Celestial and Spaceflight Mechanics Laboratory

Low-Thrust Trajectory Optimization for Maximum Missed Thrust Recovery Margin

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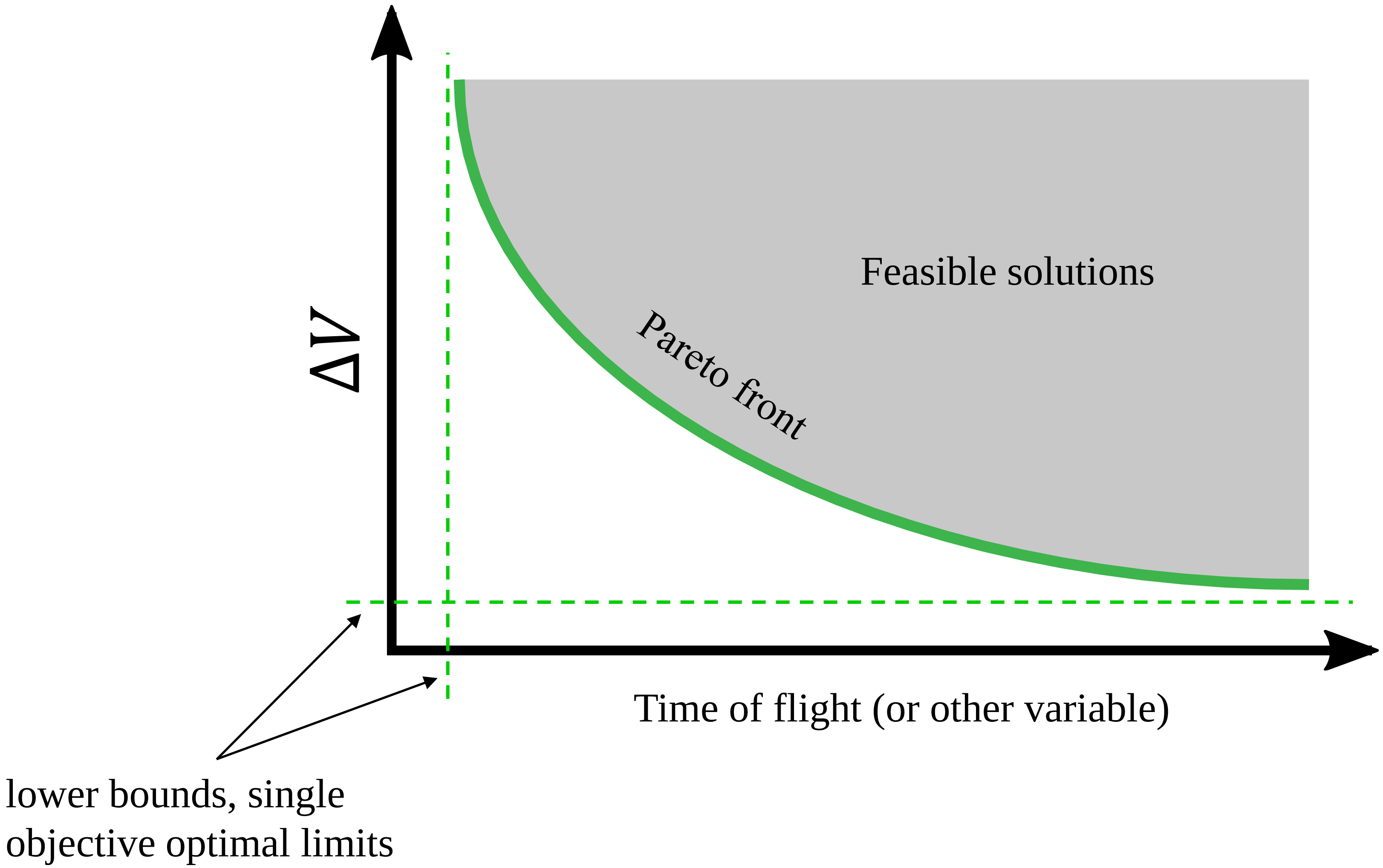
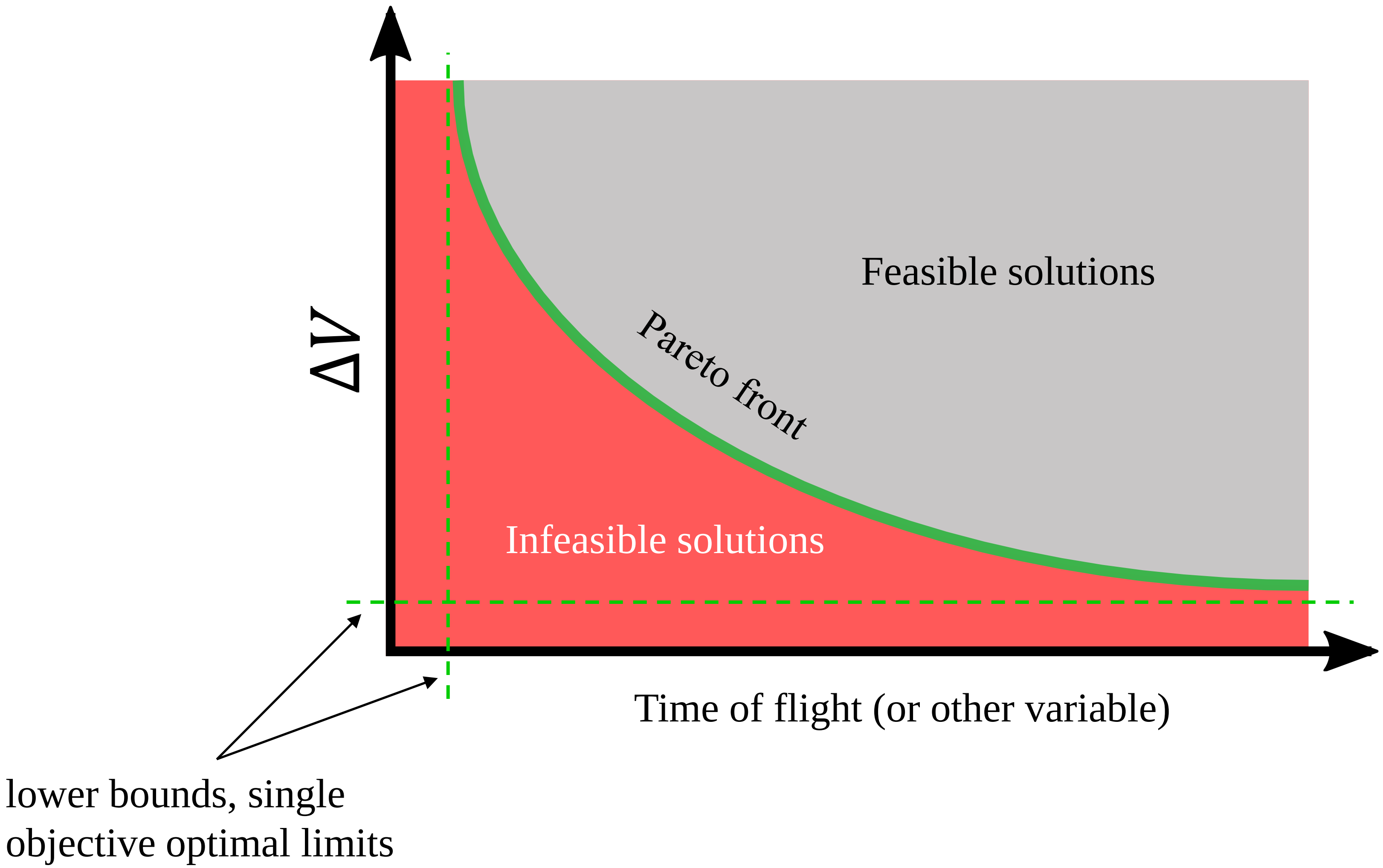
Motivation

Motivation: Multi-Objective Optimization



Motivation: Multi-Objective Optimization



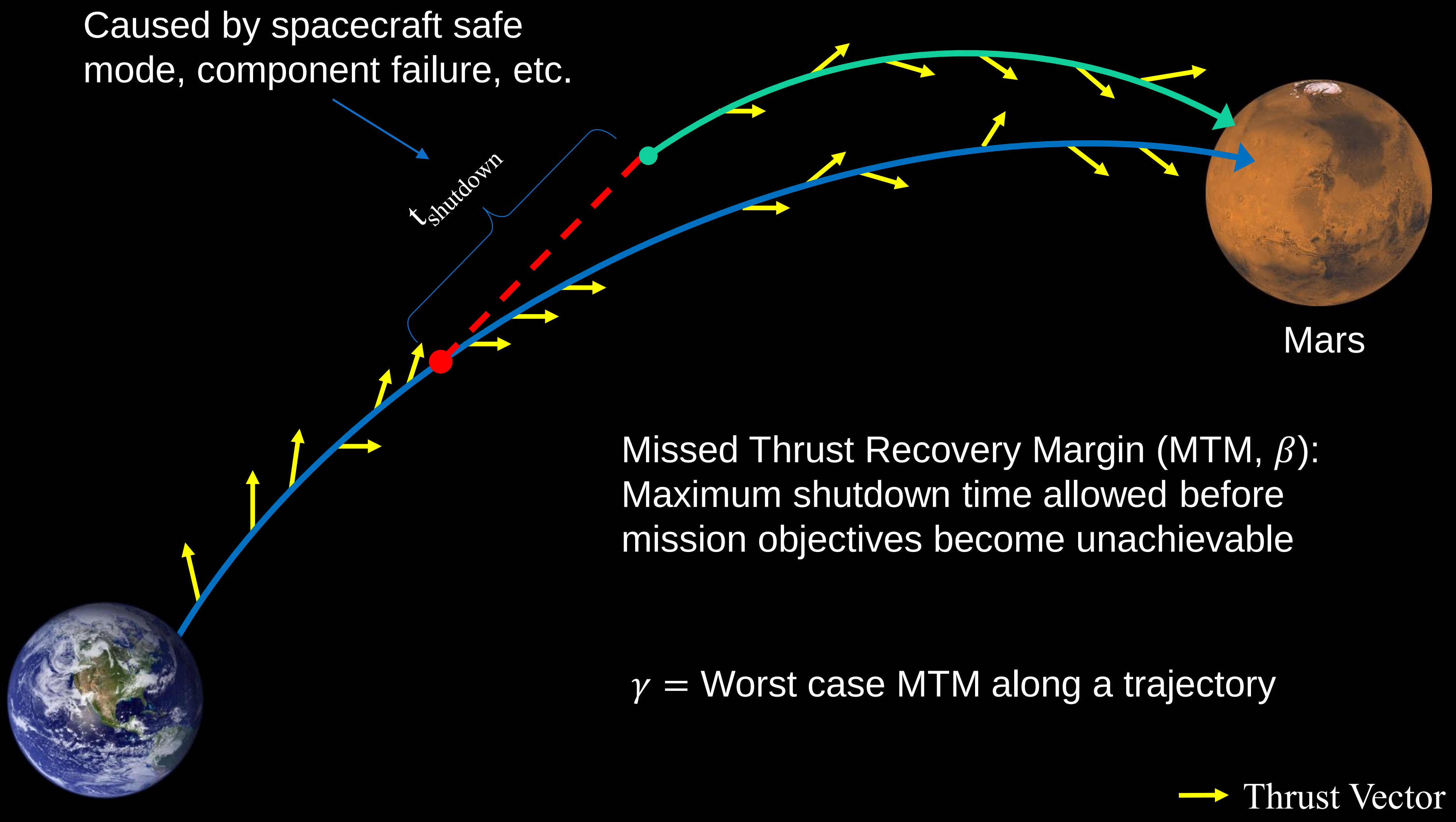
Low-Thrust Trajectory Optimization Objectives

Delivered mass/propellant mass

Time of flight

Missed thrust recovery margin

Missed Thrust Recovery Margin



Missed Thrust Recovery Margin (MTM, β): Maximum shutdown time allowed before mission objectives become unachievable

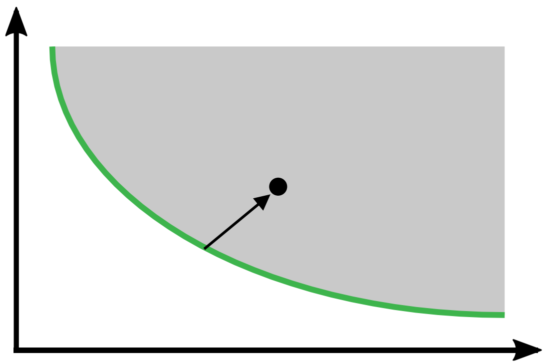
γ = Worst case MTM along a trajectory

State of the Art (simplified)

1. Find optimal trajectory for maximum delivered mass or other objective
2. Evaluate trajectory for "weakest" point MTM value γ (lowest MTM)

3a. If "weakest point" is unacceptable, modify the nominal

- Enforce coast (zero thrust) at weakest point, re-optimize
- Enforce "rolling coast"
- Modify maximum thrust levels
- Bias nominal arrival date to be earlier
- Etc.



