Nano/Micro Satellites' Contribution to Planetary Defense
Proposal for Rapid response Flyby Exploration using Deep Space Constellation

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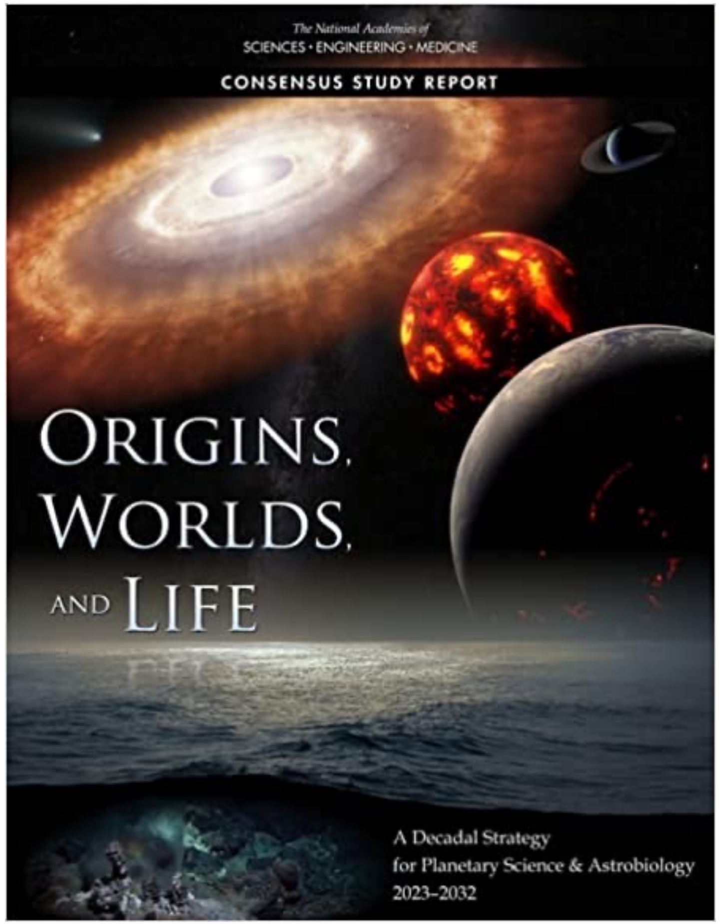
A Decadal Strategy for Planetary Science and Astrobiology 2023-2032

The U.S. Decadal Survey recommended completing the DART mission in 2023, launching the NEO Surveyor in 2026, and conducting a rapid response flyby mission by the end of 2032.



Finding: Prior characterization of a hazardous NEO via an in situ reconnaissance mission is advisable to determine its physical characteristics and to develop an appropriate mitigation response based on the available warning time. Although rendezvous missions are preferred, fast flyby missions may be required to obtain timely characterization data for short warning time scenarios.

Recommendation: The highest priority planetary defense demonstration mission to follow DART and NEO Surveyor should be a rapid-response, flyby reconnaissance mission targeted to a challenging NEO, representative of the population (~50-to-100 m in diameter) of objects posing the highest probability of a destructive Earth impact. Such a mission should assess the capabilities and limitations of flyby characterization methods to better prepare for a short-warning-time NEO threat.

Next Steps for Planetary Defense Missions (p.18-21)

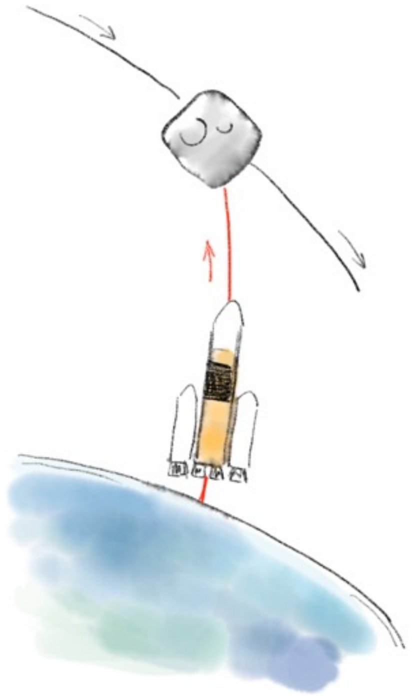
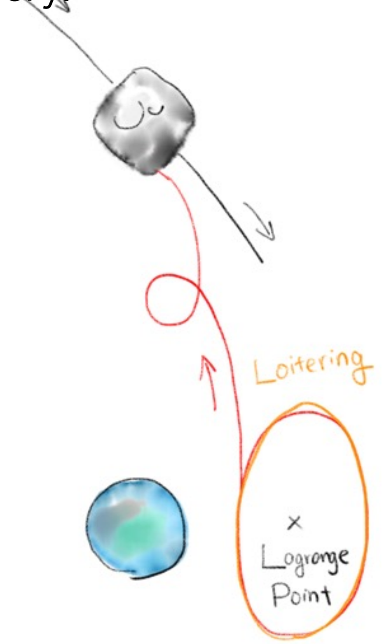
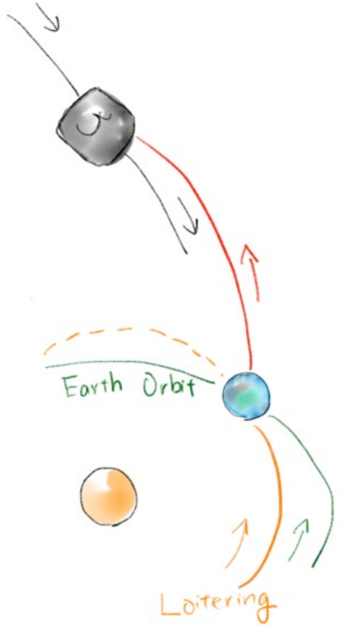
Necessity of Rapid Response Exploration 1

The U.S. Decadal Survey has asserted the importance of rapid response exploration in the planetary defense field in order to understand the characteristics of asteroids that are in danger of impacting the Earth and to take effective mitigation measures.

Necessity of Rapid Response Exploration 2

On October 19, 2017, an interstellar object flying from outside the solar system was discovered for the first time in the history of astronomical observations.
Researchers are paying attention to rapid response exploration to directly explore interstellar objects.

