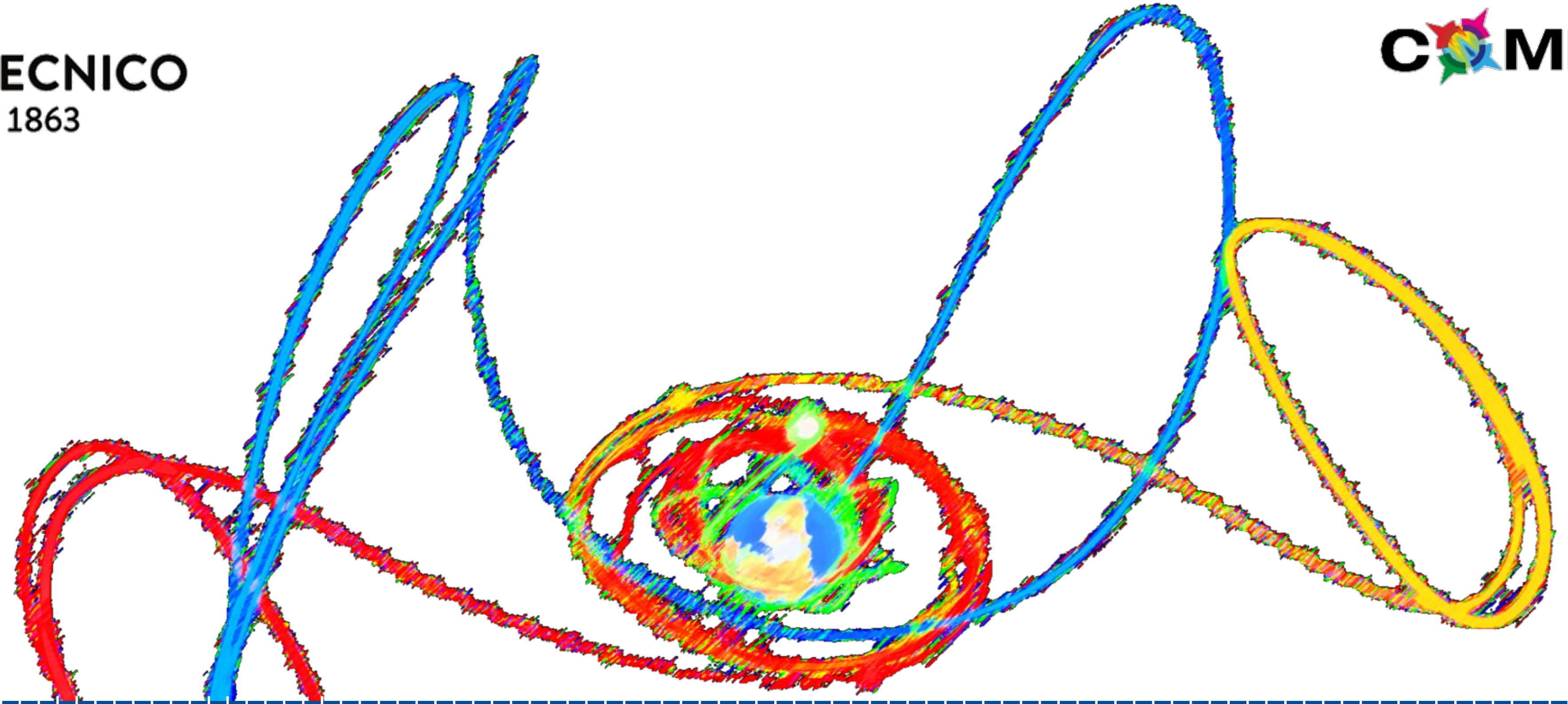


Near-Earth Objects deflection strategies: a multicriteria comparison for the target asteroid 2023 PDC

Samuele Alberti, Camilla Colombo

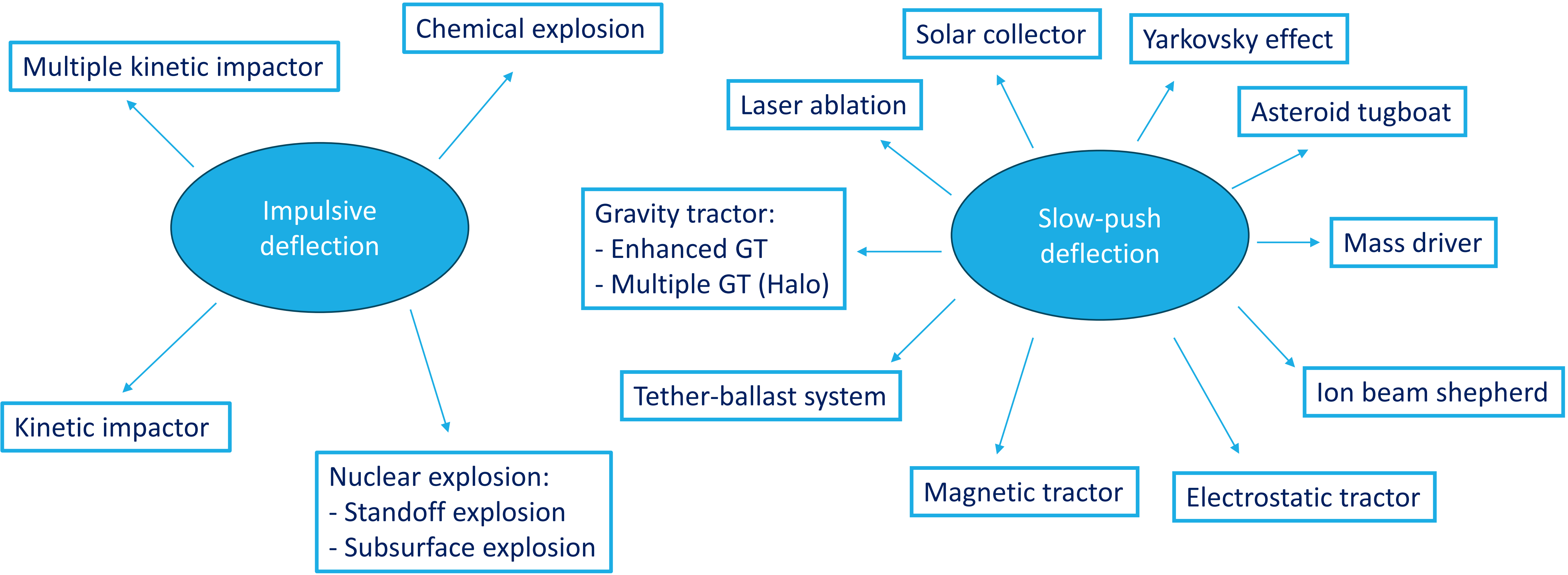
ASI delegation

SMPAG, 31 January 2024

Aim of the work

- Describe and model mathematically the deflection strategies
- Qualitative and quantitative comparison, based on: TRL, Δv provided, effectiveness, warning time, mission complexity asteroid properties
- Mult objective Pareto optimisation of four selected strategies (target 2023 PDC)
- Analyse alternative to nuclear explosion solution where possible

Asteroid deflection strategies



Impulsive deflection

Multiple kinetic impactor

Chemical explosion

Kinetic impactor

Nuclear explosion:
- Standoff explosion
- Subsurface explosion

Slow-push deflection

Laser ablation

Solar collector

Yarkovsky effect

Asteroid tugboat

Gravity tractor:
- Enhanced GT
- Multiple GT (Halo)

Mass driver

Tether-ballast system

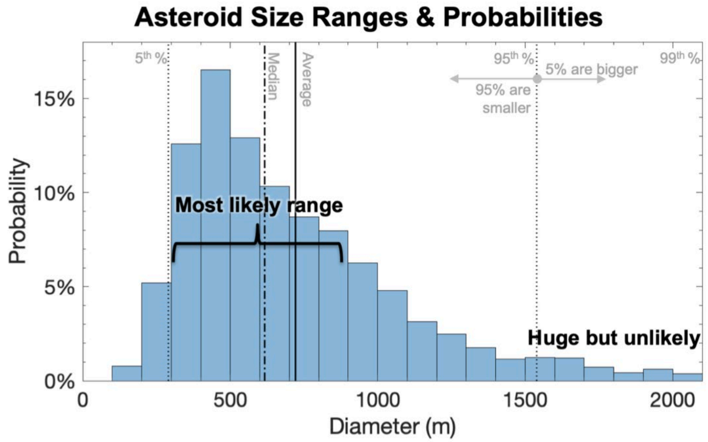
Magnetic tractor

Electrostatic tractor

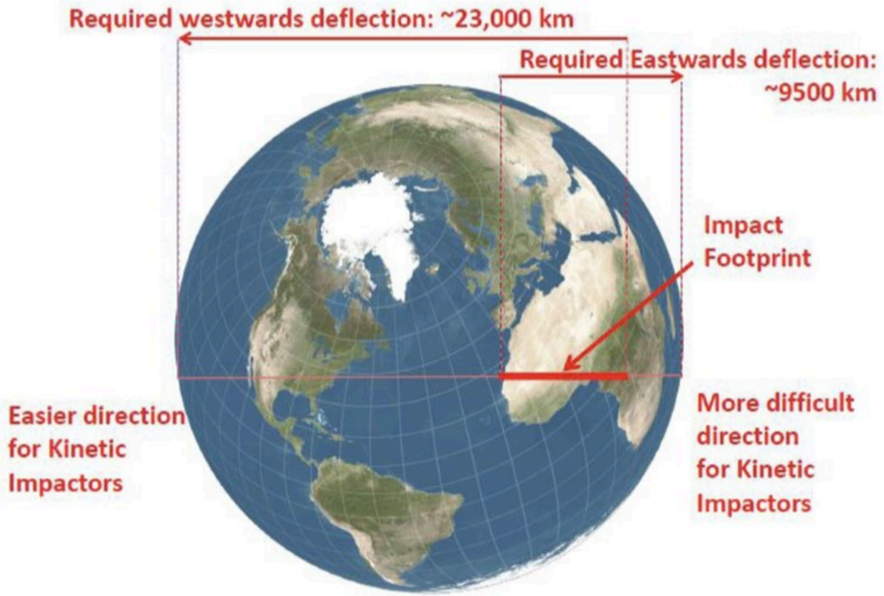
Ion beam shepherd

ASTEROID 2023 PDC

Parameter	First case 5th % percentile	Second case 50th % percentile	Third case 95th % percentile
Mass	$2.6 \cdot 10^{10}$	$2.5 \cdot 10^{11}$	$3.8 \cdot 10^{12}$
Diametre	290	617	1539

