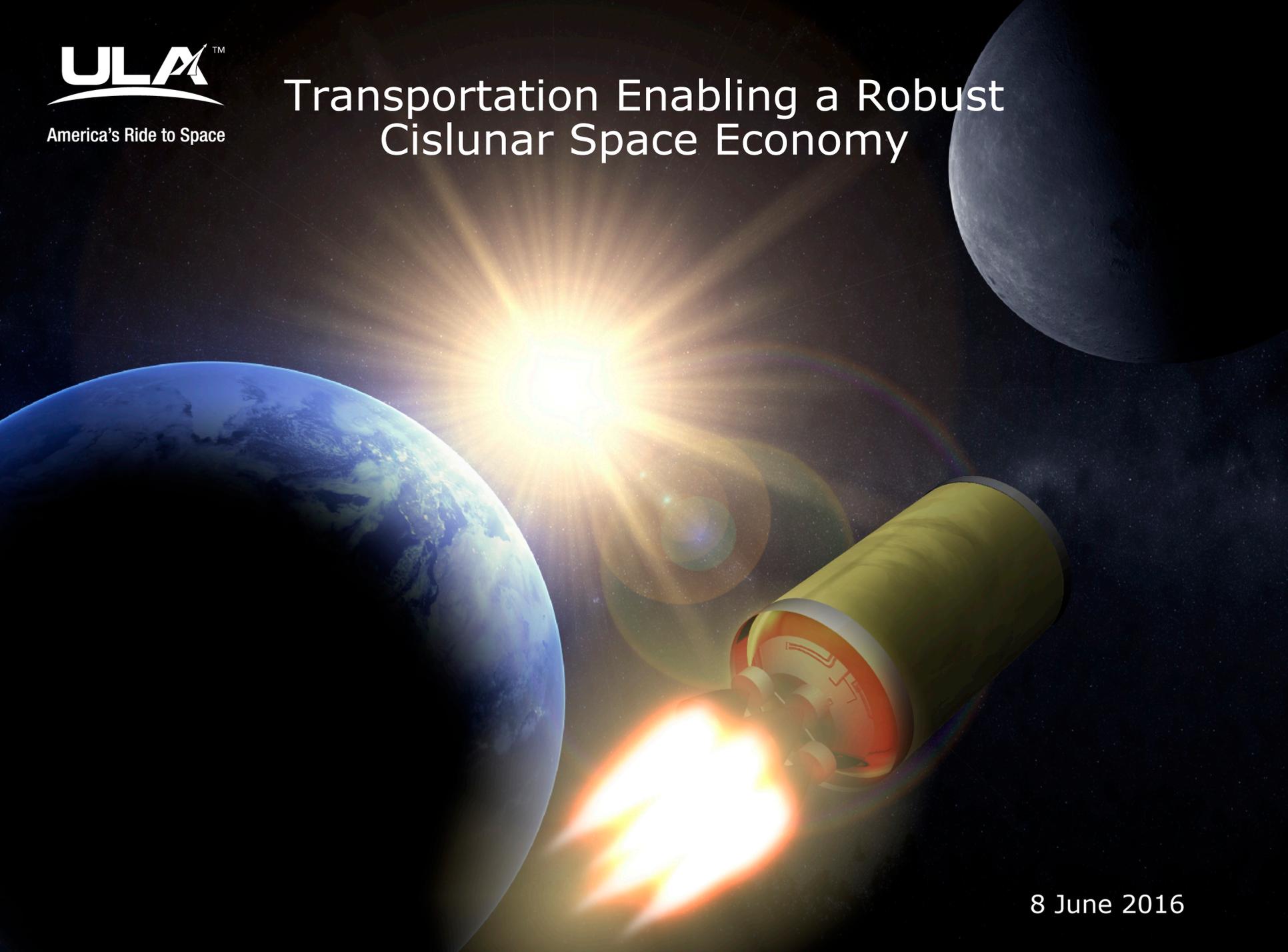




Transportation Enabling a Robust Cislunar Space Economy



8 June 2016

Space Commercialization

- ❑ The sustainability of the space enterprise hinges on the establishment of a robust space economy.
 - Otherwise, space activities are the sole purview of governments
- ❑ Commercialization of space harnesses the positive forces of the free market
 - Innovation, efficiency, competition, growth

