GTOC 12: Sustainable Asteroid Mining
Approach of the OptimiCS team

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Speakers: Vincent Debout, Sébastien Goulet

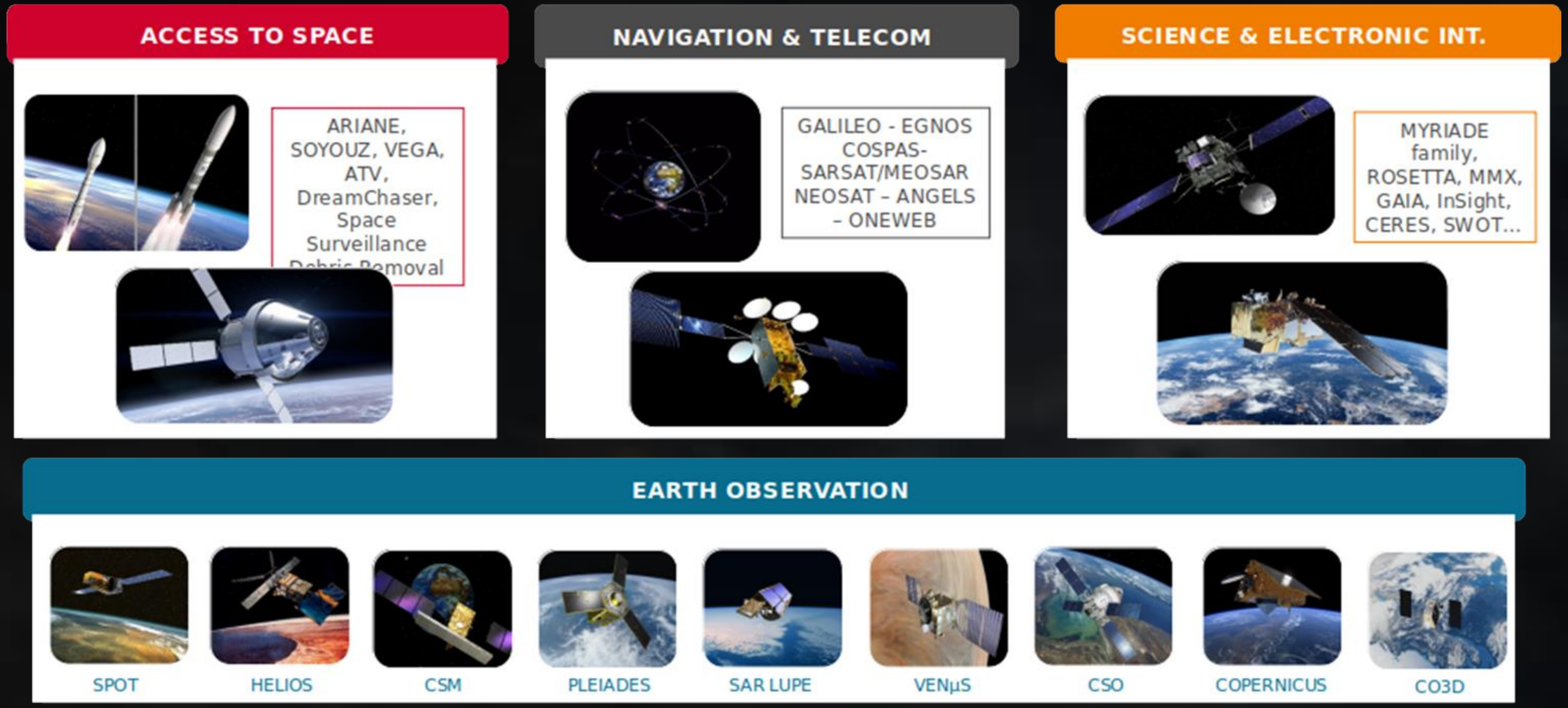
GTOC 12 Workshop

January 15th, 2024
Tsinghua University, Beijing, China

CS GROUP

Who we are

CS Group contributes to a wide range of space missions



https://www.csgroup.eu

Outline

Trajectory optimization and approximation methods

Preliminary analysis and databases

Fleet construction pipeline

Our final solution

Solving the optimal control problem

Compute the best trajectory for a body-to-body transfer duration/mass trade-off

- Direct approach (inspired from C.H. Yam et al., 2010)
  - Sims-Flanagan transcription with regular time segments
  - Constant inertial low-thrust instead of impulse
  - Taylor integration
- NLP solver: SLSQP (from NLOPT) and IPOPT

