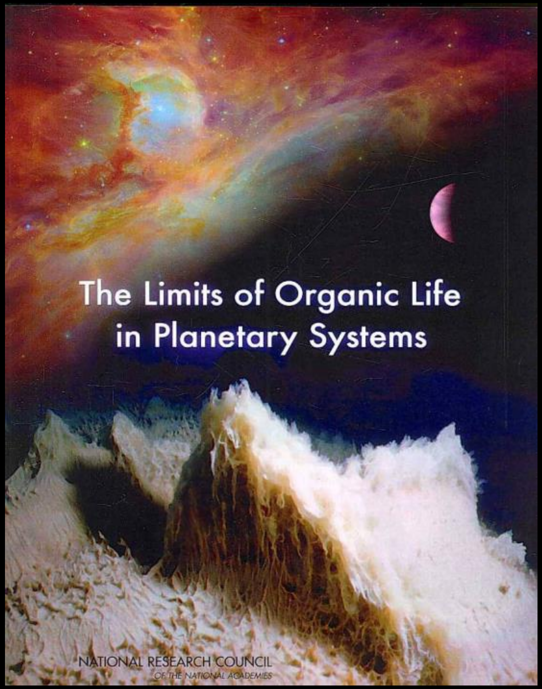
The Limits of Life and its Interaction with the Environment

Tori Hoehler (NASA Ames)

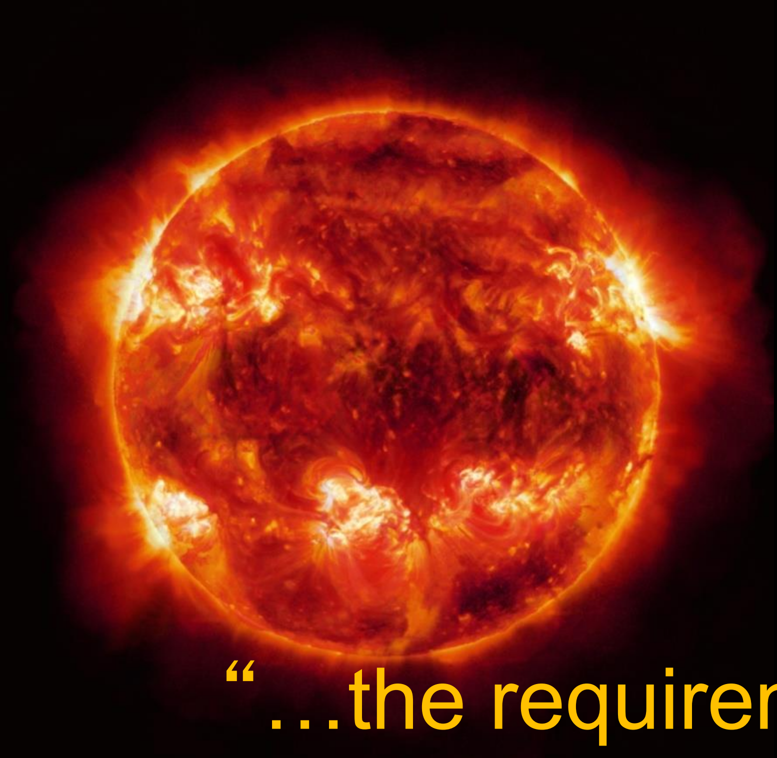


What Life Needs

"The Weird Life Report"

Theory, data, and experiments suggest that life requires (in decreasing order of certainty):

- Thermodynamic disequilibrium (Gibbs energy)*
- An environment capable of maintaining covalent bonds, especially between C, H, and other atoms
- A liquid environment**
- A molecular system that can support Darwinian evolution



Thermodynamic Disequilibrium

(Gibbs Energy)

"…the requirement for thermodynamic disequilibrium is so deeply rooted in our understanding of physics and chemistry that it is not disputable as a requirement for life.

Other criteria are not absolute."

Report of the NRC Committee on the Limits of Organic Life in Planetary Systems

Light in the visible to NIR (approx. 400-1025 nm); flux > 10^{15} photons$\cdot m^{-2} \cdot s^{-1}$

Biological Requirements for Energy

The Earthly Example

Redox chemistry

Earth life uses only a subset of available light and chemical energy, which themselves are a subset of available forms

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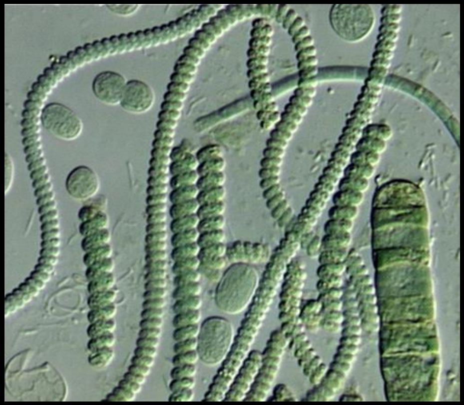

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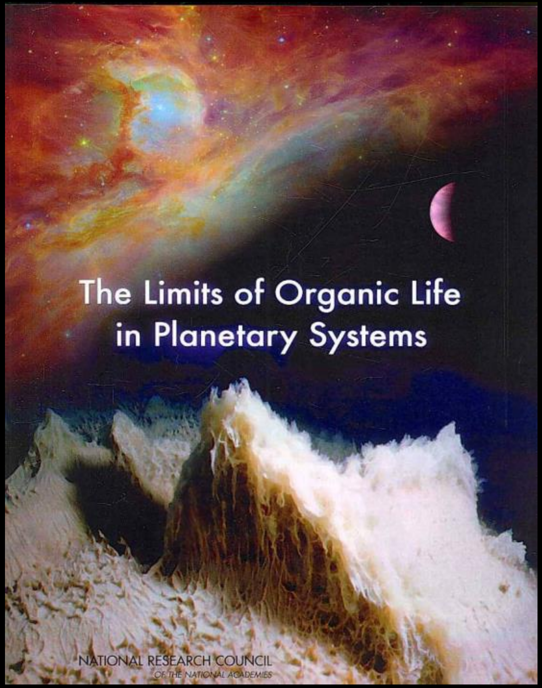
Power and voltage requirements with biochemistry- and environment-dependent lower and upper limits

