In Situ Resource Utilization on the Moon

Angel Abbud-Madrid
Director, Center for Space Resources
Colorado School of Mines

COLORADO SCHOOL OF MINES
Space Resources

Dust, Atmosphere, and Plasma Environment of the Moon and Small Bodies Workshop (DAP-2023)
June 5, 2023

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Space Resources Roundtable

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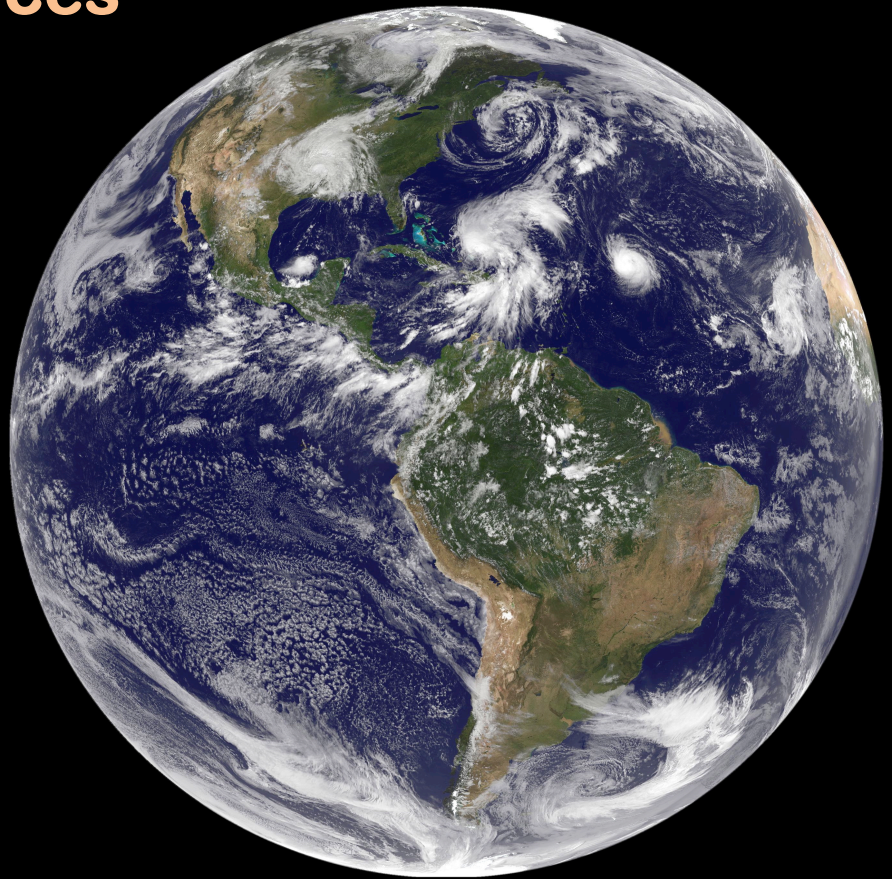
Earth Resources

