The Moon: Stepping Stone to the Planets

William A. Ambrose

Houston Geological Society

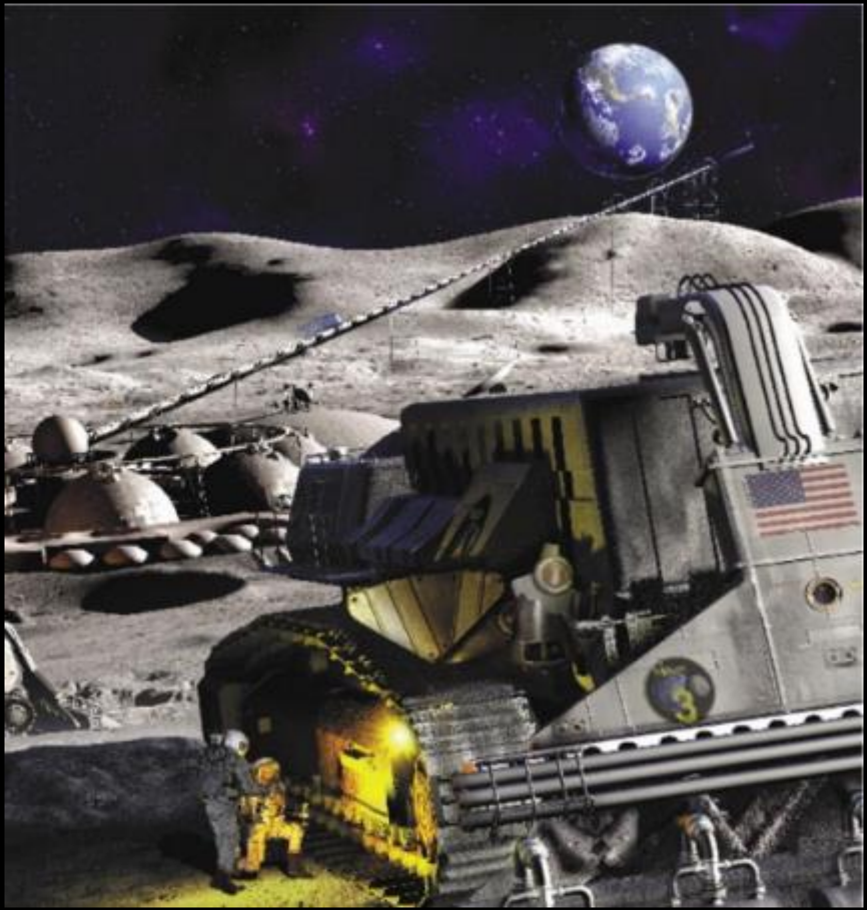
May 10, 2017

AAPG Astrogeology Committee

Bureau of Economic Geology

Project STARR

State of Texas Advanced Oil and Gas Resource Recovery



Schmitt (2004)

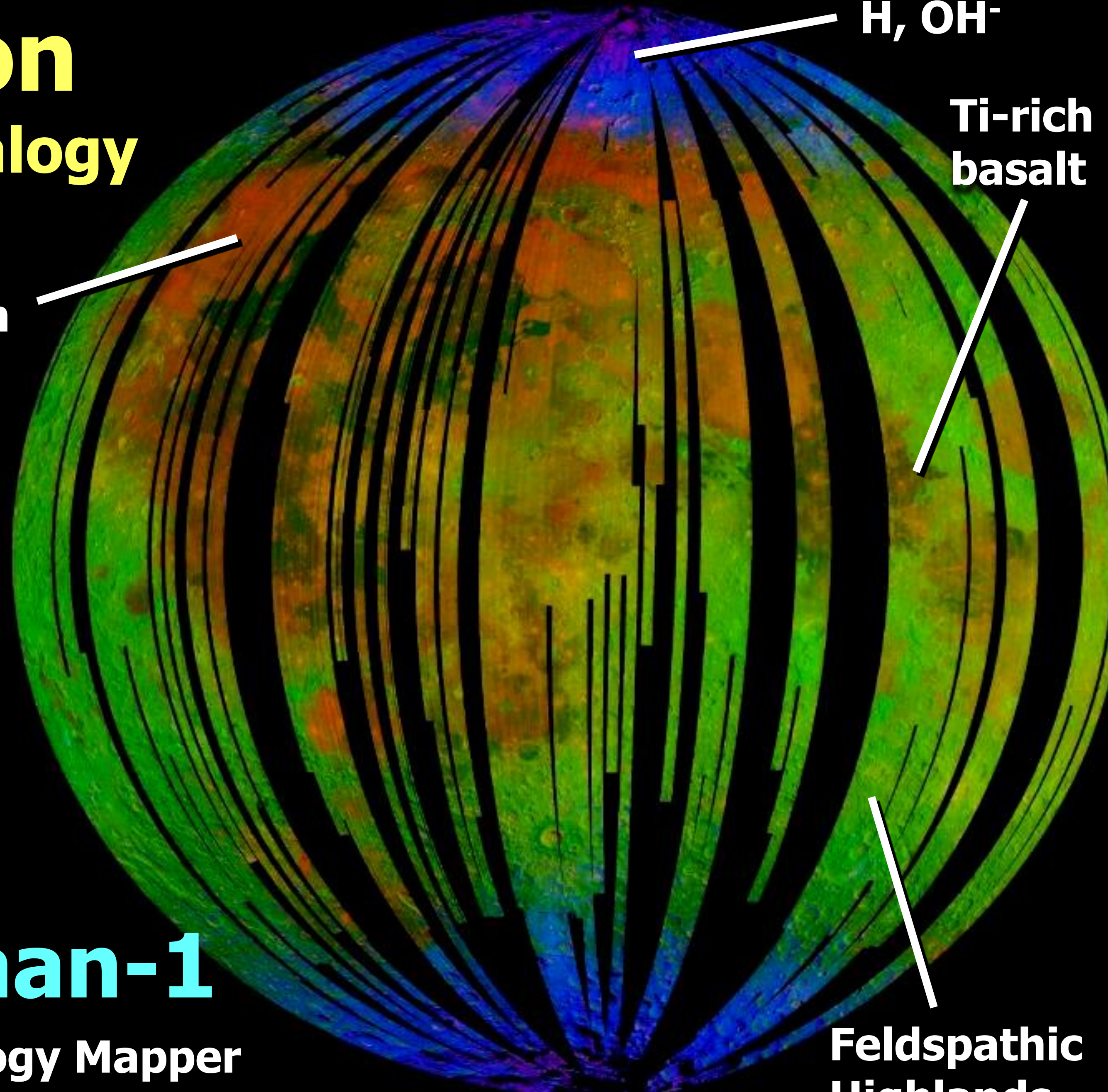
Why Return to the Moon?

- **Earth's closest neighbor**
  - *-Three-day trip*
  - *-Technology already exists to return to the Moon*
  - *- Less than 0.1% surface area visited by humans*

- **Abundant resources**
  - *-Water and volatiles for human settlement and rocket fuel*
  - *-Metals for Moon Base and solar power facilities*

- **Technology Development**
  - *-Settlements: Learning experiences for Mars*
  - *-Mining*
  - *-Space-power systems*

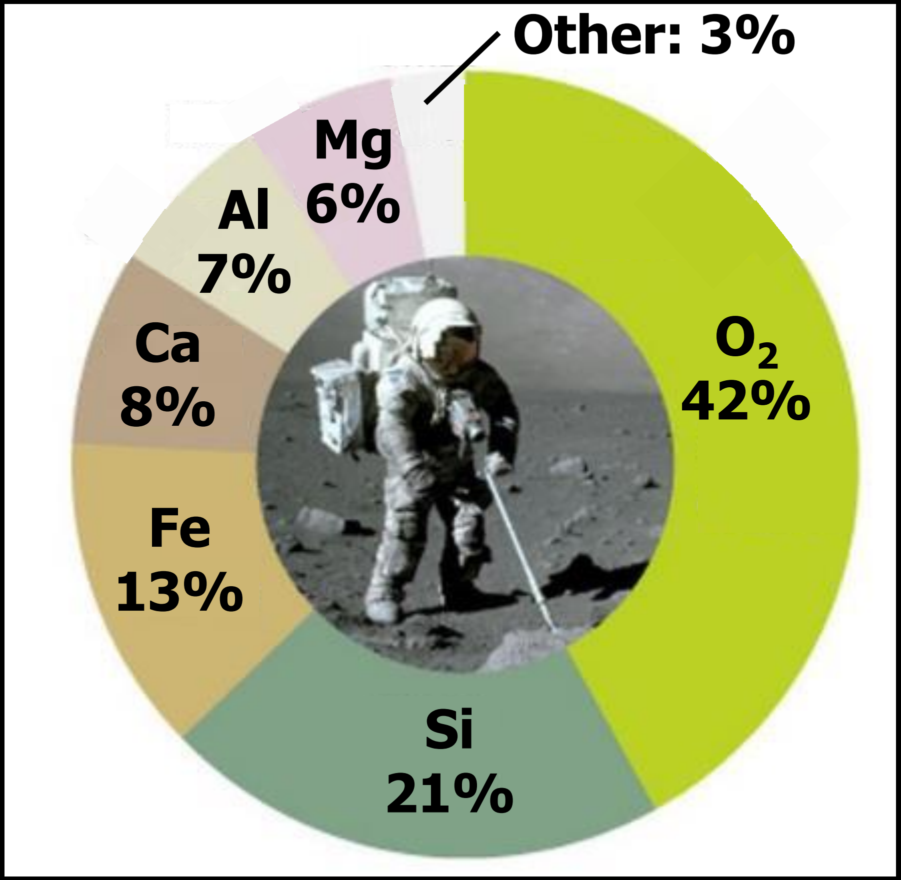
The Moon
Surface Mineralogy



Chandrayaan-1

NASA Moon Mineralogy Mapper
September 2009

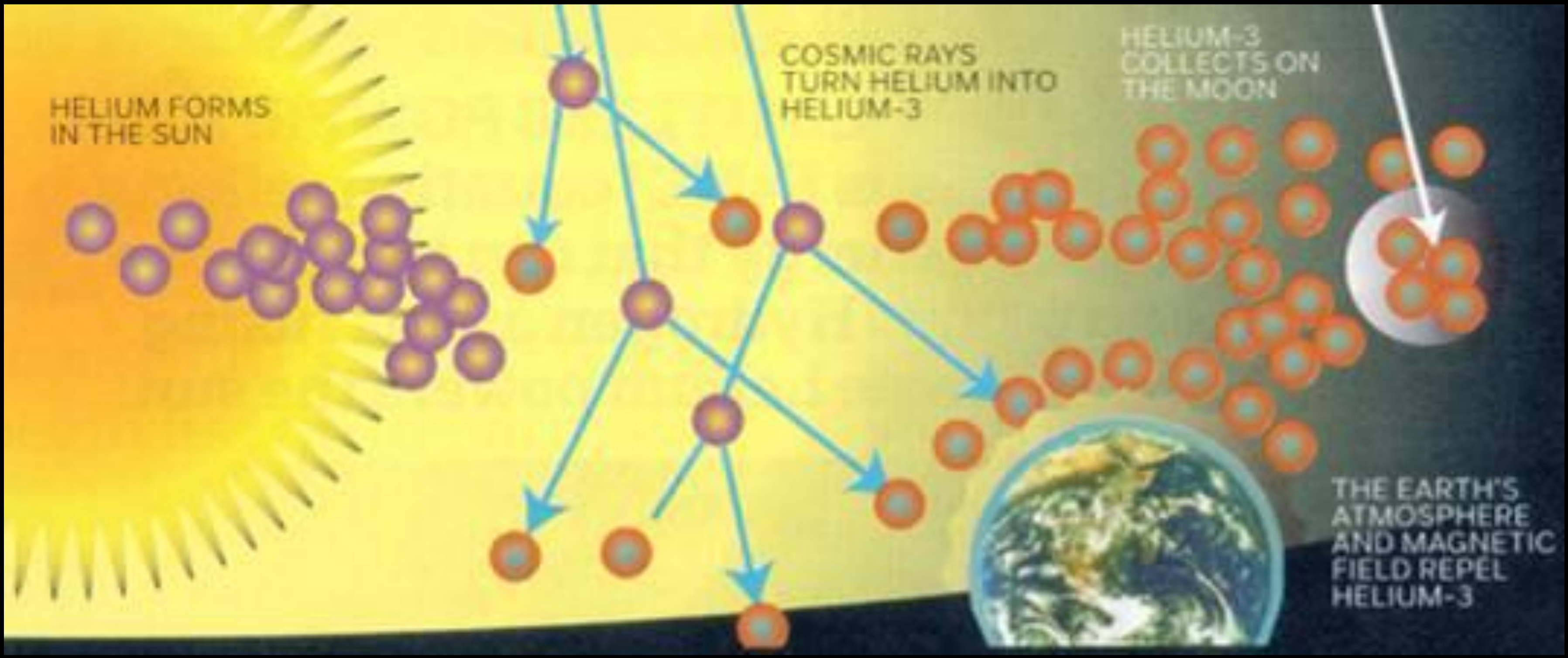
LUNAR Soil Composition



Apollo 17 Geologist
Harrison Schmitt

Lunar Helium-3

Schmitt (2004)



