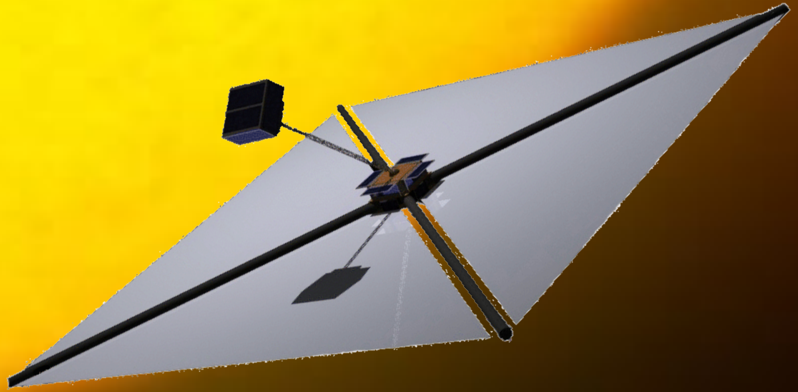
Setting Sails for Fundamental Physics Missions



656th WE-Heraeus-Seminar

Fundamental Physics in Space

23 – 27 Oct 2017
Bremen, Germany

Bernd Dachwald
FH Aachen University of Applied Sciences
Faculty of Aerospace Engineering
Aachen, Germany

dachwald@fh-aachen.de

Wolfgang Seboldt

wolfgang.seboldt@dlr.de

Claus Lämmerzahl
ZARM, University of Bremen
Bremen, Germany

laemmerzahl@zarm.uni-bremen.de

The Basic Idea of Solar Sailing


Image: NASA

Image: NASA

- The SRP force onto a 100m x 100m solar sail is F_{SRP} = 91.26mN, comparable to an ion engine
- For mission performance it is not the thrust but the acceleration that counts ($a_{SRP} = F_{SRP}/m$)
- Solar sails have to be extremely lightweight (very low mass/area ratio)
- Solar sails do not consume any propellant, thus their thrust time is only constrained by their lifetime (reasonably close to the sun)
- Solar sails do not exploit the solar wind but the solar radiation pressure (SRP)
- The solar radiation flux (at Earth, $S_0 = 1368\ \mathrm{W/m^2}$), divided by the speed of light, $c = 3 \cdot 10^8$ m/s gives the solar radiation pressure, at Earth

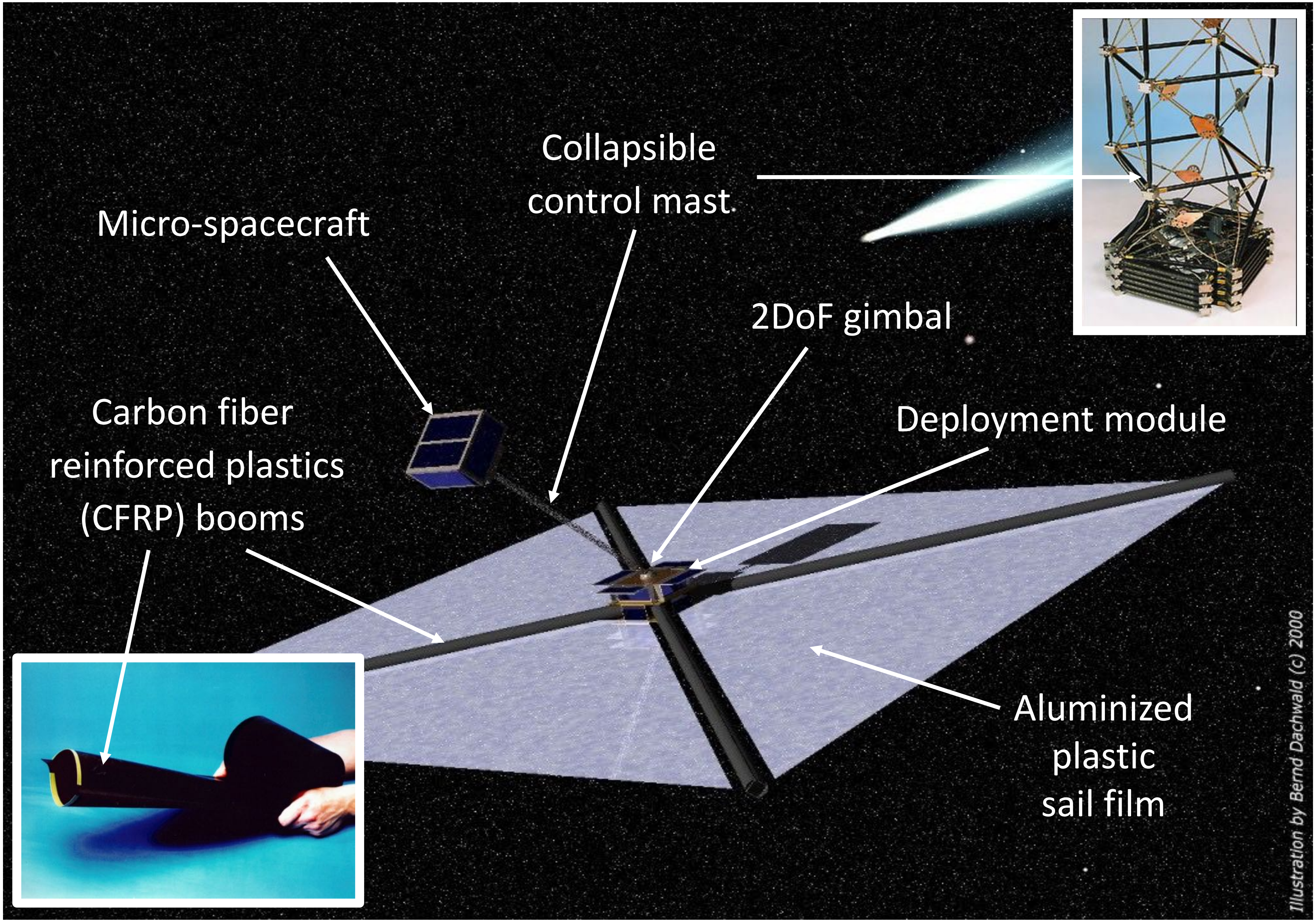
$$P_0 = S_0/c = 4.563 \cdot 10^{-6}\ \ \mathrm{N/m^2}$$

- Assuming an ideally reflecting sail surface, the pressure on the sail surface is larger by a factor of 2 (the momentum of a photon before the reflection is $\boldsymbol{p}$, afterwards it is $-\boldsymbol{p}$, therefore $\Delta p = 2|\boldsymbol{p}|$)

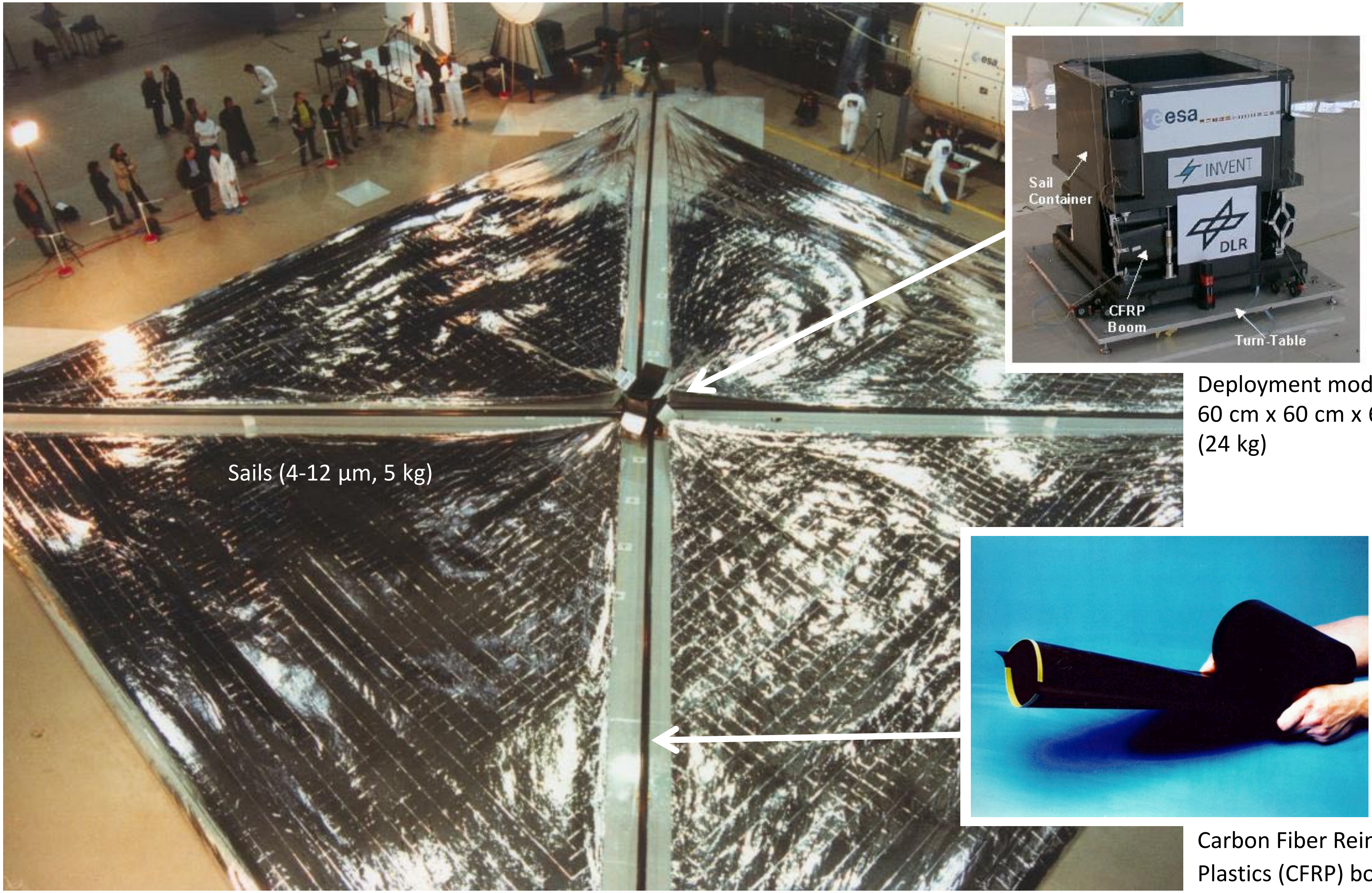
$$P_{Sail} = 2S_0/c = 9.126 \cdot 10^{-6}\ \ \mathrm{N/m^2}$$

(this is equivalent to the weight of a housefly on a 4m x 4m area)

DLR Solar Sail Design



First Solar Sail Ground Deployment at DLR

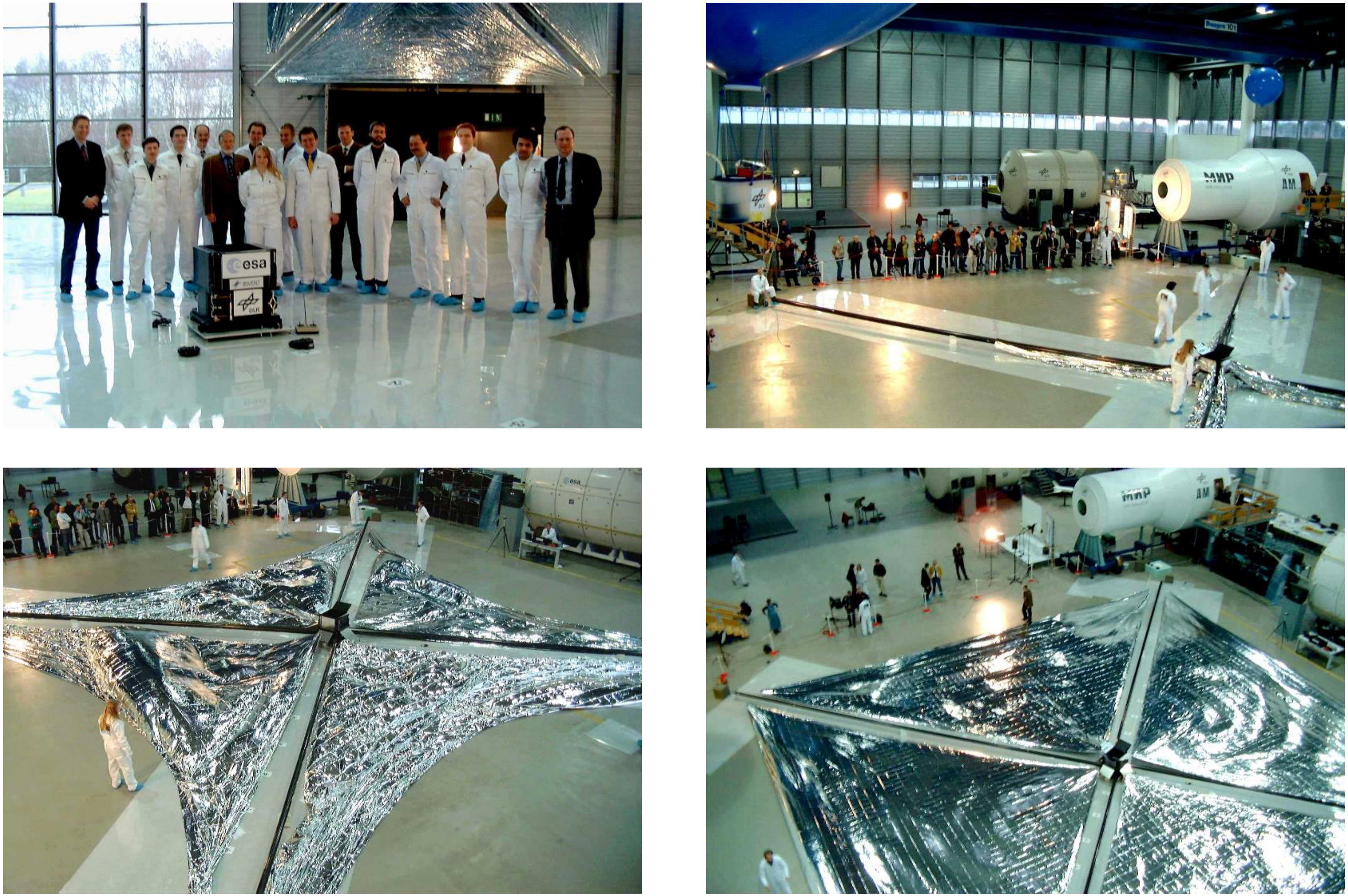


Deployment module
60 cm x 60 cm x 65 cm
(24 kg)

Carbon Fiber Reinforced
Plastics (CFRP) booms
(6 kg)

DLR deployment test of a (20 m)^2 solar sail performed 17 December 1999 at ESA CTC, Cologne

First Solar Sail Ground Deployment at DLR



Solar Sailcraft Performance Assessment

Mean solar radiation energy flux at 1 AU distance: $S_0 = 1368\,\mathrm{W/m^2}$

Mean solar radiation pressure at 1 AU distance: $\boxed{P_0 = \frac{S_0}{c}} = 4.563\,\mu\mathrm{N/m^2}$

Sailcraft mass: $m = 100\,\mathrm{kg}$ Sail area: $A = (40\,\mathrm{m})^2$ Sailcraft loading: $\boxed{\sigma = \frac{m}{A}} = 62.5\,\mathrm{g/m^2}$

Maximum propulsive SRP force exerted on the sailcraft at 1AU distance:

$$\boxed{F_{0,max} = \eta \cdot 2P_0 A} = P_{\mathrm{eff},0} \cdot A = 13.28\,\mathrm{mN} \quad \text{with} \quad P_{\mathrm{eff},0} = 8.3\,\mu\mathrm{N/m^2}$$

Sail efficiency (Al-coated plastic film): $\eta = 0.91$

Maximum propulsive acceleration at 1 AU distance (**characteristic acceleration**):

$$\boxed{a_c = a_{0,max} = \frac{F_{0,max}}{m}} = 0.1326\,\mathrm{mm/s^2}$$

Maximum total velocity change per year (theoretically, in force-free space): $\Delta V = 4.185\,\mathrm{km/s}$

