Thinking Out of the Habitability Box!

…or is that underneath the box???

Art: Adam Hetmansky

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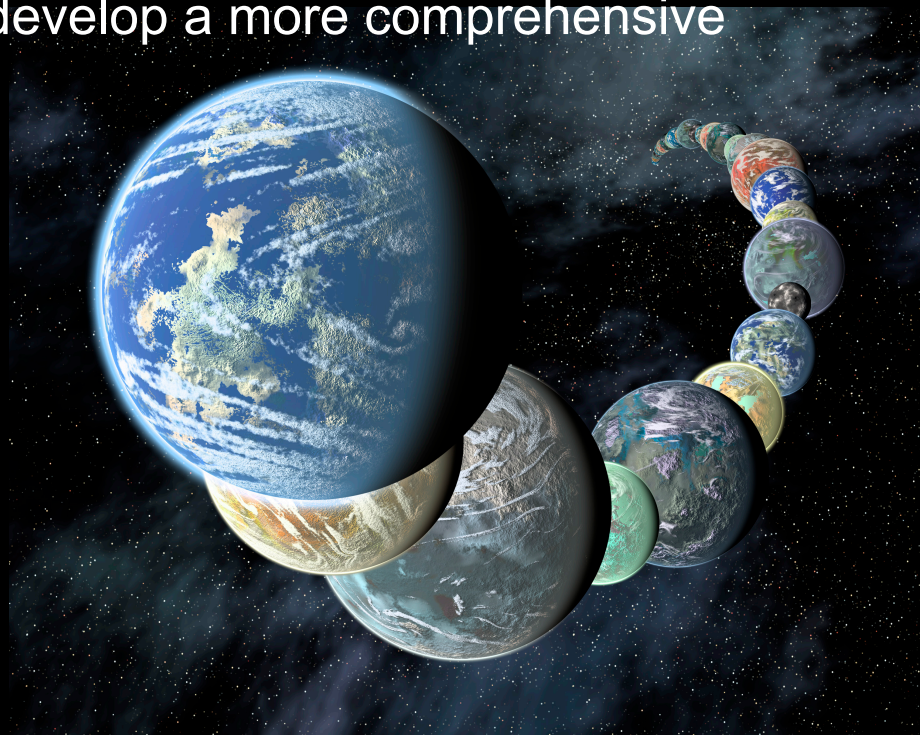
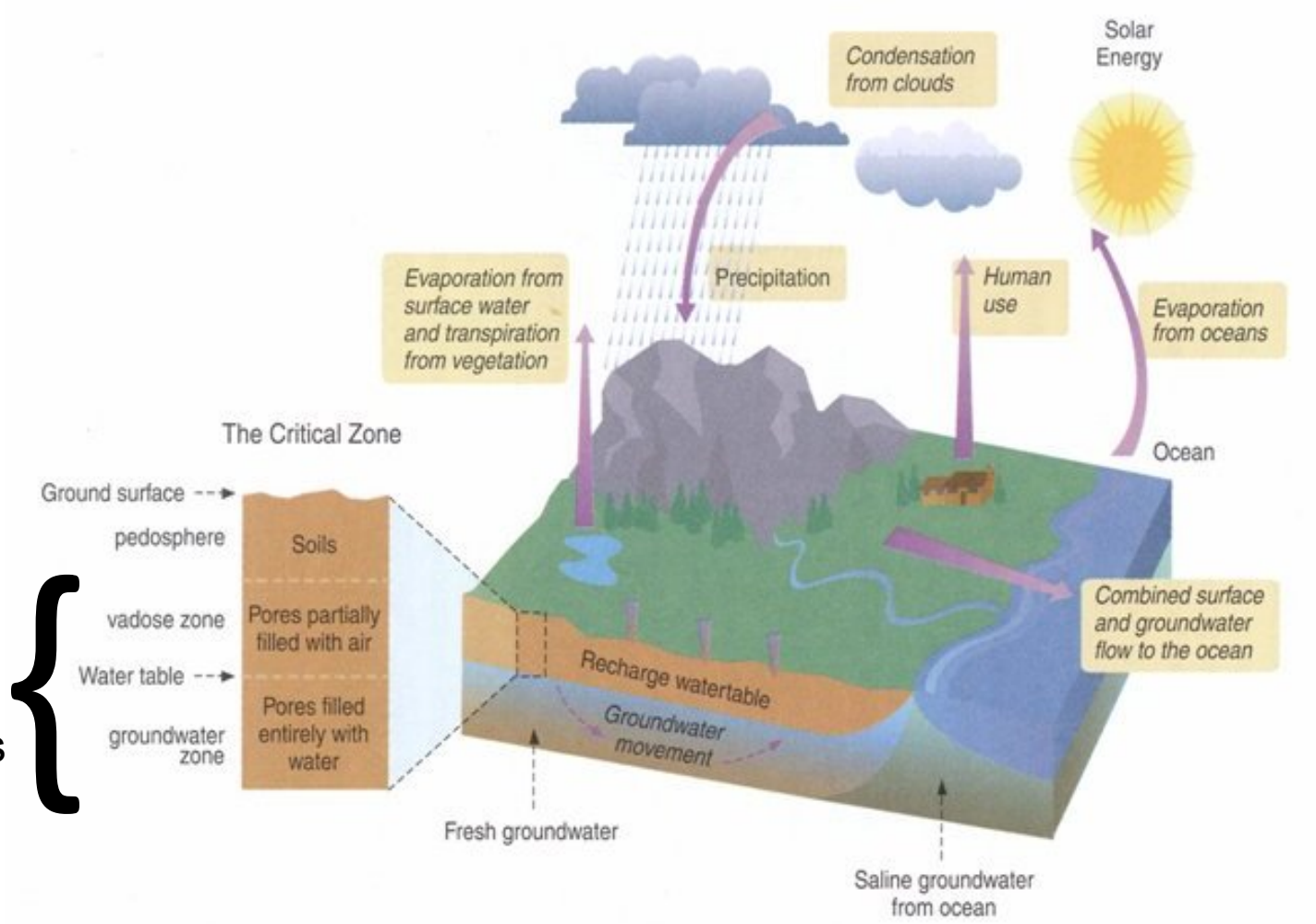
What Kind of Habitability Are We Looking For?

- ✧ Earth-like planets are the low-hanging fruit.
- ✧ How habitable does that really mean???
- ✧ From exoplanet studies so far…
  so MANY kinds we don't have in our Solar System!
- ✧ Can we, should we, attempt to develop a more comprehensive Theory of Habitability?



"***Earth's Critical Zone*** *is the heterogeneous, near surface environment in which complex* ***interactions involving rock, soil, water, air, and living organisms*** *regulate the natural habitat and determine the availability of life-sustaining resources*" (NRC, 2001)*.

Caves
Aquifers
Fractures



* National Research Council, 2001. *Basic research opportunities in earth science*.

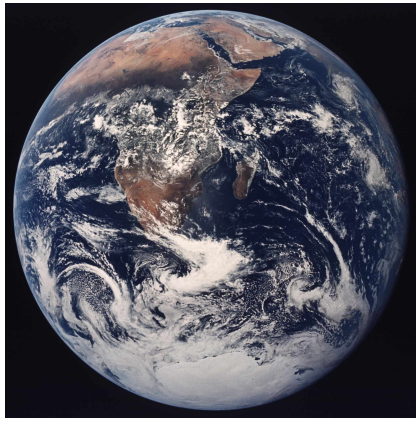
What Kind of Planet Is It?

Planet Type 1 Biosphere

Sunlight "just right"
Green
Gooey
Gases in non-equilibrium

Critical Zone is top-down
Photosynthetically driven

Well mixed-Critical Zone



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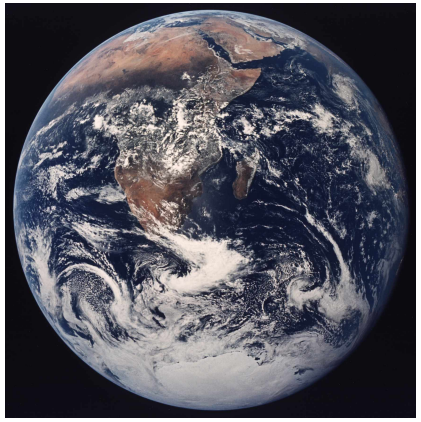
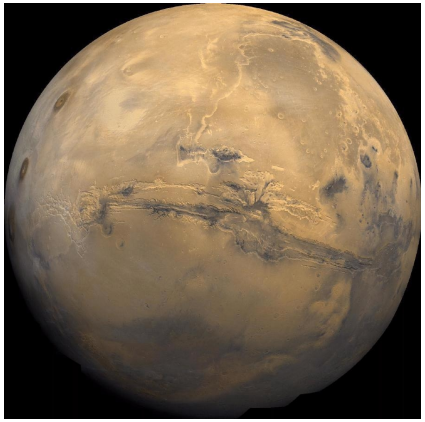


Planet Type 2 Biosphere

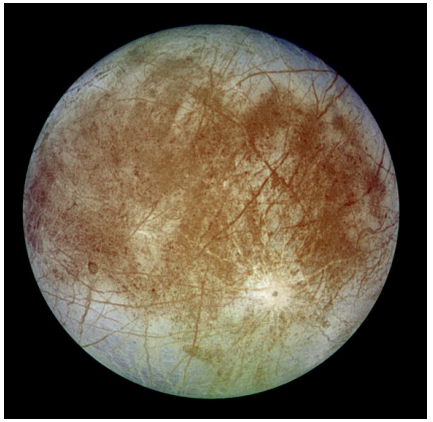
No visible means of support
Not green
Not gooey
Gases in chemical equilibrium
Exceptions dependent upon crustal leakiness

Critical Zone is bottom-up
Chemosynthetically driven

Stratified Critical Zone?

