McKinsey & Company

Mining in Space

Defining New Opportunities in the Emerging Space Economy.

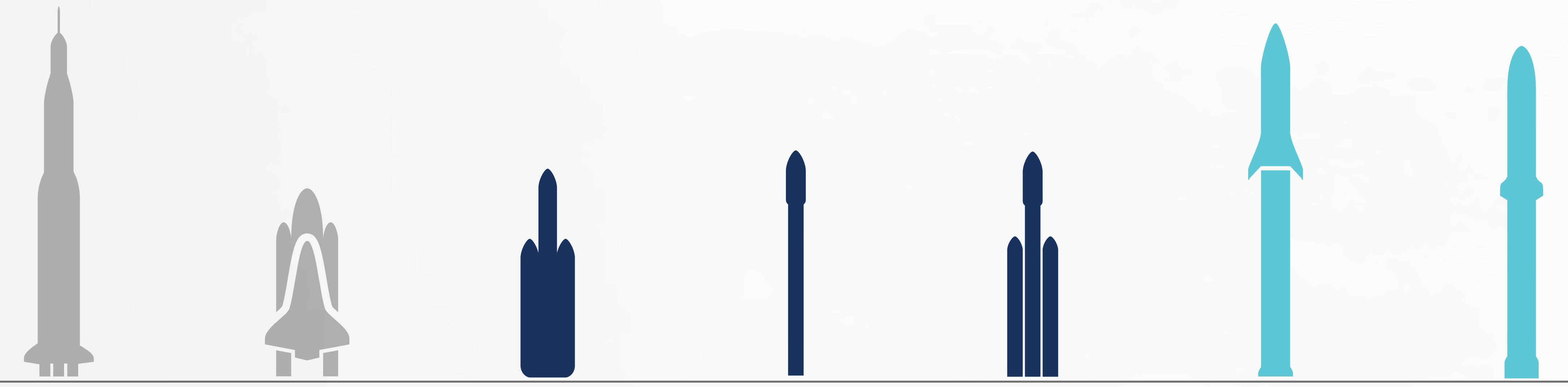
Updated April 2019

"Remember to look up at the stars and not down at your feet."

- Stephen Hawking

It’s not science fiction anymore. A new frontier is *now* open for business.

The commercial space industry has seemingly been a hobby for billionaires since the first space tourist paid $20 million to fly to the International Space Station back in April 2001. The fledgling industry has been focused on reducing launch costs for years and has now achieved over a **93.8% costs reduction*** in just 16 years. With more competition rapidly coming online over the next two years, mostly driven by SpaceX’s successful reuse of its rocket boosters, prices are expected to fall dramatically lower still.



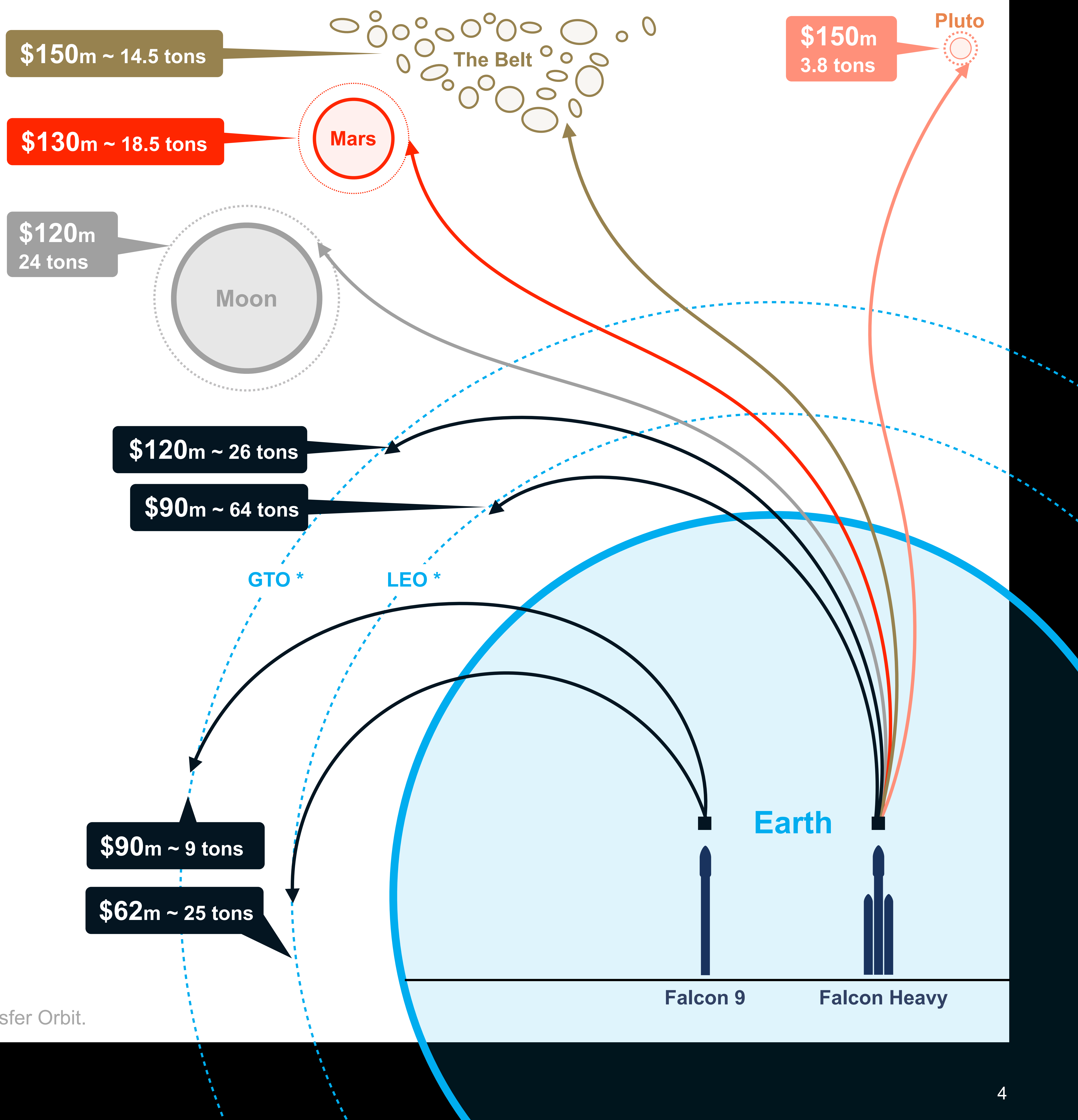
	Saturn 5	Space Shuttle	Delta IV Heavy	Falcon 9	Falcon Heavy	Starship	New Glenn
Launch:	$1.16b	$1b	$350m	$62m	$90m	$40m (est.)	N/A
Payload:	130 tons	25 tons	31 tons	25 tons	64 tons	100 tons	47 tons

Previous NASA vehicles — Current commercial vehicles — Future vehicles currently in development

Falcon Heavy
A pair of SpaceX’s Falcon Heavy boosters landing simultaneously after successful launch to orbit.

Lifting tons and tons into orbit is *no longer* a feat for governments. Even lifting tons into deep space or to other bodies is now a reality.

The Falcon Heavy currently has more lift capability than any other operational rocket in the world, with a payload of 140,660 lbs. to low Earth orbit and 37,040 lbs. to a trans-Mars injection. The rocket was designed to meet or exceed all current requirements of human rating. The structural safety margins are 40% above flight loads, higher than the 25% margins of other rockets. Falcon Heavy was designed from the outset to carry humans into space as the Falcon 9 will do this year with NASA astronauts onboard. With launch prices to any destination in the solar systems around 1/10th the price of a Space Shuttle launch just 8 years ago –
access to space is no longer an issue.



Prices are based on publicized pricing by SpaceX. *LEO is Low Earth Orbit. GTO is Geosynchronous Transfer Orbit.

Even with the lowest launch costs in human history, you can *blast into space for even less* with ride sharing services now.

Commercial space companies, such as SpaceX, have driven launch costs dramatically lower in recent years; however, it still presents a large financial commitment for a lot of businesses. If you do not need an entire, dedicated rocket to lift tons and tons into space. New companies in the United States, such as spaceflight.com, offer ride sharing services for companies that would like to launch payloads into space, but do not need the full capacity of modern rockets. Why pay for the entire FedEx plane when you just need to a ship a package?

