYING OBLIQUITY OF AXIS, OR SATURN-LIKE RINGS) ARE *AD HOC* AND CONFLICT WITH ASTRONOMICAL THEORY!

WHY DIDN'T WE STAY IN SNOWBALL EARTH?

- After all, this is a pure white globe now, reflecting most sunlight, which is much weaker than today's sunlight as well.
- Amplifying feedback of whitening glaciating Earth would just make it cooler and cooler.
- So why didn't we **stay** frozen?
- The **Walker *et al.* (1981) mechanism**, elaborated by Richard Alley - let's call it the **Walker/Alley mechanism**

LIQUID OCEANS ENFORCED BY THE WALKER/ALLEY MECHANISM

- When the ocean surfaces are frozen everywhere, they have a cap of ice which cuts off communication across that cap.
- Therefore, the atmosphere can no longer transmit CO2 to the cold oceans and the carbon cycle is halted
- Meanwhile, volcanoes don't care at all about ice and surface temperatures, and continue to erupt, injecting (at today's rate), about 300 million tons of CO2 per year into the atmosphere, which now has nowhere to go thanks to impenetrable ice-capped oceans
- Greenhouse heating therefore increases… until finally the ocean surface melts, allowing CO2 to diffuse once again into the oceans, so the long carbon cycle resumes

THIS IS THE ONLY MECHANISM WE HAVE FOUND…

- …which explains how the oceans are forced to melt if they become globally frozen.
- “Snowball Earth” phases would therefore be geologically brief, because within a few million years or less the volcanic CO2 injection would be plenty enough to melt the equatorial oceans.
- Indeed, we only see a two or three “Snowball Earth” phases in the time lines we just saw
- The last 2 was at 600-700 million years ago.

