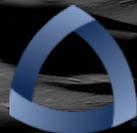




Proving Water Reserves on the Moon

George Sowers

June 13, 2019



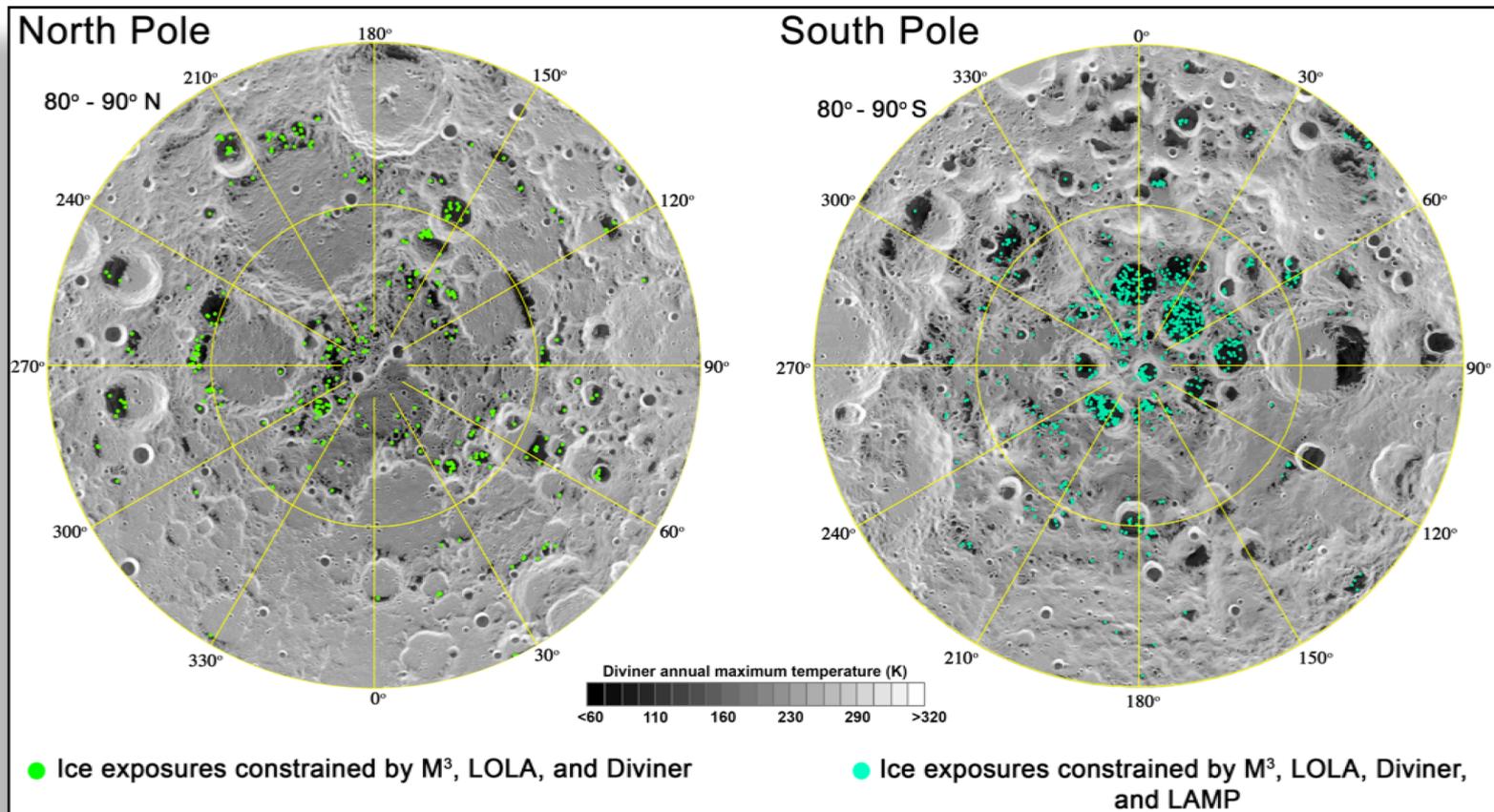
COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

