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Natural perturbations as allies to design deorbiting solutions to mitigate the space debris problem

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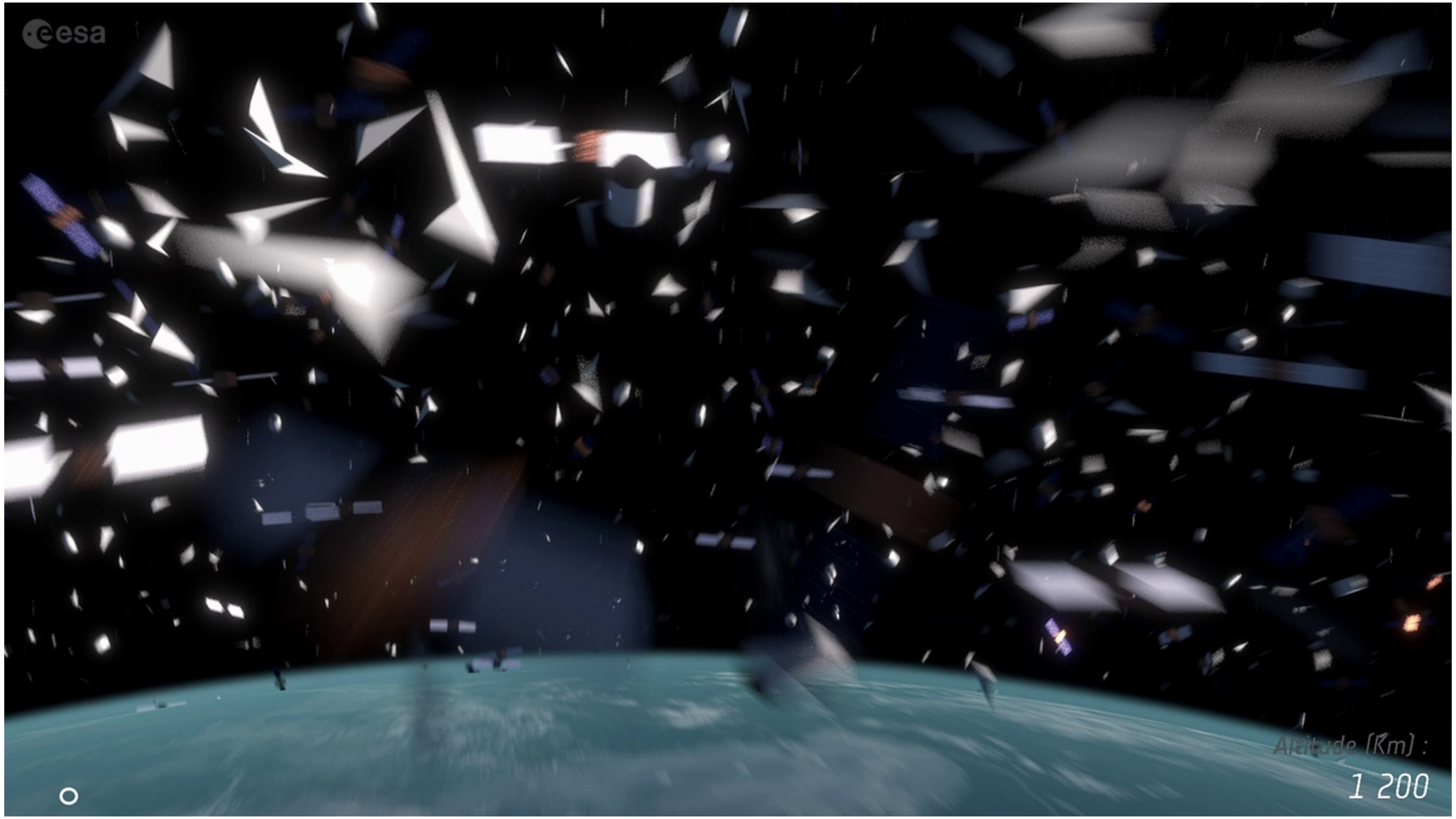
THE ORBITAL REGIONS ARE UNIQUE RESOURCES TO BE PRESERVED



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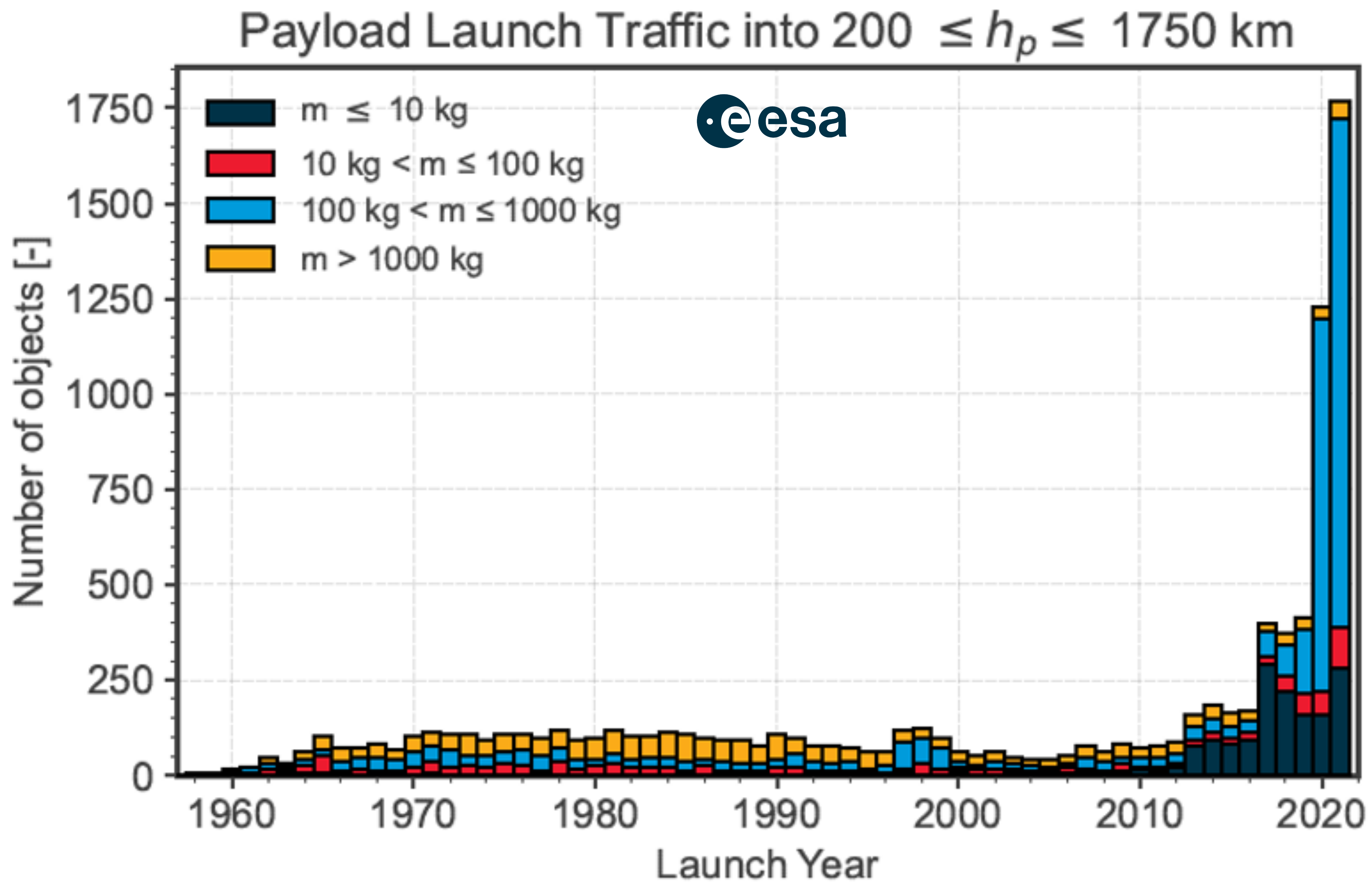
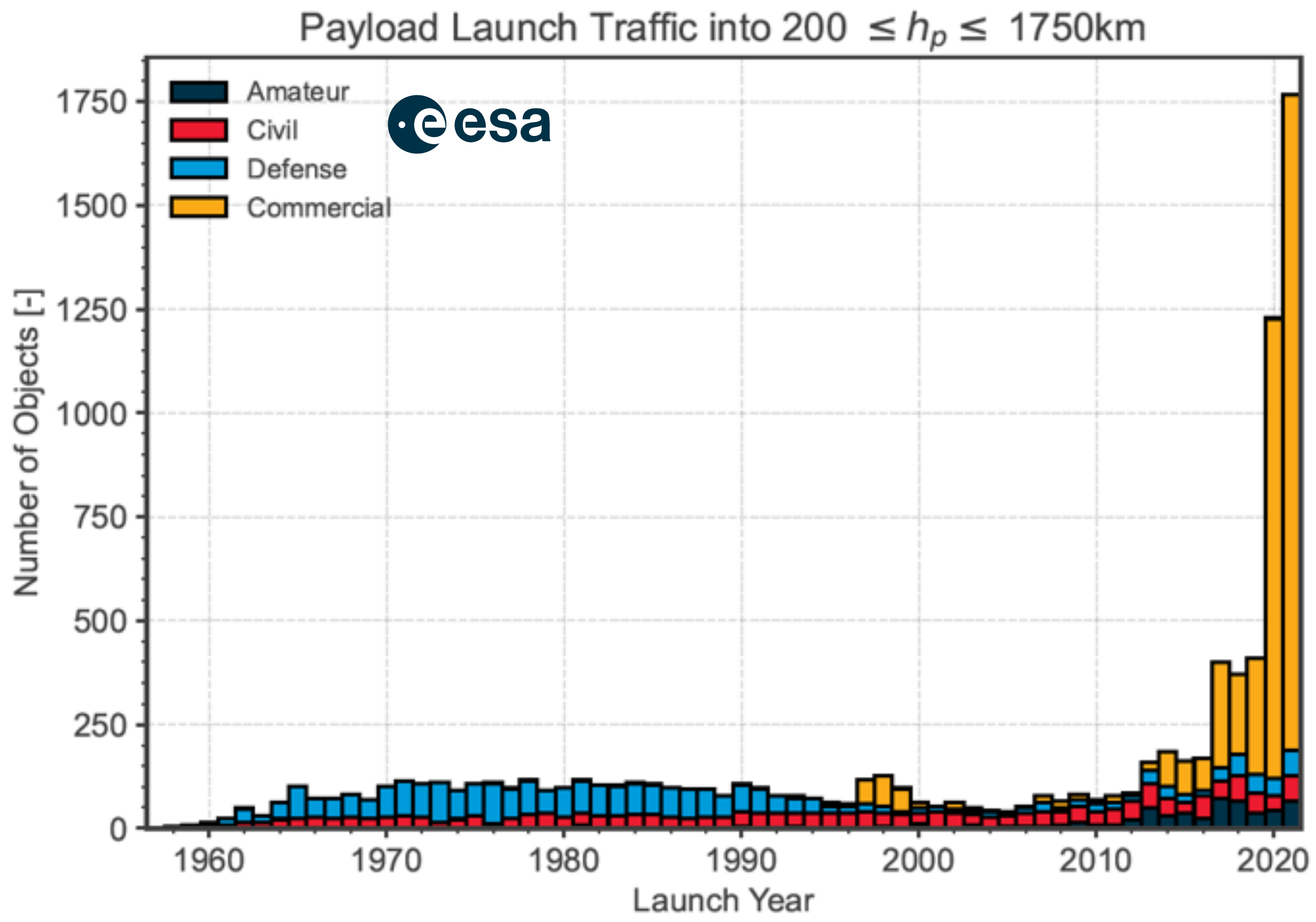
THE SATELLITES ORBITING THE EARTH





