Advanced approaches to solar sailing

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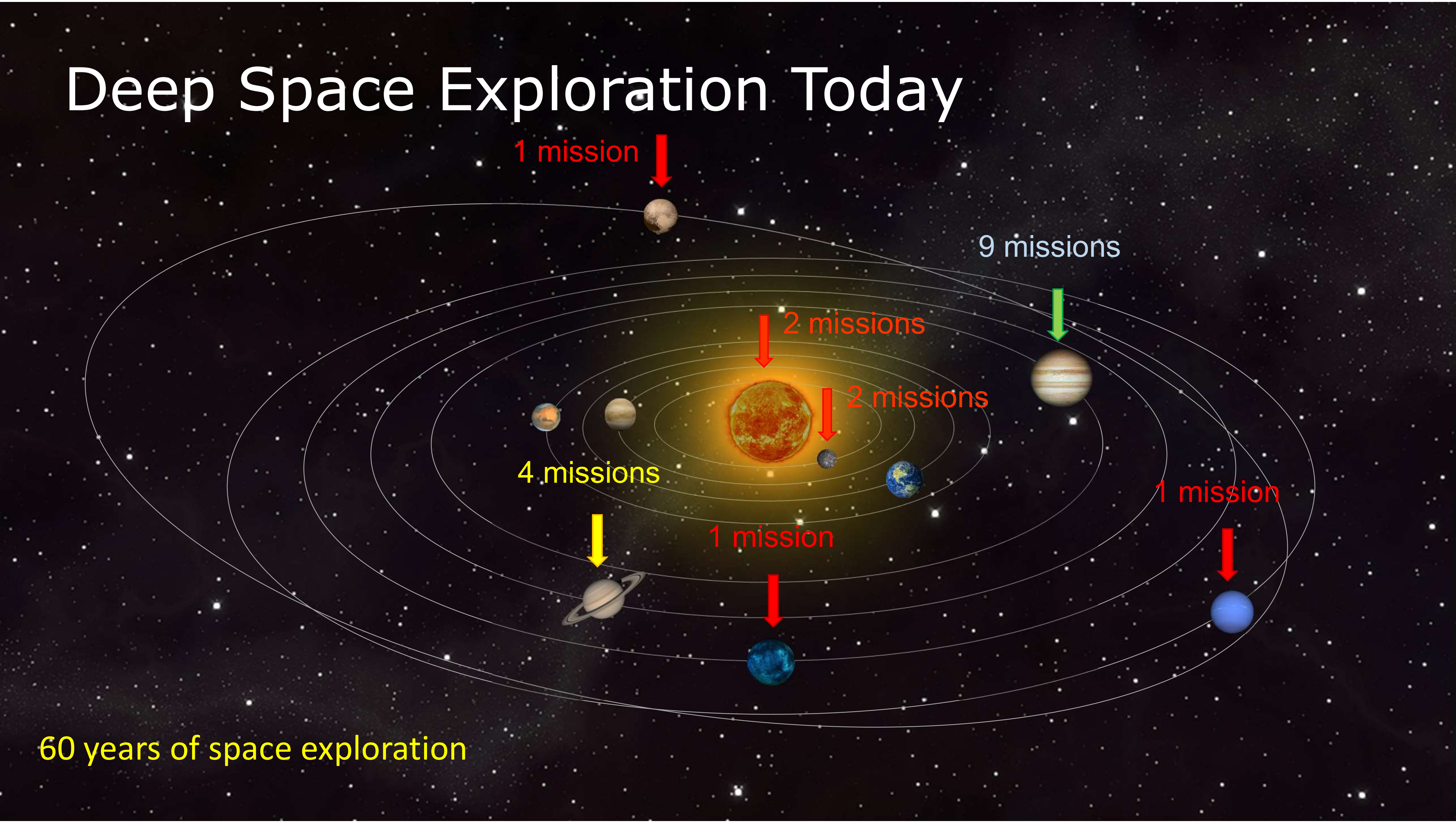
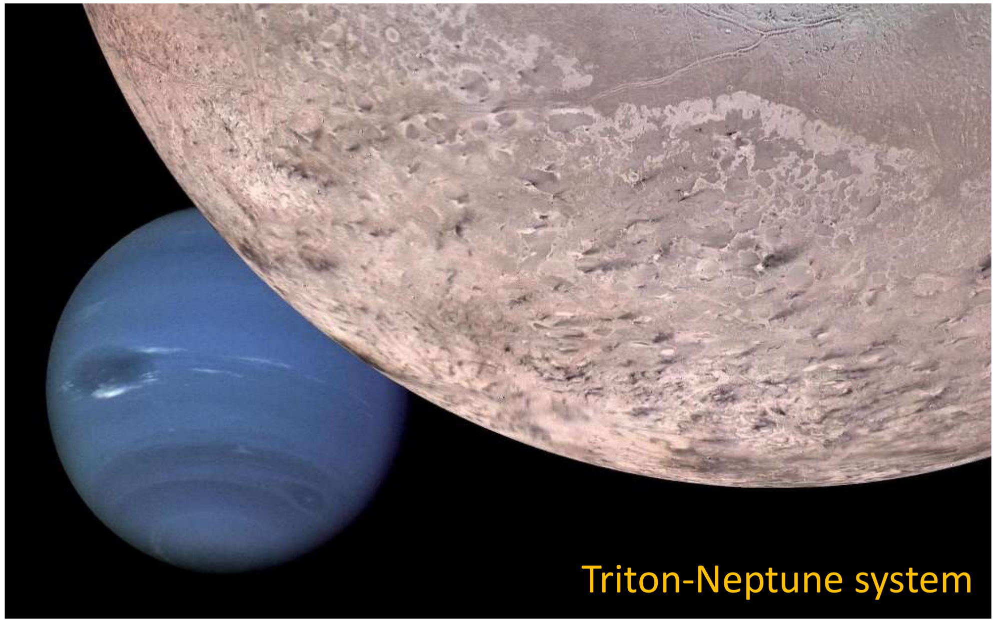

Deep Space Exploration Today
1 mission
9 missions
2 missions
2 missions
4 missions
1 mission
1 mission
60 years of space exploration

Outer Planet Exploration


Triton-Neptune system

Science Objectives

- Search for life
- Understanding planetary formation
- Understanding solar system formation

Challenges

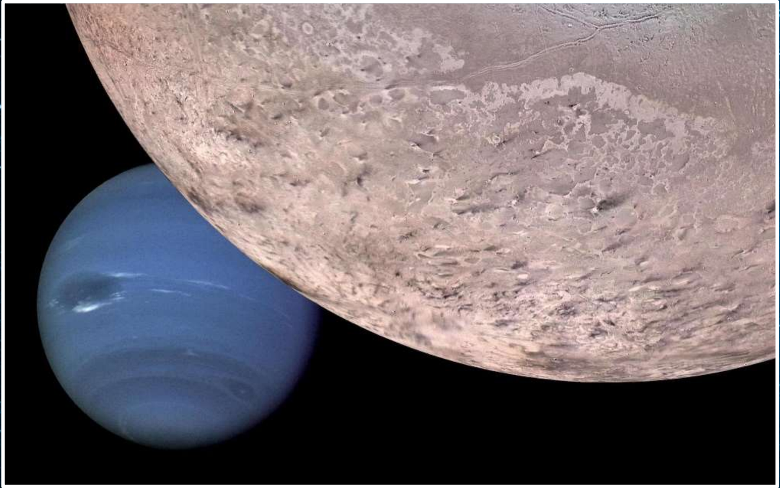
- Need to scale exploration
- Travel takes many years (>7 years to Saturn)
- Flagship missions are costly

"cursed cycle"

Not suitable for CubeSats (reliability)

Need For Breakthrough Science

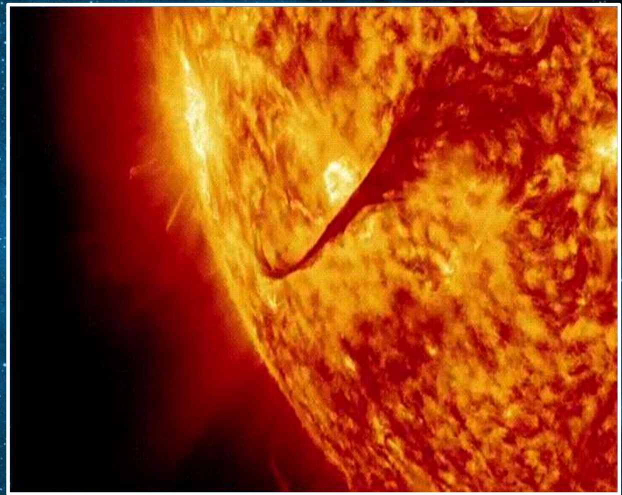
Outer planets & moons



Are we alone?

- Need to scale exploration
- Travel takes many years (>7 years to Saturn)
- Missions require decades long costly (~$1B) development

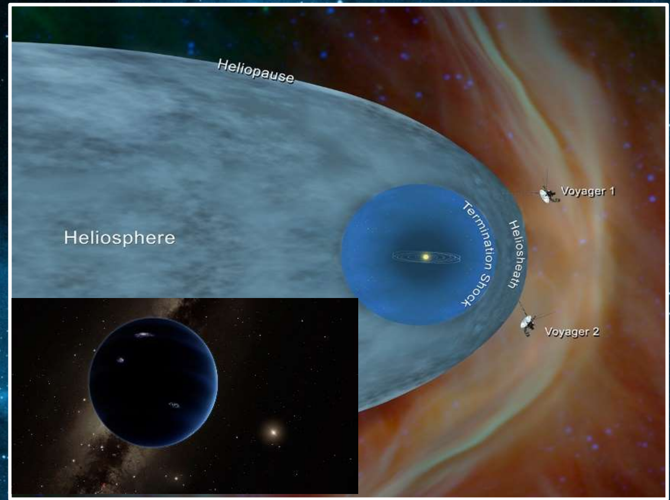
Our star



Predicting the solar dynamics

- Need inner corona observations
- 4D mapping of the corona

Interstellar medium & beyond



What is our place in the Universe?

- Only two probes have reached the interstellar medium

State Of The Art: Outer Space

- Voyager 1 (1977) is the fastest spacecraft ever built.
- Travelling at a record 17km/s it took 35 years to reach interstellar medium at 120 AU (the first spacecraft to reach this milestone).
- Most distant spacecraft as of today (155 AU after 45 years of travel).

