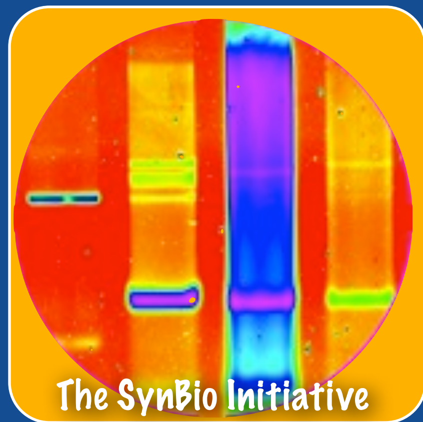
Astrobiology, the Last Great Scientific Revolution



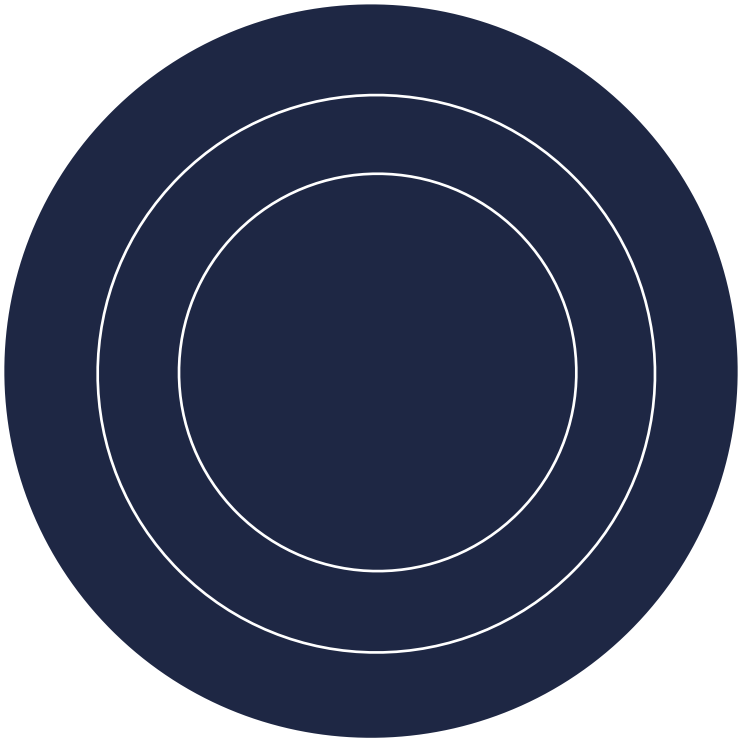
Lynn J. Rothschild

Seven Pines Symposium, 19 May 2011

The Revolutions

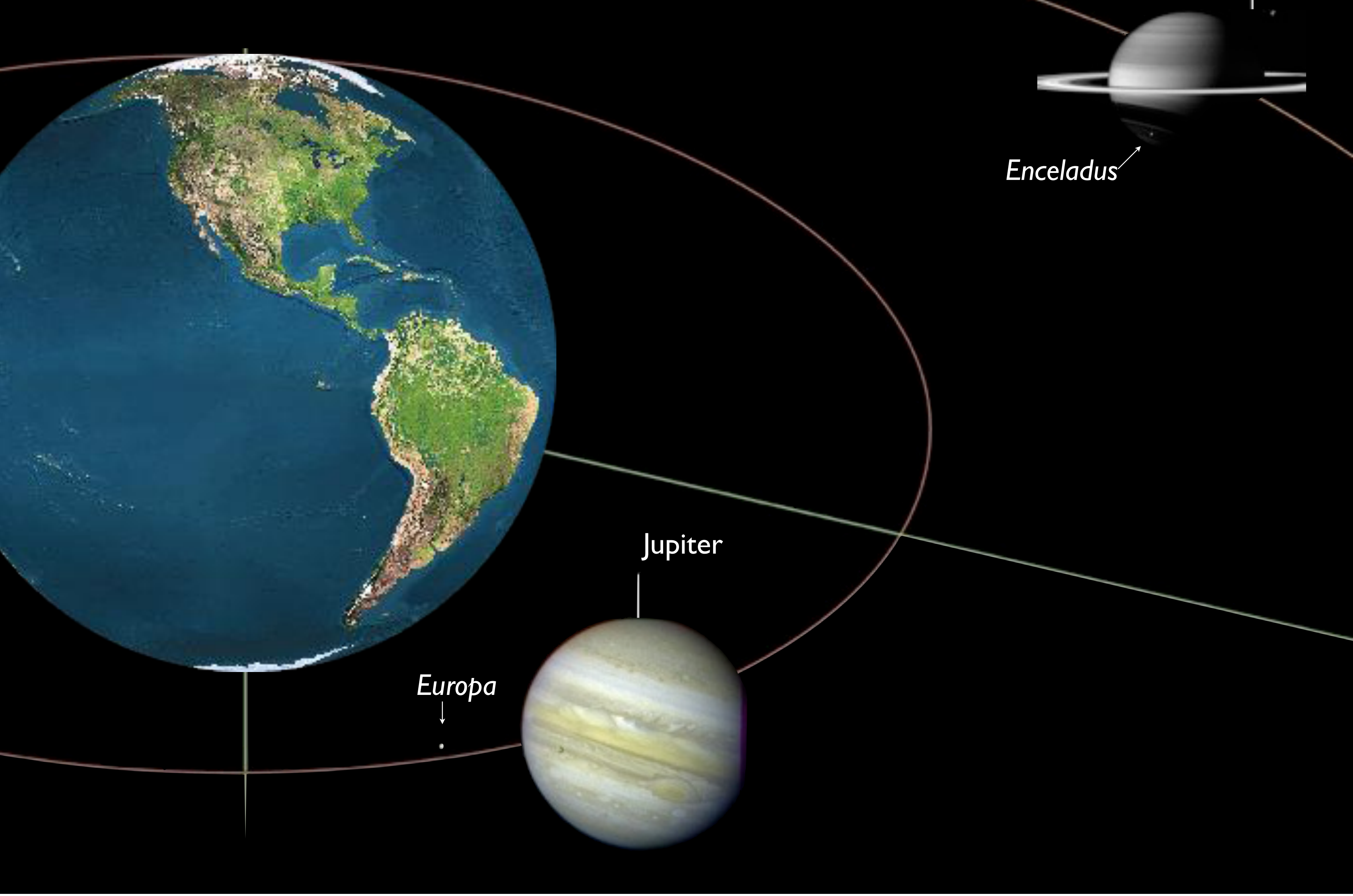
B.C. *(before Copernicus)*

★ There were the Heavens and the Earth



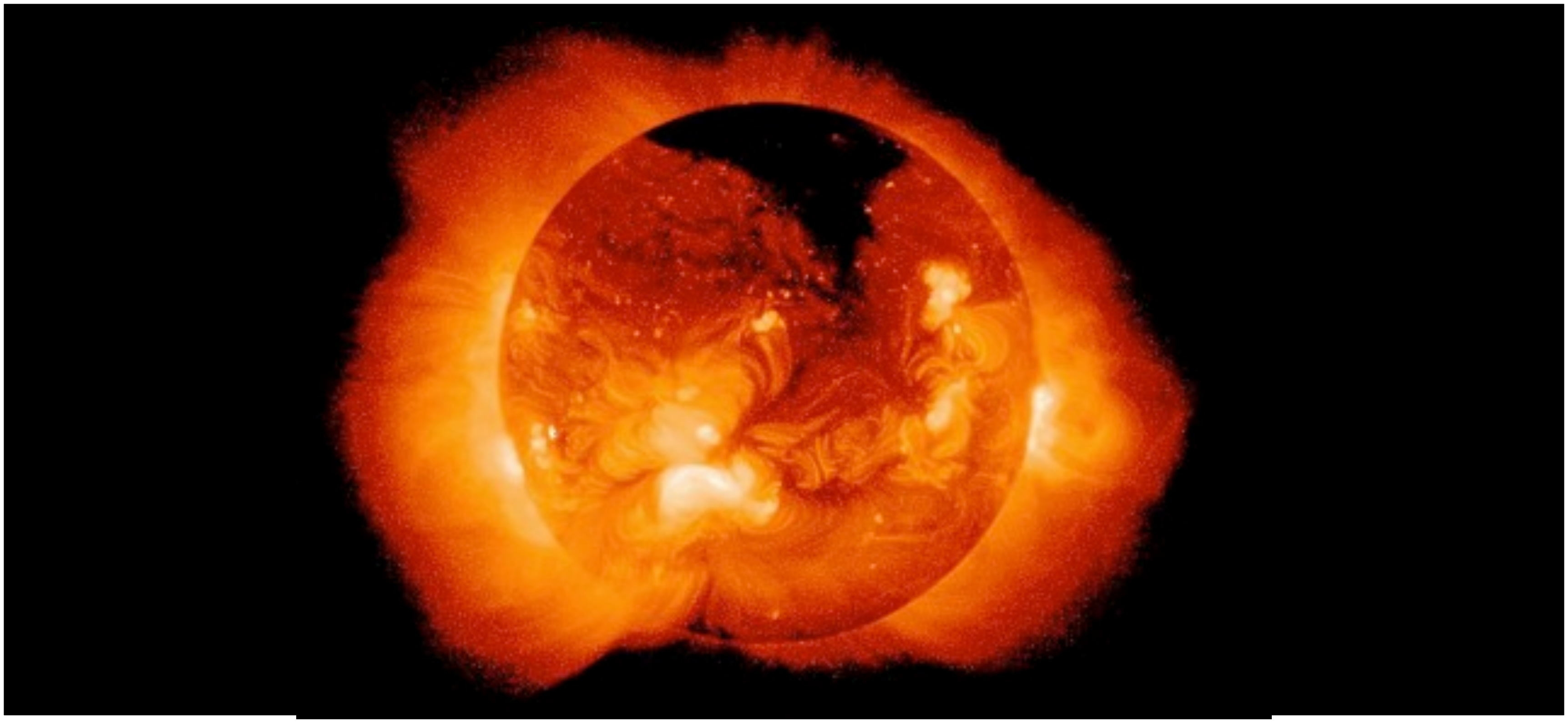
- **Copernicus put them together**

- and put us in our place

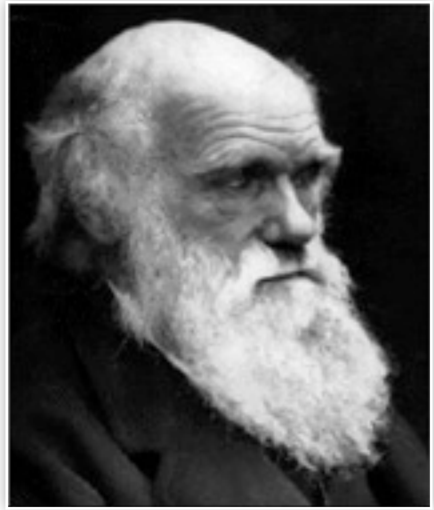


Descartes *(and his followers)*

- ★ Realized the stars were other suns like our own.



The Darwinian Revolution



- ***Darwin (1809-1882):*** *Biological world also governed by natural laws, such as natural selection. Evidence for change, mechanism for change, man's place among life on Earth.*

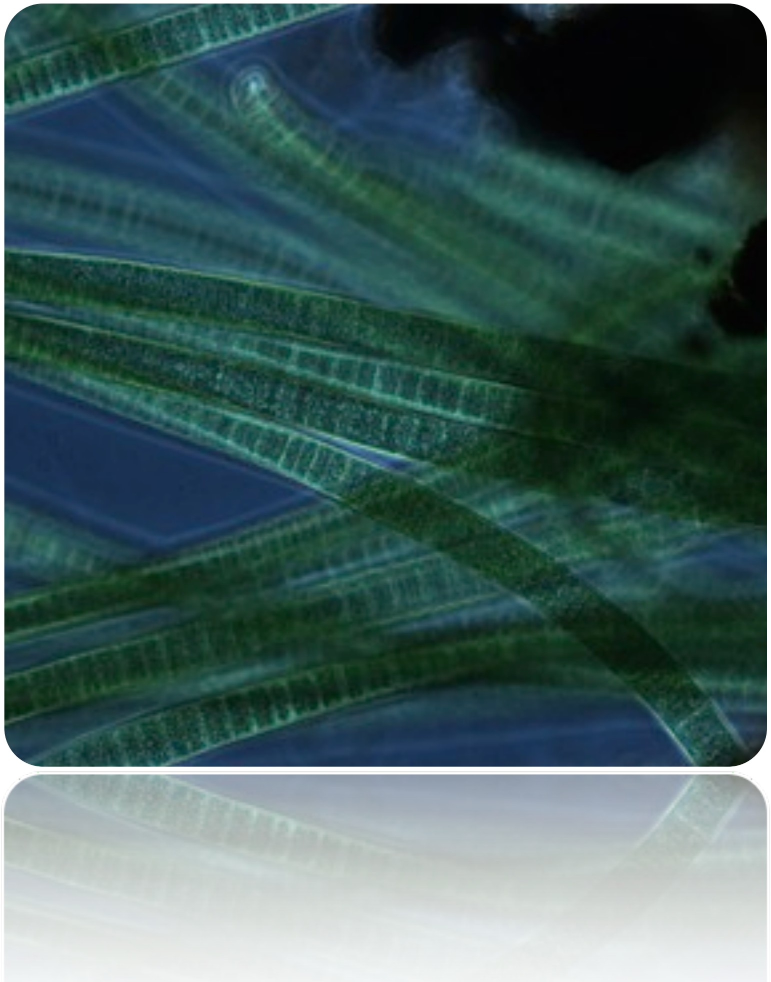
The Astrobiology Revolution

today's scientific revolution

What is
Astrobiology?

Overview: Rothschild, L.J. (2001) "Astrobiology". McGraw Hill Encyclopedia of Science & Technology, 2002. pp. 21-24; astrobiology.stanford.edu

Where do we come from?



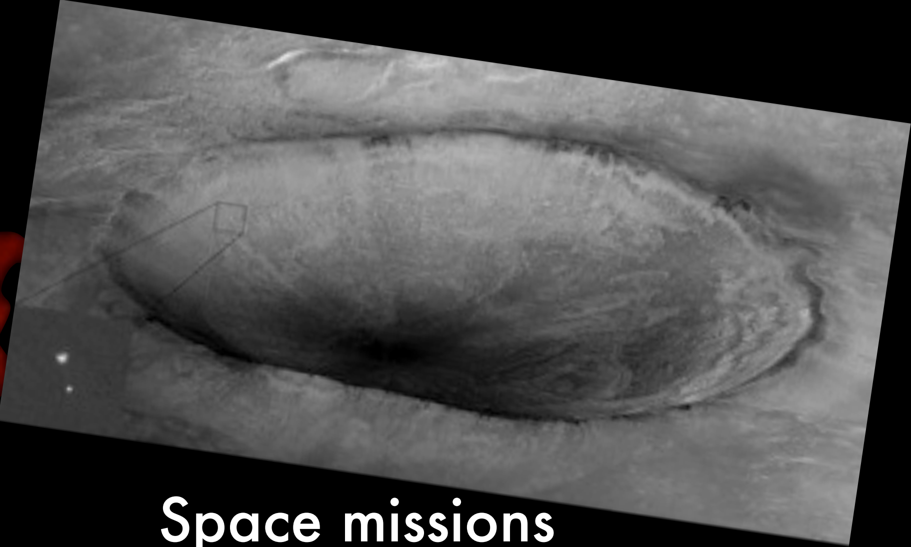
- How did we get the diversity of life we see on earth? This includes the origin of life, how we got the chemical building blocks for life an a habitable body on which to evolve.
- What are its limits?
- Is this in any way predictable?
- What is the interaction between evolution and the physical environment?

Where are we going?

- Environment of earth
- Future of solar system
- Response of life to this change
- Life beyond planet earth
- Fate of our universe

Are we alone?