- Voltage (Gibbs energy or wavelength) is like an "if-then" condition
- Energy required for both biosynthesis *and* maintenance of standing biomass; energy flux (power) sets upper limits on growth rates or biomass abundance



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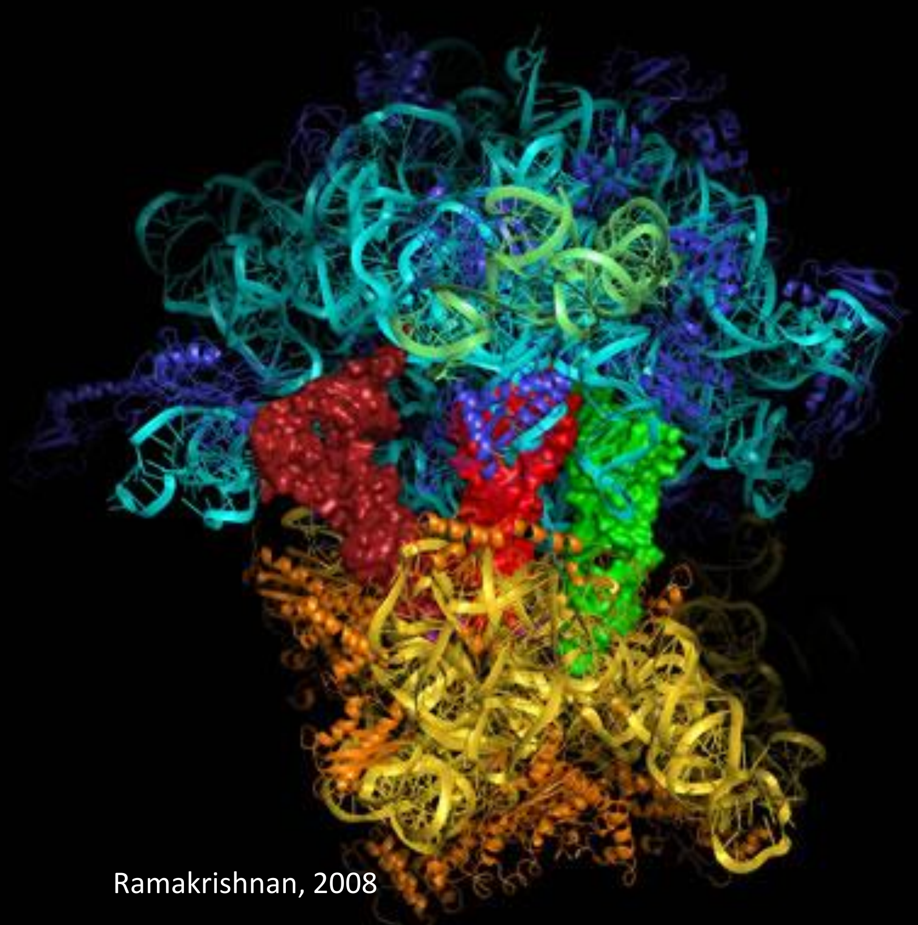
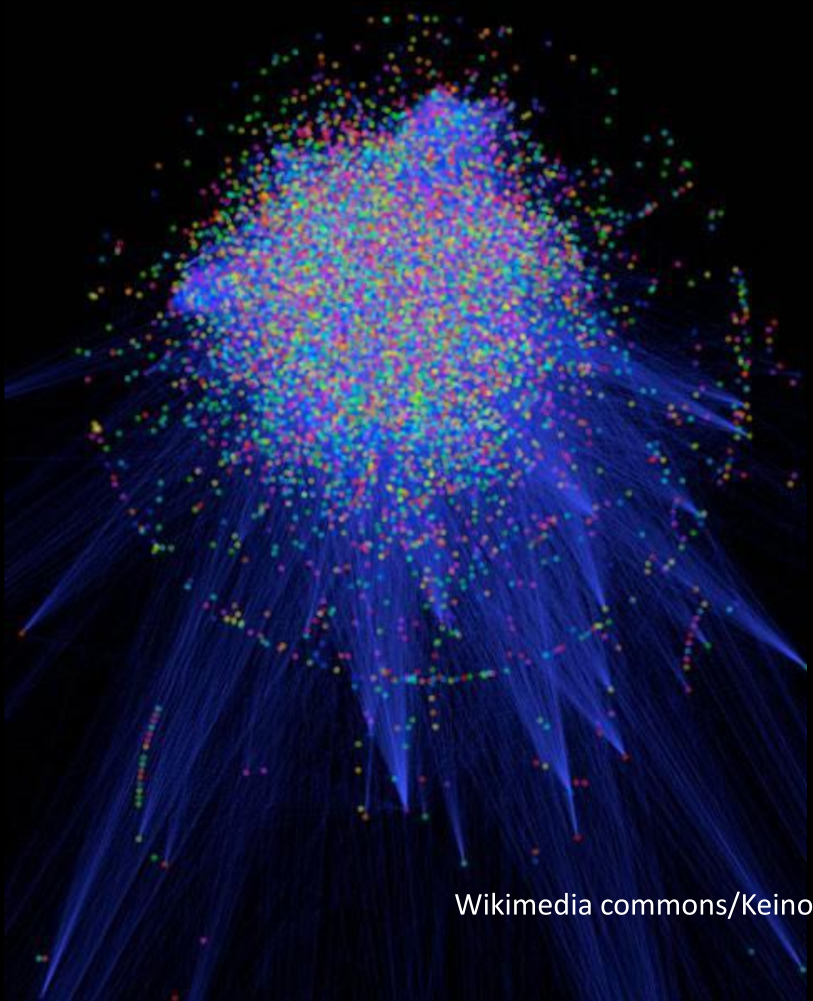
"Reversible [non-covalent] molecular interactions are at the heart of the dance of life…these bonds are profoundly affected by the presence of water."

