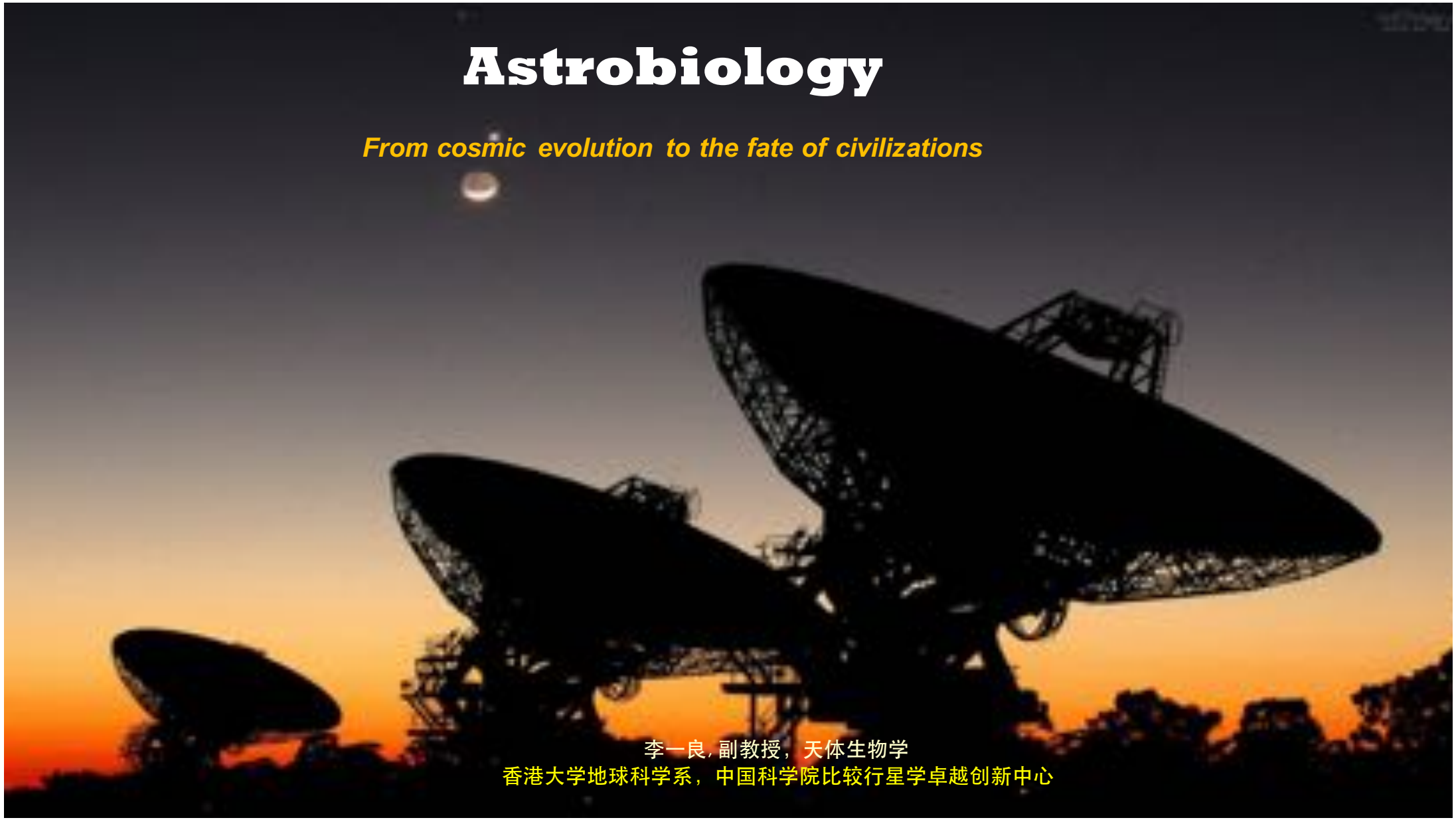


Astrobiology

From cosmic evolution to the fate of civilizations

李一良, 副教授，天体生物学
香港大学地球科学系，中国科学院比较行星学卓越创新中心

Definition of Astrobiology

- Studies the origin, evolution, distribution, and future of life on Earth and in the Universe.

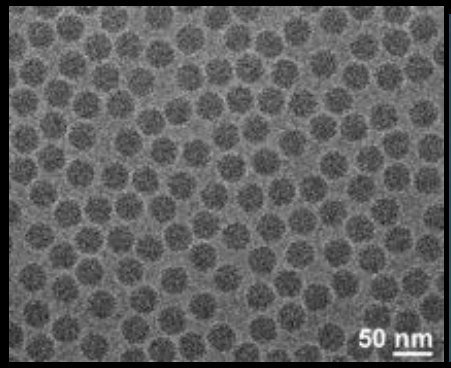
Profound questions awaiting this science to answer*:

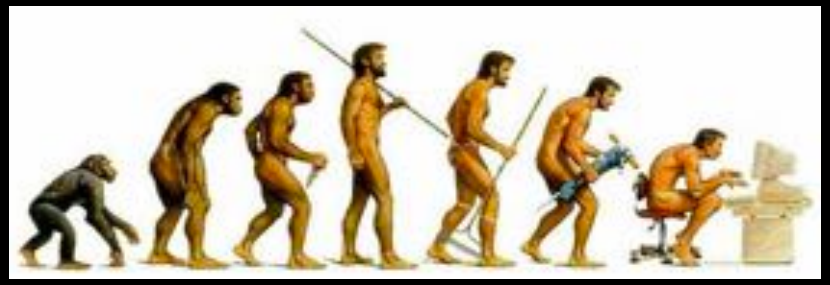
1. How does life begin and develop?
2. Does life exist elsewhere in the universe?
3. What is the future of life and intelligence on Earth and in space?

- Astrobiology is the forefront of public awareness; it represents the common human interest.
- *NASA roadmap 2003, 2008; European roadmap of Astrobiology (2016).

Definition of Life, If We Can…

- **Life is a self-sustaining chemical system capable of Darwinian evolution** (NASA definition)





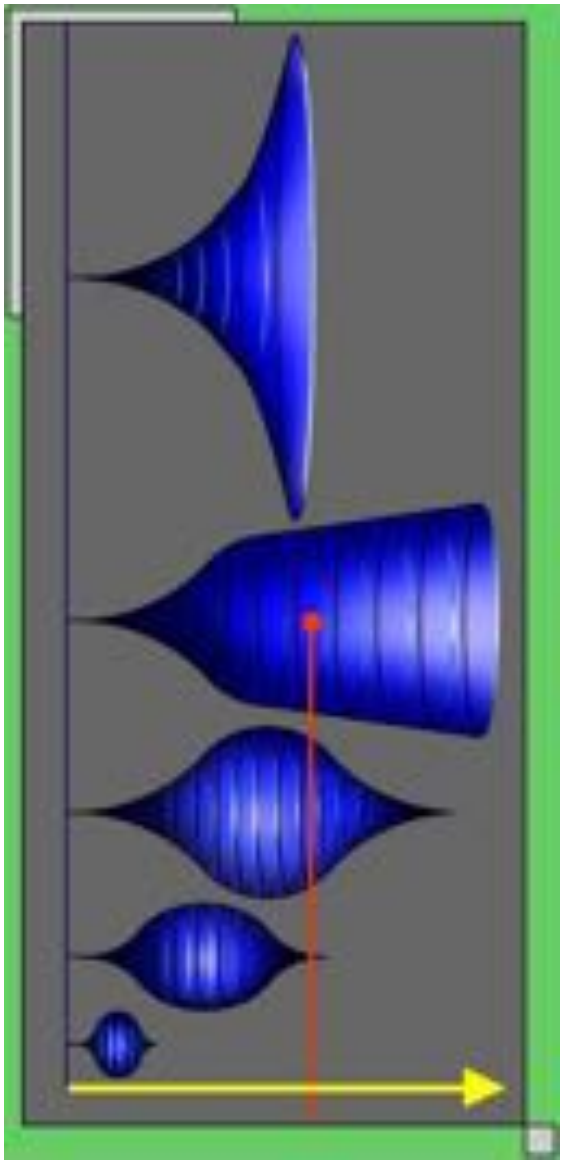
Left:
Old time evolution

Right:
Future starts here…

Are We Alone in the Universe?

An Anthropic Universe?

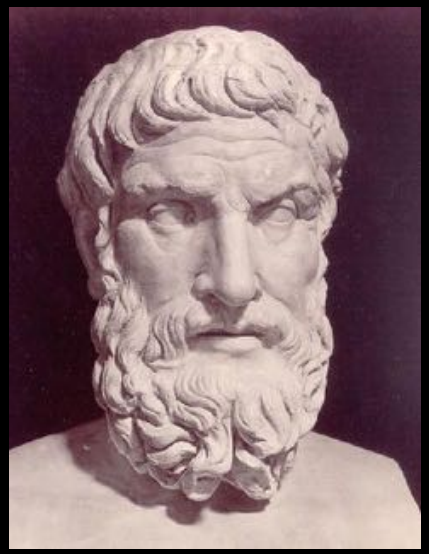
- Weak Anthropic Principle: (a) the structure of the Universe does not exclude the possibility of carbon based life developing at some sites and (b) the Universe is old enough for this to have happened.
- Strong Anthropic Principle: the properties of the Universe are such that living materials will develop within the Universe given sufficient time and that evolutionary forces will allow this to develop into advanced technological forms.



From Life on Earth to Life in the Universe

Epicurus
(to Herodotus in 300 BC):

There is an infinite number of worlds and one cannot demonstrate that they are not living in.

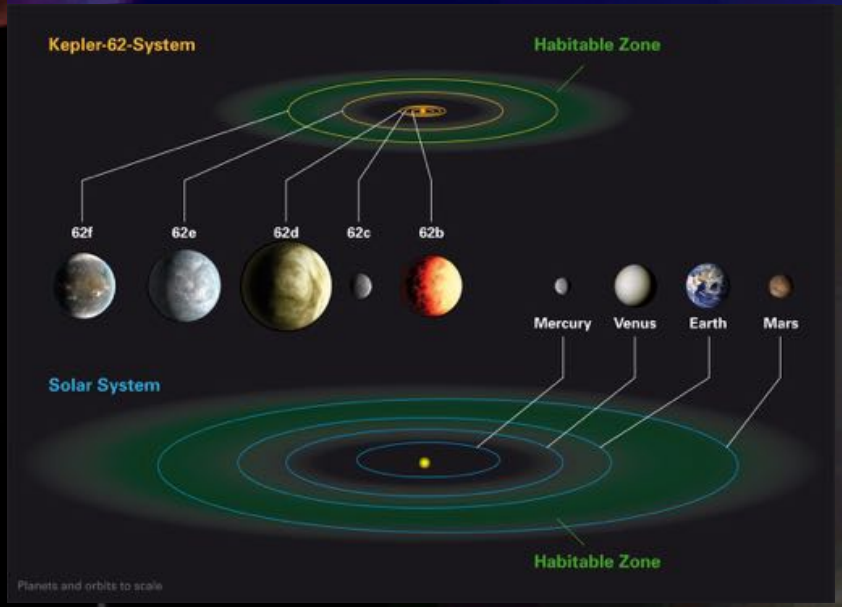


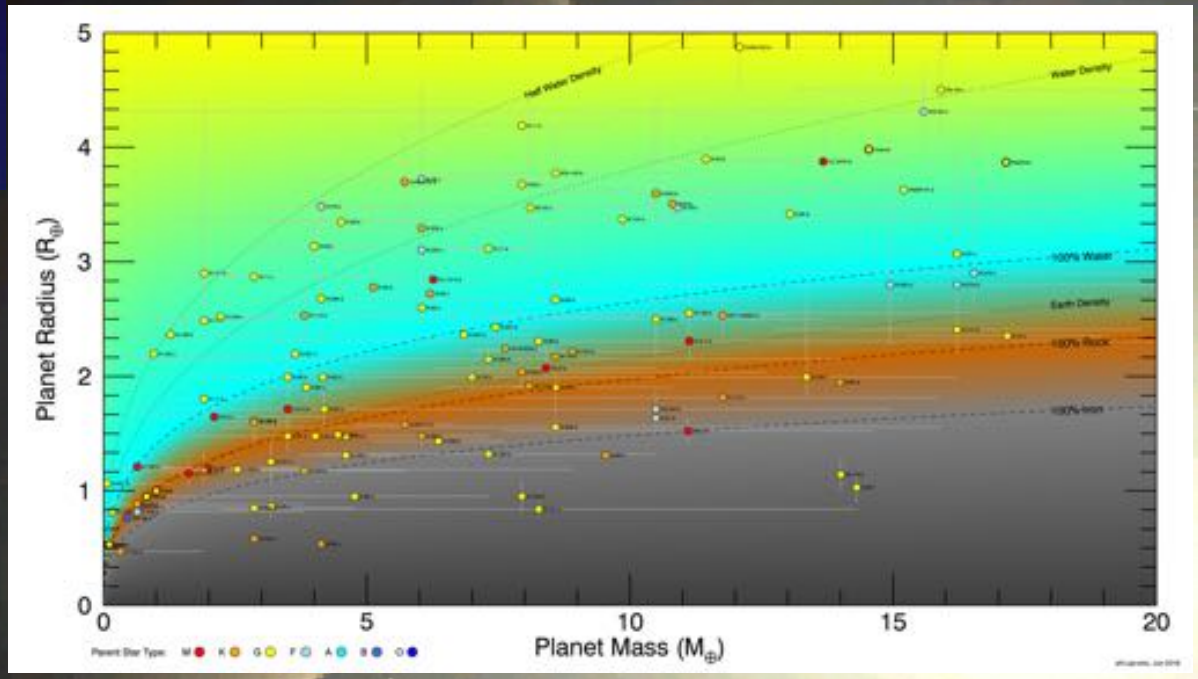
Jacques Monod
(The Nobel Prize in Physiology or Medicine 1965)

The probability of life's appearance was quasi zero.

The Diversity of Extrasolar Planets Around Solar-Type Stars

- More than 5747 extrasolar planets have been found so far (until July 04, 2020; the number was 250 in 2008).

