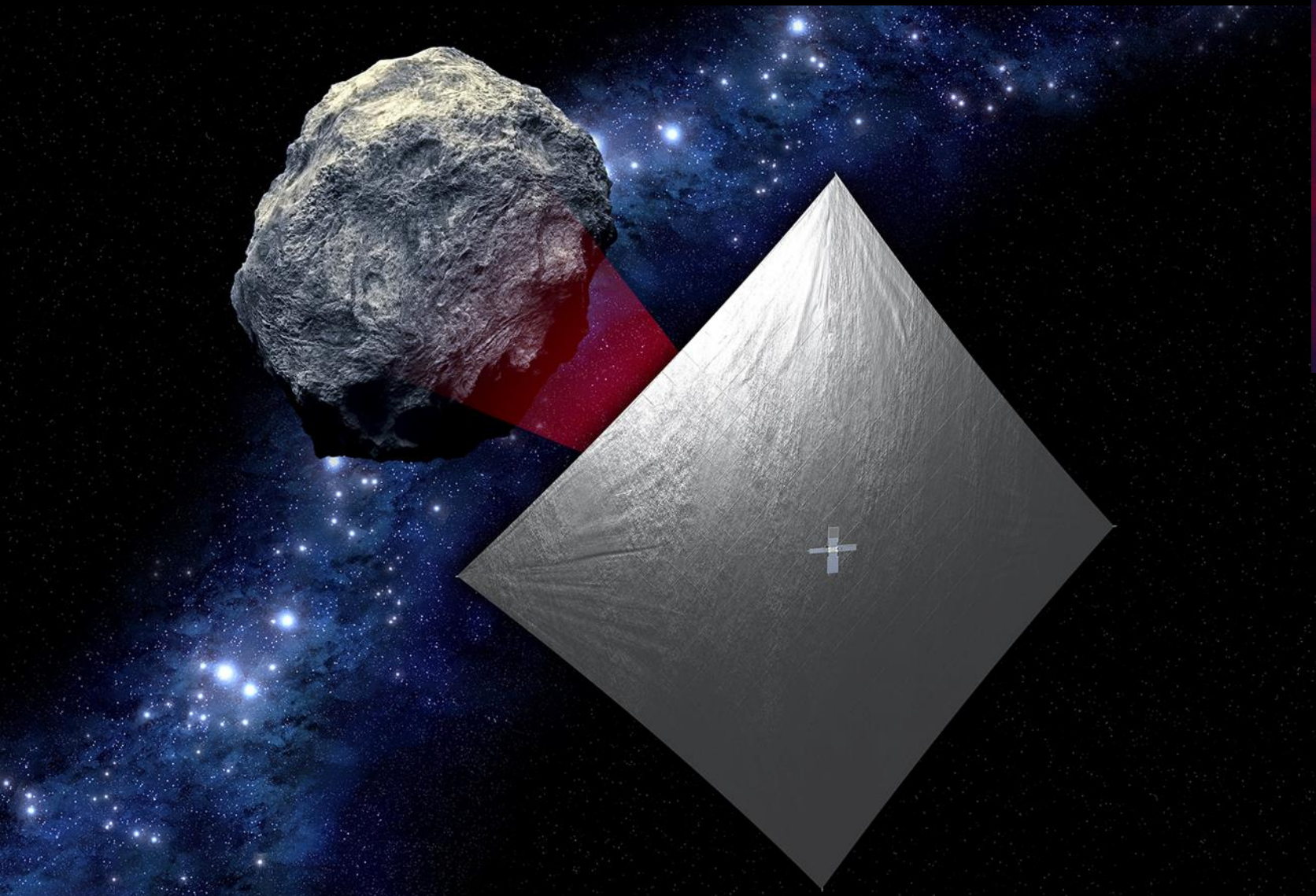
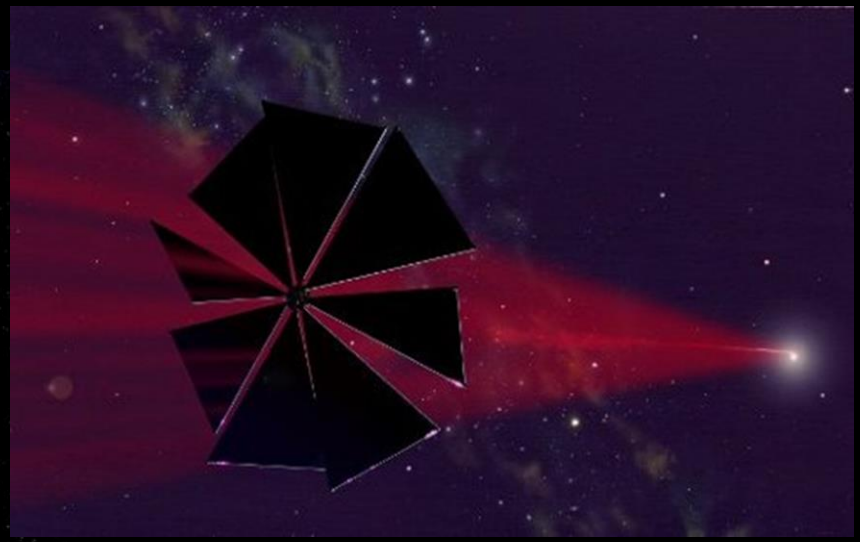
Solar Sails for Spacecraft Propulsion



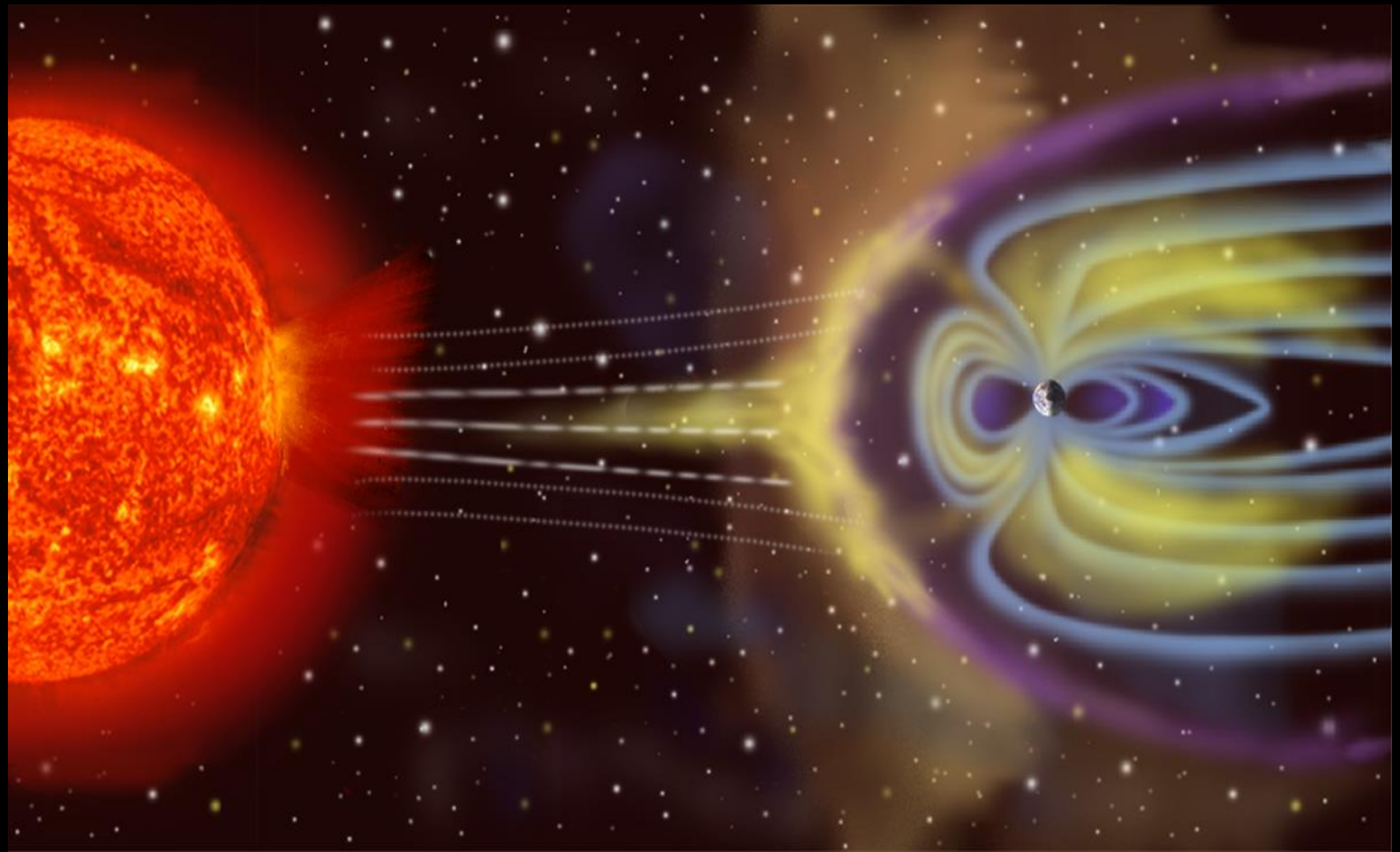


Les Johnson

NASA George C. Marshall Space Flight Center

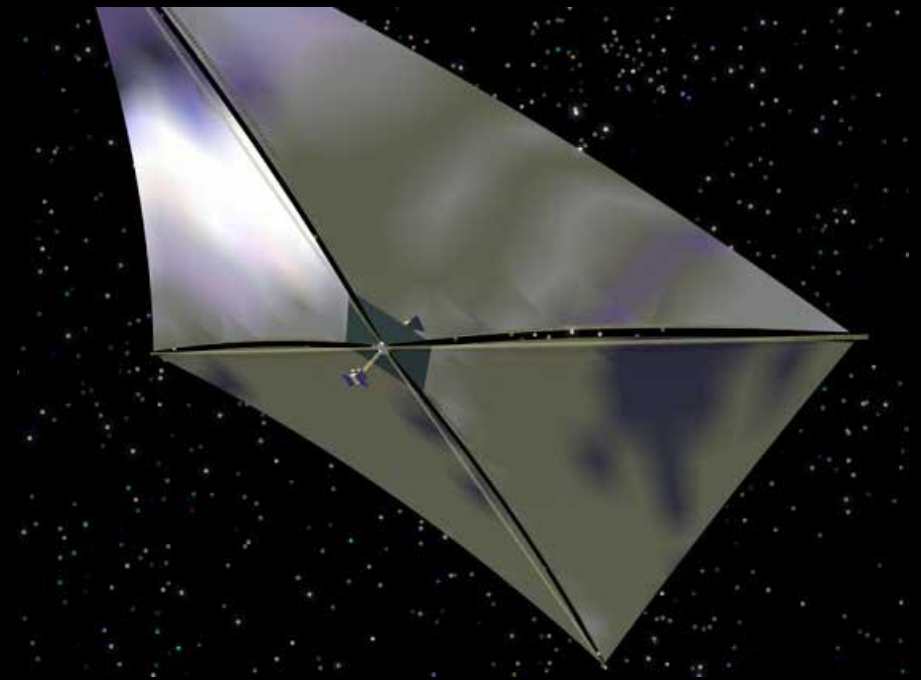
We tend to think of space as being big and empty…

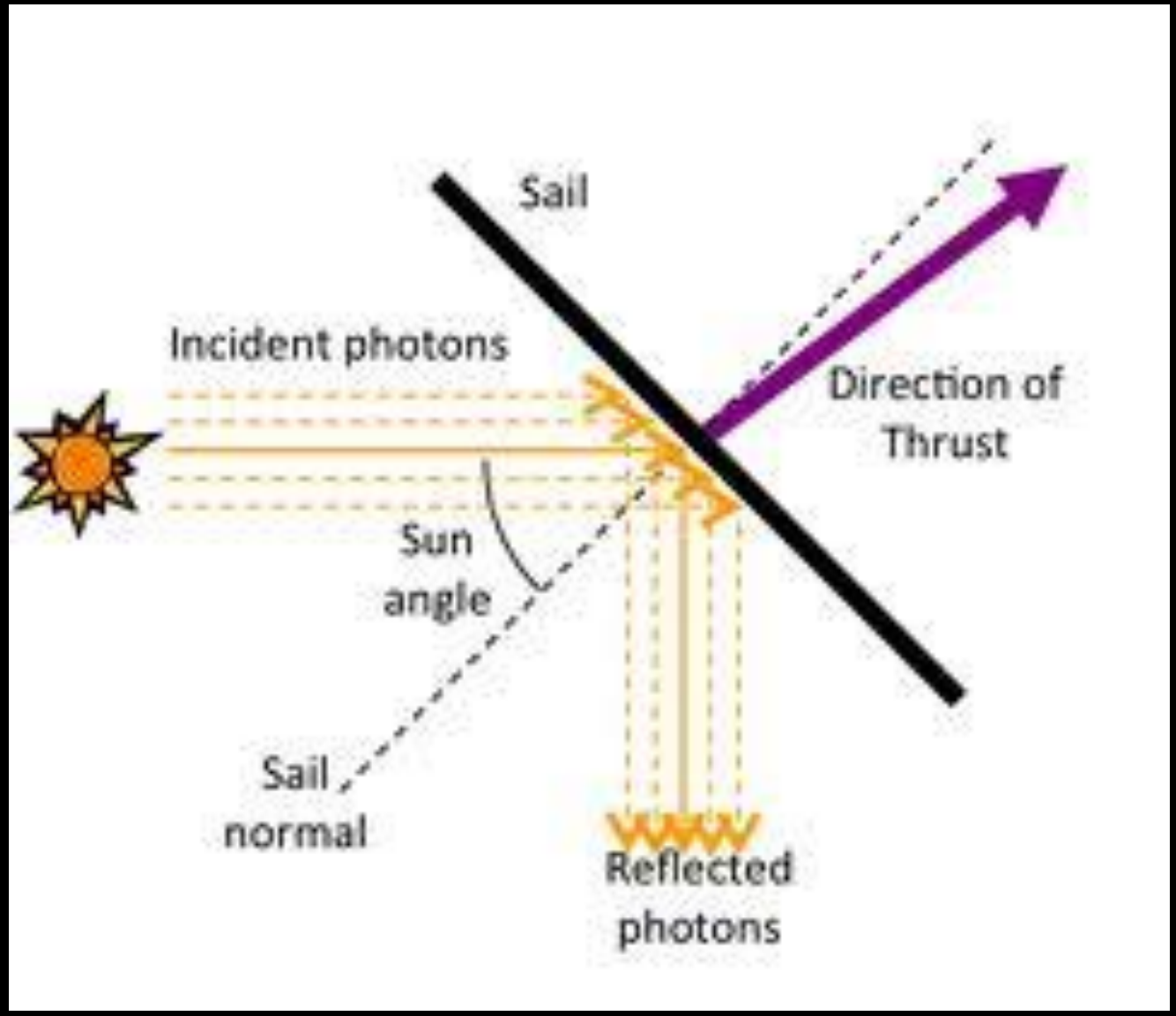
Can we use the environments of space to our advantage?



How does a solar sail work?

