The Astrobiology of the Subsurface

Caves & Rock Fracture Habitats on Earth, Mars, & Beyond

Art: Adam Hetmansky

Penelope J. Boston

Director
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NASA Ames Research Center
Moffett Field, CA 94035

"What's a Nice Girl Like You Doing in a Place Like… THAT?"

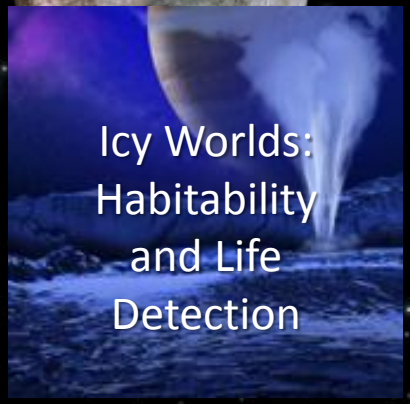
Image courtesy of T. Kieft

Unparalleled opportunity to look glamorous at all times…

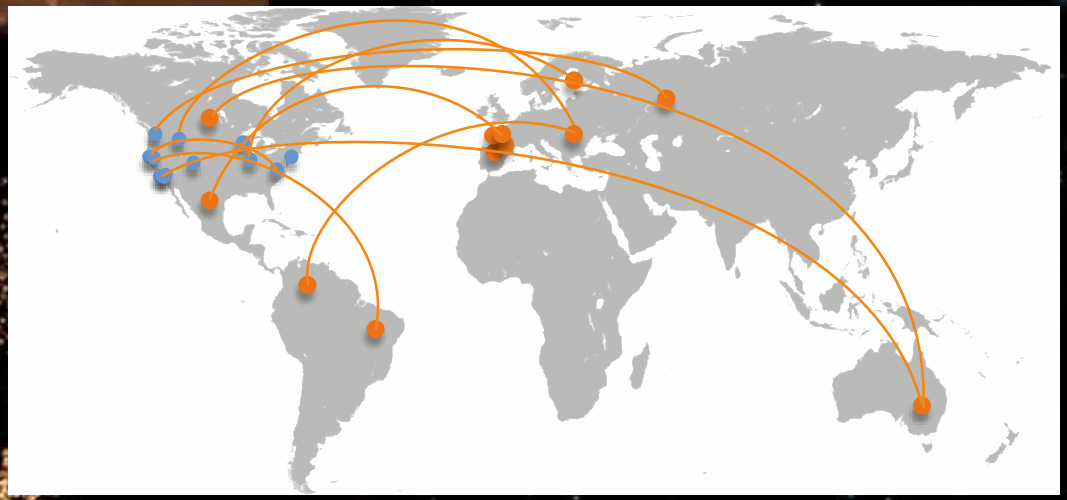
NASA Astrobiology Institute

LIFE IN THE UNIVERSE

A Division of the NASA Astrobiology Program

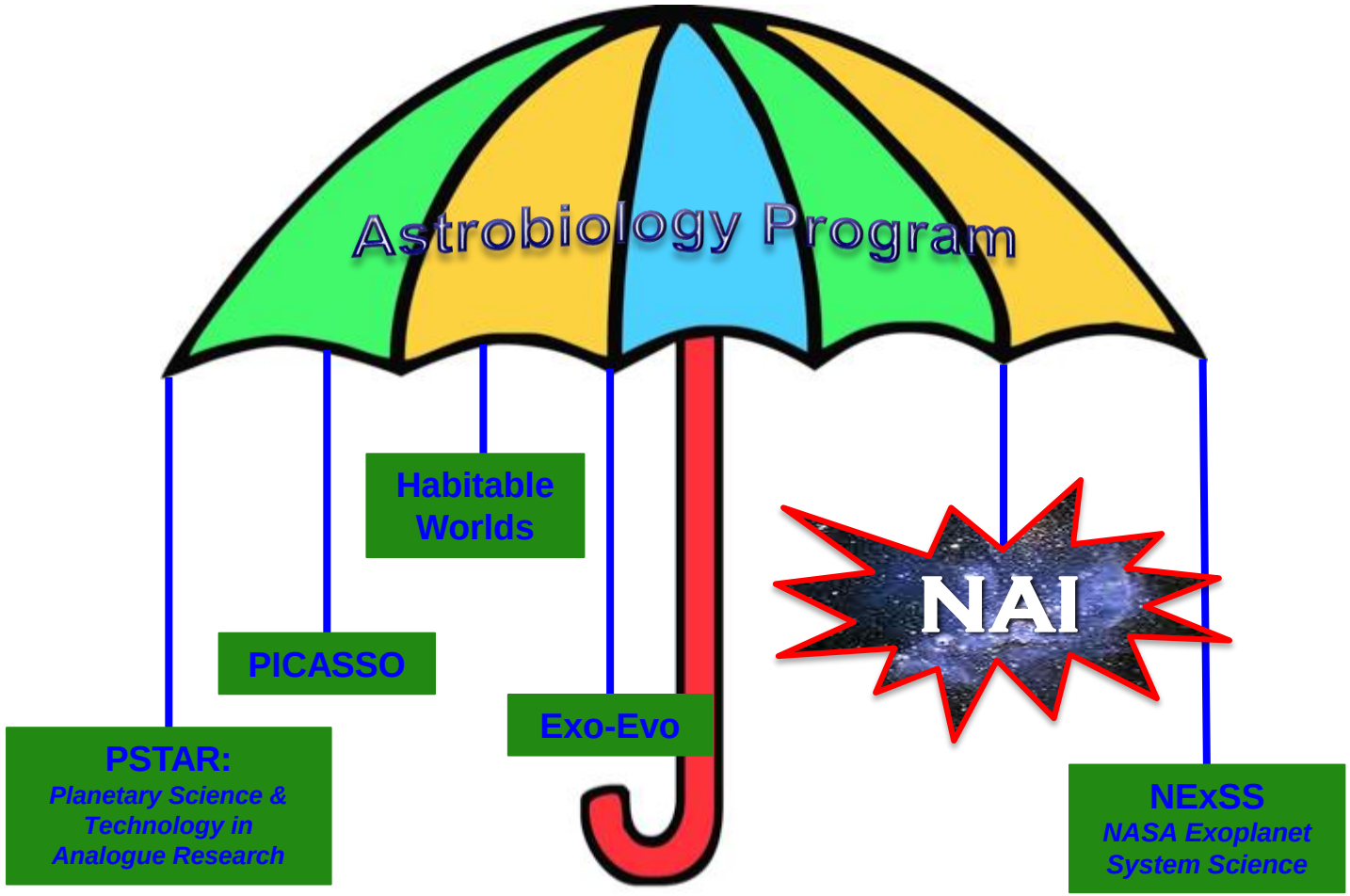


NAI: US & Global Community



NASA Science Mission Directorate

Planetary Science Division



…of NAI !

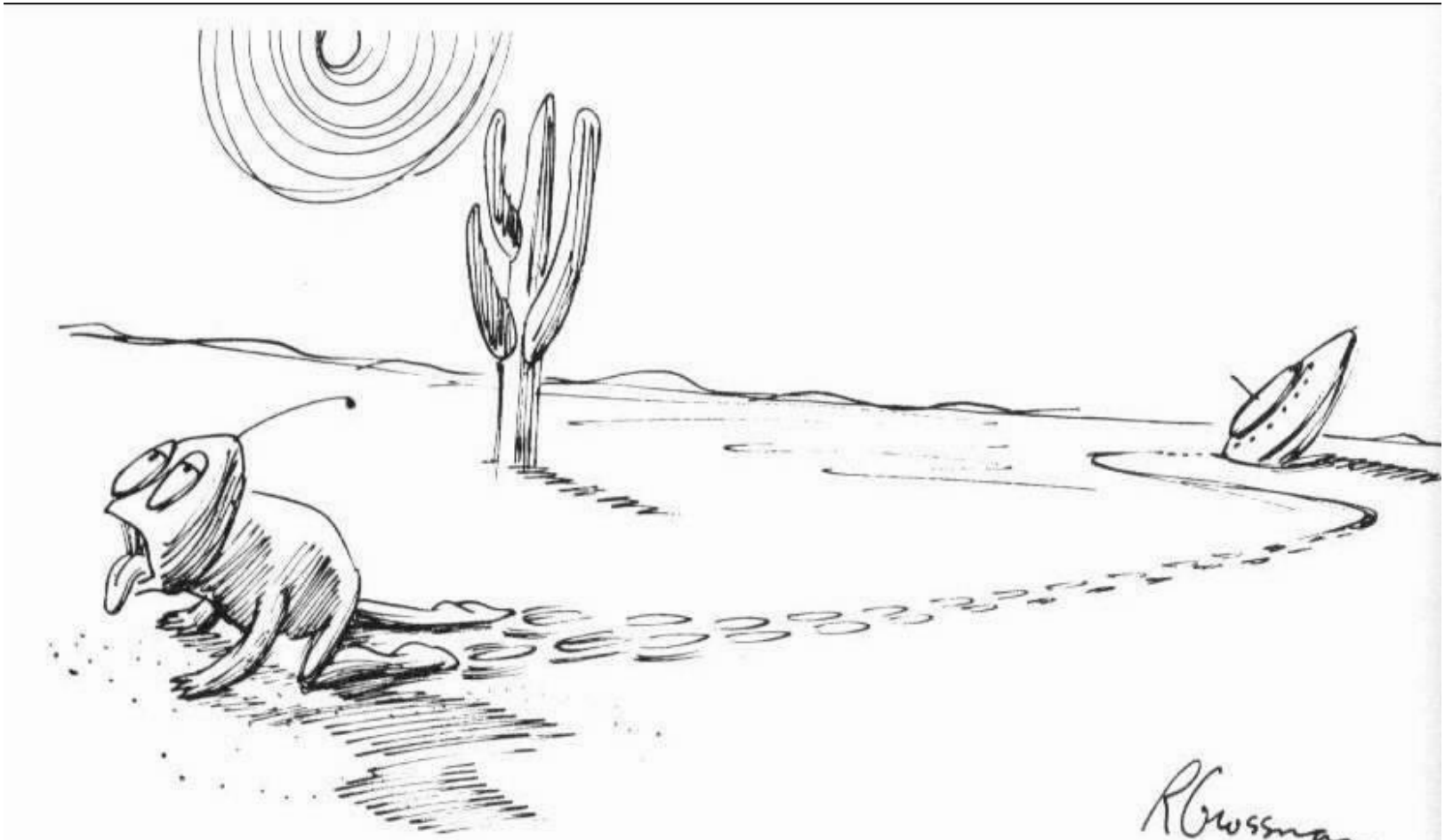
It's Good to be the Queen – By Paula Baker

- Competitively-selected science teams
  - *~320 senior scientists*
  - *~280 postdocs and students*
  - *~20 US Nat Acad Sci members*
- ~600 members
  - *~320 senior scientists*
  - *~280 postdocs and students*
  - *~20 US Nat Acad Sci members*
- ~100 participating institutions
- NAI Central - NASA Ames Research Ctr
- Programmatics– Astrobiology Program at HQ

Current Lead Institutions

- Massachusetts Institute of Technology
- University of Illinois at Urbana-Champaign
- University of Southern California
- University of Wisconsin
- VPL at University of Washington
- NASA Goddard Space Flight Center
- NASA Ames Research Center
- NASA Jet Propulsion Laboratory
- SETI Institute
- University of Colorado in Boulder
- University of California, Riverside
- University of Montana in Missoula

Astrobiology JOB 1:
Figuring out possible lifeforms from first principles!

