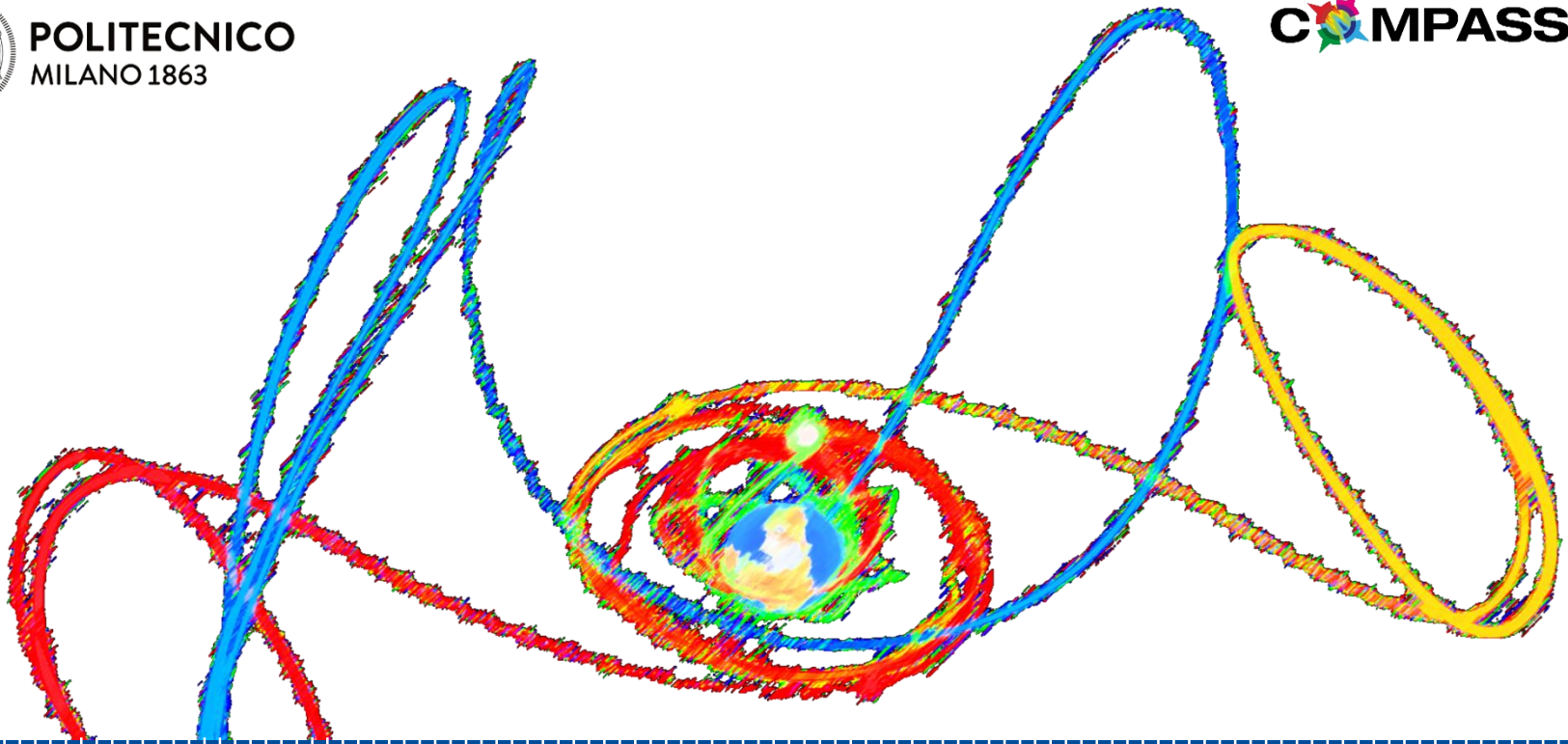




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**COMPASS**



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

Camilla Colombo and COMPASS team

Politecnico di Milano

*International Astronautical Congress 2018, Bremen*



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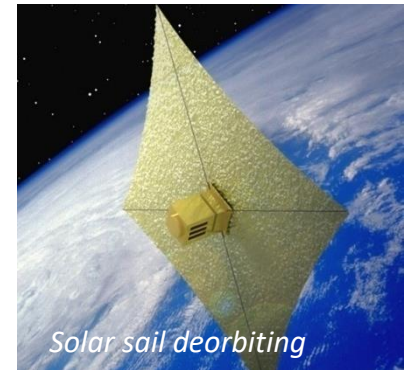
# INTRODUCTION

# Introduction

## Space transfer

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

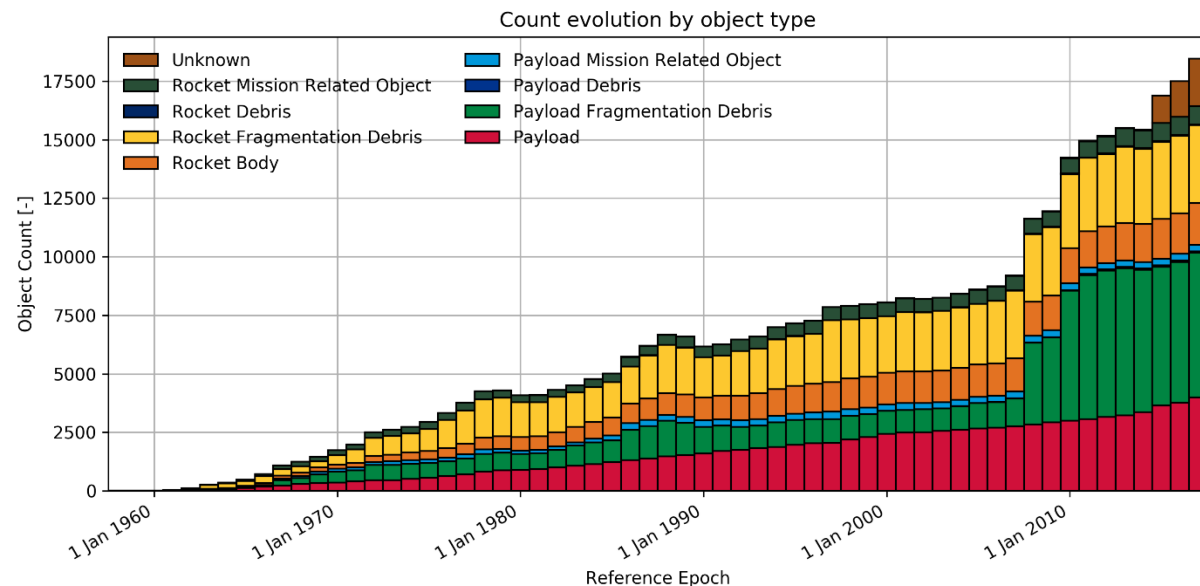
- **Trajectory design** and orbit maintenance are a challenging task
- **New Space development** towards great number of small satellites for distributed services (e.g. large-constellation, nano and micro satellites)
- As enabling technology, **electric propulsion** is increasingly selected as the primary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



## Space situation awareness: space debris

Space debris poses a threat to current and future space activities

- Currently 33000 objects > 10 cm and 600000 objects > 1-10 cm  
Breakups generate clouds of fragments difficult to track
- **Fragments** can collide at very high velocity (7-10 km/s) and damage operating satellites
- Need to define debris **mitigation guidelines** and collision avoidance manoeuvres



Artificial space object number from ESA Debris report 2018

## Space situation awareness: asteroid missions and asteroid deflection

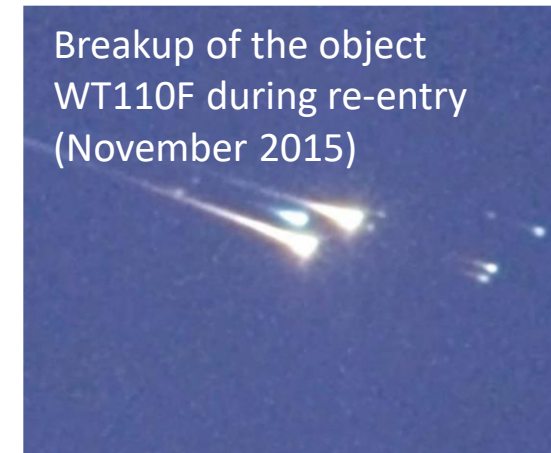
- On average a 10-km-sized asteroid strikes the Earth every 30-50 million years (globally catastrophic effects). Tunguska class (100 m in size) asteroid impact every 100 years (locally devastating effects)
- Near Earth Asteroids can be a **threat** but also an **opportunity** for science and material utilisation
- This is enabled by mission to asteroids and demonstration mission for asteroid deflection



## Space situation awareness: planetary protection

Humans now routinely venture beyond Earth and send spacecraft to explore other planets.

