Creating the Cislunar Economy

George Sowers

February 26, 2018

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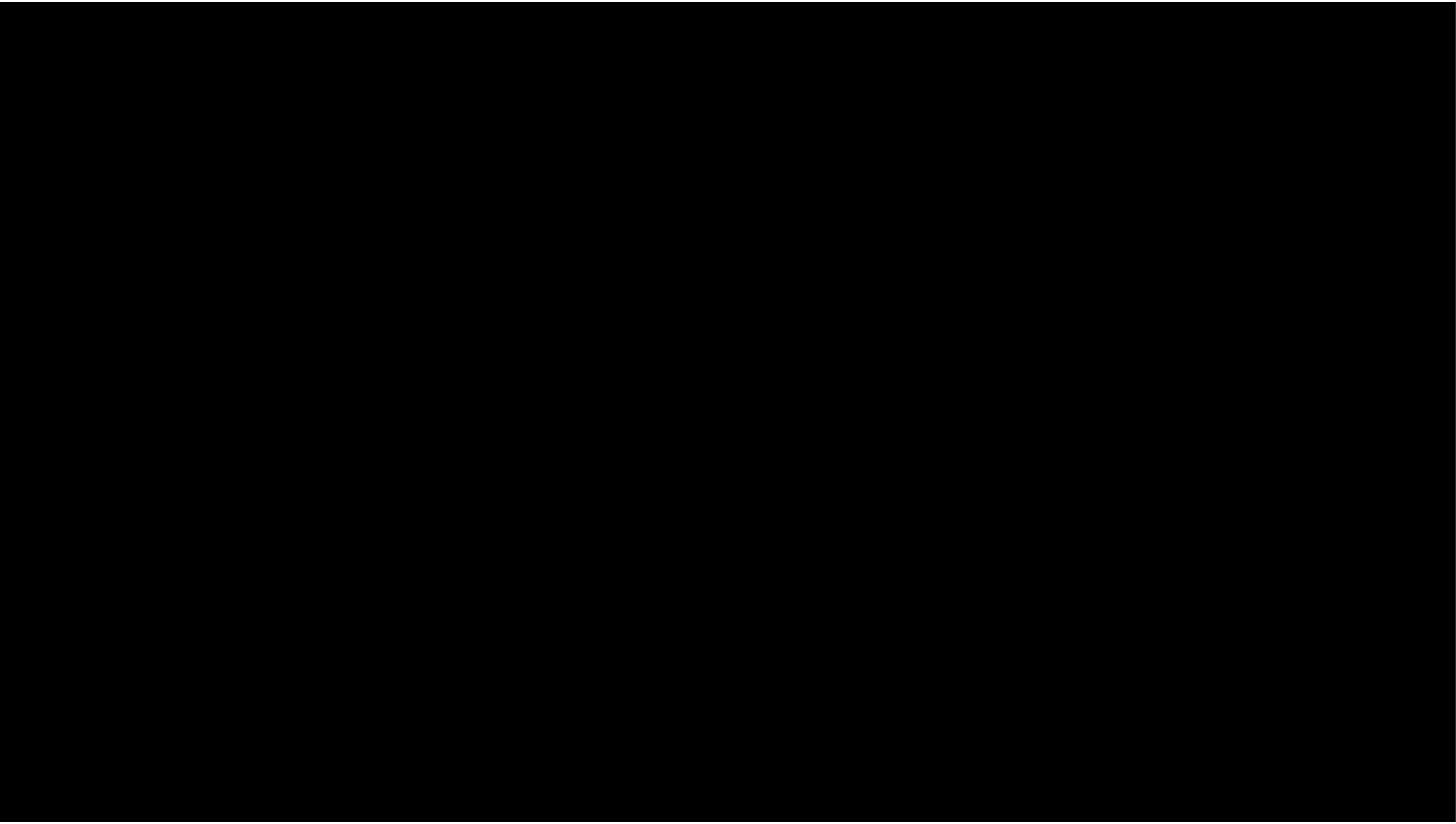

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Economic Revolutions

Revolution	Timeframe	Location	Energy capture	Impact
Evolution of modern humans, hunter-gatherers	~100,000 yrs ago	Africa	4-5,000 kcal/person/day	Spread throughout world
Agricultural	~10,000 yrs ago	Levant (hilly flanks)	High yield food, animal power: 10-30,000 kcal/person/day	Increased population, empires, crowding, disease
Industrial	~300 yrs ago	England	Fossil fuels: 50-230,000 kcal/person/day	Manufacturing, mining, transportation, prosperity, pollution, climate change
Space Resource	10-50 years from now	Cislunar space	LH2/LO2 propellants, solar power: >>250,000 kcal/person/day	Prosperity, green Earth, reduce/ eliminate scarcity, Downside?

