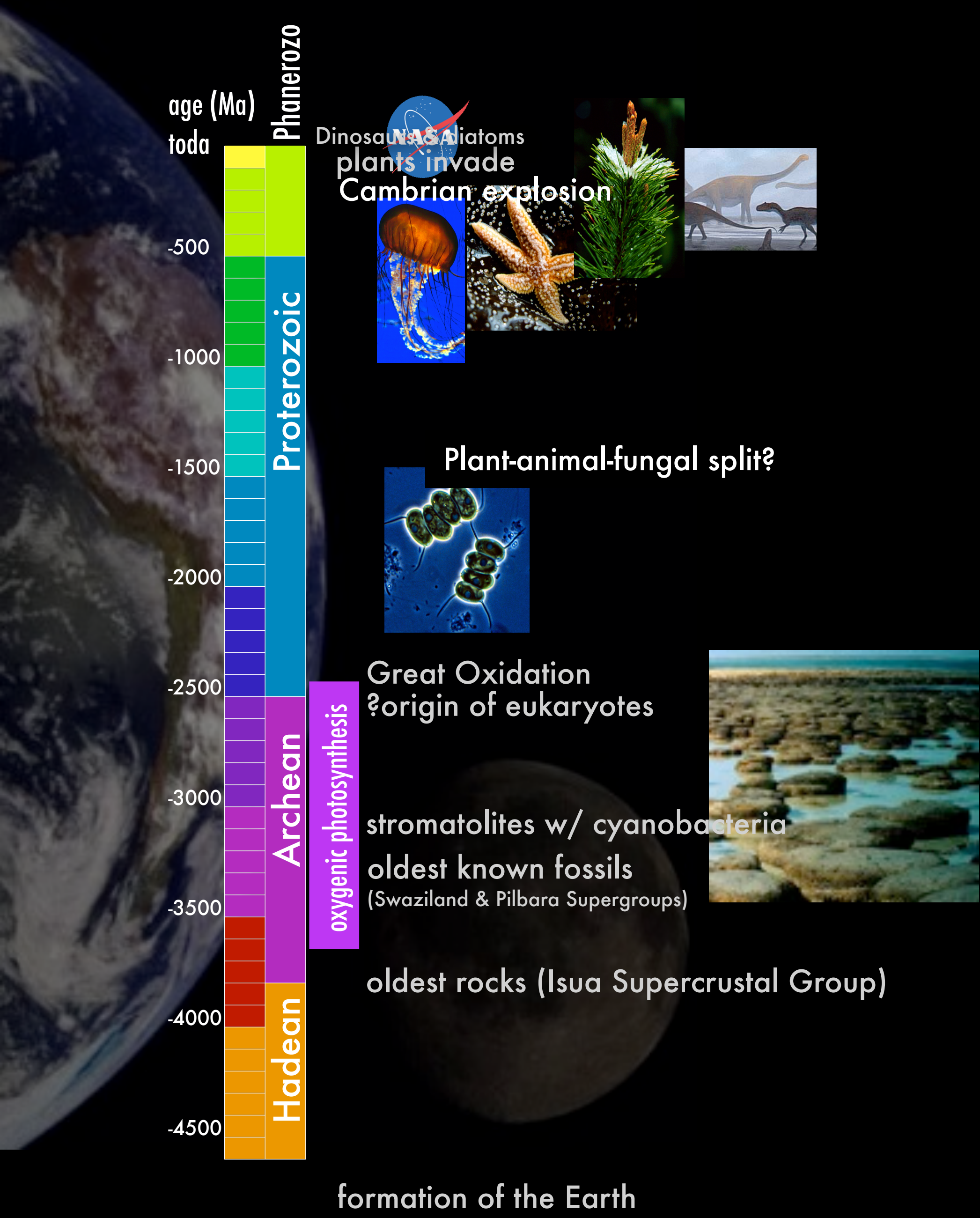
Yesterday: Great moments in evolutionary history



Today:
Life in Extreme Environments

What is Astrobiology?

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

Introduction

- *What is an extremophile?*
- *Why study them?*
- *Environmental extremes*
- *How do they do it?*
- *Examples of extreme ecosystems*
- *Space: new categories of extreme environments*

What is an **extremophile**?

“extremus”, the superlative of exter,
being on the outside

“extremus”, the superlative of exter, being on the outside

plus

“extremus”, the superlative of exter, being on the outside

plus

“philos”, love

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Extremophile

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Extremophile

Coined by Bob MacElroy, NASA Ames Research Center.

Macelroy (1974) Some comments on the evolution of extremophiles. Biosystems 6:74-75.

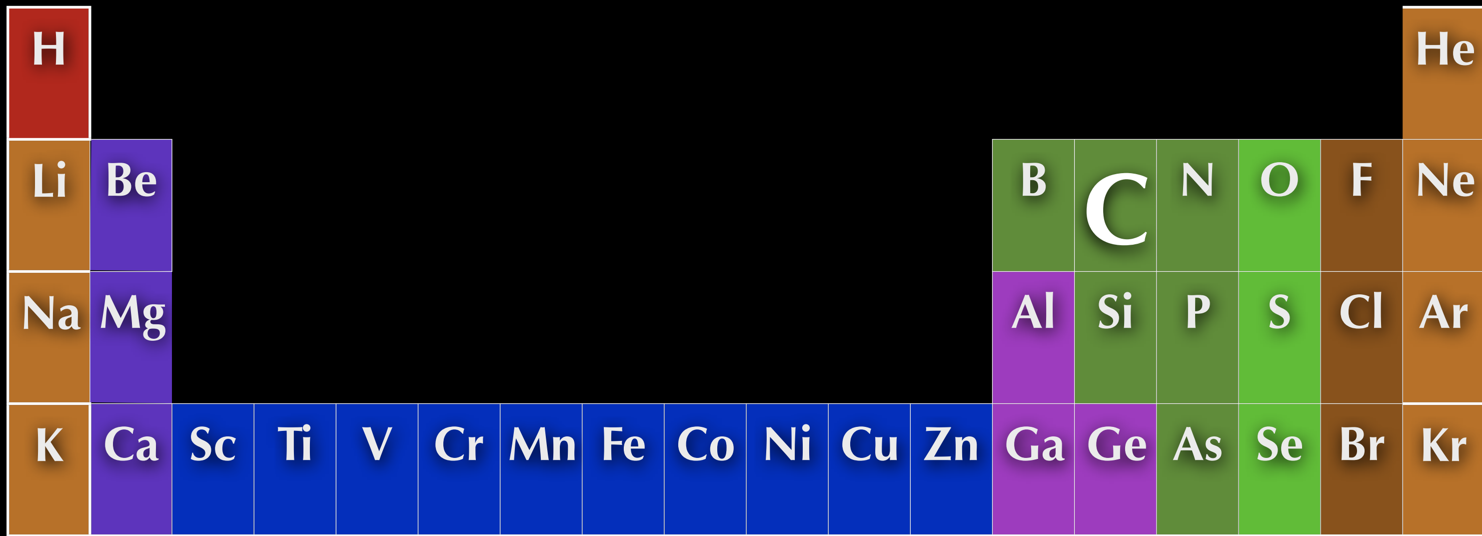
Background: At the time, MacElroy was the biochemist in the Biological Adaptation Branch at NASA Ames. He was interested in life in the atmosphere of Jupiter and Mars, and thus was looking primarily at thermophiles. The ones he collected in Yellowstone turned out to be bacilli. He wondered could tRNA survive at 92-98°C when it should melt long before that temperature? He said it was extremely common to combine Greek and Latin words in fact, the Greeks and Romans did it.

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



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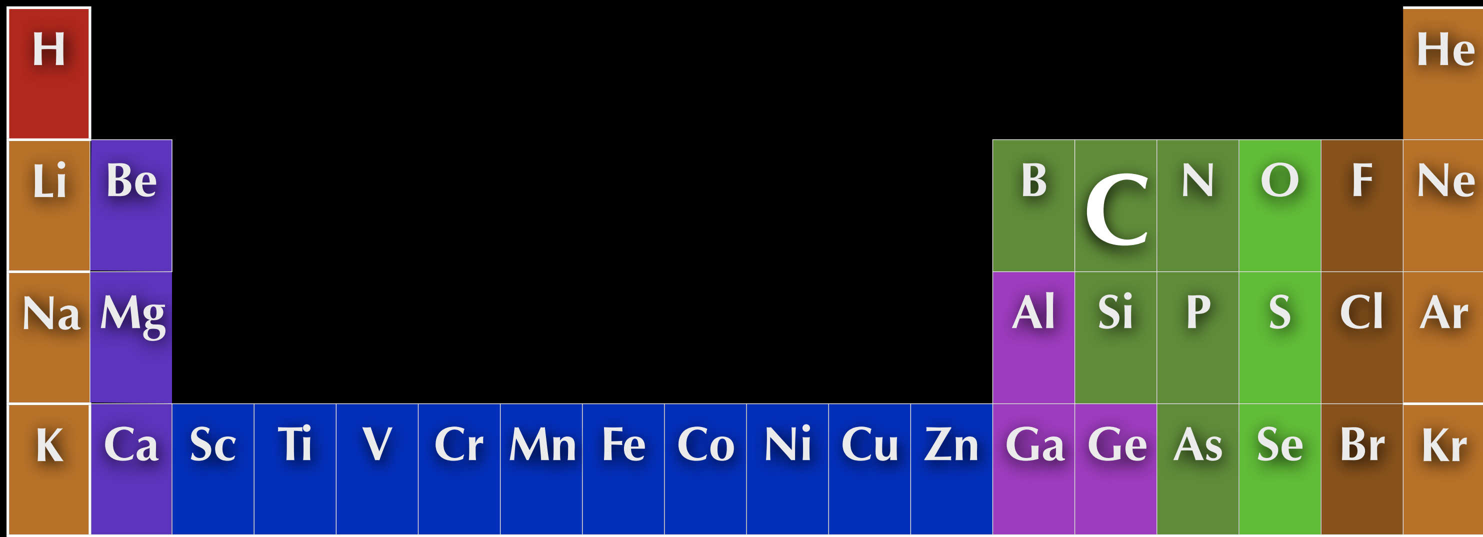

Why carbon?

Why are there limits to life?

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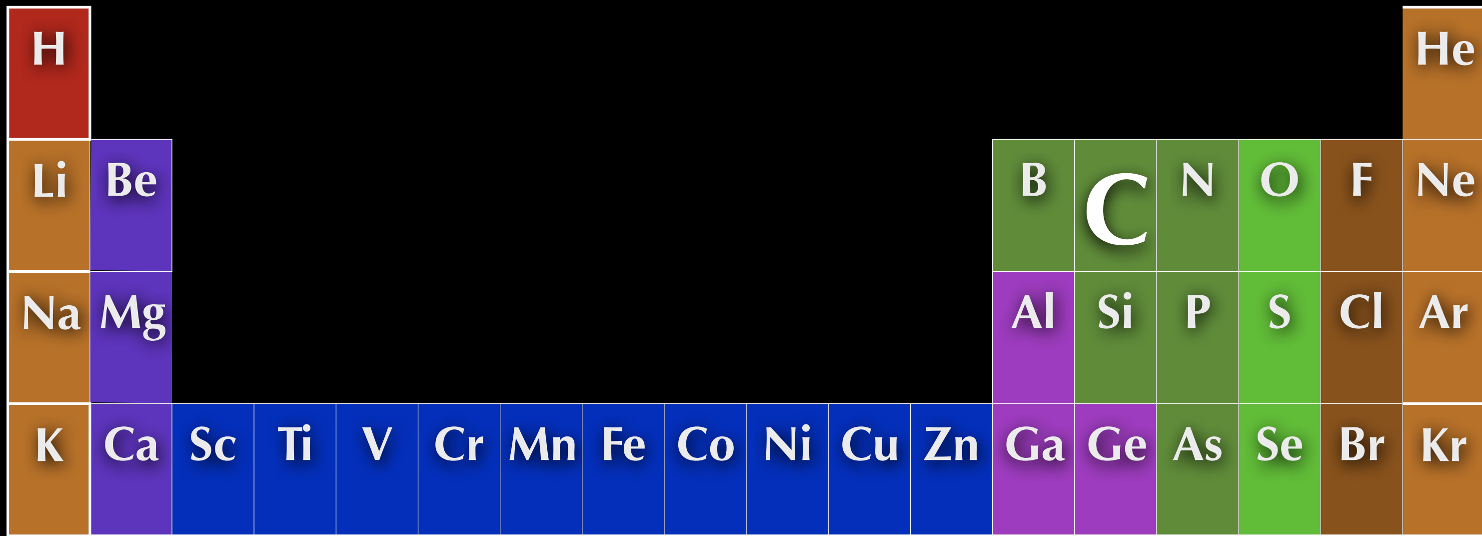

Why carbon?

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

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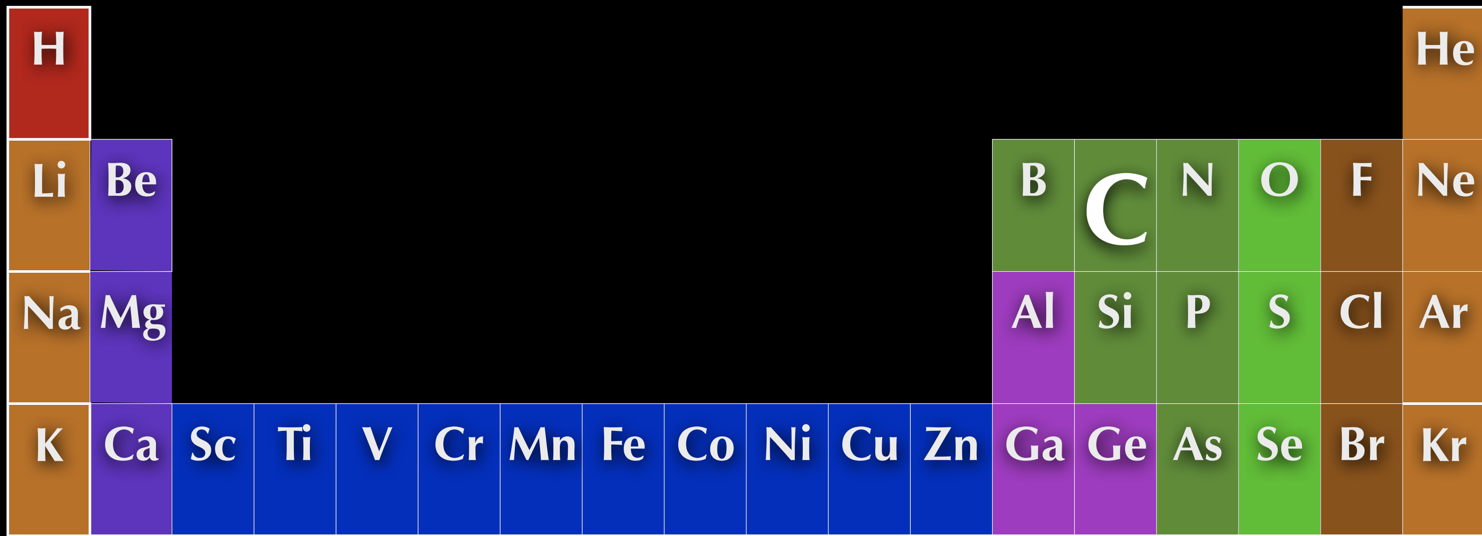

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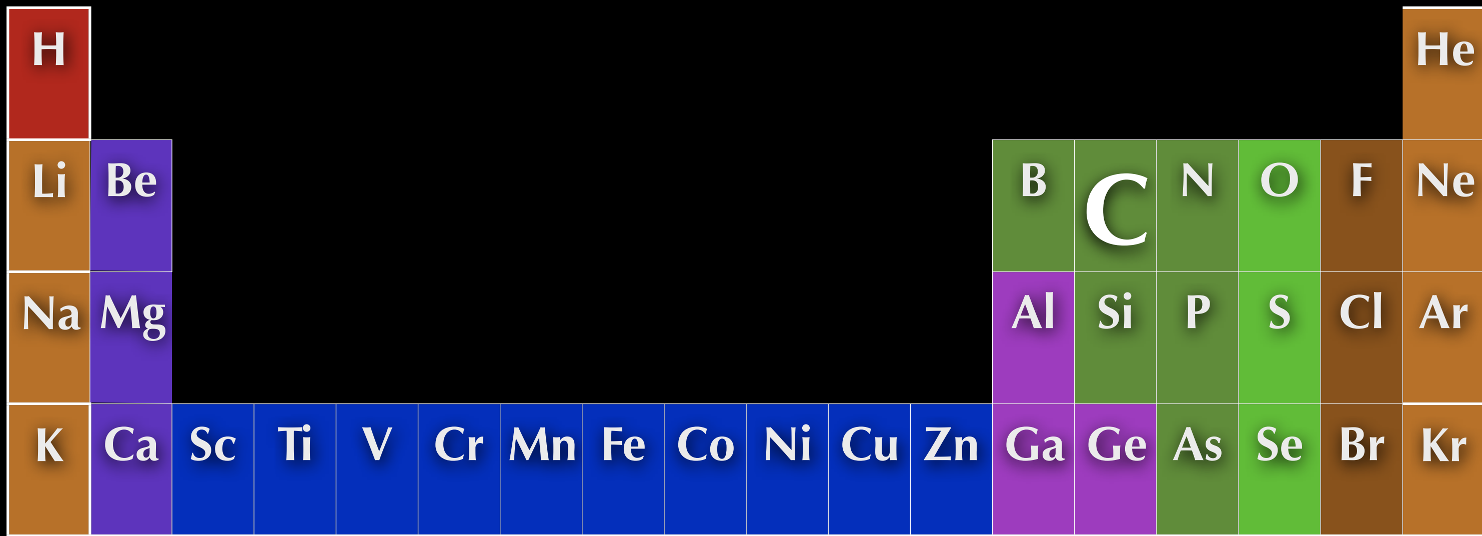

Why carbon?

- 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 study extremophiles?

- Food preservation.
- Basic research; model organisms for basic research
- Biological warfare.
- Biotech potential.
- Future use in space.
- Biodiversity on Earth. Archaea. Origin of life?
- Mechanisms of survival: divergence or convergence? Apparent convergence by LGT?
- Limits for life in the universe.

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Our only field site so far

Extremophiles

give the minimum envelope for life, as do

bizarre niches

Extremophiles

give the minimum envelope for life, as do

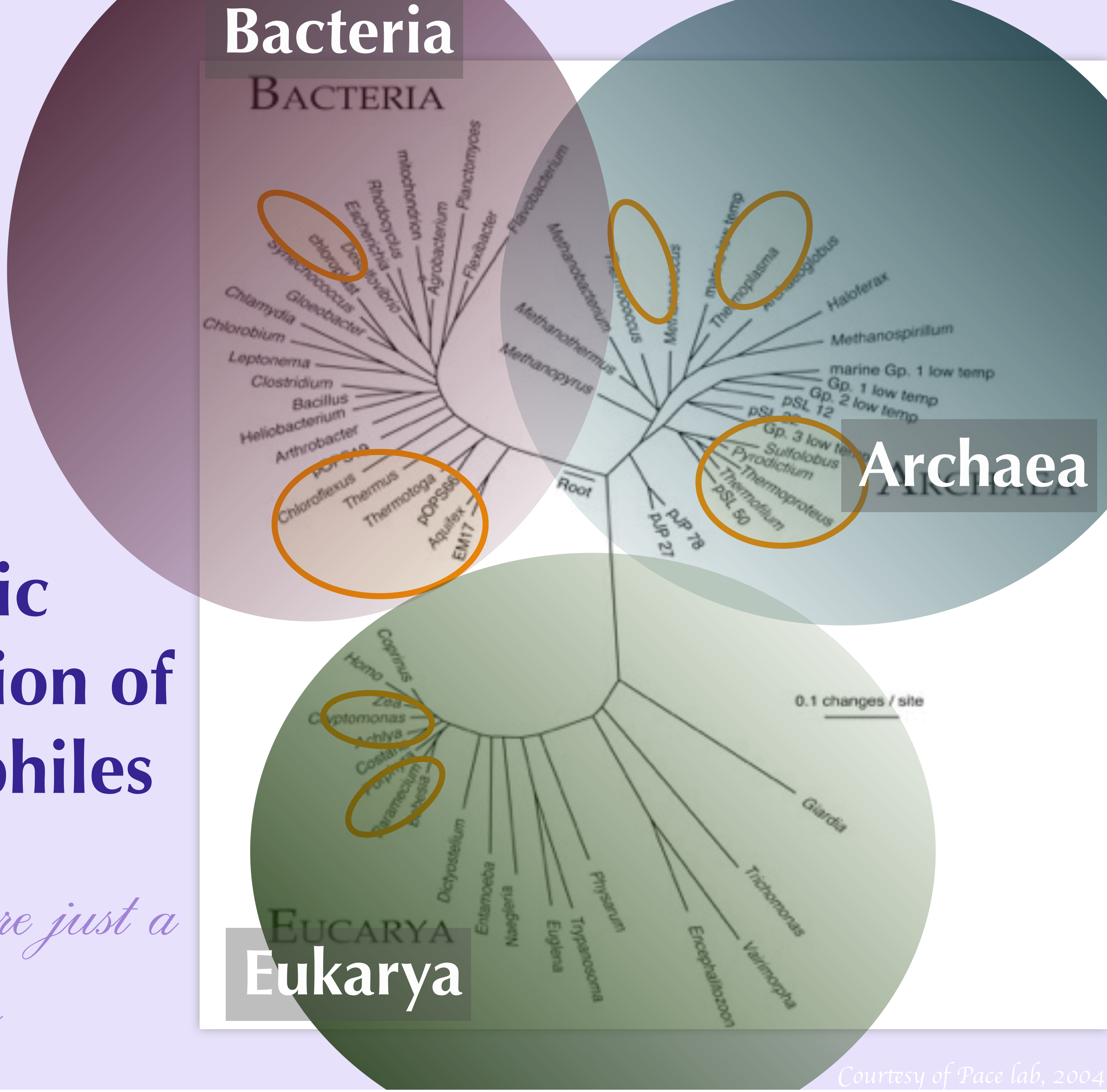
bizarre niches

Extremophiles & Life Elsewhere

- Richard Proctor. 1870. Other Worlds Than Ours. Possibly first to connect study of life in extreme environments and life on other planets.
- "If we range over the earth, from the arctic regions to the torrid zone, we find that none of the peculiarities which mark the several regions of our globe suffice to banish life from its surface." (ch. 1)