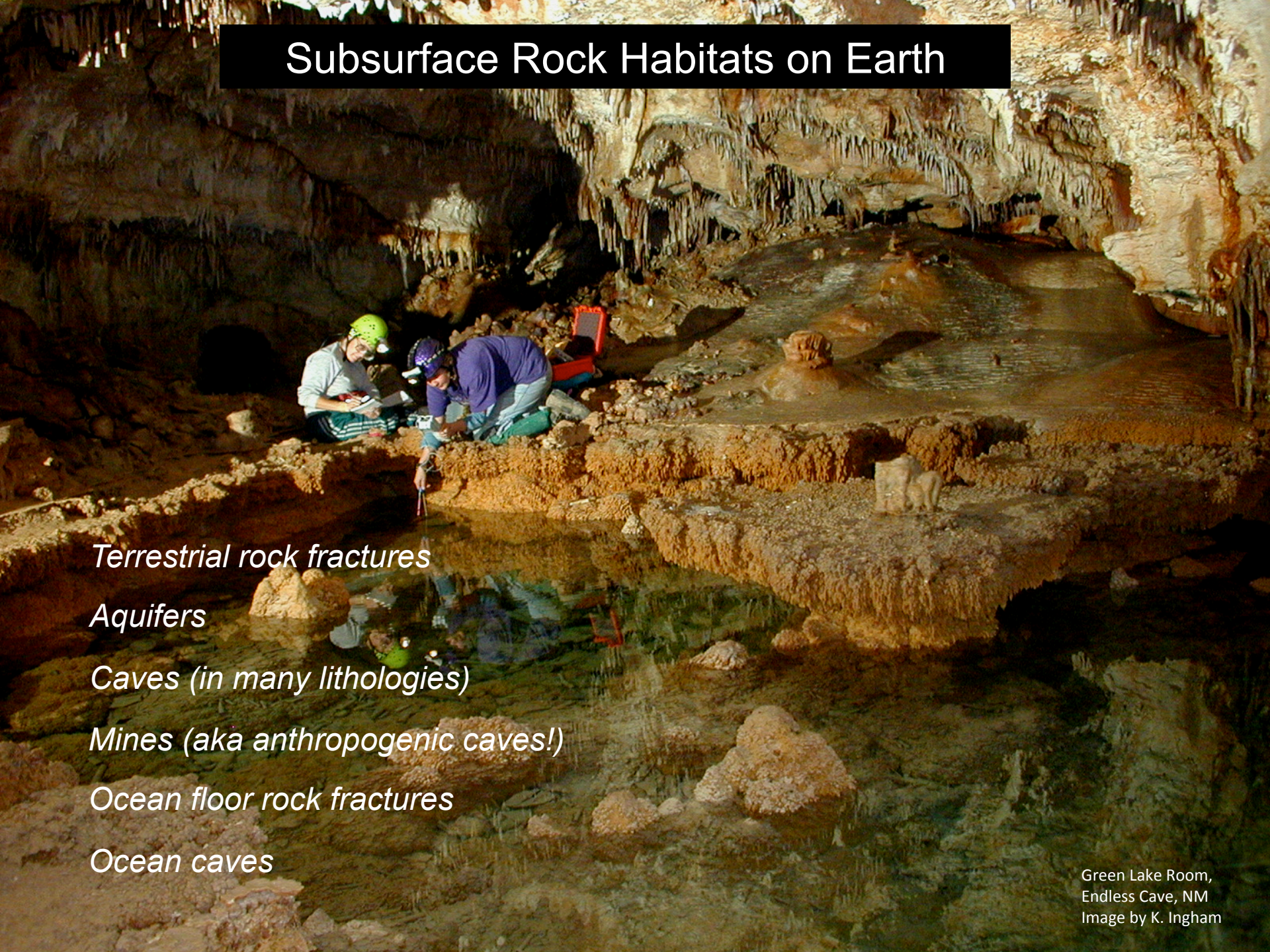


Mars



Europa

Subsurface Rock Habitats on Earth



Terrestrial rock fractures

Aquifers

Caves (in many lithologies)

Mines (aka anthropogenic caves!)

Ocean floor rock fractures

Ocean caves

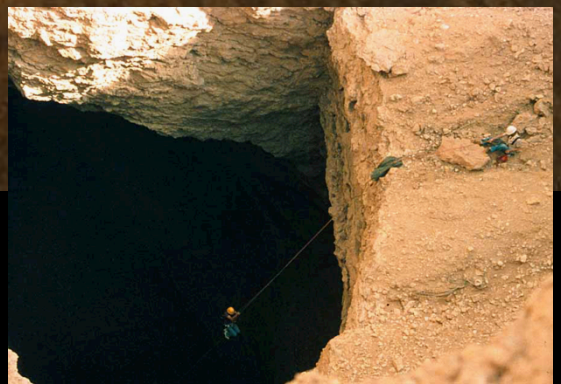
Green Lake Room,
Endless Cave, NM
Image by K. Ingham

The Planet Within

Caves & mines provide a window into a subsurface that is radically different from the surface

Images by John Pint

Rub al Khali (Empty Quarter)
Saudi Arabia, Oman, Yemen, and United Arab Emirates



Subsurface Environments

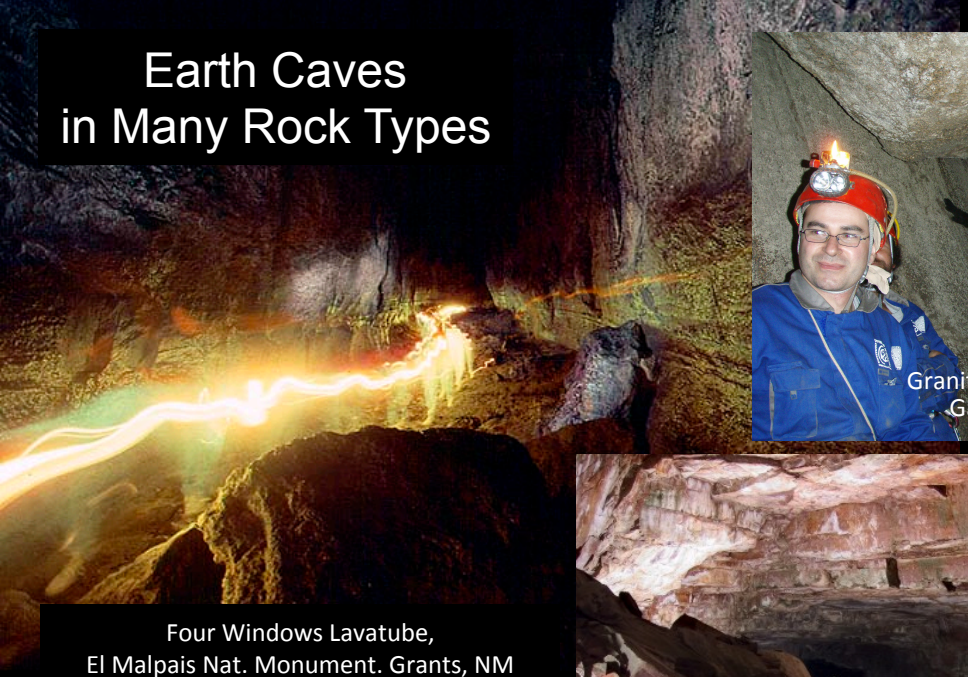
- No sunlight (past the twilight zone)
- High humidity
- Temperatures constant

- Low organic nutrients
- Mineral-rich
- Unusual chemical energy sources (e.g. H_2S)

- No surface weather
- Splendid preservation environment!

Entrance Drop
Lechuguilla Cave, NM
Photo by David Jagnow

Earth Caves in Many Rock Types



Four Windows Lavatube,
El Malpais Nat. Monument. Grants, NM

Granite spalling caves
Gallicia, Spain

Lechuguilla Cave, Carlsbad, NM
created by sulfuric acid and limestone

Cueva de Charles Brewer
Quartzite Cave, Venezuela

Antarctic caves in ice

Caves in Salt
Atacama Desert, Chile

Submarine caves
Costa Rica

Lilburn Marble Cave, CA

Parks Ranch Gypsum Cave,
Carlsbad, NM

Gee Whiz Cave Facts

Longest Limestone Cave:

Mammoth Cave, Kentucky, USA – 557 km (350 miles) total

Longest Gypsum Cave:

Optimisticeskaja Cave, Ukraine – 212 km (133 miles) total

Longest Lava Tube:

Kazumura Cave, Hawaii, USA – 66 km (42 miles) total

Longest Underwater Cave:

Sistema Ox Bel Ha, Quintana Roo, Mexico – 97 km (60 miles) total

Deepest Cave:

Voronya (Krubera) Cave, Arabica Massif, Georgia – 2.2 km (1.4 miles) deep

Deepest Mine:

