Royal Netherlands Institute for Sea Research

The origin of life, on Earth and Elsewhere

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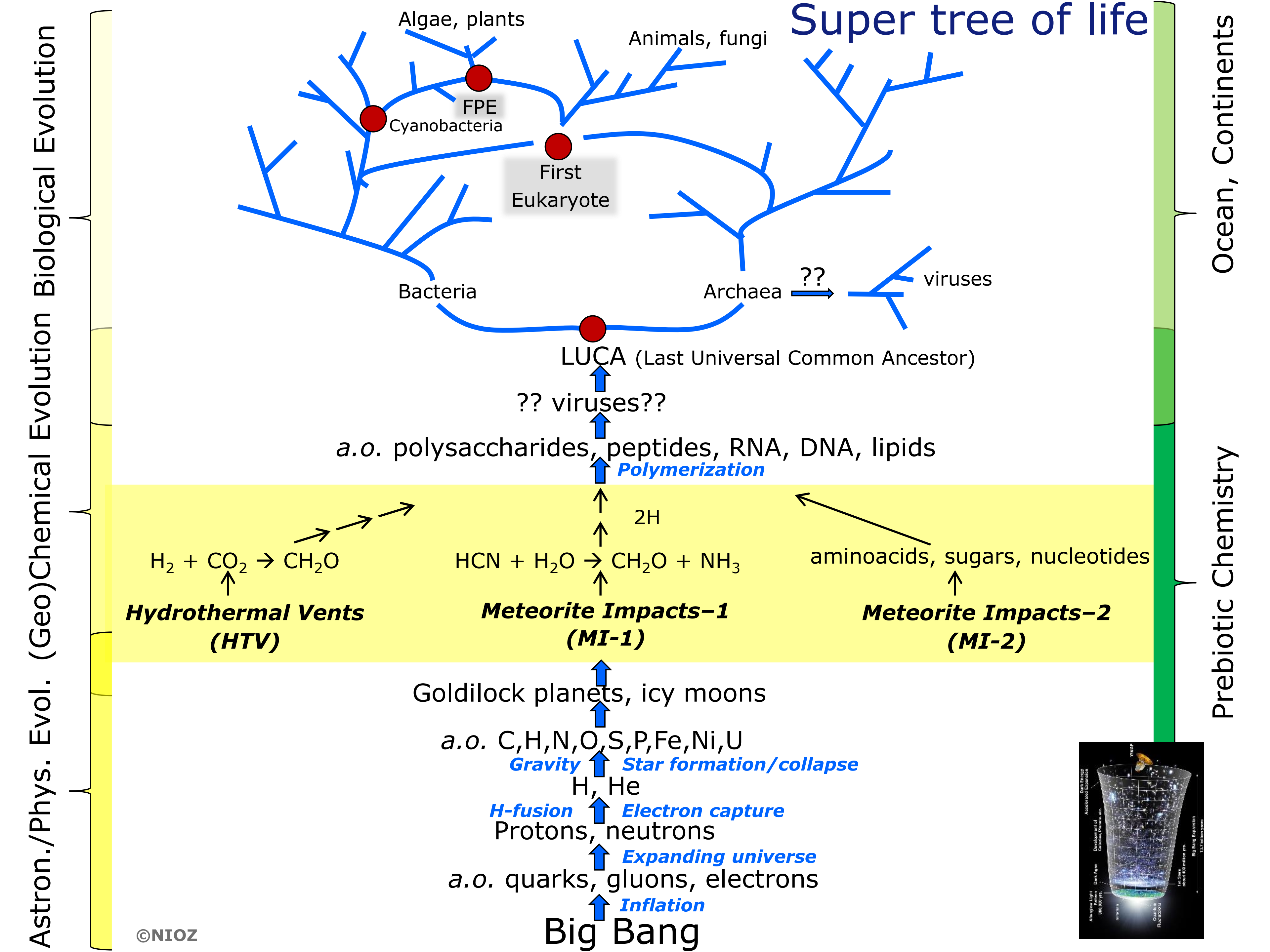
NIOZ is an institute of NWO in cooperation with Utrecht University

Conditions for life on Earth and other Goldilocks planets or icy moons

1) A continuous supply of reactive carbon for synthesizing new organics;
2) A supply of free energy to drive metabolic biochemistry – the formation of new proteins, DNA, and so on;
3) Catalysts to speed up and channel these metabolic reactions;
4) Excretion of waste, to pay the debt to the second law of thermodynamics and drive chemical reactions in the correct direction;
5) Compartmentalisation – a cell-like structure that separates the inside from the outside;
6) Hereditary material – RNA, DNA or an equivalent, to specify the detailed form and function.

Nick Lane in: 'The vital question', W.W. Norton & Company (2015)



