UNIVERSITÀ DEGLI STUDI DI TRIESTE
Dipartimento di Fisica
Dipartimento d'Eccellenza 2023-2027

Space Debris

Laboratorio di Astrofisica Spaziale

Federico Dogo

TRIESTE, 2024

CONTENTS

UNIVERSITÀ DEGLI STUDI DI TRIESTE
Dipartimento di Fisica
Dipartimento d'Eccellenza 2023-2027

Space debris

SPACE DEBRIS

Space natural hazard.

- Natural cosmic hazards are those created by near-Earth objects (NEOs) such as asteroids, meteoroids, comets and extreme solar/space weather phenomena.

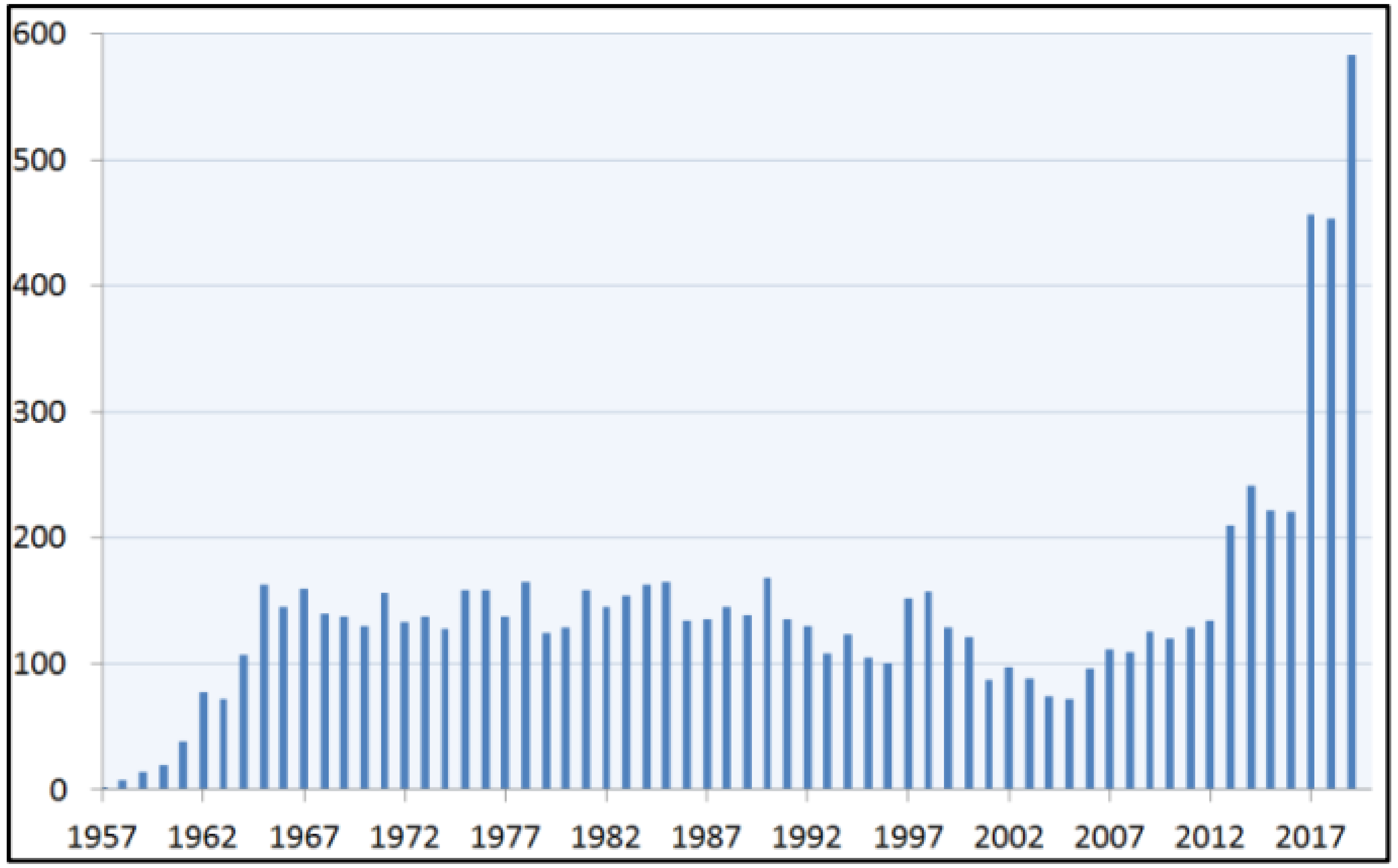
Anthropogenic debris.

- Inter-Agency Space Debris Coordination Committee (**IADC**) **defines** space debris as "all man-made objects, including fragments and their elements, that are in Earth orbit or re-entering the atmosphere and are non-functional".
- In orbit debris range from **millions of millimeter-sized particles** to thousands of much larger objects, such as **disused satellites** and **rocket parts**. Debris can cause a wide variety of problems, from **gradual degradation** of satellite parts over time to immediate and total **destruction**.

UNIVERSITÀ DEGLI STUDI DI TRIESTE
Dipartimento di Fisica
Dipartimento d'Eccellenza 2023-2027

INCREASING LAUNCHES

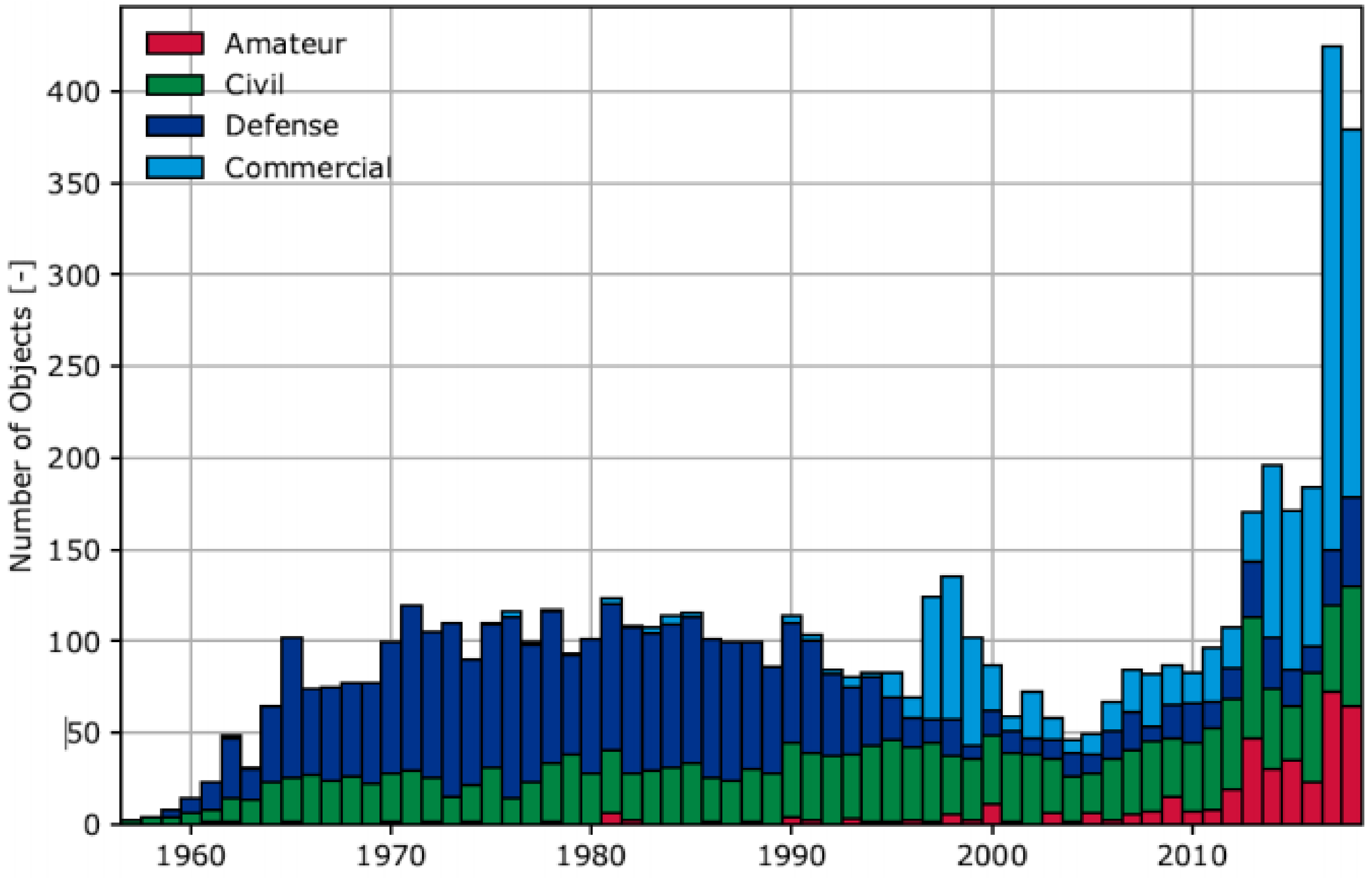
Since the beginning of satellite history in 1957, at least **9 033 satellites** have been **launched** (as of 31 December 2019), according to the United Nations Office of Outer Space Affairs (**UNOOSA**). Of the total number of launched objects, about **2 200 satellites are currently operational** in various orbits around the Earth.



Number of objects launched per year.

Source: Murtaza et al., 2019

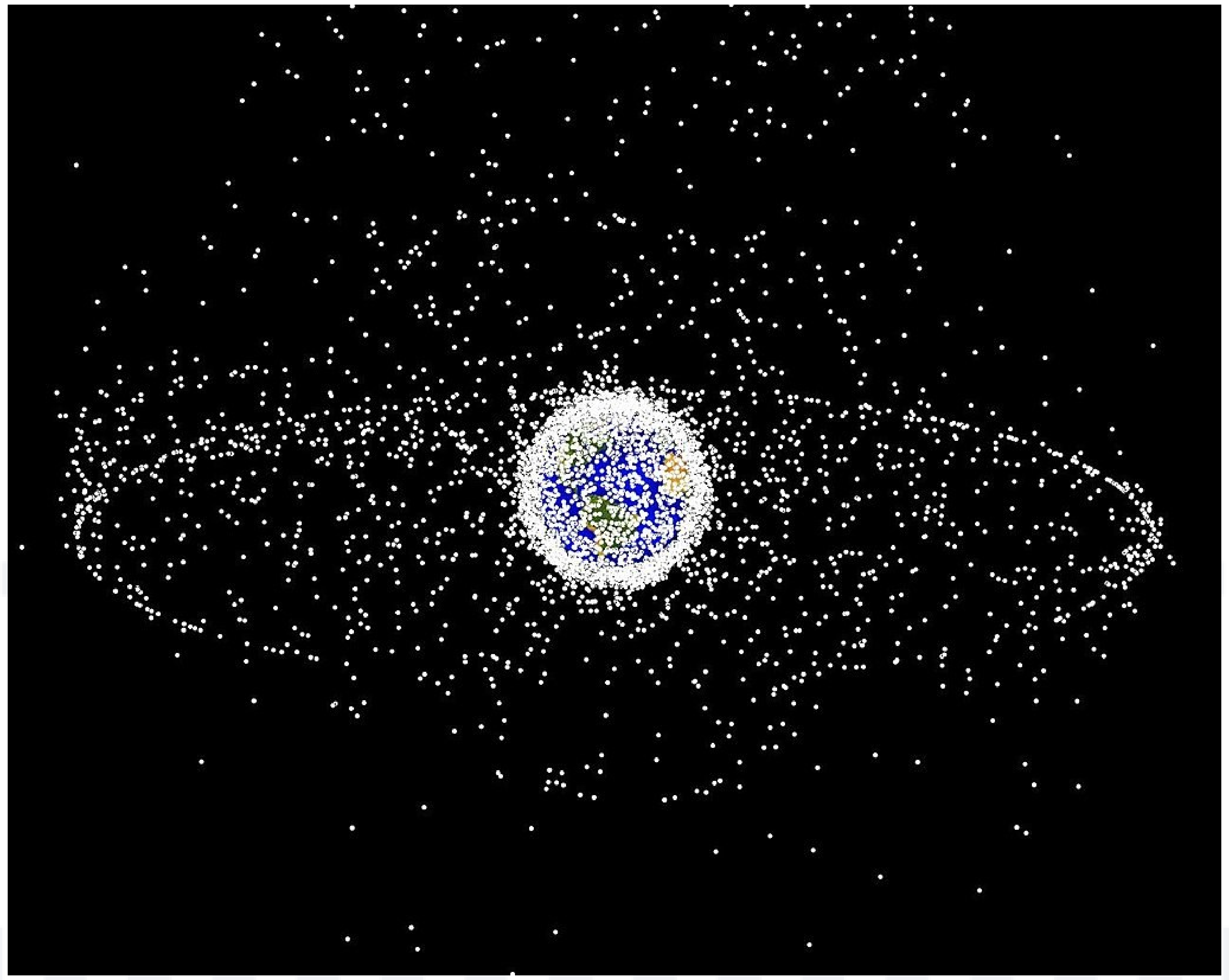
- We know that around 9 000 objects have been launched into space with the help of some **5 450 rockets**, whose final stages and fairings have also become **part of the orbiting population**.
- In the first ten months (up to and including October) of 2023, Space-X's Falcon 9 carried out some eighty launches.
- 2017, 2018 and 2019 were **three exceptional years** in the history of space, as they recorded the **highest number of launched objects** (453, 452 and 583, respectively) in history in a single year.