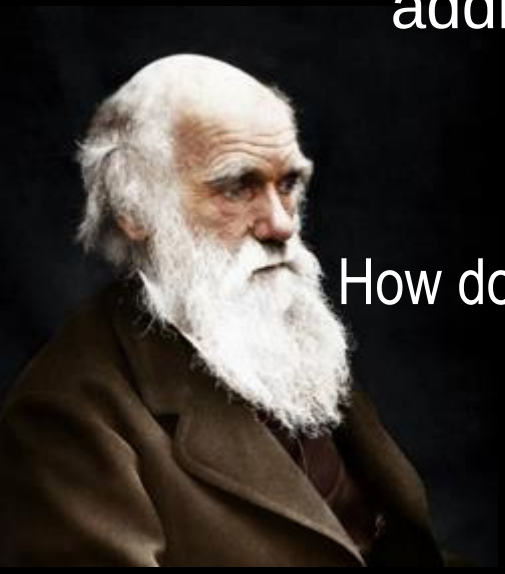


"Ammonia! Ammonia!"

Drawing by R. Grossman; © 1962.
The New Yorker Magazine, Inc.

Astrobiology

addresses three fundamental questions:

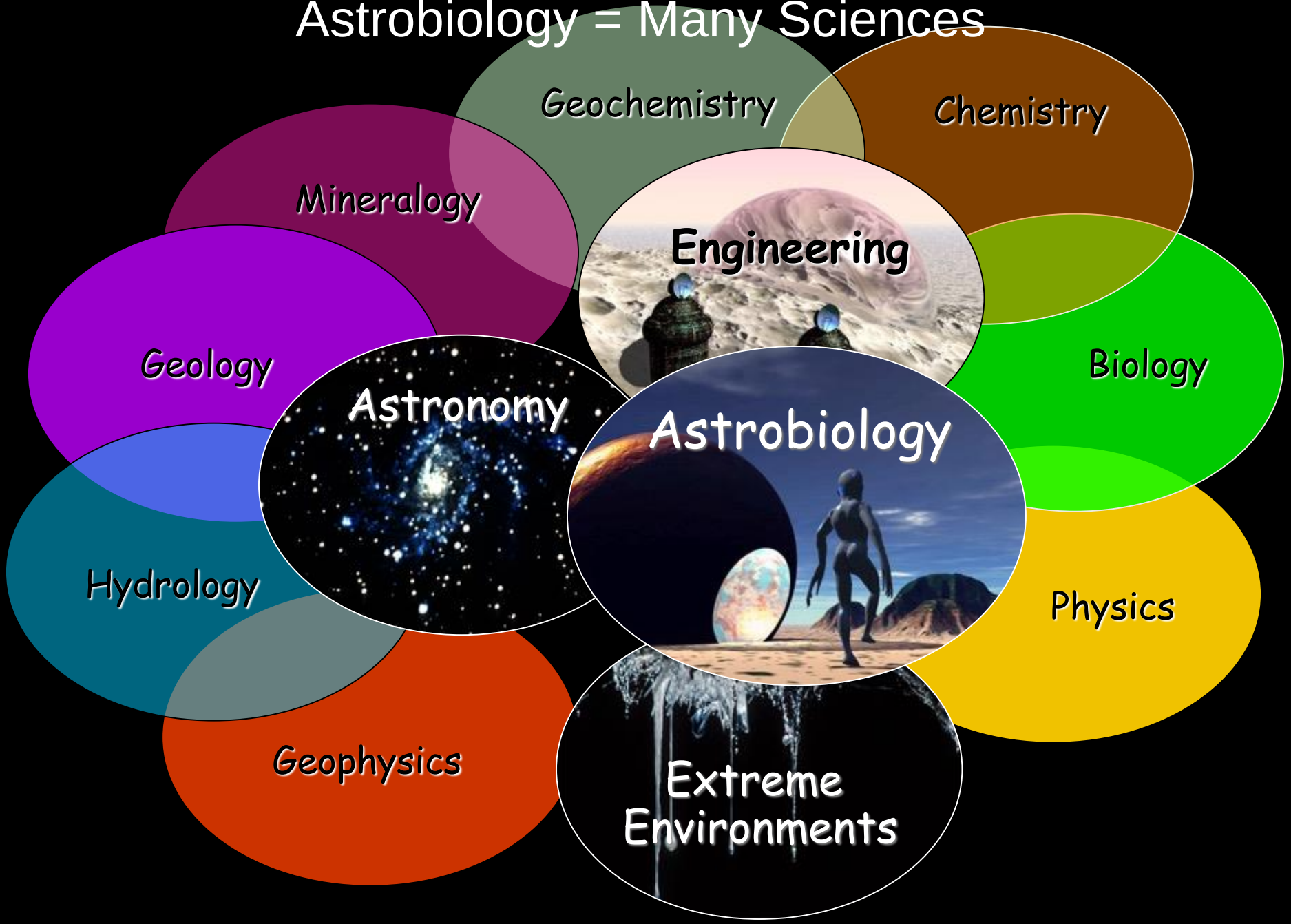


How does life begin and evolve?

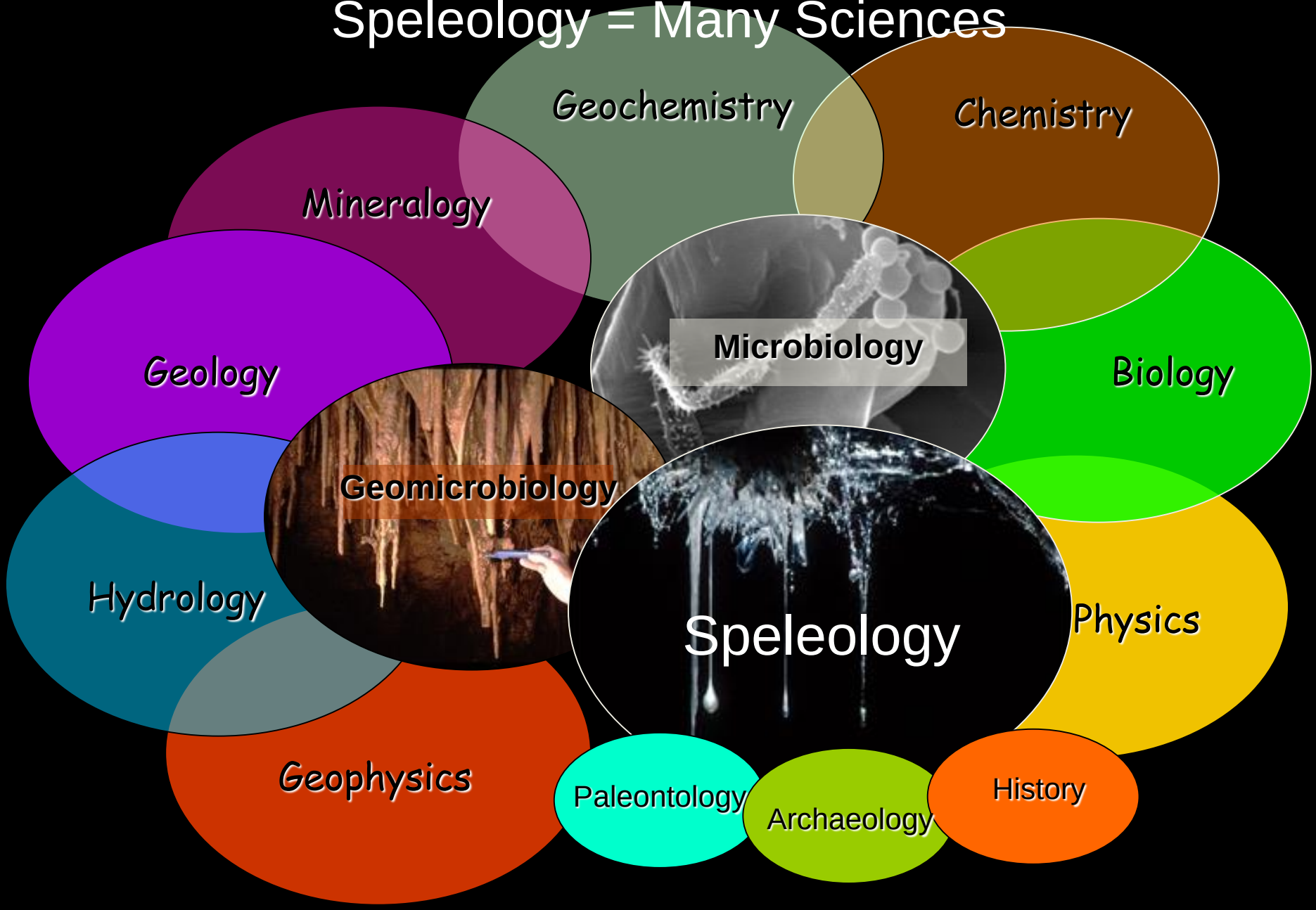
Does life exist elsewhere
in the universe?

What is the future of life
on Earth and beyond?

Astrobiology = Many Sciences



Speleology = Many Sciences



Subsurface Rock Habitats

Rock fracture habitats

- *Water-storing rocks (Aquifers)*
- *Caves*
- *Mines (anthropogenic caves!)*

- *Ocean floor rock fractures*
- *Ocean caves*

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

Snowy River Passage, Ft. Stanton Cave, NM
Image by J. Ganter

The Planet Within

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

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

Images courtesy of John Pint

Subsurface Environments

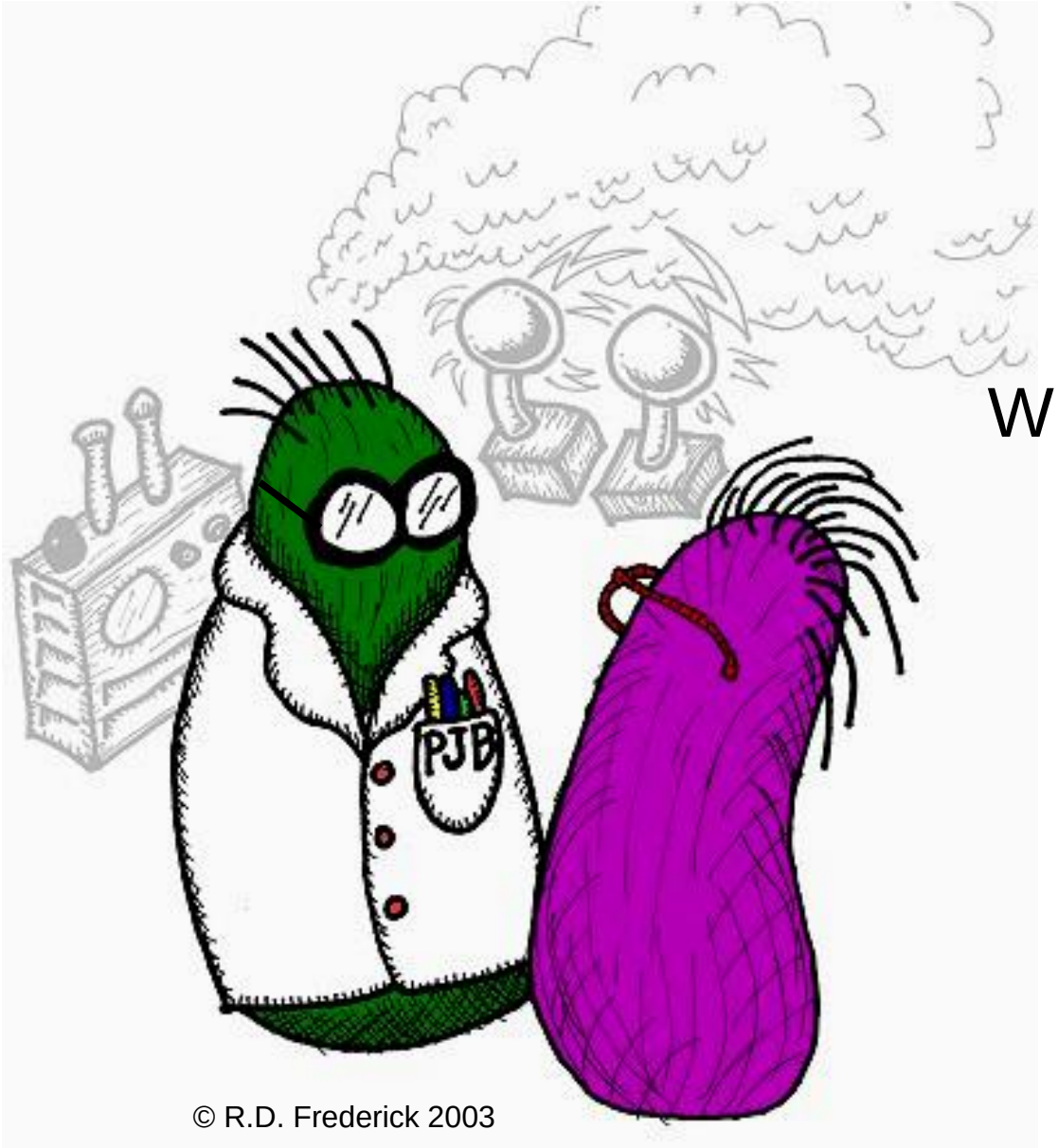
- No sunlight (past the twilight zone)
- High humidity
- Temperatures constant

