The fellowship of the Dyson ring: ACT&Friends results and methods

ESA Advanced Concepts Team & Friends

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Team Intro

- Current or former members of ESA’s Advanced Concepts Team + Associates
- Spread over 3 time-zones: Netherlands, Japan, USA

General Problem Introduction

Construction of 12 Dyson Ring stations

1. Asteroid collection by 10 motherships
2. Determination of ring parameters
3. Low-thrust continuous optimization of asteroid trajectories
4. Asteroid arrival scheduling

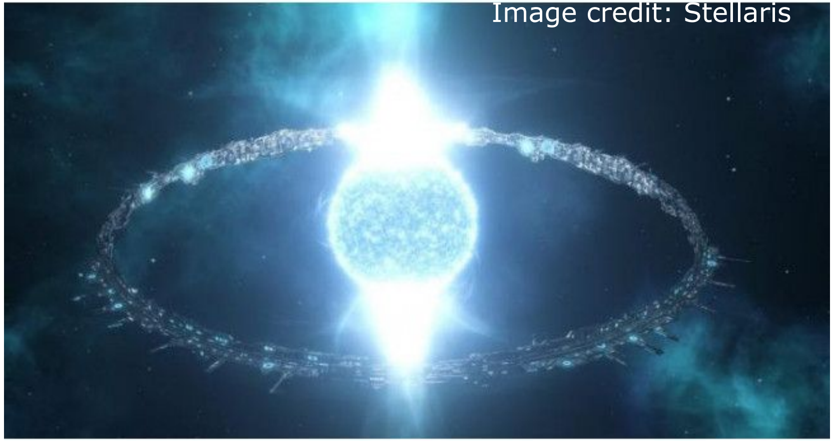


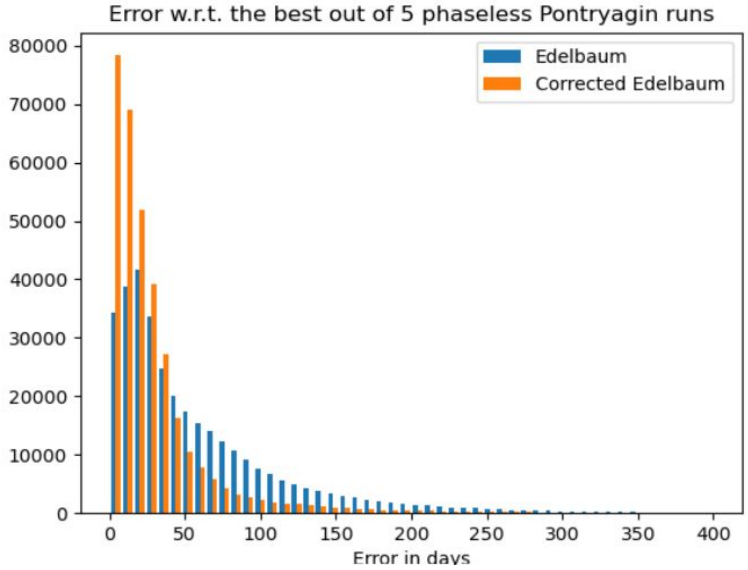
Image credit: Stellaris

Motherships: Earth-to-Asteroid and Asteroid-to-Asteroid

- Chemical leg modelled as three impulses: departure, DSM, arrival
  - Time of flight per leg between 5 and 380 days
- Asteroid selection criterion: mass left after *dt* seconds

