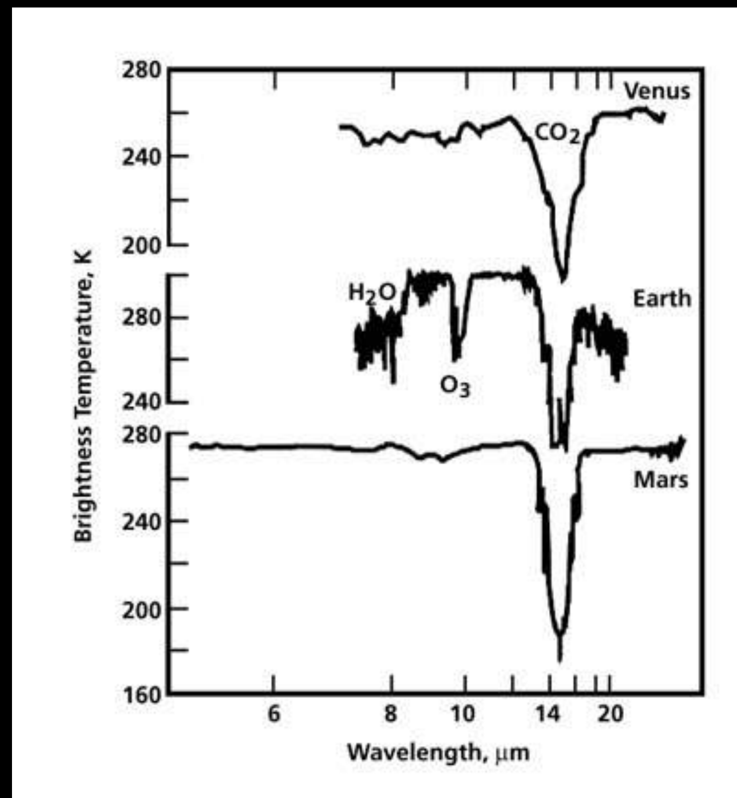
Life without Oxygen

Atmospheric oxygen informs our search for life

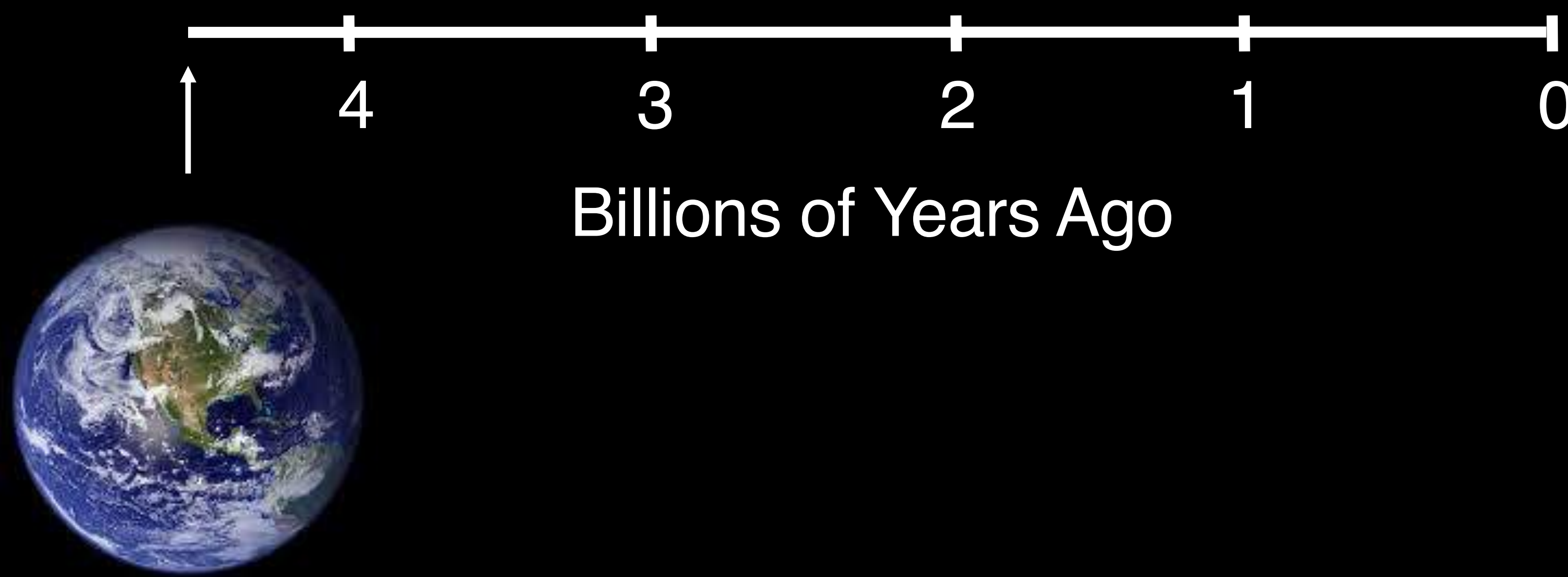
IR planetary spectra

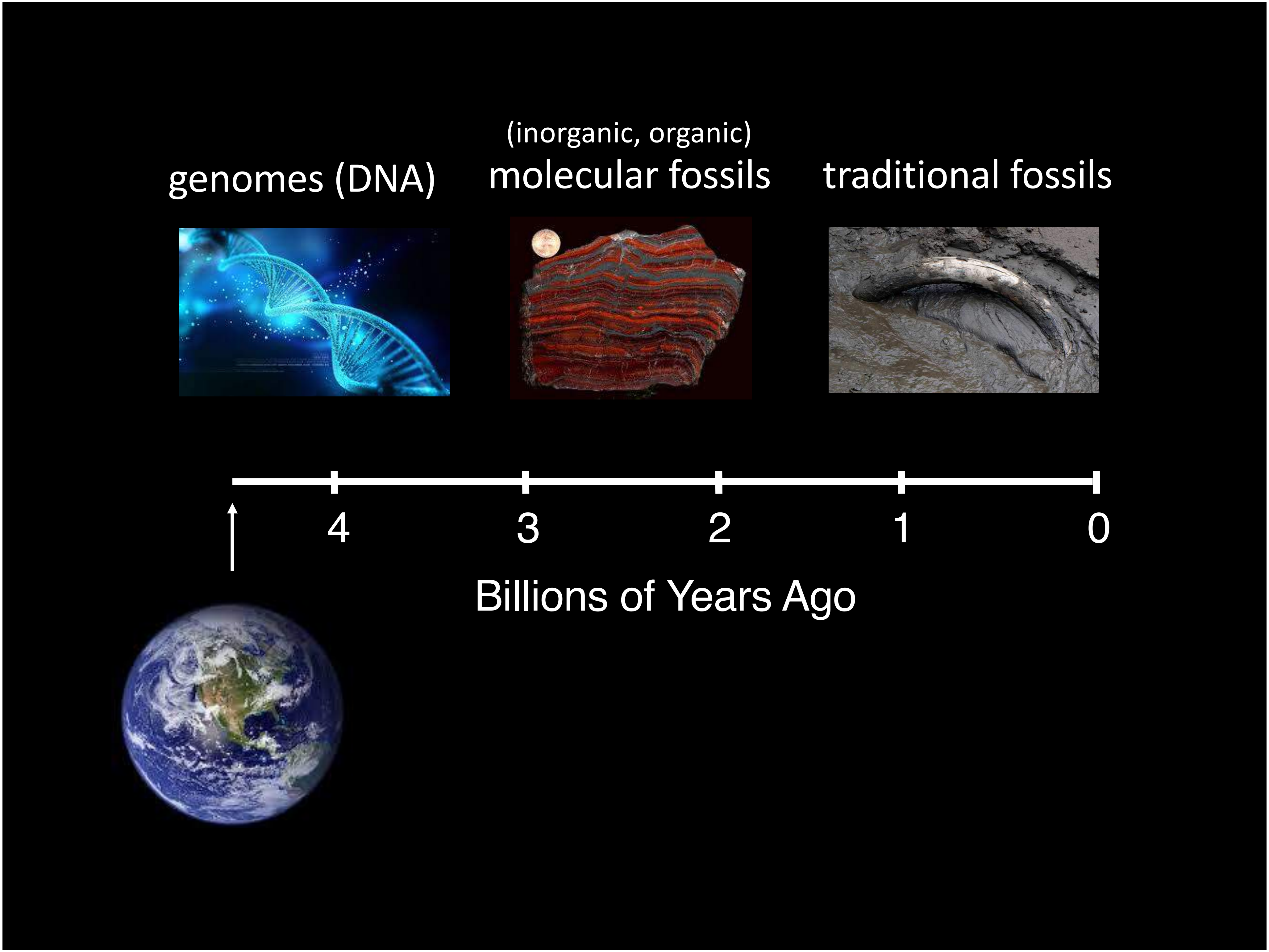


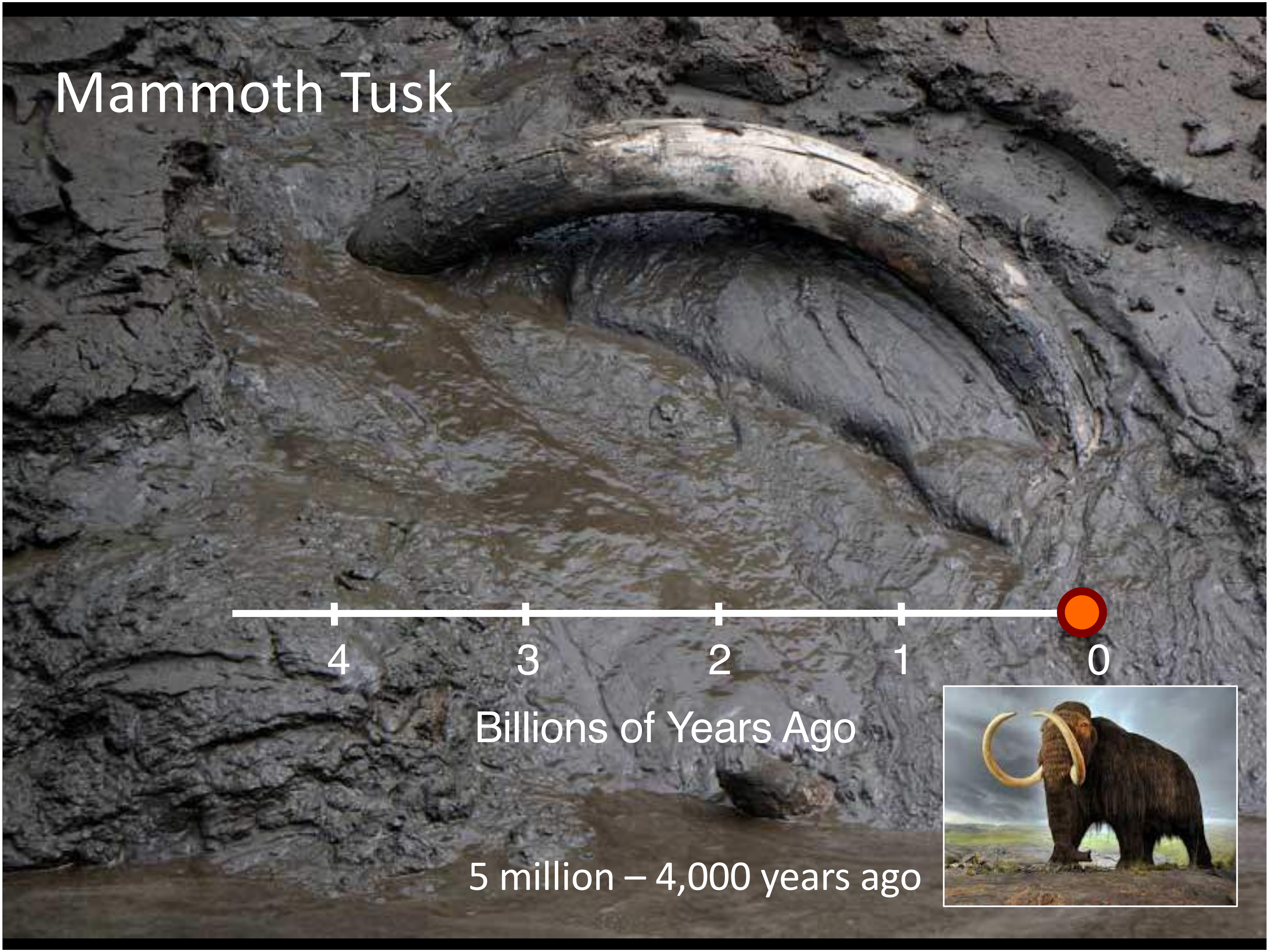
Prof. G Blake, Caltech

Yet had we been looking for oxygen, we would have missed the first billion years of life on Earth

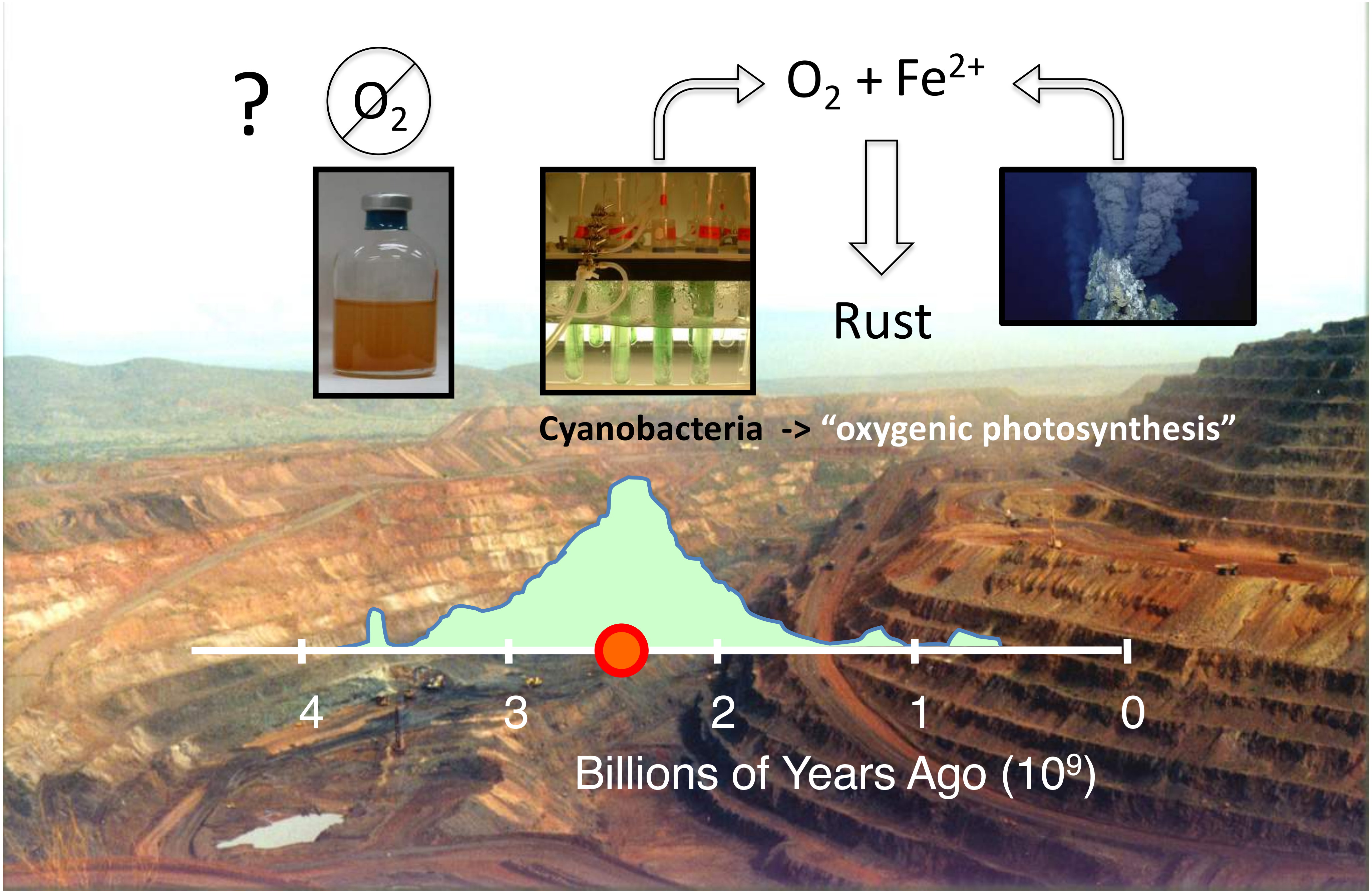
HOW DO WE RECOGNIZE ANCIENT LIFE?

