



Solar Sail Propulsion for Deep Space Exploration

Les Johnson

NASA
George C. Marshall Space Flight Center

NASA Image



We tend to think of space as being



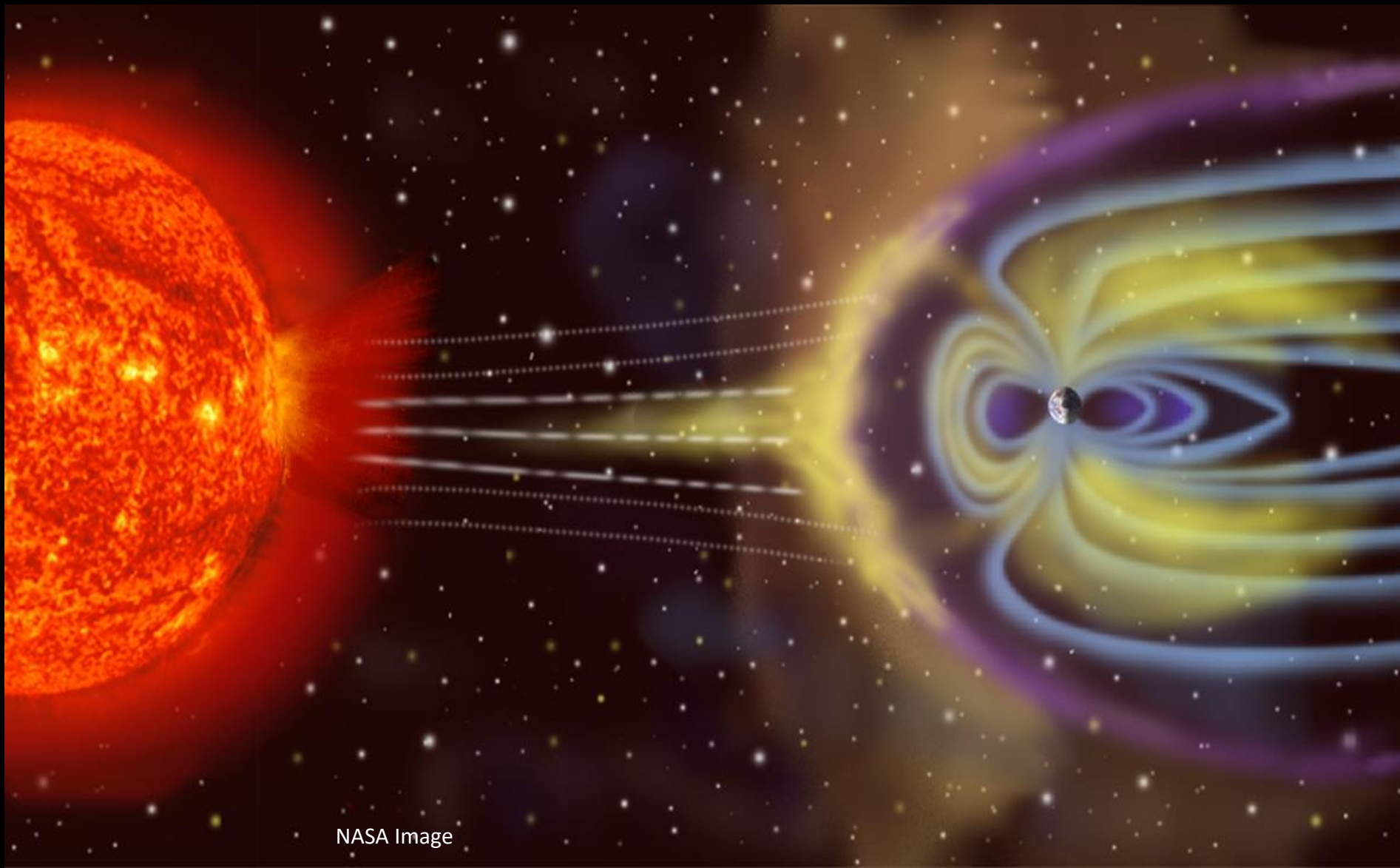
big and empty...



NASA Image



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



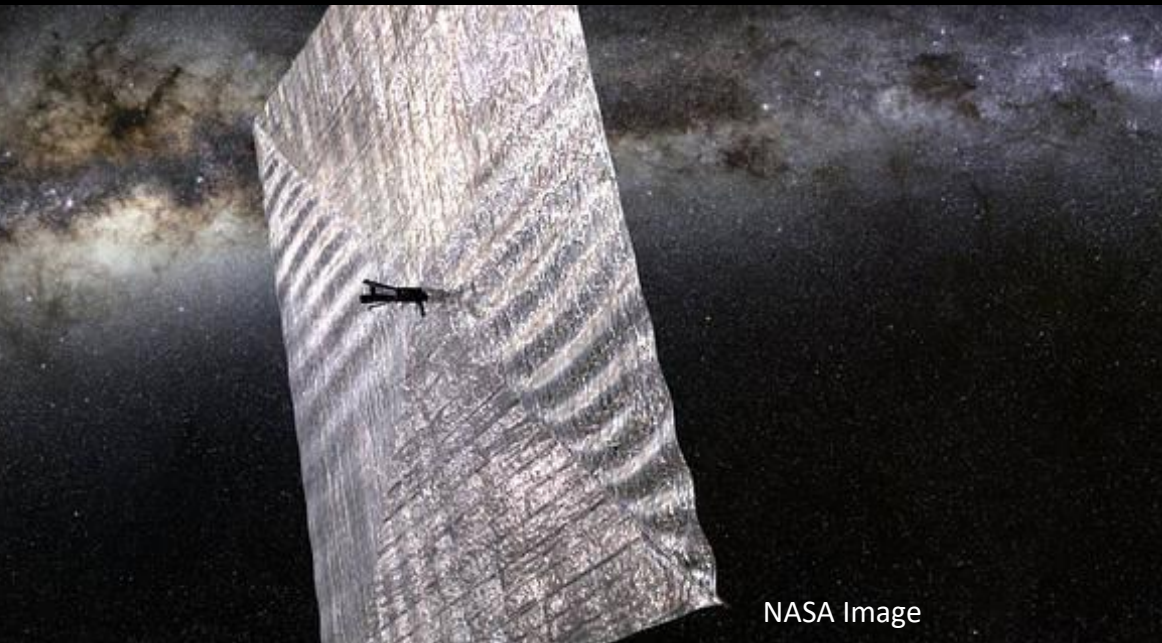
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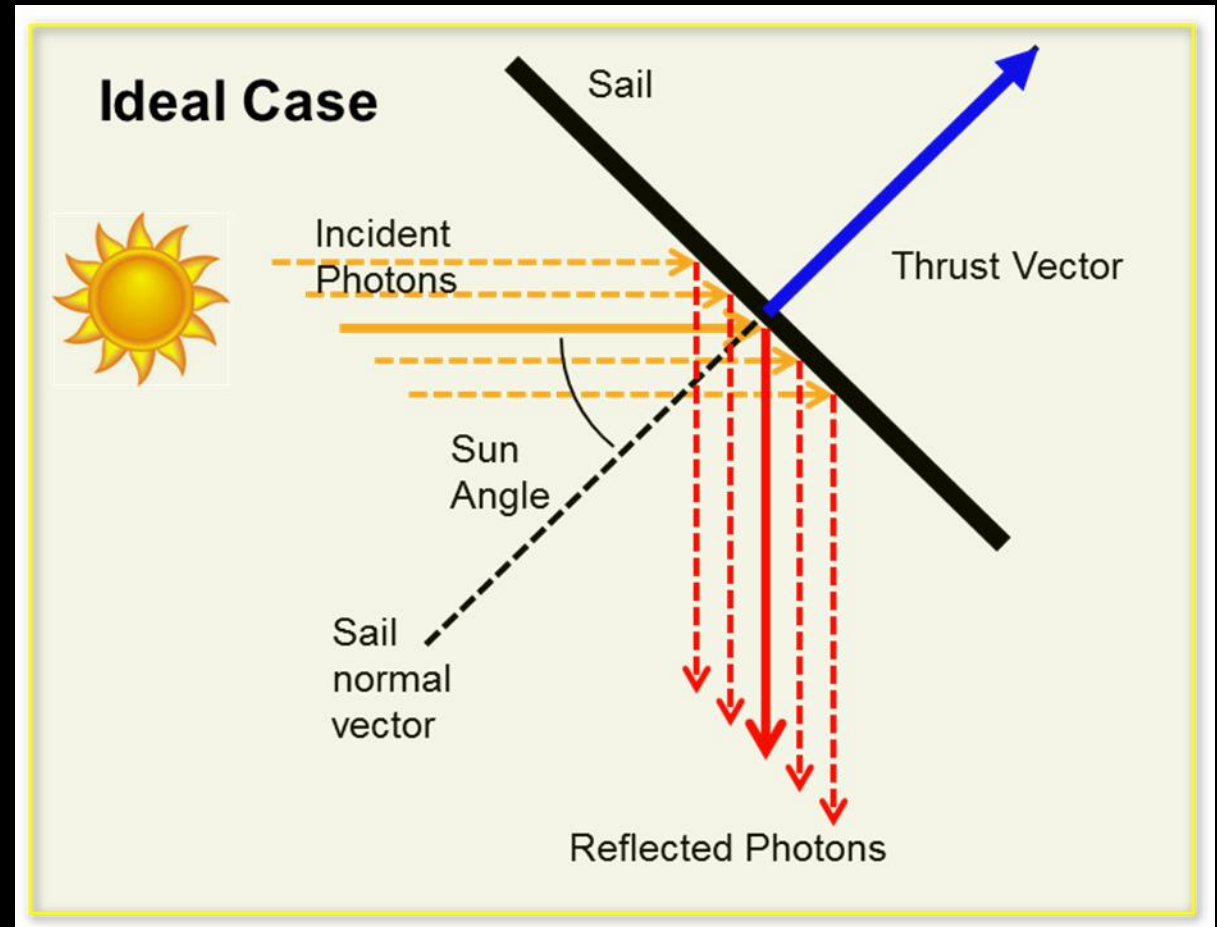
Solar Sails Derive Propulsion By Reflecting Photons



