ASTEROIDS:

STEPPING STONES TO THE FUTURE OF SPACE EXPLORATION

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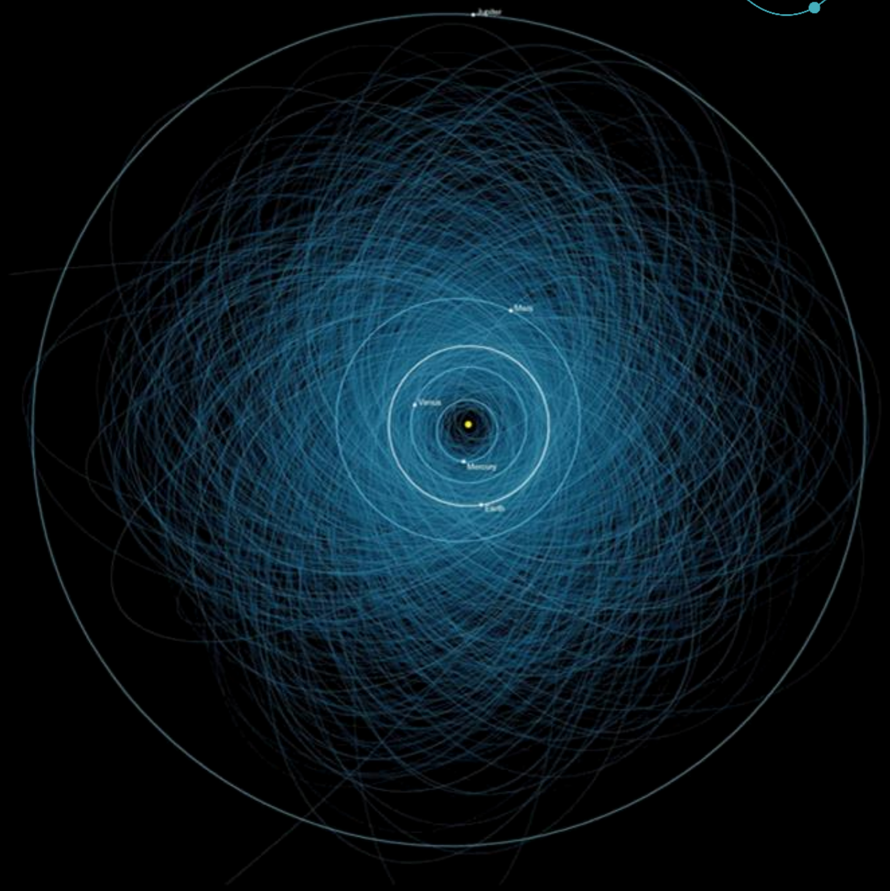
Seminar for the American Physical Society (APS) - Virtual

OVERVIEW

1. Introduction to the ASTRO Lab
2. What is asteroid engineering?
3. Why are we interested in asteroids?
4. What are the challenges and opportunities moving forward?



RESEARCH

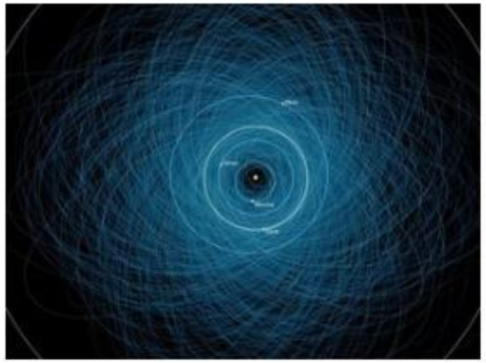
ASTROLAB

Astronautics

Asteroid Science & Engineering

Exploring the potential of small solar system bodies

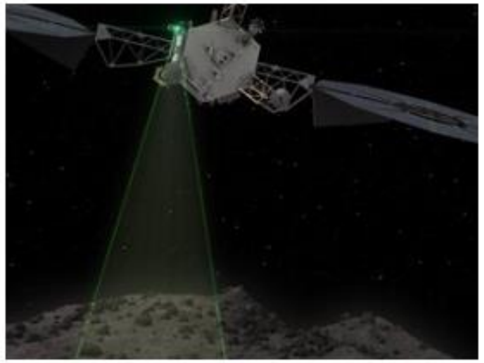
Read more



Orbital Dynamics & Control

Planning trajectories and controlling the motion of spacecraft

Read more



Mission & Systems Design

Analyzing space systems and formulating concepts for new missions

Read more

Satellites, Formations, & Debris

Tackling space debris, designing formations and miniaturizing spacecraft

Read more

Robotics

Space Robotics

Advancing space manipulation and exploration through robotics

Read more

Terrestrial Robotics

Developing intelligent robots for the world's most challenging environments

Read more

Industrial Robotics

Autonomizing robots for complex industrial challenges and applications

Read more

Personal & Assistive Robotics

Creating new robotic solutions that benefit people in their daily lives

Read more

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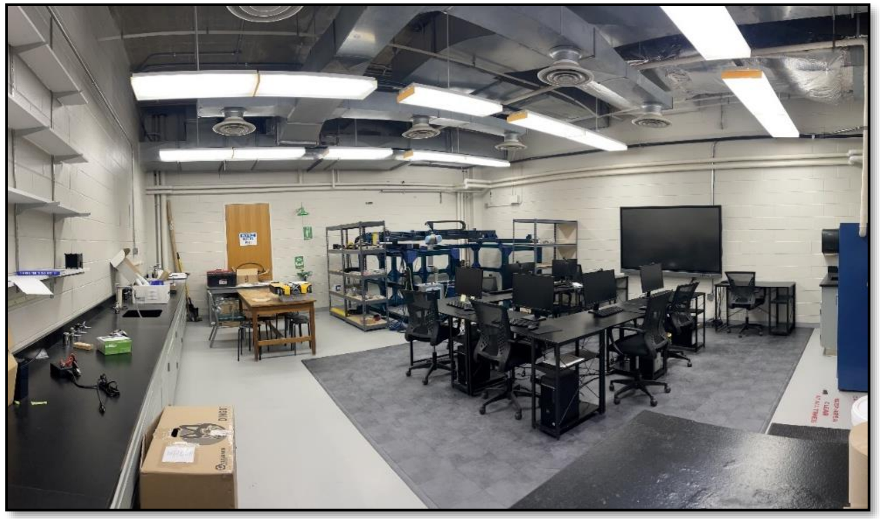
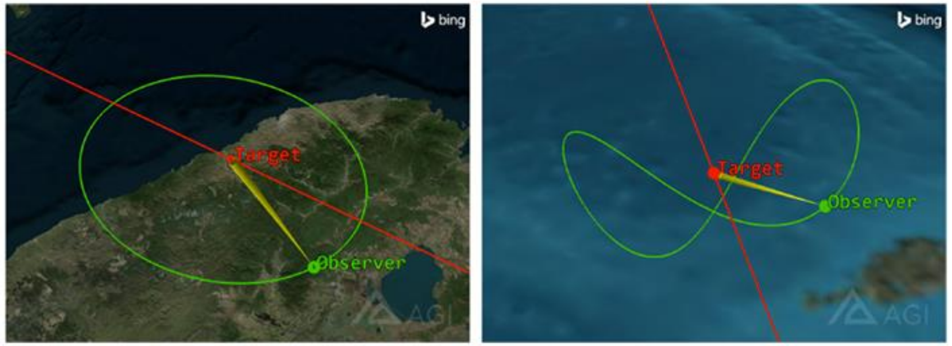
Facilities & Equipment



Robotic systems

Examples of Active Research

On-orbit tracking and formation flying



Space solar power & on-orbit assembly

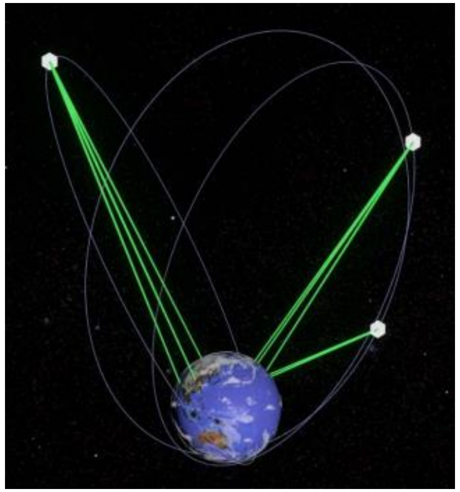
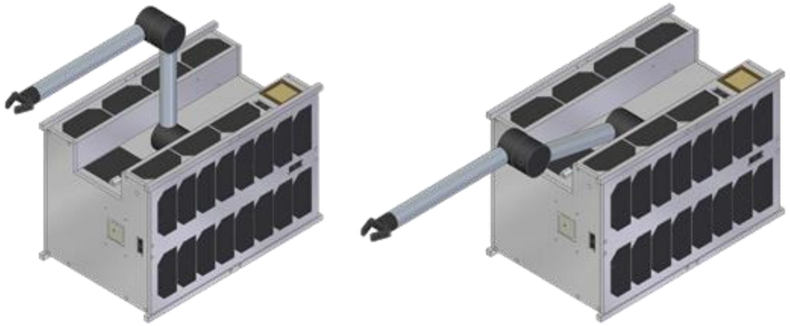


Image: Virtus Solis Technologies

Exoskeletons

Space debris removal & space systems



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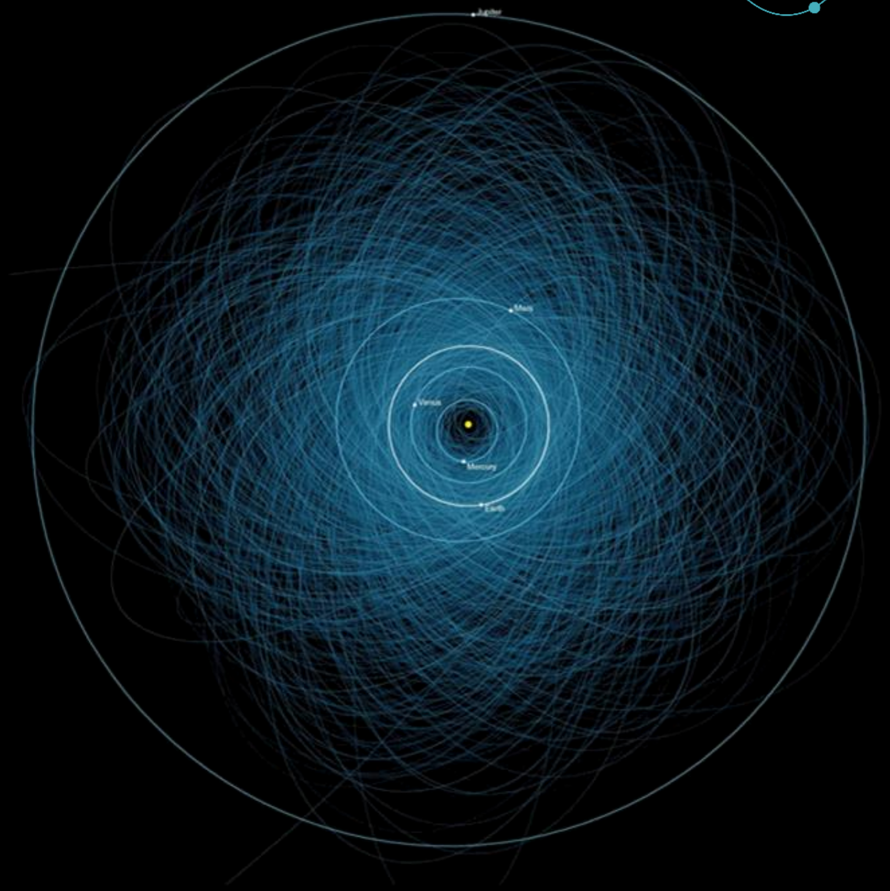
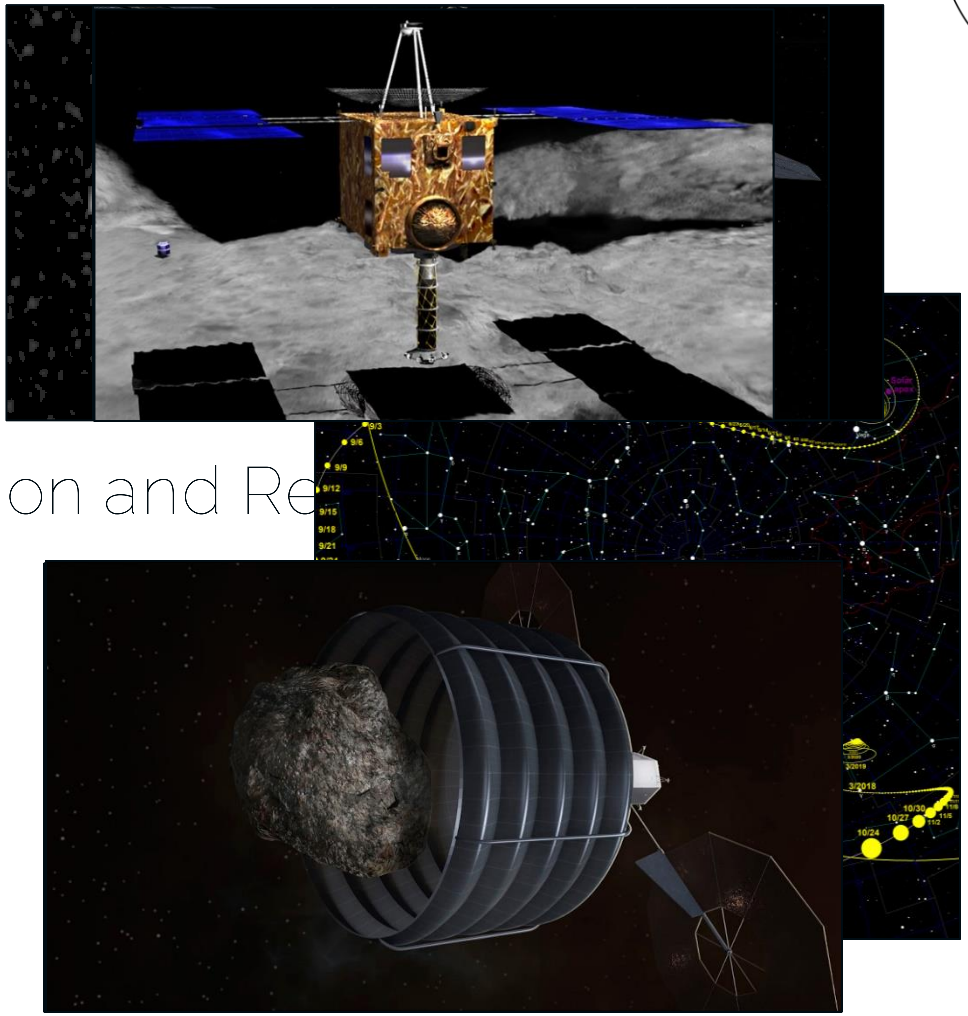