Background

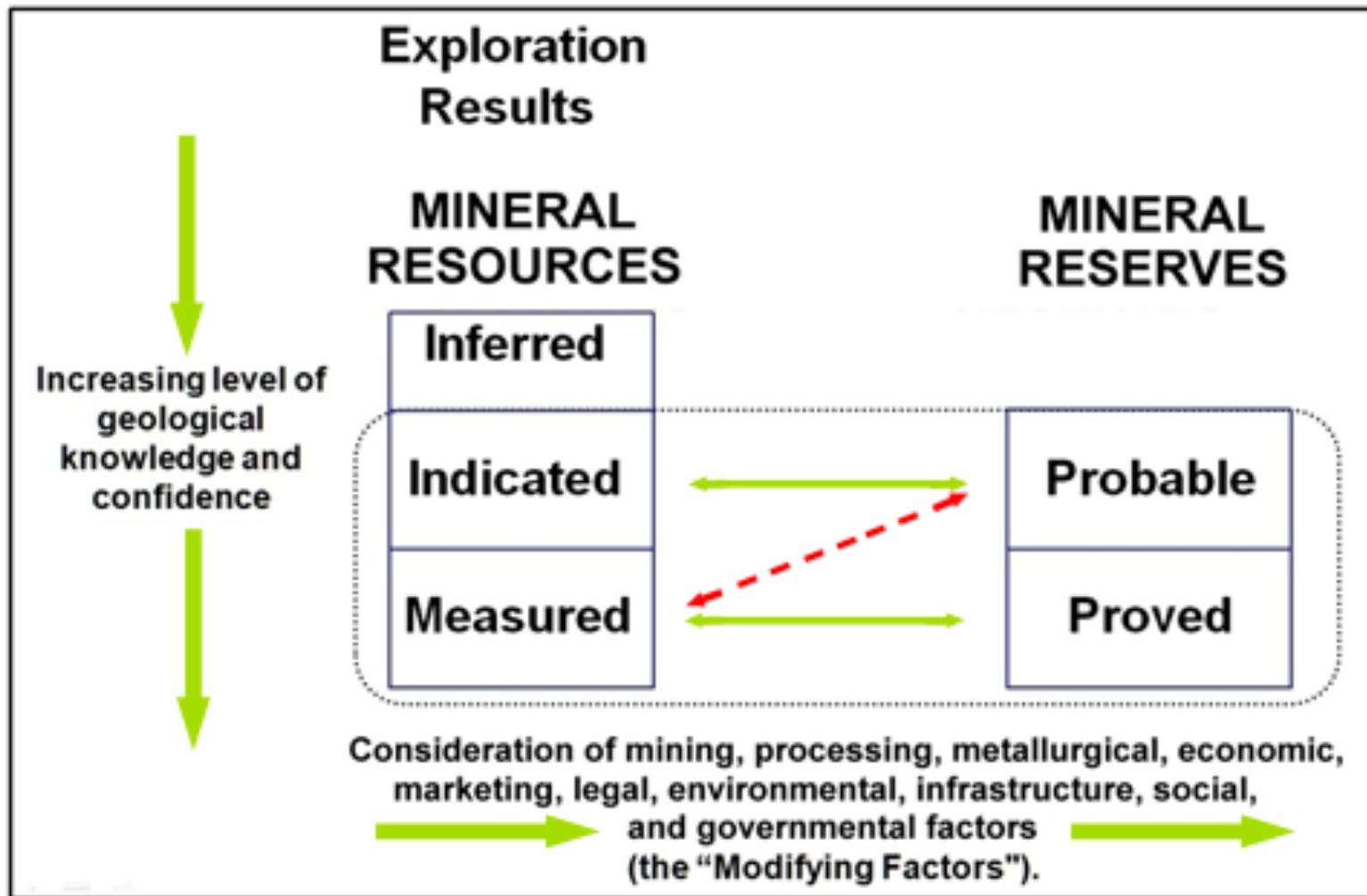
- Mounting evidence that water ice exists in large quantities near the lunar poles
- Water has many uses for sustainable space exploration & development
 - Essential for all life
 - Oxygen for breathing air
 - Radiation shielding
 - **LO₂/LH₂ rocket propellant**
- Being able to characterize lunar water resources as **proven reserves** is required for economic development of those resources

Lunar Polar Surface Ice

- Recent study by Li, et. al. indicates surface ice in concentrations of up to 30wt%