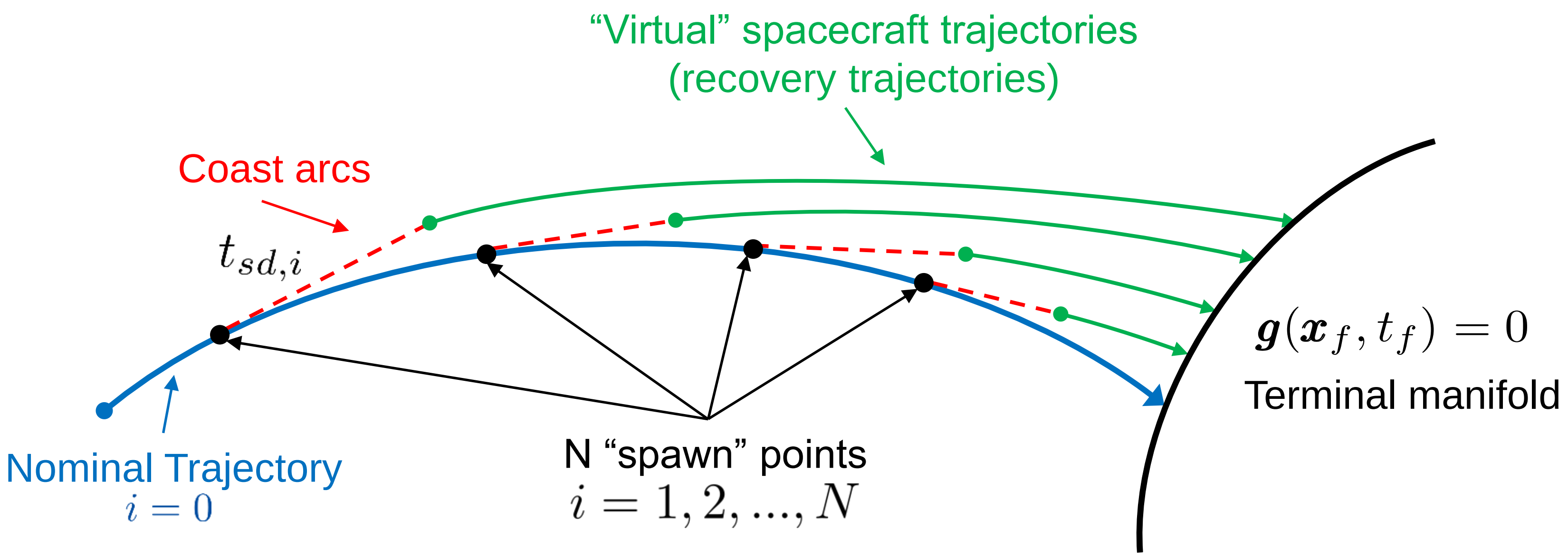
Pareto front

3b. AND/OR carry more reserve fuel, increase time of flight

Problem: Cannot directly optimize or constrain MTM at each point along the trajectory

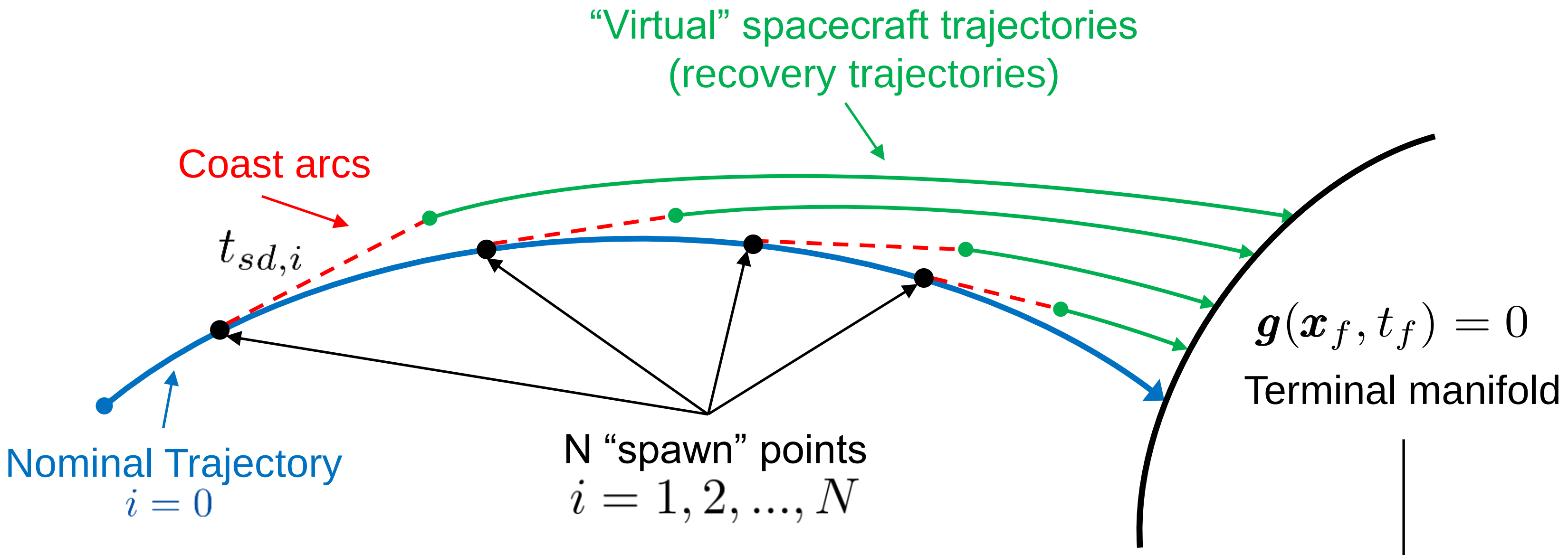
“Virtual Swarm” Method

Virtual Swarm Method



- MTM is controlled at discrete points where virtual spacecraft are spawned
- Virtual spacecraft decision variables and control profiles are independent of the nominal once spawned
- If the number and placement of virtual spacecraft is insufficient, $t_{sd,min} \neq \gamma$ (worst case MTM is not controlled)

Virtual Swarm Method: Optimize Robustness



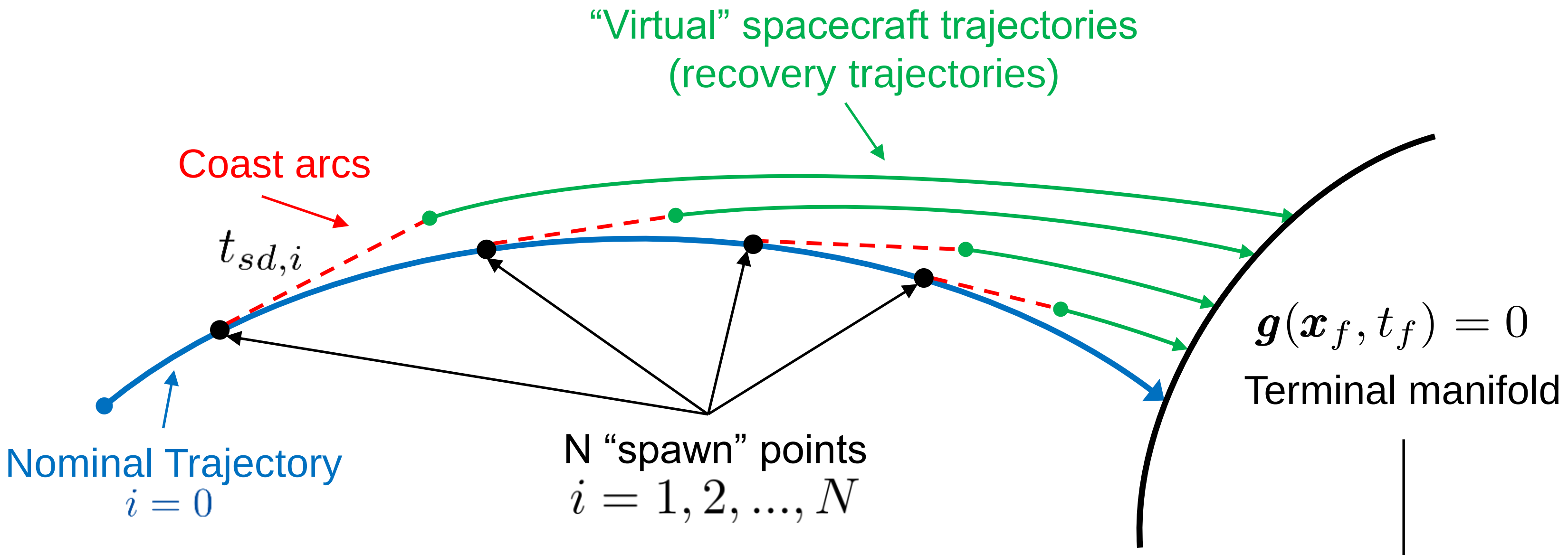
Maximize forced shutdown lower bound: $J = t_{sd,min}$

With Constraints: $t_{sd,i} \geq t_{sd,min} \quad i = 1, 2, ..., N$

$m_{f,i} \geq m_{f,min} \quad \forall i$

$t_{f,min} \leq t_{f,i} \leq t_{f,max} \quad \forall i$

Virtual Swarm Method: Constrain Robustness, Optimize Mass



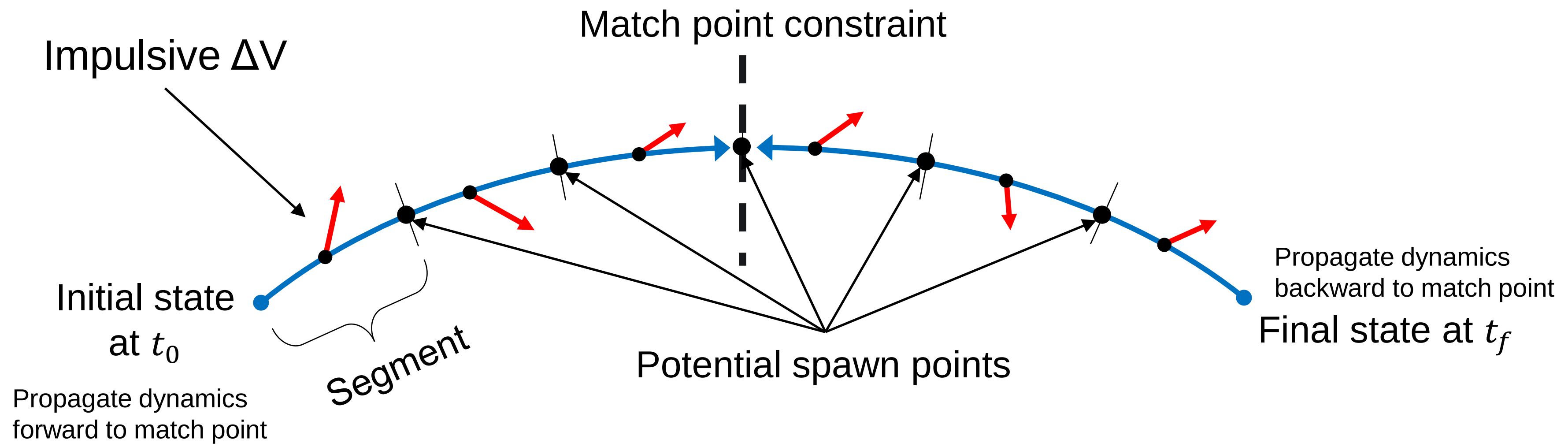
Maximize delivered mass lower bound: $J = m_{f,min}$