- 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 courtesy of David Jagnow

What is Geomicrobiology?



Microorganism interactions with rocks and minerals

What do microbes do?

Transform materials

Destroy bedrock

Precipitate biominerals
actively & passively

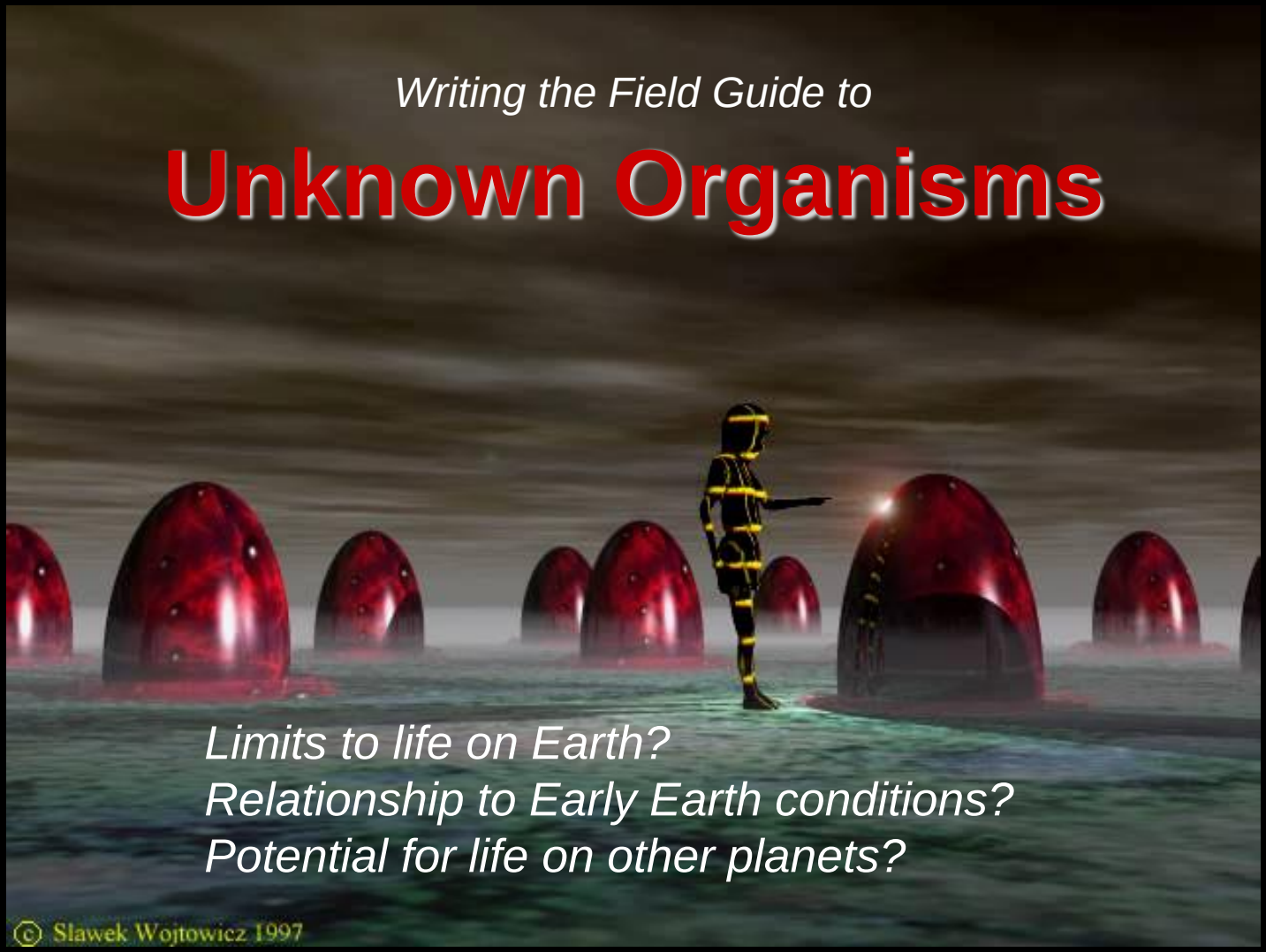
Significance of Geomicrobiology

- Geological weathering agents
- Economic minerals
- Unusual minerals

- Low temperature enzymes
- Pharmaceutical potential

- Unknown organisms & biochemistry
- Origins of life & early evolution
- **Astrobiology**

…the search for life in the universe…



By courtesy of the artist

Extraterrestrial Caves

By courtesy of the artist

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?*

Caves of Europa, P.J. Boston

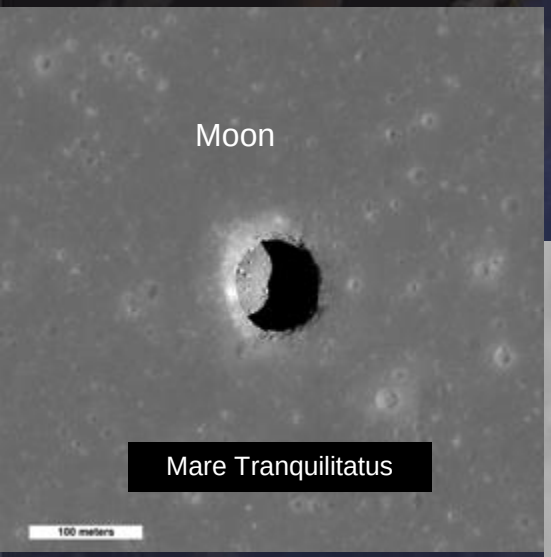
We've known about extraterrestrial cave-forming processes since the dawn of the Space Age!

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

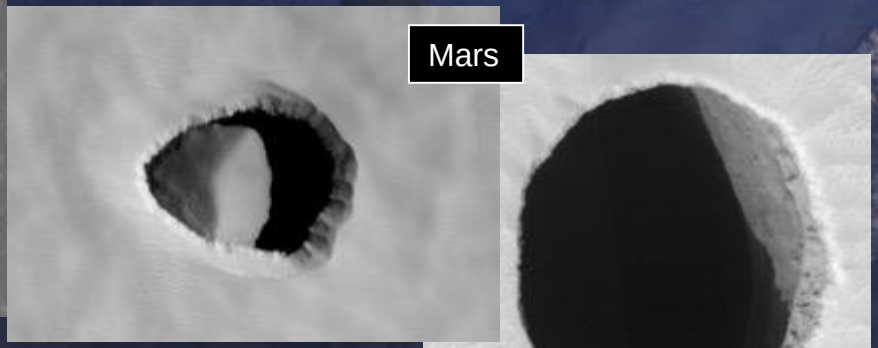
The Moon - Vallis Schroteri , Aristarchus
Image, NASA

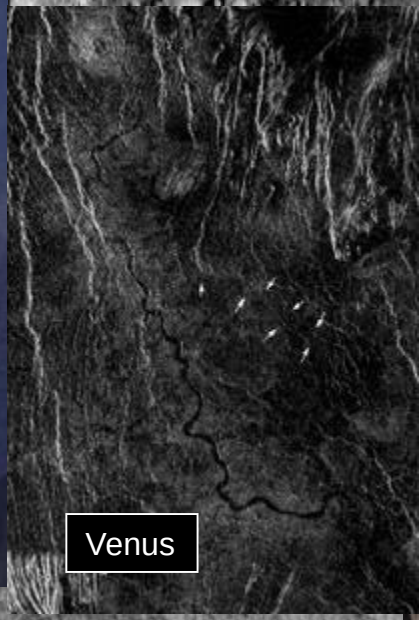
Hawaii, Open lava channels forming
Image, USGS

