Economic Pathways to Space Mining

Philip Metzger, Florida Space Institute, University of Central Florida

The Kardashev Scale of Civilizations

Type 1
Uses the energy
of an entire planet.

Type 2
…of an entire star.

Type 3
…of an entire galaxy.

The Kardashev Scale of Civilizations

Type 1
Uses the energy
of an entire planet.

Type 2
…of an entire star.

Type 3
…of an entire galaxy.

The Kardashev Scale of Civilizations

Type 1
Uses the energy
of an entire planet.

Type 2
…of an entire star.

Type 3
…of an entire galaxy.

The Kardashev Scale of Civilizations

Type 1
Uses the energy
of an entire planet.

Type 2
...of an entire star.

Type 3
...of an entire galaxy.

How About some Earlier Categories?

Type 3 …an entire galaxy

Type 2 …an entire star

Type 1 …an entire planet

How About some Earlier Categories?

Type 3 …an entire galaxy
Type 2 …an entire star
Type 1 …an entire planet
Type 0 …an entire continent →

How About some Earlier Categories?

Type 3 …an entire galaxy
Type 2 …an entire star
Type 1 …an entire planet
Type 0 …an entire continent →
Type -1 …an entire river valley

Image credit: Eric Desrentes, Panoramio

How About some Earlier Categories?

Type 3 …an entire galaxy

Type 2 …an entire star

Type 1 …an entire planet

Type 0 …an entire continent

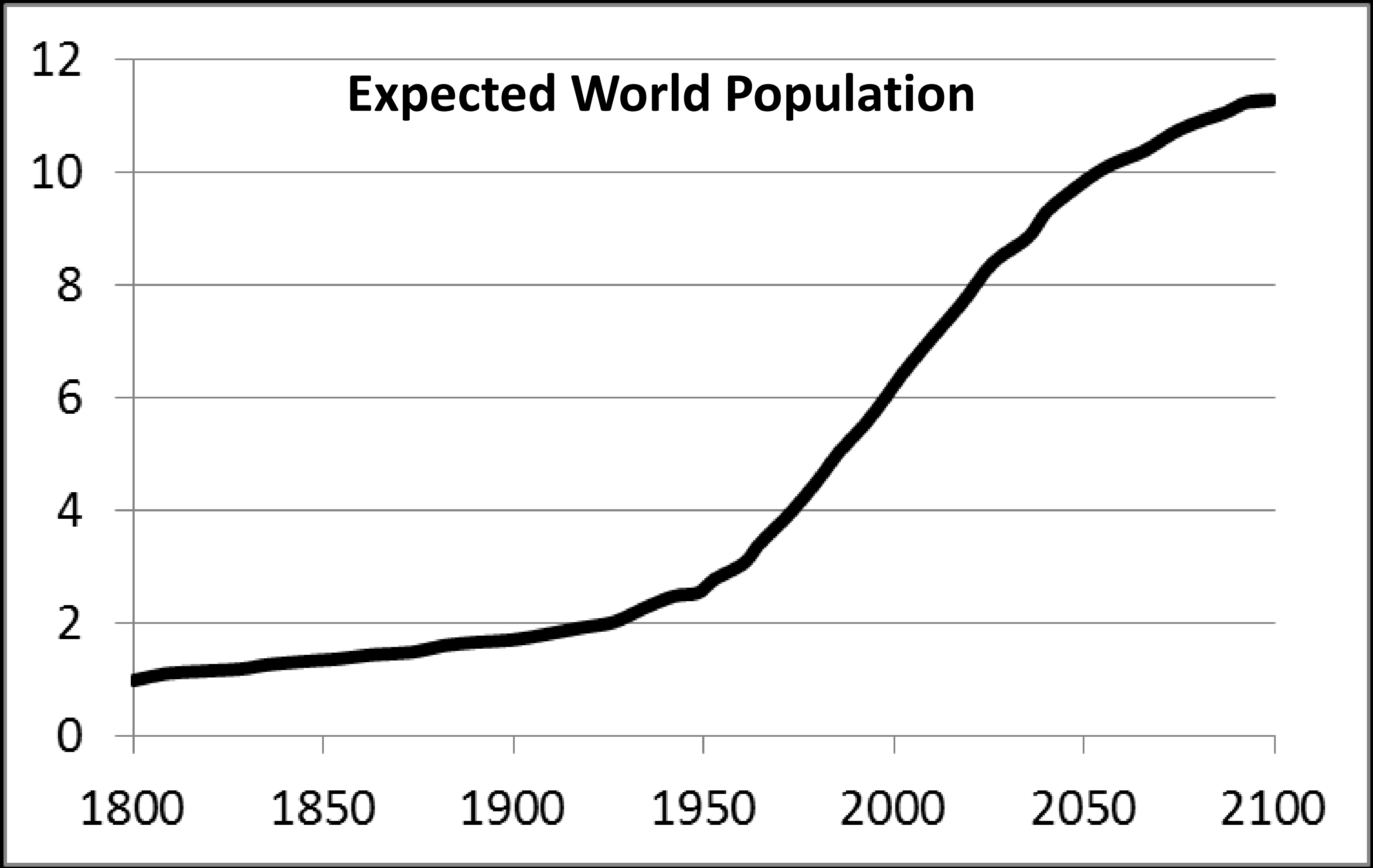
Type -1 …an entire river valley

Type -2 …an isolated enclave

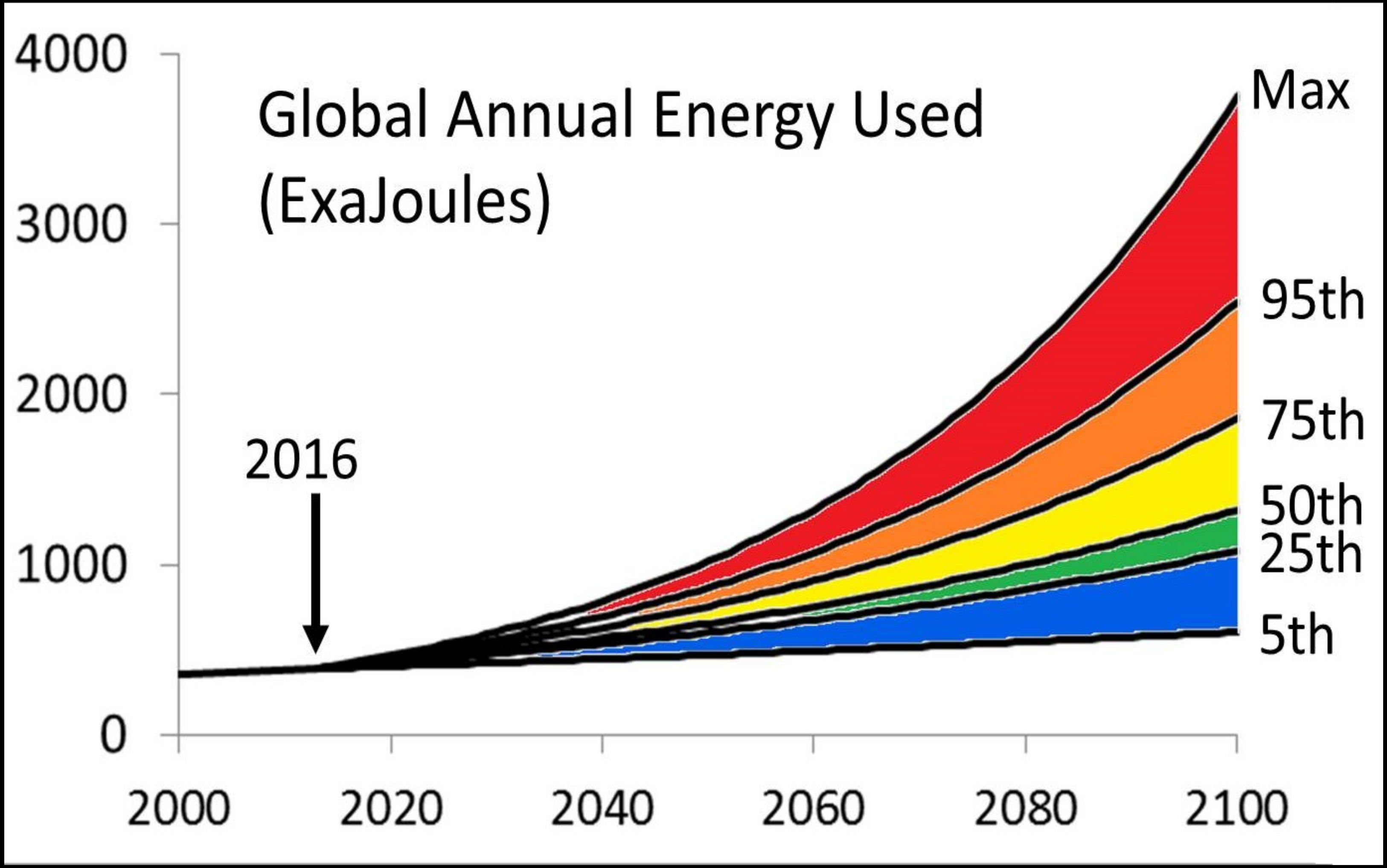
Image credit: Eric Desrentes, Panoramio

Image credit: Eric Desrentes, Panoramio

Reaching the Planetary Limit



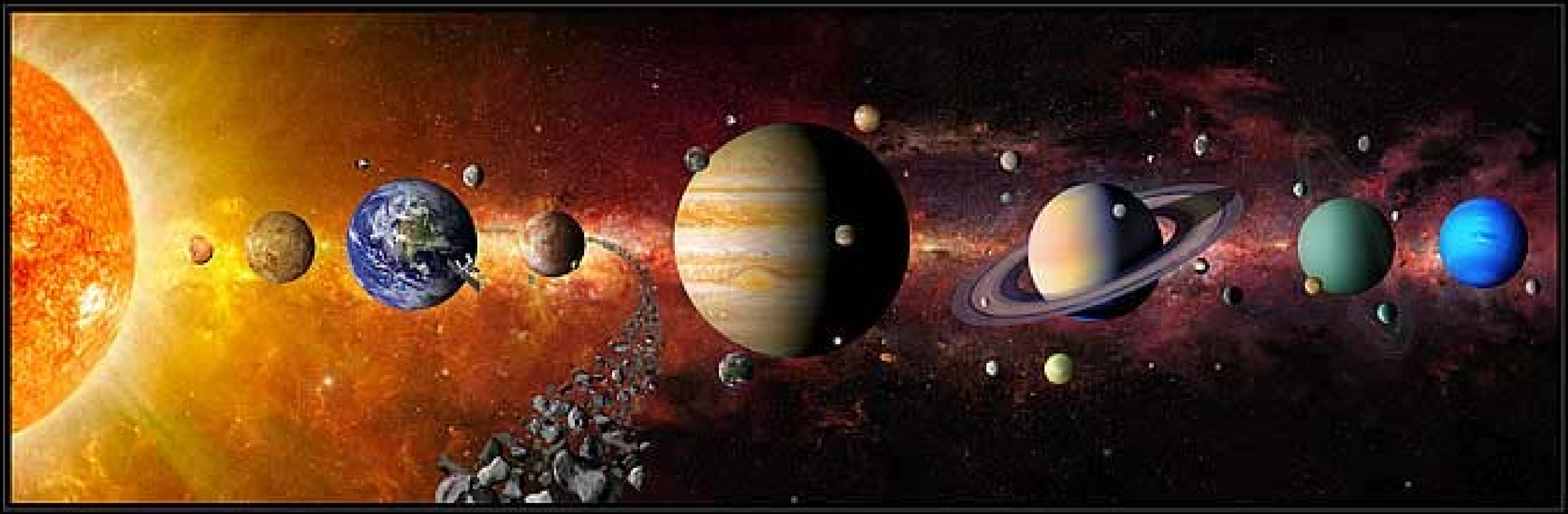
The (Practical) Planetary Energy Limit



Concerns with Planetary Limits

- Carbon in the atmosphere
- Nuclear fusion will phase in too slowly this century
- EROI from renewables is arguably too low to sustain healthy economy without greater levels of automation and industrial sprawl
- Exhaustion of the most enriched deposits of some economically important minerals
- Some of these minerals are important to renewable energy and the shortage threatens our ability to scale-up renewable energy to global levels
- Internet "capacity crunch"
- By 2040, energy to <u>operate</u> computers would consume all the energy the world produces
- Global energy limits to <u>manufacture</u> computers could be exceeded well before 2040
- Addressing some existential threats from space requires a "greater-than-planetary" level of response

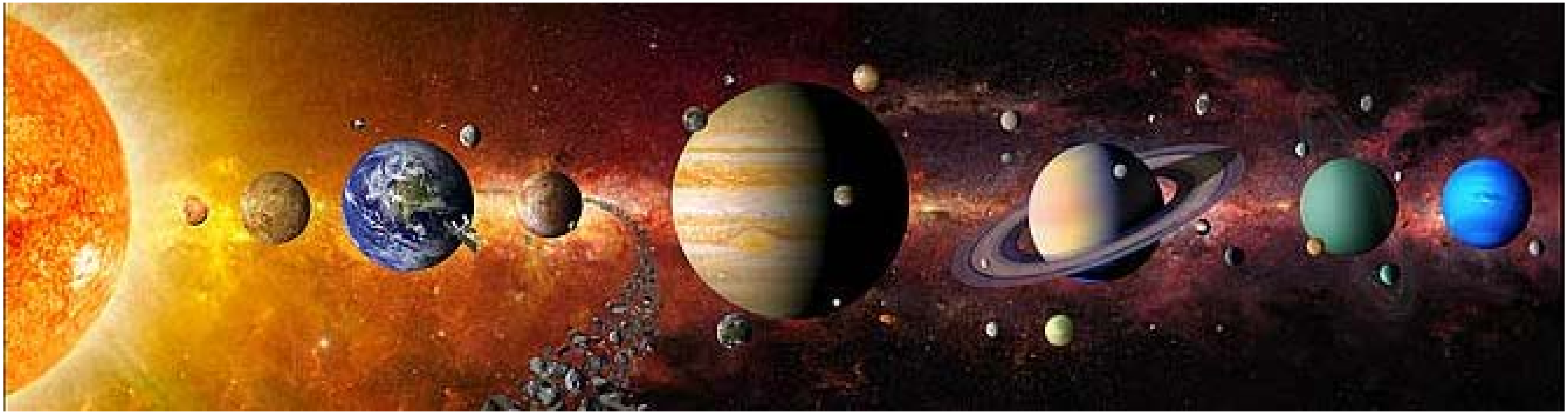
We do not have a resource problem.



What we have is an imagination problem.

Crossing the Barriers: A New Level of Civilization

Resource Zones in the Solar System

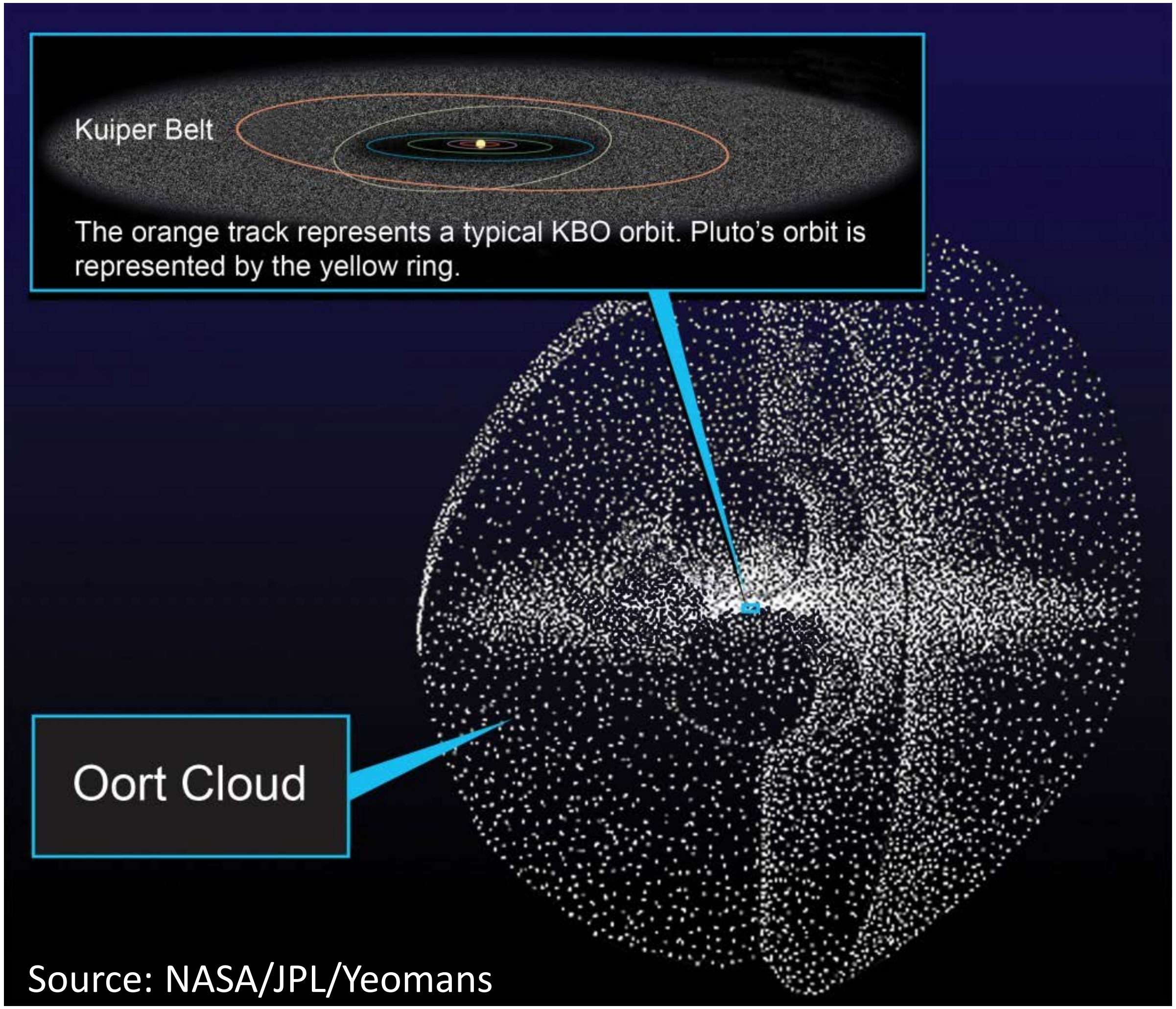


- Terrestrial Planets – materials accreting close to sun
- Main Asteroid Belt

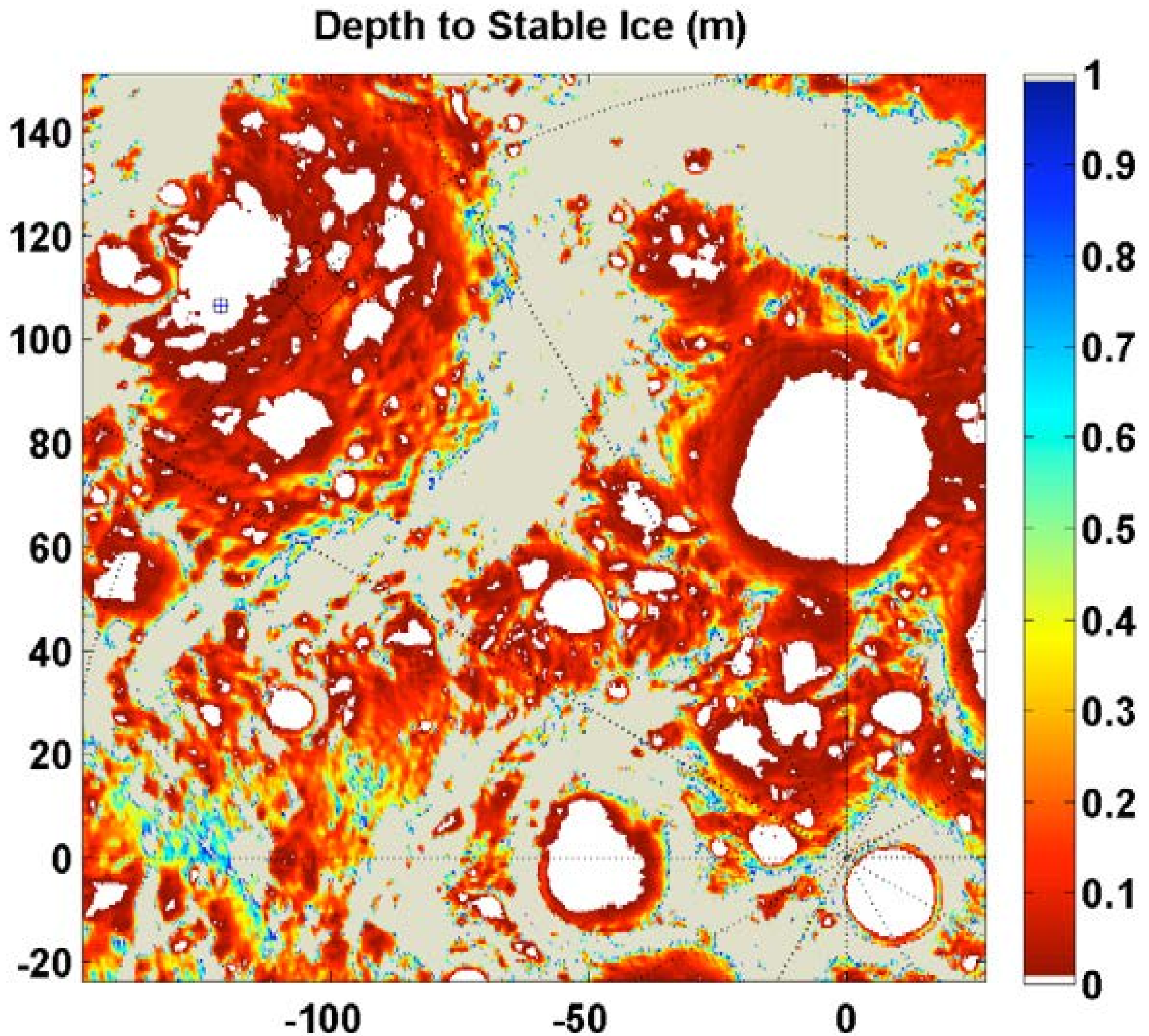
The "Frost Line"

- Gas Giants– volatiles that could accrete farther from the sun
- Moons of Gas Giants – icy bodies, some captured KBO's
- Kuiper Belt Objects (KBO's) – icy bodies
- Oort Cloud – icy bodies, the origin of comets

Kuiper Belt and Oort Cloud



Moon H_2O Resources



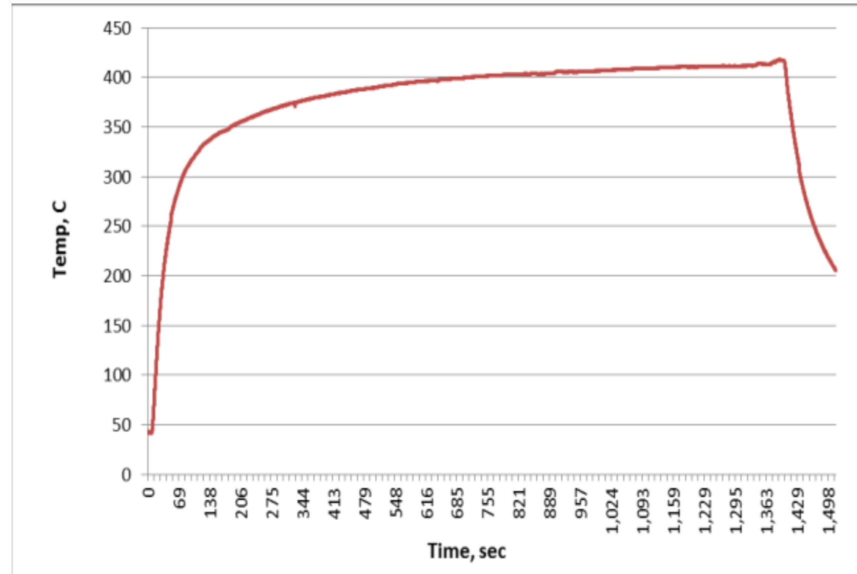
From Beyer, et al., 42nd LPSC, 2735.