With Constraints: $t_{sd,i} = \gamma_{min} \quad i = 1, 2, \ldots, N$

$m_{f,i} \geq m_{f,min} \quad \forall i$

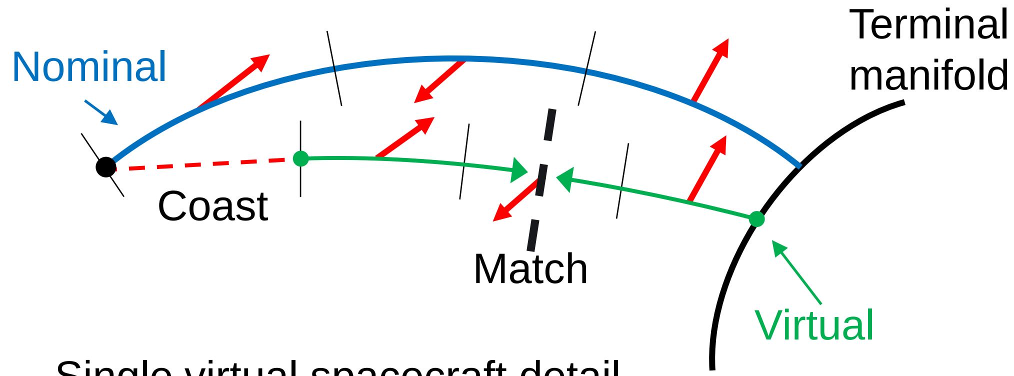
$t_{f,min} \leq t_{f,i} \leq t_{f,max} \quad \forall i$

Transcription (Sims-Flanagan)



Decision Variables (Robust-Constrained):

- All spacecraft (N+1):
  - Each impulse magnitude & direction
  - Time of flight
  - Final mass
- Minimum delivered mass constraint



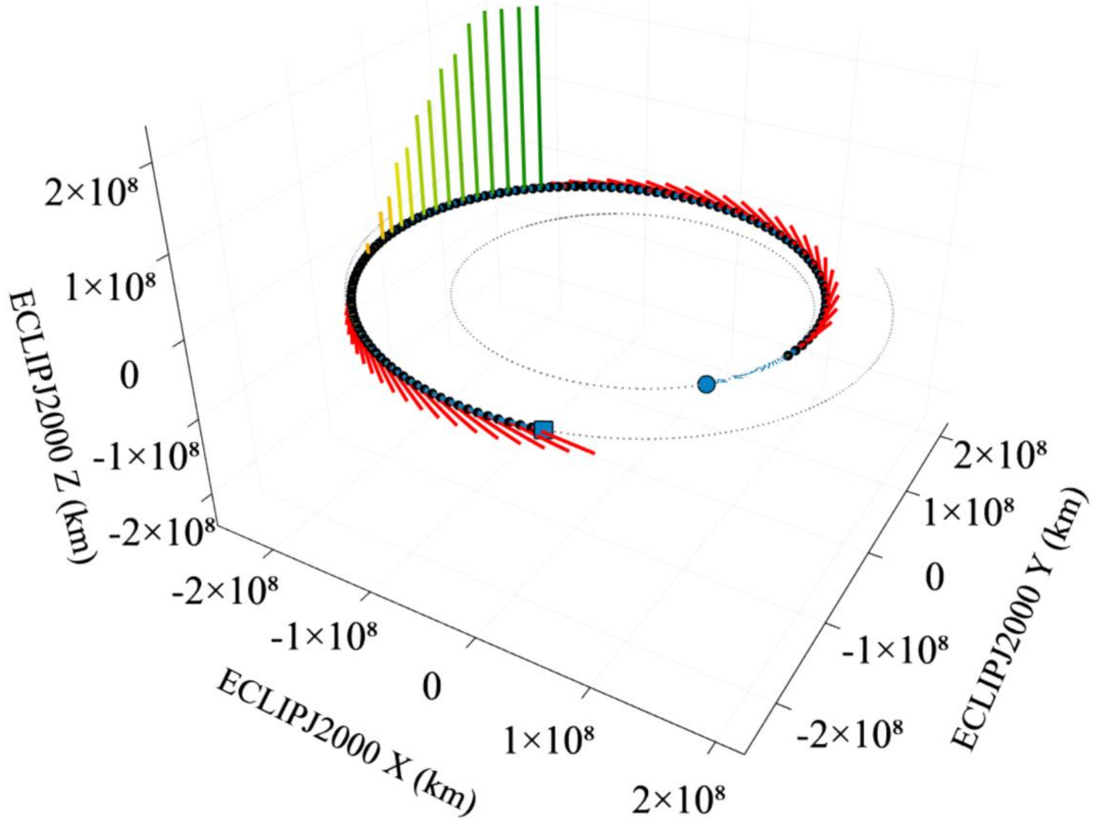
Single virtual spacecraft detail

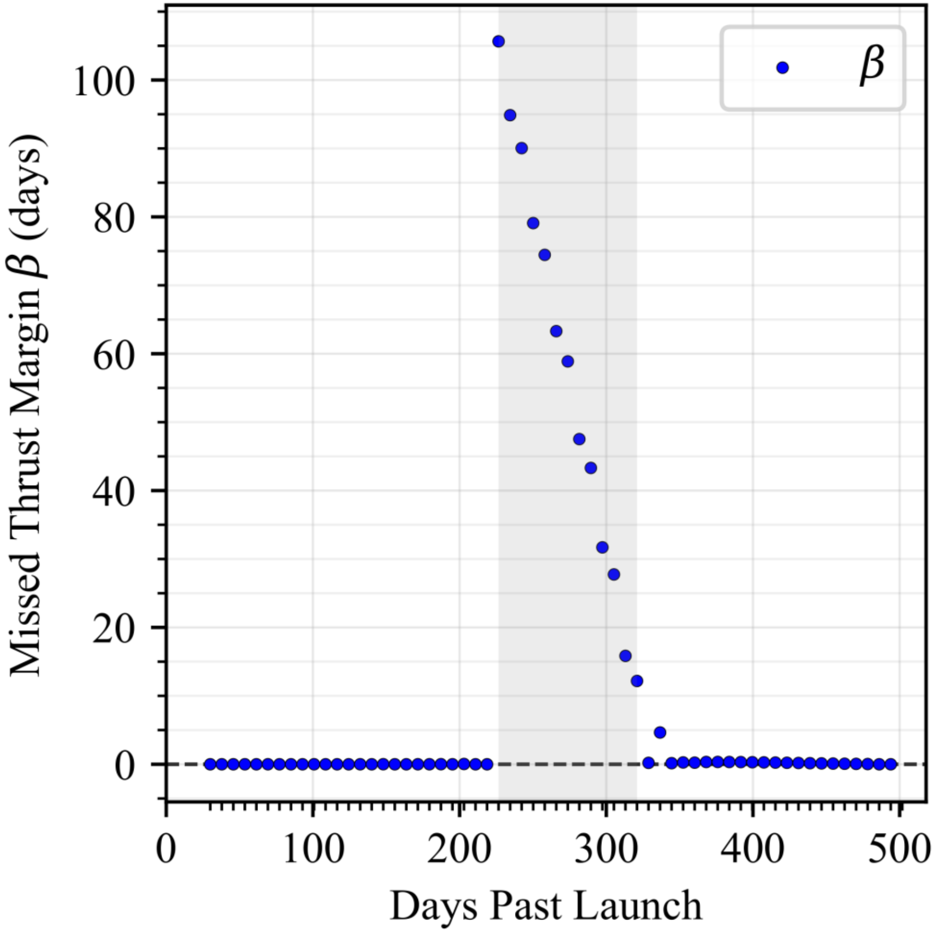
Implementation: N Spacecraft Trajectory Optimizer (NSTOP)

- SNOPT used as backend NLP solver
- Monotonic basin hopping is used to converge on solutions with poor initial guesses
- Written entirely in the Julia programming language
- Automatic differentiation used for machine precision derivatives
- Can handle arbitrary numbers of virtual spacecraft and number of phases (i.e. # of gravity assists)