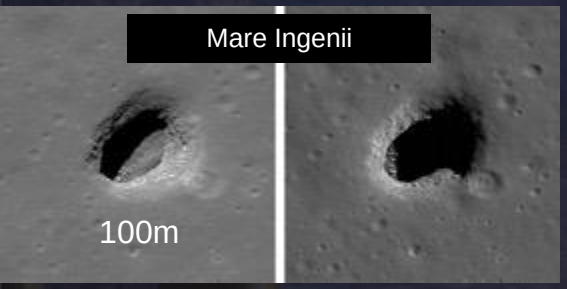
Extraterrestrial Lavatubes & Pit Caves

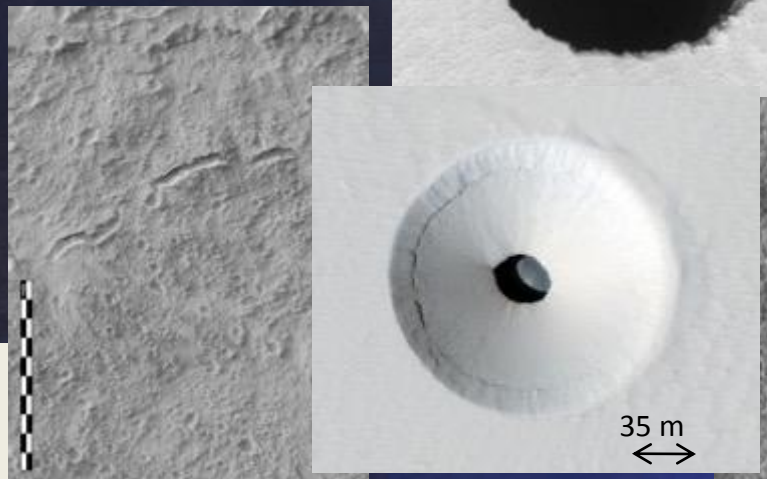


All images, NASA



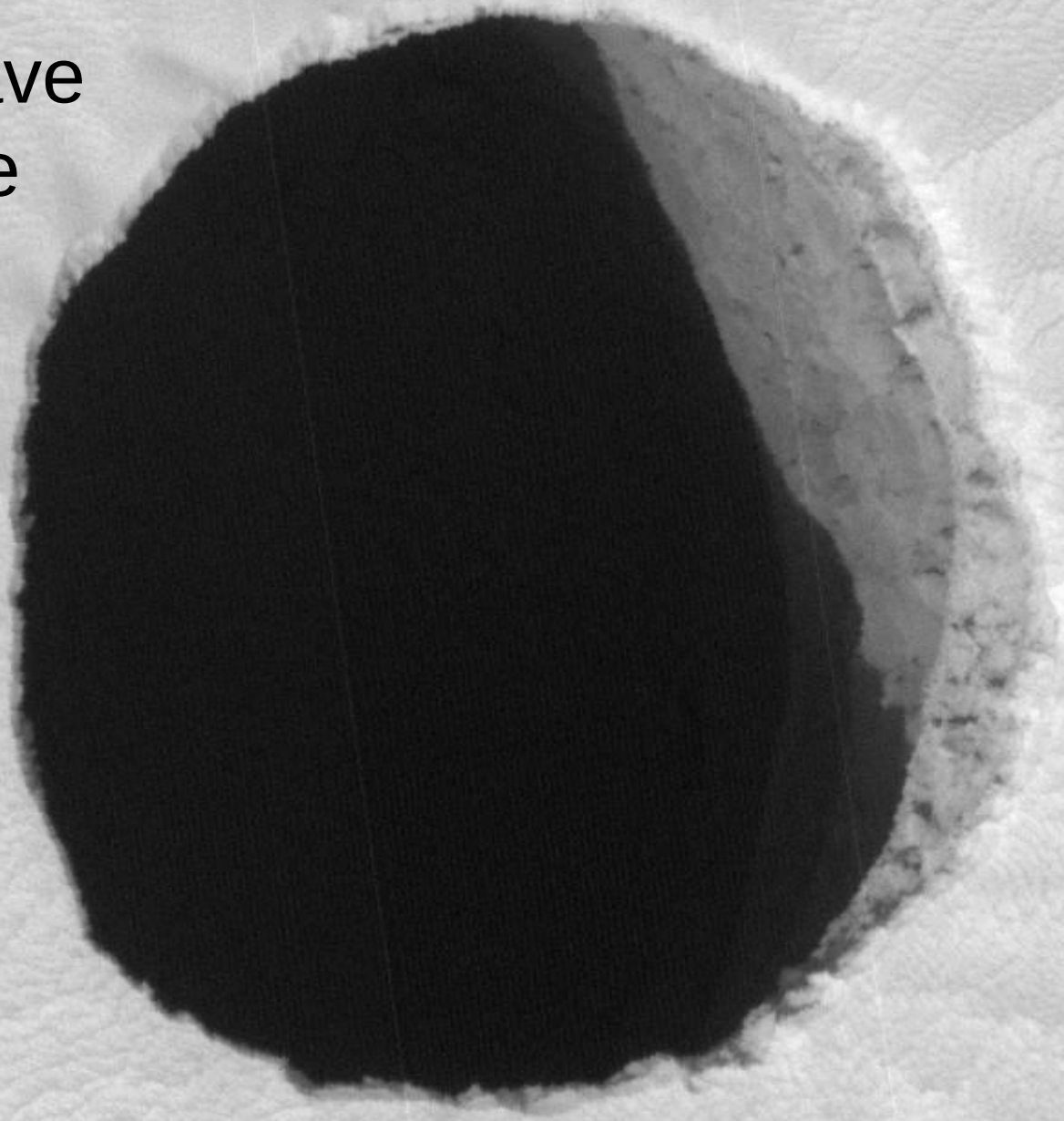






Boston, P.J. 2004. Extraterrestrial Caves. *Encyclopedia of Cave and Karst Science*. Fitzroy-Dearborn Publishers, Ltd., London, UK. Pp. 355-358.

Martian Cave Entrance

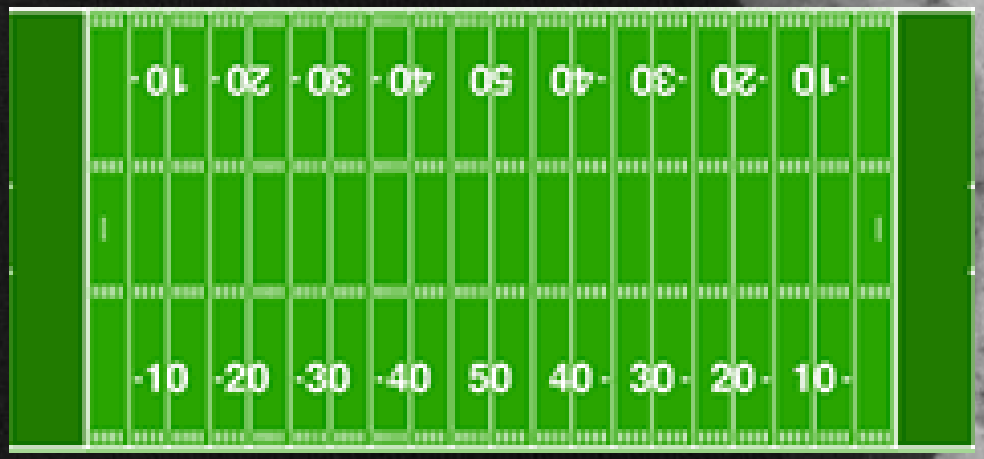


HiRise data
30 cm resolution
Hole is 100 m across!

NASA HiRise Camera Image

Martian Cave Entrance

Compared to an American football field



HiRise data
30 cm resolution
Hole is 100 m across!

NASA HiRise Camera Image

Martian Cave Entrance

compared to an American sinkhole!

West Desert Sinkhole
Utah

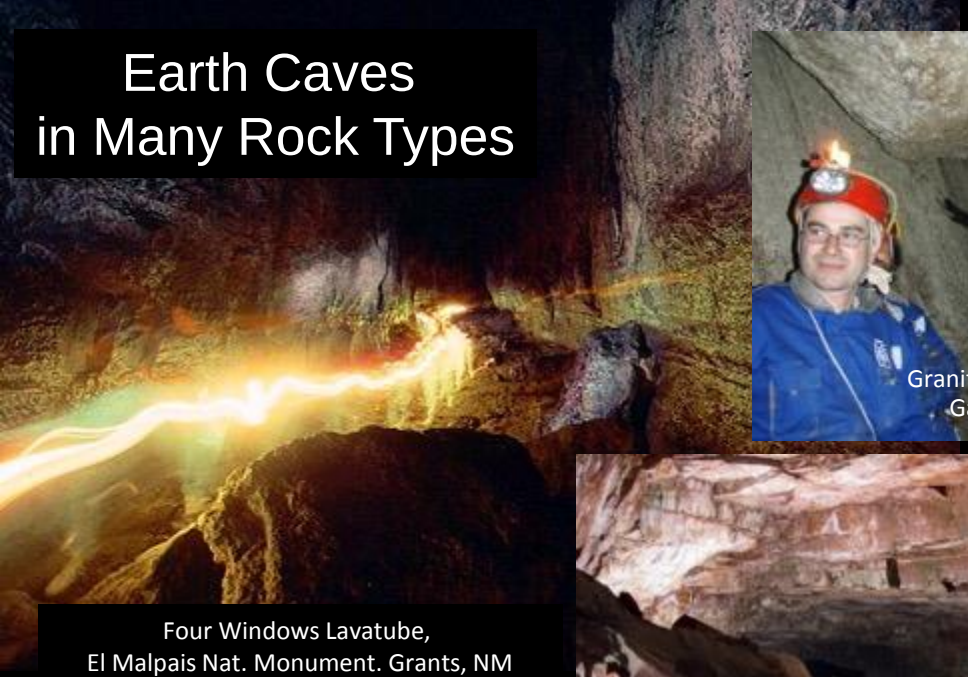
Google Earth

West Desert Sinkhole, Utah

~22 meters diameter

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

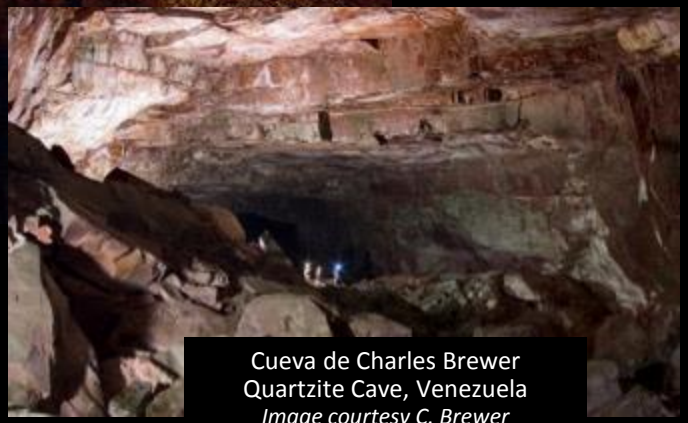
Earth Caves in Many Rock Types



Four Windows Lavatube,
El Malpais Nat. Monument. Grants, NM
Image courtesy of K. Ingham

Granite spalling caves
Gallicia, Spain

Lechuguilla Cave, Carlsbad, NM
created by sulfuric acid and limestone
Image courtesy D. Bunnell



Cueva de Charles Brewer
Quartzite Cave, Venezuela
Image courtesy C. Brewer

Antarctic ice caves, Mt. Erebus
Courtesy of A. Curtis

Caves in Salt
Atacama Desert, Chile

Submarine caves
Costa Rica
Courtesy of J. Mylroie

Lilburn Marble Cave, CA

Parks Ranch Gypsum Cave,
Carlsbad, NM

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, glaciere' caves (i.e. caves in ice as bedrock), "thermokarst"**	**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 solvent**	**Classic karst, gypsum, halite**	**Earth, Titan, Mars**
Erosional	**Mechanical erosion via wind, water, ice, crystal wedging,**	**Solid**	**Sea coast caves, ation, ian rock etc.**	**Earth** **Mars (aeolian, tafonation)** **Titan (coastal?)** **Venus (aeolian?)**
Tectonic	**Fracture or external movements**		**es**	**Earth, Europa** **Ganymede?** **Titan, Enceladus** **Mars**
Suffosional	**Cavity cons fluid-b particles**		**d caves, e nokarst**	**Earth** **Mars (poles, RSL layers?)**
Phase Transition	**Cavity construction melting, vaporization, or sublimation**	**le or able ials cap of ifying at p et- mal temperatures**	**La ube caves, glacia caves (i.e. caves in ice as bedrock)**	**Volcanic bodies (Earth, Mars, Venus, Io)** **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**

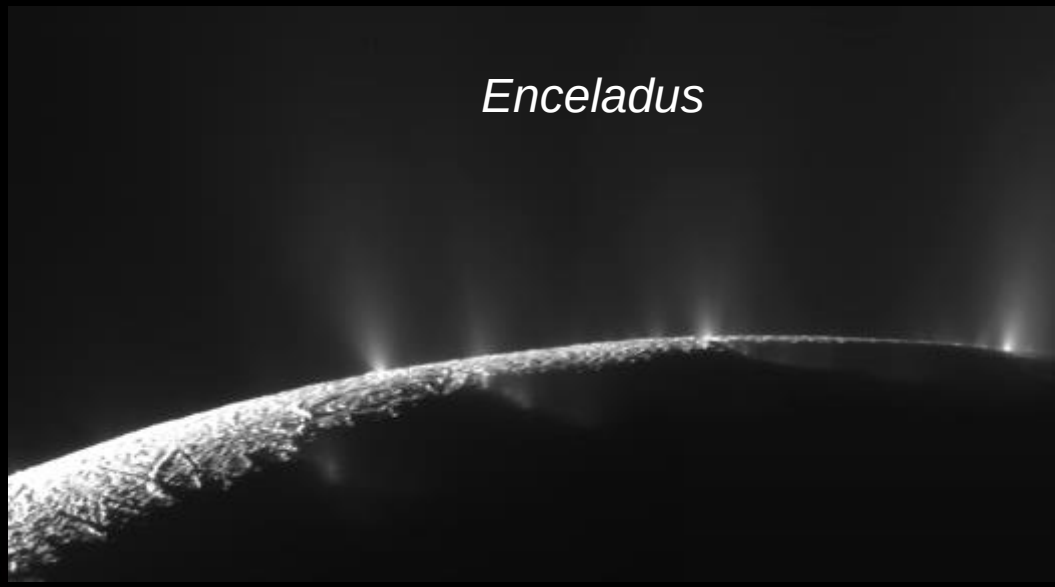
Where should we put…
Ceres?
Vesta?
Pluto?
Mercury?
Uranus' moons?