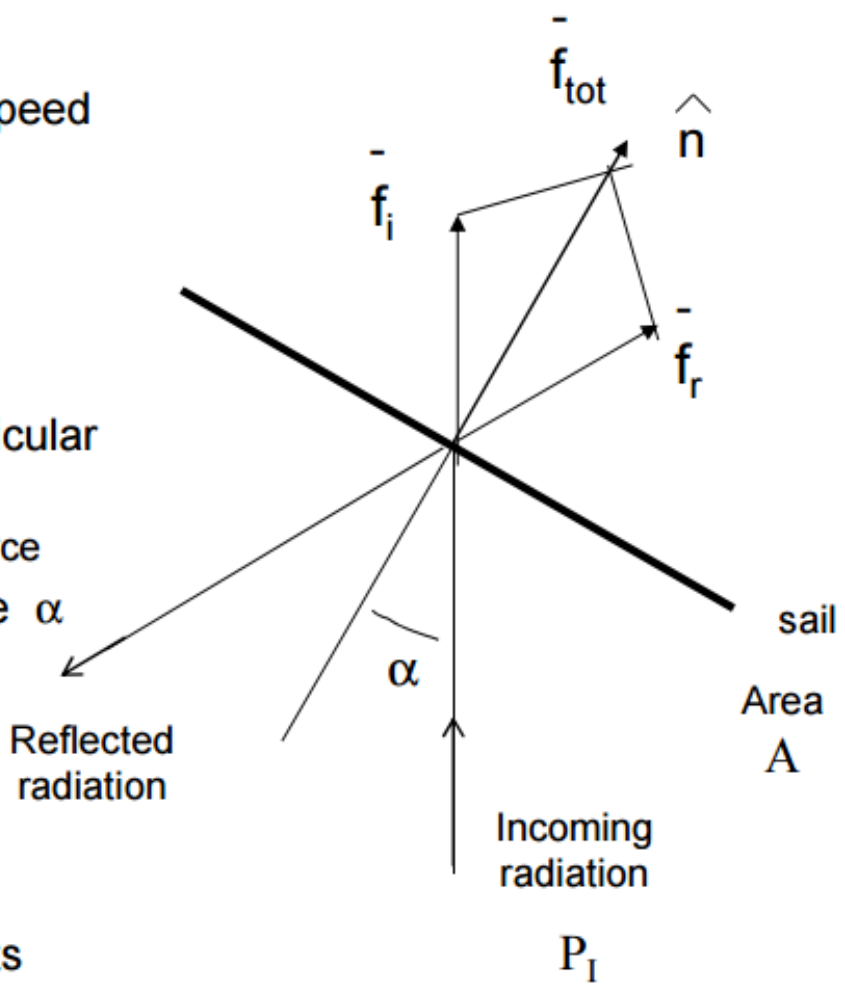
Solar sails use photon “pressure” or force on thin, lightweight reflective sheet to produce thrust.



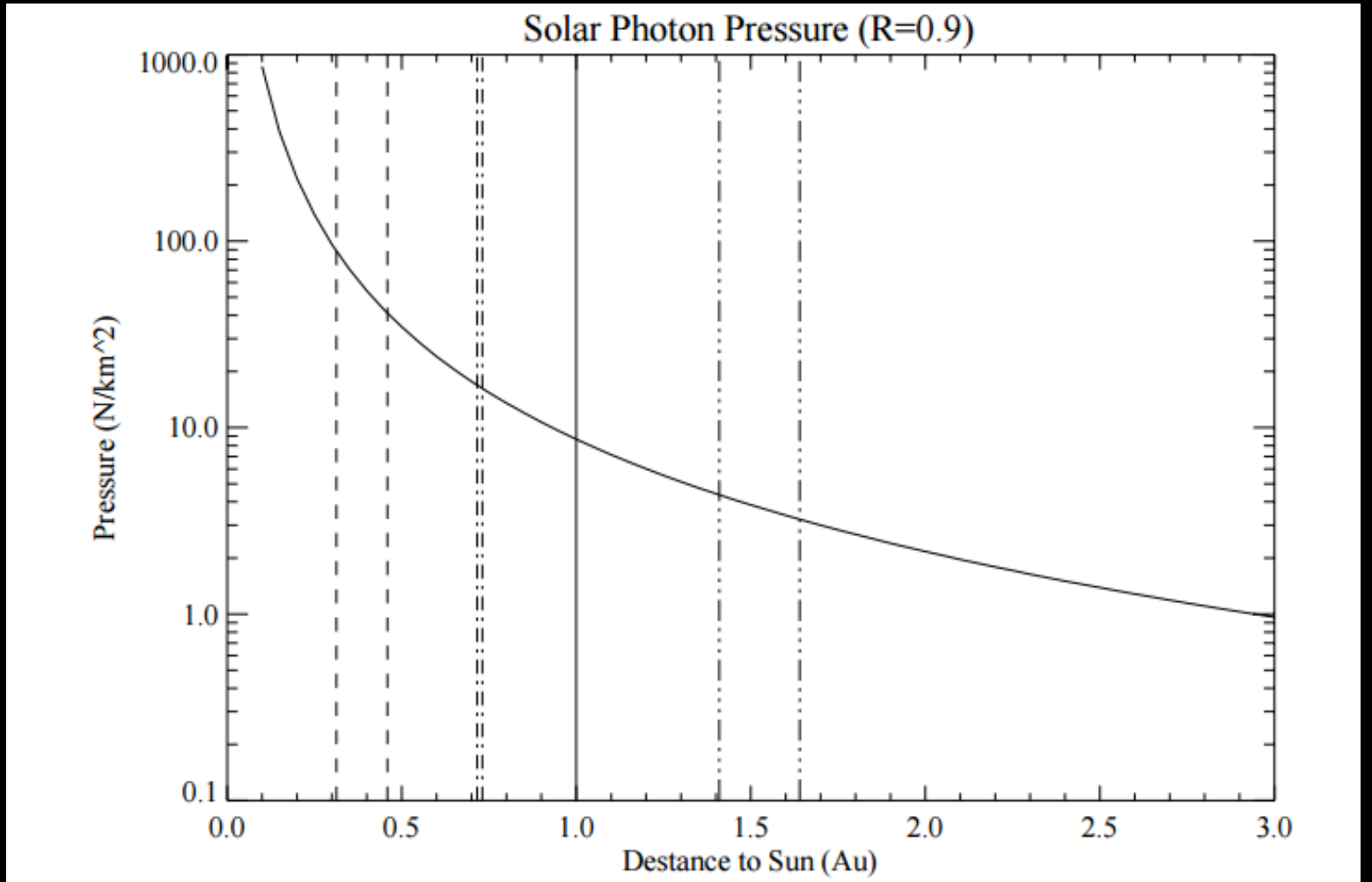


Solar Sail Propulsion Fundamental Physics

- **Photons carry Momentum**
  - $\rho = h\nu/c$
    - h = Planck's, ν = frequency, c = speed of light
- **Force generated on Reflective Surface**
  - Resultant force approximately perpendicular to surface
    - The bigger the surface, the more the force
  - Can "steer" sail by changing pitch angle α
- **Small, but potentially Constant Acceleration**
  - Potentially unlimited "delta V"
  - Allows some otherwise impossible orbits



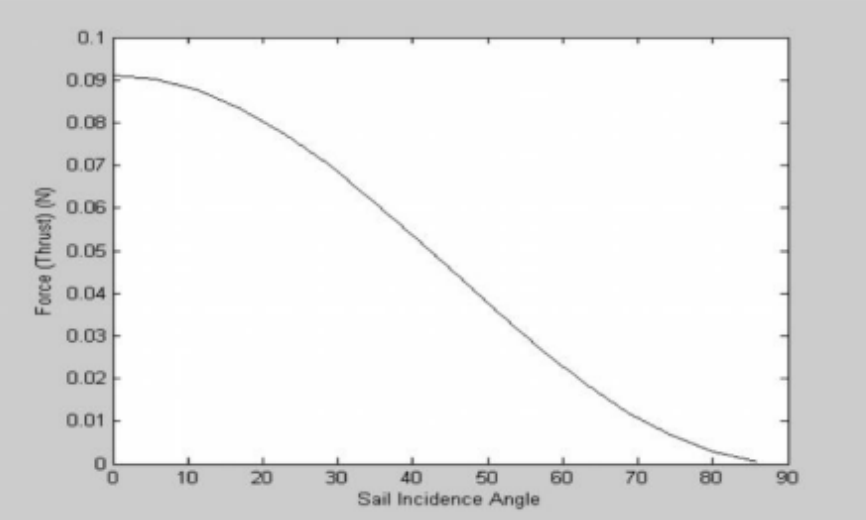
Solar Sails Provide Low Thrust Propulsion



Energy $W = \frac{L_S}{4\Pi r^2}$ Pressure $P = 2\frac{W}{c}$ $W_E = 1368\ W/m^2$ $P_E = 9.15 \times 10^{-6}\ N/m^2$

Net Force Drops with Increasing Pitch Angle

- **For a 100 kg sailcraft, 100 m x 100 m square sail:**
- **Force (maximum, perp. to sun, perfect/flat reflector)**
  - 0.09 N
- **Acceleration (maximum)**
  - 0.92 x 10^{-3} m/s^2 (0.9 millimeters/sec^2)
- **Force decreases with increasing pitch angle (or)**

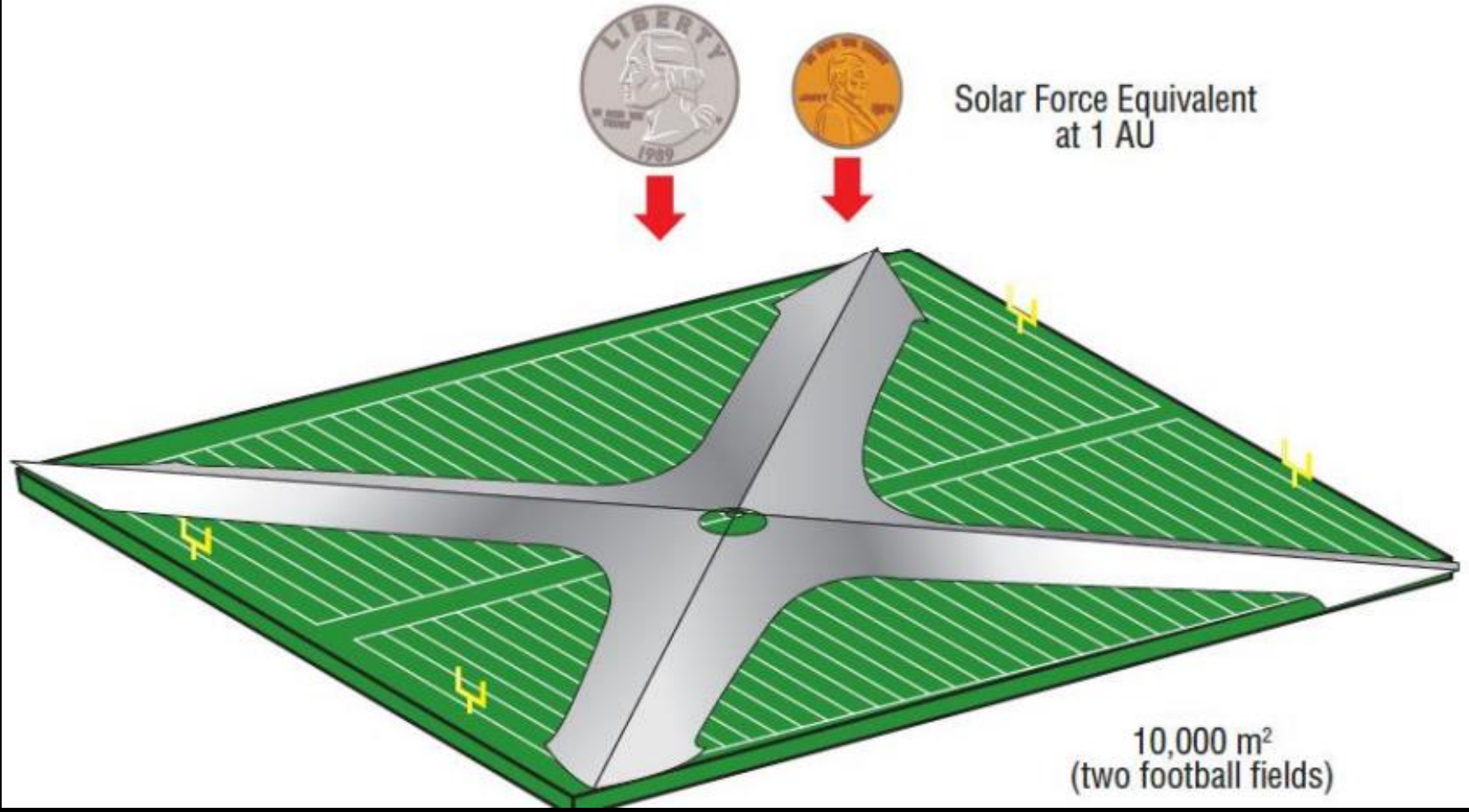


$$\bar{f}_{tot} = 2P_I A(\cos\theta_i)^2 \hat{n}$$

Solar Sail Total Force (Thrust) Vs. Sun-Incidence Angle
(For a 100 x 100 meter perfect sail @ 1 A.U.)

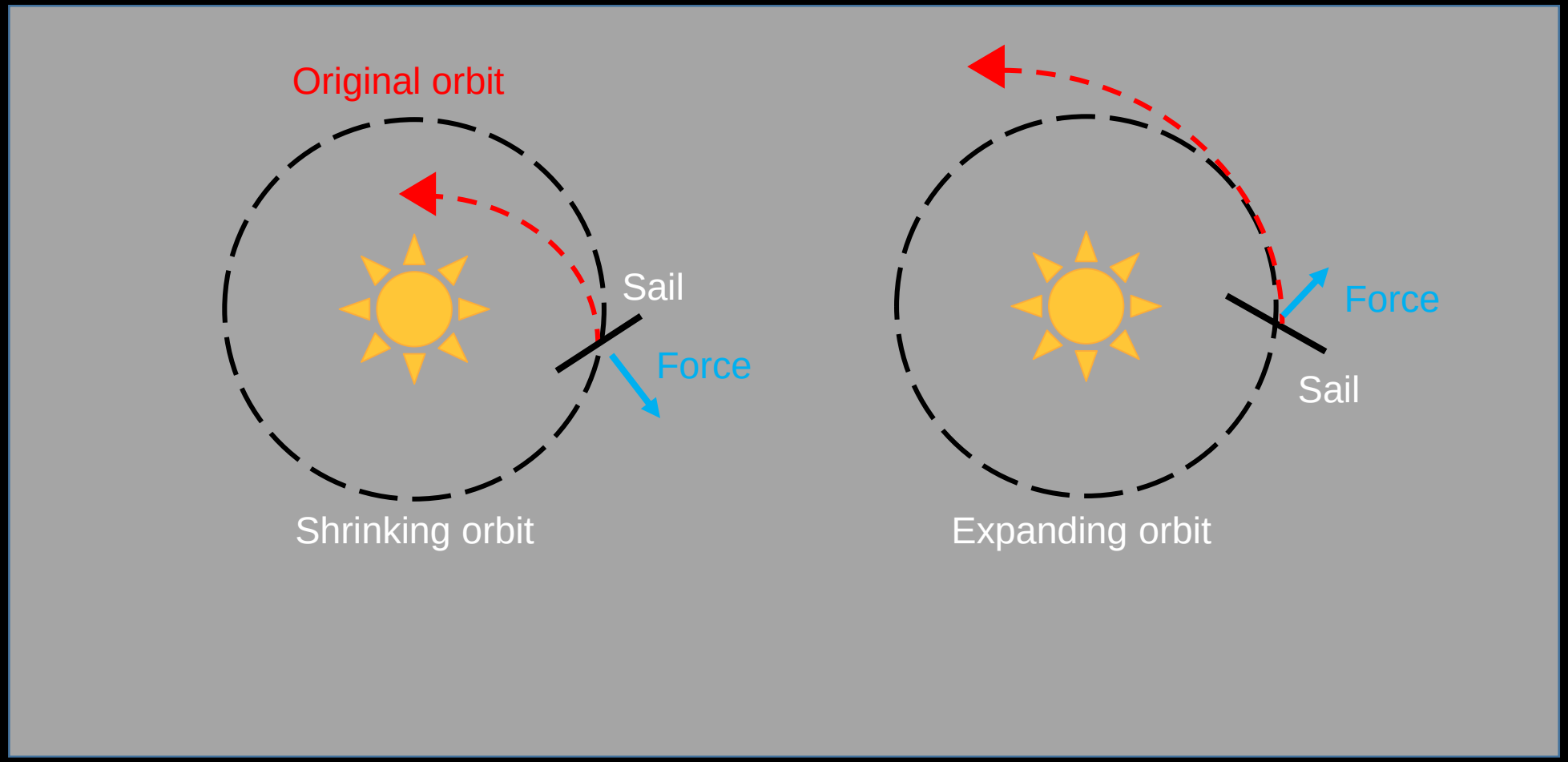
Solar Sails Experience VERY Small Forces