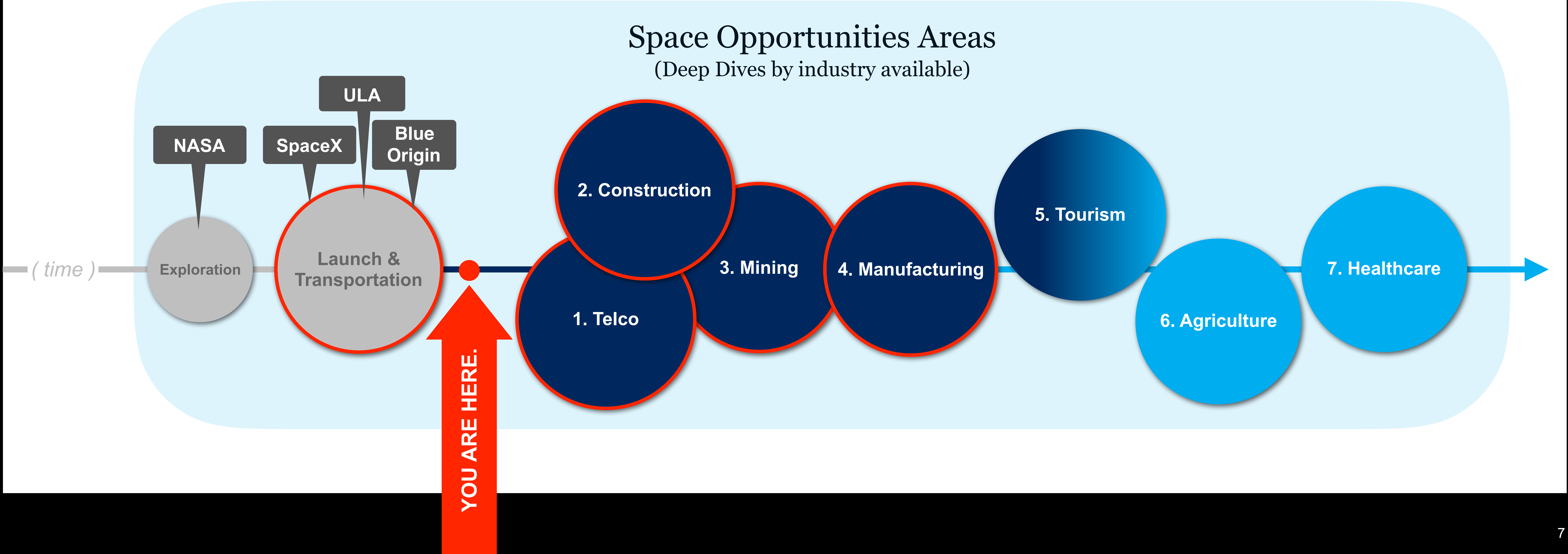
*Based on NASA Space Shuttle estimated launch costs of $1 billion per flight and its payload capacity of 25 tons versus public pricing from spaceflight.com for containerized 3U payloads.

Access to space is within the grasps of startups & corporations alike, so *who will control the new space economy?*

In the past, the risks and extremely high costs of space exploration have often led some to question why humanity should even bother with leaving our own planet. From history we know that every major movement of humanity has tapped entirely new resources, developed new technologies, and created tremendous wealth. Massive “blue chip” corporations, such as Wells Fargo, got their start in the westward expansion of the United States during the 19th century. Now, in the 21st century with the costs of access to space now racing downward; technology is getting physically smaller; natural resources are becoming increasing harder to access; and Earth’s population is growing rapidly – all mean there is a tremendous opportunity for all businesses to harness the infinity of space. The stage has been set for the visionary businesses that will capture the value and control this new economy. The next titans of industry are already writing their name in the stars today.

The New Space Economy.

The universe is a big place and the emerging space economy has endless possibilities for business. As with any new emerging economy, there are enabling or foundational industries that are needed first before the real value in other industries can be fully captured. This does not mean that economies evolve in a linear, waterfall fashion. Rather, the value pools and opportunity areas for some industries only become truly attractive once a large user base or basic capability has been established by another industry. This simply translates into bigger near term opportunities for some industries and bigger long opportunities for other industries. With the new space economy there is also a spatial lens to filter potential opportunities through since the entire solar system is now accessible. The following diagram shows when and where the broadly described industries would likely find the highest ROI of any space focused efforts.



"If I'm 80 years old, looking back on my life and the one thing I have done is make it so that there is this ***gigantic entrepreneurial explosion in space*** for the next generation, I will be a happy, happy man."

- Jeff Bezos

Industry Opportunity:

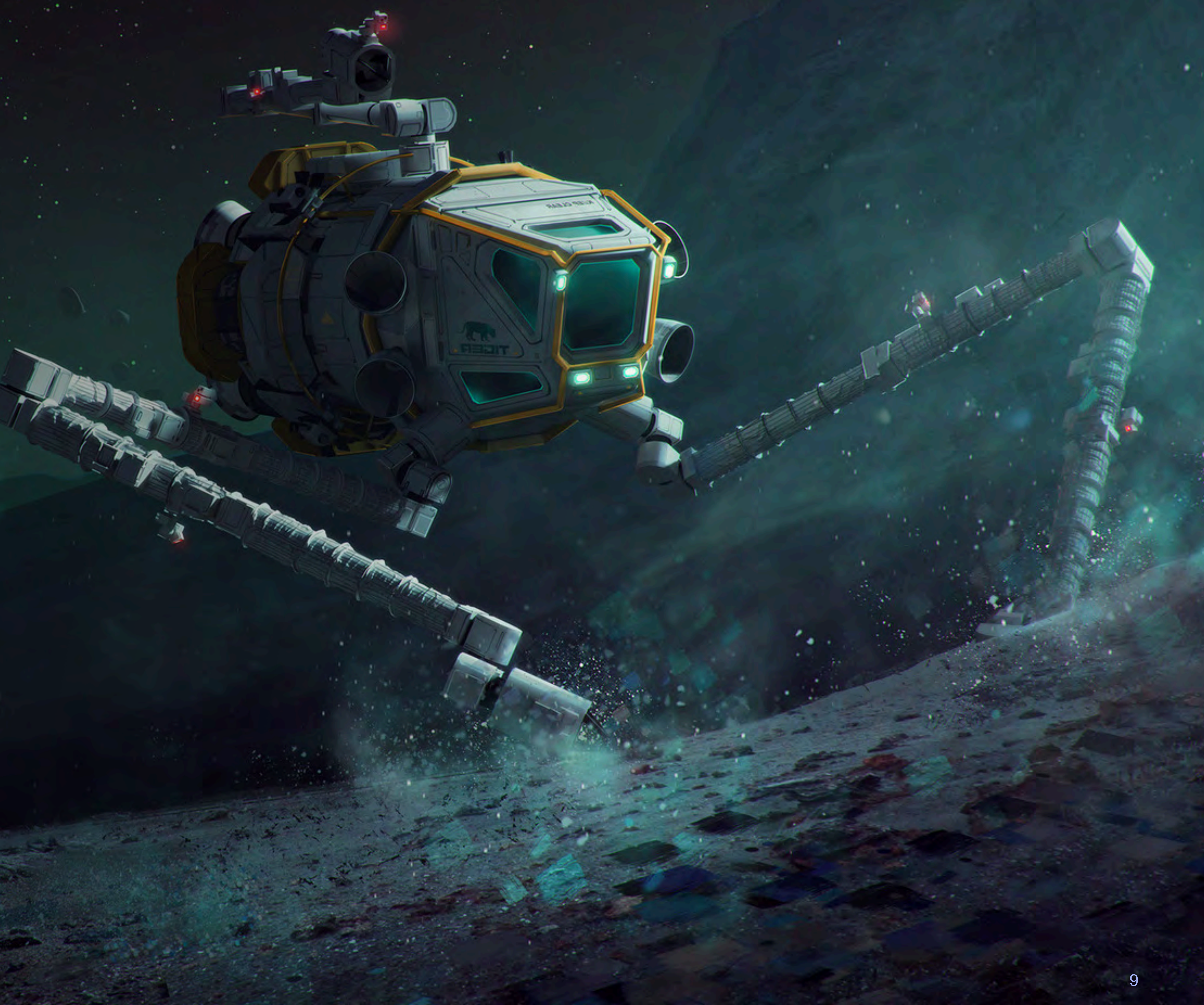
Mining

Earth only has a finite amount of every single raw material that humanity relies upon. With just over 150 years of industrial activity so far, a lot of those resources are already becoming harder and harder to find. Mining resources in space, on other planets, and on other bodies in the solar system is absolutely needed for humanity to continue to thrive.

Exploration and energy companies around the world are already pushing technology to dig and drill deeper than ever before to find new resources. However, there are new resources whizzing past Earth in space at known intervals and other bodies orbiting the Sun that have more amounts of certain raw materials than *have ever existed on Earth*. Infinite assets are all out there in space, waiting to be claimed, processed, and sold.

As such, mining presents the one of the largest near term opportunity areas for the emerging space economy.