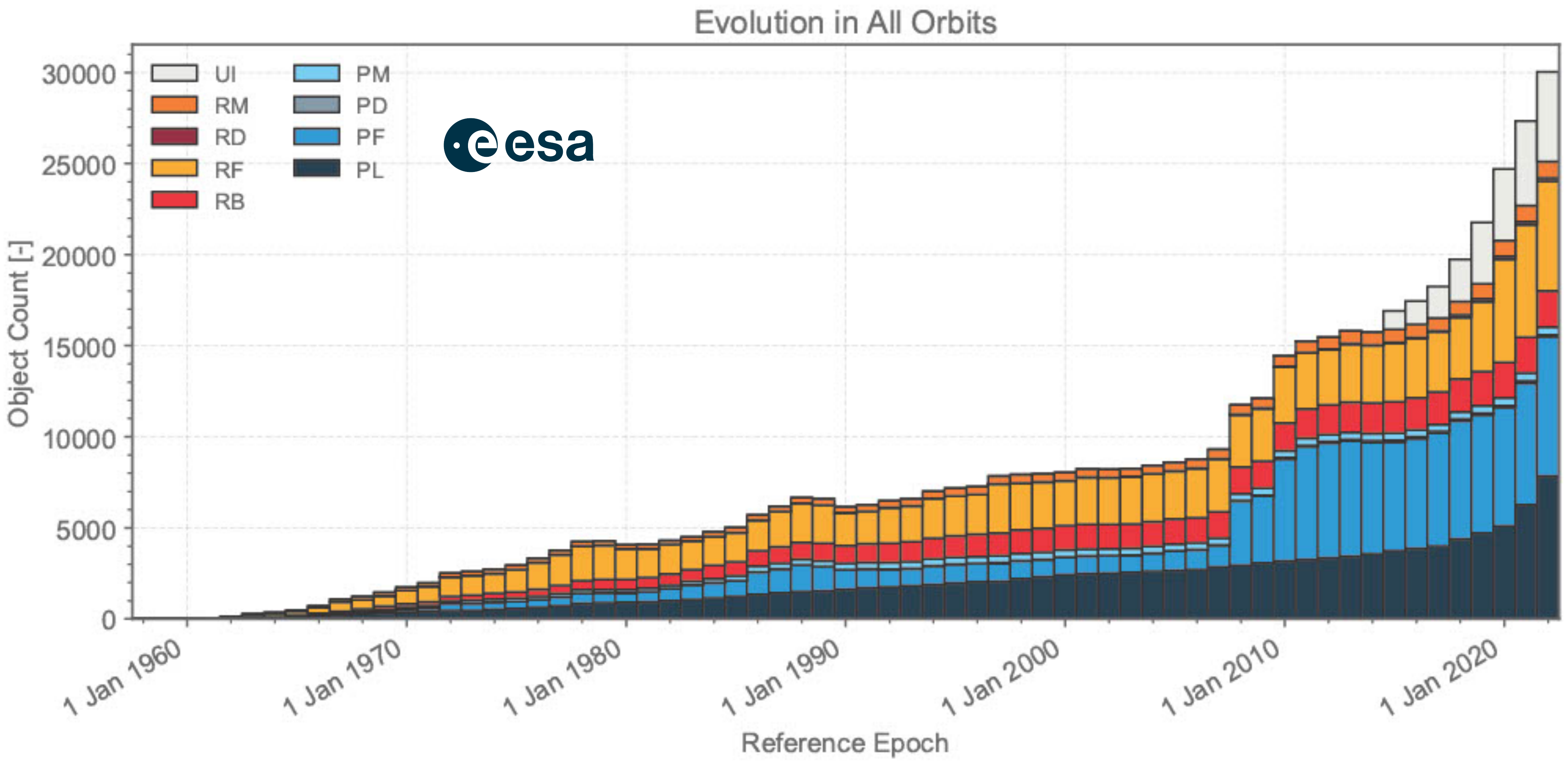
Since the start of the Space Age in 1957 and before the advent of the large constellations,

- about 5200 launches have placed more than 6600 satellites into orbit;
- **about 1100 satellites are currently operational;**
- the **large constellations** have put in orbit about **3000 additional** satellites so far.

THE SPACE DEBRIS PROBLEM

Following the most recent estimates, there are:

- more than 30000 objects larger than 10 cm (**the tracked ones**);
- more than 1 million from 1 to 10 cm;
- more than 10^8 from 1 mm to 1 cm.

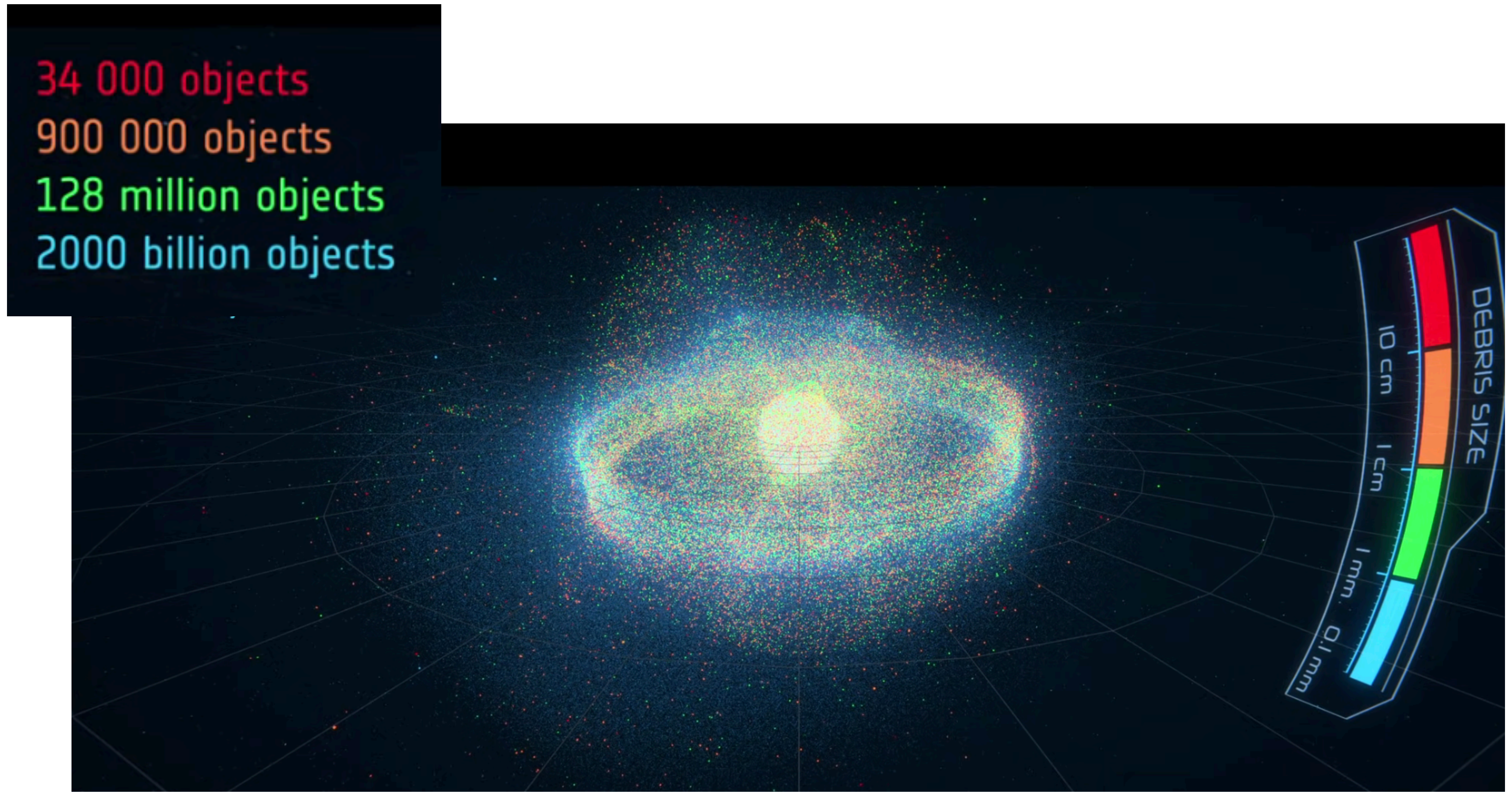


The great majority of artificial mass orbiting the Earth are non-operational spacecraft or fragments of various size, mainly due to break-up, collisions (e.g., Cosmos 2251 - Iridium 33 collision in 2009) and deliberate fragmentations (e.g., anti-satellite test).

THE SPACE DEBRIS PROBLEM

TO CONTROL THE SPACE DEBRIS POPULATION AND TO LIMIT ITS GROWTH, DIFFERENT ASPECTS PLAY A KEY ROLE:

- **Monitor and Tracking**
- **Modeling**: long-term evolution models
- **Operations**: collision avoidance, **end-of-life disposal**, reentry assessment
- **Protection**: shielding and design
- **Regulations**: mitigation guidelines and legal issues
- **Active Debris Removal**
- **Space Traffic Management**



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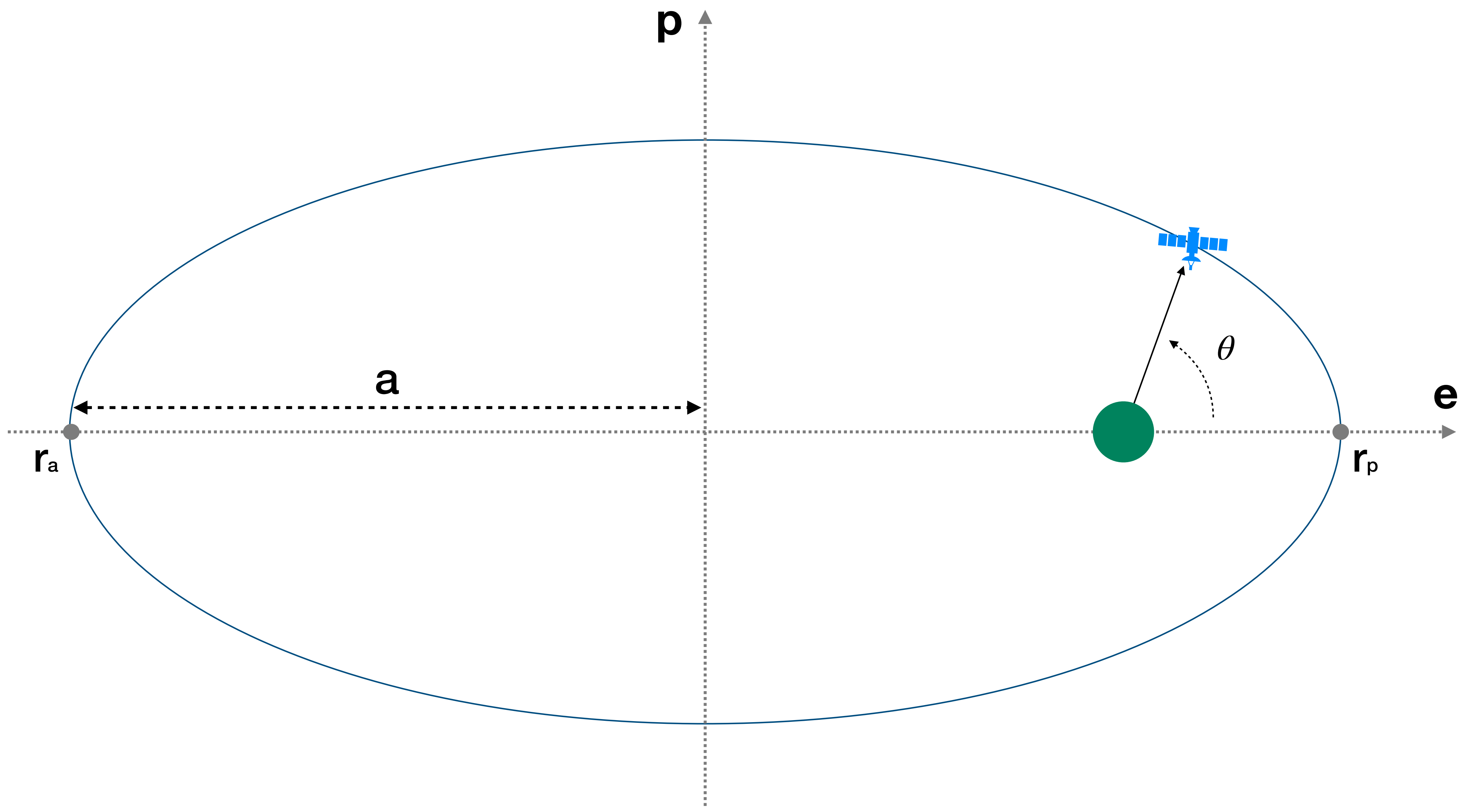
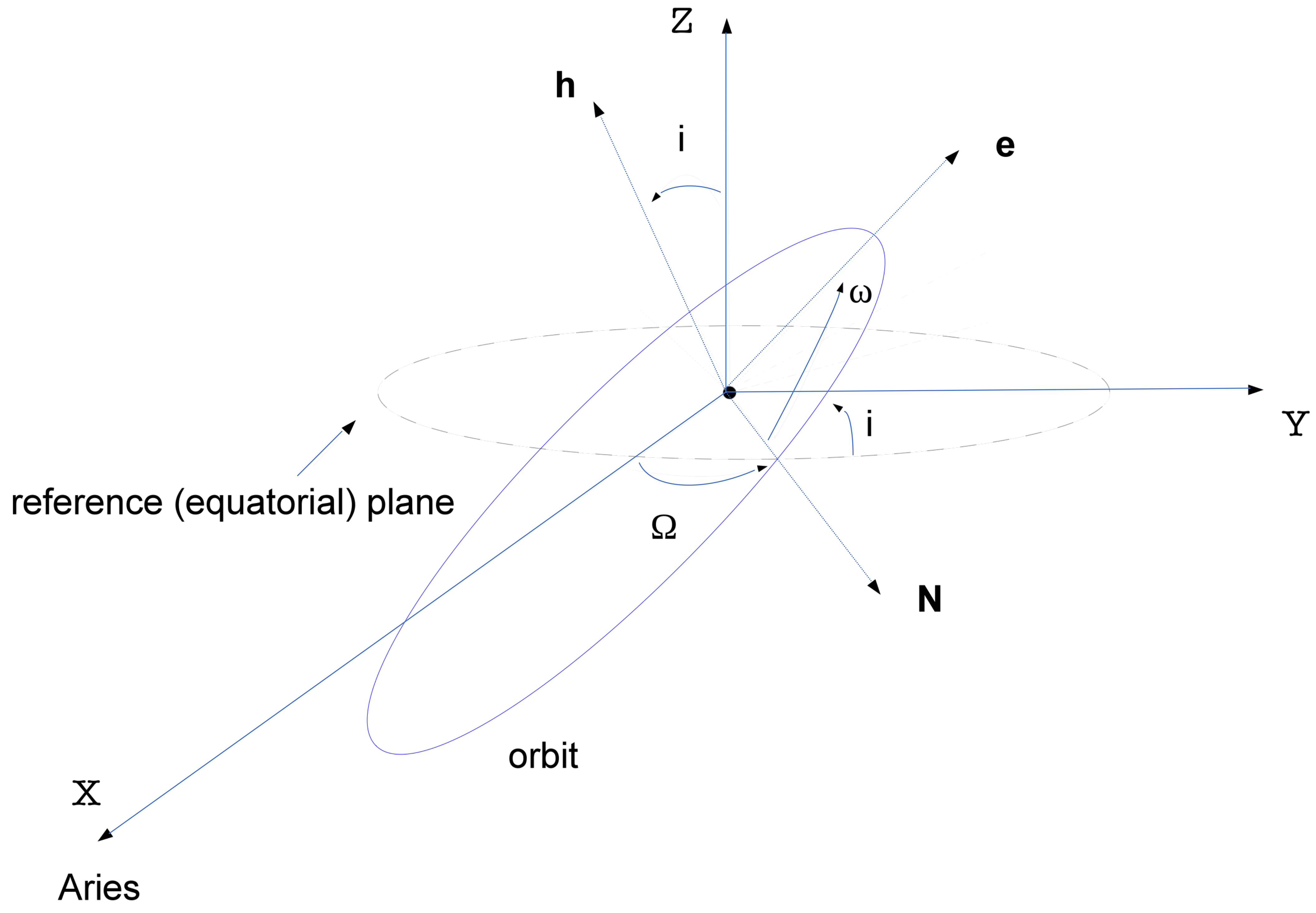
HOW TO DEFINE AN ORBIT