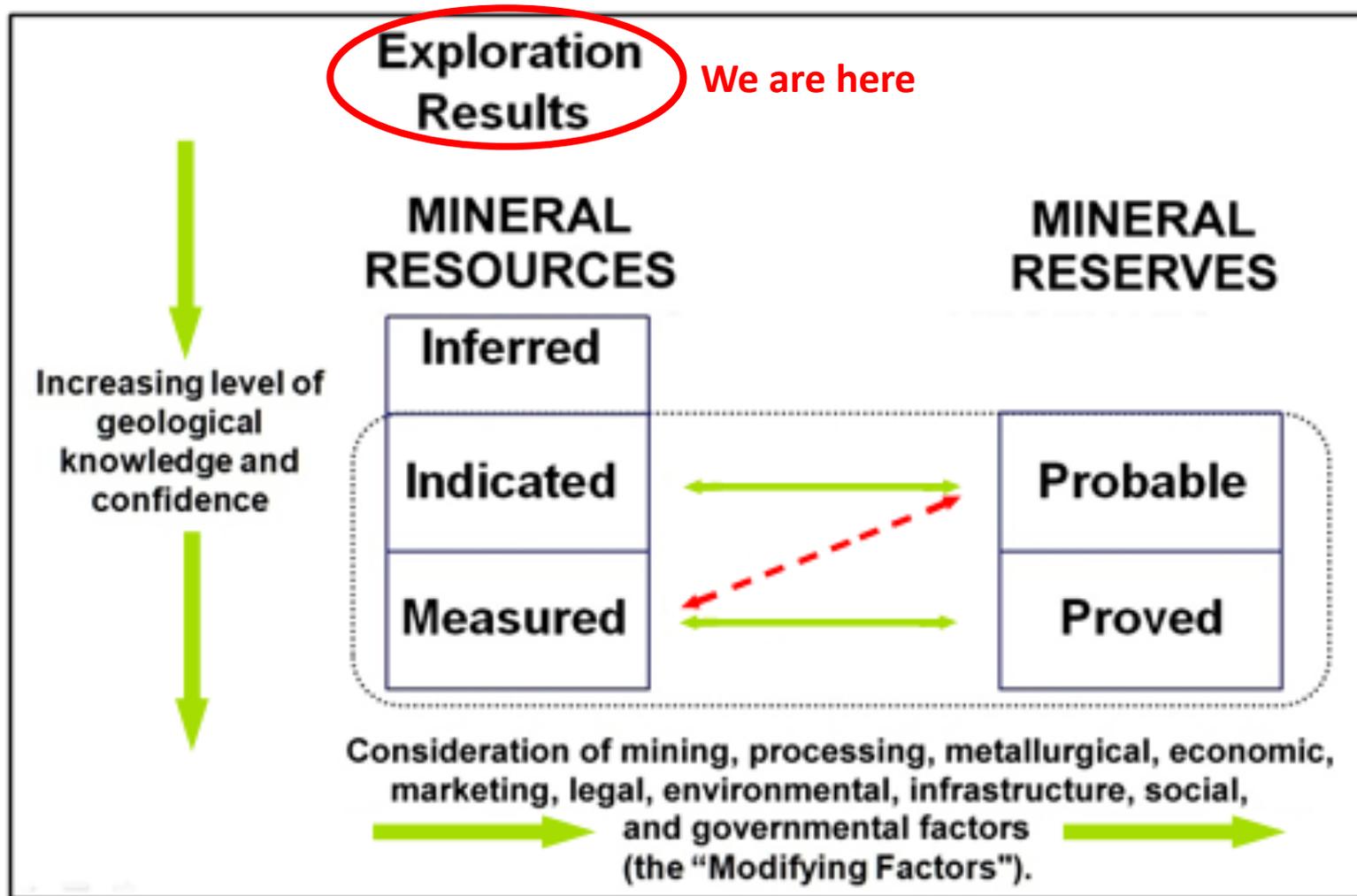


Developing a Proven Reserve



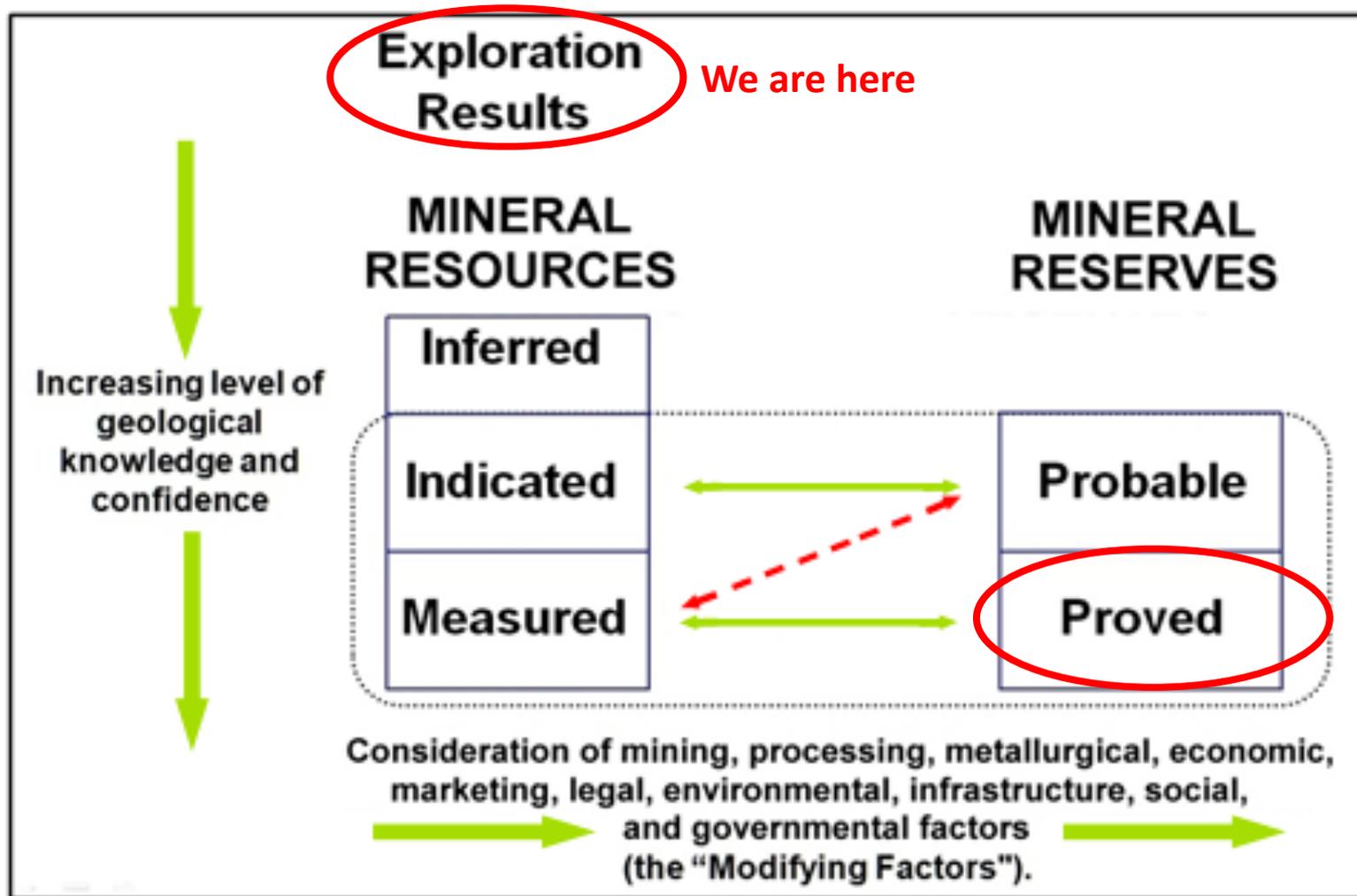
CRIRSCO, Committee for Mineral Reserves International Reporting Standards, Standard Definitions, 2012.
http://www.criresco.com/news_items/CRIRSCO_standard_definitions_oct2012.pdf

Developing a Proven Reserve