Water, Food

Gold, Silver,
Spices, Silk

Oil

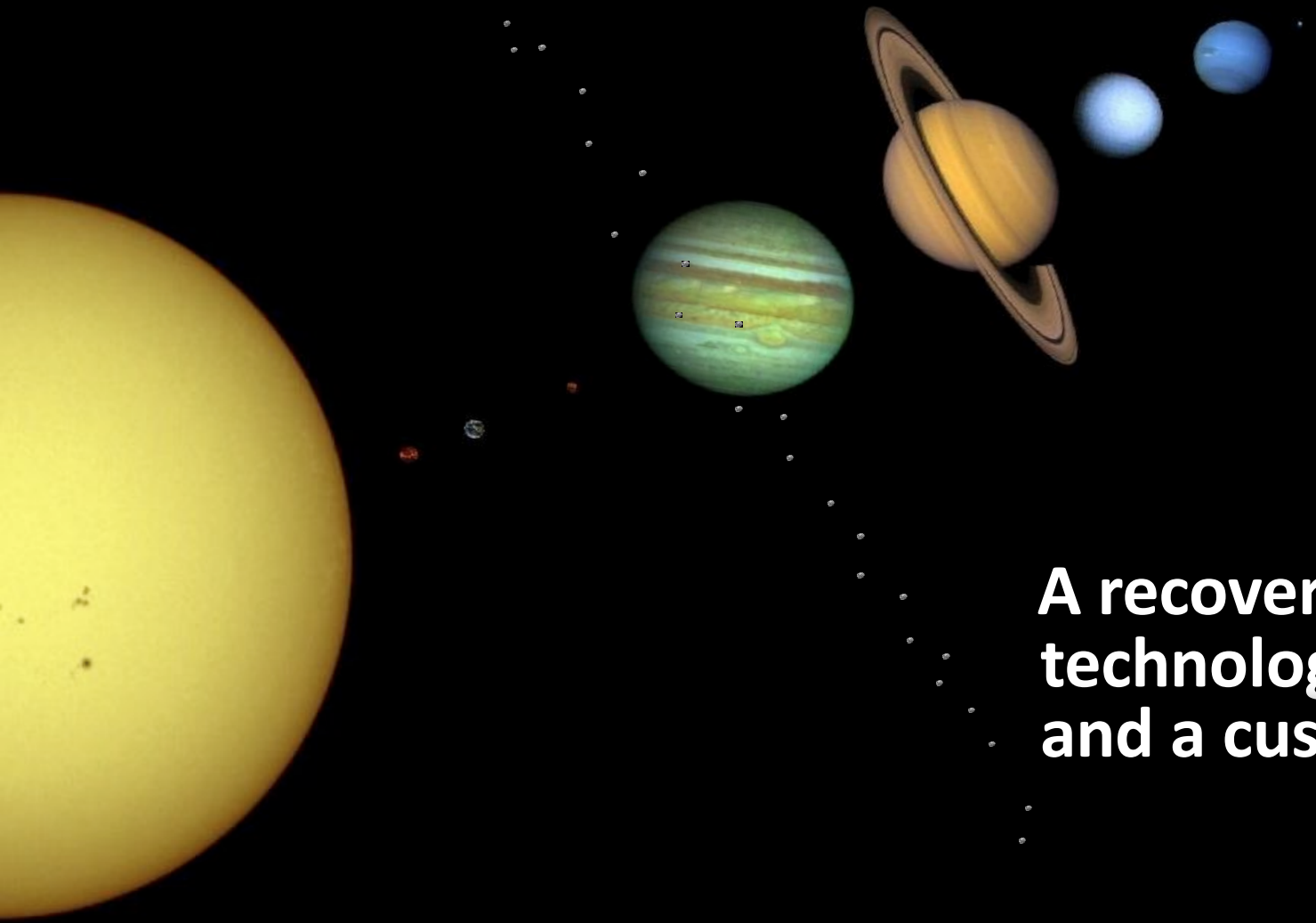


Agriculture

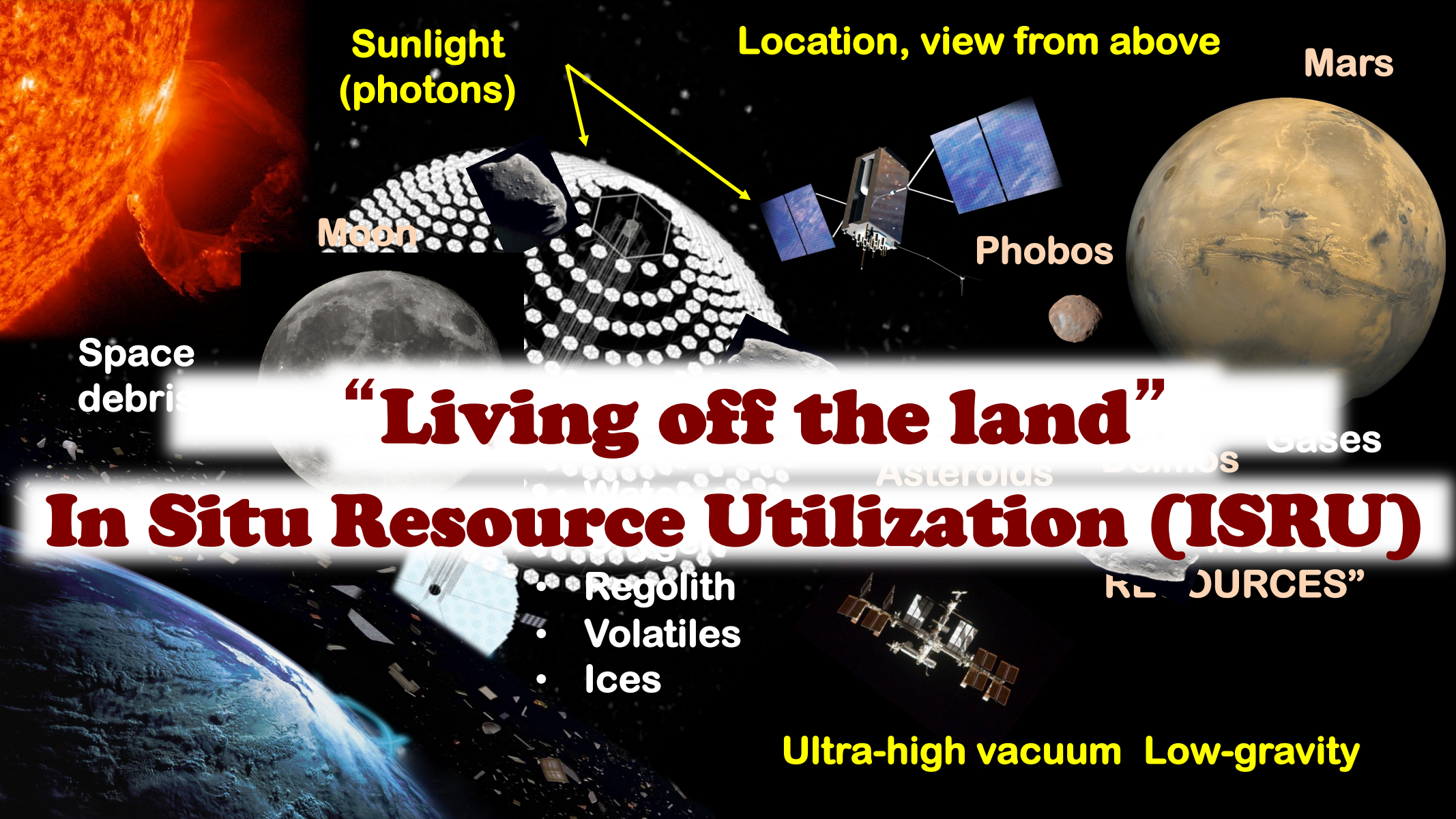
Soil

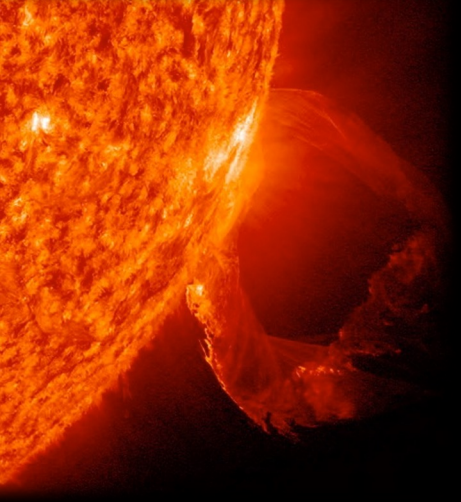
Rare Earths

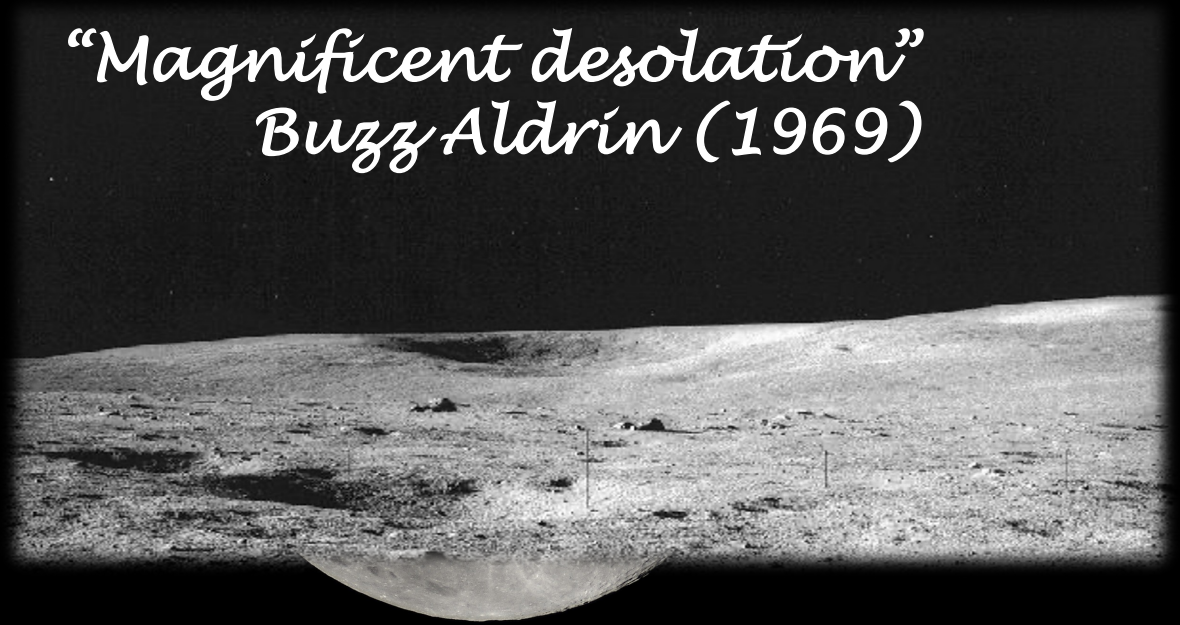
A resource has value by its utilization



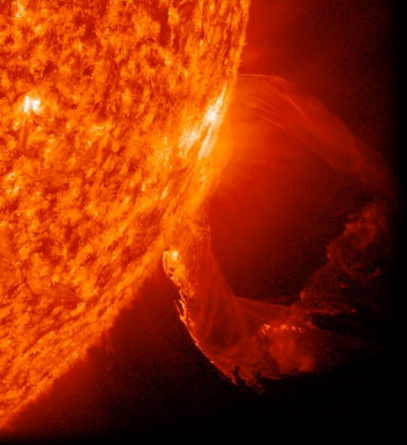
A recoverable resource, technology to recover it, and a customer.


Sunlight
(photons)
Location, view from above
Mars
Moon
Phobos
Space
debri
“Living off the land”
In Situ Resource Utilization (ISRU)
Gases
Asteroids
RESOURCES”
• Regolith
• Volatiles
• Ices
Ultra-high vacuum Low-gravity



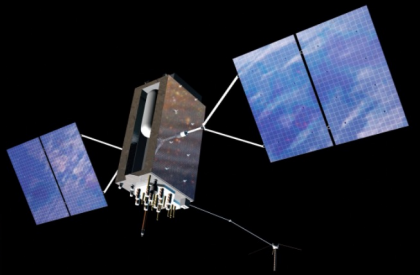


"Magnificent desolation"
Buzz Aldrin (1969)



Apollo (382 Kg)

Luna (0.22 kg)



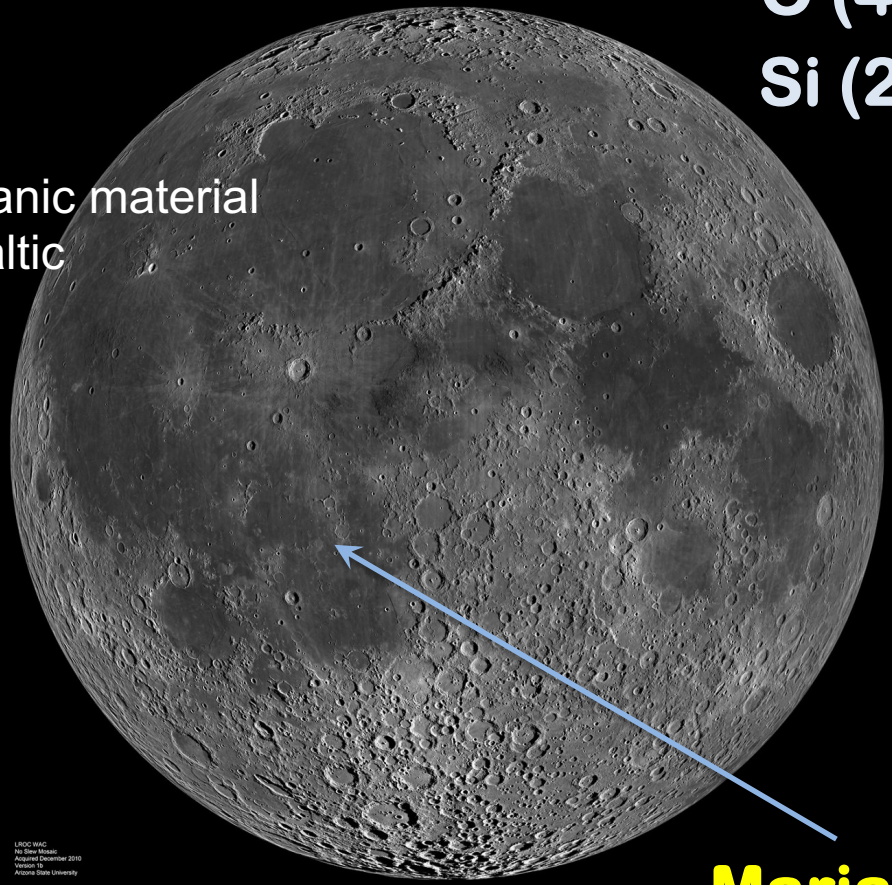
Chang'e 5 (1.7 kg)

Near Side

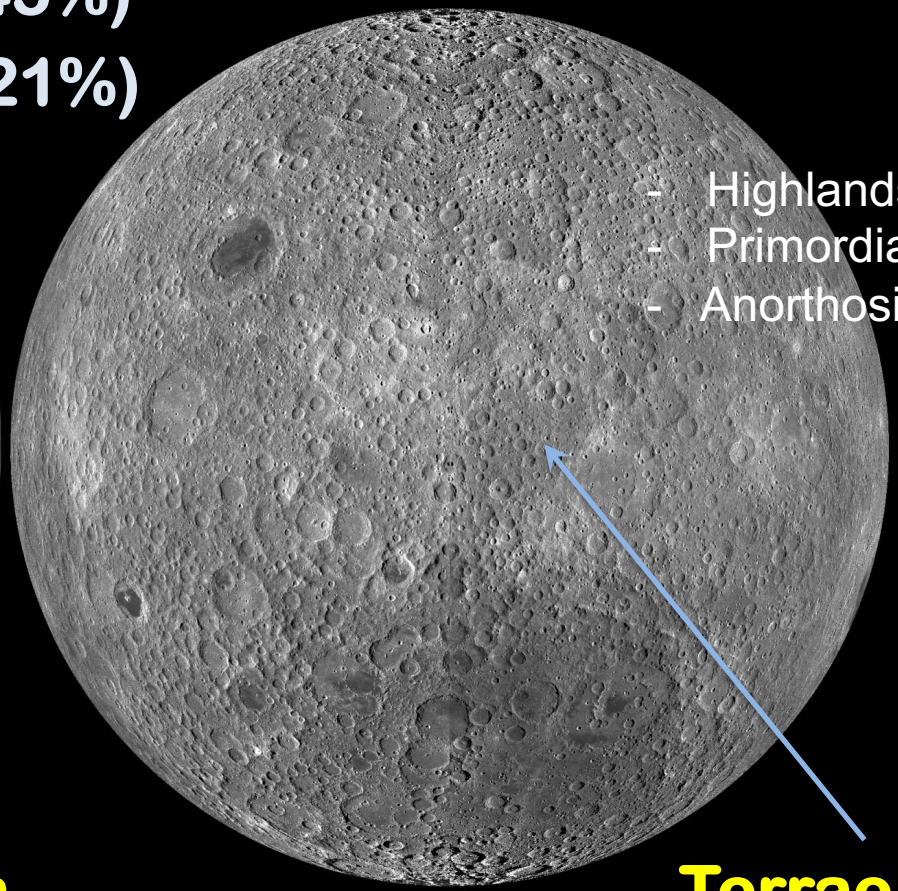
O (45%)
Si (21%)