SIX ORBITAL ELEMENTS DEFINE THE SIZE, SHAPE, ORIENTATION and POSITION ON THE ORBIT

$a, e, i, \Omega, \omega, \theta$





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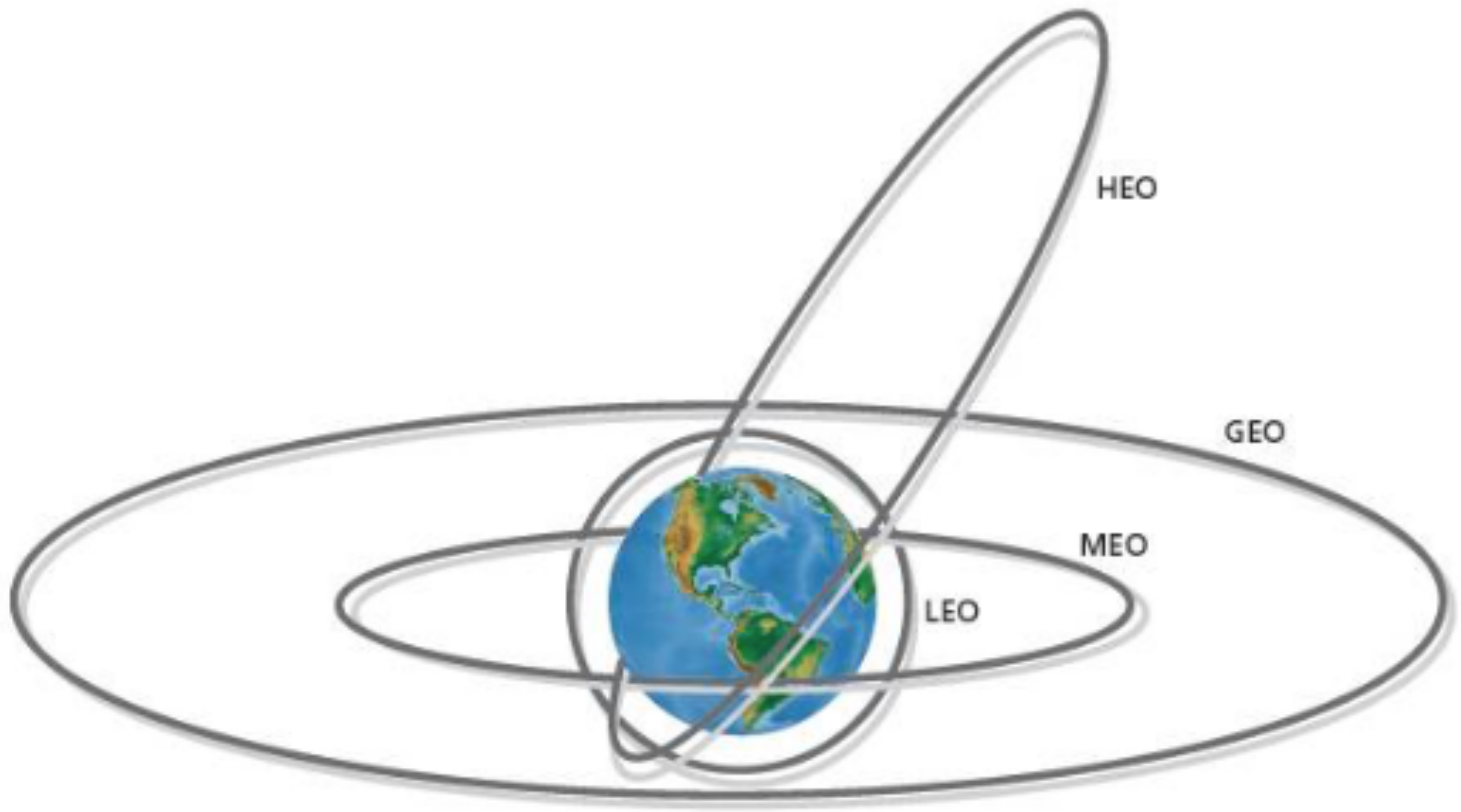
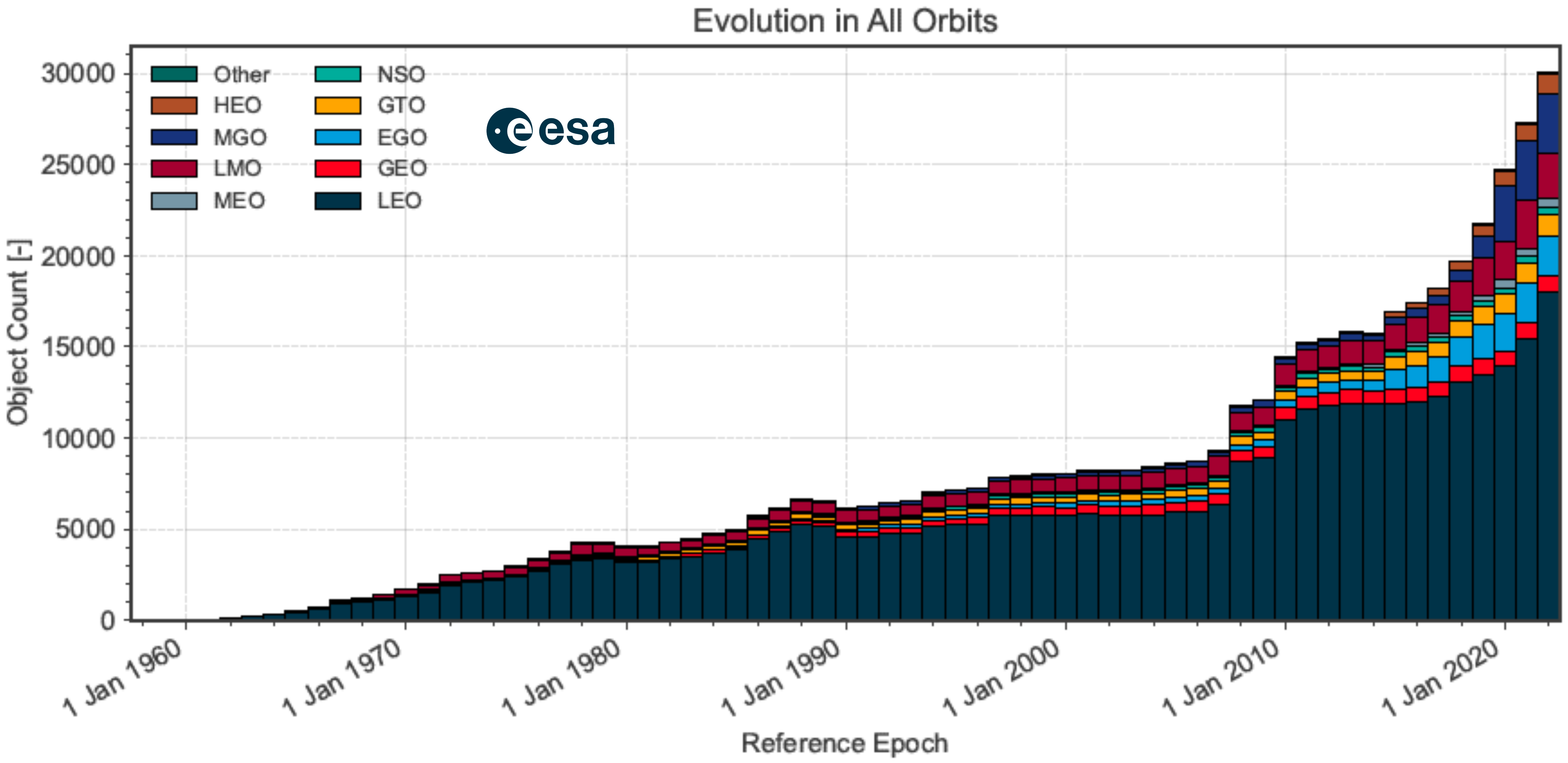
THE ORBITAL REGIONS

LOW EARTH ORBIT: up to 2000 km of altitude, Earth's observation and commercial purposes

GEOSTATIONARY ORBIT: altitude of 35786 km, circular orbit, not inclined, telecommunication purposes