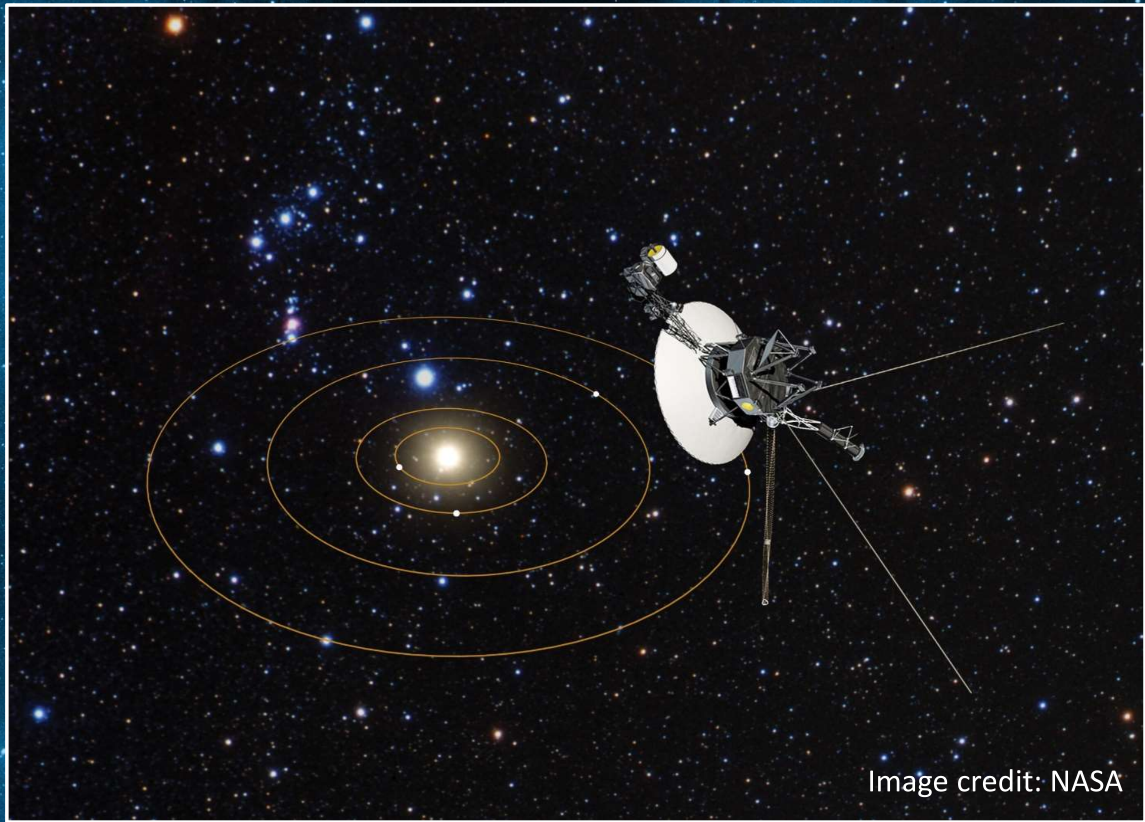


Image credit: NASA

State Of The Art: Inner Solar System

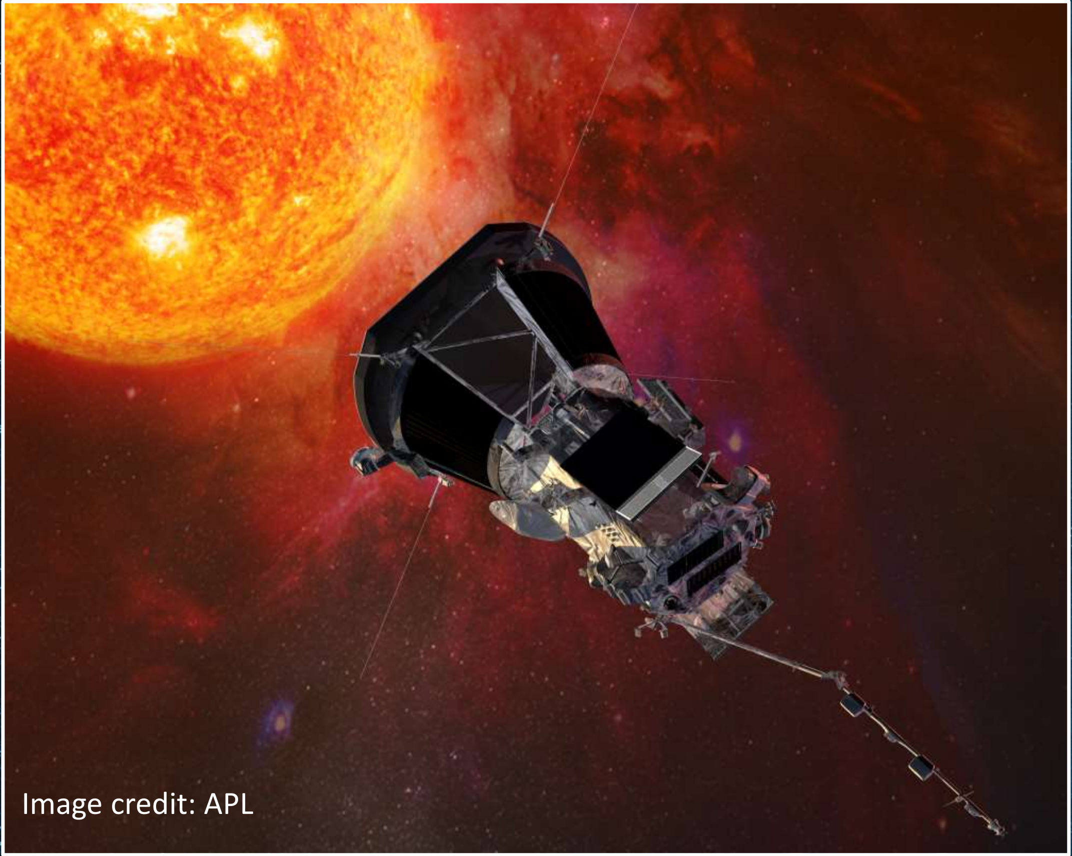
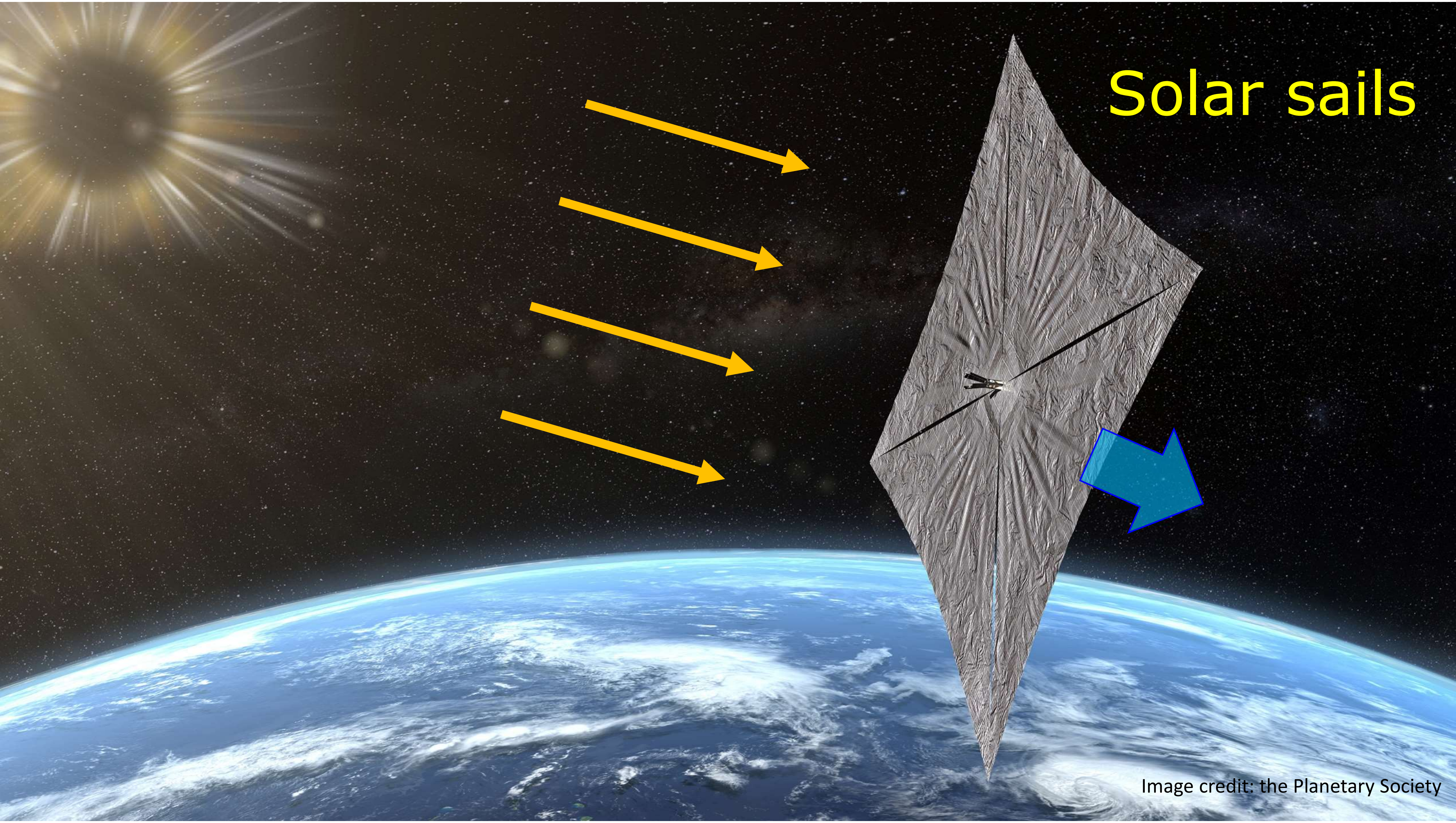
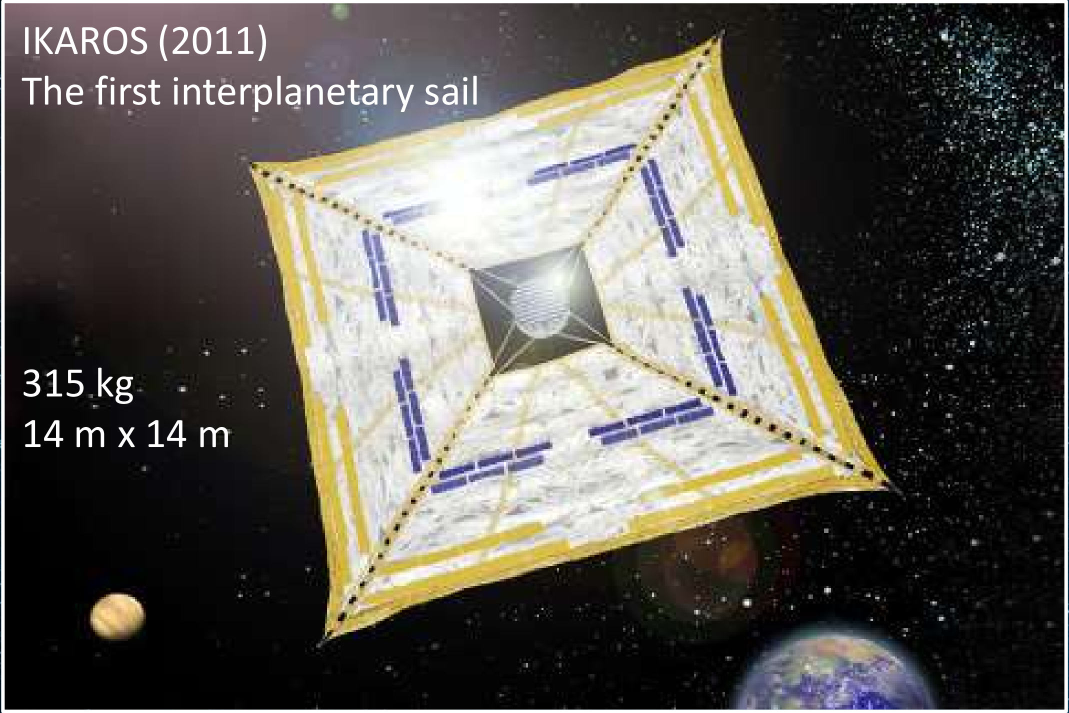


Image credit: APL

- Solar Parker Probe (2018) – closest approach to the sun (~9$R_{\odot}$)
- Need 7 Venus flybys over 7 years
- Can't get out of the ecliptic plane (only modest 3 deg inclination)
- Can't get to solar polar regions