- Tremendous ROIs possible
- Long term growth with deep space operations
- Immediate market for resources mined in space
- Can operate near Earth or the Moon or in deep space
- Near term premium pricing for first movers
- Potential to incredibly disrupt the global economy



“The first trillionaire in the world will be the person who mines asteroids.”

- Neil deGrasse Tyson

The tremendous ROI that space mining presents is why this infant industry already has numerous startups trying to be the barons of the 21st century.

Mining raw materials from space has the potential to disrupt the entire global economy, create the first trillionaires, and unleash a new technological boom from the abundance of materials. The asteroid belt, a collection of millions of celestial bodies that is located between Mars and Jupiter, is currently valued at over $700 quintillion. Individual asteroids that are part of the belt or are in Earth crossing orbits have tremendous estimated values starting in the billions and quickly moving into trillions each. Rare Earth metals and exotic materials are not rare or exotic in space. An abundance of materials are floating there waiting to be claimed.

A **Bennu**
Near-Earth asteroid
Estimated worth: $699 m*

Composition:
iron, hydrogen, ammonia, nitrogen

B **Ryugu**
Near-Earth asteroid
Estimated worth: $82.5 b*

Composition:
nickel, iron, cobalt, water, nitrogen, hydrogen, ammonia

Anteros
Near-Earth asteroid
Estimated worth: $5.5 t*

Composition:
magnesium silicate, aluminum, iron silicate

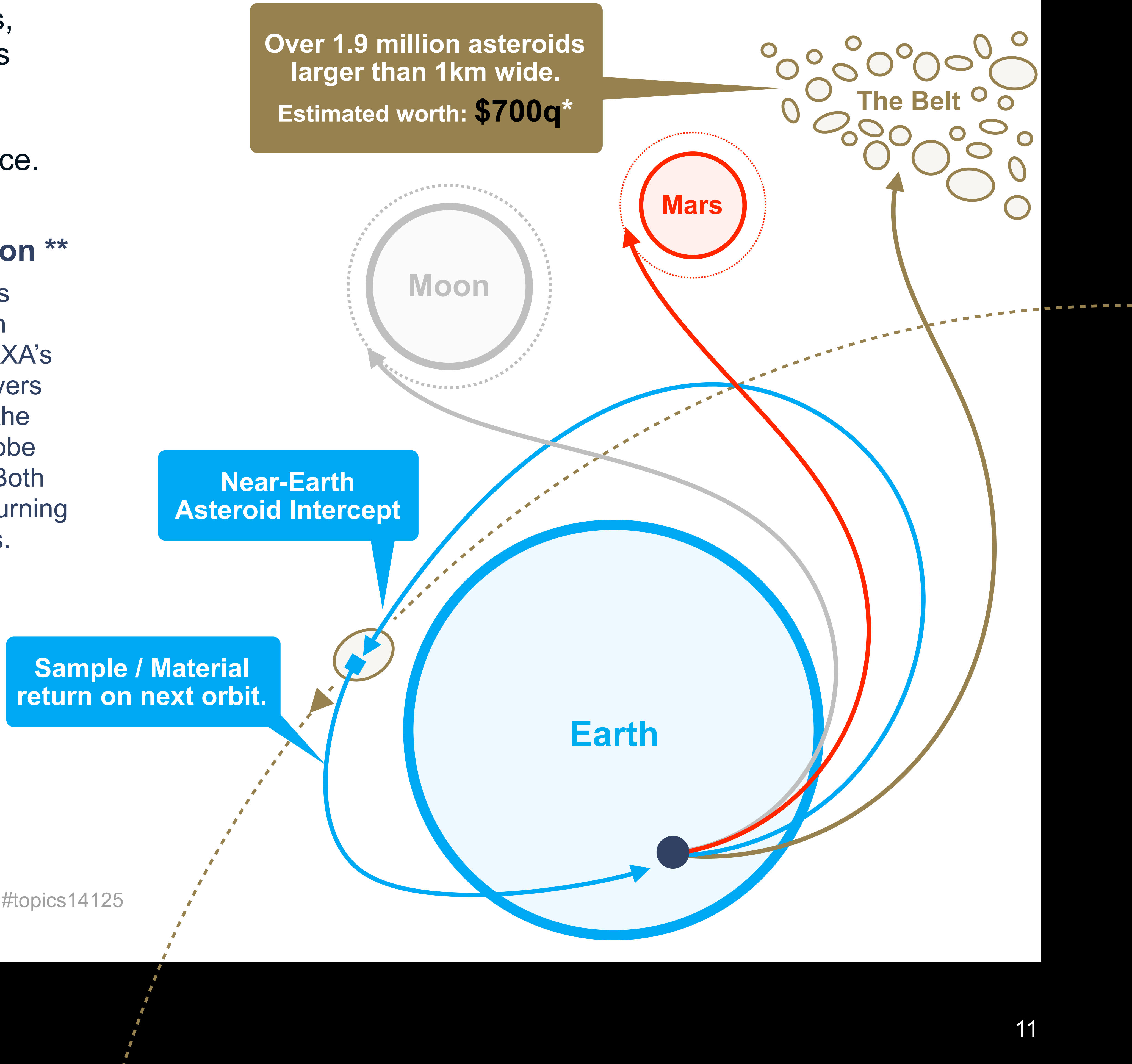
Davida
Main Belt asteroid
Estimated worth: > $100 t*

Composition:
nickel, iron, cobalt, water, nitrogen, hydrogen, ammonia

SpaceX Falcon Heavy
Launch Costs: **$90 - 150m**
Payload: **64 tons**

A B Not Science Fiction **

NASA's OSIRIS-REx probe is currently enroute to the Earth crossing asteroid, Bennu. JAXA's HAYABUSA 2 has landed rovers on Ryugu and as even shot the surface with projectiles to probe its subsurface composition. Both missions are planning on returning samples to Earth for analysis.



* All values shown in Millions (m), Billions (b), Trillions (t), and Quintillion (q).
Estimated values via Planetary Resources & [SOURCE] http://www.asterank.com

** [SOURCE] http://global.jaxa.jp/projects/sat/hayabusa2/topics.html#topics14125
[SOURCE] https://www.nasa.gov/osiris-rex

It's still early which means the largest near term opportunities are currently in ***prospecting*** where to start mining.

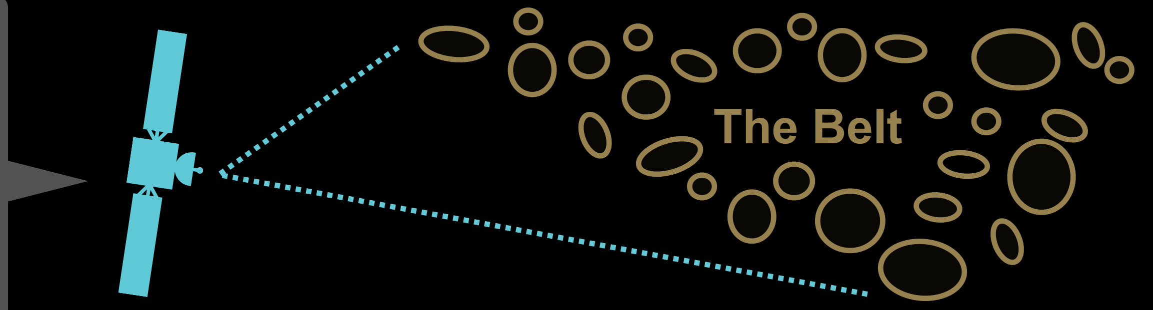
Large investments by venture capitalists have not only helped to start driving down launch costs, but also start the work to prospect asteroids, the Moon, Mars, and the entire solar system. While it is still early, there is ample room to build out the components needed in the nascent space mining industry from prospecting to mining to processing. Startups have been the first to start attempting to prospect materials in the solar system to find the first targets. Startups have already started cataloging potential valuable targets for mining with almost zero competition to date. While human miners in space is still many years away as no commercial launch providers will have human rated vehicles for at least one more year, feasibility studies and equipment R&D efforts for robotic mining are already well upon their way. For example, SpaceIL became the first private company to launch a commercial Moon lander in February 2019. Moon Express has partnerships with U.S. government and was the first private company to be granted permission to mine on the Moon by NASA under the 1967 Outer Space Treaty. The Moon will be a proving ground for mining technology that reaches out to the asteroid belt. Where to mine for the best ROI is the name of the game currently. The race is on to find and claim these resources, as legally under current international law, it is who gets there first.