Lightness number: $\boxed{\lambda = \frac{a_c}{a_{solar\ grav.,0}}} = \frac{0.1326\,\mathrm{mm/s^2}}{5.93\,\mathrm{mm/s^2}} \approx \frac{1}{45}$

20kg sail film
12kg booms
18kg deployment module
50kg micro-spacecraft

Solar Sail Development in the USA and Russia Until 2005

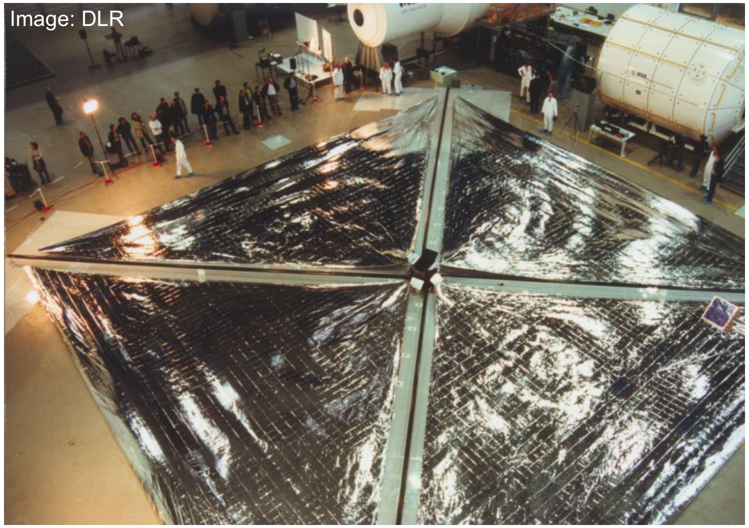


Image: DLR

DLR / ESA: Ground deployment experiment for a 20 m x 20 m, 35 kg solar sail at EAC, Cologne, Germany (December 1999)

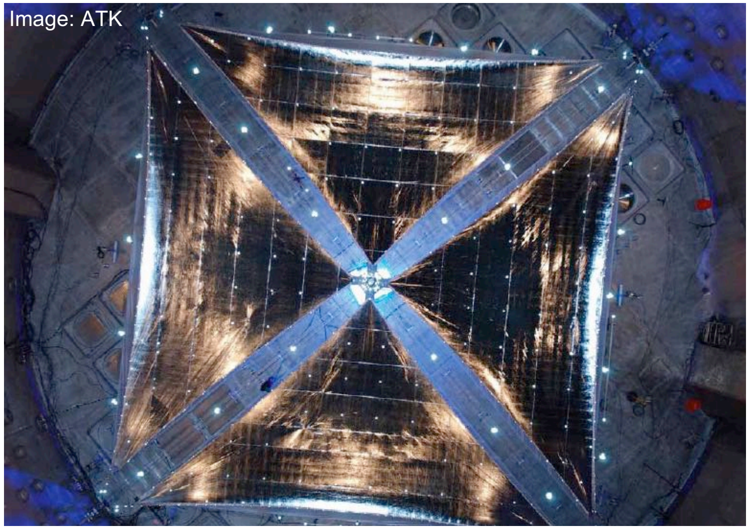


Image: ATK

NASA: Ground deployment experiment and structural tests for a 20 m x 20 m, 23 kg solar sail in the vacuum chamber (April/May 2005)

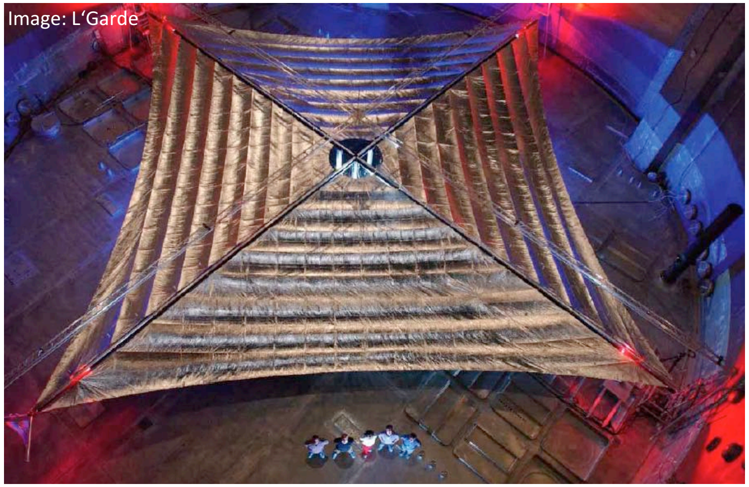


Image: L'Garde

L'Garde: Ground deployment experiment for a 20 m x 20 m, 6.2 kg (without deployment module) solar sail (July 2005)

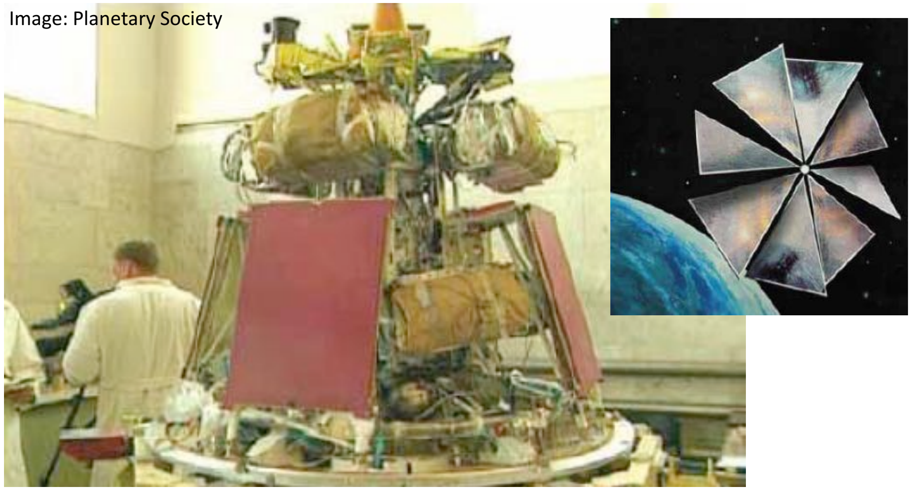


Image: Planetary Society

Planetary Society: Cosmos 1, 30 m „flower", 105 kg, planned orbital altitude: 1000 km, launcher failure (June 2005)

NanoSail-D / NanoSail-D2


Image: NASA


Image: NASA

NASA: NanoSail-D, 9.3 m^2 solar sail, 10 cm x 10 cm x 33 cm deployment module, 5.9 kg

03 Aug 2008: launcher failure during launch of NanoSail-D
20 Nov 2010: successful launch of NanoSail-D2

IKAROS

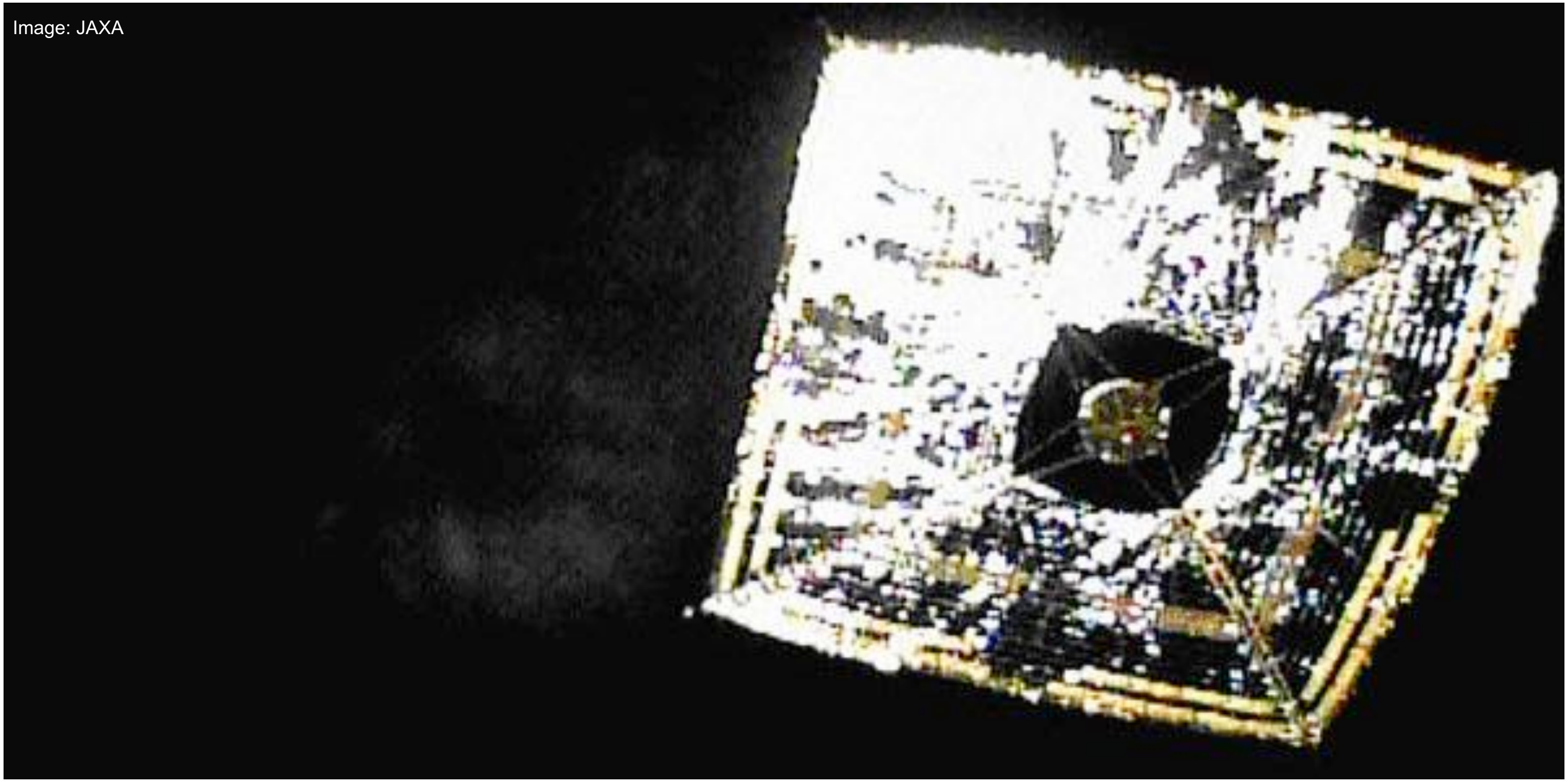
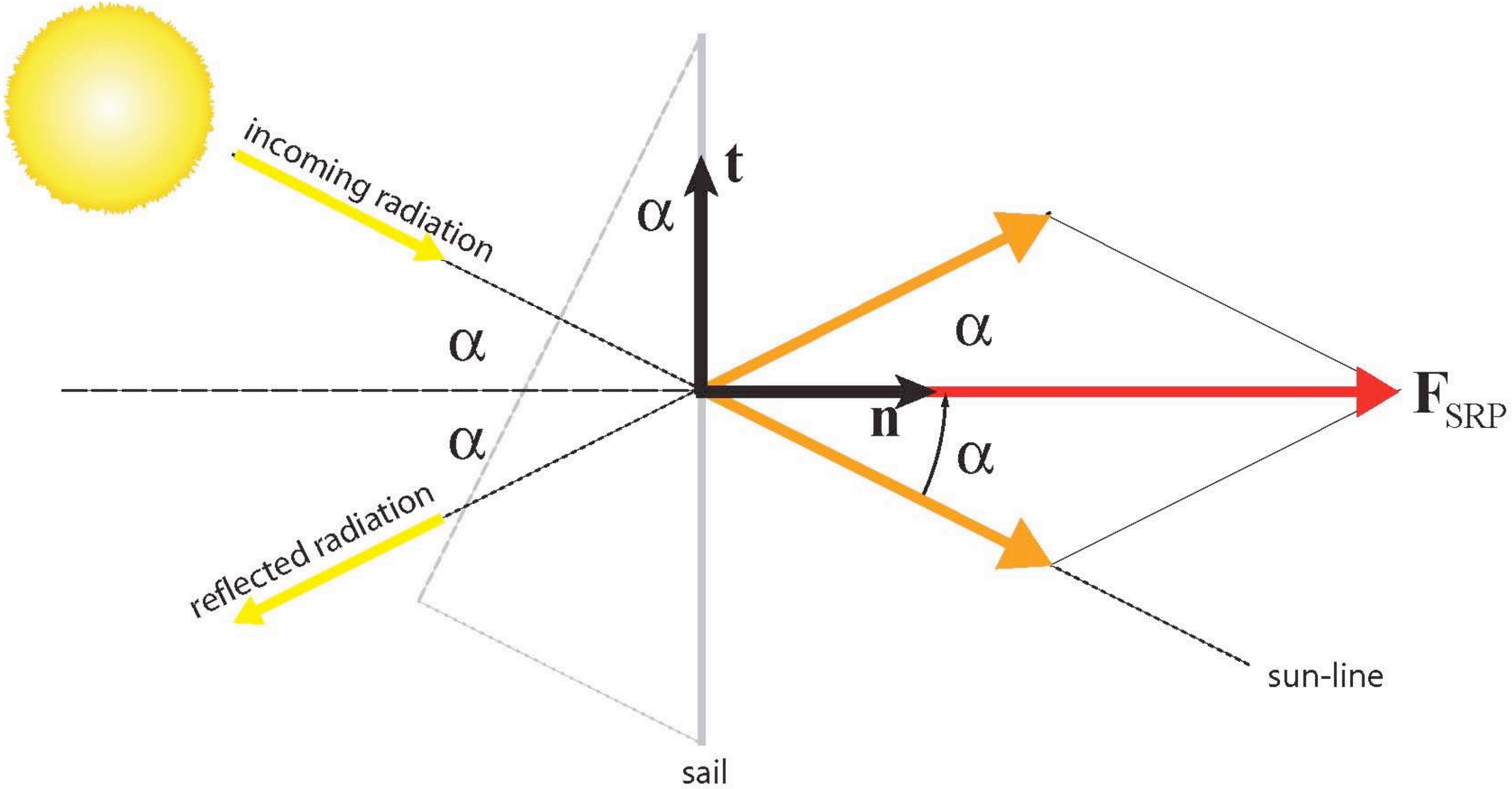


Image: JAXA

JAXA: spin stabilized solar sail, 200 m^2, 7,5 µm foil thickness,
total mass 315 kg (1.575 kg/m^2, VERY heavy)
21 May 2010: interplanetary injection to Venus together with the Akatsuki probe

Acceleration from solar radiation pressure was measured, but the main purpose was to demonstrate the technologies required for low-mass solar power generators, as required for SEP spacecraft