-- Stryer, 1988

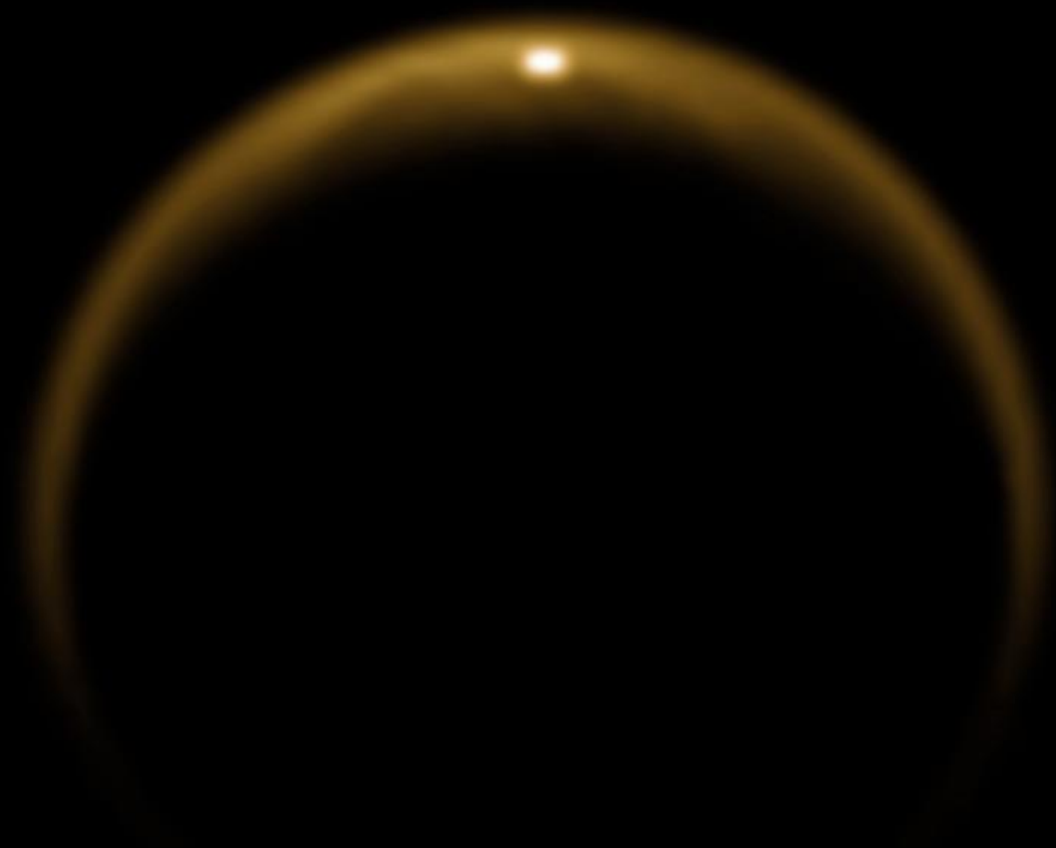


Ramakrishnan, 2008



Wikimedia commons/Keino

Is Water Special?



Alternatives to liquid water as a *solvent* for life must be evaluated not only on their potential to support covalent synthesis, but also on their ability to properly mediate the full range of non-covalent interactions required by living systems.

The stuff of life?

SPONCH: Everything a Body Needs?

Scaffolding element (C):

Creates a diverse library of possible structures through multiple bonding to itself and a variety of other elements

Dominantly in intermediate oxidation state*

Heteroatoms (SPON):

Relatively labile covalent bonding/reactivity

Electrostatic interactions

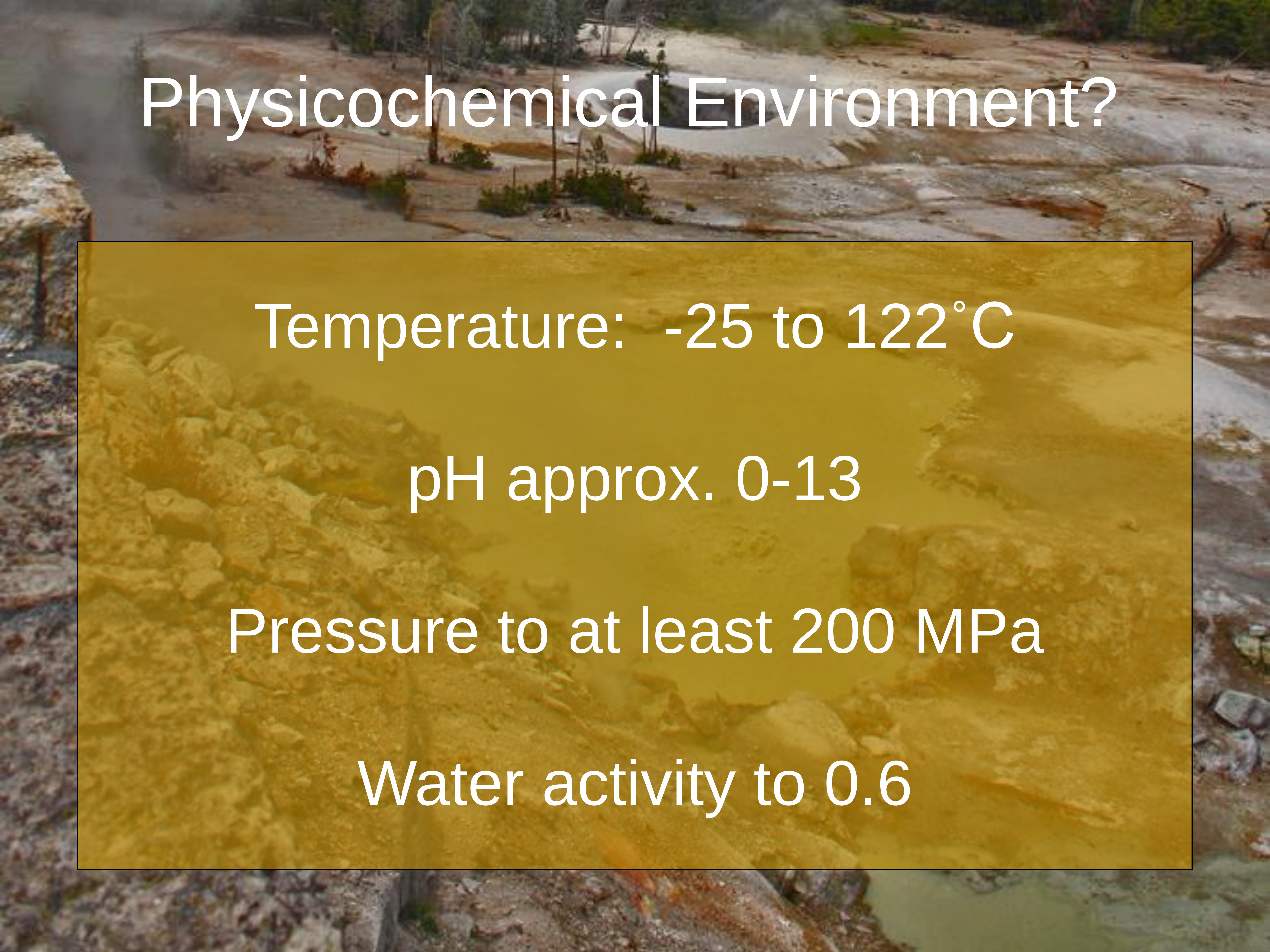
→ Tertiary structure, molecular recognition, coordination chemistry, reactivity

