Jet Propulsion Laboratory
California Institute of Technology

Ion Propulsion

and the Job-Creating Power of the Rocket Equation

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The tyranny of the rocket equation

Donald Pettit

Rocket Equation

$$\frac{m_f}{m_i} = e^{-\frac{v_{s/C}}{v_{ex}}}$$

If your exhaust velocity is about the same speed you want your spacecraft to go then nearly 2/3rds of your initial mass is propellant

Specific Impulse

$$\frac{m_f}{m_i} = e^{-\frac{\Delta V}{I_{sp} g}}$$

Specific Impulse

For a propellant mass that weighs 1 N at the Earth's surface, How long can you sustain a thrust of 1 N?

Thrust: $T = \dot{m} v_{ex}$

Time to exhaust all the propellant: $t = \frac{M_p}{\dot{m}}$

$$W_p = M_p g \rightarrow M_p = \frac{W_p}{g}$$

$$t = \frac{W_p v_{ex}}{T g}$$

$$\text{for } W_p = T = 1, \text{then } t = \frac{v_{ex}}{g} \equiv I_{sp}$$

Specific Impulse

Mono-propellant
hydrazine thruster

Isp = 220 s

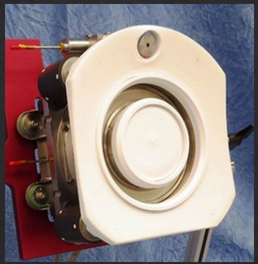
Bi-propellant
NTO/MMH

Isp = 320 s

Bi-propellant
LOX/LH2

Isp = 450 s

Aerojet XR5 Xenon
Hall Thruster

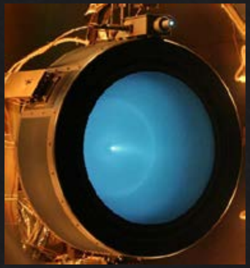


Isp = 2000 s

Xenon Ion Thruster
(Dawn)

Isp = 3100 s

Xenon Ion Thruster
(NEXT)

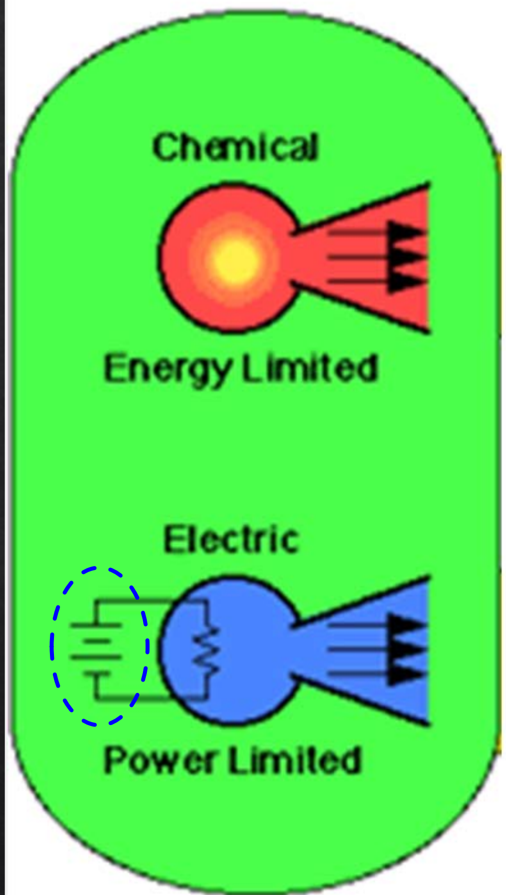


Isp = 4000 s

Chemical vs Electric Propulsion

- **Chemical propulsion systems:**
  - Carry the energy for propulsion with the propellant
  - Power is determined by the propellant mass flow rate
  - Performance is limited by the energy density of the propellants

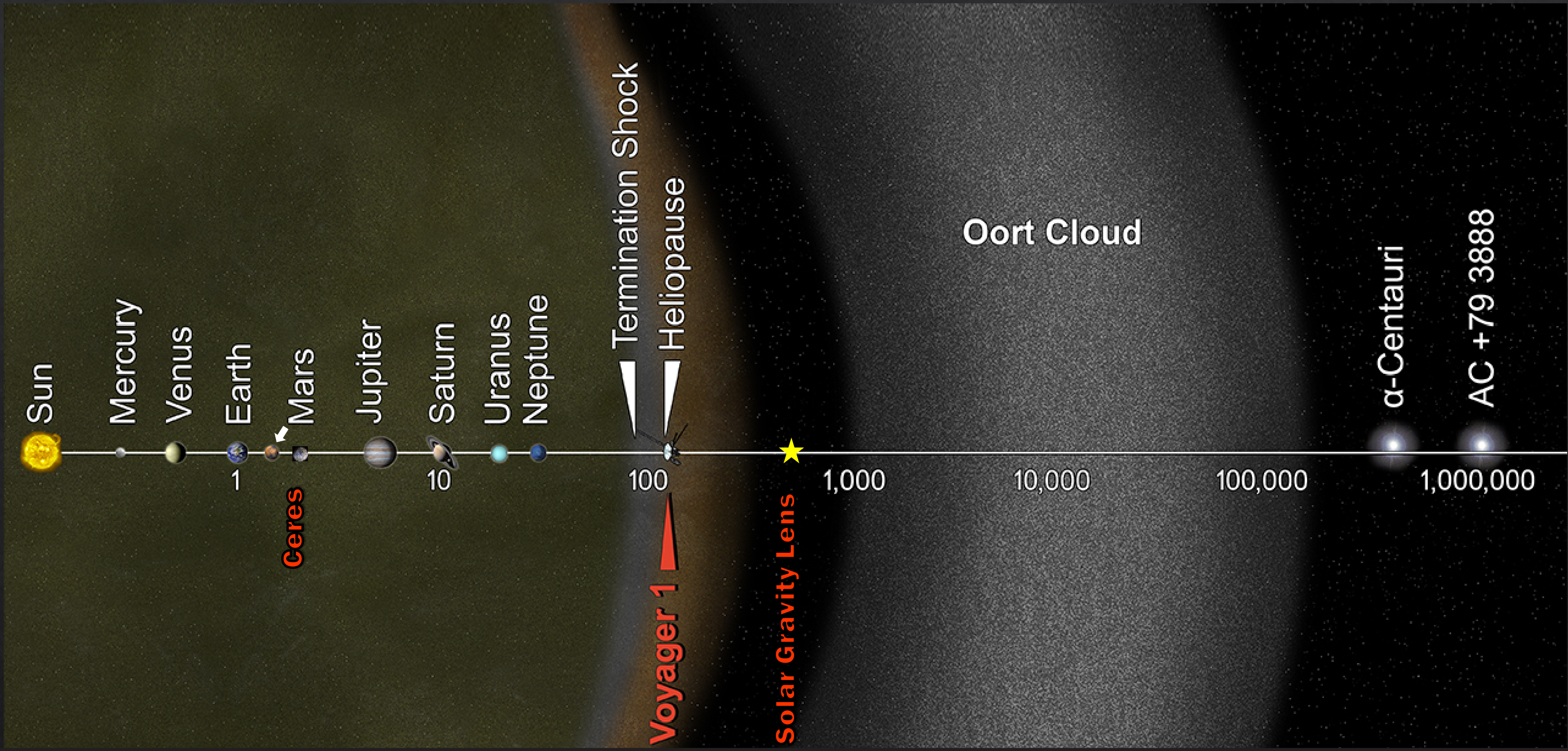
- **Electric propulsion systems:**
  - Decouple the energy for propulsion from the propellants – allows more energy to be added to each kg of propellant
  - Power is generated on-board by a separate power system
  - Performance is limited by the power generated by the power system



$$E = \frac{1}{2} m v^2 \rightarrow v = 1.41 \sqrt{\frac{E}{m}}$$

$$\left.\begin{array}{l} P = \frac{1}{2} \dot{m} v^2 \\ T = \dot{m} v \end{array}\right\} \quad v = \sqrt{\frac{2P}{\dot{m}}}, \quad \dot{m} = \frac{2P}{v^2}, \quad T = \frac{2P}{v}$$

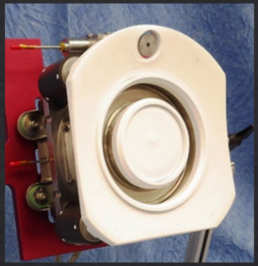
Space is BIG



3.6 AU/year

Specific Impulse

Aerojet XR5 Xenon Hall Thruster

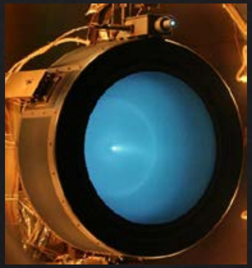


Isp = 2000 s 4.2 AU/year

Xenon Ion Thruster (Dawn)

Isp = 3100 s 6.5 AU/year

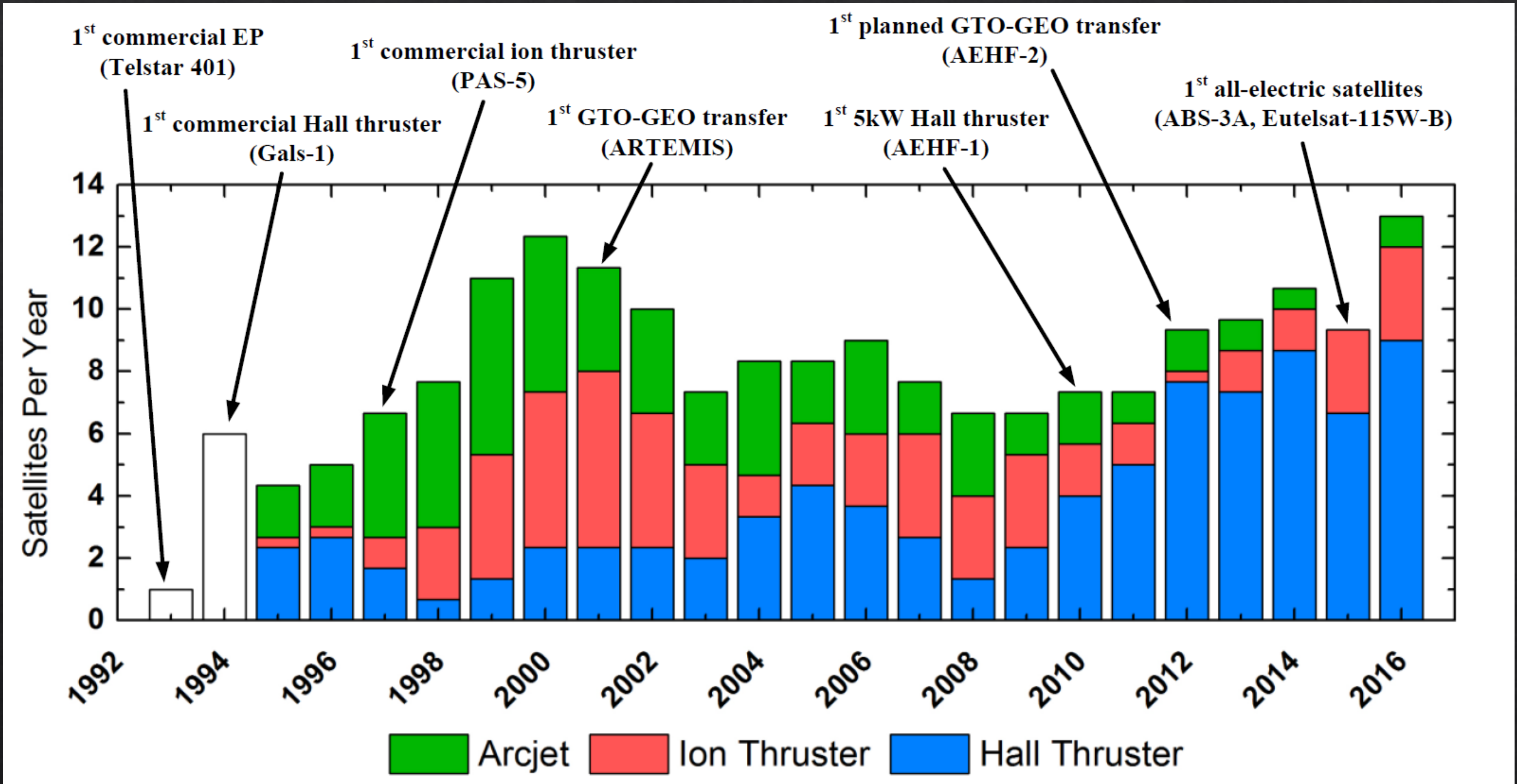
Xenon Ion Thruster (NEXT)