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



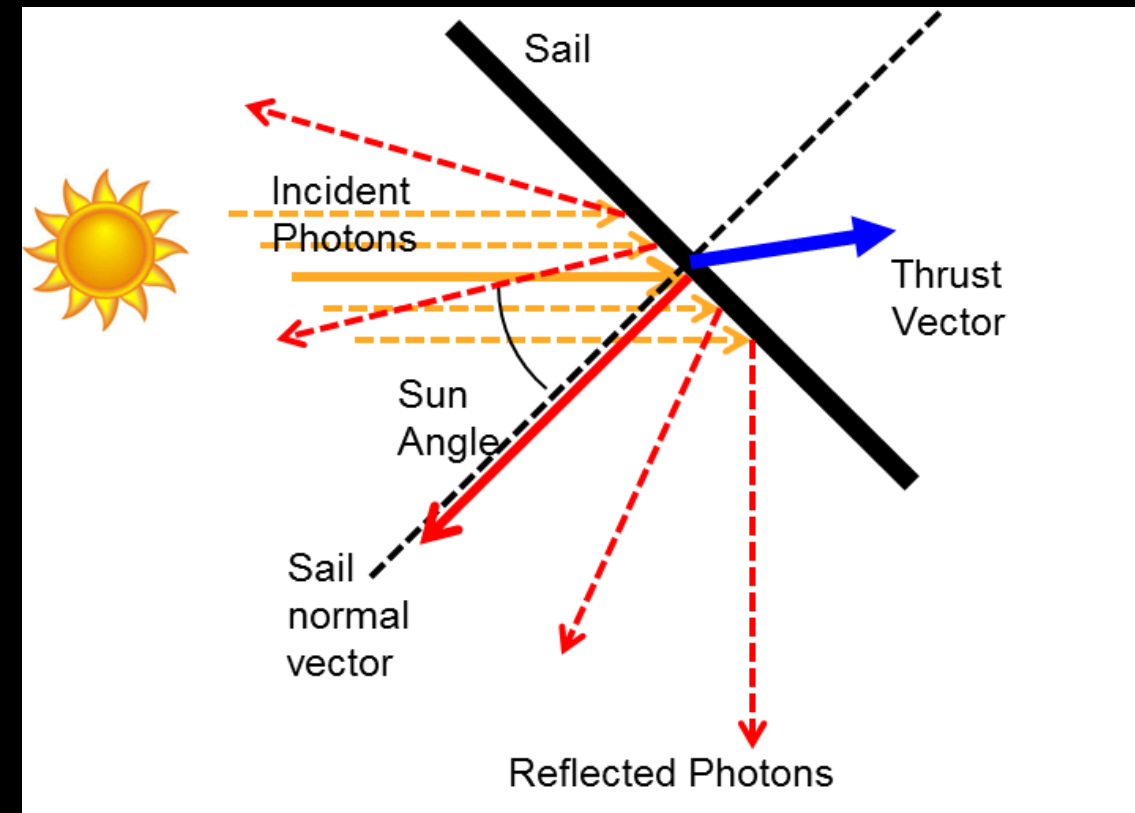
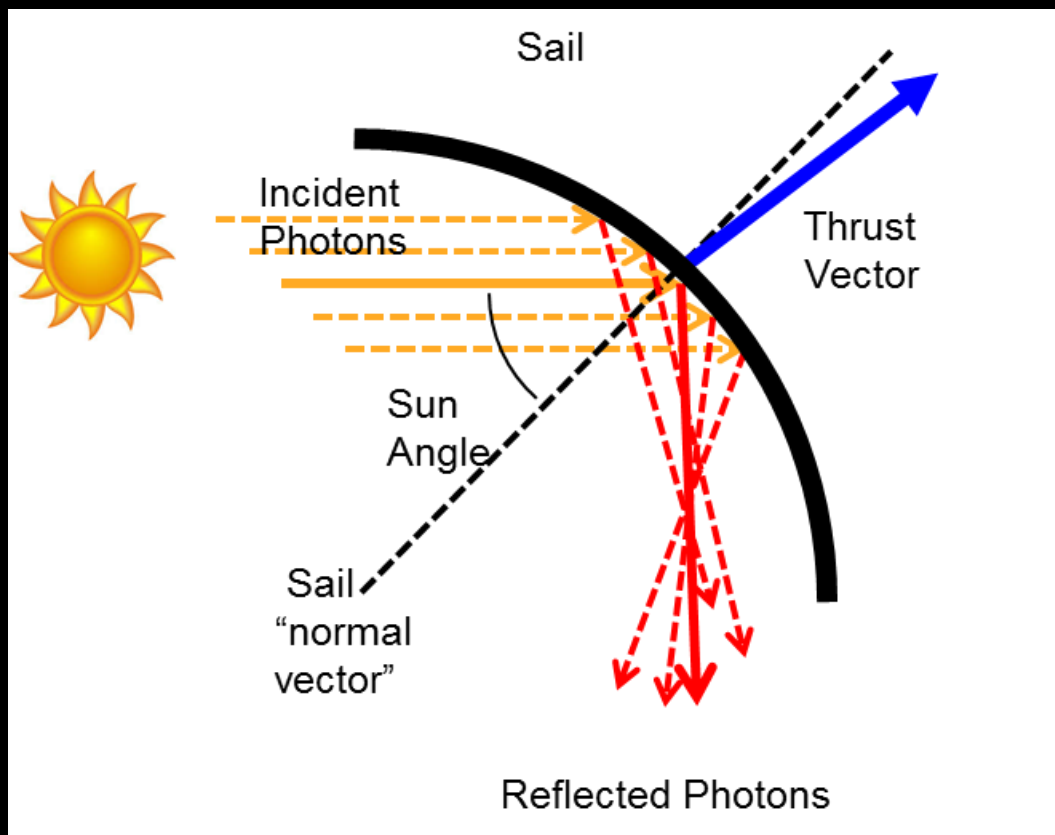
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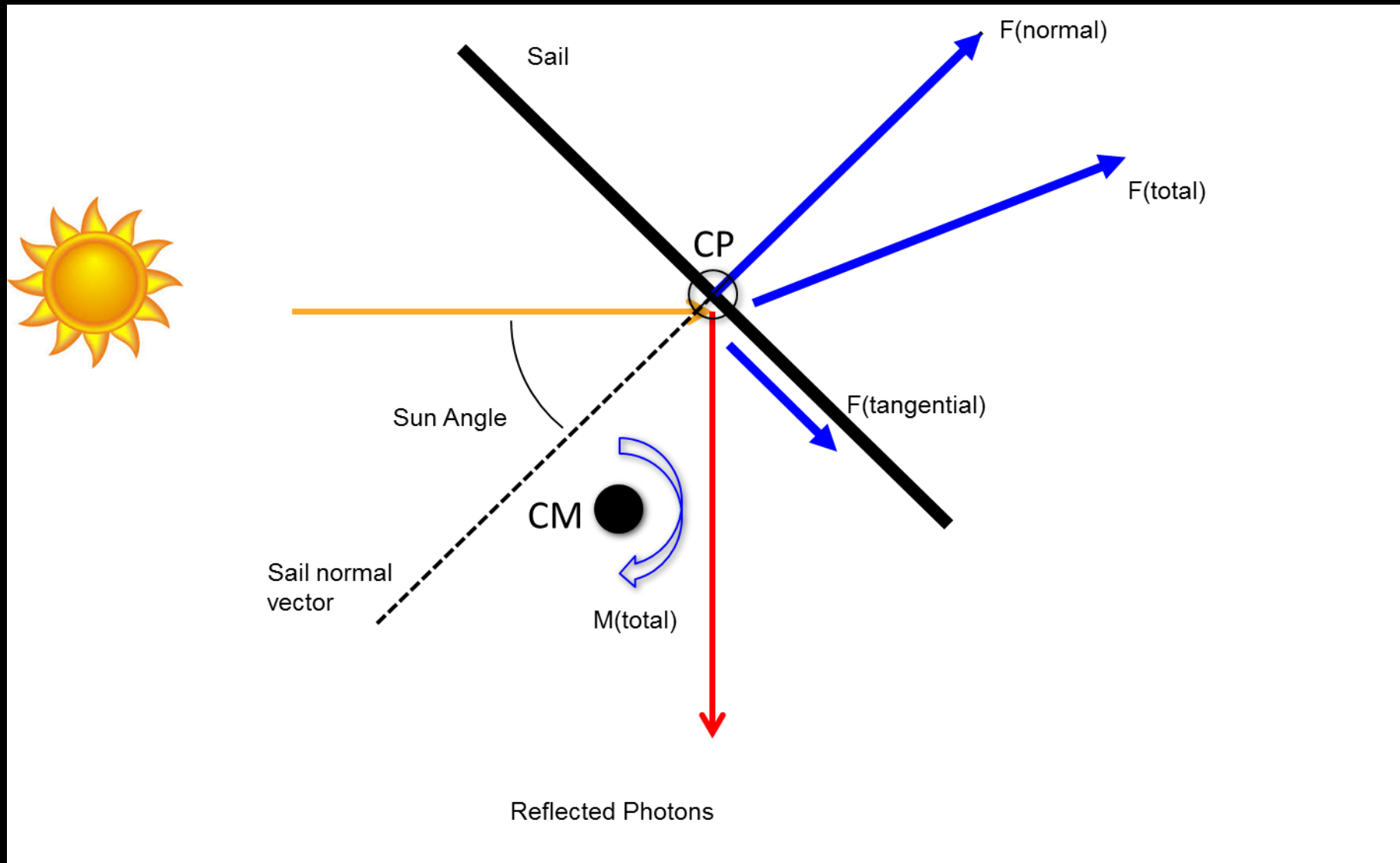
Real Solar Sails Are Not “Ideal”

Billowed Quadrant



Diffuse Reflection

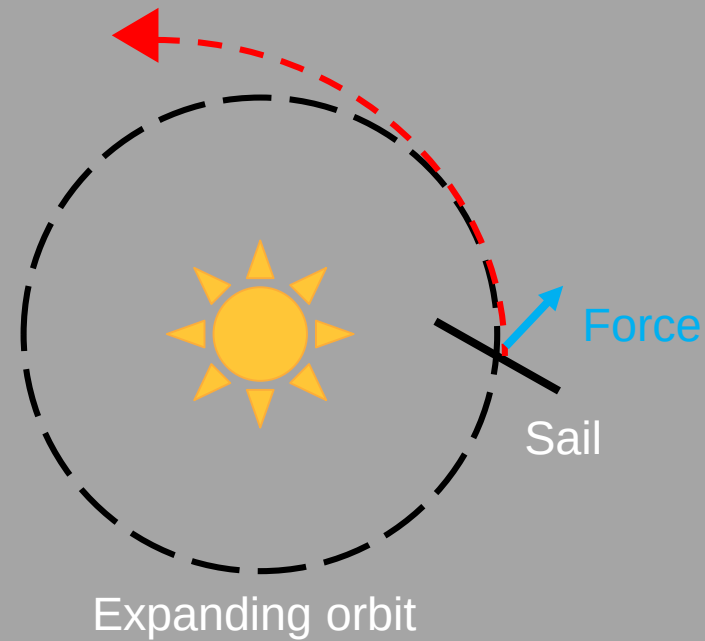
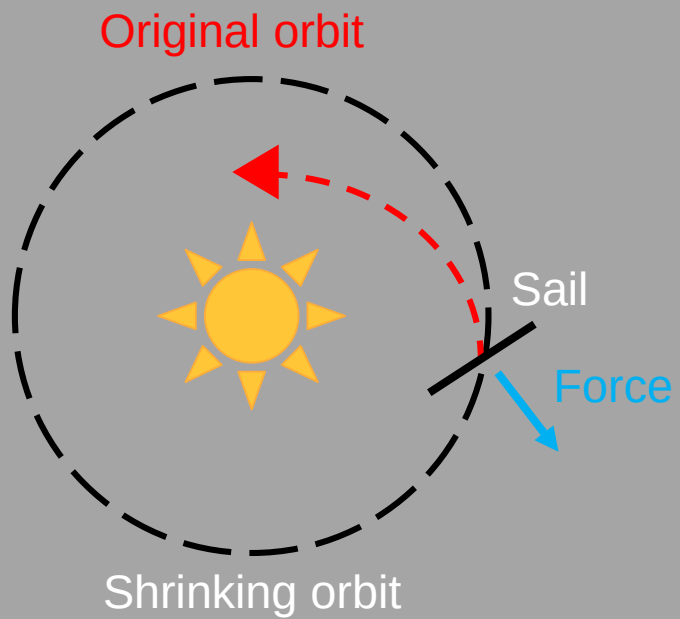
Thrust Vector Components