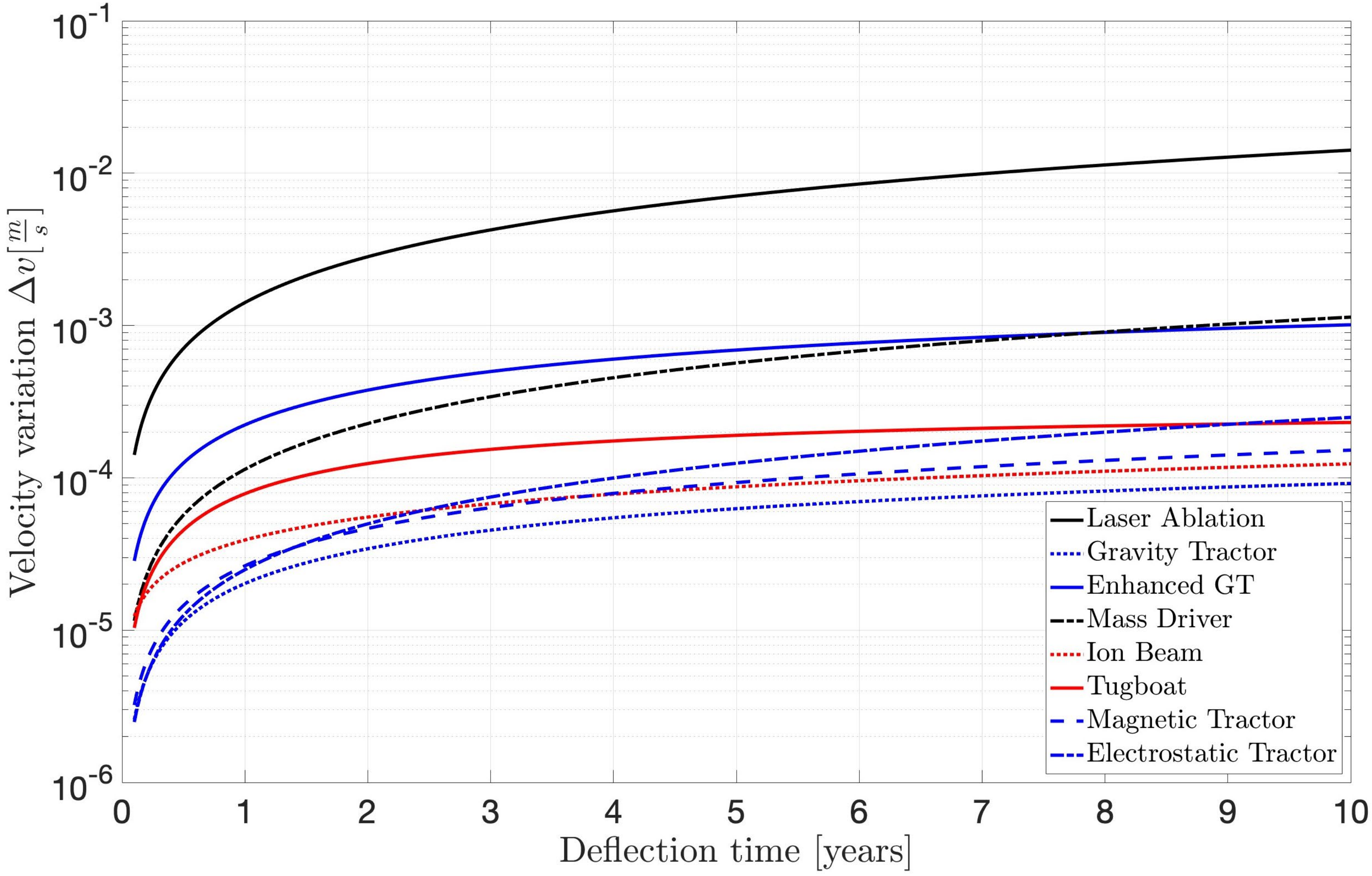


- Westward deflection ⟶ Decrease velocity
- Eastward deflection ⟶ Increase velocity



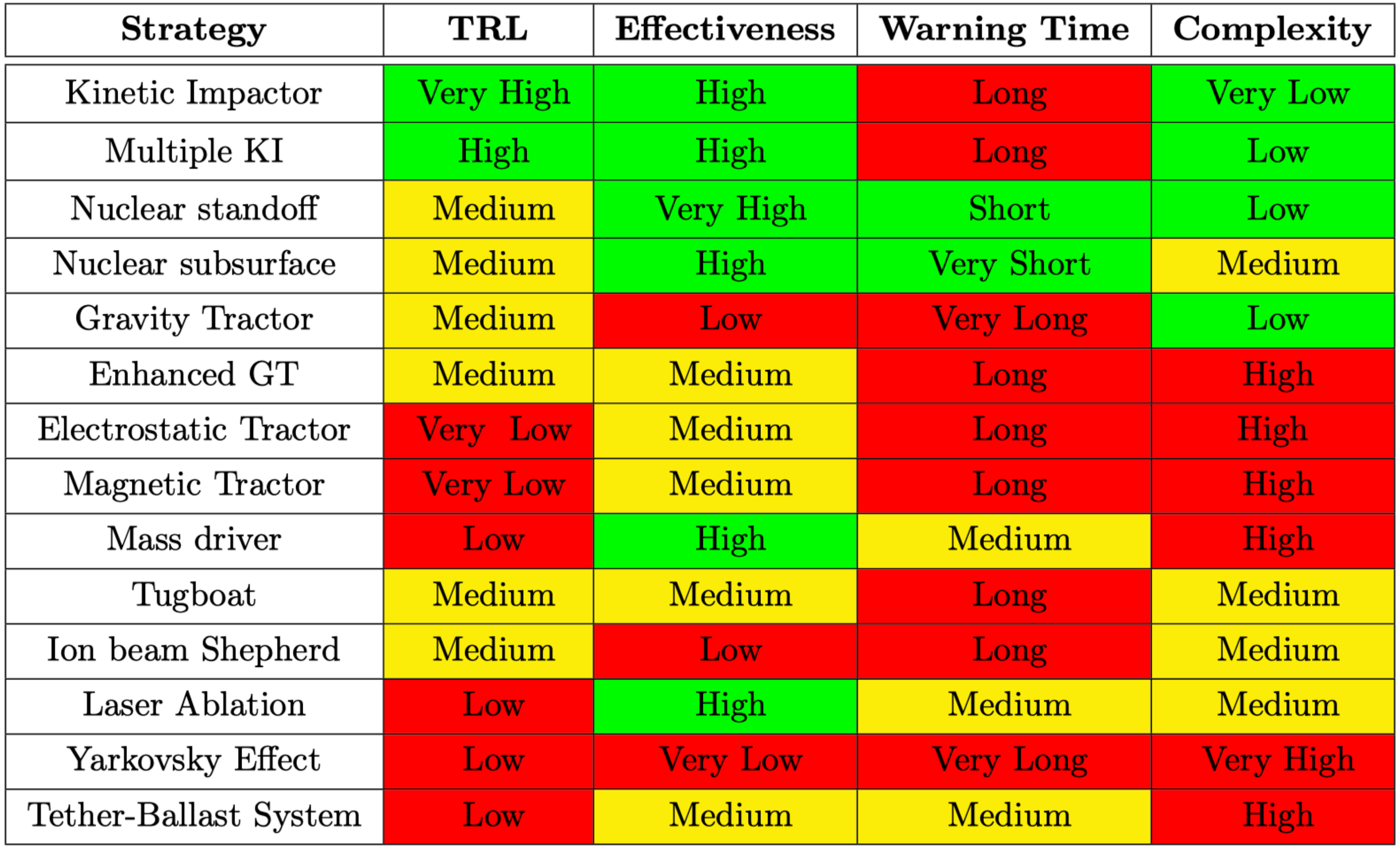
Comparison among strategies

Slow-push strategies



Comparison among strategies

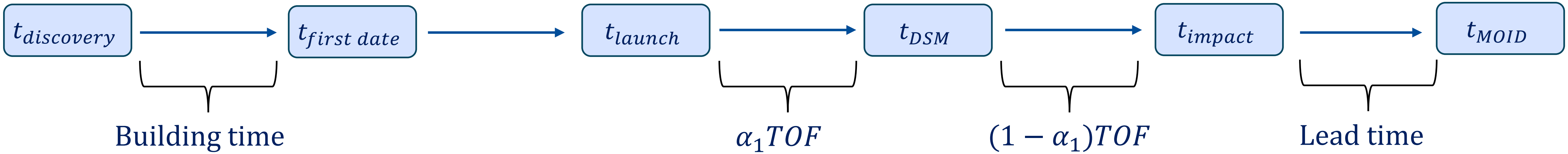
Selection for optimisation



Strategy	TRL	Effectiveness	Warning Time	Complexity
Kinetic Impactor	Very High	High	Long	Very Low
Multiple KI	High	High	Long	Low
Nuclear standoff	Medium	Very High	Short	Low
Nuclear subsurface	Medium	High	Very Short	Medium
Gravity Tractor	Medium	Low	Very Long	Low
Enhanced GT	Medium	Medium	Long	High
Electrostatic Tractor	Very Low	Medium	Long	High
Magnetic Tractor	Very Low	Medium	Long	High
Mass driver	Low	High	Medium	High
Tugboat	Medium	Medium	Long	Medium
Ion beam Shepherd	Medium	Low	Long	Medium
Laser Ablation	Low	High	Medium	Medium
Yarkovsky Effect	Low	Very Low	Very Long	Very High
Tether-Ballast System	Low	Medium	Medium	High