Rapid Response Exploration Scenarios

Option	Direct Launch	Loitering at Lagrange Points	Loitering in Earth-resonant flyby orbit (Asteroid flyby cycler)
Overview	Launch a spacecraft just after the target object is found. 	Keep the spacecraft in halo orbit, and escape and aim for the target object just after discovery.  	Keep the spacecraft in an Earth-resonant flyby orbit and target the object with the Earth gravity assist just after discovery. 

Rapid Response Exploration Scenarios

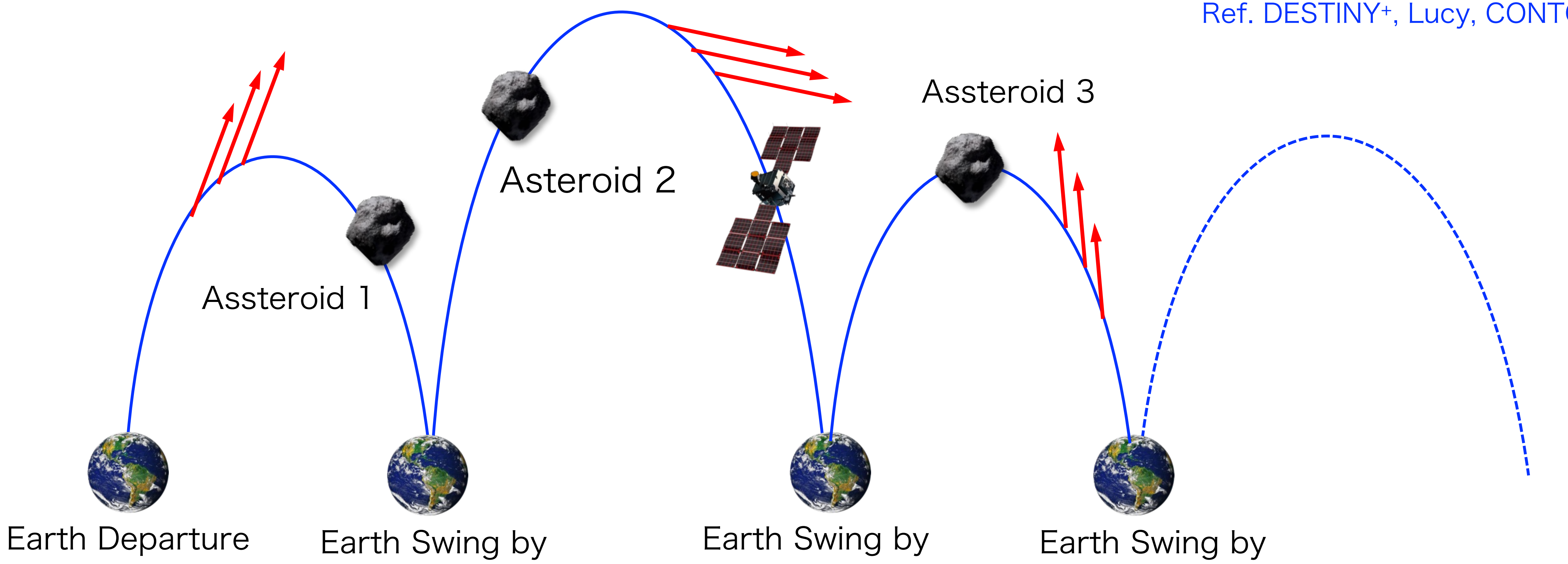
	Direct Launch	Loitering at Lagrange Points	Loitering in Earth-resonant flyby orbit (Asteroid flyby cycler)
Overview	Launch a spacecraft just after the target object is found.	Keep the spacecraft in halo orbit, and escape and aim for the target object just after discovery.	Keep the spacecraft in an Earth-resonant flyby orbit and target the object with the Earth gravity assist just after discovery.
Difficulties	The rocket must be ready for launch at any time, which is difficult to do when targeting hazardous asteroids, which occur only once every 10 years or so.	Since the escape energy from a halo orbit is low, a large acceleration is required from there by electric propulsion, etc.	It is necessary to be able to operate more than 10 probes simultaneously, and the challenge is to make them autonomous for this purpose.
Mission Class	Micro to small spacecraft (~50 kg) with large launch vehicle	Medium-size spacecraft (~500kg)	About 10 micro spacecraft (~50kg)
Note	A launch vehicle capable of immediate launch is essential.	ESA's Comet Interceptor	A cost-effective way to perform multiple asteroid flybys while waiting.

Proposed method

Asteroid Flyby Cycler Orbits

Naoya Ozaki, Kanta Yanagida, et al., " Asteroid Flyby Cycler Trajectory Design Using Deep Neural Networks," *Journal of Guidance, Control, and Dynamics*, 2022.

Ref. DESTINY+, Lucy, CONTOUR



By adopting an asteroid flyby cycler orbit (alternating asteroid flyby and Earth swing by) as shown above, it is possible to fly by one NEO (requiring ΔV consumption of about 10 m/s per year) per year.