Solar Radiation Pressure Force on an Ideal Solar Sail



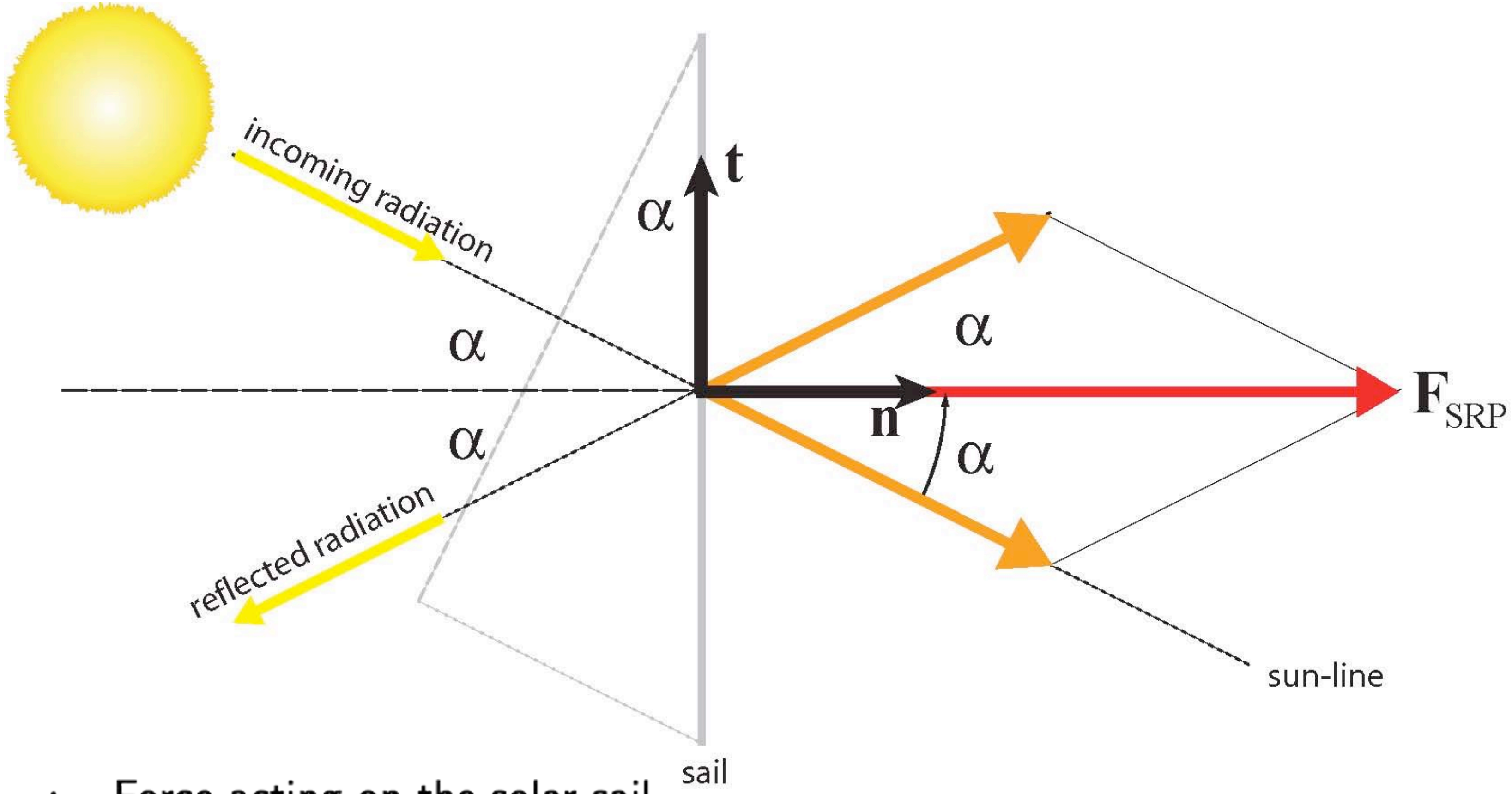
F_{SRP}:	Force acting on the solar sail
P:	Solar radiation pressure (SRP)
A:	Sail area
α:	Light incidence angle (pitch angle)
$\boldsymbol{n}$:	Sail normal vector

$$\boxed{F_{\mathrm{SRP}} = 2PA\cos\alpha\cos\alpha\,\boldsymbol{n}}$$

$2P_0 = 9.1\,\mu\mathrm{N/m^2}$ at $1\,\mathrm{AU}$

and $\propto 1/r^2$

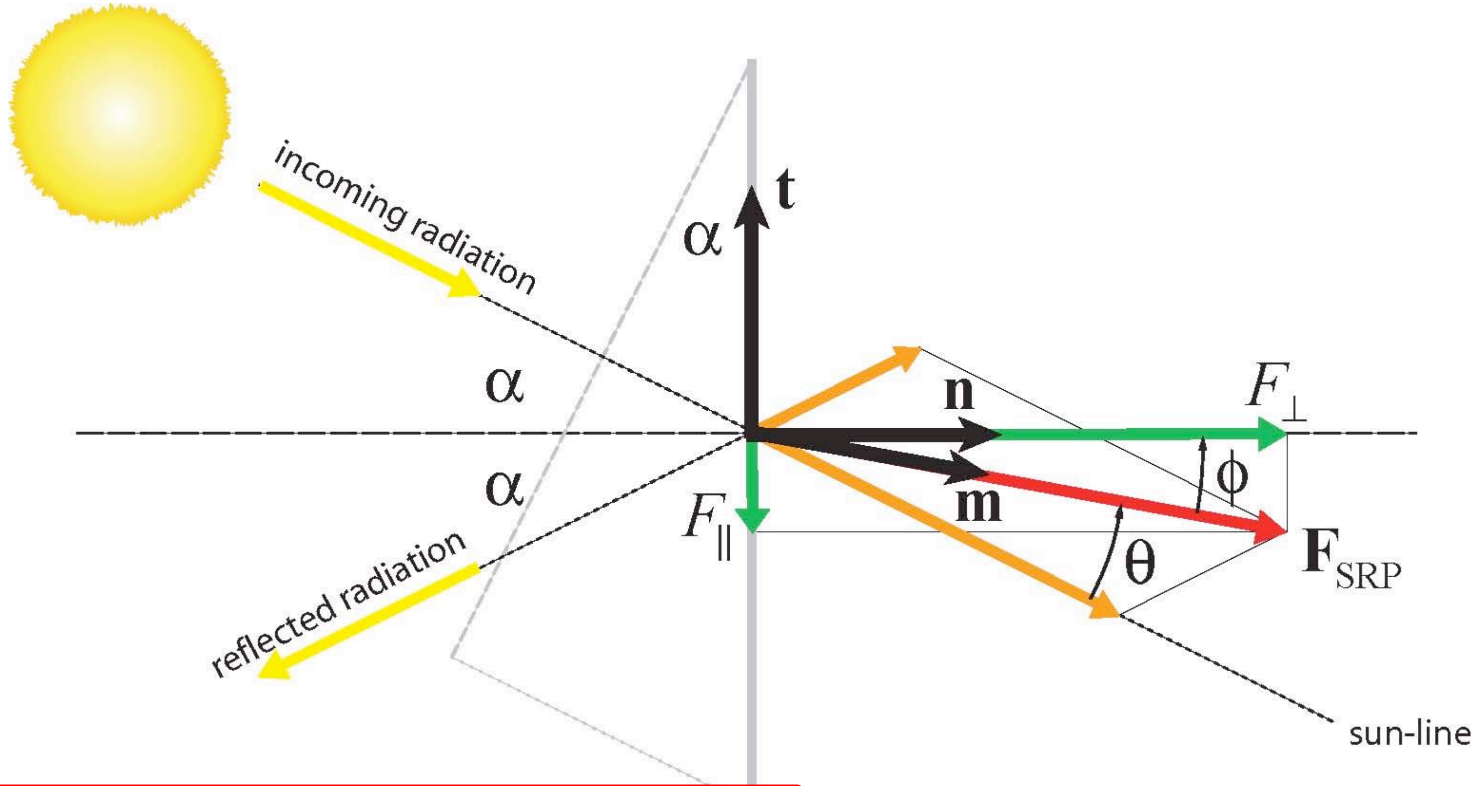
Solar Radiation Pressure Force on an Ideal Solar Sail



F_{SRP}: Force acting on the solar sail
m: Mass of the solar sailcraft
a_c: Characteristic acceleration
r_0: Reference solar distance (1 AU)
r: Sun-sail distance
α: Light incidence angle (pitch angle)
$\boldsymbol{n}$: Sail normal vector

$$\boxed{F_{\text{SRP}} = m a_c \left(\frac{r_0}{r}\right)^2 \cos^2\alpha\, \boldsymbol{n}}$$

Solar Radiation Pressure Force on a Non-Ideal Solar Sail



$$F_{\mathrm{SRP}} = 2PA\cos\alpha\,\Psi(\alpha,\mathcal{P})\,\boldsymbol{m}$$

where

$$\Psi(\alpha,\mathcal{P}) = \sqrt{\Psi_\perp^2(\alpha,\mathcal{P}) + \Psi_{||}^2(\alpha,\mathcal{P})}$$

$$\Psi_\perp(\alpha,\mathcal{P}_{\mathrm{Al|Cr}}) = 0.9136\cos\alpha - 0.00544$$

$$\Psi_{||}(\alpha,\mathcal{P}_{\mathrm{Al|Cr}}) = 0.0864\sin\alpha$$

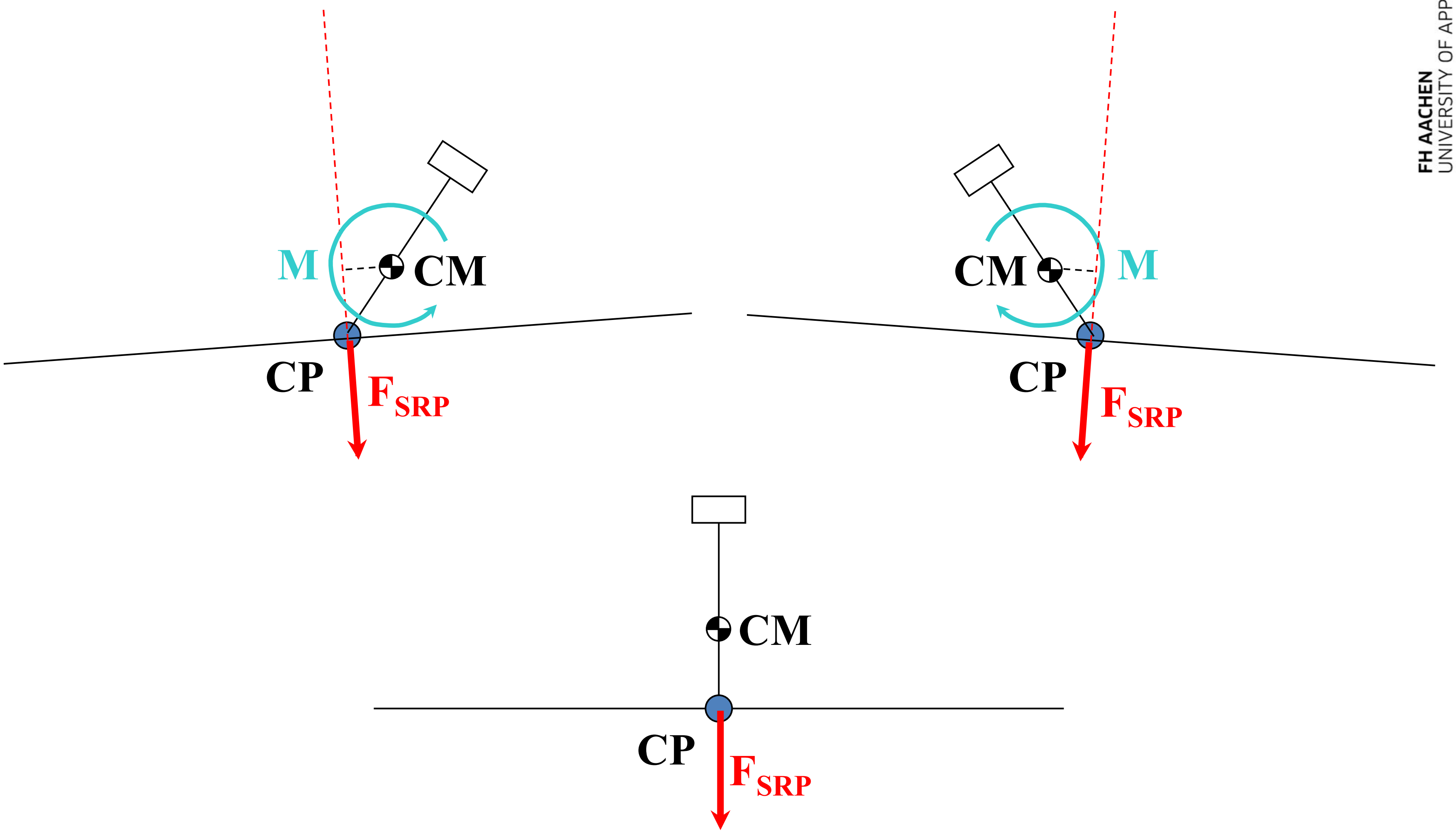
$\mathcal{P}$: set of optical sail parameters

reflectivity, emissivity etc.

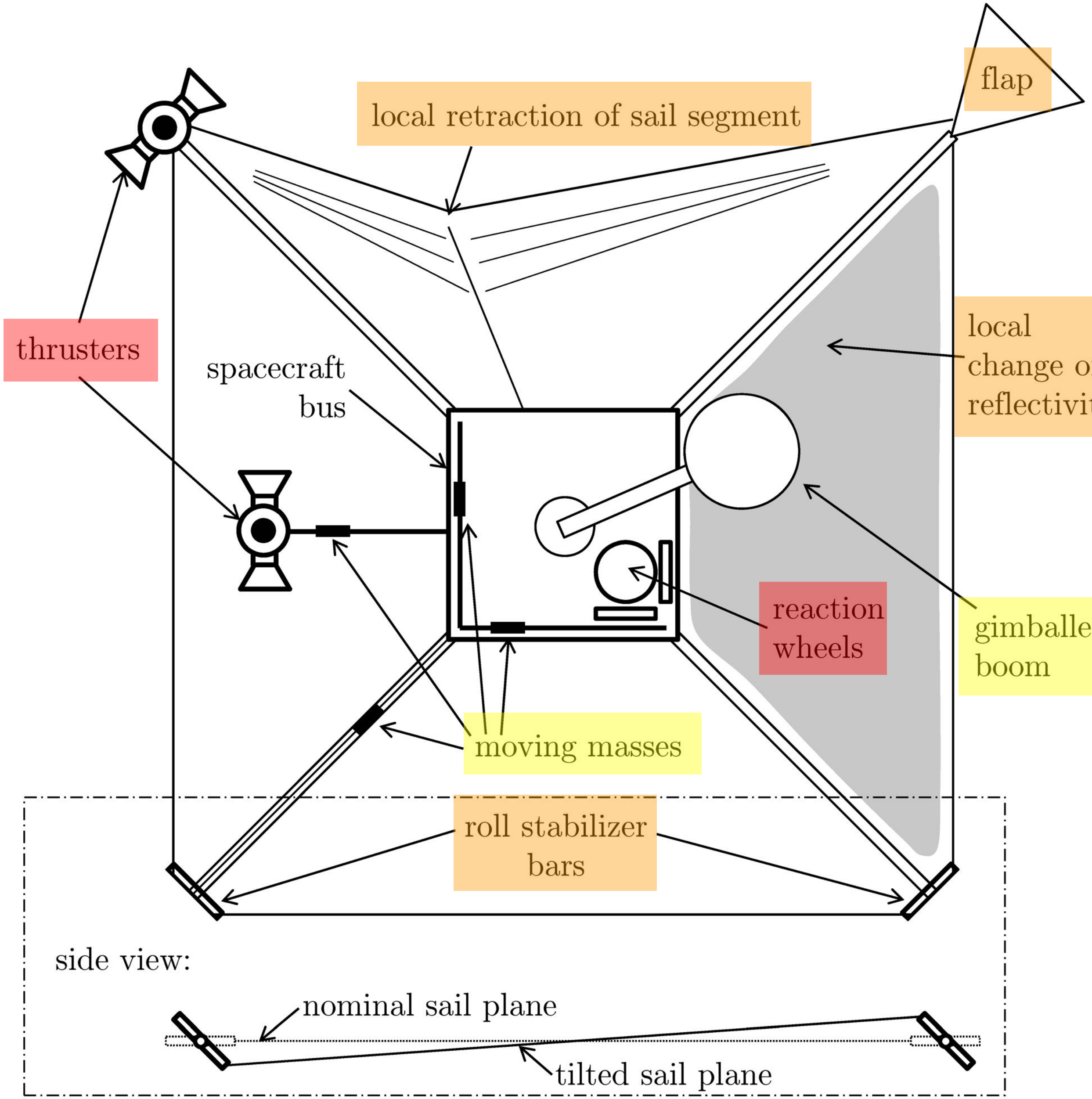
$2P_0\,\Psi(0,\mathcal{P}_{\mathrm{Al|Cr}}) = 8.3\,\mu\mathrm{N/m^2}$ at 1 AU

and $\propto 1/r^2$

Attitude Control with a Central Mast



Attitude Control Design Options



3 general attitude control design options:

1. Changing CM w.r.t. CP
2. Changing CP w.r.t. CM
3. “Traditional”

Optional solar sail attitude control methods (in a not advisable combination, size of spacecraft bus and sail are not to scale)

☞ All methods have specific advantages and disadvantages

☞ Combinations are possible

☞ Attitude control has a strong influence on sailcraft design

Criteria for Attitude Control Design Choice

> Sailcraft agility (max. torque)

> Attainable overall change of angular momentum

> Mass

> Reliability & redundancy

> Reusability (for different missions)

> Structural loads

> Complexity (structure, control, deployment)

> Available know-how

> Cost

All criteria are highly interdependent

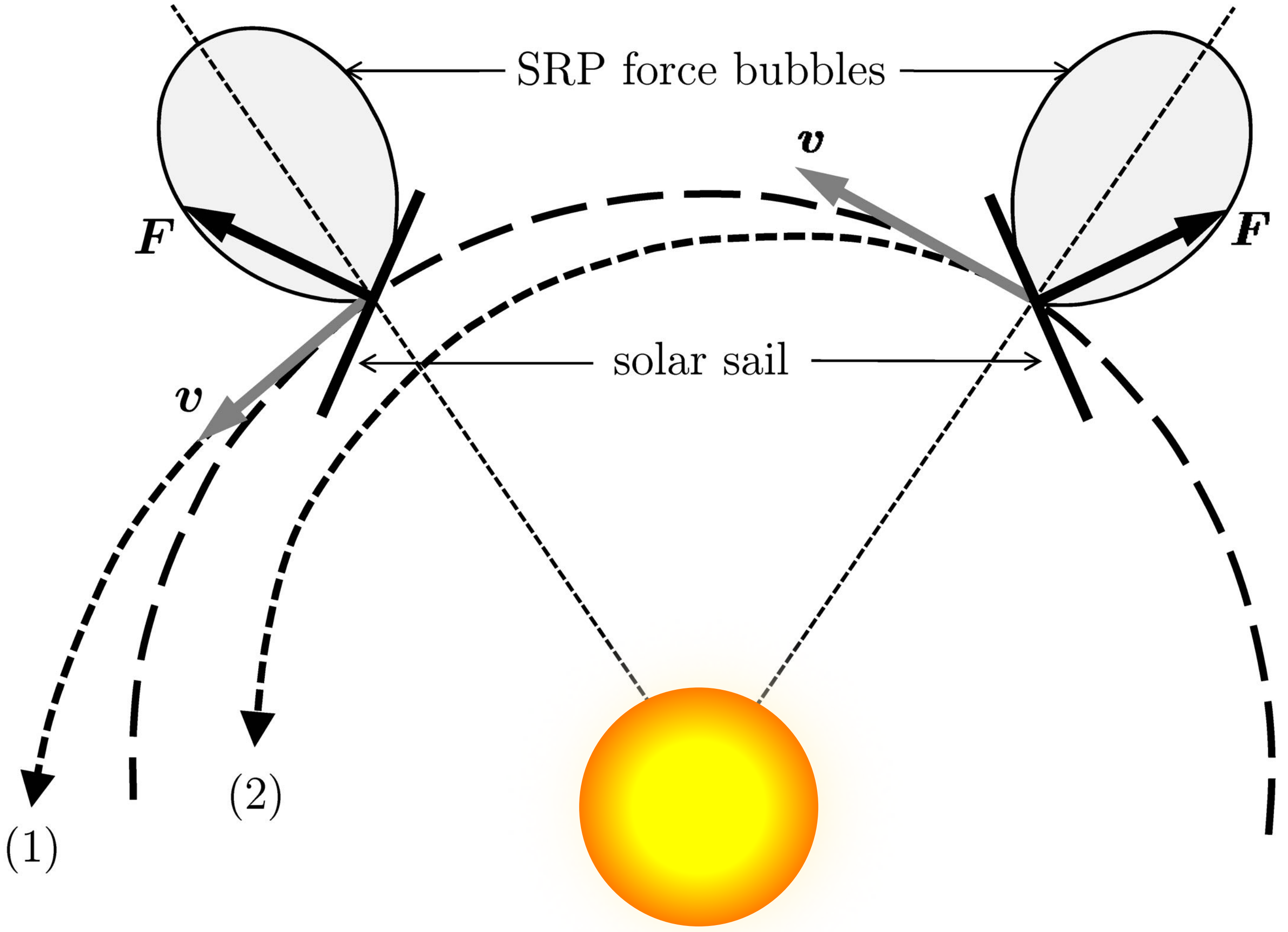
Orbital Dynamics of Solar Sails

(1) Gaining orbital energy and spiraling away from the sun

$\boldsymbol{F} \cdot \boldsymbol{v} > 0$

(2) Losing orbital energy and spiraling towards the sun

$\boldsymbol{F} \cdot \boldsymbol{v} < 0$



Solar Sail Missions to a Close Solar Orbit

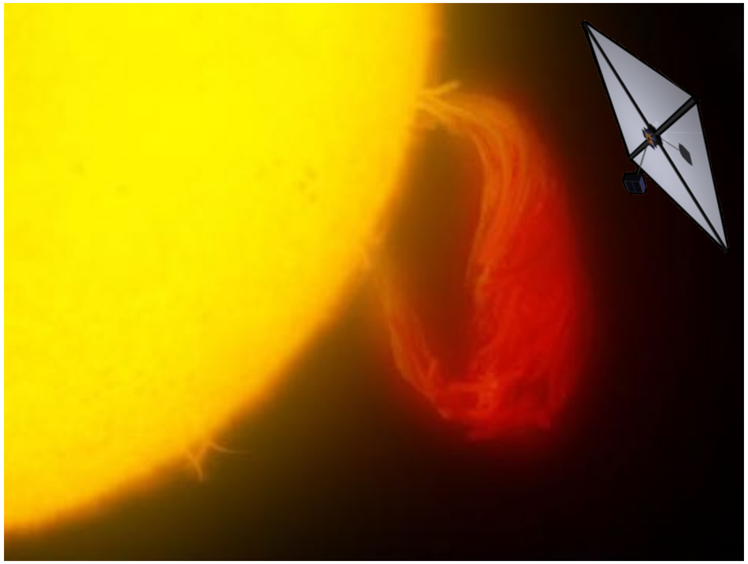
Conditions for a Mission Very Close to the Sun

Universality of grav. redshift
Constancy of constants

Equivalence principle

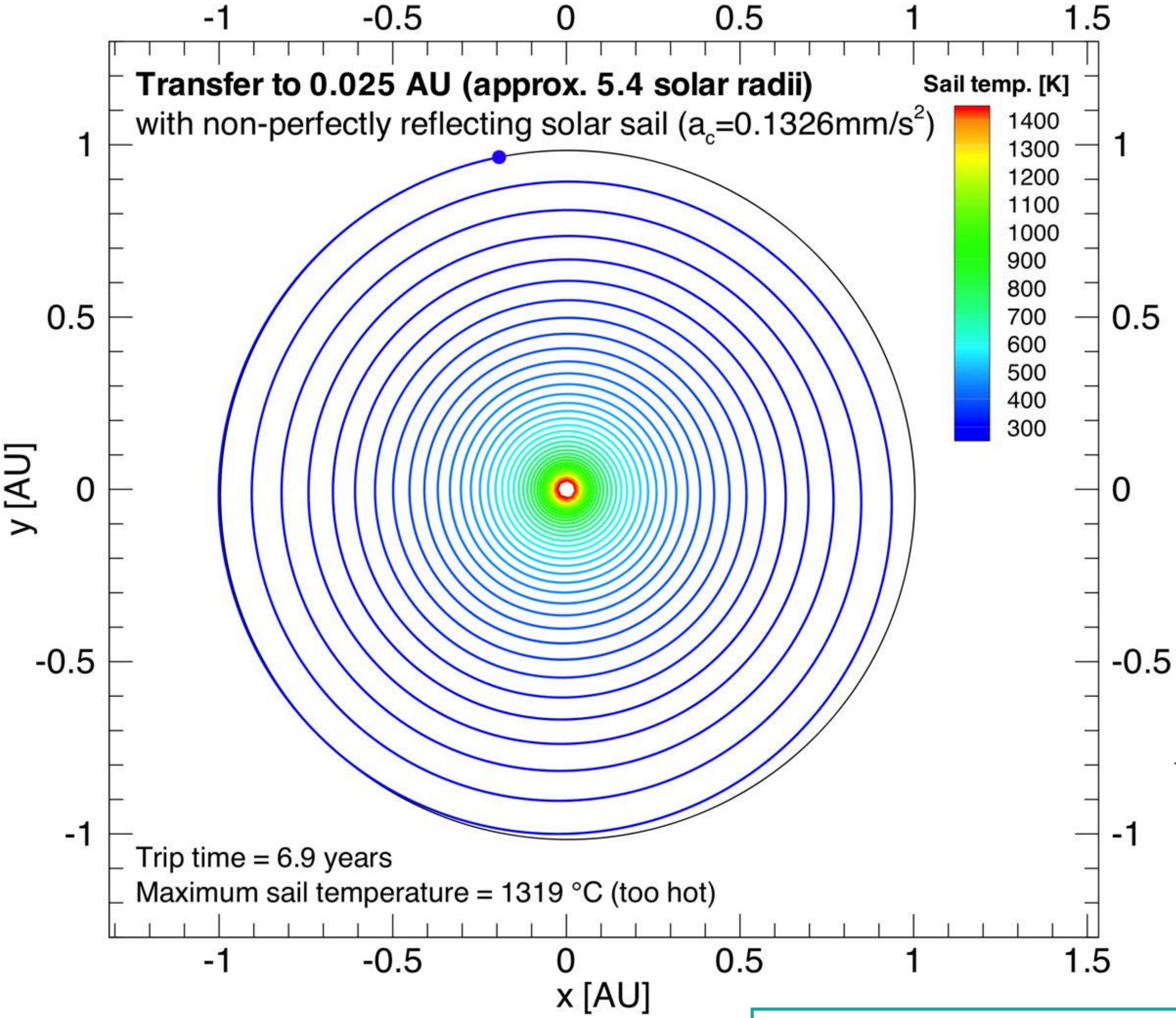
- Infinitely long free fall (drag free condition)
- Large gravitational potential differences
- Long exposure to interactions
- Large velocity differences
- No seismic noise – quiet boundary conditions

Physical necessity



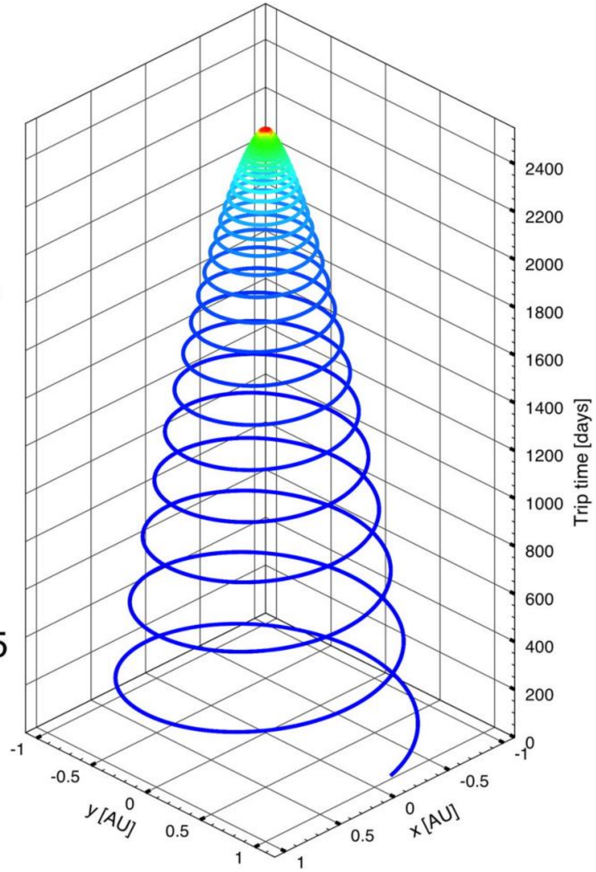
Search for weak forces
Search for anomalous weak forces

Solar Sail Mission to a Very Close Circular Solar Orbit



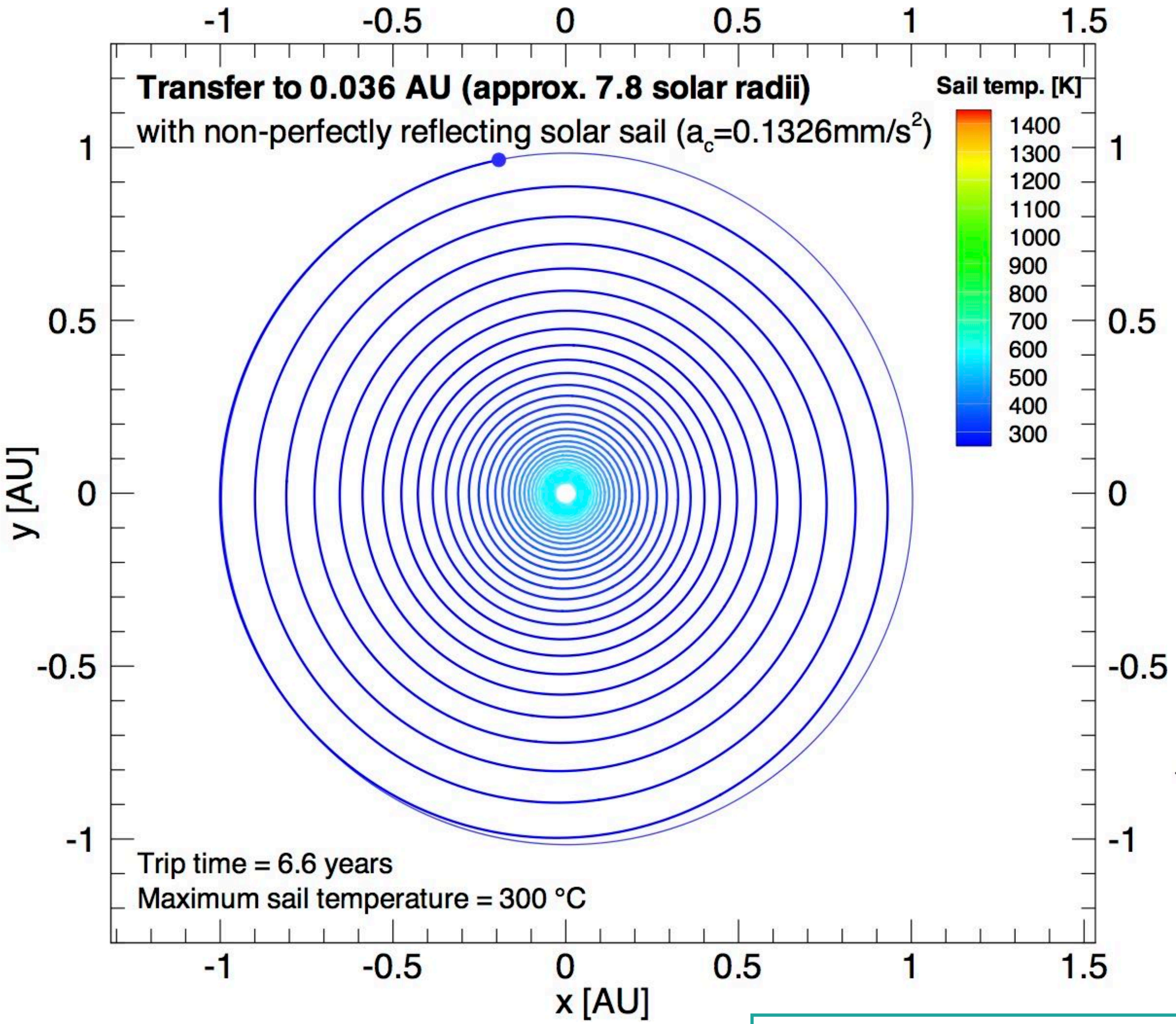
Transfer to 0.025 AU (approx. 5.4 solar radii)
with non-perfectly reflecting solar sail (a_c=0.1326mm/s^2)

