

OPTIMAL CONTROL OF SOLAR SAILS FOR A SUN OCCULTATION MISSION



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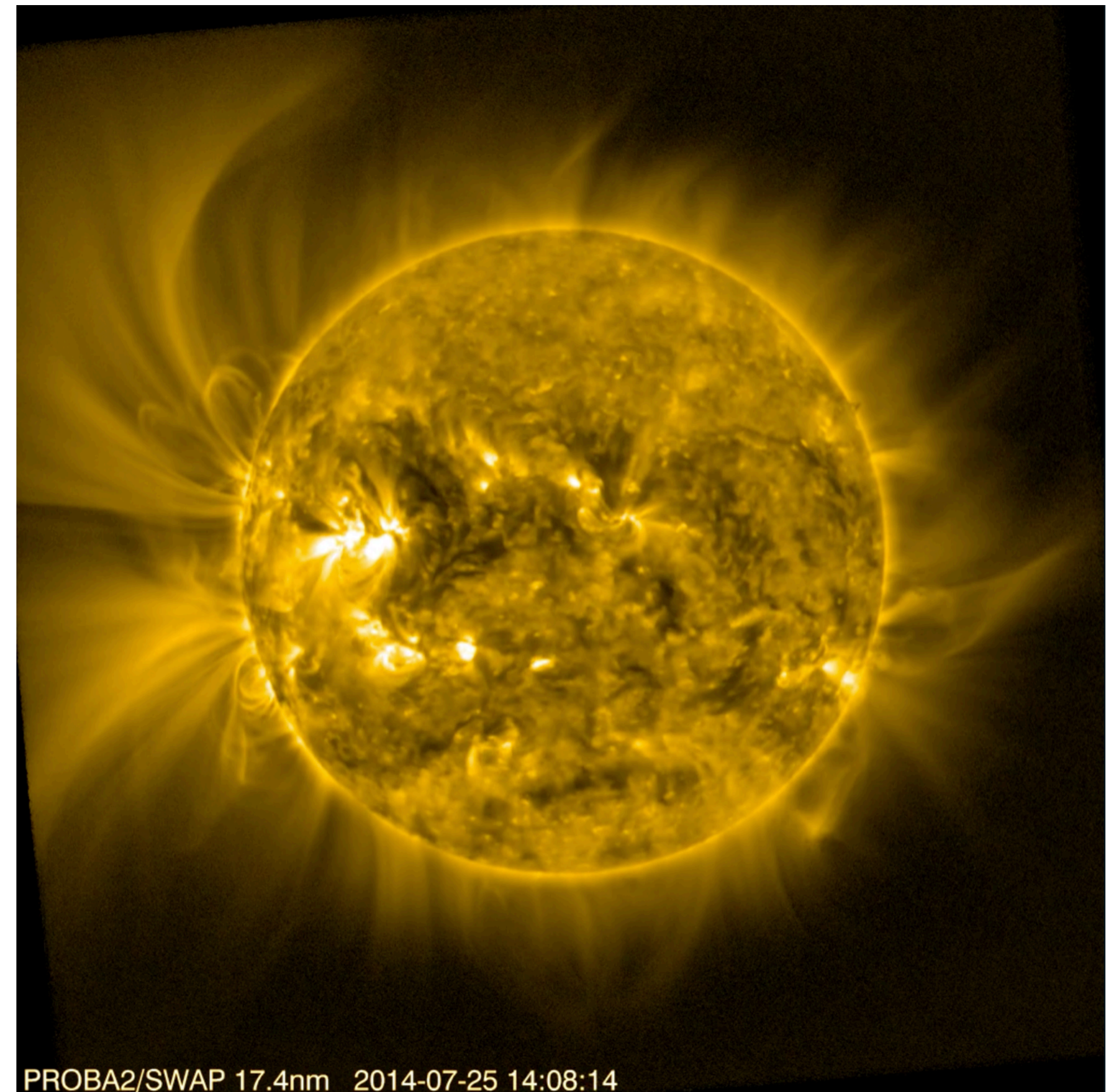
Surrey Space Center, University of Surrey

Solar corona: key element to study heliosphere

Evolution of the solar corona due to the magnetic field

Poorly understood process controlling the corona and the acceleration of the solar wind

Huge impact on space missions

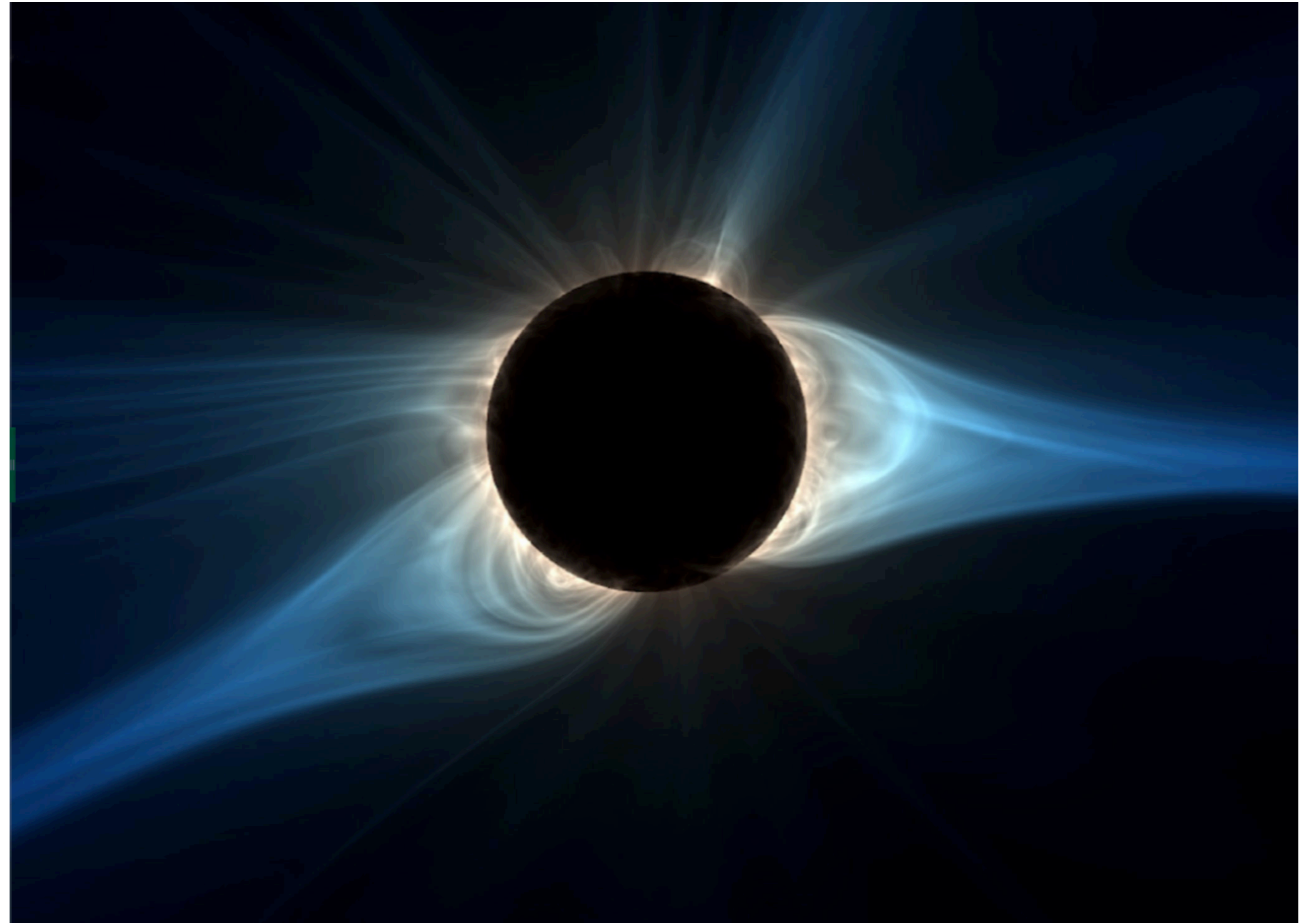


Credits: ESA

How to observe solar corona?

