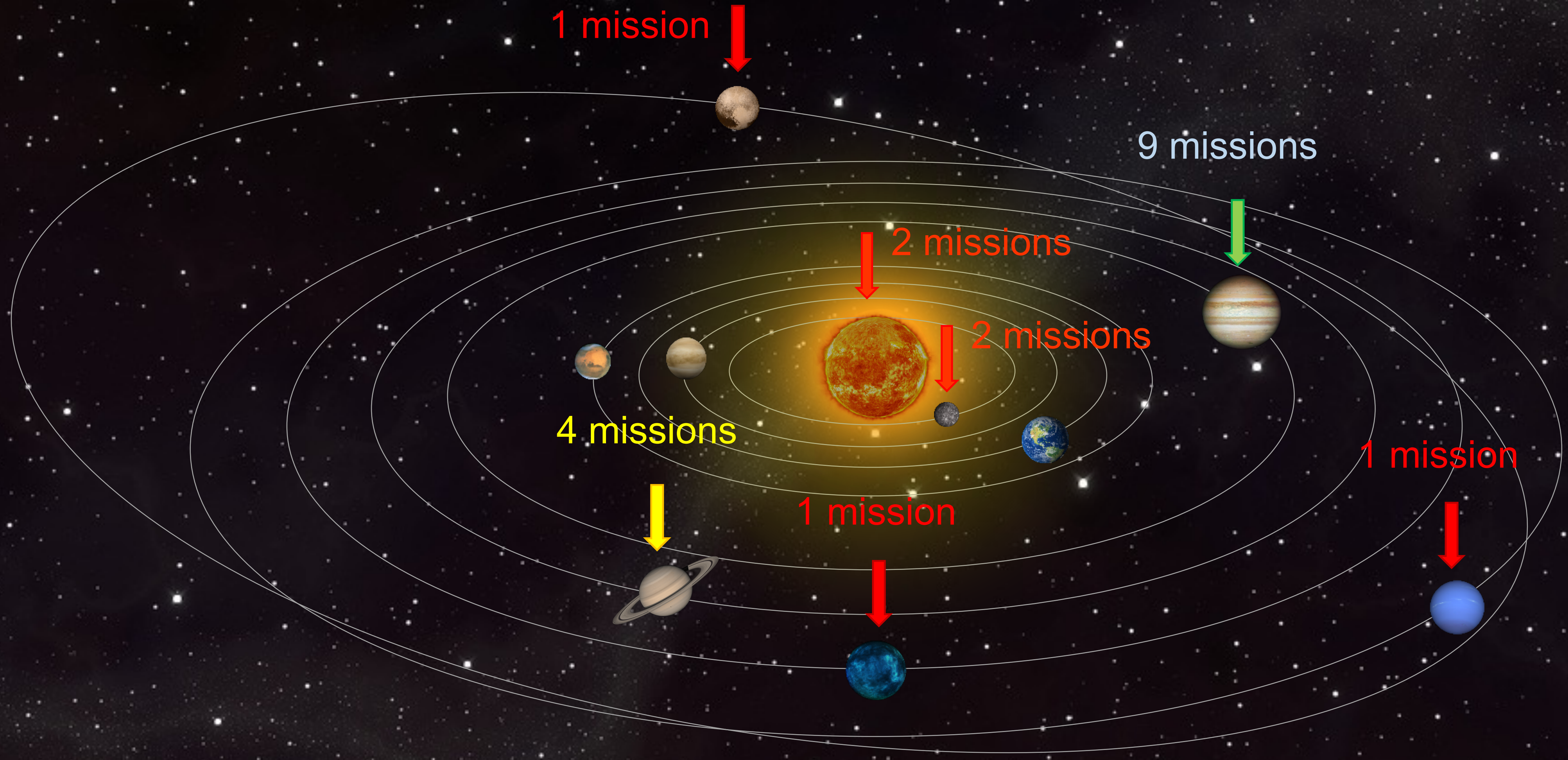
Fast Transit Missions with Extreme Solar Sailing

Artur Davoyan

University of California, Los Angeles

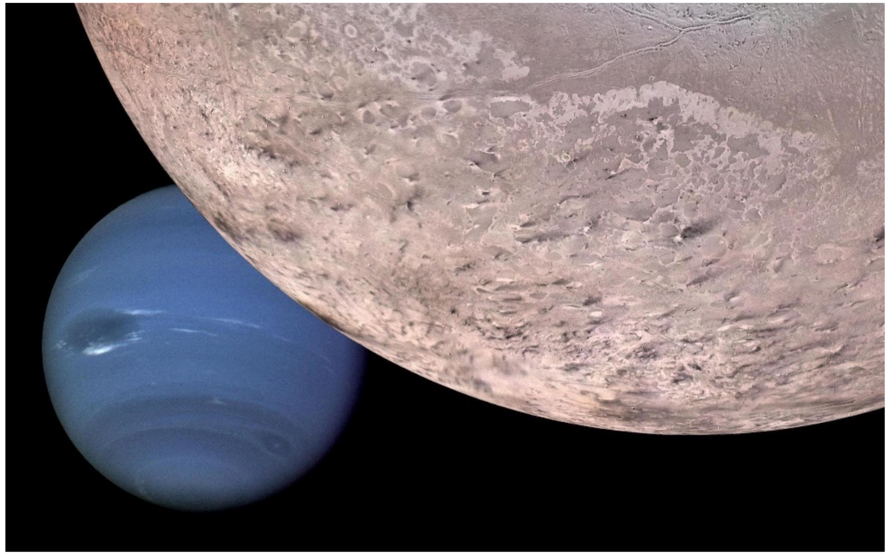
Deep Space Exploration Today



60 years of space exploration

Need For Breakthrough Science

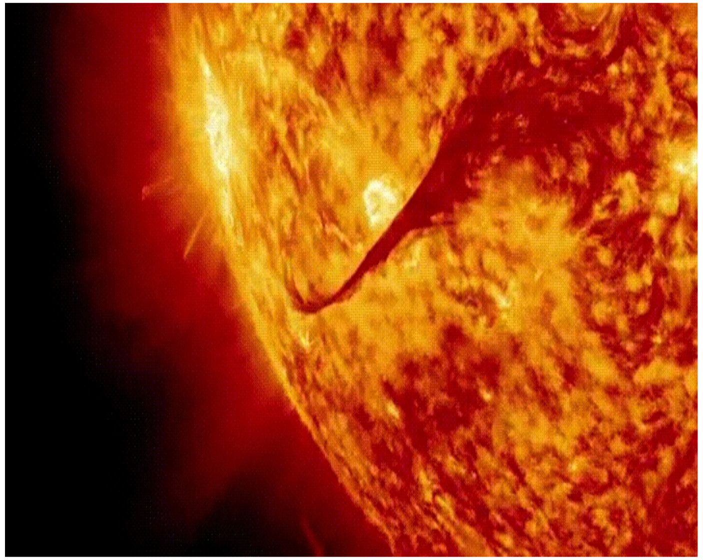
Outer planets & moons



Search for life

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

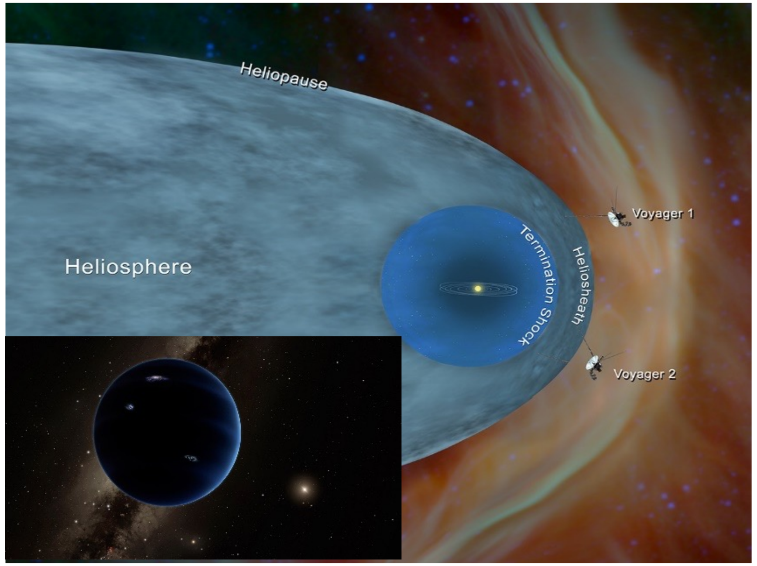
Our star



Understanding our Sun

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

Interstellar medium & beyond



Going to far reaches

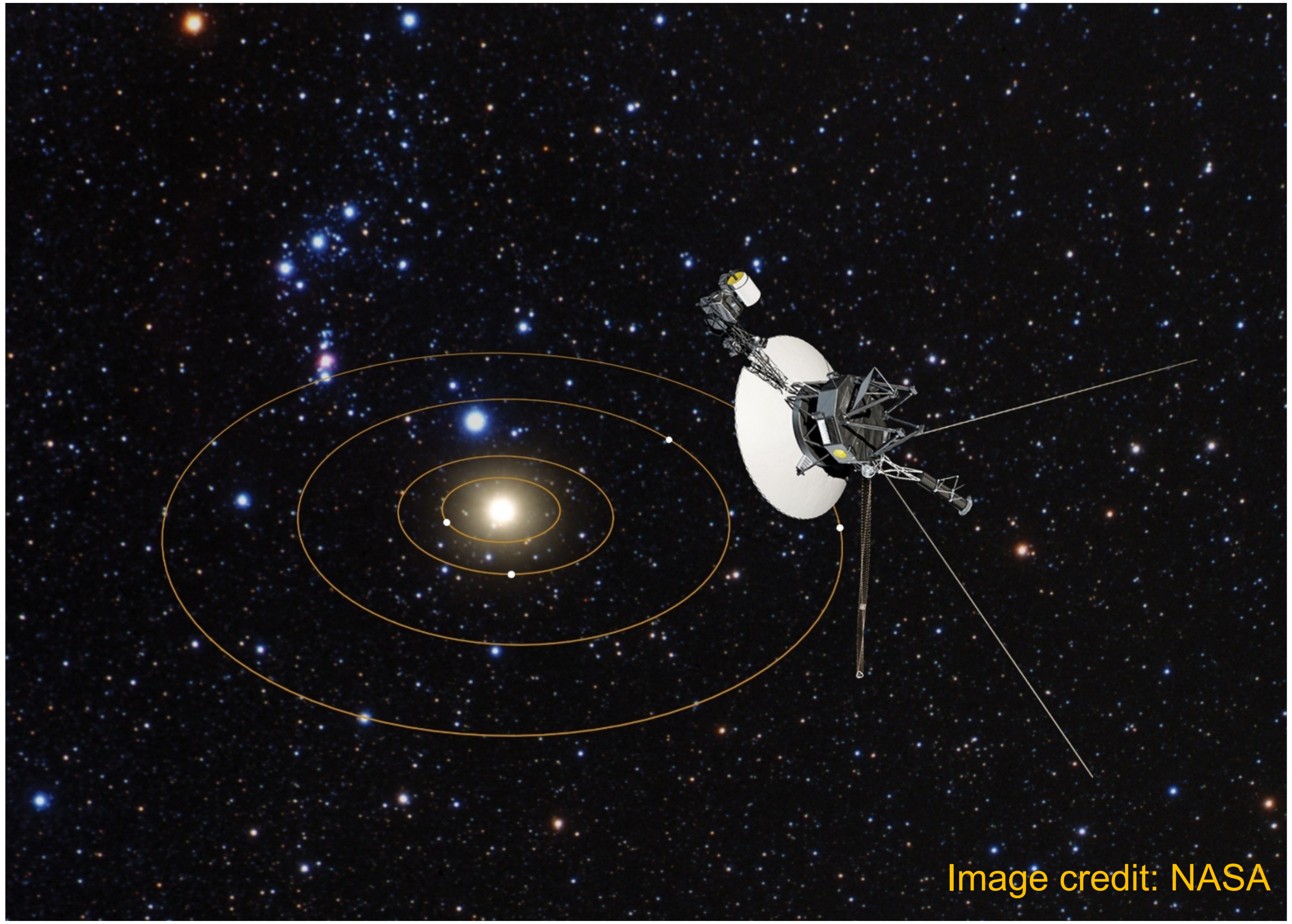
- Only two probes have reached the interstellar medium
- Planet X?
- Oort cloud
- Solar gravity lens

