UNIVERSITY OF Southampton

SNAPPshot: Suite for Numerical Analysis of Planetary Protection

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6th International Conference on Astrodynamics Tools and Techniques
Session 4: Interplanetary Flight and Non-Earth Orbits
Darmstadt, 16th March 2016

esa

Planetary protection requirements

Compliance for interplanetary missions

Spacecraft and launchers used for **interplanetary missions** and missions to the **Lagrangian points** may come back to the Earth or impact with other planets (example: Apollo launchers)

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 a **Monte Carlo** approach and the **b-plane** representation

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

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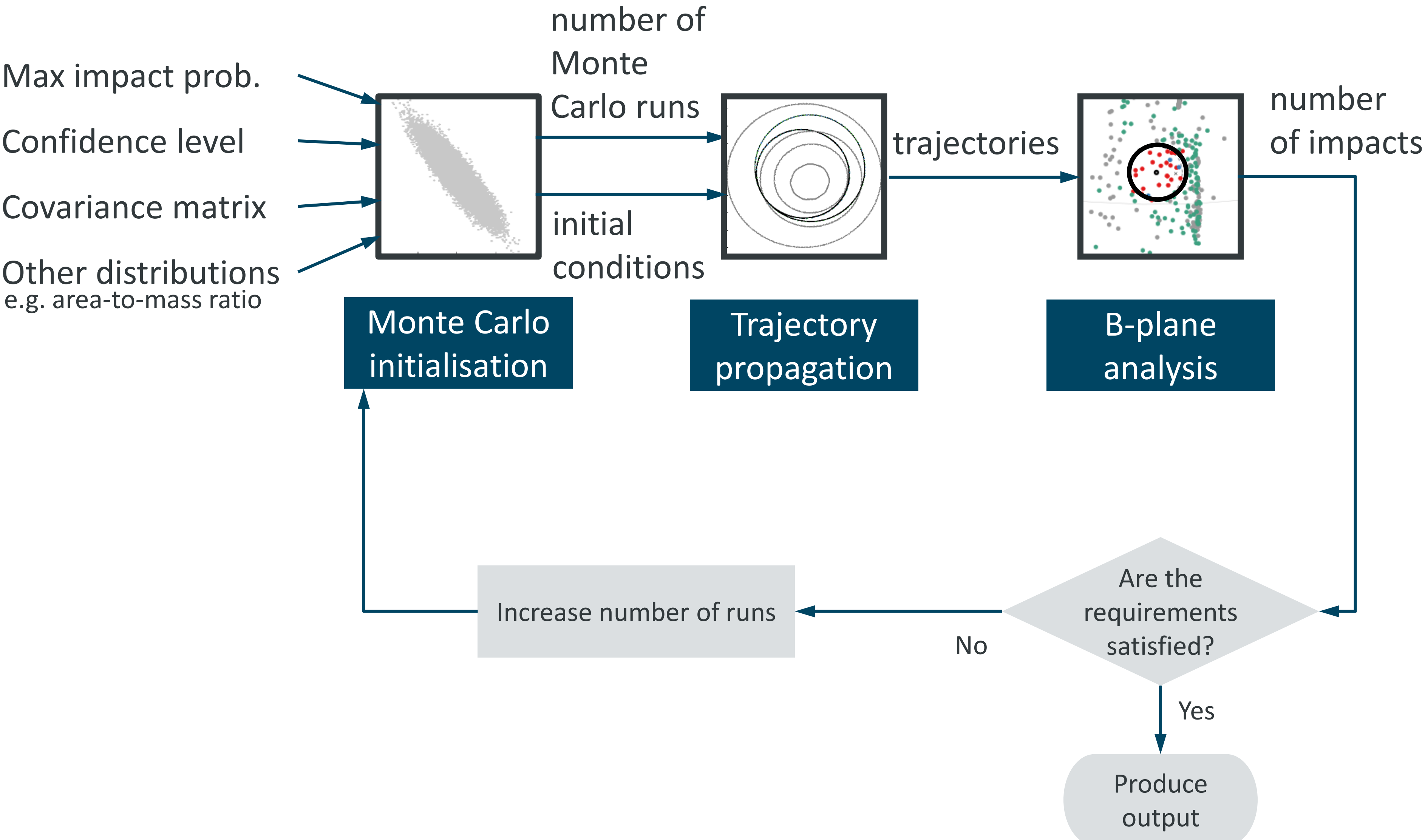


MonteCarlo initialisation

Number of runs & generation of the initial conditions

> Jehn 2015
> Wallace 2015

Number of runs (n) to verify the maximum level of impact **probability** (p), with a level of **confidence** (α), from the expression of the one-sided **Wilson's confidence interval**

$$p \leq \left(\frac{\hat{p} + \frac{z^2}{2n} + z^2 \sqrt{\frac{\hat{p}(1-\hat{p})}{n} + \frac{z^2}{4n^2}}}{1 + \frac{z^2}{n}} \right)$$

$z =$ α-quantile of a standard normal distribution

$$\hat{p} = \frac{\text{number of impacts}}{n}$$

$\hat{p} = 0$ → analytical expression for n

$\hat{p}$ **incremented** when impacts with a **reference body** (e.g. Mars) are registered

Generation of the **initial conditions**

- **launcher uncertainty**
  covariance matrix &
  Cholesky factorisation
- **failure of the propulsion system**
  random failure time &
  state vector interpolation

Additional distributions

- **area-to-mass** ratio
  user provides known values and select a distribution
  (e.g. uniform, triangular)

Trajectory propagation

Force model, ephemerides & propagator

Coordinates

Cartesian coordinates in the **J2000** reference frame centred in the **Solar System Barycentre**

Force model

gravitational forces + **solar radiation pressure** (cannonball model)