South Africa – 4.1 km (2.75 miles) deep

Sulfuric acid (pH=0), H_2S, CO, & other reduced gases

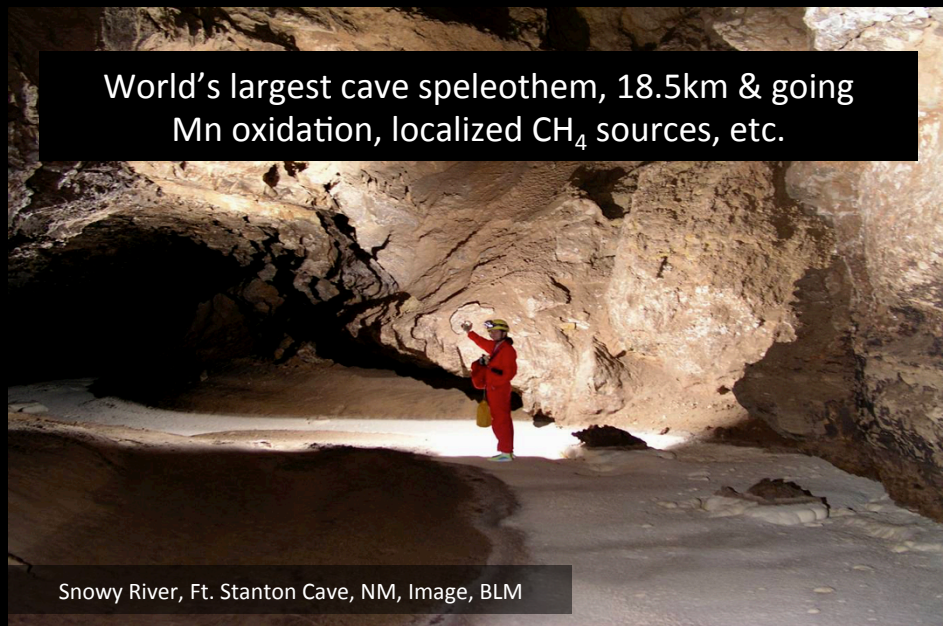
Cueva de Villa Luz, Tabasco, Mexico

-3°C, SO_2 , CO_2, CO & other gases

Fumarolic Caves in ice, Mt. Rainier, WA

40-60°C, 100% Rh

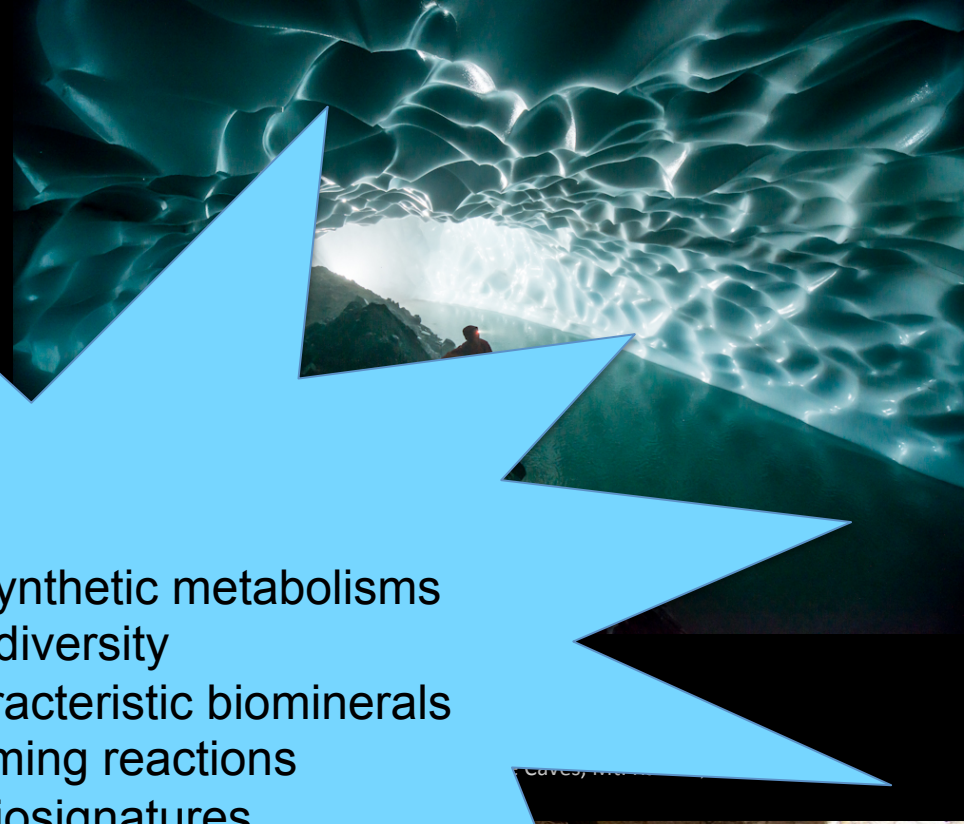
Naica Caves, Chihuahua, Mexico



World's largest cave speleothem, 18.5km & going
Mn oxidation, localized CH_4 sources, etc.

Snowy River, Ft. Stanton Cave, NM, Image, BLM

Sulfuric acid (pH=0), H-



In search of…

Novel chemosynthetic metabolisms
Stupefying biodiversity
Unique or characteristic biominerals
Metal-transforming reactions
Unequivocal biosignatures

40-60°C, 100% Rh

Naica Caves, Chihuahua, Mexico

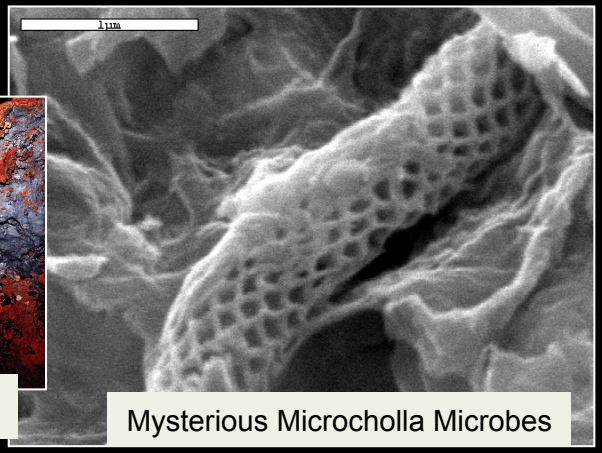
argest ca- -ion, 18.5km & going

Snowy River, Ft. Stanton Cave, NM, Image, BLM

The Hunt for Blue Goo
Copper Subsurface Organisms

snottites!

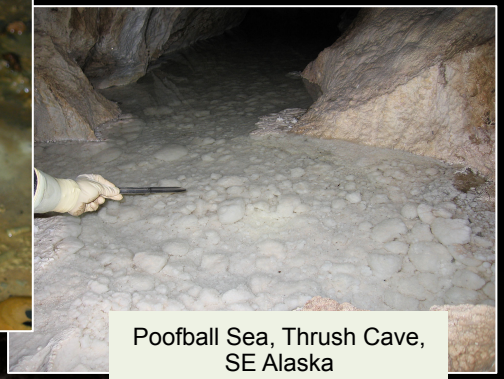
Red Tulip Microbial Iron Stalagmites, Zoloushka Cave, Ukraine



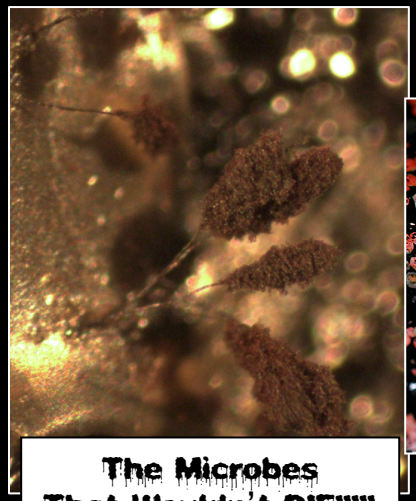
Mysterious Microcholla Microbes

Phlegm ball mats

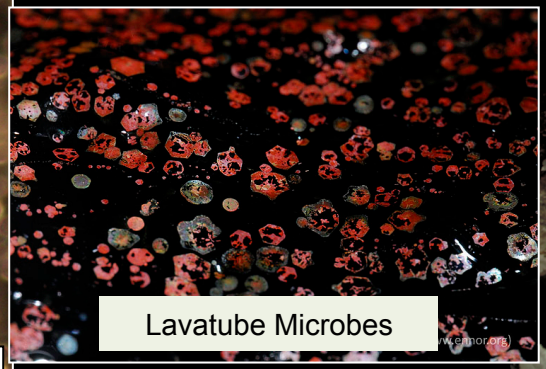
Manganese Microbe Stalagmite on Miner's Jacket, Soudan Mine, MN



Poofball Sea, Thrush Cave, SE Alaska



The Microbes That Wouldn't DIE!!!!!



Lavatube Microbes

Rock-eating Microbes
Lechuguilla Cave, NM

Extraterrestrial Caves

What Do We Know About Extraterrestrial Caves?

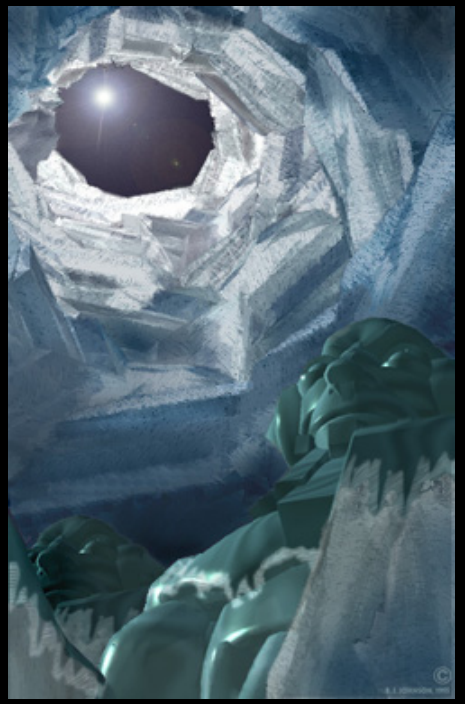
knowledge

speculation

- Lava tube caves on a number of bodies (Moon, Mars, etc.)

- Any planet with a surface will develop cracks
- Cracks provide the foundation for:
  - *dissolved caves (e.g. limestone, gypsum, salt)*
  - *crust motion (tectonic) caves*
  - *cave-formation mechanisms that don't happen on Earth*

- Caves from entirely non-Earth processes?
  - *e.g. sublimation of cometary ices or Martian poles?*
  - *Titan karst in tholin organic goo?*



Caveview of Saturn from Titan by B.J. Johnson

Process-based Cave Classification

CAVE TYPE	Dominant Processes	Parent Materials	Earth Examples	Possible Extraterrestrial Variations
Solutional	Dissolving rock by solvent *(With or without chemistry)*	Soluble solids plus a solvent	Classic karst, gypsum, halite	Non-water solvents, different thermal regimes
Erosional	Mechanical abrasion via wind, water, grinding, crystal wedging, etc.	Any solid	Sea coast caves, Tafonation, Aeolian rock shelters, etc.	Non-Earth erosional processes, e.g. radiation sputtering, frozen non-water volatile wedging
Tectonic	Fracturing due to internally or externally caused earth movements	Any rocky solid	Seismic caves	Tidal flexure from a massive primary planet or sun, impact fracturing in craters
Suffosional	Cavity construction by the fluid-borne motion of small particles	Unconsolidated sediments	Mud caves, some thermokarst	Ground ice sublimation (?) pocking at Mars poles
Phase Transition	Cavity construction by melting, vaporization, or sublimation	Meltable or sublimable materials capable of solidifying at planet-normal temperatures	Lava tube caves, glacial caves (i.e. caves in ice as bedrock)	Perihelionic sublimation of frozen volatiles in comets (Temple), frozen bubbles in non-water ices, non-basalt lavatubes (Io)
Constructional	Negative space left by incremental biological or accretional processes, often around an erodable template	Any solid capable of ordered or non-ordered accretion, or biogenic processing	Coralline algae towers, travertine spring mound caves	Crystallization in non-polar ices leaving voids?