Solar sails
Image credit: the Planetary Society

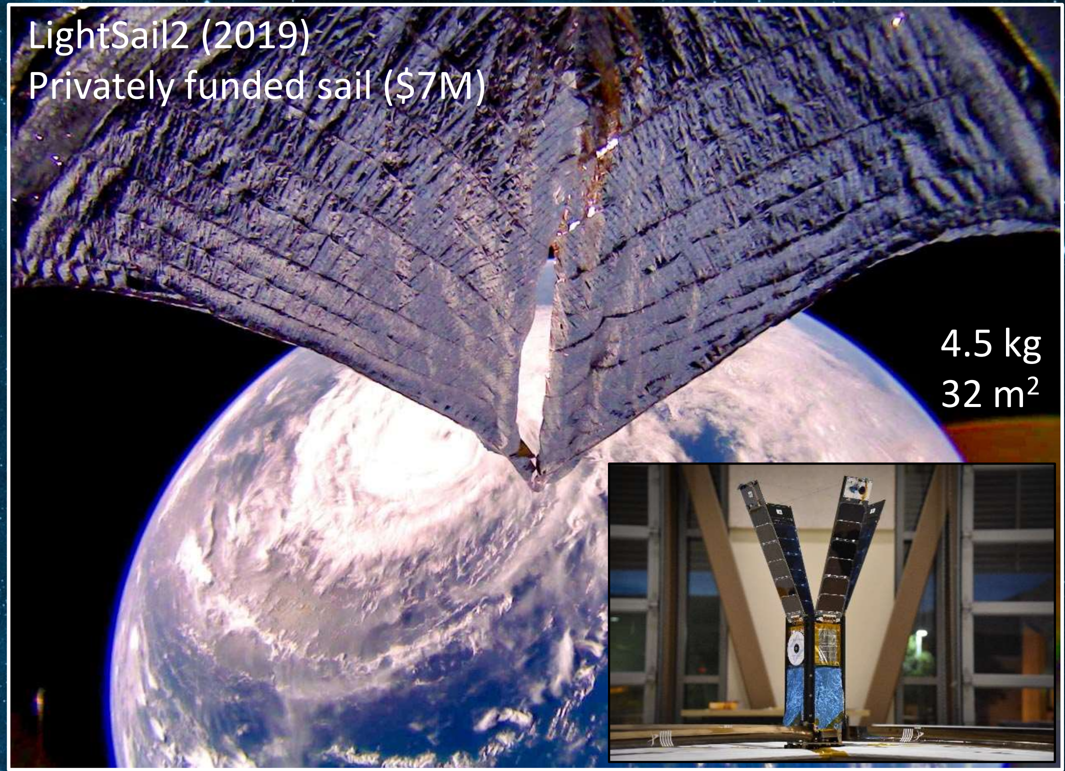
Solar Sails Flown



IKAROS (2011)
The first interplanetary sail

315 kg
14 m x 14 m

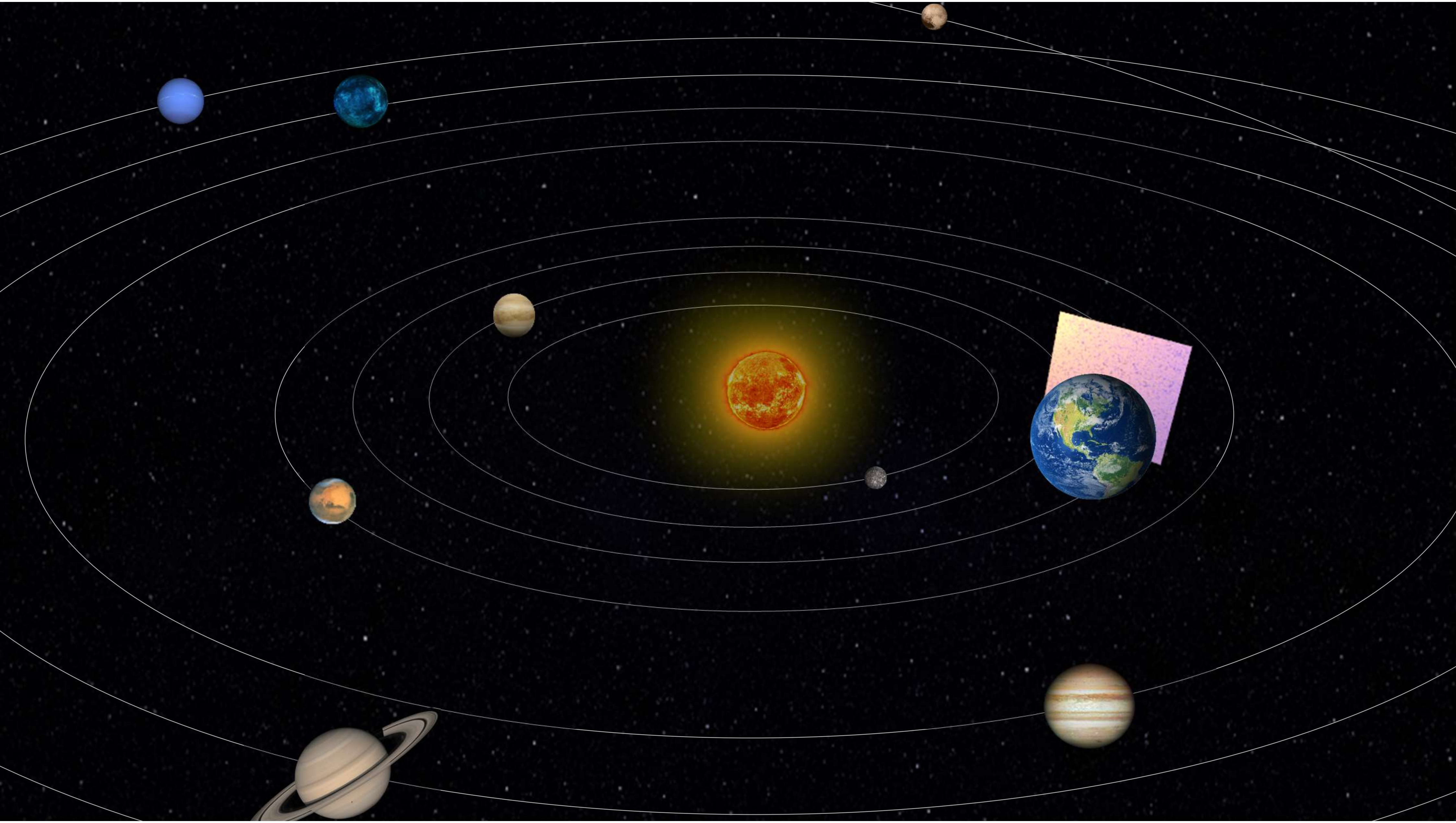
Image credit: JAXA



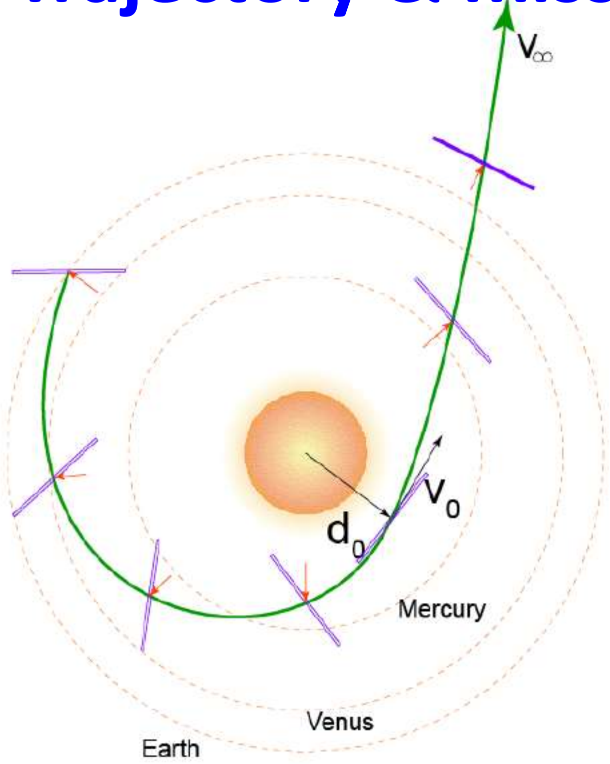
LightSail2 (2019)
Privately funded sail ($7M)