MEDIUM EARTH ORBIT: between LEO and GEO, navigation satellites

HIGHLY ELLIPTICAL ORBIT: eccentricity > 0.5, astrophysics purposes

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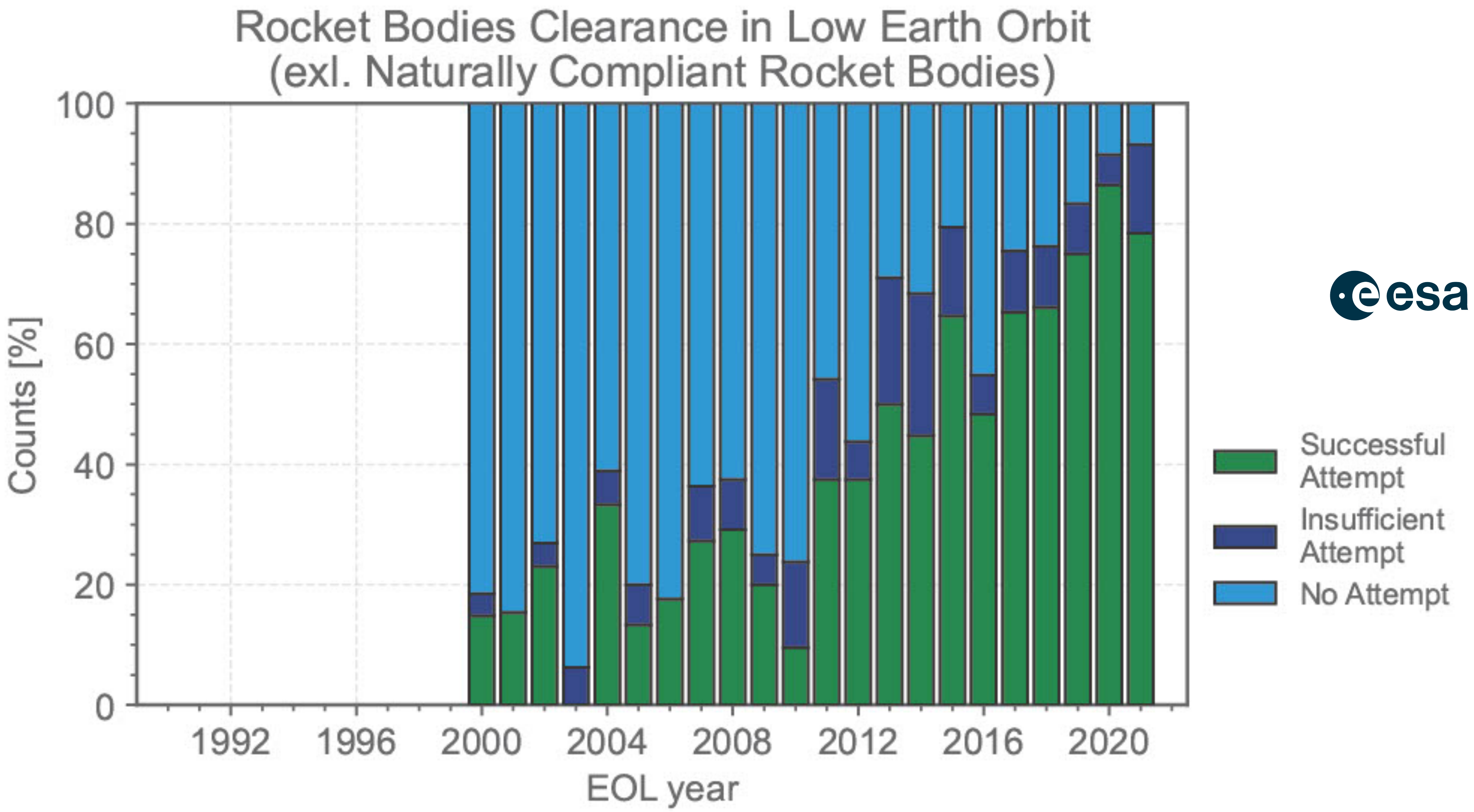
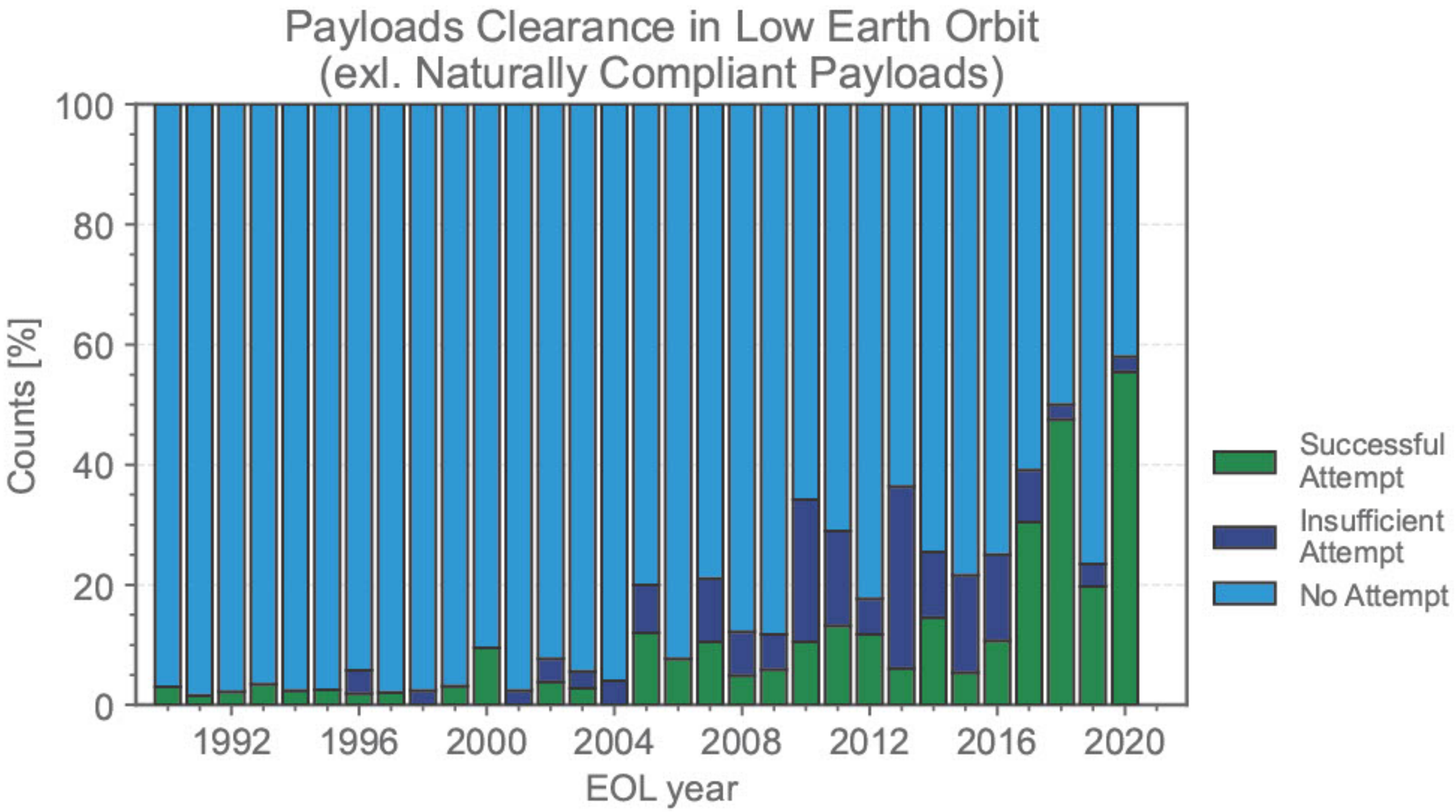
LEO END-OF-LIFE OFFICIAL RECOMMENDATION

THE LEO REGION IS ONE THE "PROTECTED REGION", DEFINED BY THE INTERNATIONAL AGREEMENTS

the mitigation guidelines require that "space systems operating in LEO shall be disposed of by reentry into the Earth's atmosphere within 25 years after the end of the operational phase"





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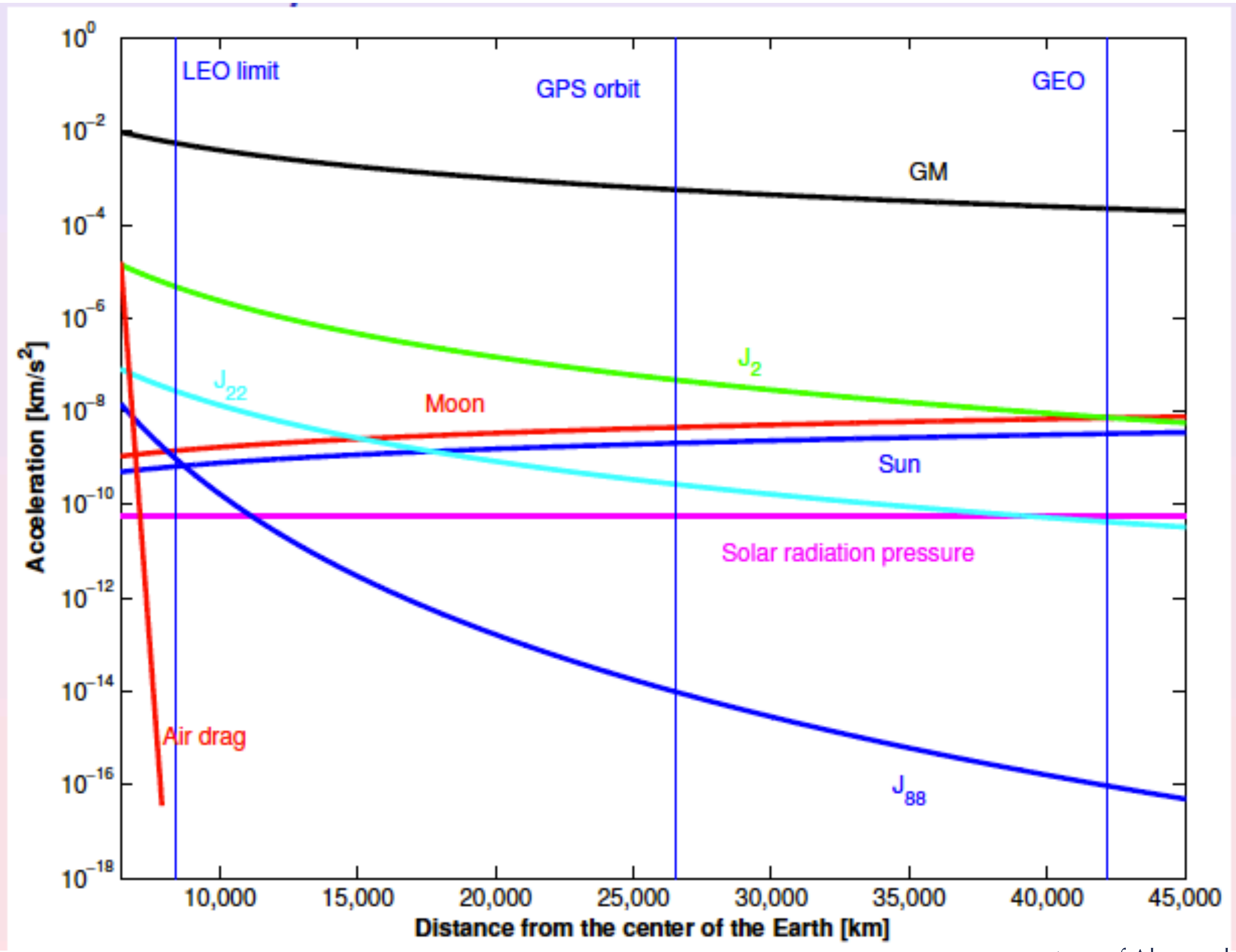
PASSIVE END-OF-LIFE DISPOSAL

- Above certain altitudes it becomes more convenient for an operator to send the satellite in a circular graveyard orbit above the protected LEO region.
- The accumulation of spent, uncontrolled spacecraft in a restricted region of space leads inevitably to a significant number of collisions.

CAN WE EXPLOIT A NATURAL PERTURBATION TO FACILITATE THE END-OF-LIFE DISPOSAL BEYOND THE ATMOSPHERIC DRAG REGIME?

MAIN NATURAL ACCELERATIONS



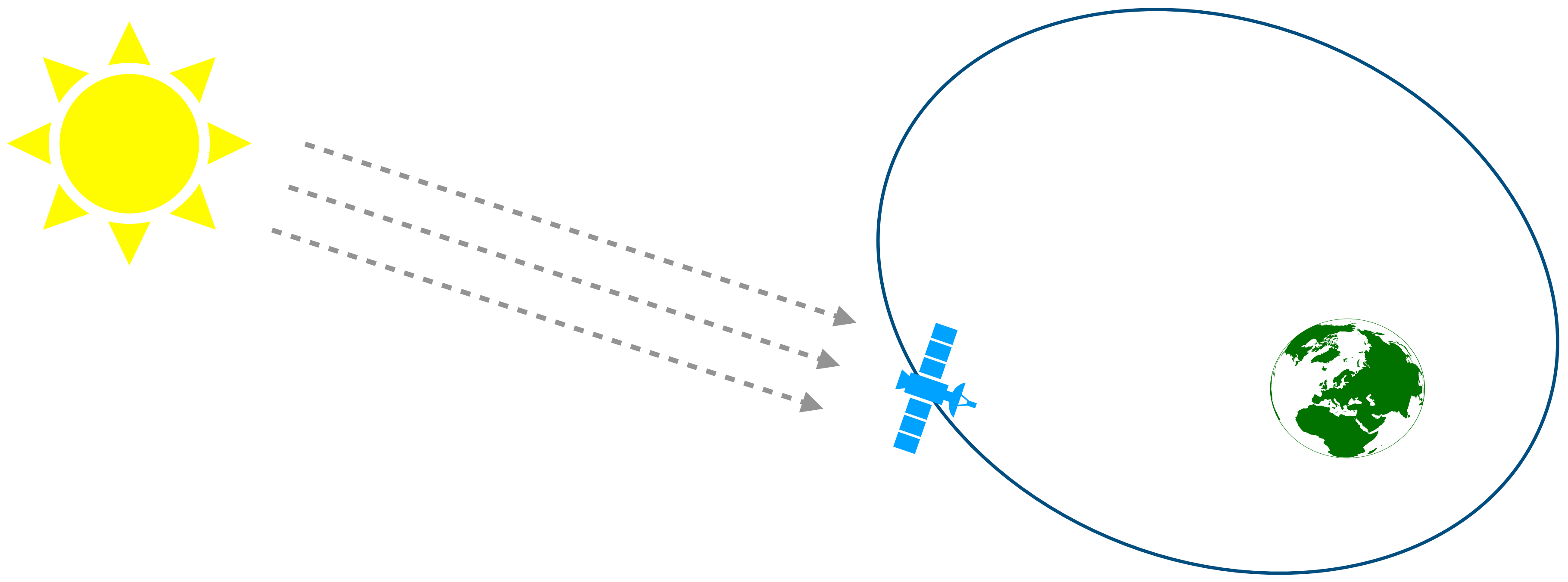
courtesy of Alessandro Rossi, IFAC-CNR

Depending on the perturbation and the timescale, we have a variation of a given orbital element.