Far Side

- Volcanic material
- Basaltic



- Highlands
- Primordial crust
- Anorthositic

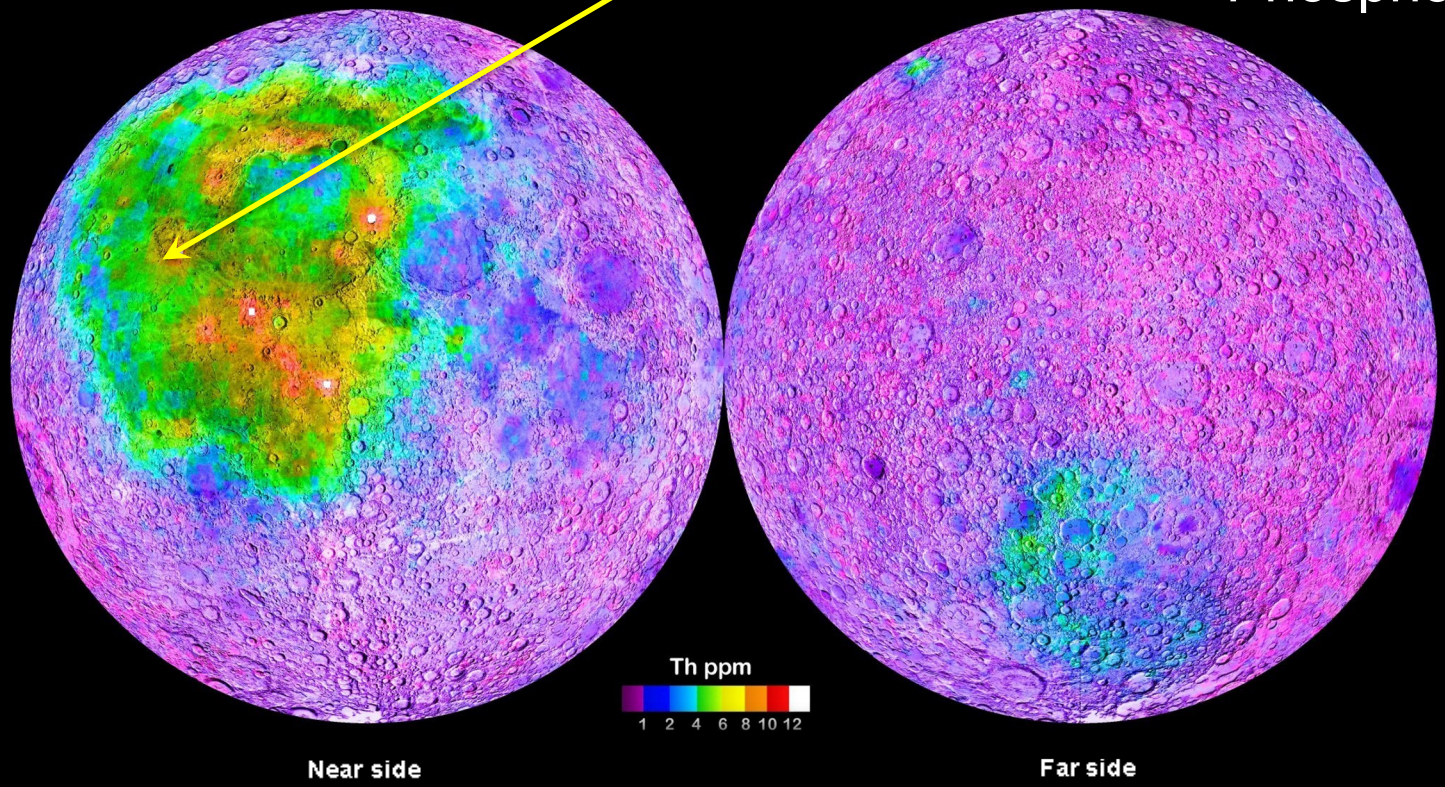


Maria

Terrae

KREEP

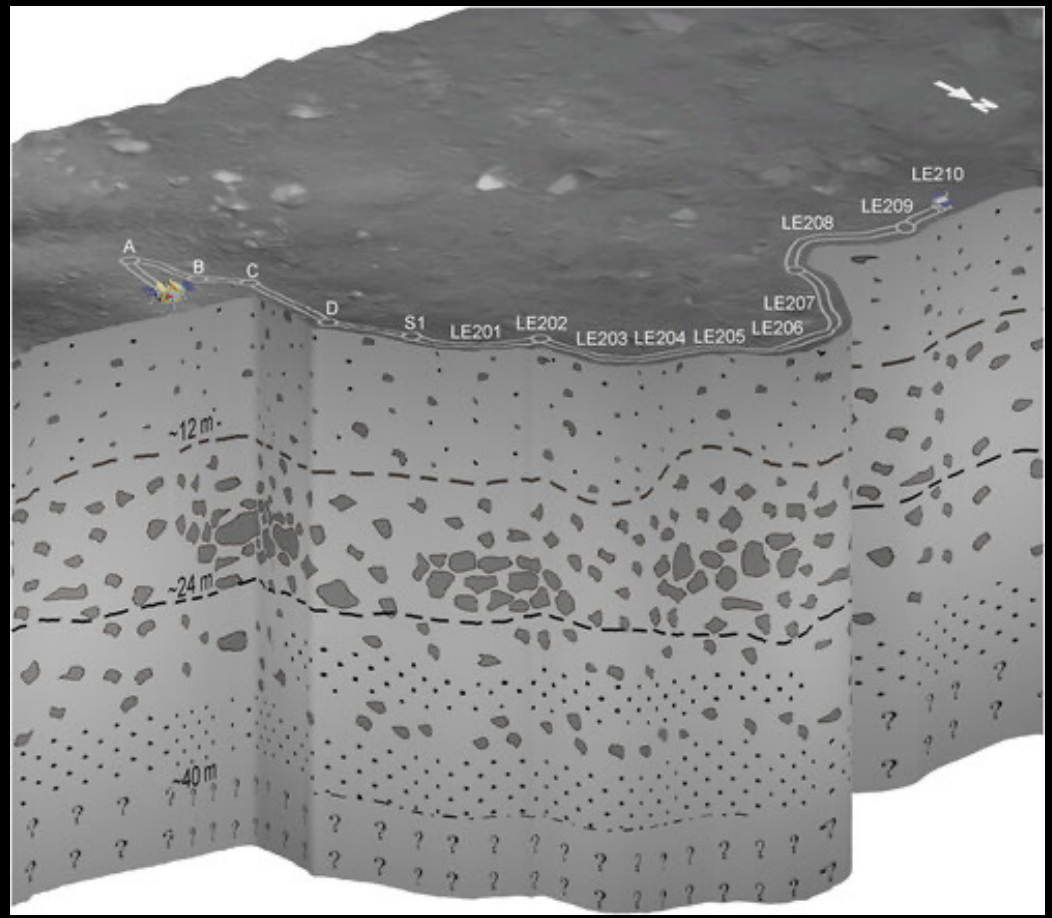
- Potassium (K)
- Rare Earths (REE)
- Phosphorous (P)



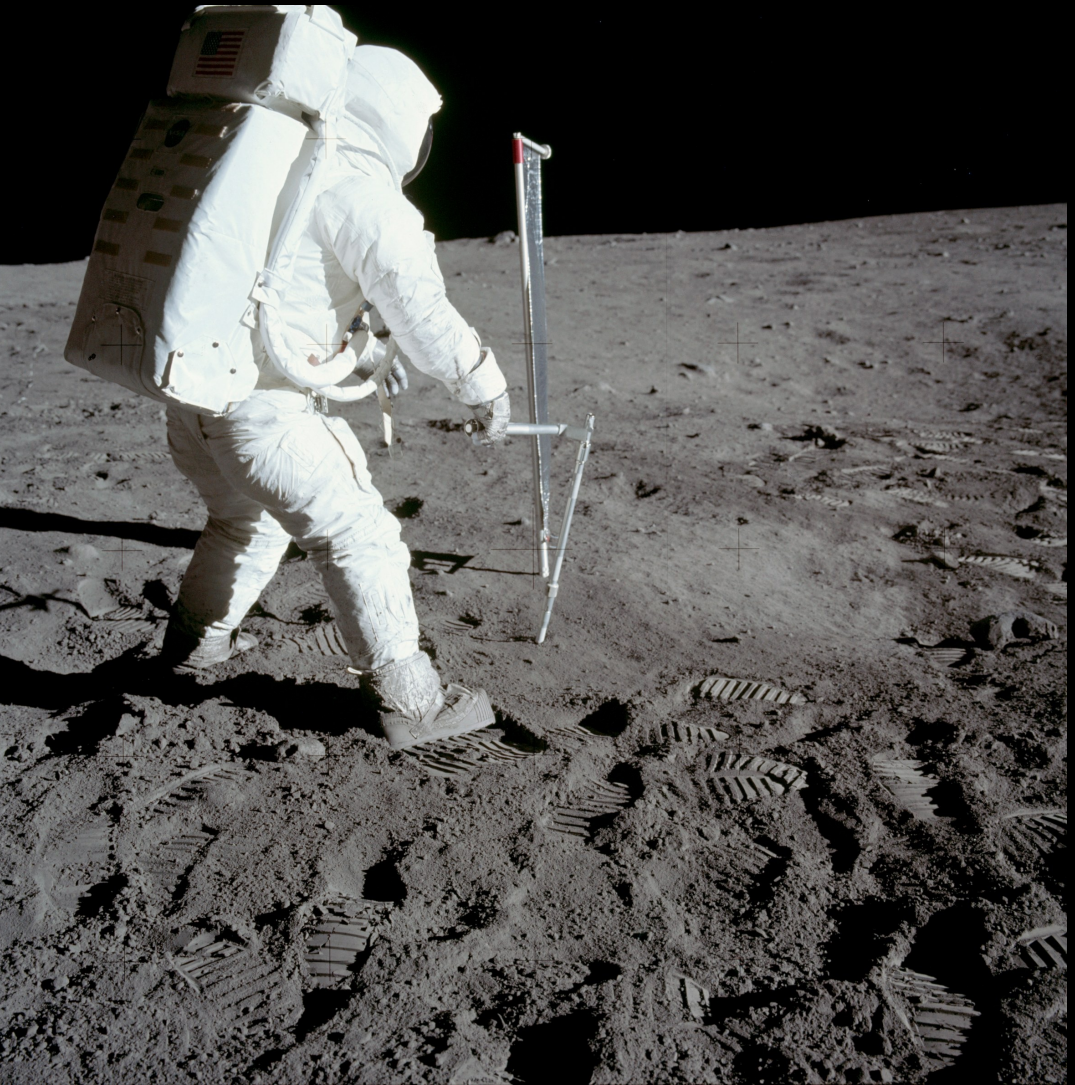
Radioactive elements:
Uranium, Thorium

Upper most ~10m is mixed in a process called “gardening”

