南京航空航天大学
Nanjing University of Aeronautics and Astronautics

航天新技术实验室
Advanced Space Technology Lab

GTOC 12: Results from Nanjing University of Aeronautics and Astronautics

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GTOC 12 Workshop

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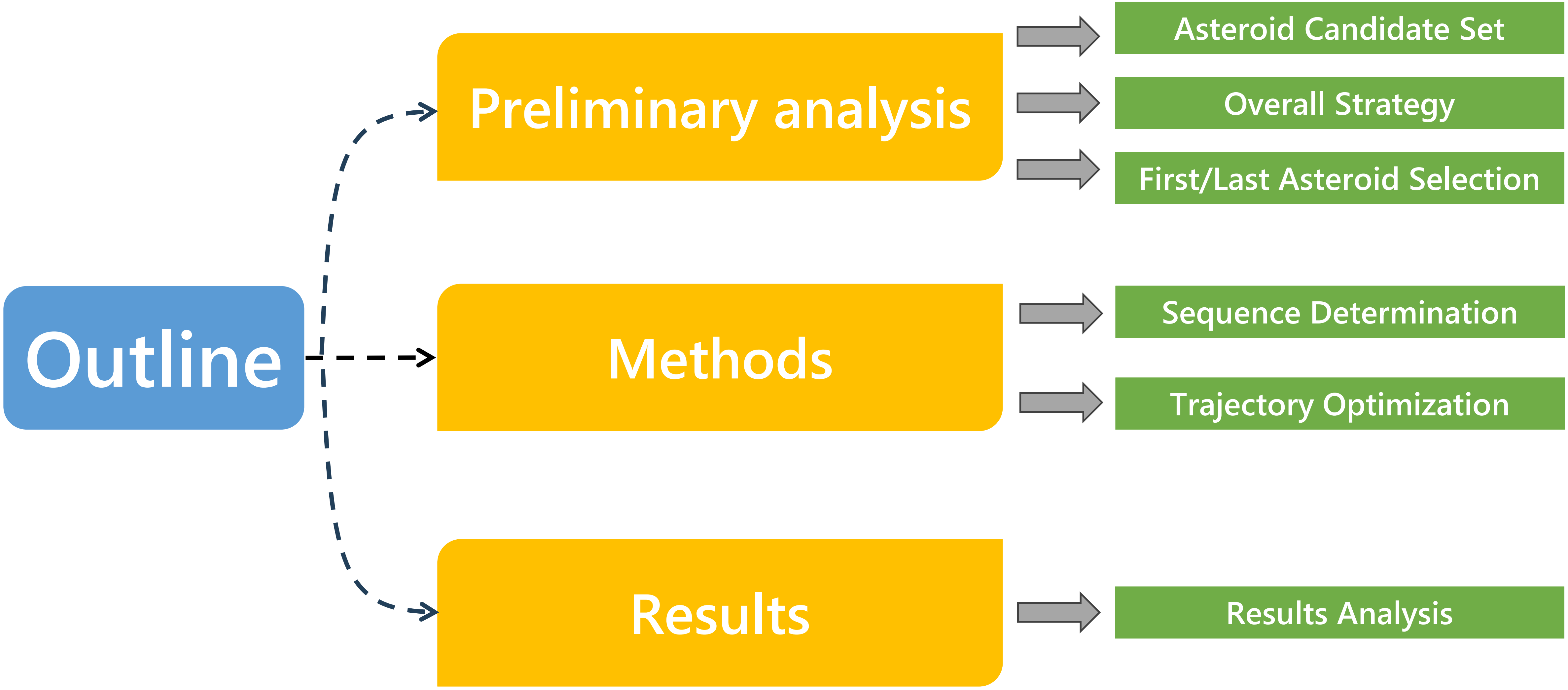
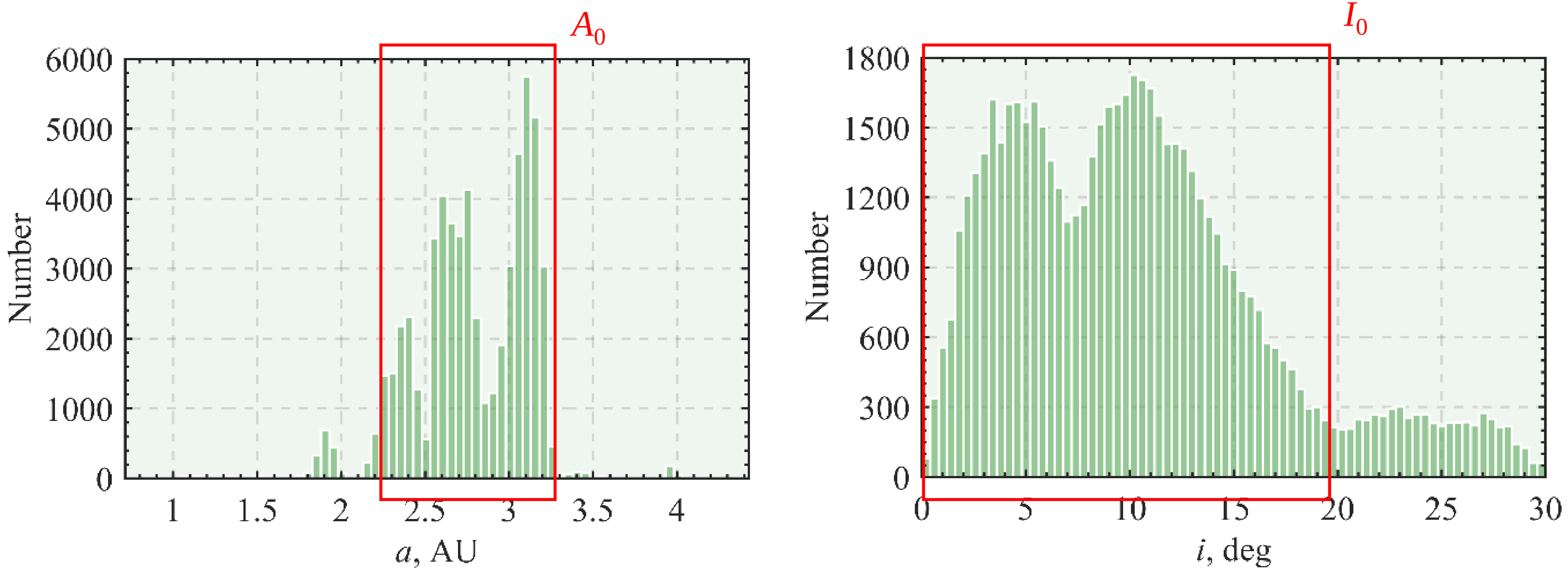
Outline



