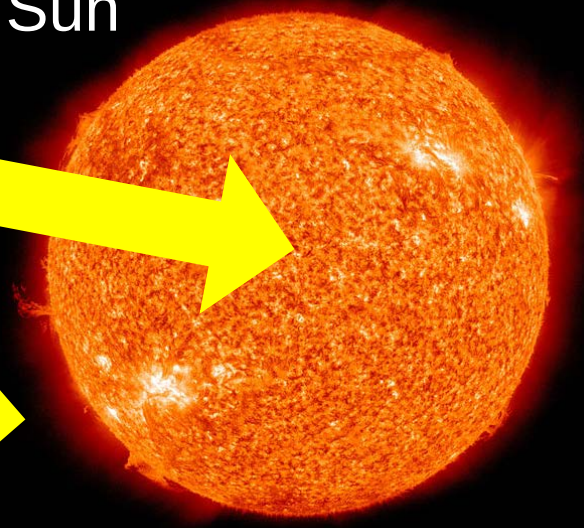
An Engineer's perspective on the Human condition the evolution of Earth

Part 2

Plasma Core Temperature
15,700,000 K
(energy release rate: 276 μWatts/ cm^3)
1.2×10^{34} J

Sun



Highly energetic low entropy visible light photons

$3–5\times10^{-19}$ J

Earth system is a dissipative heat engine. The human economy is a dissipative heat engine

0.09 Watts/m^2

5770 K

1360.8 Watts/m^2

5.5×10^{24} J

288 K

Low energy high entropy infrared heat photons

$2–3000\times10^{-22}$ J

Empty space
2.73 K^o

E=hf

2.72 Wm^{-2} Effective Radiative Forcing due to human emissions IPCC AR6

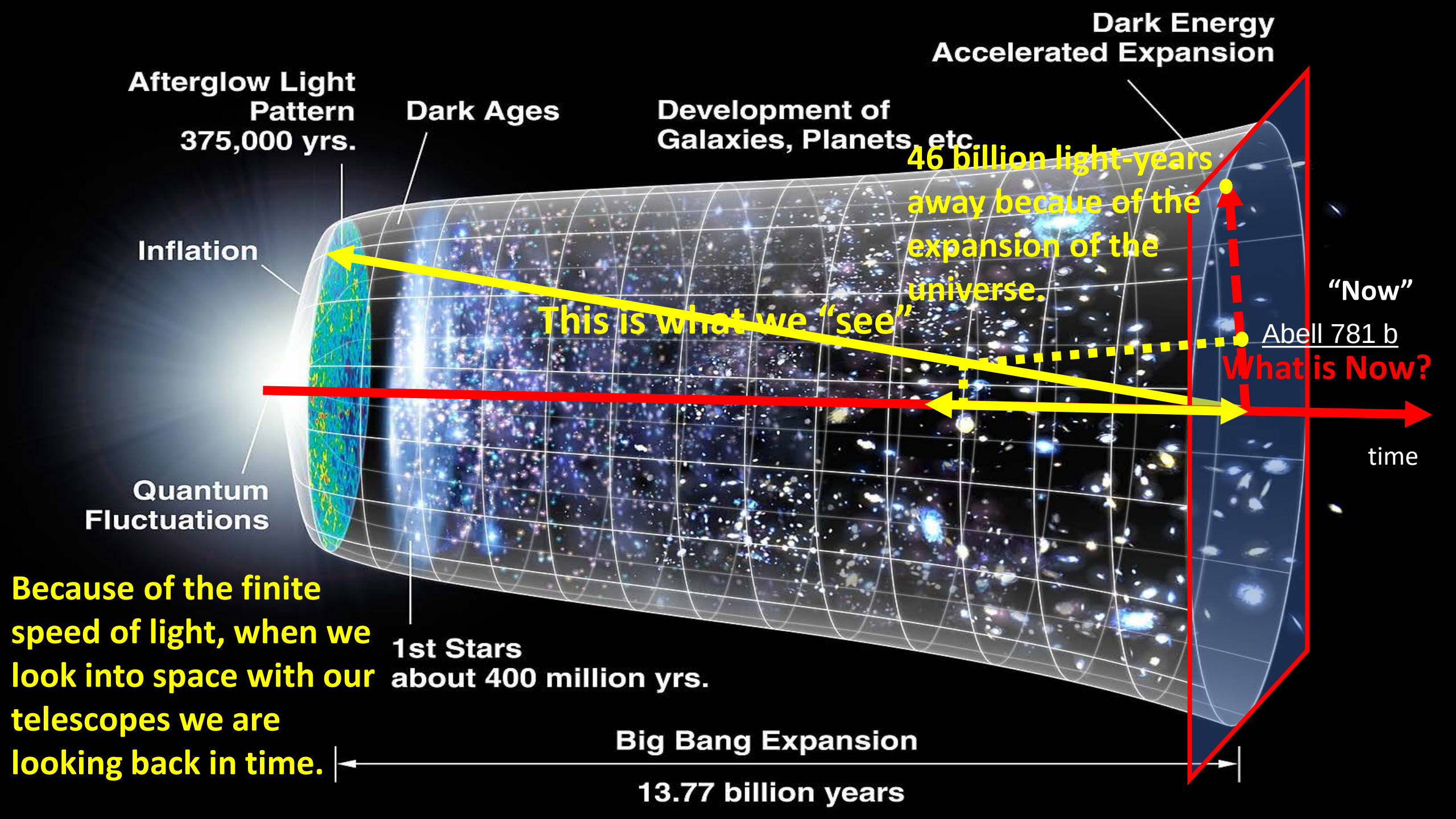
Not to scale

The entire history of the evolution of our environment

- Part 1 The evolution of the universe the first 9.3 billion years
  - Where did we come from
  - What are the laws
- Part 2 The evolution of Earth the next 4.5 billion years
  - Brief history of Earth, right up to the Cenozoic
- Part 3 The evolution of civilization, the Anthropocene
  - Current extinction event, the Holocene extinction
  - Climate change
- Part 4 The evolution of our possible futures
  - Economics (and our environment)
- Part 5 The evolution of our possible futures
  - Energy (and our environment)
- Part 6 solution space and discussion

https://www.youtube.com/watch?v=L0zlwdaPS4s
Euan Nisbet. Climate in Deep Time: From the Archean to the Ice Ages

Cliff notes version of Charles Langmuir and Wally Broecker's "How to Build a Habitable Planet" or Paolo Saraceno, "Beyond the Stars" also Stanley and Luczaj "Earth System History" and Lunine "Earth".


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
46 billion light-years
away becaue of the
expansion of the
universe.
Inflation
This is what we "see"
"Now"
Abell 781 b
What is Now?
time
Quantum
Fluctuations
Because of the finite
speed of light, when we
look into space with our
telescopes we are
looking back in time.
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

Part 2 Earth "World"

Cliff notes version of Tim Lenton and Andrew Watson, "Revolutions that made the Earth", 2011

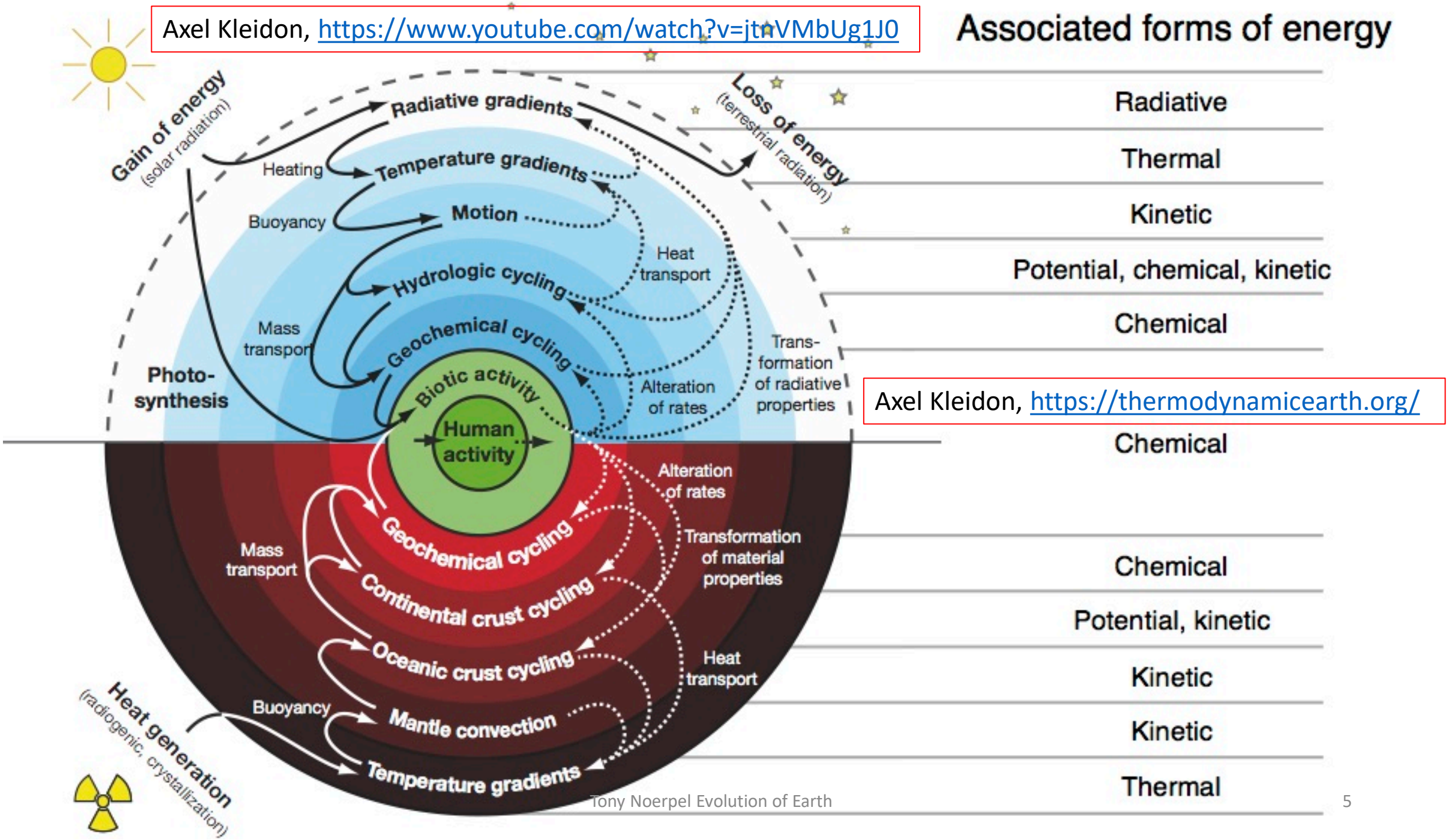
- The Earth System

$$\frac{dE}{dt} = f(A, G, I)$$

- Earth System* as "*a single, planetary-level complex system composed of the biosphere, defined here as the sum of all biota living at any one time and their interactions, including interactions and feedbacks with the geosphere defined here as the atmosphere, hydrosphere, cryosphere and upper part of the lithosphere*."
- A represents astronomical forcings such as the gravity of the Sun, moon and planets as well as solar irradiation and insolation and collisions with asteroids.
- G represents geophysical forcings such as tectonic plate movement and volcanism.
- I represents internal dynamics, including biospheric evolutionary processes

*Owen Gaffney and Will Steffen, The Anthropocene equation, The Anthropocene Review, https://doi.org/10.1177/2053019616688022

Axel Kleidon, https://www.youtube.com/watch?v=jtnVMbUg1J0



Axel Kleidon, https://thermodynamicearth.org/

Planck's Law

$$B_\nu(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{k_B T}} - 1}$$

Stefan-Boltzmann Law (Integral of B_ν)

$$F = \sigma T^4 \qquad 6.3X10^7\ W/m^2$$

Where σ is Stefan-Boltzmann constant

$$\sigma = 5.67 \times 10^{-8} \quad W/m^2/K^4$$

Planetary energy balance

Surface reflectivity of the planet, Albedo

$$\sigma T_e^4 = \frac{S}{4}(1 - \alpha)$$

Effective Temperature -18 C
Earth

Actual Temperature Earth 15 C

Greenhouse effect 33 C

$$\Delta F = -6.3 \ln\left(\frac{C}{C_o}\right)$$

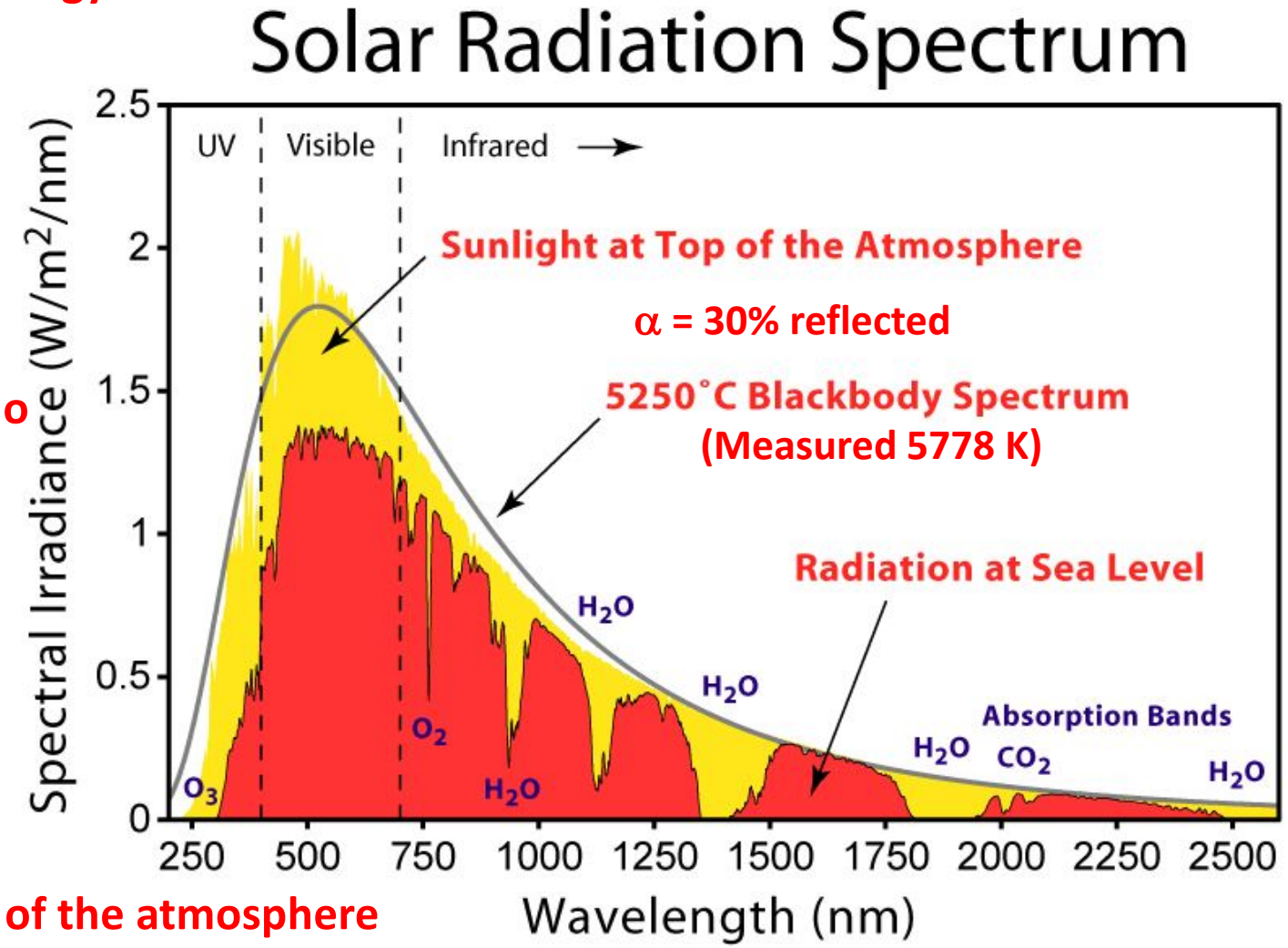
Composition of the atmosphere

Kump, Kaastings, Crane, "The Earth System"