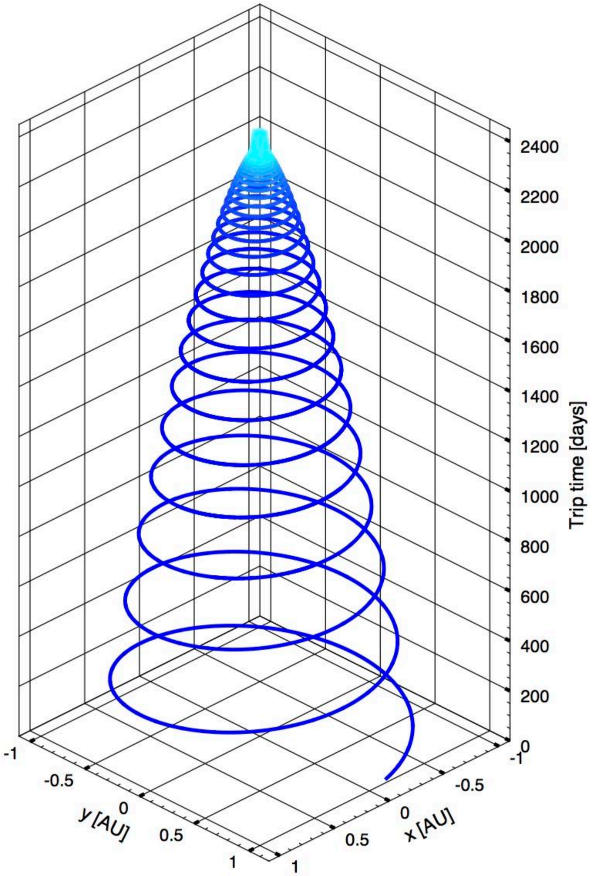
Trip time = 6.9 years
Maximum sail temperature = 1319 °C (too hot)



$$\boxed{T = \left(\frac{S_0 r_0^2}{\sigma} \frac{1-\rho}{\varepsilon_\mathrm{f} + \varepsilon_\mathrm{b}} \frac{\cos\alpha}{r^2} \right)^{1/4} \propto \frac{\cos^{1/4}\alpha}{r^{1/2}}}$$

Solar Sail Mission to a Very Close Circular Solar Orbit



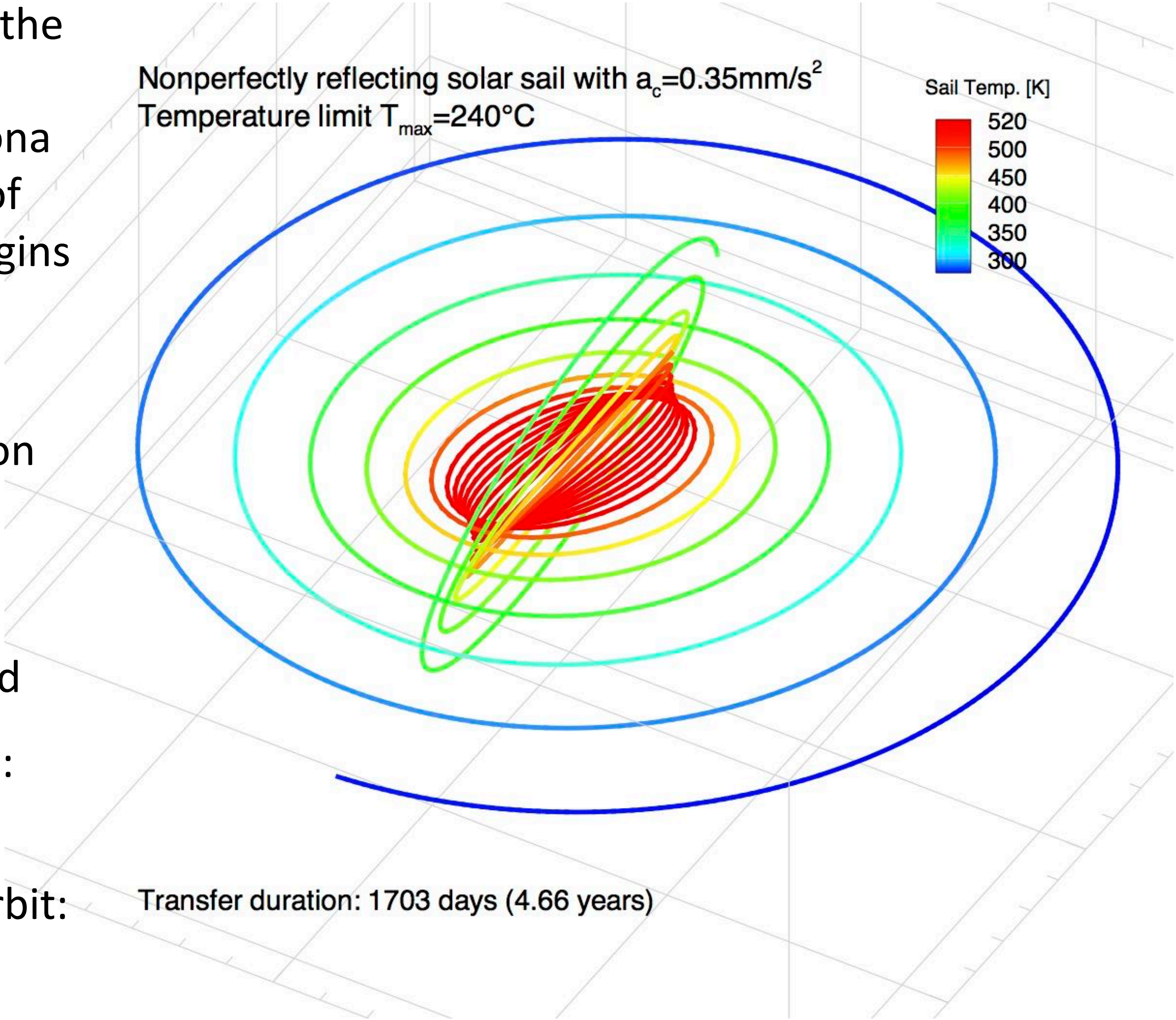


Limitation of sail pitch angle α
$\Rightarrow$ limitation of sail temperature

$$T = \left(\frac{S_0 r_0^2}{\sigma} \frac{1-\rho}{\varepsilon_\mathrm{f} + \varepsilon_\mathrm{b}} \frac{\cos\alpha}{r^2} \right)^{1/4} \propto \frac{\cos^{1/4}\alpha}{r^{1/2}}$$

NASA’s Solar Polar Imager

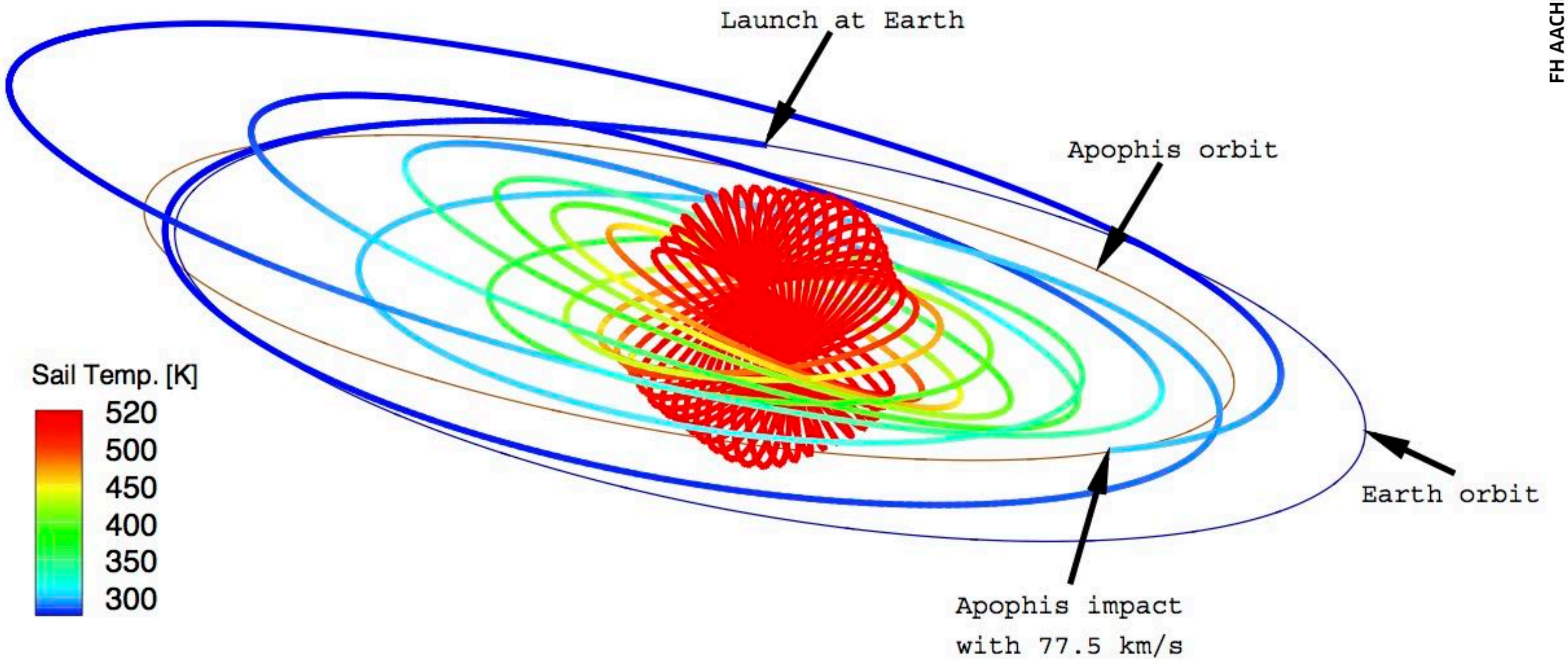
- Objective is to investigate the global structure and dynamics of the solar corona and to reveal the secrets of the solar cycle and the origins of solar activity
- Target orbit: 0.48 AU orbit with 75 deg inclination
- 160 x 160 m, 150 kg square solar sail assembly
- 300 kg S/C bus and payload
- Characteristic acceleration: 0.35 mm/s^2
- Flight duration to target orbit: 4.66 years



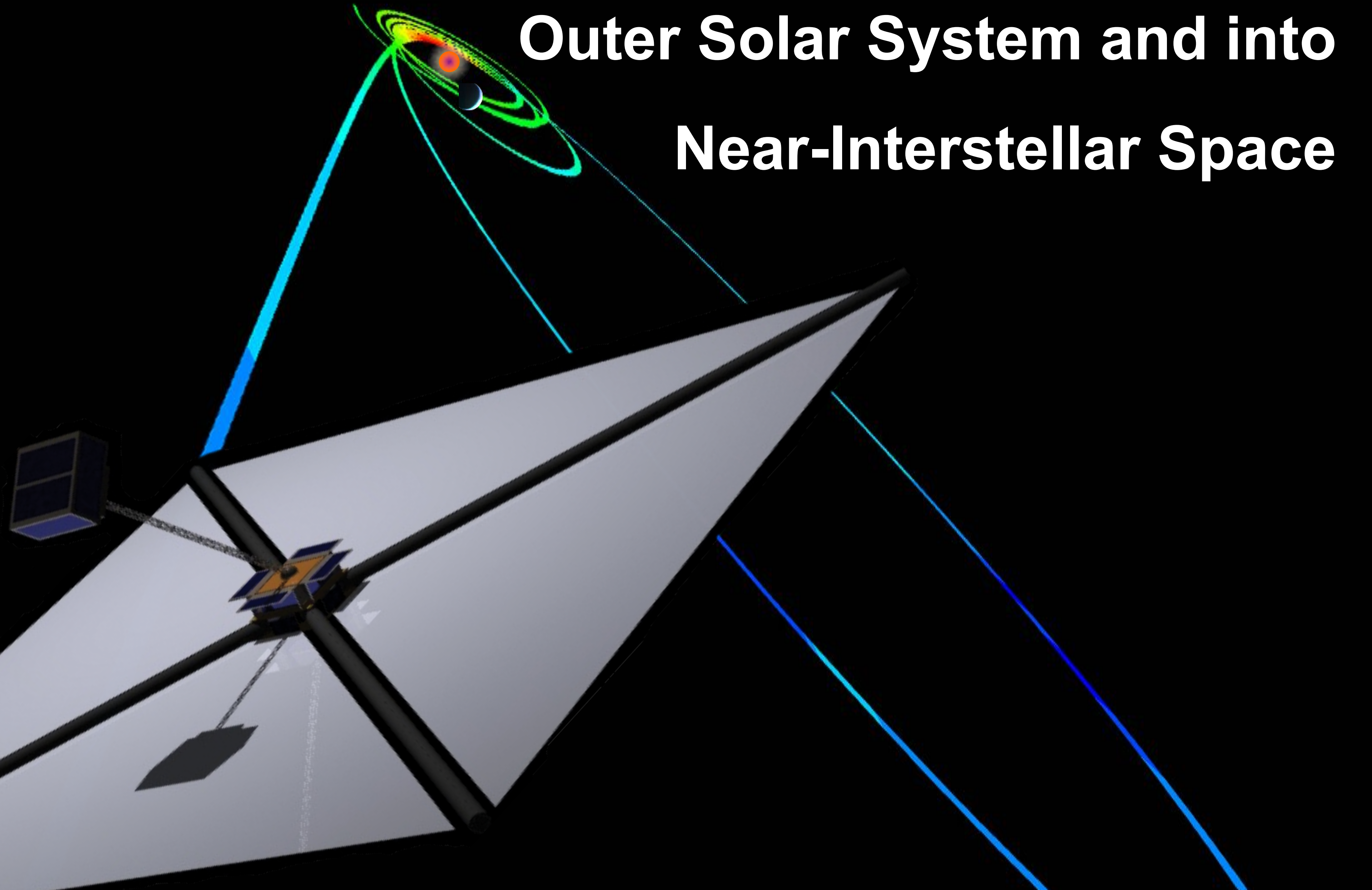
Nonperfectly reflecting solar sail with a_c=0.35mm/s^2
Temperature limit T_{max}=240°C

Transfer duration: 1703 days (4.66 years)