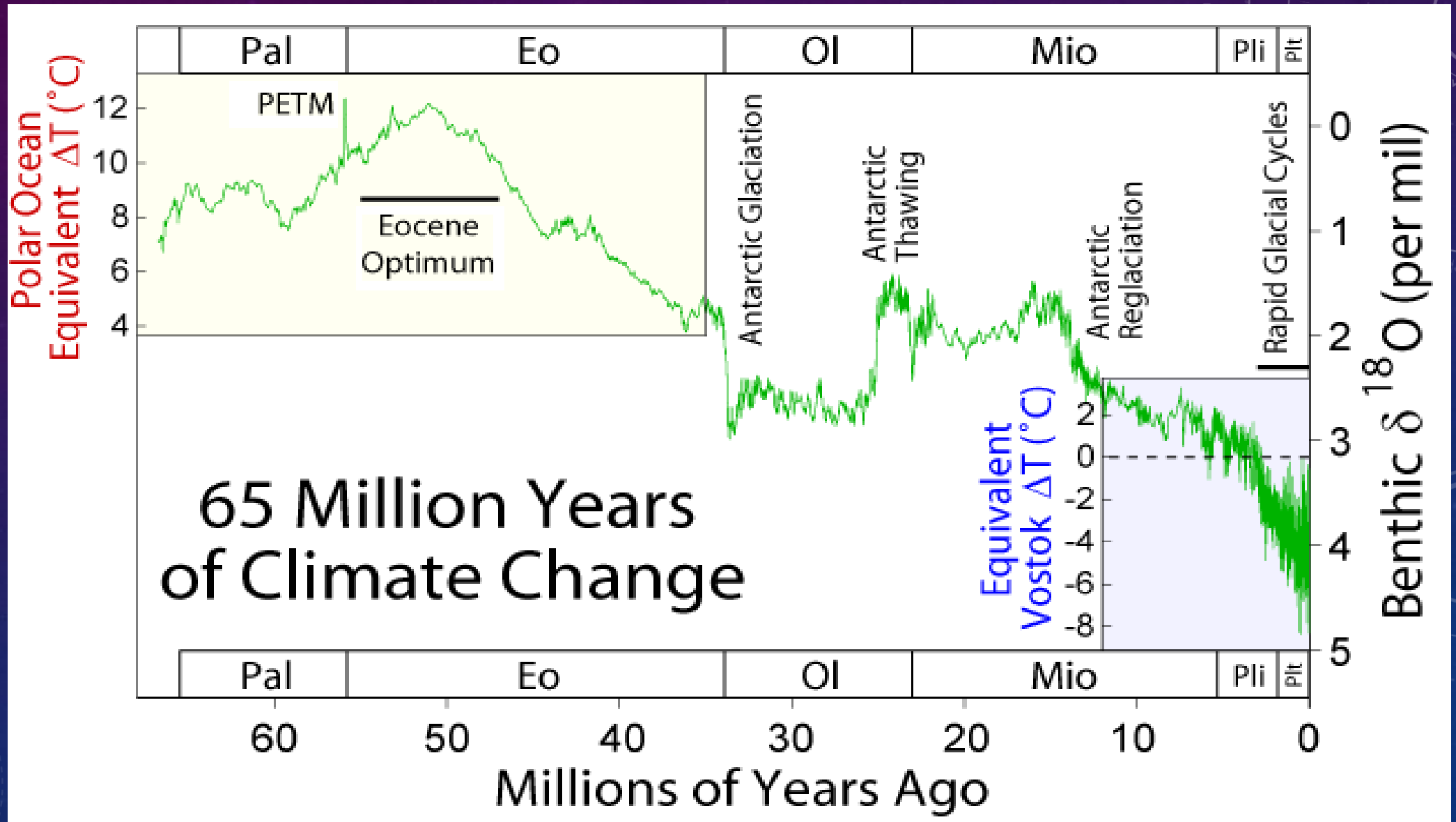
CO_2 AND METHANE – LIFE PLAYS A MAJOR ROLE IN GREENHOUSE GAS LEVELS

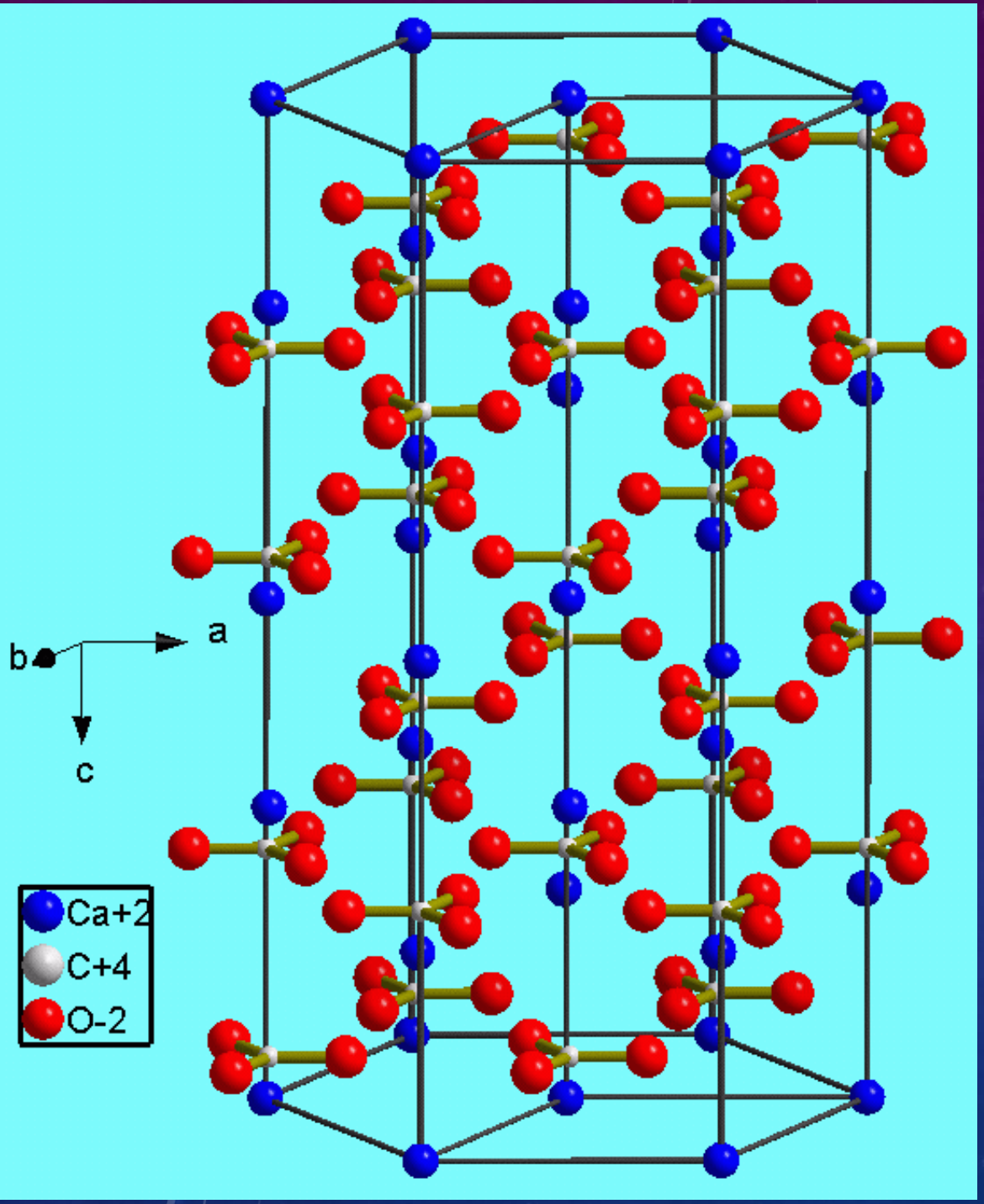
- It's believed the nitrogen composition hasn't changed much over the history of the Earth, after very early ammonia-rich atmosphere ended
- It's CO_2 and methane which have changed greatly
- Evidence – these are powerful greenhouse gases, needed to account for relatively warm Earth when sun was only 25-30% less luminous
- Absolute amounts are poorly determined however.
- Still, **why did CO_2 and methane concentrations drop so much? Life!**

