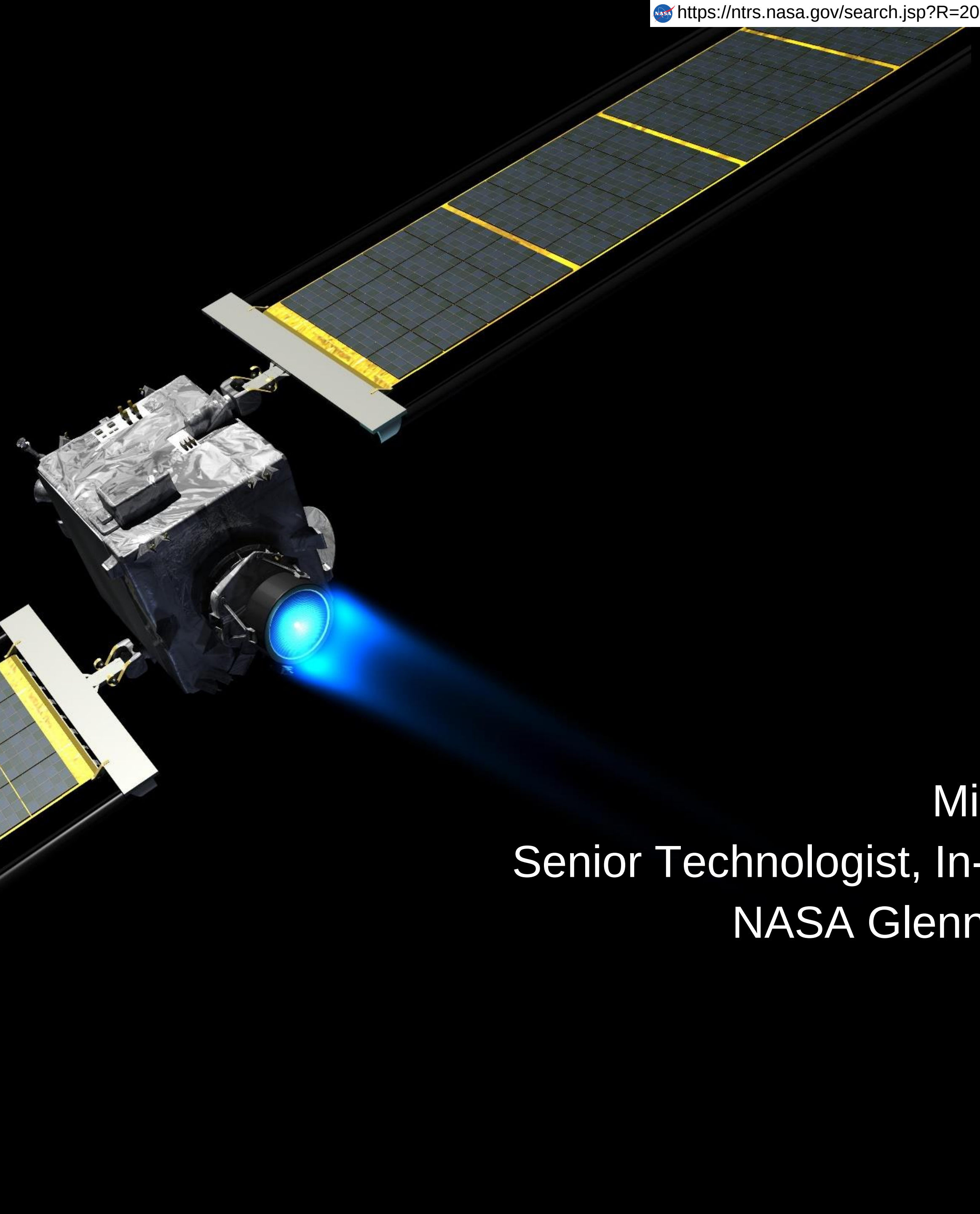
Ion Propulsion for Solar System Exploration

COMSCI: Exploring the Frontiers of Chemistry through NASA Research
ACS Spring 2019
National Meeting & Exposition



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April 02, 2019

Outline

- What is Electric Propulsion (EP)?
- What is Ion Propulsion?
- Mission Applications: NASA, Commercial, NSS
- Recent NASA Missions with Ion Propulsion: NSTAR on DS1 and Dawn
- Active Technology Development Focus: NEXT
- Future Missions: DART, and CAESAR
- Technology Barriers – Materials
- Summary

Electric Propulsion

Chemical Propulsion converts the energy stored in the molecular bonds of a propellant into kinetic energy

- Typically produces a high thrust to weight ratio, which is required for launch
- Exhaust velocity is limited by the chemical energy available
- Higher exhaust velocities can reduce required propellant mass:

- For a given change in velocity (ΔV), the delivered mass (M_f) depends on the propellant exhaust velocity (v_e)

$$\frac{Mass_{final}}{Mass_{initial}} = e^{-\Delta v / velocity_{exhaust}}$$

- Once in space, engines that provide a higher exhaust velocity can significantly reduce propellant mass requirements

Electric Propulsion

Electric Propulsion (EP) uses electrical power – from on-board power (solar or nuclear) – to provide kinetic energy to a propellant

- Decouples kinetic energy from limitations of chemical energy
- Provides higher exhaust velocities than chemical engines
  - Reduces propellant mass needed to provide a given impulse
  - Allows reduction in launch mass and/or increase in payload, which can provide substantial benefits in mission cost
- Opens launch window over chemical systems in certain scenarios

Electric Propulsion

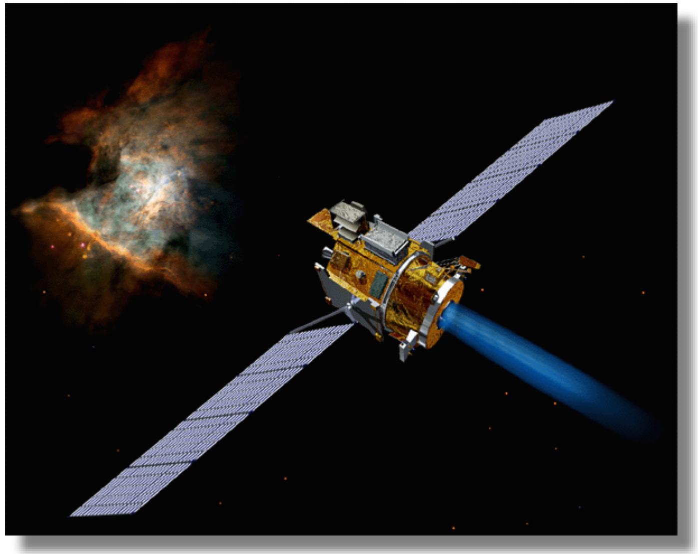
Additional Considerations for EP

EP Delivers significantly lower thrust to weight ratio than chemical engines

- Small but steady acceleration, vs. short-burn chemical engines
- EP engines must be designed for long life; typically 10’s of thousands of hours

EP also increases dry mass due to:

- Solar arrays
- Power processing unit
- and Other EP specific hardware



Spacecraft integration considerations:

- Electric power requirements
- Plasma plume
- Potential EMI

Propulsion system trades are performed to evaluate whether a given mission will benefit from the use of Electric Propulsion

Electric Propulsion

EP Engines (‘Thrusters’) are categorized by their primary acceleration mechanism:

Electrothermal

- Resistojet (flight units available)
- Arcjet (flight units available)

Electrostatic

- Hall effect thrusters (flight units + development)
- **Gridded ion thrusters (flight units + development) – ‘Ion Propulsion’**

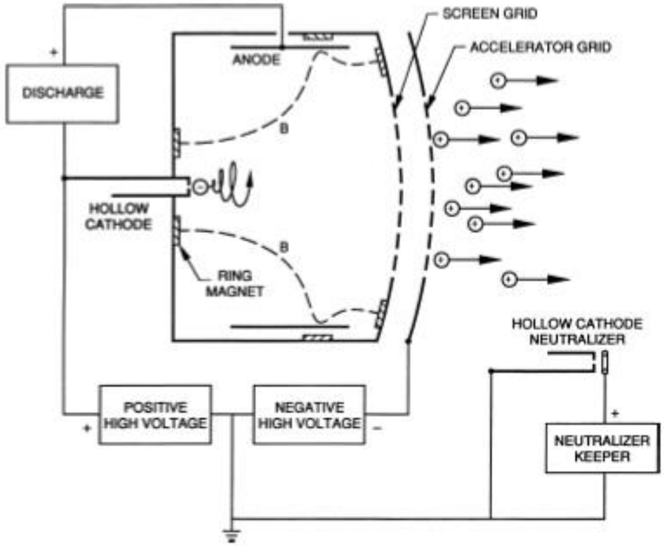
Electromagnetic

- Pulsed plasma thruster (flight units available)
- Magnetoplasmadynamic thruster (laboratory models only)
- Pulsed inductive thruster (laboratory models only)

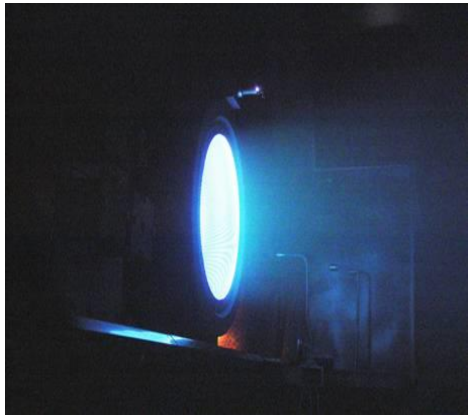
Ion Propulsion

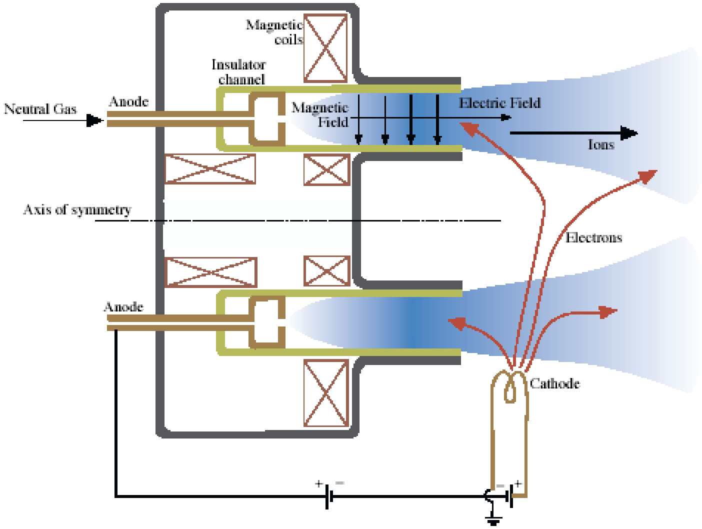
Electrostatic Thrusters

Apply high voltages for ion (plasma) acceleration

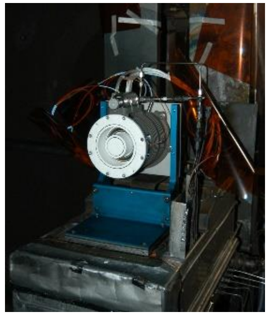


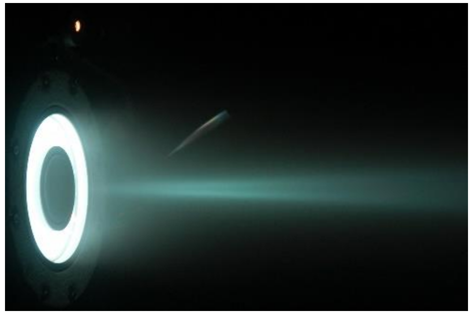
<u>Ion</u> thrusters use closely spaced high voltage grids to create an electrostatic field



