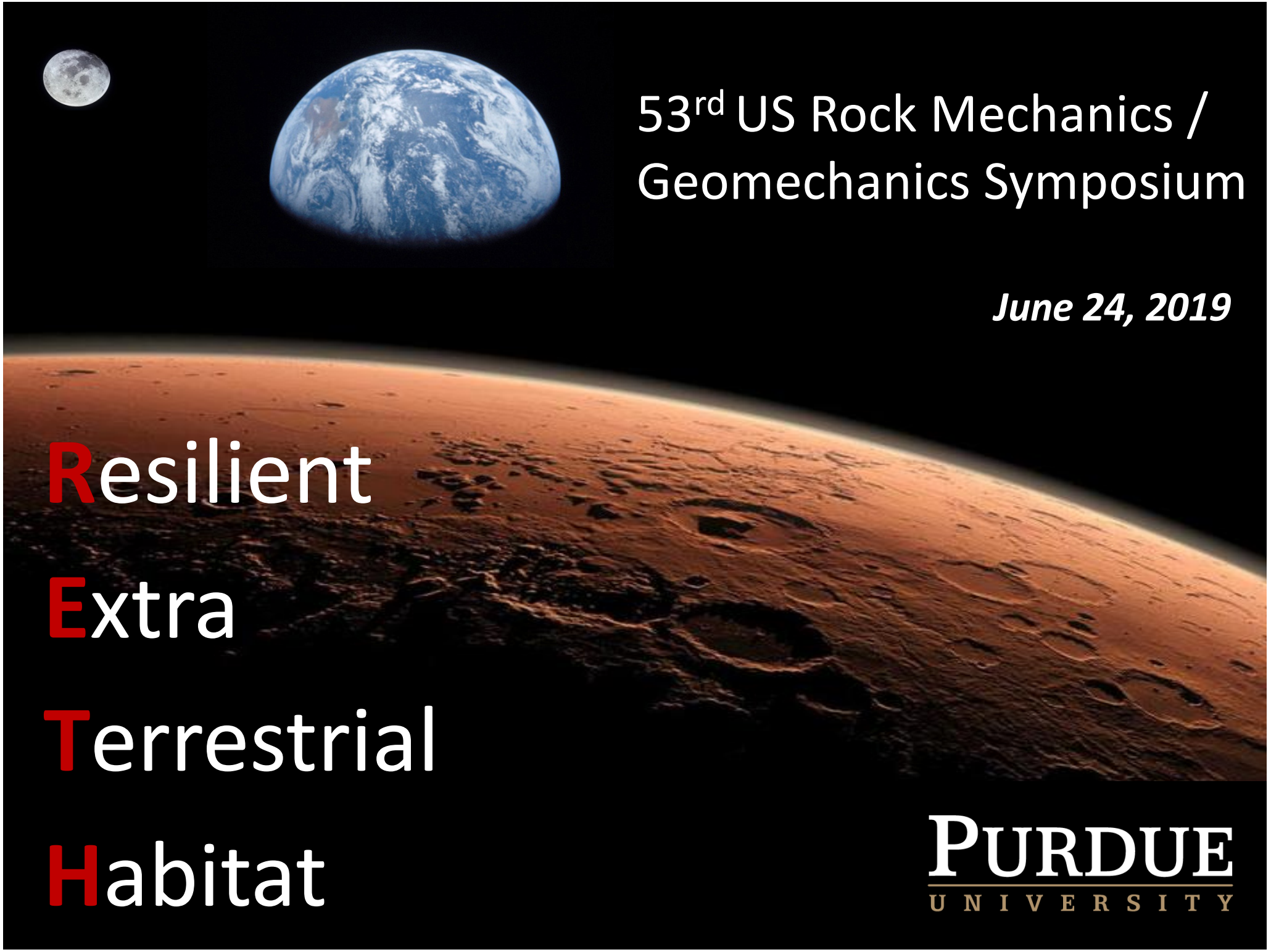
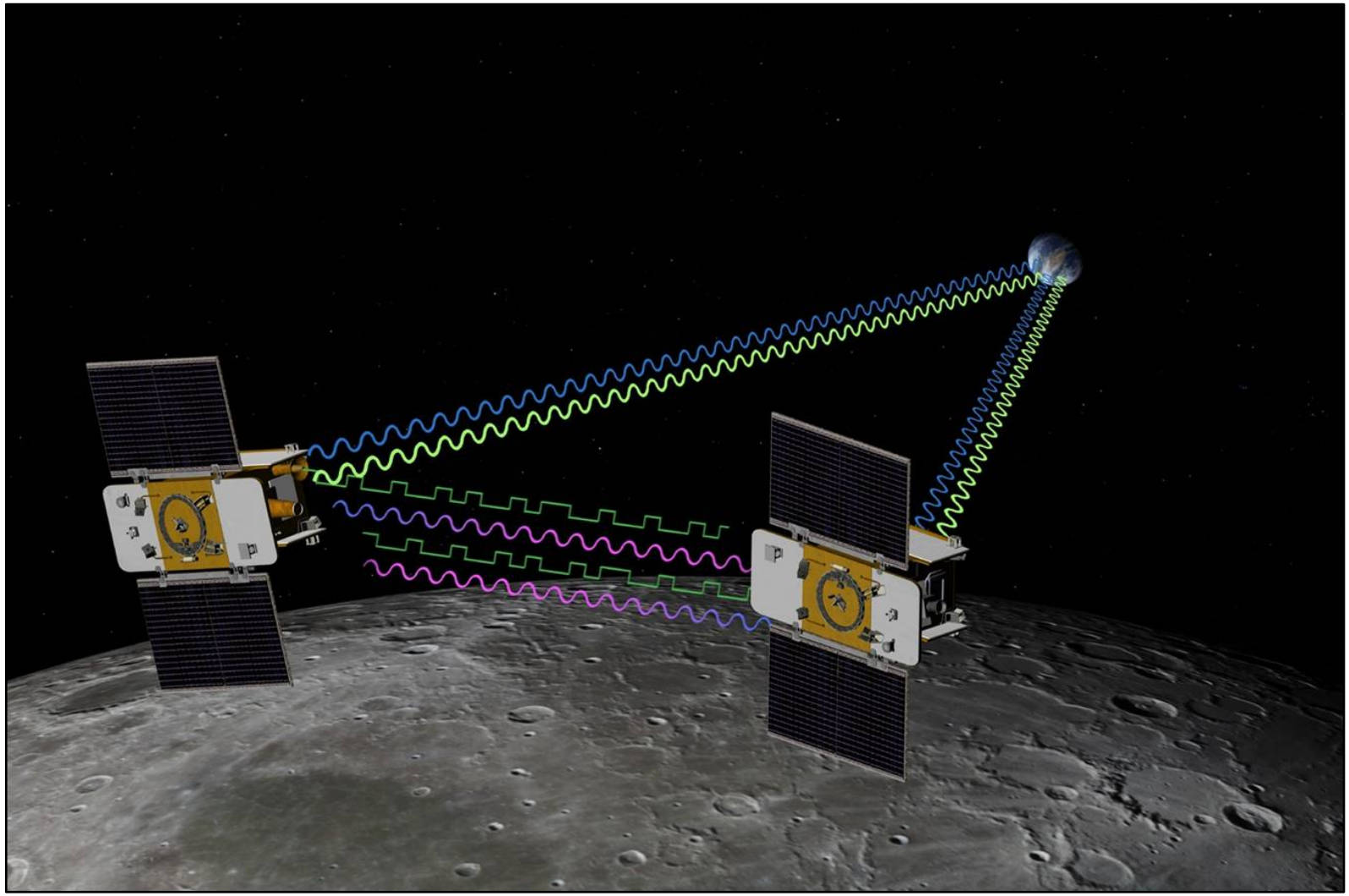

53rd US Rock Mechanics / Geomechanics Symposium
June 24, 2019
Resilient
Extra
Terrestrial
Habitat
PURDUE
UNIVERSITY

Extraterrestrial Habitat Engineering

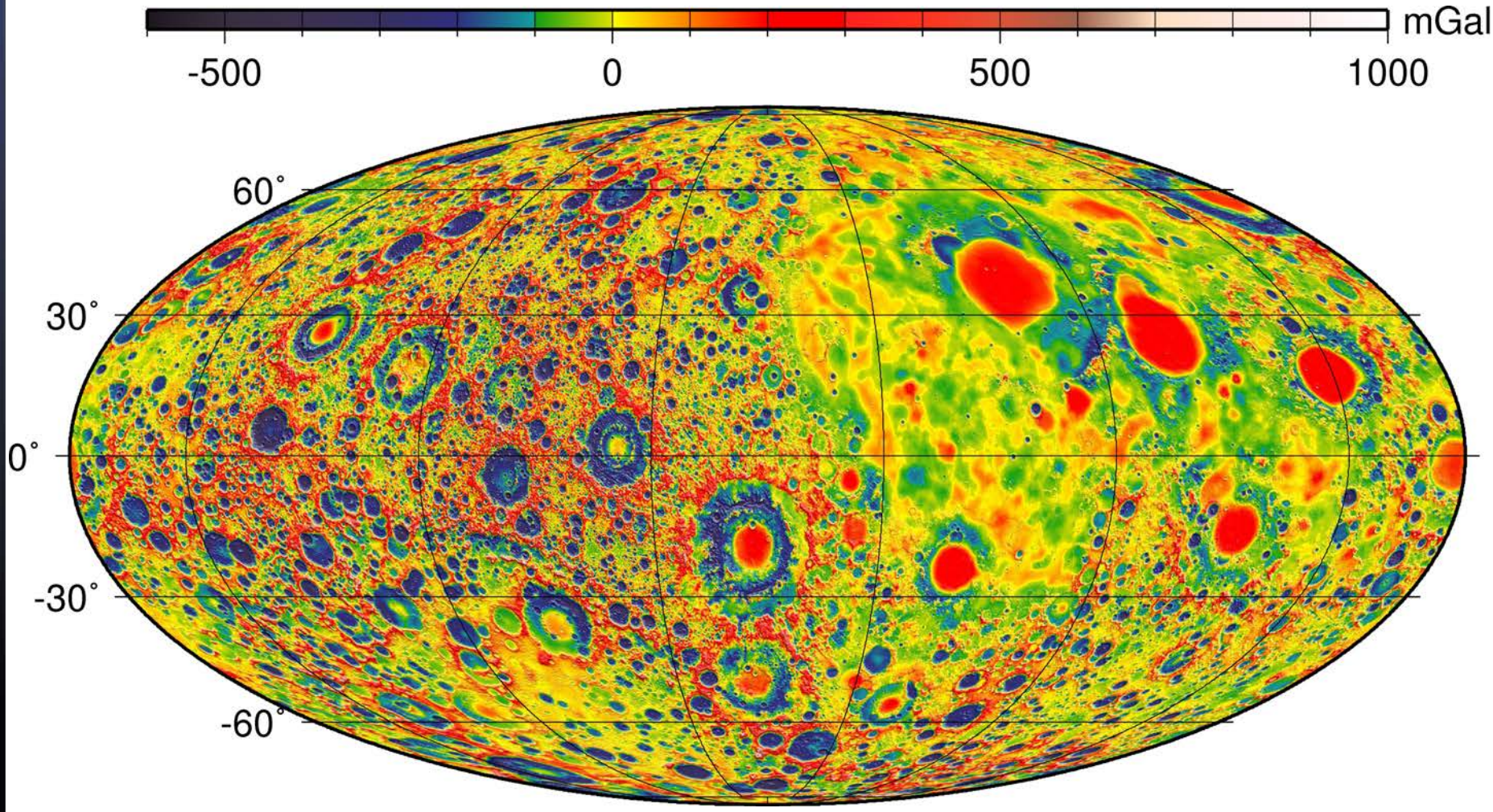
- How did this start?
- Vision & Grand Challenges
- Resilient Habitat
- Stability of Lunar Lava Tubes

the project originated with NASA's GRAIL mission to the Moon (2011-2012)



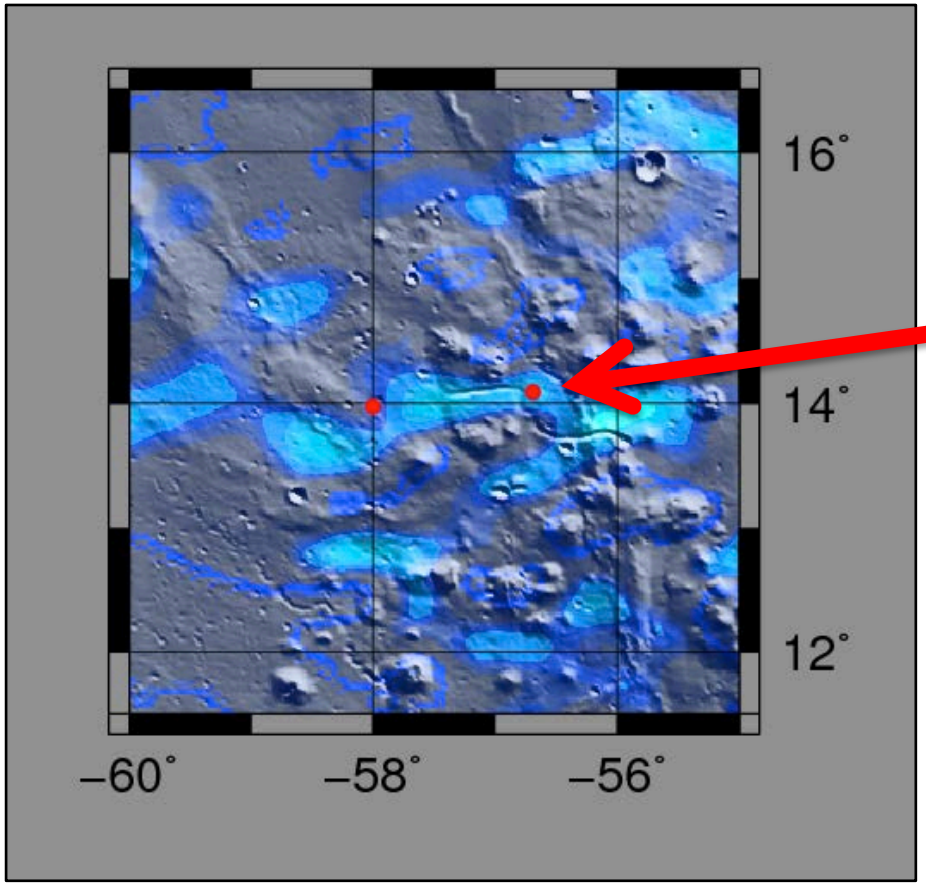
RETH

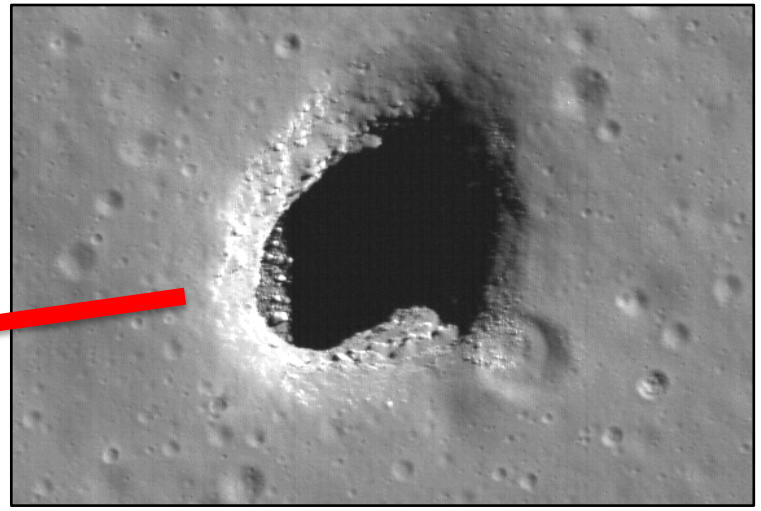
GRAIL made precision measurements of the Moon's gravity



RETH

Purdue Discovery!
Large lava tubes on the Moon

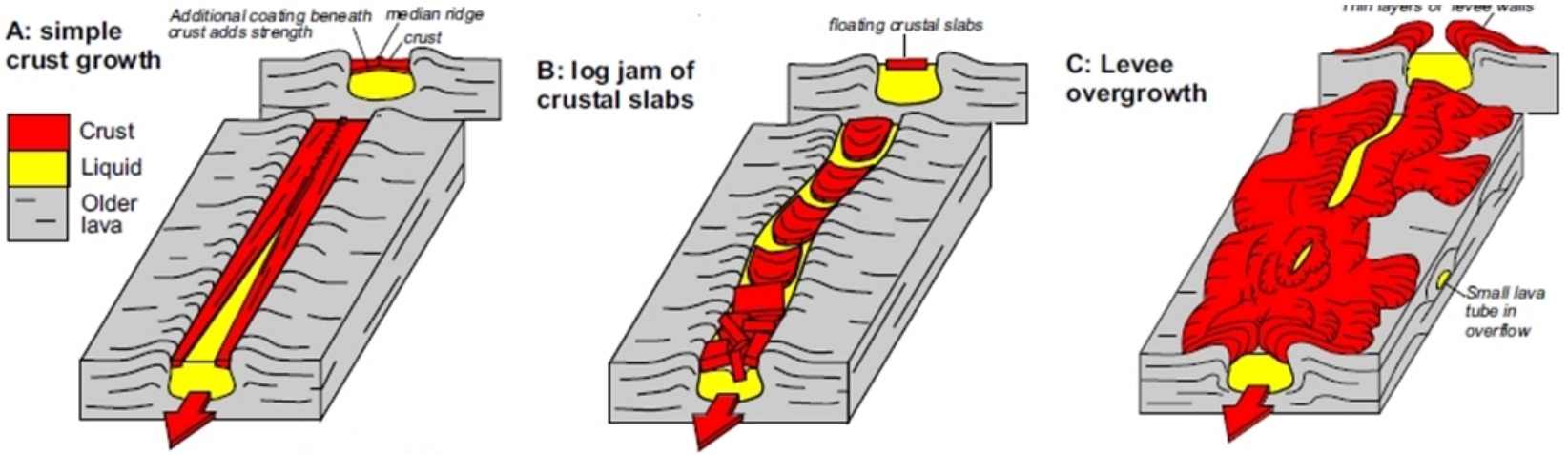




Lunar “skylight” lava cave, 130 m diameter

Cross-correlation of free-air and Bouguer gravity using along-track cross-correlation method. (Loïc Chappaz, Kathleen Howell, Rohan Sood, GRL 2017)