- Laser ablation: highest Δv
- GT for low complexity and possibility of MGT in halo orbits
- Kinetic impactor for very high TRL
- Nuclear standoff explosion is the most effective technology

Mission analysis



$t_{discovery} \rightarrow t_{first\ date} \rightarrow t_{launch} \rightarrow t_{DSM} \rightarrow t_{impact} \rightarrow t_{MOID}$

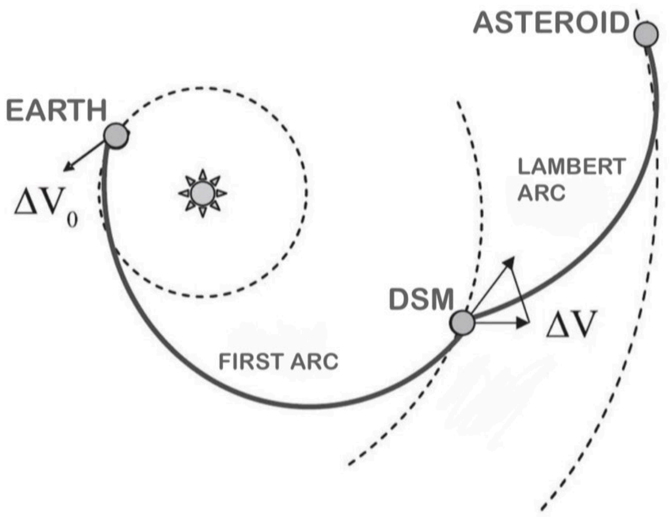
Building time

$\alpha_1 TOF$

$(1-\alpha_1)TOF$

Lead time

- Kinetic impactor, impulsive trajectory with DSM [1]:
- Nuclear explosion: impulsive trajectory with direct transfer
- Slow push strategies, low thrust trajectory [2]:
  - Shape based
  - Fourier series
  - Computationally not expensive



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[1] *I. Bolzoni. Multiple kinetic impactor for deflection of potentially hazardous asteroids. Master thesis, Politecnico di Milano, Aerospace Engineering Department, Supervisor: C. Colombo, 2021.*

[2] *K. Zeng, Y. Geng, and B. Wu. Shape-based analytic safe trajectory design for spacecraft equipped with low-thrust engines. https://doi.org/10.1016/j.ast.2016.12.006*

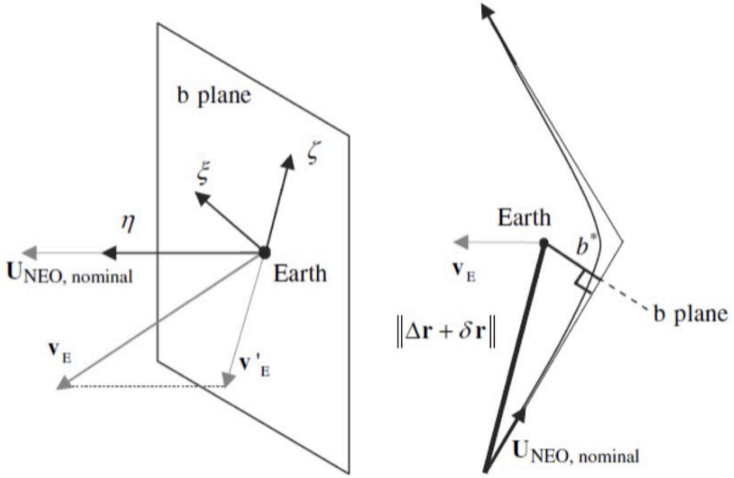
Optimisation process

Maximum deflection mission

- Maximise deviation at MOID in the b-plane[2]:

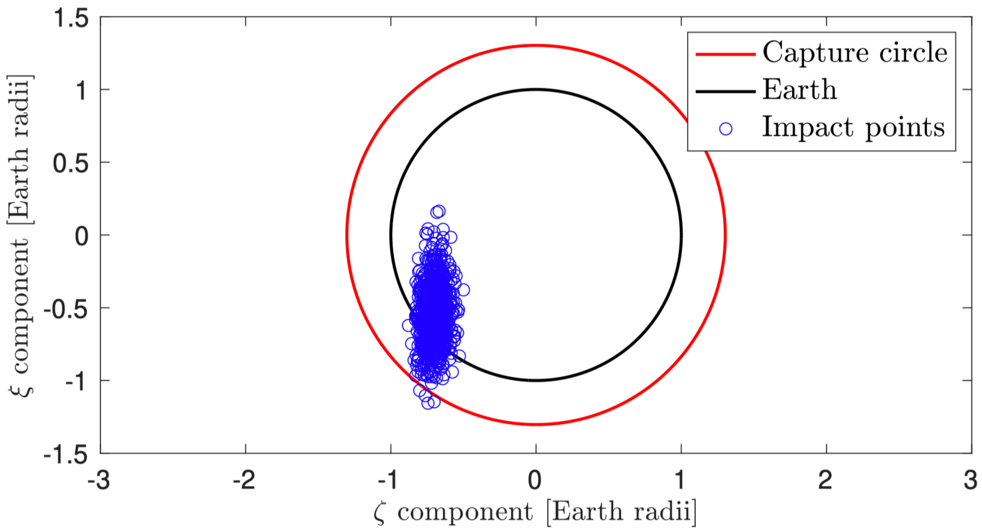
$$J_{\delta b} = \left\| \delta \vec{b} \right\|$$

- Minimise m_{sc0} and t_w [1]
- Functional to be minimised: $J = [-J_{\delta b} \quad m_{sc0} \quad t_w]$



Minimum collision probability mission

- Minimise the collision probability, m_{sc0} and t_w
- Chan's method[3]: maximise $J_P = \delta b^T \boldsymbol{Q}^* \delta b$
- Functional to be minimized: $J = [-J_P \quad m_{sc0} \quad t_w]$



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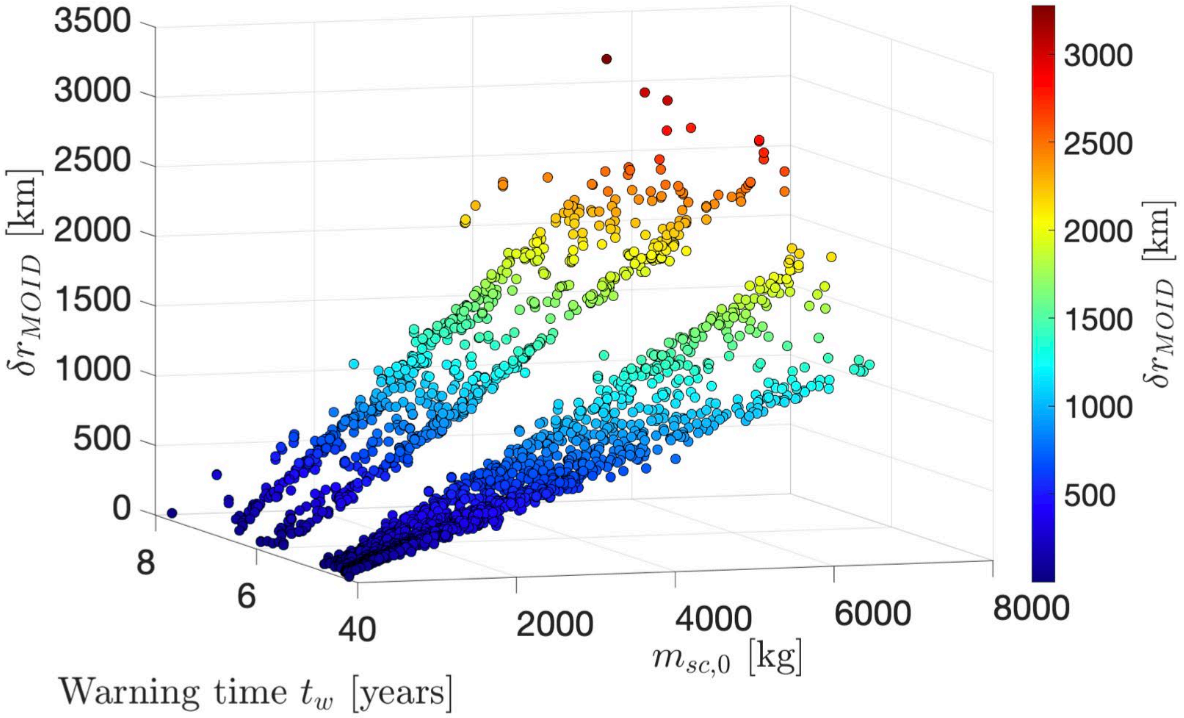
[1] J. P. Sanchez, C. Colombo, M. Vasile, and G. Radice. Multicriteria comparison among several mitigation strategies for dangerous near-Earth objects. Journal of Guidance, Control, and Dynamics.

[2] M. Petit and C. Colombo. Optimal deflection of resonant near-earth objects using the b-plane. Politecnico di Milano, 2018.

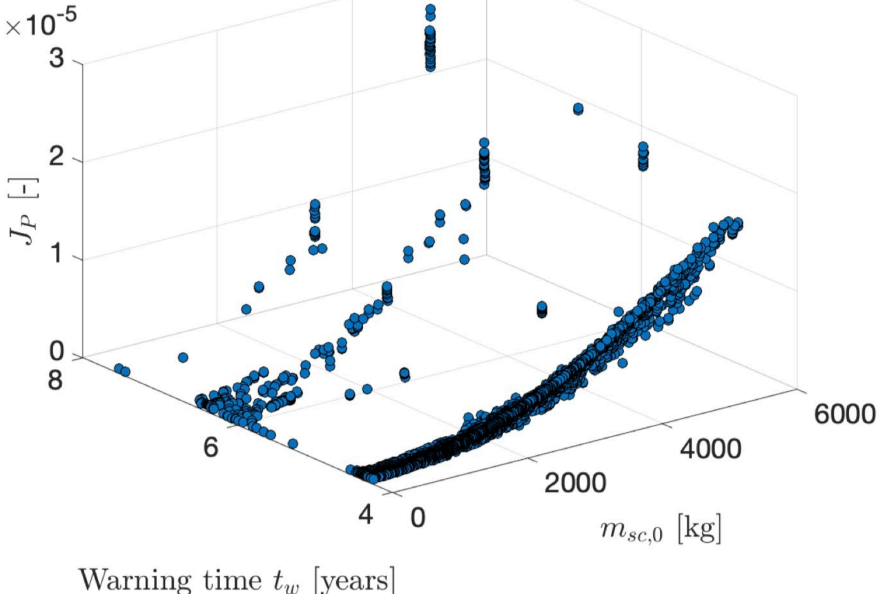
[3] J. L. Gonzalo, C. Colombo, and P. D. Lizia. Analytical framework for space debris collision avoidance maneuver design. Journal of Guidance, Control, and Dynamics. doi: 10.2514/1.G005398.