Hydrogen (H):

Hydrogen bonding

Alternatives to SPONCH must be evaluated on their ability to support the requisite covalent *and* non-covalent chemistry *and* in reference to the properties, reactivity, and phase stability of the solvent (or vice-versa…)

Physicochemical Environment?



Temperature: -25 to 122˚C

pH approx. 0-13

Pressure to at least 200 MPa

Water activity to 0.6

Physicochemical Environment?

Tabulated ranges reflect laboratory “record holders”; real world frequently more restrictive

“Extremes” (relative to what’s “nominal” for a given biochemistry) may be tolerated at the expense of diversity, abundance, productivity

Tolerated ranges reflect extant life following extensive evolution; clement range for OoL potentially much narrower

Are (must be) compatible with both covalent bonding *and* non-covalent interactions *in water*

What is the full potential of life to alter its environment?

How and how much
(in ways diagnostically biogenic)?

How does that potential vary as a function of environmental conditions?

Life's potential to create a recognizable imprint on its environment ultimately lies in the unique utilization of energy to generate otherwise improbable distributions. Energy *availability* (quality and flux) is a first order constraint on this potential.

Energy Flux on Earth

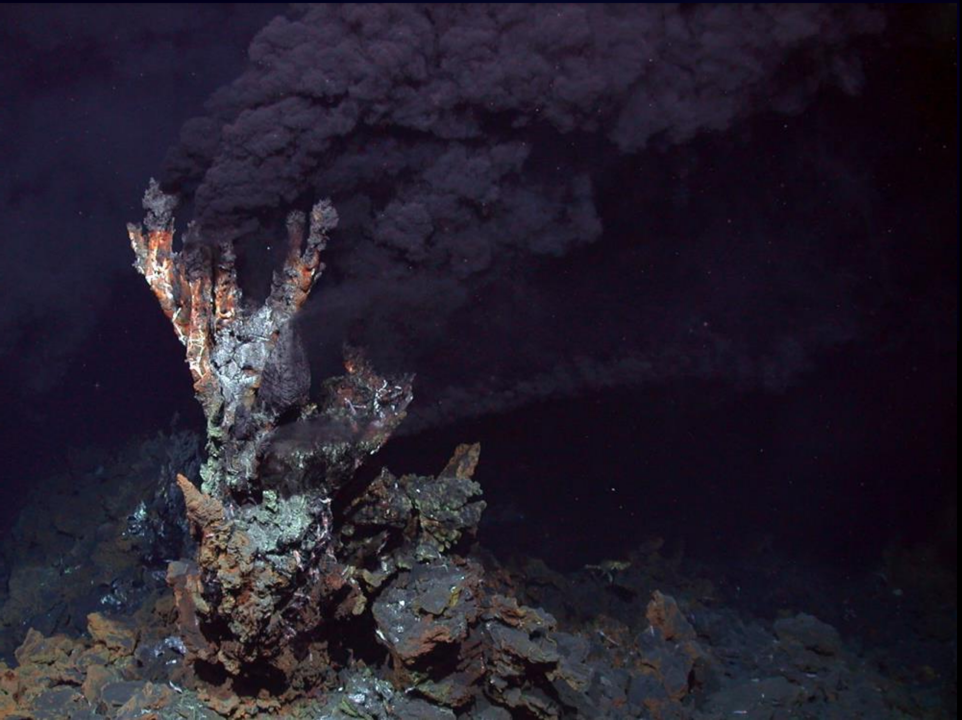
Global Irradiance — 173,000 TW

↓

Photosynthetic Energy Capture — 780-2300 TW

↓

Chemical Energy Efflux — 63-105 TW



Chemical Energy Into Oxygenated Ocean — 0.006 TW

(after McCollom 2005)

↑

Ocean-Wide Heat Flux — 30 TW

Energy flux places upper limits on…

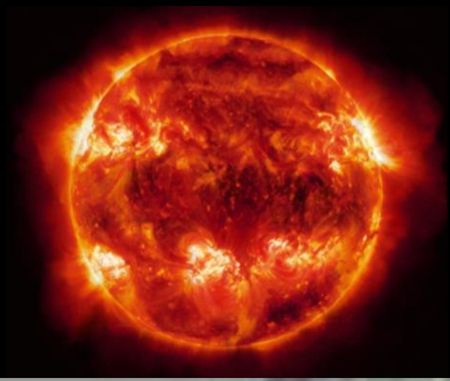
Abundance of biomass sustained (not the same for other resources)

Metabolic & Biosynthetic rate: The rate of buildup/replenishment of diagnostically biogenic species or patterns (including enantiomeric excess) against attrition by abiotic processes.

Capacity for evolution (?): The rapidity (and perhaps even potential) with which life can push out from initial conditions to a greater diversity of metabolic capability & tolerance to extremes

The existence of these relationships is fundamental (not specific to Earth life); how narrowly constrained they are in quantitative magnitude, and how well Earth life reflects that range, is uncertain (but matters!)