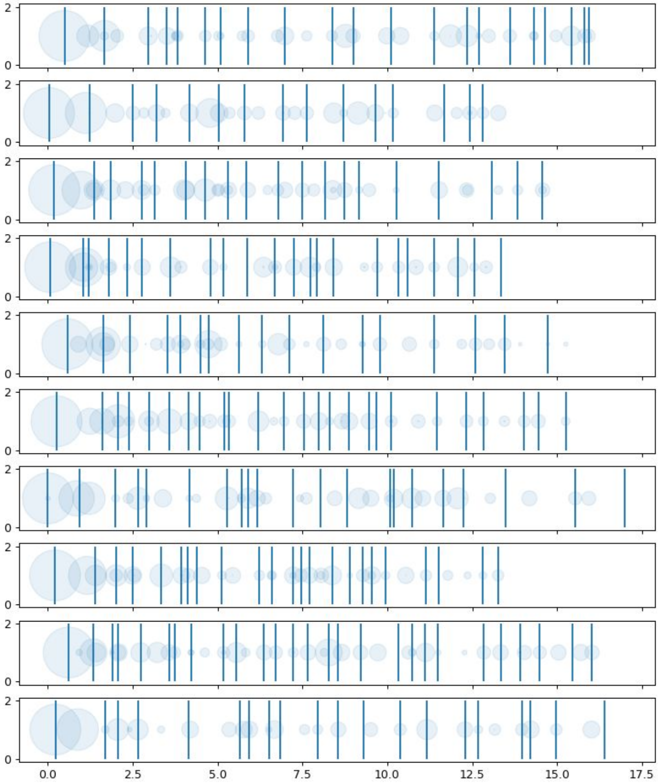
$$m_{eff} = m_{ast} \cdot (1 - \alpha \cdot \underline{dt})$$

Improving Edelbaum approximation
dt is learned by a FFNN using a dataset
Of ~5 million solved OCP problems assuming
different target SMA (0.9 to 1.3 AU) of
Dyson Ring.



Motherships: Lazy Race Tree Search

- Asteroid preselection: 0.9 quantile of effective mass
- **Branching**:
  - Candidate asteroids determined by orbital phasing indicator
  - Dt computed by ML-corrected Edelbaum approximator
  - DV computed by solving 3-impulse problem using differential evolution
- **Pruning**:
  - Per time slice by computing the accumulated J over time



Motherships: Results

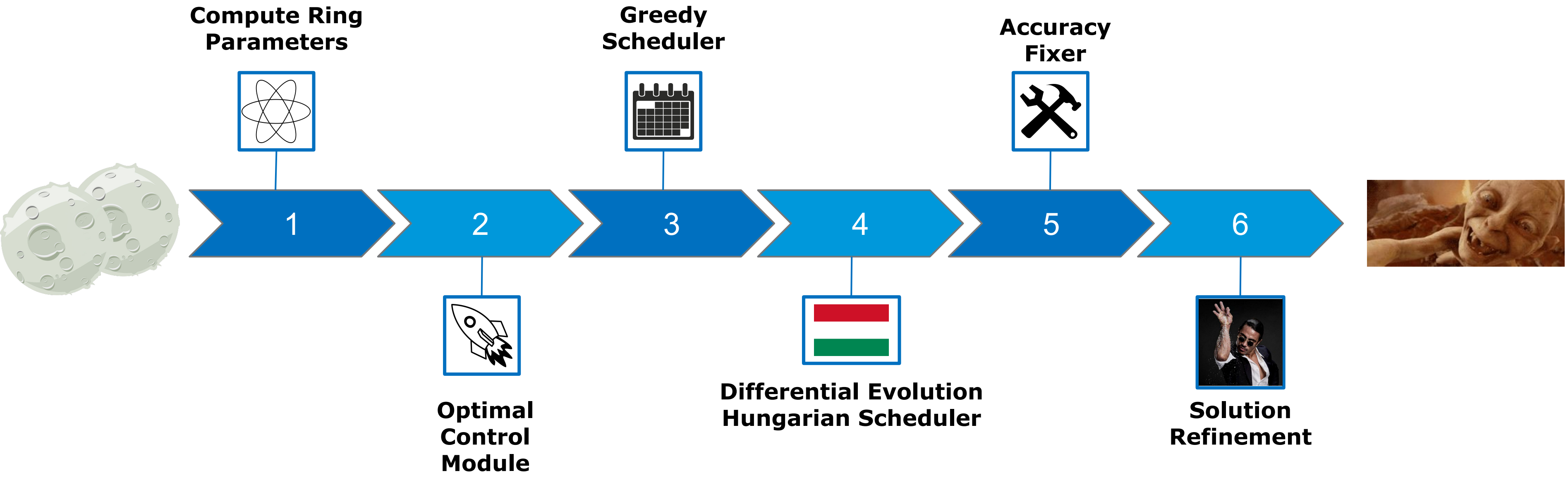
- **145k Mothership trajectories** found by tree search in total