[1] Paige, D. et al. (2010) *Science*, 330.

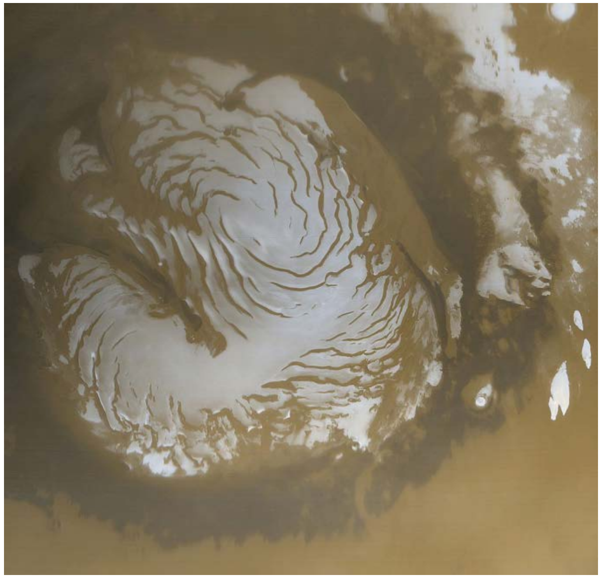
[2] Pieters, C. et al. (2009) *Science*, 326.

Depth (m) to the 1 kg/m2 per billion year ice loss isotherm, from [1]. White denotes stability within 1 cm of the surface, beige indicates stability below 1m [2].

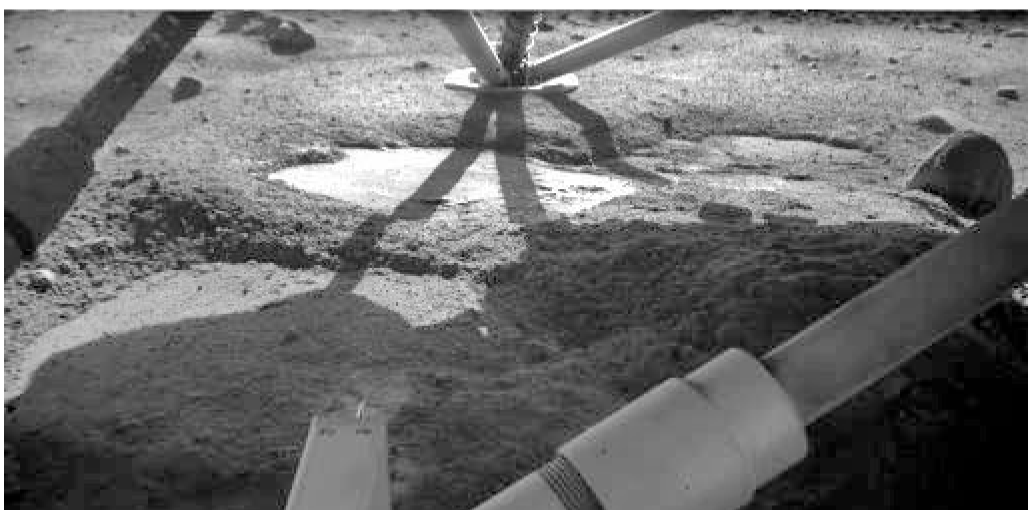
Carbonaceous Asteroid H_2O Resources



Mars H_2O Resources



Source: NASA/JPL/Malin Space Systems

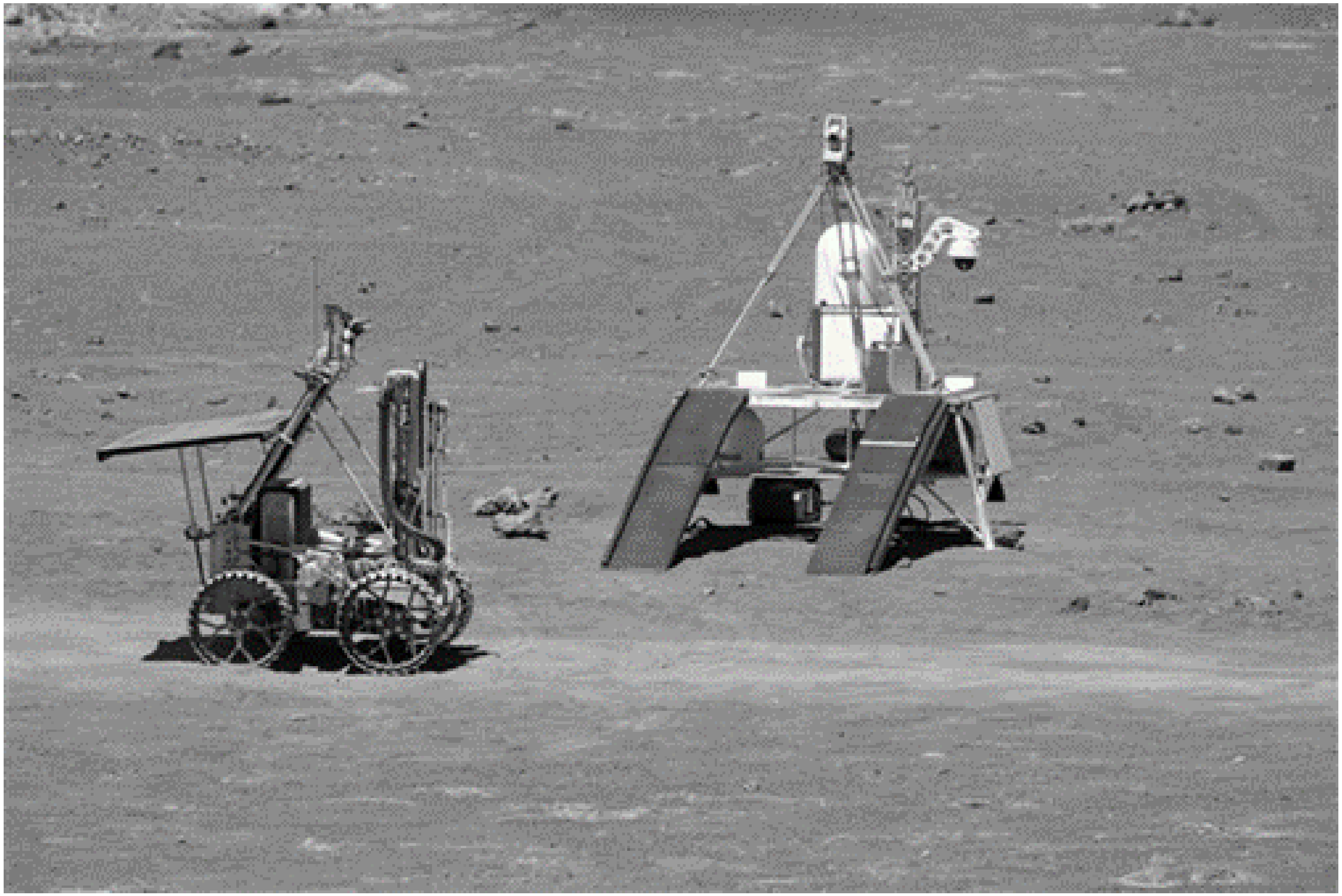


Source: NASA/JPL-Caltech/University of Arizona

Source: NASA/JPL-Caltech/University of Arizona/Texas A&M University

TECHNOLOGY TO UTILIZE SPACE RESOURCES

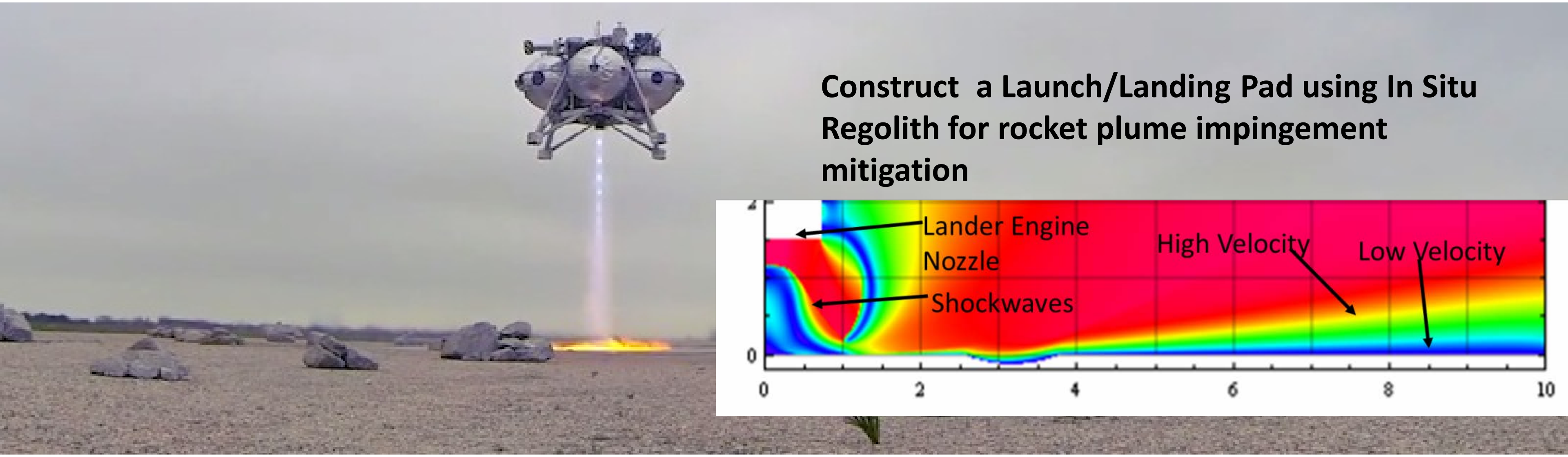
Resource Prospecting



NASA Lunar Resource Prospector -2018

Launch / Landing Pad Construction

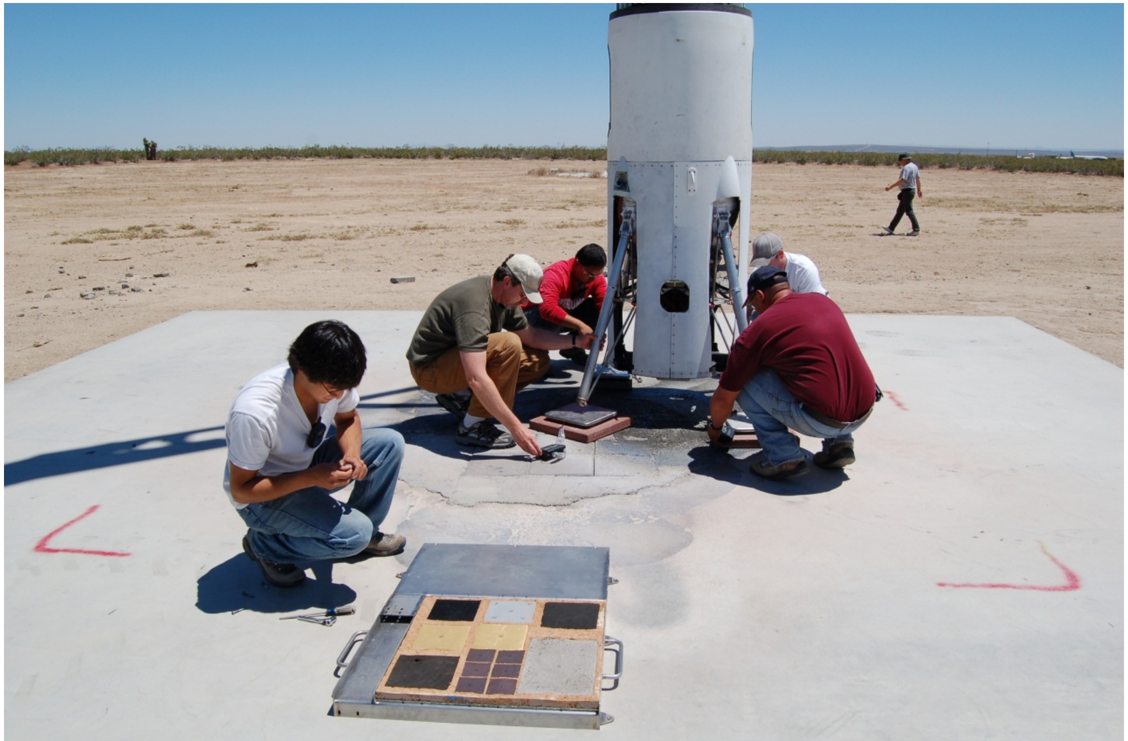
Construct a Launch/Landing Pad using In Situ Regolith for rocket plume impingement mitigation



NASA Chariot Bull Dozer

Hawaii PISCES Rover on Mauna Kea with Payloads

Landing Pads



Quick Attach and LANCE Blade

LANCE Blade on the LER

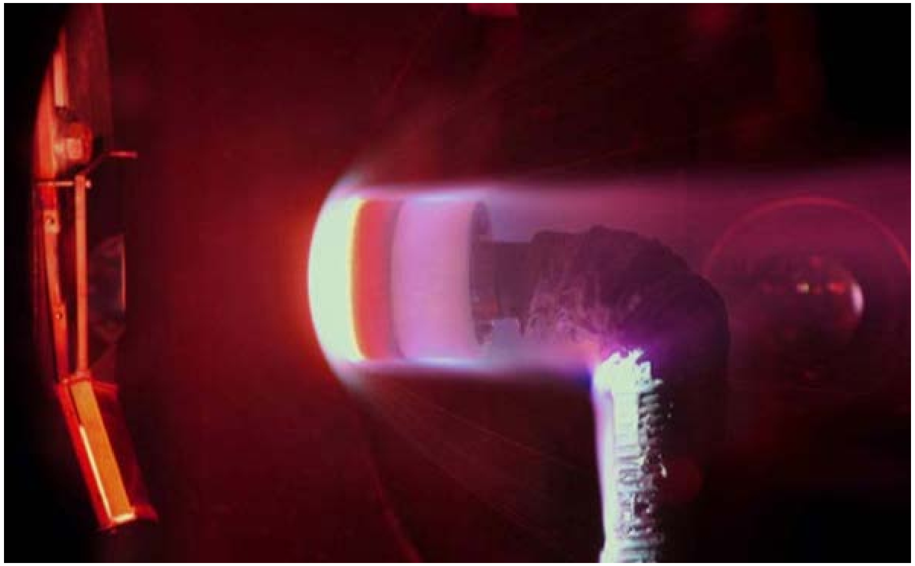
3D Additive Construction with Regolith Concrete

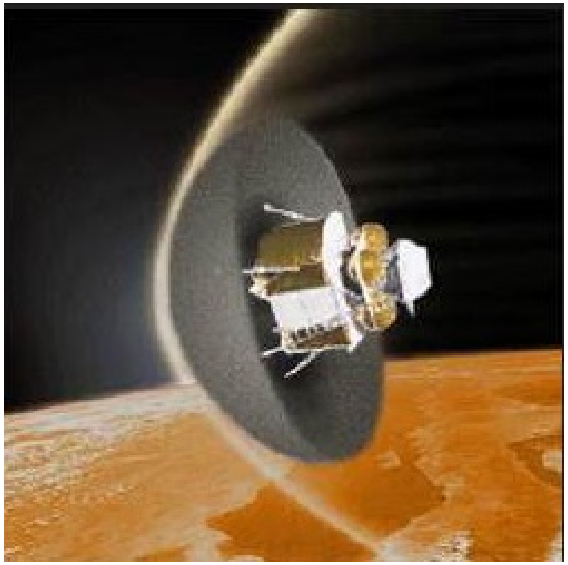
Multi-axis print head

Curved wall tool path development

Images Courtesy of Dr. B. Khoshnevis, Contour Crafting, LLC

Regolith-Derived Heat Shield





Excavation: Robotics Mining Competition

What is the Best Lunabot Regolith Mining Design for the Moon??
The Most Popular Winning Design? (50-80 Kg)

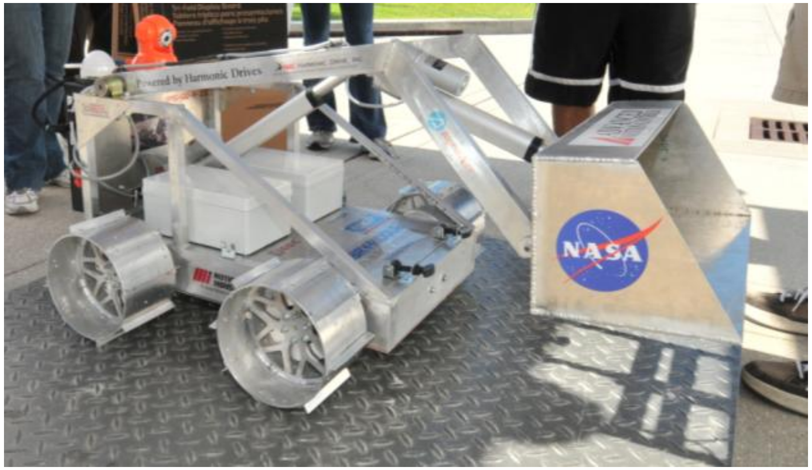
2009: Paul's Robotics WPI

2010: Montana State U

2011: Laurentian University

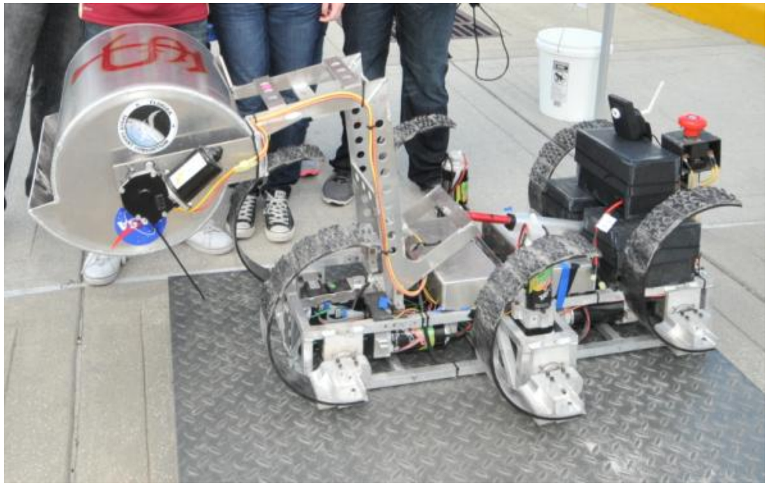
2012: Iowa State U

Or are these designs better?



2012: Embry Riddle Daytona AU

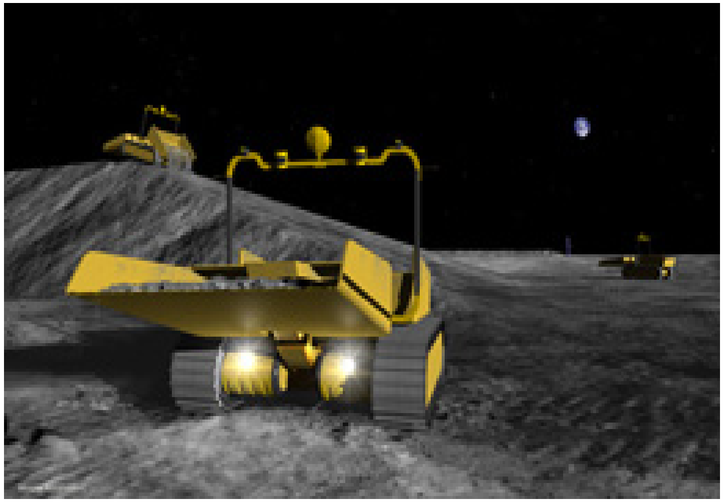
2011: U North Dakota



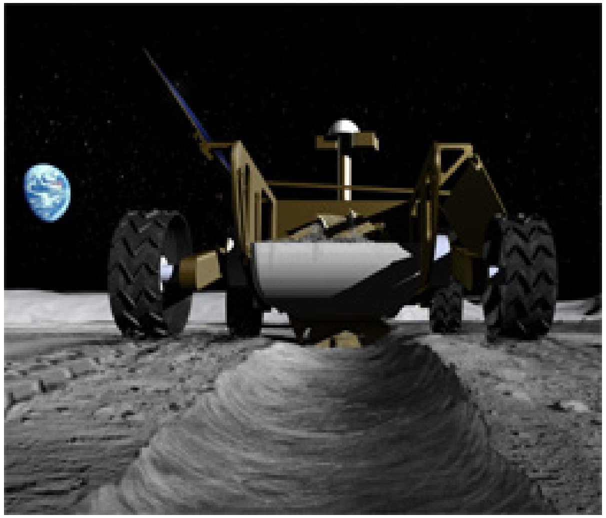
2012: FAMU/ Florida State U

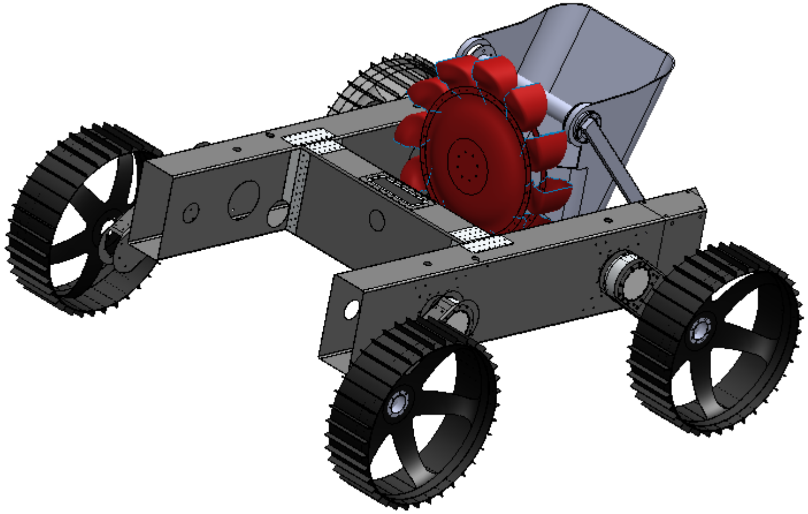
2012: Montana State U

Astrobotic Technology inc. Lunar Mining Concepts
NASA SBIR 2010-2012



ASTROBOTIC





NASA KSC Swamp Works
Regolith Advanced Surface Systems Operations Robot (RASSOR)

