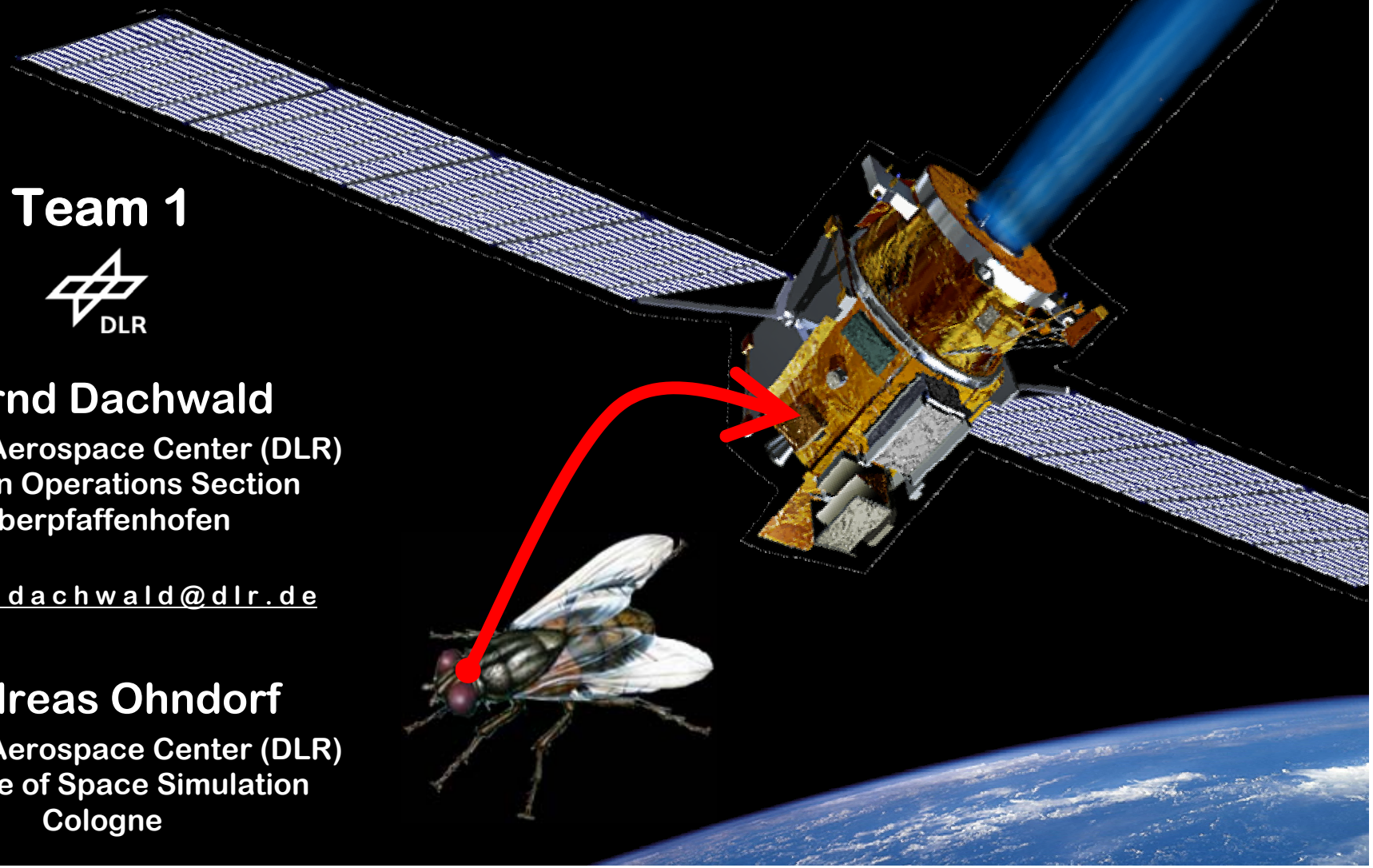
ACT Global Optimization Competition Workshop

Evolutionary Neurocontrol



Team 1

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Drawbacks of Local Trajectory Optimization Methods

- require an adequate initial guess prior to optimization
  - convergence behavior is very sensitive to the initial guess
  - similar initial guesses yield often very dissimilar optimization results
    - ➔ initial guess can not be improved iteratively
    - ➔ trajectory optimization becomes “more of an art than science”
- can only be applied by an expert in astrodynamics and optimal control theory
- require frequent interactions with the expert
- are often time-consuming (and thus expensive)
- run typically into the local optimum which is closest to the initial guess (rarely close to the global optimum)
- initial conditions are typically not optimized, although they are crucial for mission performance

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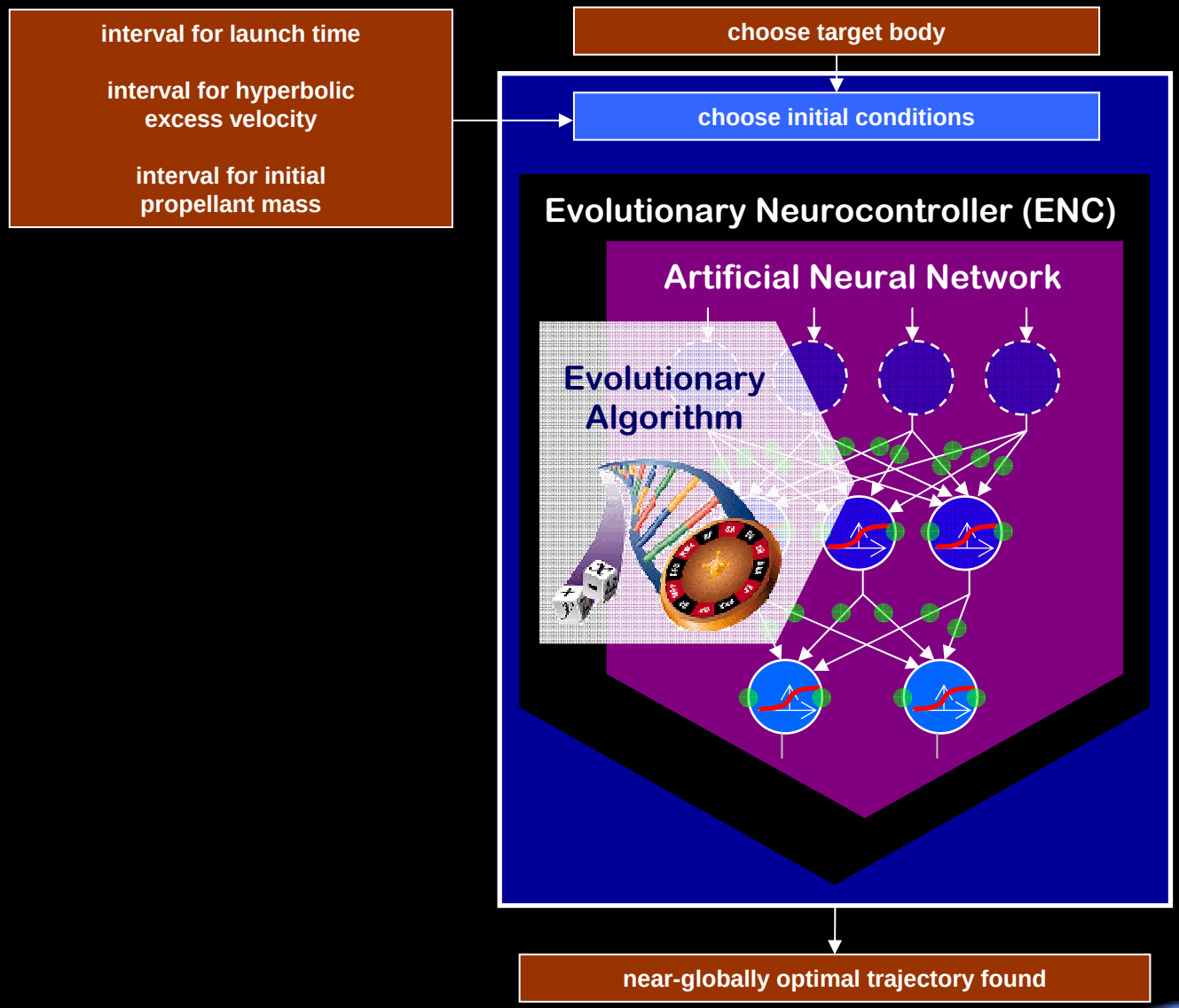
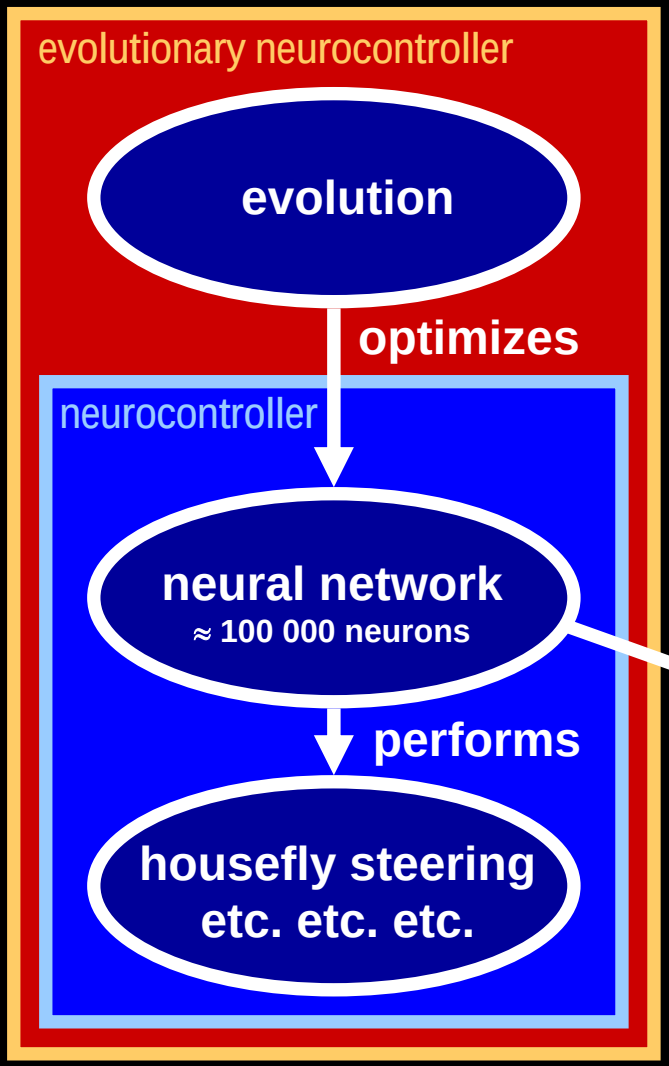
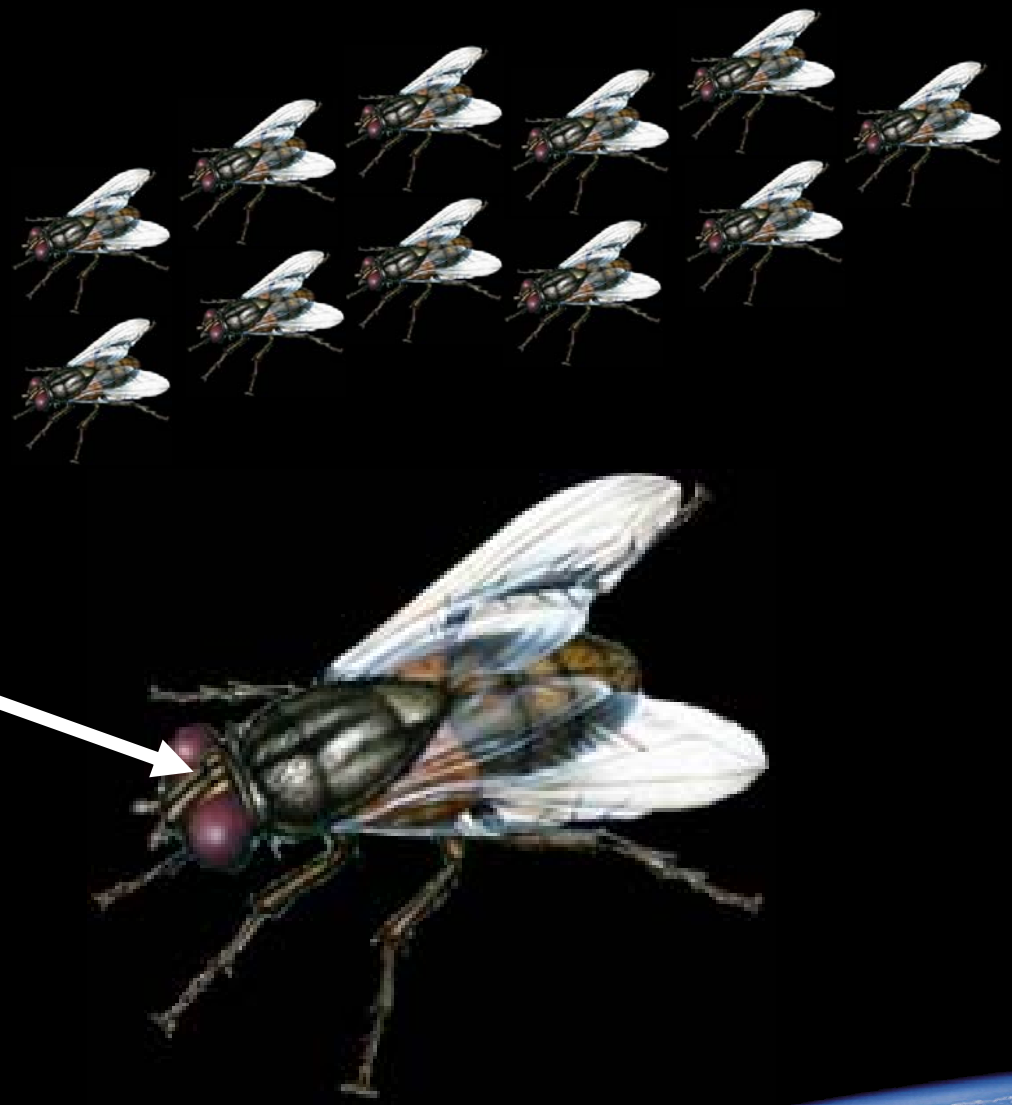
Smart Global Trajectory Optimization