- Building ensembles of 10 mothers by
  - minimizing overlap (removing duplicate asteroids)
  - Greedily adding for high J (assuming fixed SMA and effective mass)
- The set of all asteroids of a complete ensemble is the input of our **ring building pipeline**

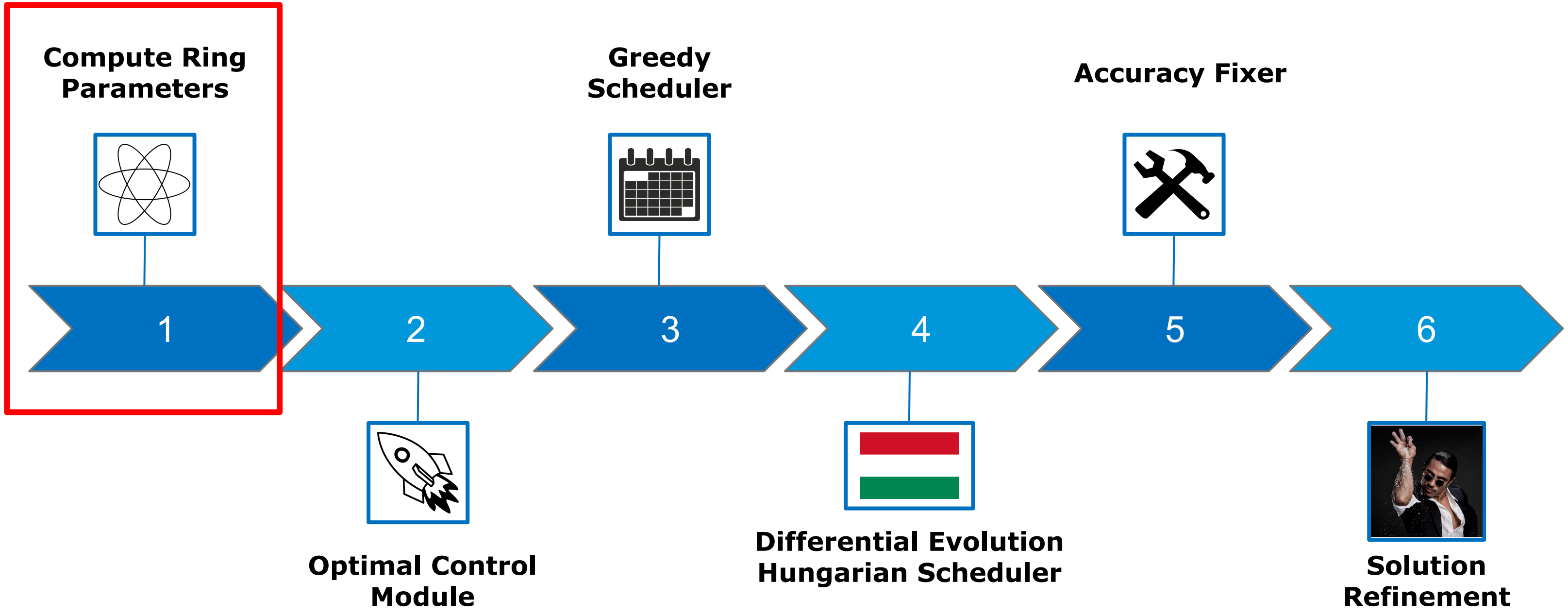
Final submission ensemble: 301 asteroids with a DV-factor of 19.1269

$$J = B \cdot \frac{10^{-10} \cdot M_{\min}}{a_{Dyson}^2 \sum_{k=1}^{10} \left(1 + \Delta V_k^{Total} / 50\right)^2}$$