- **With this extraordinary ability comes great responsibility:** do not introduce terrestrial biological contamination to other planets and moons that have potential for past or present life
- For interplanetary missions and missions at Libration Point Orbit, **planetary protection analysis** need to be performed



# Background and proposed approach

Services, technologies,  
science, space exploration

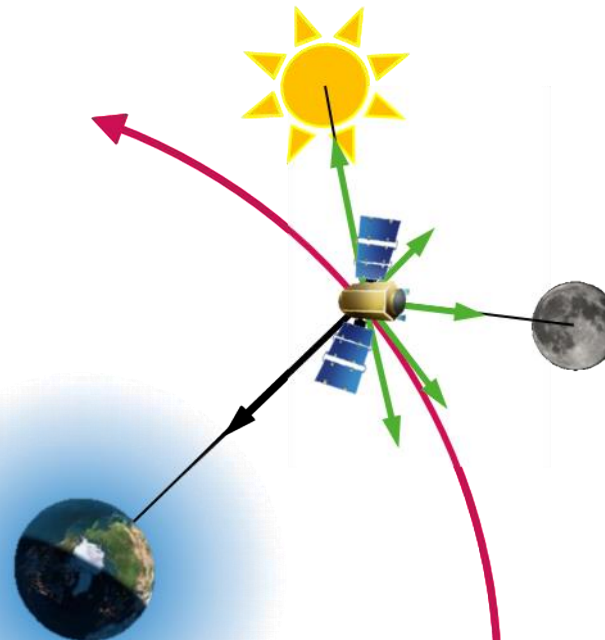
## ORBIT PERTURBATIONS

Traditional approach:  
counteract perturbations

## COMPASS

Novel approach:  
leverage perturbations

- Complex orbital dynamics
- Increase fuel requirements for orbit control

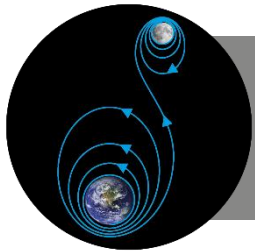


Reduce extremely high  
space mission costs

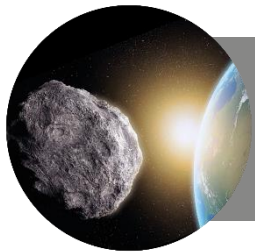
Create new opportunities for  
exploration and exploitation

Mitigate space debris

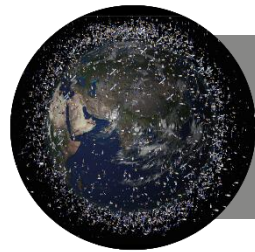
SPACE TRANSFER  
SPACE SITUATION AWARENESS



Reach, control  
operational orbit



Asteroids,  
planetary  
protection



Space debris

Develop novel techniques for orbit manoeuvring by surfing through orbit perturbations

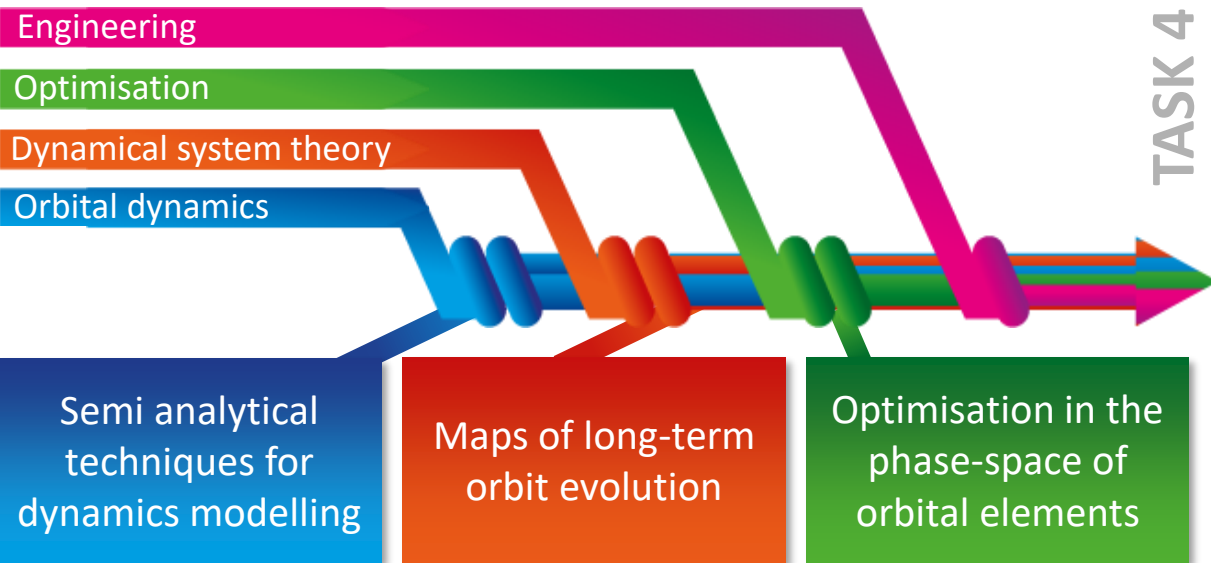


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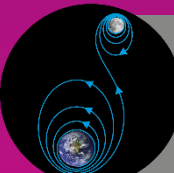



# METHODOLOGY


# Methodology and expected results



**TASK 4**

- 

Low-thrust surfing  
Station keeping, relative motion  
Planetary moon missions  
Small satellite missions
- 

Frozen orbit exploration  
Space-based detection  
Asteroid deflection
- 

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

## TASK 1

T1. Understanding of the spacecraft orbit evolution (planetary and n-body environment)

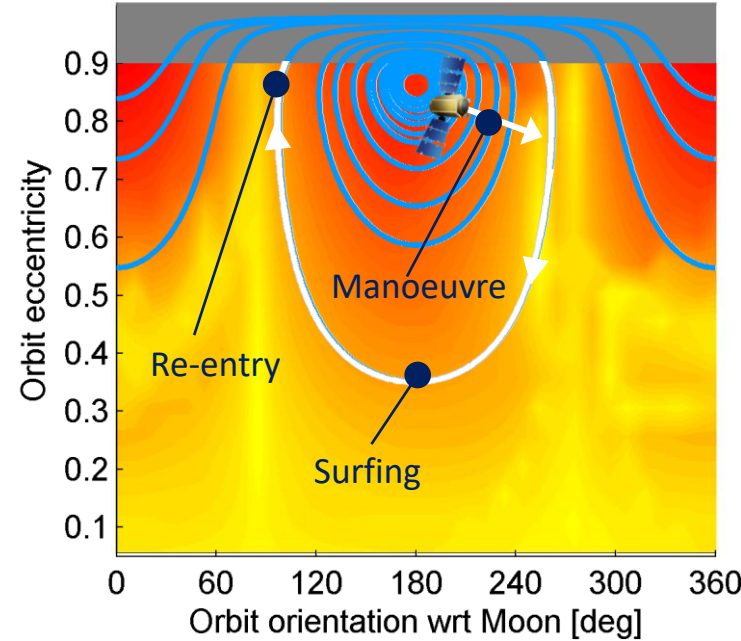
## TASK 2

T2. Topology of space of orbit perturbations and dynamics

## TASK 3

T3. Spacecraft surf these natural currents to the desired orbit

T4. Design of space missions and space applications





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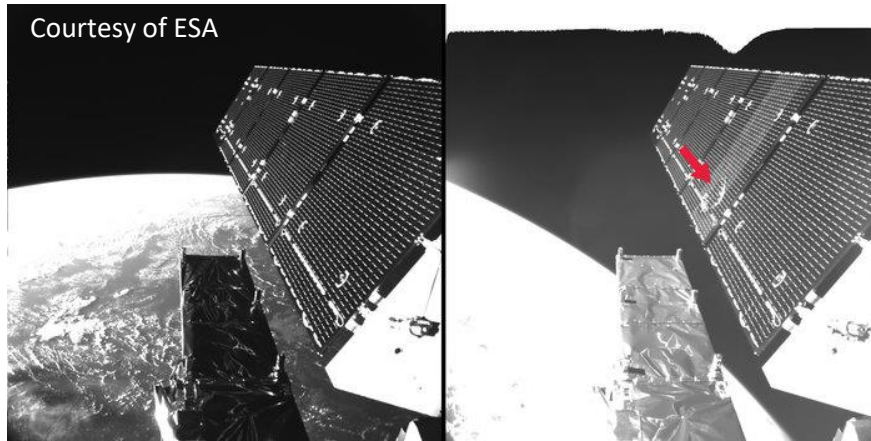
# MISSION APPLICATIONS

# Space debris

## And its danger

### Problem

How to model such a vast number of particles?