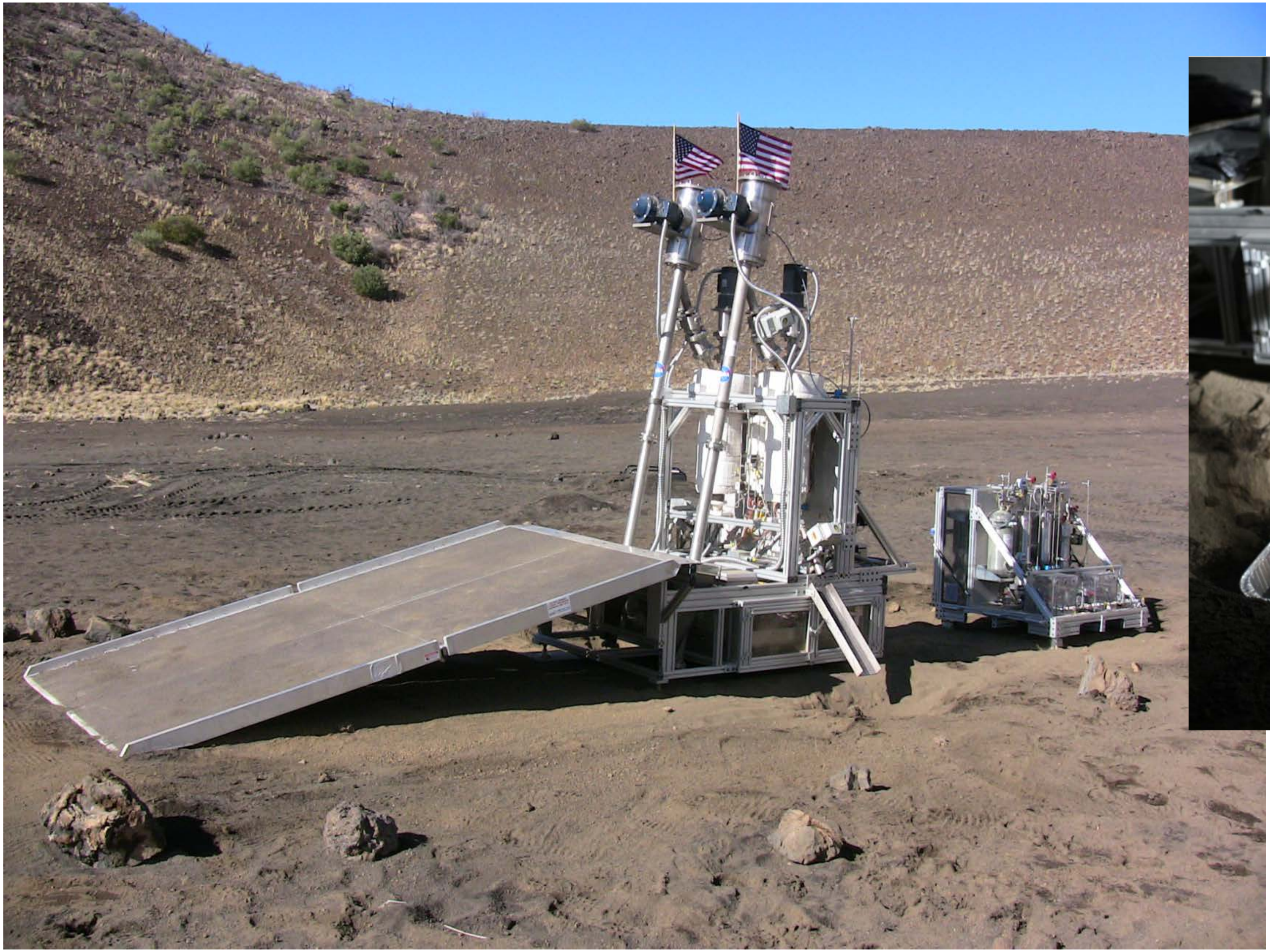
RASSOR 1.0
Prototype

RASSOR 1.5
Prototype

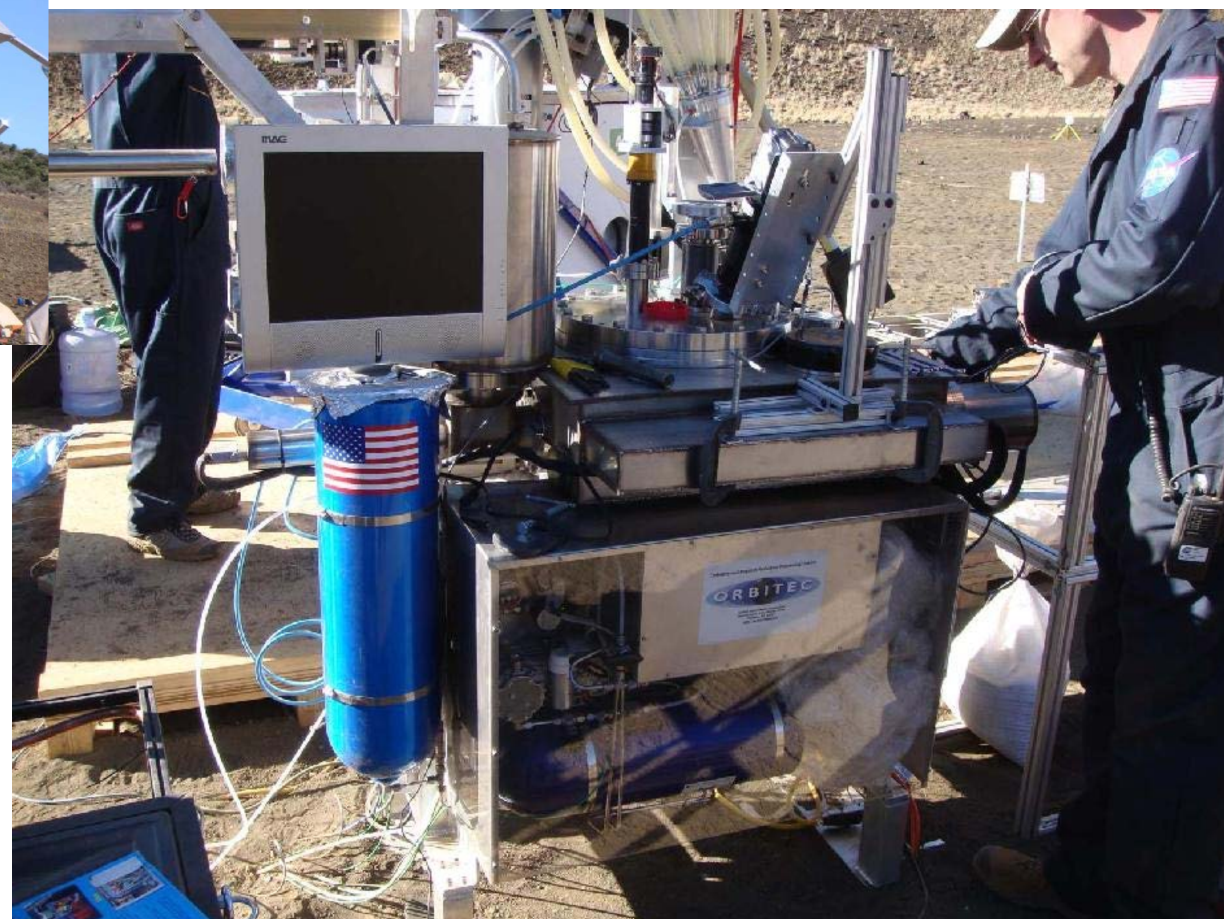
SWAMP WORKS
NASA KENNEDY SPACE CENTER

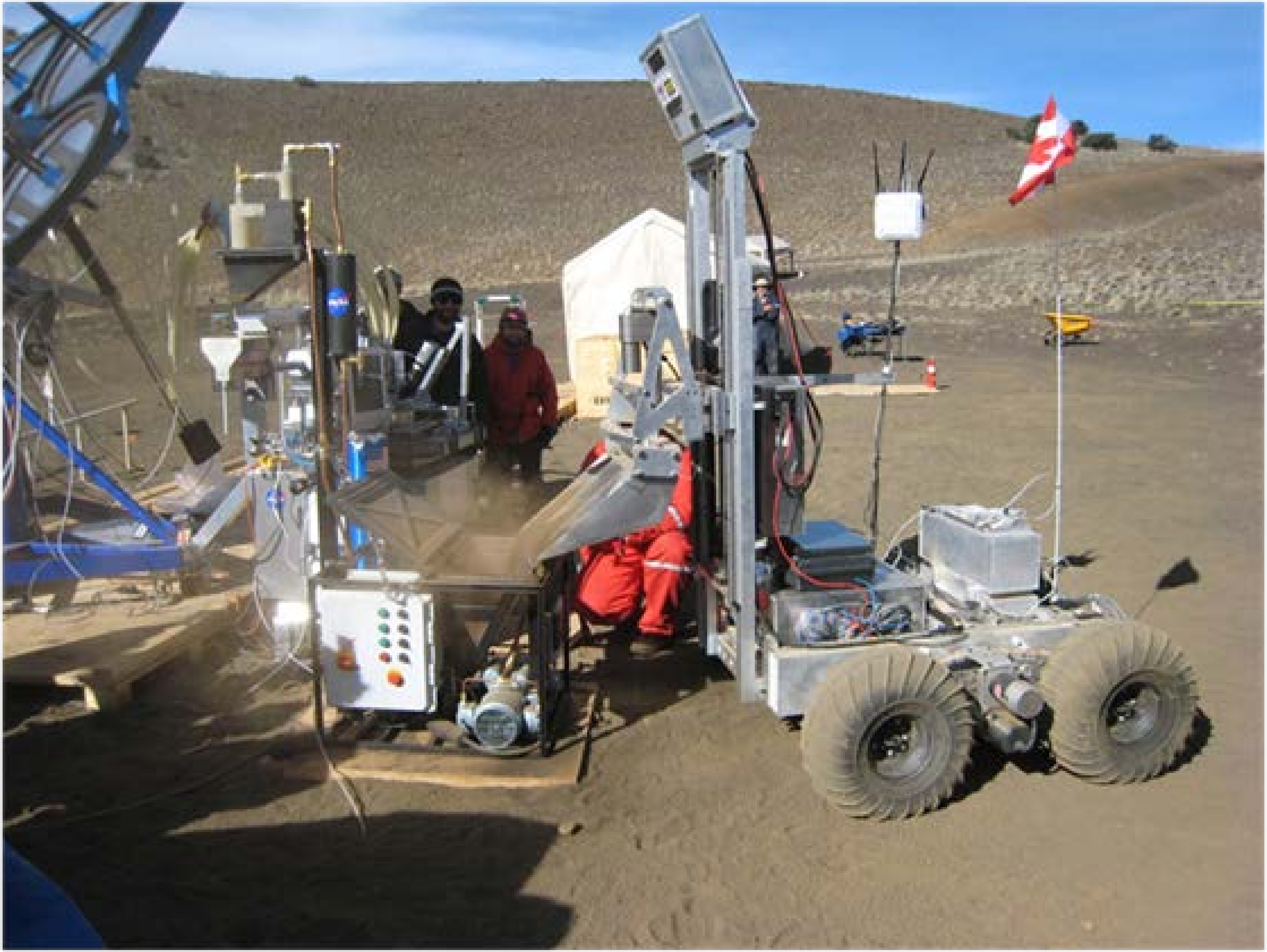
RASSOR 2.0 Prototype
Dry Mass = 50 Kg
Regolith Payload = 80 Kg
Counter-Rotating Bucket Drums = Zero Net Reaction Force

Oxygen Production
ROXYGEN: Hydrogen Reduction

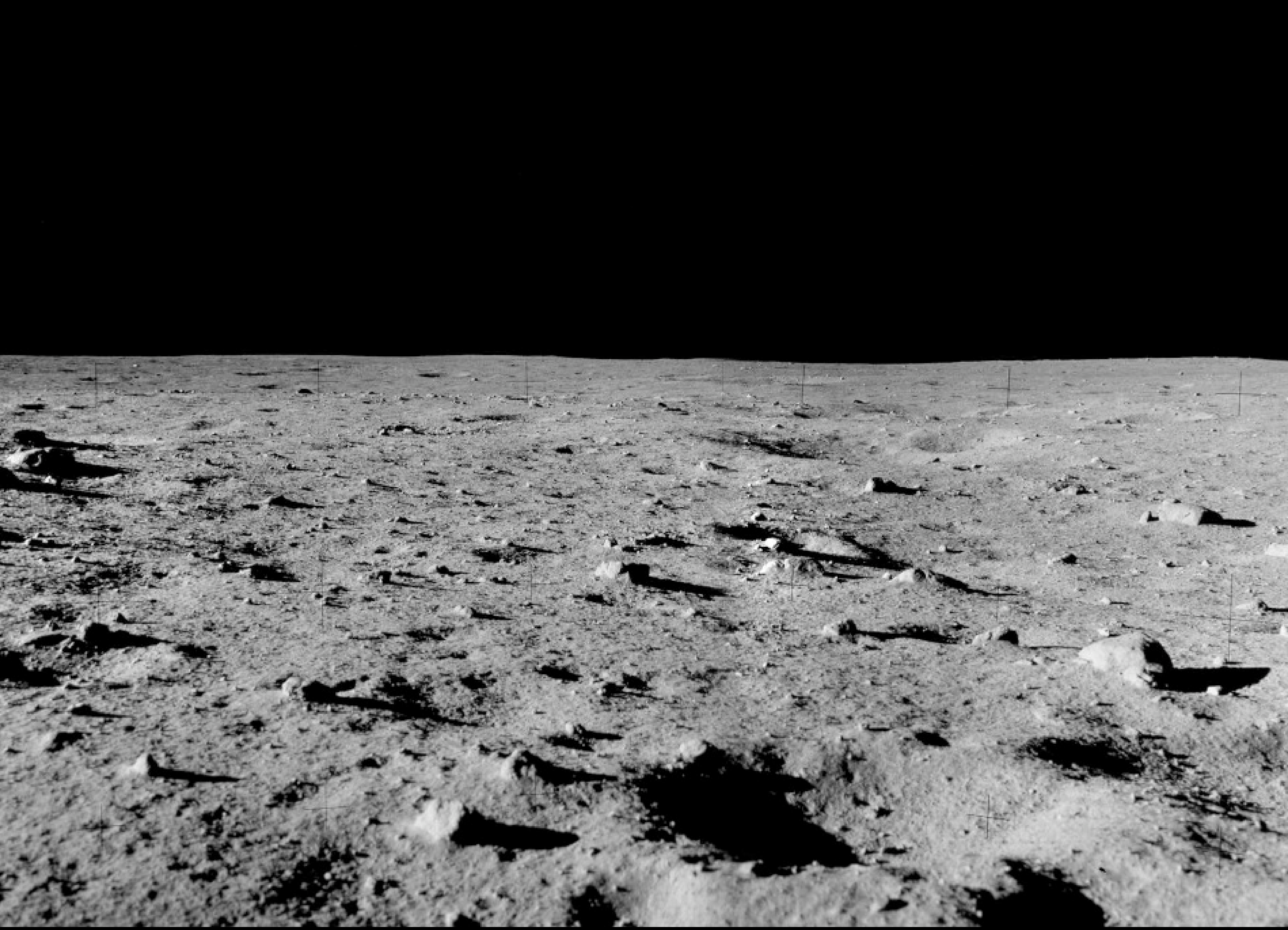


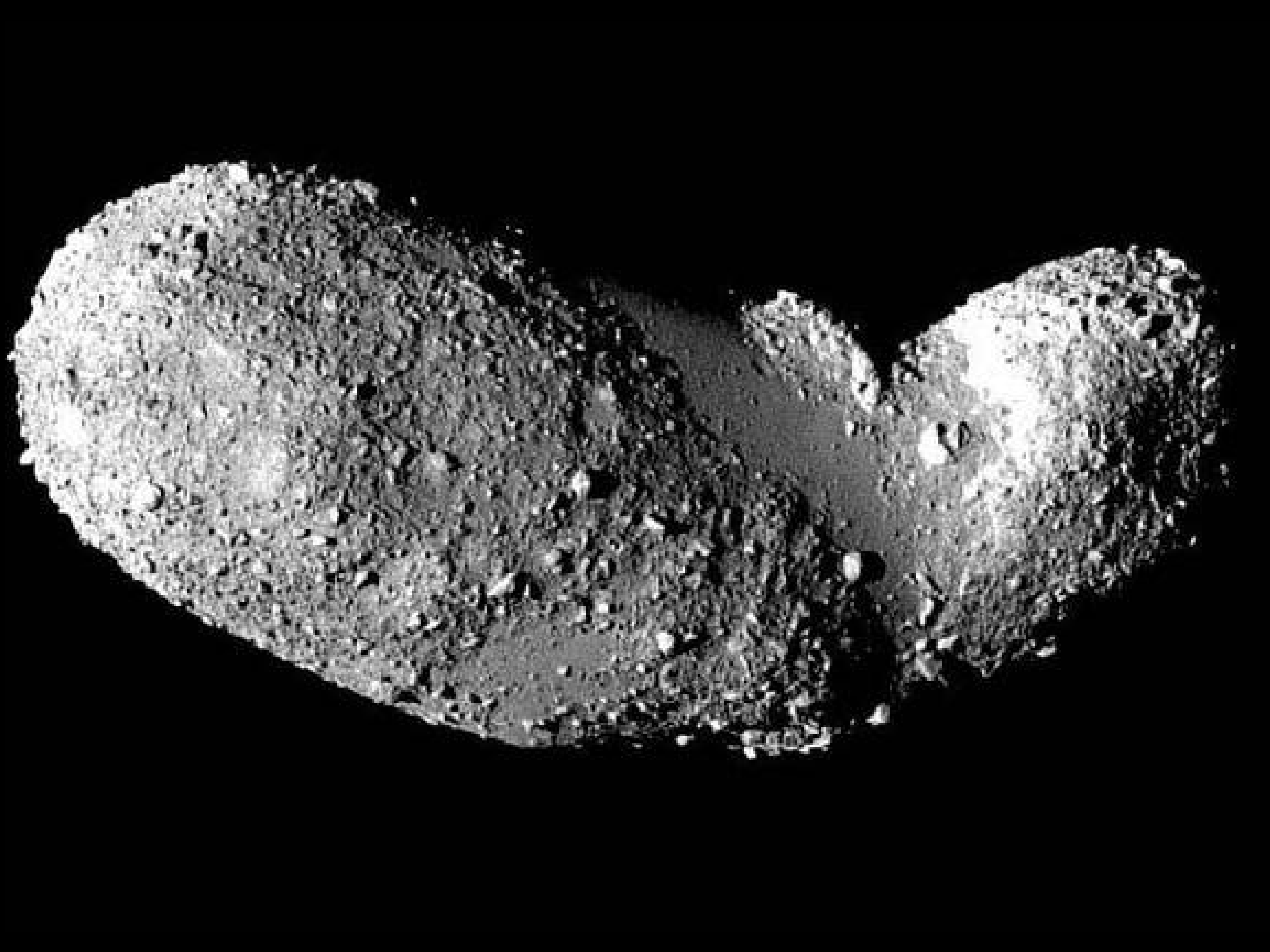
Oxygen Production
Carbothermal: Dust-to-Thrust



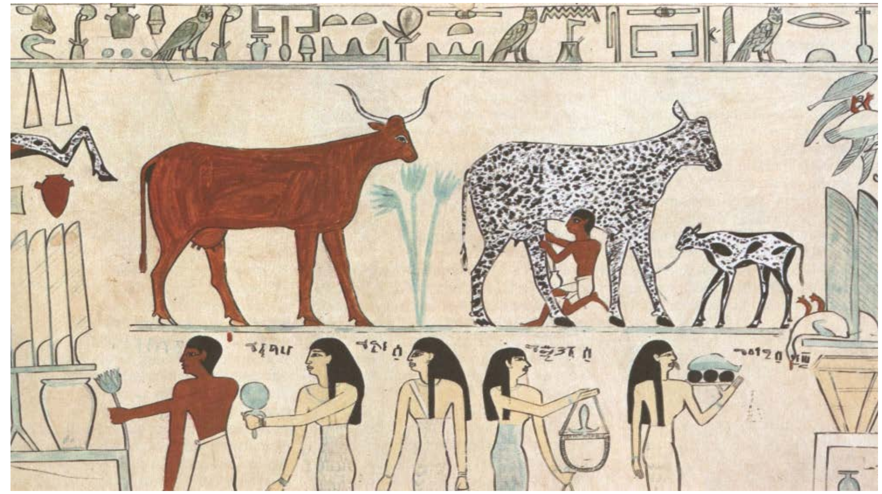


POTENTIAL FOR SETTLEMENT BEYOND EARTH



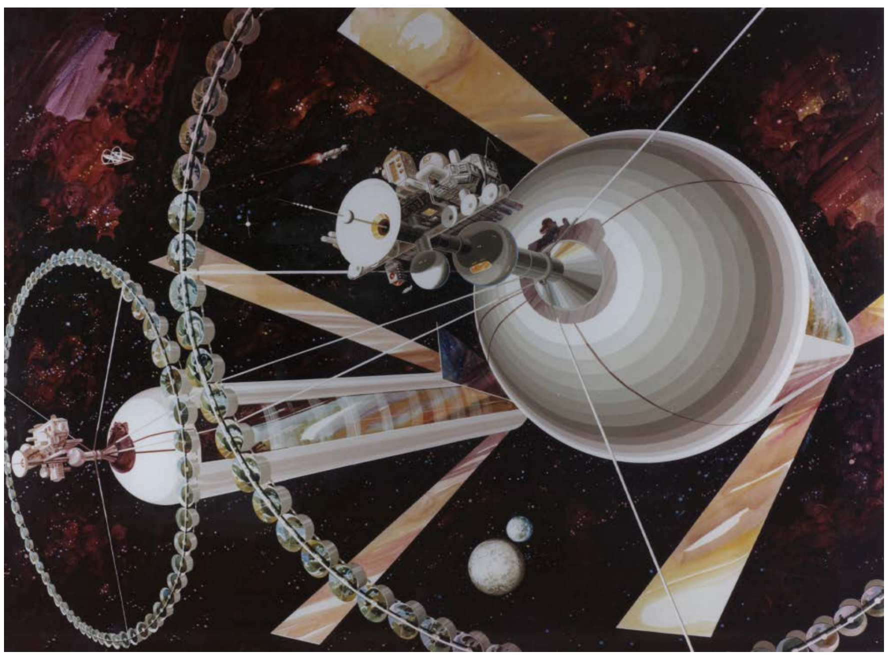


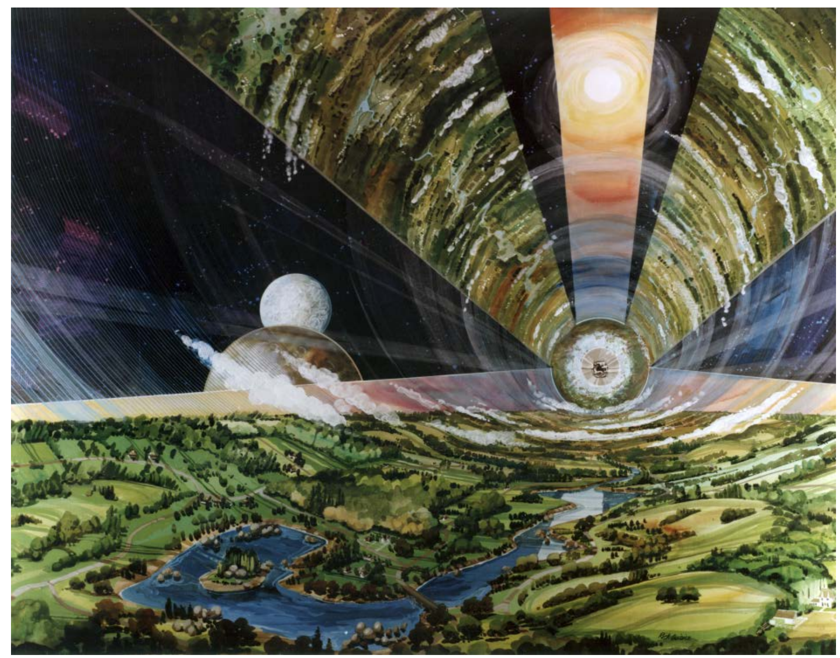
Development of Complex Supply Chain



Full-Scale Space Industry Concepts

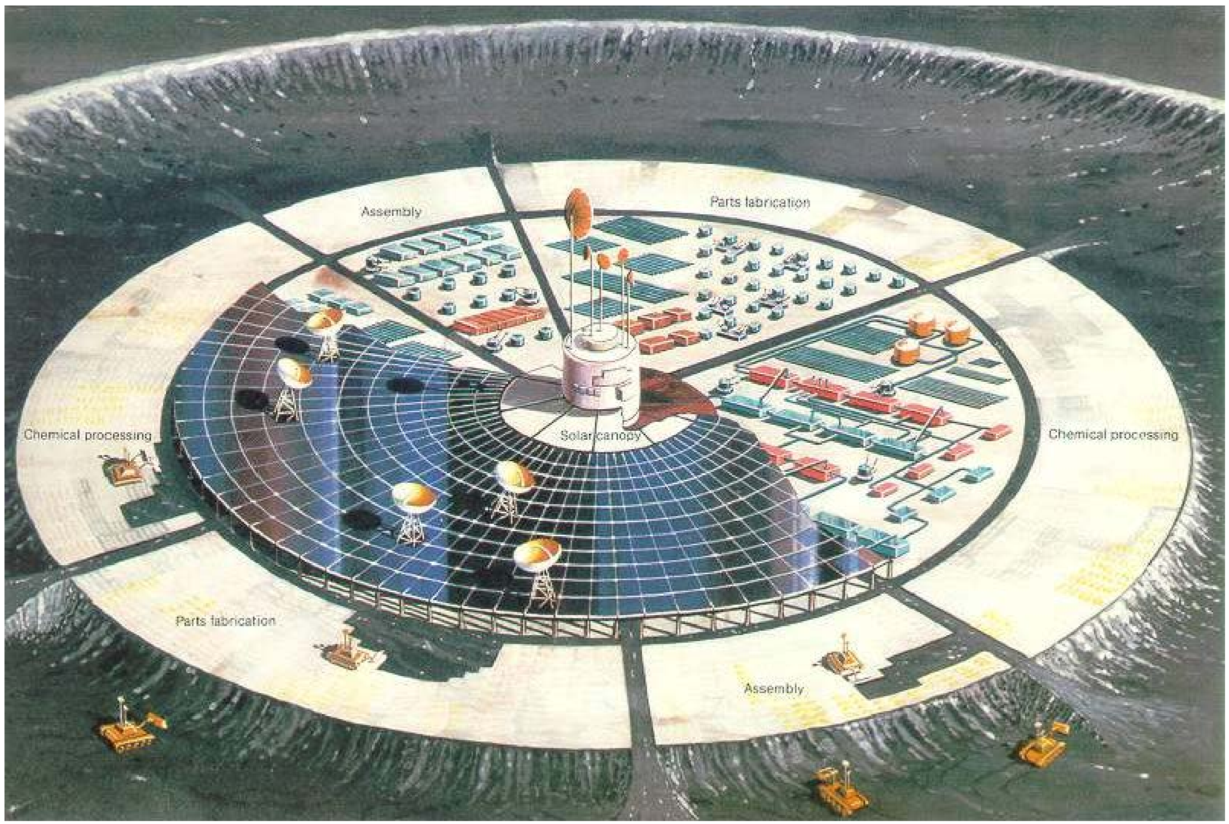
- Gerard K. O'Neill
  - Space manufacturing via humans in orbit
  - Beamed power stations
  - Requires 10,000 humans to break even