Ring-Building Pipeline



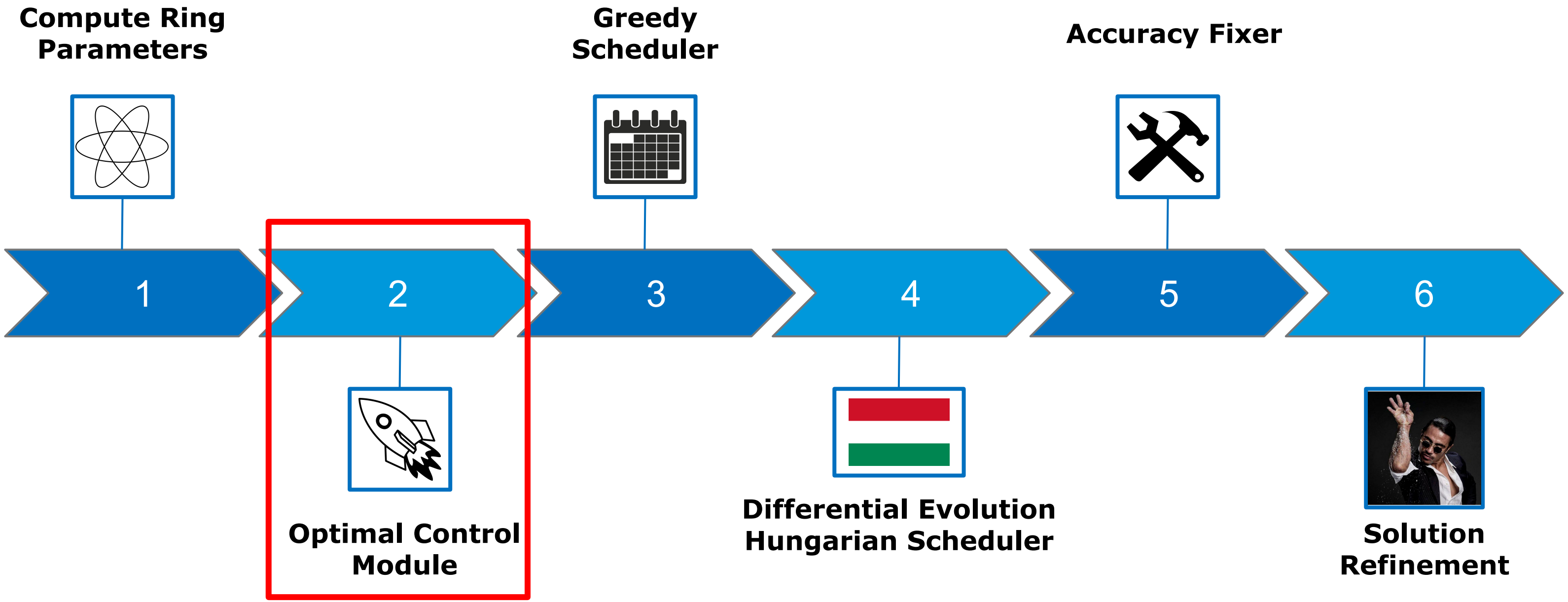
Computing Ring Parameters



Computing Ring Parameters

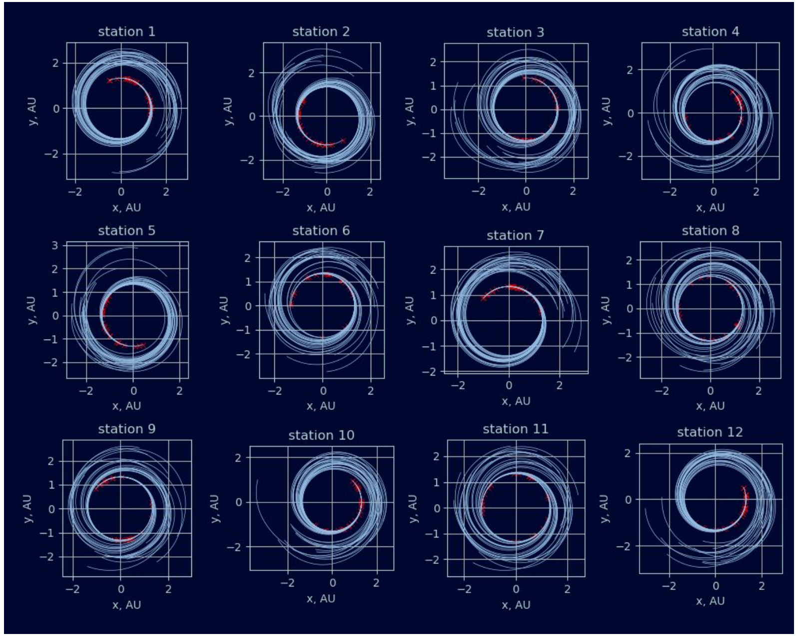
- **Global optimisation** on J
- Sequence of asteroids defined
- **Assumptions**:
  - Consider only asteroids with **non-zero arrival mass**
  - Mass equally distributed by scheduler
- ML-corrected Edelbaum used to estimate ToF