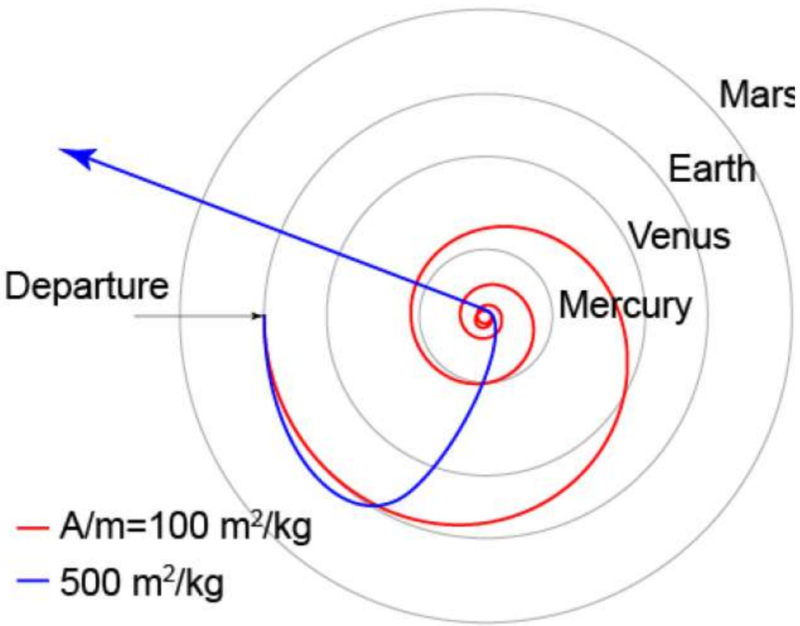
4.5 kg
32 m^2

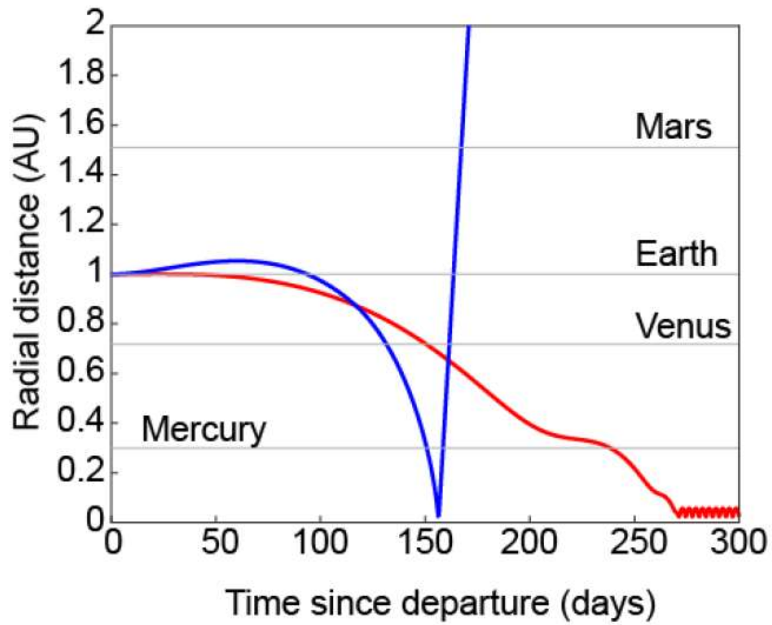
Image credit: The Planetary Society



Trajectory & mission profile







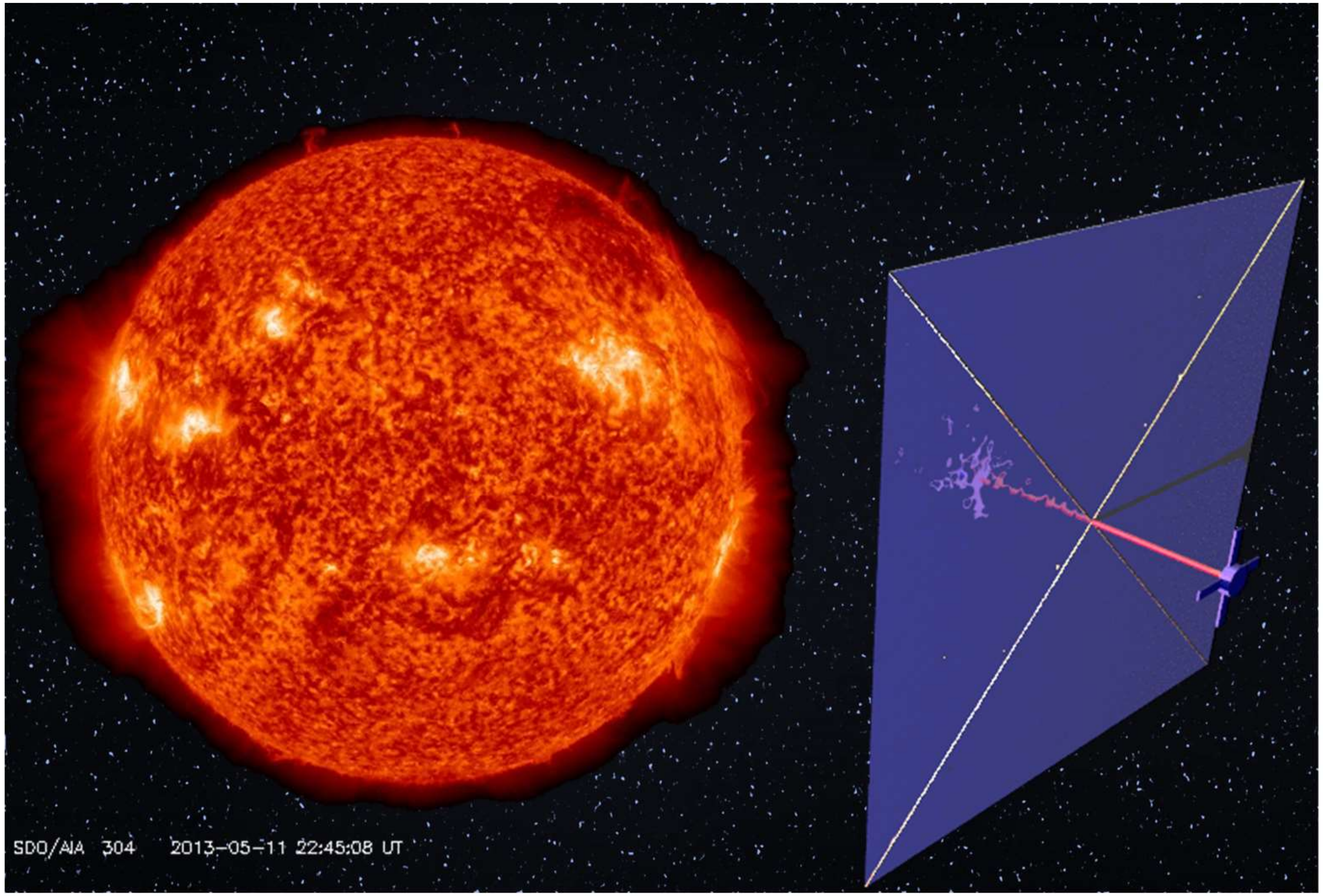
C3=0

Start with MEO and "spiral in"

A.R. Davoyan et al., Optica 8, 722 (2021)

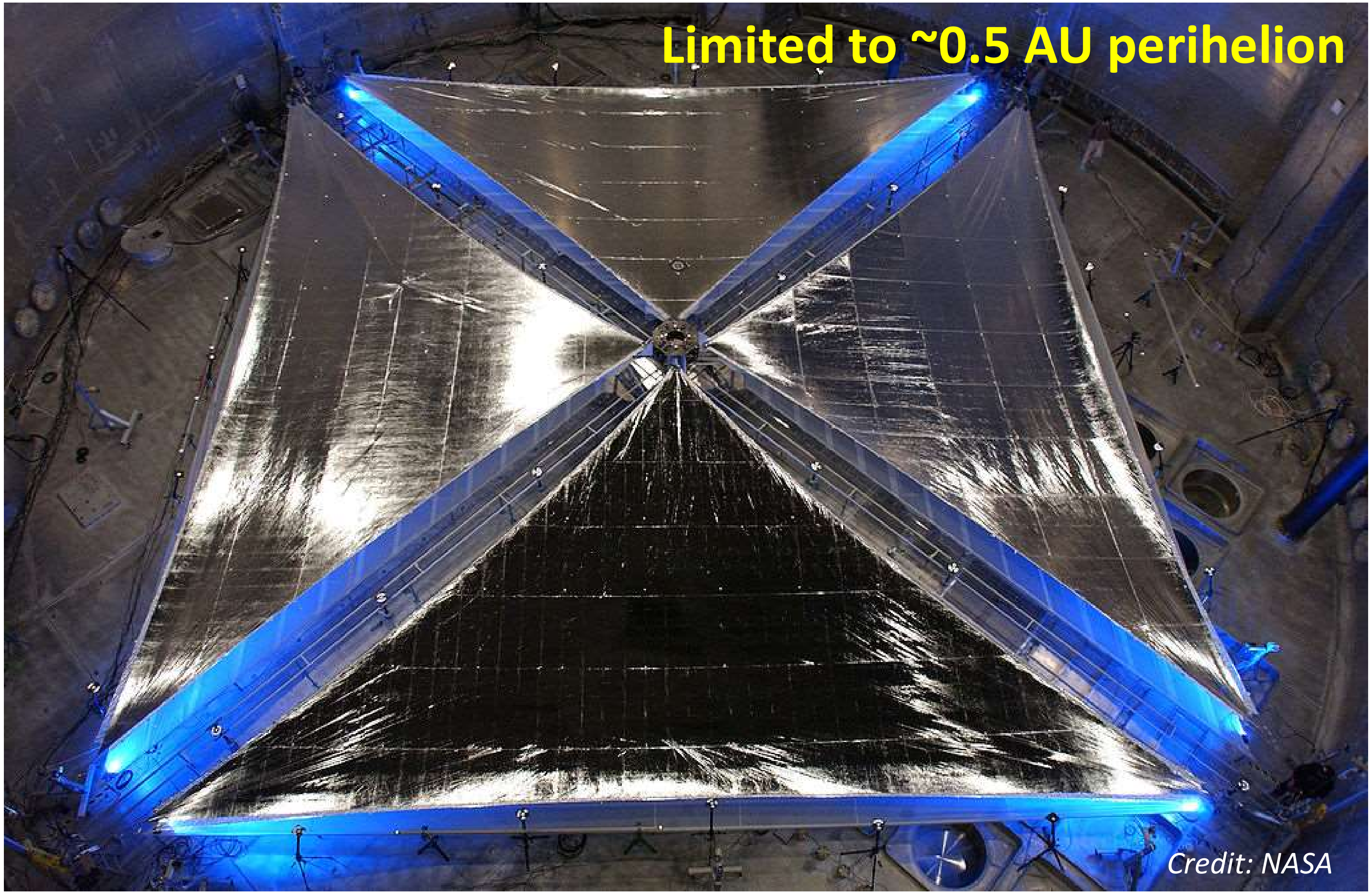
>20 AU/year for <0.2 AU perihelion with a lightweight spacecraft (A/m>50 m²/kg)

Outstanding Challenges



- Harsh environment
- Need for **new materials**
- Large lightweight architectures
- **Spacecraft controls & navigation**
- Power and communications

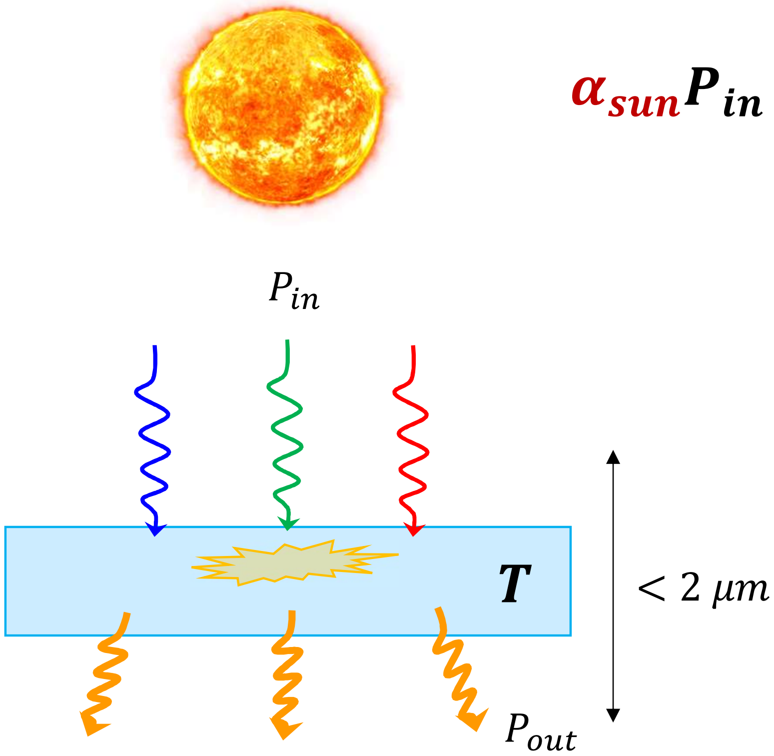
Current sail material technology

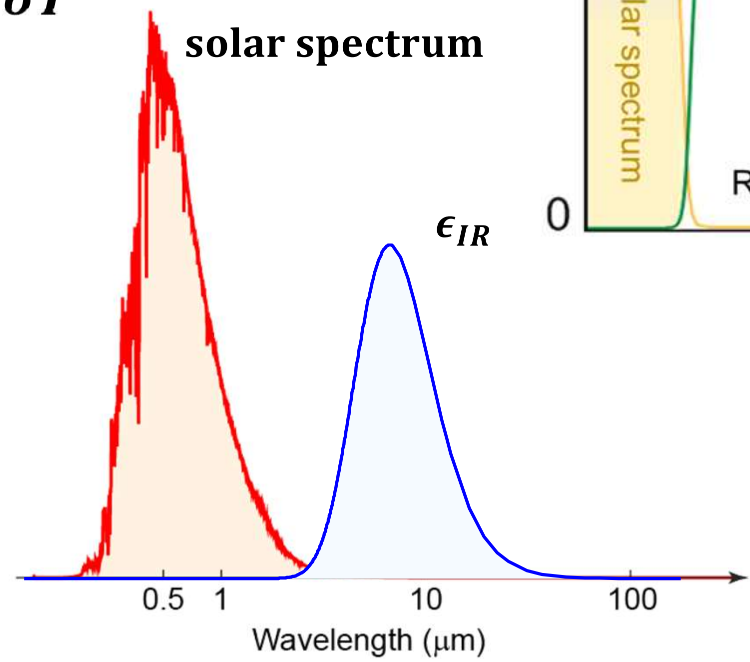


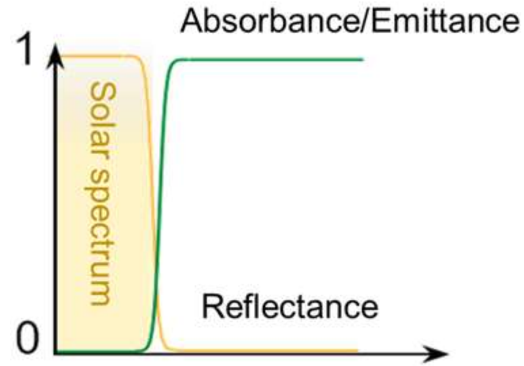
Solar radiation flux and thermal balance