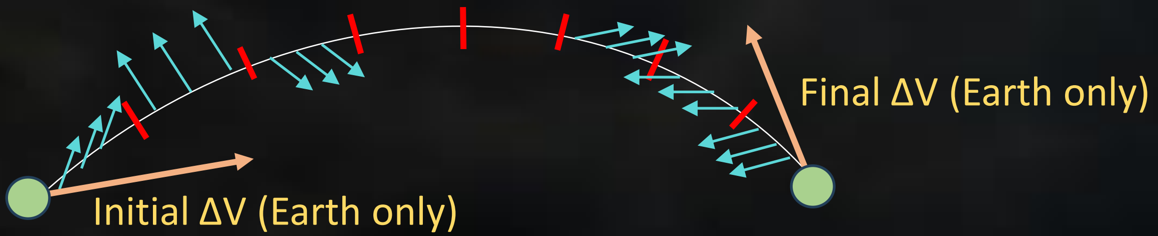
forward

Initial mass
Initial time

Final mass
Final time

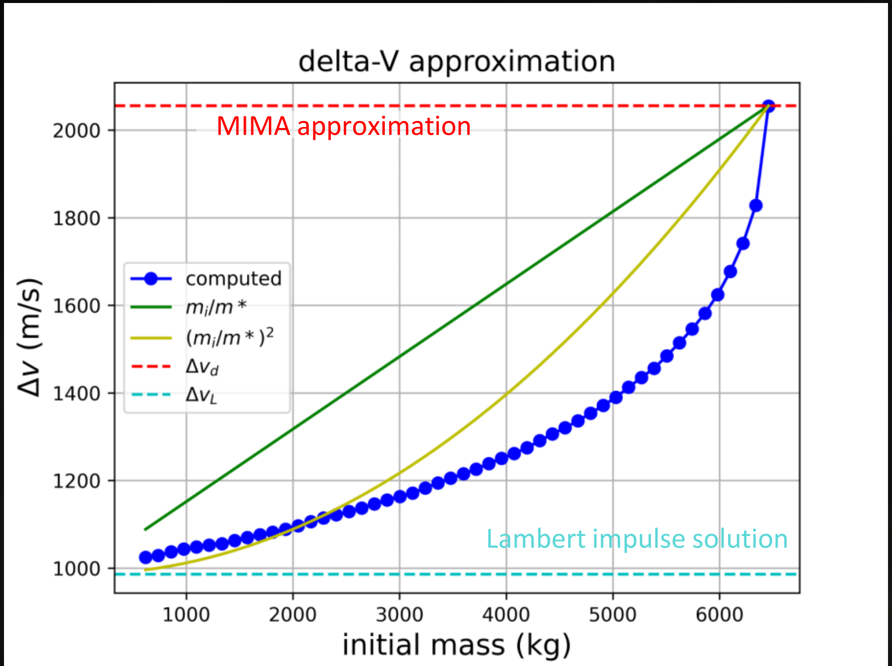
backward

For backward transfers
final mass must be estimated!



Delta-V estimation

Maximum Initial Mass (MIMA, *Hennes et al., 2016*) approximation ΔV_D overestimates ΔV
Lambert impulse solution ΔV_L underestimate it



asteroid to asteroid transfer example

Weighted ΔV estimation:

$$\Delta V = \Delta V_L * (1 - w) + \Delta V_D * w$$

with $w = m_i / m*$ or $w = (m_i / m*)^2$

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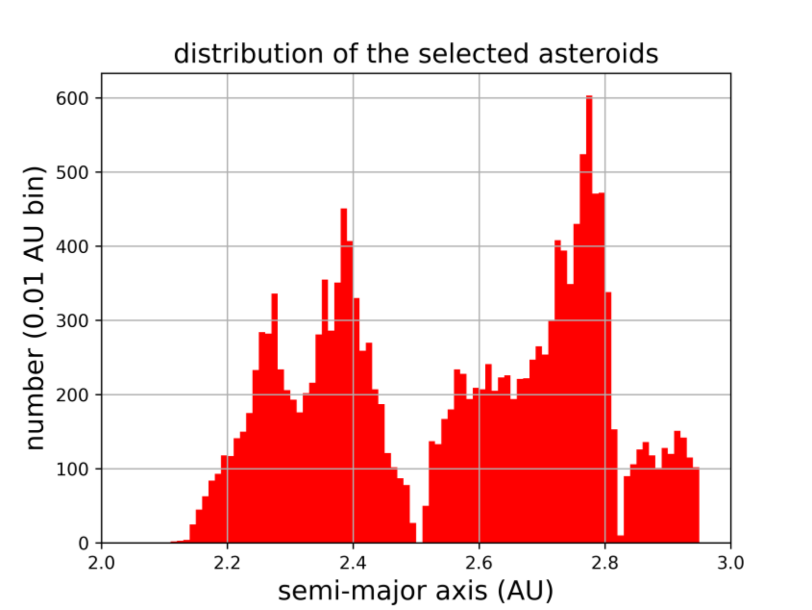
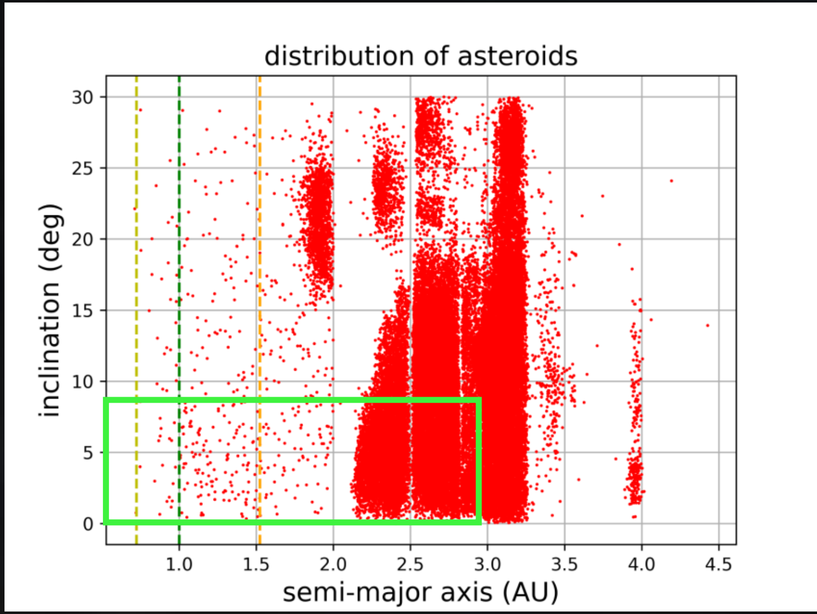
Analysis

Filtering of the most promising asteroids





Densest zones at 2.4 AU and 2.75 AU

60k → 17k asteroids

- a < 2.95 AU
- i < 8°

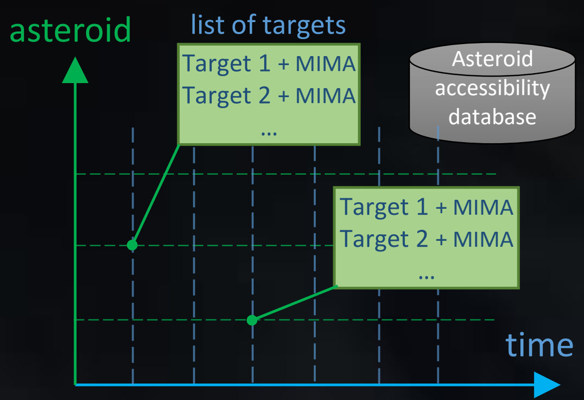
Asteroid accessibility database

Used to drive the exploration during the search

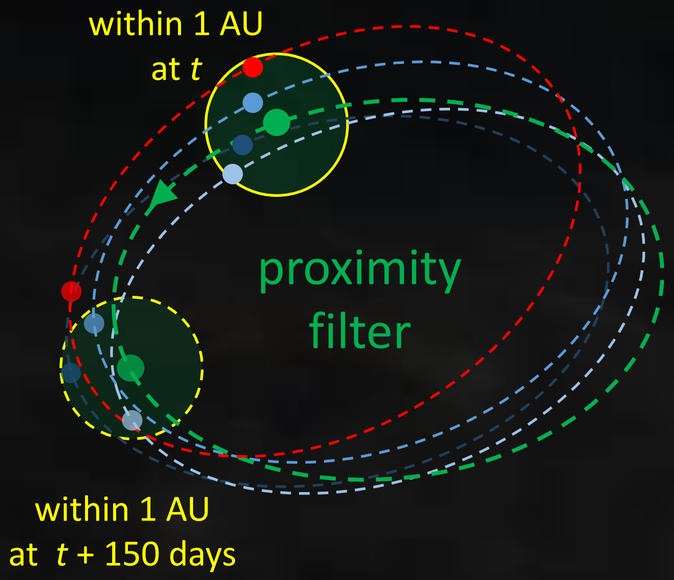
For each asteroid on a 5-day time grid:

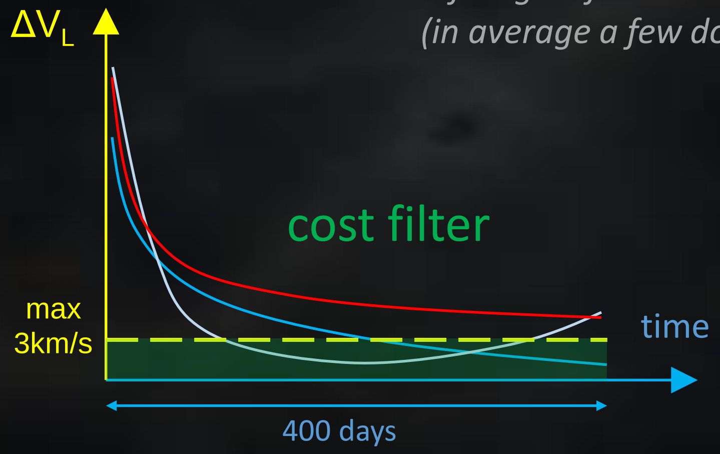
- ➢ Consider only close neighbors (within 1 AU at *t* and *t* + 150 days)
- ➢ Consider only cheap targets (min ΔV_L < 3km/s within 400 days)

➔ Store the cheapest targets and associated MIMA values



Asteroid accessibility database =
list of targets for each {asteroid, time} couple
(in average a few dozen targets per list)

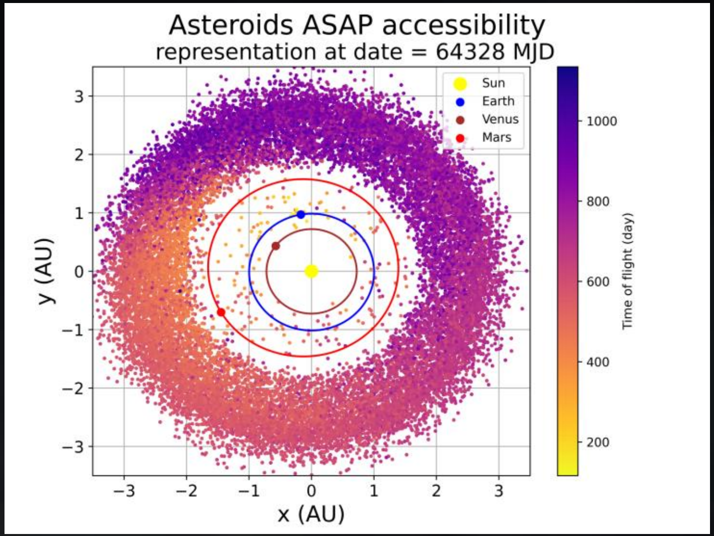


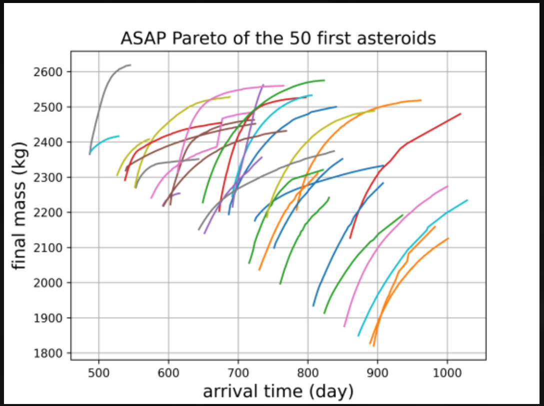


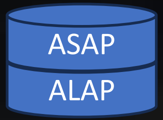
ALAP & ASAP databases

For each selected asteroid:

- ASAP: find the transfer to reach asteroid from Earth As Soon As Possible
- ALAP: find the backward transfer to reach asteroid from Earth As Late As Possible (with an estimated final mass of 1300kg)