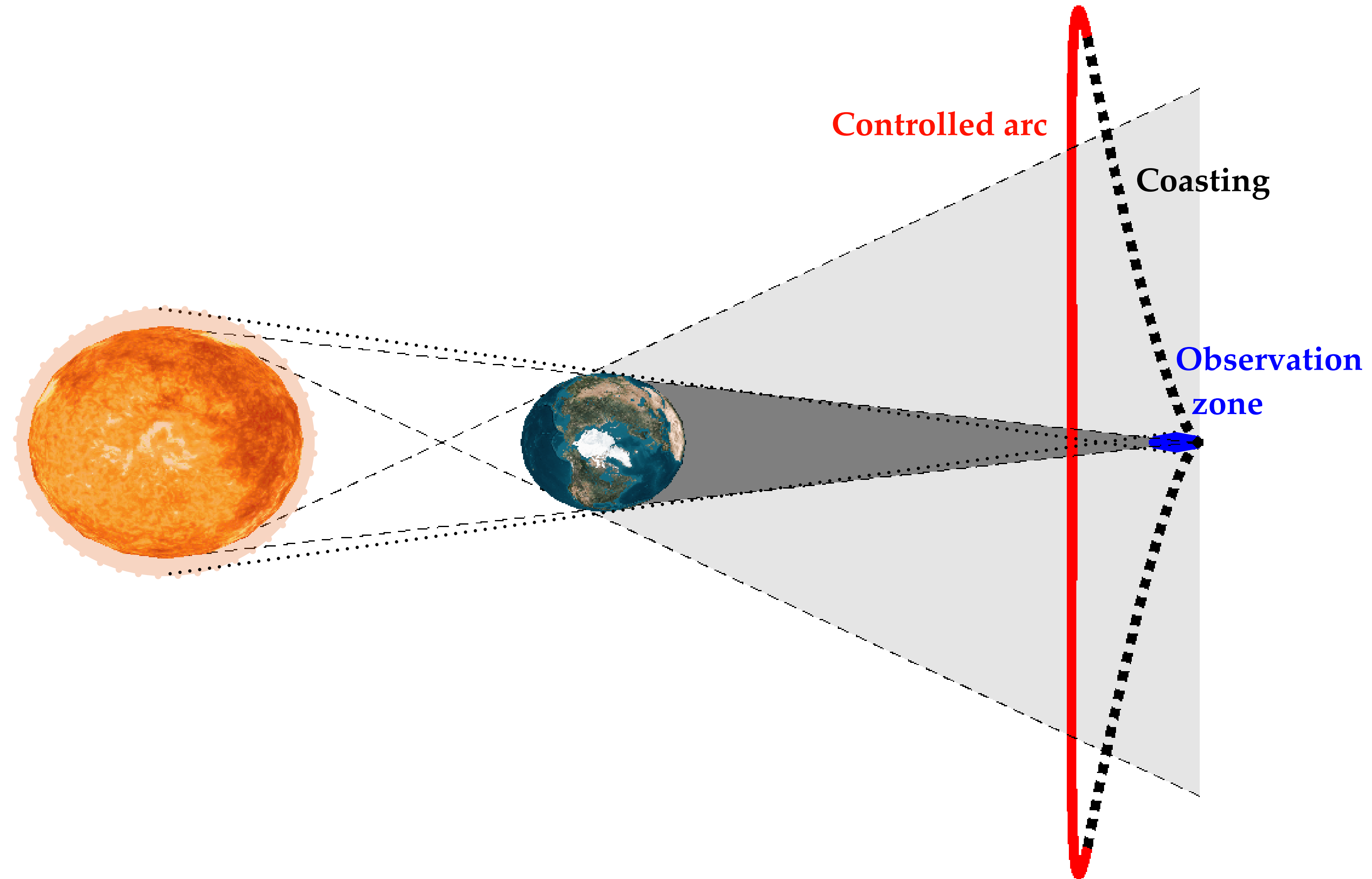
From the ground:
Eclipses every 18 months

From space:
ESA PROBA - 3 (2023)



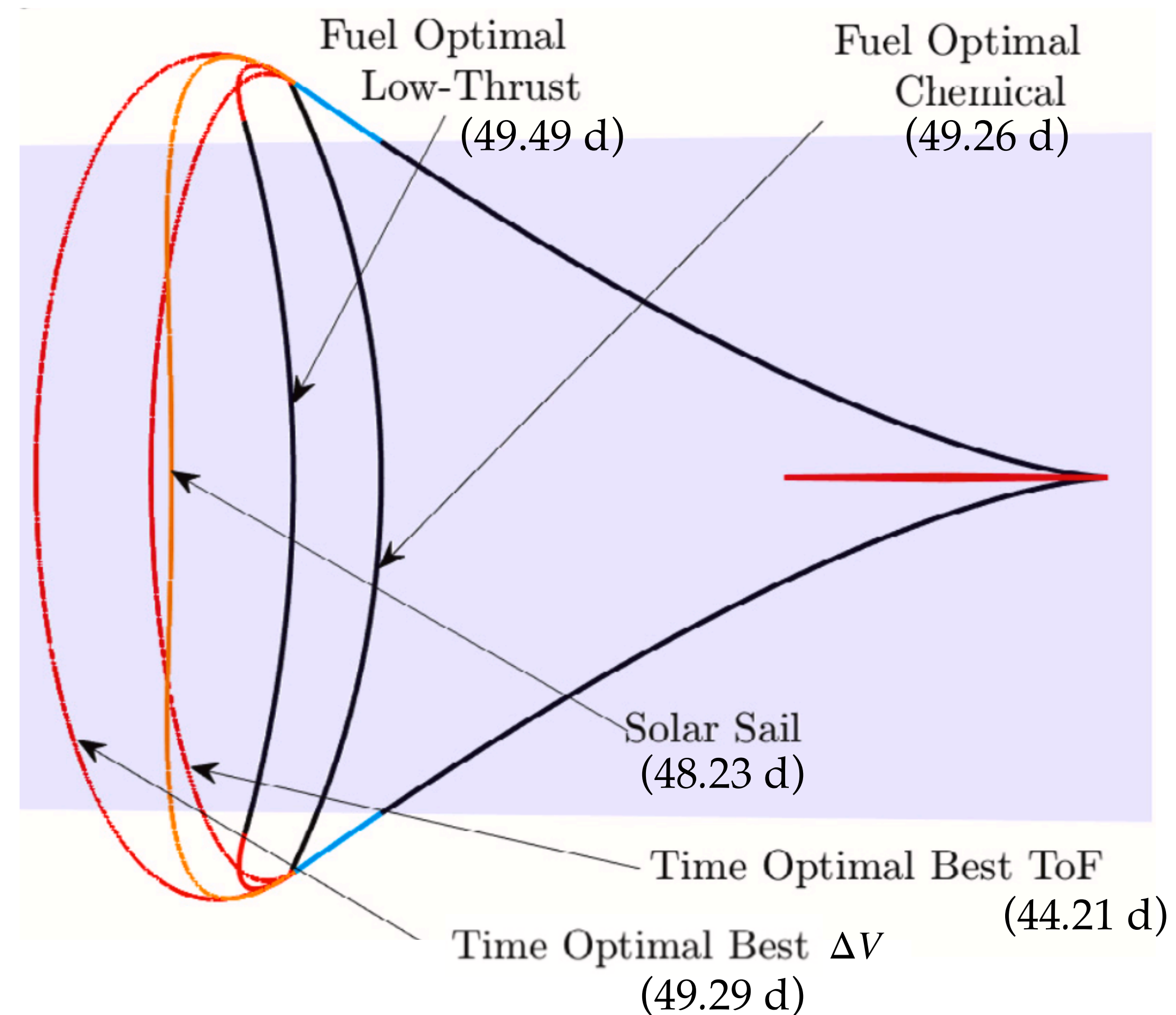
Credits: NASA Goddard

New proposition: to occult Sun with natural body

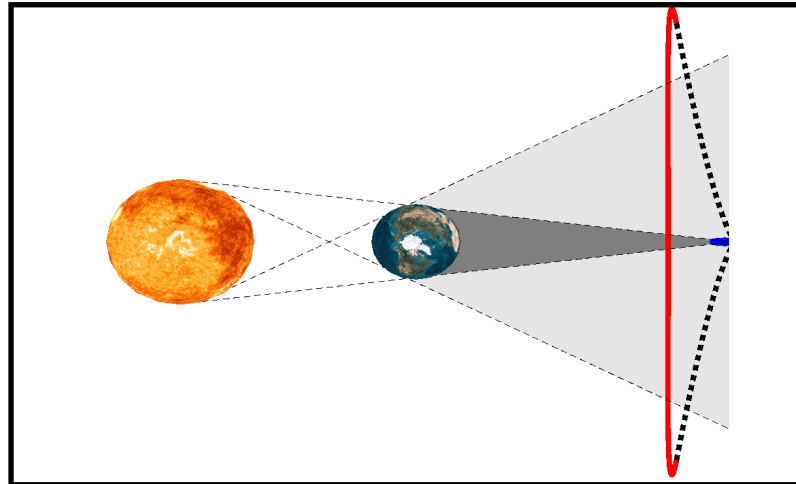


S. Eckersley, S. Kemble, Method of solar occultation, 2017, Airbus DS Patent 9, 676, 500.

Why solar sails?