Super tree of life
Algae, plants
Animals, fungi
FPE
Cyanobacteria
First Eukaryote
Bacteria
Archaea
??
viruses
LUCA (Last Universal Common Ancestor)
?? viruses??
a.o. polysaccharides, peptides, RNA, DNA, lipids
Polymerization
2H
$H_2 + CO_2 \rightarrow CH_2O$
$HCN + H_2O \rightarrow CH_2O + NH_3$
aminoacids, sugars, nucleotides
Hydrothermal Vents (HTV)
Meteorite Impacts–1 (MI-1)
Meteorite Impacts–2 (MI-2)
Goldilock planets, icy moons
a.o. C,H,N,O,S,P,Fe,Ni,U
Gravity
Star formation/collapse
H, He
H-fusion
Electron capture
Protons, neutrons
Expanding universe
a.o. quarks, gluons, electrons
Inflation
Big Bang
Biological Evolution
(Geo)Chemical Evolution
Astron./Phys. Evol.
Ocean, Continents
Prebiotic Chemistry
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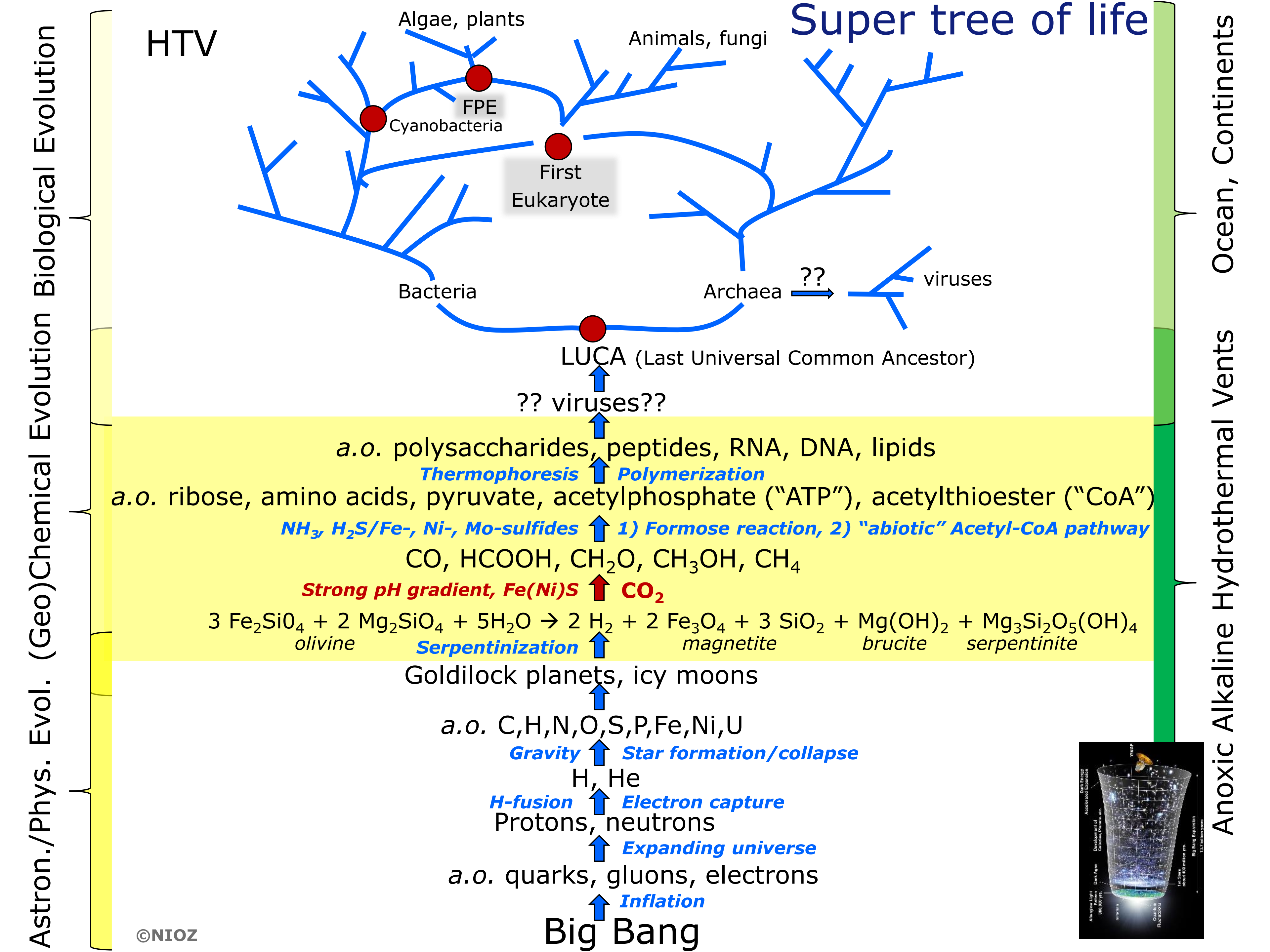
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Thermophoresis
Polymerization
a.o. ribose, amino acids, pyruvate, acetylphosphate (“ATP”), acetylthioester (“CoA”)
NH_3, H_2S/Fe-, Ni-, Mo-sulfides
1) Formose reaction, 2) “abiotic” Acetyl-CoA pathway
CO, HCOOH, CH_2O, CH_3OH, CH_4
Strong pH gradient, Fe(Ni)S
CO_2
3 Fe_2SiO_4 + 2 Mg_2SiO_4 + 5H_2O → 2 H_2 + 2 Fe_3O_4 + 3 SiO_2 + $Mg(OH)_2$ + $Mg_3Si_2O_5(OH)_4$
olivine
Serpentinization
magnetite
brucite
serpentinite
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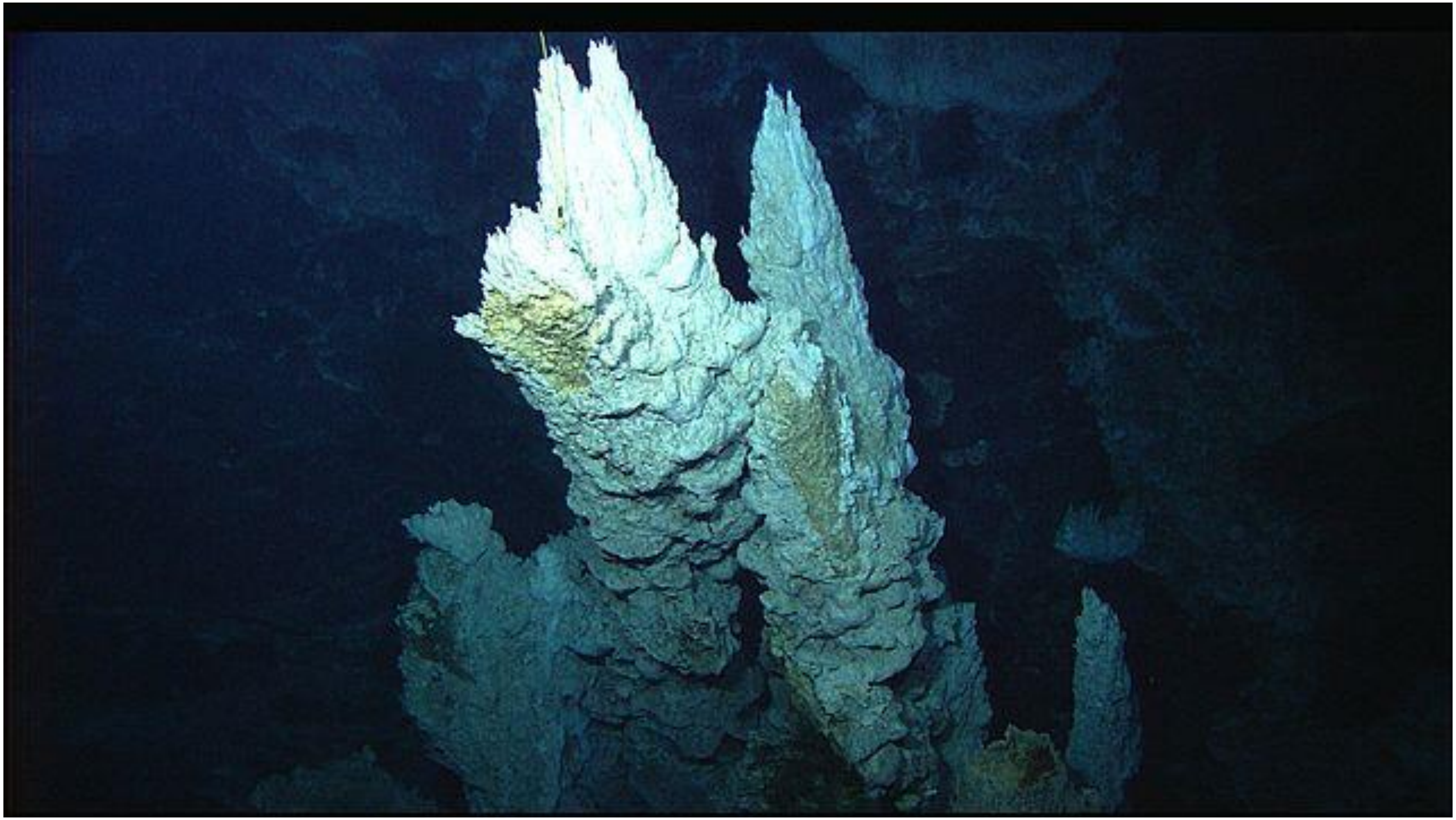
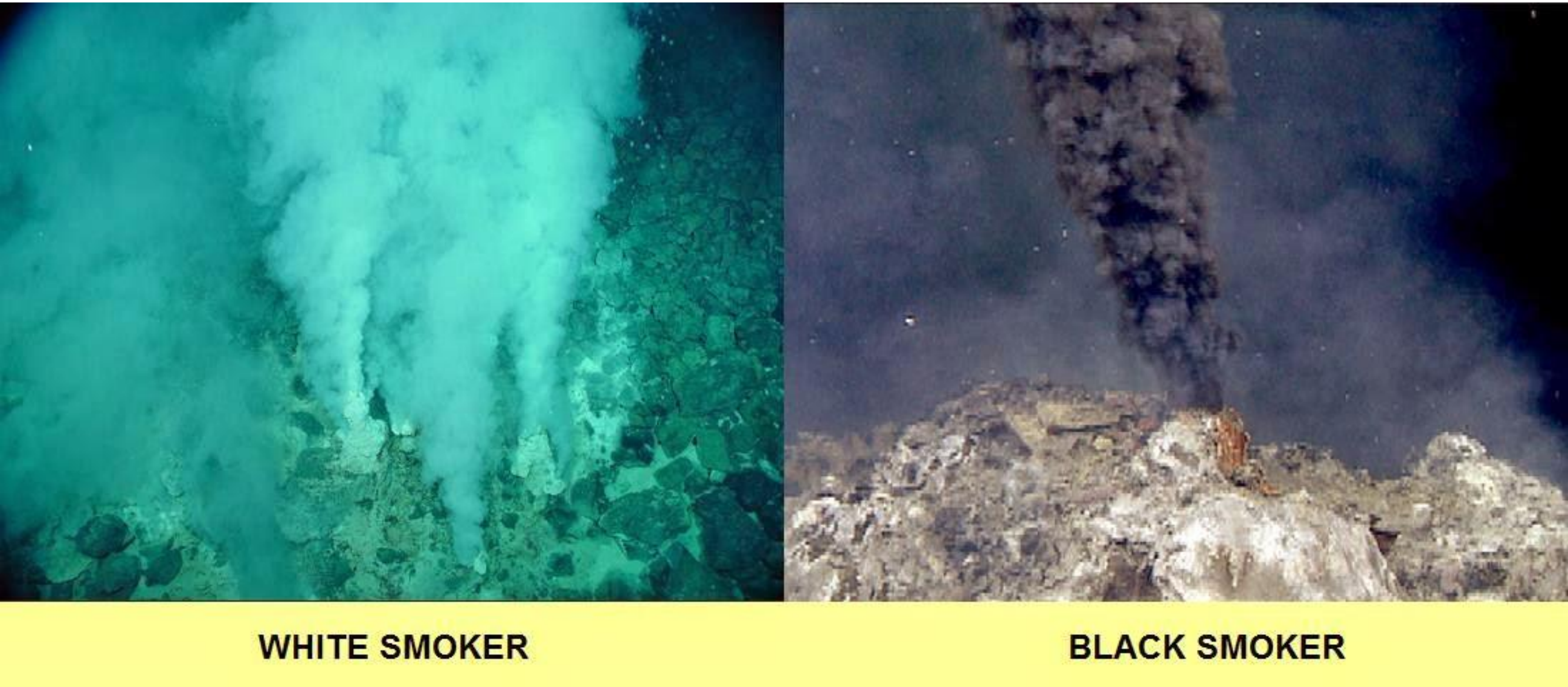
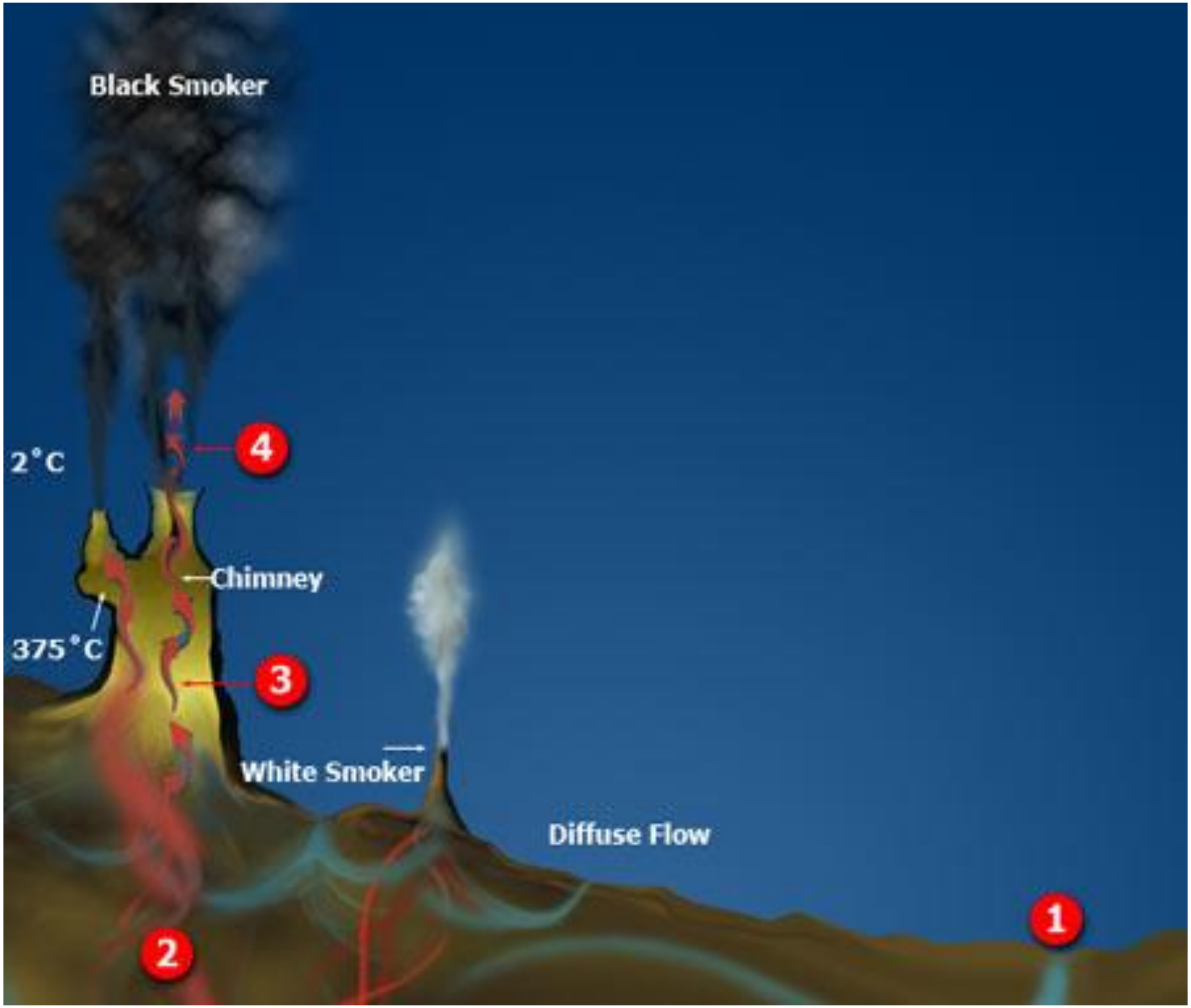
Hydrothermal vent