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The Cislunar Economy

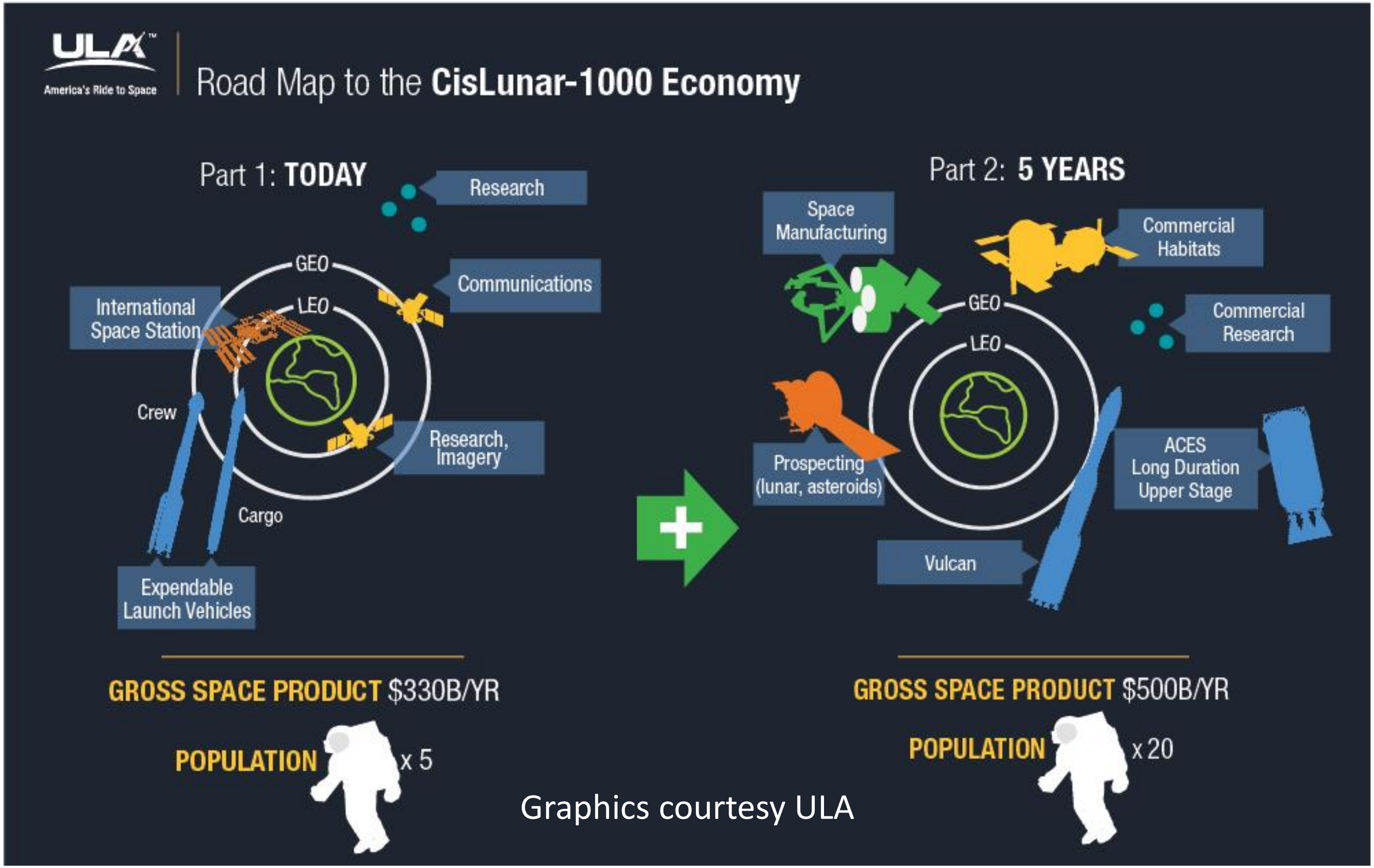
- Overarching goal: bring the resources of the solar system within the economic sphere of humankind
- Step one is creating a robust economy in cislunar space
  - Commercialization of space harnesses the positive forces of the free market
    - Competition, innovation, efficiency, growth

  For the benefit of consumers

  - Cislunar space is where it has to start because **right now all consumers live on Earth**

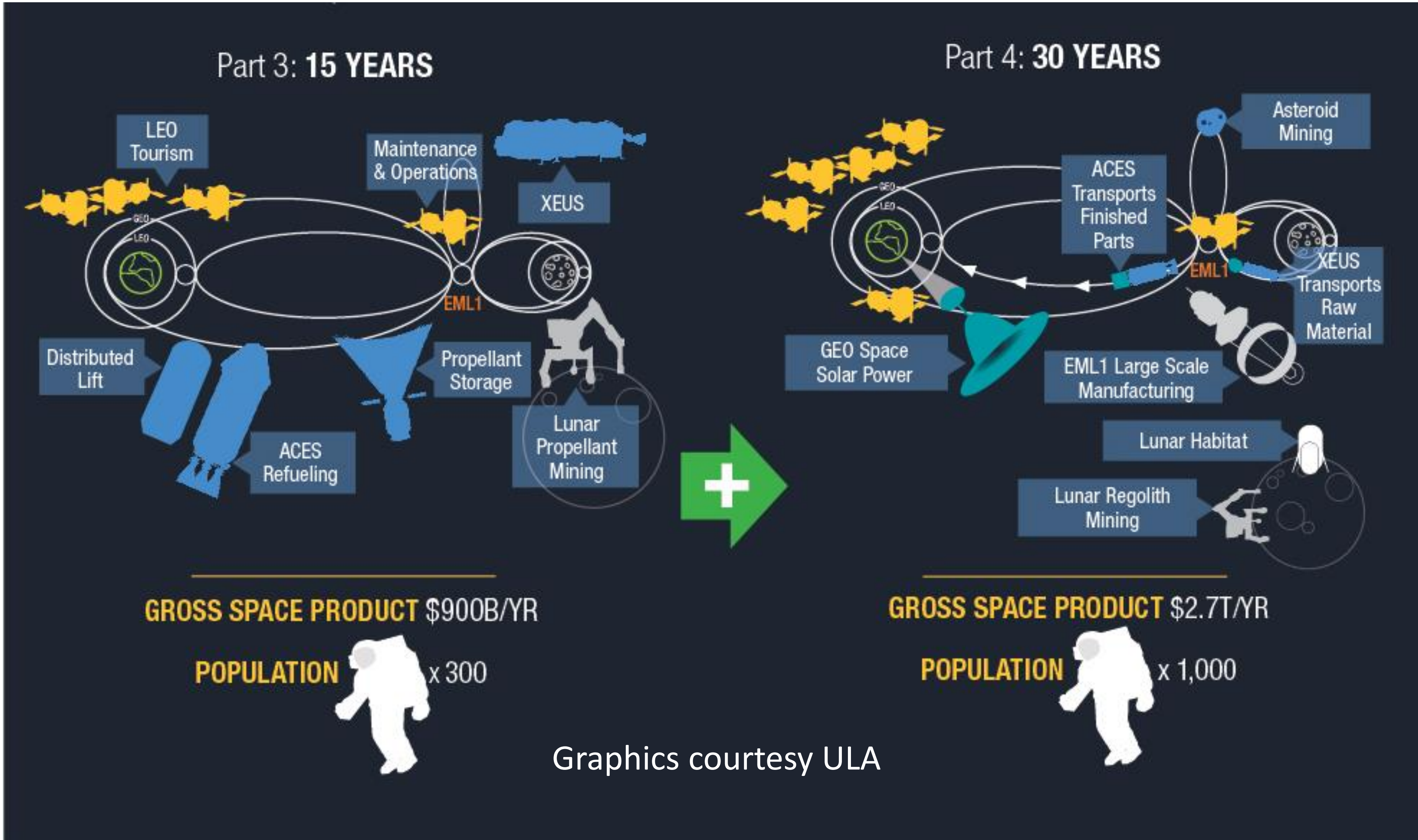
> The ultimate goal is not to impress others, or merely to explore our planetary system, but to use accessible space for the benefit of humankind.
> —John Marburger, 2006