State Of The Art: Outer Space

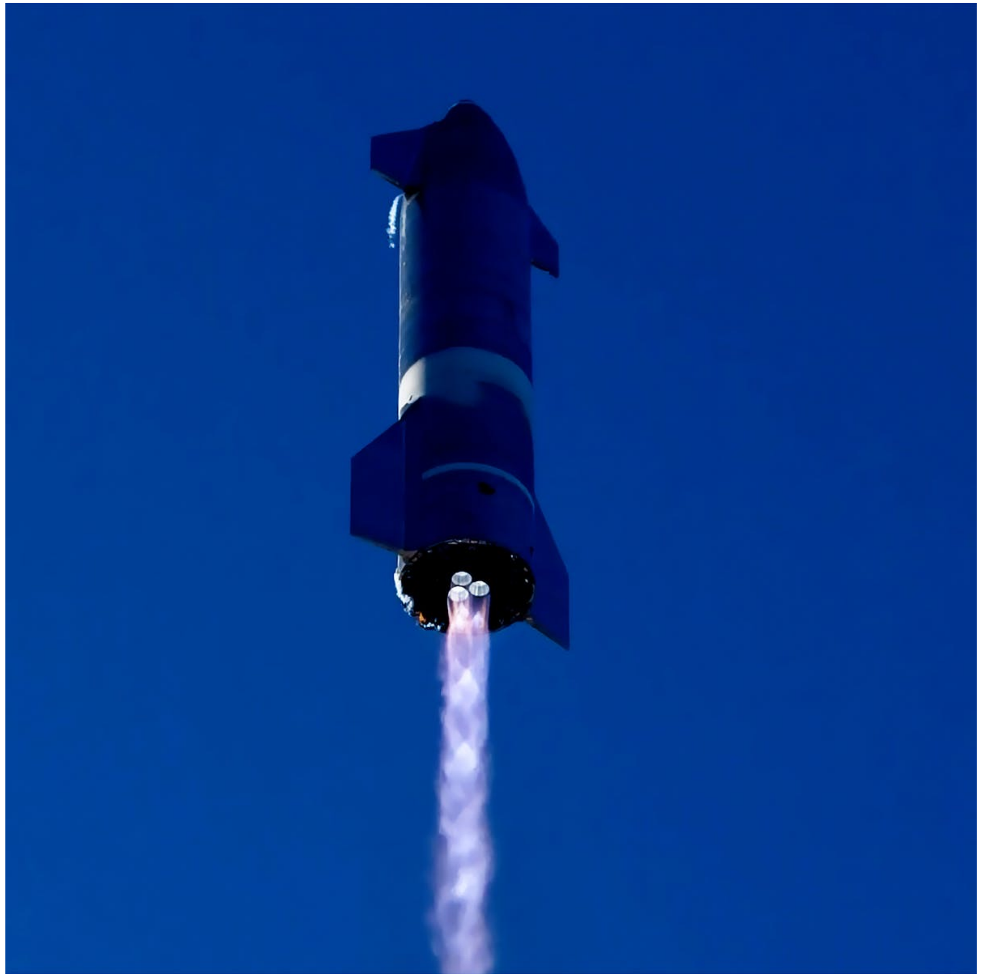
- Voyager 1 (1977) is the fastest spacecraft ever built.

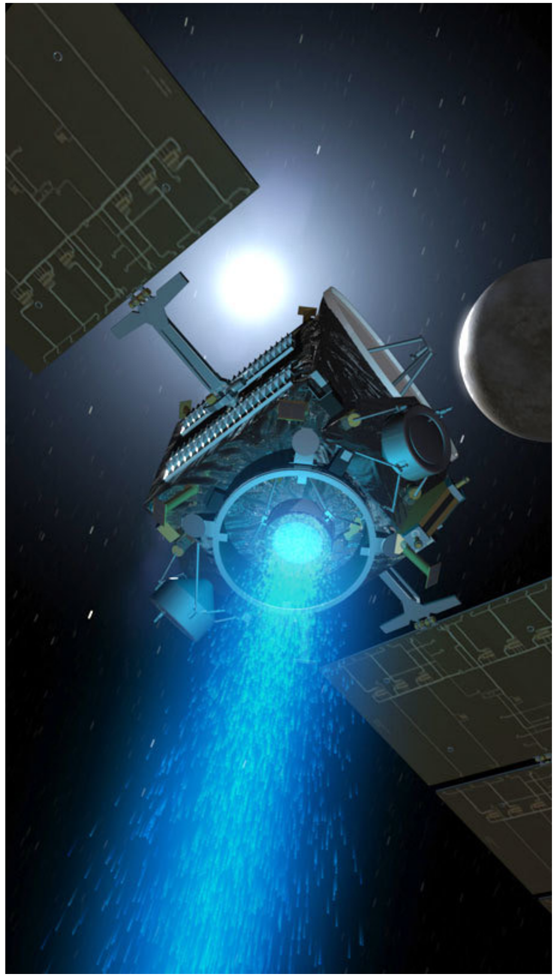
- Travelling at a record 17km/s it took 35 years to reach interstellar medium at 120 AU (the first spacecraft to reach this milestone).

- Most distant spacecraft as of today (155 AU after 45 years of travel)



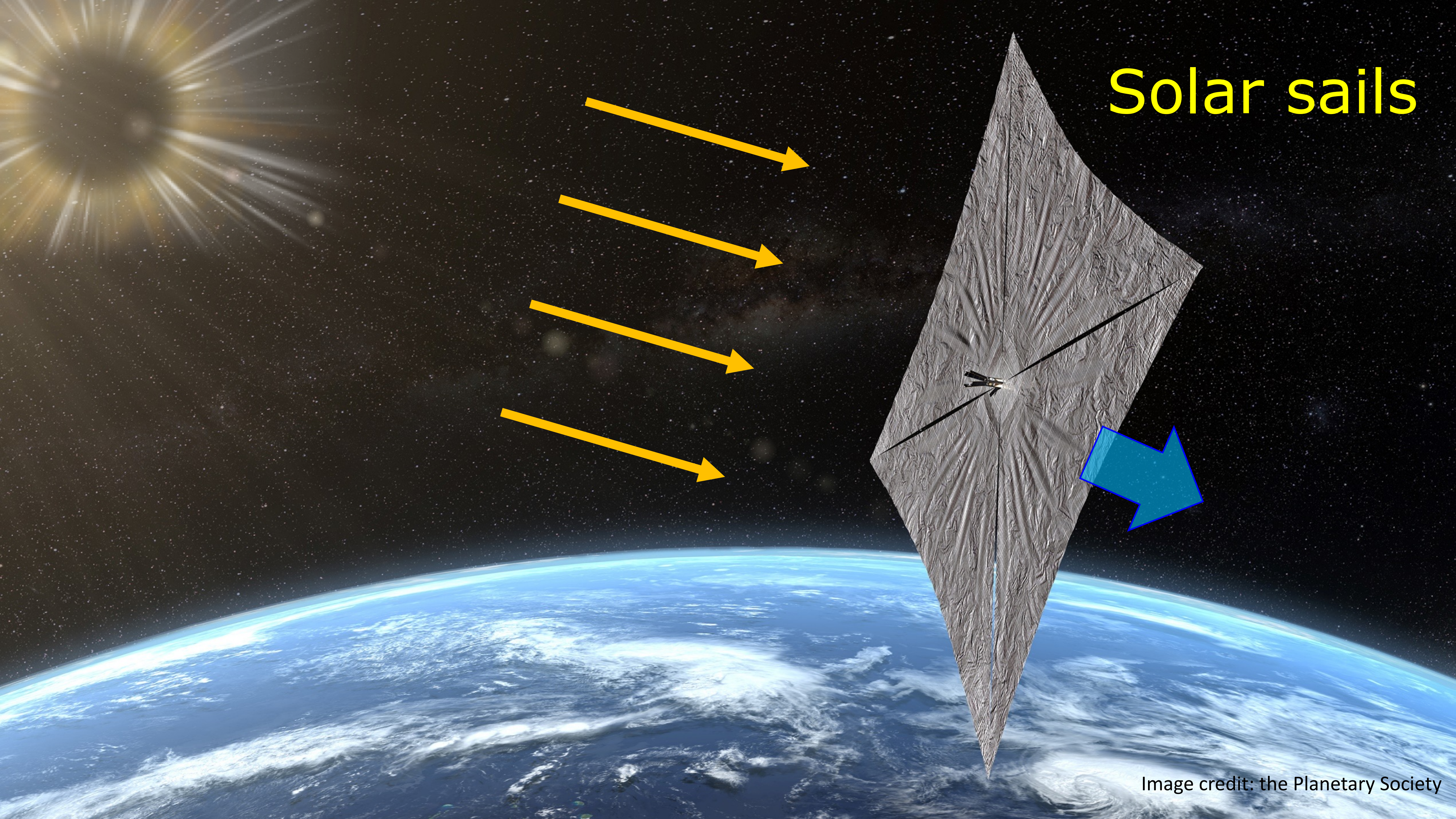
Limitations Of Propulsion





- Need to carry fuel and “throw” it away to propel
- Limited by the rocket equation

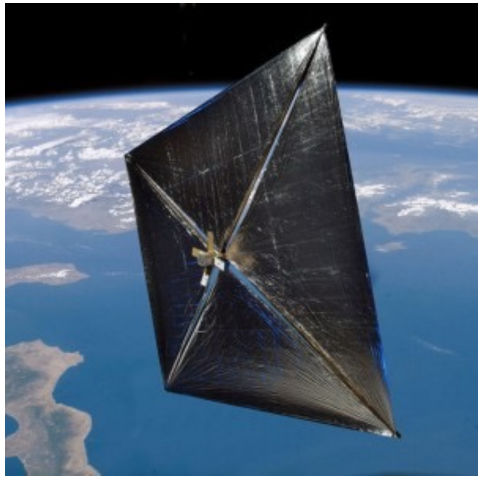
$$\Delta v = v_e \ln\left(\frac{m_0}{m_f}\right)$$