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Developing a Proven Reserve



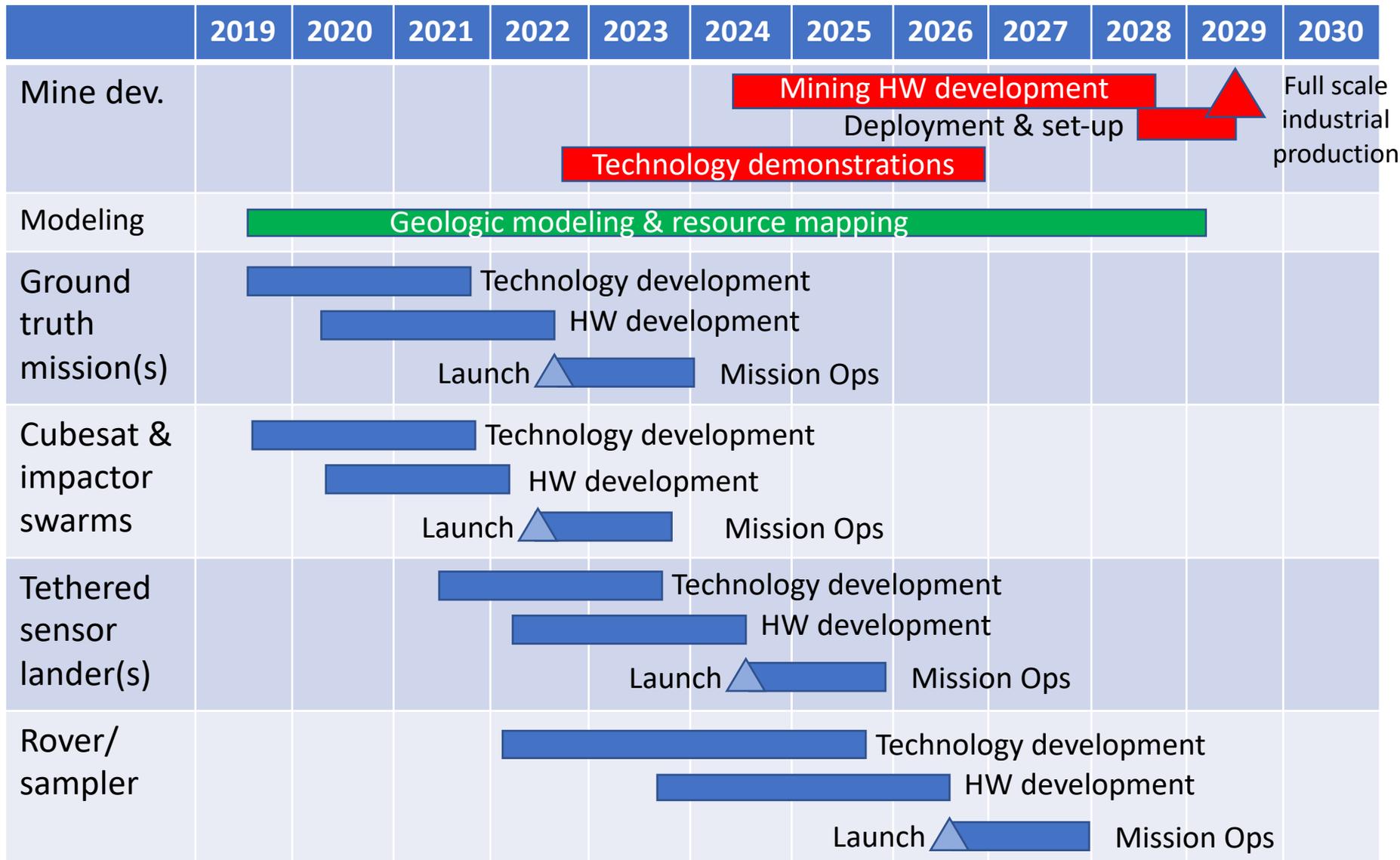
CRIRSCO, Committee for Mineral Reserves International Reporting Standards, Standard Definitions, 2012.
http://www.crirSCO.com/news_items/CRIRSCO_standard_definitions_oct2012.pdf