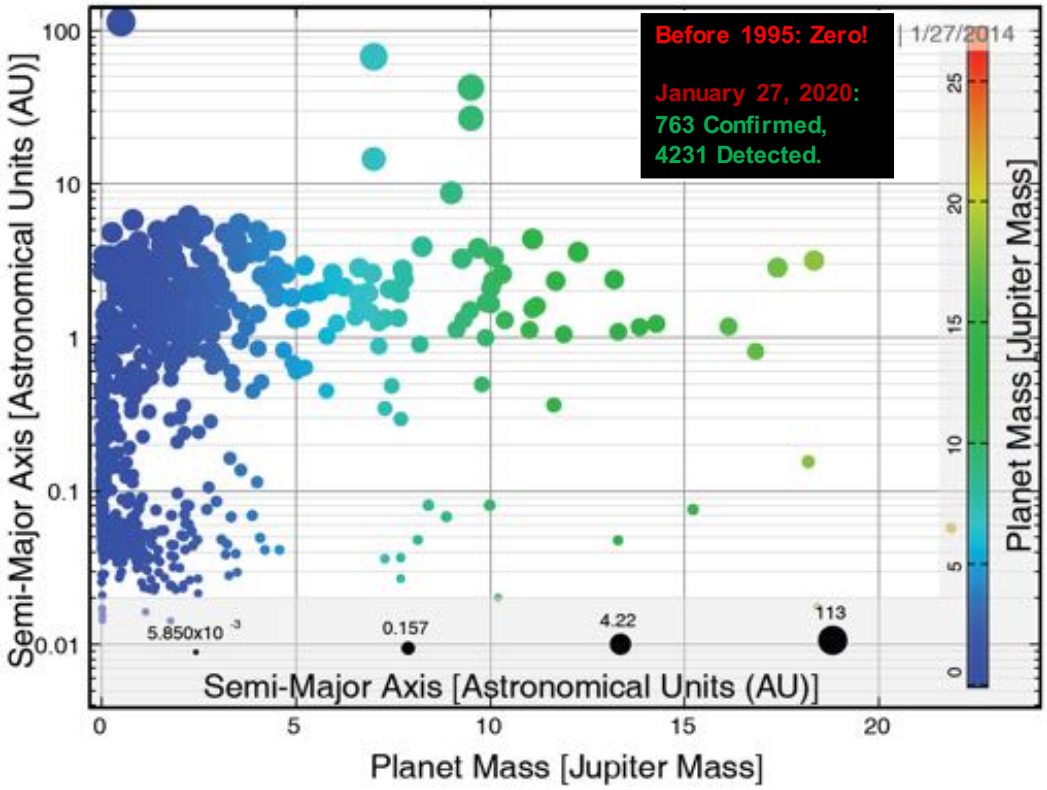


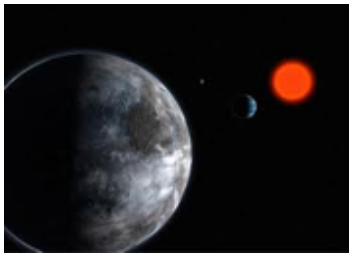


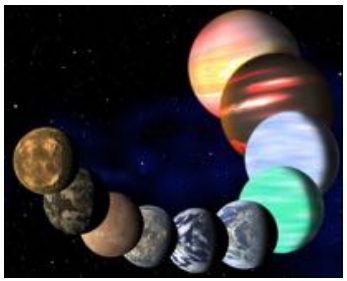
http://exoplanets.org

Around 17000000000 Earth-Like Planets in Milky Way!

Aliens Are Everywhere!





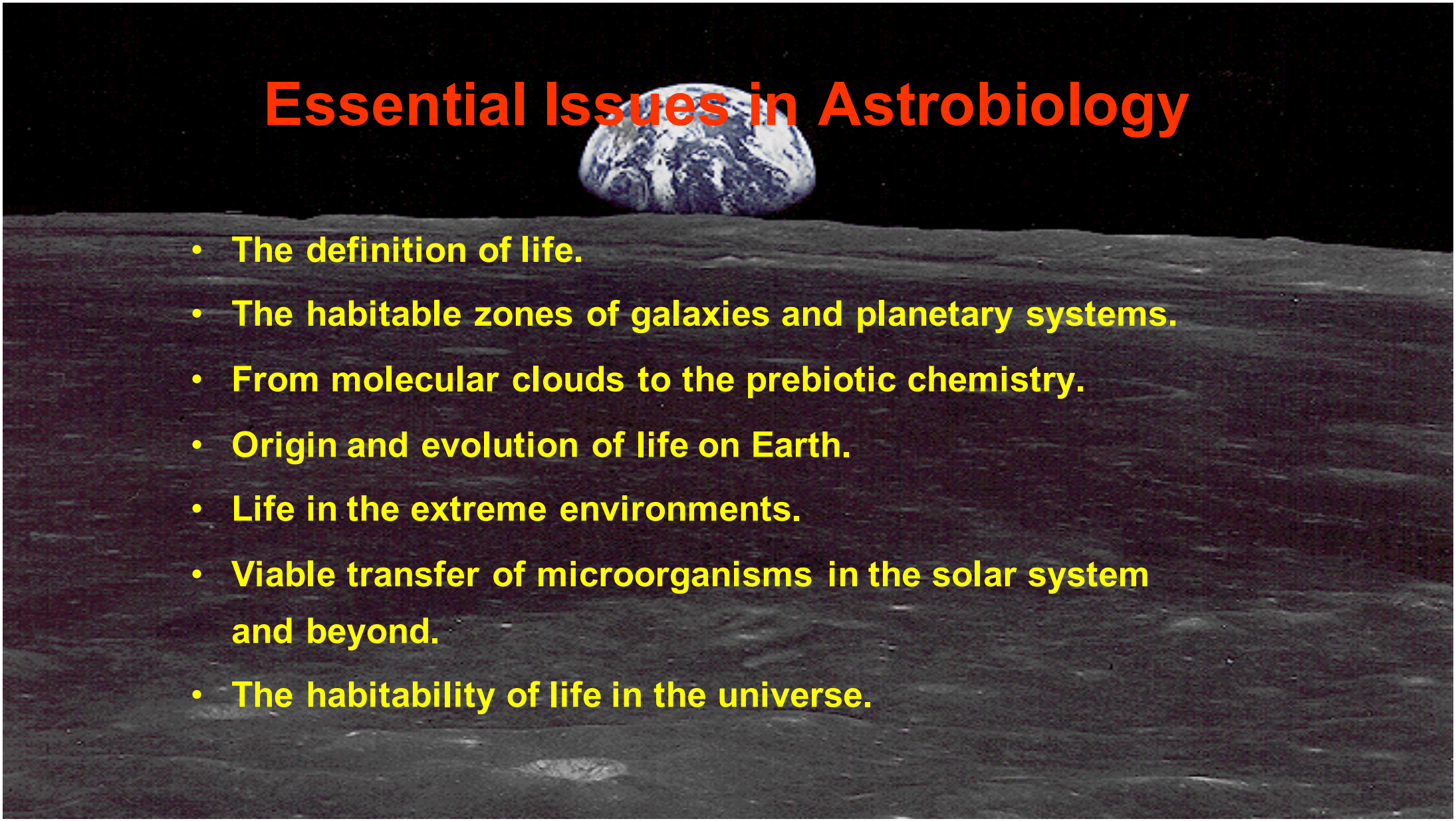


Before 1995, we didn't even know if our solar system is the only planetary system or not in the whole Universe. Now we have detected >5000 exoplanets, and we believe there are many habitable planets in the Universe.

http://exoplanets.org

Cosmic Evolution Toward Life

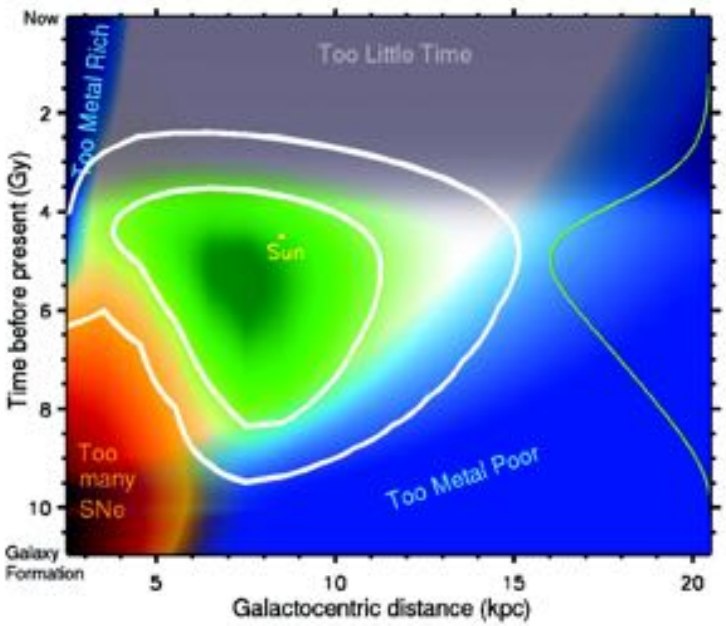
- **Big Bang: the creation of this universe and formation of H and He (~13.7 Ga).**
- **Evolution of first generation of star: the formation of heavy elements (e.g., SM0313, 100-200 million years after BB).**
- **The condensation and accretion of Solar Nebulae.**
- **Formation of planets around the Sun (4.567 billion years ago).**
- **Bombardment of asteroids/comets (4.567 – 3.85 billion years ago) and the formation of ocean.**
- **Earliest Life Detected (~3.85 billion years ago)?**



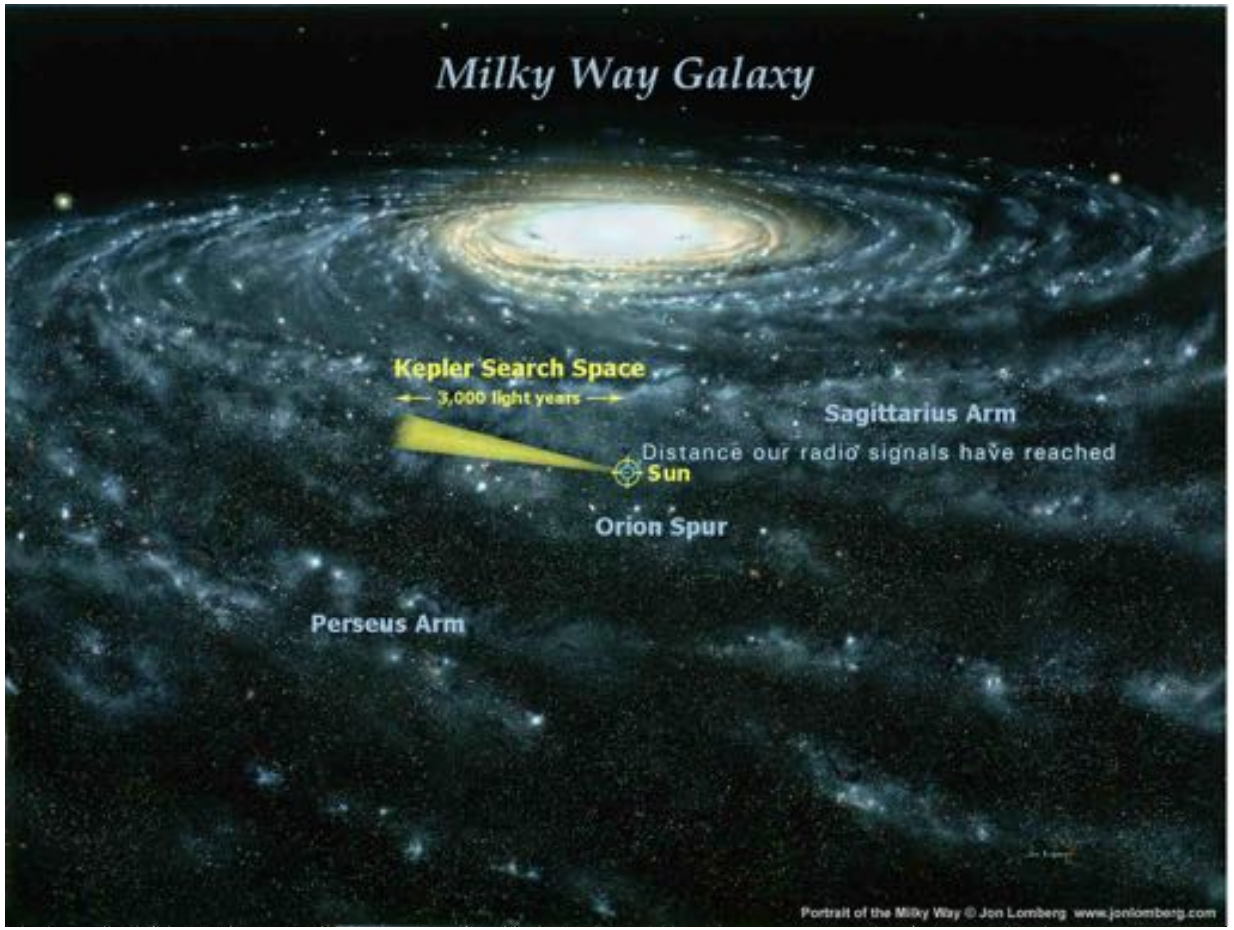
Essential Issues in Astrobiology

- The definition of life.
- The habitable zones of galaxies and planetary systems.
- From molecular clouds to the prebiotic chemistry.
- Origin and evolution of life on Earth.
- Life in the extreme environments.
- Viable transfer of microorganisms in the solar system and beyond.
- The habitability of life in the universe.