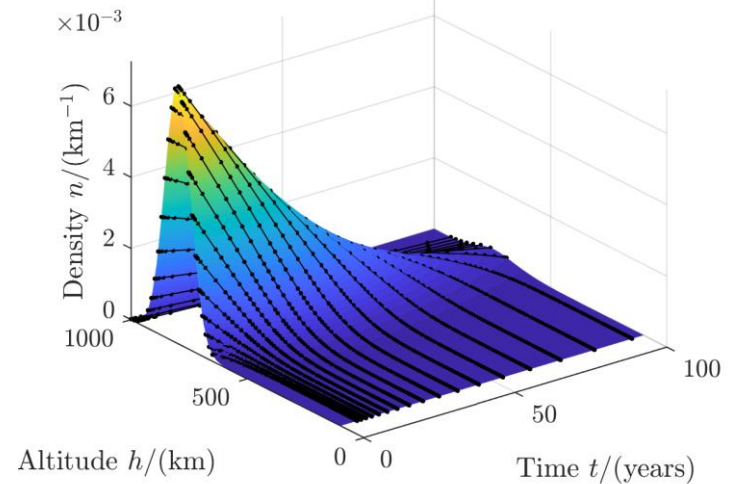
Impact crater from millimetre sized space debris on Sentiel-1A solar panel

➤ C. R. McInnes. An analytical model for the catastrophic production of orbital debris. *ESA Journal*, 1993.

### Model

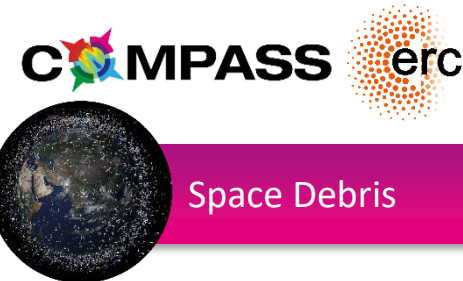
Model it as a continuum and propagate through the continuity equation

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{F}) = g$$



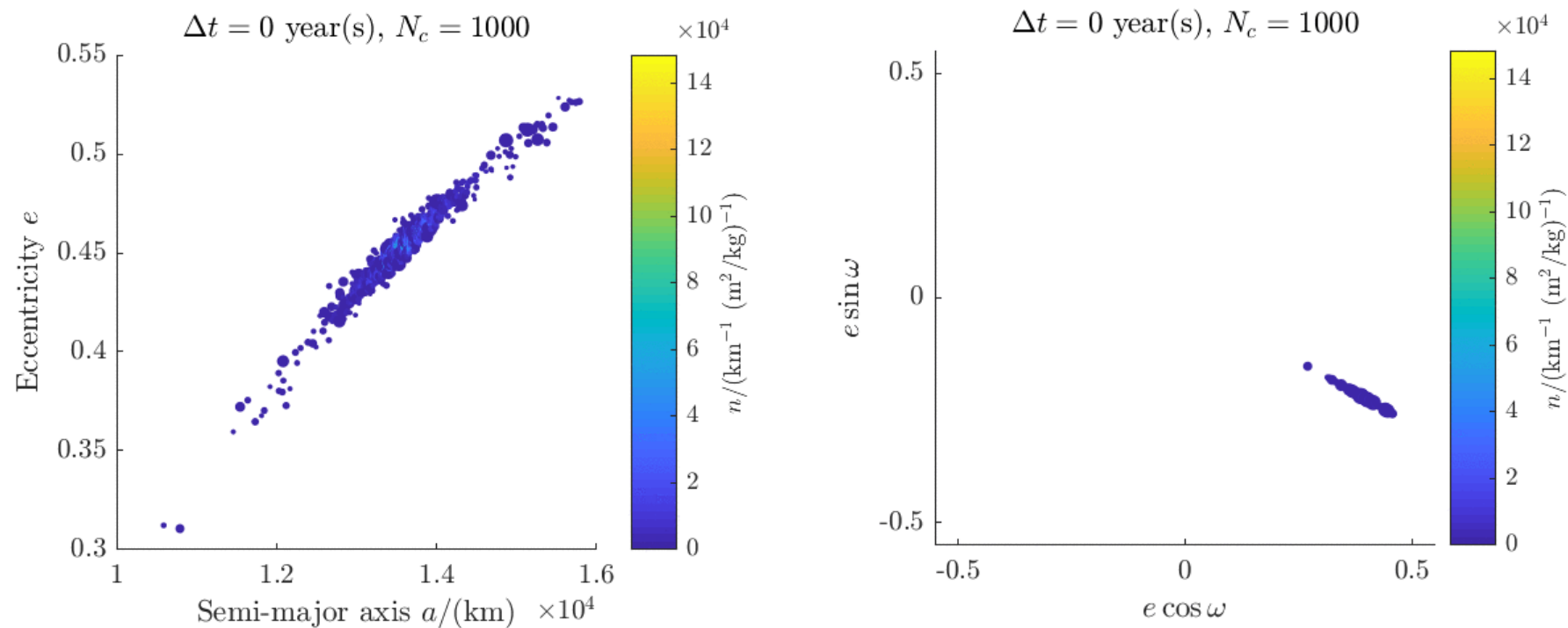
Density as a function of altitude and time, according to the continuity equation

# Space debris



## Evolution of a cloud of fragments in Molniya-type orbit

The characteristics of the system are perturbed by **solar radiation pressure**, **third bodies** – such as the Sun and the moon –, **Earth's oblate gravity field** and **atmospheric drag**.



➤ S. Frey et al. Evolution of Fragmentation Cloud in Highly Eccentric Earth Orbits through Continuum Modelling, Proceedings of the 69<sup>th</sup> IAC, 2018

# Re-entry prediction

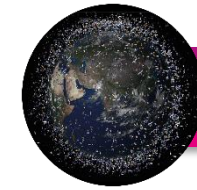
## Density-based approach

### Problem

- Propagation of re-entry uncertainties in the initial conditions and spacecraft parameters to predict spacecraft re-entries.
- Modelling of asteroids re-entries and the propagation of their fragments after break-up.

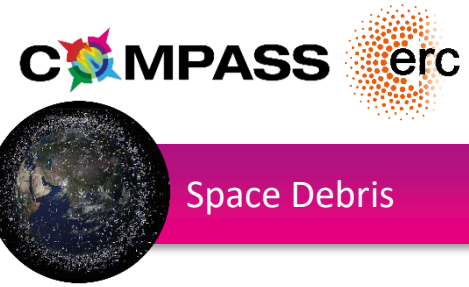
### Method

- Continuity equation together with the re-entry dynamics, the joint probability distribution function of the uncertainties is propagated
- The final uncertainties in the re-entry corridor, impact location, and casualty area are quantified



# Re-entry prediction

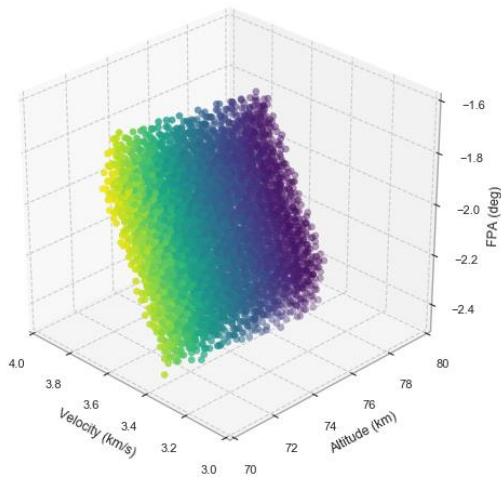
## Methodology example



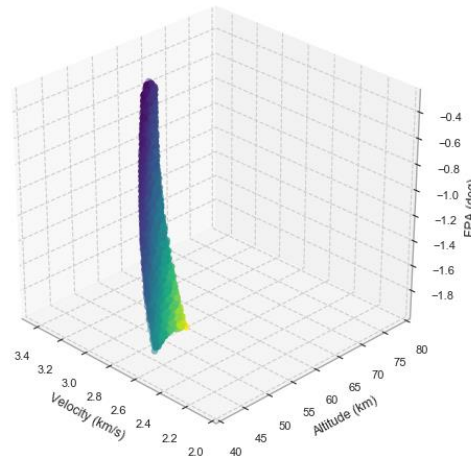
- Sampling of the initial distribution
- Numerical propagation of the density using the continuity equation
- Reconstruction of the 3D density and of the marginal densities