Black and White smokers



Black vs white smokers



Steep pH and T gradients over porous hydrothermal vent chimney

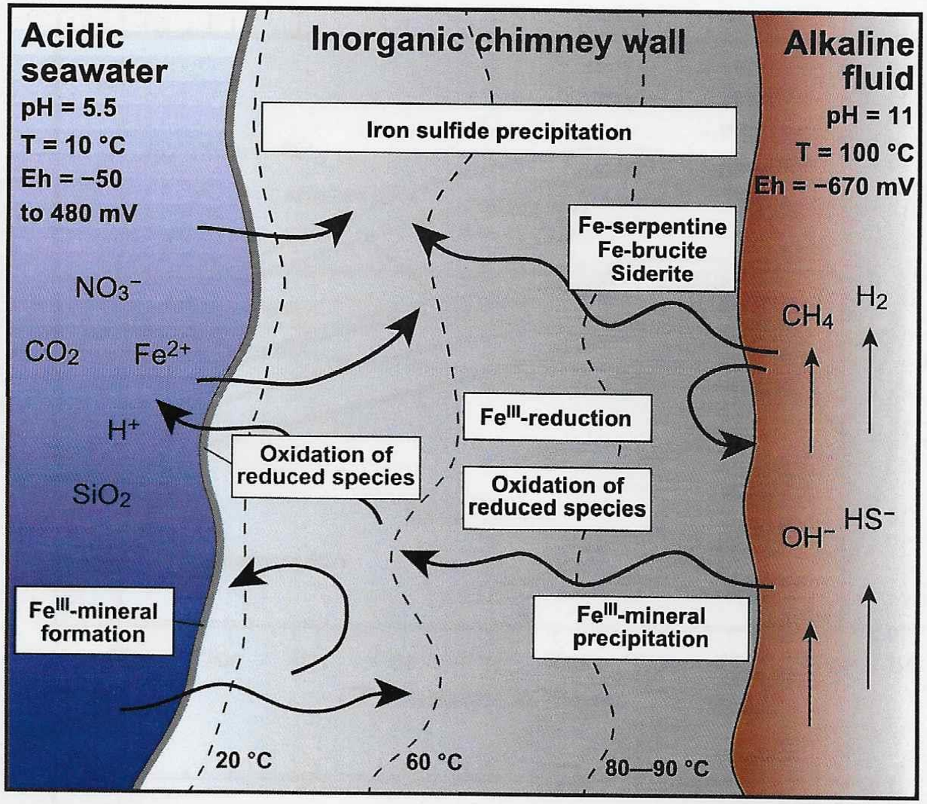
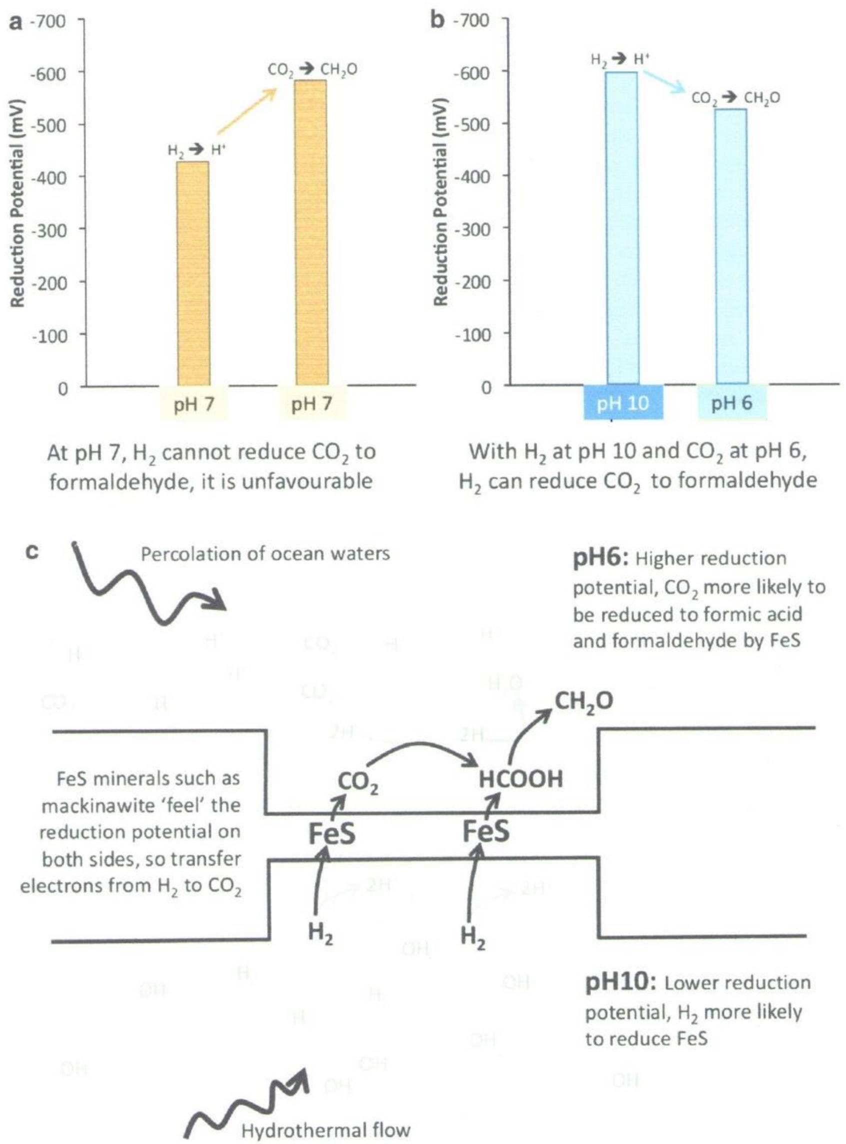


Fig. 10. Schematic cross-section of a vent chimney or compartment wall in a Hadean alkaline hydrothermal system showing spatial distributions of constituent minerals and possible redox reactions.