Resource Exploration (Prospecting)

- Measuring water resources on the Moon requires a concerted campaign
- Last year's Lunar Polar Prospecting Workshop* laid out a four phased approach
 1. Ground truth lander(s)
 2. High resolution remote sensing via cubesat swarms and/or impactors
 3. Lander(s) with ejectable sensor packages
 4. High fidelity rover/mapper
- Phases 1 and 3 are good candidates for CLPS
- Focus is on minimizing cost and risk (avoiding the dry hole)

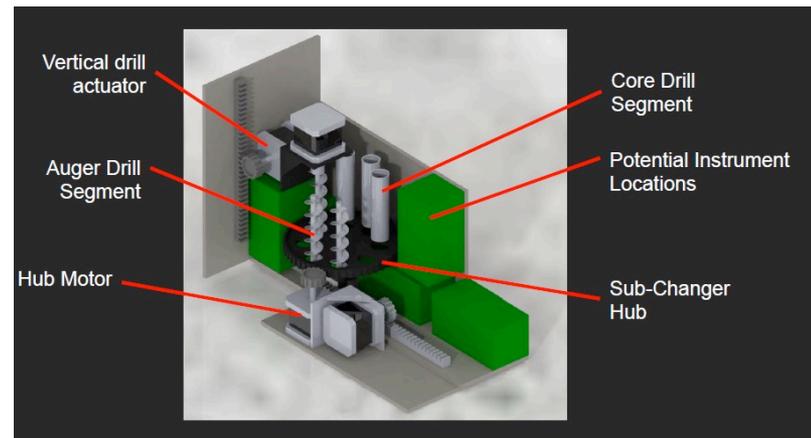
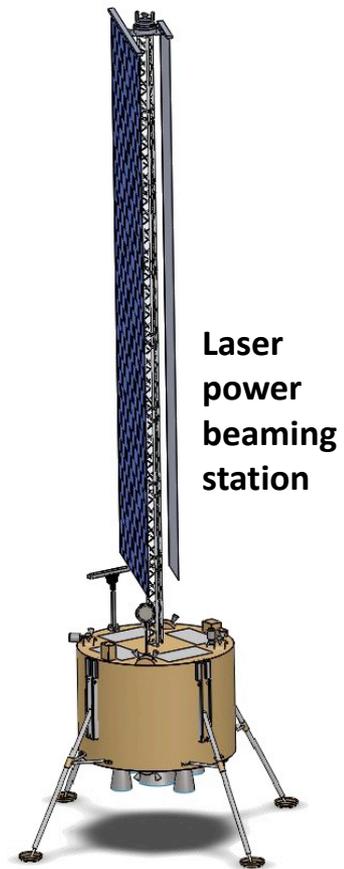
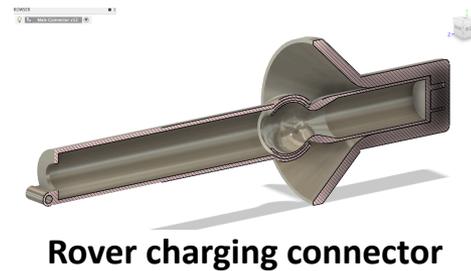
*Report available at https://isruinfo.com/public//docs/LPP_2018_final_report.pdf

