Return to the Moon: Resources, Risks, and Rewards*

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Abstract

A sustained human presence on the Moon will be an important first step in settling Mars and other bodies in the Solar System. This long-term mission will be to prove scientific and exploration technologies, provide life support for human settlements, and extract resources at cost-effective levels. Factors that will impact sustainability of lunar outposts include power generation and energy storage, radiation and micrometeorite shielding, and food cultivation. All of these factors will also have to be considered in Martian habitations. Health hazards imposed by fine-grained lunar dust represent a critical problem for human settlement. These hazards will involve not only impaired breathing as experienced in the Apollo 17 mission, but also damage to equipment, dispersal from engine blasts, and reduced mobility. Underground installations, either excavated from lunar regolith or located in subsurface lava tubes, will be necessary to mitigate radiation and impacts from micrometeorites. The Moon contains mineral and volatile resources for construction materials and propellant manufacture. Detailed mapping of pyroclastic volcanic vent deposits has identified volcanogenic elements that include iron, zinc, cadmium, mercury, lead, copper, and fluorine. Rare metals and platinum-group elements may also reside in low concentrations in regolith breccias, highland impact breccias, and possibly in layered mafic intrusives. Thorium is relatively abundant in Oceanus Procellarum, associated with late-stage melts rich in KREEP (Potassium/Rare-Earth-Elements/Phosphorus) constituents. Exhalatives and some impact breccias contain volatiles such as nitrogen and carbon, the building blocks of plastics and foodstuffs. Other volatiles, including water, also occur in lunar pyroclastic glasses and in cold, permanently shadowed areas near the poles. Lunar orbital depots for fuel and life-support materials can serve as temporary accumulation areas for transport of materials derived from volcanogenic sources to Earth's surface. Future advances in technology and planetary engineering on the Moon, a perfect proving ground, will offer humans a steppingstone to Mars, ultimately leading to a sustained human presence in space.

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Return to the Moon: Resources, Risks, and Rewards

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May 20, 2019

Bureau of Economic Geology

AAPG Astrogeology Committee

Return to the Moon

- Earth's closest neighbor
  - *-Three-day trip*
  - *-Technology already exists to return to the Moon*
  - *- Human missions: <0.1% surface area visited*

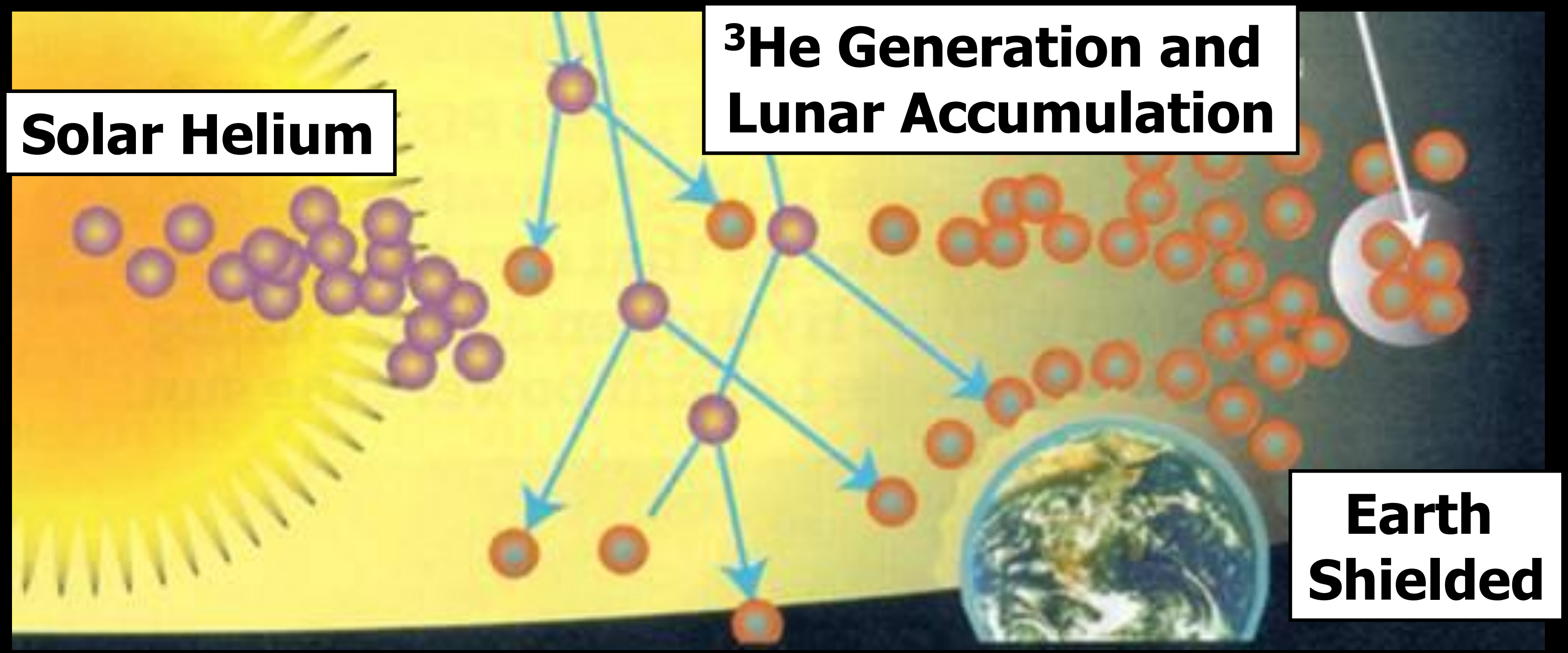
- Abundant resources
  - *-Water and volatiles for human settlement and rocket fuel*
  - *-Metals for Moon Base and solar power facilities*

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

The Moon: Private Sector

Bigelow Aerospace	Habitation modules, Lunar base
Lockheed	Orion-based lunar lander
SpaceX	Launch vehicles
Odyssey Moon	Robotic lander/rover
Honeybee Robotics	Ice drilling/testing/extraction
Cislunar Space Development	Space tugs, shuttles