Outline
Preliminary analysis
Asteroid Candidate Set
Overall Strategy
First/Last Asteroid Selection
Methods
Sequence Determination
Trajectory Optimization
Results
Results Analysis

Asteroid Candidate Set

- **Ease of departure from and return to Earth** ----▸ Energy and Inclination
- **Low transfer costs between asteroids** -----------▸ Distribution

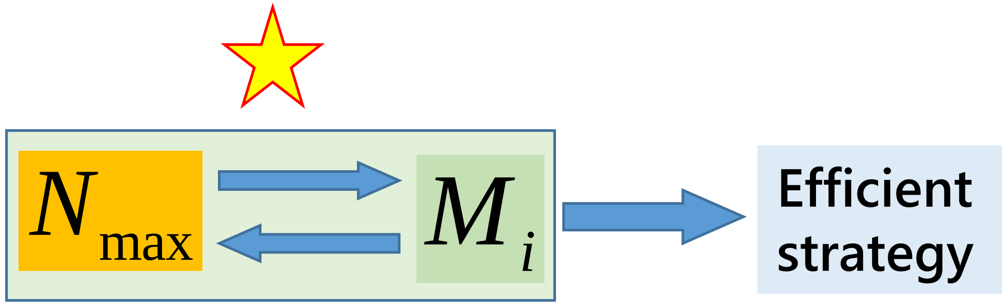


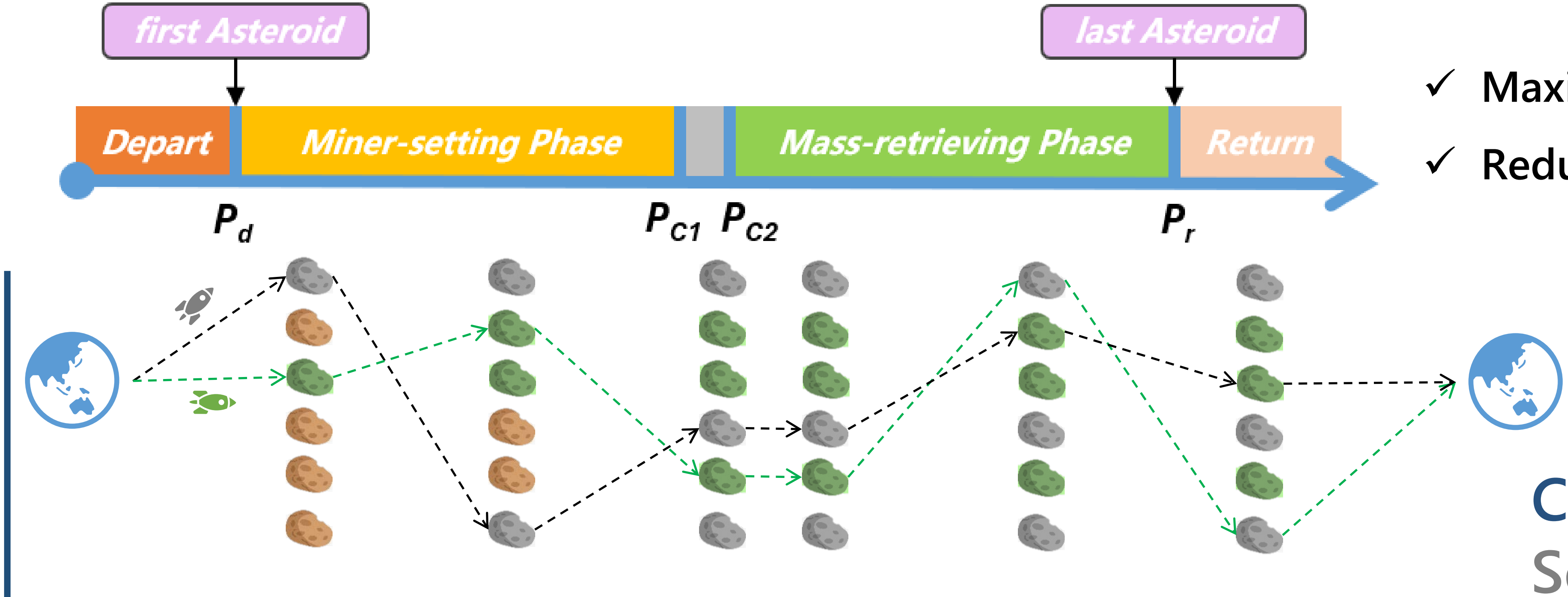
Candidate Set $C_0 = A_0 \cap I_0$

Preliminary analysis

Overall Strategy

$$J=\sum_{i=1}^{60,000} B_i M_i \longrightarrow N_{\max}=\min\left[100, 2\exp\left(\rho \bar{M}\right)\right] \longrightarrow$$