* Estimated cube satellite costs shown in Thousands (k). Source material & pricing:
https://makezine.com/2014/04/11/your-own-satellite-7-things-to-know-before-you-go/
http://spaceflight.com/schedule-pricing/

+ Cube Satellite
+ shared ride launch

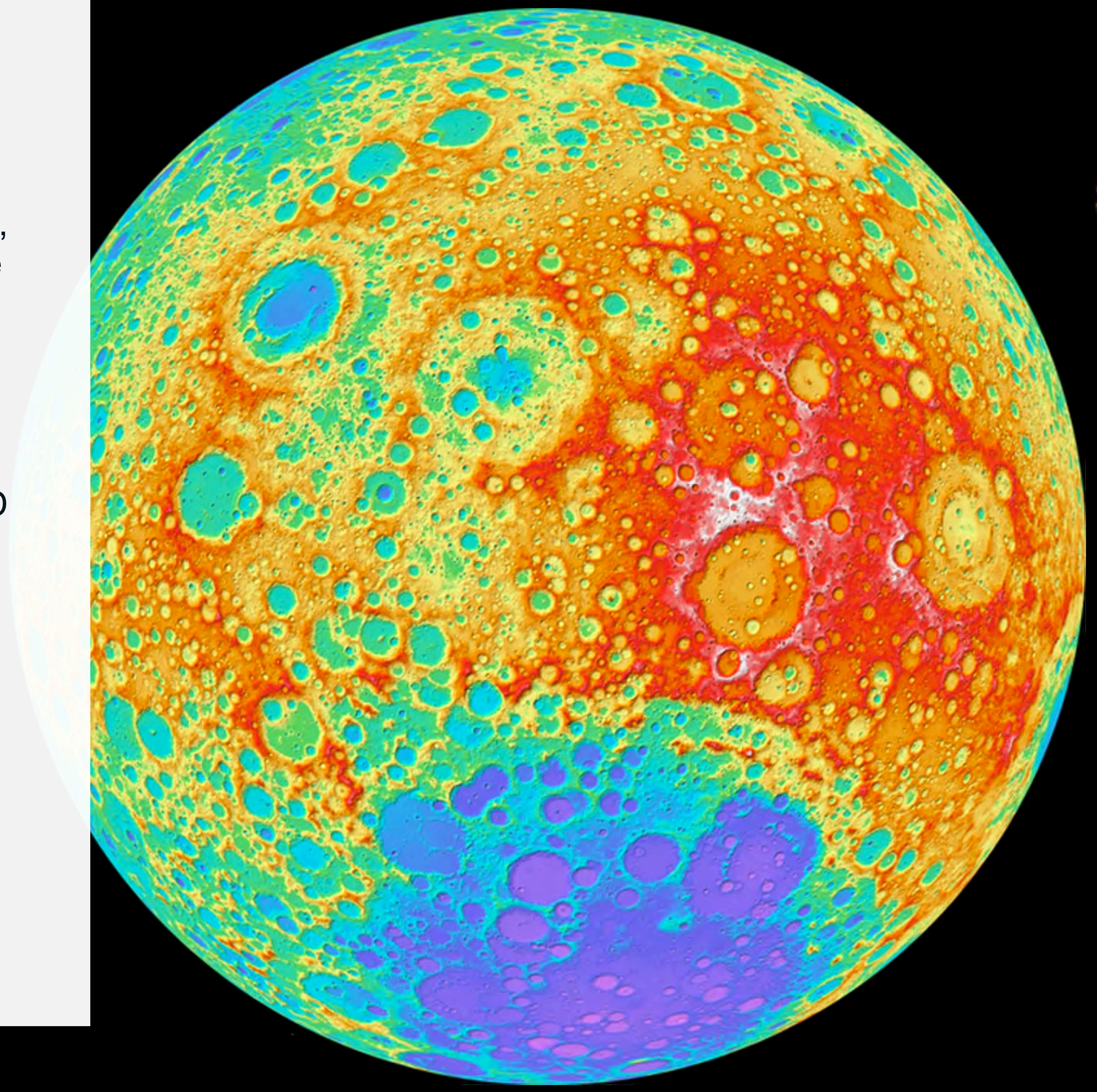
= typical luxury car

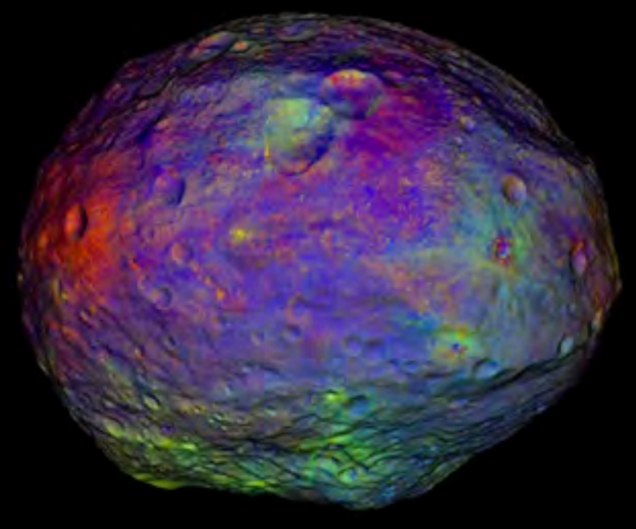
Average costs: **$50k***



PROSPECTING VIA CUBE SATELLITES

Dramatic reductions in electronics costs (driven by the smart phone, self driving cars, and 3D printing industries) have opened the doors for very inexpensive "cube sats" - very small and very cheap space craft. Hundreds to thousands of cube sats can be launched with a single flight. These inexpensive satellites are the spacecraft space mining startups have been launching into space already aboard commercial rockets.





Vesta

This false color image was taken by NASA's Dawn spacecraft in 2014. Dawn mapped the geology, composition & determined Vesta's rotational speed.

The Moon

This color-shaded relief view of the moon's far side was taken by NASA's Lunar Reconnaissance Orbiter in 2011. Multiple mining companies are currently racing to explore the Moon for valuable resources.

Development of off-world mining technology & techniques *has already begun.*

Mining off-world is not science fiction fantasy anymore. Numerous startups such as SpaceIL, Moon Express, Deep Space Industries, and Astrobotic among others are currently racing to be the first to explore and then exploit the essentially unlimited natural resources of the Solar System. As space mining moves forward rapidly over the coming decade, the early movers will have a vast technology lead over those who wait. Off-world mining techniques will be similar to our current Earth based mining processes – at least where some gravity is present. Gravity, a force we often take for granted on Earth, is a major design factor to off-world mining equipment. Low gravity environments, such as the Moon and even Mars, still have enough gravity to allow for more "traditional" approaches mining. The one technology that is often used in mining on Earth that might not translate well to mining in space is explosives. In space, controlled explosions via a rocket nozzle produce trust and acceleration. Without atmospheres and a large gravity well to slow debris and bring them back to the surface, mining issues like 'fly rock' take on a whole new meaning.

MINING WITH GRAVITY

Robotic Swarms

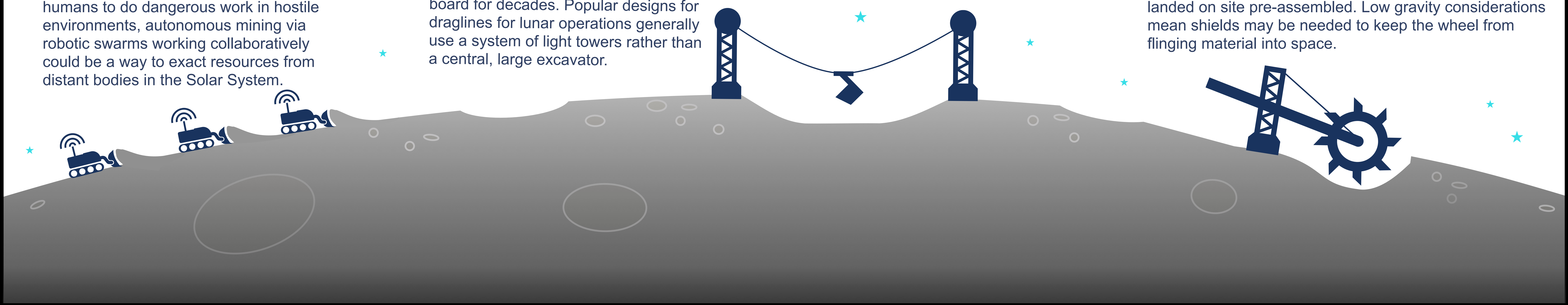
With the expense and danger of sending humans to do dangerous work in hostile environments, autonomous mining via robotic swarms working collaboratively could be a way to exact resources from distant bodies in the Solar System.

Draglines

Mass optimized, drag line excavators for the Moon have been on the drawing board for decades. Popular designs for draglines for lunar operations generally use a system of light towers rather than a central, large excavator.

Bucket Wheel Excavators

Mass optimized, bucket wheel excavators could be shipped to a site and assembled or smaller versions landed on site pre-assembled. Low gravity considerations mean shields may be needed to keep the wheel from flinging material into space.



Asteroid mining concepts have been on engineering drawing boards for almost 50 years. *Now*, the race is on to build these some of these systems & concepts.