Solar radiation at top of the atmosphere

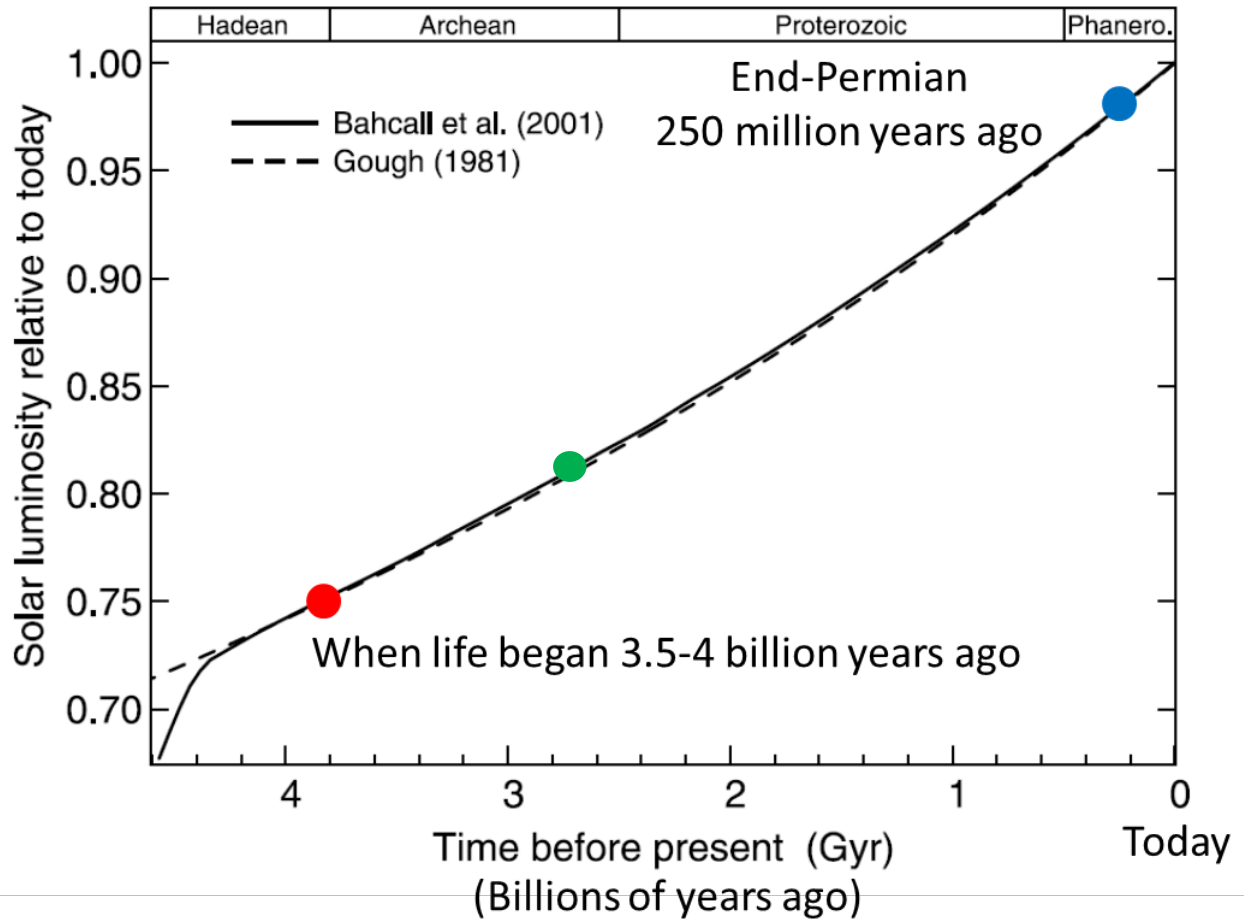
$$S = F\left(\frac{r_{sun}}{r_{earth\ orbit}}\right)^2 = 6.3 \times 10^7 \cdot \left(\frac{696{,}000\ km}{149{,}598{,}000 km}\right)^2 = 1361 \quad W/m^2$$

Energy received from the star



Source http://synergyfiles.com/2016/05/solar-radiation/

Faint young sun paradox an example of Astronomical forcing

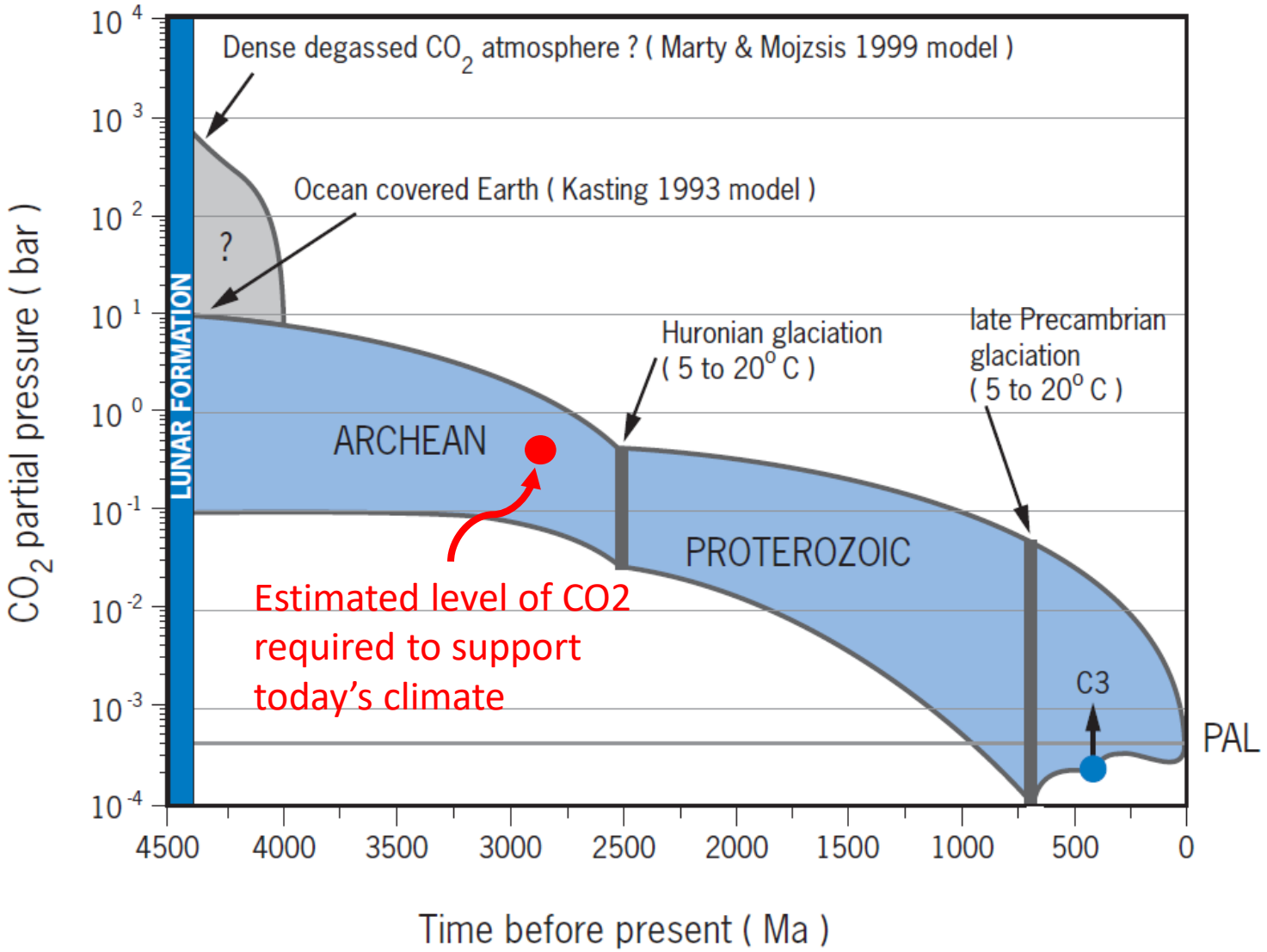


Why does a star burn hotter with time?

[Feulner] Georg Feulner, The faint young Sun problem, Rev. Geophys., 50, RG2006 https://doi.org/10.1029/2011RG000375 , 25 May 2012. [Foster] Gavin L. Foster, Dana L. Royer & Daniel J. Lunt, Future climate forcing potentially without precedent in the last 420 million years, Nature Communications, https://doi.org/10.1038/ncomms14845 www.nature.com/naturecommunications 4 April, 2017 [Gough] Gough, D. O. Solar interior structure and luminosity variations. Solar Phys. 74, 21–34 (1981).
Sagan, C., and G. Mullen (1972), Earth and Mars: Evolution of atmospheres and surface temperatures, Science, 177, 52–56, https://doi.org/10.1126/science.177.4043.52 .

Partial Pressure of CO_2 in the Atmosphere Over Time

Source: Stephen J. Mojzsis, Life and the Evolution of Earth's Atmosphere



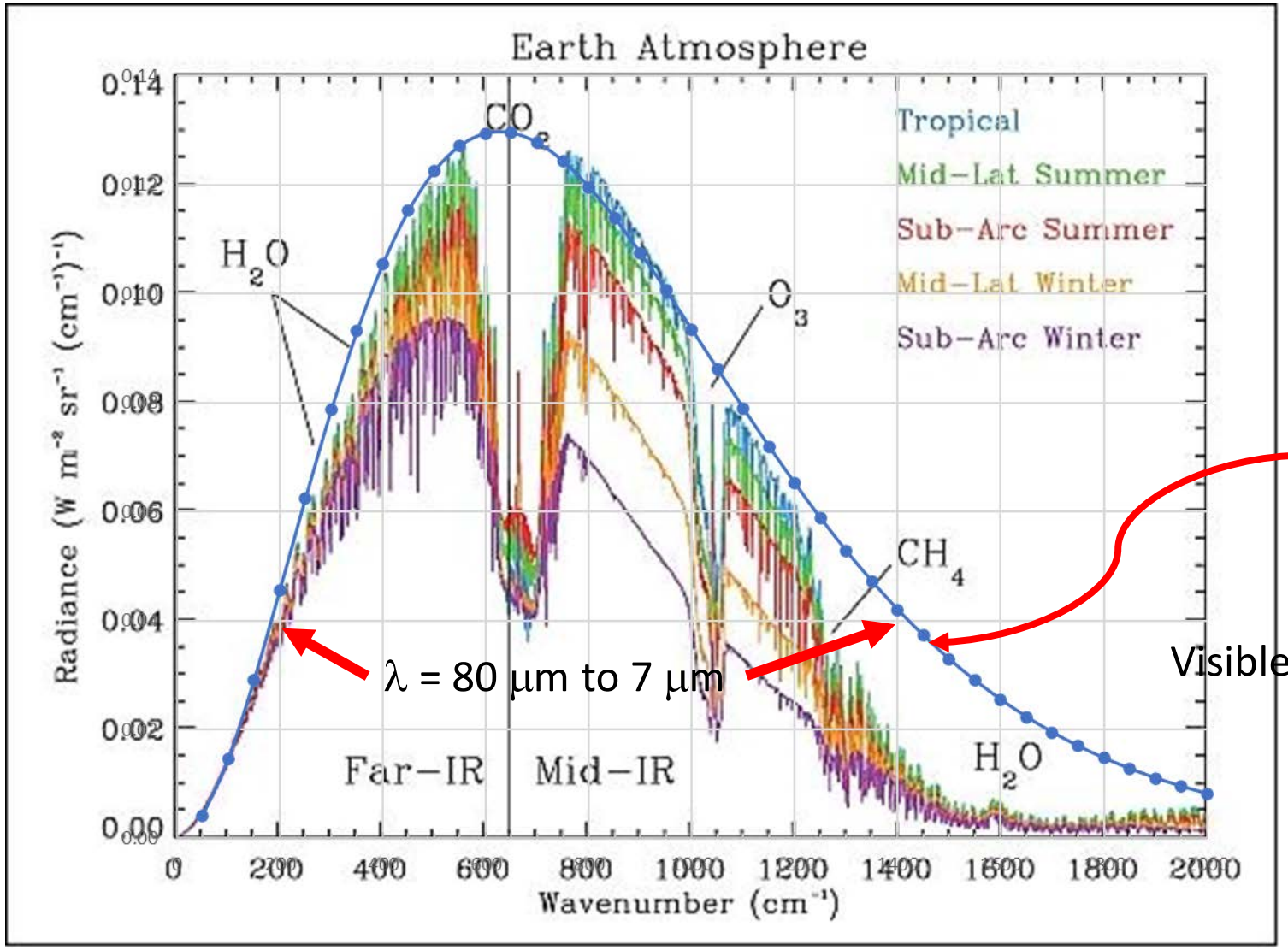
Carbon Dioxide is Earth's non-condensing greenhouse gas and is a forcing

Water vapor is Earth's condensing greenhouse gas and is a feedback

Gavin L. Foster, Dana L. Royer & Daniel J. Lunt, Future climate forcing potentially without precedent in the last 420 million years, Nature Communications, 2017 https://doi.org/10.1038/ncomms14845