ASTEROID ENGINEERING

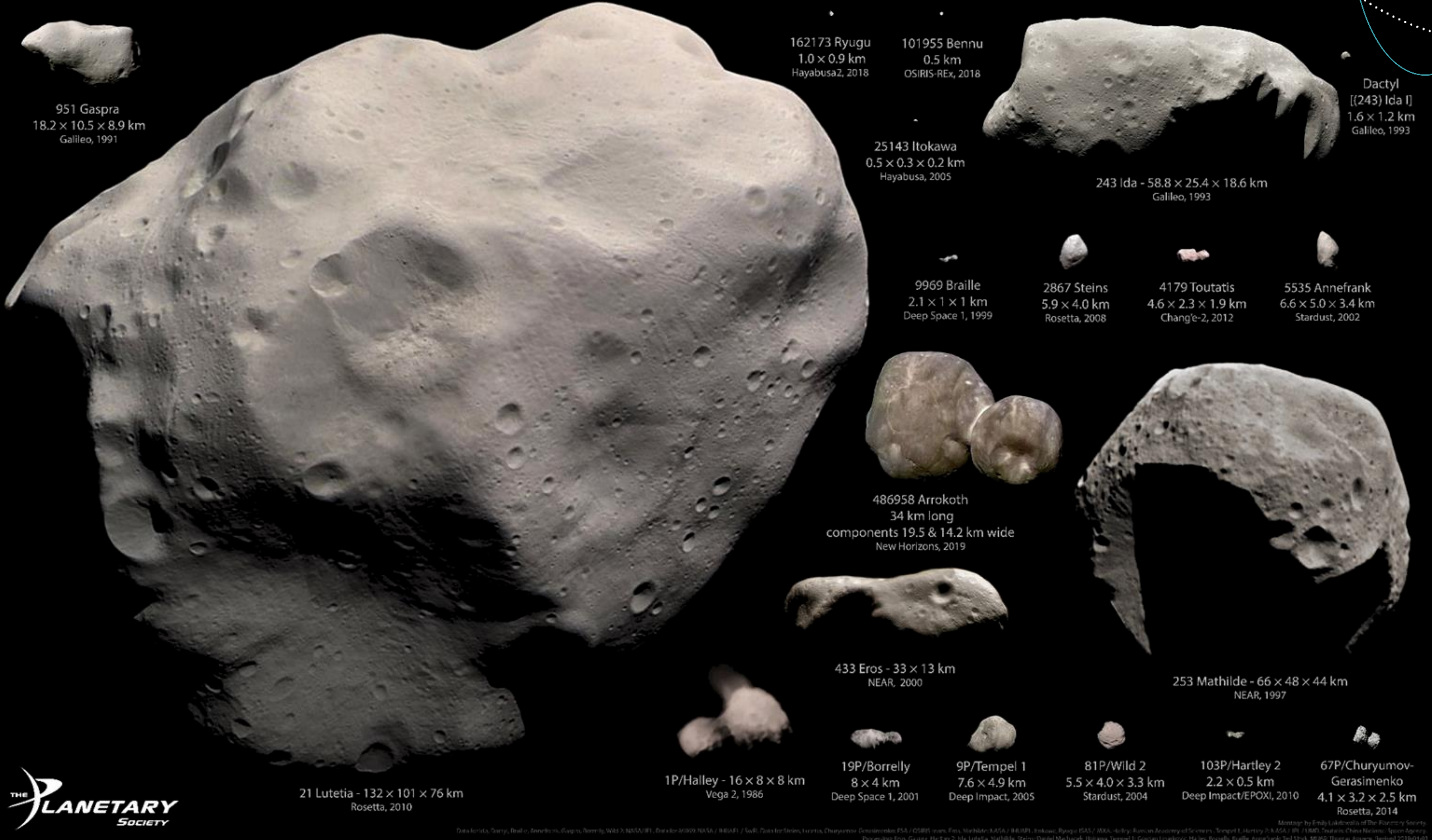
Discovery

Exploration and Re

Mining

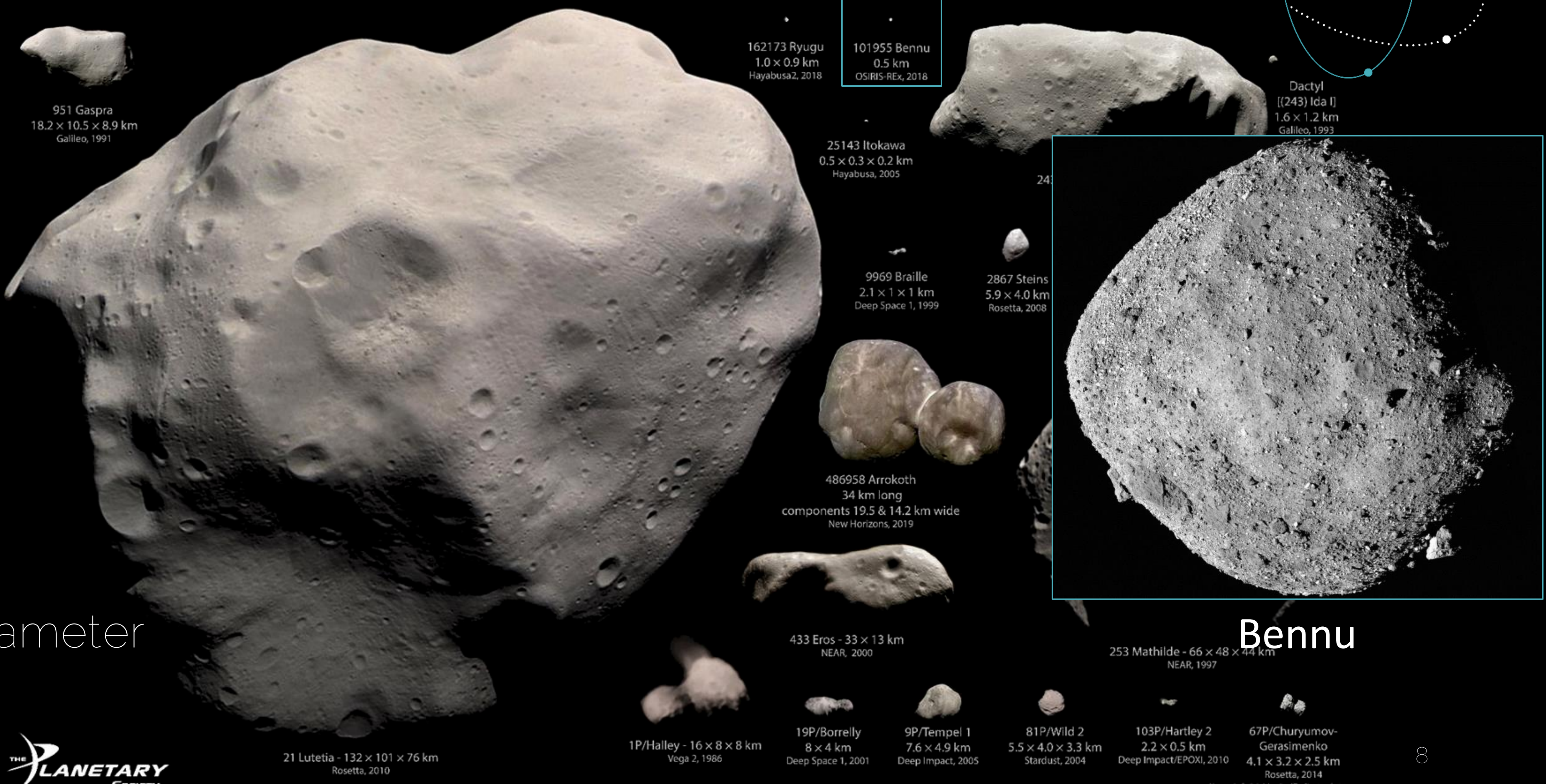


ASTEROIDS


951 Gaspra
18.2 × 10.5 × 8.9 km
Galileo, 1991
162173 Ryugu
1.0 × 0.9 km
Hayabusa2, 2018
101955 Bennu
0.5 km
OSIRIS-REx, 2018
Dactyl
[(243) Ida I]
1.6 × 1.2 km
Galileo, 1993
25143 Itokawa
0.5 × 0.3 × 0.2 km
Hayabusa, 2005
243 Ida - 58.8 × 25.4 × 18.6 km
Galileo, 1993
9969 Braille
2.1 × 1 × 1 km
Deep Space 1, 1999
2867 Steins
5.9 × 4.0 km
Rosetta, 2008
4179 Toutatis
4.6 × 2.3 × 1.9 km
Chang'e-2, 2012
5535 Annefrank
6.6 × 5.0 × 3.4 km
Stardust, 2002
486958 Arrokoth
34 km long
components 19.5 & 14.2 km wide
New Horizons, 2019
433 Eros - 33 × 13 km
NEAR, 2000
253 Mathilde - 66 × 48 × 44 km
NEAR, 1997
21 Lutetia - 132 × 101 × 76 km
Rosetta, 2010
1P/Halley - 16 × 8 × 8 km
Vega 2, 1986
19P/Borrelly
8 × 4 km
Deep Space 1, 2001
9P/Tempel 1
7.6 × 4.9 km
Deep Impact, 2005
81P/Wild 2
5.5 × 4.0 × 3.3 km
Stardust, 2004
103P/Hartley 2
2.2 × 0.5 km
Deep Impact/EPOXI, 2010
67P/Churyumov-Gerasimenko
4.1 × 3.2 × 2.5 km
Rosetta, 2014
THE PLANETARY SOCIETY

ASTEROIDS

~490 m diameter



Bennu

~100 km diameter

ASTEROIDS

[Image credit: ESA]

[Image credit: NASA/JPL-Caltech]

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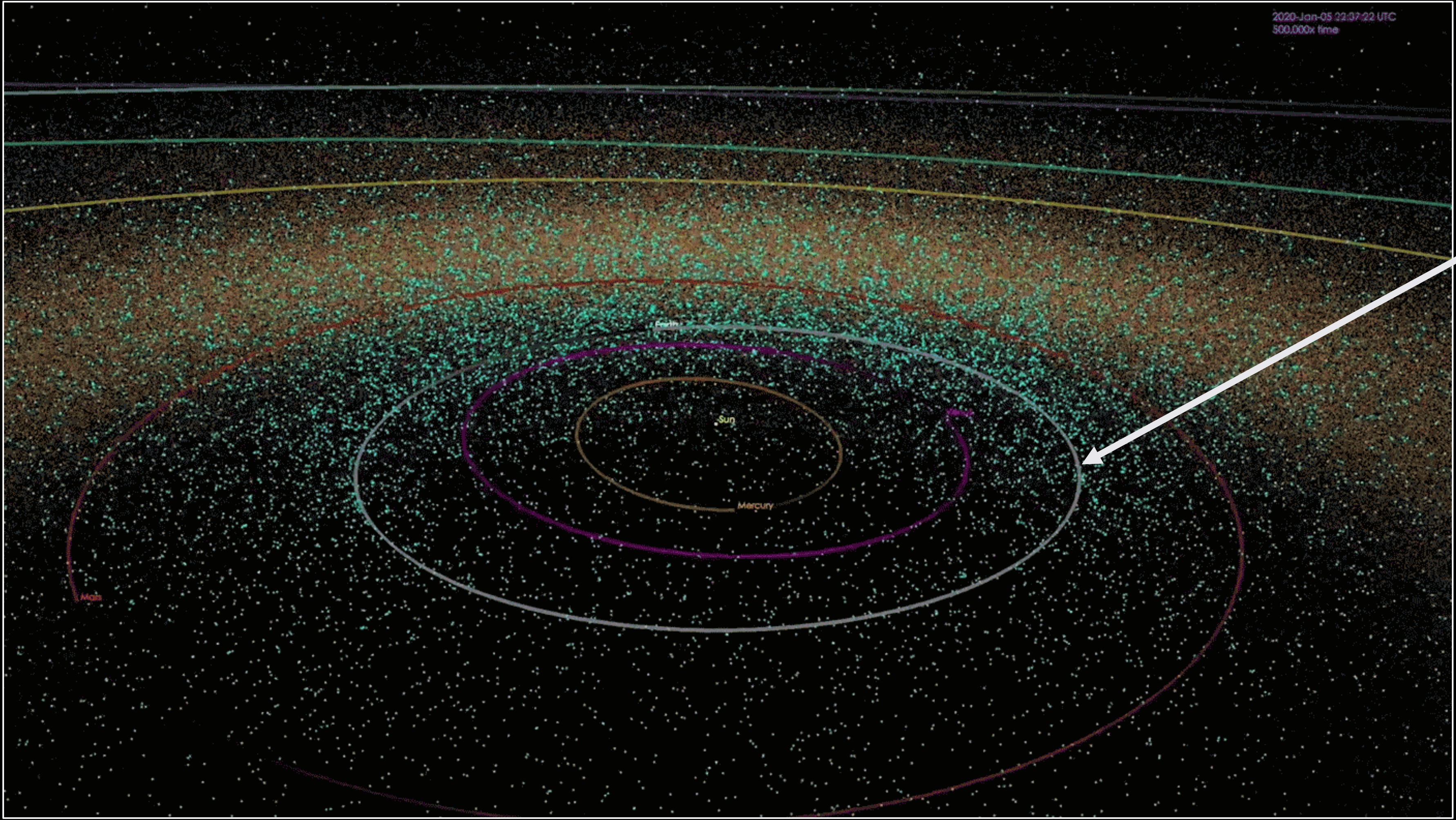
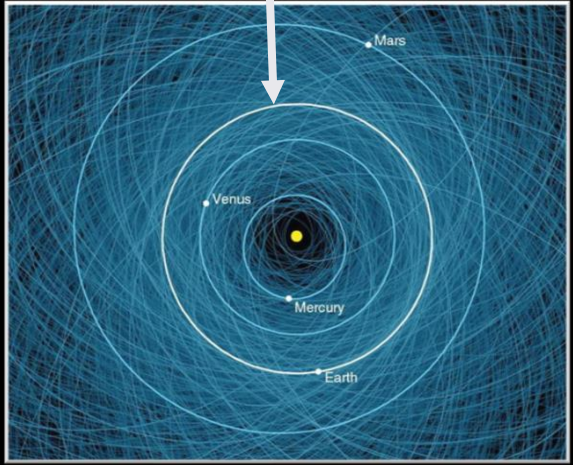


Earth's Orbit



ASTEROIDS

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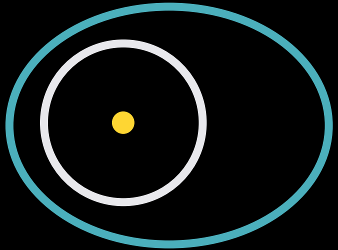
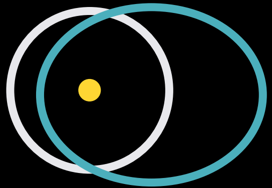


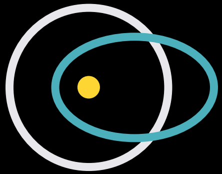
$a > 1.0$ au
$1.017 \text{ au} < q < 1.3$ au