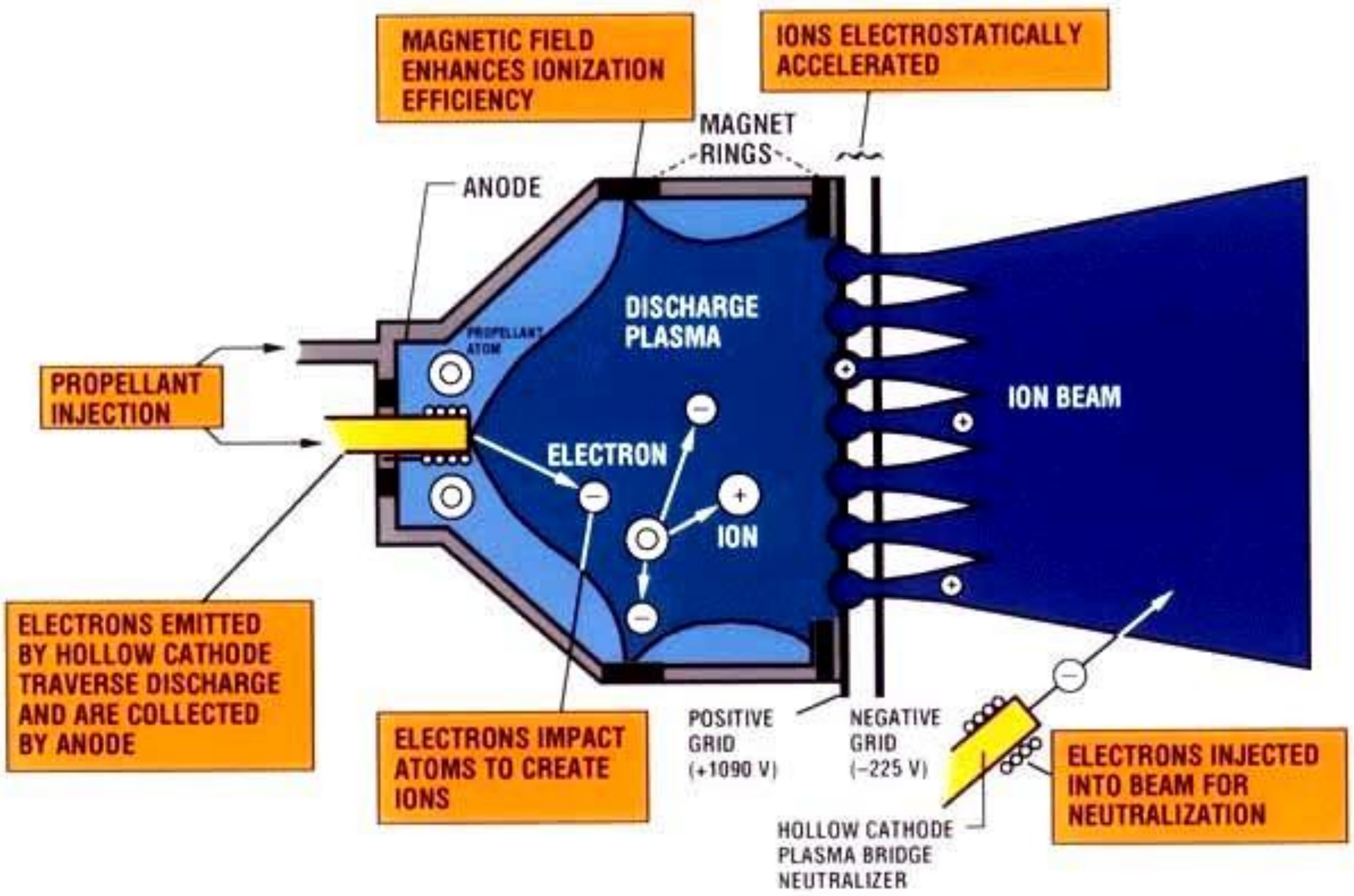


<u>Hall</u> thrusters use magnetically trapped electrons to create an electrostatic field





Ion Propulsion



MAGNETIC FIELD ENHANCES IONIZATION EFFICIENCY

IONS ELECTROSTATICALLY ACCELERATED

PROPELLANT INJECTION

ELECTRONS EMITTED BY HOLLOW CATHODE TRAVERSE DISCHARGE AND ARE COLLECTED BY ANODE

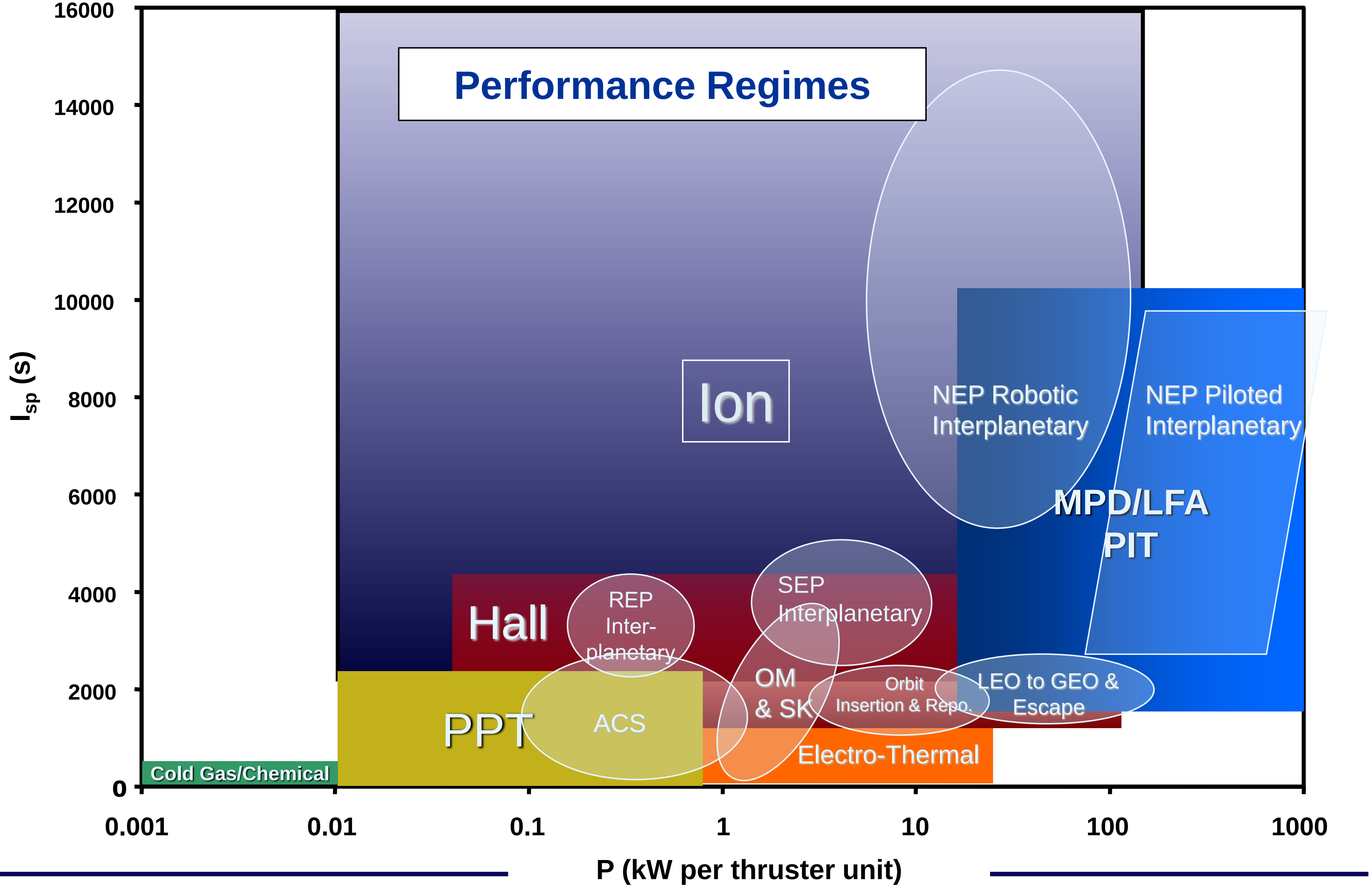
ELECTRONS IMPACT ATOMS TO CREATE IONS

ELECTRONS INJECTED INTO BEAM FOR NEUTRALIZATION

Ion Propulsion

Ion Propulsion –

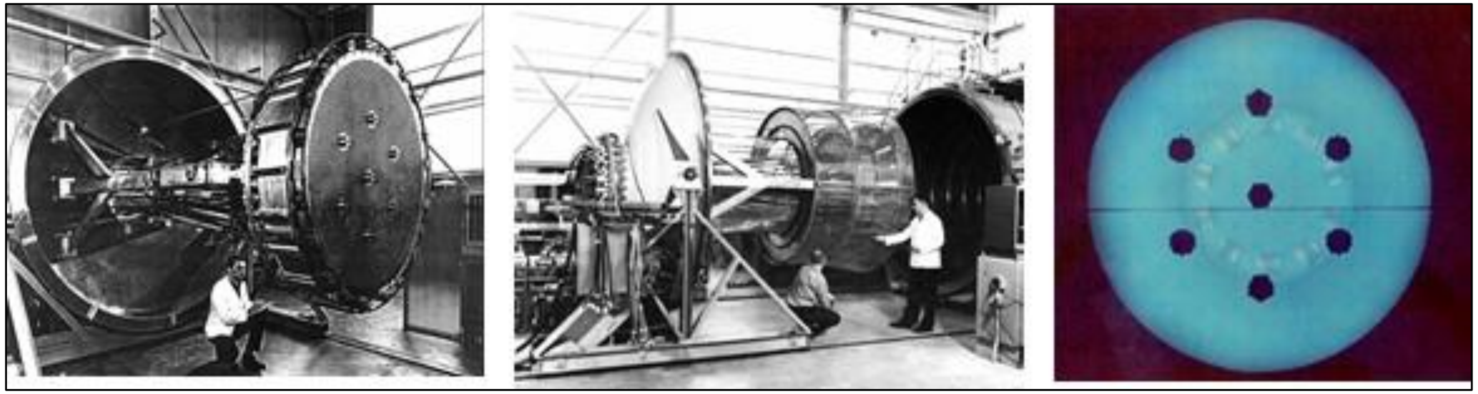
- One form of rocket propulsion which converts electrical energy to thrust via generation of a plasma and electrostatic acceleration of ions to produce thrust
- Produces extremely high exhaust velocities, but very low thrust levels, requiring long thrusting times
- **Ion has the largest performance regime of any technology option**
- **Ion's high specific impulse (exhaust velocity) yields low propellant mass requirement and high delivered payload**