HOW TO EXPLOIT NATURAL PERTURBATIONS TO MAKE THE ORBIT MORE ECCENTRIC?

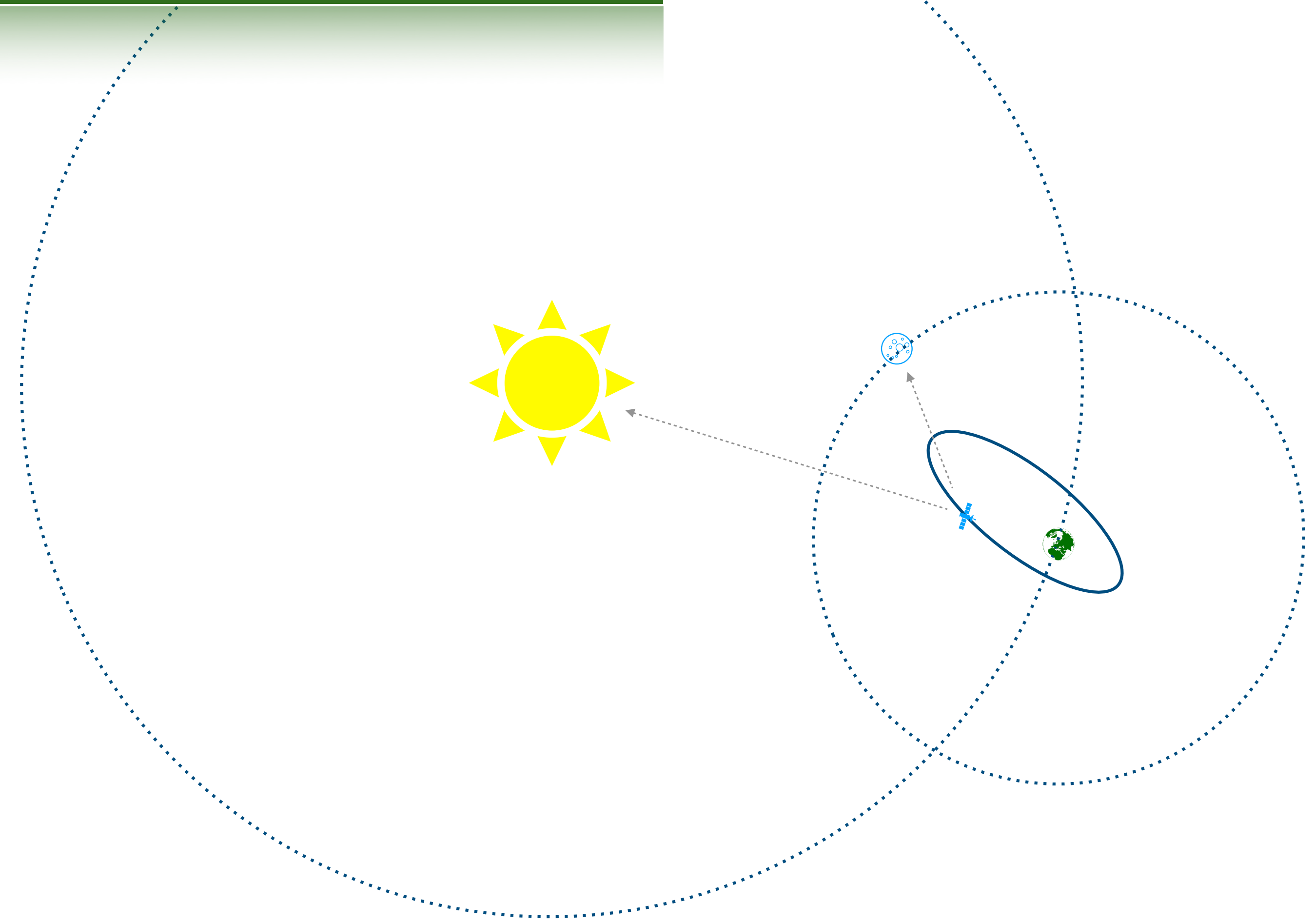
LEO

solar radiation pressure



MEO

lunisolar perturbations

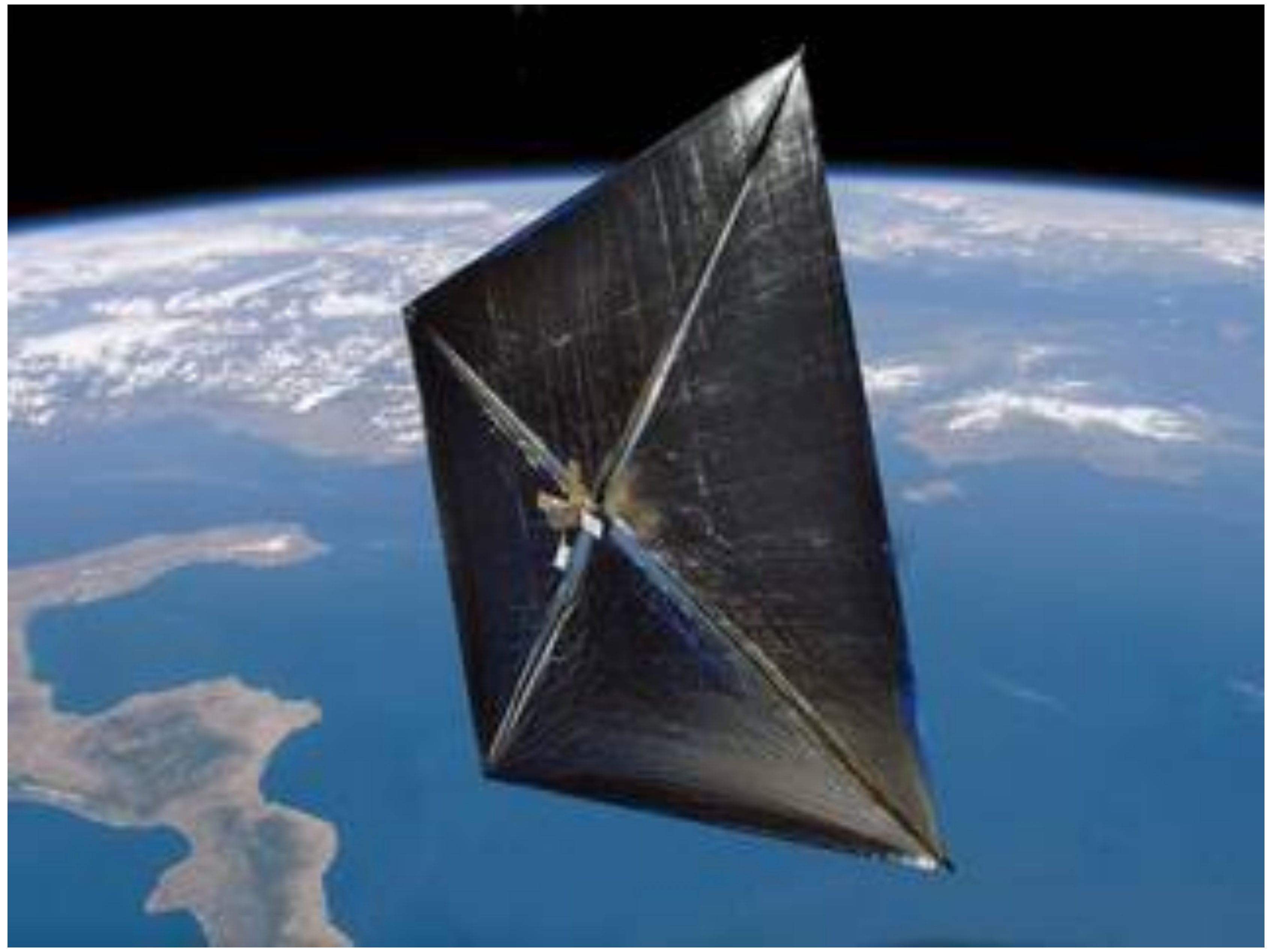


ORBITAL RESONANCES CAN LEVERAGE THE INSTABILITY OF THE ORBIT AND DRIVE THE SPACECRAFT TO THE EARTH

THE COUPLED EFFECT OF SOLAR RADIATION PRESSURE AND EARTH OBLATENESS

At the end-of-life a spacecraft equipped with a large enough solar sail can exploit the momentum imparted by the photons that hit the sail, to de-orbit naturally.