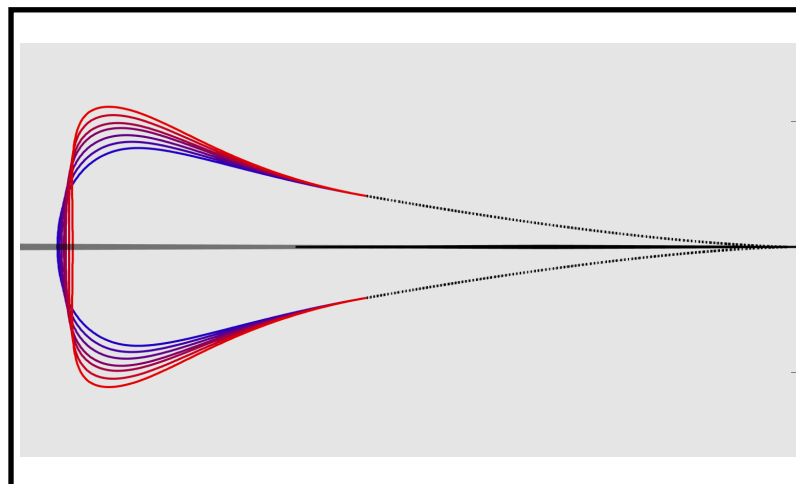
Outline



1. Equations of motion

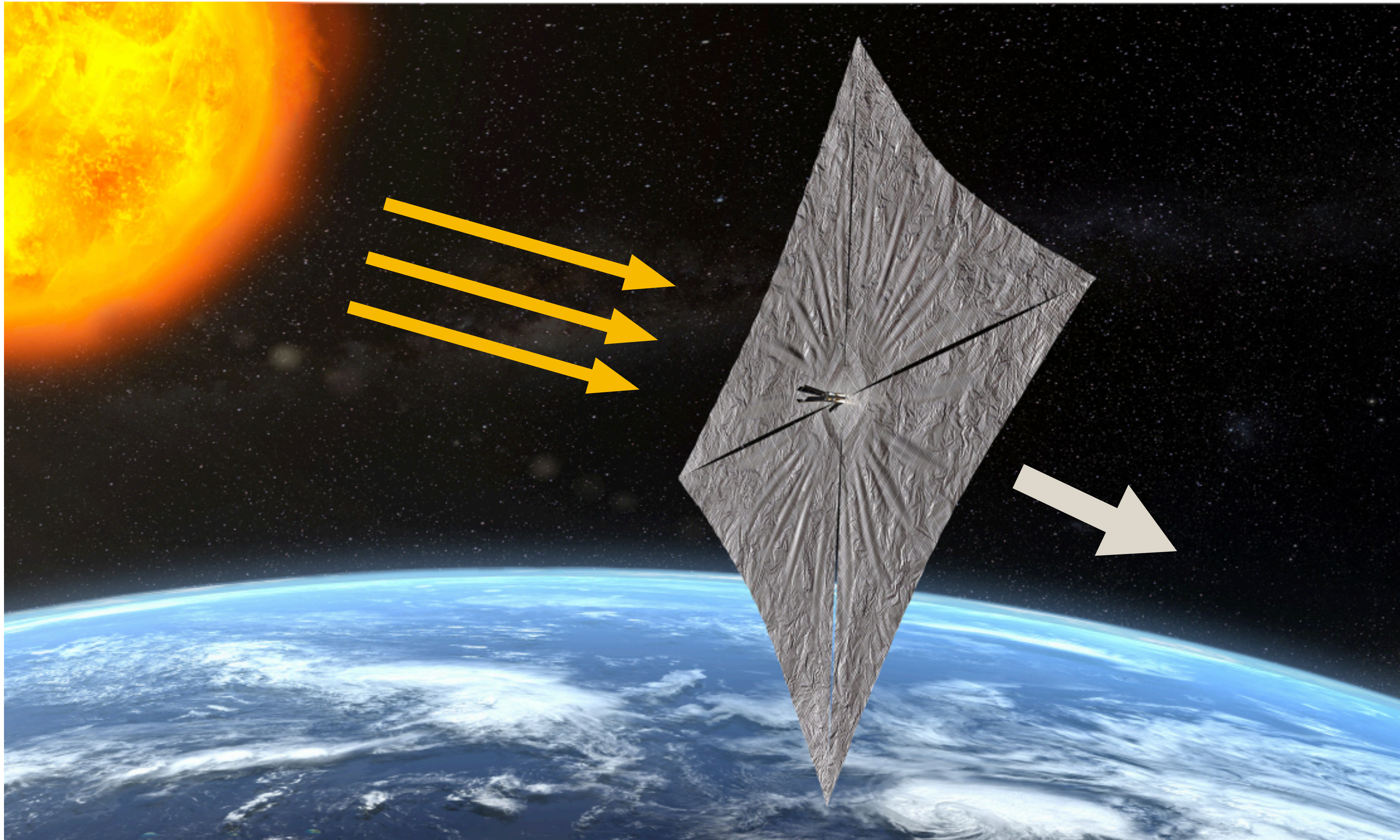
$$\max \mathcal{H}$$

2. Optimal control problem and Pontryagin's maximum principle (PMP)

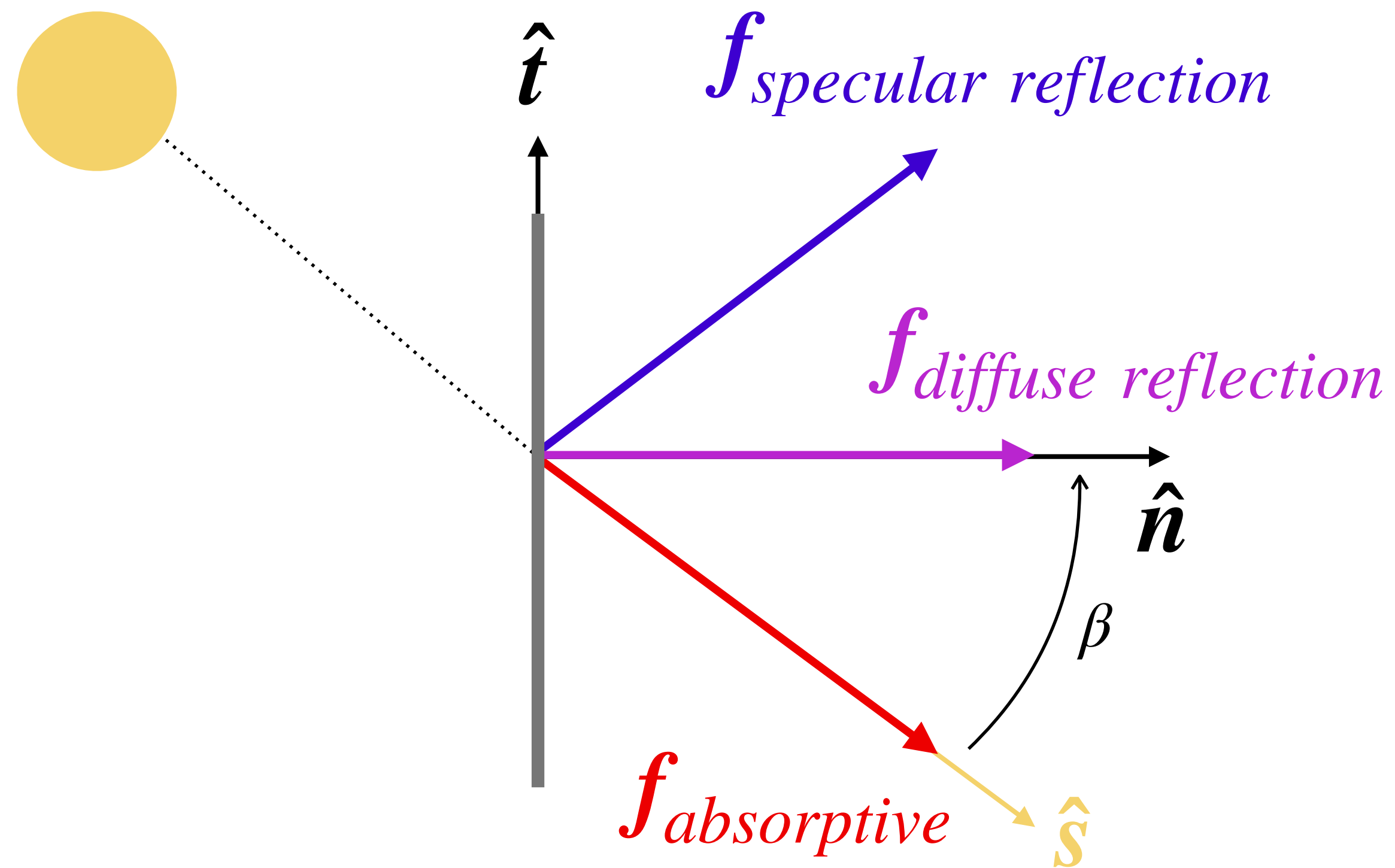


3. Results