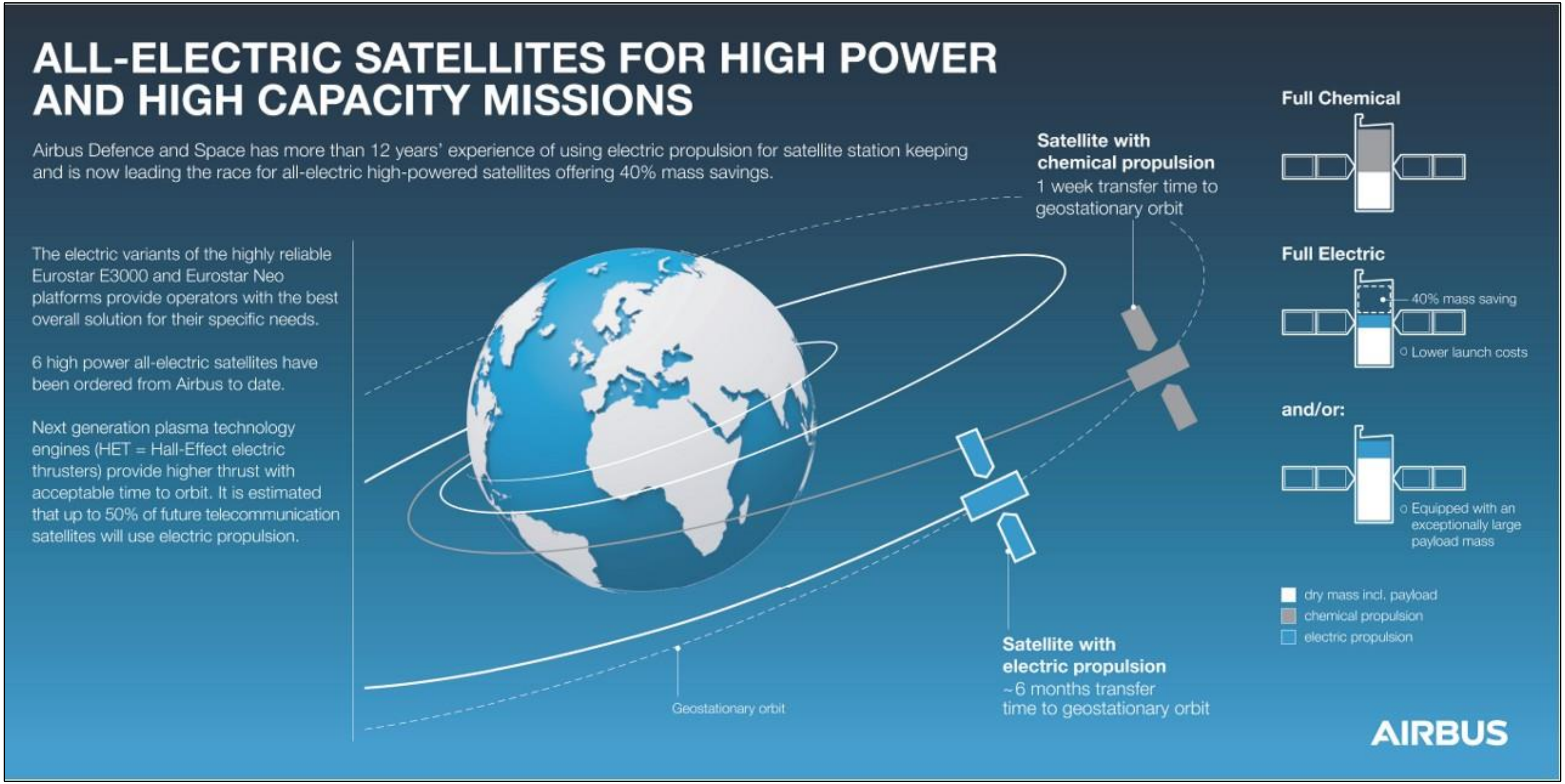
Mission Applications

Electric Propulsion primarily benefits large total impulse missions

- Orbit raising, repositioning, long-term station keeping (Ion, Hall; Commercial, NSS)
- Precise impulse bits for formation flying (NASA, NSS)
- Robotic planetary and deep space science missions (Ion; NASA)



Mission Applications



ALL-ELECTRIC SATELLITES FOR HIGH POWER AND HIGH CAPACITY MISSIONS

Airbus Defence and Space has more than 12 years' experience of using electric propulsion for satellite station keeping and is now leading the race for all-electric high-powered satellites offering 40% mass savings.

The electric variants of the highly reliable Eurostar E3000 and Eurostar Neo platforms provide operators with the best overall solution for their specific needs.

6 high power all-electric satellites have been ordered from Airbus to date.

Next generation plasma technology engines (HET = Hall-Effect electric thrusters) provide higher thrust with acceptable time to orbit. It is estimated that up to 50% of future telecommunication satellites will use electric propulsion.

Satellite with chemical propulsion
1 week transfer time to geostationary orbit

Satellite with electric propulsion
~6 months transfer time to geostationary orbit

Mission Applications

https://www.nasaspaceflight.com/2016/06/spacex-falcon-9-dual-satellite-launch/

Because of propellant mass savings and associated reduction in spacecraft mass with Ion, one can 'shoehorn' 2 spacecraft onto 1 launch vehicle

SpaceX conducts Falcon 9 dual satellite launch
June 14, 2016

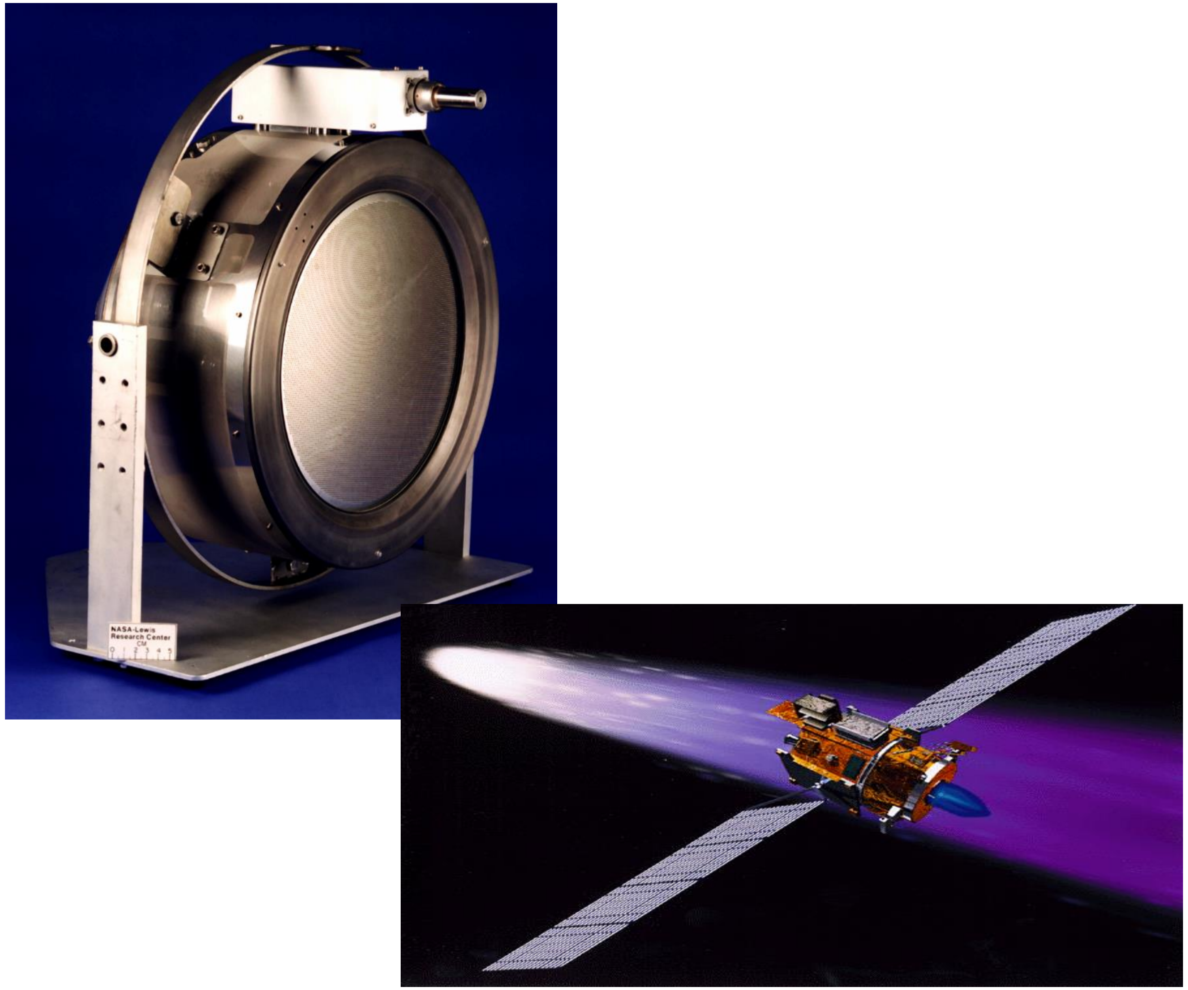
"The two satellites on Wednesday's launch were Eutelsat 117 West B and ABS-2A, which are to be operated by France's Eutelsat and Bermuda-based Asia Broadcast Satellite Limited respectively.

Both satellites were constructed by Boeing and are based on the BSS-702SP bus – a lightweight modification of the Boeing 702 platform – designed to be launched in pairs to bring down launch costs"

Recent NASA Missions with Ion Propulsion

Deep Space 1 (DS1)

- **Acronym:** DS1
- **Type:** Flyby
- **Launch Date:** October 24, 1998
- **Launch Location:** Cape Canaveral Air Force Station, Florida
- **Mission End Date:** December 18, 2001
- **Target:** asteroid 9969 Braille, comet Borrelly
- **Destination:** asteroid 9969 Braille, comet Borrelly



Recent NASA Missions with Ion Propulsion

Deep Space 1 (DS1)

First interplanetary spacecraft to use an Ion Propulsion (NSTAR)

Originally designed to test a dozen new technologies including the ion engine for spacecraft propulsion, DS1 far outstripped its primary mission goals by also successfully flying by the asteroid 9969 Braille and comet Borrelly

The flybys produced what are still considered some of the best images and data ever collected from an up-close encounter with an asteroid or comet

The success of DS1 set the stage for future ion-propelled spacecraft missions, especially those making the technically difficult journey to asteroids or comets, such as NASA's Dawn Mission

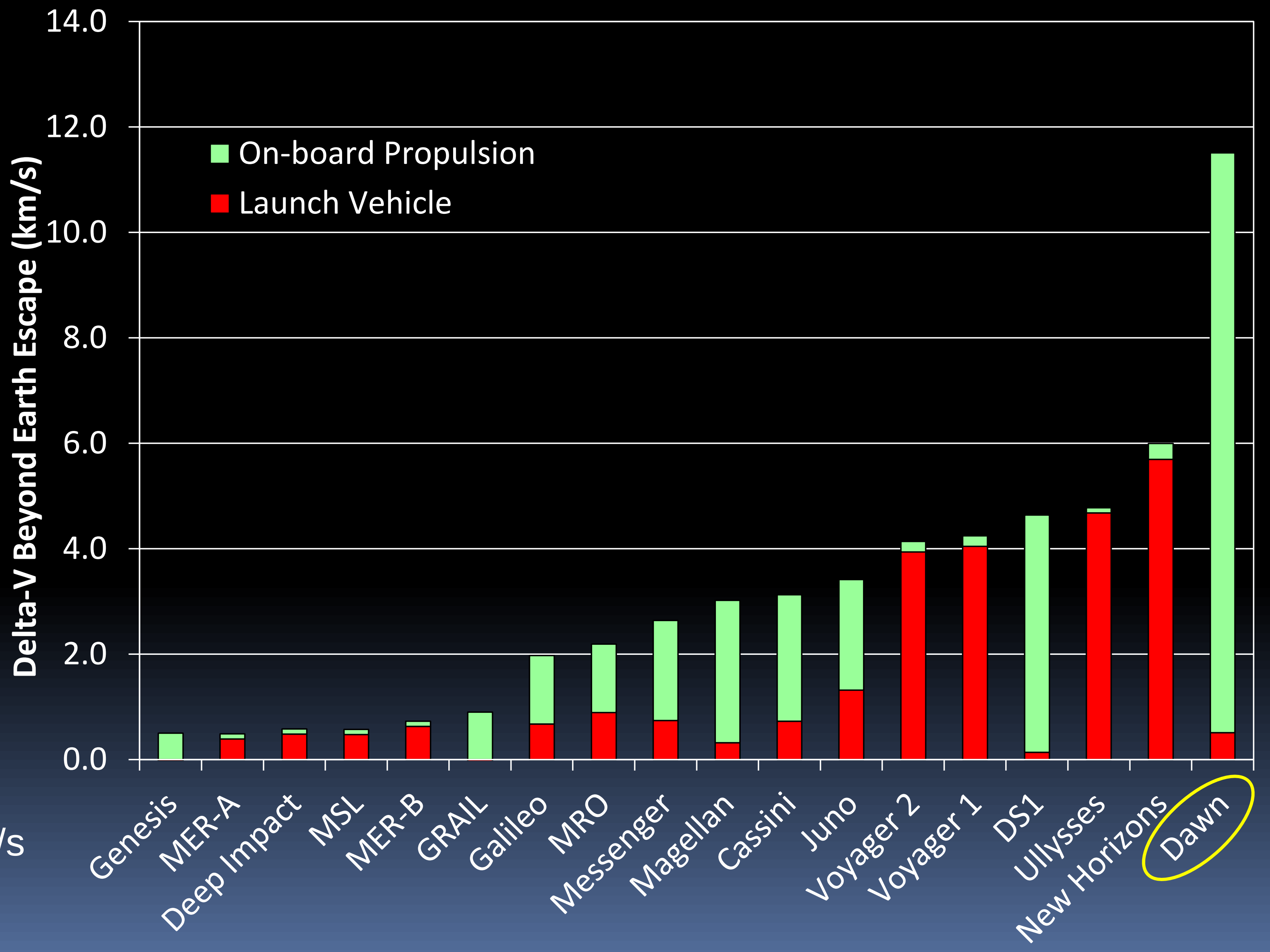
Recent NASA Missions with Ion Propulsion