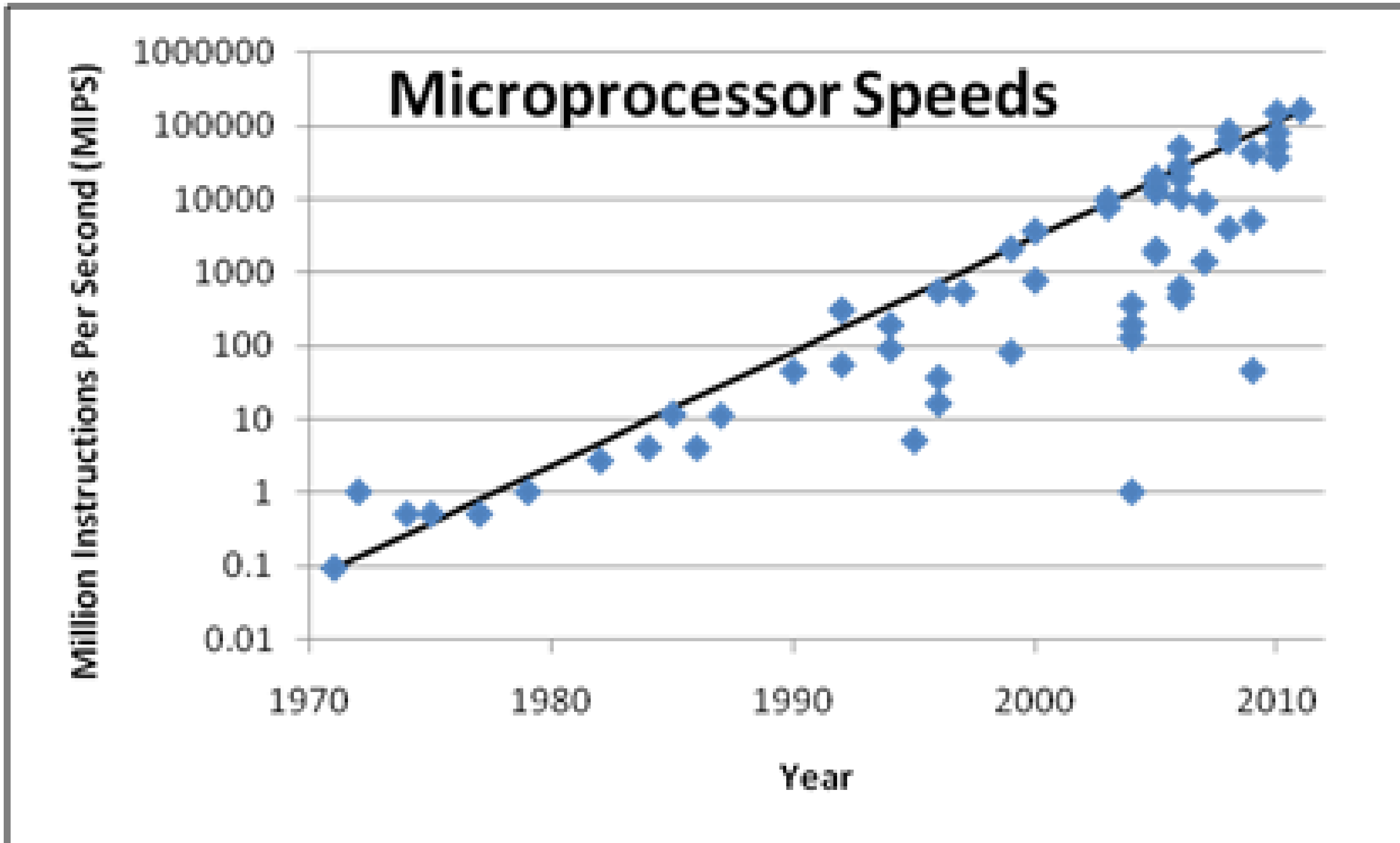


Full-Scale Space Industry Concepts

- NASA Ames Summer Study of 1980
- Self-replicating Lunar Factory, 100 tons

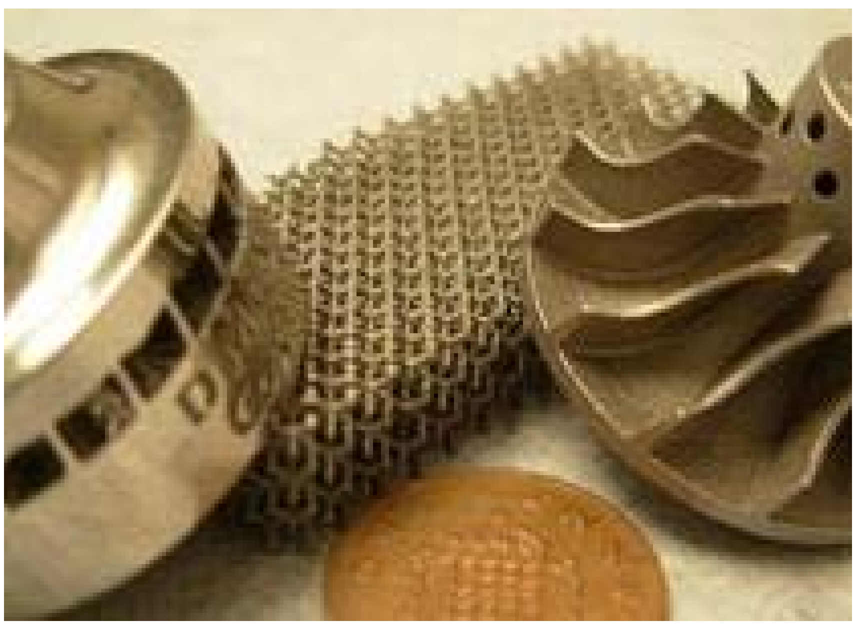


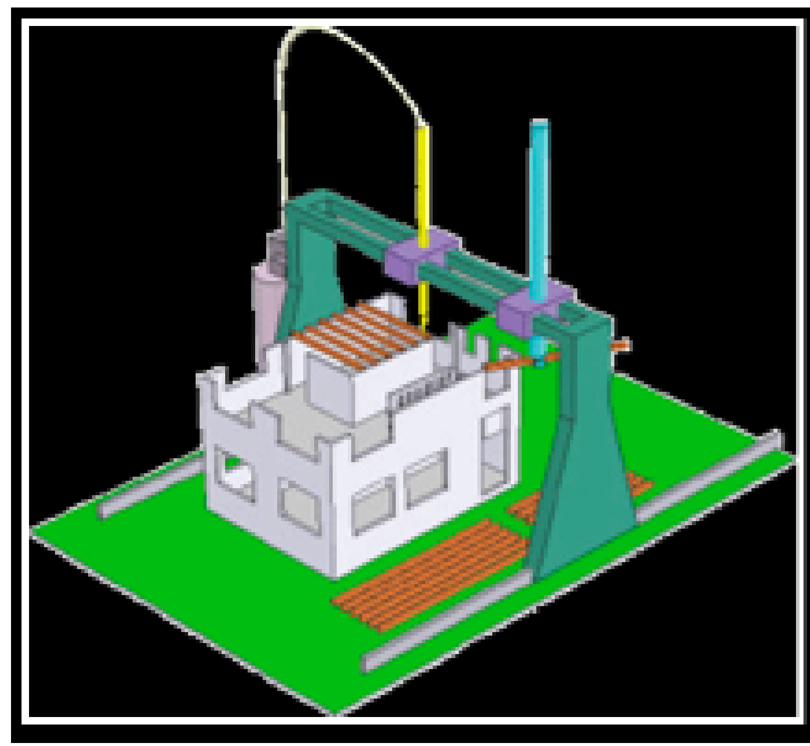
Game-Changers


Microprocessor Speeds
Million Instructions Per Second (MIPS)
1000000
100000
10000
1000
100
10
1
0.1
0.01
1970
1980
1990
2000
2010
Year


EDEN350

Direct Metal Laser Sintering (DMLS)

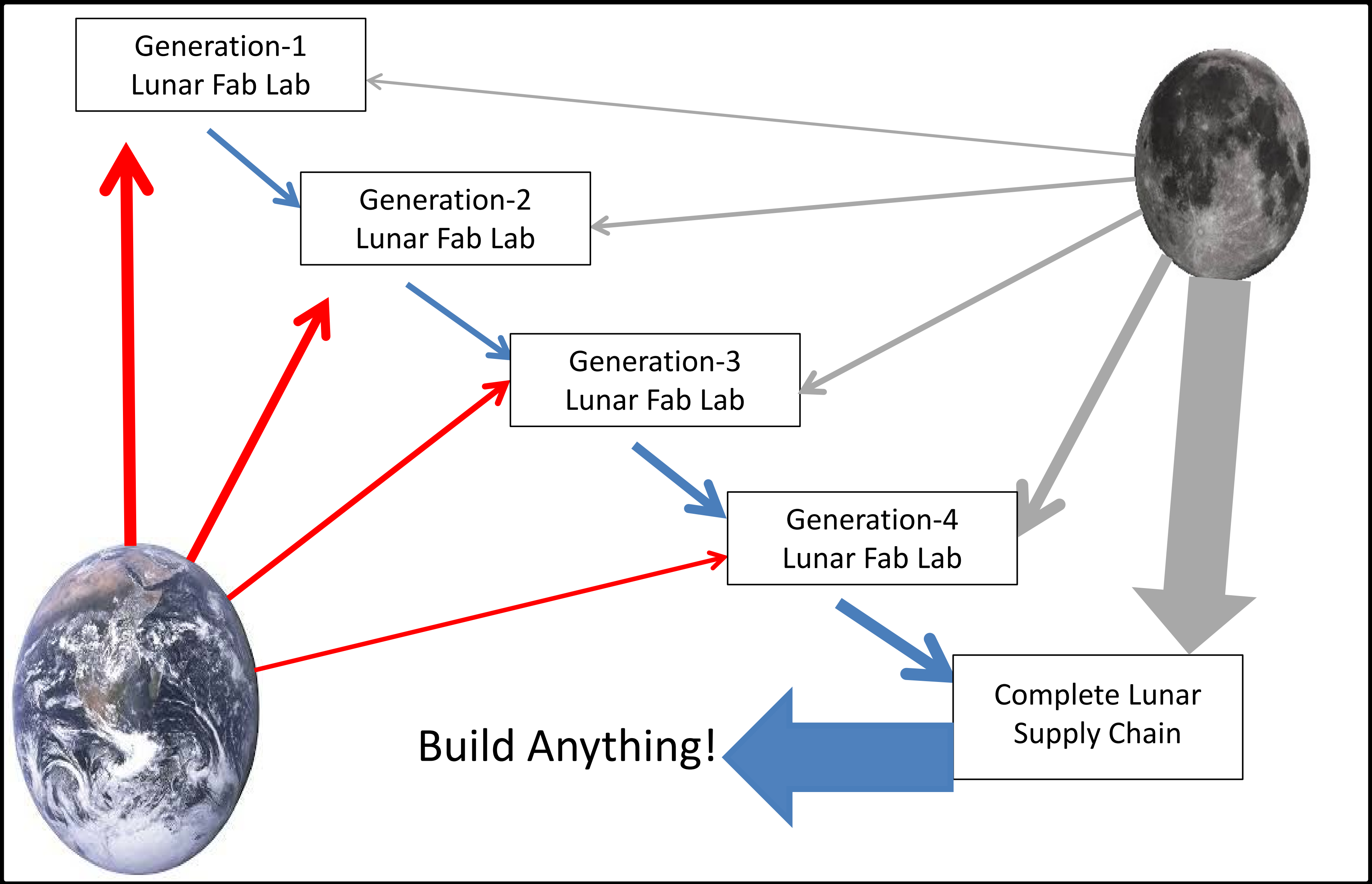




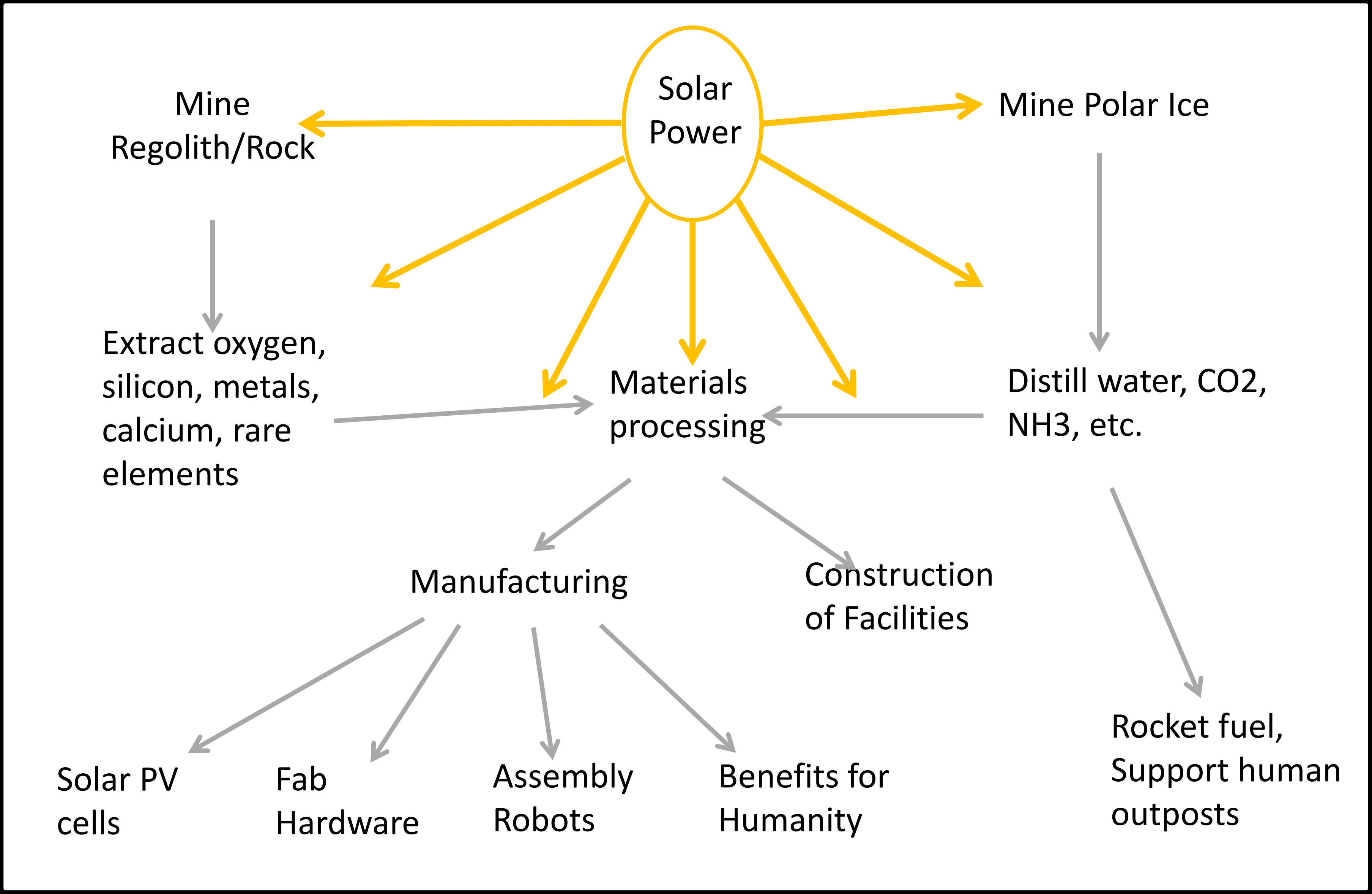
Bootstrapping Space Industry

- Develop industry *in situ* in space over time
  - but do it intentionally
  - Drive it faster than market forces
- Metzger, Muscatello, Mueller, and Mantovani, 2012
- Recent White House blog post: “Bootstrapping Solar System Civilization”
  - Send ideas to massless@ostp.gov

The Bootstrapping Approach



Mining & Manufacturing Flow



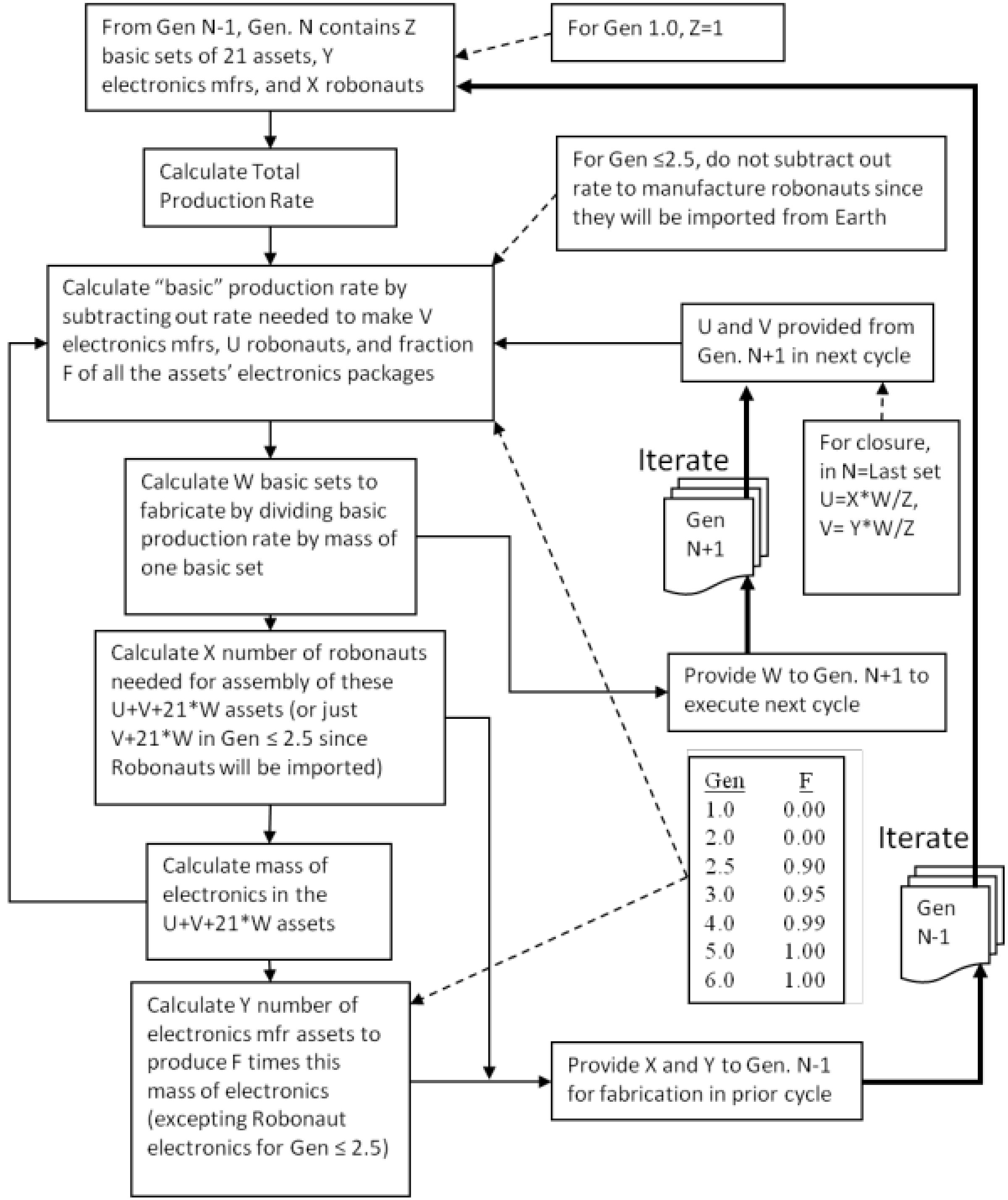
Generations of Industry (Notional)

Gen	Human/Robotic Interaction	Artificial Intelligence	Scale of Industry	Materials Manufactured	Source of Electronics
1	Teleoperated and/or locally-operated by a human outpost	Insect-like	Imported, small-scale, limited diversity	Gases, water, crude alloys, ceramics, solar cells	Import fully integrated machines
2	Teleoperated	Lizard-like	Crude fabrication, inefficient, but greater throughput than 1.0	(Same)	Import electronics boxes
2.5	Teleoperated	Lizard-like	Diversifying processes, especially volatiles and metals	Plastics, rubbers, some chemicals	Fabricate crude components plus import electronics boxes
3	Teleoperated with experiments in autonomy	Lizard-like	Larger, more complex processing plants	Diversify chemicals, Simple fabrics, eventually polymers.	Locally build PC cards, chassis and simple components, but import the chips
4	Closely supervised autonomy with some teleoperation	Mouse-like	Large plants for chemicals, fabrics, metals	Sandwiched and other advanced material processes	Building large assets such as lithography machines
5	Loosely supervised autonomy	Mouse-like	Labs and factories for electronics and robotics. Shipyards to support main belt	Large scale production	Make chips locally. Make bots in situ for export to asteroid belt
6	Nearly full autonomy	Monkey-like	Large-scale, self-supporting industry, exporting industry to asteroid main belt	Makes all necessary materials, increasing sophistication	Makes everything locally, increasing sophistication
X.0	Autonomous robotics pervasive throughout solar system enabling human presence	Human-like	Robust exports/imports through zones of solar system	Material factories specialized by zone of the solar system	Electronics factories in various locations