>270,000 km^2 minable (high- and medium-grade)

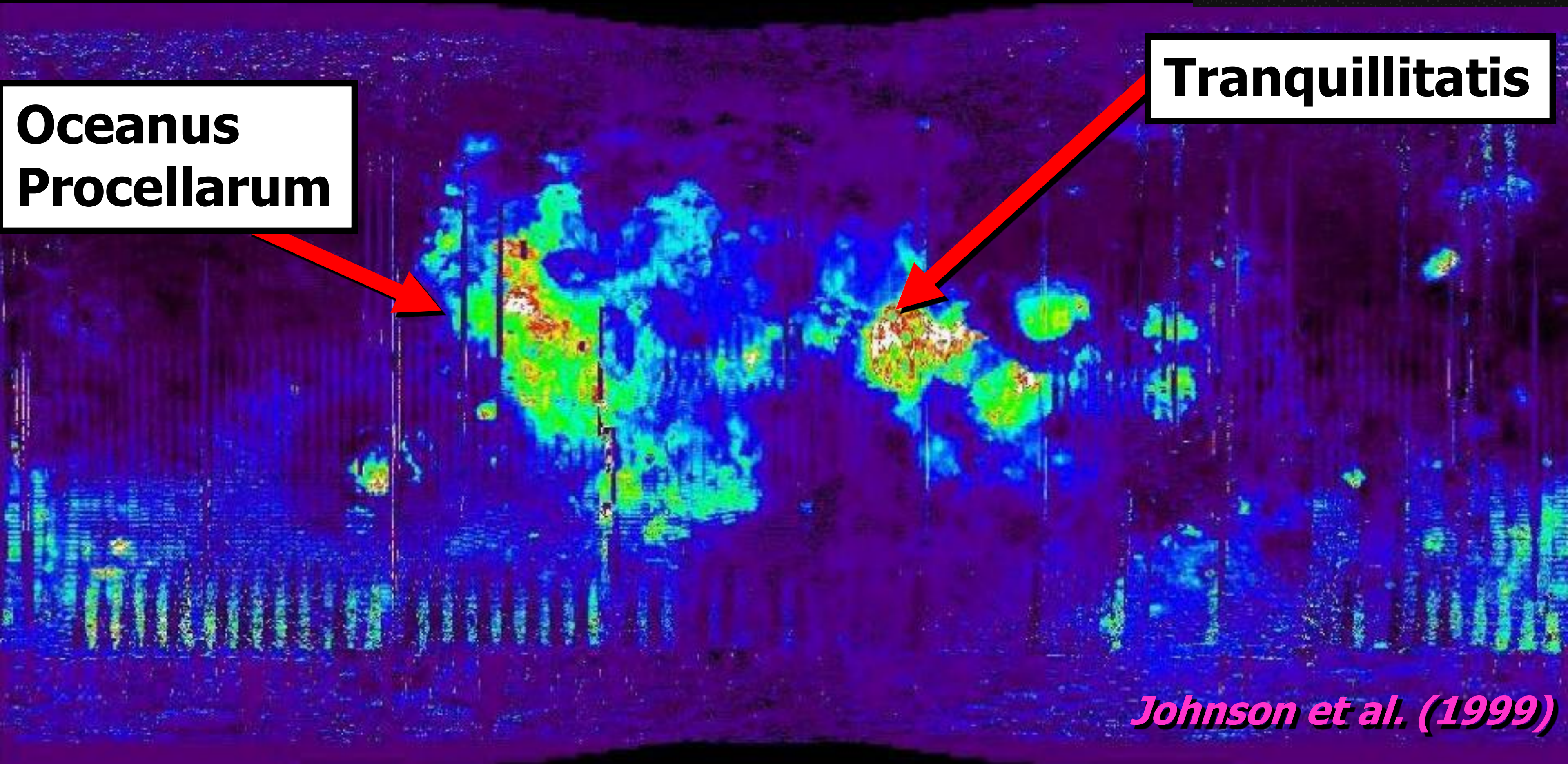
One Space Shuttle load could power the U.S for 6 months

Lewis (1996)

Lunar He-3 Distribution

>270,000 km^2 minable
(high- and medium-grade)

Lewis (1996)

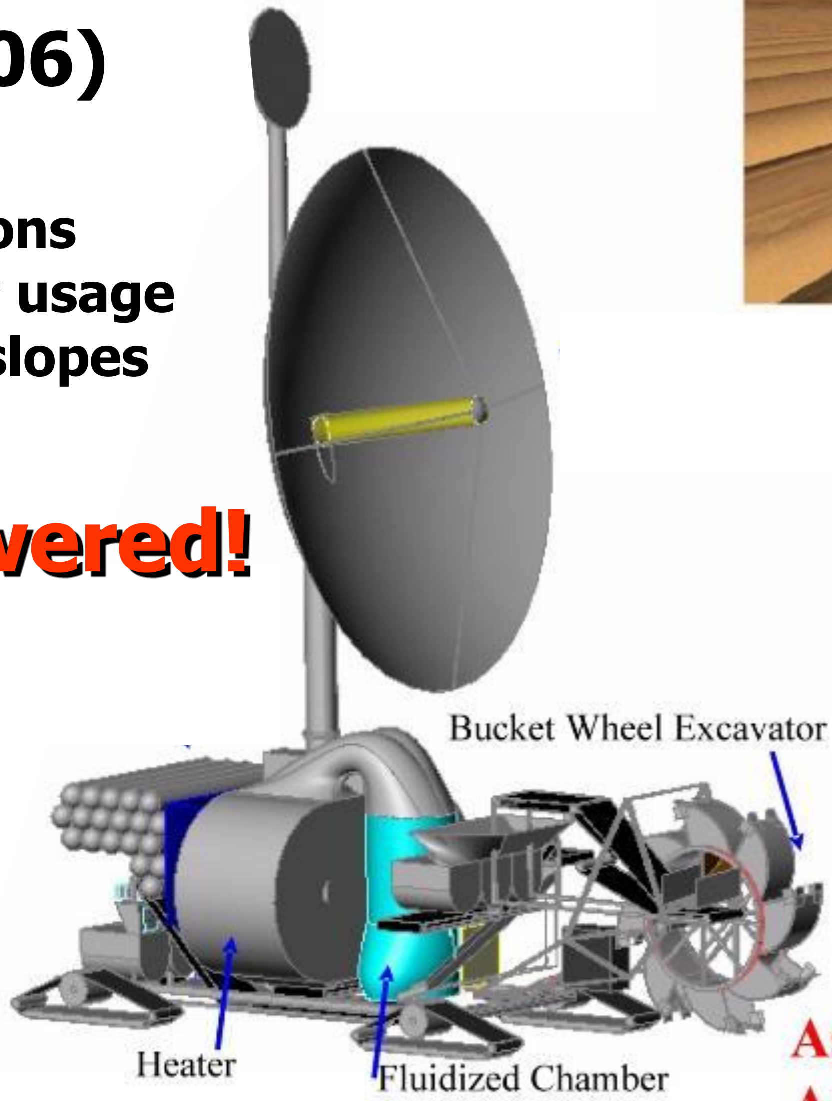


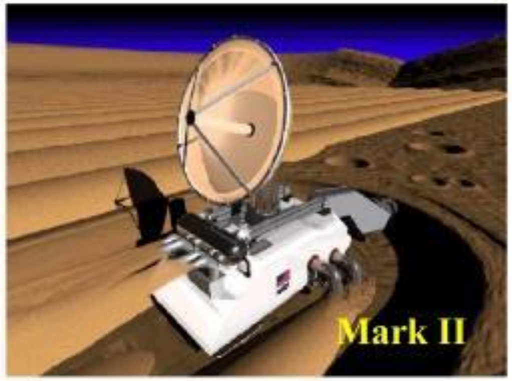
Lunar He-3 Mining

Matt Gujda et al. (2006)

Mass 9.7 tons
350 kW power usage
Handles 30° slopes

Solar Powered!



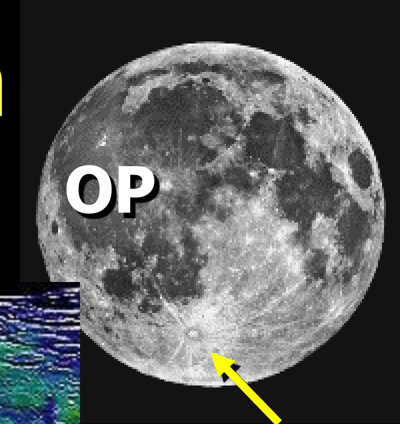


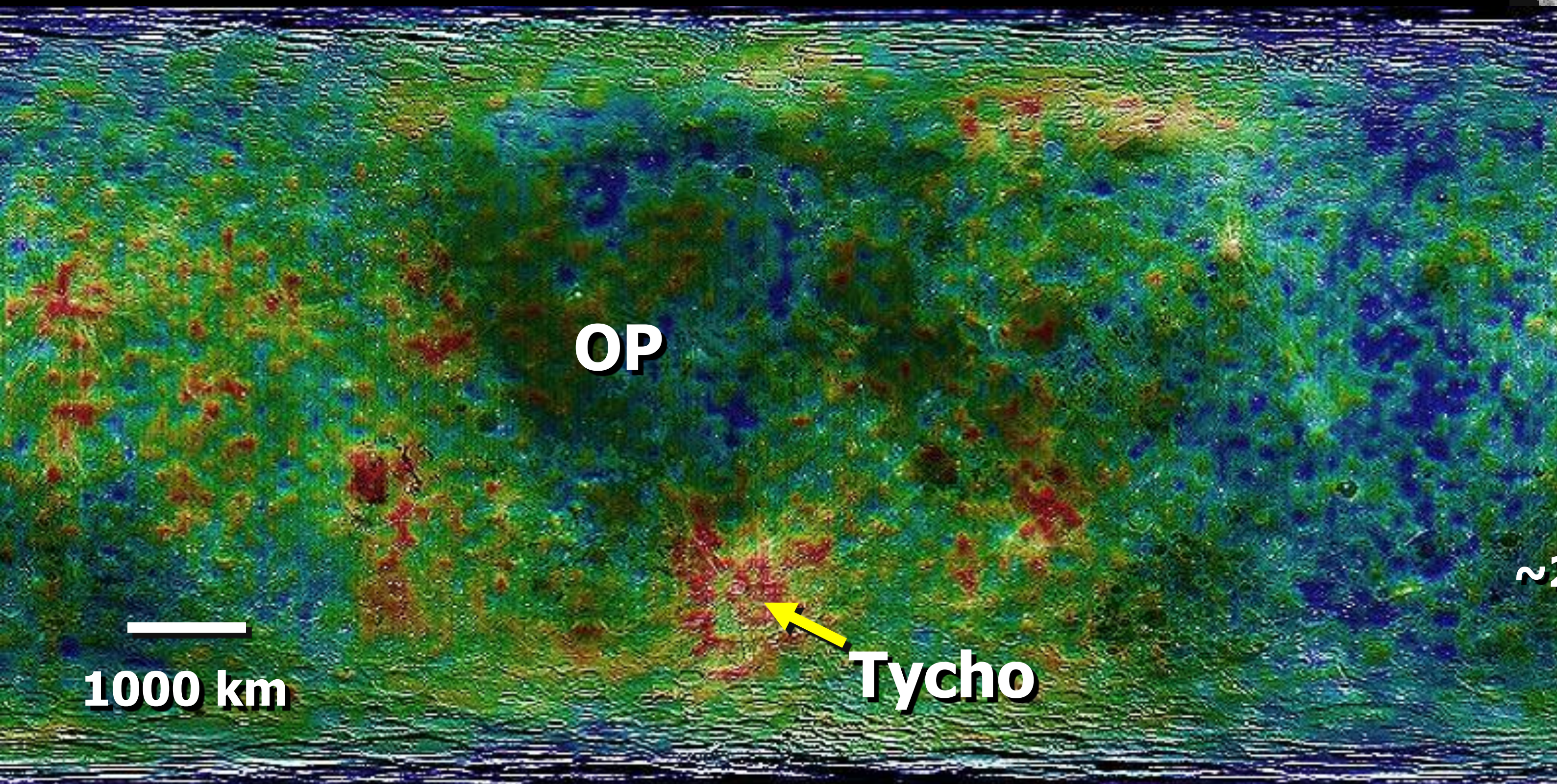
Mass of Volatiles Extracted (tonnes/yr @ 10ppb)	
H_2O	108.9
N_2	16.5
CO_2	56.1
H_2	201.3
^4He	102.3
CH_4	52.8
CO	62.7
^3He	0.033