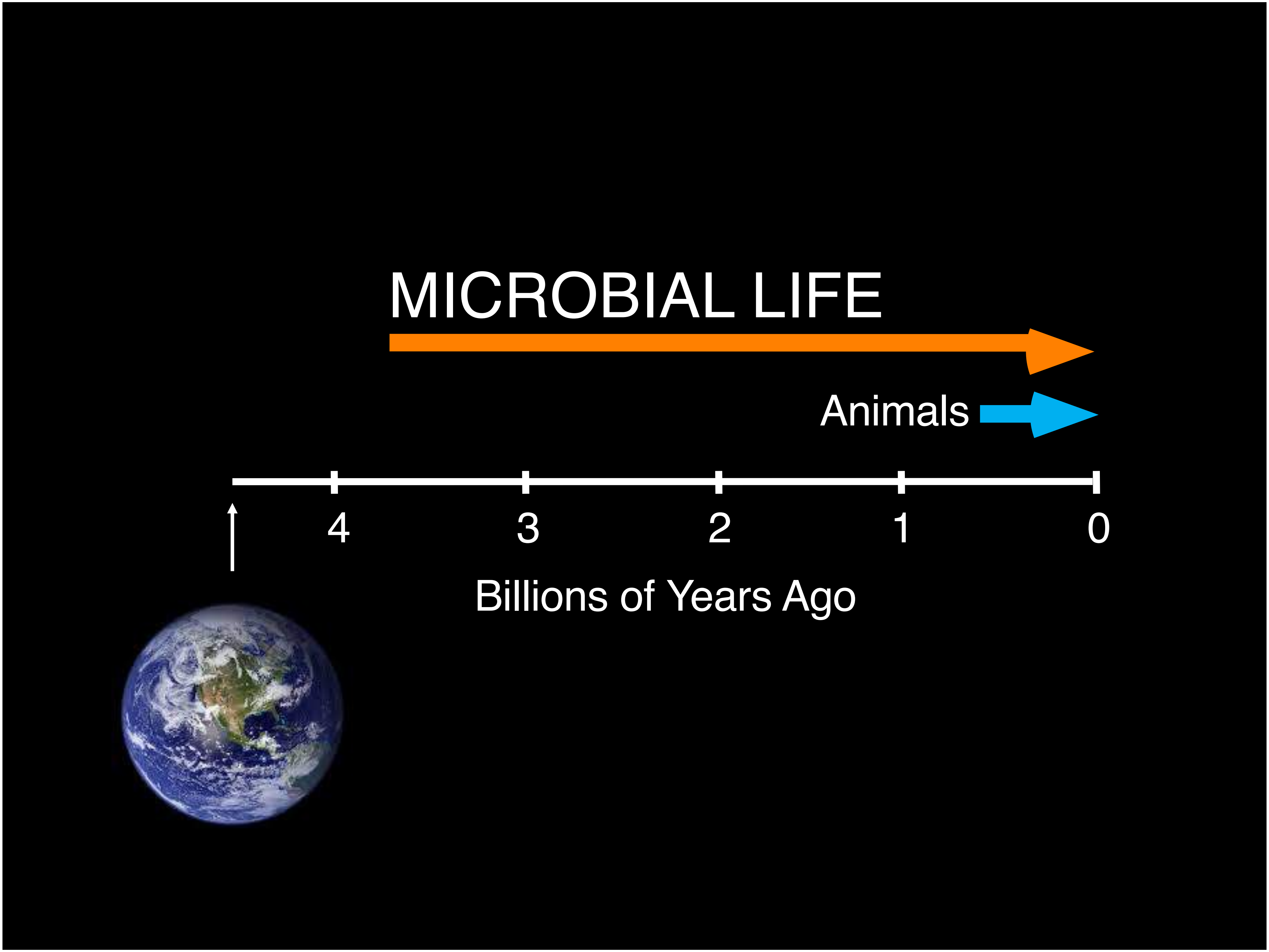


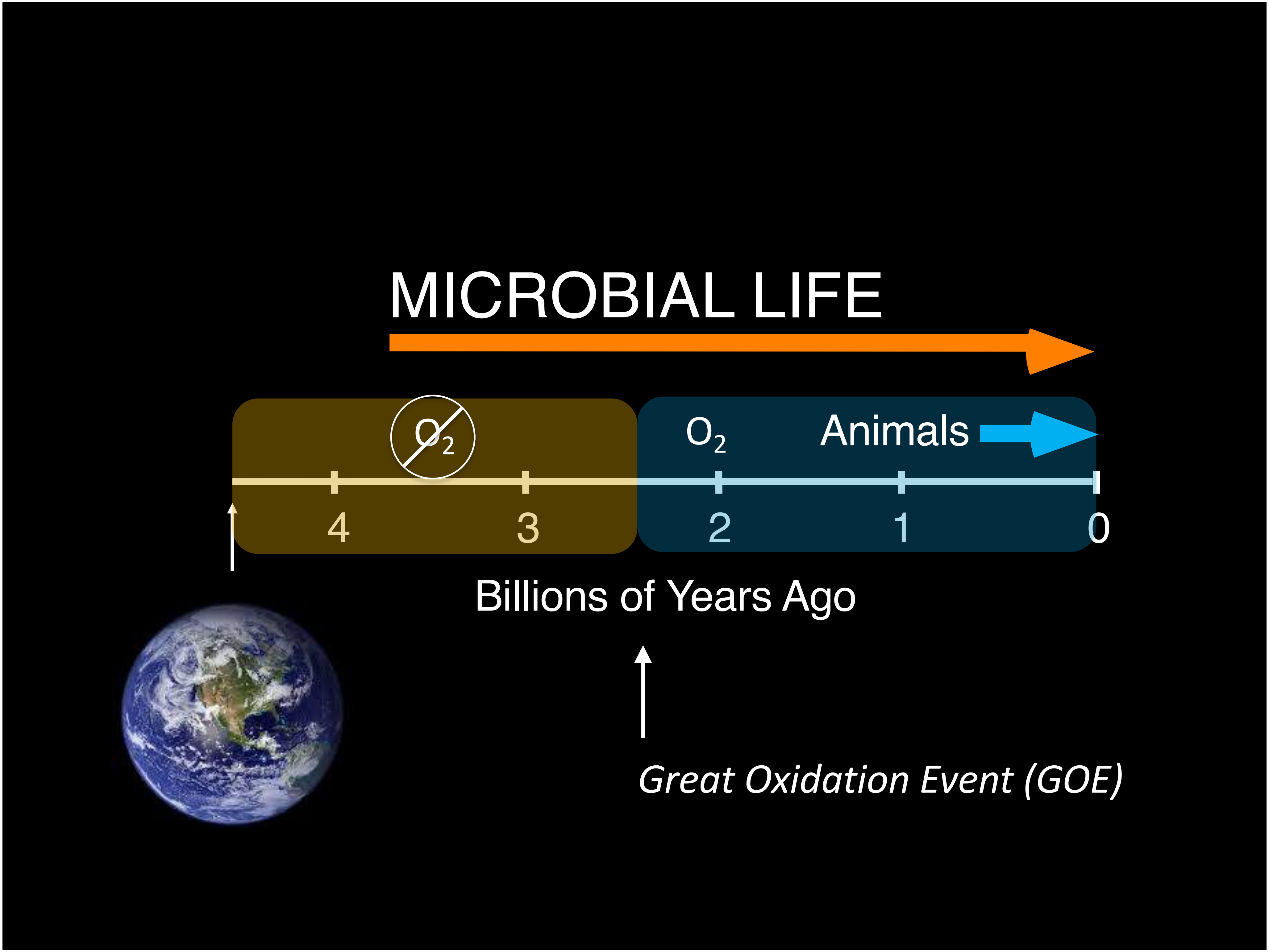

(inorganic, organic)
genomes (DNA)
molecular fossils
traditional fossils
4
3
2
1
0
Billions of Years Ago


Mammoth Tusk
4
3
2
1
0
Billions of Years Ago
5 million – 4,000 years ago

Banded Iron Formation

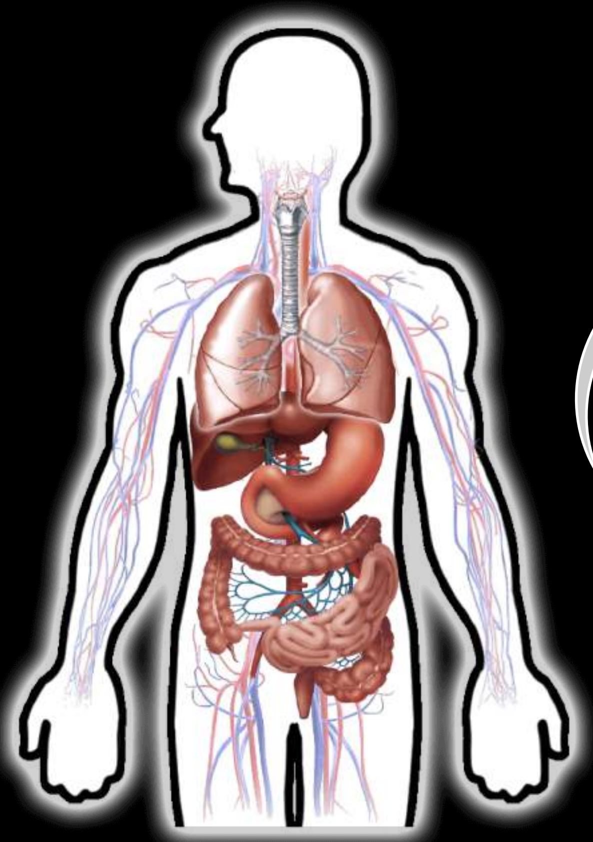



MICROBIAL LIFE
Animals
4
3
2
1
0
Billions of Years Ago


MICROBIAL LIFE
O2
O2
Animals
4
3
2
1
0
Billions of Years Ago
Great Oxidation Event (GOE)

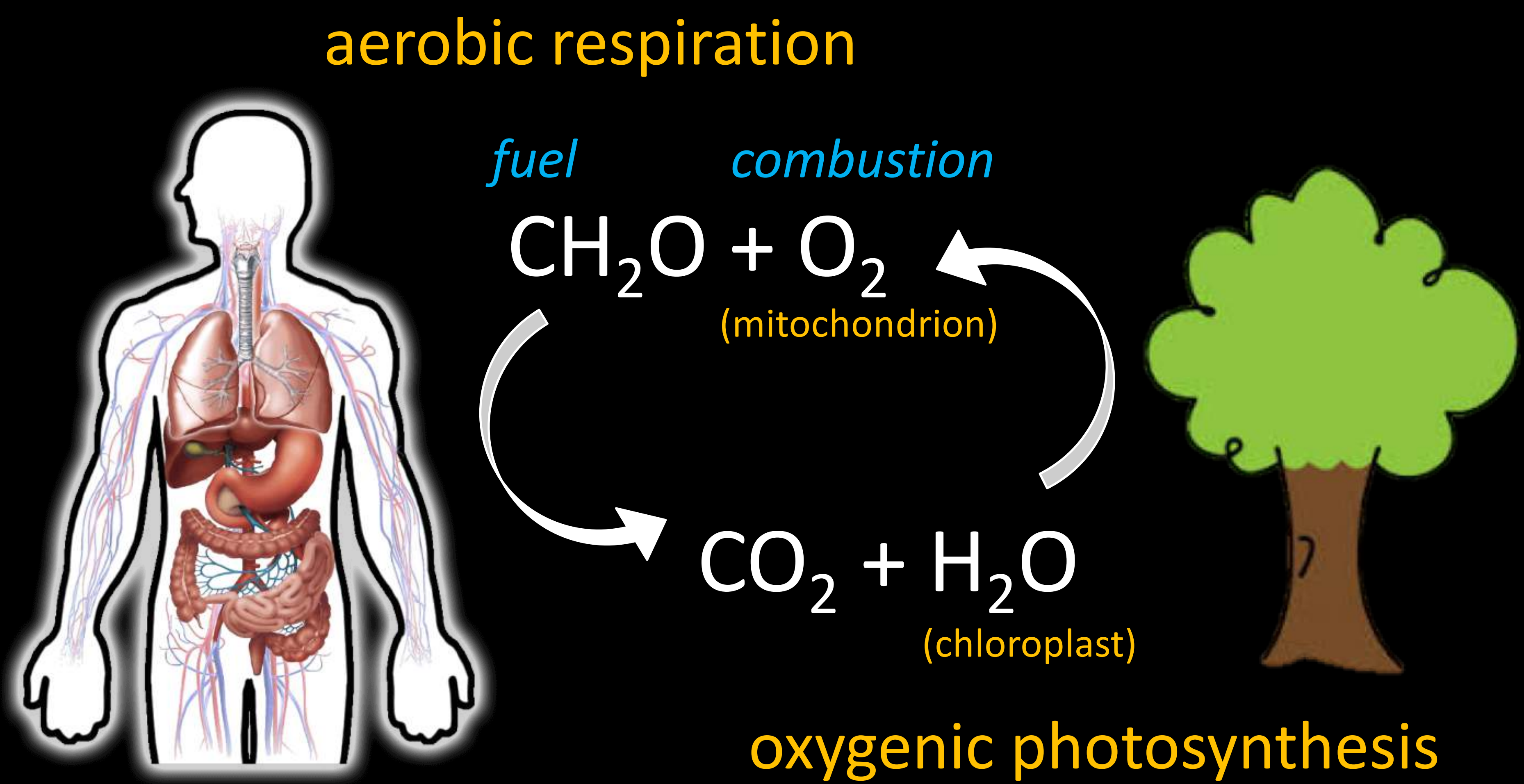
Common assumptions about metabolism derive from macroscopic eukaryotes

eating, breathing

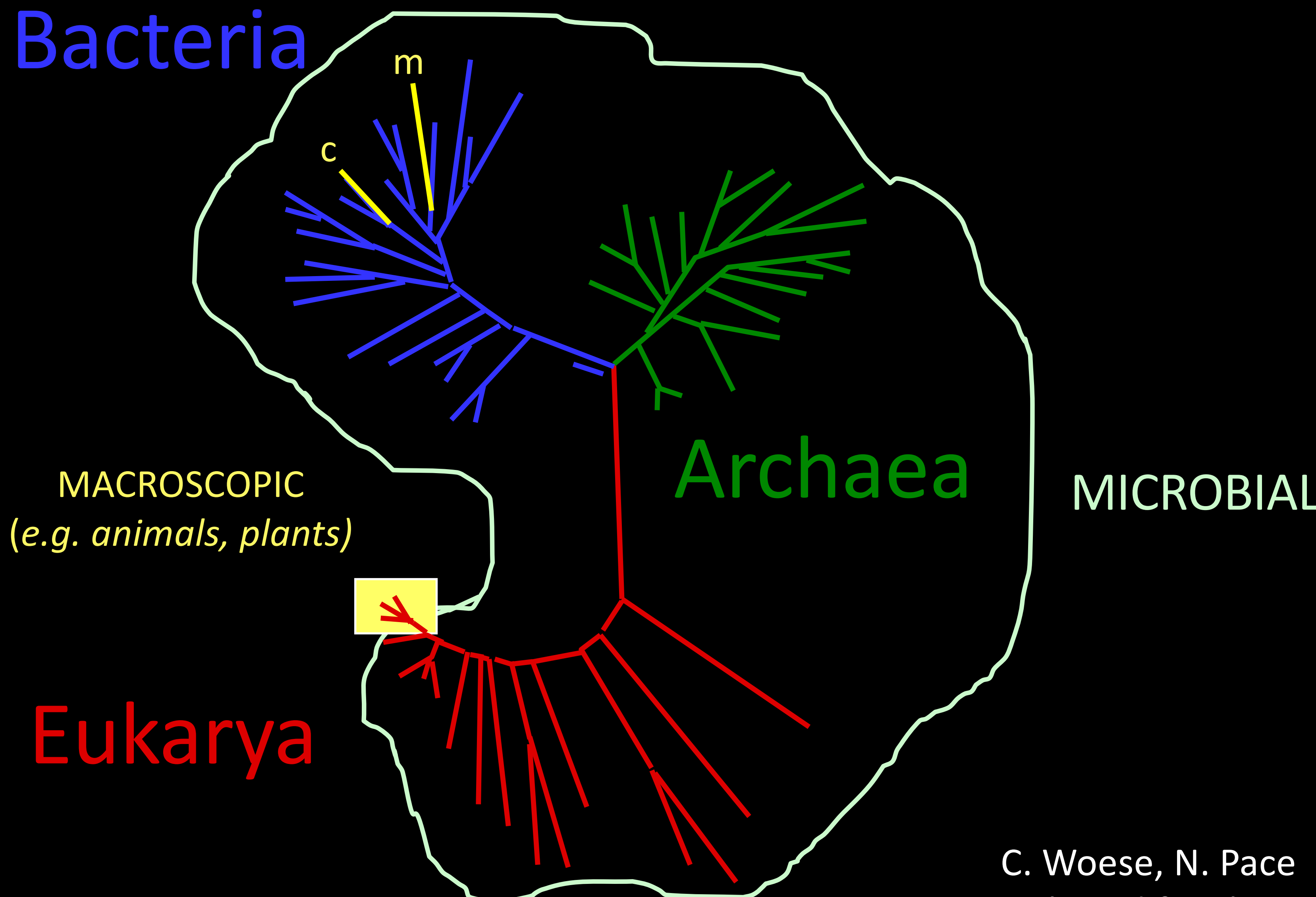


waste products

Common assumptions about metabolism derive from macroscopic eukaryotes



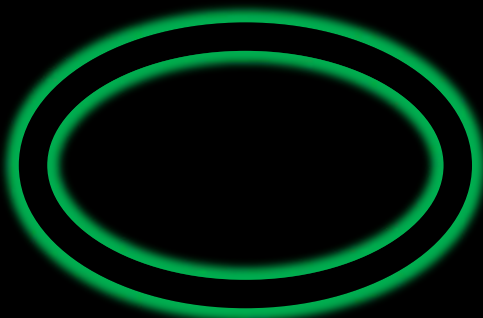
Yet most life on Earth does not require or produce O_2



C. Woese, N. Pace
RNA-based family tree

Electron transfer between <u>many</u> substrates (coupled to ion-translocation) can power cells

Electron transfer between many substrates
(coupled to ion-translocation) can power cells

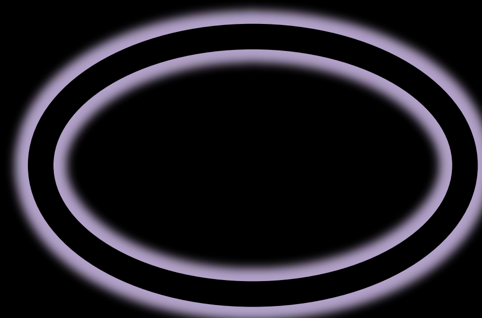


$CH_2O + O_2$

e^- donor e^- acceptor

e^- acceptor e^- donor

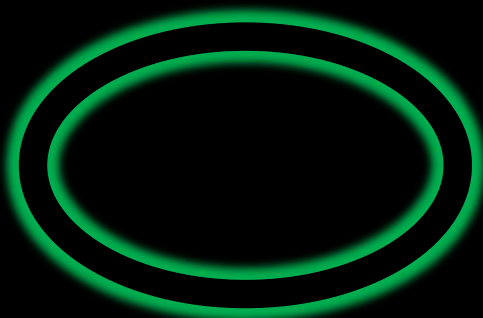
$CO_2 + H_2O$



cellular energy derives from the chemical potential difference between food substrates (e^- donor, e^- acceptor)