O. R. Lehmer, D. C. Catling, R. Buick, D. E. Brownlee and S. Newport, Atmospheric CO2 levels from 2.7 billion years ago inferred from micrometeorite oxidation, Science Advances 22 Jan 2020: Vol. 6, no. 4, eaay4644, https://doi.org/10.1126/sciadv.aay4644

C. Goldblatt, Atmospheric Evolution, Encyclopedia of Geochemistry (Editor W. White), arXiv:1710.10557. https://arxiv.org/pdf/1710.10557.pdf



Blackbody radiation using Planck's law

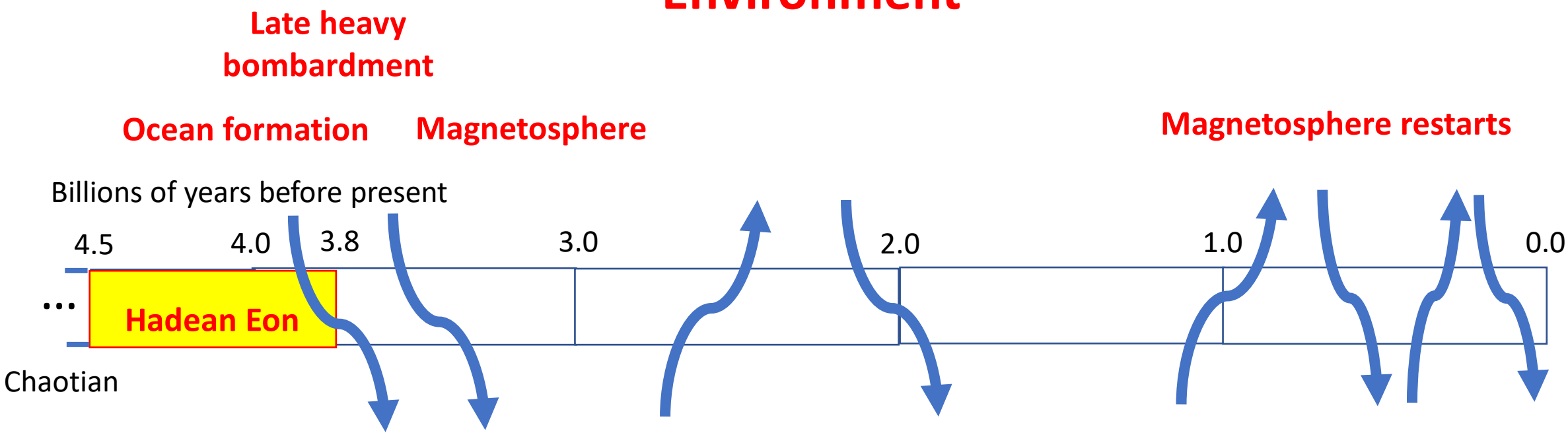
λ = 80 μm to 7 μm

Visible light from .7 to .3 μm

Source: M.G. Mlynczak, R.P. Cageao, H. Latvakoski, D. Kratz, D. Johnson, J. Mast, The Far-Infrared Spectroscopy of the Troposphere (FIRST) Instrument: New Technology for Measuring Earth's Energy Balance and Climate Change, Earthzine December 2, 2013ESTO Showcase 2013, https://earthzine.org/the-far-infrared-spectroscopy-of-the-troposphere-first-instrument-new-technology-for-measuring-earths-energy-balance-and-climate-change-2013-earth-science-technology-showcase

https://www.youtube.com/watch?v=KD7Jg5TpDvs Prebiotic Earth, Rachel Phillips, Geo Girl

Environment



How come it took 700 million years for Earth to become habitable?

Life

Tinghong Zhou, John A. Tarduno, Francis Nimmo, Rory D. Cottrell, Richard K. Bono, Mauricio Ibanez-Mejia, Wentao Huang, Matt Hamilton, Kenneth Kodama, Aleksey V. Smirnov, Ben Crummins & Frank Padgett III, Early Cambrian renewal of the geodynamo and the origin of inner core structure, Nature Communications volume 13, Article number: 4161 (2022), 19 July 2022, https://www.nature.com/articles/s41467-022-31677-7

"Planetesimal rings as the cause of the Solar System's planetary architecture" by Andre Izidoro, Rajdeep Dasgupta, Sean N. Raymond, Rogerio Deienno, Bertram Bitsch and Andrea Isella, 30 December 2021, Nature Astronomy. https://doi.org/10.1038/s41550-021-01557-z
https://scitechdaily.com/three-rings-to-bind-them-cosmic-history-can-explain-the-properties-of-mercury-venus-earth-and-mars/

PROTOPLANETARY DISC. CREDIT: ESO/L. CALÇADA
Young Star Surrounded by a Protoplanetary Disc


Hadean
Where did Earth's water come from?

How do we know the Earth is 4.5 billion years old?

- Isotope mass spectrometry - Radiometric dating – U-Pb Geochronology*
- Clair Paterson using measurements of Uranium isotopes in Zircon minerals.
  - Both U235 U238 have 92 electrons and protons
  - U235 has 140 neutrons decays to Pb207
  - U238 has 143 neutrons and decays to Pb206
  - U235 has a half life of 700 million years
  - U238 has a half life of 4.5 billion years

What is Zircon? Why did this method work?

https://www.youtube.com/watch?v=Re_DhvvYtIE

Dr. Johnson Haas, Earth Parts lectures

Why did GM try to have Paterson fired?

https://www.youtube.com/watch?v=suUX9-JAwNM

- Similar to Carbon 14 dating
  - C14 has a half life of 5,730 years so its decay is useful for archaeological dating. C14 decays into N14. Also, Beryllium 10 (1.4 million years) and Aluminum 26 decay (717,000 years).
  - Potassium - Argon dating; potassium 40 has a half life of 1.25 billion years
- Many inorganic and organic processes mass fractionate Carbon (C12, C13), Oxygen (O16, O18), Sulphur (23 isotopes, 4 stable) (S32, S33, S34, S36), … isotopes yielding temperature or other information about the environment

*Dr. Dave Dunning, https://www.youtube.com/watch?v=AwFoD2RJl1w

Arizona Laserchron center, https://www.youtube.com/watch?v=cZFX8aax6UA

Environment

First banded iron formation (BIFs)

Late heavy bombardment

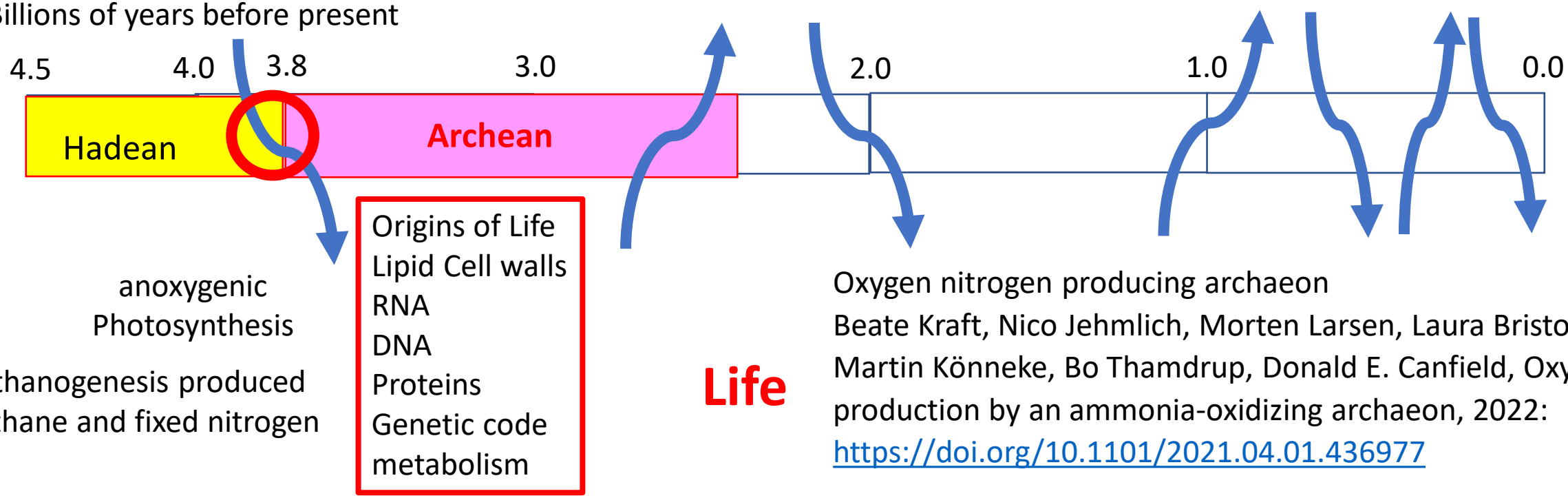
Reduced atmosphere
No ozone layer

Ocean formation

Methane and CO2 rich atmosphere

Nick Lane, "Transformer, The Deep Chemistry of Life and Death," 2022

Billions of years before present



anoxygenic Photosynthesis

Methanogenesis produced methane and fixed nitrogen

Origins of Life
Lipid Cell walls
RNA
DNA
Proteins
Genetic code
metabolism

Life

Oxygen nitrogen producing archaeon
Beate Kraft, Nico Jehmlich, Morten Larsen, Laura Bristow, Martin Könneke, Bo Thamdrup, Donald E. Canfield, Oxygen production by an ammonia-oxidizing archaeon, 2022: https://doi.org/10.1101/2021.04.01.436977

Life begins about ~3.8 billion years ago after the late heavy bombardment
The environment was right: temperature, liquid water, minerals and organic chemistry

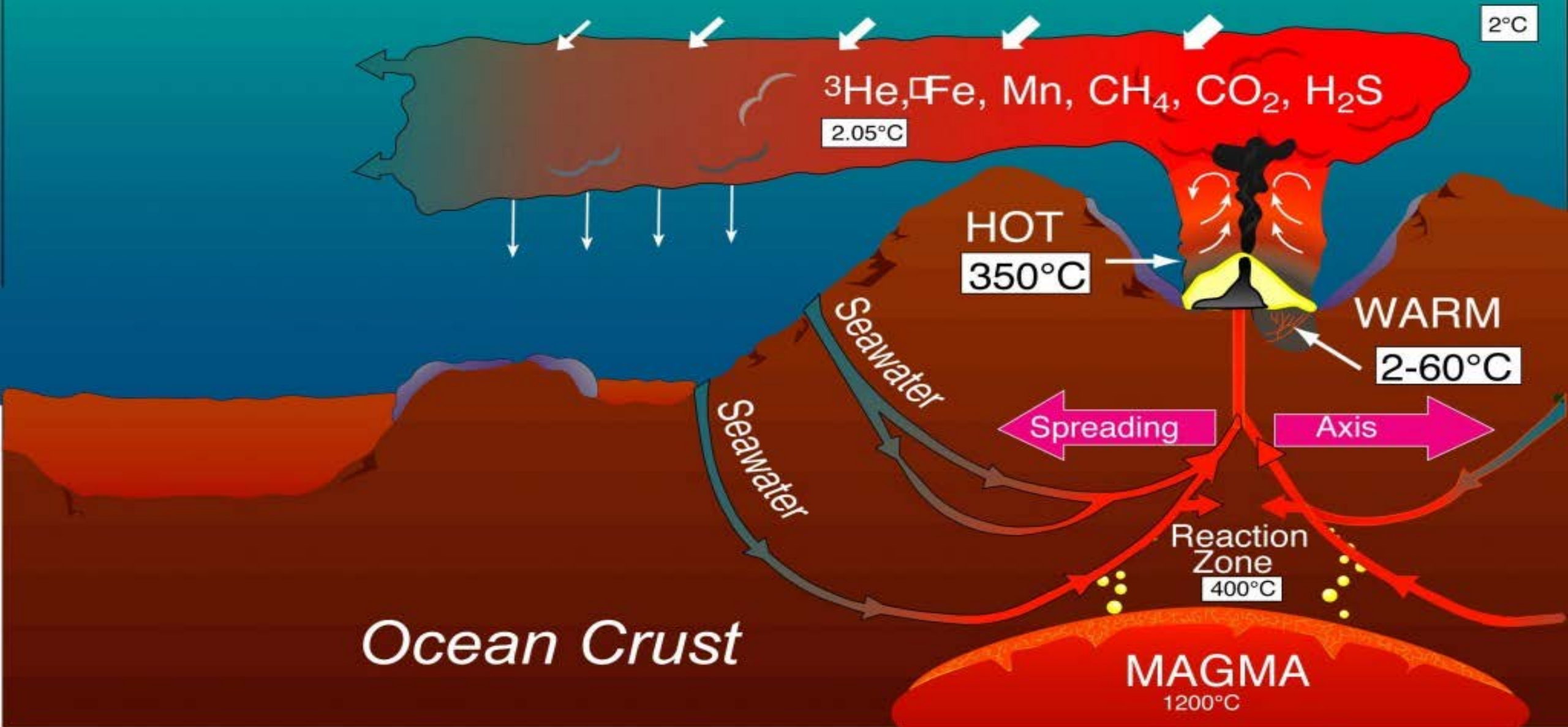
Origin of life hypotheses

- Panspermia
  - Lei Feng, Possibilities for methanogenic and acetogenic life in molecular cloud, 24 Nov 2023, https://doi.org/10.48550/arXiv.2311.14291
- Tidal pools
- Radiation from the young sun
- Hydrothermal vents
- Salt ponds