- **Force on a 100 m x 100 m square sail:**



Solar Sail Trajectory Control

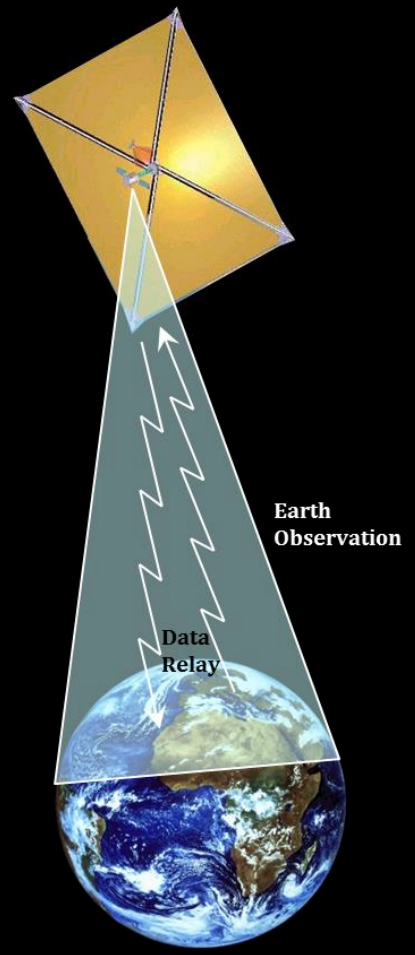
- Solar Radiation Pressure allows inward or outward Spiral



Potential Solar Sail Applications (A Partial List!)

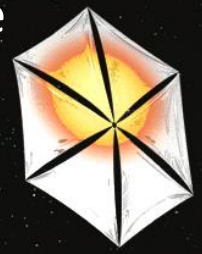
NEA Reconnaissance & Small Body Science

Earth Pole Sitting

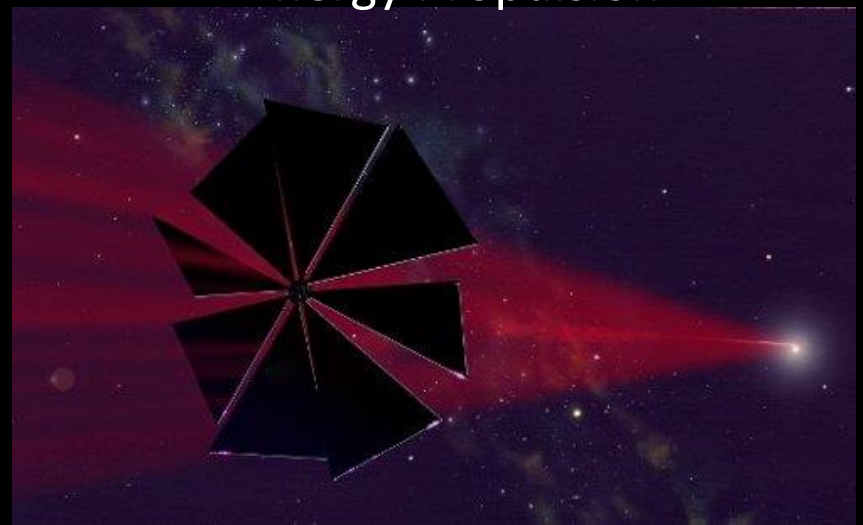


Rapid Outer Solar System Exploration and Escape

Heliophysics & Out of the Ecliptic Science



Toward Higher Performance Beamed Energy Propulsion

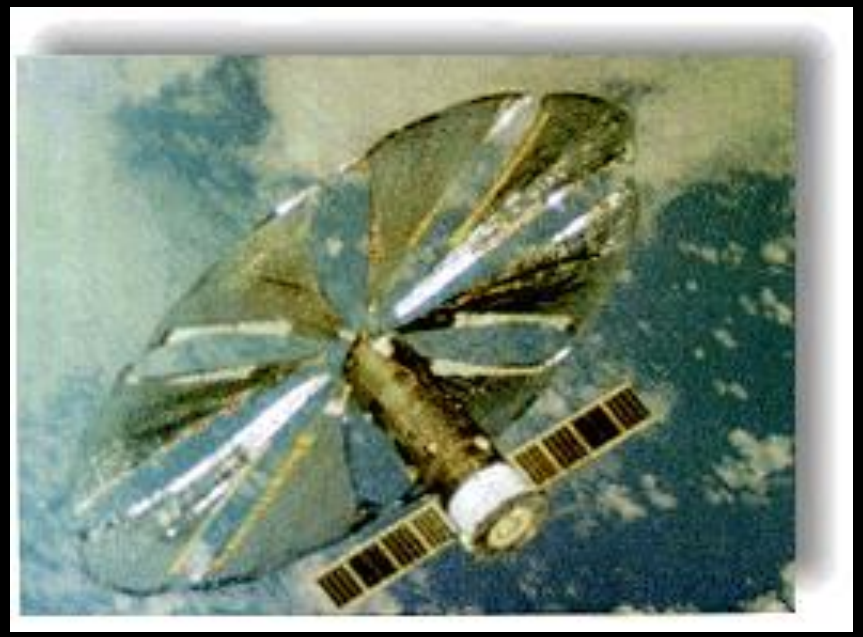


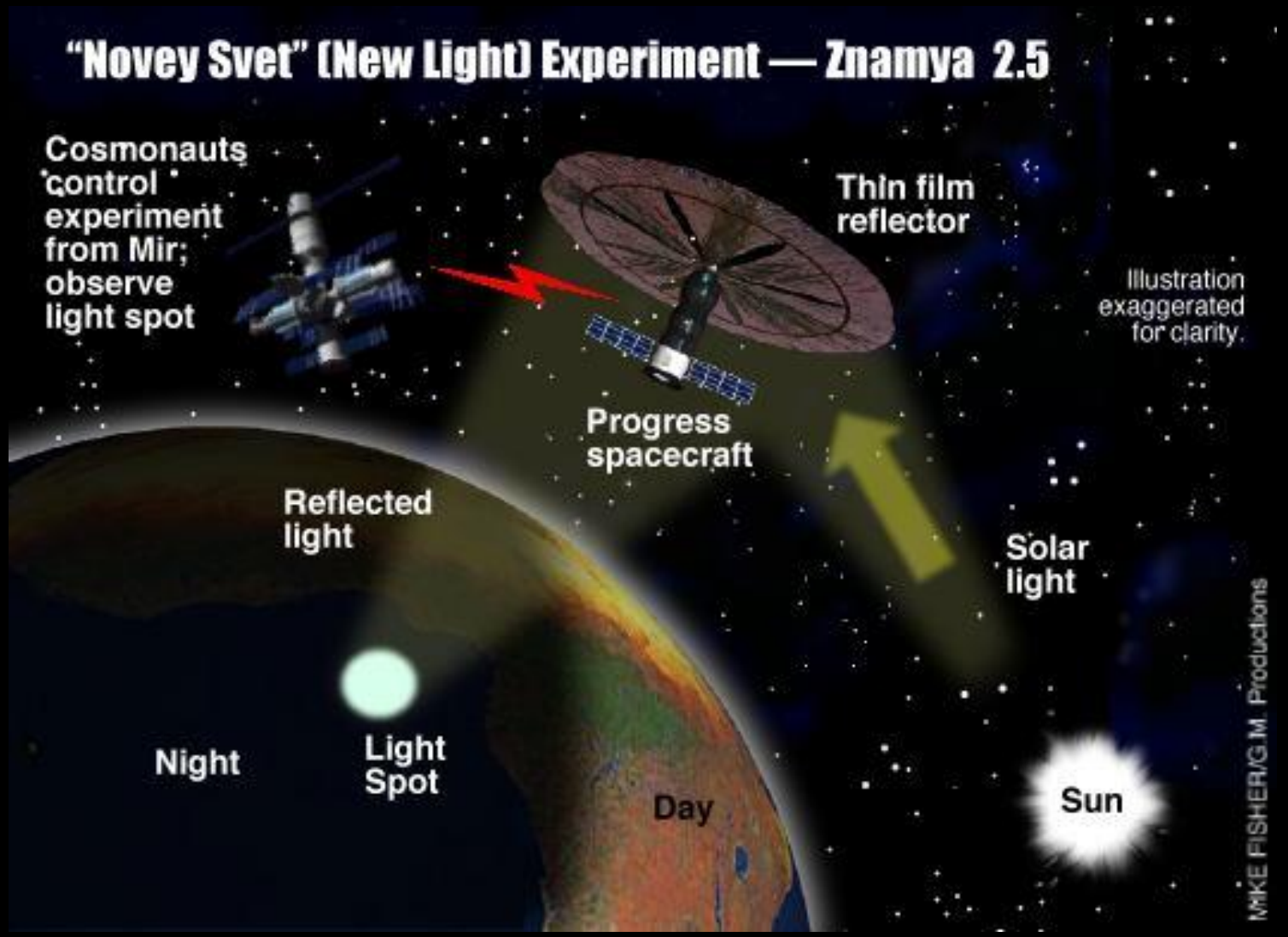
Echo II 1964
Solar thrust effect on spacecraft orbit

When folded, satellite was packed into the 41-inch diameter canister shown in the foreground.

- 135-foot rigidized inflatable balloon satellite
- laminated Mylar plastic and aluminum
- placed in near-polar Orbit
- passive communications experiment by NASA on January 25, 1964

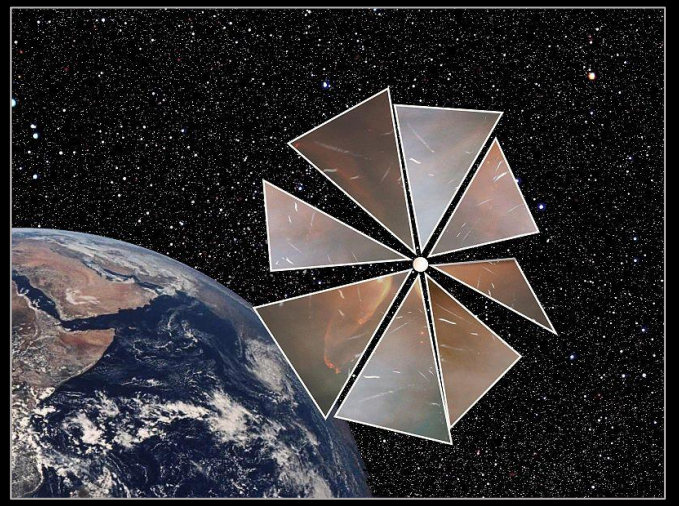
Znamya (Space Mirror)

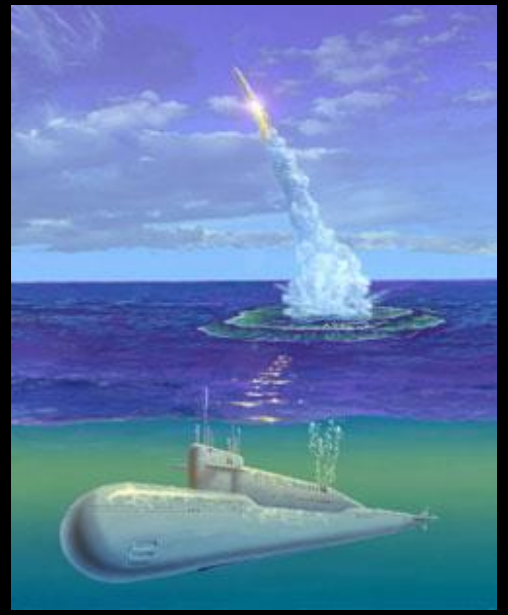




The Planetary Society's Cosmos-1 (2005)

- 100 kg spacecraft
- 8 triangular sail blades deployed from a central hub after launch by the inflating of structural tubes.
  - Sail blades were each 15 m long
  - Total surface area of 600 m^2
- Launched in 2005 from a Russian Volna Rocket from a Russian Delta III submarine in the Barents Sea:





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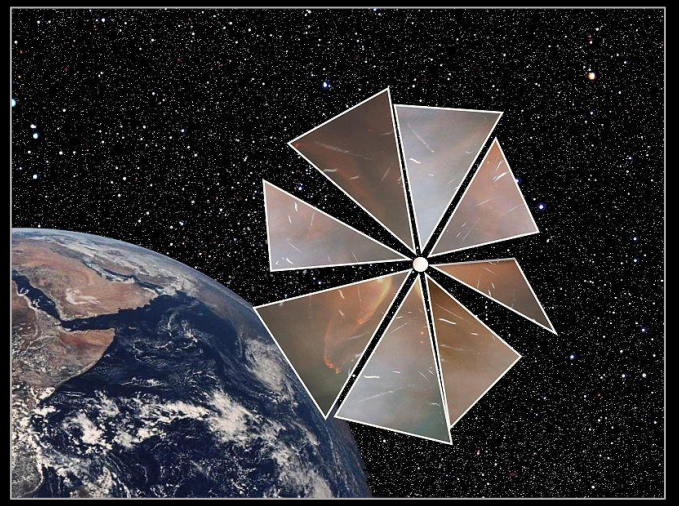
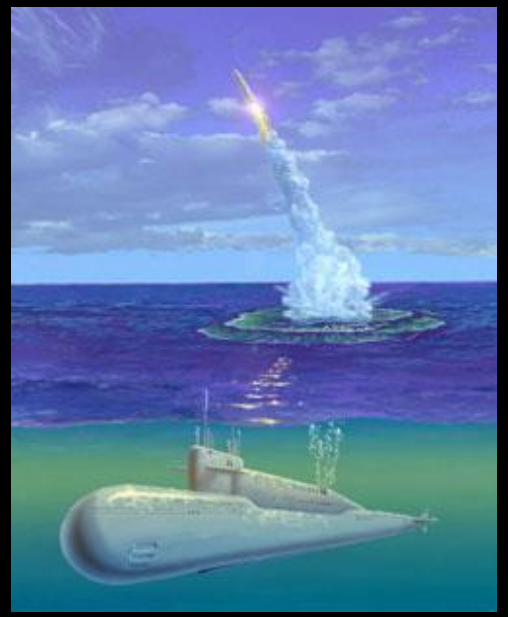
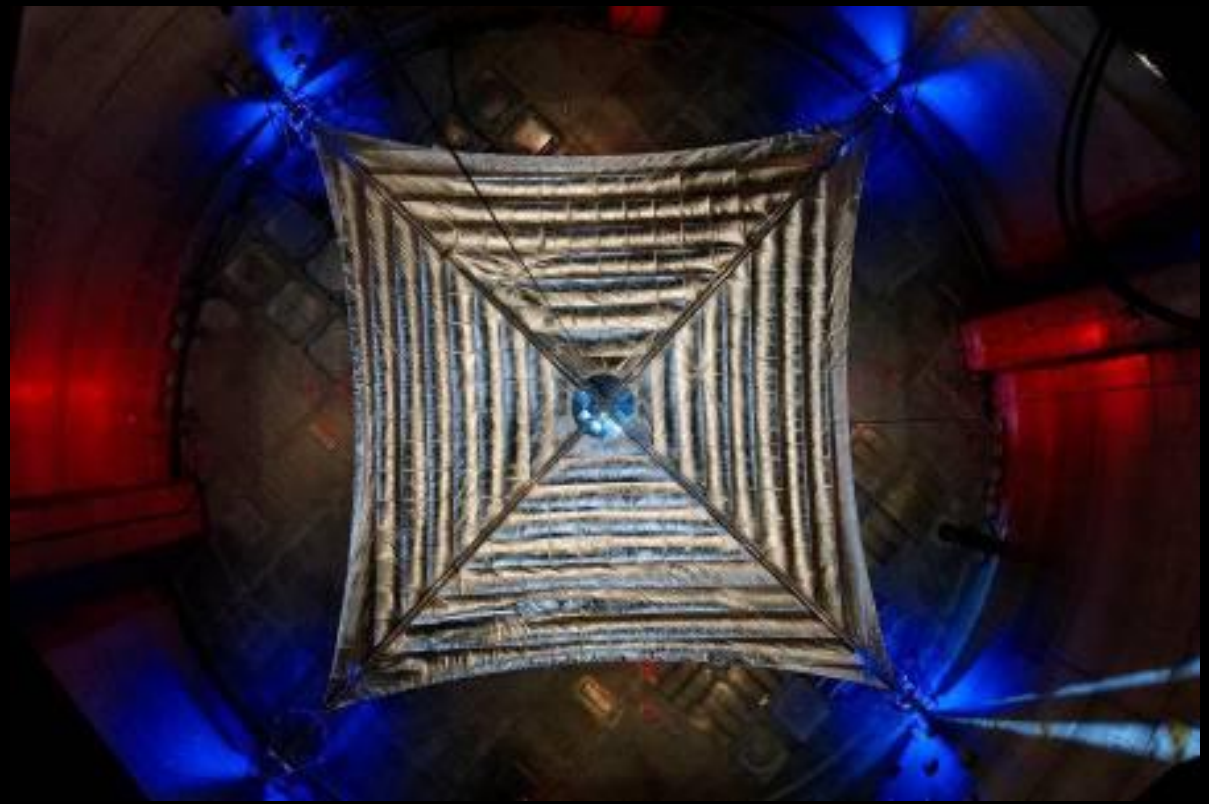
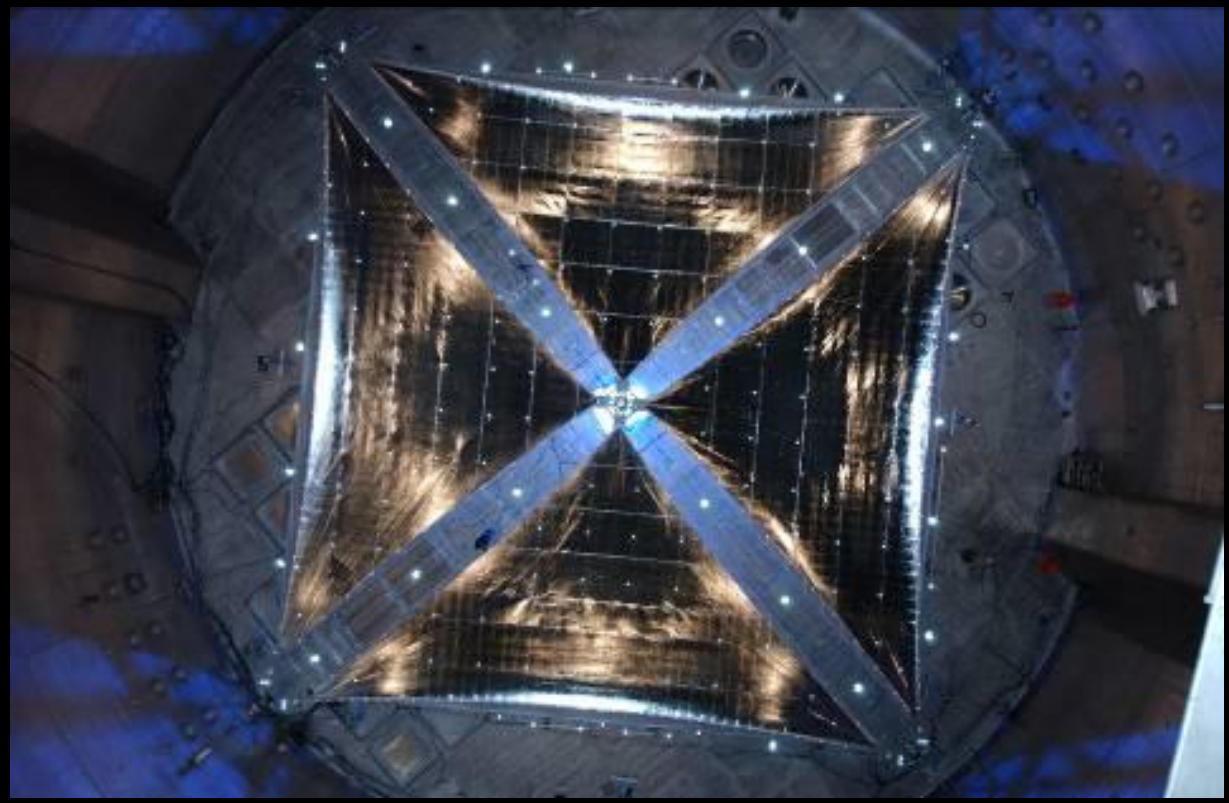




Rocket Failed

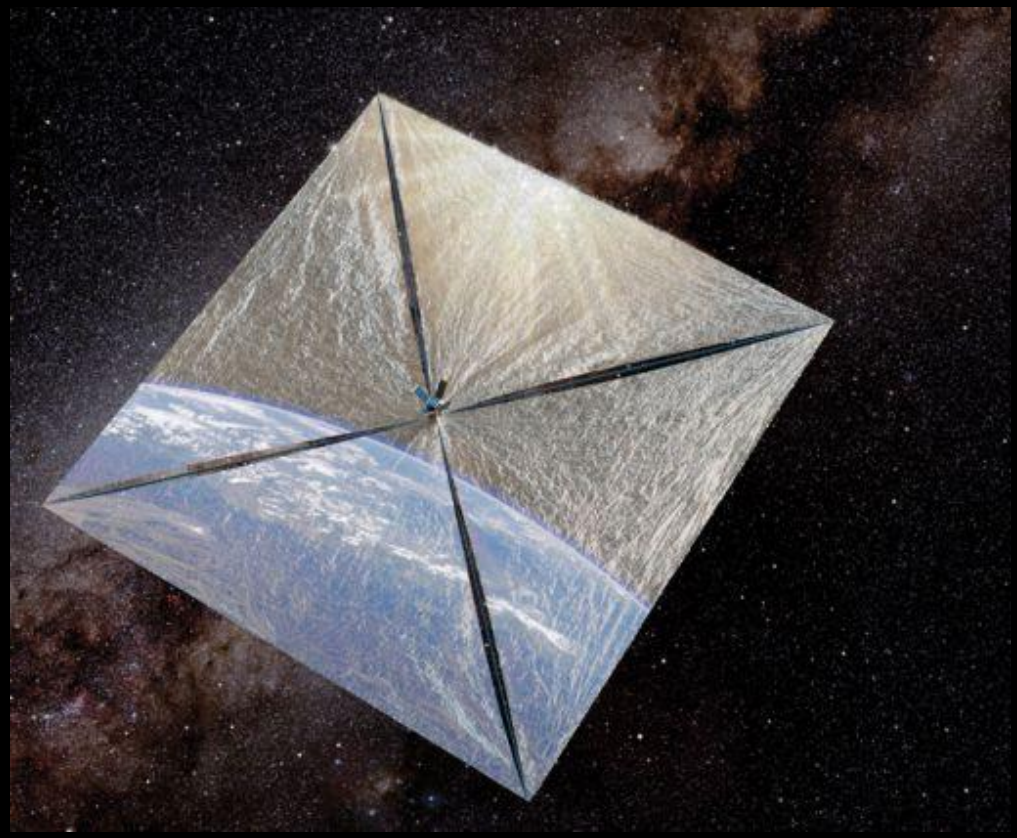
NASA Ground Tested Solar Sails in the Mid-2000's





Nasa space technology Demo (2009)

Planned to be a space flight demonstration of the solar sail developed and tested as part of the ground sail test program



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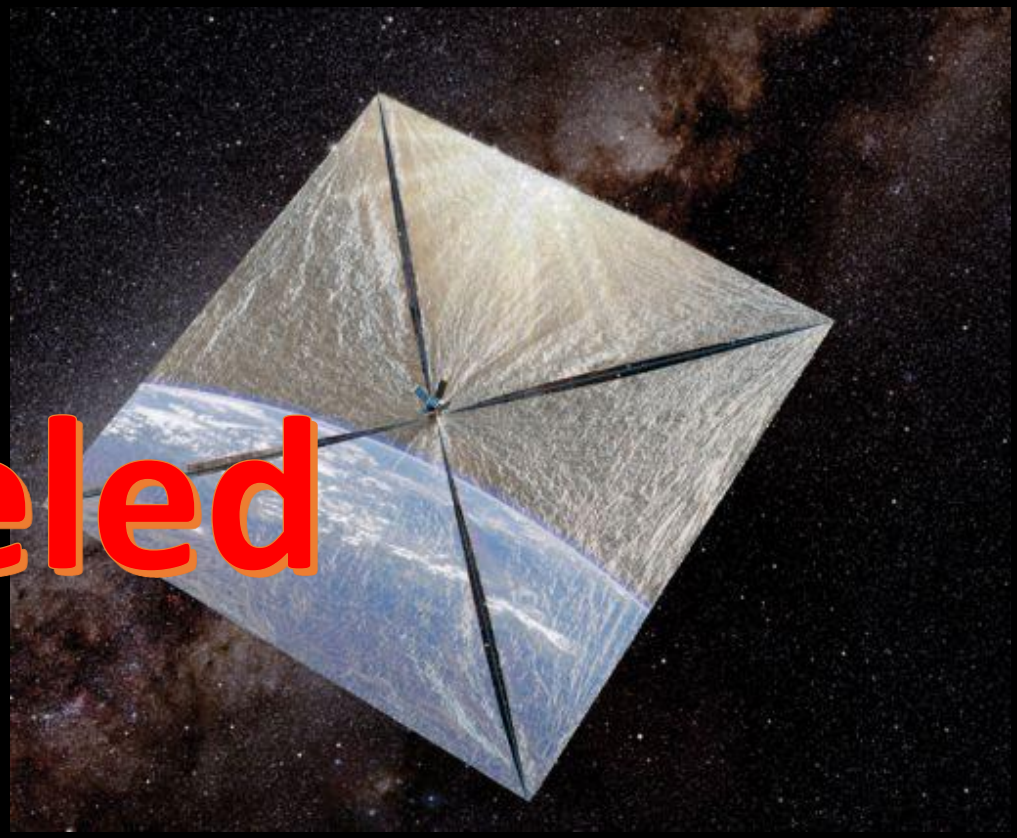
Planned to be a space flight demonstration of the solar sail developed and tested as part of the ground sail test program

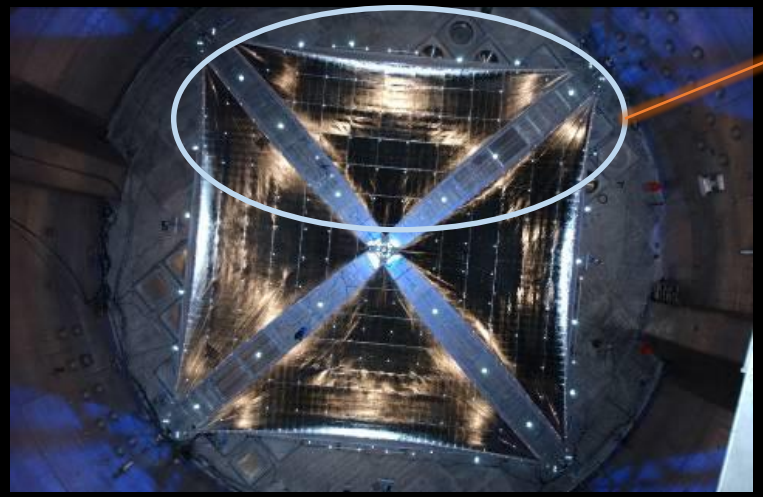
Canceled

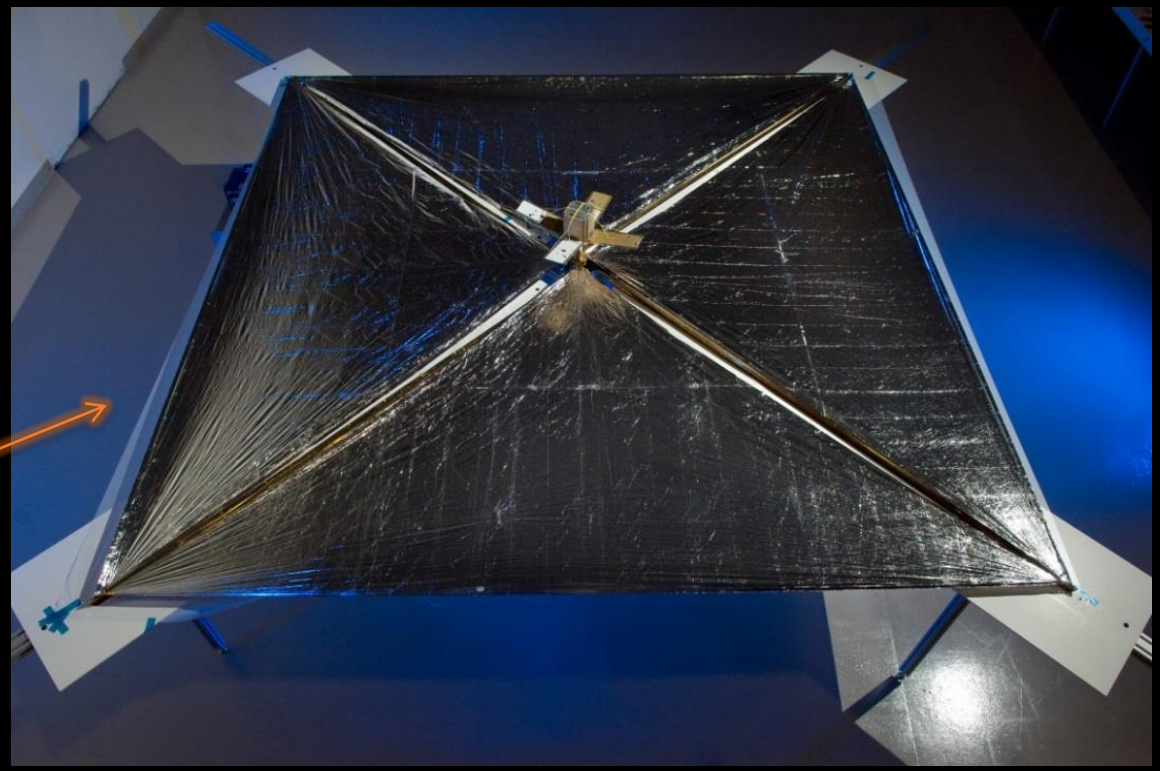


NanoSail-D Demonstration Solar Sail

Mission Description:

- 10 m^2 sail
- Made from tested ground demonstrator hardware

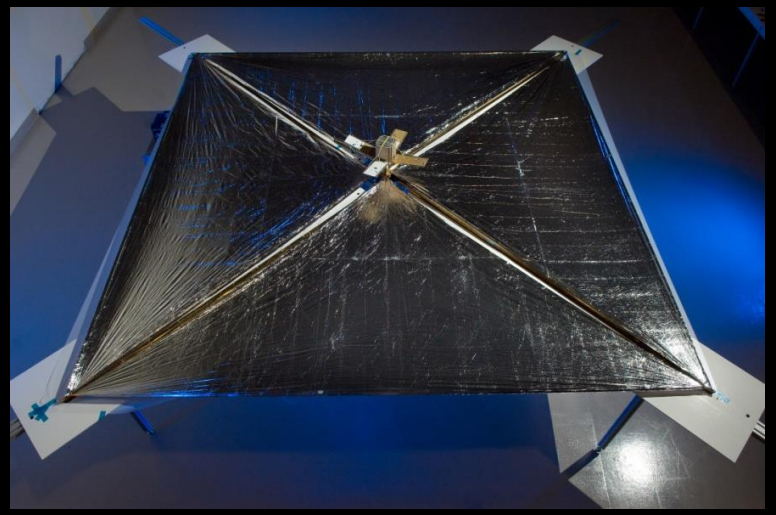




NanoSail-D1 Flight (2008)

Launch:

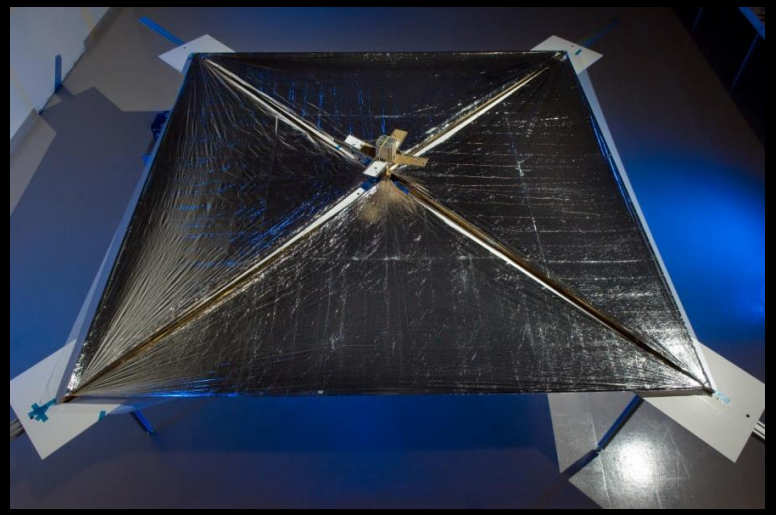
- Falcon-1, flight 3
- Kwajalein, Missile Range
- Primary payload: Air Force PnPSat



NanoSail-D1 Flight (2008)

Launch:

- Falcon-1, flight 3
- Kwajalein, Missile Range
- Primary payload: AFRL PnPSat
- Secondary P-POD payloads (2)



Rocket Failed

NanoSail-D2 Mission Configuration (2010)

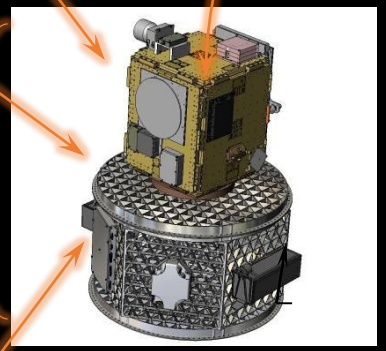
3U CubeSat: 10 cm X 10 cm X 34 cm

- Deployed CP-1 sail: 10 m^2 Sail Area (3.16 m side length)
- 2.2 m Elgiloy Trac Booms
- UHF and S-Band communications

Nanosail-D2 in Orbit August 19 2011 01h 19m 28s UT
Clay Center Observatory at Dexter and Southfield Schools
42.307404N, -71.13722W (WGS84)
www.claycenter.org Focal length:12,200mm,
Aperture = 640mm Ritchey-Chretien
Contact: Ron Dantowitz (rondantowitz@gmail.com)

HSV-1

Adapter



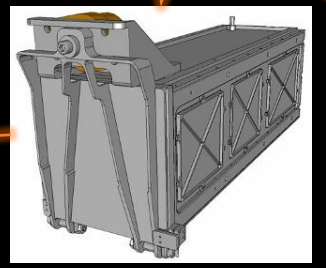
PreSat (ARC)

NanoSail-D (MSFC)

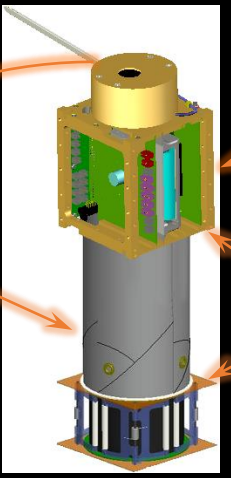
Ride Share Adapter
(Space Access Technology)

AFRL Satellite (Trailblazer)

Boom & Sail Spool (ManTech SRS)



PPOD Deployer (Cal-Poly)

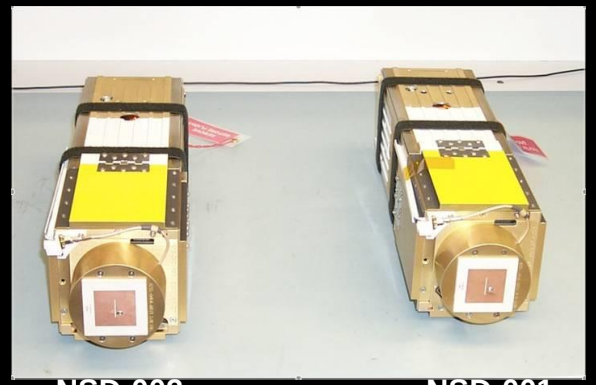


Spacecraft Bus (Ames Research Center)

Bus interfaces Actuation Electronics (MSFC/UAH)

NanoSail-D
(Aluminum Closeout Panels Not Shown)

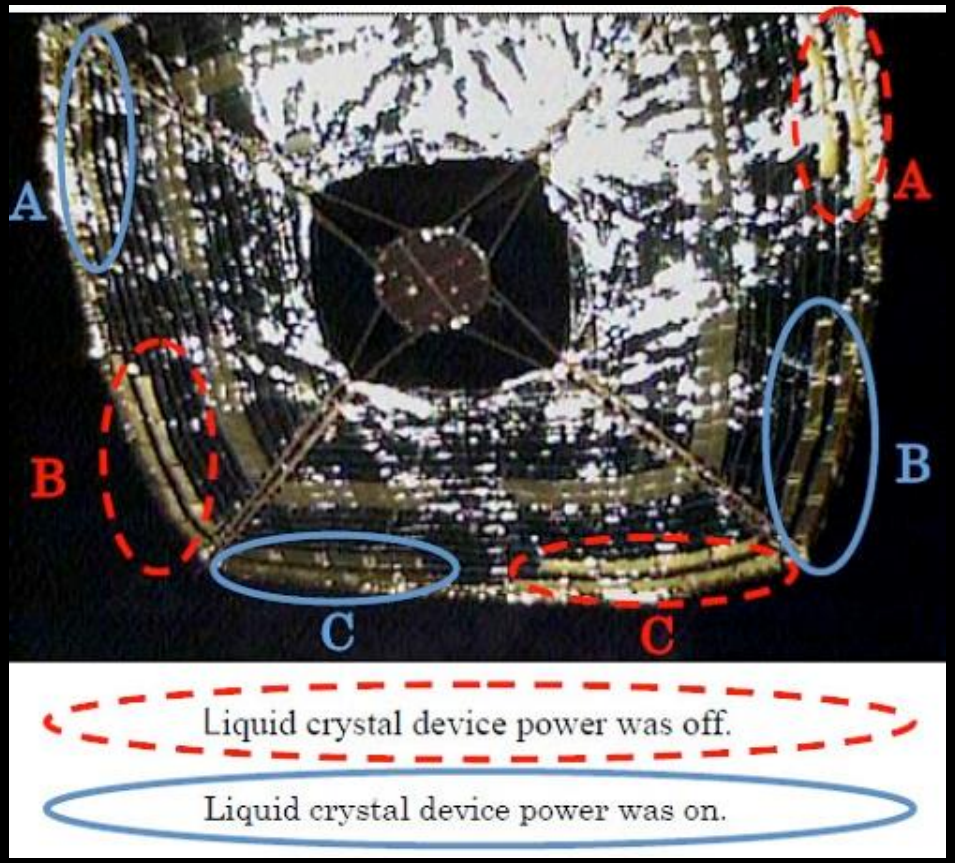
Stowed Configuration



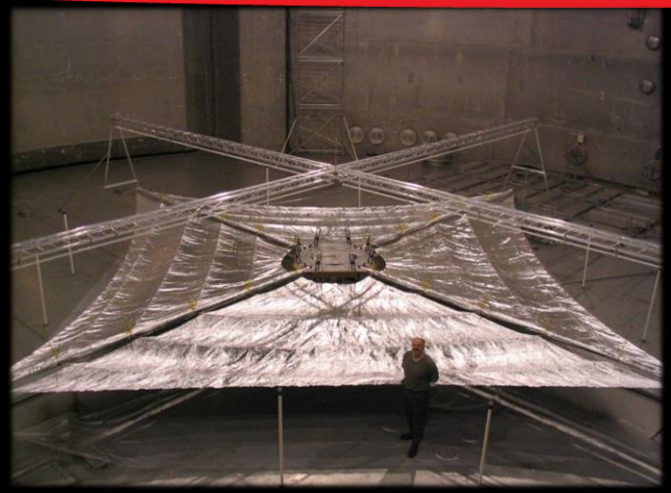
NSD-002

NSD-001

Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS)



Sunjammer Solar Sail Demonstration Mission



83 m^2 ISP L'Garde Solar Sail
2004

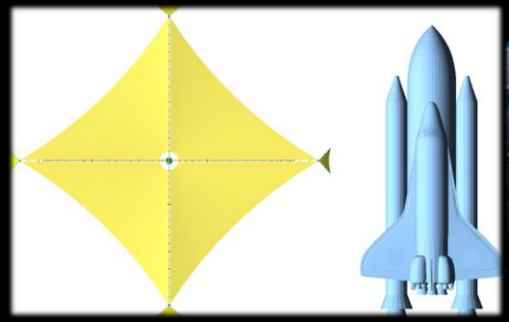
318 m^2 ISP L'Garde Solar Sail
2005

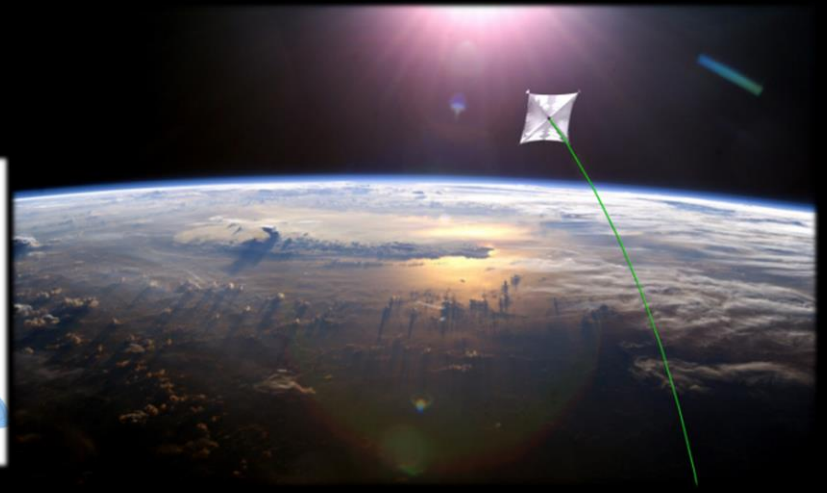
Design Heritage:

- Cold Rigidization Boom Technology
- Distributed Load Design
- Aluminized Sun Side
- High Emissivity Eclipse Surface
- Beam Tip Vane Control
- Spreader System Design

Design Features:

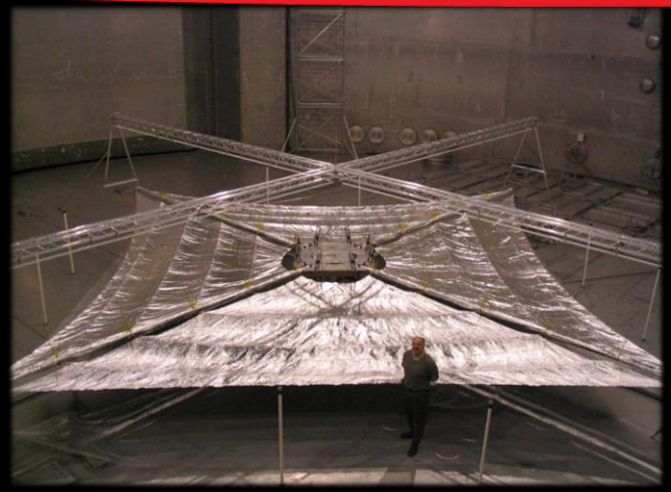
- High density packagability
- Controlled linear deployment
- Structural scalability
- Propellantless operation
- Meets current needs