Far side (Chang’e 4)



Lunar regolith

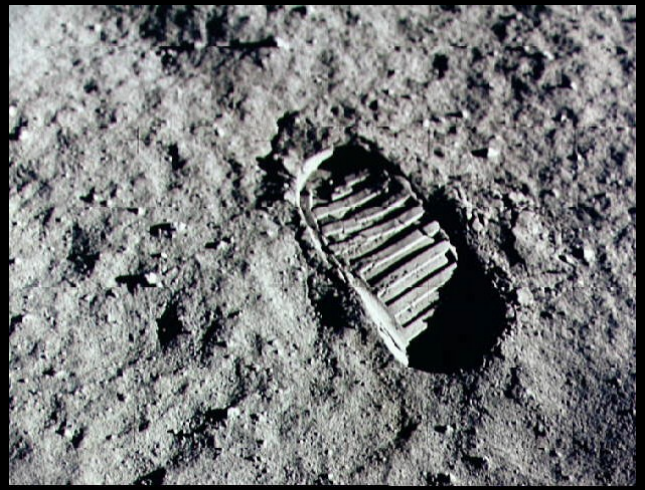


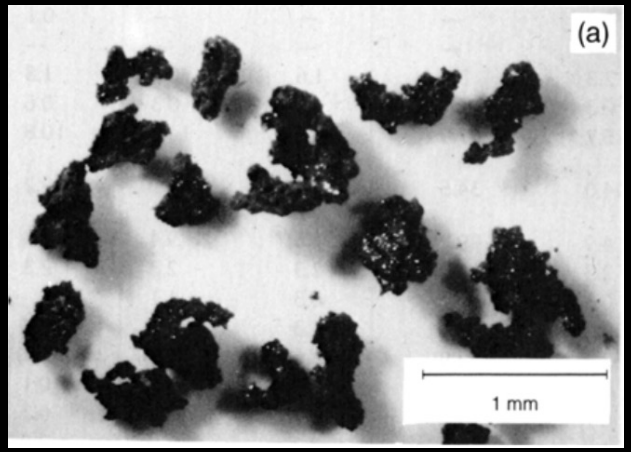
Terrestrial sand

Lunar regolith

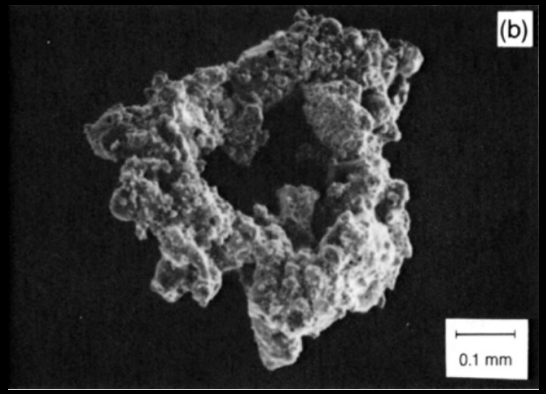
Lunar regolith

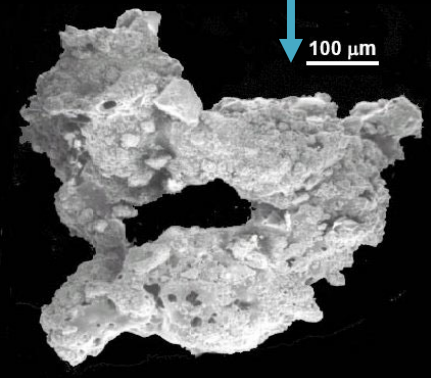
(shaped by impacts)