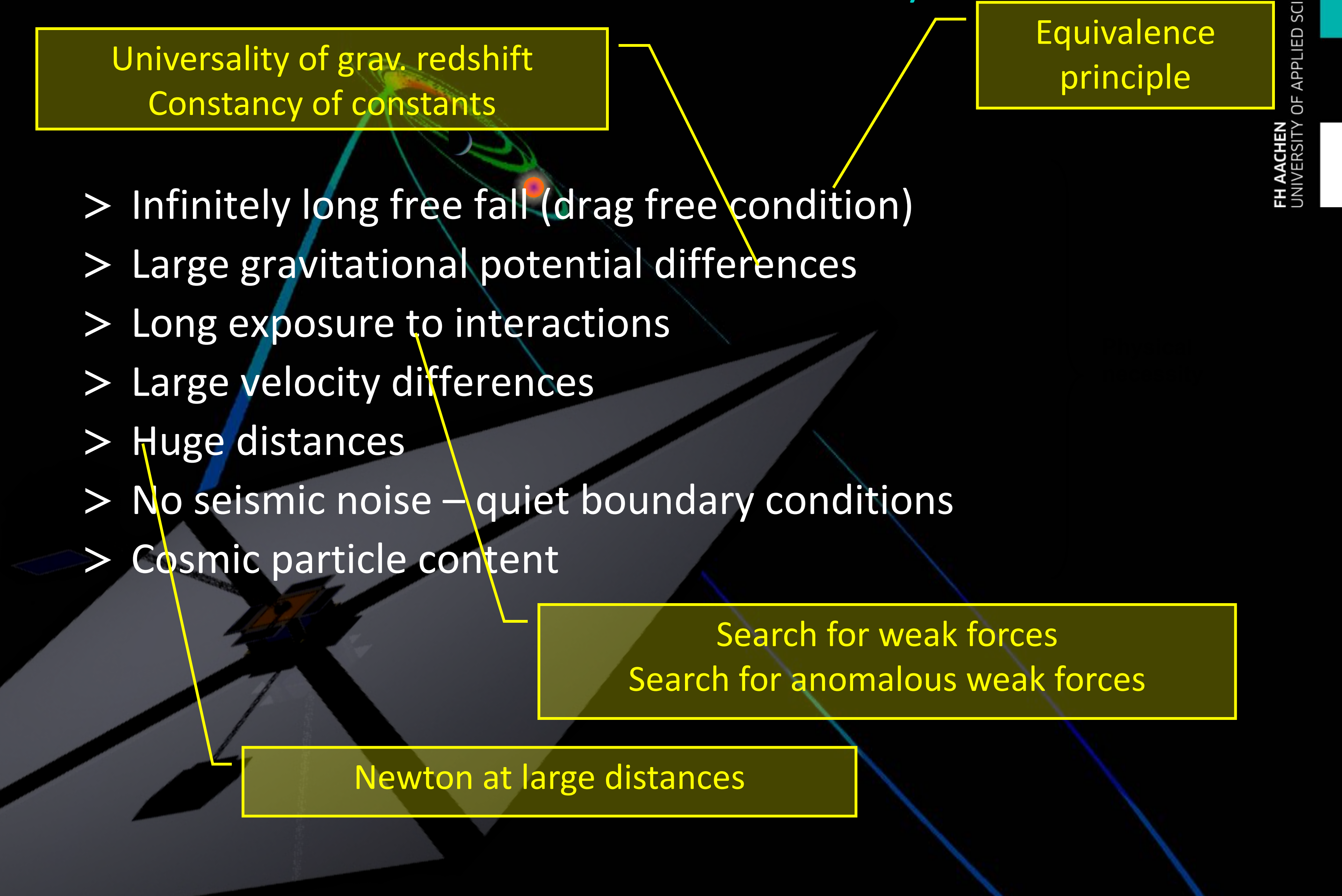
Solar Sail Asteroid Deflection from Retrograde Orbit



Solar Sail Missions to the Outer Solar System and into Near-Interstellar Space



Conditions for a Fast Mission to the Outer Solar System



Universality of grav. redshift
Constancy of constants

Equivalence principle

- Infinitely long free fall (drag free condition)
- Large gravitational potential differences
- Long exposure to interactions
- Large velocity differences
- Huge distances
- No seismic noise – quiet boundary conditions
- Cosmic particle content

Search for weak forces
Search for anomalous weak forces

Newton at large distances

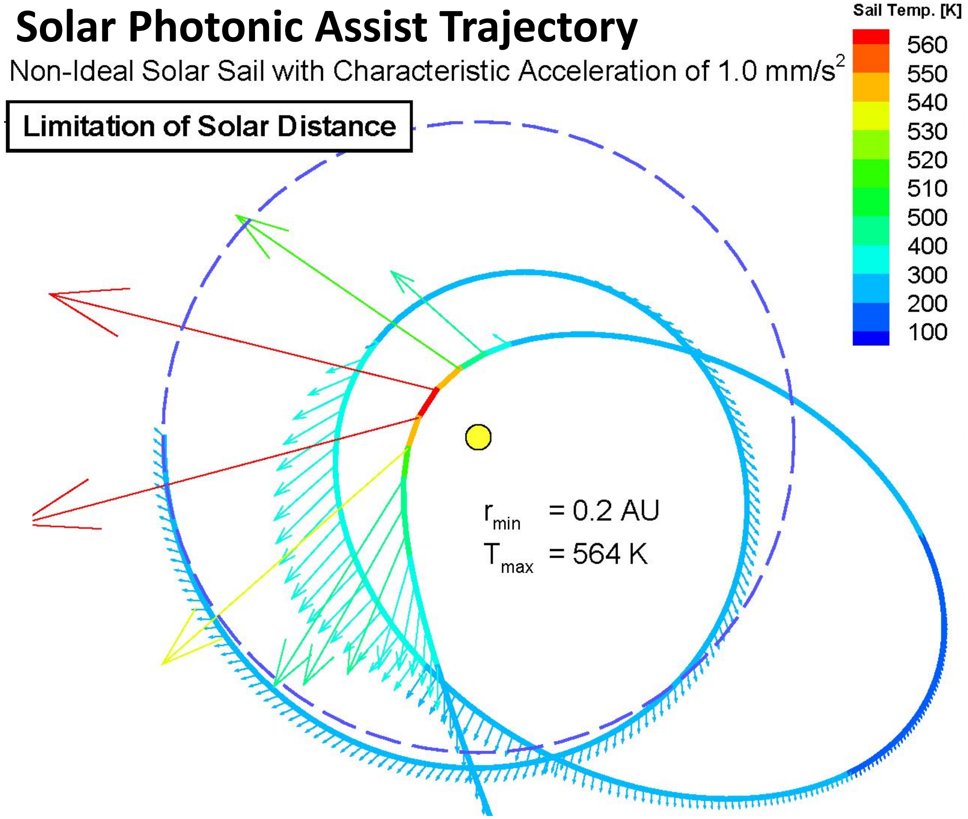
‘Solar Photonic Assist‘ Trajectories

- Minimal flight time depends not only on sail lightness but also on minimal solar distance
- The smaller the minimal solar distance, the larger the energy gain during close approach
- Sail temperature:

$$T = \left(\frac{S_0 r_0^2}{\sigma} \, \frac{1-\rho}{\varepsilon_f + \varepsilon_b} \, \frac{\cos\alpha}{r^2} \right)^{1/4} \propto \frac{\cos^{1/4}\alpha}{r^{1/2}}$$

  Minimal solar distance is limited by the solar sail temperature limit

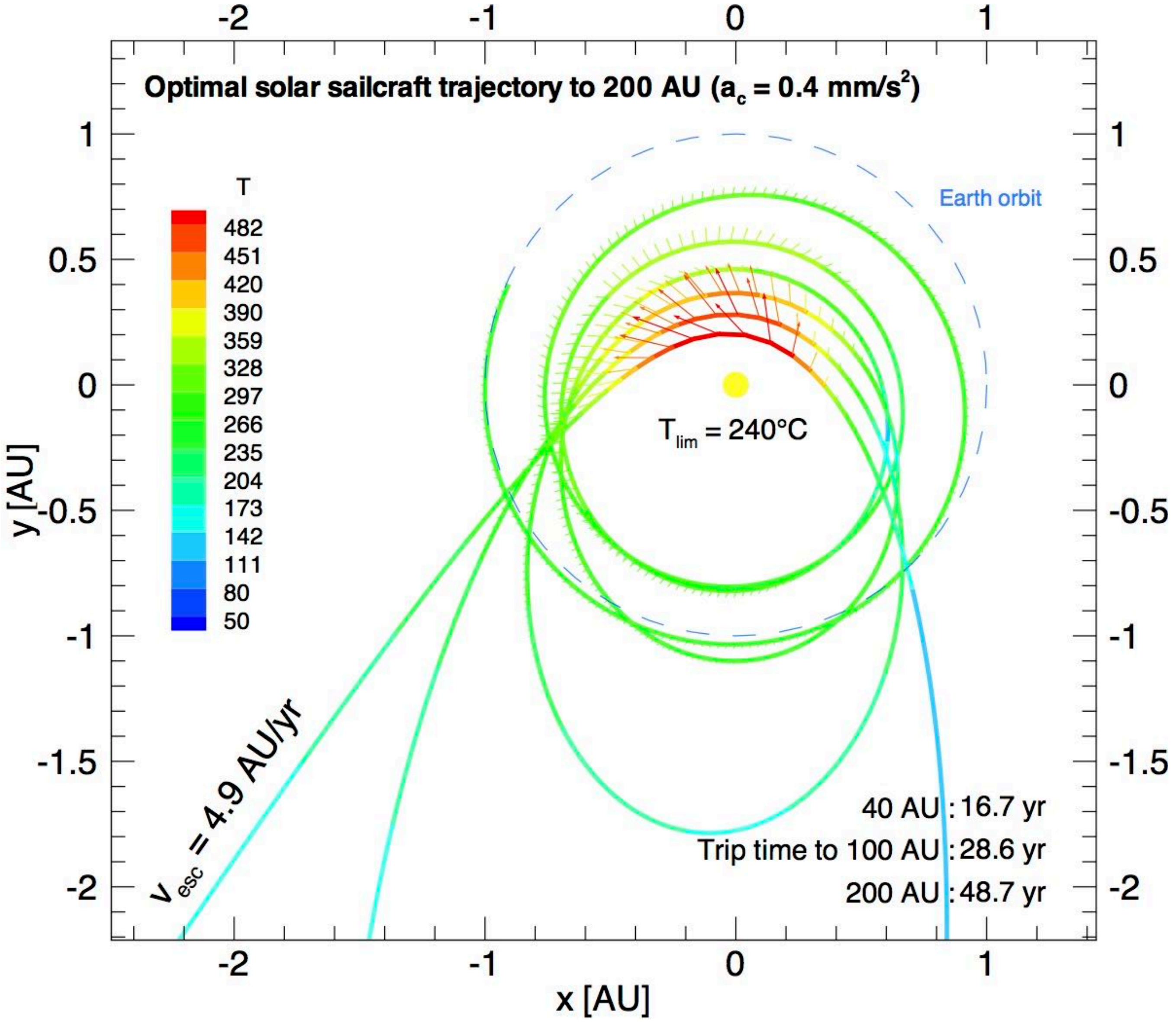
- Sail temperature depends also on the sail attitude
- Sophisticated trajectories
- Trajectory optimization is very difficult



Solar Photonic Assist Trajectory

Non-Ideal Solar Sail with Characteristic Acceleration of 1.0 mm/s^2

Mission to 200 AU with Near / Medium-Term Solar Sail (~2022–2025)

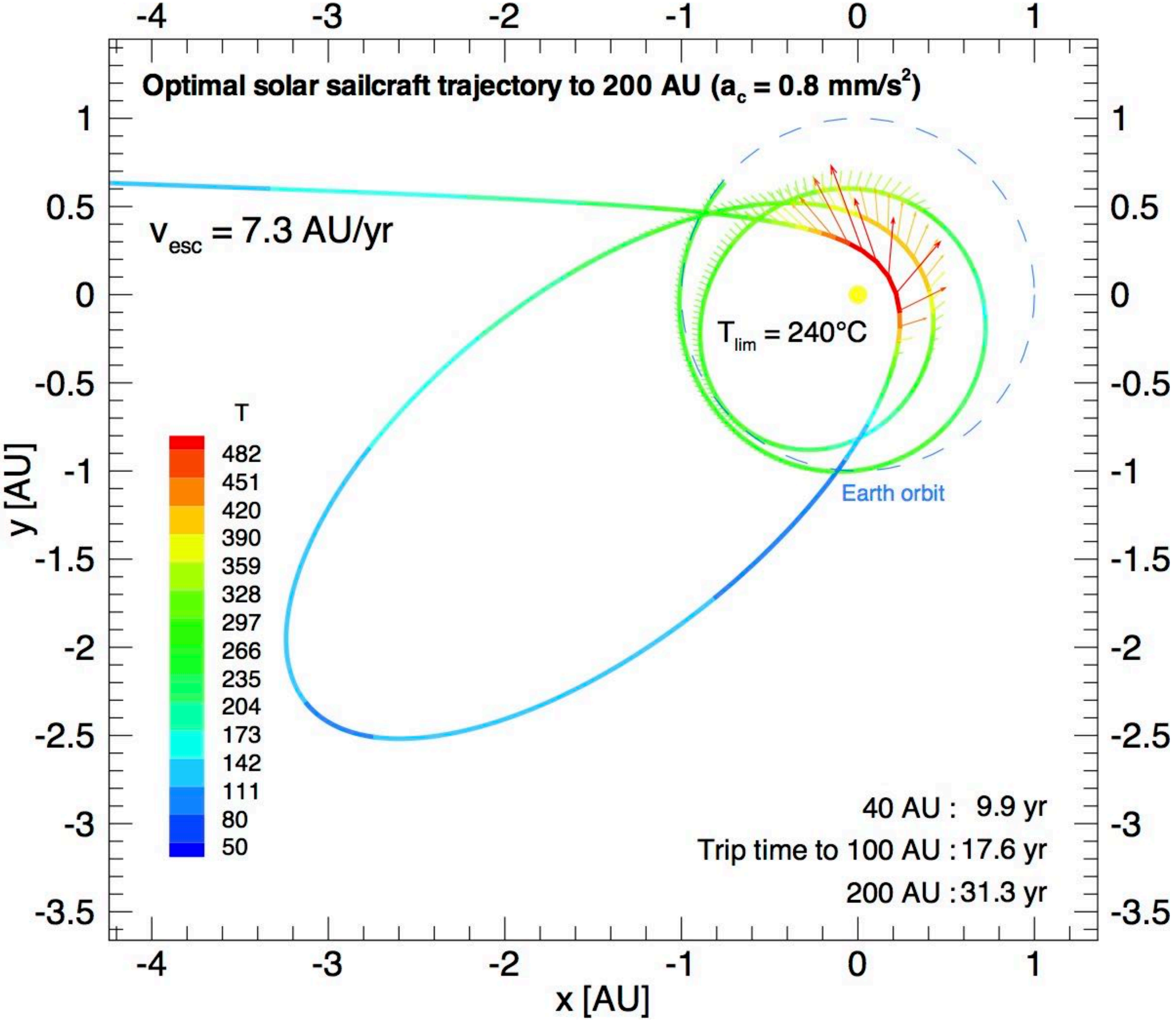


$$a_c = 0.4\,\mathrm{mm/s^2}$$

$$\sigma = 20.8\,\mathrm{g/m^2}$$

> Escape velocity 36% larger than Voyager 1

Mission to 200 AU with Medium-Term Solar Sail (~2024–2030)