For each ASAP/ALAP transfer, compute the mass optimal transfer for a 5-day grid transfer duration (starting at time optimal)
➔ databases contain a discretized Pareto of the Earth-asteroid transfers

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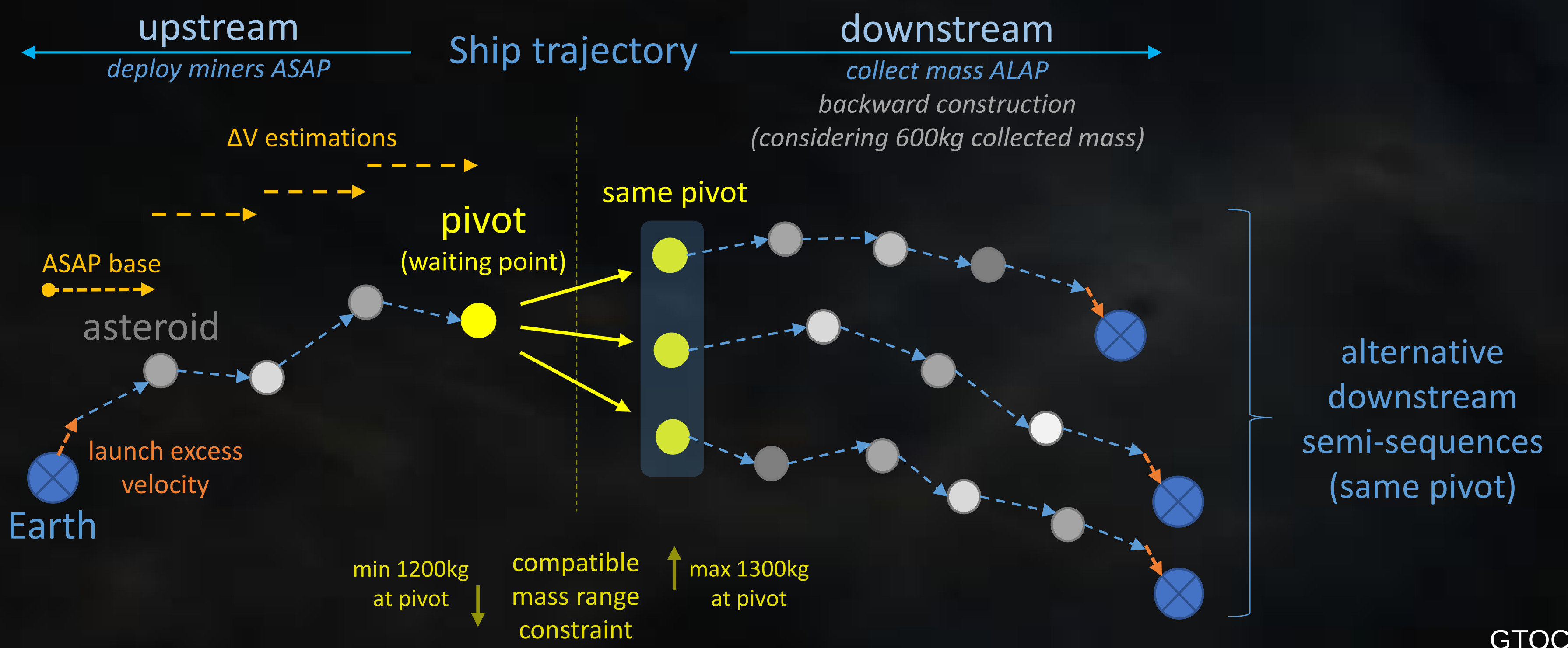
Decoupling the upstream and downstream parts of the trajectory

The list of asteroids visited by a ship is cut into upstream and downstream semi-sequences