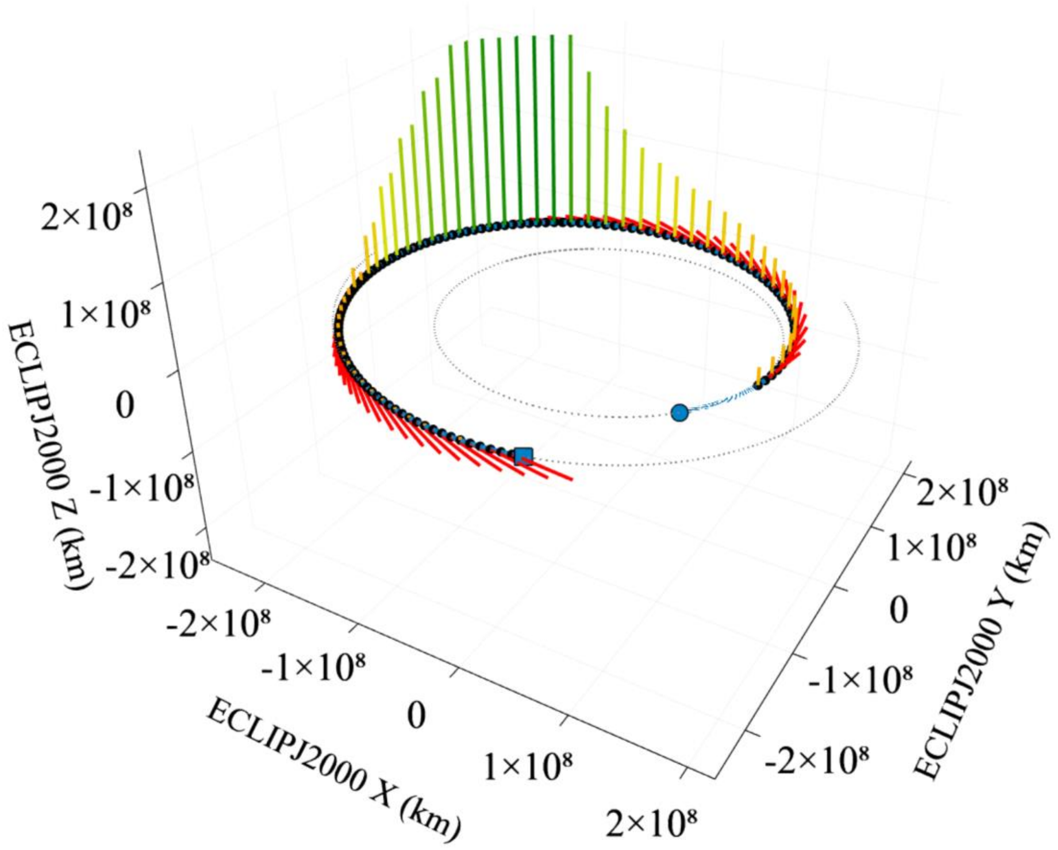
Examples

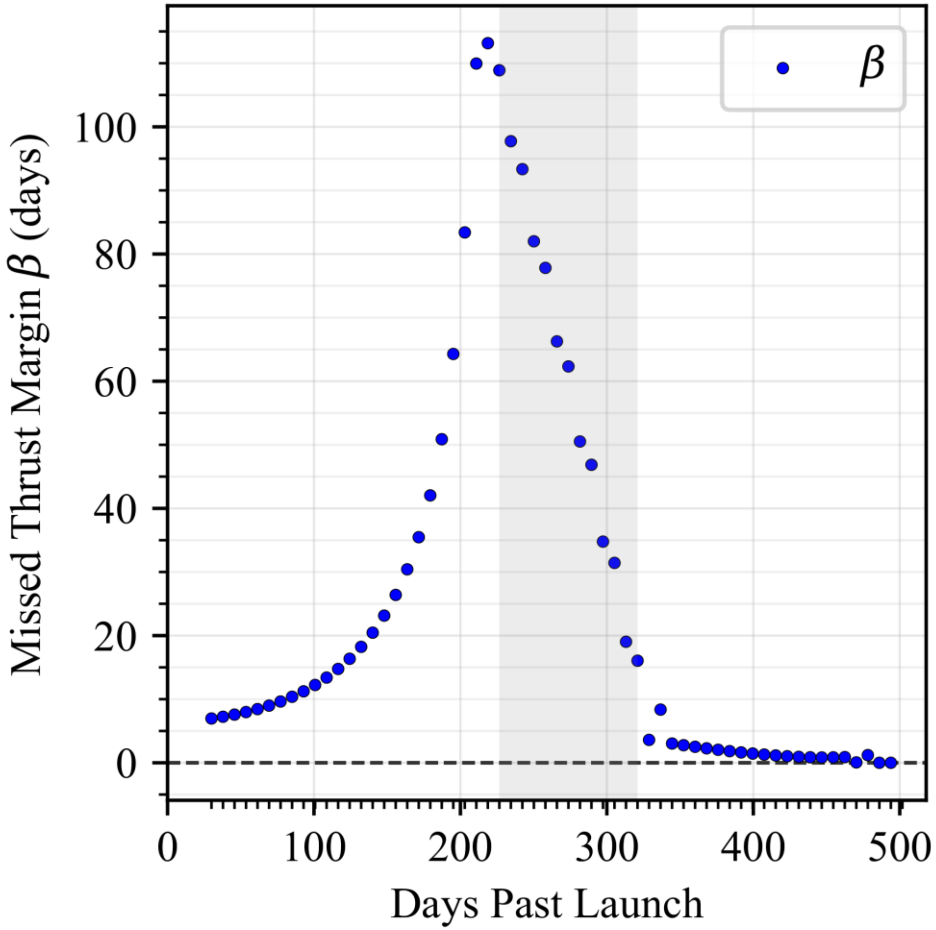
Mass Optimal Reference Trajectory: Non-Permissive Earth-Mars Transfer





Mass Optimal Reference Trajectory: Permissive (-30 kg) Earth-Mars Transfer

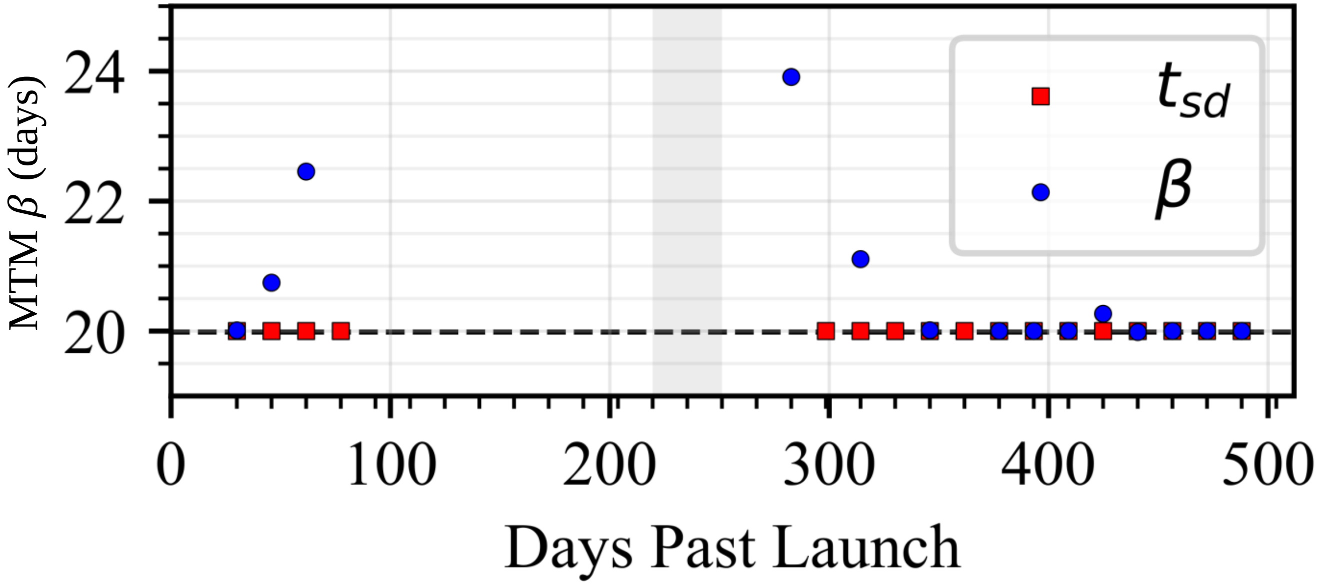




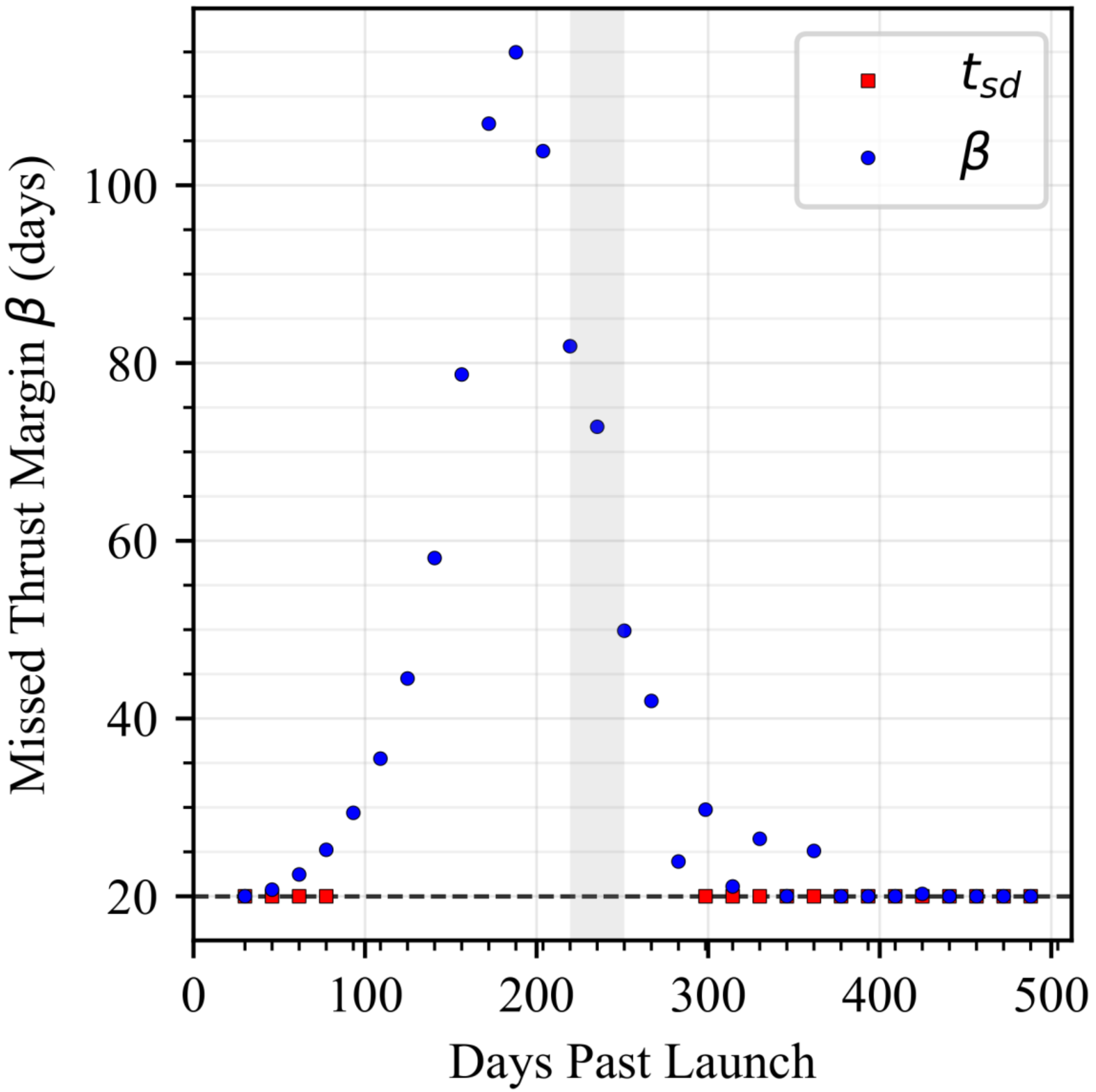
Robust-Constrained Earth-Mars Transfer

Robust constrained trajectory:

- 20 days “lateness”
- 10% propellant margin compared to mass-optimal reference



Detail view, β from 19 to 25 days



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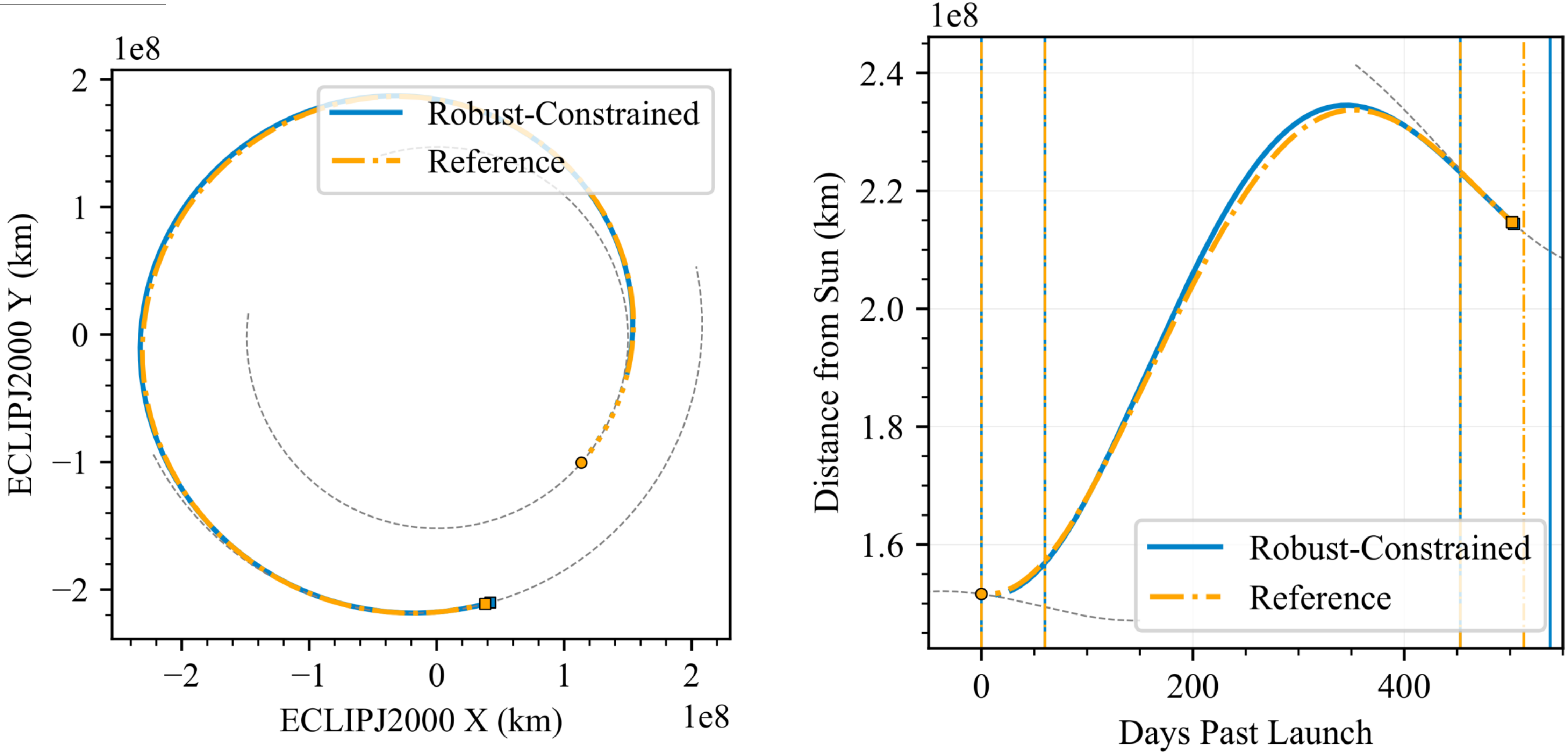