Examples of

extremophiles



Courtesy of Pace lab, 2004

Taxonomic Distribution of Extremophiles

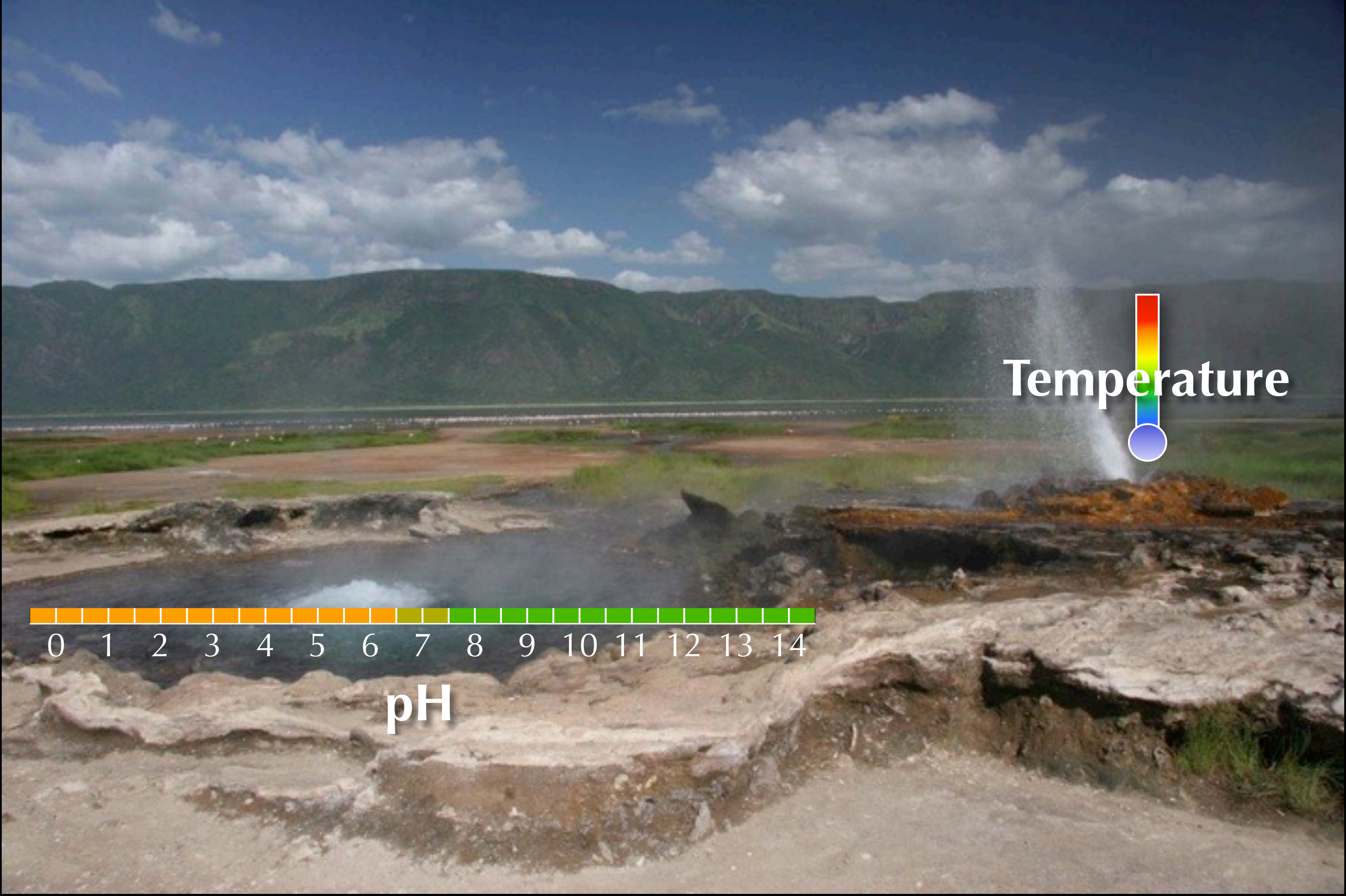
...but these are just a few examples

Examples of

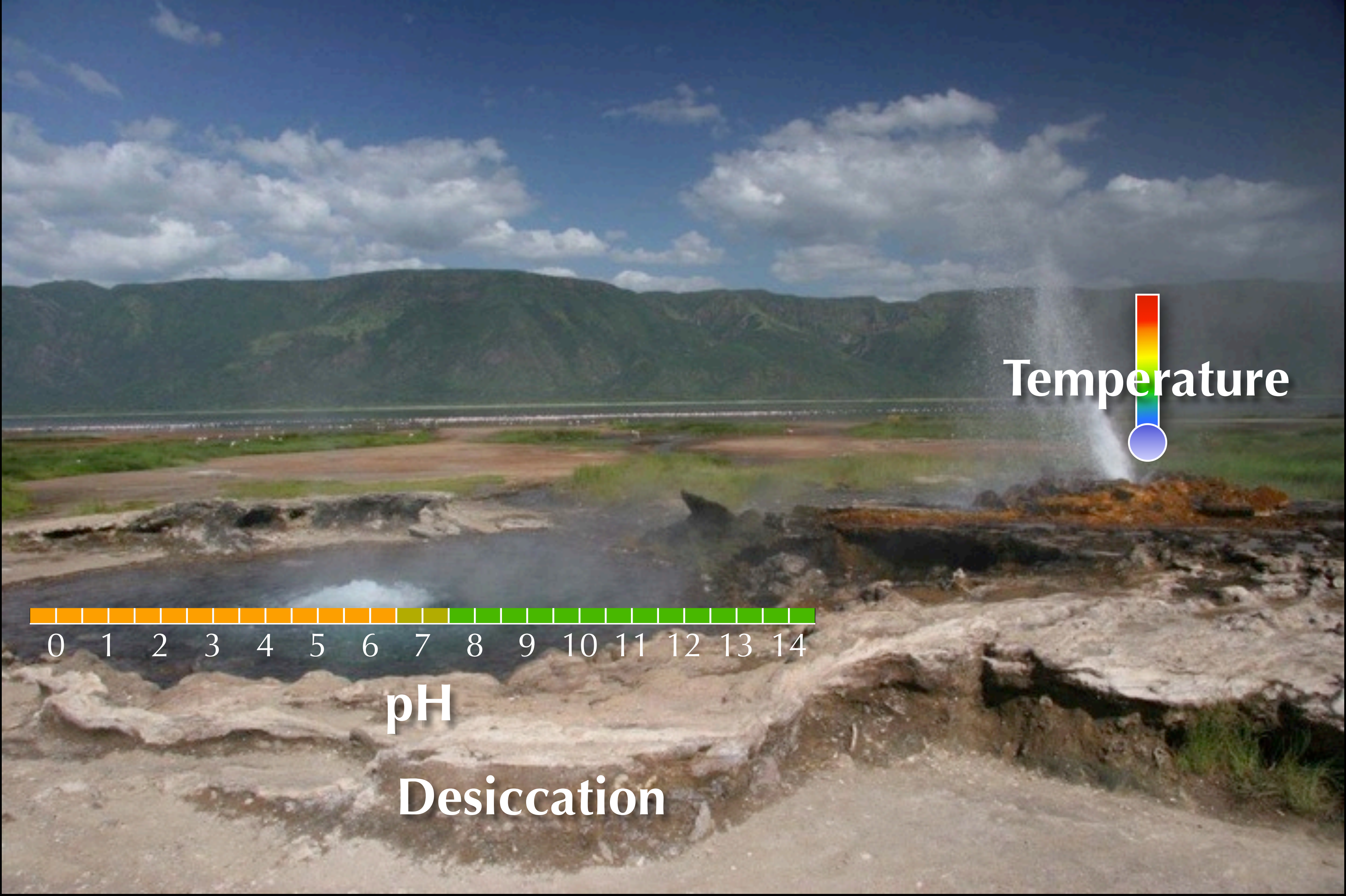
environmental extremes

Environmental extremes

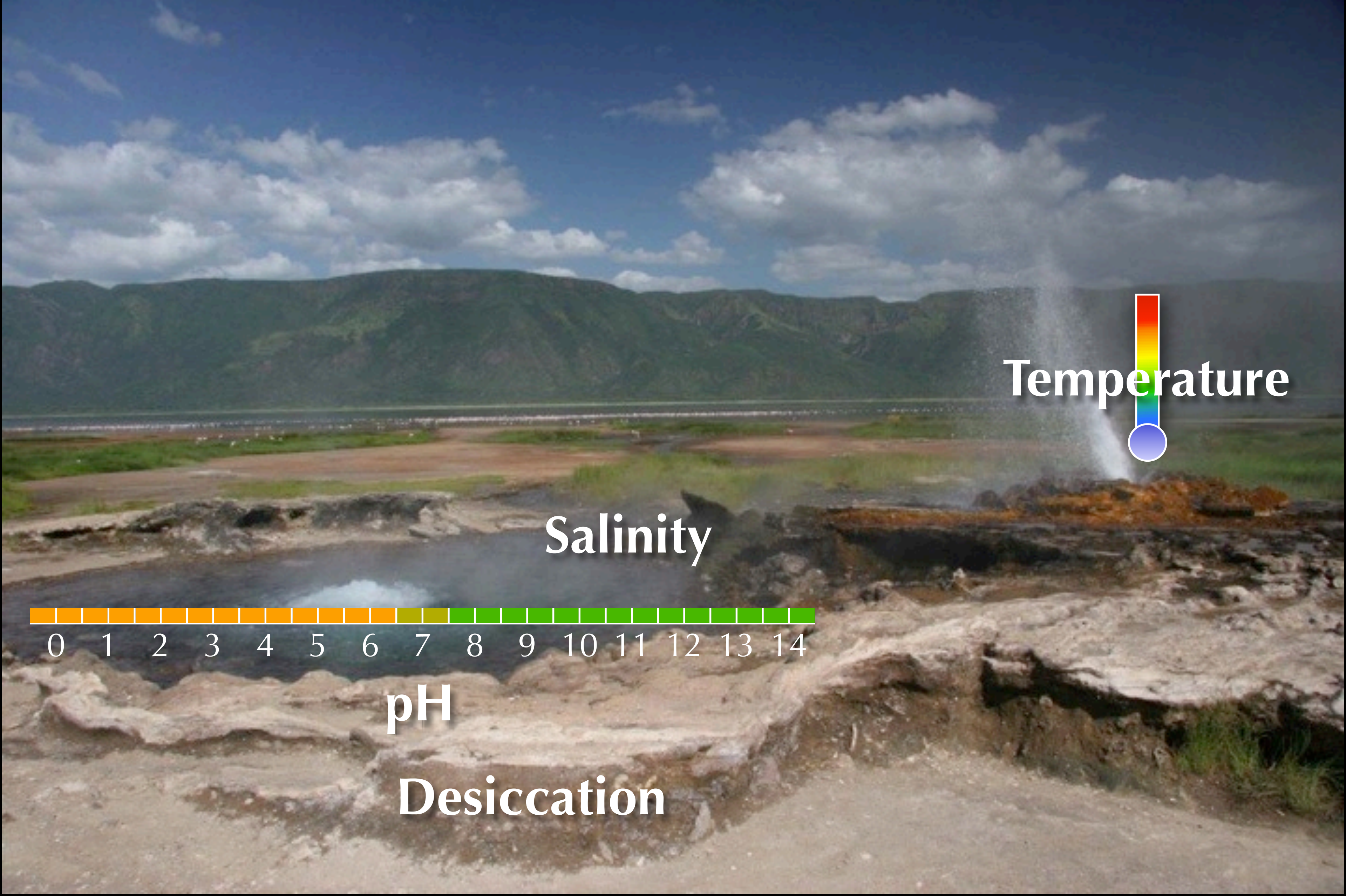
Environmental extremes



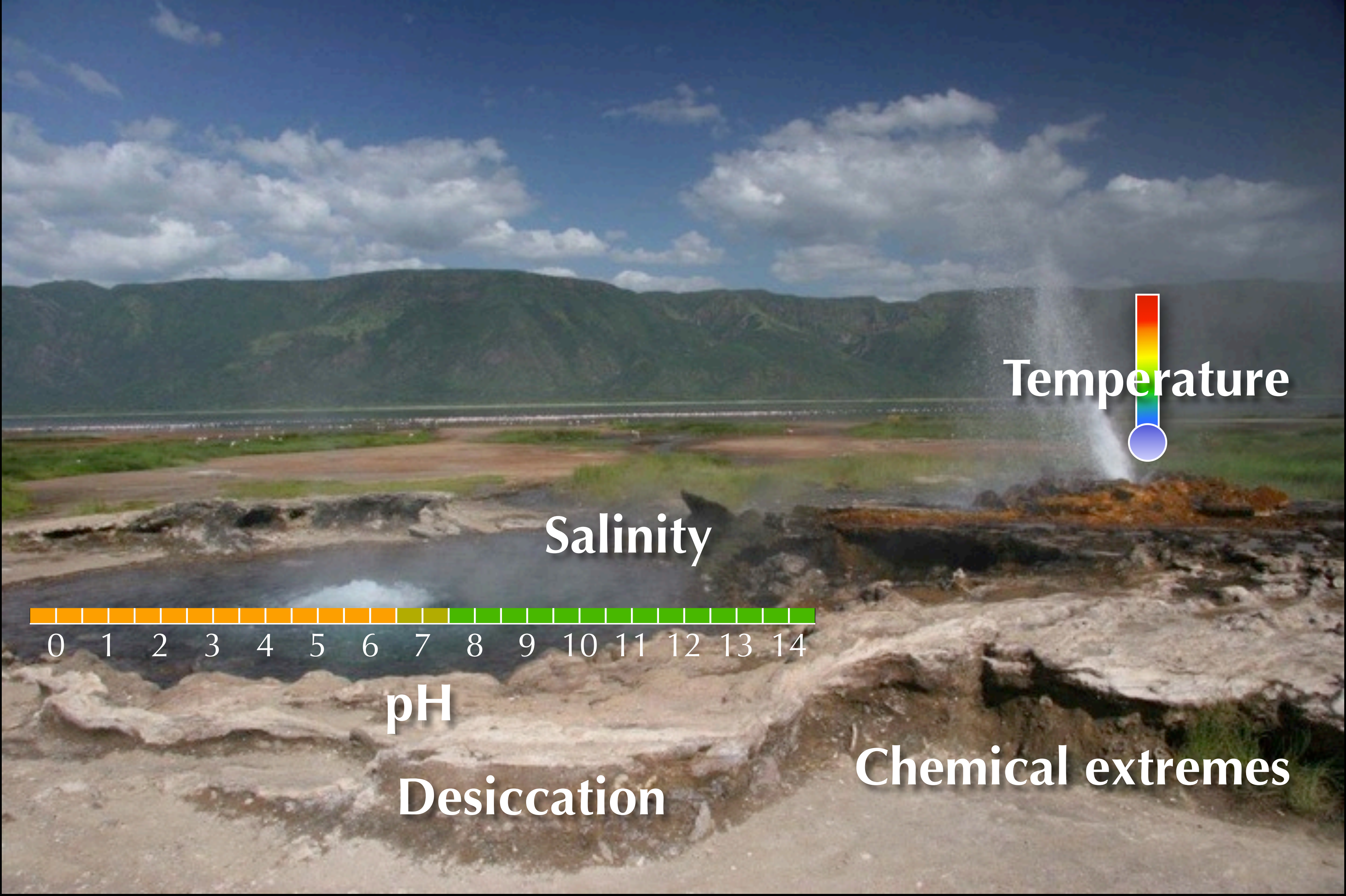
Environmental extremes



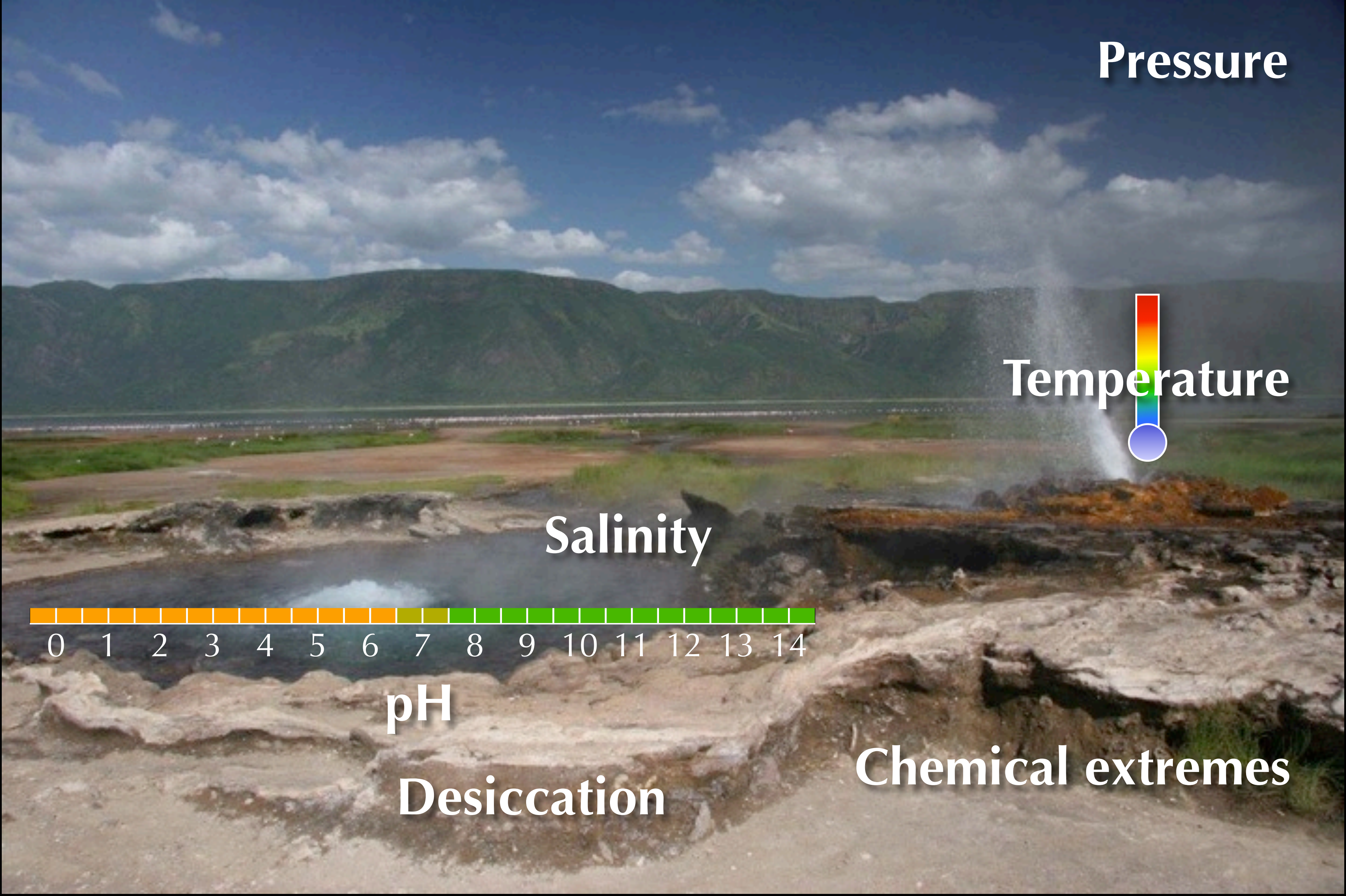
Environmental extremes



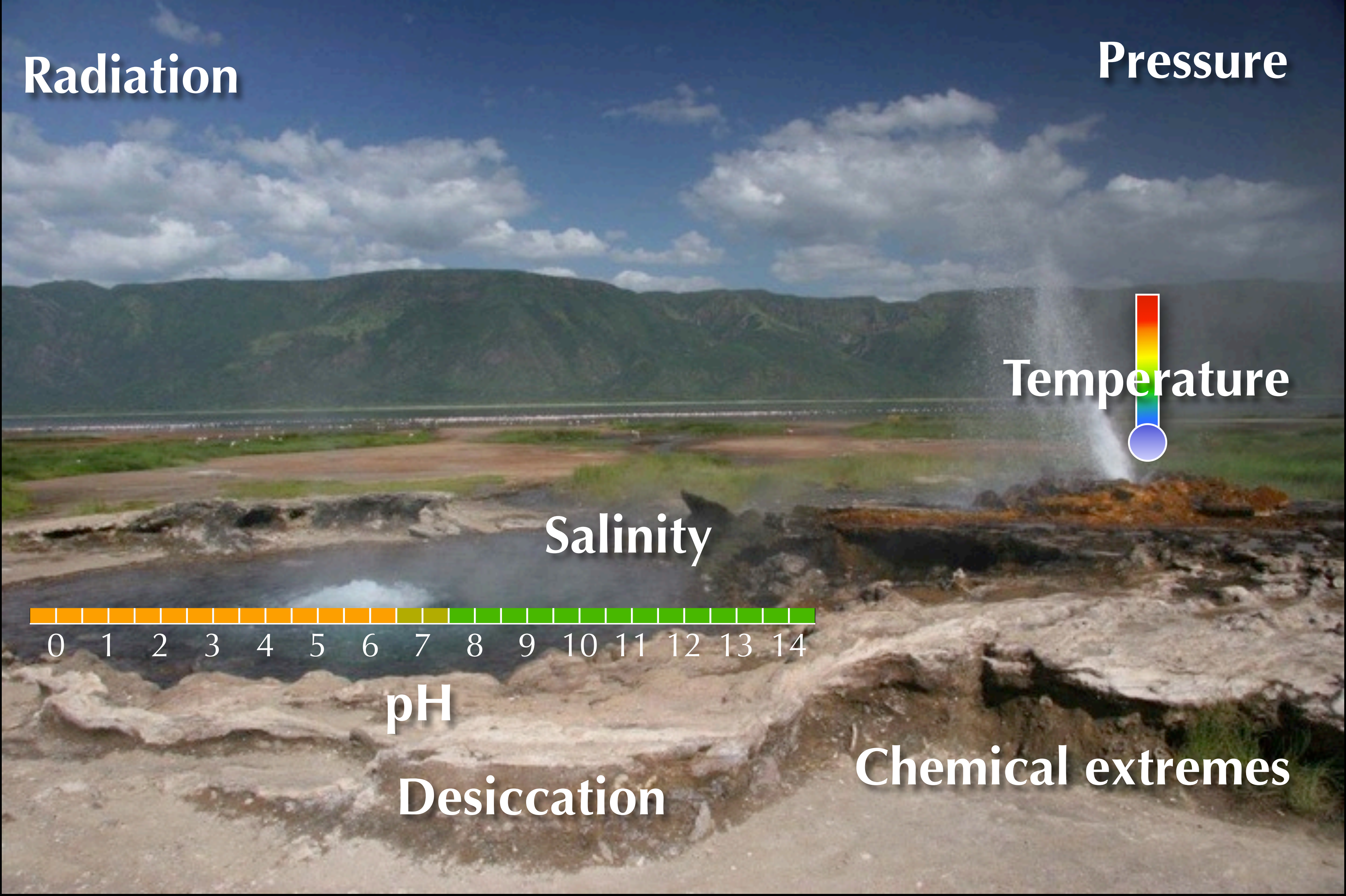
Environmental extremes



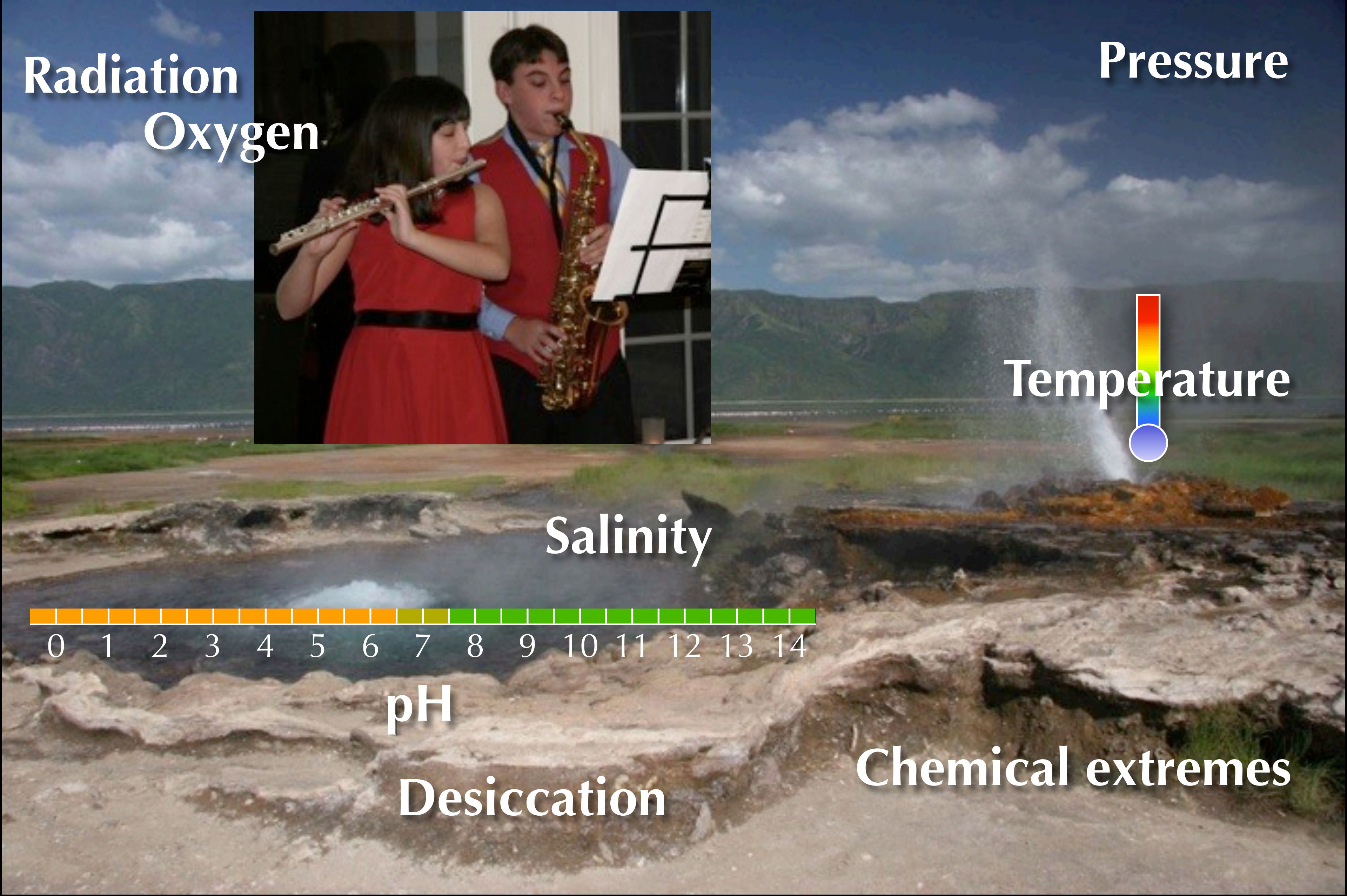
Environmental extremes



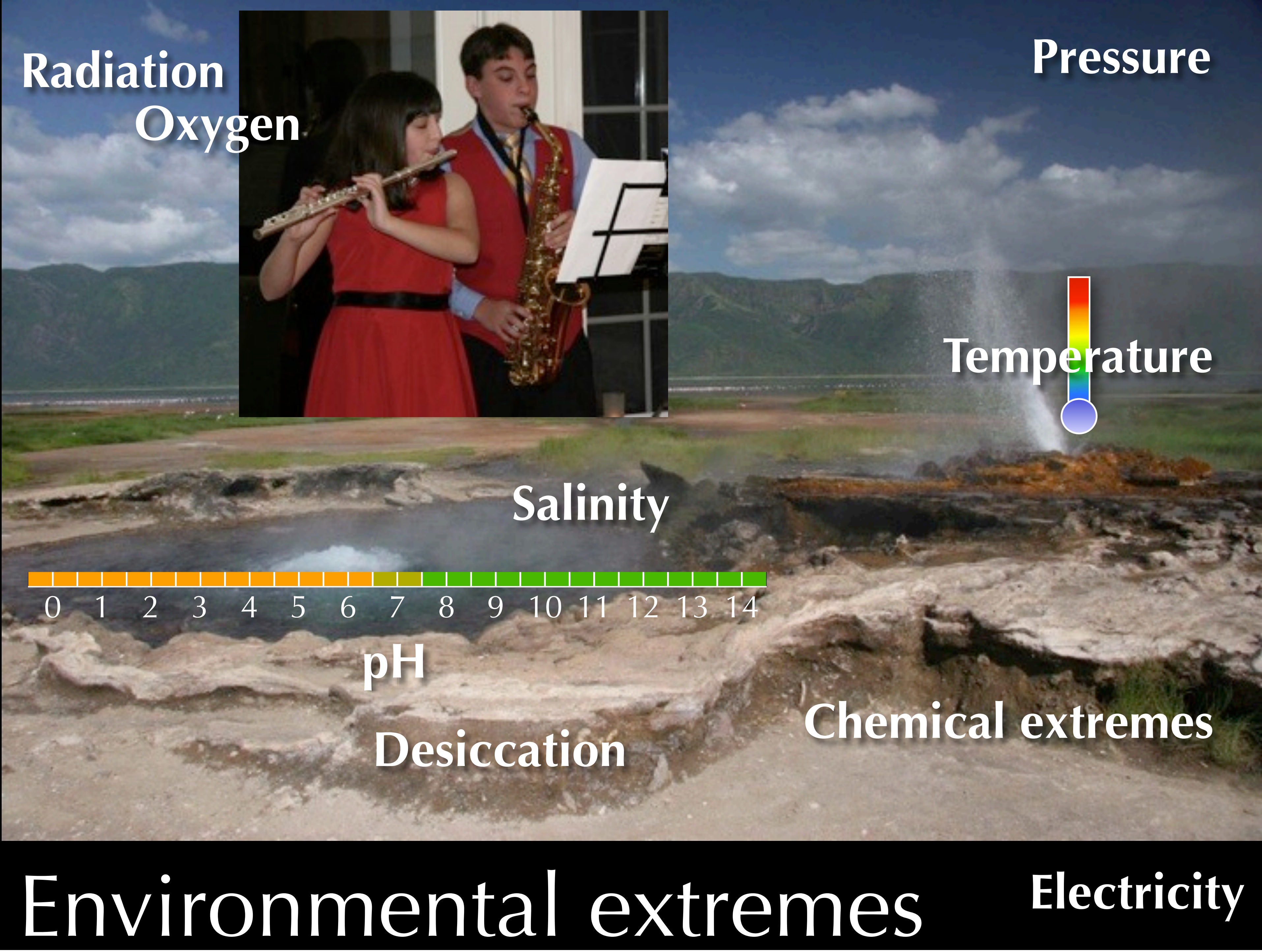
Environmental extremes



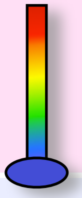
Environmental extremes

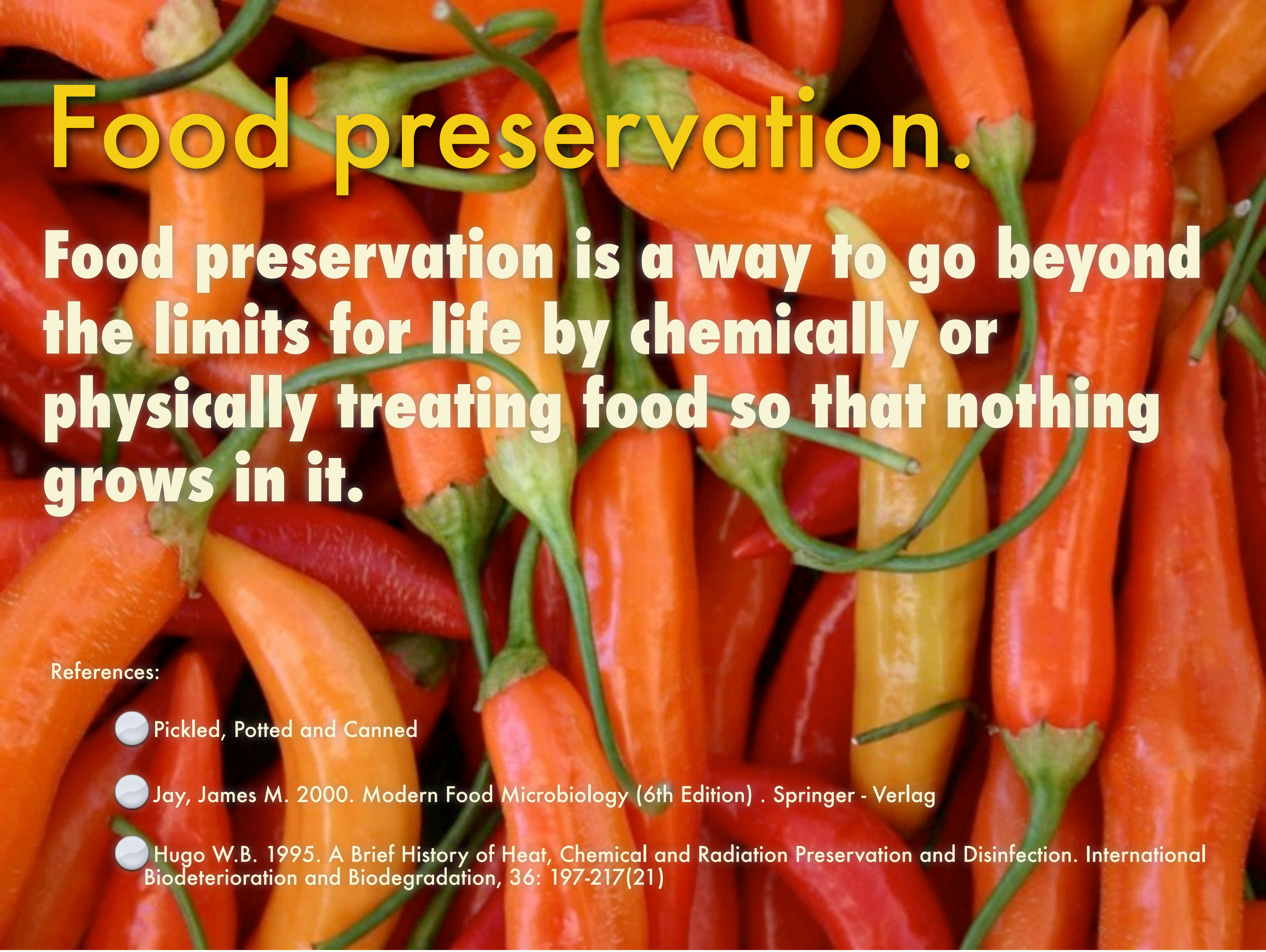


Environmental extremes


Radiation
Oxygen
Pressure
Temperature
Salinity
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
pH
Desiccation
Chemical extremes
Environmental extremes
Electricity

Categories of extremophiles

Environment	Type	Definition	Examples
Temperature 	hyperthermophile thermophile mesophile psychrophile	growth >80°C growth 60-80°C growth 15-60°C growth <15°C	*Pyrolobus fumarii -113°; strain 121* *Synechococcus lividis* humans *Psychrobacter, insects*
Radiation			*D. radiodurans*
Pressure	barophile piezophile	Weight loving Pressure loving	 *Shewanella* viable at 1600 MPa
Desiccation	xerophile	Cryptobiotic; anhydrobiotic	*Lyngbya, tun state of tardigrades*
Salinity	halophile	Salt loving (2-5 M NaCl)	*Haloarcula, Dunaliella* *Spirulina, Bacillus firmus*
pH	alkaliophile acidophile	pH >9 Low pH loving	*Spirulina, Bacillus firmus* OF4 (10.5); 12.8? *Cyanidium, Ferroplasma*
Oxygen	anaerobe aerophile	Cannot tolerate O_2	*Methanococcus jannaschii* *Homo sapiens*
Chemical		high CO_2, arsenic, mercury	*Cyanidium caldarium (pure CO_2)*
Vacuum			tardigrades
Electricity			



Food preservation.