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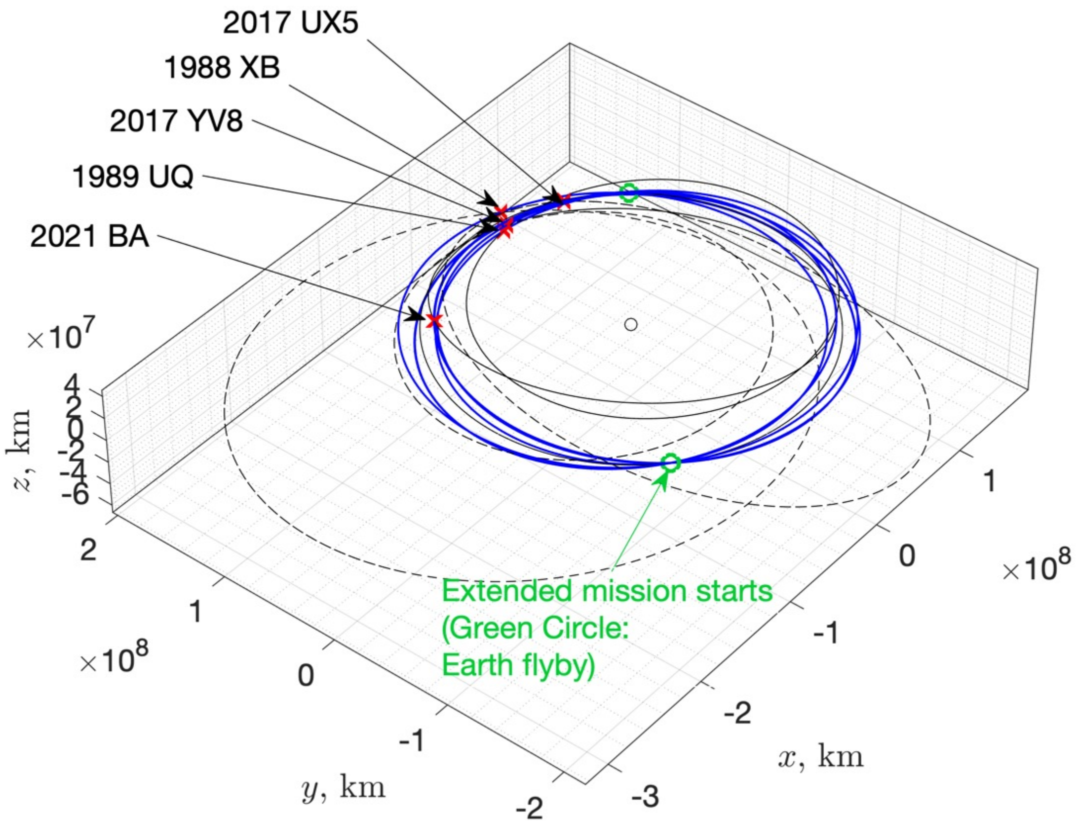