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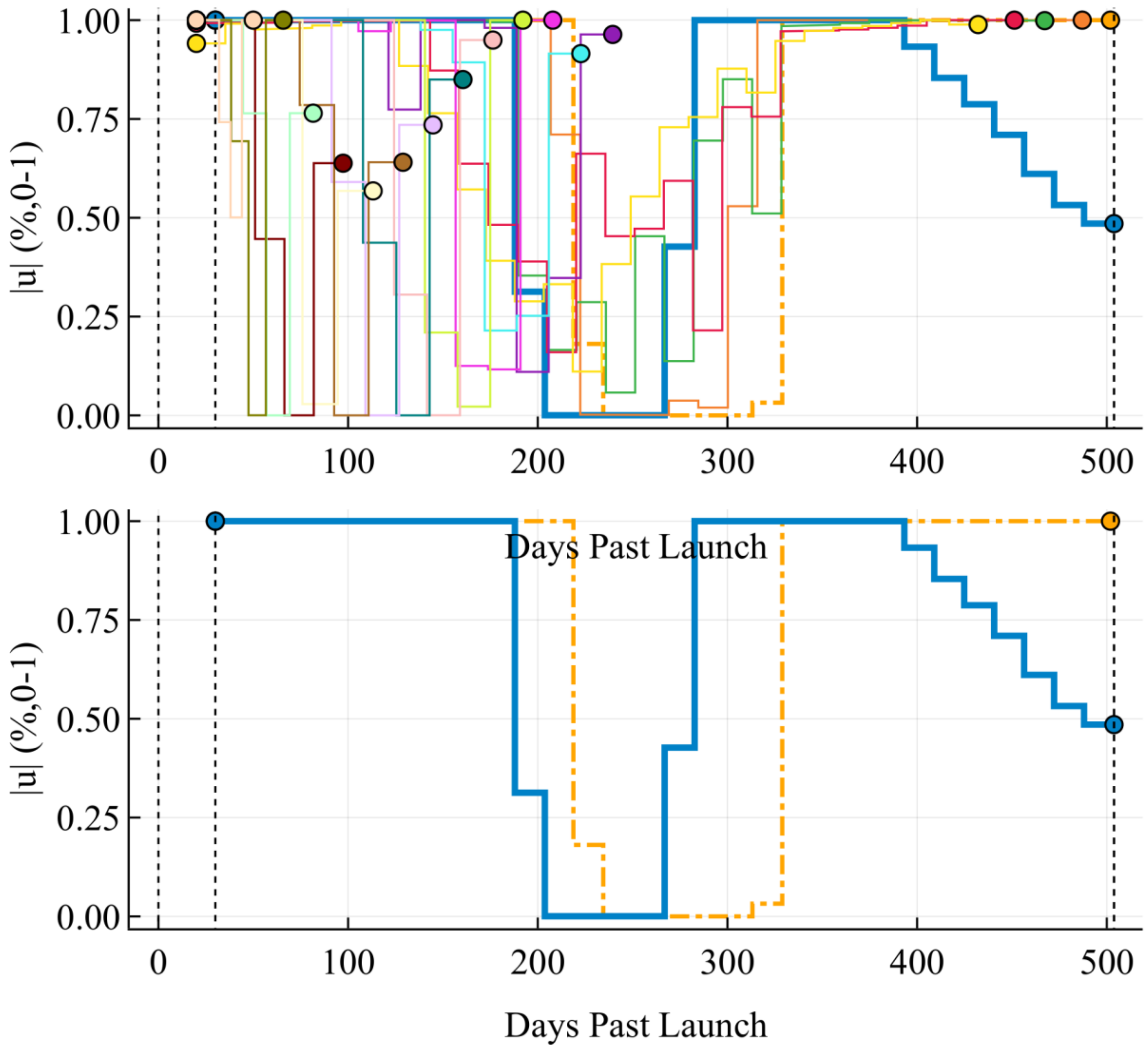
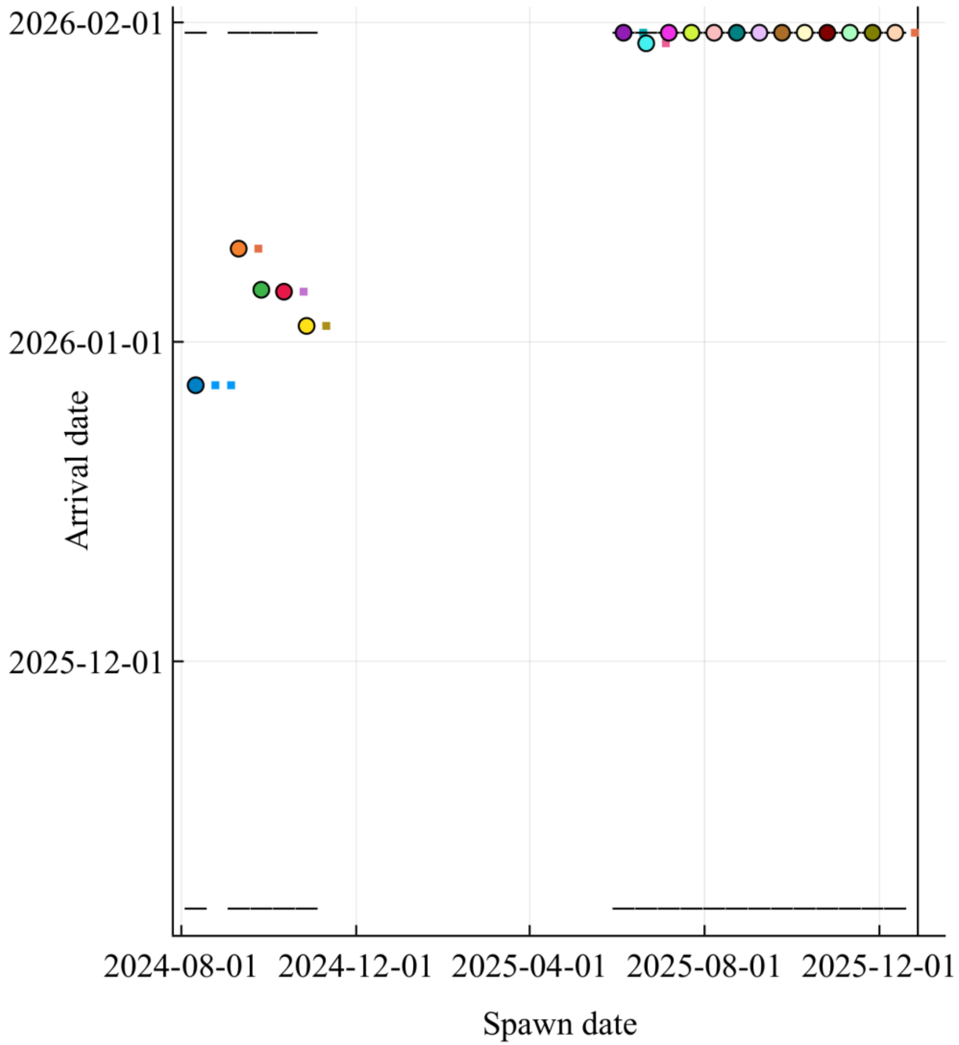
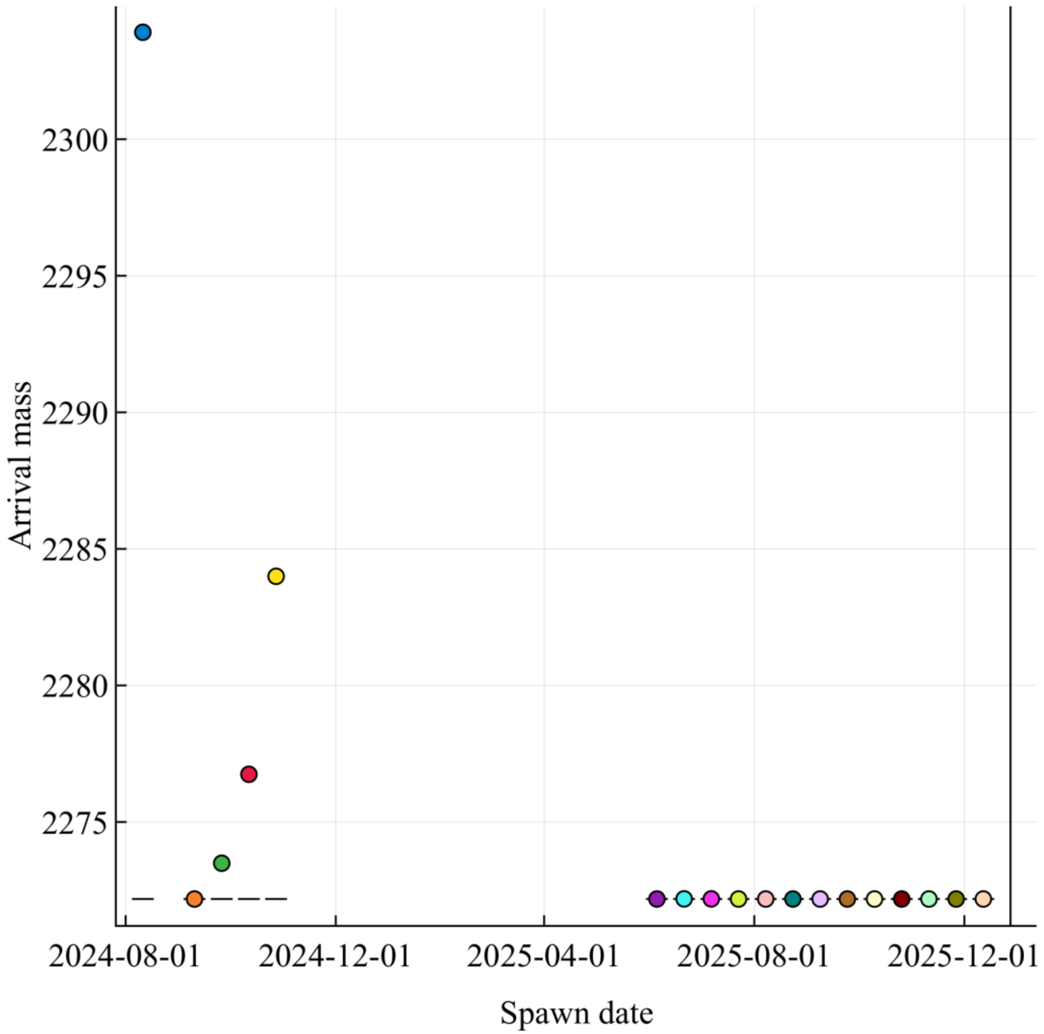