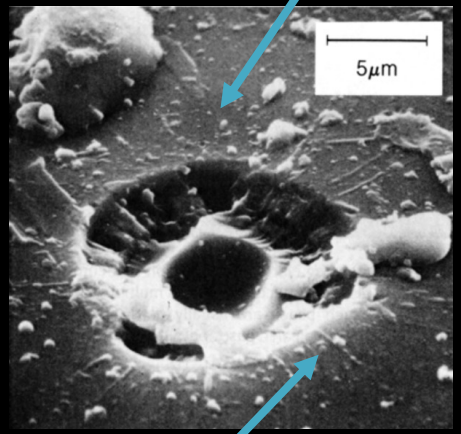


Highly angular agglutinates

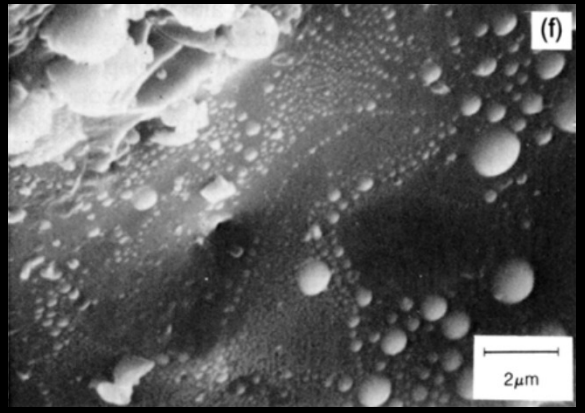




Micro-meteorite Impacts

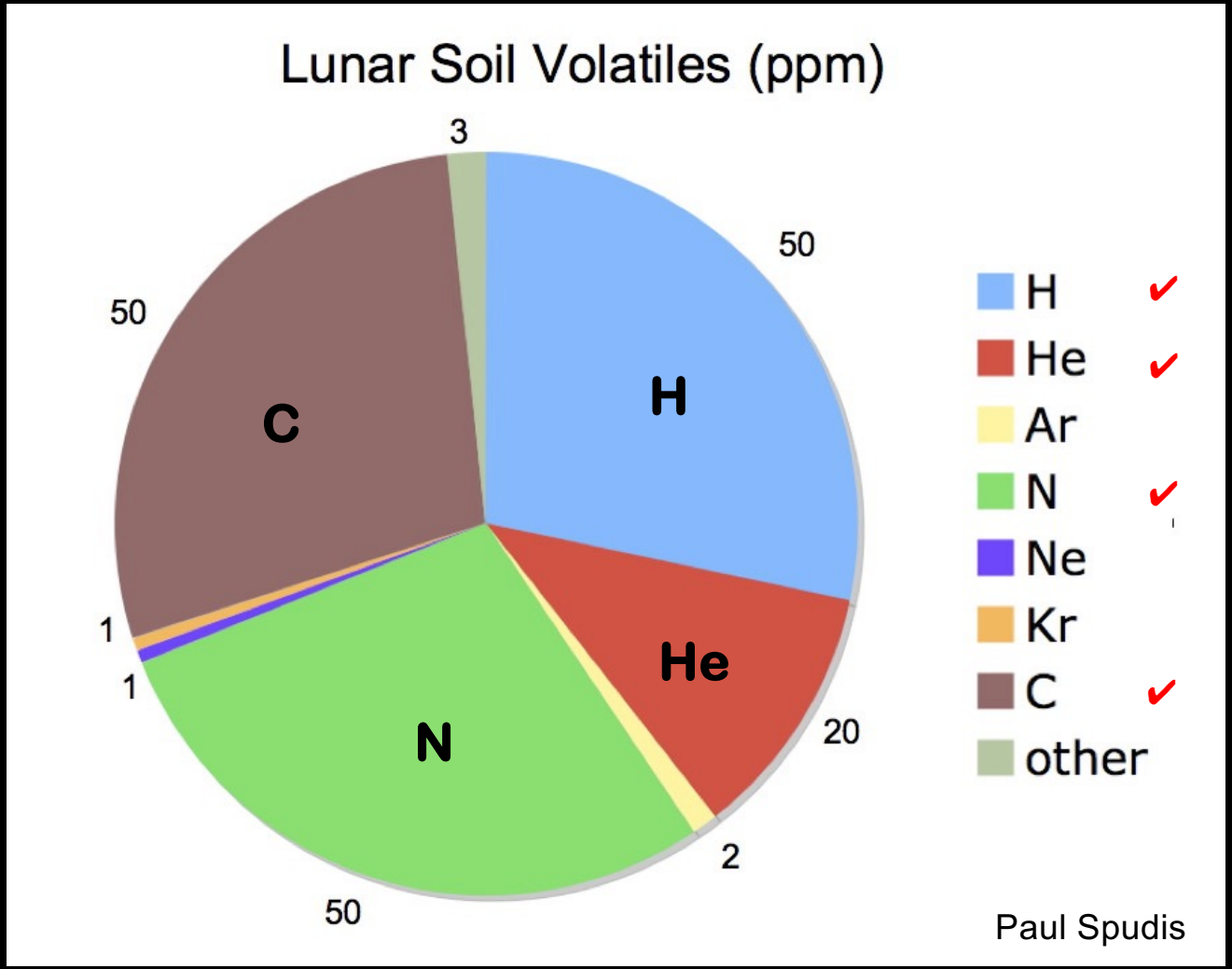


Nano-phase iron



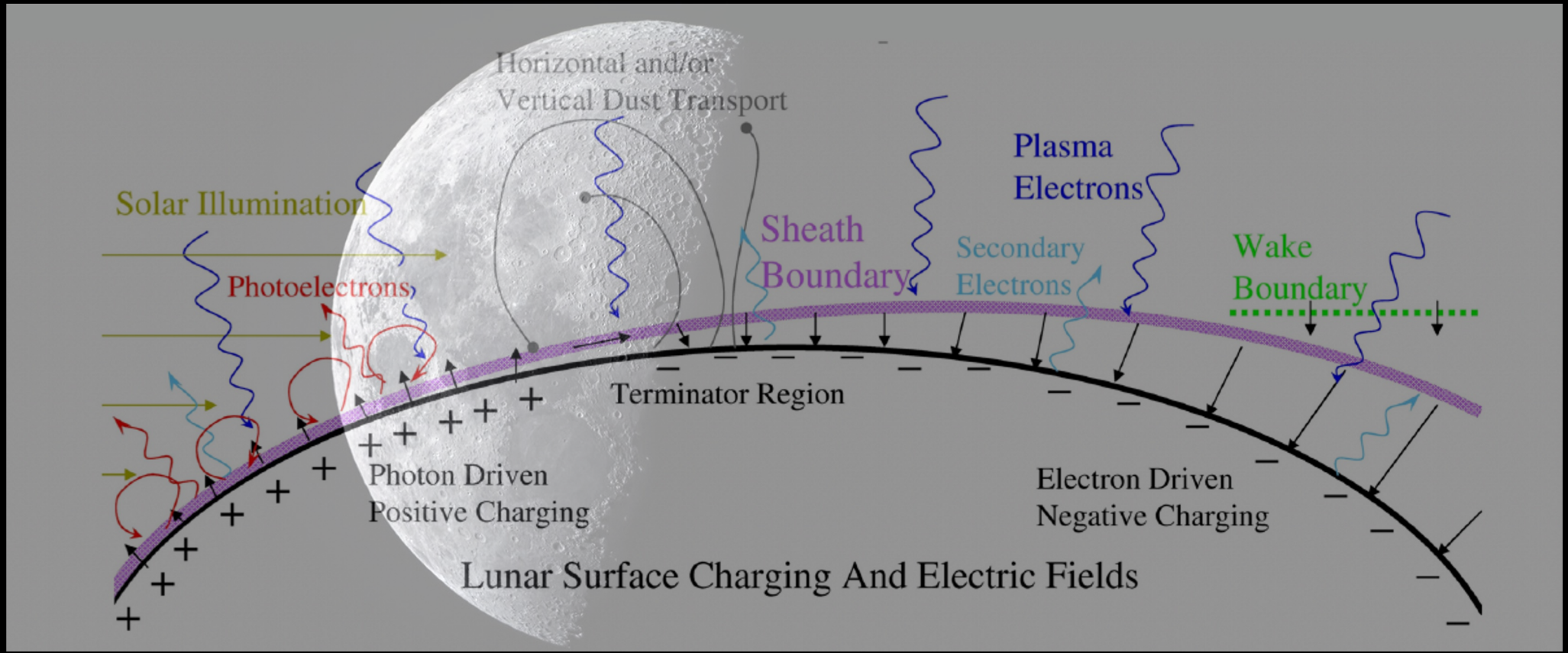
Glassy spall products

Solar wind implanted volatiles



- Found in finest grains (<20 µm)
- Retained by mineral ilmenite
- Constant within 2–3 m due to gardening process

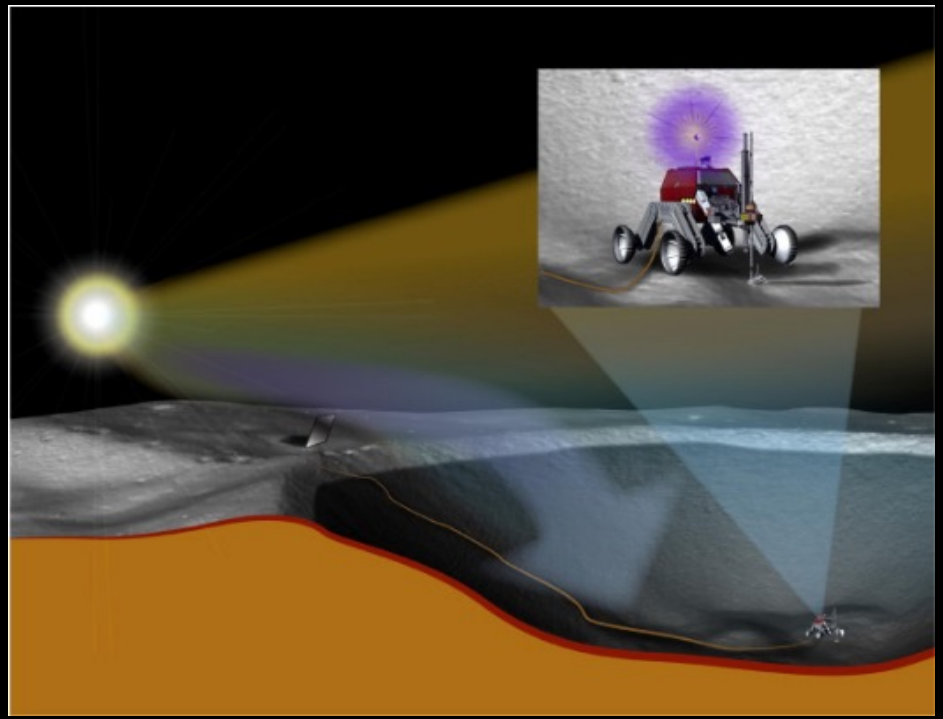
Electrostatic charging on lunar surface



Electrostatic charging experiment with lunar simulant (in vacuum)

Thrift, B., Colorado School of Mines

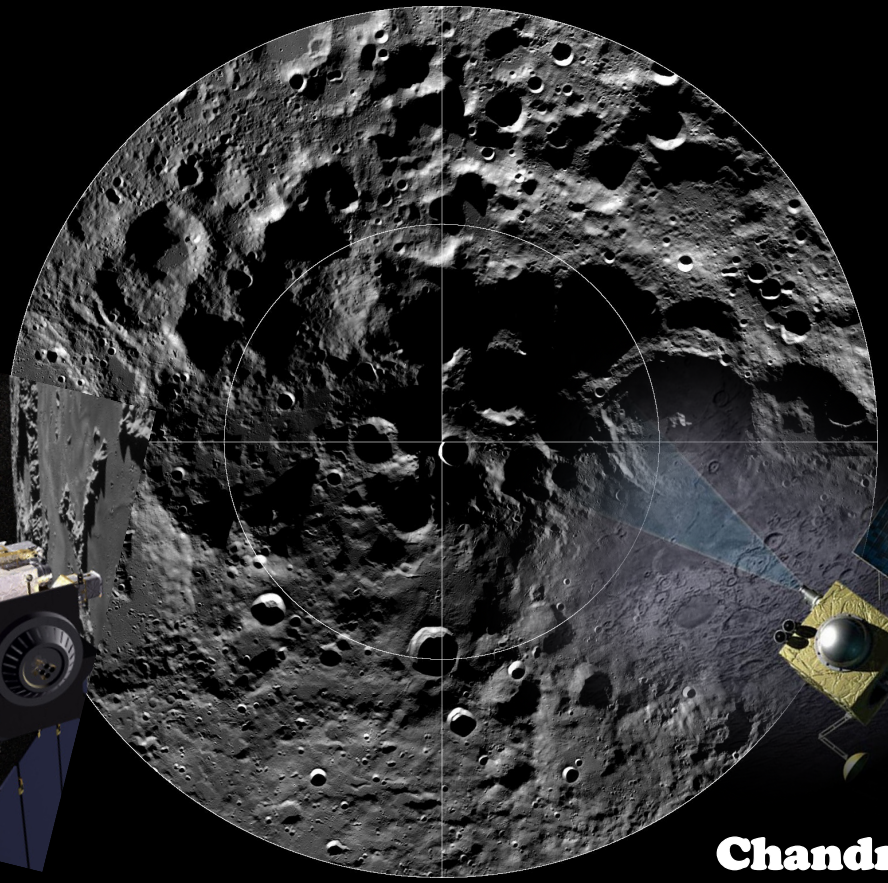
Electrostatic charging (Tribocharging issues)



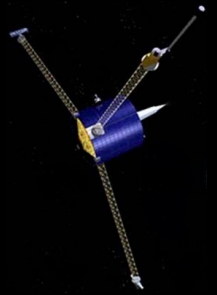
" … accumulated drill voltage is calculated to reach millions of volts within tens of seconds."

Rhodes et al. 2020, Tribocharging and electrical grounding of a drill in shadowed regions of the Moon. Advances in Space Research, 66, 753.

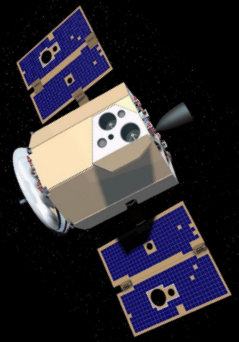
How about water?