Lava tubes form in the aftermath of lava feeder channels



Undara, Queensland, AU

Subway Cave, N. California

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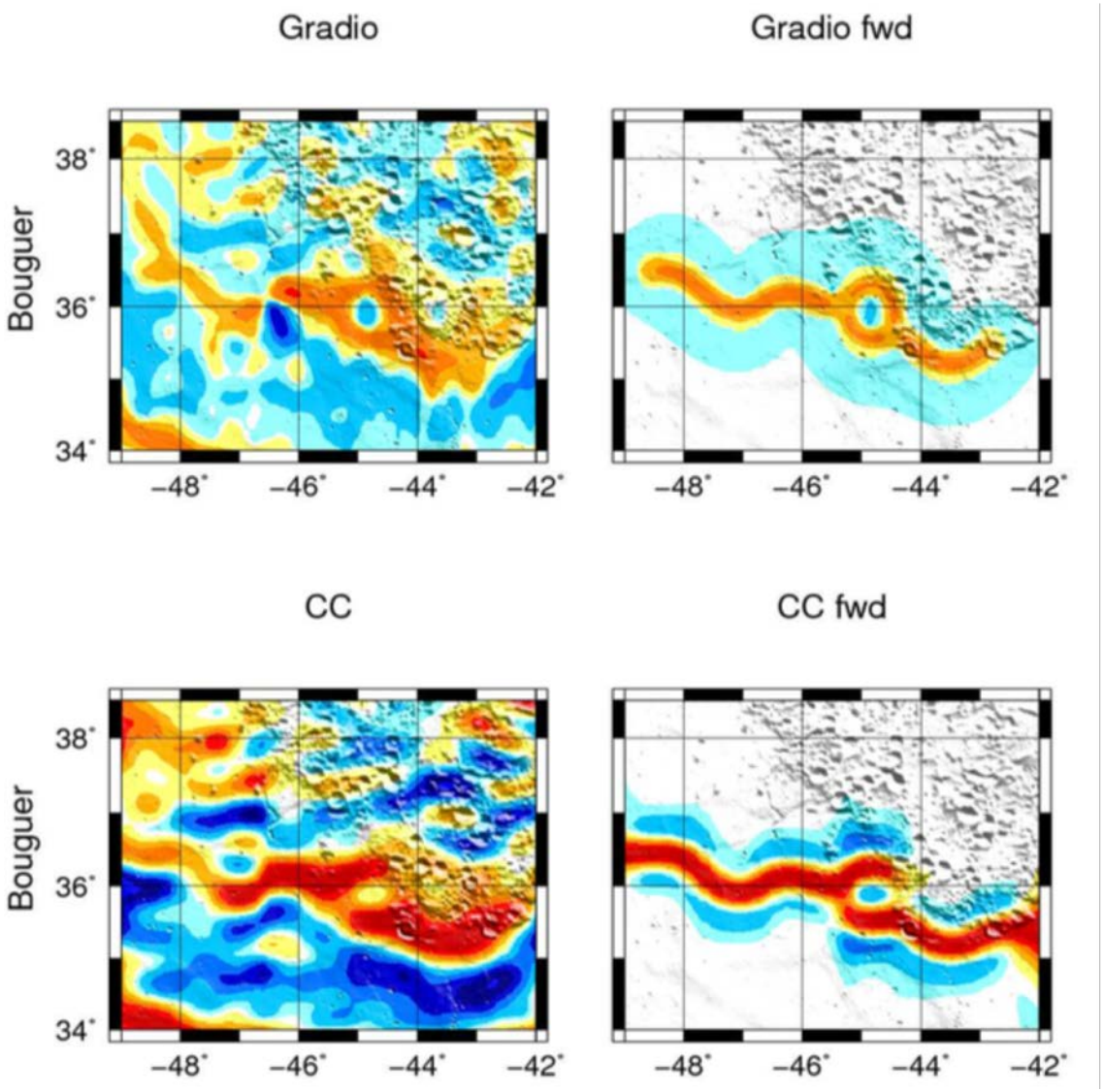
Resilient ExtraTerrestrial Habitats

The gravity signals, however, suggest km-wide openings



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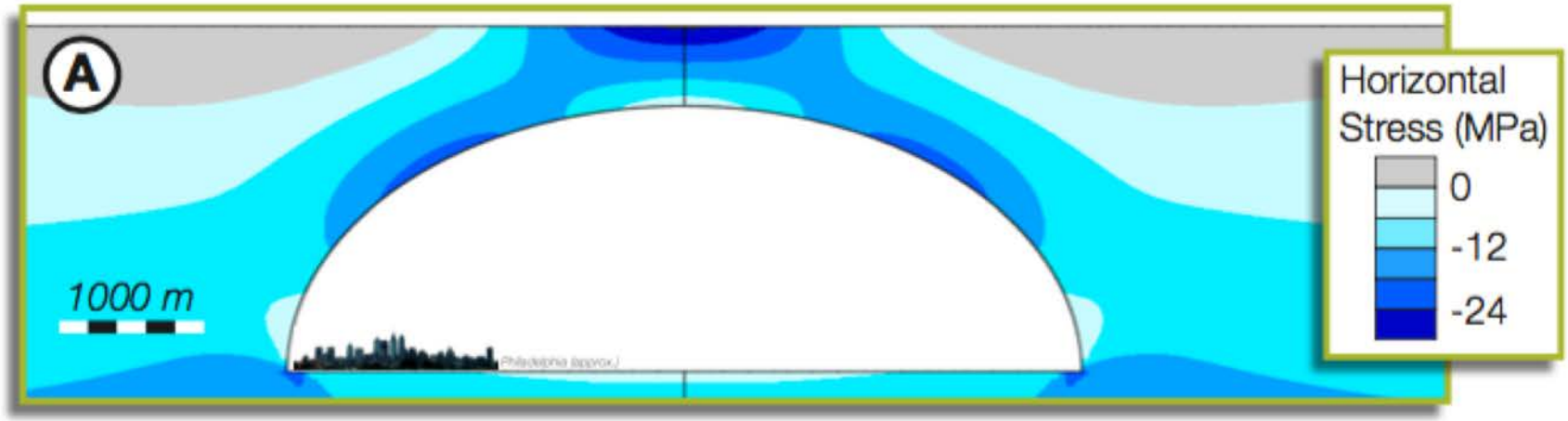
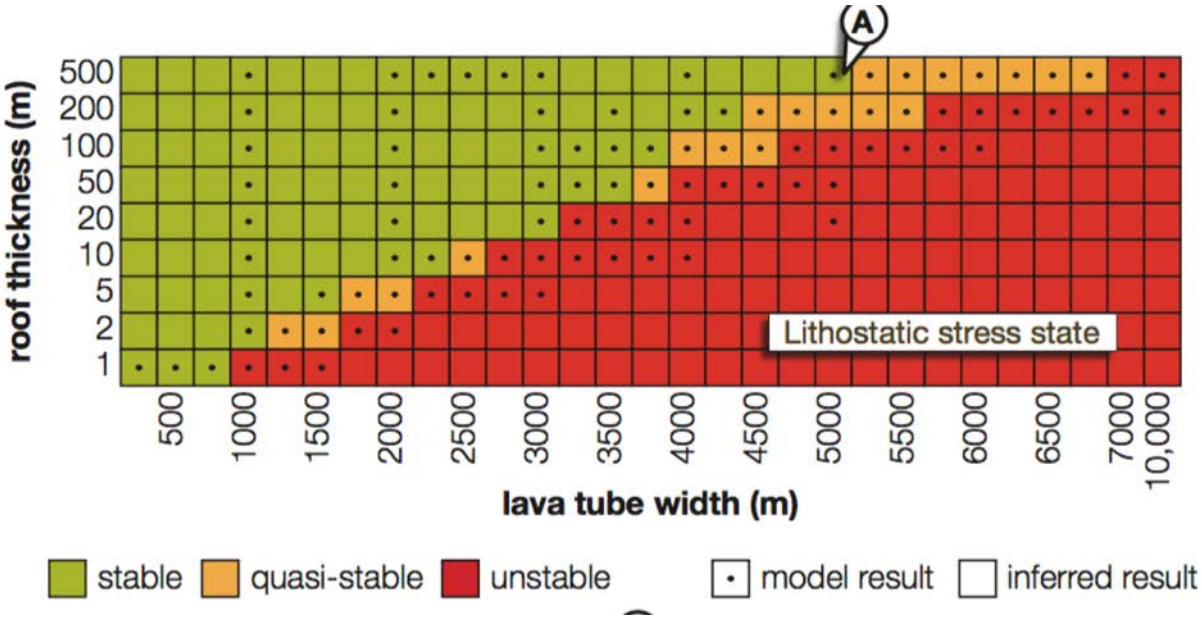
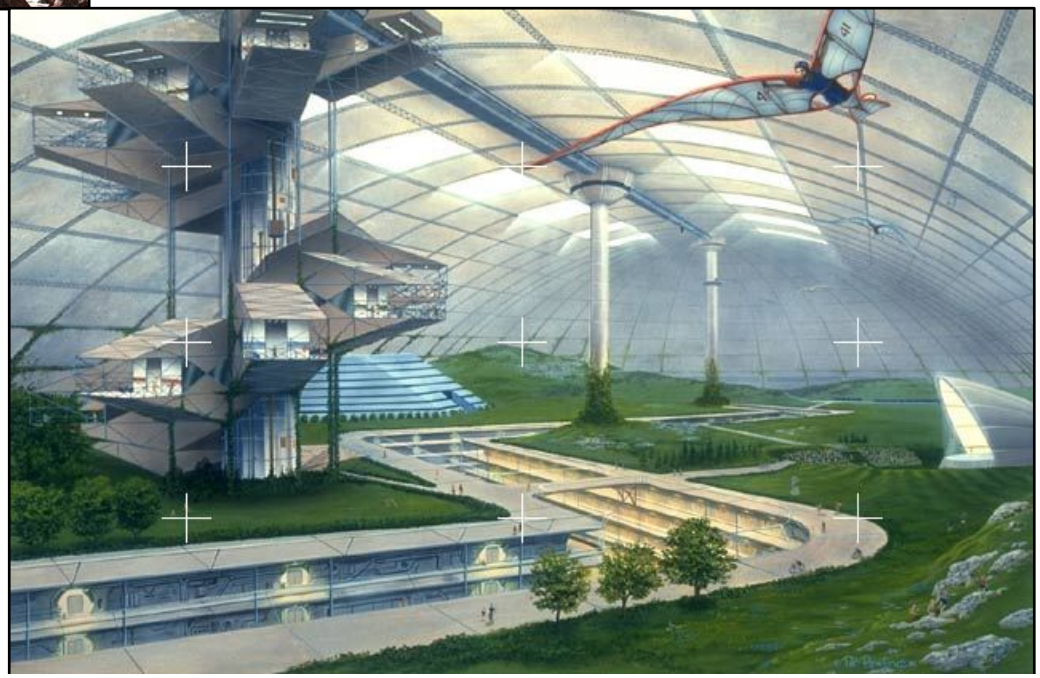
Can such large cavities be stable on the Moon?





Blair et al., Icarus (2017) 287, 47-55

Lava tubes are ideal for astronaut habitats, offering safety from radiation, temperature changes, micrometeorites and even dust



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Resilient ExtraTerrestrial Habitats

We know how to get there... then what?

(nasa.gov)

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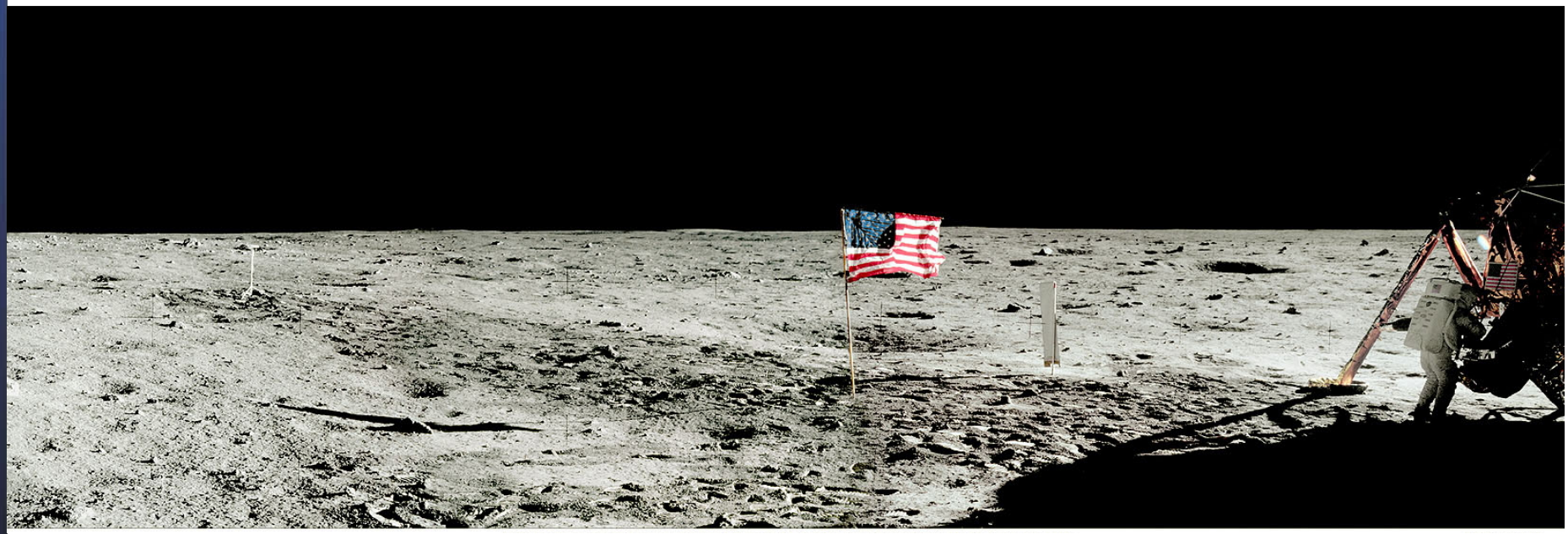
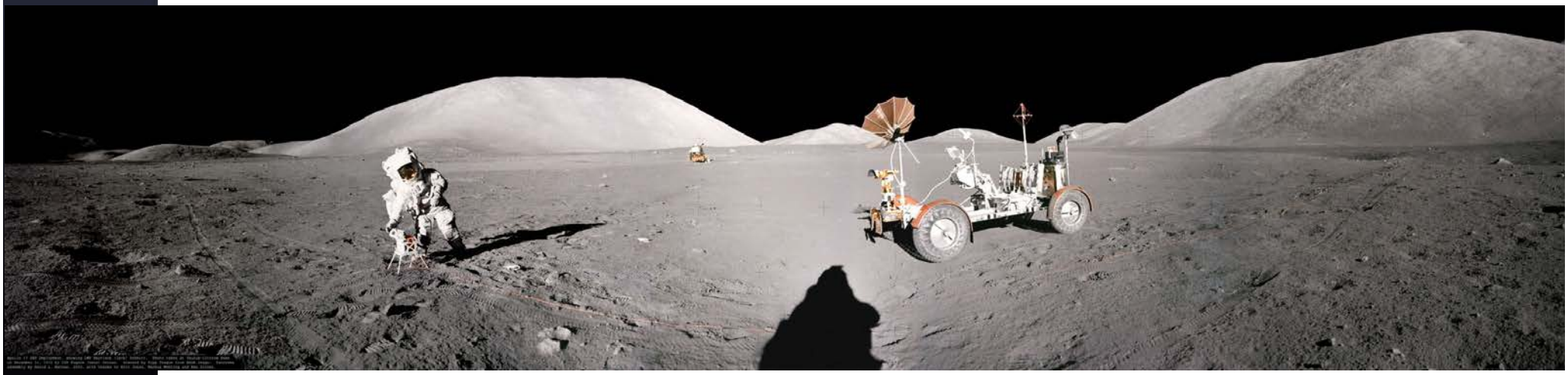
Resilient ExtraTerrestrial Habitats

We know how to get there... then what?

(Apollo 11, nasa.gov)





(Apollo 17, nasa.gov)

Will this work?