Lunar Ice Resource Exploration Roadmap



Development Progress

- CSM Space Resources graduate design classes worked on some of these missions
 - Cubesat swarm with laser illuminator and midwave infrared imaging spectrometer
 - Prospecting rover with core drill
 - Laser power beaming station for prospecting rover



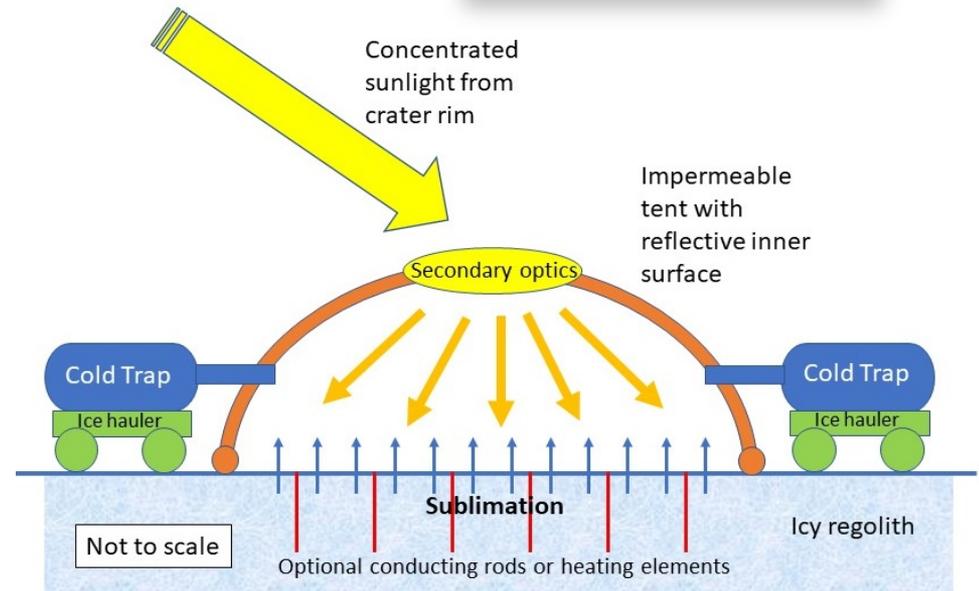
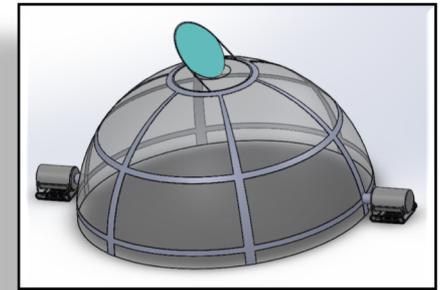
Drill assembly with multiple bits (subs) 9

The Modifying Factors

- Progress is also being made on the modifying factors
 - Mining
 - Processing
 - Markets
 - Economics
 - Legal
 - Environmental
 - Infrastructure
 - Governmental
 - Metallurgical & social factors are not applicable (yet)

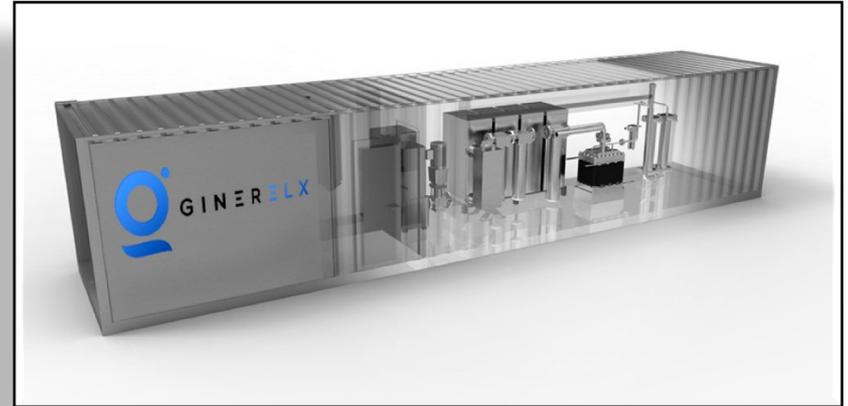
Mining

- Thermal mining concept developed by CSM
 - Excavation also studied
- Recent NIAC award to further development
 - Another NIAC award to a similar concept
- Risks
 - Nature of icy regolith
 - Effectiveness of surface heating
 - Tent leakage
 - Tent mobility