Apollos



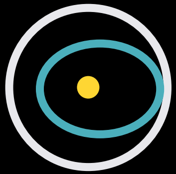
$a > 1.0$ au
$q < 1.017$ au

Atens



$a < 1.0$ au
$Q > 0.983$ au

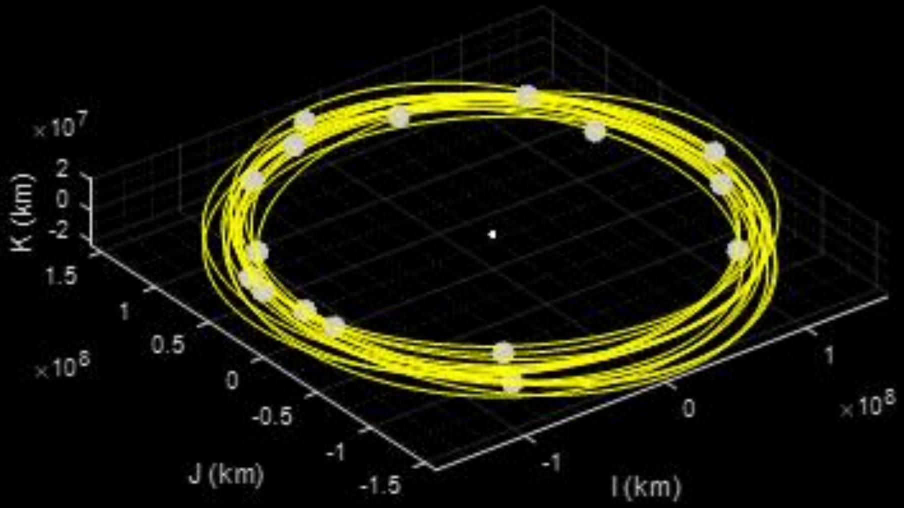
Atiras



$a < 1.0$ au
$Q < 0.983$ au

Arjuna

$0.985 \text{ au} < a < 1.013 \text{ au}$
$0 < e < 0.1$
$0° < i < 8.56°$



ASTEROIDS

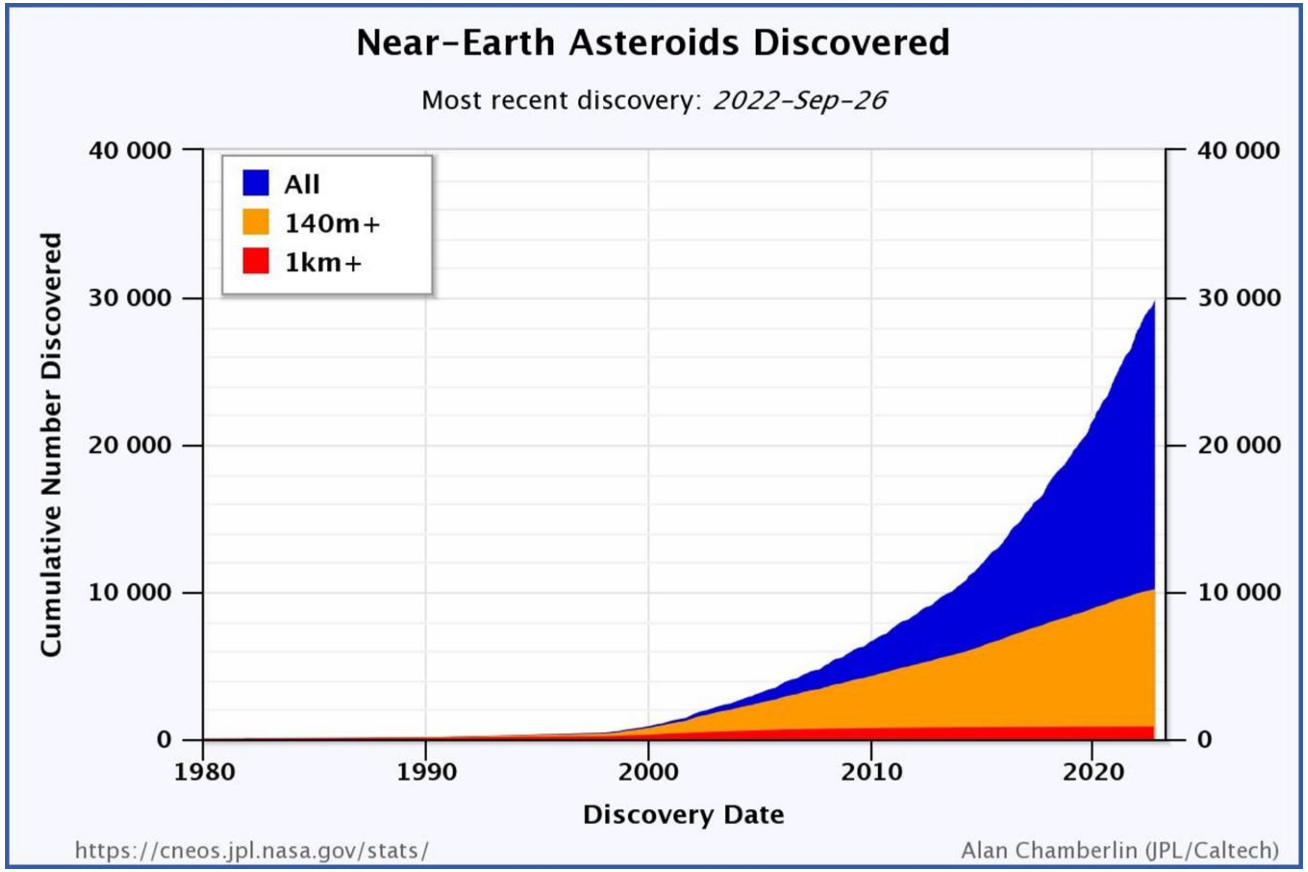
Observed Population (2022-Sep-26)

- Total: 29,901

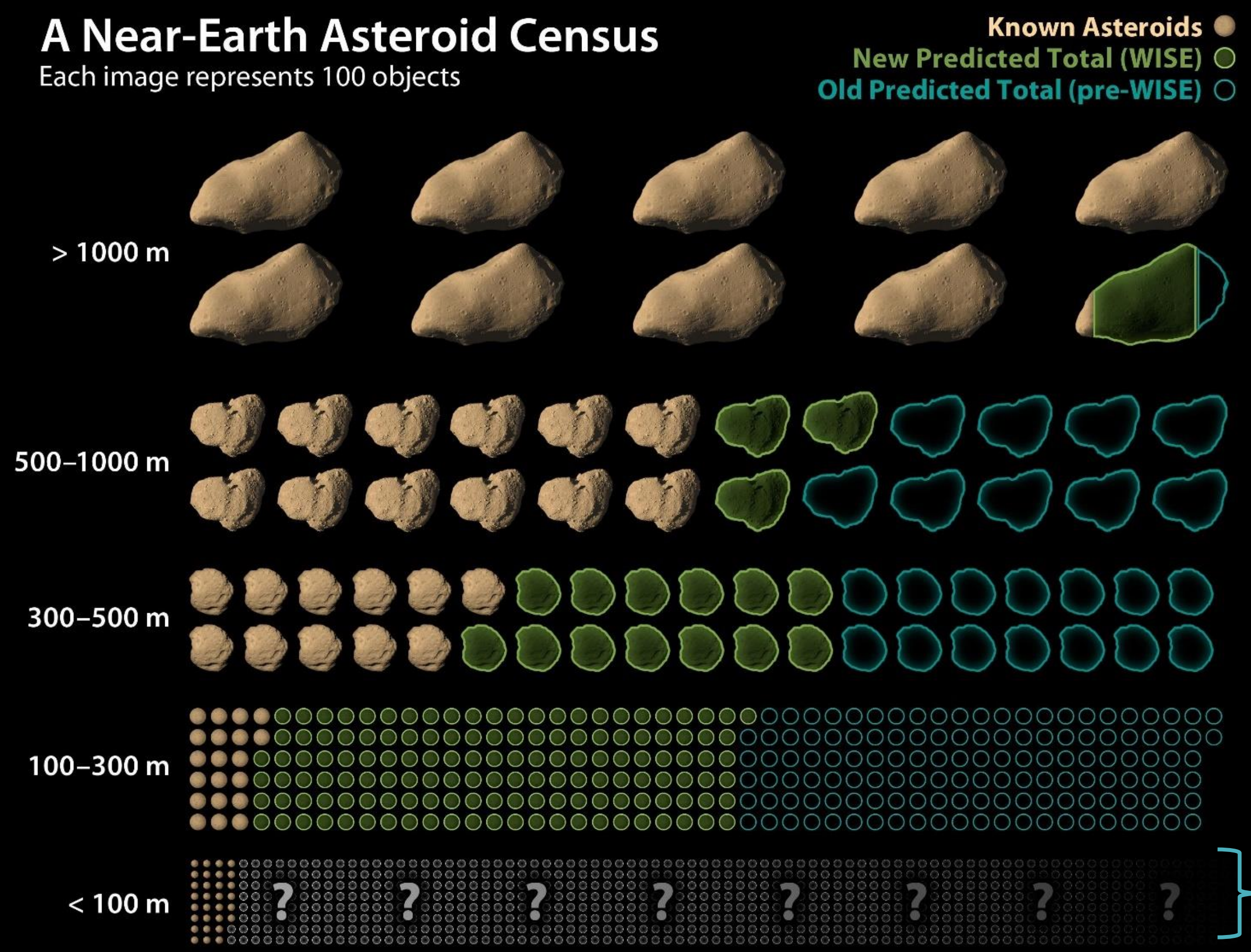
Diameter larger than:

- 1 km: 856
- 140 m: 10,206

So, how many near-Earth asteroids are estimated to exist?



ASTEROIDS



[Image credit: NASA/JPL-Caltech]

Estimated number of asteroids [1,2]:

- 10-50 m range → ~100 million

More than a
100 MILLION
expected

[1] Tricarico, P., *Icarus*, vol. 284 pp. 416-423, 2014.
[2] Harris, A. W., *Icarus*, vol. 257, pp. 302-312, 2015.

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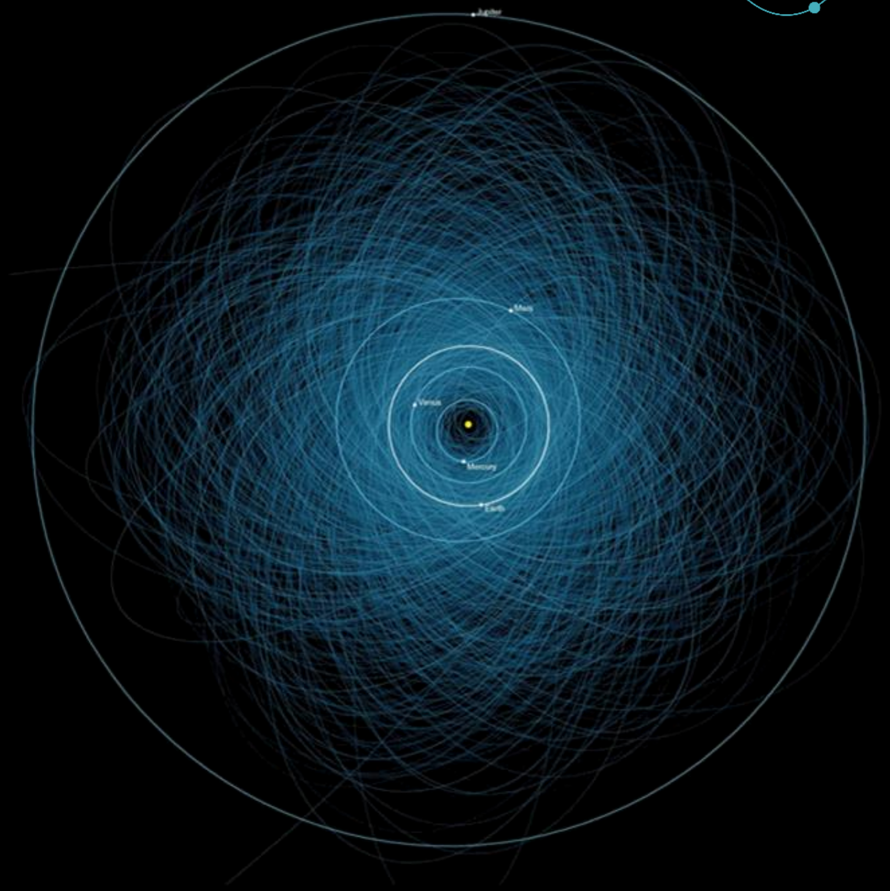


WHY ARE WE INTERESTED?

- Asteroid deflection and planetary defense

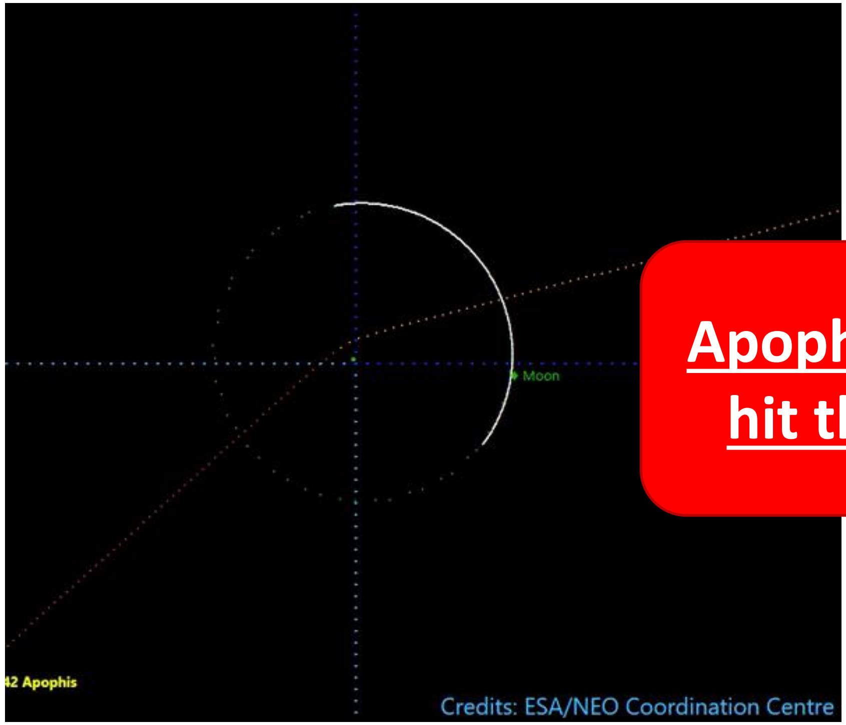
Chelyabinsk Meteor (Feb 15, 2013)

NASA DART Mission

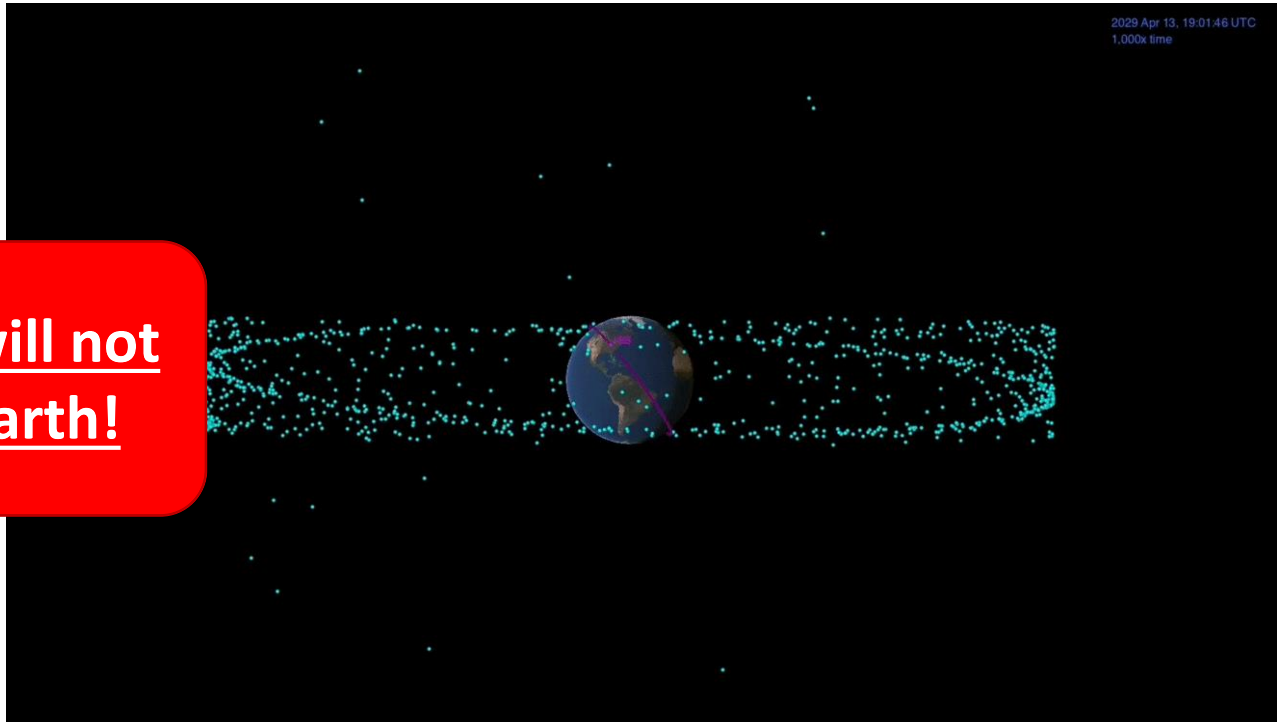
WHY ARE WE INTERESTED?

