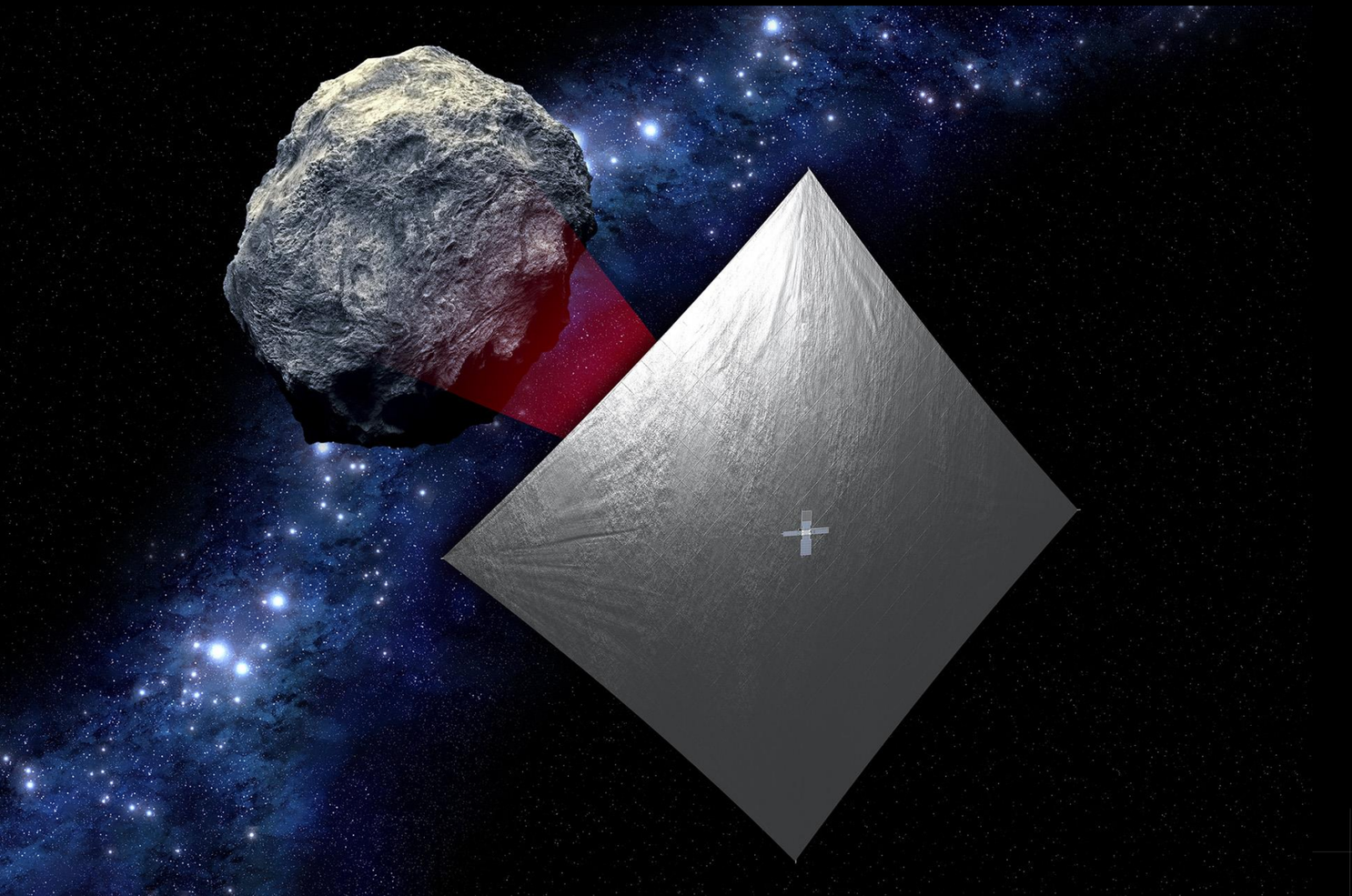
College of Engineering & Applied Science
UNIVERSITY OF COLORADO **BOULDER**

Solar Sails: Traveling the Solar System (and Beyond!) with Sunlight

September 28, 2018



Les Johnson

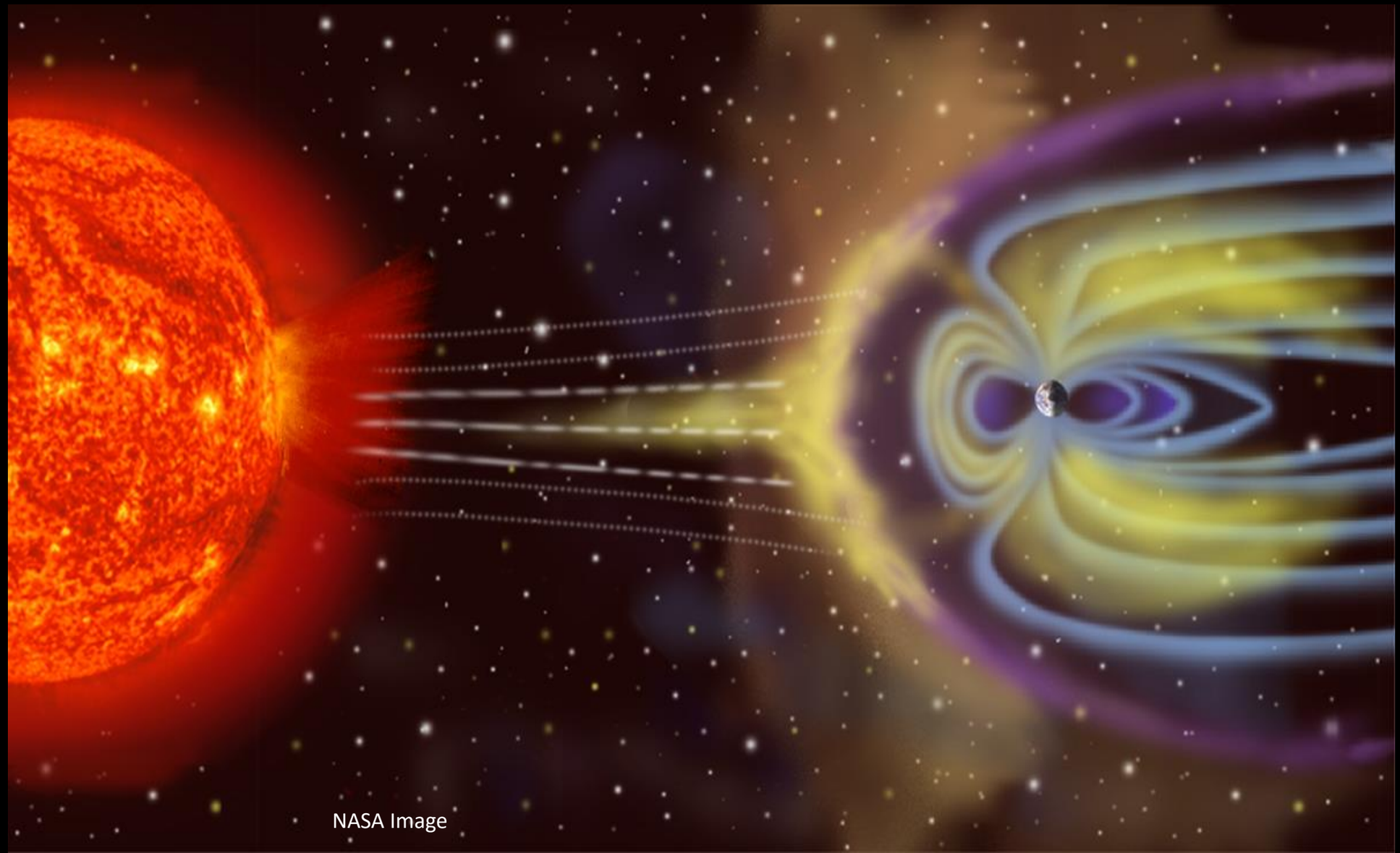
NASA George C. Marshall Space Flight Center

Science and Technology Office

We tend to think of space as being

NASA Image

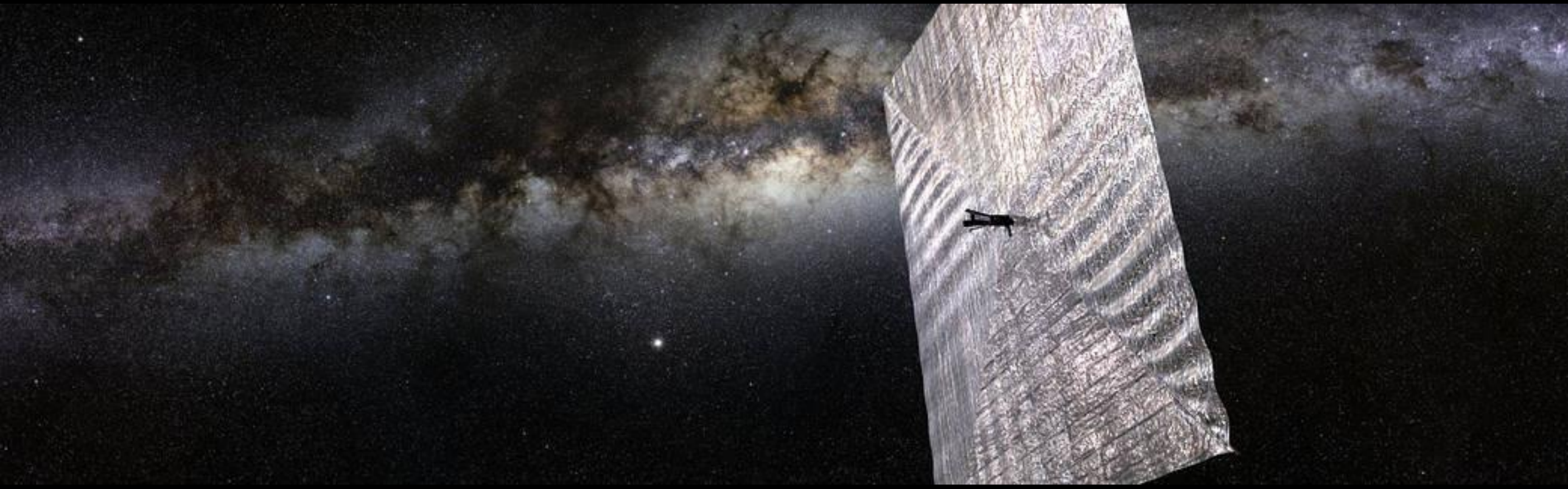
Space is NOT Empty. We can use the environments of space to our advantage



NASA Image

Just As Sailing Ships Can Use the Momentum of the Wind

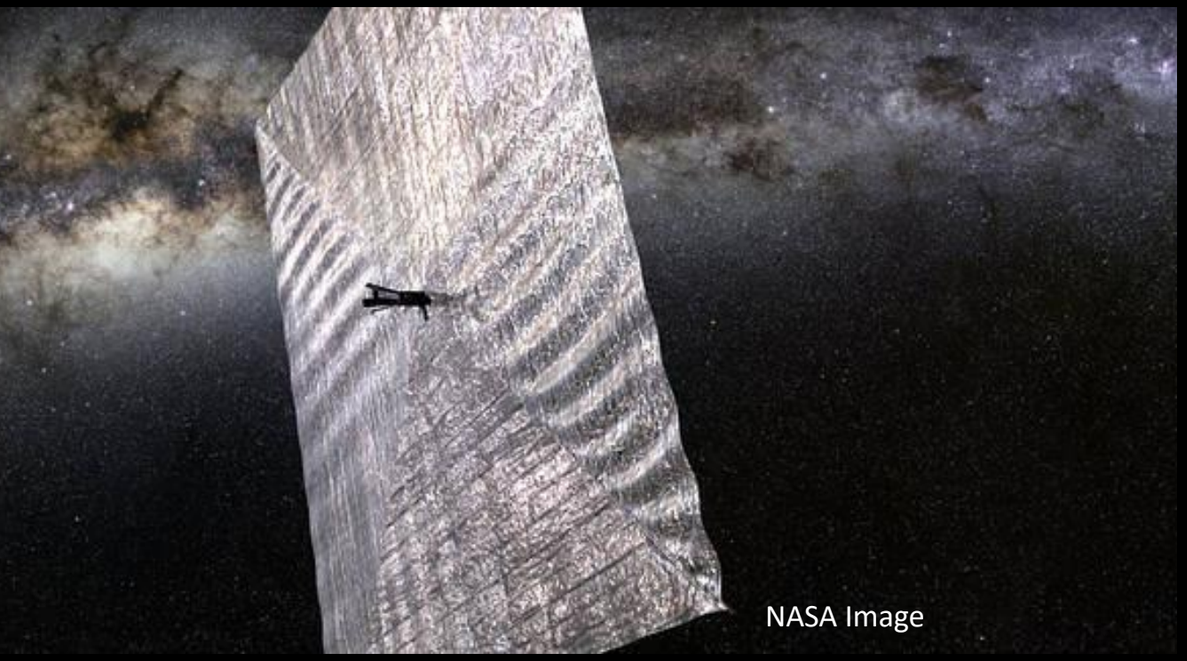
Spacecraft Can Use the Momentum of Sunlight