The Flight Control System of the Housefly:

a natural evolutionary neurocontroller (ENC)





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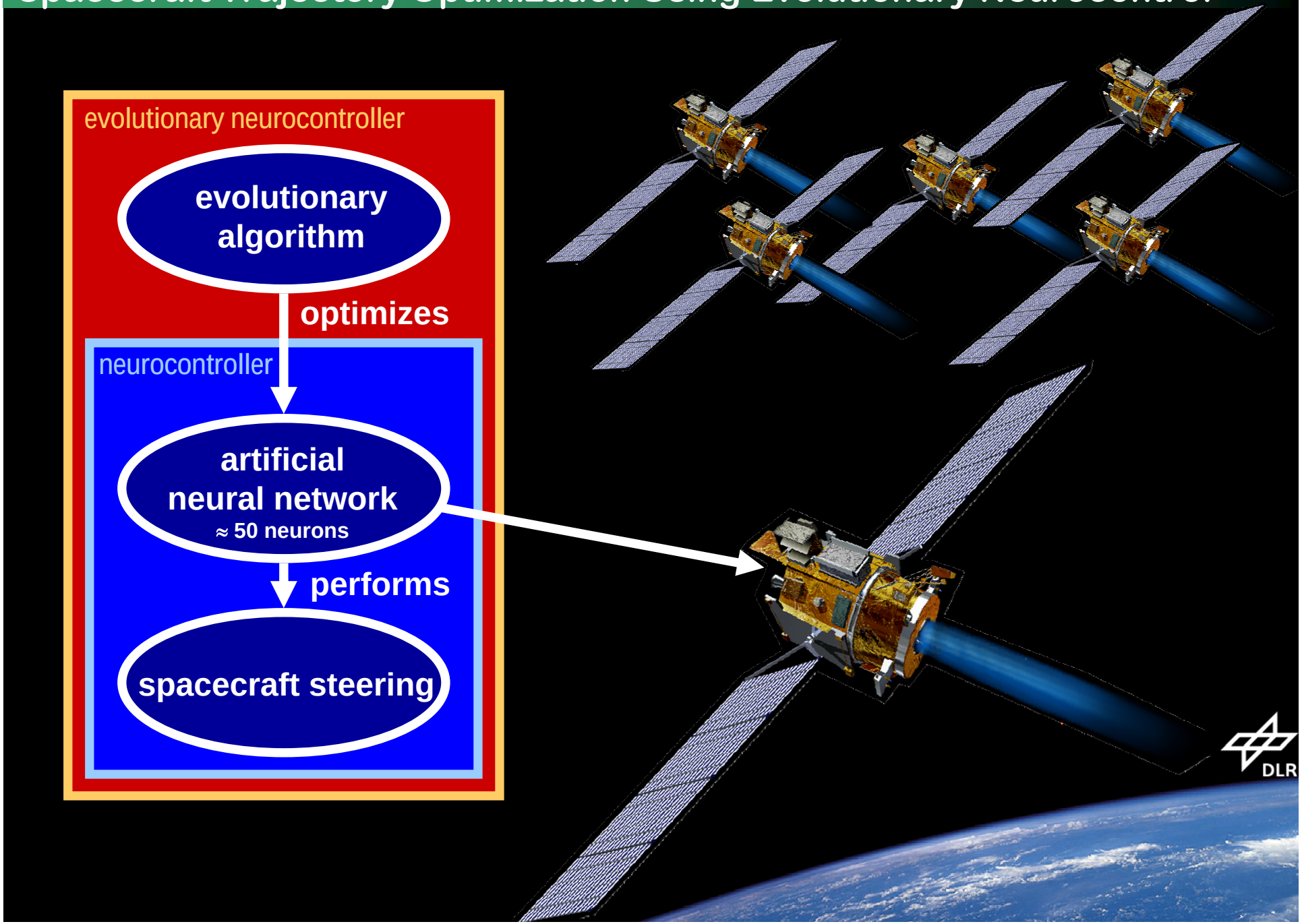
Spacecraft Trajectory Optimization Using Evolutionary Neurocontrol



Artificial Neural Networks

simulating information processing in nervous systems

- information processing and intelligence is based on the propagation of stimuli in neurons
- neurons are built relatively simple and uniform
- complexity is created by the synaptic topology of the nervous system
- learning is performed by changing the synaptic topology and the synaptic efficiency

hippocampal neurons (in culture on silicon)

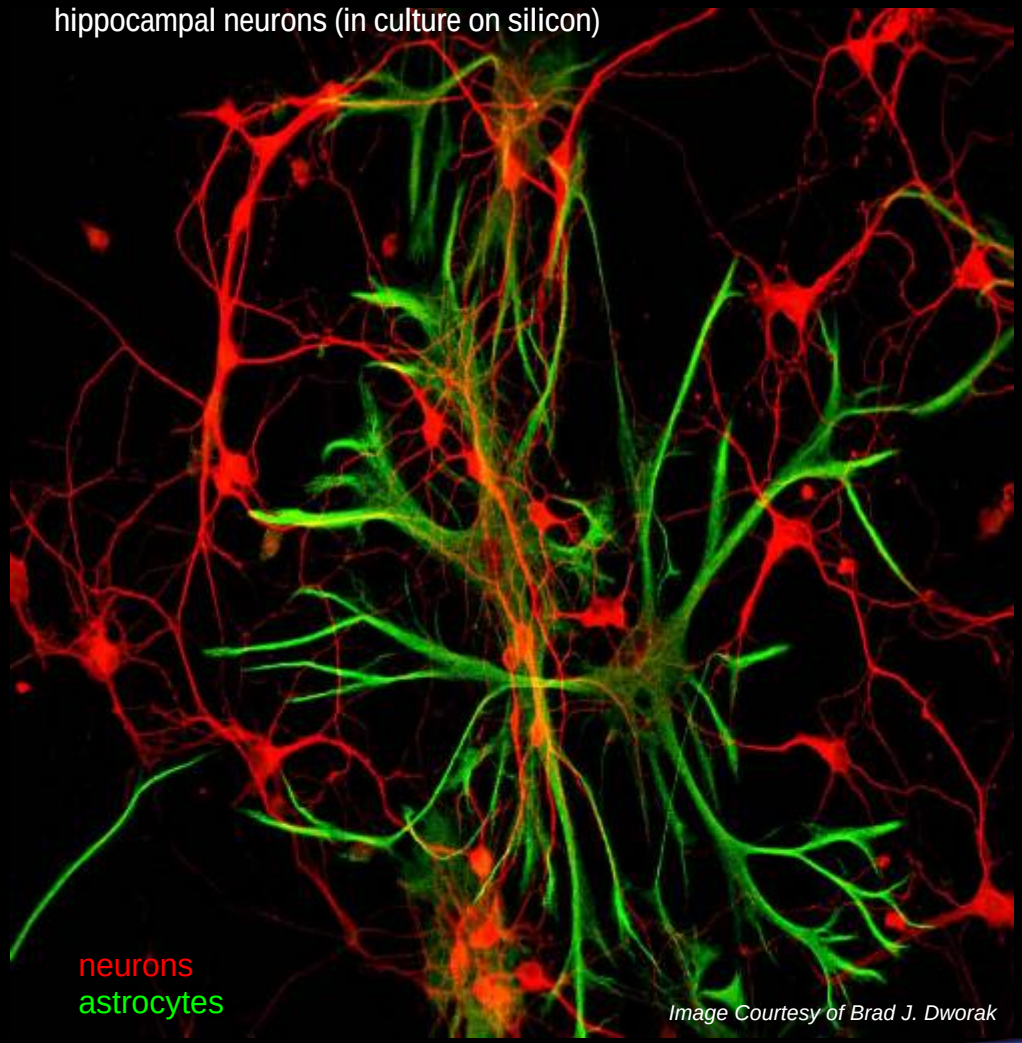
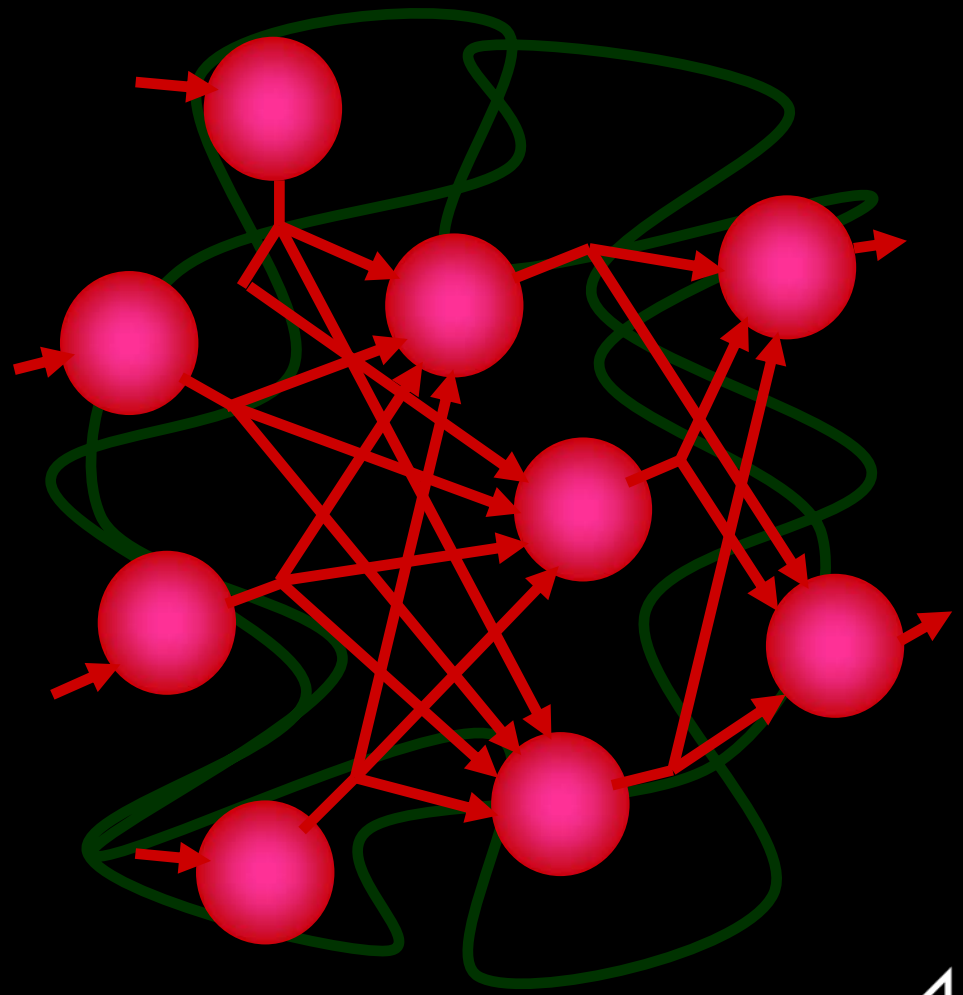