- Asteroid deflection and planetary defense

Apophis Close Approach 2029 (31,600 km above Earth's surface)



Apophis will not hit the Earth!



[Image credit: NASA/JPL-Caltech]

WHY ARE WE INTERESTED?

- Asteroid deflection and planetary defense
- Scientific exploration
  - Origins of the early solar system
  - Planet formation

OSIRIS-REx Touchdown
[Image credit: NASA/Goddard]

WHY ARE WE INTERESTED?

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- Asteroid deflection and planetary defense
- Scientific exploration
- Resource utilization

Asteroids Resources:

- Water and volatiles
- Rare-Earth metals
- Platinum group metals
- Other metals

Asteroid 1986 DA, ~2.5 km diameter

"We estimated that the amounts of Fe, Ni, Co, and the PGM present in 1986 DA could exceed the reserves worldwide. Moreover, if 1986 DA is mined and the metals marketed over 50 yr, the <u>annual value of precious metals</u> for this object would be <u>~$233 billion</u>." [3]

[3] Sanchez, et. al. *Planetary Science Journal, 2:205 (15pp), 2021.*

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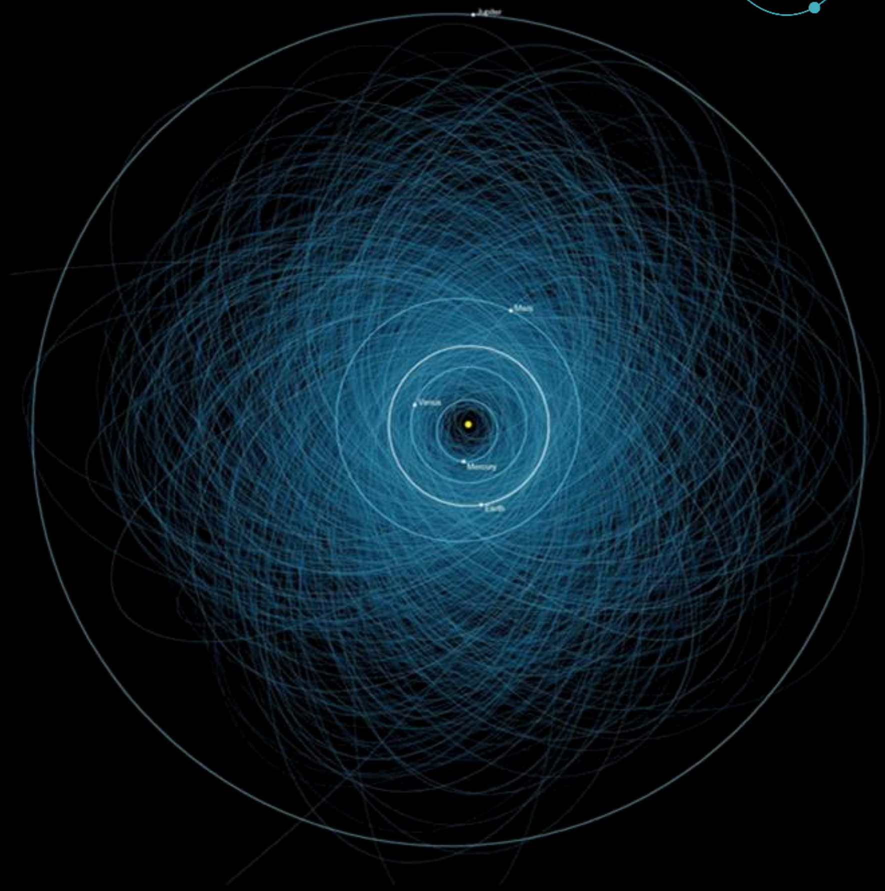

CHALLENGES & OPPORTUNITIES

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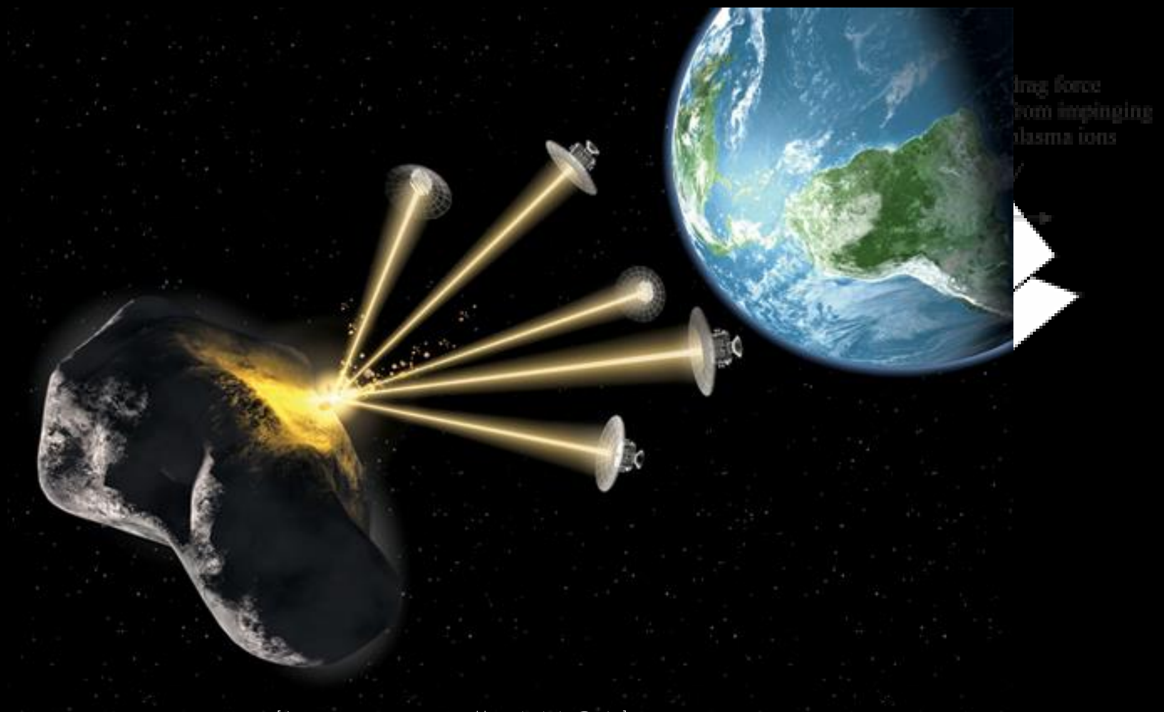
Some Open Questions

- Which asteroid redirection methods should be used?
- Which asteroids do we want to target?
- What trajectories should we use for transfers?
- How can we control asteroid motion?
- How do we improve our models of asteroids?
- .. and many more.

REDIRECTION METHODS

What are the redirection methods we might want to consider?

- RM-01: Ion beam shepherd
- RM-02: Tugboat/thruster
- RM-03: Gravity tractor
- RM-04: Laser sublimation
- RM-05: Mass ejector



[Image credit: NASA]

REDIRECTION METHODS

Comparative Analysis of Asteroid Redirection Methods:

I. Resource utilization framework → Definition of scope, objectives and constraints

II. Five redirection methods → Ion Beam, Tugboat, Laser, Mass Ejector, Gravity Tractor

III. Mission level criteria → Δv, robustness, alteration, cost, power, TRRA, mission risk, long-term value

IV. Uncertainty in physical parameters → diameter, spin, density, material ($E_S, T_S, \ldots$)

V. Monte Carlo analysis → 10 000 evaluations of system equations with uncertainty

VI. Three aggregation techniques → AHP, Utility-based, Fuzzy Aggregation

REDIRECTION METHODS

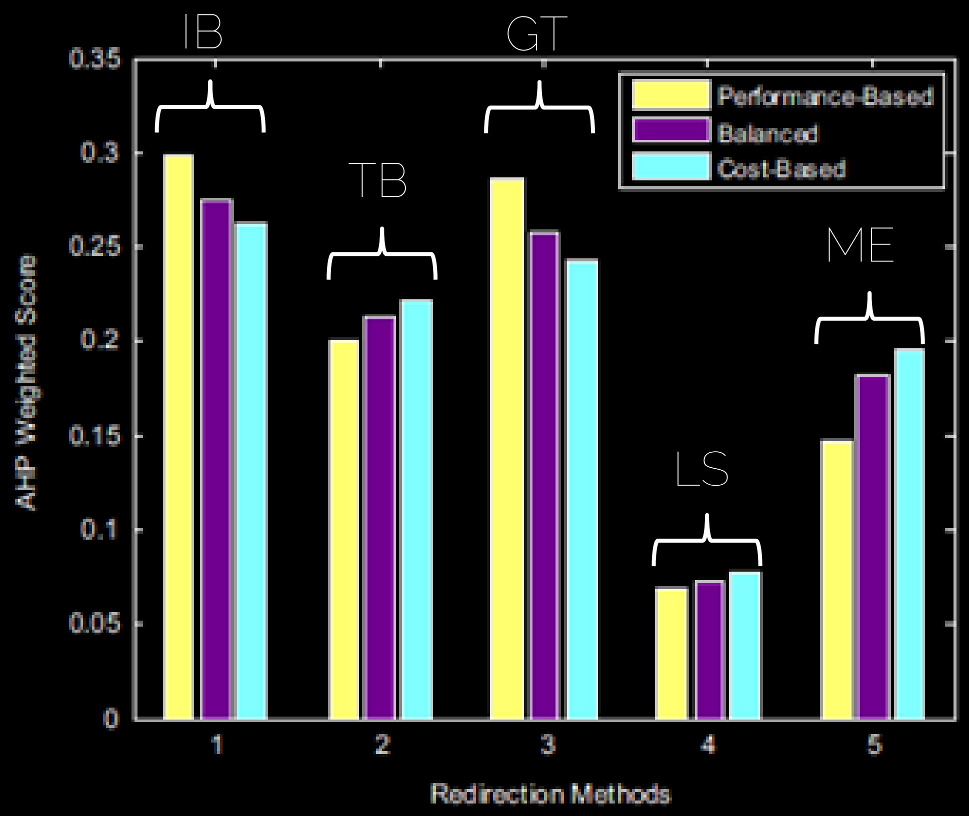


Fig. 4. AHP redirection method scores.