Lunar Prospector (1999)

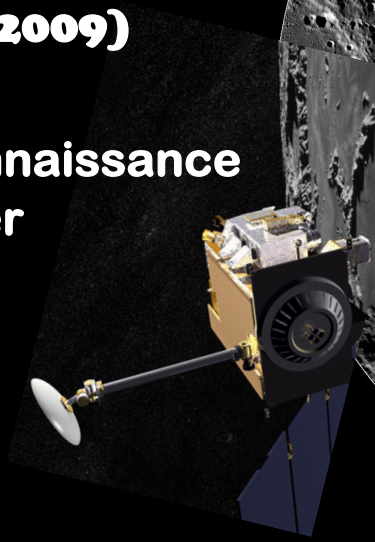


Clementine (1994)



LRO (2009)

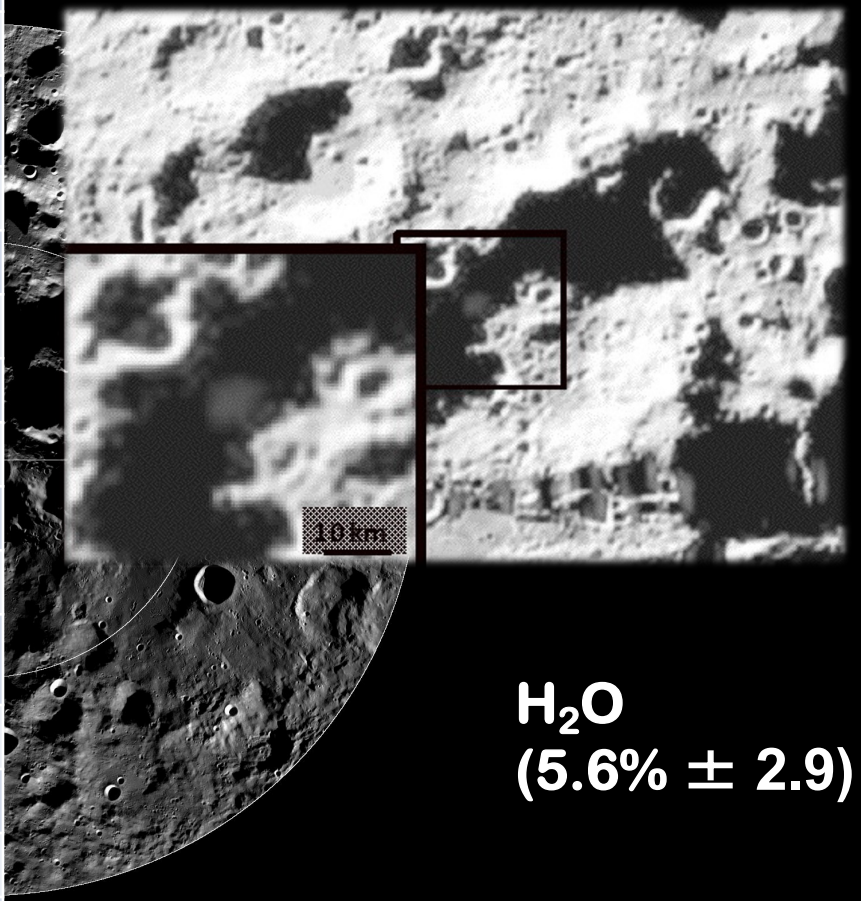
Lunar Reconnaissance Orbiter



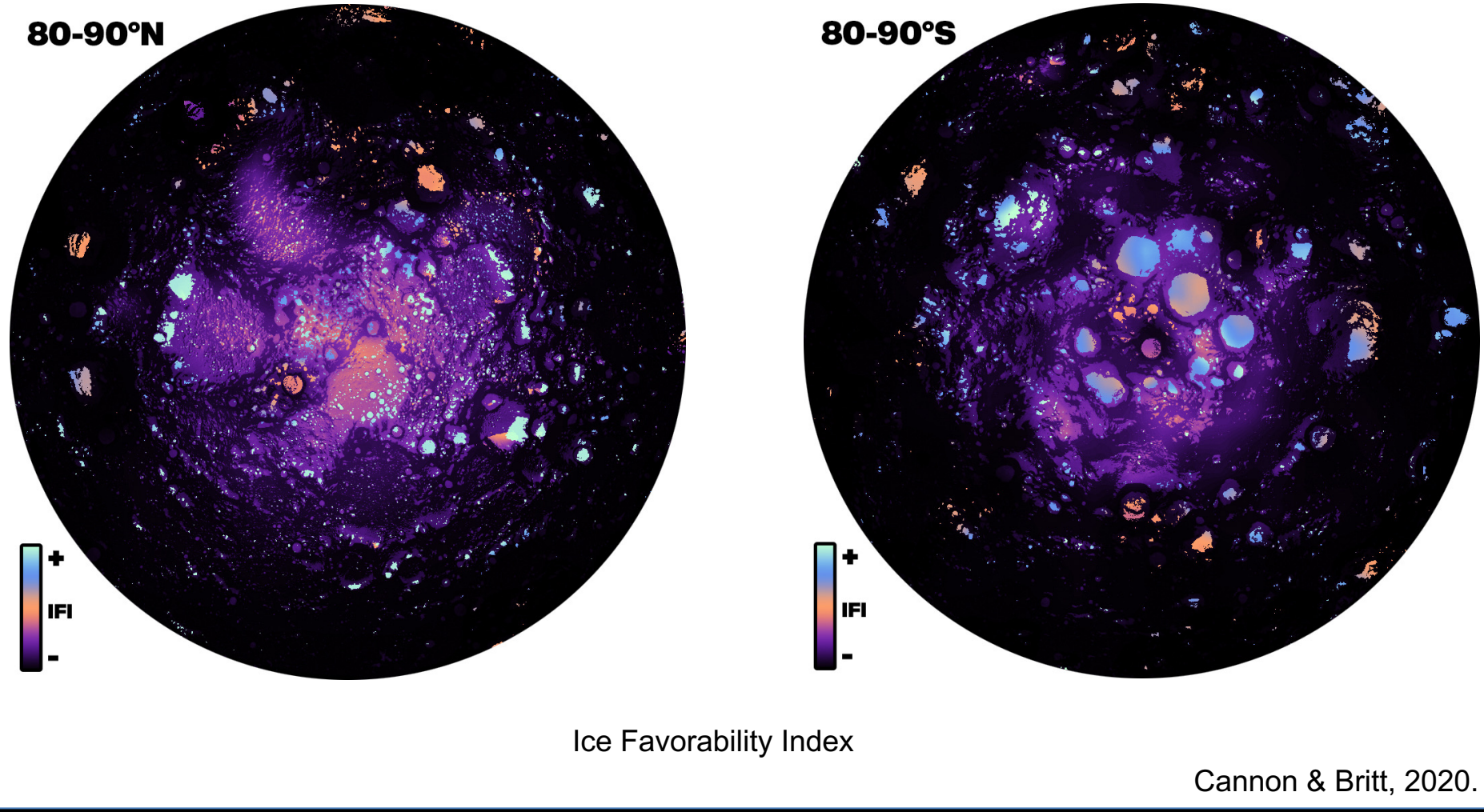
Chandrayaan-1 (2008)

ssion (2009)

Volatiles in LCROSS ejecta		
Compound	Symbol	Concentration (wt%)
Water	H_2O	5.50
Hydrogen Sulfide	H_2S	1.73
Sulfur Dioxide	SO_2	0.61
Ammonia	NH_3	0.32
Carbon Dioxide	CO_2	0.29
Ethylene	C_2H_4	0.27
Methanol	CH_3OH	0.15
Methane	CH_4	0.03
Hydroxyl	OH	0.0017
Carbon Monoxide	CO	0.000003
Calcium	Ca	0.0000008
Hydrogen Gas	H_2	0.0000007
Mercury	Hg	0.0000006
Magnesium	Mg	0.0000002



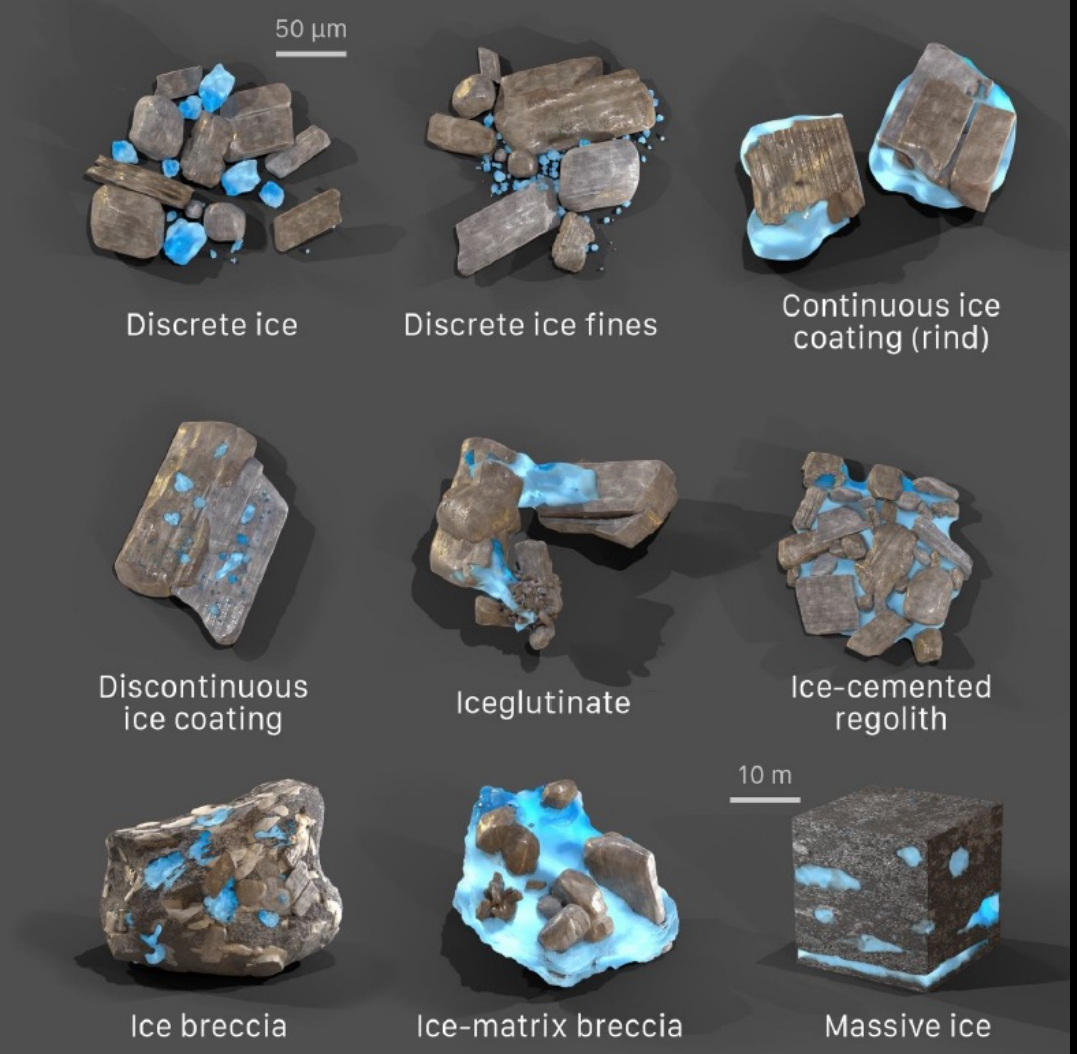
H_2O
(5.6% ± 2.9)



Ice Favorability Index

Cannon & Britt, 2020.