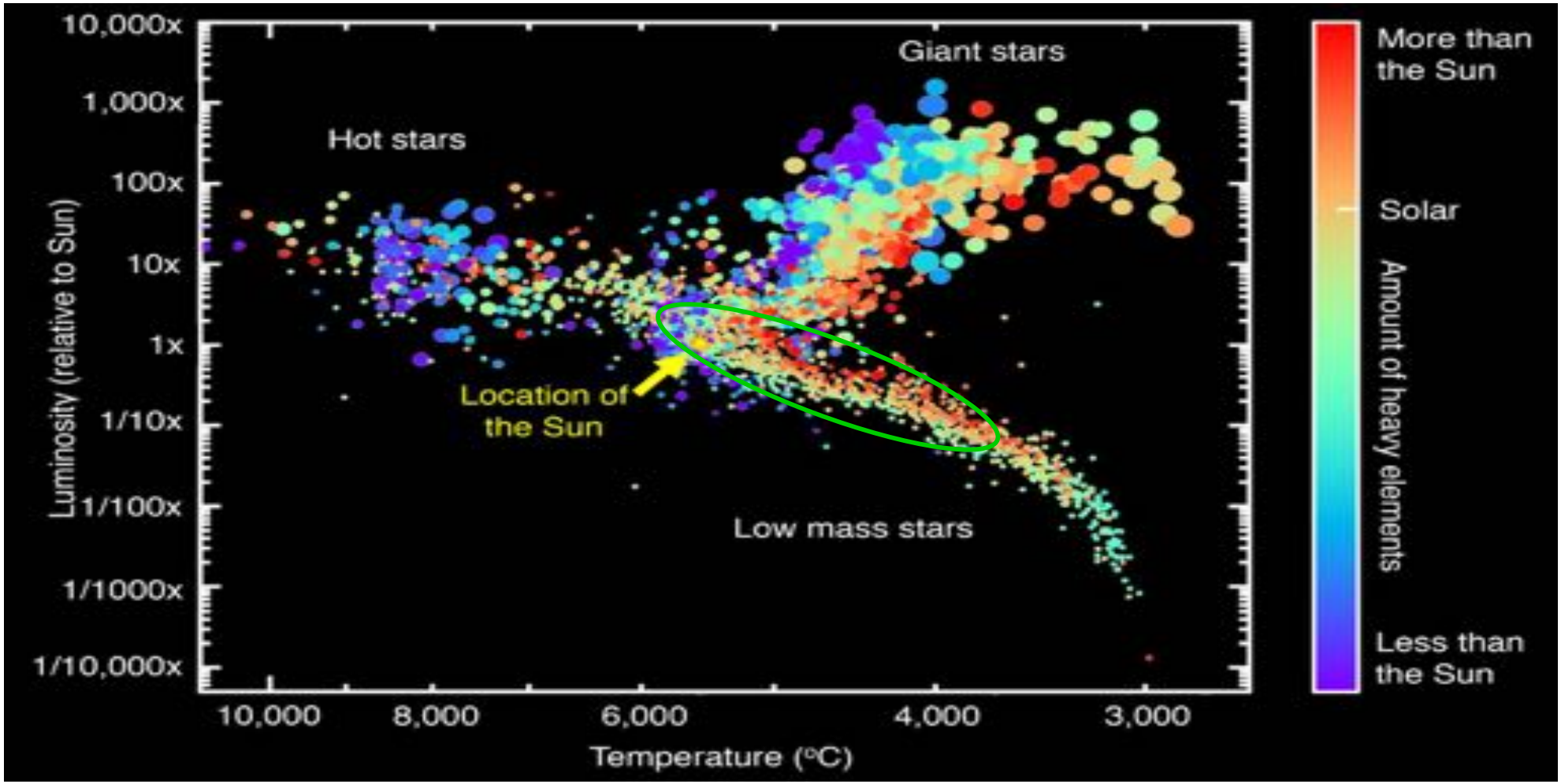
Galactic Habitable Zone



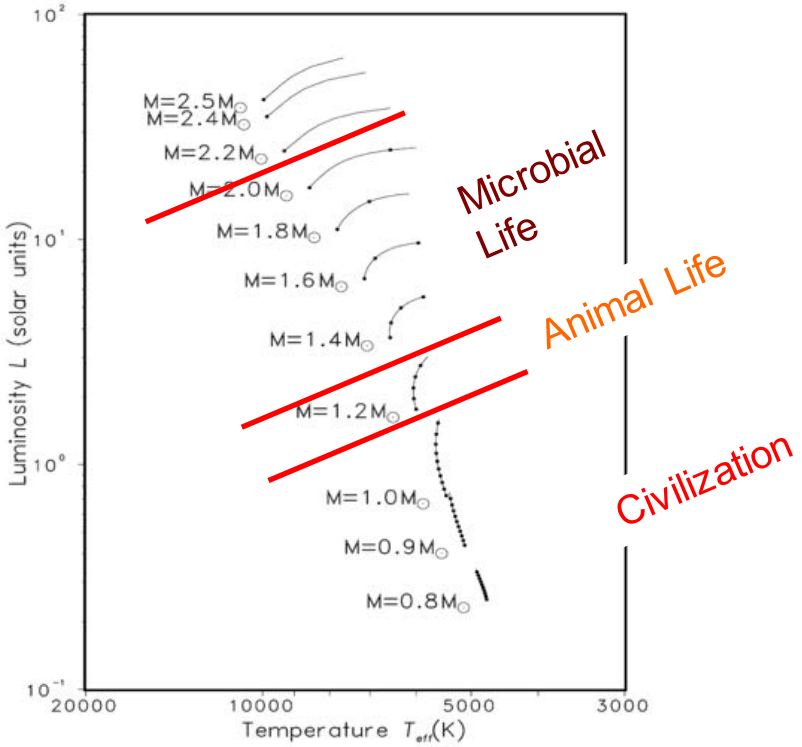
Lineweaver et al., 2004

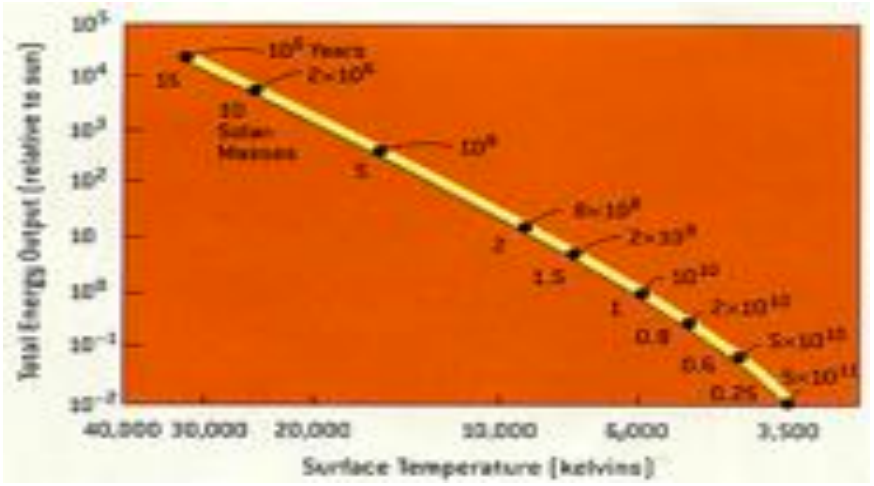


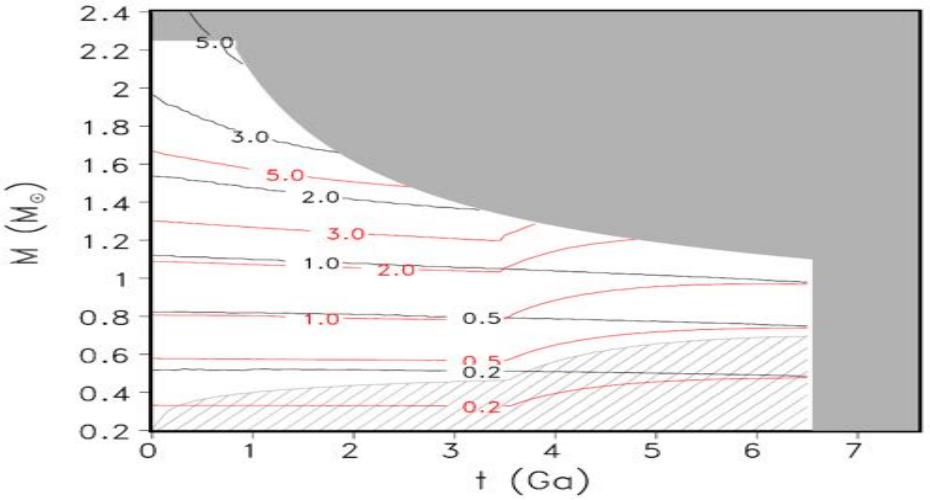
Biological Hertzsprung–Russell Diagram



The Evolution of Planetary Habitable Zone (Franck et al., 2000)

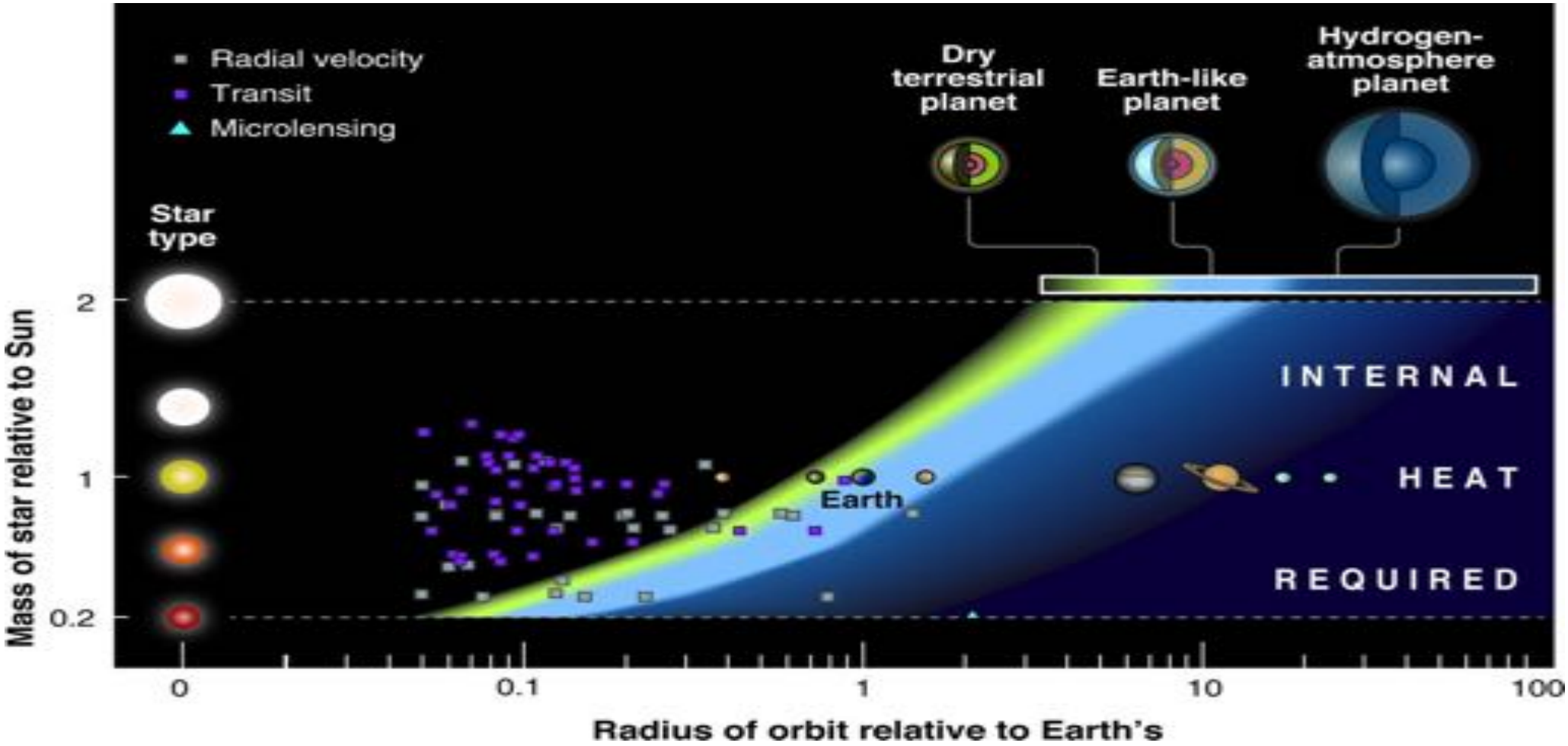






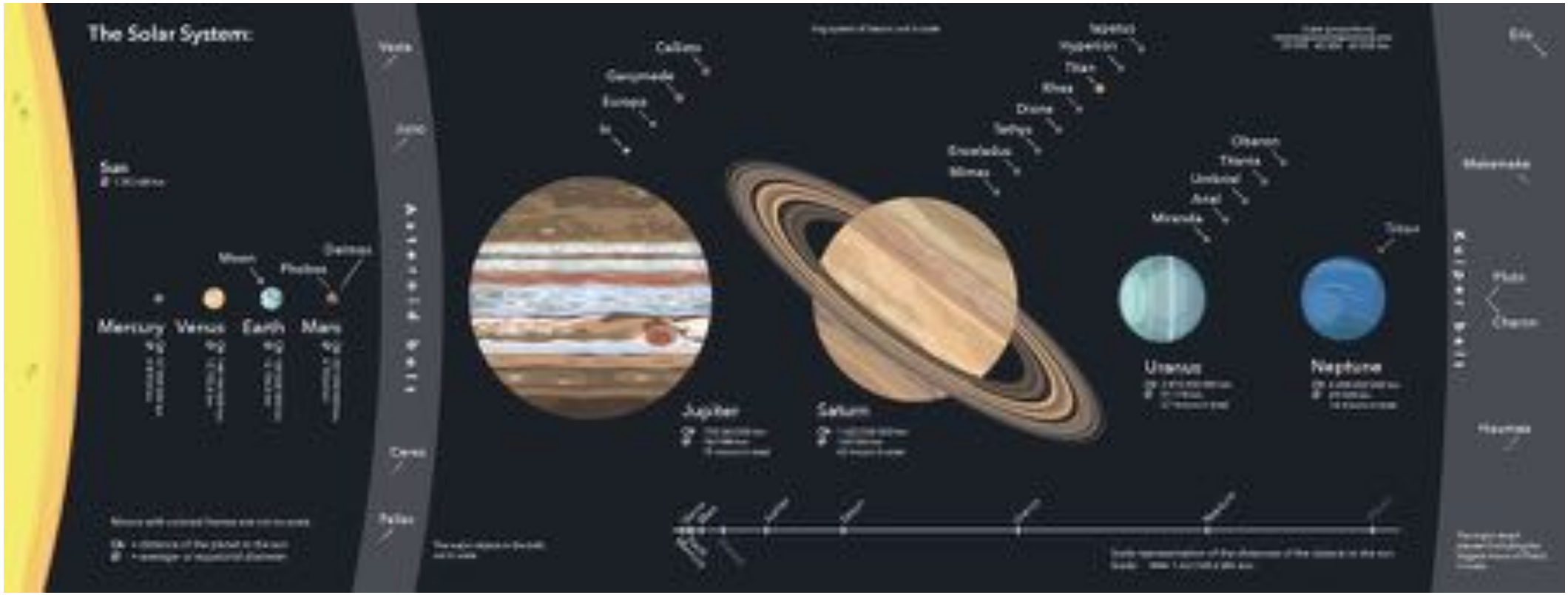
Evolution of Main Sequence Stars (The time span between two successive dots is 1 billion years)