1200 m^2 L'Garde Sunjammer Launch
2015

Sunjammer Solar Sail Demonstration Mission



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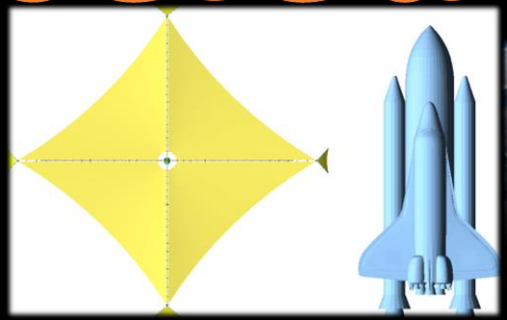
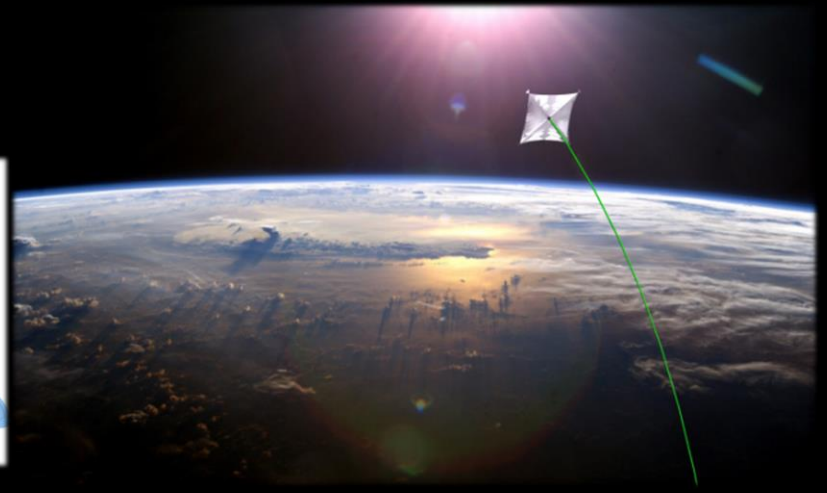
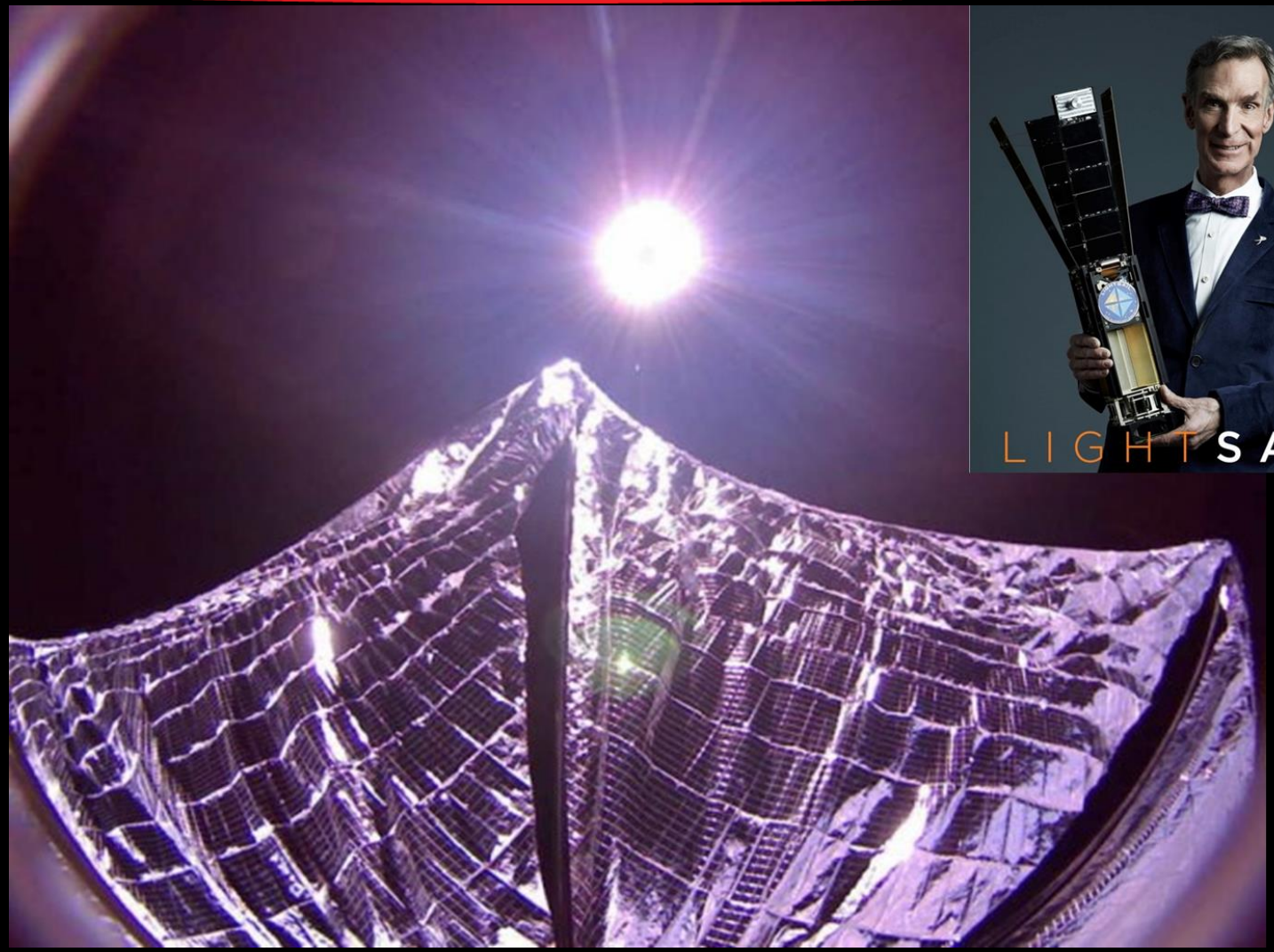




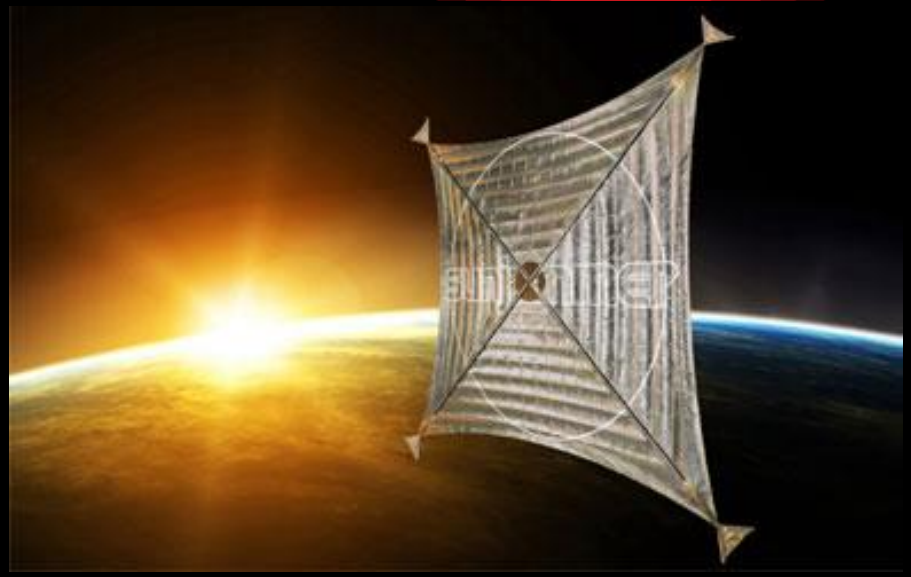
1200 m² L'Garde Sunjammer Launch
2015

Lightsail-A (The planetary society)

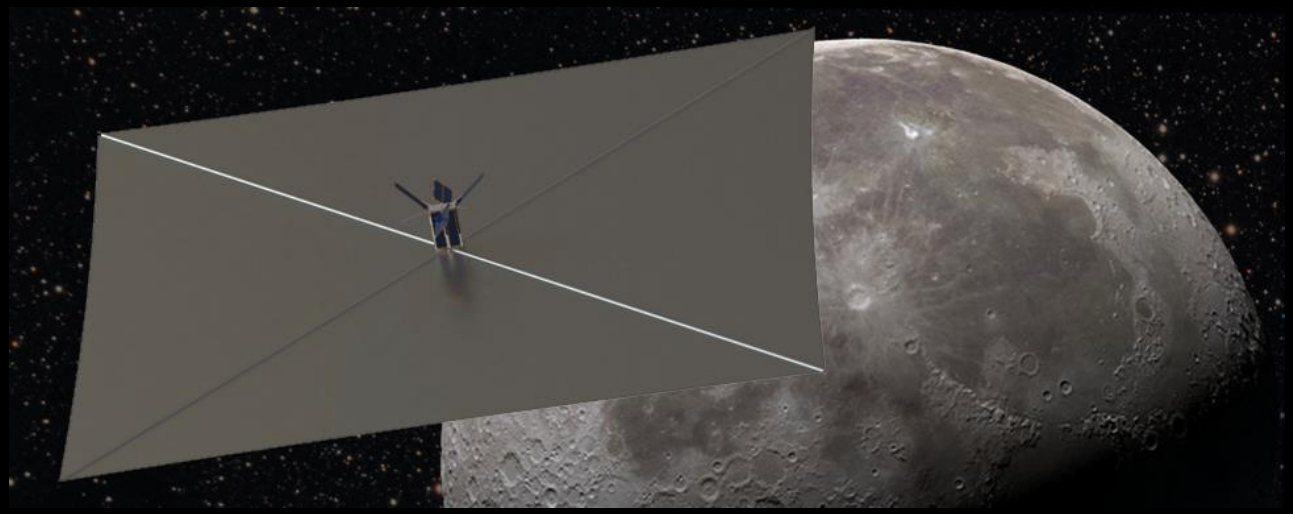


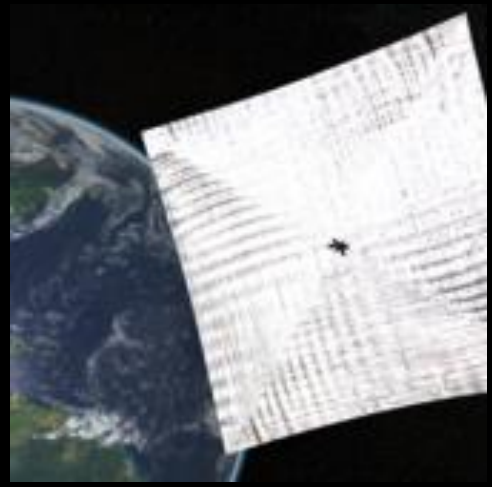
32 m^2
No active ‘sailing’
3U cubesat

Solar Sails TODAY – Many Missions Planned



- NASA's *NEA Scout*
- The Planetary Society's *LightSail-B*
- The University of Surrey's *CubeSail*, *DeorbitSail*, and *InflateSail*
- University of Illinois' *CubeSail*





Near Earth Asteroid Scout

The Near Earth Asteroid Scout Will

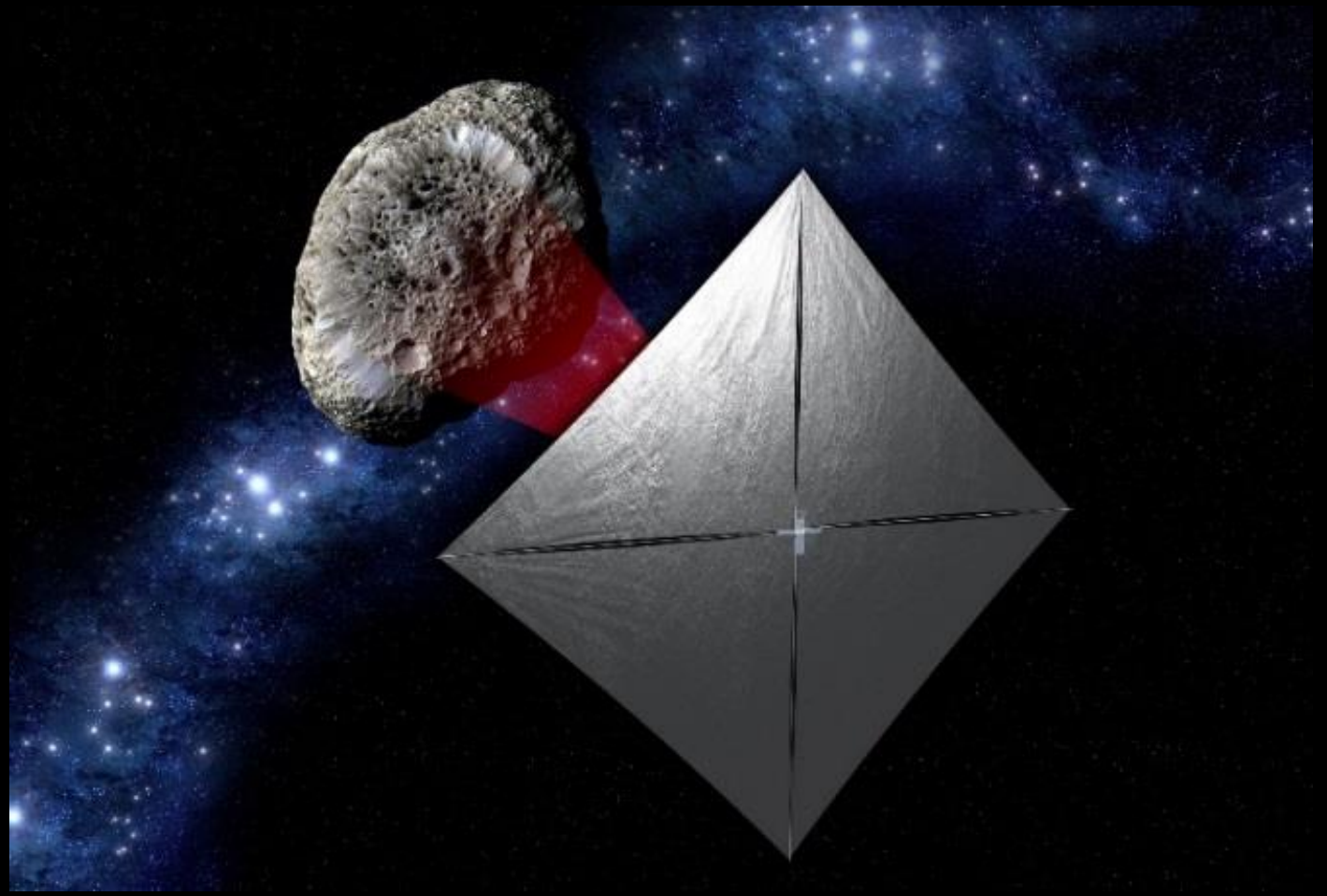
- Image/characterize a NEA during a slow flyby
- Demonstrate a low cost asteroid reconnaissance capability

Key Spacecraft & Mission Parameters

- 6U cubesat (20 cm X 10 cm X 30 cm)
- ~86 m^2 solar sail propulsion system
- Manifested for launch on the Space Launch System (EM-1/2017)
- Up to 2.5 year mission duration
- 1 AU maximum distance from Earth