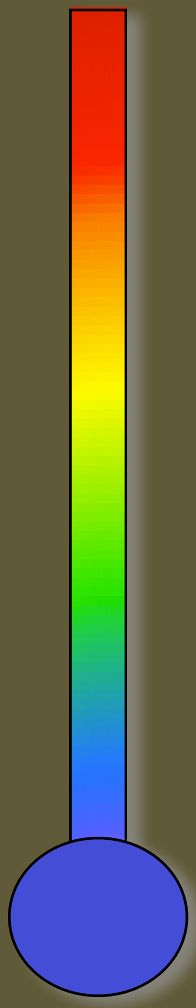
Food preservation is a way to go beyond the limits for life by chemically or physically treating food so that nothing grows in it.

References:

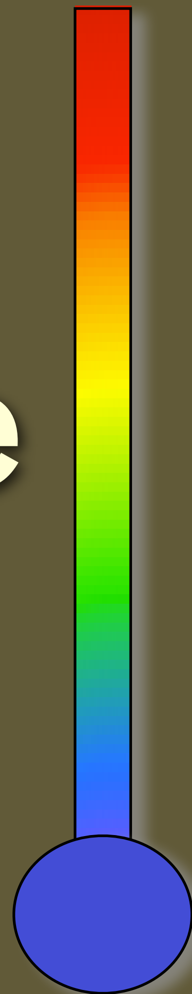
- Pickled, Potted and Canned
- Jay, James M. 2000. Modern Food Microbiology (6th Edition) . Springer - Verlag
- Hugo W.B. 1995. A Brief History of Heat, Chemical and Radiation Preservation and Disinfection. International Biodeterioration and Biodegradation, 36: 197-217(21)

Categories of food preservation

Environment	Method	Effect on microbes
Temperature	Pasteurization and appertization; cooking Refrigeration Freezing	Delivery of sufficient heat to inactivate targeted microbes to the desired extent Retard growth Retard growth and reduce water activity
Radiation	Food irradiation	Treatment with ionizing radiation. Destroy biomolecules
Pressure	Pascalization	Pressure inactivation of vegetative bacteria, yeasts and molds
Desiccation	Drying, curing	Reduction in water activity sufficient to delay or prevent growth
Salinity	Salting, brining	High osmotic pressure, low water activity
Osmotic	sugar preservation	High osmotic pressure, low water activity
pH	Addition of acids	Reduction of pH value and sometimes additional inhibition by the particular acid
Oxygen	Lactic fermentation oxygen-free or modified atmosphere	Delay or stop growth of anaerobes
Chemical extremes	Ethanol, preservatives - nitrite CO_2-enriched atmosphere smoke	Toxic inhibition; can be combined with sugar preservation Inhibition of specific groups of microbes Inhibition of some microbes by carbon dioxide. ’Toxic inhibition
Vacuum	Vacuum	Delay or stop growth of anaerobes



Temperature



History of high temperature extremophile research Tom Brock, Karl Stetter

- Brock's first visit to YNP was July 1964. He was surprised by organisms in run-off channels. Stopped again to sample later in the summer. Started to do work in YNP to get field experience before field trip to Iceland. Studies in photosynthesis, chlorophyll, RNA, DNA and protein.
- 1965 tried to culture at high temperature using spring water as culture medium and springs as incubators (didn't work.) Noticed pink, gelatinous mat at Pool A (Octopus Spring.) High temp at the time was considered 60°C.
- Fall 1965 awarded NSF funding, and serious YNP work started 1966. Hudson Freeze cultured YT-1, later known Thermus aquaticus.
- Near end of summer of 1967, starting using immersion slide technique. String in source of Octopus - first evidence for life growing in source. Later than summer showed life in boiling water.
- Stetter's original interest was looking at polymerases in Woese's newly-proposed Archaea.

History of Deep Sea Extremophile Research - Alvin

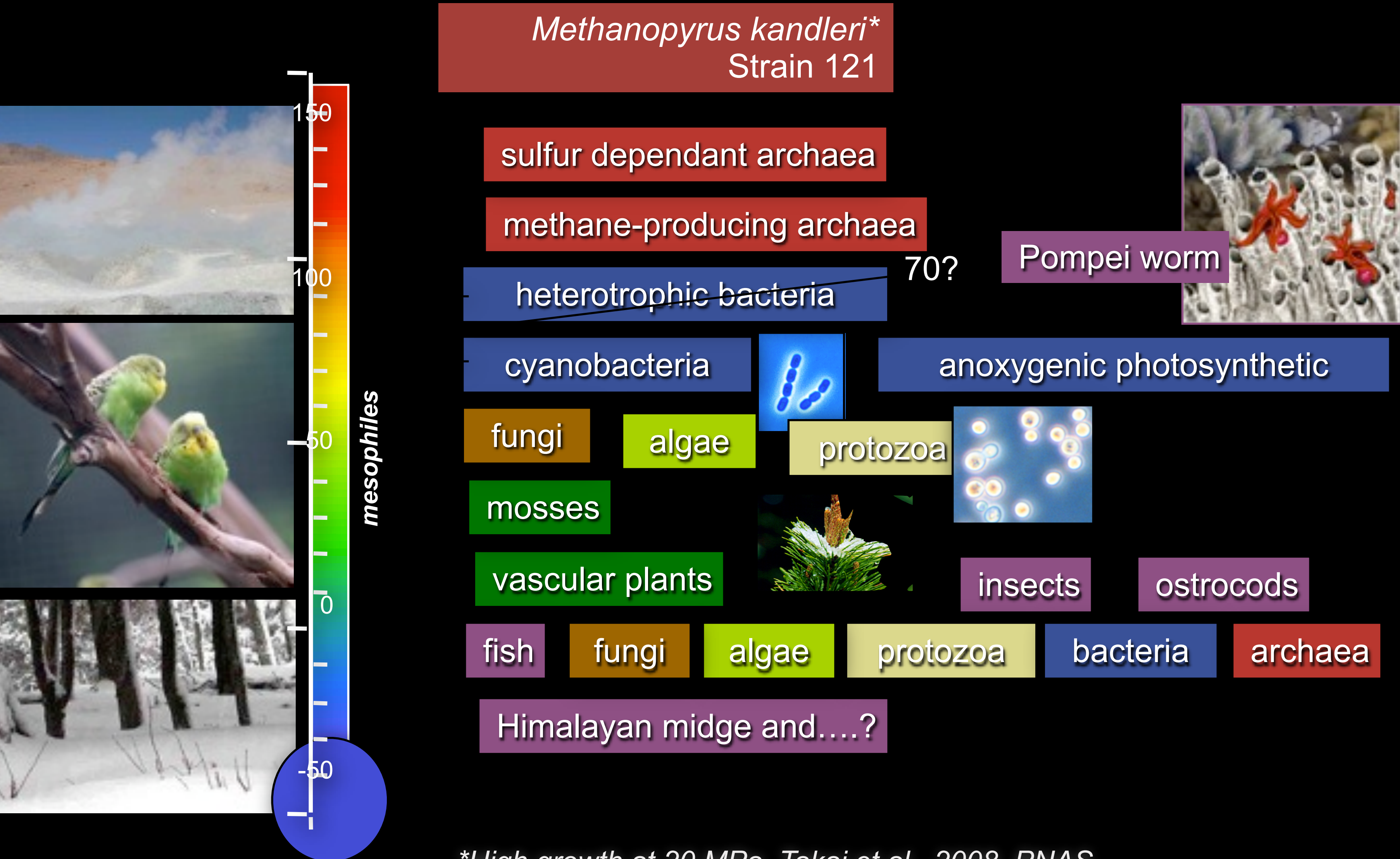
In 1977, Alvin traveled through the Panama Canal for the first time. Geology work in the Galapagos Rift was completed during February and March. Discovery of an abundance of exotic animal life on and in the immediate proximity of warm water vents prompted theories about the generation of life. Since no light penetrates through the deep waters, scientists concluded that the animal chemistry here is based on chemosynthesis, not photosynthesis.

Alvin has now found > 24 hydrothermal sites in the Atlantic and Pacific Oceans. It has allowed researchers to find and record about 300 new species of animals, including bacteria, foot-long clams and mussels, tiny shrimp, arthropods, and red-tipped tube worms that can grow up to 10 ft long in some vents.

Temperature: what difference does it make?

- Solubility of gasses goes down as temperature goes up (impetus for colonization of the land?).
- Organisms have upper temperature limits. Chlorophyll, proteins and nucleic acids denature at high temperatures.
- Enzymes have optimal temperatures for activity; slow down at low temperature
- Low temperature water freezes. Breaks membranes, increases solute concentration, etc.

Temperature limits for life*



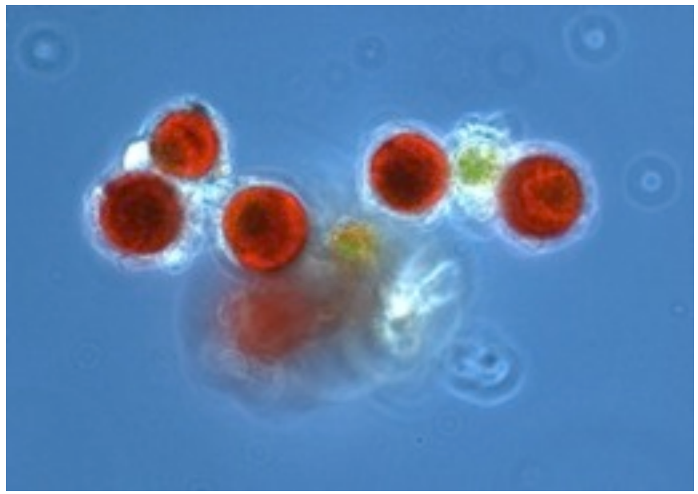
*High growth at 20 MPa. Takai et al., 2008. PNAS.
**Note many organisms, including seeds and spores, can survive at much lower and higher temperatures.

Octopus Spring

Octopus Spring, Yellowstone National Park, 4 July 1999

Sol de la Mañana

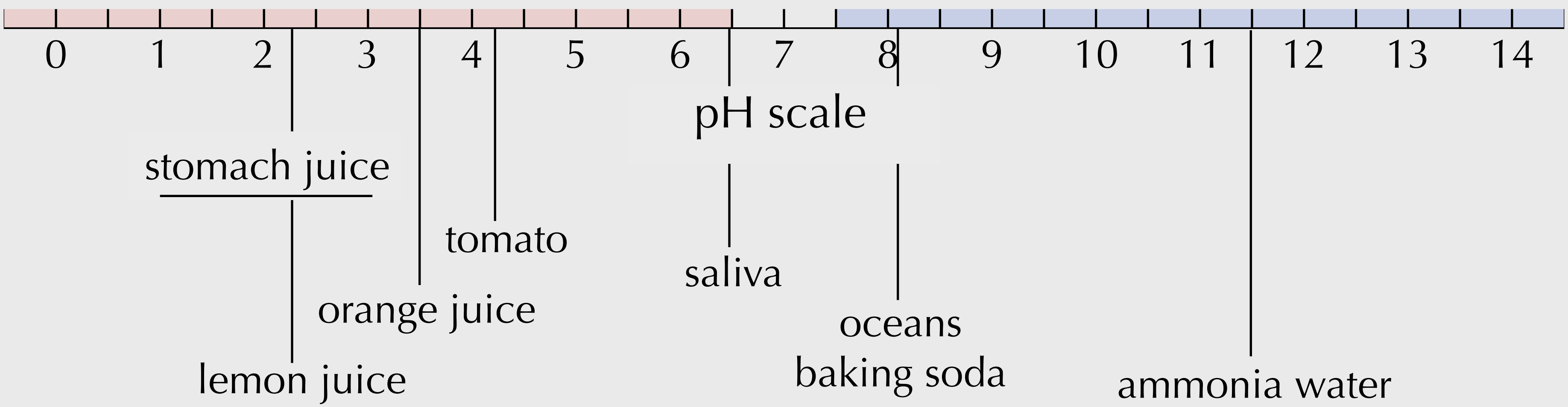
Lassen - Snow algae (watermelon snow)



- King's Creek, July 2005

pH limits for life

pH is as –log10[H+]. At pH 0, [H+] = 1 M



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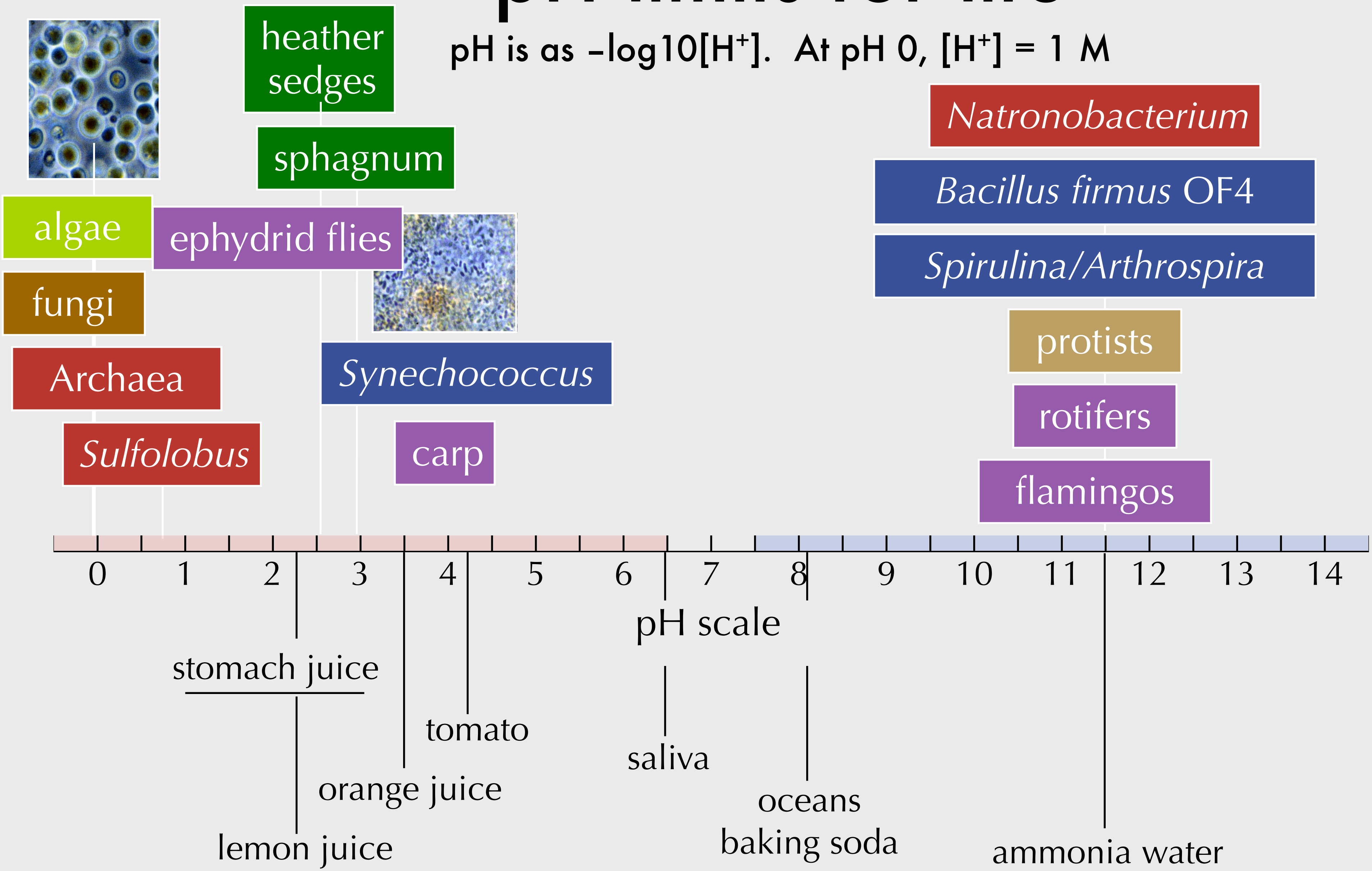

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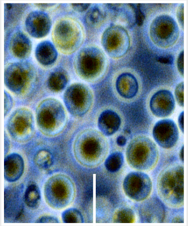
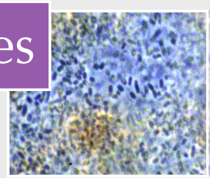


heather sedges

sphagnum

algae

ephydrid flies



fungi

Archaea

Synechococcus

Sulfolobus

carp

Natronobacterium

Bacillus firmus OF4

Spirulina/Arthrospira

protists

rotifers

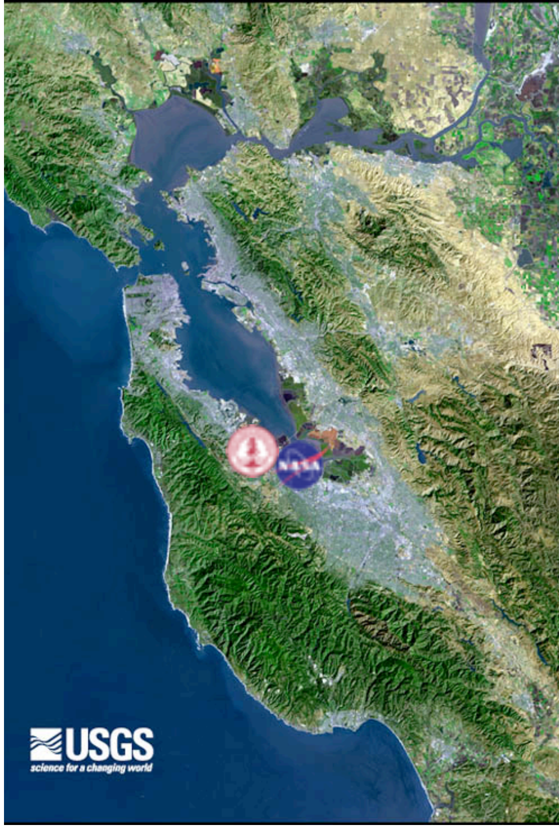
flamingos

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

pH scale

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.



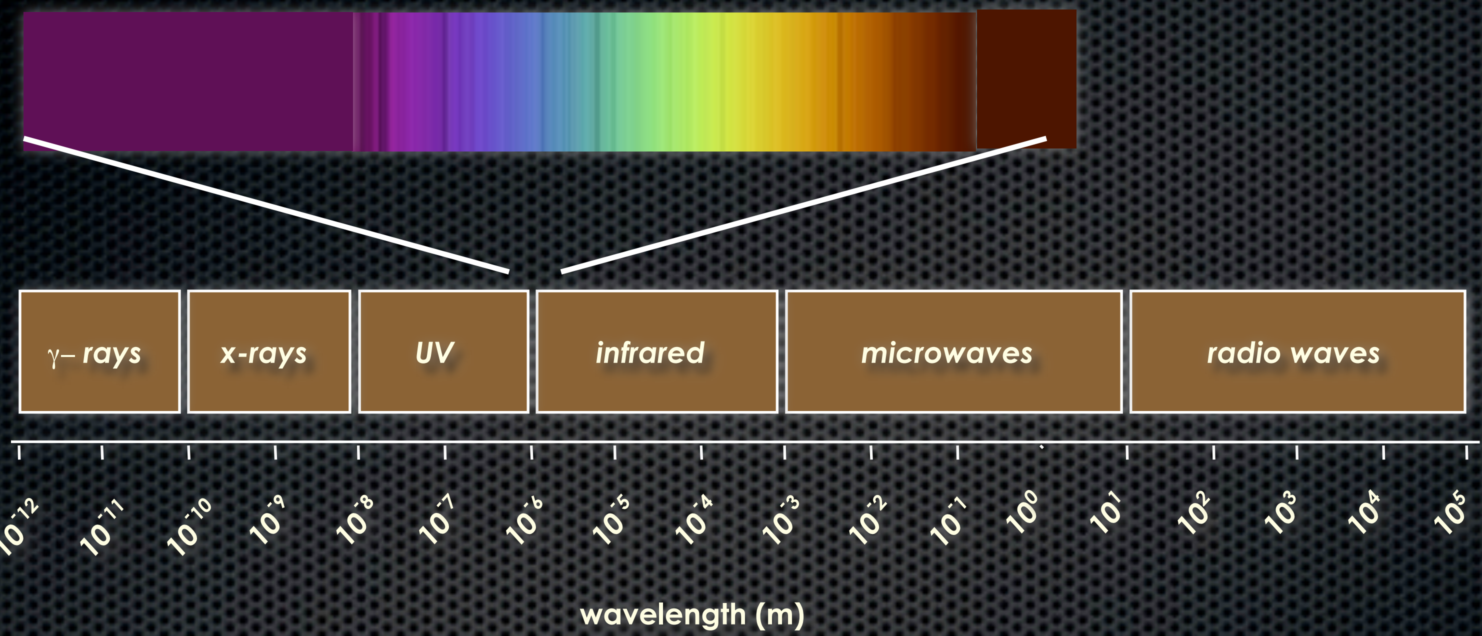
Laguna Colorada

- Samples were collected in Nalgene containers
- Quite possibly have new species

Desiccation

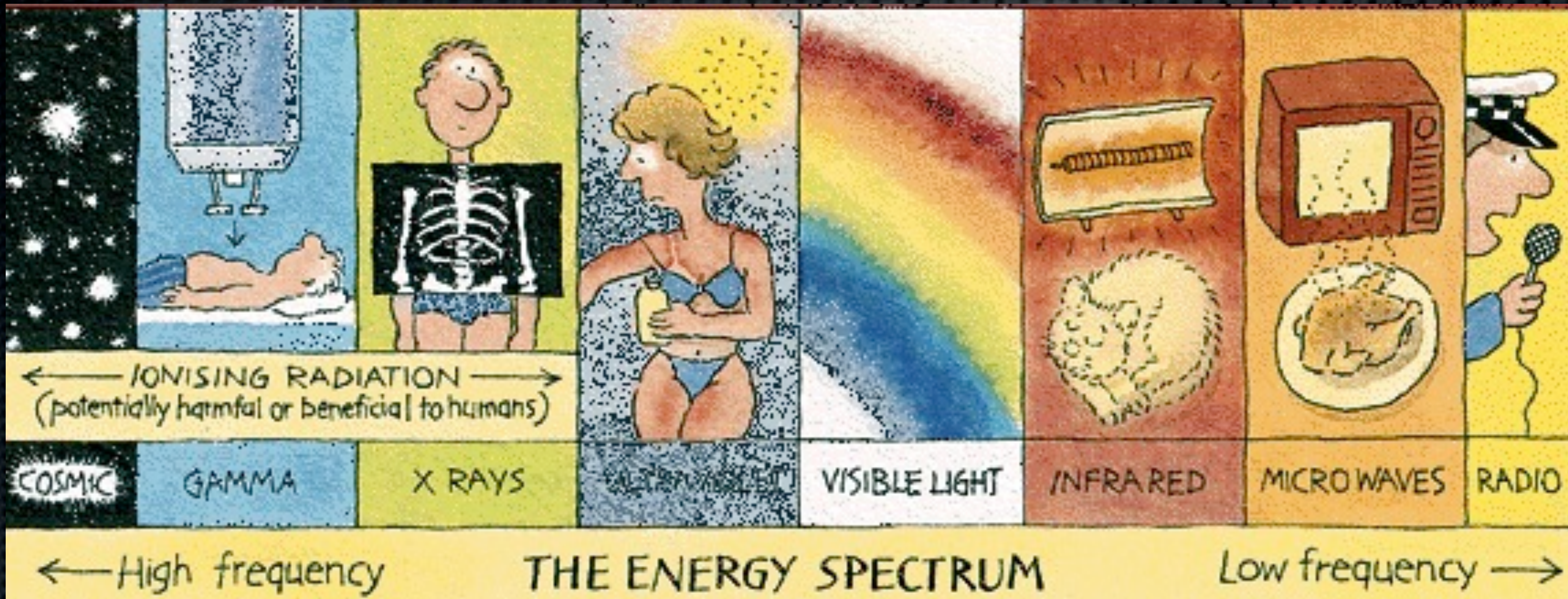
- Can be correlated with salinity tolerance.
- Cell growth at normal temperatures usually requires water potential, aw (defined as pH20 [liquid solution] / pH20 [pure liquid water], where p is the vapor pressure of the respective liquid) of >0.9 for most bacteria and >0.86 for most fungi.
- Lowest value 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.