LEO Objects Evolution [4].

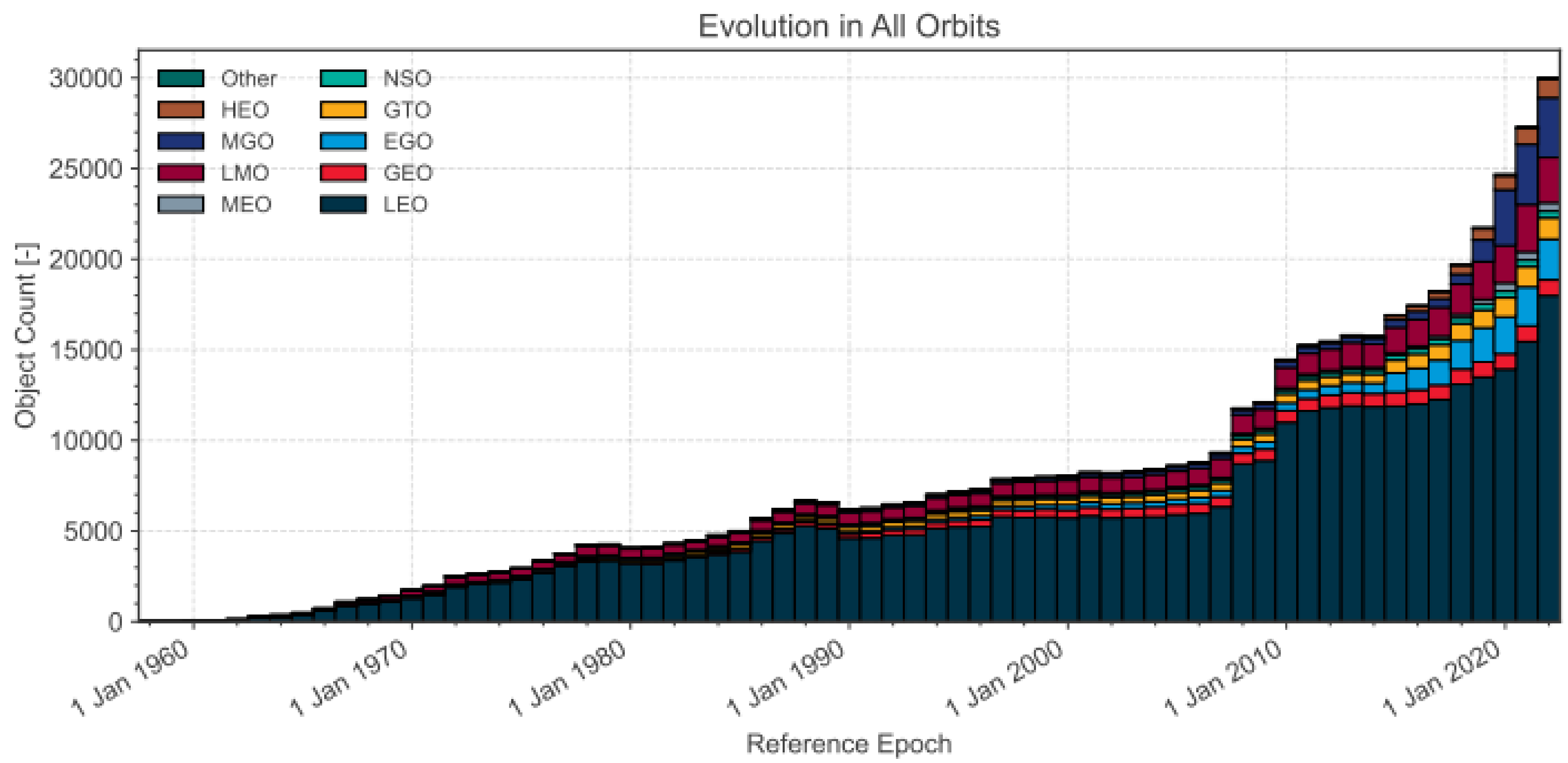
Source: Murtaza et al., 2019

SPACE POPULATION

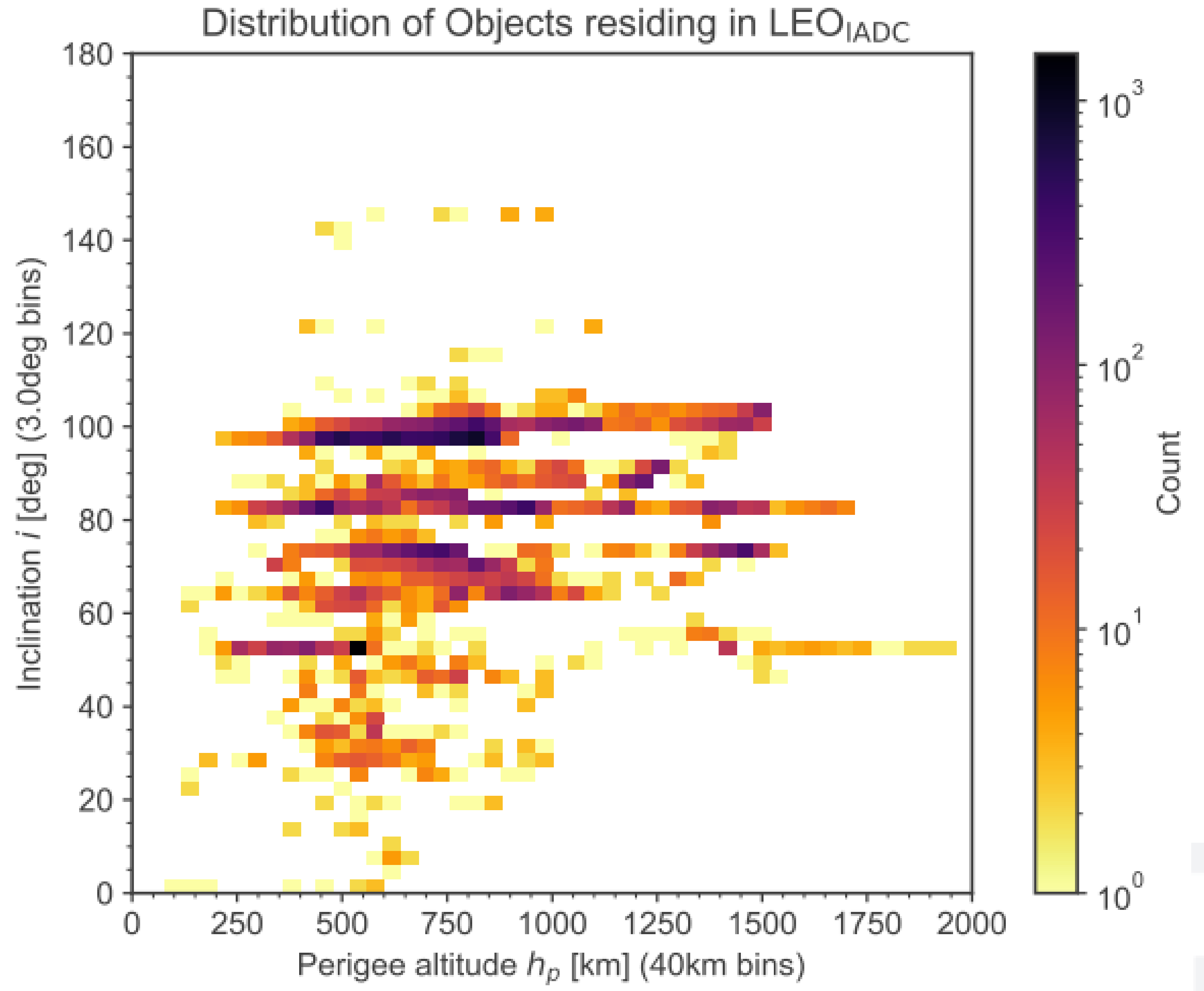


https://www.youtube.com/watch?v=O64KM4GuRPk

UNIVERSITÀ DEGLI STUDI DI TRIESTE
Dipartimento di Fisica
Dipartimento d'Eccellenza 2023-2027



(a) Evolution of number of objects.



(a) Distribution of objects residing in LEO.

Source: E.S.D. Office, ESA's Annual Space Environment Report, 2022

More than **30 000 orbiting objects** have been **tracked** in space, of which only about **10 %** are **useful** assets, while the remaining tracked objects, about 90 %, are useless objects and thus belong to space debris;

Source: Murtaza et al., 2019

- as a result of this progression, the number of **useless** objects orbiting in space has also **increased** over the years.

However, the **total orbital population**, including **untraceable** objects, is far higher (40 000):

- objects smaller than **10 cm** cannot be tracked.

UNIVERSITÀ DEGLI STUDI DI TRIESTE
Dipartimento di Fisica
Dipartimento d'Eccellenza 2023-2027