Electron transfer between many substrates

(coupled to ion-translocation) can power cells

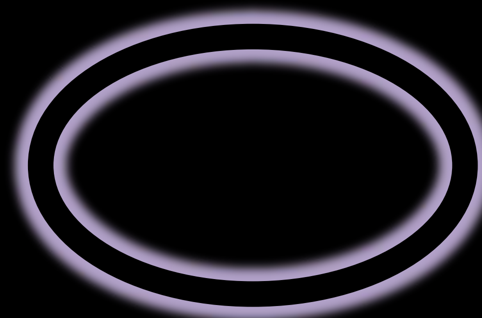


$CH_2O + Fe^{3+}$

e^- donor e^- acceptor

e^- acceptor e^- donor

$CO_2 + Fe^{2+}$



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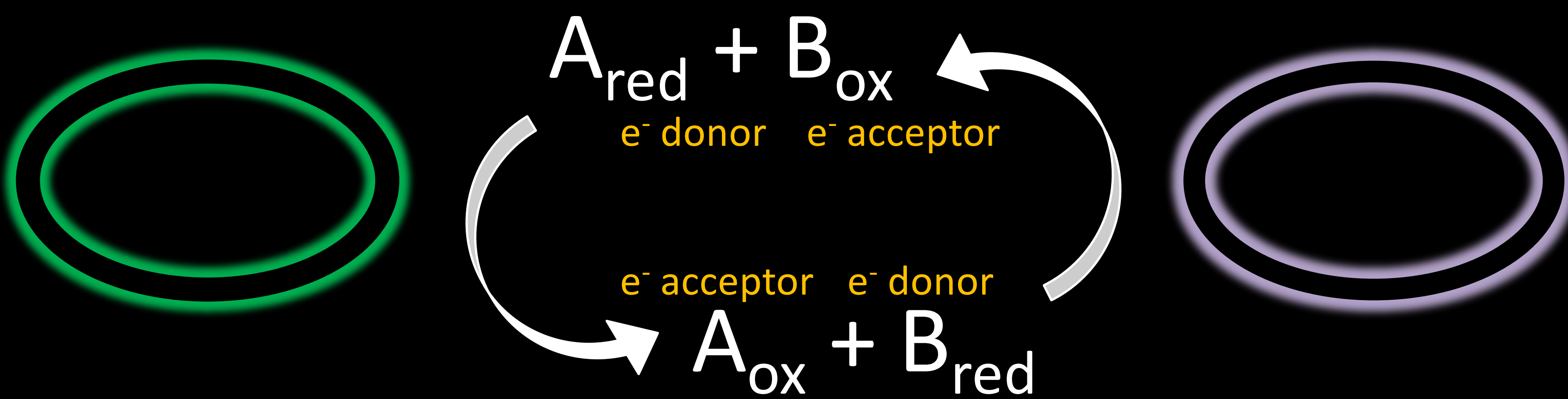
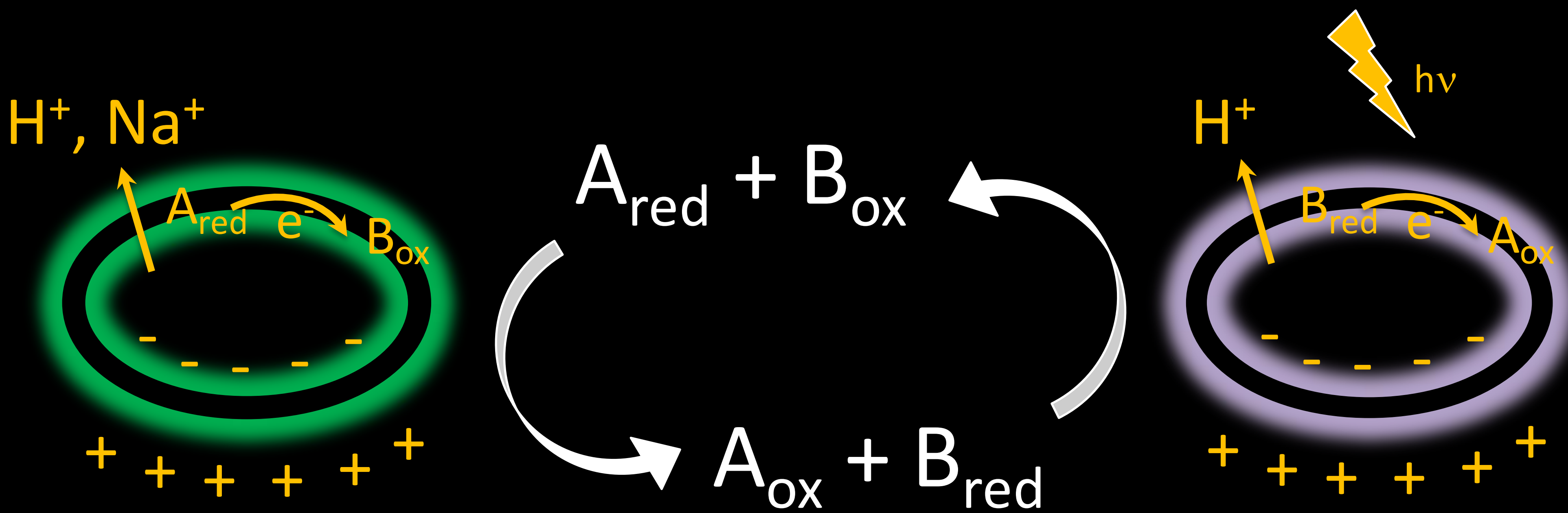


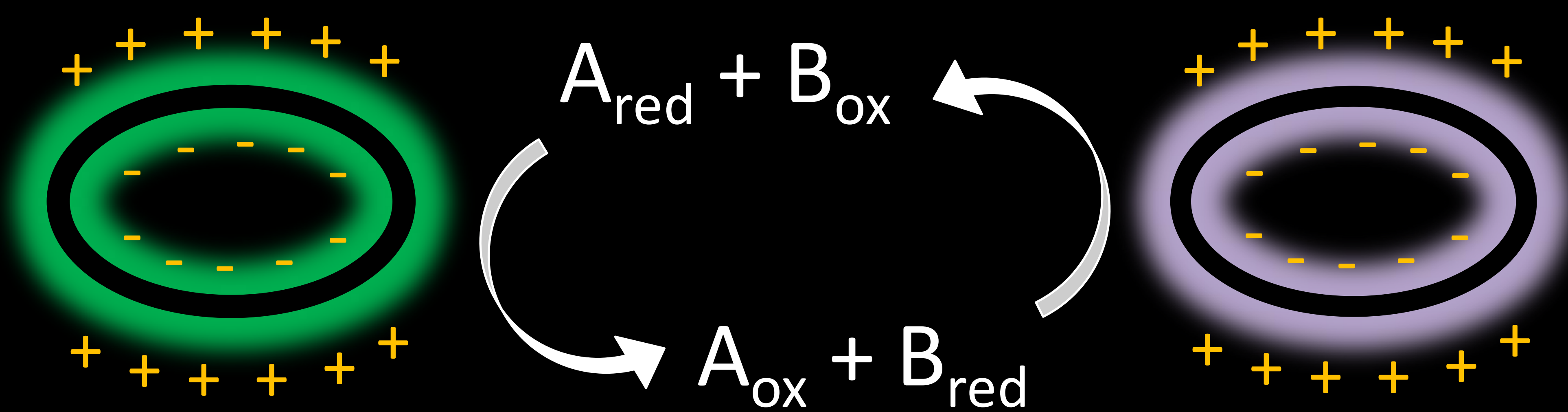
cellular energy derives from the chemical potential difference between food substrates (e^- donor, e^- acceptor)

Electron transfer between many substrates (coupled to ion-translocation) can power cells



e- flow through the membrane charges it up like a battery….

Electron transfer between many substrates (coupled to ion-translocation) can power cells



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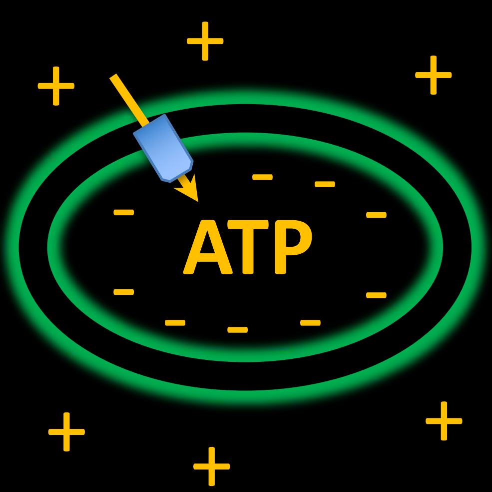
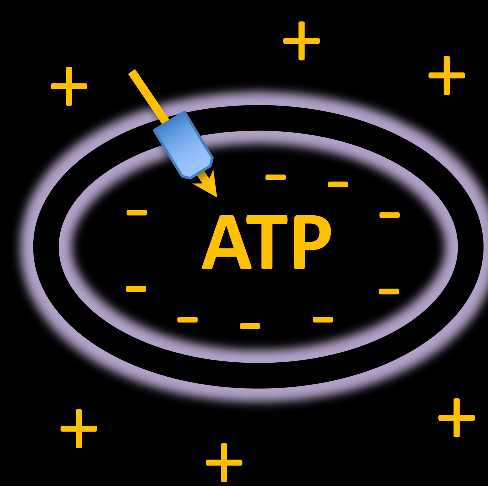
Electron transfer between many substrates (coupled to ion-translocation) can power cells



$$A_{red} + B_{ox}$$

$$A_{ox} + B_{red}$$



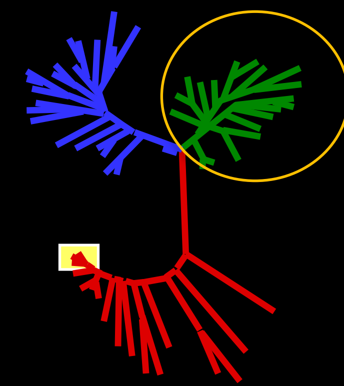
…allowing energy to be stored when the battery drains

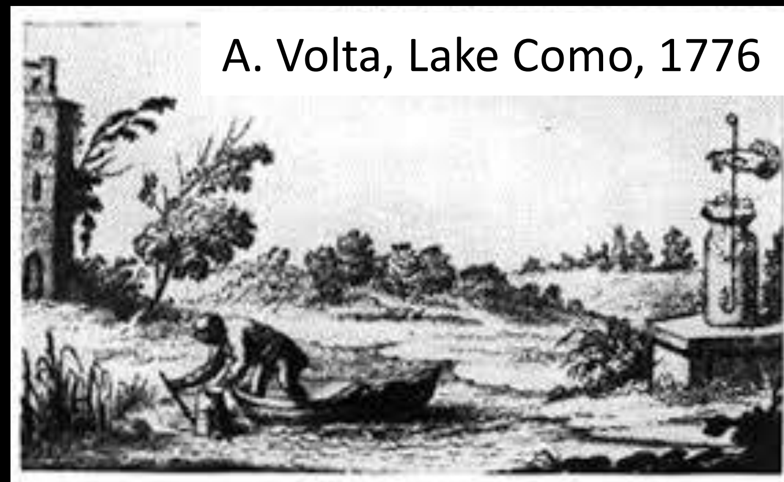
Peter Mitchell 1978 Nobel Prize

The cycling of substrates other than O_2/H_2O can have dramatic consequences *(past, present, future)*

Methanogenesis

$$A_{red} + CO_2 \rightarrow A_{ox} + CH_4$$



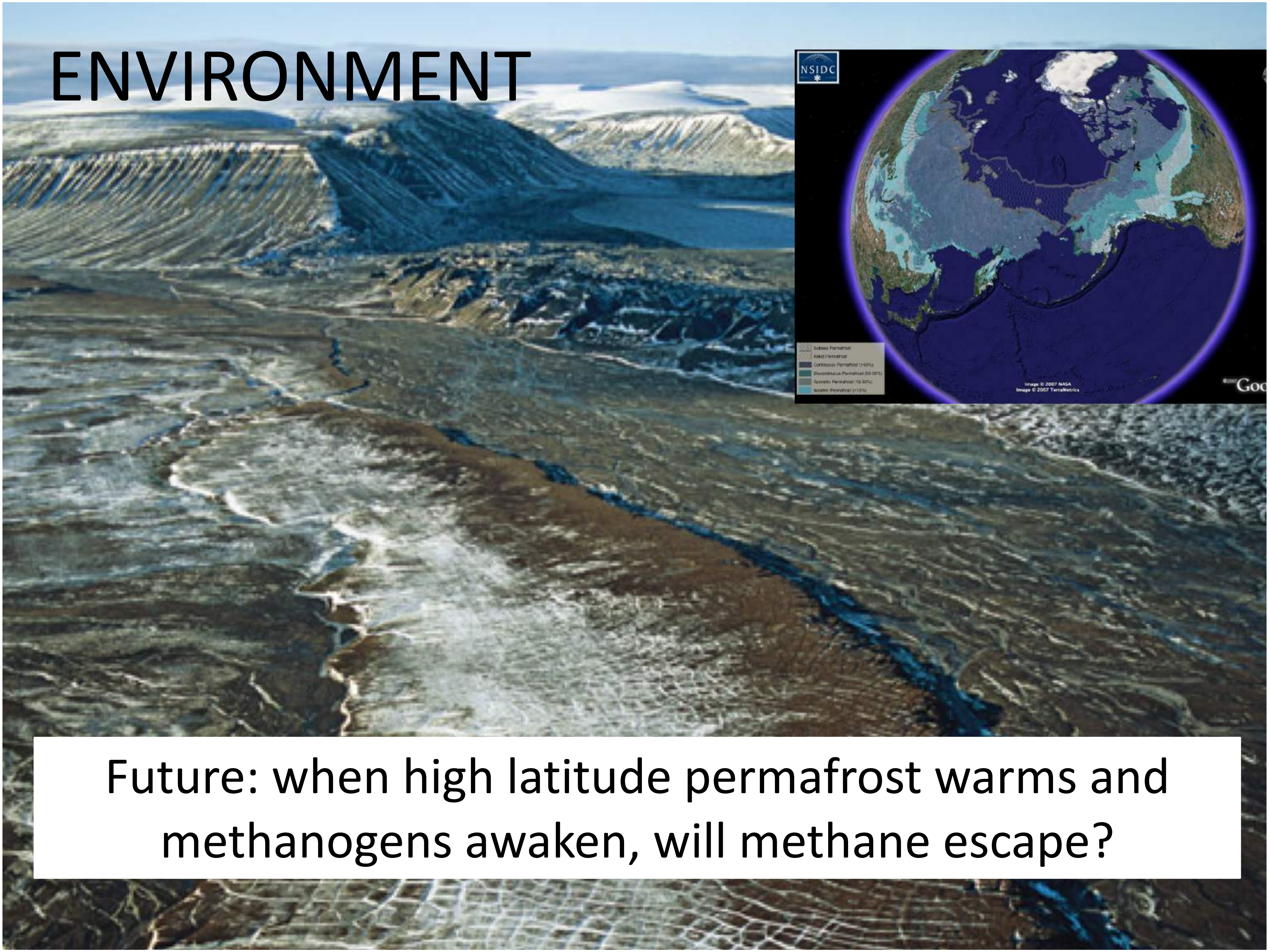


A. Volta, Lake Como, 1776

The “Volta Flame” Experiment, performed in a Minnesota bog

The "Volta Flame" Experiment, performed in Baxter Pond!

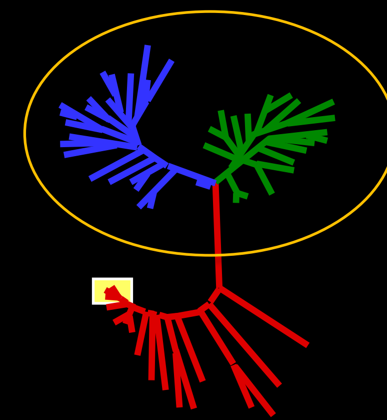
ENVIRONMENT

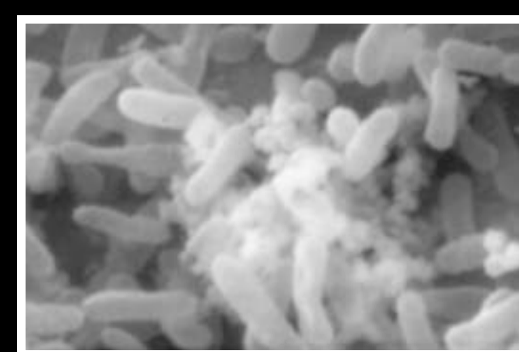


Future: when high latitude permafrost warms and methanogens awaken, will methane escape?

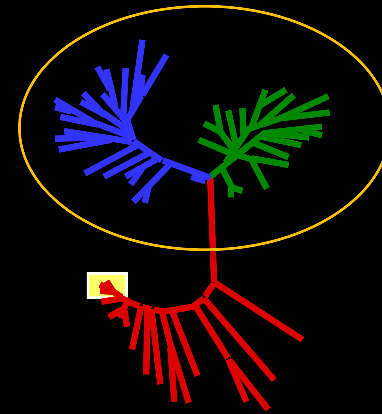
Respiring a rock:

$$CH_2O + Fe^{3+} \rightarrow CO_2 + Fe^{2+}$$





Respiring a rock:



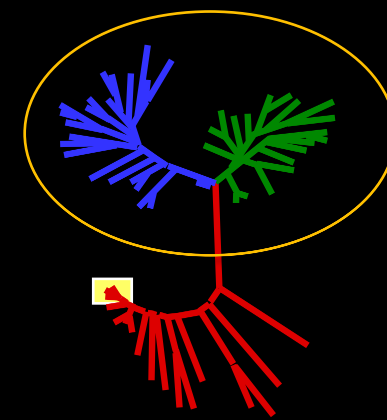
$$CH_2O + Fe(OH)_{3(s)} \rightarrow CO_2 + Fe^{2+}$$

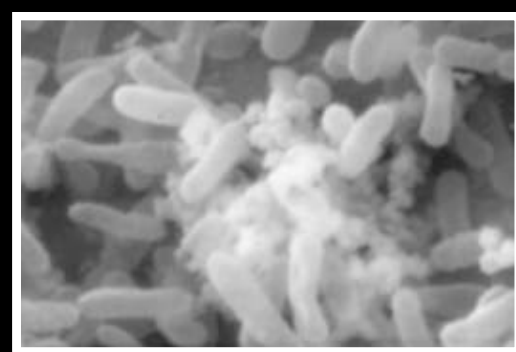
Respiring a rock can mobilize toxins:

arsenic
vvvvv

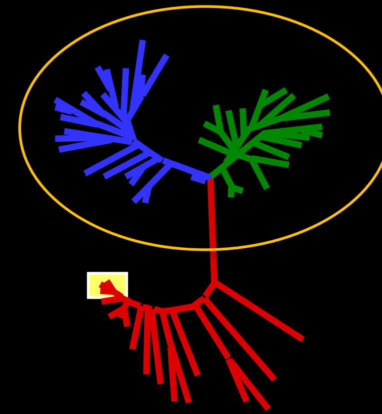
$CH_2O + Fe(OH)_{3(s)}$

$CO_2 + Fe^{2+}$ + arsenic





Respiring a rock can mobilize toxins:



arsenic
vvvvv

latrine waste + $Fe(OH)_{3(s)}$

$\longrightarrow$ $CO_2 + Fe^{2+}$ + arsenic

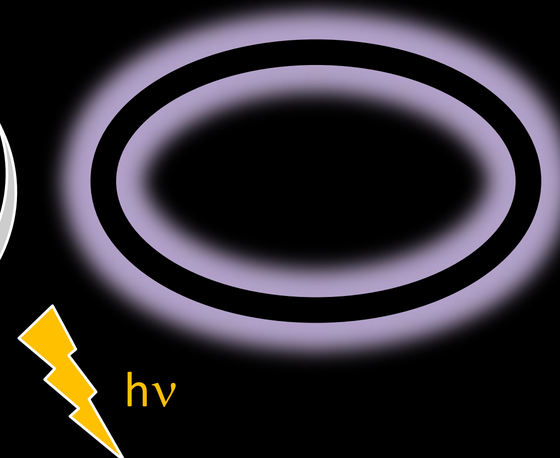
WATER QUALITY


Red pump
high arsenic

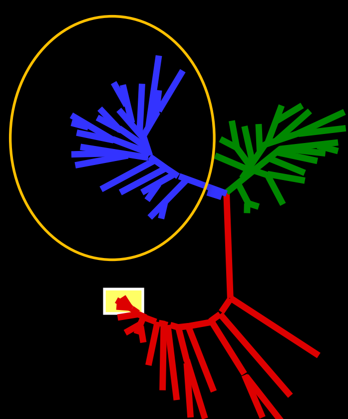

SONO FILTER

“Eating” iron with light:

$$CH_2O + Fe(OH)_{3(s)}$$



$$CO_2 + Fe^{2+}$$



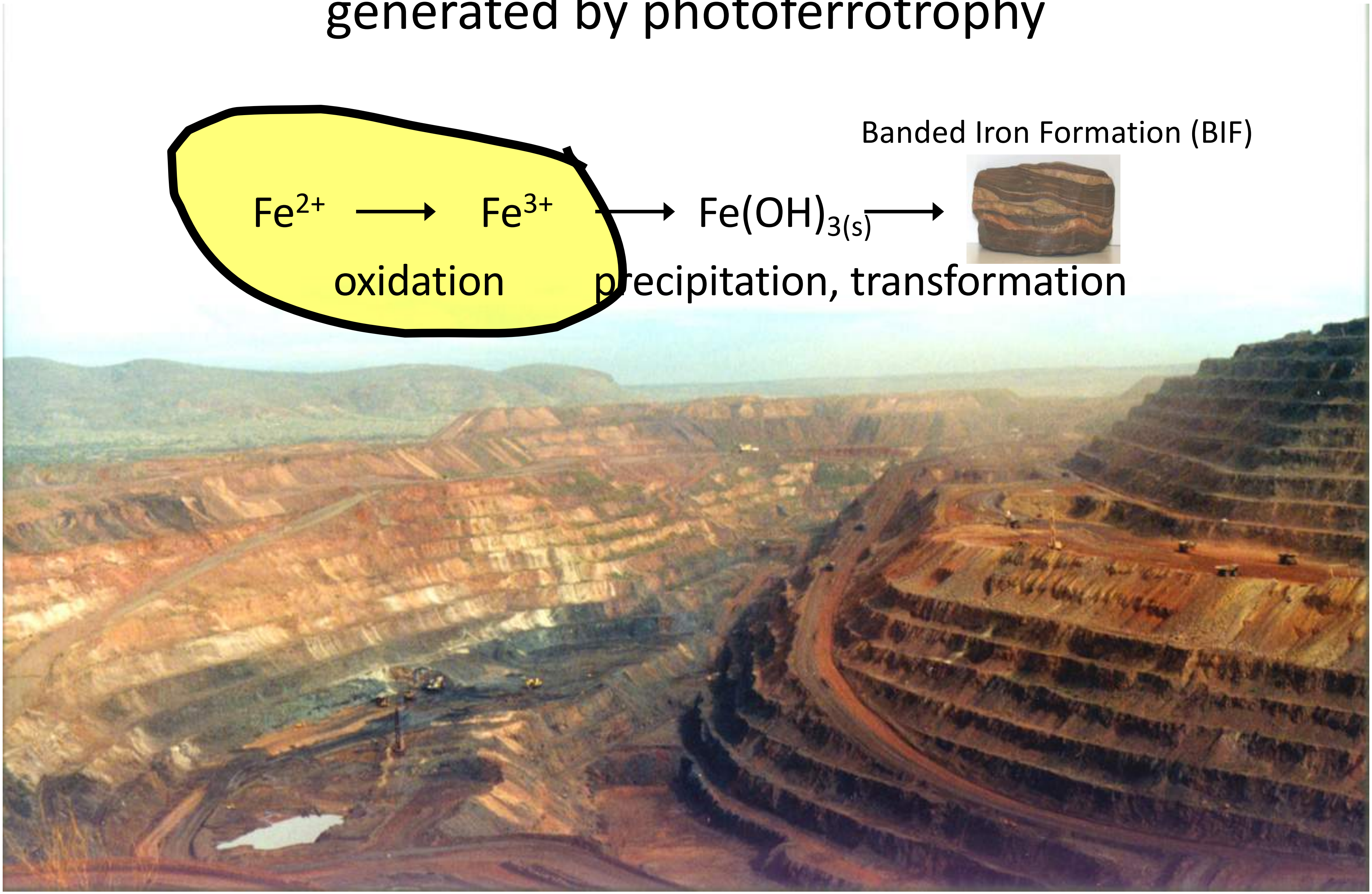
Photoferrotrophy

(anoxygenic photosynthesis)

Ancient iron ore deposits (>2.4 Ga) were likely generated by photoferrotrophy

$Fe^{2+} \xrightarrow[\text{oxidation}]{} Fe^{3+} \longrightarrow Fe(OH)_{3(s)} \longrightarrow$ Banded Iron Formation (BIF)

precipitation, transformation



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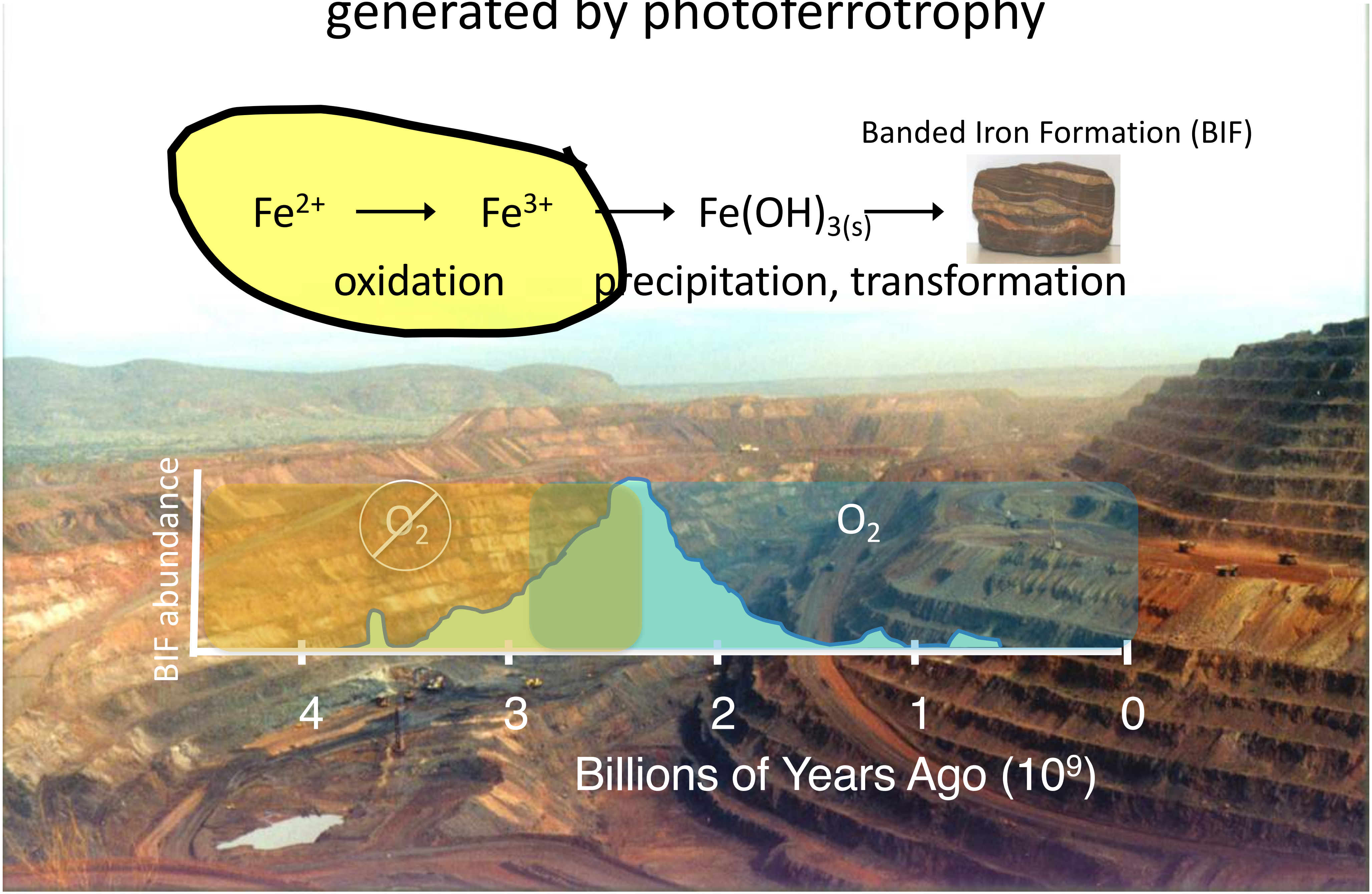
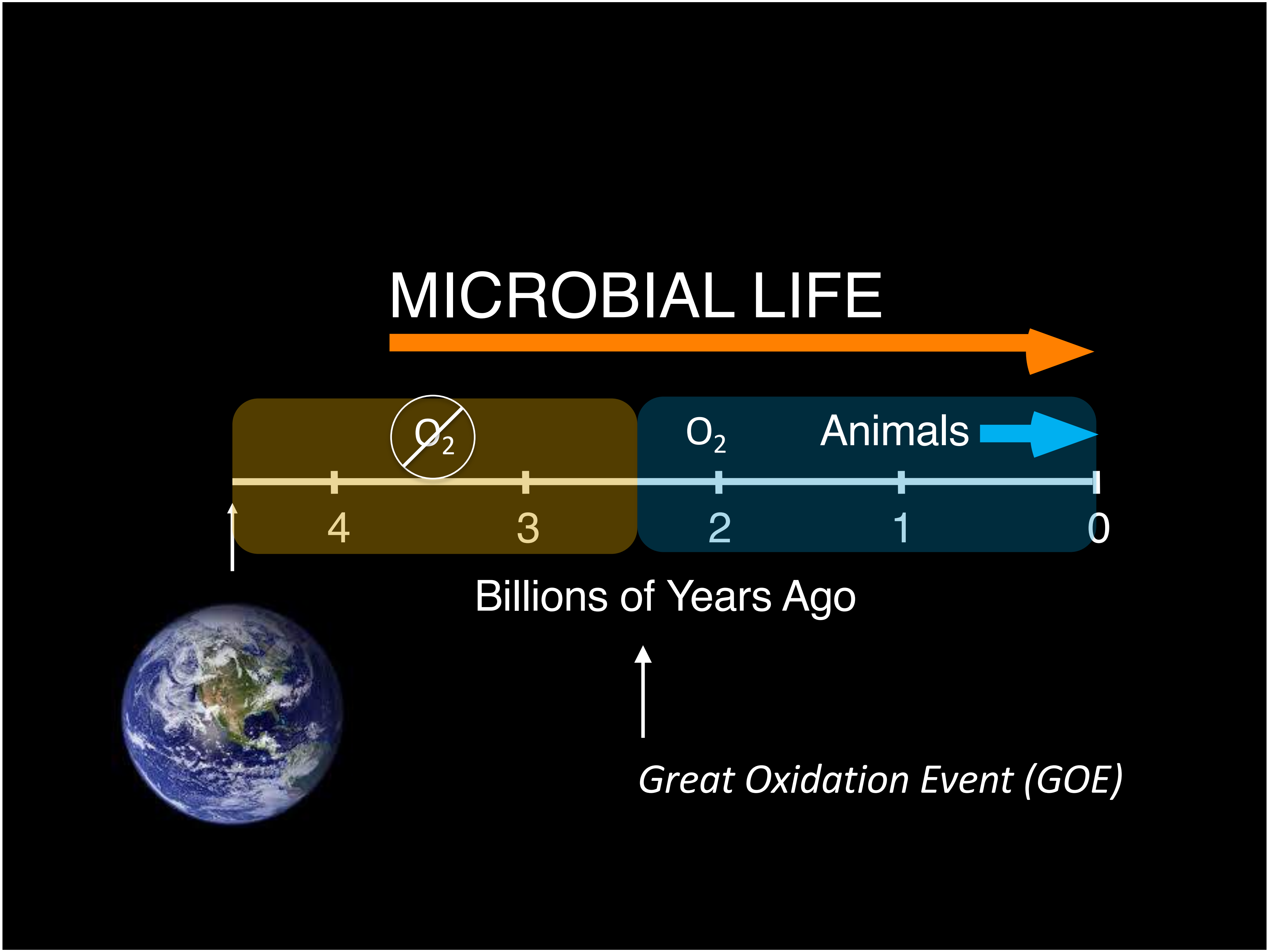
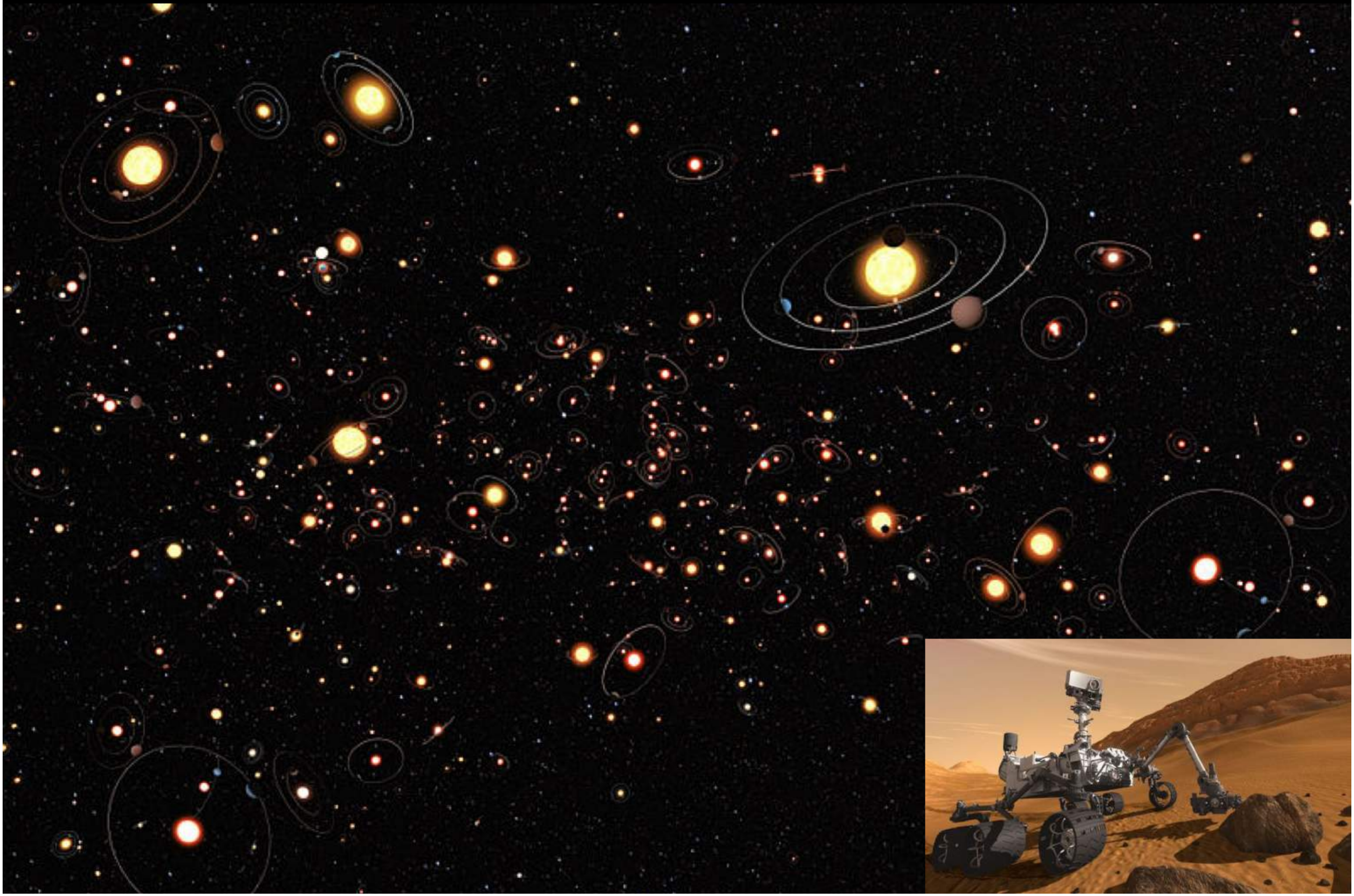



MICROBIAL LIFE
$\cancel{O_2}$
O_2
Animals
4
3
2
1
0
Billions of Years Ago
Great Oxidation Event (GOE)

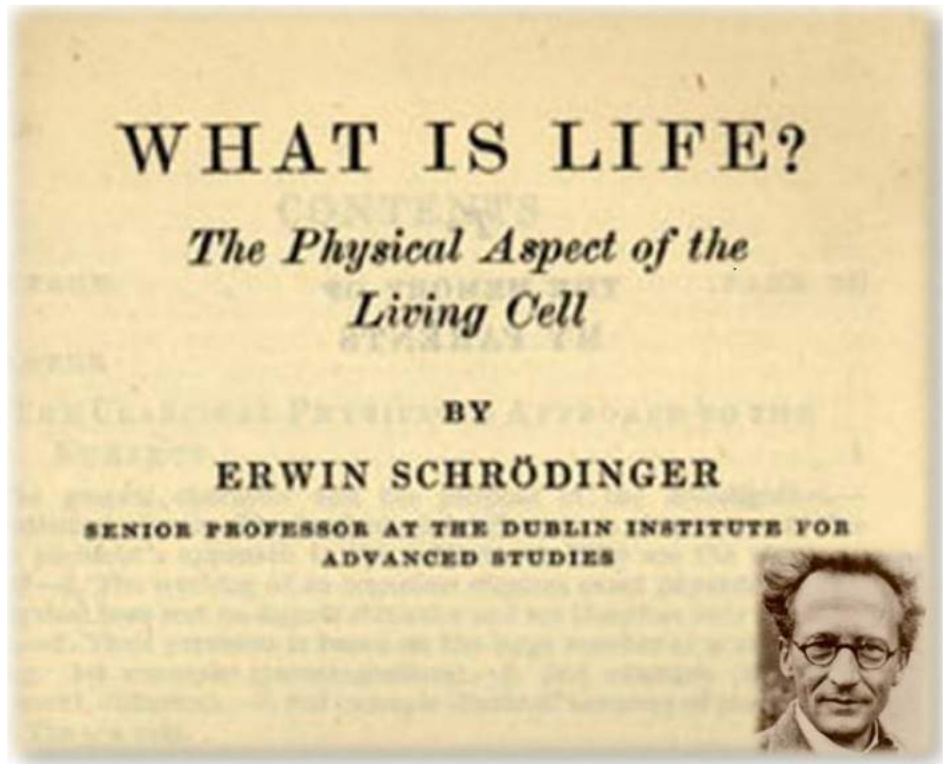
How would you recognize life if you saw it?



What is life?