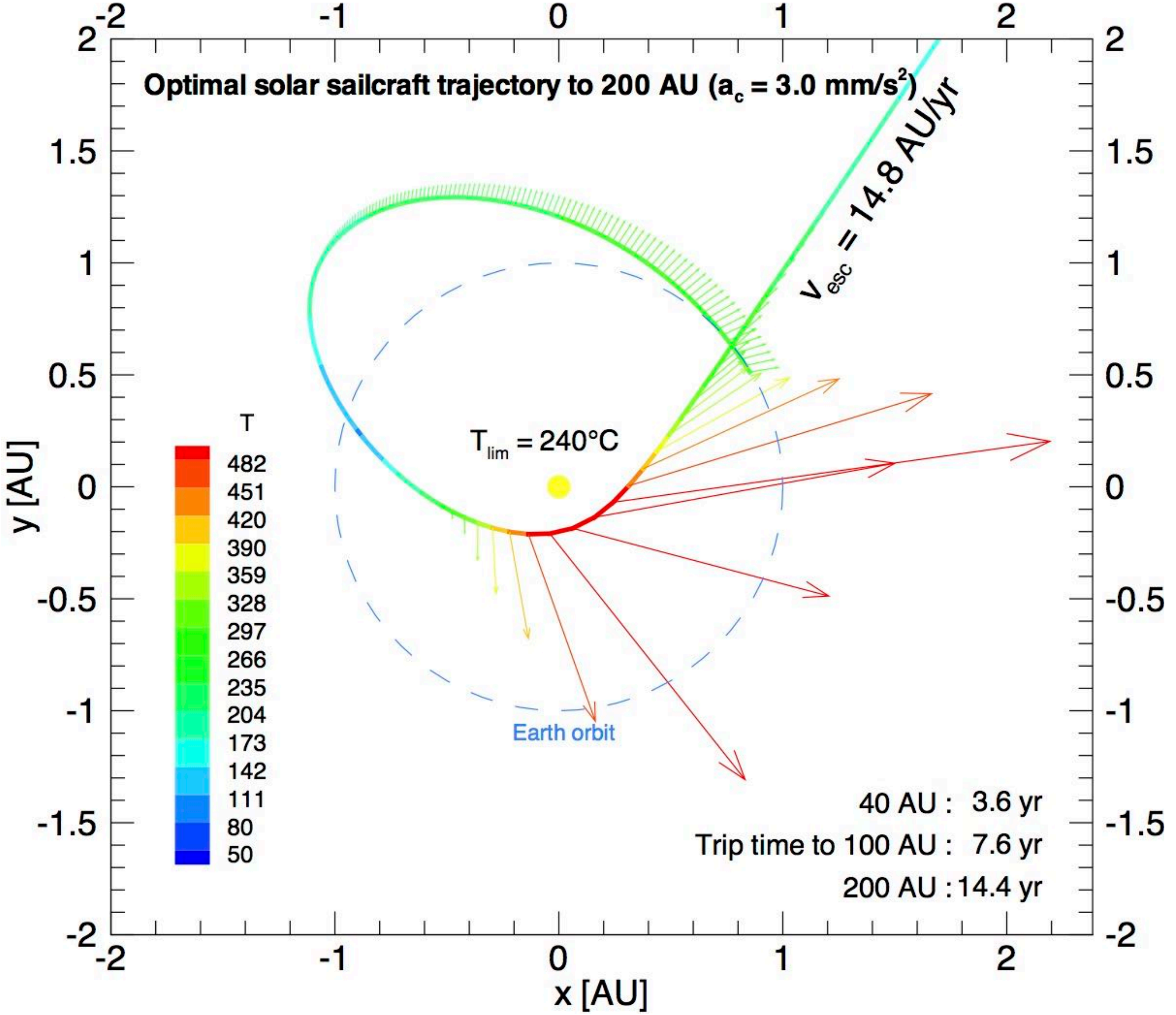


$$a_c = 0.8\,\mathrm{mm/s^2}$$

$$\sigma = 10.4\,\mathrm{g/m^2}$$

- Escape velocity twice as large as Voyager 1

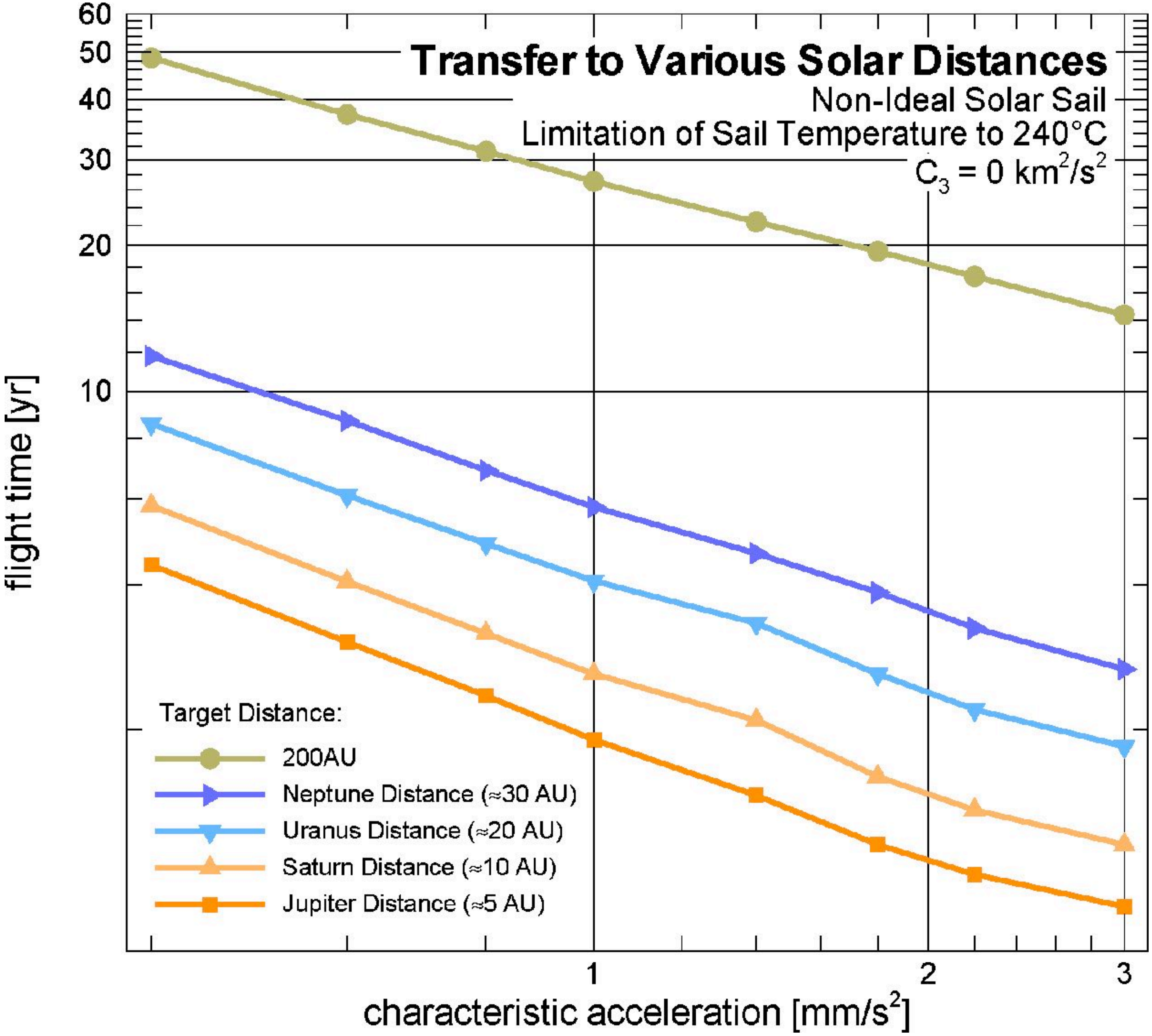
Mission to 200 AU with Very Advanced Solar Sail



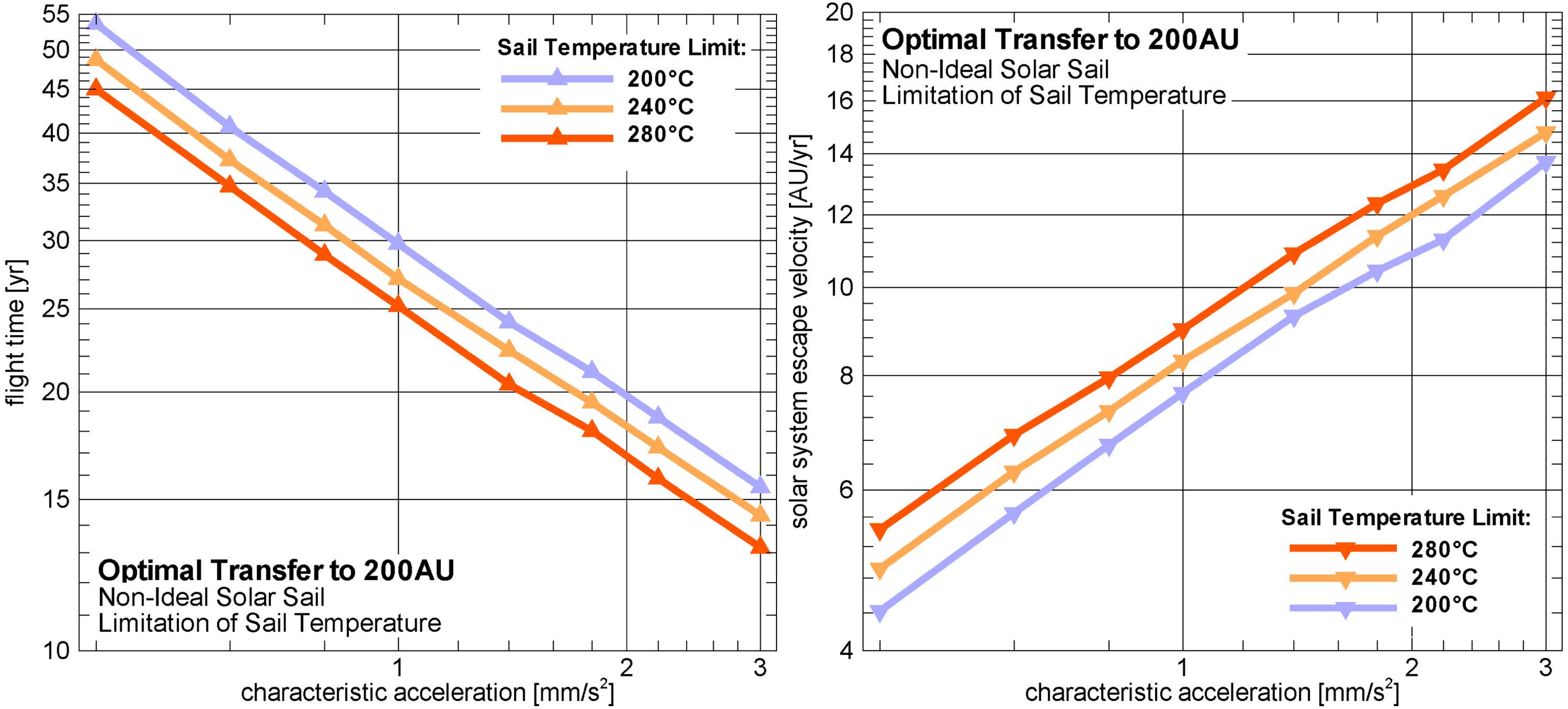
$$a_c = 3.0\,\mathrm{mm/s^2}$$
$$\sigma = 2.8\,\mathrm{g/m^2}$$

> Escape velocity 4 times larger than Voyager 1

Minimal Transfer Times to the Outer Solar System / Near-Interstellar Space



Mission to 200AU (Fast Solar System Escape)

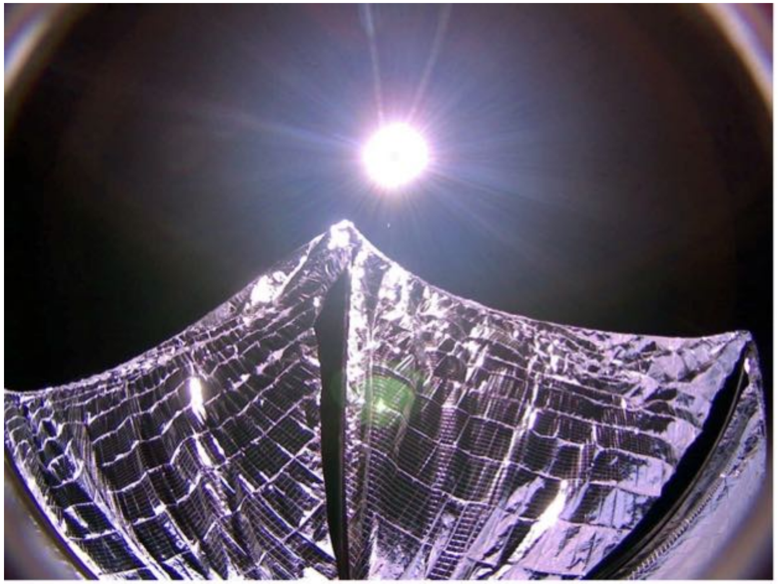


Interim Summary and Conclusions

- Solar sails allow (very-)high-energy trajectories that are difficult or even impossible for any other type of conventional propulsion system
- Solar sails are under development in USA, Russia, Japan, and Europe
- Near- to medium-term solar sails ($a_c = 0.13\,\mathrm{mm/s^2}$) can bring spacecraft to very close solar orbits (≈ 5–8 solar radii in ≈ 7 years)
- Medium-term solar sails ($a_c = 0.4\,\mathrm{mm/s^2}$) can bring spacecraft fast to the outer solar system (40 AU in ≈ 16 years) and beyond
- Advanced solar sails ($a_c = 3.0\,\mathrm{mm/s^2}$) can bring spacecraft fast to near-interstellar space (200 AU in ≈ 15 years)
- Solar sails may be the best propulsion system choice for some fundamental physics missions

LightSail

Preparation for a sail deployment test
Source: http://sail.planetary.org



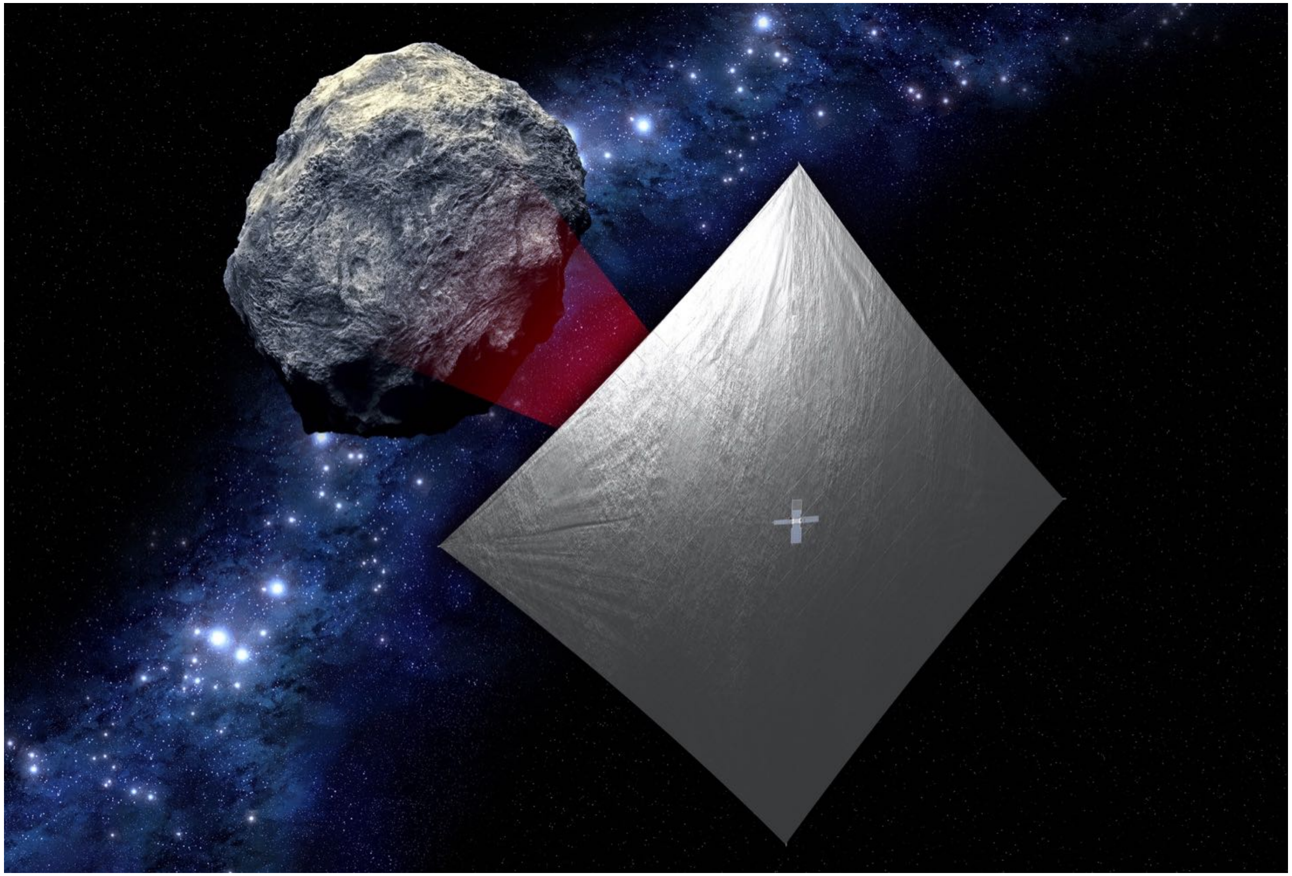
The deployed sail of LightSail 1 in Earth orbit on 08 June 2015.