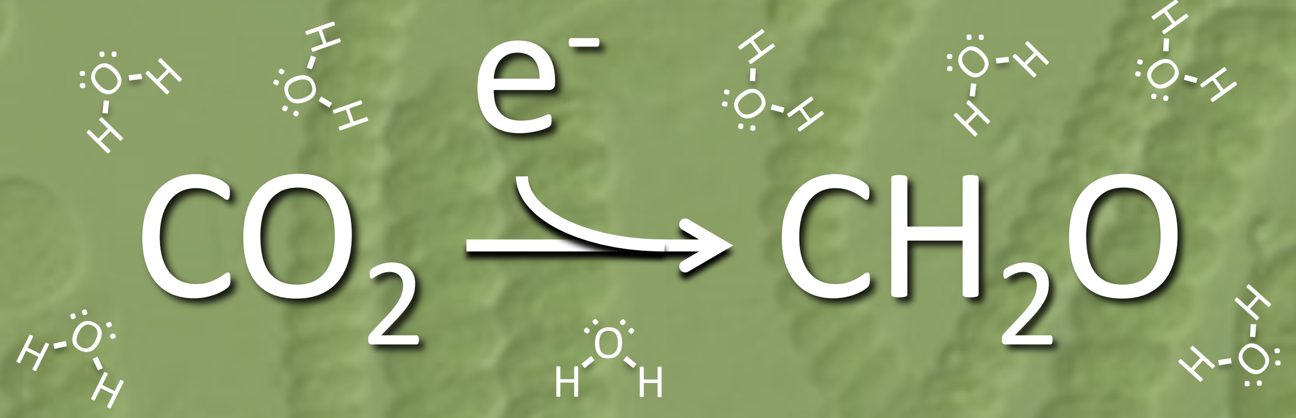
*particular uncertainty regarding the magnitude of the "maintenance energy" requirement and its dependence on environmental conditions



Disequilibrium as biosignature?

The imprint of life lies in the type *and* magnitude of the signal, *taken in environmental context*

Earth's disequilibrium biosignature is a possibility realized by virtue of biochemical and environmental context



Oxygenic photosynthesis: A biochemically complex, energy-investing solution to a problem of resource limitation that yields a volatile, low-solubility byproduct

(Image: Lee Bebout)

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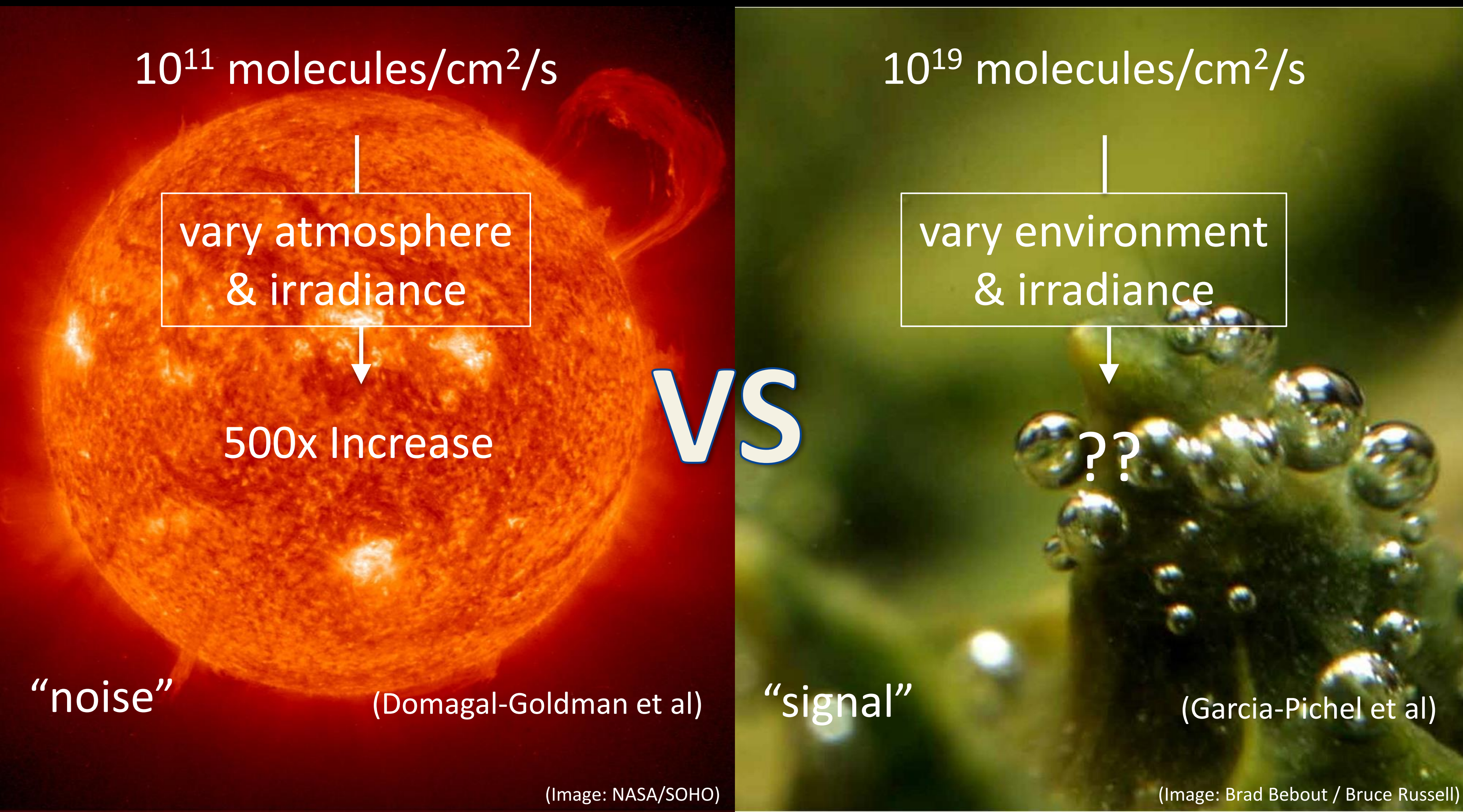