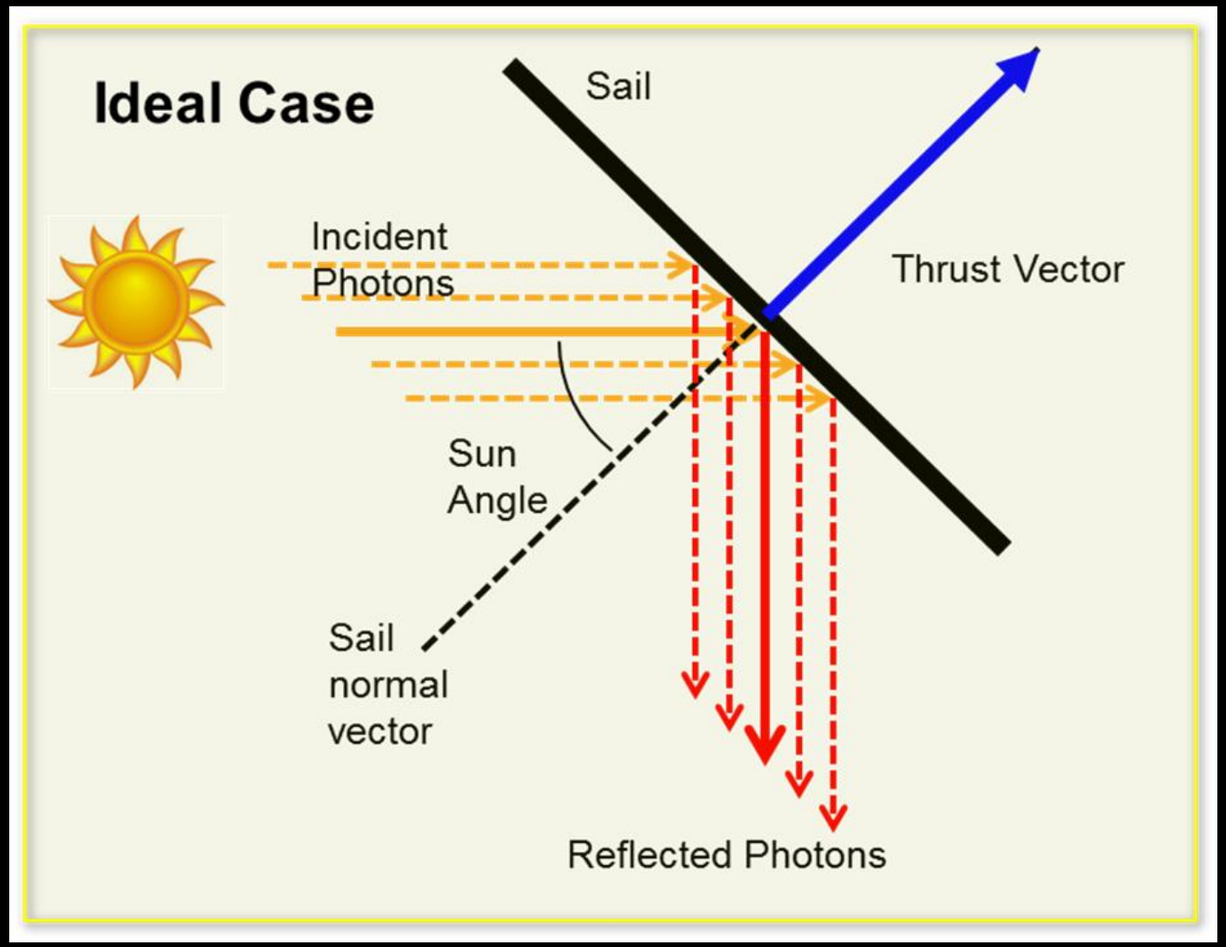
NASA Image

Solar Sails Derive Propulsion By Reflecting Photons

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

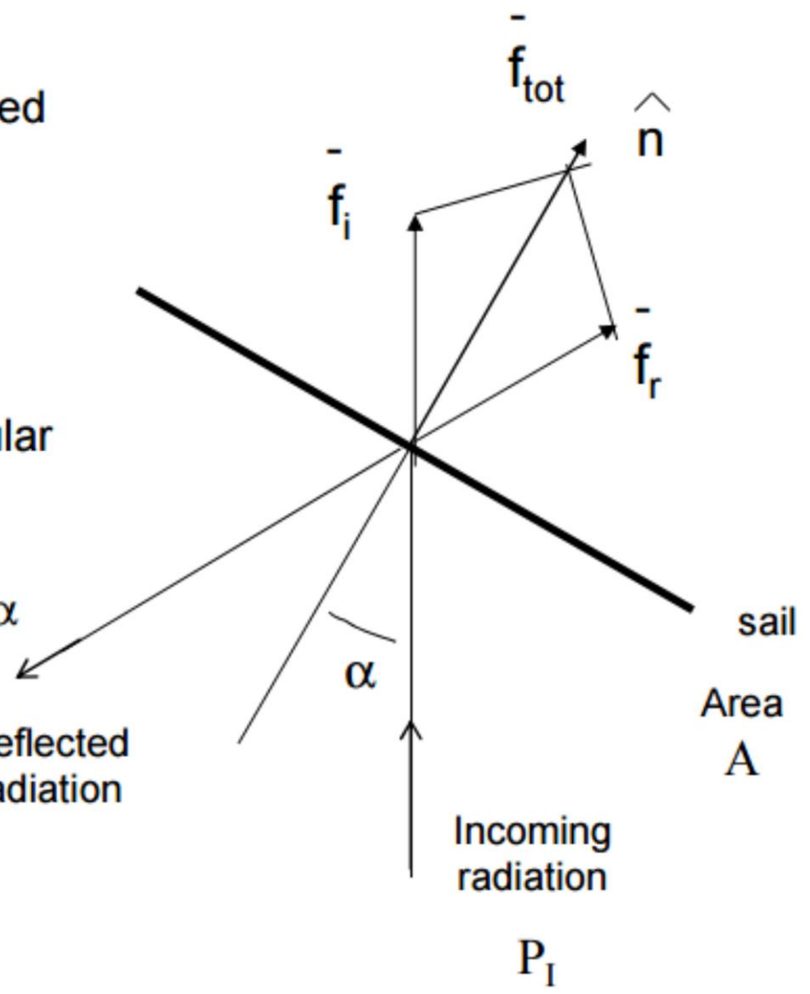


NASA Image



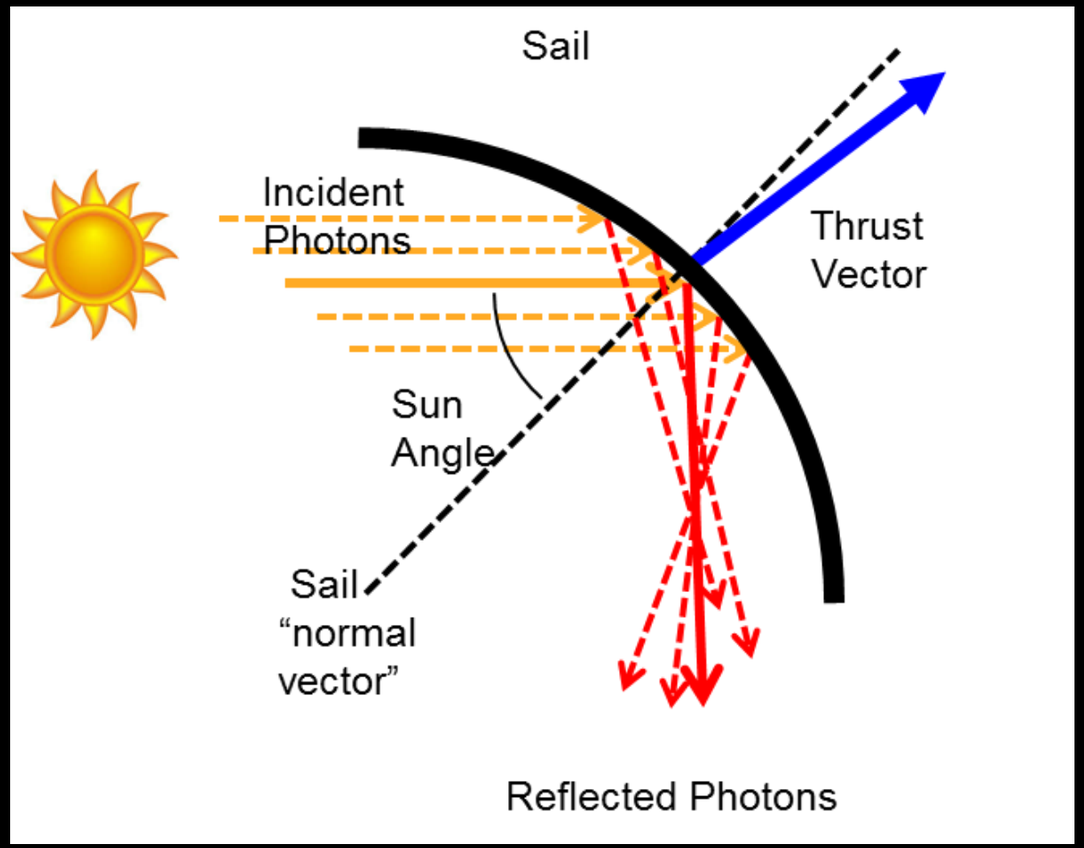
Photons Have Momentum Which Can Be Imparted to the Solar Sail

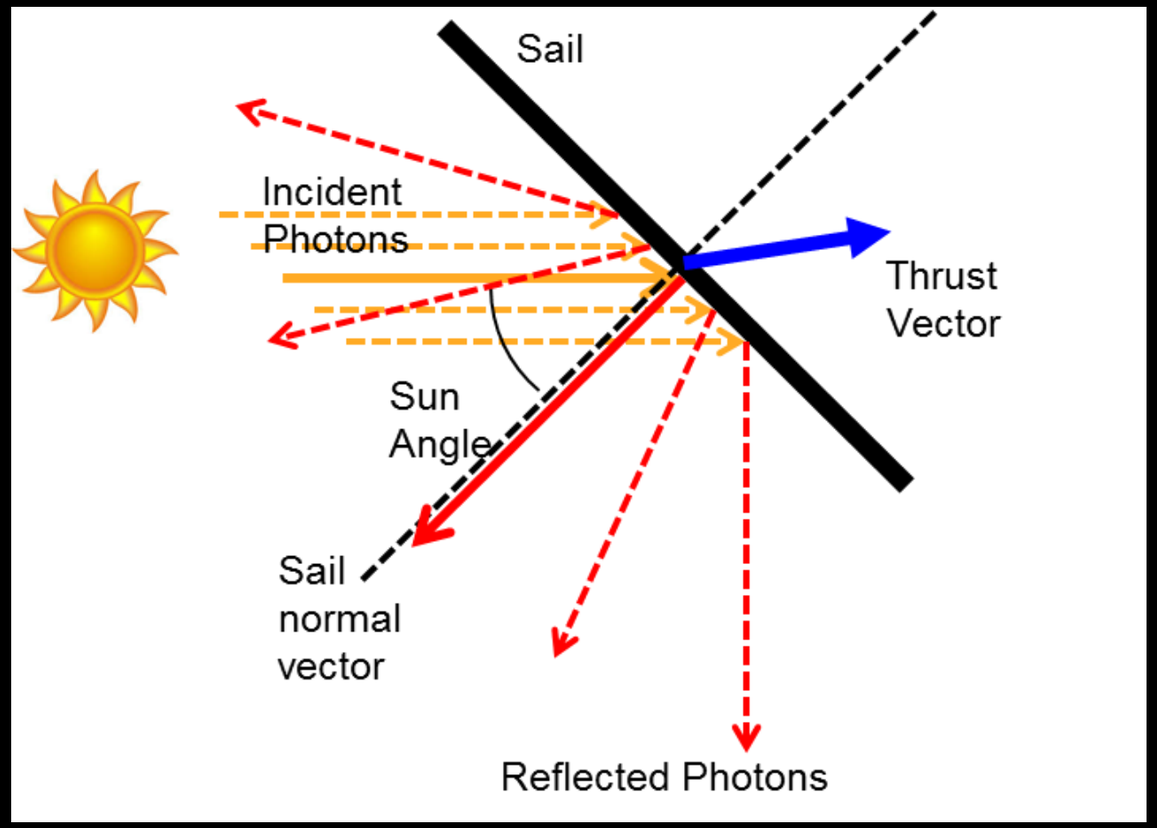
- **Photons carry Momentum**
  - $\rho = h\nu/c$
    - h = Planck's, ν = frequency, c = speed of light
- **Force generated on Reflective Surface**
  - Resultant force approximately perpendicular to surface
    - The bigger the surface, the more the force
  - Can "steer" sail by changing pitch angle α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



Real Solar Sails Are Not “Ideal”