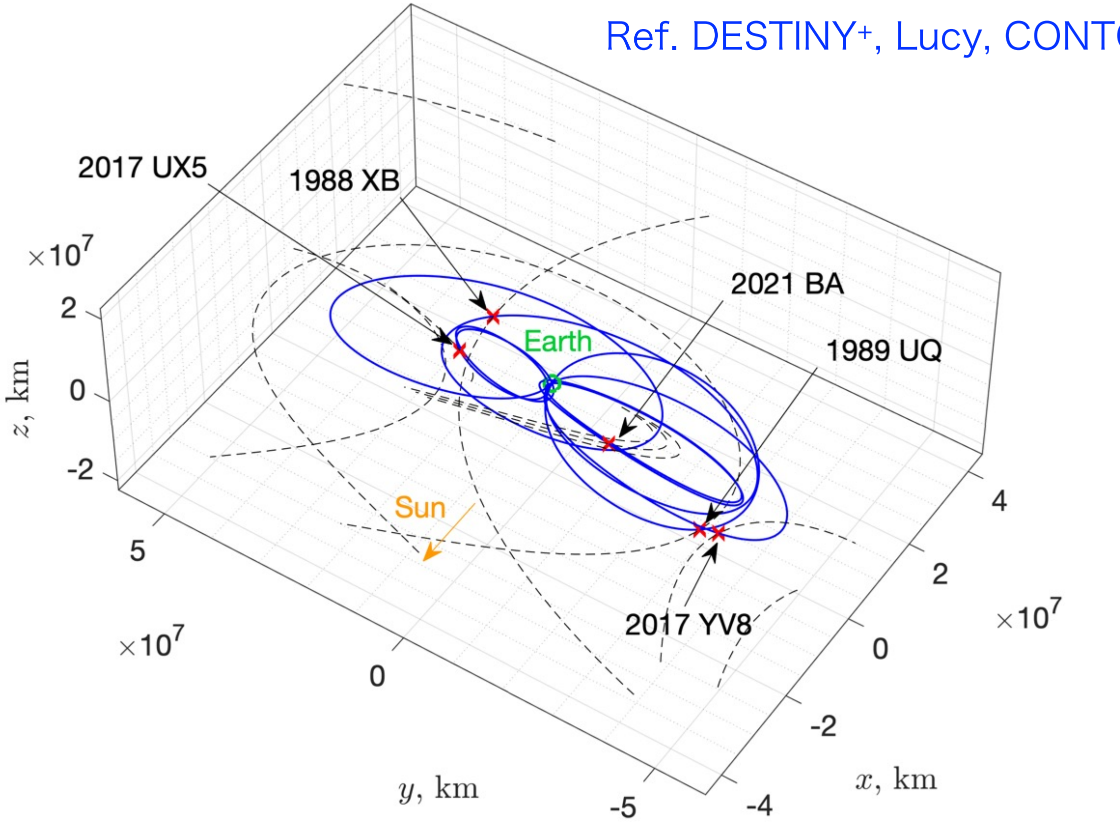

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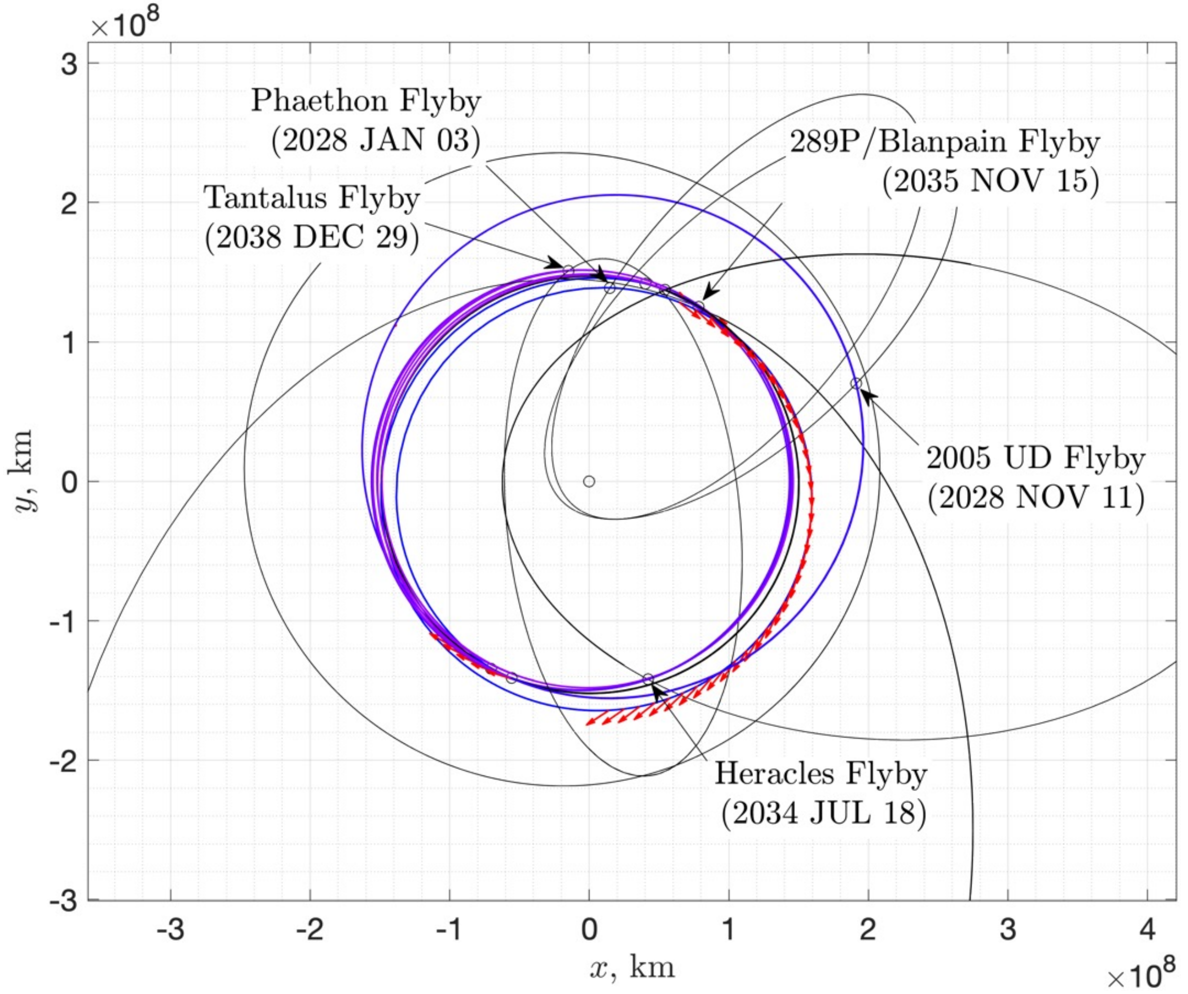
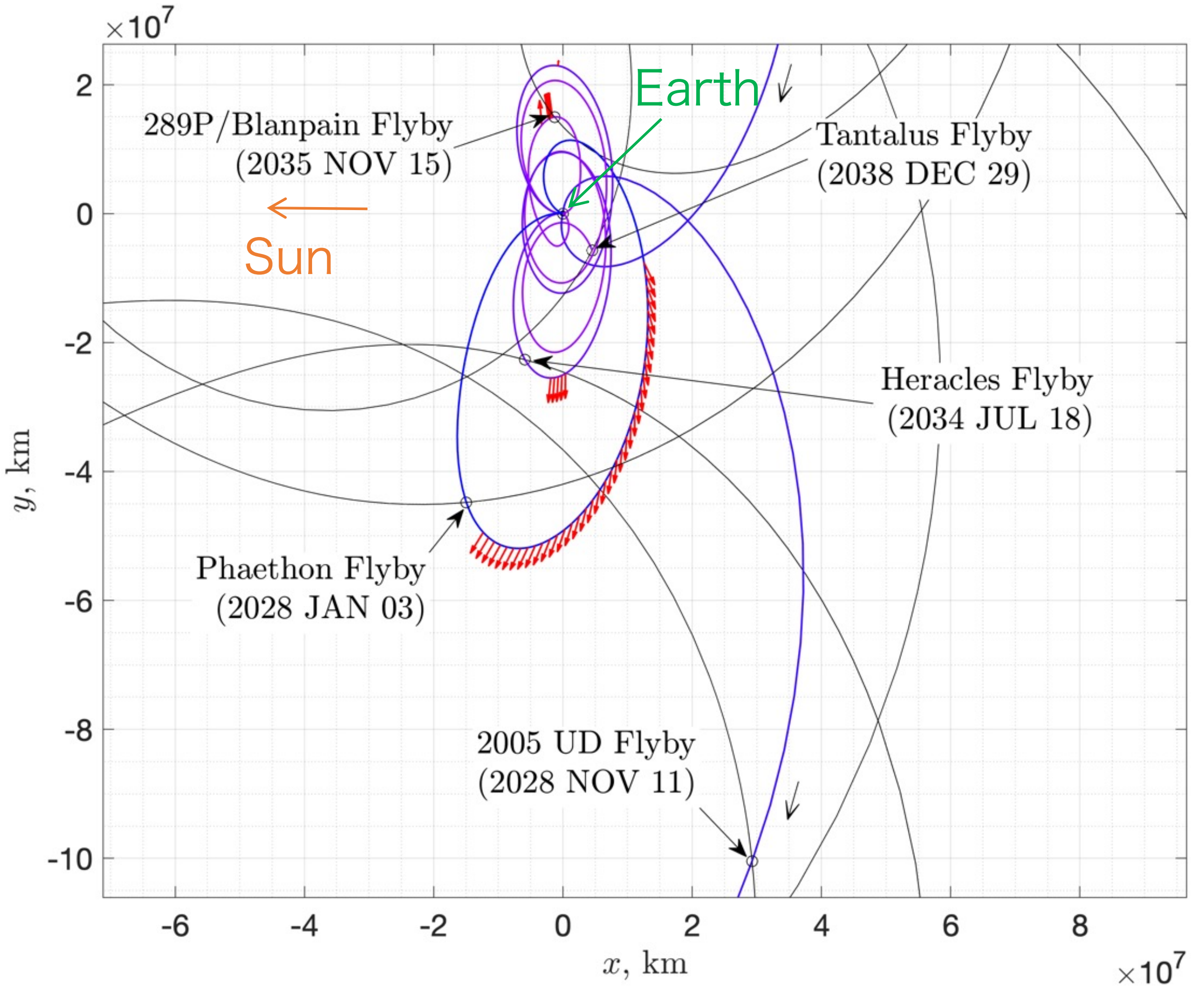
Example Trajectory of DESTINY+ Extended Mission