Baseline values for Generation 1.0 in Bootstrapping Model

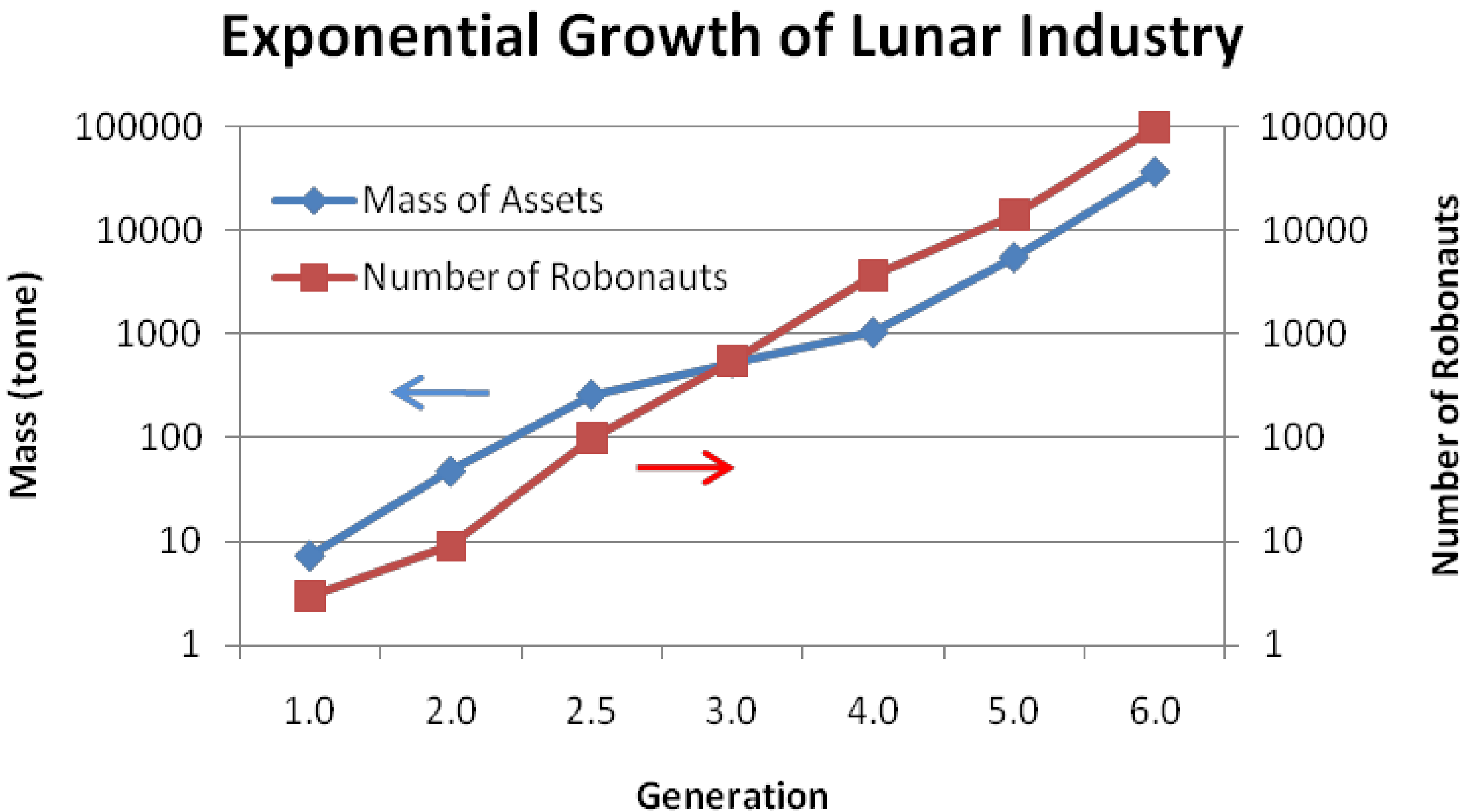
Asset	Qty. per set	Mass minus Electronics (kg)	Mass of Electronics (kg)	Power (kW)	Feedstock Input (kg/hr)	Product Output (kg/hr)
Power Distrib & Backup	1	2000	–	–	–	–
Excavators (swarming)	5	70	19	0.30	20	–
Chem Plant 1 – Gases	1	733	30	5.58	4	1.8
Chem Plant 2 – Solids	1	733	30	5.58	10	1.0
Metals Refinery	1	1019	19	10.00	20	3.15
Solar Cell Manufacturer	1	169	19	0.50	~0.3	–
3D Printer 1 – Small parts	4	169	19	5.00	0.5	0.5
3D Printer 2 – Large parts	4	300	19	5.00	0.5	0.5
Robonaut assemblers	3	135	15	0.40	–	–
Total per Set		~7.7 MT launched to Moon		64.36 kW	20 kg regolith/hr	4 kg parts/hr

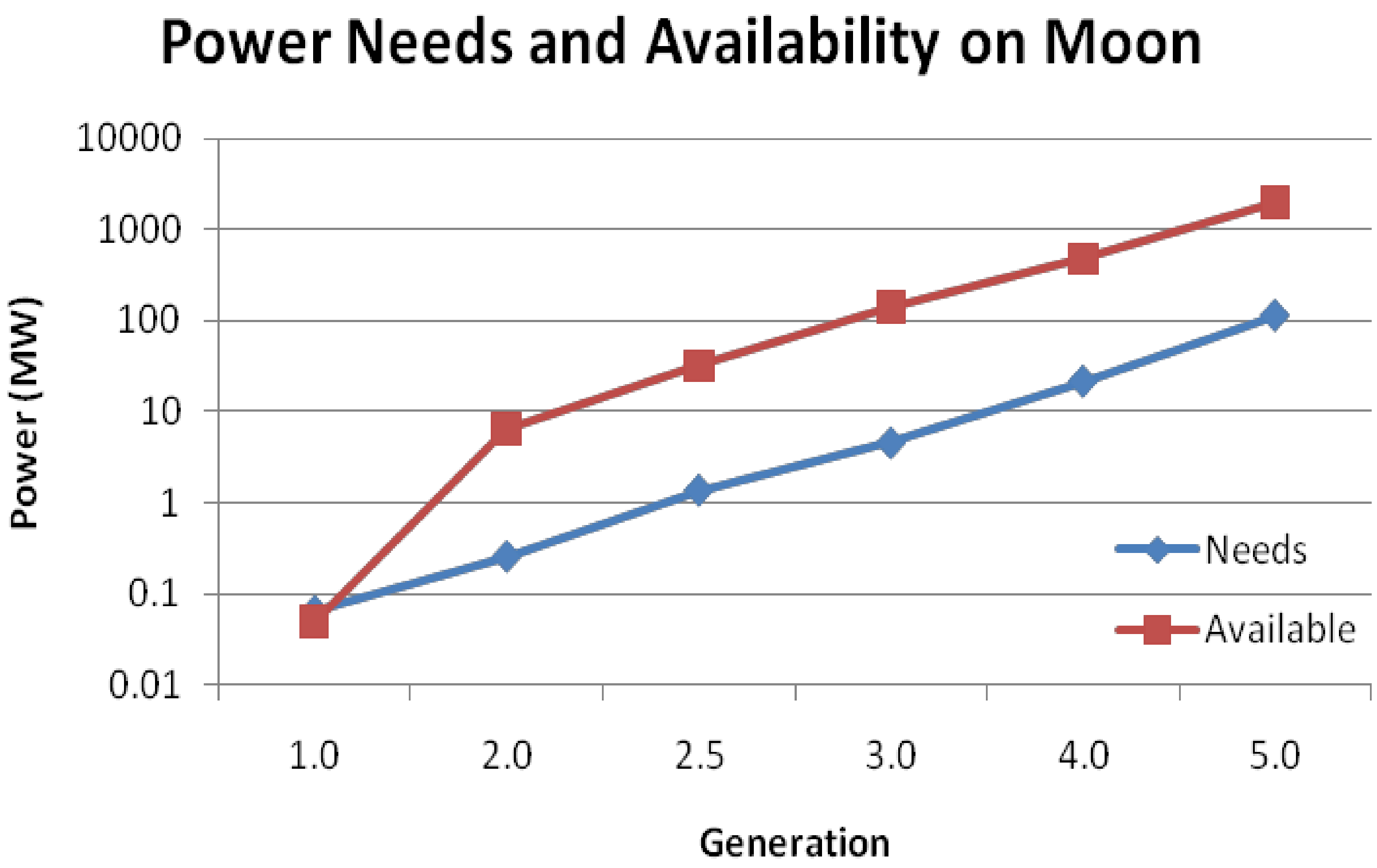
- **Simplistic Modeling**
- Not intended to be definitive
- Explores some of the key parameters
- Attempt to demonstrate basic feasibility
- Intends to generate interest and further investigation
- Needs a much larger study with a much larger group of contributors

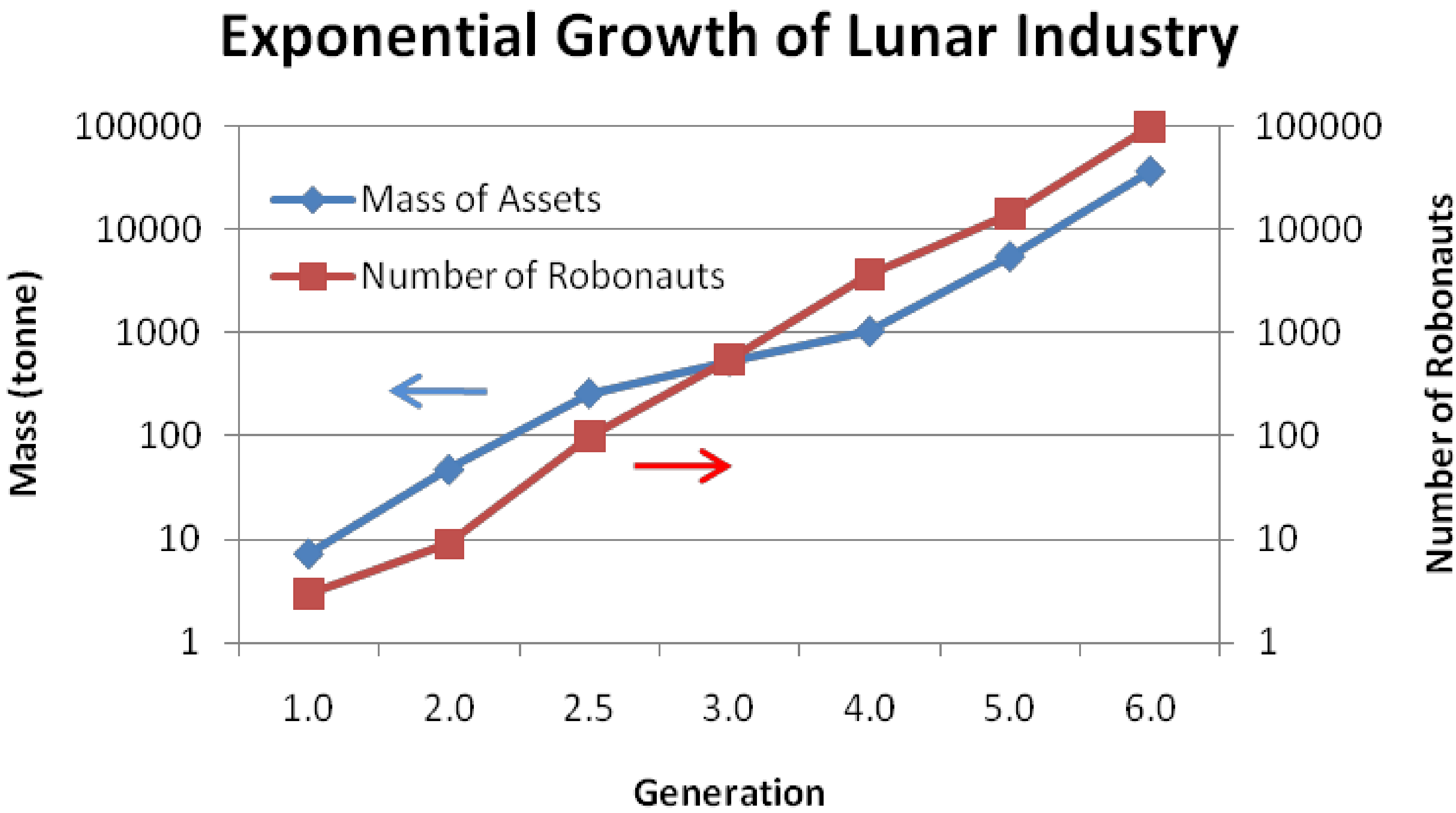


Additional Production

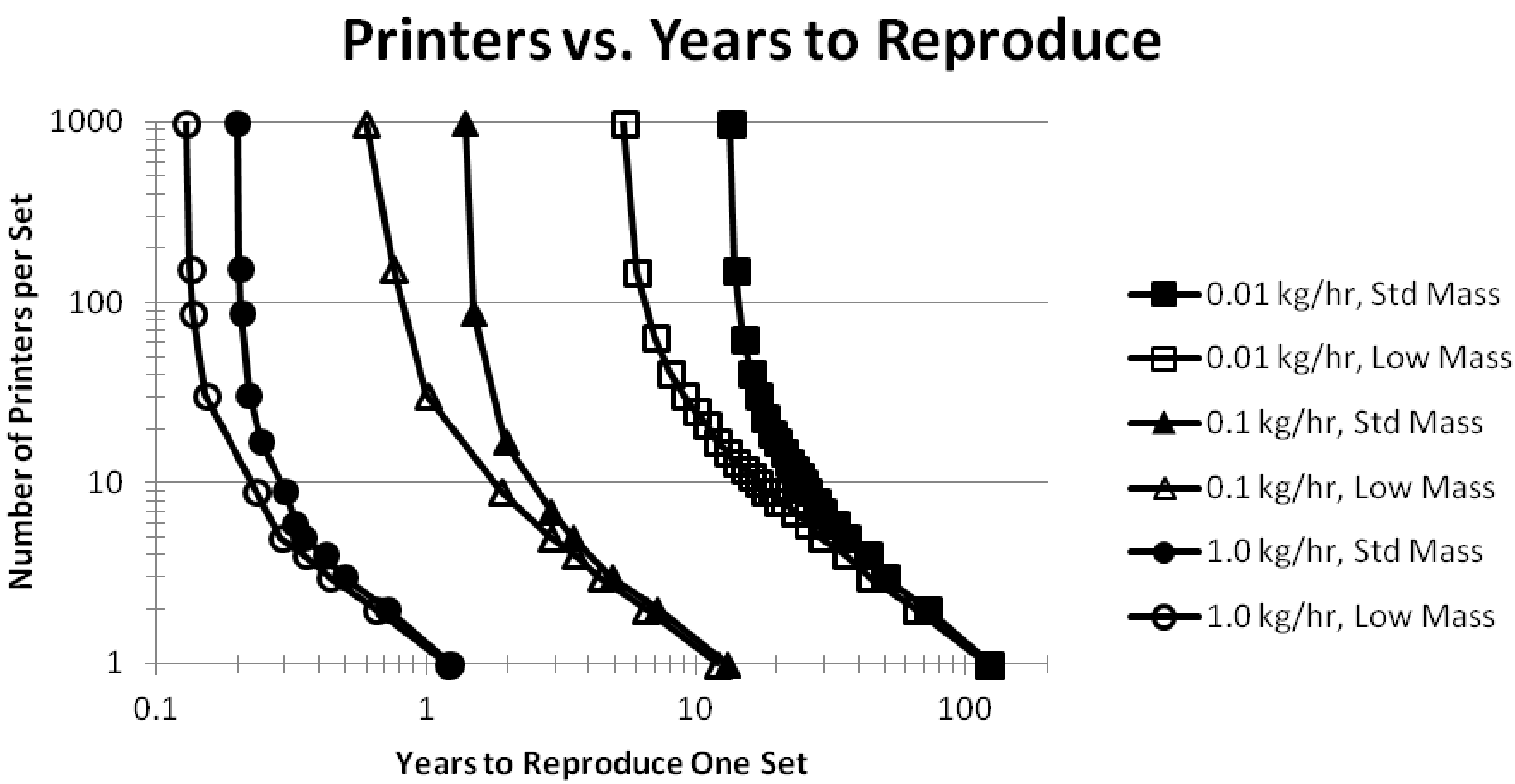
- Gen 3.0
  - 80 MT construction equipment
- Gen 4.0
  - Dust Free Laboratory Facilities
- Gen 5.0
  - 120 MT materials stockpiled to send industry to asteroid main belt
- Gen 6.0
  - Fleet of 6 spacecraft (20 MT plus 12 MT payload, each plus propellants)
  - Takes industry to Main Belt


Exponential Growth of Lunar Industry
Mass of Assets
Number of Robonauts
Mass (tonne)
Number of Robonauts
100000
10000
1000
100
10
1
1.0
2.0
2.5
3.0
4.0
5.0
6.0
Generation

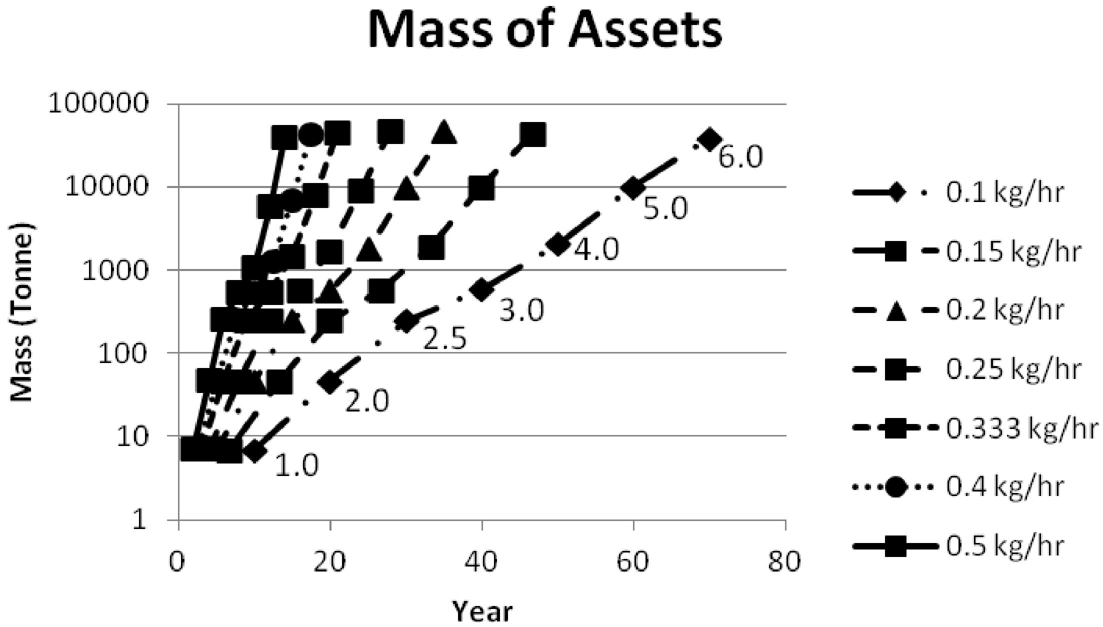

Power Needs and Availability on Moon
Power (MW)
10000
1000
100
10
1
0.1
0.01
1.0
2.0
2.5
3.0
4.0
5.0
Generation
Needs
Available

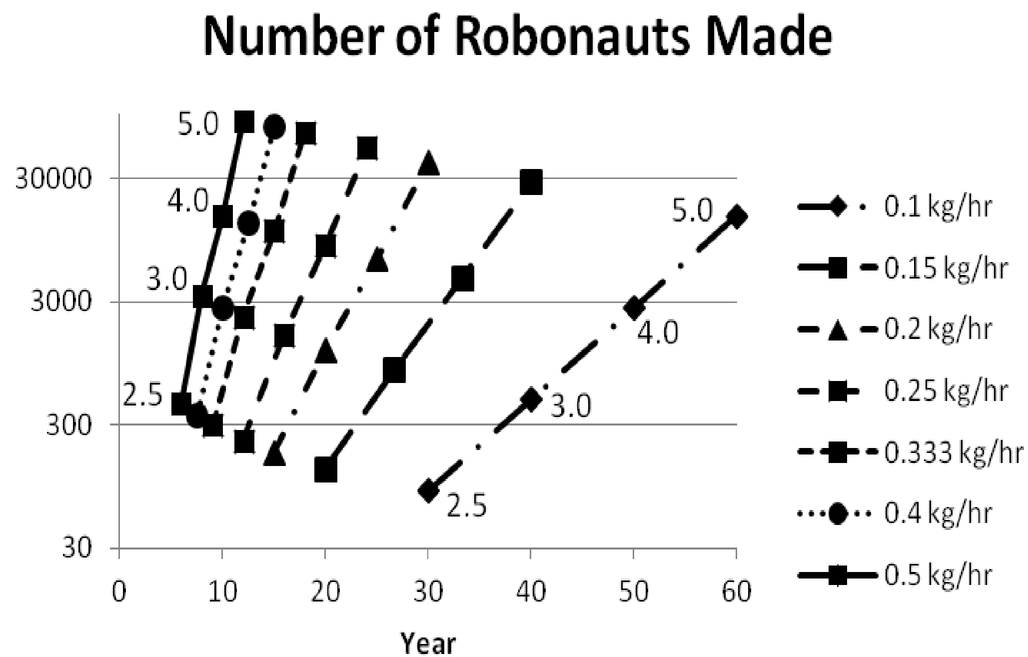


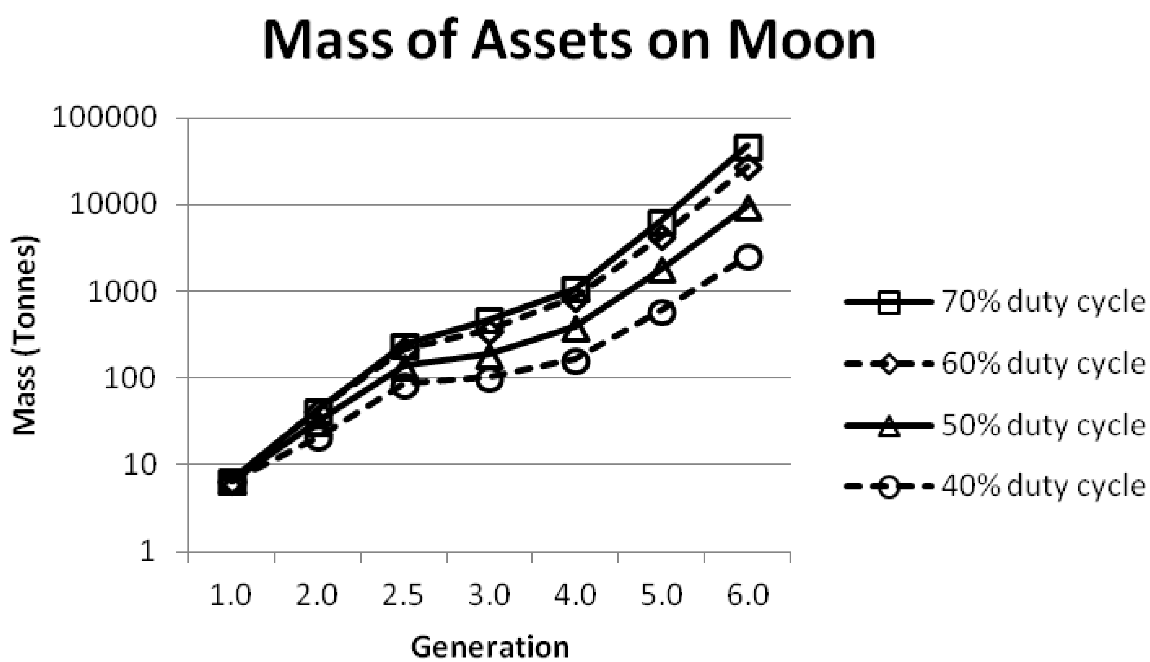
Exponential Growth of Lunar Industry
Mass of Assets
Number of Robonauts
Mass (tonne)
Number of Robonauts
100000
10000
1000
100
10
1
1.0
2.0
2.5
3.0
4.0
5.0
6.0
Generation