Ephemerides

ESA routine for planetary ephemerides (based on DE422) or **SPICE toolkit**

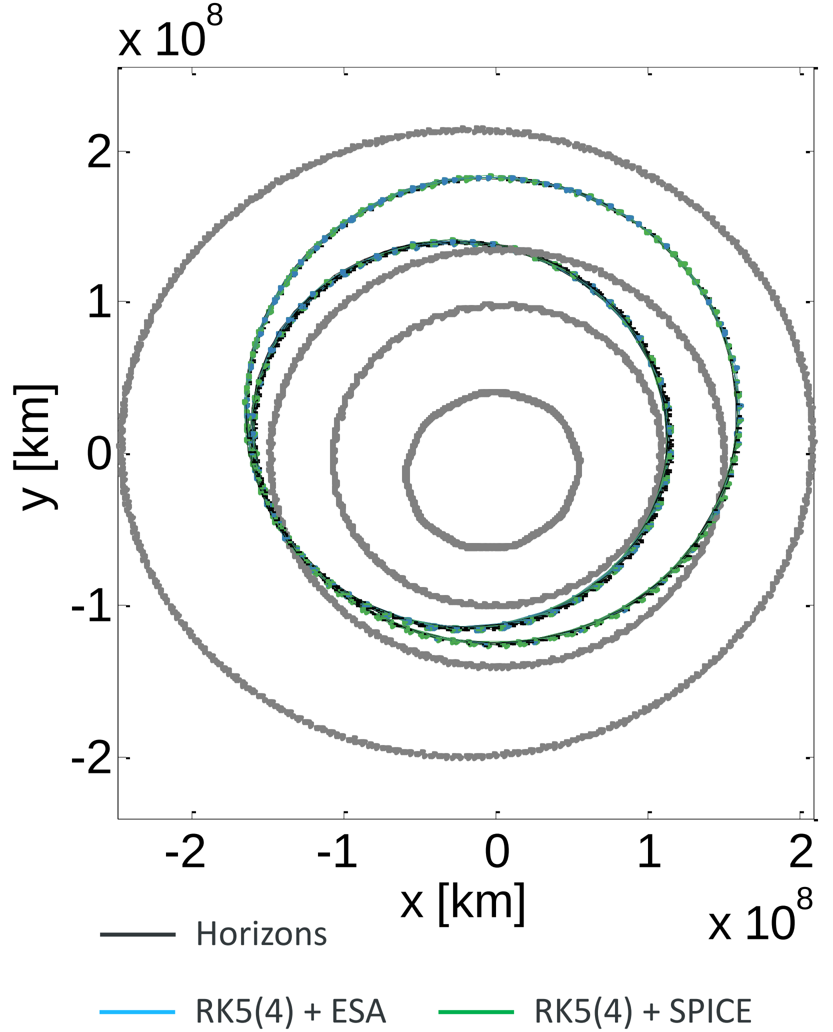
Propagator

Runge-Kutta methods with step size control technique (**adaptive** methods or **regularised steps**)