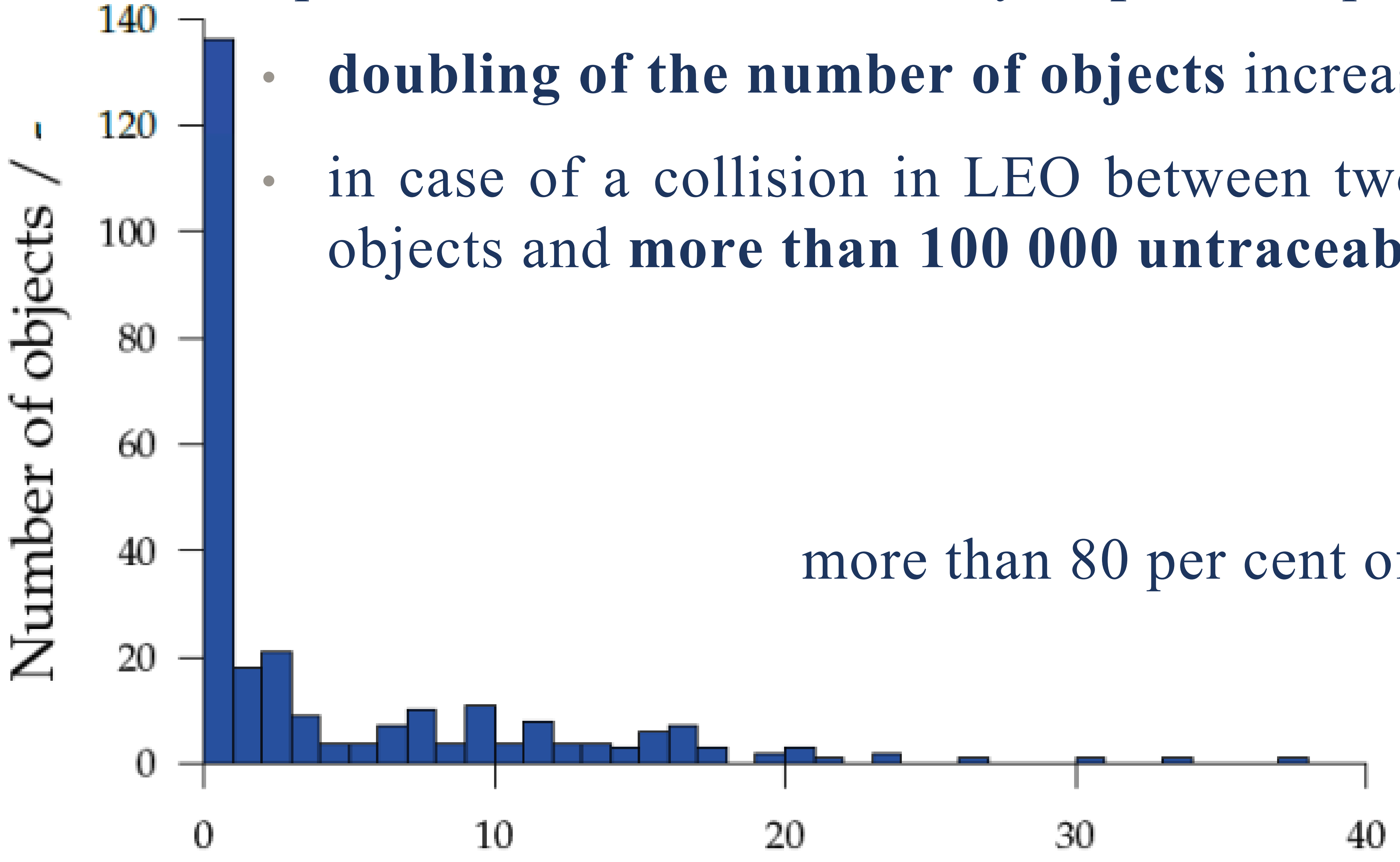
Space debris poses a significant **threat to operational satellites** due to its **high orbital velocities** (8-10 km/s) and **uncontrolled nature**.

Space debris can have a heavy **impact** on spacecraft and the space environment:

- **doubling of the number of objects** increases the risk of collision by about **four times**;
- in case of a collision in LEO between two 1 000 kg rocket parts, the collision will produce about **4 000 traceable** objects and **more than 100 000 untraceable** fragments.

The problem is not only associated with old or retired satellites:

more than 80 per cent of space objects suffered a **break-up during their first ten years** of service.

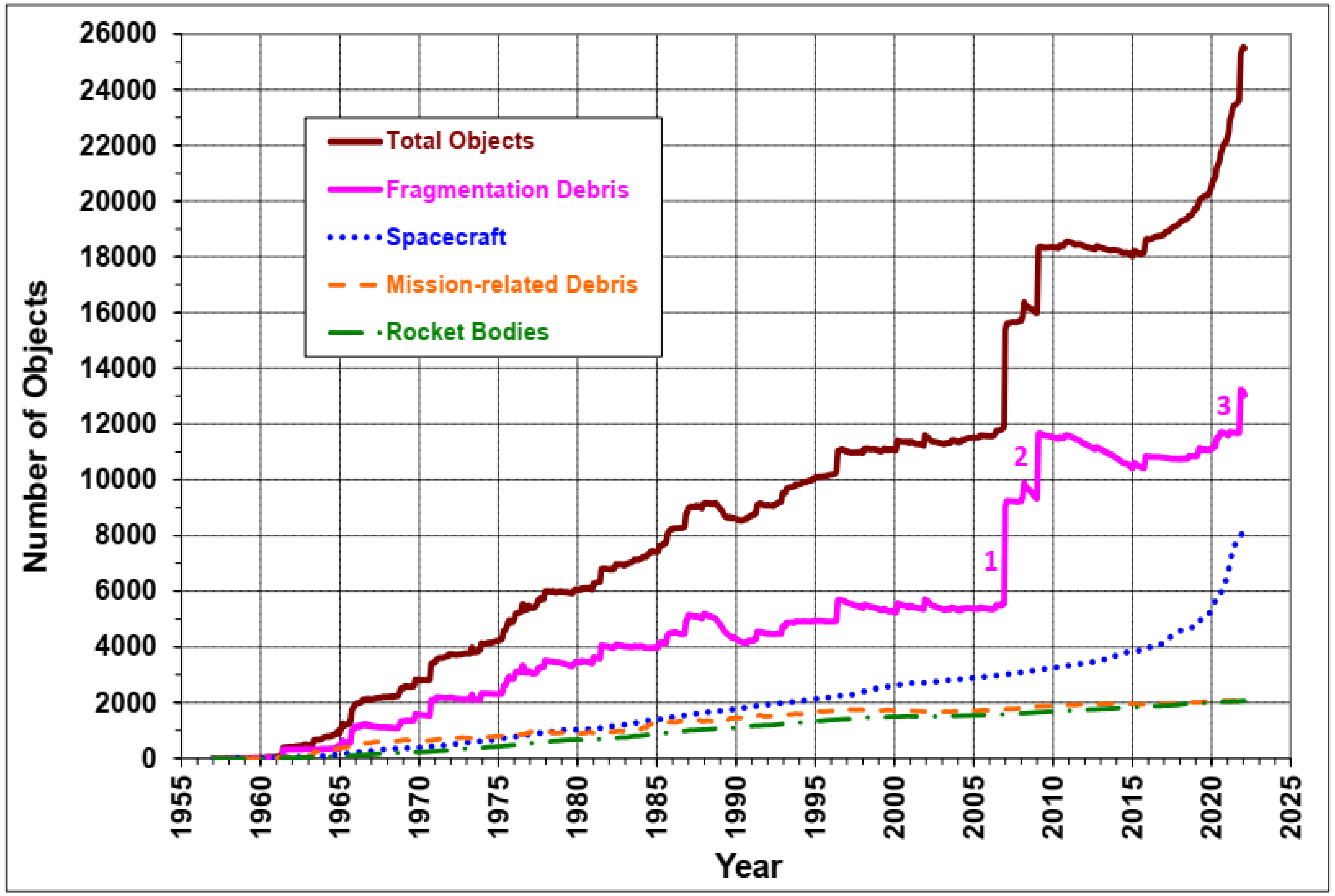


Age of object at breakup epoch [16].

Source: Murtaza et al., 2019

FRAGMENTATION

Fragmentation or disintegration of large objects, such as rocket bodies and satellites (functional or non-functional), is the main cause of unusable objects in Earth orbit.

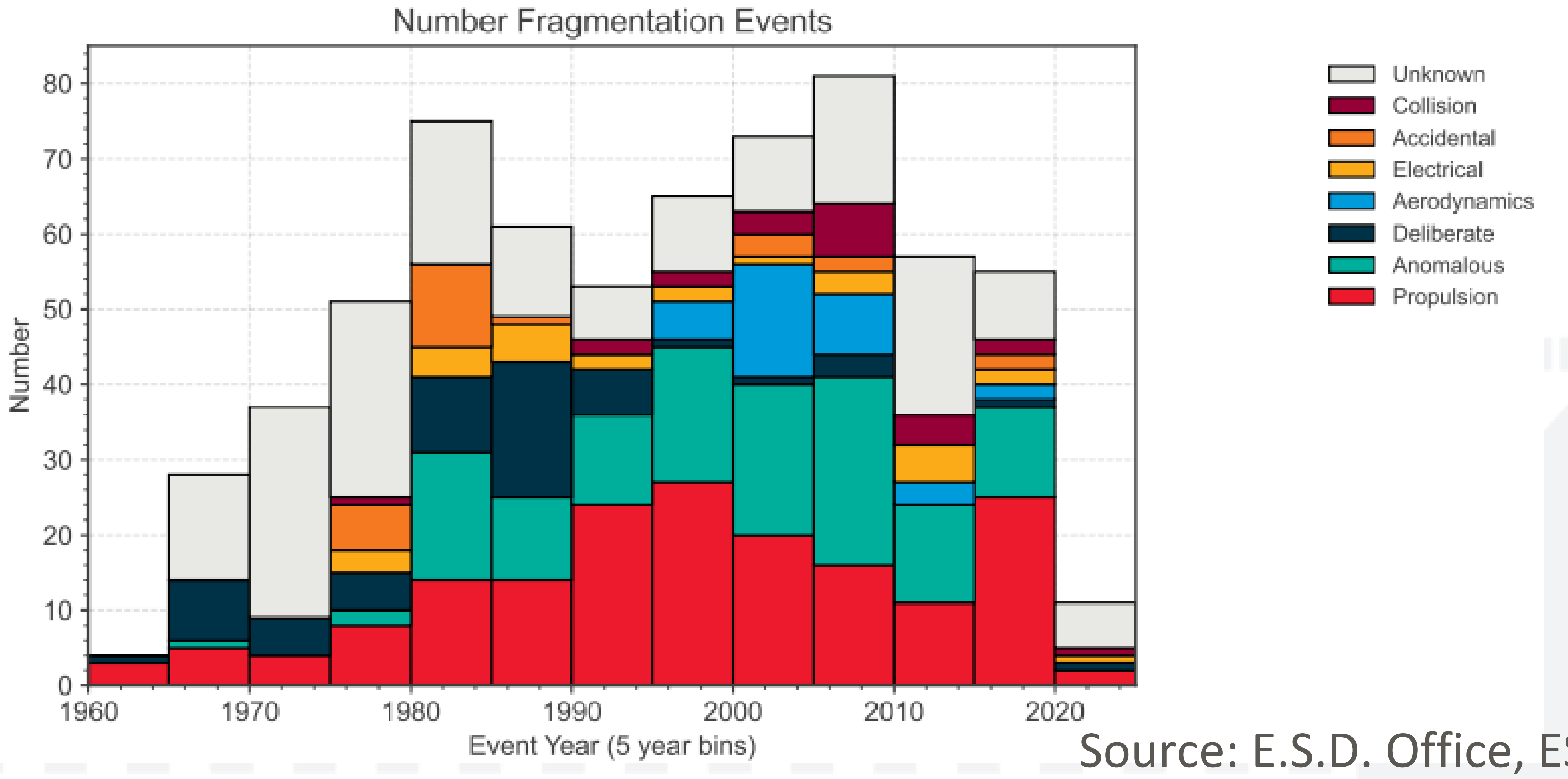


Source: Orbital Debris Quarterly News, 2022

UNIVERSITÀ DEGLI STUDI DI TRIESTE
Dipartimento di Fisica
Dipartimento d'Eccellenza 2023-2027

Up to the end of 2017, **489 fragmentation events have been confirmed** in orbit:

- although collision events are few, they are still the most significant contribution in terms of the amount of debris generated.