Modified from P.J. Boston 2004. Extraterrestrial Caves. In, *Encyclopedia of Caves and Karst, J. Gunn, ed.*
Titus & Boston, 2012. Interdisciplinary research produces results in the understanding of planetary caves. *EOS Trans. 93(20):196.*

Process-based Cave Classification of Target Bodies

CAVE TYPE	Dominant Processes	Parent Materials	Earth Examples	WHERE????
Solutional	Dissolving rock by solvent *(With or without chemistry)*	Soluble solids plus a solvent	Classic karst, gypsum, halite	Earth, Titan, Mars
Erosional	Mechanical abrasion via wind, water, grinding, crystal wedging, etc.	Any solid	Sea coast caves, Tafonation, Aeolian rock shelters, etc.	Earth Mars (aeolian, tafonation) Titan (coastal?) Venus (aeolian?)
Tectonic	Fracturing due to internally or externally caused earth movements	Any rocky solid (internal tectonism and external impacts)	Seismic caves	Earth, Europa Ganymede? Titan, Enceladus Mars
Suffosional	Cavity construction by the fluid-borne motion of small particles	Unconsolidated sediments	Mud caves, some thermokarst	Earth Mars (poles, RSL layers?)
Phase Transition	Cavity construction by melting, vaporization, or sublimation	Meltable or sublimable materials capable of solidifying at planet-normal temperatures	Lava tube caves, glacial caves (i.e. caves in ice as bedrock)	Volcanic bodies (Earth, Mars, Venus, Io) Icy fluid-filled bodies Comets
Constructional	Negative space left by incremental biological or accretional processes, often around an erodable template	Any solid capable of ordered or non-ordered accretion, or biogenic processing	Coralline algae towers, travertine spring mound caves	Earth Mars (spring mound cavities)
Compound Mechanisms *	Catastrophic speleogenesis	Rocky soluble solids	Flynn Creek Impact structure**	Earth Mars

Modified EVEN MORE from P.J. Boston 2004. Extraterrestrial Caves. In, *Encyclopedia of Caves and Karst, J. Gunn, ed.*

* Boston et al. 2006. **In,** *Karst Geomorphology, Hydrology, & Geochemistry* GSA Special Paper 404. Pp. 331-344.

** Milam et al. 2005. Flynn Creek Impact Structure. 69th Ann. Meteoritical Soc. Meeting Field Guide.

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Where should we put…
Ceres?
Vesta?
Pluto?
Mercury?
Uranus' moons?

Modified EVEN MORE from P.J. Boston 2004. Extraterrestrial Caves. In, *Encyclopedia of Caves and Karst, J. Gunn, ed.*
* Boston et al. 2006. **In,** *Karst Geomorphology, Hydrology, & Geochemistry* GSA Special Paper 404. Pp. 331-344.
** Milam et al. 2005. Flynn Creek Impact Structure. 69th Ann. Meteoritical Soc. Meeting Field Guide.

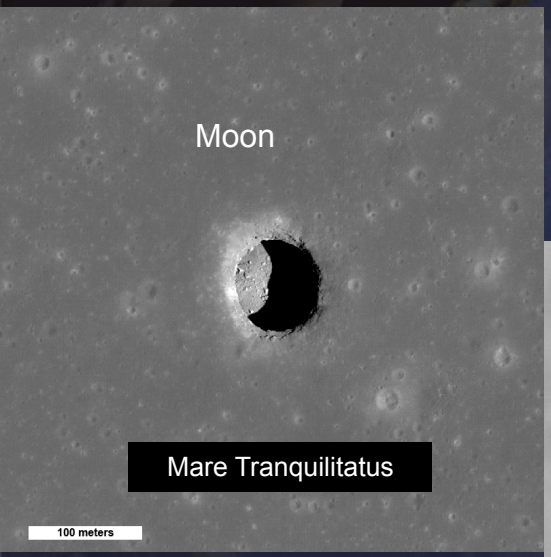
We've known about at least one extraterrestrial cave-forming process since the dawn of the Space Age!

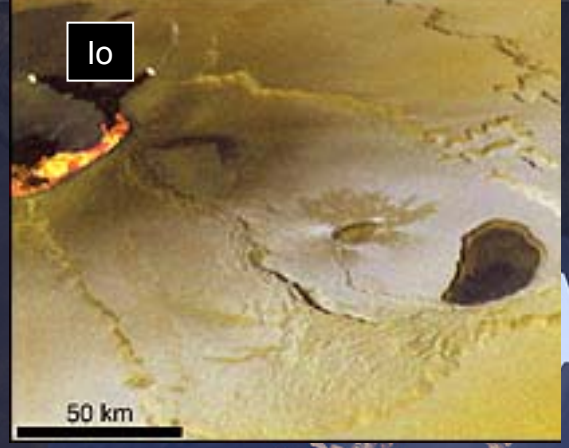
Oberbeck, V.R., Quaide, W.L., & Greeley, R.. 1969.
On the Origin of Lunar Sinuous Rilles, *Mod. Geol. 1:*75-80,

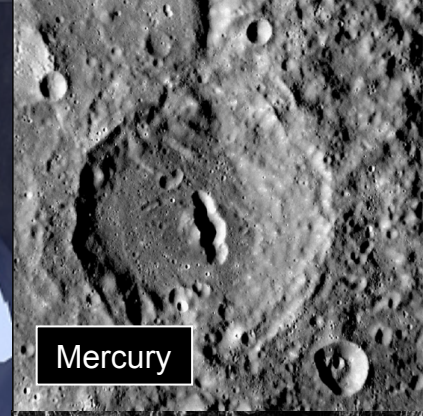
The Moon - Vallis Schroteri , Aristarchus