Helium-3 from Solar Wind

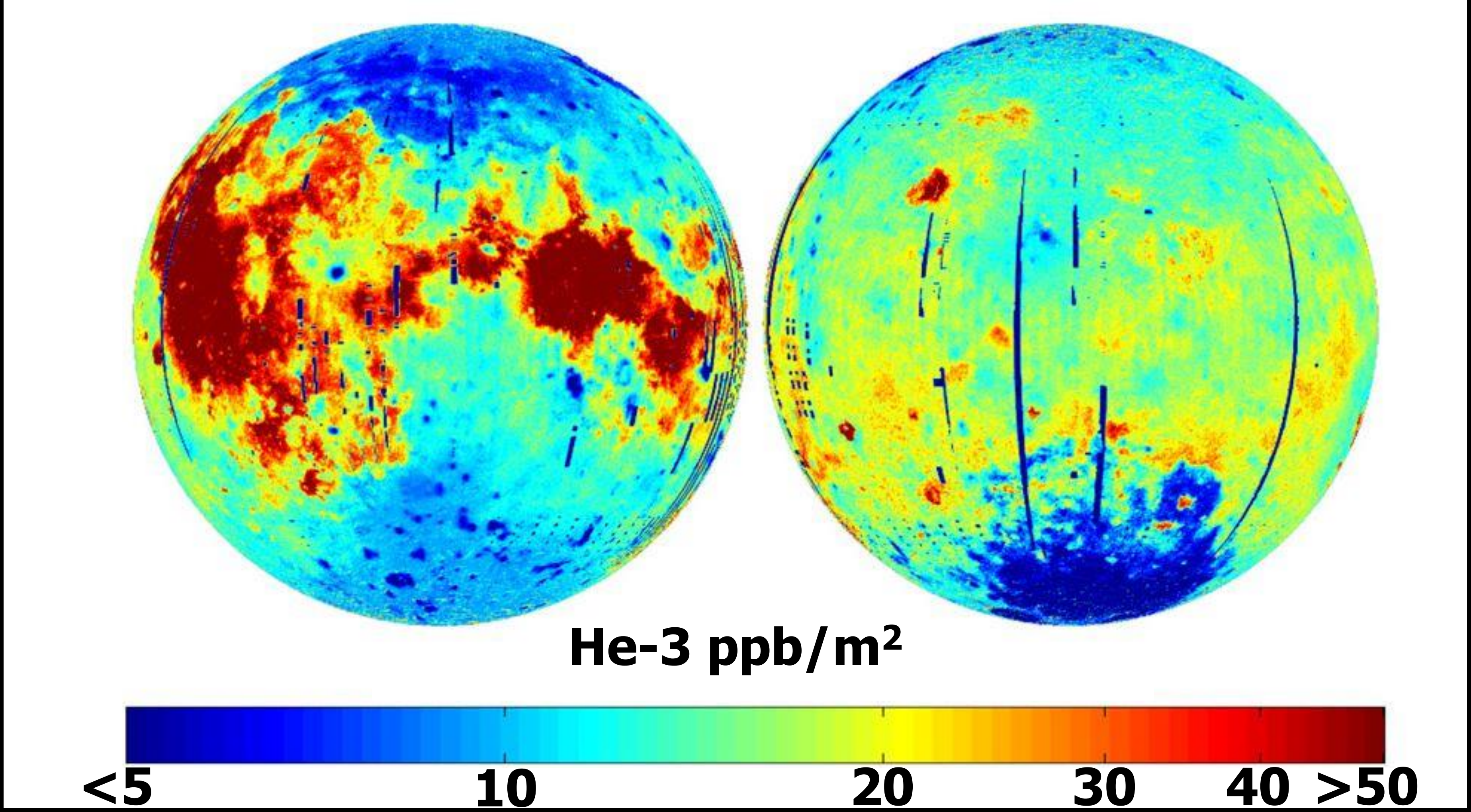


Schmitt (2004)

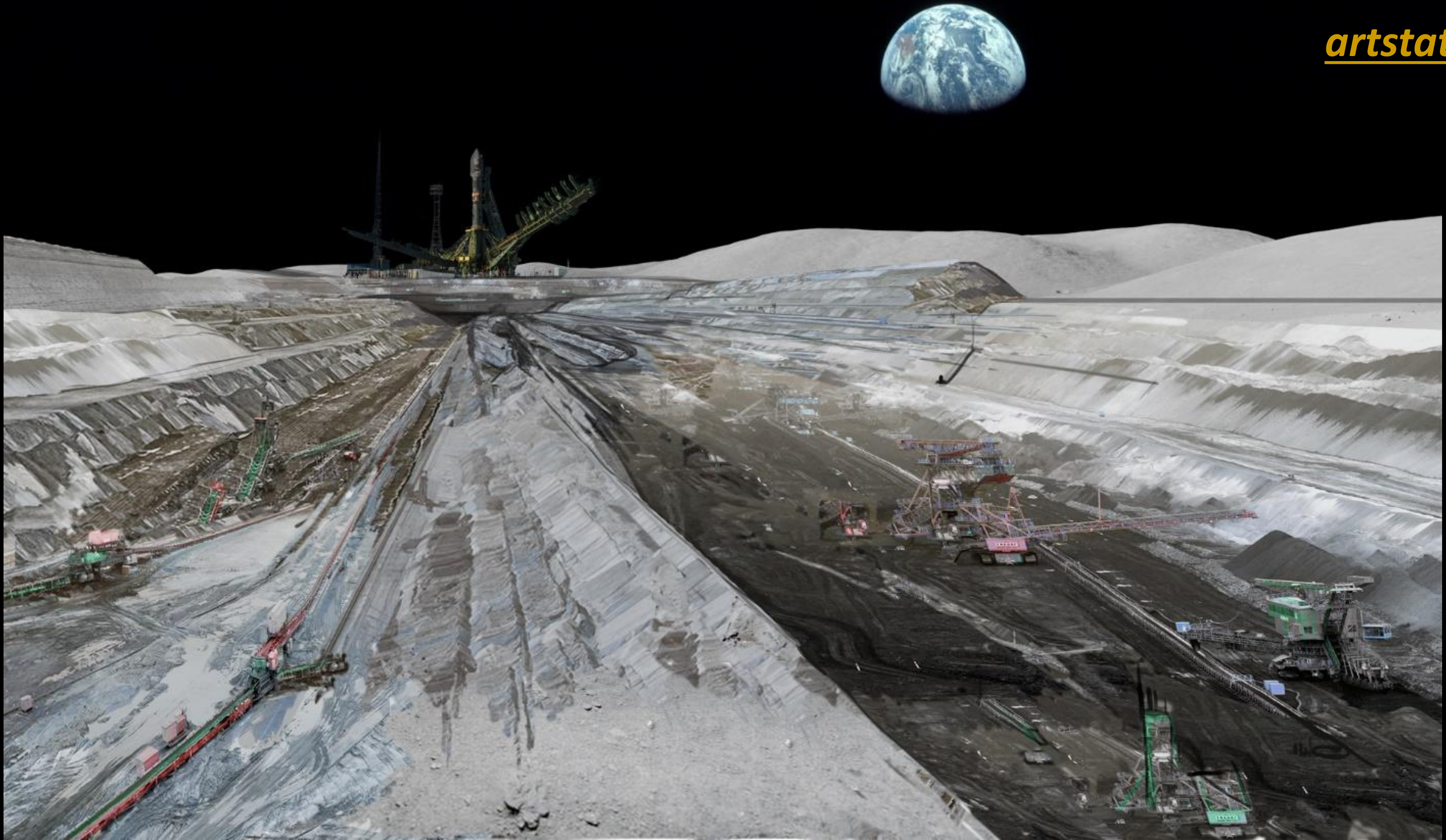
Lunar He-3 Distribution

Global: 6.5 x 10^8 kg
(715 million short tons)

Fa and Jin (2007)