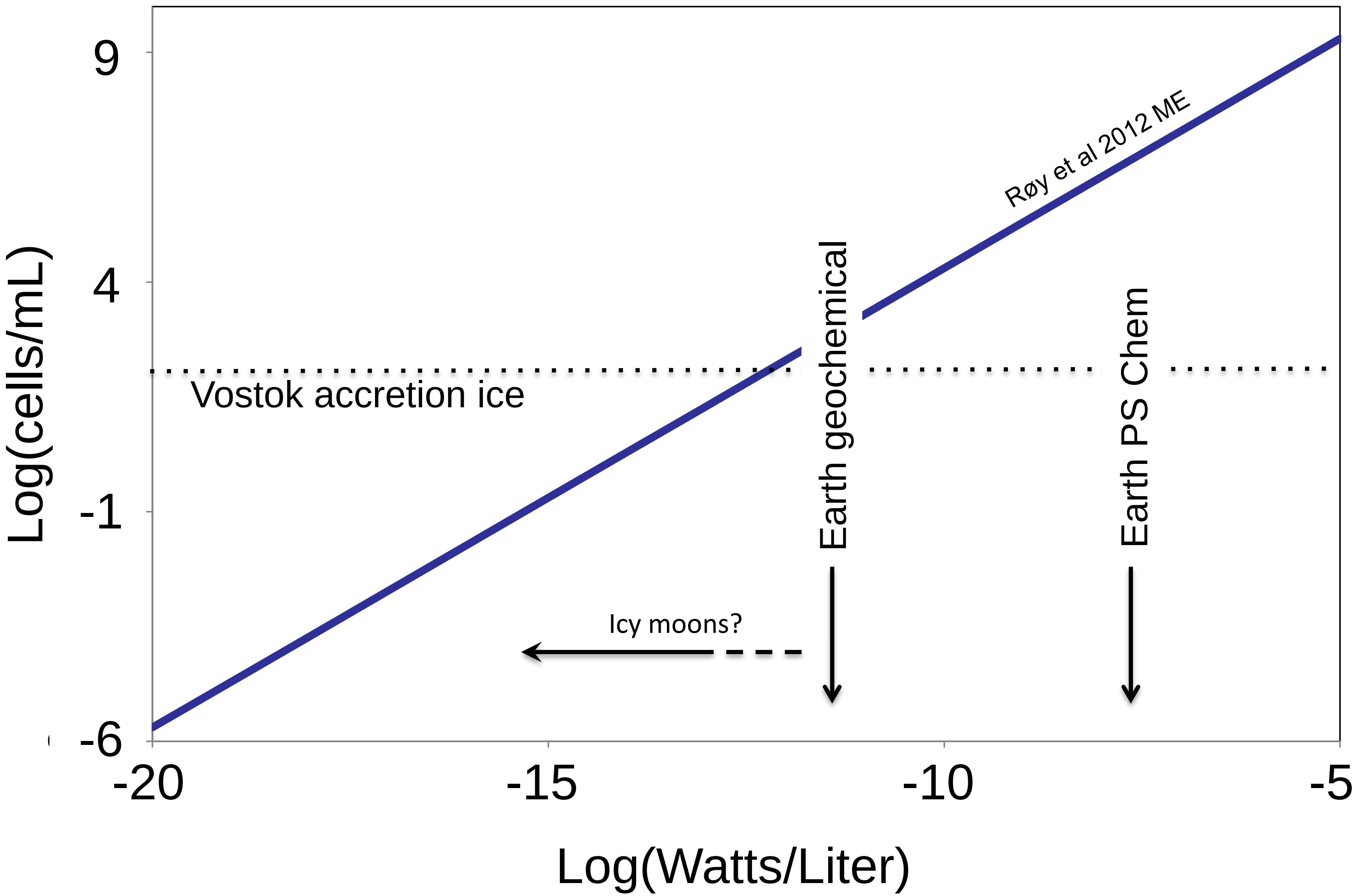
Summary

Empirical → fundamental/mechanistic: Evaluate the "how" and "why" (not just the "what") of Earth's biochemistry *as a specific solution to the generic problem* of how to build a living system

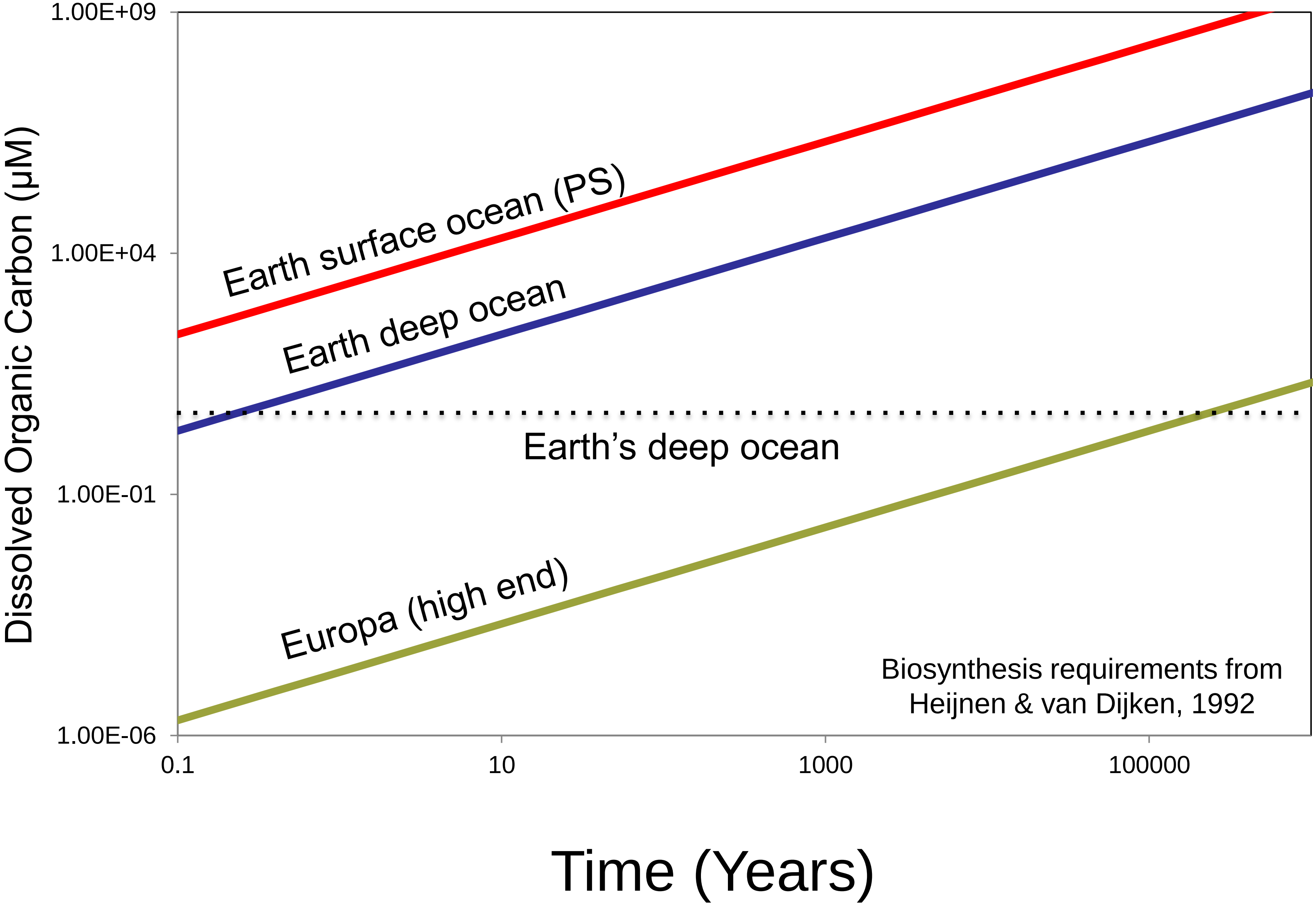
Significant constraint inherent in the non-covalent interactions required to confer life-like function (e.g. info processing) and the interdependence of suitable solvent/biochemistry/environment