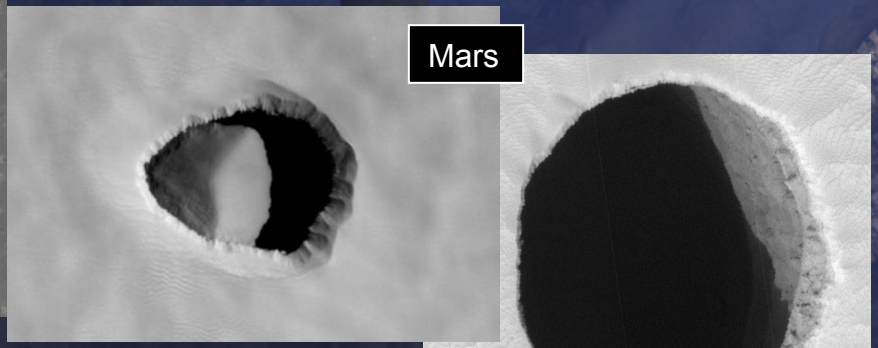
Hawaii, Open lava channels forming

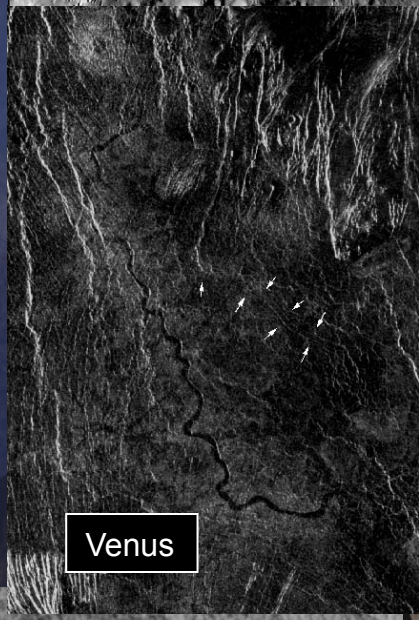
Extraterrestrial Lavatubes & Pit Caves

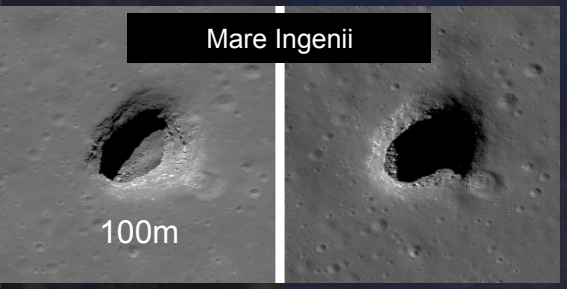


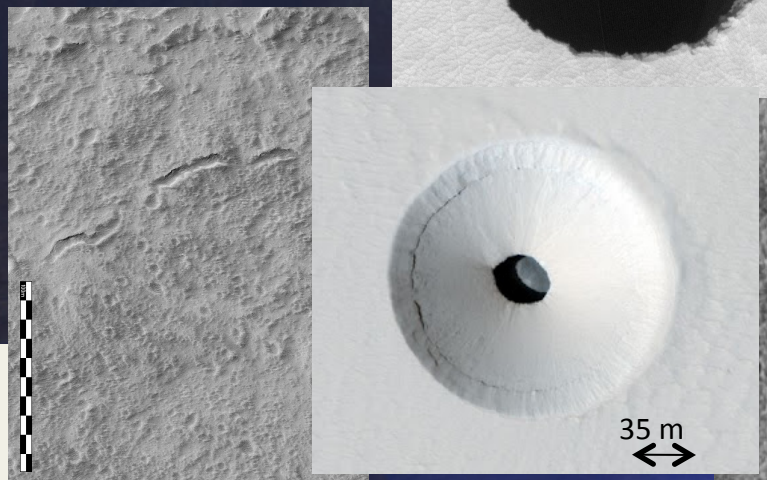


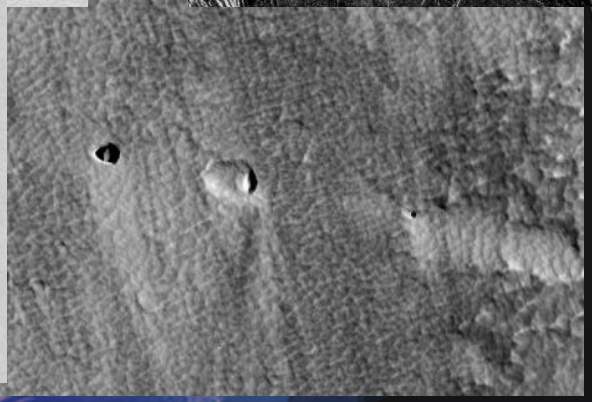






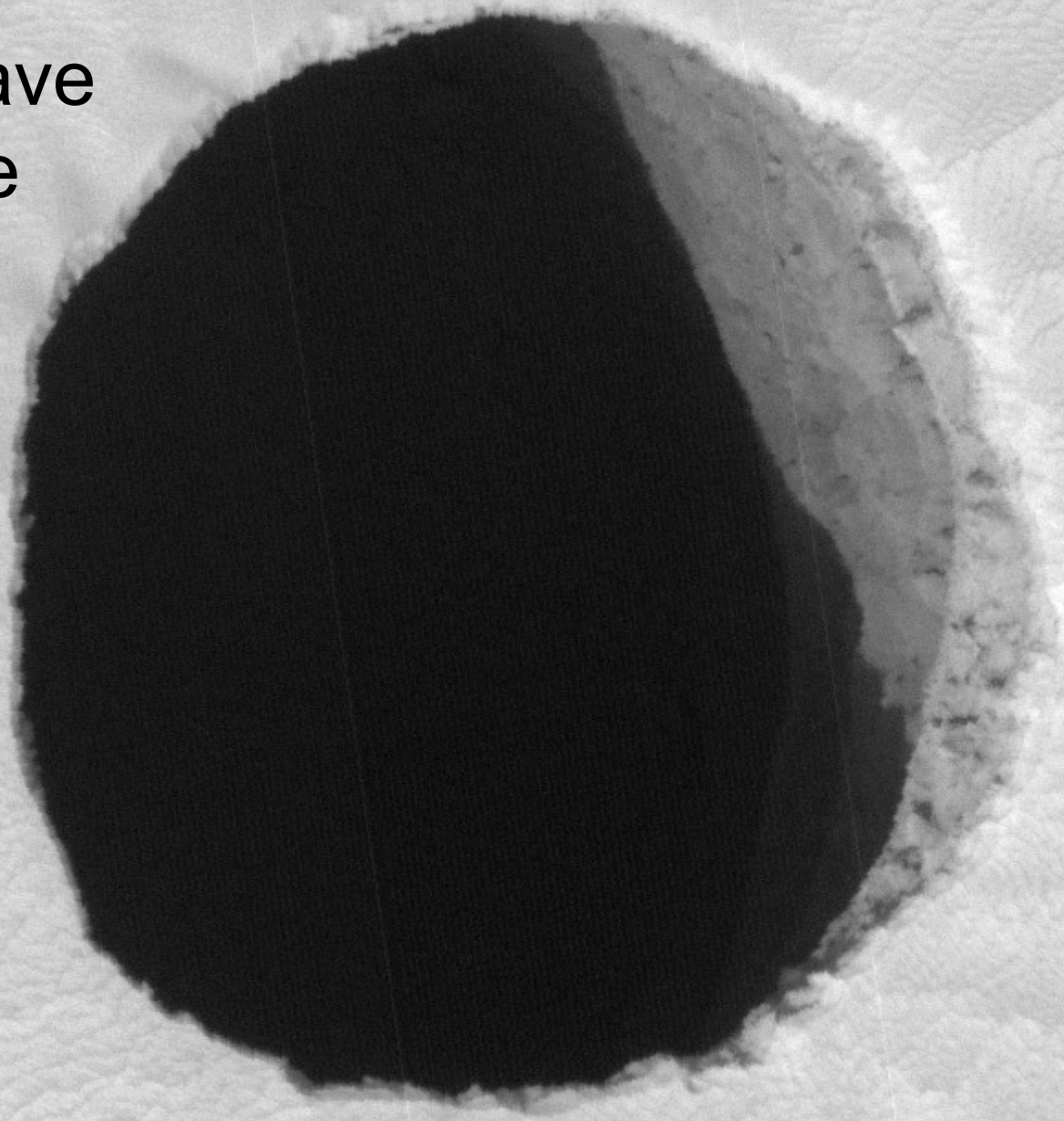






Boston, P.J. 2004. Extraterrestrial Caves. *Encyclopedia of Cave and Karst Science*. Fitzroy-Dearborn Publishers, Ltd., London, UK. Pp. 355-358.

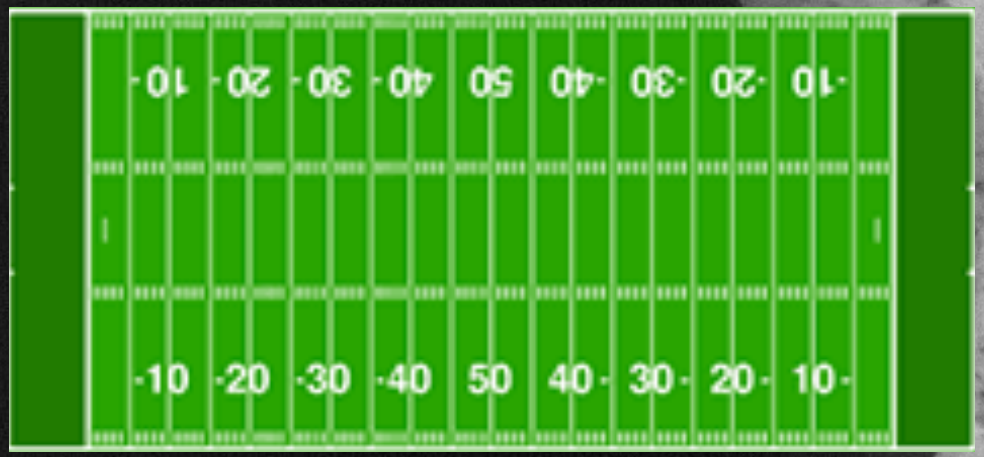
Martian Cave Entrance



HiRise data
30 cm resolution
Hole is 100 m across!

Martian Cave Entrance

Compared to an American football field

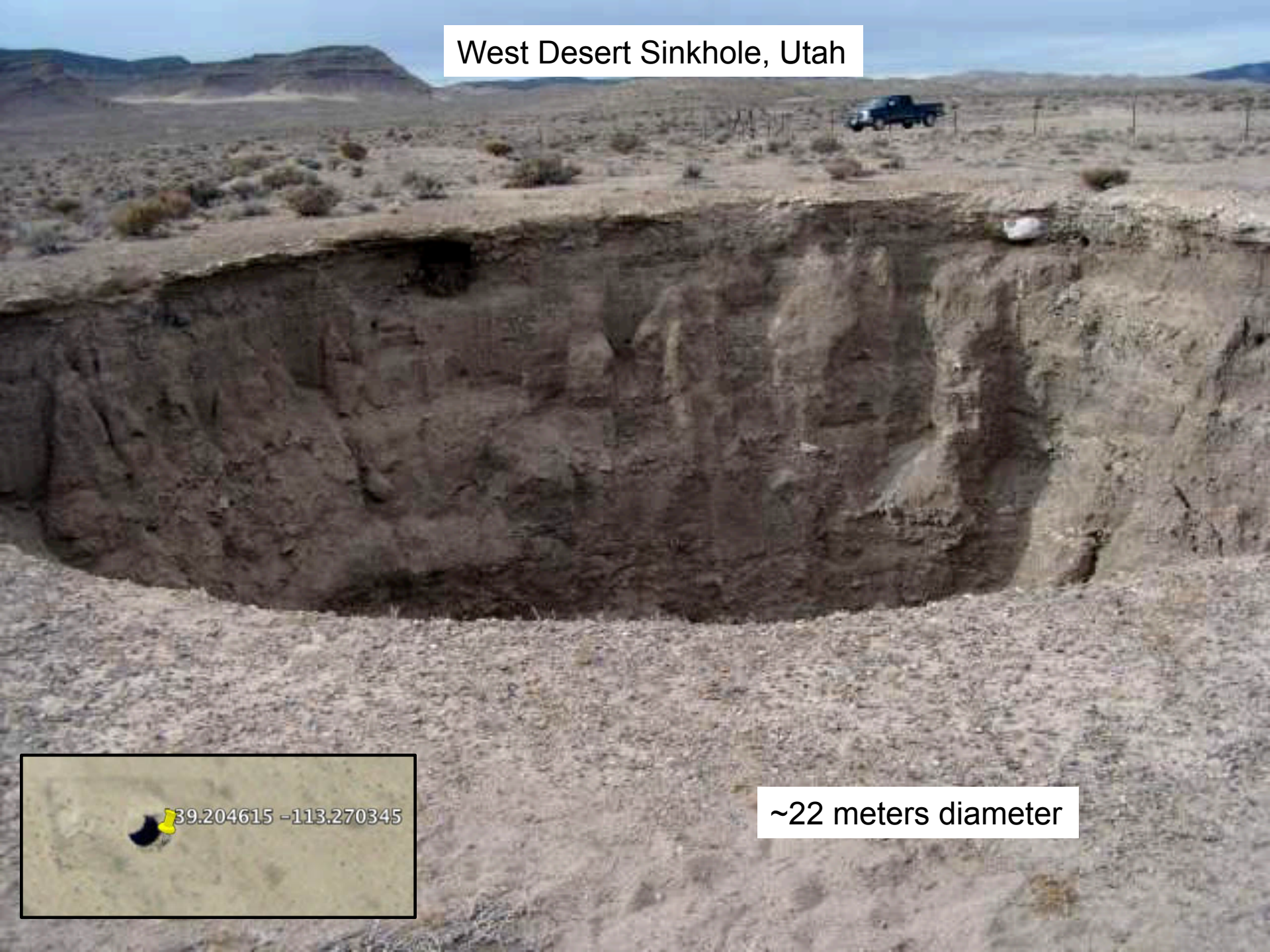


HiRise data
30 cm resolution
Hole is 100 m across!