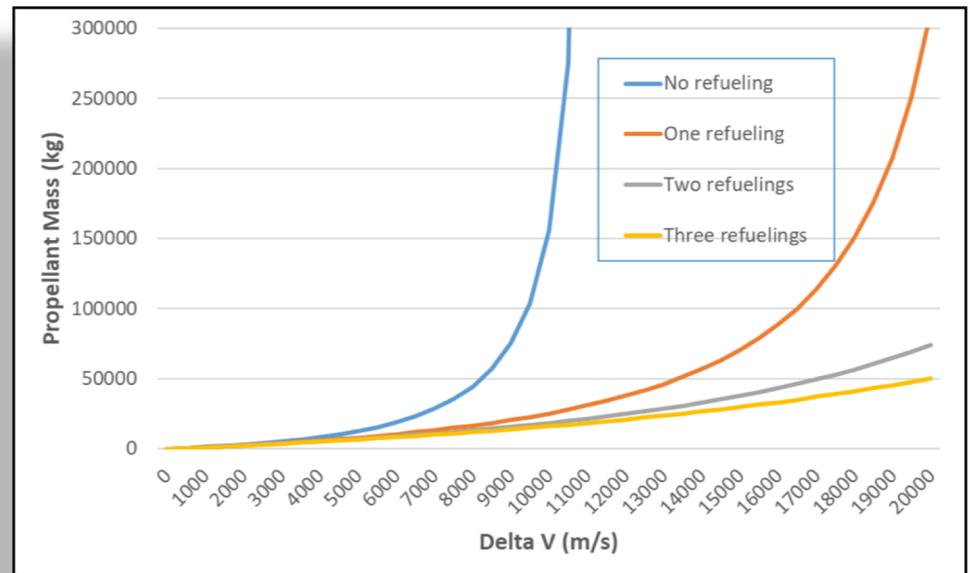
Processing

- Processing water into propellant entails purification, electrolysis & liquification
- Terrestrial purification and electrolysis technology well understood
- LO_2/LH_2 liquification aided by PSR temperature
- Paragon NASA BAA award to take IHOP system to TRL 5
- Risks
 - Thermal environment
 - Contaminants
 - Mass



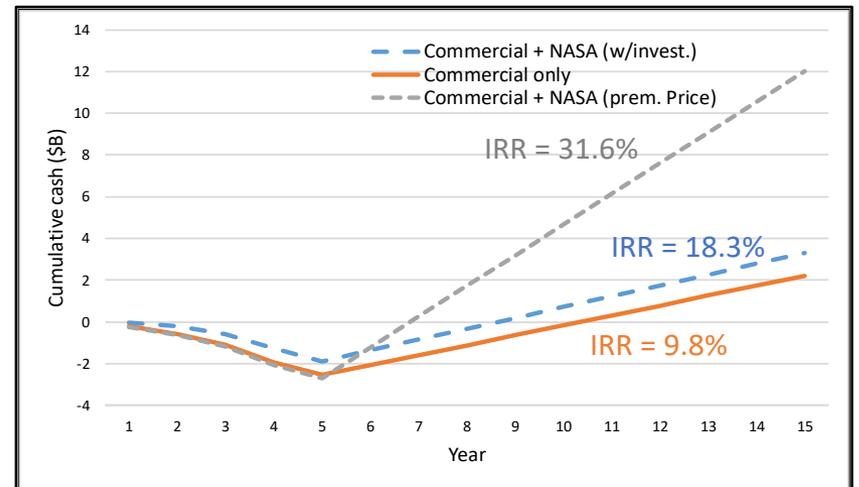
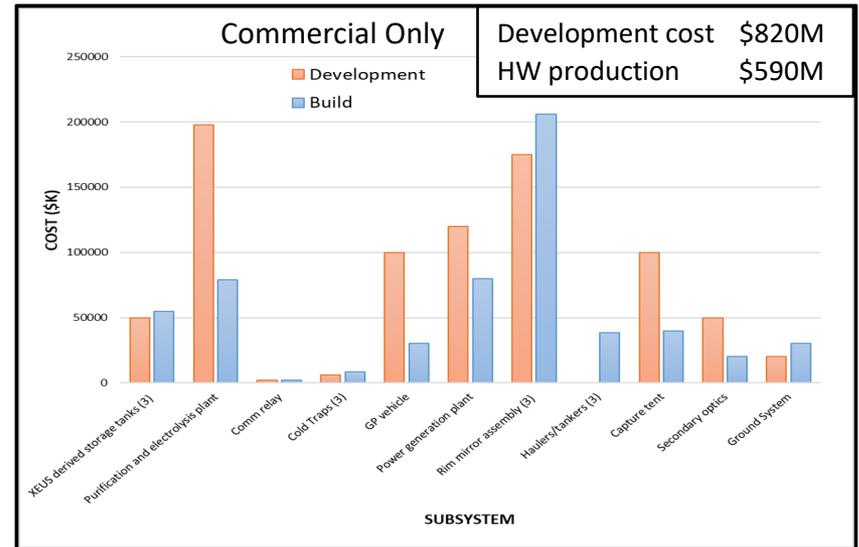
Markets

- **All** beyond LEO missions benefit from lunar propellant (refueling)
- Commercial
 - ULA
 - Blue Origin
 - SpaceX
- NASA
- International
 - ESA
 - Moon Village Association
 - Moon Valley (Japan)
- Military
- Risks
 - Cryo storage and transfer
 - Government commitment