Erwin Schrodinger (1944 book: What is Life) founding father of quantum mechanics
This book was inspired by Max Delbrück's writing (Caltech biologist)
Influenced Jim Watson & Francis Crick, who discovered structure of DNA

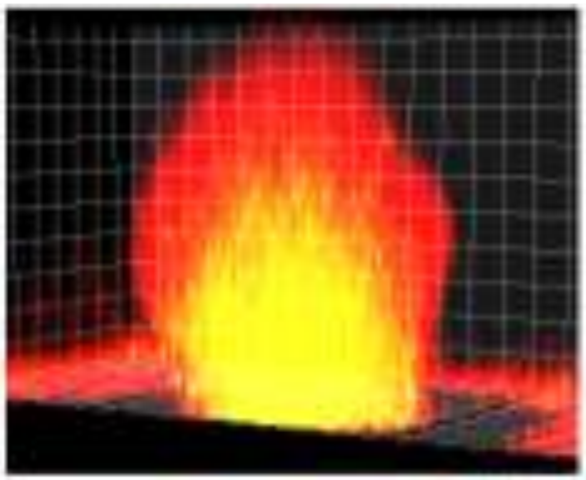
- **EXISTS** as an entity separate from its environment
    - In thermodynamic disequilibrium with environment
    - Preserves internal homeostasis
    - Requires energy to do this
- **PERSISTS**
    - Replicates, repairs, defends
    - Can sense and respond to its environment (transport, move, communicate)
- **CO-EVOLVES**
    - With abiotic factors
    - With other life forms



Concept of biogeochemical disequilibrium: predictable layered sequence of metabolites

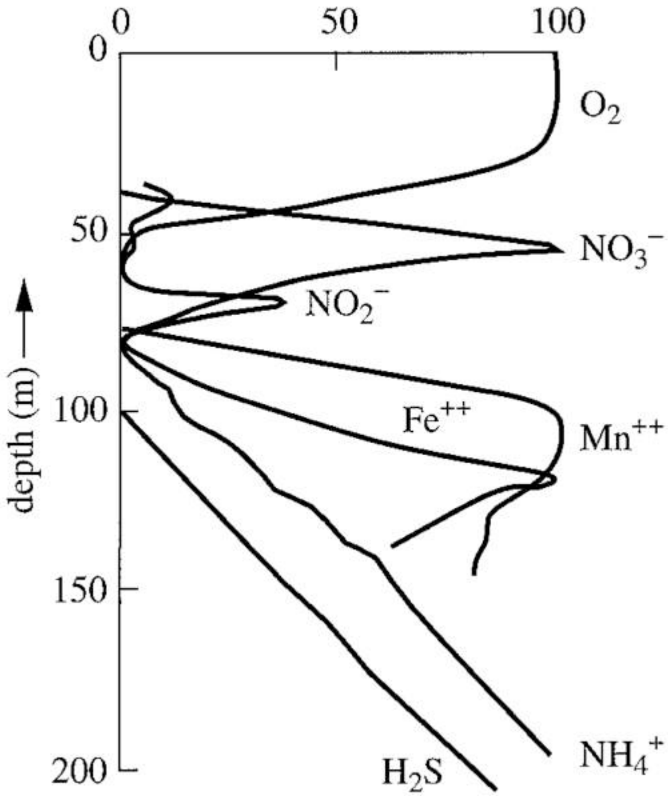
Observation: layering dissipates if system poisoned or killed
Assumptions: Prod/consump of metabolites outpaces diffusion
Hypothesis: layering is biologically catalyzed

μ-meters



centimeters

meters

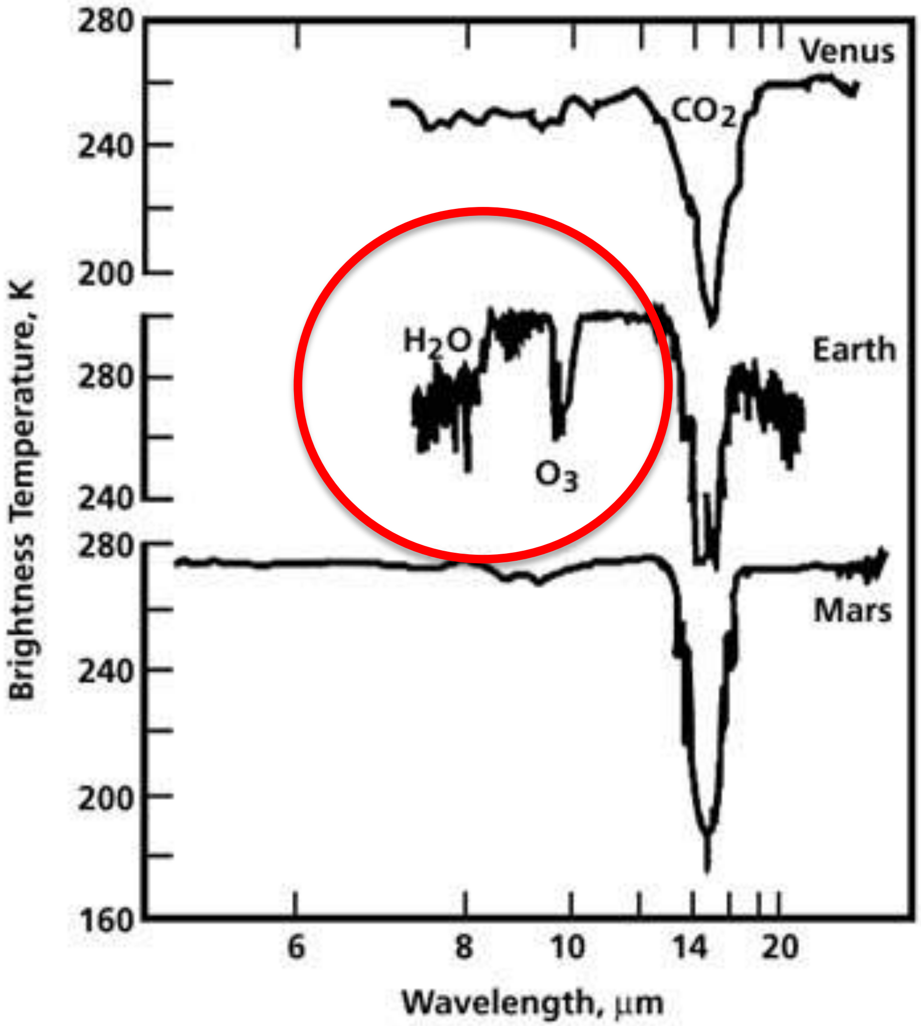


What features of life (*i.e.* necessary for it or a product of it) can you see from space?

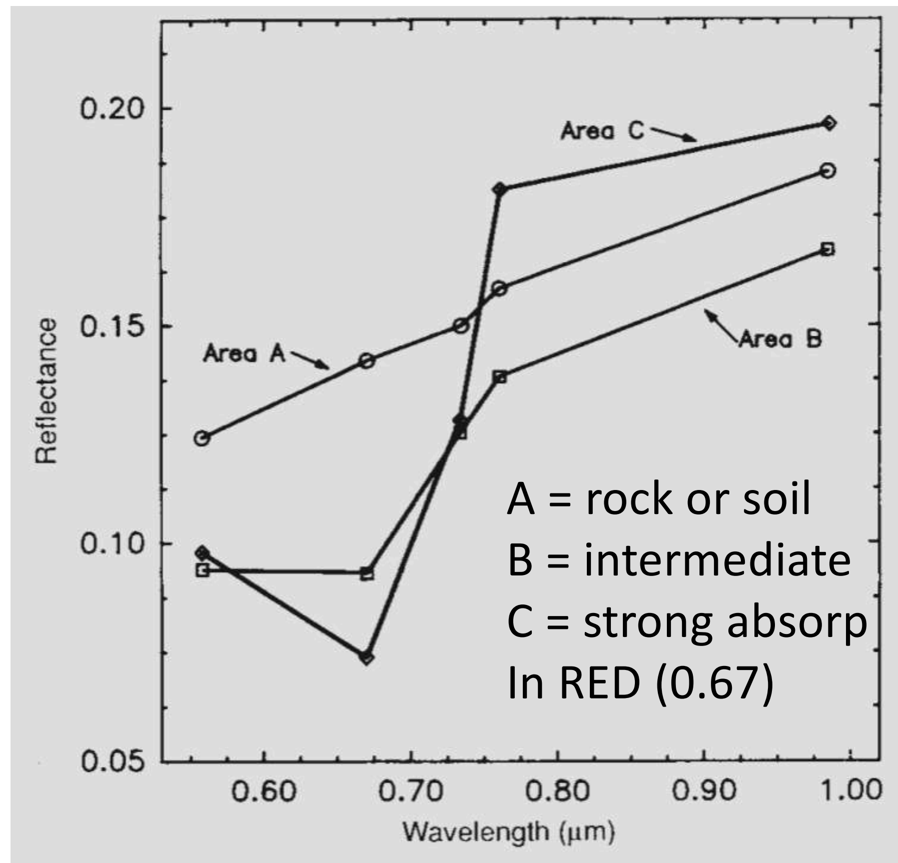
Water (in 3 phases),
Oxygen
Chlorophyll

Planetary life detection: spectral signatures

Spectra of H_2O and O_3



Photosynthetic pigments



Prof. G Blake

Sagan, 1993

Is O_2 a robust biosignature?

What sets the steady state level?

Oxygenic photosynthesis and respiration:

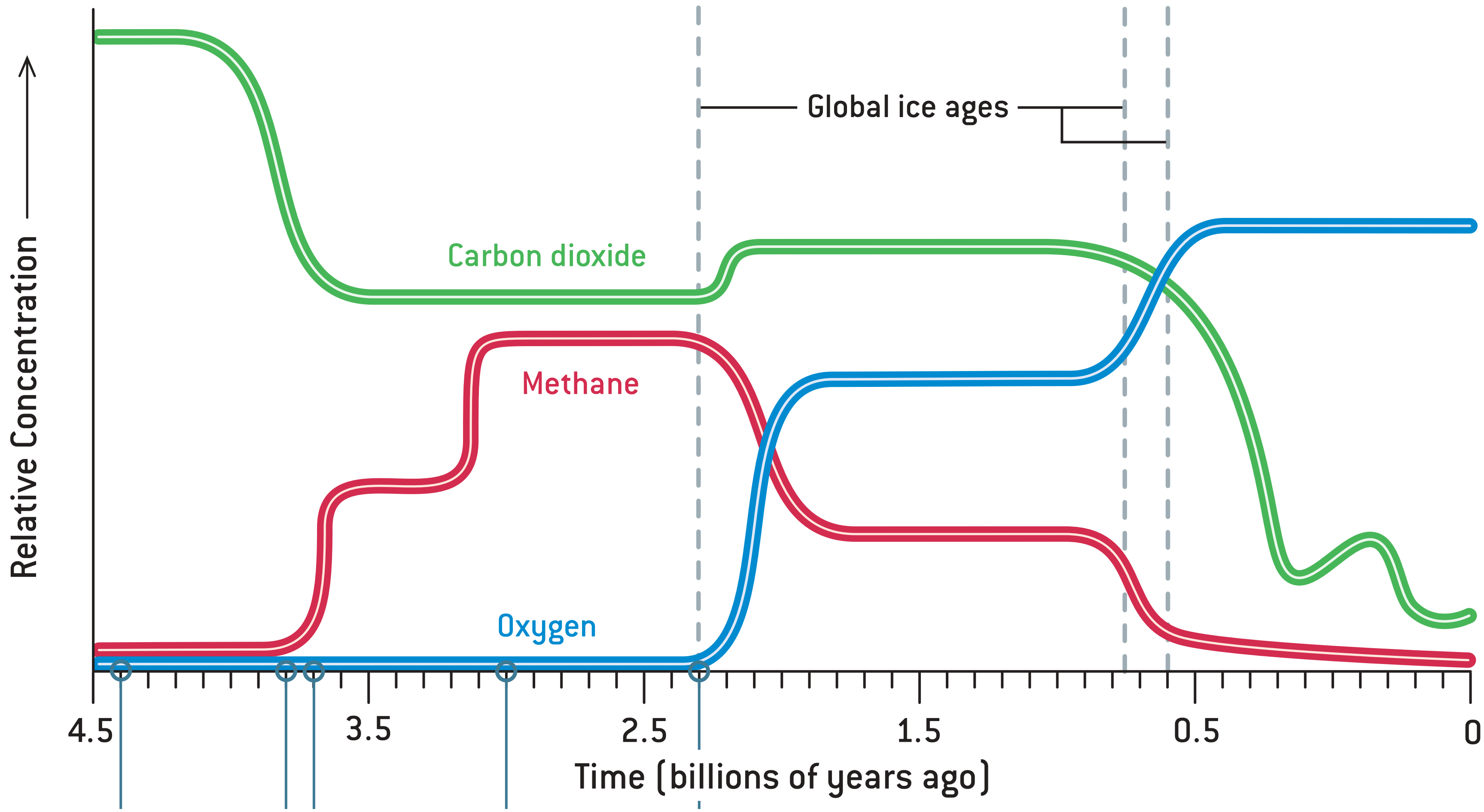
$$A_{ox}\ (CO_2) + H_2O \text{ <-> } A_{red}\ (CH_2O) + O_2$$

→ If in equilibrium, no net accumulation. So evolving oxygenic photosynthesis can't explain O_2 accumulation.

Planetary redox state is key (need to oxidize the Earth so O_2 can accumulate. Can do either by letting reductants (Ared) escape to space (e.g. H_2; but gravity constrains this) or burying them inside the Earth's interior (e.g. C_{org}).

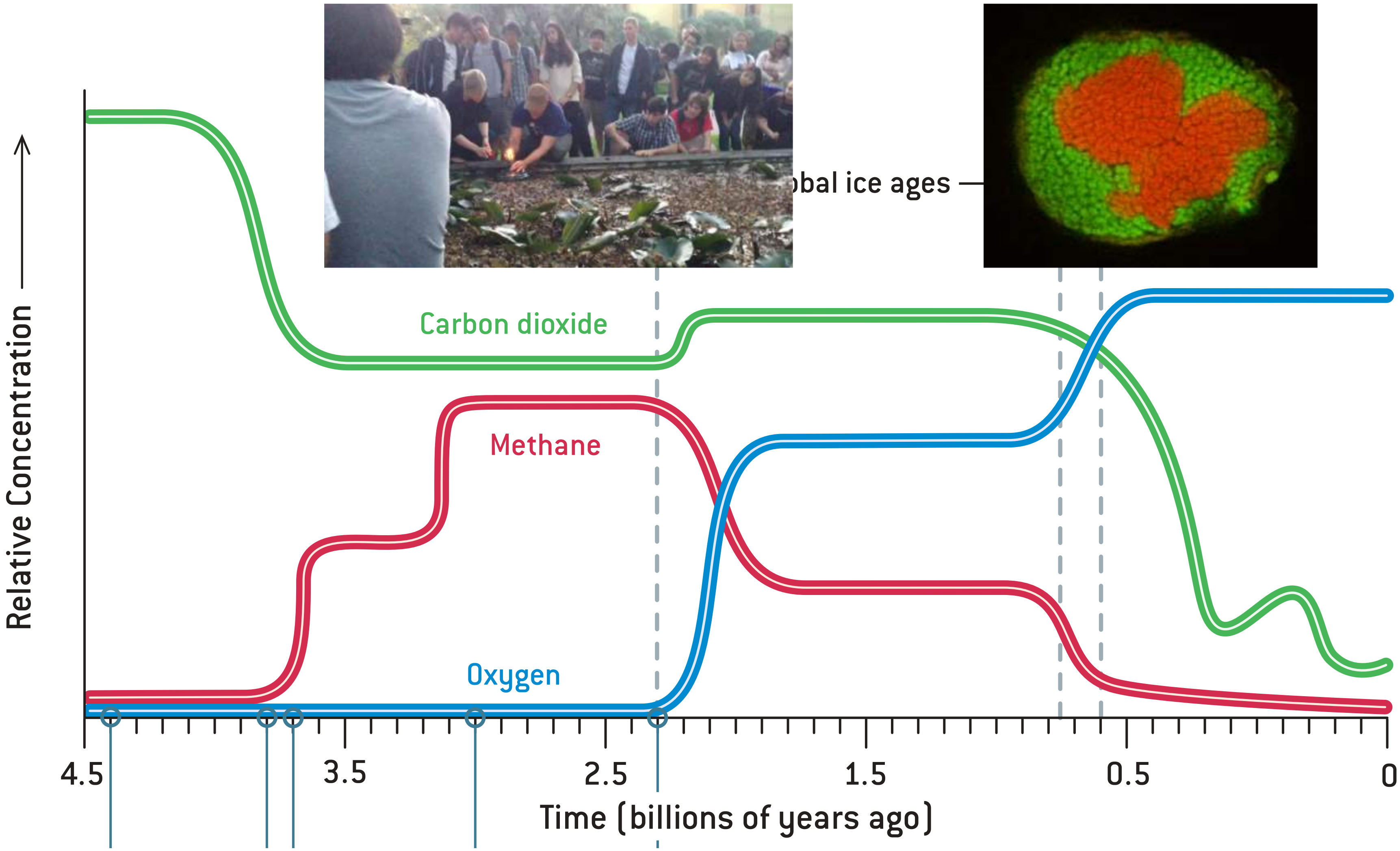
Maintenance of a steady state once Earth is oxidized is an example of CHEMICAL DISEQUILIBRIUM ON A PLANETARY SCALE!

Evolution of atmospheric chemistry



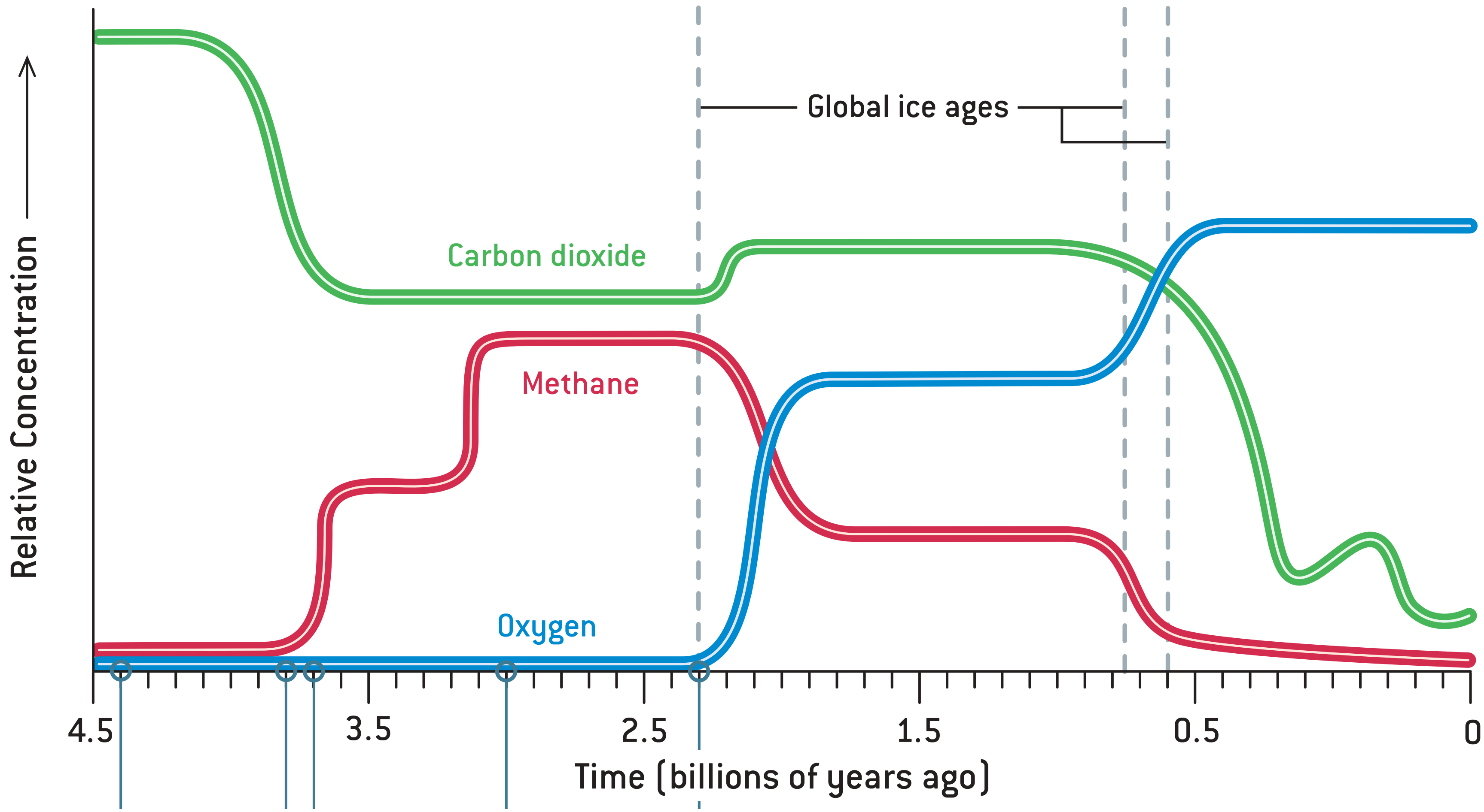
Kasting, Scientific American

What cycles methane? Sources and sinks?