Additional features

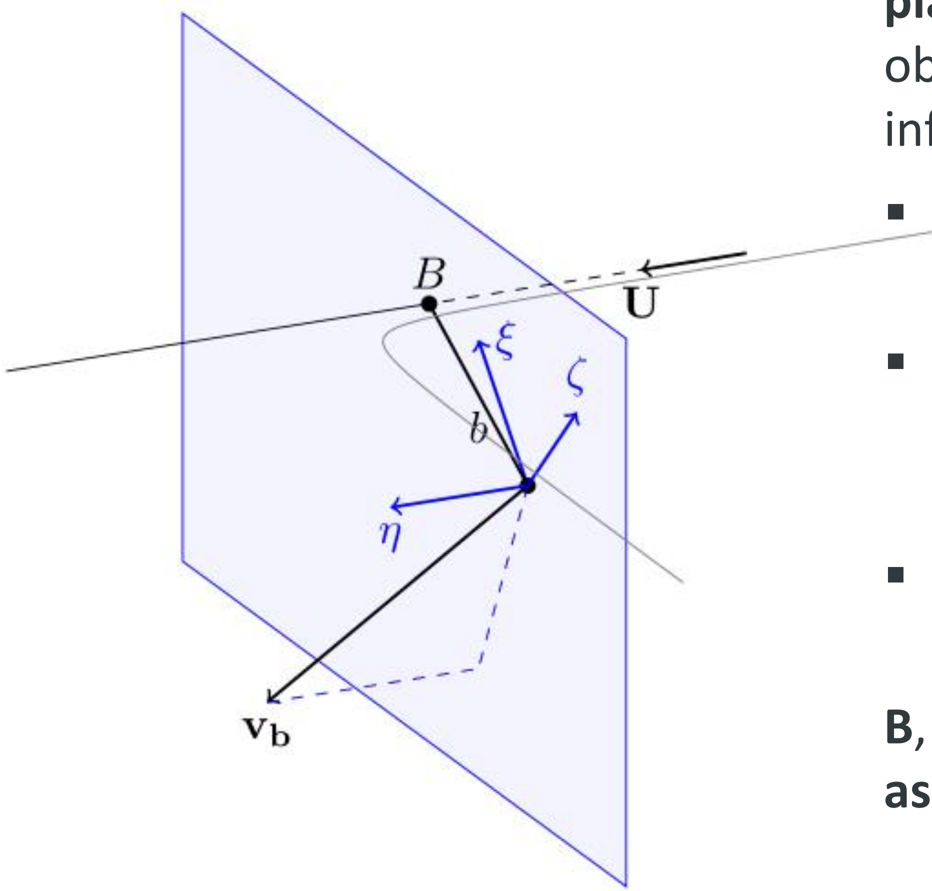
event functions and **dense output**

Integration of the trajectory of Apophis & validation against Horizons ephemeris



B-plane tool

B-plane definition



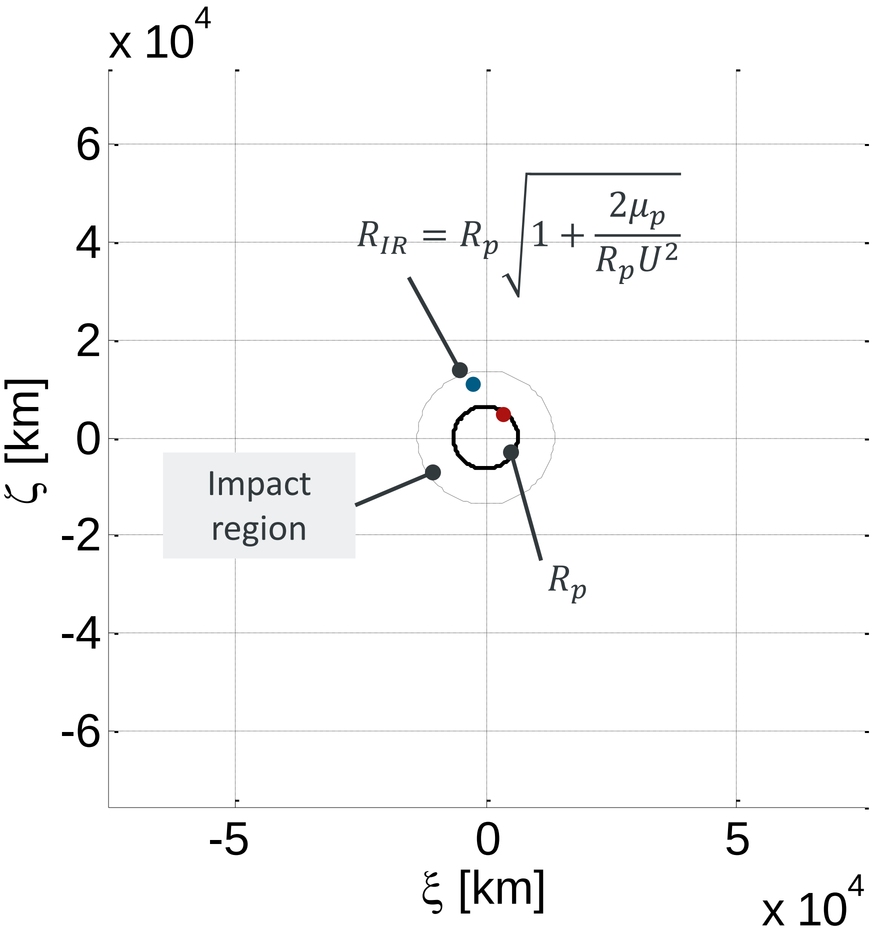
Plane **orthogonal** to the object **planetocentric velocity (U)** when the object enters the planet's sphere of influence (SOI)

- **η-axis**: parallel to the planetocentric velocity
- **ζ-axis**: parallel to the projection on the b-plane of the planet velocity, but in the opposite direction
- **ξ-axis**: to complete a positively oriented reference system

B, intersection of the **incoming asymptote** and the b-plane

B-plane tool

State characterisation: impact



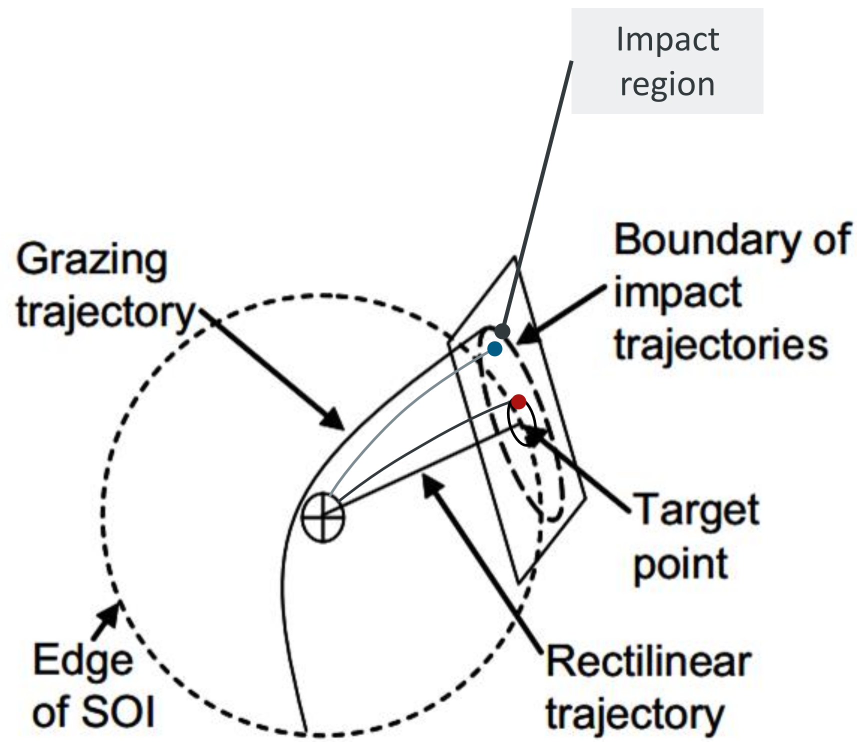
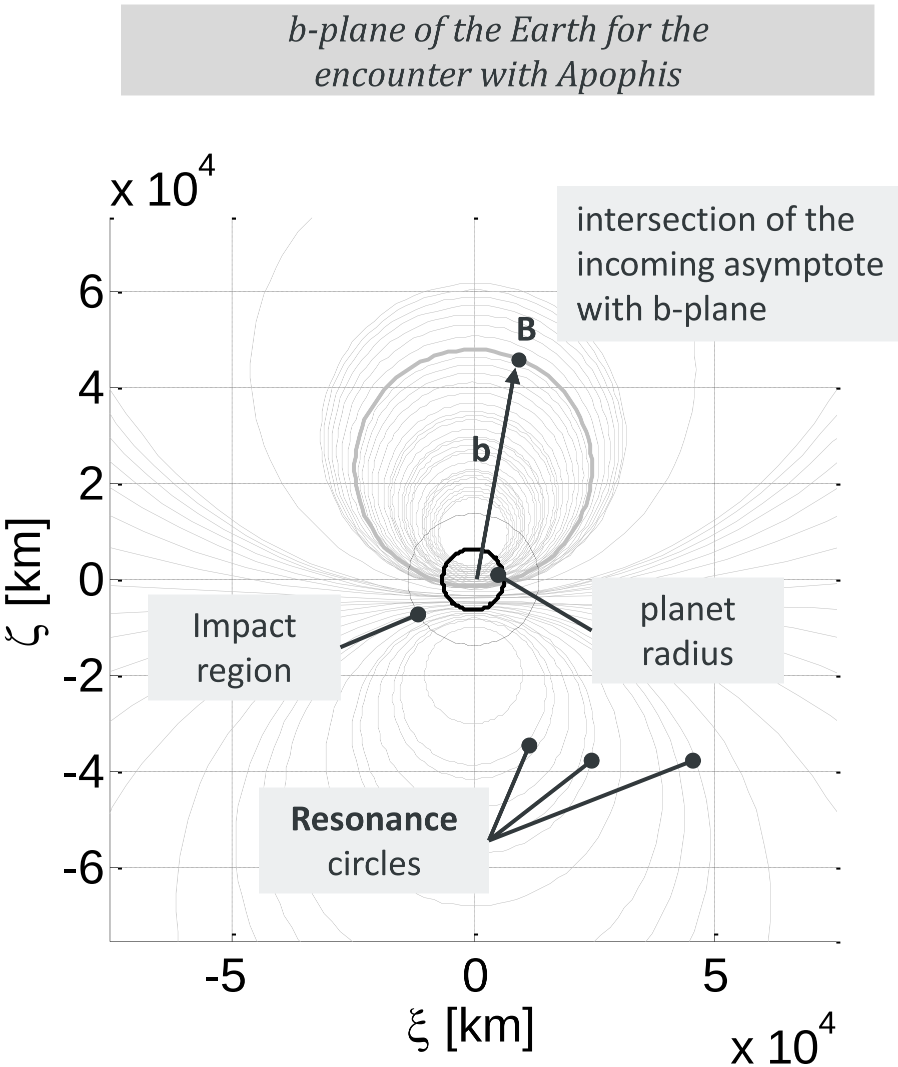