Solar Sail Trajectory Control

Solar Radiation Pressure allows inward or outward Spiral

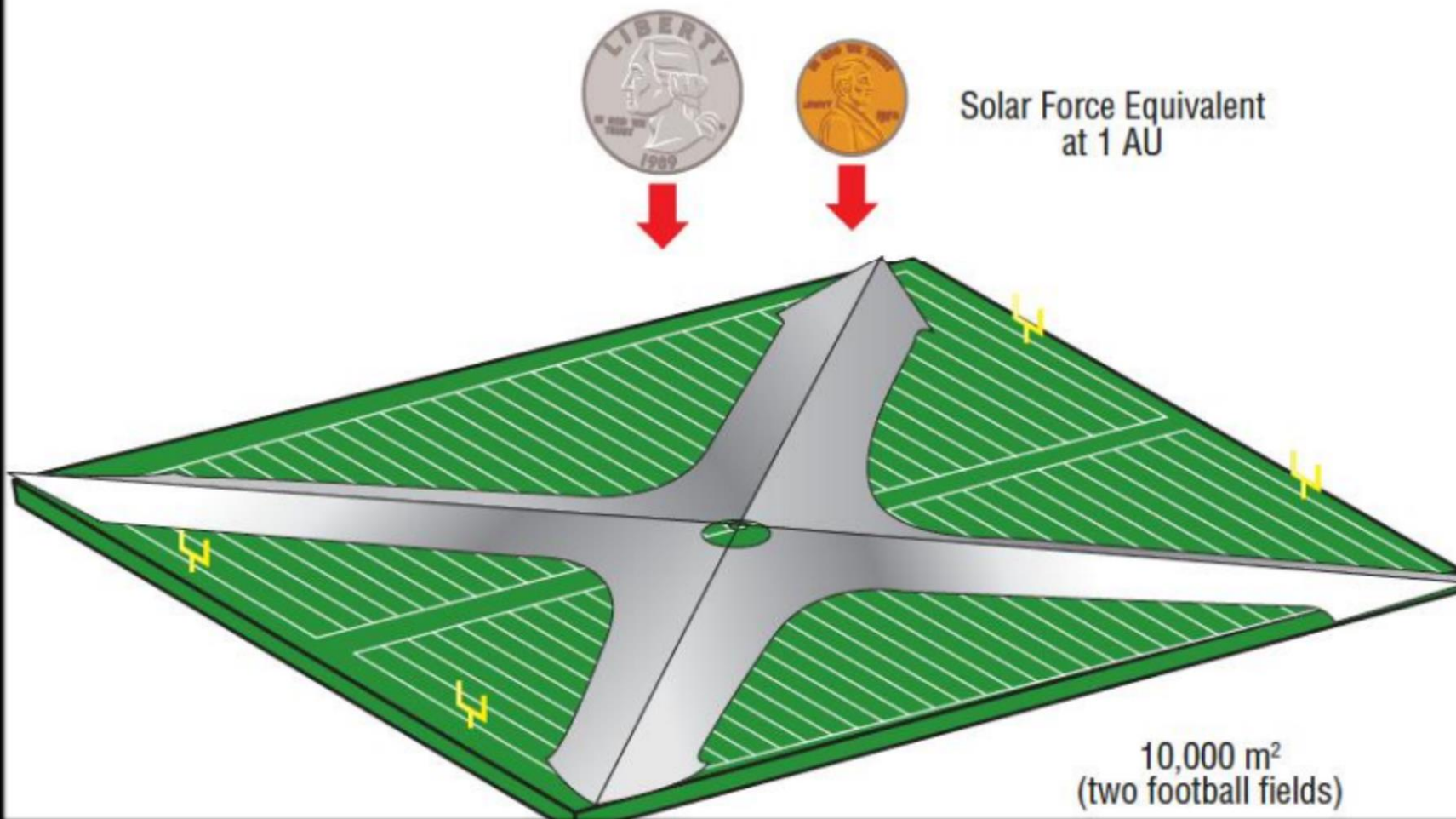




Solar Sails Experience **VERY** Small Forces



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





Solar Sail Missions Flown

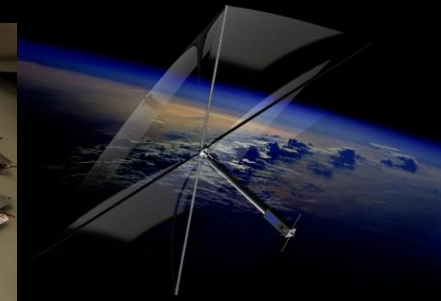
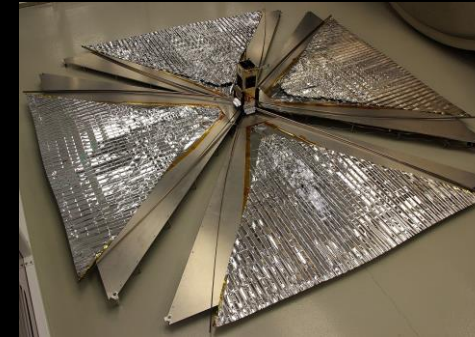
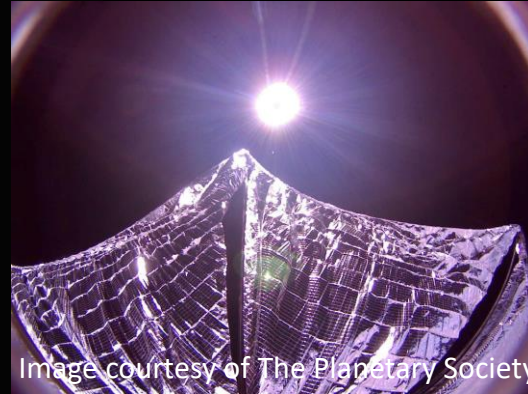
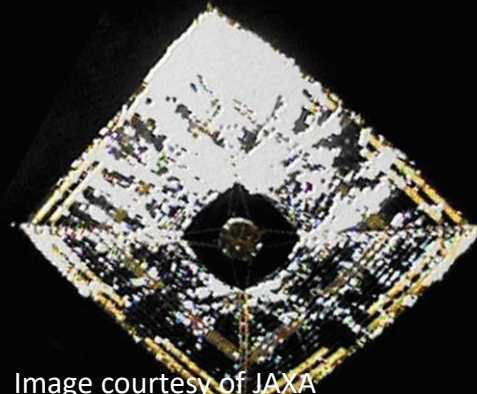
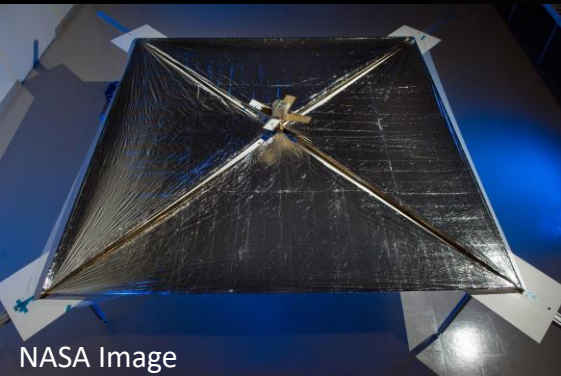


Image courtesy of Univ. Surrey

NanoSail-D (2010)
NASA

IKAROS (2010)
JAXA

LightSail-1 & 2
(2015/2019)
The Planetary Society

CanX-7 (2016)
Canada

InflateSail (2017)
EU/Univ. of Surrey

Earth Orbit
Deployment Only

Interplanetary
Full Flight

Earth Orbit
Deployment / Flight

Earth Orbit
Deployment Only

Earth Orbit
Deployment Only

3U CubeSat
10 m²

315 kg Smallsat
196 m²

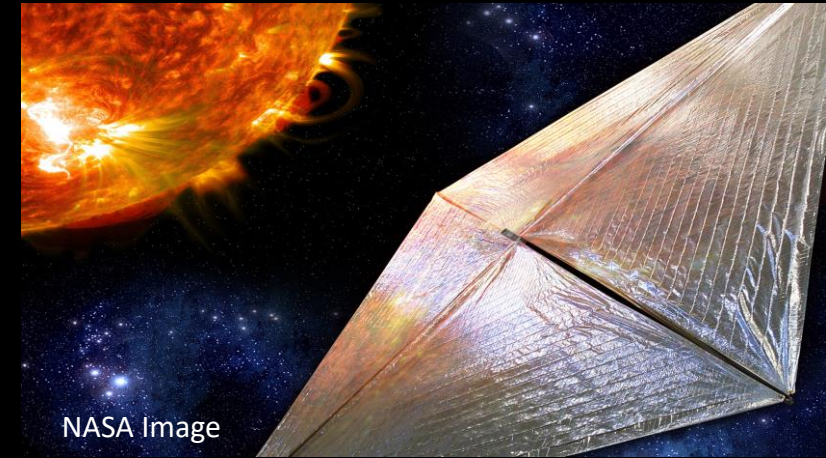
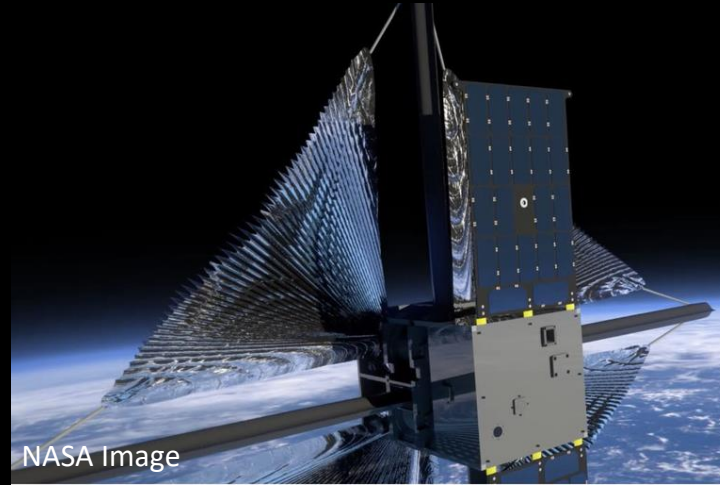
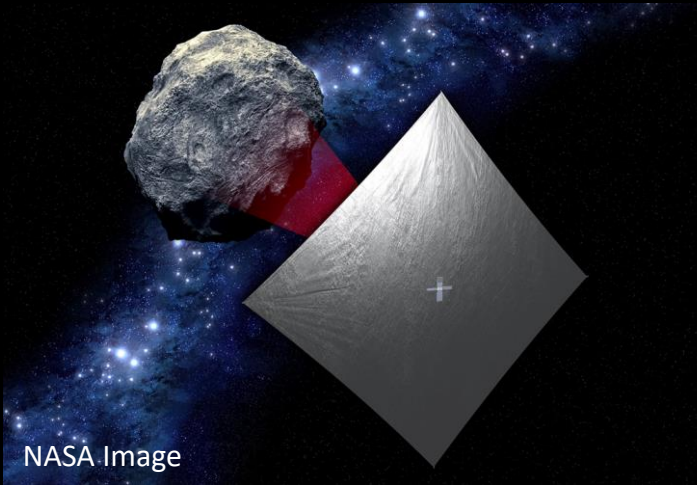
3U CubeSat
32 m²