Evaporite, Baja California Sur



Radiation

The energy spectrum



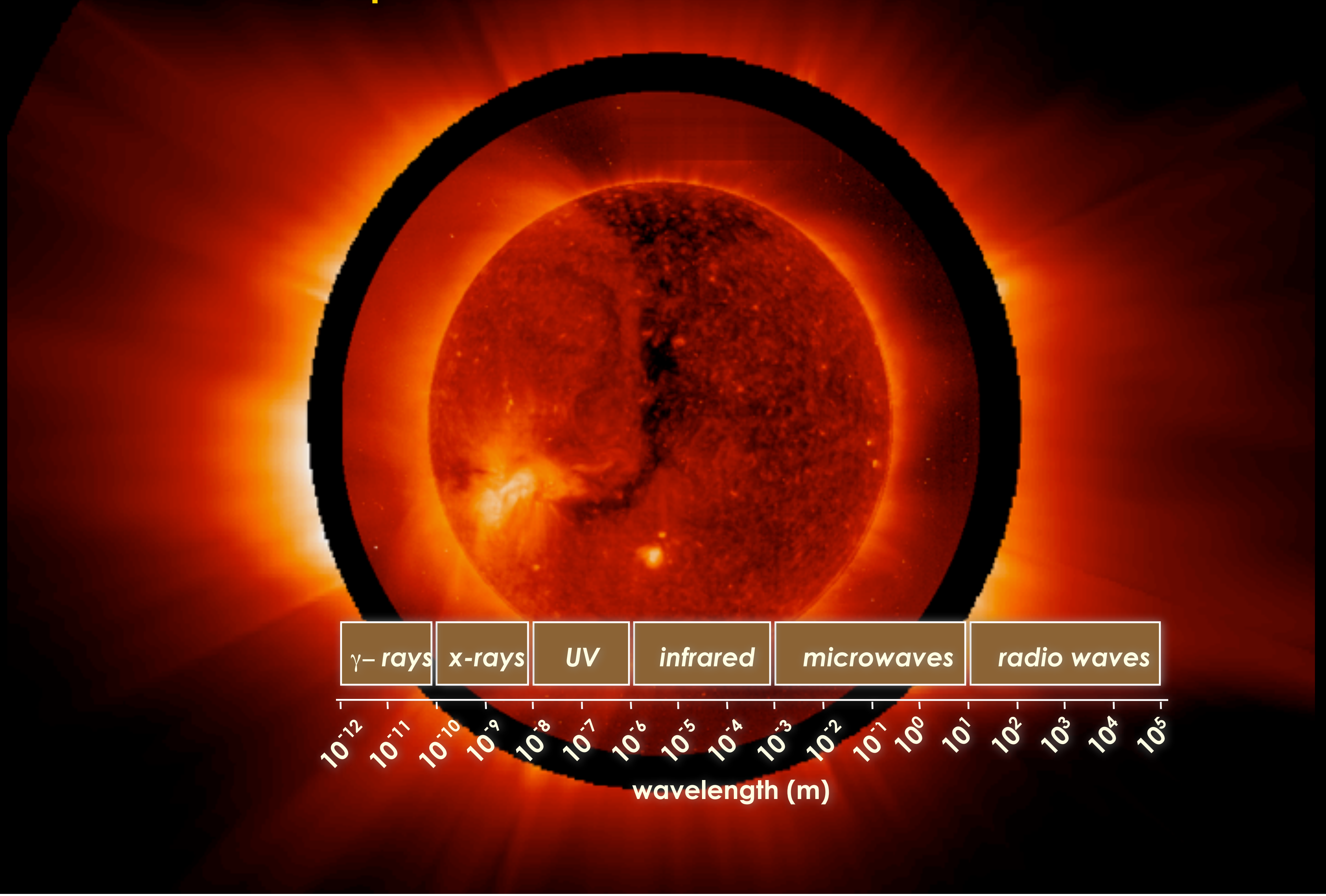
Radiation

The energy spectrum

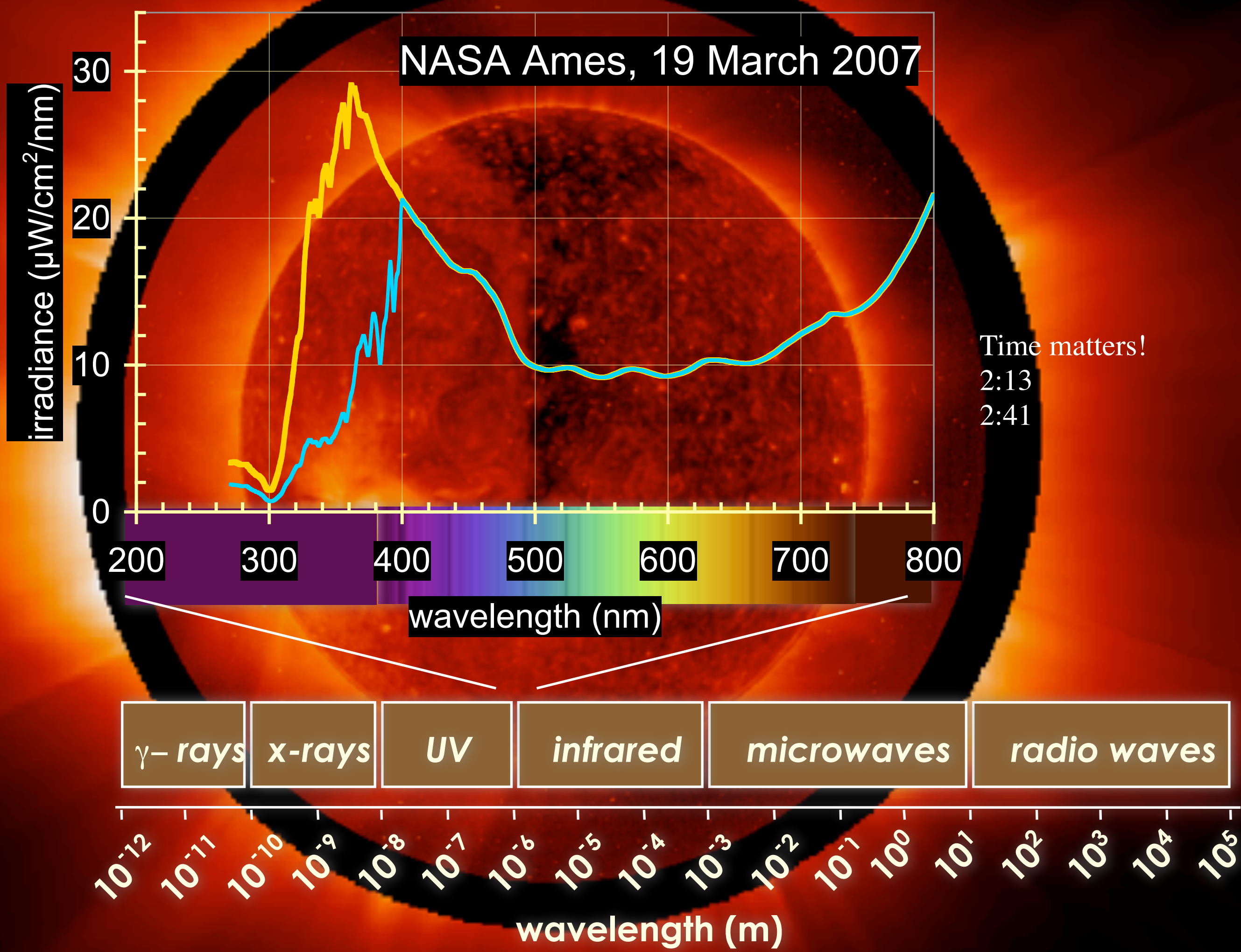
Radiation

- Some forms of radiation have been a constant for organisms over geological time, whereas others vary seasonally and diurnally. Exposure may depend on ecology.
- Man-made radiation can result in novel exposures or exposure levels.
- Some radiation is blocked by the Earth's atmosphere, and thus is newly relevant with respect to interplanetary travel or to an potential extraterrestrial biota.

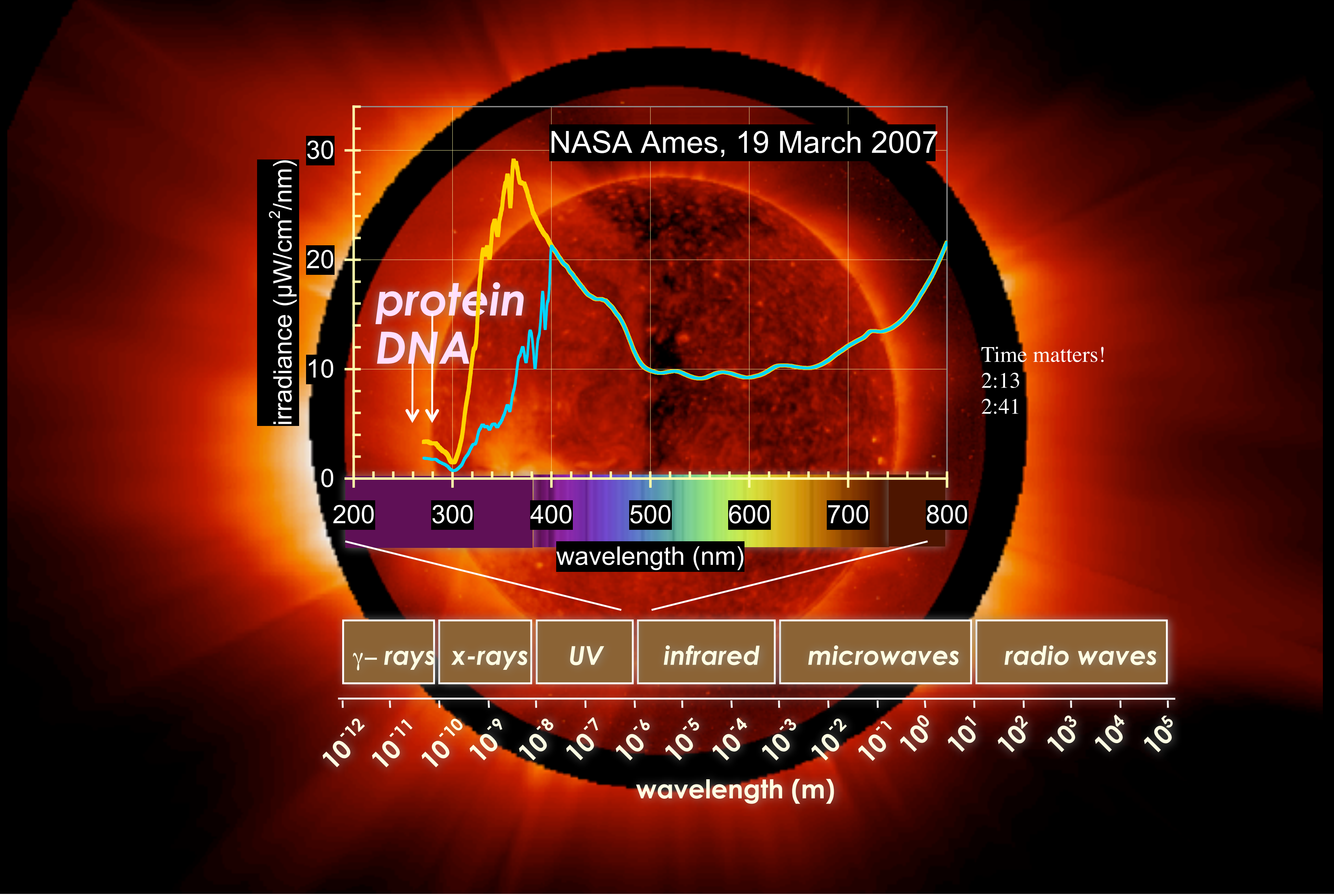
The Solar Spectrum



The Solar Spectrum



The Solar Spectrum



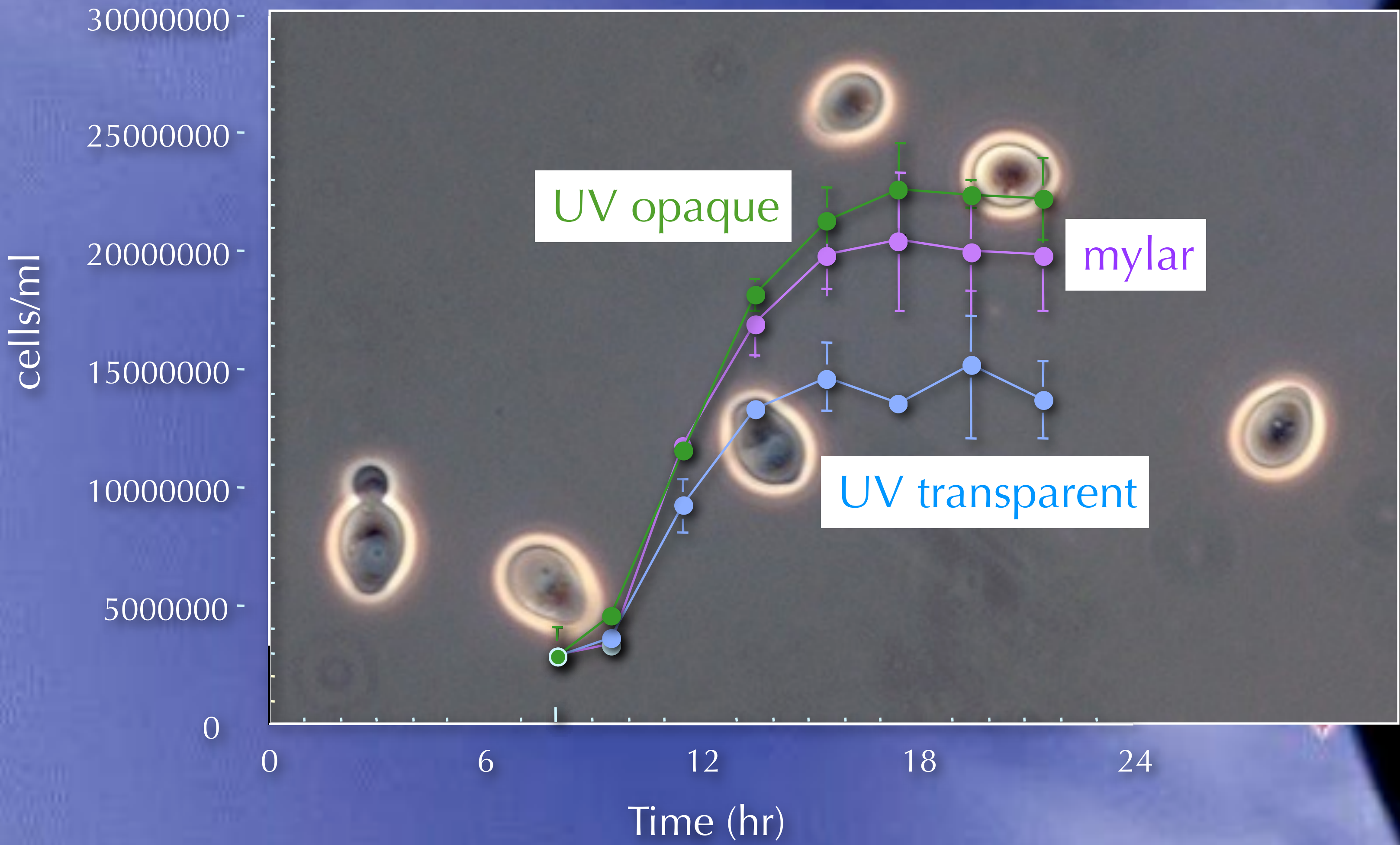
On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life.

Charles Darwin,

M.A., Fellow of the Royal, Geological, Linnæan, etc. societies; Author of "Journal of researches during H. M. S. Beagle's Voyage round the world. London: John Murray, Albemarle Street, 1859"

RADIATION IS UNUSUAL
in that it is both a mutagen and a selective agent.

UV effects: growth rate of yeast under solar radiation



Parent strain, *S. cerevisiae* obtained from Research Genetics. Yeast grown in 50% YEPD, full solar radiation. Jackie Garget, 22 March 2000. UVB had most effect.

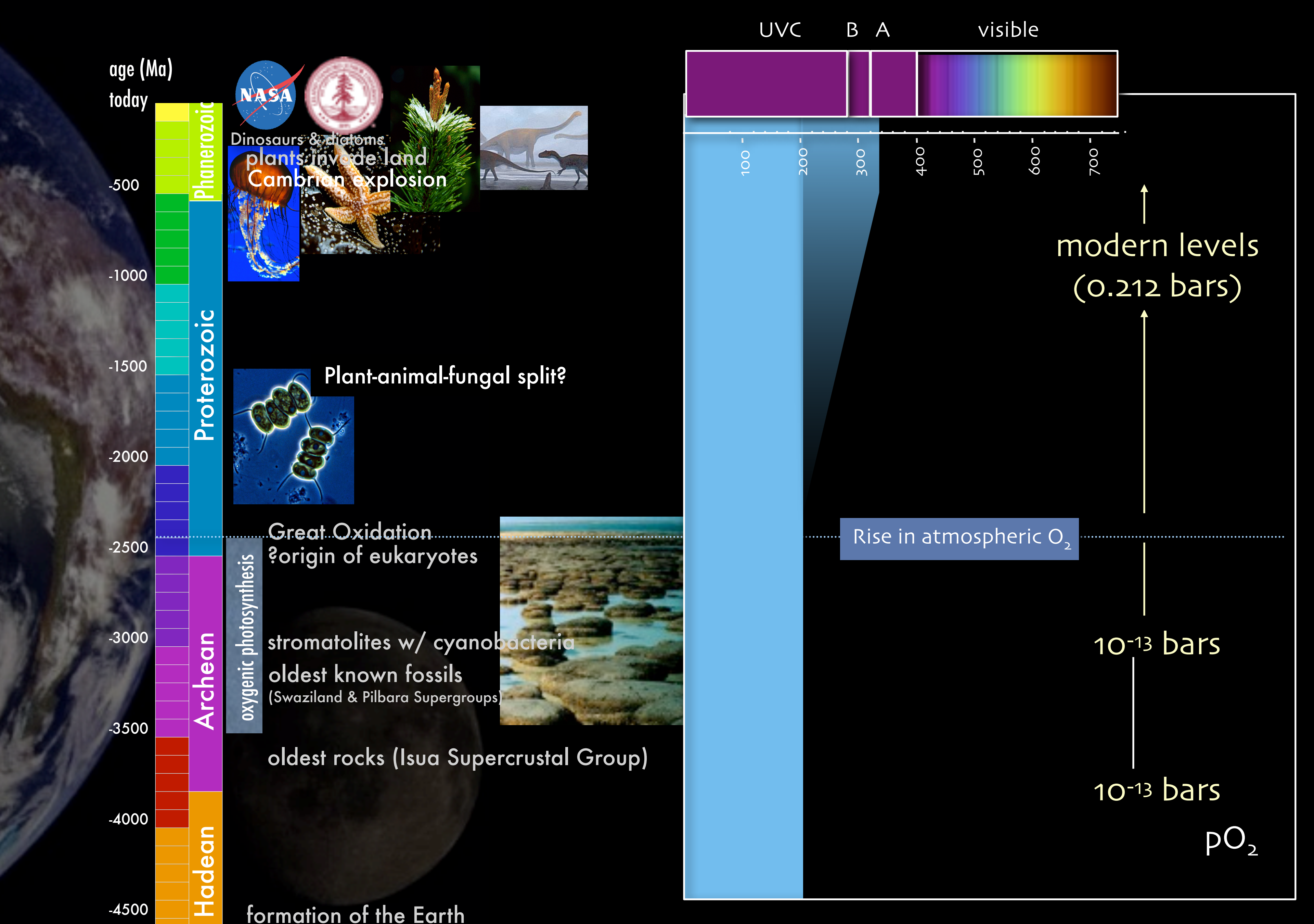
High oxygen

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

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

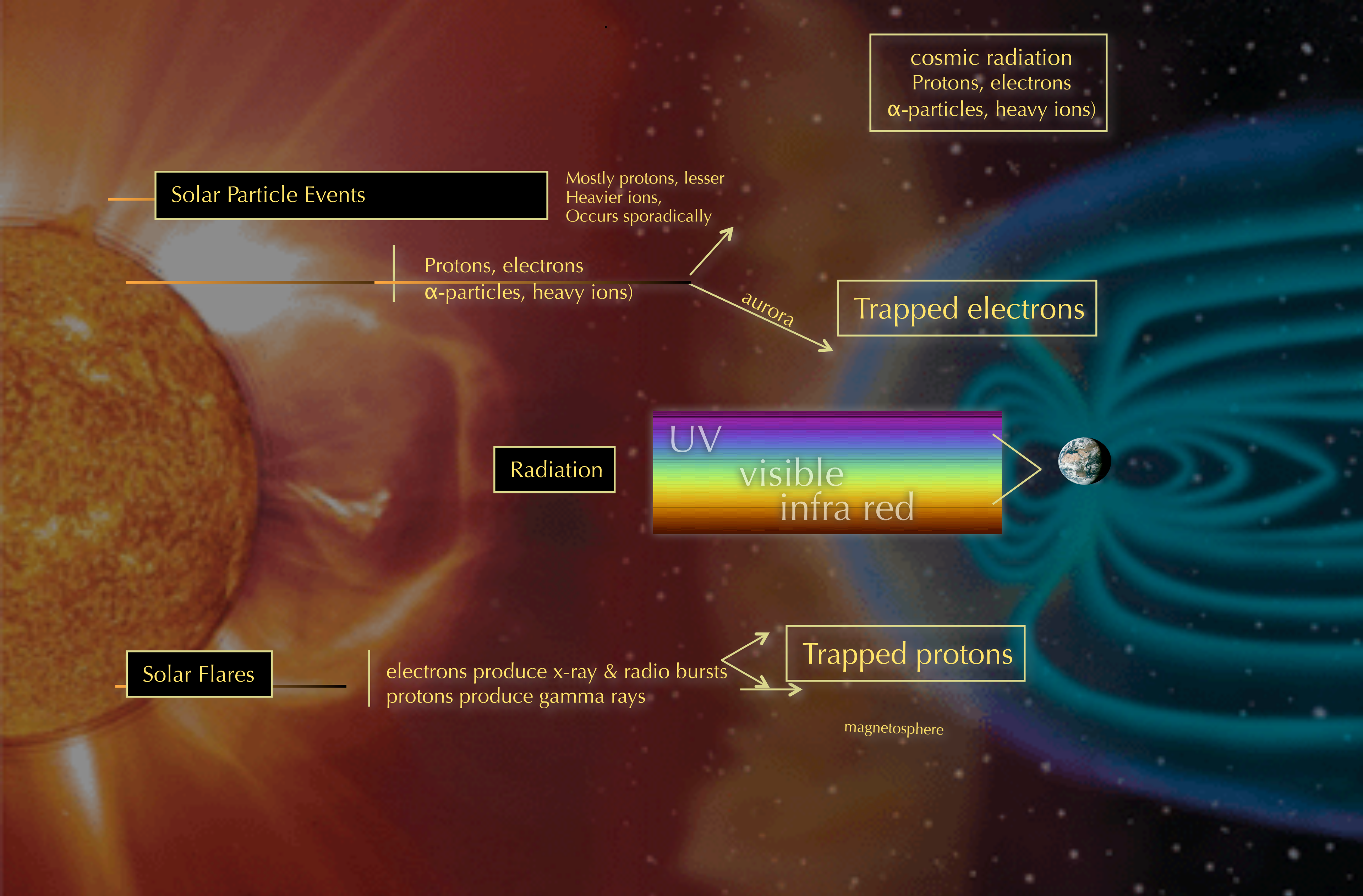
Aerobic metabolism: a critical evolutionary innovation

- Aerobic metabolism is more efficient than anaerobic
- Without it, no oxygenic photosynthesis
- Without it, the origin of large animals is unlikely



Surface UV flux has changed over time

Wednesday, August 4, 2010



Radiation is NASTY in space


Australia
Brisbane
Arkaroola
Perth
Adelaide
Sydney

Australia


Australia
Brisbane
Arkaroola
Adelaide
Sydney


Australia
Brisbane
Arkaroola
Adelaide
Sydney

Australia

Australia


SNAKES WATCH YOUR KIDS
Brisbane
Arkaroola
Adelaide
Sydney

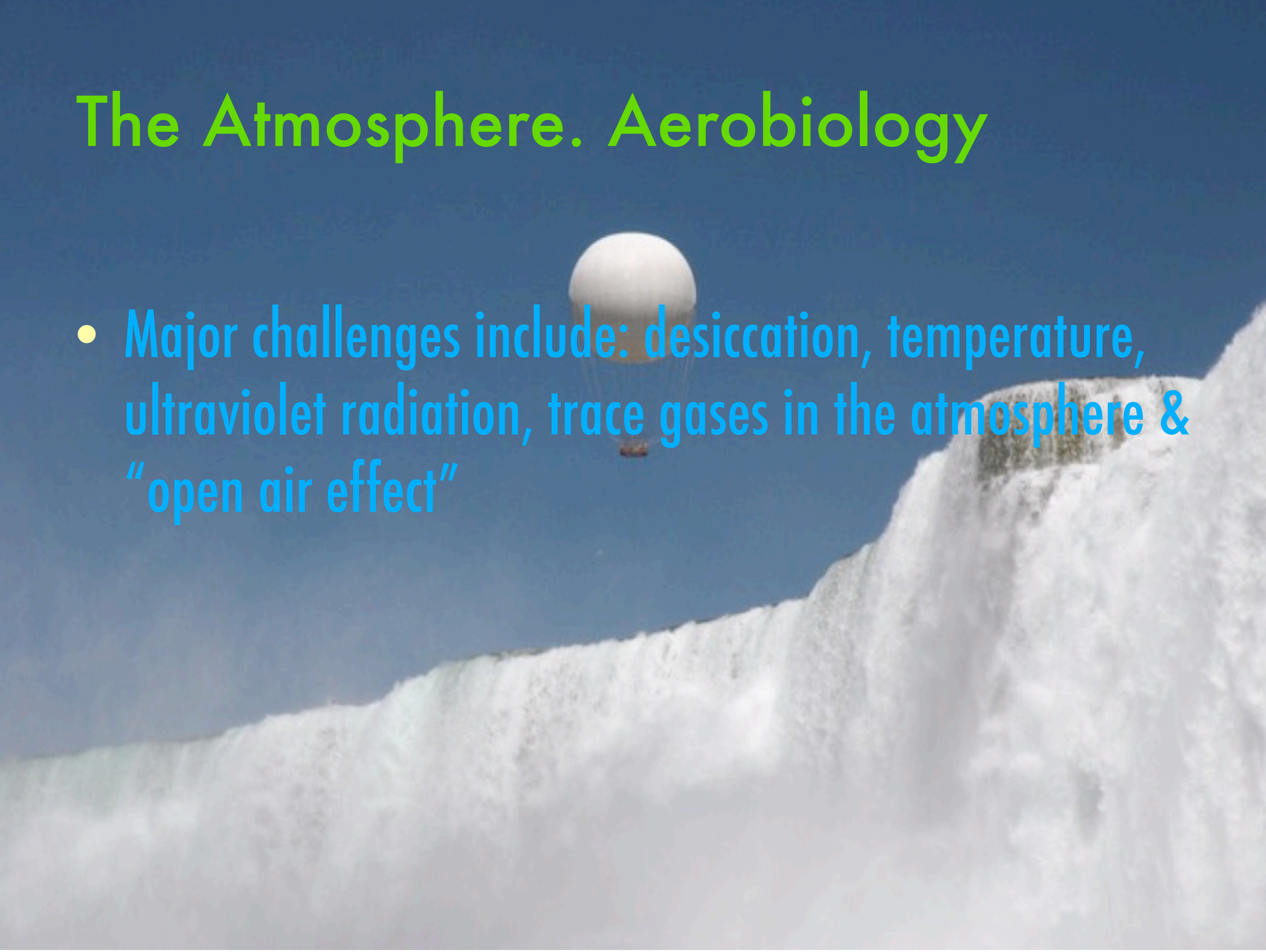
Australia

Australia


Paralana Springs


Paralana Springs

The Atmosphere. Aerobiology



The Atmosphere. Aerobiology

- Major challenges include: desiccation, temperature, ultraviolet radiation, trace gases in the atmosphere & "open air effect"

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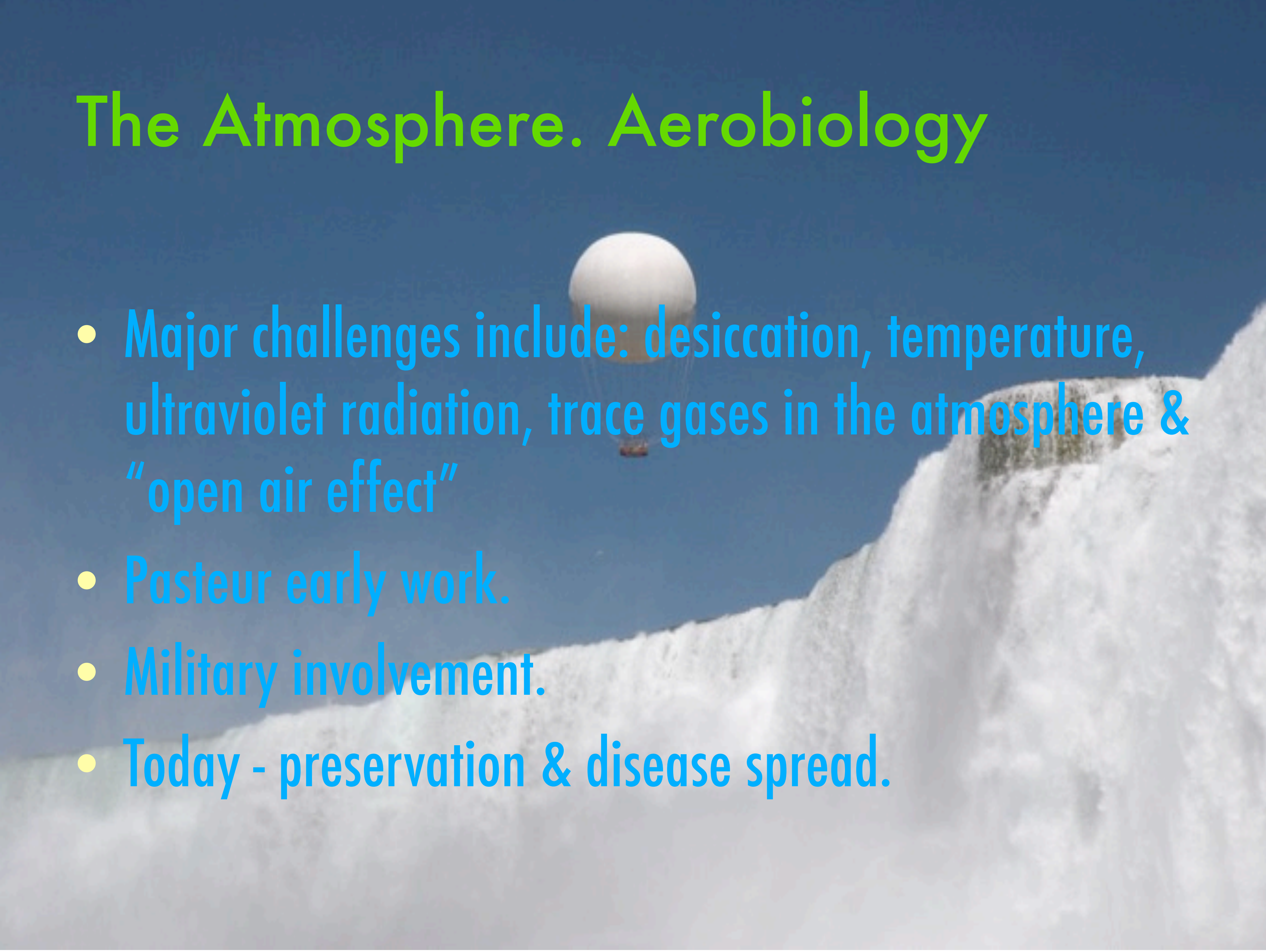
- Military involvement.