Figure readapted from Davis et al. 2006

B-plane tool

Additional information on the b-plane



- **Impact** condition if B within the area of the *projection* of planet on the b-plane

+

Decoupling distance & time

- ξ coordinate related to the **minimum geometrical distance** between the planet's and the object's orbits
- ζ coordinate related to the **phasing** between the planet and the object

+

Resonances, applying the analytical theory by Valsecchi et al. (2003)

B-plane tool

State characterisation: multiple fly-bys

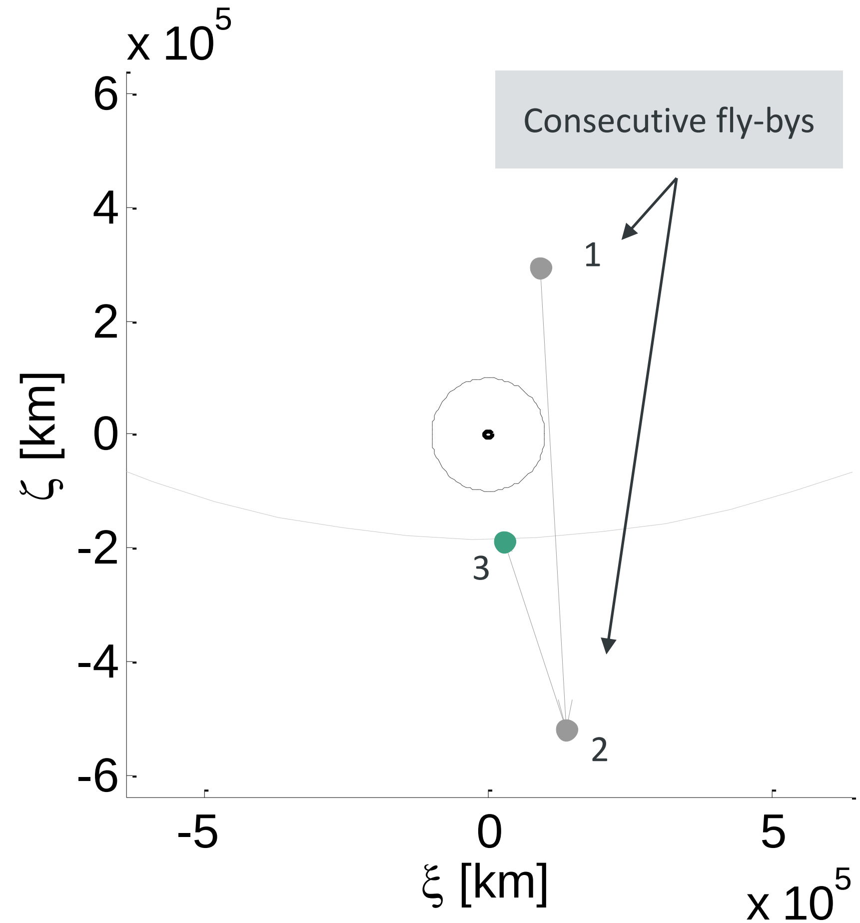
When **multiple fly-bys** are recorded, only one state should be selected to characterise the trajectory.
Two options:

- **first** encounter
- ***worst*** encounter

To select the worst encounter, the states need to be **sorted**:

- **Distance-driven**
  the worst case is the one with the minimum distance from the planet
- **State-driven**
  e.g. resonance > simple close approach
  e.g. Mars > Mercury