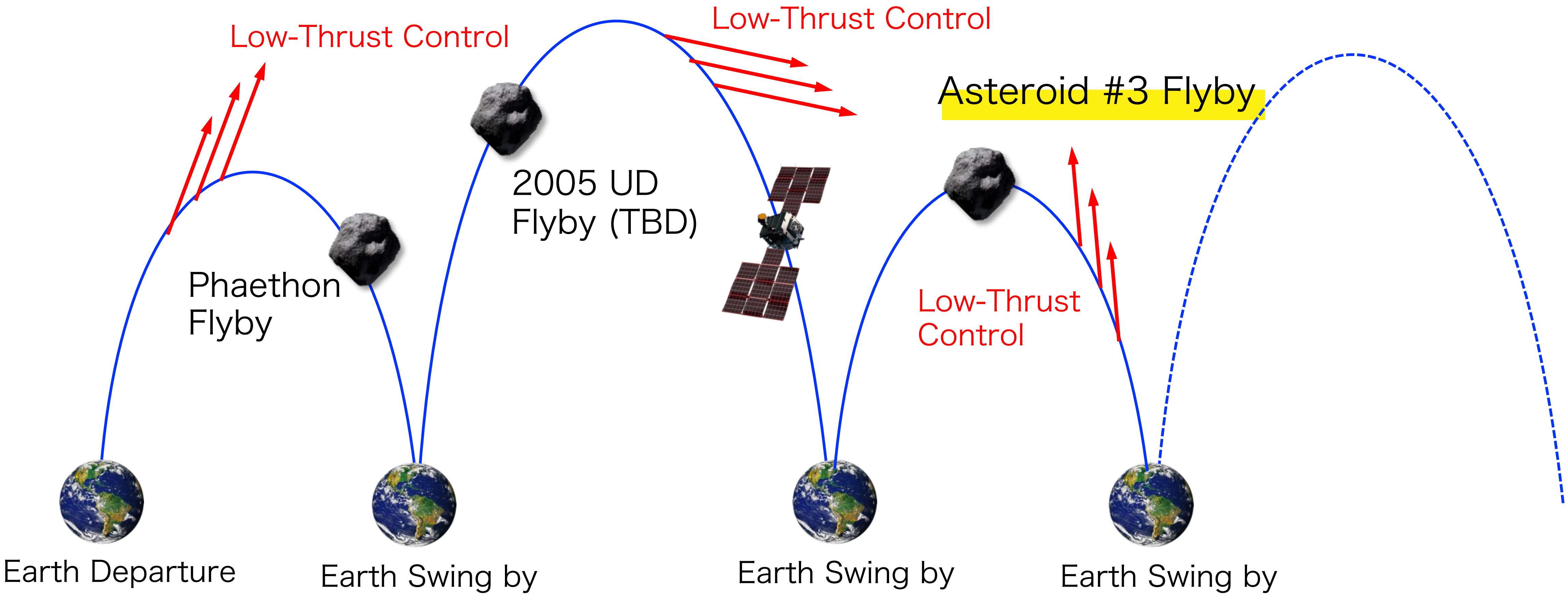


Sun-centered, inertial frame



Earth-centered, Sun-Earth fixed rotating frame

How many target bodies exist?



In the asteroid flyby cycler orbit, the flyby alternates between the Earth and asteroids.

Naoya Ozaki, Kanta Yanagida, et al., " Asteroid Flyby Cycler Trajectory Design Using Deep Neural Networks," *Journal of Guidance, Control and Dynamics*, 2022.

How many target bodies exist?

The following is a list of target asteroids that DESTINY+ can flyby after the 2005 UD flyby. There are more than 154 candidate asteroids, if they are allowed to consume ΔV<150m/s and no operational constraints are considered.

Example of 15 numbered asteroids which D+ can potentially flyby

full_name	PHA?	Spec.	Estimated ΔV, km/s
5143 Heracles (1991 VL)	N	O	0.08079354
8566 (1996 EN)	Y	U	0.01164032
25143 Itokawa (1998 SF36)	Y	S(IV)	0.01329345
68347 (2001 KB67)	Y		0.07794998
85182 (1991 AQ)	Y		0.13651477
85275 (1994 LY)	N		0.07429881
136617 (1994 CC)	Y		0.04173016
137120 (1999 BJ8)	Y		0.11488459
138258 (2000 GD2)	N	Sq	0.09844739
153201 (2000 WO107)	Y	X	0.10771823
153249 (2001 BW15)	N		0.02987912
153415 (2001 QP153)	N		0.07237215
162173 Ryugu (1999 JU3)	Y	Cg	0.02367781
164184 (2004 BF68)	N		0.08379307
199801 (2007 AE12)	Y		0.06685156
…			

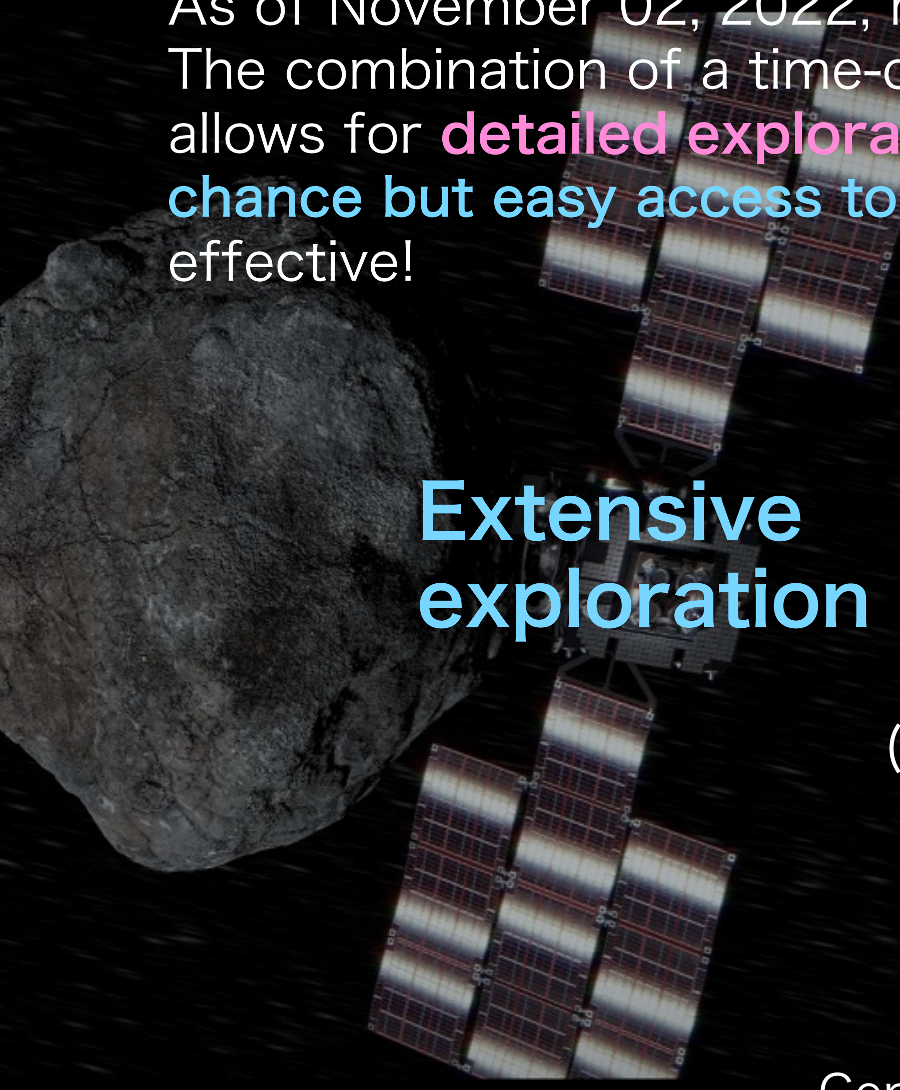
Example of 15 <u>un</u>numbered asteroids which D+ can potentially flyby