Cislunar 1000 Vision



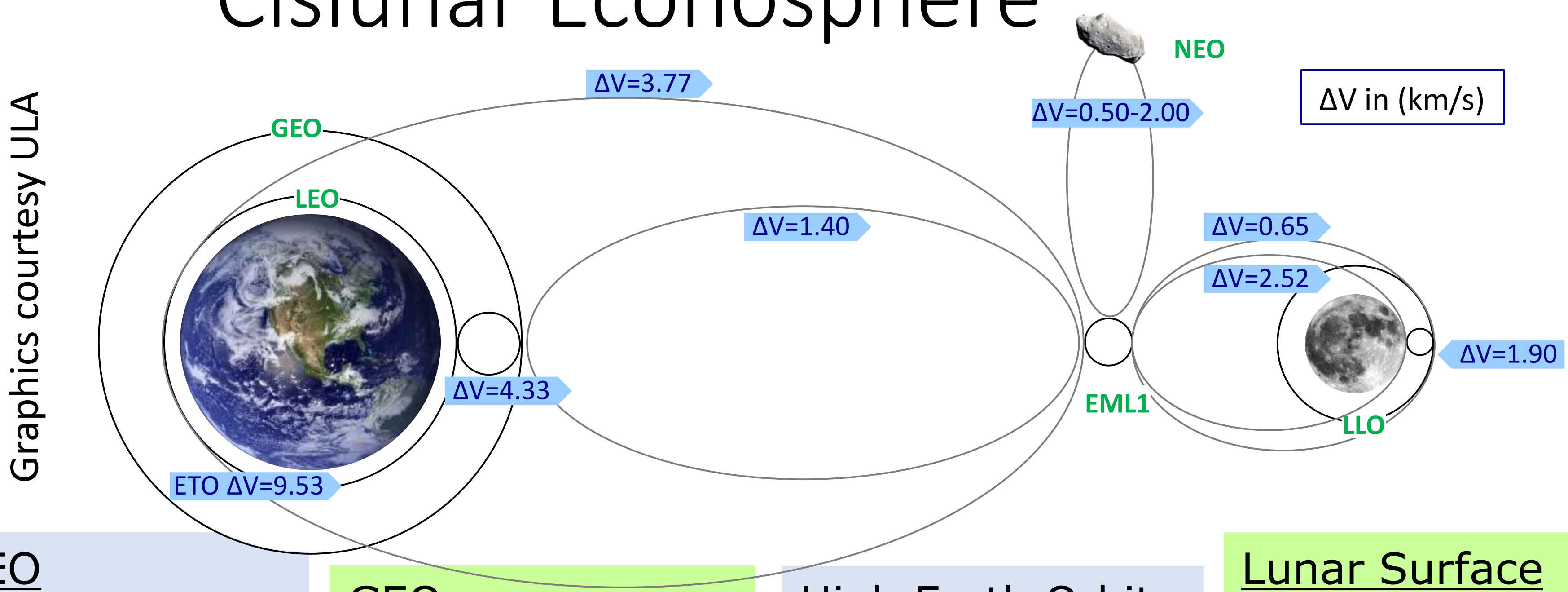
Graphics courtesy ULA

Cislunar 1000 Vision



Graphics courtesy ULA

Cislunar Econosphere



LEO
ISS
Remote Sensing
Commercial Station
Communication
Space Control
Debris mitigation
Science
R&D
Tourism
Manufacturing
Propellant Transfer
Data Servers

GEO
Observation
Communication
Space Control
Debris Mitigation
Space Solar Power
Repair Station
Satellite Life extension
Harvesting

High Earth Orbit
Science / Astronomy
Communication Link
Way Station
Propellant Depots
Repair Station
Lunar Solar Power Sat
Manufacturing
Planetary Defense

Lunar Surface
Science/Astronomy
- Lunar
- Observatory

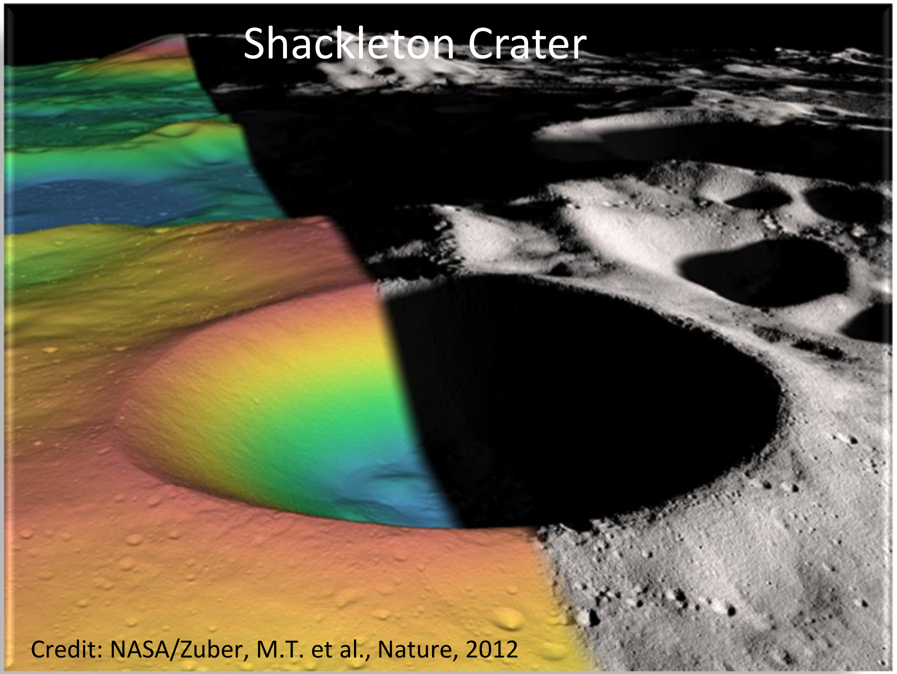
Human Outpost
Tourism
Mining
- Oxygen/Water
- Regolith
- Rare Earth Elements
- HE3