For the benefit of consumers

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

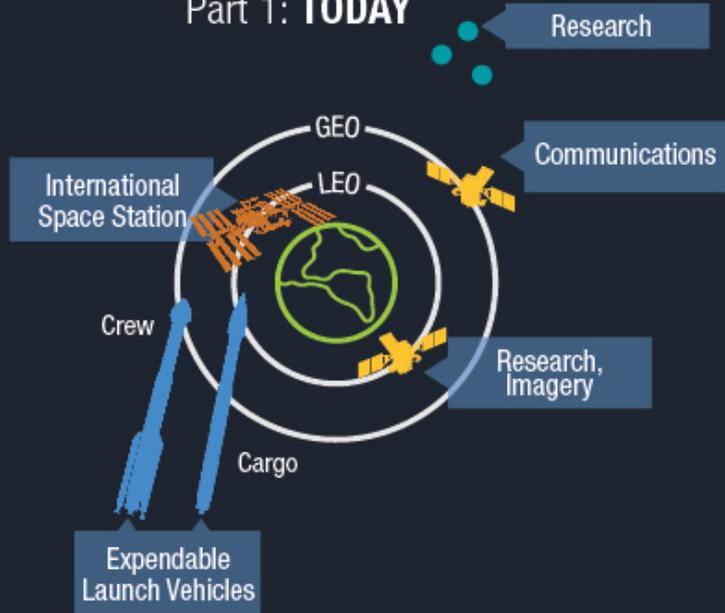
The ultimate goal is not to impress others, or merely to explore our planetary system, but to use accessible space for the benefit of humankind.