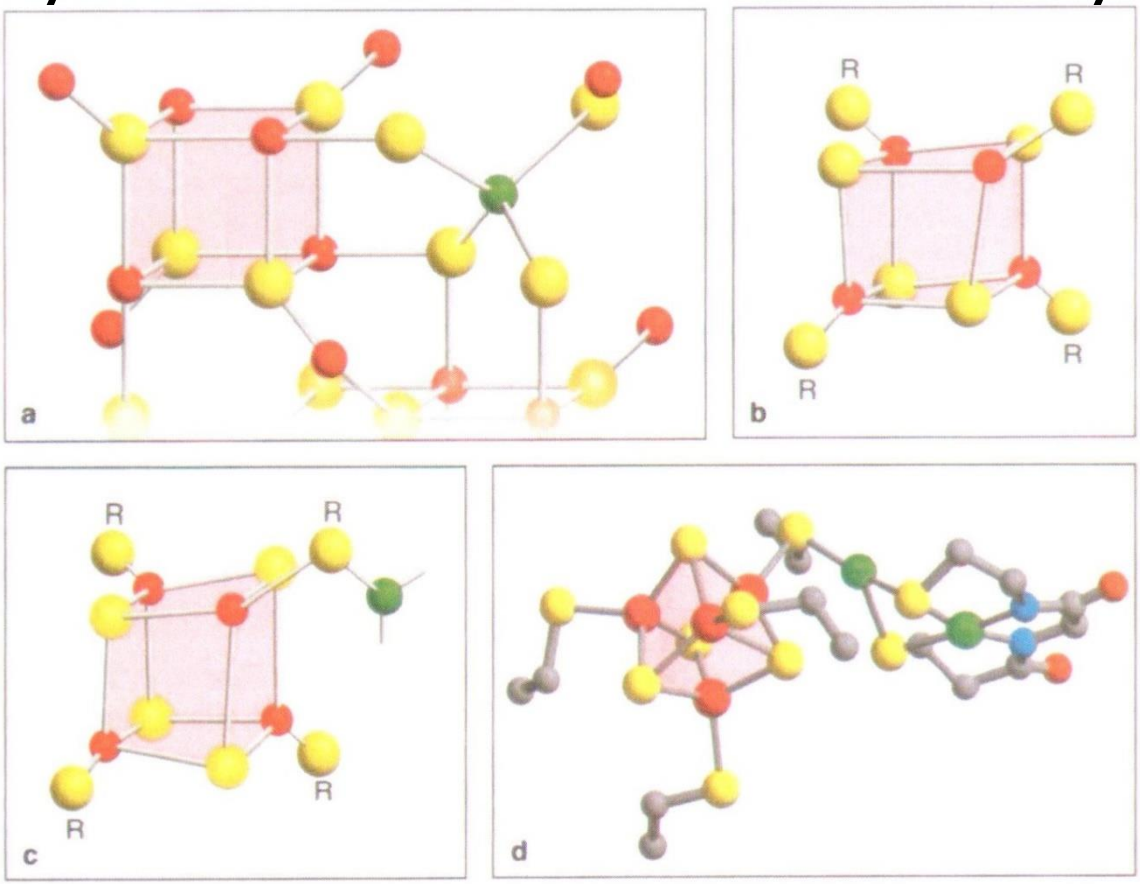
$CO_2 + 2H_2 \xrightarrow{\text{"spontaneous"}} CH_2O + H_2O$ in HTV-chimneys



Herschy et.al J. Mol. Evol. 79:213-227 (2014)

Catalytic surfaces in HTV-chimney ‘cells’

HTV minerals



Co-factor
Ferredoxin

CO-dehydrogenase/
acetyl synthase

Figure 6. The molecular structure of the mineral greigite *(a)* is very similar to that of the thiocubane unit *(b)* of the ferredoxin protein, as well as to the cuboidal complex *(c)* in the active site of the enzyme acetyl-CoA synthase/carbon monoxide dehydrogenase (shown in schematic form). The x-ray crystal structure *(d)* for the so-called A cluster of the latter confirms this similarity. Atoms are colored as follows: iron, red; sulfur, yellow; nickel, green; carbon, gray; nitrogen, blue. R signifies links through sulfur to the remainder of the protein. Part d is modified from Darnault *et al.*, 2003.

Michael Russell, American Scientist, 94: 32-39 (2006)