The Atmosphere. Aerobiology

- Major challenges include: desiccation, temperature, ultraviolet radiation, trace gases in the atmosphere & “open air effect”
- Pasteur early work.
- Military involvement.
- Today - preservation & disease spread.

How do they **do it?**

*Life is Lazy**

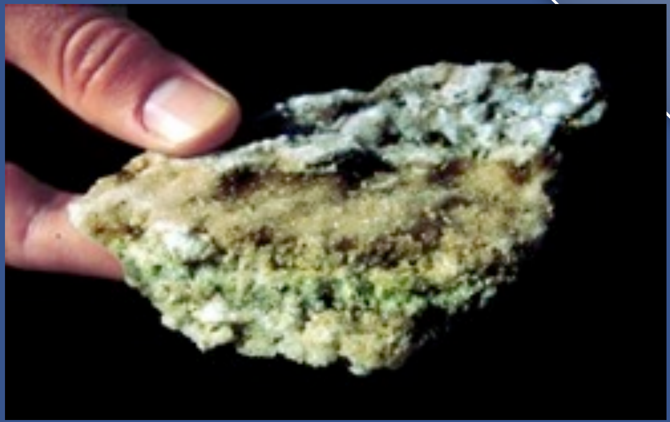
***efficient**

Easiest thing is to keep the external environment out

- Low pH organisms (acidophiles) use a proton pump to keep their cytoplasmic pH nearer neutral.
- Low temperature organisms (psychrophiles) use antifreezes to prevent ice crystal formation, and cryoprotectants to allow freezing in an organized manner. (note: this has applications from blood preservation to ice cream production)

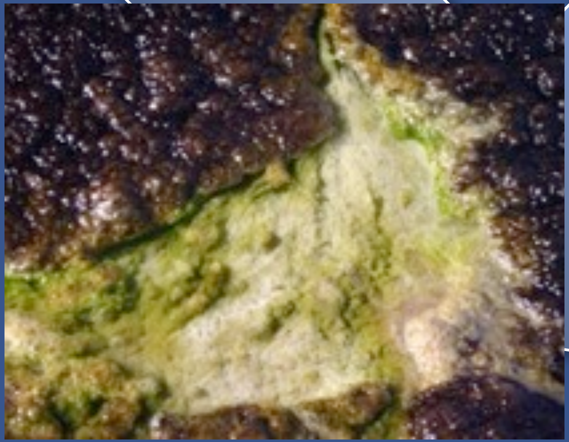
Ways to deal with UV damage...

Avoid damage



living under UV-absorbing material (water, dead cells...)

production of UV-absorbing pigments (i.e., scytonemin, MAAs, phycoerythrin)



production of quenchers, antioxidants, enzymes to neutralize radicals

Repair damage

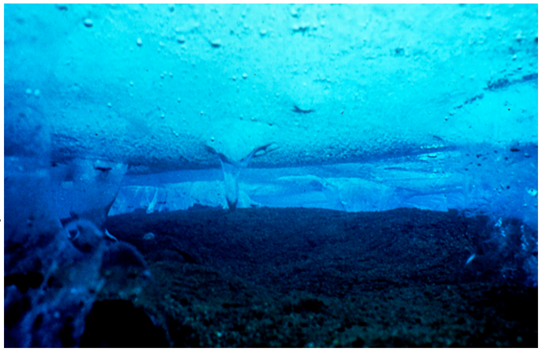
Wednesday, August 4, 2010


Examples of extreme ecosystems
• Geysers, vents
• Ice, in or beneath
• Polar regions
• Subsurface
• High altitude
• High salt
• High oxygen
• Mine drainage
• Nuclear reactors
• Soda Lakes
• Atmosphere

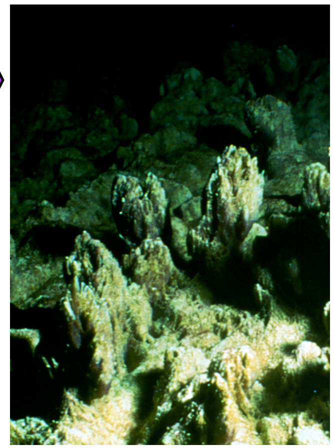
Where we have been

Lake Hoare, Dry Valleys Antarctica

preparing to dive under Lake Hoare



under Lake Hoare

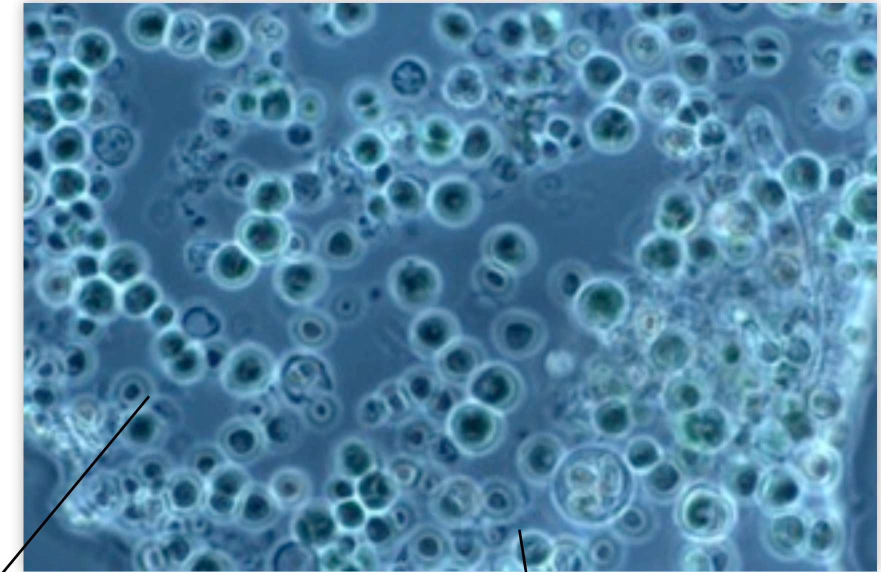


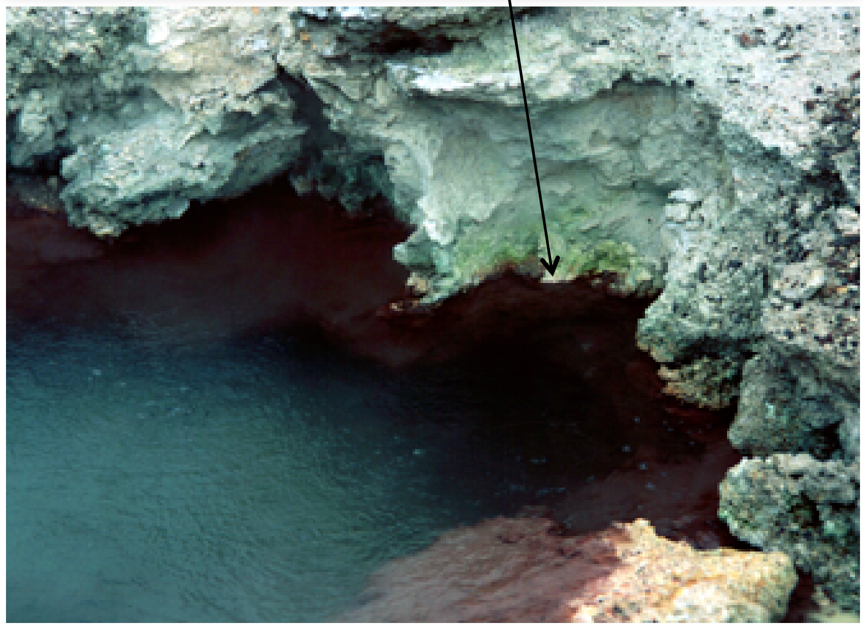
lift-off microbial mat

mat layers

Biota of with geysers

- Biota depends on pH, temperature (distance from source), chemical composition.
- Ex: When the correct combination of temp (~40°C) and pH (~2.5-3.5) exists, Cyanidium caldarium is found.

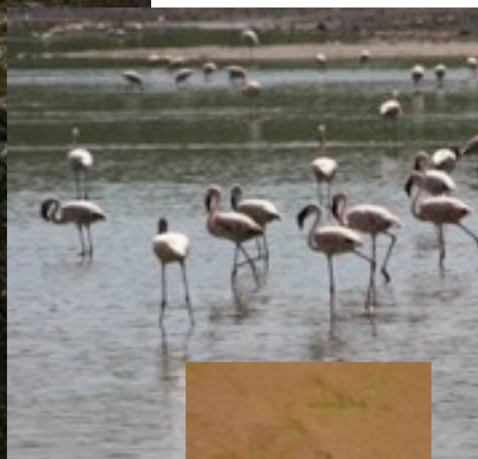




pH limits for life - Kenya

- Lakes of the Rift Valley have some of the highest pH in the world.
- Also usually high salinity because they are endorheic which means the only route for loss of water is evaporation.

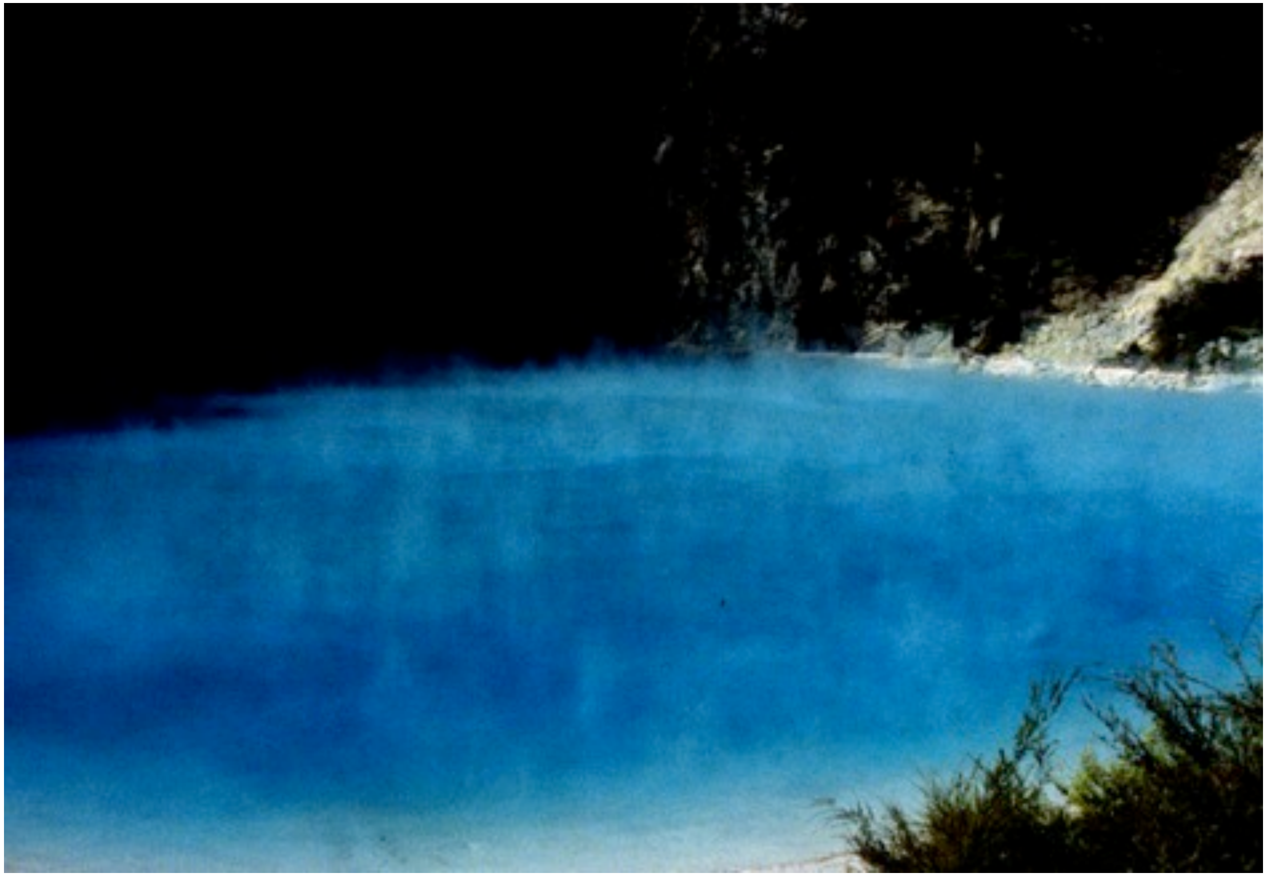
Rift Valley, Kenya 1.07 (high pH)



Roaring Mountain

- ...is home to an acidophilic thermophile community.
- The Archaeum, Sulfolobus acidocaldarius, produces sulfuric acid, which hastens the erosion of the mountainside.

New Zealand

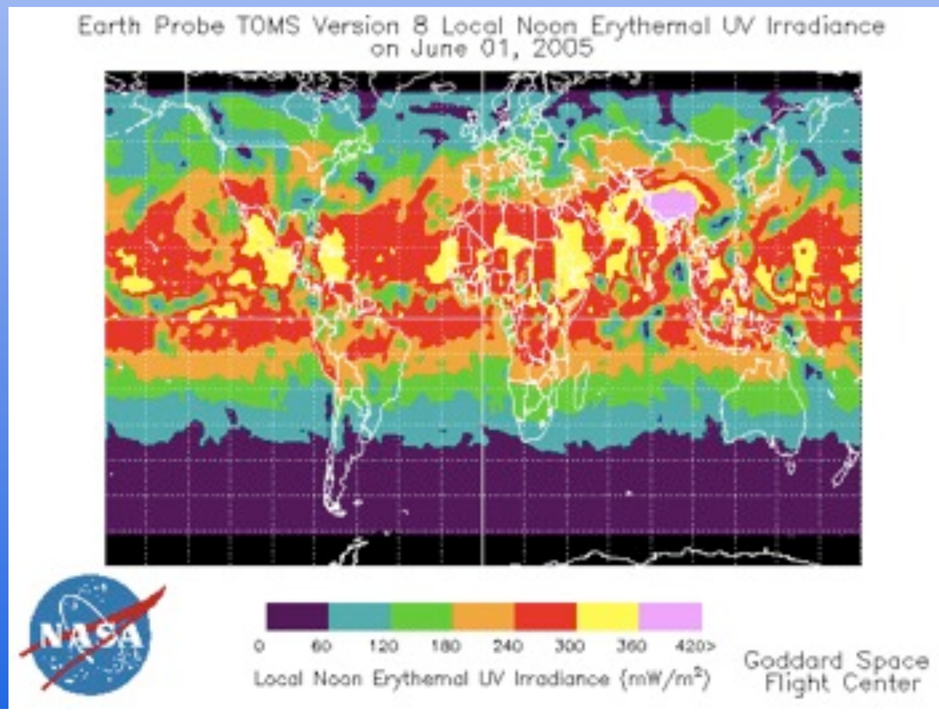


Where is the highest radiation on earth?

Satellite data suggest ...

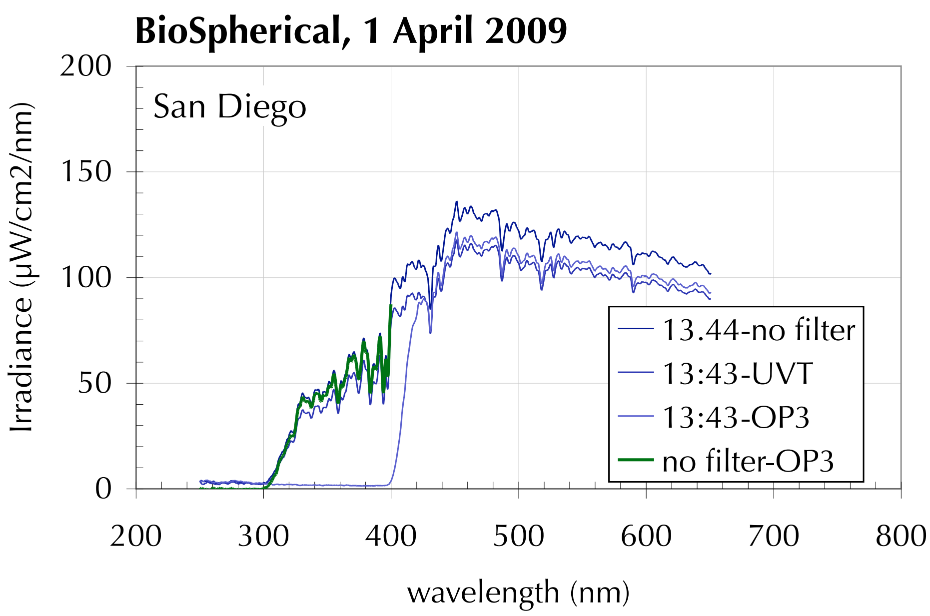
If it's northern summer, go to the Himalayas.

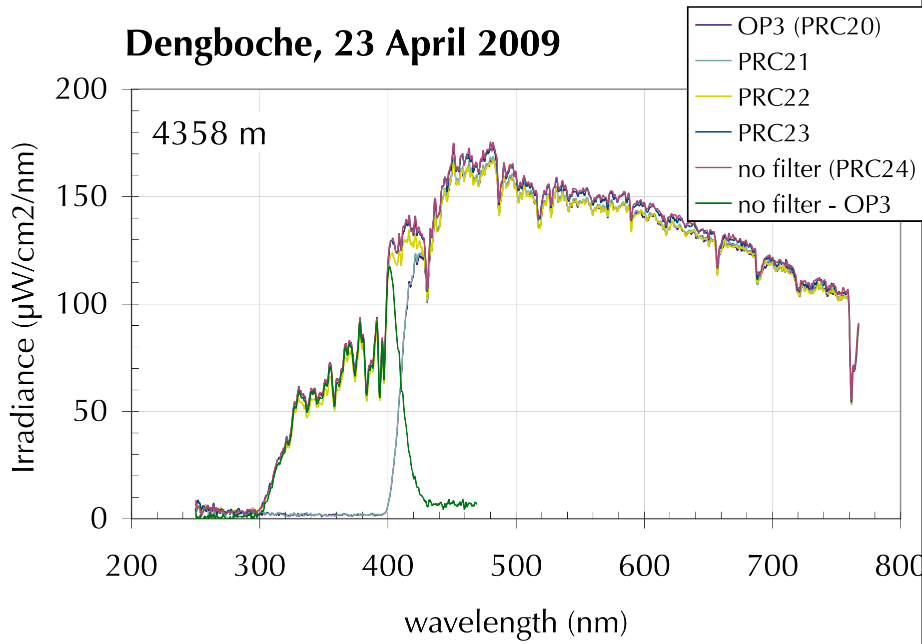
➡June 1, 2005



Mt. Everest Expedition, 2009

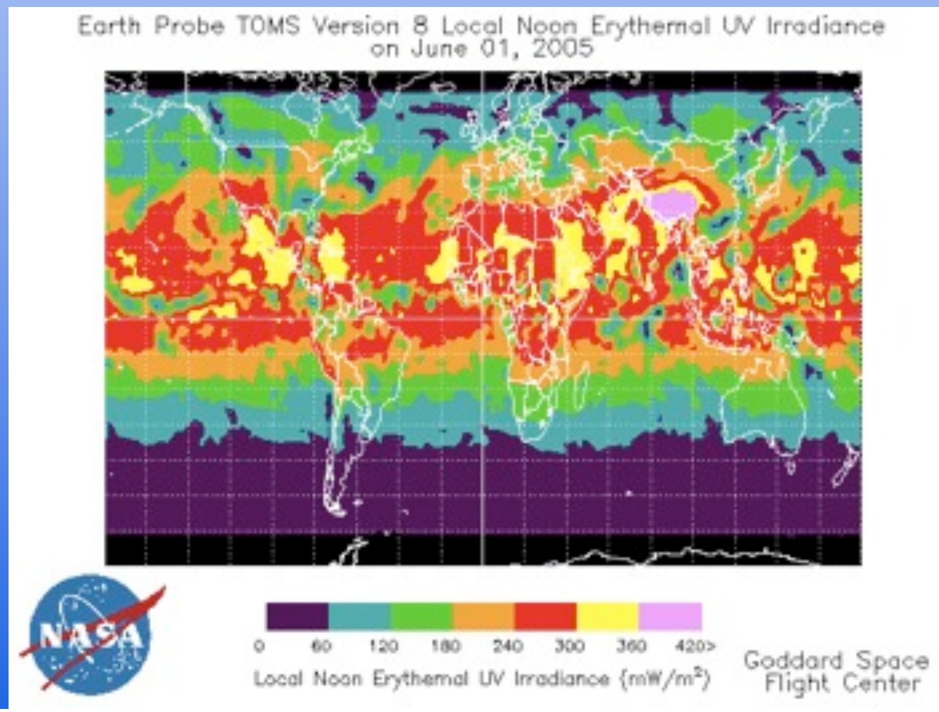
Mt. Everest Expedition, Spectra





Satellite data suggest ...

But in the austral summer, go to the SA etc.



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Satellite data suggest ...