ADVANCED TECHNOLOGY + ADVANCED ASTRODYNAMICS



complete analytical formulation for deorbiting

numerical simulations confirm the robustness of the analytical solutions

natural corridors enabled by a solar sail and a resonant condition on the orbit

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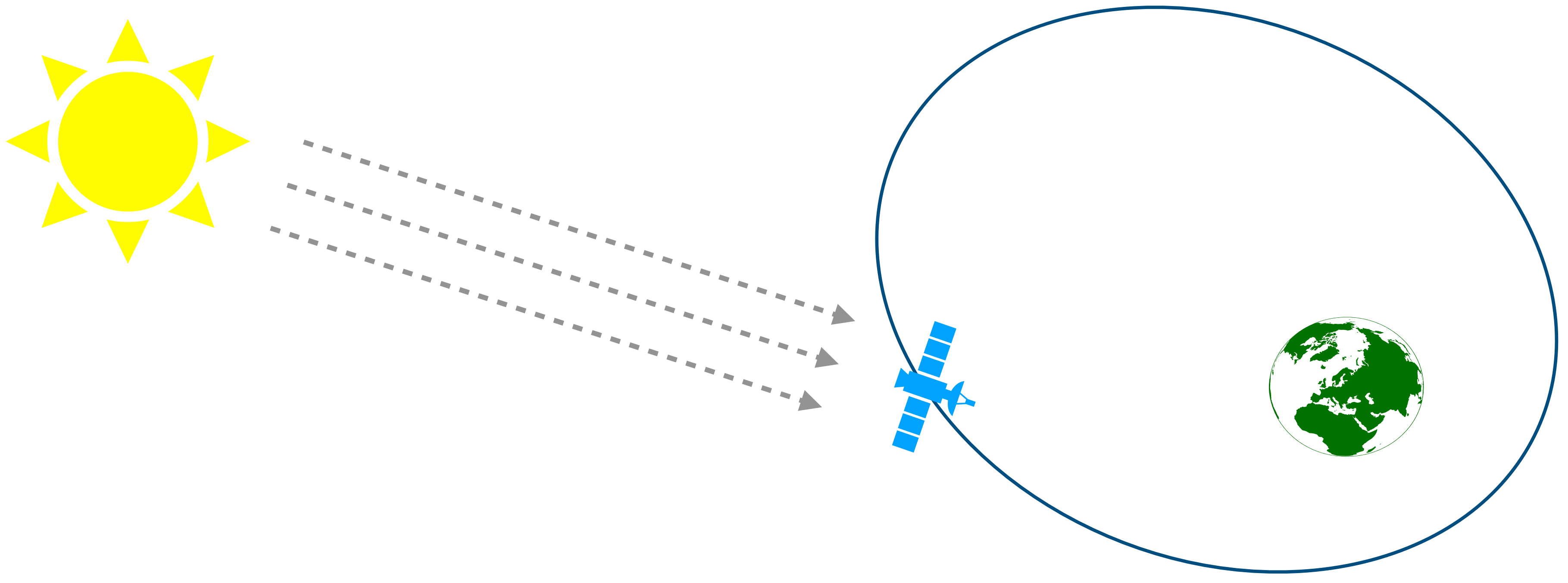
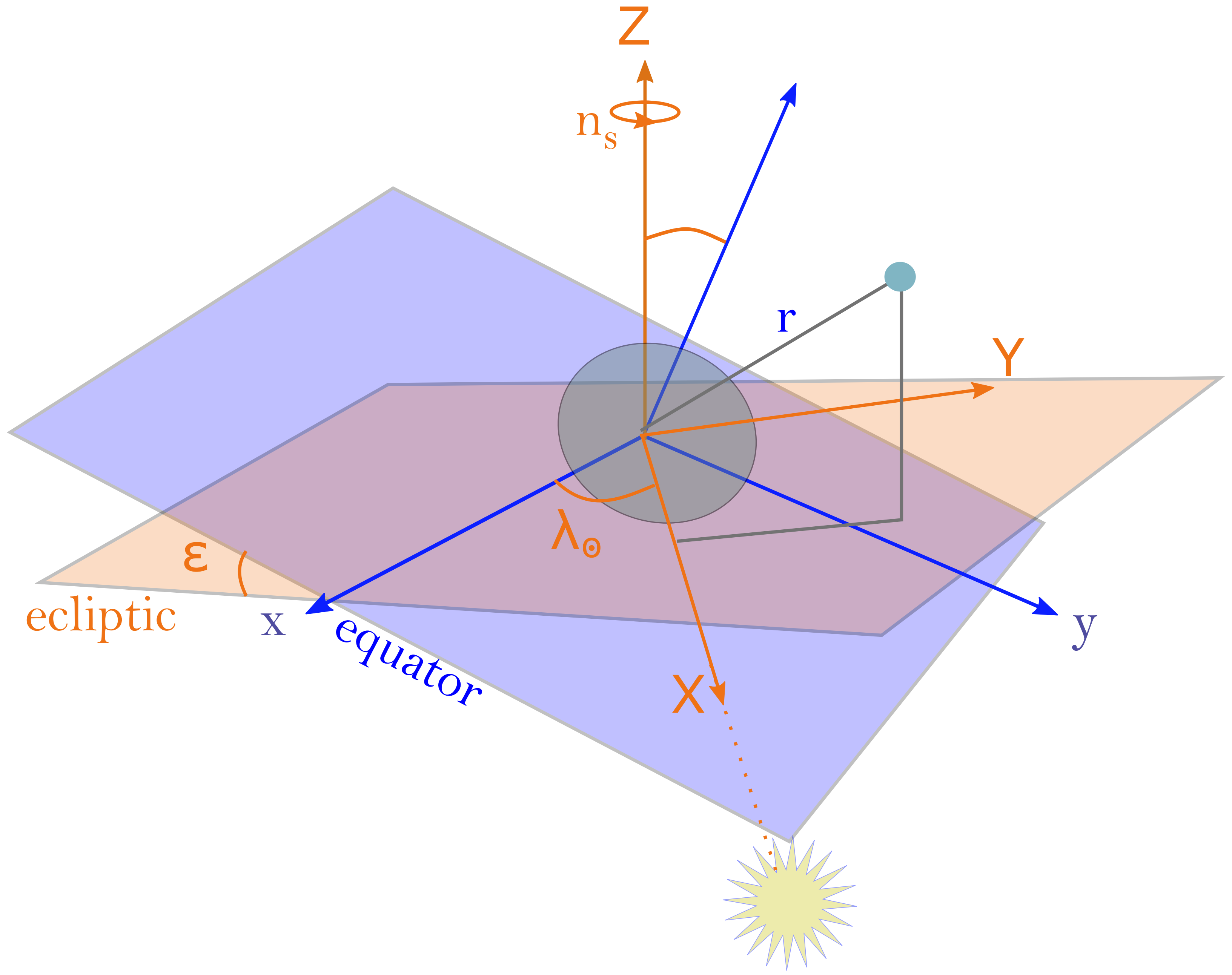
THE COUPLED EFFECT OF SOLAR RADIATION PRESSURE AND EARTH OBLATENESS

- spacecraft always in sunlight
- *cannonball model:* the Sun hits the surface of the s/c perpendicularly
- Earth's albedo is negligible





Hamiltonian formulation

$$\mathscr{H} = \mathscr{H}_{kep} + \mathscr{H}_{per}$$

with

$$\mathscr{H}_{per} = \mathscr{H}_{J_2} + \mathscr{H}_{SRP}$$

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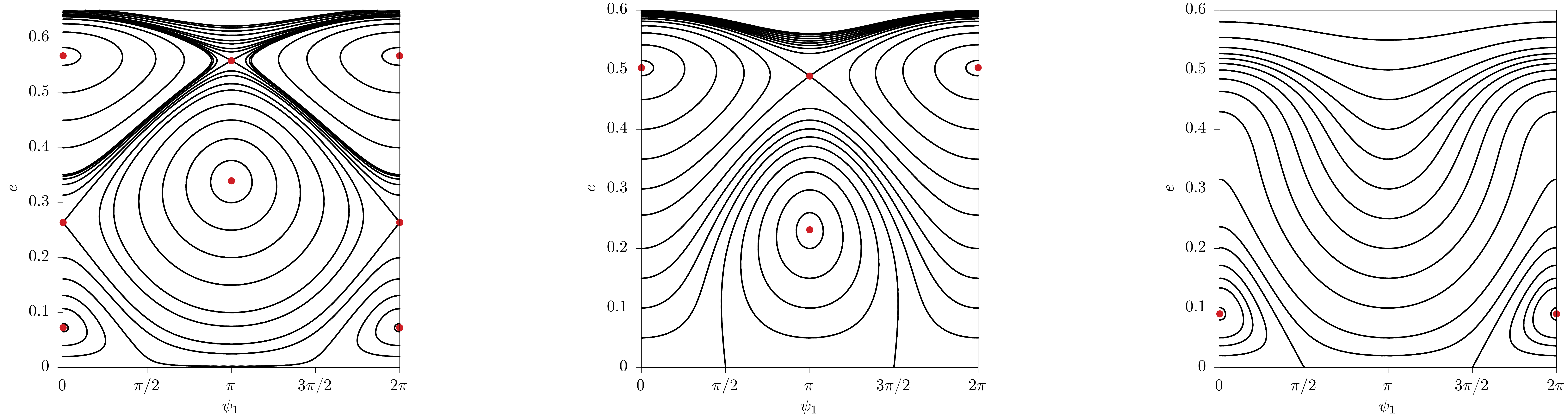
EQUILIBRIUM POINTS AND ASSOCIATED DYNAMICS

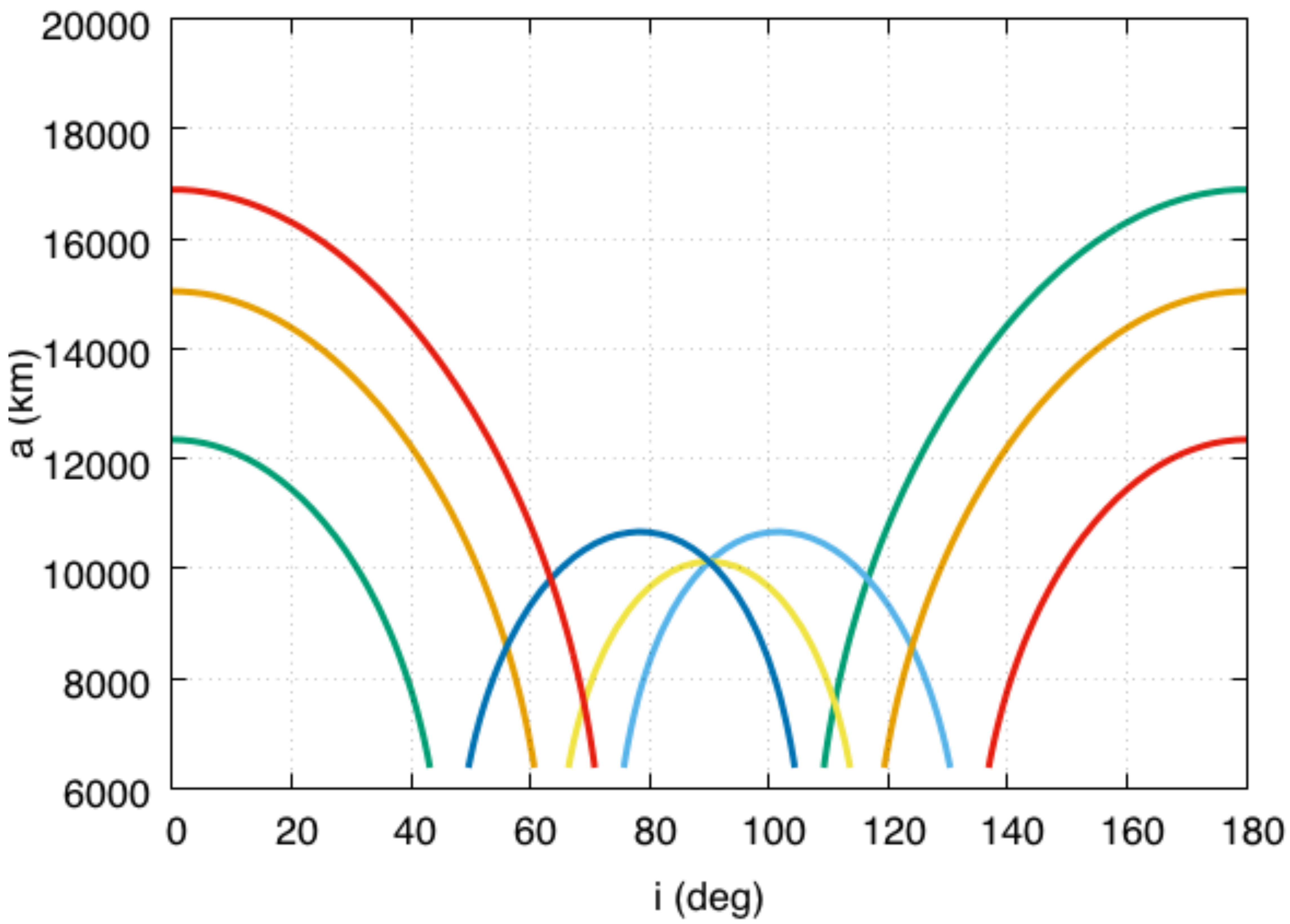
$$\frac{de}{dt} = n_1 \mathscr{C}_{SRP} \frac{\sqrt{1-e^2}}{na} \mathscr{T}_j \sin\psi_j = 0$$

$$\frac{d\psi_j}{dt} = n_1 \dot{\omega}_{(J_2,j)} + n_2 \dot{\Omega}_{(J_2,j)} + n_3 n_S = 0$$