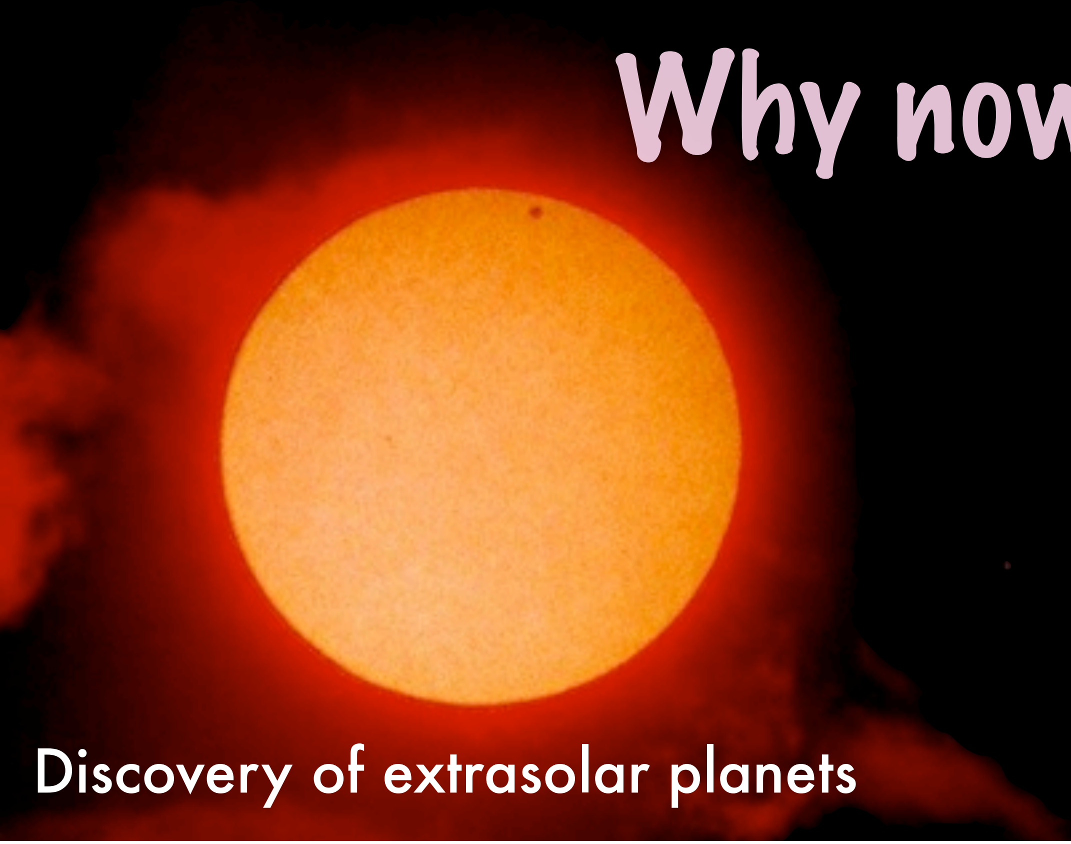
- ★ Are we the only life form?
- ★ Intelligent life form?
- ★ Ethical implications....



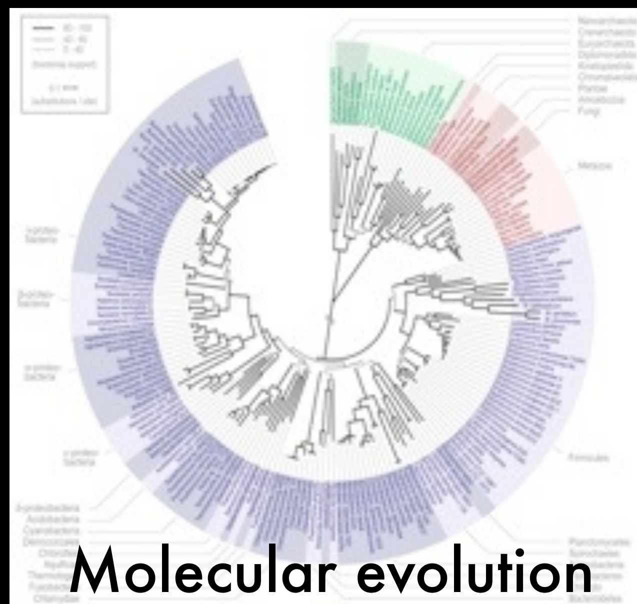
Space missions

Life in extreme environments

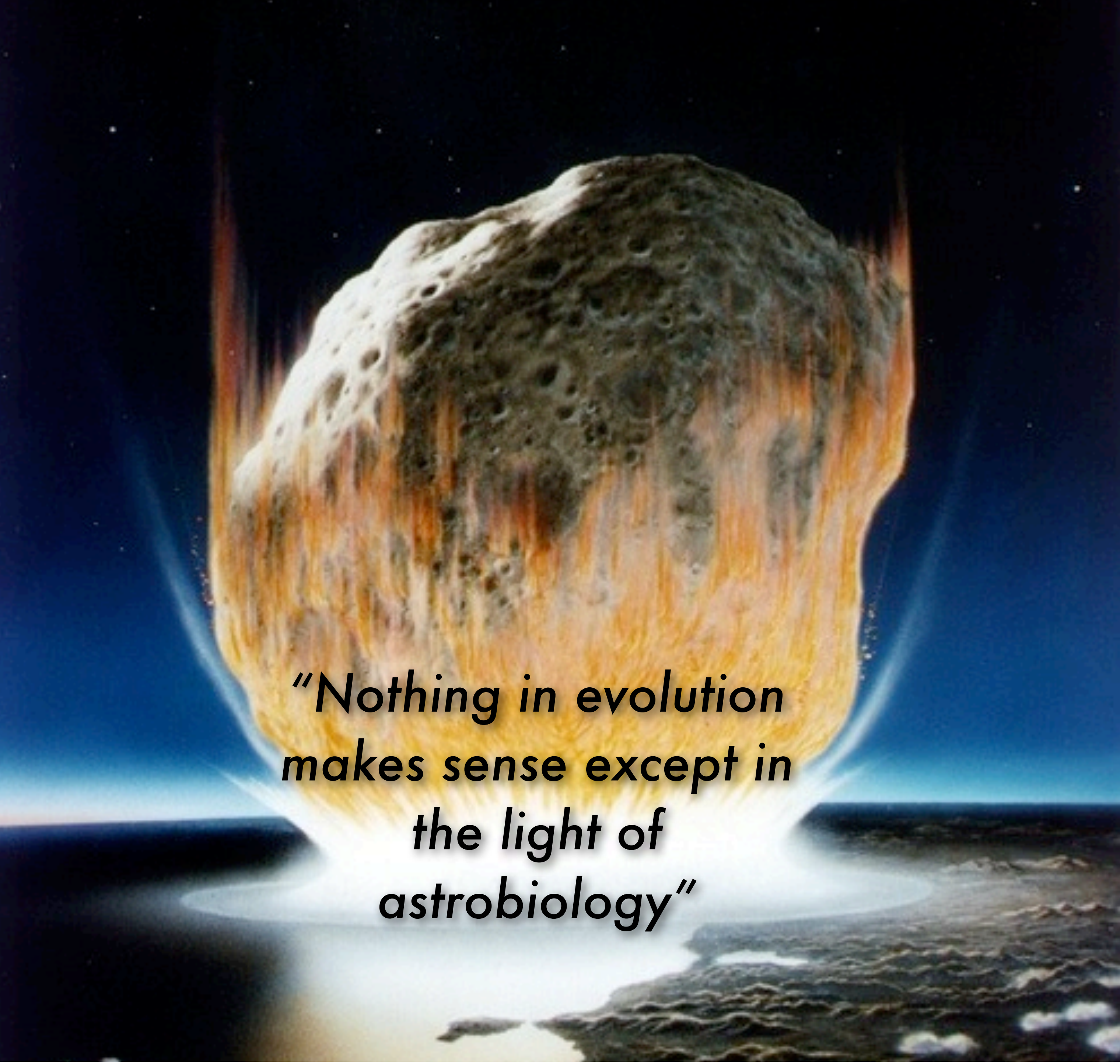
Why now?



Discovery of extrasolar planets



Molecular evolution



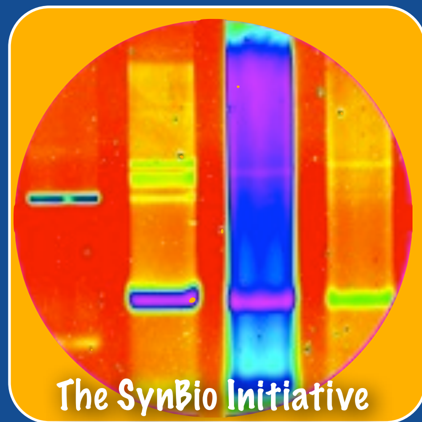
"Nothing in biology makes sense except in the light of evolution".

Toward automatic reconstruction of a highly resolved tree of life. Ciccarelli et al., Science 2006.


Battlestar Galápagos

Plan for talk

What is astro-biology?



Are there “laws” in evolution? Convergence suggesting probability.

What are the limits for life?

Introducing a new technology to approach these questions

Question for discussion

IS EVOLUTION PREDICTABLE based on the physical, chemical and biological laws,

or

CONTINGENT, that is a product of the quirks of history?

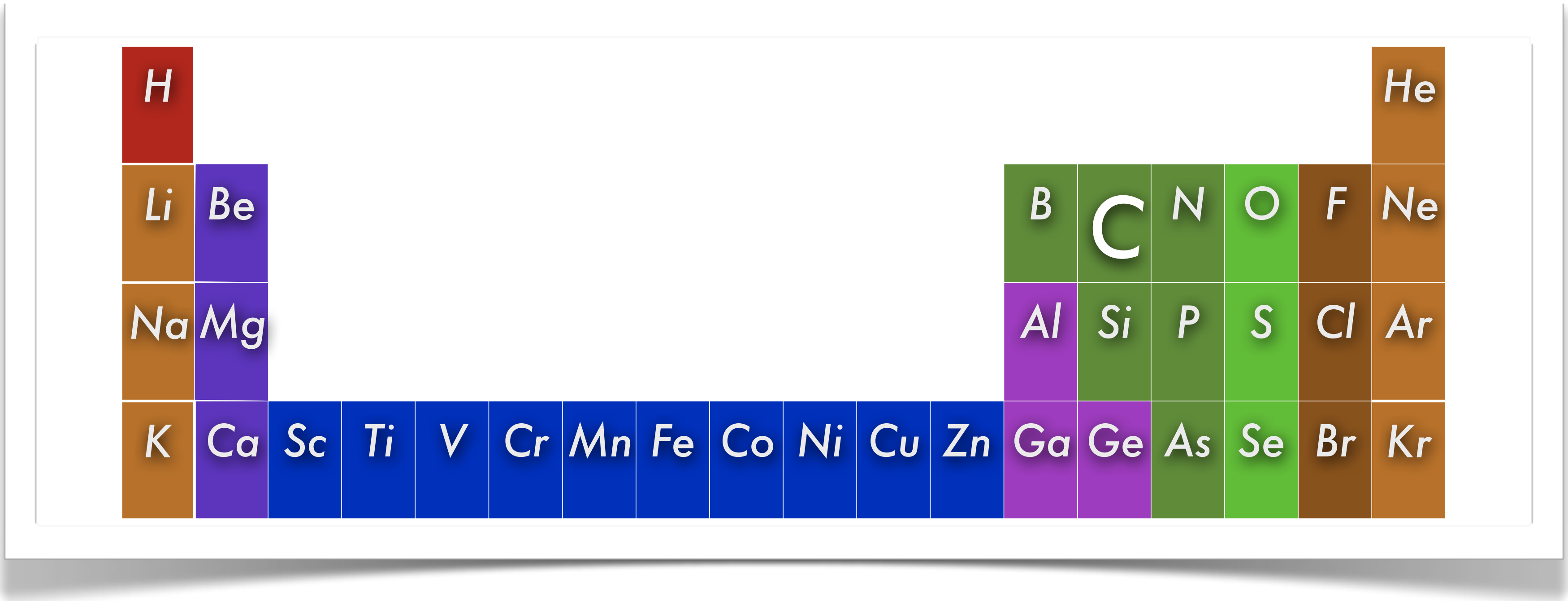
To rephrase,

- Are there laws in evolution?
- This is pertinent to
    - Understanding EVOLUTION,
    - LIFE ELSEWHERE, and the
    - FUTURE OF LIFE on earth.

I hypothesize that:

- There are biological patterns likely to be universal based on....
  - The likelihood of life based on organic carbon because of the prevalence of organic chemistry in comets, meteorites and the interstellar medium;
  - The likelihood of water as a solvent because of the widespread occurrence and chemical properties of water;
  - The universality of the laws of chemistry and physics;
  - The universality in principal of the natural selection;
  - The selective tyranny of the environment;
  - The likelihood of the availability of solar radiation as a source of energy.
- Near-term predictive power can be derived from...
  - the constraints of an ancestry, genetics, and developmental biology.
- This amalgam creates a surprising amount of predictive power in the broad outline. From these we hypothesize that life is always carbon-based, and generally similar to that on Earth. Based on what we know about the origin and evolution of life on Earth, there are certain tendencies, if not "laws", that provide predictive power.

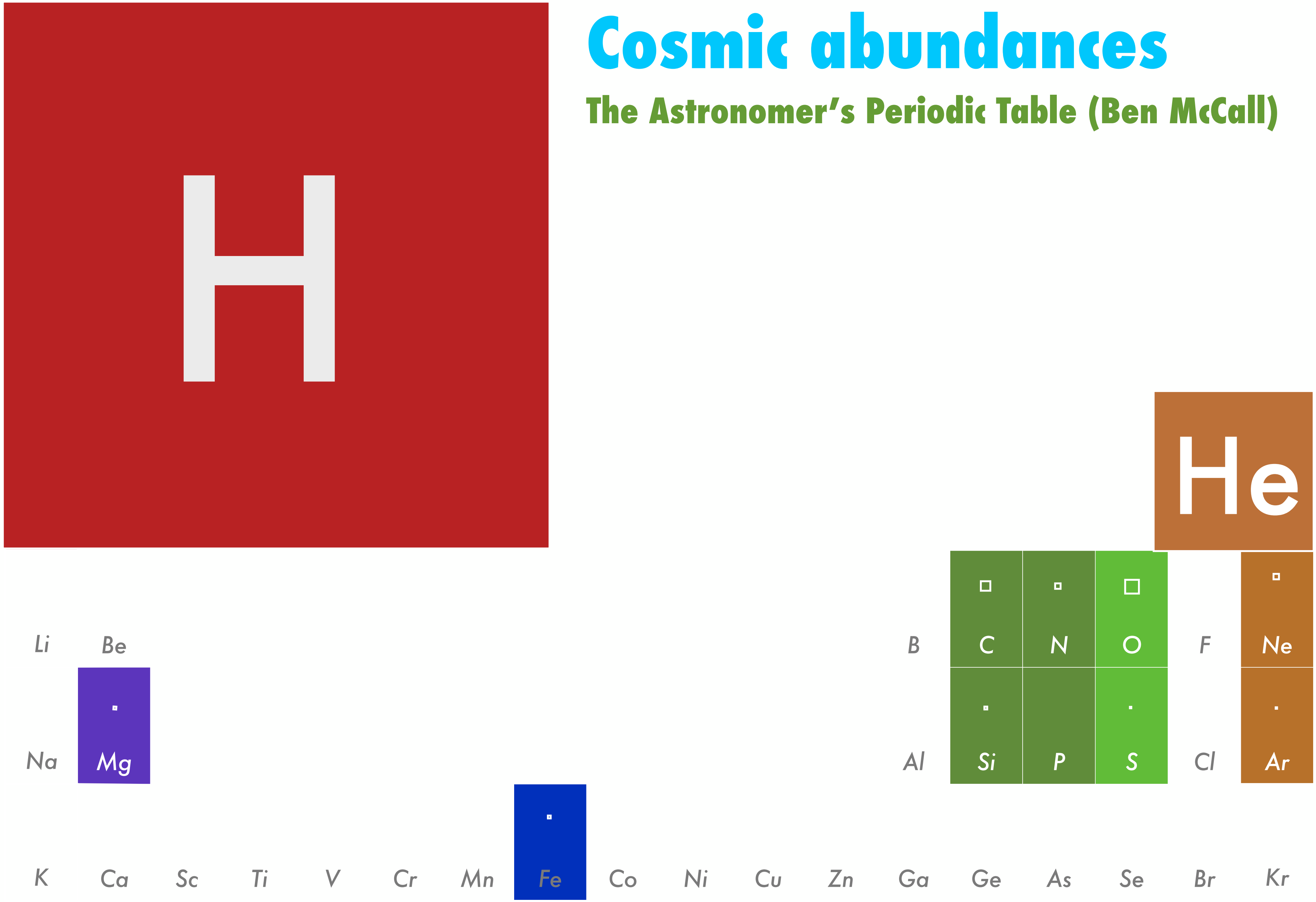
Why carbon?



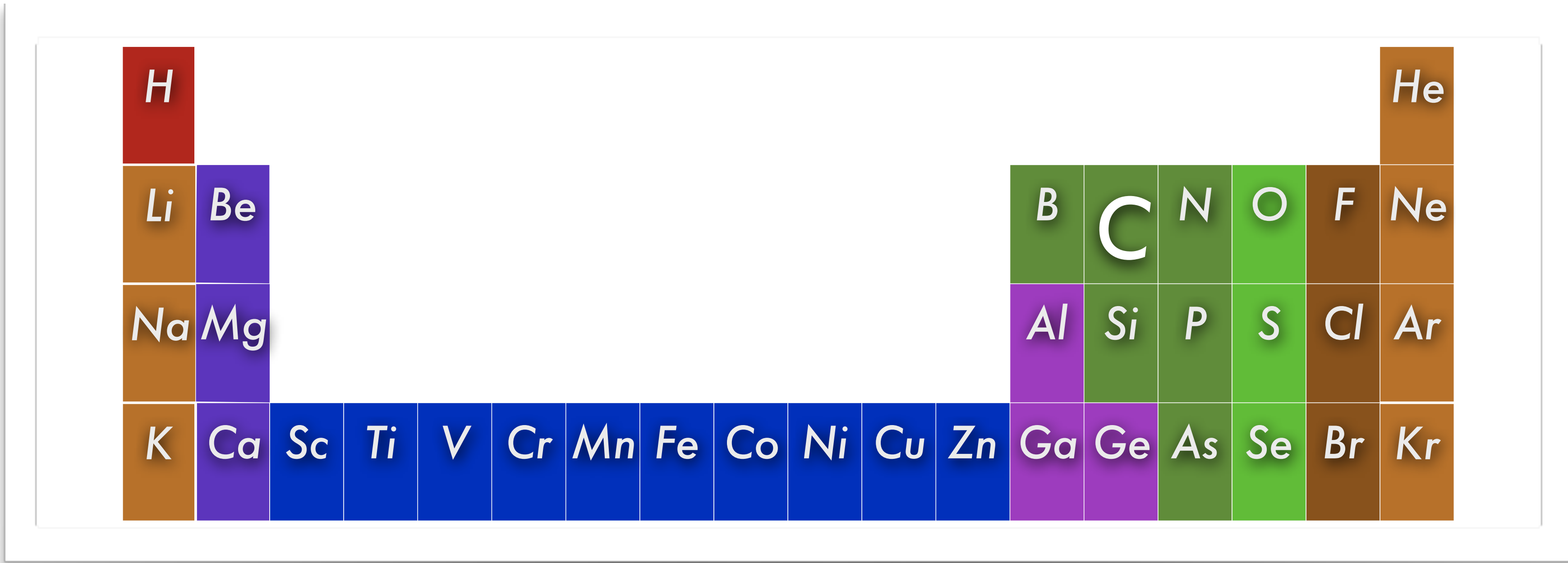
- It is the fourth most common element in the universe.