Swarm + reference control magnitude over time

Robust-constrained nominal (blue) + mass-optimal reference (orange, dashed)

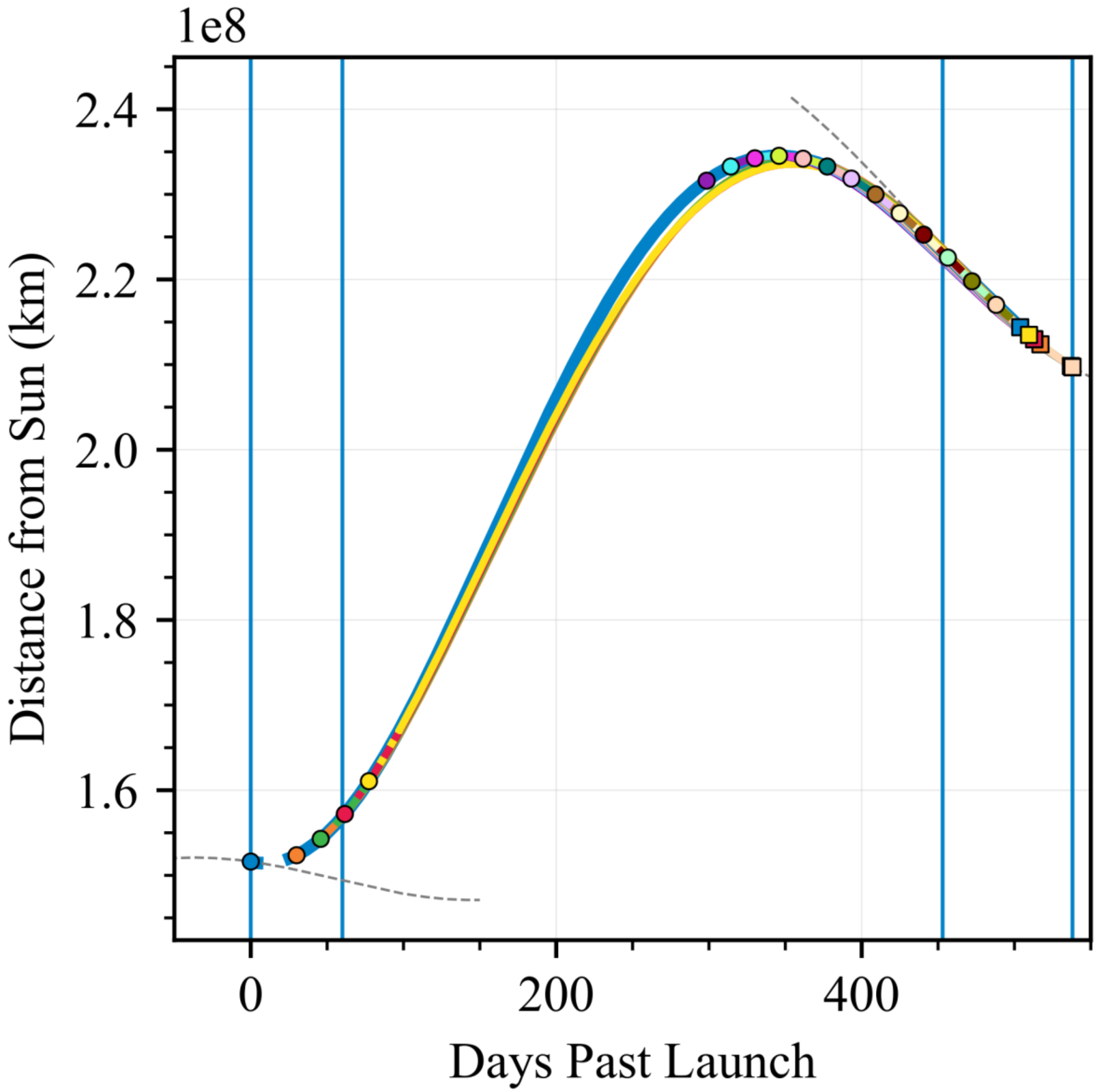
Robust-Constrained Earth-Mars Transfer





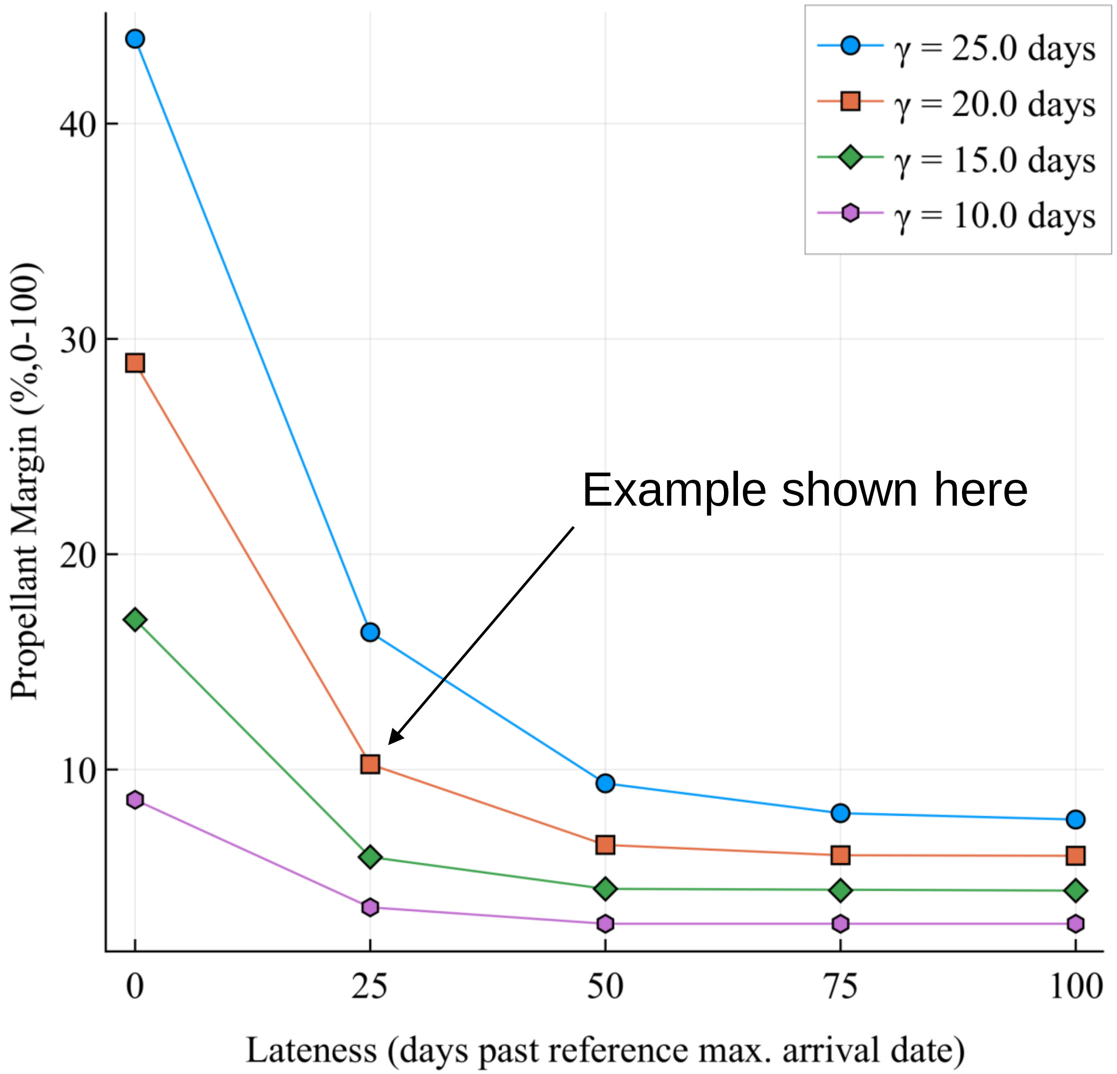
Robust-Constrained Earth-Mars Transfer

Swarm flow



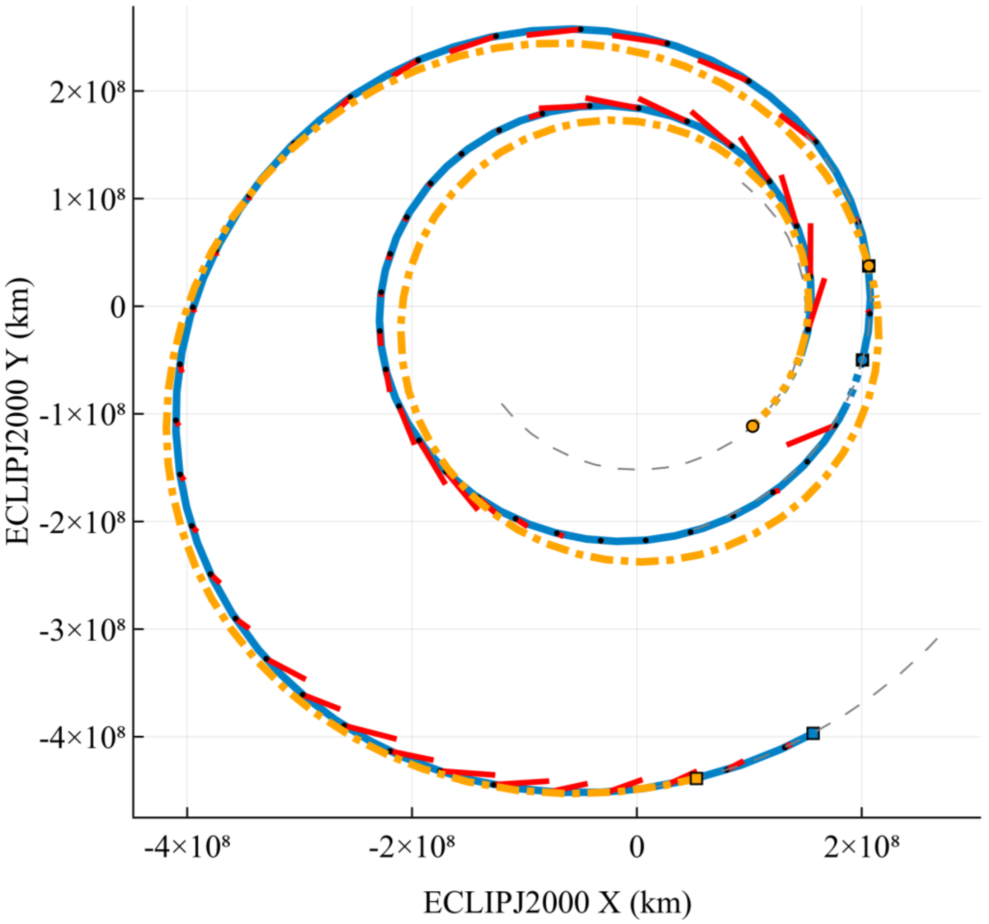
Earth-Mars Transfer Pareto Front

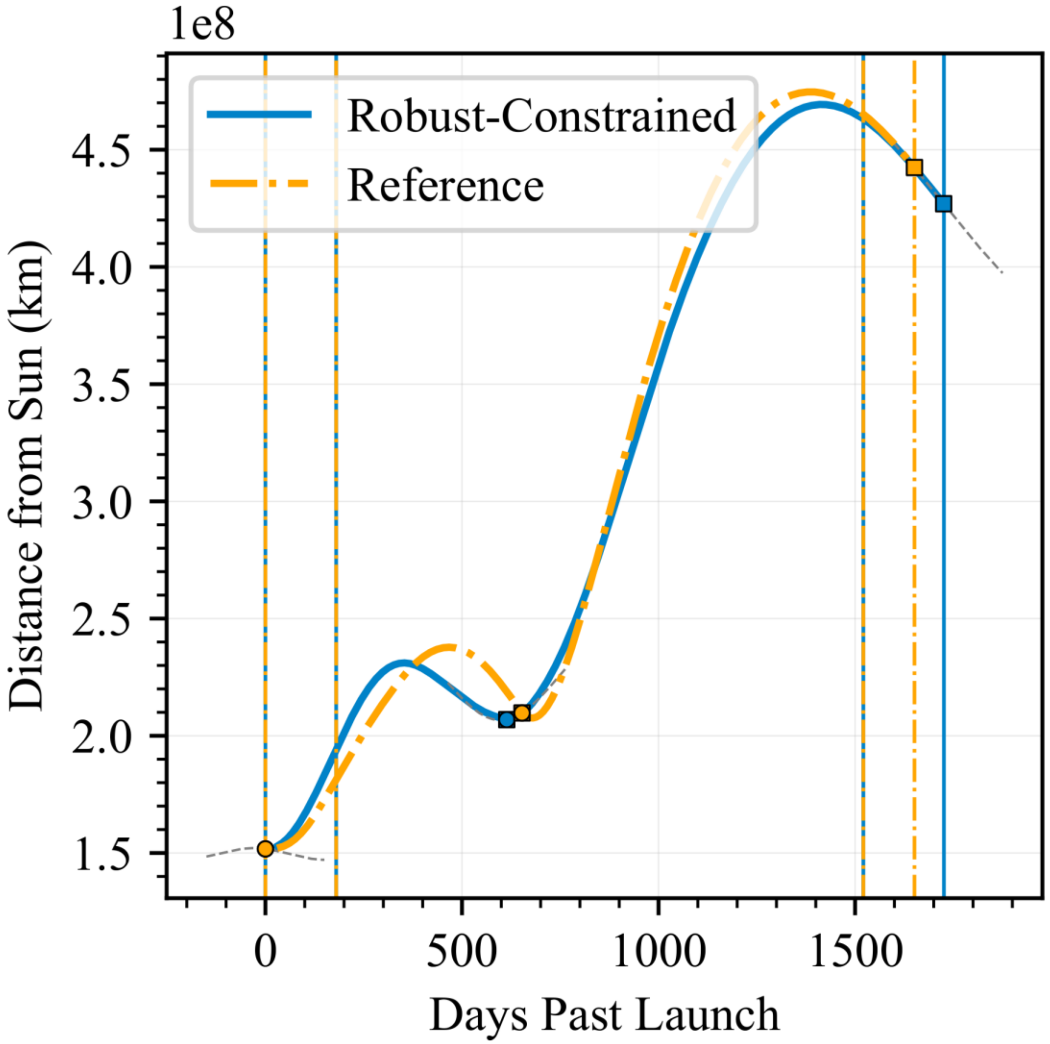