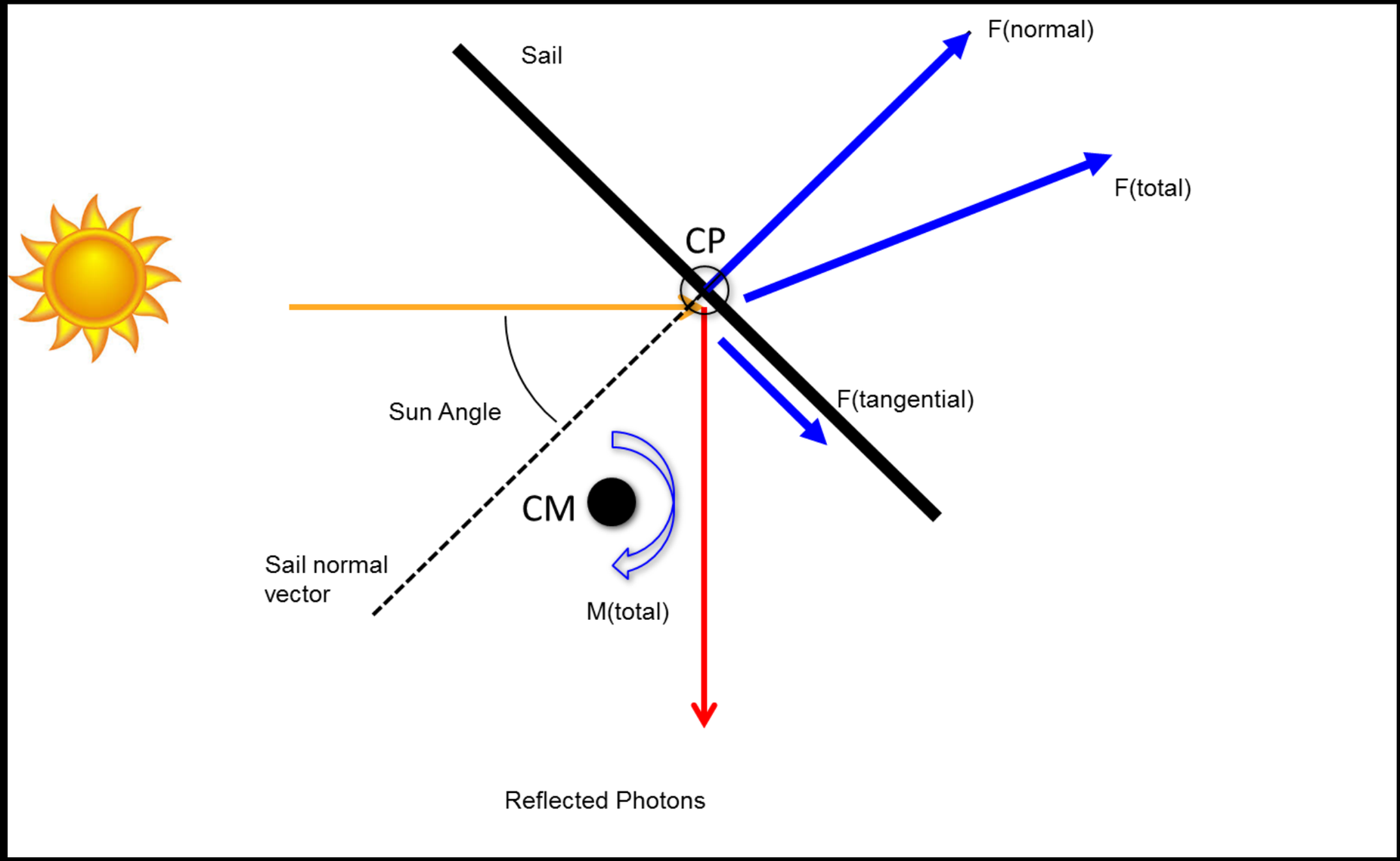
Billowed Quadrant





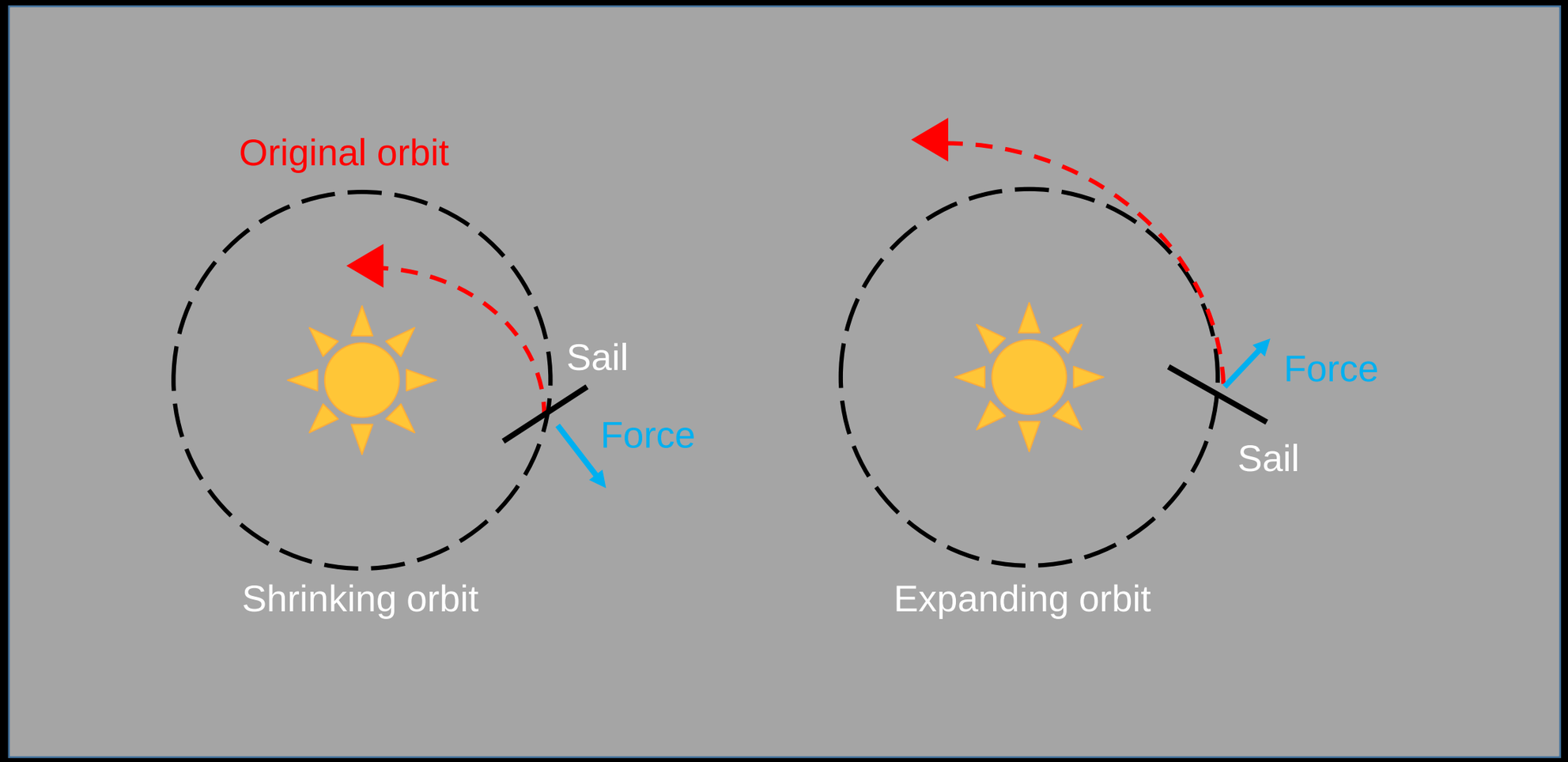
Diffuse Reflection

Thrust Vector Components



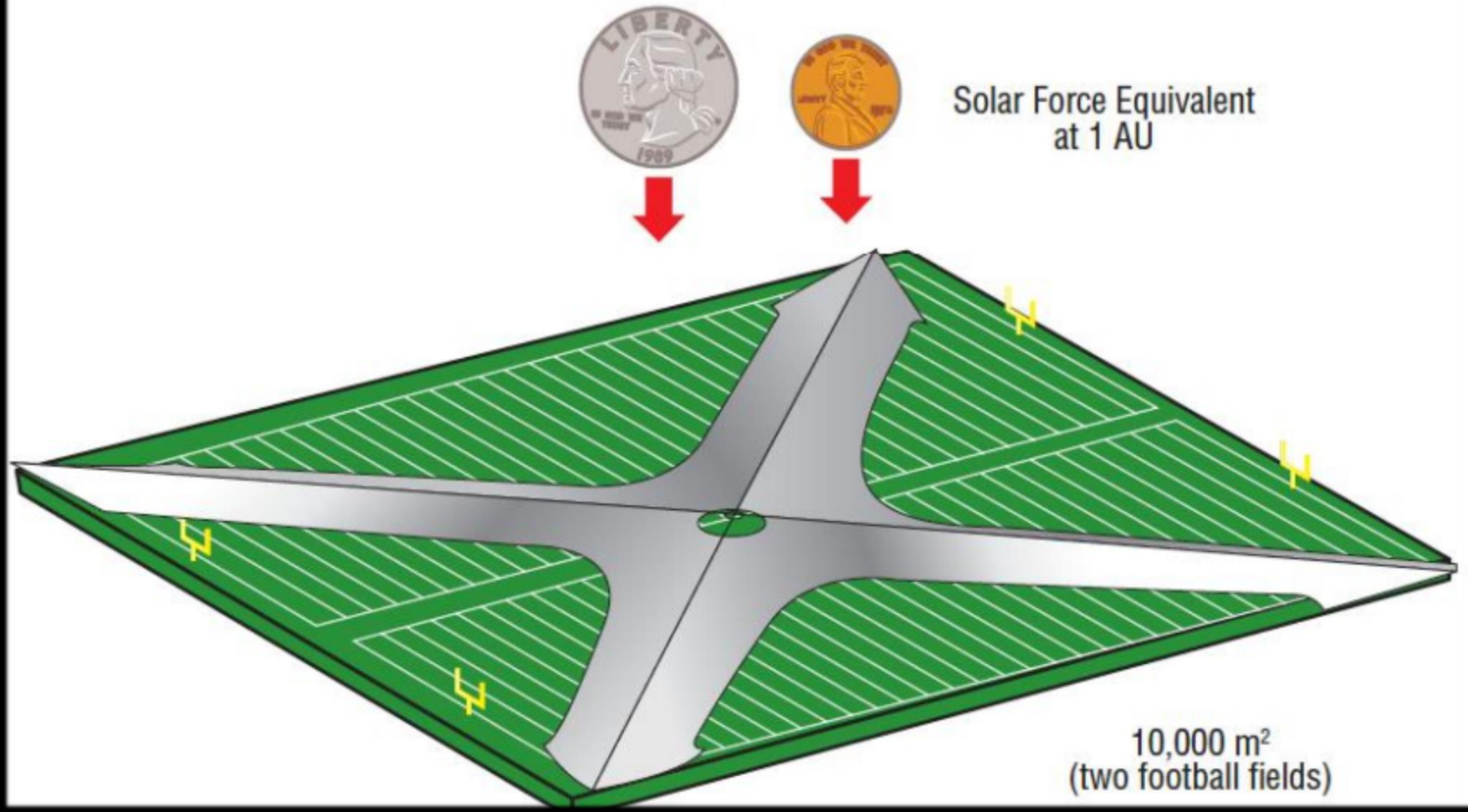
Solar Sail Trajectory Control

Solar Radiation Pressure allows inward or outward Spiral



Solar Sails Experience **VERY** Small Forces

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

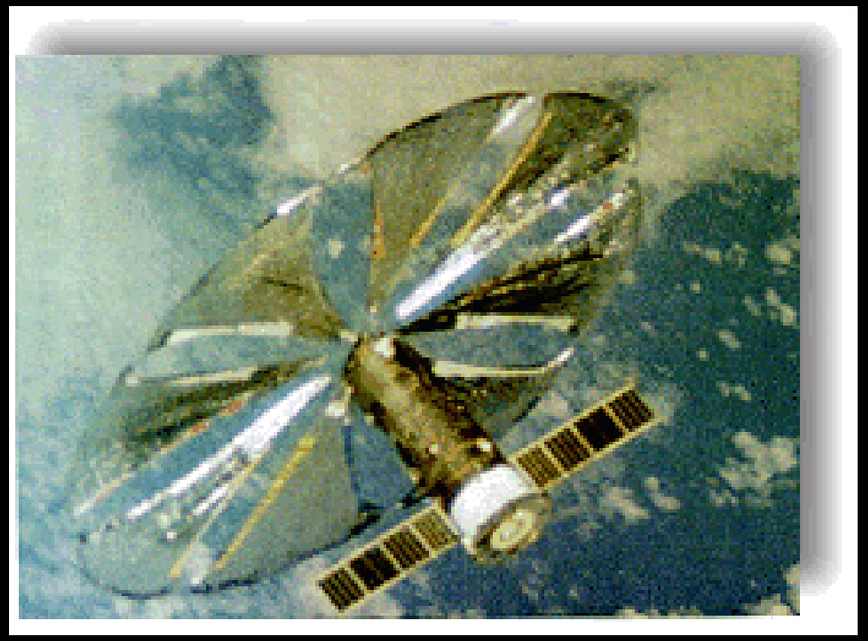


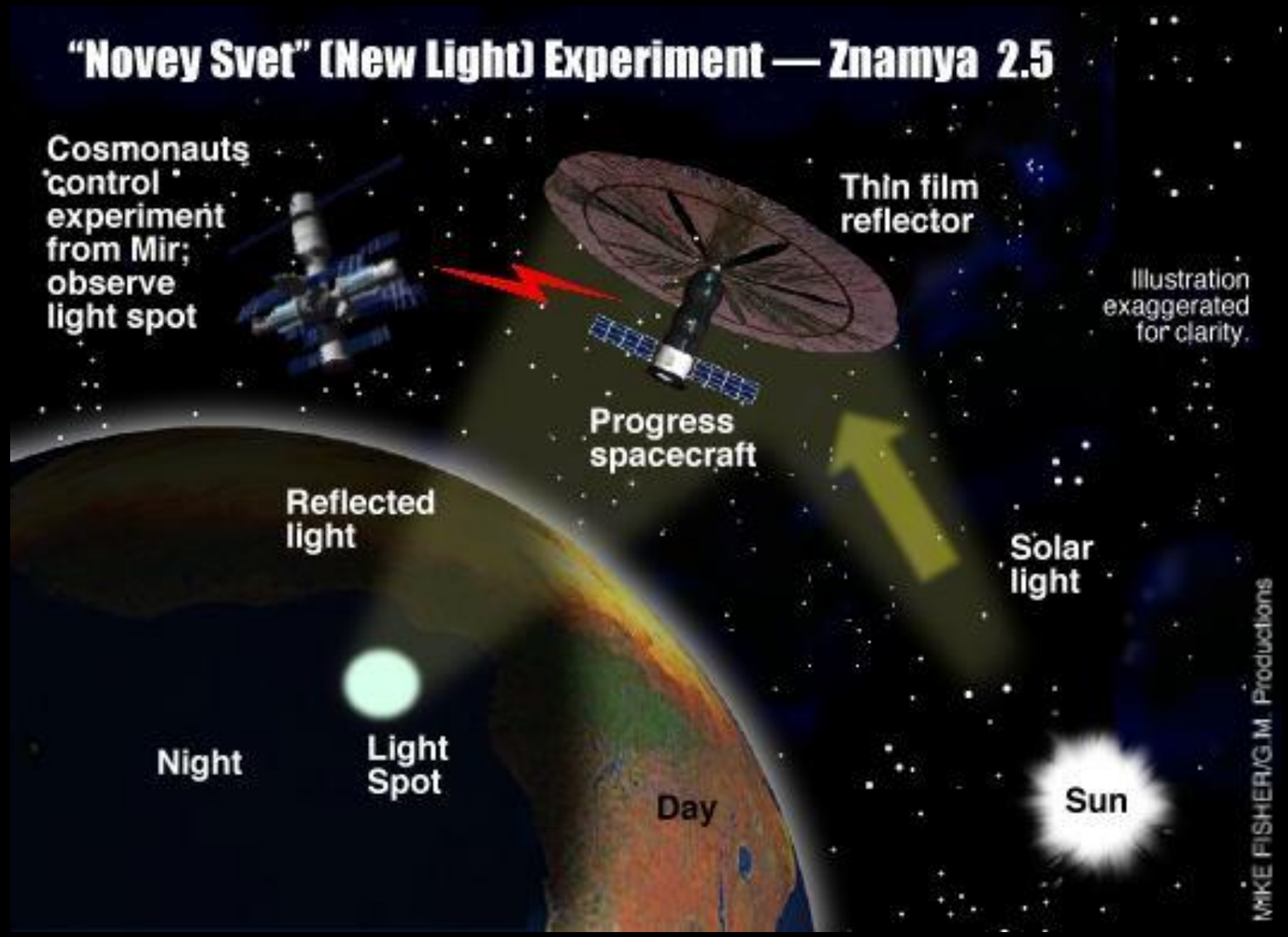
Echo II 1964
Solar thrust effect on spacecraft orbit

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

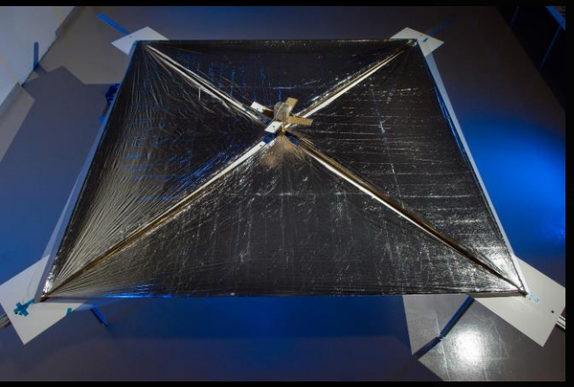
- **135-foot rigidized inflatable balloon satellite**
- **laminated Mylar plastic and aluminum**
- **placed in near-polar Orbit**
- **passive communications experiment by NASA on January 25, 1964**

Znamya (Space Mirror)





Space Sail Missions Flown (as of July 11, 2018)



NanoSail-D (2010)
NASA

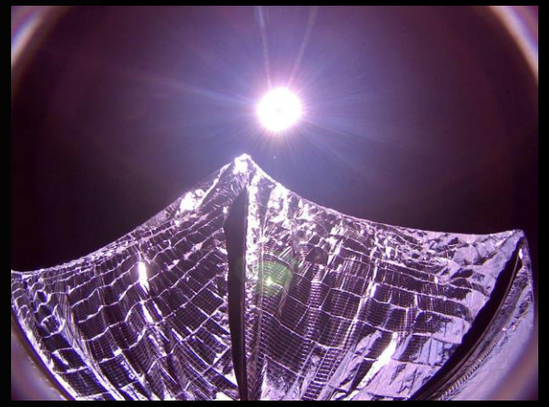
Earth Orbit
Deployment Only

3U CubeSat
10 m^2