Optimal Control Module

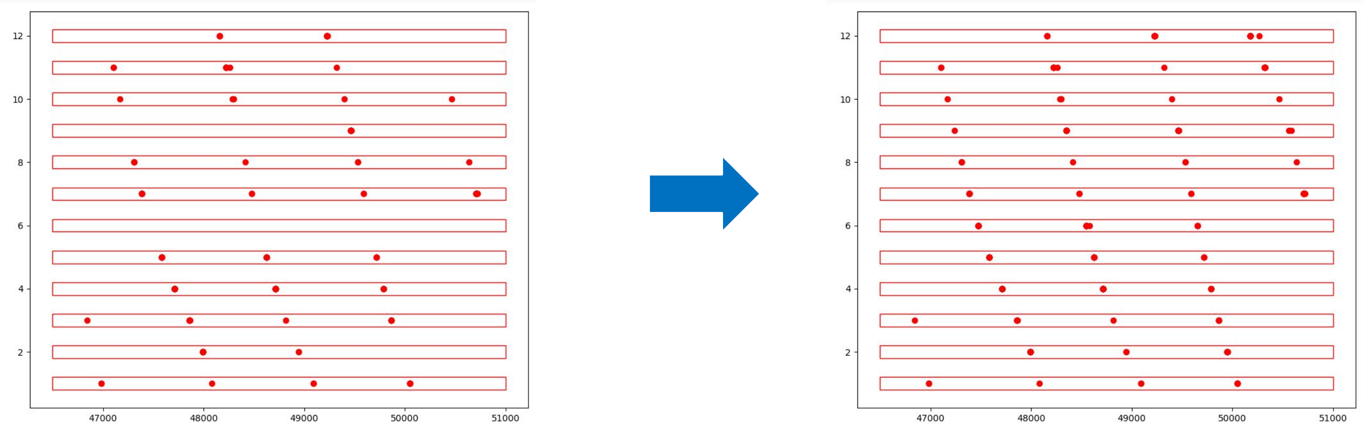


Optimal Phased Trajectories

- Computing **optimal phased** trajectories to all 12 stations for each asteroid ⇒ **Phasing Matrix**
- **Indirect** method
  - Pontryagin Maximum Principle
  - Equality constraints in **equinoctial** frame
  - **Initialization** via direct method and ML-corrected Edelbaum
  - High-performance numerical integration with **Taylor's method**