Habitability → biological potential: Map the potential for clearest signals (in type/intensity) to resource availability/environmental challenges. Critical role of energy availability…

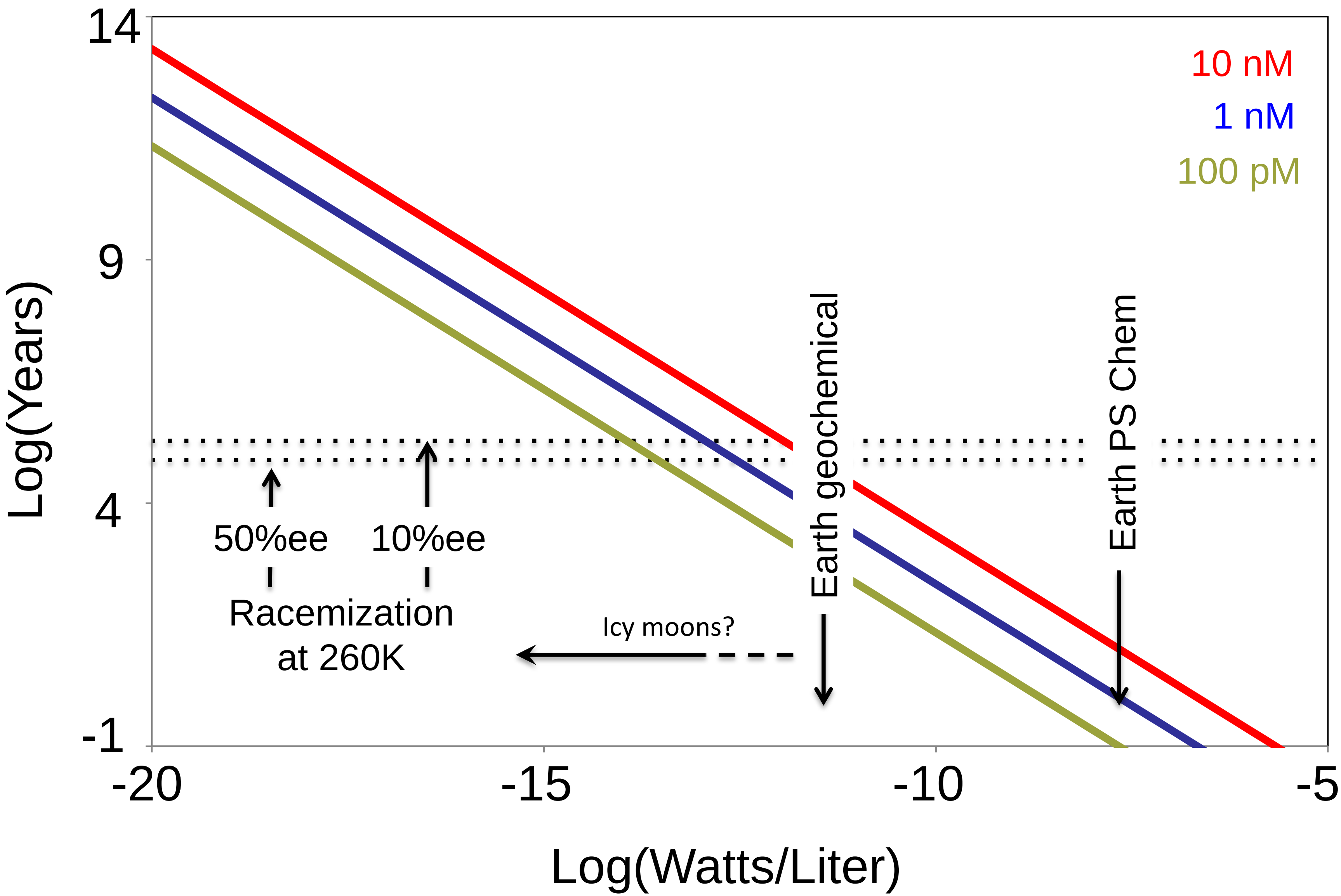
Cell Density (cells/mL) vs. Volumetric Power