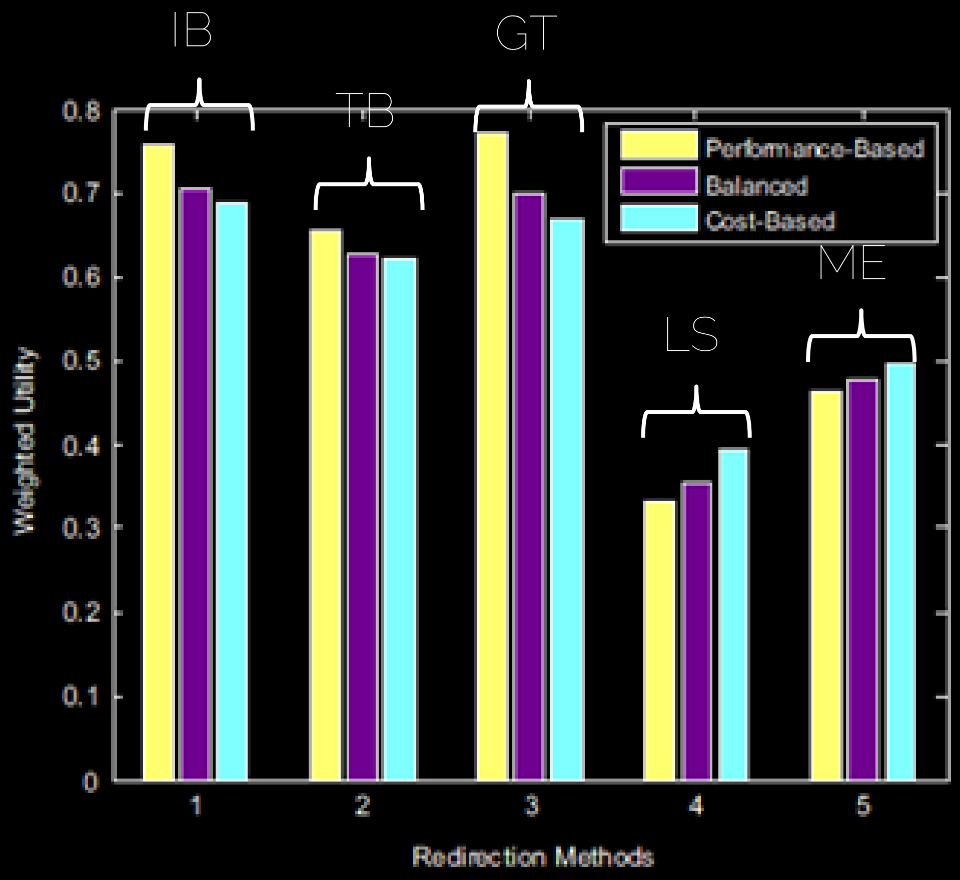
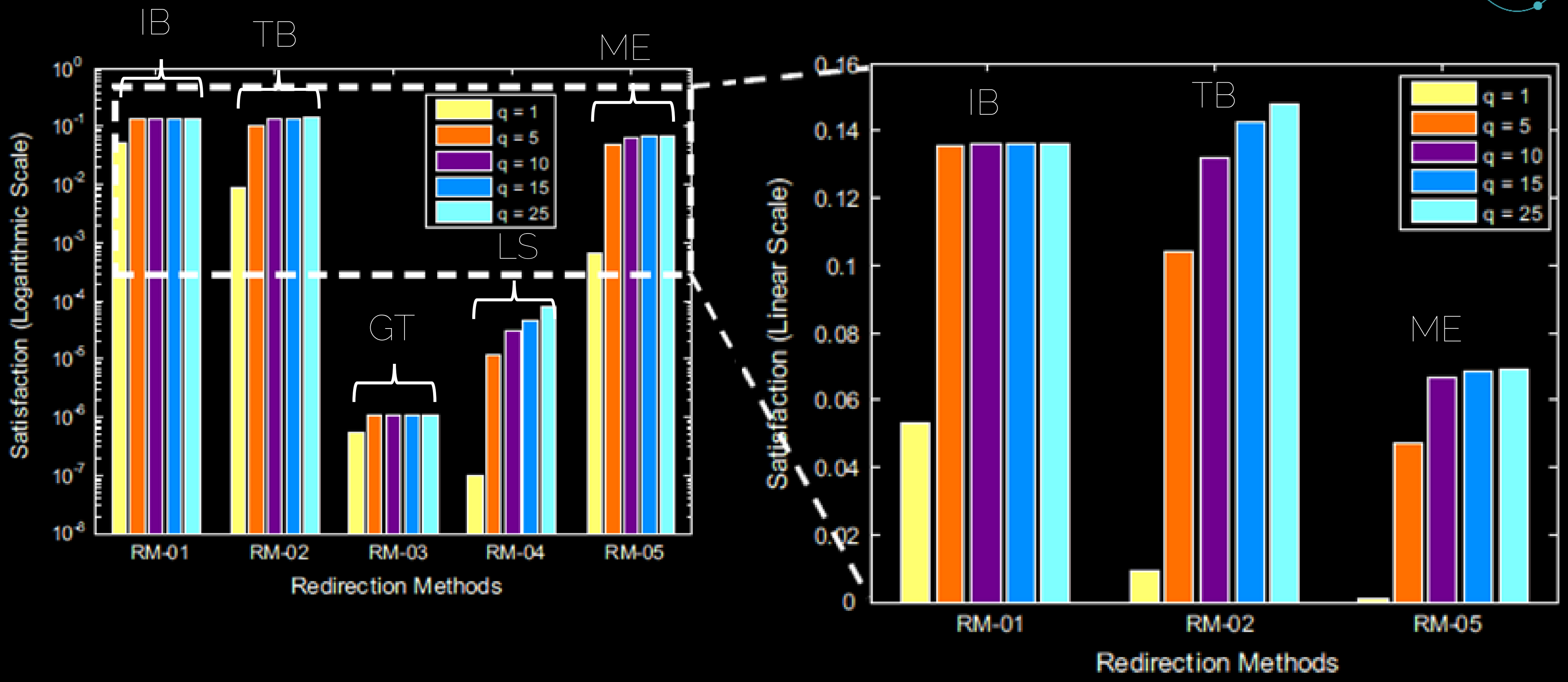


Fig. 5. Utility method redirection method scores.

REDIRECTION METHODS



REDIRECTION METHODS

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How could this be improved by using formations?

I. Resource utilization framework → Definition of scope, objectives and constraints

II. Five redirection methods → Ion Beam, Tugboat, Laser, Mass Ejector, Gravity Tractor

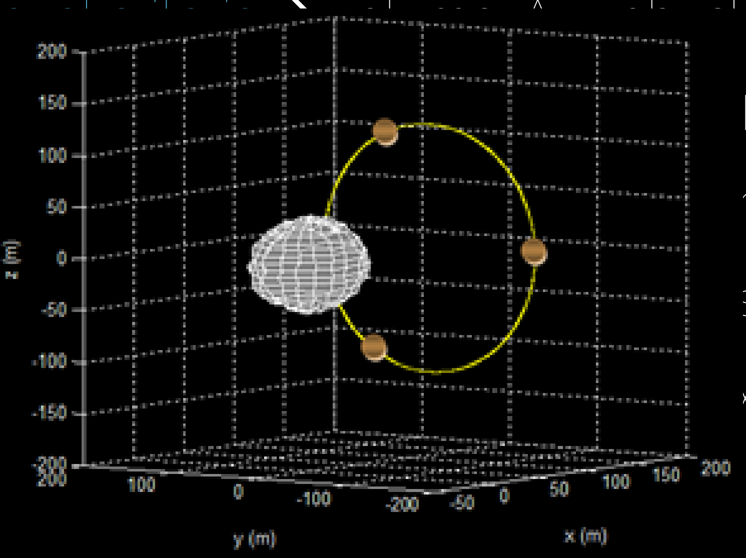
III. Spacecraft formations → Free-flying and Landed (1, 3, and 5 spacecraft)

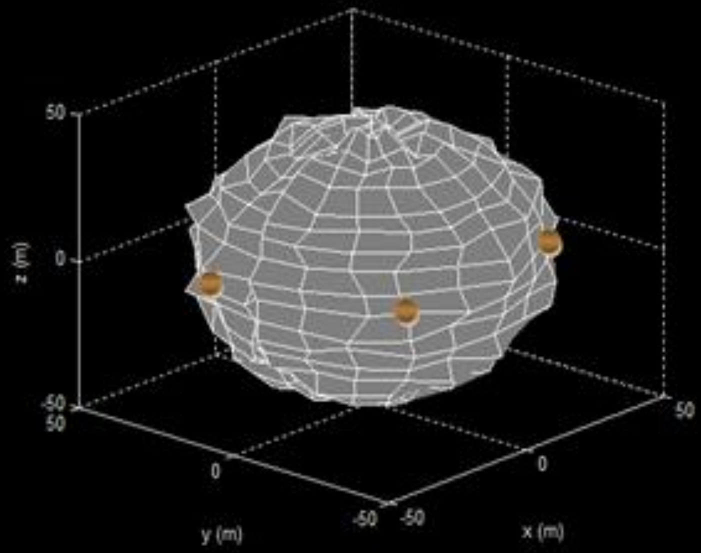
IV. Mission l ... 'ness, ... sion risk, long-term val ... ple sp

V. Uncertai ... neter,

VI. Monte C ... s of sy

VII. Aggrega ... with s





REDIRECTION METHODS

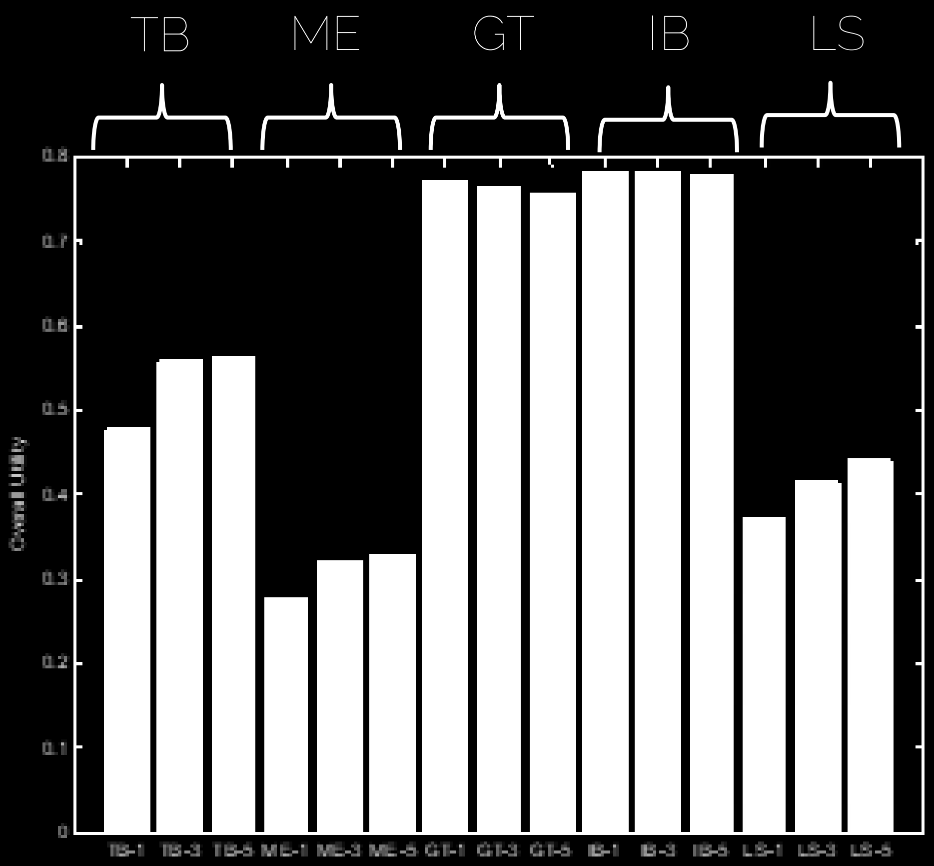


Figure 3-10. Overall weighted utility of each method

Ion Beam

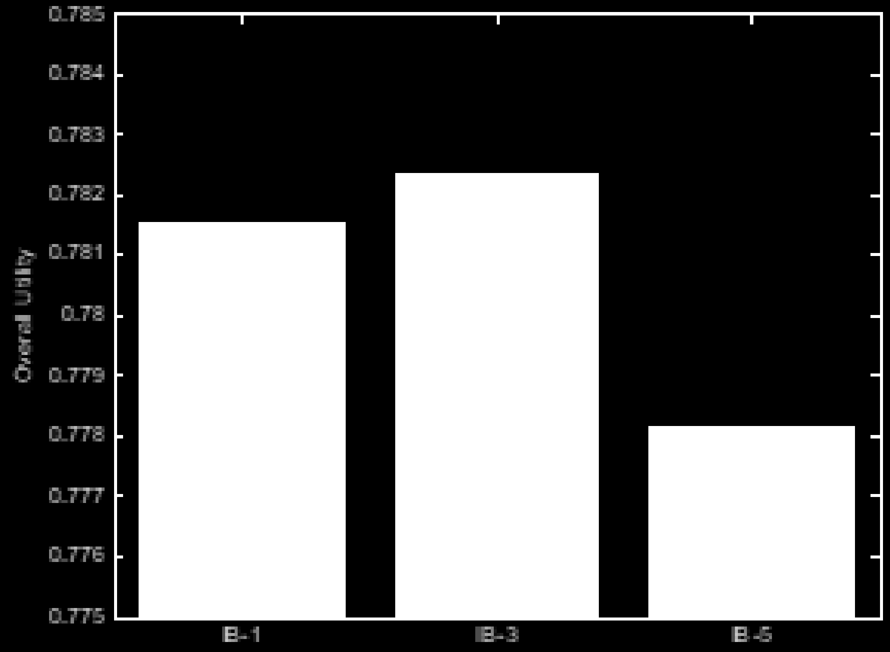


Figure 3-11. Overall weighted utility of each ion beam formation approach

ASTEROID EVALUATION

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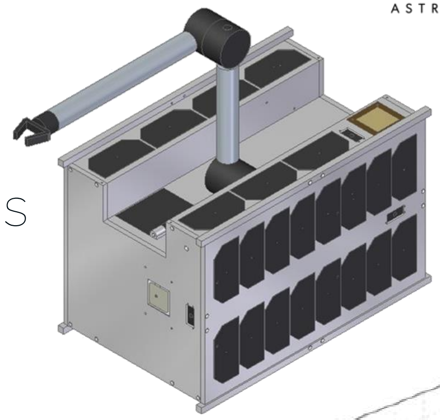
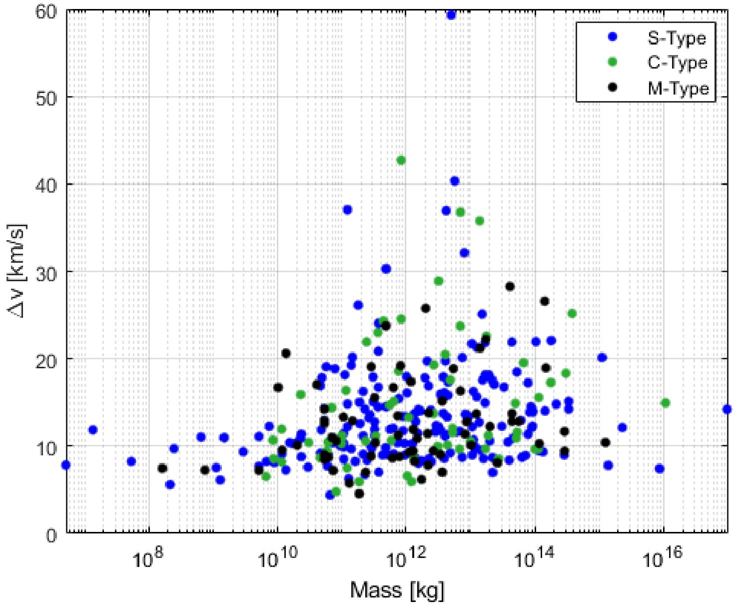
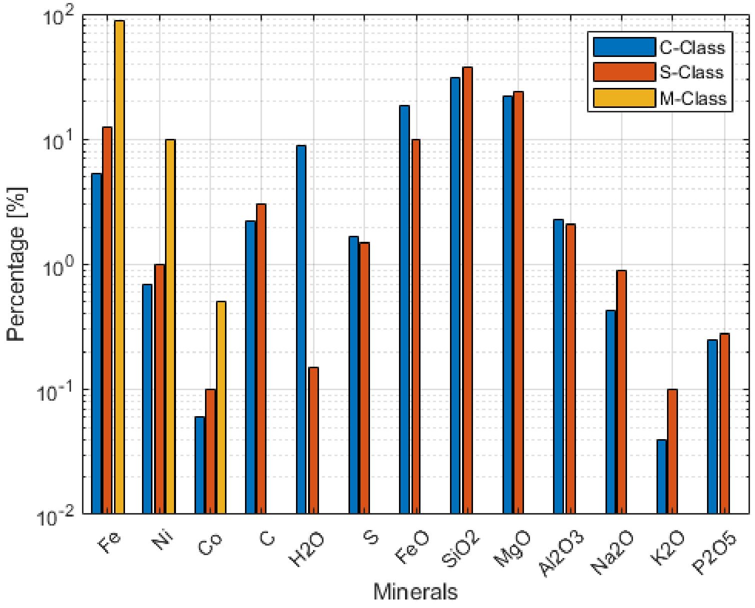
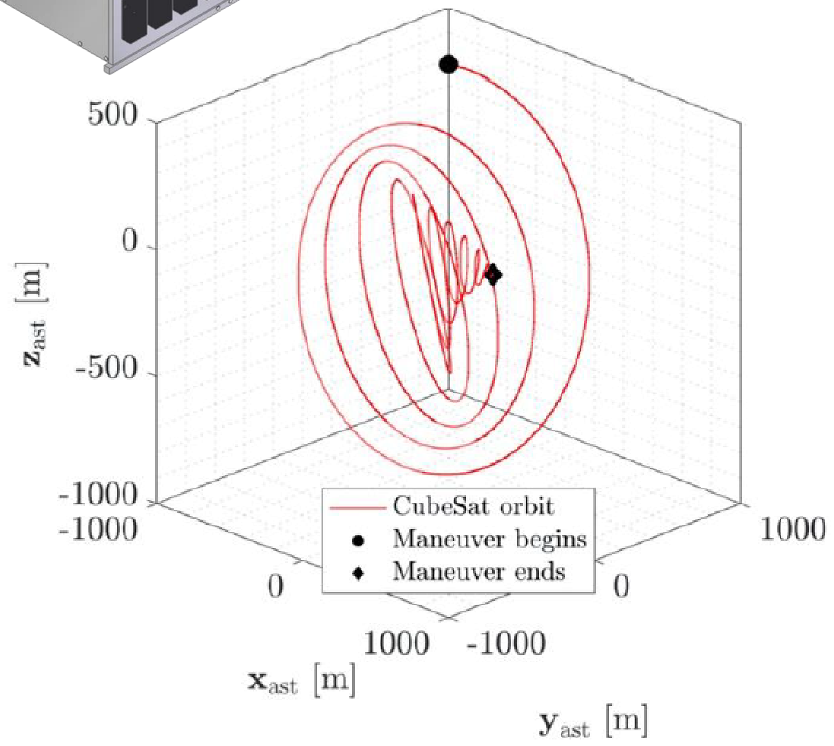
- Development of an impulsive orbital transfer stochastic optimization scheme with material resource expectations
- Small satellite with low-thrust attitude and orbit controller for rapid prospecting using sampling arm









TRAJECTORY PLANNING

With low-thrust techniques,

- What is the target range of asteroids for redirection?
- How do we optimize transfer trajectories considering uncertainty?