Evolution of one GAIA Fregat trajectory on the Earth's b-plane for 100 years of propagation



RESULTS

Solo launcher

Simulation settings

Uncertainty: **initial position** and **velocity** (covariance matrix)

Propagator: RK8(7)

Propagation time: 100 years

When multiple encounters: worst

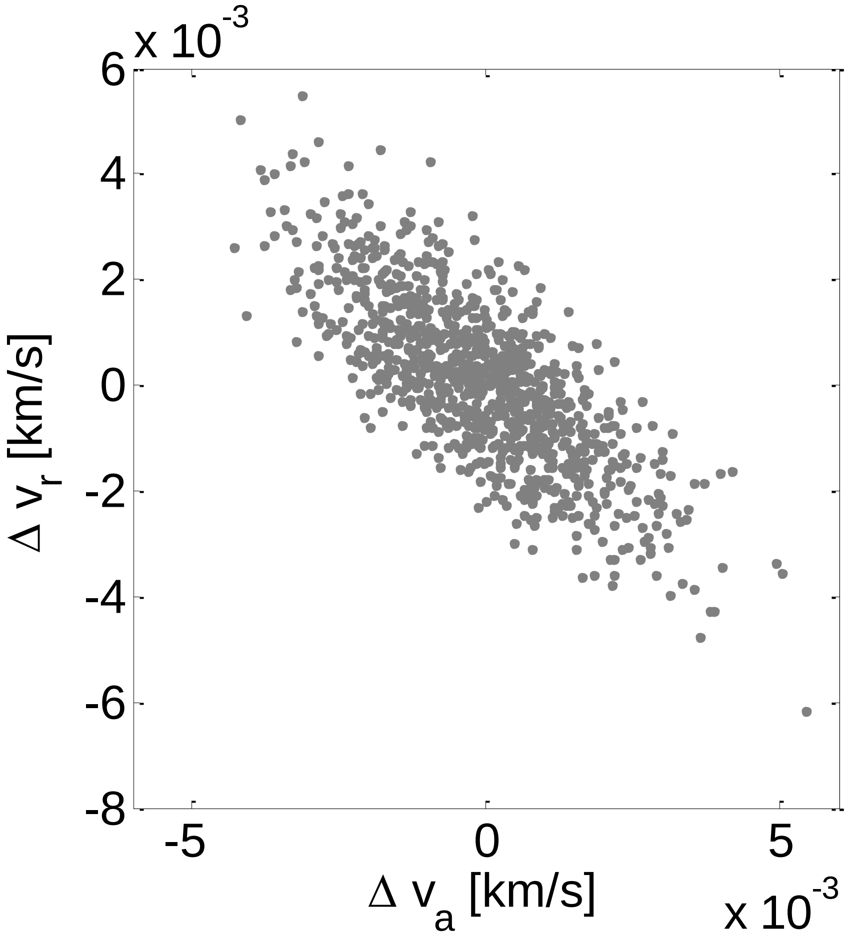
Encounter ranking: state

Number of runs = **1000**

Number of impacts = **51** (Venus)