(The Martian)

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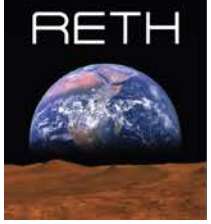
Resilient ExtraTerrestrial Habitats

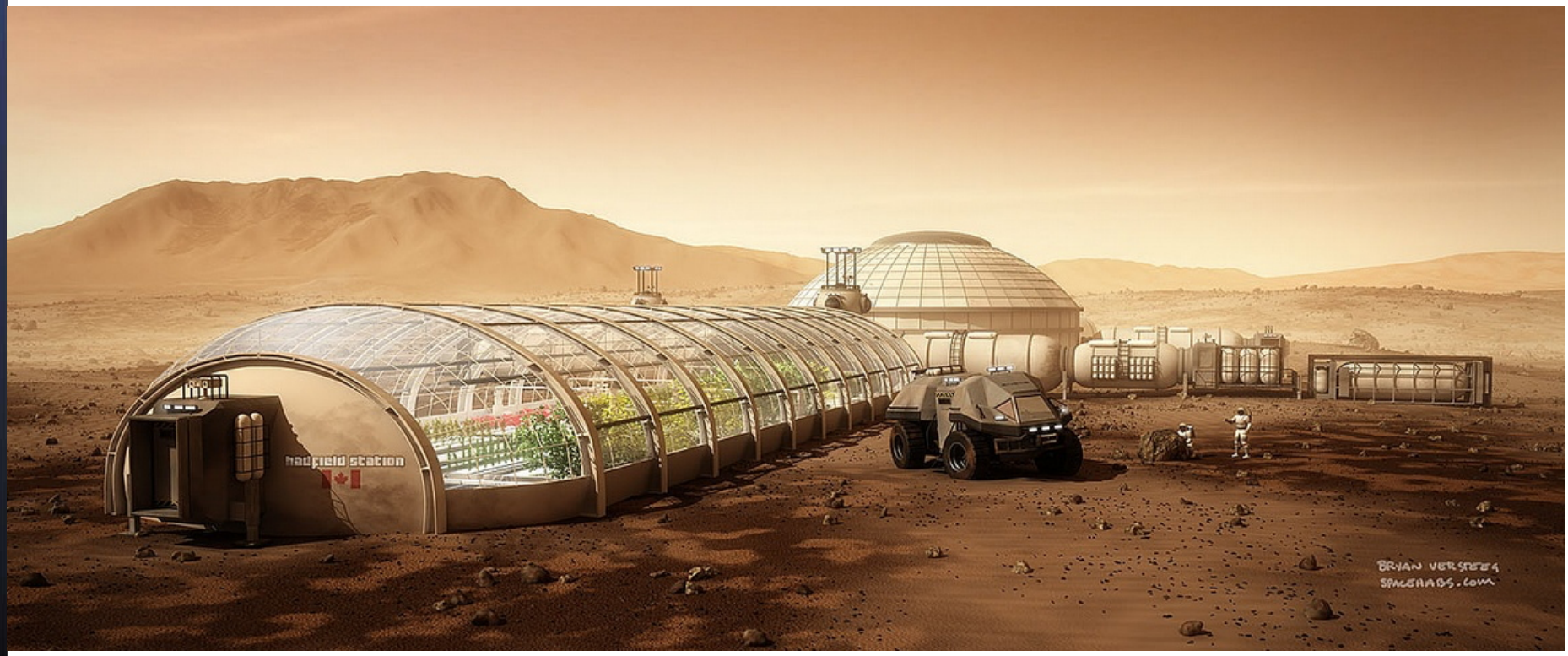
Extraterrestrial Habitat Engineering

- How did this start?
- **Vision & Grand Challenges**
- Resilient Habitat
- Stability of Lunar Lava Tubes



And now... what lies ahead?

Our Vision...



(spacehabs.com)

... we need the Science & Engineering

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Resilient ExtraTerrestrial Habitats

The surfaces of the Moon and Mars are extremely hostile for humans

- Little or no air
- Cosmic radiation
- Meteorite impacts, direct and secondary
- Extreme temperature variations

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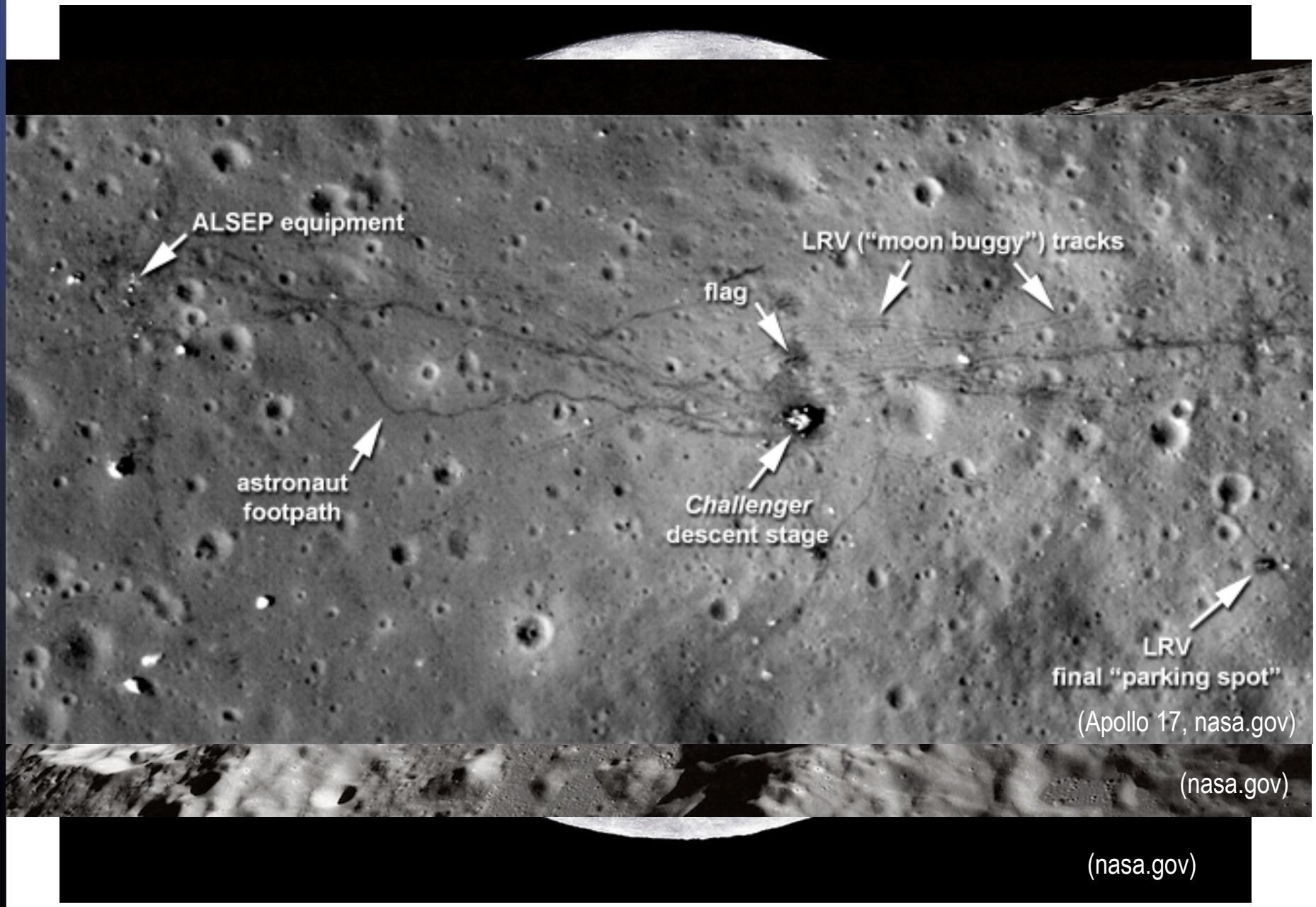
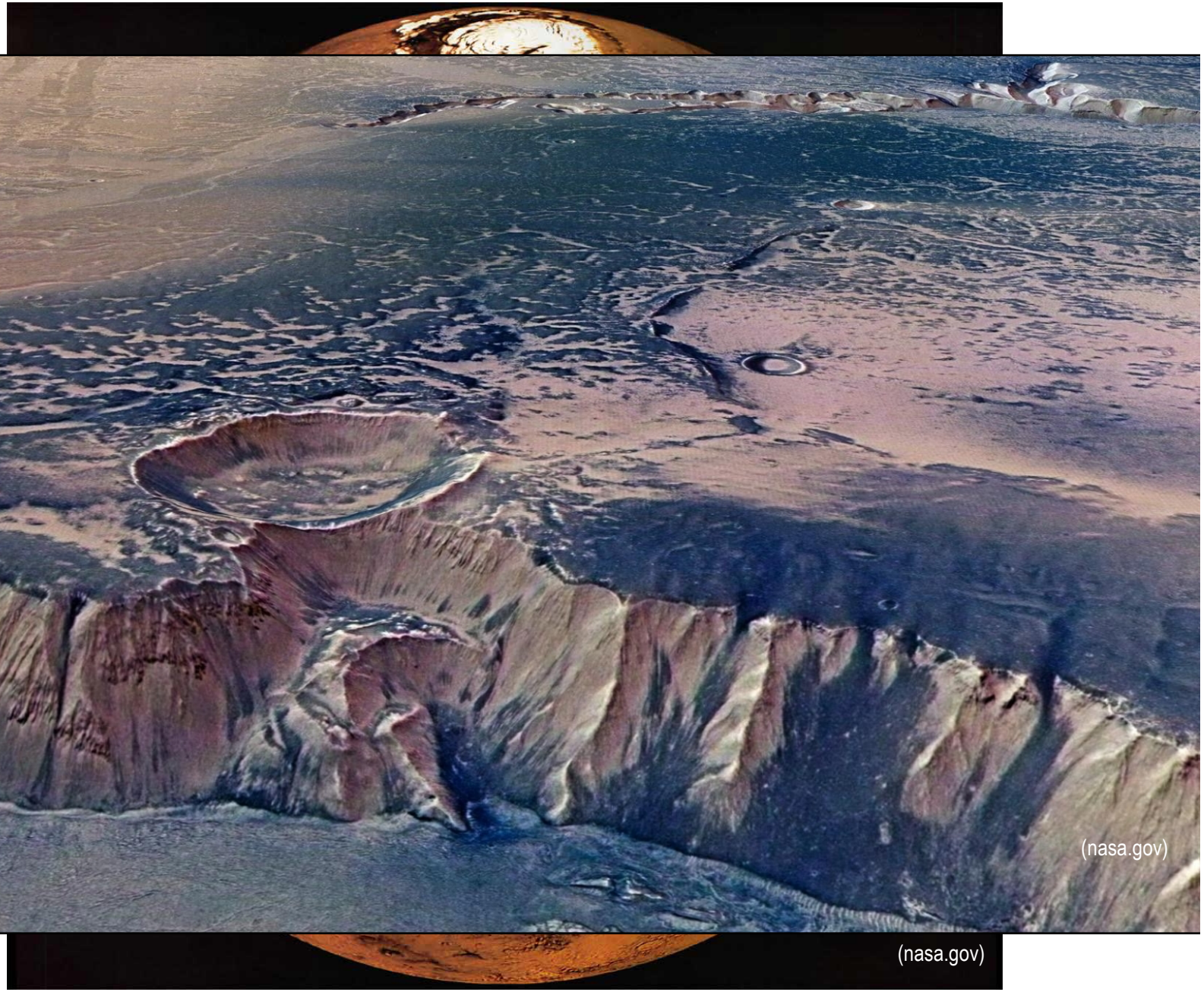
The Grand Challenges: Identify Hazards



Identify Hazards



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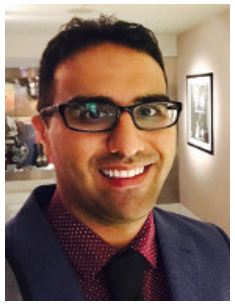
RETH Team...

Faculty Members



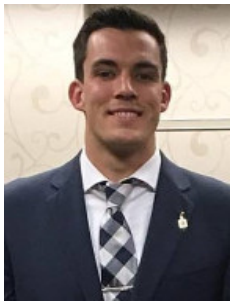


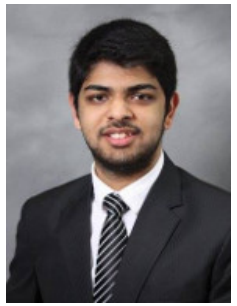
Postdoctoral and Graduate Researchers





Undergraduate Researchers



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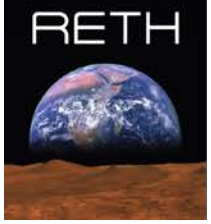
Resilient ExtraTerrestrial Habitats

Extraterrestrial Habitat Engineering

- How did this start?
- Vision & Grand Challenges
- **Resilient Habitat**
- Stability of Lunar Lava Tubes



How we design...

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Resilient ExtraTerrestrial Habitats

... then Katrina happened: Systems Design (SD)

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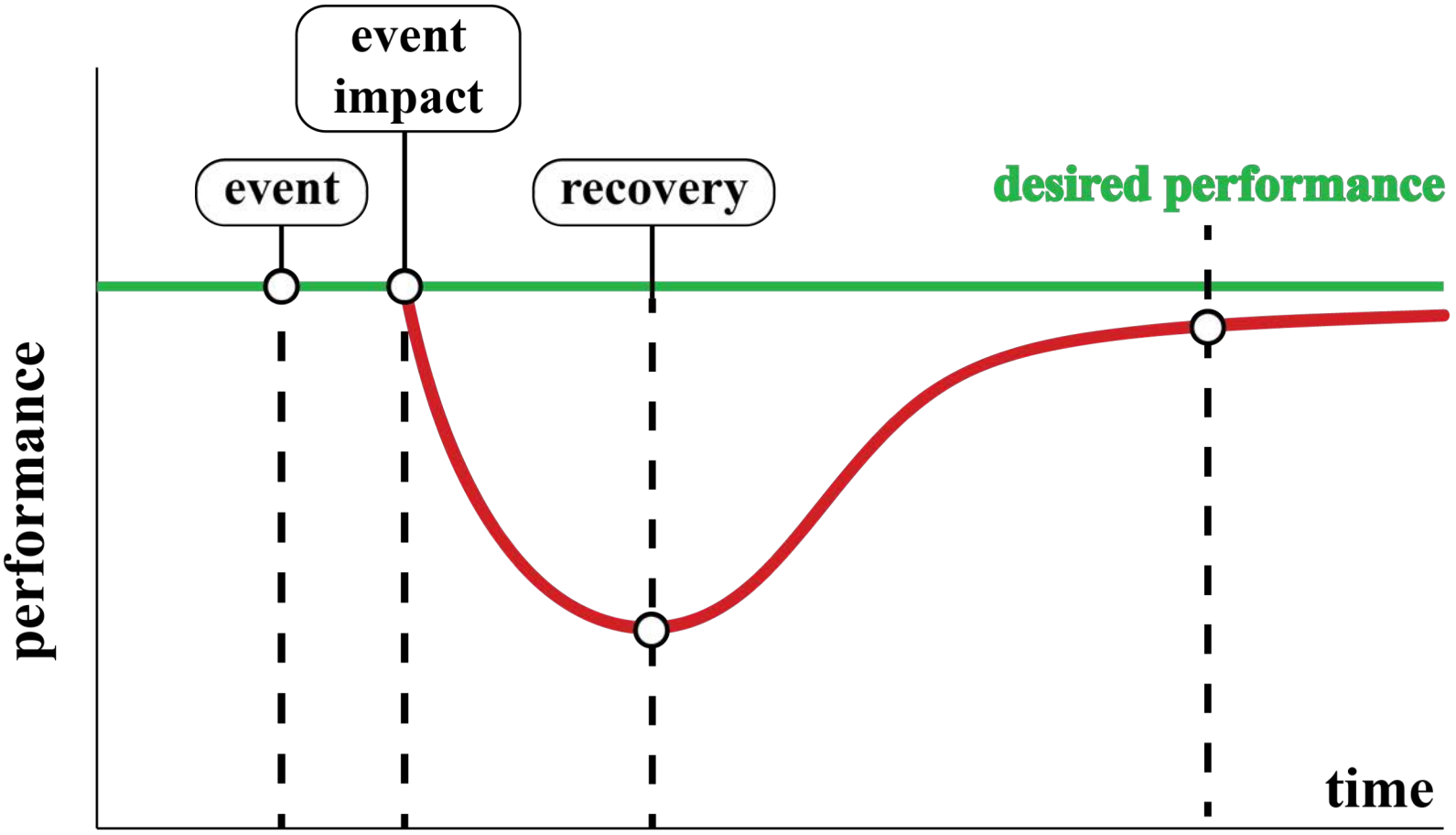
Resilient Design:

it is a comprehensive approach to account for disruptions through the design process and to adapt to them in operation.



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Resilient Design

- **Safe?**
- **Resilient?**
- **Feasible?**

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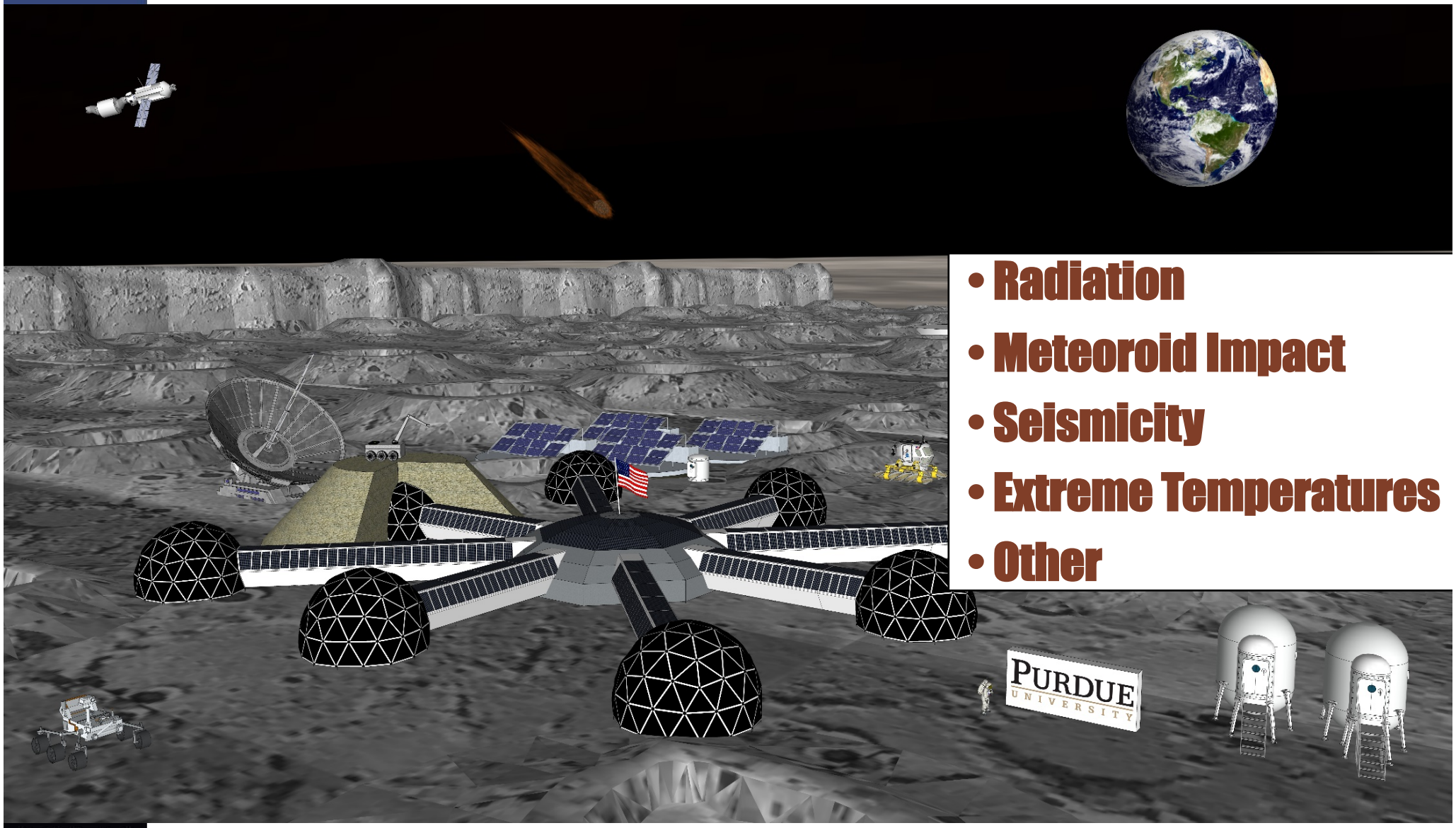
If humans are to live and work out there, they must be prepared to deal with an array of hazards



