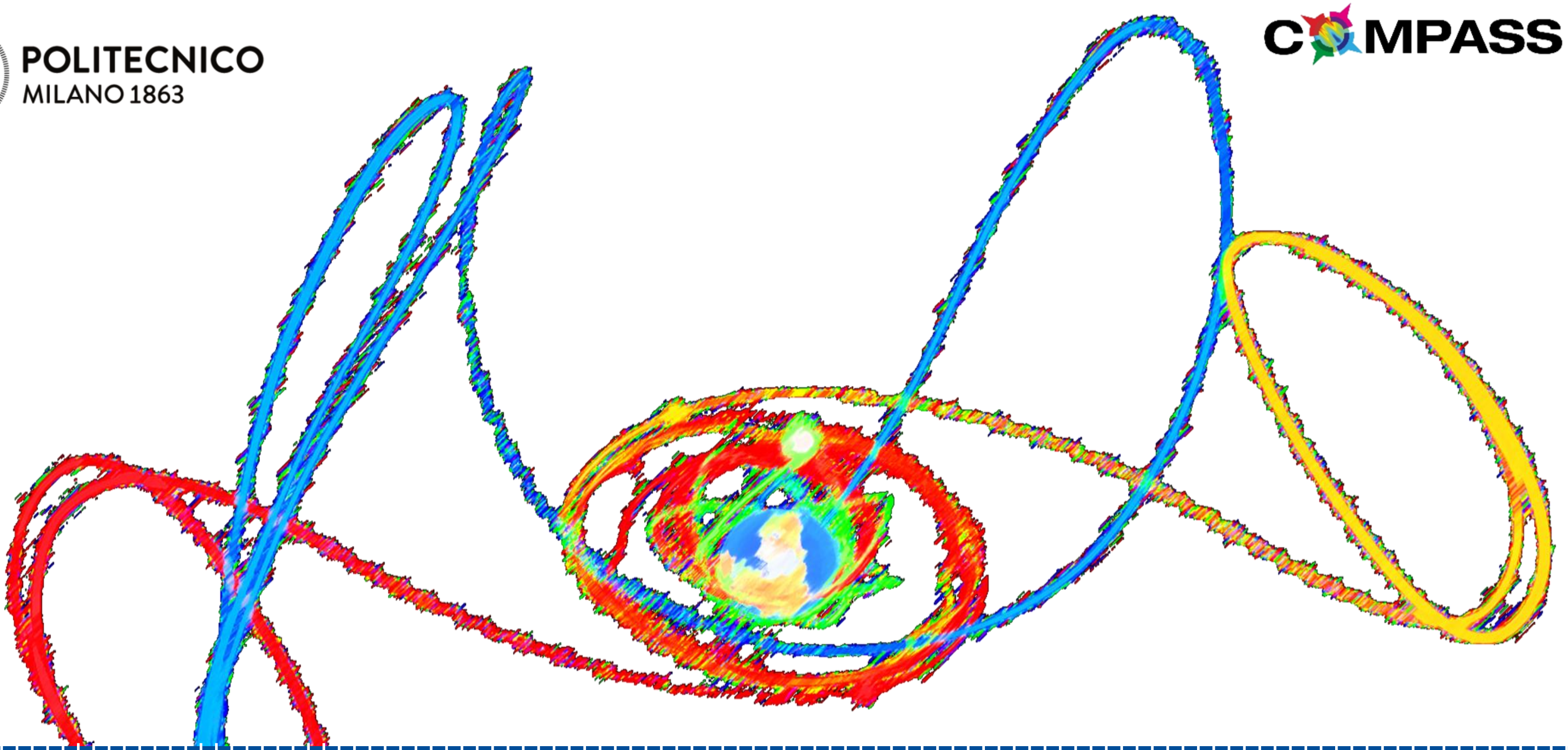


# Control for Orbit Manoeuvring through Perturbations for Application to Space Systems

Camilla Colombo, Politecnico di Milano
Email: camilla.colombo@polimi.it

Beijing Institute of Technology – 02 November 2017

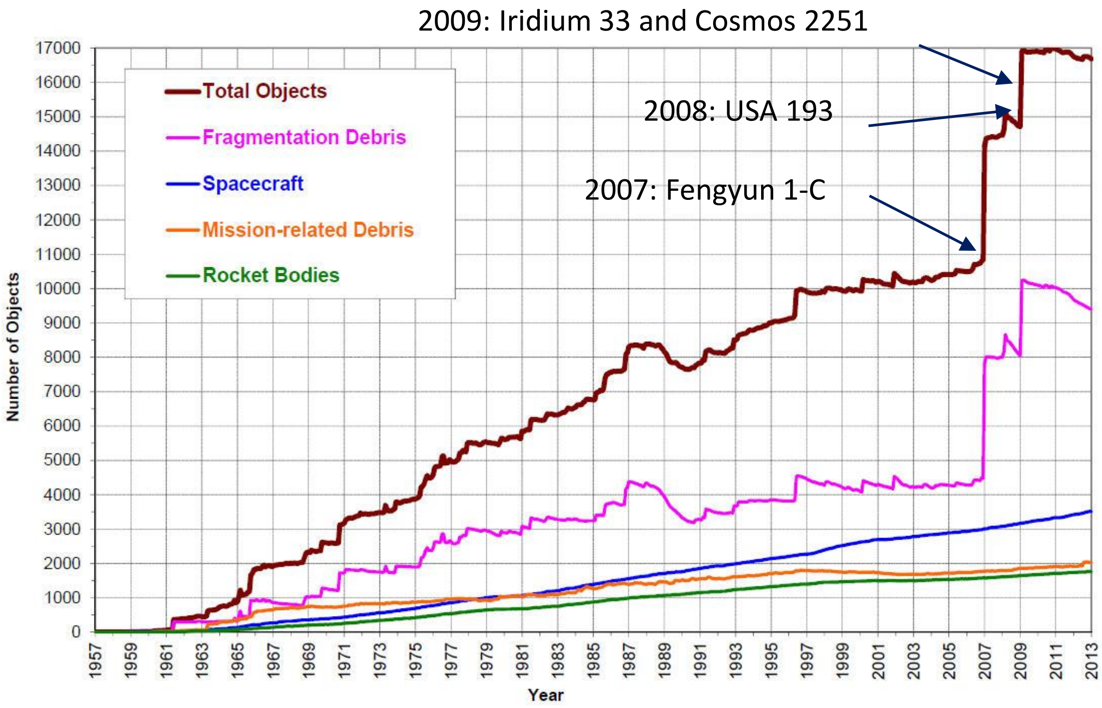
# INTRODUCTION

# Introduction

## Space situation awareness

Space debris poses a threat to current and future space activities

- Currently 22000 objects > 10 cm and 500000 objects > 1-10 cm
  Breakups generate clouds of fragments difficult to track
- Fragments can collide at very high velocity and damage operating satellites
- Need to define debris mitigation guidelines and collision avoidance manoeuvres