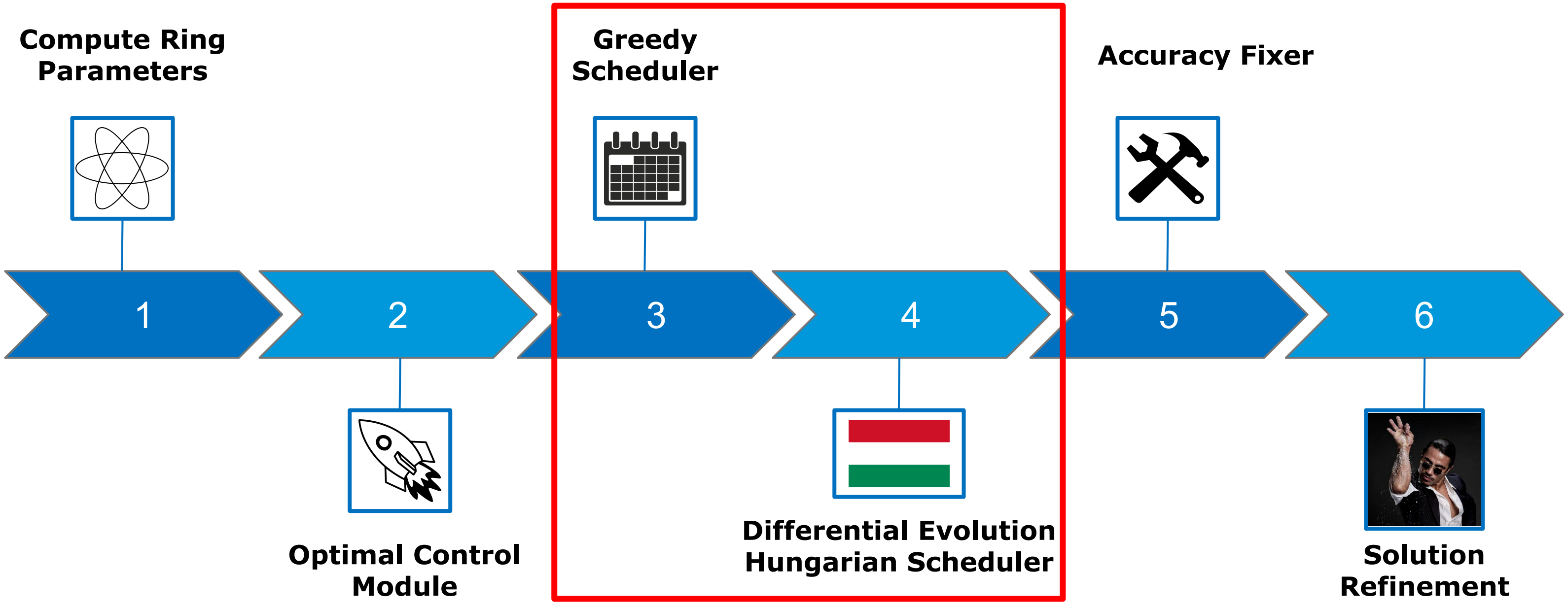
Optimal Phased Trajectories



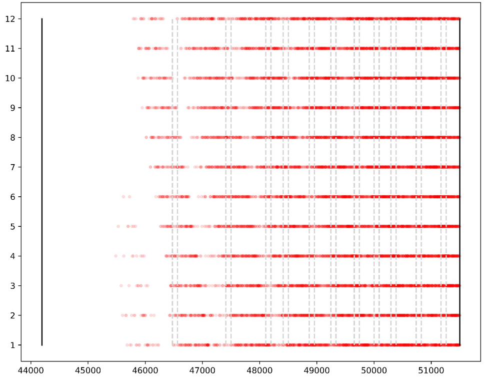
- **Multiple options** per asteroid, and some gaps appear!

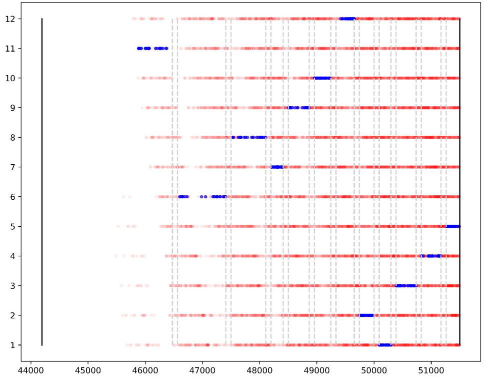
- Exploiting the **synodic periodicity** to refine the search and fill in the gaps.