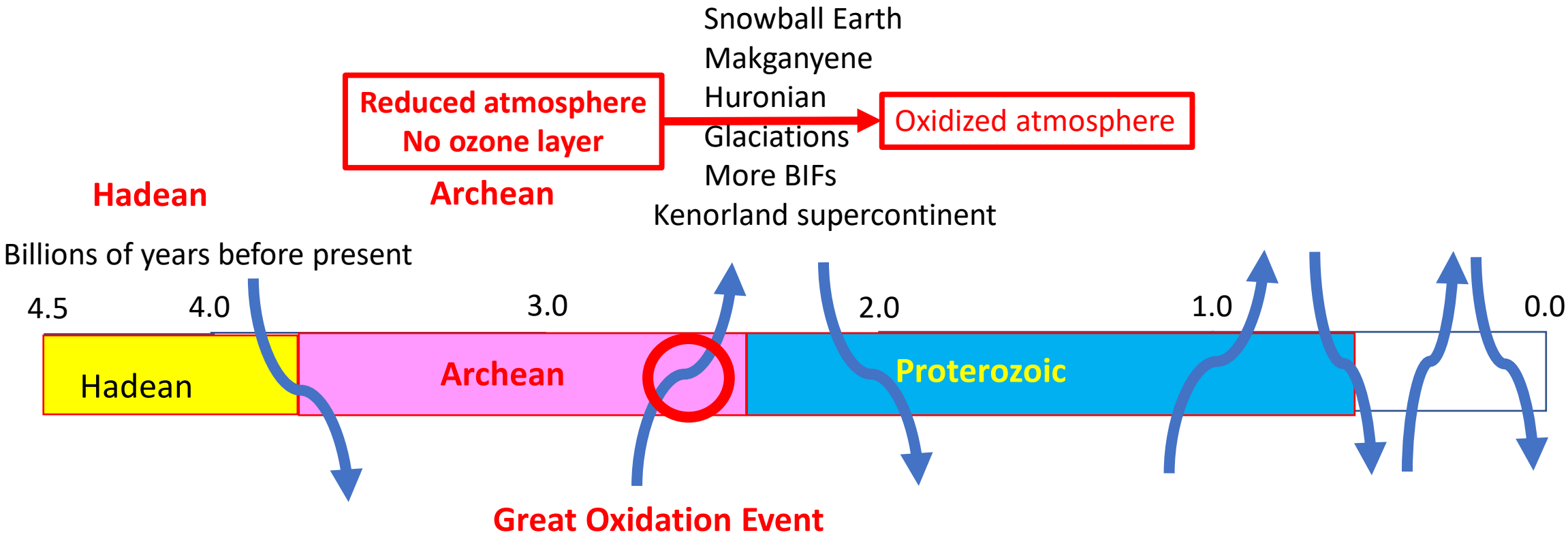
Life is a self-sustaining chemical system capable of undergoing Darwinian evolution. – NASA

"Every species of living thing can make a copy of itself by exchanging energy and matter with its surroundings." – Jeremy England, Statistical physics of self-replication, J. Chem. Phys. 139, 121923 (2013); http://dx.doi.org/10.1063/1.4818538

https://blogs.agu.org/geospace/2015/11/25/tracking-down-hydrothermal-vents/



Environment



Life

Cyanobacteria invent oxygenic photosynthesis ~2,7 billion years ago

The Earth System transitioned from reducing to oxidizing

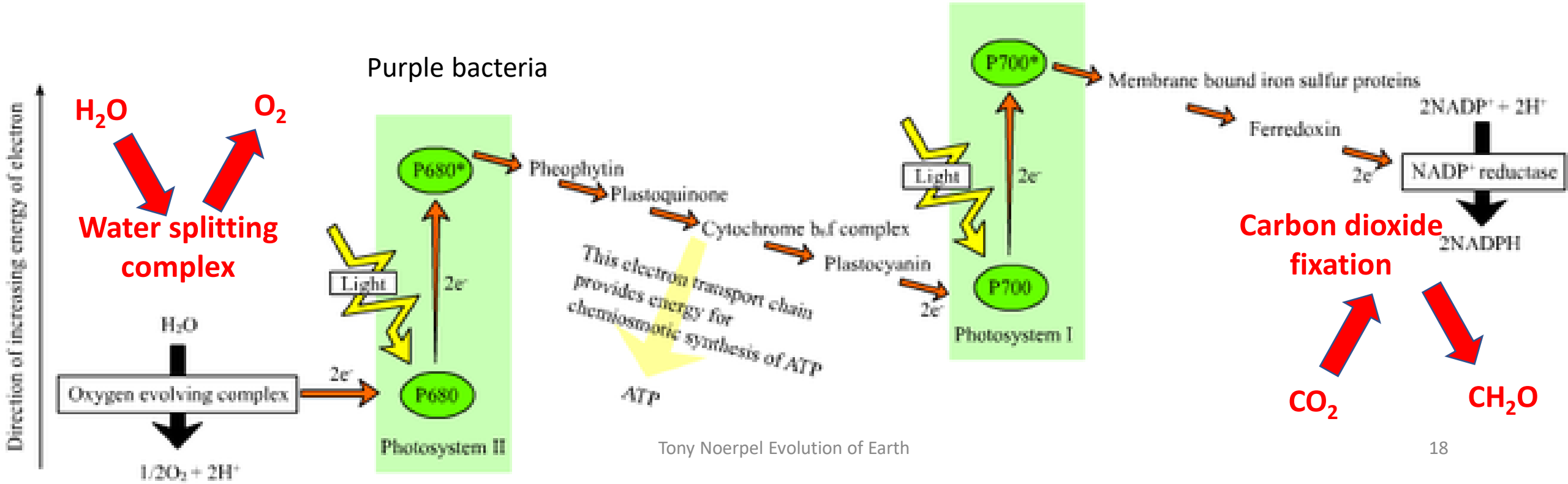
Photosynthesis

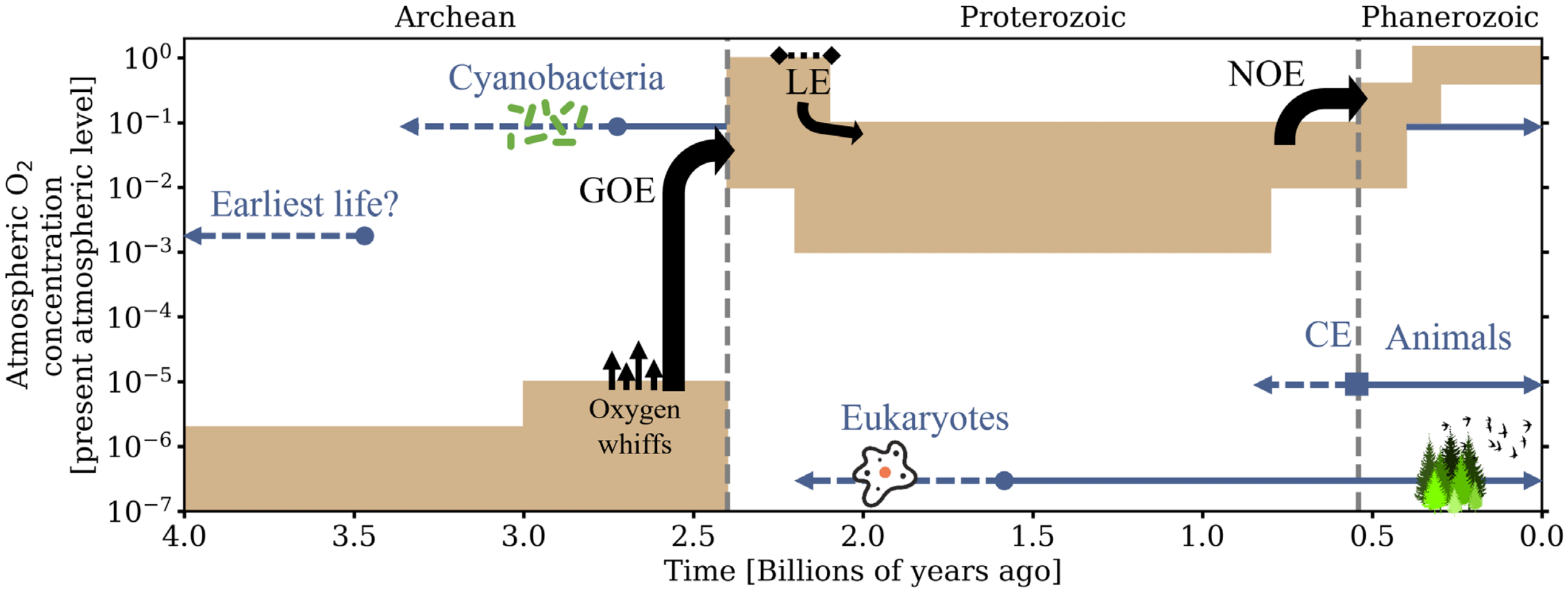
Oxygen: “As little as one breath is known to produce a life-loving addiction to the gas, which … invariably ends in death.” D. L. Gilbert in “Oxygen and Living Processes”, 1981, pp. 376-92.

“Light makes life out of water and thin air.” J. F. Allen, W. Martin, Out of thin air, Nature 445, 610, 2007.

Green Sulphur bacteria which use hydrogen-Sulphide as an electron doner and fix carbon dioxide

Purple bacteria





A rough outline of oxygen (O2) concentrations in Earth's atmosphere through time are illustrated in this figure. Brown blocks show the estimated range for O2 in terms of its present atmospheric level (which is 21% by volume). Grey-blue lines indicated various important events for the evolution of life, including the emergence of eukaryotes and animals. Black arrows refer to important events where atmospheric oxygen concentration changed. The Archean, Proterozoic, and Phanerozoic are geological eons. GOE = Great Oxidation Event; NOE = Neoproterozoic Oxidation Event; CE = Cambrian Explosion; LE = Lomagundi Excursion. Credit: Gregory Cooke/ Royal Society Open Science

A revised lower estimate of ozone columns during Earth's oxygenated history" by G. J. Cooke, D. R. Marsh, C. Walsh, B. Black and J.-F. Lamarque, 5 January 2022, *Royal Society Open Science*. https://doi.org/10.1098/rsos.211165

What caused the Snowball Earth?

- Silicate rock weathering
  - Breaking up of supercontinent, collision of plates, uplifted mountains, enhanced silicate rock weathering drew down carbon dioxide

$$CO_2 + CaSiO_3 \rightarrow CaCO_3 + SiO_2$$

Calcium carbonate and silica or quartz

- Photosynthesis drew down carbon dioxide and converted it to organic matter which got buried

$$CO_2 + H_2O \rightarrow CH_2O + O_2$$

- Photosynthesized oxygen reacted with atmospheric methane

$$CH_4 + 2O_2 \rightarrow CO_2 + 2\ H_2O$$

- High altitude volcanic emissions
- Recovery by volcanos releasing CO2

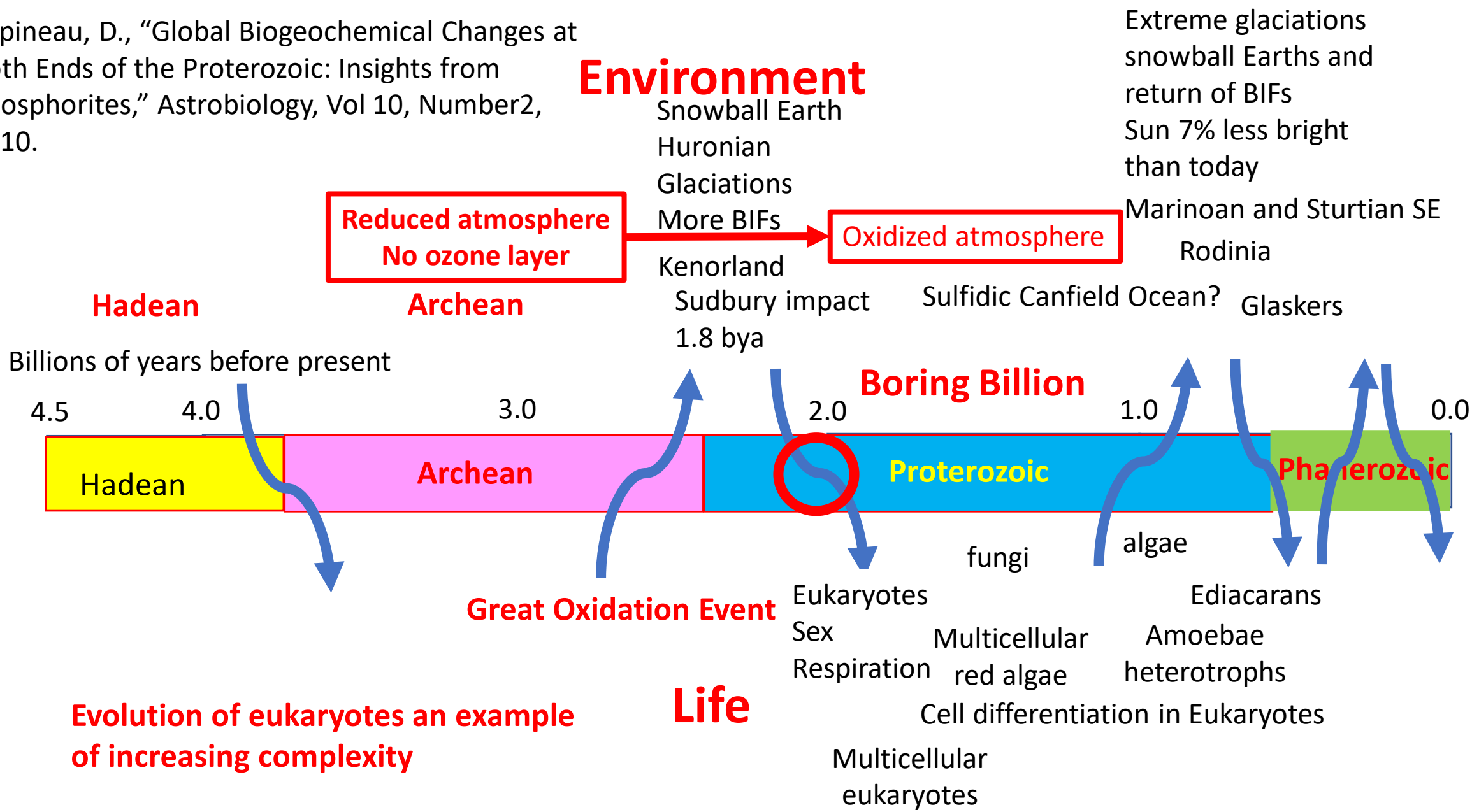
Rachel Phillips, https://www.youtube.com/watch?v=MzYy9bEZnbw
https://www.youtube.com/watch?v=vntVVcazJD4

From Reducing to Oxidizing

- Four causes
  - An increase in global net primary productivity from oxi-photosynthesis
  - A decline in the input of reduced material coming from the mantle
  - A sustained increase in organic carbon burial, and
  - An increase in hydrogen escape to space

First mass extinction event, caused by cyanobacteria

Papineau, D., “Global Biogeochemical Changes at Both Ends of the Proterozoic: Insights from Phosphorites,” Astrobiology, Vol 10, Number2, 2010.