Genetic reconstruction of LUCA

6.1×10^6 genes

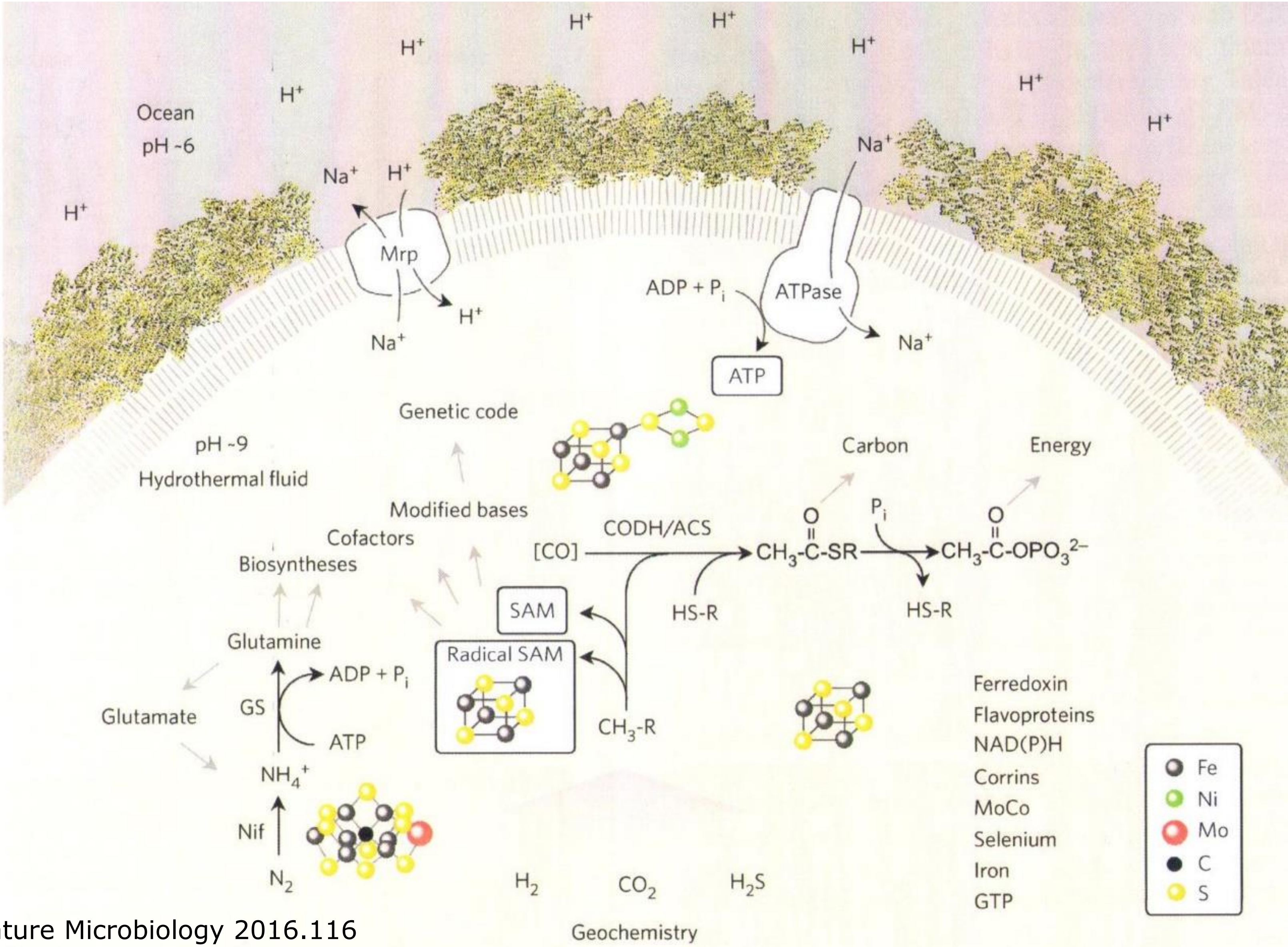
↓

355 protein families present in both bacteria and archaea phyla

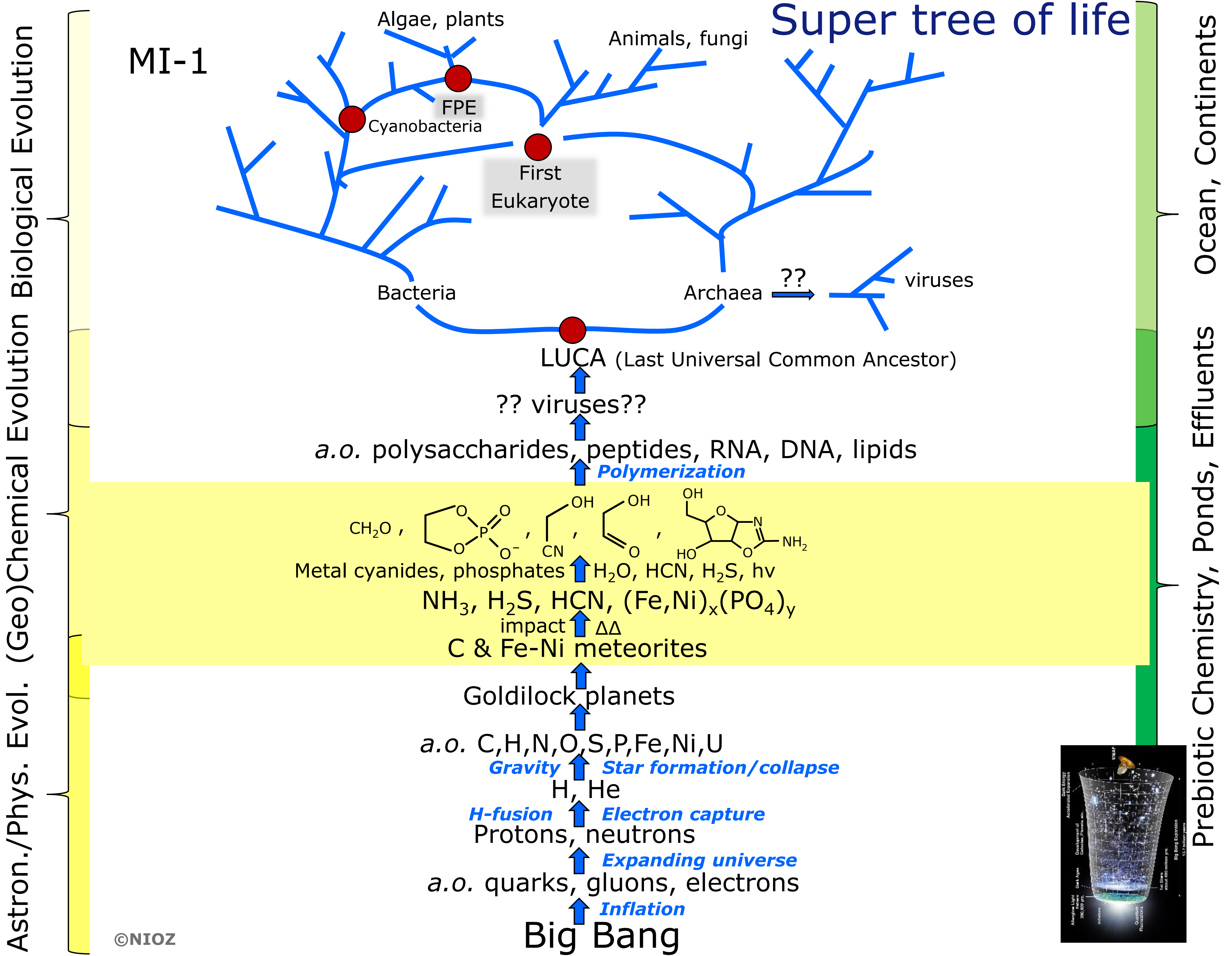
↓

LUCA: Anaerobic, CO_2-fixing, WL-pathway, N_2-fixing, à la *Clostridia* (bacteria) and methanogens (archaea)

In Hydrothermal vents



Weiss et. al, Nature Microbiology 2016.116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Polymerization
CH_2O ,
OH
O
P
O^-
CN
NH$_2$
HO
N
Metal cyanides, phosphates
H_2O, HCN, H_2S, hv
NH_3, H_2S, HCN, $(Fe,Ni)_x(PO_4)_y$
impact
ΔΔ
C & Fe-Ni meteorites
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Prebiotic Chemistry, Ponds, Effluents
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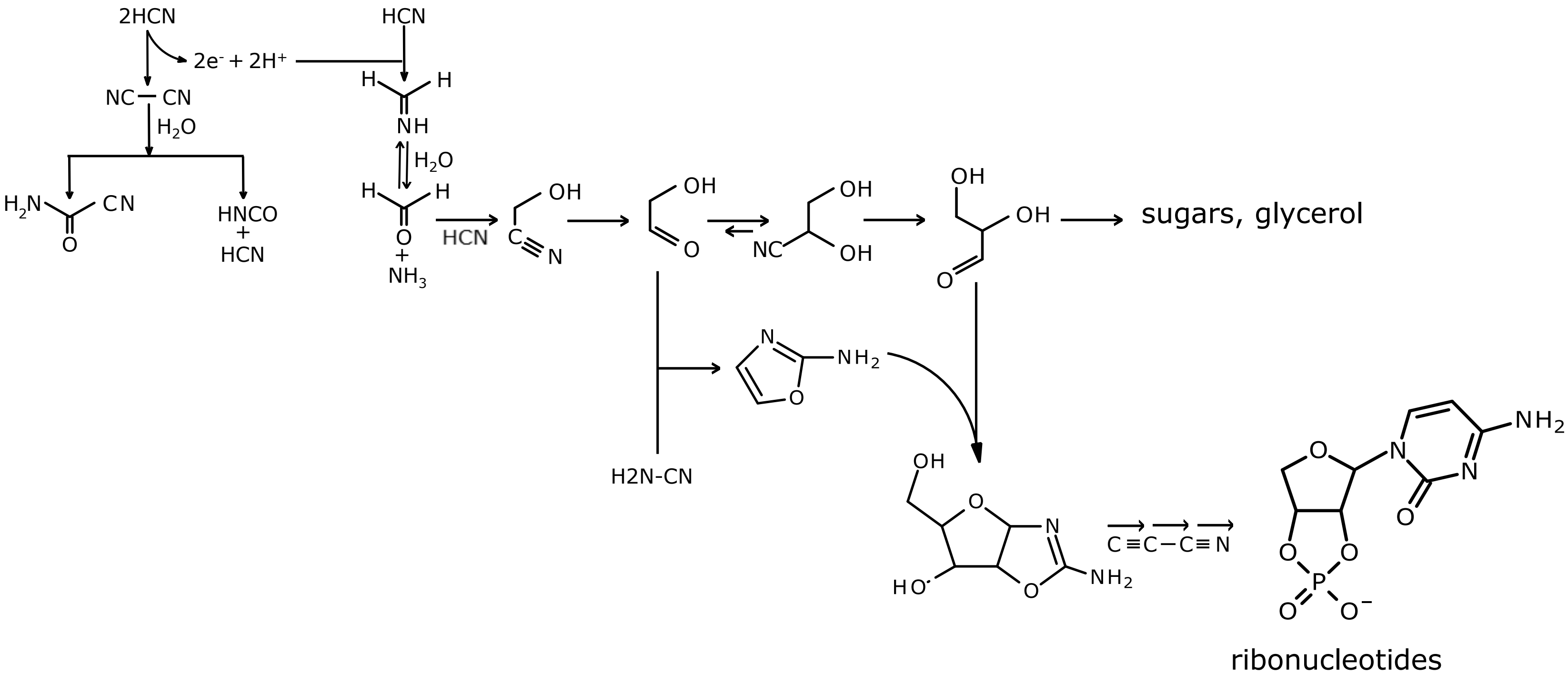
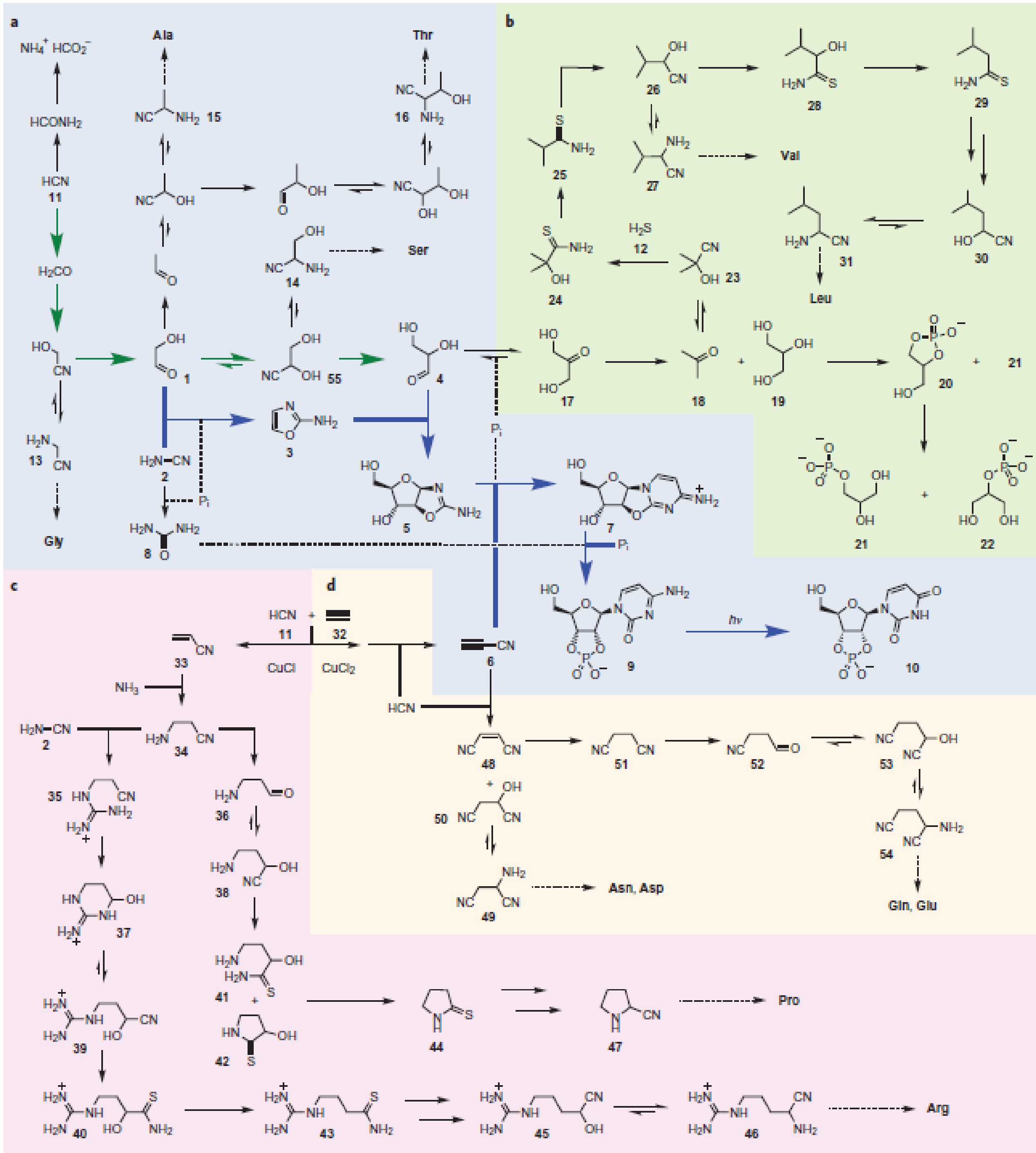
MI-1: Prebiotic chemistry "out of the blue"

