Mining the Moon for Fun and Profit

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FISO Telecon Presentation

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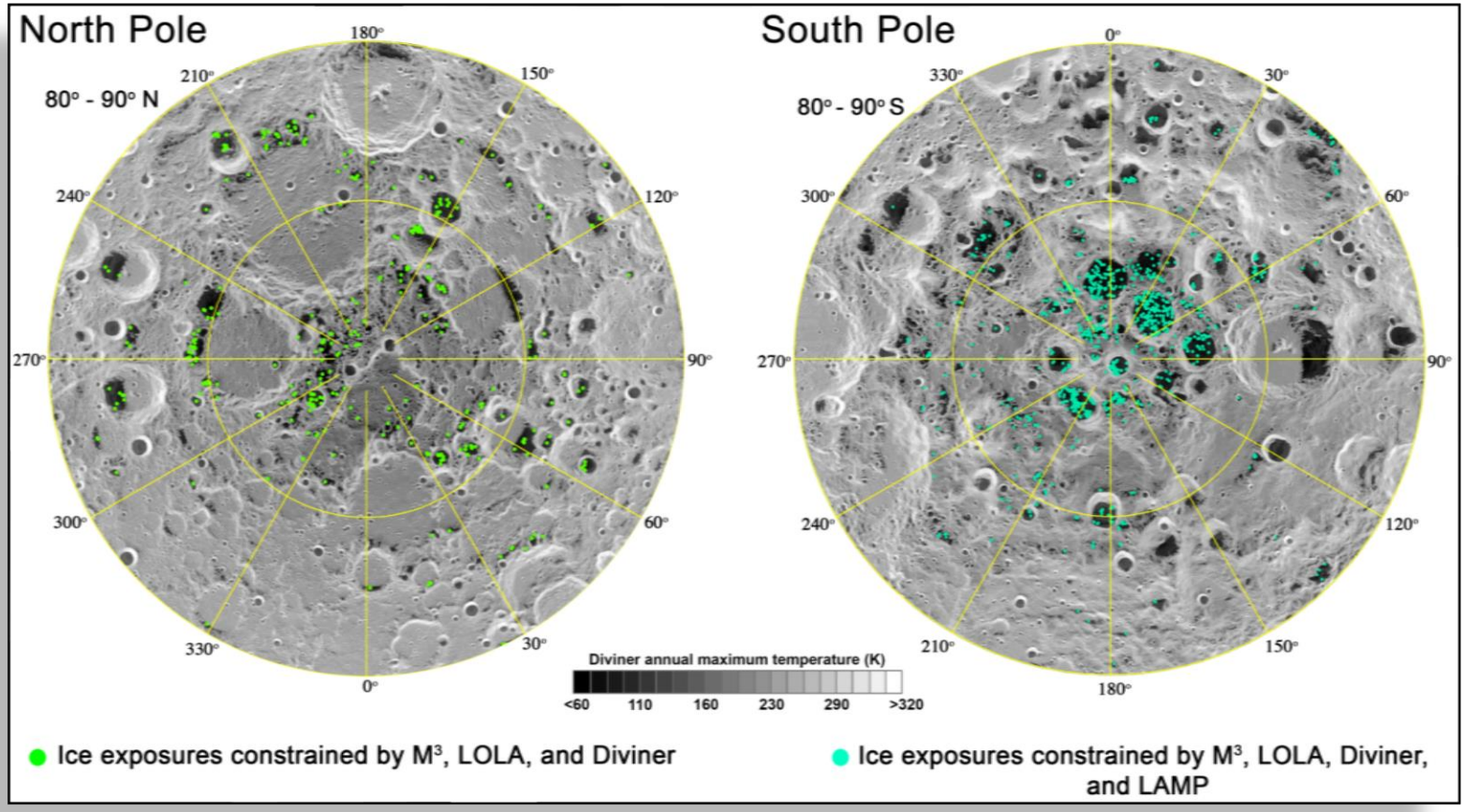
Background

- 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
  - **LO_2/LH_2 rocket propellant**
- Use of space-sourced propellant dramatically lowers the cost of all beyond Low Earth Orbit (LEO) transportation
  - Enables the **commercialization** of cislunar space
  - Enables **affordable** Mars missions