Isp = 4000 s 8.4 AU/year

Commercial Spacecraft

Commercial Satellites with EP

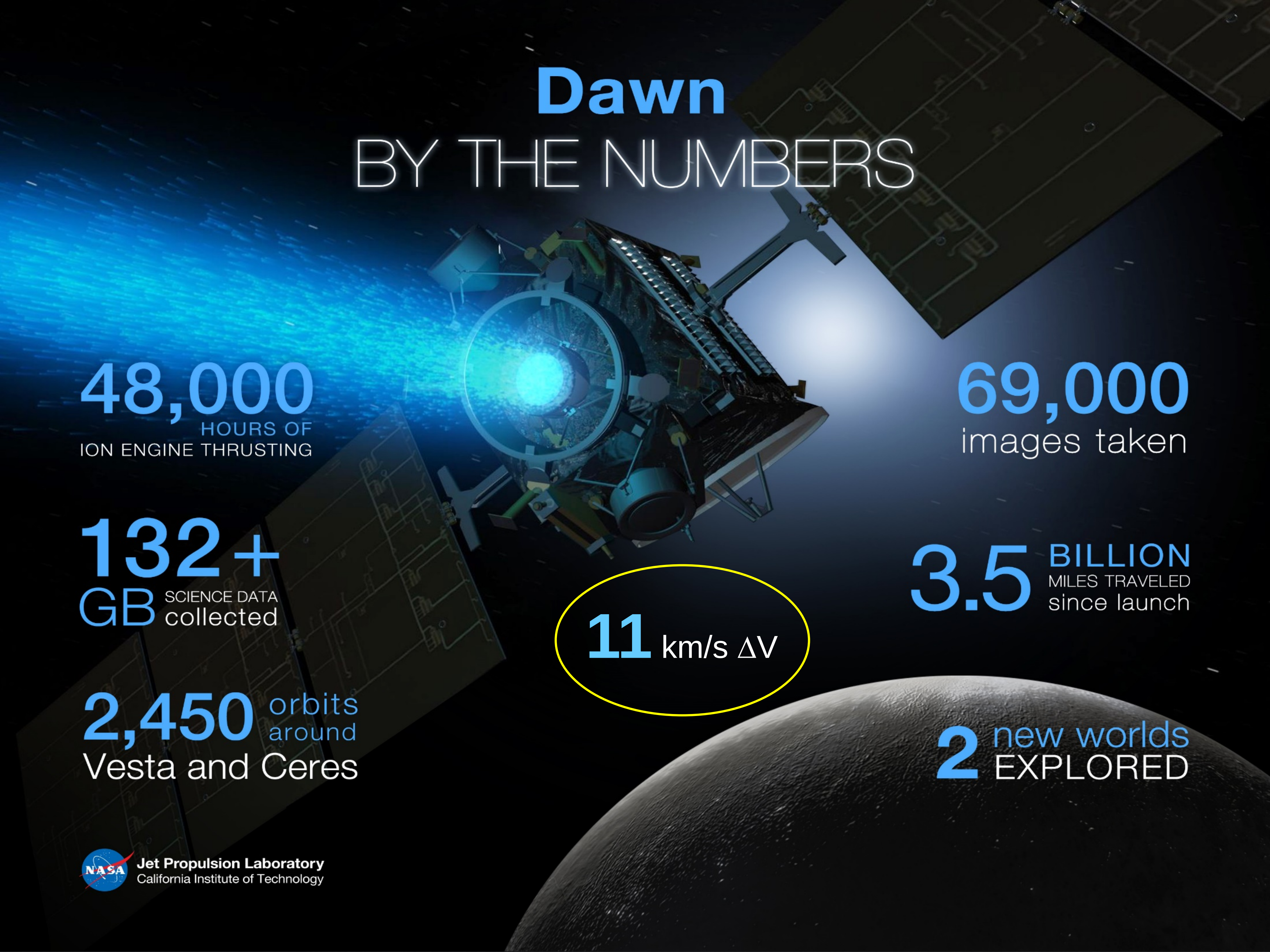


Lev, D., et al, "The Technological and Commercial Expansion of Electric Propulsion in the Past 24 Years, IEPC-2017-242, Presented at the 35th International Electric Propulsion Conference, Georgia Institute of Technology • Atlanta, Georgia • USA, October 8 – 12, 2017

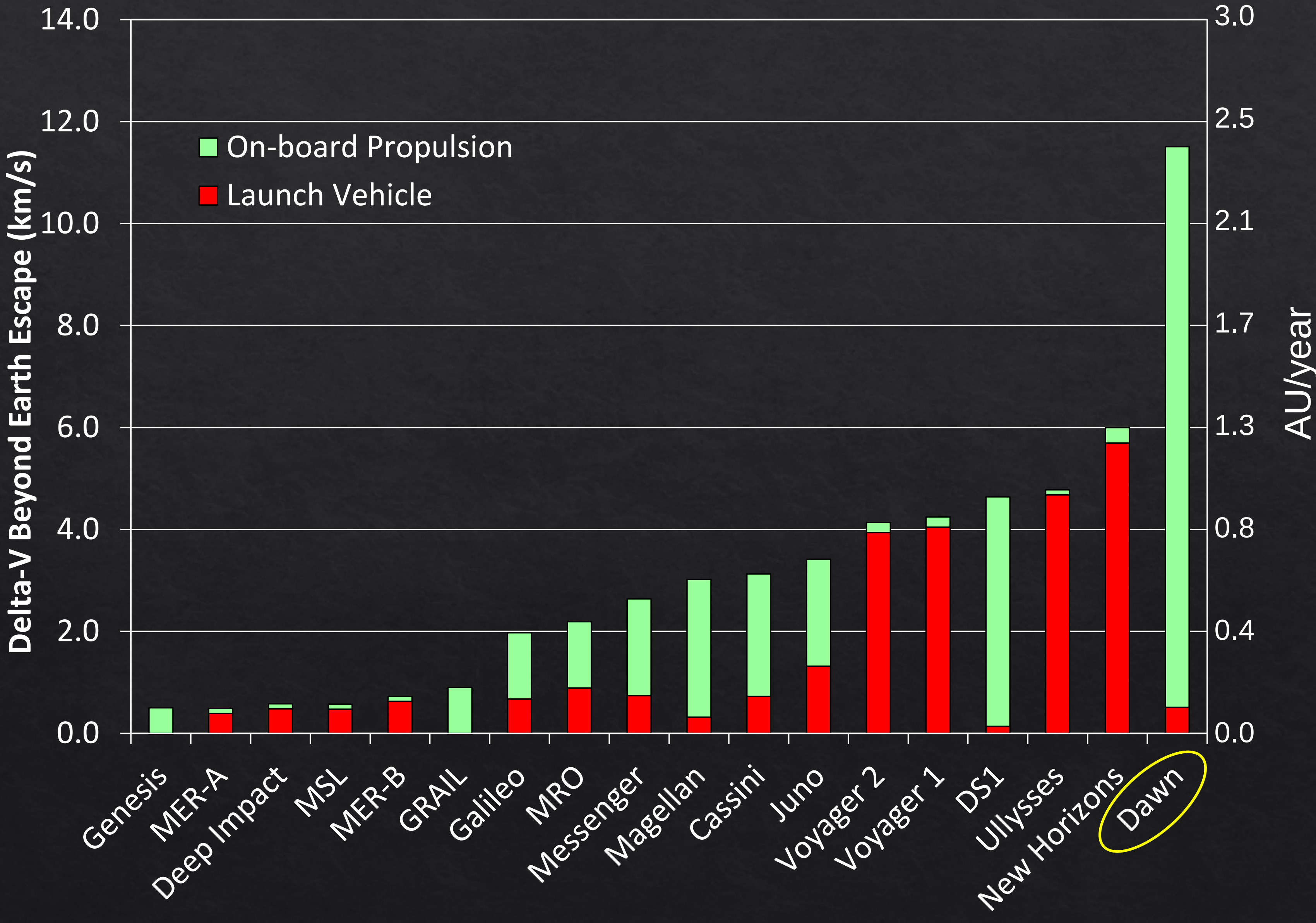
JPL

Boeing All Electric Satellites

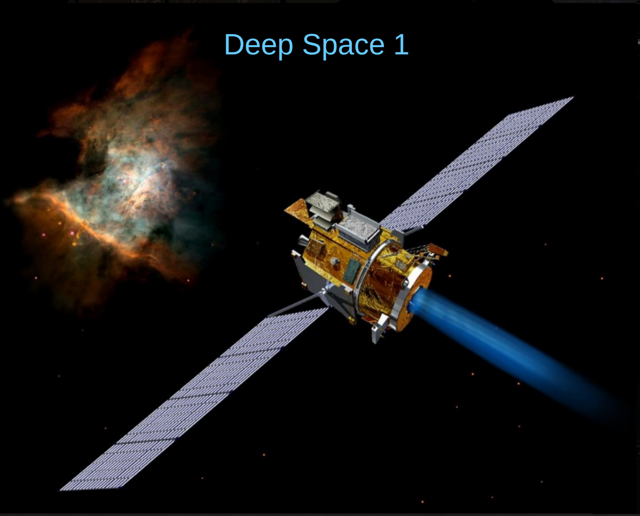
Deep Space Missions


Dawn
BY THE NUMBERS
48,000
HOURS OF
ION ENGINE THRUSTING
69,000
images taken
132+
GB
SCIENCE DATA
collected
11 km/s ΔV
3.5 BILLION
MILES TRAVELED
since launch
2,450 orbits around
Vesta and Ceres
2 new worlds
EXPLORED
NASA
Jet Propulsion Laboratory
California Institute of Technology