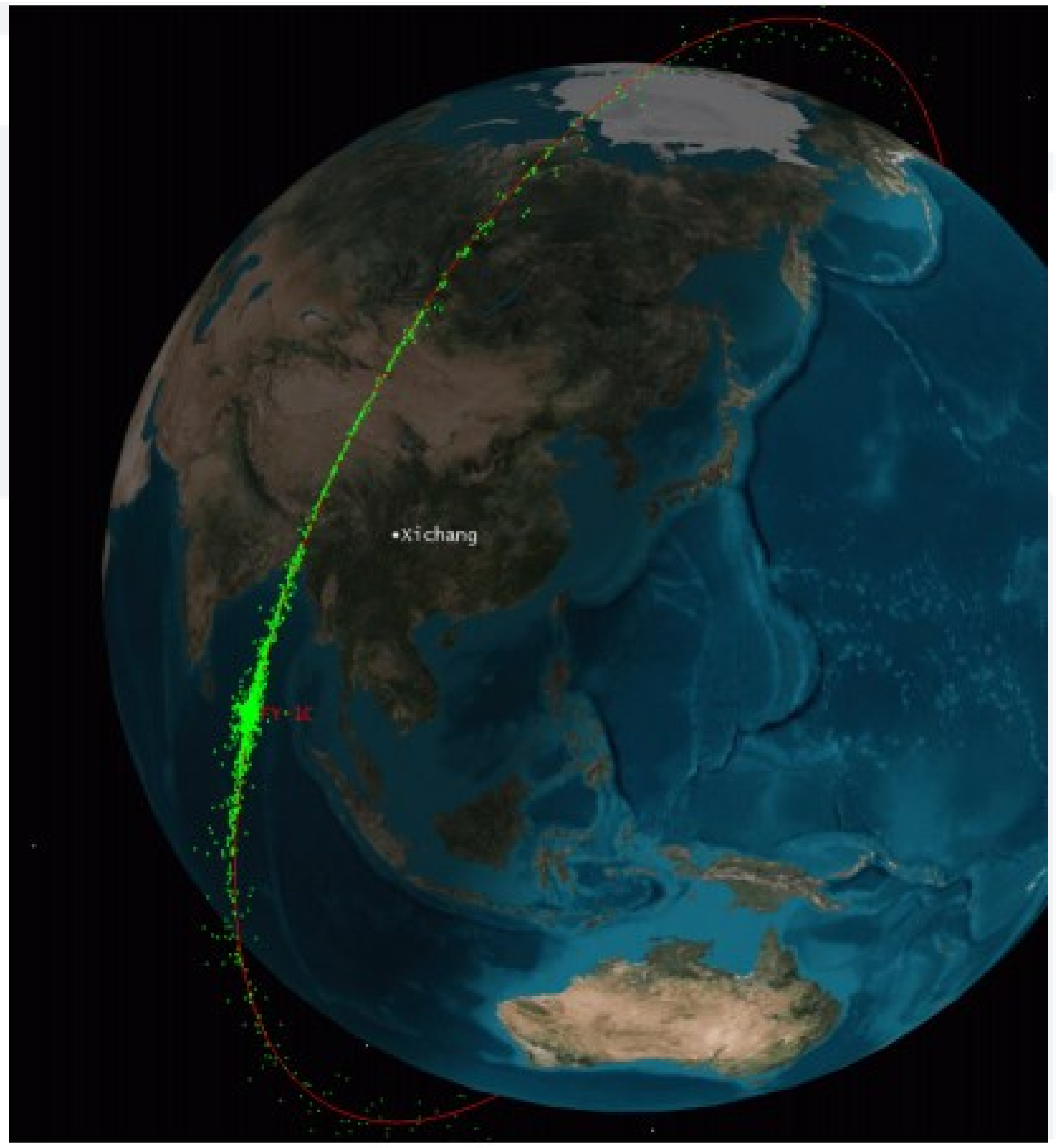
Source: E.S.D. Office, ESA's Annual Space Environment Report, 2022

The **Kessler Syndrome** is the most critical aspect, as each collision can trigger an ever-increasing production of orbital avalanche debris:

- a debris of about **10 cm** can **demolish** an operational **satellite** in the event of a collision,
- but more importantly **create thousands of other smaller hazardous objects** in orbit for several years or decades.

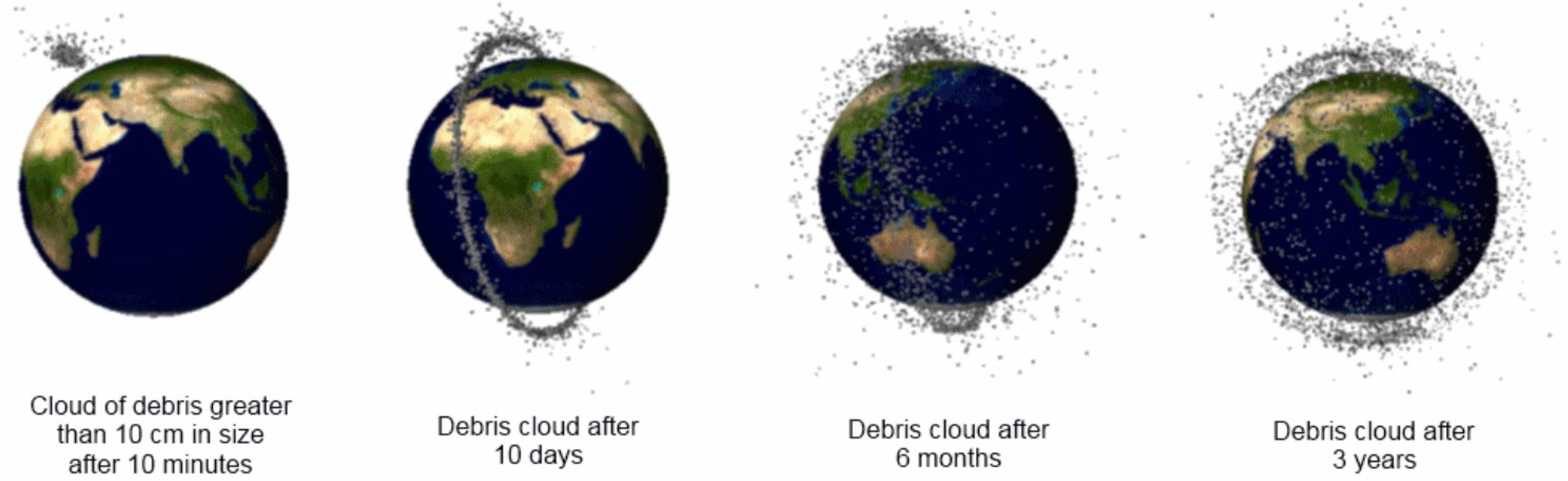
JUST AN ACCIDENTAL EFFECT?

On 11 January 2007, China carried out an **anti-satellite missile attack**. It launched a missile from the Xichang space launch centre. The payload was a **Kinetic Kill Vehicle** (KKV) that never entered into orbit, travelling through space along a ballistic arc, to collide with a non-operational Chinese weather satellite, the Fengyun-1C (FY-1C), at an altitude of 863 km and inclination of 99 %, completely destroying the satellite.



Simulation of the ASAT test 5 minute after impact [1]

The destruction created a cloud of more than **3 000 pieces** of space debris, the largest ever, and many of them will remain in orbit for **decades**, posing a significant collision threat to other space objects in low Earth orbit.



Evolution of the debris cloud from a kinetic kill ASAT attack [9]

The New York Times

The space station just dodged debris from a 2007 Chinese weapons test.

Nov. 10, 2021

- On Wednesday, about six hours before NASA's Crew-3 mission launched to orbit, the **International Space Station was forced to maneuver itself to avoid a piece of debris** spawned by a Chinese antisatellite weapon test in 2007.
- The piece of junk was projected to enter what's called the "**pizza box**", a square-shaped zone 2.5 miles deep and 30 miles wide, where the station sits in the middle.

RELATED ISSUES

Allocation

Another significant and related concern is the **saturation** of **space resources**, such as **orbital slots** and **telecommunication frequencies**, which could limit the accommodation of many more satellites in the future:

- many countries in the world want to have their own independent space resources: for example, the US, ESA, China, Russia, India, Japan have or are in the process of having their own **own satellite navigation system**;
- in addition, **private** projects such as **mega constellations** may pave the way to other similar large-scale projects for the same or other applications by different commercial and governmental entities.

Lack of organisation and sharing.

Allocation

NASA SPACEFLIGHT.COM

FORUMS L2 SIGN UP ARTEMIS

SpaceX launches the 3,500th Starlink satellite

written by Alejandro Alcantarilla Romera | October 20, 2022

Home > News > Networking

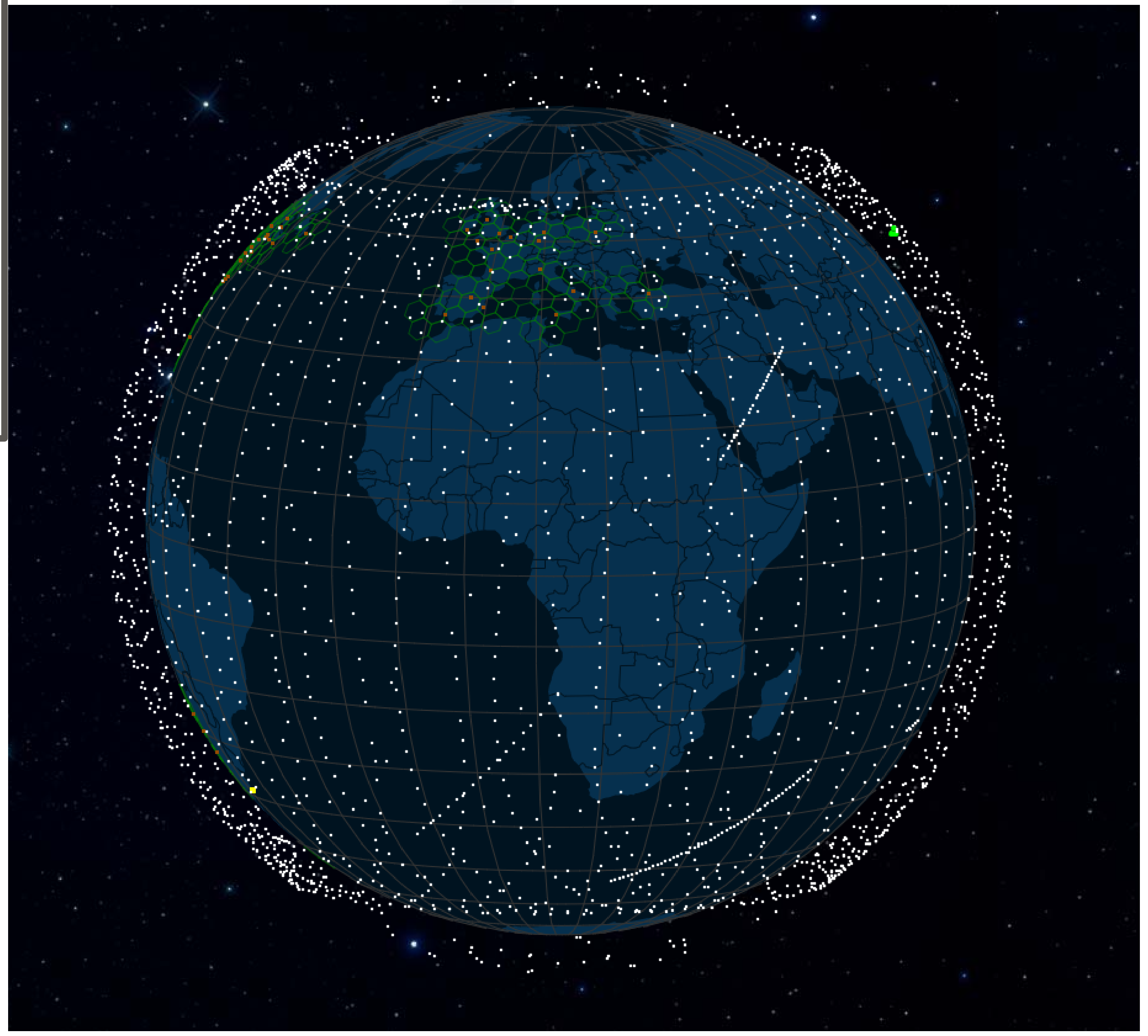
SpaceX Sidesteps Amazon Spat, Eyes March Launch for 2nd-Gen Starlink Satellites

The company is no longer asking the FCC for approval for two configurations of the second-generation Starlink satellite constellation, which will span nearly 30,000 satellites.