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.

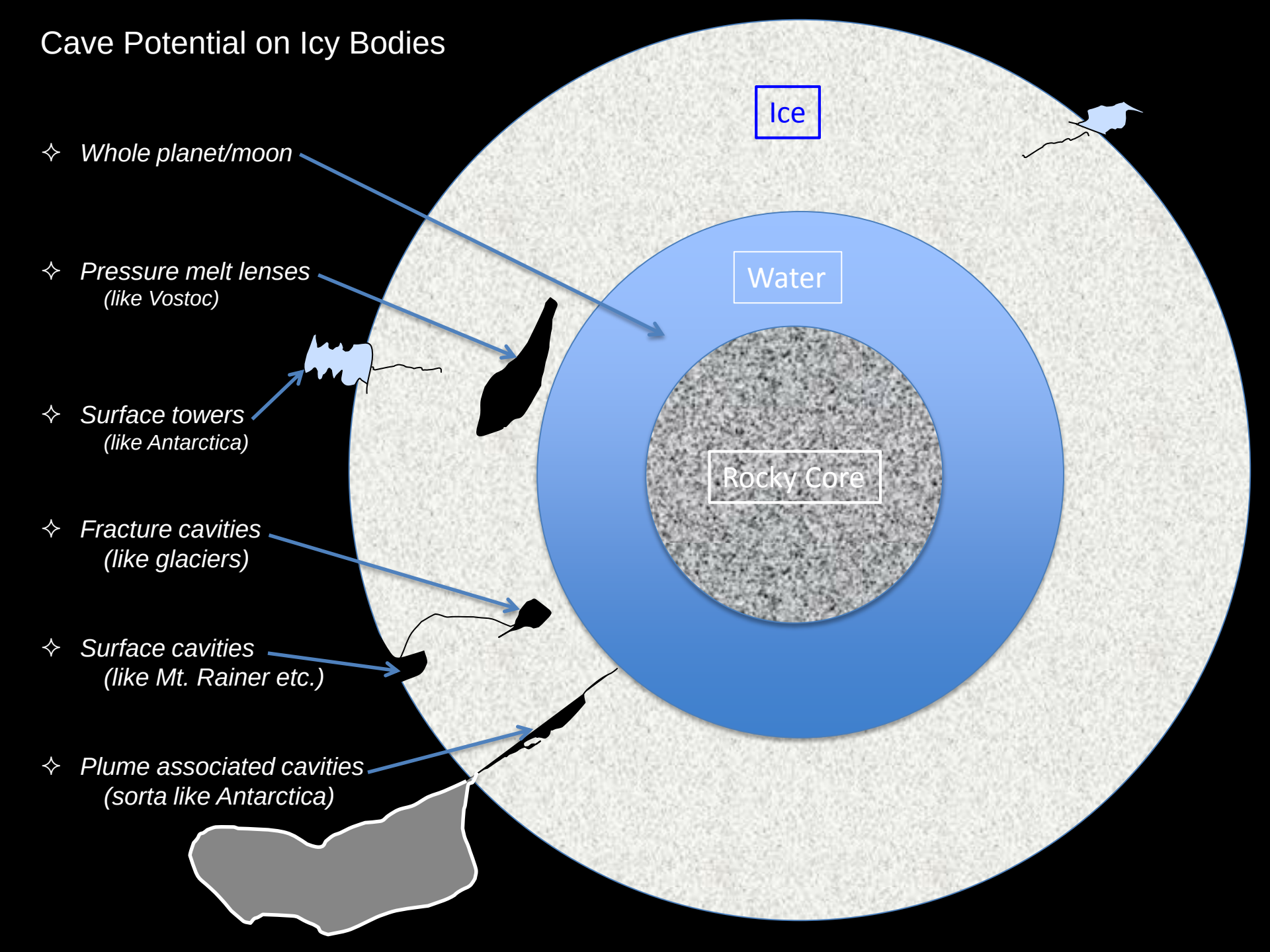
Icy Satellites…not “ocean worlds”, but planet-sized aqueous caves!

Europa

Enceladus



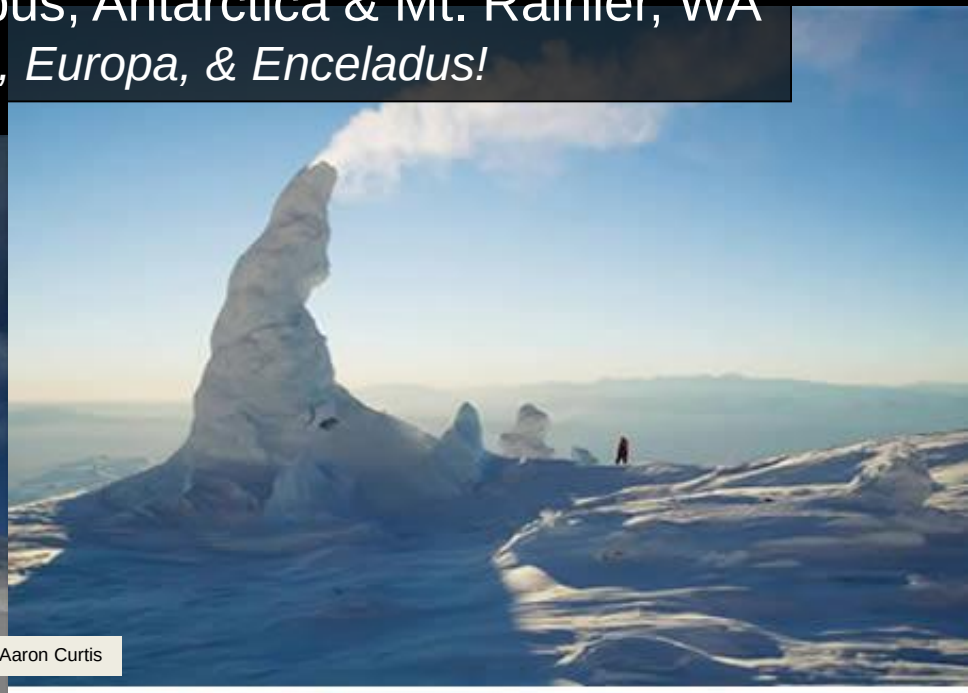
Cave Potential on Icy Bodies



- *Whole planet/moon*
- *Pressure melt lenses*
  (like Vostoc)
- *Surface towers*
  (like Antarctica)
- *Fracture cavities*
  (like glaciers)
- *Surface cavities*
  (like Mt. Rainer etc.)
- *Plume associated cavities*
  (sorta like Antarctica)

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

May be some on Mars, Europa, & Enceladus!



Courtesy, Aaron Curtis

Historical Photograph

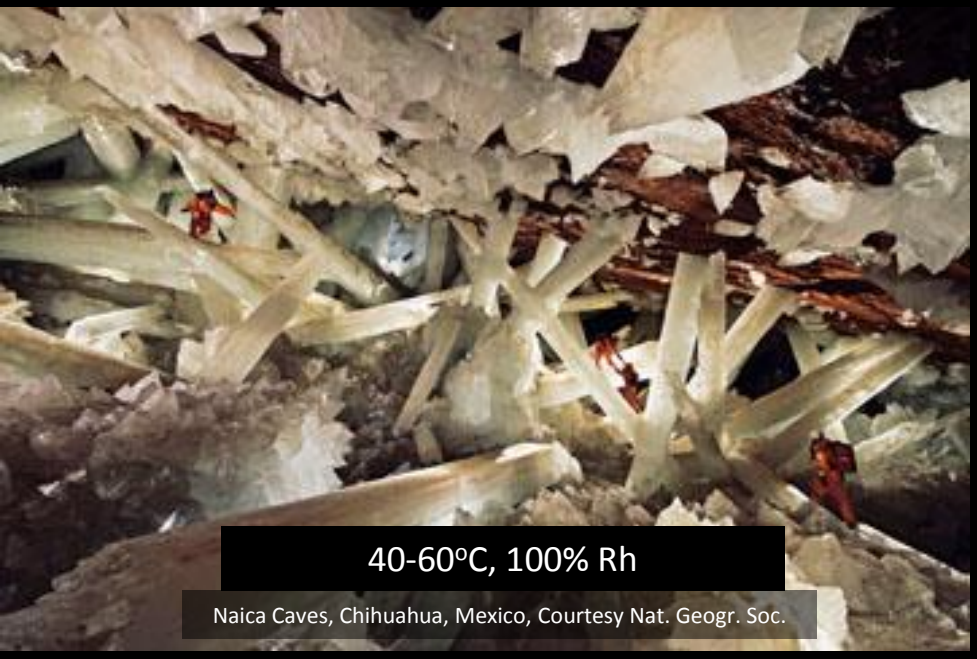
Courtesy, Eddy Cartaya

Sulfuric acid (pH=0), H_2 S, CO, & other poisonous gases

Cueva de Villa Luz, Tabasco, Mexico, Courtesy Nat. Geogr. Soc.

-3°C, poisonous SO_2 & other gases

Fumarolic Ice Caves, Mt. Rainier, WA, Courtesy Eddy Cartaya



40-60°C, 100% Rh

Naica Caves, Chihuahua, Mexico, Courtesy Nat. Geogr. Soc.

World's largest cave decoration, 18.5km & going

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

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

Planet Type 2 Biosphere

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

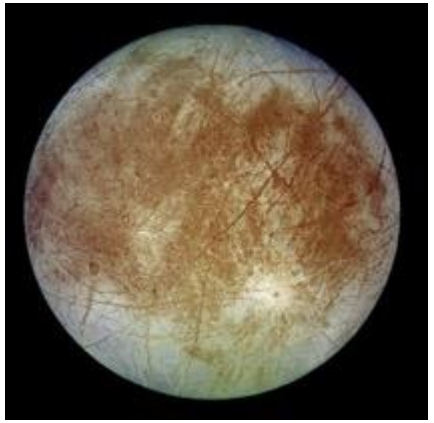
Critical Zone is bottom-up
Chemosynthetically driven

Well mixed-Critical Zone

Earth

Stratified Critical Zone?