RESONANT ARGUMENT: STEEPEST VARIATION IN e

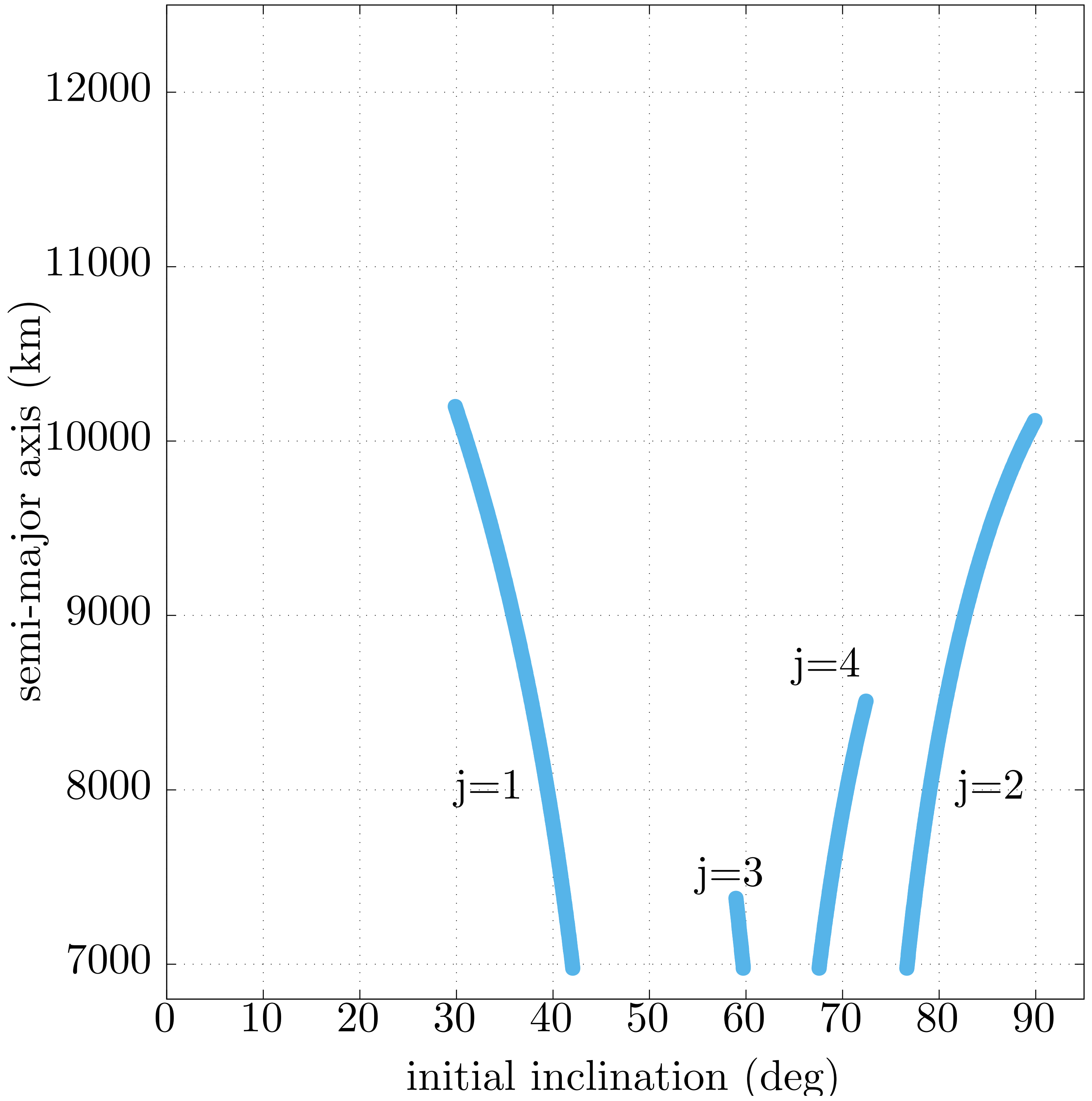


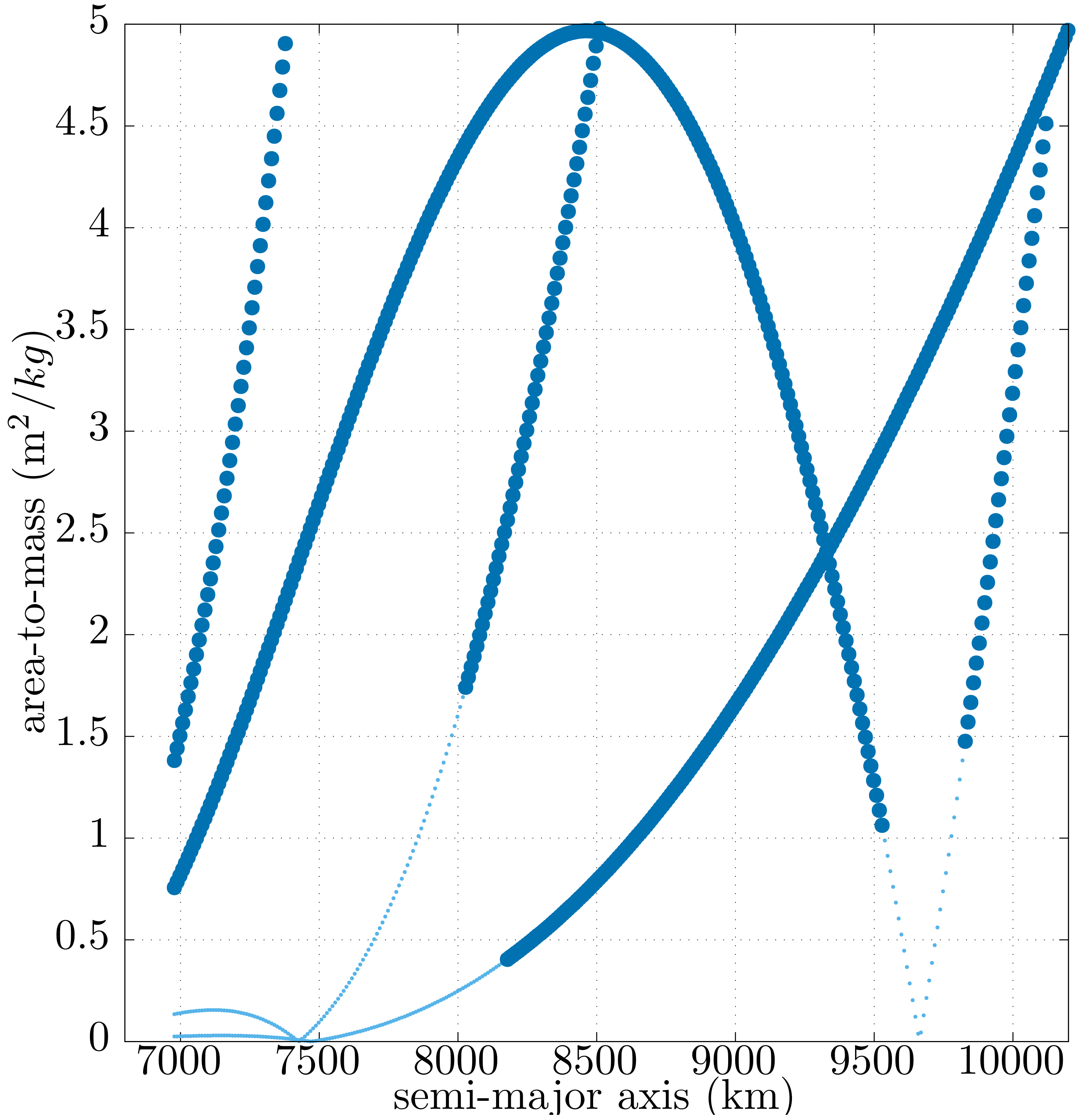
SRP-J2 RESONANCES: DEORBITING CORRIDORS



$$\psi_1 = \Omega + \omega - \lambda_\odot, \qquad \psi_2 = \Omega - \omega - \lambda_\odot$$
$$\psi_3 = \omega - \lambda_\odot, \qquad \psi_4 = \omega + \lambda_\odot$$
$$\psi_5 = \Omega + \omega + \lambda_\odot, \qquad \psi_6 = \Omega - \omega + \lambda_\odot$$