IKAROS (2010)
JAXA

Interplanetary
Full Flight

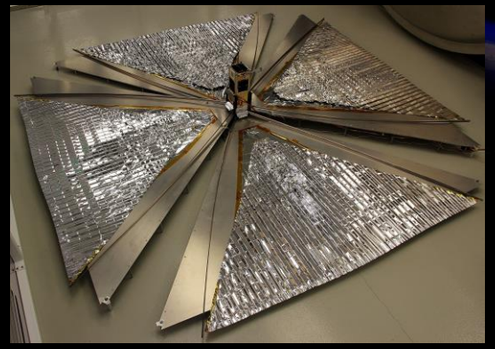
315 kg Smallsat
196 m^2



LightSail-1 (2015)
The Planetary Society

Earth Orbit
Deployment Only

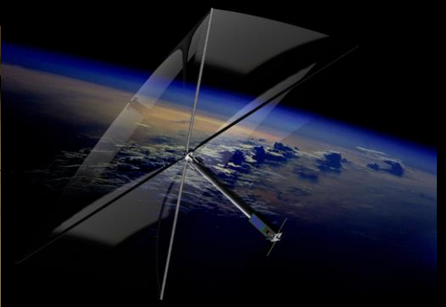
3U CubeSat
32 m^2



CanX-7 (2016)
Canada

Earth Orbit
Deployment Only

3U CubeSat
<10 m^2

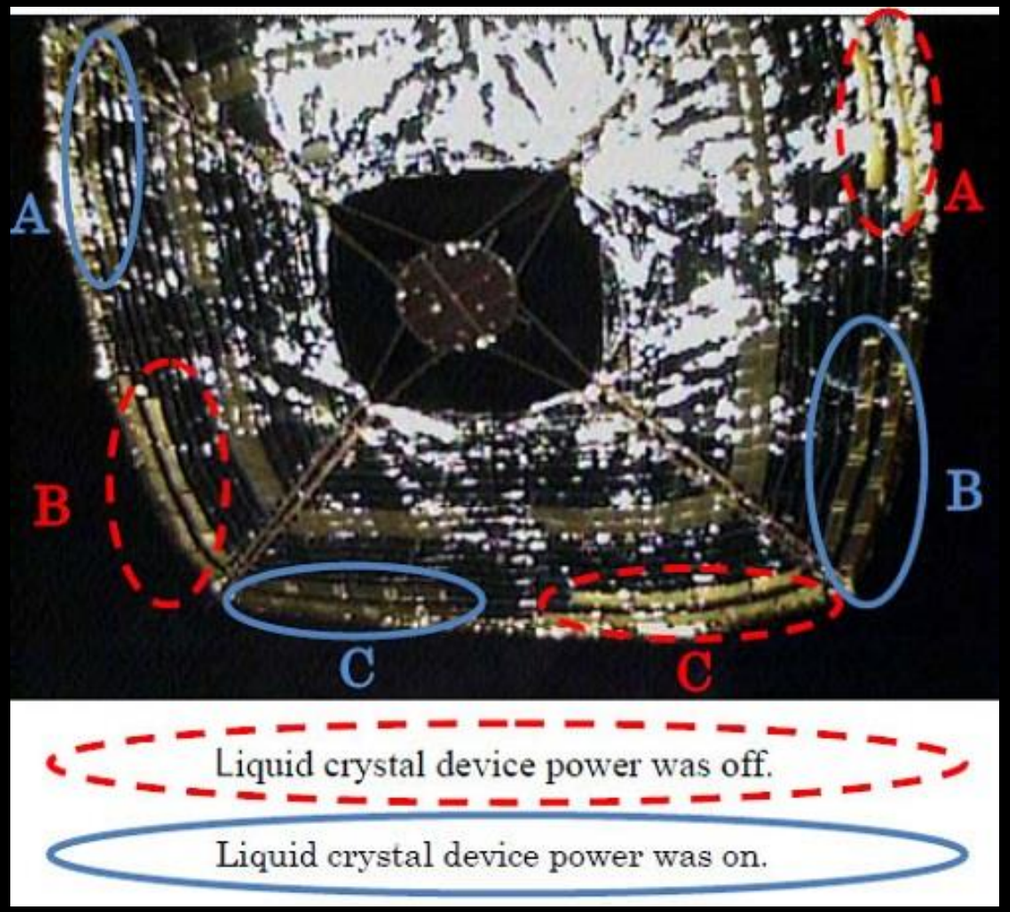


InflateSail (2017)
EU/Univ. of Surrey

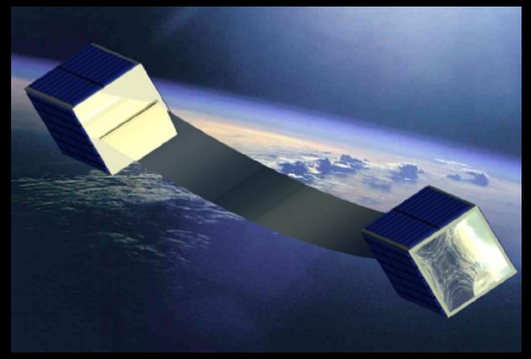
Earth Orbit
Deployment Only

3U CubeSat
10 m^2

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



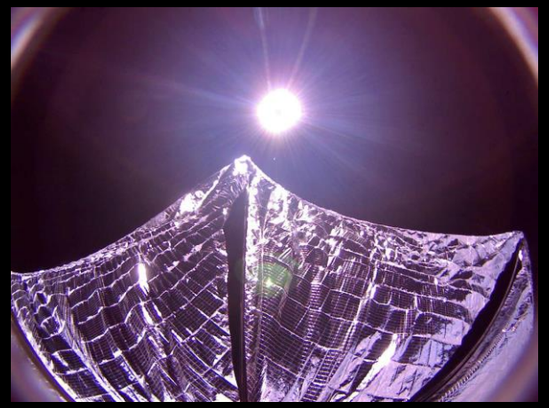
Planned Solar Sail Missions (as of Sept. 28, 2018)



CU Aerospace (2018)
Univ. Illinois / NASA

Earth Orbit
Full Flight

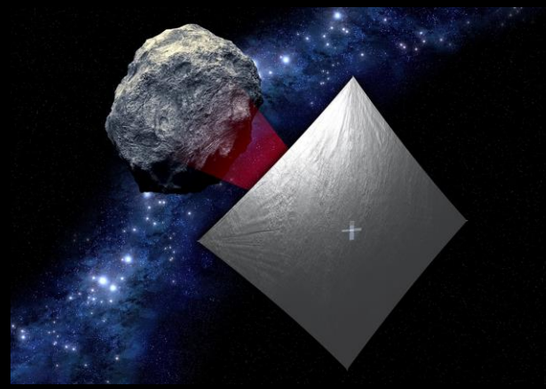
3U CubeSat
20 m^2



LightSail-2 (2018)
The Planetary Society

Earth Orbit
Full Flight

3U CubeSat
32 m^2



Near Earth Asteroid Scout (2020) NASA

Interplanetary
Full Flight

6U CubeSat
86 m^2

NASA's Near Earth Asteroid Scout

The Near Earth Asteroid Scout Will:

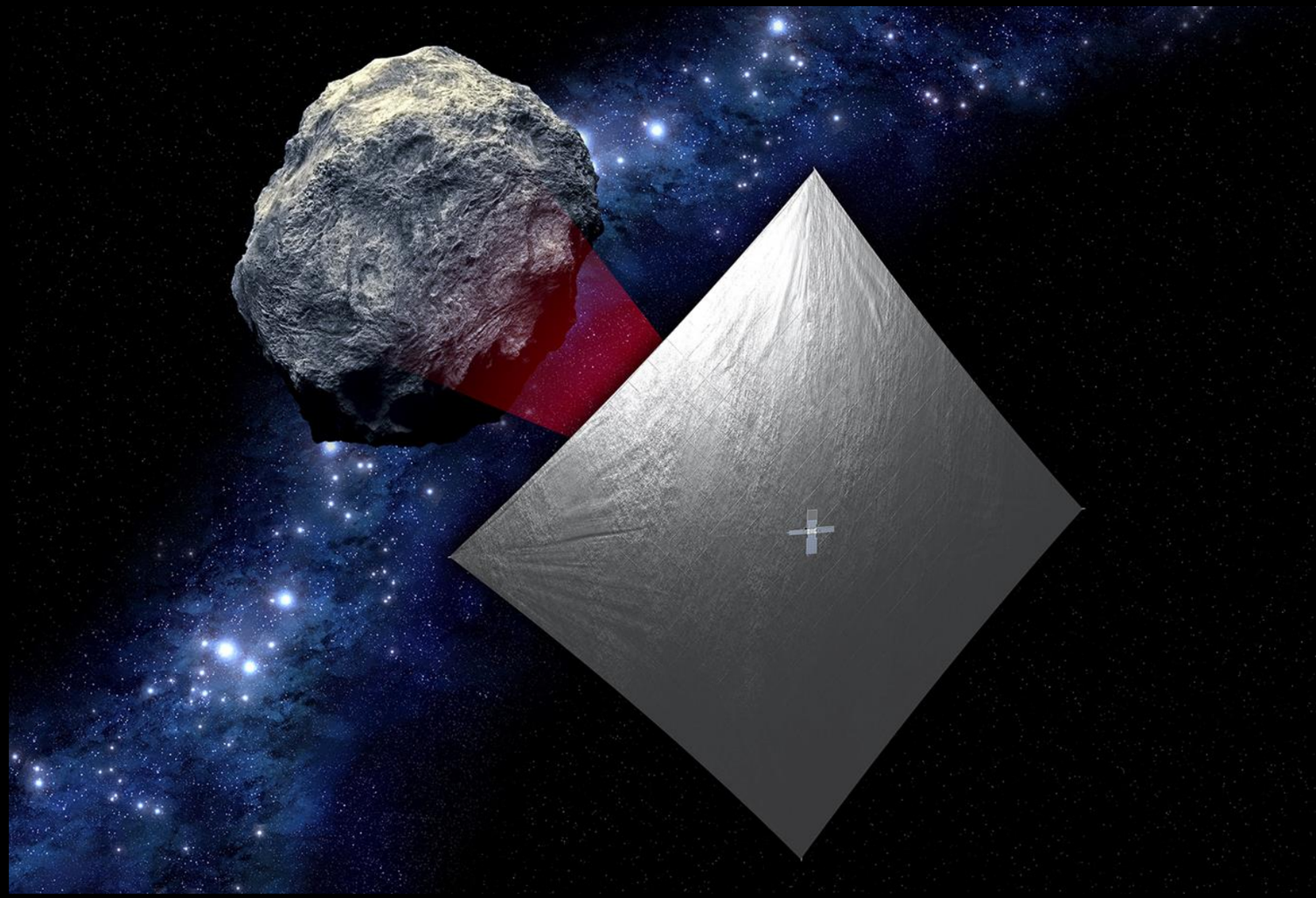
- Image/characterize a NEA during a slow flyby
- Demonstrate a low cost asteroid reconnaissance capability

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-1/2019)
- Up to 2.5 year mission duration
- 1 AU maximum distance from Earth

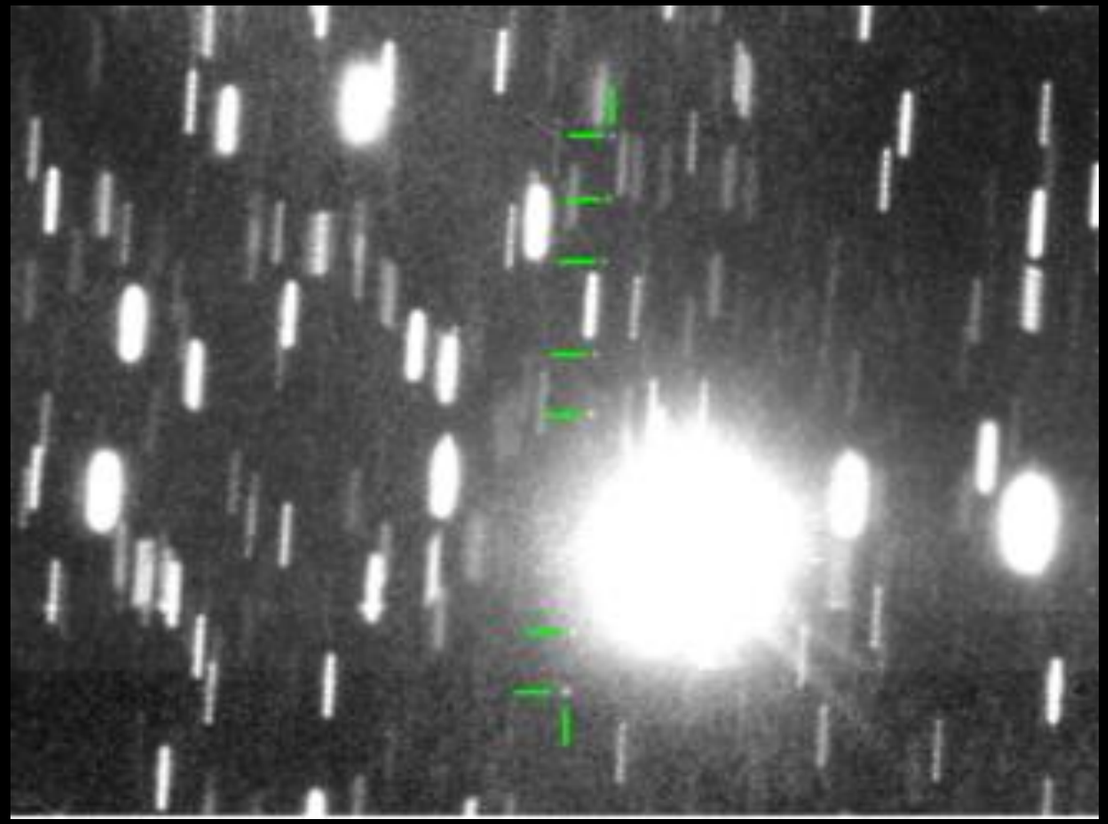
Solar Sail Propulsion System Characteristics

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



NASA Image

Baseline Target Asteroid: 1991 VG

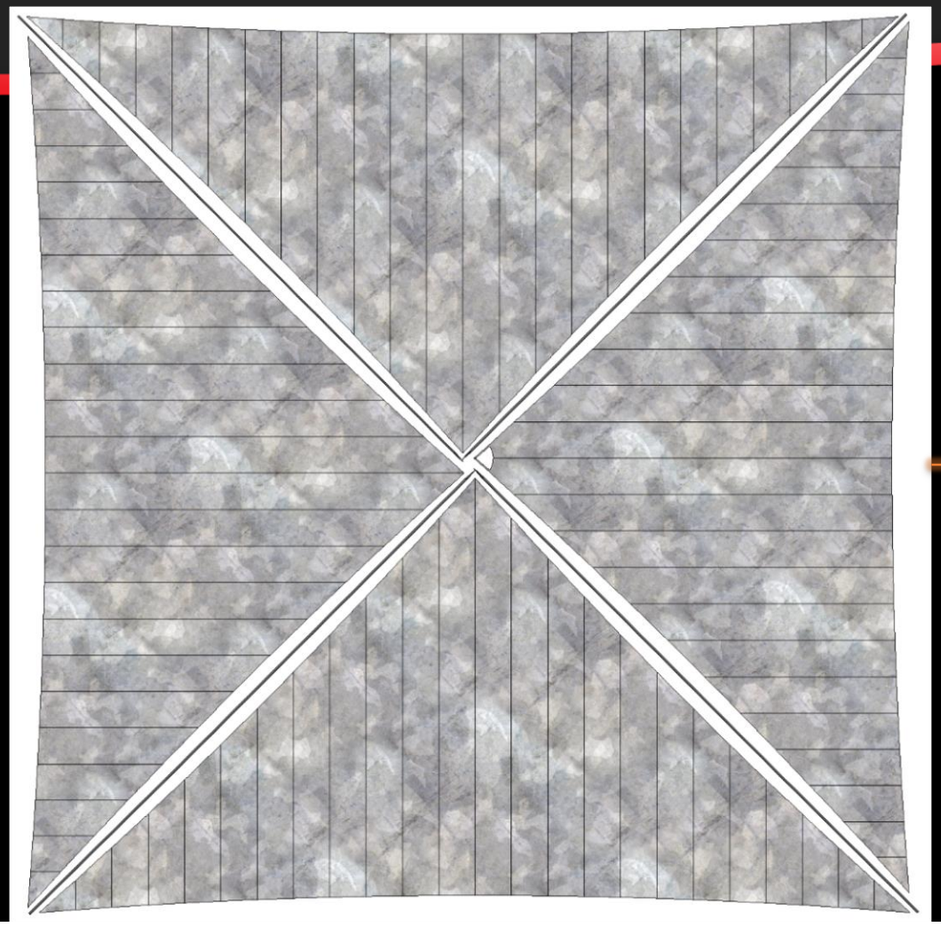


Near-Earth Asteroid 1991VG (marked with green lines) on 2017 May 30. This is a composite of several images obtained with the ESO VLT. The images have been combined in 7 stacks tracking the position of the asteroid, resulting in the object appearing as 7 dots as it moves in front of the background stars. The stars appear trailed due to the motion of the asteroid during each series. Credit Hainaut/Micheli/Koschny

- Diameter ~ 5 -12 meters
- Rotation period between a few minutes and less than 1 hour
- Unlikely to have a companion
- Unlikely to retain an exosphere or dust cloud
  - Solar radiation pressure sweeps dust on timescales of hours or day