History of the Earth, November 30, 2021 https://www.youtube.com/watch?v=HDim45WdlLs

“Never in the course of Earth history did so little happen to so much for so long” Geochemist Roger Buick, 1995*

“The Mesoproterozoic was the most smelliest time on Earth” Geochemist Linda Kah**

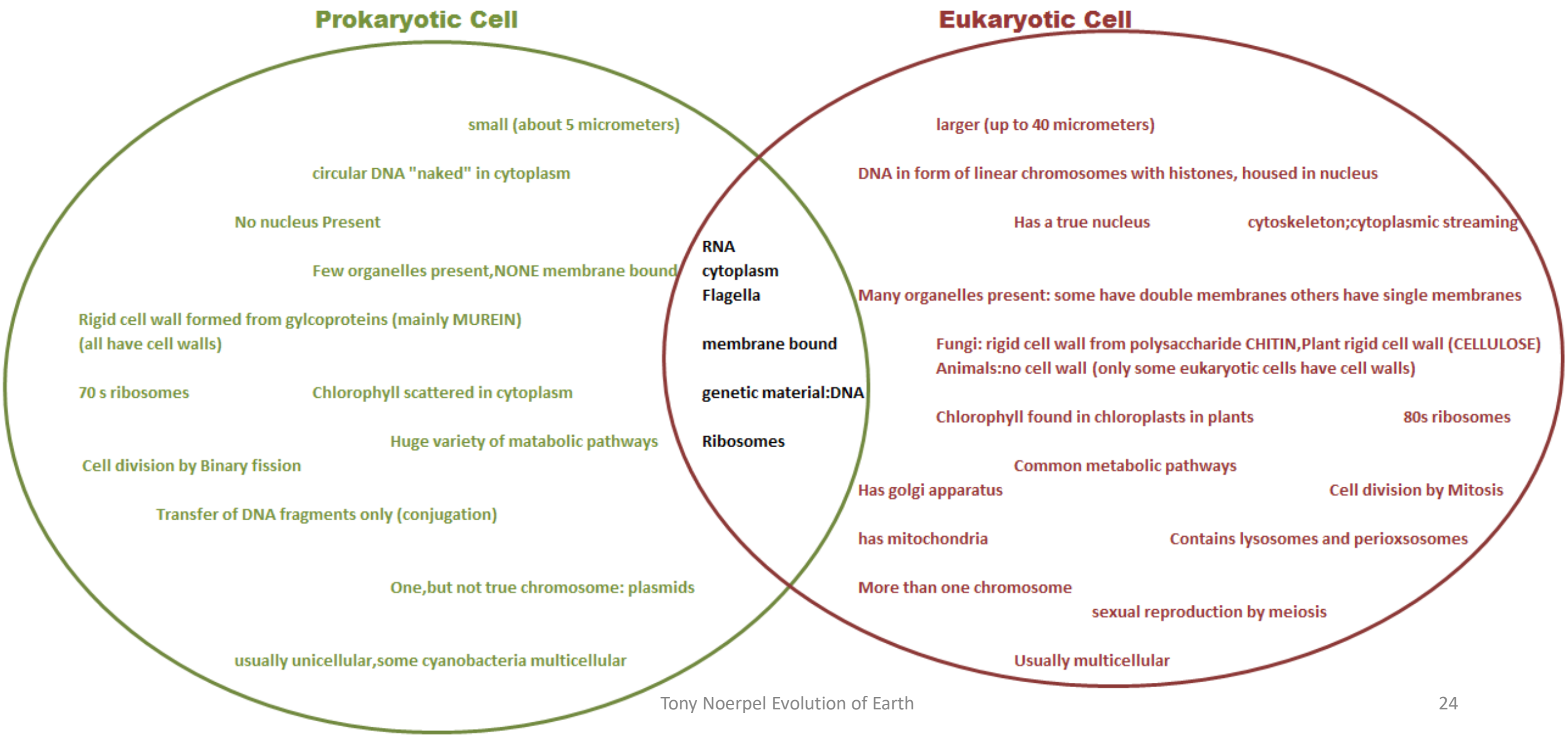
*https://www.youtube.com/watch?v=0sbwUeTyDb0

** Robert Hazen, The Story of Earth, p. 199

https://www.youtube.com/watch?v=0sbwUeTyDb0

Biologically, it was a revolution!

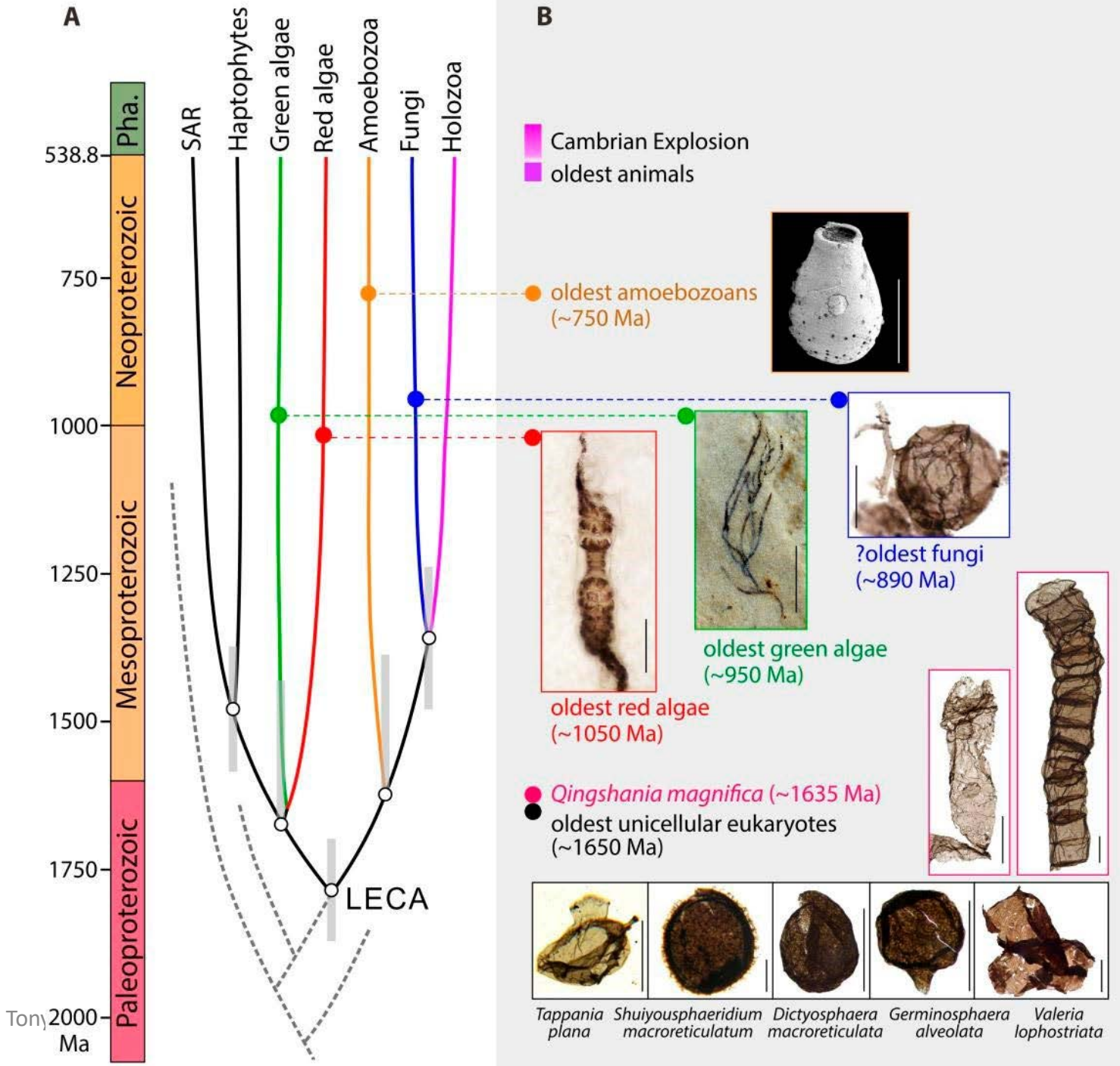
https://www.youtube.com/watch?v=fH81o3yJ5yU



1.65 billion year old multicellular fossil

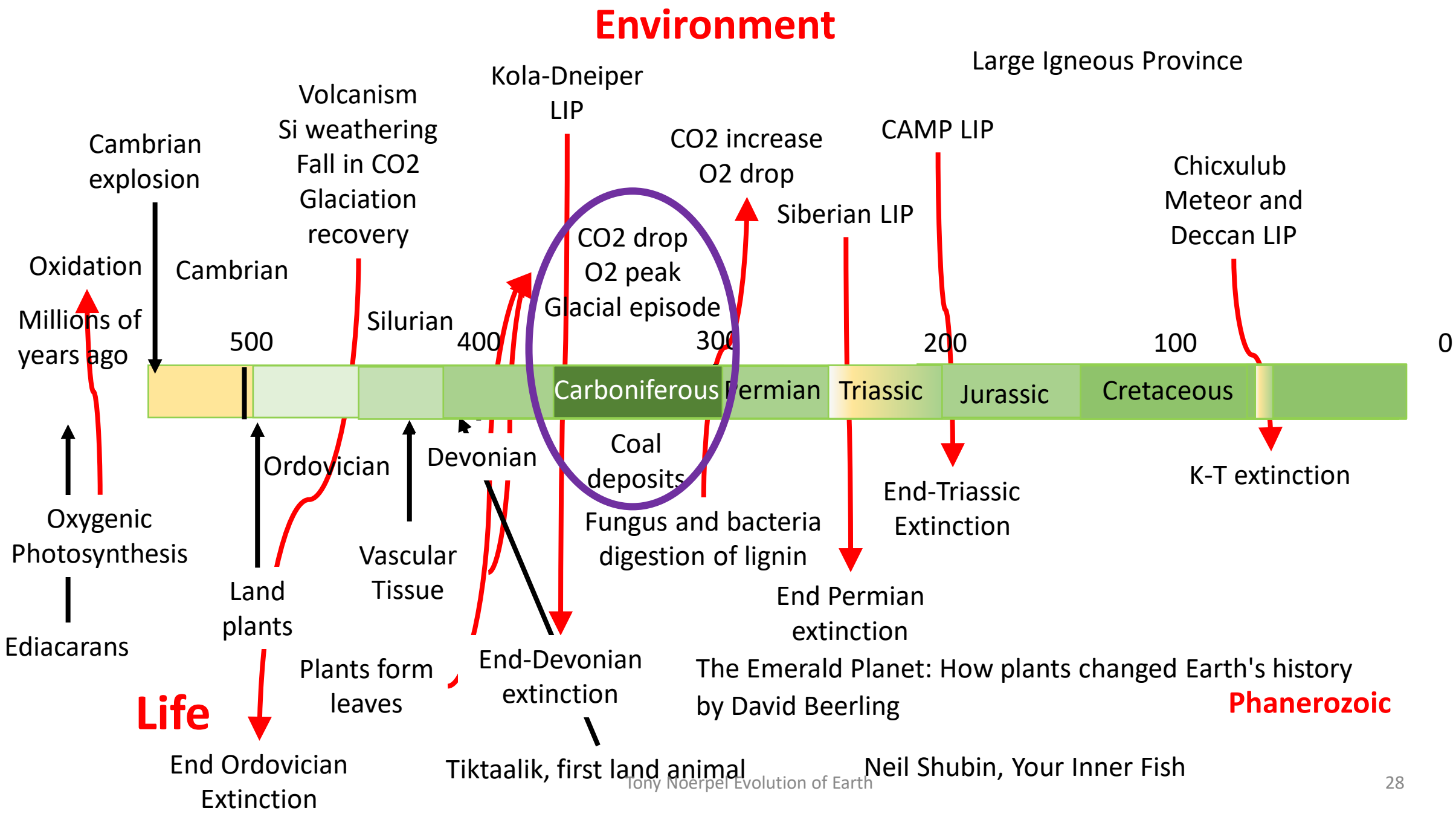
https://scitechdaily.com/early-complex-life-forms-revealed-1-63-billion-year-old-multicellular-fossils-unearthed-in-china/

In eukaryotic tree, grey dash lines represent stem group eukaryotes. Solid lines denote crown group eukaryotes (LECA plus its descendants). Grey bars at nodes display the estimated age range of divergence of major branches from a molecular clock study (Parfrey et al., 2011, PNAS). Scale bar in the green algal fossil equals 500 µm; the rest are 50 µm. Credit: Lanyun Miao



Proterozoic

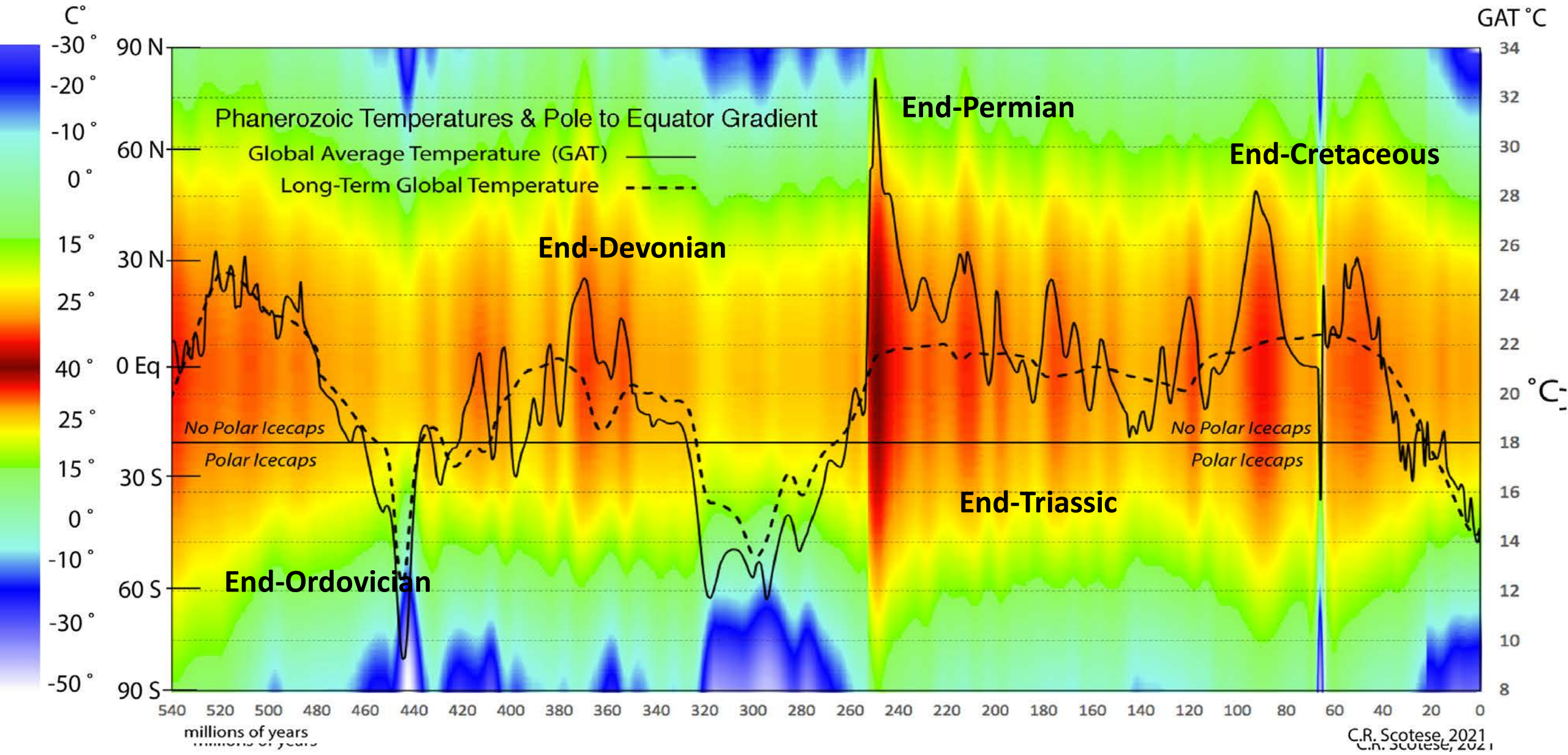
Brandon Weissbourd, Tsuyoshi Momose, Aditya Nair, Ann Kennedy, Bridgett Hunt, David J. Anderson, A genetically tractable jellyfish model for systems and evolutionary neuroscience, Cell, V 184, issue 24, p5854-5854.e20, November 24, 2021, https://doi.org/10.1016/j.cell.2021.10.021
Reference: "Associative learning in the box jellyfish Tripedalia Cystophora" 22 September 2023, Current Biology. , https://doi.org/10.1016/j.cub.2023.08.056