γ = Worst case MTM along a trajectory



Robust Constrained Earth-Mars-Psyche Transfer

75 days "lateness"
24% propellant margin compared to mass-optimal reference





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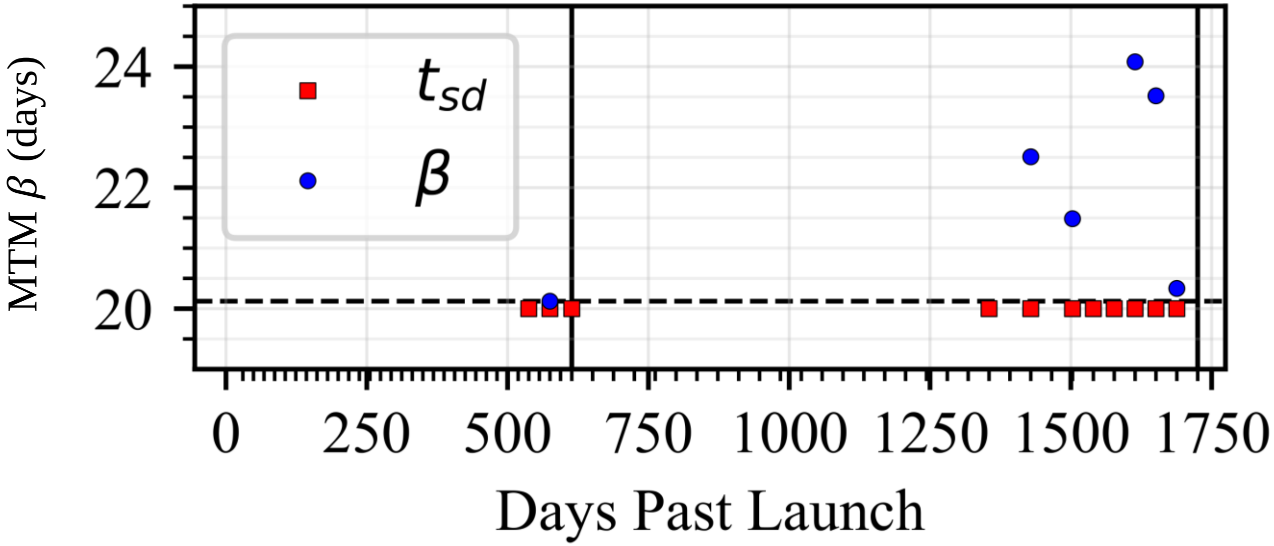

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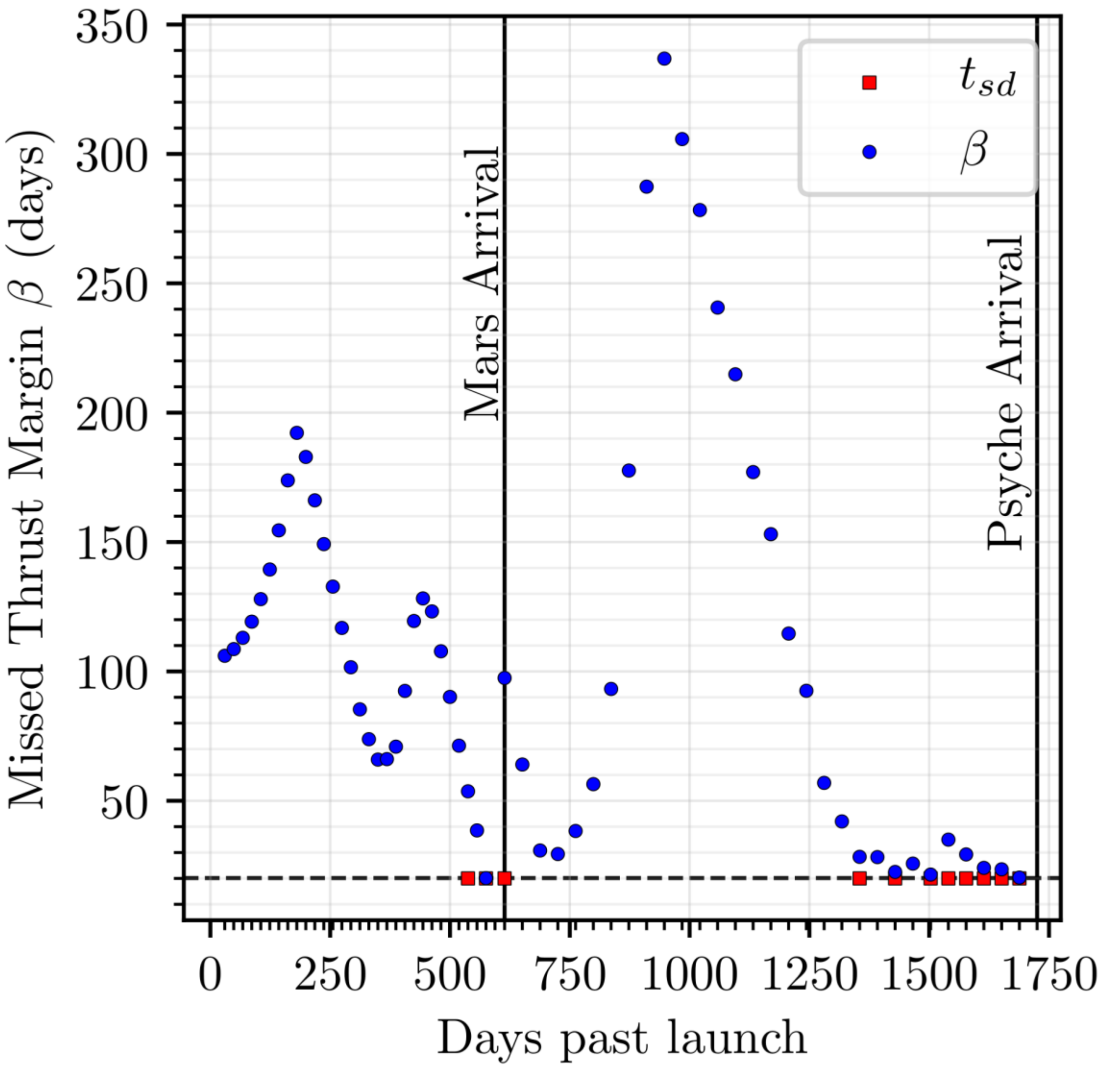

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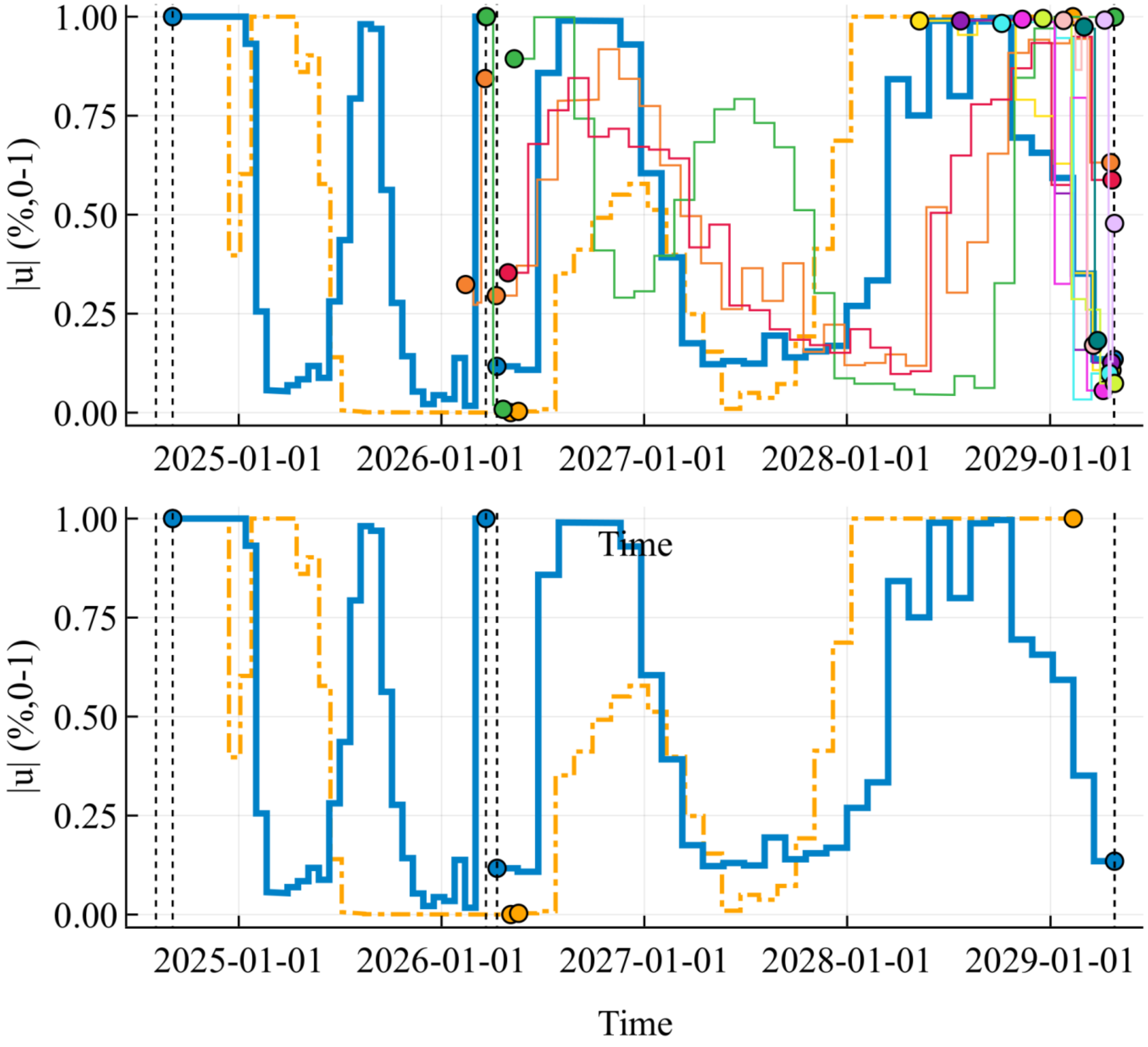