- Radiation
- Meteoroid Impact
- Seismicity
- Extreme Temperatures
- Other

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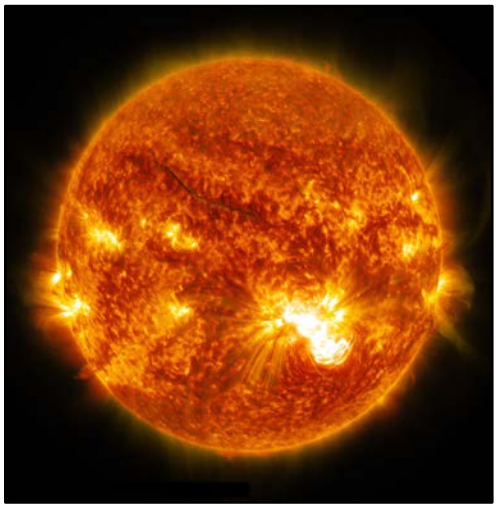
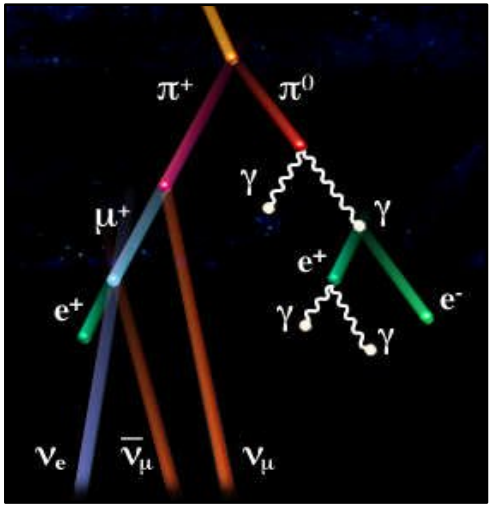
Resilient ExtraTerrestrial Habitats

Radiation: Types

Galactic Cosmic Rays (GCR)

Solar Particle Events (SPE)



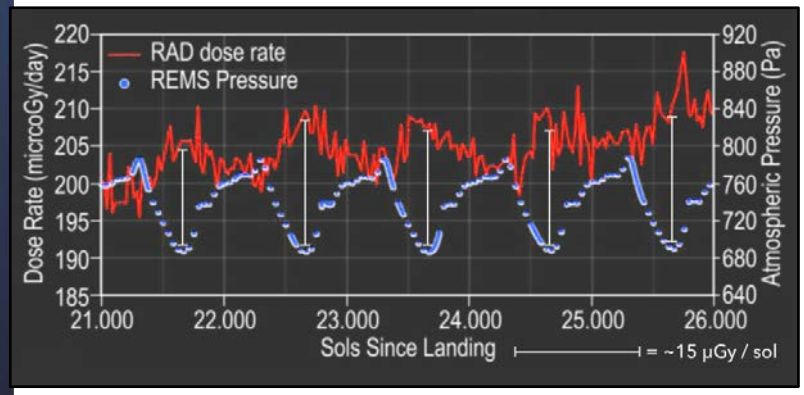


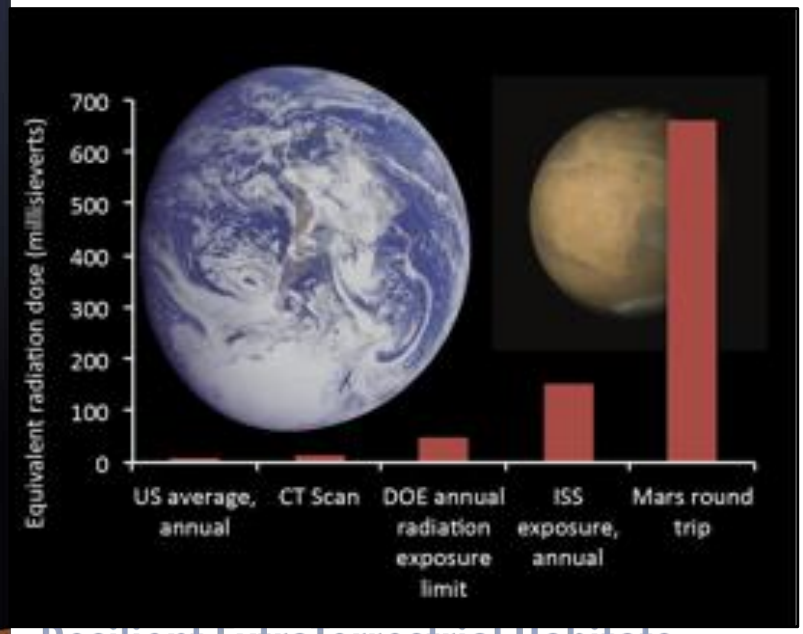
Secondary Particles

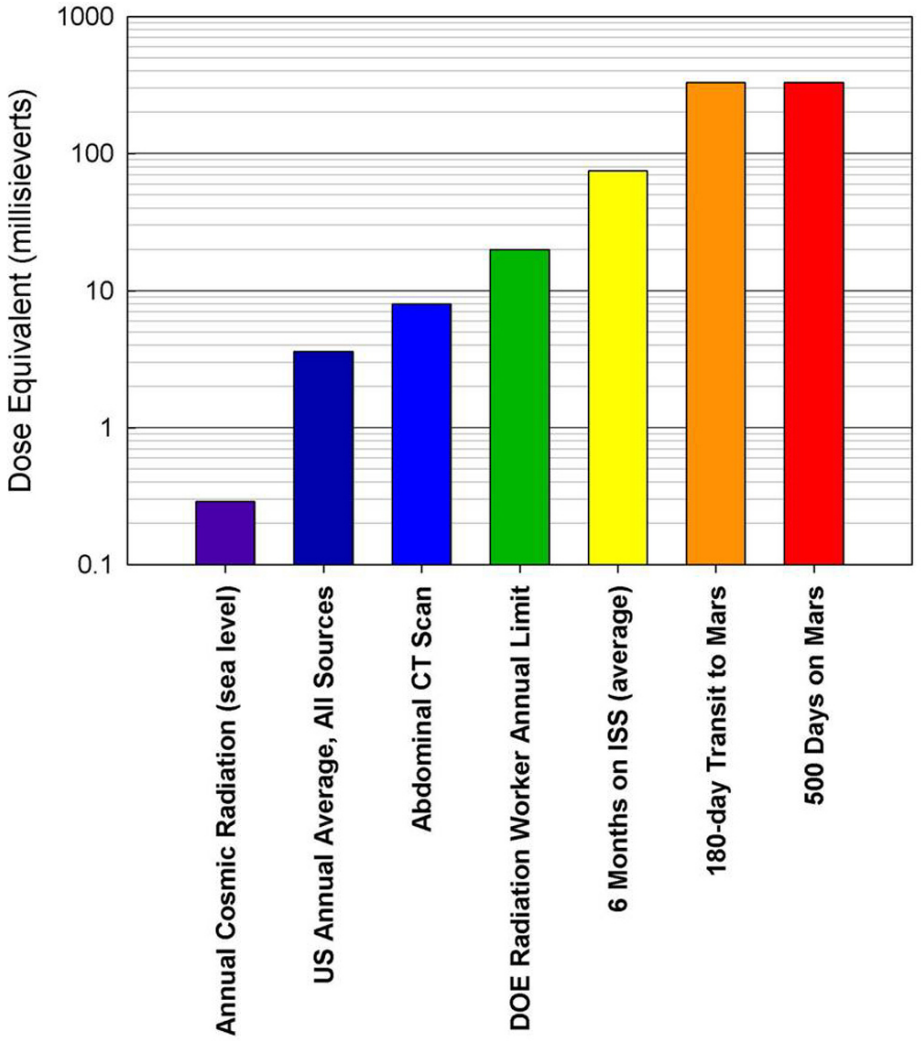
Lunar Regolith (Soil)

Radiation

MSL carried the first ever dosimeter for both the cruise to Mars and surface exposure







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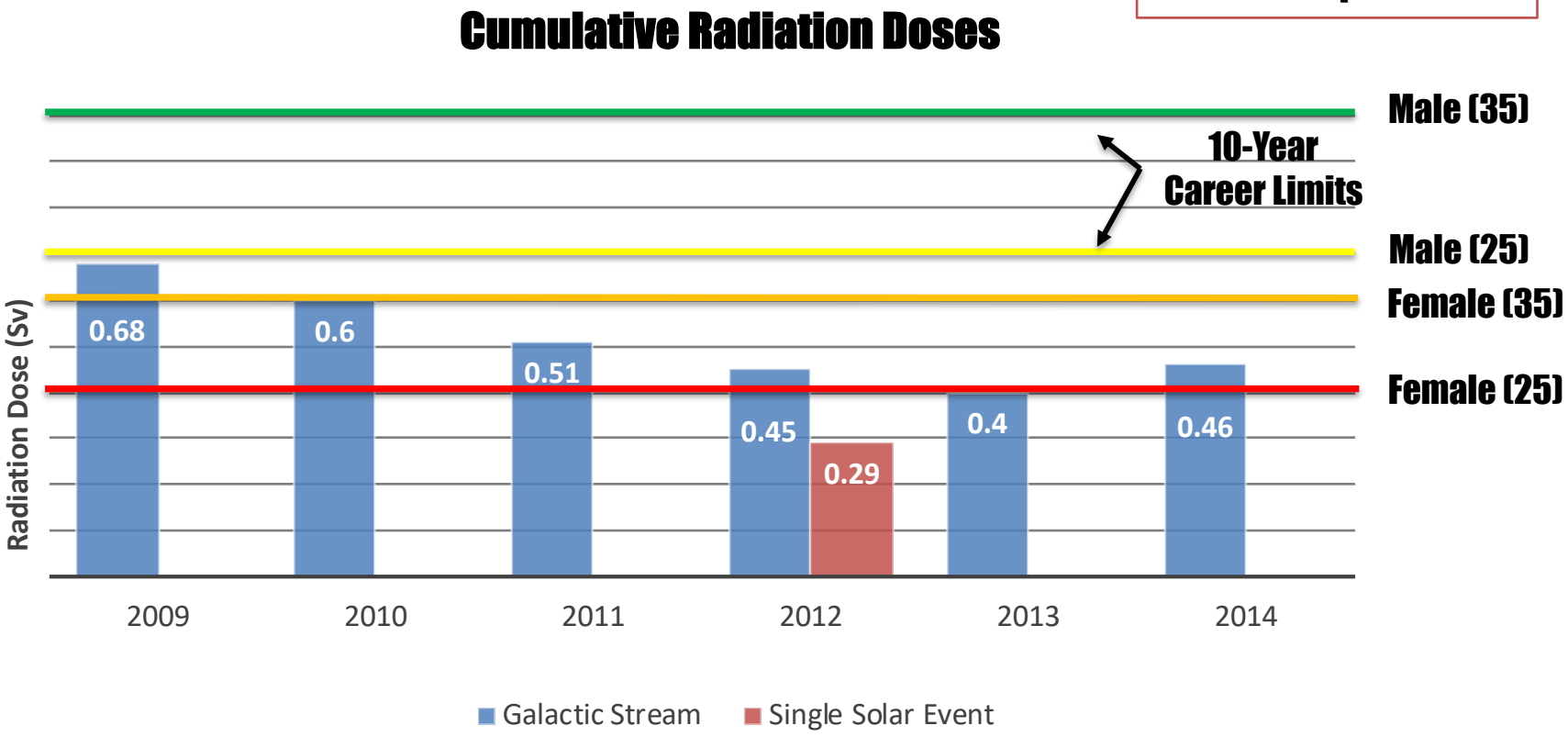
Radiation

Expected Radiation Levels:

Career limits correspond to an excess of 3% chance of fatal cancer development

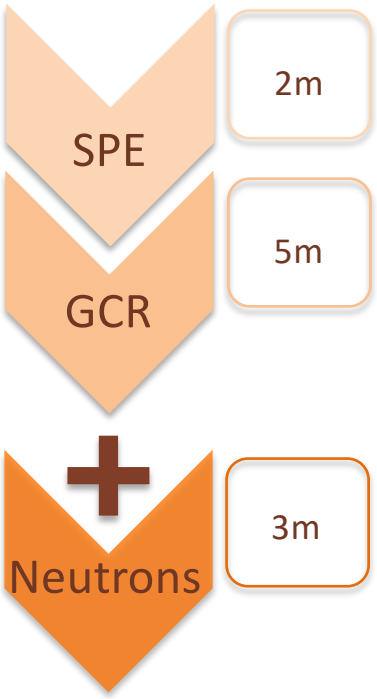


(Data gathered from the University of New Hampshire in collaboration with NASA)

(Radiation Limits given by the National Council on Radiation Protection and Measurements)

Radiation

Hazard Mitigation



(Images courtesy of NASA and ESA)

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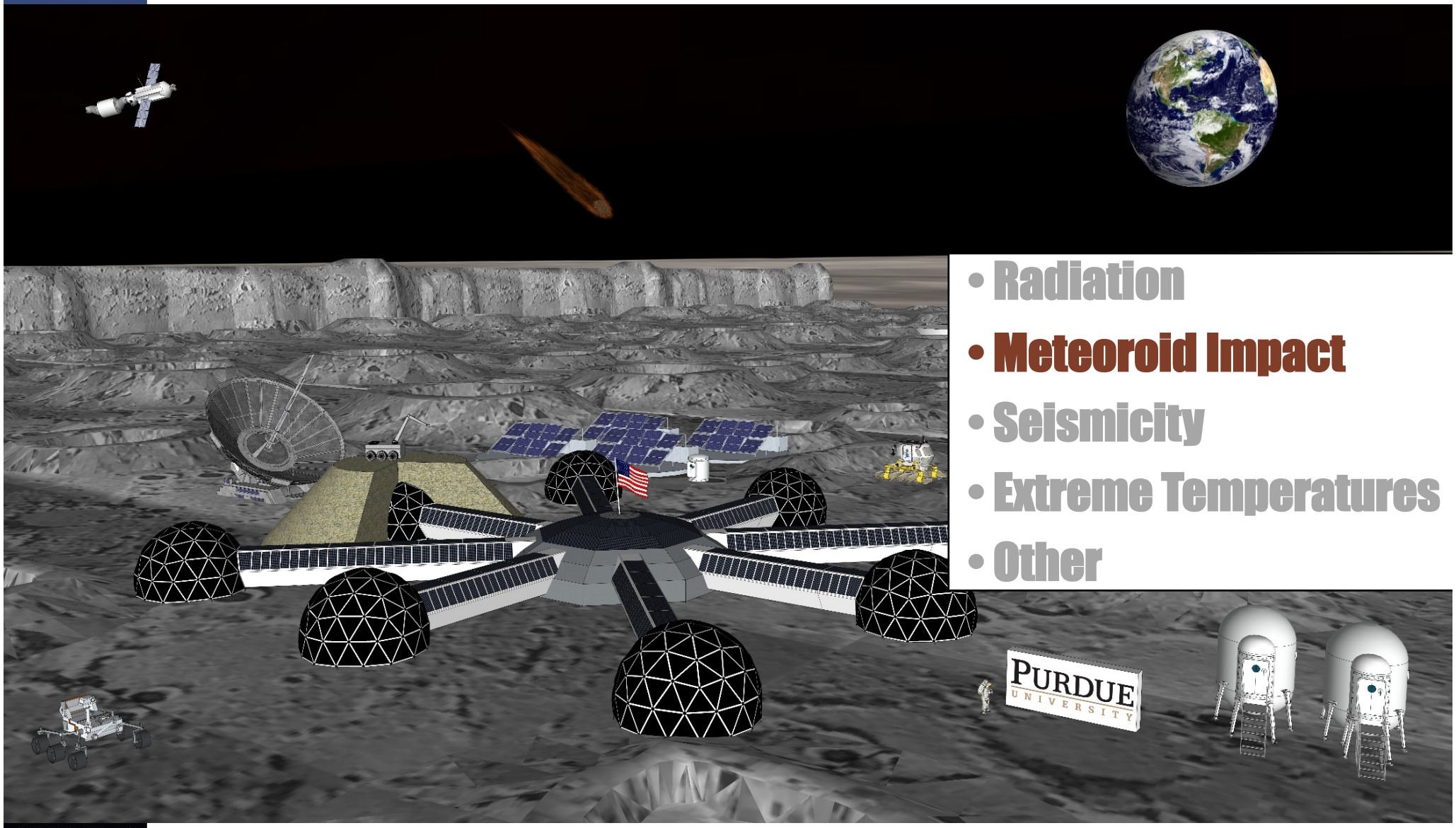
If humans are to live and work out there, they must be prepared to deal with an array of hazards



- Radiation
- **Meteoroid Impact**
- Seismicity
- Extreme Temperatures
- Other

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Resilient ExtraTerrestrial Habitats

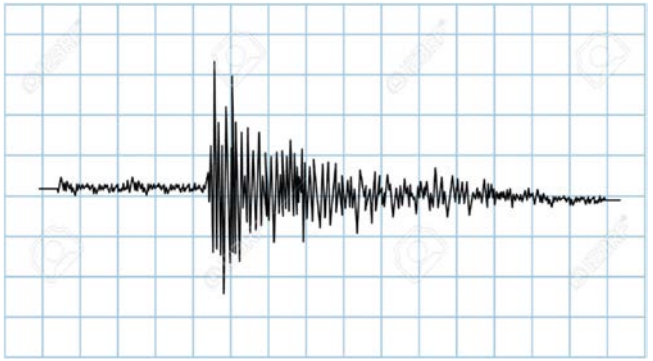
Meteoroid impact

Primary impact:

Direct damage

Secondary impact:

Ejected particles



Seismic activity

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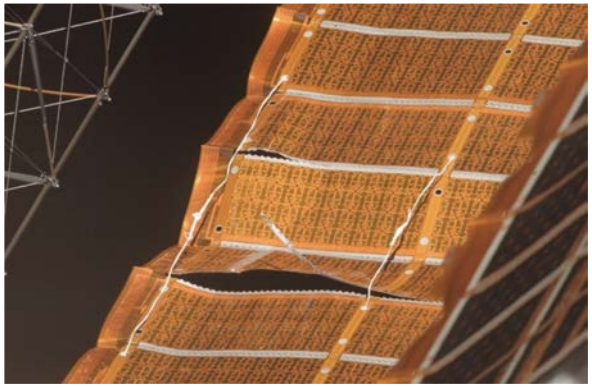
Resilient ExtraTerrestrial Habitats

Meteoroid impact

Perforation

Deterioration

Damage equipment



Credit Images: ESA and NASA

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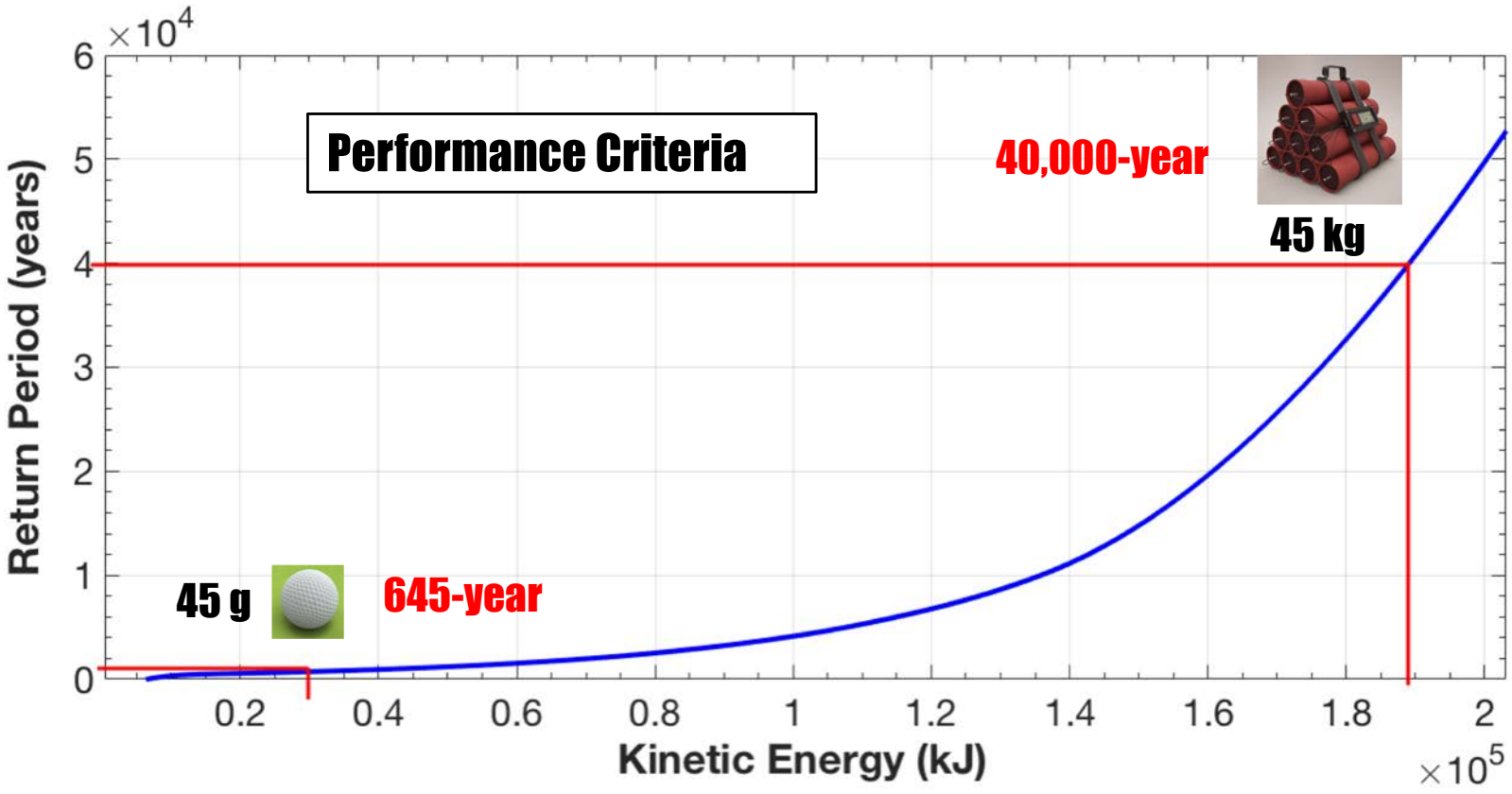
Resilient ExtraTerrestrial Habitats

Meteoroid impact

Numerical Approach: Estimates for Period of Return for WL-Area



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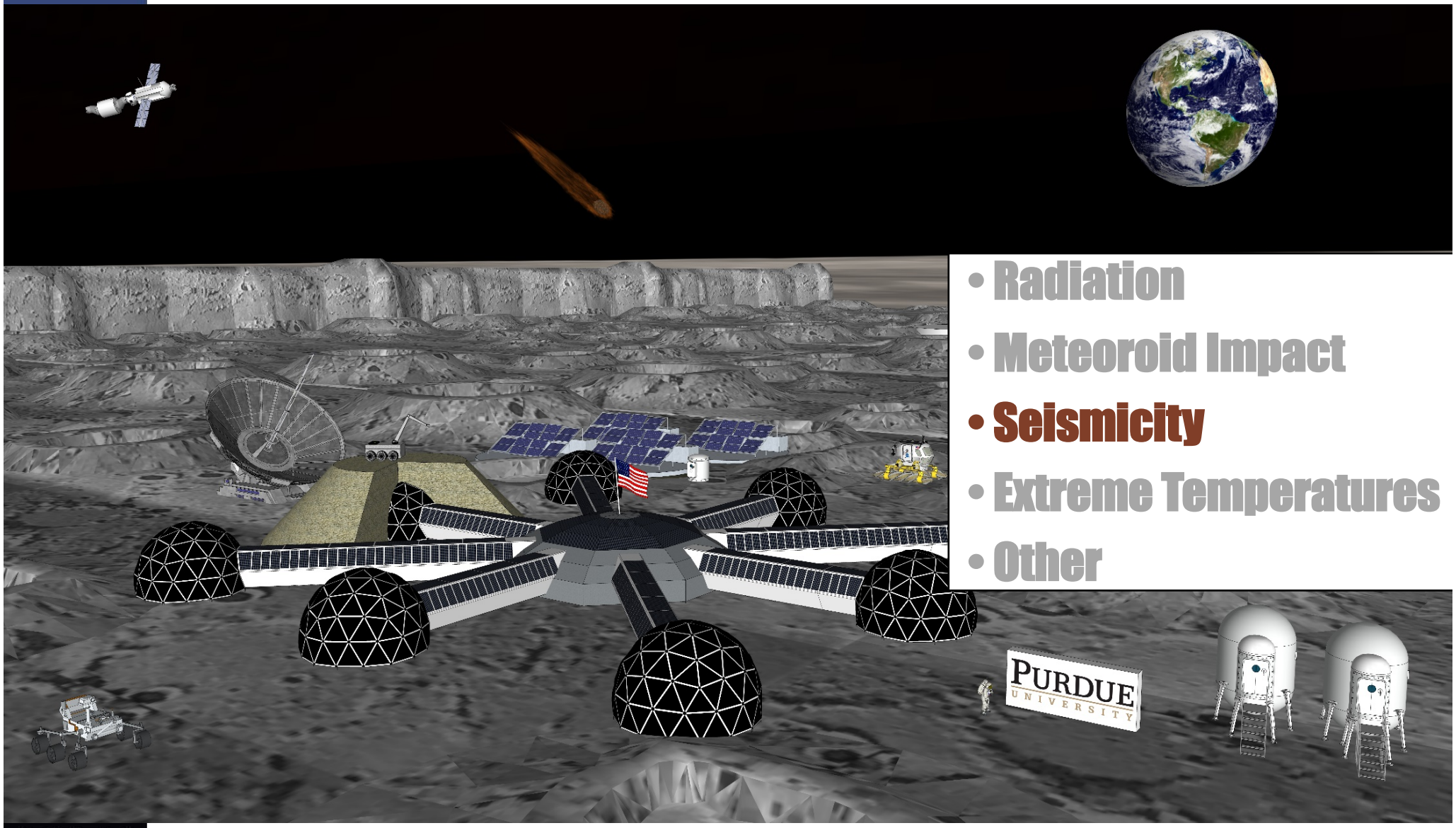
Resilient ExtraTerrestrial Habitats

If humans are to live and work out there, they must be prepared to deal with an array of hazards

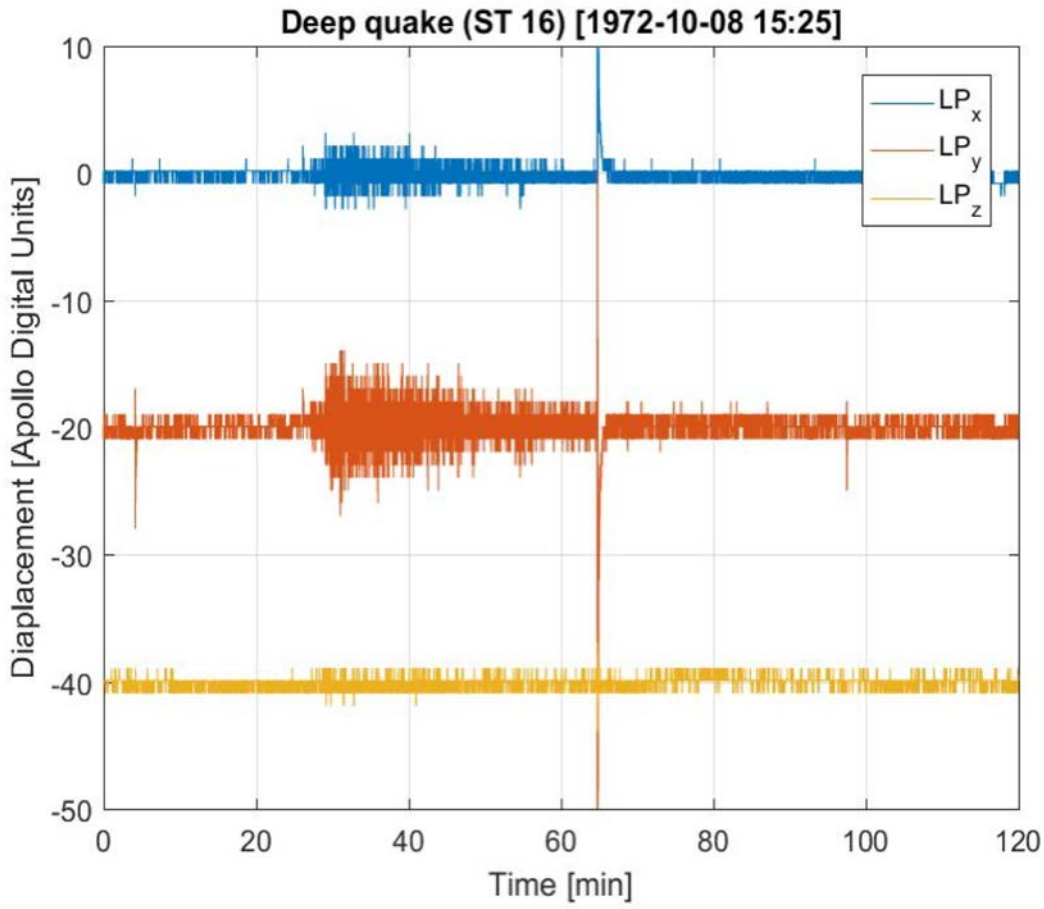


- Radiation
- Meteoroid Impact
- **Seismicity**
- Extreme Temperatures
- Other

Moonquakes

Deep moonquakes:

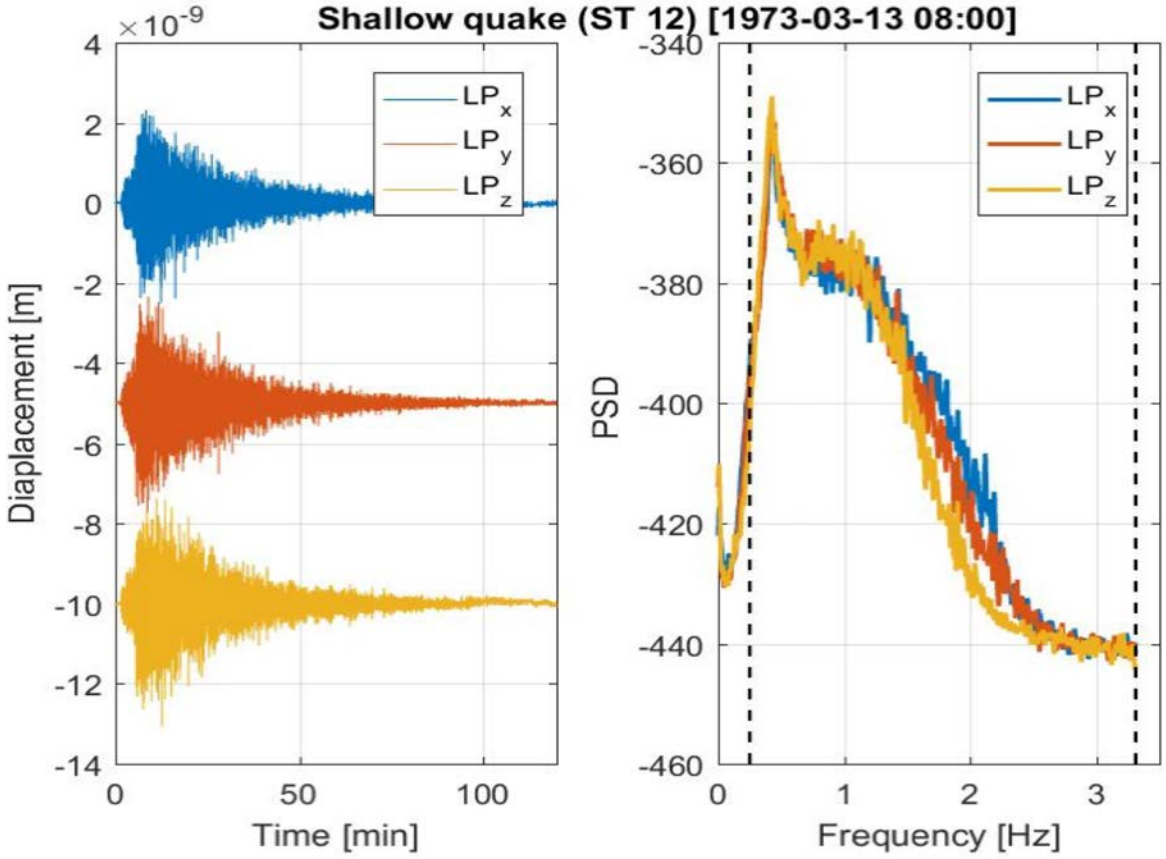
- At depths of 700 - 1000 km.
- Frequent events, but low energy
- Most less than magnitude 2
- Terrestrial tidal forces influence the occurrence and periodicity of deep events.
- 7000 events identified!!!