Image Courtesy of Brad J. Dworak

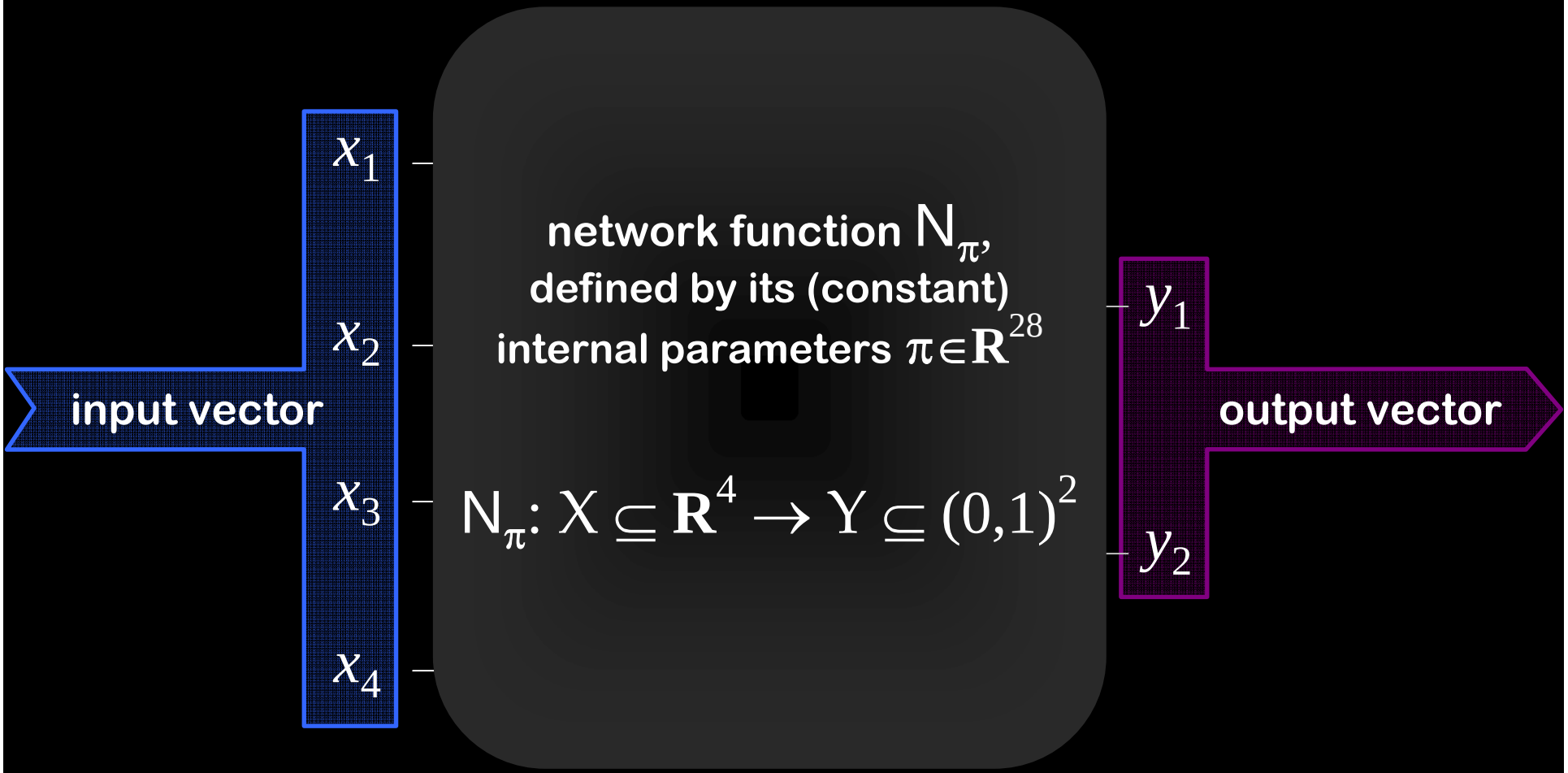
Artificial Neural Networks

- computability paradigm alternative to conventional serial digital computers
  - massively parallel
  - analog
  - fault tolerant
  - adaptive
- comprise information processing elements that model the most essential features of biological neurons
- show some characteristics of the brain
  - learning from experience
  - generalizing from previous examples to new ones
  - extracting essential characteristics from inputs that contain noisy and/or irrelevant data



Artificial Neural Networks

as associative mapping functions



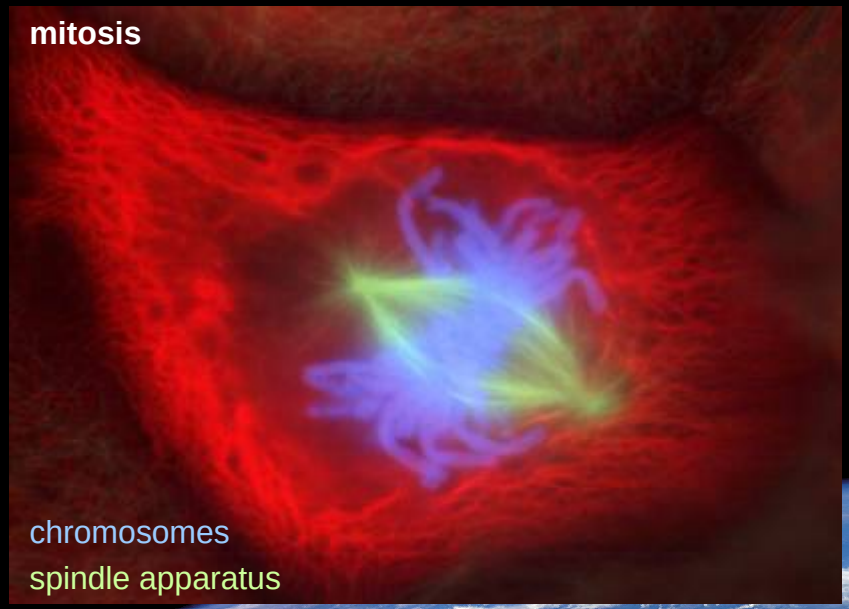
this neural network maps a 4D input space onto a 2D output space

Evolutionary Algorithms

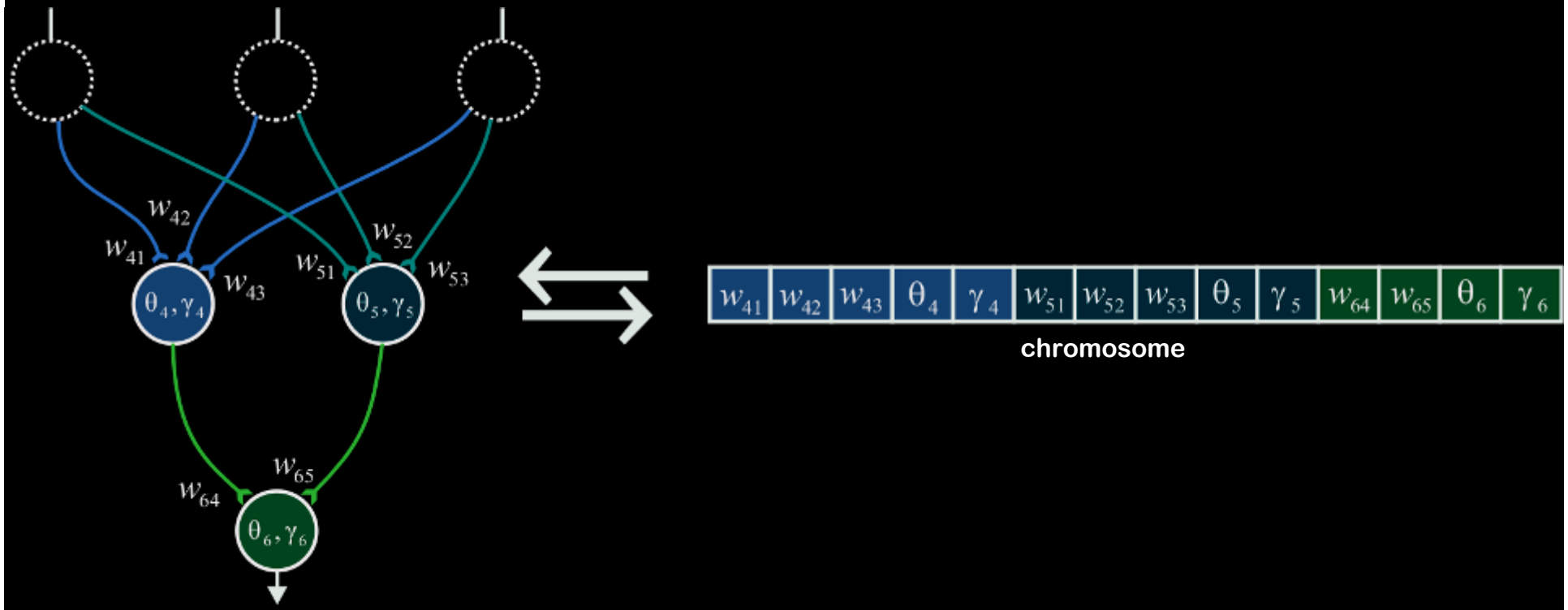
simulating the optimization principles of genetics and evolution

- as a rule, all life forms are most advantageously adapted to their environment, i.e. they are possible solutions to the difficult optimization problem „survive under the current environmental conditions to create offspring"

- evolutionary algorithms are optimization methods based on the principles of genetics and natural evolution
  - inheritance
  - mutation and recombination of genetic material
  - natural selection
  - survival of the fittest