Solar power absorbed = Thermal power emitted

$$\alpha_{sun} P_{in} = \epsilon_{IR} \sigma T^4$$

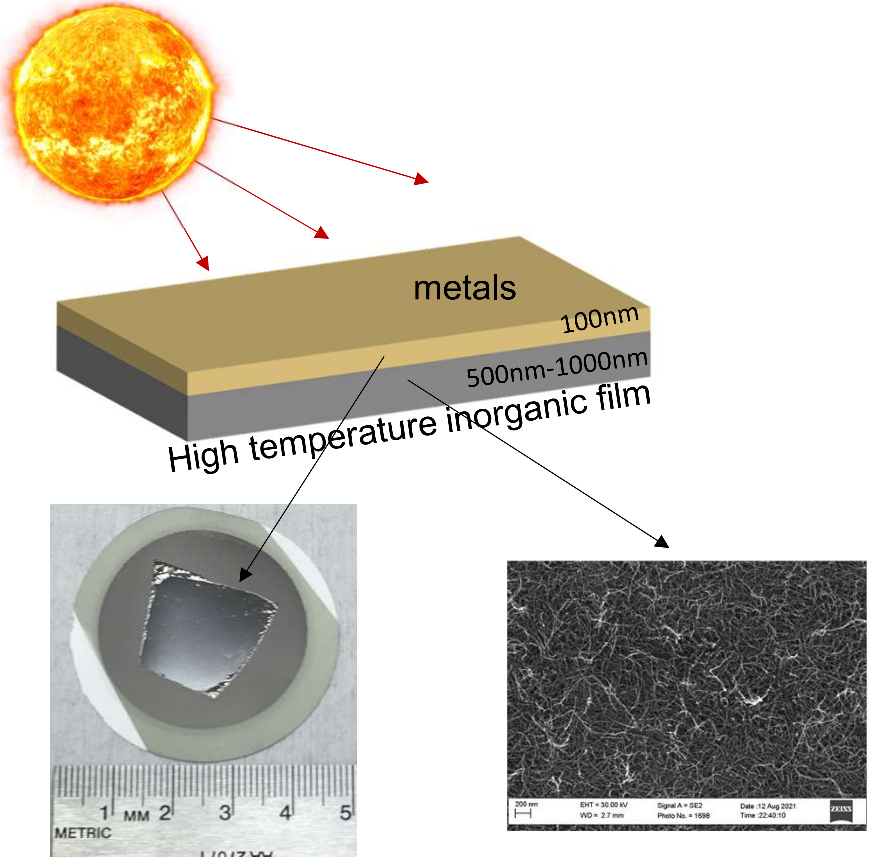






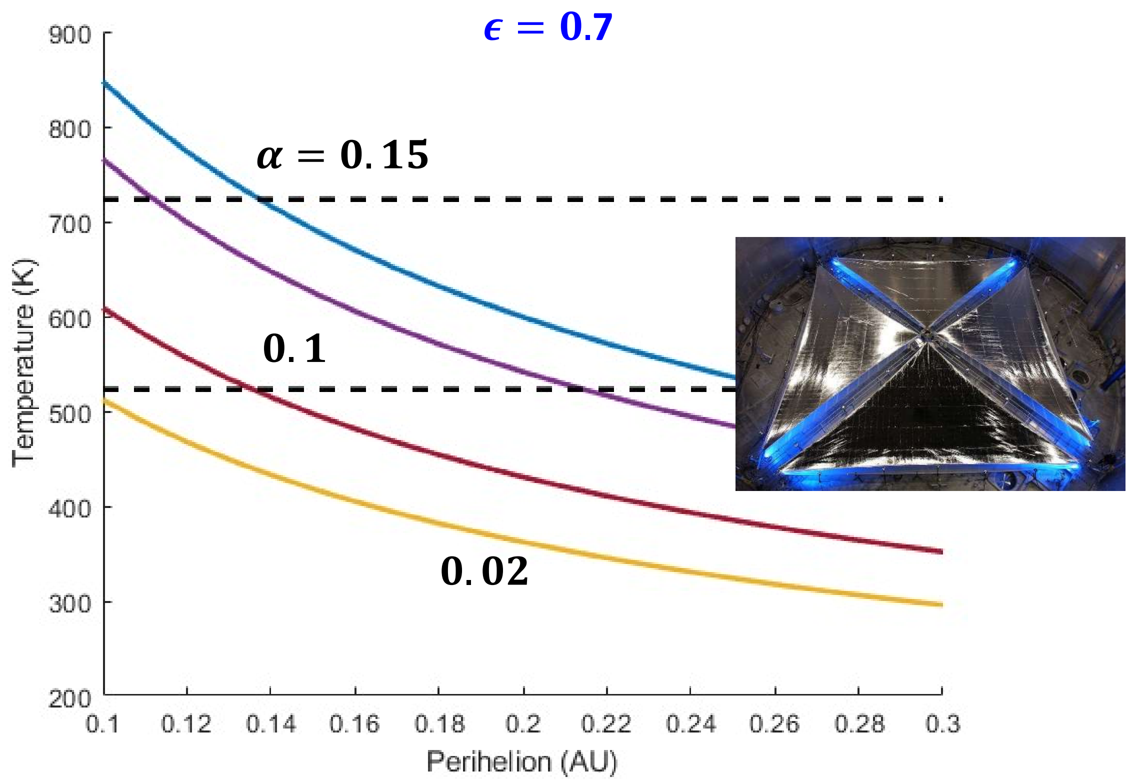
A. Davoyan et al., Optica 8, 722 (2021)

Sail Materials for Small Perihelion Pass



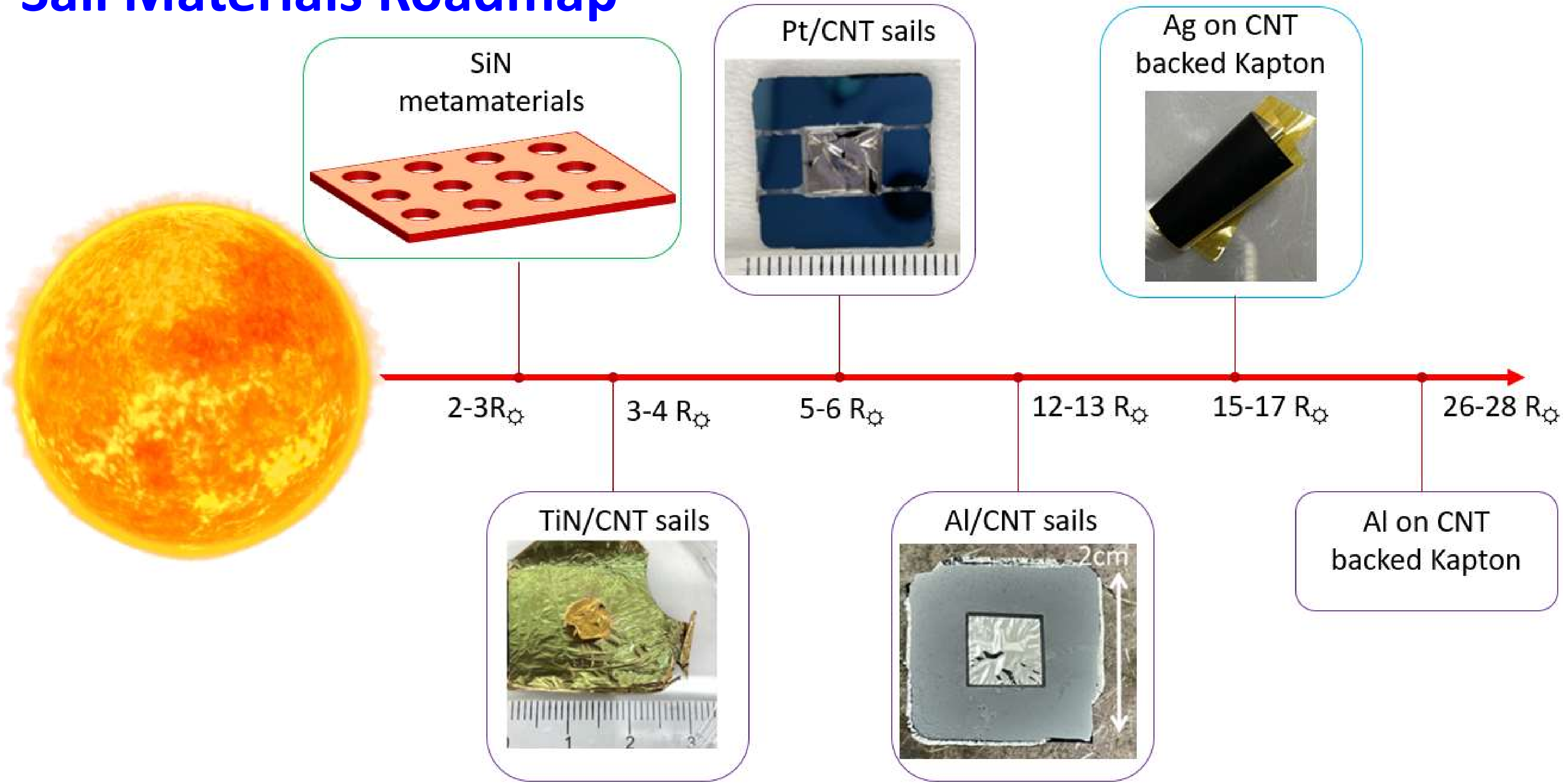
Estimated density: <1.5 g/m²

Tested at ~500 °C (no degradation found)



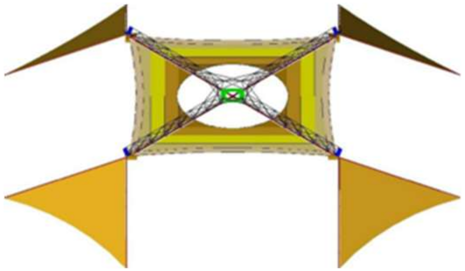
- **Range of materials developed for small perihelion missions**
- **Sail temperature <700 K at 0.1 AU perihelion**

Sail Materials Roadmap



Current Sail Attitude Controls Systems

Mechanical systems



Tip Vanes

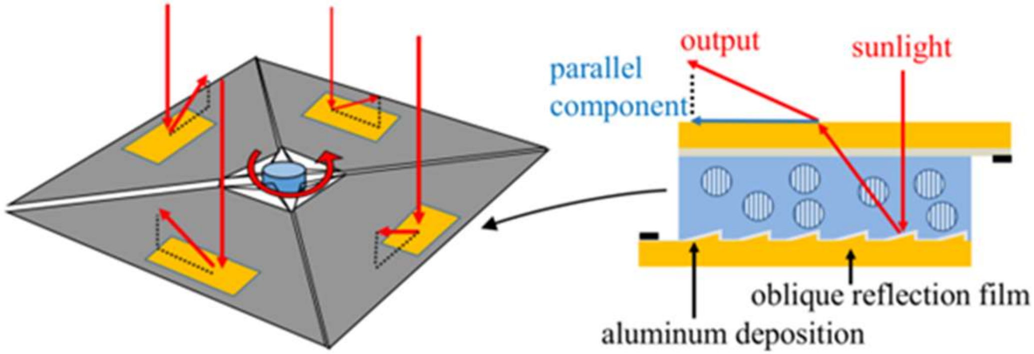
Russell, Tiffany E., et al.,
Adv. in Solar Sailing. 2014