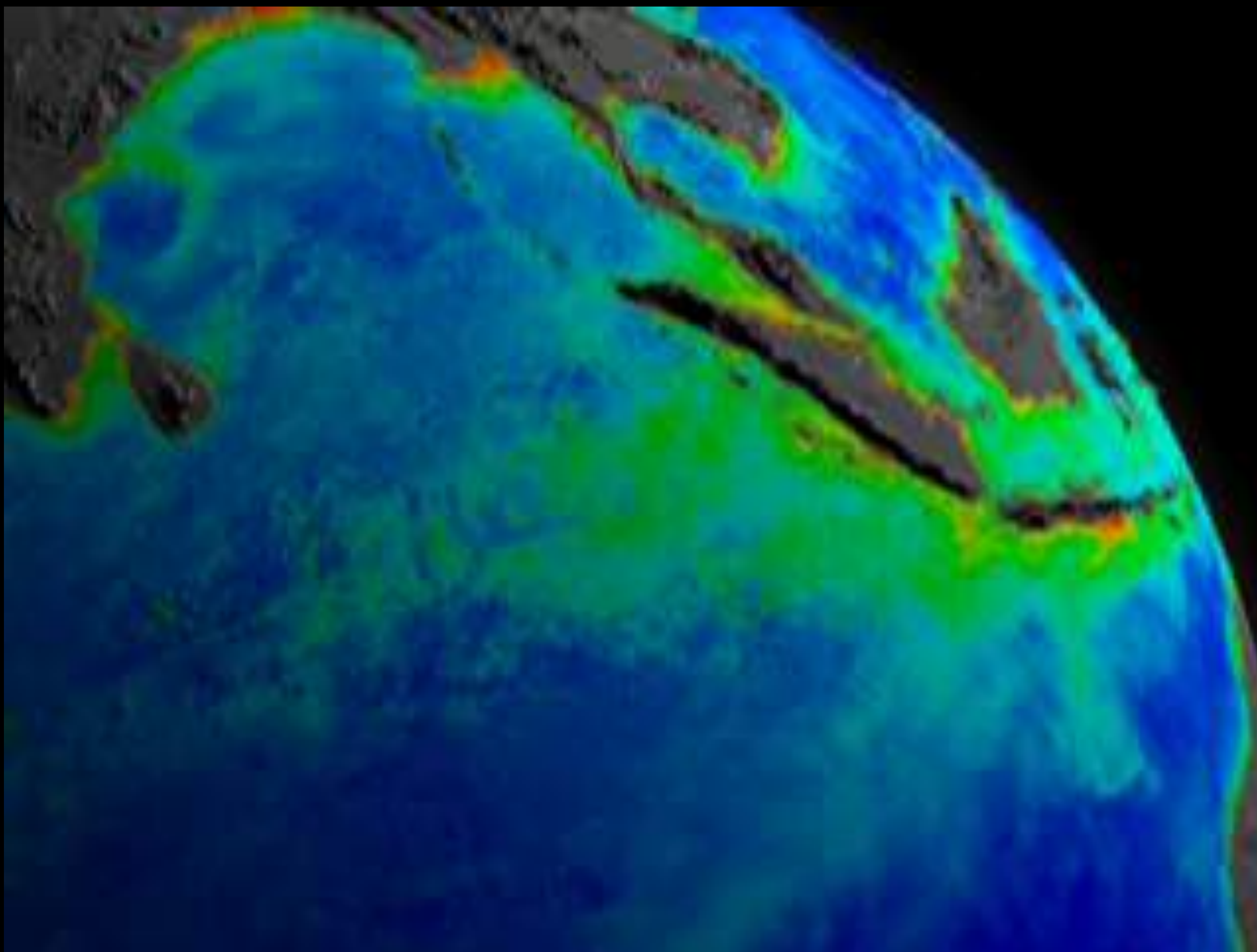
Kasting, Scientific American

How did O_2 accumulate in the atmosphere?

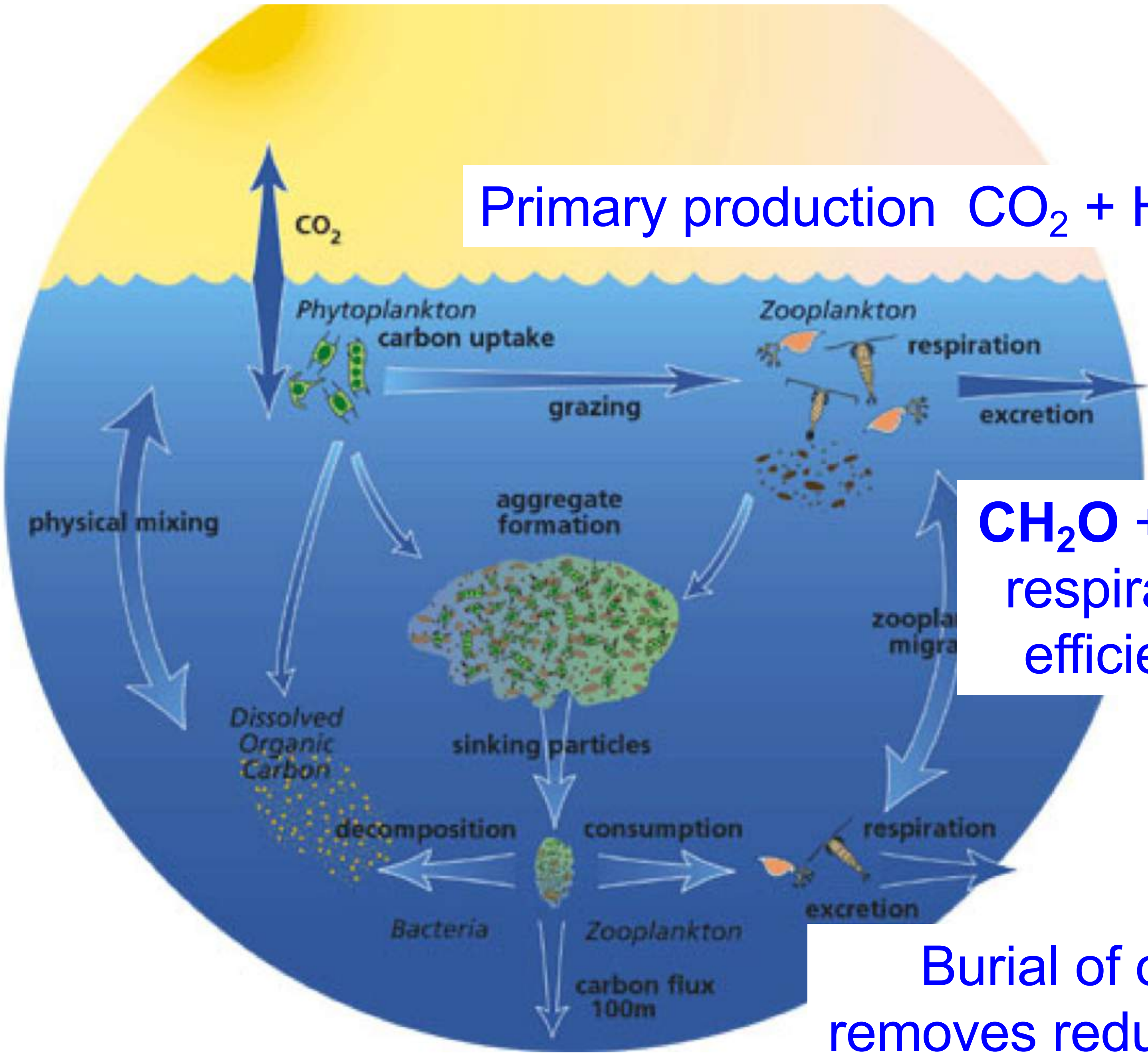


Kasting, Scientific American

Today, ~50% O_2 produced by phytoplankton and maintained at high levels by the “biological pump”



What is the Biological Pump?

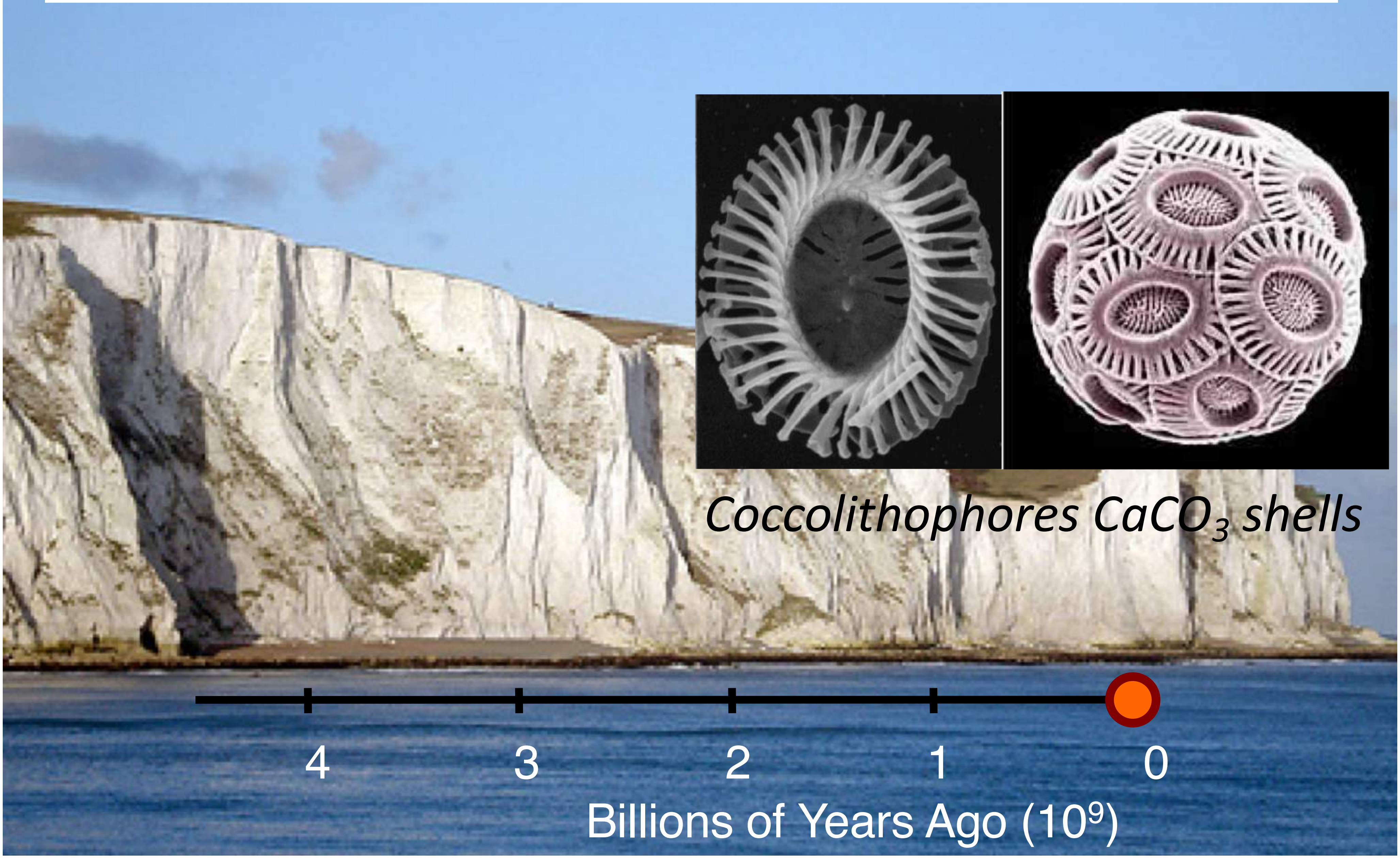


Primary production $CO_2 + H_2O \rightarrow CH_2O + O_2$

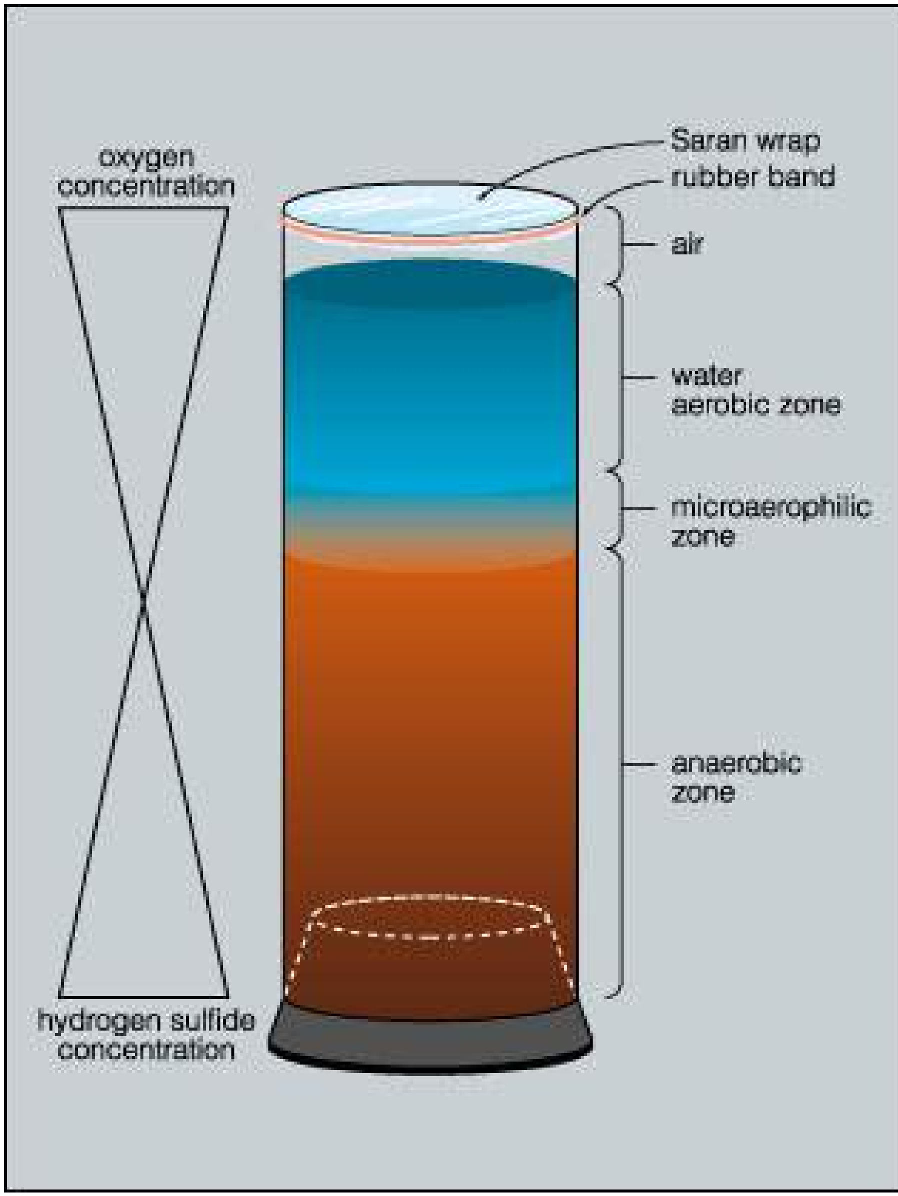
$\mathbf{CH_2O} + O_2 \rightarrow CO_2 + H_2O$
respiration is not 100% efficient; particles sink

Burial of organic matter removes reductant from system

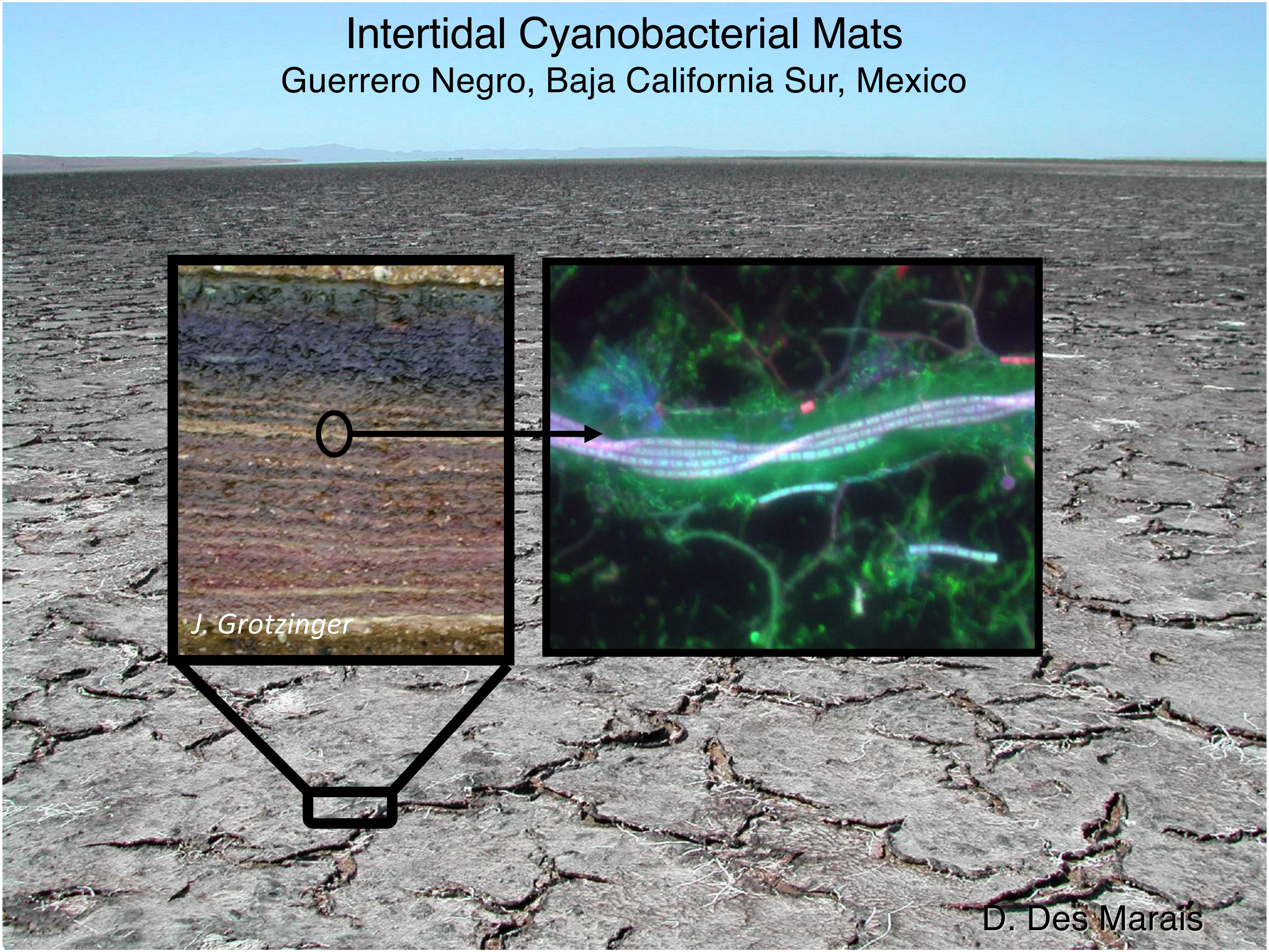
Example of the biological pump when dinosaurs roamed the Earth (Late Cretaceous, ~89 Ma)



Winogradsky Column: metabolic stratification (co-selection by λ, $[O_2]/[HS^-]$)




Yellowstone, Dave Ward


Intertidal Cyanobacterial Mats
Guerrero Negro, Baja California Sur, Mexico
J. Grotzinger
D. Des Marais

What is the basis for this layering?