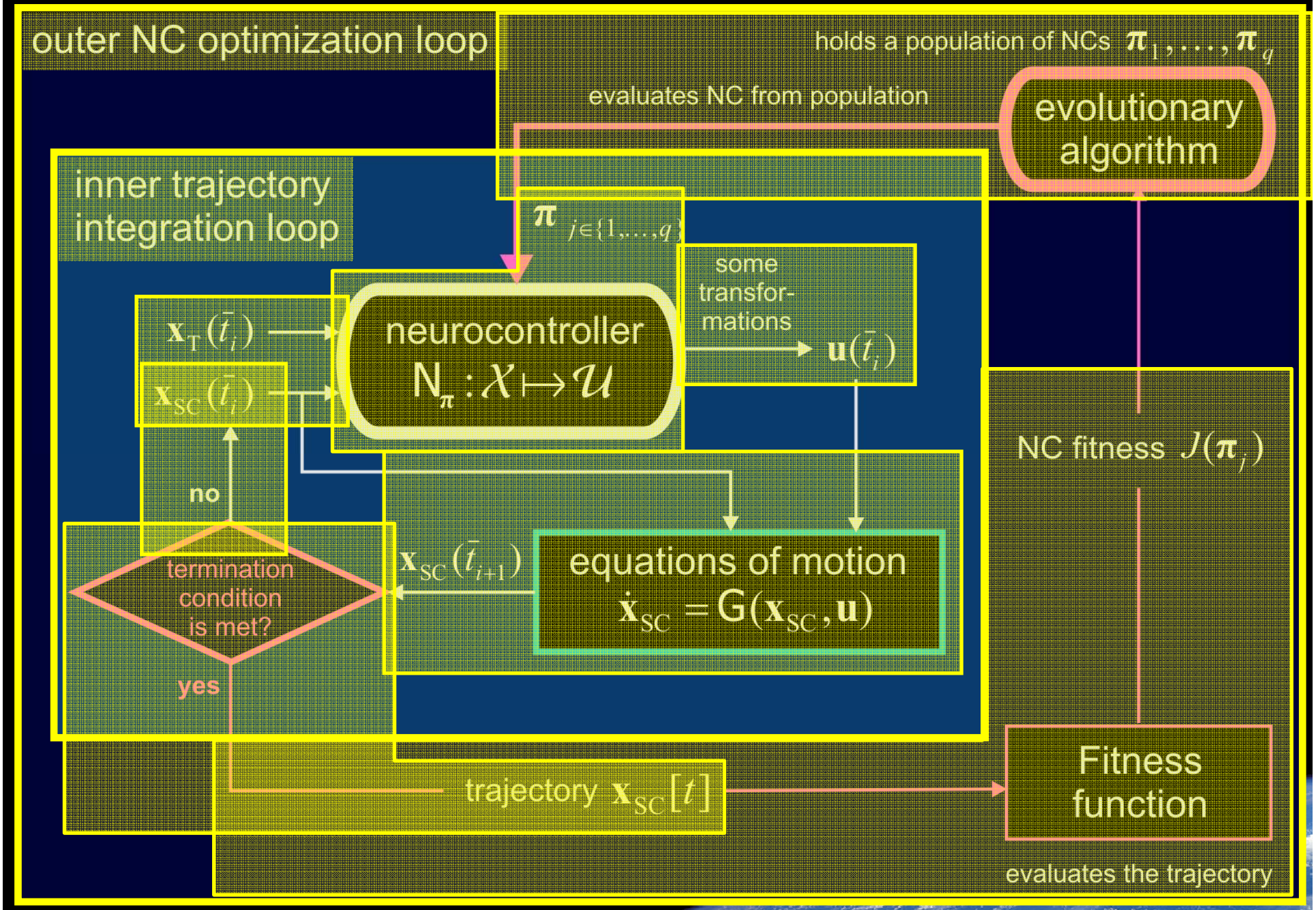


Combining Artificial Neural Networks and Evolutionary Algorithms

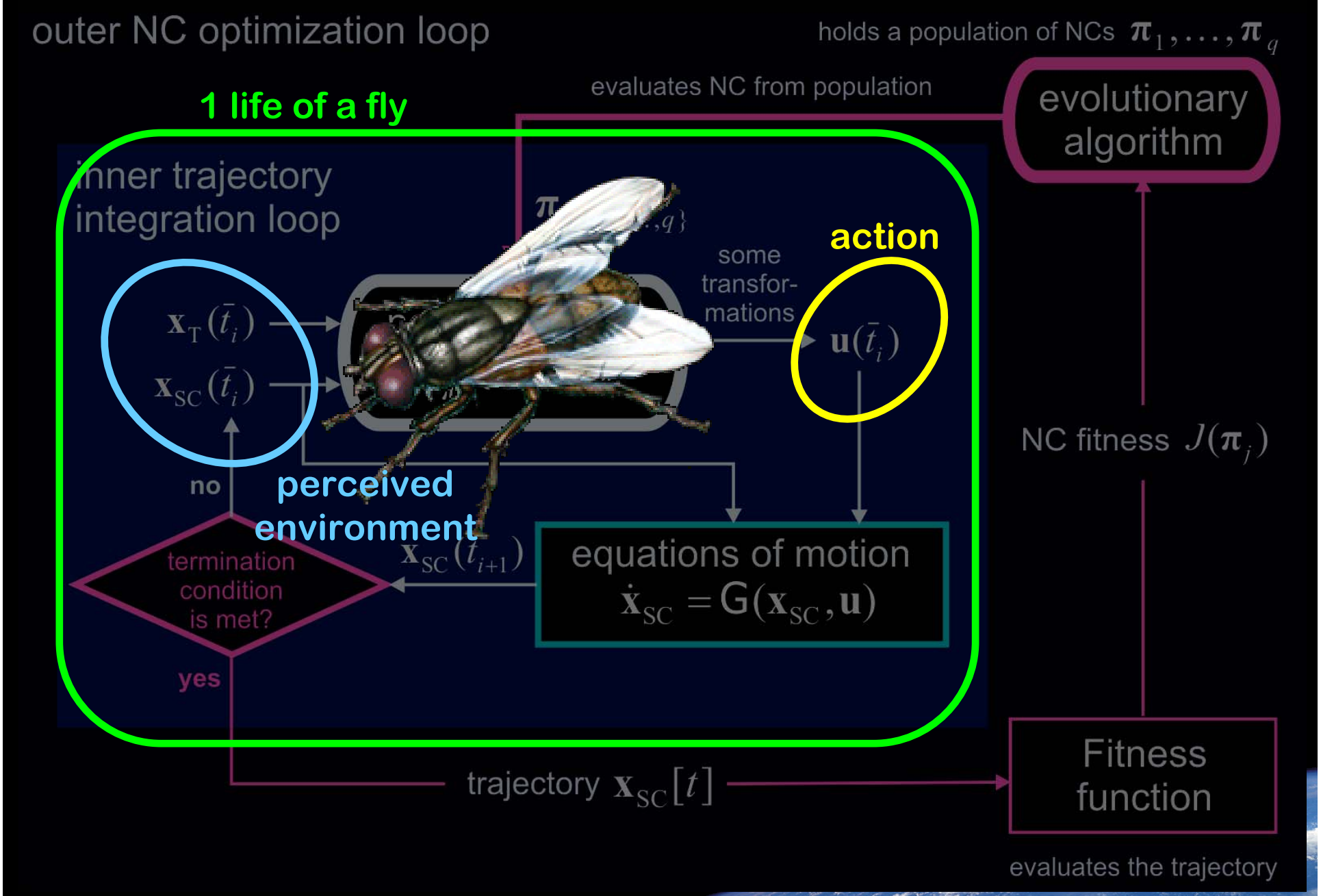


- an artificial neural network can be mapped onto a “chromosome“
- the artificial neural network that performs best on a given task can be „bred“ with an evolutionary algorithm

Trajectory Optimization Using Evolutionary Neurocontrol



Trajectory Optimization Using Evolutionary Neurocontrol



Transformation Chromosome → Trajectory

chromosome/individual/string $\boldsymbol{\xi}$

=

NC parameter set $\boldsymbol{\pi}$

↓

NC network function N

=

spacecraft steering strategy S

↓

spacecraft control function $\mathbf{u}[t]$

↓

spacecraft trajectory $\mathbf{x}_{\mathrm{SC}}[t]$

InTrance: Evolutionary Neurocontrol Implementation

*"**In**telligent **Tra**jectory optimization using **n**euro**c**ontroller **e**volution"*

InTrance uses a non-standard evolutionary algorithm

- **tailored to optimal control problems**
- **based on approaches that have been proposed to avoid the problems associated with standard genetic algorithms**

  - **real-valued parameter encoding**
  - **multi-objective tournament selection**
  - **real delta coding**
  - **non-standard evolutionary operators**
  - **tailored fitness function**