TRAJECTORY PLANNING

Feasibility of Low-thrust Asteroid Orbital Transfer:

I. Characterize target asteroid range and generate candidate database → Arjuna-type (semi-major axis and transfer angle), physical characteristics, number of revolutions

II. Low-thrust redirection method → Ion beam shepherd and spacecraft specifications

III. Trajectory design model → Minimized form of Gauss' Variational Equations and transfer angle formulations

IV. Spacecraft sizing model → Relationships for mass, power, fuel, and thrust

V. System costing model → NPV analysis and NASA QuickCost model

VI. Analysis → Full database, positive return space and investment range

TRAJECTORY PLANNING

Results

- Many feasible scenarios over the entire domain, some with very high return
- Small asteroids in the range of ~2-15 m very feasible
- Excellent overall mission characteristics:
  - 60-70% fuel ratio
  - 1-4 year timeframes
  - Mass < 5 tonnes
  - Cost ~100s of millions

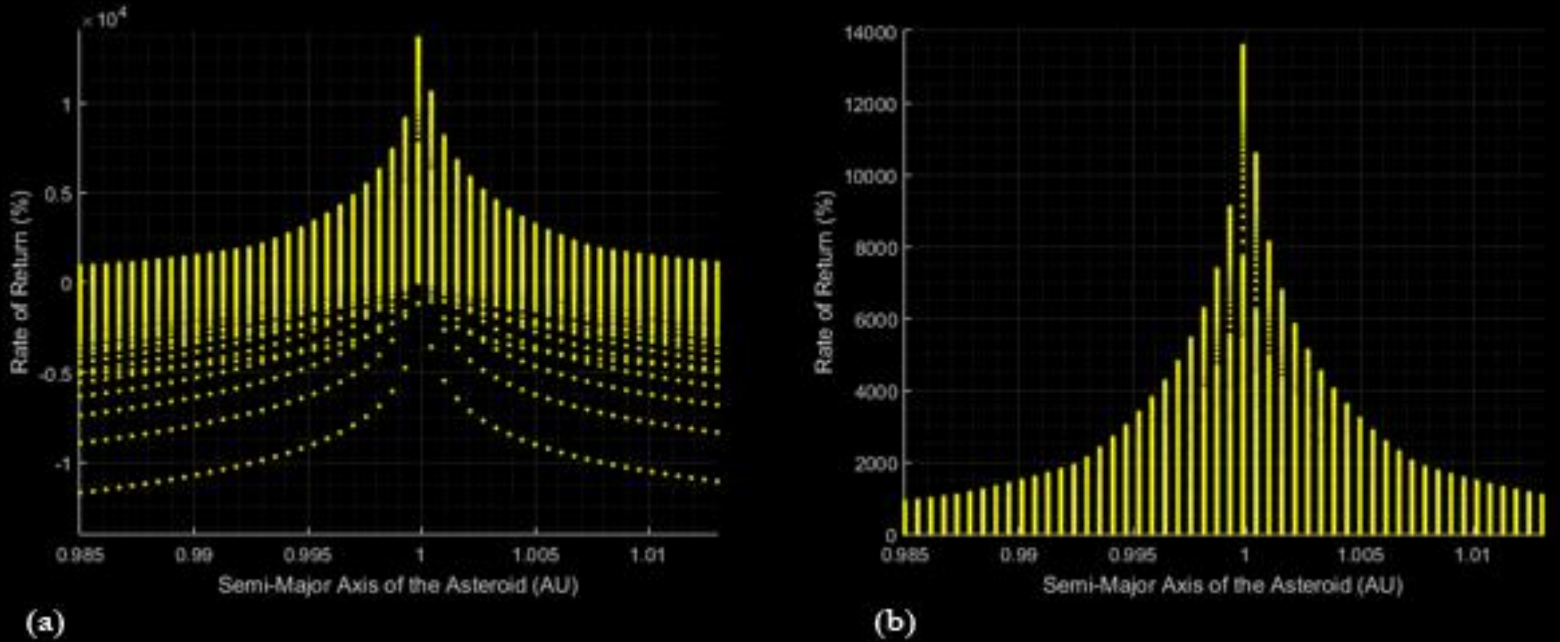


Figure 4-4. Scatter plots of semi-major axis versus return rate; (a) all results; and (b) positive return rates

TRAJECTORY PLANNING

Optimization of Asteroid Three-dimensional Transfer:

I. Problem formulation → 2-phase transfer using patched conic approximation (initial orbit to rendezvous, rendezvous to capture orbit), low-thrust (Asteroid: 2013 RZ_{53})

II. Uncertainty models → Magnitude, albedo, and density distributions and relationships

III. Uncertainty quantification → Monte Carlo analysis of near-optimal solutions for 100 candidate asteroids

IV. Trajectory design → Pseudo-equinoctial shaping transfer design in two phases

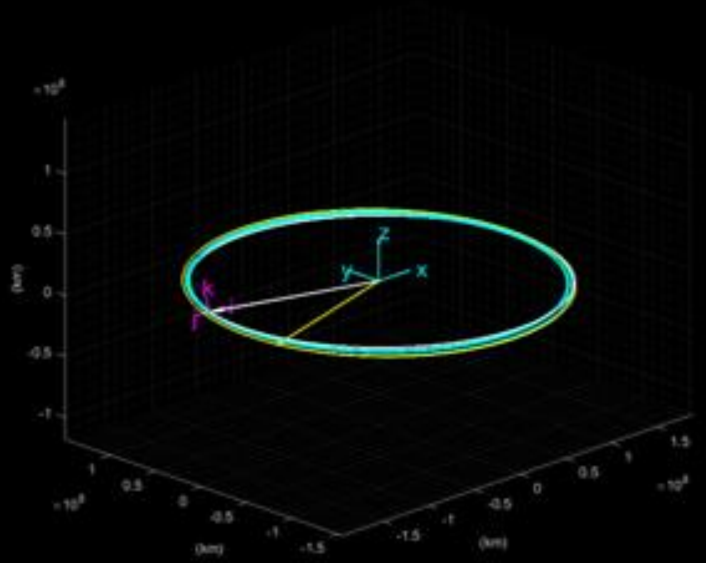
V. Optimization design → Minimize Δv, 21 decision variables, system/transfer/target-orbit constraints, two step: global (GA) and local (SQP)

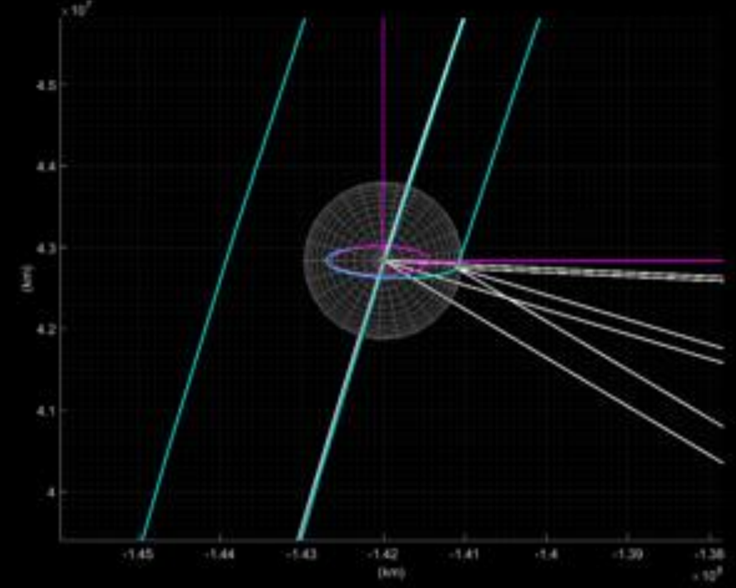
ASTEROID CONTROL

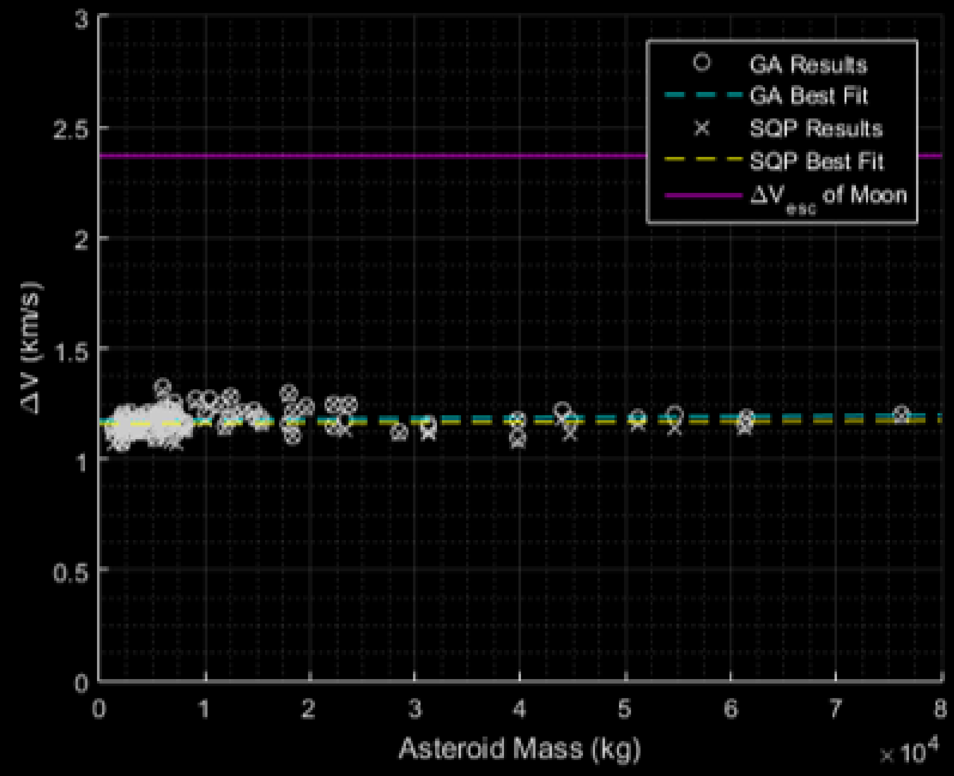
- Low-thrust orbit transfer optimization with uncertainty using pseudo-equinoctial elements

$\Delta v = 1.068\ \mathrm{km/s}$

Transfer time ~3 years

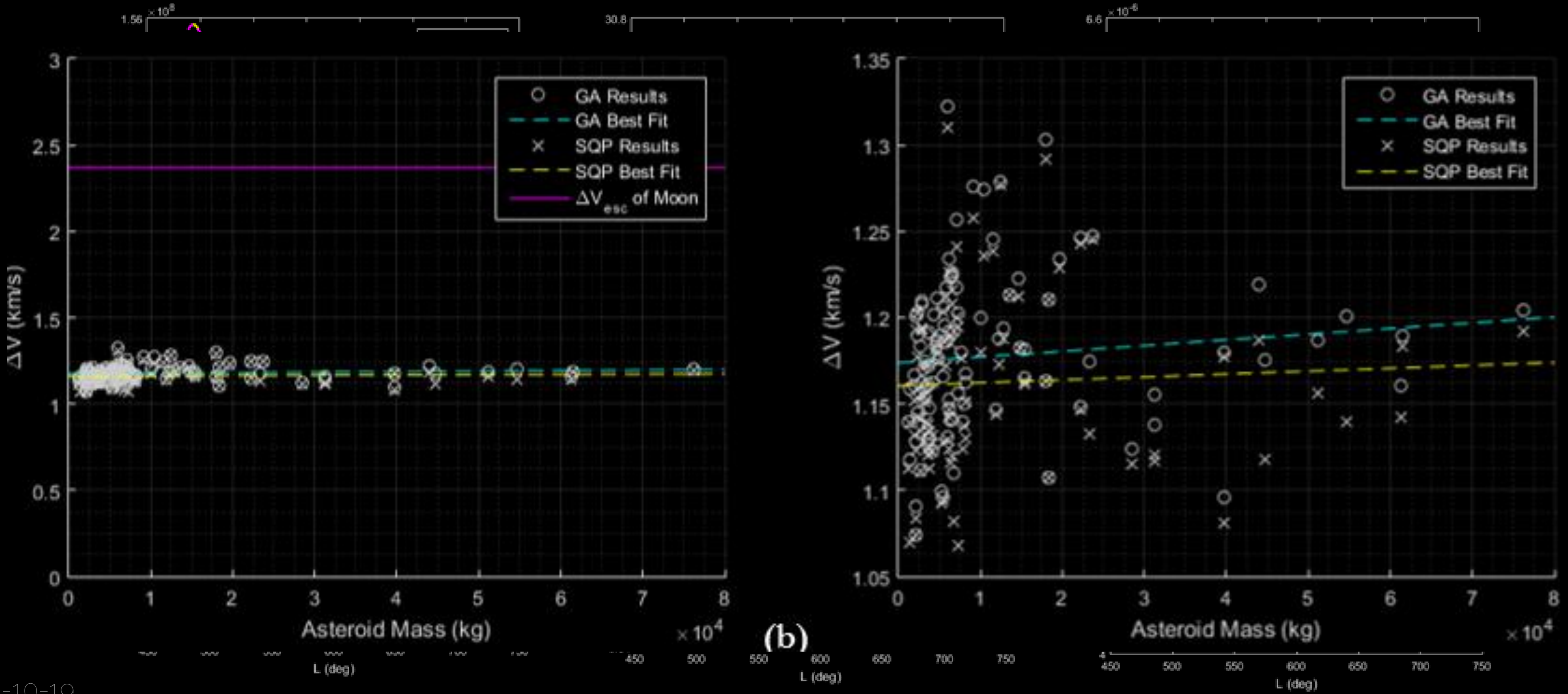






ASTEROID CONTROL

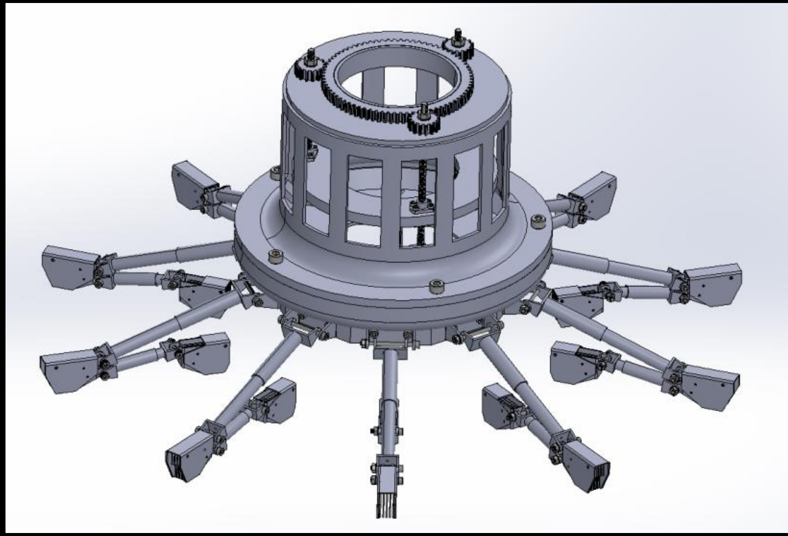
- Low-thrust orbit transfer optimization with uncertainty using pseudo-equinoctial elements



LANDED FORMATION CONTROL

With landed formations,

- For what size of asteroids are landed formations most viable?
- Where should we place landers to best control an asteroid?