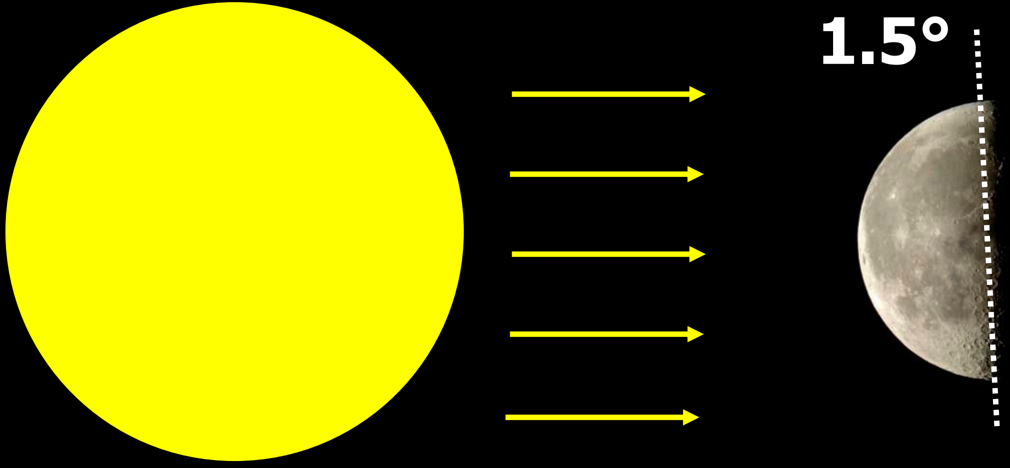
Lunar He-3 and Hydrogen Mining

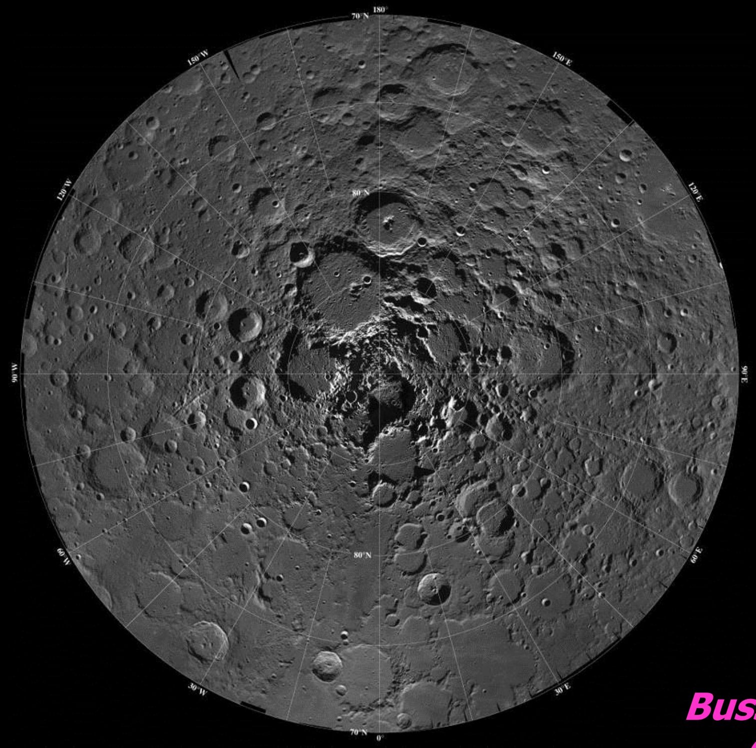


artstation.com

Volatiles at the Poles

Impacts from volatile-rich comets/asteroids
10^{13} kg water: past 2 Ga (Arnold, 1979)

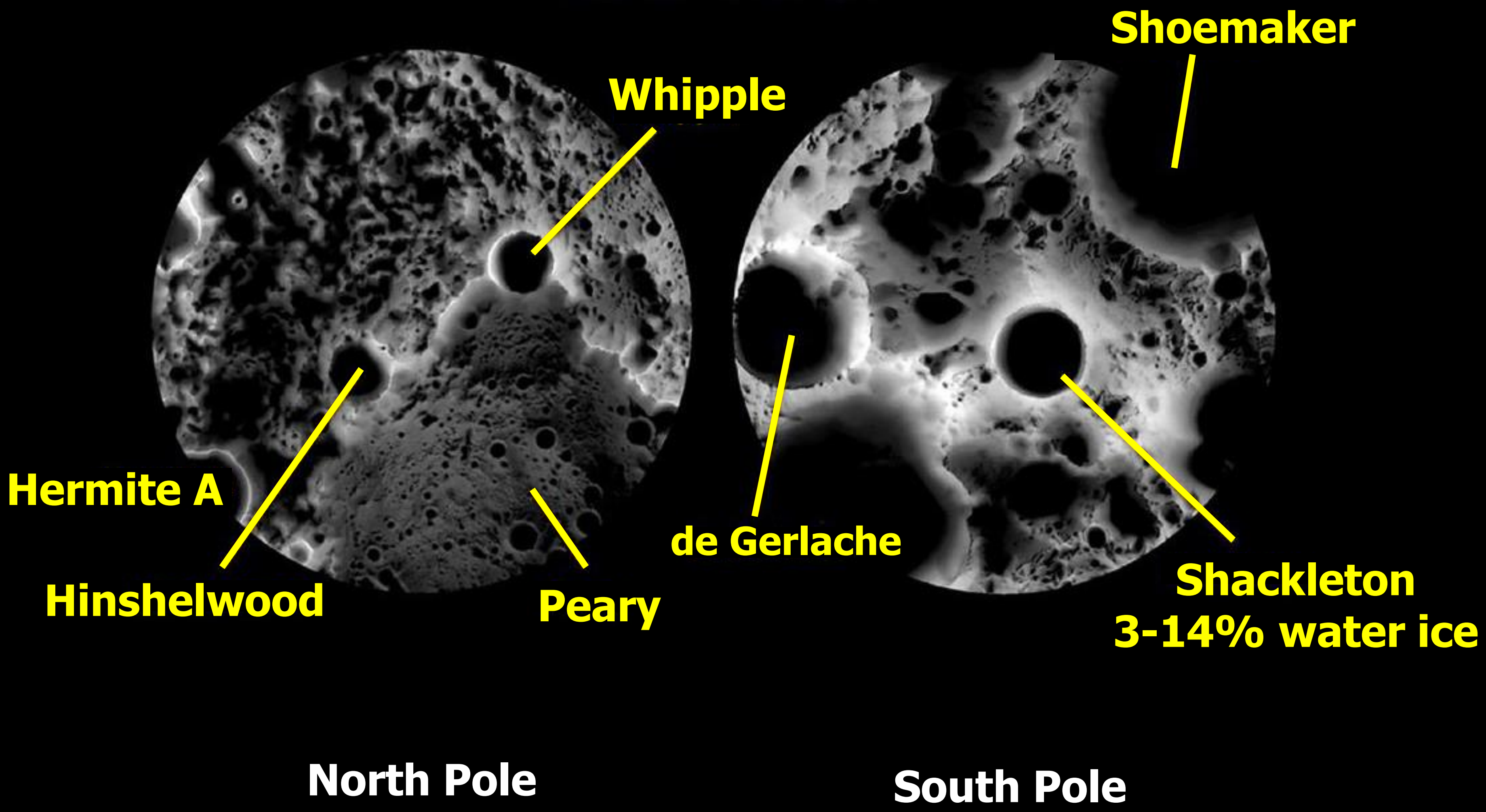




Bussey et al. (2005)