Martian Cave Entrance

compared to an American sinkhole!

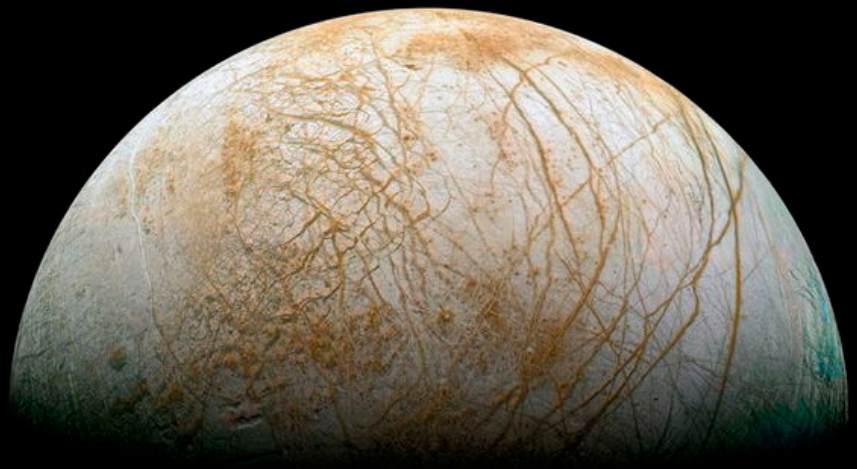
West Desert Sinkhole
Utah


West Desert Sinkhole, Utah
39.204615 -113.270345
~22 meters diameter

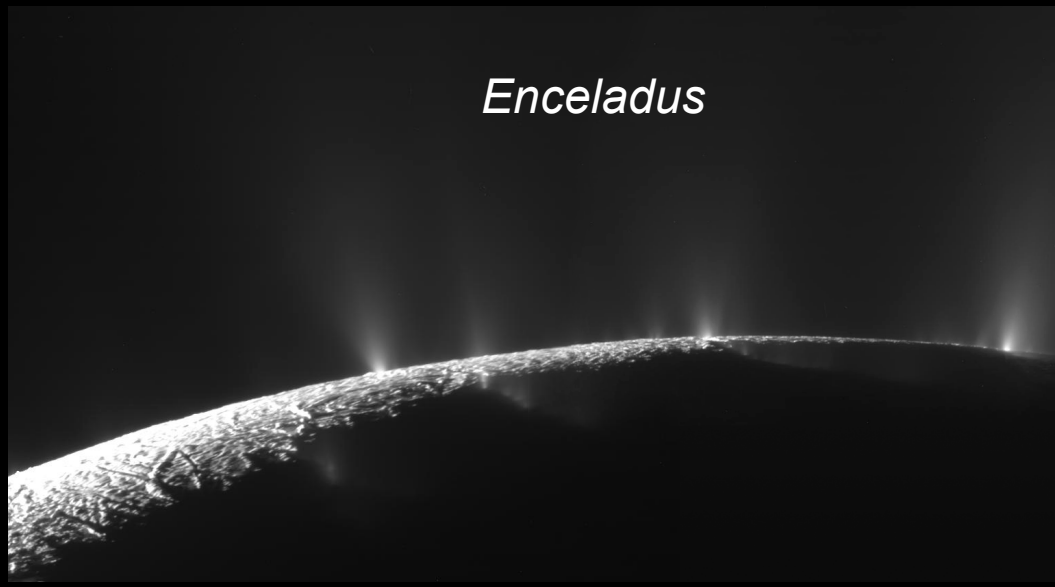

Santa Cruz Is., Galapagos Is
~80m diam volcanic collapse feature

Icy Satellites…not “ocean worlds”, but planet-sized ocean caves!

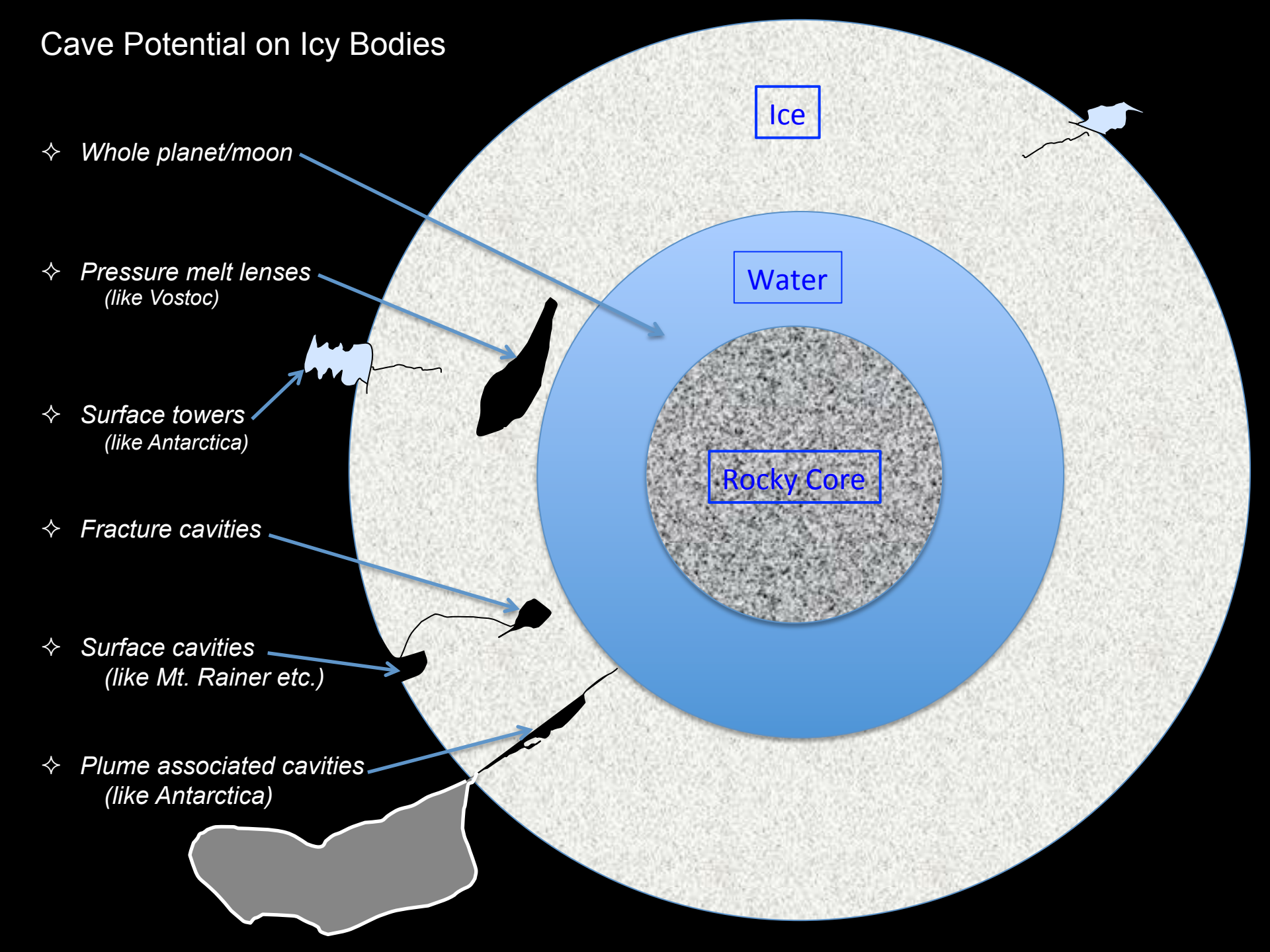
Europa



Enceladus



Cave Potential on Icy Bodies



Ice Towers & Caves on Mt. Erebus, Antarctica & Mt. Rainier, WA

May be some on Mars, Europa, & Enceladus!

Mt. Erebus ice towers, Antarctica

Mt. Erebus fumarole over ice cave, Antarctica

Mt. Erebus Ice Cave, Antarctica

Mt. Rainer fumarolic ice caves

So, a Lovely Story, but What is Predictable & Testable NOW?

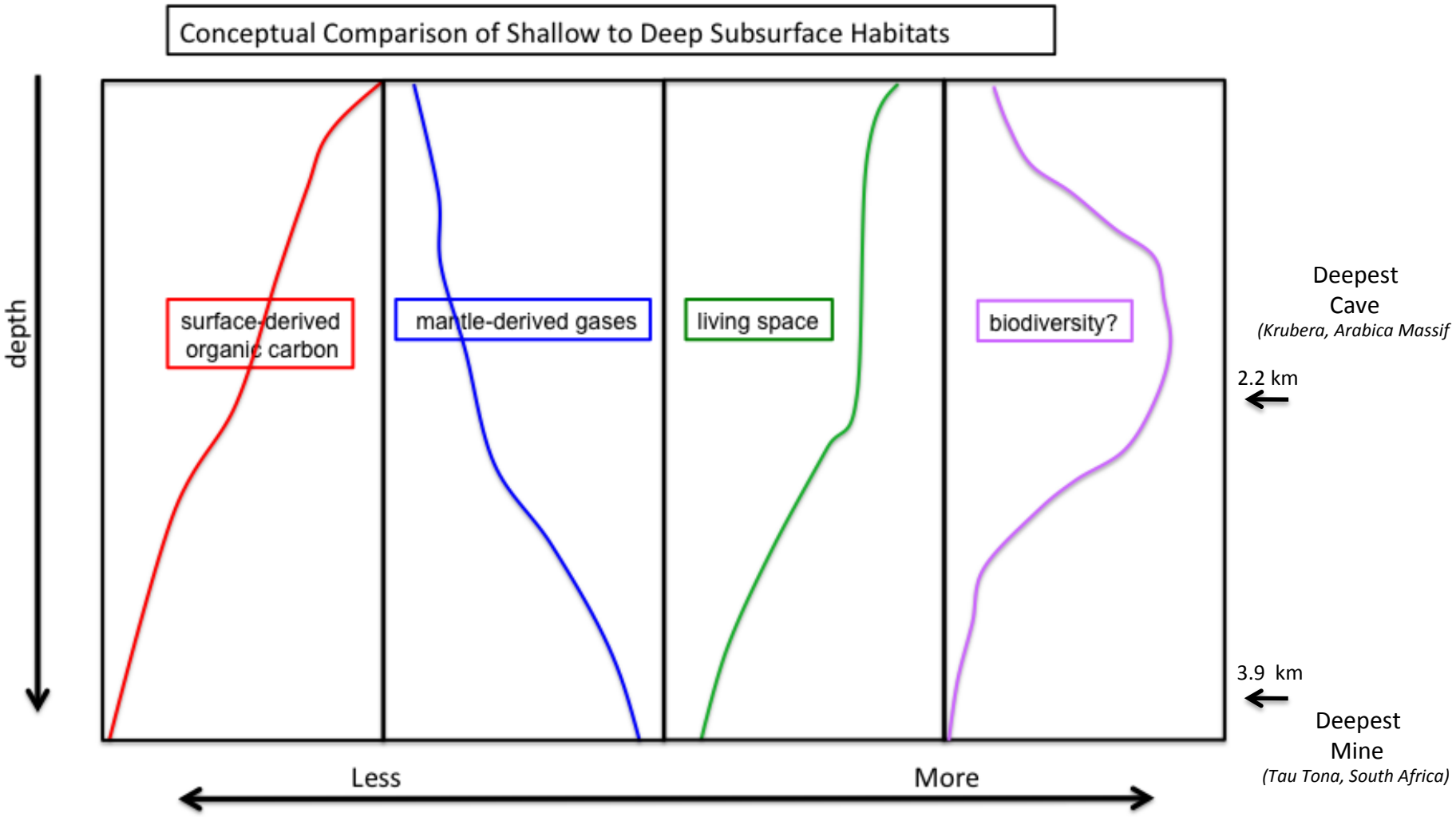
- **Earth actually is a hybrid biosphere case**
  - *Type 1 Dominant*
  - *Type 2 can be significant*