Environment
Large Igneous Province
Kola-Dneiper LIP
Volcanism
Si weathering
Fall in CO2
Glaciation
recovery
CO2 increase
O2 drop
CAMP LIP
Siberian LIP
Chicxulub Meteor and Deccan LIP
Cambrian explosion
Oxidation
Cambrian
Silurian
CO2 drop
O2 peak
Glacial episode
Millions of years ago
500
400
300
200
100
0
Carboniferous
Permian
Triassic
Jurassic
Cretaceous
Ordovician
Devonian
Coal deposits
Fungus and bacteria digestion of lignin
End-Triassic Extinction
K-T extinction
Oxygenic Photosynthesis
Vascular Tissue
Land plants
End Permian extinction
Ediacarans
Plants form leaves
End-Devonian extinction
The Emerald Planet: How plants changed Earth's history
by David Beerling
Phanerozoic
Life
End Ordovician Extinction
Tiktaalik, first land animal
Neil Shubin, Your Inner Fish

Davies,Neil S. et al., The largest arthropod in Earth history: insights from newly discovered Arthropleura remains (Serpukhovian Stainmore Formation, Northumberland, England), Journal of the Geological Society(2021),:jgs2021-115, http://dx.doi.org/10.1144/jgs2021-115

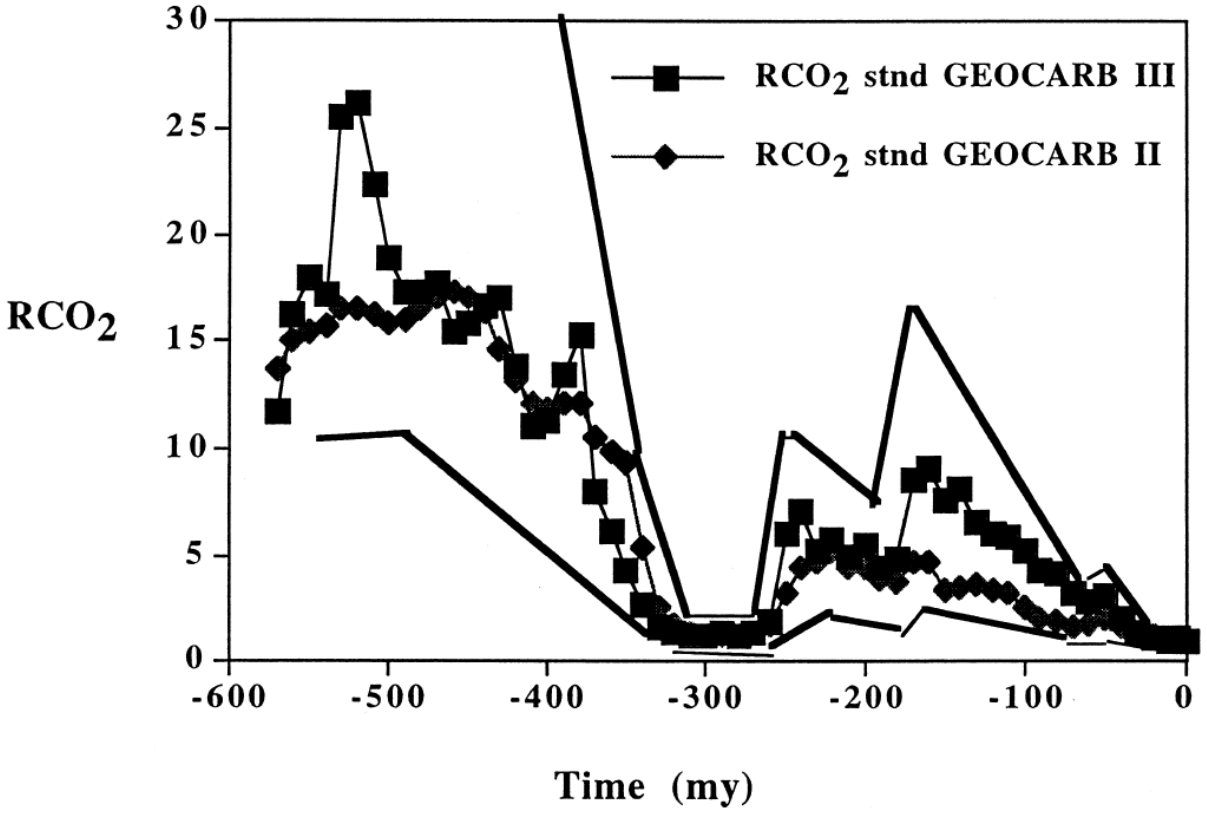
Arthropleura 8.5 feet long weighing 110 lbs.

Phanerozoic temperatures and pole-to-equator temperature gradients. Data from recent paleo-temperature reconstruction for the Phanerozoic (Scotese et al. 2021). Douwe G. van der Meer, Long-term Phanerozoic



Atmospheric Carbon Dioxide during the Phanerozoic

"…over the long term there is indeed a correlation between CO2 and paleotemperature, as manifested by the atmospheric greenhouse effect." Robert Berner and Zavareth Kothavala



millions of years ago	CO2 needed for current climate (ppmV)	Est. CO2 (ppmV) [Note 1]	Est. temp. relative to current (degrees C)
50	480	1000	2.4
100	580	1000	1.8
150	690	1000	1.2
200	820	2000	2.9
250	970	1000	0.11
300	1130	500	-2.7
350	1320	600	-2.6
400	1540	2000	0.86
450	1790	5550	3.7
500	2060	5550	3.3
550	2370	9250	4.5
600	2720	5550	2.4
Note 1: Estimated CO2 levels 50-400 million years ago from [Foster]. 450-600 million years ago from [Berner]			

R. A. Berner, Z. Kothavala, Am. J. Sci. 301, 182–204 (2001).

Two mass extinction events caused by life

- End-Ordovician caused by spread of moss(cryptogamic cover) over continental rock discovering acids that accelerated the weathering of rocks, leaching minerals such as phosphorus, 60 times faster than from bare rocks. They also developed hard shelled spores so they could spread over dryer rocky land. These nutrients caused algae blooms (eutrophication) which caused ocean hypoxia or anoxia, and the burial of carbon which caused an ice age. This together with a subsequent warming pulse caused the extinction of 85% of animal species and 25% of all marine families.

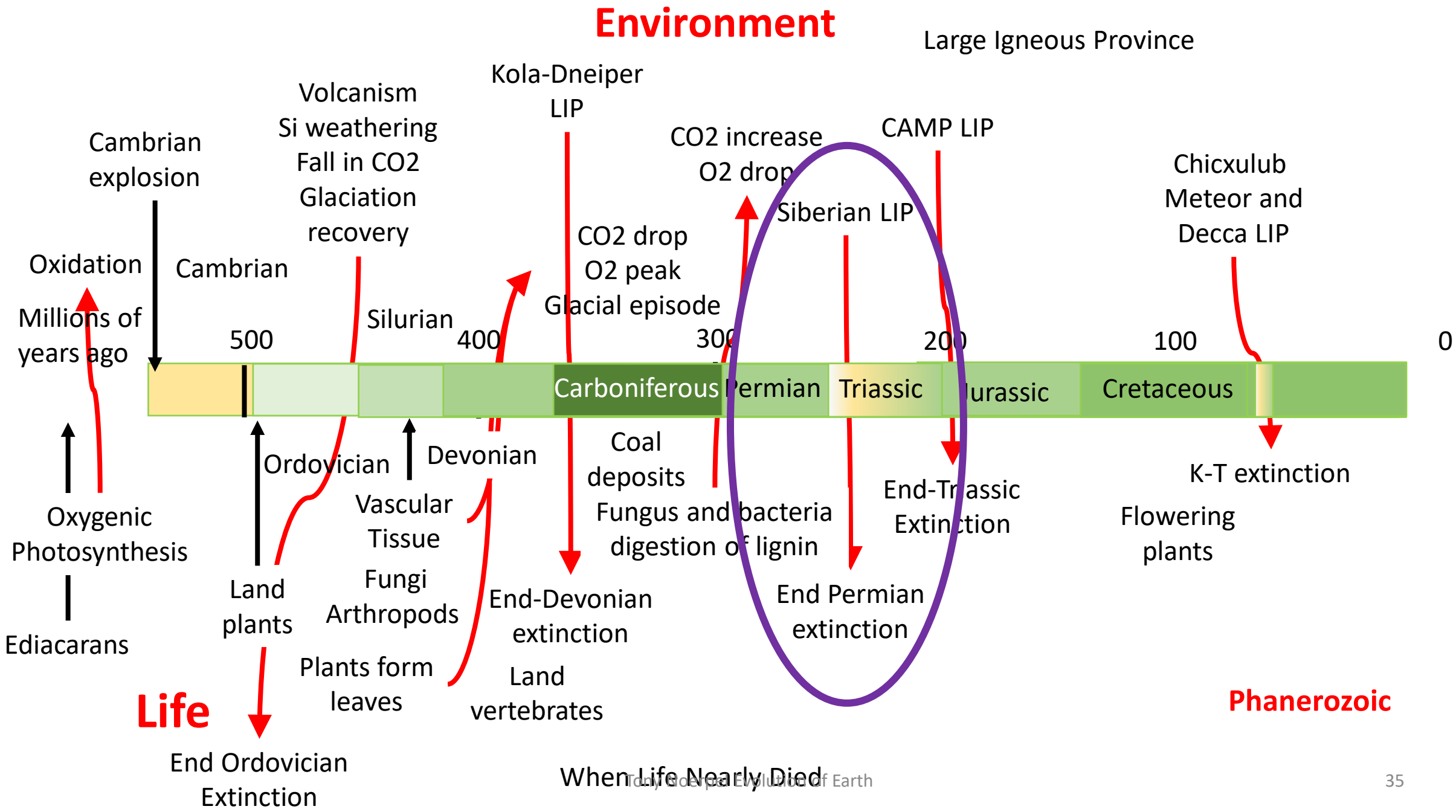
PBS EONS https://www.youtube.com/watch?v=mAkjETPM1s4
Rachel Philips, https://www.youtube.com/watch?v=DODZo8EgLg8&t=2s

- End-Devonian caused by vascular plants using roots to break up rocks even more. They also developed seeds which could spread to dryer regions. These plants grew tall and their roots formed the first soils. But like moss, they could extract even more nutrients from rock.

Rachel Phillips, https://www.youtube.com/watch?v=AE92ESdnuU0

Comparison of extinction events

Date/event	organism	innovation	consequences
2400mya/The Great Oxidation Event	cyanobacteria	Oxi-photosynthesis	Oxygen atmosphere, Global cooling, CO2 and CH4 drawdown. Extinction event
440 mya End Ordovician extinction	Moss (cryptogamic cover)	Acids that could erode rocks releasing nutrient minerals. Hard cover for spoors.	Extinction event in two phases. Cooling then warming. Enhanced nutrient runoff causes eutrophication and anoxia and withdrawal of CO2 from atmosphere. Then recovery
360 mya Devonian extinction	Vascular plants	Root systems increase rock weathering	Extinction event in two phases. Both cooling events. Enhanced nutrient runoff causes eutrophication and anoxia and withdrawal of CO2 from atmosphere.
Present Holocene extinction	Human	Fossil fuel metabolism Chemical farming Over exploitation Habitat destruction pollution	Increase CO2 and other GHG causing global warming. Enhanced nutrient runoff causes 500 estuary dead zones. Endocrine disruptors cause infertility, etc.