Assumed 10ppb!
Actual >20ppb

Surficial Hydrogen Distribution

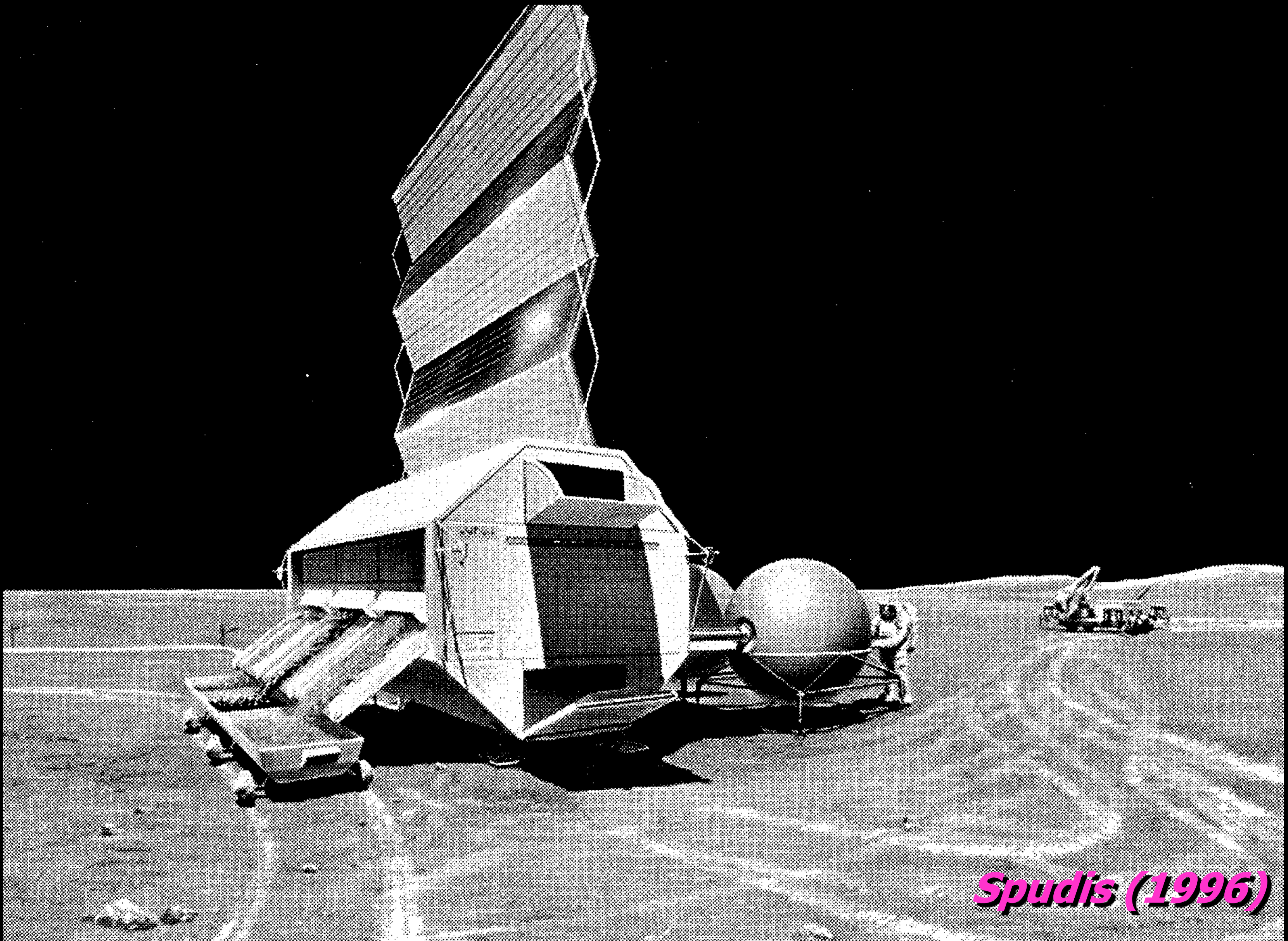
Implantation from Solar Wind





A ~0.4-mi^2 (1-km^2) area of mare regolith at 40-ppm hydrogen could be mined to a depth of ~3.3 ft (1 m) to extract an equivalent amount of hydrogen for launching the Space Shuttle (Spudis, 1996).

Hydrogen-Producing Station

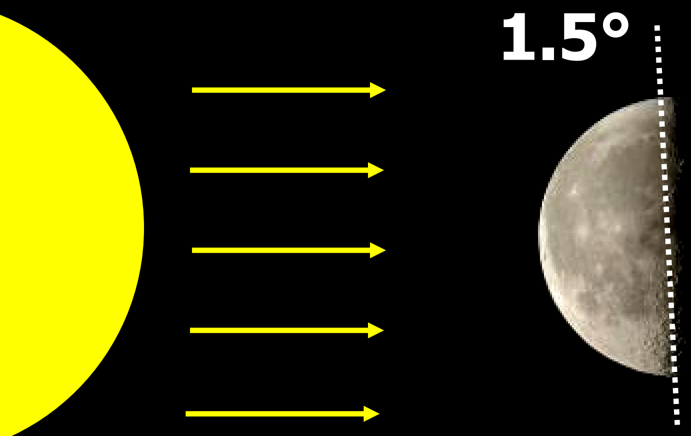


Spudis (1996)

Volatiles at the Poles

Impacts from Comets

10^{13} kg water
past 2 Ga (Arnold, 1979)

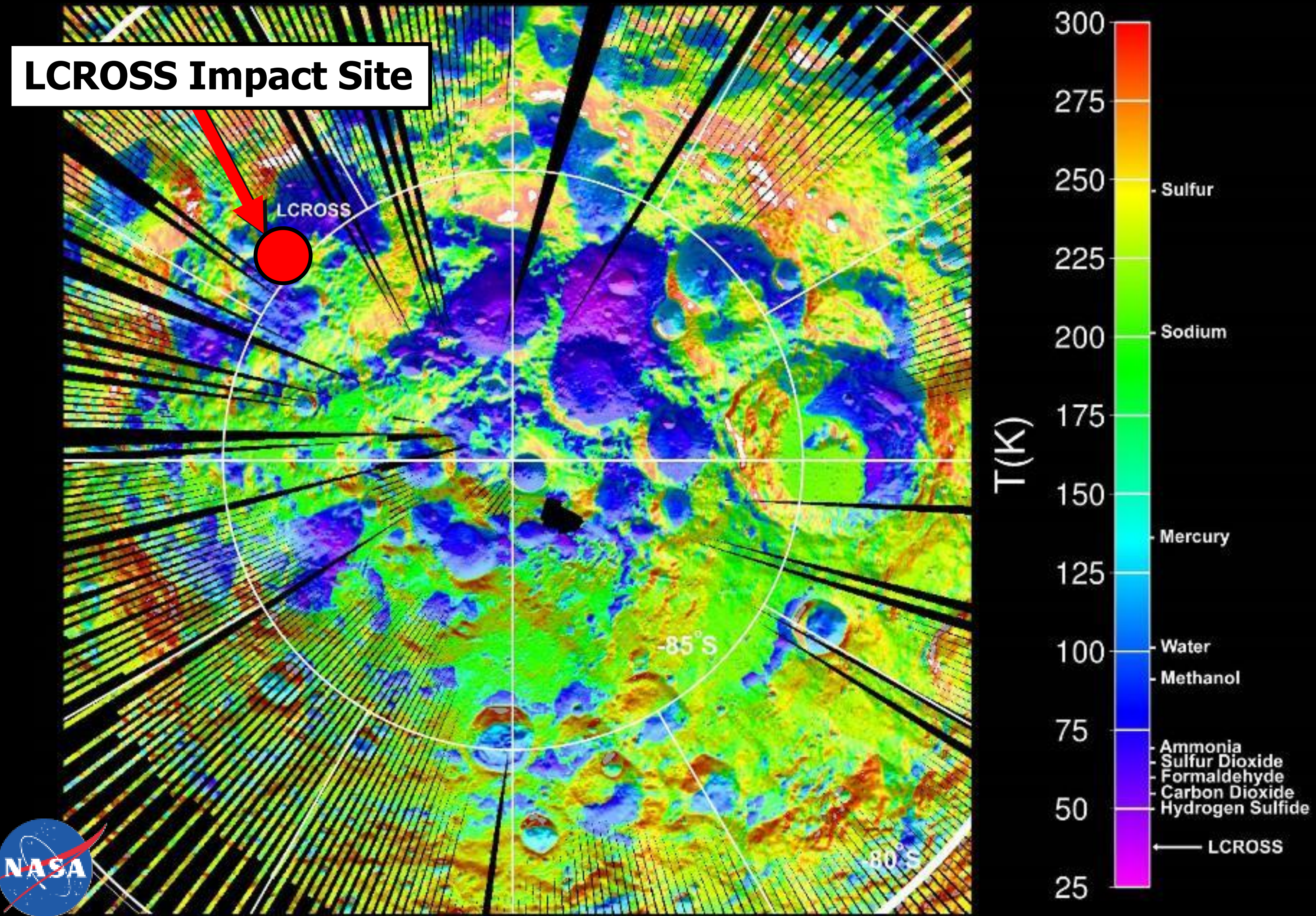


Bussey and Spudis (2006)