2009: Iridium 33 and Cosmos 2251

2008: USA 193

2007: Fengyun 1-C

# Introduction

## Planetary protection

- On average a 10-km-sized asteroid strikes the Earth every 30-50 million years (globally catastrophic effects)
- Tunguska class (100 m in size) asteroid impact every 100 years (locally devastating effects)
- Very small asteroids are very frequent but generally burn in the atmosphere
- Spacecraft and launcher for interplanetary missions remain in resonance with the Earth and other planets, planetary protection requirements to be verified


Chelyabinsk, Russia (2013), 17-30 m diameter asteroid


Tunguska, Siberia (1908), flattening 2000 km$^2$ of forest, 50-70 m asteroid

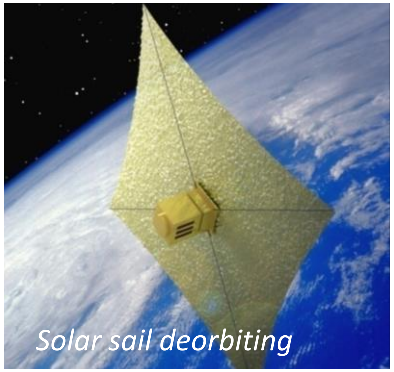

Breakup of the object WT110F during re-entry (November 2015)

# Introduction

## Space transfer

Space transfer allows the colonisation of new habitats and reaching operational orbits for science missions and space services.

- Trajectory design and orbit maintenance are a challenging task
- New Space development towards great number of small satellite for distributed services (e.g. large-constellation, nano and micro satellites)
- As enabling technology, electric propulsion is increasingly selected as the primary option for near future missions, while novel propulsion systems for de-orbiting and orbit-raising are being proposed (e.g., solar sailing).
- Natural dynamics can be leveraged to reduce the extremely high mission cost.



*Solar sail deorbiting*

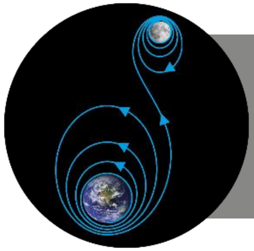
*Large constellations*
*Credit: Airbus video still*

*Credit: The University of Michigan*

# Background and proposed approach

Services, technologies, science, space exploration

SPACE TRANSFER



Reach, control operational orbit

SPACE SITUATION AWARENESS

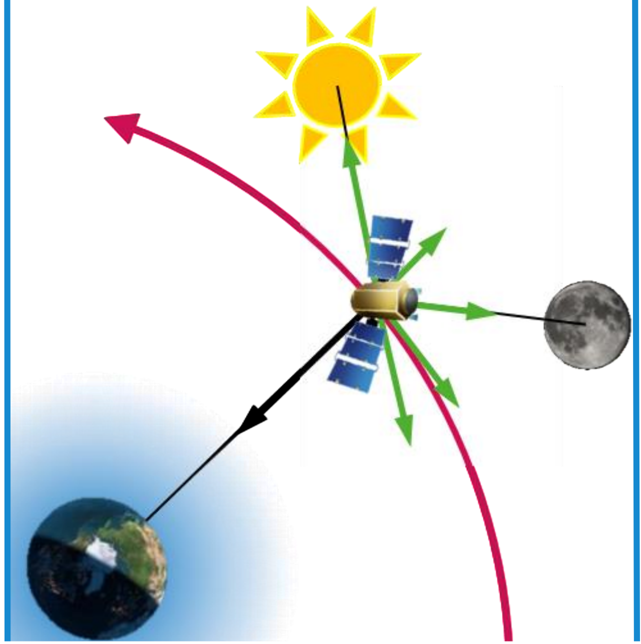
Asteroids. Planetary protection

Space debris

## ORBIT PERTURBATIONS

Traditional approach: counteract perturbations

- Complex orbital dynamics
- Increase fuel requirements for orbit control



## COMPASS

Novel approach: leverage perturbations

Reduce extremely high space mission costs

Create new opportunities for exploration and exploitation

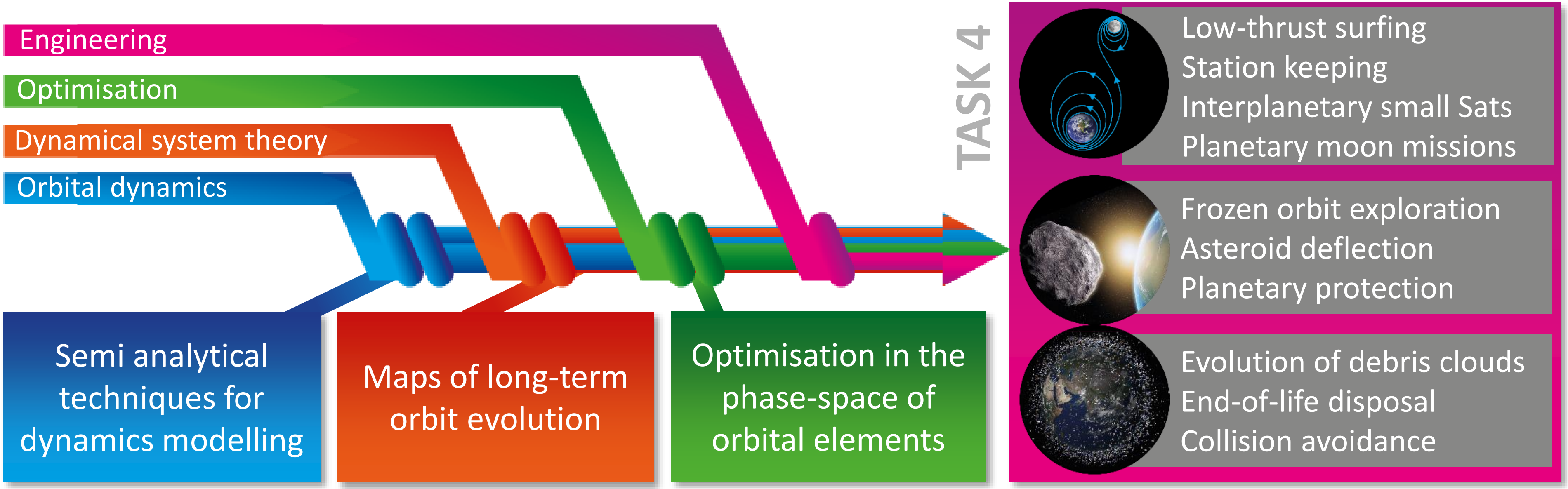
Mitigate space debris

Develop novel techniques for orbit manoeuvring by surfing through orbit perturbations