3U CubeSat
<10 m²

3U CubeSat
10 m²



Planned Solar Sail Missions



**Near Earth Asteroid Scout
(2021) NASA**

**Interplanetary
Full Flight**

**6U CubeSat
86 m²**

**Advanced Composite Solar
Sail System (TBD) NASA**

**Earth Orbit
Full Flight**

**12U CubeSat
74 m²**

Solar Cruiser (2025) NASA

**Interplanetary
Full Flight**

**100 kg spacecraft
1653 m²**



Near Earth Asteroid Scout

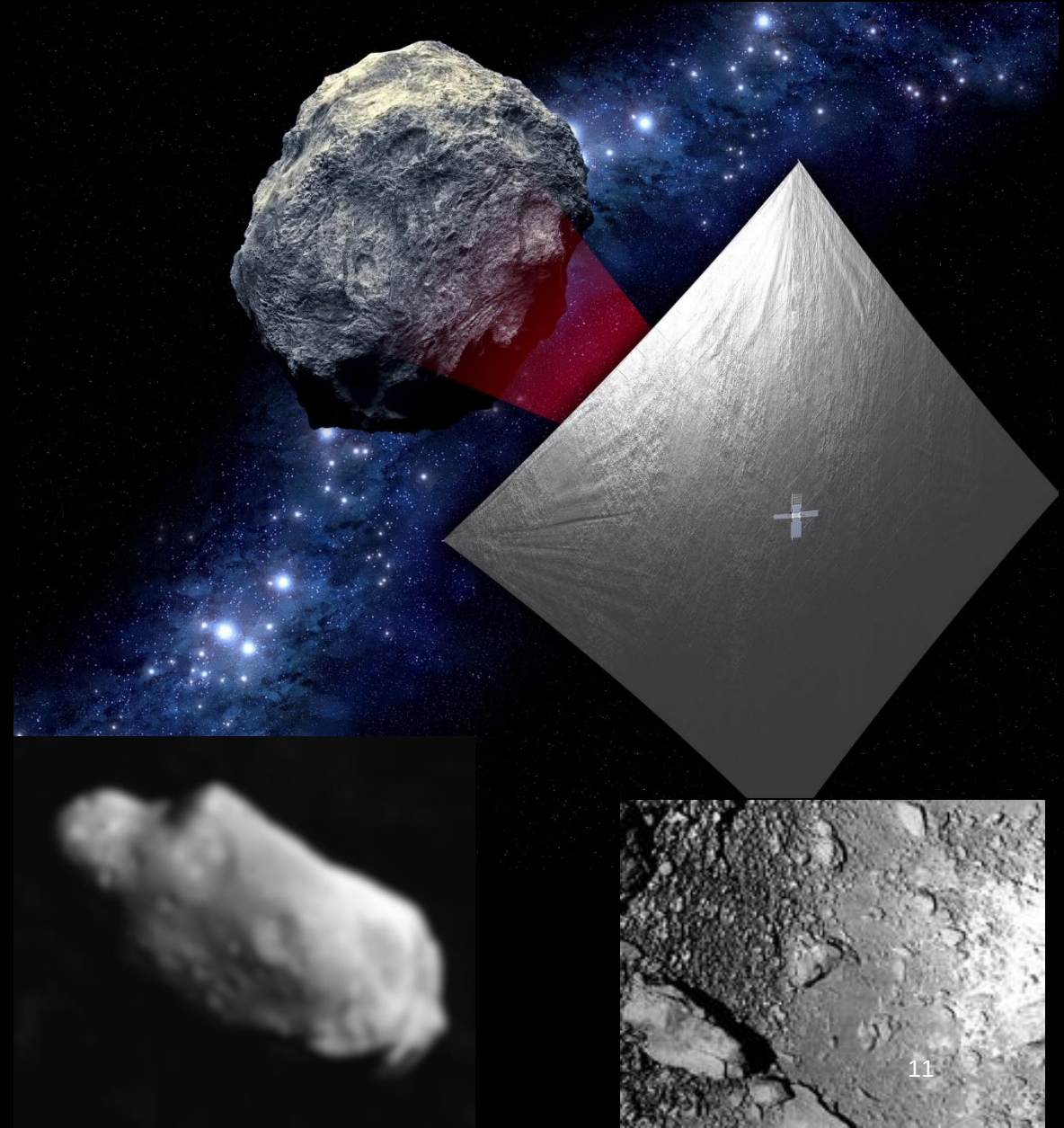


GOALS

- Characterize a Near Earth Asteroid for possible future human visits

Key Spacecraft & Mission Parameters

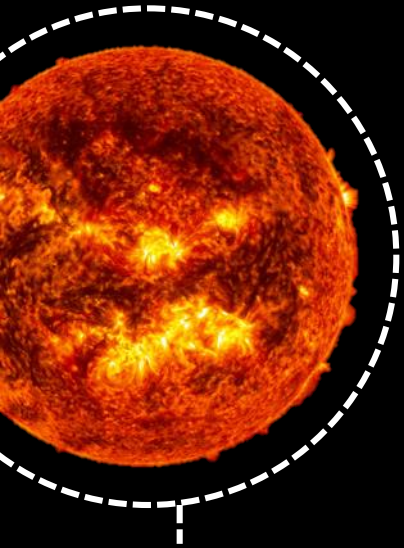
- 6U cubesat (20cm X 10cm X 30 cm)
- ~86 m² solar sail propulsion system
- Manifested for launch on the Space Launch System (Artemis 1 / 2021)
- 1 AU maximum distance from Earth



NEA Scout is one of 13 Secondary Payloads on Artemis 1



SMALLSATS TO BE DEPLOYED FROM THE ORION STAGE ADAPTER



SUN

- CuSP (Southwest Research Institute)

MOON

- Lunar Flashlight (NASA)
- Lunar IceCube (Morehead State University)
- LunaH-Map (Arizona State University)
- OMOTENASHI (JAXA)
- LunIR (Lockheed Martin)
- EQUULEUS (JAXA)



EARTH-MOON

- ArgoMoon (ESA/ASI)

ASTEROID

- NEA Scout (NASA)



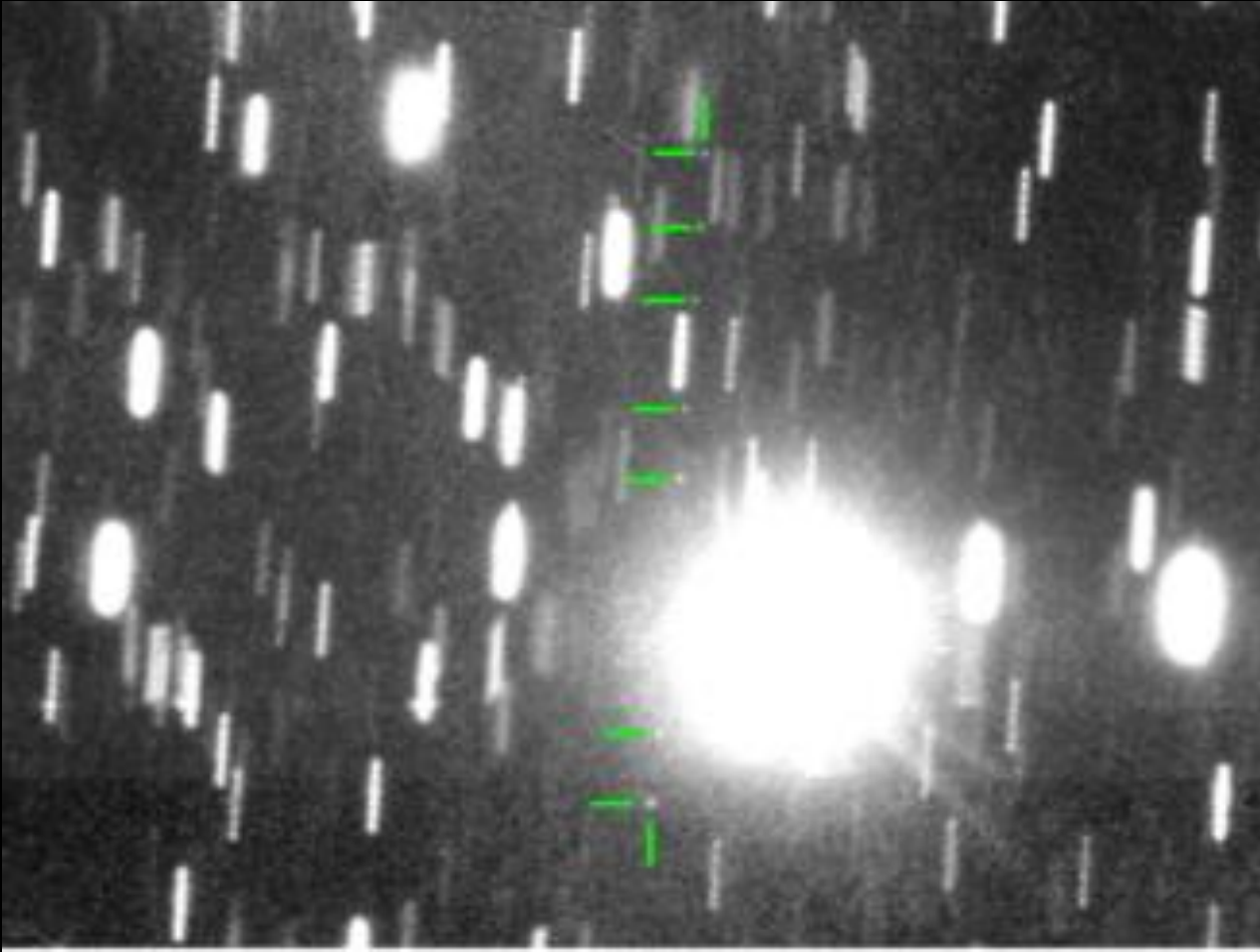
...AND MORE

- Biosentinel (NASA)
- Cislunar Explorers (Cornell University)
- CU-E³ (University of Colorado Boulder)
- Team Miles (Miles Space)



NEA Scout

Candidate Asteroid: 1991 VG



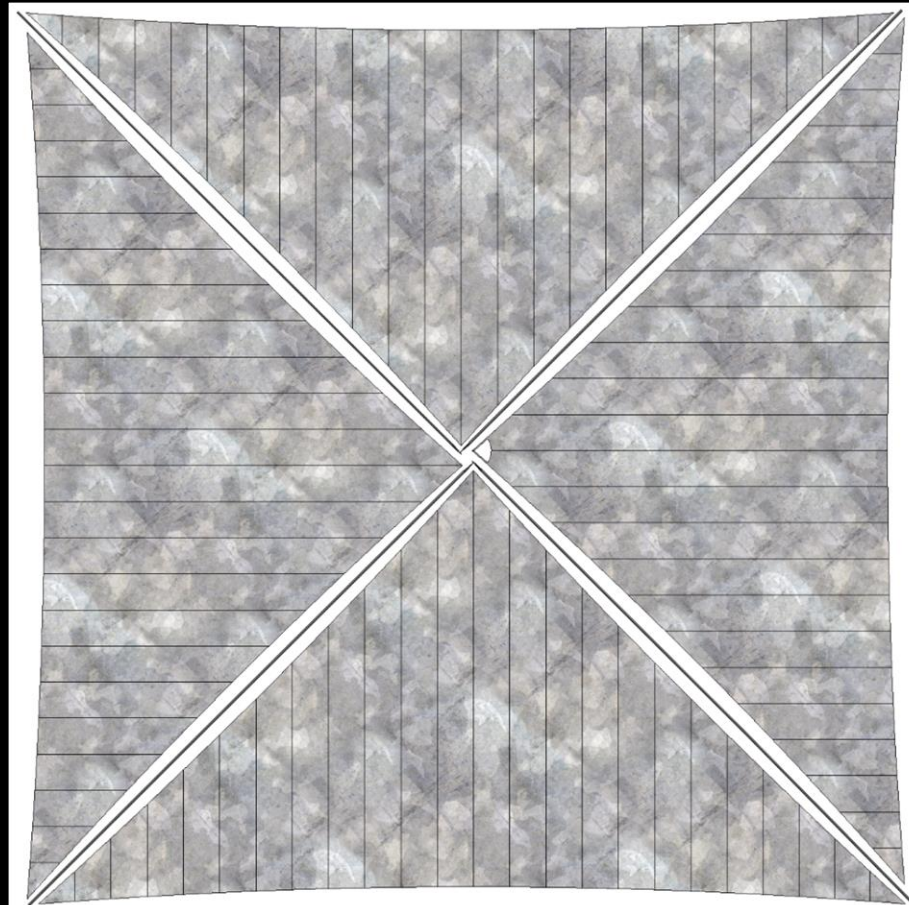
- Diameter ~ 5 -12 meters
- Rotation period between a few minutes and less than 1 hour
- Unlikely to have a companion
- Unlikely to retain an exosphere or dust cloud
 - Solar radiation pressure sweeps dust on timescales of hours or day



~9 x ~9m Solar Sail (NEA Scout)