1. Solar sail



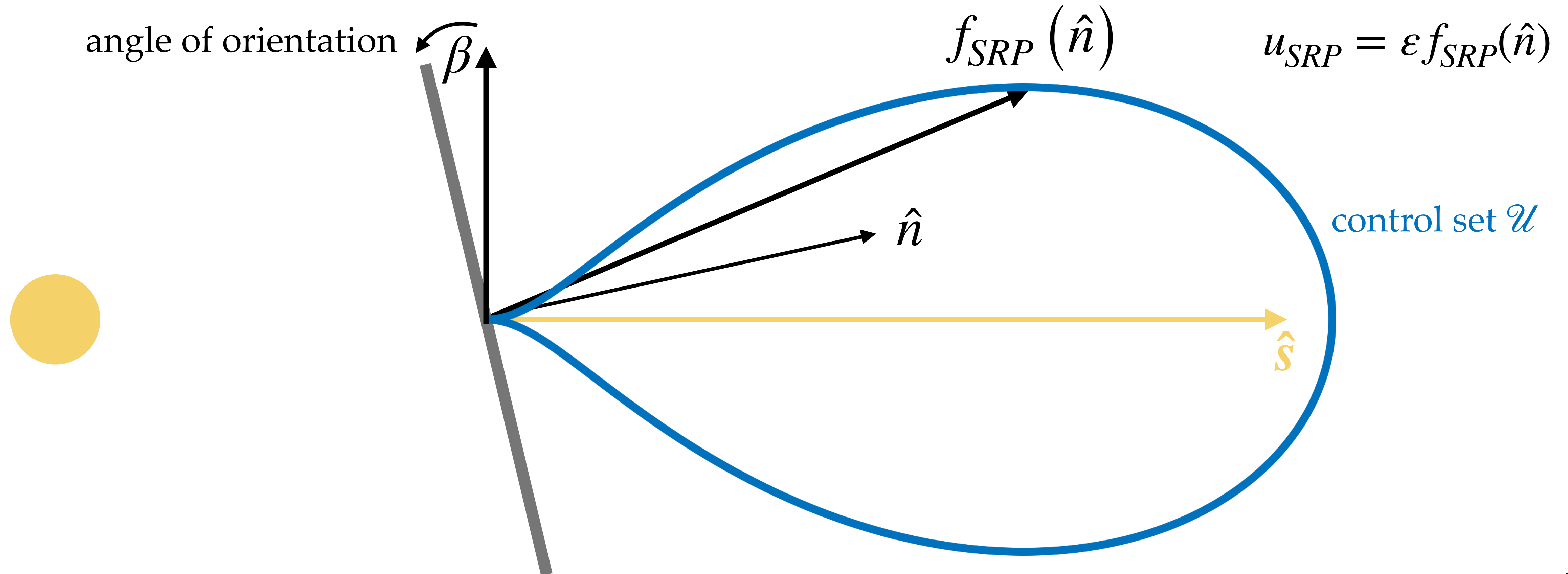
1. Force components of solar sail



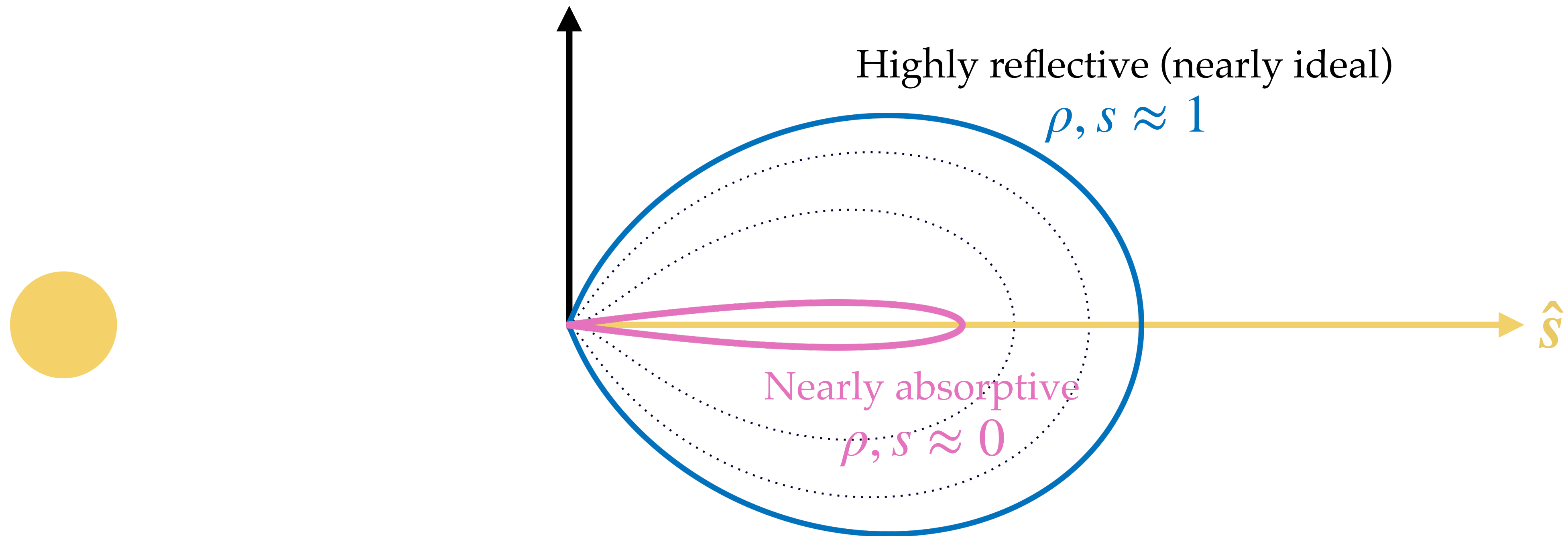
$$\mathbf{f}_{SRP} = \mathbf{f}_{absorptive} + \mathbf{f}_{specular\ reflection} + \mathbf{f}_{diffuse\ reflection}$$