Kinetic impactor



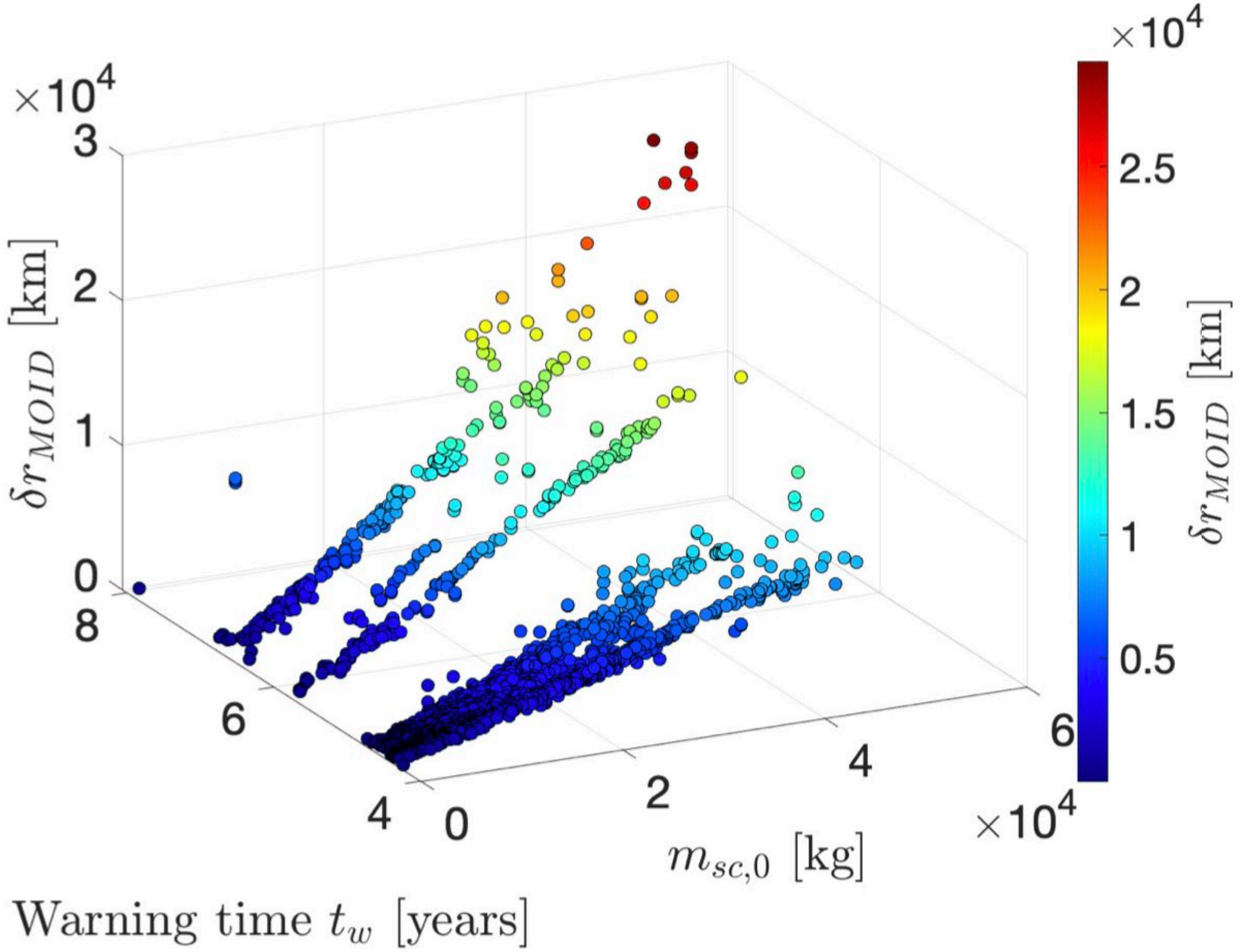
Parameter	First case
Launch date	2029-08-13
Impact date	2030-07-13
$m_{sc,0}$ $[kg]$	5154.6
$m_{sc,f}$ $[kg]$	4363.5
$\|\|\Delta v_{KI}\|\|$ $[m/s]$	$5.05 \cdot 10^{-3}$
$\|\|\delta r_{MOID}\|\|$ $[km]$	3305.3

Parameter	First case
Launch date	2029-09-05
$m_{sc,0}$ $[kg]$	5151.9
Warning time	*7.9 years*
J_P	$2.7 \cdot 10^{-5}$

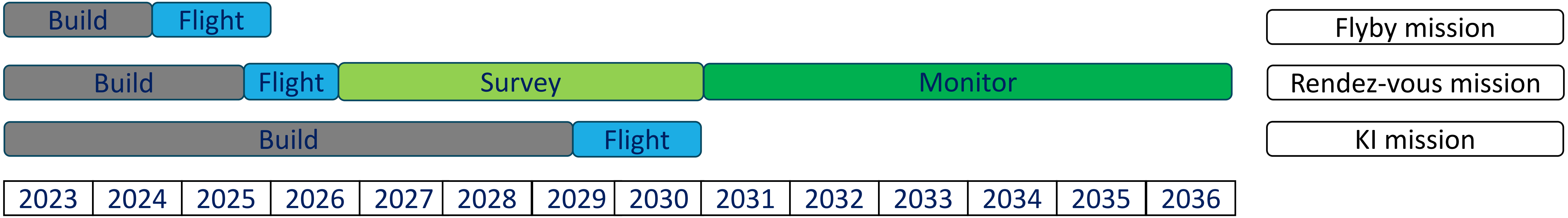


Multiple kinetic impactor

- **7 satellites** needed in the first case
- NASA solution considered direct transfer: 9 launches
- $\delta r_{MOID} = 29301\ km > 2300\ km$
- For the second case 63 launches are needed