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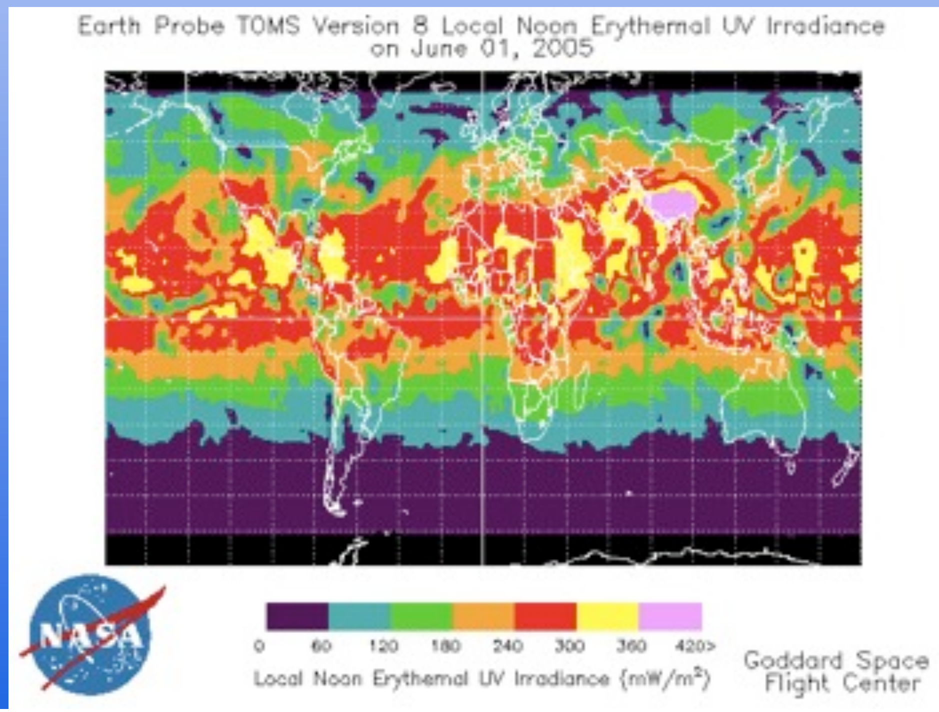
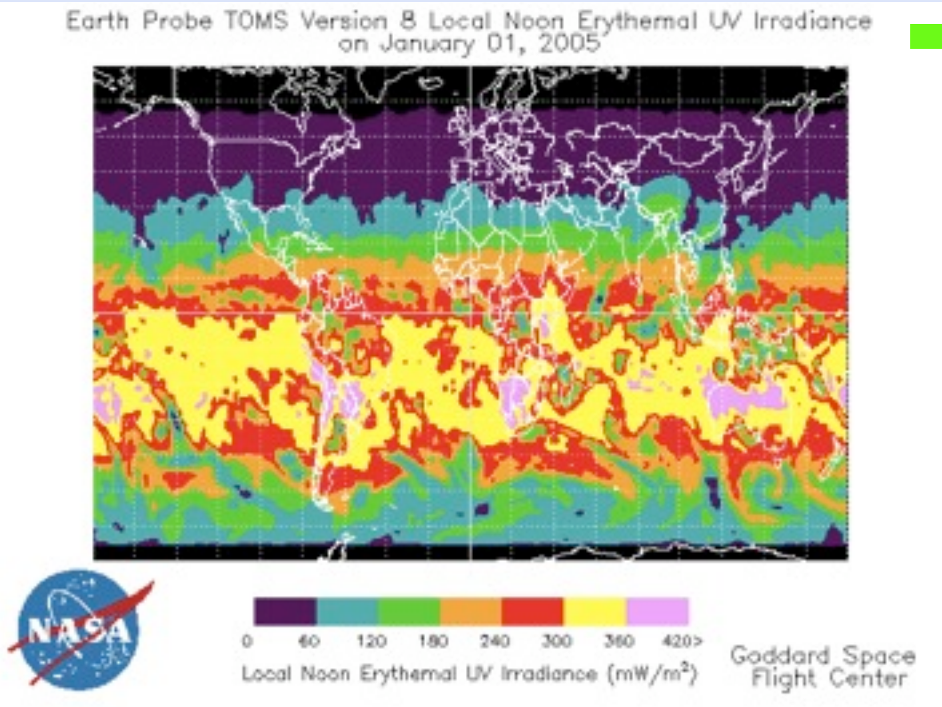
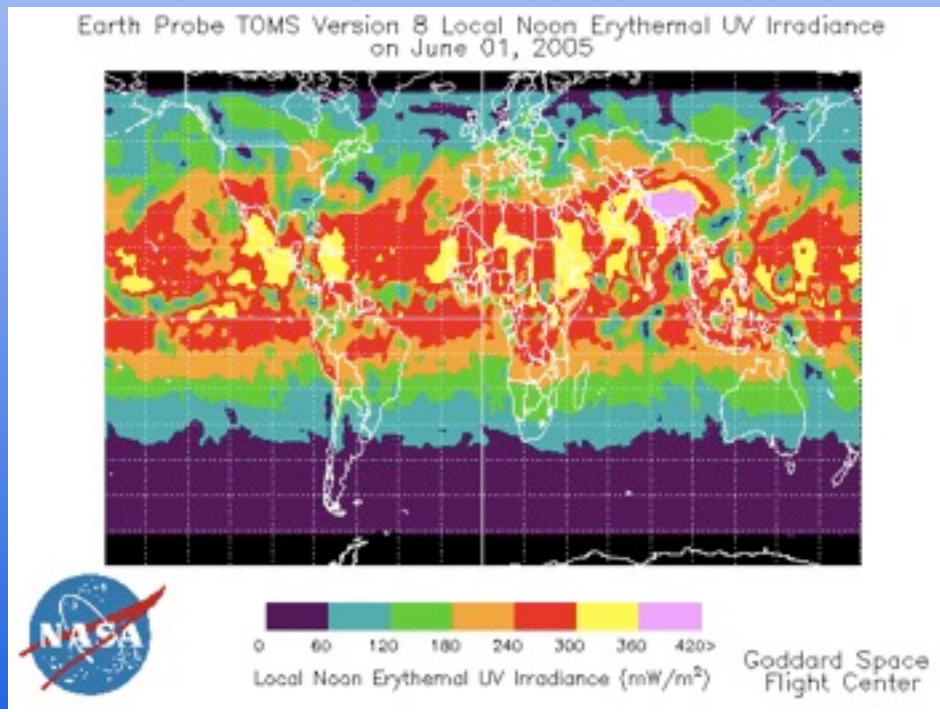


Satellite data suggest ...

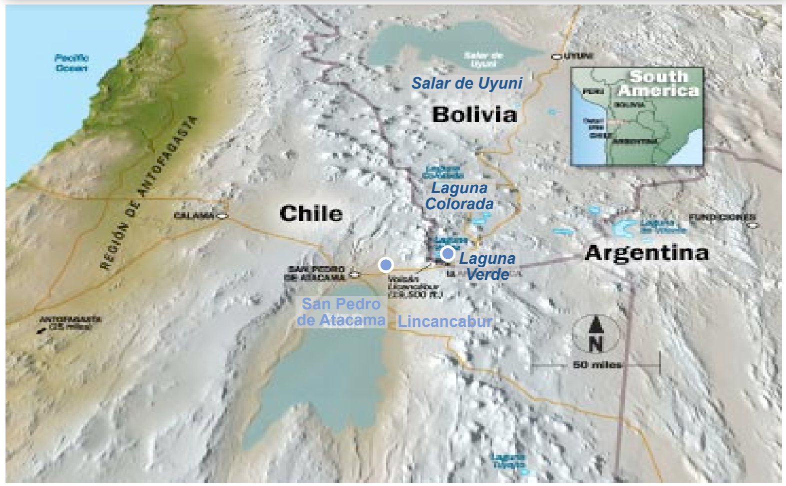


➡January 1, 2005



➡June 1, 2005

Getting there - San Pedro to Altiplano

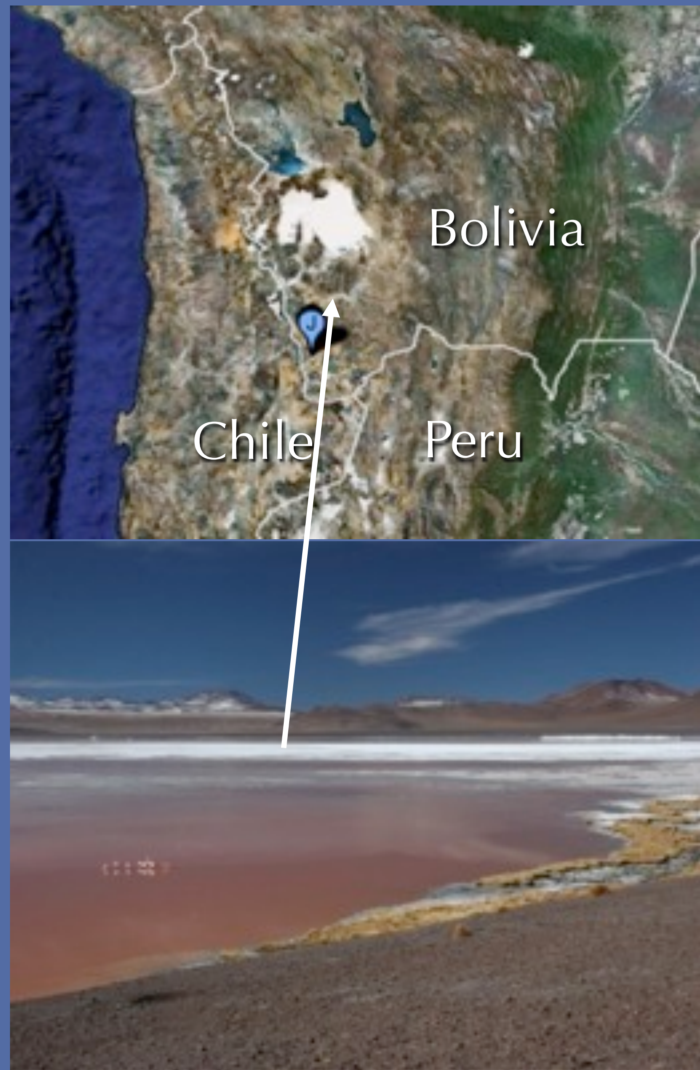


Altiplano, June 2007

Sol de la Mañana

Laguna Colorada, Bolivia

- ~ 4500 m high on the Bolivian Altiplano
- Shallow (avg. ~52 cm)
- Area = 5240 hectares
- T = 4-12 ^{o}C
- Fresh water springs, but lake mostly saline (average varies 10-20%)
- Saturated with borax



What if we go up?

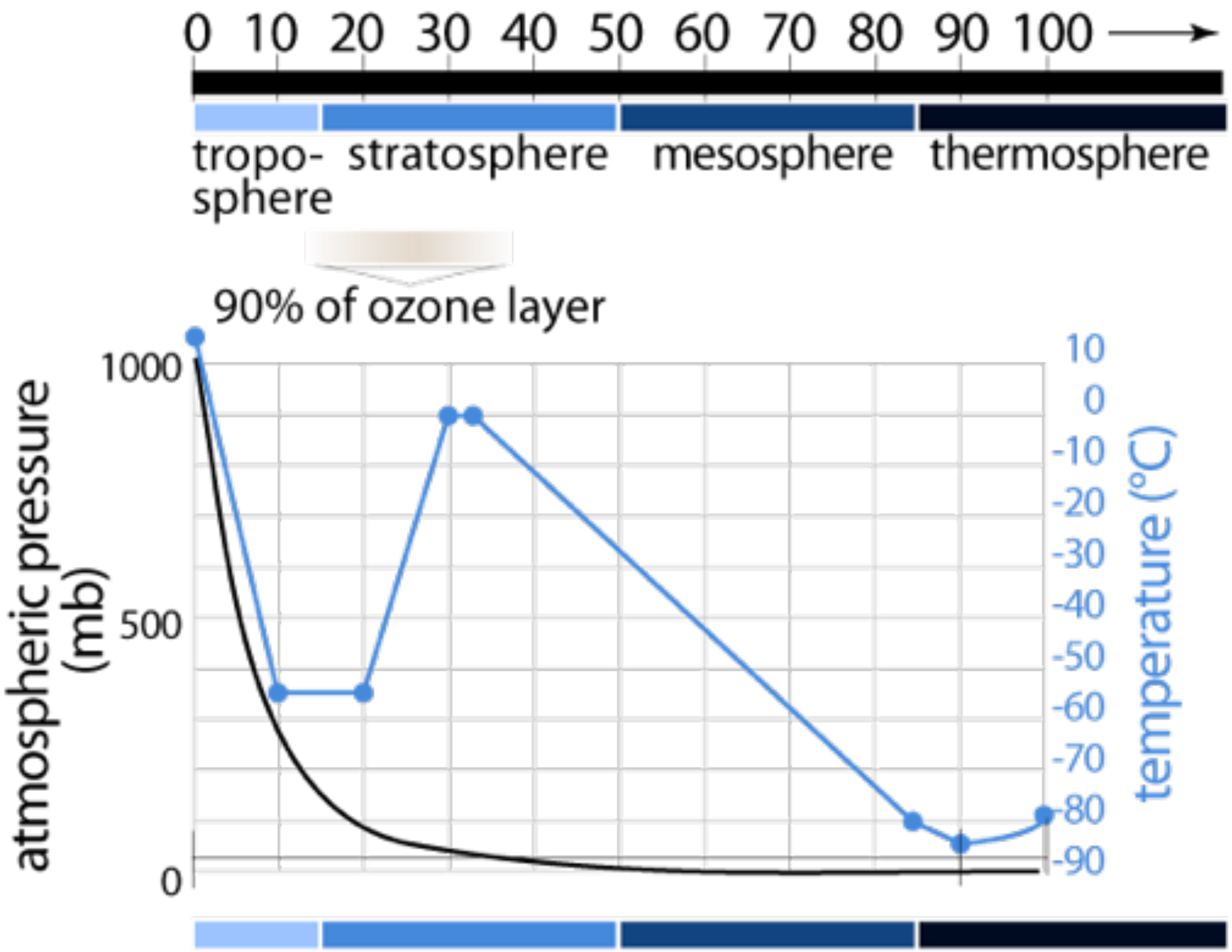
Challenges include: desiccation, temperature, ultraviolet radiation, trace gases in the atmosphere & "open air effect"

What if we go up?

Challenges include: desiccation, temperature, ultraviolet radiation, trace gases in the atmosphere & "open air effect"

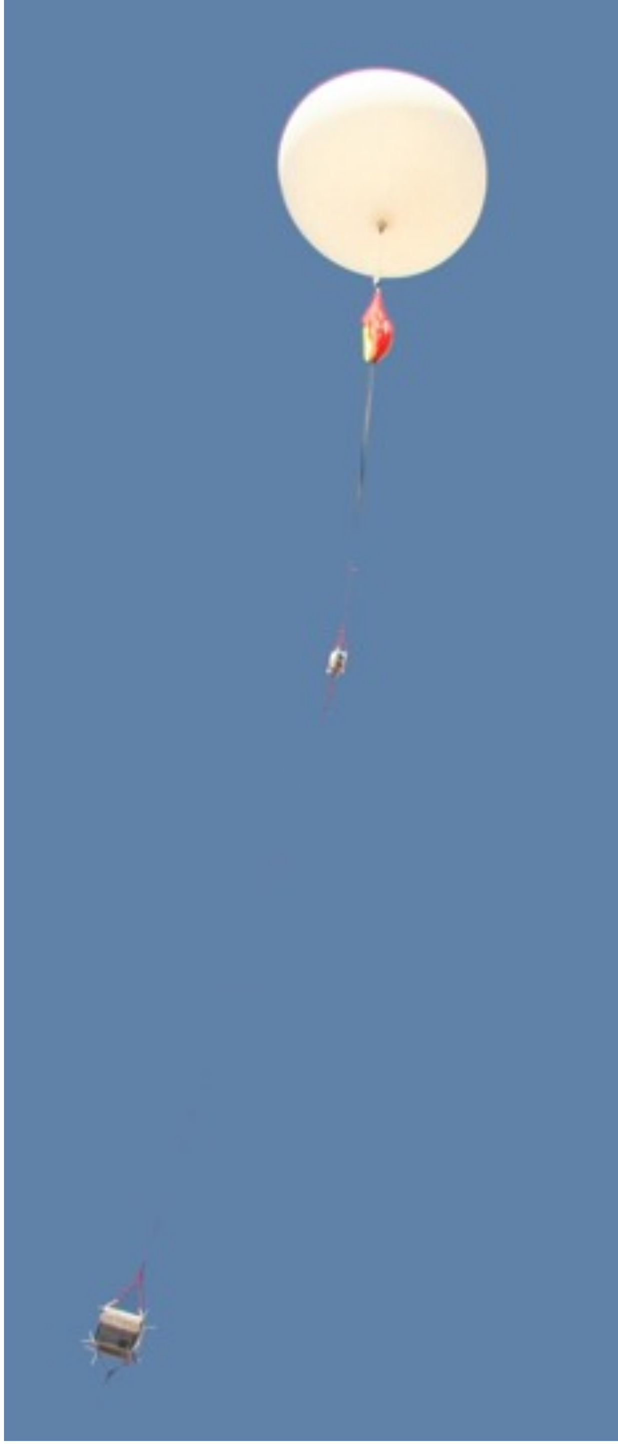
Answer: BioLaunch

lowest 100 km of atmosphere

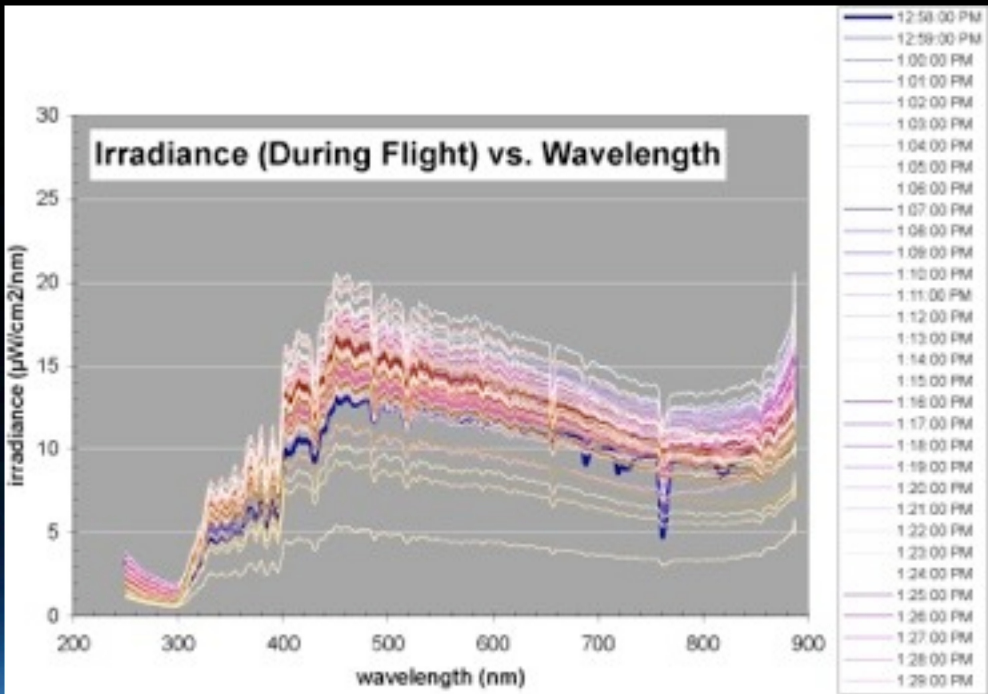


Why balloons?

- Go through much of stratospheric ozone layer (time travel)
- At 33 km ~ atmospheric pressure of Mars
- Fast (h), inexpensive, repeatable
- Last minute biological sample loading



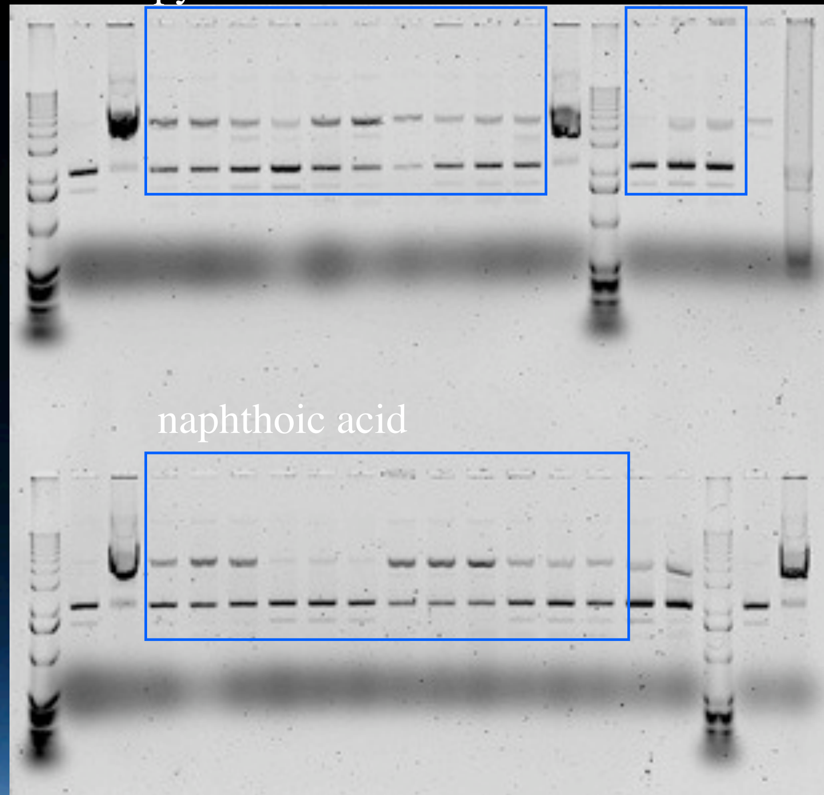
Results



BioLaunch B07A

pyrene

D L L



and last week....

- First sounding rocket launch, with Mavericks Civilian Rocketry Foundation Clotho project, and balloon shots (BioLaunch B10A).
- Product launch with Sony and Intel.
- Permits to nearly 100 km for future flights.
- Future: Brazilian flights?

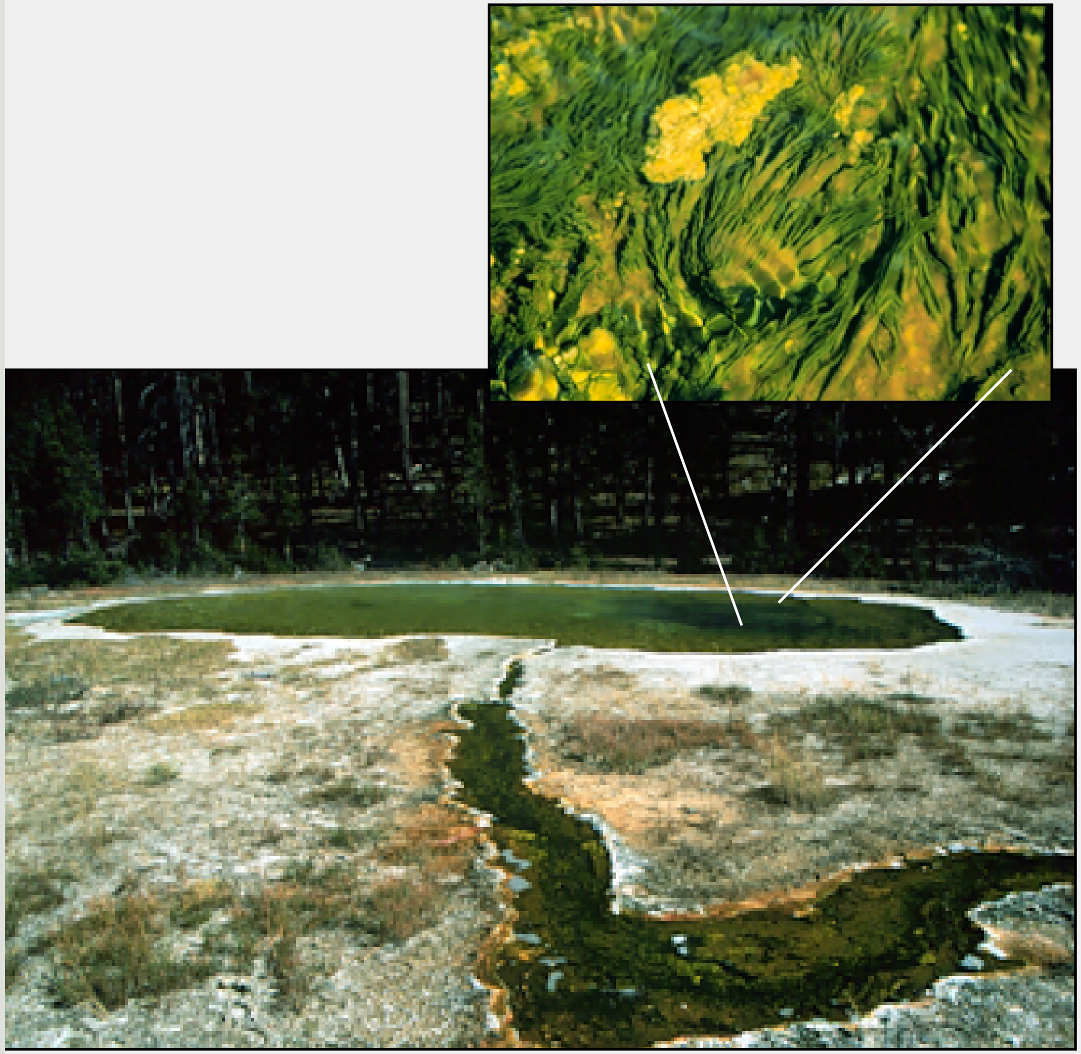
What next?

What next? Basic research

- Continue exploration of Earth
- Survival and evolution of terrestrial organisms in space
- Search for life elsewhere based on what we find on earth.

What next? Applied research

- Big biotech effort on Earth. Search for extremophile biomolecules to improve industrial processes. Use of extremophiles themselves in bioremediation.
- Suggest new field: biotech in space. Life support, terraforming.
- Biomining for synthetic biology.
- Medical - human limits



Commercial Extremozymes

http://www.mediscover.net/Extremophiles.cfm

organisms	enzyme	applications
Thermophiles	DNA polymerases	DNA amplification
	Lipases, pullulanases and proteases	Baking and brewing
	Xylanases	Paper bleaching
Halophiles	bacteriorhodopsin	Optical switches and photocurrent generators
	lipids	Liposomes for drug delivery and cosmetics
	Compatible solutes e.g. Ectoin	Protein, DNA and cell protectants
	g-Linoleic acid, b-carotene and cell extracts,e.g. Spirulina and Dunaliella	Health foods, dietary supplements, food colouring and feedstock
Psychrophiles	Alkaline phosphatase	Molecular biology
	Proteases, lipases, cellulases and amylases	detergents
	Polyunsaturated fatty acids	Food additives, dietary supplements
	Ice nucleating proteins	Artificial snow, food industry e.g. ice cream
Alkaliphiles and Acidophiles	Proteases, cellulases, lipases and pullulanases	detergents
	Elastases, keritinases	Hide de-hairing
	Cyclodextrins	Foodstuffs, chemicals and pharmaceuticals
Acidophiles		Fine papers, waste treatment and de-gumming
Sulfur-oxidizing acidophiles		Recovery of metals and de-sulphurication of coal

Text

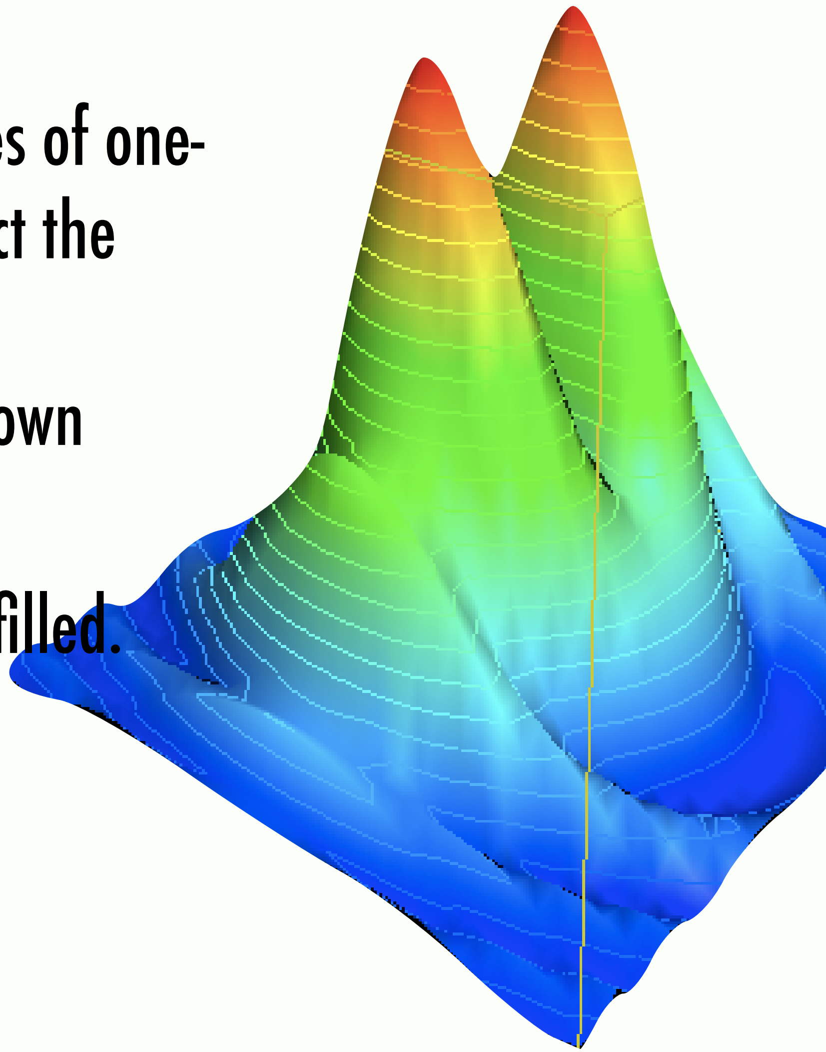
What

does this

mean?

Suggestion

- Evolution makes its way to localized adaptive peaks.
- Thus, although we have presented a series of one-dimensional environmental ranges, in fact the environment is n-dimensional. Some I've mentioned (high temp + acid), others known (e.g., alkaline + saline).
- Probably this n-dimensional space is not filled.



Concluding thoughts.