1. Control set

$$\dot{x} = F^0(x) + \sum_i u_i F^i(x), \quad u \in \mathcal{U}$$



1. Parametrisation of the control set



$\rho, s \in [0,1]$ portion of specular, diffuse reflection

1. Dynamics of the system

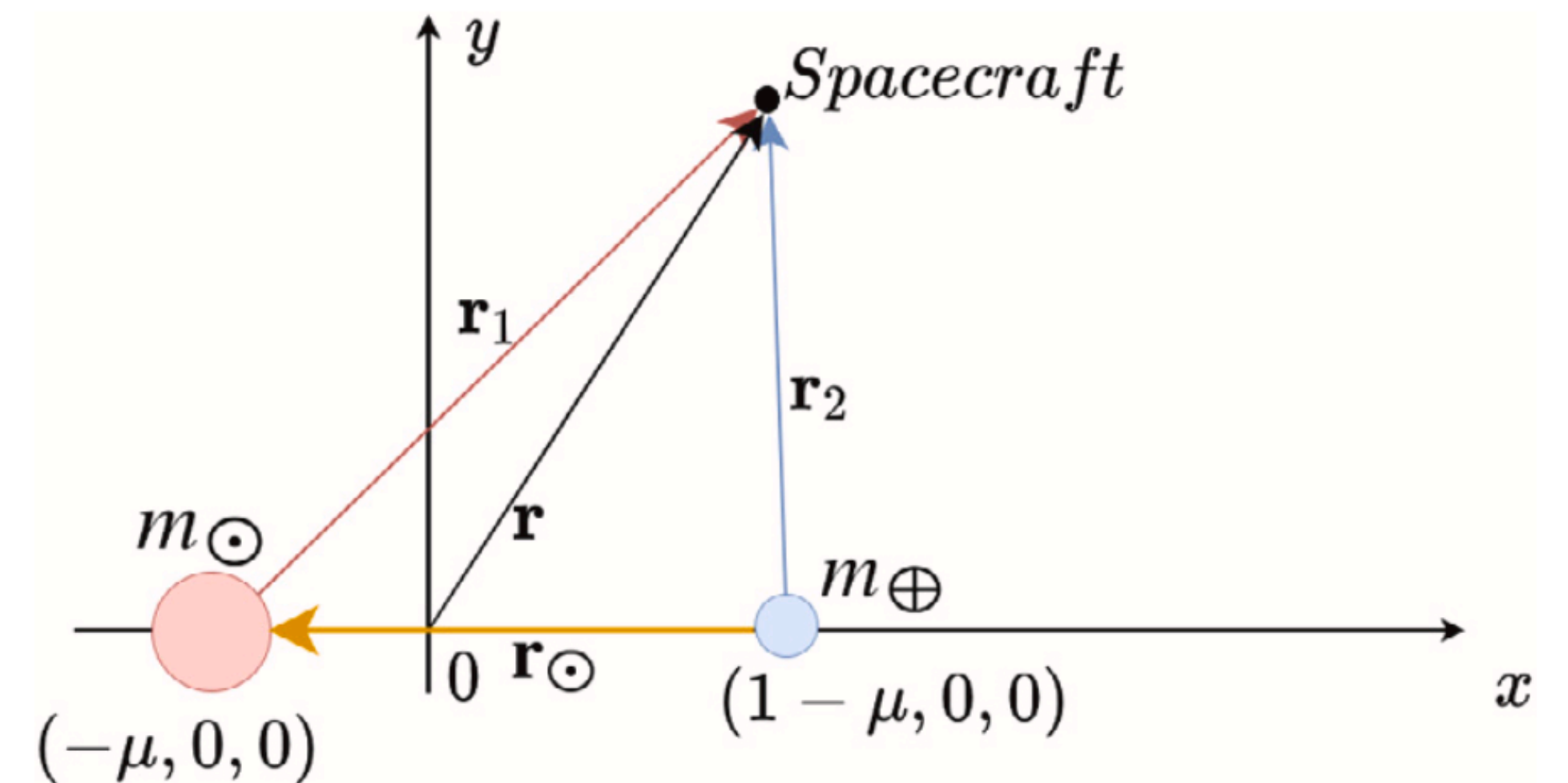
$$(r, v) \in \mathbb{R}^6$$

$$\begin{cases} \dot{r} = v \\ \dot{v} = -\frac{1-\mu}{\|r_1\|^3}r_1 - \frac{\mu}{\|r_2\|^3}r_2 + g(r, v) + \varepsilon \tau u_{SRP} \end{cases}$$

$= f(r, v)$

where $g(r, v) = \begin{pmatrix} r_x \\ r_y \\ 0 \end{pmatrix} + 2 \begin{pmatrix} v_y \\ -v_x \\ 0 \end{pmatrix}$

$$\tau = \begin{cases} 1 & \text{in sunlight} \\ 0 & \text{in umbra} \\ (0,1) & \text{in penumbra} \end{cases}$$



2. Periodic optimal control problem

$\min J = t_f$ subject to

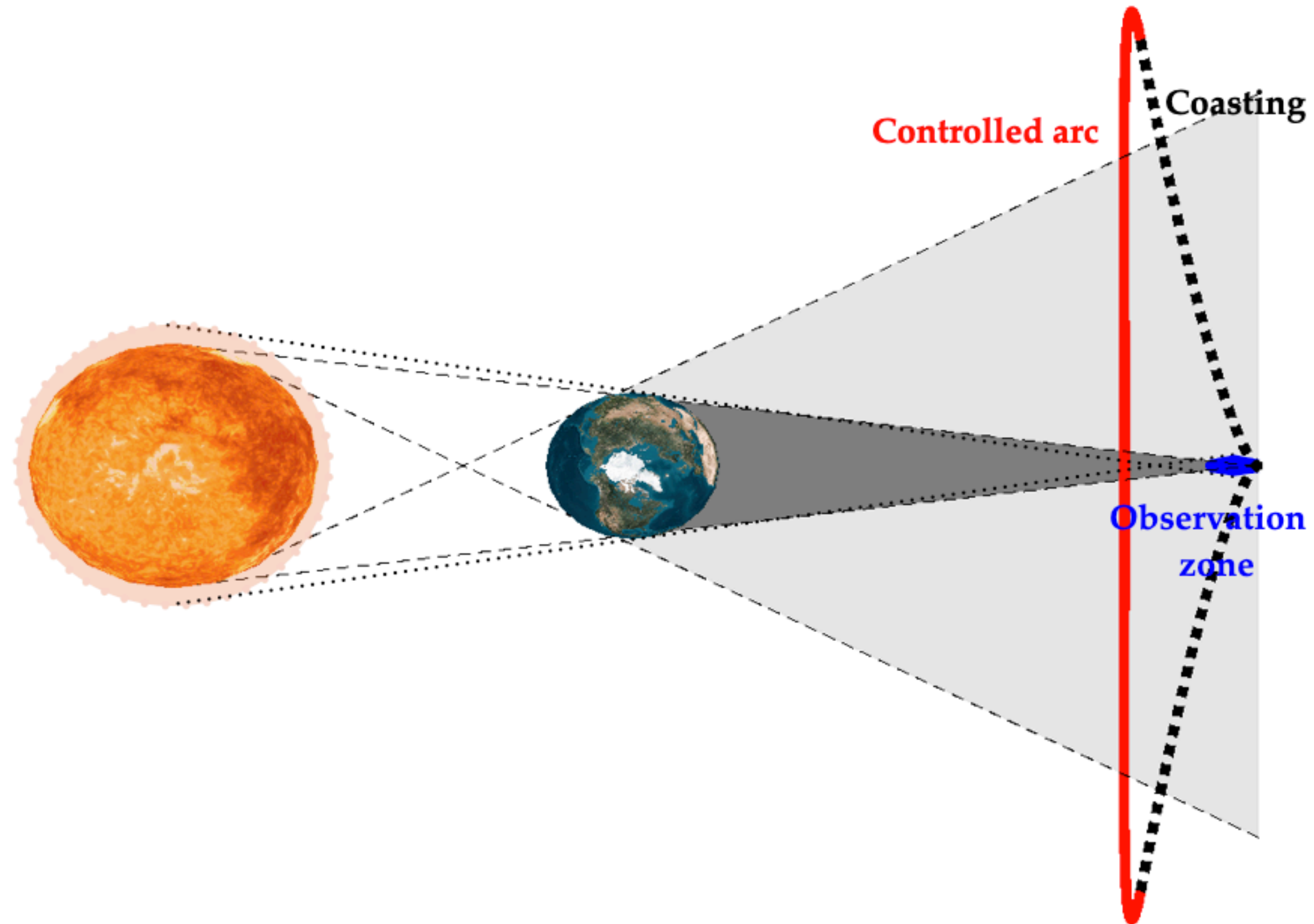
$$\begin{cases} \dot{r} = v \\ \dot{v} = f(r, v) + \varepsilon \tau u_{SRP} \\ \dot{s} = \tau \end{cases}$$