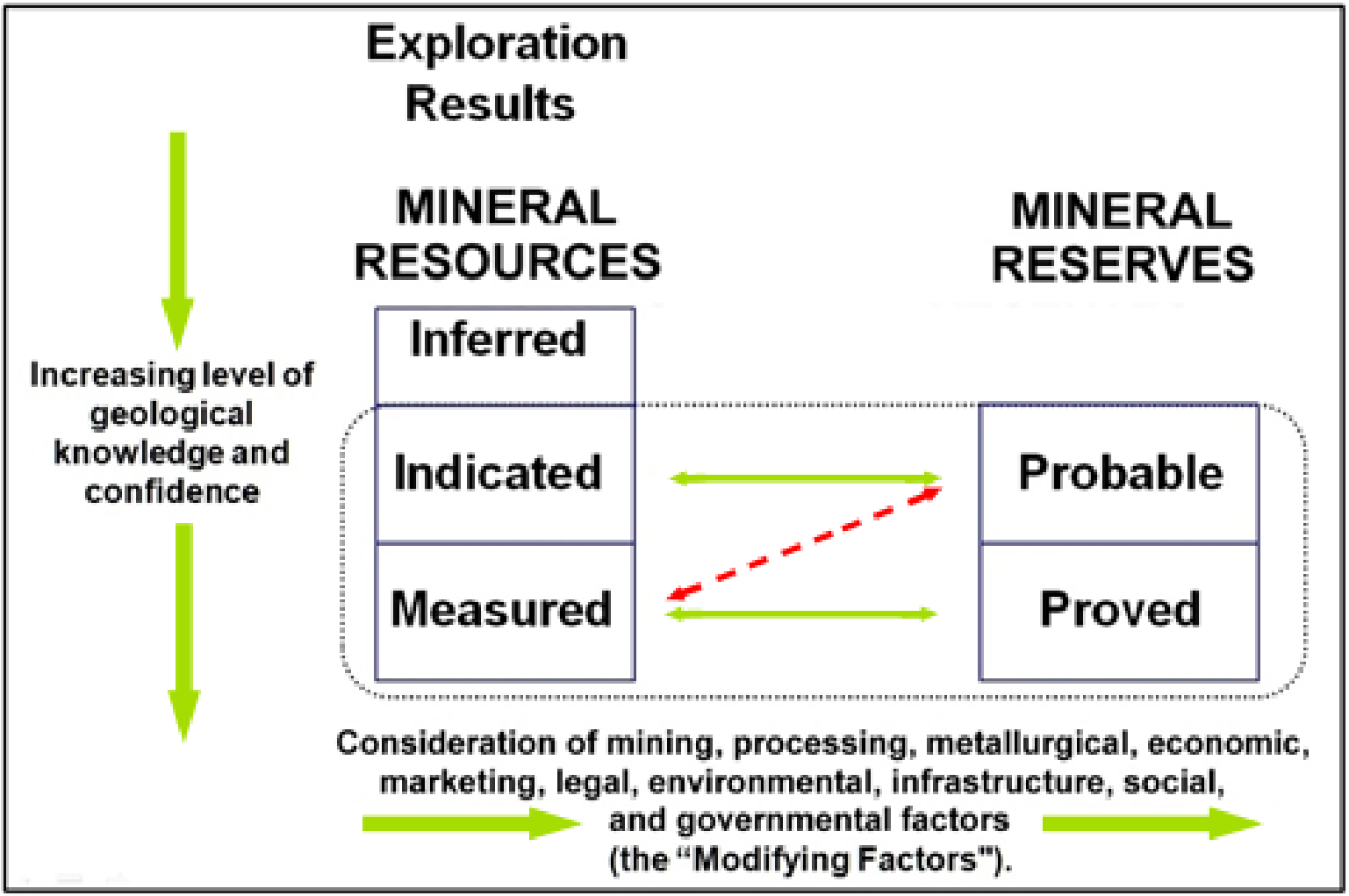
Lunar Polar Surface Ice

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



Li, S, Lucey, P.G., Milliken, R.E., Hayne, P.O., Fisher, E., Williams, J.P., Hurley, D.M., Elphic, R.C., Direct evidence of surface exposed water ice in the lunar polar regions. PNAS (2018). https://doi.org/10.1073/pnas.1802345115