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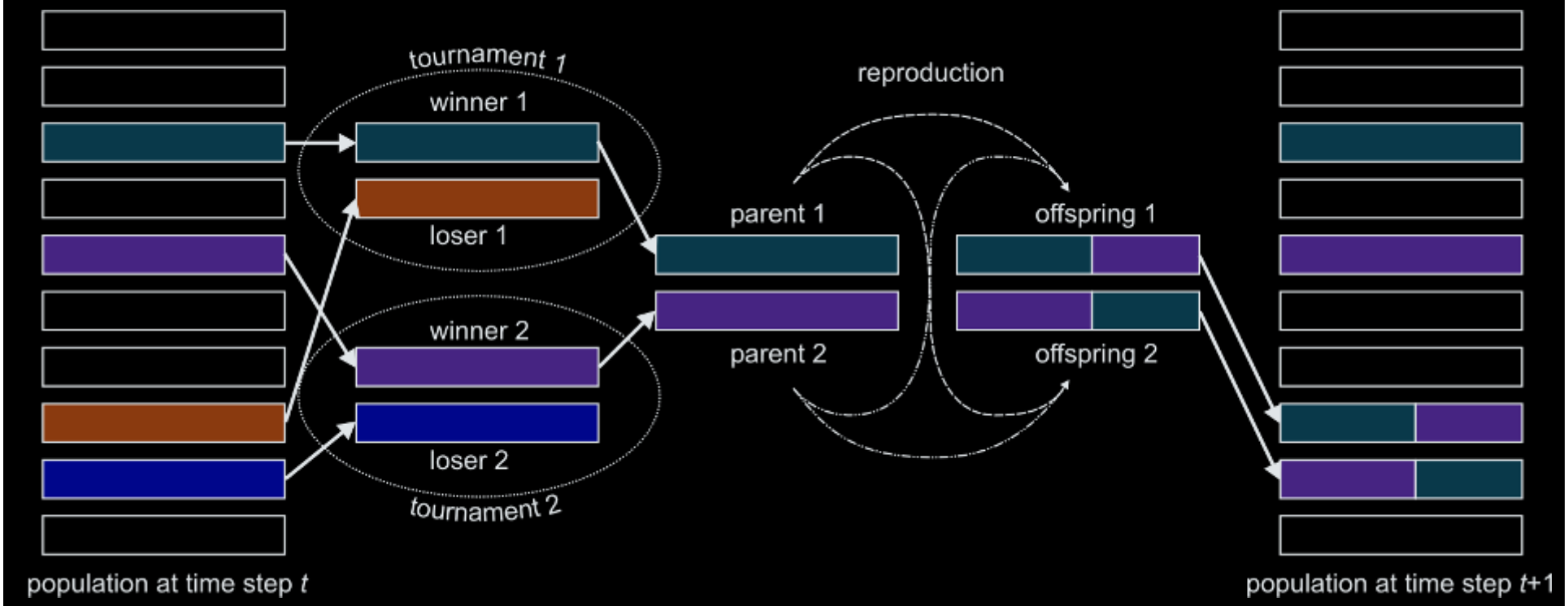
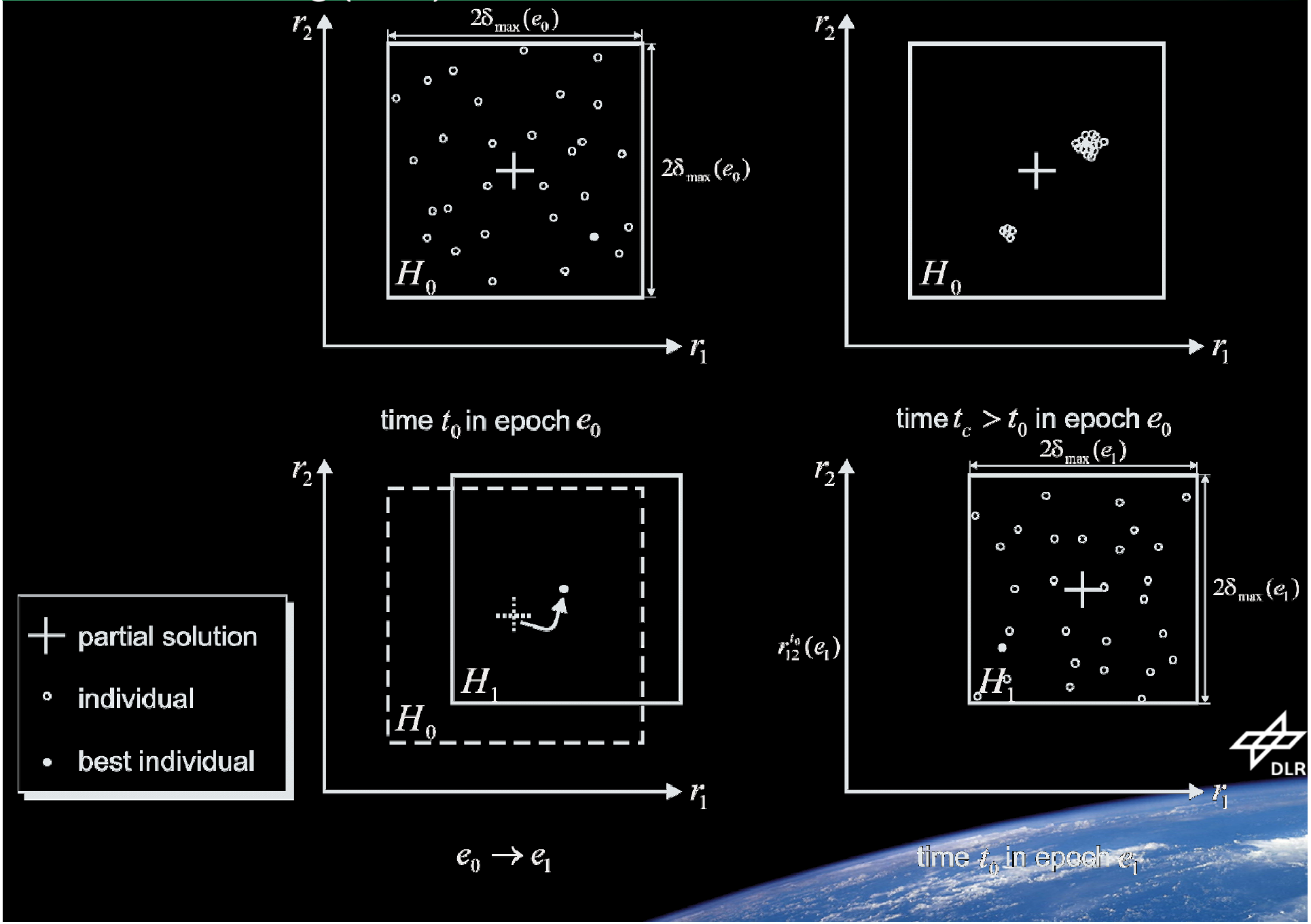
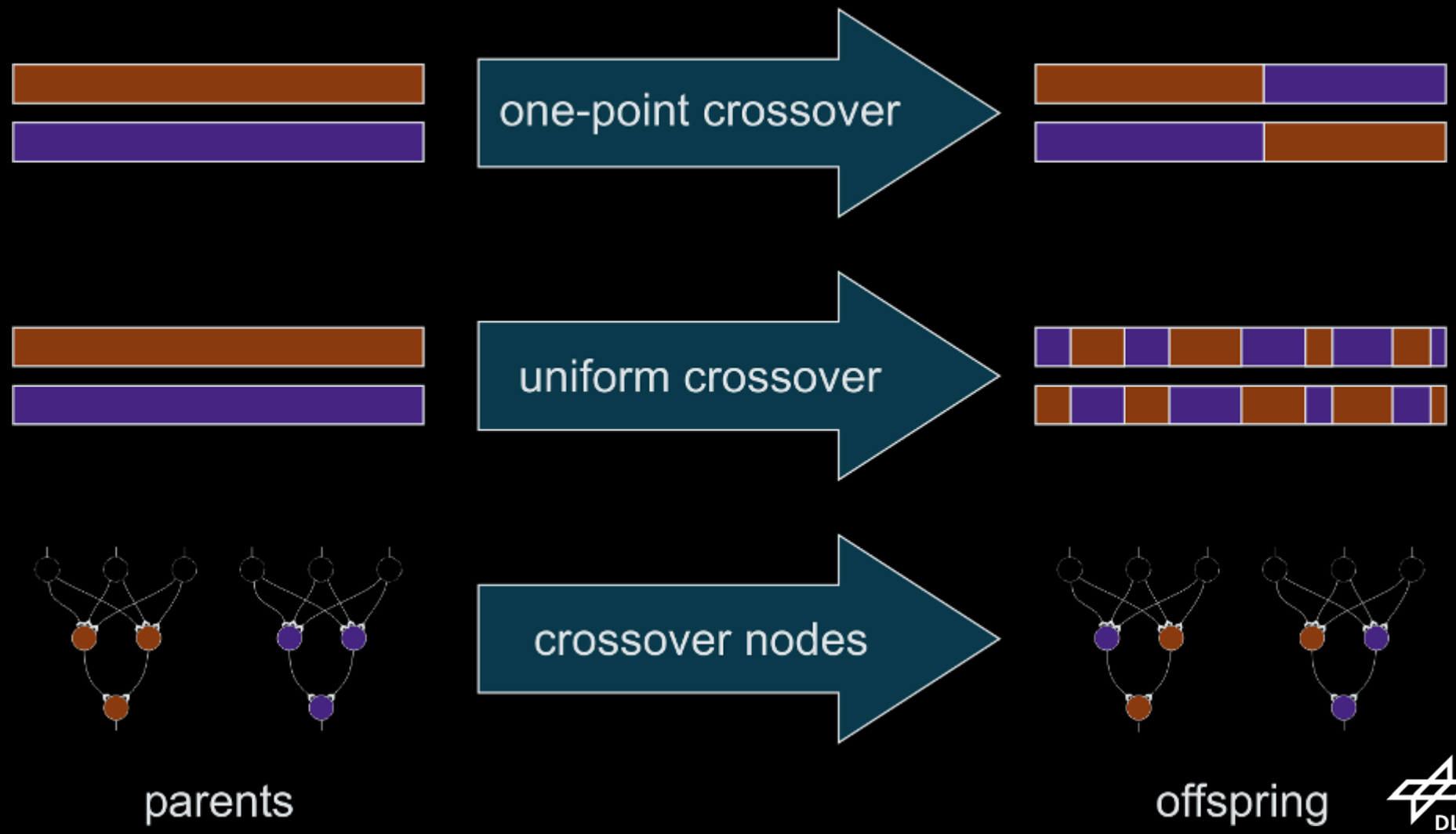
Multi-Objective Tournament Selection



Real Delta Coding (RDC)



Evolutionary Operators



(Sub)fitness Function Definition

$$J = J(J_r, J_v, J_{ACT}) = \begin{cases} -10 & : \quad J_r \leq -10 \\ J_r - J_v & : \quad J_r > -10 \\ J_{ACT} & : \quad J_r > 0 \end{cases}$$

$$J_r = \log_{10}\left(\frac{\Delta r_{max}}{\Delta r_f}\right)$$

$$J_v = \frac{|\vec{v}_f|}{v_{max}}$$

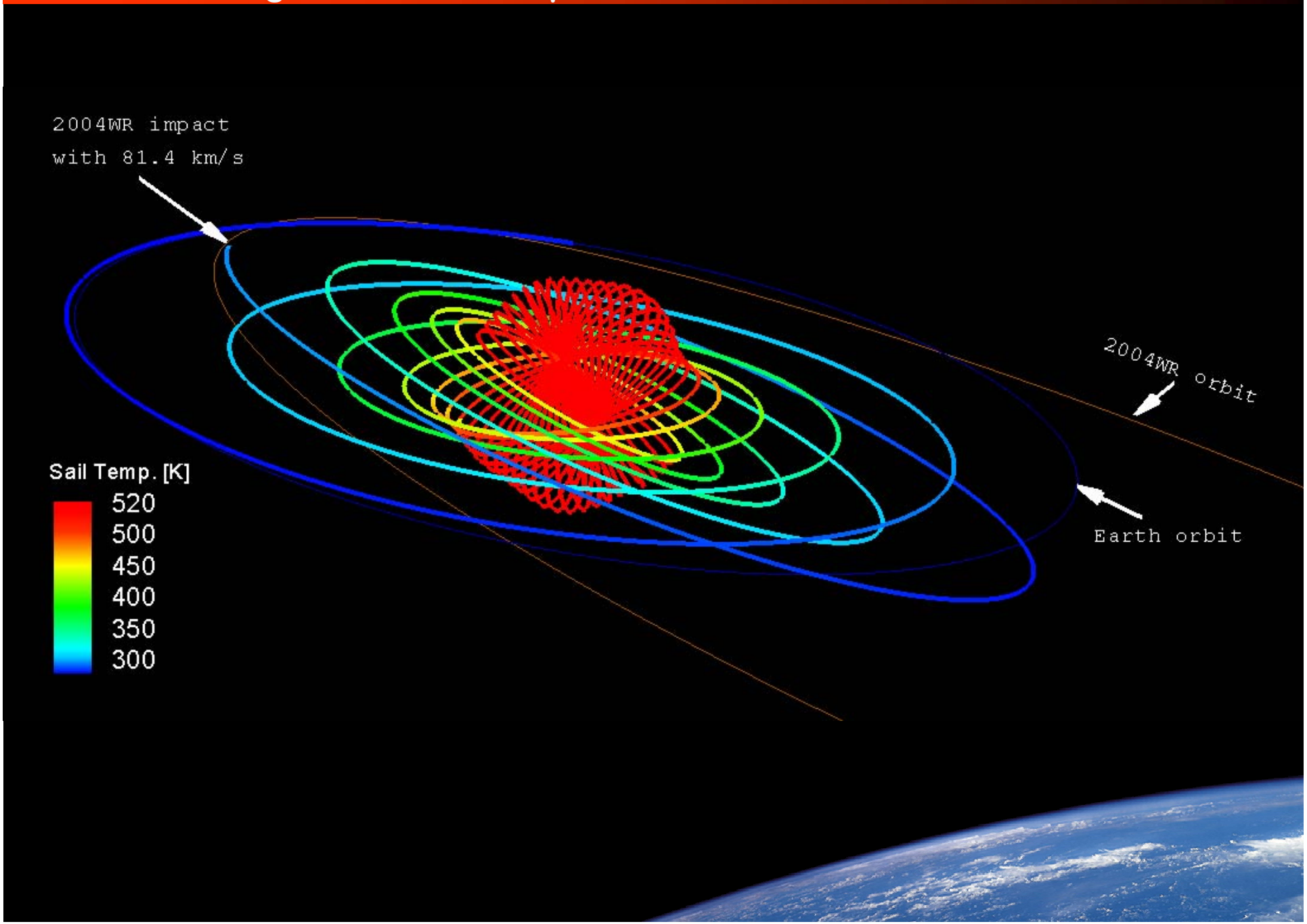
$$J_{ACT} = m_f \cdot \left| \underbrace{\left(\vec{v}_{ast} - \vec{v}_f\right)}_{\vec{U}_{rel}} \cdot \vec{v}_{ast} \right|$$

maximum final distance

achieved final distance

„guidance“ velocity (6..8 km/s)

InTrance: Retrograde Asteroid Impact with a Solar Sail



Determination of Optimal Launch and Impact Date

- asteroid has highest orbital velocity at perihelion
- s/c must impact impact asteroid at its perihelion with low transversal velocity (or even negative transversal velocity $\Rightarrow$ retrograde impact)
- without gravity assists, we considered a retrograde impact to be infeasible
- what would be the optimal impact orbit?
- our first guess (before the first optimization runs):
    - perihelion must be as close as possible near the sun (0.2 AU constraint)
    - aphelion must be at asteroids perihelion

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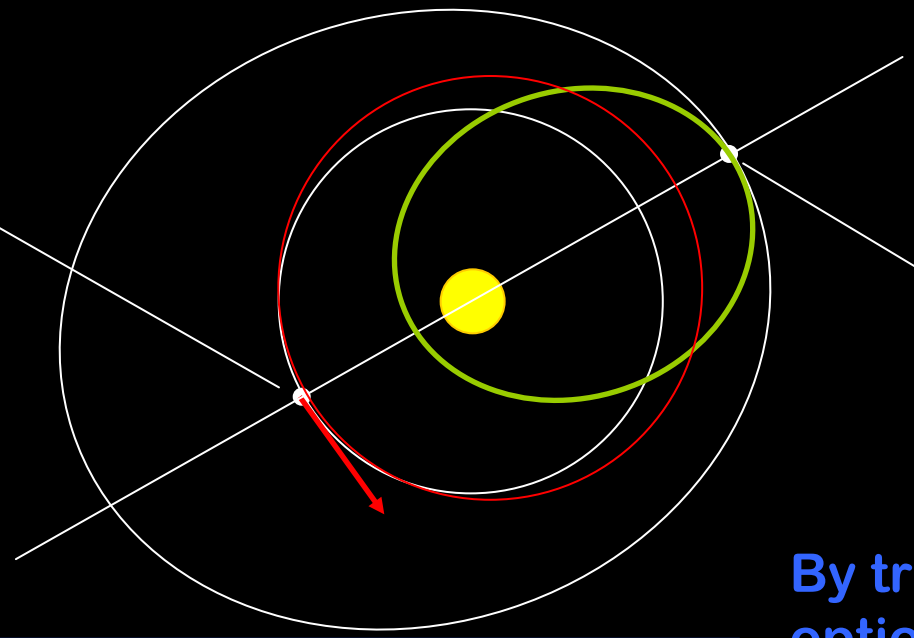
Optimal Launch Constellation