Mars



Europa

Biosignature Suites at Many Scales

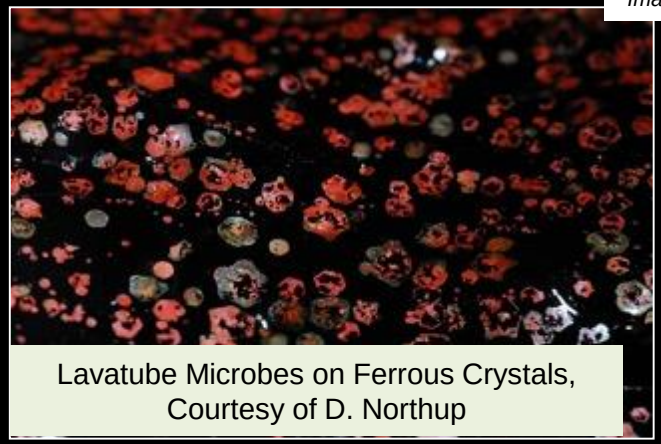
The Hunt for Blue Goo
Copper Subsurface Organisms

snottites!
Image courtesy K. Ingham

Red Tulip Microbial Iron Stalagmites, Zoloushka Cave, Ukraine

Phlegm ball mats
Image courtesy K. Ingham

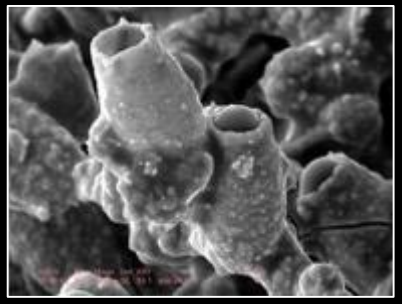
Poofball Sea, Thrush Cave, SE Alaska



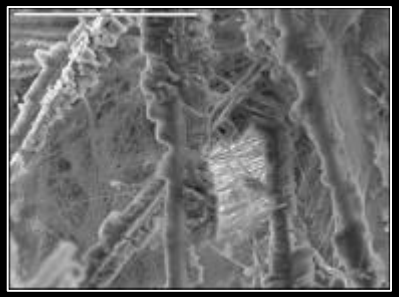
Lavatube Microbes on Ferrous Crystals, Courtesy of D. Northup

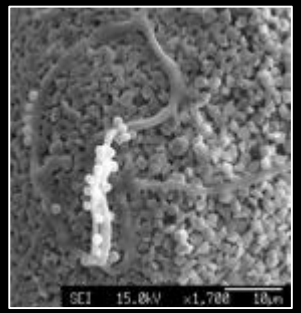
Manganese Microbe Stalagmite on Miner's Jacket, Soudan Mine, MN

Red Tulip Microbial Iron Stalagmites, Zoloushka Cave, Ukraine



Poofball Sea, Thrush Cave, SE Alaska





SEMs by M. Spilde & P. Boston

Boston, P.J. et al 2001. Cave biosignature suites: Microbes, minerals and Mars. *Astrobiology* 1(1):25-55.

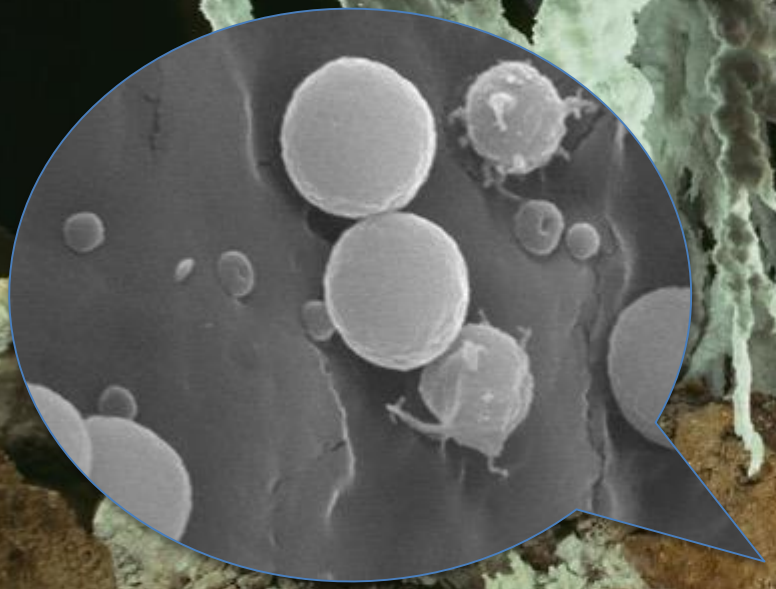
Subsurface Inventors of New Biochemistry

- ✧ Highly partitioned environments
- ✧ Extreme isolation of habitats

- ✧ Limited mobility
- ✧ Inhibition of gene flow
- ✧ Physical limitation of space

- ✧ STRONG evolutionary pressures

Stupefying Biodiversity!
Almost everybody is new to science….



e.g. Lechuguilla Cave, NM
145 miles mapped passages so far
~ 2X that volume by argon tracer tests
100s of isolated pools
Extreme wall heterogeneity
Widely varying chemistries

Image courtesy of Peter Jones

Energy Enriched Sulfuric Acid Cave

Cueva de Villa Luz, Tabasco, Mexico

Biodiversity rich!
Biomass rich!
pH ranges from 9.2 down to 0 !
Energy:
- *Subsurface H_2S*
- *Surface-derived organics*

Cave-adapted acid tolerant fish!

Biofilm on beetles!

snottites!

microbial biofilms

5 species bats

Photos by Kenneth Ingham,
Background by Steve Alvarez

Nat Geog 1998, 2000, 2014
BBC 1999, 2005, 2012, 2013
NHK 2003, etc.

Whoa! Is this a photoshop hoax?

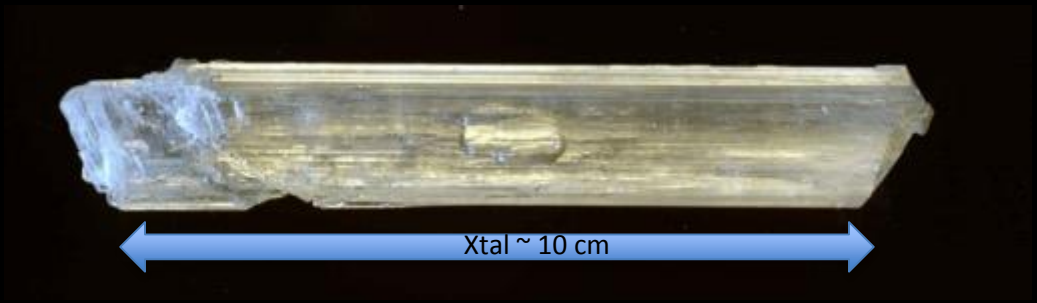
Giant Crystal Cave - National Geographic TV Special, Oct 2008
& National Geographic Magazine, Nov. 2008
Into the Lost Crystal Cave – National Geographic TV Sequel, Oct. 2010

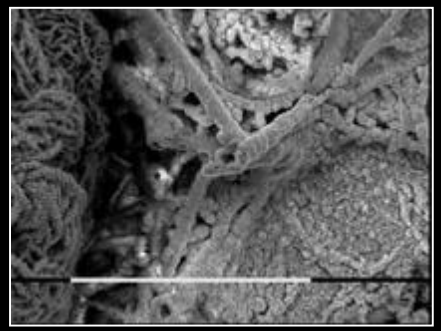
Naica Mine, Naica Cave System
Chihuahua, Mexico

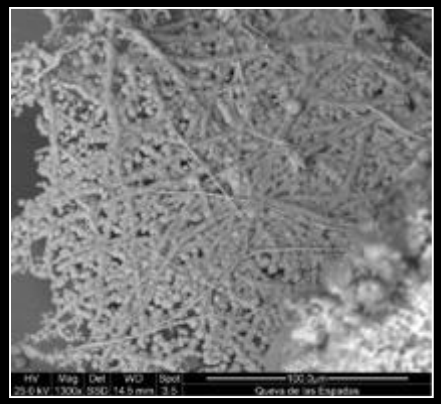
- Giant selenite crystals
  ($CaSO_4$ same mineral as wallboard…)
- 40-60°C (105-140°F, whew!)
- Water drained for mining
- Saturated humidity
- Iron oxide deposits

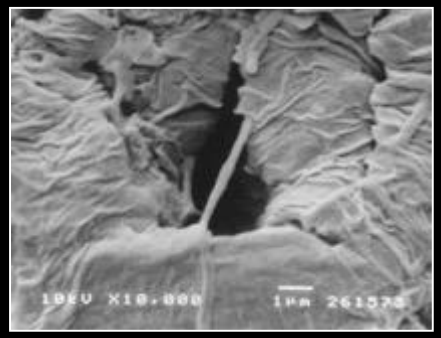
Courtesy, La Venta Cave Project

- Inclusions (holes in the crystals)
- Solid & fluid
- Iron and manganese deposits on walls & in inclusions

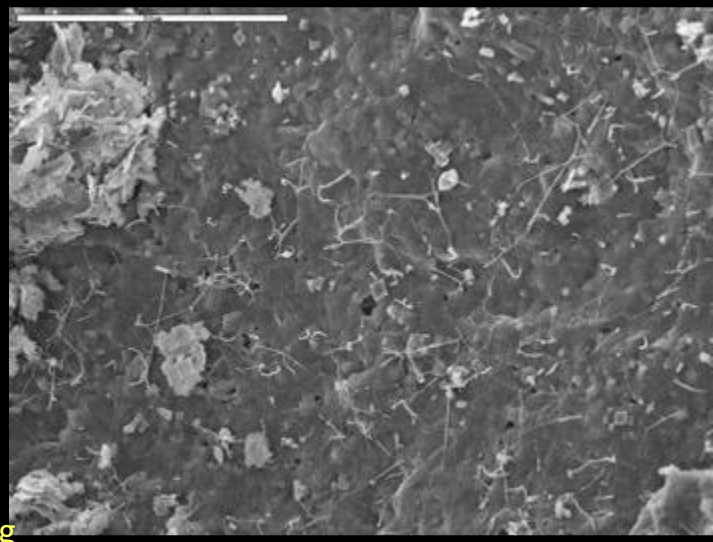




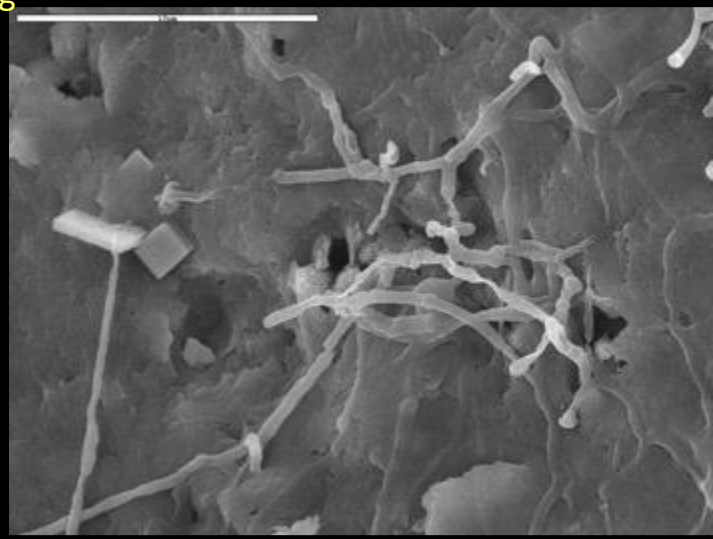




Microbial fossils in inclusions



Live microorganisms encrusting clay & iron oxide walls



Micrographs on left, courtesy of P. Forti

Micrographs on right M. Spilde & P. Boston

- Results so far….
- Xtals ~500, 000+ yrs old
  (Forti et al., Lauritzen et al.)
- Sampled inclus. ~10-50, 000 yrs old
- DNA directly recovered
  & sequenced, ~ 40+ strains
- 65+ live cultures growing!
- Many viruses present!
  (Suttle, Chan, Winget at UBC)