Polar Illumination

Within 2° latitude: White areas: sunlight >50% lunar day



LRO-Based Photo-Mapping of Permanent Shadow

- South Polar Region (60-90º S. Lat.)
  - 91,409 km^2
- North Polar Region (60-90º N. Lat.)
  - 169,508 km^2
- Total: 260,917 km^2
- Potential Helium-3 resources at 40 ppb
  - 33,563 tonnes
- Areas minable to 3 m based on 50% of area of smooth plains >25 km^2

Schmitt (2014)

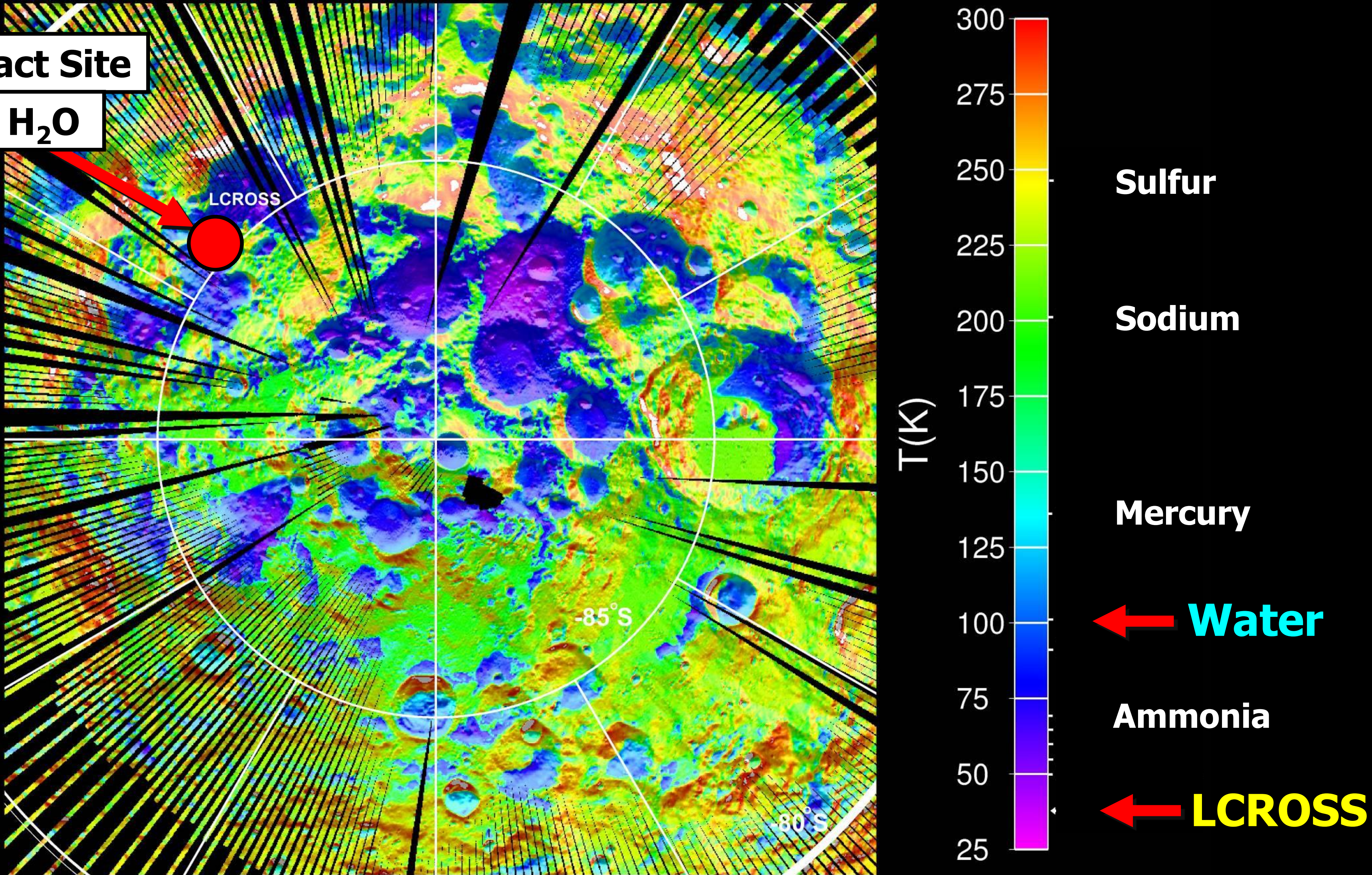
Kaguya Photograph

South Polar Temperature

LCROSS Impact Site