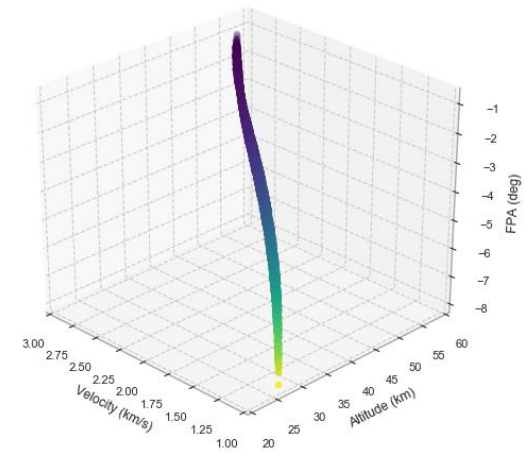
Compute the casualty area on ground



Density distribution at t=10 s



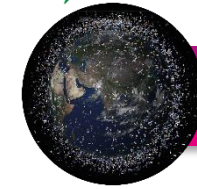
Density distribution at t=120 s



Density distribution at t=200 s

# Disposal design

## Disposal design for distant Earth orbits



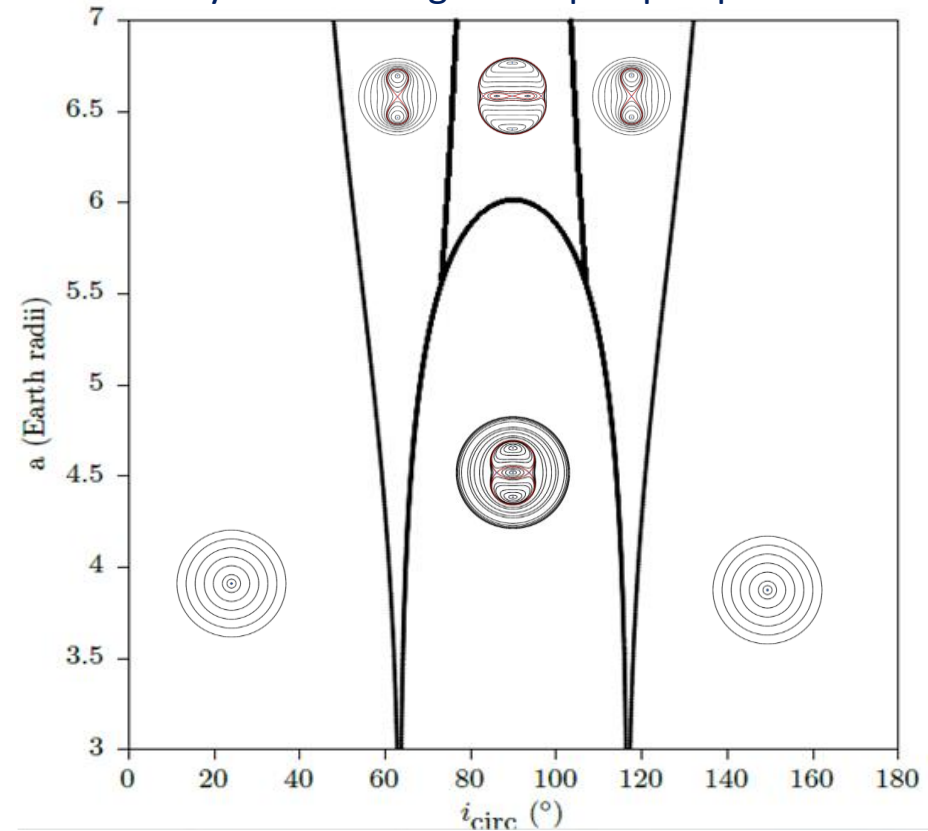
### Problem

Provide efficient disposal scenarios for distant Earth satellites

### Methods

- Averaging techniques
- Analytical modelling
- Semi-analytical propagations

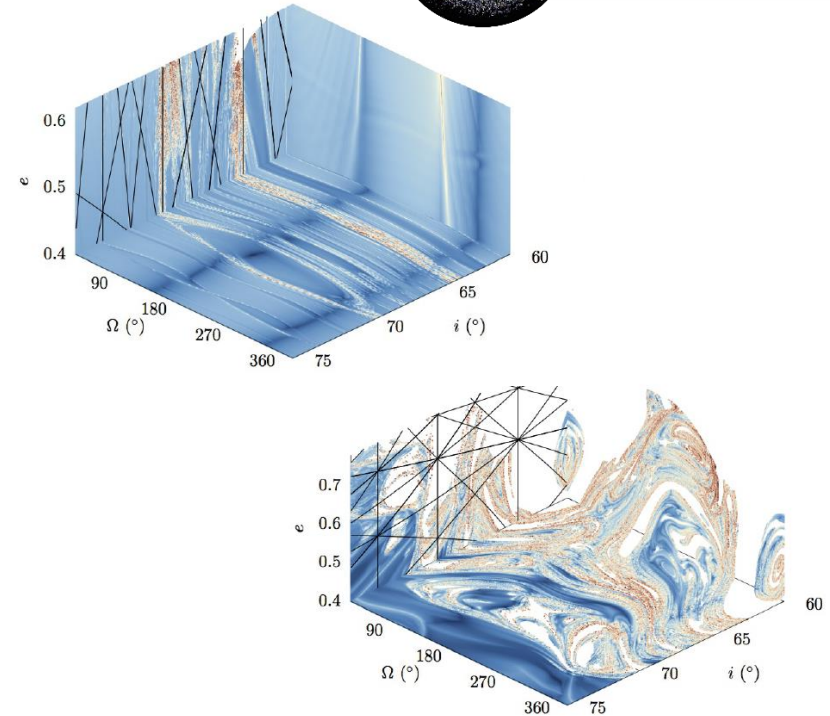
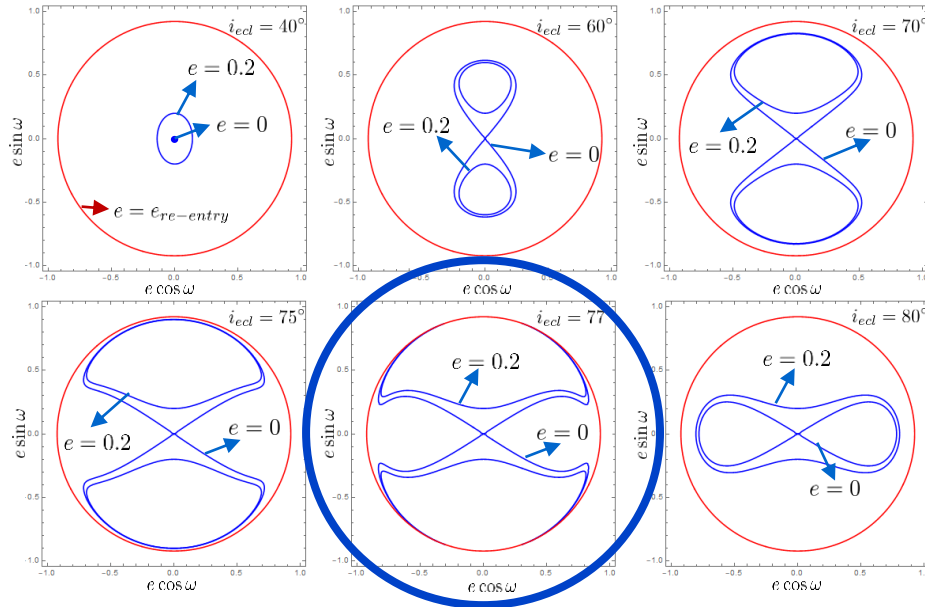
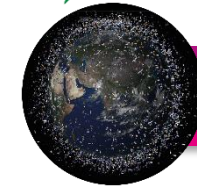
Analytical modelling of distant Earth satellites' dynamics using an ecliptic perspective