Solar sails
Image credit: the Planetary Society

Solar sail missions flown and planned

NanoSail-D (2010)
NASA

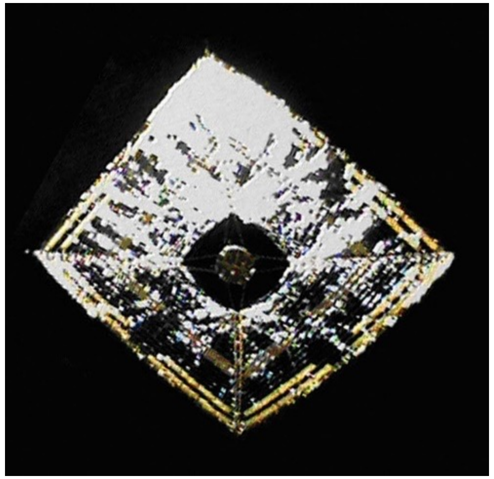


Earth orbit
Deployment Test

3U CubeSat
10 m^2

$A/m = 2.2\ m^2/kg$

IKAROS (2010)
JAXA

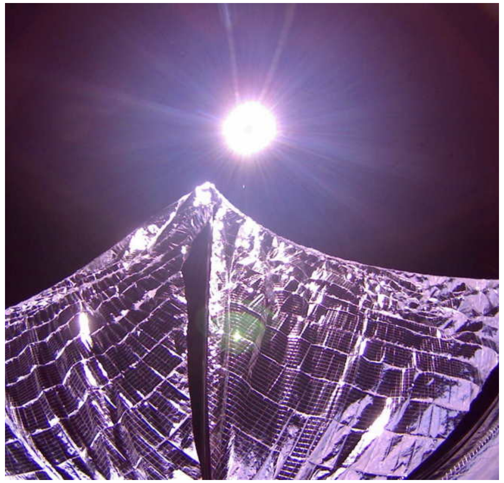


Interplanetary
mission

315 kg, SmallSat
196 m^2

$1.3\ m^2/kg$

LightSail-1 (2015)
The Planetary Society

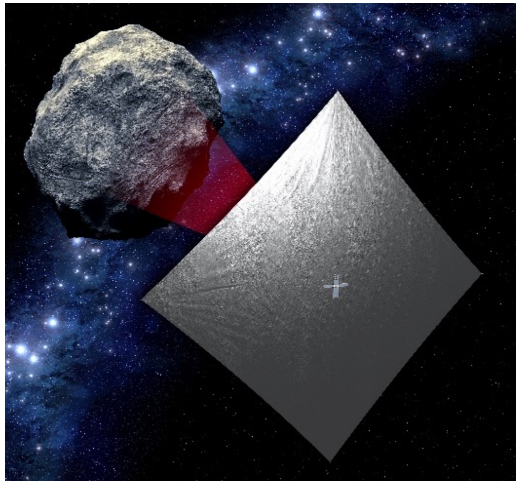


Earth Orbit
Deployment Test

3U CubeSat
32 m^2

$7\ m^2/kg$

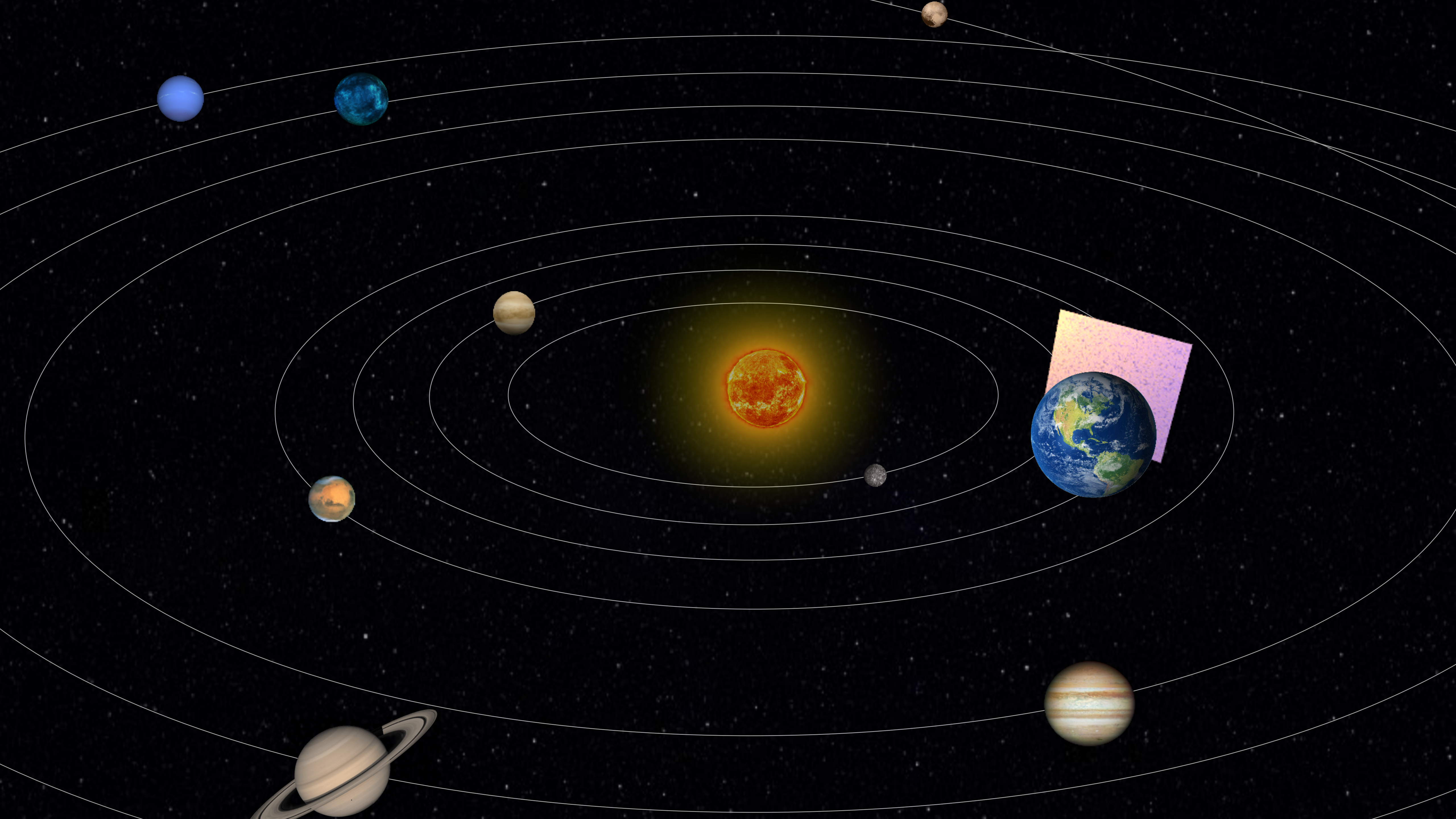
NEA Scout (2021)
NASA



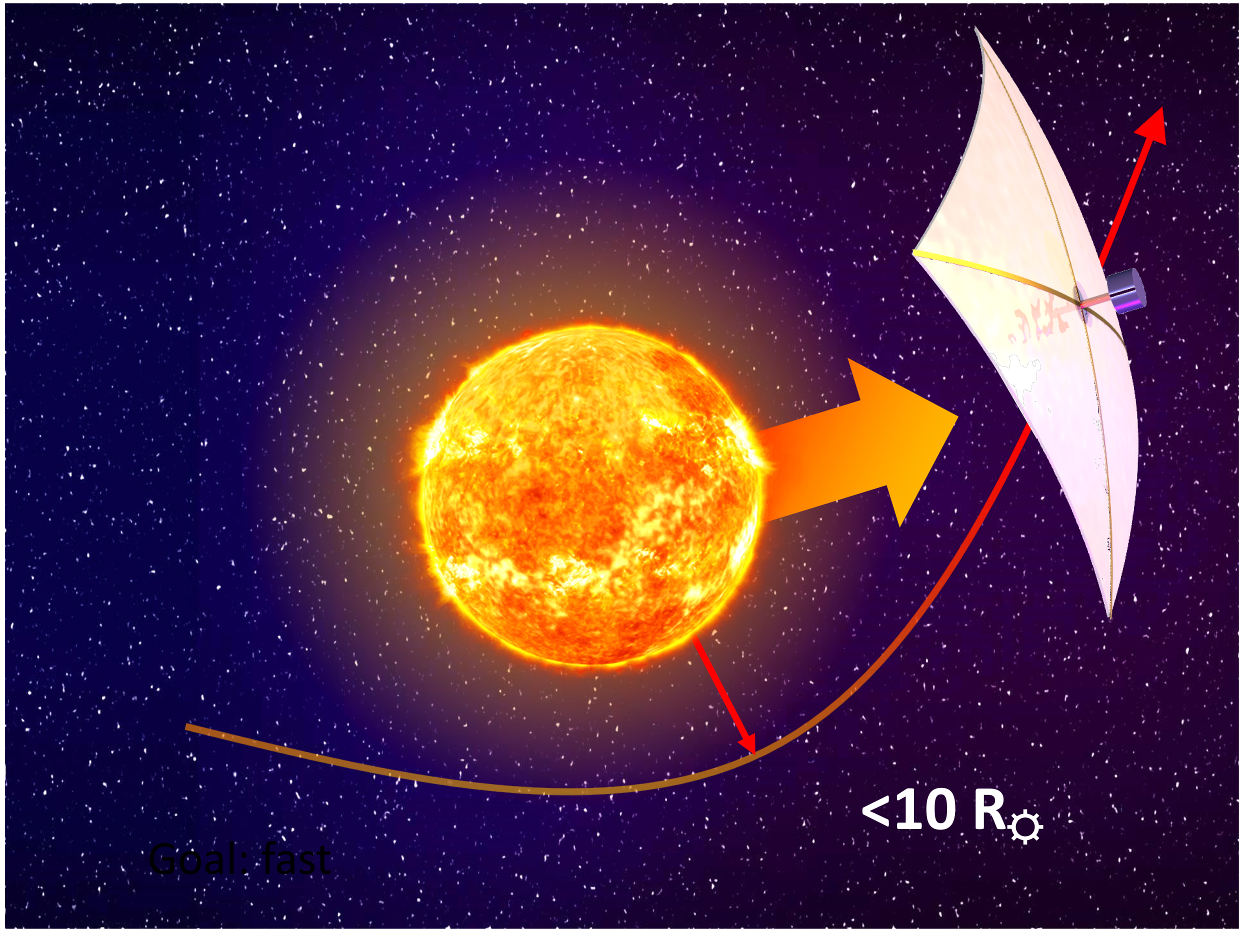