Dawn

Recent NASA Missions with Ion Propulsion

Dawn

ΔV Beyond Earth Escape



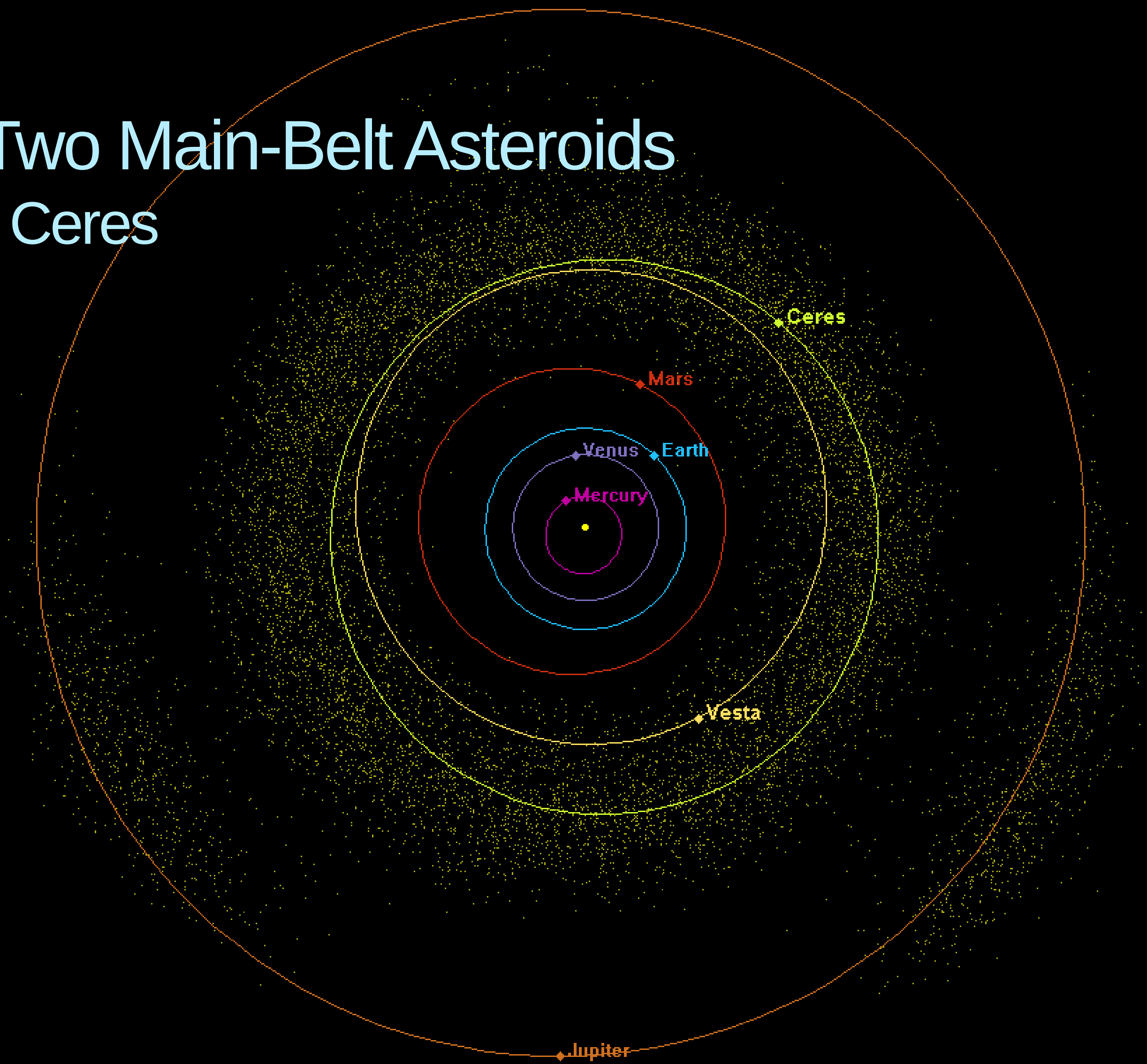
Earth Escape Velocity: ~11 km/s

Recent NASA Missions with Ion Propulsion

Dawn

Orbited Two Main-Belt Asteroids

Vesta and Ceres

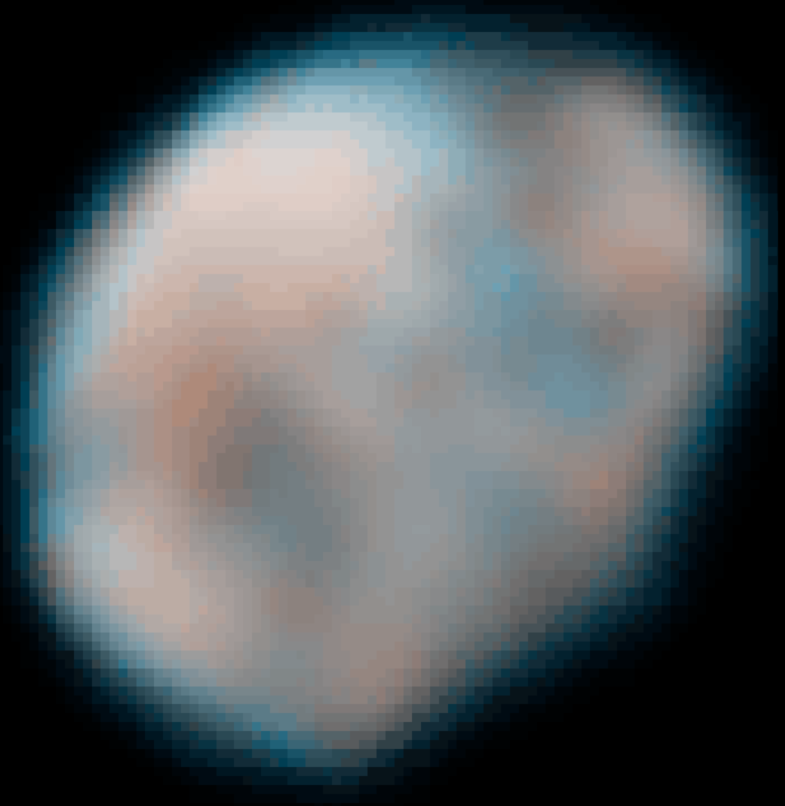


Vesta and Ceres seem to straddle the boundary between the rocky bodies of the inner solar system and the icy bodies of the outer solar system