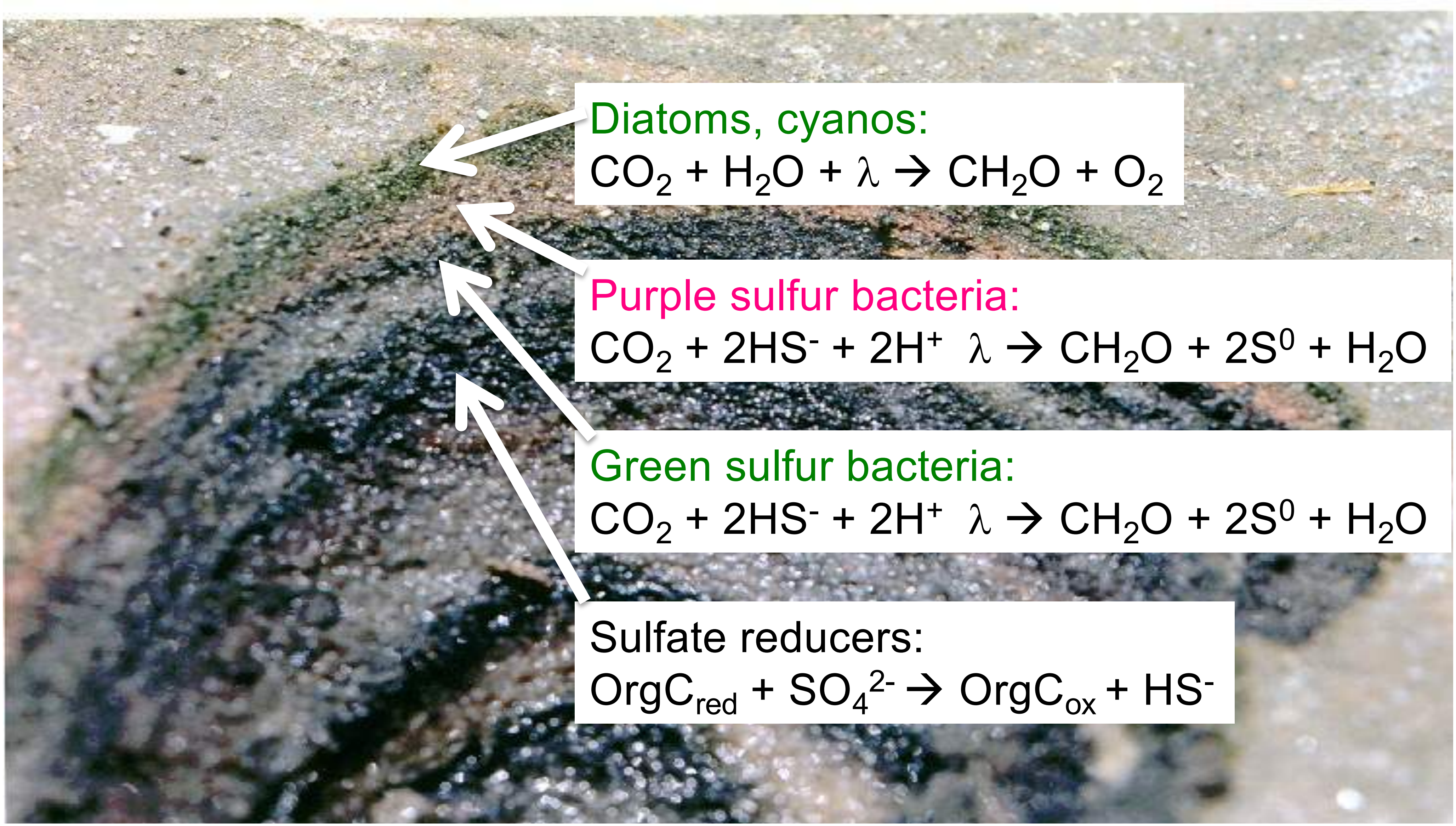
- Abiotic factors: positive: penetration of light
  negative: avoidance of toxins (sulfide)

- Biological factors: positive: metabolic cooperation
  negative: competition for resources

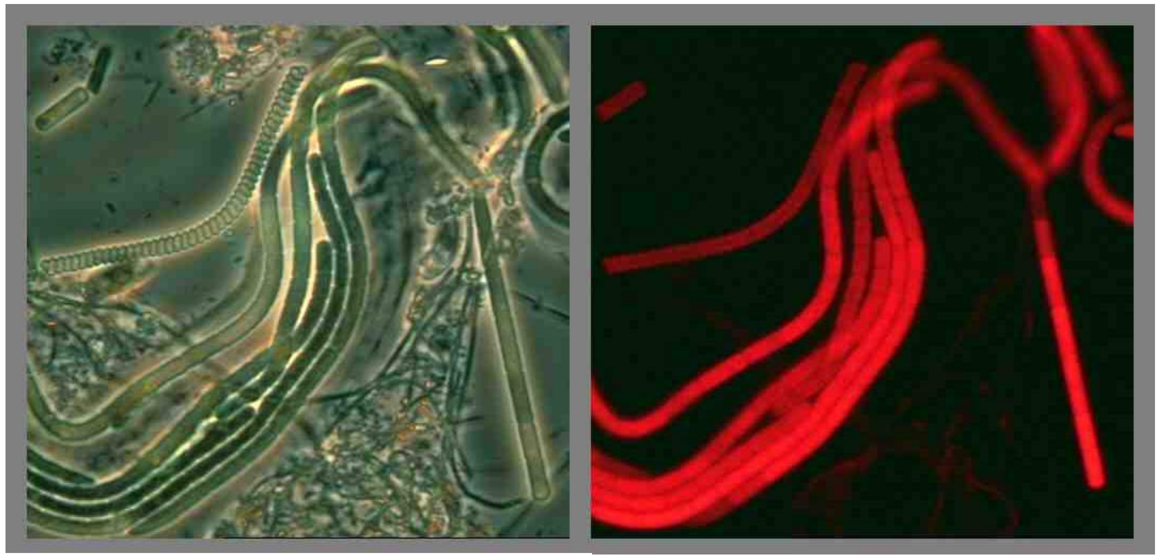
* Role of viruses? Predators? Recyclers?

Note: the position of the organisms in these layers is highly dynamic (temporal resource partitioning)

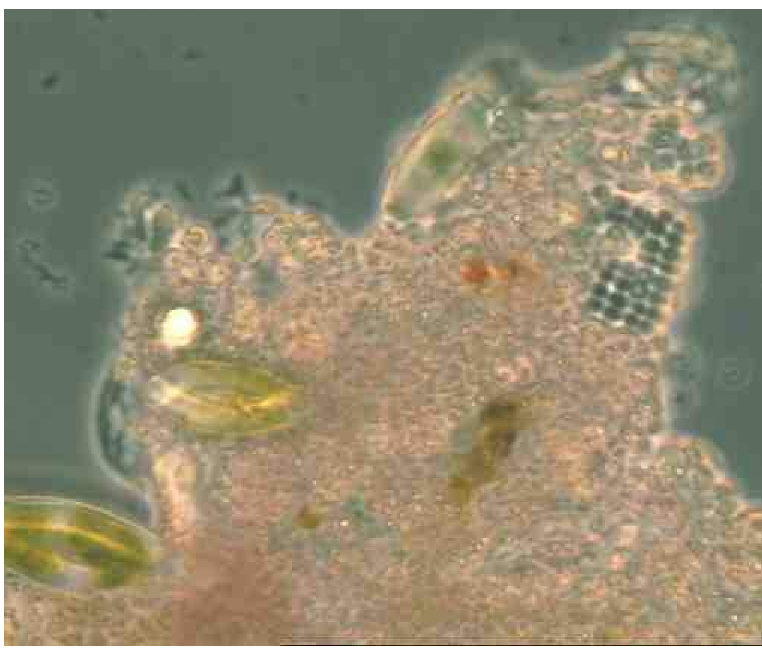
Metabolic organization - Sippewissett Salt Marsh



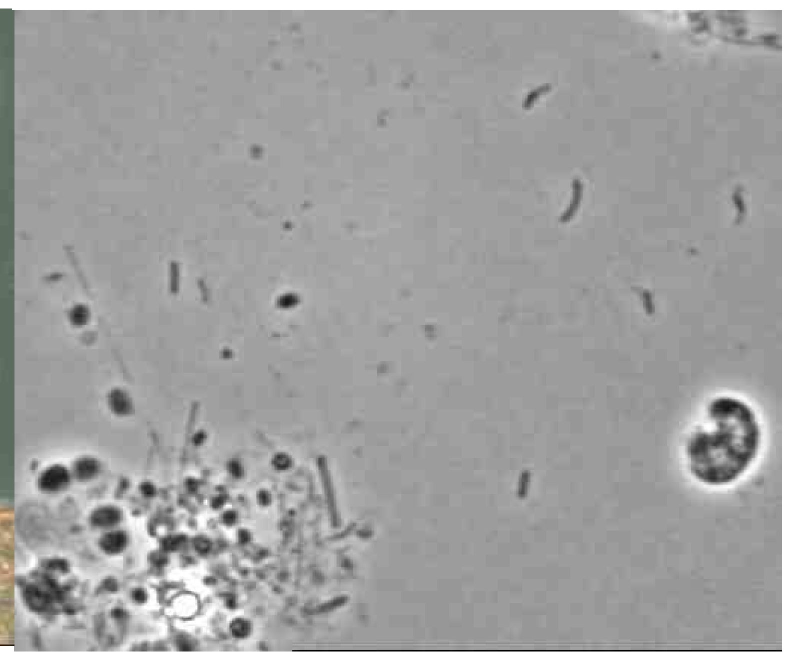
Upper green layer: filamentous cyanobacteria/ red = autofluorescence of light-harvesting pigments