Habitable Zone in Solar Systems

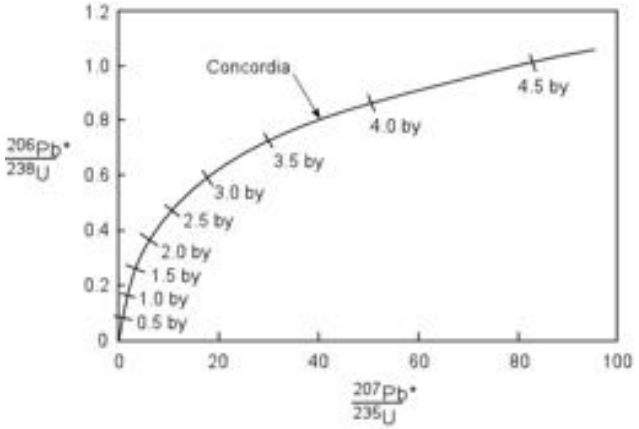


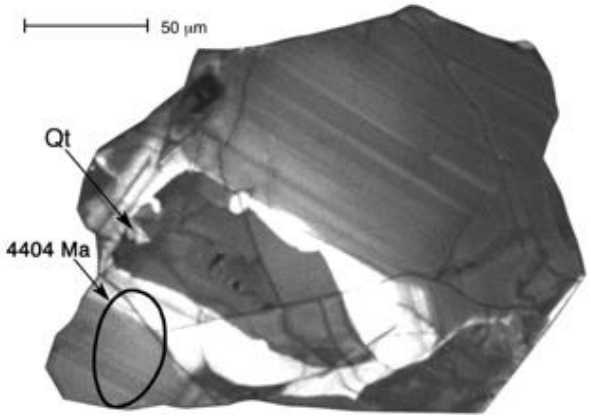
Solar system HZ. Kasting et al., 1993; Exoplanet Habitability by Seager, 2013

The Habitable Zone of Our Solar System: More Than Planets



Zircon: Let Love Start With a Geological Age!





The oldest mineral on Earth

Europa: An Ocean of Water Underneath the Surface Ice

- The presence of large blocks may have once been mobile icebergs (Pappalardo et al., 1999).
- Electromagnetic induction indicating presumably a salty liquid-water layer (Khurana et al., 1998).
- Features indicating flow of surface materials and softening of terrain, presumably due to subsurface warming (Greeley et al., 1998).
- The surface layers are dominated by water or ice (Pappalardo et al., 1998).

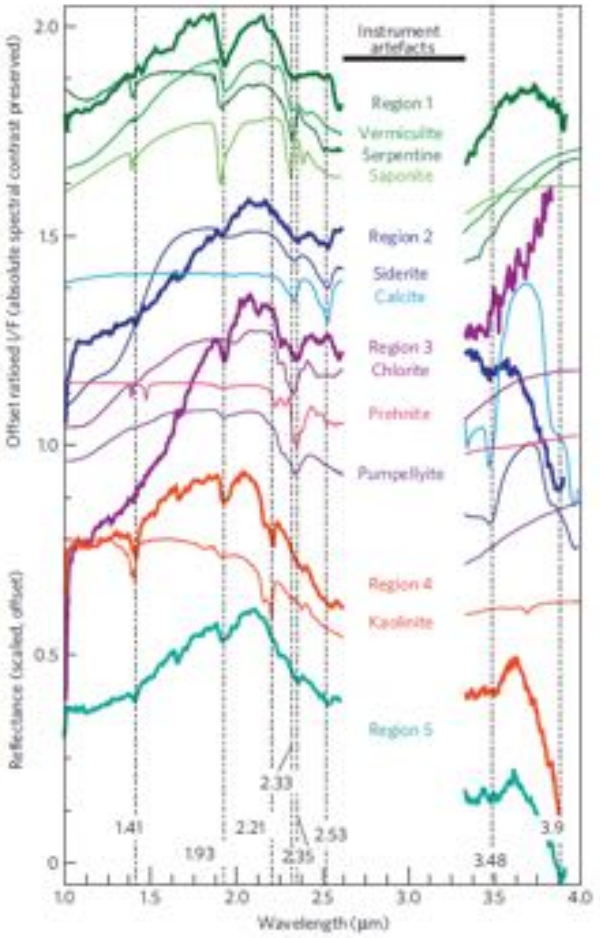
http://fineartamerica.com/featured/ocean-on-europa-detlev-van-ravenswaay.html

Following Water!

- **Water, the spring of life.**
- **Geomorphological record of water-related erosion on Mars (NASA Slogan for Martian Exploration).**
- **Europa's crust and ocean.**
- **Permafrost model of extraterrestrial habitat (& "deep-cold, biosphere?).**
- **Microbial life in terrestrial permafrost.**
- **Life in cold lakes (e.g., Vostok, Kargel et al., 2000, Icarus).**

Earliest Atmosphere-Rust Interaction on Mars?

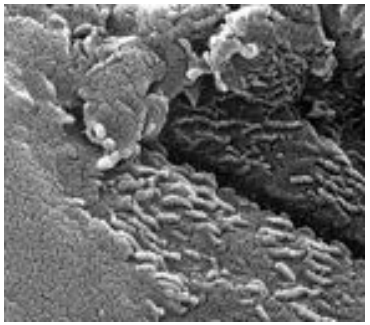
- Carbonate and phyllosilicate

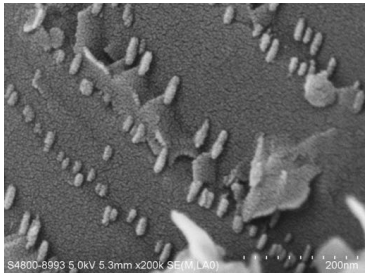


JR Michalski & PB Niles 2010

Life on Mars: What ALH84001 Told US?

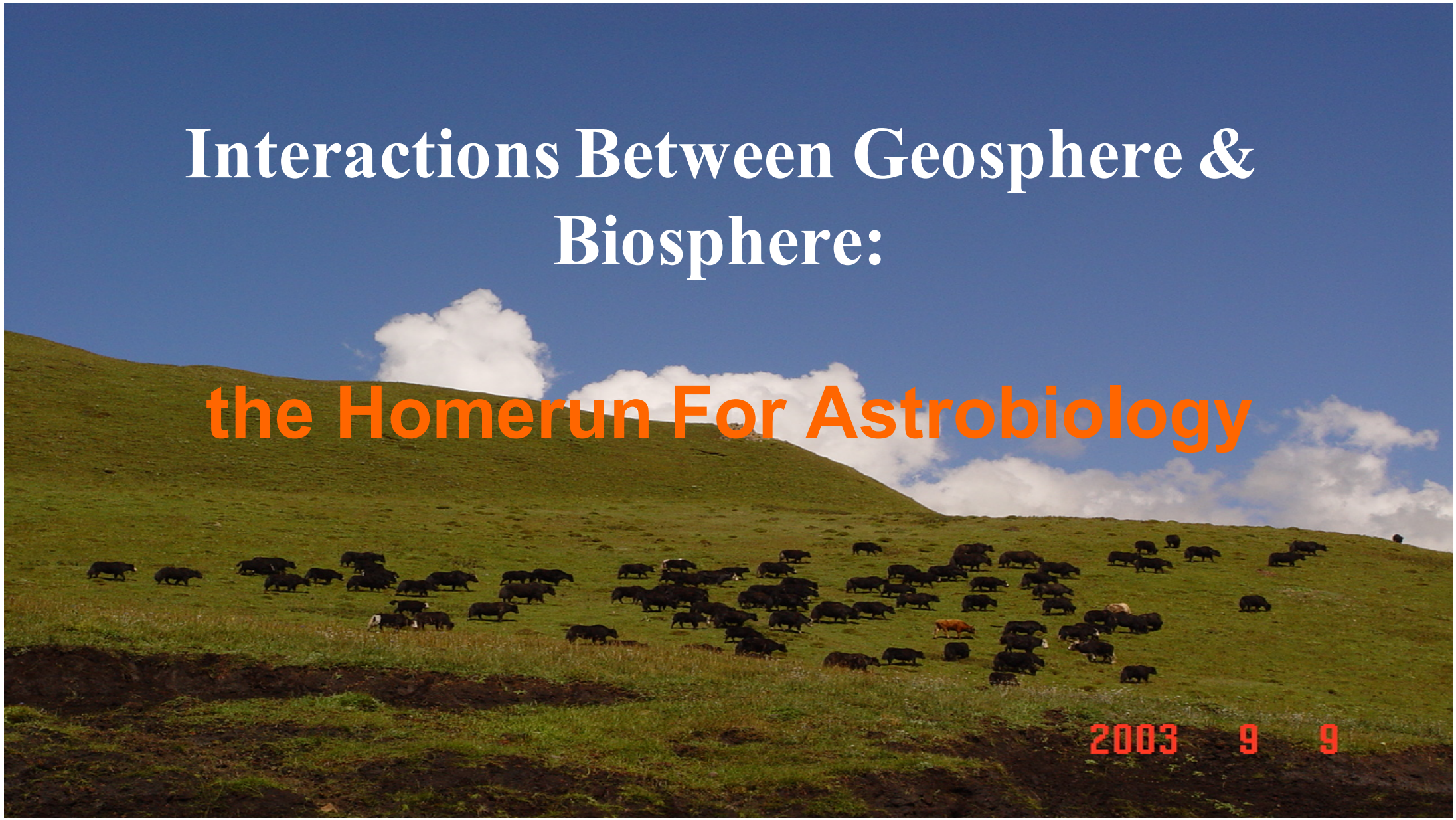
Martian Meteorite ALH84001, NASA Johnson Space Center



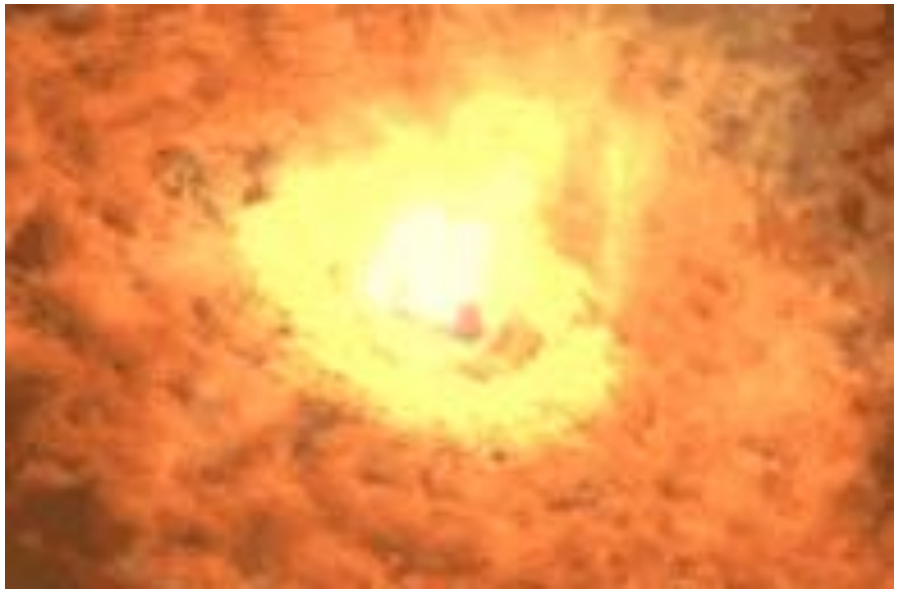


Interactions Between Geosphere & Biosphere:

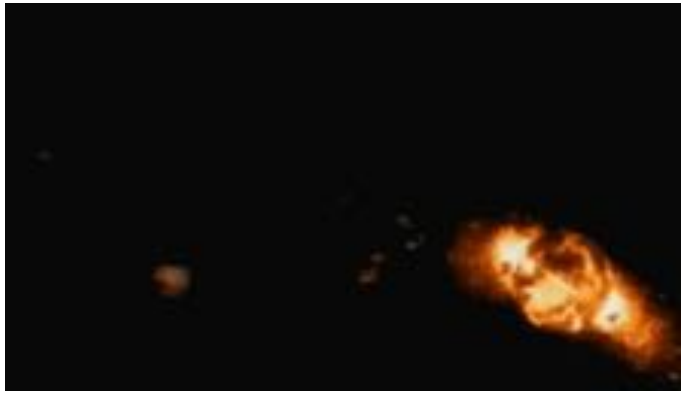
the Homerun For Astrobiology

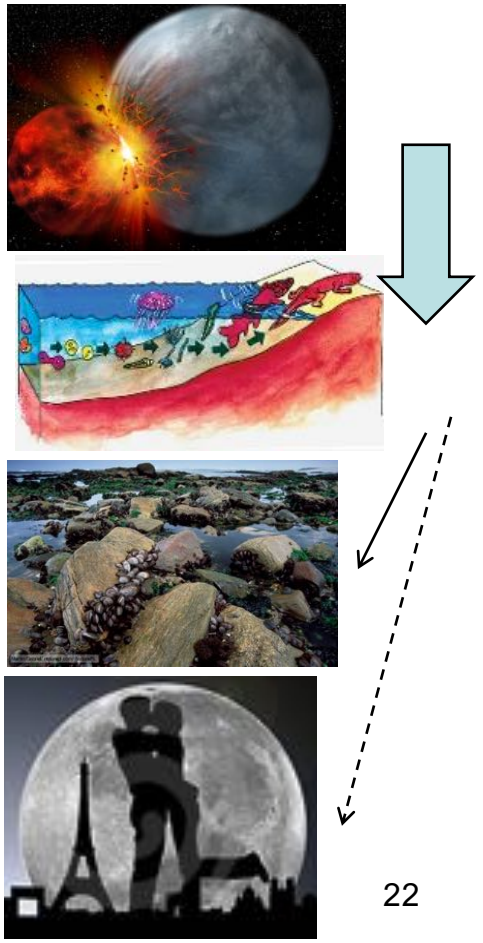


Origin of the Earth-Moon System

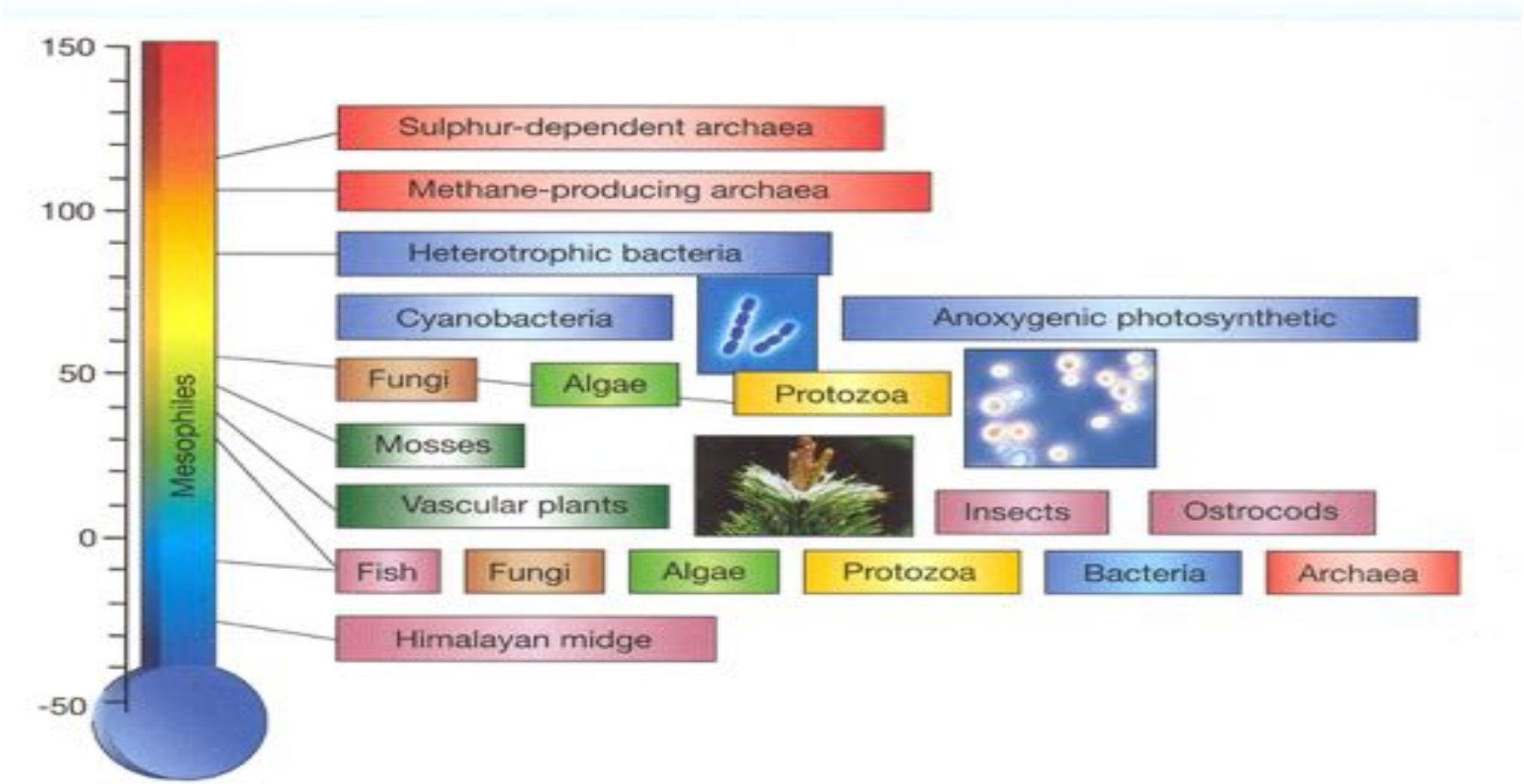


A.G.W. Cameron, Harvard College Observatory





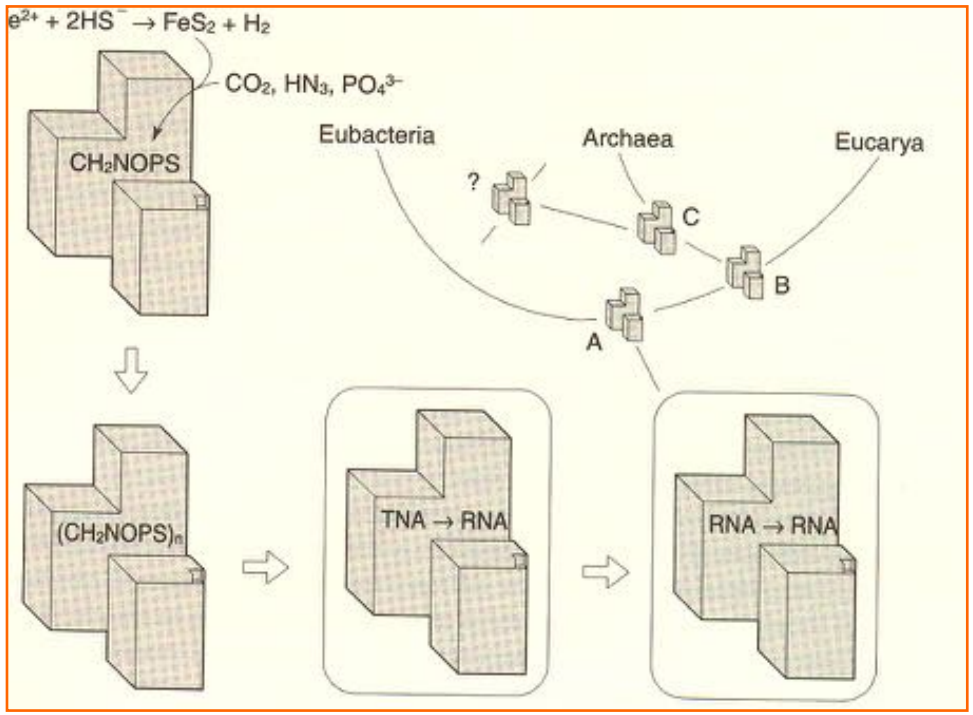
Temperature Limits for Life



Rothschild & Mancinelli, 2001

Archaea: red; Bacteria: blue; Algae: light green; Fungi: brown; Protozoa: yellow; Plants: dark green; Animal: purple.

A Sulfur-Based World Before RNA … Did Life Ever Choose?



Wächtershäuser (1988) suggested a pyrite-based model for origin of life. Pyrite synthesis provides the driving force for organic synthesis; pyrite also provides a surface for stabilizing and protecting synthetic reactions, leading to complex polymerization and early cellularization.

Origin of Life: Theories of Location

- Primordial broth (Oparin, Haldane)
- Evaporative intertidal lagoons “warm pond” (Darwin)
- Life in the deep sea vents (Baross)
- Life in clouds (Woese)
- Life in the subsurface
- Life from Mars (Panspermia)

Mud volcano

Euphotic zone; Lagoon

Deep-sea Hydrothermal Vent

Venus

Mars

Exoplanet

Extreme Environments as the Planetary Boundaries of Life

Deep Ocean

Permafrost Area

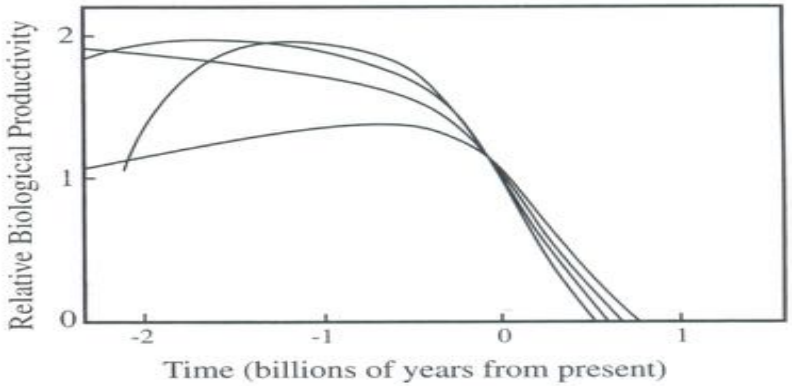
Qaidam Basin, China

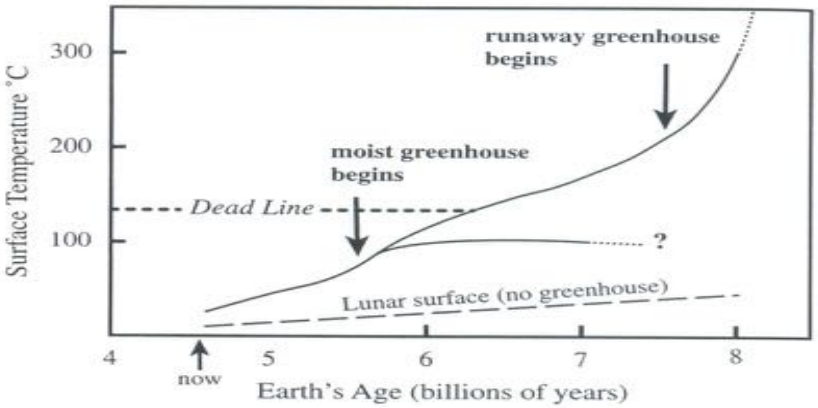
Grand Prismatic Spring (Yellowstone)

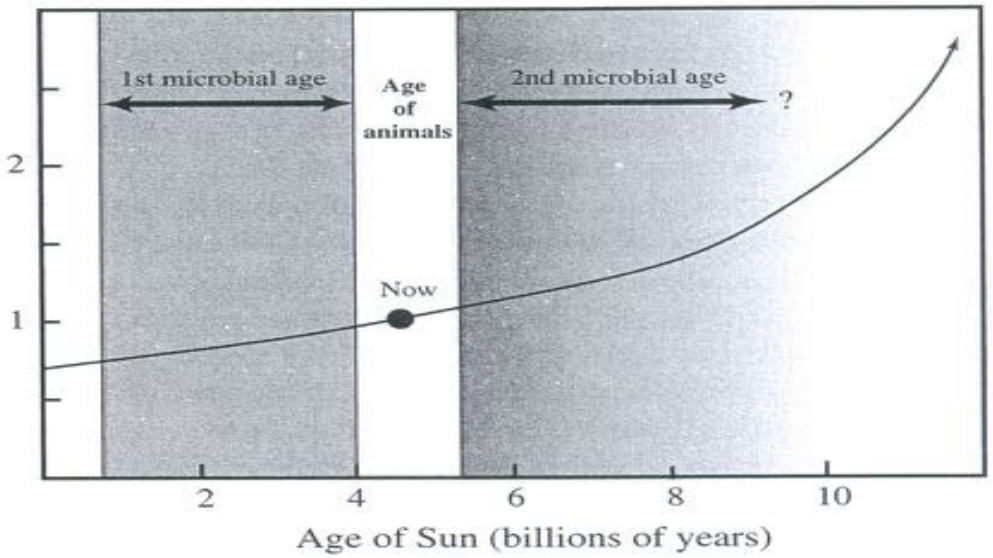
Acid Mine Drainage

Salty Lake

Planetary Evolution of Earth Ecosystem: From the Beginning to the End

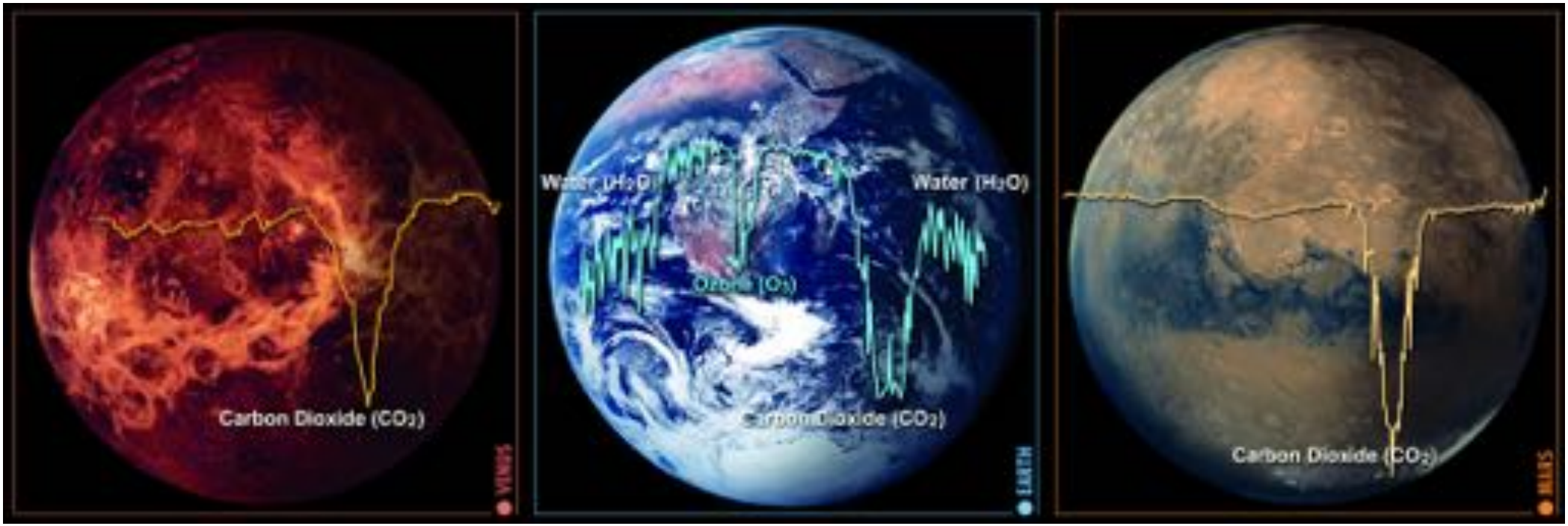






Donald Brownlee & Peter Ward, 2002

The Infrared Spectra of a Living Planet With Photosynthesis



Thermal infrared spectra of Venus, Earth, and Mars. The 9.6-micron band of ozone is a potential bioindicator. (From R. Hanel, NASA Goddard Space Flight Center.)