Deployed Solar Sail



School Bus



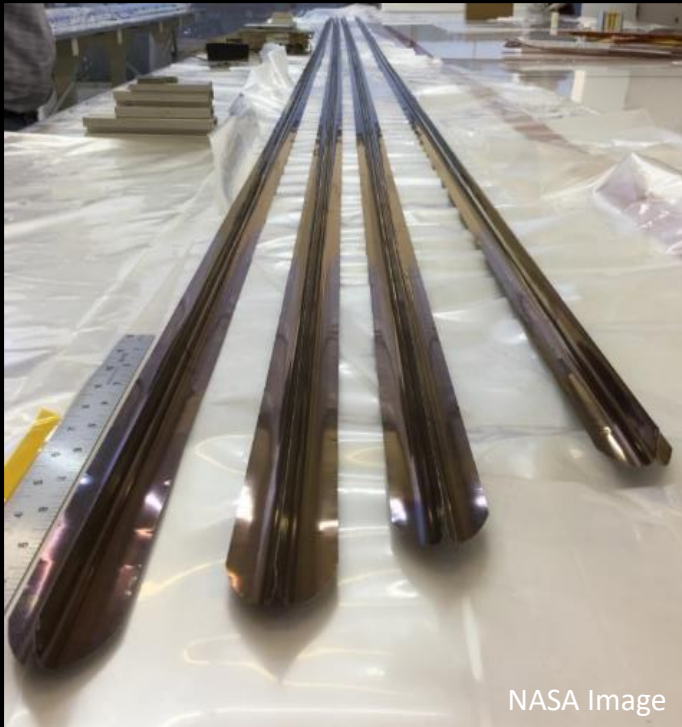
6U
Stowed
Flight
System



Folded, spooled and packaged in here



NEA Scout Flight Sail Testing



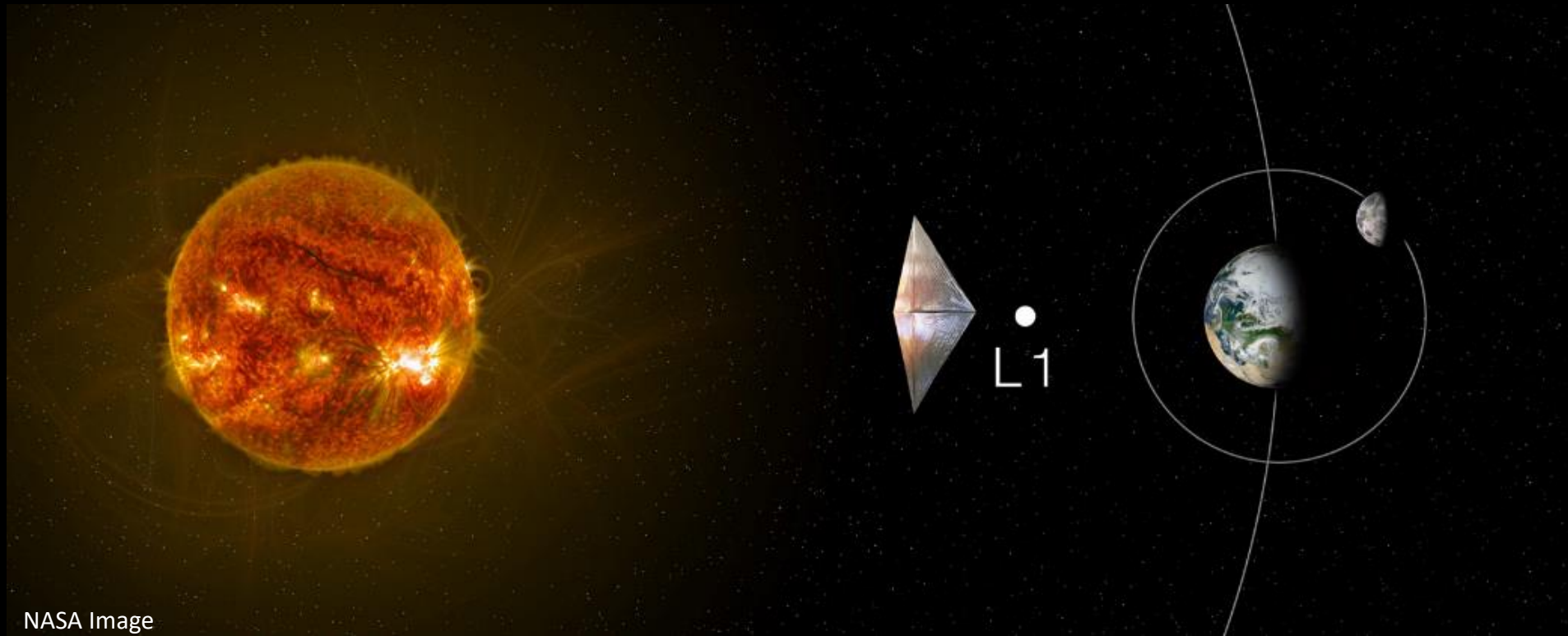
NASA Image

7.3 m booms



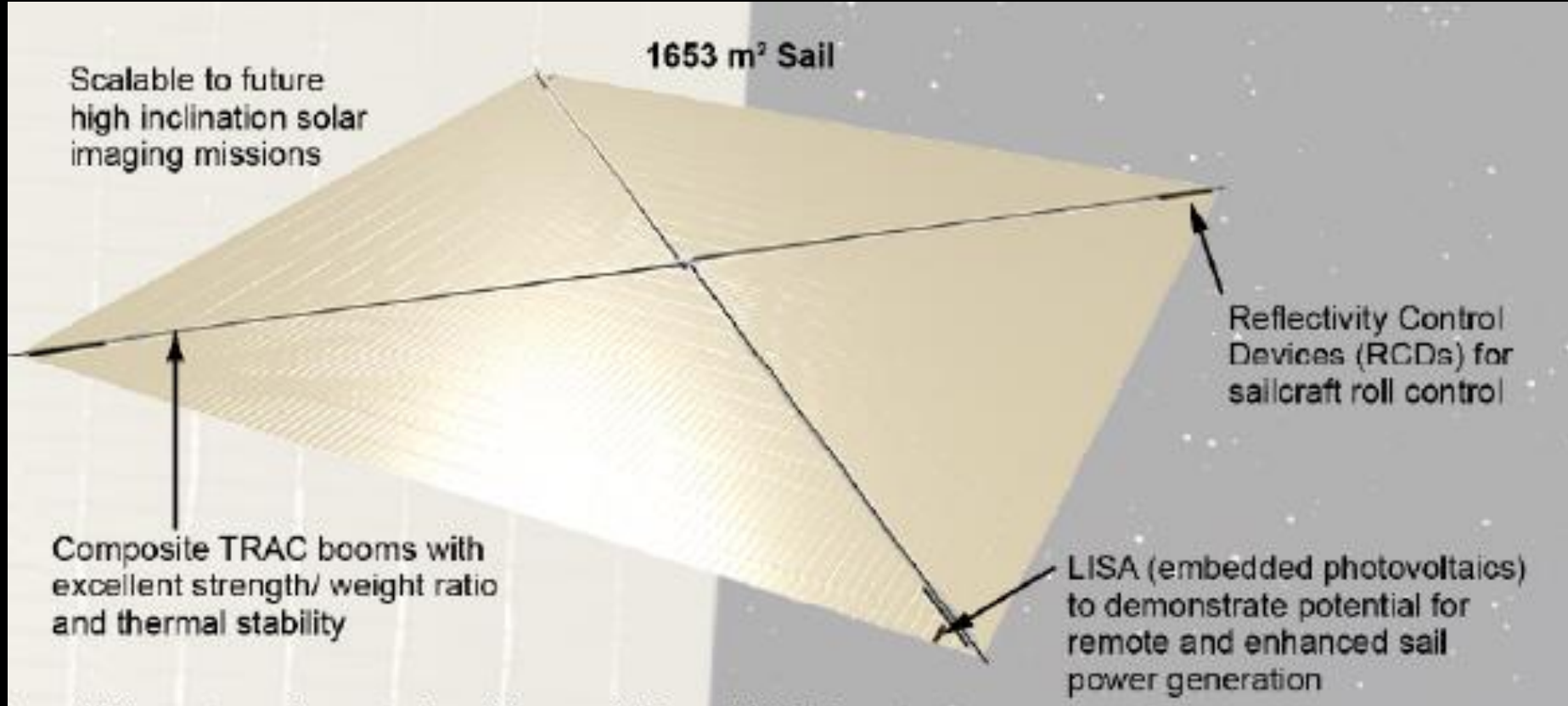
NASA Image

NASA Image



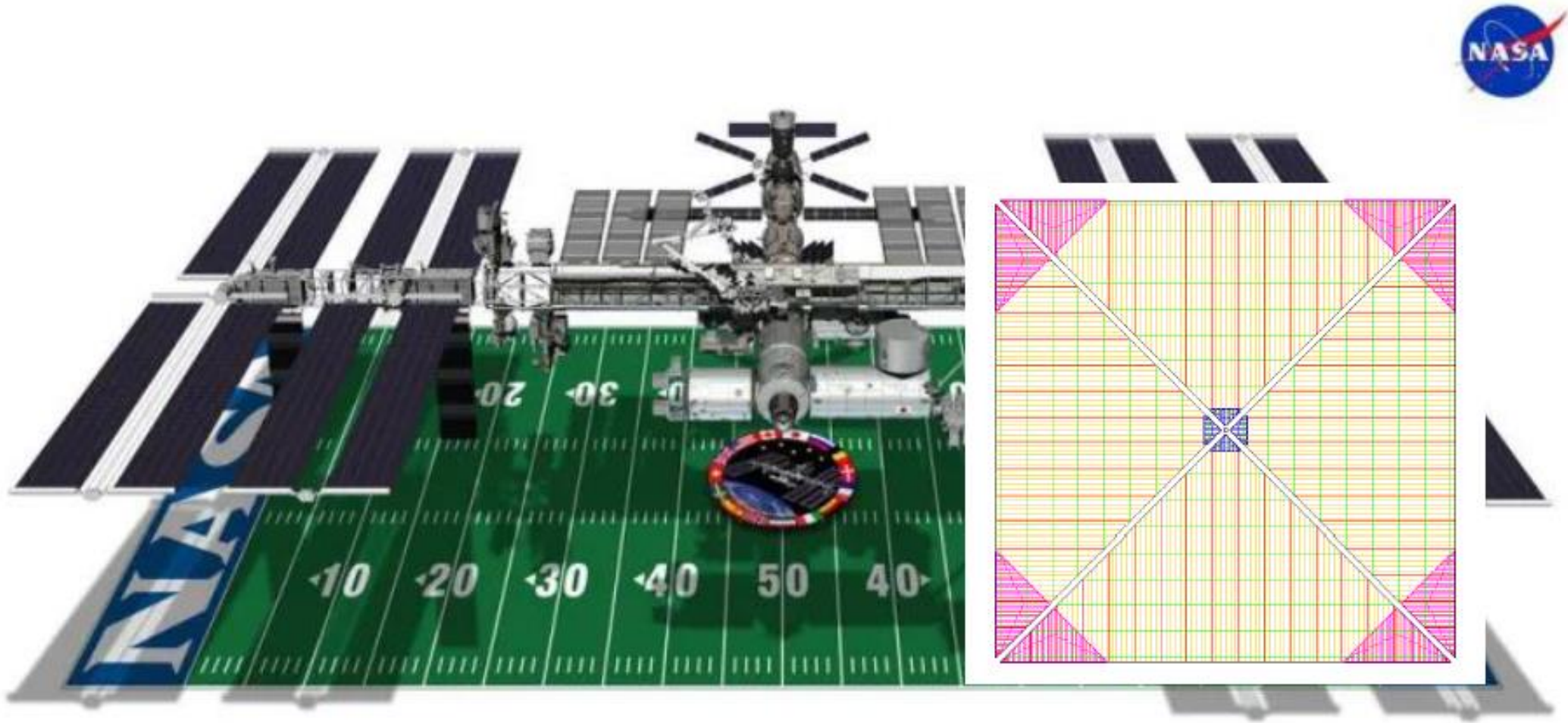
Solar Cruiser will launch as a secondary payload on the NASA IMAP mission in 2025. Using a solar sail, it will cruise past Sun-Earth L-1, demonstrating a solar sail's ability to fly a non-Keplerian trajectory, perform *propellantless* station keeping at an artificial equilibrium point (sub L-1), change heliocentric inclination, and demonstrate other solar sail propulsion unique maneuvers.