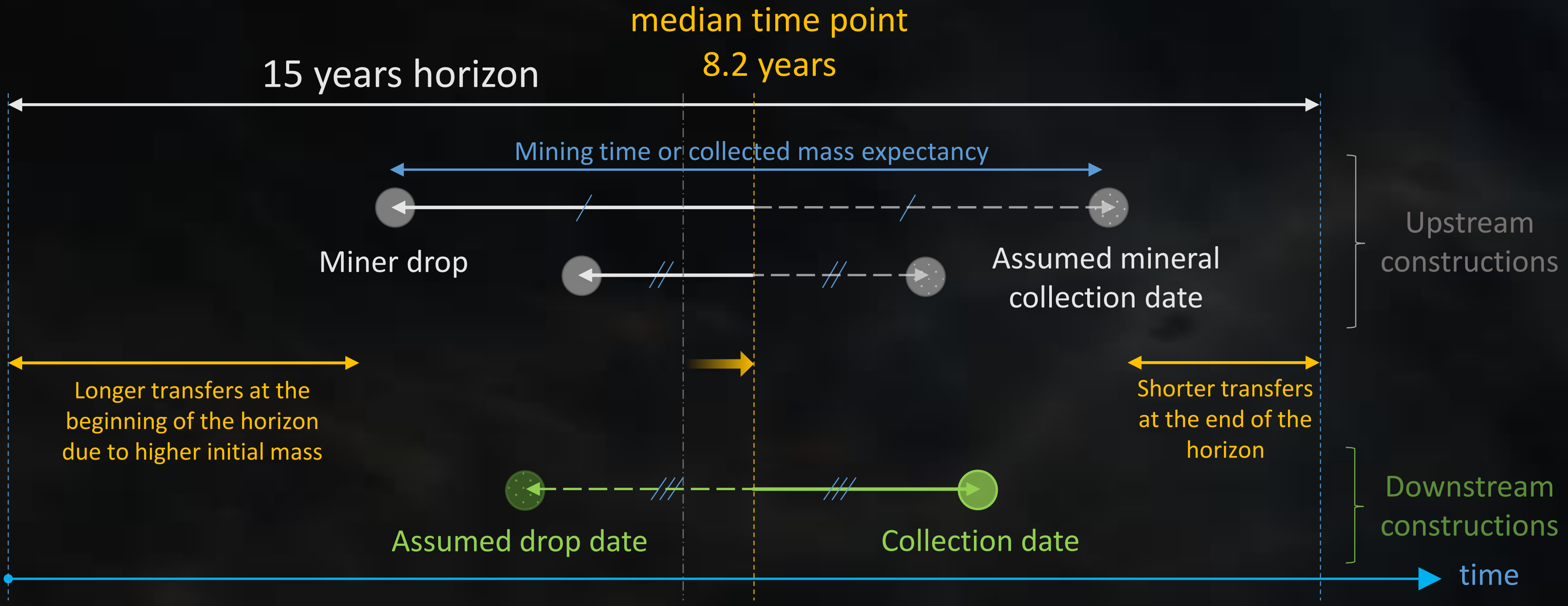
- Constructed independently, maximizing the collected mass expectancy
- Semi-sequences that share a pivot asteroid can be merged