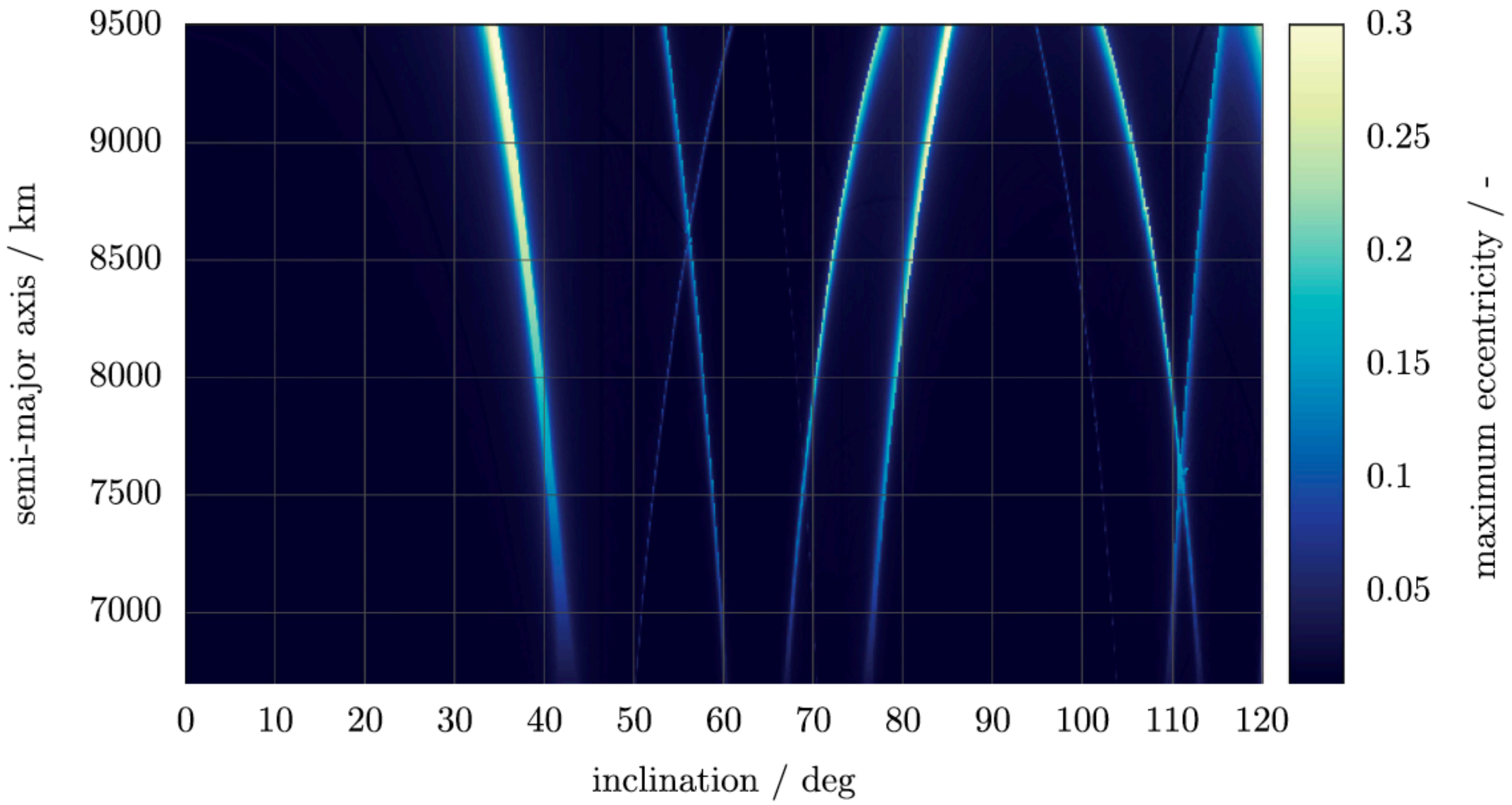
AREA-TO-MASS RATIO AND DEORBITING TIME

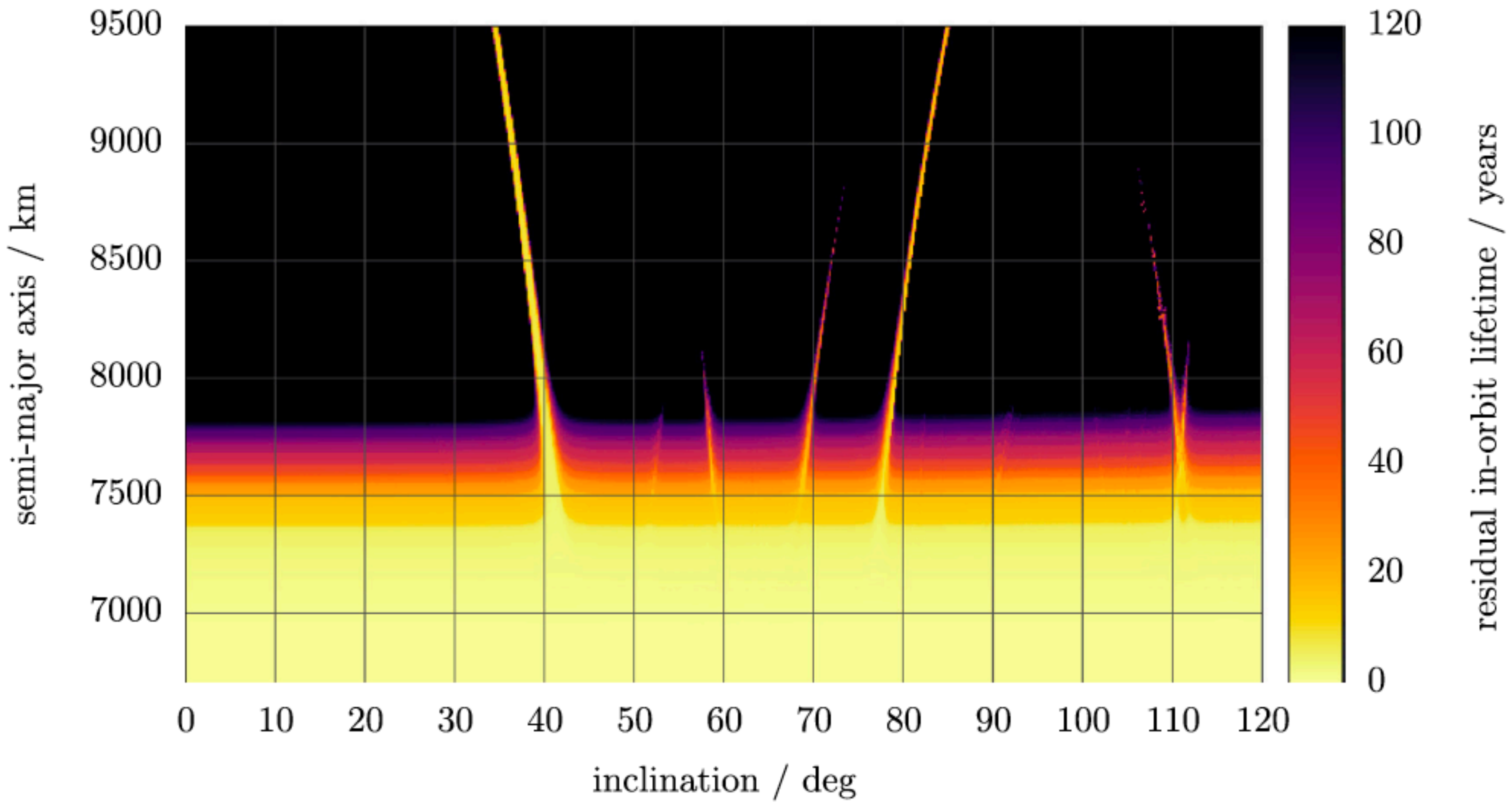




minimum area-to-mass to deorbit thanks to the SRP in less than 25 years

CONSIDERING A MORE COMPLEX MODEL

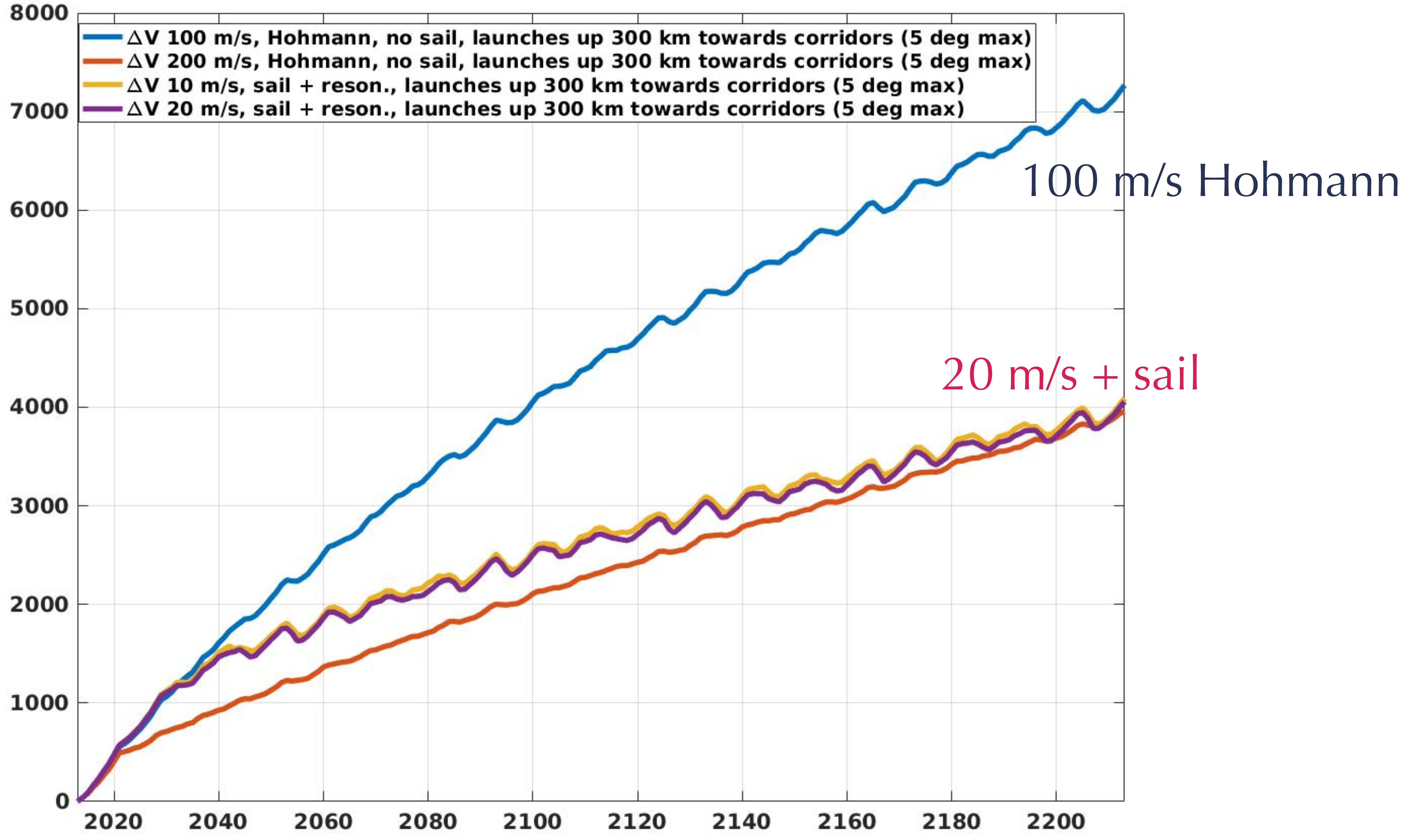




Numerical simulations, averaged and non, accounting also for the geopotential, third-body and atmospheric drag perturbations, have shown the robustness of the deorbiting corridors.

EFFECTIVENESS OF THE DEORBITING CORRIDORS

Comparative evaluation based on the number of objects at the end of the long-term simulations and the Δ v-budget required to dispose the spacecraft.



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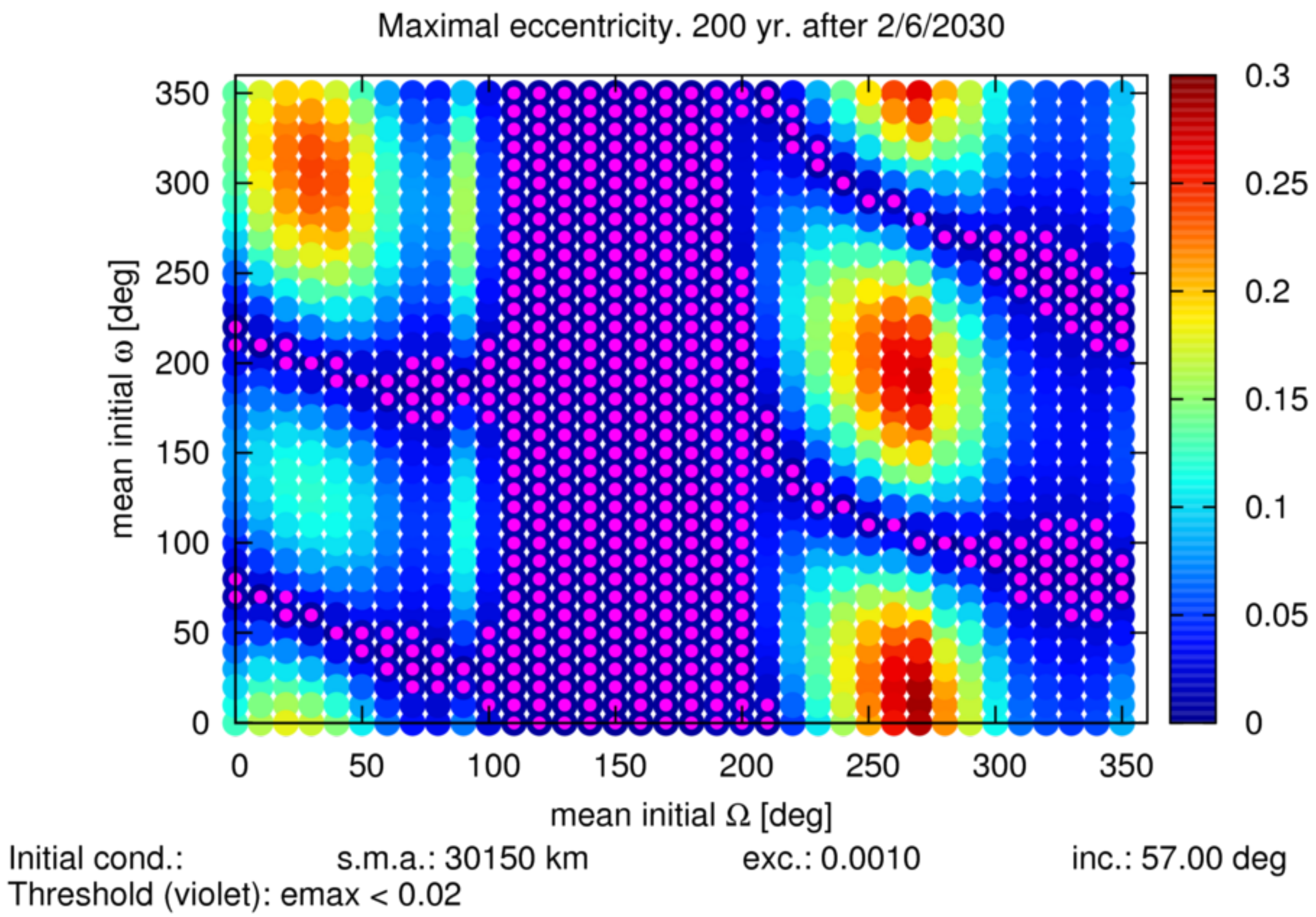
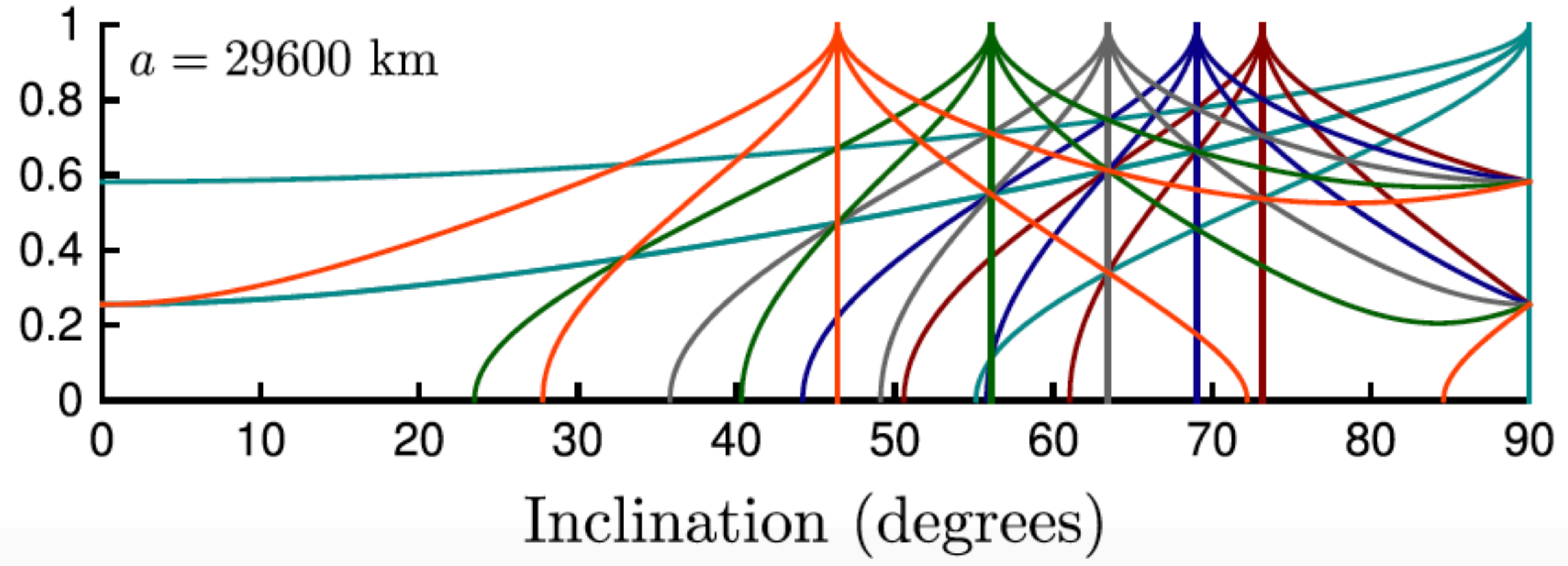
MEO DISPOSAL AND LUNISOLAR PERTURBATIONS



- **natural eccentricity growth is due to chaos?**
- **how to target optimally the stable/unstable solutions?**



Numerical simulations have identified the initial conditions:

- ensuring a stable graveyard orbit in the long term
- leading to the Earth

THIS DYNAMICAL AWARENESS REPRESENTS A NEW PARADIGM IN MISSION PLANNING, WHERE THE WHOLE LIFECYCLE OF THE SPACECRAFT, INCLUDING DISPOSAL, IS CONSIDERED FROM THE VERY BEGINNING OF THE DESIGN.

Thank you