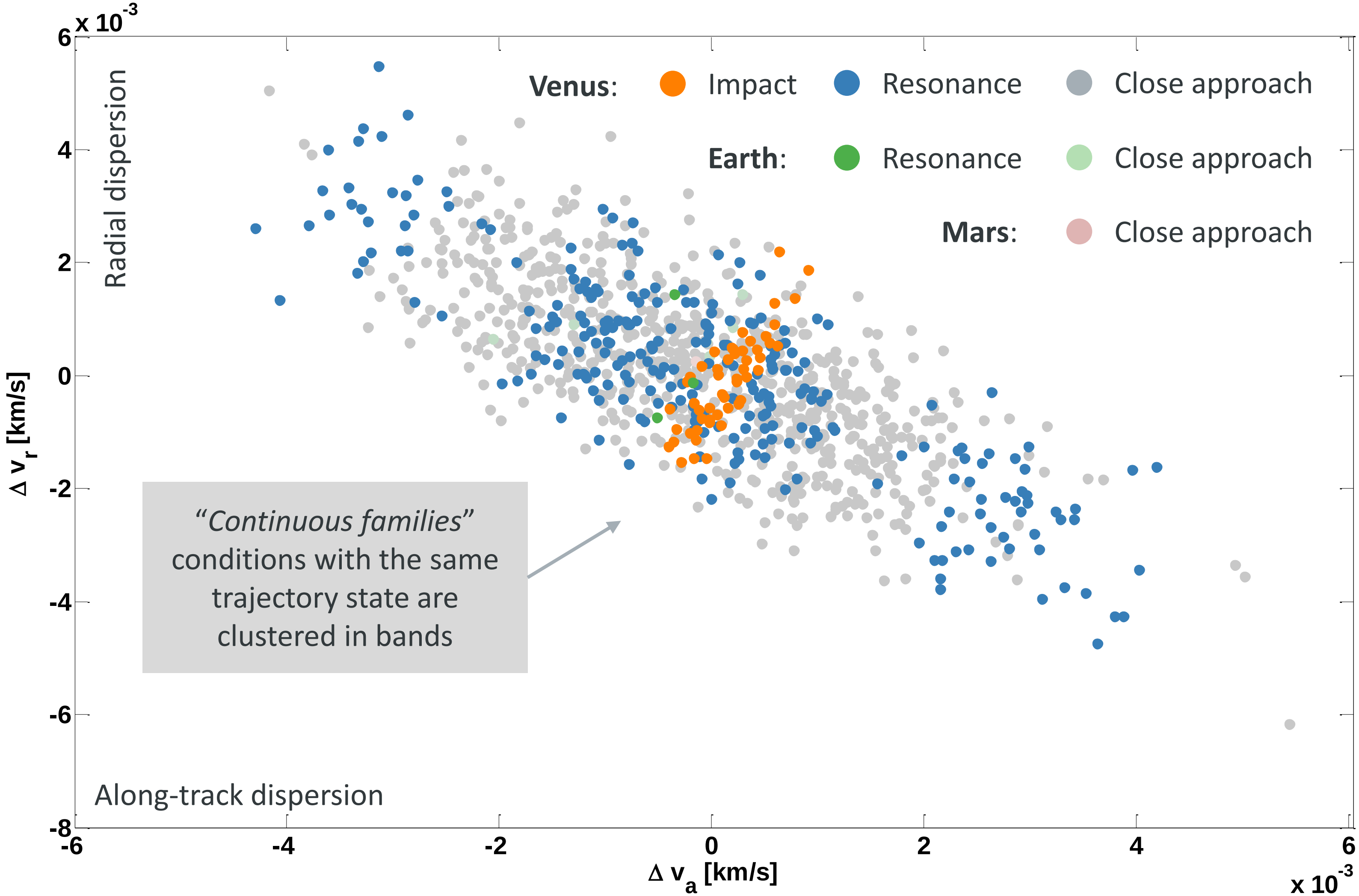
Running time = 17 minutes

Initial velocity dispersion for the Ariane launcher of Solo



Solo launcher

Velocity dispersion & trajectory characterisation



Solo launcher

B-plane visualisation (Venus)

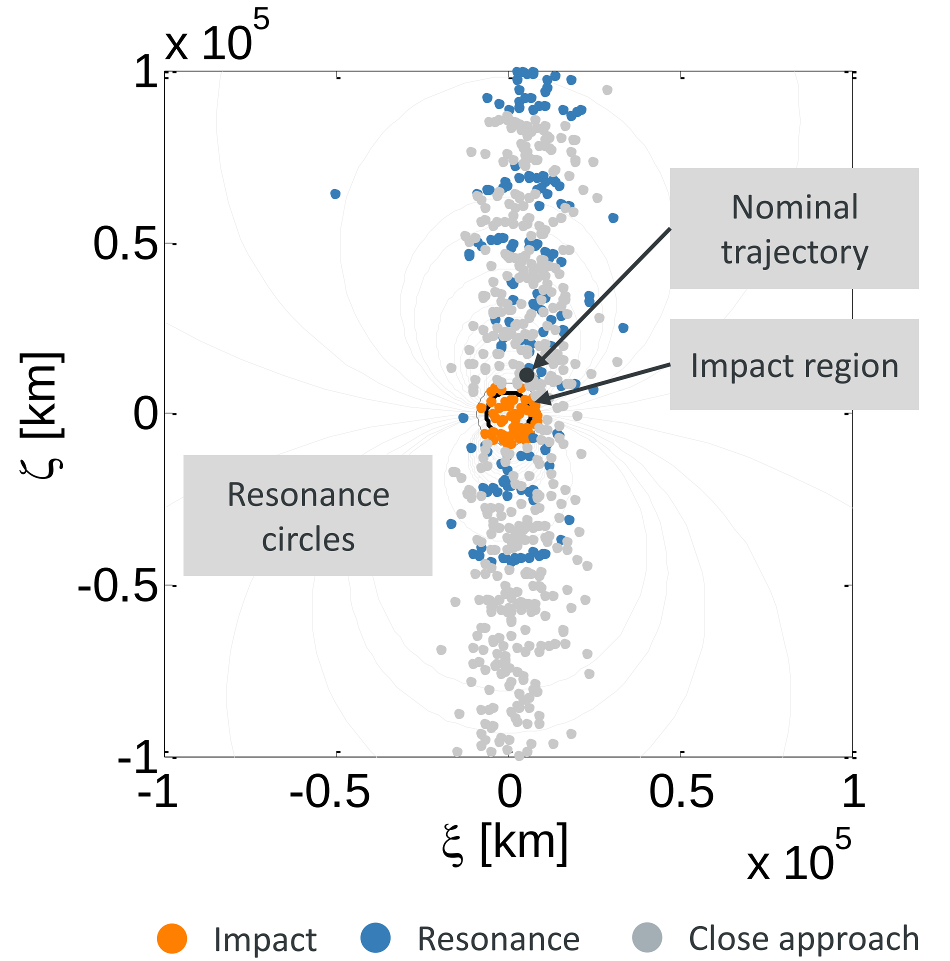
B-plane elements (impact region and resonance circles) defined for the **nominal trajectory**

All runs represented on the same plane, so the points may represent encounters at **different time instants**

In this case (different from the launcher of BepiColombo) the launcher goes **directly** to Venus

The dispersion in the initial condition affects mostly the **phasing** between the object and Venus

Representation on the b-plane of the Venus for the launcher of Solo



BepiColombo: failure of the propulsion system

Simulation settings

Uncertainty: **failure time** (during thrust arcs in the Earth-Earth phase)

Propagator: RK8(7)