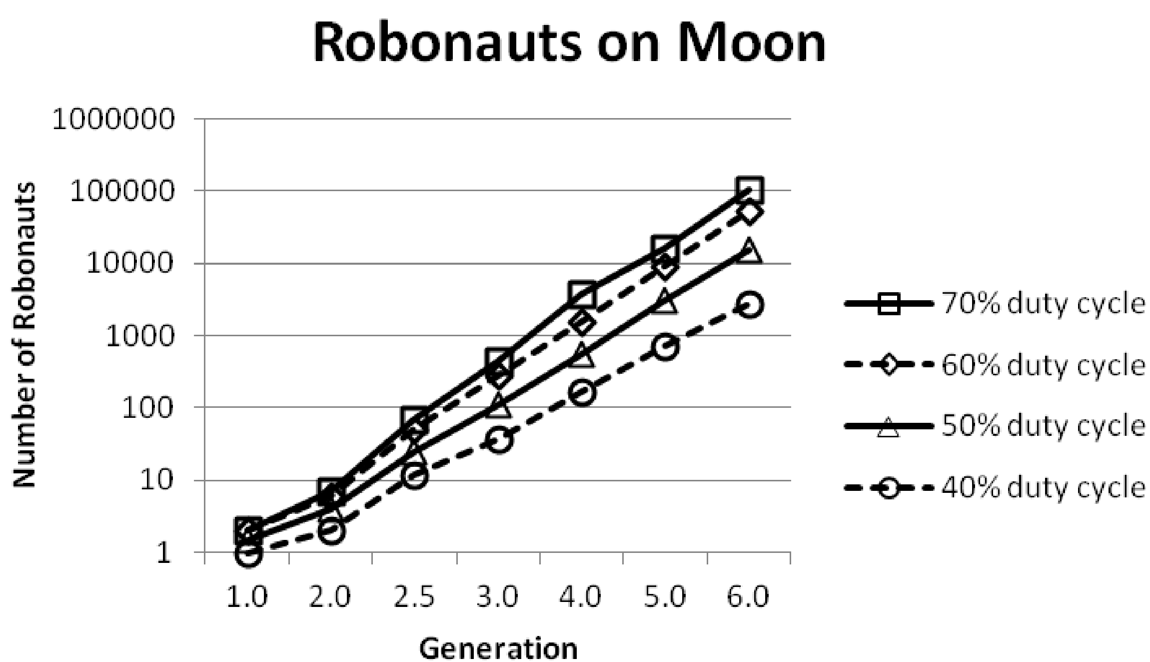
Printers vs. Years to Reproduce
Number of Printers per Set
1000
100
10
1
0.1
1
10
100
Years to Reproduce One Set
0.01 kg/hr, Std Mass
0.01 kg/hr, Low Mass
0.1 kg/hr, Std Mass
0.1 kg/hr, Low Mass
1.0 kg/hr, Std Mass
1.0 kg/hr, Low Mass


Mass of Assets
Mass (Tonne)
100000
10000
1000
100
10
1
0
20
40
60
80
Year
1.0
2.0
2.5
3.0
4.0
5.0
6.0
0.1 kg/hr
0.15 kg/hr
0.2 kg/hr
0.25 kg/hr
0.333 kg/hr
0.4 kg/hr
0.5 kg/hr

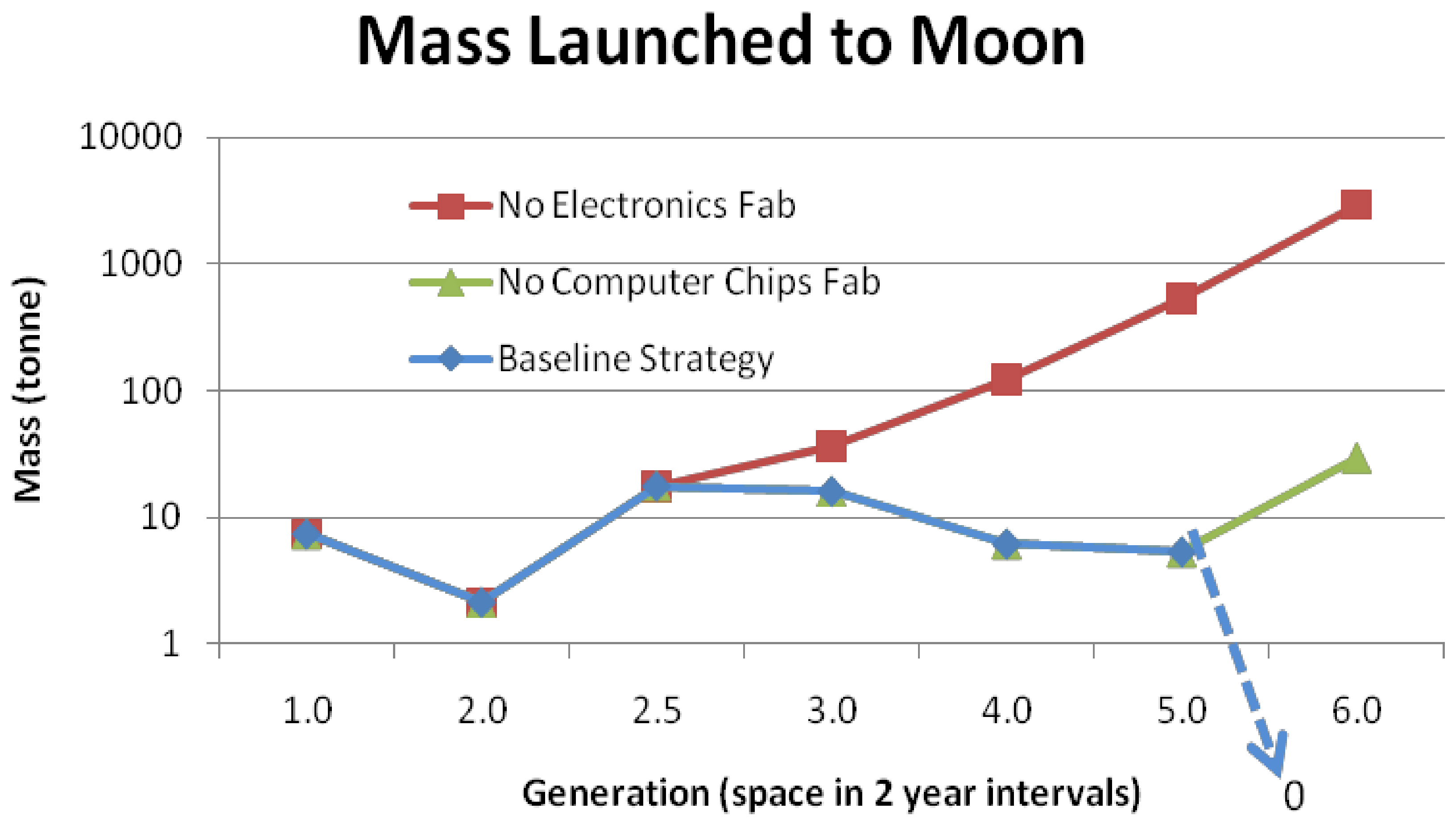

Number of Robonauts Made
30000
3000
300
30
0
10
20
30
40
50
60
Year
5.0
4.0
3.0
2.5
5.0
4.0
3.0
2.5
0.1 kg/hr
0.15 kg/hr
0.2 kg/hr
0.25 kg/hr
0.333 kg/hr
0.4 kg/hr
0.5 kg/hr



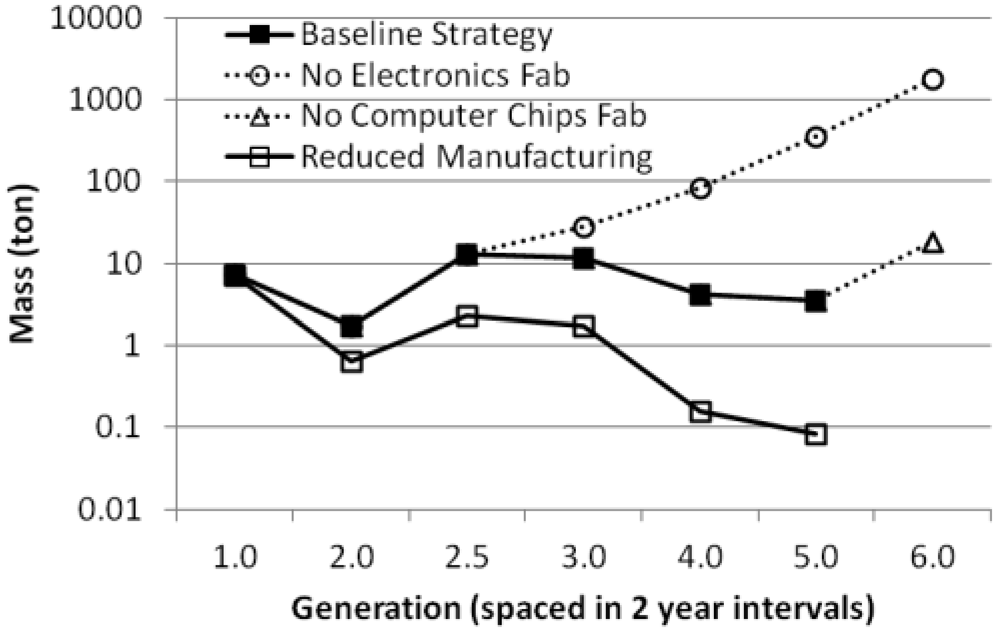
Mass of Assets on Moon
Mass (Tonnes)
100000
10000
1000
100
10
1
1.0
2.0
2.5
3.0
4.0
5.0
6.0
Generation
70% duty cycle
60% duty cycle
50% duty cycle
40% duty cycle

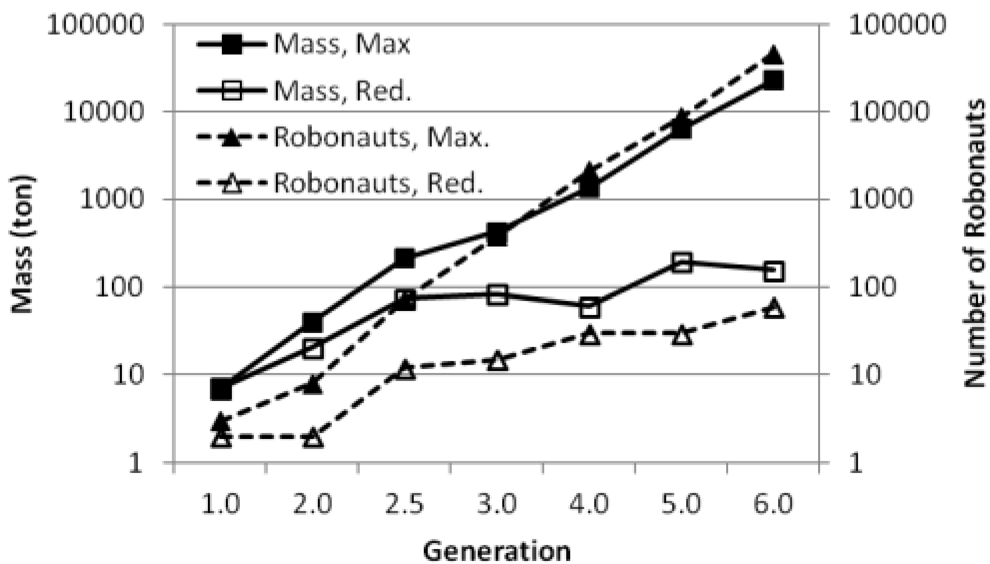


Robonauts on Moon
Number of Robonauts
1000000
100000
10000
1000
100
10
1
1.0
2.0
2.5
3.0
4.0
5.0
6.0
Generation
70% duty cycle
60% duty cycle
50% duty cycle
40% duty cycle


Mass Launched to Moon
10000
1000
100
10
1
Mass (tonne)
No Electronics Fab
No Computer Chips Fab
Baseline Strategy
1.0
2.0
2.5
3.0
4.0
5.0
6.0
Generation (space in 2 year intervals)
0

Minimizing Launch Mass





Beyond Gen 6.0

- After bootstrapping on the Moon, it moves to the asteroid belt where the best resources are.
- After 20 years in the asteroid belt, it will have 1,000,000 times the industrial capacity of the entire United States.
- After another 10 years, and it will have a billion times the capacity of the U.S.
- What could humanity do with so much capacity?

What Great Things Follow?

- Space-based solar power stations
- Internet servers and high power computing
- Planetary defense
- Transportation hubs and spacecraft
- Outposts on all the planets and moons
- Great telescopes and particle colliders
- Terraforming Mars
- Ships to other stars

Cost/Benefit

- Cost:
  - 1/3 the existing budgets of the ISS Partner Nations sustained for 30-40 years
  - This supports a lunar outpost for science PLUS development of space industry
- Benefit
  - Better science for the money we spend on space
  - Move to a Type 2 civilization
  - Energy
  - Economy
  - Environment
  - Existential Threats
- Problem
  - It sounds like science fiction

PRACTICAL STRATEGY

Three Stages

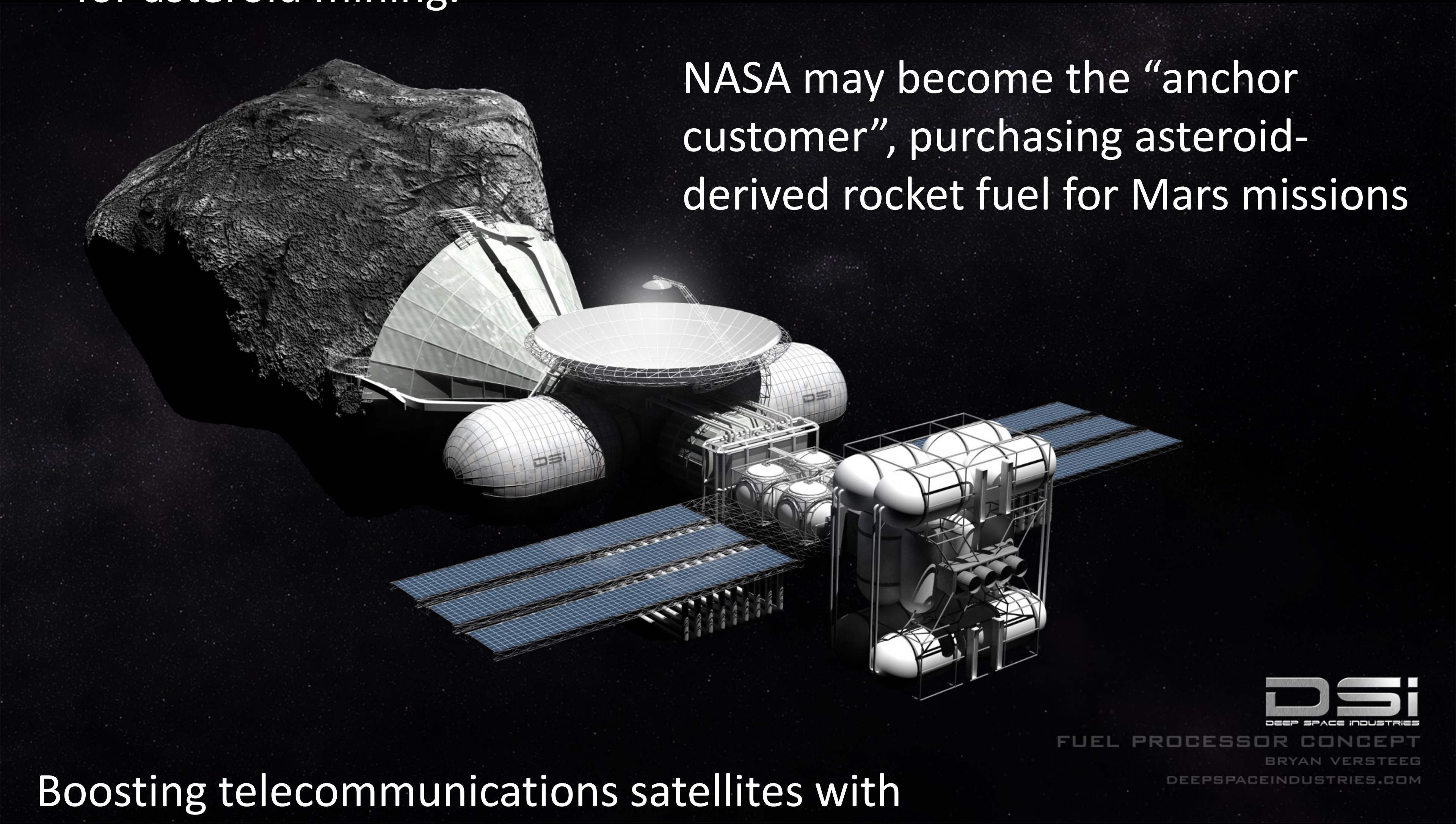
- Stage 1
  - Convince policymakers to embrace this vision
  - How long? As long as it takes
- Stage 2
  - Bootstrap industry in cislunar space
  - 30 to 40 years
- Stage 3
  - Benefit by building space internet, space solar power, support great science, terraform Mars, etc.
  - Perpetually

Activities in Stage 1

- Space agencies develop space resource utilization technologies for sortie missions
- Space agencies develop propellant depot in Earth orbit for affordable space missions
- Asteroid mining companies begin making propellant for orbiting depots (cash flow!)
- Lunar outpost becomes affordable; agencies begin developing more crucial technologies
- Space tourism including on the Moon
- Mars colonization attempts create demand for industry in space, provide more cash flow
- Robotics industry continues on Earth
- It becomes apparent that we can achieve Stage 2

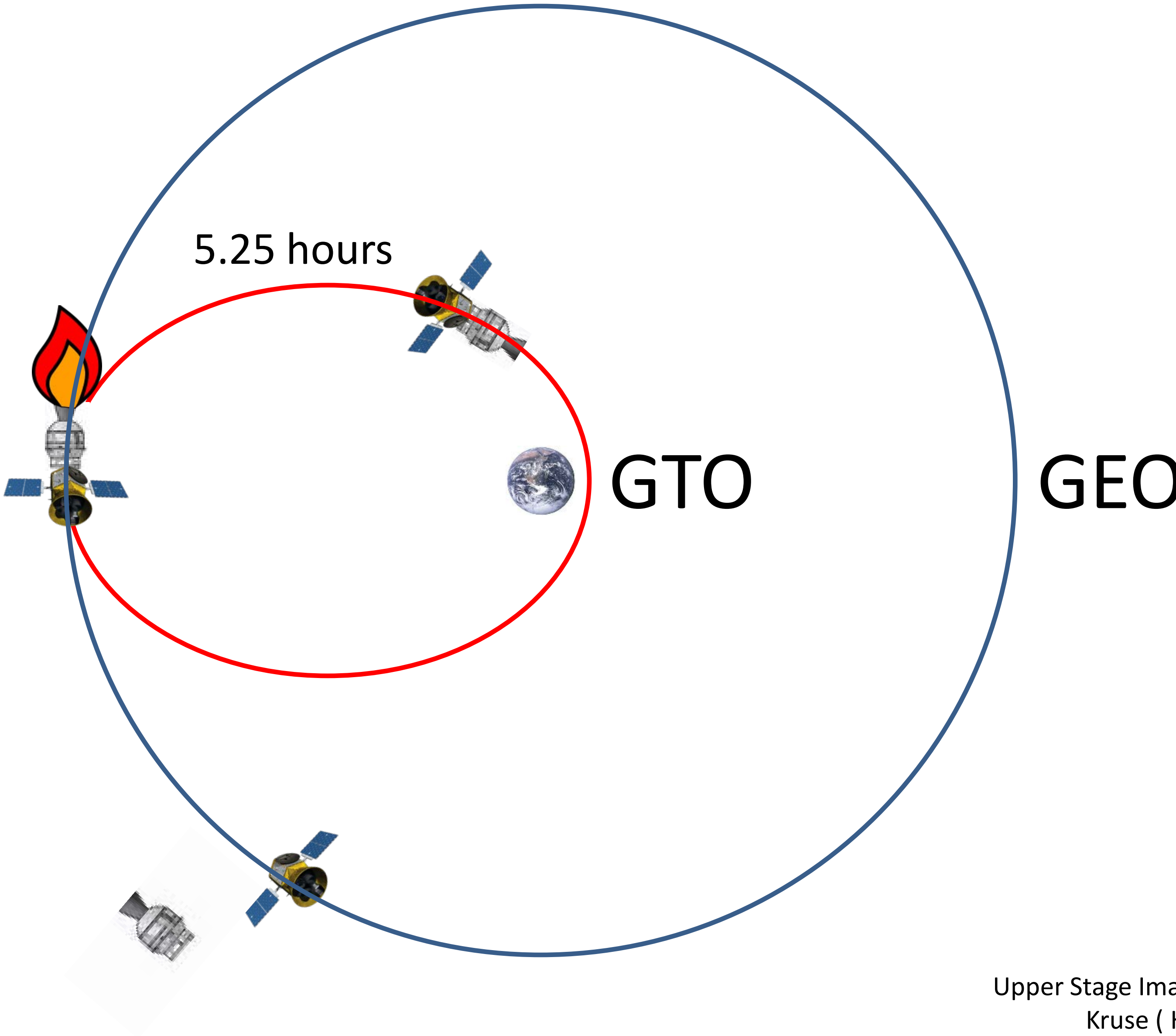
NASA, Luxembourg, and private investors are funding technology for asteroid mining.

NASA may become the “anchor customer”, purchasing asteroid-derived rocket fuel for Mars missions



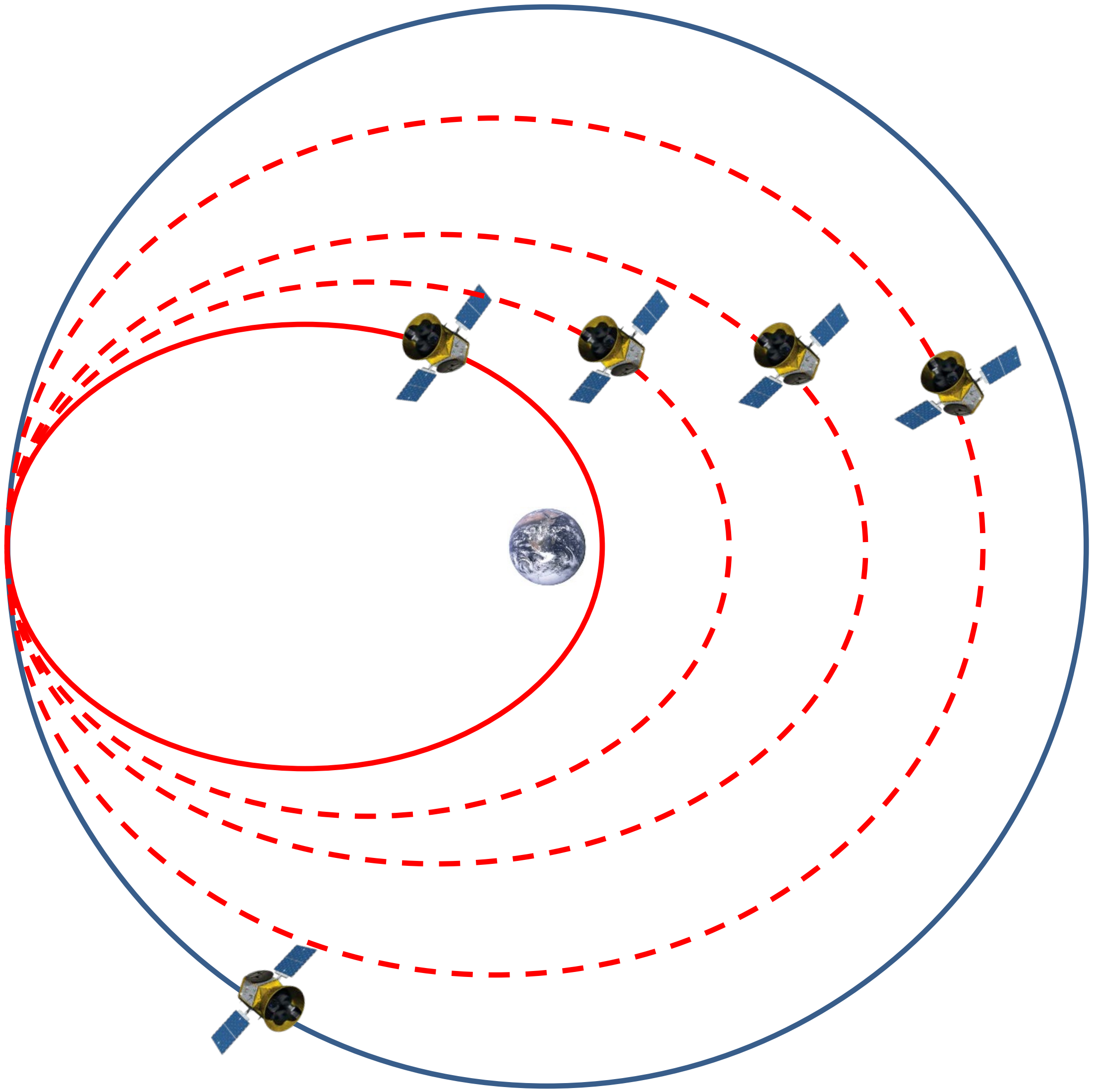
Boosting telecommunications satellites with asteroid-derived rocket fuel is a viable commercial business