$$u_{SRP} \in \mathcal{U}, \quad \varepsilon \in \mathbb{R}$$

$$r(t_0) = r_0, \quad v(t_0) = 0, \quad s(t_0) = 0$$

$$r(t_f) = r(t_0), \quad v(t_f) = v(t_0)$$

$$s(t_f) \geq s_{\min}$$



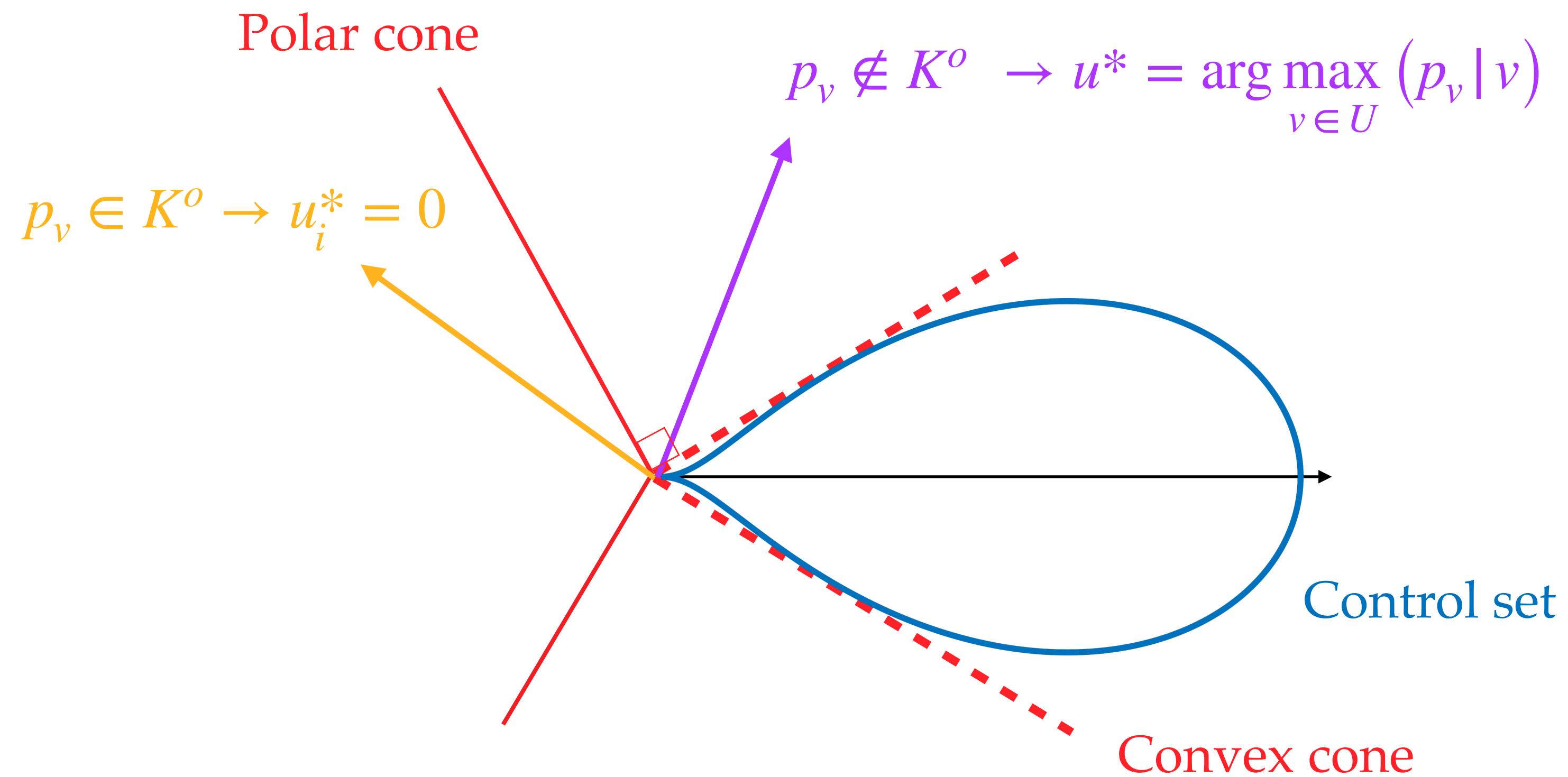
2. Hamiltonian dynamics and PMP

$$H = p_0 + p_r \dot{r} + p_v \dot{v} = p_0 + p_r v + p_v f(r, v) + p_v \varepsilon \tau u_{SRP}$$

$$u_{SRP}^* = \arg \max_{v \in U} H = \arg \max_{v \in U} (p_v | v_{SRP})$$

2. Geometric illustration of local maximisation in PMP

$$u_{SRP}^* = \arg \max_{v \in U} (p_v | v_{SRP})$$



2. Necessary conditions for optimality

Shooting function for a two-point boundary value problem

find $y = (t_f, p_r(t_0), p_v(t_0), p_s(t_0))$ such that

$$r(t_f) = r(t_0), \quad v(t_f) = v(t_0)$$

$$\|p(t_0)\| = 1$$

$$(s_{min} - s(t_f)) \leq 0, \quad p_s(t_f) \geq 0$$

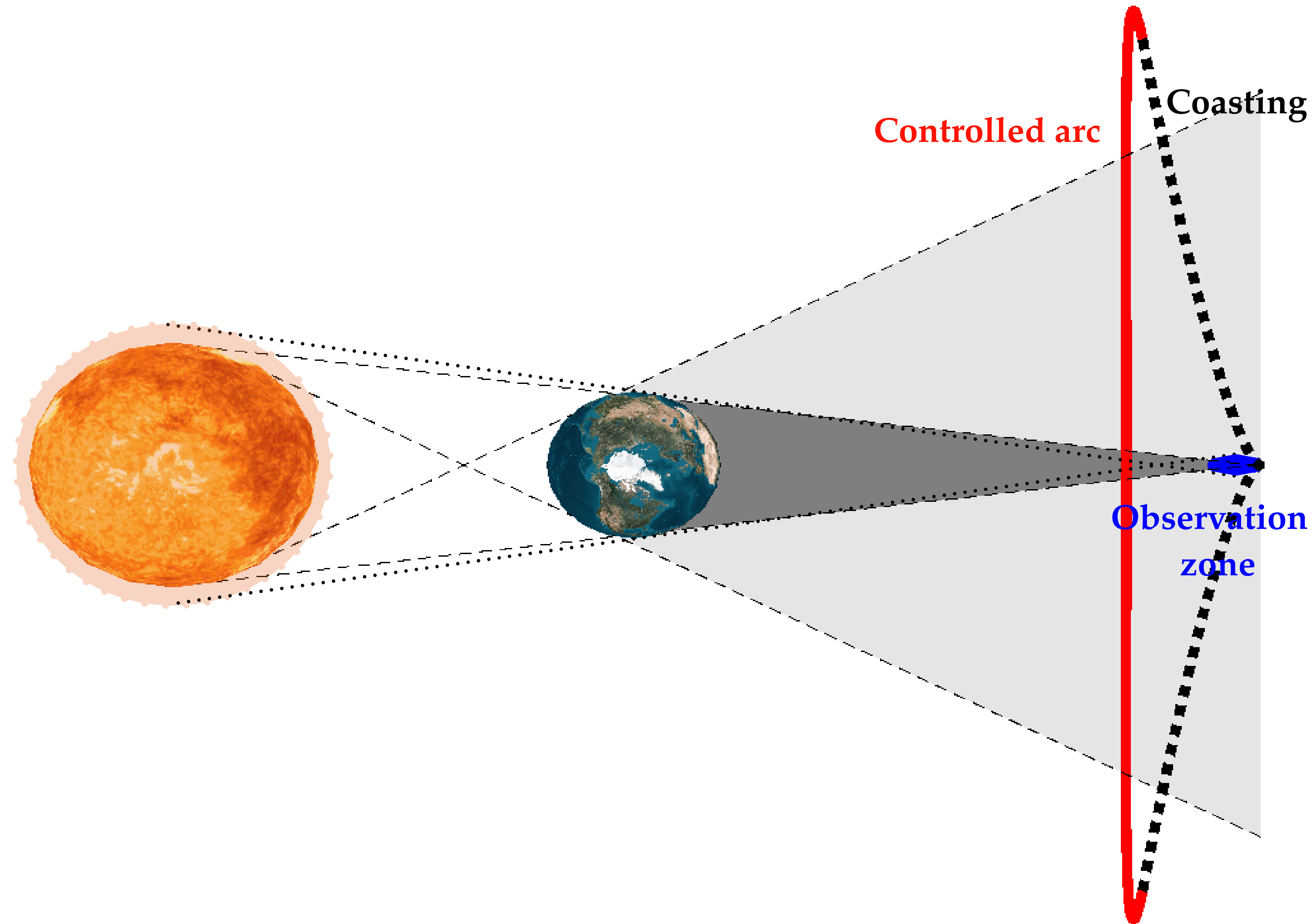
$$p_s(t_f) \cdot (s_{min} - s(t_f)) = 0$$