Cosmic abundances

The Astronomer's Periodic Table (Ben McCall)



Why carbon?

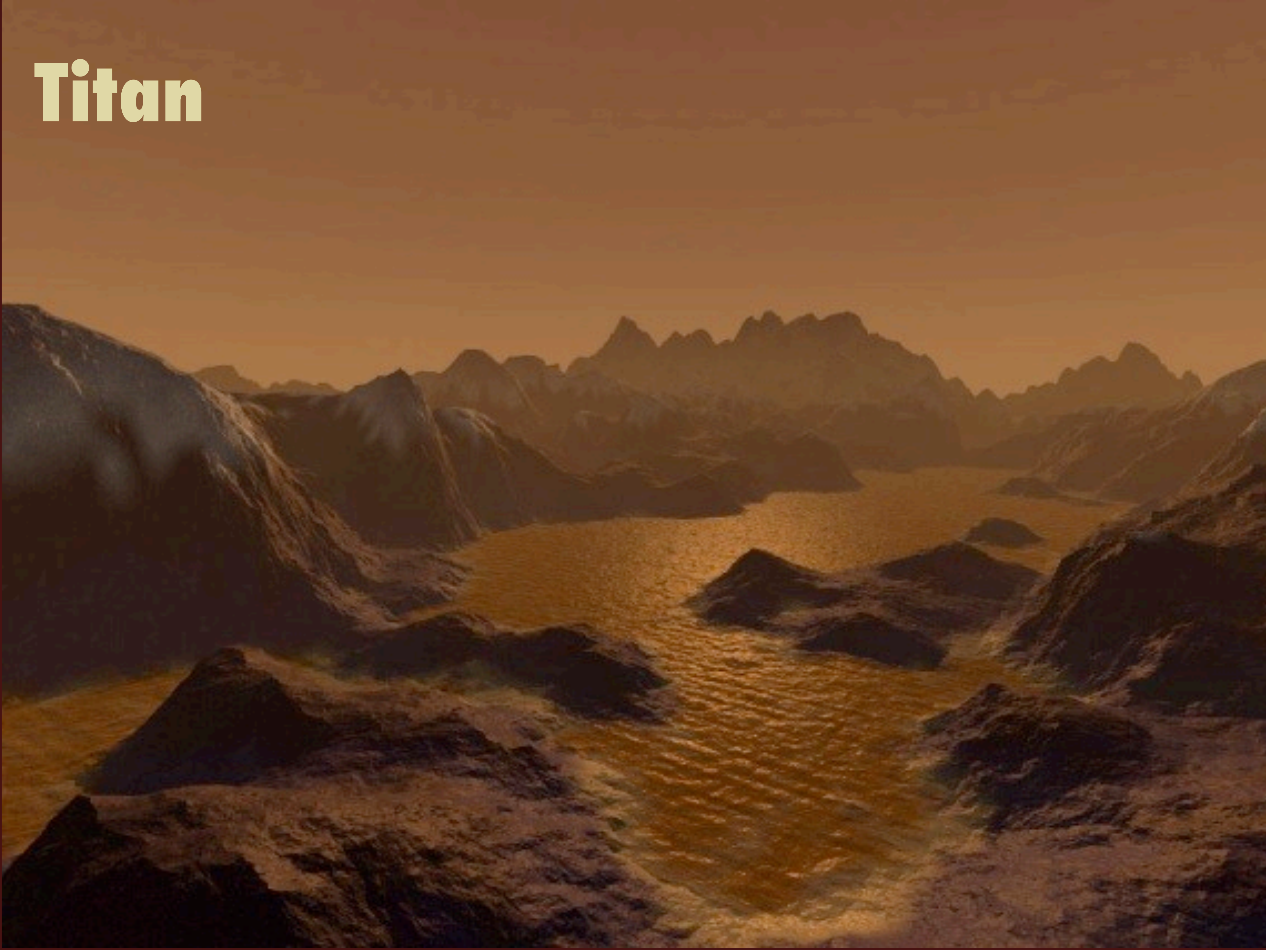


- It is the fourth most common element in the universe.
- It is capable of forming compounds, from CH_4 to DNA.
- Atomic carbon and simple compounds with up to 13 atoms have been either detected in interstellar space by spectrometry or produced in laboratory simulations. These include amino acids and nucleotide bases.

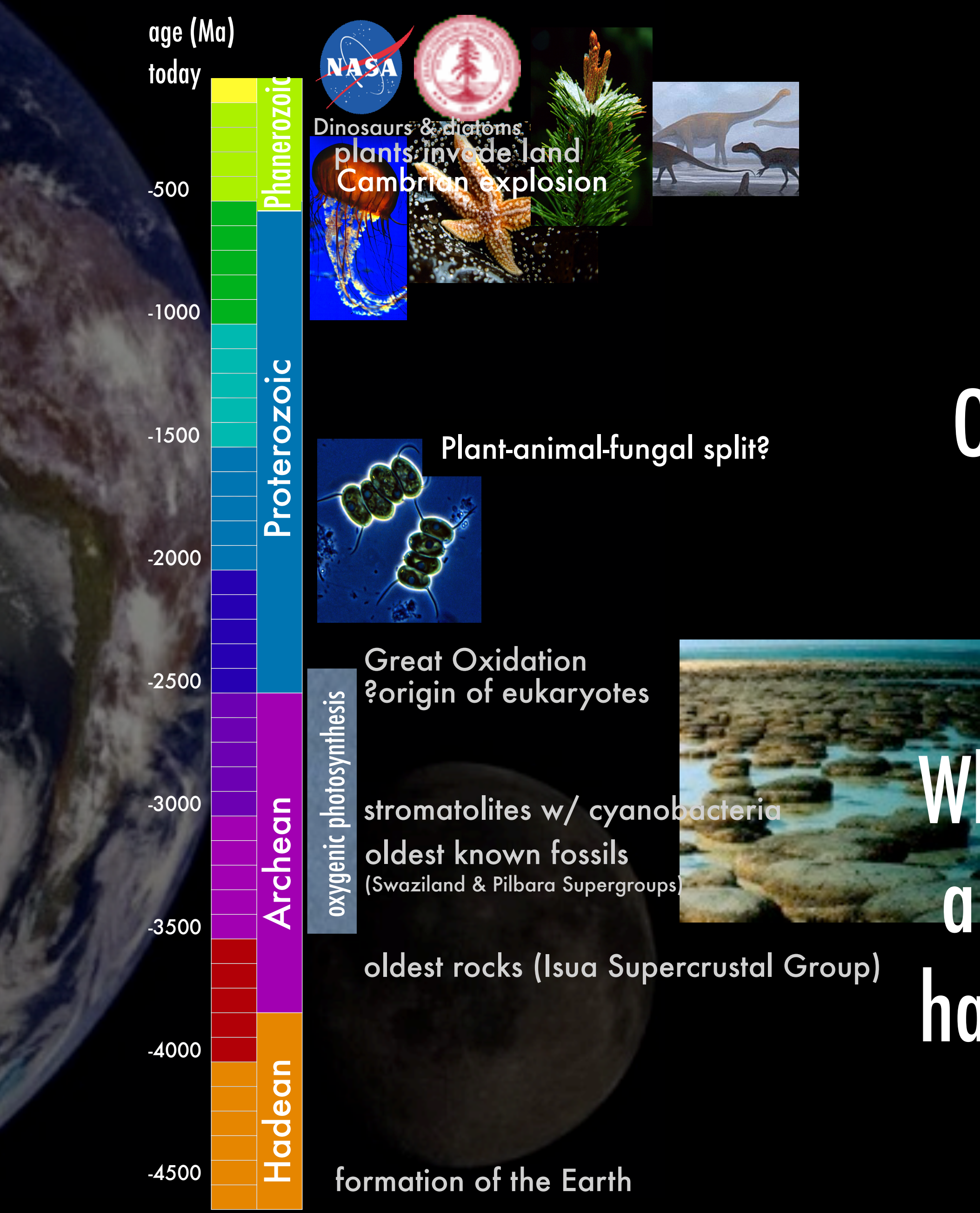
Why water?

★ Water is likely as a solvent because of its widespread occurrence and chemical properties of water

Titan



Time



Poorly constrained.

Only have one narrative - Planet Earth.

What would we hypothesize about literature if we only had "Alice in Wonderland"?

Time

Implies stellar size,

and other environmental factors such as...

the moon?!

Examples of predictable biology

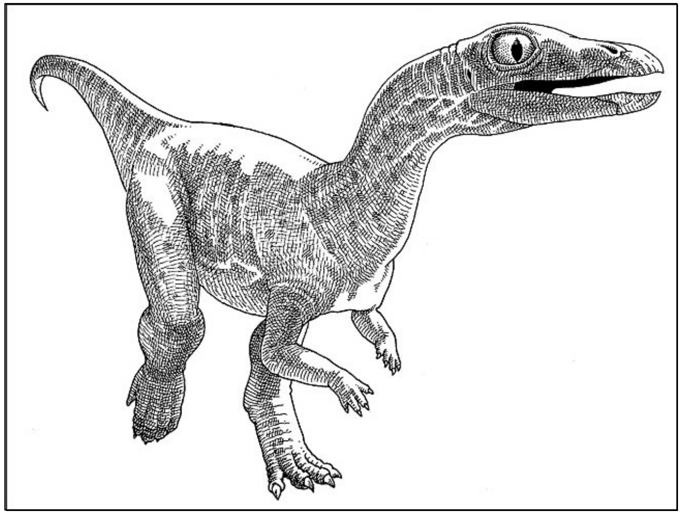
- Convergence
- Bergman’s and Allen’s rule
- Photosynthesis
- Amino acid usage

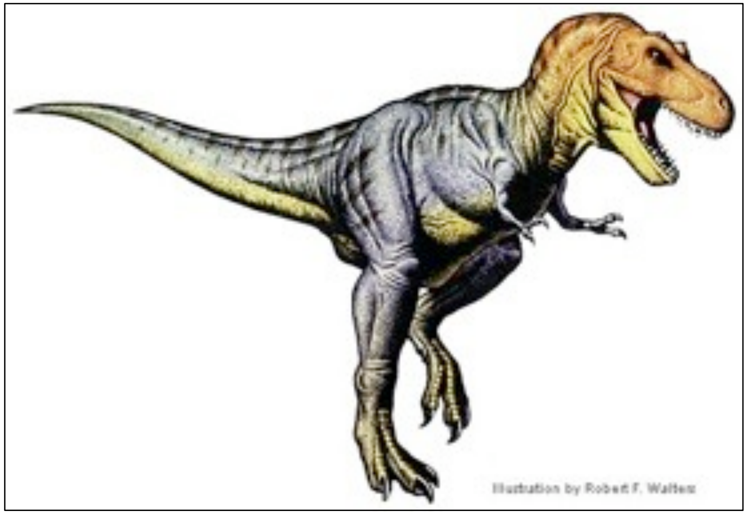
Convergence



- ★Independent evolution of the same solution.
- ★Example: protective thorns, wings

Convergence: Two-legged reptiles





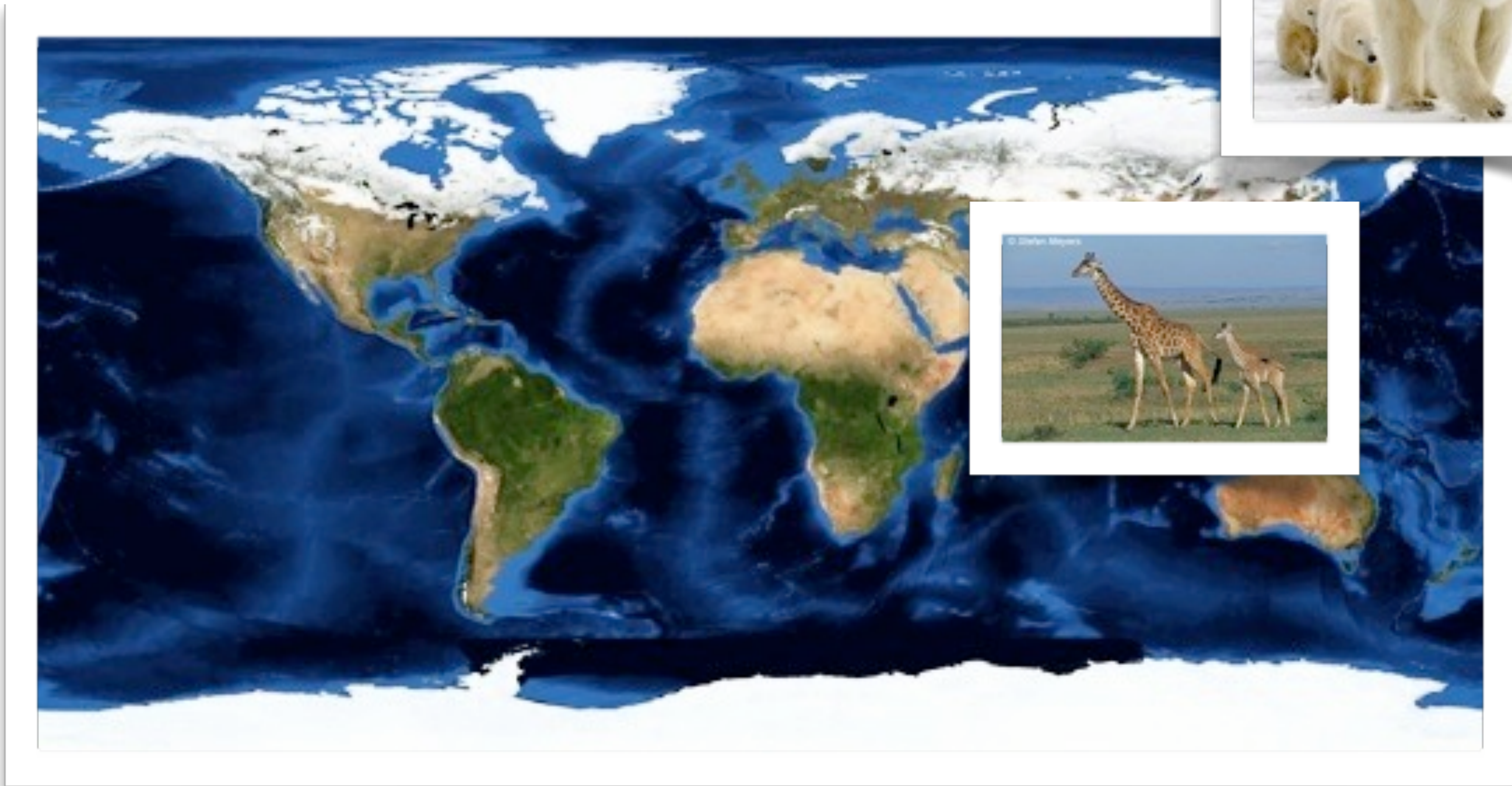
From left to right: crocodile, tyrannosaur, velocirapter

Scientists at the American Museum of Natural History have discovered a fossil in New Mexico that looks like a six-foot-long, two-legged dinosaur along the lines of a tyrannosaur or a velociraptor. But it is actually an 210-million year old relative of today's alligators and crocodiles.

pH

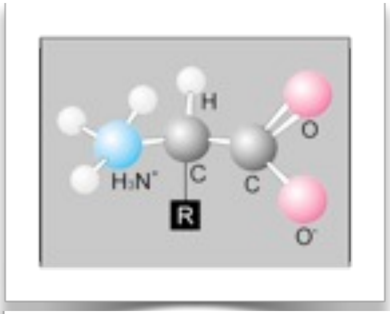
- pH is as −log10[H+]. At pH 0, [H+] = 1 M.
- Easiest is to keep internal pH near neutral.
- Acidophiles: maintain neutral pH. Strong proton pump or low proton membrane permeability.
- Alkaliphiles: internal pH 2+ units below medium. Need effective proton transport system. Serious problem if for membrane-bound ATP synthase system in bacteria.