# METHODOLOGY

# Methodology and expected results

COMPASS erc



Engineering

Optimisation

Dynamical system theory

Orbital dynamics

TASK 4

Semi analytical techniques for dynamics modelling

Maps of long-term orbit evolution

Optimisation in the phase-space of orbital elements

- Low-thrust surfing
- Station keeping
- Interplanetary small Sats
- Planetary moon missions

- Frozen orbit exploration
- Asteroid deflection
- Planetary protection

- Evolution of debris clouds
- End-of-life disposal
- Collision avoidance

TASK 1

TASK 2

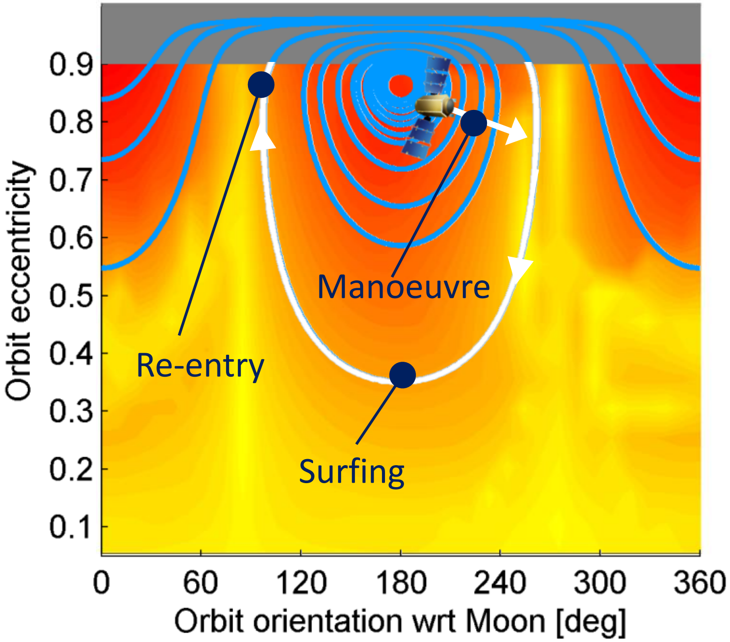
TASK 3

T1. Understanding of the spacecraft/space debris/asteroid orbit evolution in the planetary/interplanetary environment

T2. Topology of space of orbit perturbations (stability, resonances, equilibria)

T3. Spacecraft/space debris/asteroid surfs these natural currents to the desired orbit (control of dynamics)

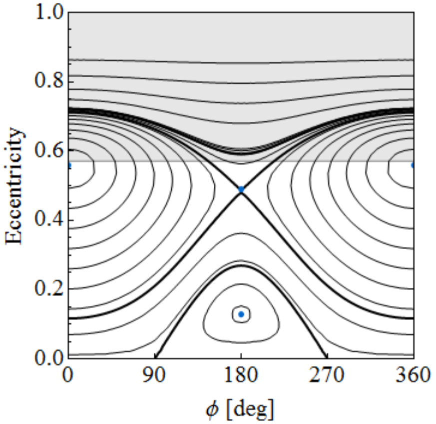
T4. Design of space missions: understanding of the dynamics, optimisation, application to space mission



# Task 1. Orbit perturbation modelling

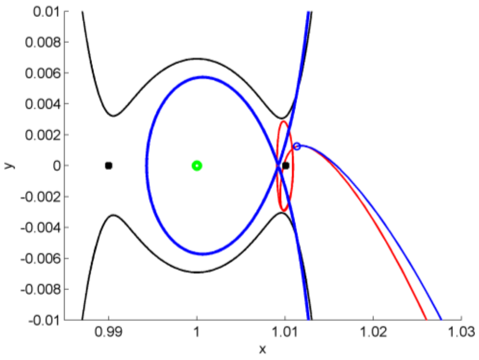
## Understanding the spacecraft orbit evolution

- Semi-analytical techniques to understand effects of natural and artificial orbit perturbations
  - in planetary systems (solar radiation pressure, aerodynamic drag, third-body effect, non-uniform gravity potential, Lorentz force etc.)
  - in interplanetary space (resonances, close approaches)
  - artificial manoeuvres (low-thrust propulsion, impulsive manoeuvres, solar sails, etc.)



*Solar radiation pressure and Earth's oblateness*

- Surrogate models with dynamics system theory
  - semi-analytical single and double-averaging techniques
  - manifold dynamics
  - domain of application of simplified models

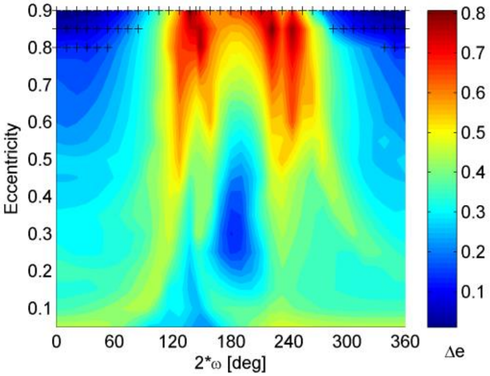


*Three-body problem*

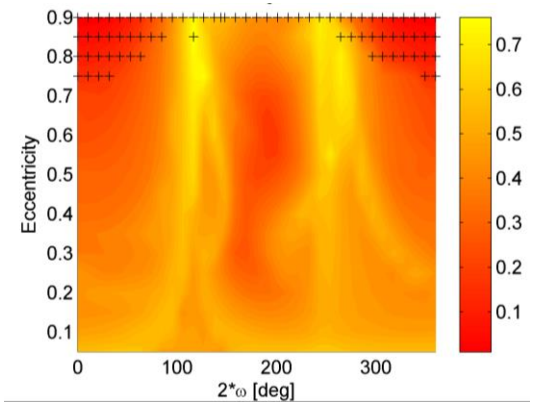
# Task 2. Maps of long-term evolution

## Topology of space of orbit perturbations

- Coordinate transformation
  - variables choice and formalism, normal forms
  - dynamics in the phase space
  - b-plane representation
- Perturbation analysis
  - frequency analysis for autonomous on-board orbit prediction
  - dynamic indicators for orbital/attitude chaotic region definitions
  - high order expansions techniques with averaged dynamics
- Perturbation maps and dynamics maps