OCEAN LIFE TRANSFORMED OUR ATMOSPHERE FROM CO2-RICH, TO CO2-POOR, VIA THE "SLOW CARBON CYCLE"

- CO2 will dissolve into raindrops, forming carbonic acid, falling on rocks (chem weathering) and then into the rivers and oceans. Then…
- Calcium + dissolved CO2 in the ocean was used by forams and other sea animals to produce CaCO3 = calcium carbonate as a protective shell or skeletal material.
- When they die, they carry that CaCO3 to the ocean bottom where it is eventually subducted into the mantel.
- Only SOME of CO2 is recycled by outgasing tectonic volcanoes. The rest remains in the mantle

TEMPERATURE PROXY O_{18}/O_{16} RATIO SHOWS DROPPING TEMPERATURES GO WITH DROPPING CO2, OVER PAST 65 MILLION YEARS





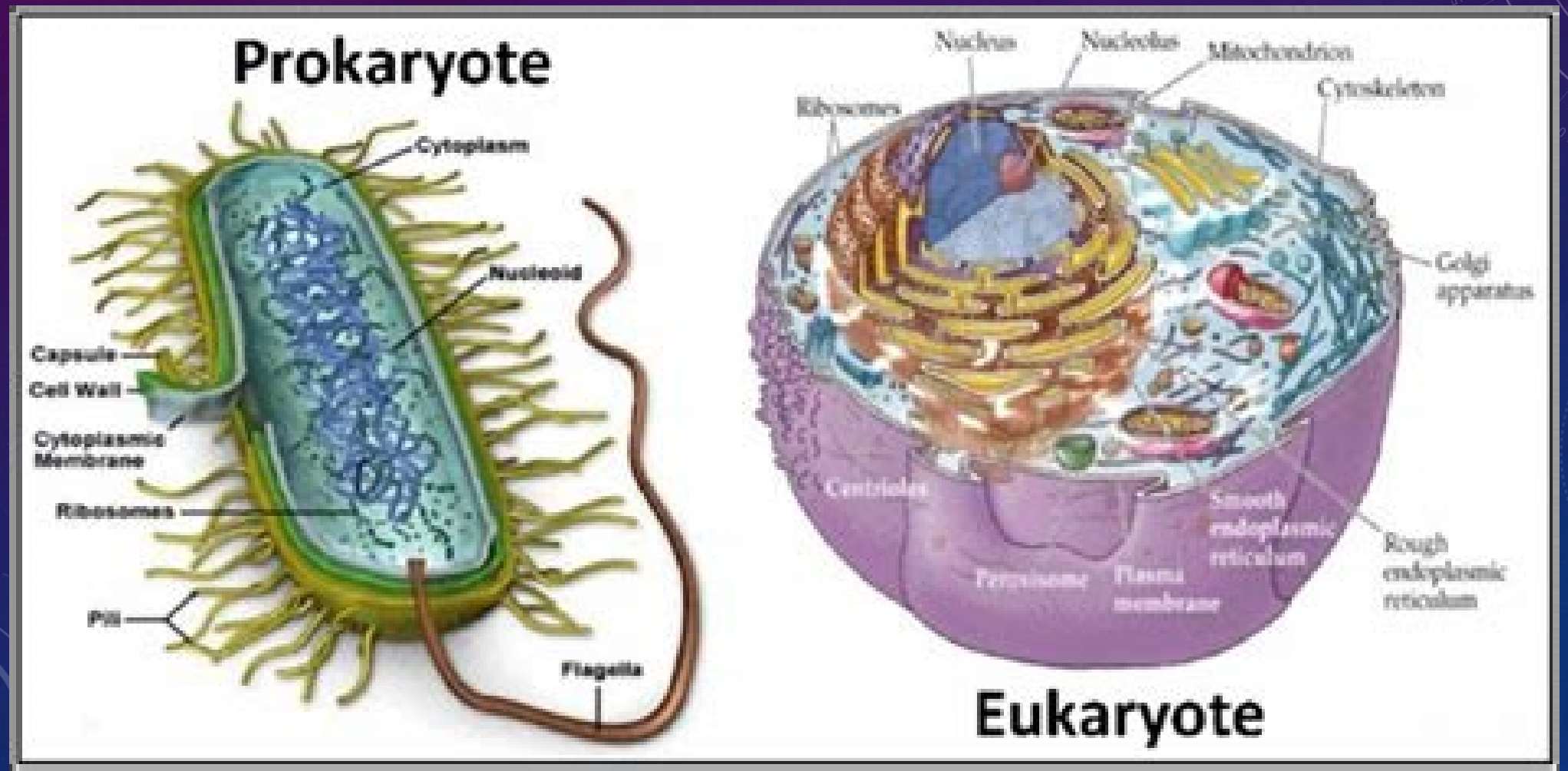