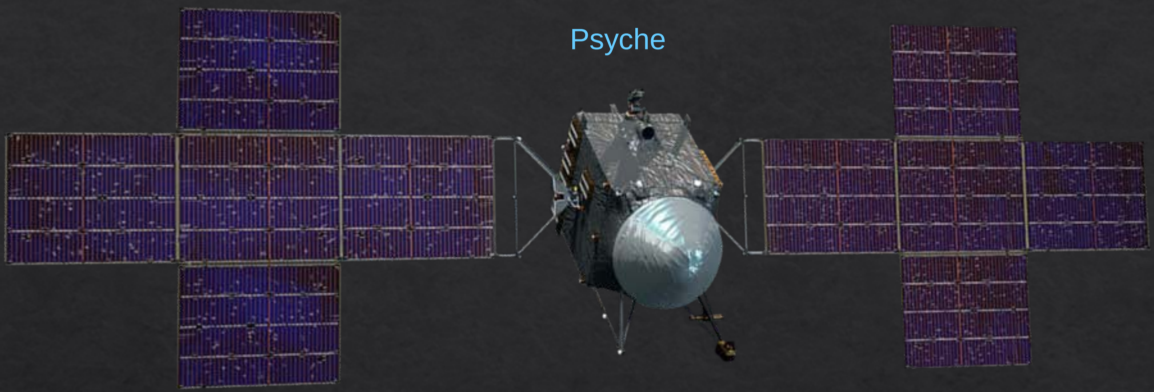
ΔV Beyond Earth Escape

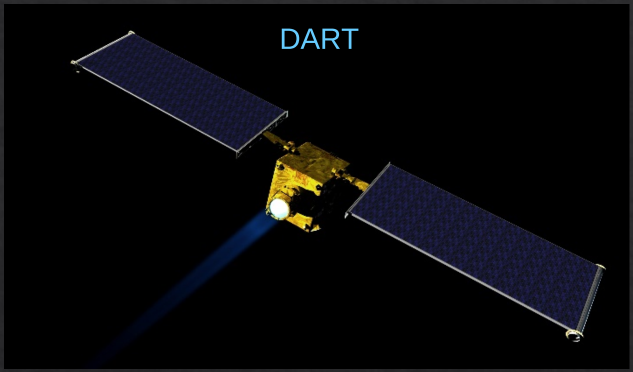


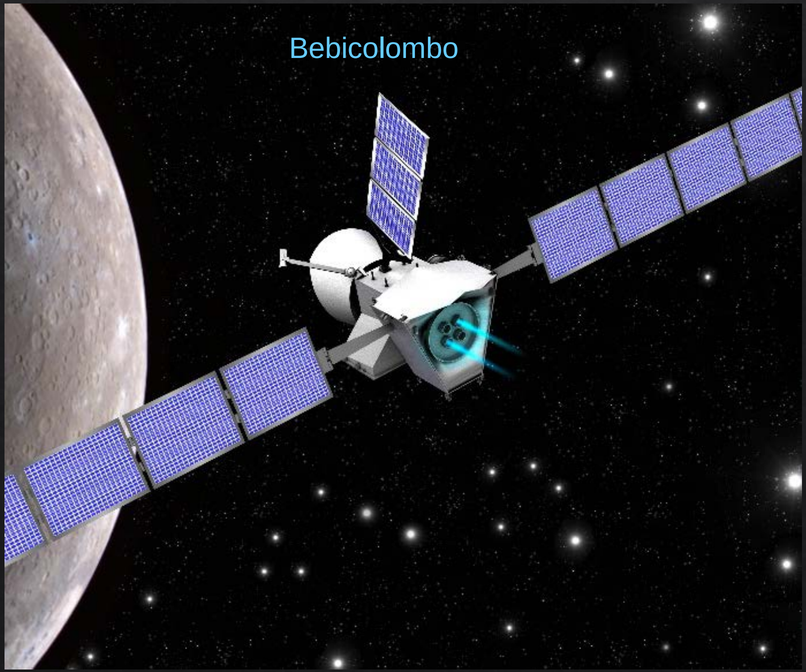
JPL

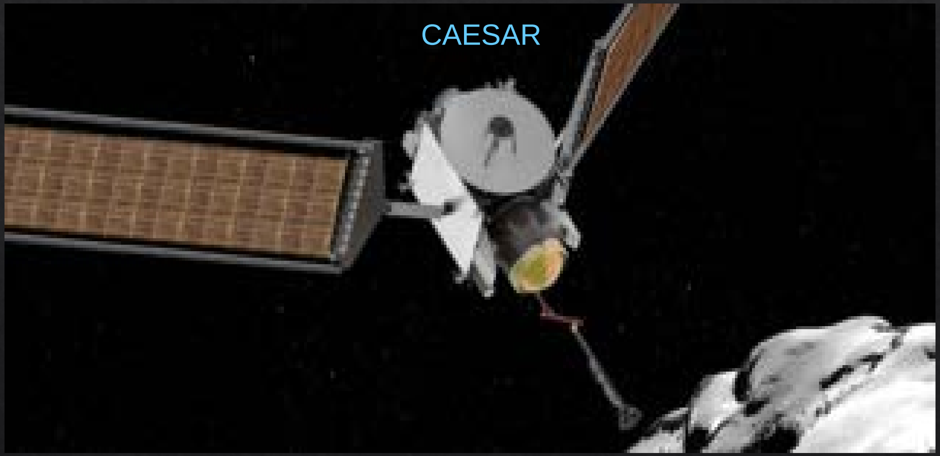


JPL Near-Term Potential Future Missions





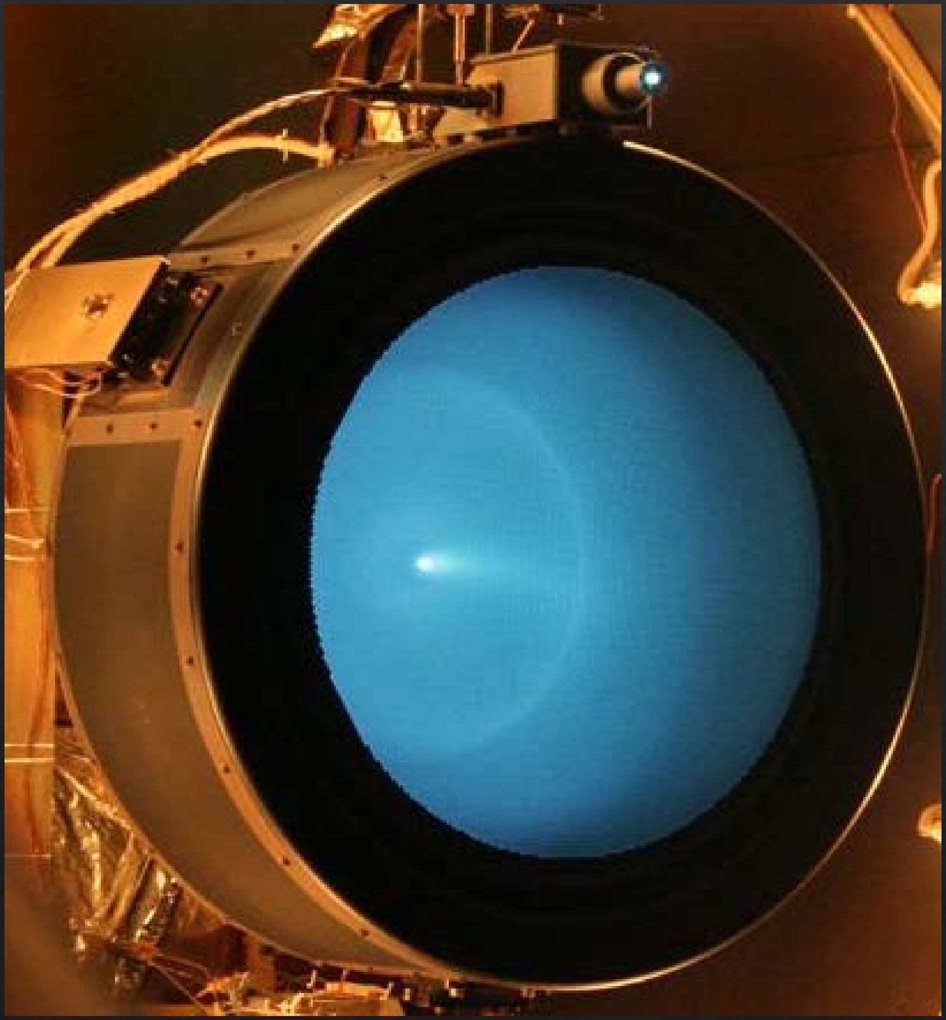




Pre-Decisional Mission Concepts

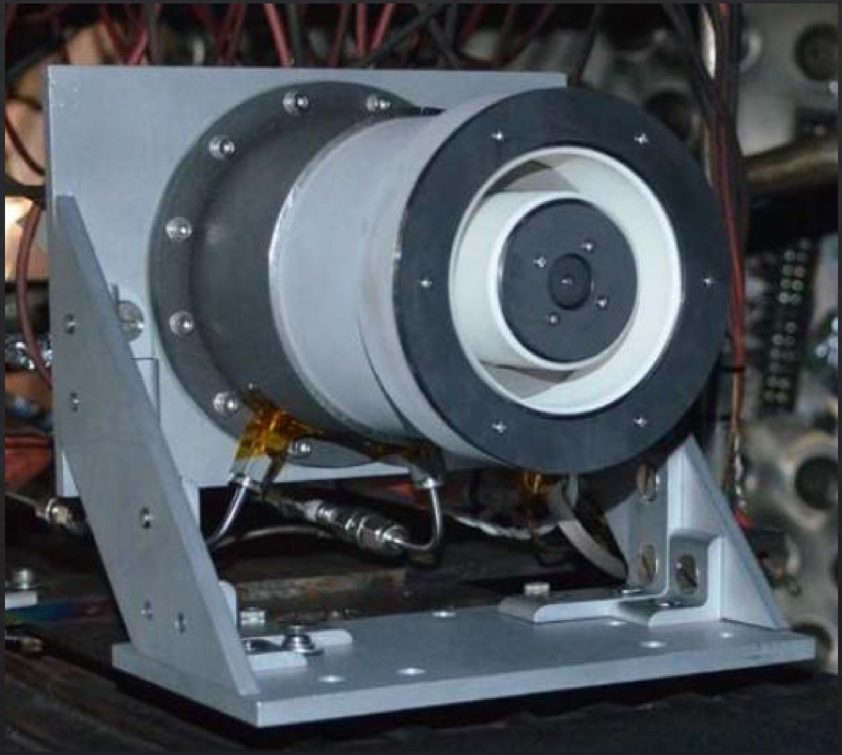
NEXT

- Under development since 2001
- Possible flight application on DART and CAESAR
- Life qualification is the key issue for the thruster
- Long-duration test results clouded by facility effects
- Using 2D and 3D ion optics codes to extract as much information from the long-duration test as possible



Low-Power Hall Thrusters

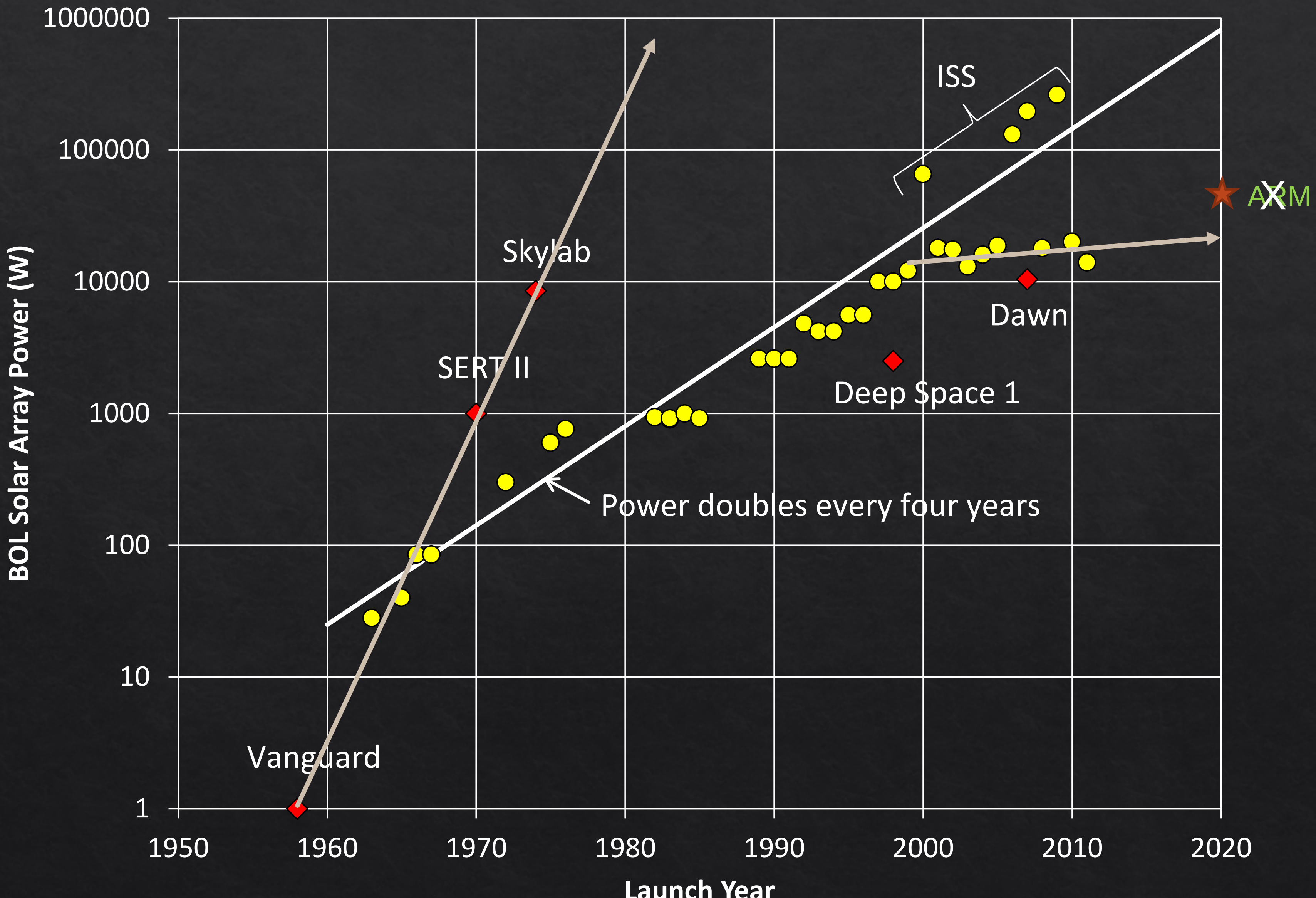
- 500-W Hall thruster
- Magnetically-shielded Miniature (MASMI) Hall Thruster
  - With a centrally-mounted hollow cathode
- Key Issues
  - Performance
  - Life Qualification