*XMM-Newton orbit evolution*



*INTEGRAL orbit evolution*

# Task 3. Optimisation and control

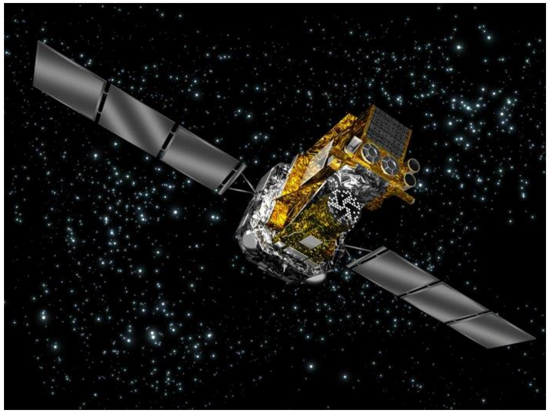
## Trajectory design through perturbation and artificial manoeuvres

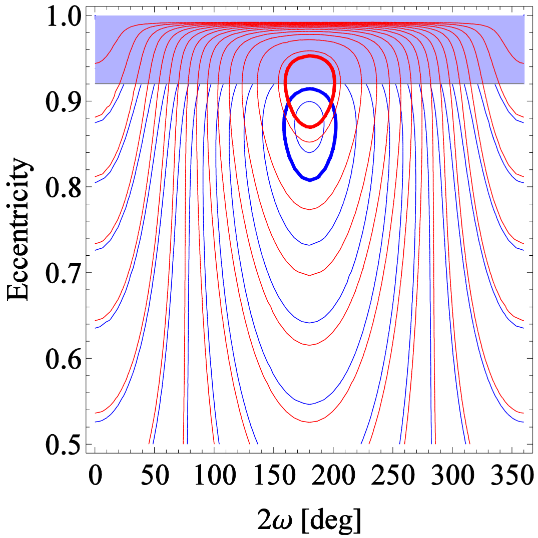
- Phase-space global optimisation (naturally or artificially perturbed trajectories)
  - multiple singular events (e.g., impulsive manoeuvres, gravity kicks)
  - multi-scale dynamics (i.e., escape and capture phases)
  - optimisation in the phase-space
- Phase-space local optimisation
  - continuation techniques
  - direct and indirect methods and hybrid techniques
- Blended optimisation
  - solution on different levels
  - automatic blending of dynamical models
  - optimiser explores the phase space and progressively learn its structure

# Concept demonstration

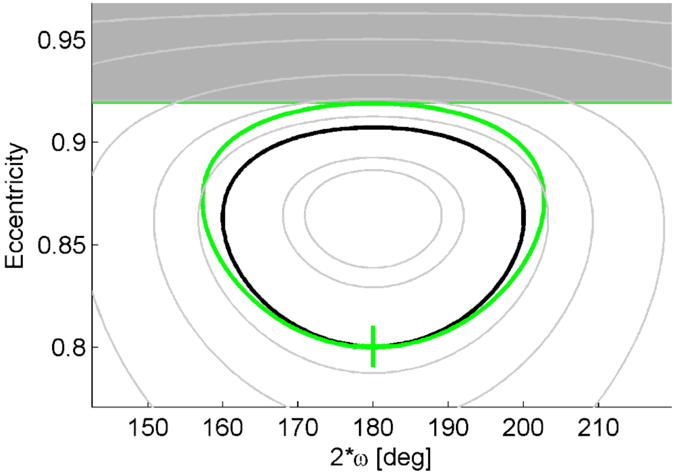
## Perturbation enhanced end-of-life design of INTEGRAL mission

- Astrophysics and astronomy missions (e.g., INTEGRAL)
- Very complex dynamics under the effects of Moon and Sun perturbation and Earth's oblateness
- End-of-life disposal with limited amount of propellant





*Orbit phase-space evolution*



*Trajectory design in the phase space*

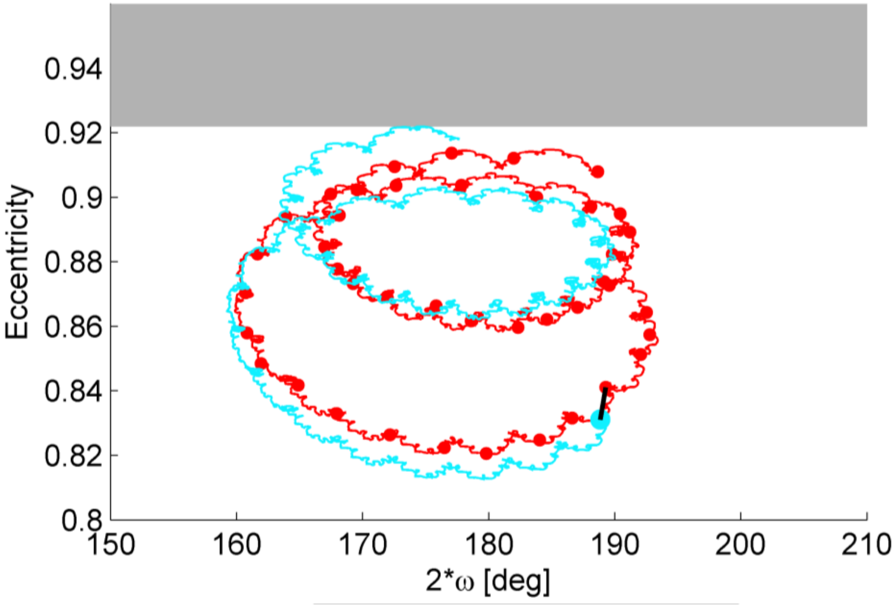
# Concept demonstration

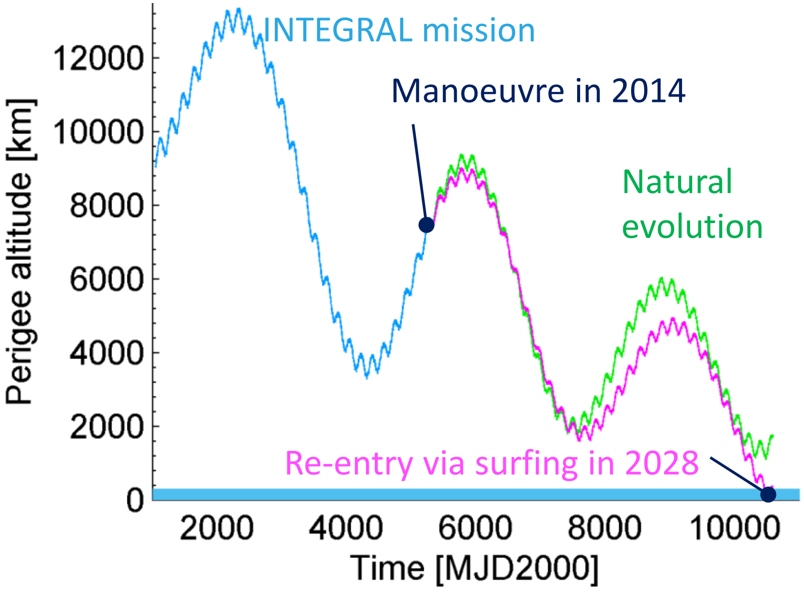
## Perturbation enhanced end-of-life design of INTEGRAL mission