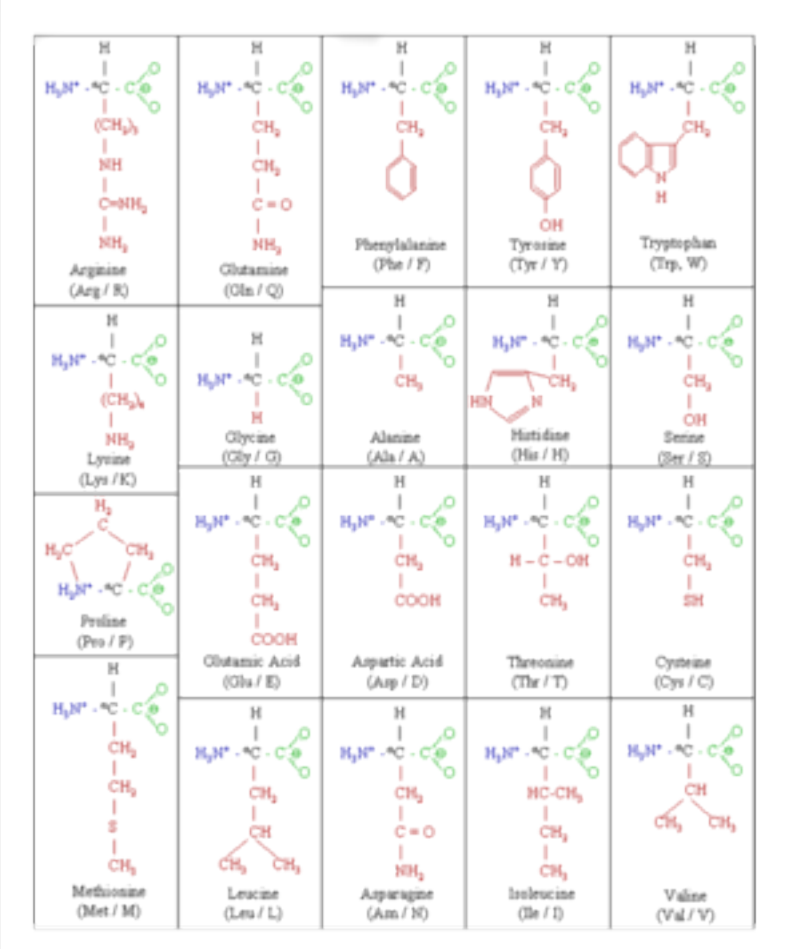
Rules in evolution



- Bergman's rule (related group, larger towards pole)
- Allen's rule (related group, shorter limbs toward pole)
- Both are based on surface area: volume ratio considerations, e.g., physical factors

What about our 20 amino acids?

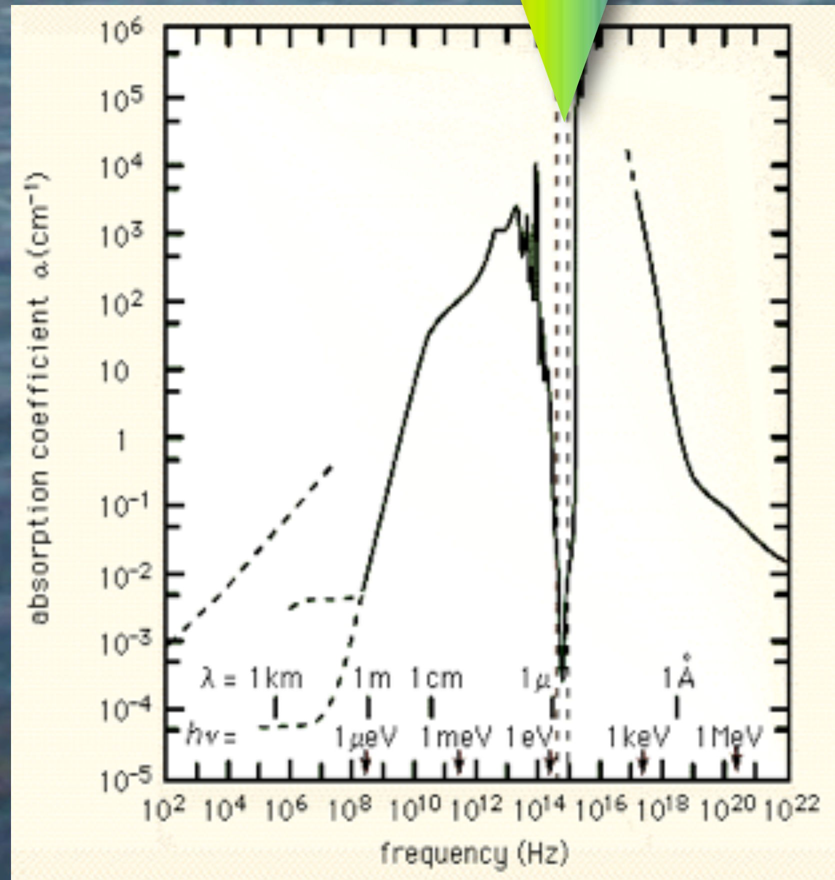




- Of the 20 amino acids used in proteins, 10 were formed in Miller's atmospheric discharge experiments.
- The two other major proposed sources of prebiotic amino acid synthesis include formation in hydrothermal vents and delivery to Earth via meteorites.
- We combine observational and experimental data of amino acid frequencies formed by these diverse mechanisms and show that, regardless of the source, these 10 early amino acids can be ranked in order of decreasing abundance in prebiotic contexts. This order can be predicted by thermodynamics. The relative abundances of the early amino acids were most likely reflected in the composition of the first proteins at the time the genetic code originated. The remaining amino acids were incorporated into proteins after pathways for their biochemical synthesis evolved. This is consistent with theories of the evolution of the genetic code by stepwise addition of new amino acids. These are hints that key aspects of early biochemistry may be universal.
- Higgs & Pudritz (2009). A Thermodynamic Basis for Prebiotic Amino Acid Synthesis and the Nature of the First Genetic Code. ASTROBIOLOGY 9: 483-490.

Eukaryotes and cyanobacteria use radiation 400-700 nm for photosynthesis. Why?

- Window between infrared (which is not very energetic) and UV (which is damaging.)
- Or does it have to do with water chemistry?
- see also , "The Color of Plants on Other Worlds" (Nancy Kiang, Scientific American)



seawater

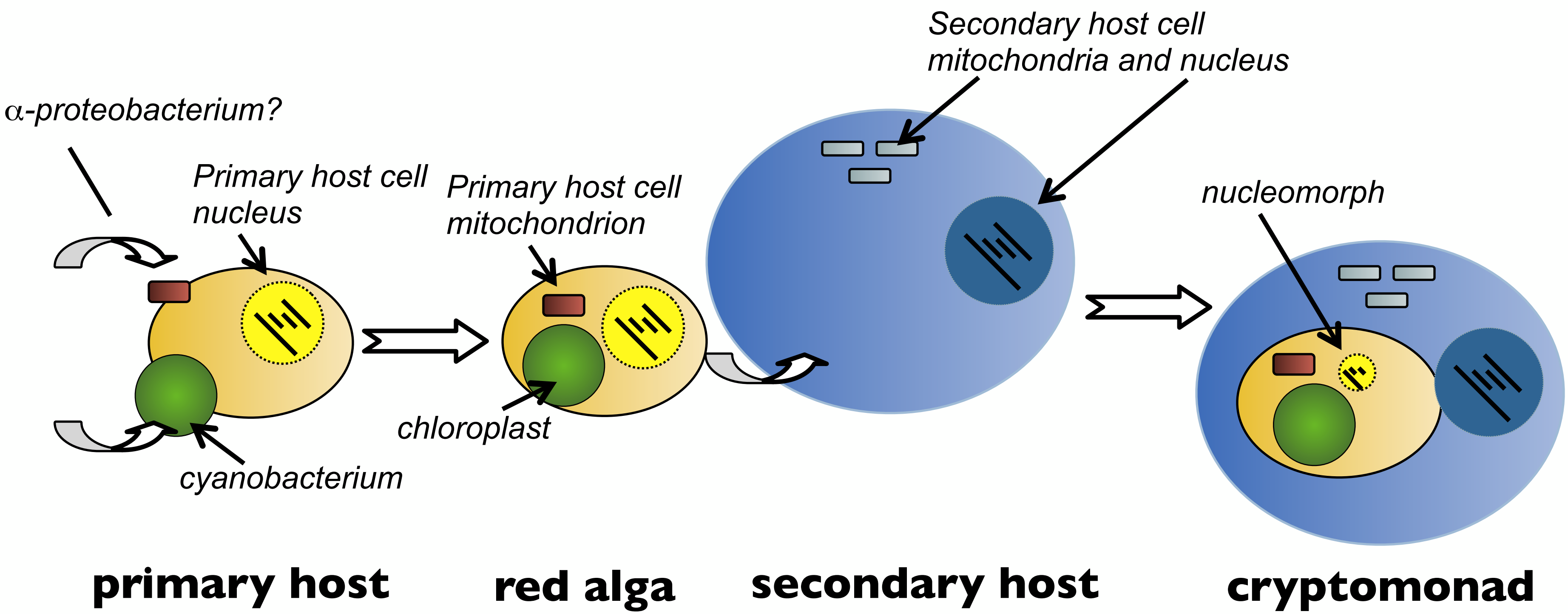
Absorption of radiation by H2O

Ingredients for photosynthesis

Convergence?

- Redundancy (genes, proteins, etc.)
- Symbiosis
- Multicellularity
- Transition to land - and back to water
- Skin color
- Intelligence

The origin of the eukaryotic cell by primary and secondary endosymbiosis.