Interplanetary
mission

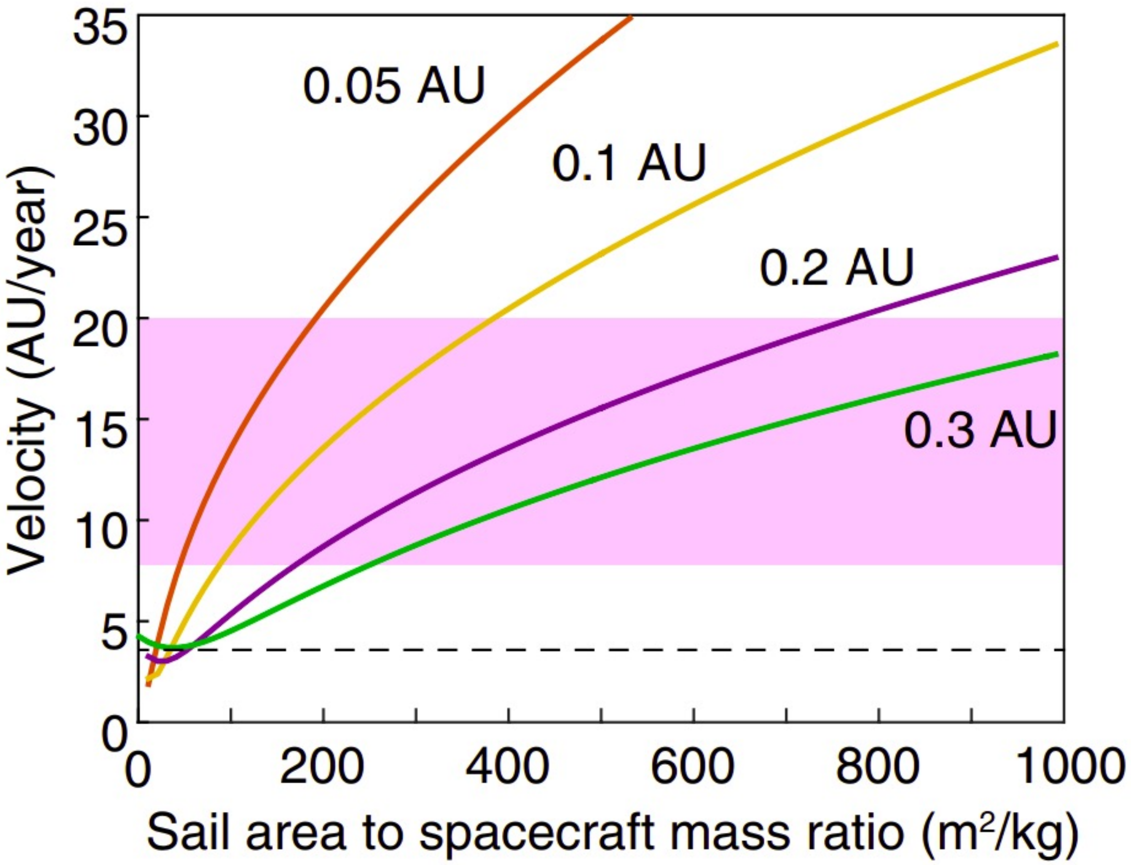
6U CubeSat
86 m^2

$8\ m^2/kg$

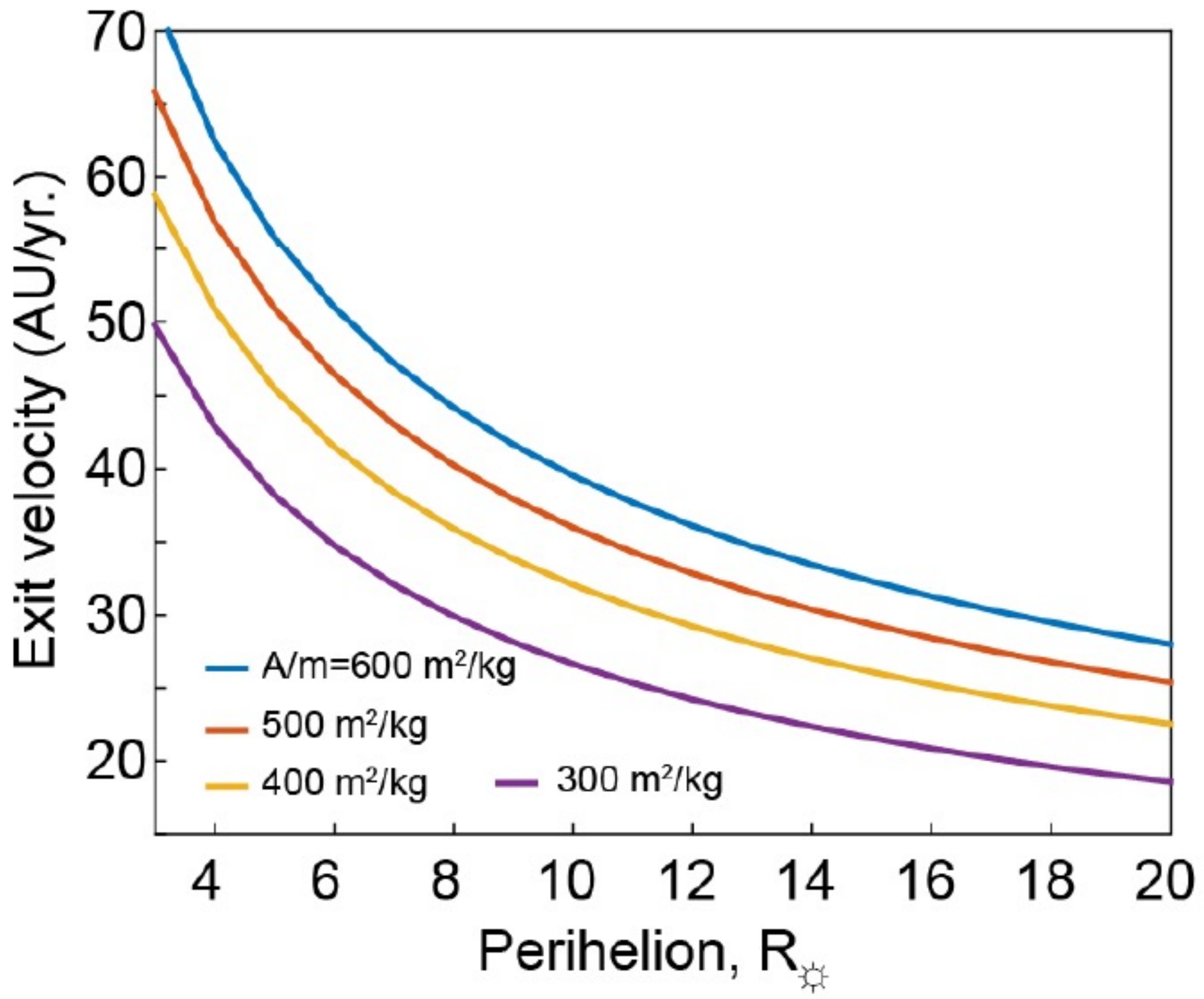


How fast can we go?



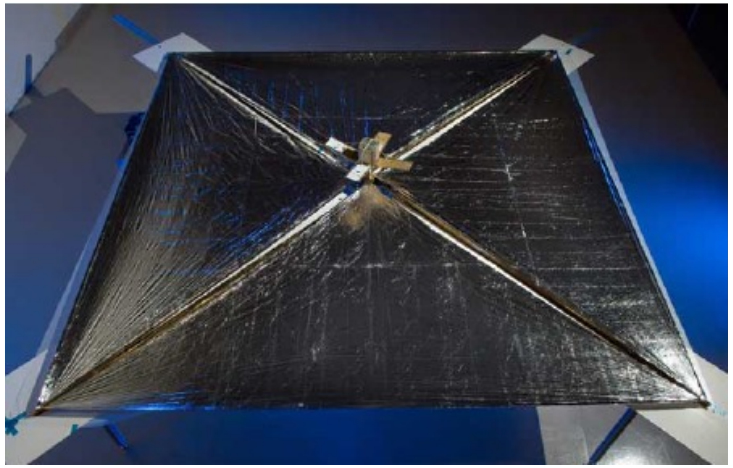


Where is the limit?

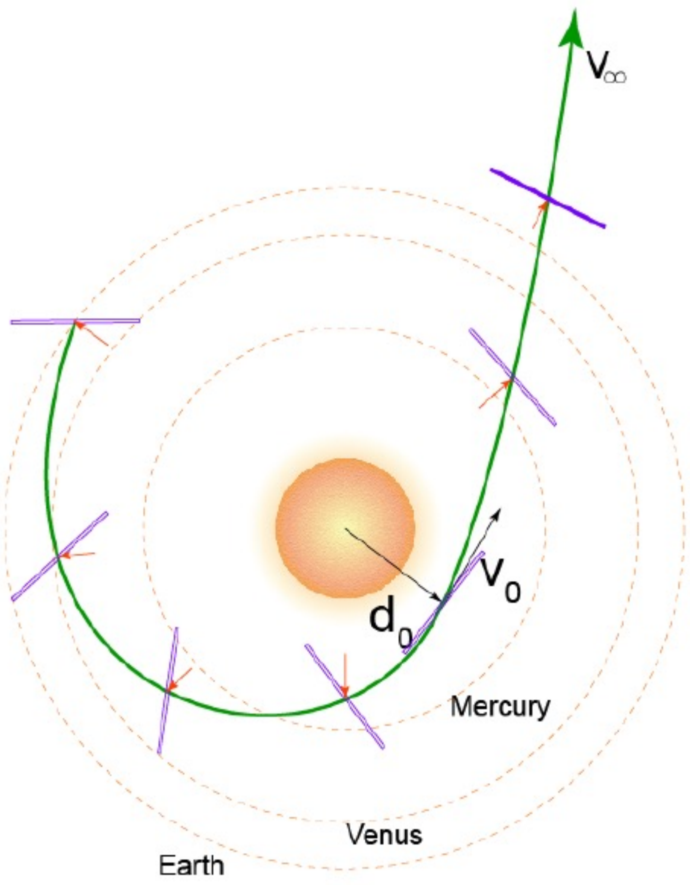


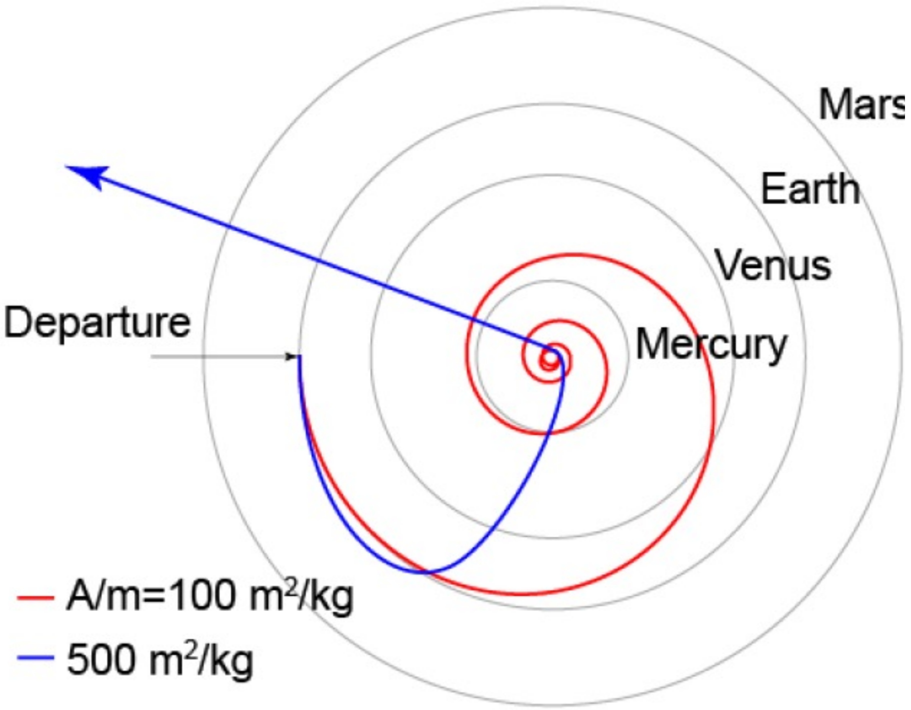
Parameters needed for 60 AU/yr

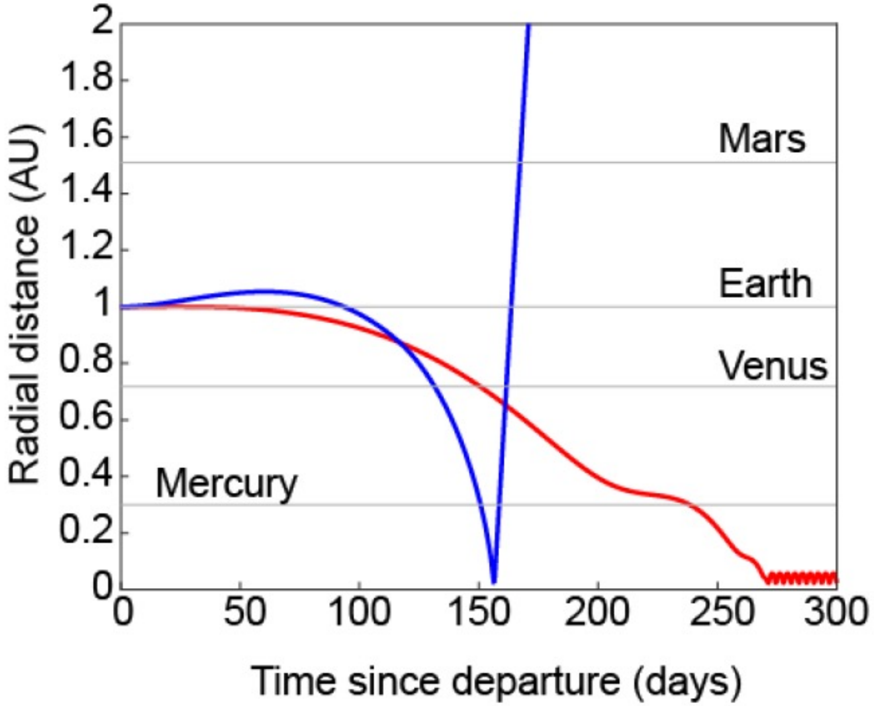
Parameter	Range
Spacecraft bus mass (excluding sail systems)	10-20 kg
Sail area	10,000 m^2 – 25,000 m^2
Perihelion pass	3-5R☼
Sail material density	<1 g/m^2
Sail material reflectivity	> 0.7