Example: 2 mining ships cooperating to mine 6 asteroids

- ✓ Maximum mining time
- ✓ Reduce design difficulties

Cooperative ✓

Separate

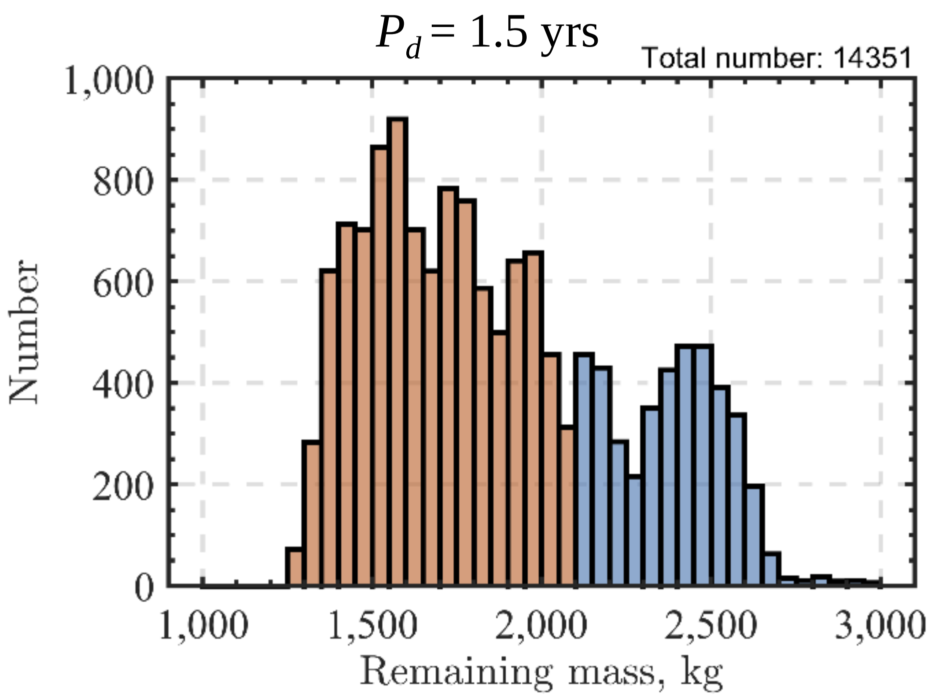
Selections on the first and last asteroids

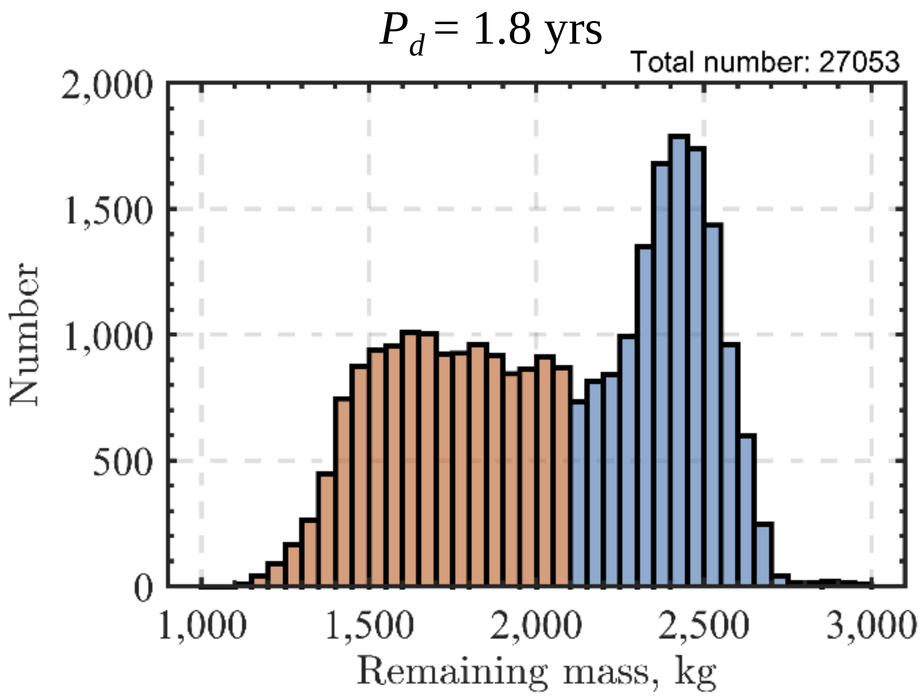
Databases for departure and returning asteroids

$$\mathrm{DB}_d = \{ast_i, \Delta m, t_0, t_d\} \quad \mathrm{DB}_r = \{ast_i, \Delta m, t_r, t_f\}$$