- Extremophiles are intimately connected with the fact that we are based on organic carbon in liquid water.
- The story of extremophile research is many stories that have come together in the field of astrobiology.
- The envelope for life is far beyond what we could have imagined; thus, the habitats for life have been expanded.
- Some adaptations to life in extreme environments are biochemically simple or convergent, suggesting that it could happen elsewhere.
- The reasonable man adapts himself to the world; the unreasonable one persists in trying to adapt the world to himself. Therefore, all progress depends on the unreasonable man. George Bernard Shaw

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

life beyond earth?

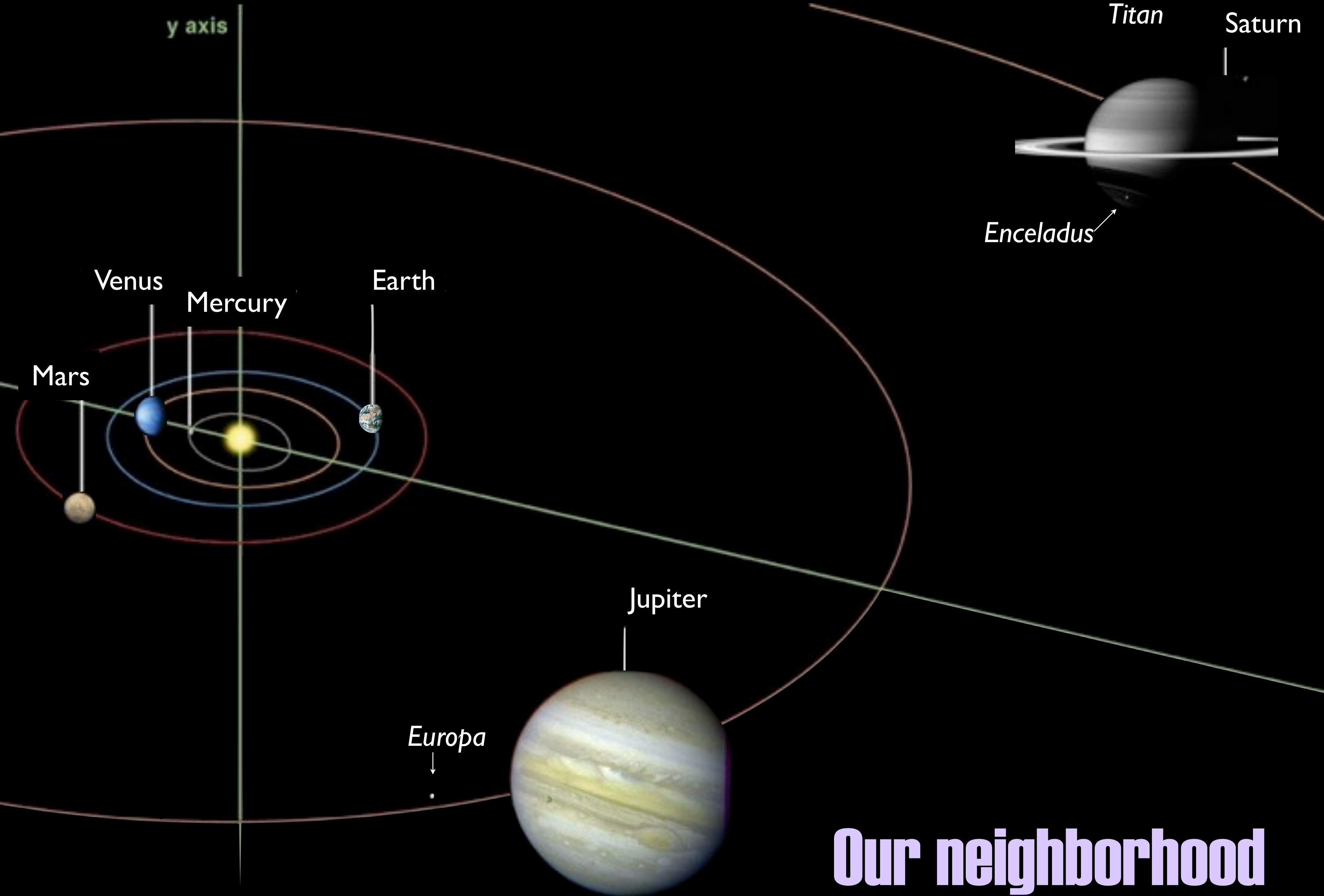

"This is Iowa. Io is a moon of Jupiter."

life beyond earth?

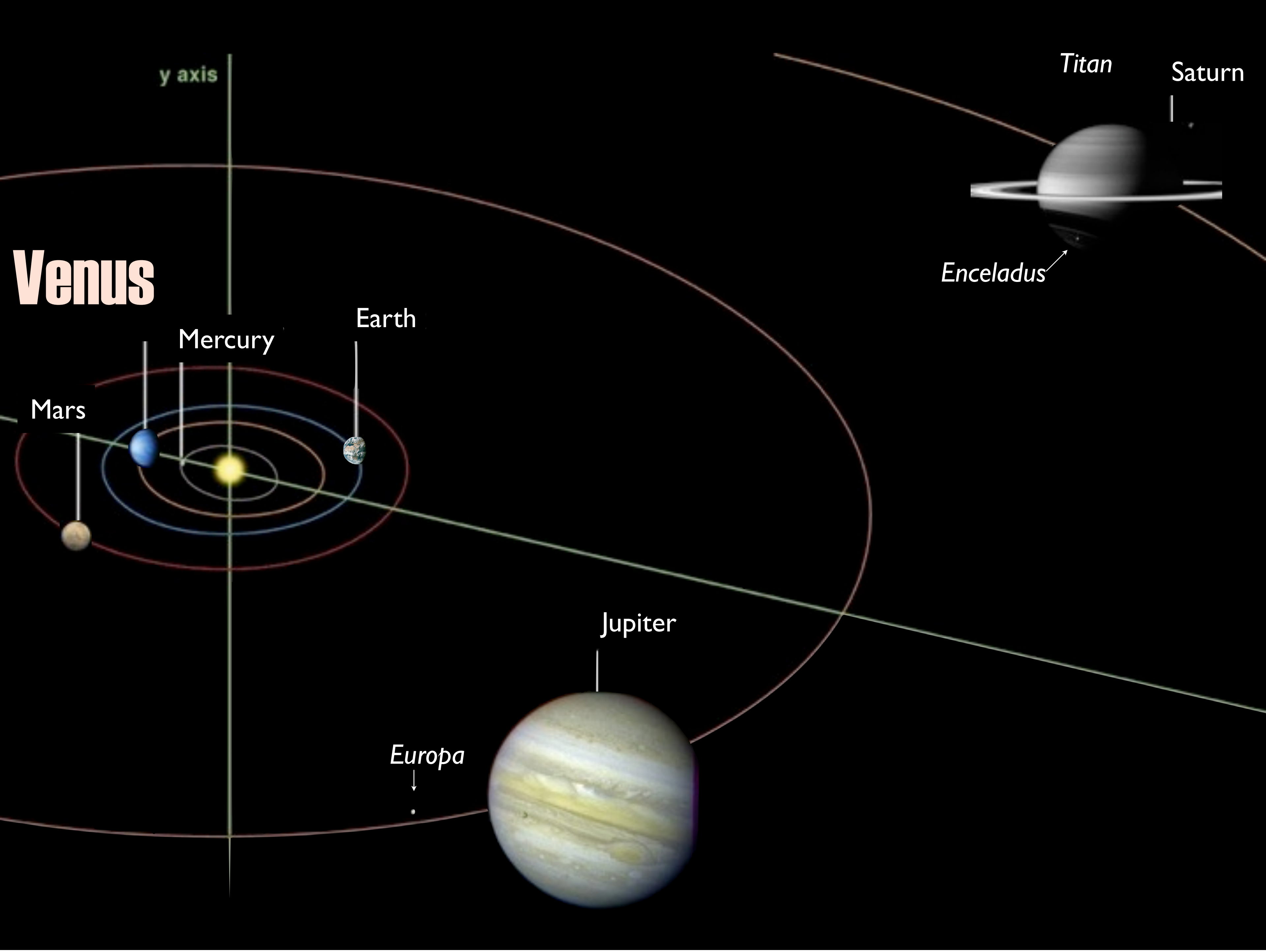
NASA's Mantra: *Follow the water*

Space: a new category of extreme environment

- Differences in atmospheric composition
- Altered gravity
- Space vacuum
- Temperature extremes
- Nutrient sources (e.g., organic carbon, nitrogen)
- Different radiation regime (solar and cosmic)

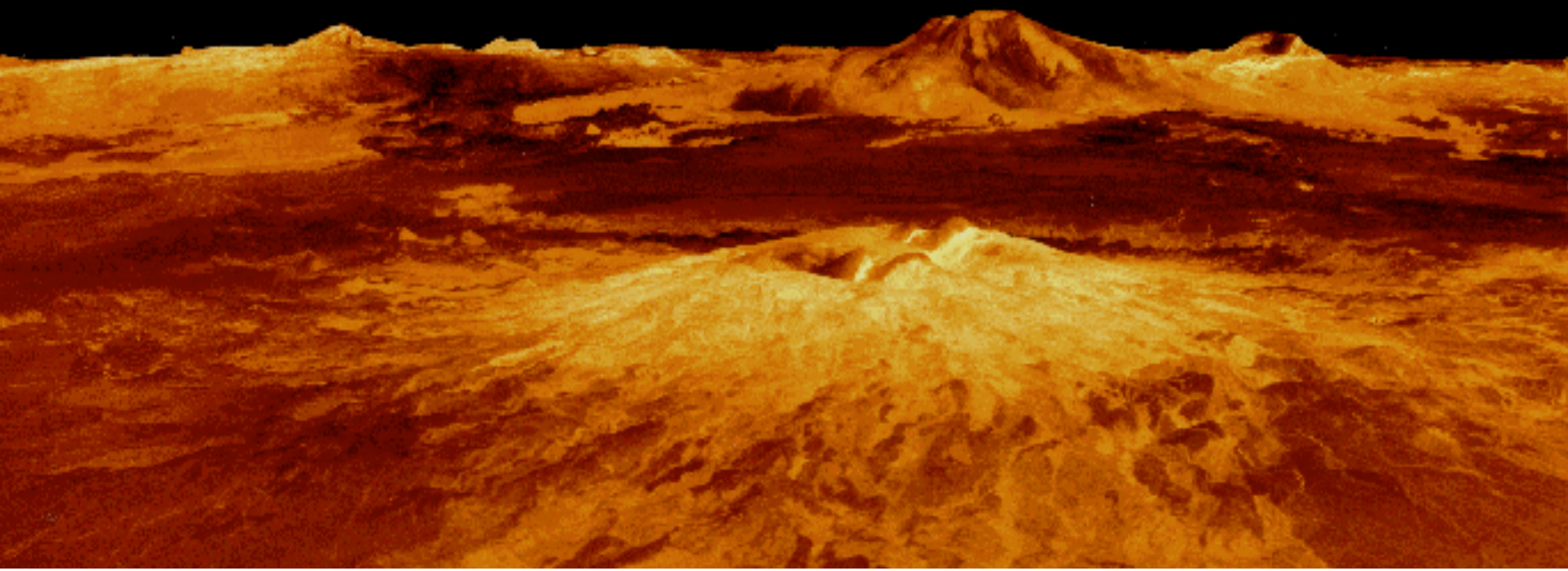


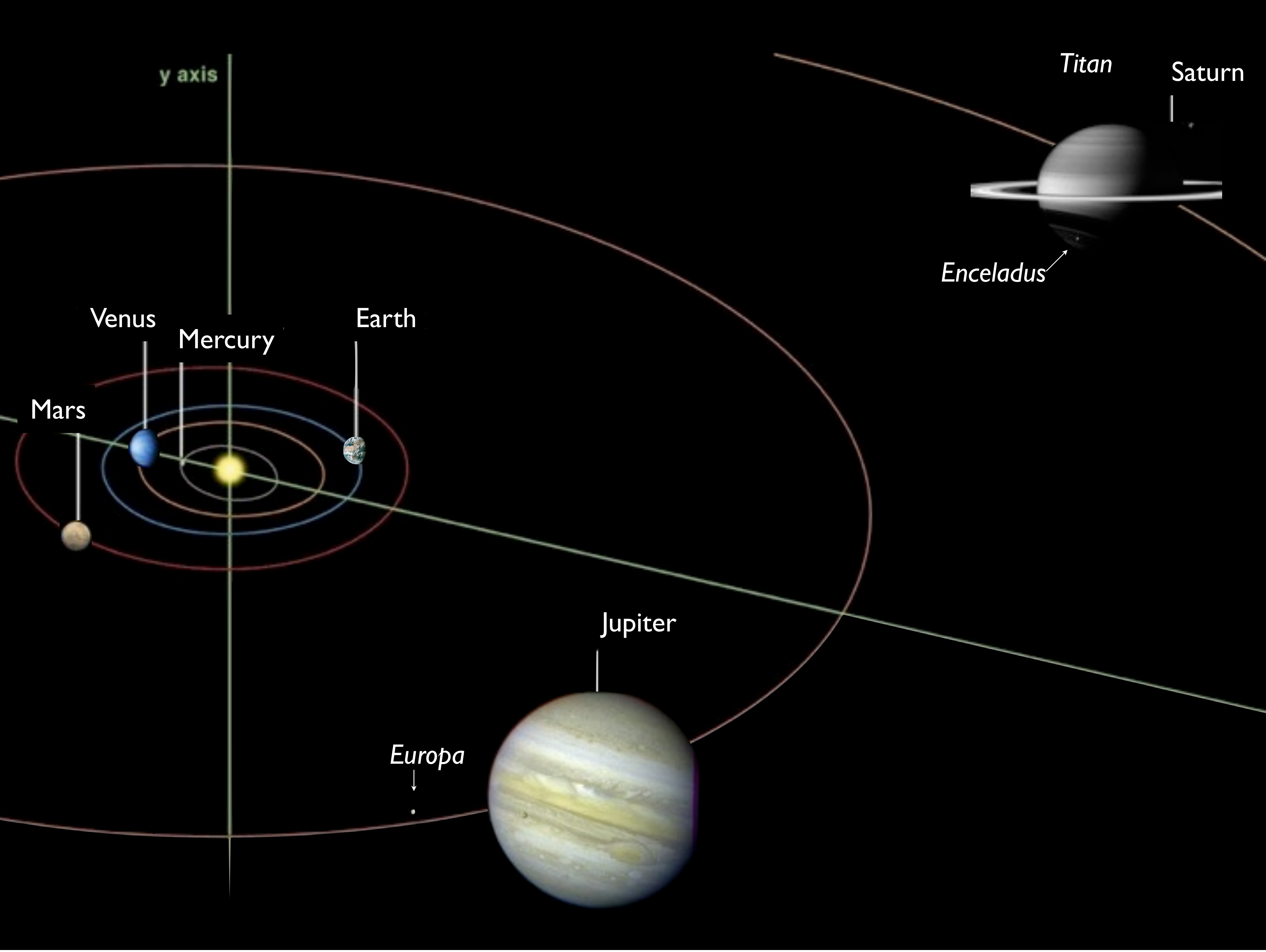
Our neighborhood


Venus
y axis
Titan
Saturn
Enceladus
Mercury
Earth
Mars
Jupiter
Europa

Why even talk about Venus?

- Earth's "twin" that went bad: lessons for us?
- Chemically lively surface (tectonics, but not plate tectonics) and chemistry
- Potential for past life on surface *(Grinspoon, Lonely Planets: the Natural Philosophy of Alien Life)*
- Potential for life in the clouds

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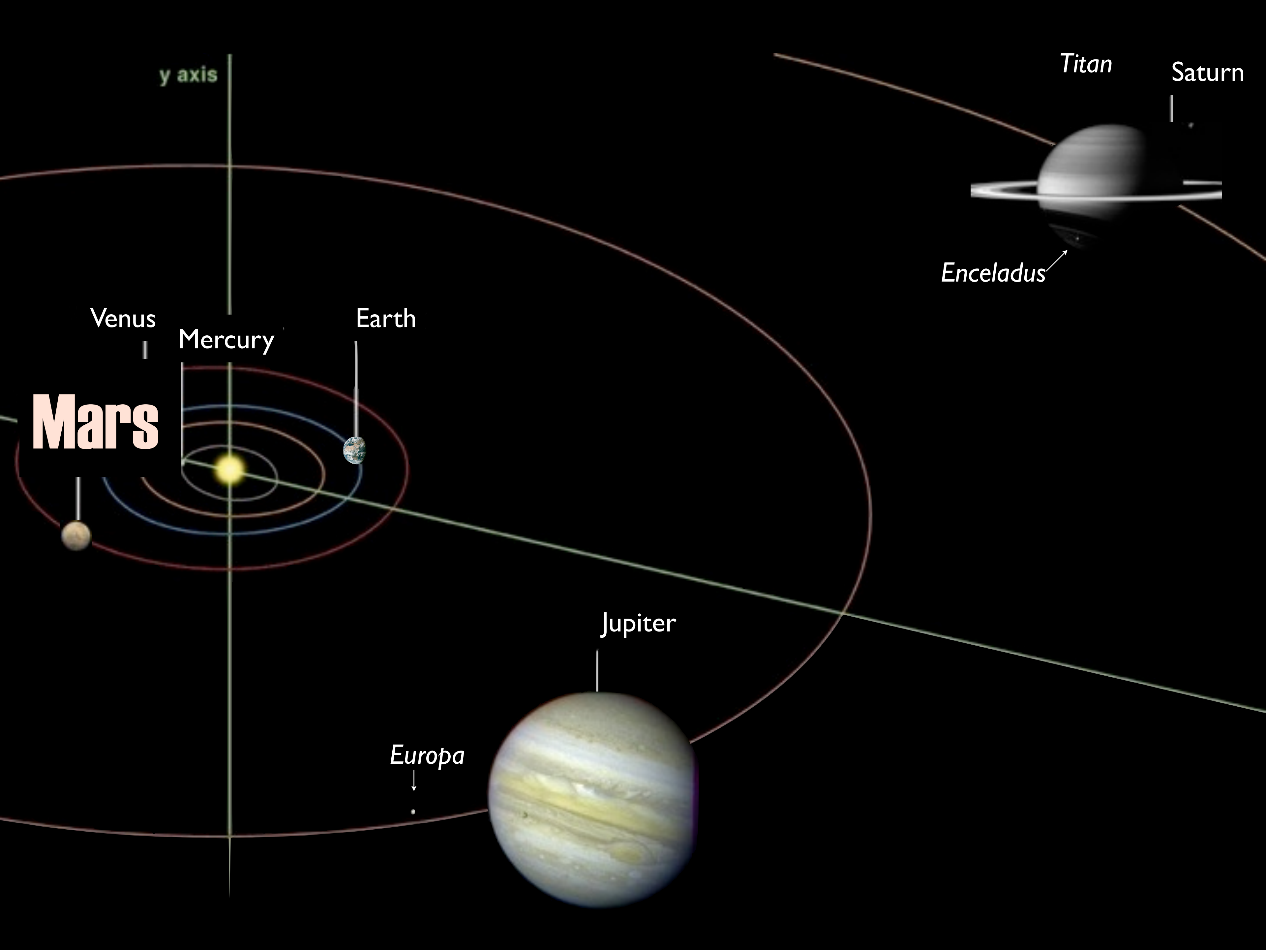
y axis
Titan
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Earth
Mars
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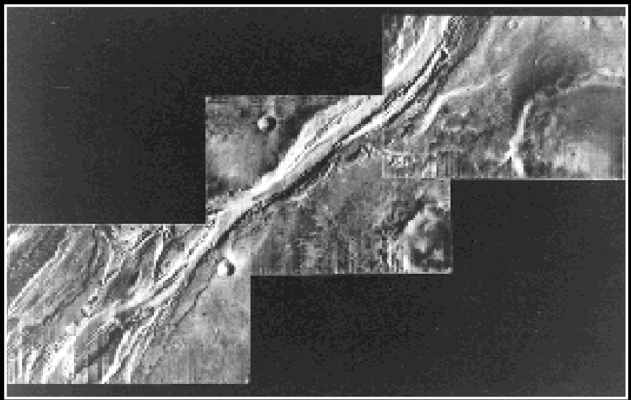
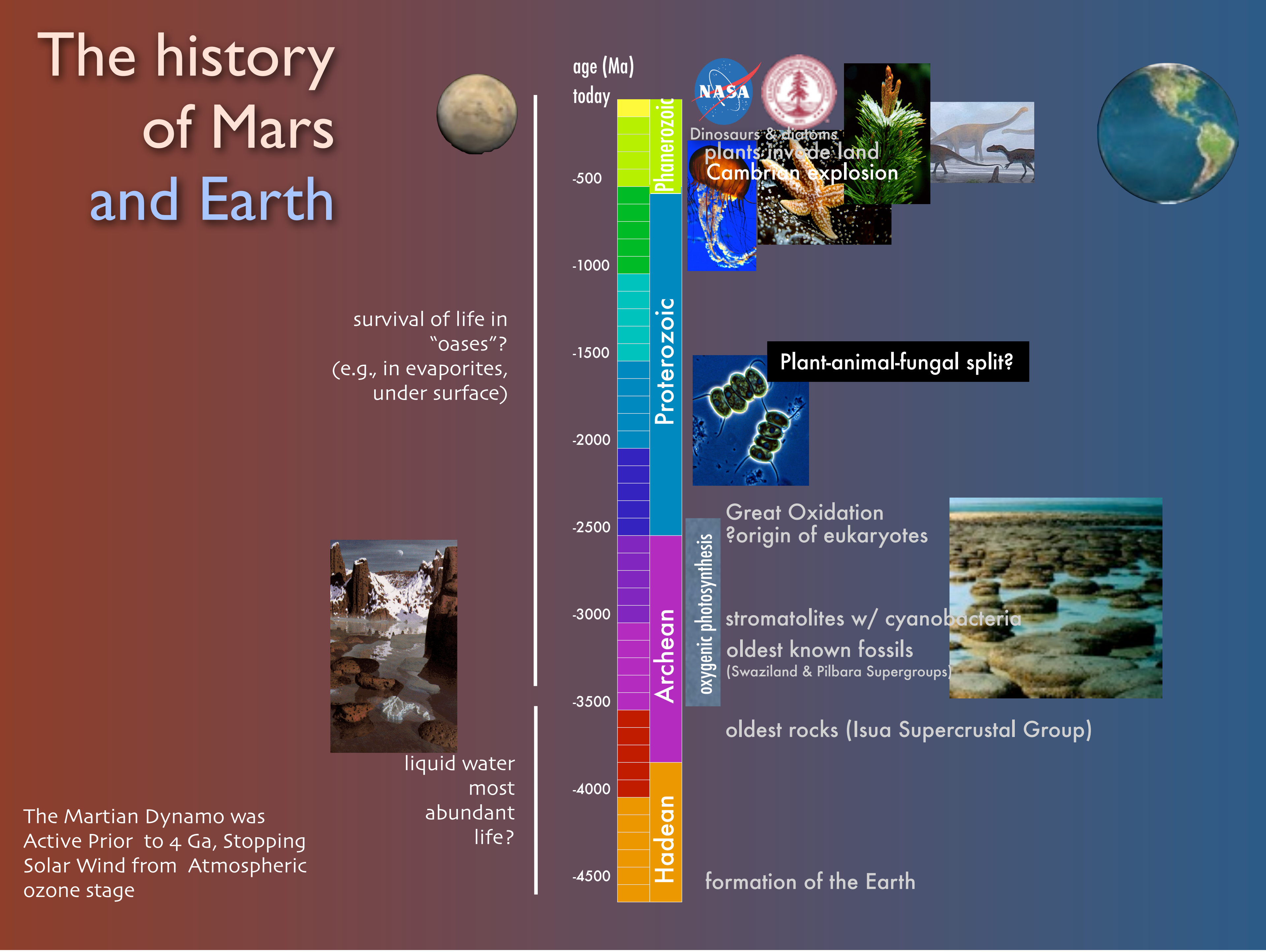
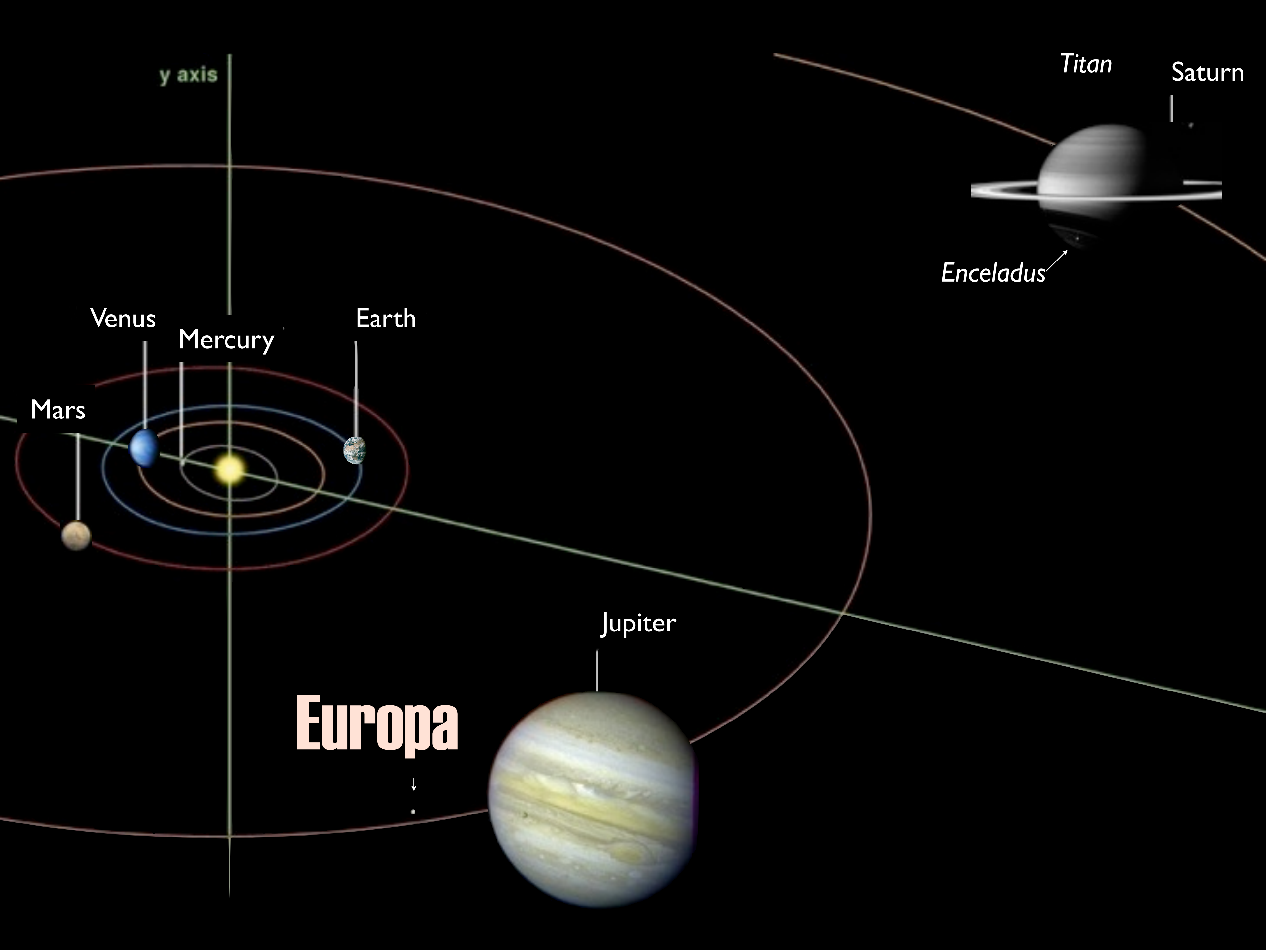
Europa

Mariners

- Mariner 4 (launched 1964) gave the first glimpse of Mars at close range, putting to rest myths that Mars may have harbored an advanced civilization.