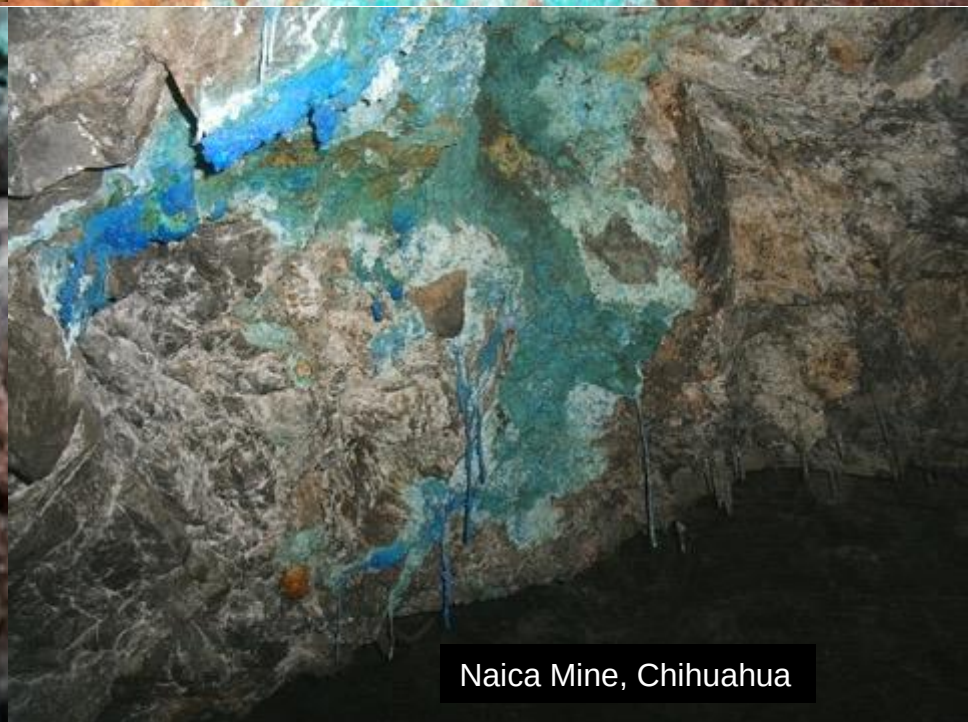
Images by Paolo Forti, Tom Kieft, Tullio Bernabei, Mike Spilde

The Hunt for Blue Goo
Copper Subsurface Organisms

"Diseased" Botallackite
Harvard Mineral Museum

Malequita Cave,
Venezuela

Maelstrom Lavatube, Hawaii

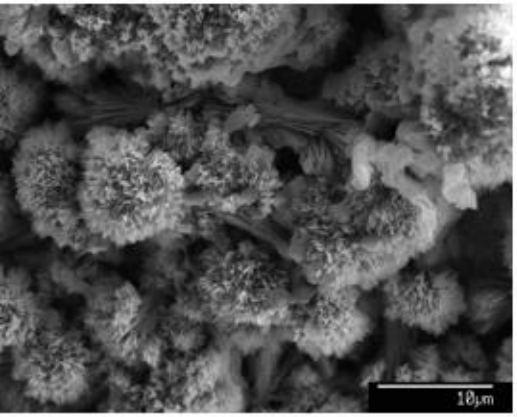


Naica Mine, Chihuahua

30 months after inoculation growth is visible

4.5 years significant mineral precipitation

Fungal/bacterial consortium
Copper sulfide oxidizer bacteria
Elemental copper stored in fungal hyphae
Copper oxides produced (malachite, azurite)

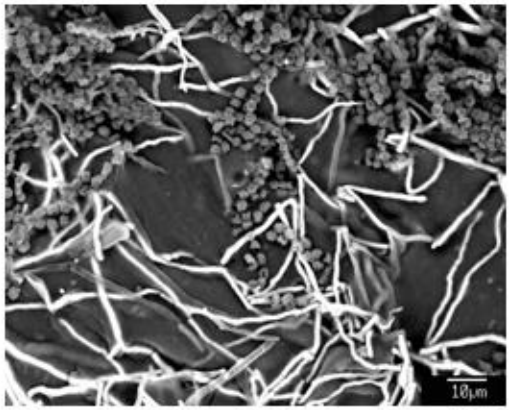


~~*Now at 8 yrs…*~~

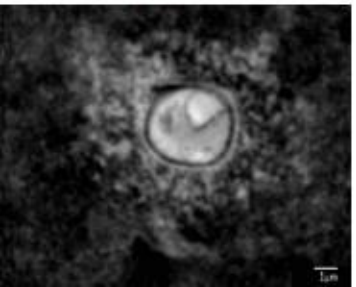
~~Now at 13 yrs!~~

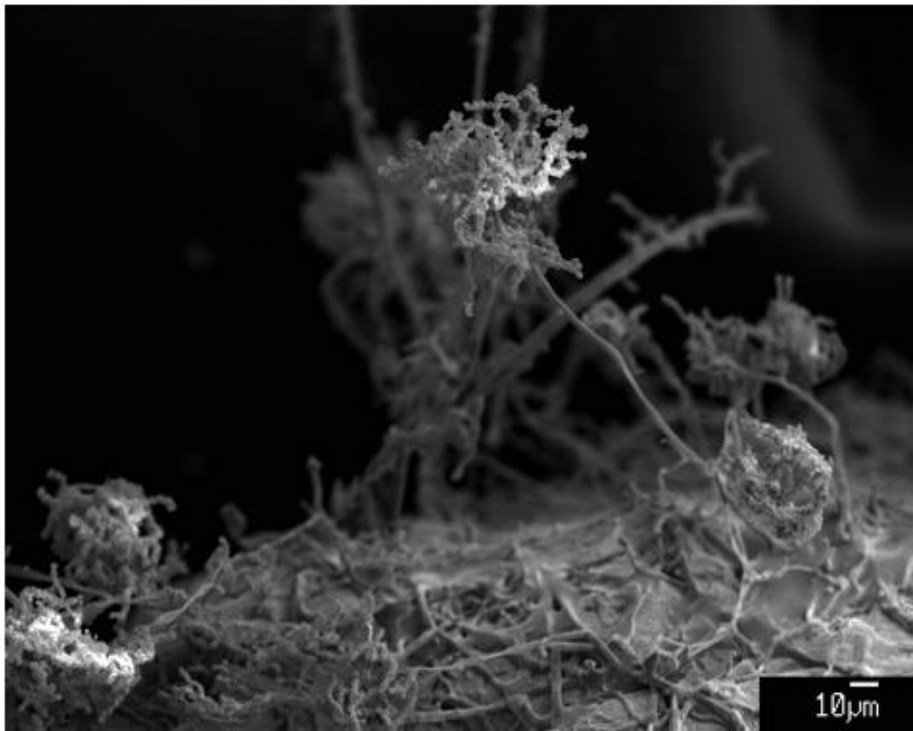
Now at 15 yrs!

SEM backscatter



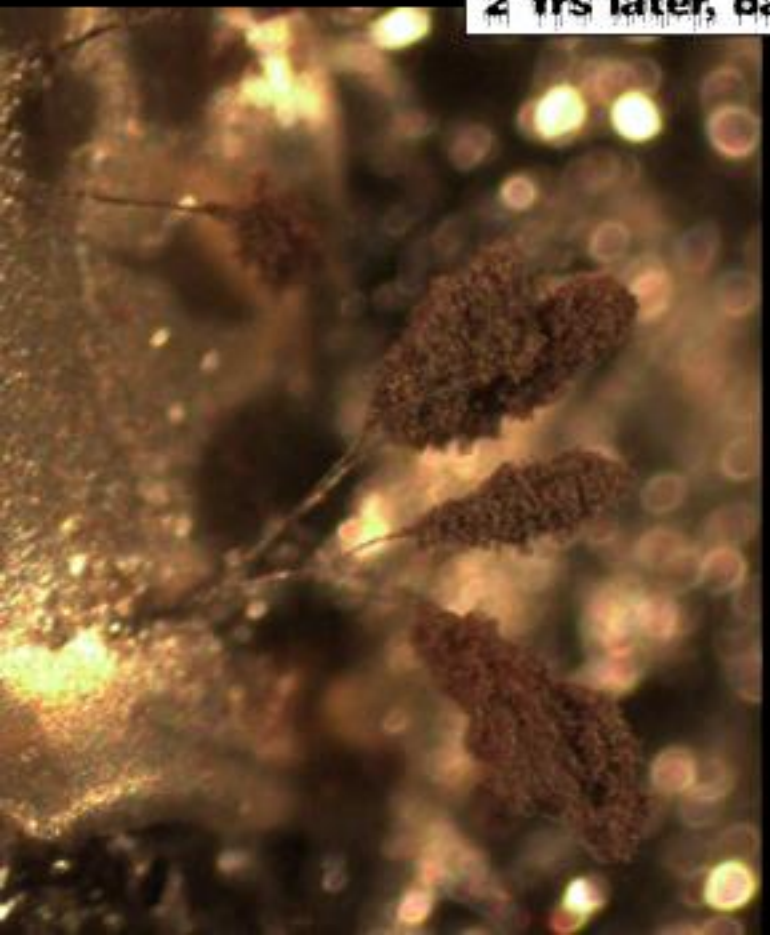
TEM

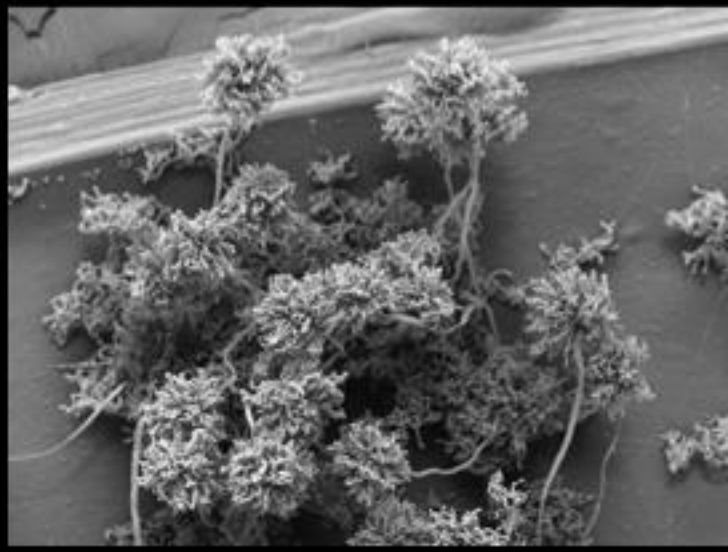




The Microbes That Wouldn't DIE!!!!!