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

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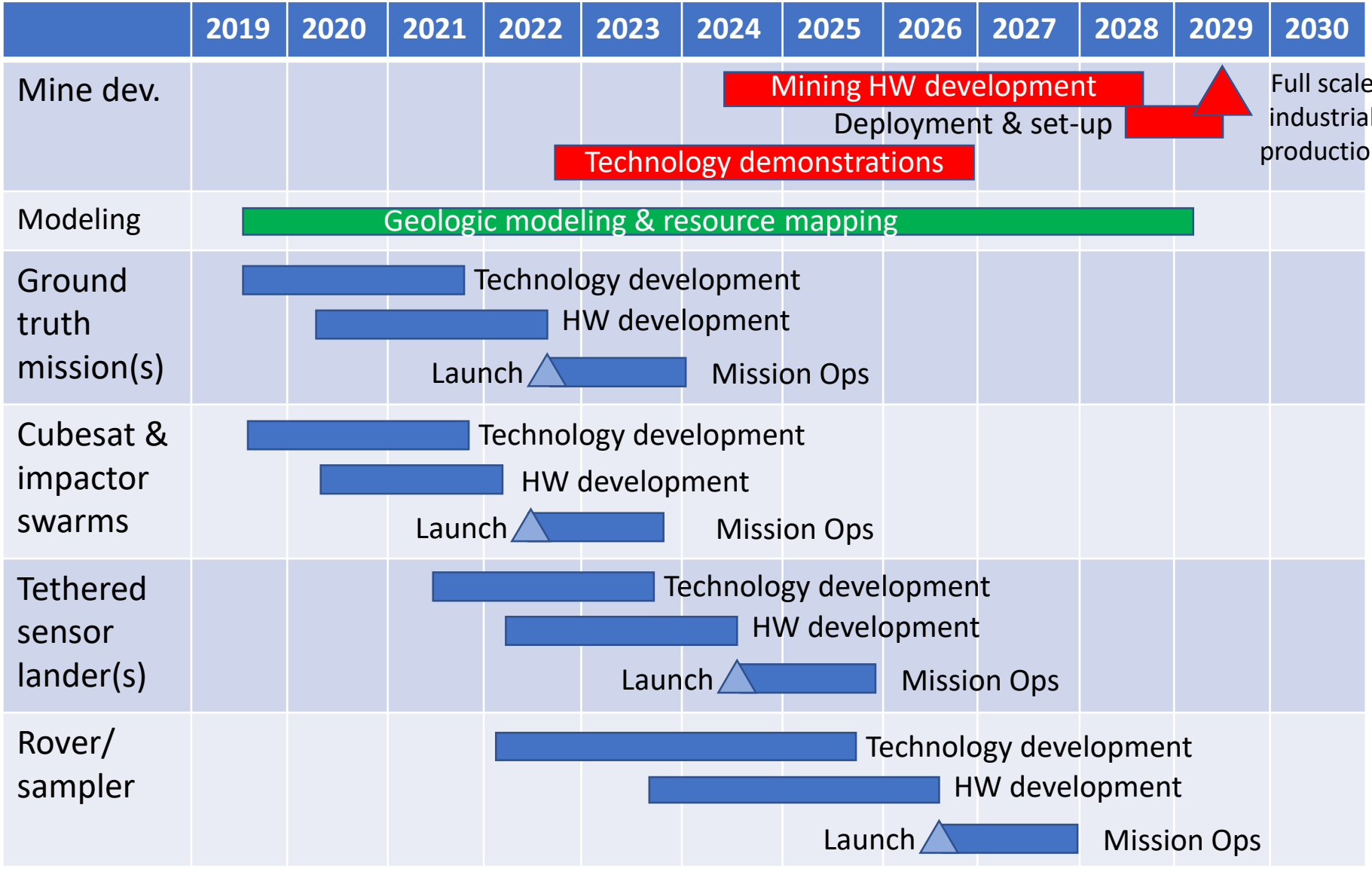
Lunar Ice Resource Exploration Roadmap



Propellant Business Case

- In 2016, United Launch Alliance (ULA) developed a business case for purchasing LO_2/LH_2 propellant in cislunar space
  - Based entirely on lowering the cost to launch satellites to GEO
- ULA set prices at various points in cislunar space based on the cost to transport propellant from the point of origin to the point of use (sale)
- To close this business case, **1100 mT** of propellant must be produced on the Moon for **$500/kg** or less