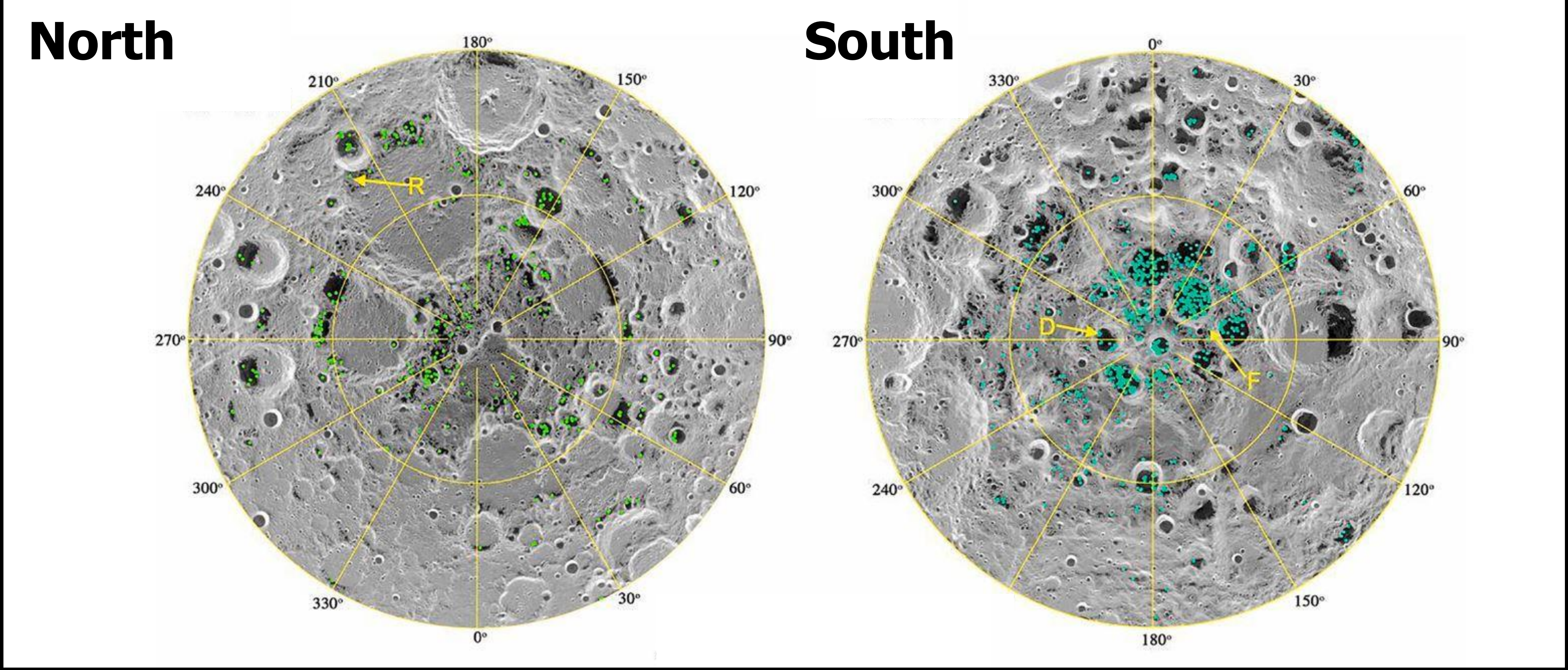
5.6 ± 2.9% H_2O

Colaprete et al. (2010)



Polar Surface Water Ice

Kornuta et al. (2019)



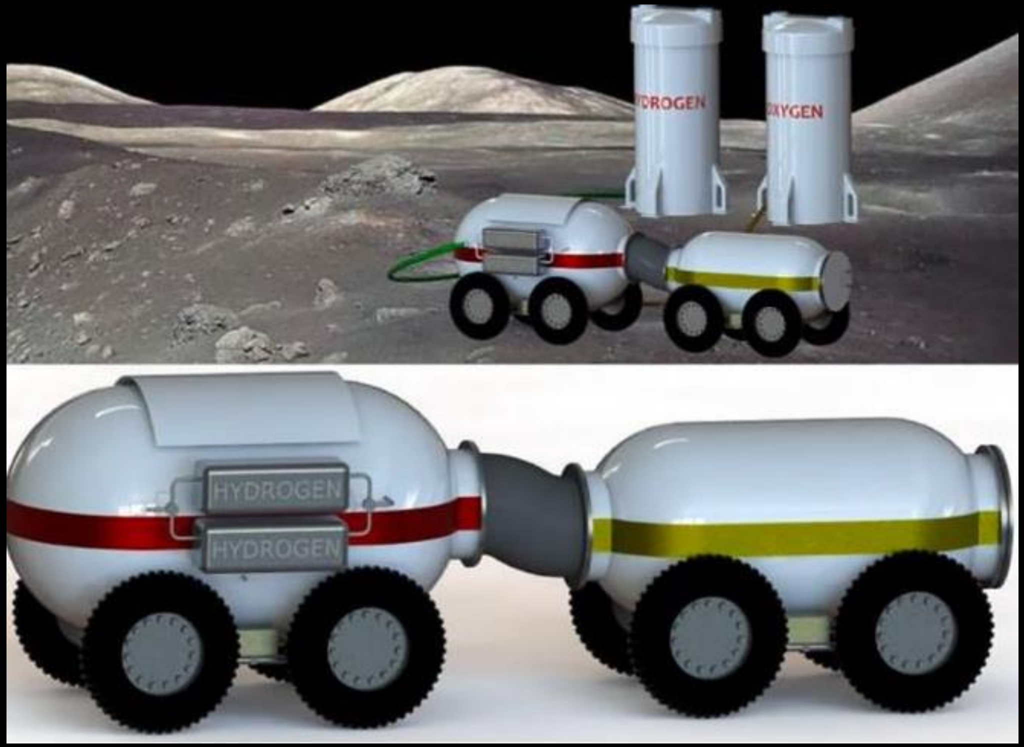
● M³, LOLA, Diviner ● M³, LOLA, Diviner, LAMP

Water Ice Extraction: Solar Power

Heliostats

Room.eu.com (2017)

Collection: IHOP*



Kornuta et al. (2019)

***Hydrogen Oxygen Production**

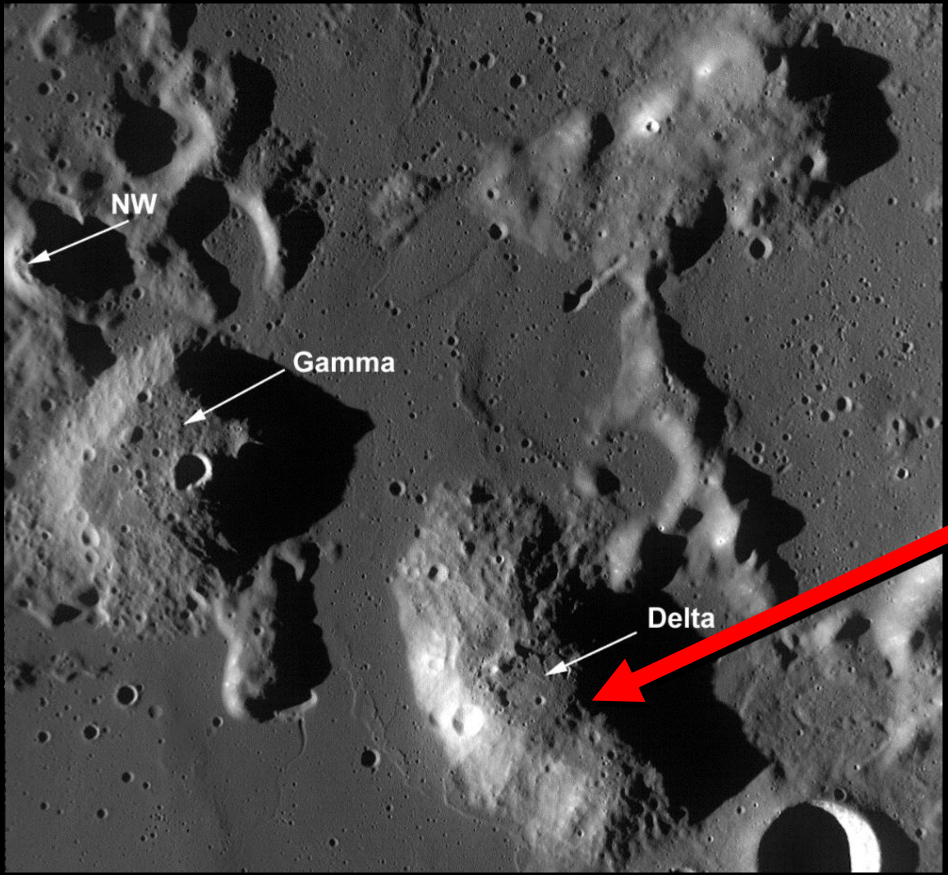
Lunar TiO_2 Basalts

- TiO_2 >7 wt.%
- TiO_2 3-7 wt.%
- TiO_2 <2 wt.%
- Old highlands/ejecta
- Recent ejecta