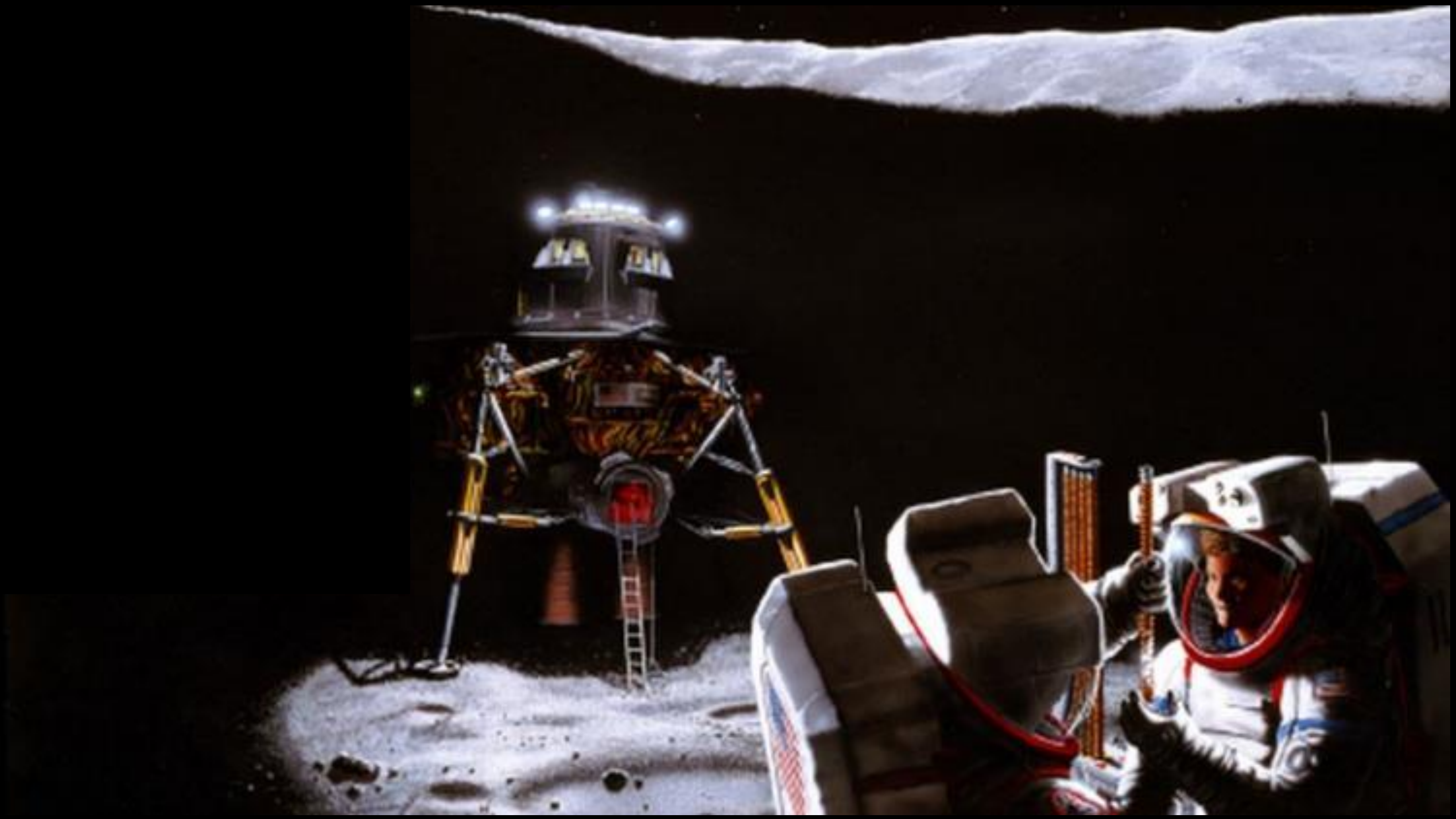
View from the Moon’s South Pole

Kaguya Photograph

South Polar Temperature



Mission to Shadowed Crater



Lunar Ice Drill

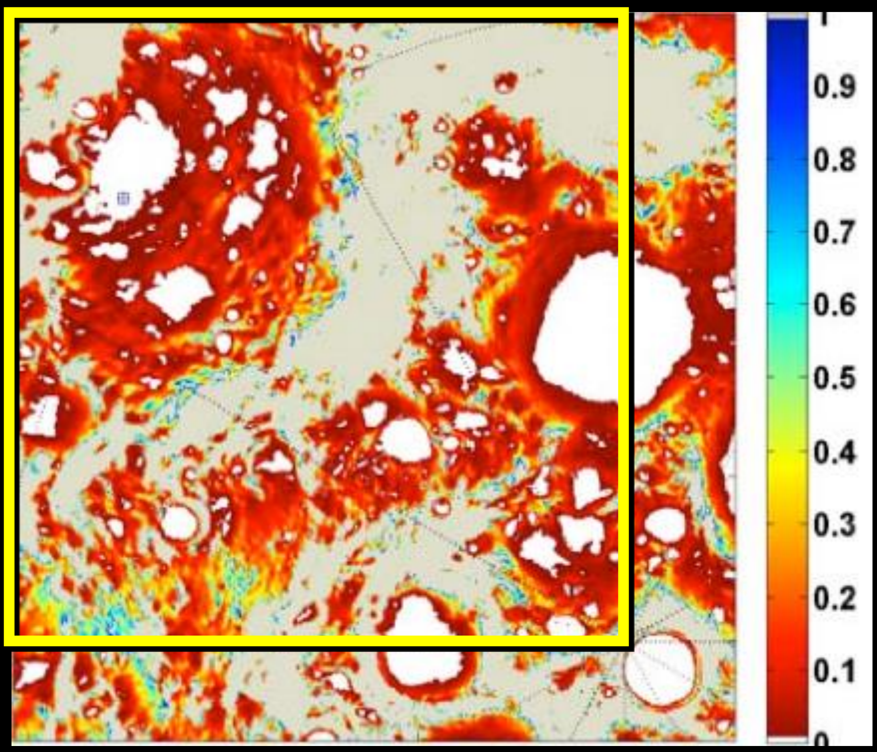
1-2 m depth of investigation
Luna-27 lander in 2020: -140°C

ESA/Finmeccanica (2016)

LCROSS

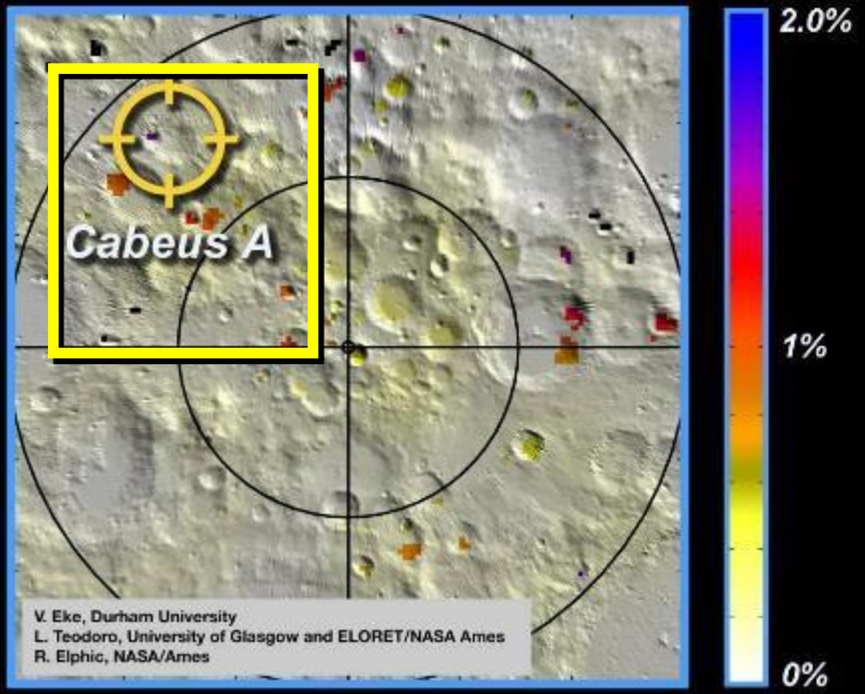
Impact Site Selection near South Pole

Depth to Stable Ice (m)



Elphic et al. (2011)

Water Equivalent Hydrogen



Eke et al. (2009)

100 km

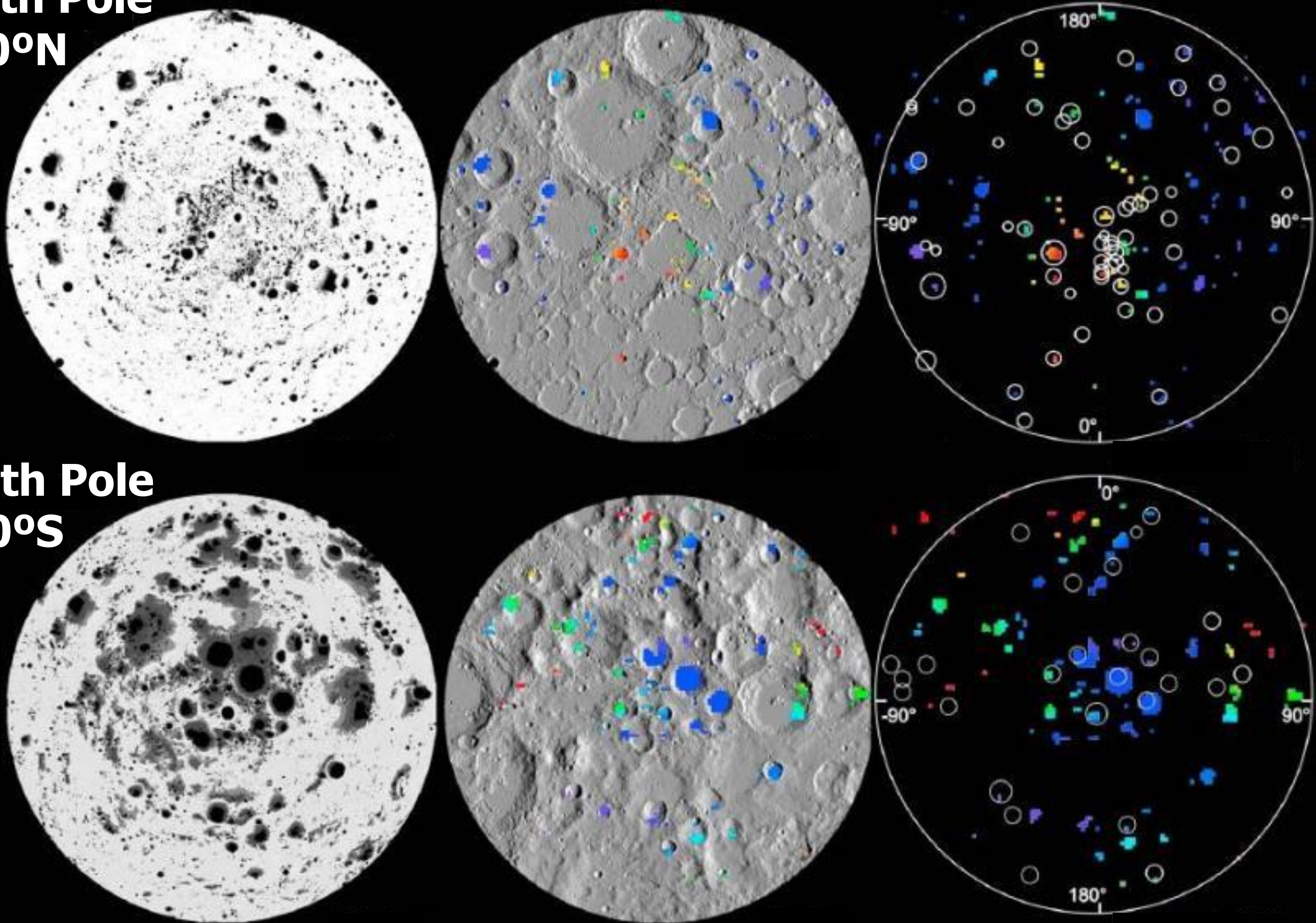
■ 1 cm ■ > 1 m

Lunar Polar Crater Anomalies

Modified from Spudis et al. (2013)