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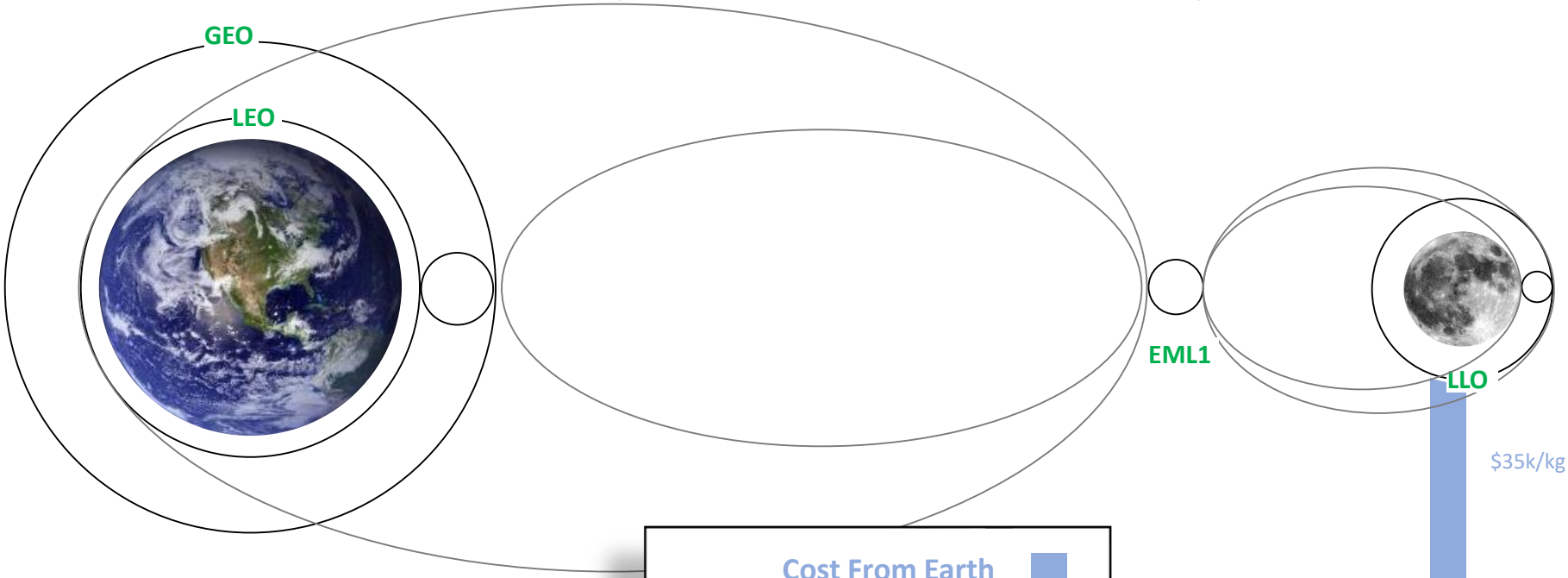