The history
of Mars
and Earth
age (Ma)
today
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
Phanerozoic
Proterozoic
Archean
Hadean
oxygenic photosynthesis
Dinosaurs & diatoms
plants invade land
Cambrian explosion
Plant-animal-fungal split?
Great Oxidation
?origin of eukaryotes
stromatolites w/ cyanobacteria
oldest known fossils
(Swaziland & Pilbara Supergroups)
oldest rocks (Isua Supercrustal Group)
formation of the Earth
survival of life in
"oases"?
(e.g., in evaporites,
under surface)
liquid water
most
abundant
life?
The Martian Dynamo was
Active Prior to 4 Ga, Stopping
Solar Wind from Atmospheric
ozone stage


y axis
Titan
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Earth
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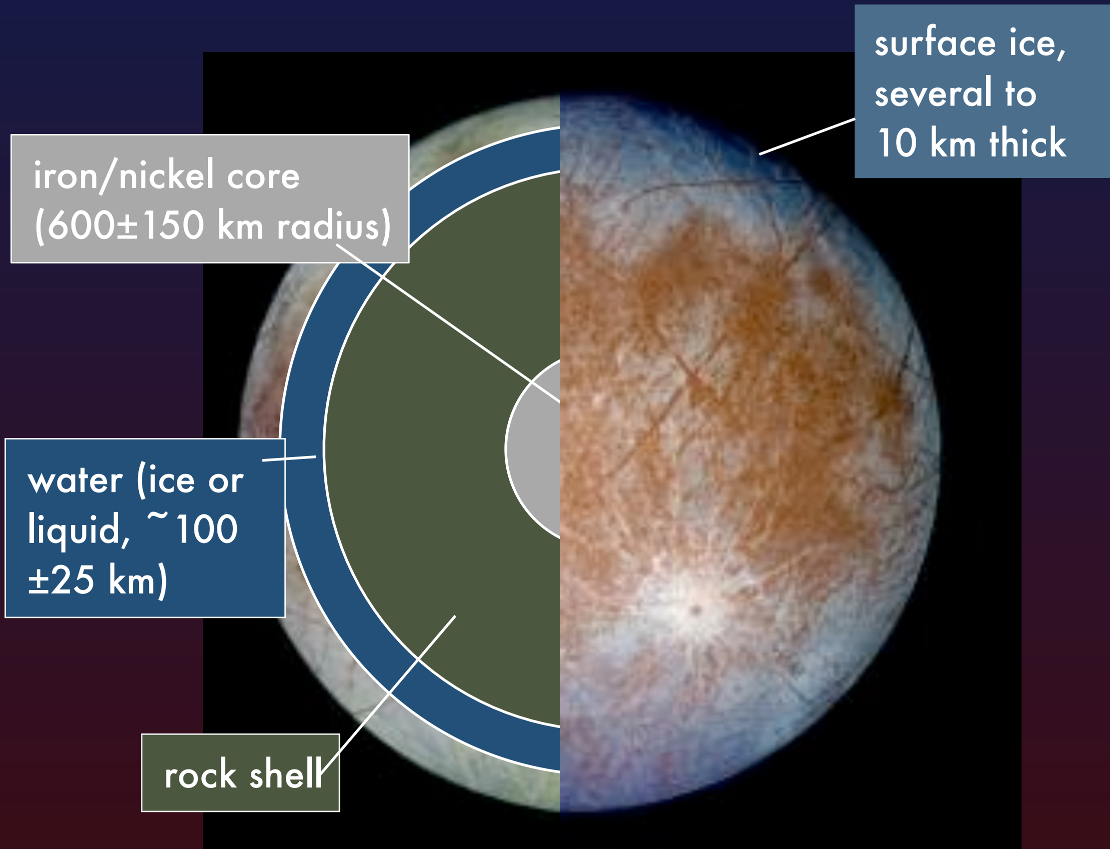
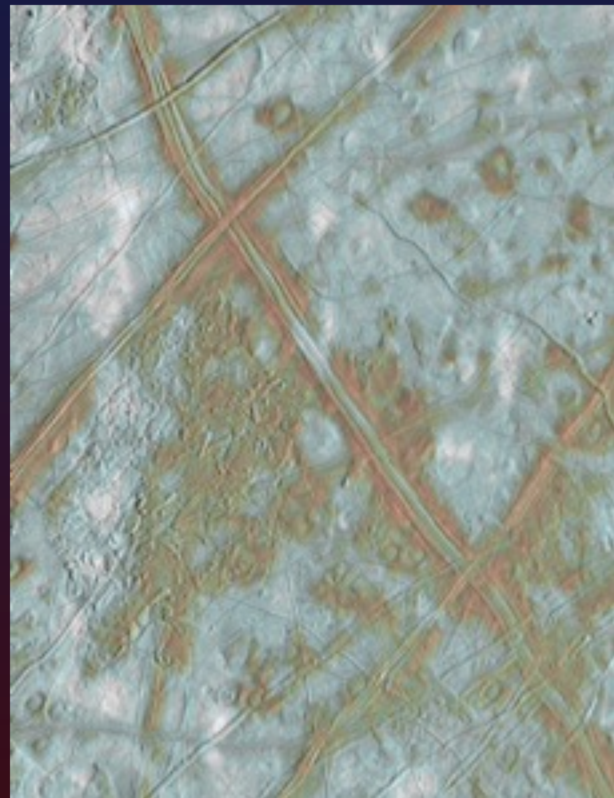
Jupiter
Europa

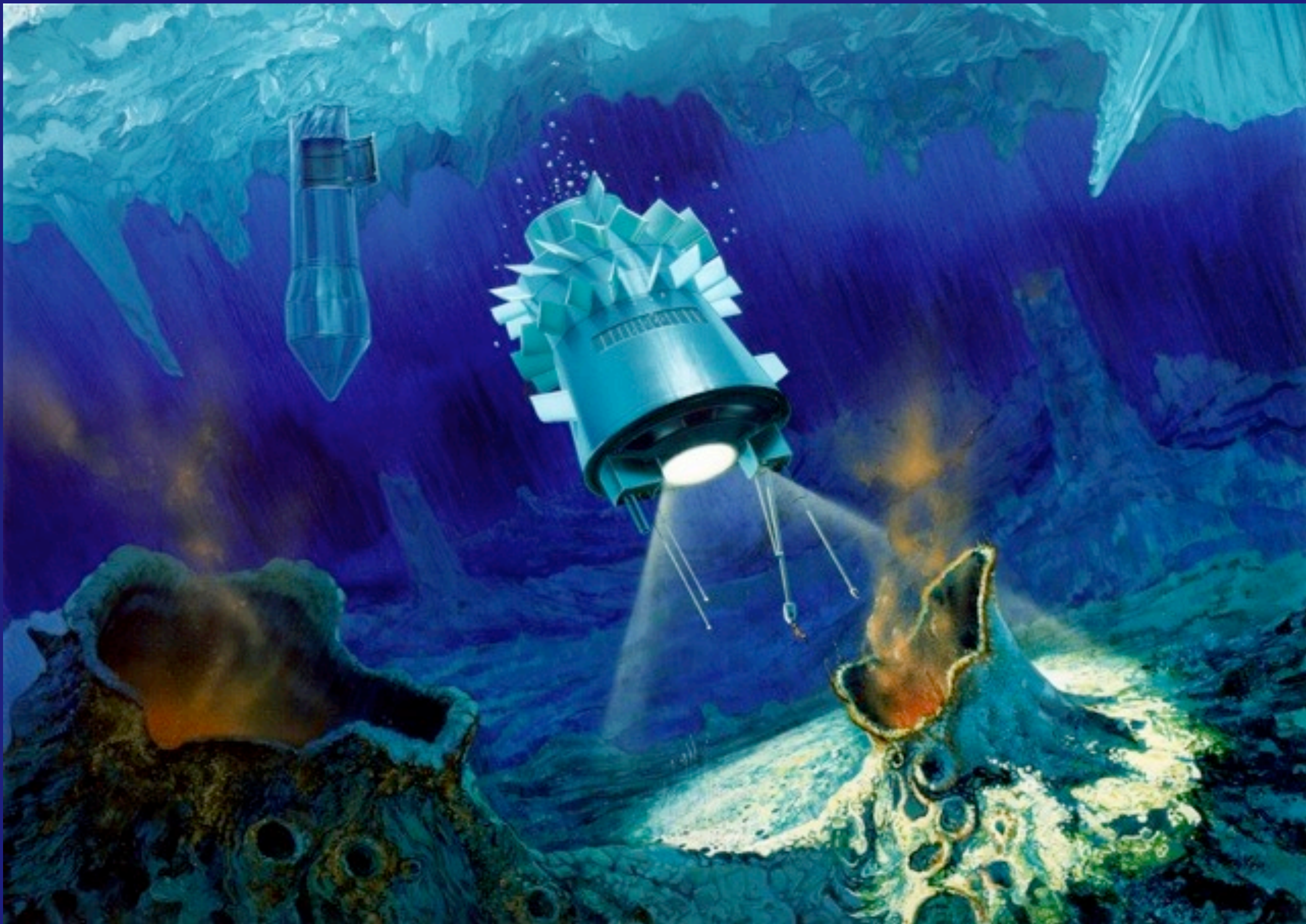
Why Europa?
Liquid water, charged particle-induced chemistry, volcanic activity(?)



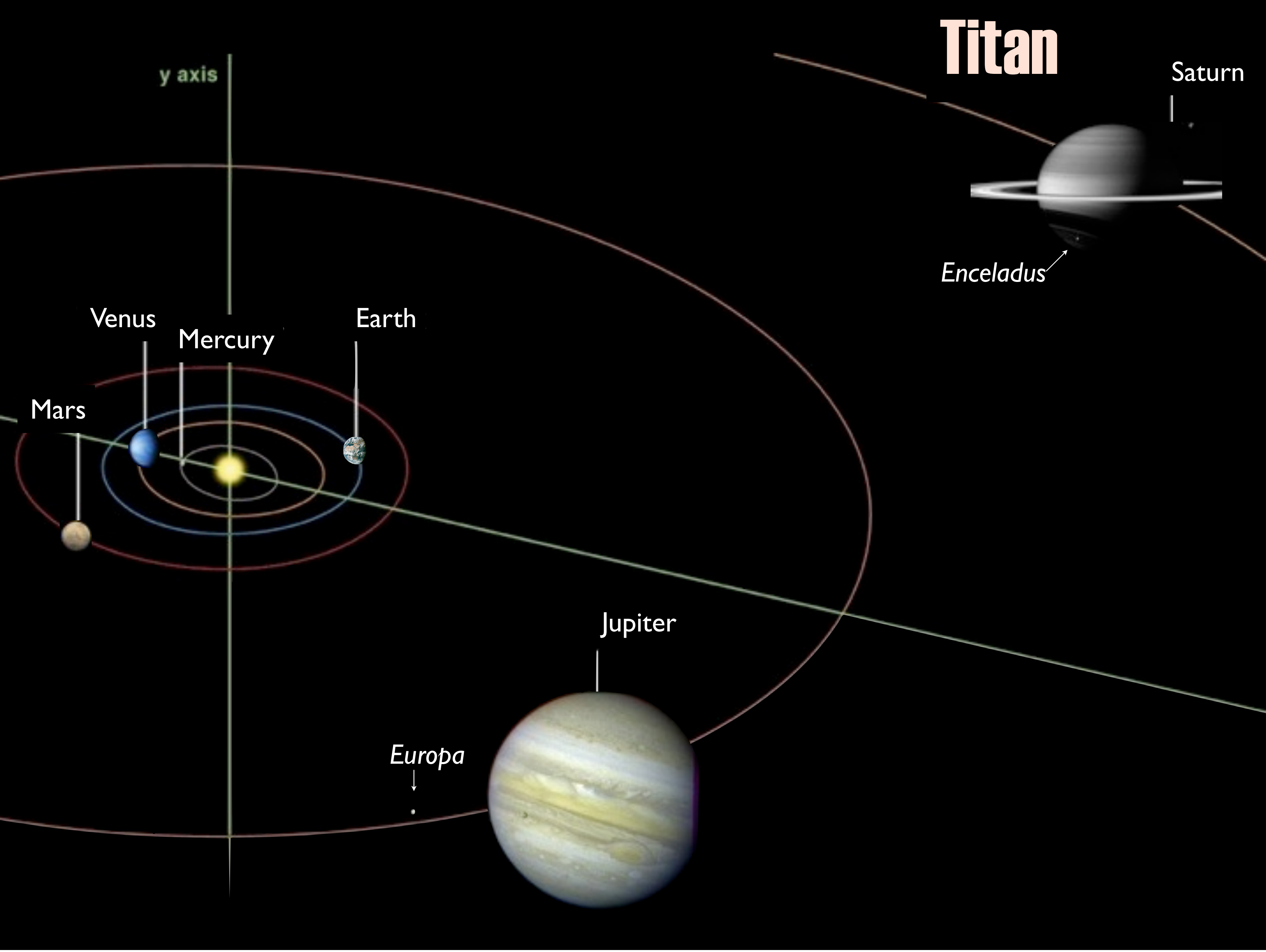
Radius of Europa: 1565 km, a little smaller than our Moon's radius.



Thin, disrupted, ice crust. Images collected in 1996 by Galileo.



A mission could be devised that would drill through the ice layer and release a probe into the liquid underneath. This is the "hydrobot" concept. http://www.resa.net/nasa/europa_life.htm


Titan
Saturn
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y axis
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Europa

Headline, 14 January 2005:

Huygens’ has touched down on Titan

Huygens' primary goal was to return information on the atmosphere; data about the surface was a bonus. (Image: ESA)

Composite of Titan's varied terrain

When the probe landed, it was not with a thud, or a splash, but a 'splat'. It landed in Titanian 'mud'.

- This composite was produced from images returned January 14, 2005, by the European Space Agency's Huygens probe during its successful descent to land on Titan. It shows the boundary between the lighter-colored uplifted terrain, marked with what appear to be drainage channels, and darker lower areas.
- These images were taken from an altitude of about 8 kilometers (about 5 miles) and a resolution of about 20 meters (about 65 feet) per pixel. The images were taken by the Descent Imager/Spectral Radiometer, one of two NASA instruments on the probe.

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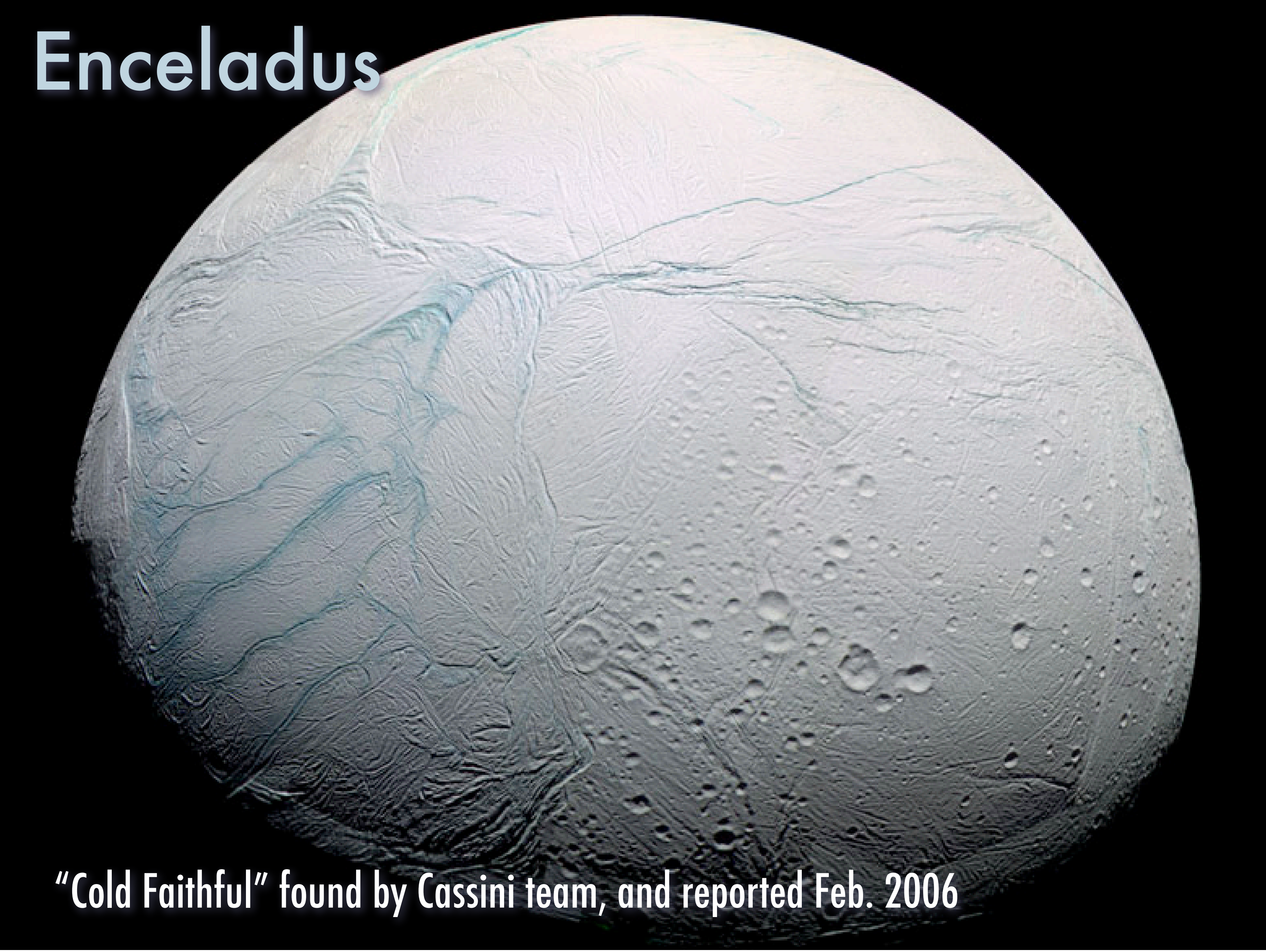
Enceladus

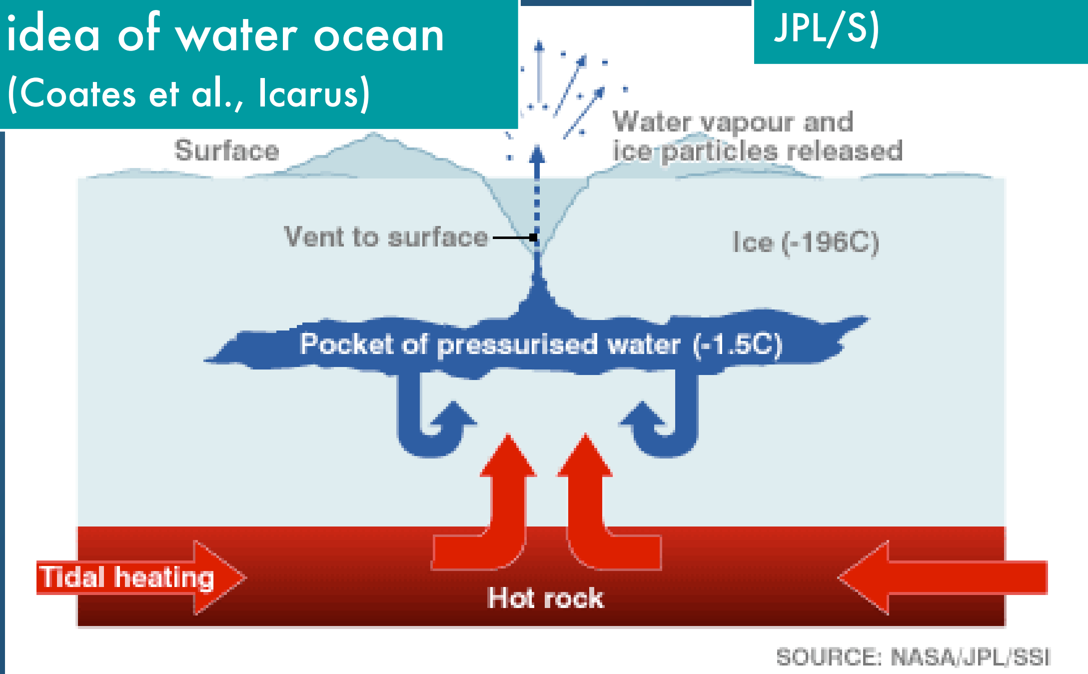


“Cold Faithful” found by Cassini team, and reported Feb. 2006

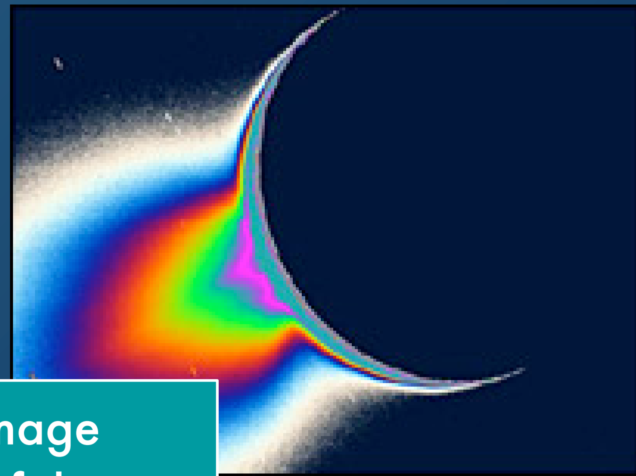
Enceladus

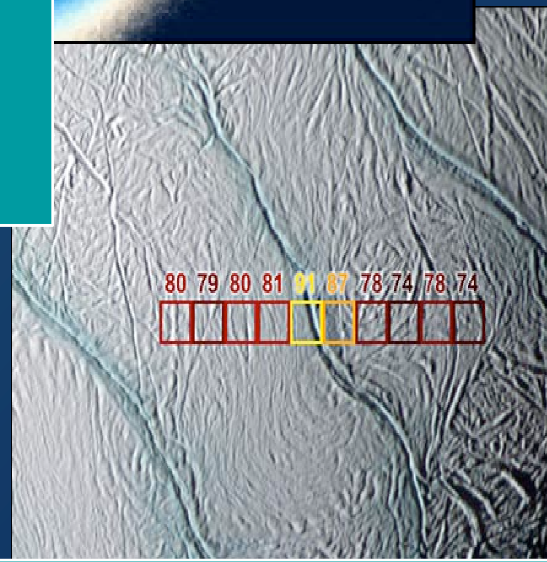
"Cold Faithful" found by Cassini team, and reported February 2006!

There is sodium and negatively charged water molecules in plumes supporting idea of water ocean (Coates et al., Icarus)



This false-colour image shows the extent of the active region (Image: Nasa/ JPL/S)

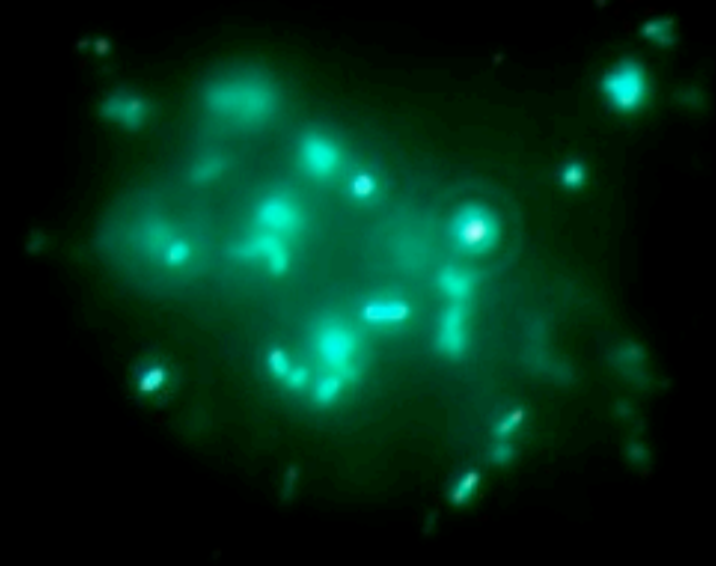




The heat emission is associated with the tiger stripe features which mark the southern pole. The temperatures are in Kelvin (zero K equals -273C).

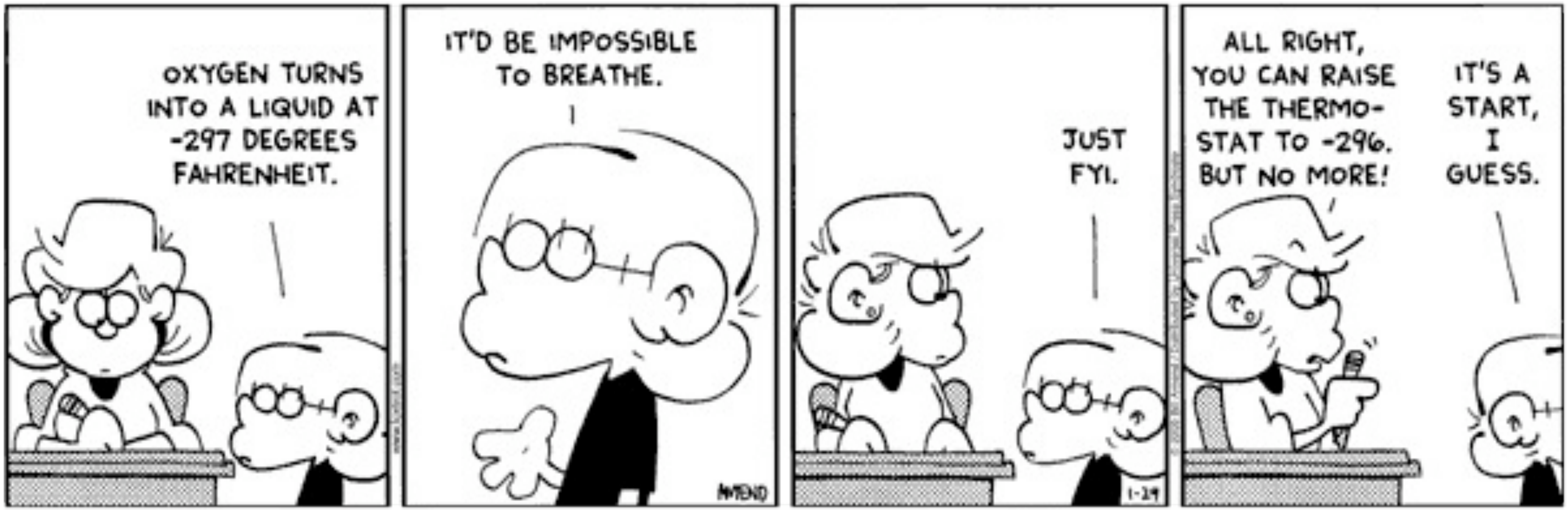
http://news.bbc.co.uk/2/hi/science/nature/4895358.stm

What about the origin of life?



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

Concluding thought, part 2.



A good start in the literature

- Rothschild, L.J. & R.L. Mancinelli (2001) Life in extreme environments. Nature (London) 409: 1092-1101.
- Rothschild, L.J. and Giver, L.J. (2003) Photosynthesis below the surface in a cryptic microbial mat. Intl. J. Astrobiology 1: 295-304.
- Rothschild, L.J. & A. Lister (eds.) Evolution on Planet Earth: The Impact of the Physical Environment. Academic Press. 2003. 456 pp.
- Human adaptation: Frances Ashcroft (2001) Life at the Extremes. The Science of Survival. Flamingo Press, London. 326 pp.

horizon are we alone in the universe?

The hunt for second Earth
Tuesday 4 March at 9pm on BBC TWO
'Told via stunning visuals and a playful narrative'
Time Out London

Written & Directed **Gideon Bradshaw**
Camera **Kevin White**
Sound **David Strayer**
Edited **Darren Jonunas & Martin Johnson**
Graphics **Jason White & Rob Chiu**
Research **Tom Ranson**
Horizon Editor **Andrew Cohen**