AMT in NEA Scout

Few, Alex, et al.,
Aero. Mech. Symp. 2018

Challenges: Not scalable, not deployable, requires high mass & space budgets

Reflection Control Devices



RCD in IKAROS

Chujo, Toshihiro, et al., J. of Spacecraft and Rockets, 2018

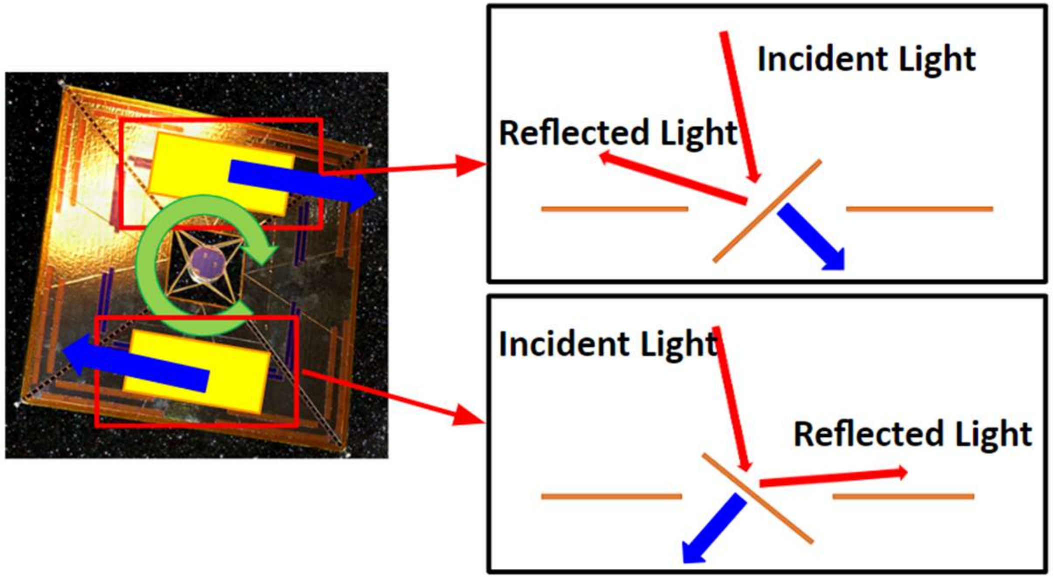
Challenges: intended mostly for roll

Sail Attitude Control by Surface Control

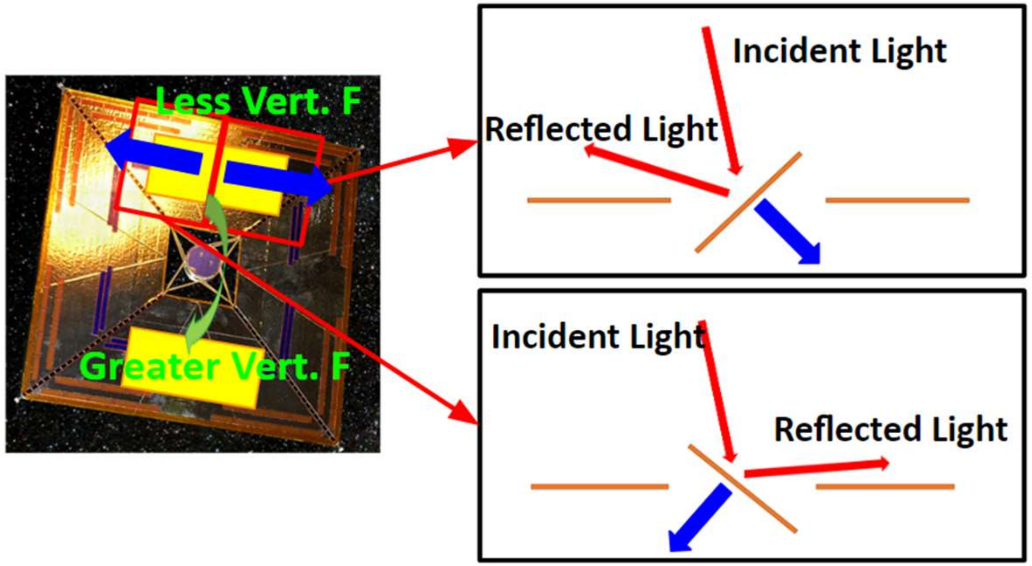
Controlling the solar sail surface changes the **direction of the light reflected**

Control system integrated into the **sail film** itself

Roll Maneuver



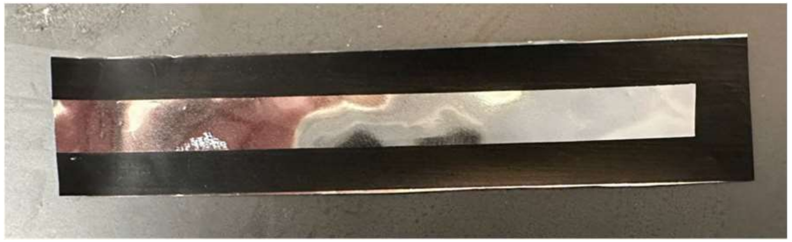
Pitch/Yaw Maneuver

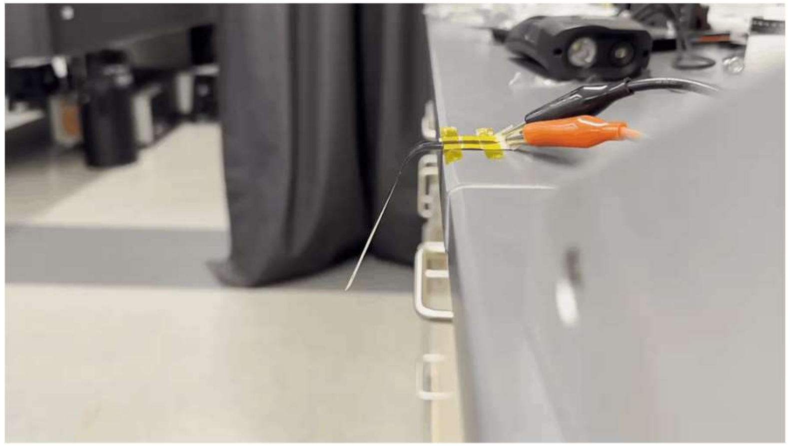


Actuation methods: **electrostatic** (repulsive & attractive), **electrothermal** (bimorph)

Electrothermal Actuation for Solar Sail Controls

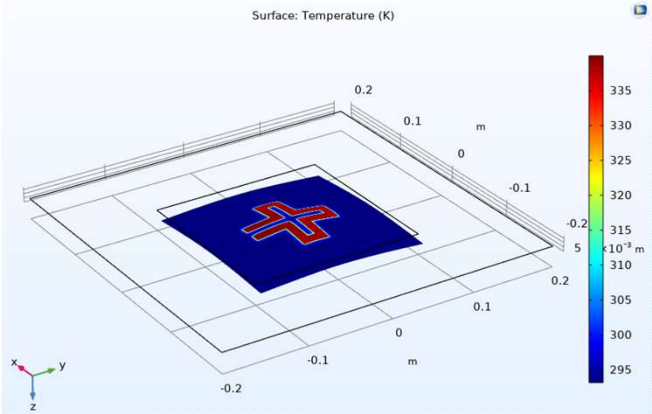
Simple Actuators

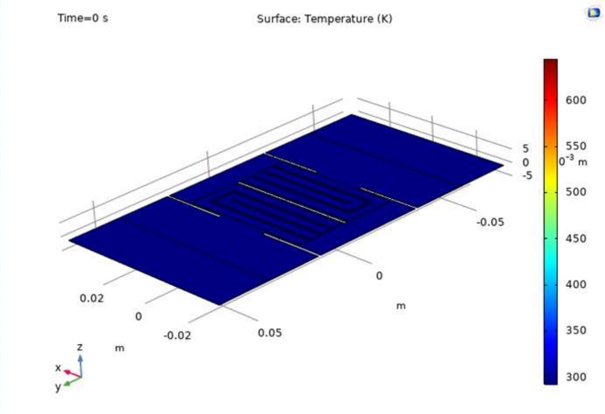


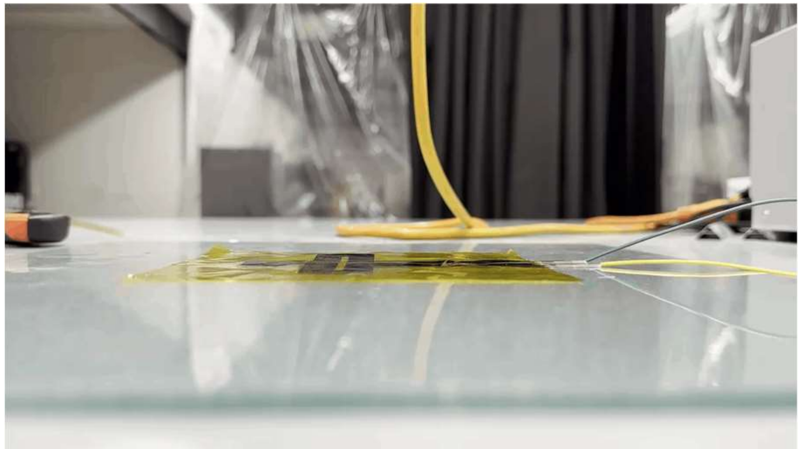


CNT film on Mylar

Surface Control



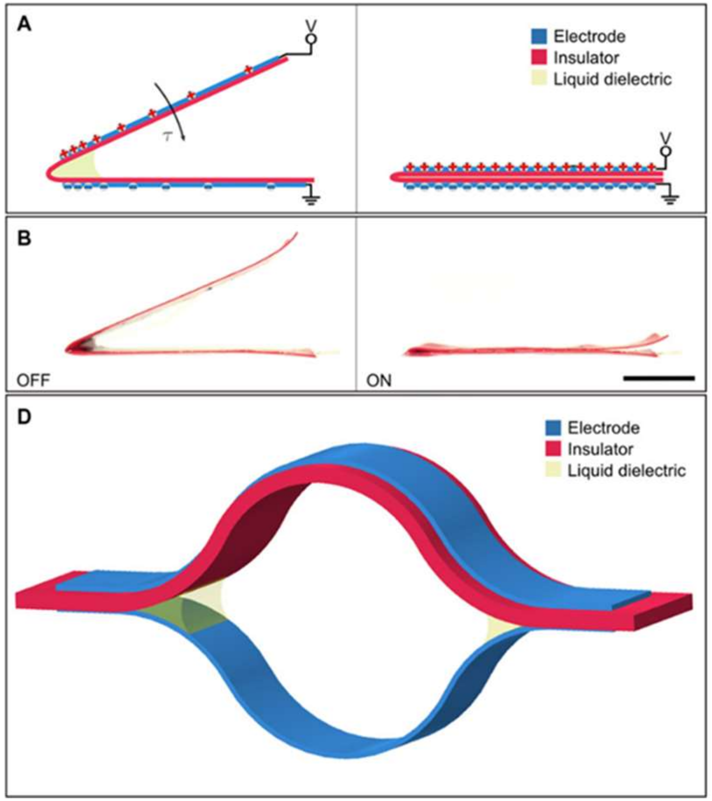




CNT film on Kapton

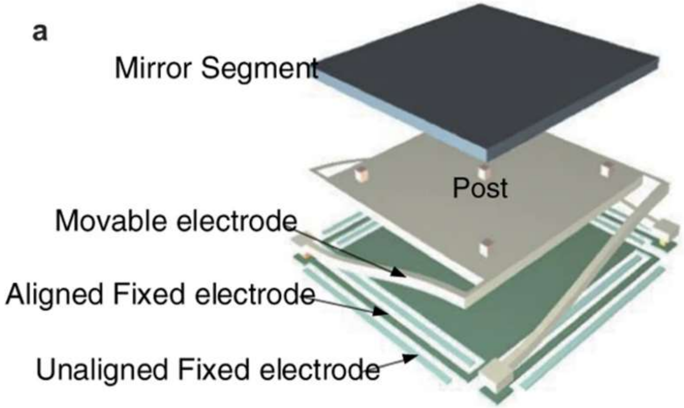
Electrostatic Actuation for Solar Sail Controls