Optimised solution

- Moon + Sun + $J_2$
- Single averaged dynamics + global optimisation

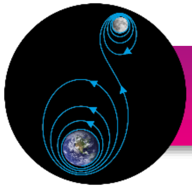
Luni-solar perturbation surfing made re-entry of INTEGRAL mission possible





Space transfer

# MISSION APPLICATIONS



Space transfer

# Interplanetary trajectory design

## Combined phase-energy solution for interplanetary trajectory with fly-by

### Background

- Interplanetary mission for Mars colonisation, exploration (Europa, Titan, Enceladus, Triton), asteroid exploration (main asteroid belt and Kuiper belt)
- Variety of tools for preliminary trajectory design

### Aim

- Integrate phasing analysis (Lambert problem) with energy-based methods (Jacobi constant) into a unique approach
- Refinement of the trajectory in the circular-restricted three body problem
- Design through trajectory maps

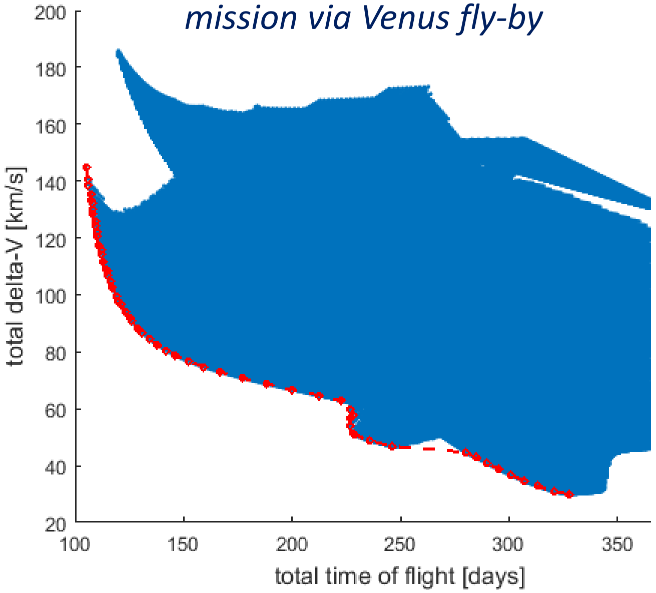
# Interplanetary trajectory design

## Combined phase-energy solution for interplanetary trajectory with fly-by

### Preliminary design

- 2-body problem with patched conic approximation for estimation of the Δ*v:* Lambert problem solution in the rotating synodic frame
- Tisserand criterion for refinement in the circular restricted 3-body problem and $v_\infty$ estimation

*Pareto front for Earth-Mars mission via Venus fly-by*



### Trajectory refinement

- Optimisation based on minimisation of the energy jump (i.e. Tisserand parameter) due to the Δ*v* manoeuvre at fly-by

$$\overline{T_b} = \frac{1}{\overline{a_b}} + 2\sqrt{\overline{a_b}(1-e_b^2)} + 2\mu^*\left(-\frac{1}{r_1} + \frac{1}{r_2}\right)$$

- Local numerical optimisation convergency improved with energy-phase method

Space transfer

# Spacecraft constellation design

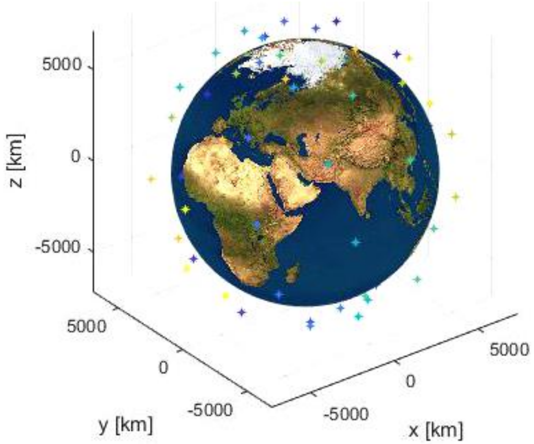
## Optimisation of constellation geometries for space-based applications

### Background

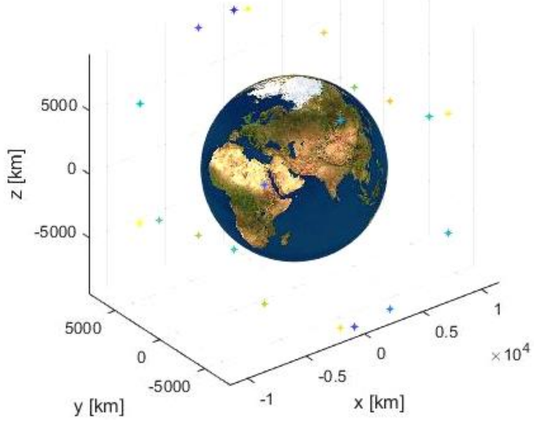
- Recent advances in satellite constellations for surveillance, communication, navigation and positioning, defence.
- Large Constellation plans for global internet (i.e. OneWeb, Samsung, SpaceX etc.)

### Aim

- Comparative assessment of different constellation geometries for space-based applications
- Multi-objective optimisation for optimal geometry design for given mission



*IRIDIUM constellation*



*GPS constellation*

Space transfer

# Spacecraft constellation design

## Optimisation of constellation geometries for space-based applications

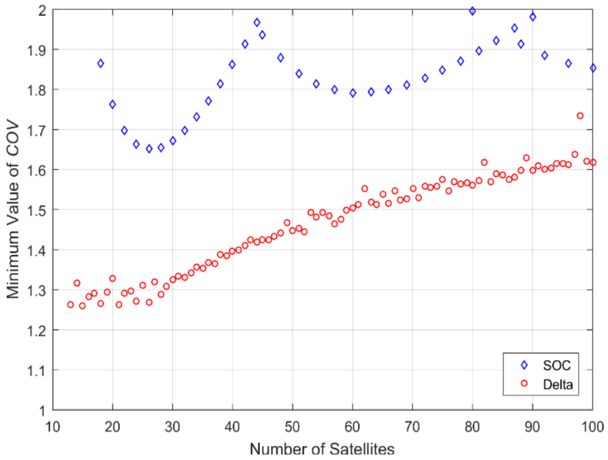
### Constellation geometry design

- Parameters: number of orbital planes, relative inter-plane phase angle, inclination, angular radius of coverage circle, elevation angle
- Two constellation pattern analysed: Street-of-Coverage (SOC) pattern, Delta pattern