North Pole ≥80ºN

South Pole ≥80ºS

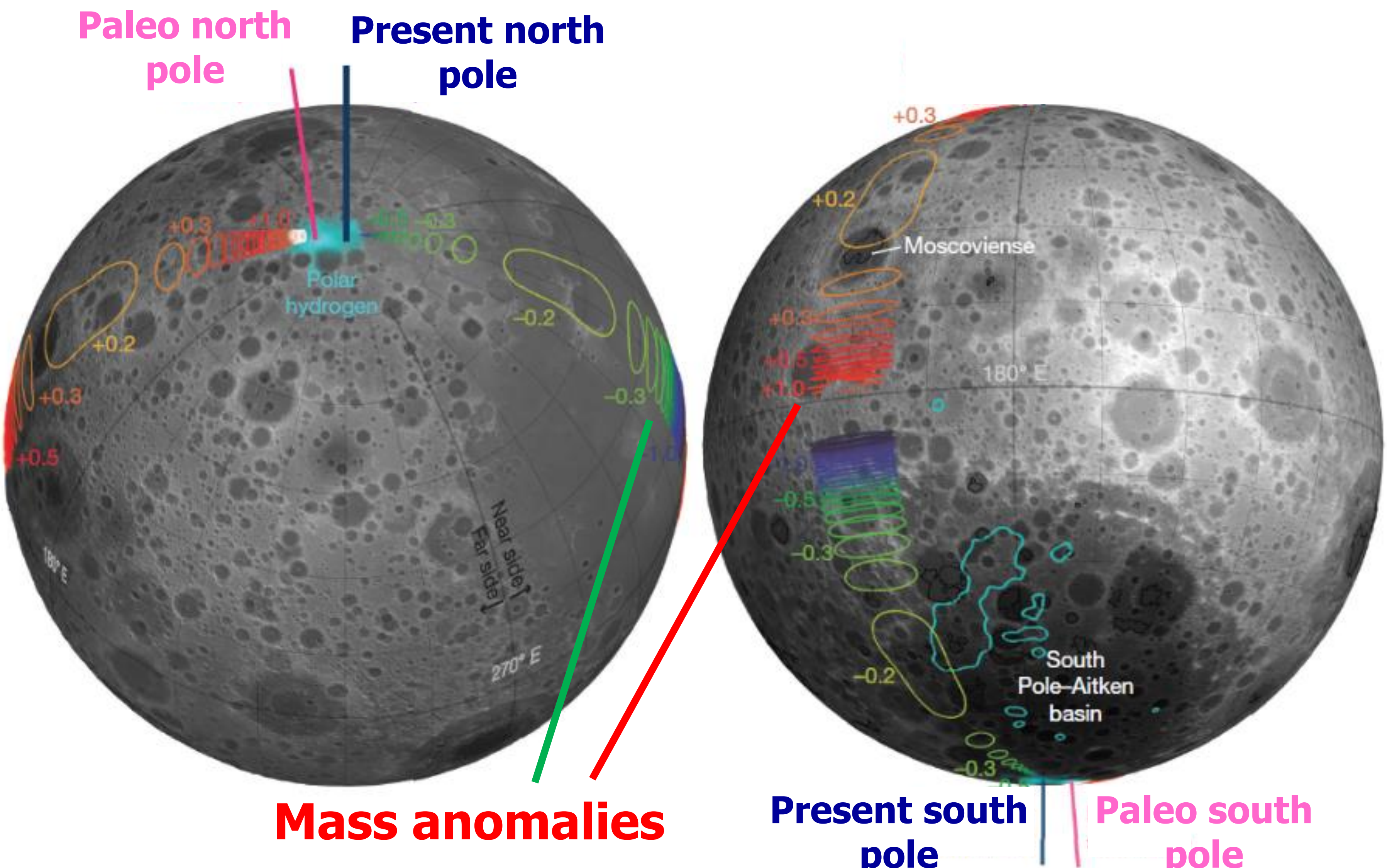


Shadowed Craters

Neutron Spectrometer
Red: High Hydrogen

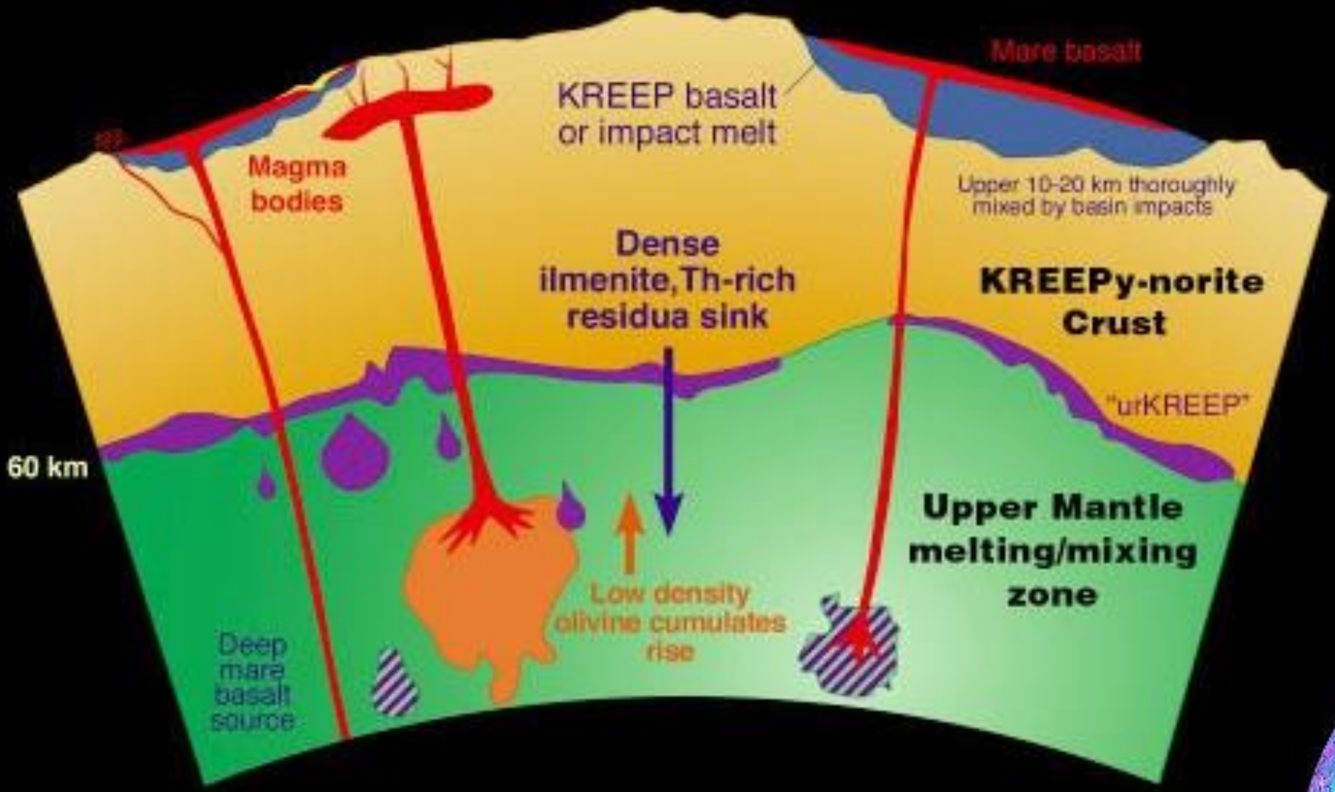
Neutron + CPR

Off-axis Polar Hydrogen

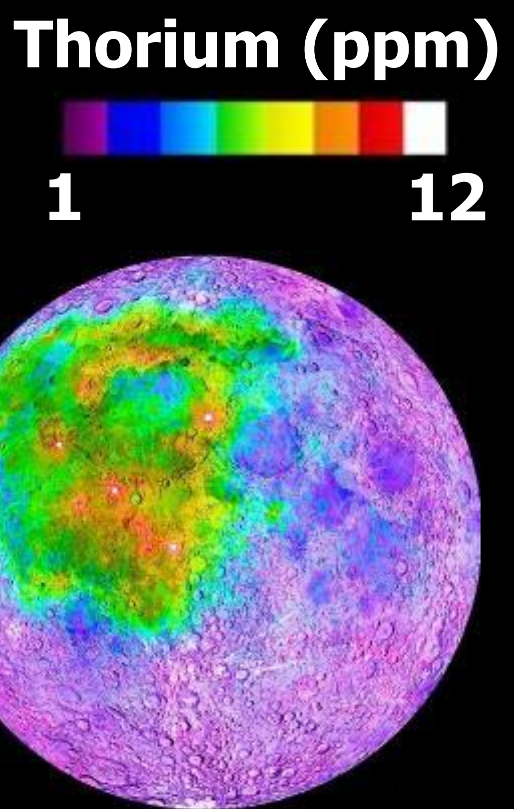


Modified from Siegler et al. (2016)

Procellarum KREEP Terrane

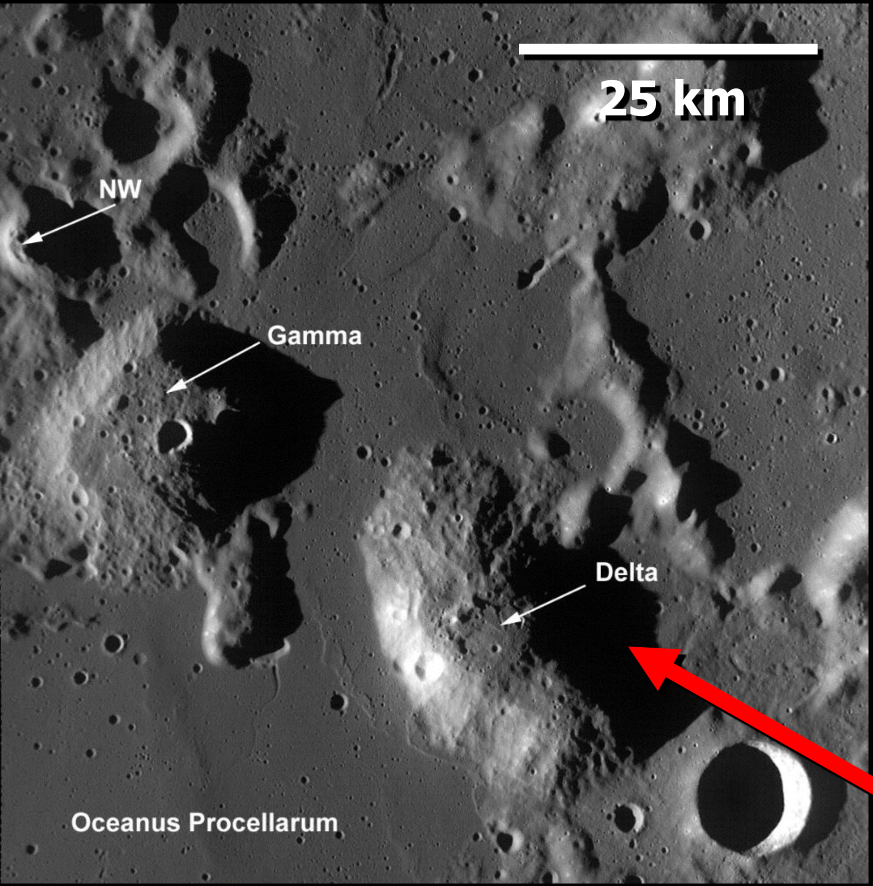


Jolliff, et al. (2000)



Spudis (2005)

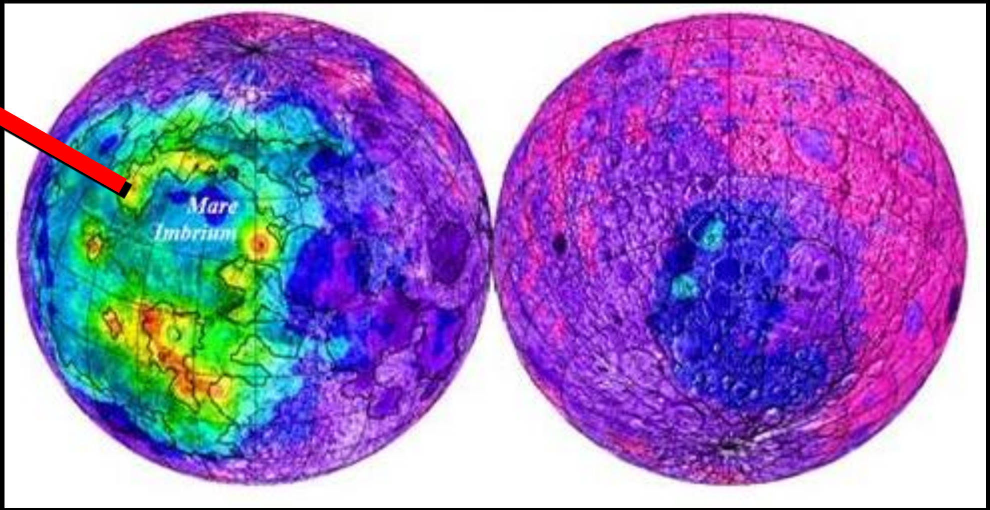
Mons Gruithuisen



LOLA M117752970ME

Thorium
Silicic Domes

>90 ppm

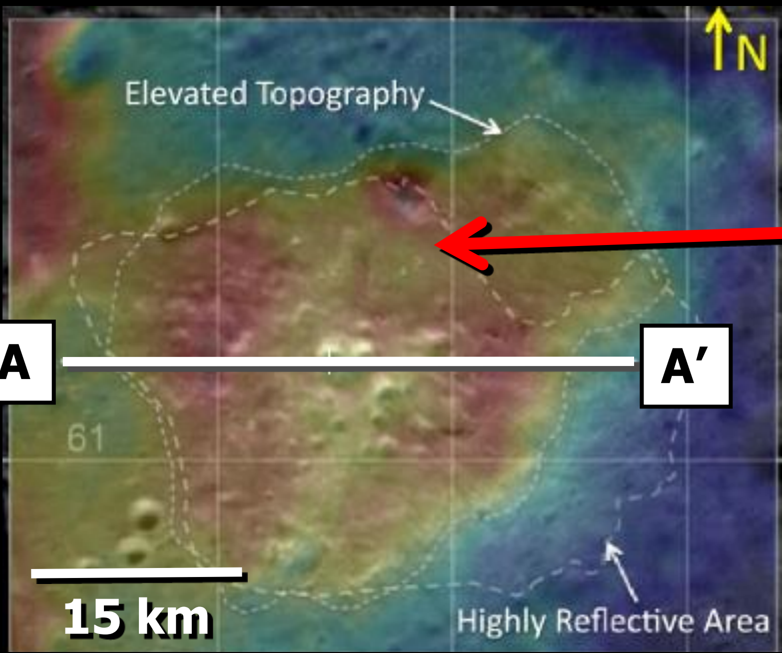


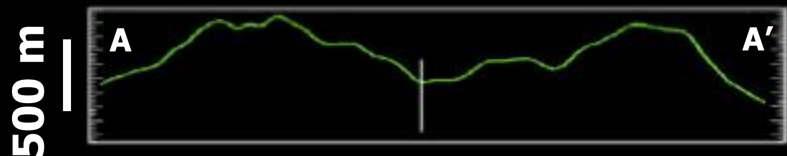
Yamashita (2009)