Potential physical textures of ice and regolith in lunar cold trap environments



Cannon, 2021.

A resource has value by its utilization

A recoverable resource, technology to recover it, and a customer.

Summary of extractive technologies

- Fundamental properties
- Drilling
- Excavation
- Comminution & beneficiation
- Extraction
- Separation & Purification
- Utilization

* Lunar Regolith geotechnical properties

* Lunar Regolith properties in situ

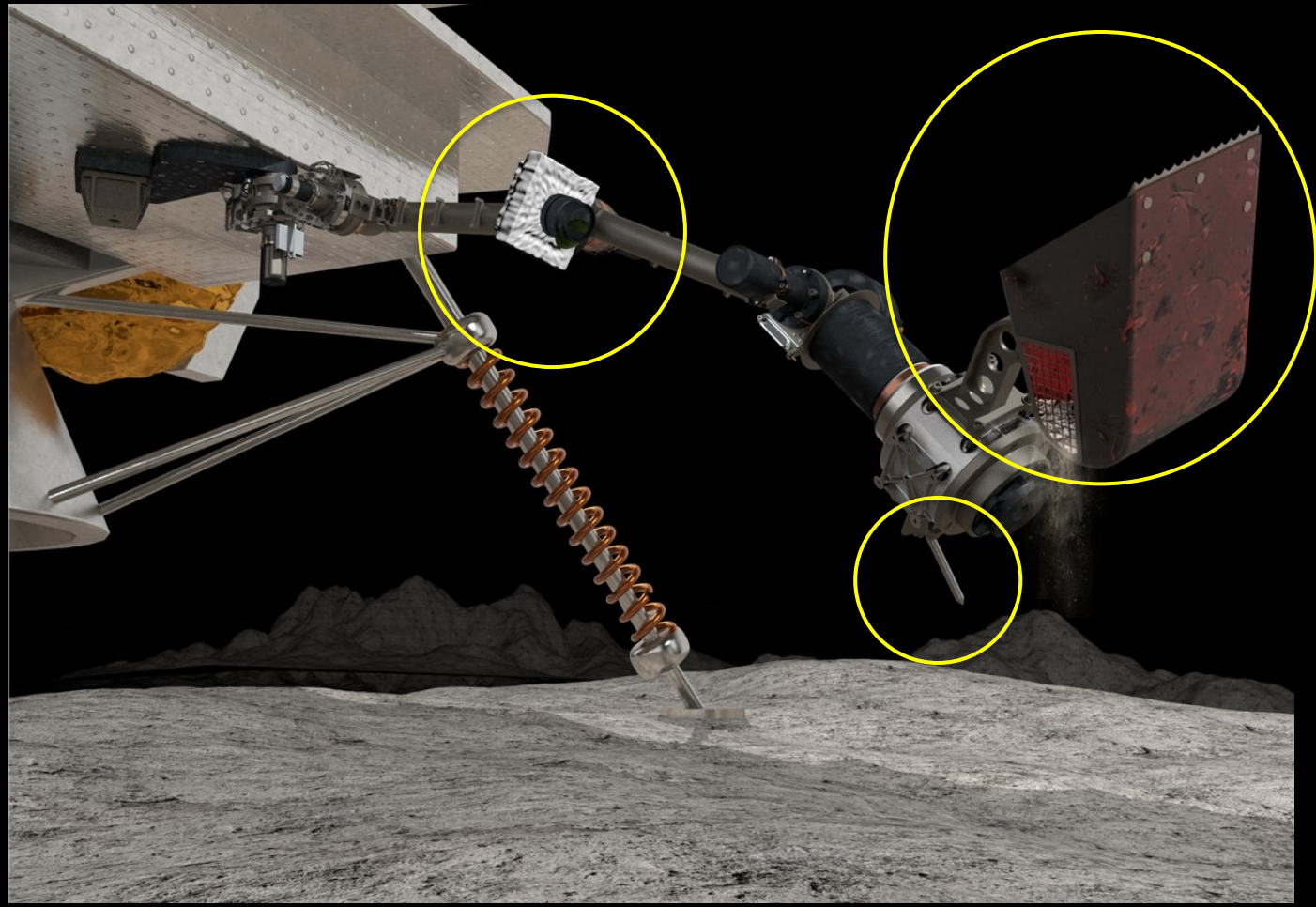
CLPS-LSITP

MAXAR TECHNOLOGIES

SCHOOL OF MINES 1874 COLORADO

Sample Acquisition, Morphology Filtering, and Probing of Lunar Regolith (**SAMPLR**)

Moon mission (2025)



Drilling

(PRIME-1 Mission to Moon in 2023)

NASA VIPER Mission (The Moon - 2025)

Drilling

Excavation

* **Excavation**: Autonomous Excavators

Excavation

Thermal Mining (H_2O)

Extraction

Lunar Environment and Thermal Mining

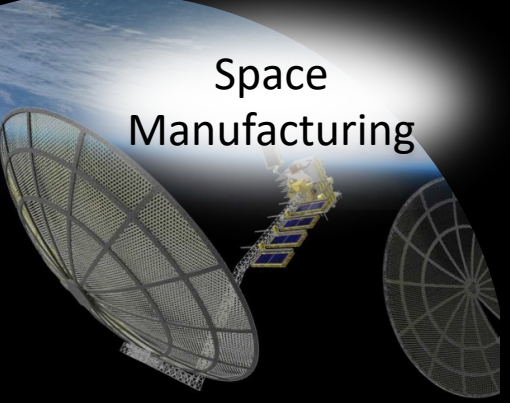
Lunar simulant
(granular ice/regolith-Highlands)
1.362 kW/m²

Space Construction
& Manufacturing

Use of lunar regolith for infrastructure construction (additive manufacturing)

esa
European Space Agency

Metals: for tools, spare parts



* 3-D regolith sintering

Lunar simulant

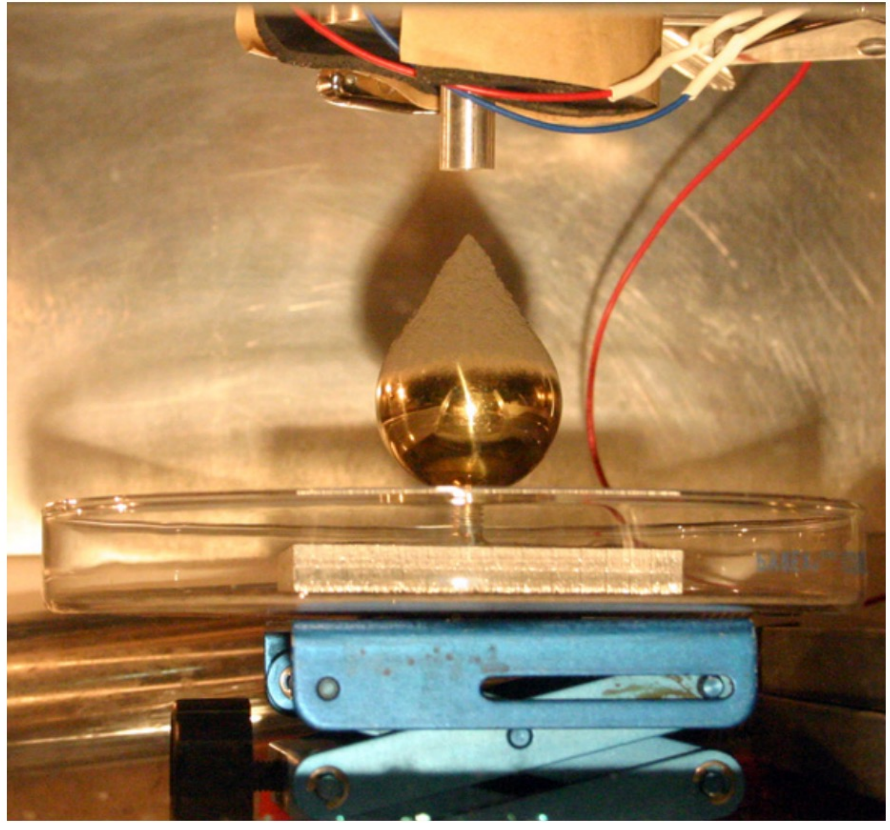
(Physical, Mechanical, and/or Chemical properties)

Carr Flow Classifications

Description	Repose Angle
Very free flowing (sand, wheat)	<30°
Free flowing	30°-38°
Fair to passable flow (ashes, coconut)	38°-45°
Cohesive	45°-55°
Very cohesive (non-flowing)	>55°

Apollo sample & Simulant (JSC-1A)

- Test purpose:
  - Measure angle of repose
- Apollo 14163
  - Angle of Repose: 58°
  - Carr Classification: Very Cohesive
- JSC-1A
  - Angle of Repose: 37°
  - Carr Classification: Free Flowing



A resource has **value** by its **utilization**

A recoverable resource, technology to recover it, and a customer.