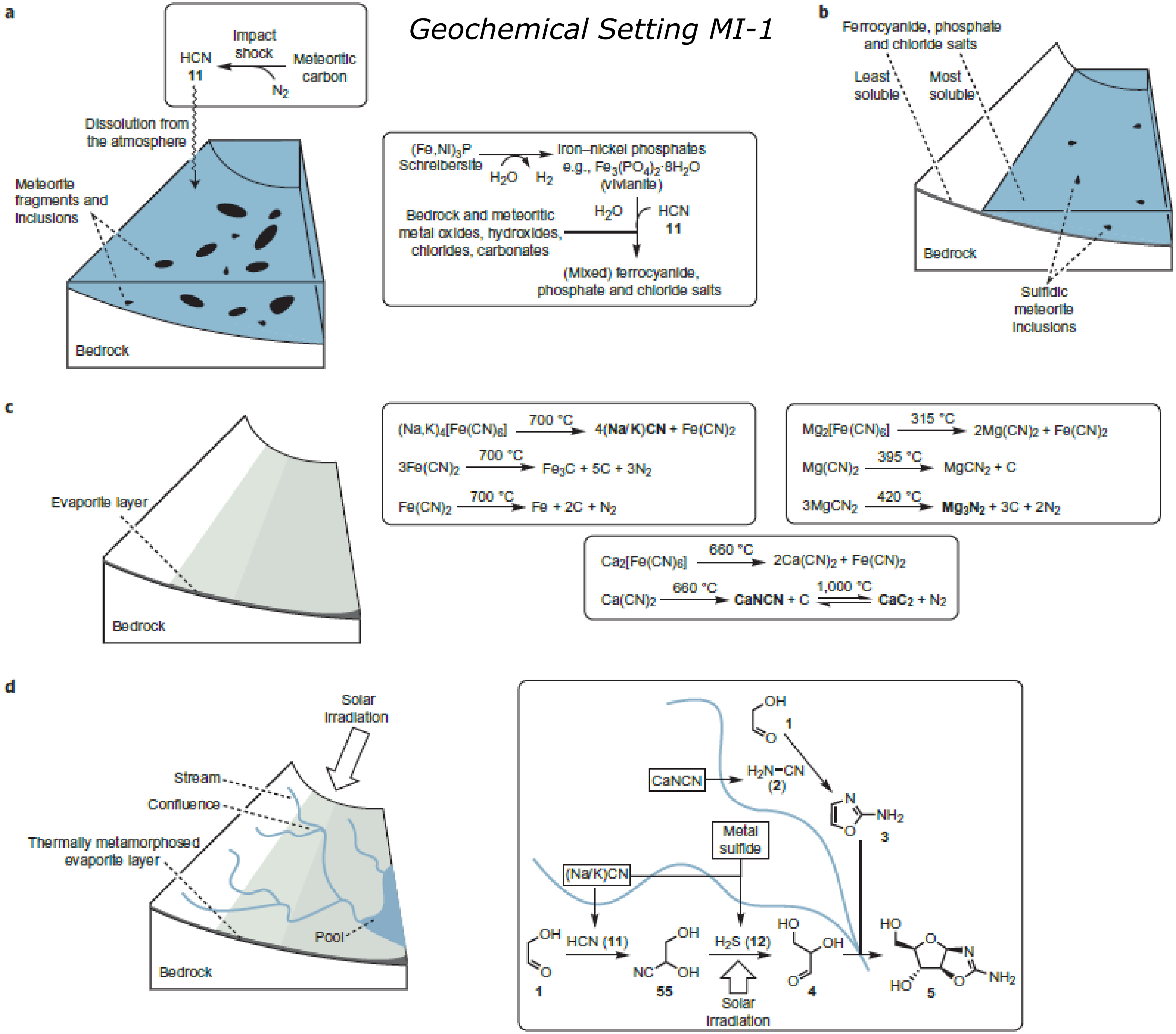


Patel et al, Nature Chem. 7, 301-307 (2015)



Patel et al, Nature Chemistry 7 (2015) 301

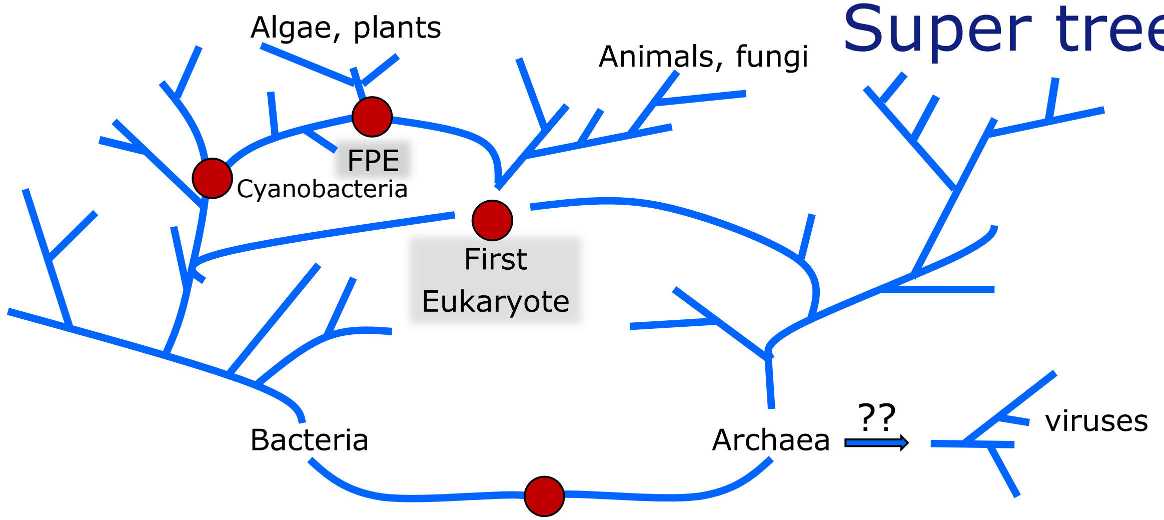
Geochemical Setting MI-1



Patel et al, Nature Chemistry 7 (2015) 301

Super tree of life

HTV



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Thermophoresis ↑ ***Polymerization***

a.o. ribose, amino acids, pyruvate, acetylphosphate ("ATP"), acetylthioester ("CoA")

NH_3, H_2S/Fe-, Ni-, Mo-sulfides ↑ ***1) Formose reaction, 2) "abiotic" Acetyl-CoA pathway***