Manufacturing
Propellant Depots
Solar Power to Earth

Existing market / Emerging market \ Future market

Example: Propellant

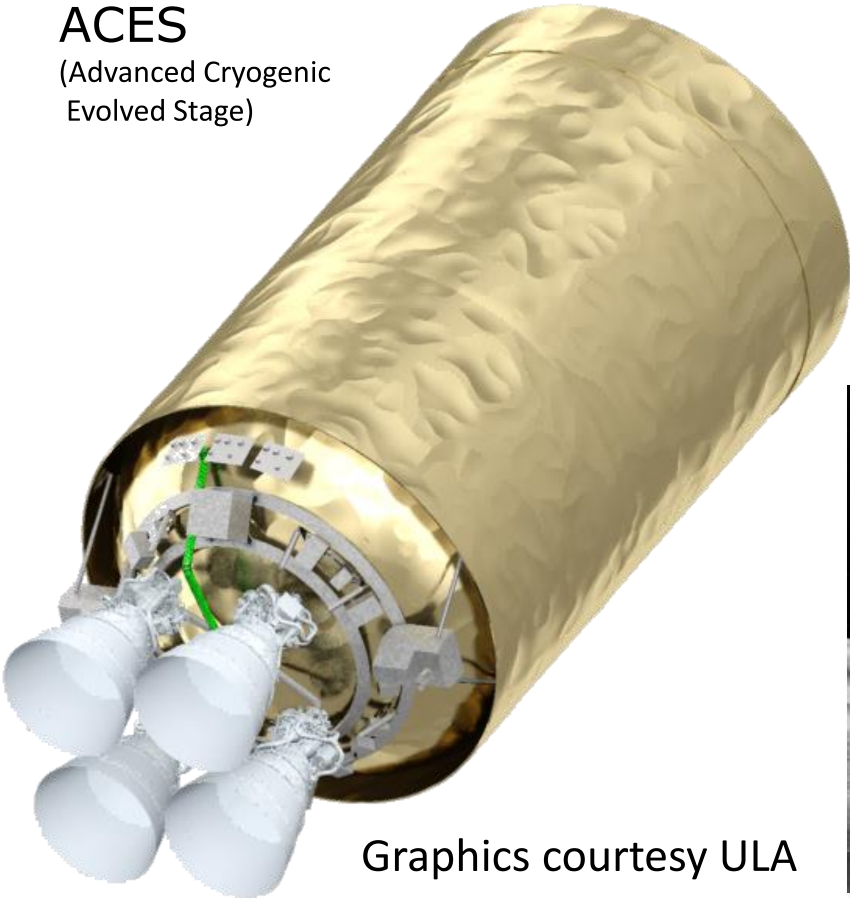
- One of the first economically viable uses of space resources will be propellant from water
  - Water is ubiquitous in the inner solar system
  - Water can be electrolyzed in to Hydrogen and Oxygen, then liquified into LO2/LH2 propellants
- Use of lunar or asteroid sourced propellant can:
  - Reduce the cost of a satellite to GEO
  - Reduce to the cost to launch to the lunar surface by 3X
  - Reduce the cost of a Mars mission by 2-3X
  - Enable a very low cost in-space transportation system



Credit: NASA/Zuber, M.T. et al., Nature, 2012

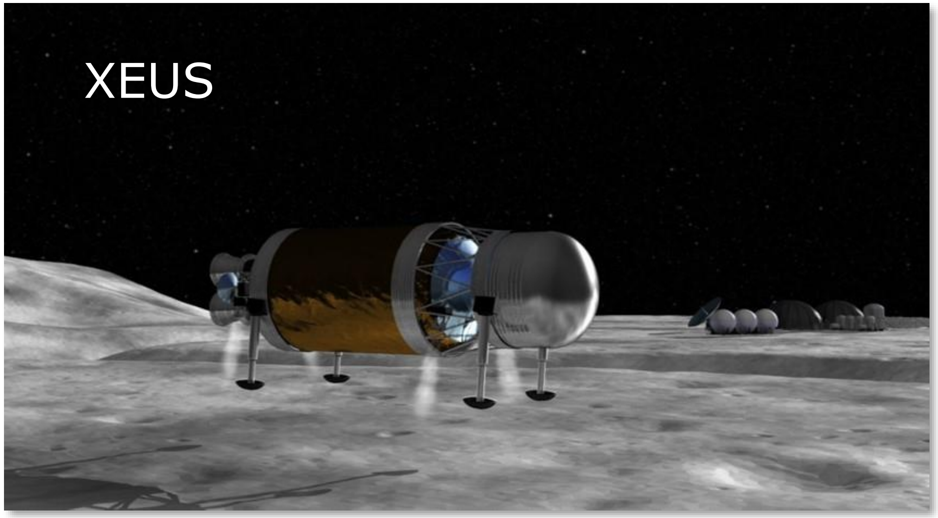
Cislunar Transportation System

ACES
(Advanced Cryogenic
Evolved Stage)



Graphics courtesy ULA

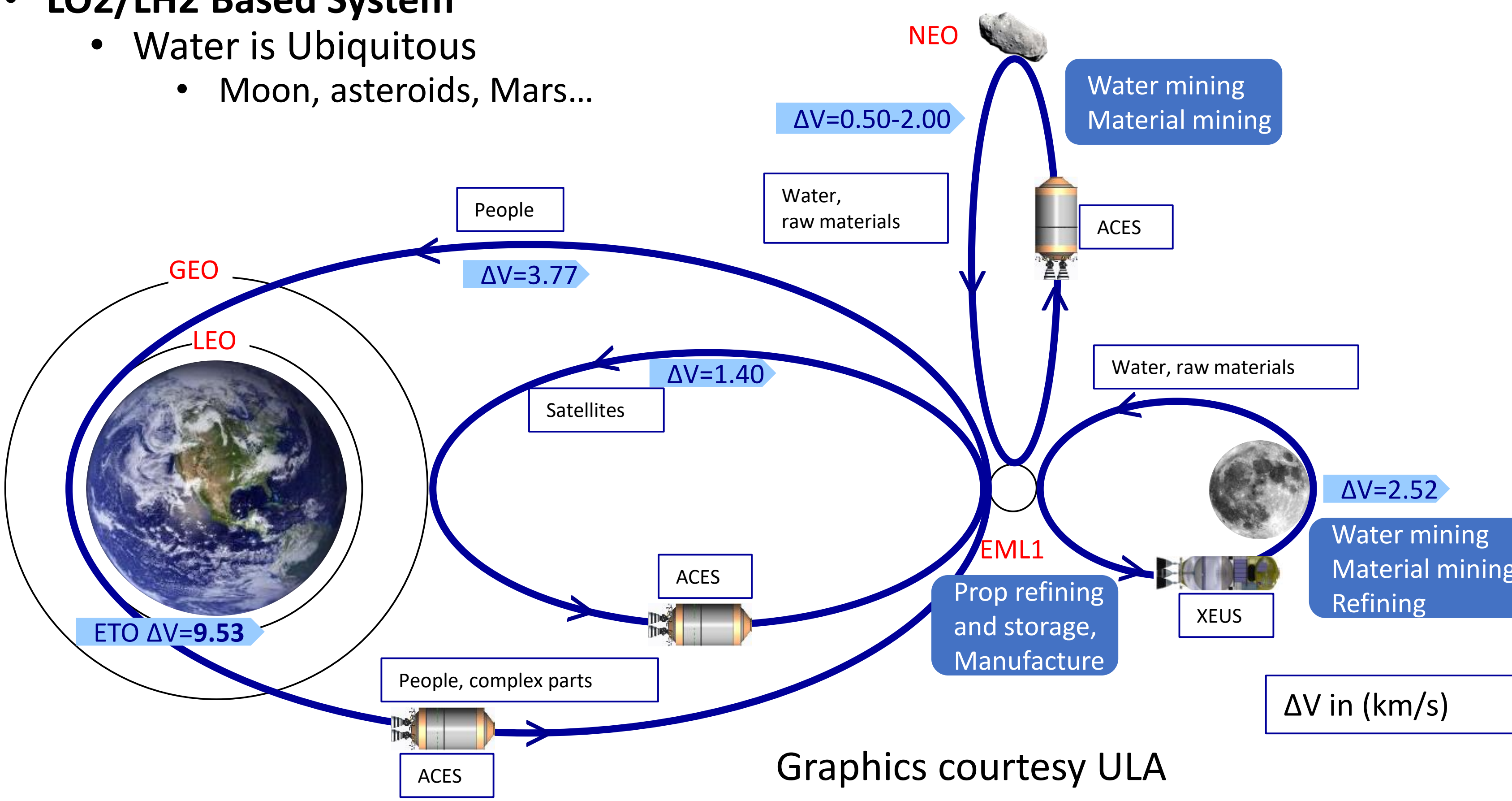
Fueled with LO2 and LH2 propellant provided from:
- Earth
- Moon
- Asteroids