Trajectory & mission profile







C3=0

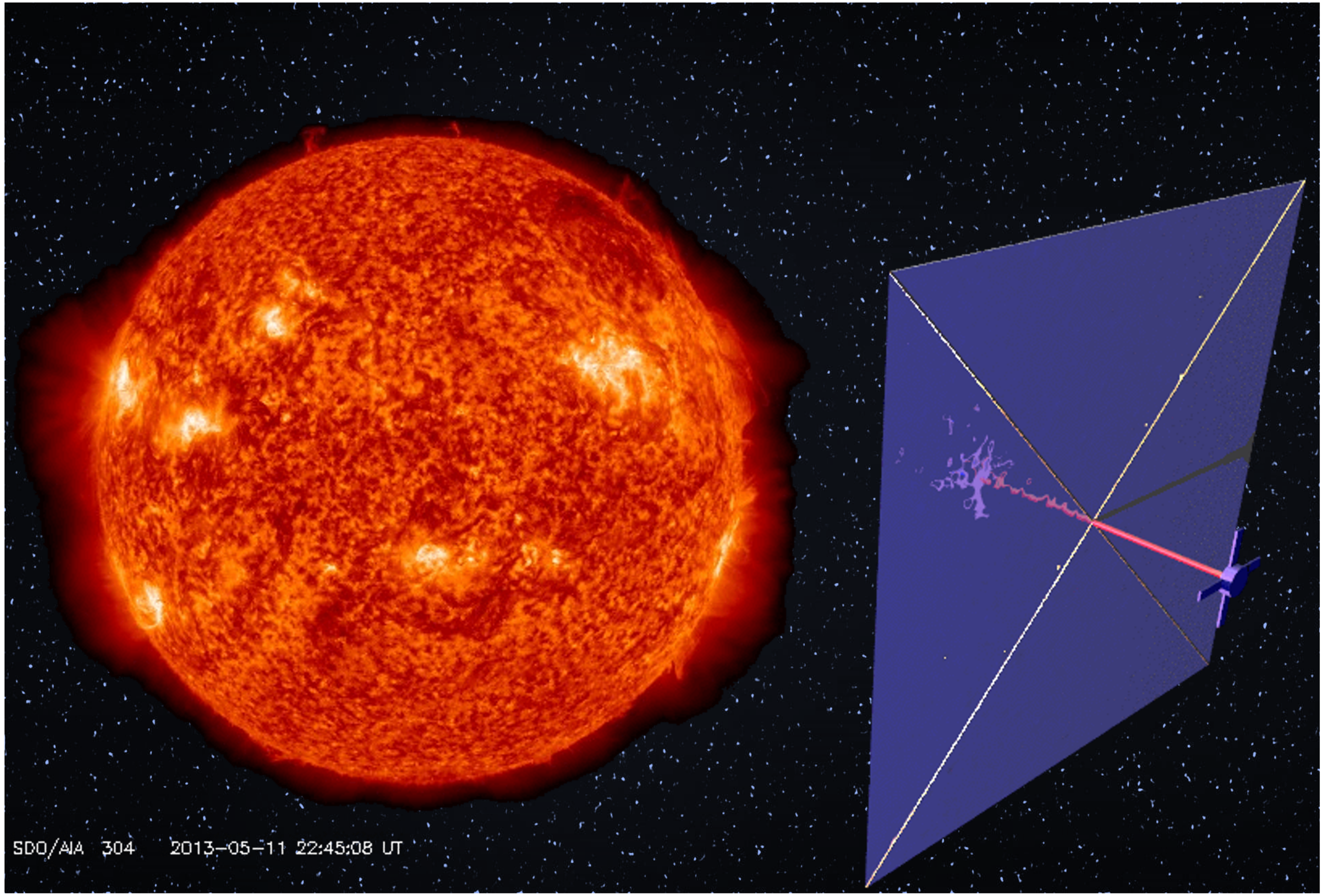
Start with MEO and "spiral out"

- $5R_\odot$ perihelion
- 100% reflectivity

- **7 days** between entering and leaving Mercury orbit
- 150 days to reach perihelion