Collected mass expectancy: mirror hypothesis

Estimation of the mining time expectancy for an asteroid

- Hypothetical symmetric event with respect to a median time point



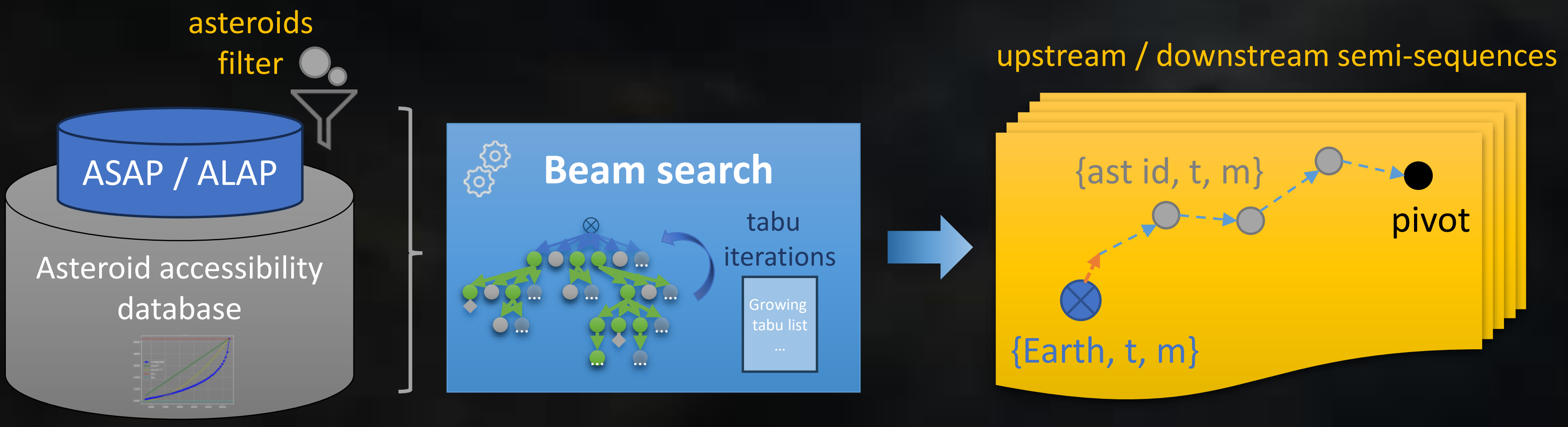
Banks of semi-sequences

Beam search

- Initialization: from ASAP or ALAP databases + asteroids filter
- Exploration: asteroid accessibility database + weighted ΔV estimation, revisit not allowed
- Heuristic: total ΔV / transfer time / collected mass expectancy compromise + mass range constraint

Filters

- Tabu iterations: Concatenation of successive runs removing the most frequently visited asteroids
- Downstream filter: Only consider the set of asteroids retained in the upstream phase

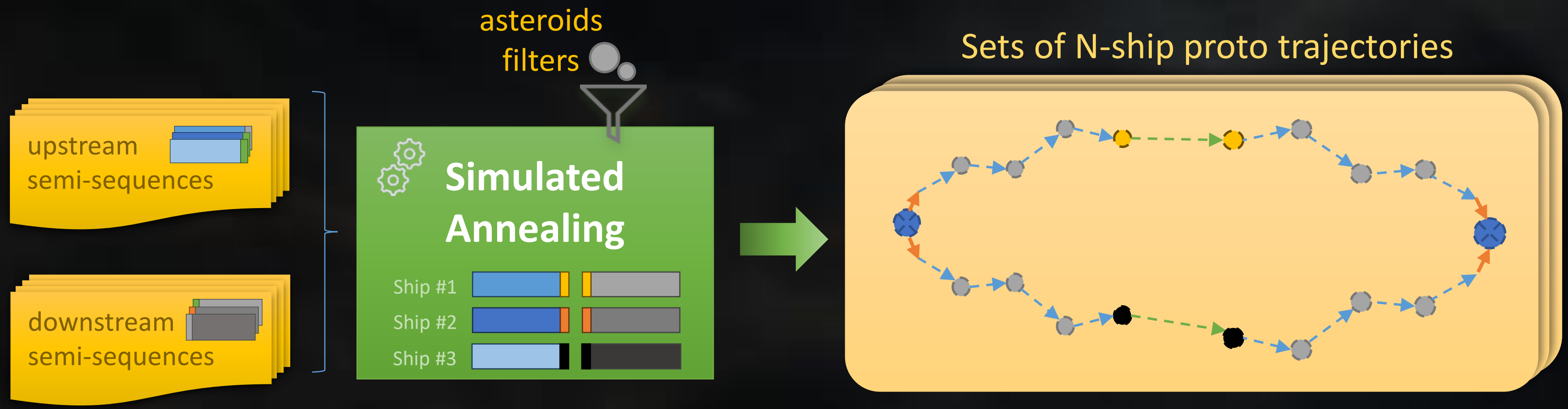


Assembling into fleets

Simulated annealing

- Parameters: ships count, forbidden asteroids
- Variables: pivots and associated pairs of upstream/downstream semi-sequences
- Mutations: change a pivot (and the associated pair) or change a semi-sequence
- Heuristic: average collected mass