By Michael Kan January 10, 2022

COUNTDOWN BEGINS FOR EU SATELLITE INTERNET CONSTELLATION

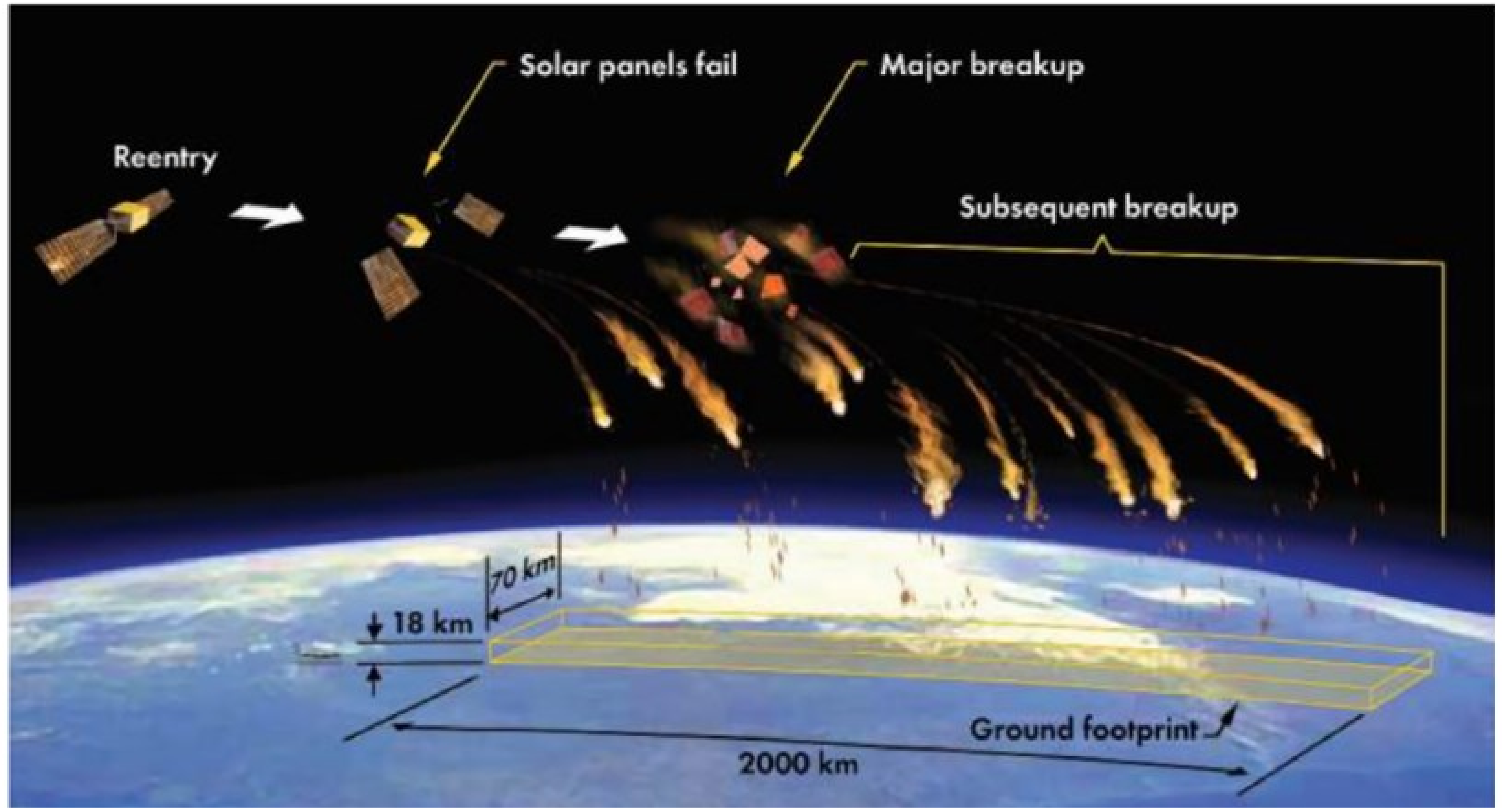
Posted by Harry Baldock | Nov 11, 2022 | Investment, INFRASTRUCTURE, Satellite, Public Sector, People, Digital Divide, Governance, Asia-Pacific, Europe, Latin America, Middle East & Africa, North America, News



Re-entry

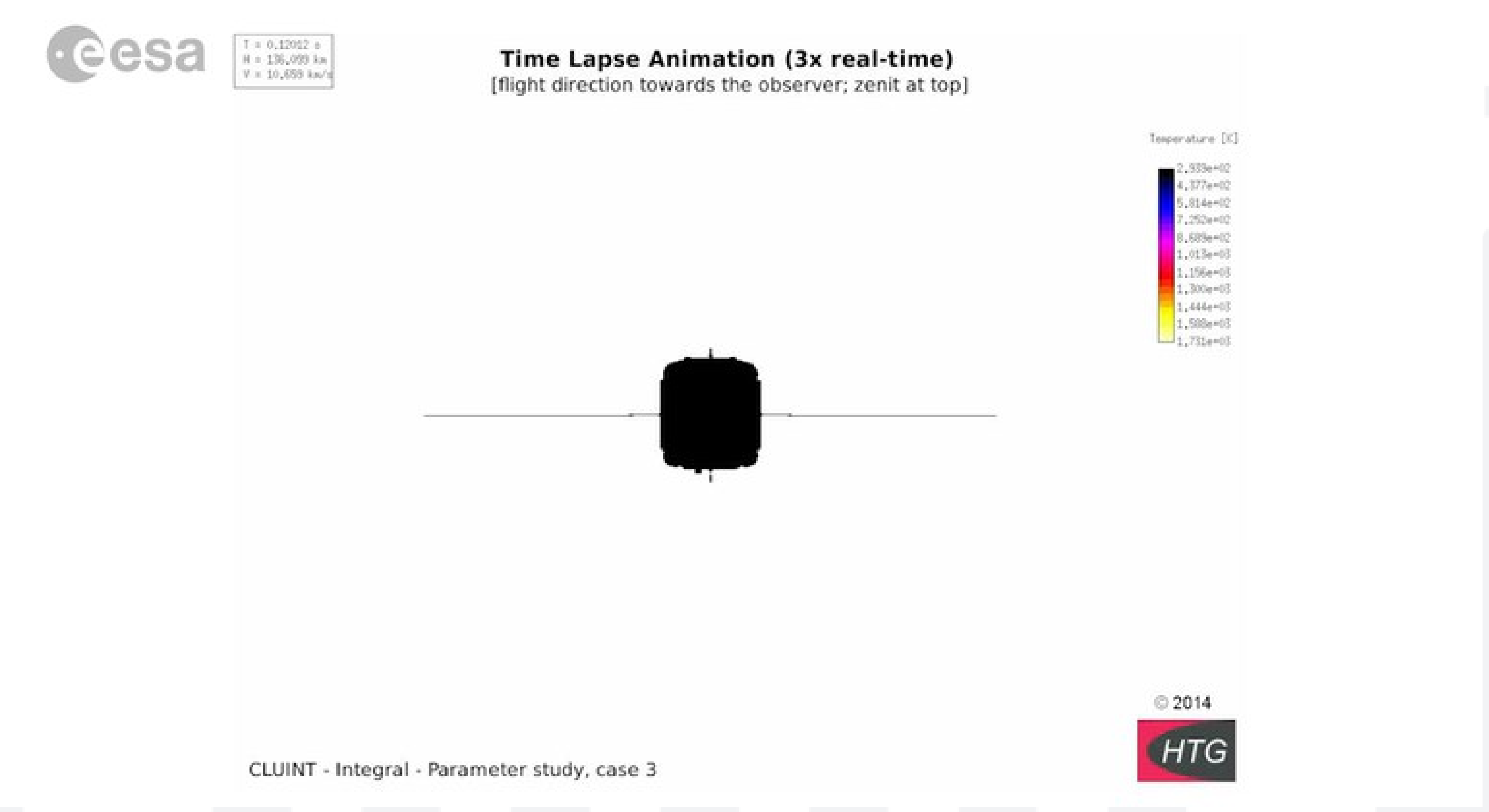
Another issue. During **re-entry into the atmosphere**, at an altitude of around 100 km, the **thermomechanical and hydrodynamic stresses** become so intense that they lead to the complete destruction of the satellite:

- if the satellite has a **small mass**, the **ablative process** that degrades the satellite is activated at a relatively **low temperature**;
- but **the greater the mass**, and depending on the type of material (ceramics such as silicon carbide), **the greater the heat required for fusion**.



We can see the **simulation of a re-entry**:

- the solar panels, as external appendages, are the first to be lost;
- in order to make the satellite deteriorate completely, it is **better to compose it of more small objects** than a larger piece, because the outer layers of the large object shield the innermost part.



- **Re-entries** to the atmosphere are usually **controlled**, but not always. In the latter case, the **tanks** containing the fuel are made of titanium, precisely to withstand high **temperatures**: and therefore also resist atmospheric friction. Consequently, they can reach the ground. **Optical systems** (and reaction wheels) are also candidates to reach the ground, because they are made not to deform with changing temperatures.

nature > nature astronomy > analyses > article

Analysis | Open Access | Published: 11 July 2022

Unnecessary risks created by uncontrolled rocket reentries

Michael Byers, Ewan Wright, Aaron Boley & Cameron Byers

Nature Astronomy **6**, 1093–1097 (2022) | Cite this article

13k Accesses | **1914** Altmetric | Metrics

TIMES NOW

Latest News India Business Education Entertainment News Viral Sports Health Videos Cryptonow LOT 2022 Live TV

TRENDING: Gujarat Elections Children's Day 2022 Pak vs Eng Memes Ajay Devgn Viral Video Ben Stokes T20 World Cup

Yet another 20 ton Chinese rocket set to make an uncontrolled re-entry to Earth on November 5th

Current estimated date for entry is November 5, and where the rocket debris will land is unknown

...d Nov 3, 2022 | 08:52 PM IST

Fig. 5. Delta II State 2 debris: Left: Lottie Williams holding reentered debris fragment (photo courtesy Brandi Stafford, Tulsa World); Right, Propellant tank in Texas field (photo courtesy NASA).

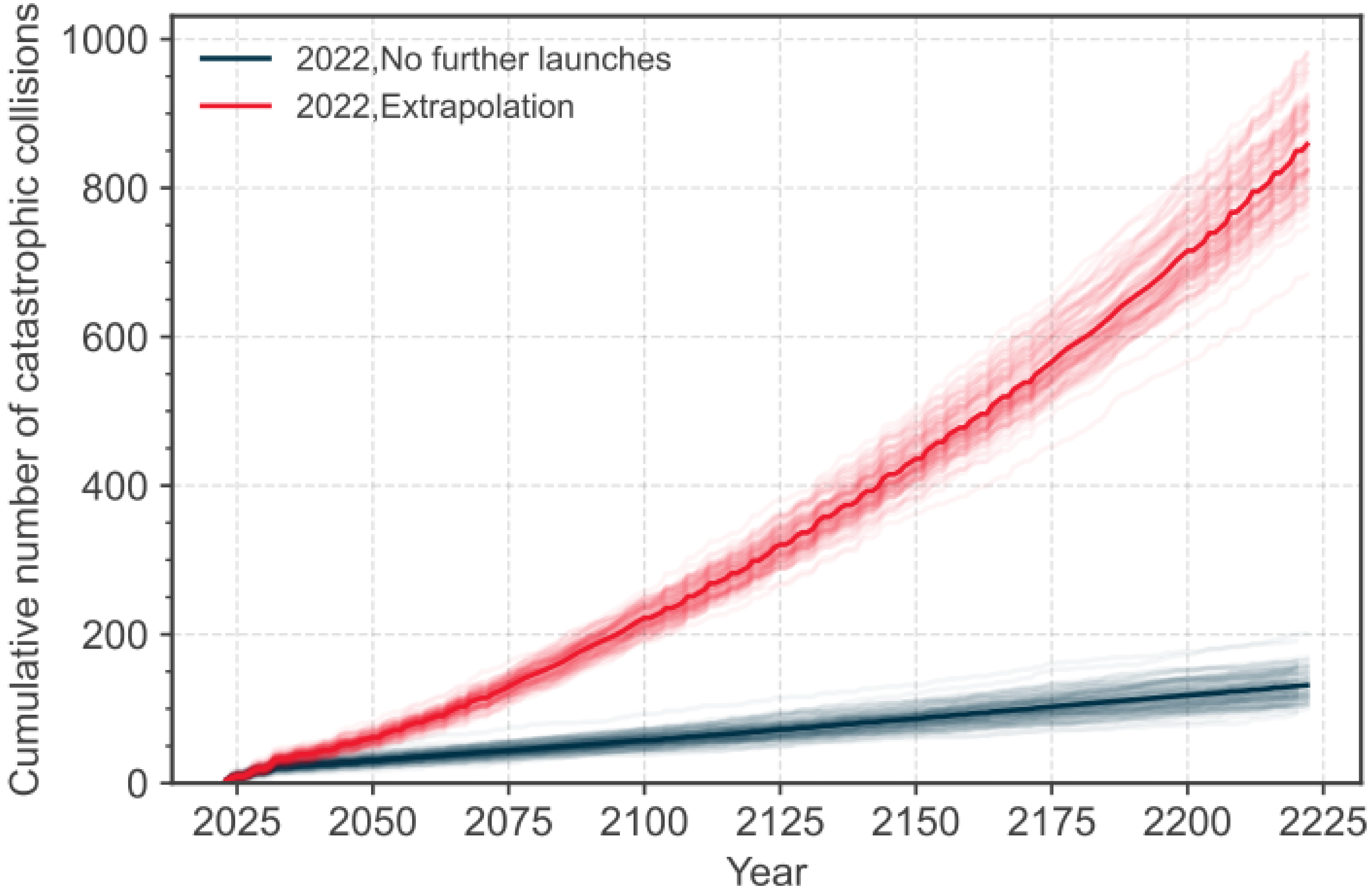
Source: W.H. Ailor, Hazards of reentry disposal of satellites from large constellations, J. Sp. Saf. Eng. 6 (2019) 113–121. https://doi.org/10.1016/j.jsse.2019.06.005.