➤ I. Gkolias, M. Lara, C. Colombo, "An ecliptic perspective to analytical satellite theories", AAS-18-370, Proceedings of the AIAA/AAS Astrodynamic Specialist Conference, AIAA/AAS Snowbird, Utah, 2018

# Disposal design

## Disposal design for distant Earth orbits



Exploitation of the analytical modelling in the design of end-of-life disposal manoeuvres at GEO altitude

Study of the diffusive behaviour in Medium Earth Orbits due to lunisolar resonances

- I. Gkolias, M. Lara, C. Colombo, "An ecliptic perspective to analytical satellite theories", AAS-18-370, Proceedings of the AIAA/AAS Astrodynamics Specialist Conference, AIAA/AAS Snowbird, Utah, 2018
- J. Daquin, I. Gkolias, and A. J. Rosengren. "Drift and its mediation in terrestrial orbits." Frontiers in Applied Mathematics and Statistics, 4:35, 2018

# Large constellations

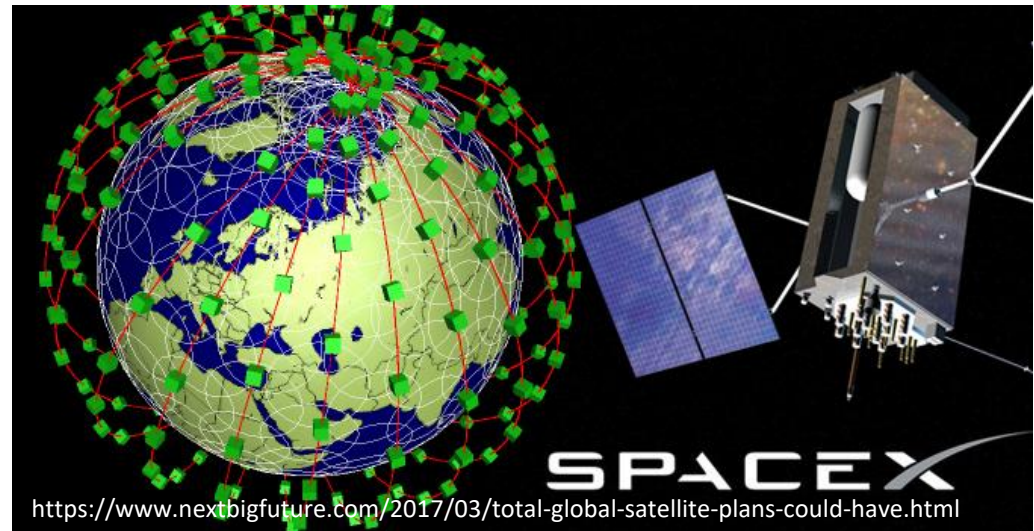
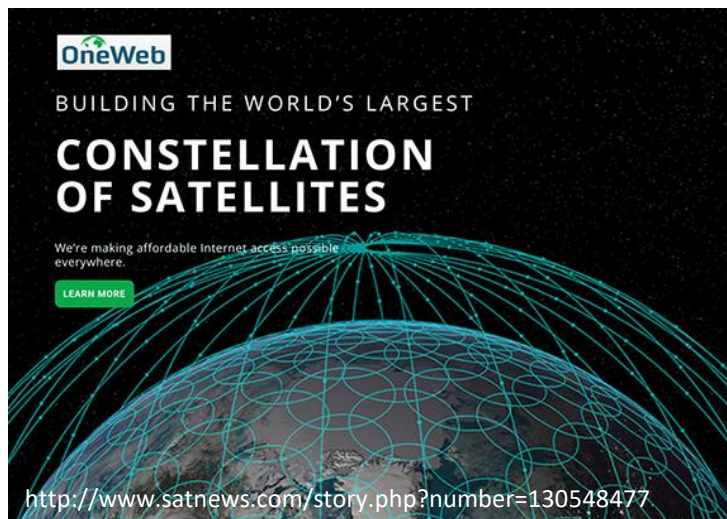
## Design of large constellations for space-based services



## Why

Large constellation of small satellites proposed for space based services

- Optimal design
- Space debris interaction
- Inner-constellation collision

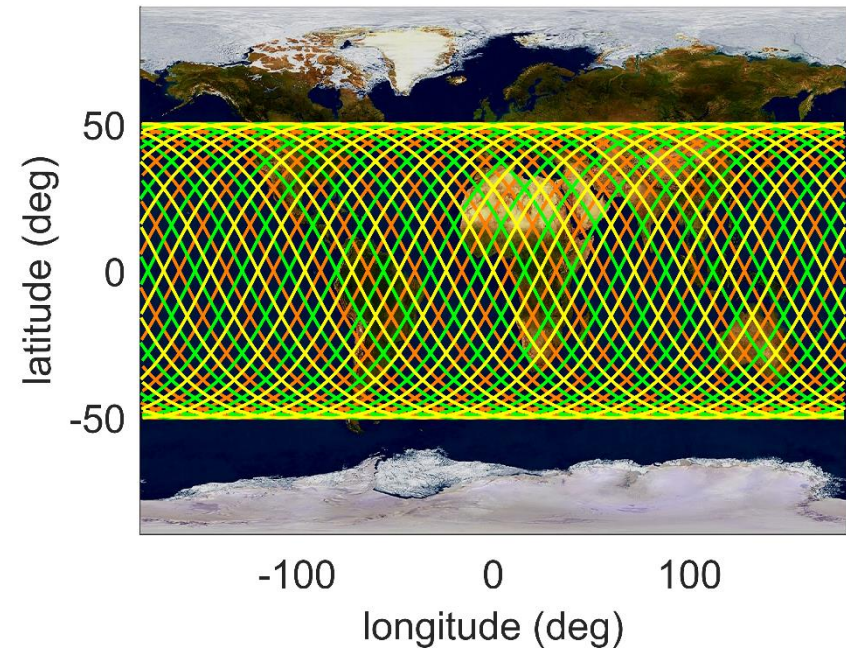


# Large constellations

## Design of large constellations for space-based services

### Methods:

- Comparative assessment of different constellation geometries for space-based applications
- Optimisation of constellation design
  - Optimal orbit raising or deorbiting design
  - Optimisation of the whole constellation plan
- Debris interaction and end-of-life
- Perturbation enhanced frozen orbits

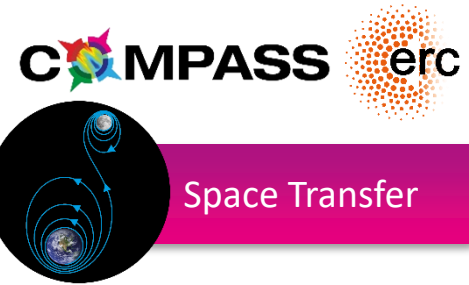


*Constellation design in LEO*

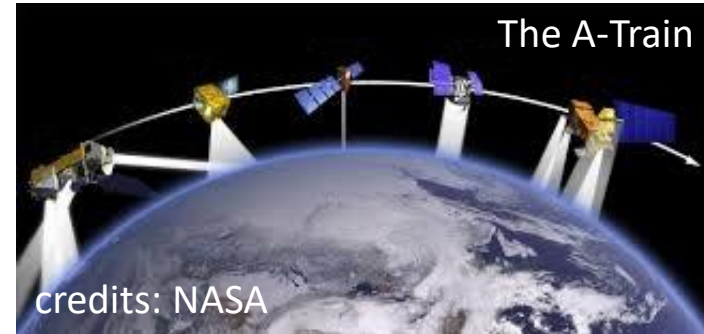
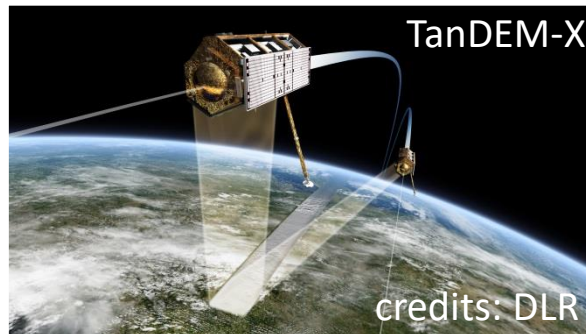
- S. Huang, C. Colombo and F. Bernelli-Zazzera, "Comparative Assessment of Different Constellation Geometries for Space-Based Application." 68th International Astronautical Congress. Adelaide, Australia, 25-29 September 2017, IAC-17, C1, IP, 31, x41252.
- S. Huang, C. Colombo and F. Bernelli Zazzera, "Orbit Raising and De-Orbiting for Coplanar Satellite Constellations with Low-Thrust Propulsion." under review.