—John Marburger, 2006

Cislunar 1000 Vision

Road Map to the **CisLunar-1000 Economy**

Part 1: **TODAY**



GROSS SPACE PRODUCT \$330B/YR

POPULATION  x 5

Part 2: **5 YEARS**

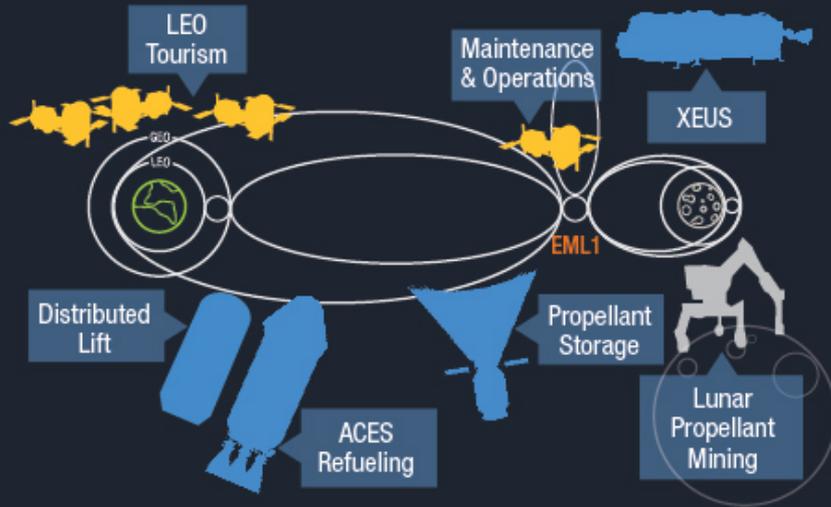


GROSS SPACE PRODUCT \$500B/YR

POPULATION  x 20

Cislunar 1000 Vision

Part 3: 15 YEARS

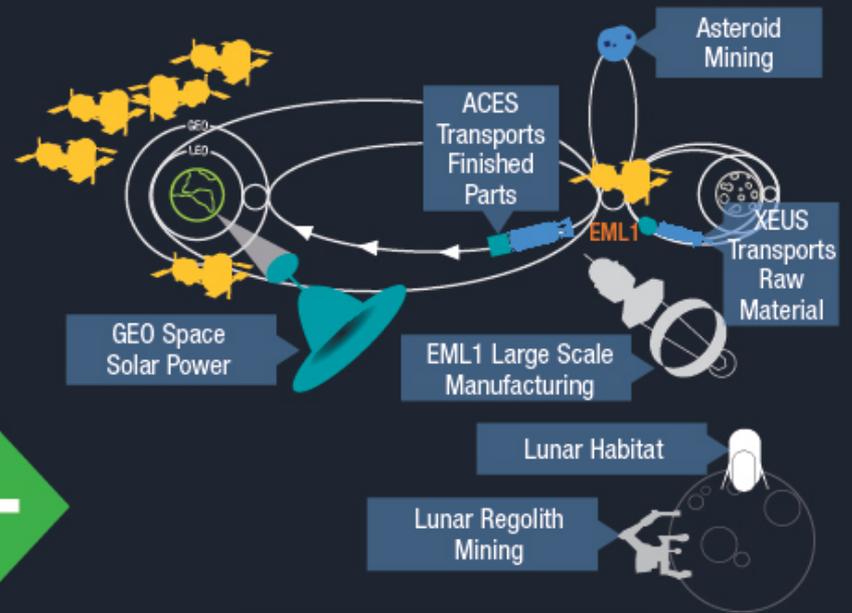