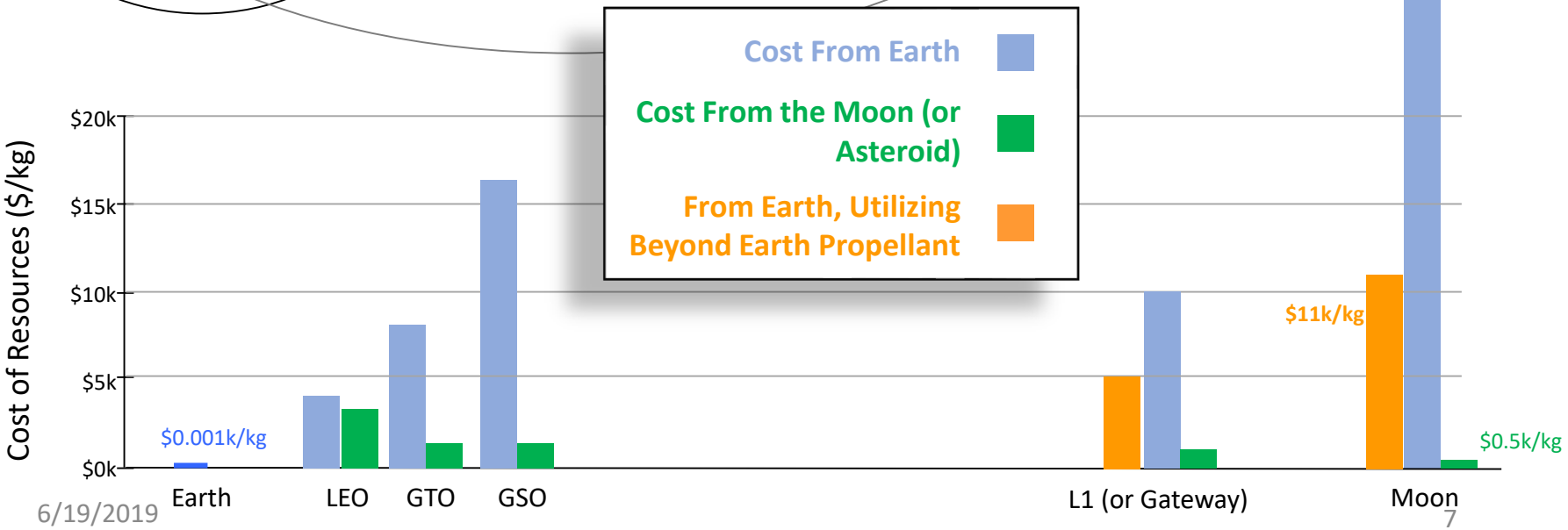
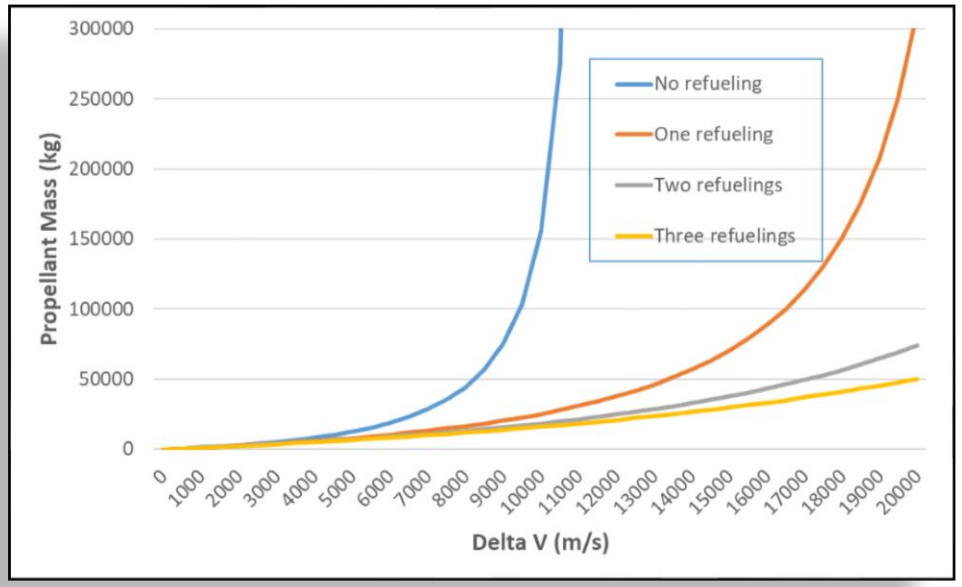
Costs of Propellant in Cislunar Space