full_name	PHA?	Spec.	Estimated ΔV, km/s
(1995 CR)	Y		0.07028112
(1999 XK136)	Y		0.10879055
(2000 EU70)	Y		0.02295236
(2000 KA)	Y		0.07023434
(2000 UK11)	N		0.11568255
(2000 WC1)	Y		0.03025382
(2001 BX15)	N		0.02123321
(2001 XG1)	N		0.02768027
(2002 TX55)	N		0.09856524
(2003 BB21)	Y		0.1251176
(2003 YR1)	N		0.1200036
(2004 CO49)	Y		0.06009359
(2005 GU)	Y		0.11234109
(2005 QQ87)	N		0.03188114
(2005 QZ151)	Y		0.03513121
…			

*ΔV is estimated using the surrogate model made of deep neural networks (ref. Ozaki, et al., JGCD, 2022)

New Small Body Exploration Strategy of ISAS

As of November 02, 2022, more than 1.23 million small bodies have been discovered. The combination of a time-consuming (rendezvous-type) sample return mission, which allows for **detailed exploration**, and a multi-flyby mission, which allows for **one-chance but easy access to multiple bodies**, makes small body exploration even more effective!



Increasing "Value" by Precursor

Extensive exploration

DESTINY+

(Multiple flyby)

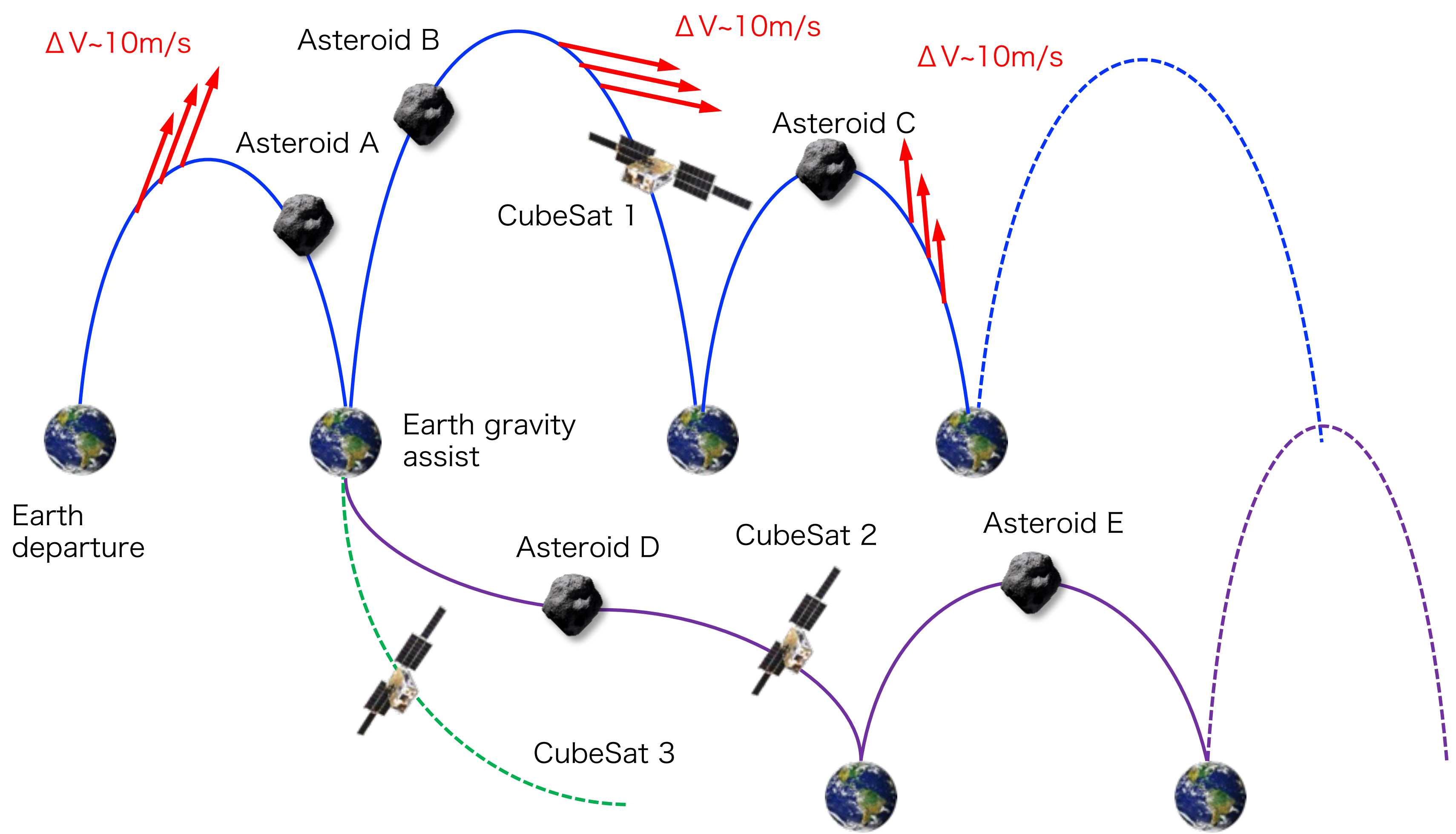
Hayabusa 2

(Sample Return)