Scheduler


Compute Ring Parameters
Optimal Control Module
Greedy Scheduler
Differential Evolution Hungarian Scheduler
Accuracy Fixer
Solution Refinement
1
2
3
4
5
6

Scheduler





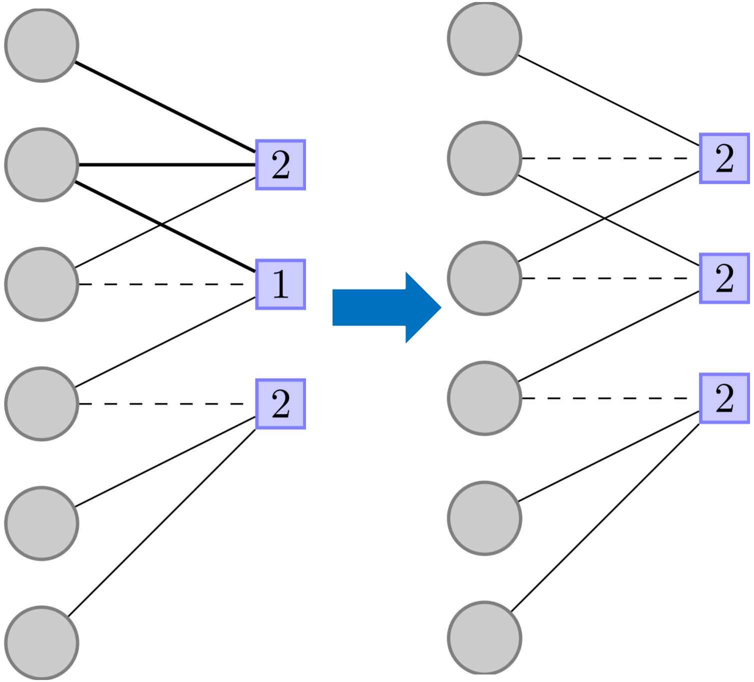
- Preliminary allocation with a **greedy** scheduler.

- Refinement with **bi-level scheduler** via **differential evolution** and a modified heuristic **hungarian** approach to the scheduling problem.