Recent NASA Missions with Ion Propulsion

Dawn

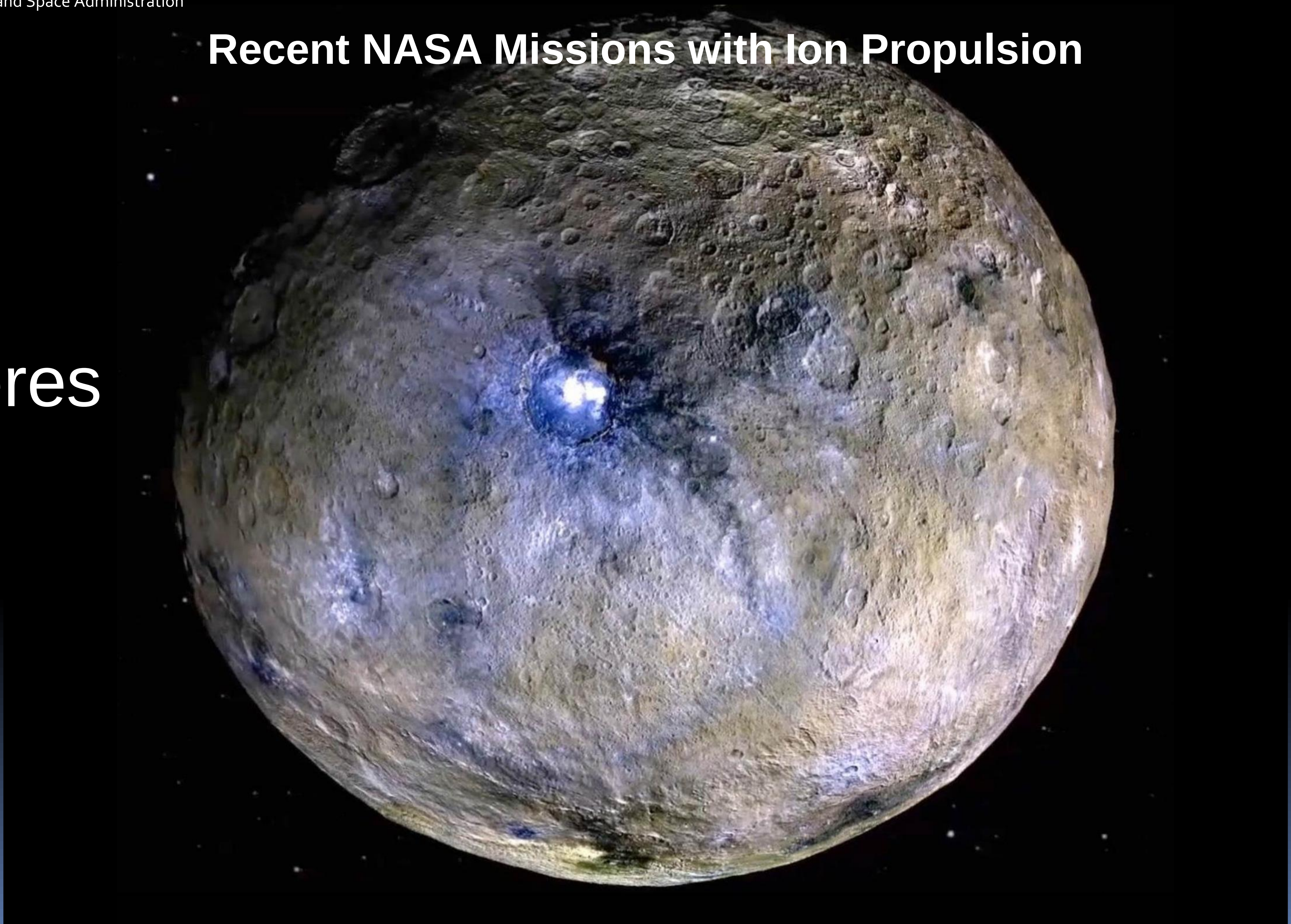
Vesta



Best Hubble Image

Dawn Image from July 18, 2011

Recent NASA Missions with Ion Propulsion



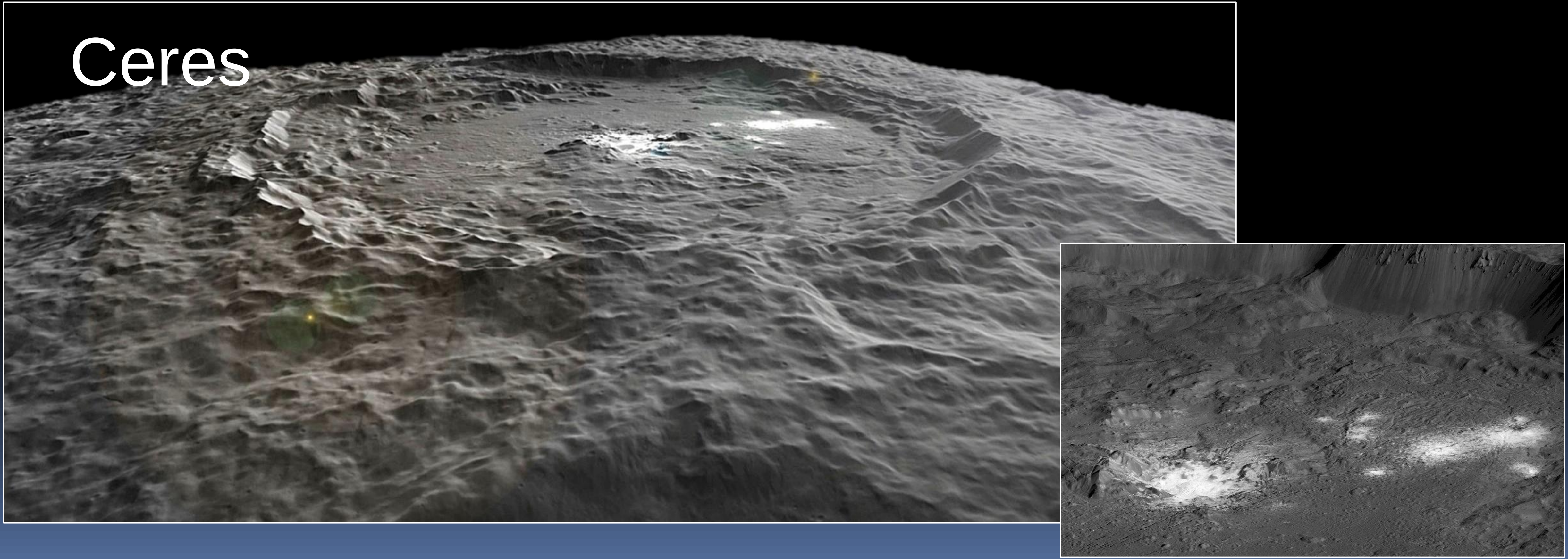
Dawn

Ceres

Recent NASA Missions with Ion Propulsion

Dawn

Occator crater, ~92 km

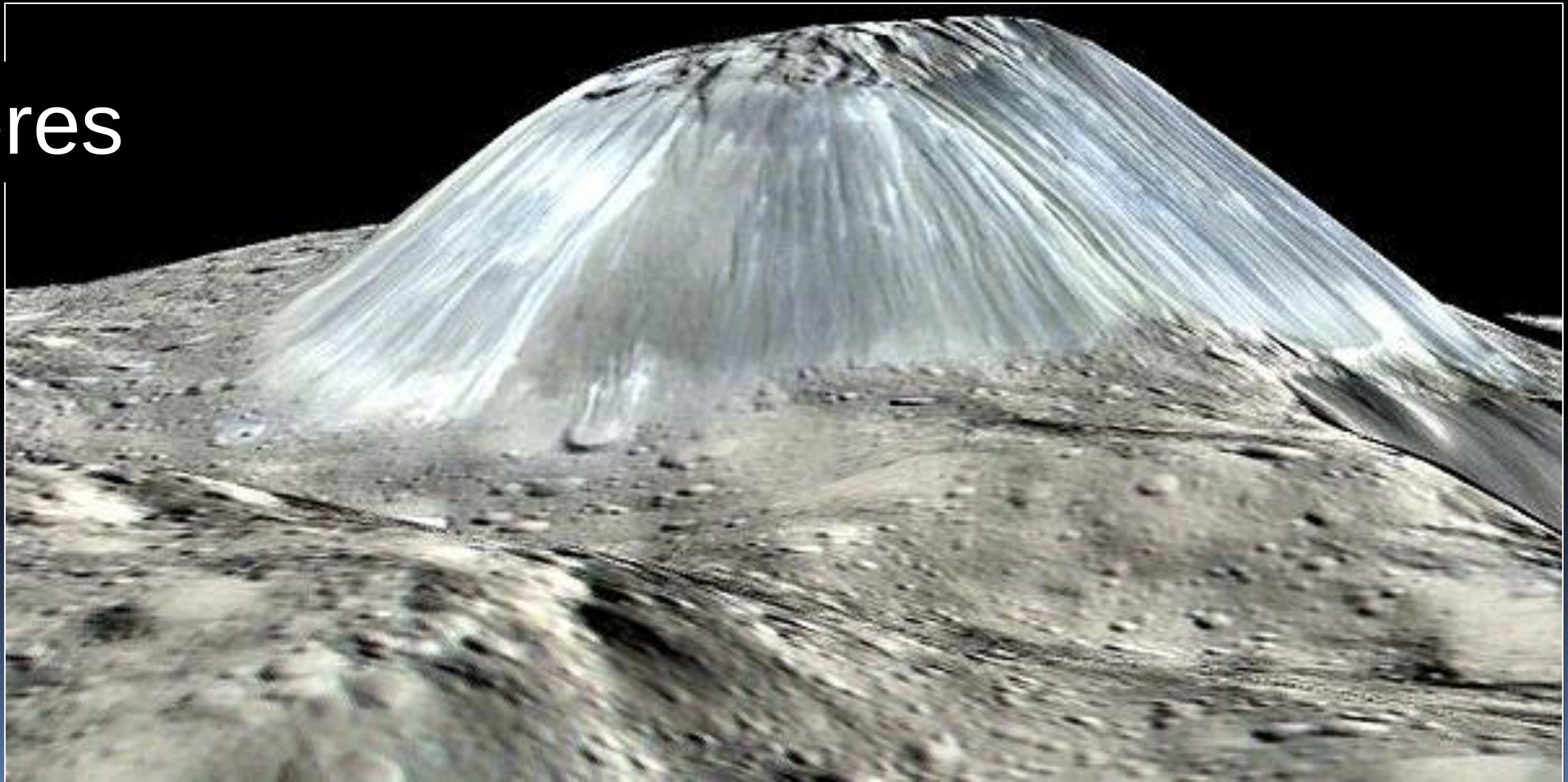


Recent NASA Missions with Ion Propulsion

Dawn

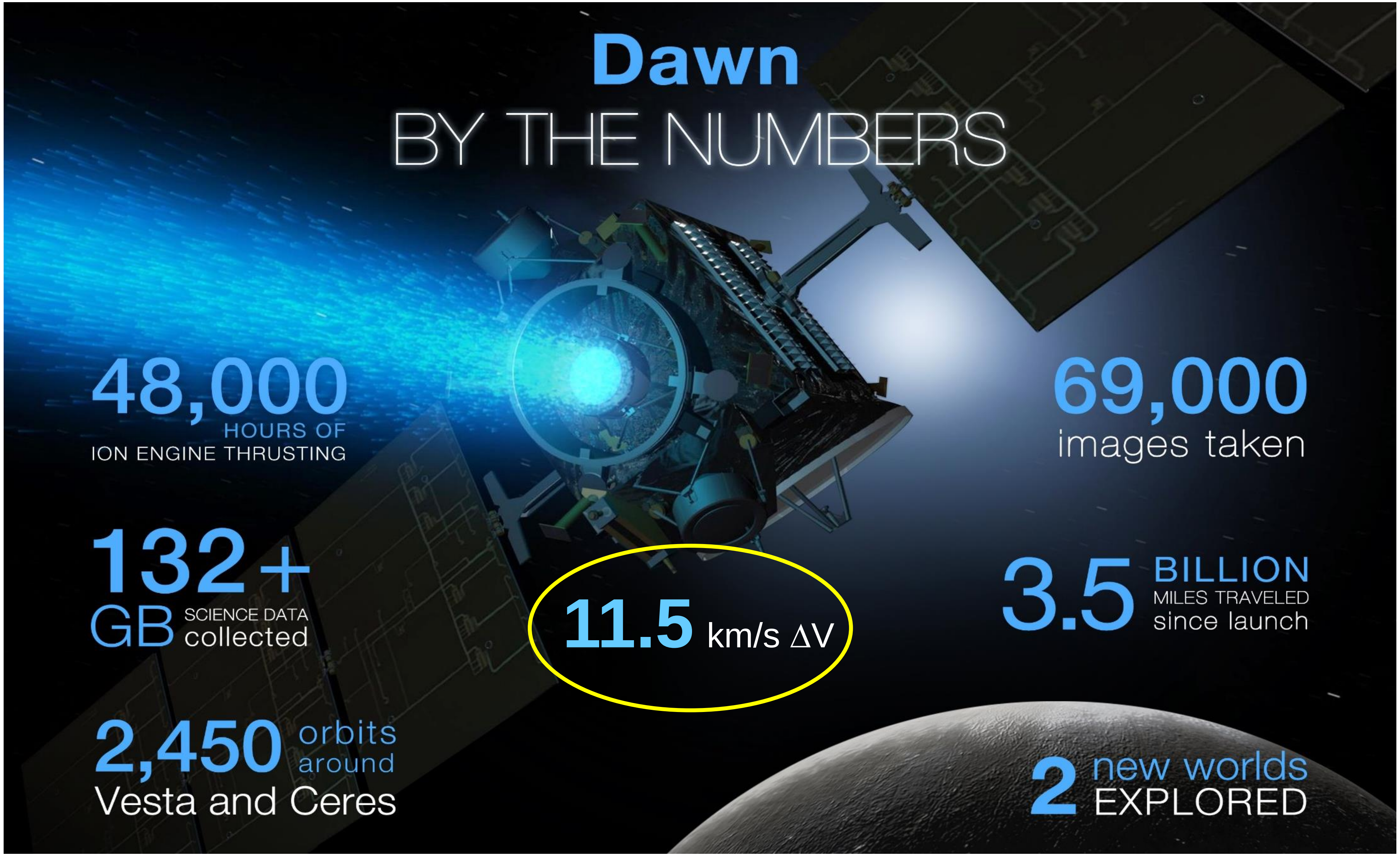
Ahuan mons, ~4 km (height)

Ceres



National Aeronautics and Space Administration

Recent NASA Missions with Ion Propulsion



Dawn

BY THE NUMBERS

48,000 HOURS OF ION ENGINE THRUSTING

69,000 images taken

132+ GB SCIENCE DATA collected

11.5 km/s ΔV

3.5 BILLION MILES TRAVELED since launch

2,450 orbits around Vesta and Ceres

2 new worlds EXPLORED

NASA’s NEXT

Original Objectives

- Advance next-generation **Ion Propulsion System** (IPS) technology to TRL 5/6
- Demonstrate significant performance and engineering improvements over SOA
- Power and thrust hit “sweet spot” for next-generation IPS – *applicable to broad range of NASA Discovery, New Frontiers and Flagship-class missions*

Phase 2 Completed CY14

- Development of high fidelity components to TRL 5 with significant progress towards TRL 6
- Thruster Long Duration Test (LDT) successfully exceeded duration records: >900 kg throughput, 50,000 hrs over 8 yrs, 34.8 MN-s total impulse

Forward Focus

- Develop NEXT system to TRL 5/6 to enable new New Frontiers and Discovery missions
- Develop capability to provide operations in close near-Earth applications