Since the 1950s, numerous engineering concepts for mining in space have been developed; however, most have been waiting on technology advances and changes in economic factors to be practical. Over 50 years later, massive technological leaps combined with massive drops in launch costs from private launch providers have changed the equation where space mining is now practical. The businesses “waiting to see” if the commercial space mining takes off before developing their own capabilities will be rapidly left behind in the coming decade and even potentially blocked by competitors from even entering the market.

MINING IN LOW OR ZERO GRAVITY

Rock Hoppers

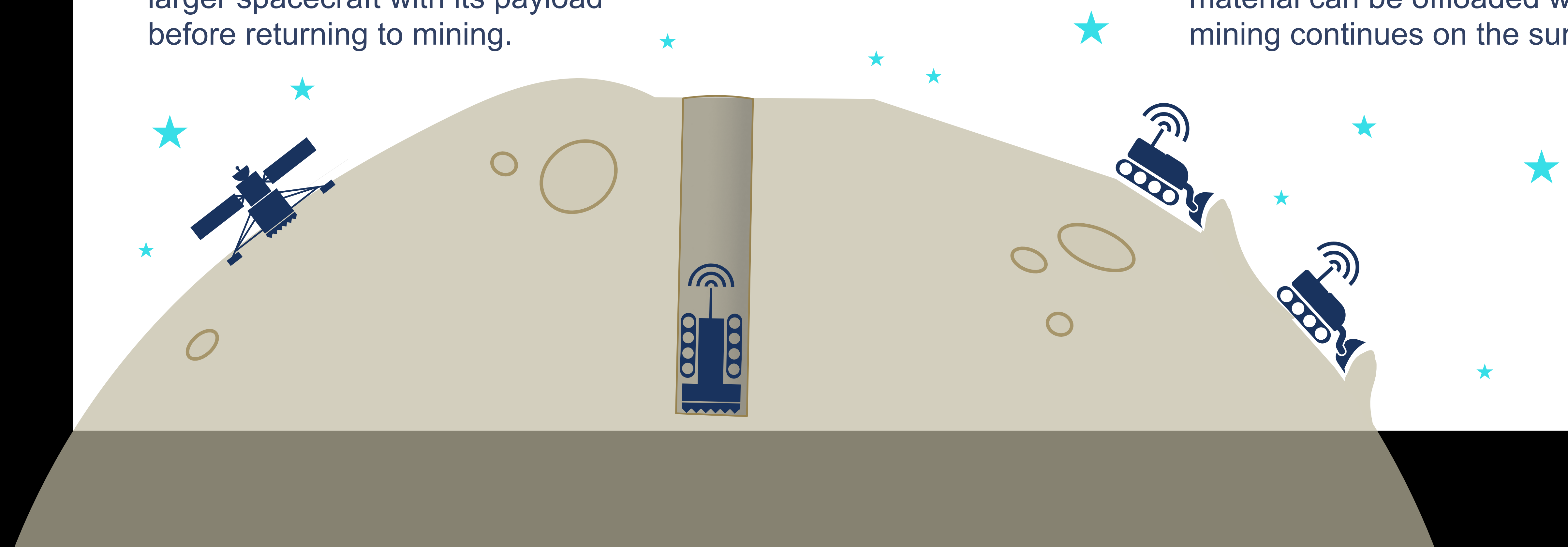
Robotic landers that anchor themselves to the surface of small asteroids to stay in position while mining. A slight push off of the surface lets the lander return to a larger spacecraft with its payload before returning to mining.

Autonomous Shaft Mining

Robotic tunneling equipment can burrow into an asteroid’s surface to get to deep ore bodies without using explosives that could scatter material into space.

Robotic Swarms

Autonomous, robotic swarms can be landed on asteroids to mine while the asteroid orbits the Sun. Every time the asteroid nears the Earth / Moon system (cis space), material can be offloaded while mining continues on the surface.



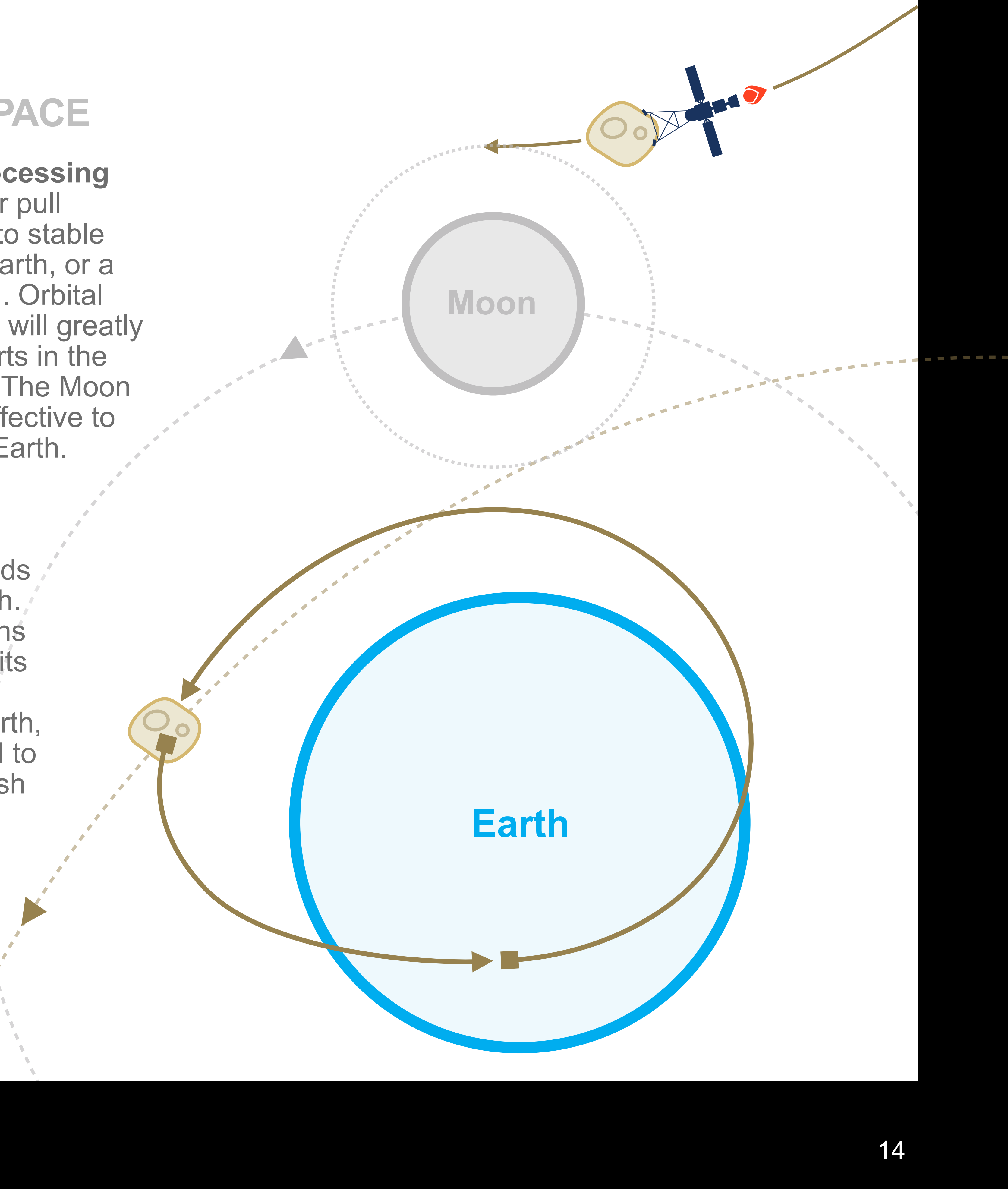
PROCESSING IN SPACE

Lunar / Earth Orbital Processing

Robotic tugs could push or pull asteroids of interest back to stable orbits around the Moon, Earth, or a Lagrange point near Earth. Orbital processing closer to Earth will greatly simplify space mining efforts in the early days of the industry. The Moon itself is much more cost effective to launch rockets from than Earth.

Ride Alongs

Robotic mining operations land on near-Earth asteroids as they pass close to Earth. The autonomous operations mine the asteroid as it orbits the Sun. On the asteroid’s next close approach to Earth, materials can be offloaded to the Moon or Earth and fresh supplies can land for the next mining orbit.