3. Initial conditions and constraints

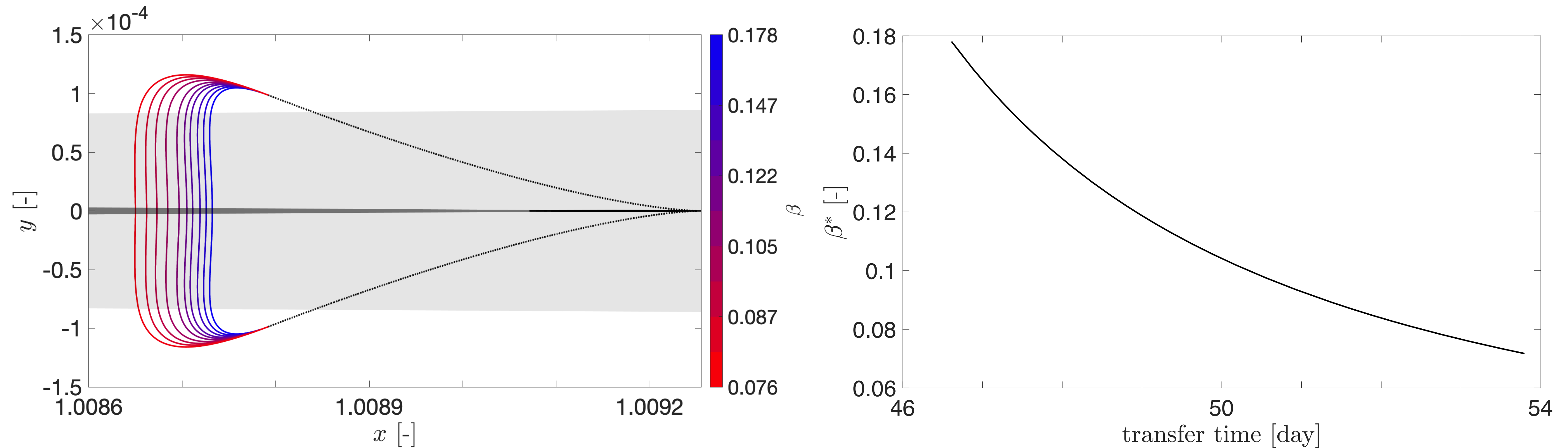
Initial guess: ideal sail

Homotopy: realistic size,
non-ideal sails

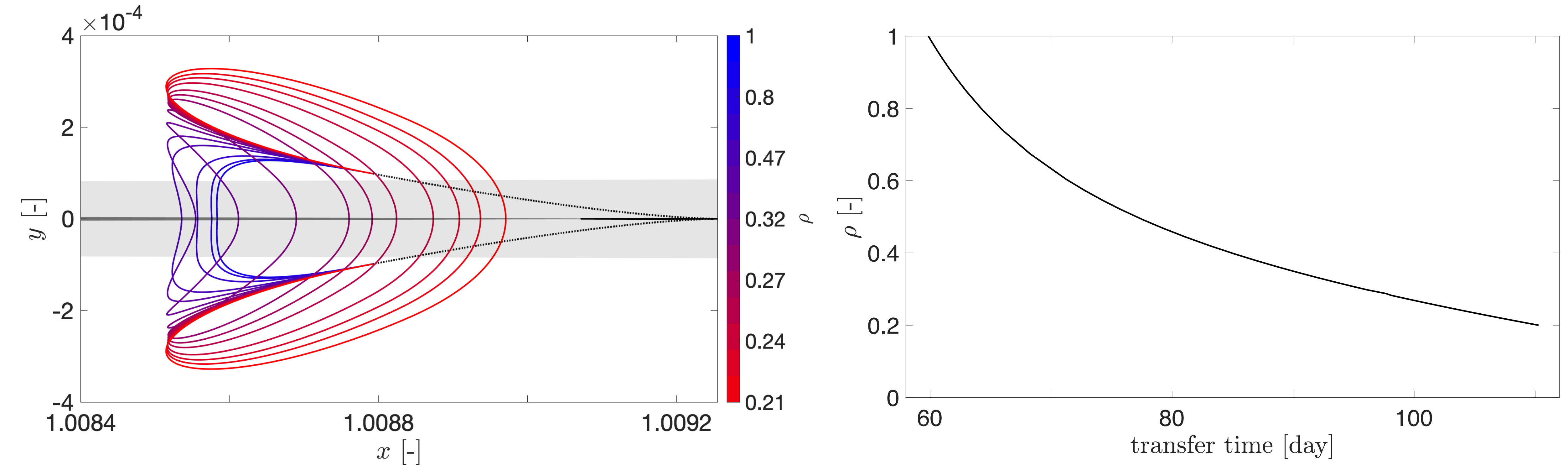
Resolution using Hampath



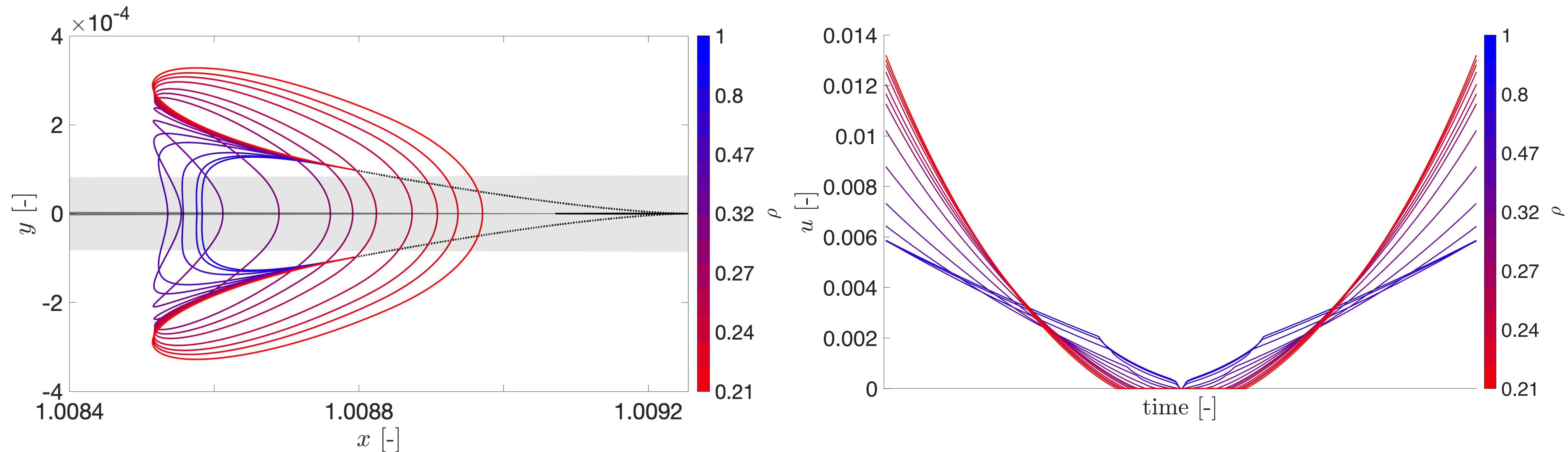
3. Results for a real-size ideal solar sail