Option 1:

launch at Earth with injection in direction of Earth's orbital velocity

⇒ raises aphelion



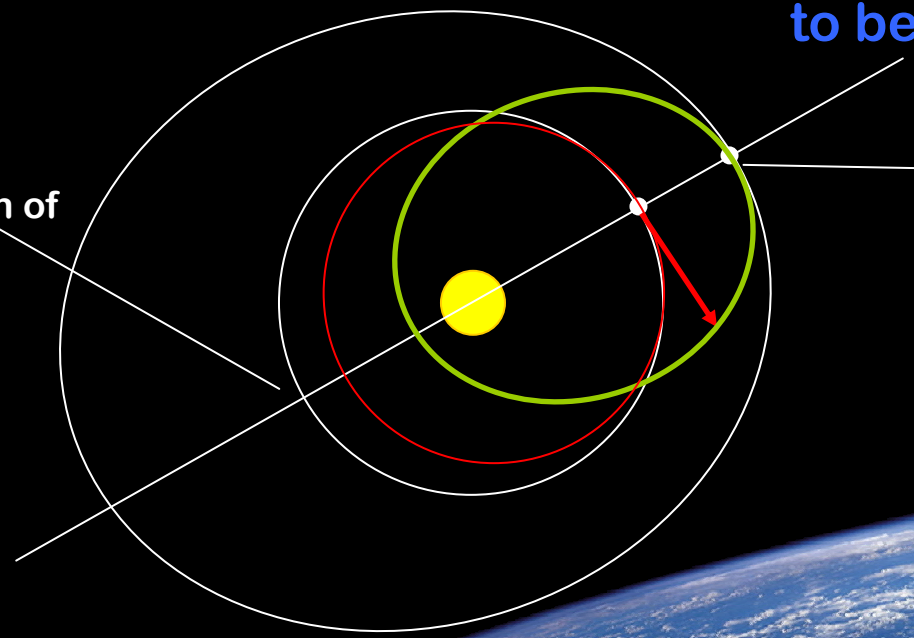
asteroid impact at its aphelion passage

By trial & error, option 1 was found to be superior

Option 2:

launch at Earth with injection against direction of Earth's orbital velocity

⇒ lowers perihelion



asteroid impact at its aphelion passage

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Optimal Launch Constellation

Option 1:

launch at Earth with injection in direction of Earth's orbital velocity

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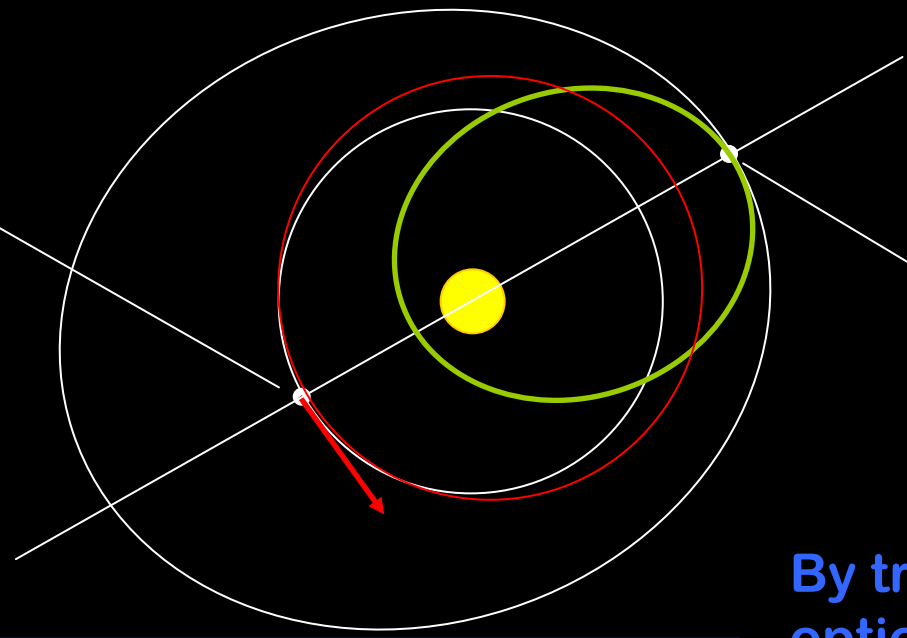

asteroid impact at its aphelion passage

By trial & error, option 1 was found to be superior

the longest interval between the Earth being at launch position and the asteroid being at the impact position is 10880.2 days

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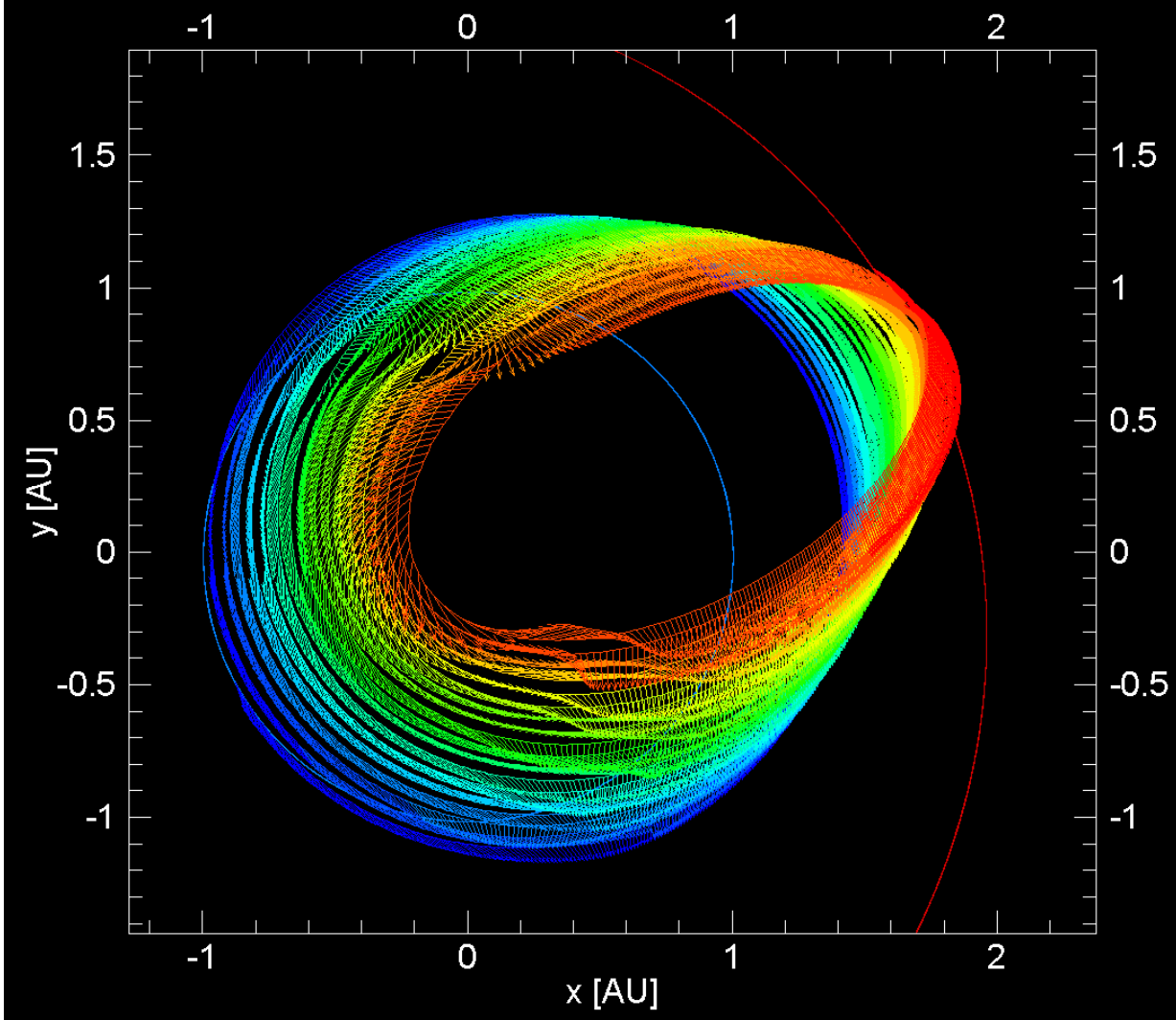
Best Solution with Variable Control



Launch time:
19 Apr 2014 (MJD2000 5222.181)

Hyperbolic excess velocity:
2.5 km/s

Arrival time:
09 Apr 2035 (MJD2000 12882.181)

Impact velocity:
16.28552 km/s

Flight time:
7,660 days (20.972 years)

Final mass:
768.0744 kg

Objective function value:
292071.194

Final distance to target:
99,952 km

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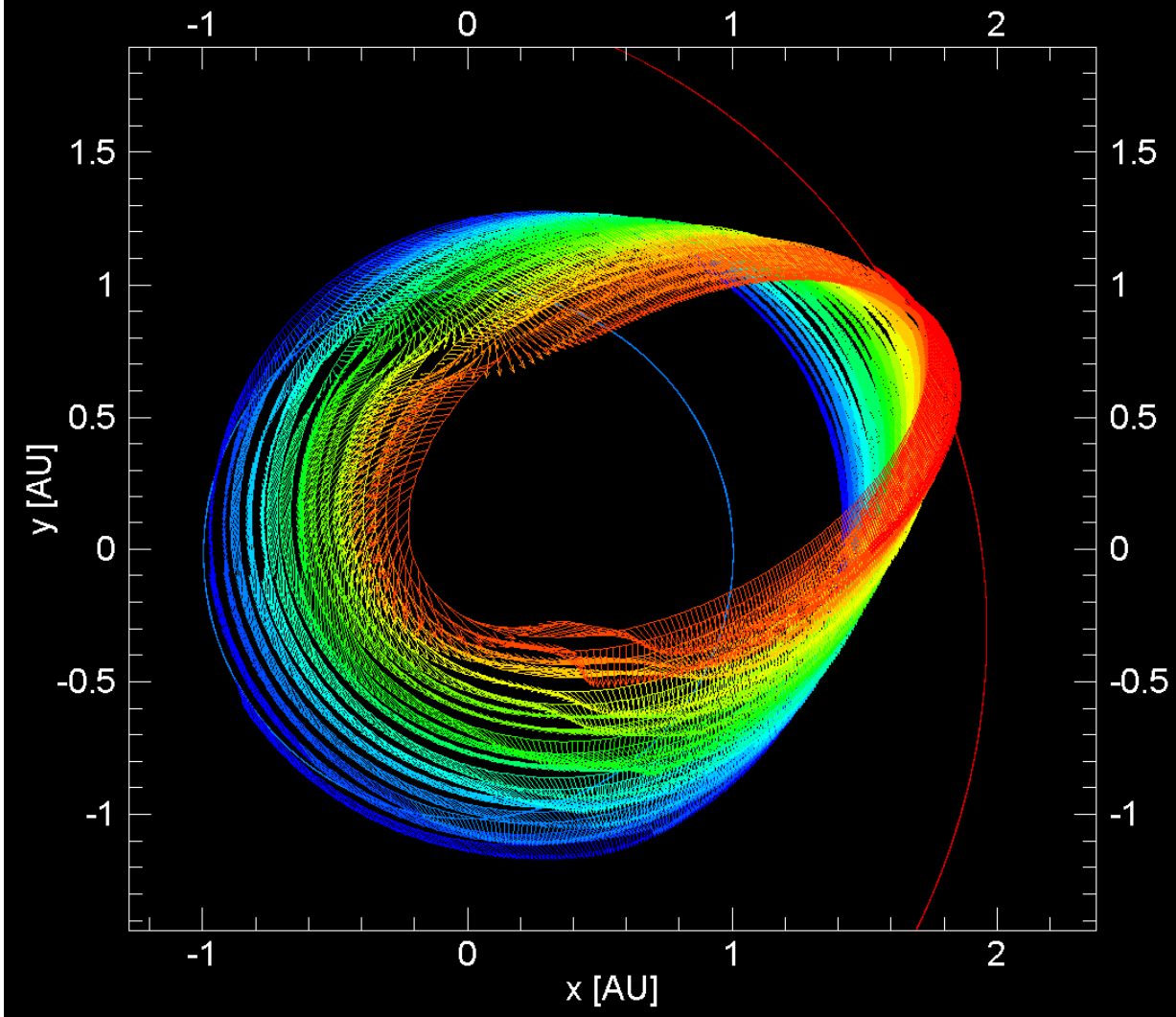
Best Solution with Variable Control - Surprises