Electro-ribbon Actuators

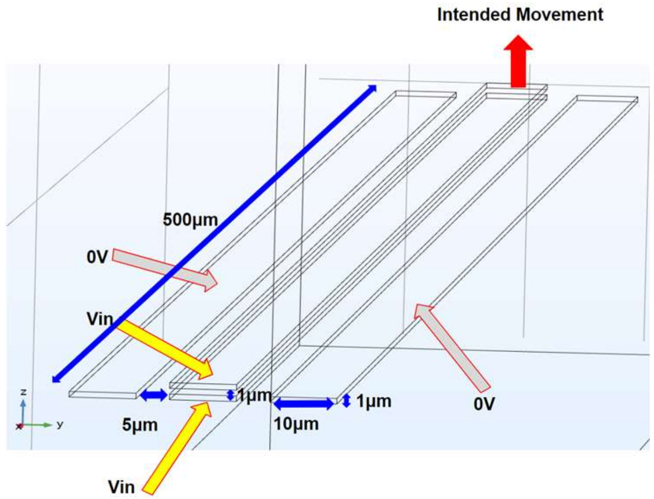


Credit: *Taghavi et al. Science Robotics, 2018*

Electrorepulsive Actuators



Electrorepulsive Actuation for Deformable Mirrors
Credit: *Wang et al., Scientific Reports, 2016*

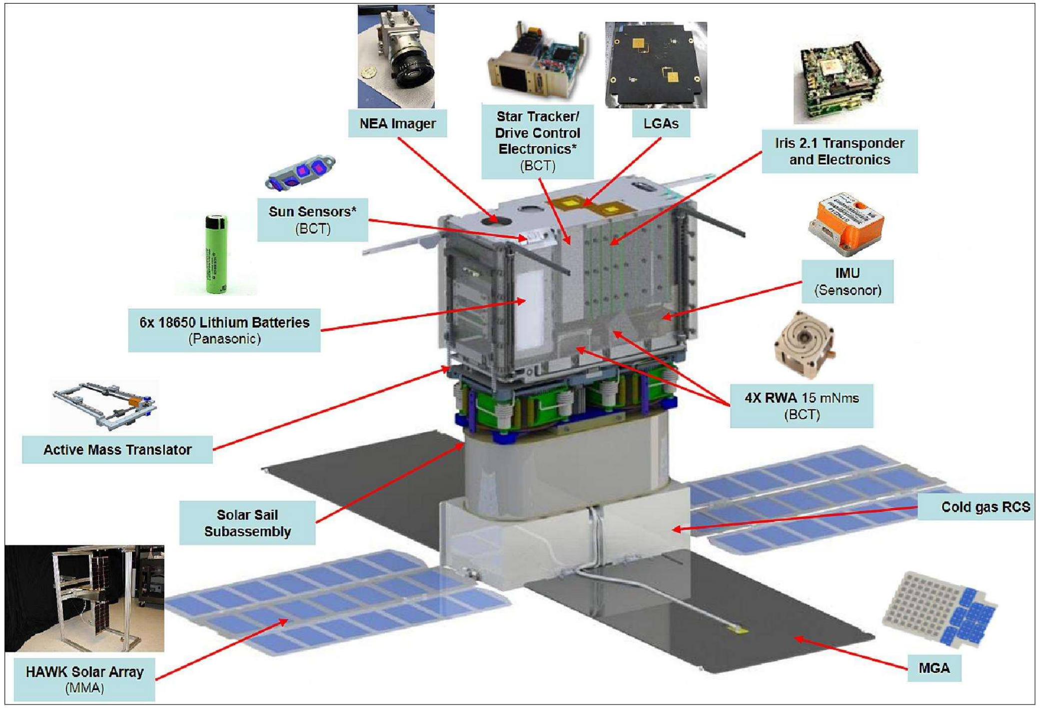


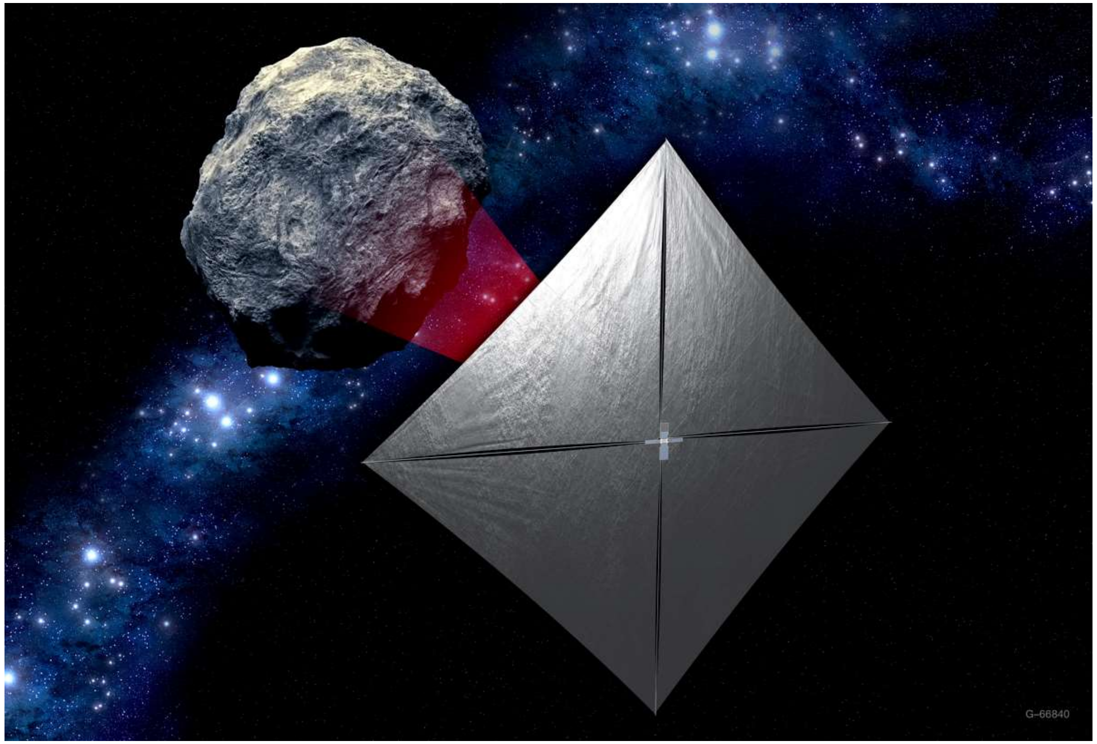
Geometric Configuration

Electrostatic actuators can be ultra thin & provide useful actuation with minimal power consumption