CALCITE *VS.* ARAGONITE

- The most stable form of CaCO3 is calcite. Some clams use this.
- It's the other form – aragonite - which is most common but most fragile in an ocean where the alkalinity is dropping, such as today. Corals, most phytoplankton, use aragonite.

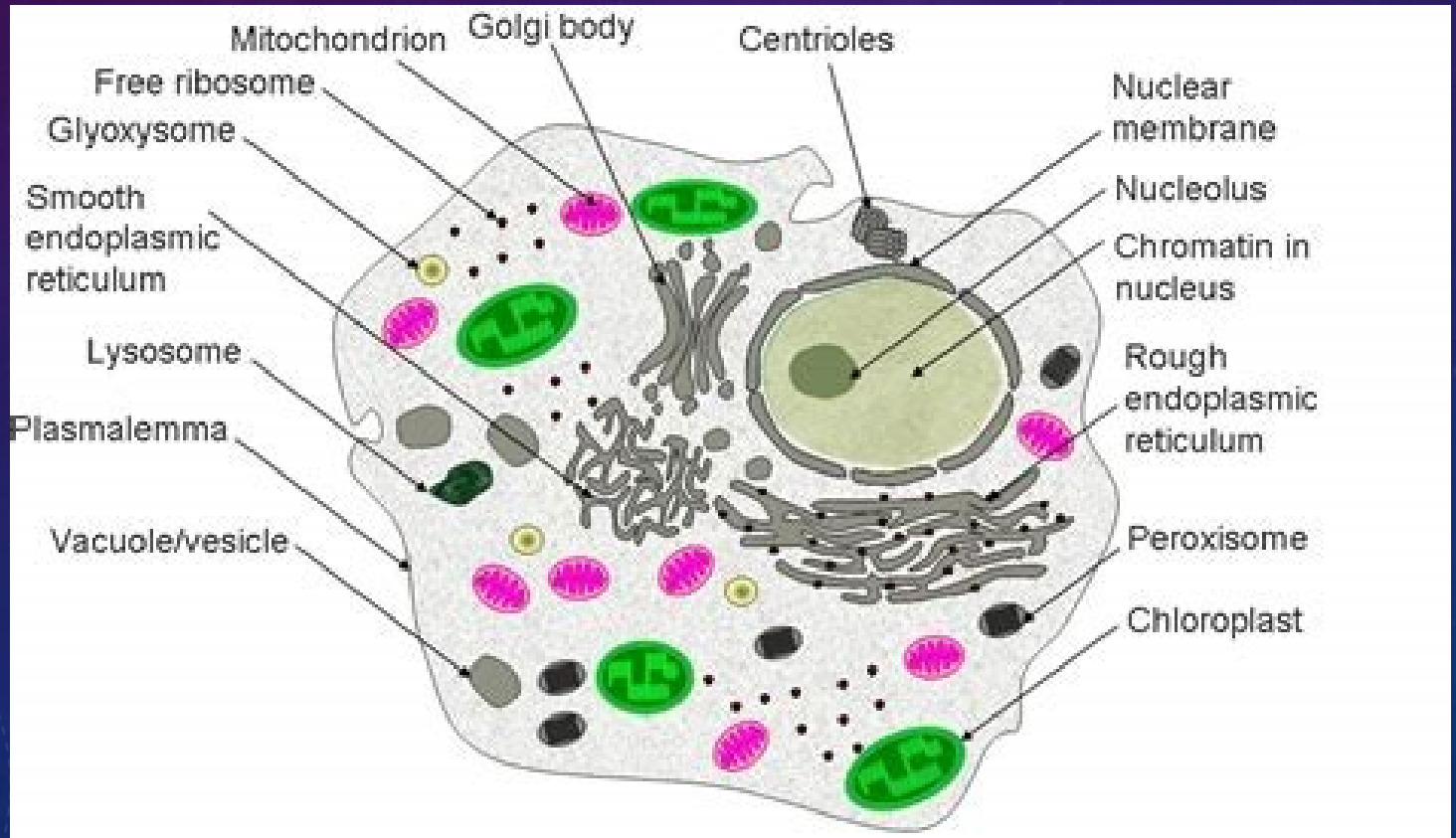
THUS: NET LOSS OF CO_2 FROM ATMOSPHERE AND INTO THE MANTLE: FALLING ATMOSPHERIC CO_2 OVER GEOLOGIC TIME SCALES

- The lowered CO_2 level in the ocean then pulls CO_2 out of the atmosphere to try to re-attain equilibrium.
- Result: Falling atmospheric CO_2 levels over geologic time.
- There can be other processes that come in, but we expect (and see) that over the billion year time scales, CO_2 has indeed been on a downward path on Earth.