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



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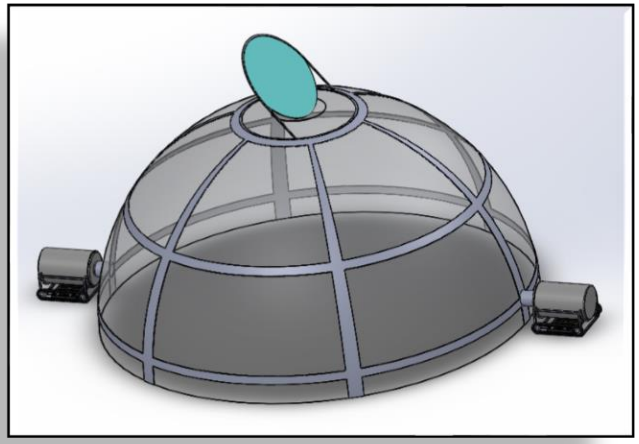
Lunar Propellant Mine Overview

Credit: ULA

Capture Tent Concept



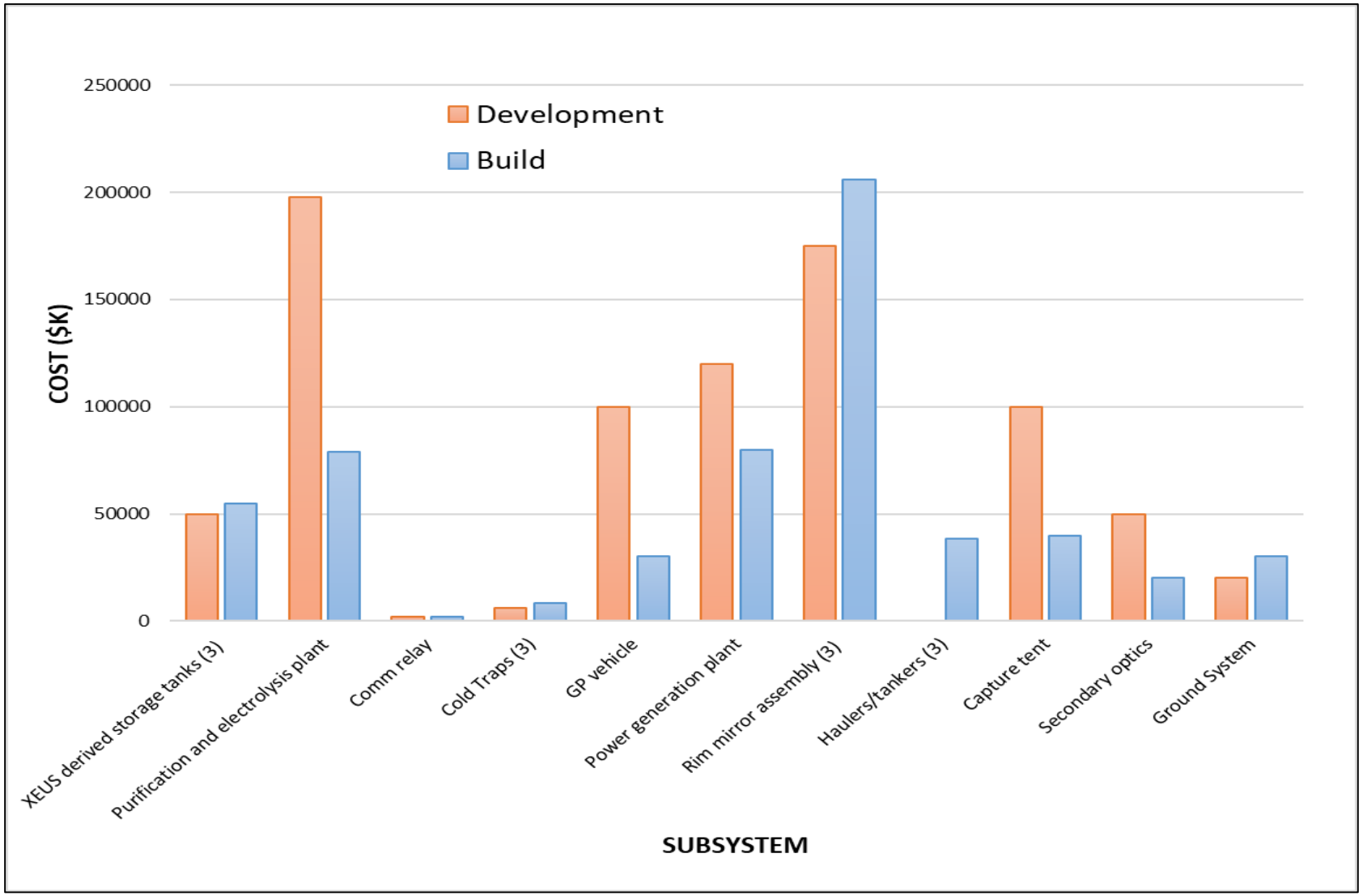
Phase I NIAC Award

- Phase I NIAC recently awarded to further Thermal Mining concept
  - Survey the solar system for Thermal mining targets
  - Enhance the lunar propellant architecture
  - Conduct proof of concept testing on icy regolith samples in our cryogenic vacuum chamber

Fines Ice Highlands Simulant

Crushed Snow Highlands Simulant

Estimated Architecture Costs



General Business Case Assumptions

- Resource exploration campaign cost born by governments
  - Great synergy with science
  - Great benefit to long term sustainability of government exploration programs
- Four year development and build for ice mining and propellant production systems
- One year delivery and set up on lunar surface
- Ten year operational life

Scenarios

1. Commercial only
   - Market is propellant delivered to LEO
     - Used to refuel upper stages delivering mass to GEO or other beyond LEO destination
     - Price is $3000/kg in LEO, equates to $500/kg on lunar surface
     - Demand is 1100 mT/yr
2. Commercial + NASA (w/investment)
   - Commercial demand as above
   - NASA demand is 100 mT/yr delivered on the lunar surface
     - Refuel landers
   - NASA COTS-like investment of $800M in the development of the system