NASA's NEXT

NEXT represents a significant step forward in Ion Propulsion SOA and Capability

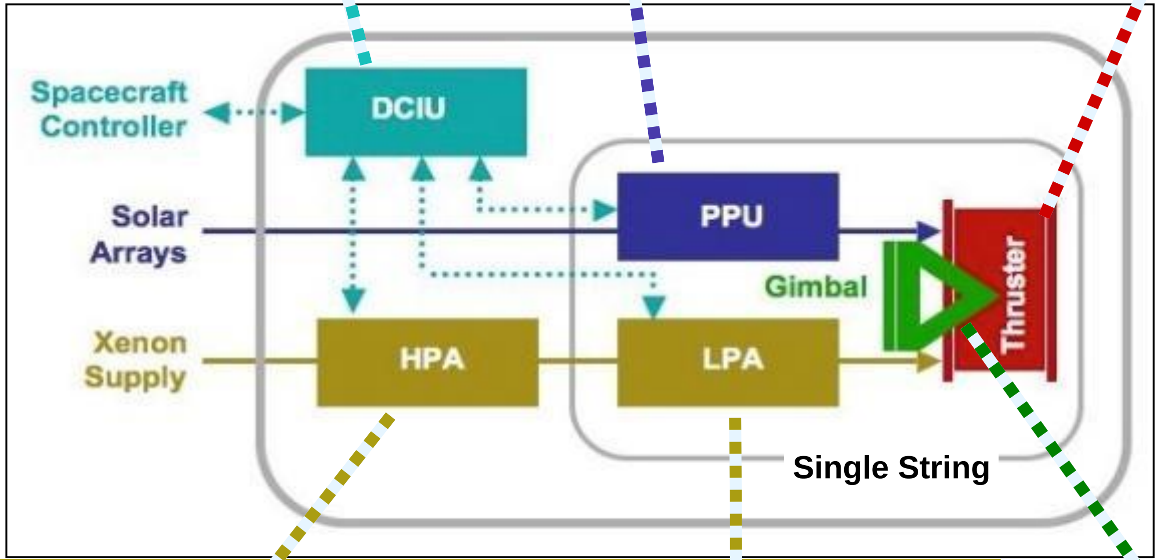
CHARACTERISTIC	NSTAR (SOA)	NEXT	BENEFIT
Max. Thruster Power (kW)	2.3	6.9	Enables high power missions with fewer thruster strings
Max. Thrust (mN)	91	236	
Throttling Range (Max./Min. Thrust)	4.9	13.8	Allows use over broader range of distances from Sun
Max. Specific Impulse (sec)	3120	4190	Reduces propellant mass, thus enabling more payload and/or lighter spacecraft
Total Impulse (10^6 N-sec)	~7	>34.8	Enables low power, high ΔV Discovery-class missions with a single thruster
Propellant Throughput (kg)	235	>900	

NASA’s NEXT

**Digital Control
Interface Unit (DCIU)
Simulator [Aerojet]**

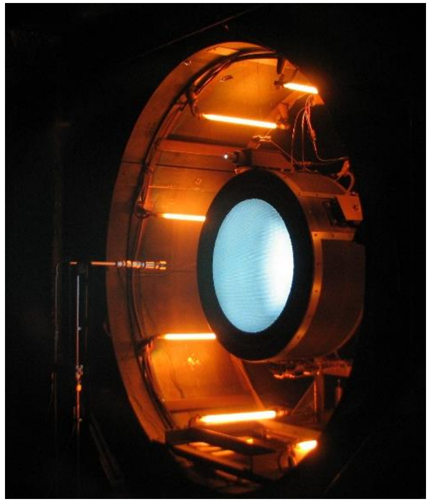
**Power Processing Unit (PPU)
[L-3 Com, Eng Model]**

Thruster [Aerojet, Prototype Model]



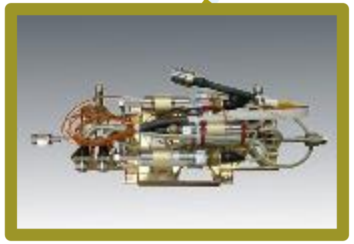
Single String

NEXT system testing at GRC

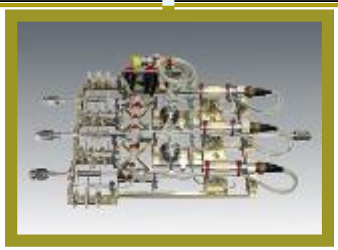


**NEXT environmental testing
at JPL**

Gimbal [ATK, Breadboard]



High Pressure Assembly (HPA)



Low Pressure Assembly (LPA)

Propellant Mgmt System (PMS) [Aerojet, Eng Model]

National Aeronautics and
Space Administration

NASA’s NEXT

- After successful NEXT Technology to Flight Technical Interchange with US Industry in December 2013, a decision to transition the technology to flight through procurement of flight thruster and PPU shipsets was made

- In 2015 a contract was awarded to Aerojet Rocketdyne to build 2 flight NEXT thrusters and PPUs, and take steps towards commercializing system:
    - Provide two flight fidelity thrusters /PPUs strings for use on NASA missions
    - Establish commercial platform for high-power ion thruster system

- CDR successfully completed in April 2018

NASA’s NEXT

NEXT Enables many compelling science missions: >40 NASA Mission Studies, and its use has been incentivized on multiple Discovery and New Frontier Mission proposal rounds

- Flagship Technology Demonstration-1 (SEPM)
- Saturn System Exploration (SEPM – jettison @ 3.5 AU)
- Saturn-Titan Orbiter/“Titan Explorer” (SEPM)
- Titan Saturn System Missio (SEPM)
- Saturn Ring Observer (SEPM)
- Saturn/Titan Flyby
- Titan (SEPM)
- Enceladus (SEPM)
- Neptune Orbiter & Probe (SEPM)
- Neptune Flyby
- Neptune-Triton-KBO (SEPM for cruise)
- Kuiper Belt Object Orbiter
- Uranus Orbiter (SEPM – jettison @ 3 AU)
- Uranus Orbiter & Probe (SEPM)
- Uranus Orbiter & Probe (SEPM) (2nd)
- Vesta-Ceres Rendezvous
- Scarlatti
- Comet Wild 2 Rendezvous
- Comet Kopff Rendezvous
- Vesta-Ceres Rendezvous
- Mercury Lander
- Near-Earth Asteroids Rendezvous and Sample Earth Returns
- (NEARER) (SR)
- Sample Return Main Belt Asteroid SAMBA (SR)
- Ceres (Main Belt) Ceres (SR)
- Comet Surface Sample Return (SEP)
- Venus Lander
- Comet Tempel 1 (SR)
- Comet Tempel 1 Nucleus SR
- Comet Wirtanen SR
- Jupiter-Europa Flybyn
- Titan Lander (SEPM jettisoned @ Titan)
- Titan Orbiter (SEPM @ 3)
- Trojan/Centaur Recon Flybys
- Extra Zodiacal Explorer (SEPM jettison after science orbit insertion)
- Jupiter-Europa Orbiter
- New Worlds Observer
- Jupiter Polar Orbiter w/Probes (SEPM – jettisoned @ 2.5 AU)
- Phobos & Deimos SR
- Mars Earth Return Vehicle SR
- Neptune-Triton-KBO

Future Missions

NEXT has been selected for DART and other potential missions

DART (Double Asteroid Redirection Test)

- First planned mission using NEXT-C
- Led by APL - NEXT-C is Government Furnished Equipment (Shipset 1)
- Spacecraft kinetically impact an asteroid

CAESAR (Comet Astrobiology Exploration SAmple Return)

- One of two possible missions selected for New Frontiers Phase A
- Led by GSFC with Orbital ATK, AR, and GRC support
- Mission to acquire a sample from a comet and return it to Earth

Interest from other missions including potential US Govt. Earth-Orbital demonstration

Asteroid Impact & Deflection Assessment (AIDA)

DART

Double Asteroid Redirection Test

NASA
Goddard Space Flight Center
Johnson Space Center
Langley Research Center
Glenn Research Center
Marshall Space Flight Center
Planetary Defense Coordination Office

Johns Hopkins Applied Physics Laboratory

Jet Propulsion Laboratory
California Institute of Technology

University of Colorado Boulder

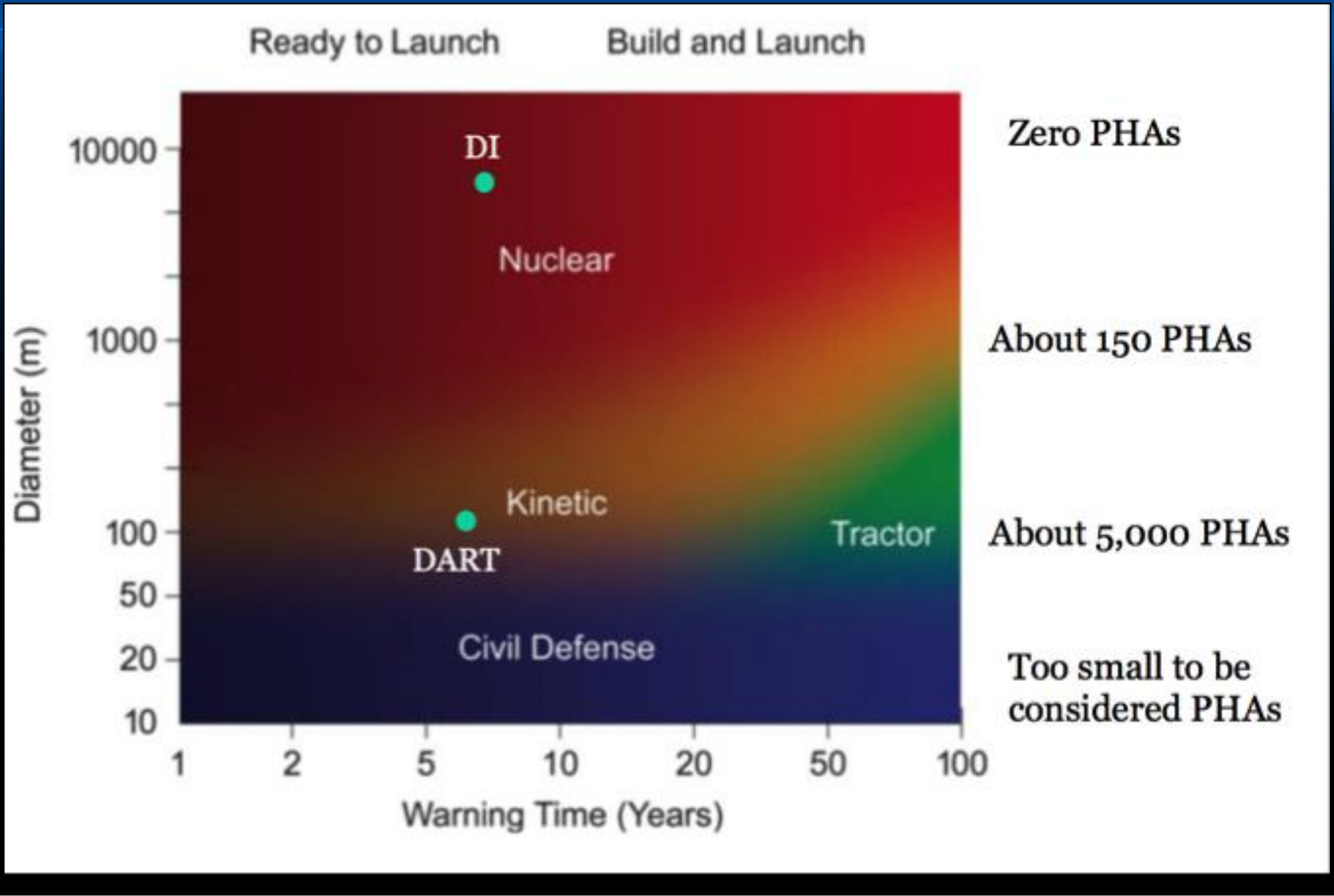
University of Maryland

Lawrence Livermore National Laboratory

Aerojet Rocketdyne

Regimes of Primary Applicability of the Four types of **Planetary Defense** Mitigation