UNIVERSITÀ DEGLI STUDI DI TRIESTE
Dipartimento di Fisica
Dipartimento d'Eccellenza 2023-2027

Nuclear sources

Another issue. **Nuclear power sources** (NPS) have been used in space as an efficient way to produce large amounts of energy or heat, commonly implemented as small fission reactors or radioisotope thermoelectric generators. Since the beginning of the space age, these energy systems have been used in Earth orbit, but were largely **abandoned after the 1980s** due to safety concerns. The safety problems associated with NPS in Earth orbit concerned the **risks associated with re-entry into the atmosphere and rupture**. To mitigate this risk, reactor cores were generally injected into orbits with long orbital durations after the end of payload operations. There are 61 known NPS-related objects in Earth orbit: three of them have been declared but **not catalogued**.

FORECAST



Extrapolation of the current change in orbit use and launch traffic, combined with **continued fragmentation** and the **limited success rate of post-mission disposal**, could lead to a cascade of collision events in the coming centuries.

- **Even without further launches into orbit**, collisions between existing space debris are expected to lead to further growth in the space debris population.

SOLUTIONS

If the satellite is equipped with a propulsion system, it can avoid tracked space debris:

- but, what about untracked ones?
- and,… if the satellite has not a propulsion system?

A more systemic approach is needed...

END-OF-LIFE AND PROTECTED REGIONS

Post-mission mitigation is specifically aimed at **reducing the long-term interference** that an object in the space environment might produce.

Two regions are often identified as so-called **protected regions** by international standards, guidelines and national legislation: LEO_{IADC} and GEO_{IADC}.

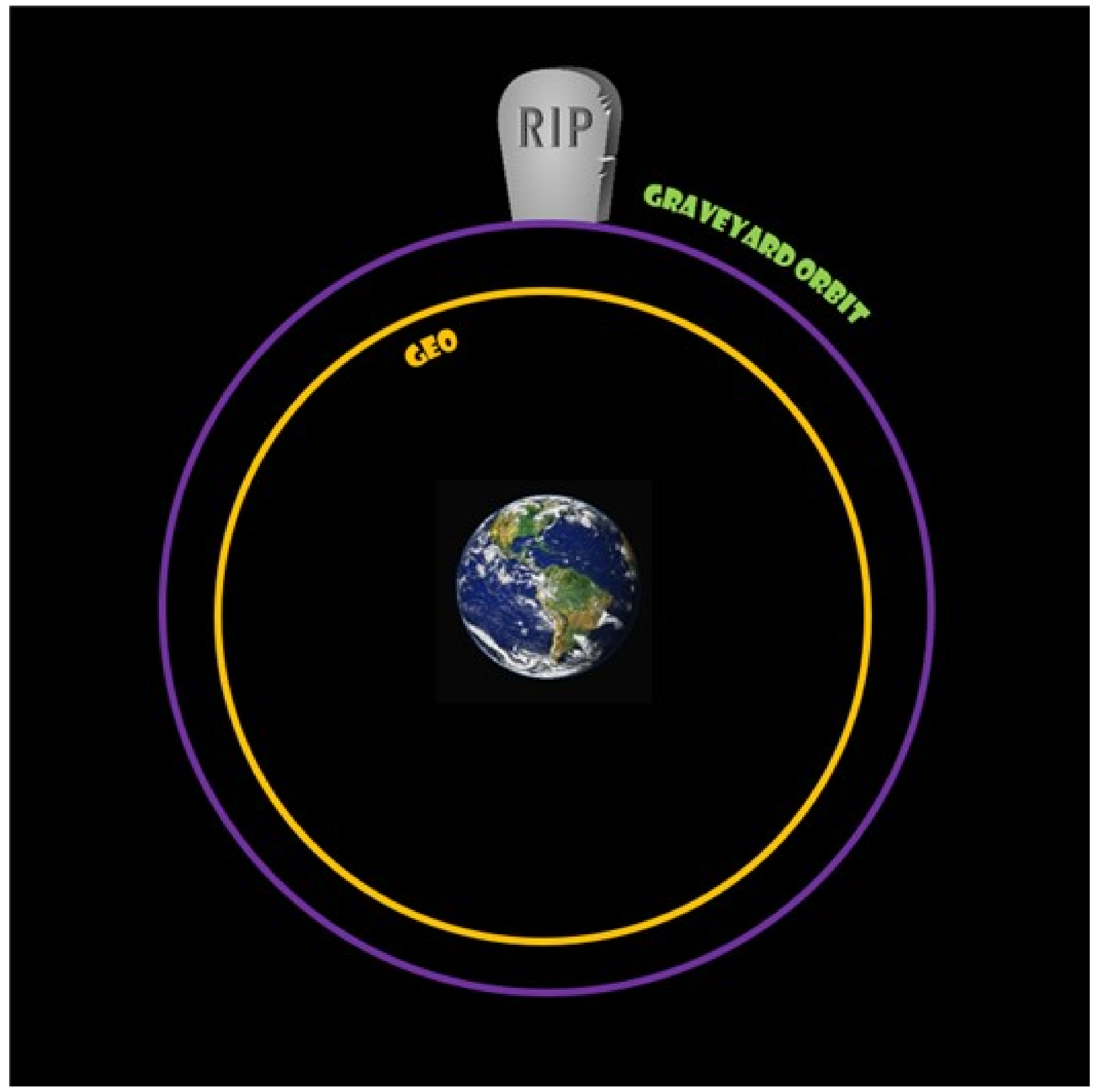
Orbit	Description	Definition	
LEO_{IADC}	IADC LEO Protected Region	$h \in [0, 2000]$	
GEO_{IADC}	IADC GEO Protected Region	$h \in [35586, 35986]$	$\delta \in [-15, 15]$

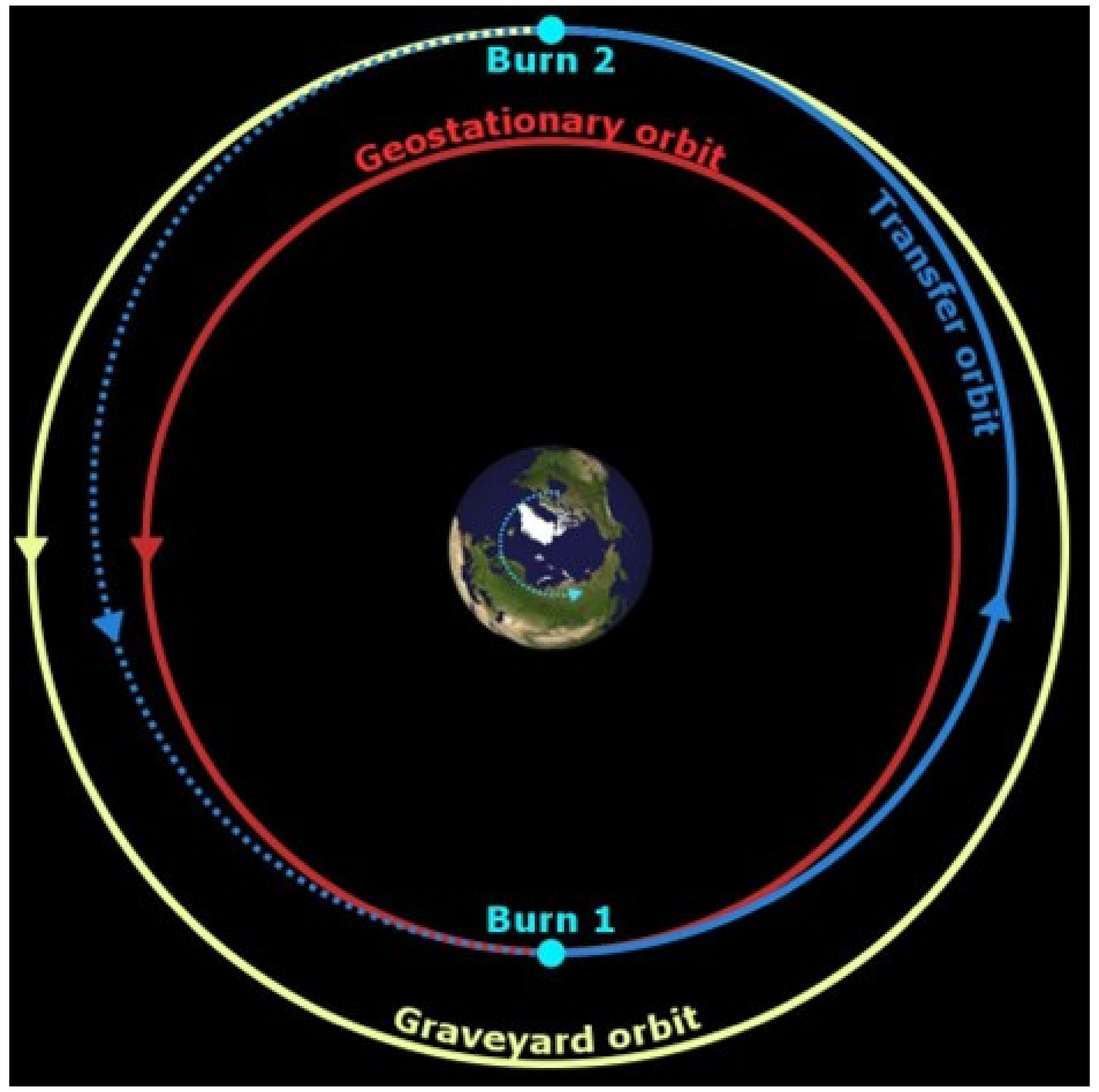
These mitigation measures are associated with **time criteria**, i.e. so-called orbital lifetimes or orbital region clearance, and thus require the assessment of the long-term evolution of orbits. For both protected regions, **different mitigation strategies imply different end-of-life operations**.

UNIVERSITÀ DEGLI STUDI DI TRIESTE
Dipartimento di Fisica
Dipartimento d'Eccellenza 2023-2027

LEO.