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

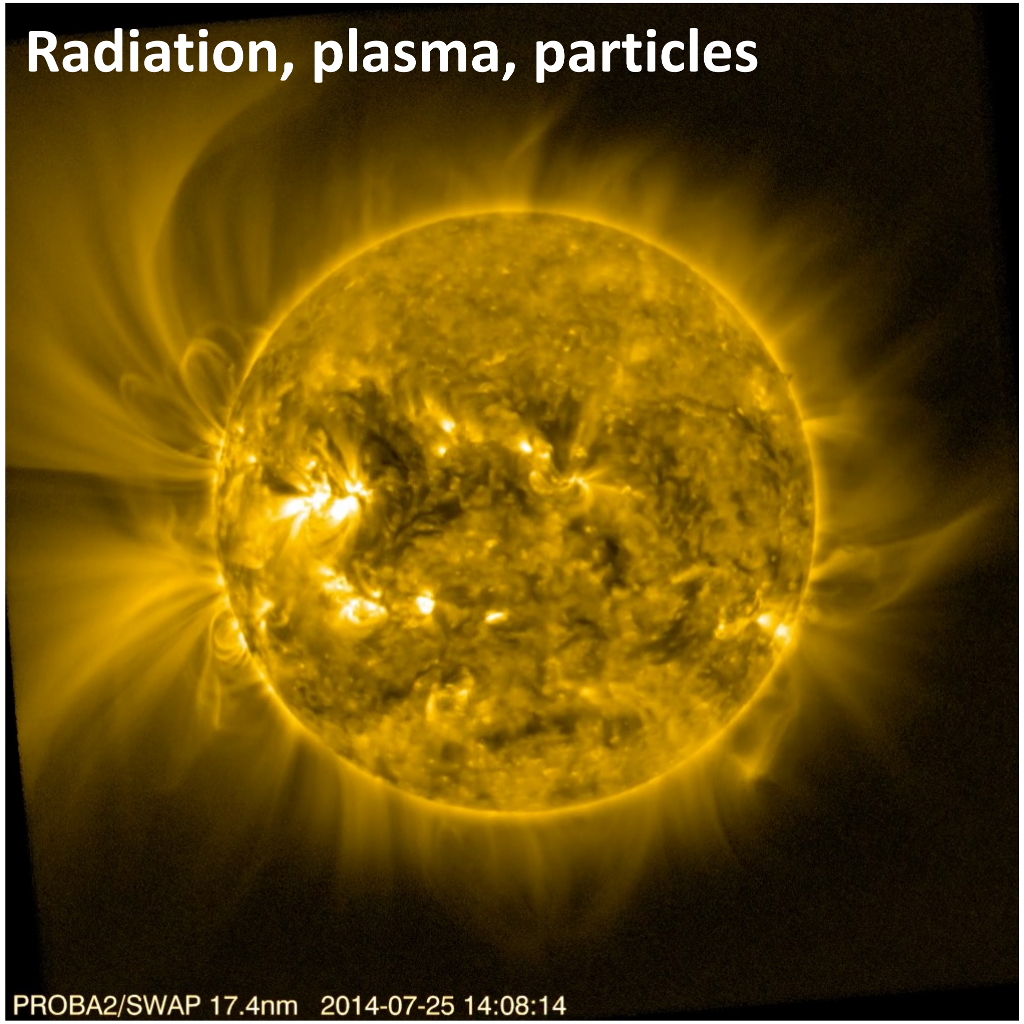
Getting Close To The Sun

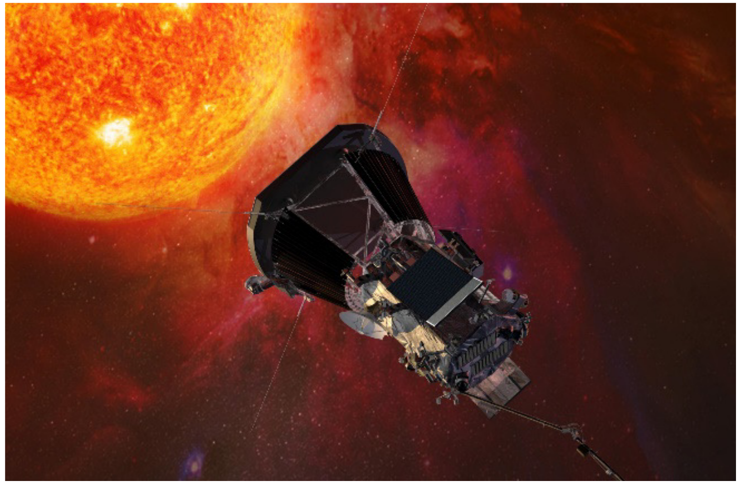


Outstanding mission challenges

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

Grand challenge

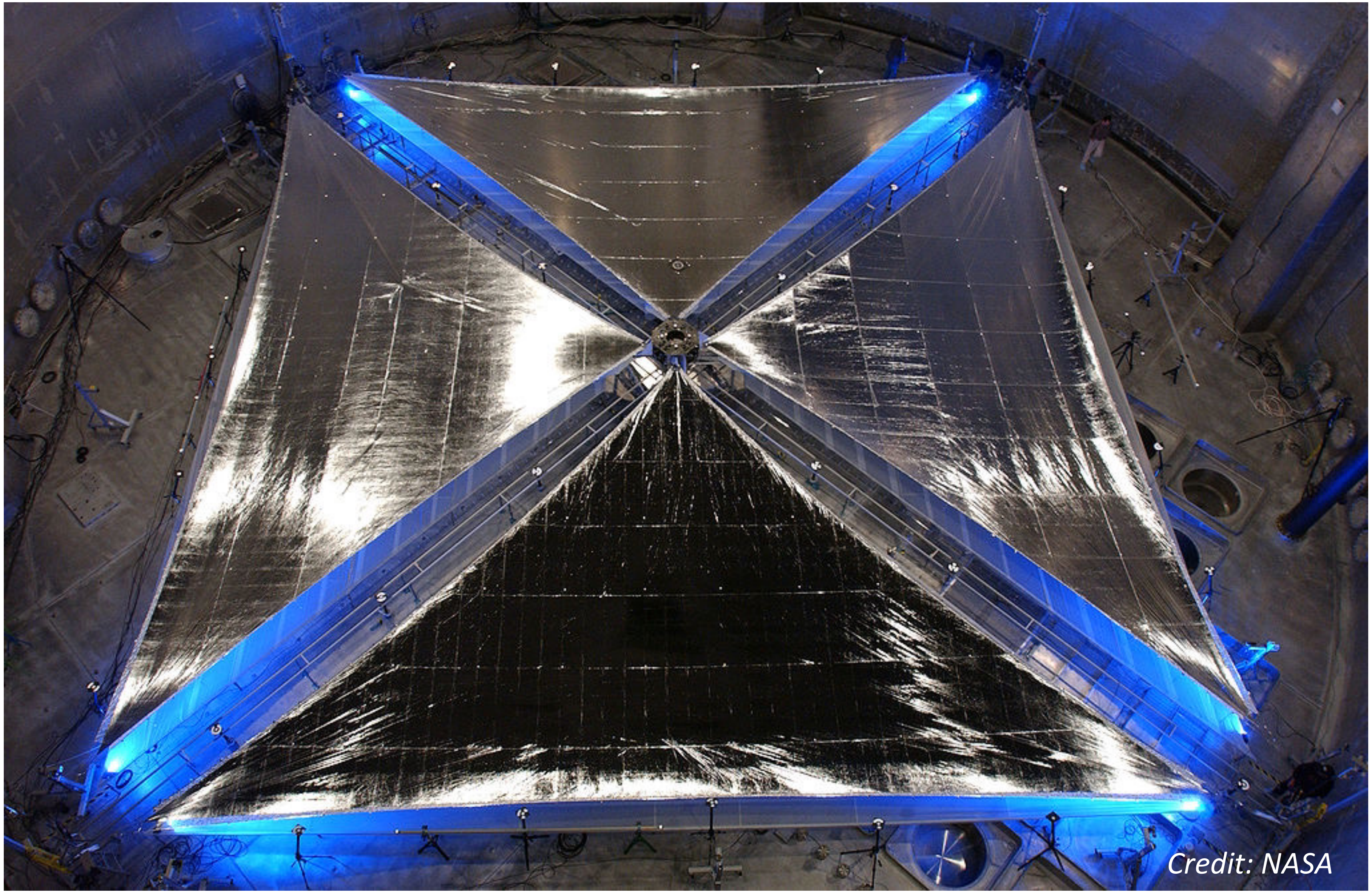




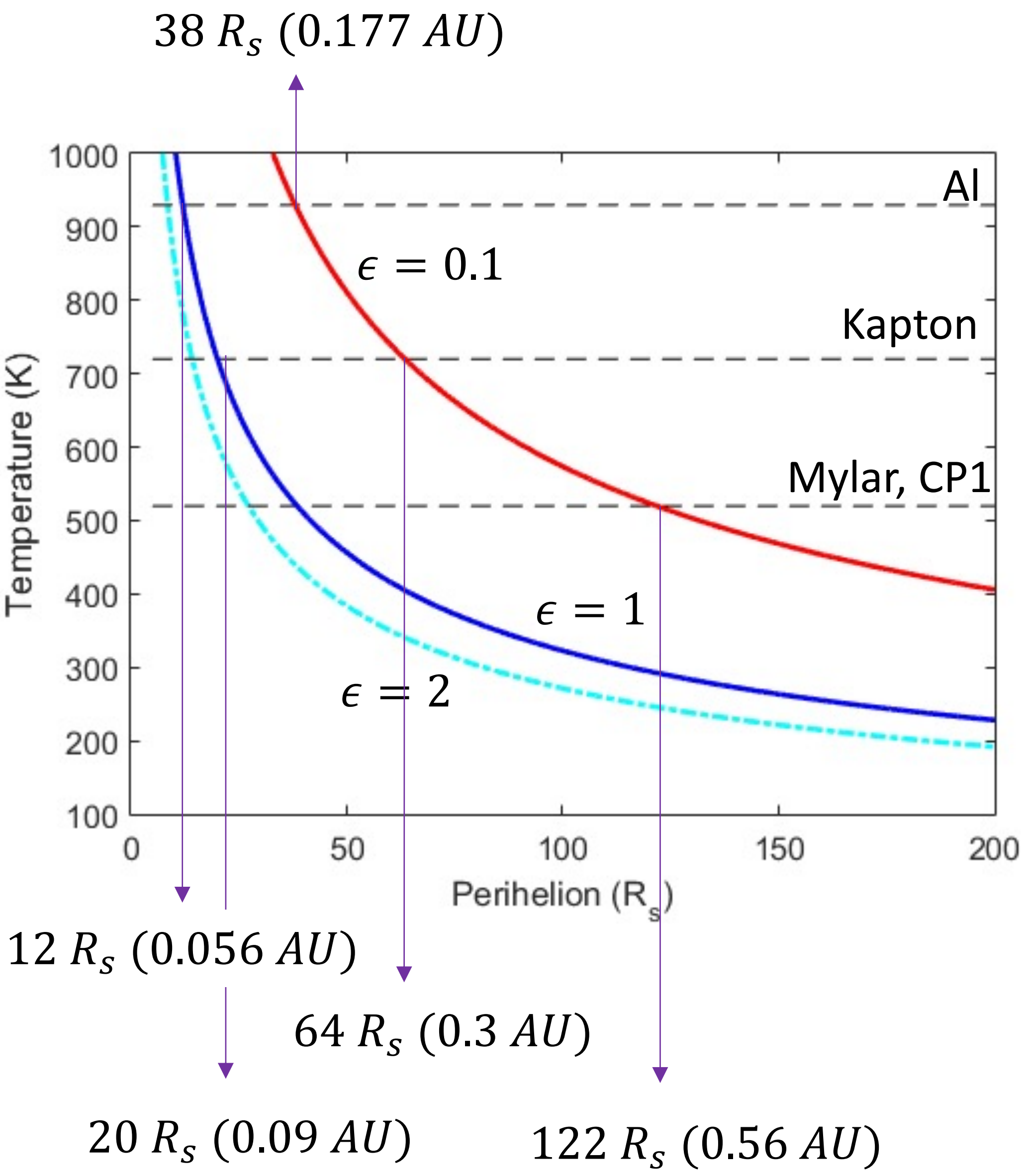
Parker solar probe
($9 R_\odot$)

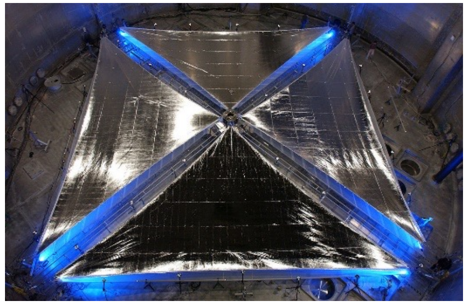
Heavy heat shield

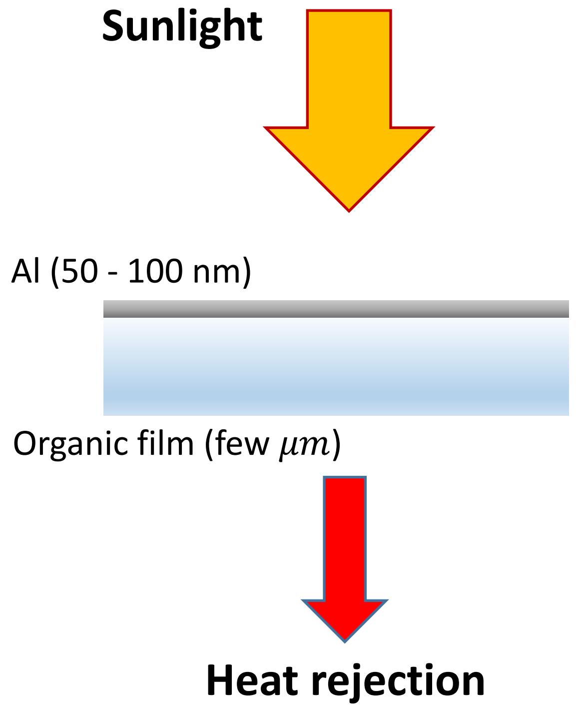
Current sail material technology



Limitations of current materials



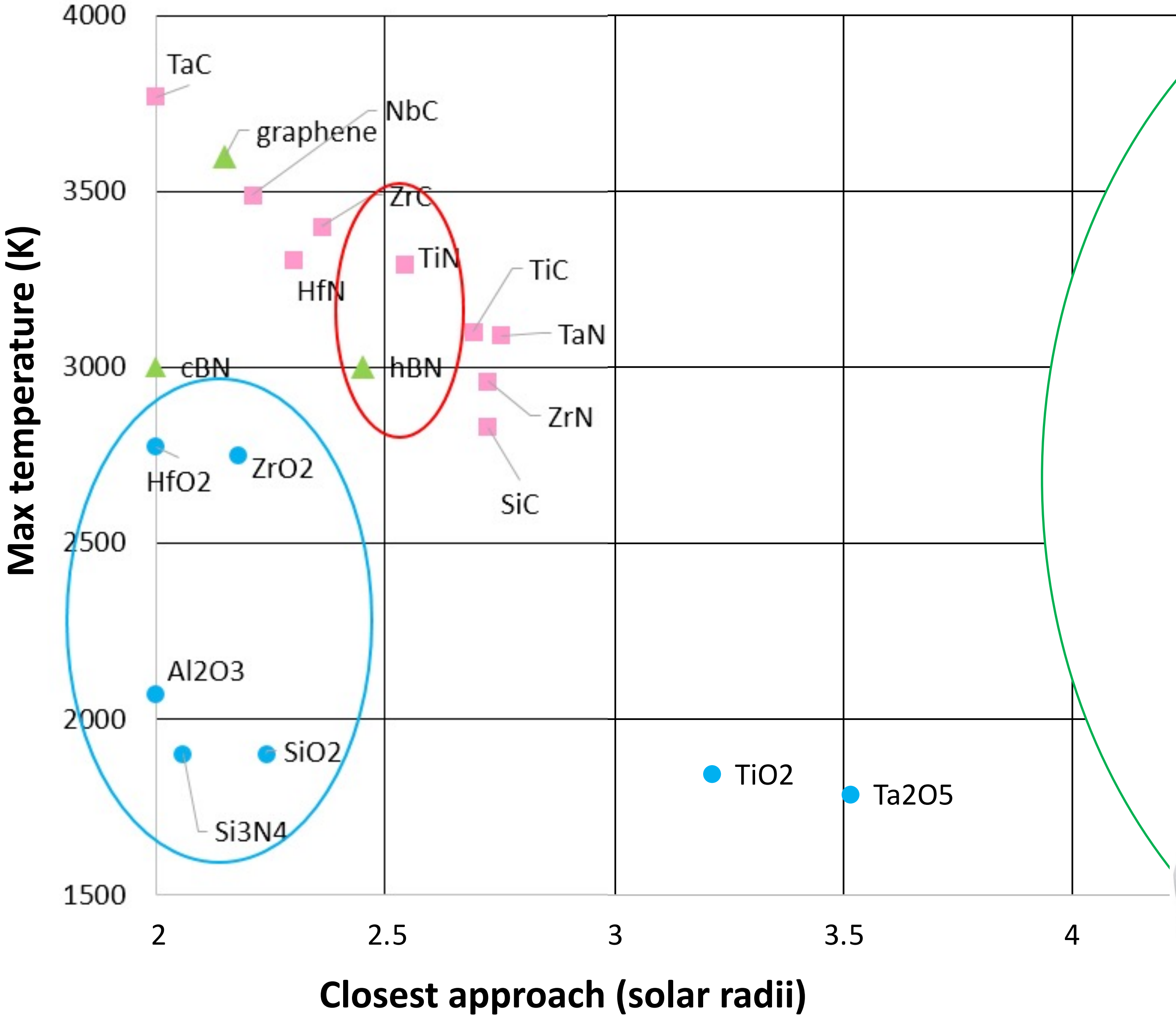




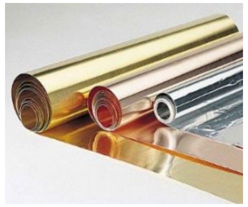
*10% - Al absorbance

*0.04 – Al emissivity

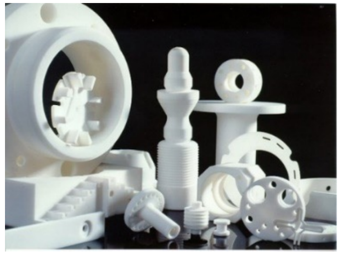
Extreme sail materials

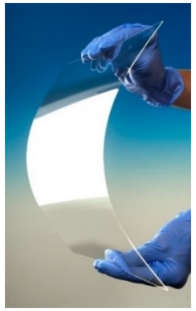


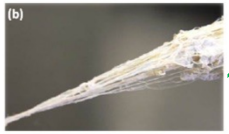
Refractory metals: Titanium nitride, tungsten