CO, HCOOH, CH_2O, CH_3OH, CH_4

Strong pH gradient, Fe(Ni)S ↑ **CO_2**

$3\ Fe_2Si0_4 + 2\ Mg_2SiO_4 + 5H_2O \rightarrow 2\ H_2 + 2\ Fe_3O_4 + 3\ SiO_2 + Mg(OH)_2 + Mg_3Si_2O_5(OH)_4$

olivine ***Serpentinization*** ↑ *magnetite* *brucite* *serpentinite*

Goldilock planets, icy moons

a.o. C,H,N,O,S,P,Fe,Ni,U

Gravity ↑ ***Star formation/collapse***

H, He

H-fusion ↑ ***Electron capture***

Protons, neutrons

↑ ***Expanding universe***

a.o. quarks, gluons, electrons

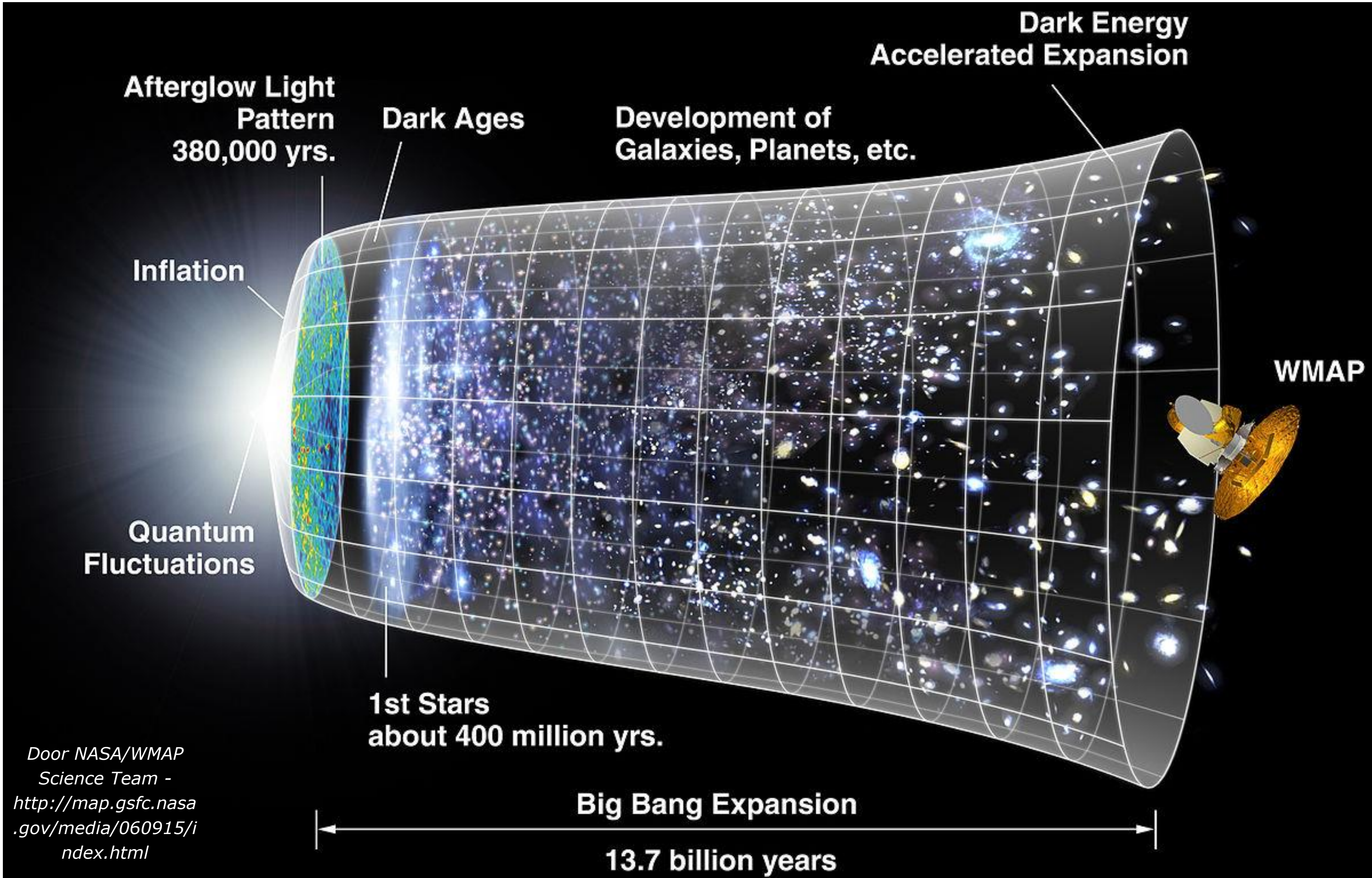
↑ ***Inflation***

Big Bang

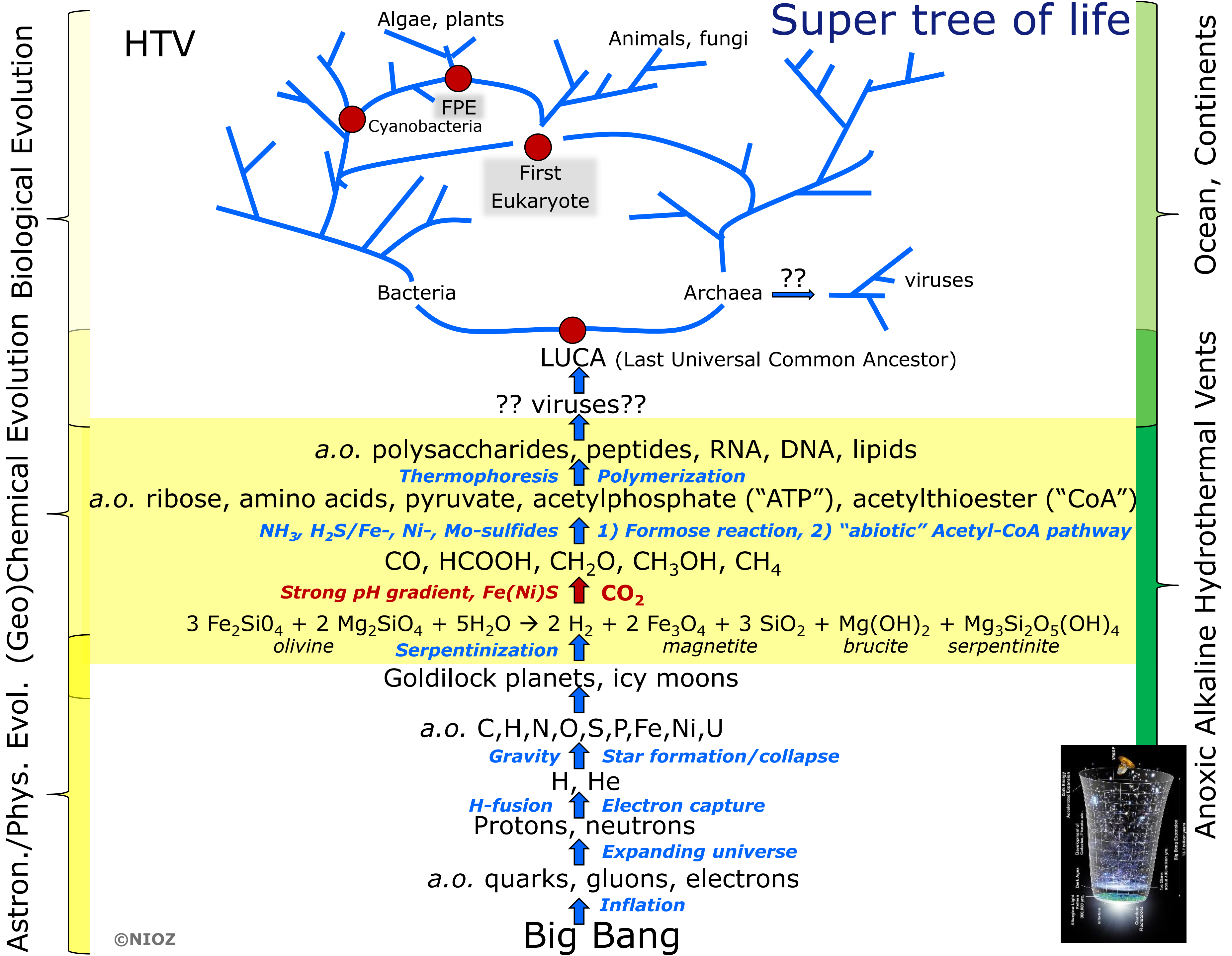
Astron./Phys. Evol. (Geo)Chemical Evolution Biological Evolution