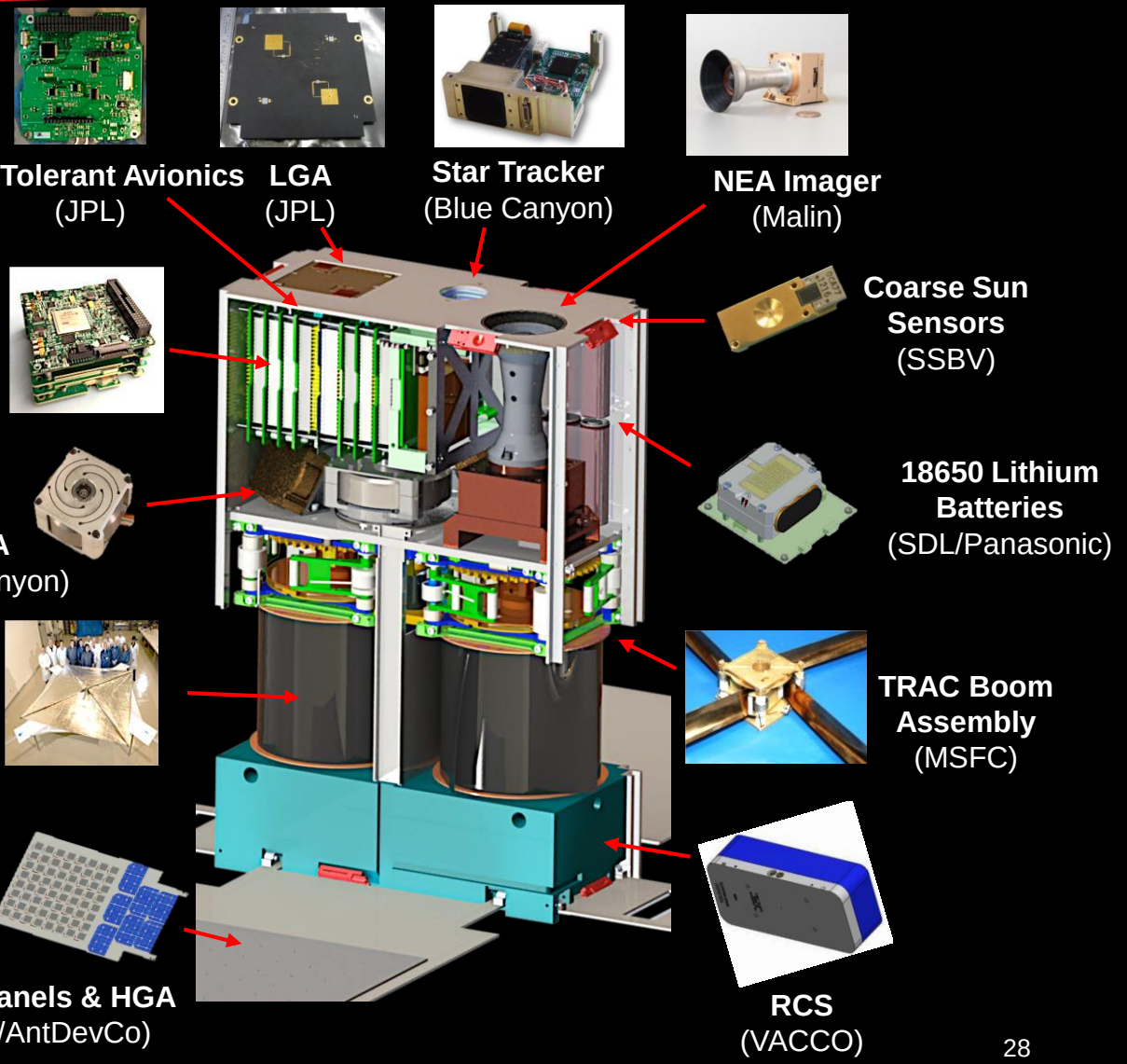
Solar Sail Propulsion System Characteristics

- ~ 7.3 m Trac booms
- 2.5μ aluminized CP-1 substrate
- > 90% reflectivity



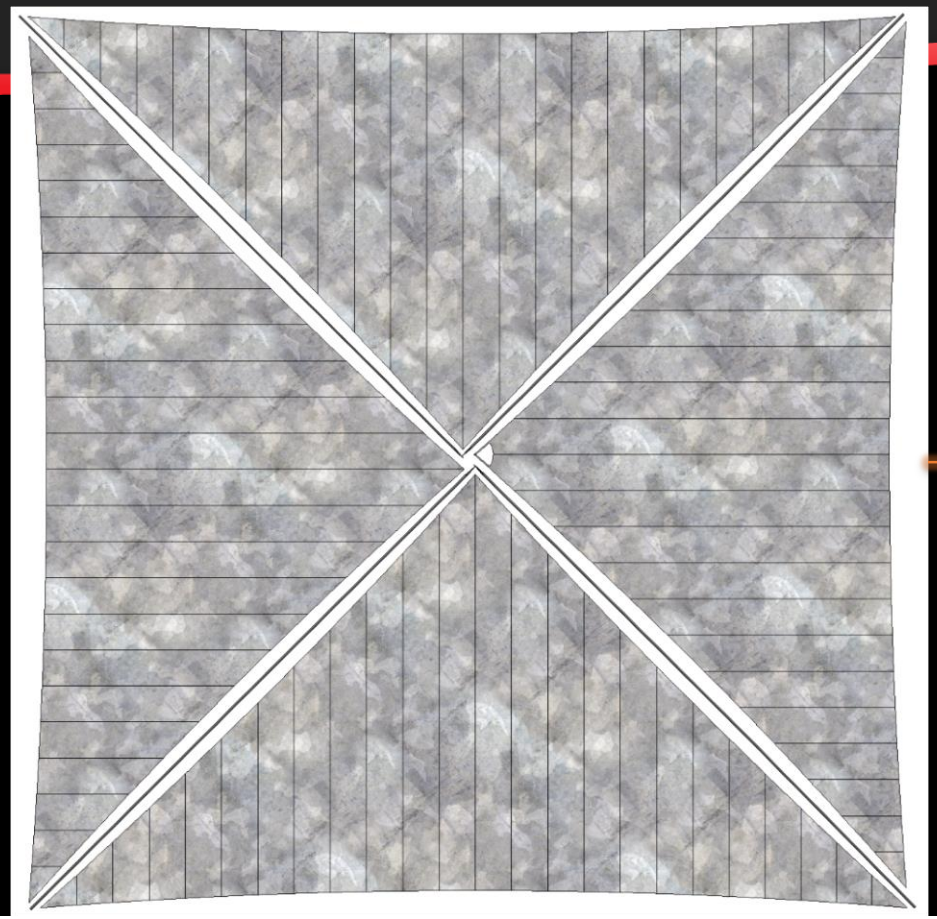
Flight System Overview

Mission Concept	Characterize a Near Earth Asteroid with an optical instrument during a close, slow flyby
Payload	Malin Space Science Systems ECAM-M50 imager
Mechanical& Structure	“6U” CubeSat form factor (~10x20x30 cm)
Propulsion	CP-1 solar sail (based on NanoSail-D2)
Avionics	Radiation tolerant LEON3-FT architecture
Electrical Power System	Simple deployable solar arrays
Telecom	JPL Iris 2 pairs of INSPIRE-heritage LGAs (RX/TX) 8x8 element microstrip array HGA (TX)



NEA Scout Approximate Scale

Deployed Solar Sail

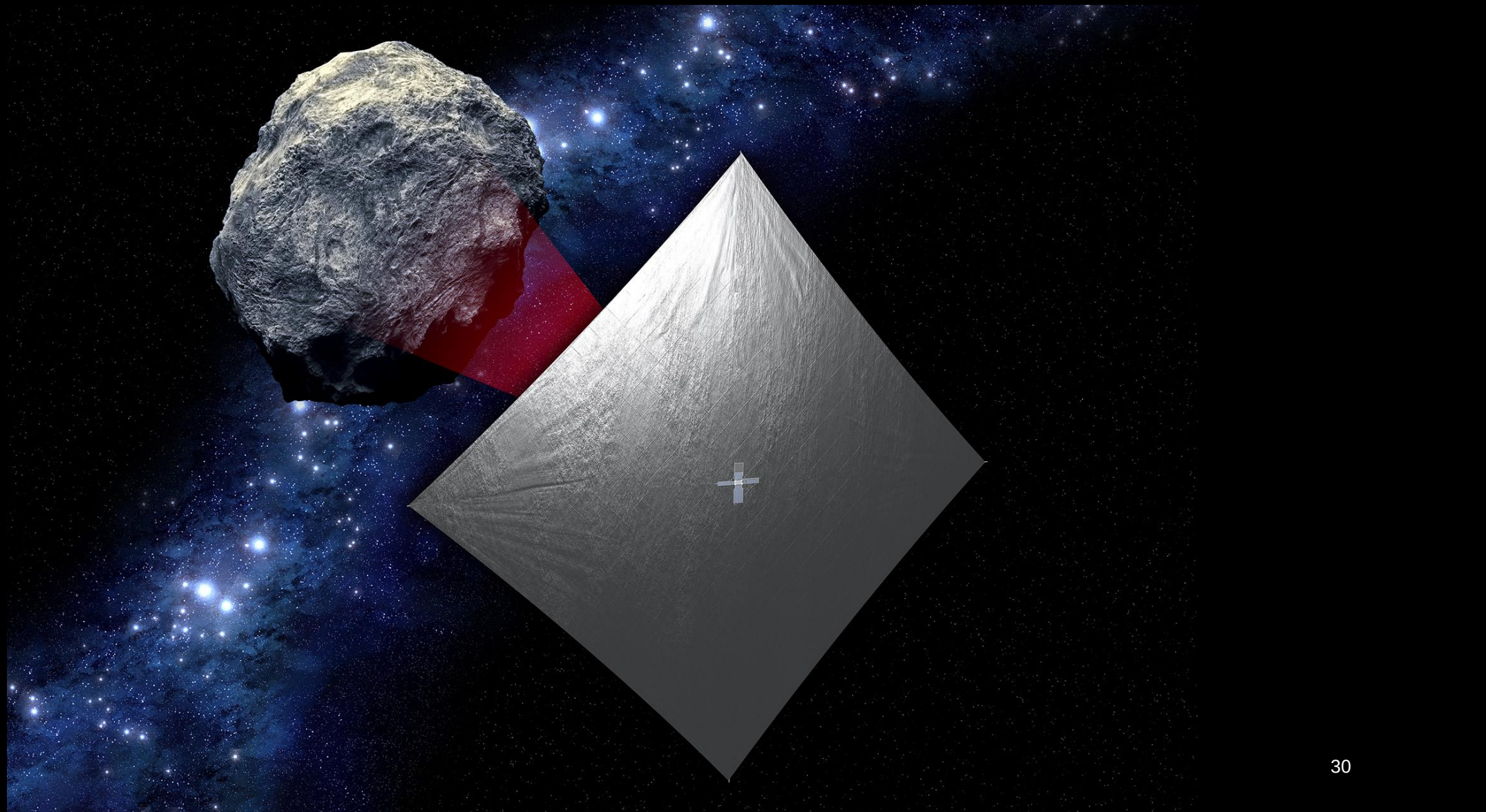


School Bus

6U Stowed Flight System

Folded, spooled and packaged in here

Near Earth Asteroid (NEA) Scout



University of Surrey's InflateSail

- **InflateSail** is an inflatable, rigidizable sail for flight in Low Earth Orbit:
  - 3U CubeSat with deployed sail area of 10 m^2
  - Sail supported by bistable booms
  - Inflation is driven by Cool Gas Generators (CGG): low system mass, long lifespan

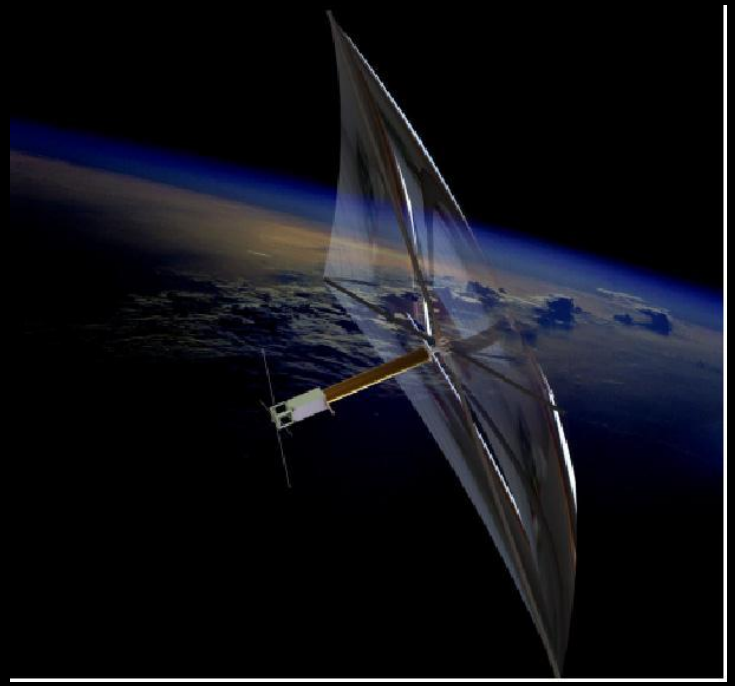


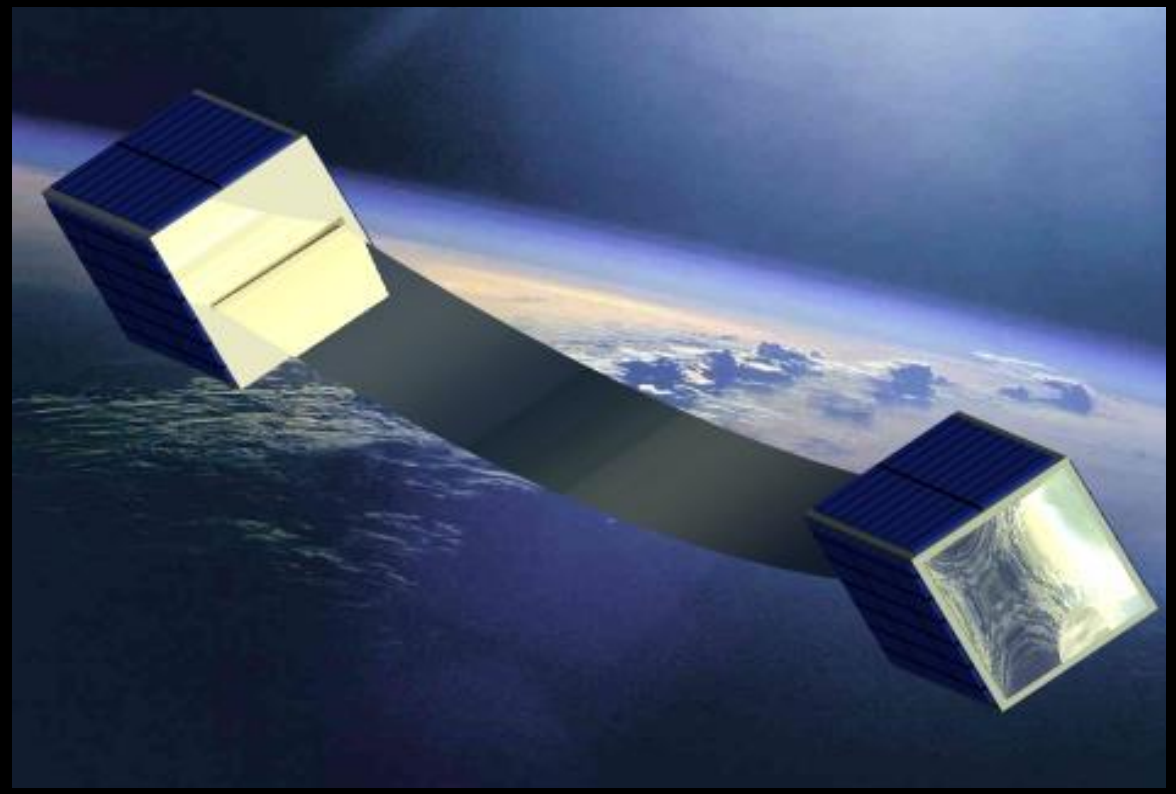
***Fig. 1**: InflateSail design concept*