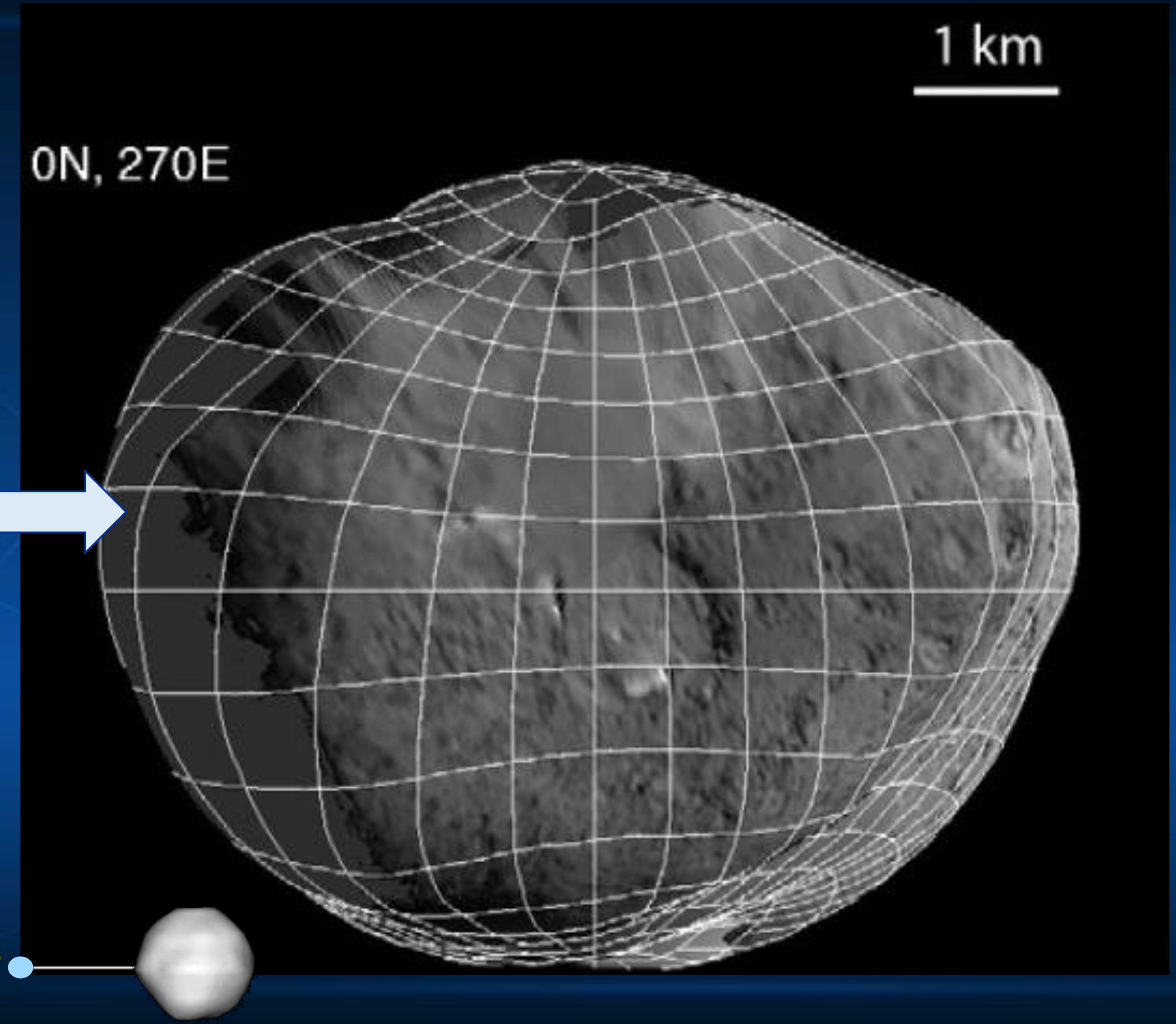
DART



First Kinetic Impact Test at Realistic Scale for Planetary Defense

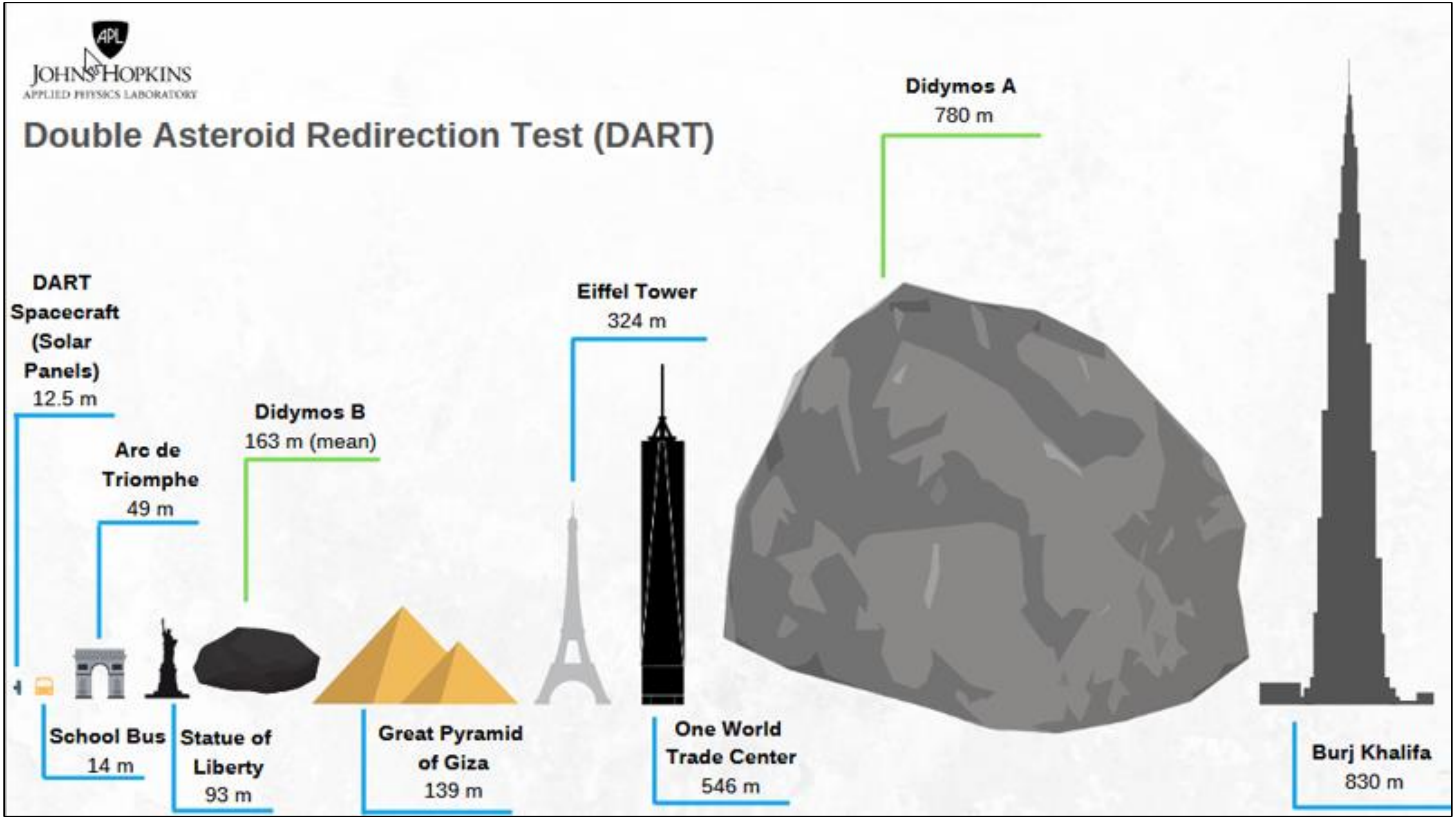
DART

DART target much smaller than the Deep Impact target



Comet 9P/Tempel 1
Deep Impact target

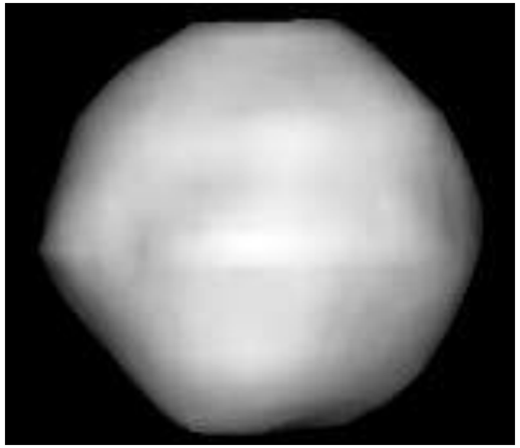
DART target
Didymos moon



Johns Hopkins
Applied Physics Laboratory

Double Asteroid Redirection Test (DART)

Targeting the Didymos system in October, 2022

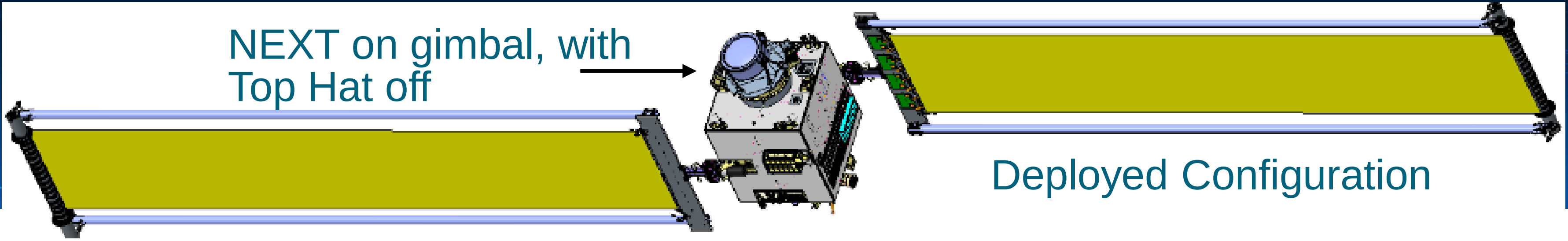


Primary Diameter	**780 m ± 10%**
Secondary Diameter	**163 m ± 18 m**
Total System Mass	**$(5.278 \pm 0.54) \times 10^{11}$ kg**
Component Bulk Density	**2,100 kg m^{-3} ± 30%**
Primary Rotation Period	**2.2600 ± 0.0001 h**
Component Separation	**1180 +40/-20 m**
Secondary Orbital Period	**11.920 +0.004/−0.006 h**
Spectral Class	**S**

- **Didymos is a well-characterized asteroid that approaches close to Earth, enabling ground-based observations of impact demonstration**