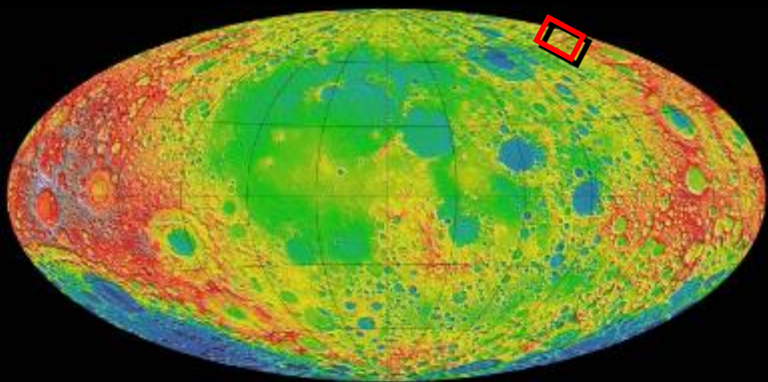
Compton Belkovich Lava Domes

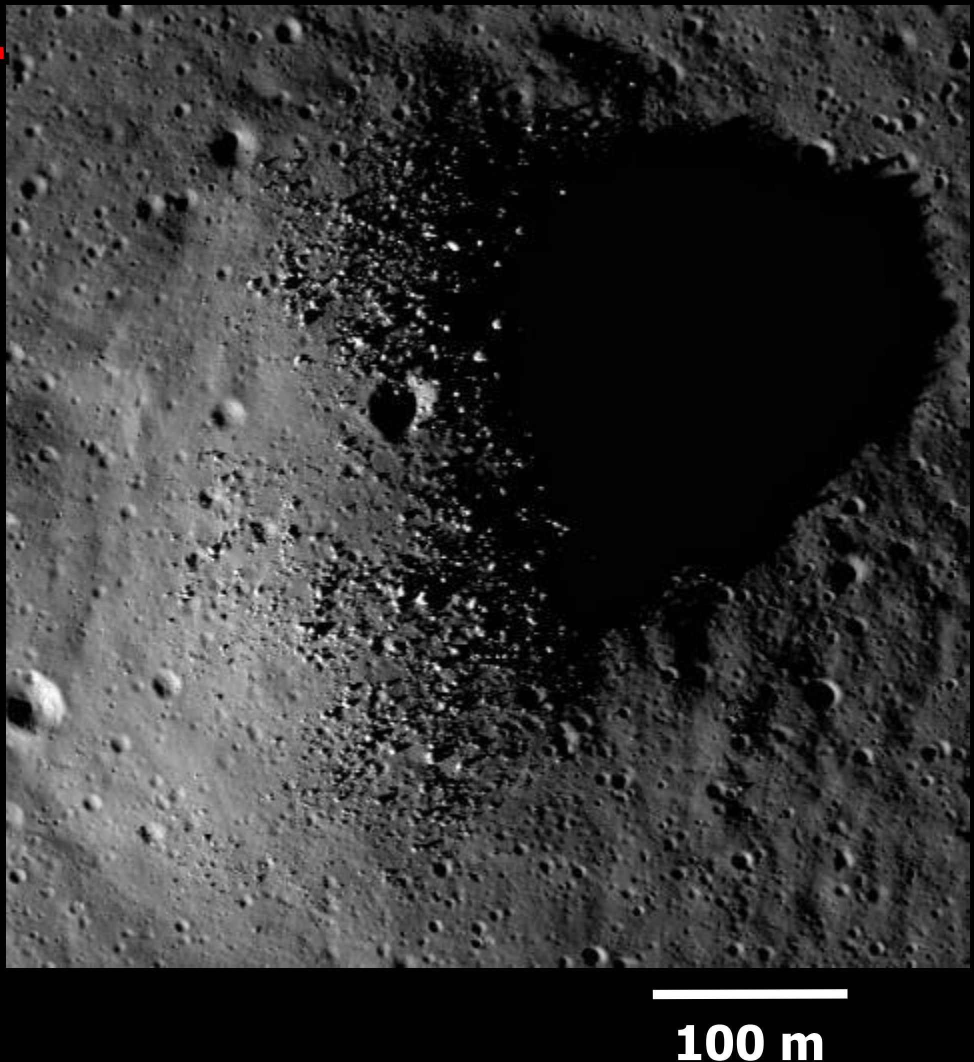
Modified from Jolliff et al. (2011)

40-55 ppm Th









Mars: Surface Radiation Risks

RAD on Mars Curiosity

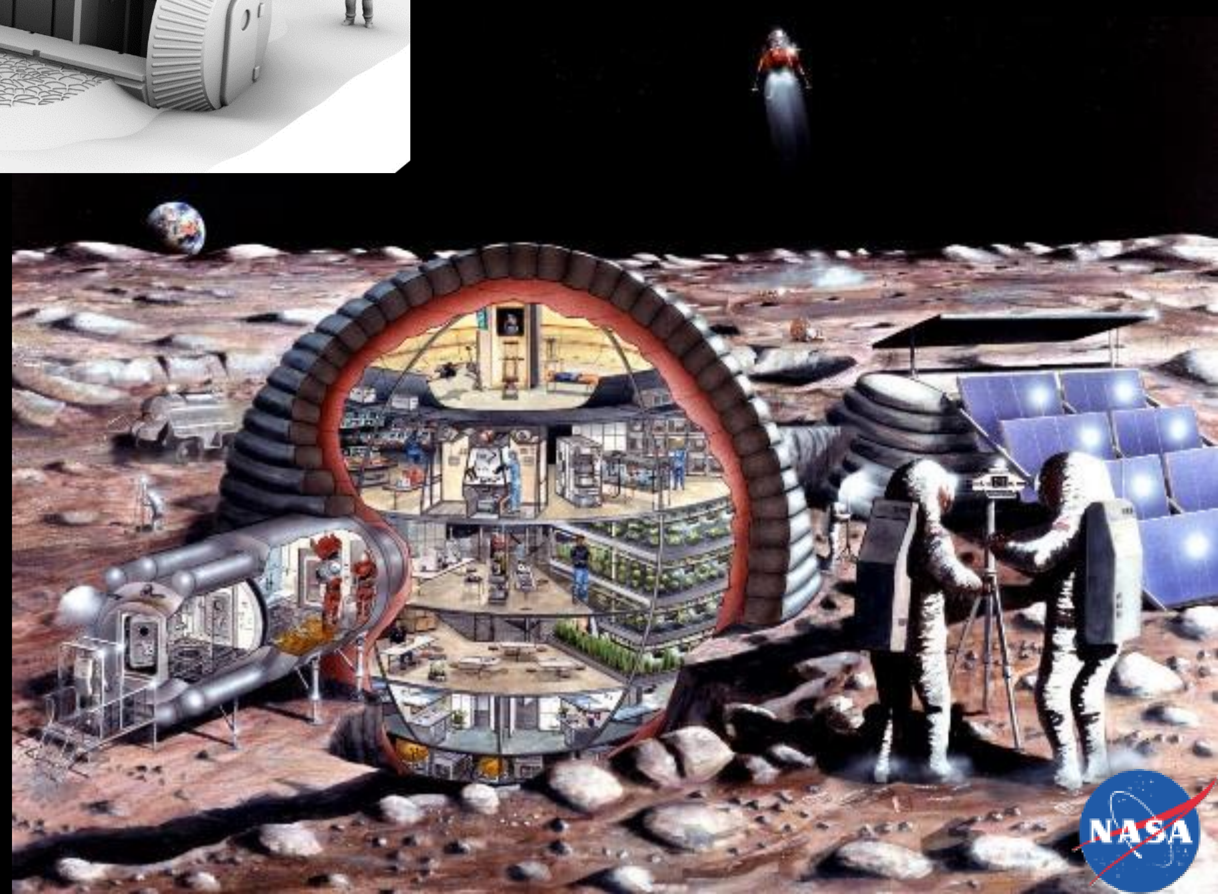
Galactic Cosmic Rays, Solar Particle Events

Radiation equivalent to whole-body
Computed Axial Tomography (CAT) scan every 5 days
Lifetime cancer risk increase of 5%

Lunar Base Designs

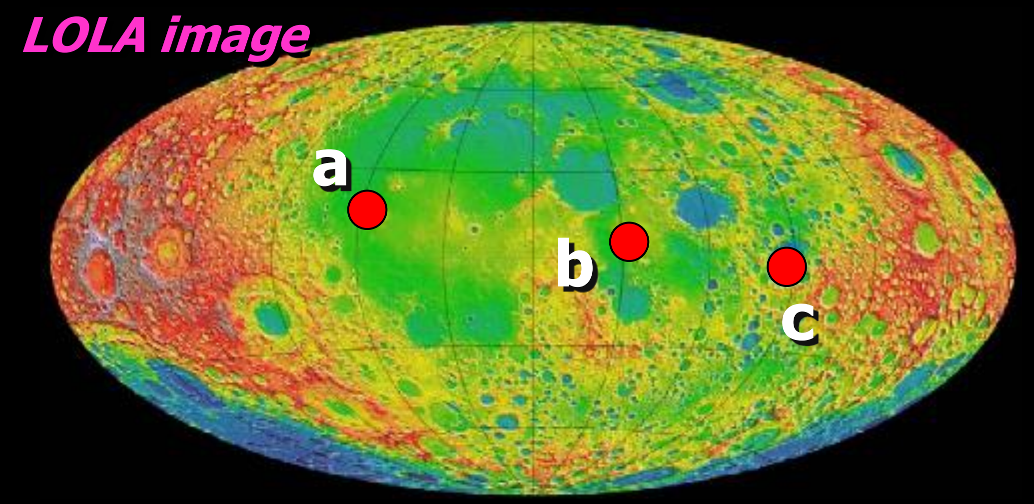
Sinterhab

ESA/Foster + Partners (2013)

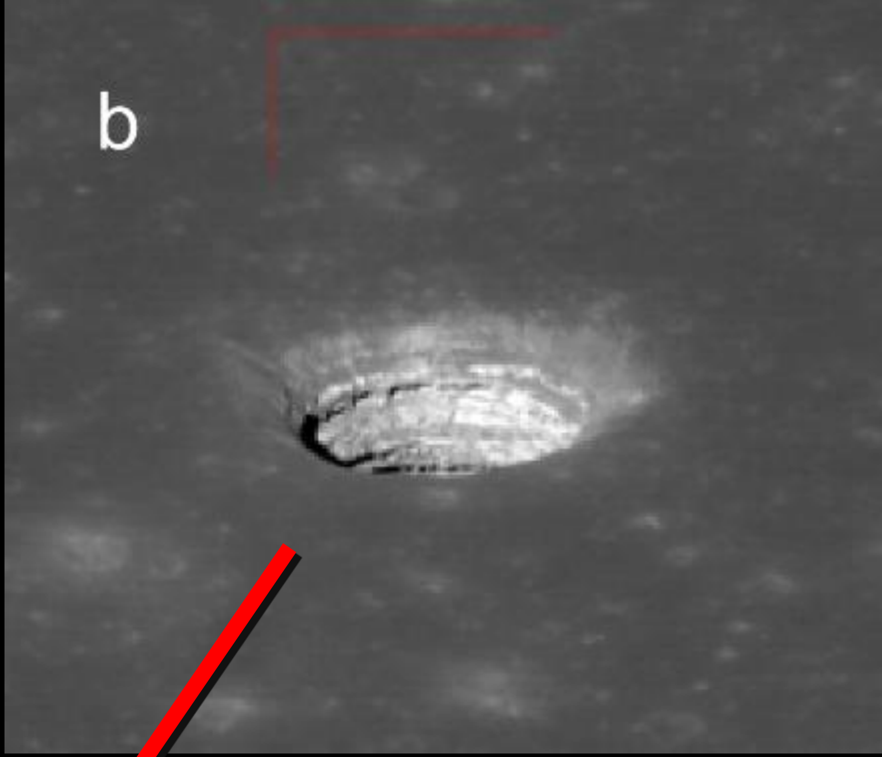


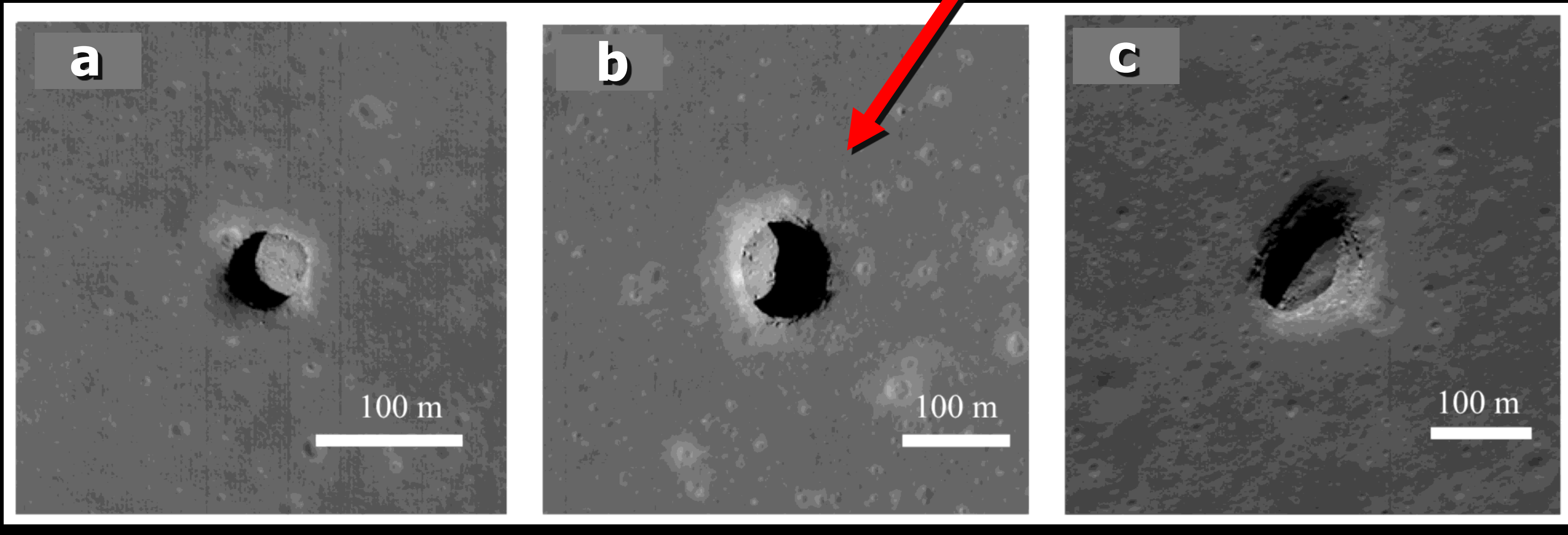
Inflatable
Lunar Base

Lunar Pits



Modified from Haruyama et al. (2011)