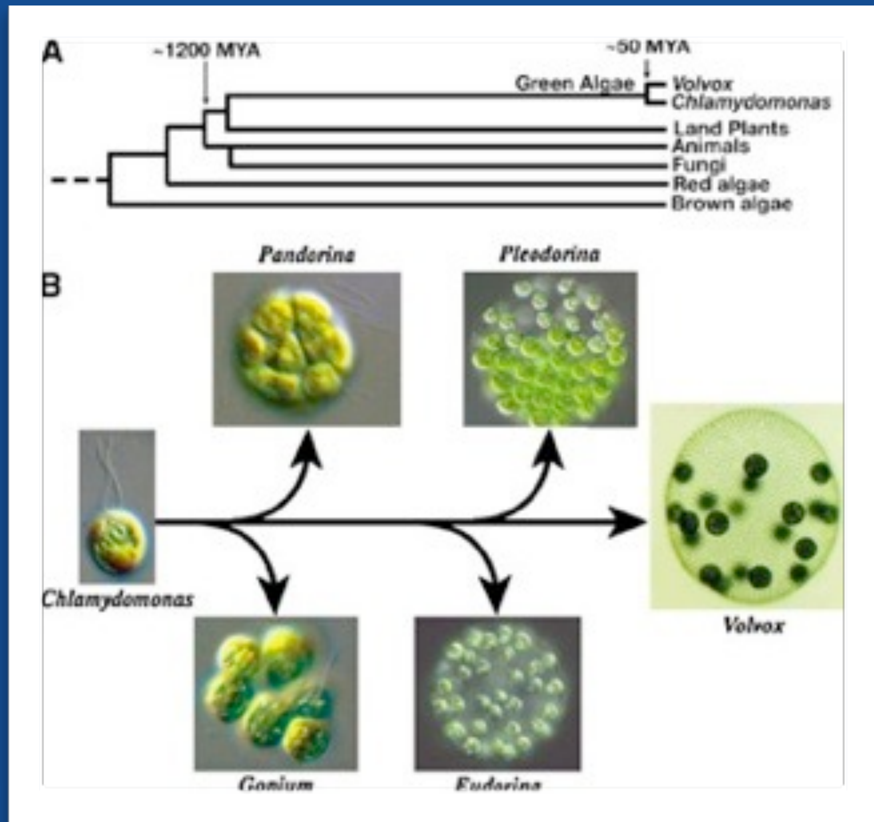


Rothschild, JEM 2004

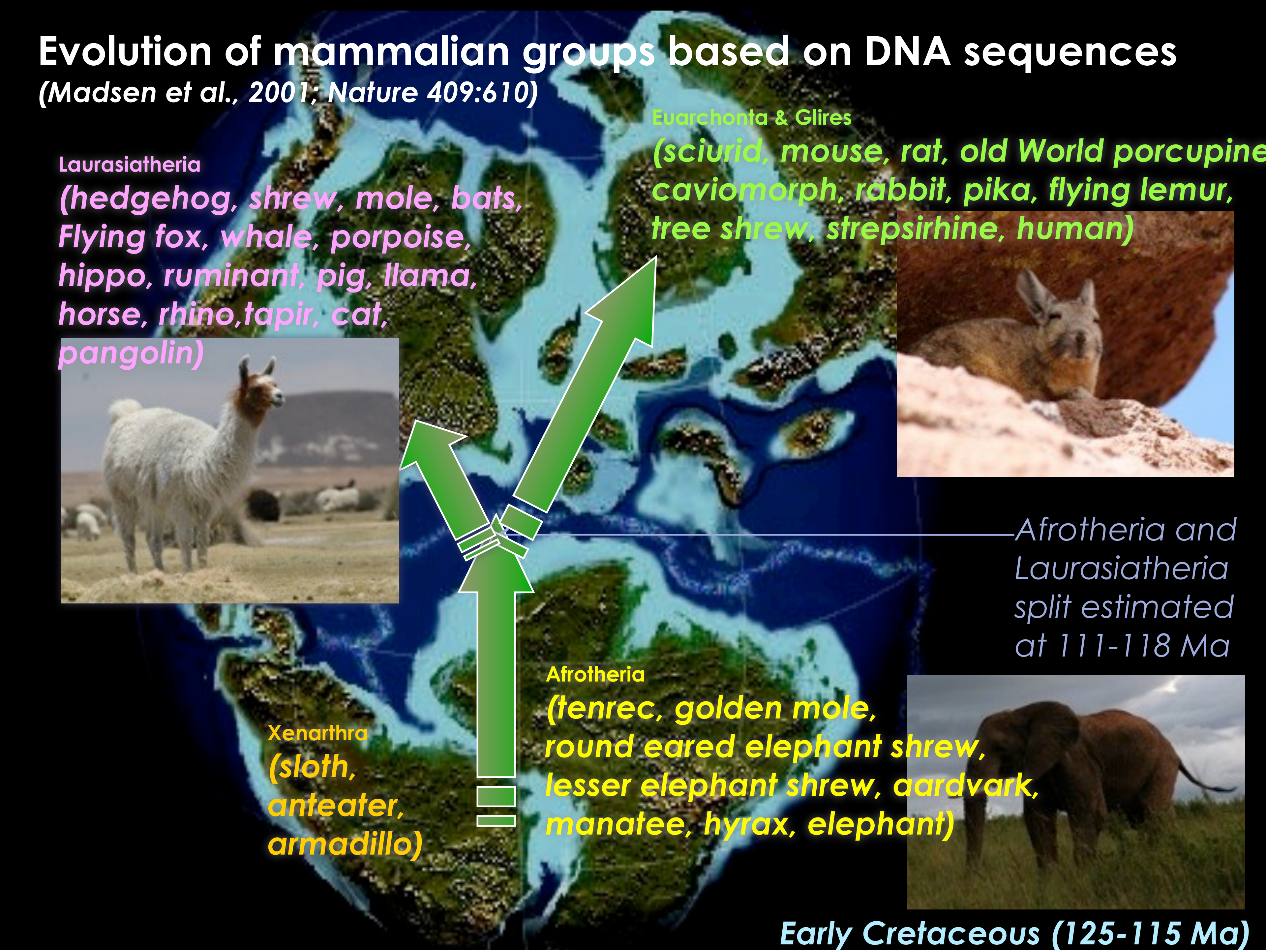
Multicellularity

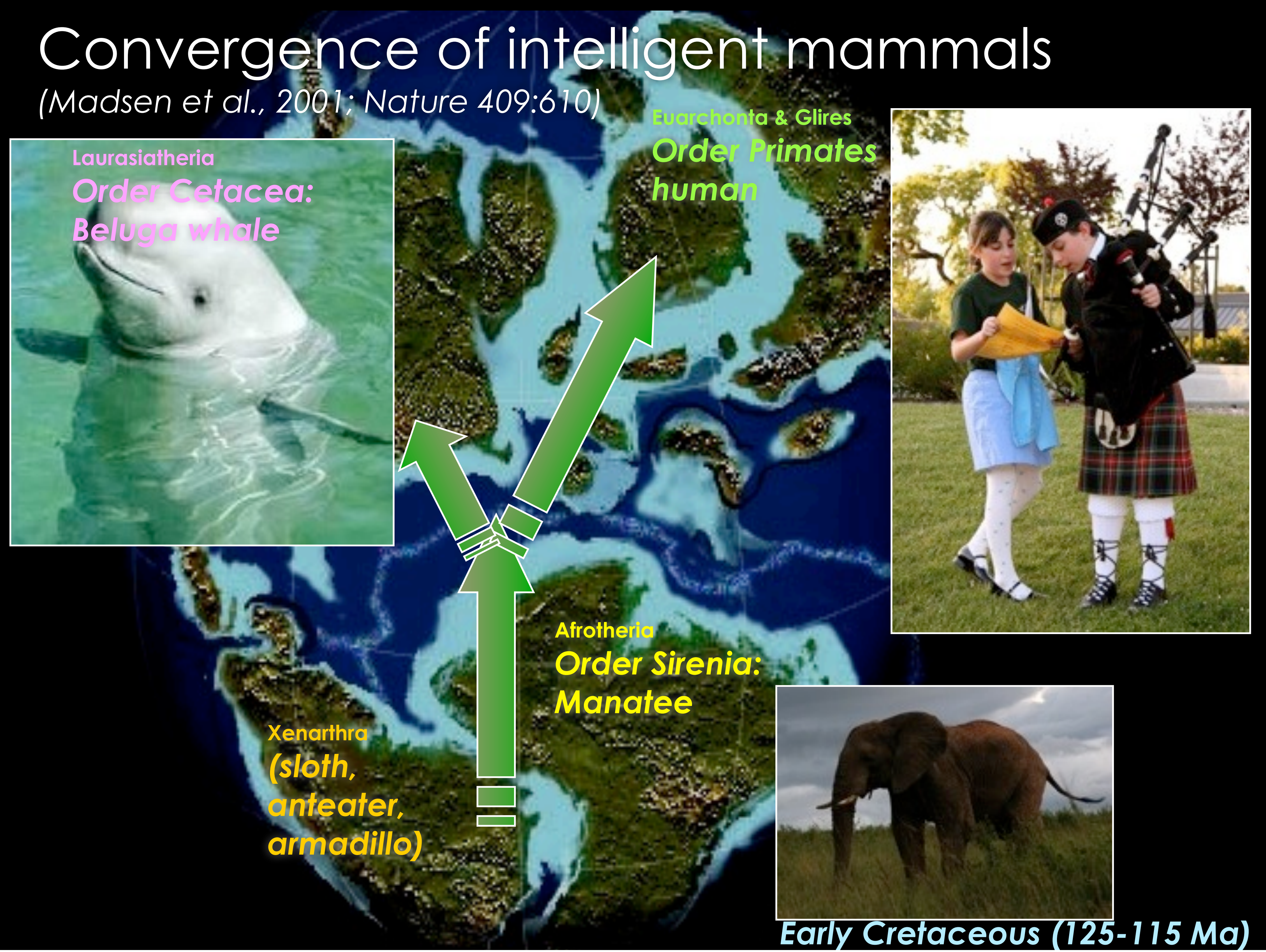
- Advantages:
  - Size. Avoiding prey, faster movement, different scale sensing of environment.
  - If large and "unicellular", have
    - diffusion problems (but could get around this geometrically to a certain extent)
    - co-ordination of self
  - Senescence
  - Sequestering germ line

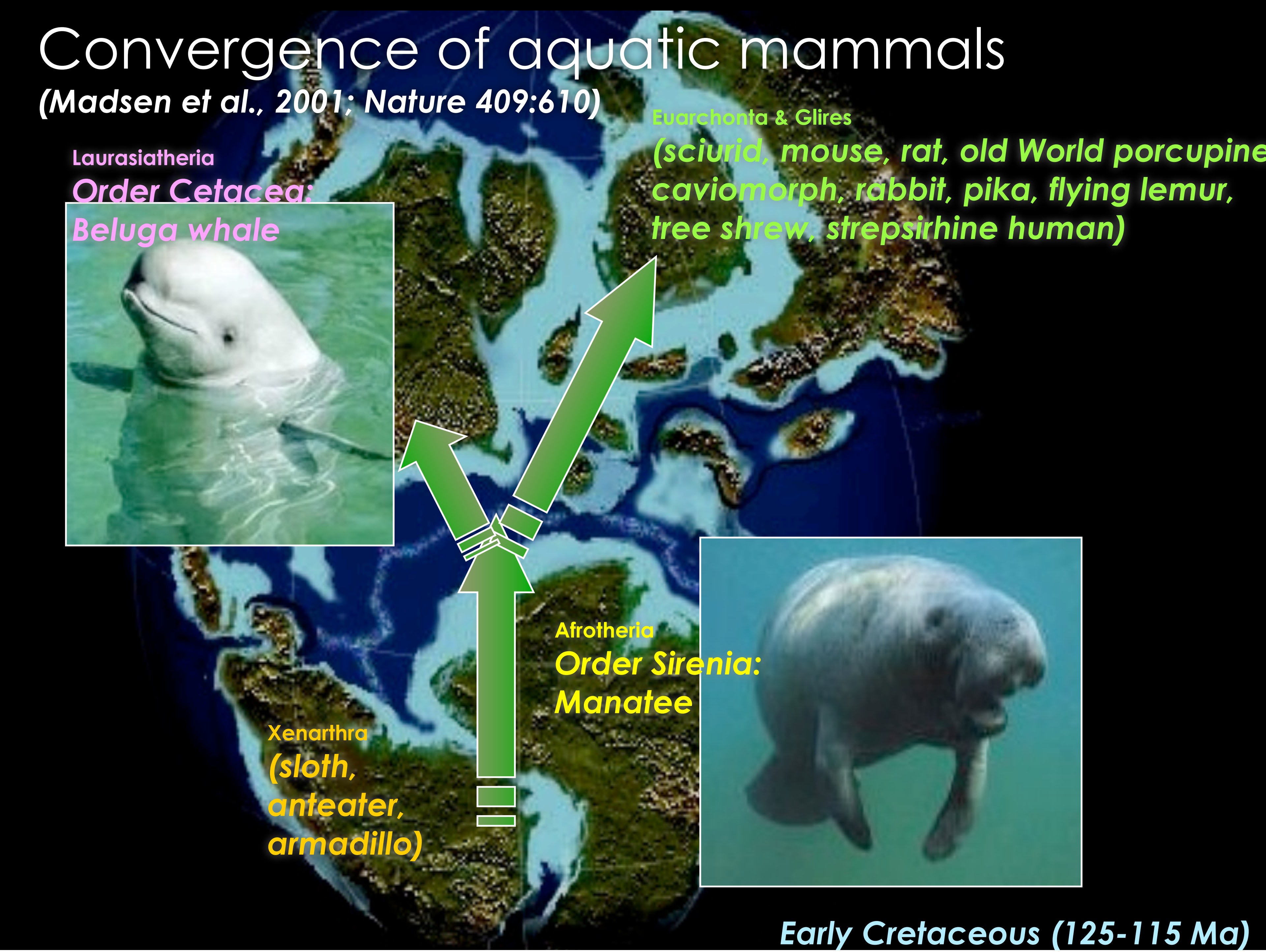
So, it is not surprising that it has arisen multiple times.

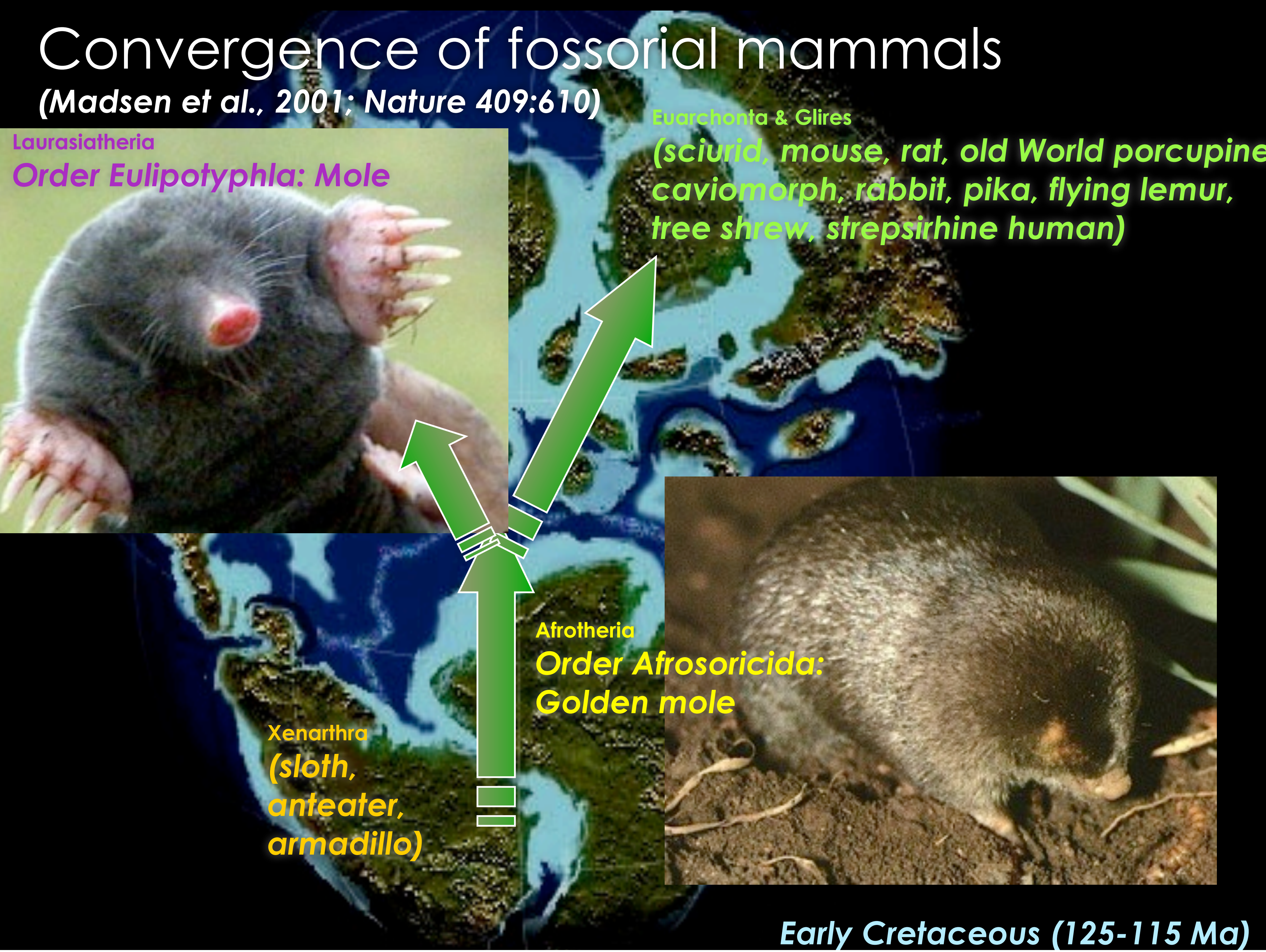


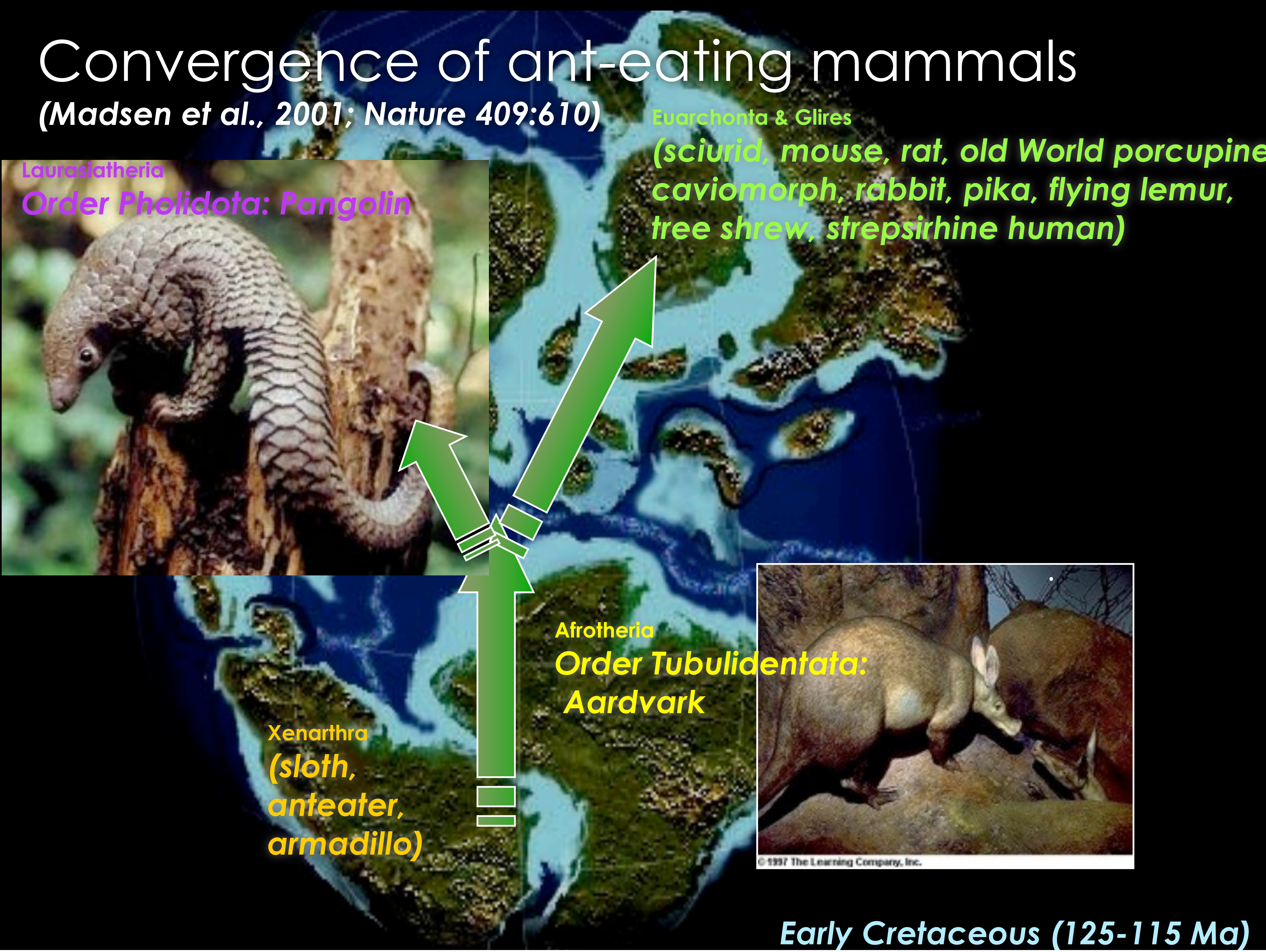
Kirk. 2005. A twelve-step program for evolving multicellularity and a division of labor. Bioessays 27:299-310.


Evolution of mammalian groups based on DNA sequences
(Madsen et al., 2001; Nature 409:610)
Laurasiatheria
(hedgehog, shrew, mole, bats, Flying fox, whale, porpoise, hippo, ruminant, pig, llama, horse, rhino,tapir, cat, pangolin)
Euarchonta & Glires
(sciurid, mouse, rat, old World porcupine, caviomorph, rabbit, pika, flying lemur, tree shrew, strepsirhine, human)
Afrotheria and Laurasiatheria split estimated at 111-118 Ma
Xenarthra
(sloth, anteater, armadillo)
Afrotheria
(tenrec, golden mole, round eared elephant shrew, lesser elephant shrew, aardvark, manatee, hyrax, elephant)
Early Cretaceous (125-115 Ma)


Convergence of intelligent mammals
(Madsen et al., 2001; Nature 409:610)
Laurasiatheria
Order Cetacea:
Beluga whale
Euarchonta & Glires
Order Primates
human
Afrotheria
Order Sirenia:
Manatee
Xenarthra
(sloth,
anteater,
armadillo)
Early Cretaceous (125-115 Ma)


Convergence of aquatic mammals
(Madsen et al., 2001; Nature 409:610)
Laurasiatheria
Order Cetacea:
Beluga whale
Euarchonta & Glires
(sciurid, mouse, rat, old World porcupine
caviomorph, rabbit, pika, flying lemur,
tree shrew, strepsirhine human)
Afrotheria
Order Sirenia:
Manatee
Xenarthra
(sloth,
anteater,
armadillo)
Early Cretaceous (125-115 Ma)


Convergence of fossorial mammals
(Madsen et al., 2001; Nature 409:610)
Laurasiatheria
Order Eulipotyphla: Mole
Euarchonta & Glires
(sciurid, mouse, rat, old World porcupine
caviomorph, rabbit, pika, flying lemur,
tree shrew, strepsirhine human)
Afrotheria
Order Afrosoricida:
Golden mole
Xenarthra
(sloth,
anteater,
armadillo)
Early Cretaceous (125-115 Ma)


Convergence of ant-eating mammals
(Madsen et al., 2001; Nature 409:610)
Euarchonta & Glires
(sciurid, mouse, rat, old World porcupine
caviomorph, rabbit, pika, flying lemur,
tree shrew, strepsirhine human)
Laurasiatheria
Order Pholidota: Pangolin
Afrotheria
Order Tubulidentata:
Aardvark
Xenarthra
(sloth,
anteater,
armadillo)
©1997 The Learning Company, Inc.
Early Cretaceous (125-115 Ma)

Question for discussion

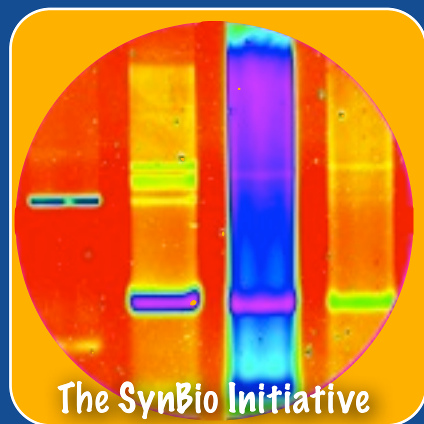
IS EVOLUTION PREDICTABLE based on the physical, chemical and biological laws,

or

CONTINGENT, that is product of the quirks of history?