Reusable Transportation Avoids Earth's Deep Gravity Well

Transportation System & Trade Routes

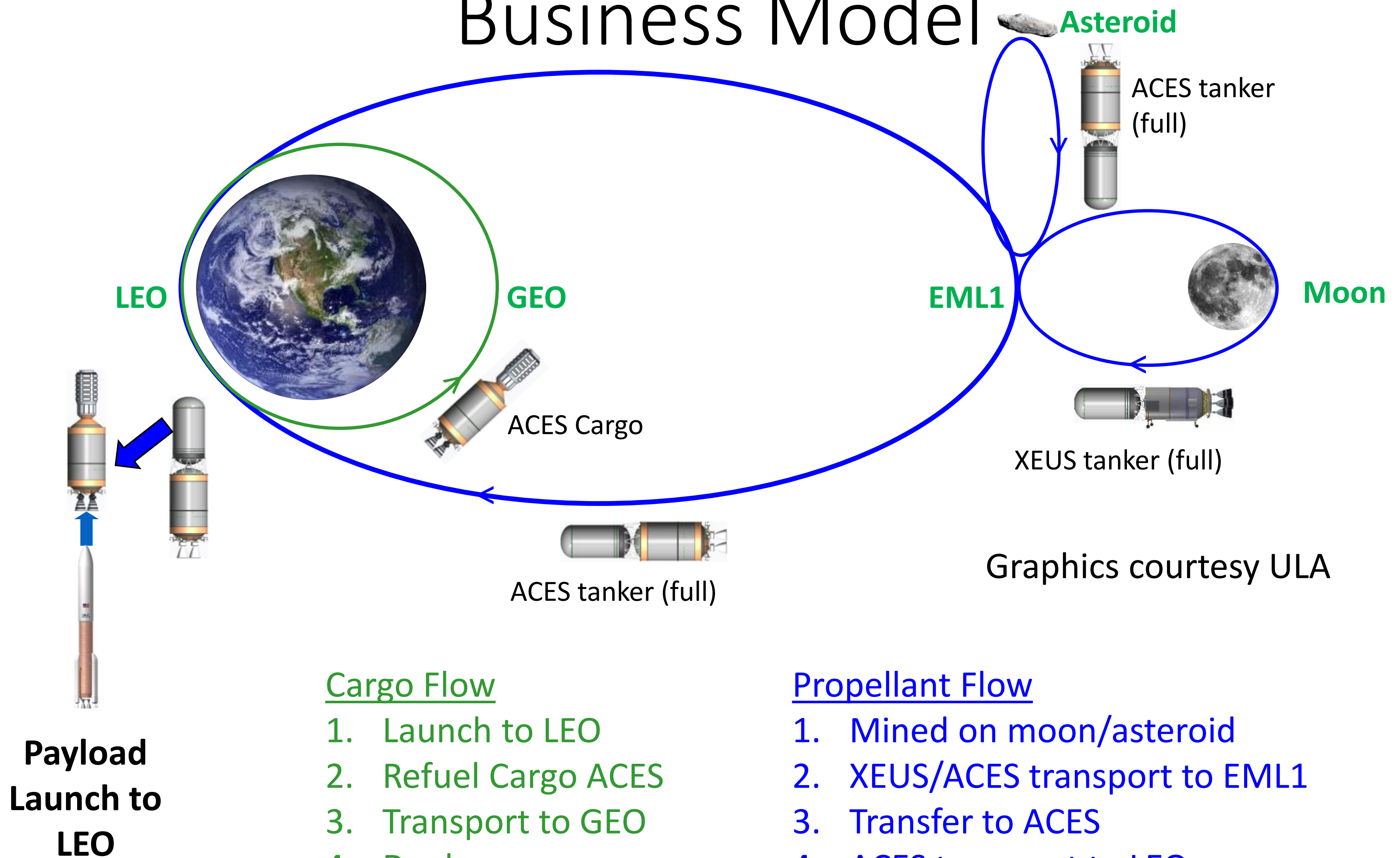
- **LO2/LH2 Based System**
  - Water is Ubiquitous
    - Moon, asteroids, Mars…



Graphics courtesy ULA

Fully Reusable Transportation System Serving Robust Cislunar Economy

Business Model



Graphics courtesy ULA

Cargo Flow

1. Launch to LEO
2. Refuel Cargo ACES
3. Transport to GEO
4. Deploy cargo

Propellant Flow

1. Mined on moon/asteroid
2. XEUS/ACES transport to EML1
3. Transfer to ACES
4. ACES transport to LEO
5. Transfer to cargo ACES

Business Case

- Key assumptions
  - If propellant can be purchased in LEO for less than the cost to ship it from Earth, then the price per kg to GEO can be reduced

    Price point = $3000/kg
  - For sizing, assume 3 ACES cargo flights per year
- Derived requirements:

Price in LEO	$3000/kg	Required to close business case
Prop delivered to LEO	210 mT/yr	assumption
Lunar propellant produced	1050 mT/yr	Based on ACES/XEUS transport from moon to LEO
Water mined	1575 mT/yr	Based on propellant MR of 5.5
Price at the moon	$500/kg	Based on cost to transport to LEO. Aerobraking could increase affordability by 2-3X

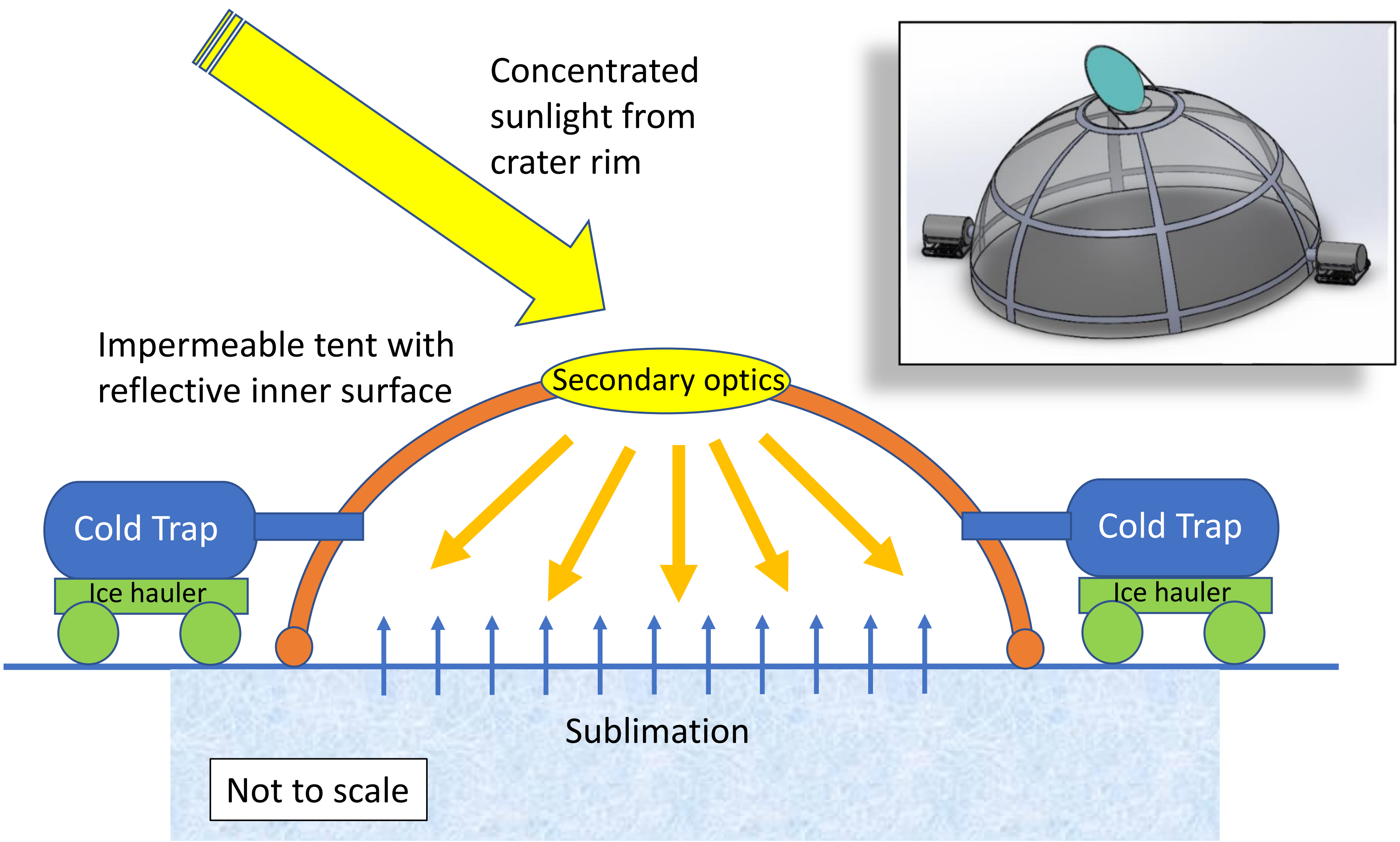
Lunar Mining

- More assumptions:
  - 10 year life of mining/production facility
  - 10% return on sales (ROS)
  - $50k/kg cost of to design/produce equipment on Earth
  - $35k/kg cost to transport to lunar surface (Vulcan/XEUS)
  - $3k/kg-yr cost to operate plant
- More derived requirements:

Plant mass	40.5 mT	Affordability limit
Plant efficiency	25.5 kg/yr /kg	Annual propellant output per kg of plant HW
Plant development cost	$2.02B	$50,000/kg
Plant delivery cost	$1.47B	$35,000/kg
Total non-recurring cost	$3.49B	Development + delivery

Lunar Mining Overview

Capture Tent Concept



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Option Comparison

Parameter	Option 1 Excavation	Option 2 Drilling	Option 3 Passive
Mass (kg)	40400	31900	29000
Development cost ($)	3.43B	2.71B	2.47B
Availability/ Maintainability	Medium	Medium-high	High
Risk	Low	Medium	Medium

Developing and fielding a Lunar mining operation to meet the business case *is feasible*