Lava Tubes on Earth

Craters of the Moon National Park

Layering

Filled

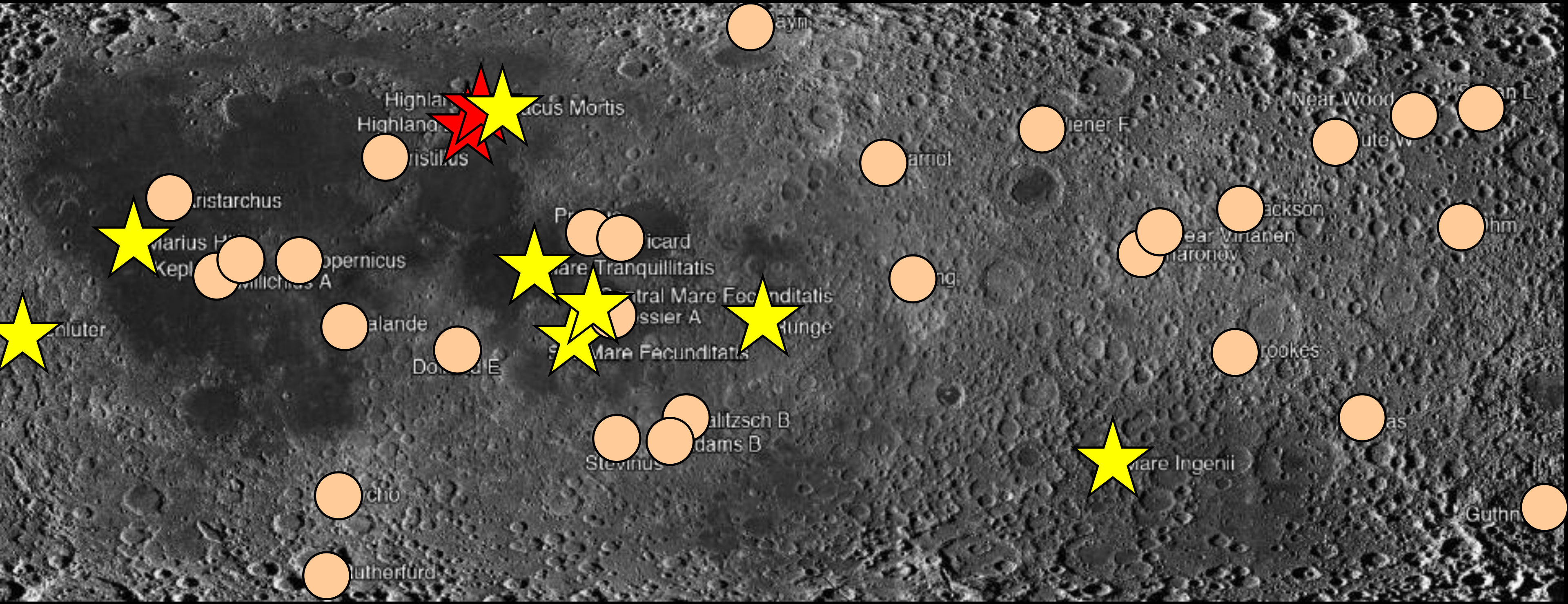
Mollica et al. (2011)

Open

U.S. National Park Service

Distribution of Lunar Pits

Modified from
Wagner and Robinson (2014)



Mare pits

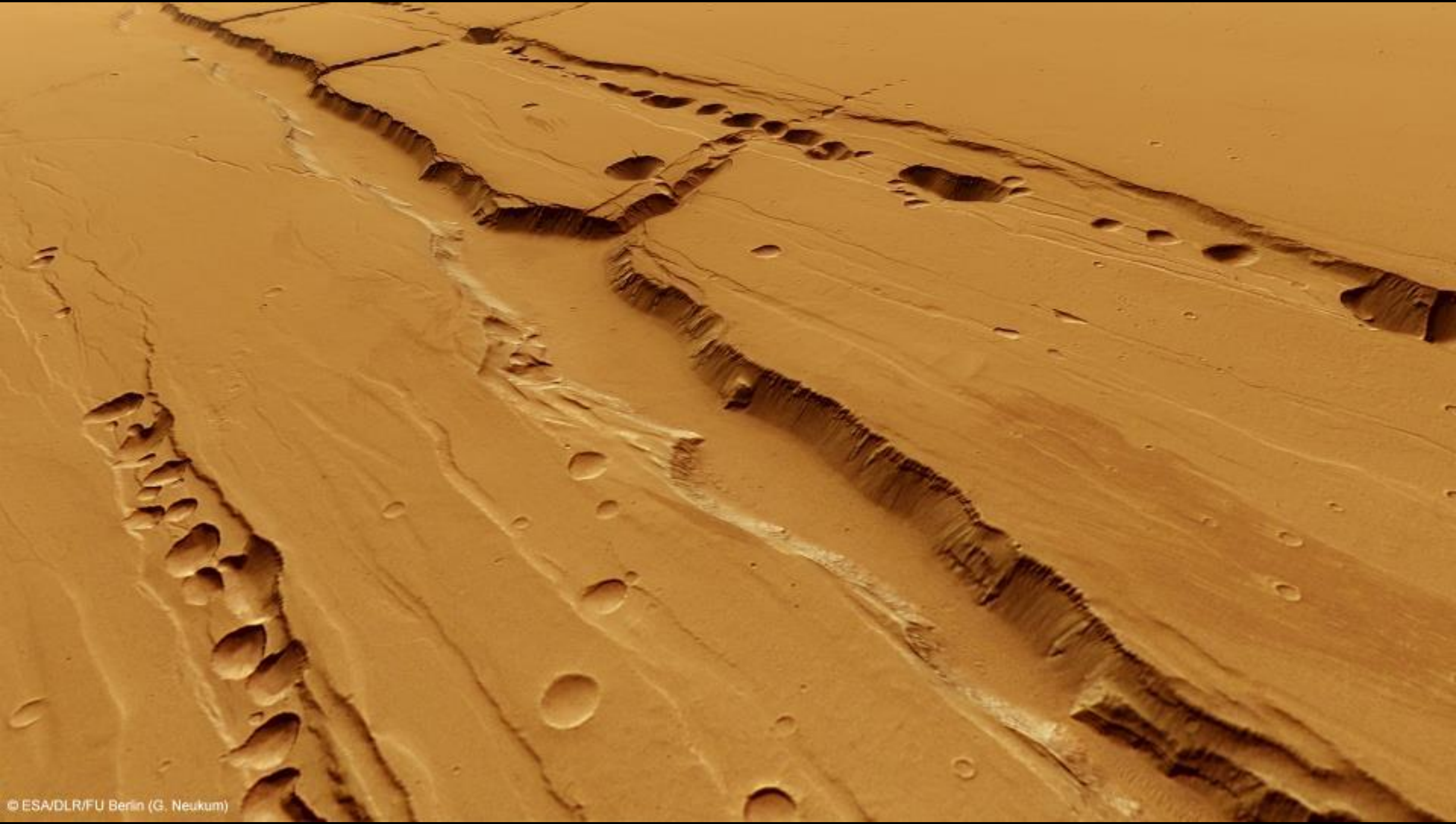
Highland pits

Impact melt pits

1,000 km

Mars: Collapsed Lava Tubes

Pit Chains in Tharsis



Mars Express (2012)

Global Space Economy

- **$330 Billion in 2015**
  - *-Commercial activities: 76 percent*
  - *-Global navigation systems*
  - *-Infrastructure and support*
  - *-Transportation systems (ISS, Space Tourism)*
- **NASA: $ 19.3 Billion: 2016 (0.5% US Federal Budget)**

Falcon 9: May 18, 2015

Private Space Sector

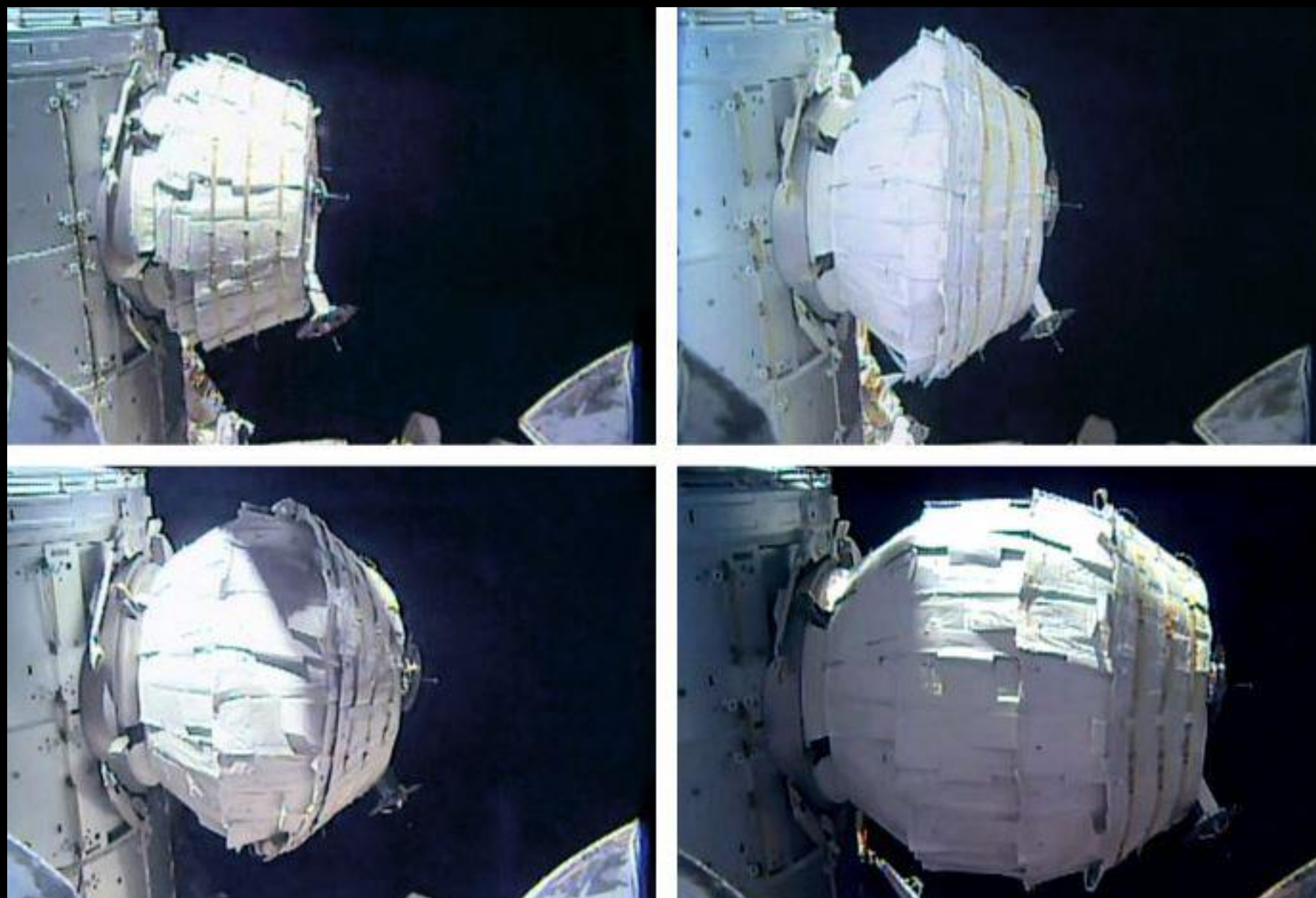
Offworld: ***Robots***
Shackleton Energy Company: ***Ice Mining***
Bigelow Aerospace: ***Habitation Modules, Lunar Base***
SpaceX: ***Launch vehicles***
Odyssey Moon: ***Rovers***
Infinite Space Dynamics, Planetary Resources: ***NEAs***
Deep Space Industries: ***Space manufacturing, solar***
Mars One: ***Mars colonization***