- no coast phases
- aphelion of s/c orbit is larger than asteroid's perihelion
- ⇒ the line of apsides of the impact orbit is slightly rotated
- ⇒ transveral velocity component is lower ...
- ... but it costs propellant
- ⇒ optimizer must perform a trade-off between aphelion of impact orbit and consumed propellant

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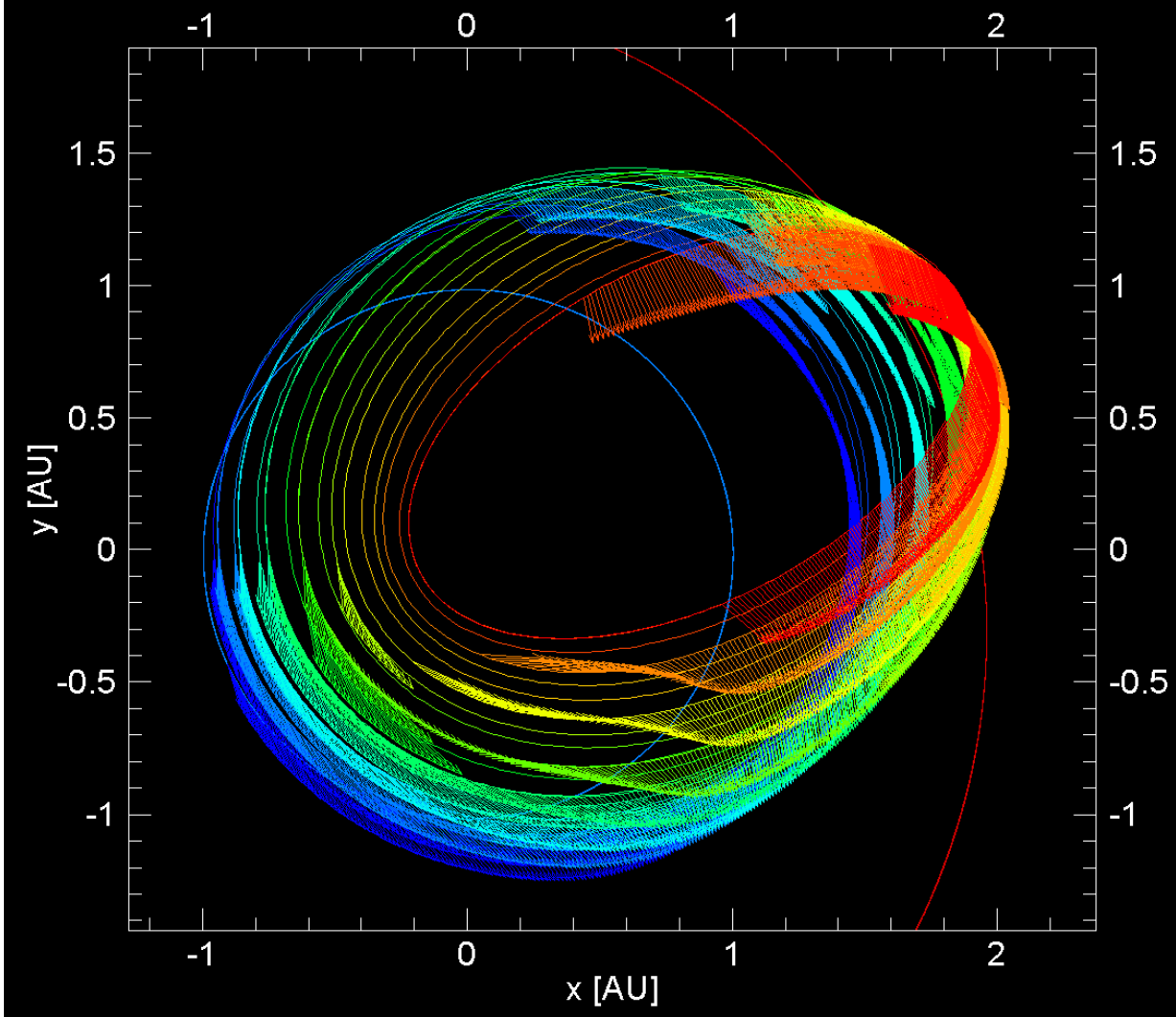
Best Solution with Bang-Bang Control



Launch time:
15 Apr 2026 (MJD2000 9601.415)

Hyperbolic excess velocity:
2.5 km/s

Arrival time:
11 Feb 2056 (MJD2000 20495.415)

Impact velocity:
18.58612 km/s

Flight time:
10,894 days (29.826 years)

Final mass:
838.3076 kg

Objective function value:
337,015.018

Final distance to target:
9,991,860 km (0.0679 AU)

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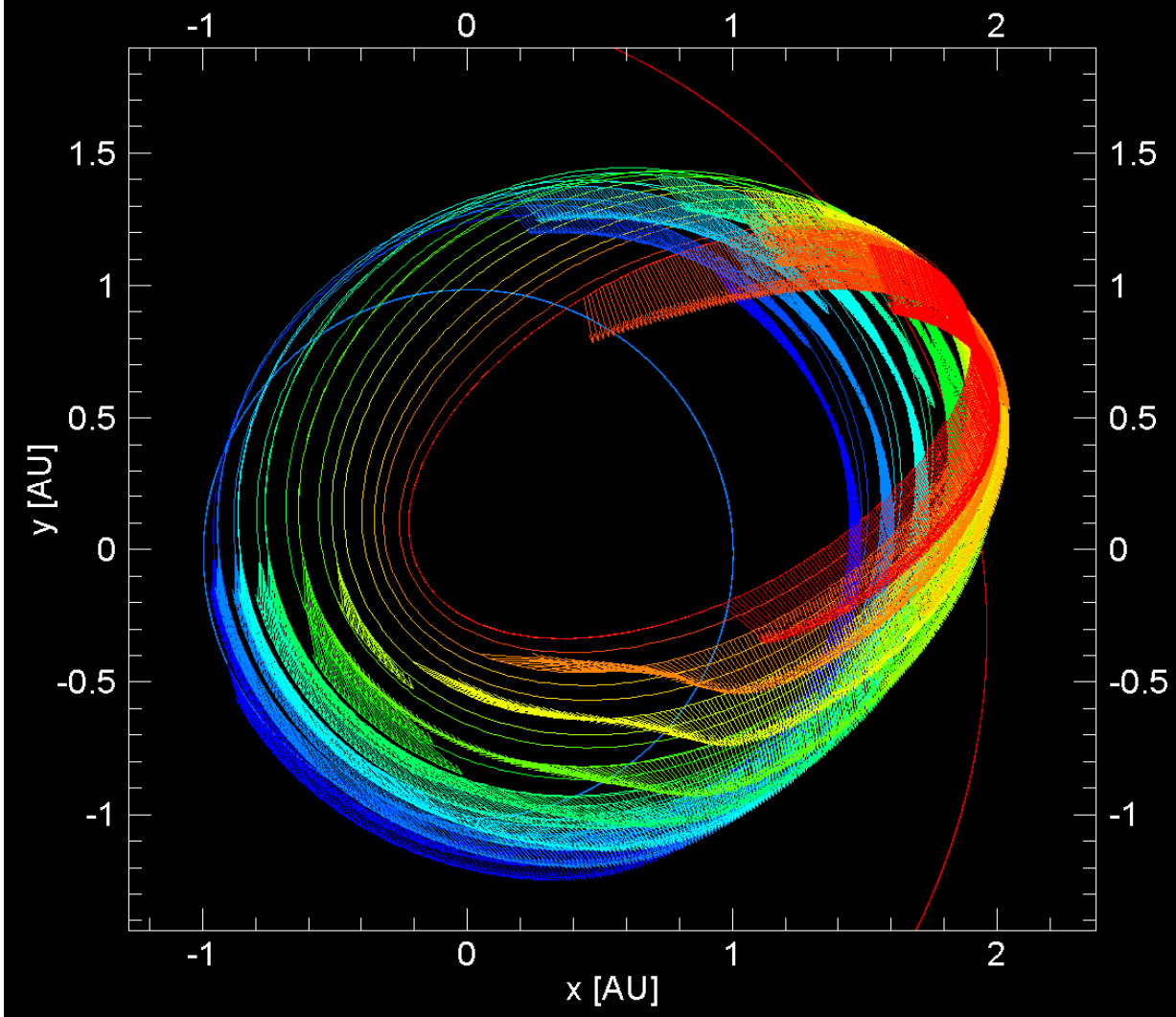
Best Solution with Bang-Bang Control



- coast phases occur
- aphelion of s/c orbit is again larger than asteroid's perihelion
- ⇒ the line of apsides of the impact orbit is again slightly rotated
- the distribution of thrust and coast phases is clearly sub-optimal
- the trajectory looks ugly

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Why has InTrance not found the global optimum (without gravity assist) ?

- In Trance has problems with finetuning the solution locally because it is not an analytic method
- InTrance is not good for finding solutions for problems with very tight final constraints
- the tighter the requested accuracy of the final constraint, the easier it get‘s stuck to a local optimum because
  - it first optimizes the accuracy of the final constraint and then
  - it optimizes the objective function
  - (thereby it is not allowed to „loose the final constraint“ again)
- the basin of attraction of the global solution seems to be very small because slightest changes in the steering result in “loosing the final constraint”
- Therefore, InTrance searches for more robust solutions w.r.t. changes in the steering
- $\Rightarrow$ InTrance should be hybridized with a local optimization method
- $\Rightarrow$ gravity assist trajectory optimization should be implemented into InTrance

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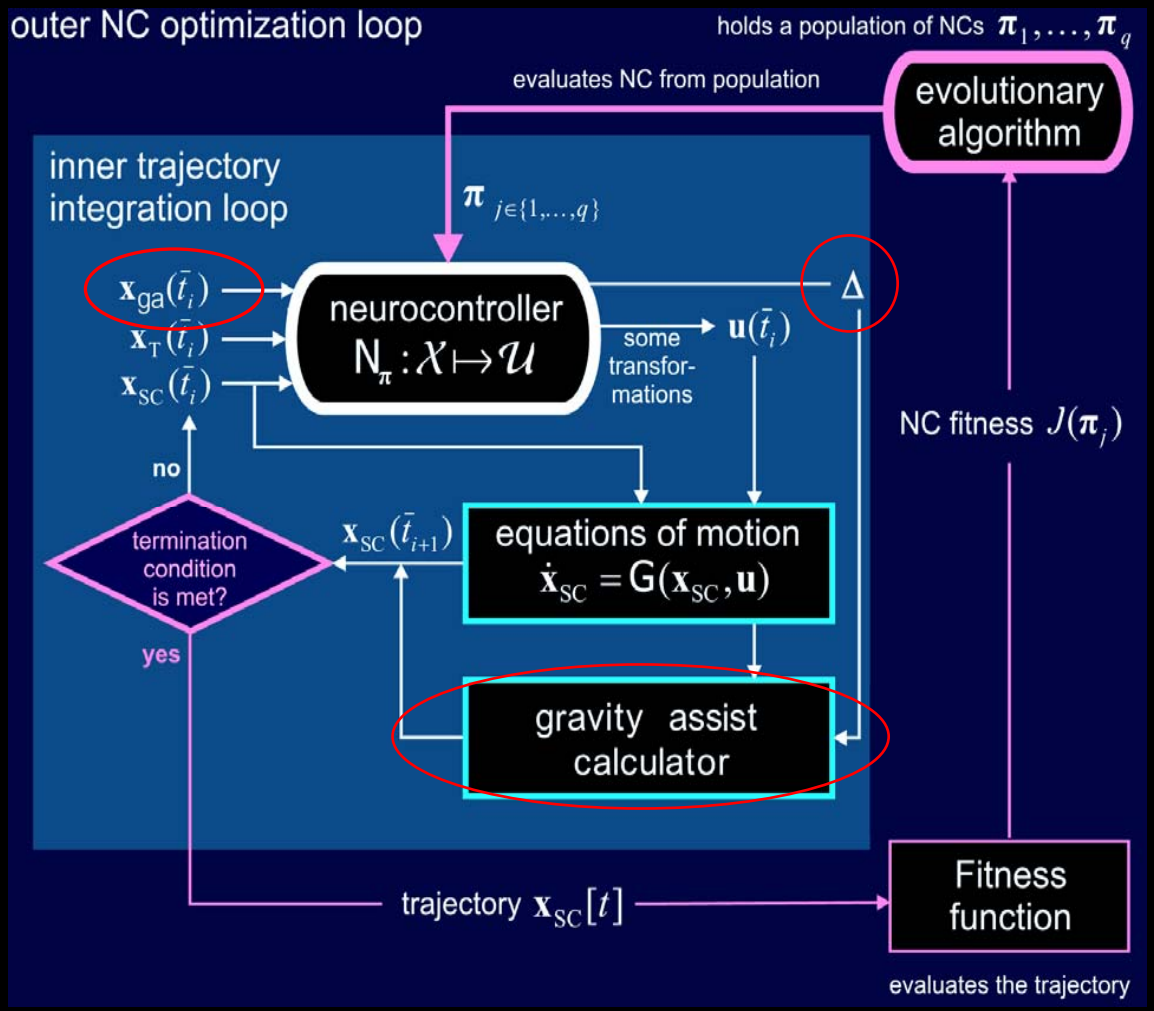
Outlook: Preliminary Investigation of InTrance with Gravity Assist (InTranceGA)