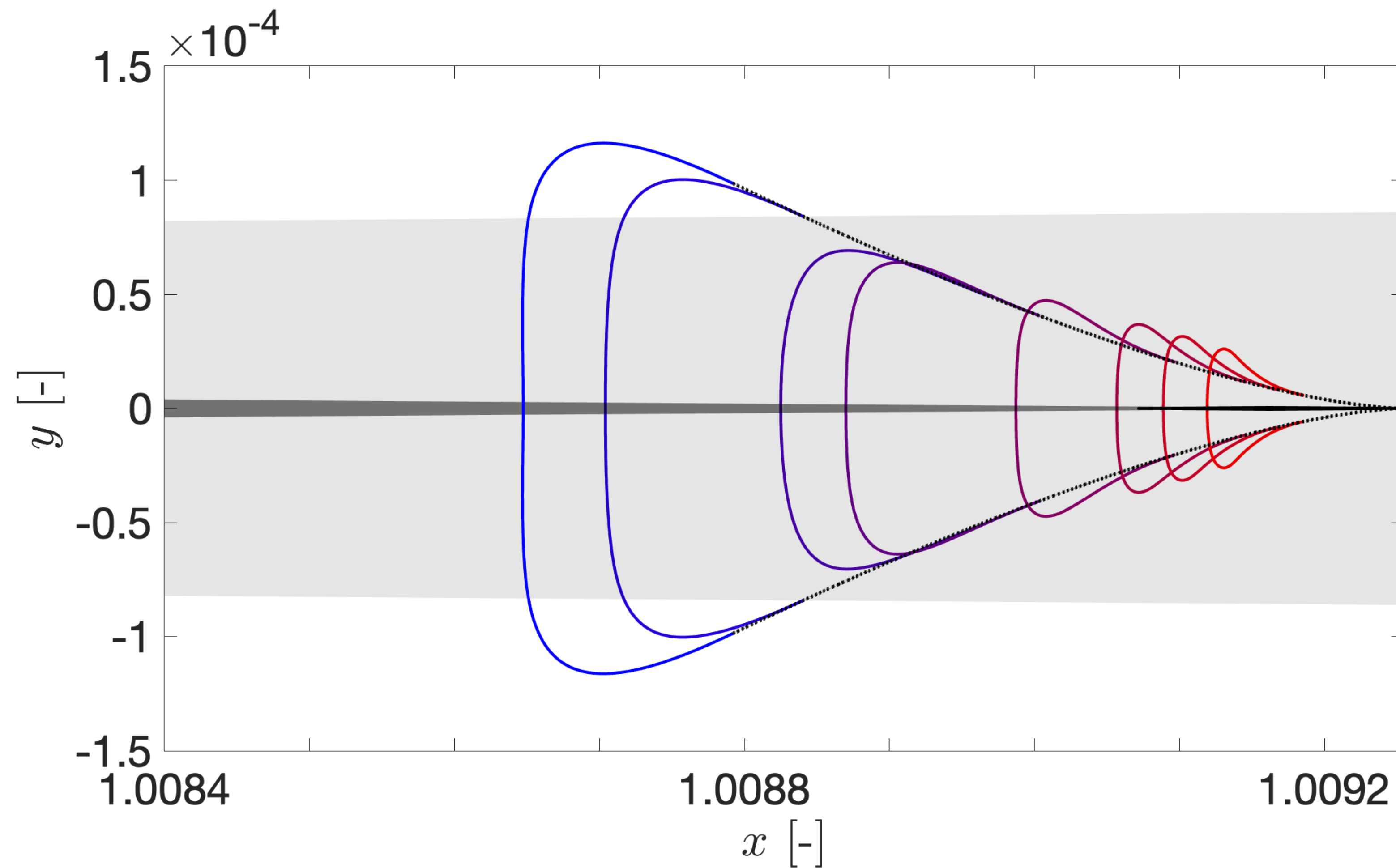
3. Results for a real-size non-ideal sail



3. Results for a real-size non-ideal sail

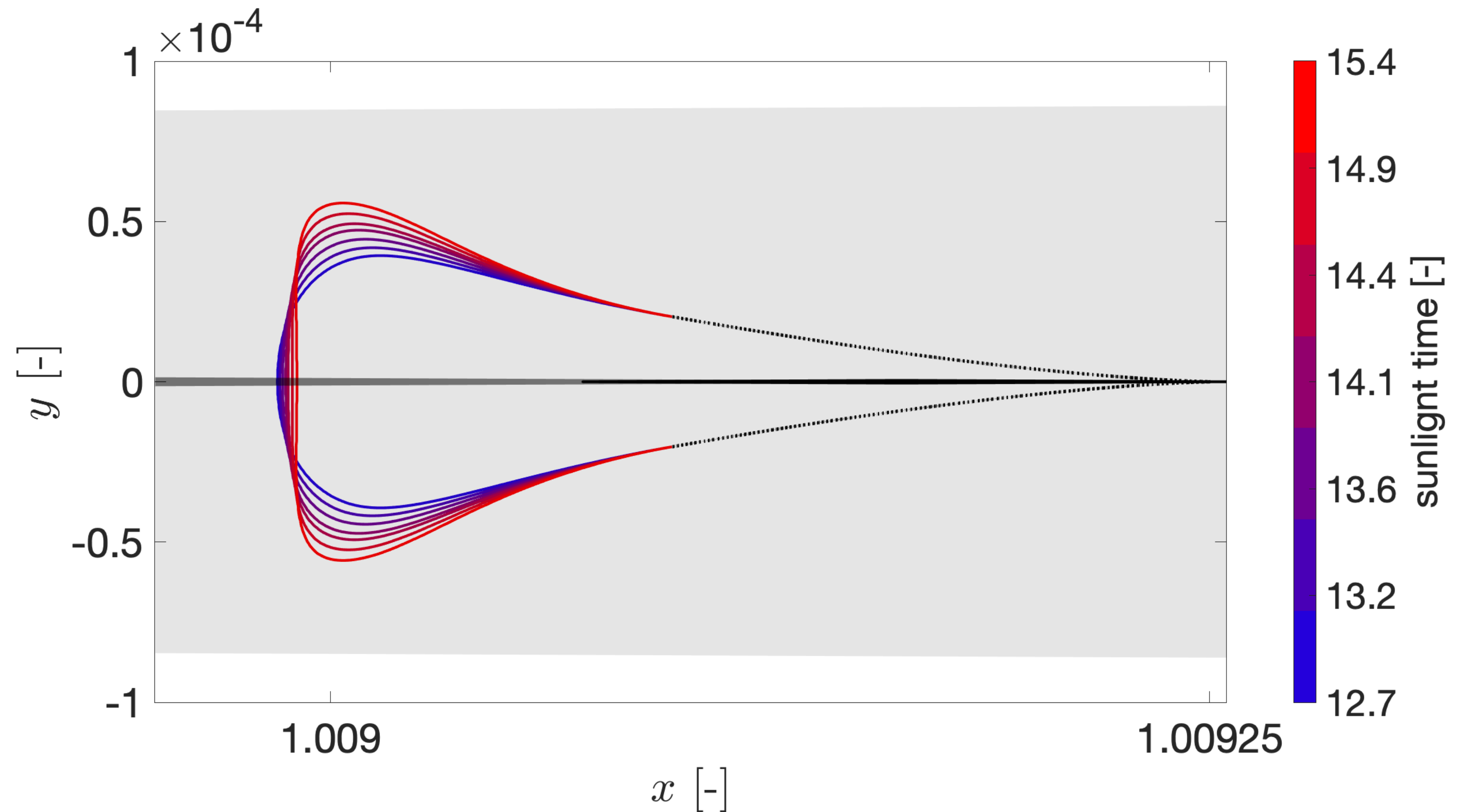


3. Results for different boundary conditions



3. Results for time of sun exposition

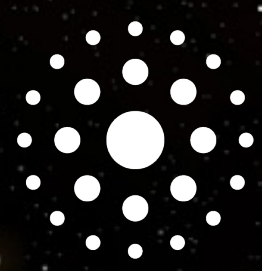
$$s = \int_{t_0}^{t_f} \tau dt$$



Conclusion

Feasibility of the concept: possible trajectories using real-size non ideal solar sail

Way forward: detailed temperature analysis, 3D trajectories



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