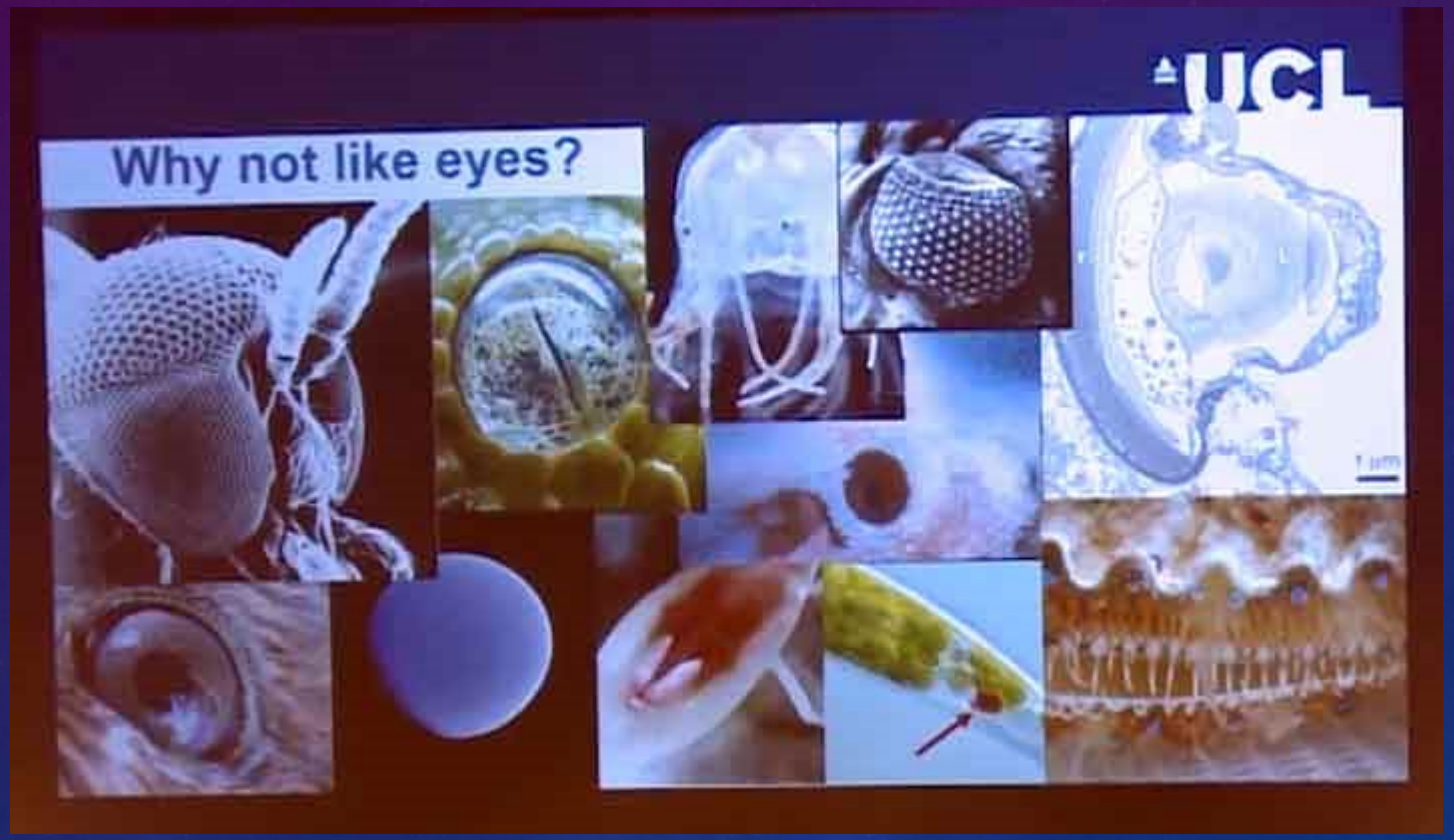
PRO-KARYOTES *VS.* EU-KARYOTES. MAJOR INCREASE IN COMPLEXITY AND ADAPTABILITY. CELL MEMBRANES PERMIT NETWORK DEVELOPMENT (LATER LECTURE ON THAT) SUPPORTING LARGE ANIMALS AND PLANTS. PROKARYOTE STRUCTURE PERMITS ONLY SINGLE CELL SMALL ORGANISMS