- Due to the presence of **atmospheric drag** in the **lower** levels of the LEO region, a **natural cleaning** of space debris from these regions occurs.
- **25-year rule**: a spacecraft or rocket part operating in the LEO protected region, with permanent or periodic presence, must limit its post-mission stay in the LEO protected region to a maximum of 25 years after the end of the mission;
  - this limit in itself will not lead to a long-term reduction in the amount of space debris, but it is an important step in **limiting the growth rate of space debris** in LEO_{IADC};
  - the **5-year limit for commercial satellites** is now mentioned, as 25 years is a long time;
  - mitigation itself **does not indicate how de-orbiting should take place**, so there is no standard methodology: e.g. accelerated natural orbital decay, controlled re-entry, etc.
- **Relocation** from LEO_{IADC} to orbits with a perigee altitude above 2 000 kilometers is no longer a practice for end-of-life debris mitigation.





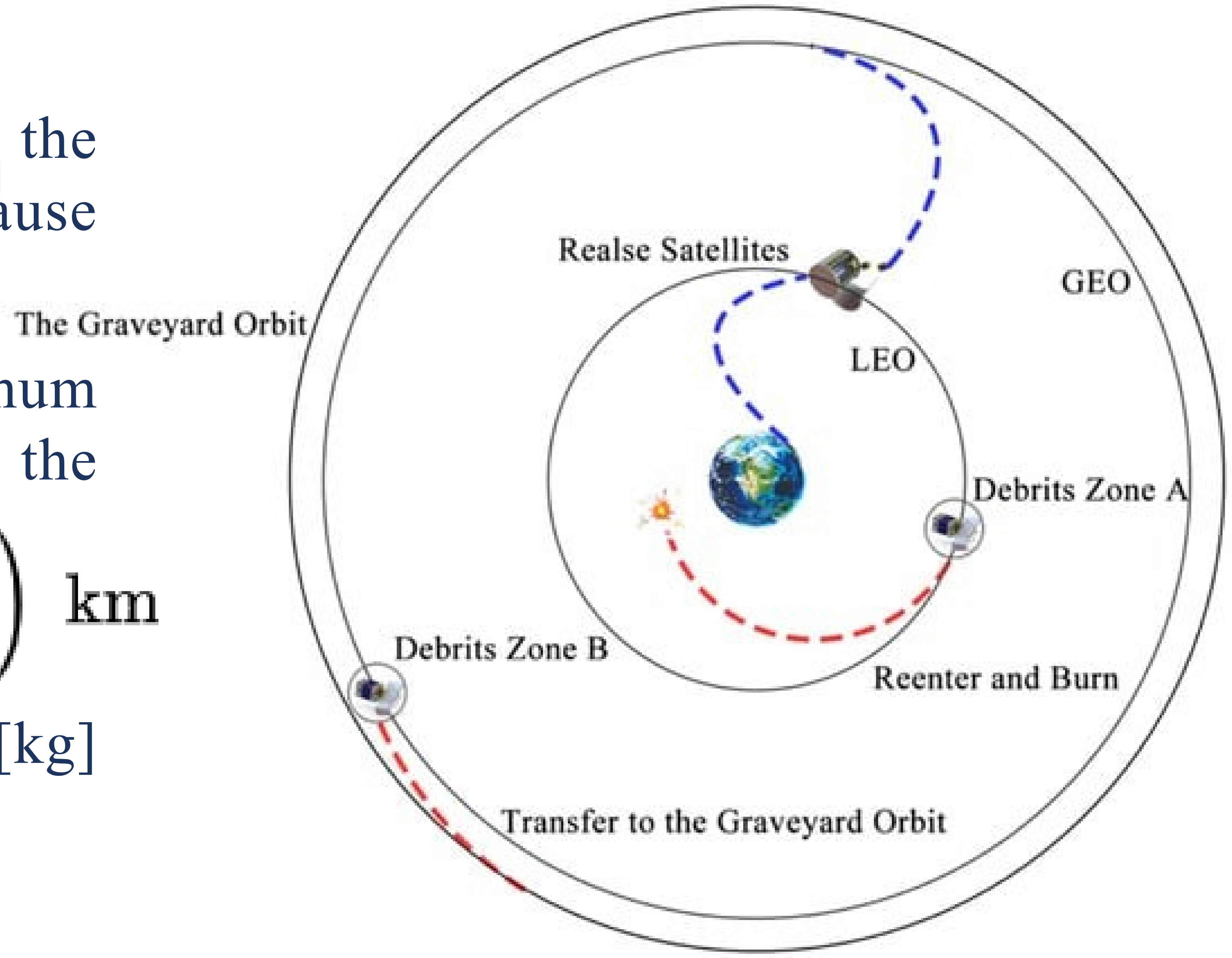
GEO.

- Unlike in LEO, there is **no natural fall mechanism** available in the protected GEO region by which objects can clear the area.
- A **graveyard orbit**, also called a **junk orbit** or **disposal orbit**, is an orbit that lies far from the common operational orbits: an important graveyard orbit tends to be a **super-synchronous orbit**, far beyond the geosynchronous orbit.
  - Some satellites are moved into these orbits at the end of their operational life to reduce the probability of colliding with operational spacecraft and generating space debris.
  - A graveyard orbit is used when the velocity change required to perform a **de-orbiting manoeuvre is too great**: geostationary de-orbiting requires a Δv of about 1 500 metres per second, while relocation to graveyard orbit requires only about 11 metres per second.

- A spacecraft or rocket part operating in the GEO Protected Region, with a permanent or periodic presence, must be **manoeuvred in a controlled manner** during the disposal phase to an orbit that is entirely outside the GEO Protected Region.
- According to the Inter-Agency Space Debris Coordination Committee (IADC), **at least one** of the following **condition**s must be verified:
  - the target orbit has a **perigee altitude sufficiently higher** than the geostationary altitude so that long-term perturbation forces do not cause spacecraft to enter the GEO protected region within **100 years**;
  - the target orbit has an initial eccentricity less than 0.003 and a minimum perigee altitude ΔH (in km) above the geostationary altitude, according to the equation:

$$\Delta H = 235\ \mathrm{km} + \left(1000 C_R \frac{A}{m}\right)\ \mathrm{km}$$

    - A/m is the ratio between the area of incidence [m2] and the dry mass [kg] of the satellite
    - C_R is the solar radiation pressure coefficient

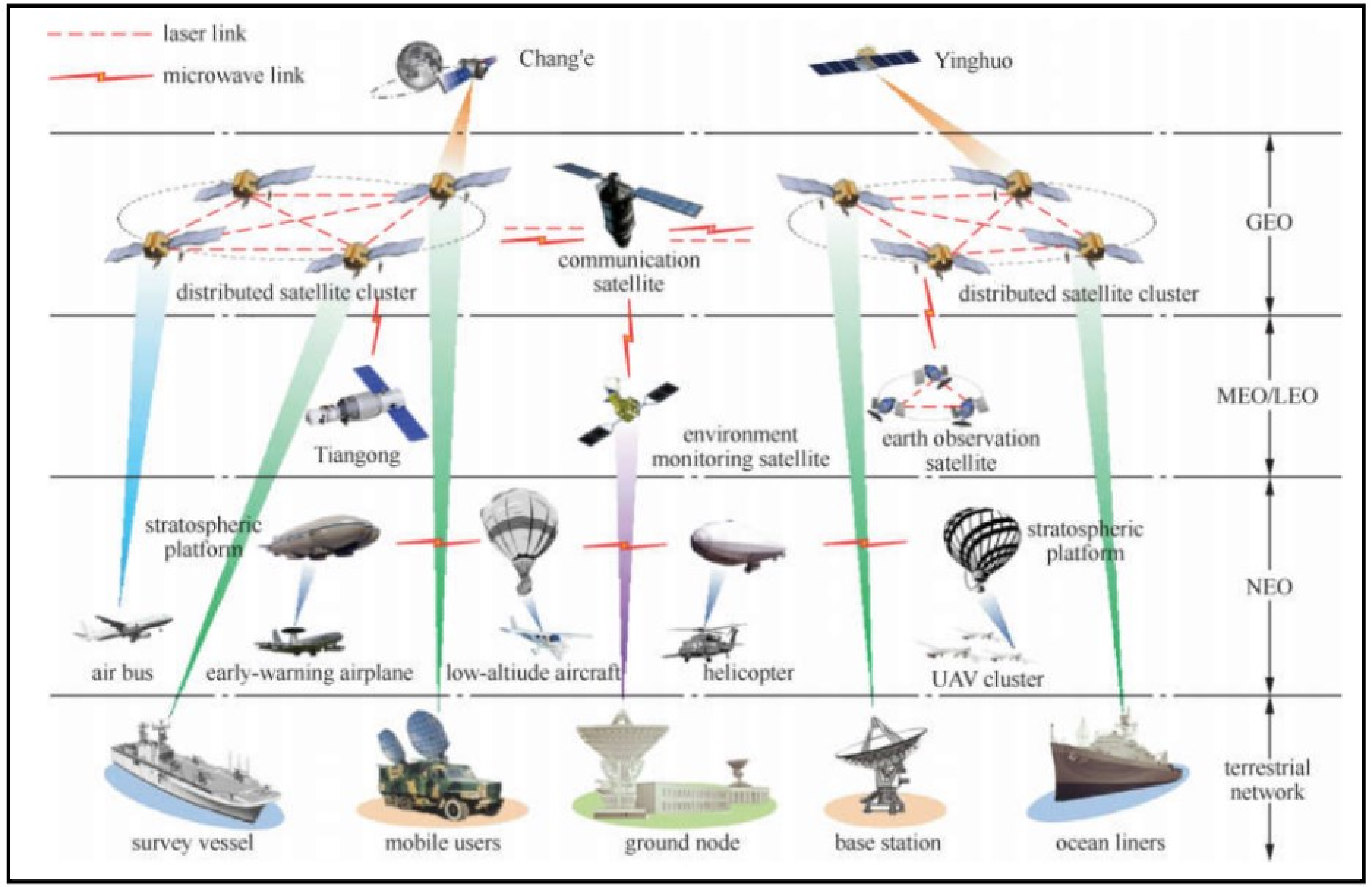


DECOMMISSIONING

In order to avoid unexpected explosions and the consequently increase of the space debris, it is important:

- to discharge the batteries,
- to empty all the propellants tanks, and
- to unload the reaction wheels.