B330 Habitation: Bigelow Aerospace

330 m^3 volume (ISS 900 m^3): Arrived at ISS, April 10, 2016

BEAM

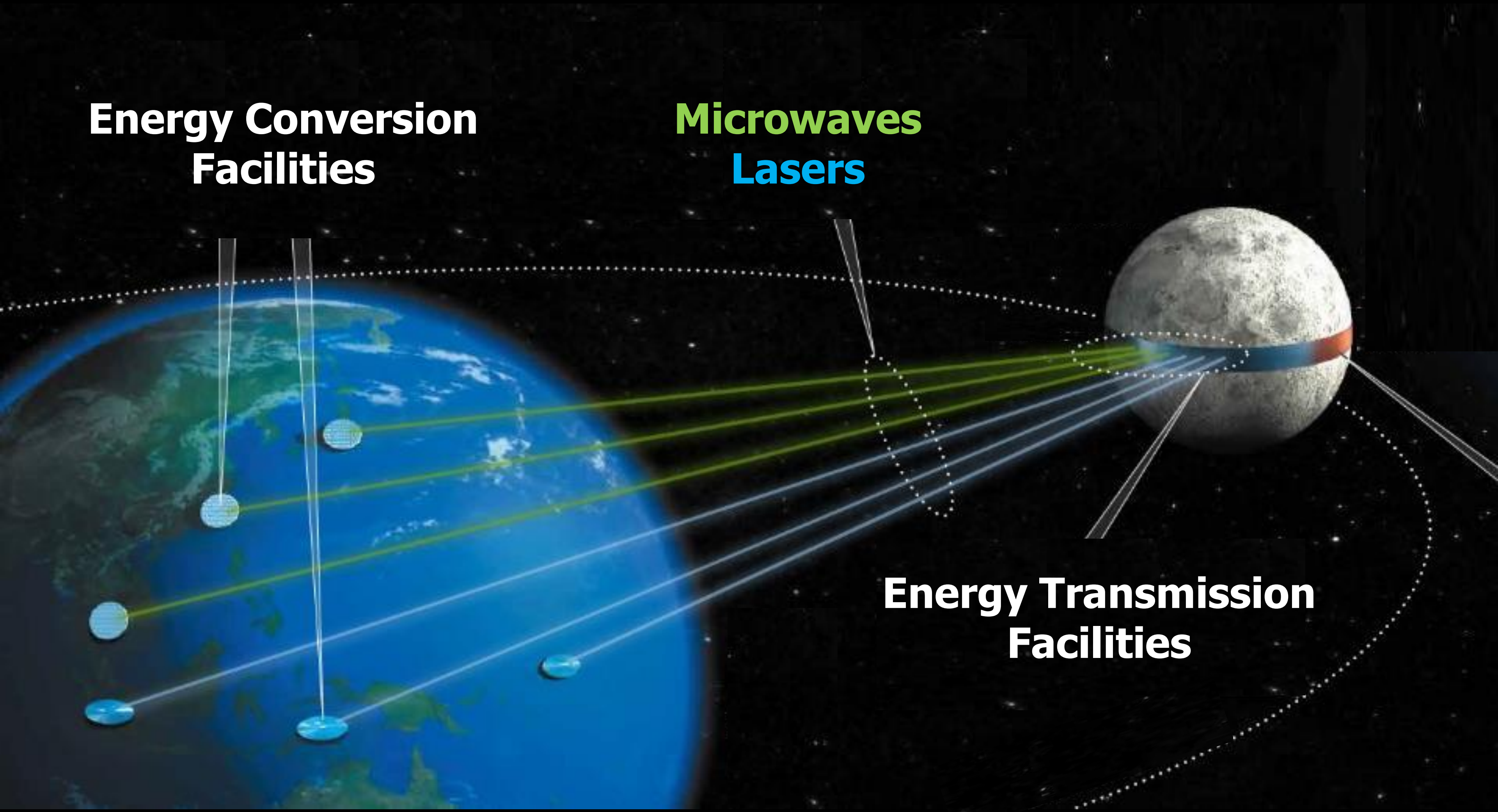
Bigelow Expandable Activity Module



May 28, 2016

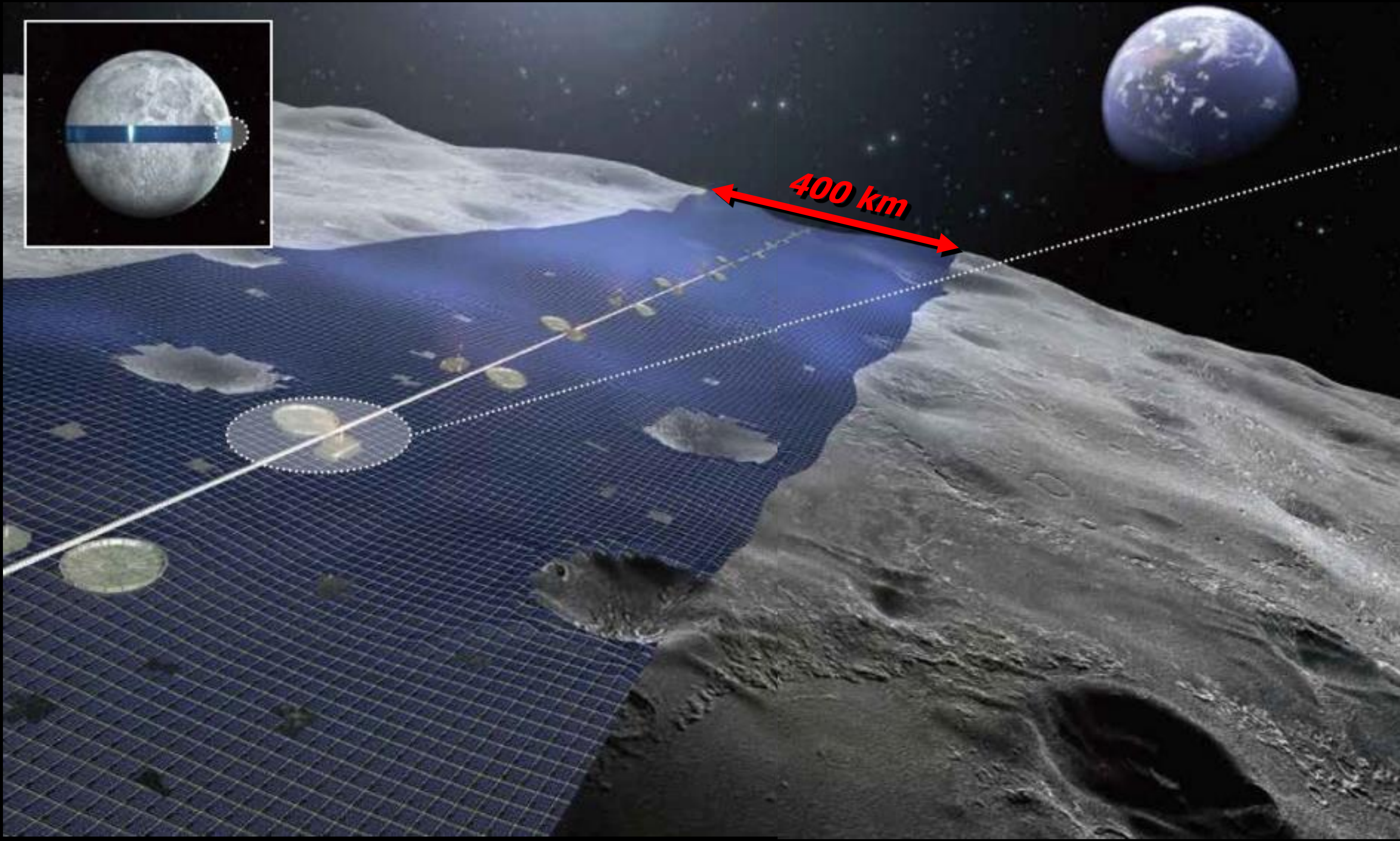
BIGELOW AEROSPACE

Luna Ring: Shimizu Corporation



Modified from Shimizu Corporation (2016)

Luna Ring: Close View



Shimizu Corporation (2016)

Cislunar Space and Economic Potential

Modified from Duke et al. (2003); Kutter (2015)

LEO
Remote Sensing
Communications
Observations
Debris Mitigation
Propellant Transfer

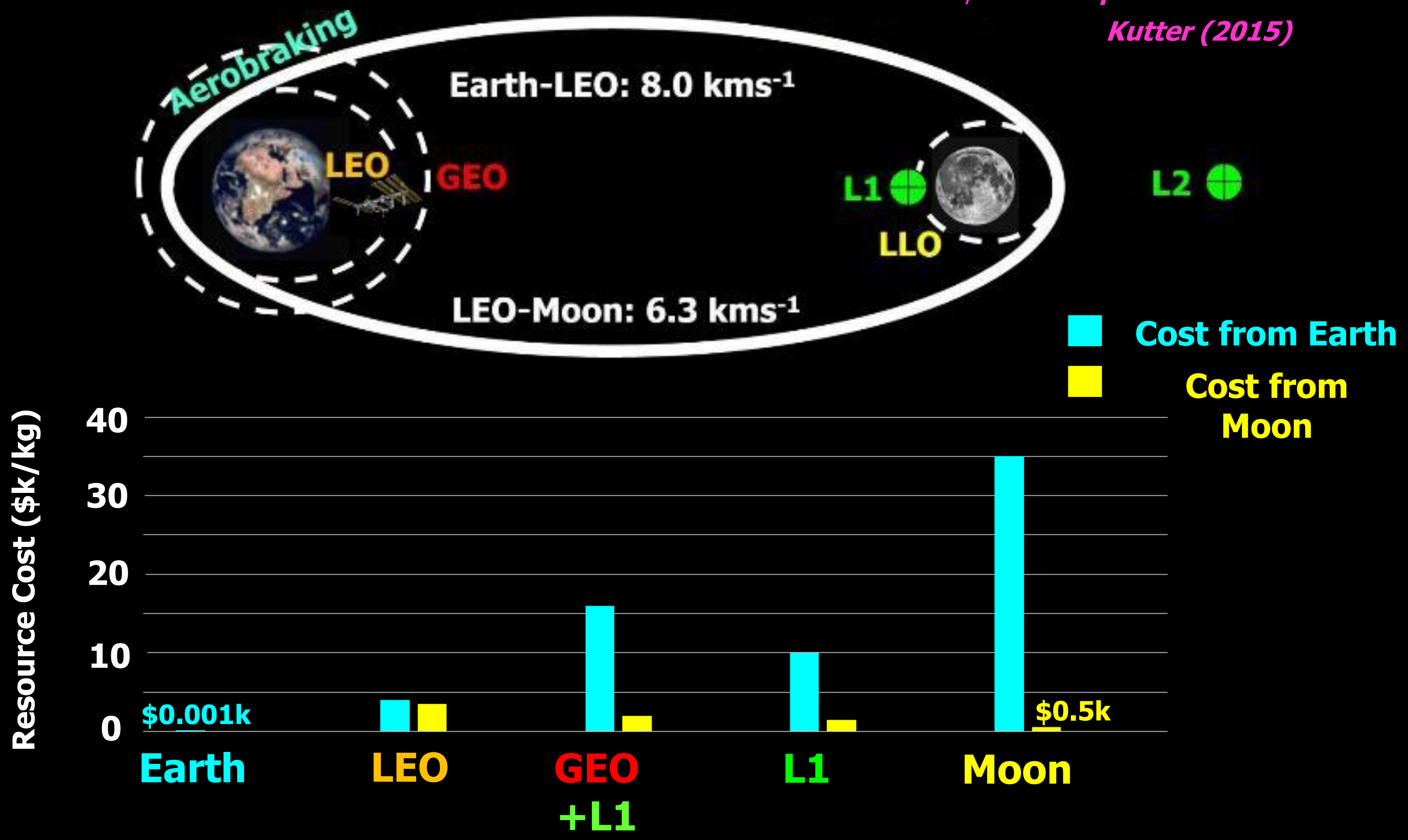
GEO
Communications
Solar Power
Observations
Satellite Life Extension

L1 and L2
Fuel Depot
Communication Link
Lunar Observations
Repair Station

Moon
Mining
Fuel Depots
Manufacturing
Habitations
Solar Power to Earth

Propellant Costs

Based on $3 million per ton at LEO
Kutter (2015)



Future Lunar Outpost

For Additional Information, see the EMD-AAPG Memoir 101

http://www.i2massociates.com/downloads/Memoir101-T0fC2016.pdf

Especially Chapter 1, 8, and 9:

William A. Ambrose, Bureau of Economic Geology, University of Texas at Austin, Chapter 1
http://i2massociates.com/downloads/CHAPTER01.pdf

David R. Criswell, University of Houston, Chapter 8
http://www.i2massociates.com/downloads/CHAPTER08.pdf

Michael D. Campbell, I2M Associates, llc, and others, Houston, Chapter 9
http://www.i2massociates.com/downloads/Memoir101-CHAPTER09Rev.pdf

http://bit.ly/2r7RhPf

I2M Web Portal: Search Results for “Moon”.