ALL OF THESE LIFE FORMS ARE EUKARYOTES… MULTI-CELLULAR LIFE WITH CELL NUCLEI BOUNDED BY MEMBRANES CONTAINING DNA, REPRODUCING SEXUALLY, WITH MITOCHONDRIA POWERING THEIR HIGH ENERGY LIVES. ITS EXTREMELY SUCCESSFUL, AND ADAPTABLE.

- 

TRAITS WHICH ARE USEFUL TO AN ORGANISM – UNIVERSALLY USEFUL LIKE EUKARYOTIC CHARACTERISTICS – TEND TO SHOW "CONVERGENT EVOLUTION"



- Example: Eyes – they arose essentially independently across widely divergent species many dozens of times (Nick Lane's excellent talk, 11 minutes in).

BUT EUKARYOTES AROSE ONLY ONCE, IN 4 BILLION YEARS OF EVOLUTION.

- Genetic variation through sex is extremely adaptable without as much chance of killing the organism as one gets by cosmic rays or radioactivity induced changes in DNA. Two compatible adaptable adult members mix their clearly already ~successful gametes to make a new and potentially even better adapted progeny.
- One would think this would evolve independently in bacteria and archaea or at least independently in widely differing species before the eukaryotic change happened.
- Does this mean the circumstances of its creation were extremely unlikely? Some evolutionary biologists think so.

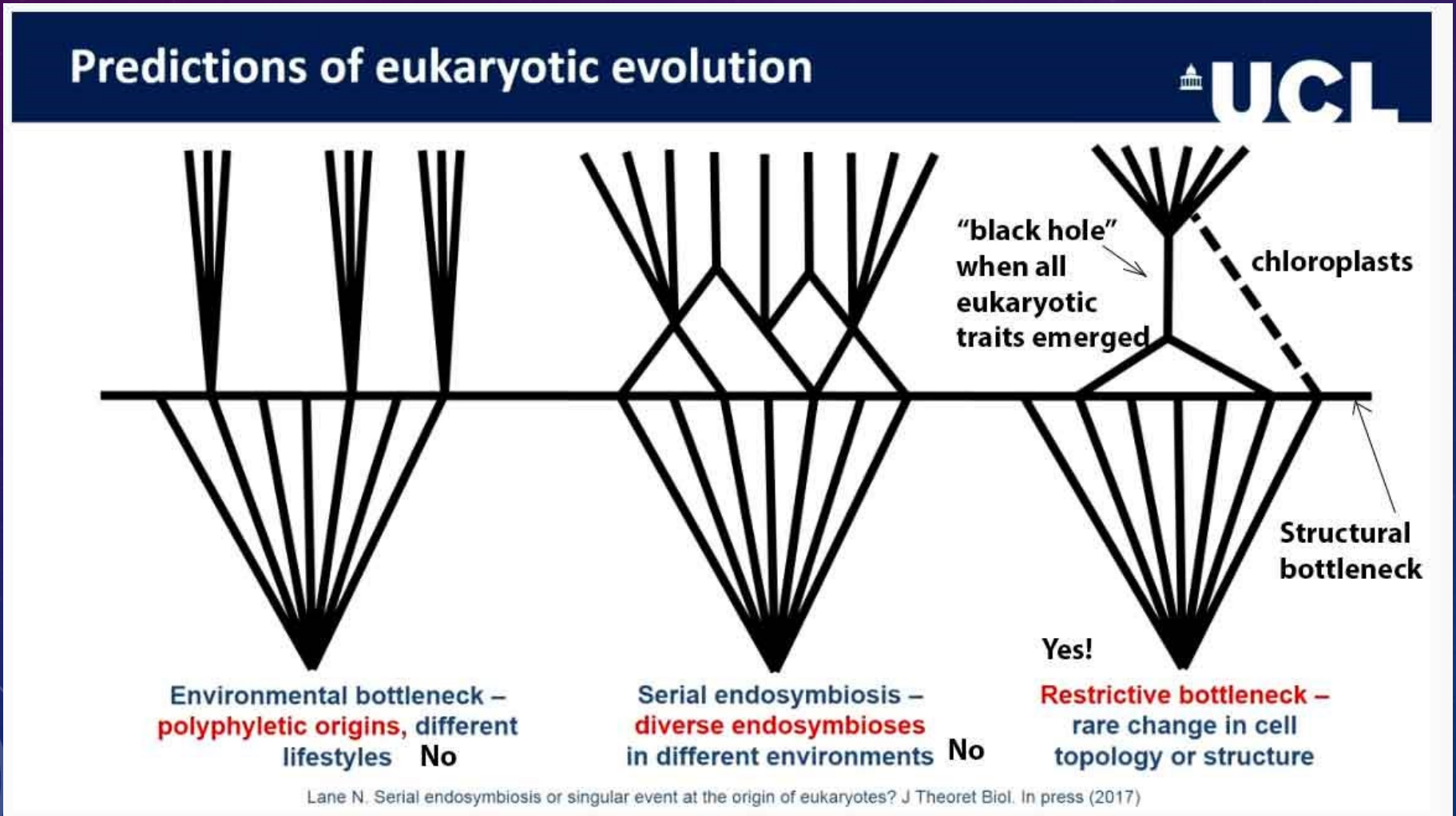
BUT COULD IT ALSO BE…?