Environment
Large Igneous Province
Kola-Dneiper LIP
Volcanism
Si weathering
Fall in CO2
Glaciation
recovery
Cambrian explosion
CO2 increase
O2 drop
CAMP LIP
Siberian LIP
Chicxulub Meteor and Decca LIP
CO2 drop
O2 peak
Glacial episode
Oxidation
Cambrian
Silurian
Millions of years ago
500
400
300
200
100
0
Carboniferous
Permian
Triassic
Jurassic
Cretaceous
Coal deposits
Fungus and bacteria digestion of lignin
End-Triassic Extinction
K-T extinction
Flowering plants
Oxygenic Photosynthesis
Ordovician
Devonian
Vascular Tissue
Fungi
Arthropods
Land plants
Ediacarans
End-Devonian extinction
End Permian extinction
Plants form leaves
Land vertebrates
Life
End Ordovician Extinction
When Life Nearly Died
Phanerozoic

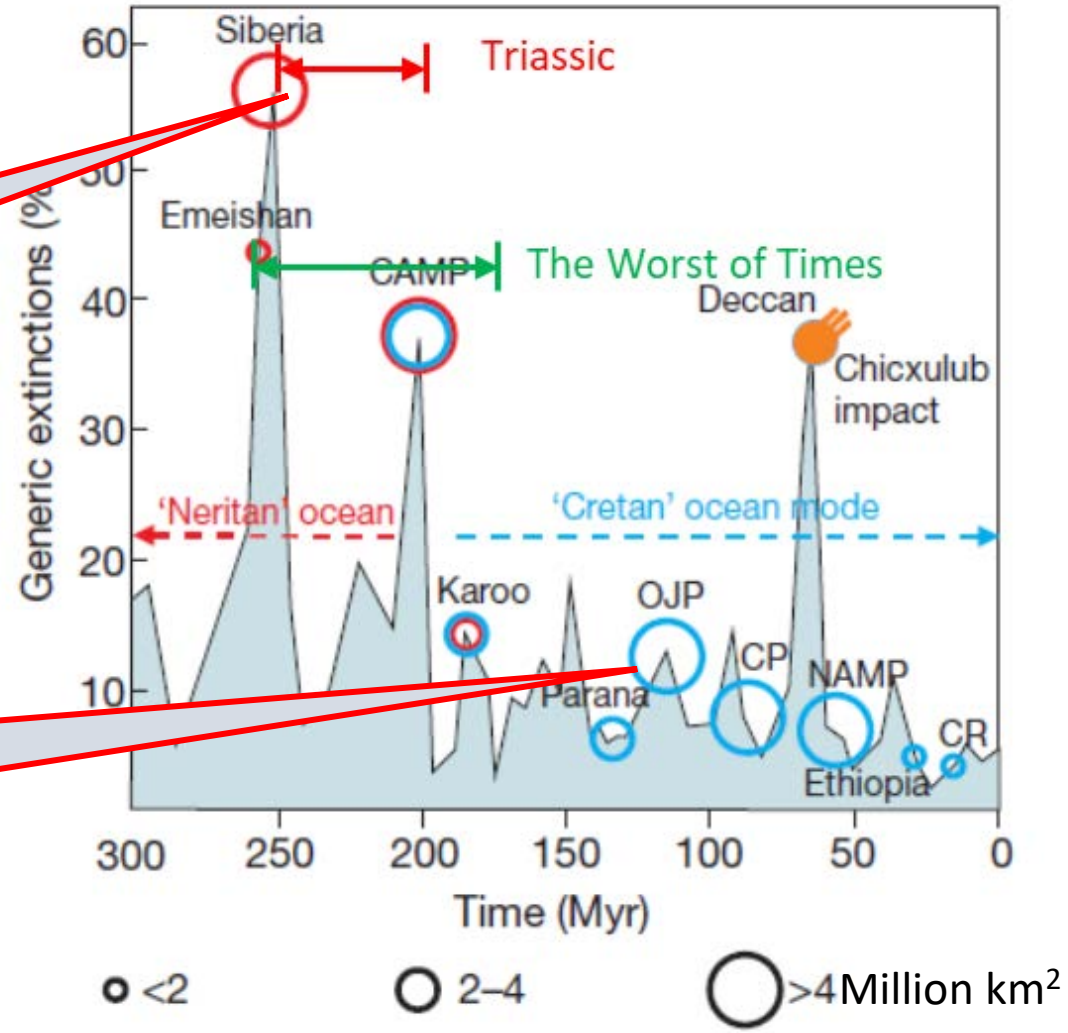
Extinction events

Analogue for current crisis
96% of plant and animal species go extinct, 99% of all life perished

Genus Homo, species sapiens

[LIP] http://www.largeigneousprovinces.org/

Why didn't these volcanic events cause major extinctions

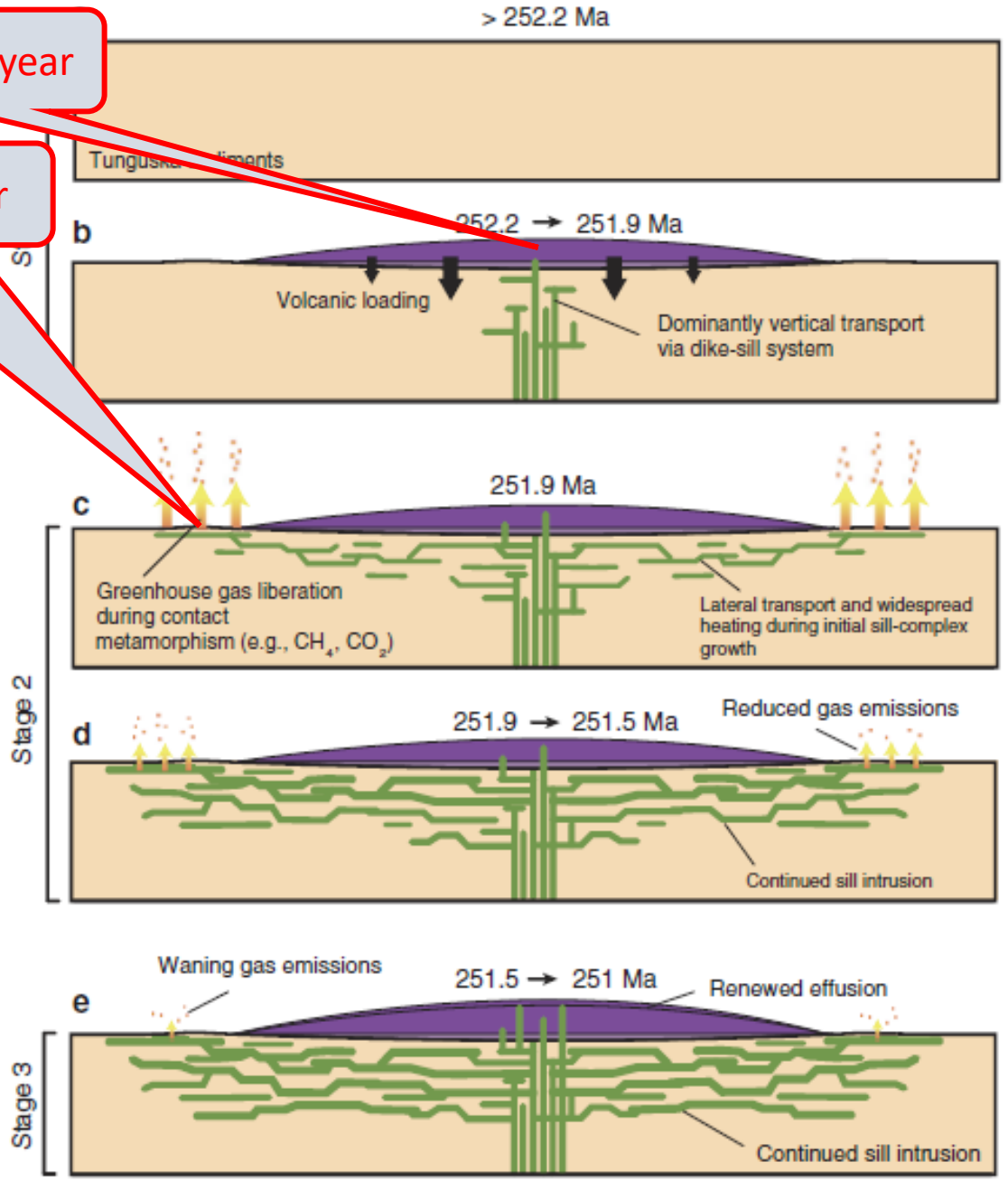


Plot of mass extinction intensity (light blue field) with major LIPs (circles) against geological time Stephan V. Sobolev, Alexander V. Sobolev, Dmitry V. Kuzmin, Nadezhda A. Krivolutskaya, Alexey G. Petrunin, Nicholas T. Arndt, Viktor A. Radko & Yuri R. Vasiliev, Linking mantle plumes, large igneous provinces and environmental catastrophes, Nature, Vol. 477, 15 September, 2011.

Kill mechanism carbon emissions from carbon rich sediment same source as human emissi 10% rate

< 100 MtC/year

About 1,000 MtC/year



[Burgess] S.D. Burgess, J.D. Muirhead & S.A. Bowring, Initial pulse of Siberian Traps sills as the trigger of the end-Permian mass extinction, Nature Comm. 2017, http://dx.doi.org/10.1038/s41467-017-00083-9

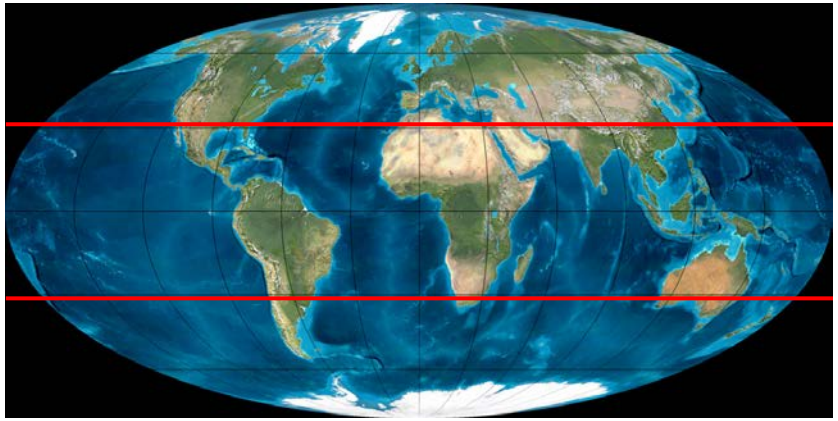
Kump LR. 2018 Prolonged Late Permian–Early Triassic hyperthermal: failure of climate regulation? Phil. Trans. R. Soc. A 376: 20170078. http://dx.doi.org/10.1098/rsta.2017.0078

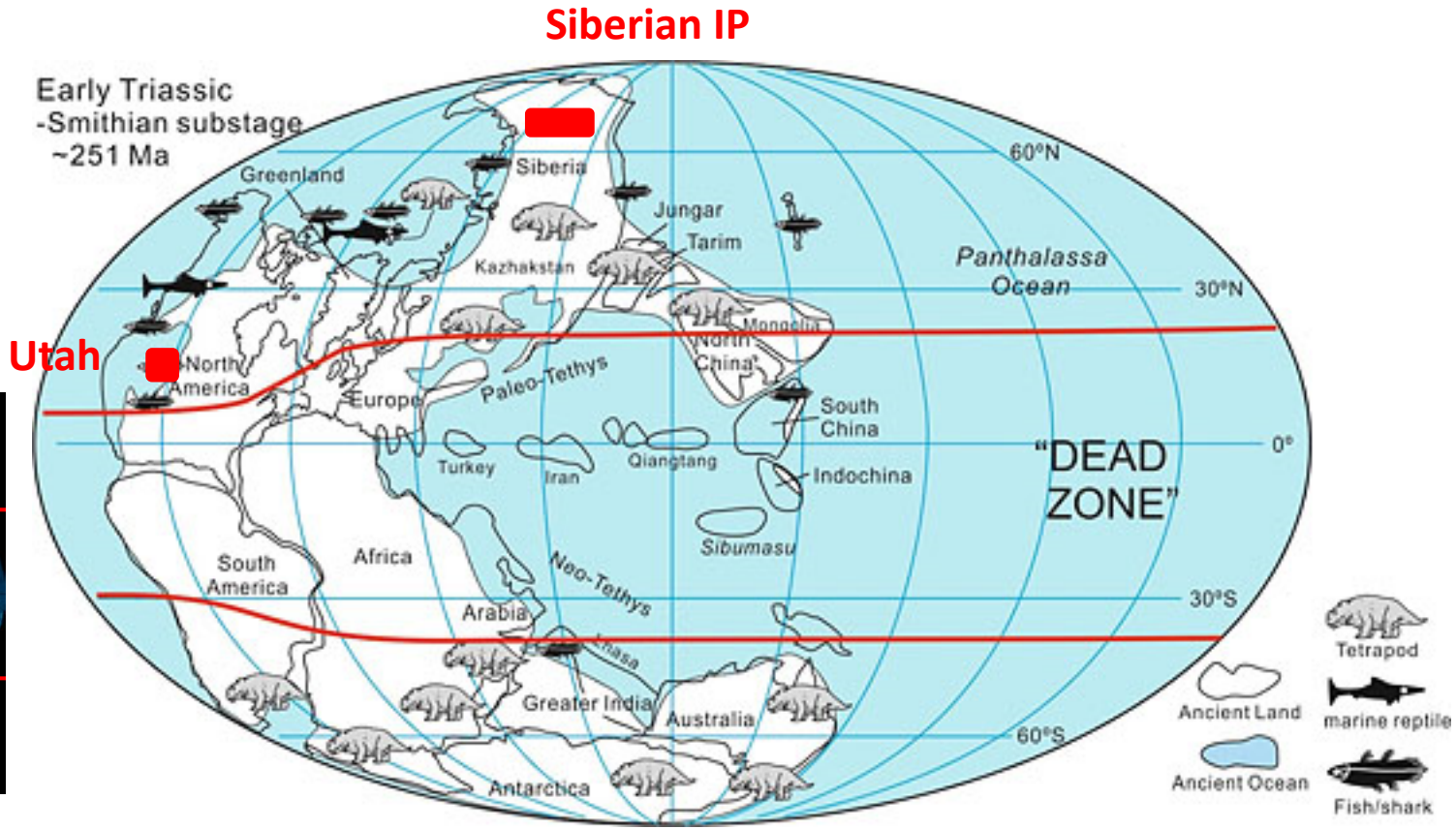
Jun Shen, et al. Evidence for a prolonged Permian–Triassic extinction interval from global marine mercury records. Nature Communications, 2019; 10 (1) https://doi.org/10.1038/s41467-019-09620-0

"Mercury evidence from southern Pangea terrestrial sections for end-Permian global volcanic effects" by Jun Shen et al., 3 January 2023, Nature Communications. https://doi.org/10.1038/s41467-022-35272-8

https://www.youtube.com/watch?v=uDH05Pgpel4
Benjamin J. Burger, What caused Earth's largest mass extinction event? New evidence from the Permian-Triassic boundary in northeastern Utah, submitted to Global and Planetary Change, a pre-print is available at: https://eartharxiv.org/khd9y

End Permian Extinction dead zone – 50% of Earth surface





Dead zone in the tropics (Source: University of Leeds). https://www.asianscientist.com/2012/10/in-the-lab/earth-hot-mass-extinction-250-million-years/ Yadong Sun, Michael M. Joachimski, Paul B. Wignall, Chunbo Yan, Yanlong Chen, Haishui Jiang, Lina Wang, Xulong Lai, Lethally Hot Temperatures During the Early Triassic Greenhouse, Science 19 Oct 2012: Vol. 338, Issue 6105, pp. 366-370 DOI: 10.1126/science.1224126
Alexandra Witze, Ancient volcanoes exposed, Geologists unearth signs of huge planet-altering events stretching back 3 billion years Nature, 16 March 2017, Vol. 543.