Detailed exploration

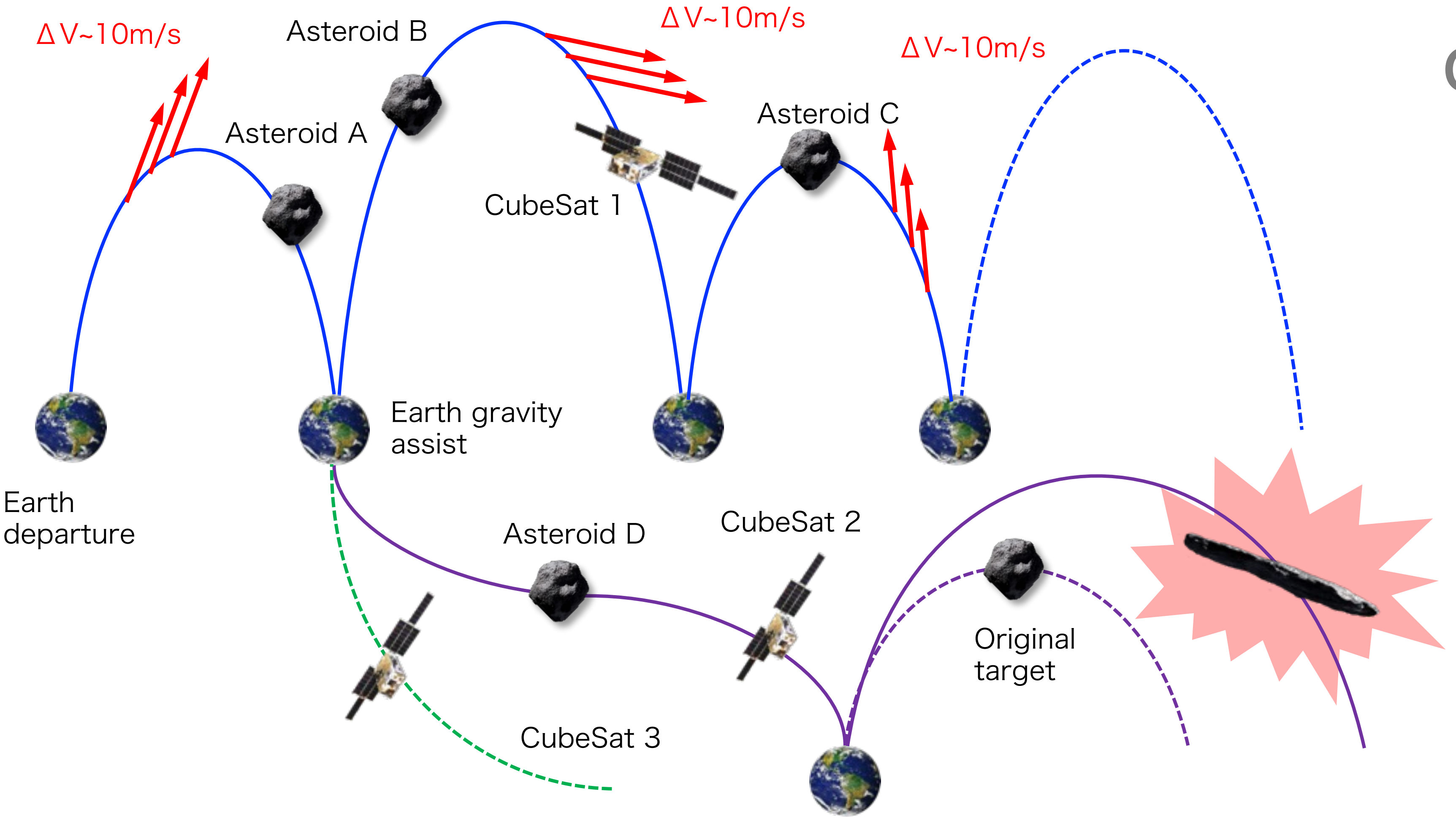
Generalizing discoveries to specific bodies