Early reconnaissance missions



Build Flight

Flyby mission

Build Flight Survey Monitor

Rendez-vous mission

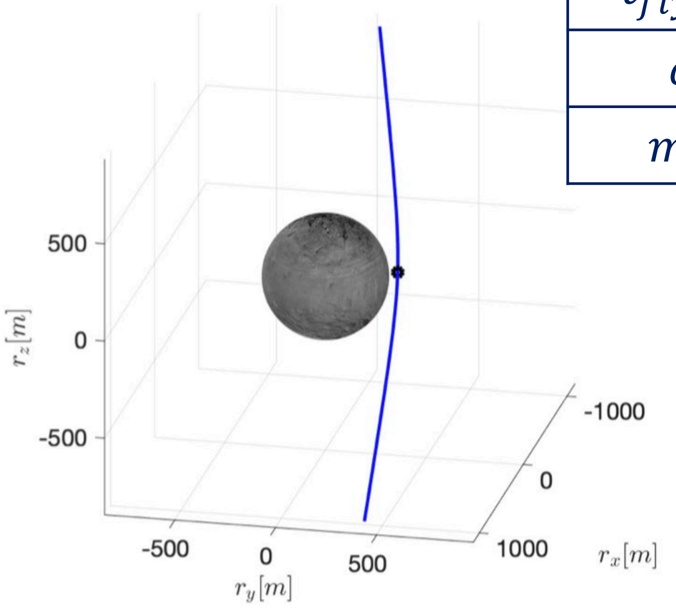
Build Flight

KI mission

2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036

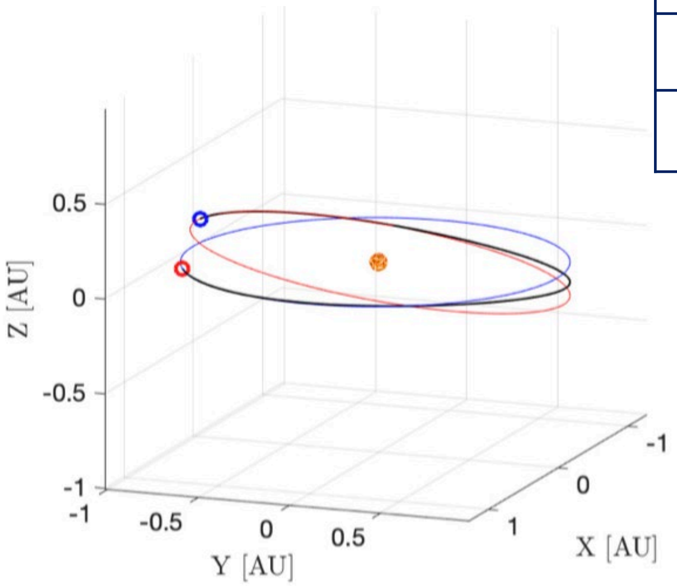
Fly-by mission

t_{fly-by}	2025-12-04
$c3$	$69.1\ km^2/s^2$
m_{sc}	$1420\ kg$



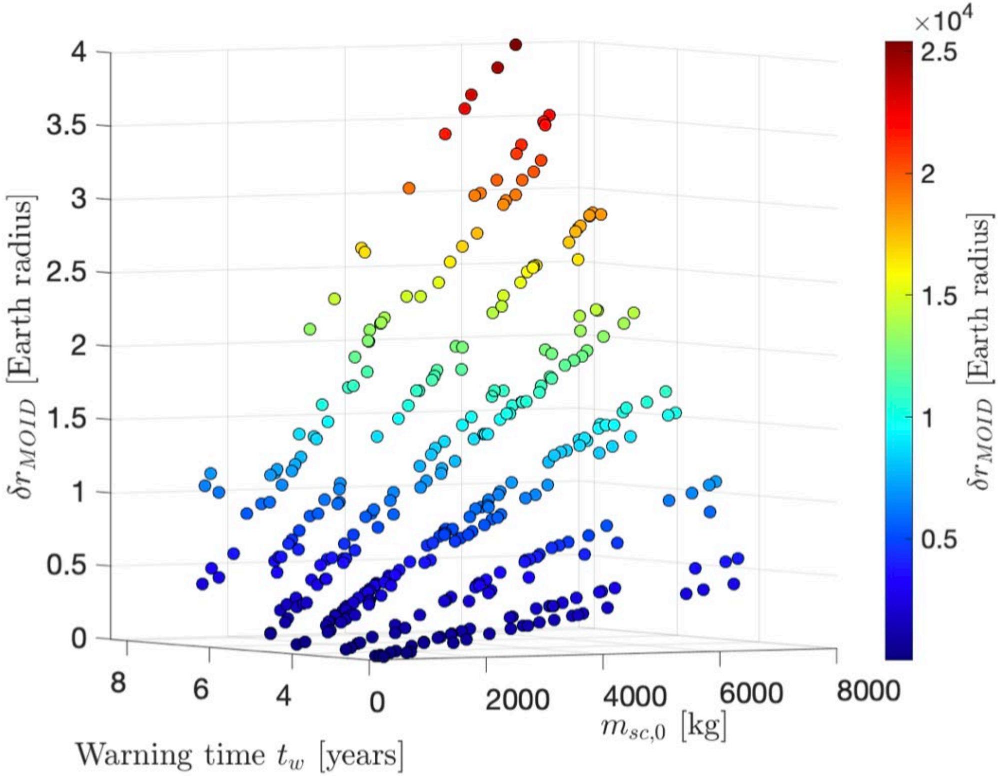
Rendez-vous mission

t_{rv}	2026-06-21
Δv_{LT}	$9.56\ km/s$
$m_{sc,f}$	$2332.6\ kg$



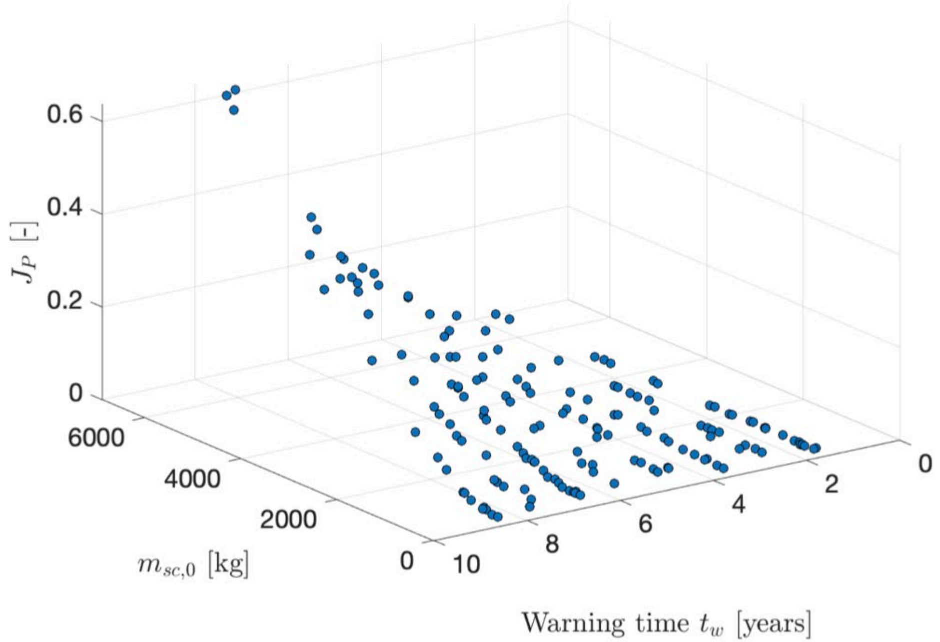
C. Colombo, M. Castronuovo, et al. First SMPAG hypothetical NEO threat exercise Splinter 1. Space Mission Planning Advisory Group, issue1.0, 2023.

Nuclear standoff explosion

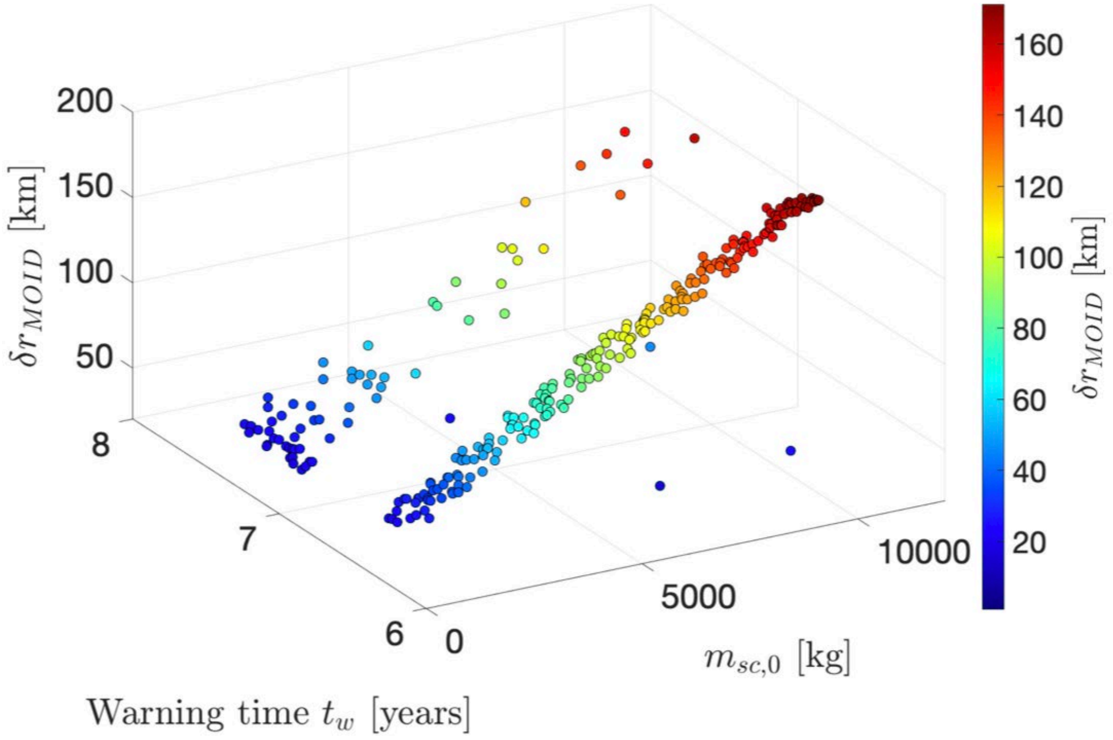


Parameter	Third case
Launch date	2028-08-17
Arrival date	2030-01-02
$m_{sc,0}$ $[kg]$	6465.9
$\|\Delta v_{NUC}\|$ $[m/s]$	0.03575
$c3$ $[km^2/s^2]$	16.3
$\|\delta r_{MOID}\|$ $[km]$	24639

Parameter	Third case
Launch date	2028-06-11
$m_{sc,0}$ $[kg]$	5772.3
Warning time	8.31 *years*
J_P	0.6368