SailCraft Architecture

NEA Scout example

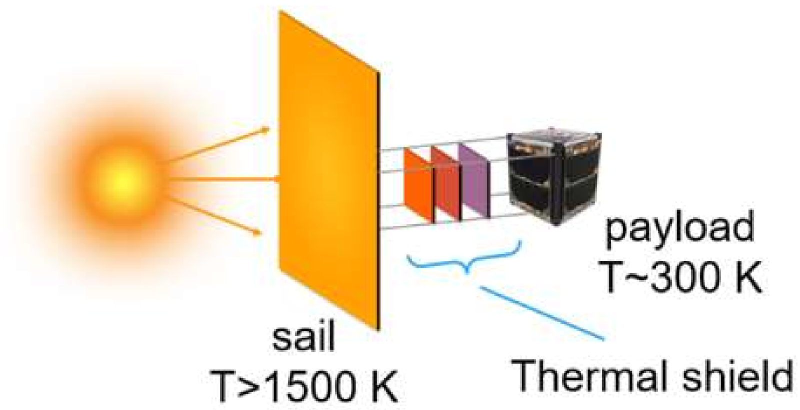


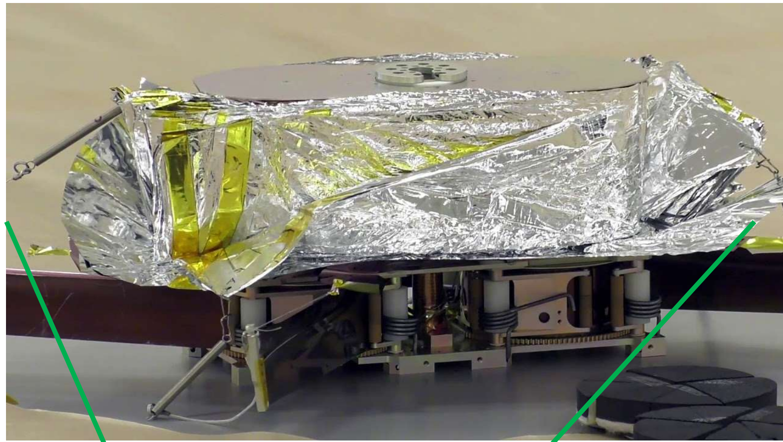


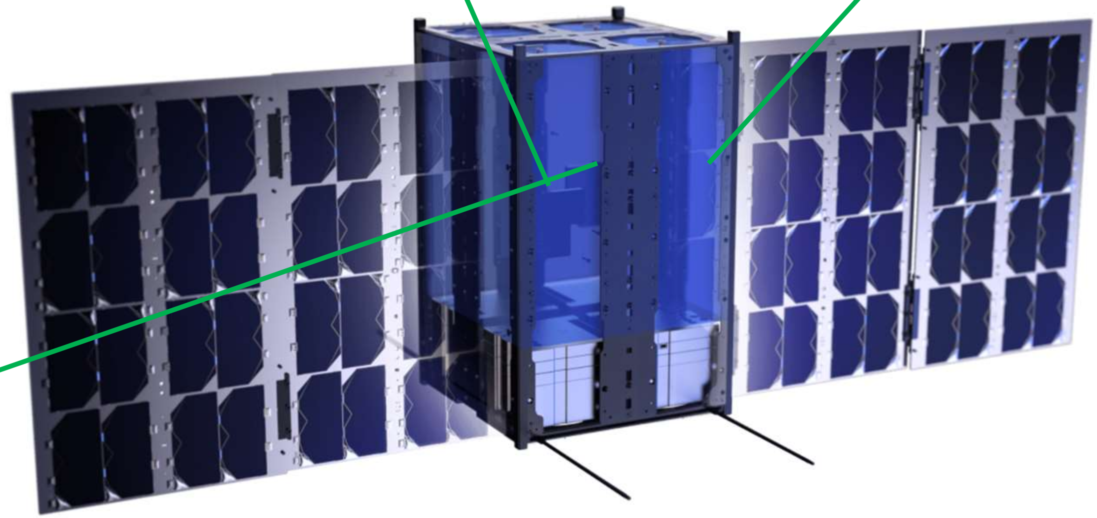
- 6U cubesat
- 14 kg mass
- 85 m^2 sail

SailCraft Architecture

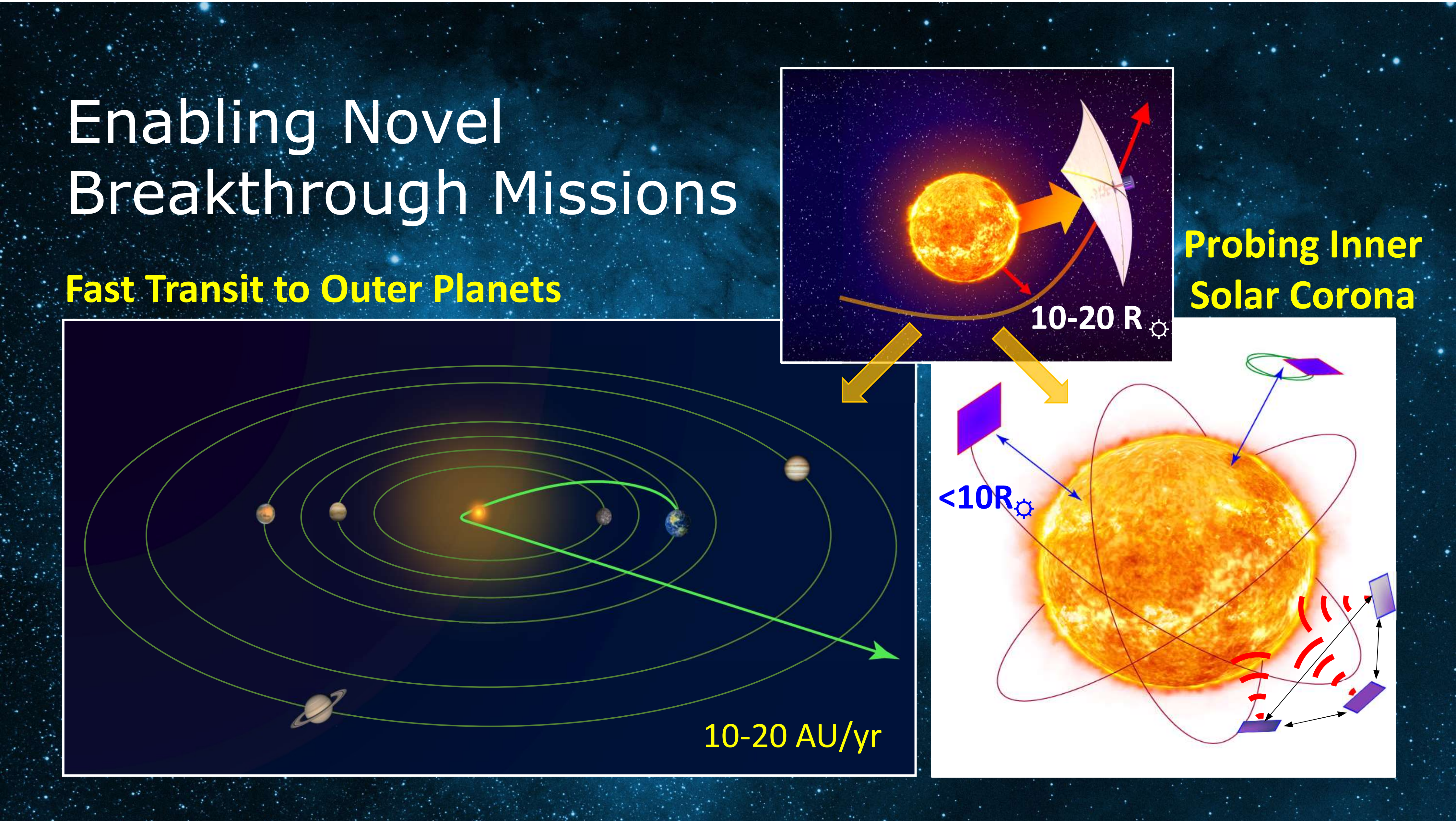
- ~15 kg spacecraft bus
- ~2 g/m^2 sail material areal density
- 50-70 g/m boom density
- 50 m x 50 m sail area
- ~25 kg total mass

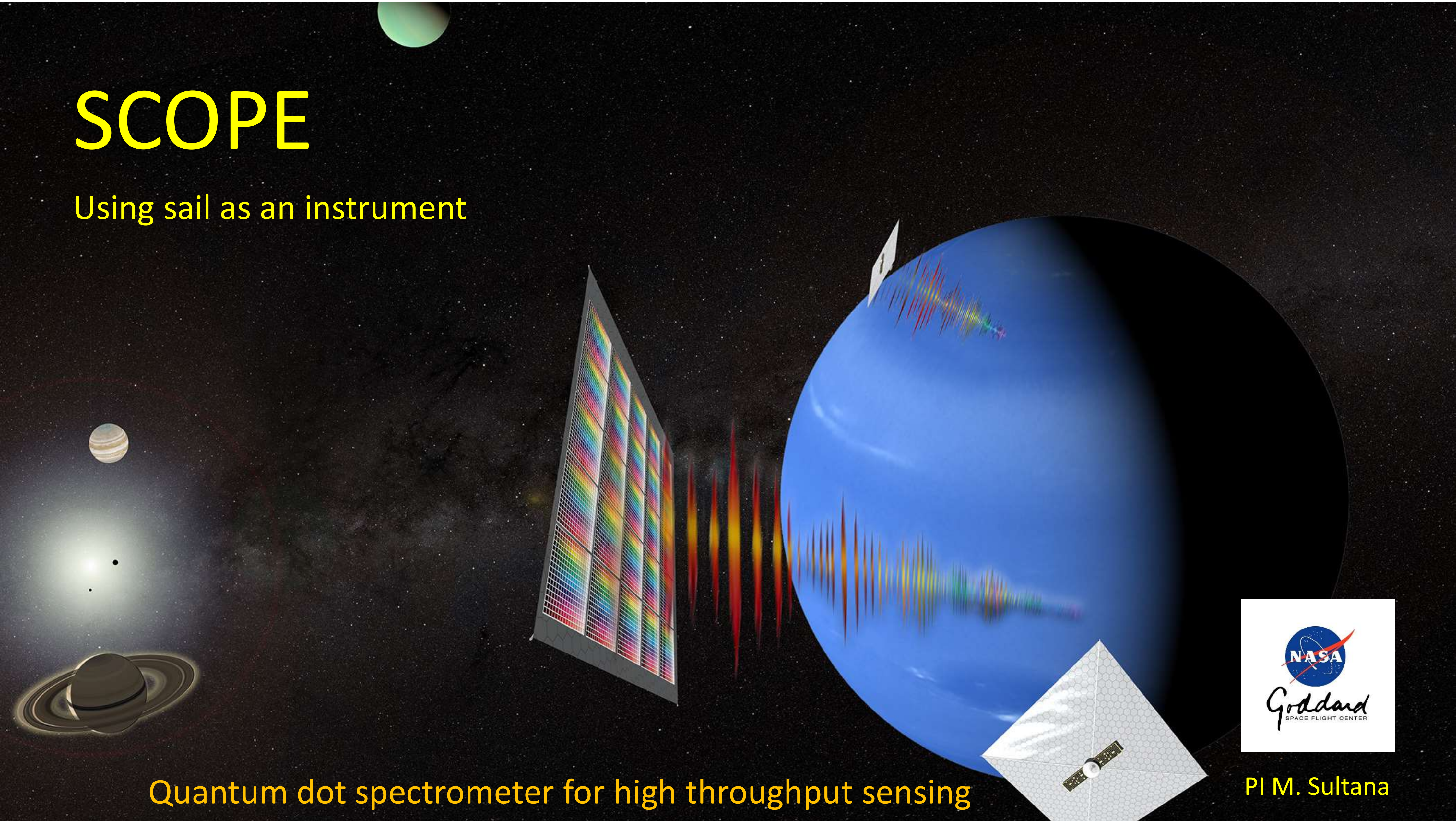




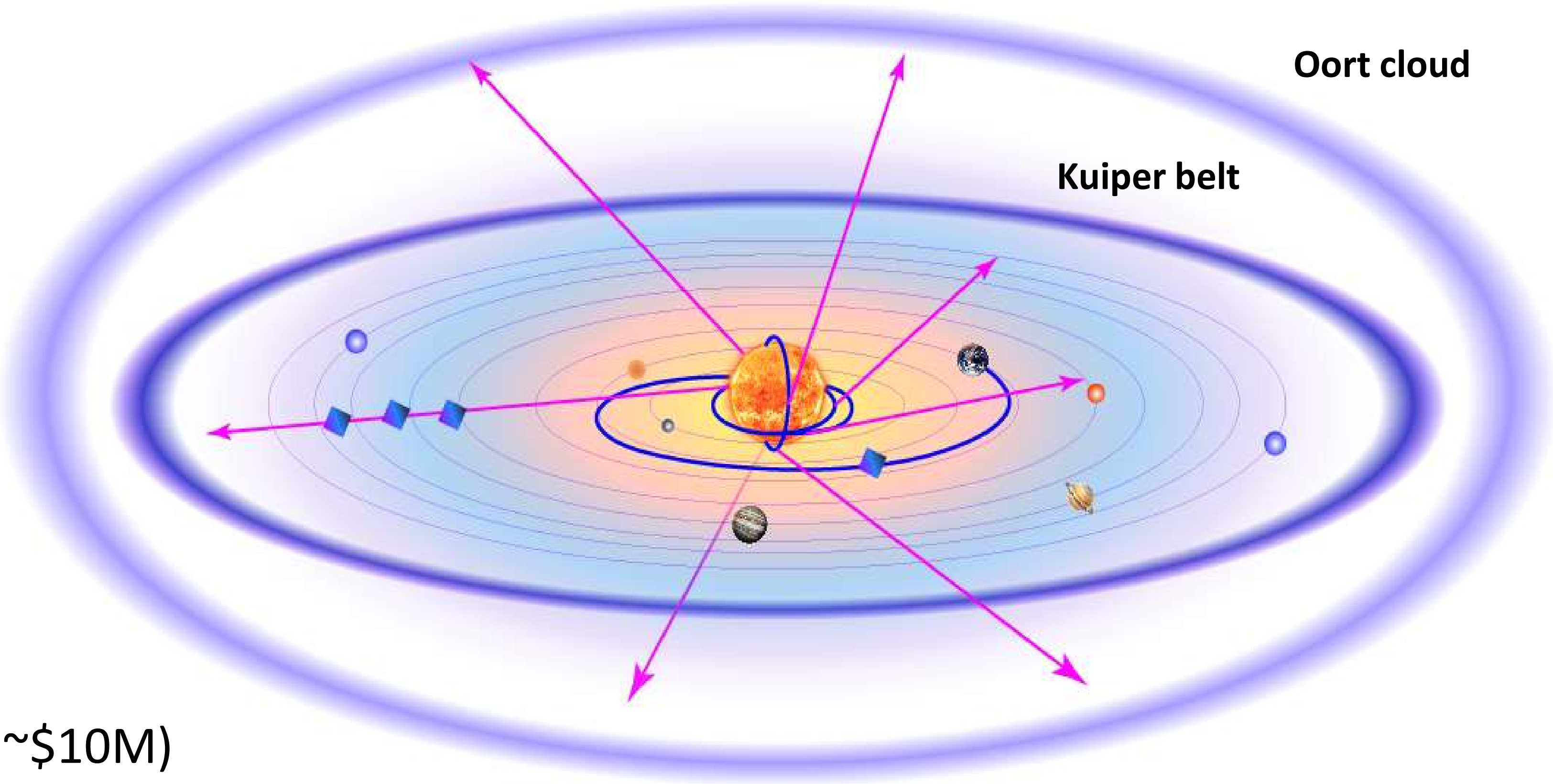


12U – 16U CubeSat


Enabling Novel Breakthrough Missions
Fast Transit to Outer Planets
10-20 AU/yr
10-20 R☉
Probing Inner Solar Corona
<10R☉


SCOPE
Using sail as an instrument
Quantum dot spectrometer for high throughput sensing
PI M. Sultana
NASA
Goddard
SPACE FLIGHT CENTER

Vision: Sun as a Launch Pad



Goals:

- low cost (~$10M)
- short lead time
- missions to arbitrary destinations (e.g., high inclination)
- fast (>20 AU/year)

Team and Acknowledgements

Collaborators: L. Johnson, A. Heaton, S. Mahmooda, H. Helvajian, M. Velli,, S. Turyshev, D. Garber, L. Friedman

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