Three-impulse transfer → optimal times

Indirect method → fuel-optimal trajectory





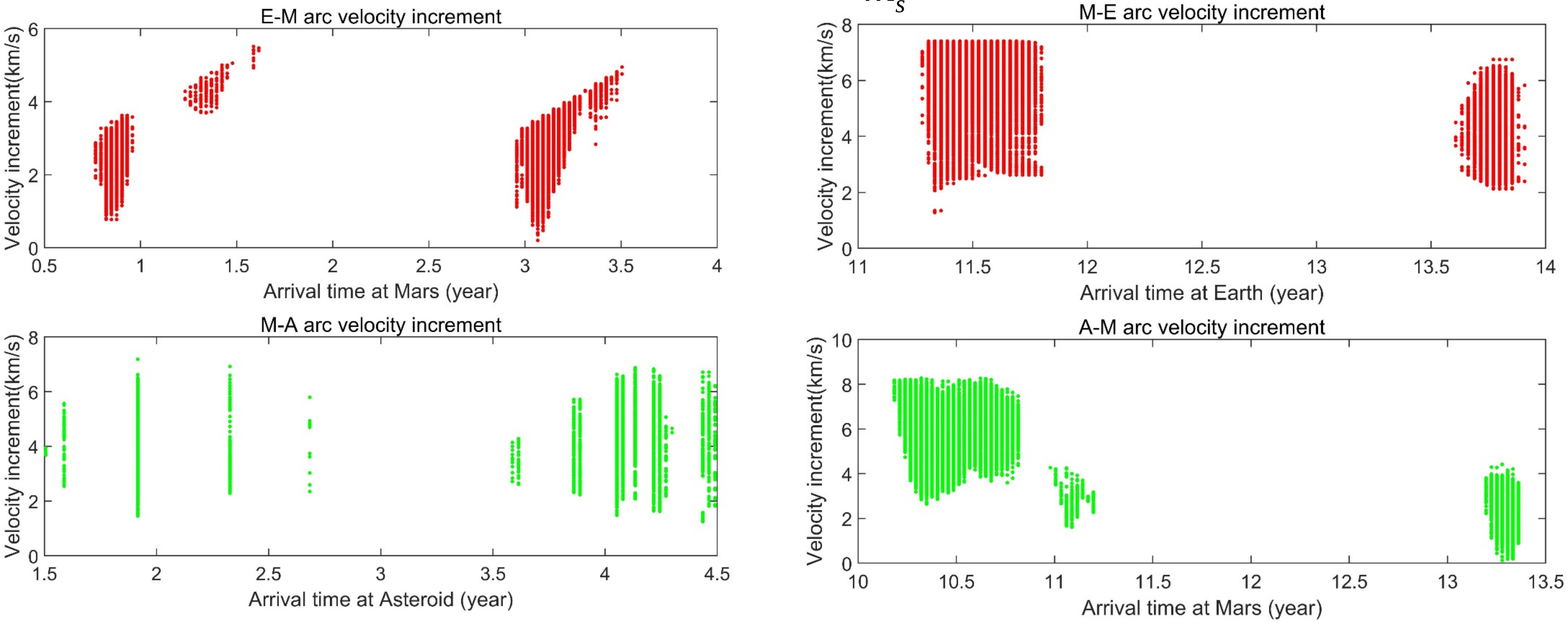
Direct transfer

For the departure segment, the remaining mass of the spacecraft corresponding to different transfer upper limit time P_d

Selections on the first and last asteroids

- For the MGA, the optimal times are estimated using the three-impulse transfer, while excluding unreasonable results according to the following equation

$$\Delta v \le \beta \frac{T_{\max}}{m_s} \Delta T, \quad \beta = 0.5$$



Number of asteroids: 805

Number of asteroids: 1108

- Direct transfer was ultimately used

Asteroid sequence determination

How to calculate the transfer cost between asteroids in a sequence search?

Uniform rectilinear motion assumption → Analytical orbital indicator*(OI)