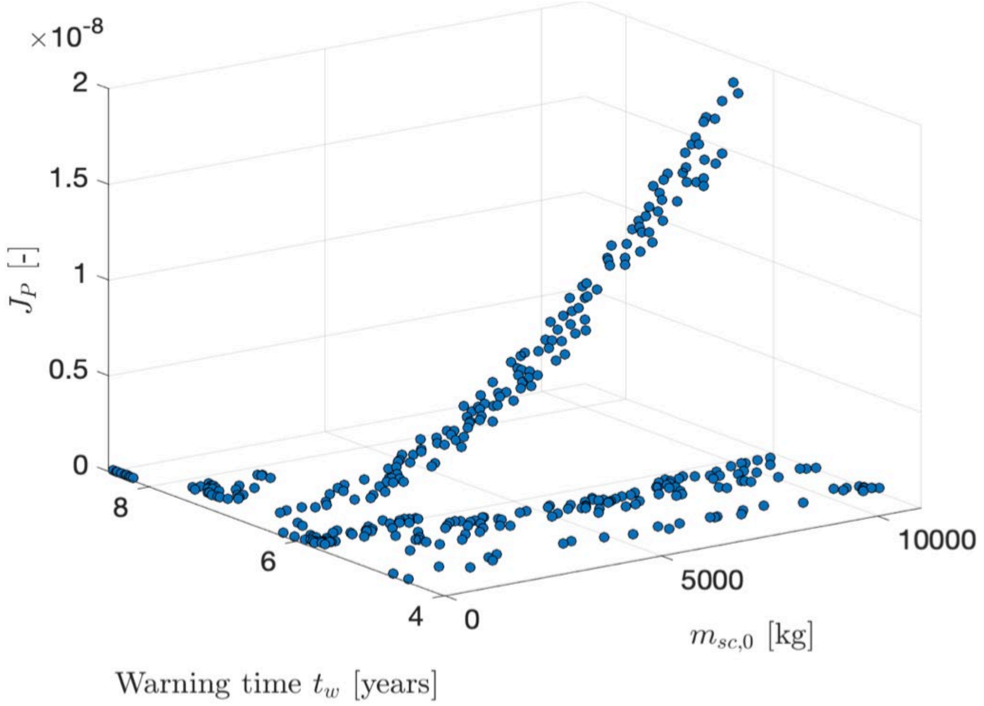


Gravity tractor

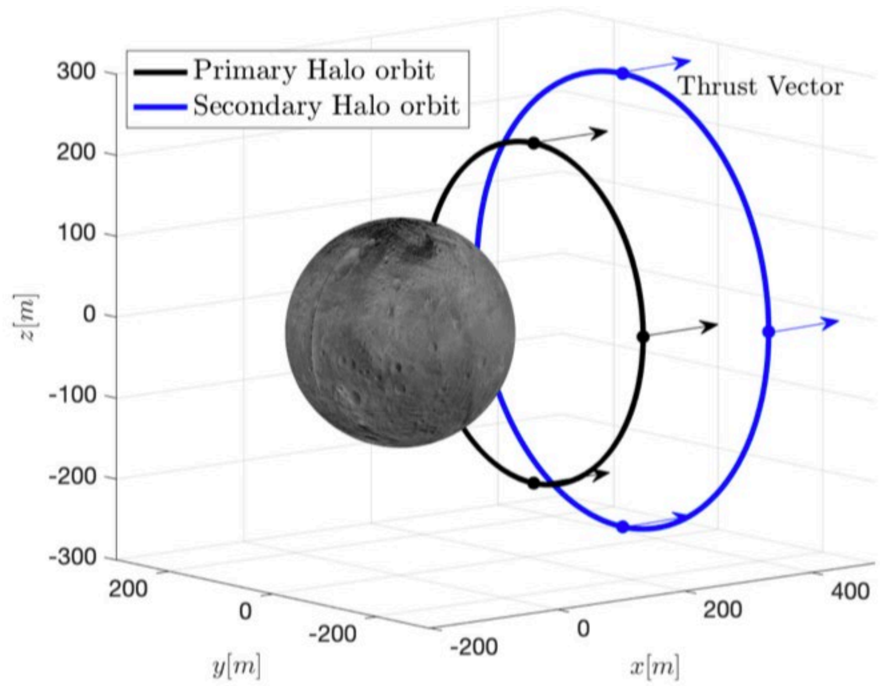


Parameter	First case
Launch date	2030-03-21
Arrival date	2031-07-11
$m_{sc,0}$ $[kg]$	10848.2
$m_{sc,f}$	8146.5
$\|\delta r_{MOID}\|$ $[km]$	169.24

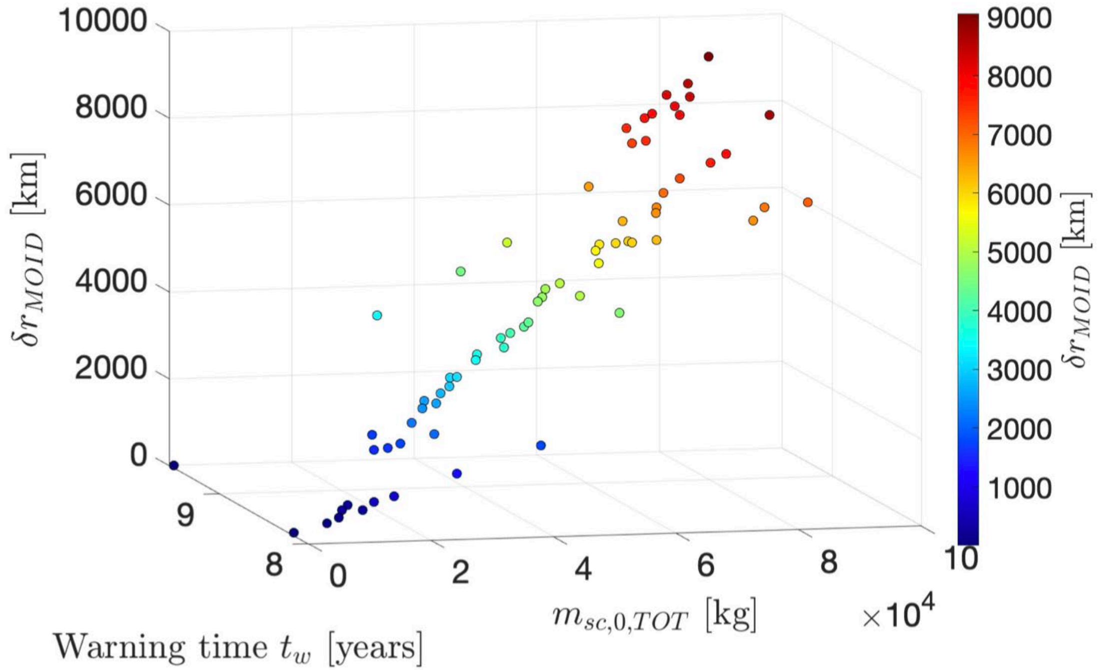
Parameter	First case
Launch date	2030-04-06
$m_{sc,0}$ $[kg]$	10959
Warning time	6.51 *years*
J_P	$1.8 \cdot 10^{-8}$



Multiple gravity tractor in Halo orbits



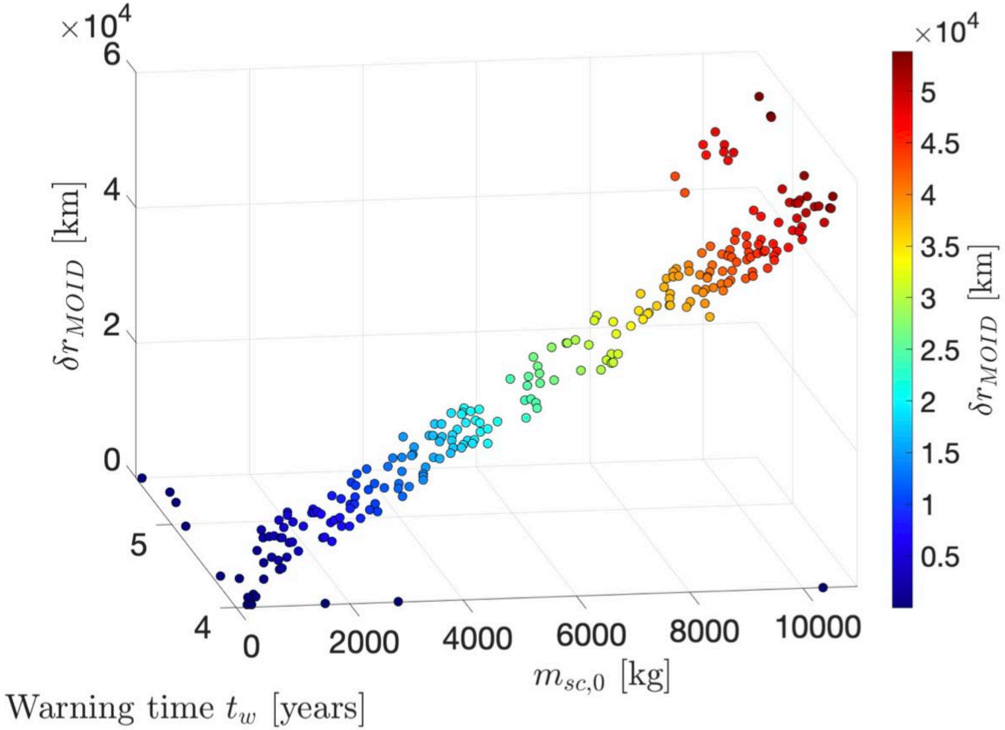
- Two Halo orbits, four satellites each orbit: 8 FH launches needed
- Less propellant consumption than hovering



- First case : $\delta r_{MOID} = 9652\ km > 9500\ km$
- For the other cases not feasible

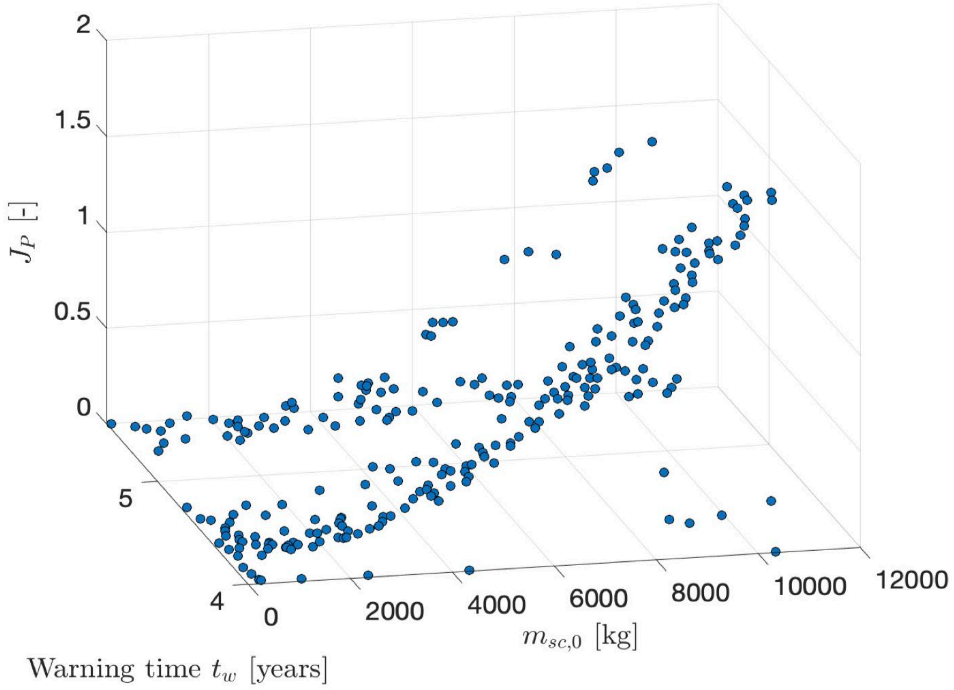
B. Wie. Dynamics and control of gravity tractor spacecraft for asteroid deflection. Journal of Guidance Control and Dynamics, 2008.