LANDED FORMATION CONTROL

Redirection Mission Evaluation Using Multiple Landers:

I. Problem formulation → Multiple landed tugboat spacecraft, scope, and constraints

II. Asteroid target range → Establish properties, bounds, to create 10 000 redirection scenarios (d_{ast} ≤150 m) and (Δv ranging from 1-2370 m/s)

III. Spacecraft sizing model → Relationships for mass, power, fuel, thrust, and # of s/c

IV. System costing model → Multiple s/c modelling for cost learning curve, data rate and communications requirements, return, NPV analysis, and NASA QuickCost model

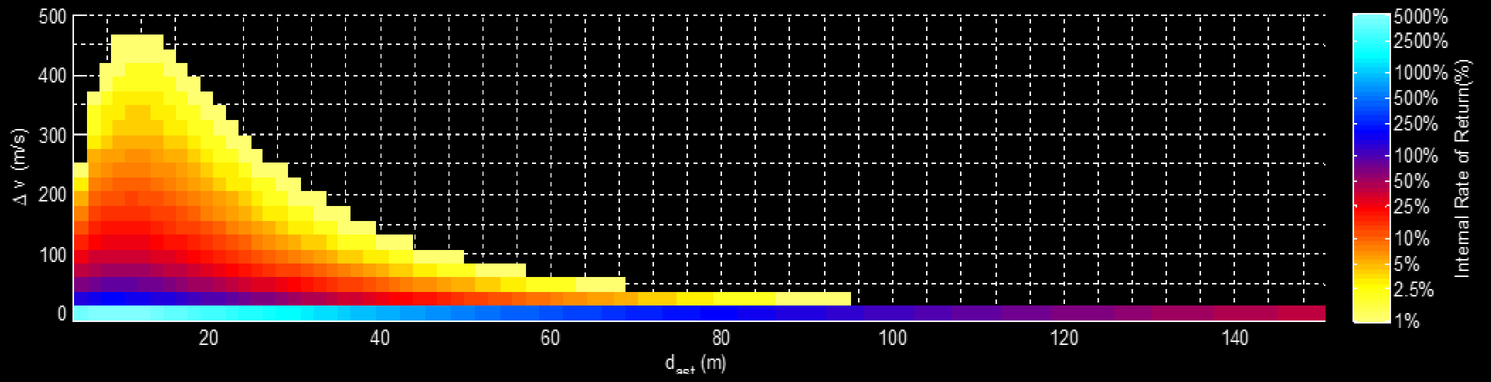
V. Optimization across scenarios → Best return on investment, presented with respect to key optimization parameters, particularly number of spacecraft

LANDED FORMATION CONTROL

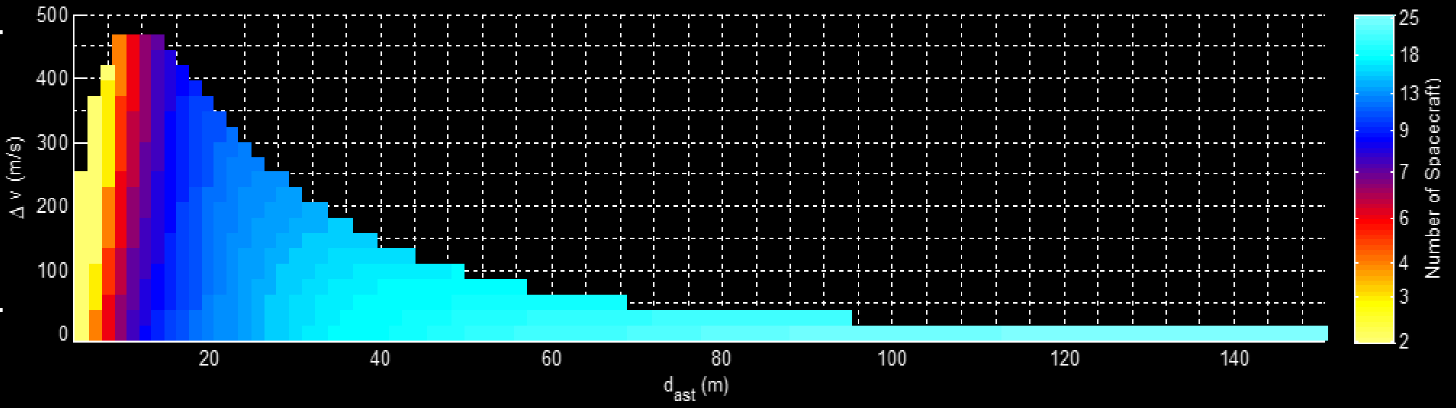
Redirection Mission Evaluation Using Multiple Landers

- Low-thrust tugboats are a valid approach for small-medium sized asteroids with low Δv

Asteroid Range
d_{ast} < 40 m
Δv < 500 m/s
Return ~10-250%



Number of S/C
~3-10



LANDED FORMATION CONTROL

Optimal Formation for Multiple Landers for Asteroid Detumbling:

I. Formation model → Four landers for detumbling

II. Asteroid modelling → Triangularly faceted convex polyhedra, computing mass and inertial properties through divergence and Green's theorems

III. Thrust locations and orientations → Determine viability using specific thruster/lander constraints and ensure non-intersection via polyhedral parametric line-clipping

IV. Control allocation → Ensure full attitude/torque control for feasible combinations

V. Detumbling control → Four thrusters with proportional-derivative control law based

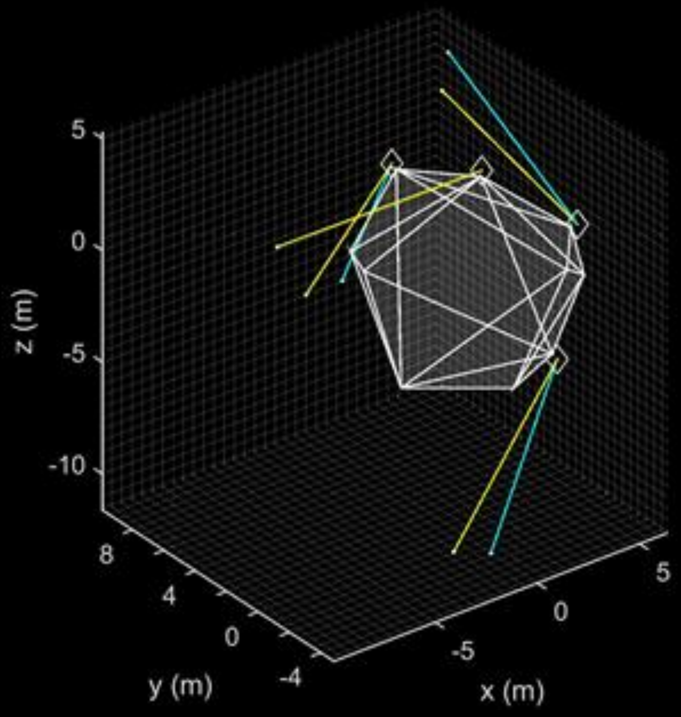
VI. Optimality measures → Time-optimal detumbling of the asteroid

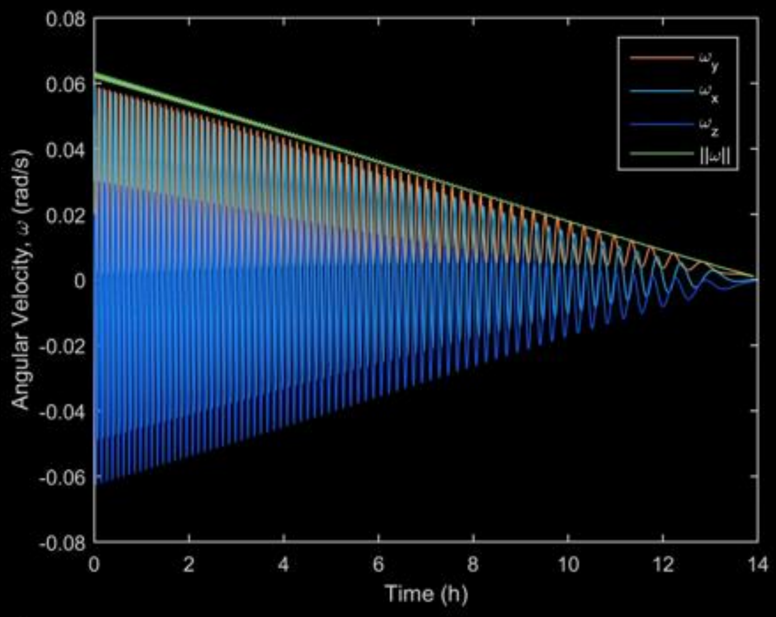
VII. Simulation and sensitivity analysis → Fictitious asteroid w/ results of simulation

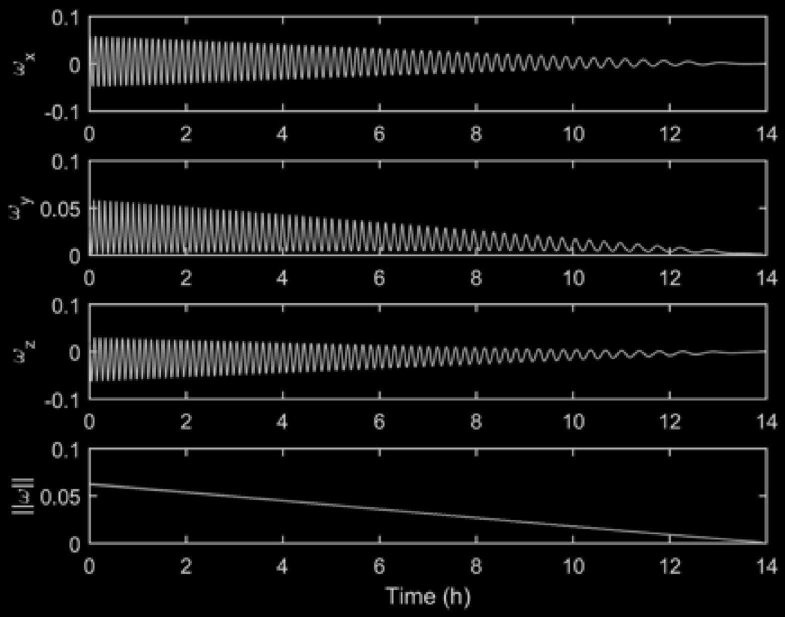
LANDED FORMATION CONTROL

Table 5-7. Simulation results

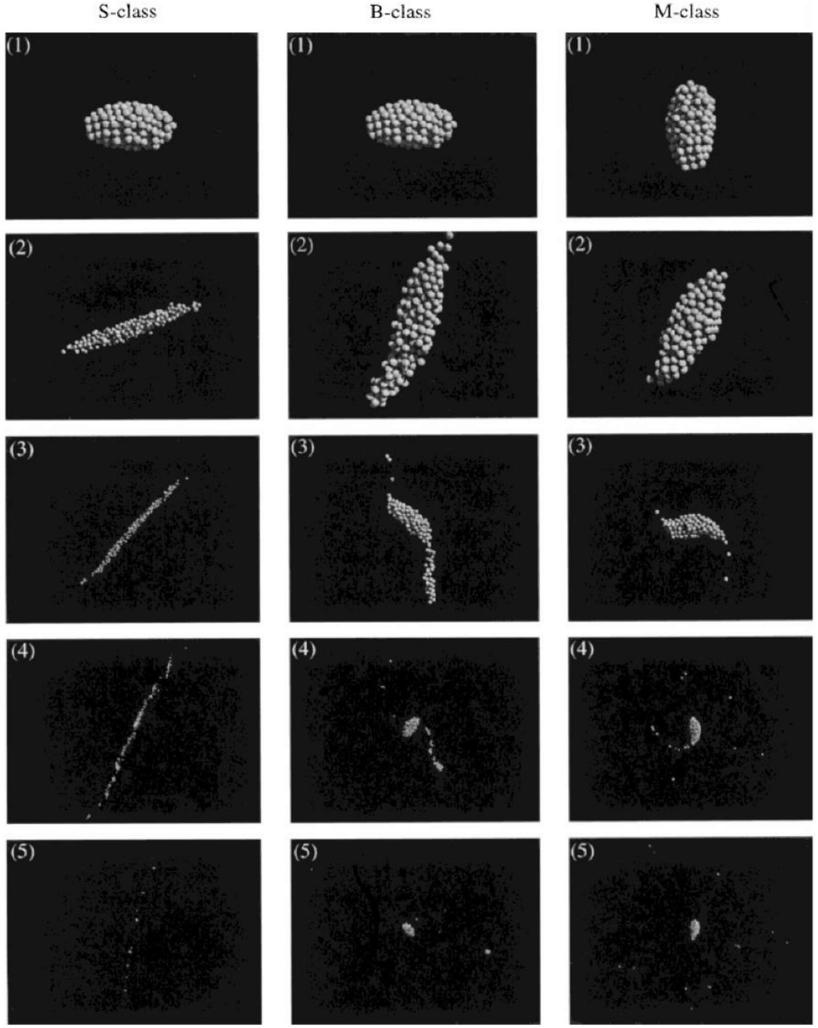
Variable	Optimization	Sensitivity Analysis	Unit
Detumbling time	14.5136	13.9217	h
Total mass of fuel	1.0318	1.0023	kg
Fuel mass – thruster 1	0.3149	0.3115	kg
Fuel mass – thruster 2	0.3310	0.2944	kg
Fuel mass – thruster 3	0.1792	0.1902	kg
Fuel mass – thruster 4	0.2066	0.2061	kg