Rolf Wahl Olsen

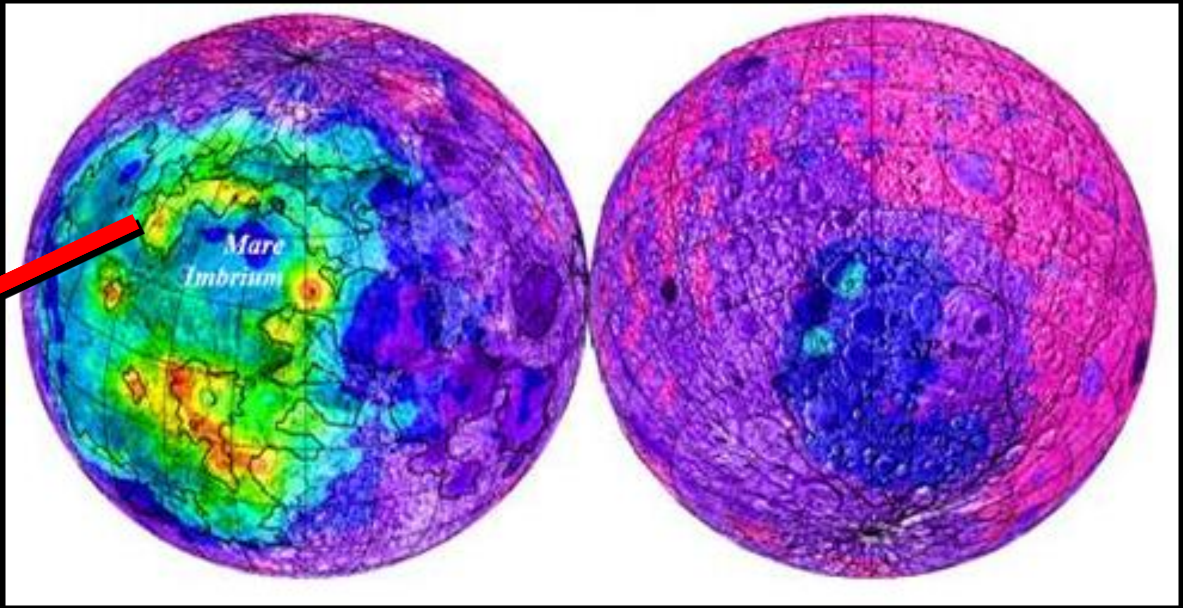
Thorium: Silicic Domes

Mons Gruithuisen



25 km

LOLA M117752970ME



>90 ppm

Yamashita (2009)