Transparent ceramics

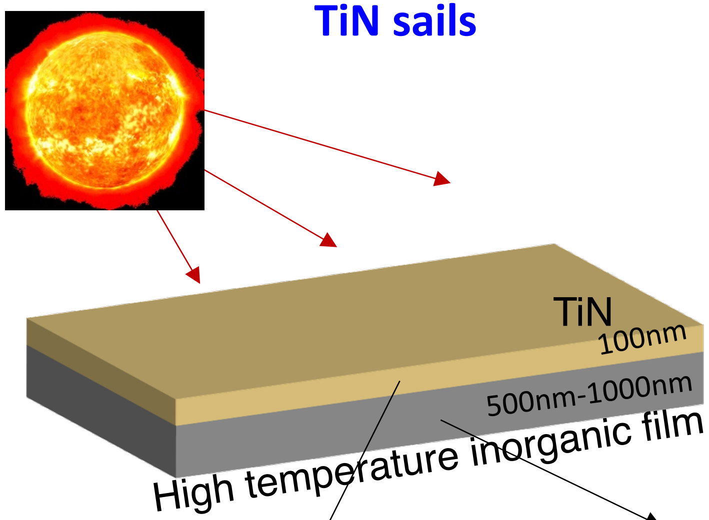


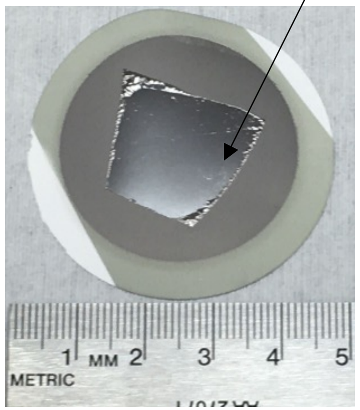


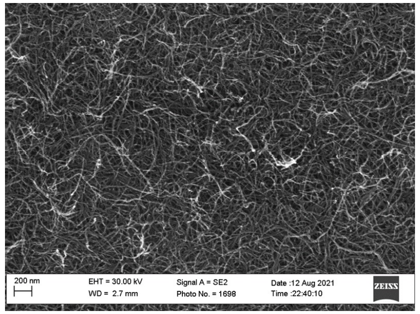


Two types of sail materials

TiN sails

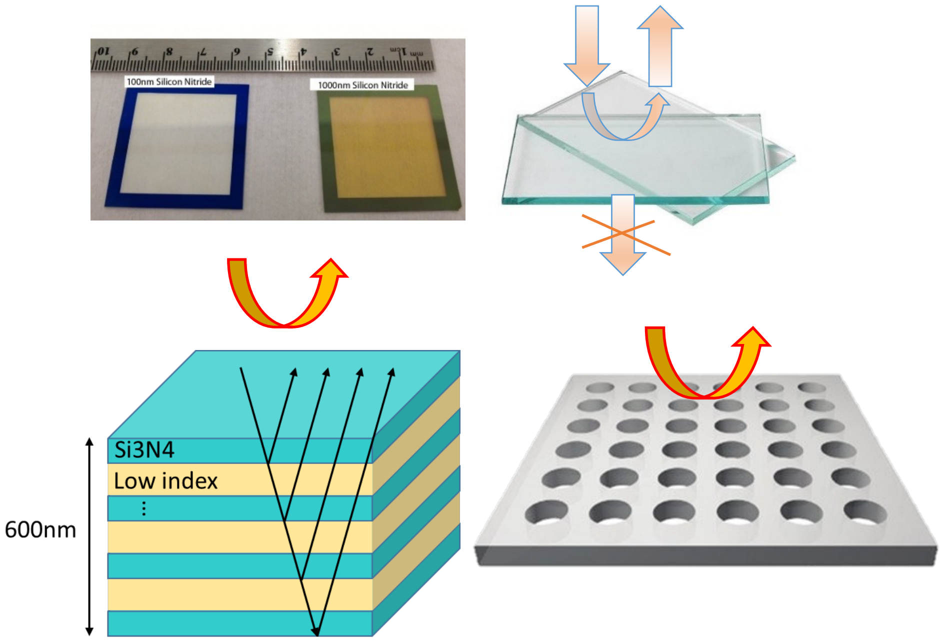






- High T
- Easy to make

SiN metamaterial sails



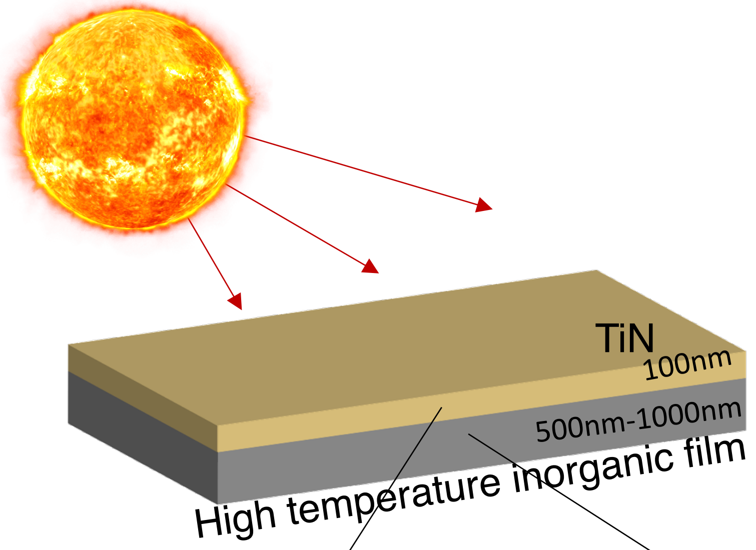
Bragg reflectors

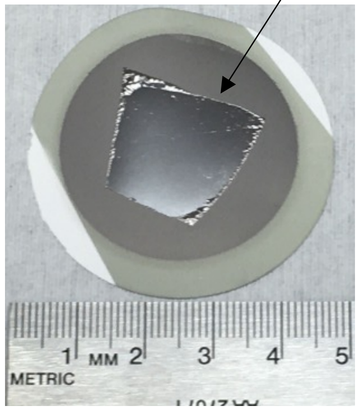
Photonic crystals

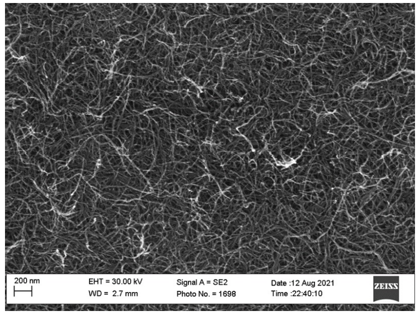
- Lower T
- Harder to make

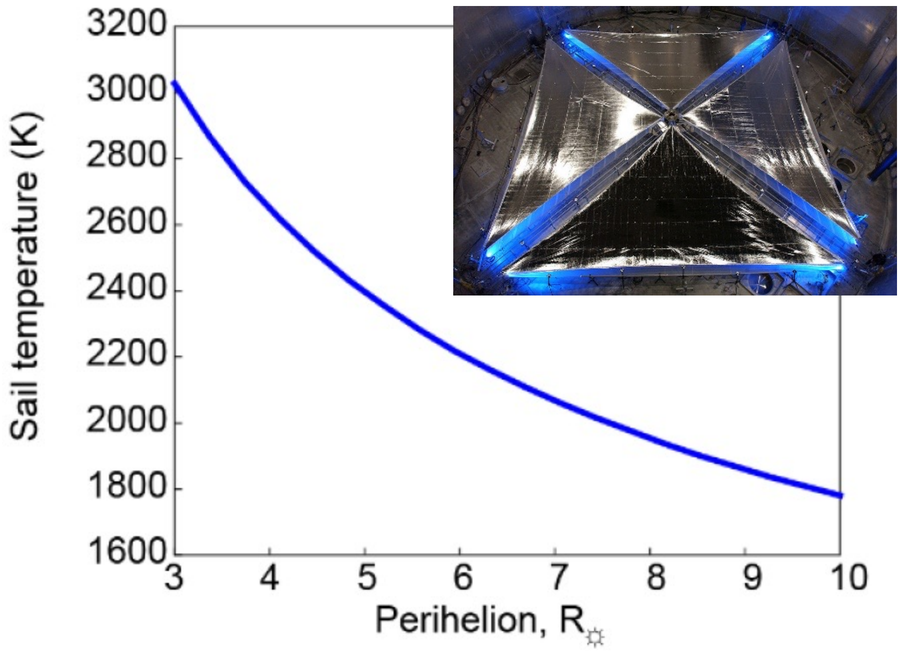
>70% reflection, <0.7 g/m^2, survive at <5$R_{\odot}$

TiN sails







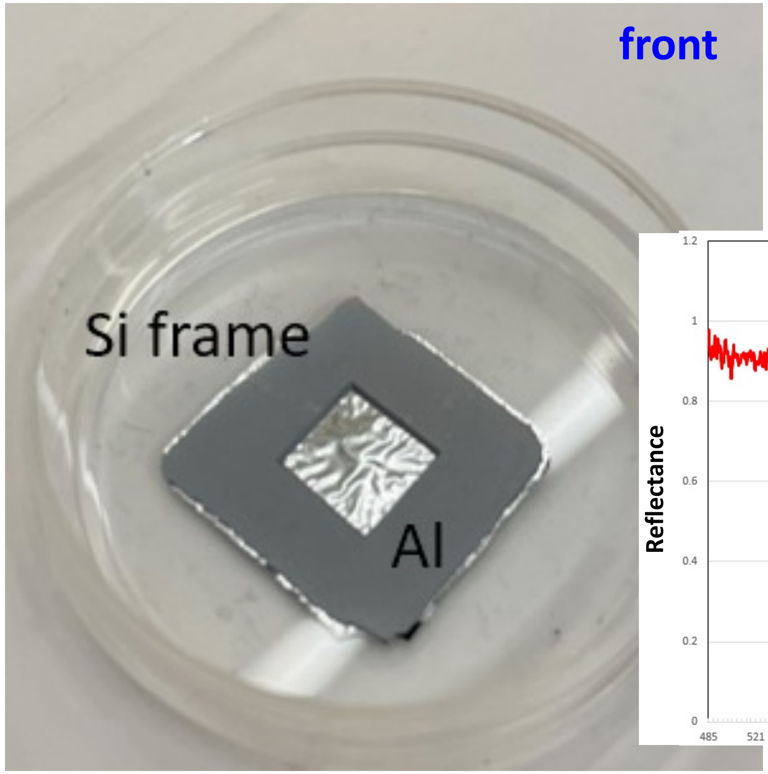


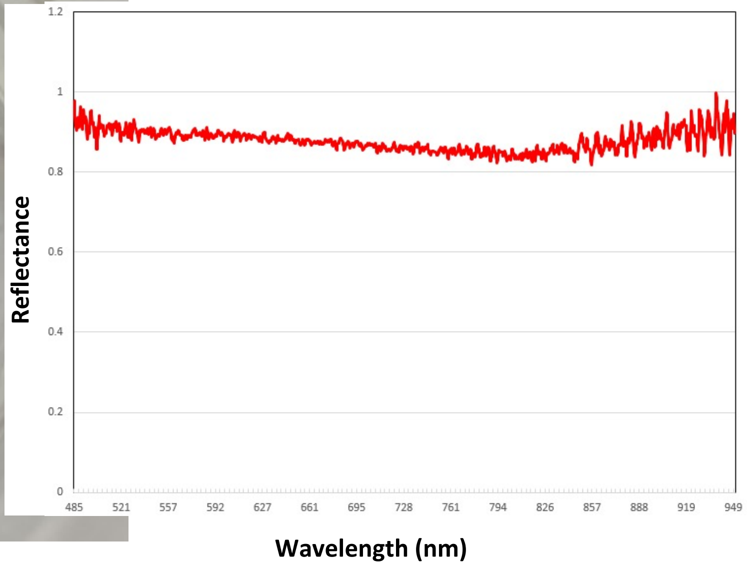
Estimated density: <1.5 g/m²

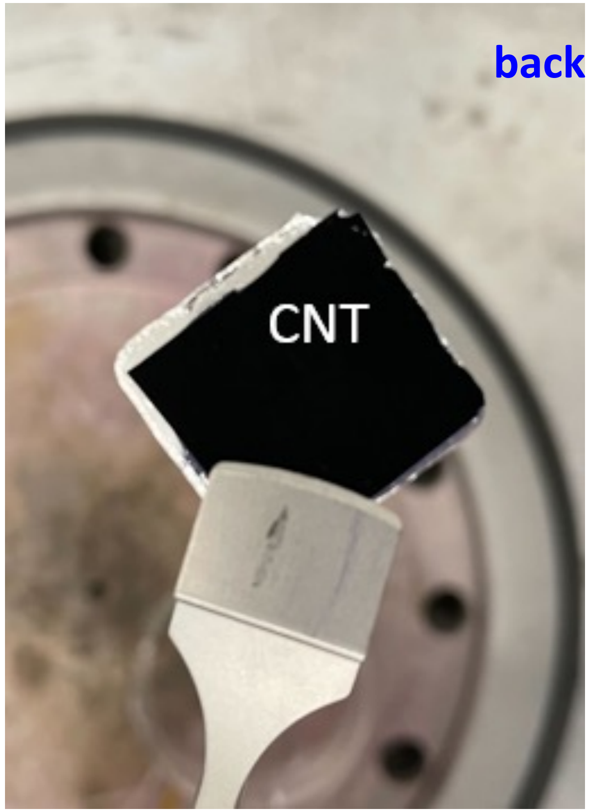
Tested at ~500C (no degradation found)

- **High T**
- **Easy to make**
- High melting point (3200 degree C) – can survive around 2.5 solar radii
- Density: 5.4 g/cm^3
- ***Absorbs 40% of sunlight***

Ultrathin films







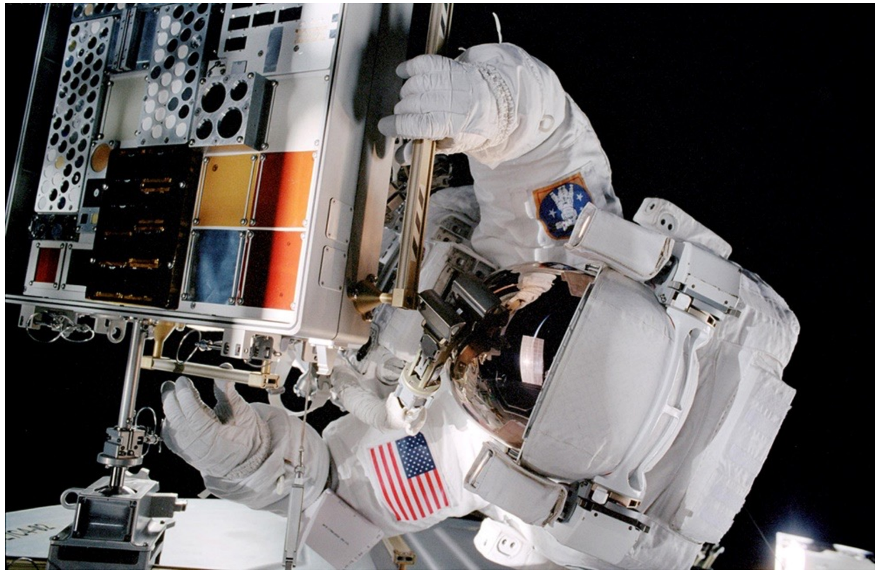
~100 nm thick free standing Al/CNT films