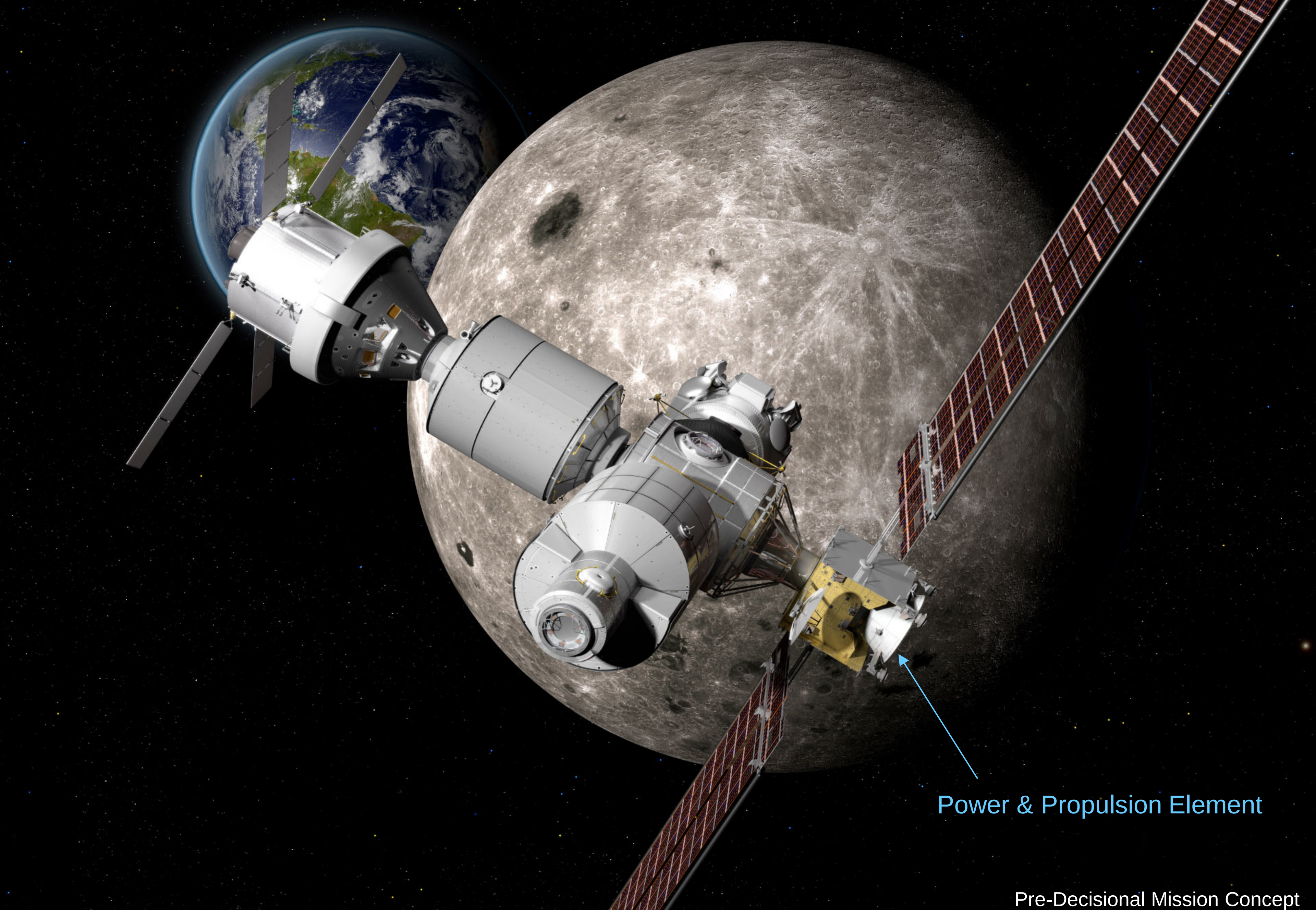
Targeted for deep-space science missions with small spacecraft (~100 kg)

Human Exploration Beyond Low-Earth Orbit

It's All About Power
Space Solar Power History



NASA's Deep Space Gateway Concept

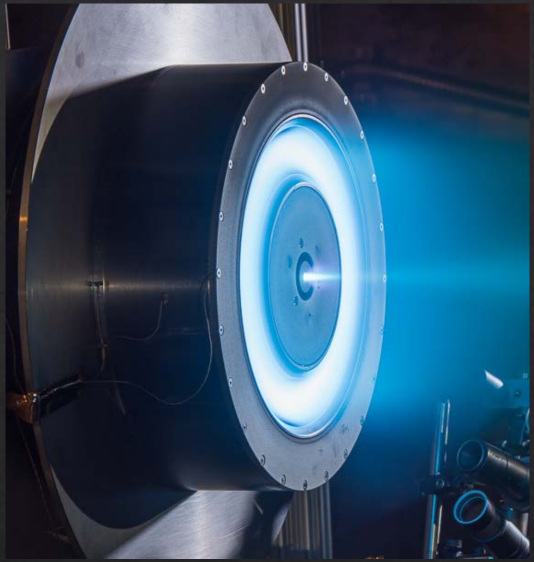


Pre-Decisional Mission Concept

High-power Hall Thrusters

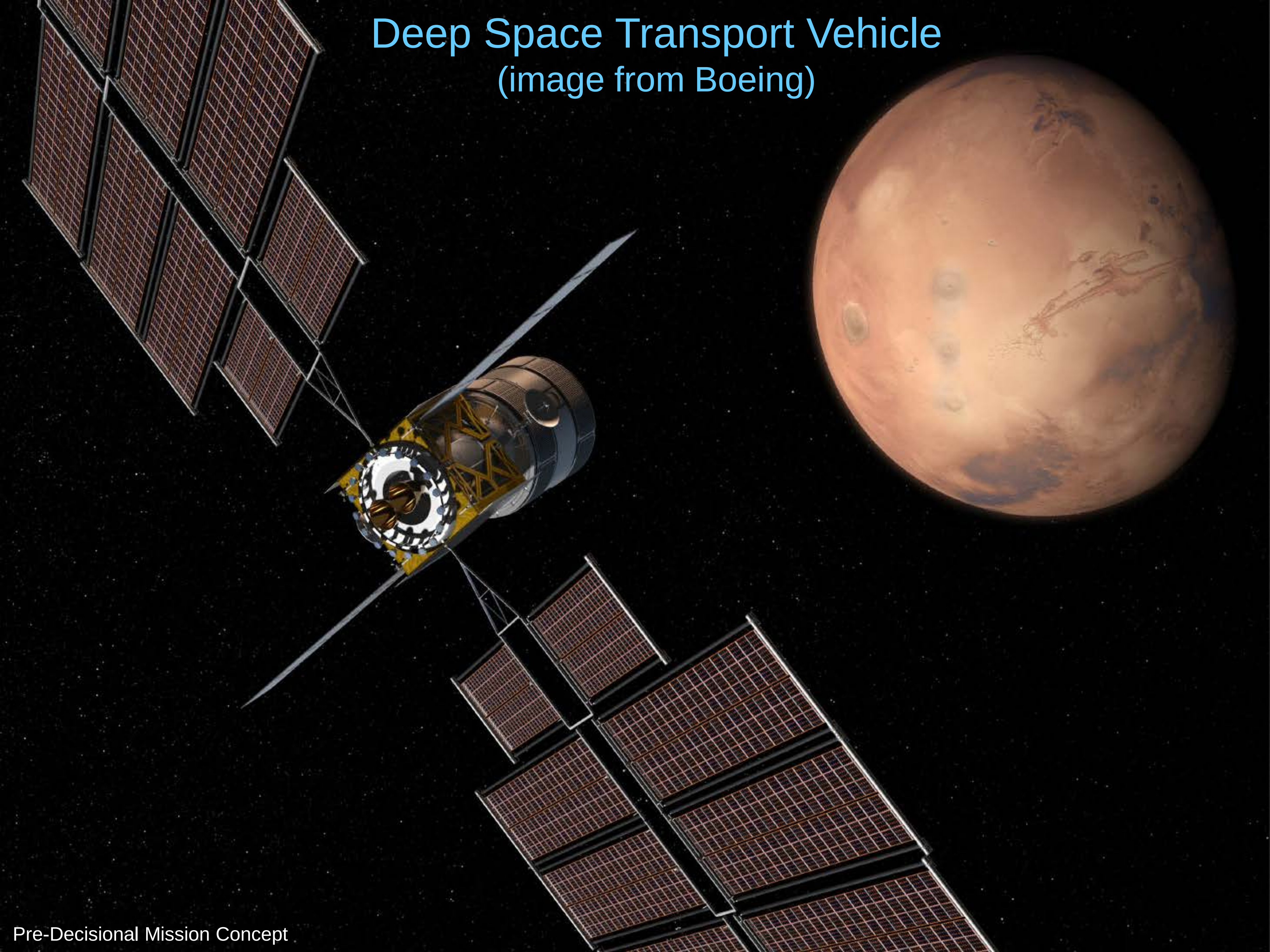
HERMES

- 12.5-kW, 2600-s Hall Thruster
- Key Issues
  - Performance
  - Life Qualification
  - Spacecraft Interactions



NEXTStep 100-kW Hall

- Operate for 100 hrs at 100 kW


Deep Space Transport Vehicle
(image from Boeing)
Pre-Decisional Mission Concept

Extreme SEP

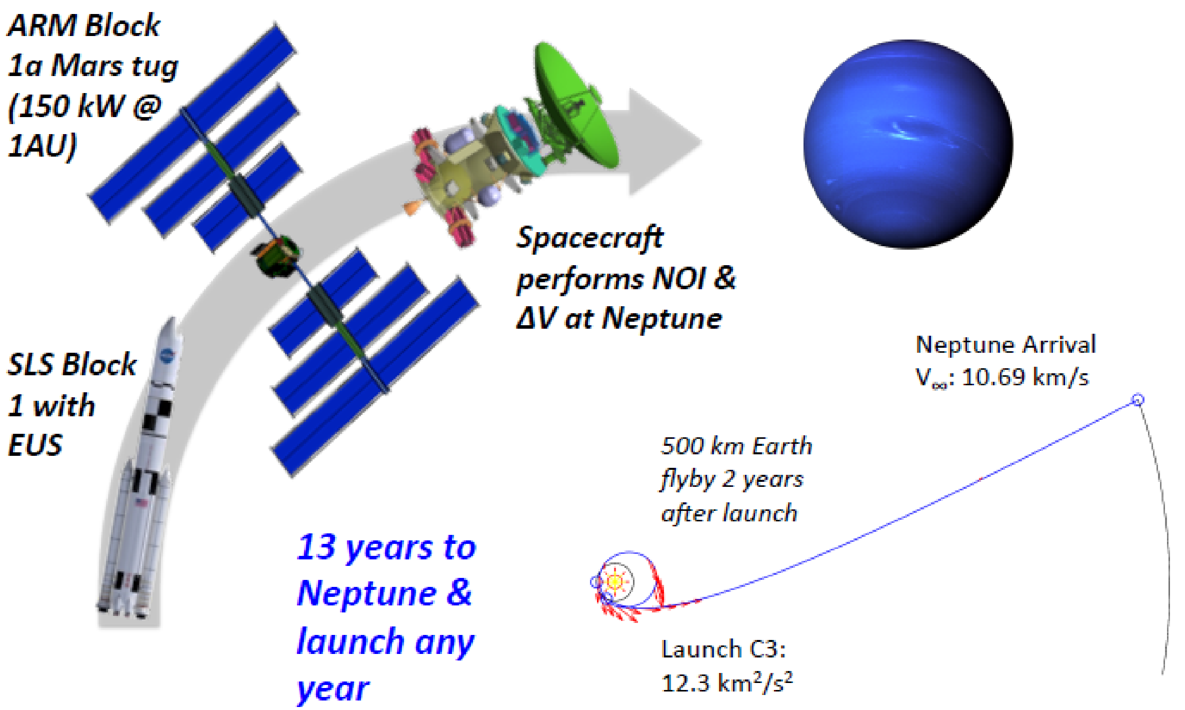
Damon Landau (JPL) and Nathan Strange (JPL)

SLS+ARM Neptune Flagship

SLS+ARM could deliver 4,500 kg to Neptune orbit in 13 yrs.

This is 3X the mass of a comparable chemical propulsion trajectory.