- …That it was SUCH a valuable evolutionary change that it only HAD to happen once, and its inheritors were so successful they relegated all other life (bacteria and archea) to be only in tiny niches.
- We don’t know…

BIOLOGIST NICK LANE REFERS TO THIS AS THE "BLACK HOLE" AT THE HEART OF BIOLOGY

- We see huge variation in the eukaryotes throughout the plant and animal kingdoms, and they all trace their genomes back to a common ancestor. But we don't know what that ancestor was.
- And we don't know how it arose, or the environmental steps that made it.
- Sort of like the lucky Monkey who types the plays of Shakespeare – so completely incredibly valuable and successful are the many characteristics of eukaryotes.

WE DON'T SEE ENVIRO INDUCED HALT AND THEN CONVERGENT EVOLUTION, NOR SERIAL ENDOSYMBIOSIS (MARGULIS), INSTEAD LOOKS LIKE A BIOLOGICAL STRUCTURE BOTTLENECK.



ENERGY PRODUCING BACTERIA INVADED, THESE SYMBIONTS BECAME MITOCHONDRIA.

- A very unlikely "deal" was somehow struck: *"Yes, I know I invaded you – but don't kill me now. Instead, if you give me shelter inside your cell walls, and I'll give you incredible energy for both of us".*
- Most biologists believe this is the most likely origin for these organelles – the energy producing bacteria get a home and some protection, and in return then give energy to the cell for its metabolism
- Similar for chloroplasts – they also are believed to have been earlier bacteria which provided a similar energy advantage for what became photosynthetic plant cells.
- Funny, though, that in the immediate cell division called "mitosis" that eukaryotes do, that the invaders get copied too. That seems strange to me. How likely was THAT to have been worked into the machinery?

NEXT: SOCIALITY - A SOLUTION TO SUCCESSFUL COMPETITION FOR GROWTH

- We’re seeing a pattern…
- Life got to a point of being cells – a social network of DNA producing nuclei, and cytoplasm
- Then an invasive bacteria (we think) which has the capability of using ATP to produce energy, and a symbiosis of this ancient bacteria to find shelter inside the cell, while “paying rent” by producing energy for the cell – a great advance
- Then Natural Selection favored cells that could group together and specialize as “organs”. Just like a company of specialists all producing a common product as goal. Now you’ve got a primitive organism

BOTH PRIMITIVE AND ADVANCED LIFE FEELS INTRINSIC REWARDS FOR SOCIALITY. OBVIOUSLY TRUE IN HUMANS TOO!

THIS SPECIALIZATION AND COMPLEXITY COULD GO A LONG WAYS BEFORE THE FUNDAMENTAL LIMITATIONS OF GRAVITY AND NETWORK LIMITS WERE REACHED.

- So we eventually get to dinosaurs and whales as fundamental limits to “sociality of cells”.
- In parallel, a new sociality developed – family, first! You protect your own genes if you help protect family members from harm and helping their growth
- Later, families found advantage if they could use brains to identify and extend “family-ism” to include members of your tribe – tribalism develops
- For humans, tribalism has extended from family, to friends, to neighborhoods and then to cities (like who root for a common sport team)
- Cities, to states, another advance
- And to then Nation-States.