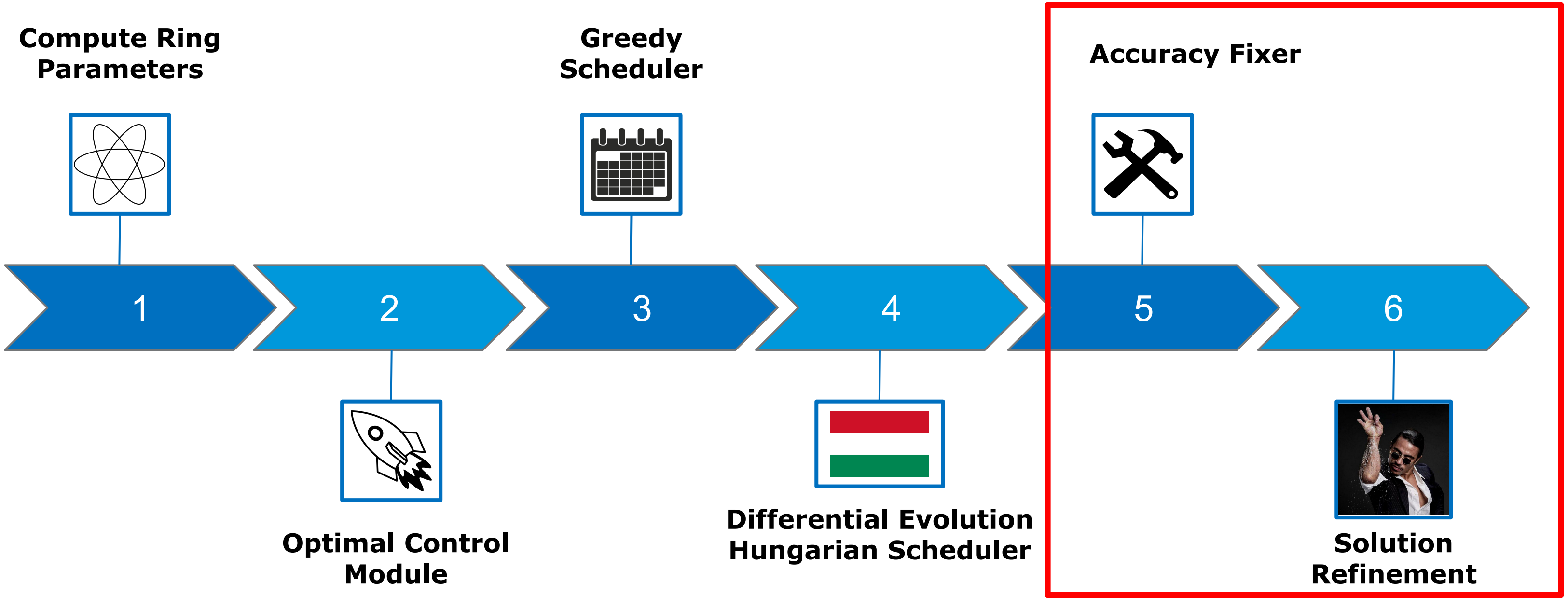
Bi-level Scheduler

1. **Inner Level**
   - Station windows are **assigned**
   - Heuristic approach based on **Hungarian** algorithm
   - **Assignment problem** with **additional balancing** (NP-complete)
   - Search for augmented paths along edges of a graph (defined by Phasing Matrix)
   - Low depth at first, then refined at higher depths

2. **Outer Level**
   - Change **window allocation**
   - **Differential evolution**
   - Log/alpha encoding for equal repartition



Fixer and Refinement



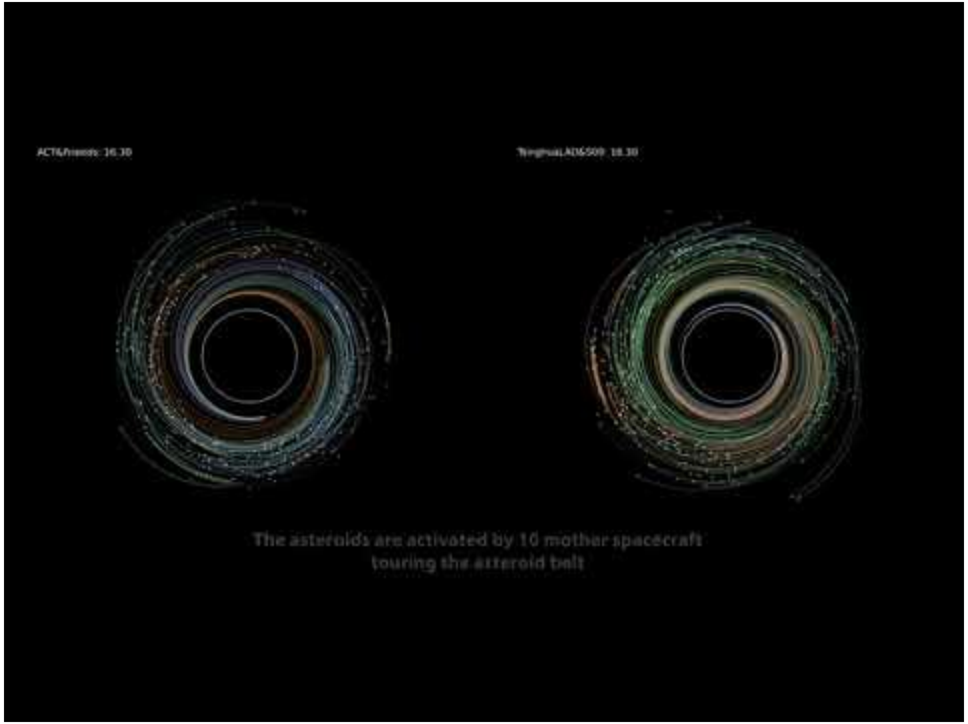
Fixing and refining the solutions

- **Fixing**:
  - Adjusting the accuracy in pos/vel of each trajectory
  - Forward integration RK78 + cubic spline interpolation
  - Resetting OCP until desired accuracy is reached

- **Refining**:
  - **Trimming**: removing unassigned and negative contribution asteroids
  - **Mother Boosting**: refining local optimas for MGA 1-DSMs
  - **Solution Boosting**: local refinement of low-thrust OCPs

Final solution

- **J = 6359.7249**
- M_{min}=2.0125 x 10^5
- **301 Asteroids**
- $\Delta V_{mother,\ max}$ = 19.44 km/s
  $\Delta V_{mother,\ min}$ = 15.09 km/s



Thank you for your attention!

Any questions? Contact us!

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