# Formation flying

Exploiting satellites which fly close to each other

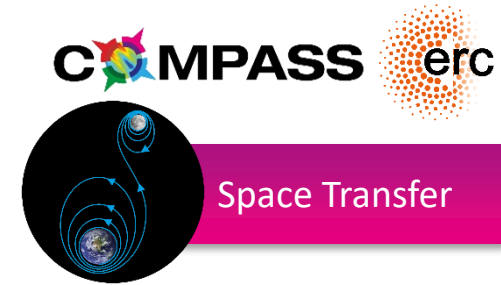


- Formation flying embraces several applications
  - Sparse instruments (e.g., Earth observation, communication ...)
  - On-orbit servicing
  - Active debris removal
  
- Several applications occur in low-Earth orbits (harsh environment)



# Formation flying

Focus on satellites' relative motion



## Goal:

Understanding and use of the orbital perturbations in the relative motion to

- Enhance current Guidance Navigation and Control (GNC) algorithms that enable formation flying activities
- Improve the level of autonomy of such GNC systems

## Method:

Use of orbital elements based semi-analytical approaches to

- Exploit the peculiarities of the orbital dynamics
- Develop a framework suitable to run on spaceborne processors

# Orbit and attitude of solar sails

## Problem setting

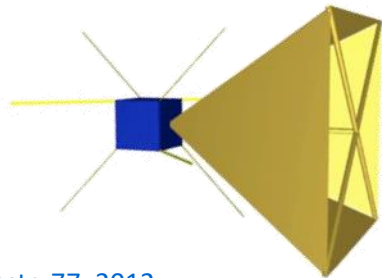
### Problem:

- Fast orbit and attitude propagation of **uncontrolled spacecraft in strongly perturbed environments**.
- To be applied in the context of **passive mitigation strategies with the aid of Solar Radiation Pressure acceleration**.

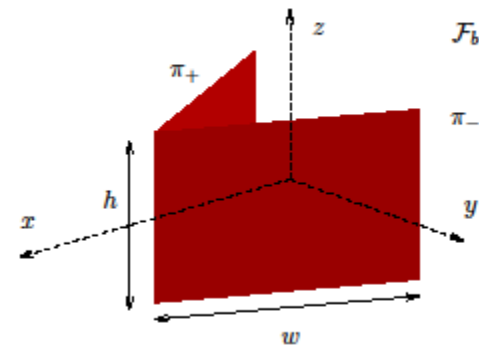
### How:

- Strategies rely on attitude control (e.g., helio-stable shape).

3D concept



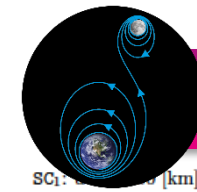
2D simplified



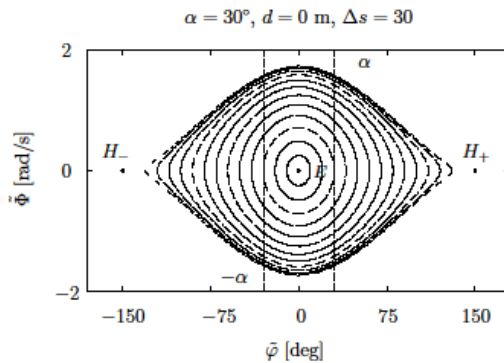
- Lücking et al. *Acta Astr.* 77, 2012
- Colombo et al. *Acta Astr.* 81, 2012
- Ceriotti et al. *Adv. Solar Sailing* 2014

# Orbit and attitude of Solar Sails

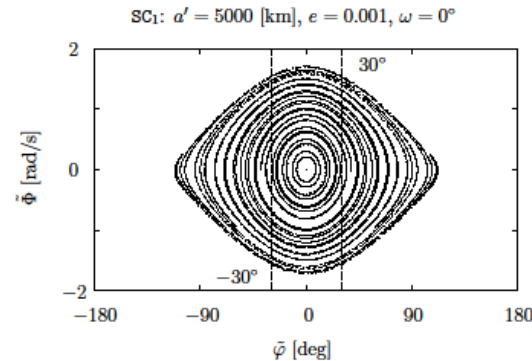
## Dynamics close to Sun-pointing attitude



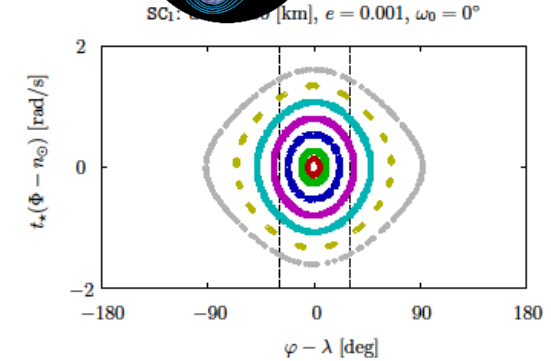
Space Transfer



Only attitude, only SRP



Only attitude, SRP+gravity gradient



Attitude + Orbit

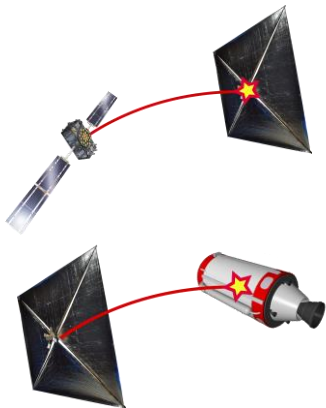
- Dynamics: Orbit + fixed attitude and attitude + fixed orbit are **Hamiltonian systems**.
- Coupled dynamics: **Slow-fast system** (orbit-attitude, resp.).
- Analytical results in the planar case: explicit (and averaged) equations for a large family of spacecraft, static stability of Sun-pointing direction.
- Analysis depends on **shape, center of mass-center of pressure offset, area-to-mass ratio**.

# Solar sails and collision avoidance

Collision avoidance manoeuvres for solar sail missions

Solar sails are a **cost-effective alternative to reduce de-orbit** time for satellites reaching their end of life

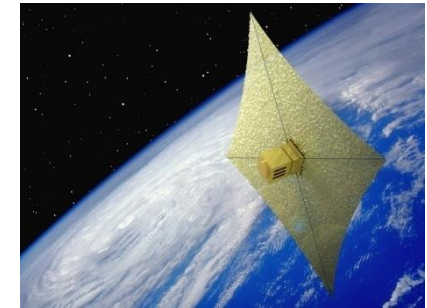
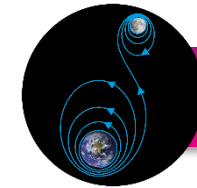
- Comply with space debris mitigation policies
- Reduce/eliminate need for additional fuel (costly)



But their large cross-sectional area **increases collision risk**

**New insights and tools on collision avoidance manoeuvres involving large objects (as sails) need to be developed**

Results can be applied to other missions such as **asteroid deflection or redirection**

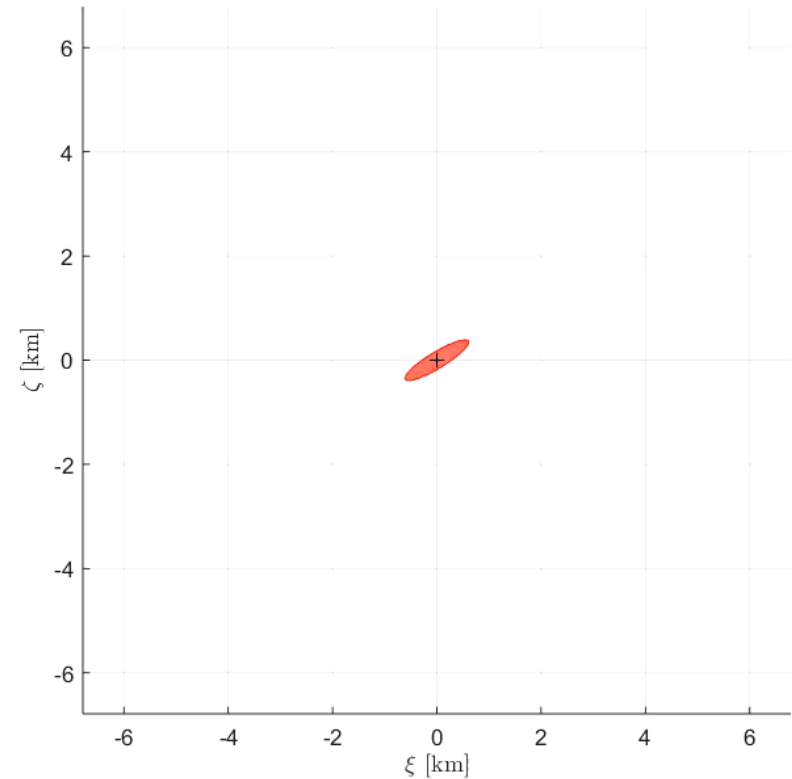


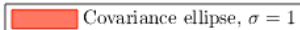
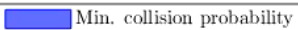
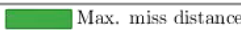
# Solar sails and collision avoidance