Clustering →

Initial scoping

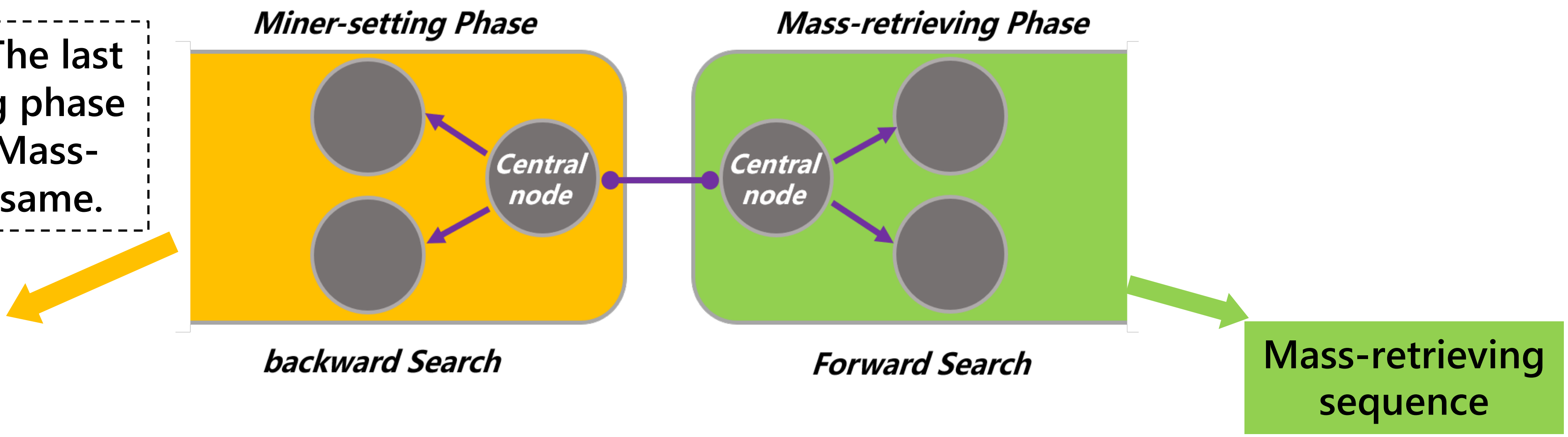
transfer opportunity at time t with asteroid a

→

Two-impulse transfer → Lambert Solver

How to perform searches to achieve repeat rendezvous to the target asteroids?

Central Node Asteroid: The last asteroid in Miner-setting phase and the first asteroid in Mass-retrieving phase are the same.



*Hennes, D., Izzo, D., and Landau, D. Fast approximators for optimal low-thrust hops between main belt asteroids. 2016 IEEE Symposium Series on Computational Intelligence, **2016**: 1-7.

Central Node Method and database generation

- ✓ Reduce the size of the sequence search
- ✓ Less computationally intensive compared to the start-to-finish sequence search strategy due to the fact that it splits the entire sequence into two segments

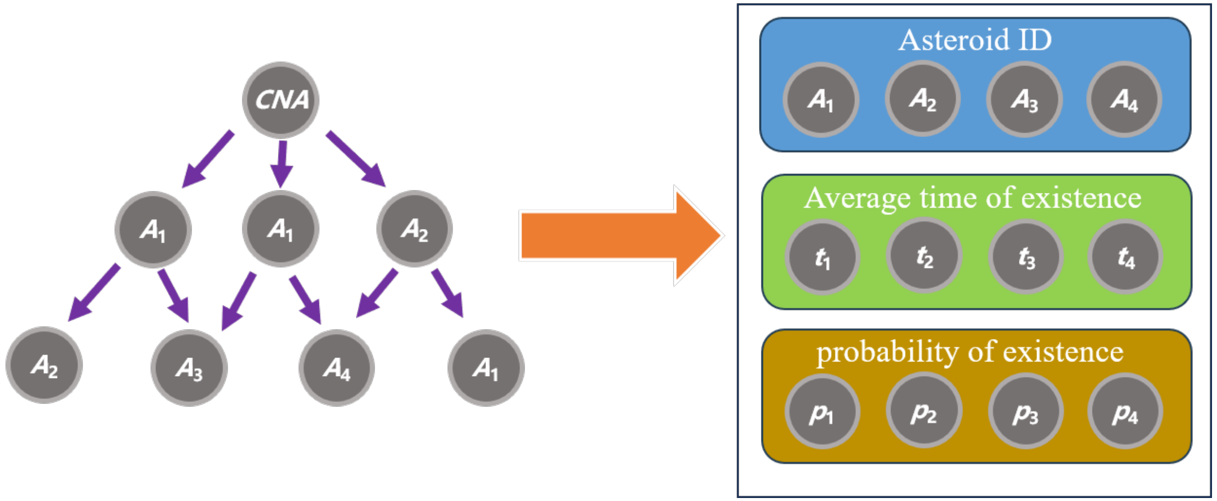
- ➢ In order to determine the CNAs, OI was first used to obtain the largest asteroid clusters in the intermediate phase of the entire mission time as the initial CNA set.
- ➢ Then, a tree search was performed for each CNA using Multi-Objective Beam Search (MOBS) and a database was got, and the "feature" of CNAs were constructed from the results.