SOME STRATEGIES



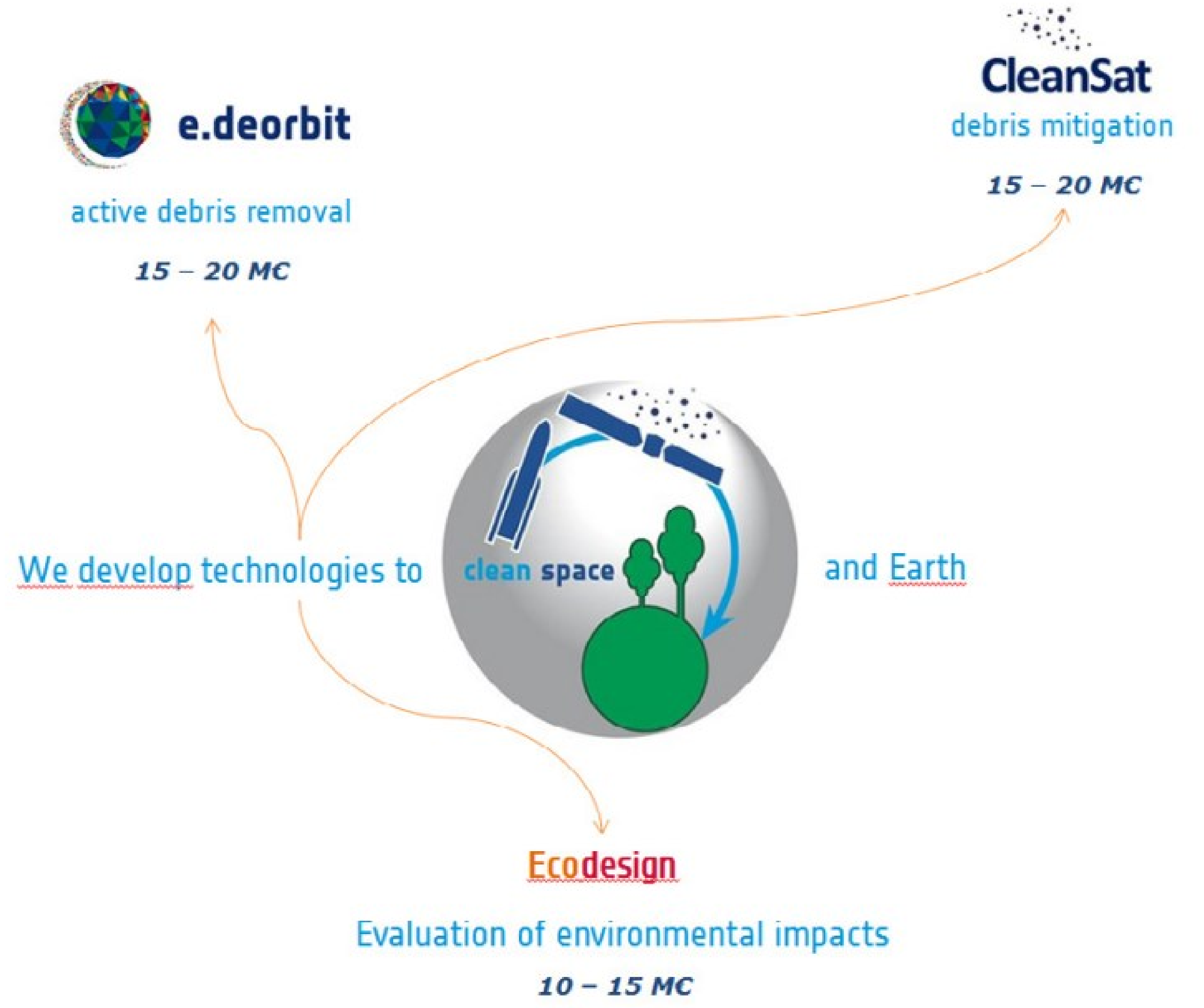
- **Multi-mission satellites**: moving from the traditional single-target satellite approach to an optimised approach in which a dual or multi-mission satellite can serve **multiple purposes simultaneously rather than a single dedicated purpose**; thus multi-mission satellites could significantly **reduce the number of launches**.

- The vast **majority** of satellites in LEO orbit are **isolated independent satellites**, and there are very few constellations. A much better and optimised approach could be to form **a network of satellites in different orbits** through the Intersatellite Link (ISL) and integrate it with the terrestrial network.

SOLUTION APPROACHES

In order to become **more effective**, these guidelines **should be binding for all**, regulated by international law rather than being left to voluntary choice.

The space community (ESA in particular) has identified **three different approaches** to address this challenge.



Removal of debris from orbit.

Some studies suggest that **removing 5-10 large objects per year** from the LEO region **can prevent debris collisions** from cascading. The selected objects must:

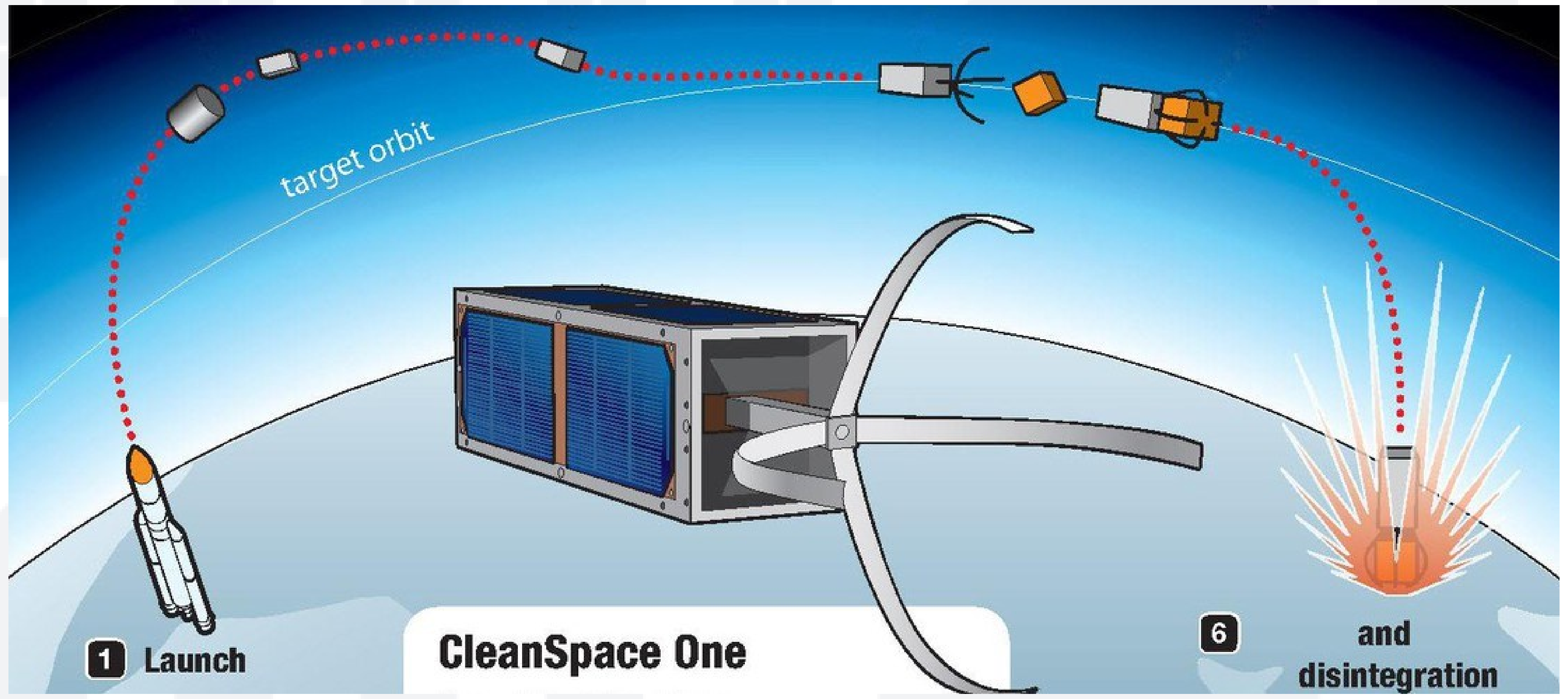
- have a **high mass**,
- have a **large cross section**,
- be located in **densely populated regions**,
- be **at high altitudes** (i.e. have a longer orbital lifetime than the resulting debris).

In practice . . .

Reclaim

- **In-orbit servicing**:
  - **re-fuelling** to extend the mission lifetime;
  - **in-orbit** (or upon **Moon**/Mars) **manufacturing**;
  - in-orbit.

- **Active debris removal**.



Mitigation

Preventing the generation of further satellite-generated **debris** (in a passive way):

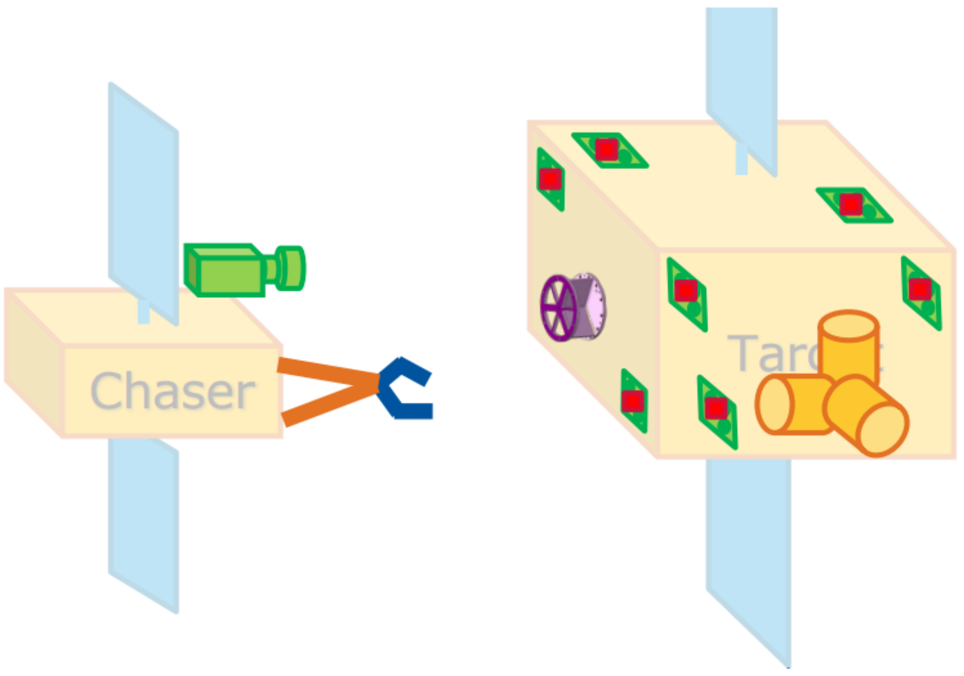
- **to limit debris released** during normal operations;
- **to avoid intentional destruction** and other harmful activities;
- **to minimise** the potential for **break-up** during operational and post-mission phases;
- **to dispose properly** spacecrafts **at the end of the mission**: in GEO in a graveyard orbit and in LEO in an orbit that can guarantee a maximum of 25 years of post-mission orbital life.

In practice . . .

UNIVERSITÀ DEGLI STUDI DI TRIESTE
Dipartimento di Fisica
Dipartimento d'Eccellenza 2023-2027

Mitigation

- **Passivation** of propulsion and power. Certain materials (fuels) can explode in an impact, so these **materials are taken out before de-orbiting** in order to make the satellite passive.
- **Design for Demise (D4D)** proposes several solutions, ranging from **modifying the material** the components are made of, **relocating** them to locations where they receive a greater heating effect in the early stages of **re-entry**, up to triggering a partial rupture of the satellite structure during re-entry to aid de-orbiting.
    - For example, the option of controlled de-orbiting in a safe ocean dive could cost up to 4 or 5 times the propellant needed on board, resulting in an increase in the size, mass and cost of the satellite, which might even require a larger launcher!
    - The problem is not to worsen the performance.
- **Design for Removal (D4R)**: debris are not designed for capture! The communication/printing of specific indications (where the grips are, ...) on the satellites to be de-orbited is expected to facilitate the de-orbiter: without D4R, all active debris removal solutions would have to adapt to the specificities of each spacecraft, whereas if D4R technologies are incorporated from the very beginning of the design of a new satellite, some standardised technologies could be developed.



Awareness

Knowledge of the environment **to prevent** collision of operational satellites.

- **Eco-design**:
  - **LCA** (Life Cycle Assessment), already established in the field of land-based activities, is a comprehensive quantitative assessment from raw materials, production, use, disposal, of what impacts a given environment.

- **Continuous tracking** of orbiting satellites and debris by ground-based radar and optical stations, so that the orbital paths of debris can be predicted and satellite operators can avoid possible collisions with space debris by **manoeuvring the operational spacecraft in advance** of the debris' predicted orbit.
  - However, there are still many **limitations**. Among these, the first and most significant weakness is that only **objects larger than 10 cm** can be **tracked** and catalogued. Therefore, a collision with **debris smaller than 10 cm cannot be predicted and avoided**. Although we are already aware of the threat of debris smaller than 10 cm, it is essential to have systems in place that allow us to obtain information on the movement of smaller debris objects.

ANALYSIS BY MASTER/DRAMA

Two ESA software packages enable analyses:

- on the presence of space debris (Meteoroid and Space Debris Terrestrial Environment Reference – MASTER), and
- as a consequence, on orbit management (Debris Risk Assessment and Mitigation Analysis – DRAMA).

Download and install MASTER and DRAMA in this order from https://sdup.esoc.esa.int/

UNIVERSITÀ DEGLI STUDI DI TRIESTE
Dipartimento di Fisica
Dipartimento d'Eccellenza 2023-2027

REFERENCES

- ESA's Annual Space Environment Report; 2023
- Abid Murtaza, Syed J. Hussain Pirzada, Tongge Xu, Liu Jianwei; Orbital Debris Threat for Space Sustainability and Way Forward; 2019