Laser ablation



Parameter	Second case
Launch date	2031-04-16
Arrival date	2035-06-26
$m_{sc,0}$ $[kg]$	10947
$m_{sc,f}$	7832
$\|\delta r_{MOID}\|$ $[km]$	51671

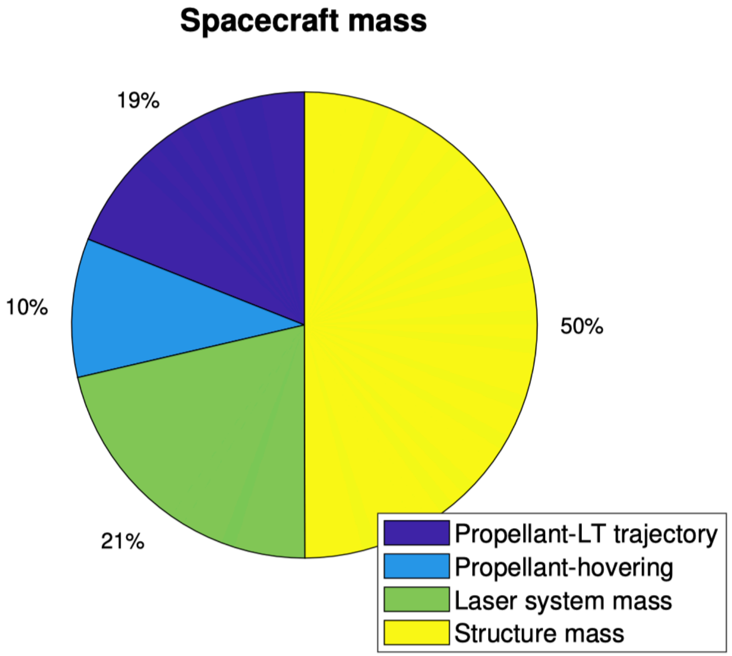
Parameter	Second case
Launch date	2032-06-29
$m_{sc,0}$ $[kg]$	10830
Warning time	4.32 *years*
J_P	1.7



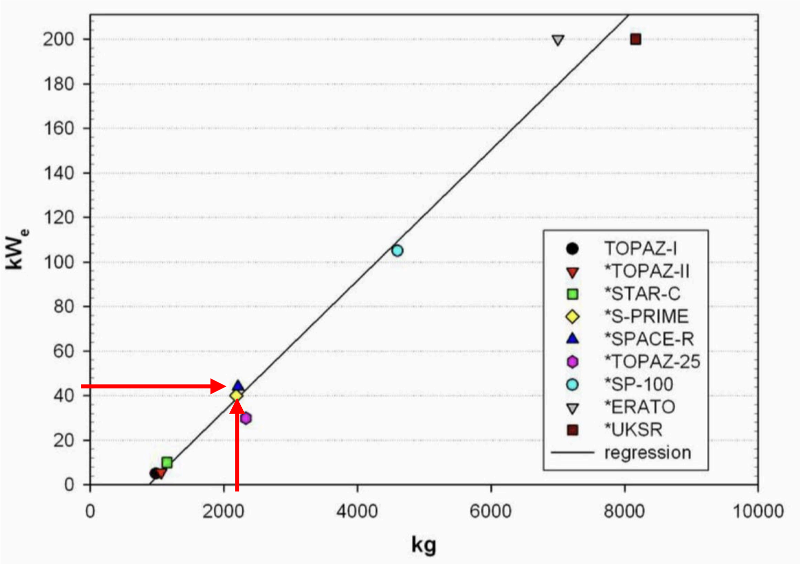
Laser ablation

Mission design

- $m_{sc0} = m_{LS} + m_{prop} + m_{structure}$
- Constraint imposed: $m_{structure} = 0.5\, m_{sc0}$
- $m_{LS} = \alpha_P P_L + \frac{P_L}{\sigma \epsilon_R T_R^4} \rho_R (1 - \eta_L) + \alpha_L P_L$



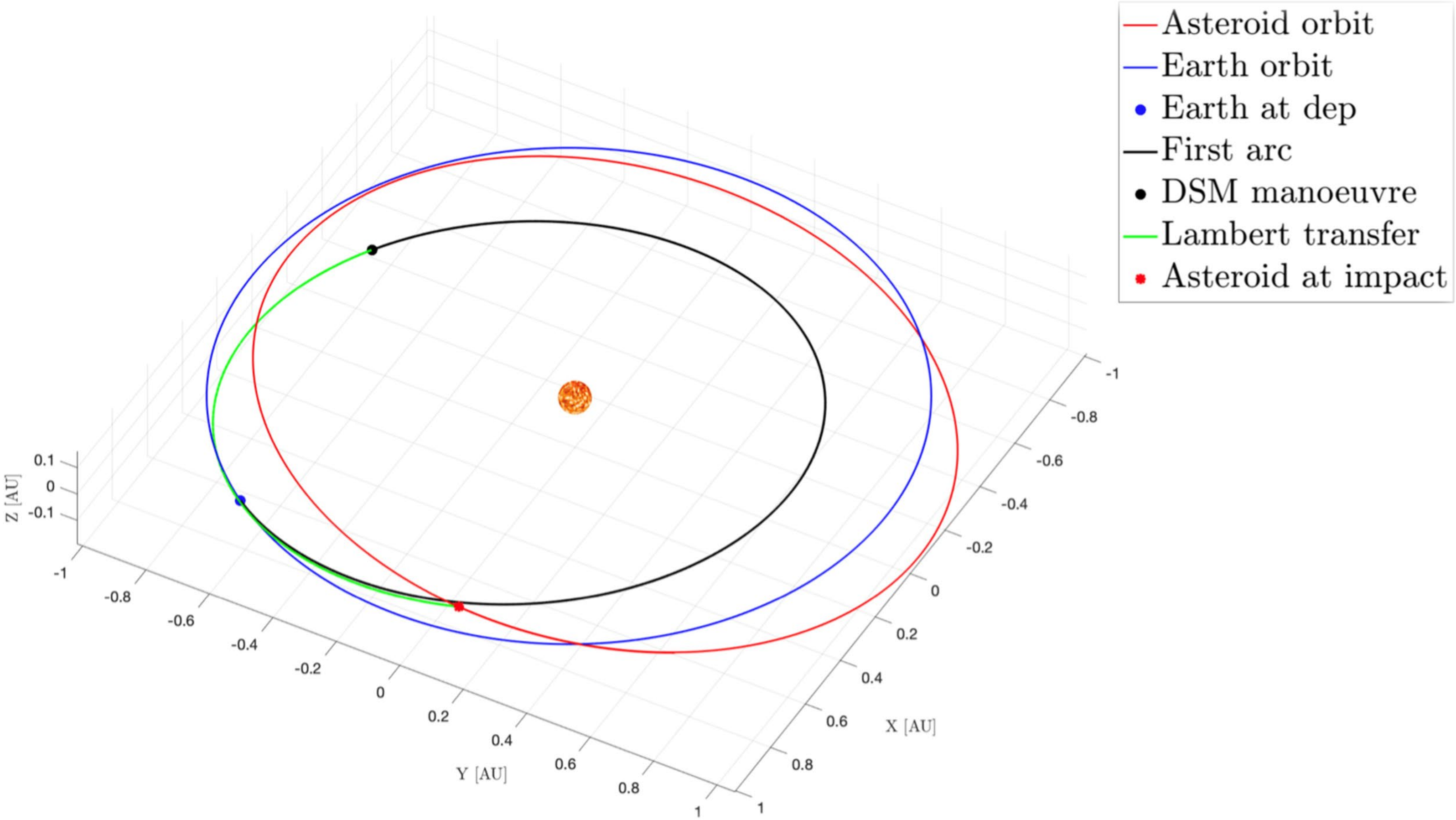
- Two mission phases:
  - Transfer: $P_{transfer} = P_{e,LT} + P_{s/s}$
  - Hovering: $P_{hovering} = P_{e,hov} + P_L + P_{s/s}$
- Bottleneck: generate P_L ⟶ Nuclear reactor



R. Walker, D. Izzo et Al. Concepts for Near-Earth Asteroid Deflection using Spacecraft with Advanced Nuclear and Solar Electric Propulsion Systems. Journal of the British Interplanetary Society, 2005.

Conclusions

	Deviation obtained [km]		
Strategy	**First case** $M = 10^{10}\ kg, d = 290\ m$	**Second case** $M = 10^{11}\ kg, d = 617\ m$	**Third case** $M = 10^{12}\ kg, d = 1539\ m$
Kinetic impactor	3304.3	370.9	19.6



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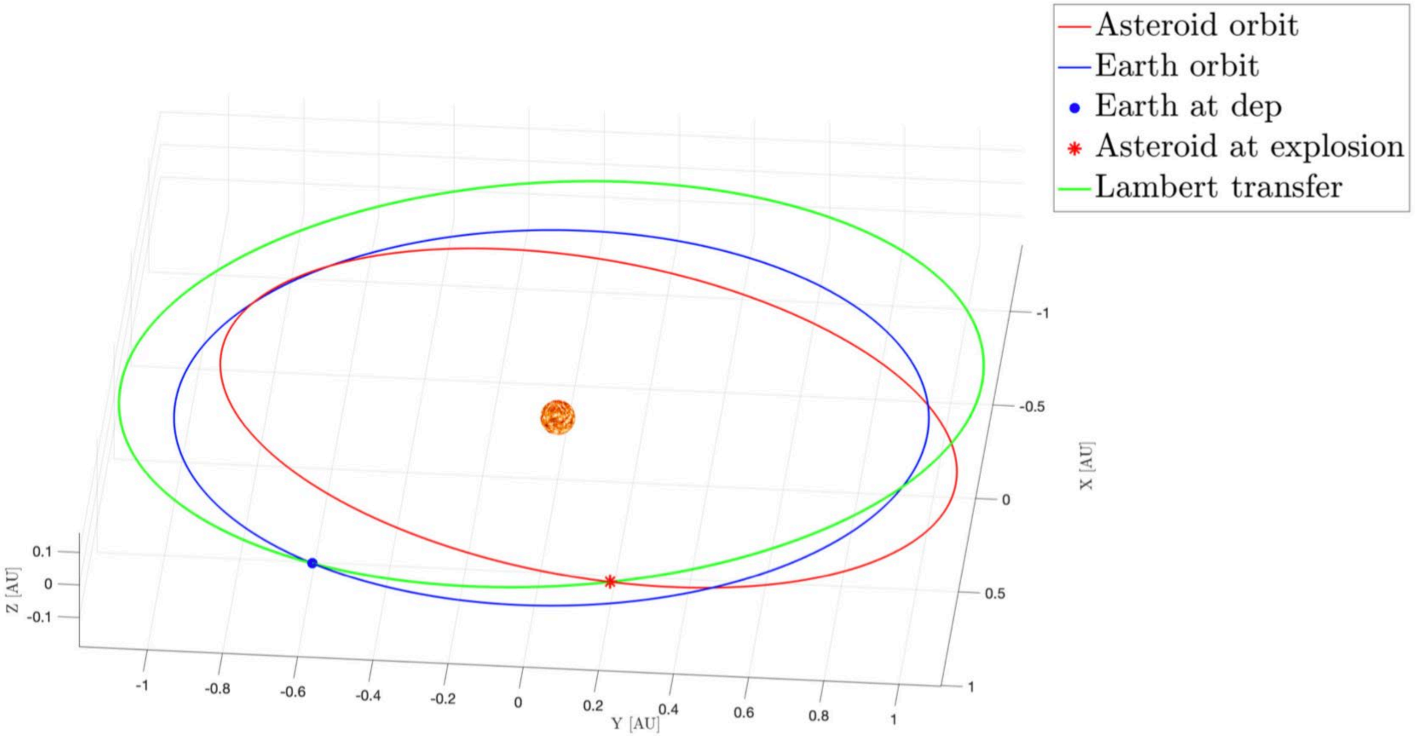
Kinetic impactor	3304.3	370.9	19.6
Multiple kinetic impactor (7 s/c)	29301	Not possible	Not possible
Nuclear standoff explosion	1074158	129340	24639