GROSS SPACE PRODUCT \$900B/YR

POPULATION x 300



Part 4: 30 YEARS

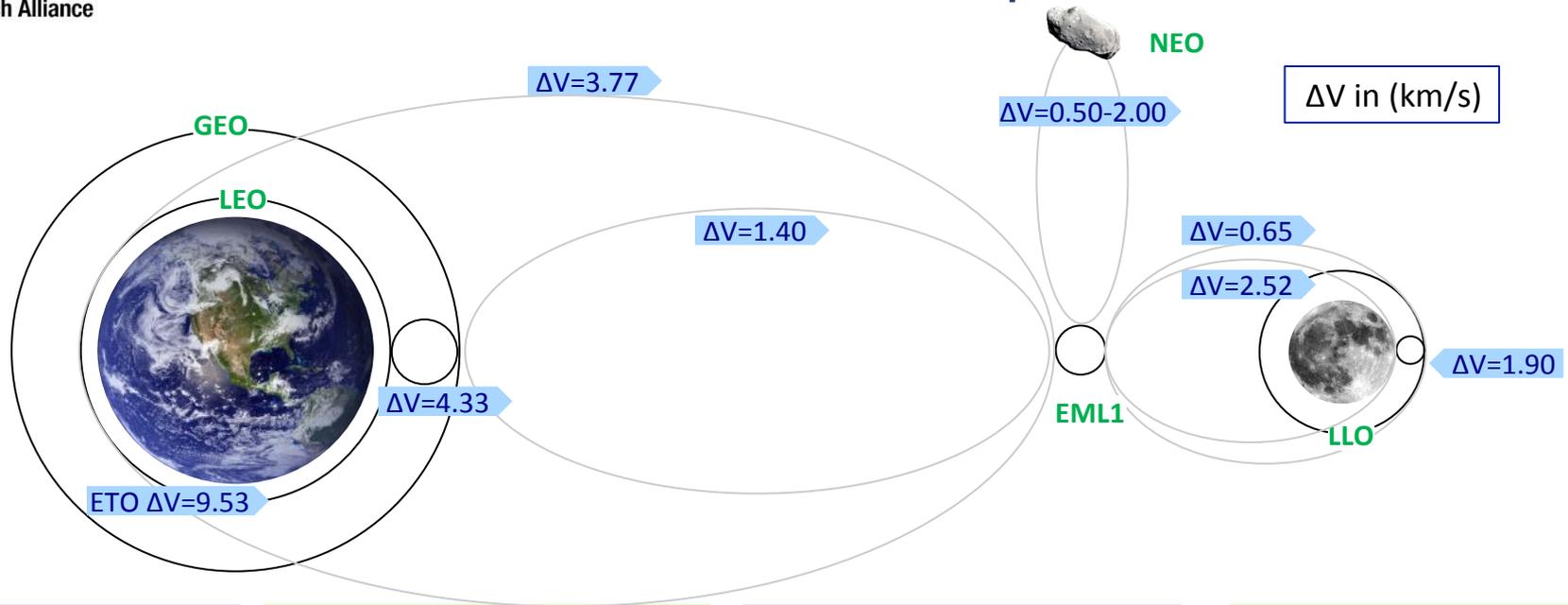


GROSS SPACE PRODUCT \$2.7T/YR

POPULATION x 1,000



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

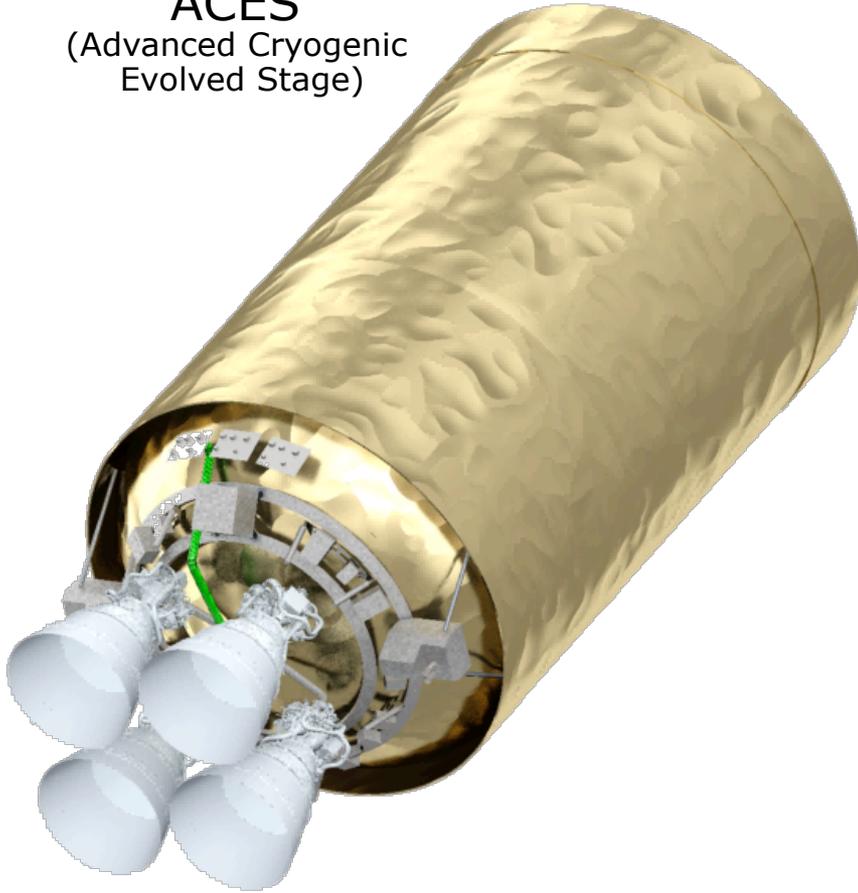
- Oxygen/Water
- Regolith
- Rare Earth Elements
- HE3