Generating the aiming point on the B-plane with the ENC

- ✓ the GA parameters are co-optimized by the EA.
- ✓ At every integration step a Δ is provided so that every GA is optimized.
- ✗ The task for the EA is extremely difficult!

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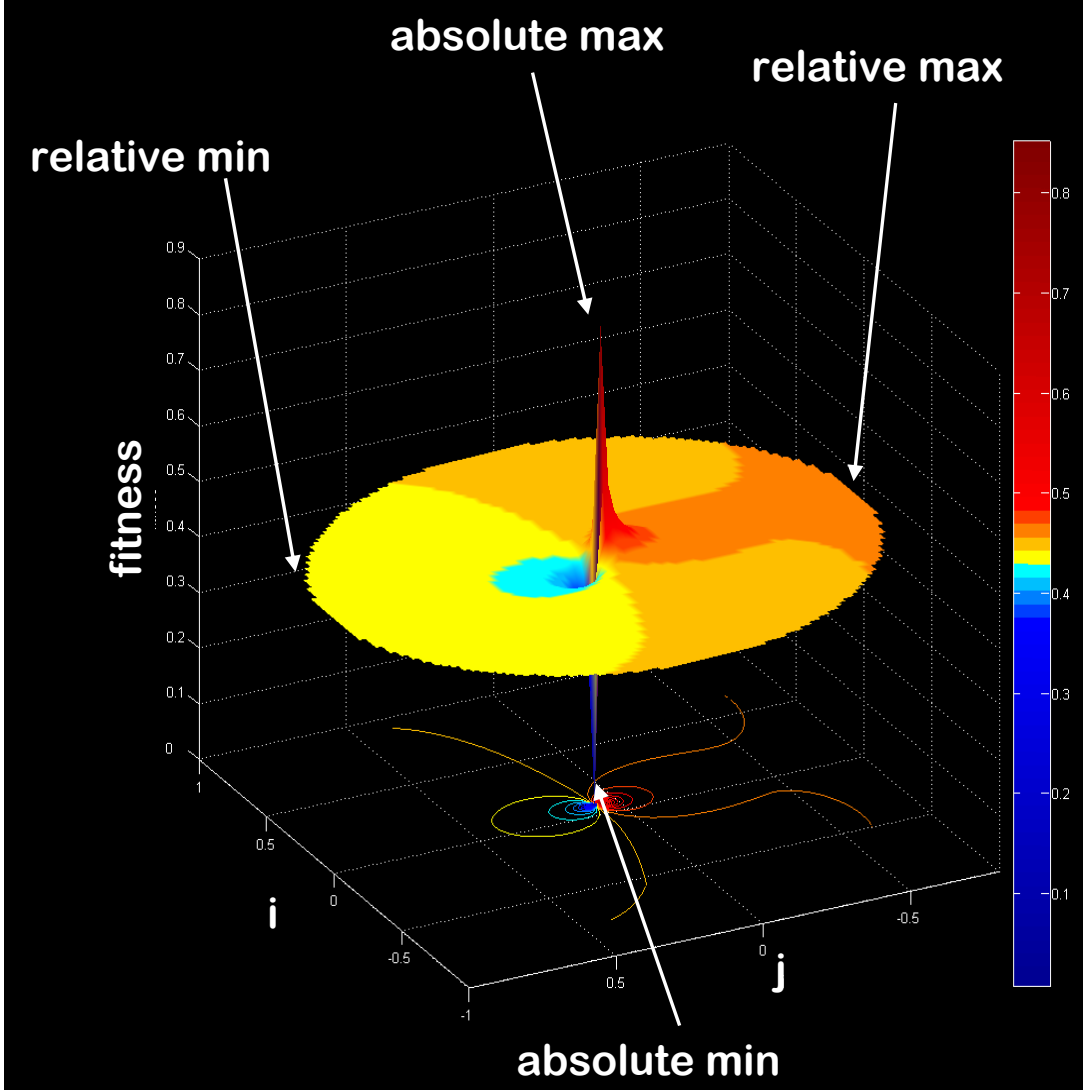
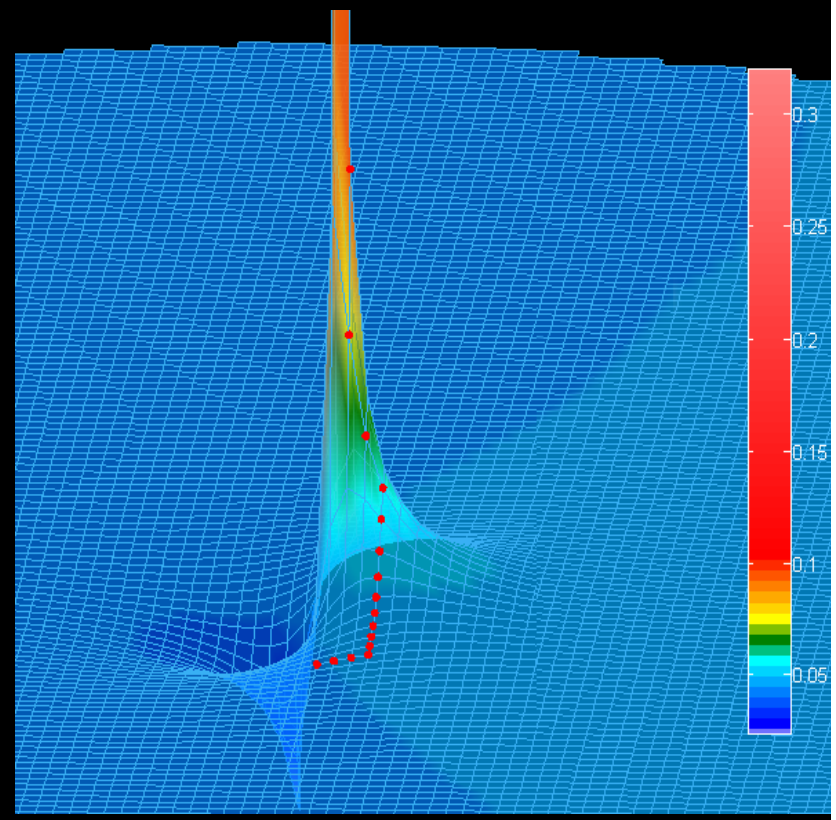
Outlook: InTranceGA: Optimization of B-Plane Aiming with a Hill-Climber





GA maneuver optimization

in 16 iterations

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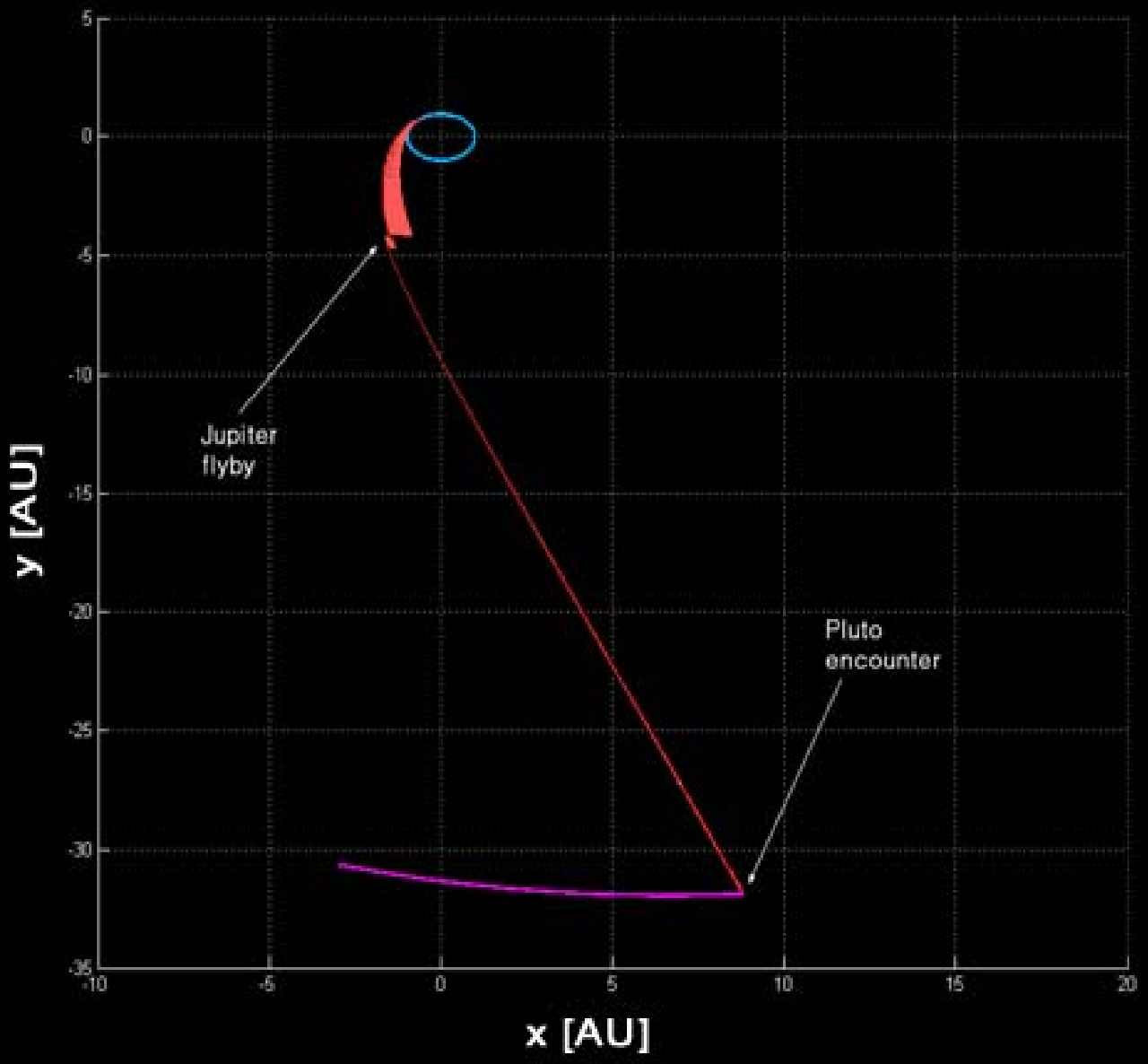
Outlook: InTranceGA Results – Pluto Flyby



Outlook: InTranceGA Results – Mercury Rendezvous