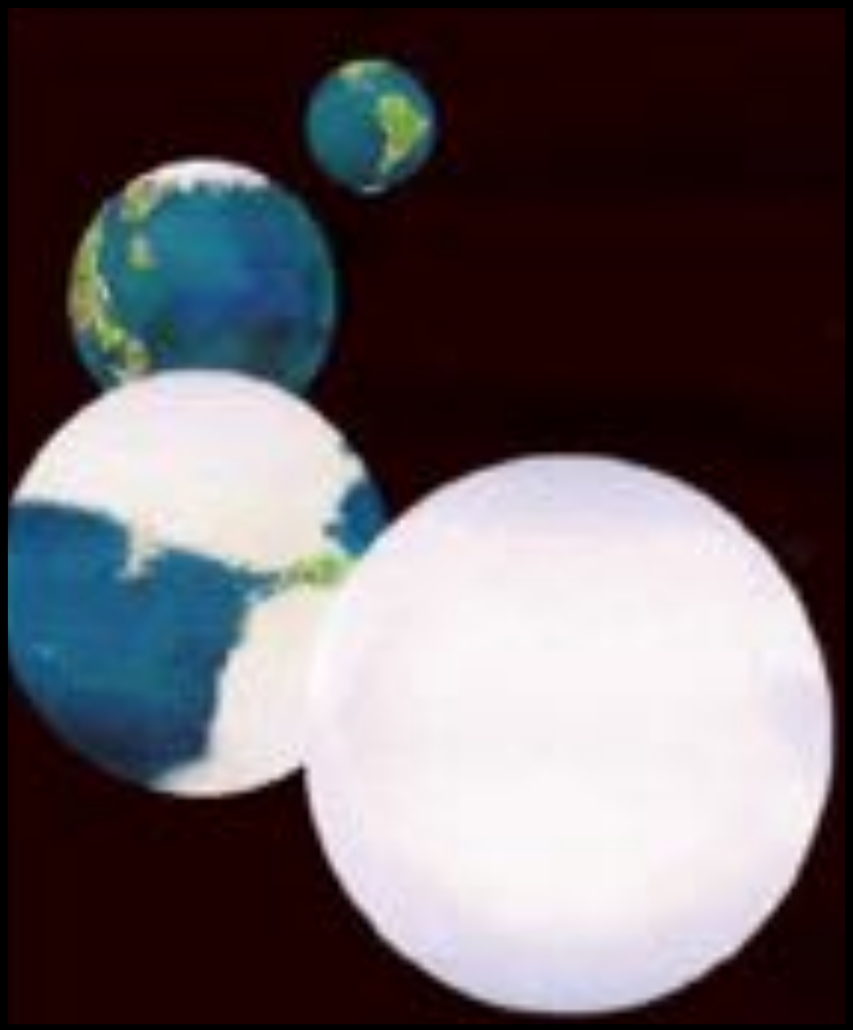
Two Extreme Ends of the Climate Temperature of Earth: Runaway Greenhouse & Runaway Glaciation

Too hot

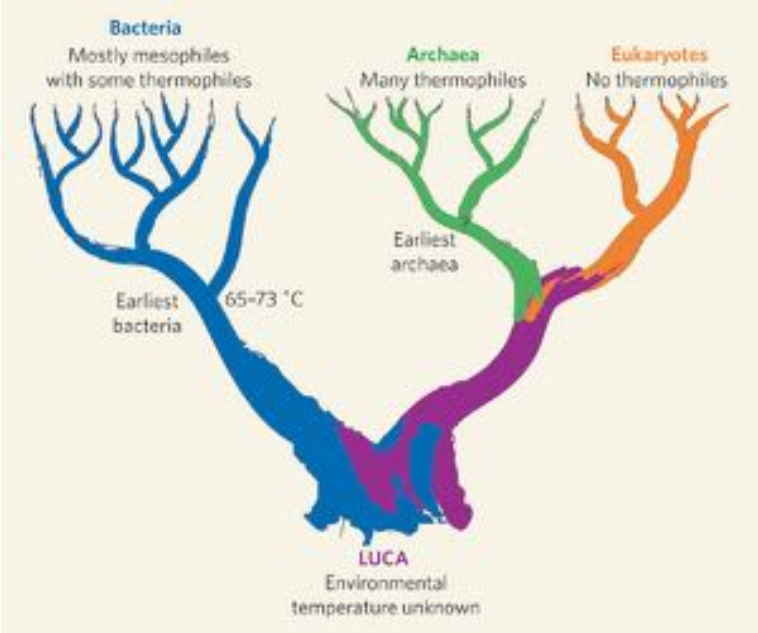
Just right

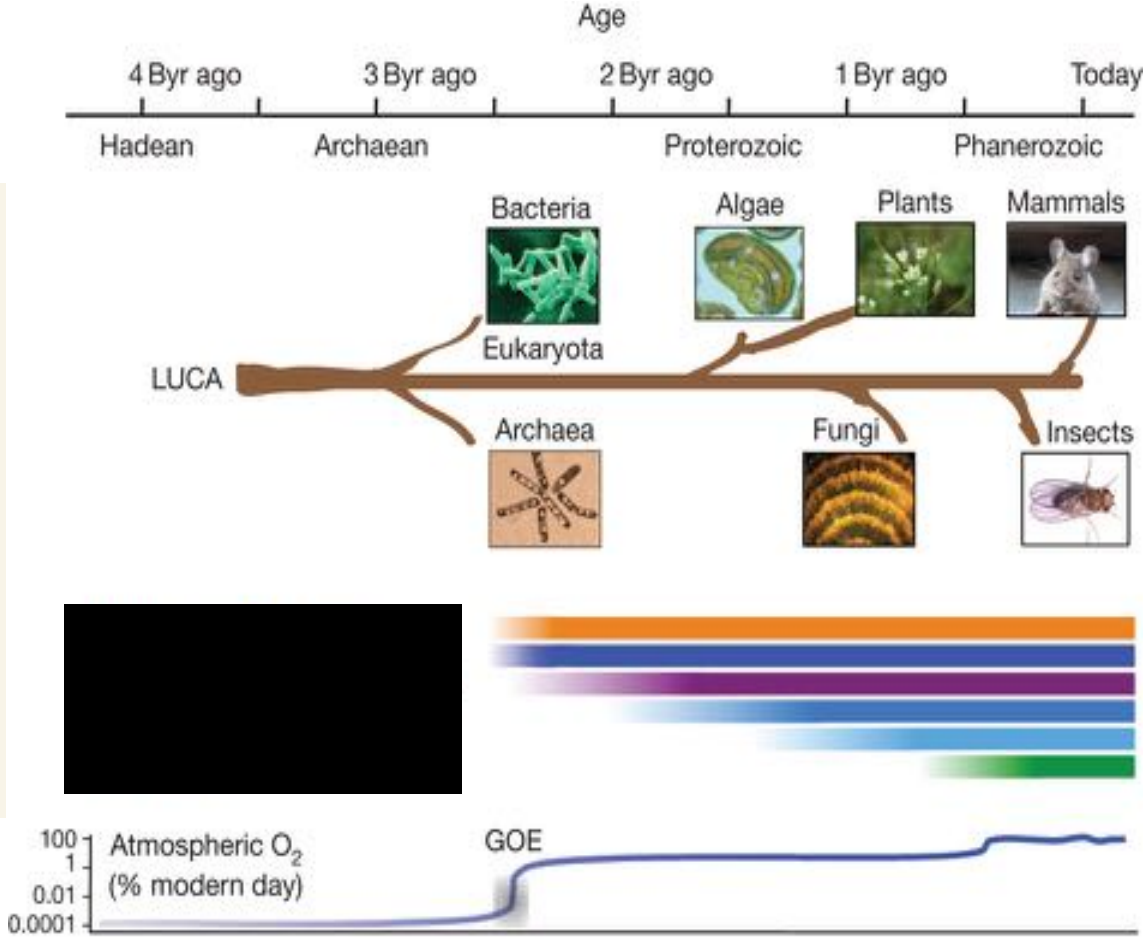
(Mostly) too cold

- **Runaway Green House Effect**
- **Runaway Glaciation**
- **(SnowballEarth)**
- **Moderately Tuned Negative-Feedback System**



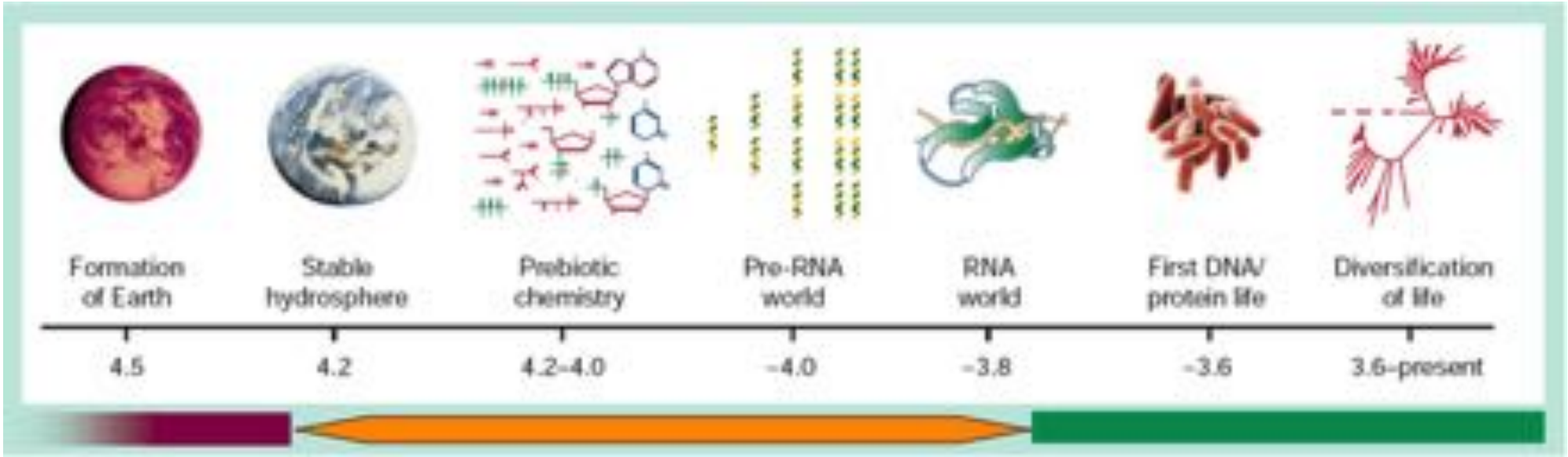
Universal Last Common Ancestor





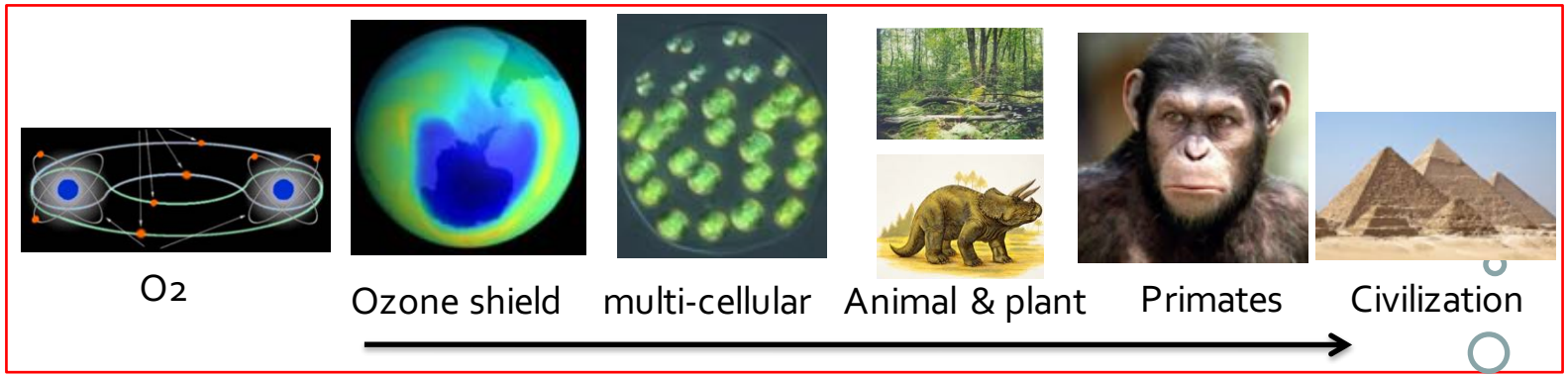
Timeline for Early Life on Earth

- [**Chemical Evidence**] $\delta^{13}C$ of graphite from **38.5** 亿年 Akilia metasedimentary rock (Mojzsis et al., 1996). → Questioned!
- [**Fossil Evidence**] **34.65** 亿年 old Apex chert of Western Australia. → Questioned!
- [**Lipid Biomarker**] **27** 亿年 Origin of oxygenic photosynthesis. → Questioned!



nature.com

The Advent of Oxygen-Evolving Photosynthesis Is One of the Central Events in the Development of Life on Earth



Aerobic Respiration: 38 ATP

Glucose + O_2 →Energy + CO_2 + H_2O

Anaerobic Respiration: 2 ATP

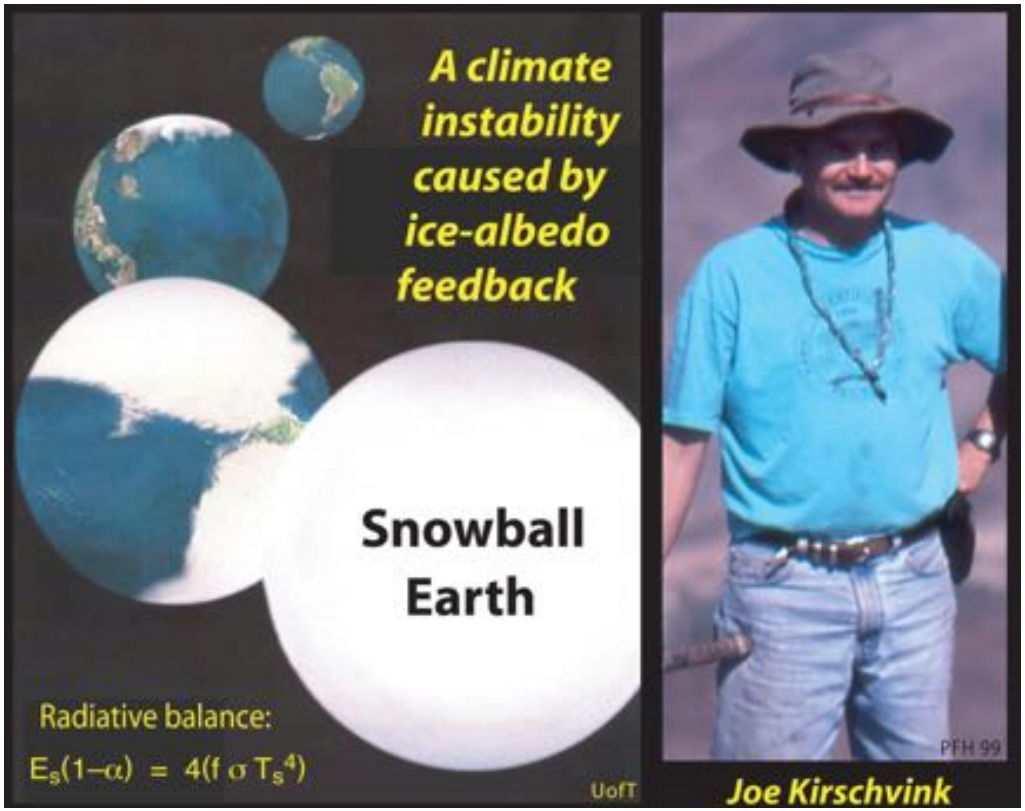
Glucose →Energy (ATP) + Ethanol + CO_2

Glucose →Energy (ATP) + Lactic acid

Needs More O_2!