 Manufacturing
 Fuel Depots
 Solar Power to Earth

Existing market / Emerging market \ Future market

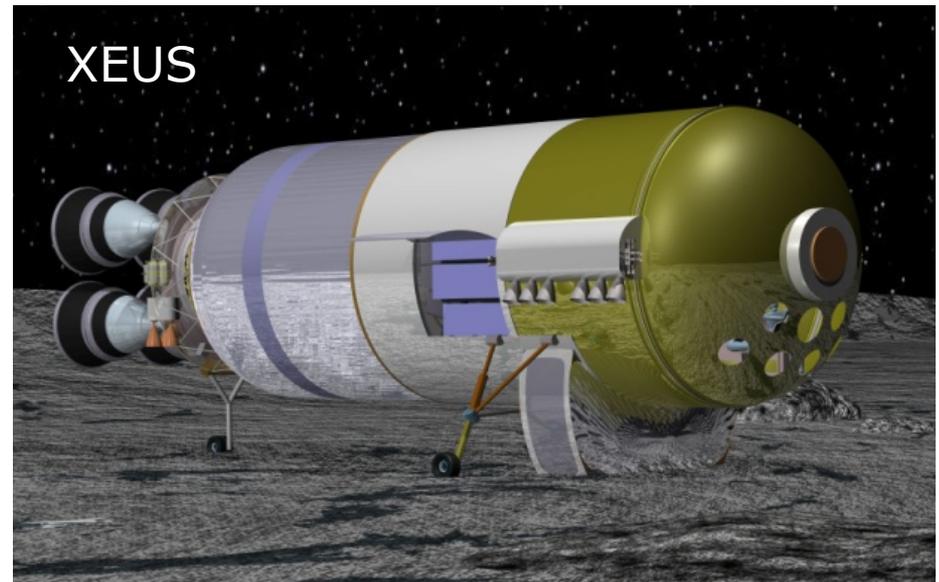
Cislunar Transportation System

ACES
(Advanced Cryogenic
Evolved Stage)



Fueled with LO2 and LH2
propellant provided from:

- Earth
- Moon
- Asteroids



Reusable Transportation Avoids Earth's Deep Gravity Well

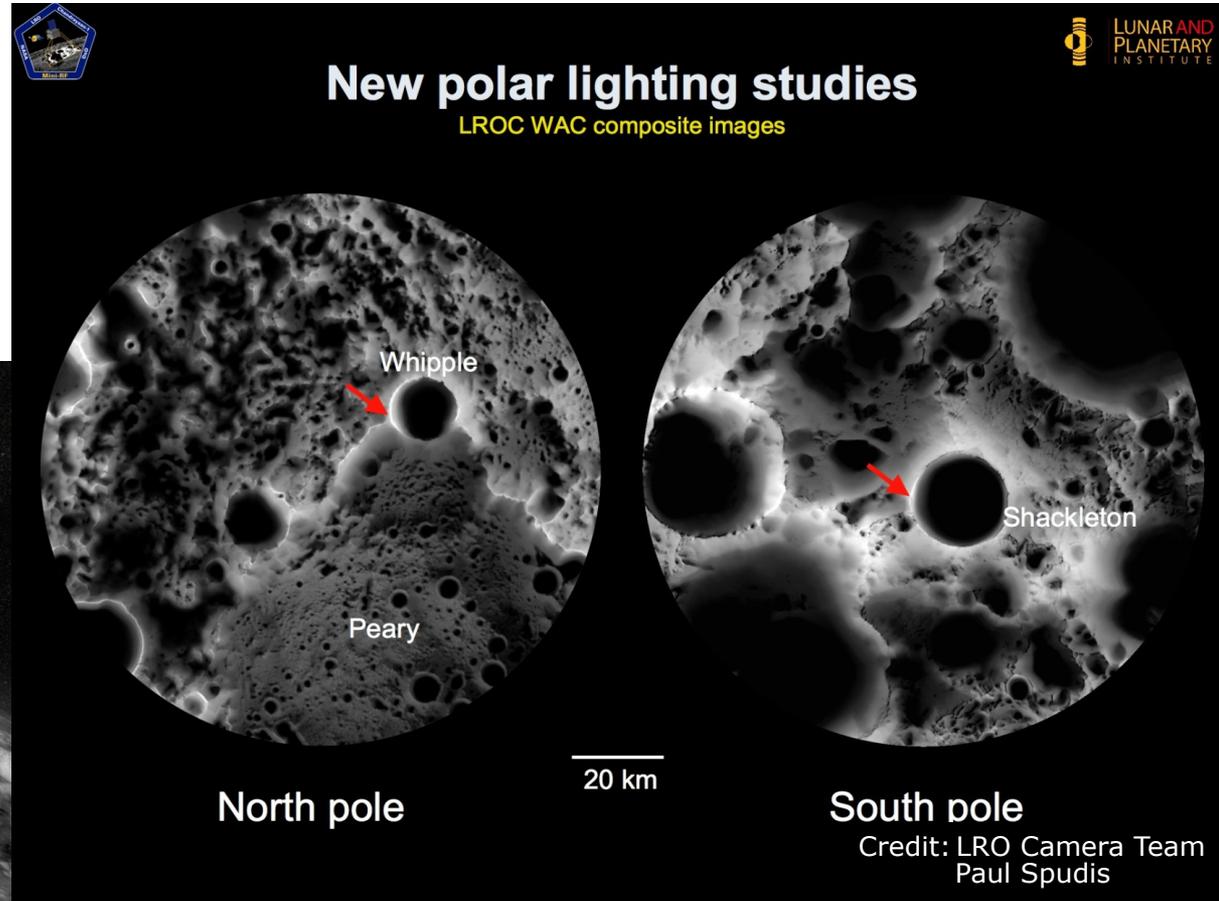
Lunar Water

- ❑ Water at Lunar poles
 - Cold Traps in Craters
 - ~10B mT per pole
- ❑ Fuel, Water, Oxygen