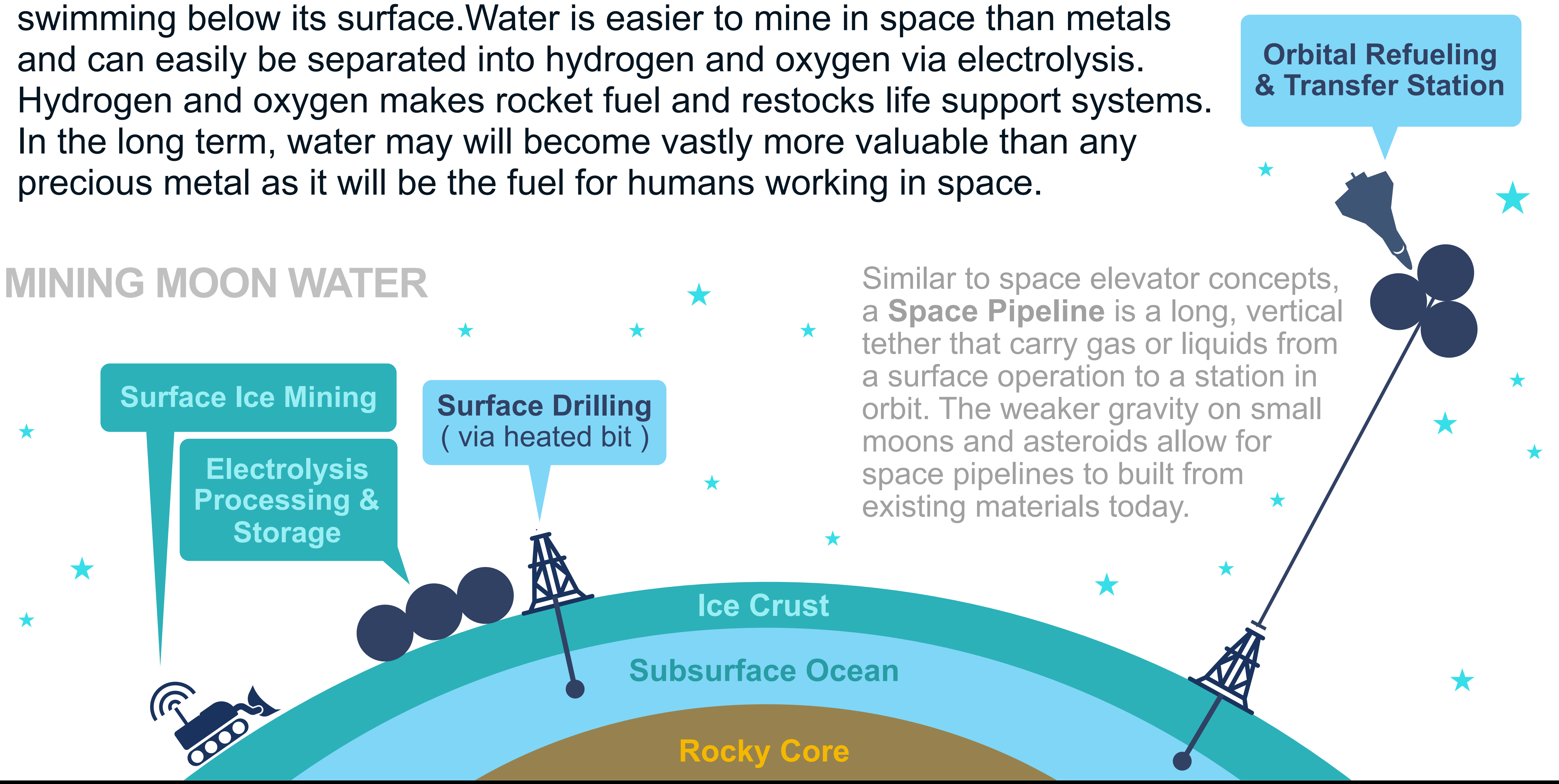


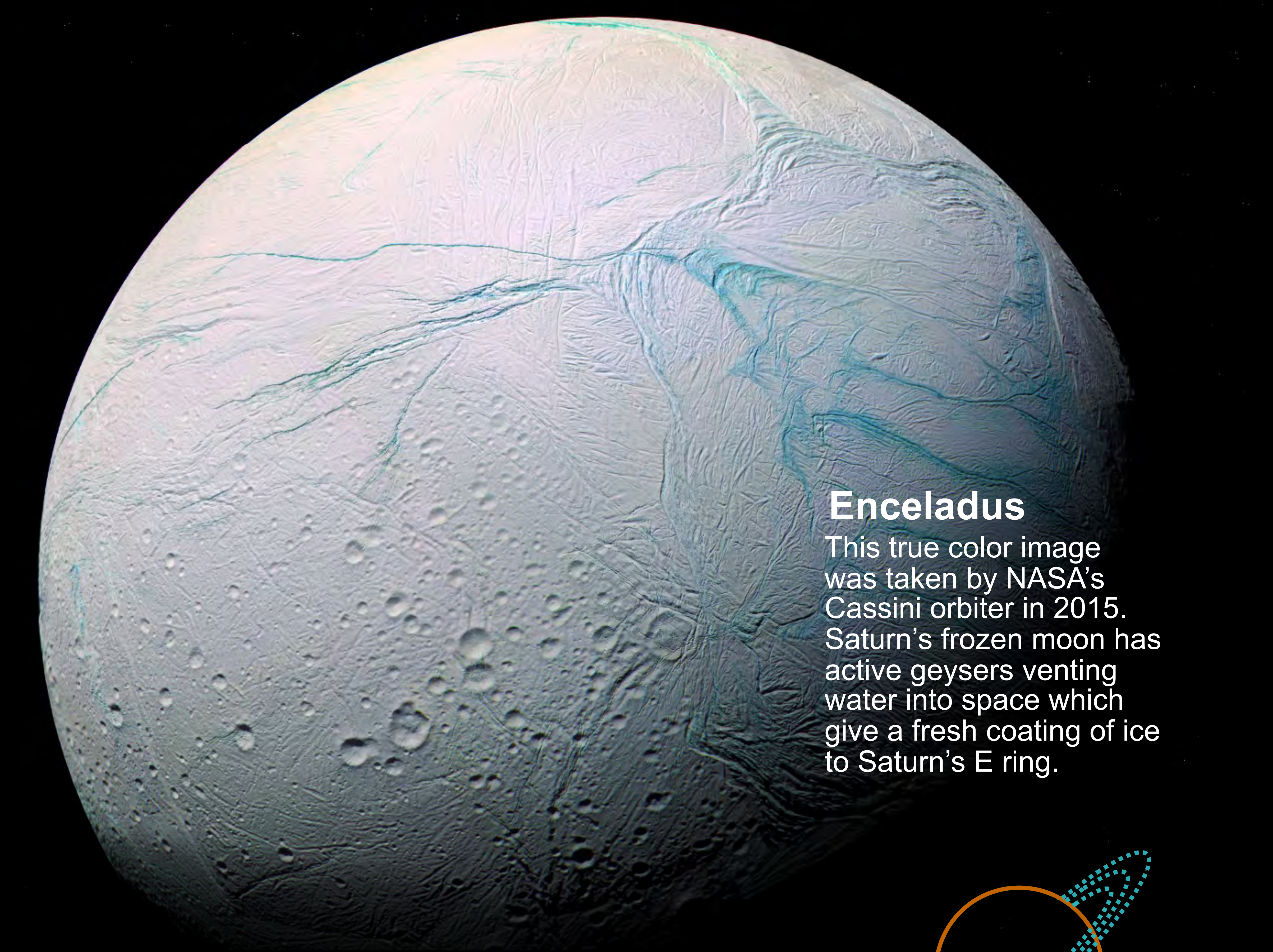
Water will be the most important resource.

Water is the elixir of life and our over 70% of our planet's surface is covered with it. Recent NASA expeditions to the asteroid belt, plus the systems of Jupiter and Saturn, have shown that some of these bodies to have frozen water ice on the surface with some even having entire subsurface oceans below their frozen crusts. Active water geysers erupting through ice surfaces of moons around both Jupiter and Saturn have been documented and sampled by NASA spacecraft. The subsurface oceans of Europa are currently calculated to contain more water than all of the oceans on Earth combined. Saturn's moon, Enceladus, has active water geysers from its subsurface oceans that generate a water vapor plume behind the moon coating Saturn's E ring with a fresh coating of ice. Enceladus' geysers have also been found to contain organic compounds that may indicate life swimming below its surface.Water is easier to mine in space than metals and can easily be separated into hydrogen and oxygen via electrolysis. Hydrogen and oxygen makes rocket fuel and restocks life support systems. In the long term, water may will become vastly more valuable than any precious metal as it will be the fuel for humans working in space.

MINING MOON WATER

Similar to space elevator concepts, a **Space Pipeline** is a long, vertical tether that carry gas or liquids from a surface operation to a station in orbit. The weaker gravity on small moons and asteroids allow for space pipelines to built from existing materials today.