Snowball Earth: Extreme Climate Before the Origin of Animal Life

Joe Kirschvink at the California Institute of Technology in Pasadena, USA, coined the name "snowball earth". He proposed three independent tests of his hypothesis: global synchroneity, ocean anoxia, and ultra-greenhouse aftermaths.



Cambrian Explosion (@540 Ma, Within 35-40 Million Years)

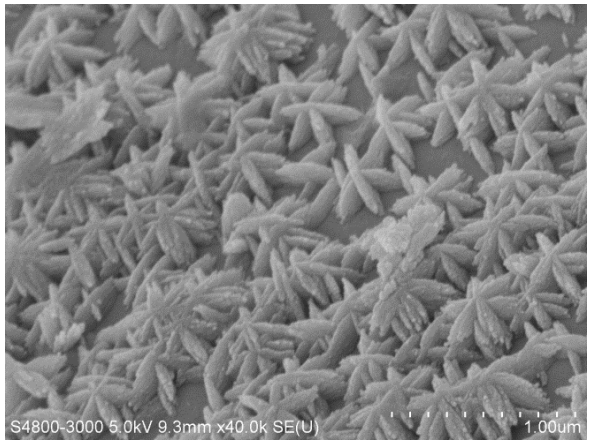
It appeared that in 35-40 million years, ancestors of all but two of living phyla came into being.

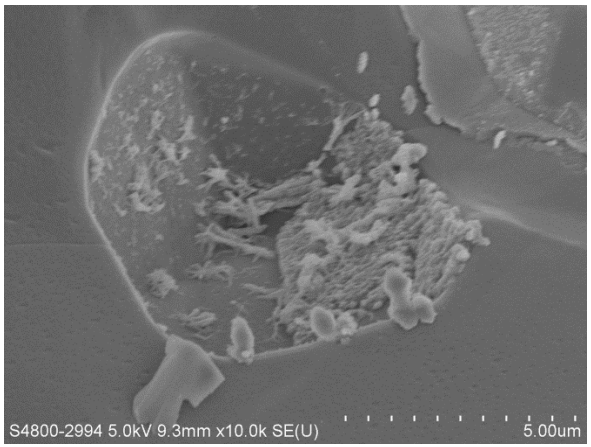
Trilobites (1) live among many species that are not normally preserved. A typical Cambrian outcrop might produce only trilobites, brachiopods (2), mollusks (3), and crinoids (4). That is a tiny fraction of the full Cambrian biota, better represented by the roster of the Burgess Shale Cambrian Konservat-Lagerstätten. That community includes sponges *Vauxia* (5), *Hazelia* (6), and *Eifellia* (7); brachipods *Nisusia* (2); priapulid worms *Ottoia* (8); trilobites *Olenoides* (1); other arthropods such as *Sidneyia* (9), *Leanchoilia* (10), *Marella* (11), *Canadaspis* (12), *Helmetia* (13), *Burgessia* (14), *Tegopelte* (15), *Naraoia* (16), *Waptia* (17), *Sanctacaris* (18), and *Odaraia* (19); lobopods *Hallucigenia* (20) and *Aysheaia* (21); mollusks *Scenella* (3); echinoderms *Echmatocrinus* (4); and chordates *Pikaia* (22); among other oddities, including *Haplophrentis* (23), *Opabinia* (24), *Dinomischus* (25), *Wiwaxia* (26), *Amiskwia* (27), and *Anomalocaris* (28). ©2002 by S.M. Gon III (composition & linework) & John Whorral (color rendering)

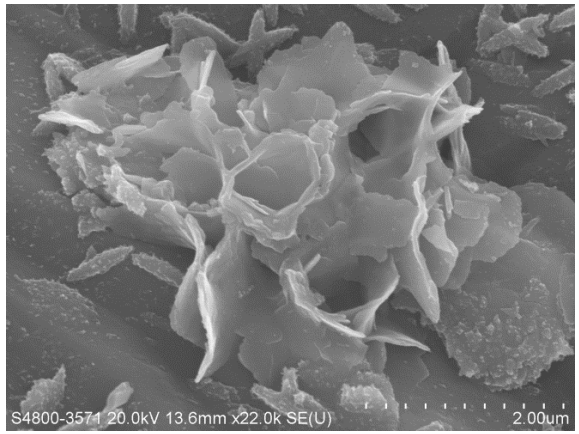
Opabinia: of Uncertain Taxonomic Group

Opabinia shows a segment body, but has ***five eyes (!)*** and a feeding appendage. No living animal is similar.

Earliest Sedimentary Rocks: Earliest Ocean, Earliest Life?



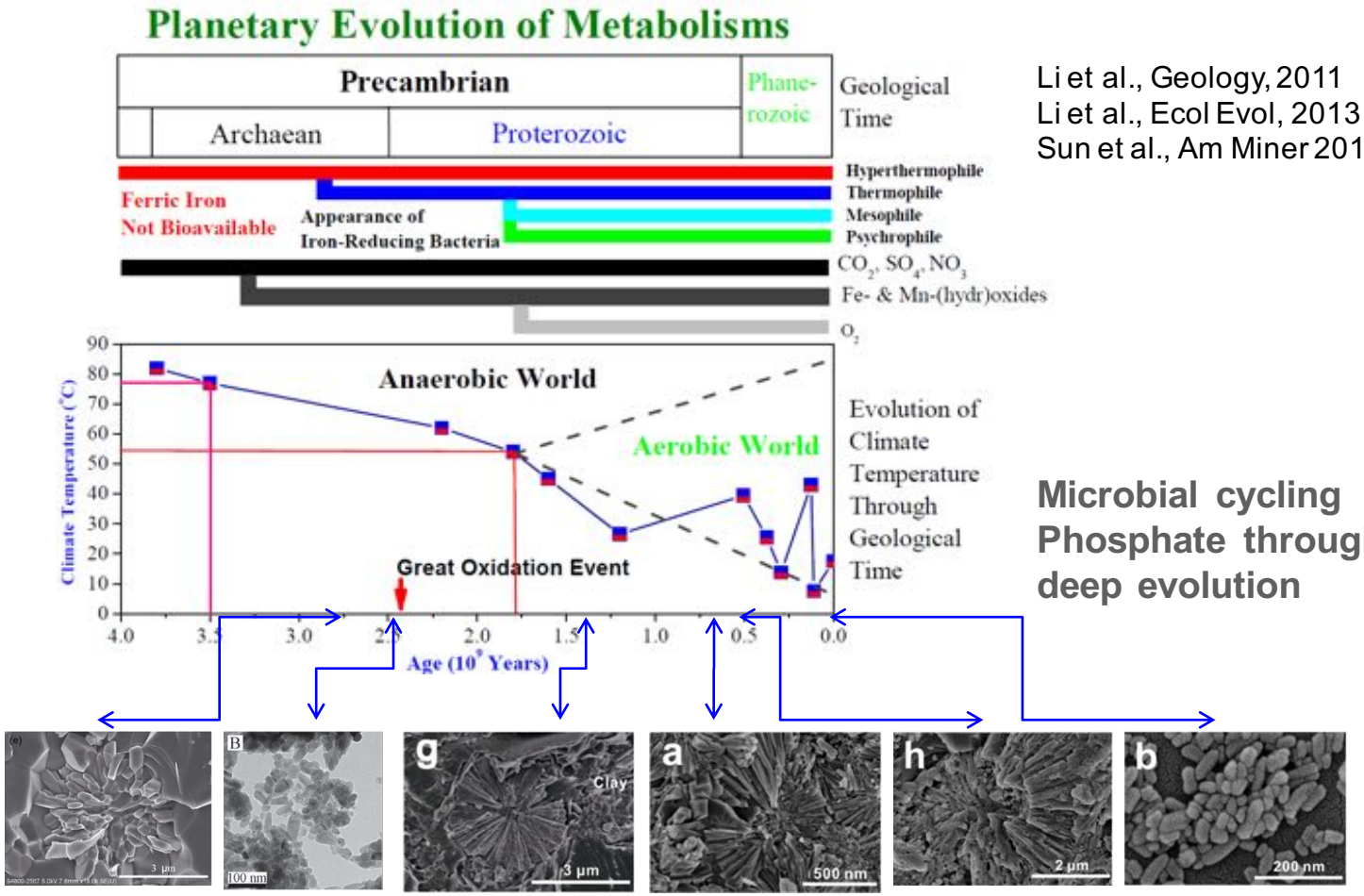




3.85 billion years old BIF from Isua, Greenland

Li et al., under preparation.

A Deep, Hot Biosphere Back in Deep Time



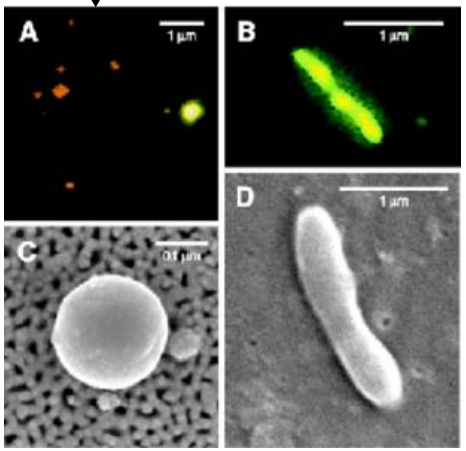
Li et al., Geology, 2011
Li et al., Ecol Evol, 2013
Sun et al., Am Miner 2014

Microbial cycling Phosphate through deep evolution

Deep Biosphere: When the Surface of the Planet Is No More Habitable

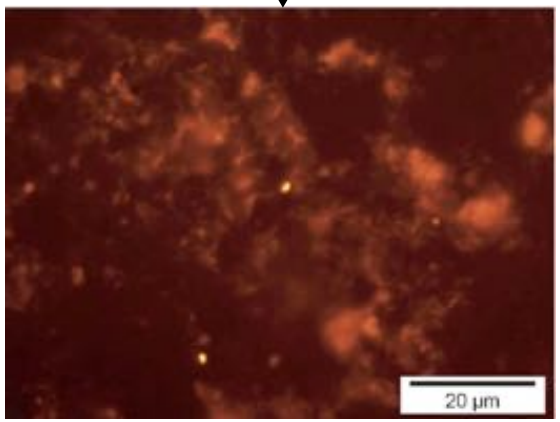
Currently Claimed Depths:

- 1.0 km in marine sediment.
- 2.8 km in continental rock.
- 3.6 km in Antarctic ice.



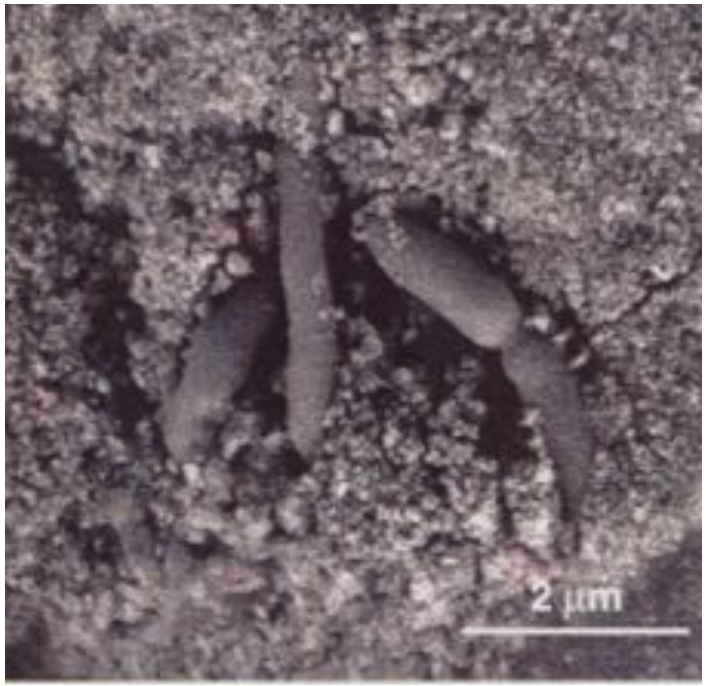
Karl et al. 1999, Science

Liu et al., 1997, Science

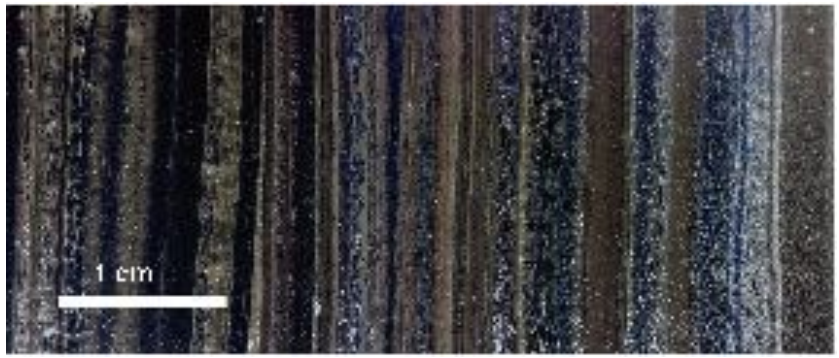


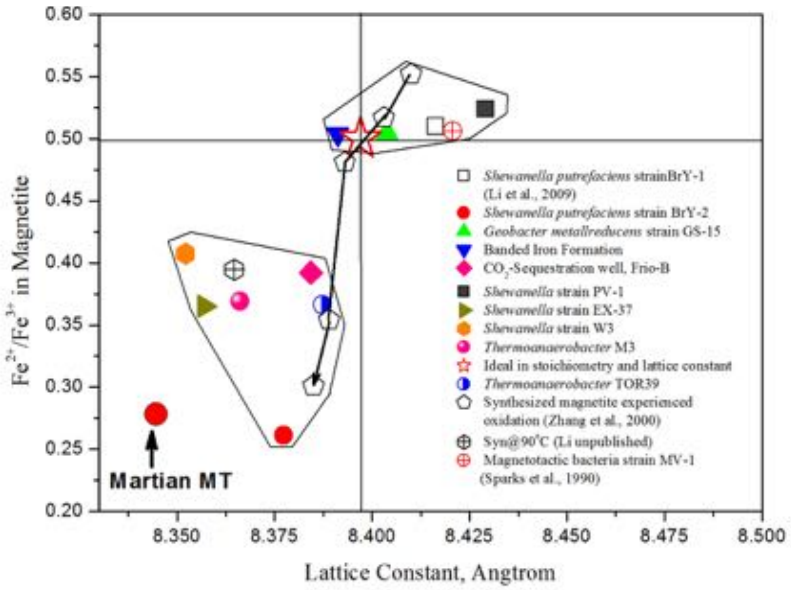
Teske, 2005, Trends Biol. (4 miles below the ocean surface)