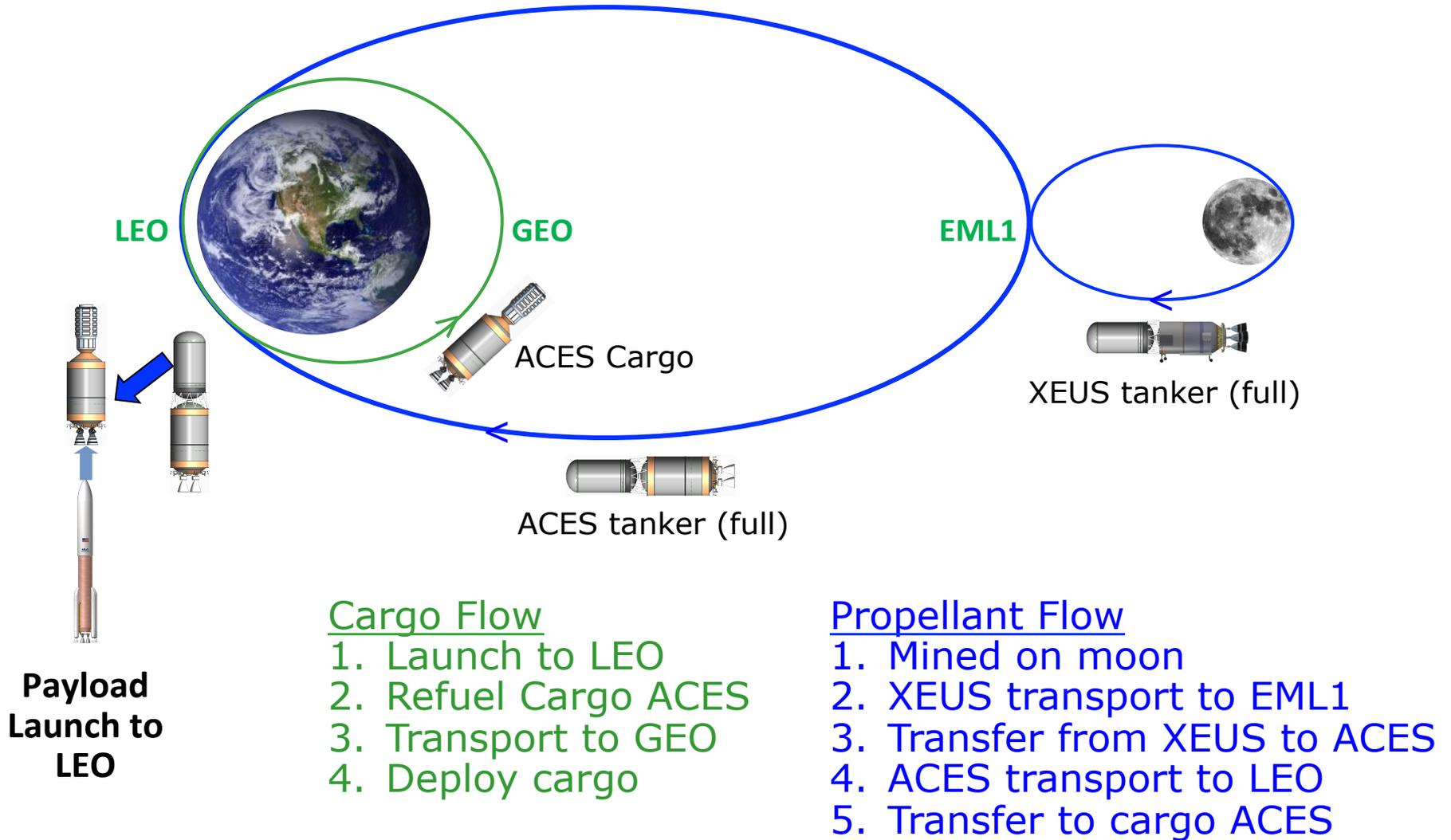
Lunar Reconnaissance Orbiter



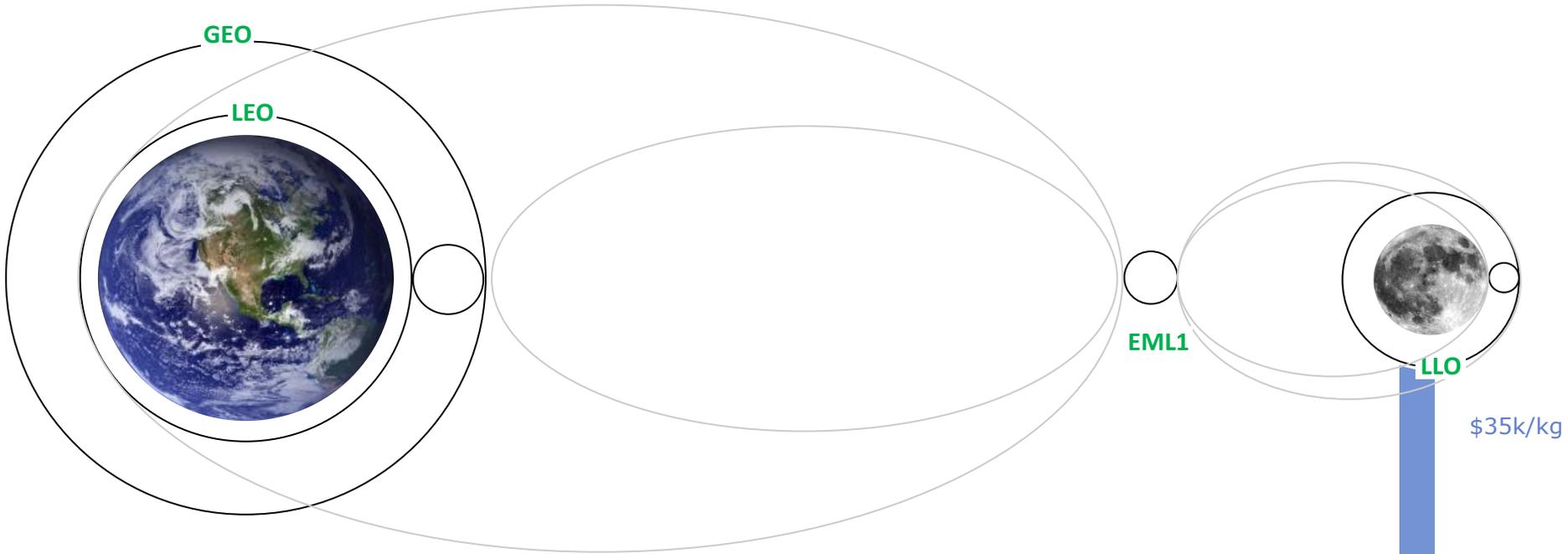
Credit: Chris Meaney / NASA 2008



Business Model



Costs of Resource in Cislunar Space



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 = \$3M/mT

- For sizing, assume 3 ACES cargo flights per year

□ Derived requirements:

Price in LEO	\$3M/mT	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	\$0.5M/mT	Based on cost to transport to LEO. Aerobraking could increase affordability by 2-3X

Lunar Mining

□ More assumptions:

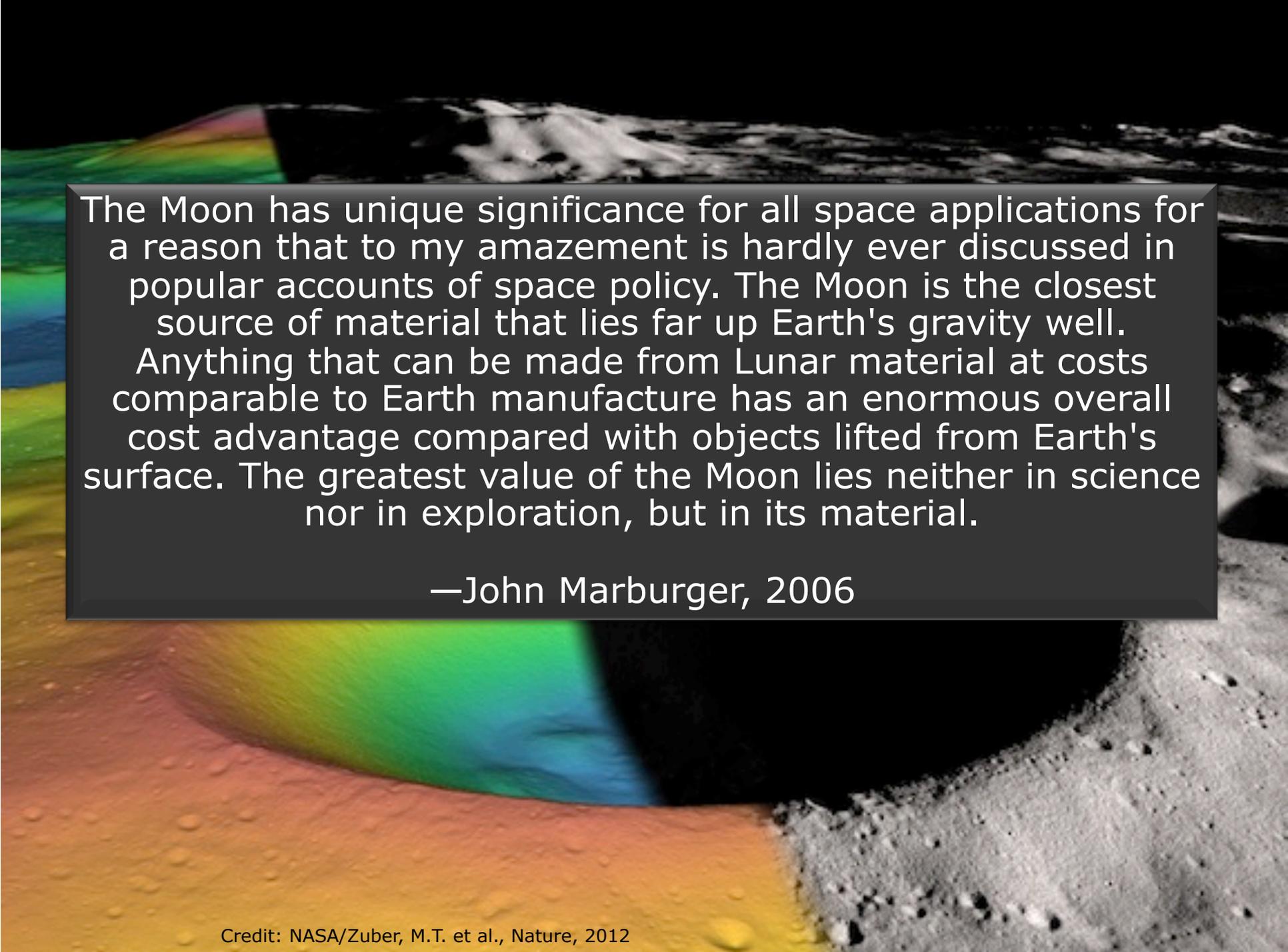
- 10 year life of mining/production facility
- 10% return on sales (ROS)
- \$50k/kg cost of equipment on Earth
- \$35k/kg cost to transport to lunar surface (Vulcan/XEUS)
- \$3k/kg-yr cost to operate plant

□ 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

What next?

- ❑ Is a lunar mining operation feasible within the parameters given?
 - Likely requires full robotics, very rich ice fields, clever extraction approaches, catalytic electrolysis, etc.
 - Solar power is unlimited but consumes budget.
- ❑ Improvements can be made
 - Aerobraking can significantly improve the business case
 - Propellant at higher orbits can potentially command higher prices
 - Private-public partnerships
- ❑ However, once started, a virtuous cycle can be sparked
 - The second propellant plant will be much lower cost
 - Transport cost reduced by >2X using lunar propellant
 - HW cost for 2nd unit should be much less



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