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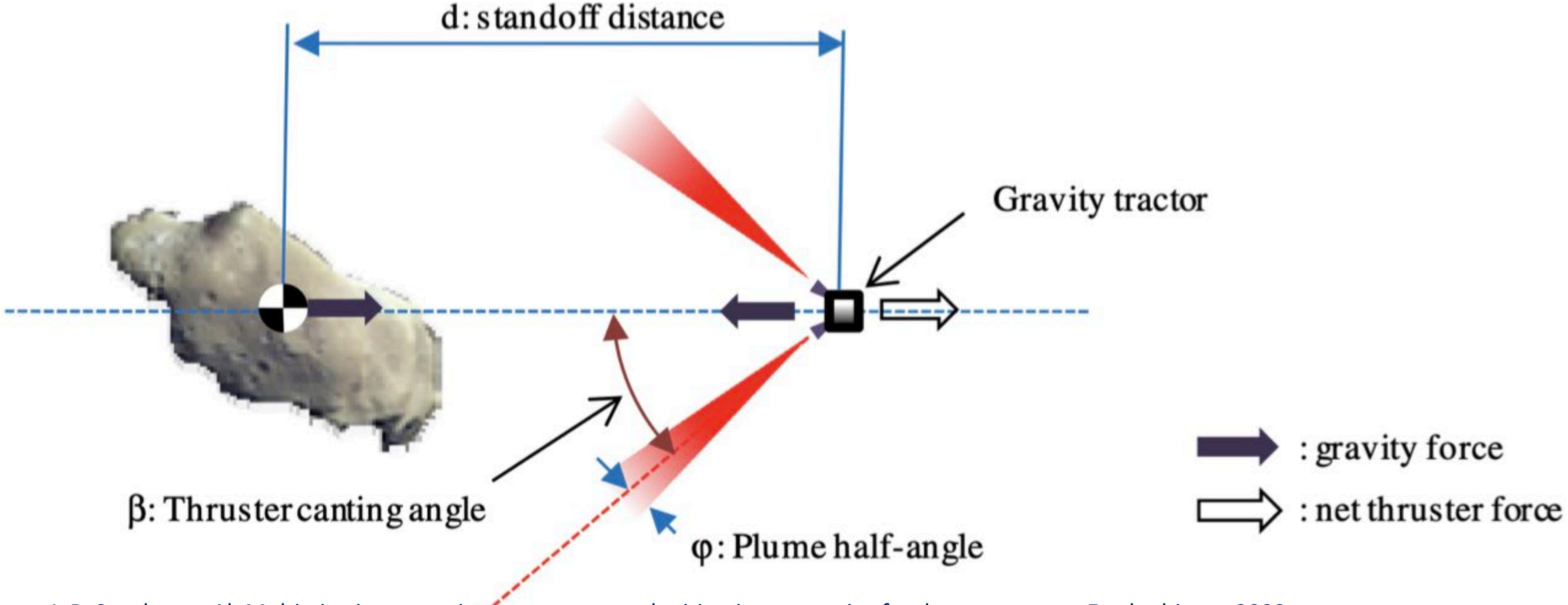

J. P. Sanchez et Al. Multicriteria comparison among several mitigation strategies for dangerous near-Earth objects, 2009

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Gravity tractor	169.2	34.1	Not possible
Multiple gravity tractor (8 s/c)	9652.7	Not possible	Not possible

Conclusions

Deviation obtained [km]

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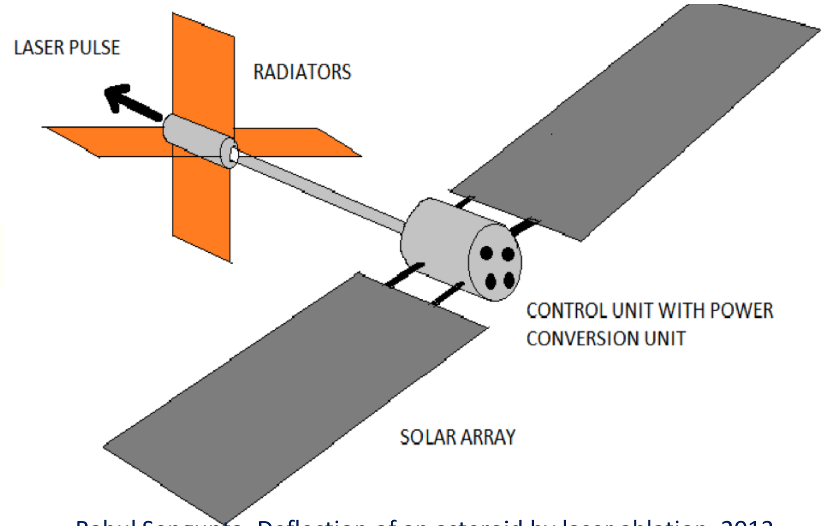
Laser ablation	1544862	51671	1397.4



Rahul Sengupta. Deflection of an asteroid by laser ablation. 2013

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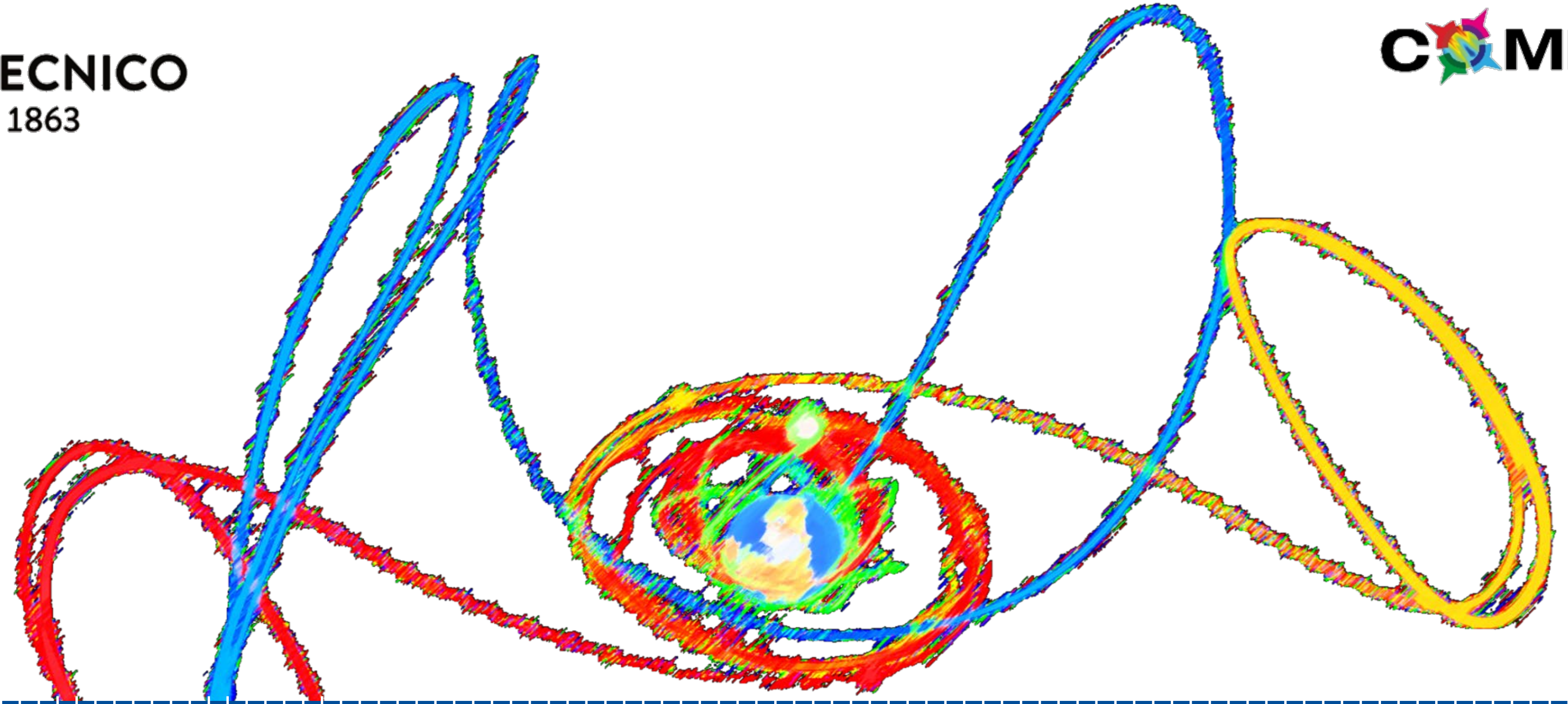
Laser ablation	1544862	51671	1397.4

Future work

- Improve the mathematical model of the strategies
- The work is limited by the information on asteroid properties available
- More detailed studies on multiple satellites launches



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SMPAG, 31 January 2024