Propagation time: 100 years

When multiple encounters: worst

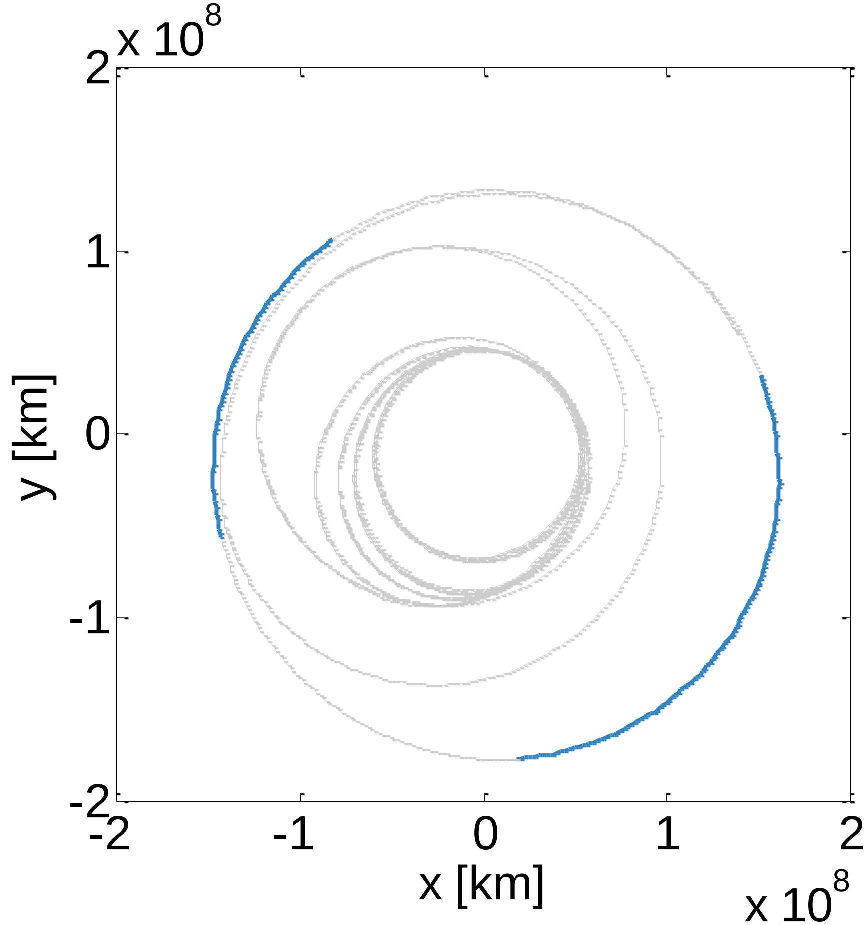
Encounter ranking: state

Number of runs = **54114**
(max probability of collision: 10^{-4}, confidence level: 99%)

Number of impacts = **28** (Earth)

Running time = 104 minutes

BepiColombo trajectory and thrust-arcs where the potential failures were studied

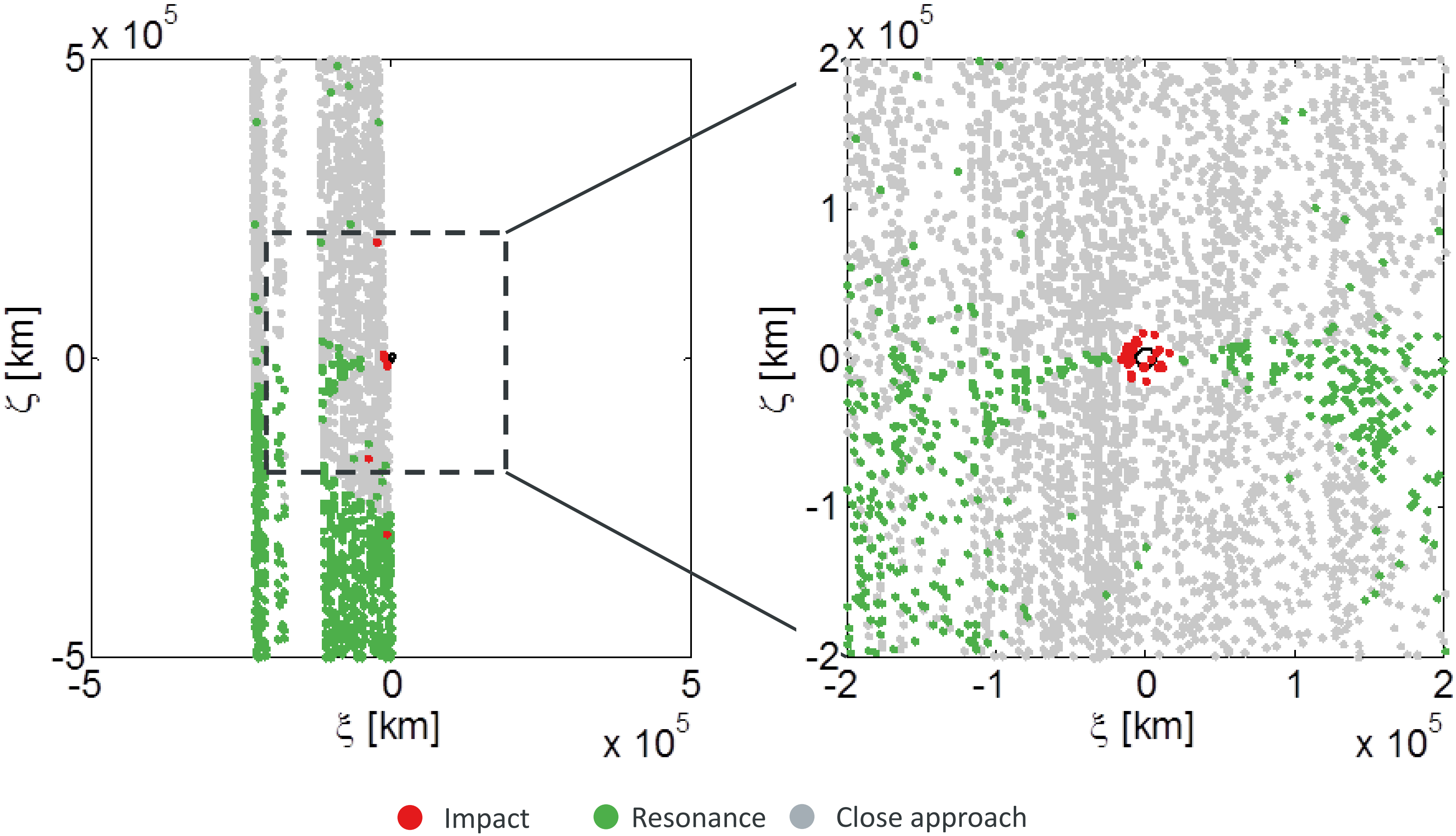


BepiColombo: failure of the propulsion system

B-plane visualisation (Earth)