Multiple Asteroid Flyby Exploration by Deep Space Constellation



One asteroid flyby per month for a 12-spacecraft configuration

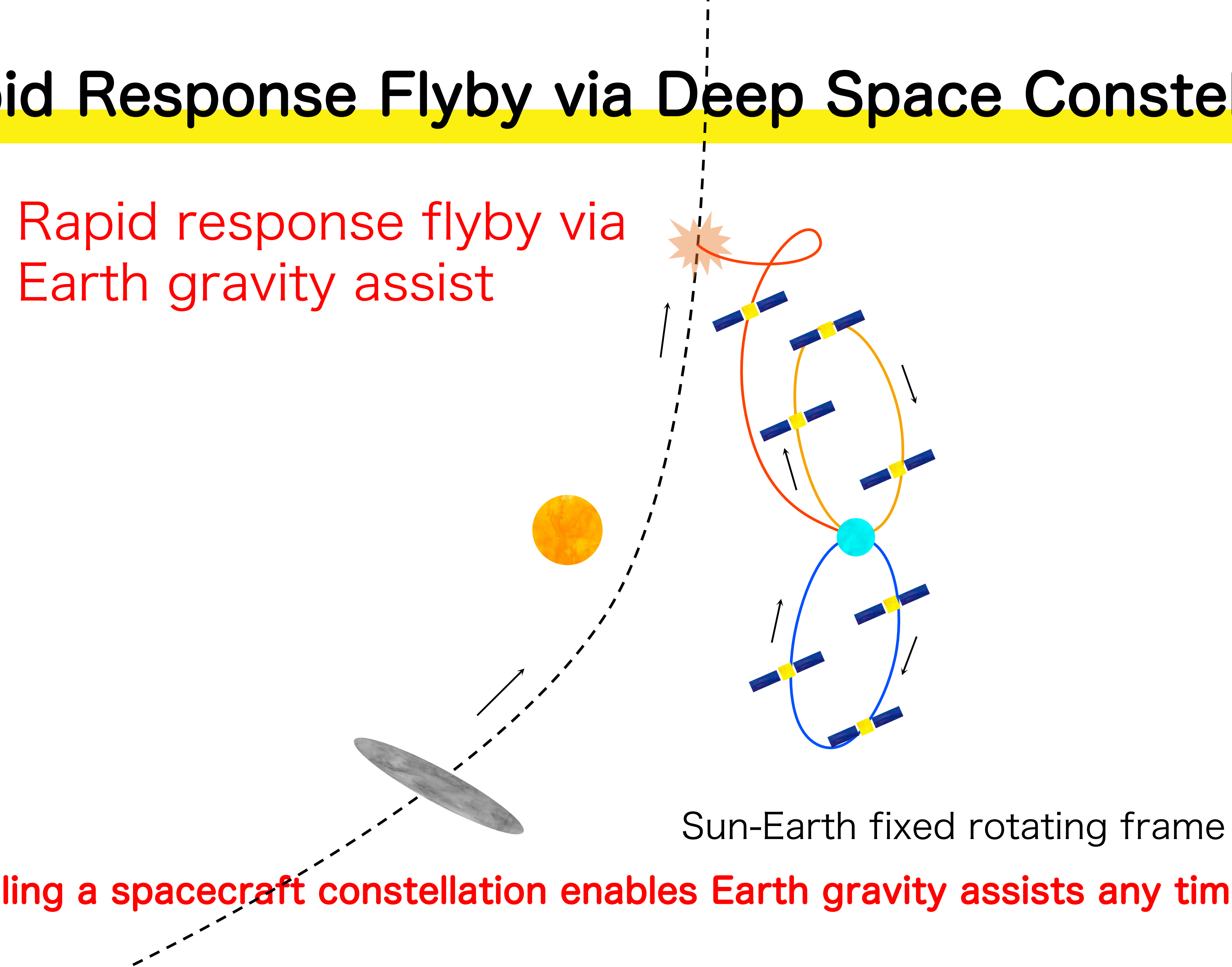
Multiple Asteroid Flyby Exploration by Deep Space Constellation



One asteroid flyby per month for a 12-spacecraft configuration

Orbit correction by the Earth gravity assist can also realize rapid response exploration

Rapid Response Flyby via Deep Space Constellation

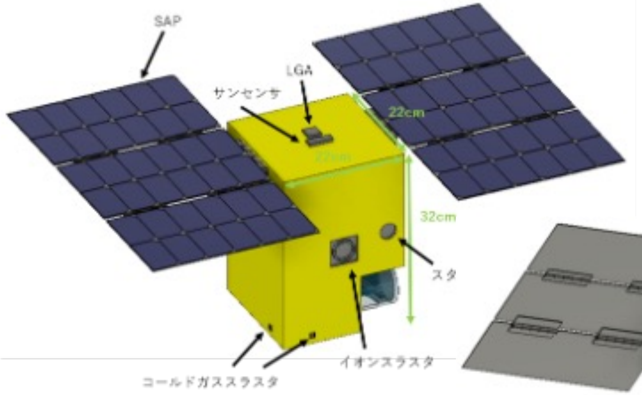


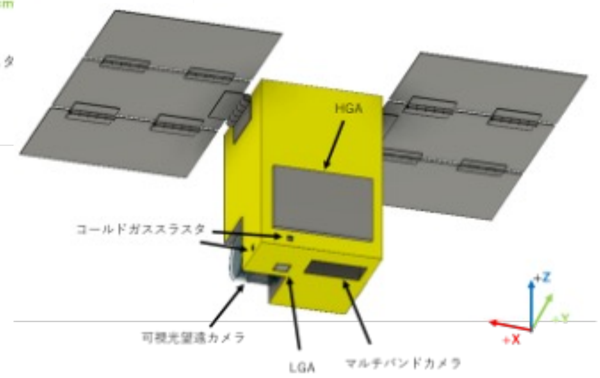
Assembling a spacecraft constellation enables Earth gravity assists any time.

Conceptual Study on Spacecraft System

Requirements for the spacecraft system

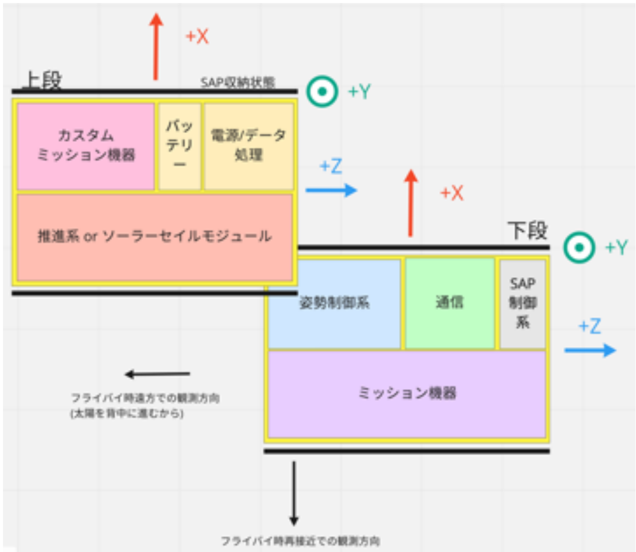
- Science requirements need to carry scientific instruments of 3-8 kg (feasible with 12U or more?)
- Propulsion system capable of 10m/s or more delta-V per year should be installed.
- Autonomous orbit determination and operation technology is necessary because of the need to build a constellation of 10 spacecraft in deep space (Earth distance is about 0.5 au).





(Tsutsui, Koizuka, 2021)

(Chofuku, Ozaki, Ukai, Hisamoto
, 2021)



Significance of the Deep Space Constellation Concept

Planetary Defense

International cooperation through SmallSat-based deep space exploration missions to protect the Earth together in the world.

Space Exploration Technologies

Improvement of technological capabilities and development of industry and human resources through continuous technology demonstration.

Planetary Science

1) Statistical information on small bodies by super multiple asteroid flybys

2) the world's first direct exploration of interstellar objects and/or long-period comets.

Conclusiton

✓In order to realize multiple asteroid flyby and rapid response flyby of small bodies, we proposed the concept of deep space constellations using asteroid flyby cycler orbits.

✓The significance of this concept is presented from the three viewpoints of "planetary defense," "planetary science," and "space exploration technology.

Why don't we work together to realize the "world's first interstellar object exploration" and "protecting the earth from asteroid impact" mission?