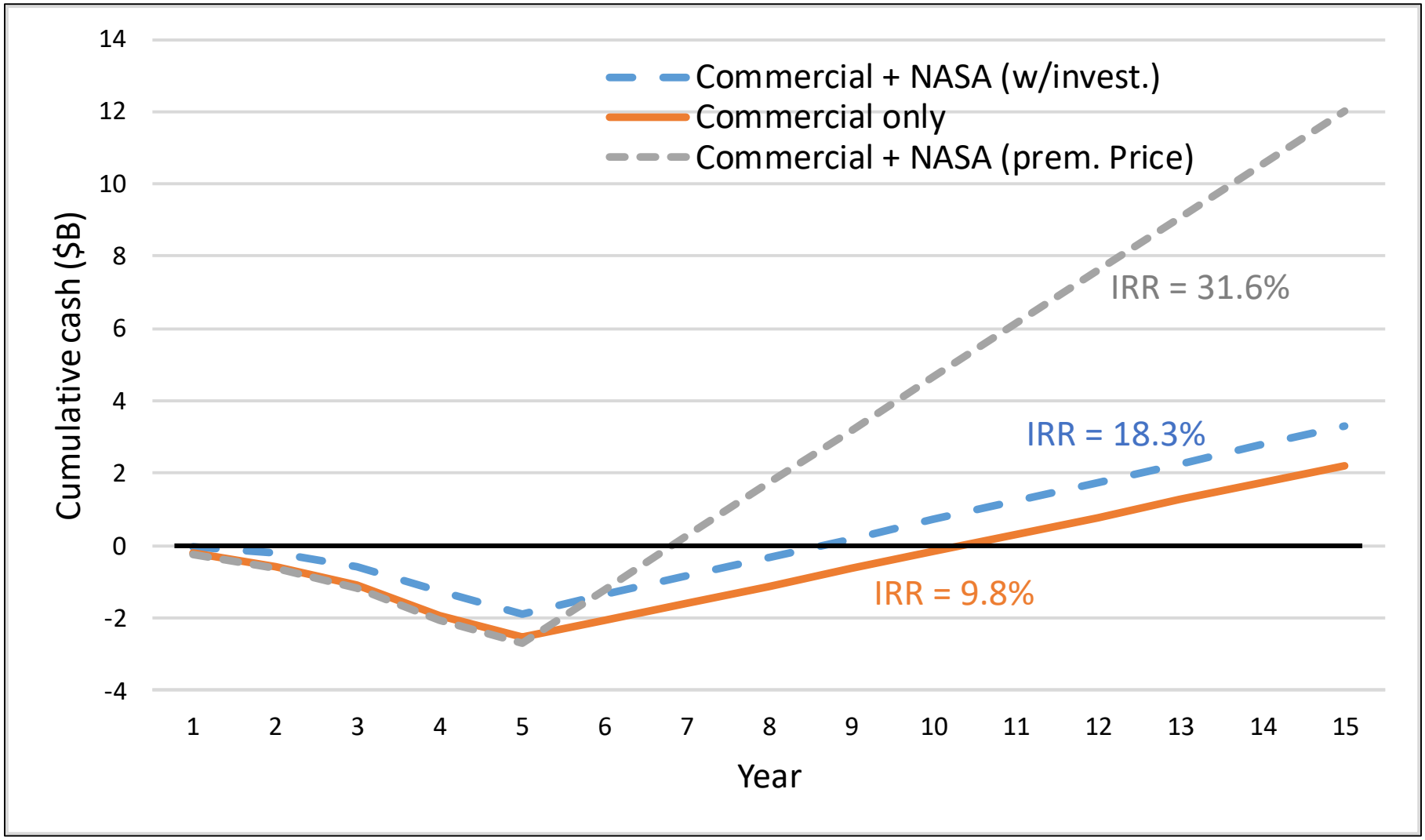
Scenarios, Cont'd

3. Commercial + NASA (w/price premium)
   - Commercial demand as above
   - NASA demand is 100 mT/yr delivered on the lunar surface
     - Refuel landers
   - No NASA investment
   - NASA pays $10,000/kg for propellant on lunar surface

Business Case Analysis

Parameter	Commercial Only	Commercial + NASA (w/invest.)	Commercial + NASA (prem. price)
Propellant production rate	1100 mT/yr	1200 mT/yr	1200 mT/yr
Com. price (Moon)	$500/kg	$500/kg	$500/kg
NASA price (Moon)	NA	$500/kg	$10,000/kg
HW Dev. cost	$820M	$895M	$895M
HW Production cost	$590M	$640M	$640M
Transportation cost	$1062M	$1062M	$1062M
Annual ops & maintenance cost	$75M	$82M	$82M
Annual revenue	$550M	$600M	$1550M
NASA investment	$0M	$800M	$0M
Internal Rate of Return (IRR)	9.8%	18.3%	31.6%