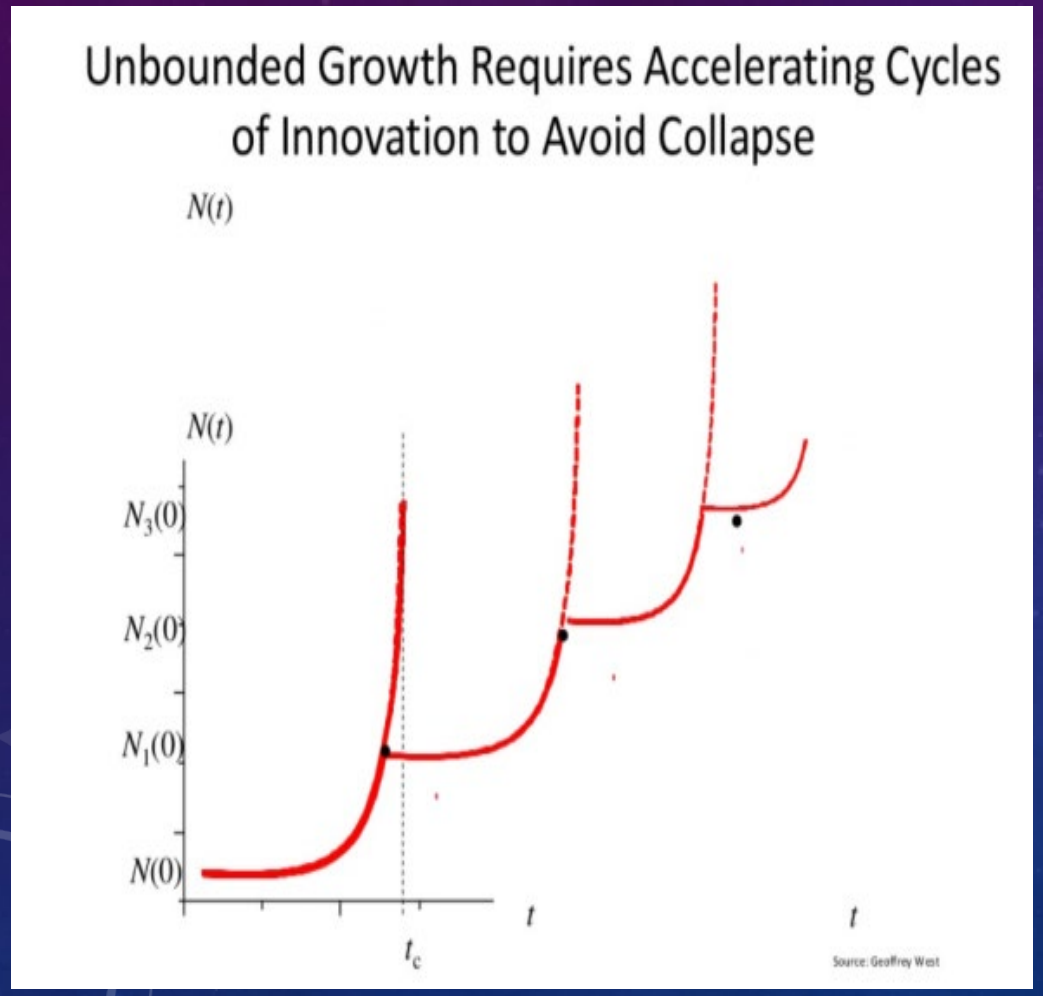
BUT FURTHER SURVIVAL AND WELL-BEING IS THREATENED YET STILL…

- Because as brains develop and as the success of growth continues, eventually the carrying capacity of the planetary home is challenged
- The species (all species, really, but certainly the DOMINANT species for certain), must change its orientation from competitive "Growth Uber Alles" mentality…
- …To an orientation of limiting growth and planning much longer term, for the survival of the entire ecosystems supporting the living planet as a whole.

TO AVOID COMPETITIVE "TRAGEDY OF THE COMMONS", WE NEED ONE MORE STEP IN OUR PROGRESS OF SOCIALITY…

- **A united global realization of the Limits to Growth, and full appreciation of the dangers of unlimited technological power on a finite planet.**
- **One-World.**
- **(The UN is only a very imperfect stage for squabbles, so far. It's not served the purpose I'm trying to convey)**

IN THE END, INNOVATION CANNOT SUCCEED:



- Avoiding collapse is only temporary
- Innovative Cycles accelerate if they are true innovations - Collapse keeps gaining on you
- This is from the brilliant work of physicist Geoff West 20 years ago, investigating scaling laws in biology and extending them, verifying them, in global civilization. "Scale"

THE BIG QUESTION…

WILL WE ACHIEVE SUFFICIENT GLOBAL SOCIALITY BEFORE WE FOLLOW OUR *GROWTH UBER ALLES* BIOLOGICAL PROGRAMMING TO THE POINT OF KILLING THE FUTURE?

- Is this the “Great Filter” that stops advanced life in its Infancy?

THIS RAMBLING LECTURE INCLUDES MANY KEY POINTS WHICH WILL BE EXAMINED MORE DEEPLY LATER IN THIS COURSE

- But it gives an overview of life from start to “finish” on the only planet we know of which actually HAS life.
- It’s a framework on which we can better grasp other thoughts and details on searching for ET and pondering visits from other stars