Original Method to Boost Comsats



Upper Stage Image credits: Richard Kruse (Historic Spacecraft)

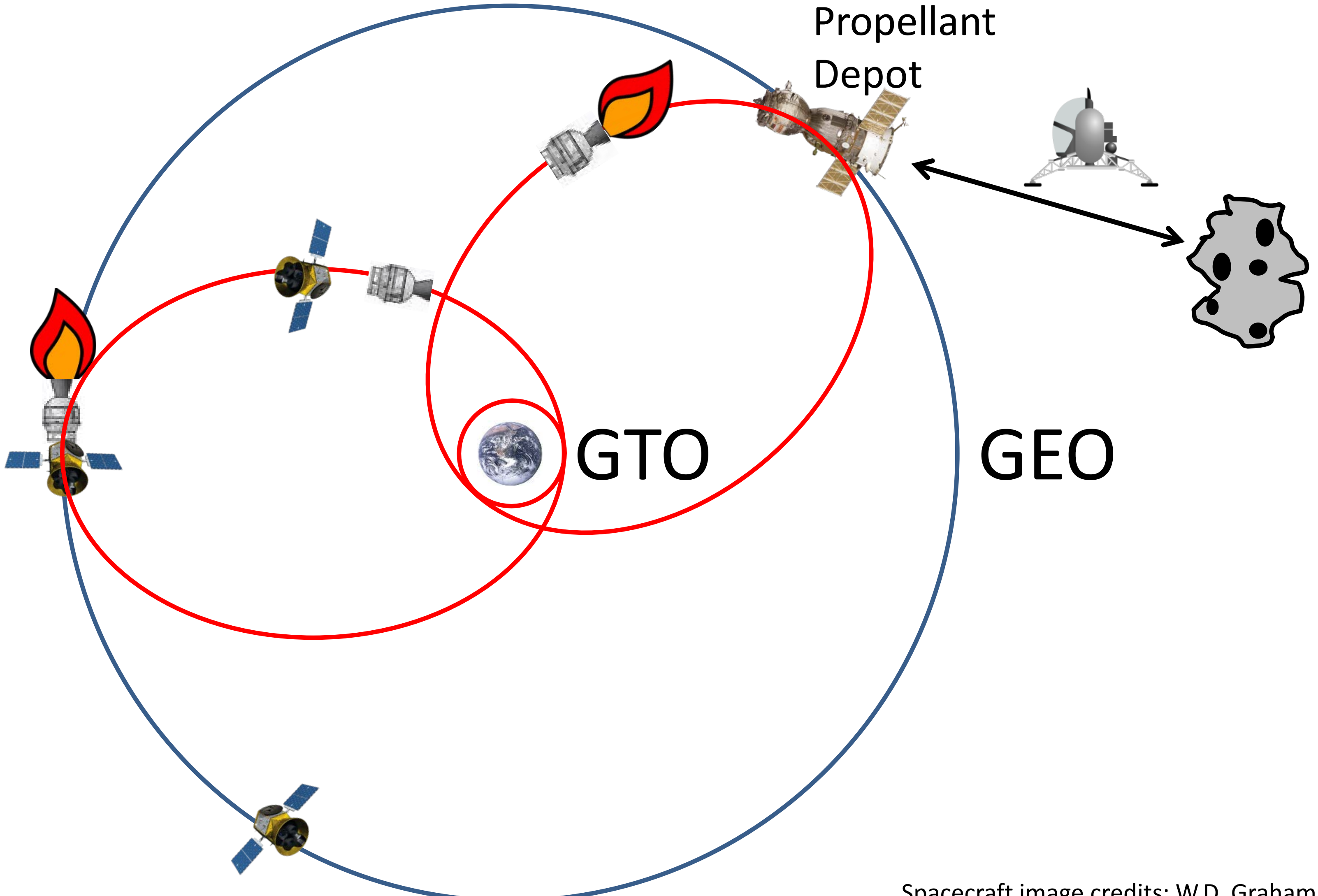
Improved Method to Boost Comsats



6 - 12 Months!

Loss of Revenues in >$100M

Business Case for Asteroid Mining



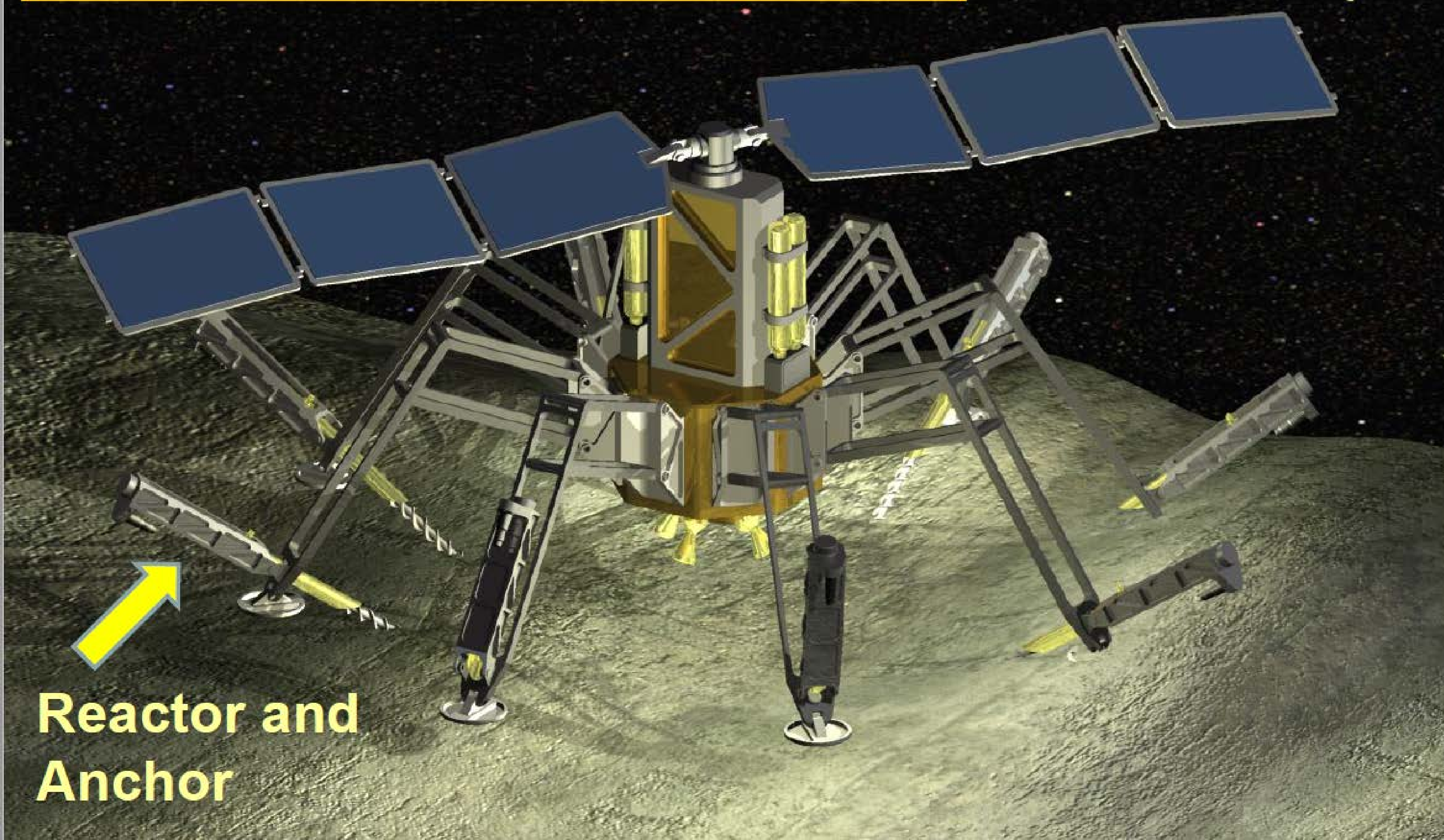
Spacecraft image credits: W.D. Graham (Wikimedia), Richard Kruse (Historic Spacecraft)

Deep Space Industries / UCF Asteroid Simulant

Spider Miner For Large Asteroids

Captures, Processes and Recovers in Situ

Chart credit: Kris Zacny, Honeybee Robotics



Honey Bee Robotic Asteroid Capture for ISRU Resource Return

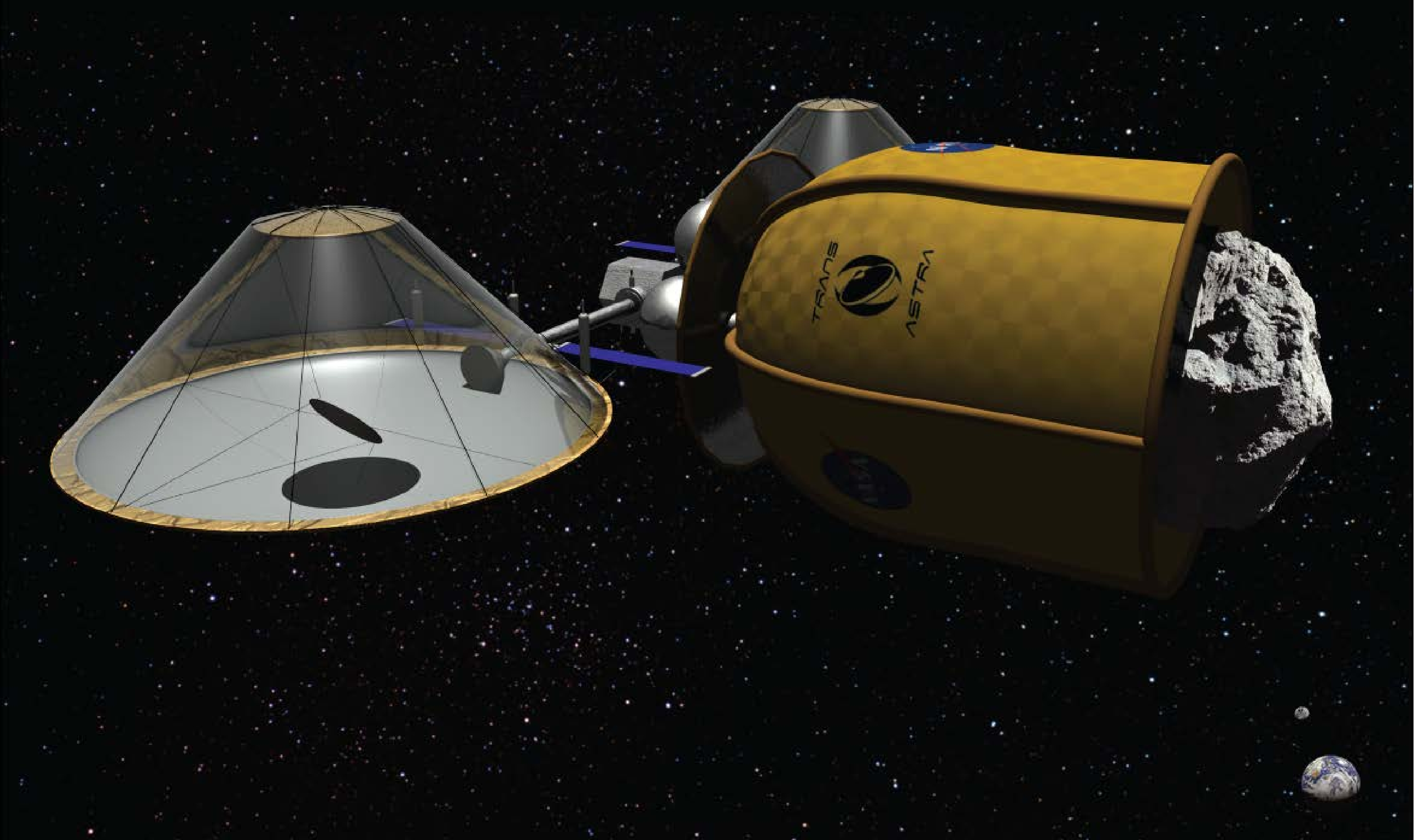
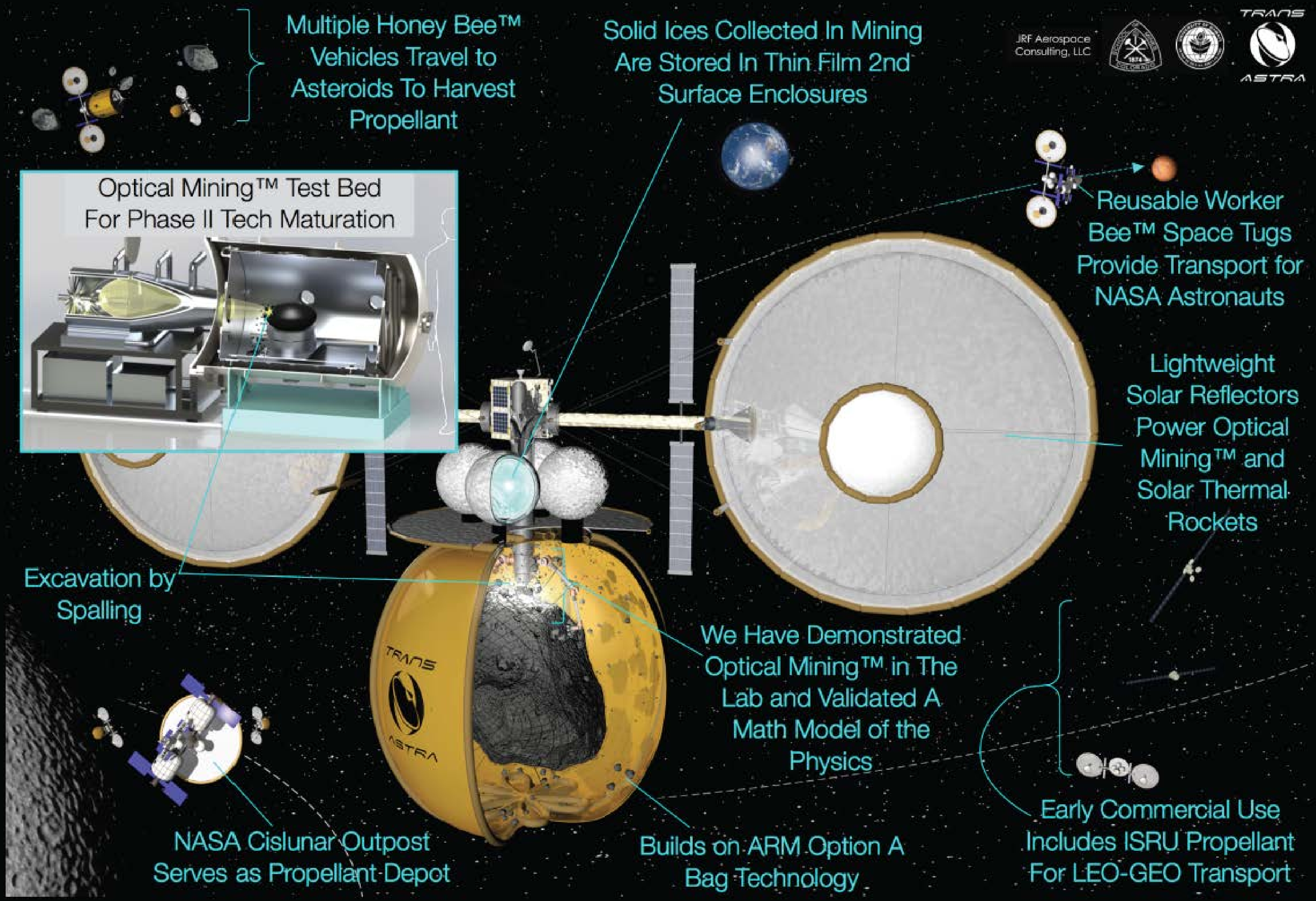
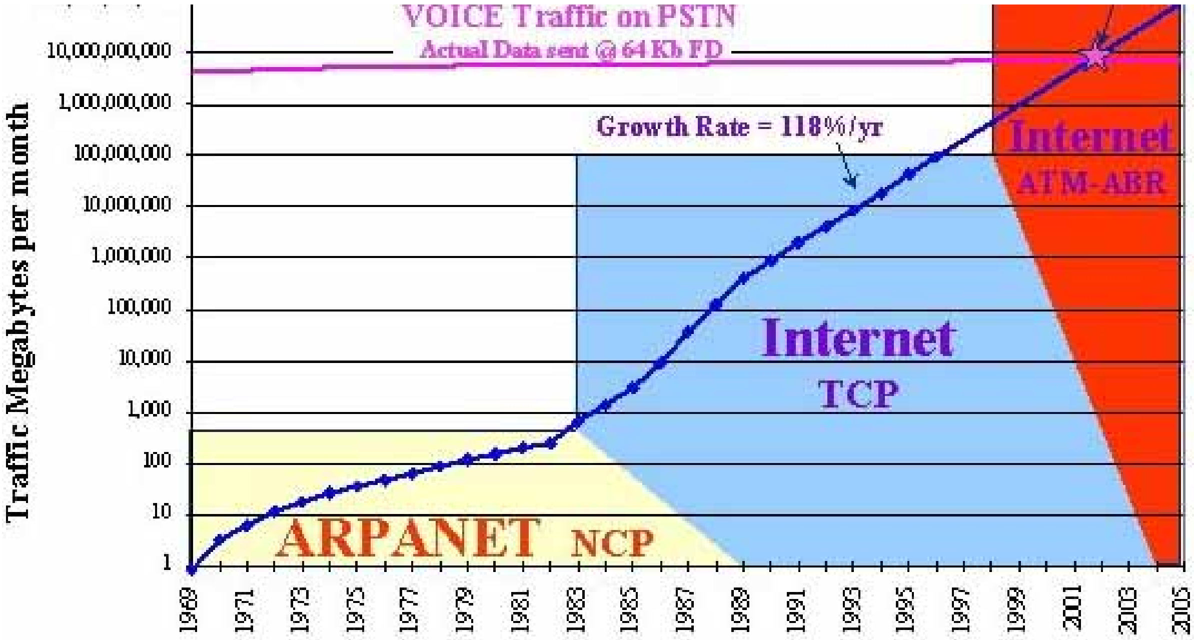


Chart courtesy of TransAstra

Chart courtesy of TransAstra



Exponential Growth of the Internet



Source: The Roads and Crossroads of Internet History by Gregory R. Gromov

Source: Wikimedia

Source: Wikimedia

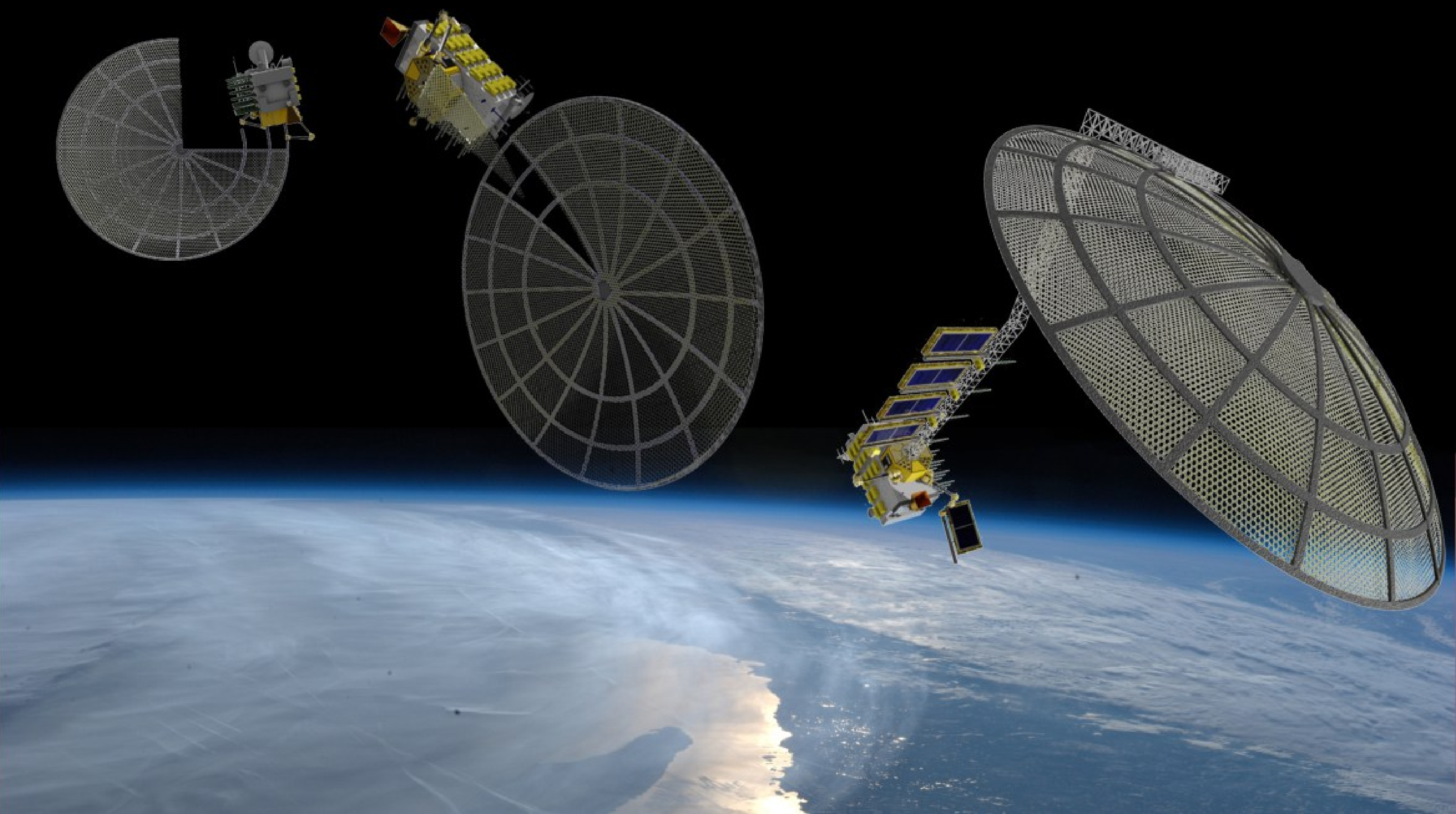
- 50 to 100 billion physical objects will be using the internet by 2020
- User interfaces grow exponentially 50% per year