Some yes, some no

Plan for talk



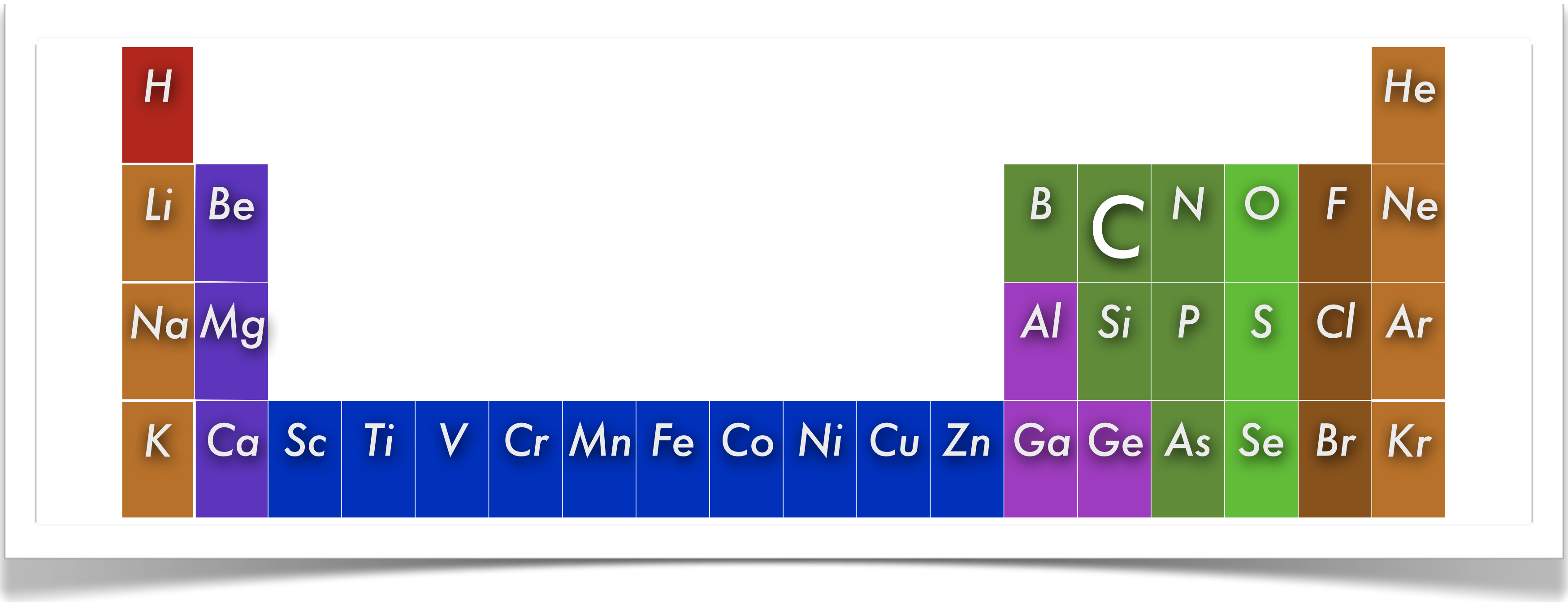
What are the limits for life? Extremophiles on earth help us to put constraints on the minimum envelope for life.

Philosophical issues

- ★Physical, chemical, biological(?) extremes?
- ★What is "extreme"? Simply in the eye of the beholder? Evolutionary definition? Objective definition?
- ★Must extremophiles love extreme conditions?

- ★Must extremophile apply to all life stages? At all times? Deinococcus and frogs.

Why are there limits to life?
because life is based on organic carbon in aqueous solution

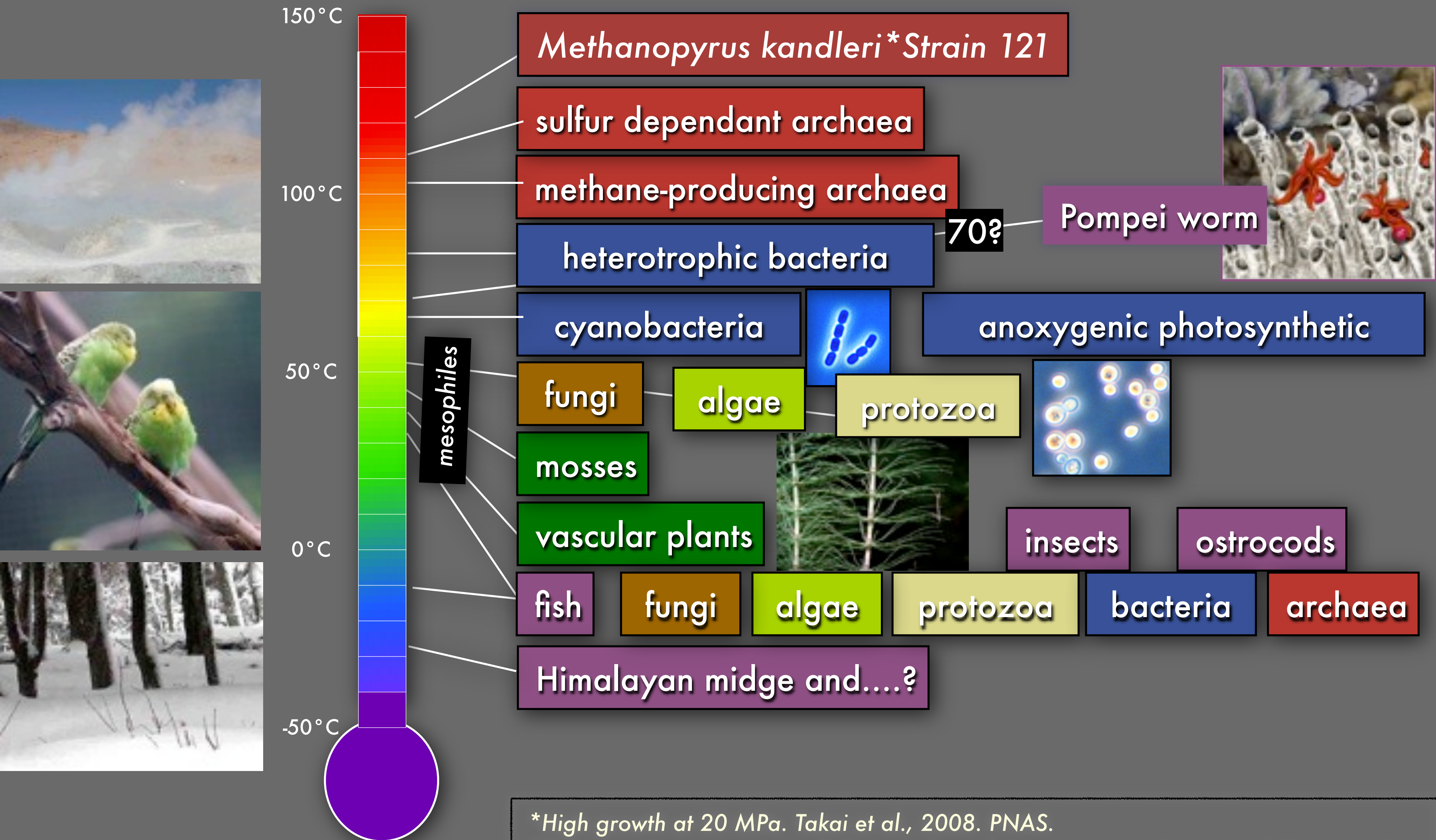


What are the **limits** *to* **life?**

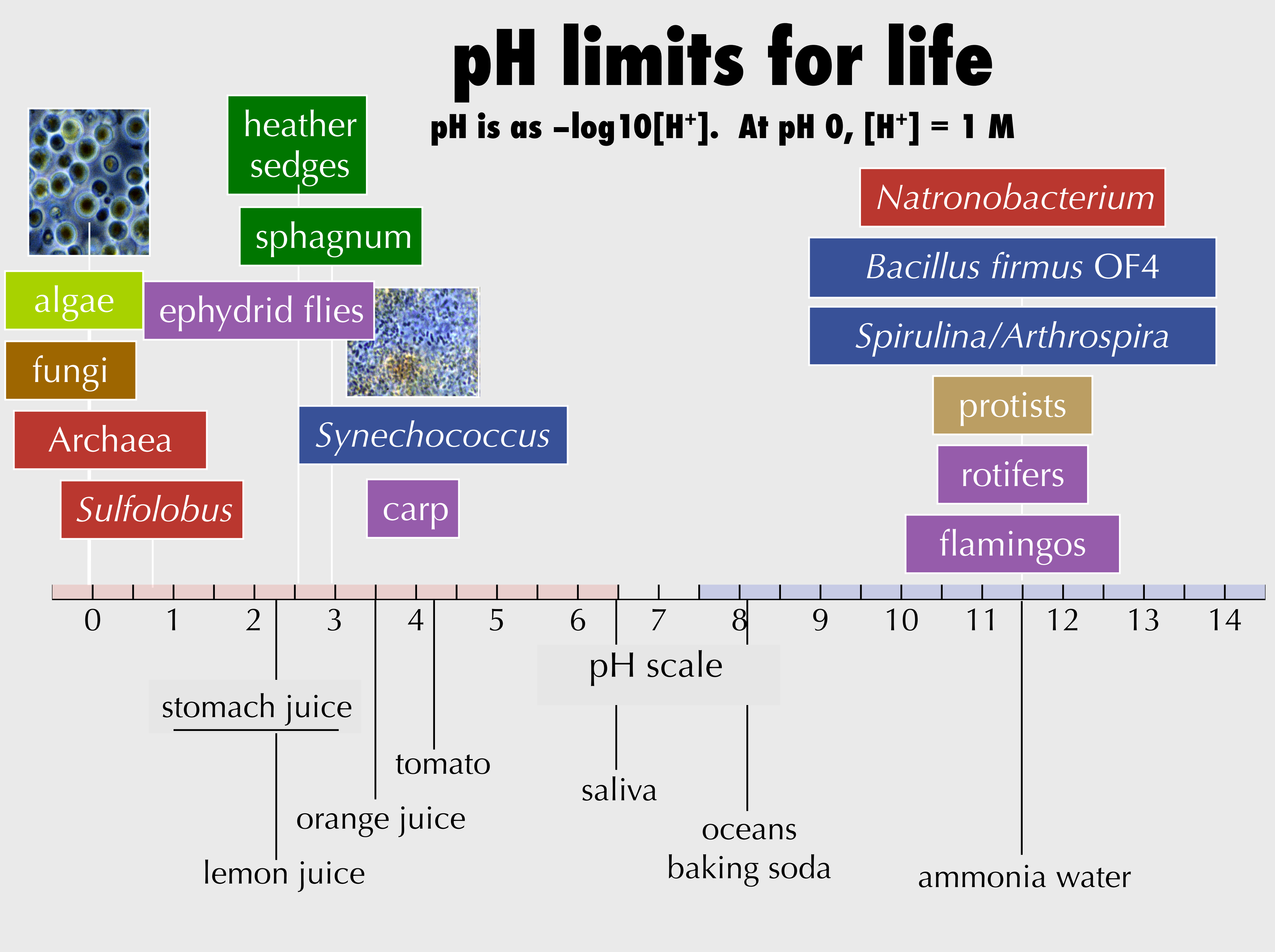
Our only field site so far


On, over and in it swarms life in a multidimensional niche space
Radiation
Temperature
Salinity
Desiccation
Chemical extremes
pH
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
Pressure
Electricity

Temperature limits for life*

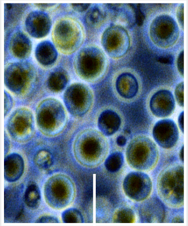


*High growth at 20 MPa. Takai et al., 2008. PNAS.
**Note many organisms, including seeds and spores, can survive at much lower and higher temperatures.


pH limits for life
pH is as –log10[H+]. At pH 0, [H+] = 1 M
heather
sedges
sphagnum
algae
ephydrid flies
fungi
Archaea
Sulfolobus
Synechococcus
carp
Natronobacterium
Bacillus firmus OF4
Spirulina/Arthrospira
protists
rotifers
flamingos
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
pH scale
stomach juice
lemon juice
orange juice
tomato
saliva
oceans
baking soda
ammonia water

pH limits for life

pH is as $-\log_{10}[H^+]$. At pH 0, $[H^+] = 1$ M

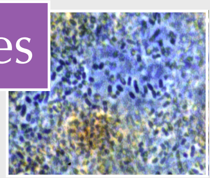


heather sedges

sphagnum

algae

ephydrid flies



fungi

Archaea

Sulfolobus

Synechococcus

carp

Natronobacterium

Bacillus firmus OF4

Spirulina/Arthrospira

protists

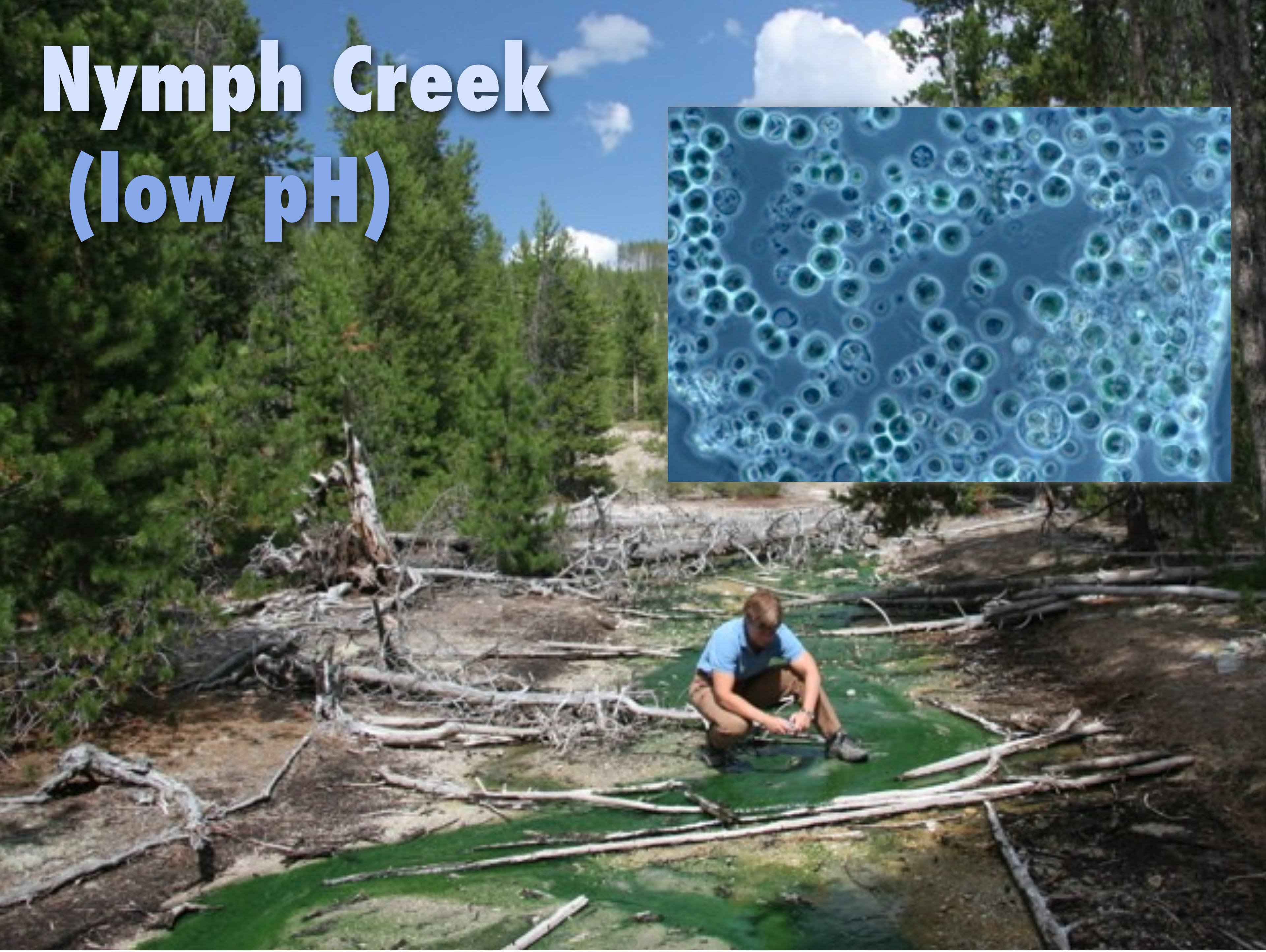
rotifers

flamingos

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14

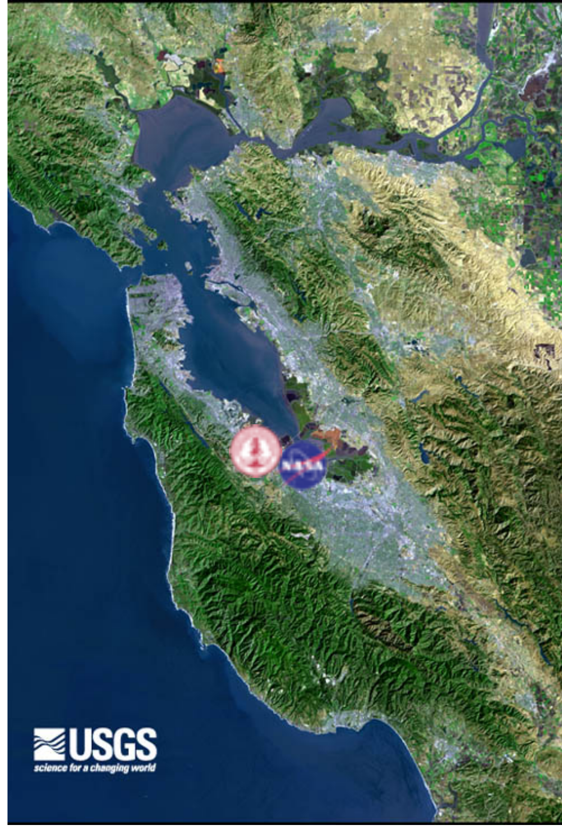
pH scale

Nymph Creek (low pH)