NEA Scout Approximate Scale

Deployed Solar Sail

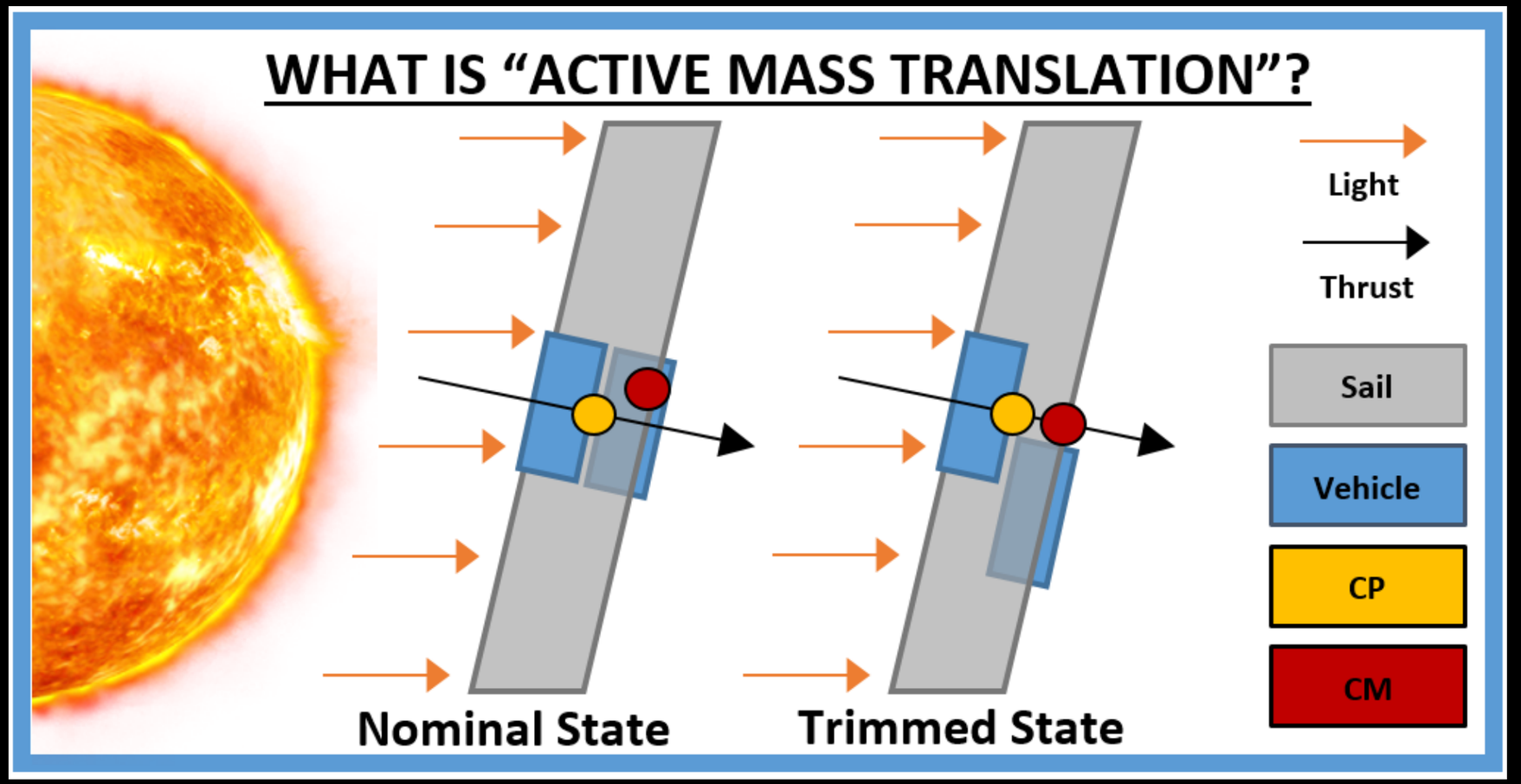


School Bus

6U Stowed Flight System

Folded, spooled and packaged in here

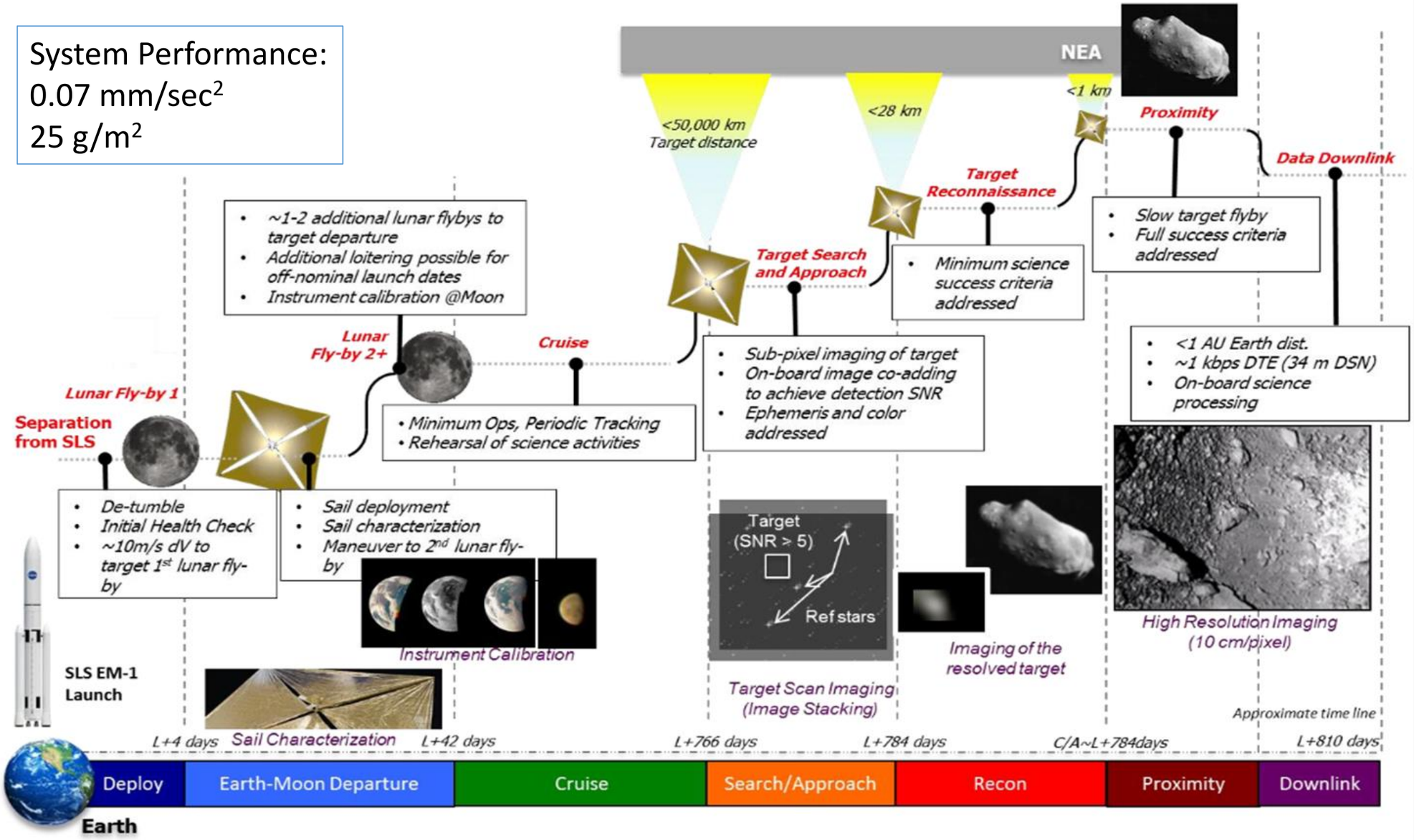
The Need for CM/CP Adjustment



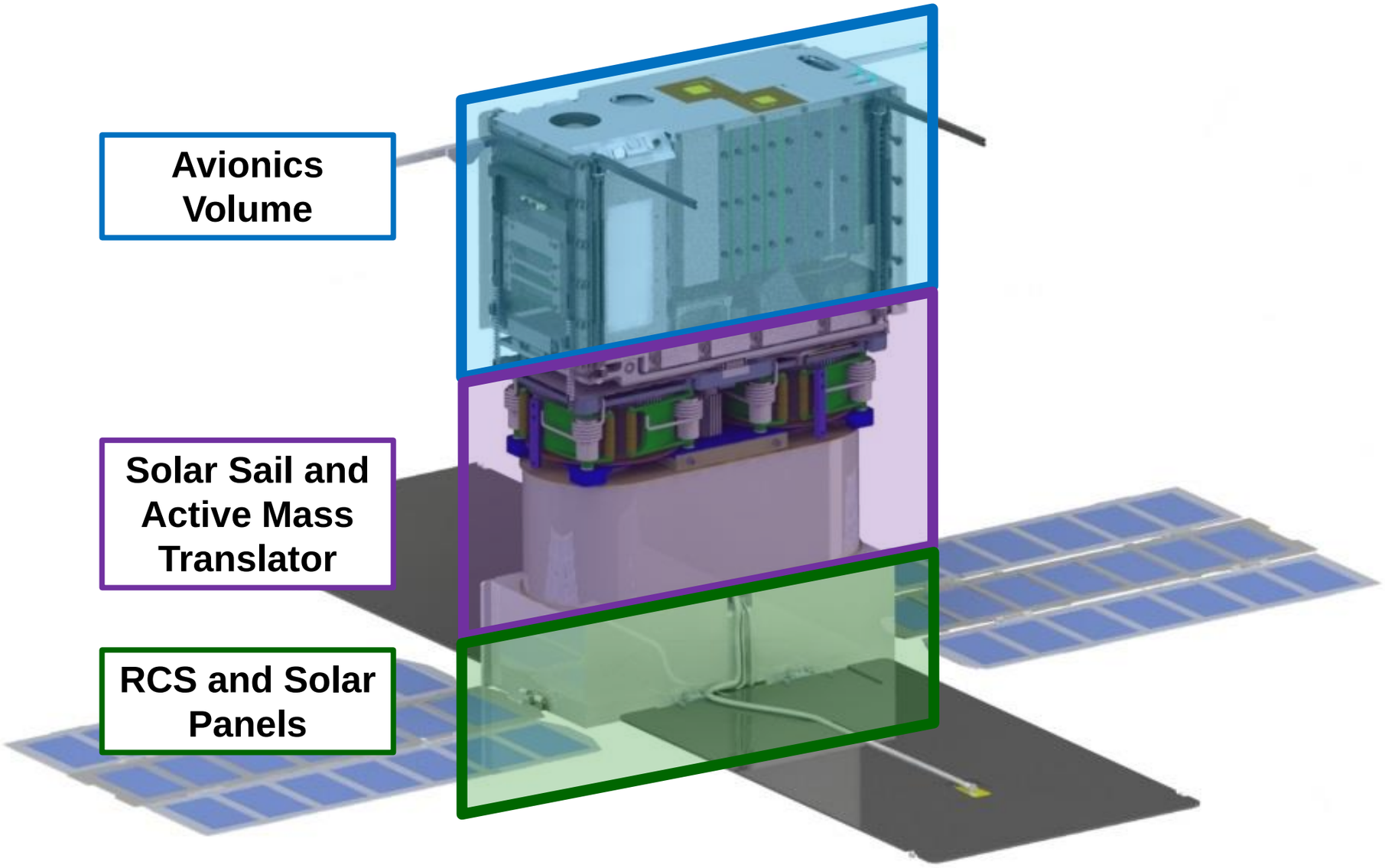
The AMT will move one portion of the NEA Scout relative to the other. This translation of mass will alter the inertial properties of the vehicle and align the CP and CM