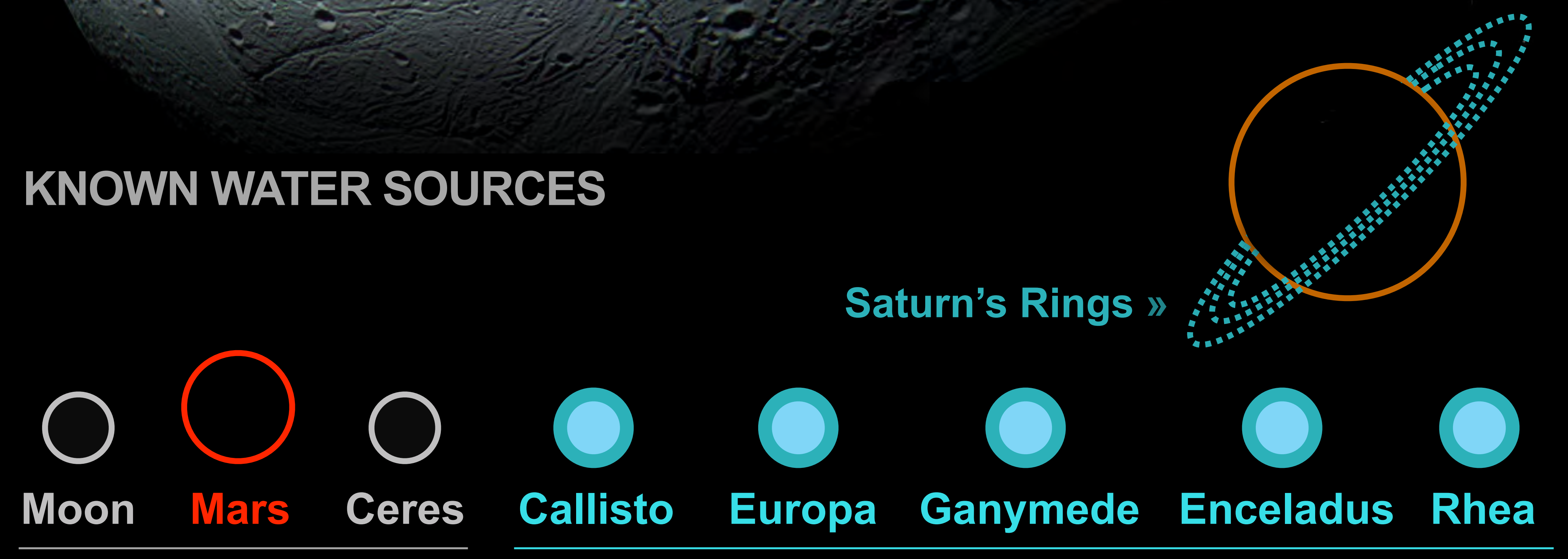




Enceladus

This true color image was taken by NASA's Cassini orbiter in 2015. Saturn's frozen moon has active geysers venting water into space which give a fresh coating of ice to Saturn's E ring.

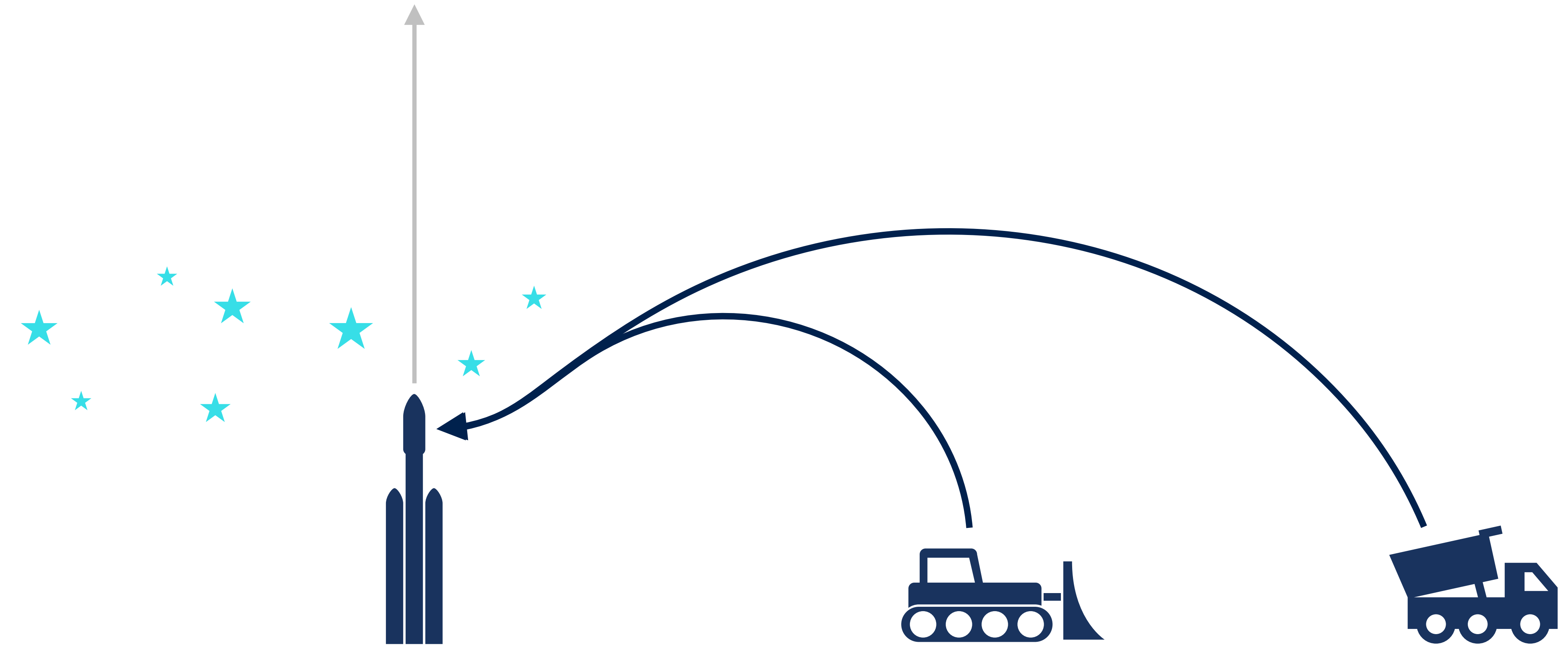
KNOWN WATER SOURCES



Beyond Earth, water/ice has been found across the Solar System. From surface ice to subsurface oceans containing more water than all the oceans of Earth combined, the solar system is wetter than we ever imagined just 20 years ago.

What if a bulldozer had launched on the Falcon Heavy instead of an electric sports car?

After offering multiple free rides to various parties on the maiden test flight of the Falcon Heavy in 2018 *and getting no takers*, SpaceX was forced to go with their backup plan. The backup plan was just to have some fun by launching Elon Musk's personal Tesla roadster into space towards Mars. Imagine the headlines when someone lands the first bulldozer prototype on the Moon or Mars? Serious science and innovation make good business.



SpaceX Falcon Heavy		Caterpillar D9	Caterpillar 785D
Launch Costs:	$90 - 150m	Fits onboard	Fits onboard
Payload / Mass:	64 tons	54 tons	24 tons each

Mining in space presents two big opportunity areas:

1. DON'T PACK EVERYTHING WITH YOU

With humans pushing beyond Earth's orbit in space over the next few years, we will need appropriate materials to survive away from the Earth's resources.

2. AS HUMANITY GROWS, SO DOES ITS RESOURCE NEEDS

In less than 120 years, the human population has exploded from 1.6 billion people in 1900 to over 7.5 billion people in 2018. If we want to expand the possibilities of human existence, we will need to mine resources from somewhere other than Earth. Near Earth, resource rich asteroids will be the source of valuable raw materials and water and once properly tapped with be a driver of economic expansion.

However, the impact of space mining isn't purely utopian. Rare earth materials currently hold their value because they are rare on Earth. If we generate a new, near limitless material supply from deep space, we run the risk of potentially devaluing such materials and tanking the global economy. The conditions for space mining are still being understood and as we begin to harvest orbital resources, we risk asteroid impact and other unforeseen complications. With so many unknown, or both space mining and it's impact on other industries, now is the time to explore the constraints and opportunities.

Apollo 17

Harrison Schmitt, one of the last two humans to stand on the Moon, is seen here near the Moon Buggy at Shorty Crater in 1972.

“ I would like to die on Mars. Just not on impact.”

- Elon Musk

Holistic solutions: The magic of McKinsey

There is significant upside for specific industries, especially those that specialize in creating the infrastructure and physical foundations for the new space economy. But there is also a need for a systems based approach that facilitates connected opportunities and the development of new ecosystems.