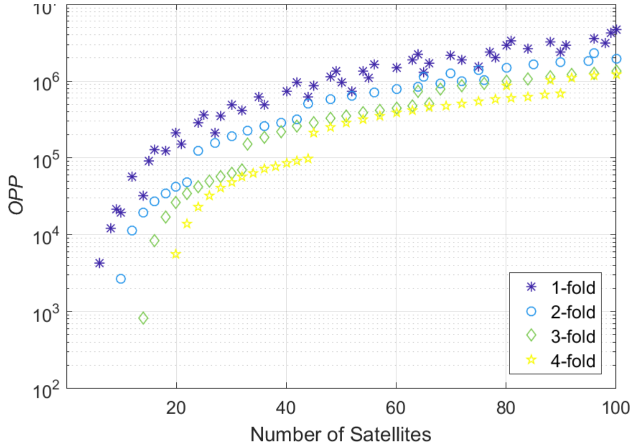
### Optimisation of constellation design

- Coverage: excess coverage
- Launchability: Inclination of s/c and launch site
- Robustness: mean value of coverage percentage
- Constellation build-up: number of orbital planes
- Stationkeeping: $\Delta v$ budget for altitude maintenance
- Collision avoidance: collision opportunities per year, minimum angular separation
- End-of-life disposal: $\Delta v$ budget for de-orbiting

*Excess coverage for 4-fold constellation*



*Collision opportunities for SOC pattern*



Space transfer

Space debris

# MISSION APPLICATIONS

Space debris

# Debris fragment evolution

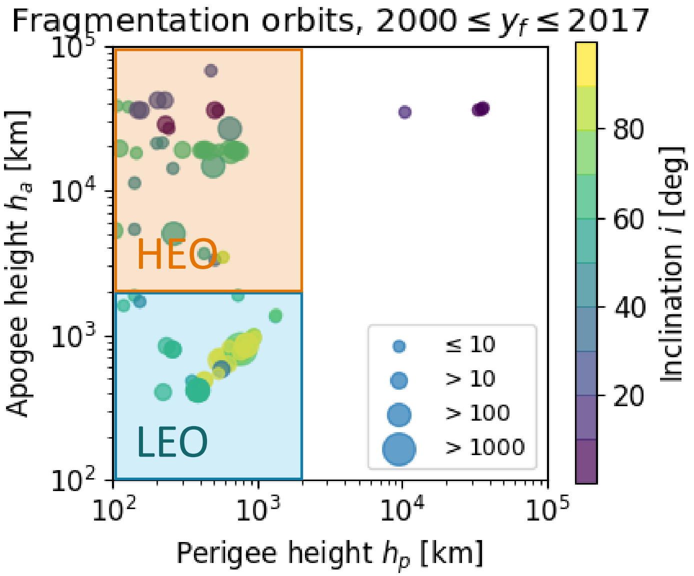
## Evolution and collision risk of debris clouds via a density-based approach

### Background

- 90 satellites and upper stages fragmented since 2000 alone
- Debris fragments subject to a multitude of perturbations
- Need to predict collision risk with active missions especially in LEO

### Aim

- Cloud model based on the evolution of fragment density in the space of orbital elements
- Collision risk calculation
- Index for orbiting spacecraft to describe interaction with space debris



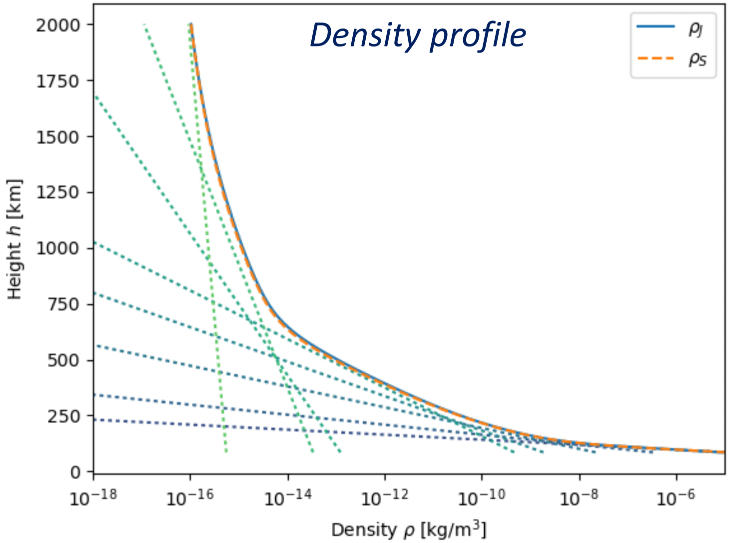
*On orbit fragmentations between 2000 and 2017*

# Debris fragment evolution

## Evolution and collision risk of debris clouds via a density-based approach

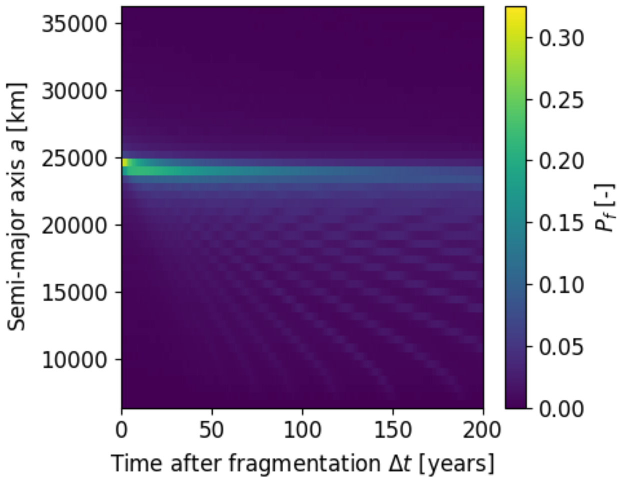
### Cloud evolution model

- NASA’s break-up model to give initial fragment distribution
- Smooth exponential atmosphere model and improved semi-analytical method
- Gridding method in the phase space



### Quickly assessment of

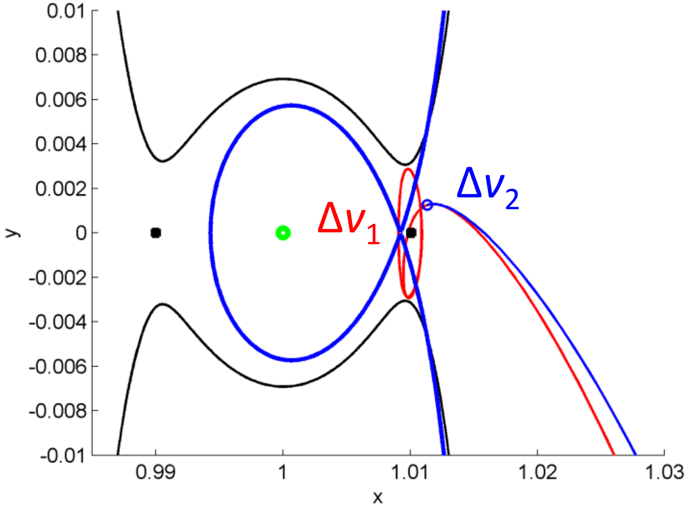
- Time of band closure for distinguishing cloud evolution phases (i.e. cloud occupies orbit → ring → band)
- Fragment evolution in the orbital element space