Moonquakes

Shallow moonquakes:

- **Infrequent, with no pattern in position or time of occurrence**
- **Exceptional high-frequency content.**
- **Only 28 detected.**
- **Depth <300 km.**
- **Magnitude ~5.**
- **Similar to intraplate Earth quakes**



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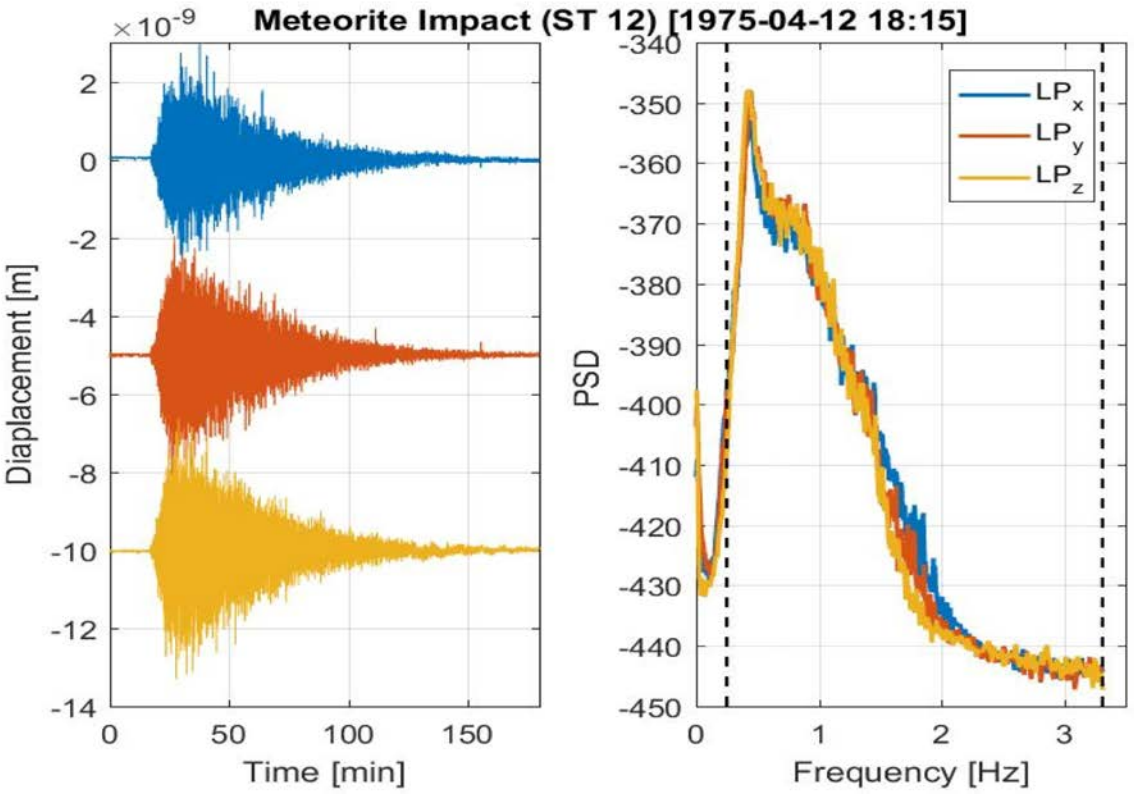
Resilient ExtraTerrestrial Habitats

Moonquakes

Meteorite moonquakes:

- **~1700 events detected with estimated masses 0.5 to 50 kg, from long-period sensors**
- **Short-period sensors detected many more impacts, from smaller meteoroids**



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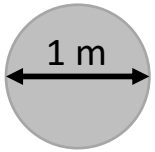
Resilient ExtraTerrestrial Habitats

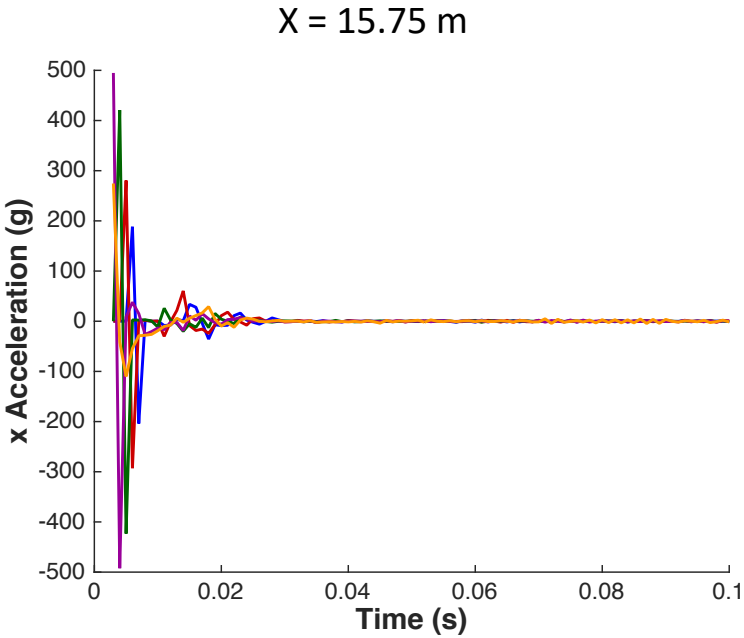
Barringer Crater, AZ.

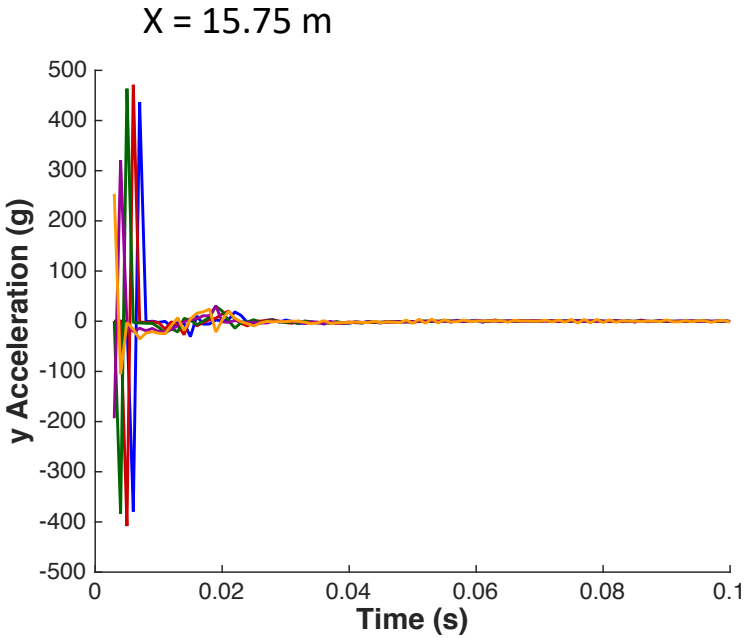
1.2 km diameter, 170 m deep; 50 m impactor (764 yr. return period)

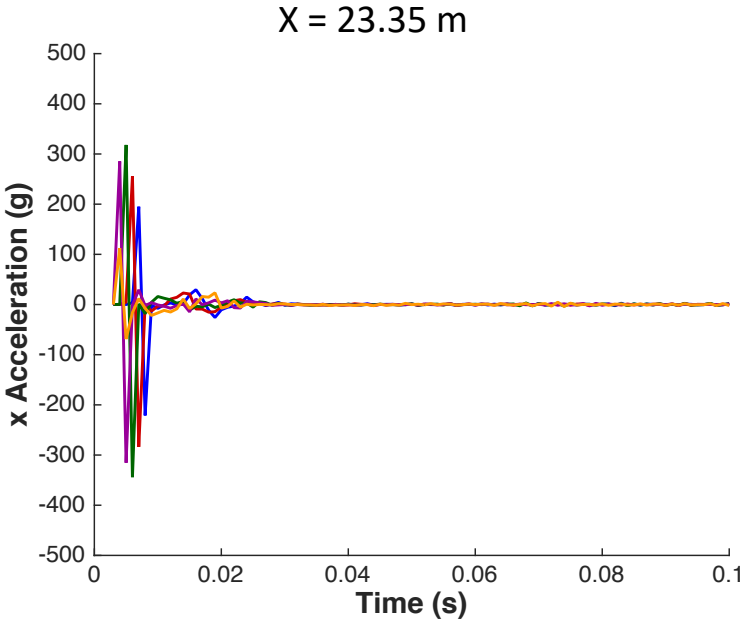
Accelerations

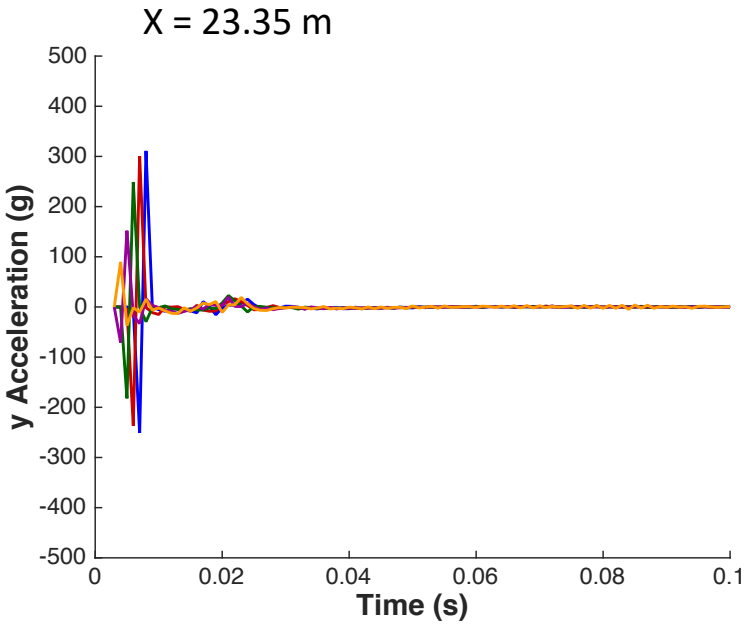


y = -0.05 m
-8.35
-16.65
-24.95
-33.25
-41.45









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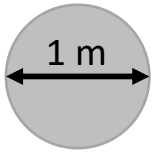
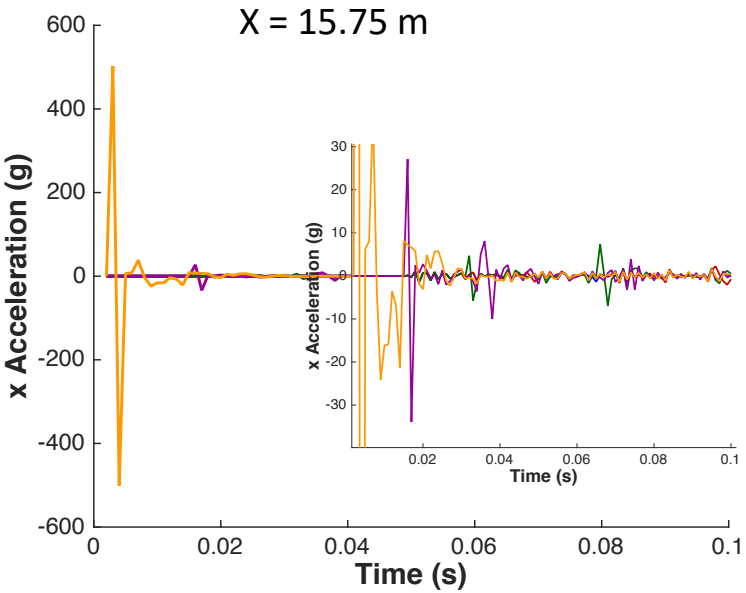
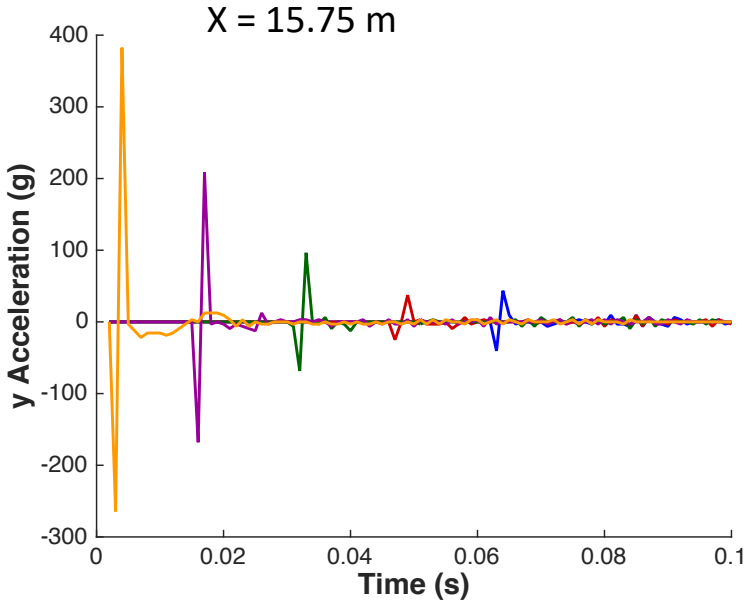
Resilient ExtraTerrestrial Habitats

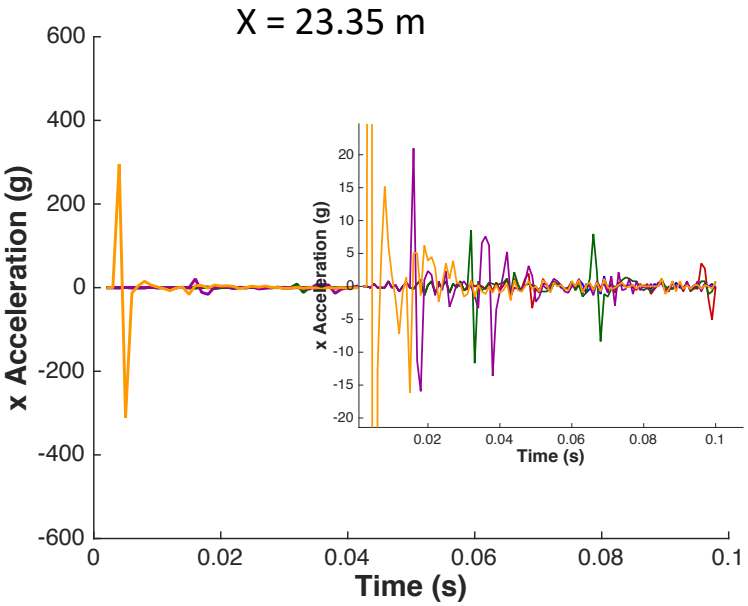
Accelerations

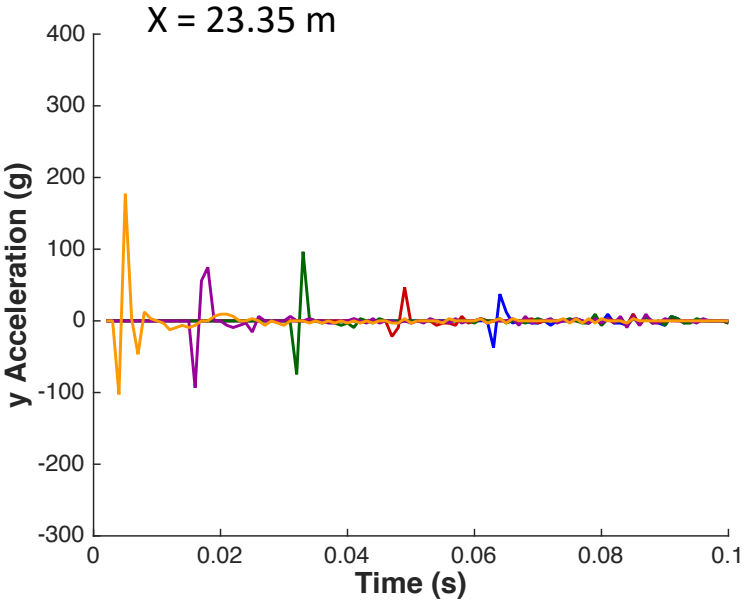


y = -9.85 m
-99.85
-199.85
-299.85
-399.85
-499.85



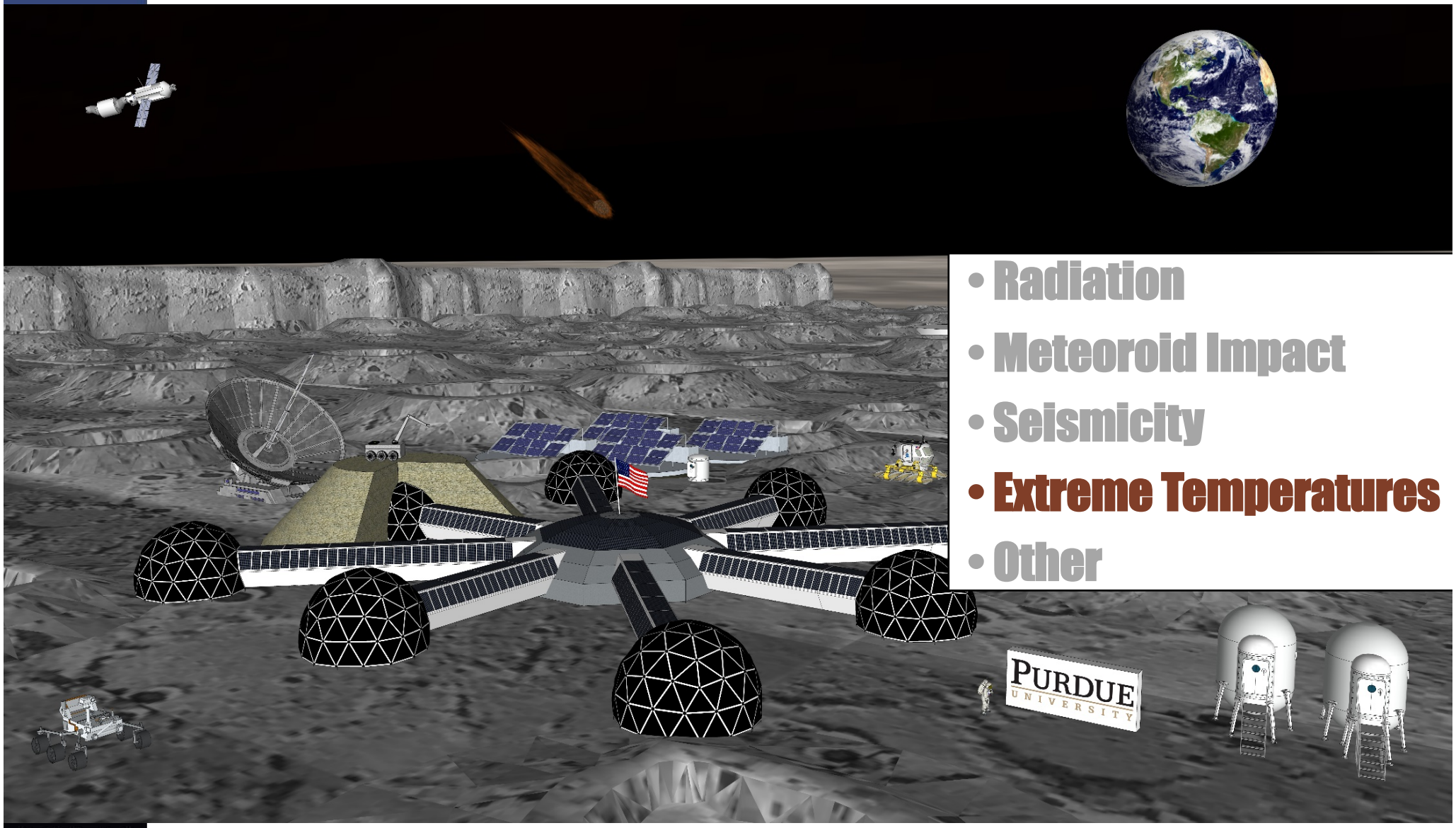






RETH

If humans are to live and work out there, they must be prepared to deal with an array of hazards