Mining Company Cash Flow



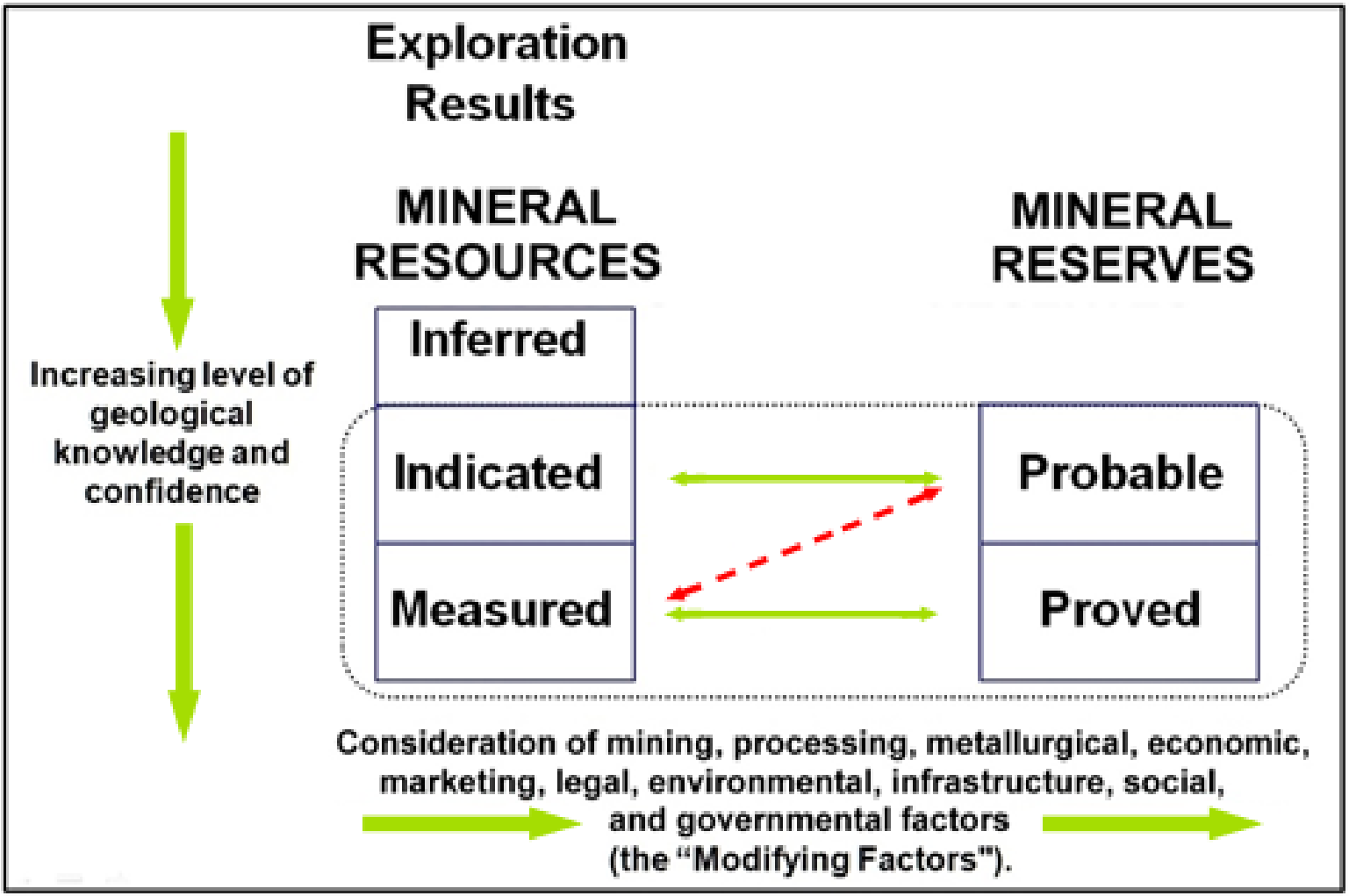
NASA Benefit

- Scenario 2
  - $800M initial investment
  - $1.3B total cost for 10 years of propellant supply
  - $3.45B annual savings (versus launching propellant from Earth)
  - 80% IRR
- Scenario 3
  - No initial investment
  - $10B total cost for 10 years of propellant supply
  - $2.5B annual savings (versus launching propellant from Earth)

Discussion

- Public-Private partnership constructs can substantially increase the returns to a commercial lunar propellant company
- Both models work
  - NASA up front investment to receive commodity price for propellant
  - NASA pledge (guarantee) to buy propellant at a pre-negotiated price for 10 years
    - Substantially below cost to transport propellant from Earth,
    - But above commercial commodity price
- NASA investment reduces up front cash well (debt) and provides early NASA commitment
  - The more NASA investment, the better
- NASA paying a premium price may generate higher returns in the long run, but entails the risk of long term government commitment

Developing a Proven Reserve



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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		Mining concept developed
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

Shoemaker Crater in 2030