Solar Cruiser's Solar Sail



NASA Image

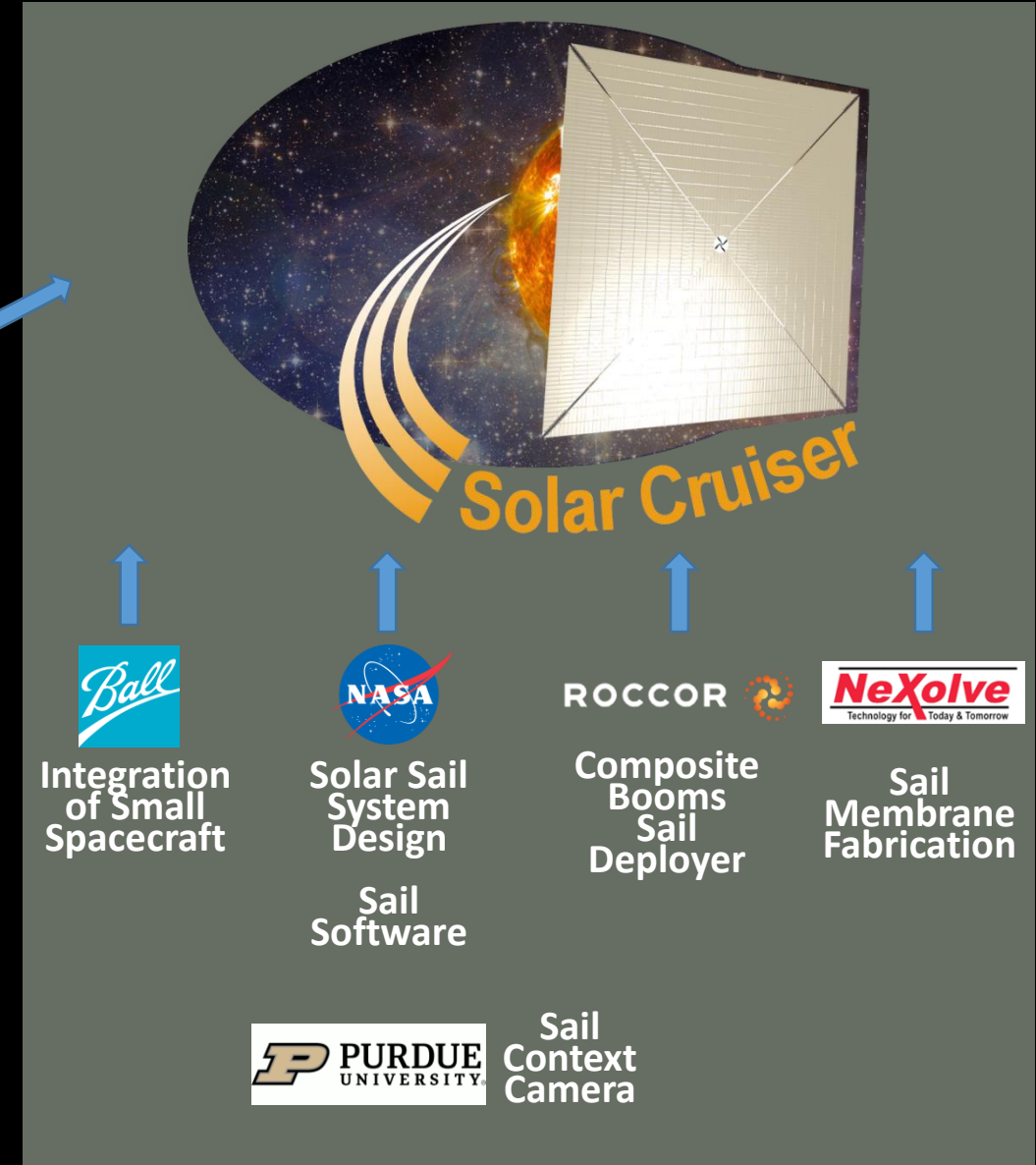
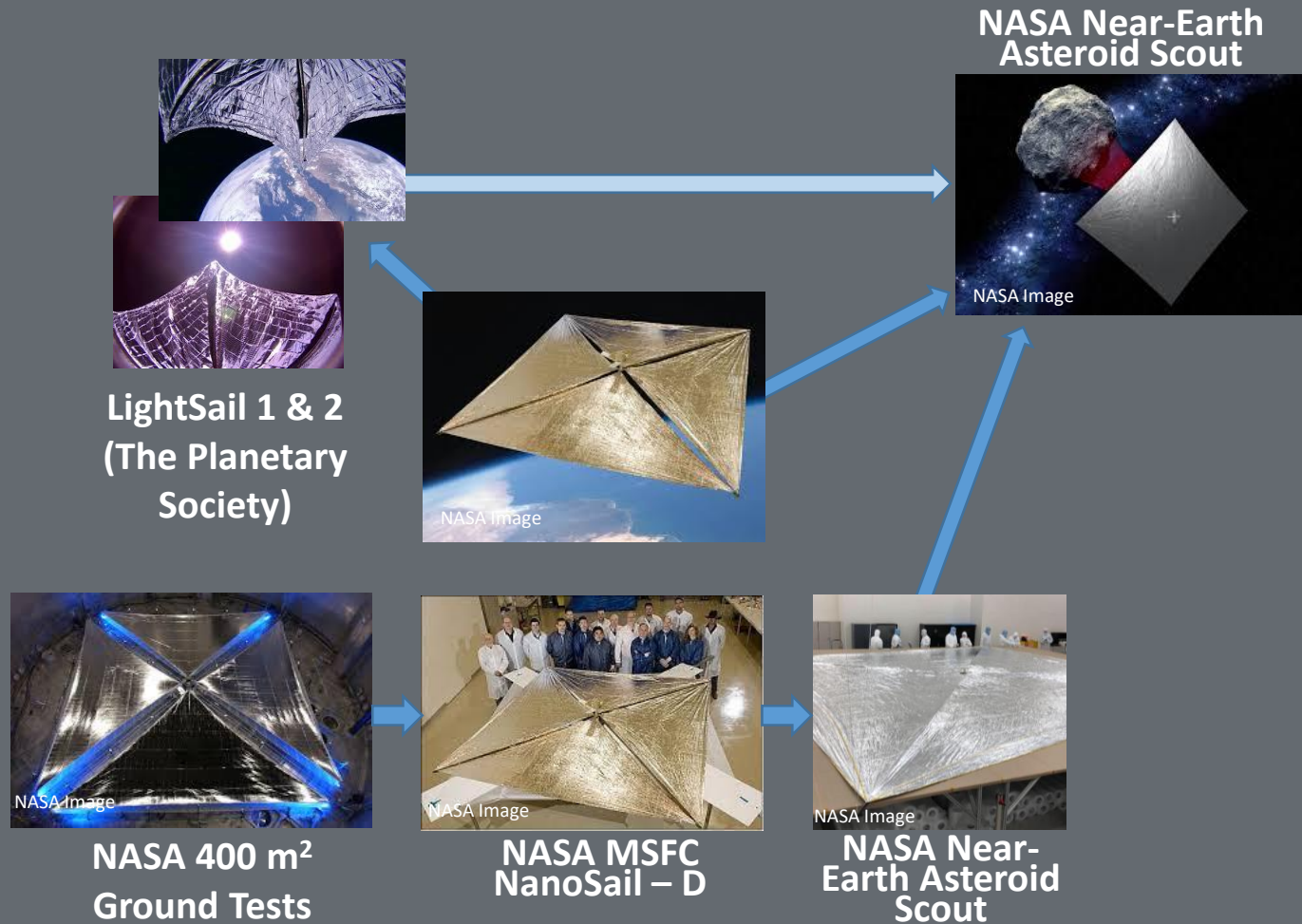
Solar Cruiser: 1/3 the size of a football field



NASA Image

Sail Developments Leading to Solar Cruiser

Solar Cruiser Team Members Have Been Involved In Each Of These Maturation Efforts

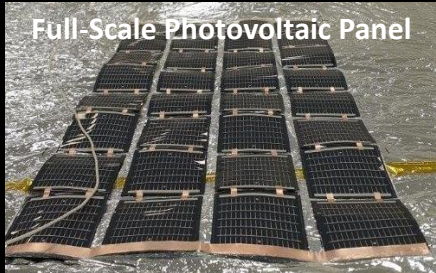


Solar Cruiser Technology Status

Reflective Control Device (RCD)



Full-Scale Photovoltaic Panel



1/16th-scale Sail Membranes (larger than NEA Scout sail!)



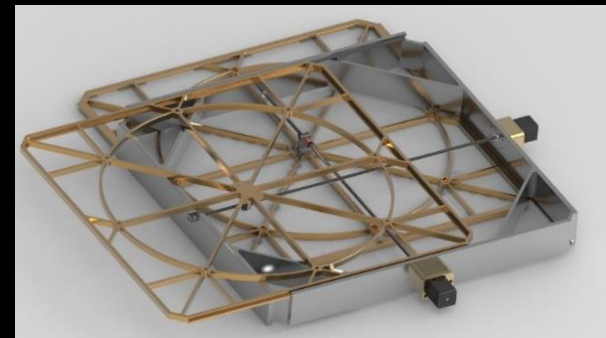
Full-Scale Deployer Hub with Trac Booms



Full-Scale Trac Boom



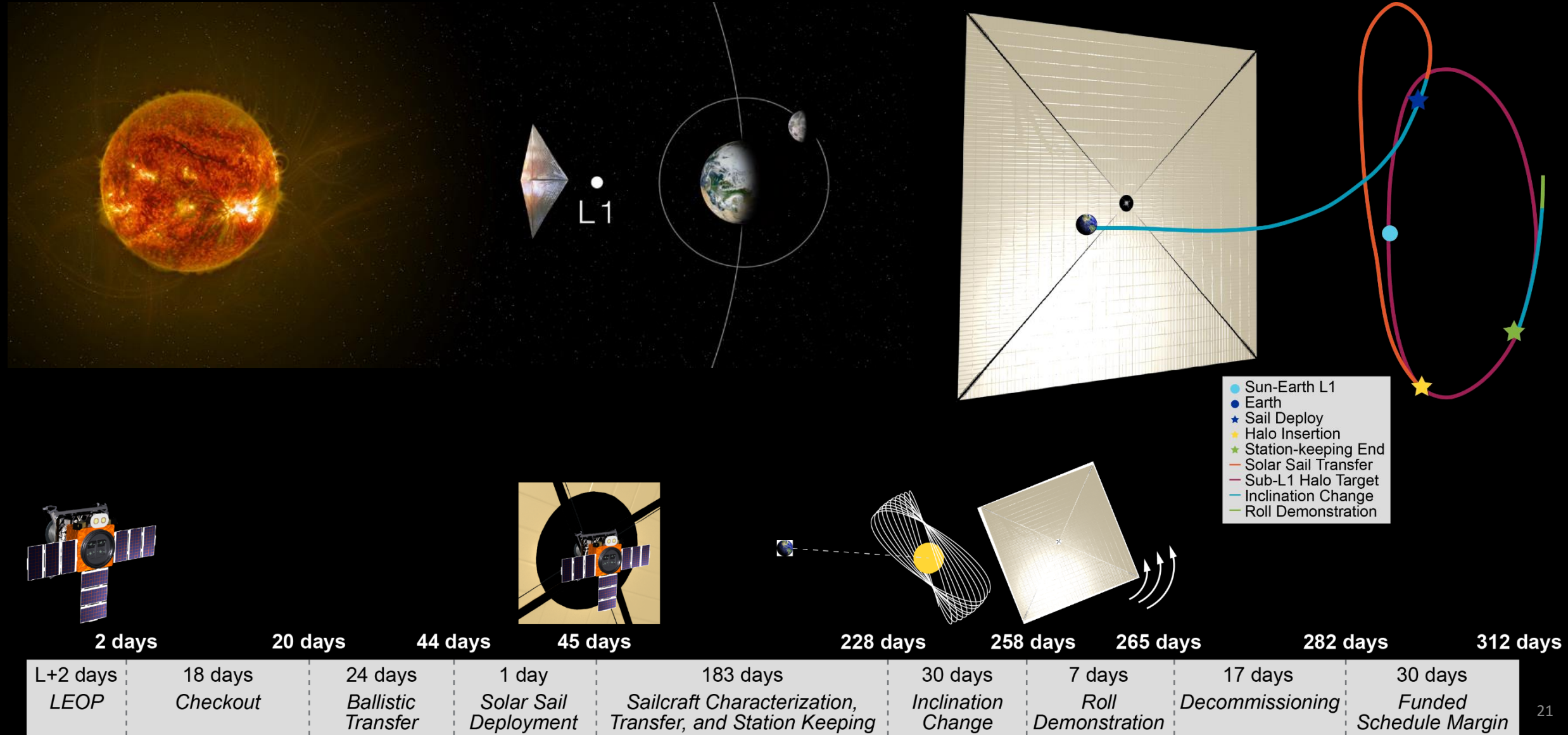
1/4-scale Trac Booms, Deployed



Full-scale 3D-printed Active Mass Translator



Solar Cruiser Will Demonstrate Solar Sail Propulsion Enabling Novel Orbits and Destinations