☐ Determination of CNA combinations

- ➢ Utilize GA to select *N* central nodes that have the maximum number of asteroids that have been visited in both phases according to the feature.

N: The number of Mining ships

Feature of CNA



Central Node Method and database generation

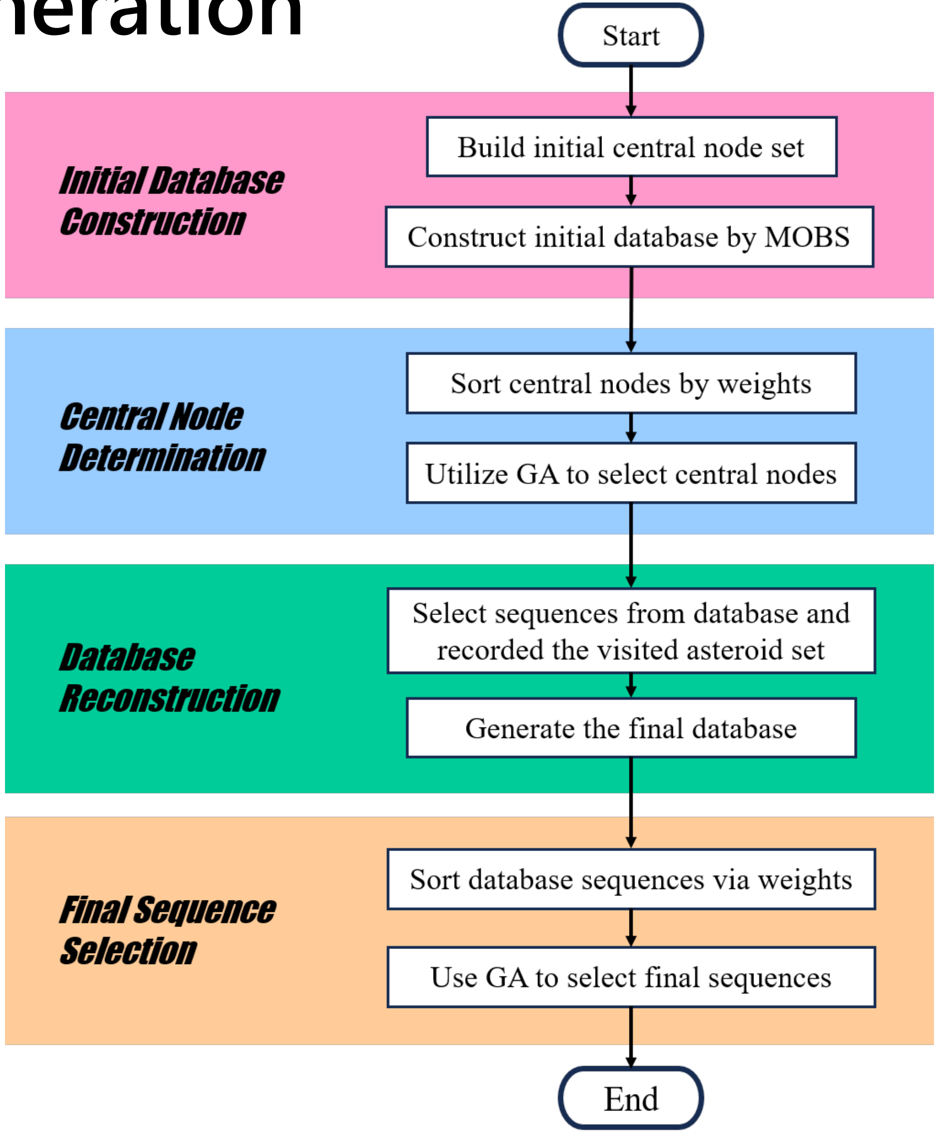
☐ Determination of asteroid combinations

- Use GA to select the set of asteroid combinations from the CNA features that might make the score the highest. Restricting transfer targets between asteroids to reconstructing the database only for asteroids in that set.