Air Dried
Vacuum Dried, ~100°C
Coated in Au/Pd
Zapped repeatedly w/ electron beams in a hard vacuum!!!
2 Yrs later, back from the dead





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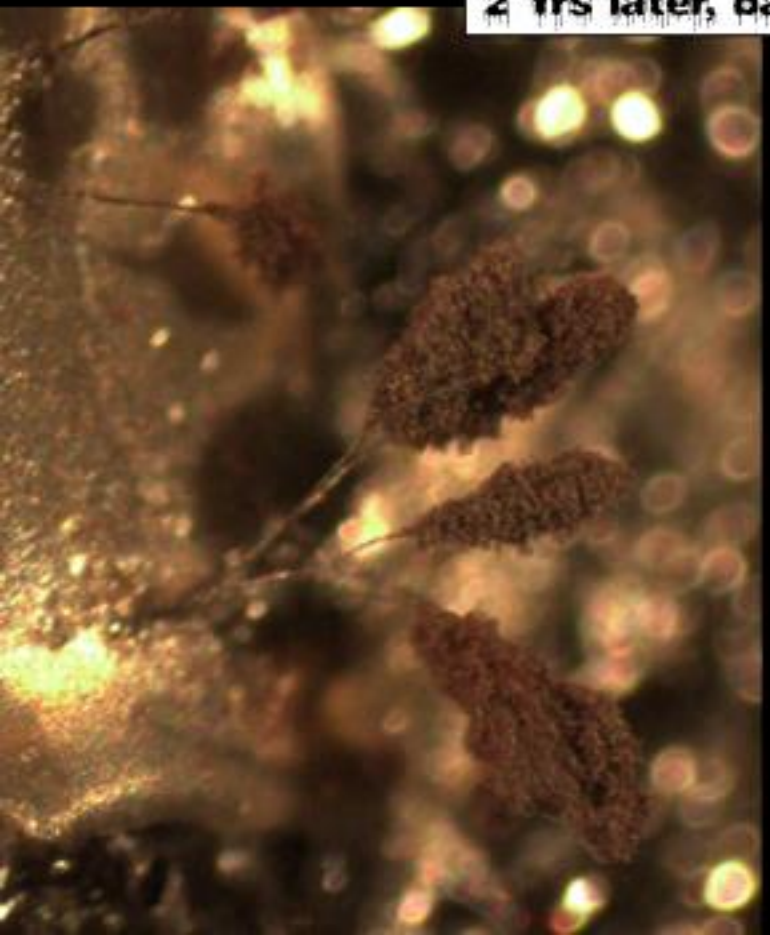
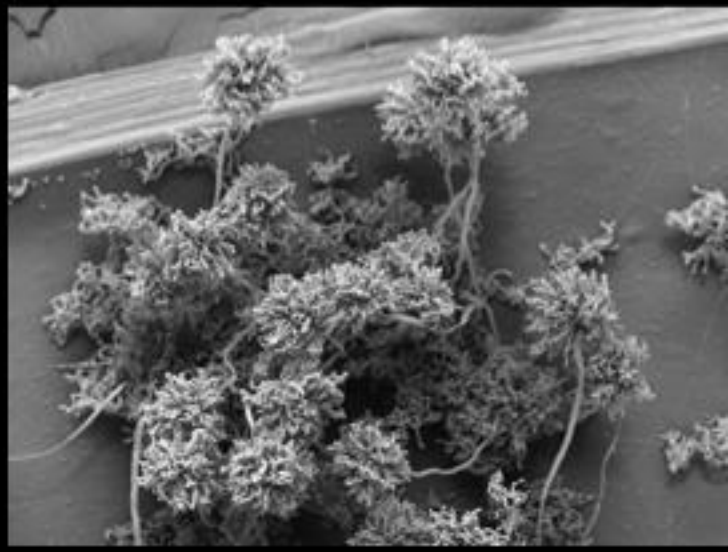


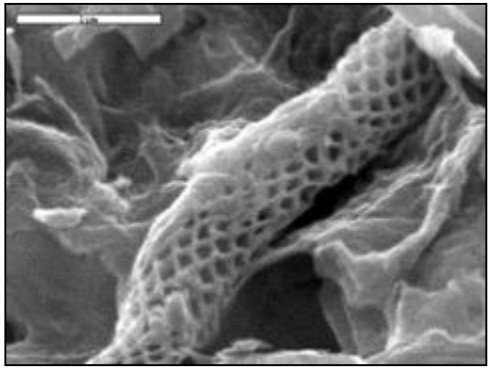
We've now done this 4 times!

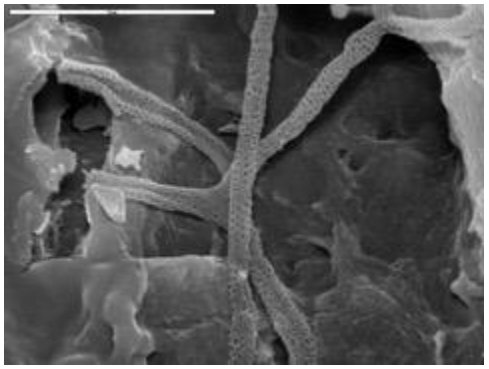


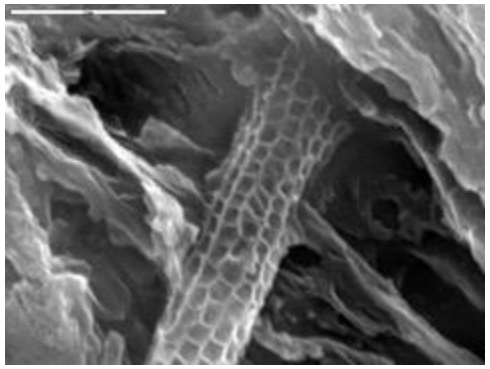
In our cave work, we are already dealing with sensitive “alien” biology…

What are these??? Do you know? We don’t….

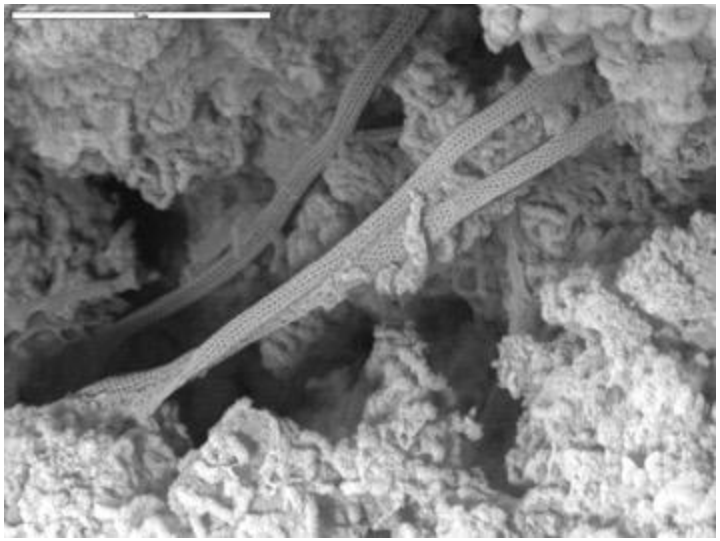
We are finding them in caves all over the world.

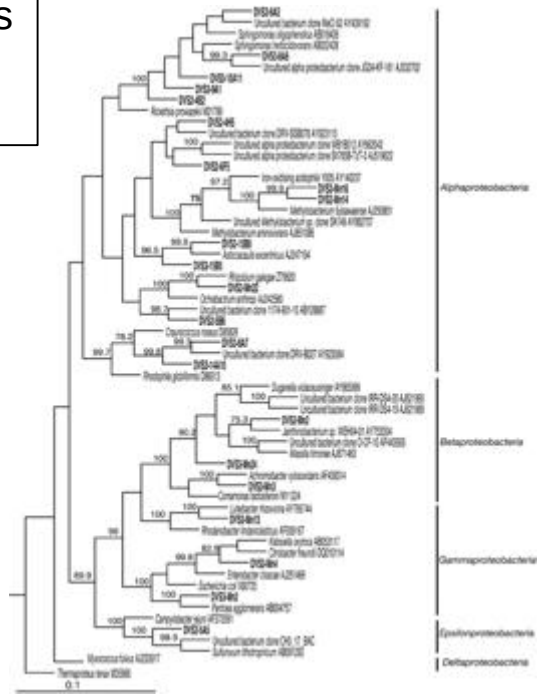






Subsurface geomicrobiology is helping us to prepare for the search for life in caves on Earth, on Mars, & icy moons.





DNA analysis doesn’t help us…
Too many organisms!

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

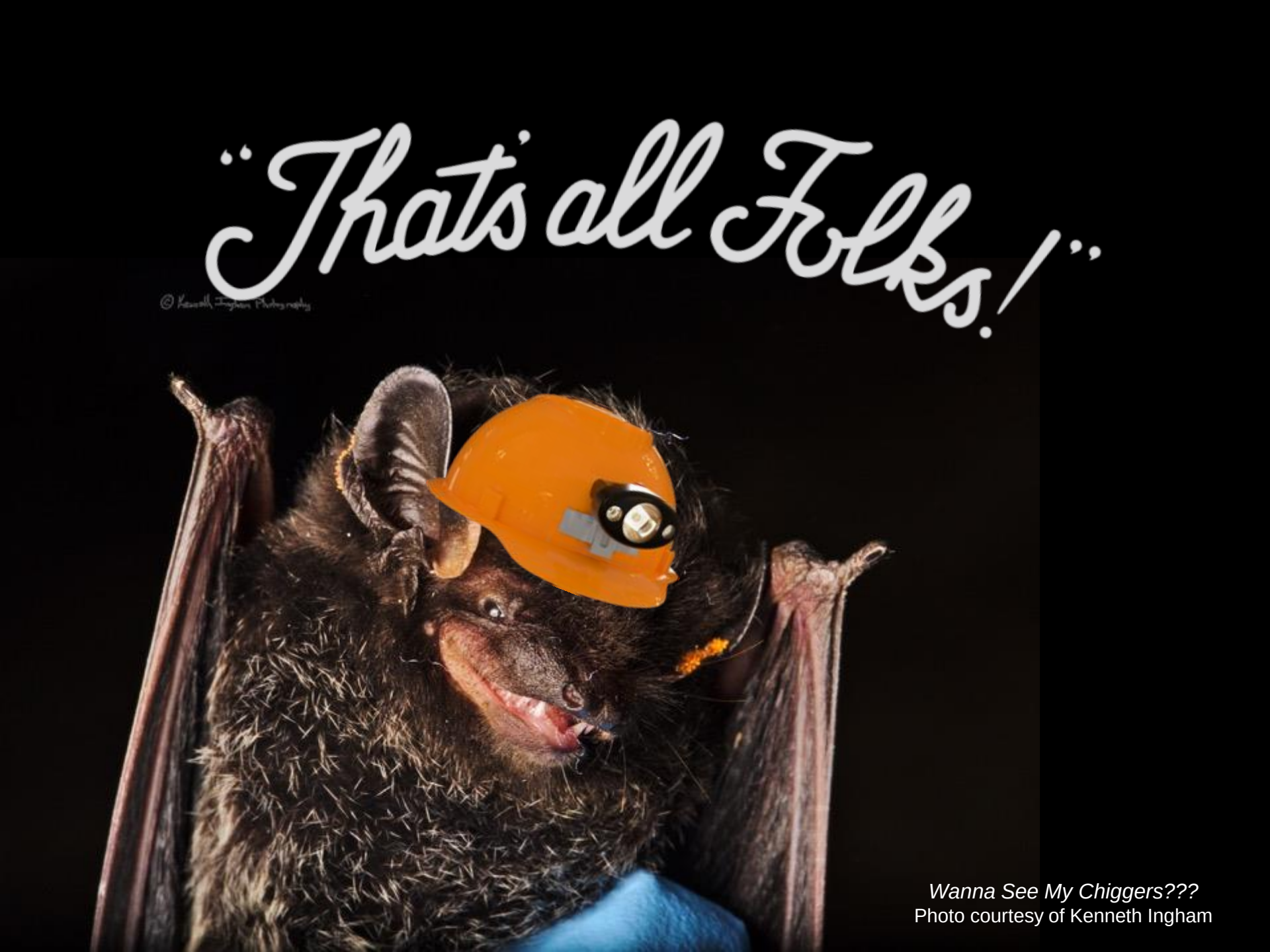
powers of observation are distilled

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



Wanna See My Chiggers???
Photo courtesy of Kenneth Ingham