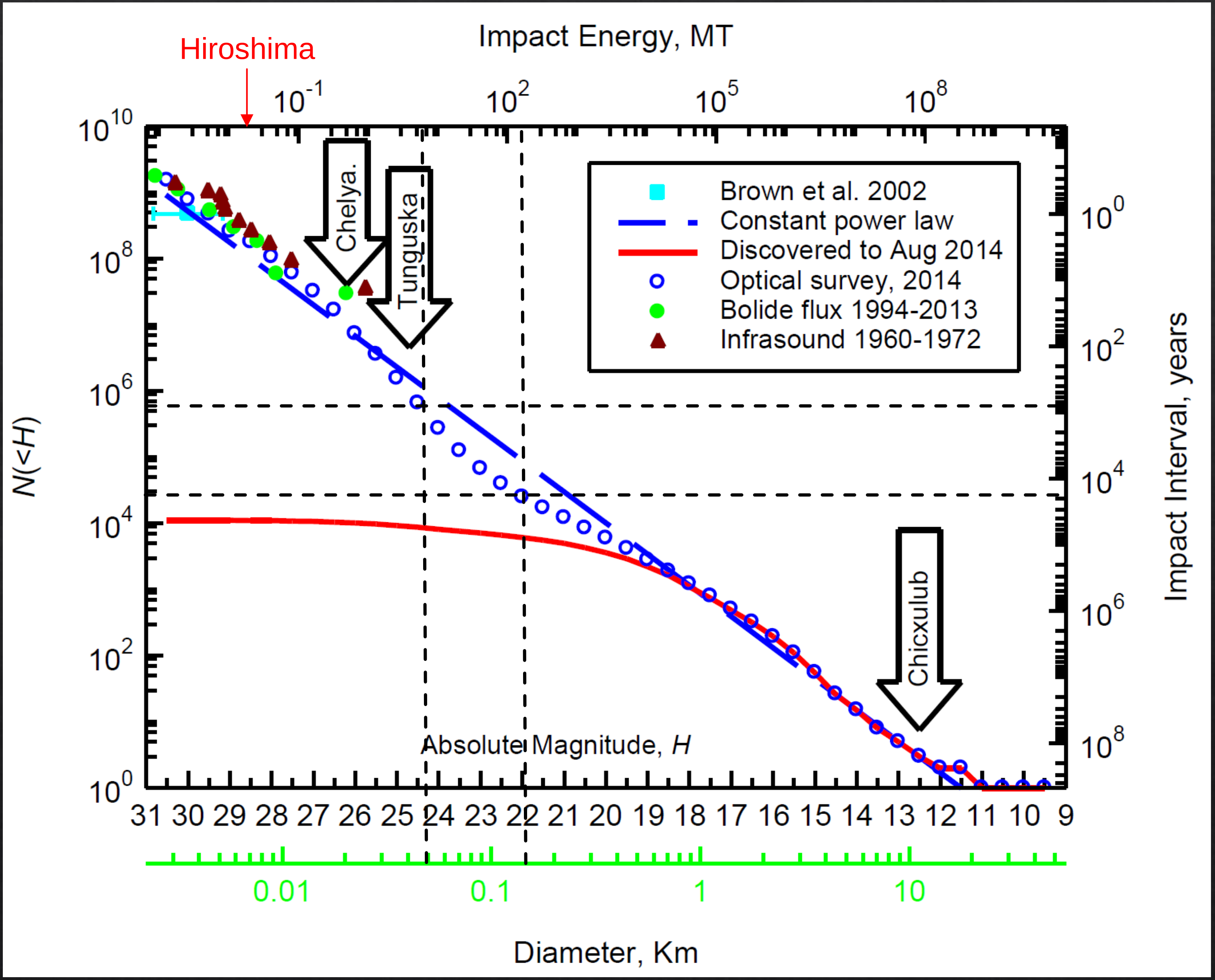
Neptune Arrival Mass	20,260 kg
SEP Tug Mass	8,000 kg
NOI Propellant (bi-prop)	7,760 kg
Mass in Neptune Orbit	4,500 kg



Planetary Defense

- After discovery, this becomes primarily a propulsion problem
- What size asteroids do we need to be concerned with?

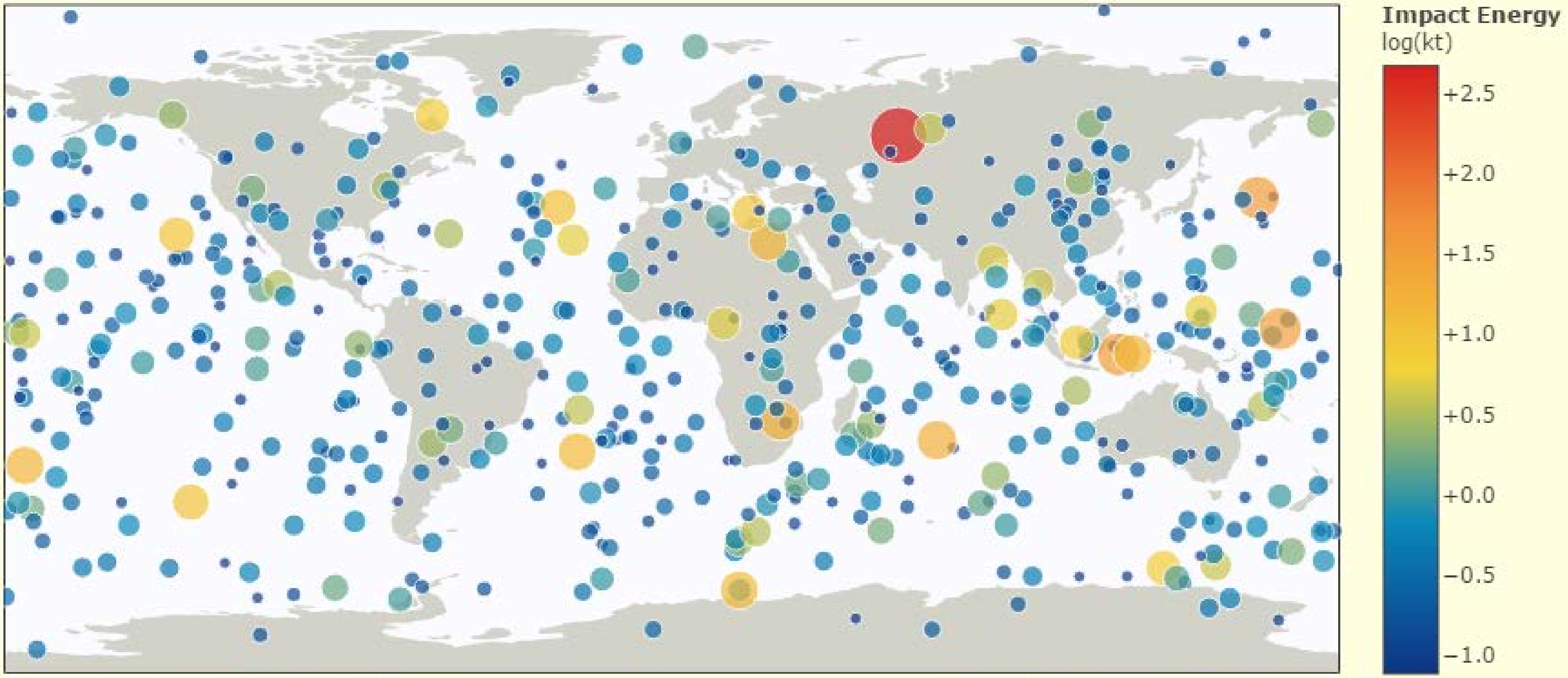
NEA Size-Frequency Distribution



Boslough, M., Brown, P., and Harris, A., "Updated Populsion and Risk Assessment for Airburst from Near-Earth Objects (NEOs)," 2015 IEEE Aerospace Conference, Big Sky, MT.

Fireballs Reported by US Government Sensors

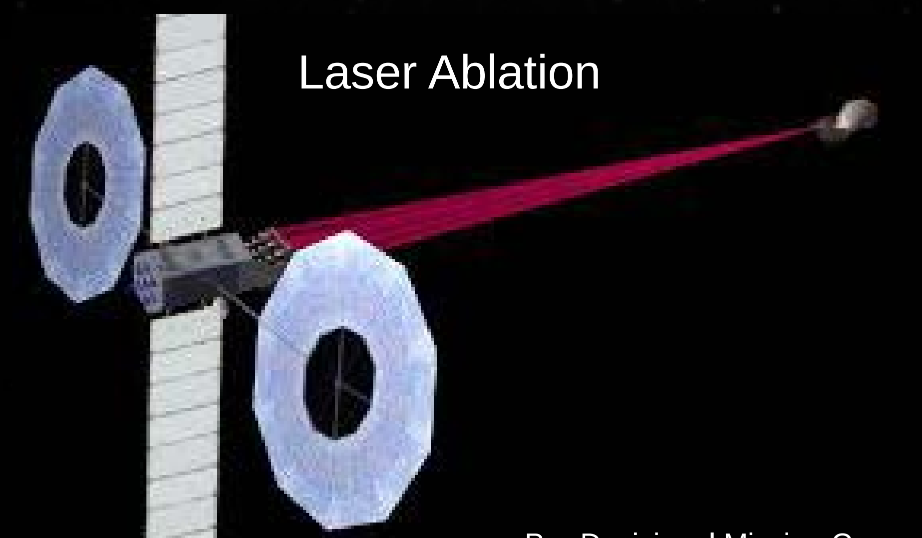
(1988-Apr-15 to 2017-Mar-11)



https://cneos.jpl.nasa.gov/fireballs/ Alan B. Chamberlin (JPL/Caltech)

Most likely threat objects may turn out to be in the 50 m to 140 m size

Planetary Defense Techniques

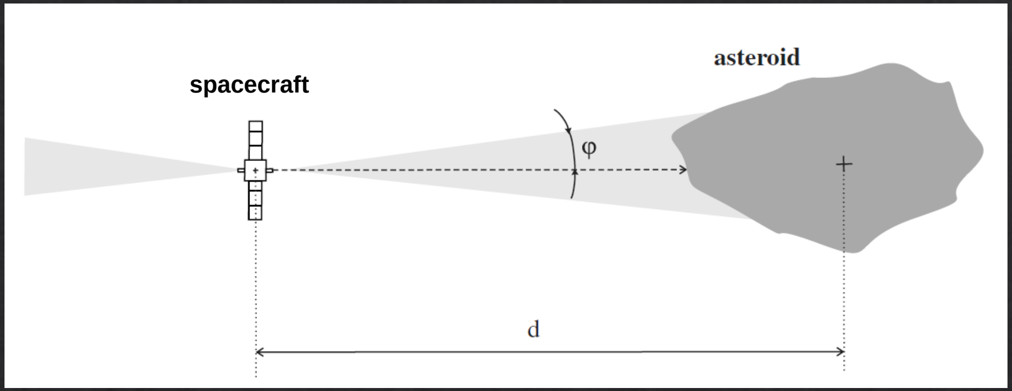


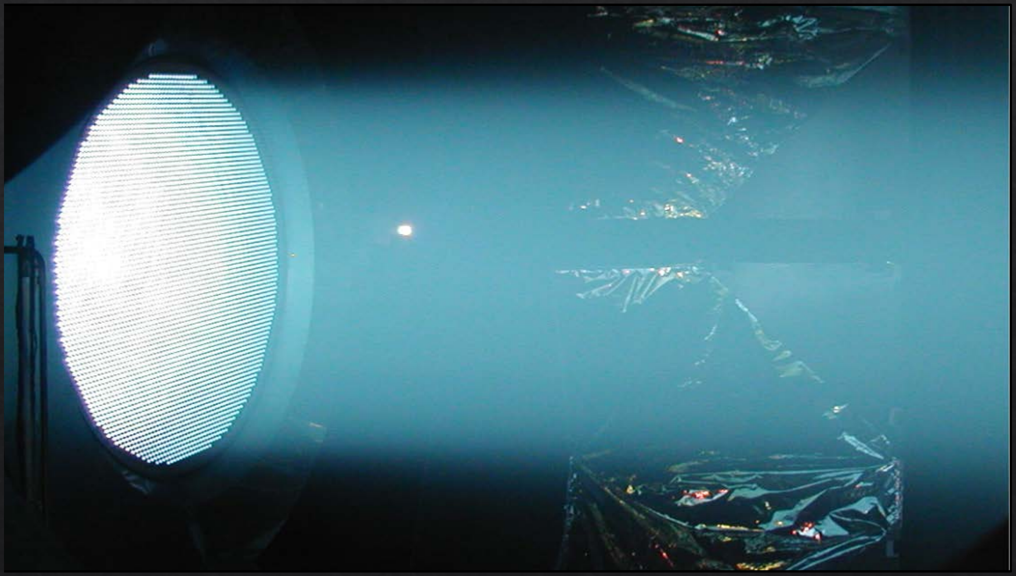
Pre-Decisional Mission Concepts

Ion Beam Deflection

Key Features

- Applied force is essentially independent of the asteroid characteristics
- Ions act as kinetic impactors
- Can engineer the applied force (power) and propellant usage (specific impulse)
- Must thrust in opposite directions simultaneously
- Enables large stand-off distance from the asteroid
  - Requires small ion beam divergence angle