Several successive runs with varying ship count and sets of forbidden asteroids

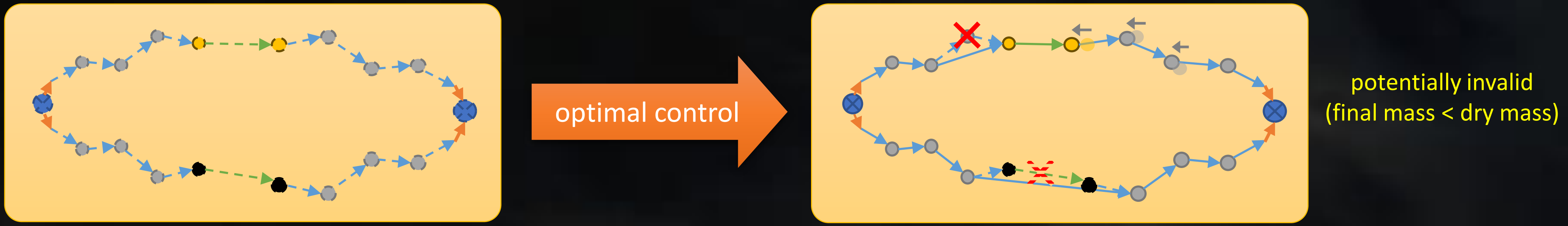


Finalizing the low-thrust trajectories

I. Preliminary real trajectories

- Forward pass: optimal control, updates of mass events, removal of spurious asteroid visits
- Relaxations needed to improve the feasibility on some difficult trajectories:

  Reduction of the initial mass, events shifting toward the median date, or removal of the pivot

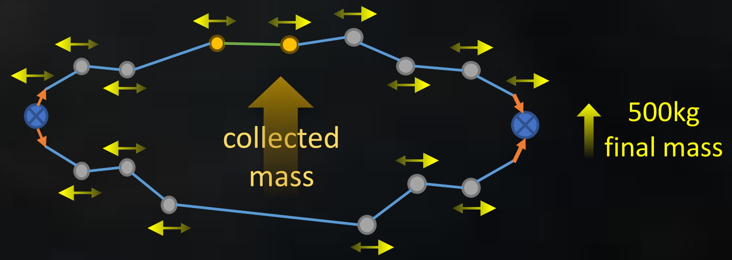


N-ship proto (approximate) trajectories

N-ship preliminary real trajectories

II. Global sub-fleet level optimization

- Preliminary real trajectories used as first guess
- Simultaneously optimize all legs and adjust asteroid visit dates
- Ensure the final 500kg mass constraint
- Maximize the collected mass



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Our final solution Score 17081 (3rd place)

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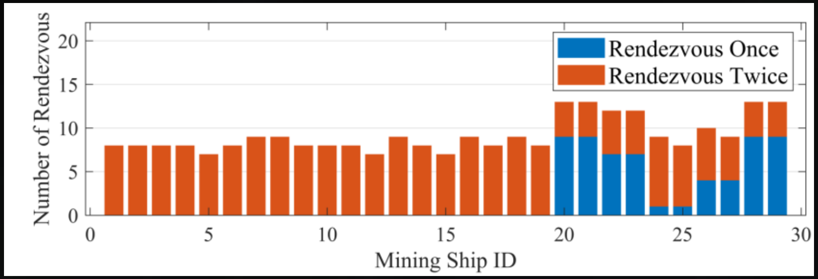
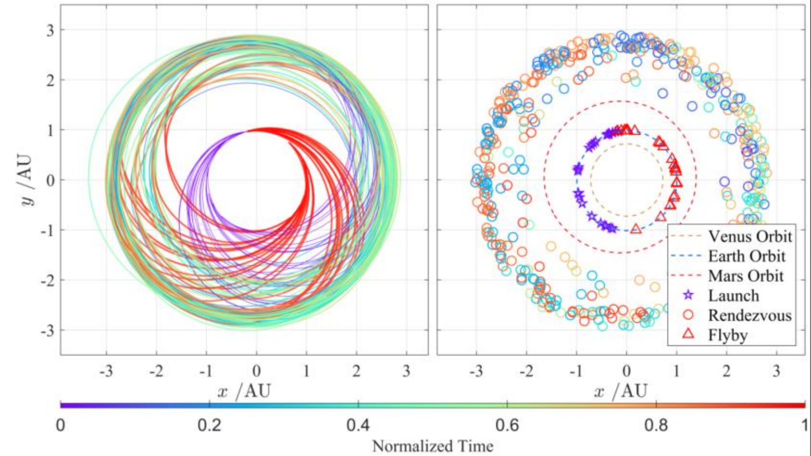
Final fleet assembly

Concatenation of our best compatible solo ships and sub-fleets

Considering the bonus coefficients, and with potential simplification of duplicates and slight re-optimization





Courtesy of Tsinghua University

29 Mining Ships
- 5 pairs of cooperating ships
- 19 individual ships

236 mined asteroids

673kg in average collected per ship

Relative lack of ship cooperation

Our first fleets presented larger independent groups (up to 7 ships) that were progressively replaced by smaller sub-fleets

Most of the exploited asteroids are close to 3 AU

Thank you!

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