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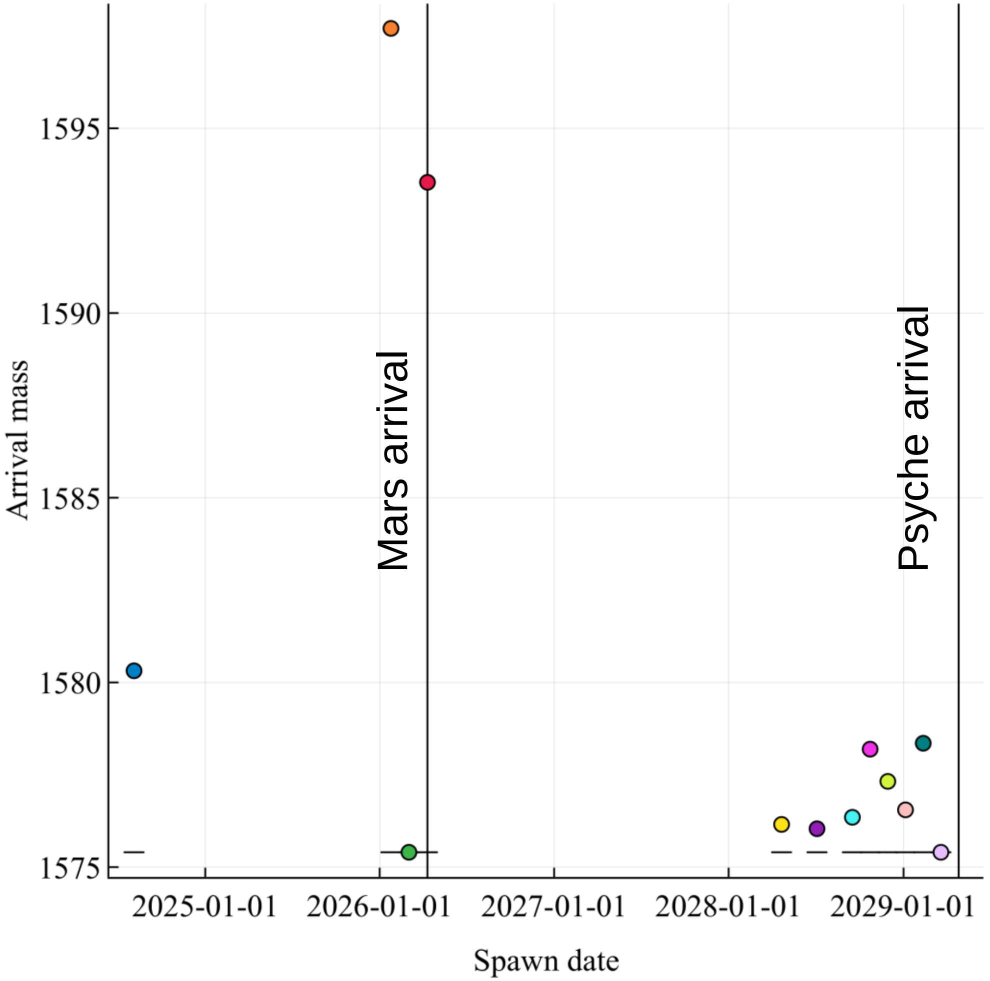

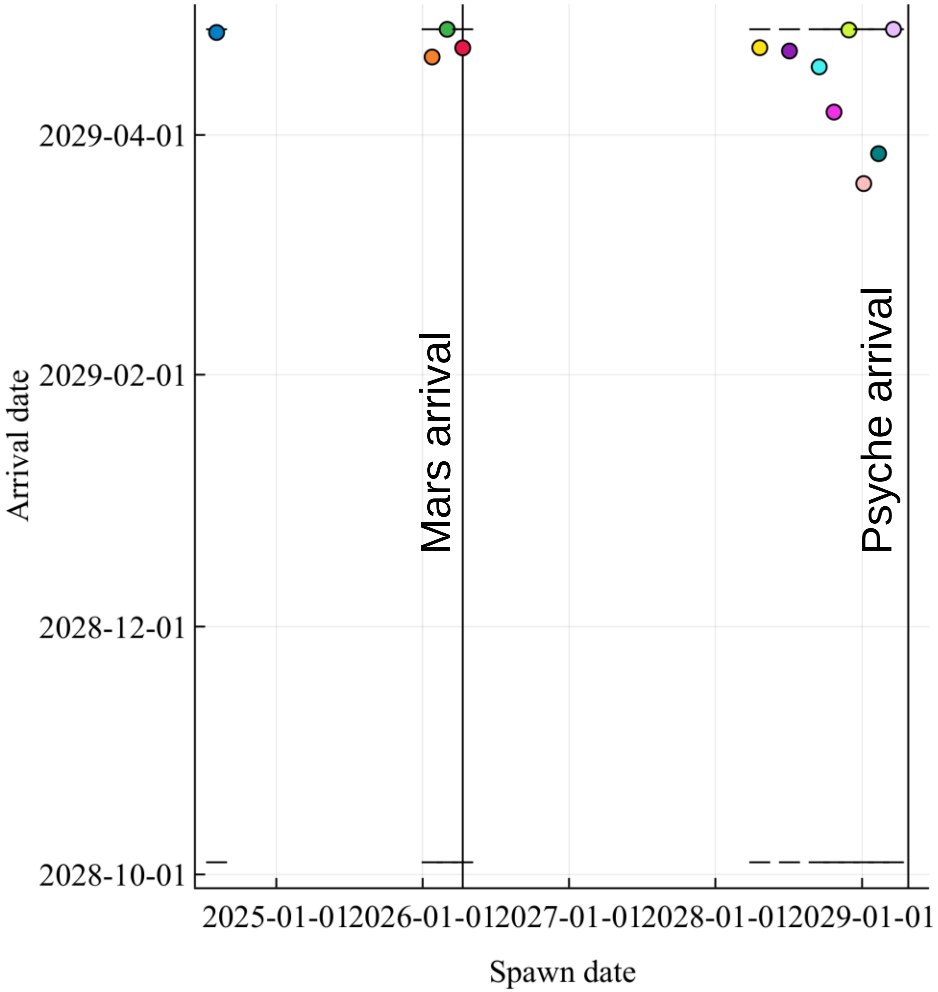

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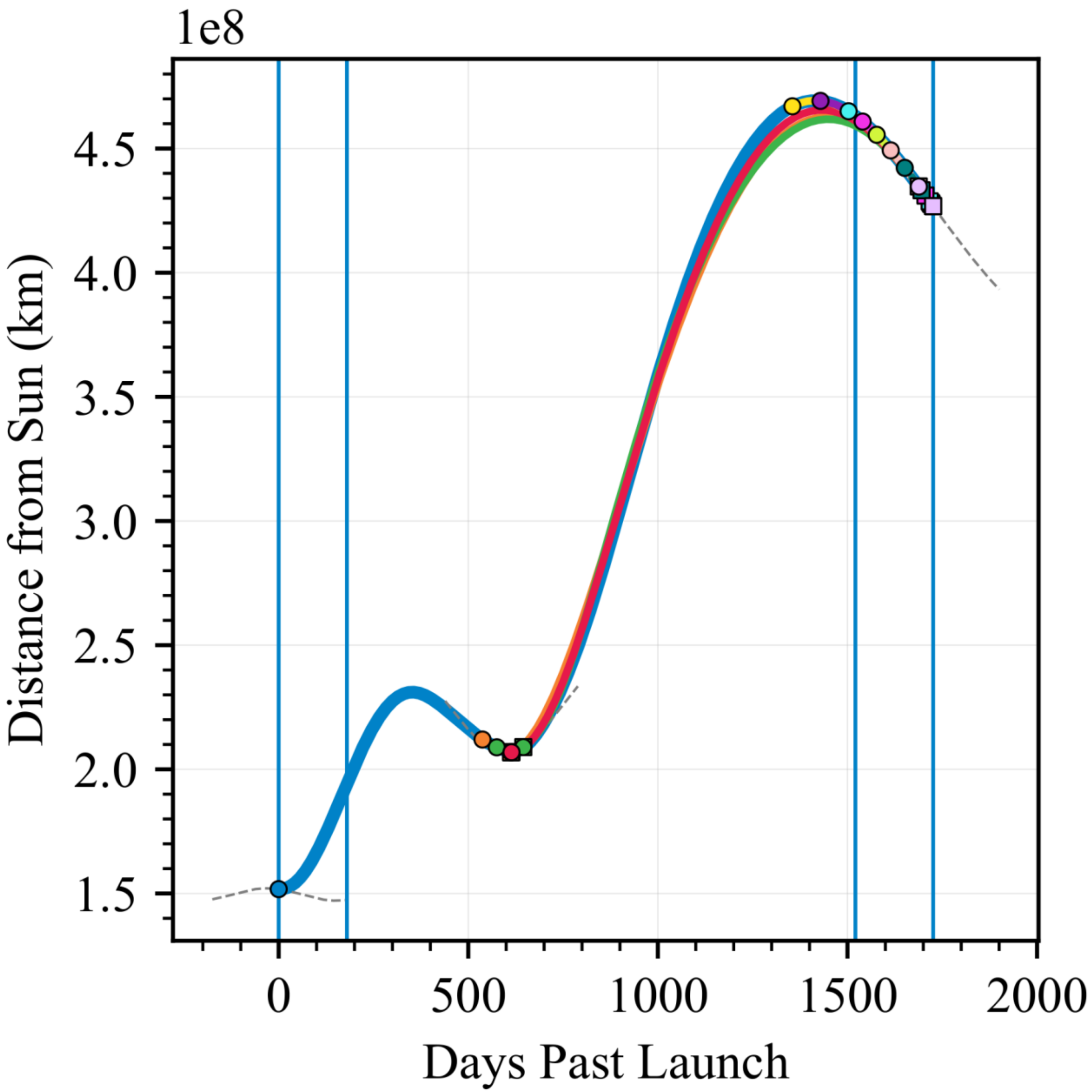
Swarm flow



Conclusions

- Virtual swarm technique: deterministic method to efficiently optimize low-thrust trajectories with consideration for robustness to missed thrust events
- Method reshapes a nominal trajectory to account for robustness constraints or objectives
- Method enables automated trade space exploration for multiple objectives

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