Estimated density: <1.5 g/m²

Tested at ~500C (no degradation found)

Coated with CNTs on the backside

Toward TiN sail materials



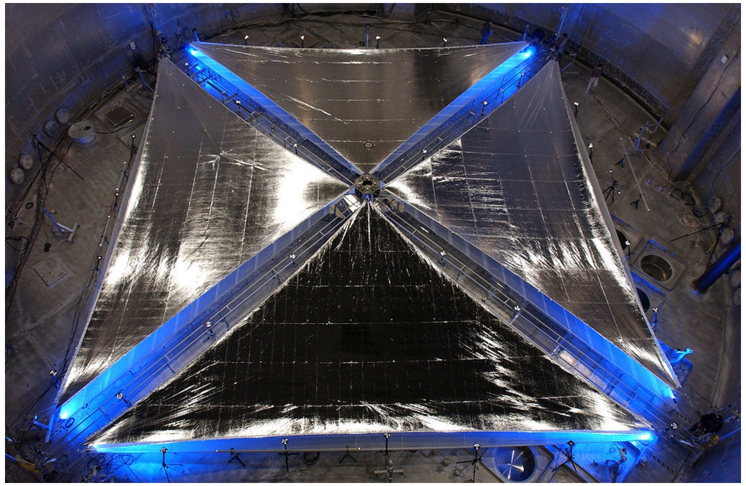
LEO environmental testing via MISSE mission
(launched Aug 29th, 2021)
Thanks to Miria Finckenor (NASA MSFC)

Sail craft architecture

- ~10kg spacecraft bus,
- ~0.7g/m^2 sail material areal density,
- 50-70g/m boom density
- 150m by 150m sail

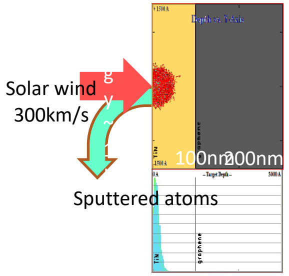
(A/m = 554 m^2/kg) & v>50 AU/yr

All aspects of the mission are feasible and doable

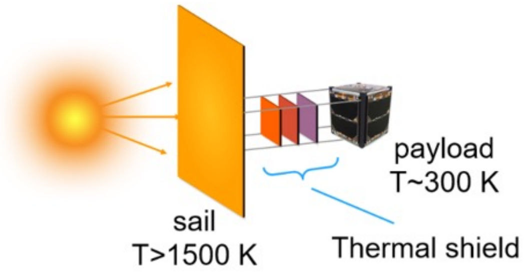


	Bus	Sail support/booms	Sail material	Total
Mass (kg)	10	14.8	15.75	40.55
Fraction (%)	25%	36%	39%	100%

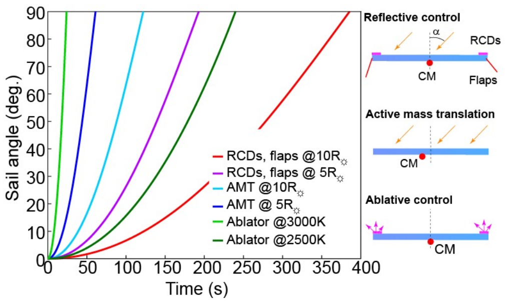
Interaction with solar plasma



Payload protection



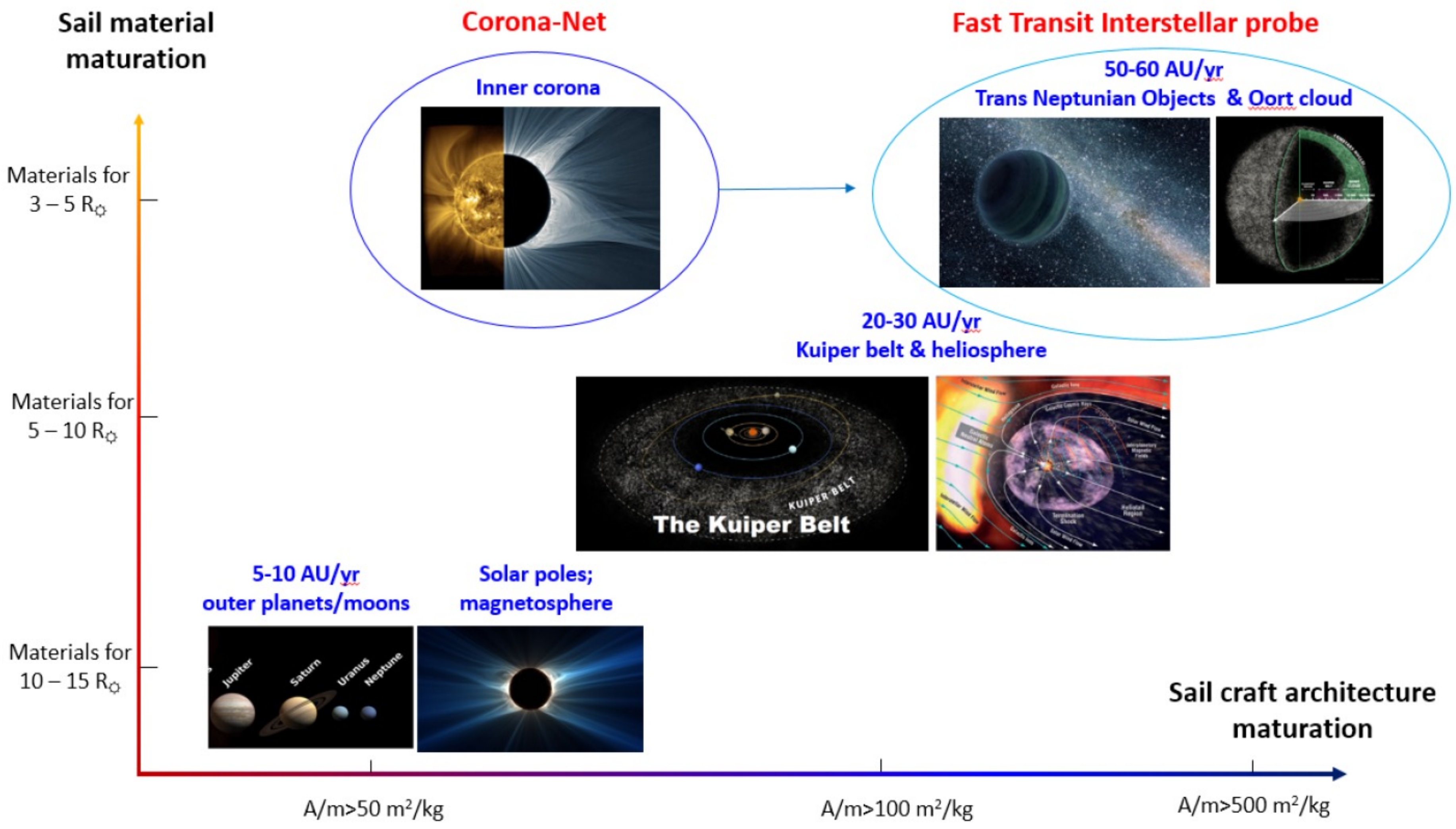
Control authority



Power & mass budget

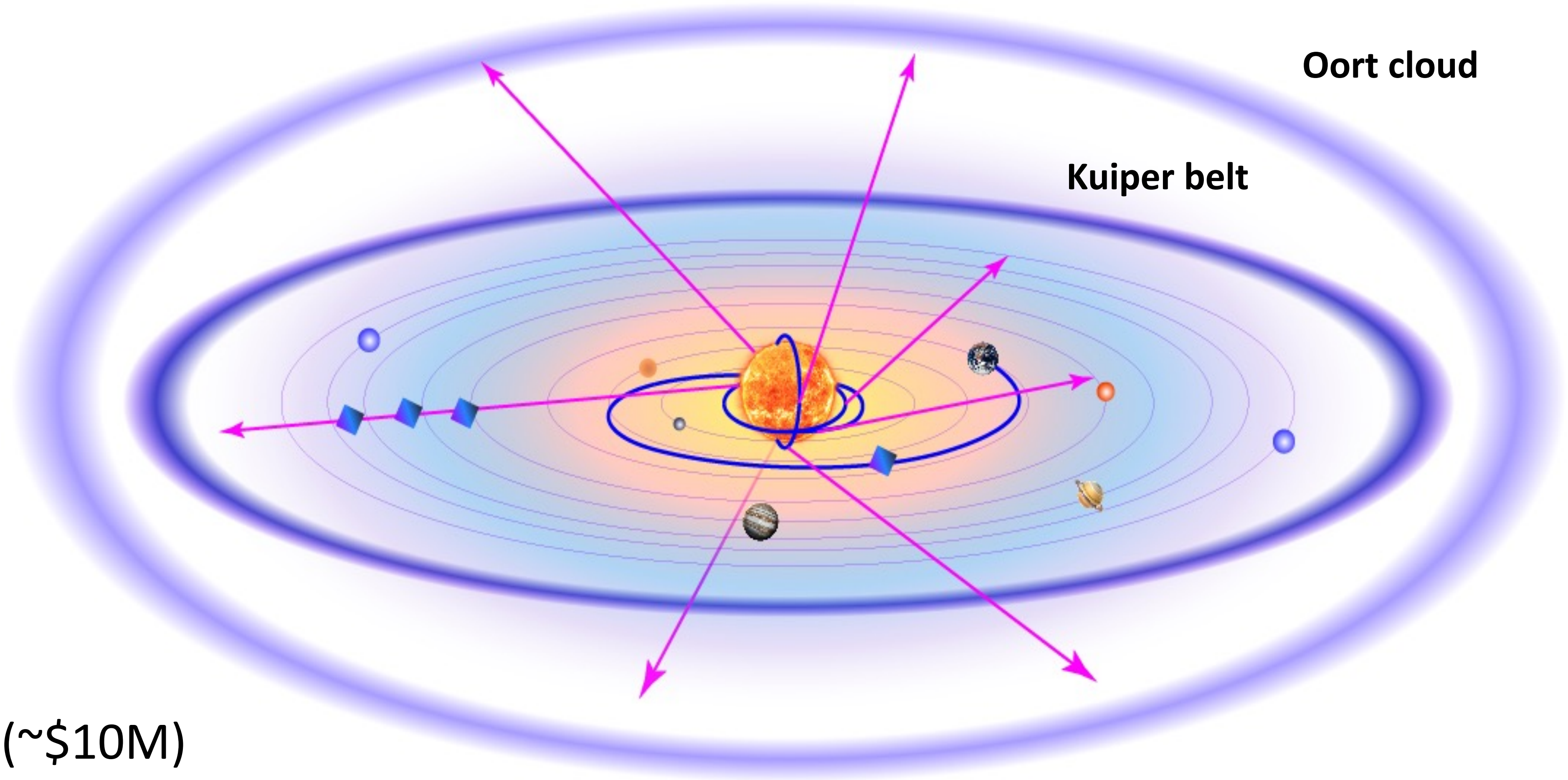
- <50 W (RTG)
- Optical comms
- Total bus mass ~10 kg

Roadmap



Sail material maturation
Corona-Net
Fast Transit Interstellar probe
Inner corona
50-60 AU/yr
Trans Neptunian Objects & Oort cloud
Materials for 3 – 5 R☉
20-30 AU/yr
Kuiper belt & heliosphere
Materials for 5 – 10 R☉
KUIPER BELT
The Kuiper Belt
5-10 AU/yr
outer planets/moons
Solar poles; magnetosphere
Jupiter
Saturn
Uranus
Neptune
Materials for 10 – 15 R☉
Sail craft architecture maturation
A/m>50 m²/kg
A/m>100 m²/kg
A/m>500 m²/kg

Vision: Sun as a Launch Pad



Goals:

- low cost (~$10M)
- short lead time
- missions to arbitrary destinations (e.g., high inclination)
- fast (50-60 AU/year)

Team and Acknowledgements

PI: Artur Davoyan

Co-Pis: Henry Helvajian, Les Johnson, Marco Velli

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