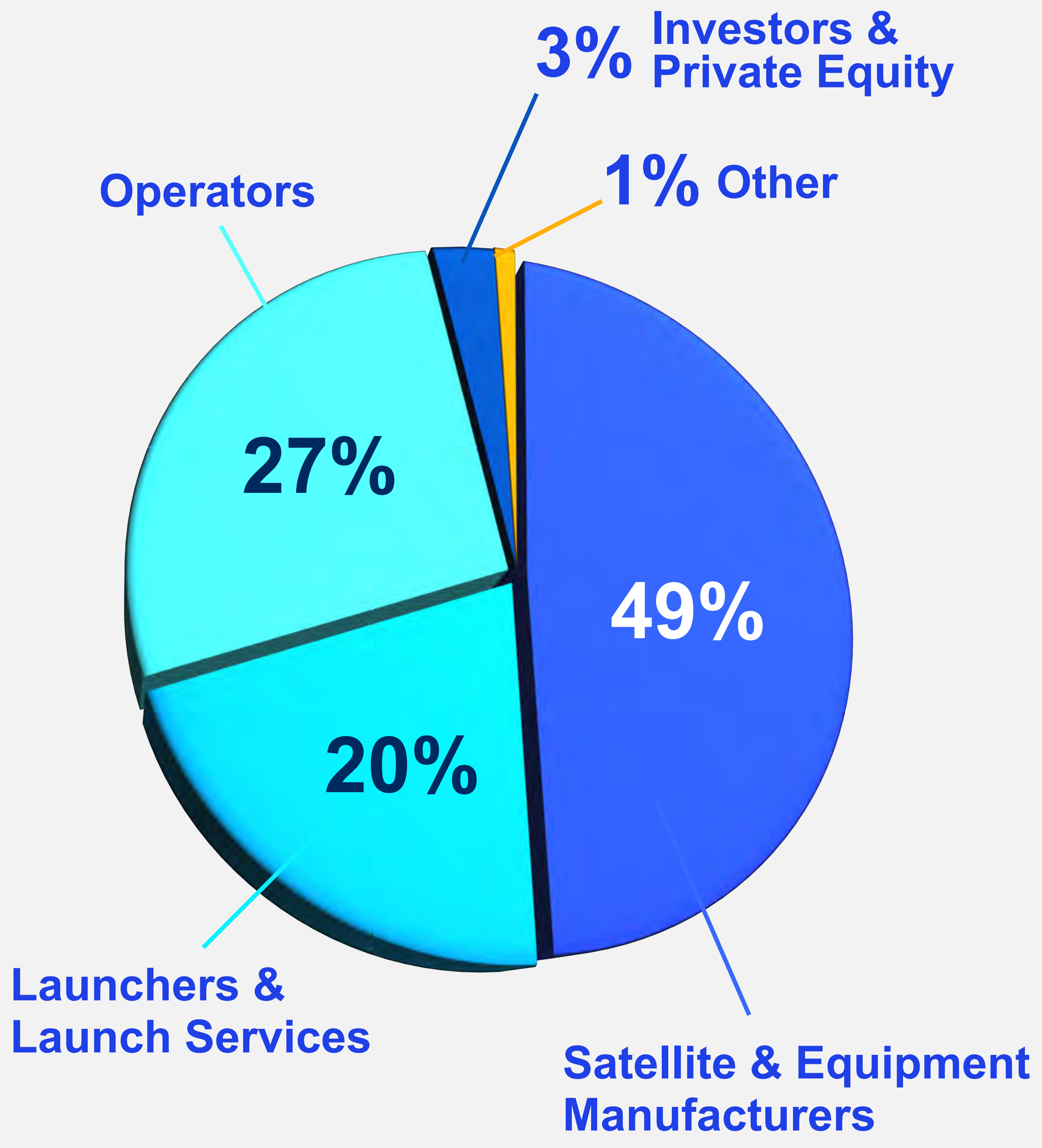
Our magic lies in creating new economies, products and services across planetary boundaries, creating new industries or extensions of existing ones. These problems are human, industrial and perhaps extra-terrestrial which require us to think across sectors.

McKinsey already serves clients across the space value chain globally,

ranging from satellite manufacturing to launch to operations & services provisioning.

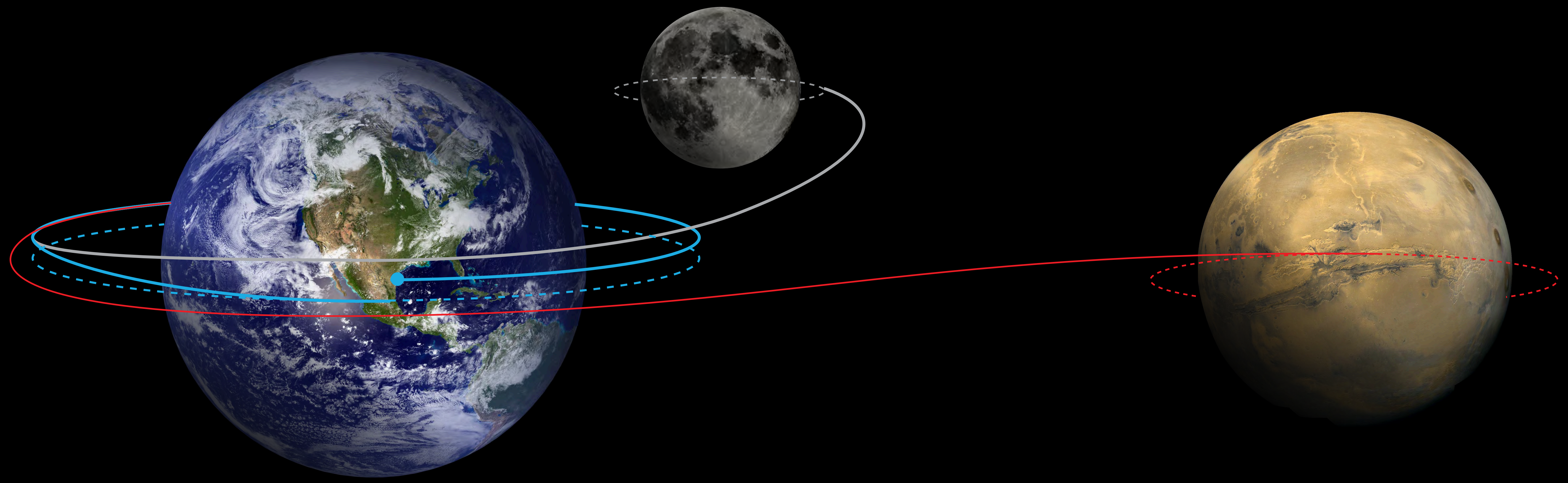
Aerospace expertise runs deep at the firm. We didn't just jump into space recently following the buzz and hype from VC and billionaire funded "new space" enterprises. The firm has been there in the background from the Apollo moon landings in the 1960s to helping modern aerospace businesses adapt to the quicken pace of disruption in the 21st century.

AT RIGHT »
McKinsey's activity in space by sector over the past seven years (2012 - 2019).



McKinsey combines financial, legal, policy, design, engineering, and technology capabilities together for clients who want to *be proactive*, rather than *reactive* to coming disruptions & market shifts.

From former NASA engineers to former Presidential administrations to some of the most creative minds in the world, no other organization is better positioned to help industry envision the future and then actually build it. Change is happening faster and faster now in the 21st century. Technology is driving massive disruptions across every industry, country, and organization in the world. At McKinsey, we know this all too well given our unique global perspective. The businesses and industries that are not disrupting through innovation today, will be left attempting to react to competition's disruptions until the velocity of change simply overwhelms them. Defensive postures for even the healthiest organizations can only be held as long as they have the stamina. In the end, defensive postures reacting only to change is a zero sum game. McKinsey is uniquely positioned to teach organizations how to be proactive and disrupt not only their competitors, but their entire industry.



The New Space Economy is ***waiting*** for the first movers & McKinsey can help you explore your options.

There is a reason why Venture Capitalists are pouring money into space based ventures. It is early and the value pools that can be captured are truly mind boggling. The first companies to move business into space will set a highly defensible position for decades to come in a market with few (if any) existing competitors.

There are multiple ways to get started exploring your options in commercial space:

A). Feasibility Studies - quick projects to explore possible options for a given business in commercial space on a near term or long basis. Selected concepts and idea can also be studied further in depth to determine costs and feasibility.

B). Product R&D - McKinsey’s top talent can help you devise a product/service roadmap, identify opportunity costs and design/build your commercial space products via McKinsey Digital Labs.

C). Leap by McKinsey - research, build, operate and transfer a new business entity focused on commercial space operations.

D). Product & Service Development - from concept to prototyping to build and launch, McKinsey Design can help you realize an early mover advantage into space.

Commercial Space Ventures

The commercial space ventures program is based in McKinsey Digital Labs' design studios in Austin + London to serve both North American and European clients.

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Updated April 2019

Designed by McKinsey Design

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