*Evolution of fragment cloud in GTO*

# End-of-life disposal trajectory design

## Lagrangian point mission end-of-life disposal

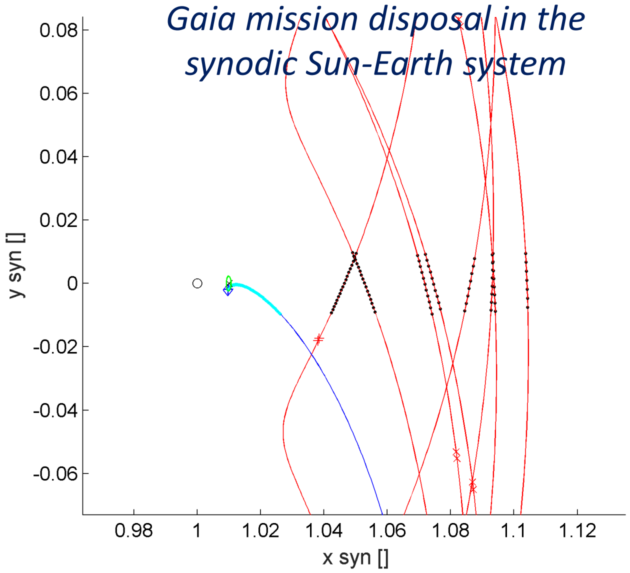


### Aim

- End-of-life trajectory design for missions at the Lagrangian point
- Study of re-entry conditions
- Study of resonances

### Design approach

- Energetic method based on the analysis of the Jacobi integral
- Manoeuvre sequence optimisation in the rotating *n*-body problem
- Mission application to Gaia and Lisa Pathfinder missions



*Gaia mission disposal in the synodic Sun-Earth system*

# End-of-life disposal trajectory design

## Solar sail end-of-life deorbiting

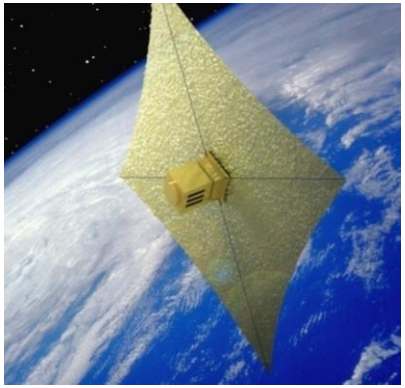
### Solar sail deorbiting

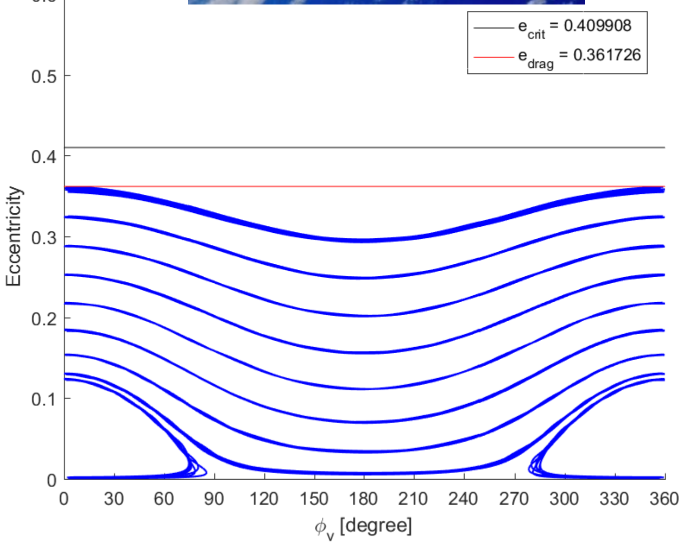
- Solar sail for end-of life deorbiting in Earth centred orbit
- Novel technique for solar sailing to maximise deorbiting effect

### Method

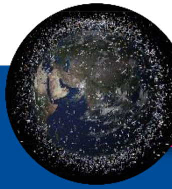
- Study of the orbit evolution in the phase space considering Earth’s oblateness, atmospheric drag and solar radiation pressure
- Definition of sailing law for quasi-passive end-of-life deorbiting via long-term modulation of solar radiation pressure

*Solar sailing deorbiting*





*Phase space: SRP, J2 and atmospheric drag, propagation over 45 years, $i_0$ = 10 deg, $a_0$ = 11000 km*



## Planetary protection

# MISSION APPLICATIONS

Planetary protection

# Planetary protection analysis

## Evolution and collision risk of debris clouds via a density-based approach

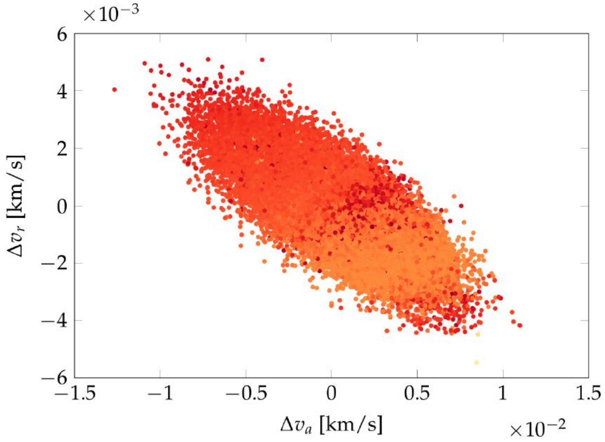
### Background

- Interplanetary missions must satisfy planetary protection requirements (no biological contamination of sensible scientific planets, i.e. Mars, Europa, etc.)
- Uncertainty in the orbit propagation due to launcher injection error, uncertain spacecraft design parameters, propulsion system failure

### Aim

- Develop tools for *n*-body propagation over 100 years
- Verification of planetary protection requirements of European Space Agency missions