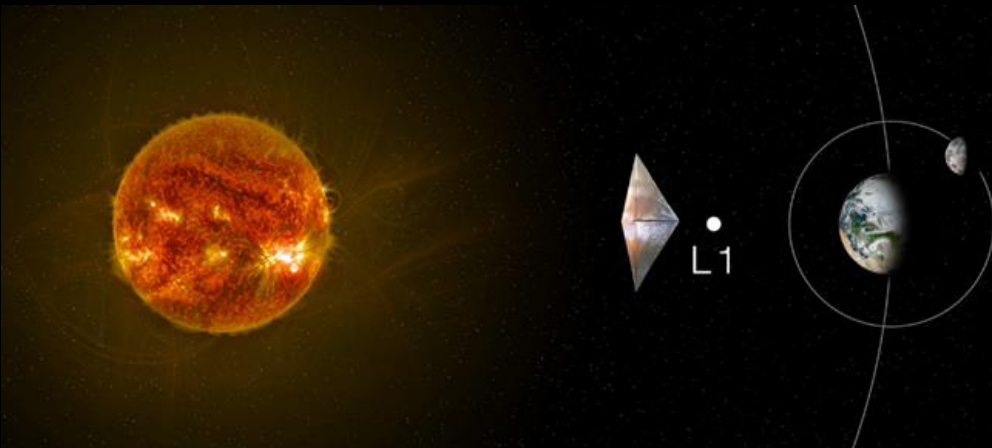




Solar Cruiser *Immediately* Enables Sub-L1 Heliophysics and Solar Storm Monitoring



- Science: Address such key questions as:
 - How do Coronal Mass Ejections (CME) and shock properties vary on moderate radial distances (~ 0.1 AU)?
 - How do CME and shock properties vary with moderate angular distance?
 - What is the structure of interplanetary CME, etc.?



Space Weather Applications:

- Increase the warning times by up to 50% for both “typical” and “fast” Coronal Mass Ejections (CMEs) from ~ 55 min. to 83 min., and 20 min. to 30 min.
- Directly benefits human exploration beyond LEO

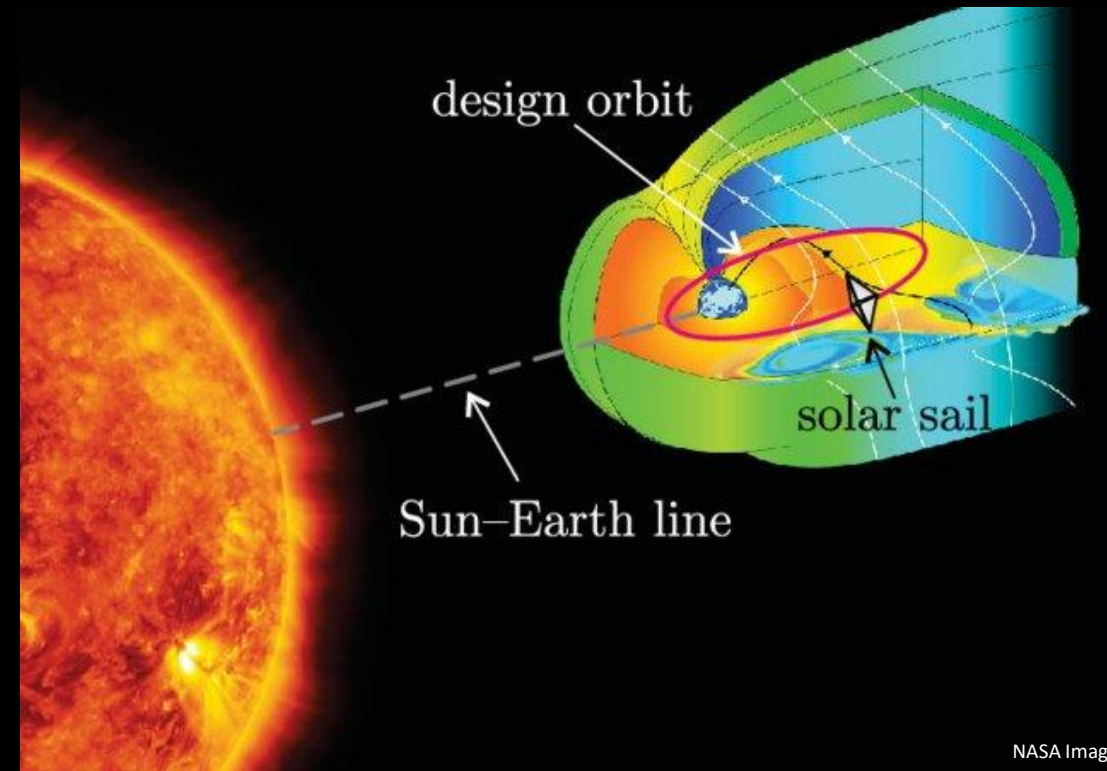




Immediately Enables Sustained In-situ Observations of the Earth's Bow Shock and Magnetotail

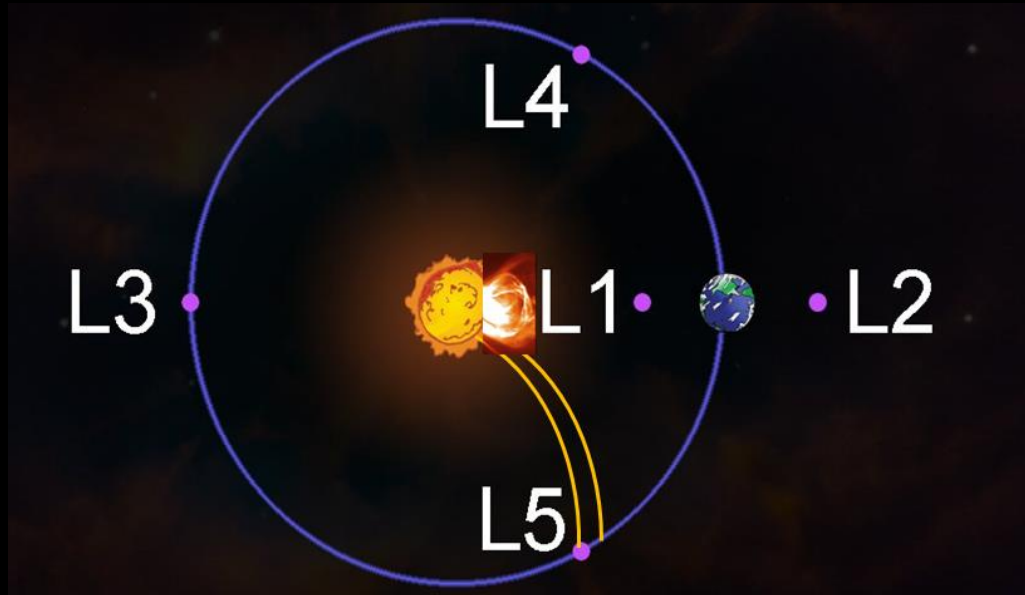


- Artificially precess apse line to increase time in geomagnetic tail
 - Long term science measurements *in-situ*
- Using multiple sailcraft, the entire geomagnetic tail could be populated by particle and field instruments that precess with the annual rotation of the geomagnetic tail, allowing real-time visualization of the 3-D plasma structure of the geomagnetic tail



NASA Image

Immediately Enables Sustained Solar Observations Off the SEL



Observations enabled include imaging coronal mass ejections (CMEs) between the sun and Earth and in-situ measurements of solar wind streams in the vicinity of L5 before they rotate into Earth

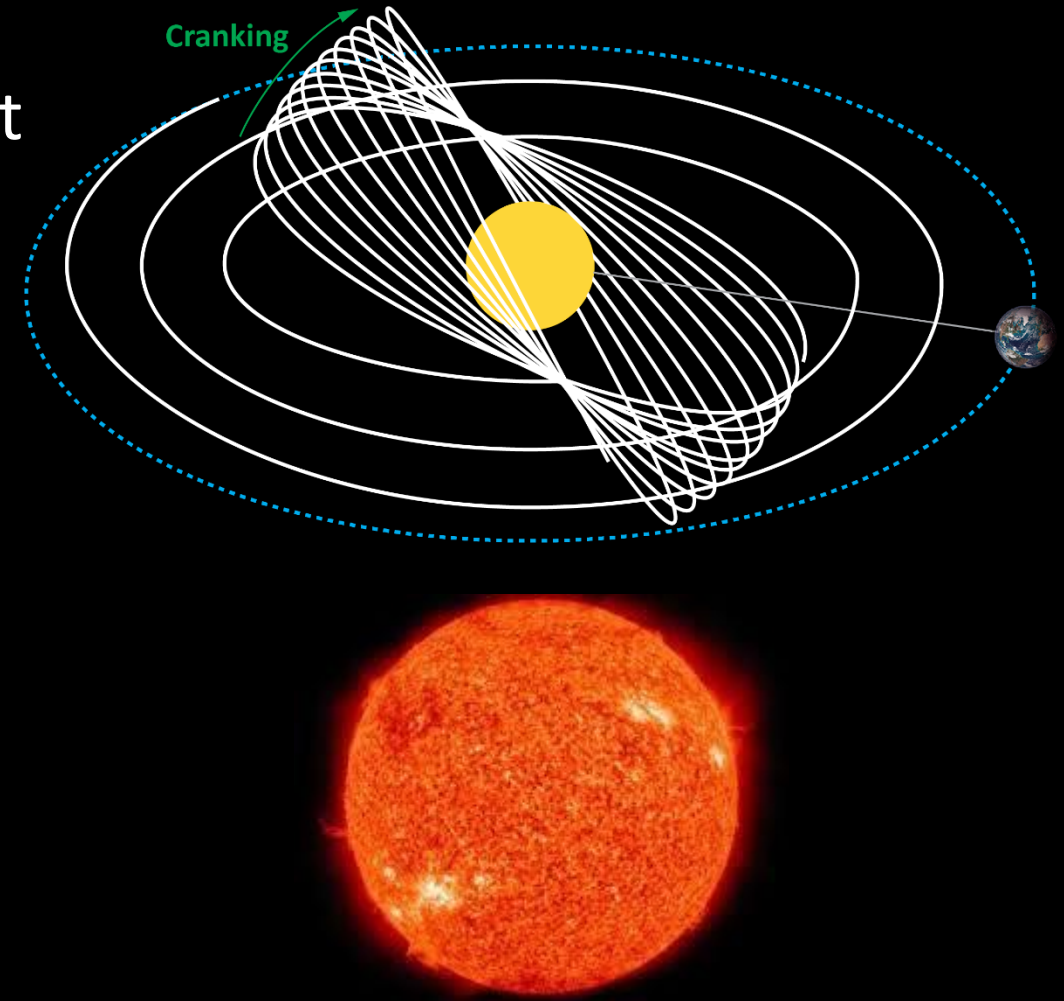
- Create artificial equilibria and *indefinite station keeping* at locations at any desired offset from the SEL leading or trailing the Earth in its orbit
- Long term station keeping and flexible repositioning to be responsive to changing solar conditions