ASTEROID MODELING



K. J. Walsh, et al, 2009.

- Development of nonhomogeneous, polyhedral granular model using soft-body dynamics

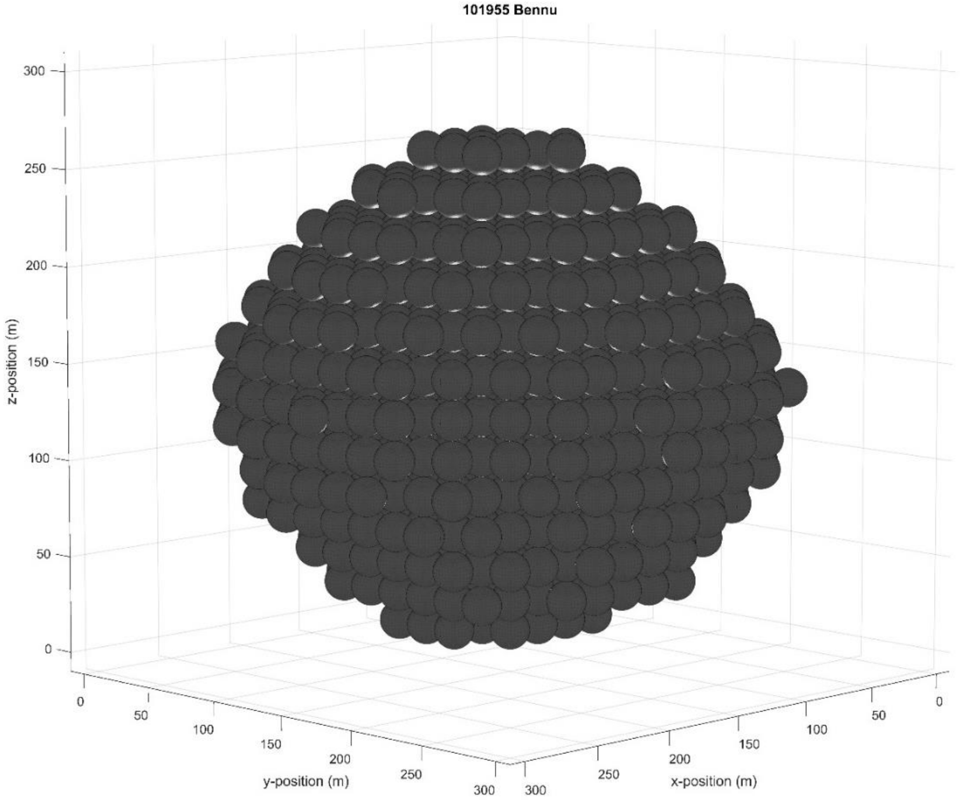
Image: ESA

- Binary asteroid formation
- DART/Hera mission for planetary defense

ASTEROID MODELING

Investigating the probability of binary asteroid formation mechanisms, i.e., re-aggregation after YORP spin-up, tidal disruption, or a collision,

- Develop granular model code that follows the soft-sphere discrete elements method (SSDEM)
- Simulating a variety of formation scenarios with a range of initial conditions



Preliminary results for a collisional scenario using the parameters of the Didymos-Dimorphos system

ASTEROID MODELING

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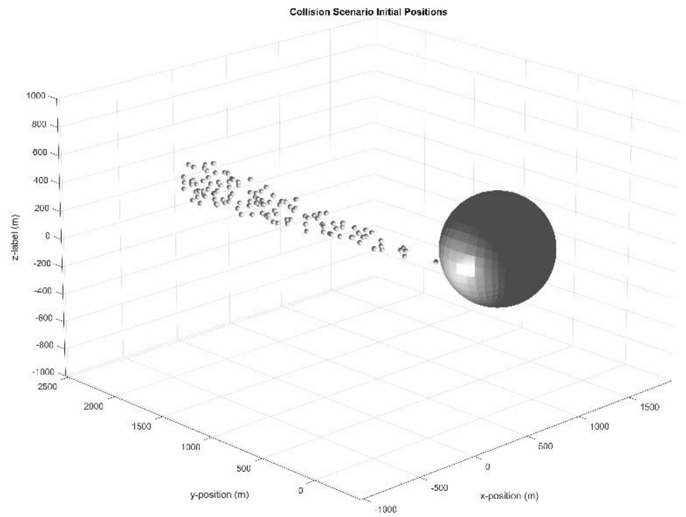

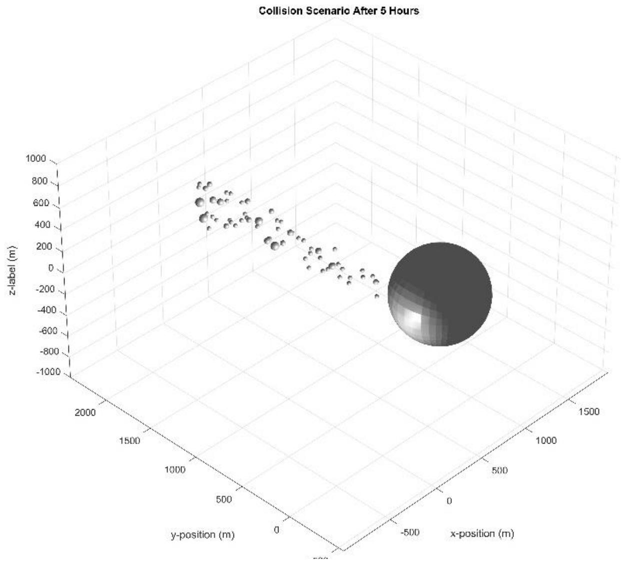

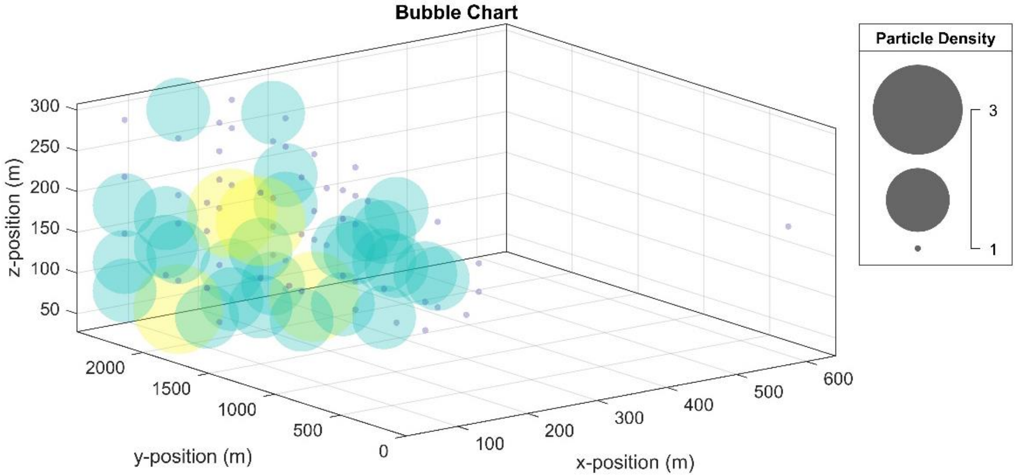

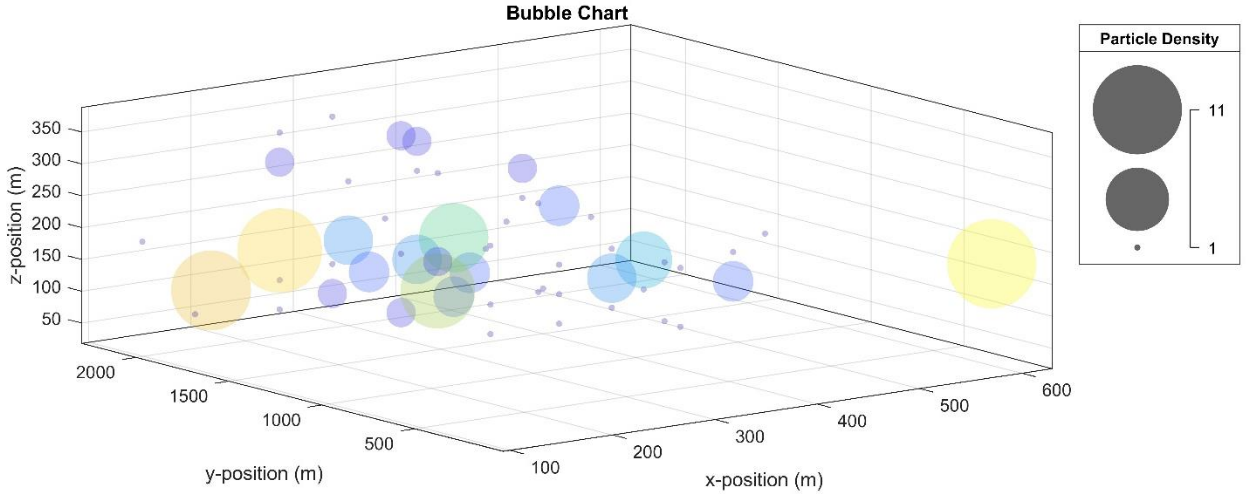

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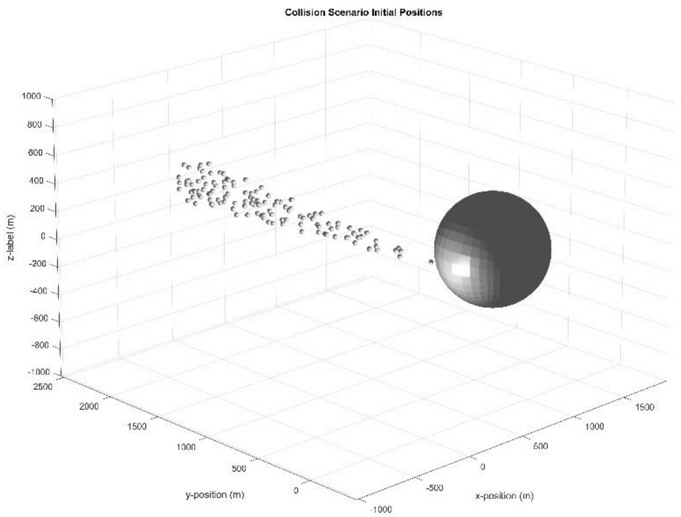

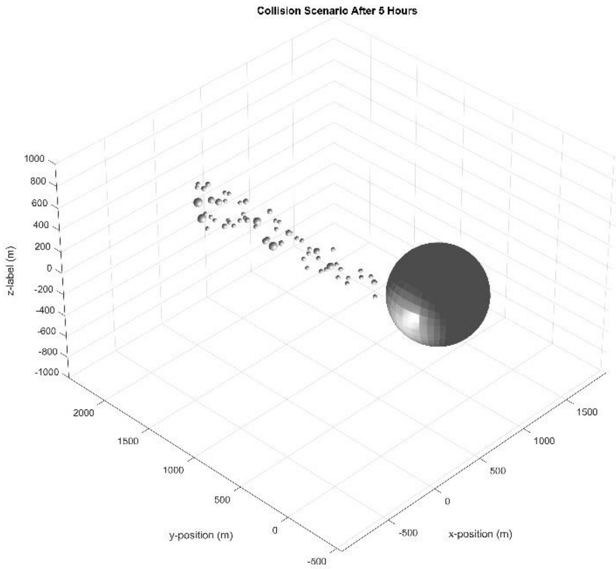

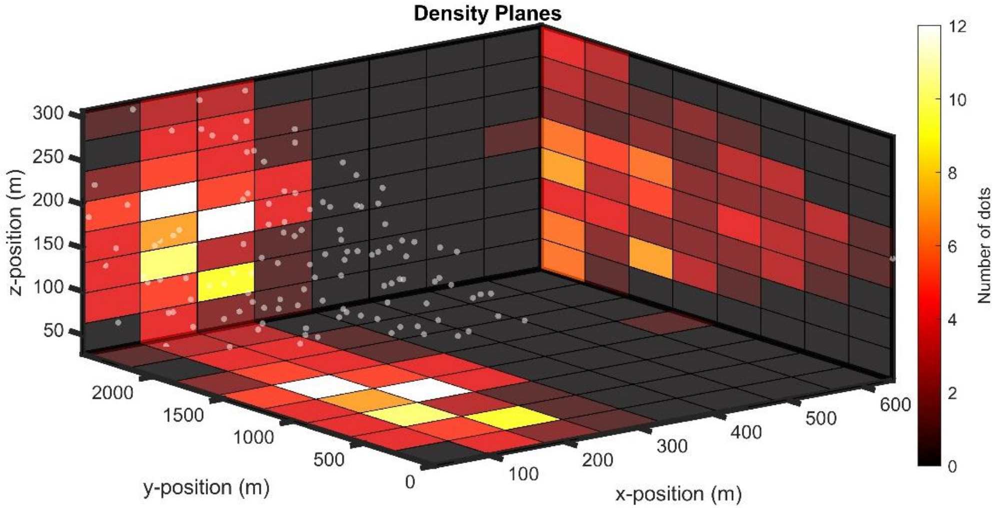

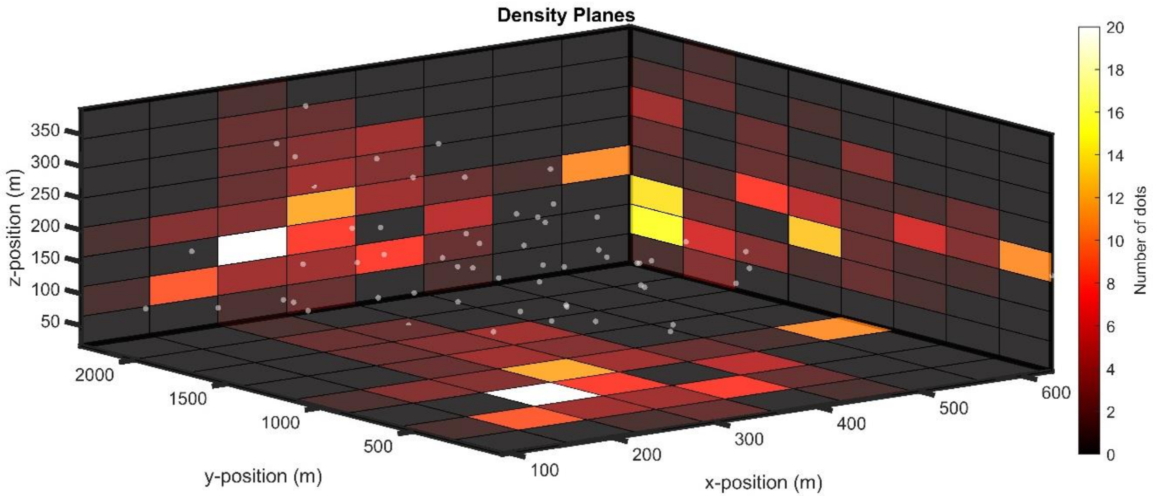

Key takeaways…

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THANK YOU

Any Questions?

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