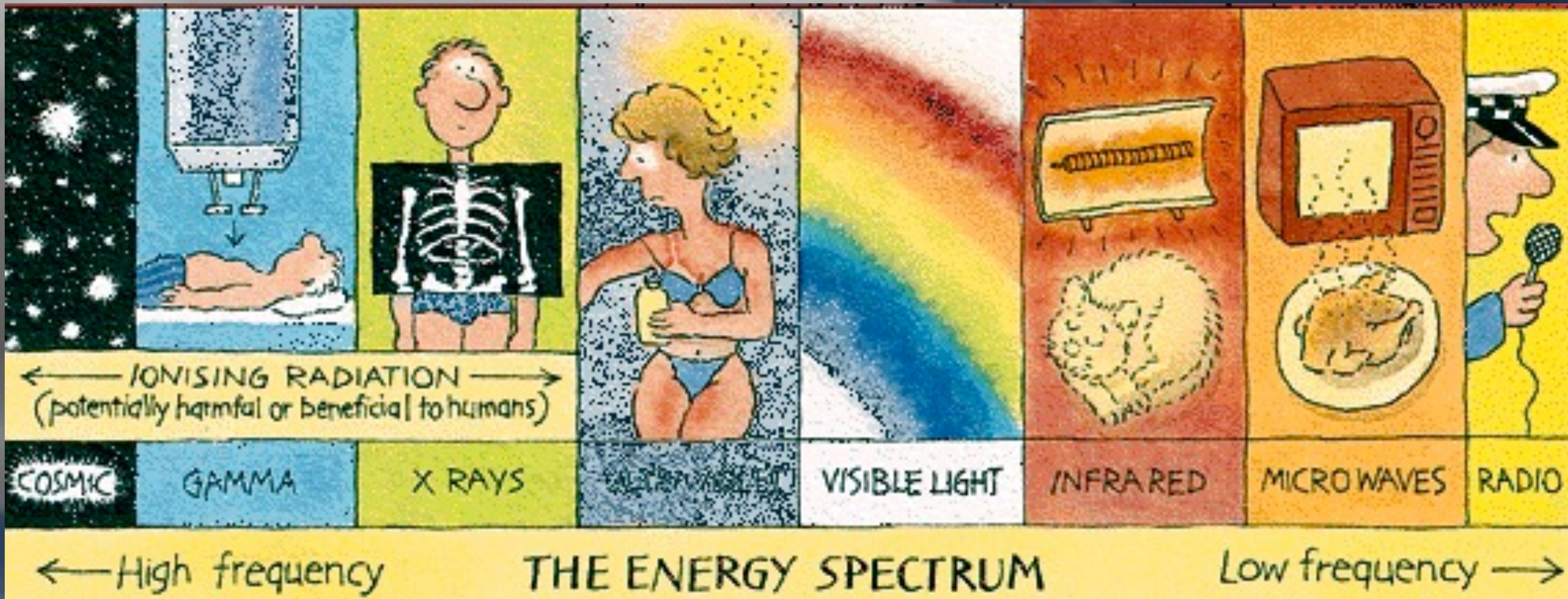
Salinity

- Halophiles: 2-5 M salt
- Include Archaea and a eukaryote.
- Dunaliella salina is used in biotech industry. Produces glycerol and β-carotene.
- Bacterial halophiles were flown in space.



Desiccation

- ★ Can be correlated with salinity tolerance.
- ★ Cell growth at normal temperatures usually requires water potential, aw (defined as pH20 [liquid solution] / pH20 [pure liquid water], where p is the vapor pressure of the respective liquid) of >0.9 for most bacteria and >0.86 for most fungi.
- ★ Lowest value known for growth of a bacterium at normal temperatures is aw = 0.76 for Halobacterium.
- ★ Possibly a few organisms, e.g. lichens in the Negev Desert, can survive on water vapor rather than liquid water.
- ★ Don't repair cell damage during desiccation, so must be good at repair upon rehydration.



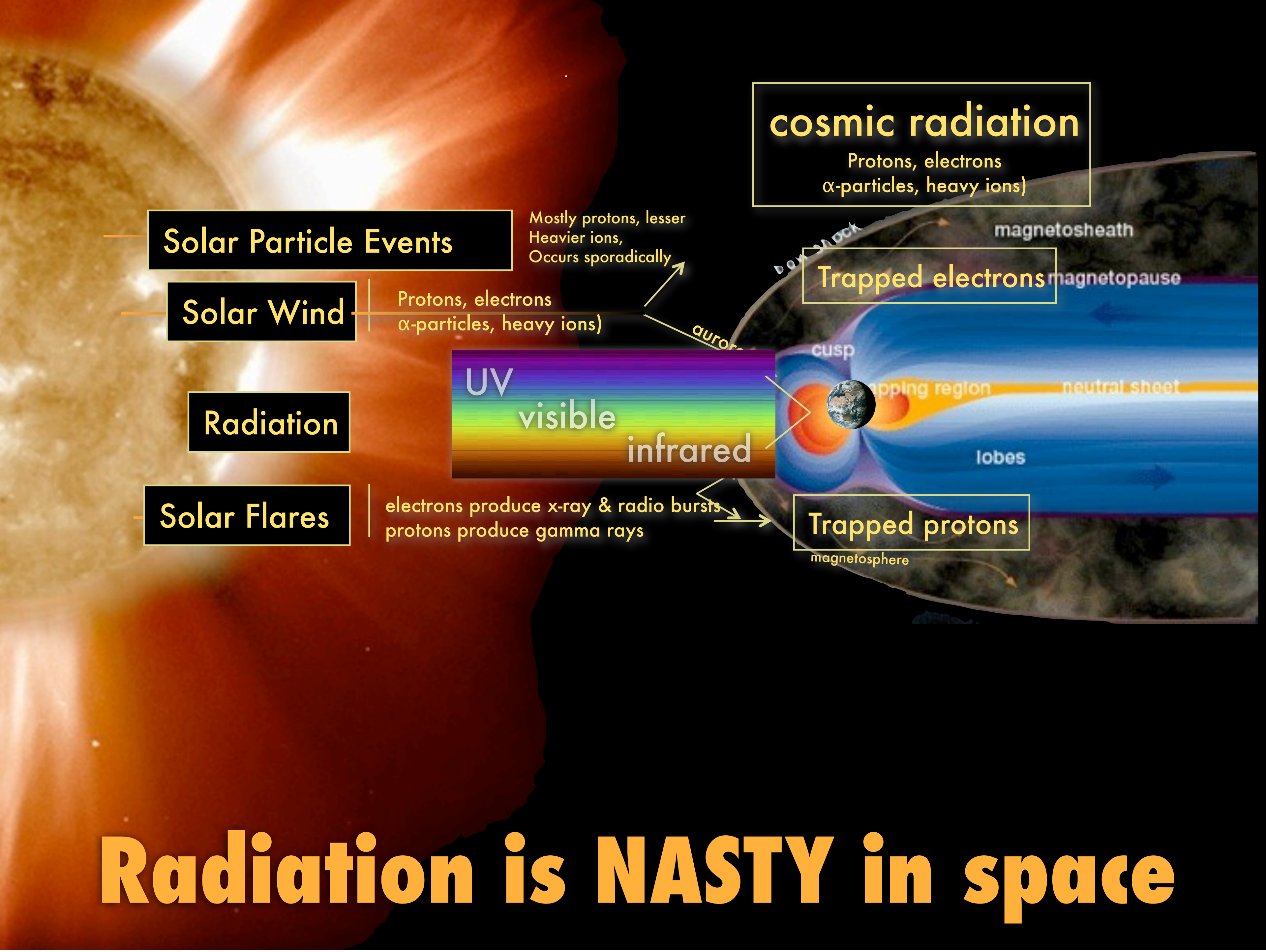
Radiation

The energy spectrum

High oxygen

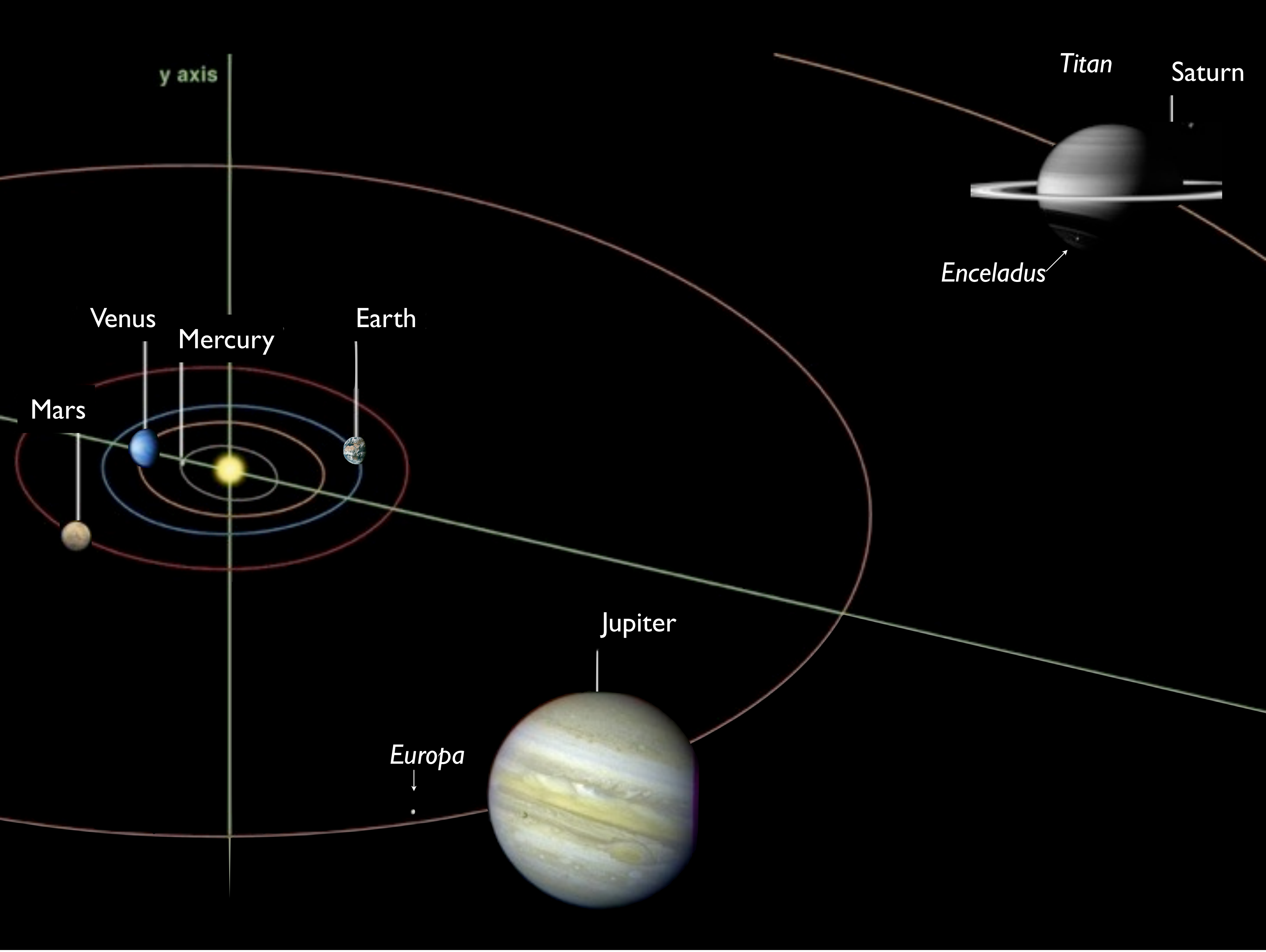
- ★Oxygen is the one environmental extreme that we consider "NORMAL"
- ★Actually this is one of the WORST environmental extremes.
- ★Conclusion: WE are extremophiles too.

$$O_2 \rightarrow O_2^{-} \rightarrow H_2O_2 \rightarrow \cdot OH \rightarrow H_2O$$


cosmic radiation
Protons, electrons
α-particles, heavy ions)
Solar Particle Events
Mostly protons, lesser
Heavier ions,
Occurs sporadically
Solar Wind
Protons, electrons
α-particles, heavy ions)
Radiation
UV
visible
infrared
Solar Flares
electrons produce x-ray & radio bursts
protons produce gamma rays
magnetosheath
Trapped electrons
magnetopause
cusp
neutral sheet
lobes
Trapped protons
magnetosphere
Radiation is NASTY in space

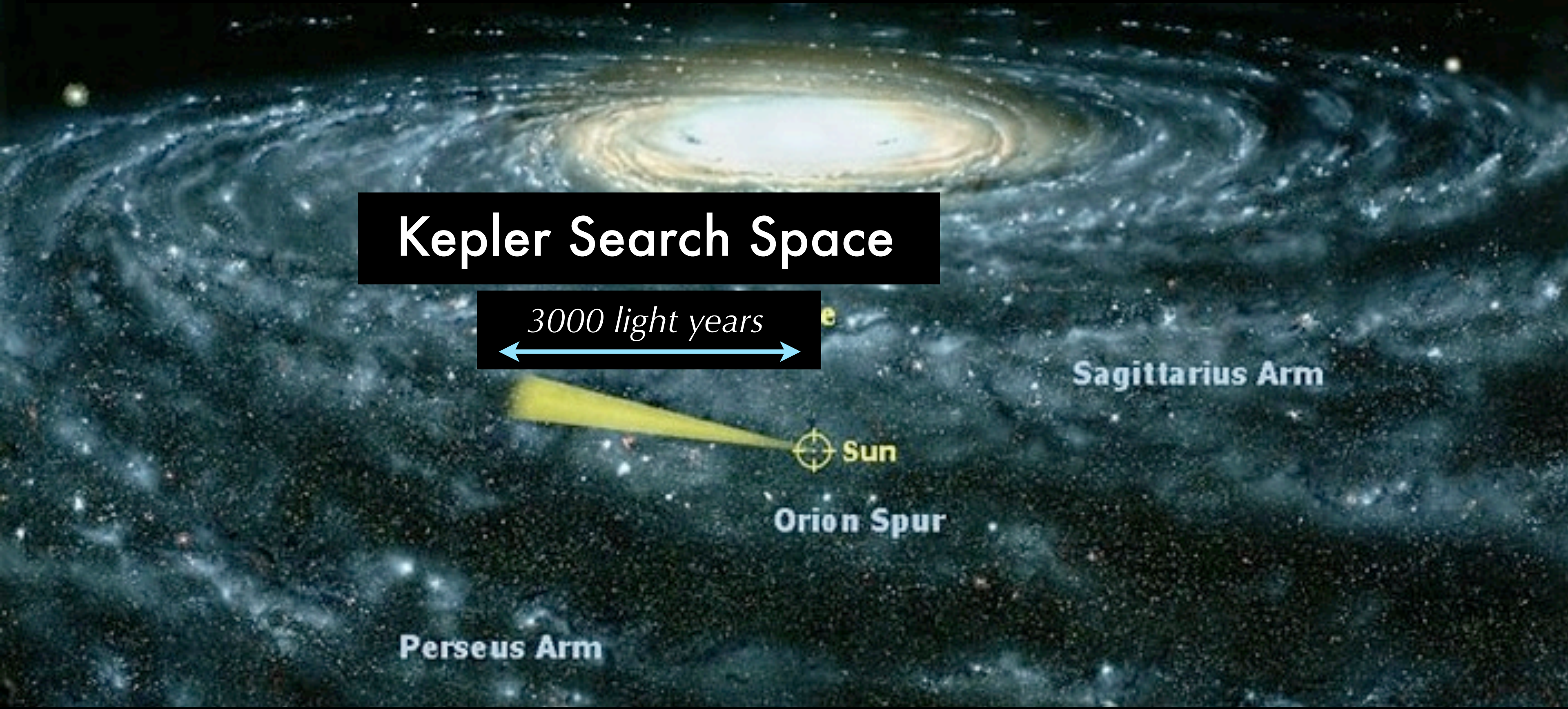
Are there other abodes for life?