*Breakup of the object WT110F during re-entry (November 2015)*



- *Letizia et al.*
*Miss-distance resulting from launcher inection error*

Planetary protection

# Planetary protection analysis

## Evolution and collision risk of debris clouds via a density-based approach

### Numerical integration

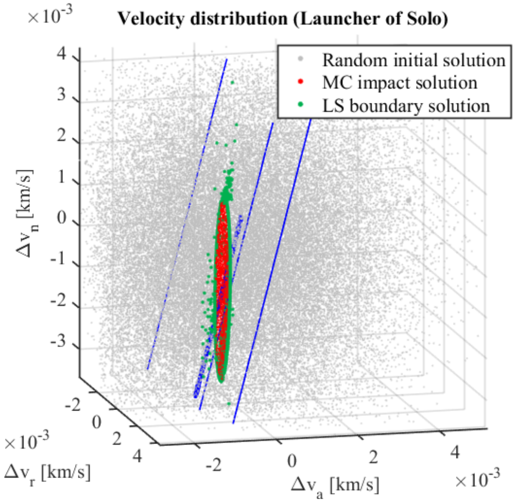
- Understand how the errors in a single propagation may affect planetary protection verification
- Development of symplectic and energy-preserving methods

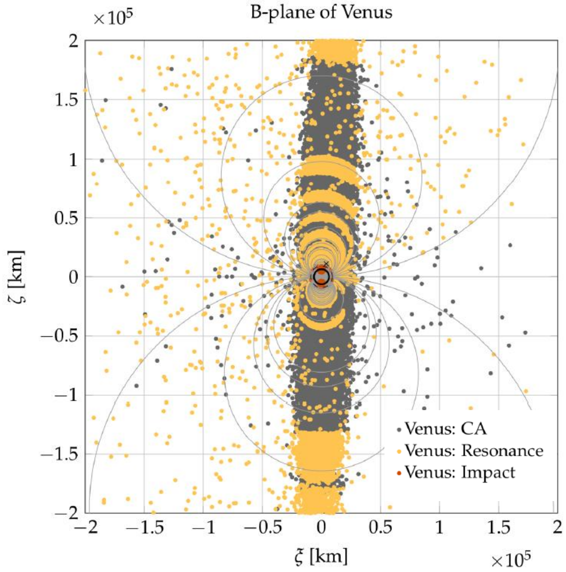
### Sampling of the uncertainty domain

- Efficient methods to sample the initial dispersion (i.e. line sampling and subset decomposition)
- Comparison with traditional Monte Carlo approach

### Representation

- B-plane analysis of impact and resonance conditions



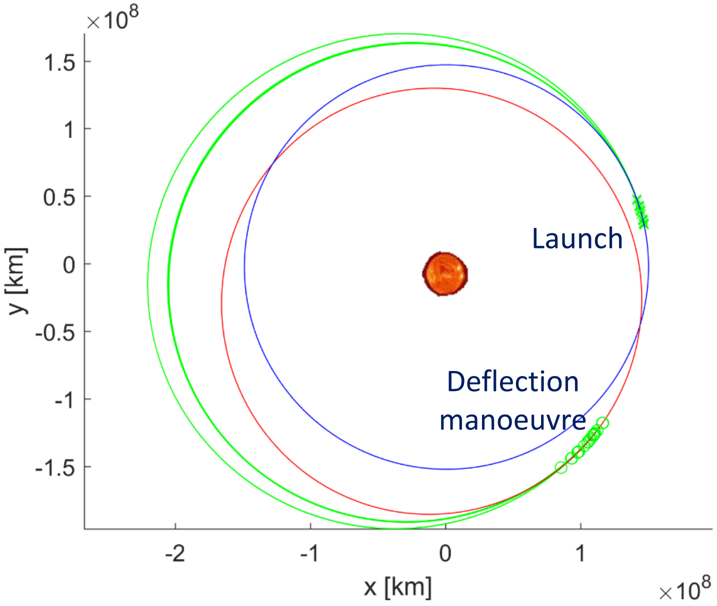


➢ *Letizia et al.: representation of the worst close approaches for the 1000 Monte Carlo runs of the launcher of Solo on the b-plane of Venus.*

# Planetary protection

## Reference missions for different NEA threat scenarios

- Prepare a response to an Near Earth Asteroid (NEA) impact threat scenario
- Study mission design for NEA deflection mission
- Consider a diversity of cases: asteroids have different orbit and physical properties
- Study of selected case for direct and resonant encounter
- Design of robust deflection manoeuvre
  - Uncertainties on asteroid characteristics
  - Uncertainties on orbit determination and manoeuvre error



*Direct deflection mission to 2010RF12*

# CONSLUSION

# Conclusions

## Contributions

- Beauty: Understanding of perturbations dynamics
- Novelty: Surf by exploiting natural disturbances (Problem into opportunity)
- Impact: Perturbation-enhanced mission design

# Research team

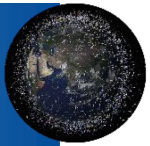
COMPASS erc *

ReDSHIFT European Commission +

POLITECNICO
MILANO 1863
DIPARTIMENTO DI
SCIENZE E TECNOLOGIE AEROSPAZIALI

**PI Camilla Colombo**

**Ioannis Gkolias +**
Postdoc:
Orbit perturbations

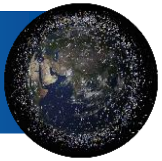


**Simeng Huang ***
PhD: Large constellations

**Postdocs**

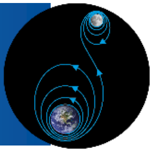
- Applied maths
- Computer science
- Engineering

**Stefan Frey ***
PhD: Space debris



**Matteo Romano ***
PhD Planetary protection

**Davide Menzio ***
PhD: Space transfer



## Scientific Advisory Board

esa European Space Agency

NASA

Italian Space Agency

cnes Centre National d'Études Spatiales

JAXA Japan Aerospace Exploration Agency

# Collaborations

## COMPASS project

项目负责人: Camilla Colombo

基金：150万欧元

- 欧洲研究基金启动金

研究目的：

- 降低航天任务成本
- 为空间探测及应用提供新的技术支持
- 减少空间碎片

应用：

- 空间碎片
- 小行星任务
- 星座
- 小卫星
- 星际 & 行星小推力轨道

PI: Camilla Colombo

Funding: 1.5M€ European Research Funding Start Grant

Aim:

- Reduce high space mission costs
- Create new opportunities for space exploration and exploitation
- Mitigate space debris

Applications:

- Space debris
- Asteroid missions
- Constellation
- Small satellites
- Interplanetary & planetary trajectories with low thrust

# Collaboration

## COMPASS project

合作与机遇：

- 非欧盟地区学者
- 博士&博士后
- European Research Council and 中国国家自然科学基金

Collaboration:

- Non-European researcher
- PhD, Post Doc and researchers
- European Research Council and Chinese National Natural Science Foundation

For info see:

https://erc.europa.eu/sites/default/files/document/file/agreement_ERC_NSFC_zh.pdf

https://erc.europa.eu/sites/default/files/document/file/agreement_ERC_NSFC_en.pdf

http://www.nsfc.gov.cn/publish/portal0/tab87/info51450.htm

Moreover:

PhD @PoliMi by Chinese State Scholarship Fund