NEA Scout – Mission Overview

System Performance:
0.07 mm/sec^2
25 g/m^2

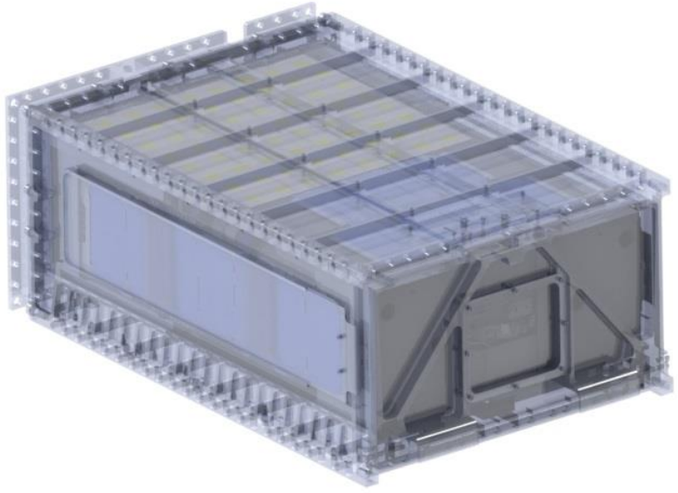


NEA Scout Flight System has 3 Main Sections

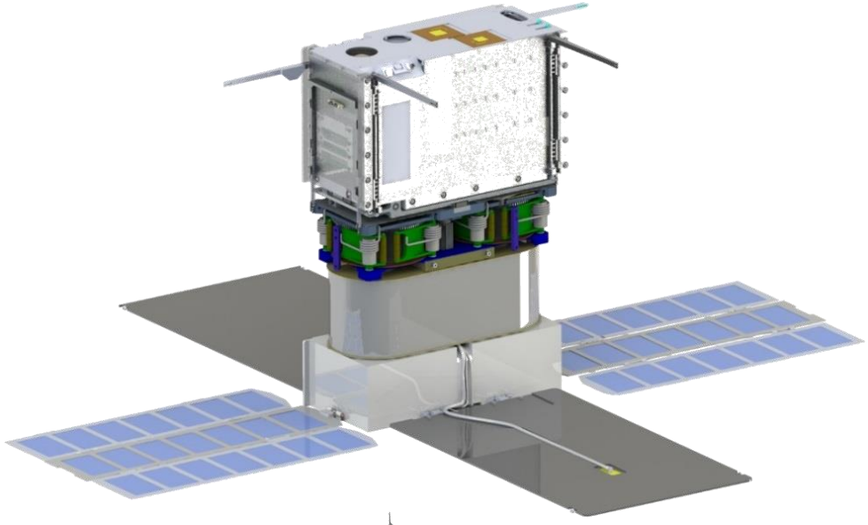


NEAS Configurations

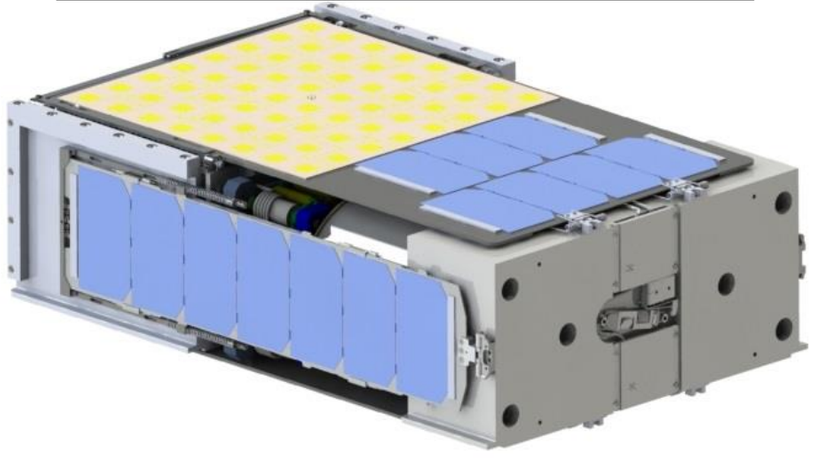
Stowed in Dispenser

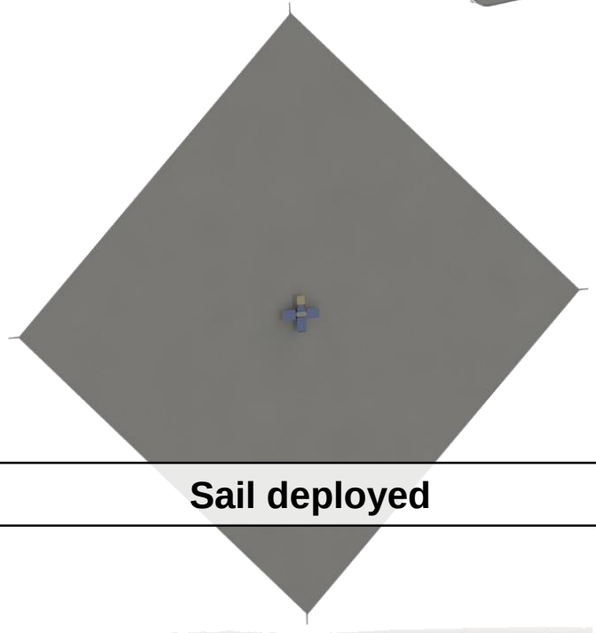


Configuration before sail deployment



Ejection, before panel deployments

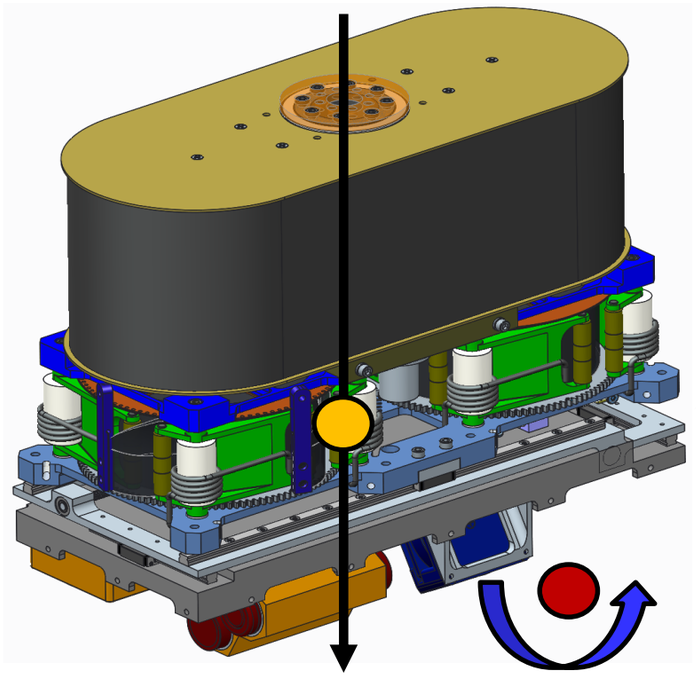




Sail deployed

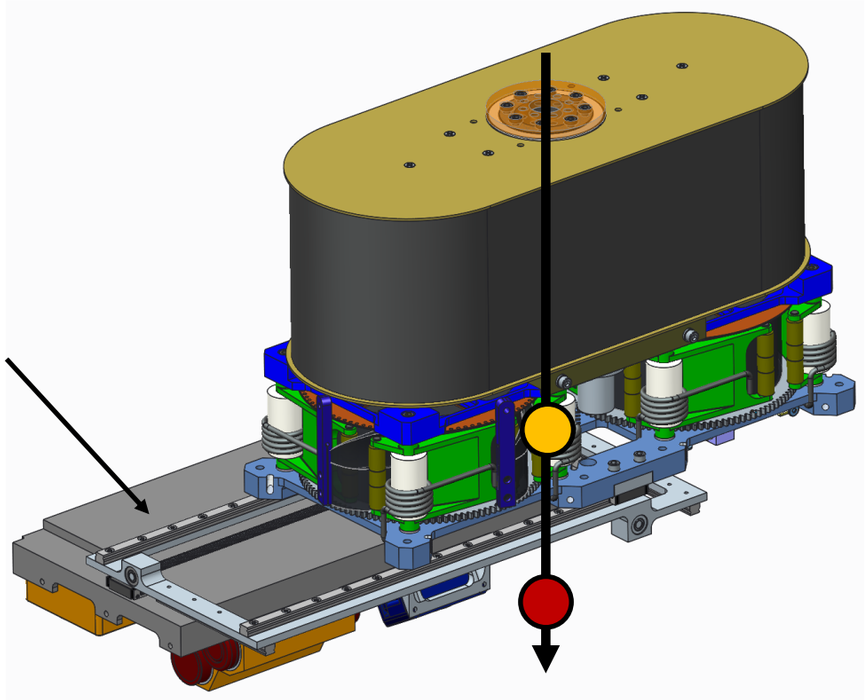
AMT Overview

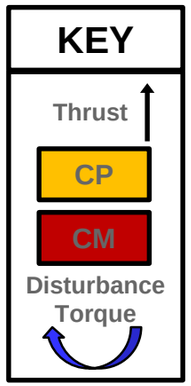
Nominal State

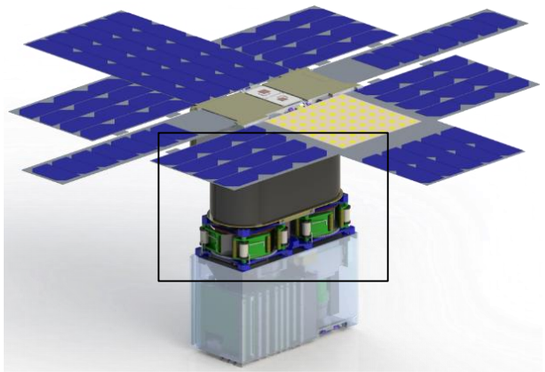


AMT

Trimmed State



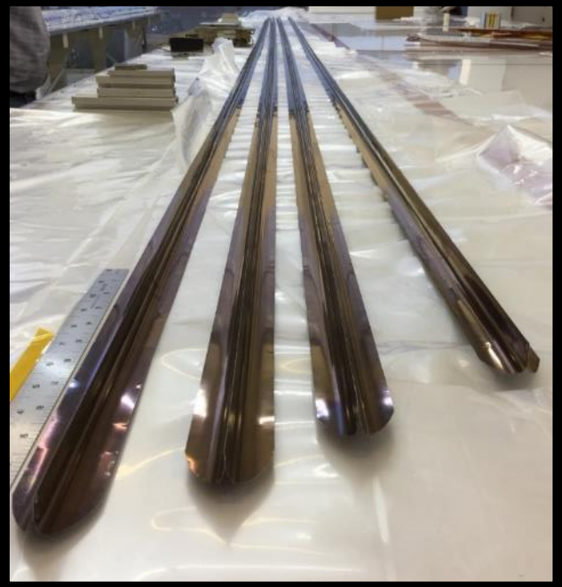


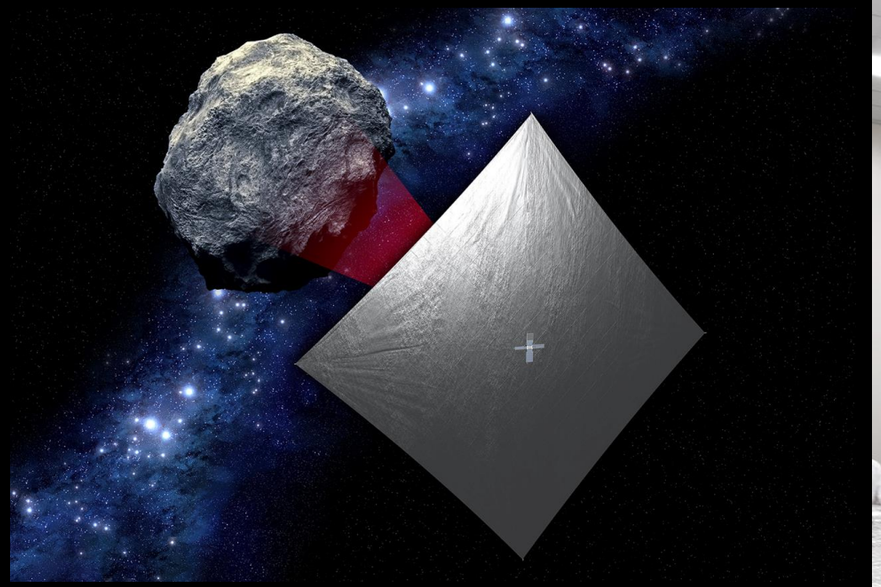


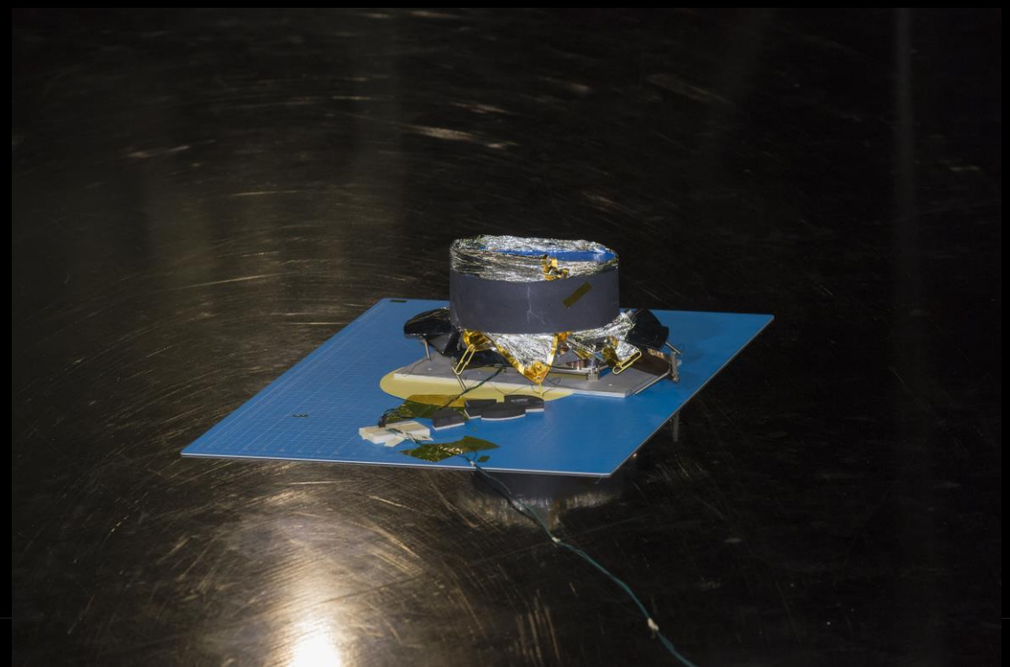
NASA's Near Earth Asteroid Scout Full Scale Successful Deployment

NASA Image

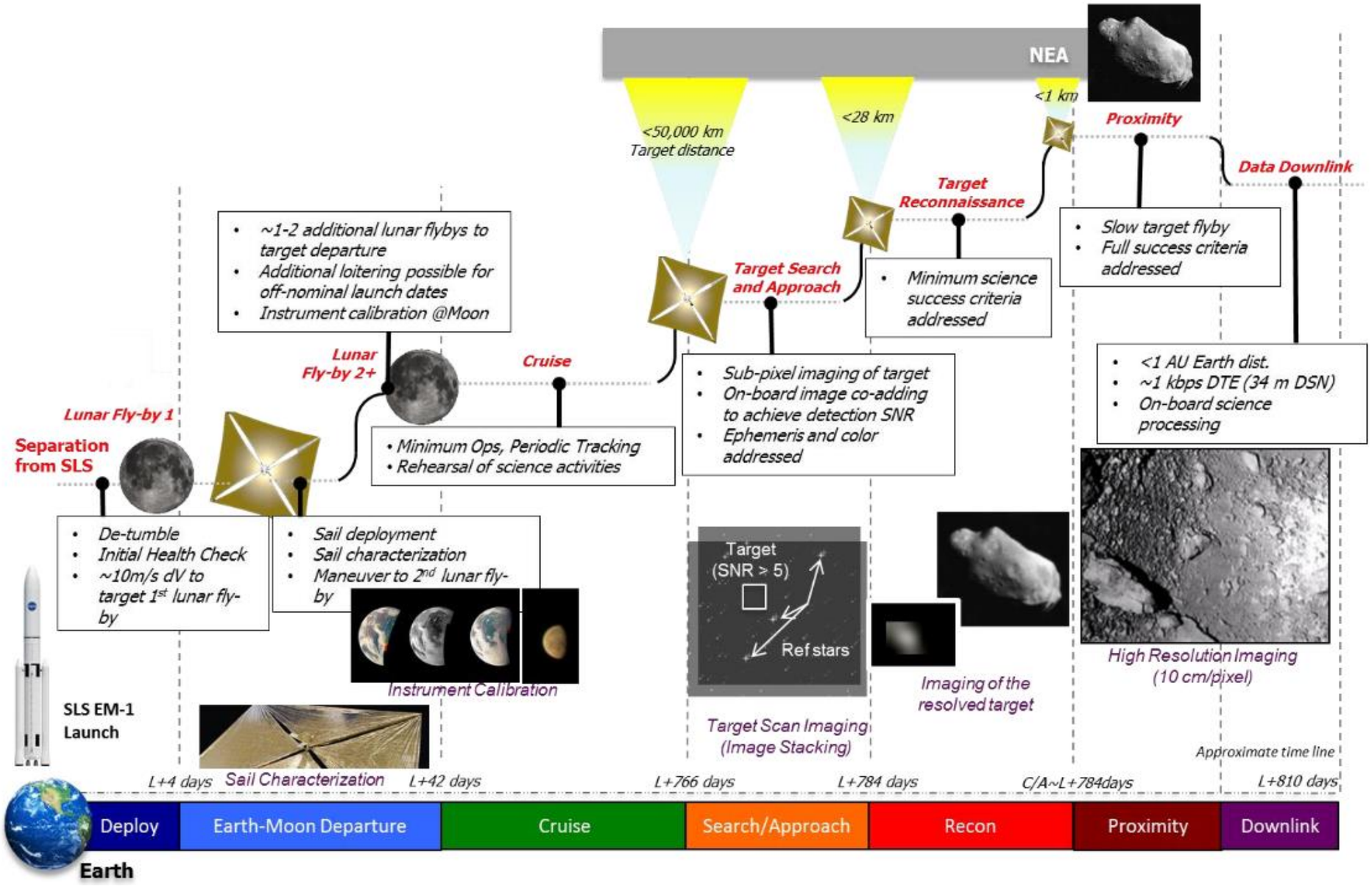
NEA Scout Hardware Ready for Integration





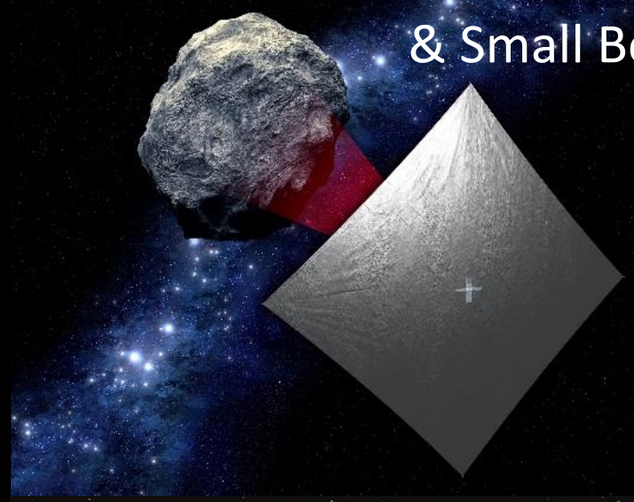


NEA Scout: Concept of Operations Overview

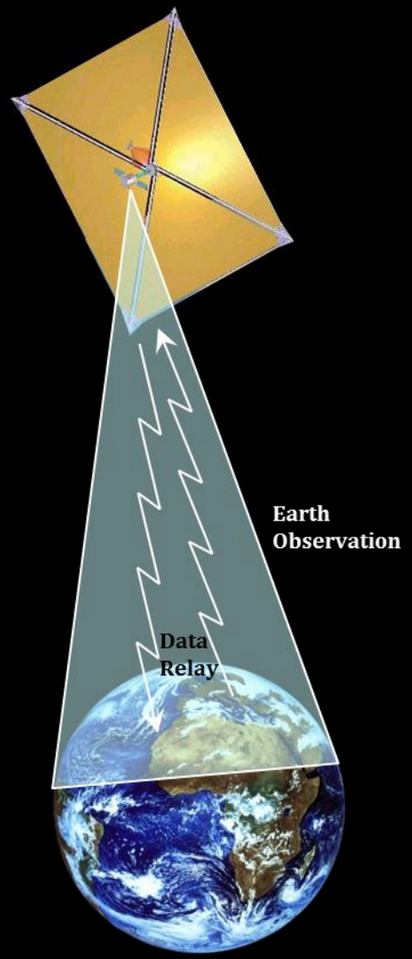


Potential Future Solar Sail Applications
(A Partial List!)