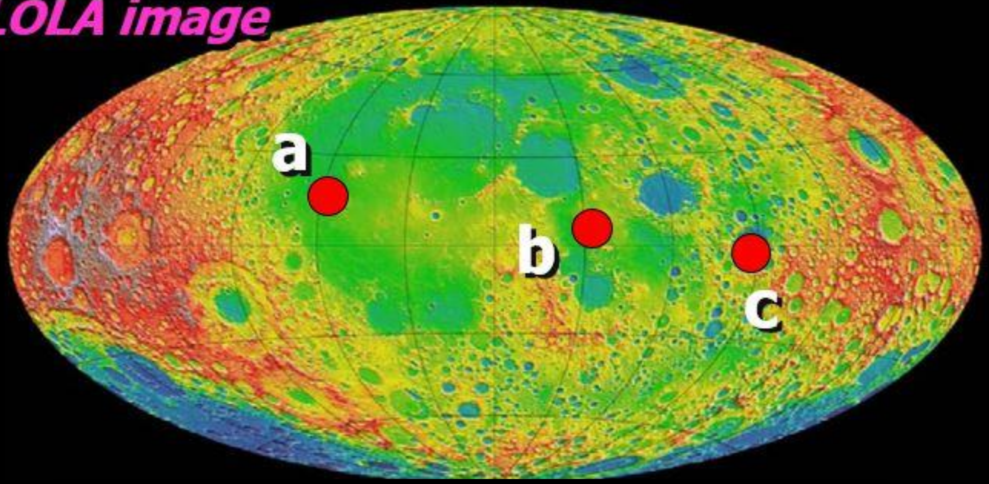
Lunar Habitations

Sinterhab Design

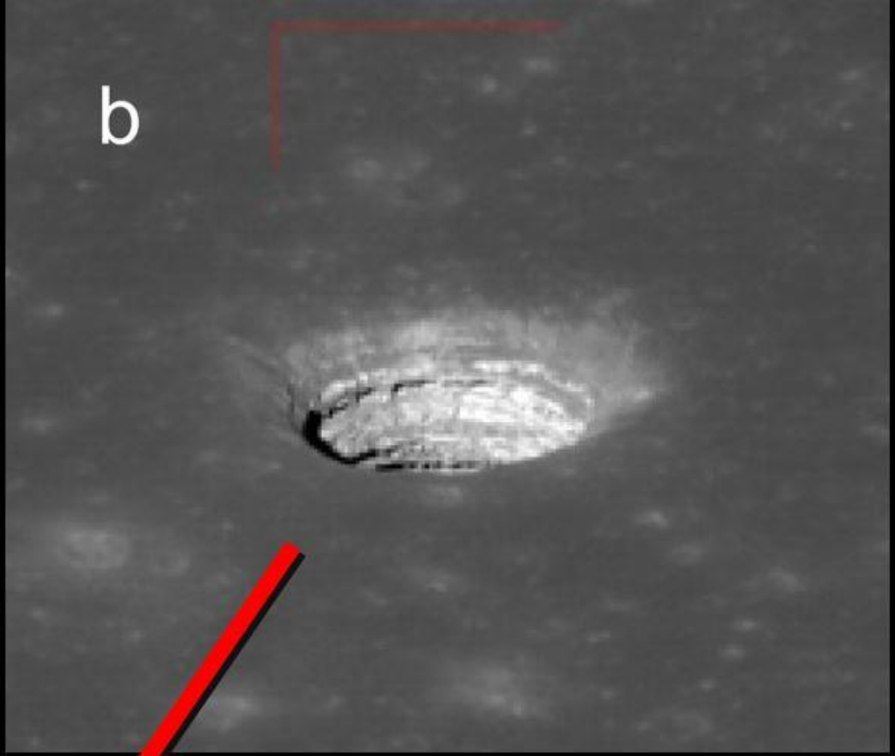
Installation

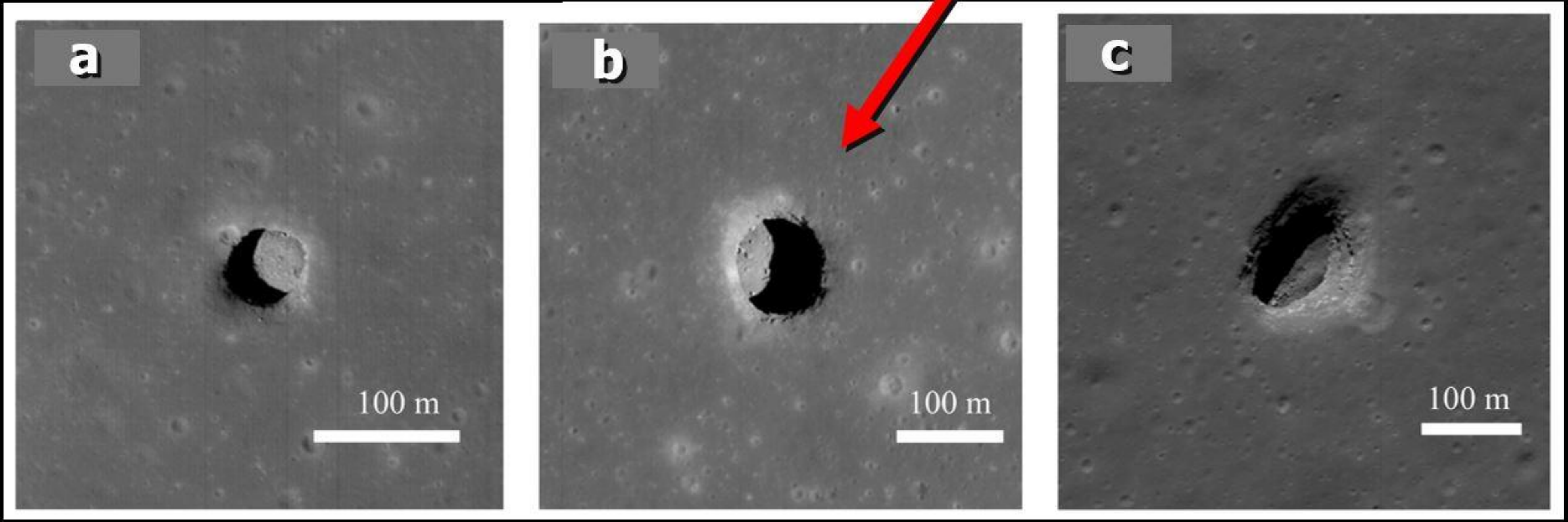
ESA/Foster + Partners

Mare Pits



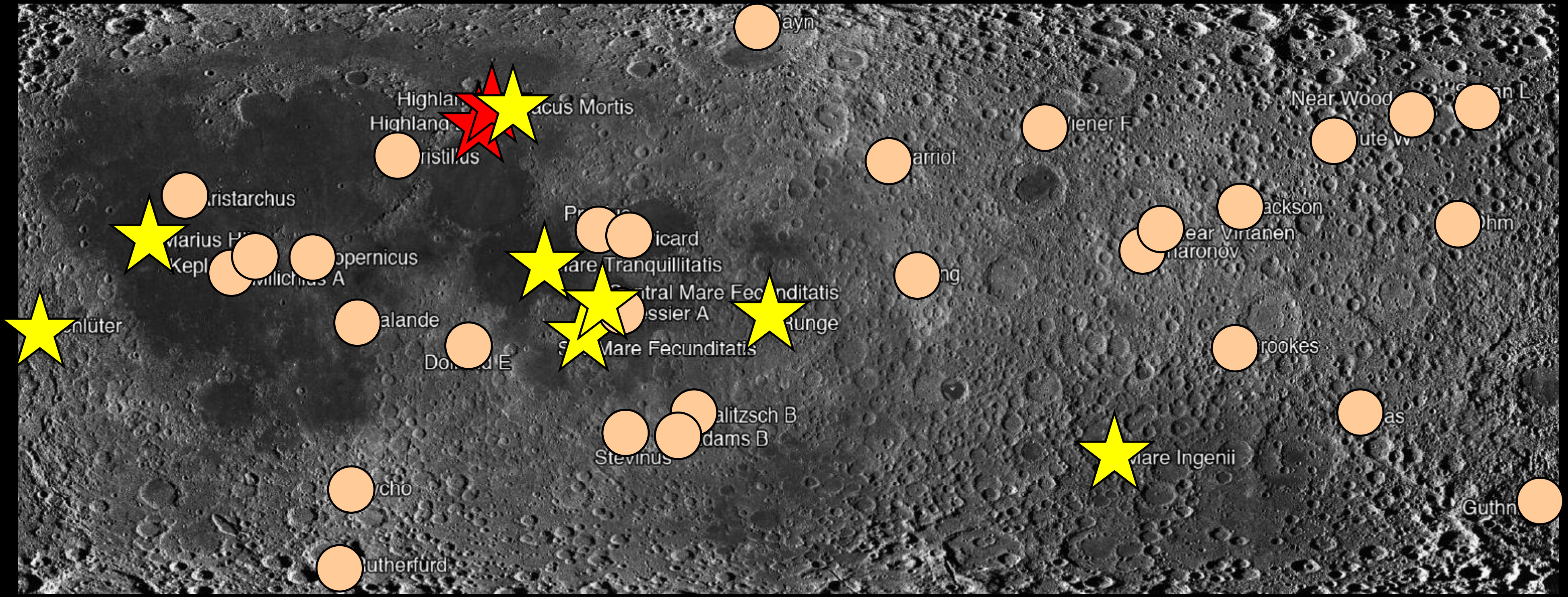
Modified from
Haruyama et al. (2011)





Distribution of Lunar Pits

Modified from Wagner and Robinson (2014)



Mare pits

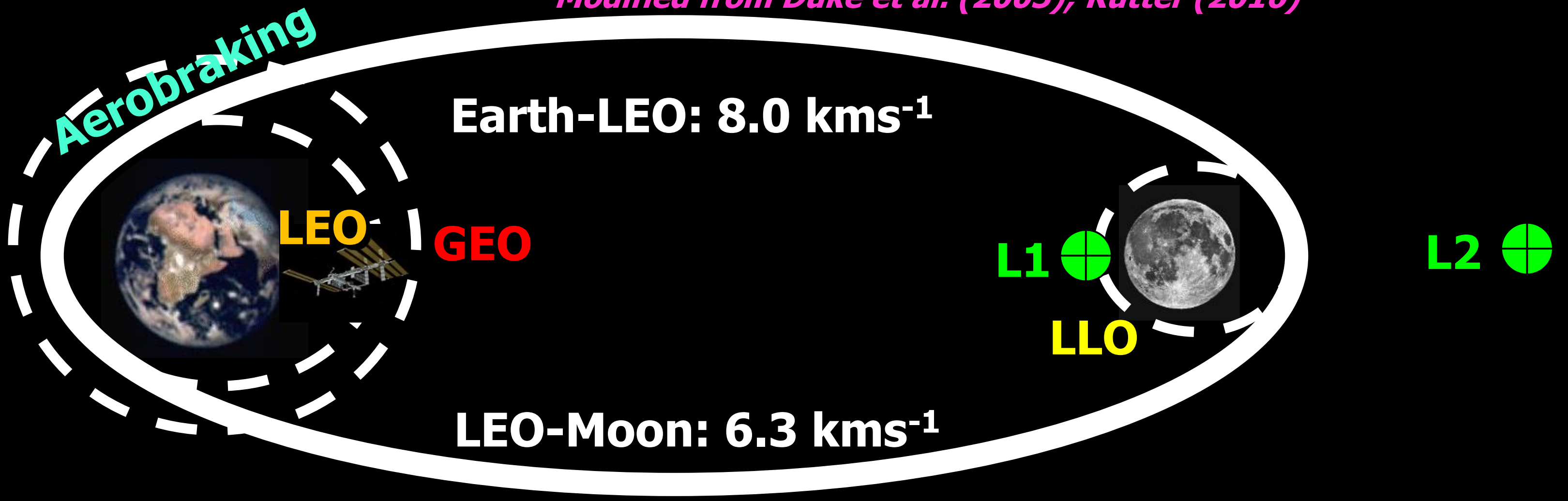
Highland pits

Impact melt pits

1,000 km

Cislunar Space and Economic Potential

Modified from Duke et al. (2003); Kutter (2016)