"This is Iowa. Io is a moon of Jupiter."



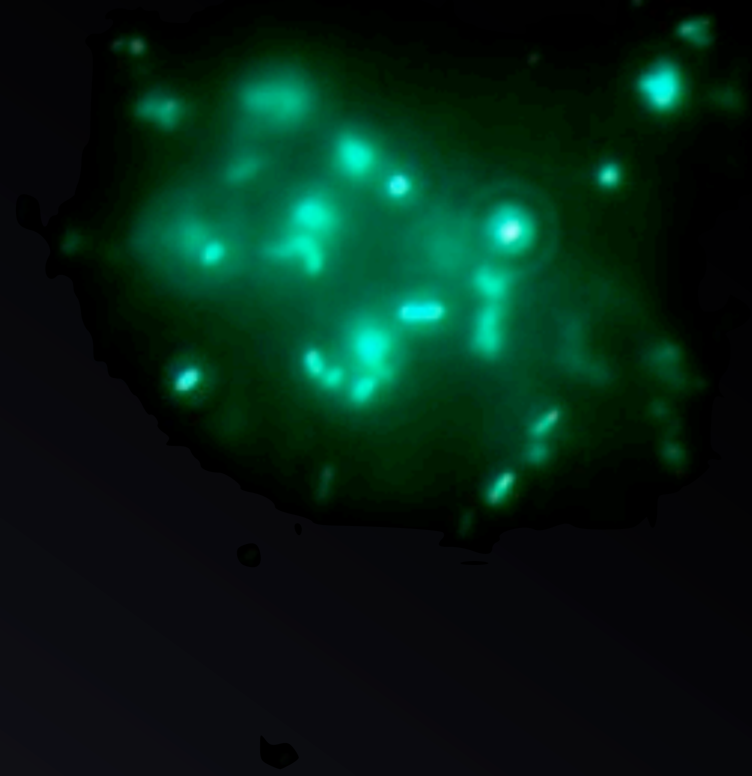
y axis
Titan
Saturn
Enceladus
Venus
Mercury
Earth
Mars
Jupiter
Europa

In our galaxy,



Kepler looks for earth-like planets.

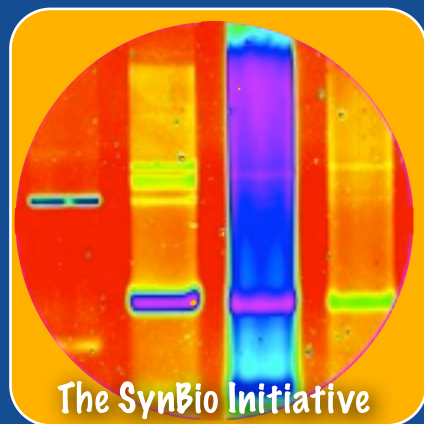
What about the origin of life?



Easy to talk about pre-requisites, but we have yet to create life

Can we use an experimental approach?

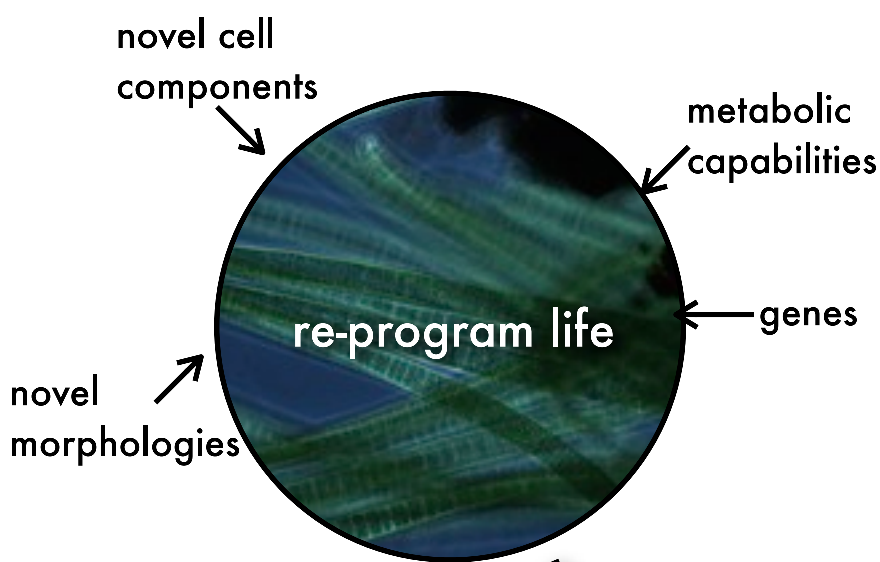
Plan for talk



Introducing a new technology to approach these questions

What is Synthetic Biology?

- The emerging field of synthetic biology is dedicated to the design and construction of artificial biological systems "to extend or modify the behavior of organisms and engineer them to perform new tasks"...or make new organisms altogether. Beyond genetic engineering to synthesis of an artificial "chassis". In the process, biology is digitized and becomes "re-programmable".
- "Big idea" - digitize and reprogram life at a high level. Put together parts to get something new.
- Current applications on earth range from manufacturing of fuels, materials and pharmaceuticals, to enhanced food production.
- The promise over the next few decades will be breathtaking. Undergraduate student projects through the iGEM (international genetically engineered microbe) competition have already pushed the boundaries into electrical systems, bioremediation, diagnostics etc.
- Much more to come....

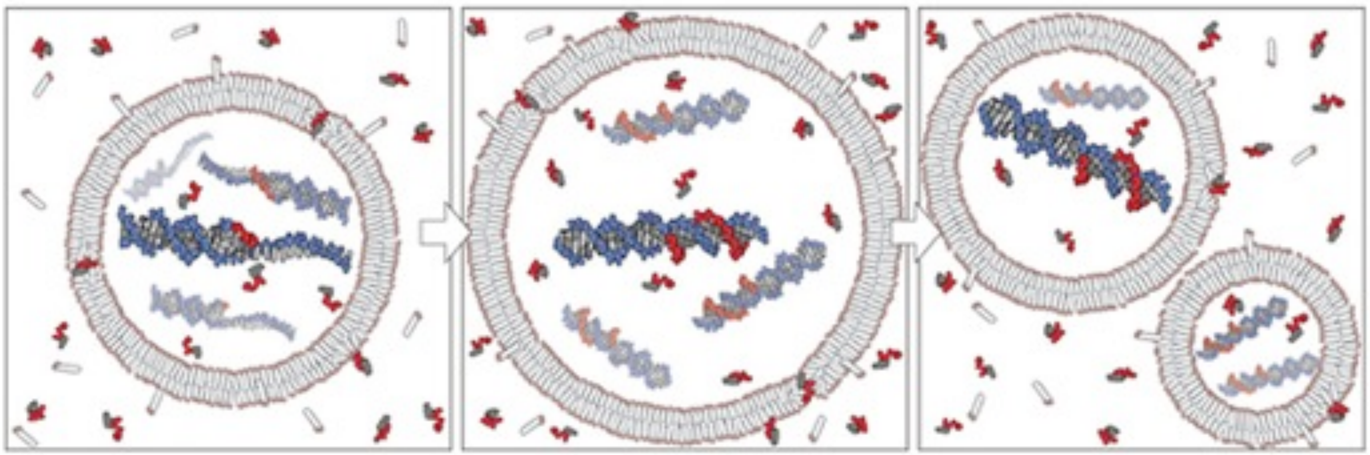


Where do we come from?
origin and evolution of life.

Template-directed synthesis of a genetic polymer in a model protocell

Sheref S. Mansy , Jason P. Schrum , Mathangi Krishnamurthy , Sylvia Tobé , Douglas A. Treco & Jack W. Szostak

Nature 2008

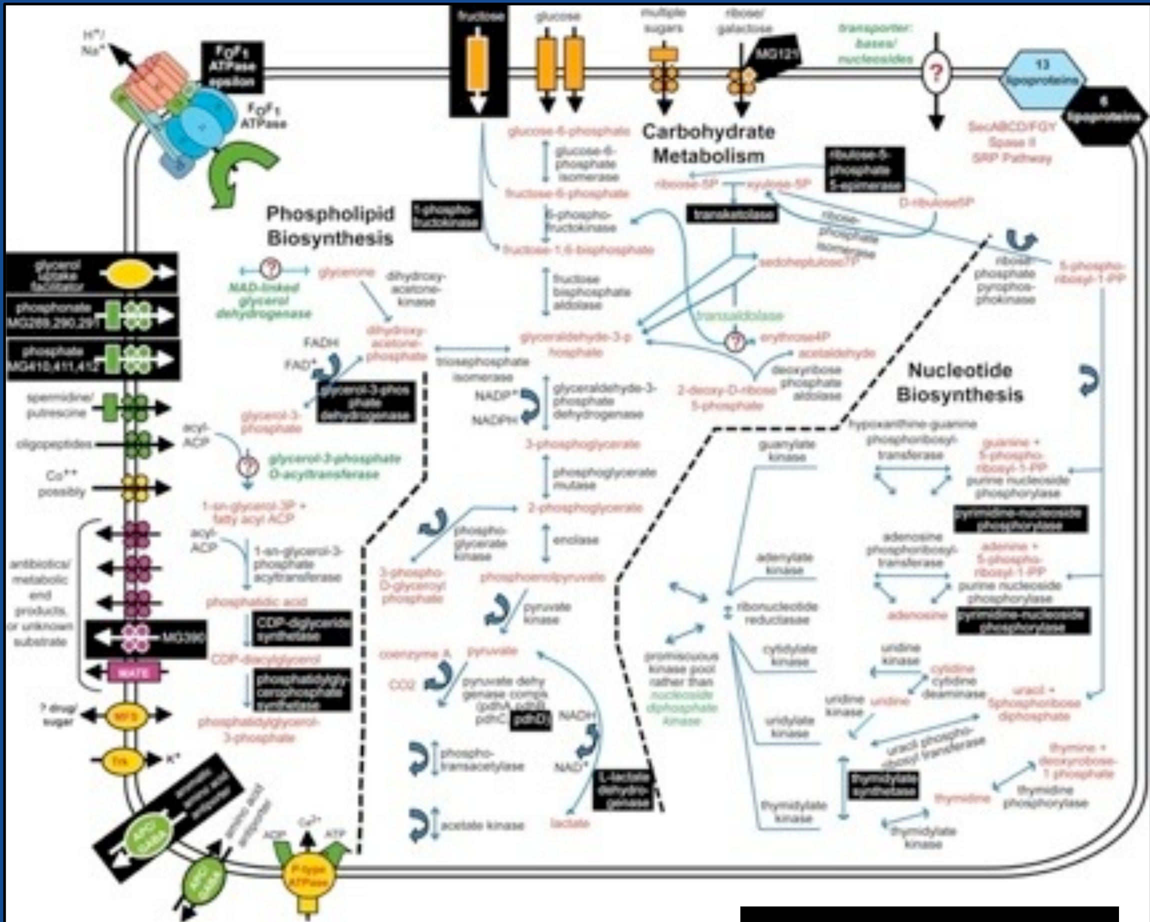


Big question: what is the simplest cell? Bottom up from synthesizing cell to top down by simplifying current life.

Use: such stripped down "cells" might also be a model for drug production etc.

(Amidi et al., 2010, Antigen-expressing immunostimulatory liposomes as a genetically programmable synthetic vaccine, Syst Syn Bio, DOI 10.1007/s11693-010-9066-z)

Essential genes of a minimal bacterium.



nonessential functions or proteins

Abstract: Mycoplasma genitalium has the smallest genome of any organism that can be grown in pure culture. It has a minimal metabolism and little genomic redundancy. Consequently, its genome is expected to be a close approximation to the minimal set of genes needed to sustain bacterial life. Using global transposon mutagenesis, we isolated and characterized gene disruption mutants for 100 different nonessential protein-coding genes. None of the 43 RNA-coding genes were disrupted. Herein, we identify 382 of the 482 M. genitalium protein-coding genes as essential, plus five sets of disrupted genes that encode proteins with potentially redundant essential functions, such as phosphate transport. Genes encoding proteins of unknown function constitute 28% of the essential protein-coding genes set. Disruption of some genes accelerated M. genitalium growth.

Glass, J. I. et al. Essential genes of a minimal bacterium. Proc. Natl Acad. Sci. USA 103, 425–430 (2006).

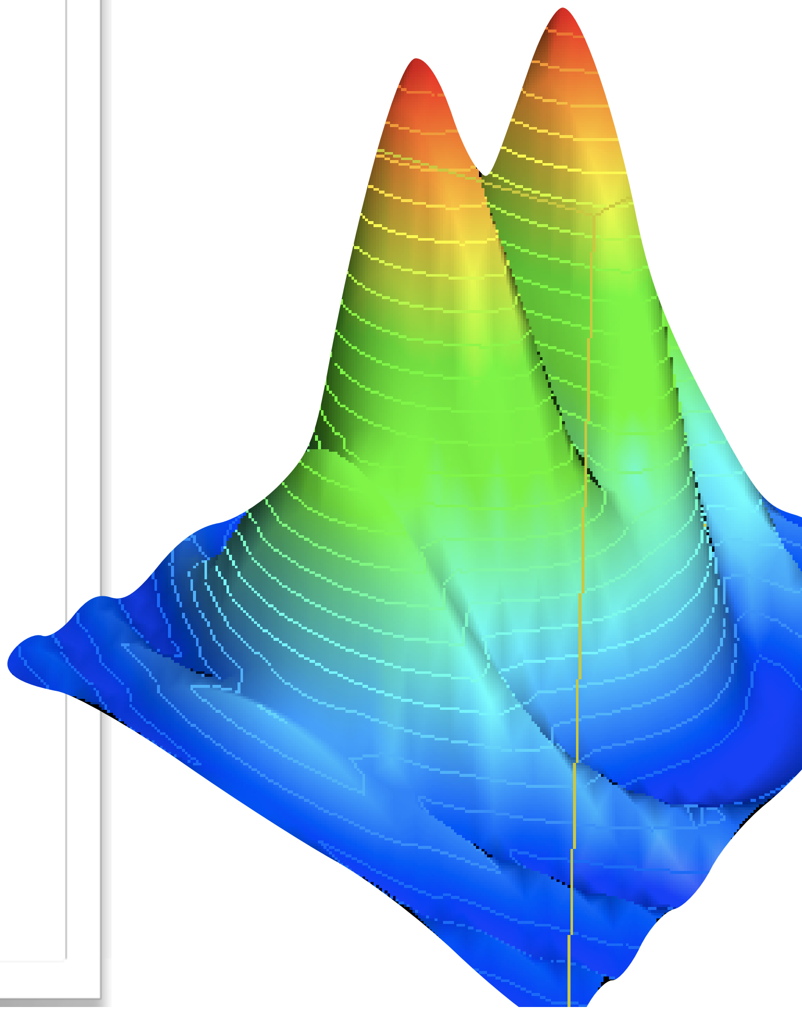
Fig. 3. Metabolic pathways and substrate transport mechanisms encoded by M. genitalium. Metabolic products are colored red, and mycoplasma proteins are black. White letters on black boxes mark nonessential functions or proteins based on our current gene disruption study. Question marks denote enzymes or transporters not identified that would be necessary to complete pathways, and those missing enzyme and transporter names are colored green. Transporters are colored according to their substrates: yellow, cations; green, anions and amino acids; orange, carbohydrates; purple, multidrug and metabolic end product efflux. The arrows indicate the predicted direction of substrate transport. The ABC type transporters are drawn as follows: rectangle, substrate-binding protein; diamonds, membrane-spanning permeases; circles, ATP-binding subunits.

Synthesis of **Life**

- ★ Replication of life's origins on earth
- ★ Synthesis of a minimalist organism
- ★ Synthesis of cellular components
  - Metabolic pathway (artemesian)
  - Genetic component (e.g., plasmid)
  - Organelle (artificial golgi)

Life on earth is found in a patchy distribution

- ★Neither organisms nor sequence space form a complete continuum.
- ★Why are there empty spaces? Is it because of evolution has not occupied these due to chance (lack of genetic opportunity or co-selection) or because organisms in these spaces are unfit to survive?
- ★Synthetic biology is being used to ask "why?"
- ★Synthetic biology is being used to create proposed ancestral genes



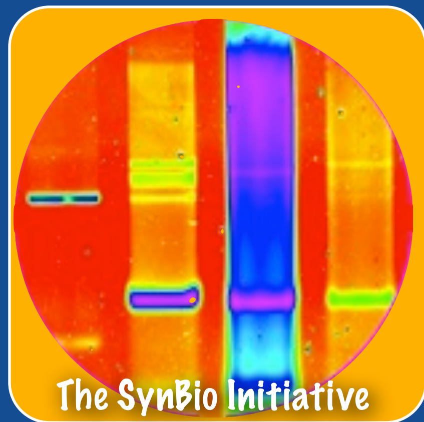
Where are we going?

the future of life

★ and beyond.

Plan for talk

What is astro-biology?



Are there “laws” in evolution? Convergence suggesting probability.

What are the limits for life?

Introducing a new technology to approach these questions