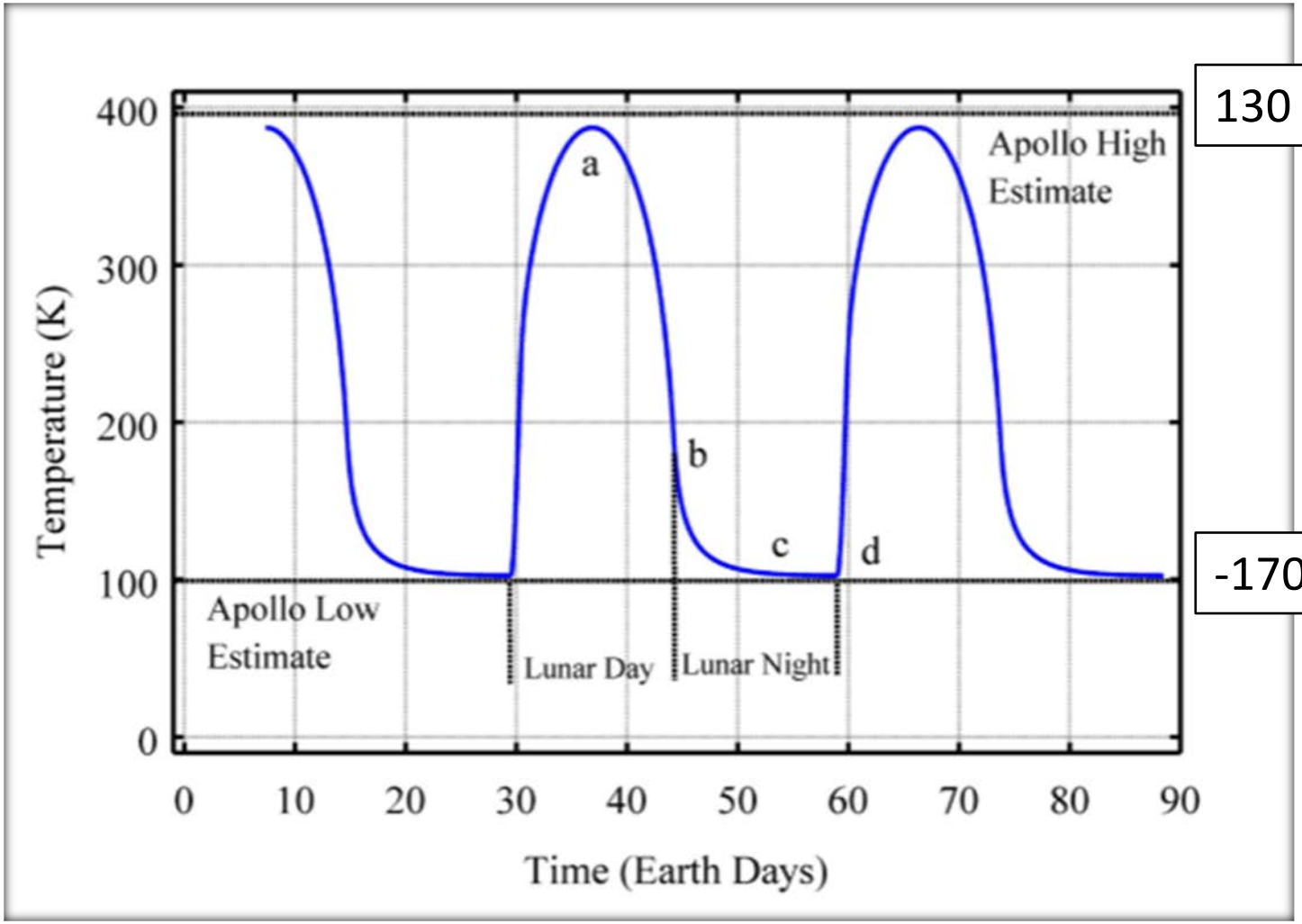


- Radiation
- Meteoroid Impact
- Seismicity
- **Extreme Temperatures**
- Other

RETH

Resilient ExtraTerrestrial Habitats

Extreme Temperatures



130 °C

-170 °C

RETH

Resilient ExtraTerrestrial Habitats

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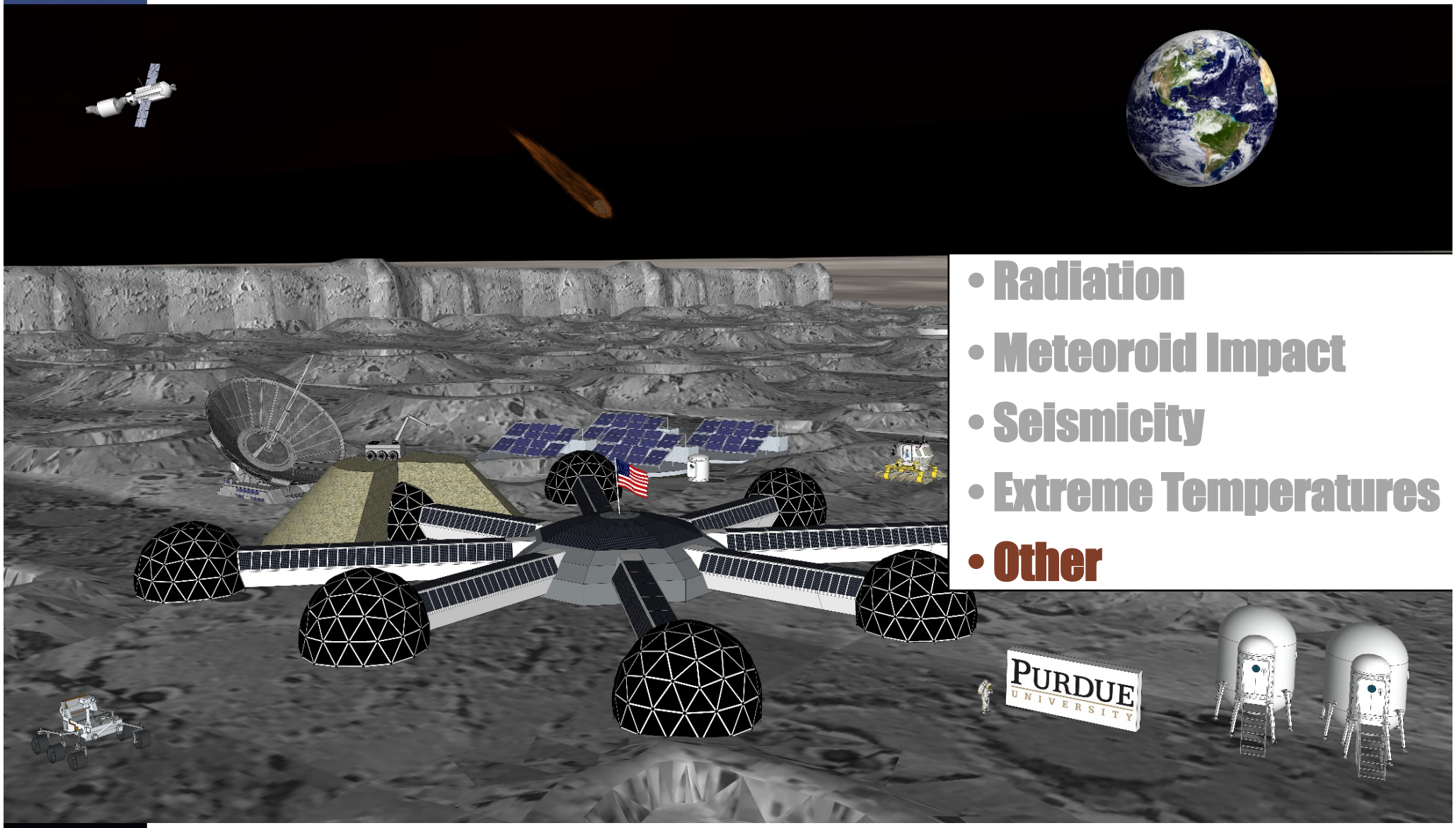
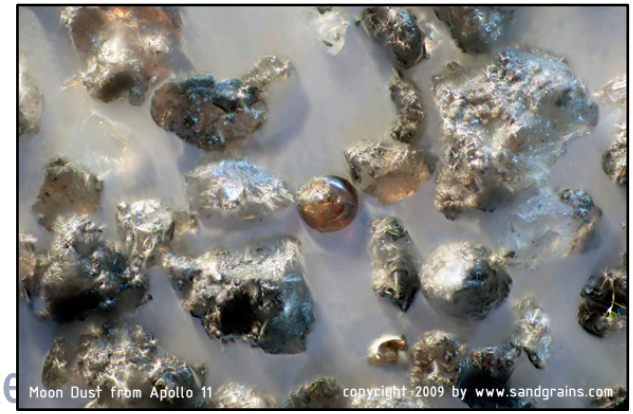


- Radiation
- Meteoroid Impact
- Seismicity
- Extreme Temperatures
- **Other**

On the Moon, lunar dust gets into everything and ruins spacesuit seals



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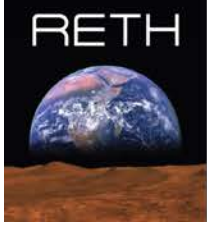
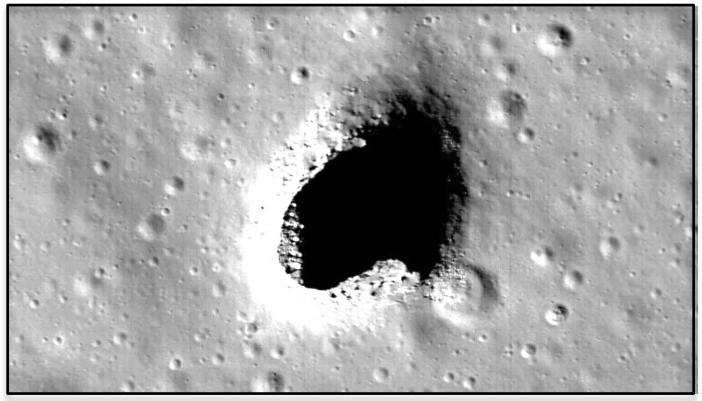
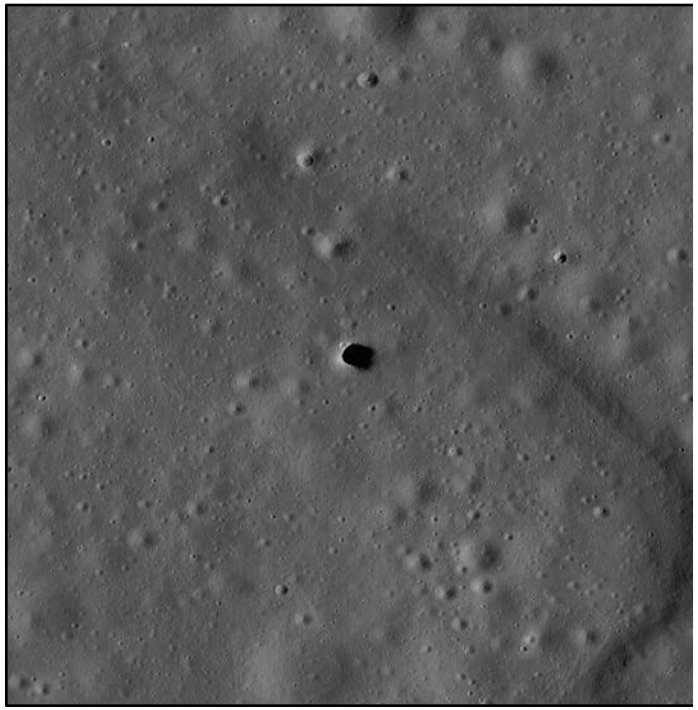
Extraterrestrial Habitat Engineering

- How did this start?
- Vision & Grand Challenges
- Resilient Habitat
- **Stability of Lunar Lava Tubes**



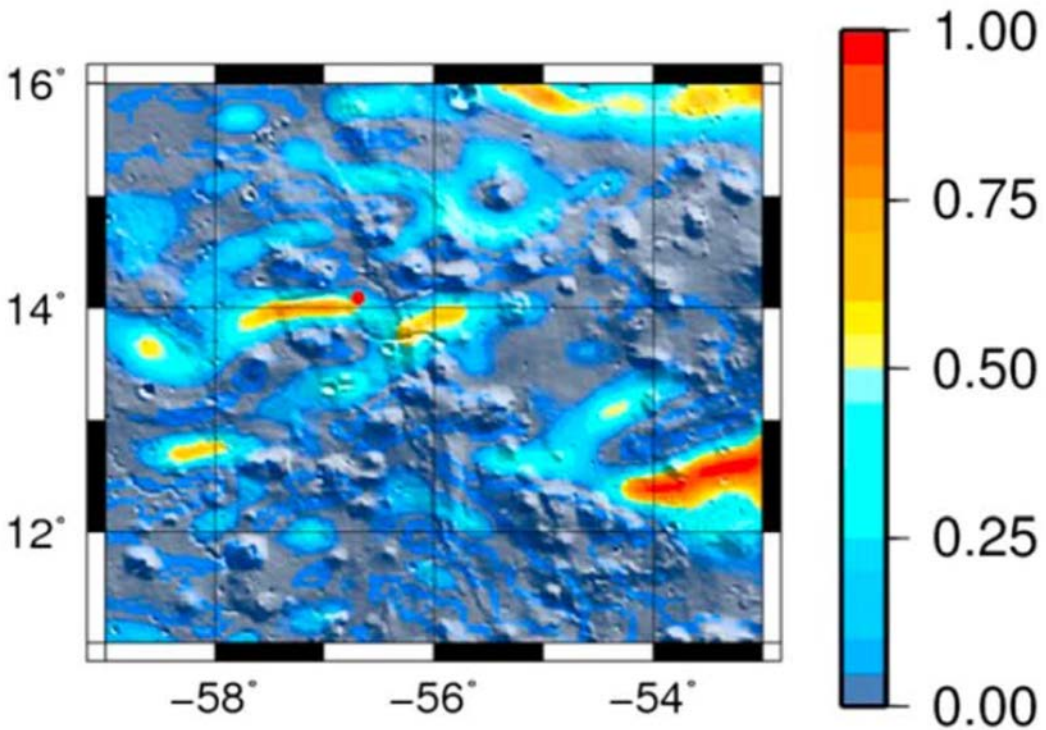
Purdue Discovery!
Large lava tubes on the Moon





GRAIL Players from AAE and EAPS:

Rohan Sood, Loic Chappaz, Jay Melosh, Kathleen Howell, David Blair, Colleen Milbury



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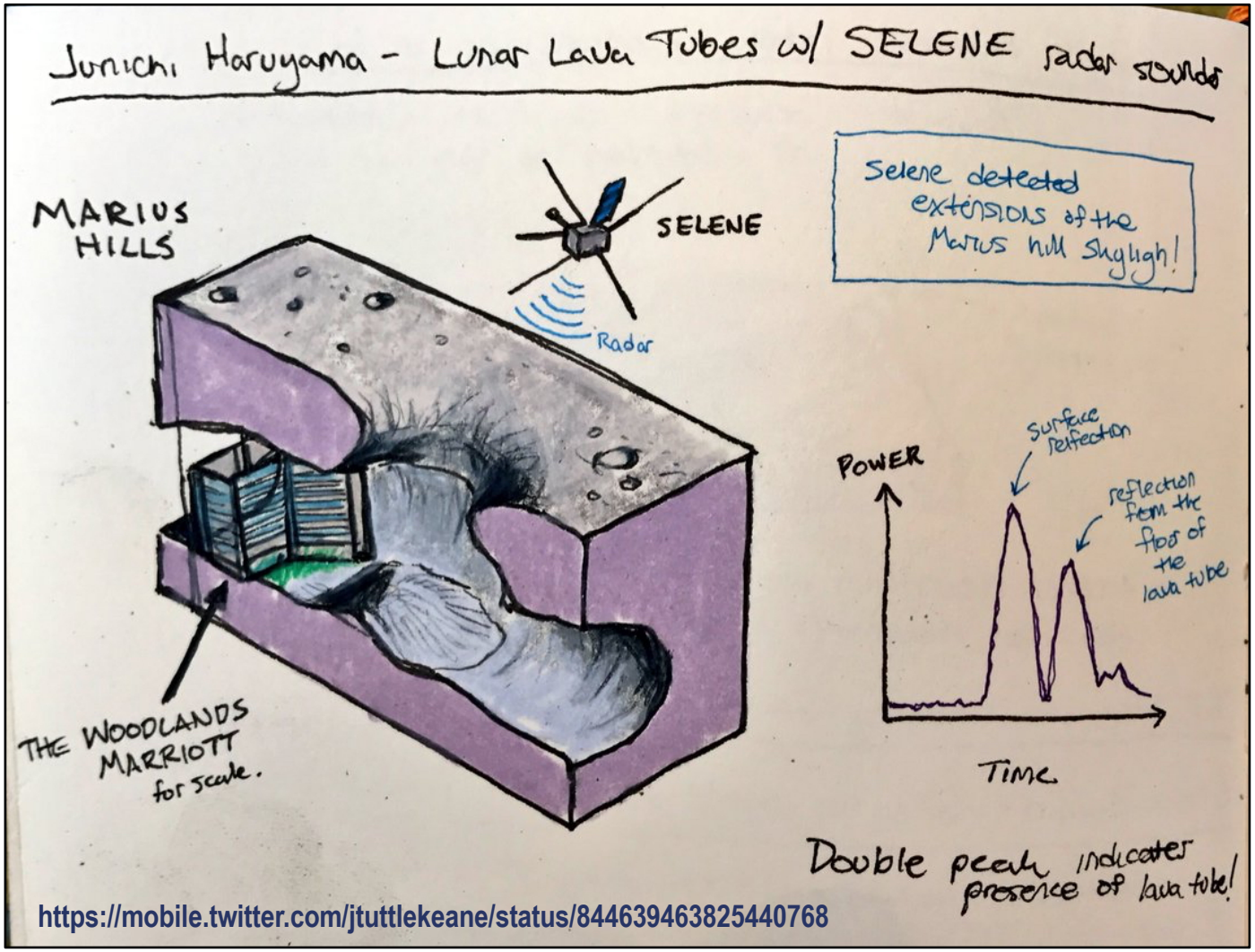
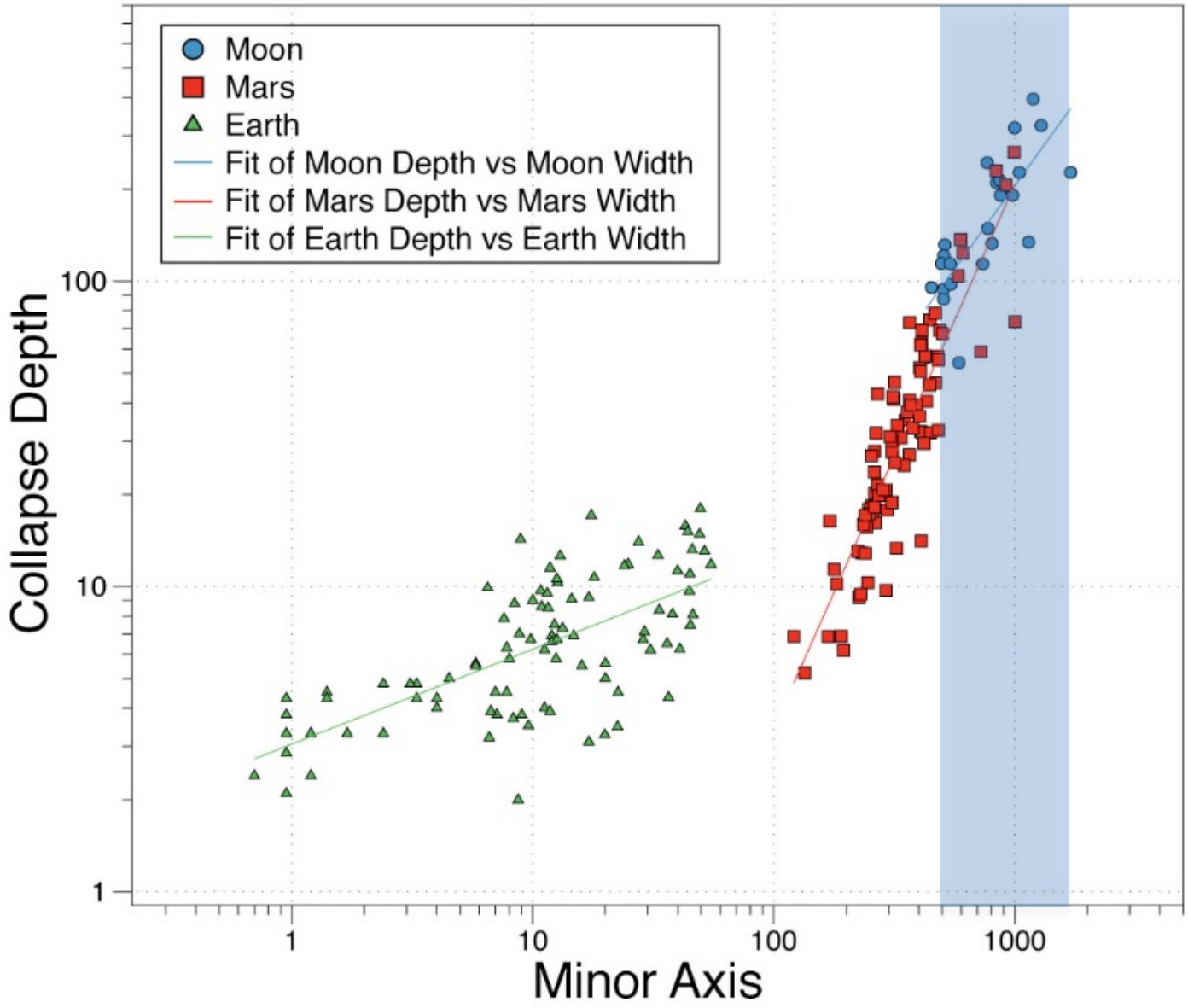
Large lava tubes on the Moon – independent confirmation