- **On Earth microbial types as indicators of geochemical conditions**
  - *Heterotrophs receiving surface created organics*
  - *Chemotrophs using geological energy sources (bedrock, geogases, etc.)*

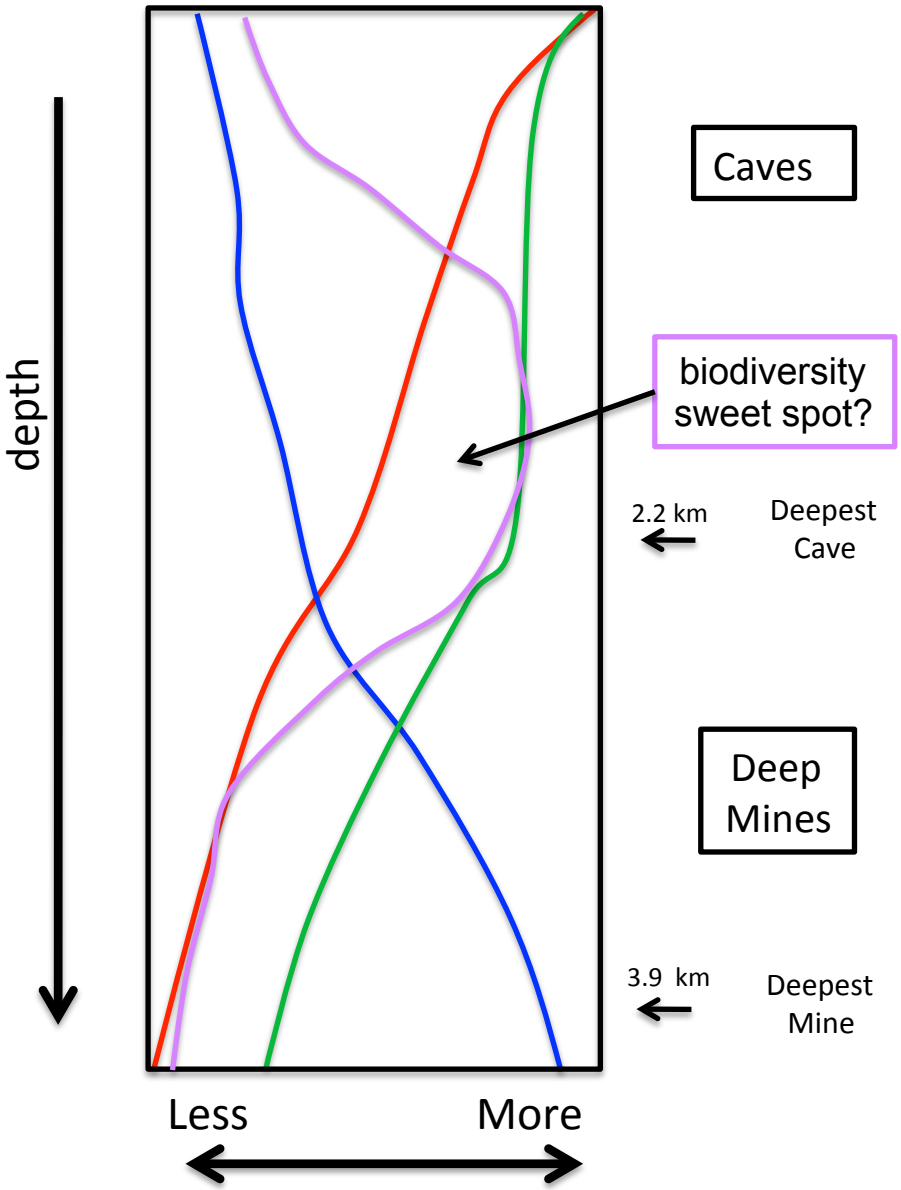
- **Depth of the habitable crust**
  - *Low gravity bodies should have crustal habitable zones to greater depth*
  - *Dependent upon lithostatic pressure allowing for habitable space*
  - *Caveats on thermally habitable zone*

- **Tectonic recycling?**
  - *Longevity of a biosphere dependent upon this*
  - *Recycling mechanism of some sort*
  - *Europa and Enceladus appear to have this…*

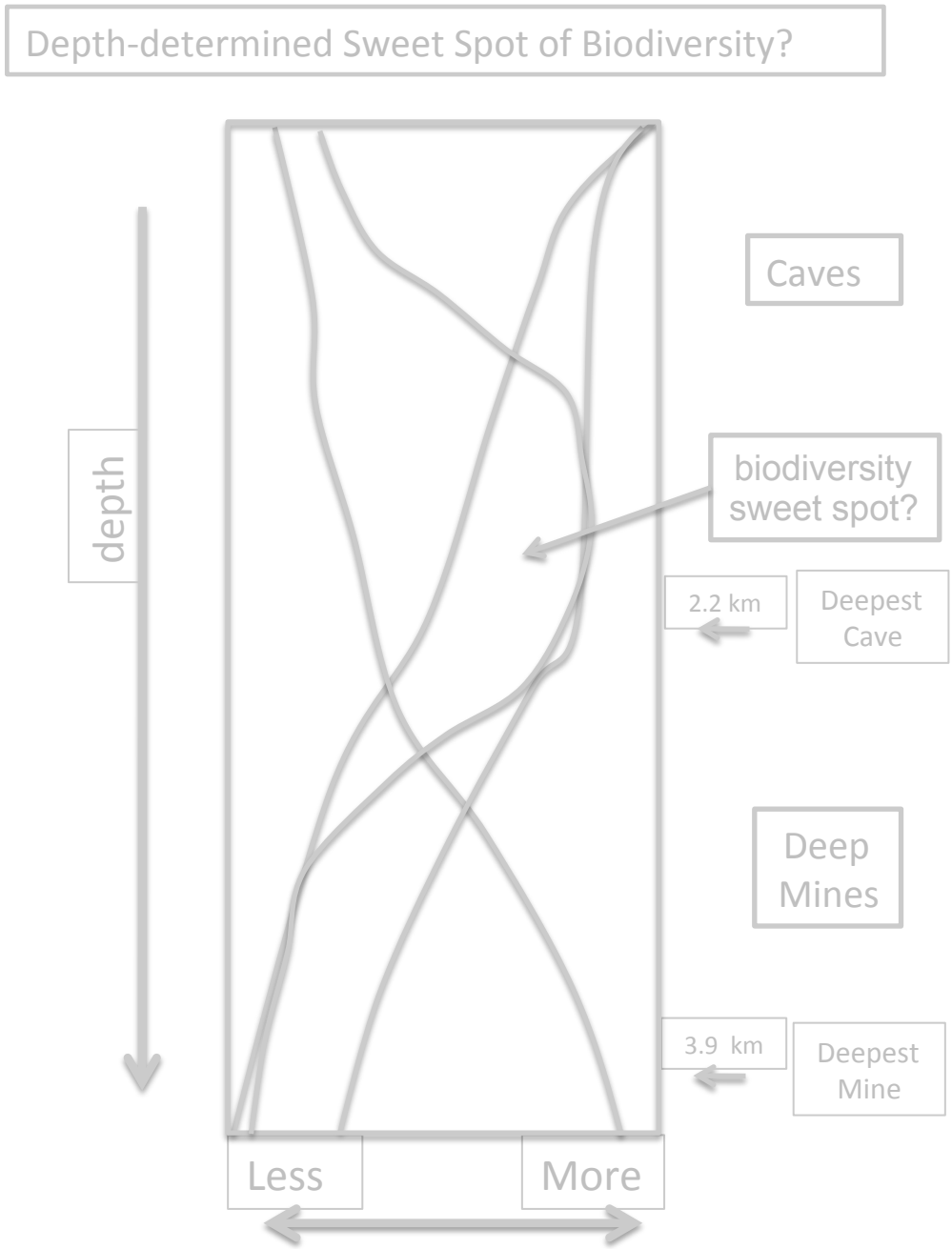
How Much Biodiversity at Depth?



Is There a Depth-determined Sweet Spot of Biodiversity?



Ecotone!