## Method and results

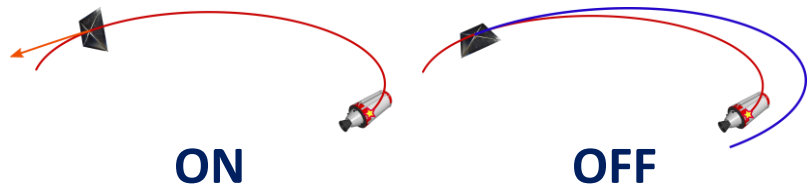
Analytic, semi-analytic and numerical approaches:

- Manoeuvring either the sail or the incoming object
- Representation of dynamics at the close approach (b-plane)
- Max. miss distance and min. collision probability strategies
- Taking into account the effect of the uncertainties



 Covariance ellipse,  $\sigma = 1$   Min. collision probability  Max. miss distance

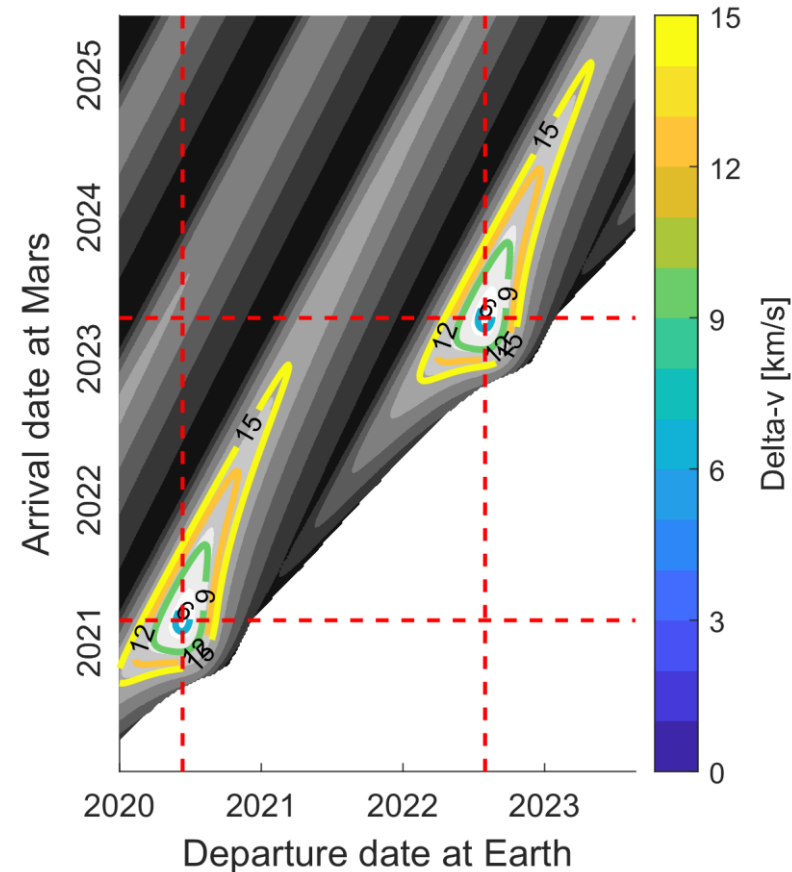
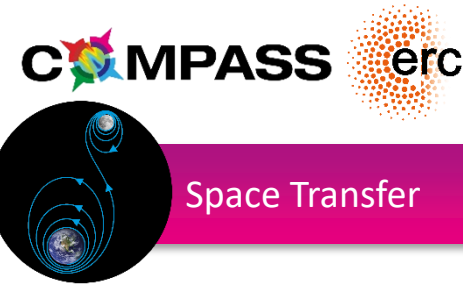
Max. miss distance vs min. collision probability manoeuvres, with time-evolving uncertainties



# Interplanetary transfer

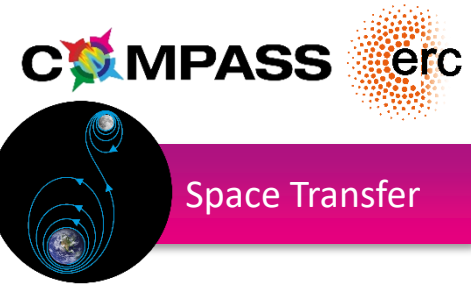
## Fly-by design through maps

- Solution of interplanetary trajectory optimisation problem
- Tisserand energetic manner method to identify reachable bodies and encounter conditions
- Extension to 3D porkchop plot to allow elegant resolution for the flyby problem
- Syzygy function, borrowed from astronomy for designing gravity assists assisted trajectories

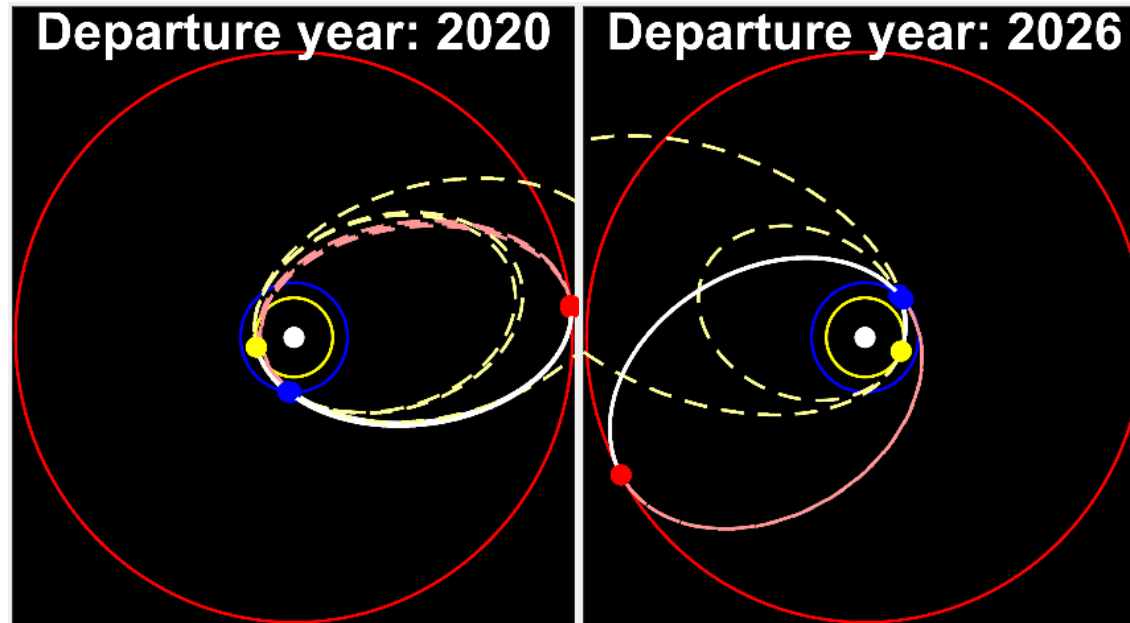


# Interplanetary transfer

## Fly-by design through maps



Syzygy function, borrowed from astronomy, extended to designing gravity assists assisted trajectories