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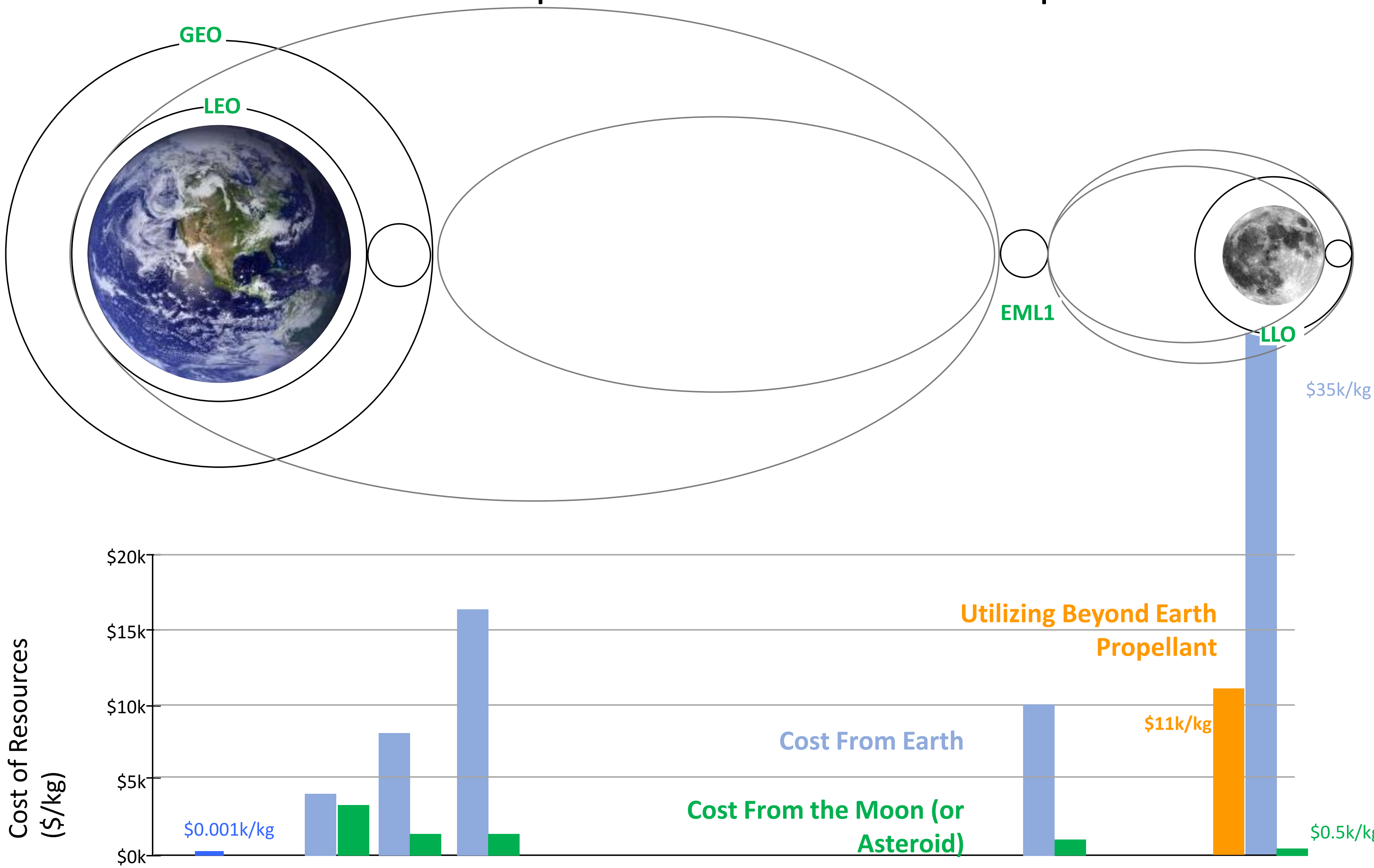
Costs of Propellant in Cislunar Space



Graphics courtesy ULA

Example: Space Solar Power

- Space Solar Power can transform the energy markets of Earth
  - $7T annual market
  - No carbon, unlimited
  - Available worldwide, 24/7

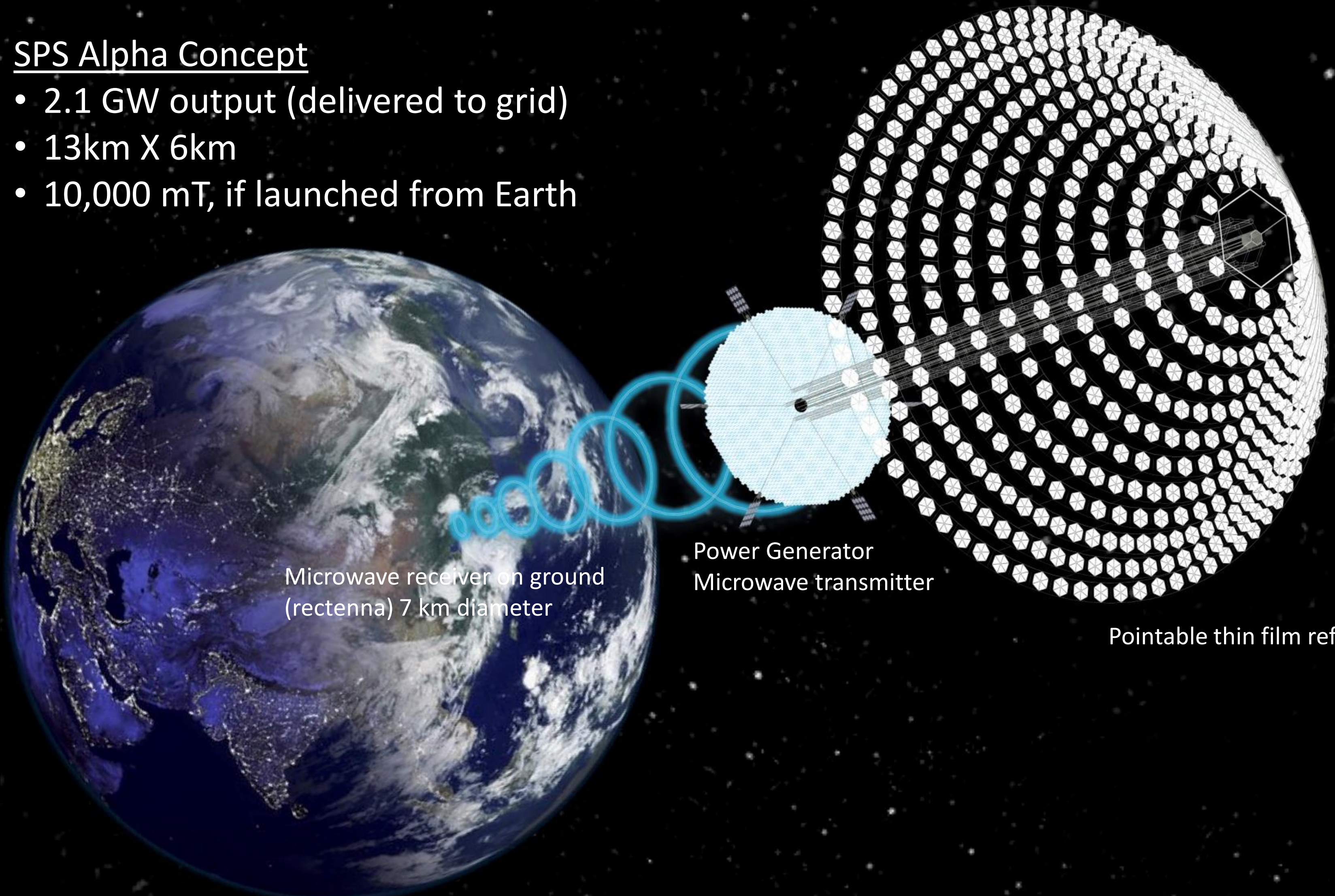
	Geosynchronous orbit	Golden, CO June	Golden, CO December
Average Daily Solar Power Incidence (kW-hr/m^2-day)	32.8	7.5*	2.5*