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

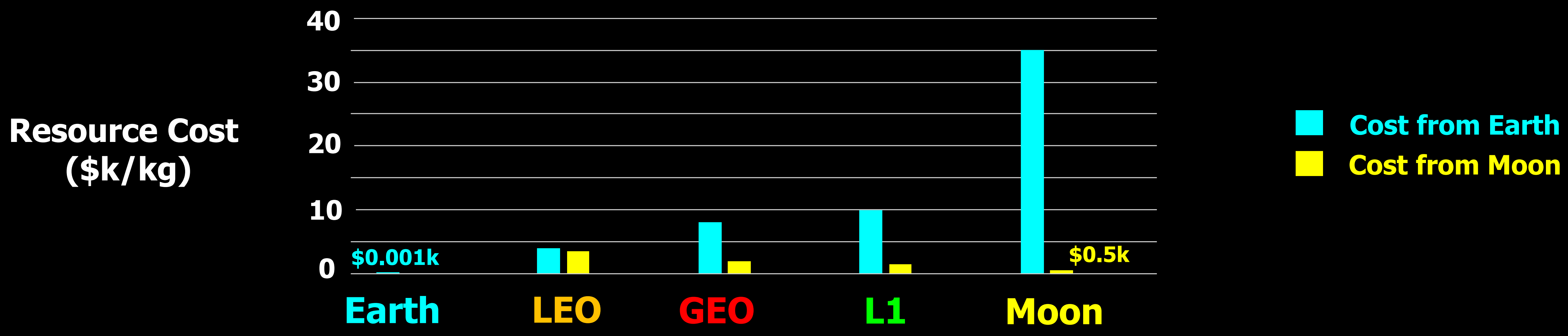
Moon
Mining
Fuel Depots
Manufacturing
Habitations
Solar Power to Earth

Propellant Costs

Based on $3 million per ton at LEO

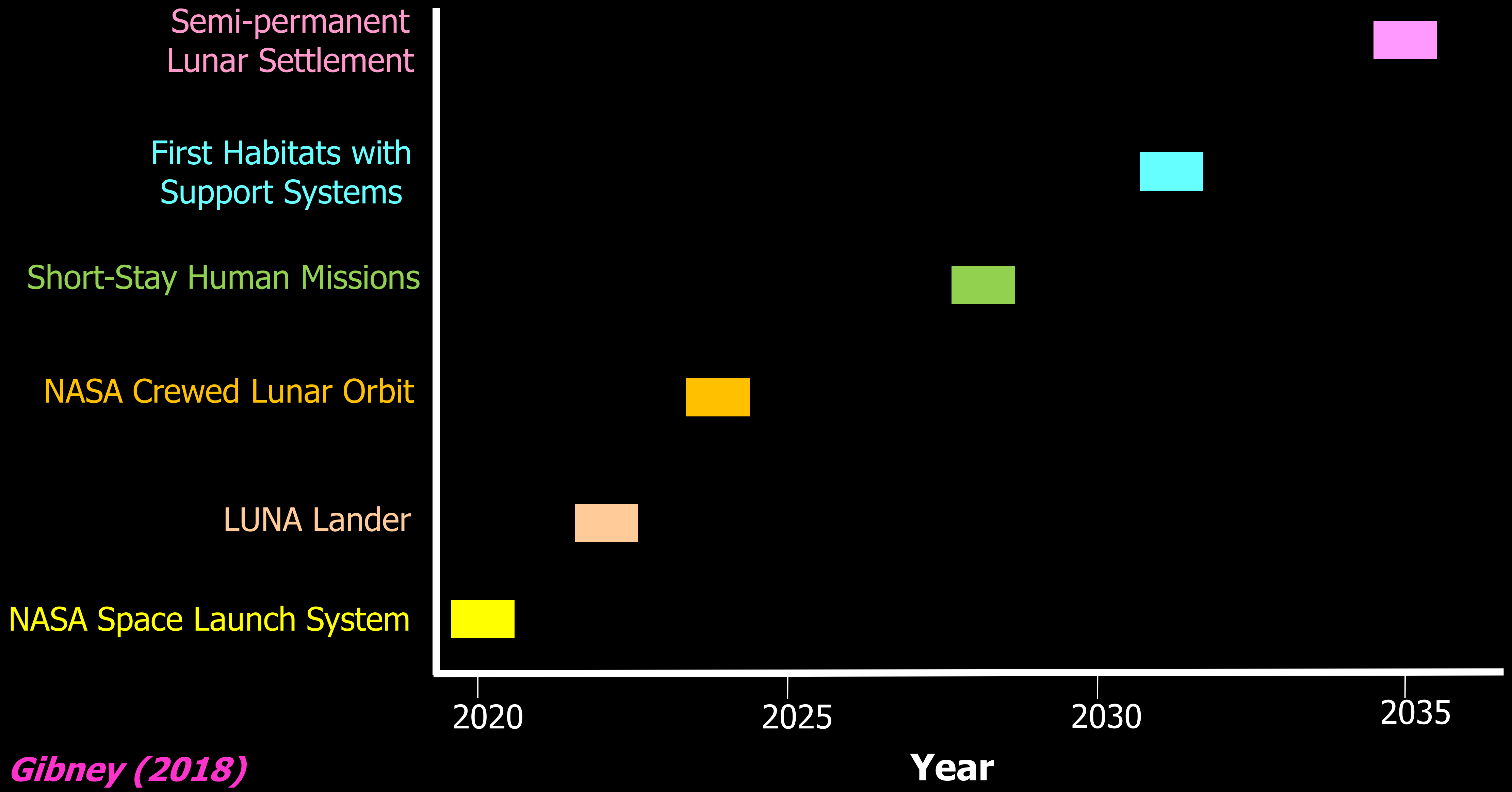
Kutter (2016)

Kornuta et al. (2019)



450 metric tons lunar propellant yr^{-1}: $2.4 Billion revenue

Return to the Moon: Timeline



Gibney (2018)

Summary

- **Resources**
  - *Helium-3*
  - *Hydrogen*
  - *Ti-rich basalts*
  - *Thorium and Uranium*
- **Lunar Bases**
  - *Polar facilities*
  - *Sinterhab/Inflatable designs*
  - *Mare Pits*
- **Private Sector**
  - *Lunar landers*
  - *Habitation modules*
  - *Navigational and transportation systems*