Anoxic Alkaline Hydrothermal Vents Ocean, Continents

Big Bang



Door NASA/WMAP Science Team - http://map.gsfc.nasa.gov/media/060915/index.html



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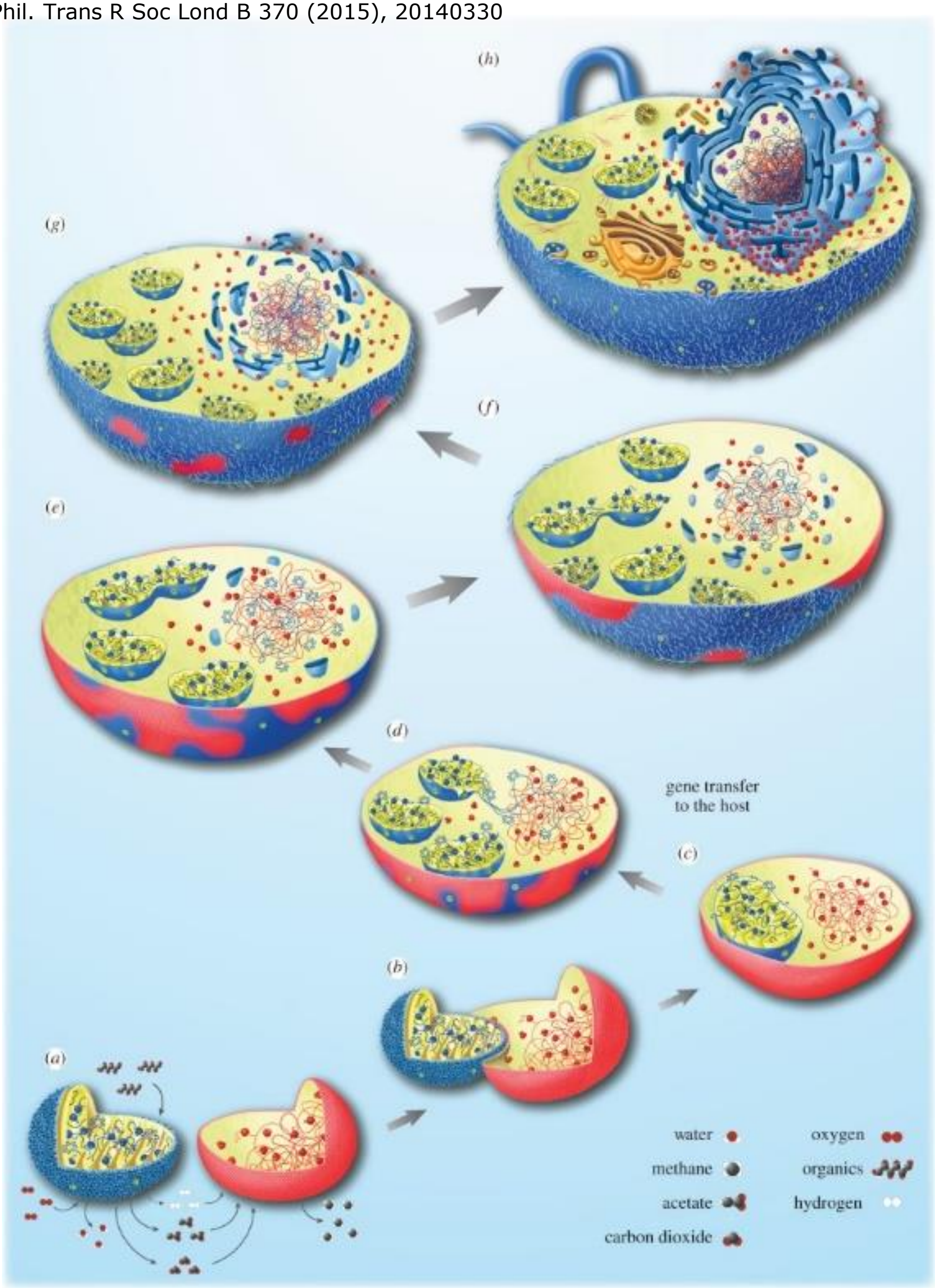
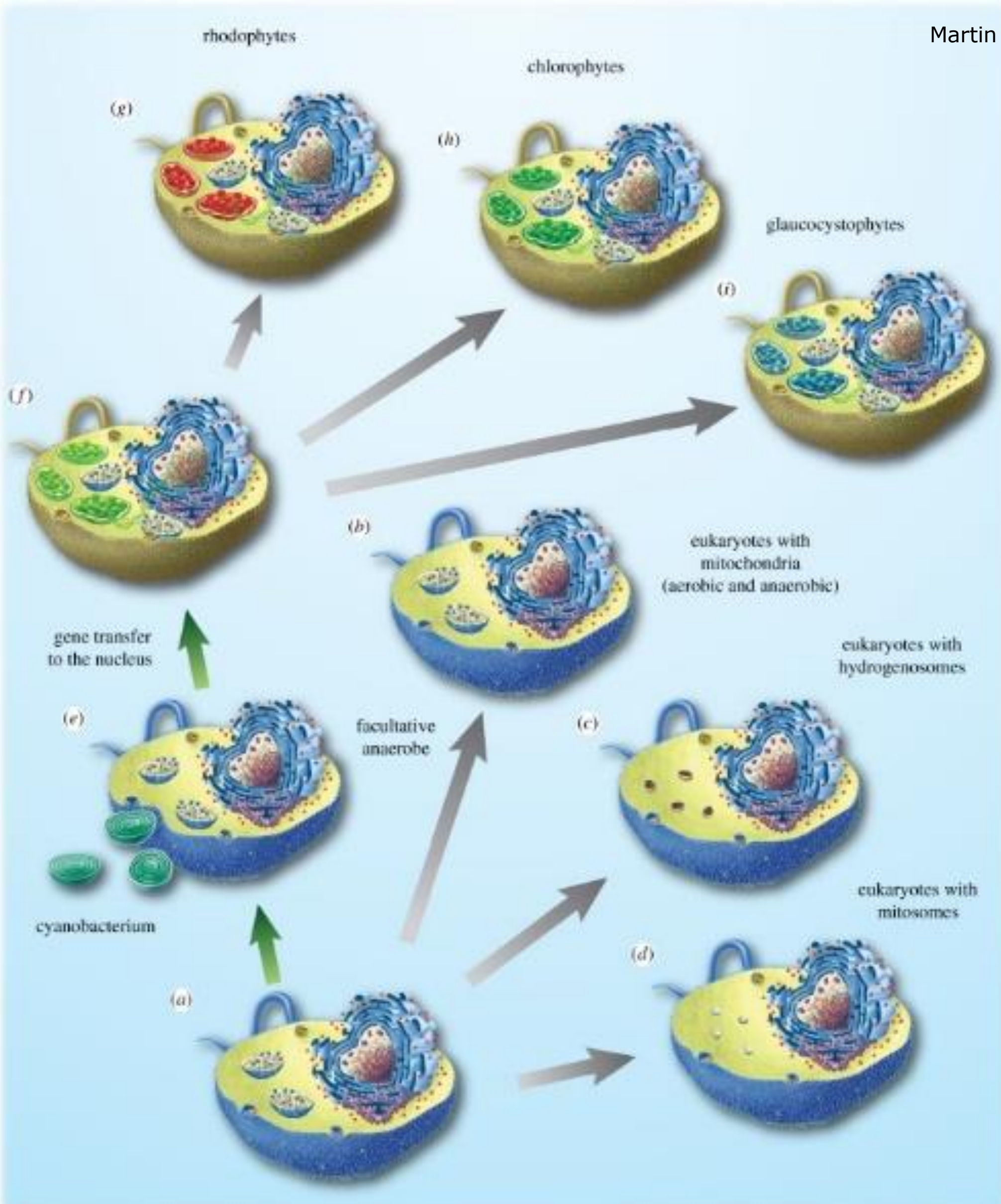
Martin et al., Phil. Trans R Soc Lond B 370 (2015), 20140330



Origin of first eukaryote:

bacterium-archae merge
Happened once in ~ 4Gy

Mitochondrial origin in a prokaryotic host. (*a*–*h*) Illustrations for various stages depicting the transition of a H_2-dependent archaeal host (in red) and a facultatively anaerobic *α*-proteobacterium (in blue) to an eukaryote



Origin of first photosynthetic eukaryote:

cyanobacterium-eukaryote merge

Also happened once in 4 Gy

Evolution of anaerobes and the plastid. (*a*–*d*) Diversification of the mitochondria-containing ancestor to eukaryotes containing specialized forms of the organelle, hydrogenosomes, mitosomes and anaerobic mitochondria. (*e*,*f*) Primary symbiotic origin of a plastid involving a cyanobacterium in a facultative anaerobic host, followed by gene transfer to the nucleus resulting in a plastid-bearing ancestor. (*g*–*i*) Diversification of the plastid-bearing ancestor to glaucocystophytes, chlorophytes and rhodophytes.

Final remarks

- 3 Origin of Life scenario’s considered: HTV, MI-1, MI-2
    - HTV: Geochemical setting excellent, Chemistry to be explored further
    - MI-1: Chemistry seems excellent, Geochemical setting not convincing
    - MI-2: Chemistry highly limited, Geochemical setting poor
- Life in Exo-oceans?
    - Search for microbial signals
    - Don’t search for “intelligent life”.