Caveats

- ✧ VAST genetic datasets probably necessary!
- ✧ Detection Limitations
  - *Genetic techniques*
  - *Some other proxies?*
- ✧ Temperature Anomalies
  - *Ore bodies*
  - *Ventilation*
- ✧ Lithology
  - *Limiting nutrients, e.g. P, Fe*
  - *Pore space, cavity space*
- ✧ Hydrology
  - *Flowpath*
  - *Degree of conductivity*
  - *Hyporheic anoxic fluctuation*
- ✧ Resource Anomalies
  - *Non-mantle reduced gases*
  - *Stored ancient carbon (e.g. oil)*

Exploration presents unparalleled value but also risk.

Mario Corsalini, Dec. 2009
NGS expedition to Naica
Image by M.N. Spilde

Lost Dec. 2010 in climbing accident at Hielo Patagonico, Argentina

Danger Focuses the Mind!

- poisonous atmospheres
- great heat or cold
- unstable rock masses
- gear failure
- you name it

powers of observation are distilled

Iceland Cave
Image by Sky Cohen, Mind_Virus, imgur

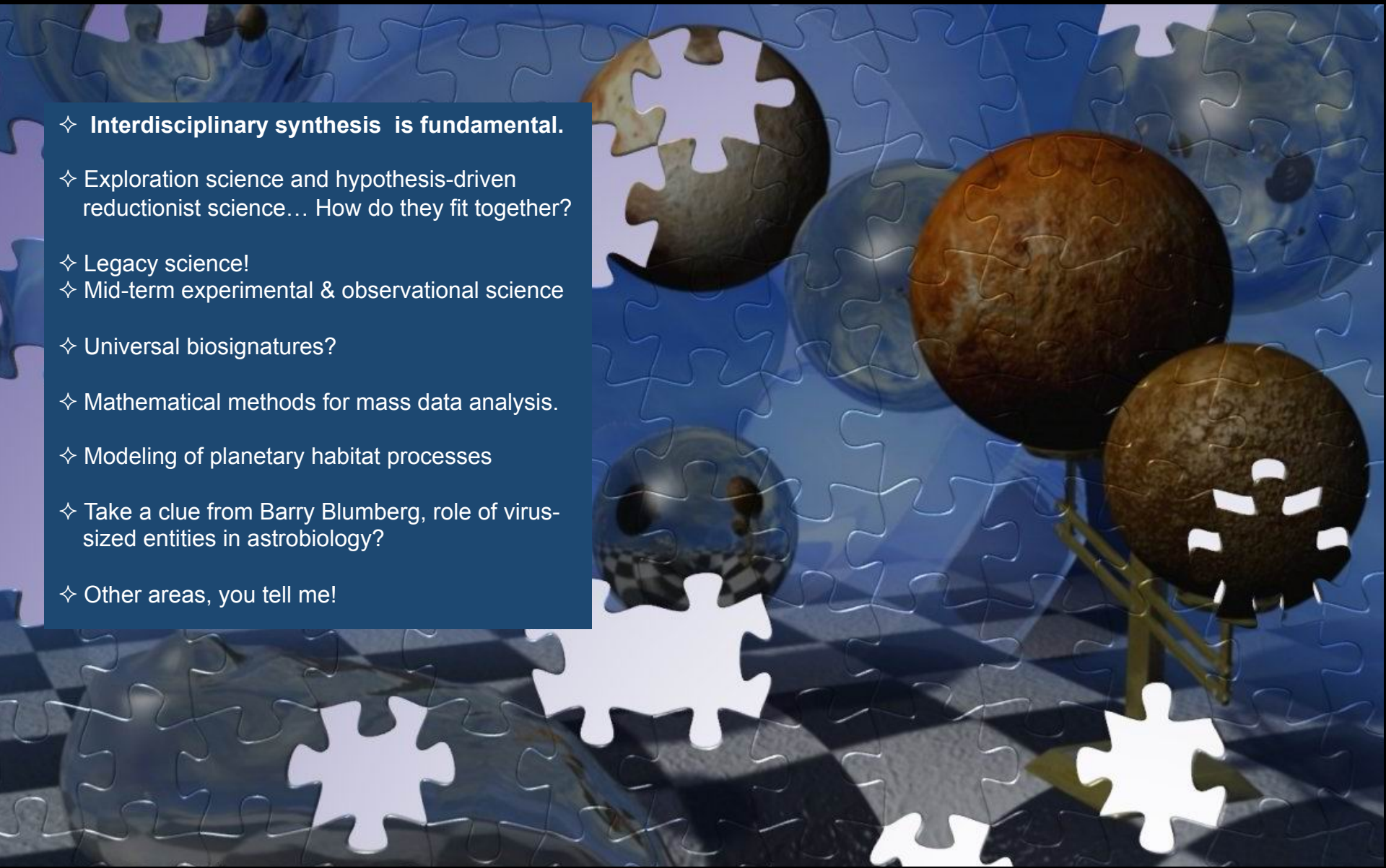
When exploration is coupled with the intellectual discipline of science, understanding happens.

Aaron Curtis, Warren Ice Cave, Mt. Erebus, Antarctica

Big Questions

- ✧ Type 1, Type 2, or Hybrid Biosphere?
- ✧ Can we imagine any other types???
- ✧ Surface indicators of a Type 2 Biosphere?
- ✧ How can we test these notions on Earth?
- ✧ Elsewhere in Solar System?
- ✧ Using Earth as a model for all biospheres is probably a big mistake!
- ✧ CAN we develop a Theory of Habitabiity broad enough to be useful for assessing Solar System and exoplanet bodies?

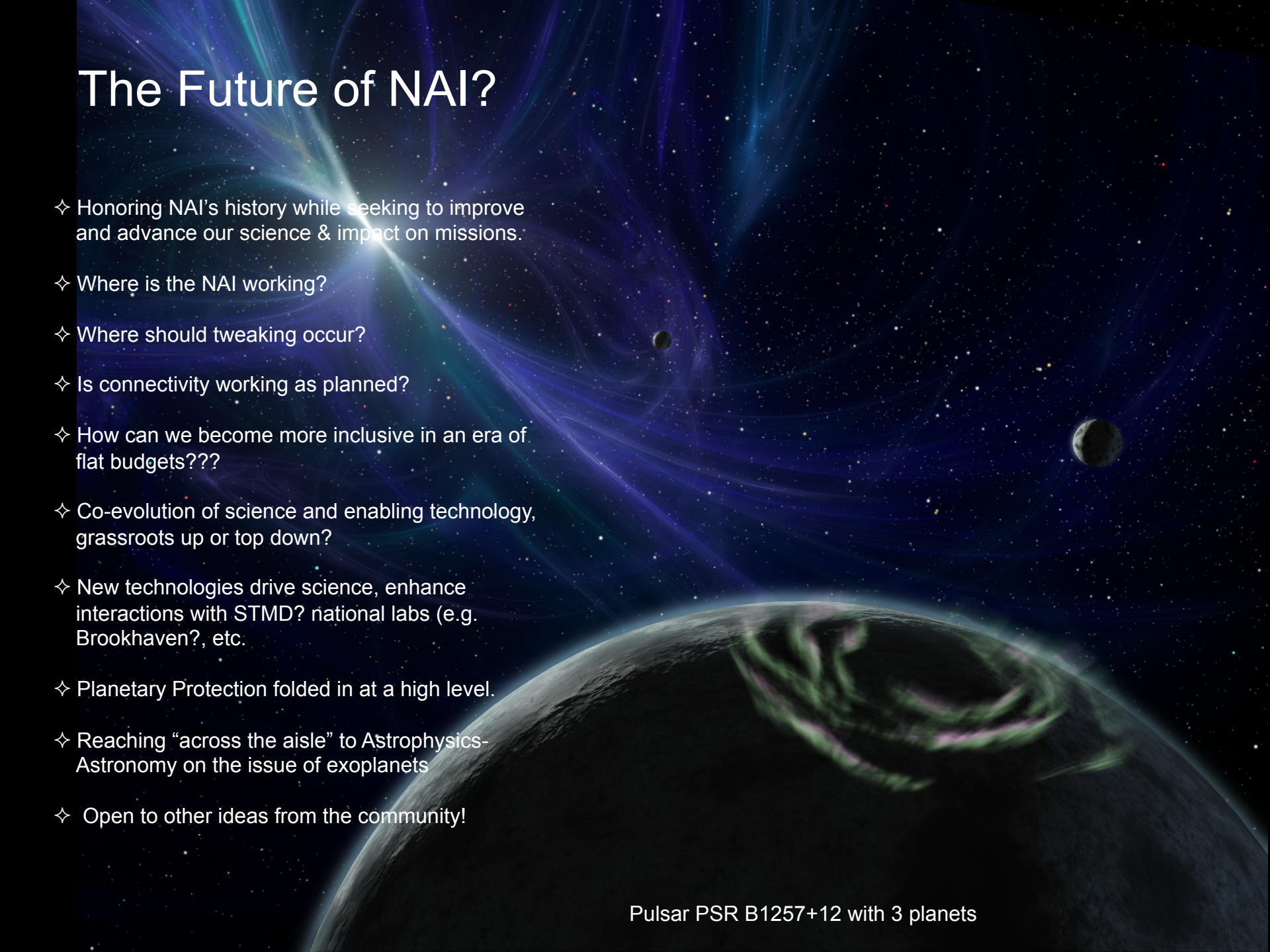
The Future of Astrobiology?



- **Interdisciplinary synthesis is fundamental.**
- Exploration science and hypothesis-driven reductionist science… How do they fit together?
- Legacy science!
- Mid-term experimental & observational science
- Universal biosignatures?
- Mathematical methods for mass data analysis.
- Modeling of planetary habitat processes
- Take a clue from Barry Blumberg, role of virus-sized entities in astrobiology?
- Other areas, you tell me!

The Future of NAI?

- Honoring NAI's history while seeking to improve and advance our science & impact on missions.
- Where is the NAI working?
- Where should tweaking occur?
- Is connectivity working as planned?
- How can we become more inclusive in an era of flat budgets???
- Co-evolution of science and enabling technology, grassroots up or top down?
- New technologies drive science, enhance interactions with STMD? national labs (e.g. Brookhaven?, etc.
- Planetary Protection folded in at a high level.
- Reaching "across the aisle" to Astrophysics-Astronomy on the issue of exoplanets
- Open to other ideas from the community!



Pulsar PSR B1257+12 with 3 planets