Immediately Enables SmallSat Missions for Studying High Solar Latitudes

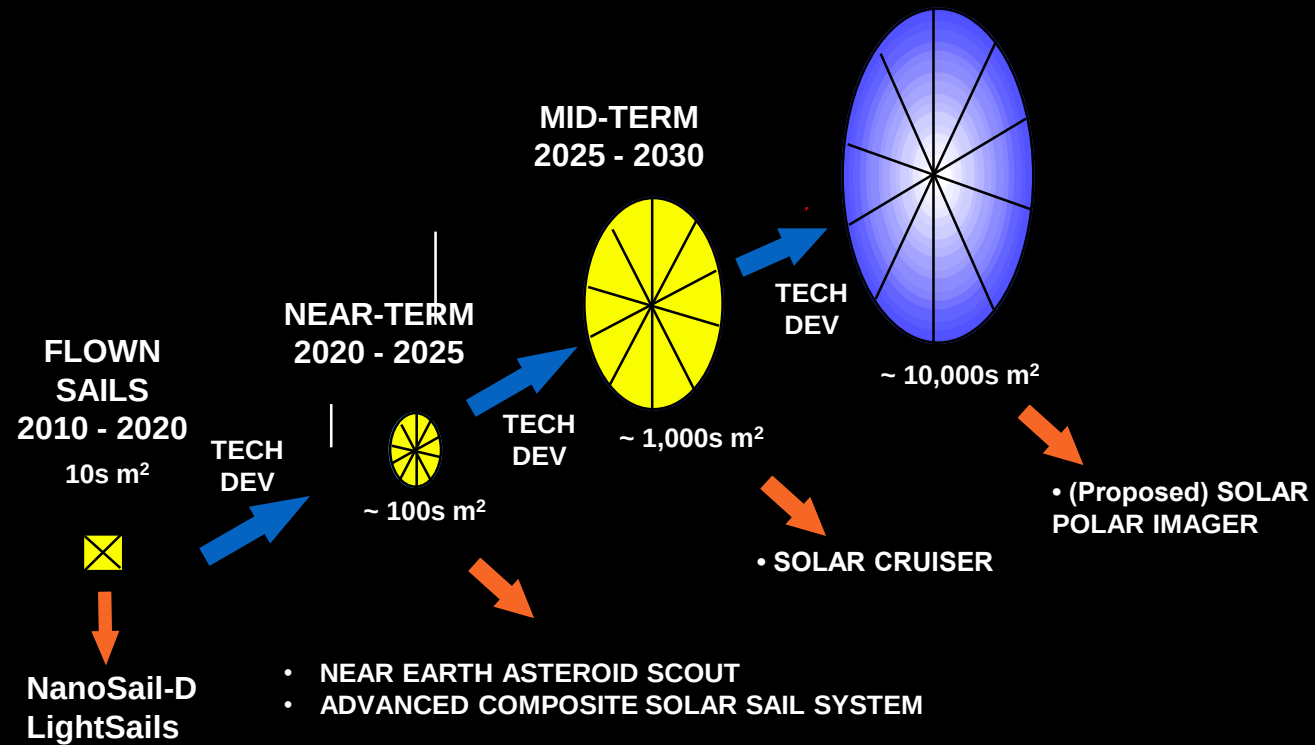


- A 3-axis stabilized Solar Cruiser-class sailcraft (*without scaling*) can perform out of the ecliptic science, changing inclination at a rate of $\sim 7 - 10$ deg/year (assumes low-mass sailcraft and instruments are optimized for an inclination changing mission)
 - Remote sensing (e.g., Doppler Magnetograph)
 - In-situ (particles and fields)





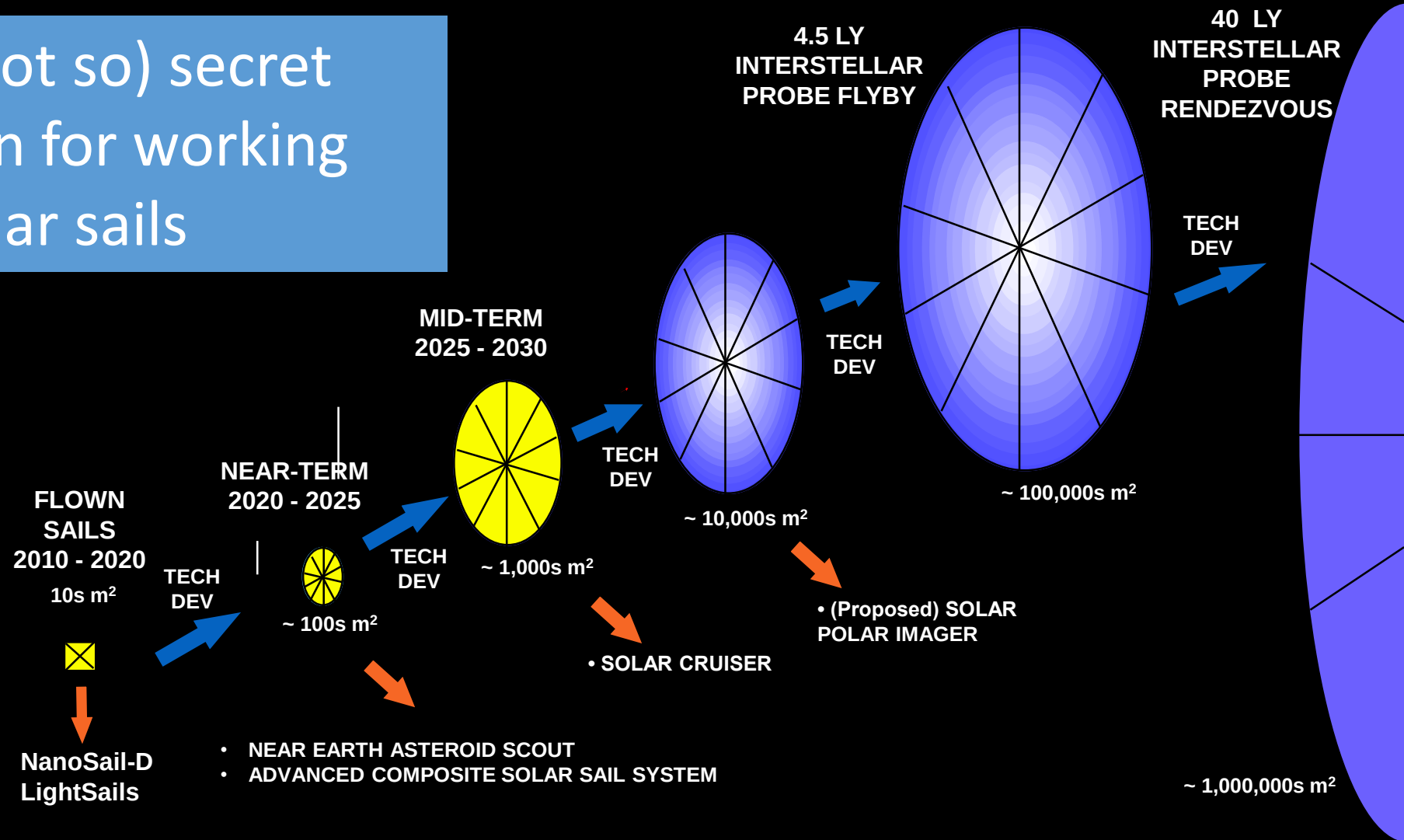
Evolution of Solar Sail Propulsion

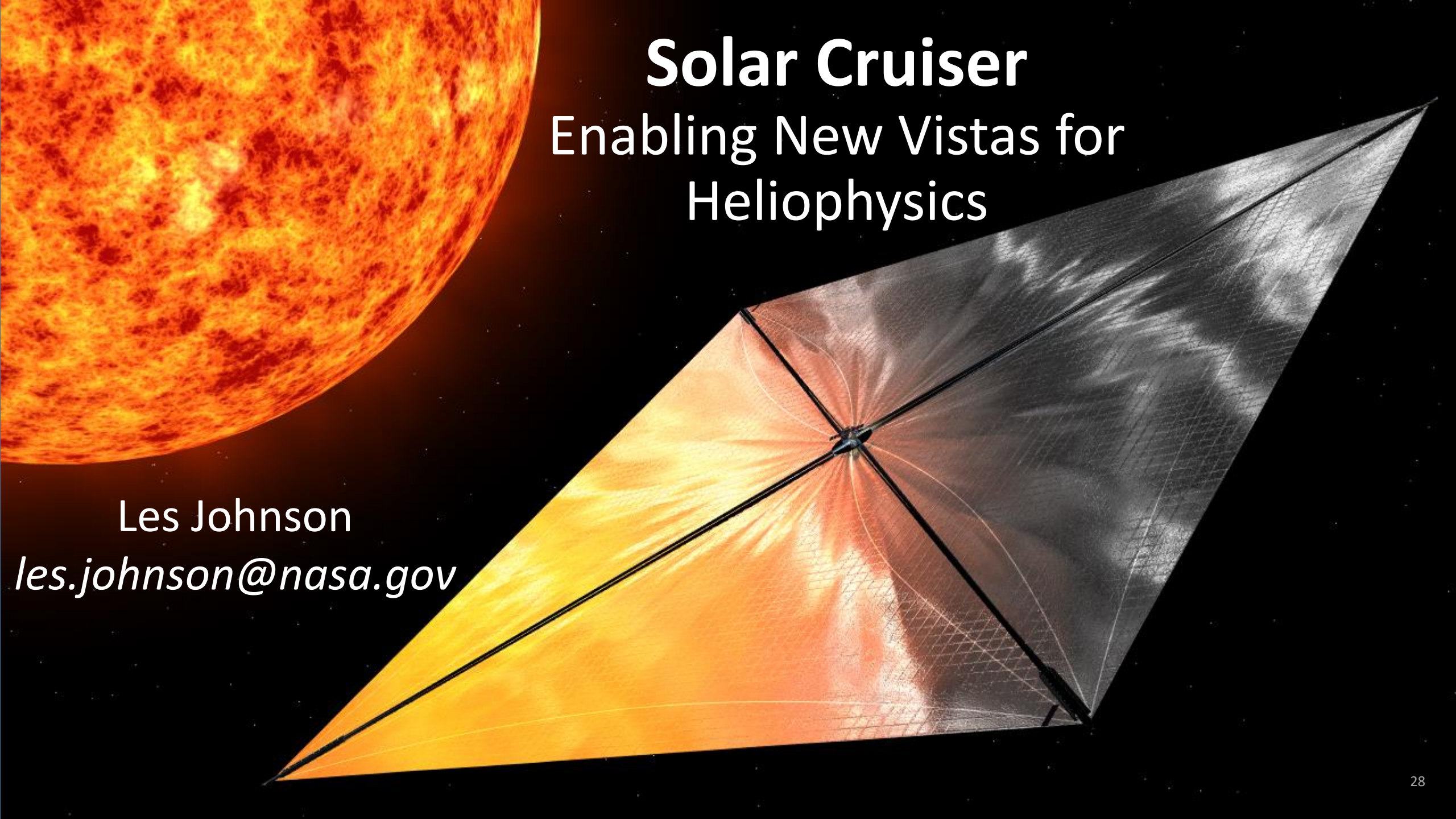




Evolution of Solar Sail Propulsion Toward Interstellar Travel

My (not so) secret
reason for working
on solar sails



The background of the slide features a large, bright orange and yellow sun on the left side, partially cut off. On the right side, there is a detailed illustration of the Solar Cruiser spacecraft, which has a large, triangular, gold-colored solar sail and a black, diamond-shaped structure. The spacecraft is positioned as if it is approaching the sun. The text is overlaid on this background.

Solar Cruiser

Enabling New Vistas for Heliophysics

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