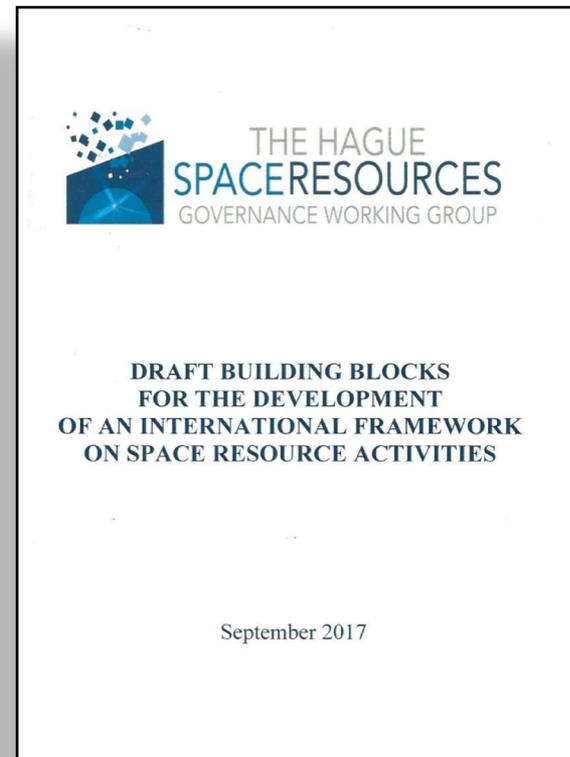
Economics

- Business case analysis shows positive returns for commercial-only scenarios
- Adding government markets and public-private partnership models improves returns
- Risks
 - Cost/price uncertainty
 - Markets
 - Government commitment



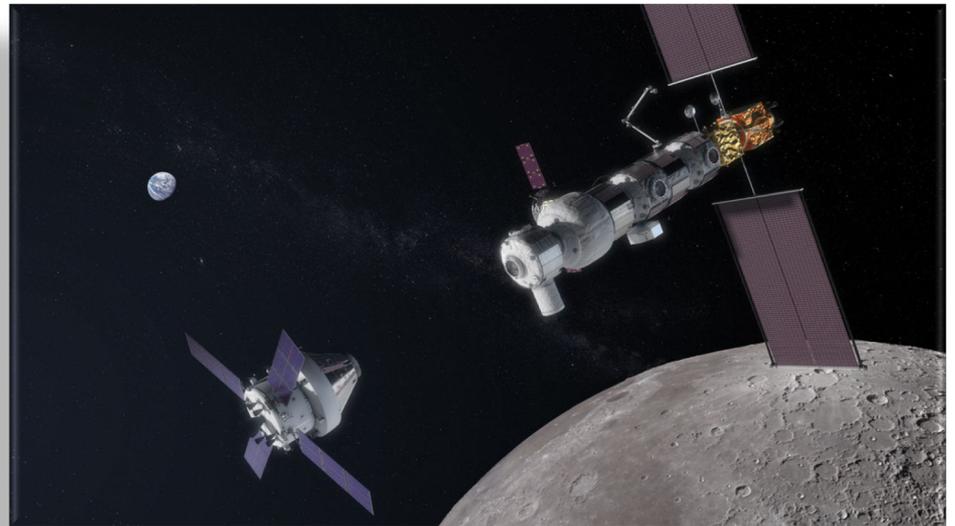
Legal, Environmental

- 2015 US Commercial Space Launch Competitiveness Act (CSLA) allows ownership of extracted materials
- The Hague Group has developed a legal framework for space resources
- Environmental frameworks under development
- Risks
 - Policy changes
 - Lack of international consensus



Infrastructure, Governmental

- NASA & international plans in work for lunar return
- Infrastructure in planning stage via NASA and international lunar programs
 - Transportation
 - Communications
 - Gateway?
- Various public-private partnership models for mining show promise
- Risks
 - Every election



Lunar Water Resource Maturity Model

- Maturity model captures progress toward “Proven Reserve”
- All green = Proven Reserve

Resource Factor	Maturity	Comments
Geologic knowledge		Some remote sensing data, no ground truth
Mining		Various mining concepts in development
Processing		Terrestrial processes well developed
Markets		No current buyers but strong incentives
Economics		Initial analysis favorable, but large uncertainties
Legal		US legislation, but still regulatory gaps
Environmental		No regulations yet
Infrastructure		No current infrastructure, plan in early stages
Governmental		US, Europe currently focused on the Moon, subject to political process



Factor immature or unfavorable



Factor moderately mature/favorable



Factor mature & favorable

The Lunar South Pole in 2030



James Vaughan/ROOM - the Space Journal
www.room.eu.com