Key Technology is to design ion optics to provide < 3 degree ion beam divergence

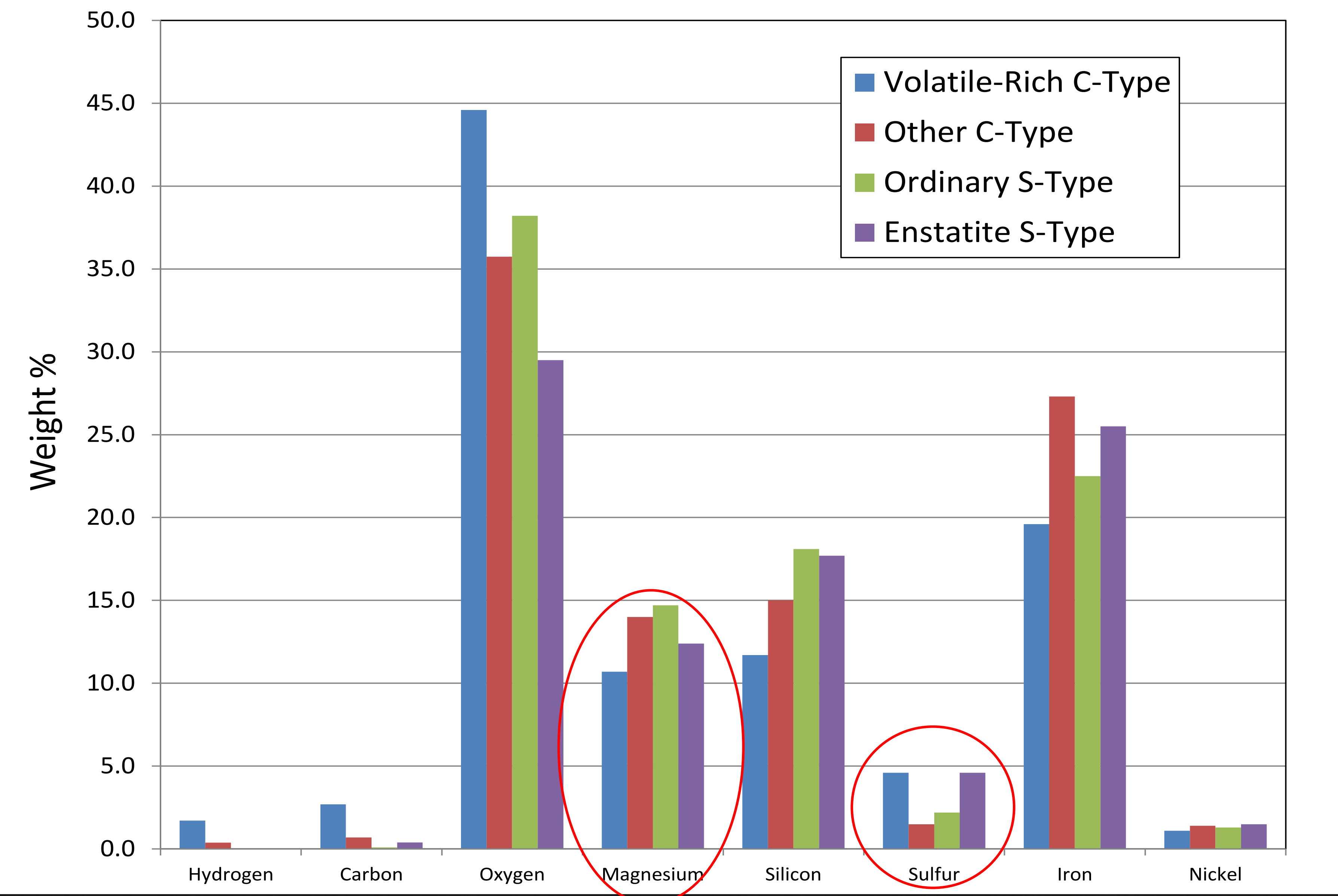
Asteroid Mining

- Has long been recognized as a propulsion problem
- Probably only feasible in the long run if you can use asteroid-derived propellants

Past proposals include:

- Water
- Mass drivers (throwing rocks)
- Even billards (colliding one NEA with another)

What are Asteroids Made of?

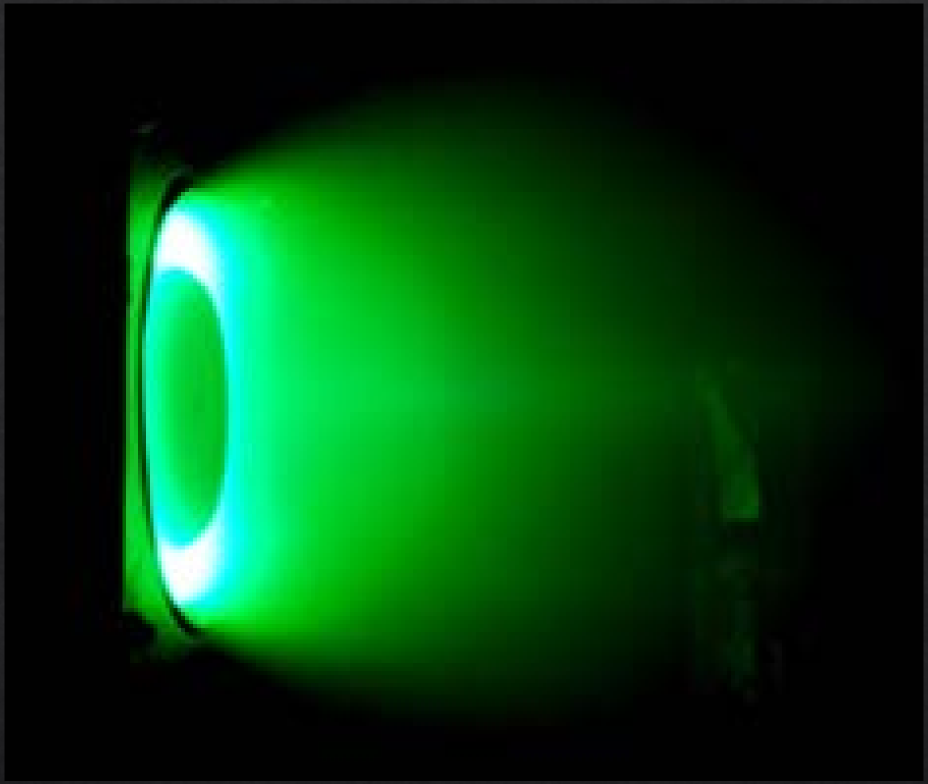


Hutchison, R., "Meteorites, A Petrologic, Chemical and Isotopic Synthesis," *Cambridge University Press*, 2004, ISBN 0 521 47010 2.

Asteroid-Derived Hall Thruster Propellants

State-of-the-art flight Hall thrusters use xenon as the propellant, but laboratory tests have also demonstrated operation on argon, krypton, iodine, and bismuth.

What about magnesium?



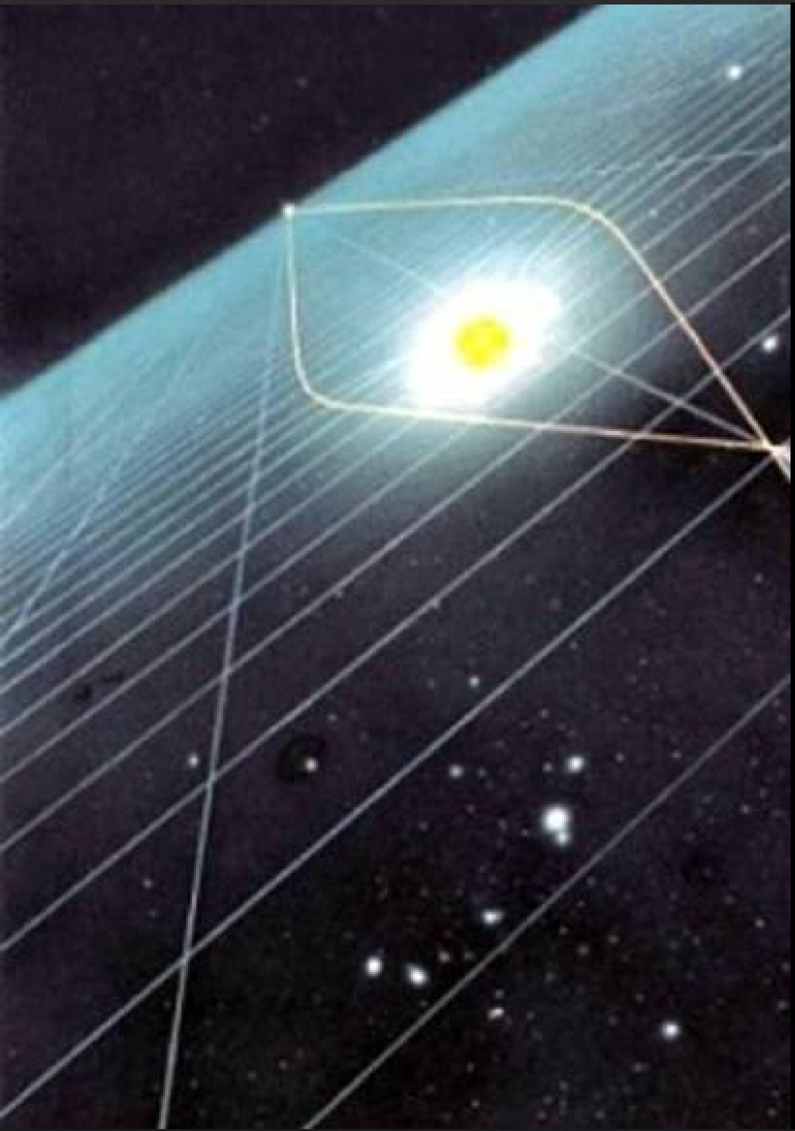
A magnesium-fueled Hall thruster from Michigan Technological University

	Molecular Weight	Melting Point	Boiling Point	Ionization Energy (eV)			Vapor Pressure			
	(AMU)	(C)	(C)	1st	2nd	Temperature	1 Pa	10 Pa	100 Pa	1000 Pa
Magnesium	24.31	650	1091	7.65	15.04	T (K)	701	773	861	971
Sulfur	32.06	115	445	10.36	23.34	T (K)	375	408	449	508
Xenon	131.3	-112	-108	12.13	21.21	T (K)	83	92	103	117

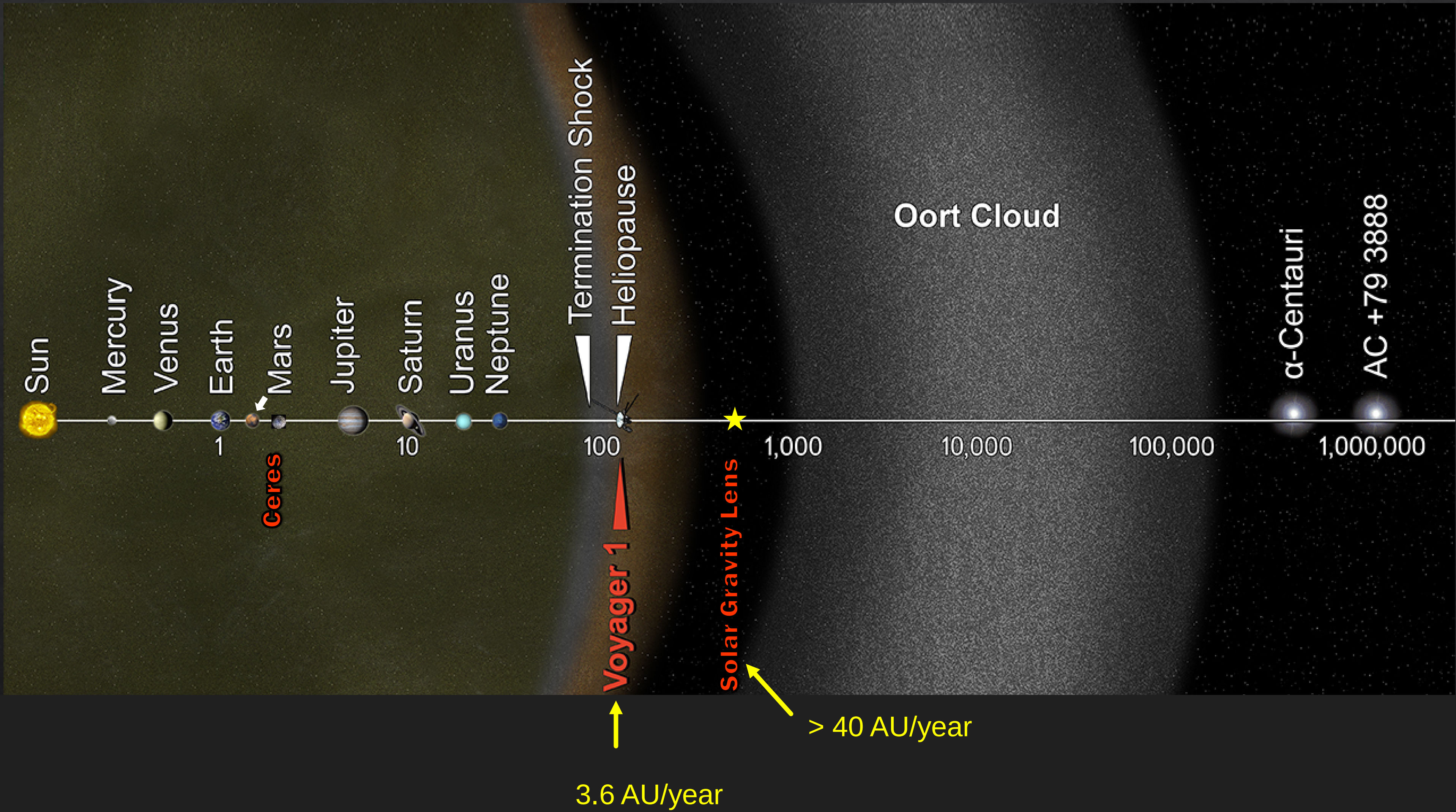
Ultra-High ΔV Missions

Solar Gravity Lens Mission Concept

Want to go to > 550 AU in less than 15 years (~40 AU/year)

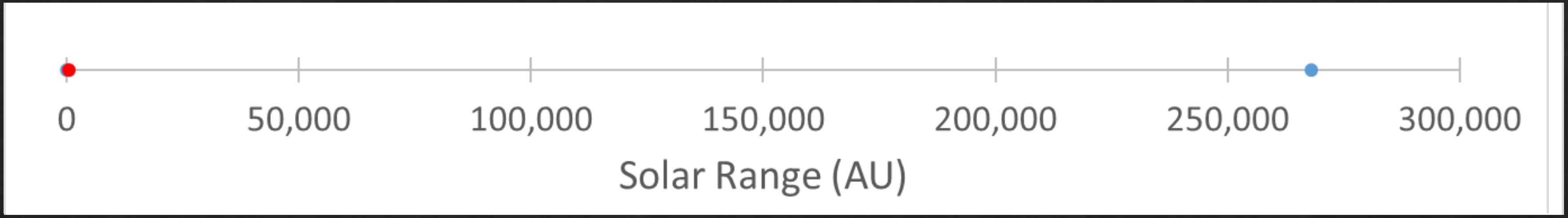


Space is BIG



Sun
Mercury
Venus
Earth
Mars
Ceres
Jupiter
Saturn
Uranus
Neptune
Termination Shock
Heliopause
Voyager 1
Solar Gravity Lens
Oort Cloud
α-Centauri
AC +79 3888
1
10
100
1,000
10,000
100,000
1,000,000
> 40 AU/year
3.6 AU/year

Solar Gravity Lens Focus



How Fast Do We Want to Go?