☐ Final Sequence Selection

- In order to characterize the database as a "gradient", the database was sorted and the final sequence selection was performed using GA.

$$W_{seq}=\frac{1}{1+\sum_{1}^{m}p_m}$$



Trajectory Optimization

Low-thrust trajectory optimization

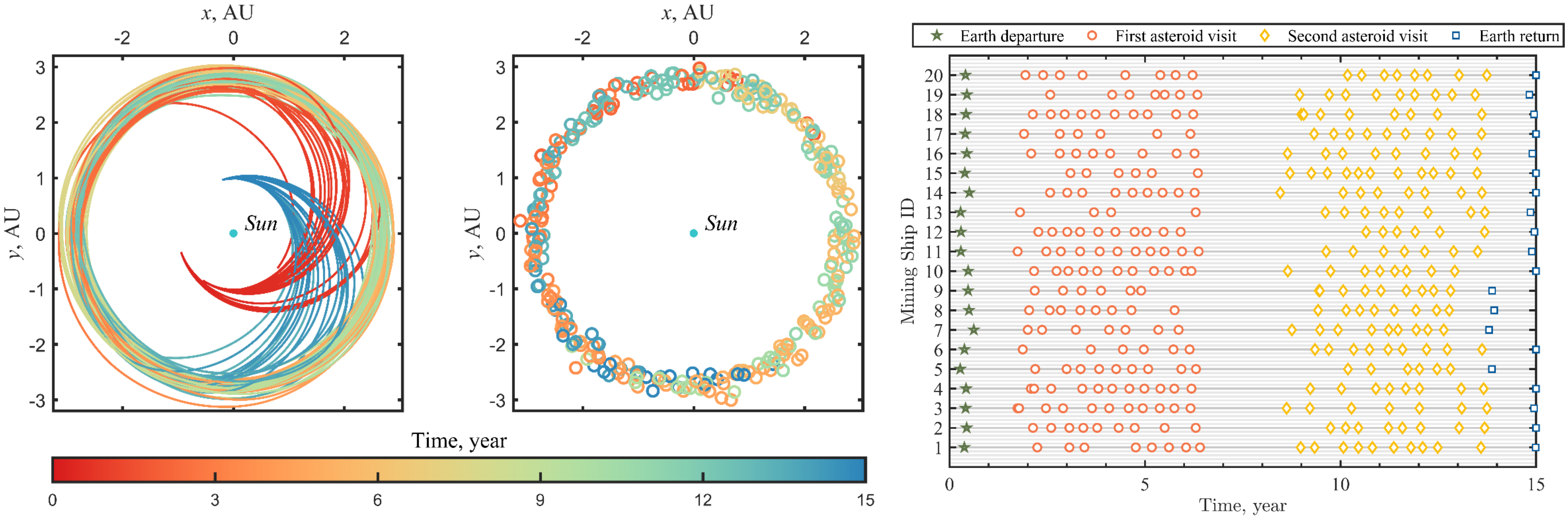
- The boundary conditions are provided by CNM to calculate the fuel-optimal low-thrust trajectory using an indirect method based on Fortran.
- Efficient computation using homotopic technique and normalization of initial costates*, 0.06s for a single low-thrust trajectory

Global optimization of sequence

- Time optimization for low-thrust trajectories using NSGA II
- The two objectives of the optimization were to increase the final score and to reduce the fuel consumption, respectively.

*Jiang, F., Baoyin, H., and Li, J. Practical techniques for low-thrust trajectory optimization with homotopic approach, *Journal of Guidance, Control, and Dynamics* **2012**, 35(1): 245-258

Results



Final score	10,667.468
Total collected mass	11,513.708 kg
Number of mining ships	20
Number of mined asteroids	161

Thanks!