*From National Renewable Energy Lab (NREL), Golden Colorado

Space Solar Power

SPS Alpha Concept

- 2.1 GW output (delivered to grid)
- 13km X 6km
- 10,000 mT, if launched from Earth



SPS-ALPHA concept by John C. Mankins

SSP Business Case

- Scenario
  - Mine raw material on lunar surface
  - XEUS transfer to EML1
  - Manufacture Solar Power Satellite Components at EML1
  - ACES transfer from EML1 to GEO
  - Satellite assembly in GEO

- Business case assumptions
  - Solar power satellite mass (if manufactured in space)
    = 1/2 Solar power satellite mass (if launched from Earth)
  - Manufacturing cost in L1 = $1000/kg
  - Ground Infrastructure non-recurring cost = $100M
  - 10% additional material delivered from lunar surface to EML1
  - $2M operations cost for each ACES/XEUS trip, HW is free
  - Cost of propellant per previous business case: $500/kg on Moon, $1000/kg at EML1
  - 10 year amortization period
  - Annual operating cost = $200M

SSP Business Case Results

- Analysis
  - ACES can deliver 160mT from EML1 to GEO and return
  - XEUS can deliver 70mT from lunar surface to EML1 and return
  - Total transportation cost = $5.23B
  - Total manufacturing cost = $5.1B
  - Total non-recurring cost = $10.3B
- Results
  - Annual Revenue = $1.84B ($0.1/kW-hr)
  - Annual profit = $607M
  - Return on sales = 33%

Business case is feasible, costs comparable to large scale nuclear powerplant

Conclusion

- Space resources will spur the next economic revolution for humankind
  - Unlimited resource potential
  - Universal prosperity
  - Preserve the Earth for people
- The cislunar economy is the enabler
- Mining Lunar ice for propellant is the first step

We've always been able to imagine the future…
Now we see the path

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Space Resources Roundtable

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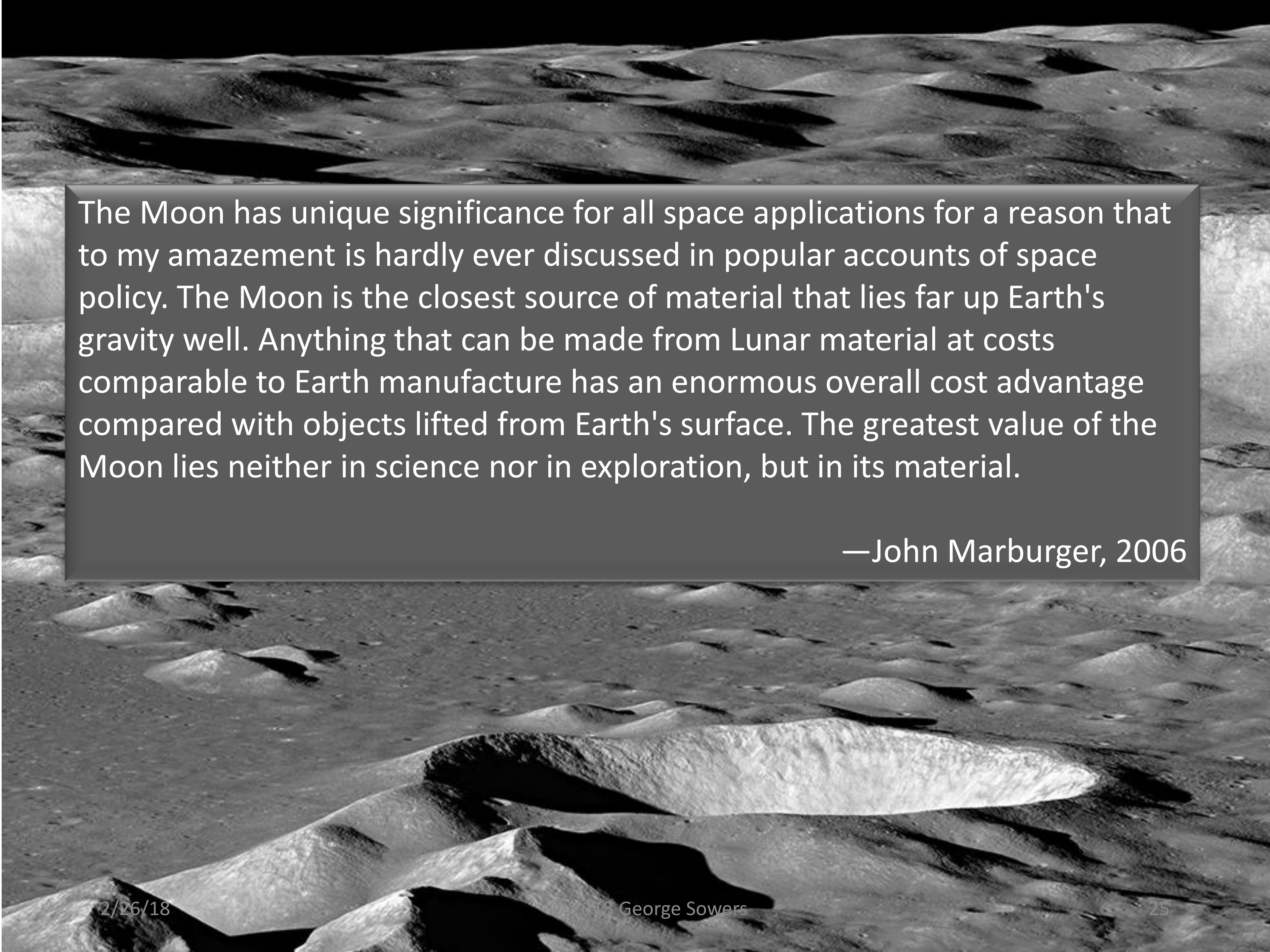
Lunar Polar Prospecting Workshop

June 12-15, 2018



The Moon has unique significance for all space applications for a reason that to my amazement is hardly ever discussed in popular accounts of space policy. The Moon is the closest source of material that lies far up Earth's gravity well. Anything that can be made from Lunar material at costs comparable to Earth manufacture has an enormous overall cost advantage compared with objects lifted from Earth's surface. The greatest value of the Moon lies neither in science nor in exploration, but in its material.

—John Marburger, 2006