Faster than a speeding bullet? 0.8 km/s

325X

- A speeding bullet would take > 3000 years to g… the solar gravity lens location

NASA's Dawn spacecraft has an ion propulsion system on board. It is the best on-board propulsion system ever flown in deep space.

- How fast did Dawn go? 11 km/s

NASA's Voyager 1 spacecraft used Jupiter and Saturn gravity assists to make it the fastest spacecraft ever flown

- How fast is Voyager 1? 17 km/s

If we want to go to the solar gravity lens location in … years.

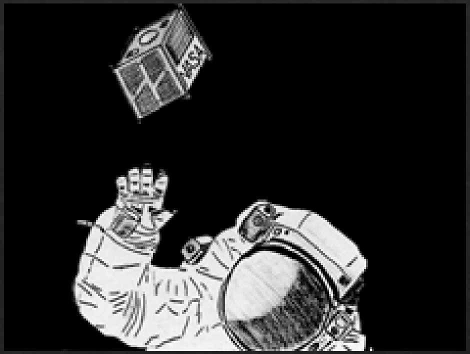
- How fast do we have to go? 260 km/s

Three Key Features of Our Proposed Architecture to Go Fast

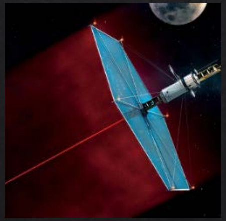
1 High Power

Don't carry the power source—laser beam power to the spacecraft

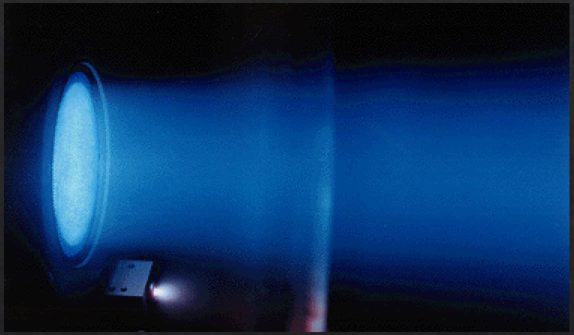
2 Small Dry Mass

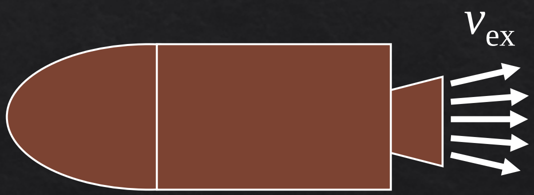


Collect the laser power and convert it to electricity to power the ion drive system



3 Small Propellant Mass

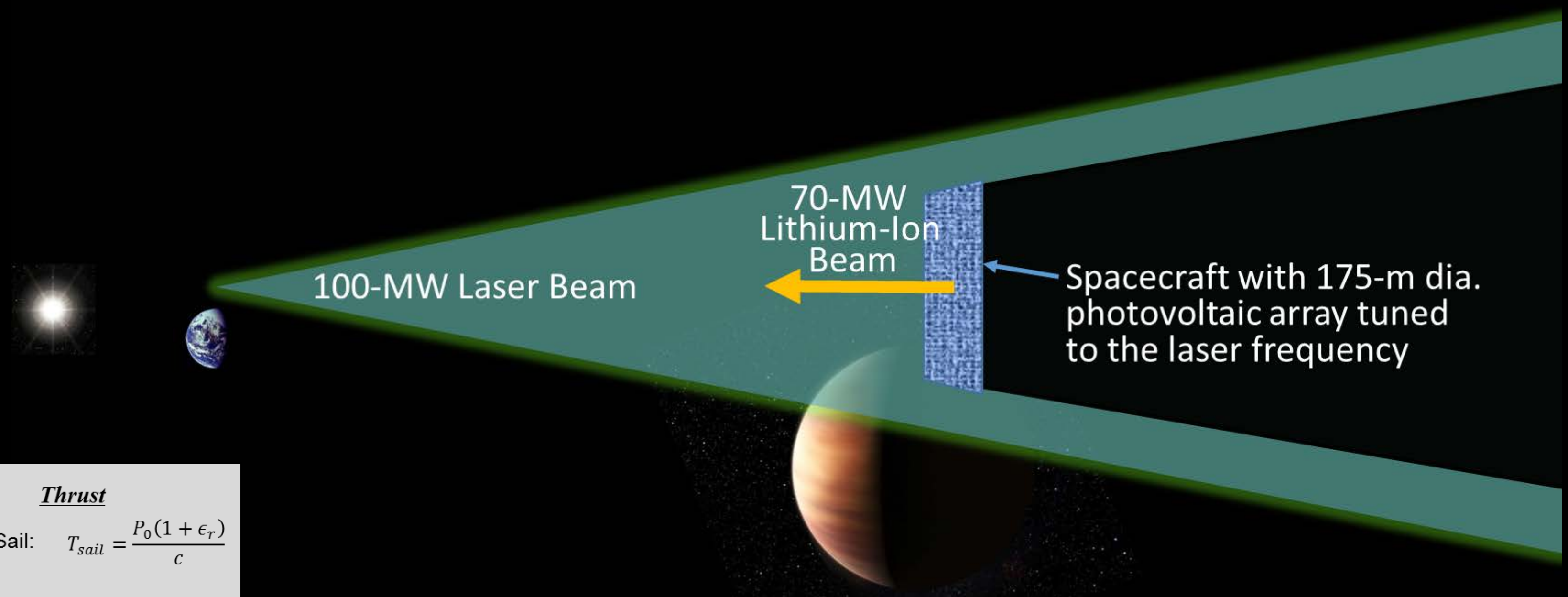




Increase the exhaust velocity, v_{ex} by a factor of 10 over the best ion engines today

Artist's concepts

Laser Electric Propulsion (LEP) Concept



Thrust

Laser Sail: $T_{sail} = \frac{P_0(1+\epsilon_r)}{c}$

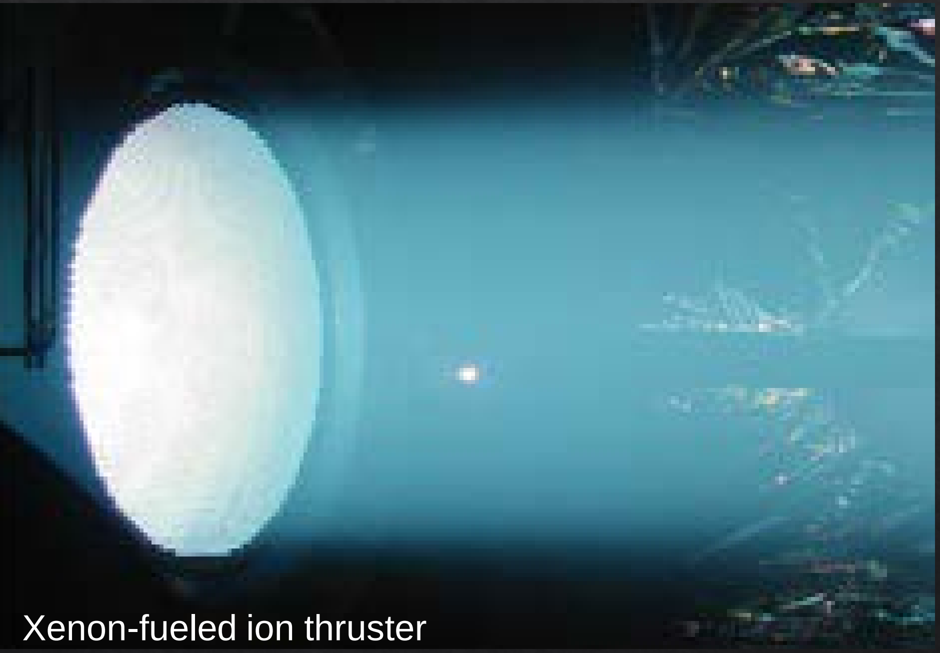
Laser EP: $T_{EP} = \frac{2\eta P_0 \epsilon_{S/A}}{I_{sp} g}$

Ratio: $\frac{T_{EP}}{T_{sail}} = \frac{2\eta\epsilon_{S/A}}{1+\epsilon_r}\left(\frac{c}{I_{sp} g}\right)$

Space-based laser powers a 60,000-s Isp vehicle past Jupiter on a 12-year trip to 500 AU

Lithium-fueled Ion Thruster

Xenon ion thrusters have 10X the exhaust velocity of the best chemical rockets today

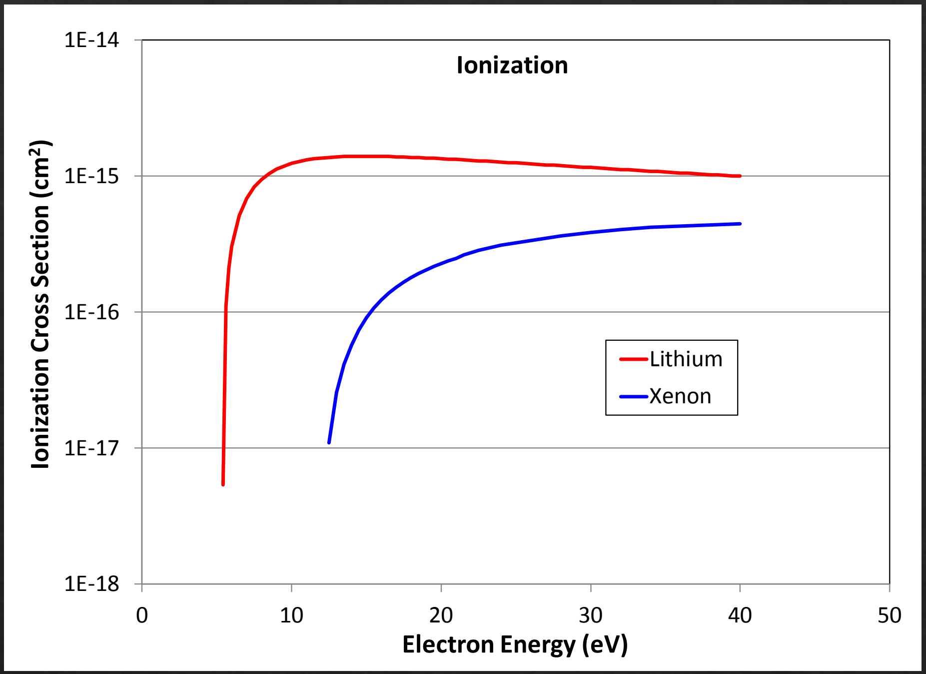


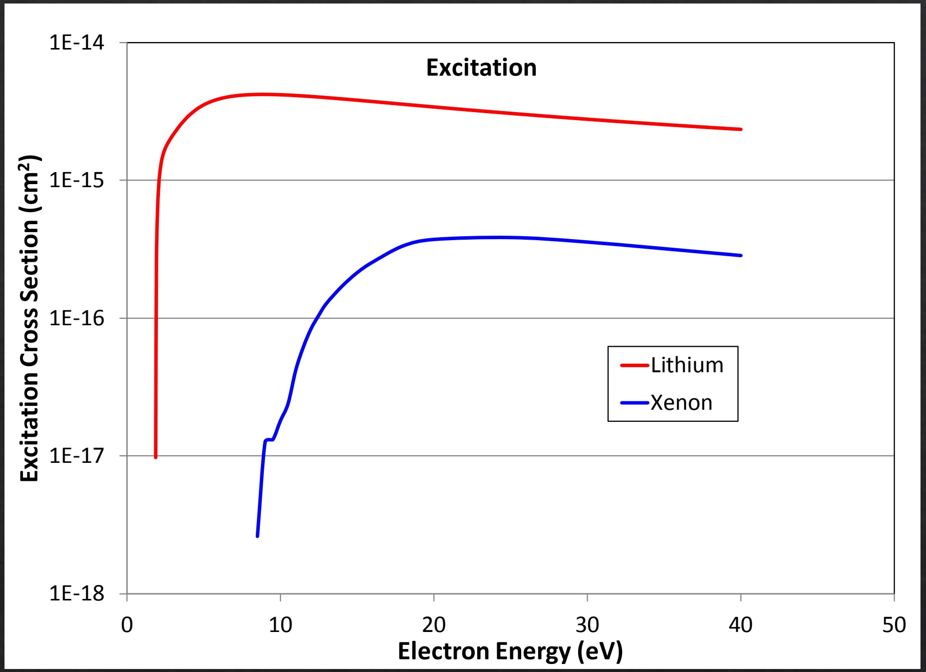
Xenon-fueled ion thruster

A lithium ion thruster would have 10X the exhaust velocity of the best ion engines today