Planetary Metabolism: Biological Precipitation of Iron Minerals During 3800-1800 Million Years



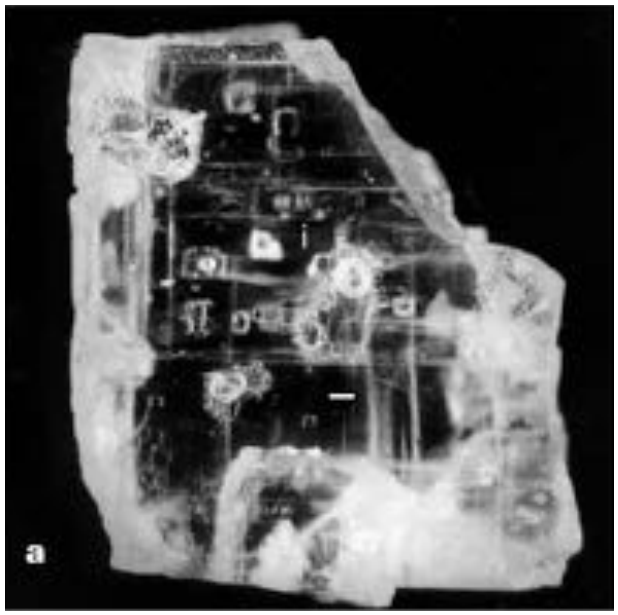
Thermoananaerobacter ethanolicus TOR39 (Phelps, unpublished data.





1. Liu et al., 1997, Science, 277. 2. Knauth, 2005, Paleos, 219; Robert and Chaussidon, 2006, Nature, 443.
3. Zhang et al., 1997, GCA, 61. 4. Canfield et al., 1998, Science, 396.
5. Li et al., EPSL, 2013, 2014, 2017.

Reincarnated Dormant Life in 250 Million-Year-Old Salt!

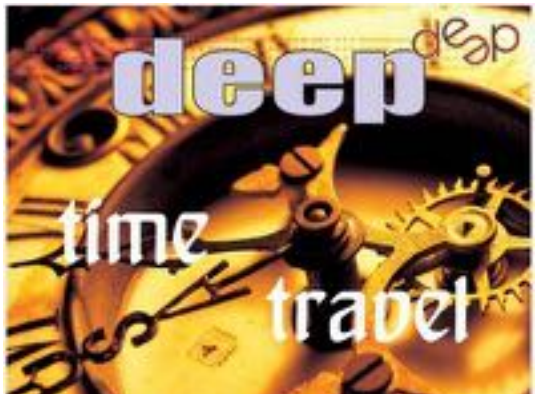


3.2×2.8×0.9 cm^3

Permian Salado Formation

(Vreeland et al., 2000, Nature)

This discovery expands dramatically the maximum proposed age for microbial survivability.



Stromatolites: the Planetary Records of Life From 3.5 to 2.1 Ga on Earth

Modern. Shark Bay, Australia

1.8 billion year old fossil stromatolites at Great Slave Lake, Canada

Long-Term Preservation of Evidence of Life: Prepare For Sample Return From Mars

- Search for a second origin of life (on Mars). Not a piece of bone, but a new GENETIC system.
- Bacteria in old bearing conglomerates at 60ºC, 3.5 km below the surface in South Africa (IPT NASA Astrobio Institut.)
- Bacteria 2.7 km below the surface (Liu et al., 1997)
- Bacteria in basalt 1.5 km below the surface in Washington living on carbon dioxide and hydrogen from weathering of basalt (80-160 million years) (Stevens and McKinley, 1995)
- Study of Martian analogs is very important in designing Martian rovers!

Martian Sample Return

Martian Analog

Microbial World Should Be Very Common In the Universe

Some of these stellar systems could have formed 5 billion years before the Earth. So why is the galaxy not crawling with self-designing mechanical or biological life forms?" ----Stephen Hawking

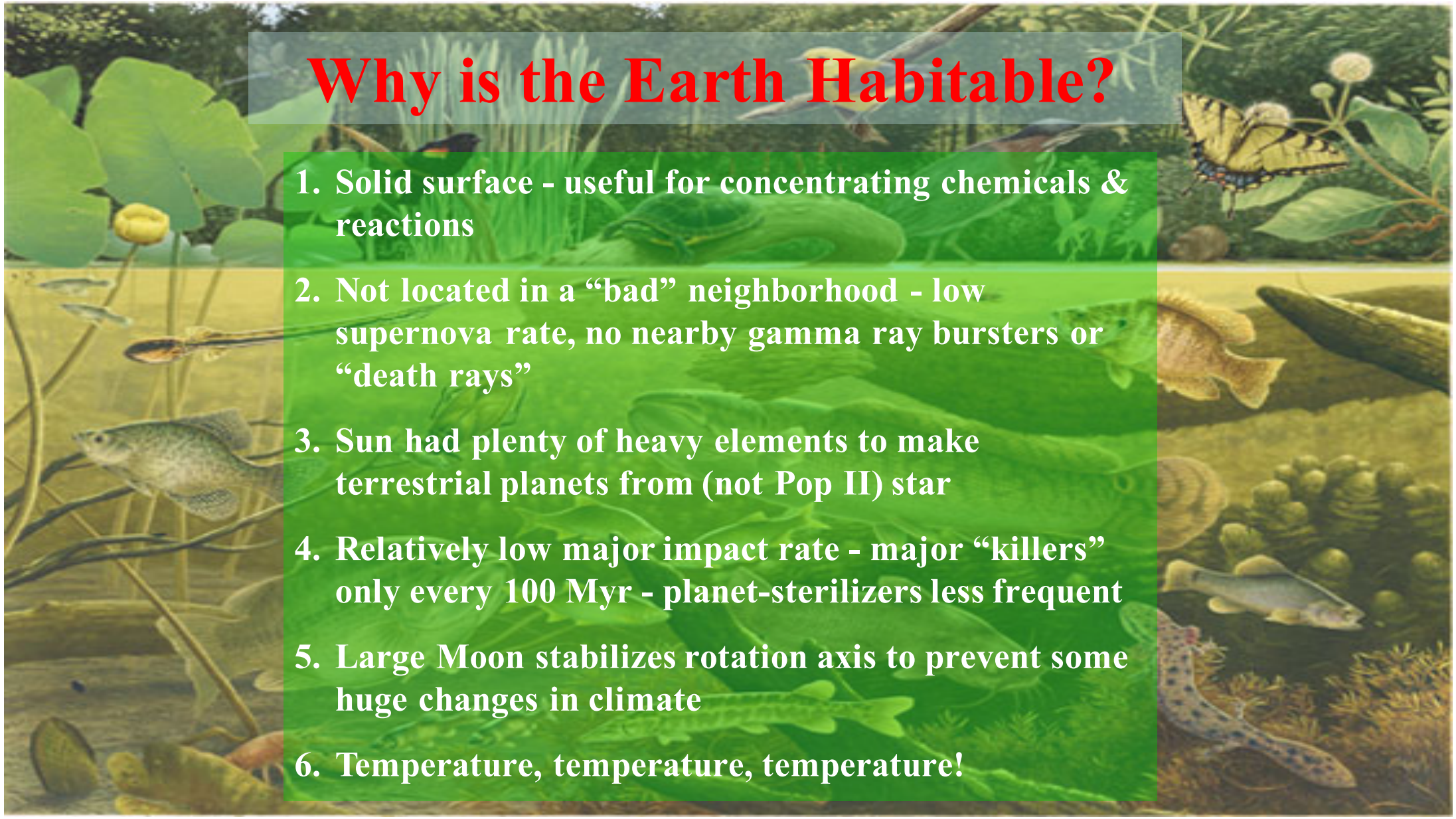
Agree! – Peter Ward & Donald Brownlee (Rare Earth: why complex life is uncommon in the universe, 2000)

The Deep Biosphere: Lessons for Planetary Exploration

- **Life needs a source of energy, carbon and some other elements.**
- **Liquid water is the quintessential requirement for life.**
- **Subsurface life: the current upper limit for demonstrated growth is 113°C (ca. 5 km in the crust).**

➢ **The longest demonstrated dormancy period is 25 million years for bacteria encased in amber (Cano and Borucki, 1994).**

➢ **Theoretical arguments suggest that dormancy may be possible for more than 100 million years and in the case of radiation resistant strains, up to 900 million years.**

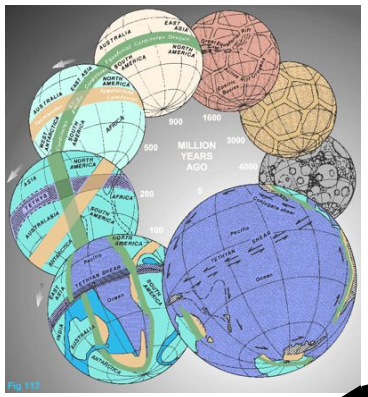


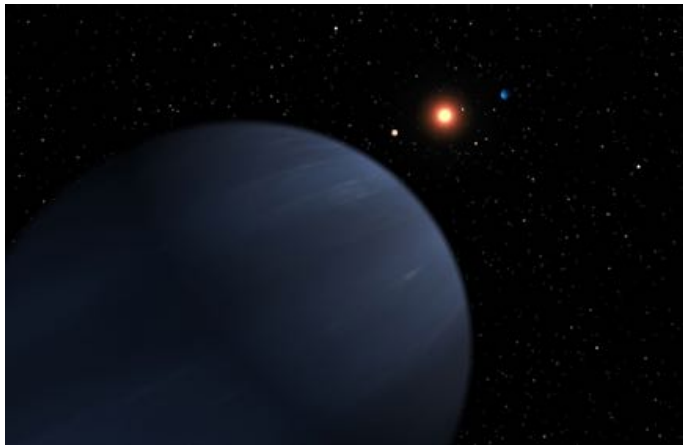
Why is the Earth Habitable?

1. Solid surface - useful for concentrating chemicals & reactions
2. Not located in a "bad" neighborhood - low supernova rate, no nearby gamma ray bursters or "death rays"
3. Sun had plenty of heavy elements to make terrestrial planets from (not Pop II) star
4. Relatively low major impact rate - major "killers" only every 100 Myr - planet-sterilizers less frequent
5. Large Moon stabilizes rotation axis to prevent some huge changes in climate
6. Temperature, temperature, temperature!

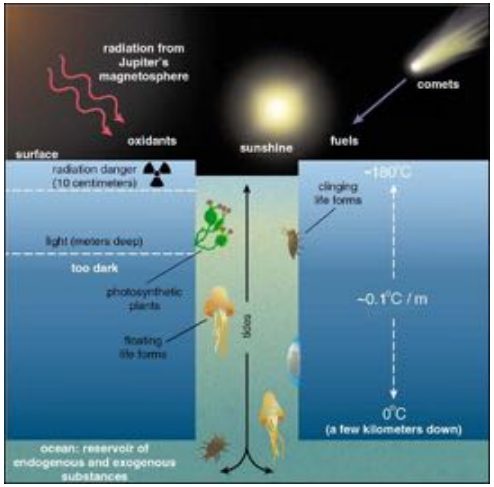
Modeling Conditions for Extraterrestrial Life

Evolution and Longevity of Earth ecosystem





Habitability of exoplanet



Life in the Ocean of Europa

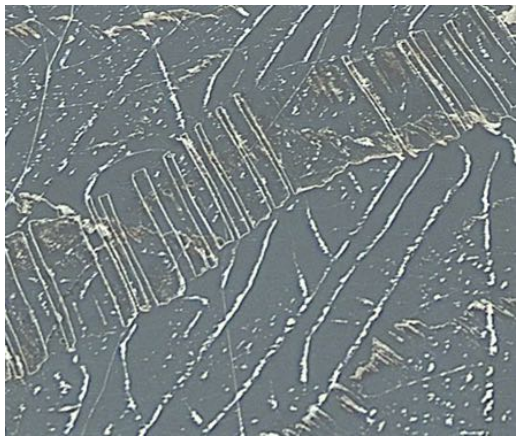
Extraterrestrial civilization

Earth & Mars as Habitable Planet (Li's Astrobiology Group)

- The precipitation of carbonate facilitates the rapid sequestration of atmospheric CO_2 and cooling of Earth (Hao & Li, *Frontiers in Earth Sciences*, 2018).
- Oxygen-free biochemistry for a hydrocarbon world (Lv, Norman & Li, *Astrobiology*, 2017).
- Qaidam Basin as the largest terrestrial Martian analog (Angles & Li, *JGR-Planets*, 2017).
- Ongoing projects: Archean ecology (Lv); Martian analog (Cheng, Boppart); Gray hematite on Mars (Ding & Qiu); Mineral Biosignature in carbonates from brine lake (Sun); Inverted Channels on Mars and Tibetan Plateau.

Earth & Mars as Habitable Planets (Li's Astrobiology Group)

- Qaidam Basin As a Martian Analog in its climate, material, surface structure and life at dry-edge.



JAROSITE? | Cryoconite life?

RINGS

Acknowledgements

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Astrobiology: an integrative approach on "origin & evolution of life in the universe"

中国科学院比较行星学卓越创新中心