***Fig. 2**: 80 mg CGG*

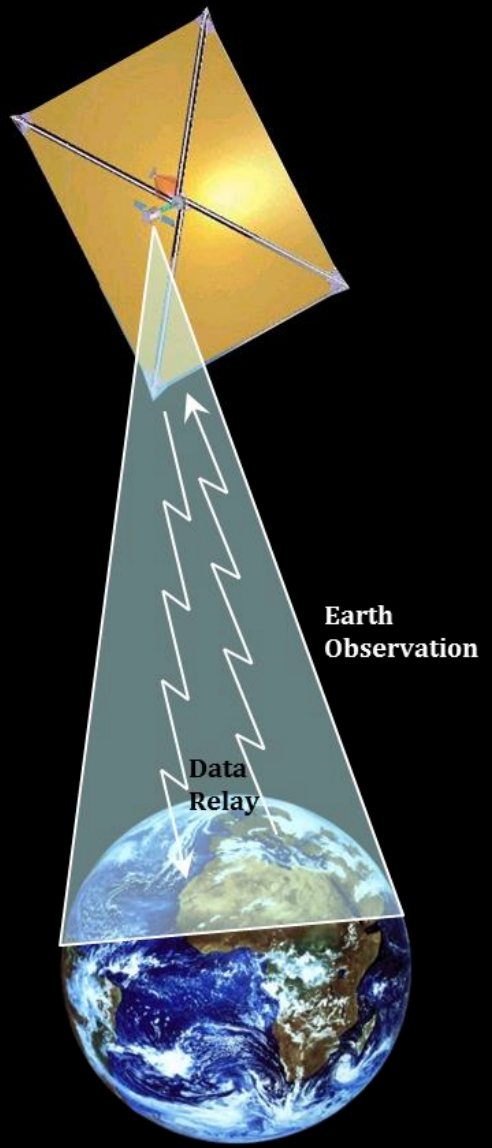
George C. Marshall Space Flight Center

Cubesail CubeSat Solar Sail Propulsion Demonstration

- The University of Illinois at Urbana-Champaign (UIUC), working with NASA MSFC, NSF, and CU Aerospace, built the flight hardware for a CubeSat-based 20 m^2 solar sail orbit raising demonstration mission
- Selected for flight under the NASA CubeSat Launch Initiative



Continuous Polar Observations



Sailcraft over the polar regions of the Earth

Sail tilted so the light pressure from the sunlight reflecting from it is exactly equal and opposite to the gravity pull of the Earth.

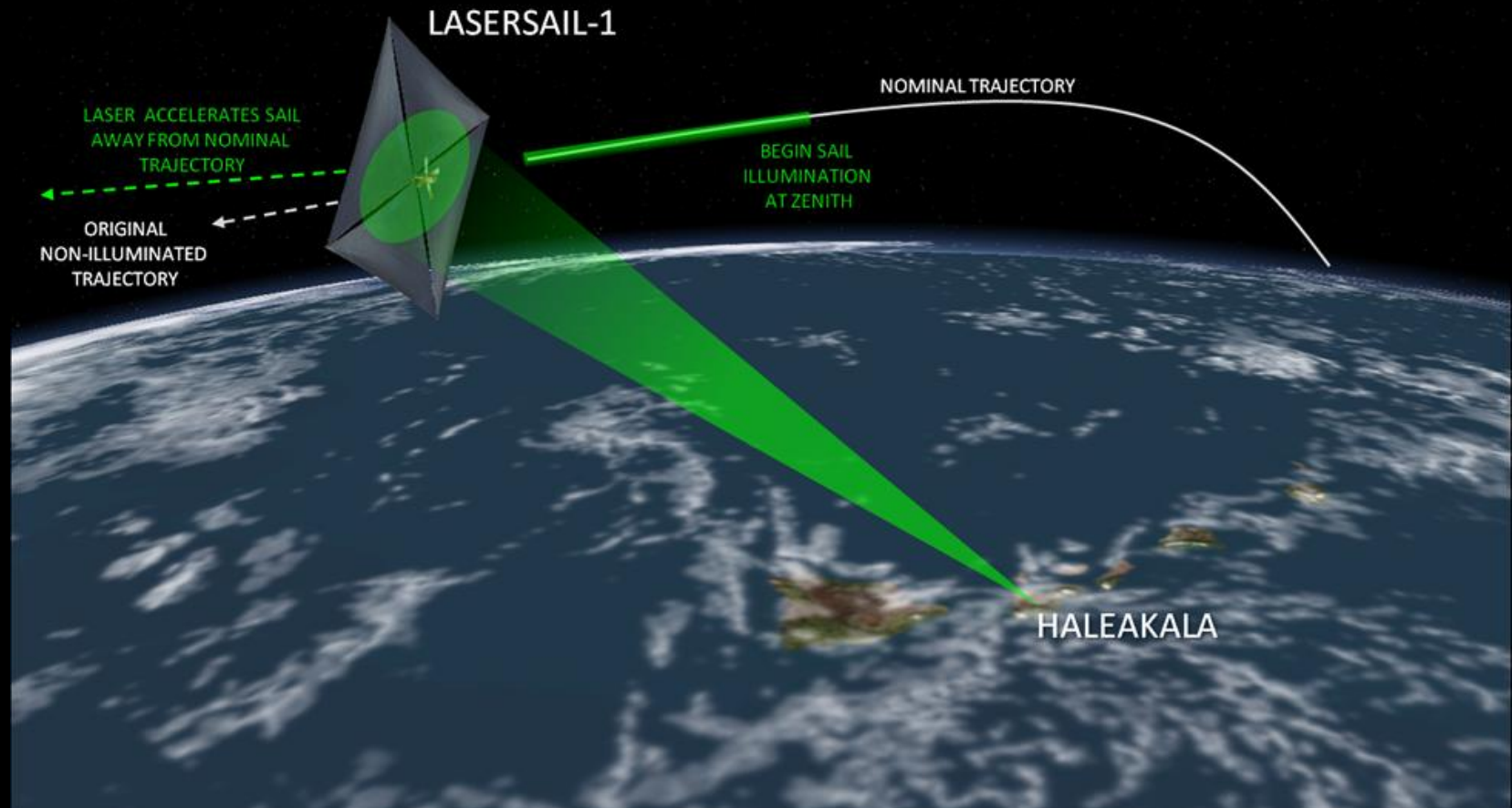
Interstellar Probe

Deploy a large (>10,000 m^2) solar sail near the sun to enable travel 5X faster than Voyager

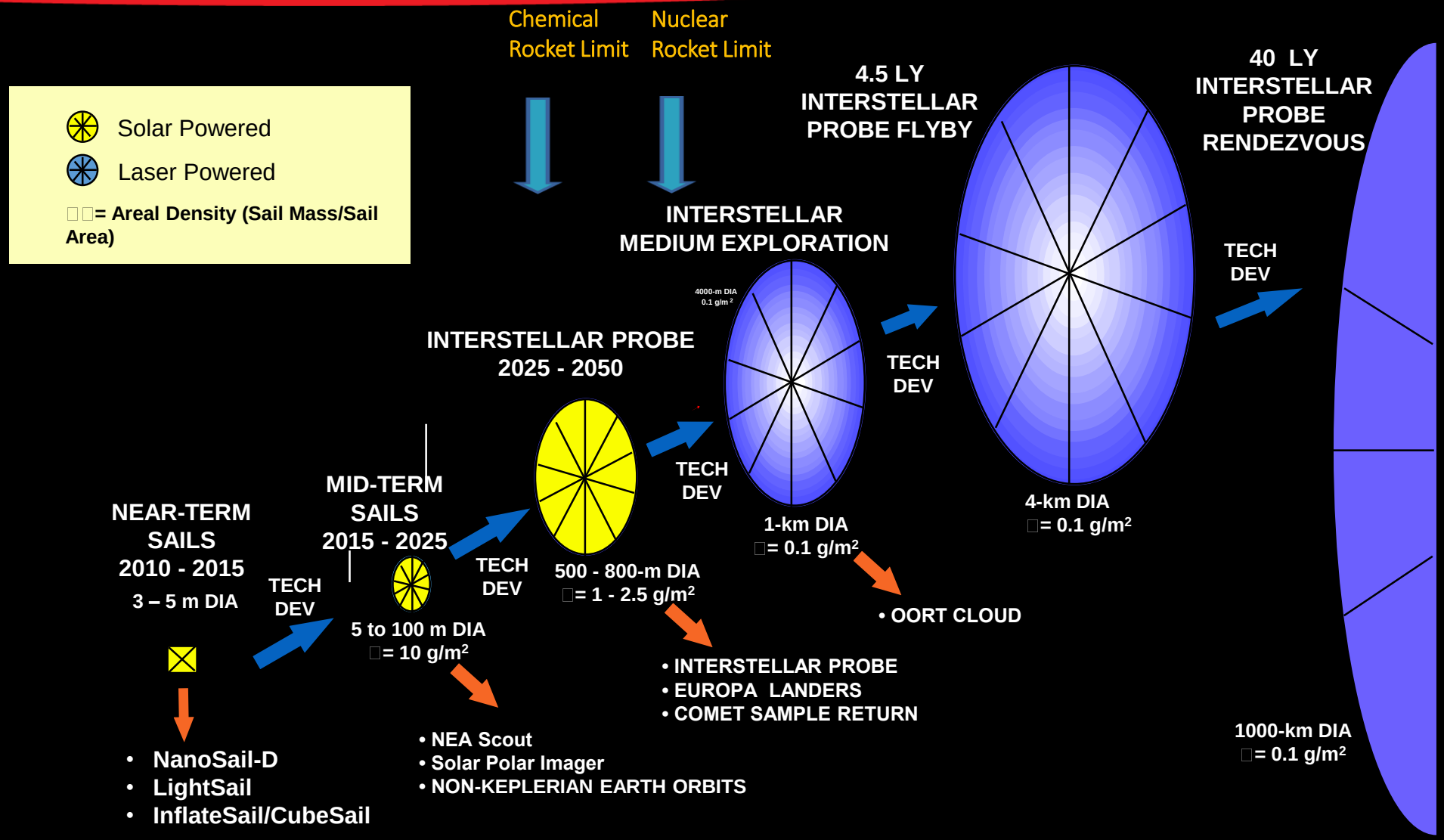
Goal: Reach 250 Astronomical Units within 20 years of launch

Laser Sailing: The Next Big Step

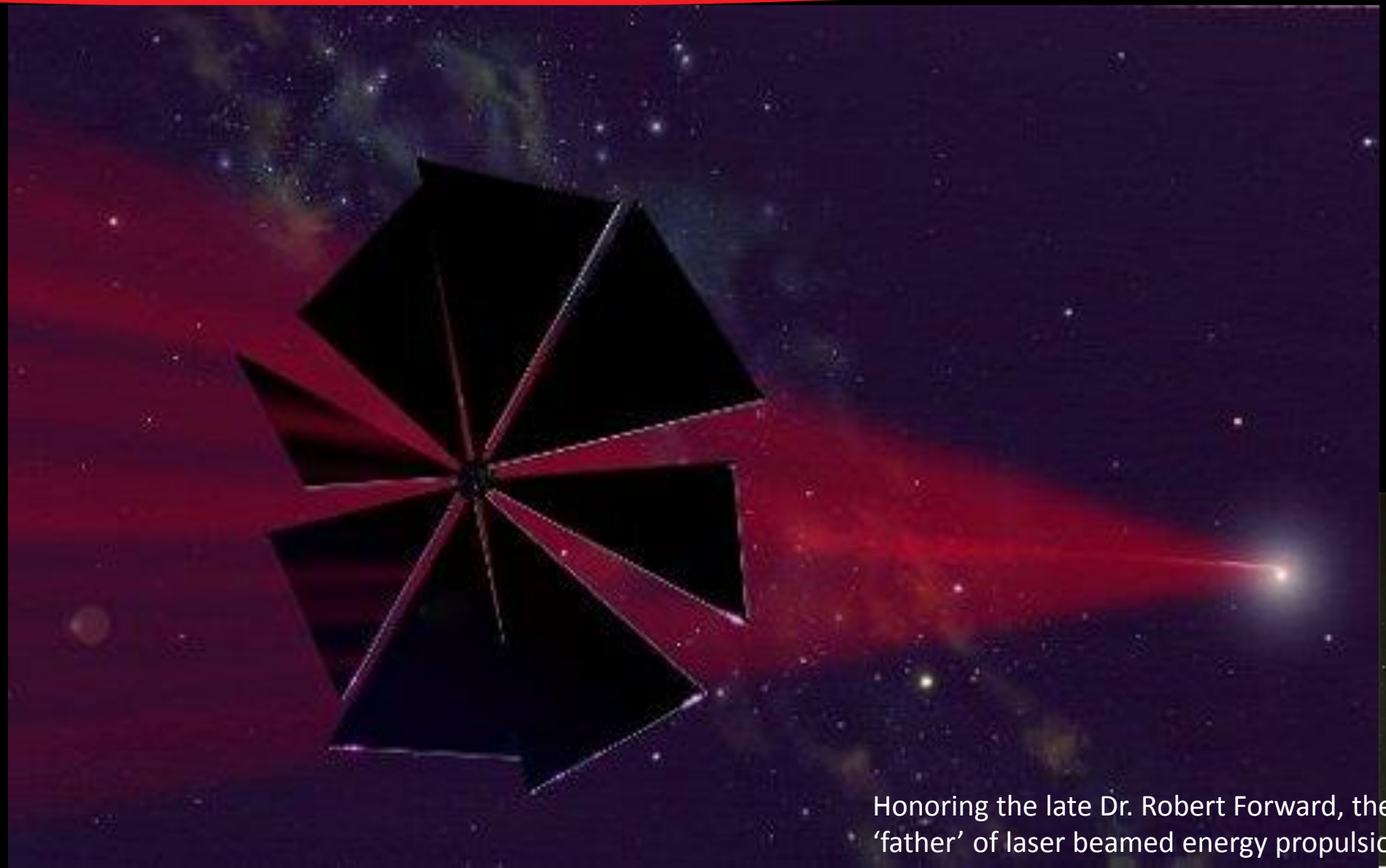
Ground to space laser illumination of a solar sail to impart measurable ΔV

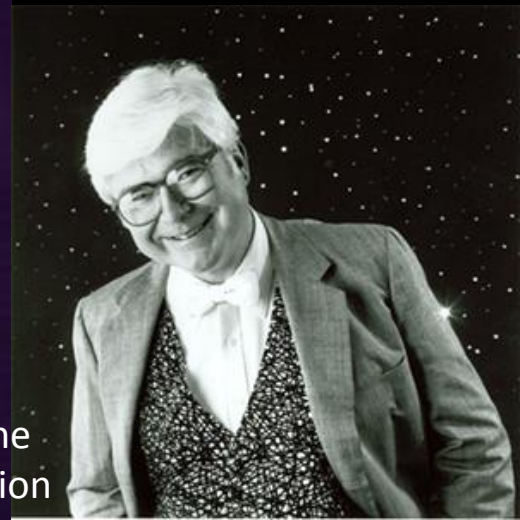


My Real Motive…



Solar Sails: A Step Toward the Stars





Honoring the late Dr. Robert Forward, the ‘father’ of laser beamed energy propulsion