Parameter	State of the Art	Lithium Thruster
Propellant	Xenon	Lithium
Exhaust Velocity	50 km/s	500 km/s
Input Power	16 kW	7,000 kW
Thrust	0.4 N	26 N
Efficiency	0.74	0.95

Xenon vs Lithium Plasmas

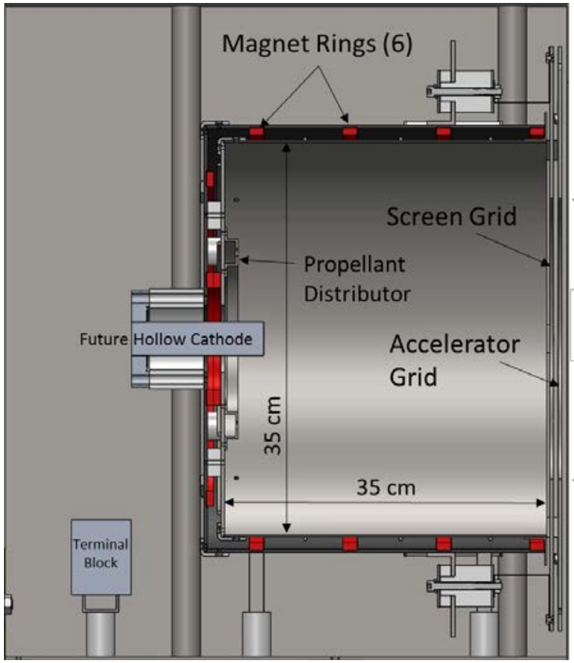




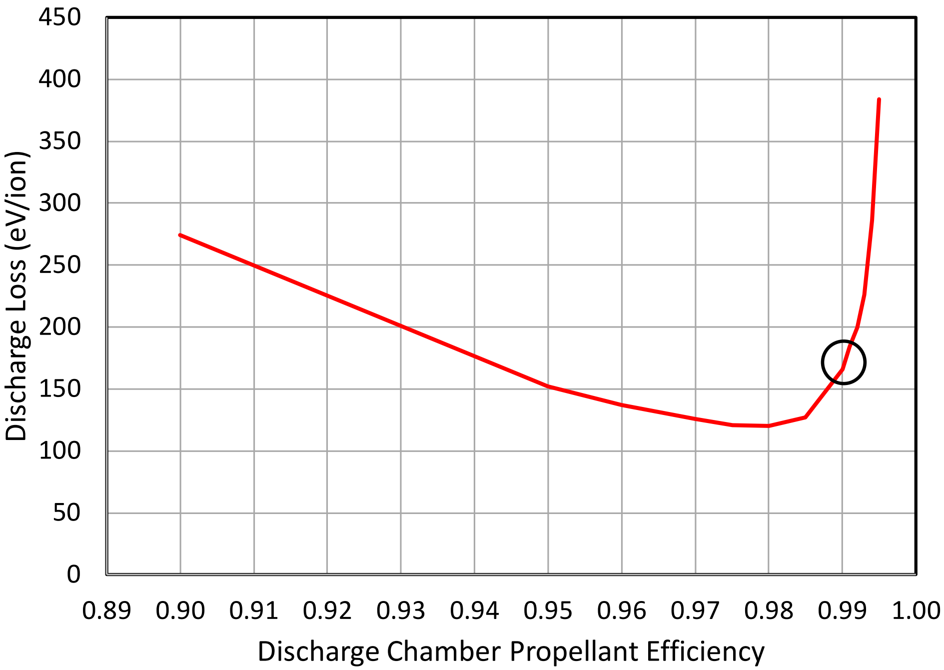
- Lithium is much easier to ionize than xenon
- Lithium also has a much larger excitation cross section than xenon
- The first ionization potential for lithium is 5.39 eV and the second ionization potential is 75.64 eV
  - For low voltage discharges, lithium will be nearly impossible to doubly ionize

Discharge Chamber

Configuration

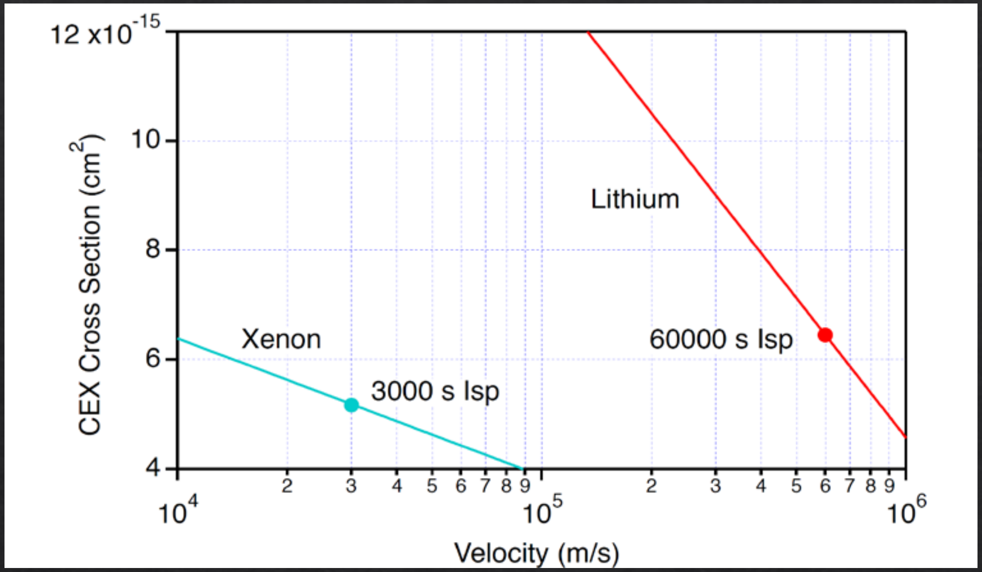


Discharge Performance Curve

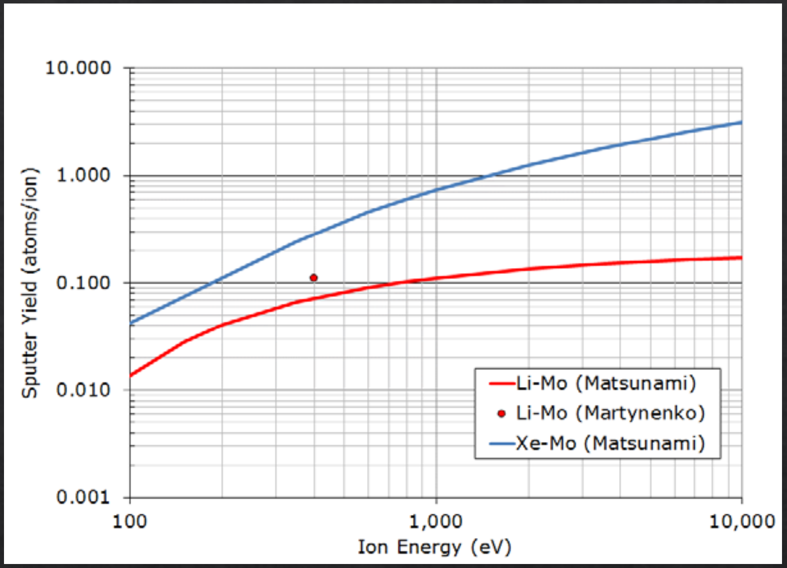


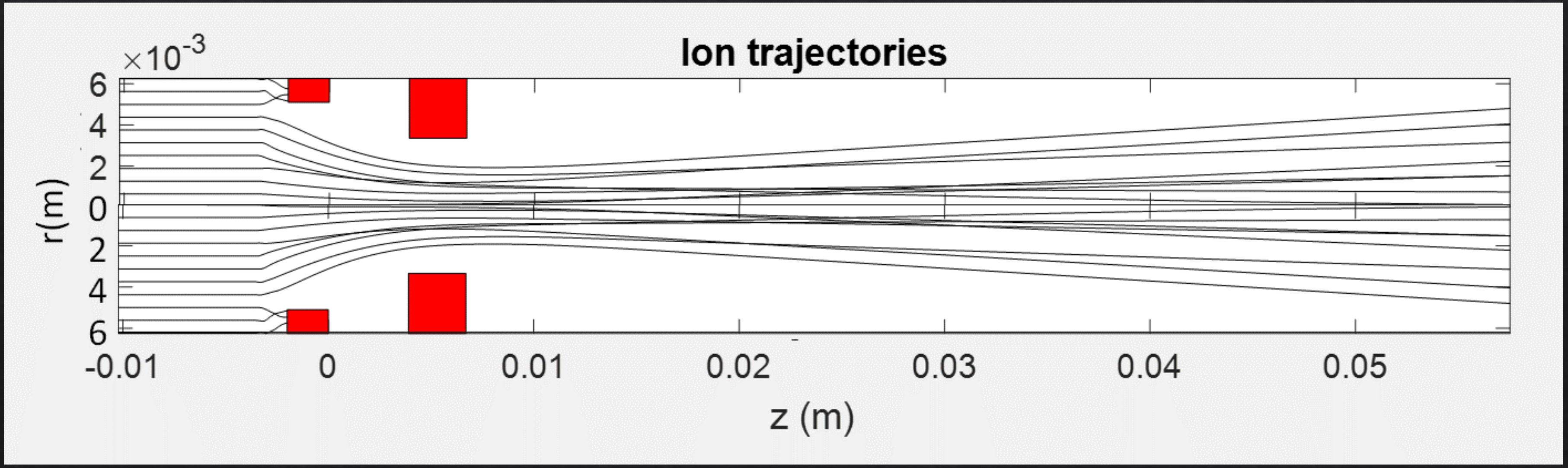
Ion Optics

Charge Exchange Collision Cross Sections



Sputter Yield





Lithium-Test Facility

Lithium-Test Chamber

- 3 m diameter x 8 m long
- Conical Liner
  - 1.68 m to 2.44 m
  - 5.16 m long
  - 38 m^2 surface area
- Lithium Pumping Speed
  - 9,000,000 L/s

Why Lithium?

- *Lithium is way cool!*
- An ion thruster with a specific impulse of 50,000 s would enable deep space missions with characteristic velocities in the range 100 km/s to 200 km/s (> 40 AU/year).
- Lithium enables specific impulses of tens of thousands of seconds at voltages less than 10 kV.
- Discharge chamber modeling suggests that it may be possible to operate the discharge chamber at a propellant efficiency of 99%.
  - Minimize charge-exchange erosion of the accelerator grid
  - Minimize CEX plasma interaction with a high-voltage PV array
- Lithium is much easier to store on a spacecraft than hydrogen or helium.

Summary

- The Rocket Equation drives the need for Electric Propulsion
  - Has resulted in 20 countries around the world developing this technology
- Electric Propulsion is in widespread use on Commercial Communication Satellites
- Electric Propulsion is expanding its footprint on deep space robotic science missions
- Electric Propulsion is currently the technology of choice for human missions to Mars
- Electric Propulsion is applicable to most Planetary Defense techniques (KI, nuclear deflection, gravity tractor, laser ablation)
  - It's largest contribution may be through ion beam deflection
- Electric Propulsion may play a dominant role in asteroid mining
- Electric Propulsion, in combination with power beaming, may enable fast transportation throughout the solar system up to approximately the solar gravity lens location