# Planetary protection

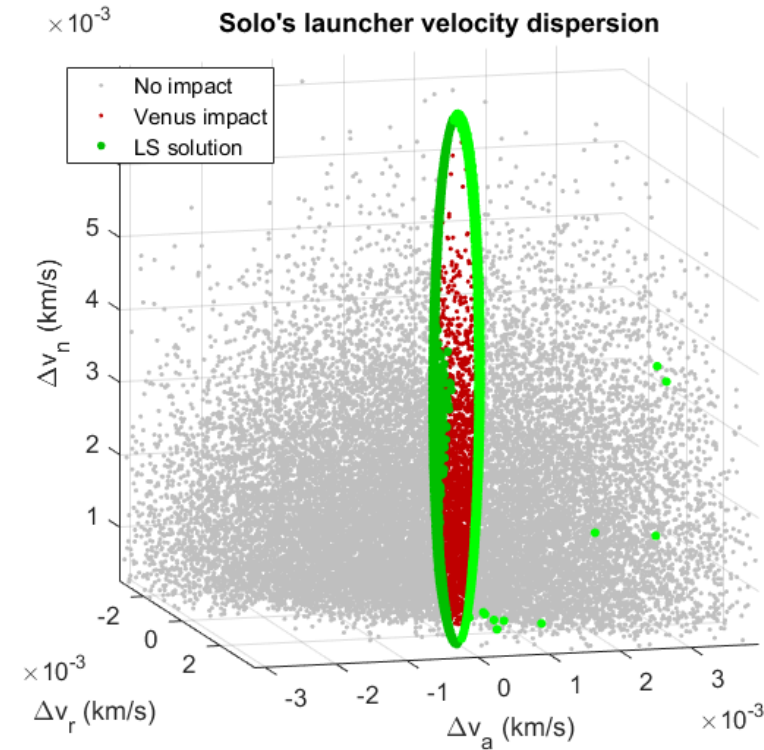
## Analysis of planetary protection requirements

### Problem:

Spacecraft and launchers used for interplanetary missions and missions to the Lagrangian points may come back to the Earth or impact with other planets

### Method:

- Planetary protection requirements: avoid the risk of contamination = check maximum impact probability with planets over 50-100 years
- Development of a tool for the verification of the compliance using an efficient sampling and integration techniques and smart representation (b-plane)



*Solo launcher velocity dispersion:  
impact condition with Venus*

# Research team



05/10/2018

# Research team



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Department of Aerospace  
Science and Technology



Camilla Colombo



Mirko Trisolini  
Space debris



Stefan Frey  
Space debris



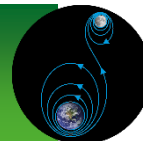
Ioannis Gkolas  
Space debris



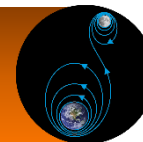
Gabriella Gaias  
Space transfers



Davide Menzio  
Space transfer



Narcis Miguel  
Solar Sails



Juan Luis Gonzalo  
Space debris  
asteroids



Matteo Romano  
planetary  
protection



Simeng Huang PhD  
Mega-constellations



## Scientific Advisory Board



European Space Agency



Centre National  
d'Études Spatiales



NASA

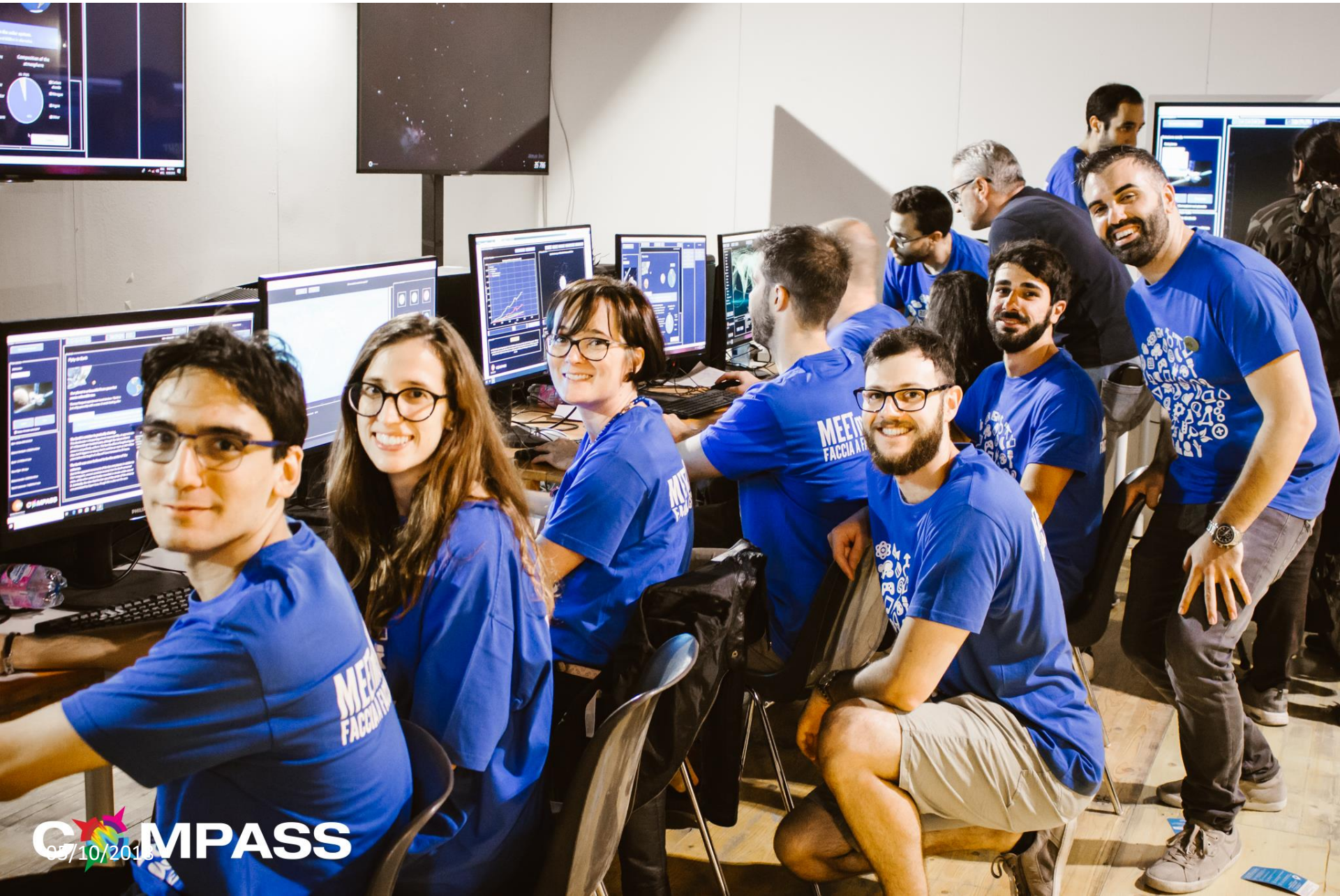


Japan Aerospace  
Exploration Agency



UK Space Agency

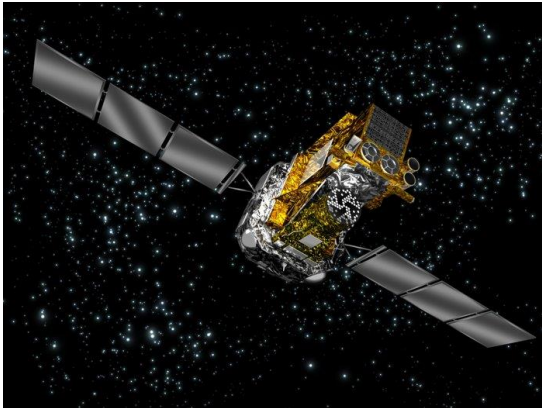




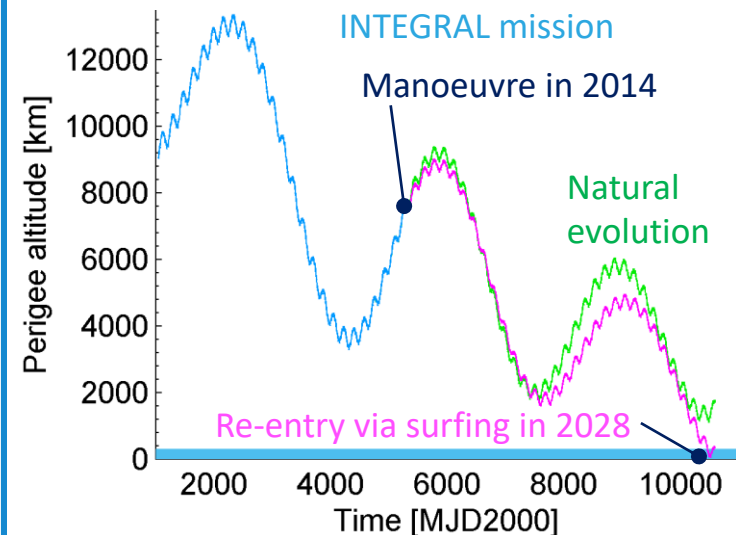


## Contributions

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



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





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**COMPASS**



This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 679086 – COMPASS)

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