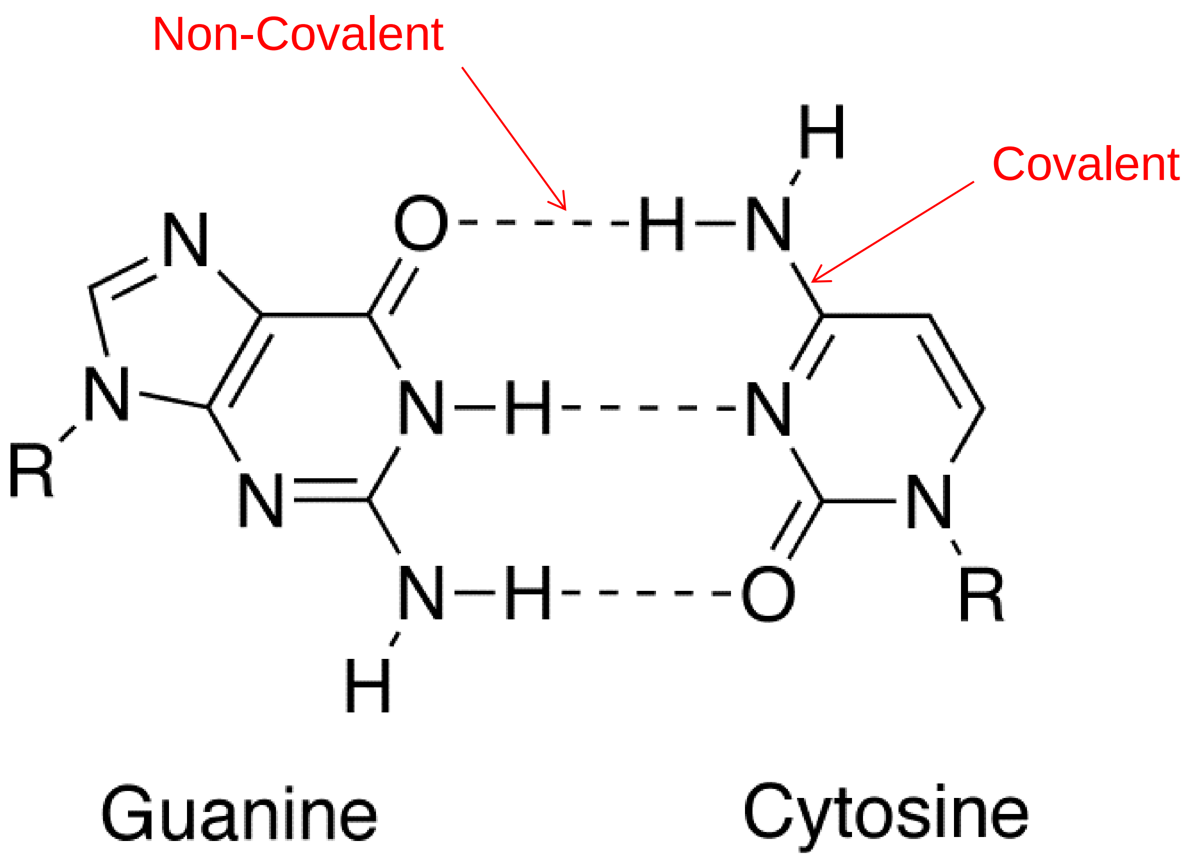
DOC Concentration vs. Time



Aspartate Residence Time vs. Volumetric Power



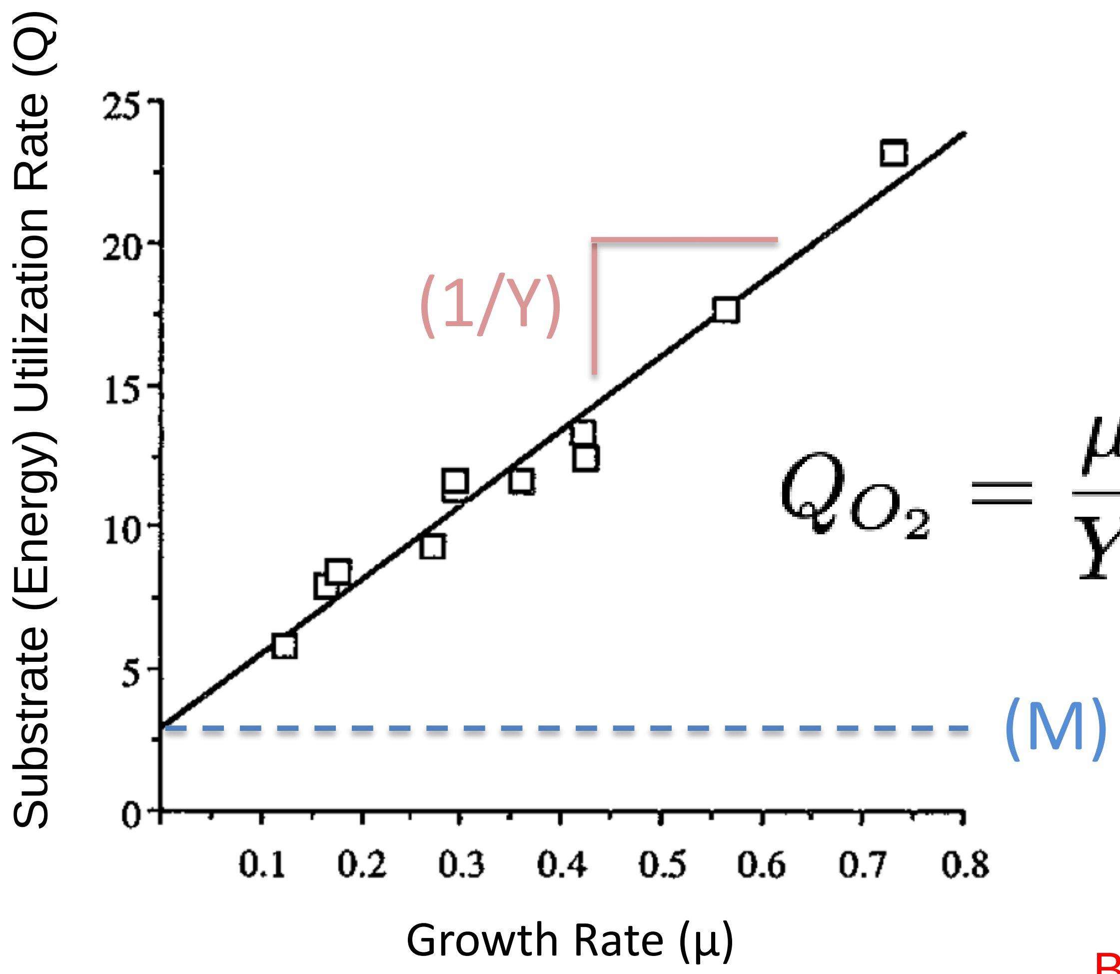
Covalent vs. Non-Covalent Interactions



Covalent: Shared electrons. Primary molecular structure and properties. "Marriage"

Non-Covalent: No shared electrons. Interactions (molecular recognition, tertiary structure, self-organization). "Dating"

Energy is used for Growth *and* Maintenance



$$Q_{O_2} = \frac{\mu}{Y} + M$$

Biomass-dependent
(e.g., "mol substrate/g biomass/d")

Sauer, Appl and Environ Microbiol, 1996