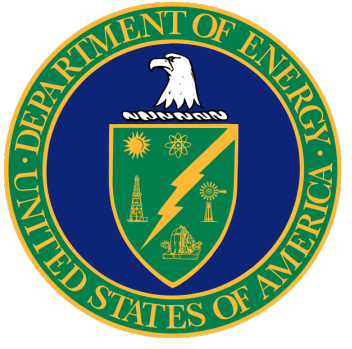
Space.com > Tech

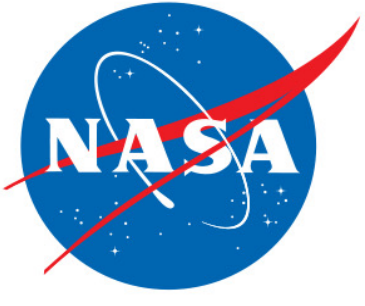
The US Geological Survey Is Getting Serious About Space Resources and Mining

By Leonard David, Space.com's Space Insider Columnist | September 4, 2018 07:00am ET

Department of Energy Releases 'Energy for Space' Strategy

JANUARY 6, 2021





Commerce Department to create "SPACE Administration"

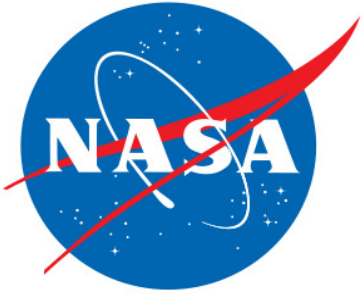
by **Jeff Foust** — May 27, 2018

United Arab Emirates

وكالة الإمارات للفضاء

UAE SPACE AGENCY

Australian Space Agency



LUXEMBOURG SPACE AGENCY


ULA
United Launch Alliance


NORTHROP GRUMMAN


SPACEX

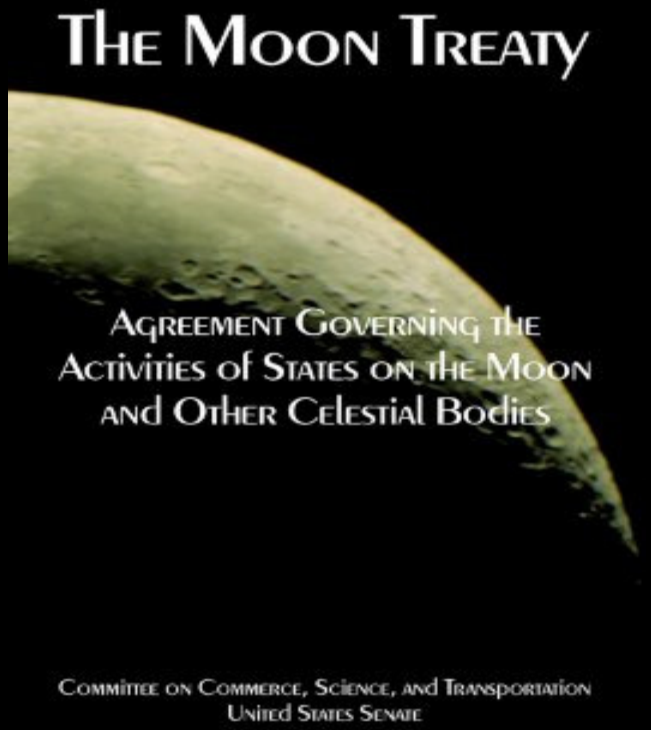

BLUE ORIGIN


LOCKHEED MARTIN

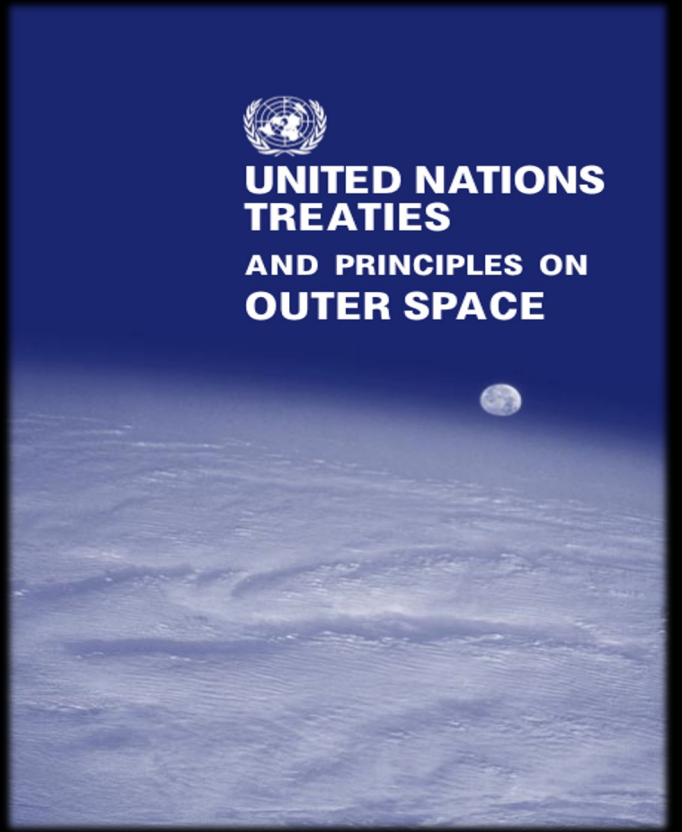

BOEING


HONEYBEE ROBOTICS
Spacecraft Mechanisms Corporation
LIGHTIGO
SPACE
MAANA
ELECTRIC
Astroscale
ASTROBOTIC
ORBITFAB
CISLUNAR
INDUSTRIES
CATERPILLAR®
ROLLS
ROYCE
BECHTEL
METALYSIS
MAXAR
TECHNOLOGIES
Nanoracks
Schlumberger
OUTWARD
TECHNOLOGIES
ATOMOS
NUCLEAR AND SPACE
OxEon
energy
Beyond current potential
REDWIRE
SHMZ
PARAGON
SPACE DEVELOPMENT CORPORATION
ICON
HONDA
ispace
OFFWORLD
Lunar Outpost™
spaceapplications
SERVICES
TRANS
ASTRA
PIONEER
ASTRONAUTICS
Air Liquide
air squared
Advanced
SPACE
THERMAL
SPACE

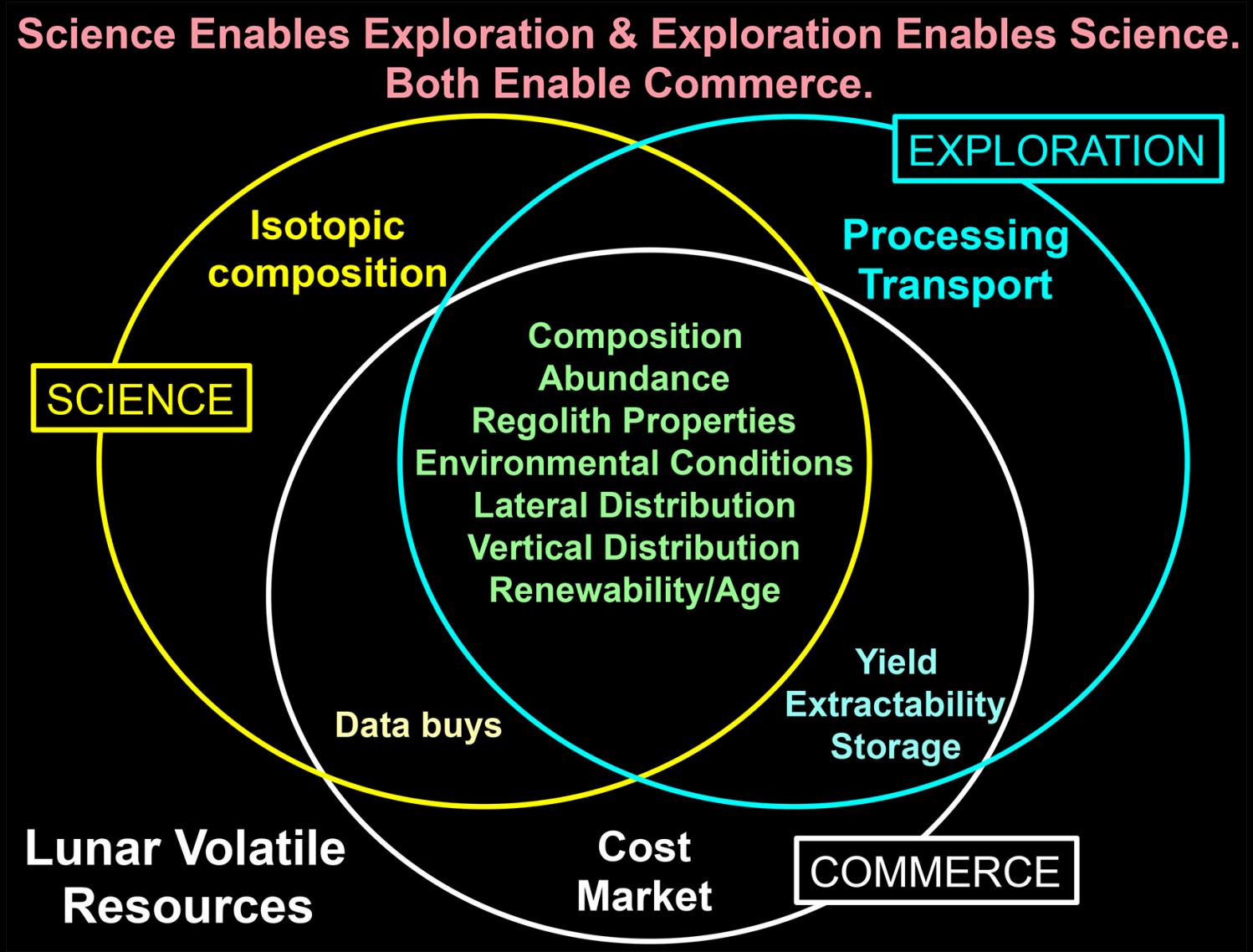
Is this legal?



1979



1967


Science Enables Exploration & Exploration Enables Science.
Both Enable Commerce.
EXPLORATION
Isotopic composition
Processing
Transport
SCIENCE
Composition
Abundance
Regolith Properties
Environmental Conditions
Lateral Distribution
Vertical Distribution
Renewability/Age
Yield
Extractability
Storage
Data buys
Lunar Volatile Resources
Cost
Market
COMMERCE

Neal, C., 2019

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