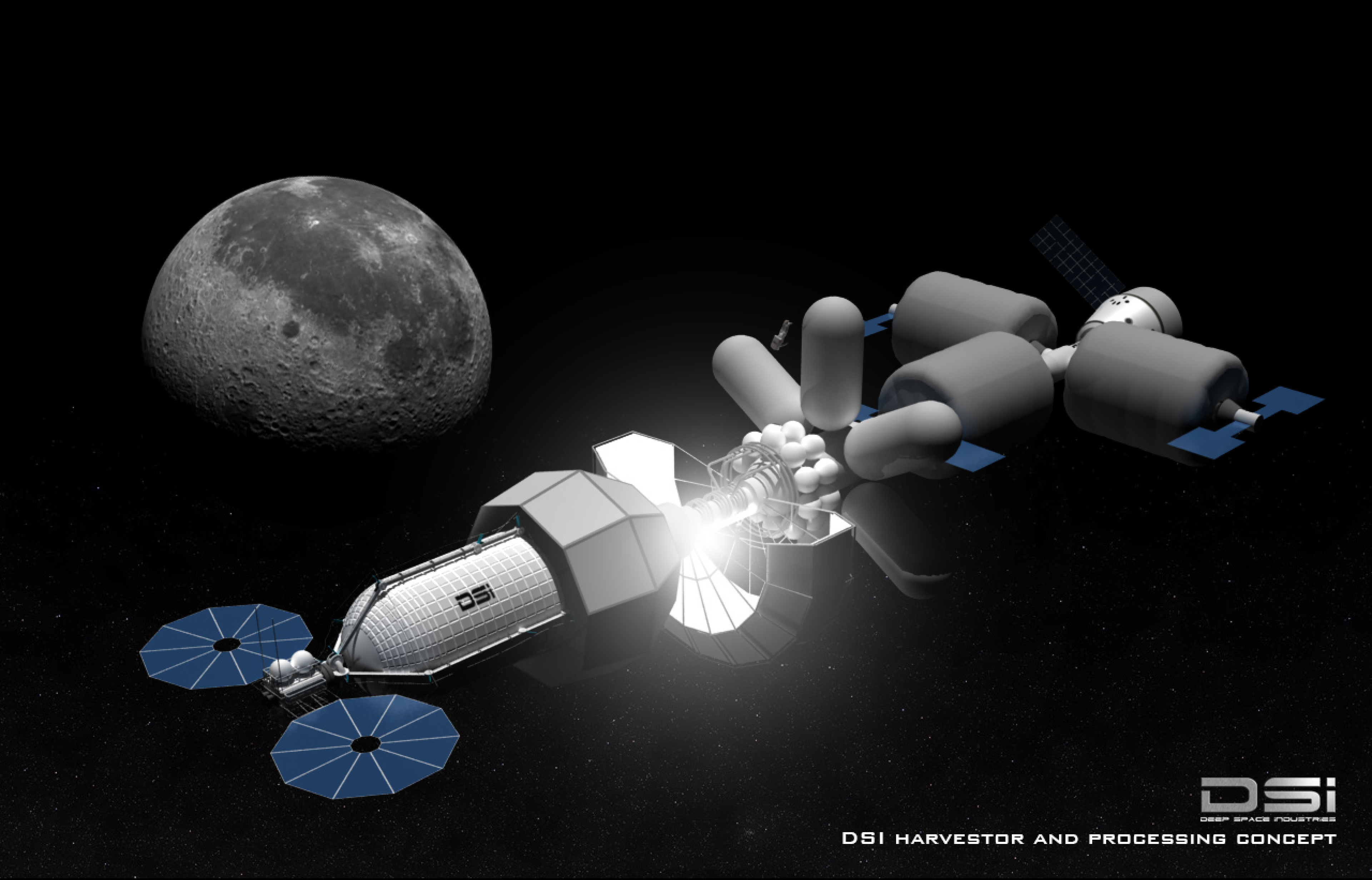
Meeting Demand for Data

- Royal Society: we are nearing the “capacity crunch” of Shannon’s Law
- A 2015 report by the Semiconductor Industry Association and the Semiconductor Research Corporation: “Unfortunately, neither existing technologies nor current deployment models will be able to support the skyrocketing demand for communication, especially in the wireless sector”
- LEO and MEO constellations (OneWeb, SpaceX, etc.) can extend Internet growth only a couple decades
- Building giant antennas in space can sustain Internet growth through end-of-century
- In-space construction opens additional business opportunities

Archinaut: 3D Printing Giant Antennas in Space

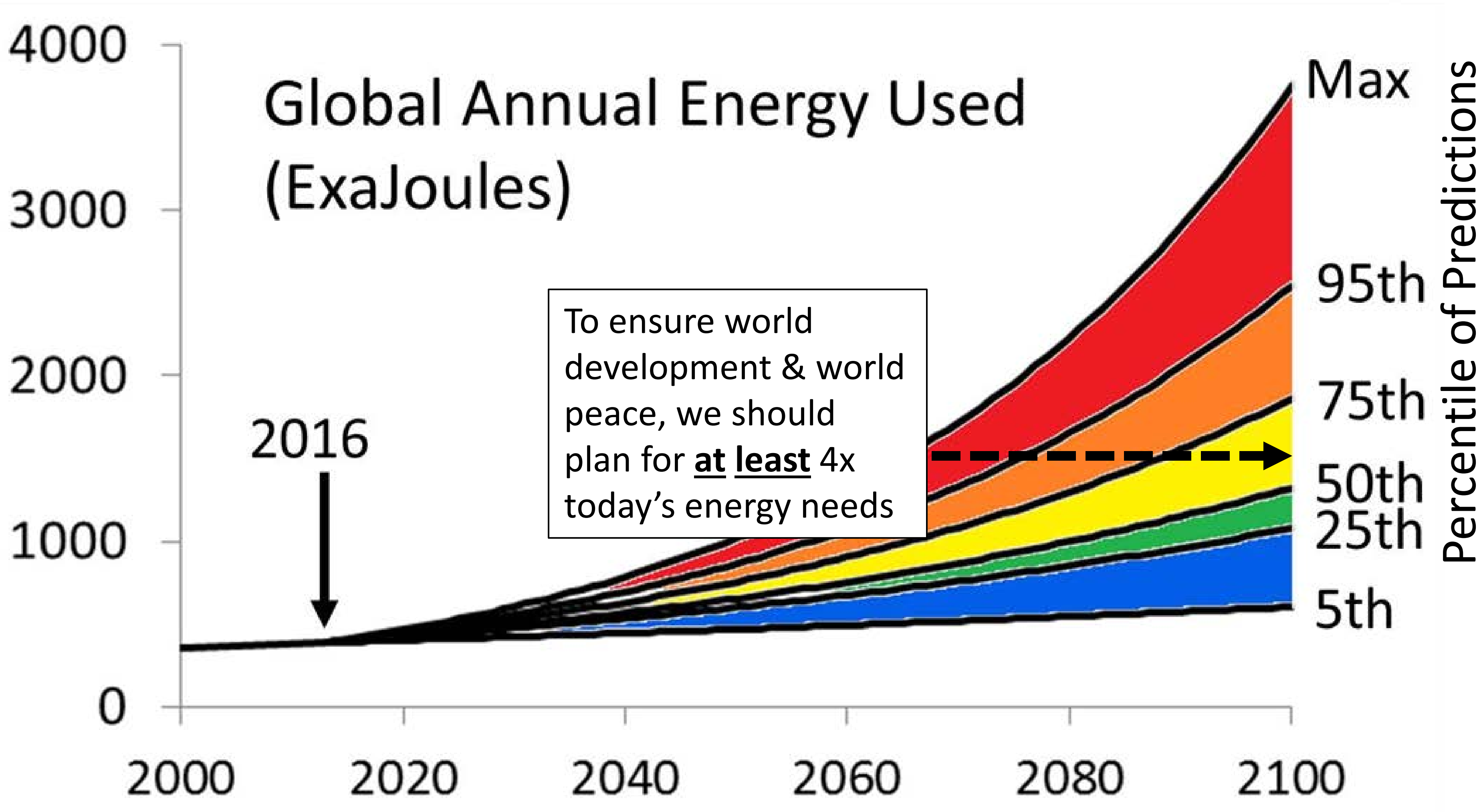
Made In Space, Northrop Grumman, and Oceaneering, funded by NASA



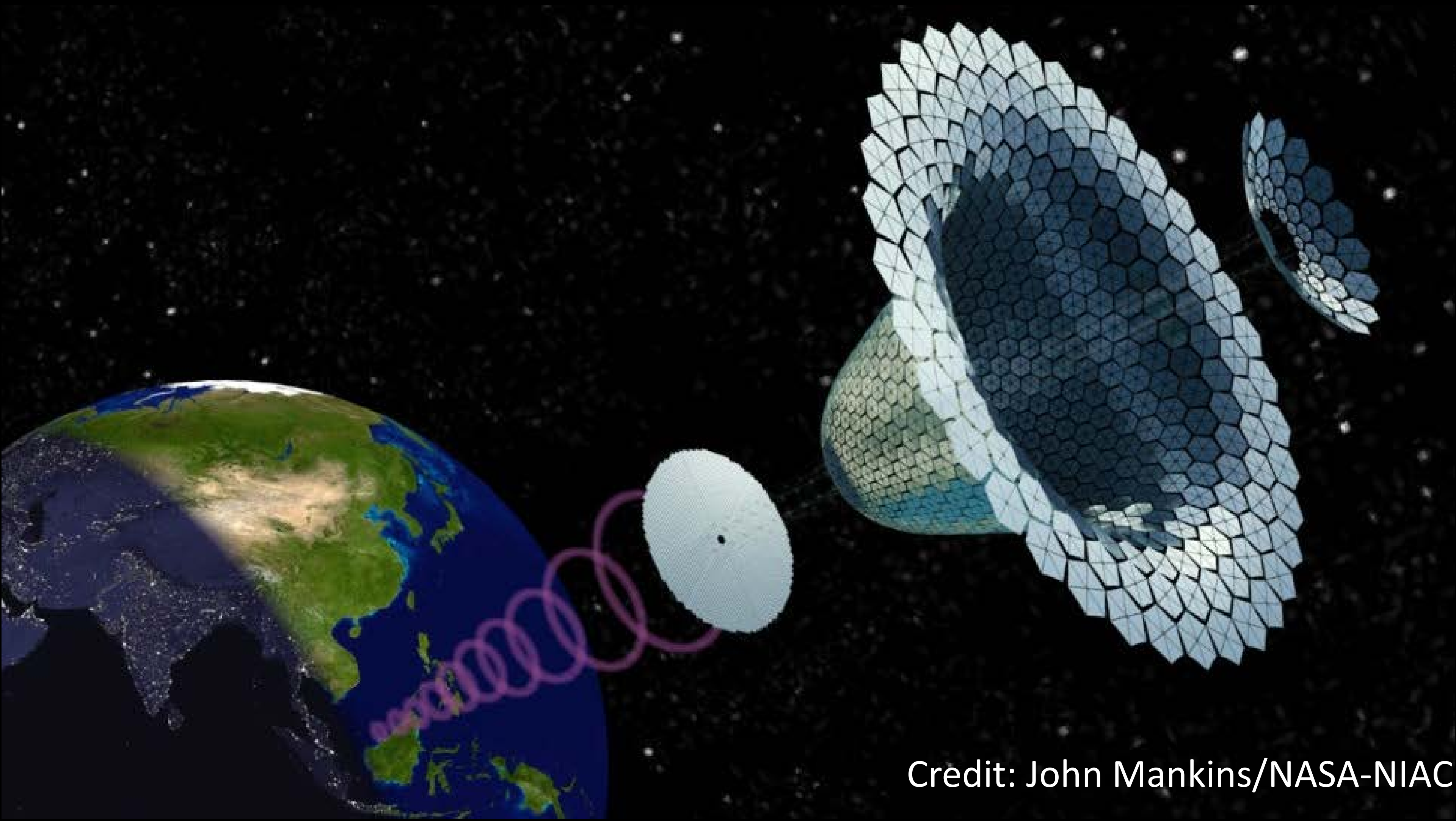

DSi
DSI HARVESTOR AND PROCESSING CONCEPT

Energy Needs to 2100

UN analysis of 133 Published Economic Simulations



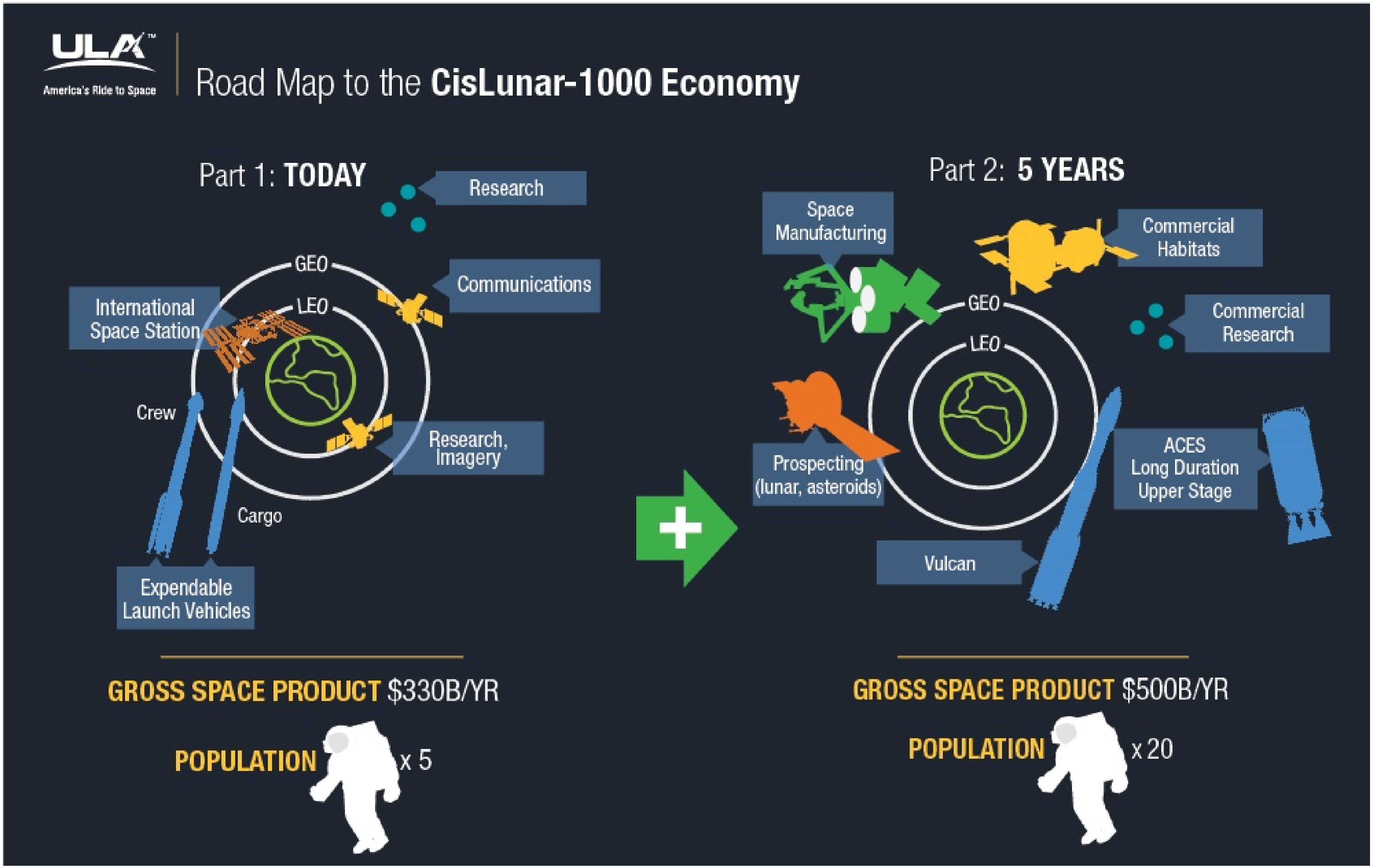
Space-Based Solar Power



Credit: John Mankins/NASA-NIAC

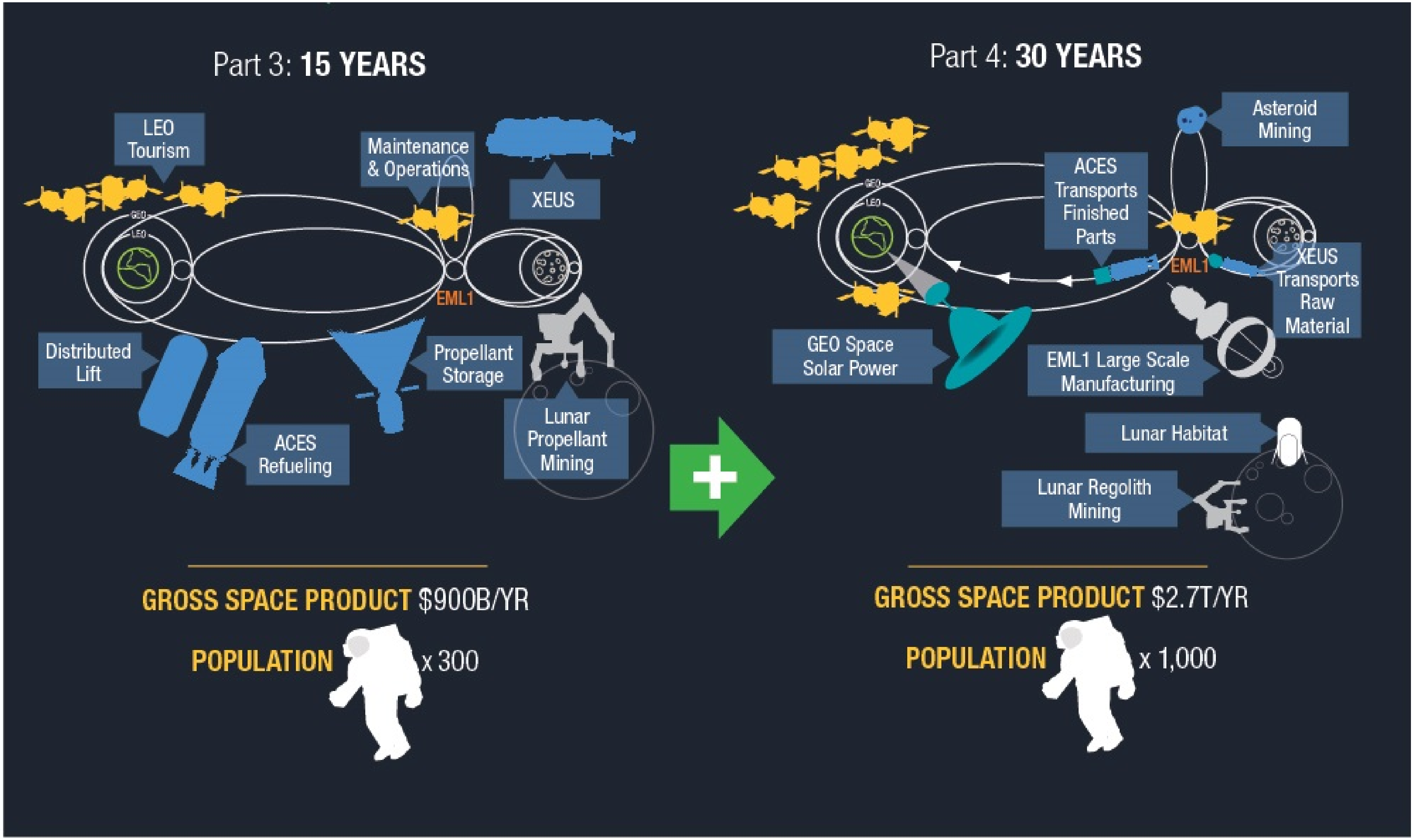
Cislunar 1000 Vision

(Chart courtesy of United Launch Alliance)



Cislunar 1000 Vision

(Chart courtesy of United Launch Alliance)



The 21st Century is When This Will Happen

This will lead to a new profession and a new academic discipline:

"Economic Planetary Science"

Development of Economic Geology

- Stanford Professor of Economic Geology, C.F. Tolman (1939) Sigma Xi Quarterly:
- Period of Uncontrolled Speculation
  - Prehistory until 1830
- Period of General Observation
  - Geological Surveys, until 1914
- Period of Detailed Observation
  - Economic geology takes a leading role, e.g. driven by mining & petroleum exploration

Tolman's Observations

- "Descriptive paleontology, especially of microfauna, has grown by leaps and bounds since laboratories were established by the oil companies for the purpose of studying the fauna as an aid to the working out of the stratigraphy of the oil fields. There are probably over one hundred well equipped micro paleontologic laboratories in this country "

Tolman's Observations

- "The stratigraphy and the compilation of the geological column in the oil fields has been worked out in greater detail than would have been possible for investigators without the facilities given the geologist by the operating companies."

Tolman’s Observations

- “Ralph Reed's book, *The Geology of California*, is a compilation chiefly of the detailed work of the oil geologists and paleontologists because most of the detailed work in California geology has been done by them. This work was financed by the Texas Oil Company and was published by the American Association of Petroleum Geologists.”

Tolman’s Observations

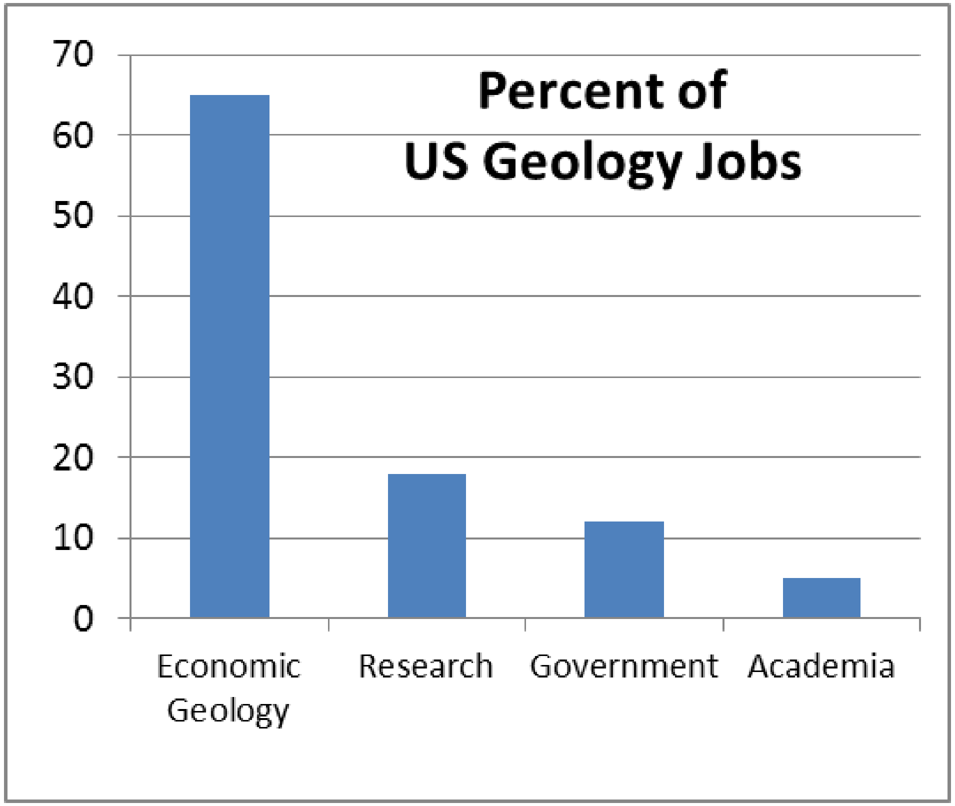
- “Since the Great War the greatest advances in ore deposits is due to the development of special detailed method of underground mapping in mines…The fundamental data thus collected now furnishes material that can be analyzed by the structural geologist.”

Tolman's Observations

- "Finally, ground water hydrology…one of the important specialized fields of economic geology. As an example…the Hawaiian Islands…This detailed mapping of the ground water geologist has furnished us pictures of the structure of the Hawaiian volcanoes which could not be obtained by any other method of investigation."

US Geology Jobs

- US Bureau of Labor Statistics
- 65% in economic geology such as mining
- 18% in research
  - many funded by economic interests
- 12% in government
  - mostly managing economic activities
- 5% in academia
  - with most of their students going into economic geology



Correlation of Science & Economics

- 2012 study of the publishing record of scientists in 147 countries
- Scientific productivity correlates with 2 things:
  - 1. How developed the country is (intensive)
    - Better tools, infrastructure, and opportunity for working scientists
  - 2. How large the economy is (extensive)
    - More funding for the leaders to command into science

What is true of these 147 countries should be true of the country we call "Space", and as citizens of that country our productivity should rise dramatically as it is economically developed.

Will Space Mining Hurt Space Science?

- Ruin sites of high scientific value?
  - Lunar Polar Ice Deposits
- Example: NASA’s policy for visiting the Apollo landing sites
- **<u>More such policy will be needed</u>**
- Mining companies desire the clarity it brings
  - Reduces uncertainty for potential investors
- On balance, space development will <u>dramatically</u> <u>help</u> space science

Demand for Human Spaceflight

- Robotics are increasingly capable for sortie science missions without humans
- Robots cannot (yet) repair and develop other robots
- Human astronauts will be vital for in-space industry
- In-space industry will then make human spaceflight affordable and permanent
- Robots will <u>not</u> replace humans in spaceflight

The Golden Age of Planetary Science

- Our civilization is outgrowing our planet.
- Planetary science is becoming vital to the health of our civilization and of our planet.
- The Golden Age of Planetary Science is about to begin.

Chart courtesy Chris Lewicki, Planetary Resources

Think Outside the Sphere