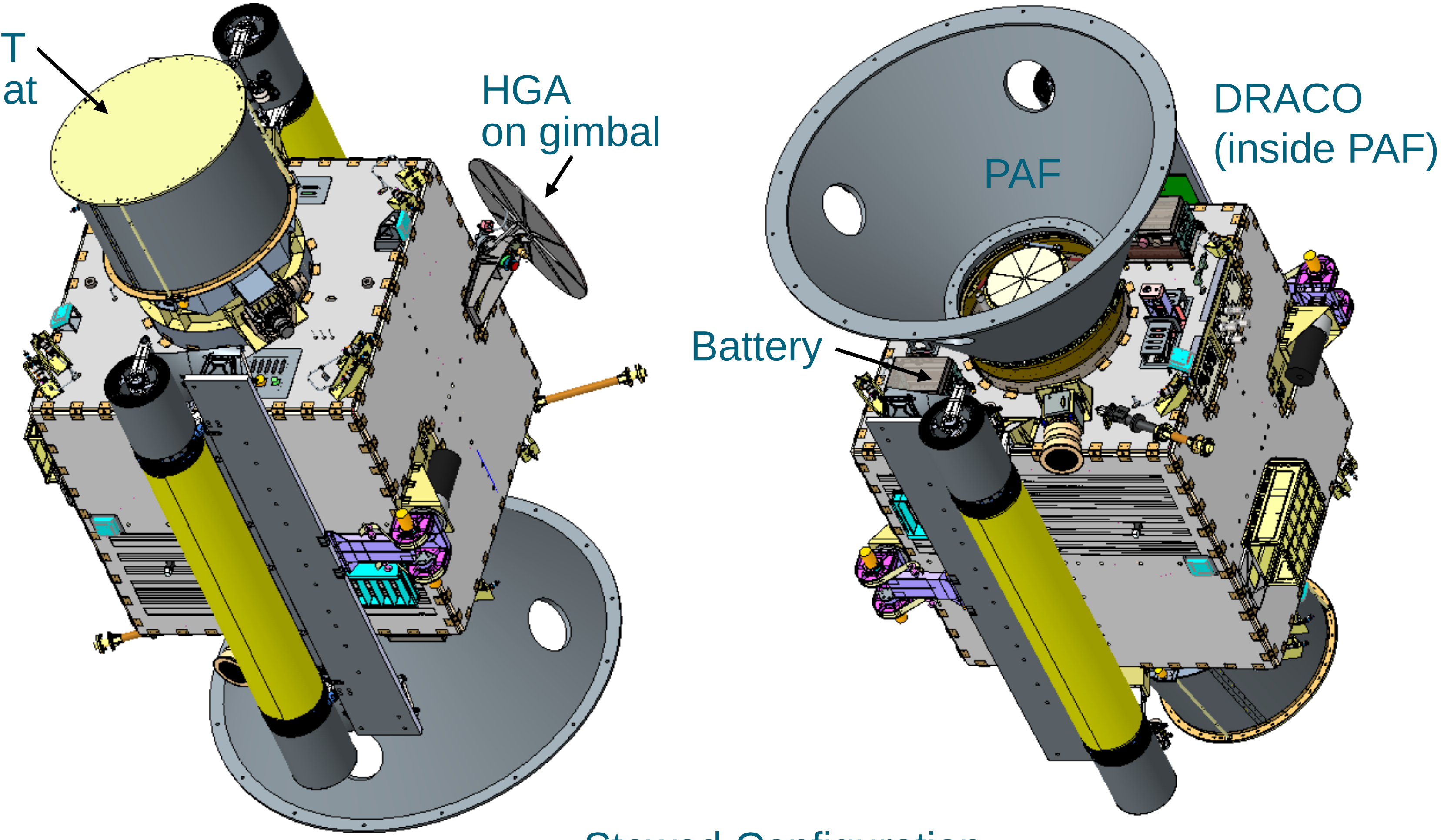
- **The secondary (“Didymoon”) is realistic scale**
  - Small enough to deflect kinetically and measure result
  - Smaller NEOs represent a more frequent threat to Earth

DART



NEXT on gimbal, with
Top Hat off

Deployed Configuration



NEXT
Top Hat

HGA
on gimbal

PAF

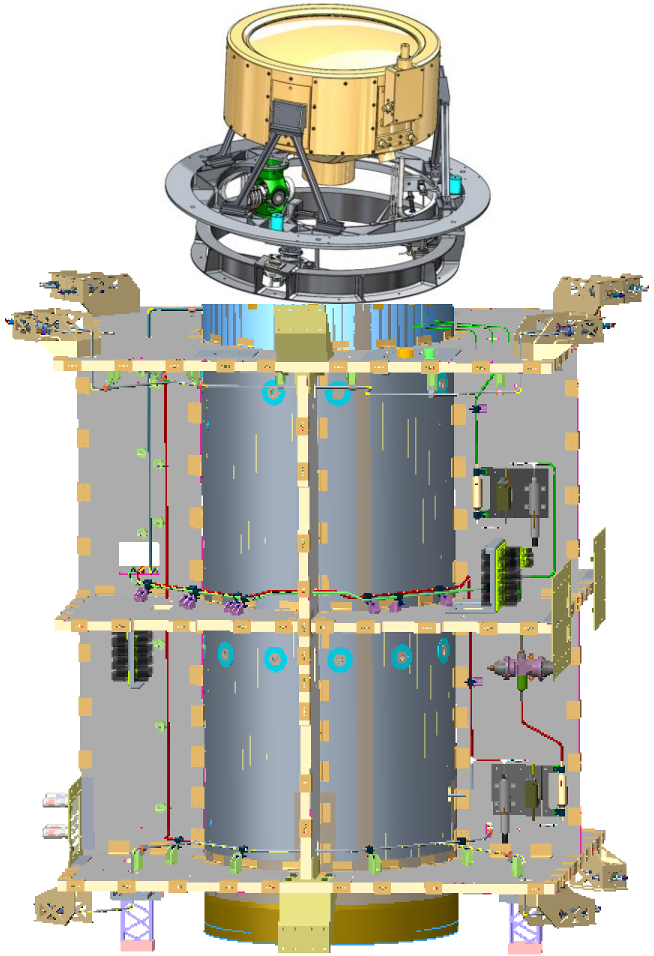
DRACO
(inside PAF)

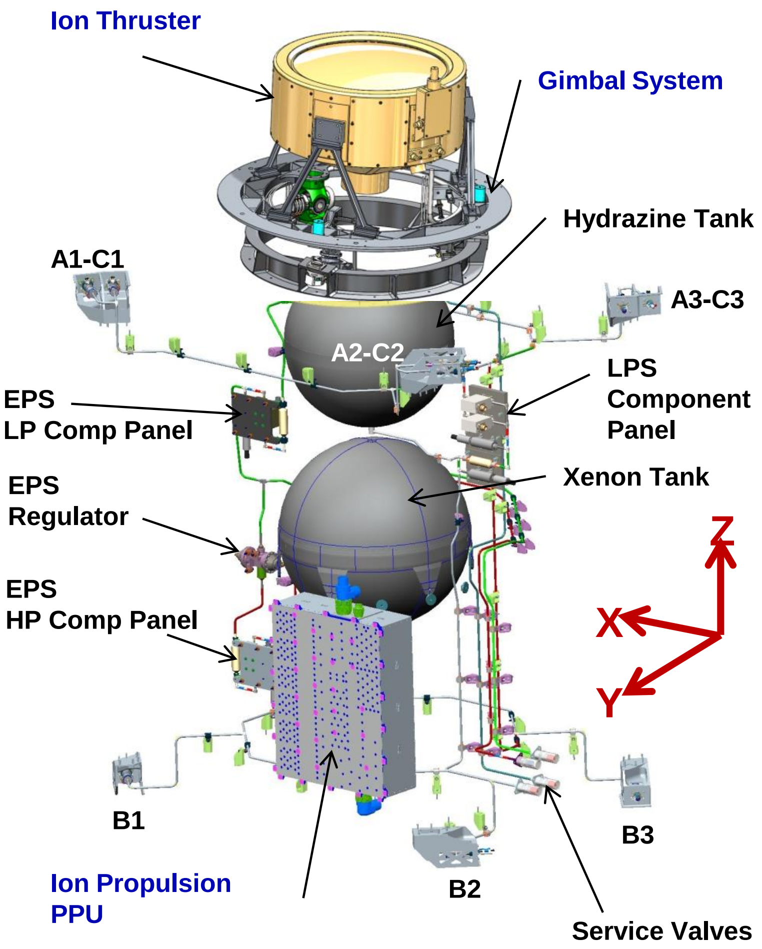
Battery

Stowed Configuration

DART Propulsion System

DART





DART

Technology Barriers – Materials

EP Thruster Materials needs:

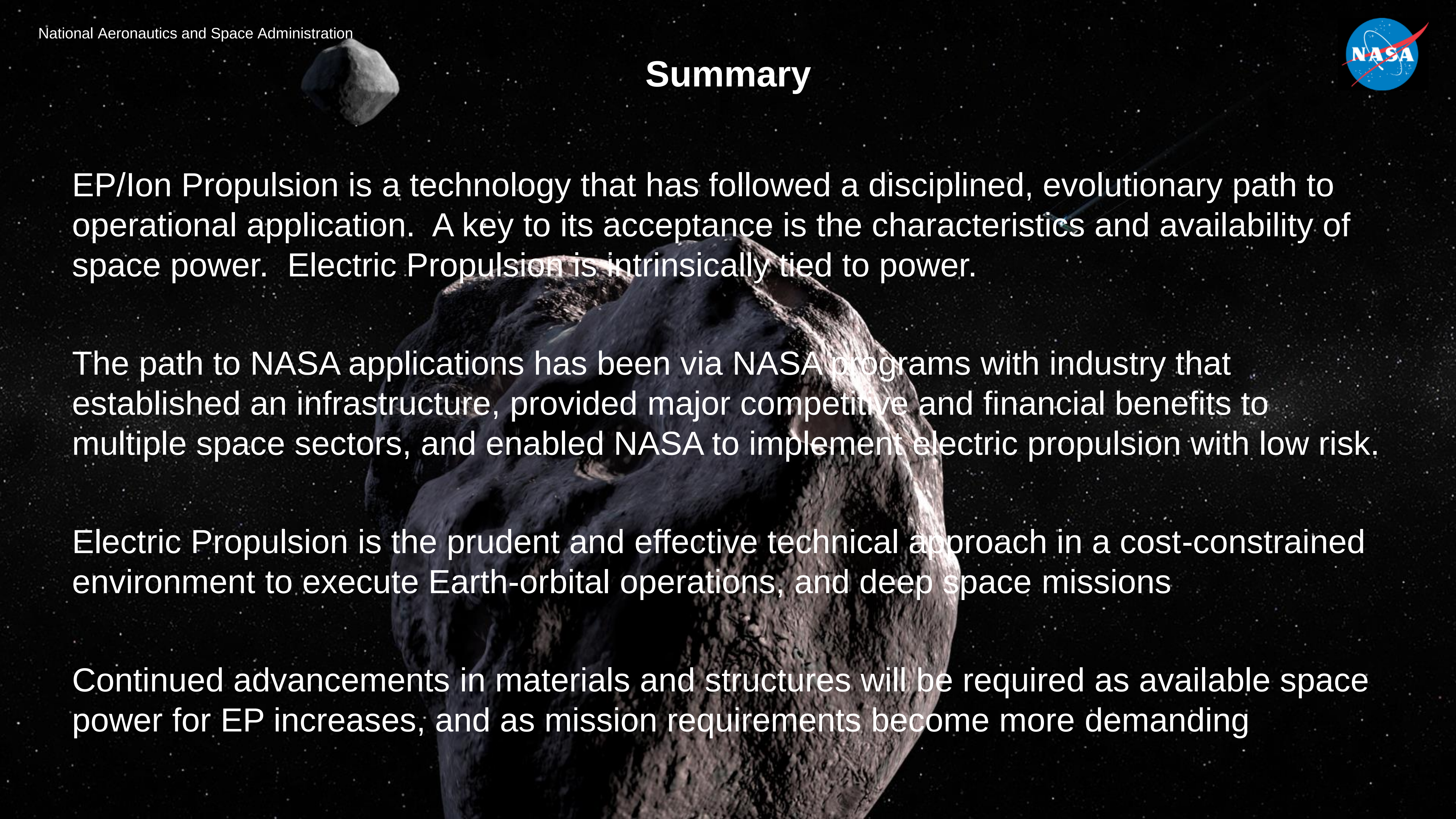
- High-temperature sputter-resistant electrodes and ceramics
- Long-life low-work function robust cathodes
- High-temperature rare-earth and superconducting magnets, electromagnets
- Radiation-tolerant [carbon-, Teflon, polymer-based] thruster materials

Power Processing Materials and Structures needs:

- Lightweight deployable radiators
- Lightweight radiation shielding
- Lightweight high-temperature power electronics components (SiC, other)
- Carbon-based heat sink technology integrated with power electronic components

Propellant Management Materials and Structures needs – dependent on propellant; for Xe:

- Lightweight composite tankage
- Long-term storage and management of Xe in low gravity: trade between thermodynamic options of high-pressure, medium-density supercritical gas and low-pressure, high-density subcritical liquid storage
- Thermal control for subcritical storage



Summary

EP/Ion Propulsion is a technology that has followed a disciplined, evolutionary path to operational application. A key to its acceptance is the characteristics and availability of space power. Electric Propulsion is intrinsically tied to power.

The path to NASA applications has been via NASA programs with industry that established an infrastructure, provided major competitive and financial benefits to multiple space sectors, and enabled NASA to implement electric propulsion with low risk.

Electric Propulsion is the prudent and effective technical approach in a cost-constrained environment to execute Earth-orbital operations, and deep space missions

Continued advancements in materials and structures will be required as available space power for EP increases, and as mission requirements become more demanding

Questions?