Radar detection of lava tubes, from Haruyama (2017)

Earth, Moon and Mars Lava Tubes



Sauro et al. (2018)

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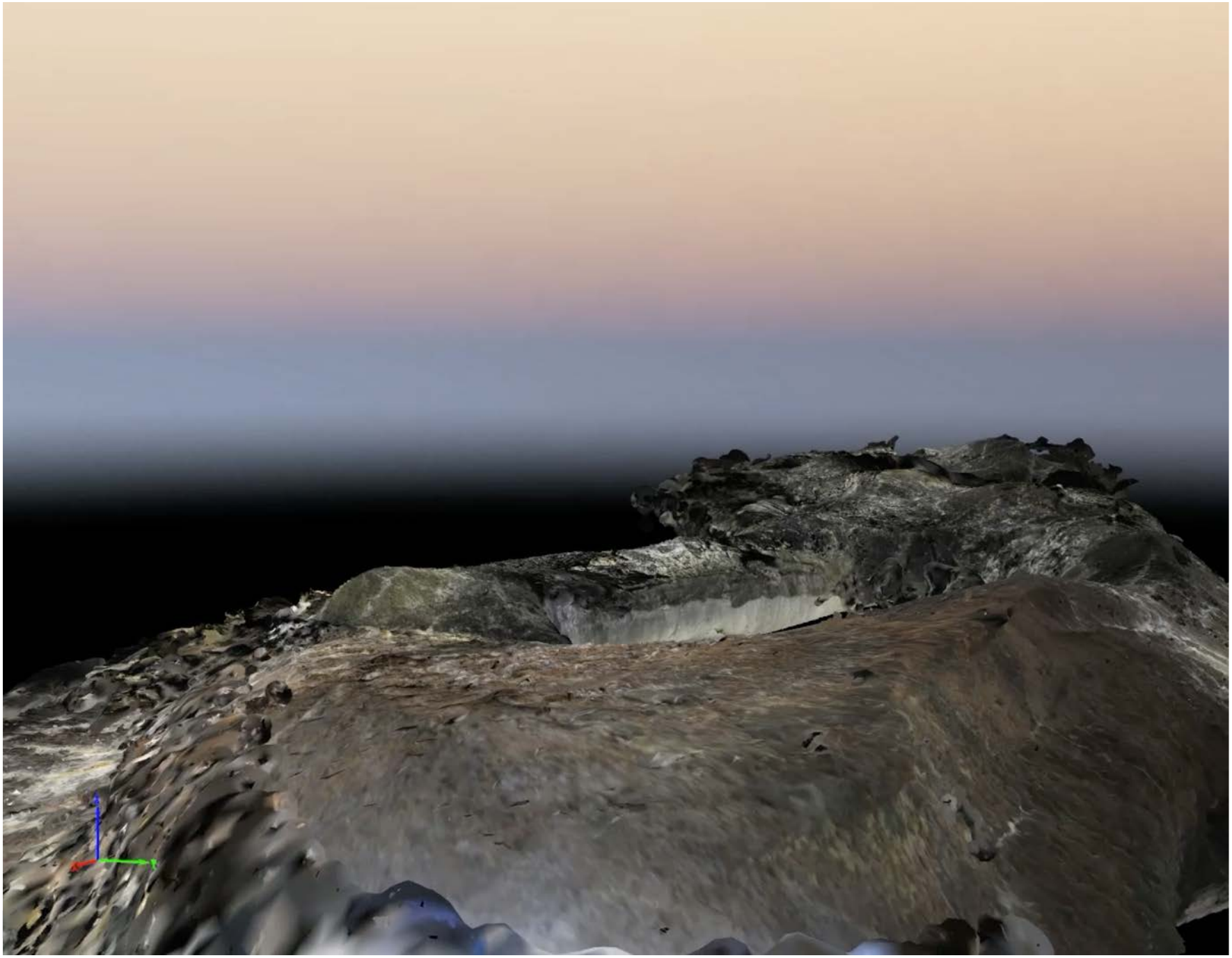
Valentine Cave, Tulelake, CA



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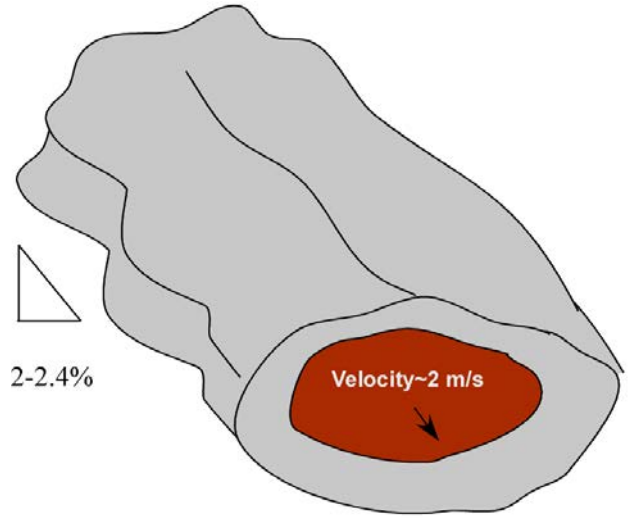
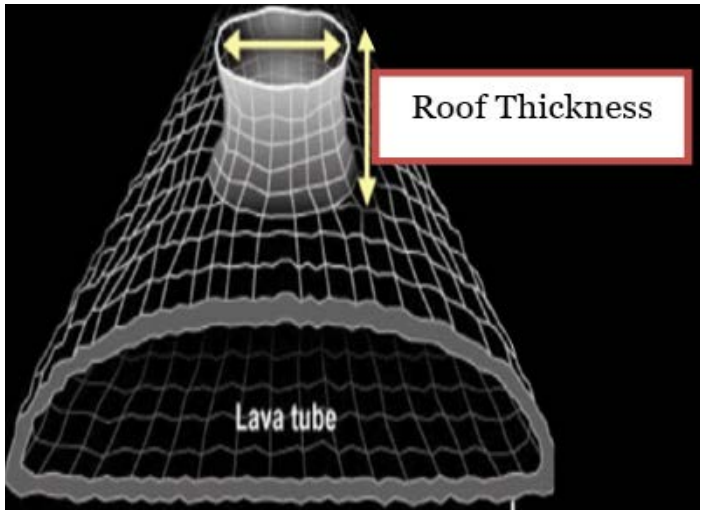
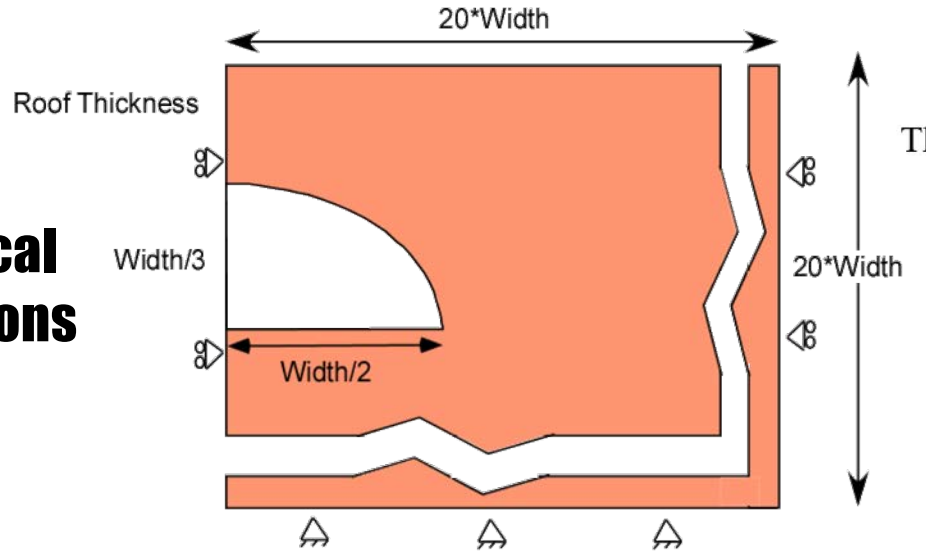
Size and Stability of Lava Tubes

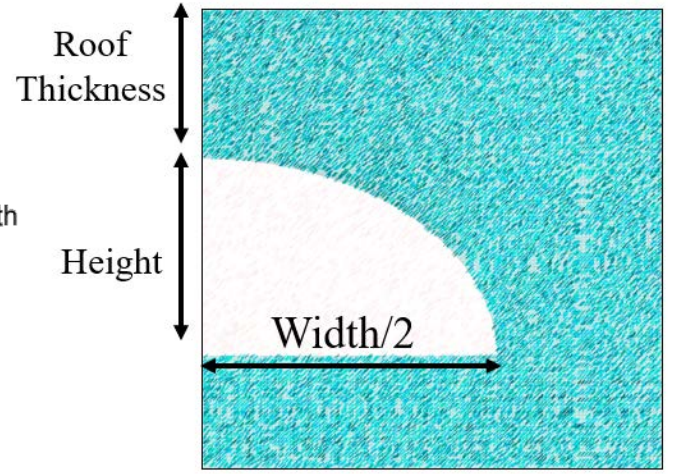
Analytical Solution





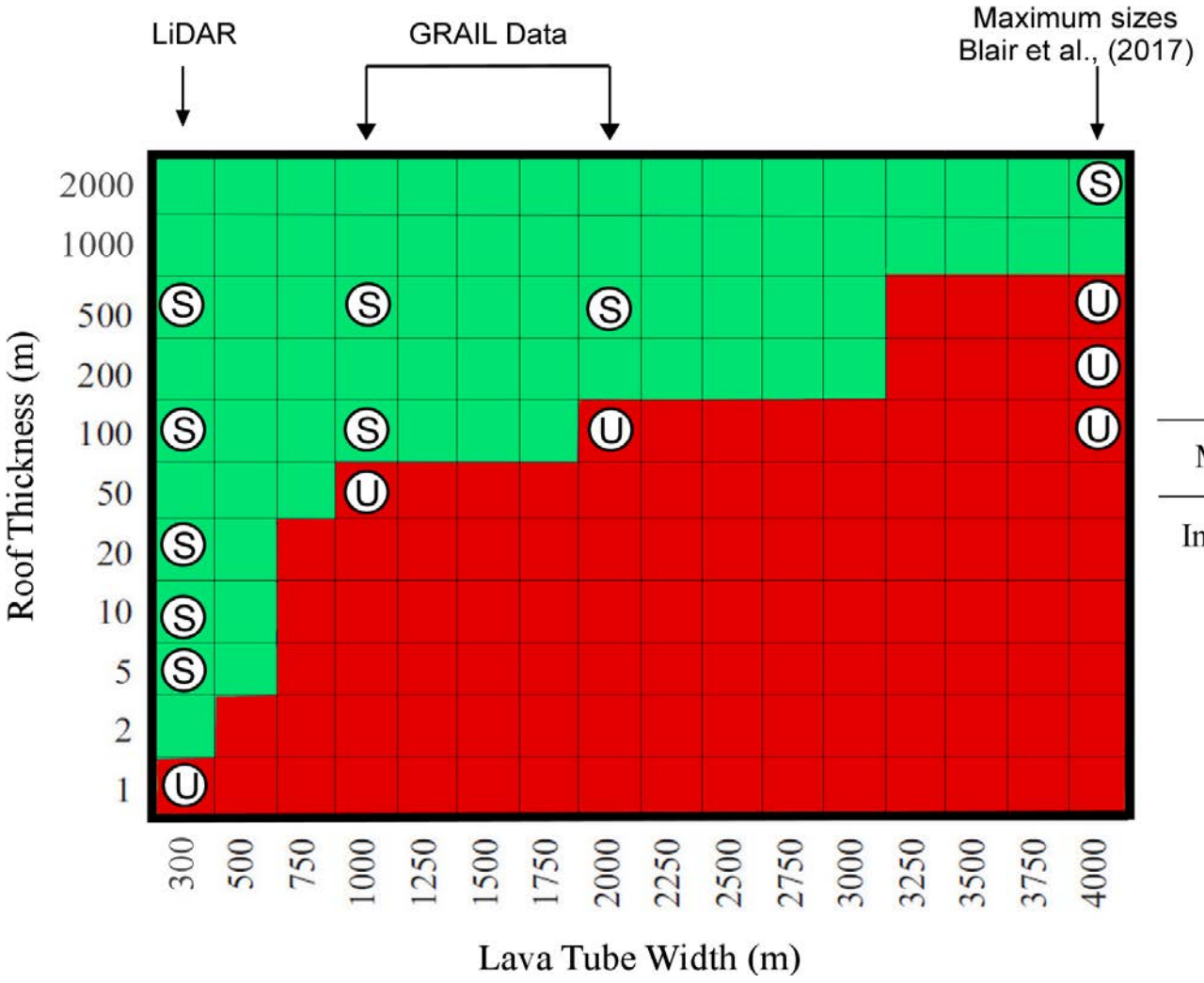
Numerical Simulations





Size and Geometry: Structural Stability

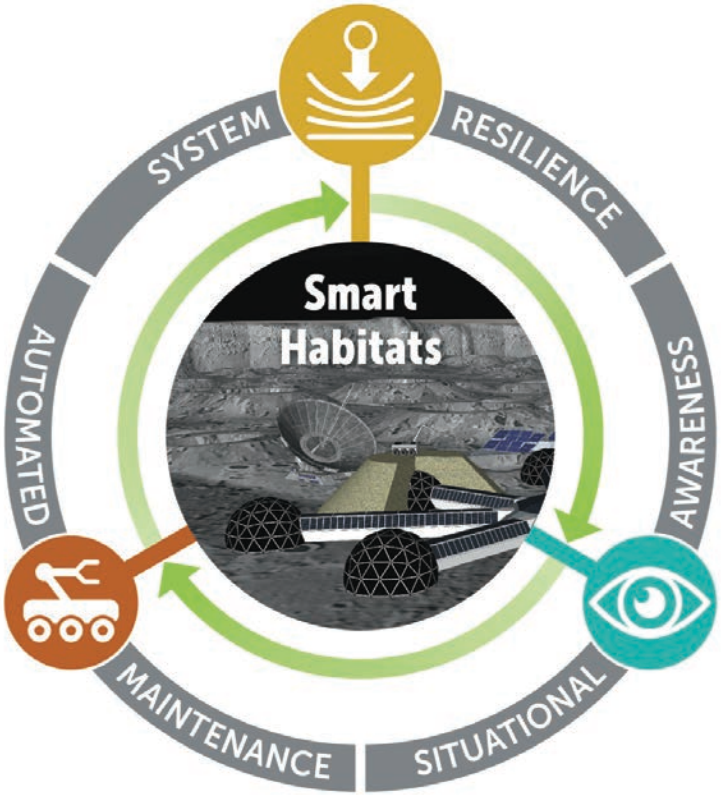
Criteria: Convergence



	Stable	Unstable
Model Results	S	U
Inferred Results		

RETH Institute

https://www.purdue.edu/RETH



Develop and demonstrate transformative smart autonomous habitats and related technologies that will adapt, absorb and rapidly recover from expected and unexpected disruptions to deep space habitat systems without fundamental changes in function or sacrifices in safety

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150 YEARS OF GIANT LEAPS