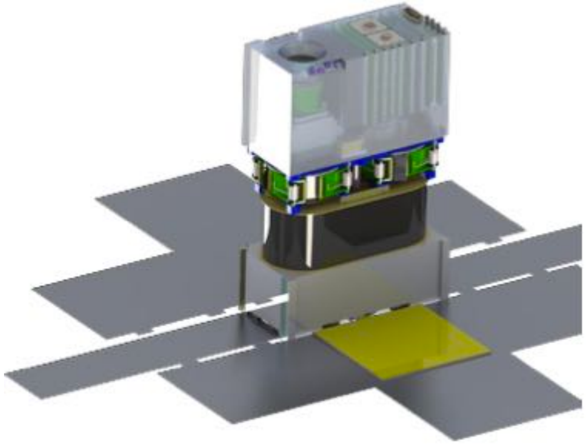
The Planetary Society: solar sail based on CubeSat standard (3U), 32 m^2, total mass ≈ 5 kg (≈ 150 g/m^2, still quite heavy)

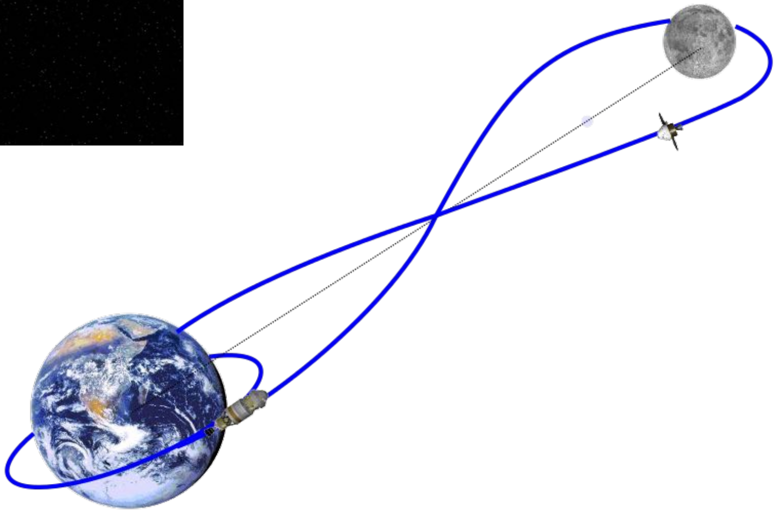
LightSail 1:
Launched in May 2015 with an Atlas V into a low-Earth orbit with high drag (quick re-entry)

LightSail 2:
Planned to launch in early 2018 with a Falcon Heavy into 720-km Earth orbit

NEA Scout







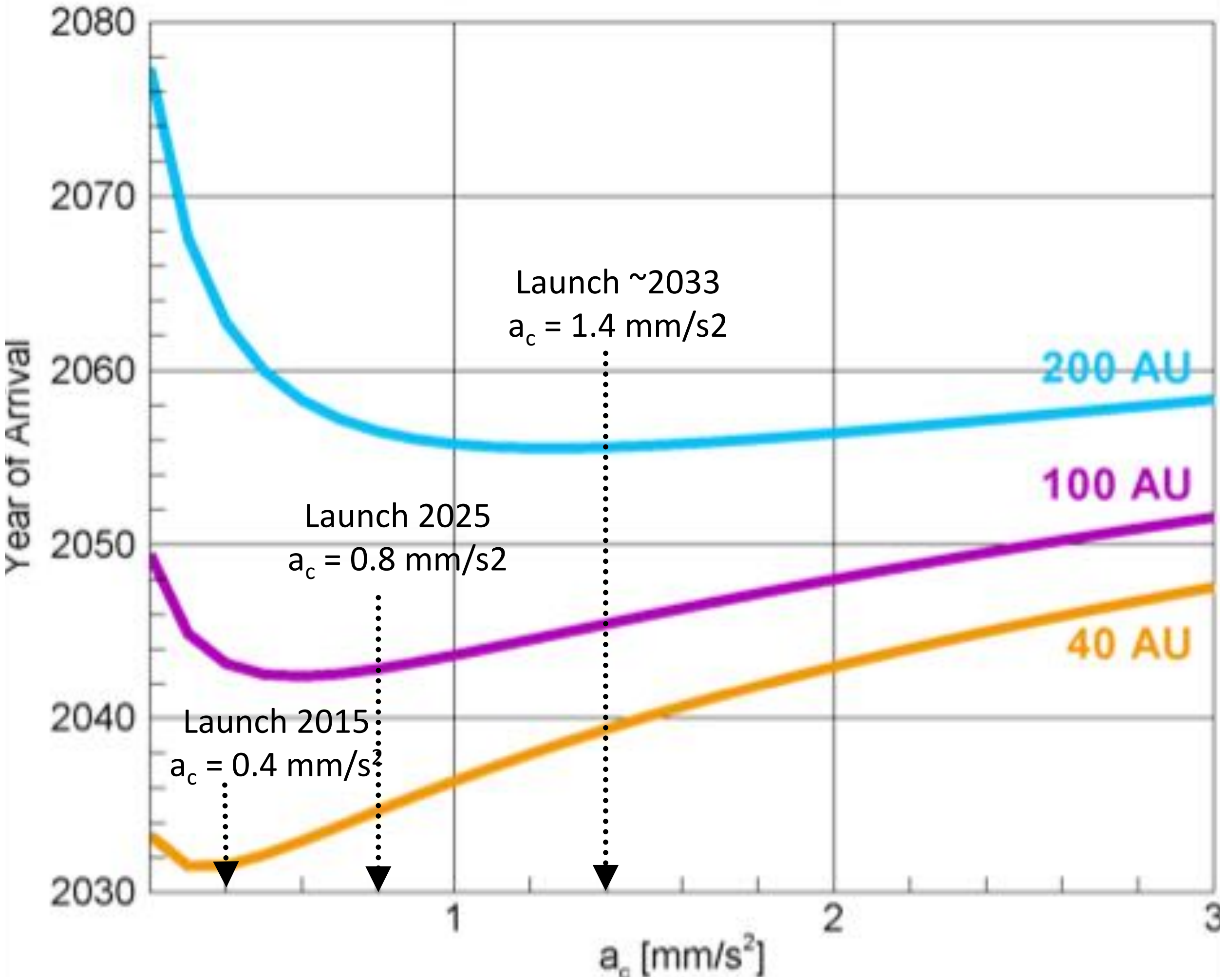
NASA: solar sail based on CubeSat standard (6U), 83 m^2, total mass < 12 kg (< 145 g/m^2, still quite heavy)
Planned to be launched in 2019 with Space Launch System (SLS) maiden flight into cis-lunar heliocentric orbit and to fly to near-Earth asteroid 1991 VG, 5–12 m in size (target may change, depending on exact launch date)

When Should We Go?

Technological Assumptions:

1) We can build a sailcraft with $a_c = 0.4$ mm/s^2 by 2015

2) We can double a_c every 10 years (for $a_c < 3$ mm/s^2)

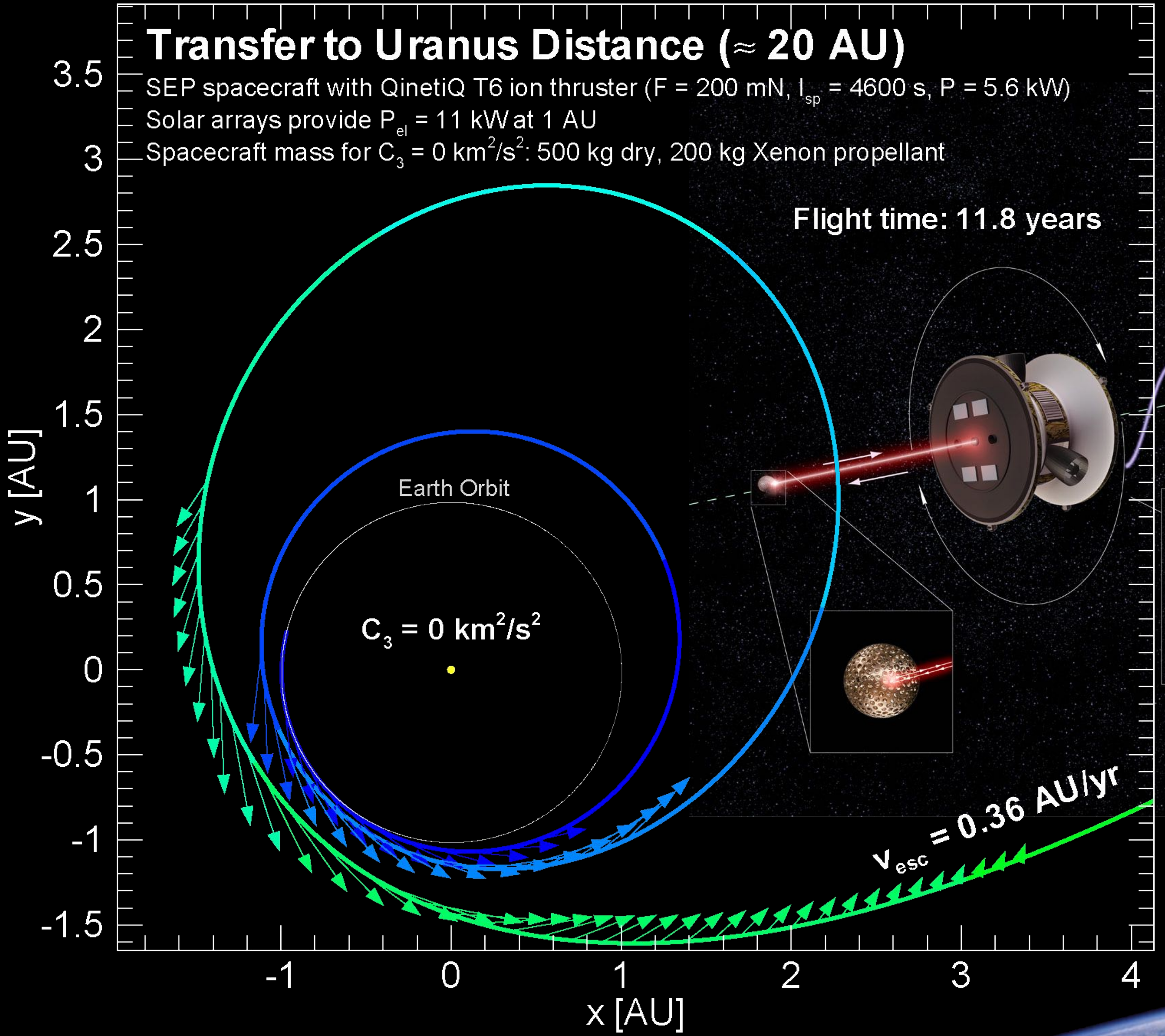


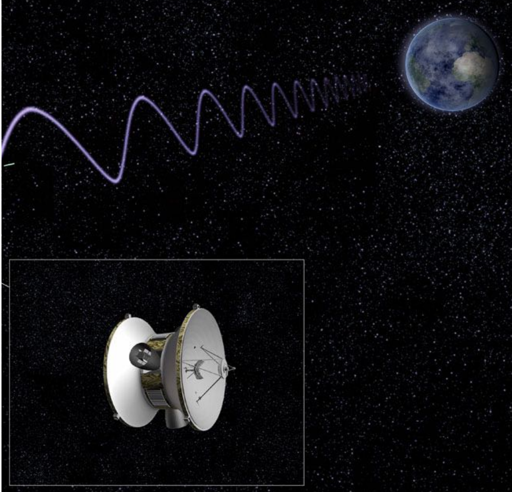
Launch ~2033
a_c = 1.4 mm/s2

Launch 2025
a_c = 0.8 mm/s2

Launch 2015
a_c = 0.4 mm/s^2

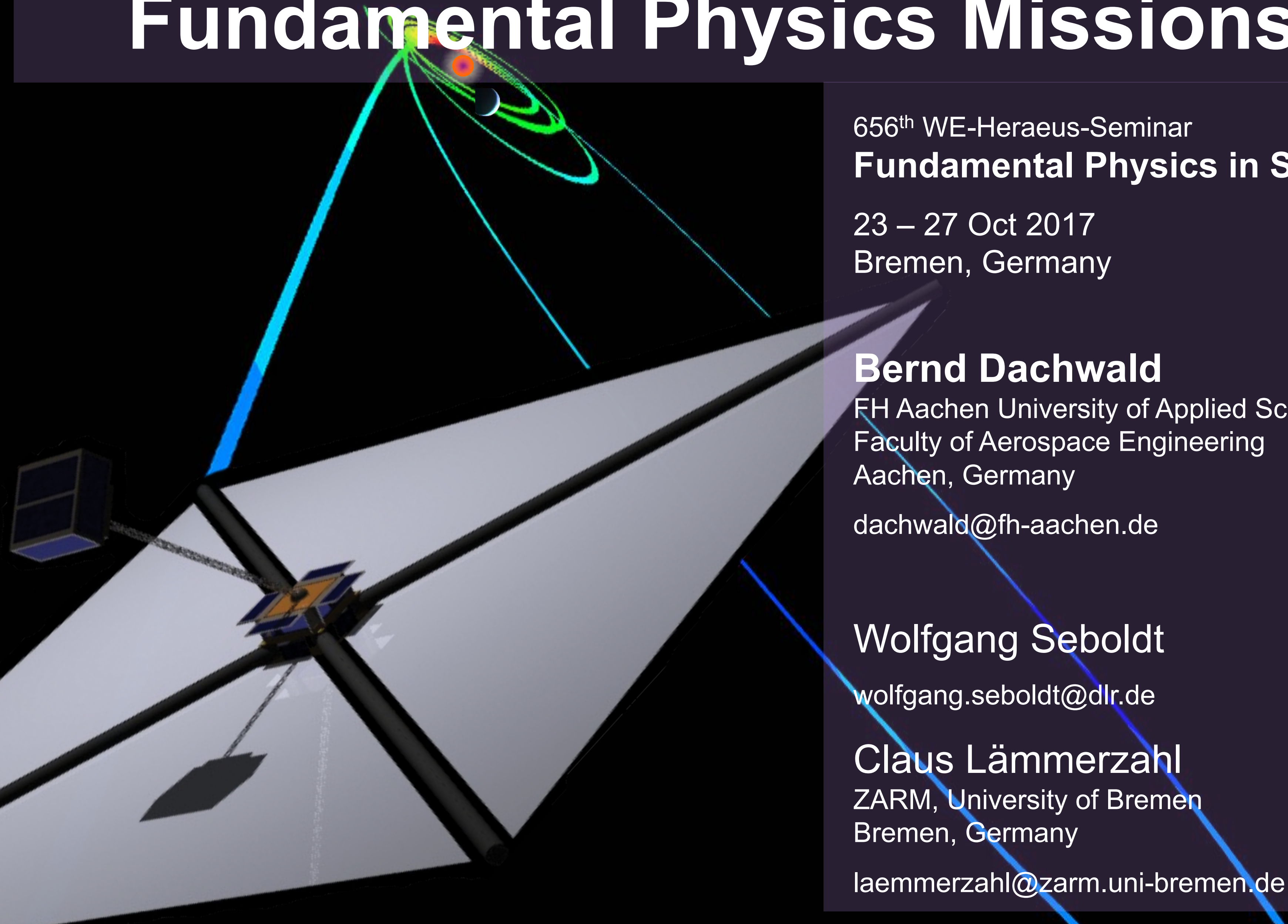
Solar System Escape Trajectory for Spacecraft with Solar Electric Propulsion





Trajectory calculated for a mission to test the anomalies experienced by the two Pioneer probes

Setting Sails for Fundamental Physics Missions



656th WE-Heraeus-Seminar

Fundamental Physics in Space

23 – 27 Oct 2017
Bremen, Germany

Bernd Dachwald
FH Aachen University of Applied Sciences
Faculty of Aerospace Engineering
Aachen, Germany

dachwald@fh-aachen.de

Wolfgang Seboldt

wolfgang.seboldt@dlr.de

Claus Lämmerzahl
ZARM, University of Bremen
Bremen, Germany

laemmerzahl@zarm.uni-bremen.de