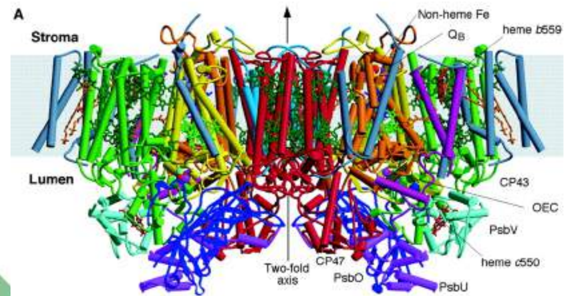
Purple layer: purple sulfur bacteria

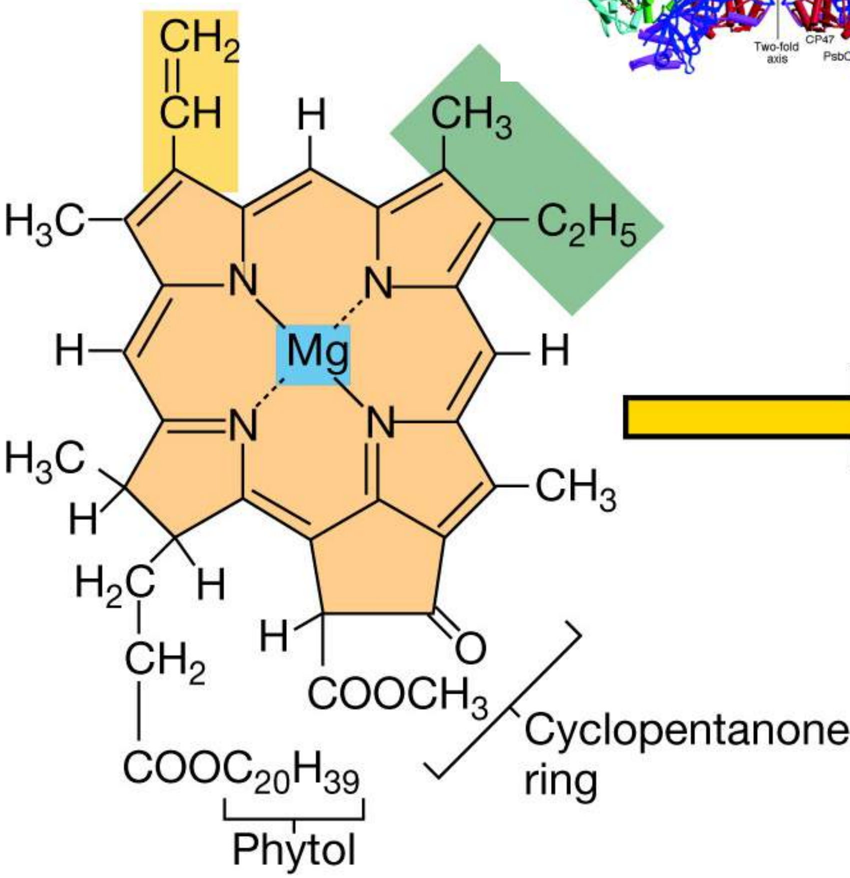


Black layer: sulfate reducers

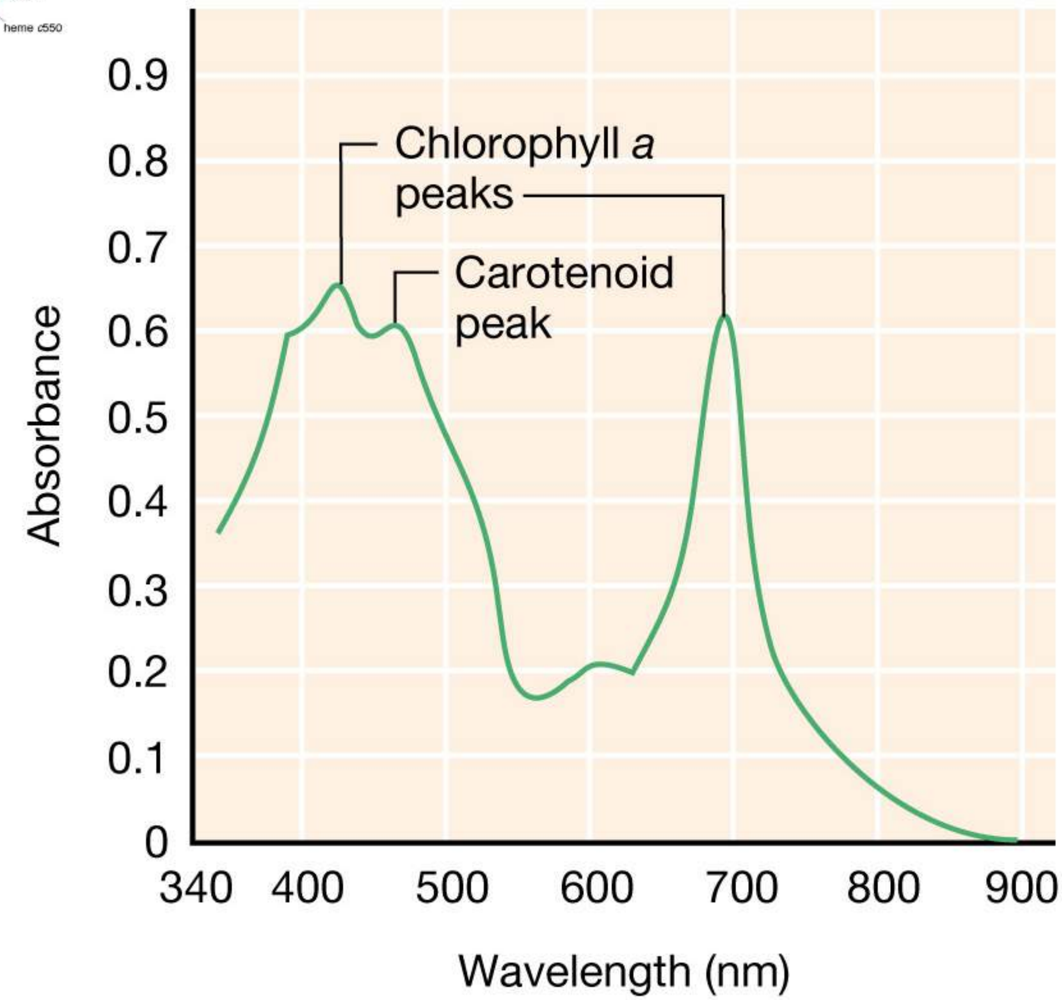


Light absorbing pigments in cyanos/diatoms

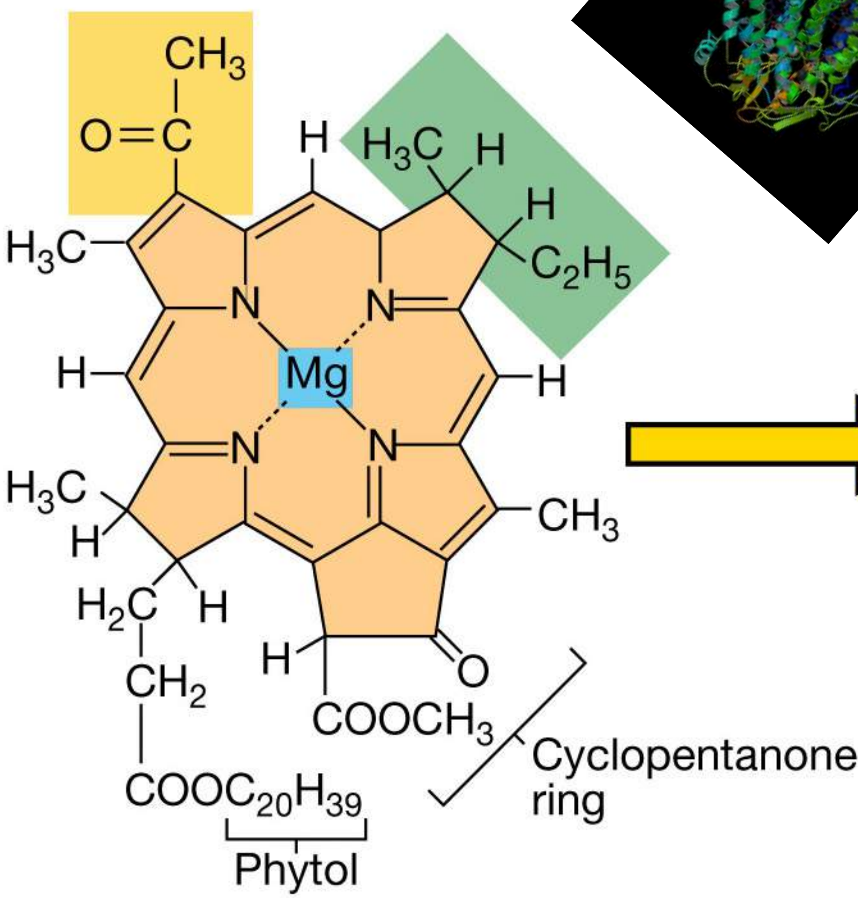




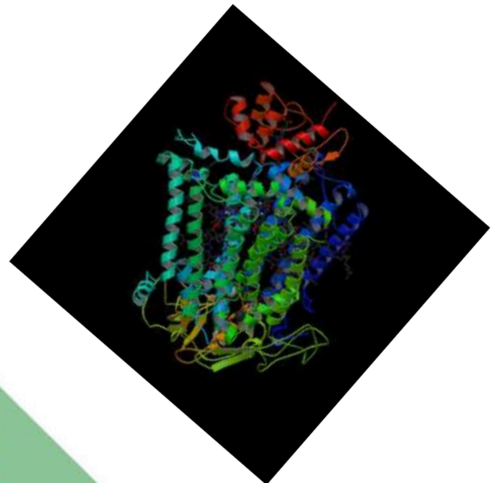
Chlorophyll *a*

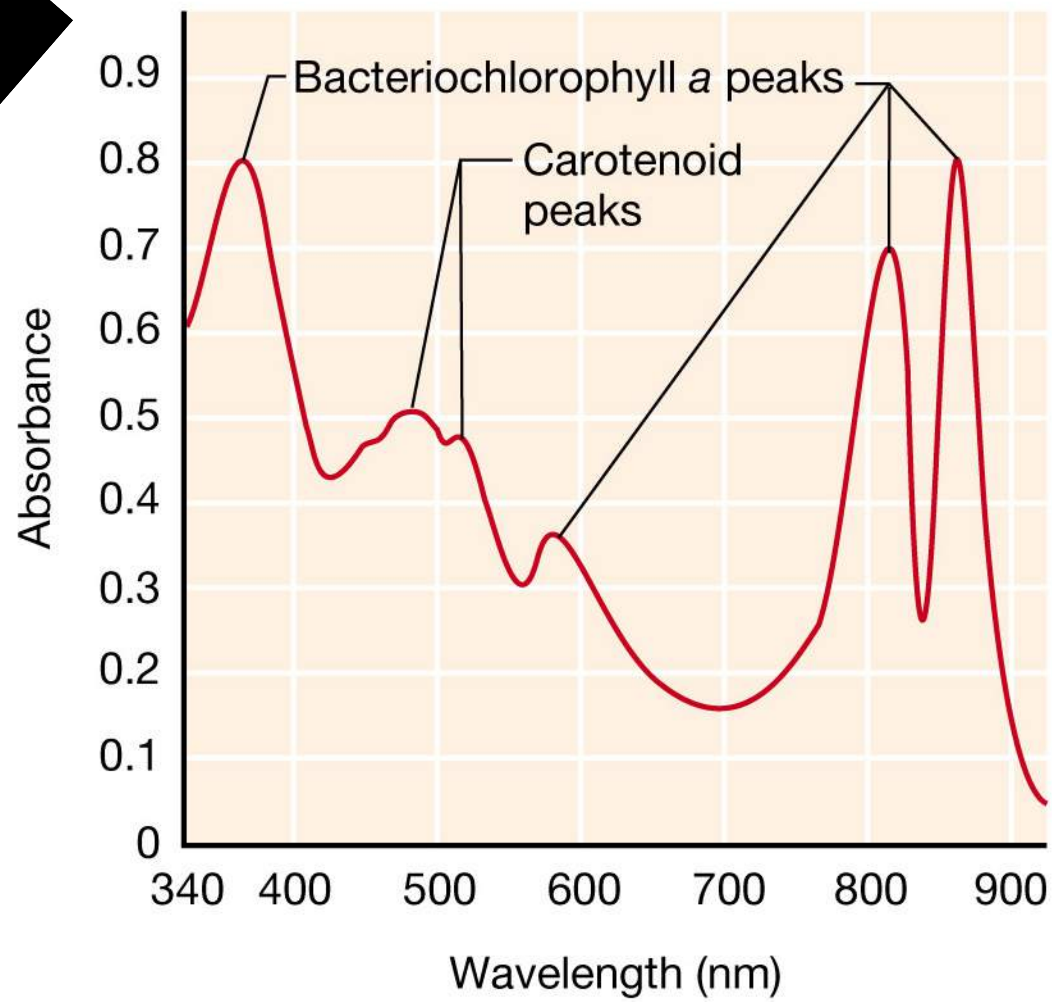


Light absorbing pigments in purple sulfur bacteria

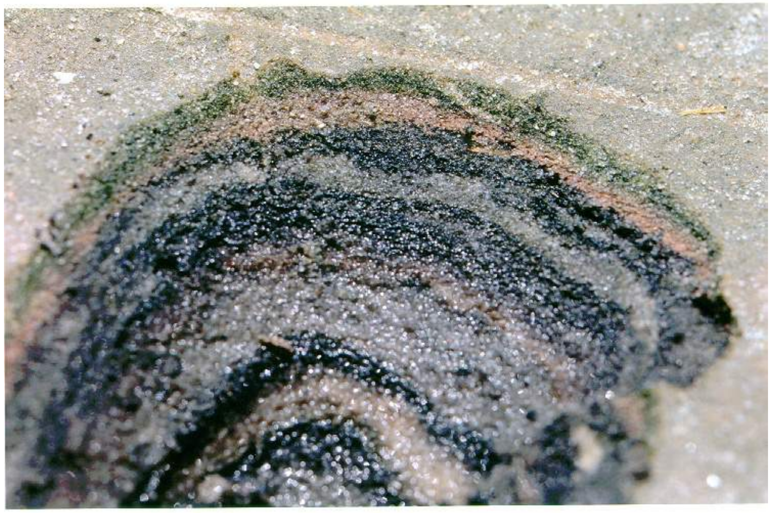


Bacteriochlorophyll *a*





Penetration of light in sand

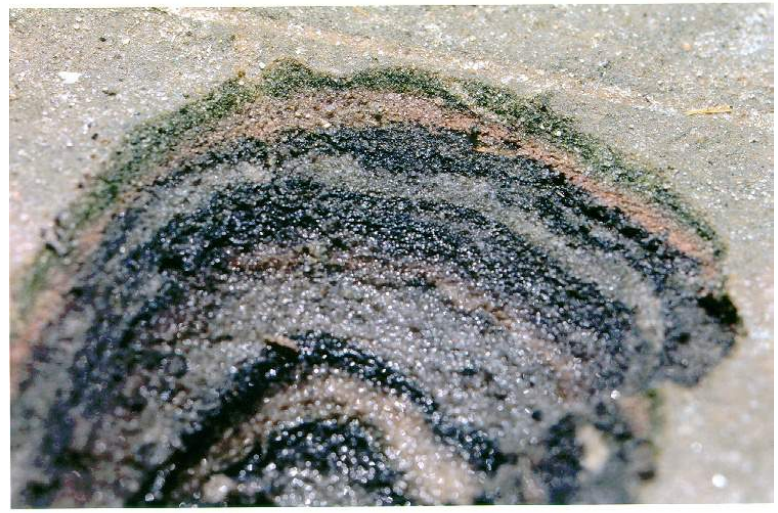


Draw out penetration of different wavelengths through sand

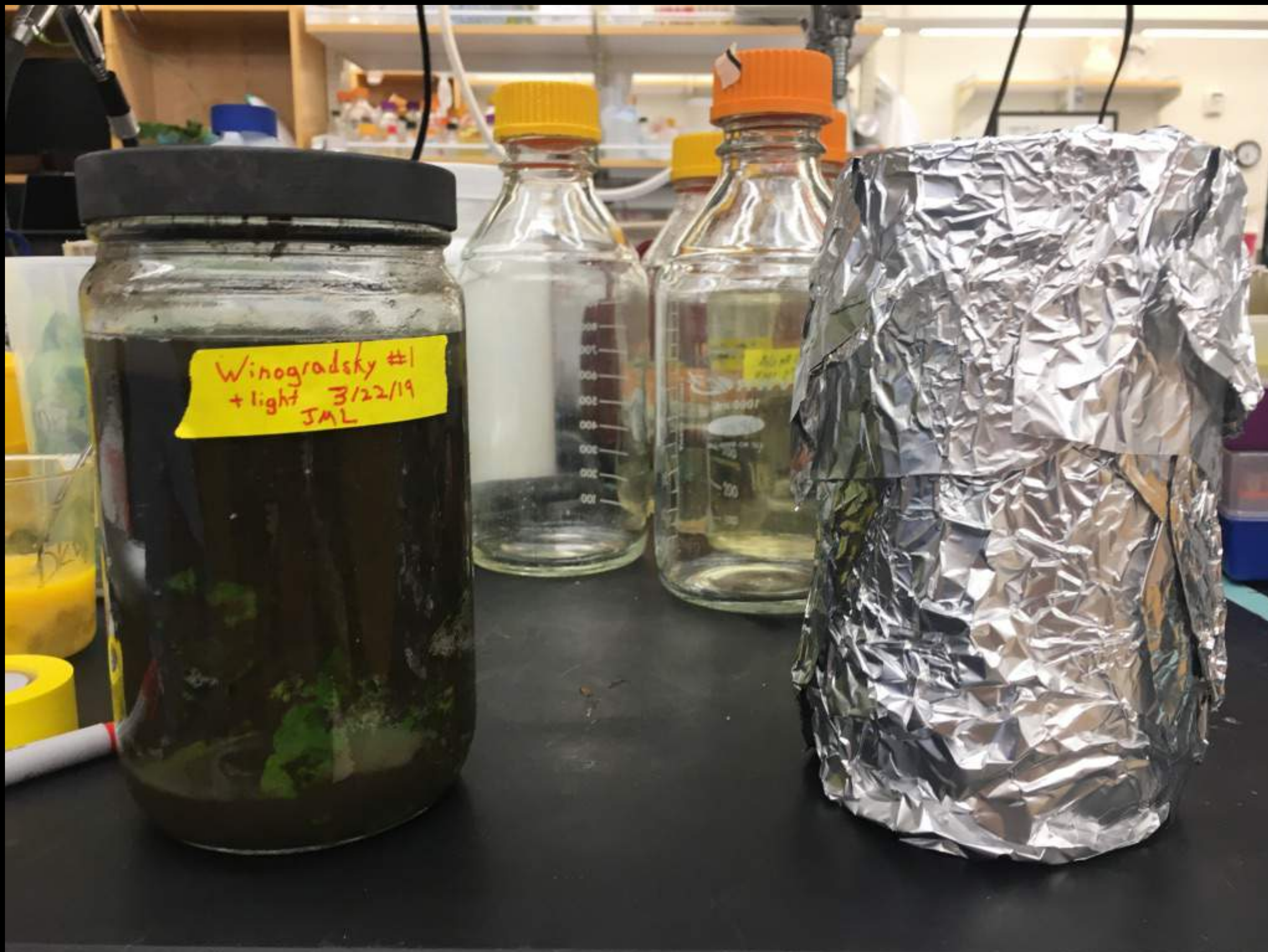
TAKE HOME POINTS:

- Shorter wavelengths don’t transmit very deeply
- Only longer (IR) wavelengths get down below a couple mm depth
- The photosynthetic machinery in the different phototrophs is optimized to absorb maximally in different regions, that coincide with where light of those wavelengths penetrate

Differential sulfide tolerance

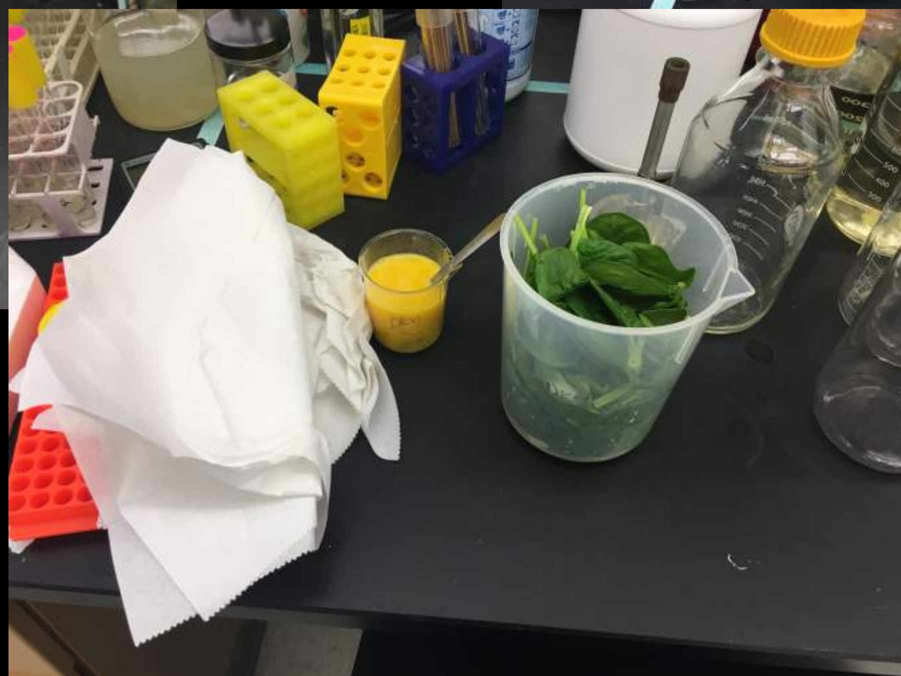


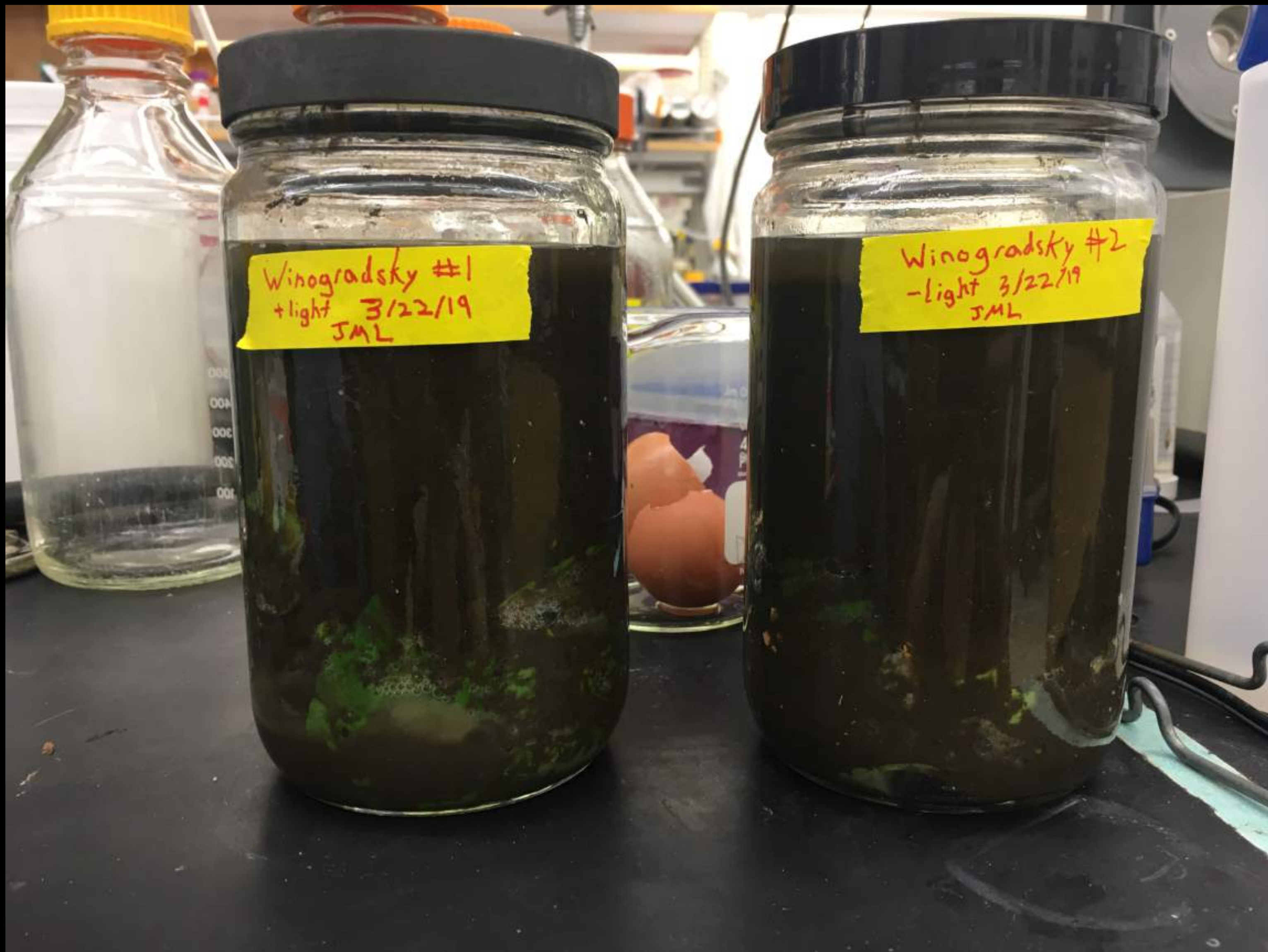
- Draw out specific growth rate curve vs. HS-concentration



Winogradsky #1
+ light 3/22/19
JML




Winogradsky #1
+light 3/22/19
JML
Winogradsky #2
-light 3/22/19
JML