Comparison of current extinction event and the End-Permian

"It would be speculative to superimpose the ancient mass extinction event on today's planet," Hülse said. "However, the study does show us that the ocean's response to higher carbon dioxide concentrations in the atmosphere may be underestimated."

"End-Permian marine extinction due to temperature-driven nutrient recycling and euxinia" by Dominik Hülse, Kimberly V. Lau, Sebastiaan J. van de Velde, Sandra Arndt, Katja M. Meyer and Andy Ridgwell, 28 October 2021, Nature Geoscience. https://doi.org/10.1038/s41561-021-00829-7

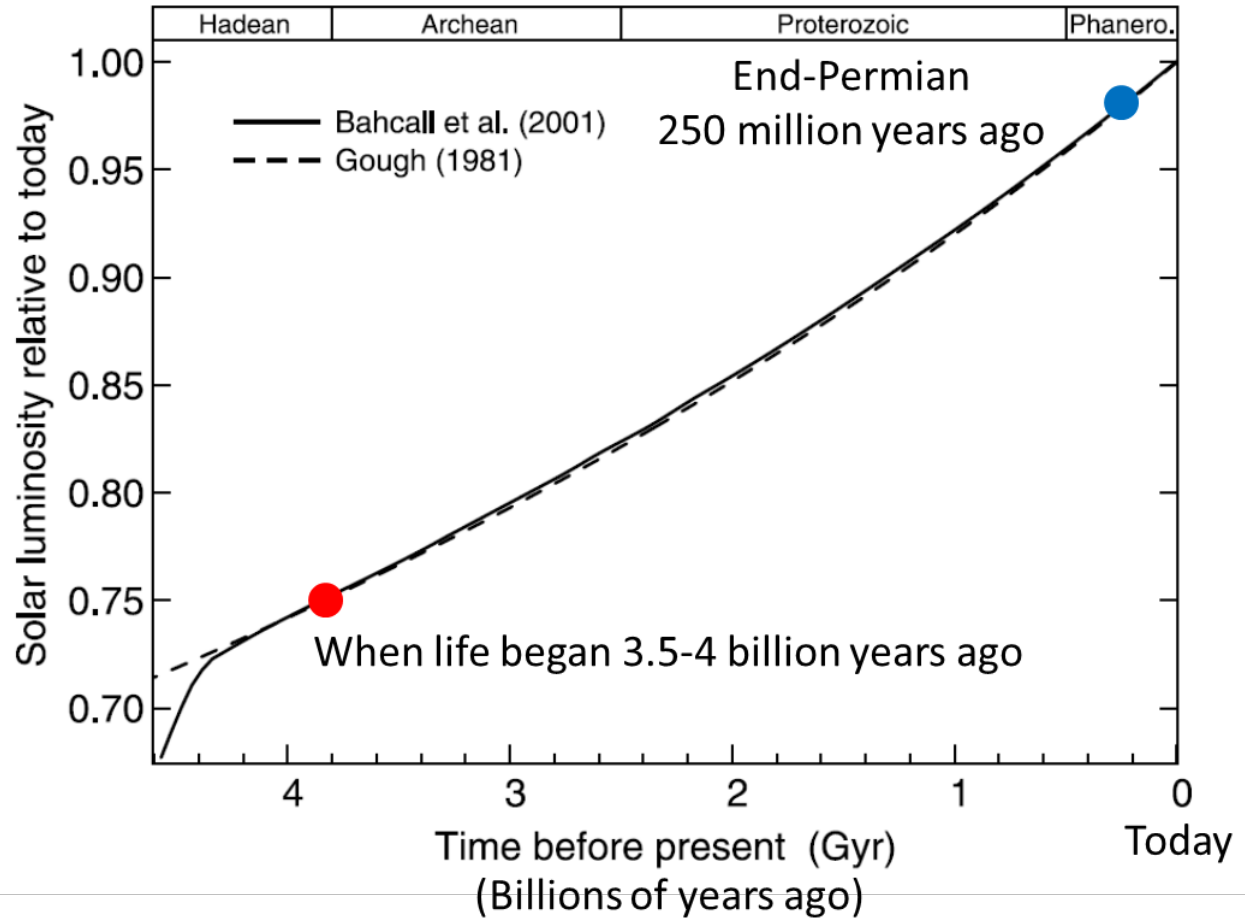
Conodonts were not doing any of this 250 million years ago and even if we managed to get our emissions under control, we'd still be killing lots of life on the planet.

Comparison between anthropogenic climate change and the End Permian mass extinction		
	End Holocene	**End Permian**
Sea level rise	**Up to 45 mm/yr [Garner]**	Low (?)
Ocean acidification rate	Extremely high [Honisch]	High
Total ocean acidification	High	High
Ocean anoxia	**Hypoxia [Breitburg]**	Anoxia [Lau]
Climate change rate	Extremely high	High
Total climate change	High	High
Rate of carbon emissions as CO2 [Kump]	**10 GtC/y**	1 GtC/y [Kump]
Rate of GHG emissions (CO2-equivalent)	**16 GtC/y**	?
Total carbon emissions	**650 GtC**	**10,000 GtC [Foster]**
Storm intensity	High	?
Disease	**High**	Low
Invasive species	**High**	Low
Pollution	**High**	None
Over exploitation	**High**	None
Loss of habitat	**High**	None
Disruption of P and N cycles	**High**	?
Coral extinction	?	High

Human innovation

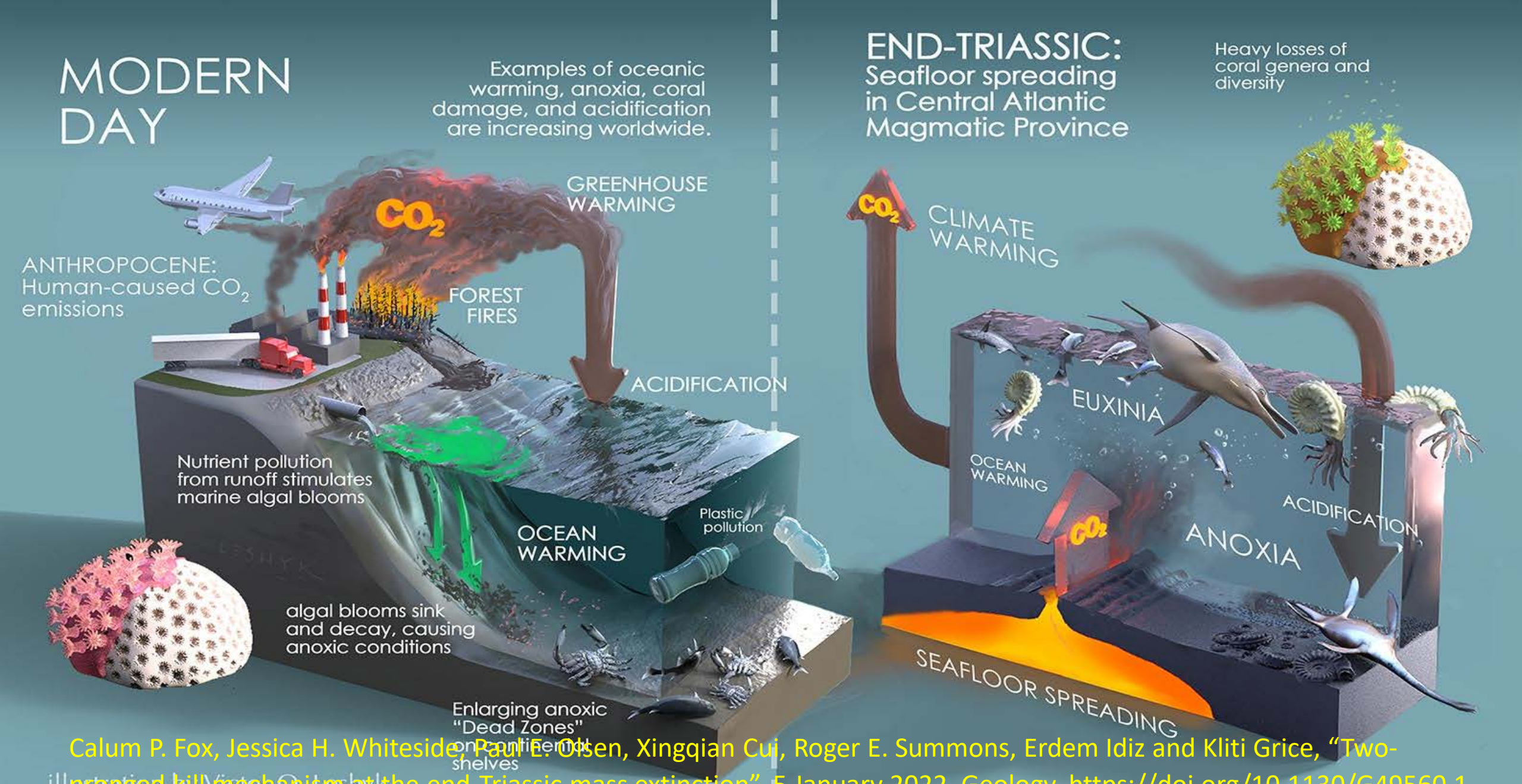
Faint young sun paradox – climate is more sensitive today to carbon emissions

Time period	Solar intensity Relative to today	Atmospheric Carbon dioxide (ppmV)	
		Modern climate	+ 7-10 °C
End Permian	**98%**	**700**	2800-5600
Today	100%	**300**	1200-2400
2.7 Mya* (Archaea)	80%	4000X current CO2	



* Using Royer et al. we calculate that atmospheric CO2 had to be about 4000 times the current level in order to have the same climate as today. [Lehmer] estimates based on geochemical arguments that carbon dioxide had to have been about 4000 times higher in order to explain certain rock formations in Australia. My calculation: https://blueridgeleader.com/looking-for-skepticism-part-4/

[Feulner] Georg Feulner, The faint young Sun problem, Rev. Geophys., 50, RG2006, doi:10.1029/2011RG000375, 25 May 2012. [Foster] Gavin L. Foster, Dana L. Royer & Daniel J. Lunt, Future climate forcing potentially without precedent in the last 420 million years, Nature Communications, DOI: 10.1038/ncomms14845 www.nature.com/naturecommunications 4 April, 2017 [Gough] Gough, D. O. Solar interior structure and luminosity variations. Solar Phys. 74, 21–34 (1981).



Calum P. Fox, Jessica H. Whiteside, Paul E. Olsen, Xingqian Cui, Roger E. Summons, Erdem Idiz and Kliti Grice, "Two-pronged kill mechanism at the end-Triassic mass extinction", 5 January 2022, Geology. https://doi.org/10.1130/G49560.1

https://scitechdaily.com/double-whammy-two-pronged-kill-mechanism-in-triassic-era-extinction-event/

Where did fossil fuels come from? – Buried sunshine

- Coal from trees that did not decompose during the Carboniferous
- Oil from marine life that did not decompose before subduction under continental plates during the Phanerozoic
- Methane from both
- USGS estimates there are 5,000 billion tons of carbon in the form of fossil fuels created over 500 million years or 10,000 tons per year on average
- We are using 10 billion tons of fossil carbon or about 1,000,000 years worth every year.

What we may have learned in Part 2

- The habitability of a planet depends in part on whether it is inhabited
- Life is far from thermodynamic equilibrium, i.e., in a low entropy state and requires a flow of energy to maintain that state and therefore increases total universal entropy
- At least three mass extinctions were caused by an organism developing a new metabolism and/or new reproductive trick.
- A planet probably has to be billions of years old to develop complex life
- We are emitting carbon dioxide 10 times faster into the atmosphere than the most extreme event during the Phanerozoic, and the worst extinction event of all time.
- We are burning about 1,000,000 years of sequestered carbon every year.
- Anthropogenic climate change denial is a form of mass psychosis

The entire history of the evolution of our environment

- Part 1 The evolution of the universe the first 9.3 billion years
  - Where did we come from
  - What are the laws
- Part 2 The evolution of Earth the next 4.5 billion years
  - Brief history of Earth, right up to the Cenozoic
- Part 3 The evolution of civilization, the Anthropocene
  - Current extinction event, the Holocene extinction
  - Climate change
- Part 4 The evolution of our possible futures
  - Economics (and our environment)
- Part 5 The evolution of our possible futures
  - Energy (and our environment)
- Part 6 solution space and discussion

https://www.youtube.com/watch?v=L0zlwdaPS4s
Euan Nisbet. Climate in Deep Time: From the Archean to the Ice Ages

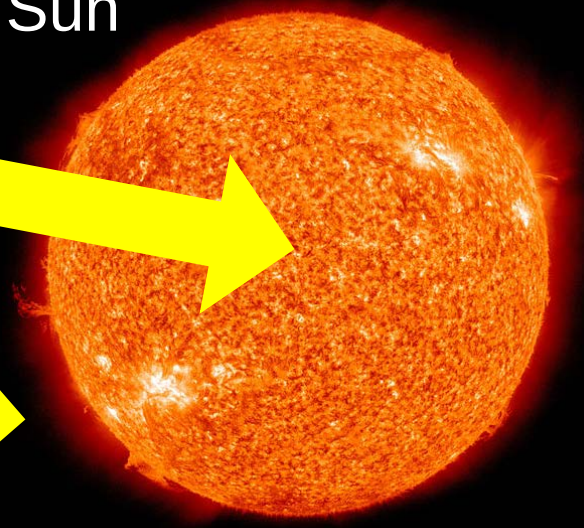
Cliff notes version of Charles Langmuir and Wally Broecker's "How to Build a Habitable Planet" or Paolo Saraceno, "Beyond the Stars" also Stanley and Luczaj "Earth System History" and Lunine "Earth".

An Engineer's perspective on the Human condition the evolution of civilization

Part 3

Plasma Core Temperature
15,700,000 K
(energy release rate: 276 μWatts/ cm^3)
1.2×10^{34} J

Sun



Highly energetic low entropy visible light photons

$3–5\times10^{-19}$ J

Earth system is a dissipative heat engine. The human economy is a dissipative heat engine

0.09 Watts/m^2

5770 K

1360.8 Watts/m^2

5.5×10^{24} J

288 K

Low energy high entropy infrared heat photons

$2–3000\times10^{-22}$ J

Empty space
2.73 K^o

E=hf

Not to scale

2.72 Wm^{-2} Effective Radiative Forcing due to human emissions IPCC AR6