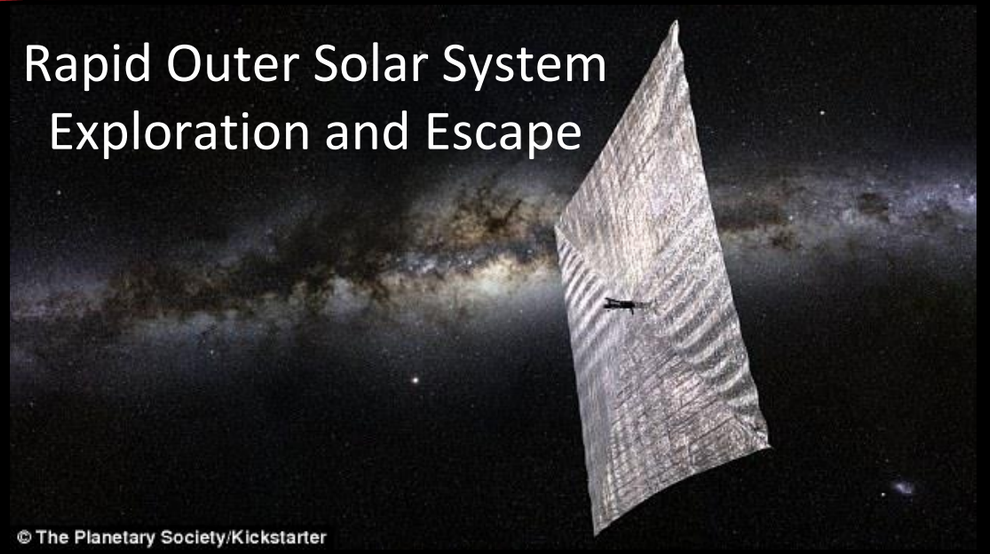
NEA Reconnaissance & Small Body Science



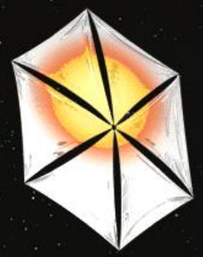
Earth Pole Sitting



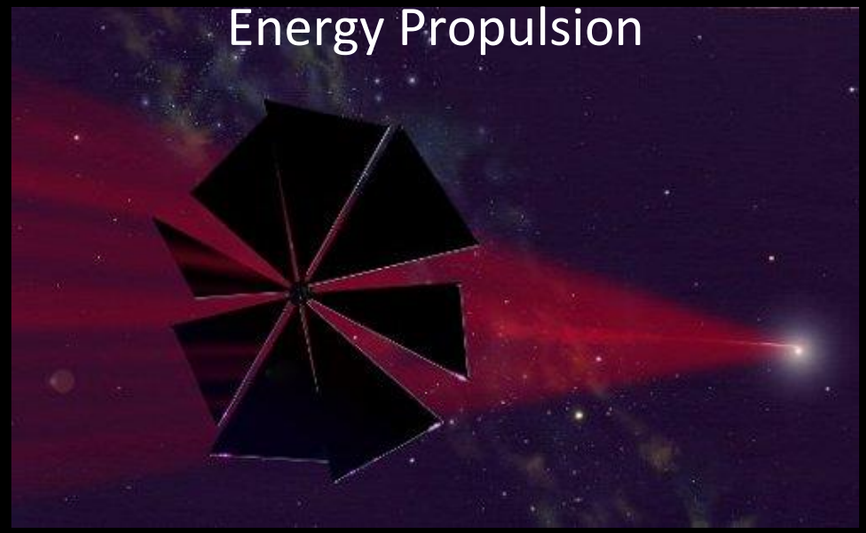
Rapid Outer Solar System Exploration and Escape



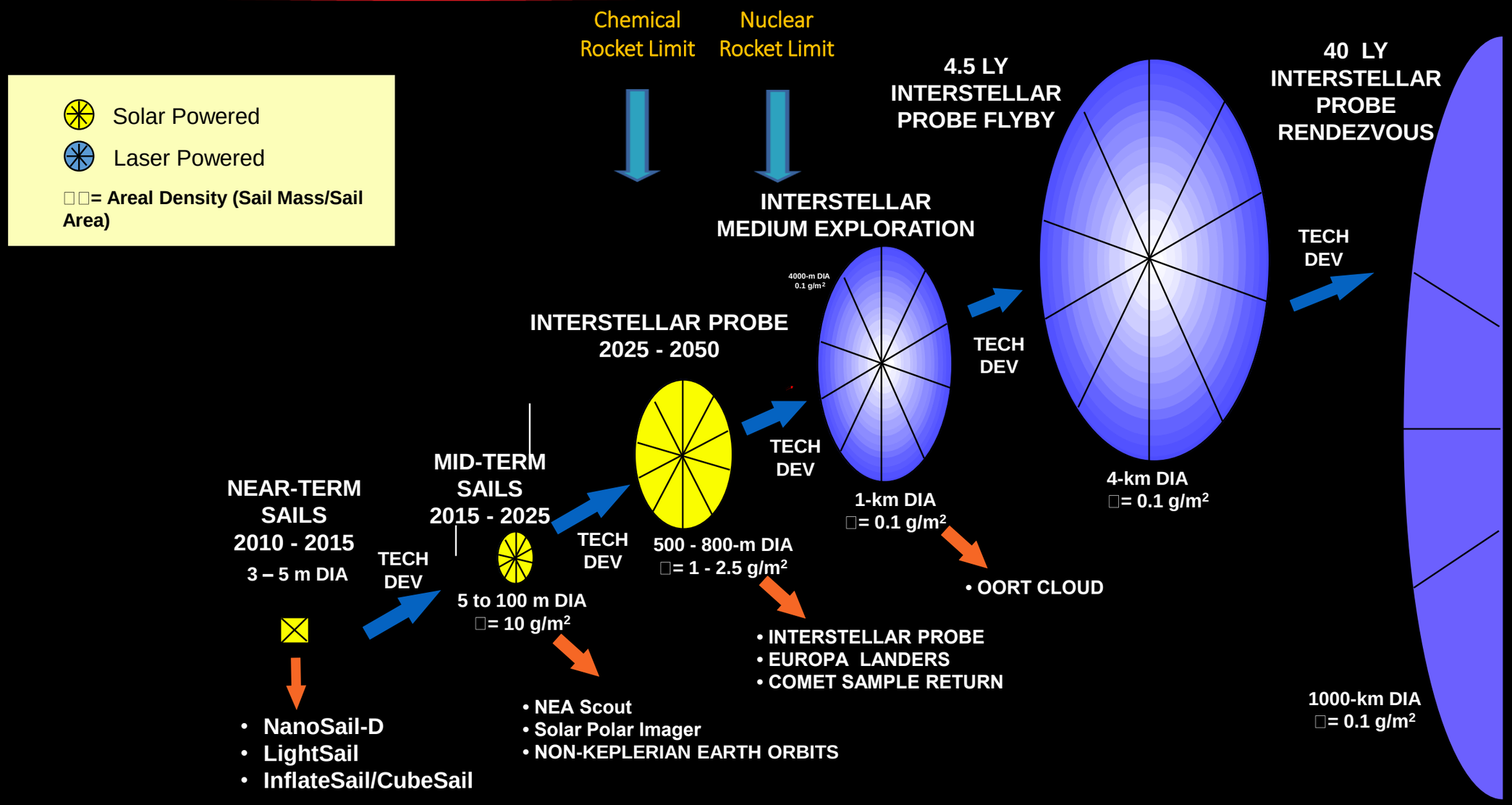
Heliophysics & Out of the Ecliptic Science



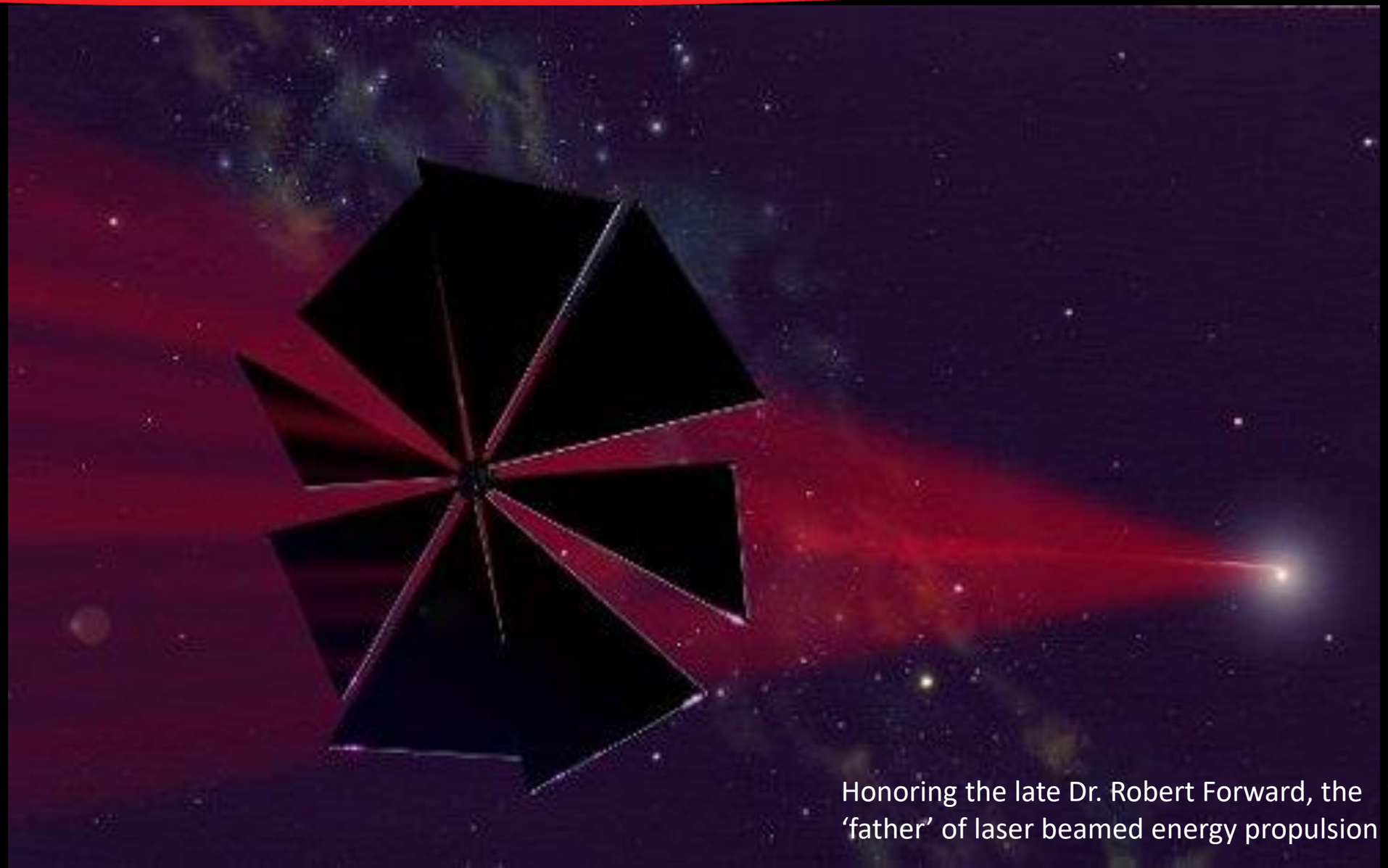
Toward Higher Performance Beamed Energy Propulsion



My Real Motive…
Going to the Stars!



Solar Sails: A Step Toward the Stars



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

Questions?