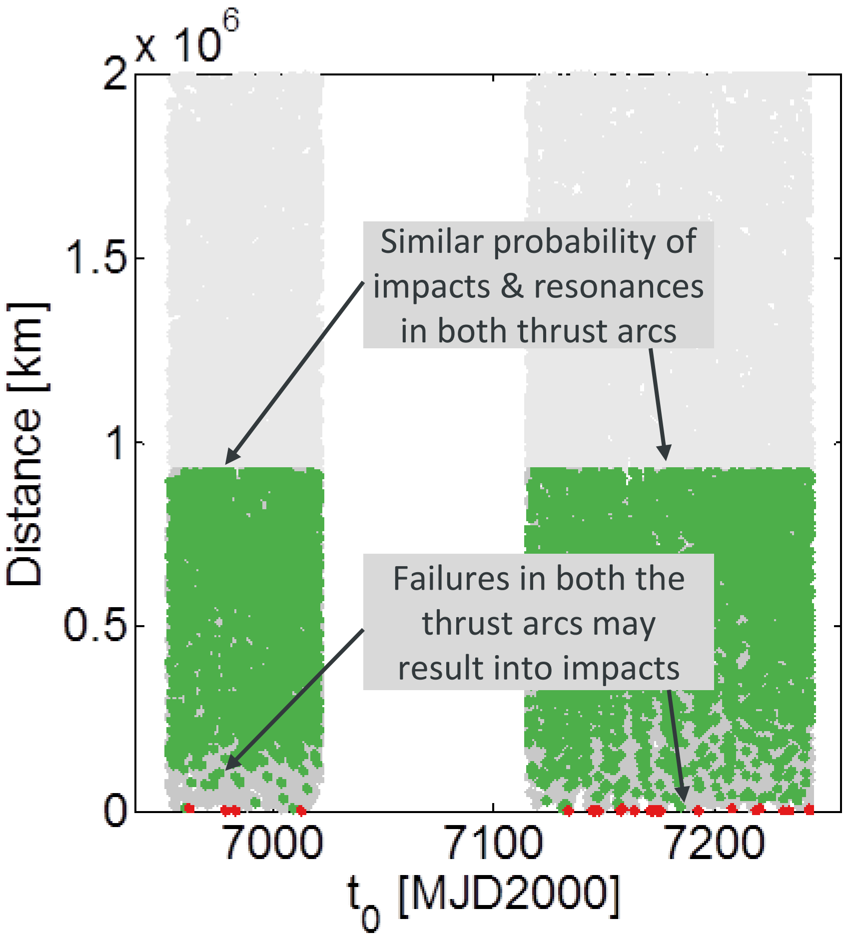
Representation on the b-plane of the Earth for the failure of BepiColombo (first fly-by)

Representation on the b-plane of the Earth for the failure of BepiColombo (worst fly-by)

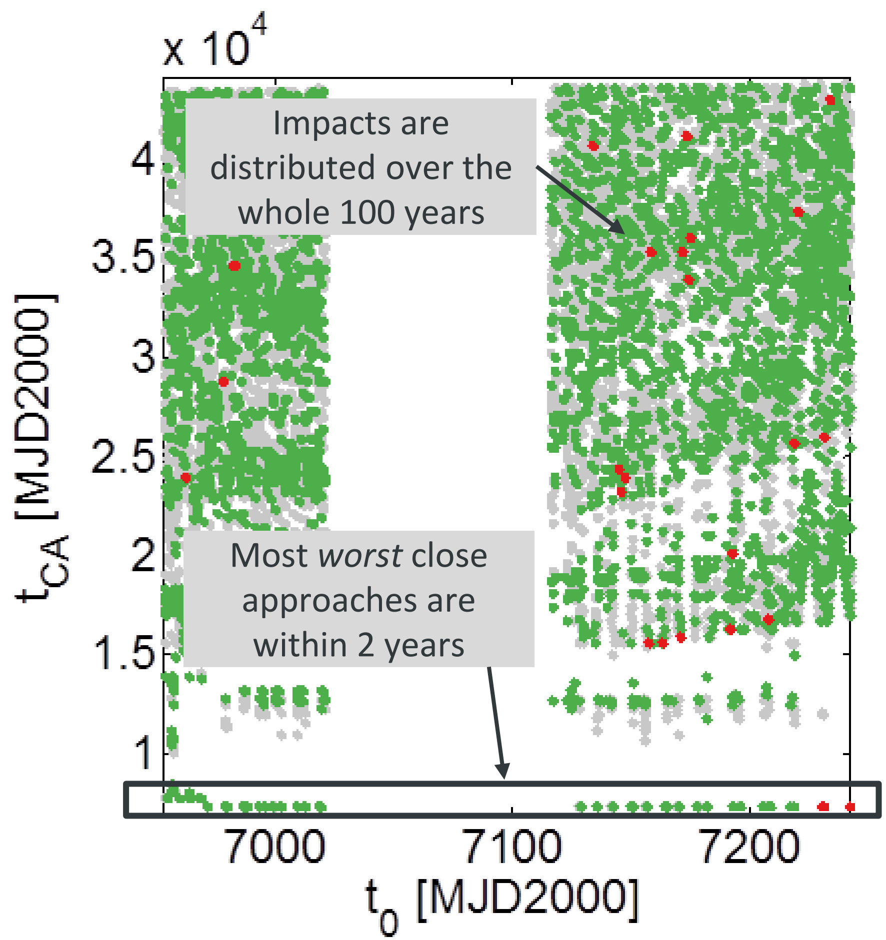


BepiColombo: failure of the propulsion system
Distribution with time of failure

Distribution of MC runs with failure time and miss distance



Distribution of MC runs with failure time and time of worst close approach



Impact Resonance Close approach

Conclusions

Launchers and spacecraft used for interplanetary missions and missions to the Lagrangian points may be inserted in trajectory that will impact a celestial body. Need to estimate their compliance with **planetary protection requirements**.

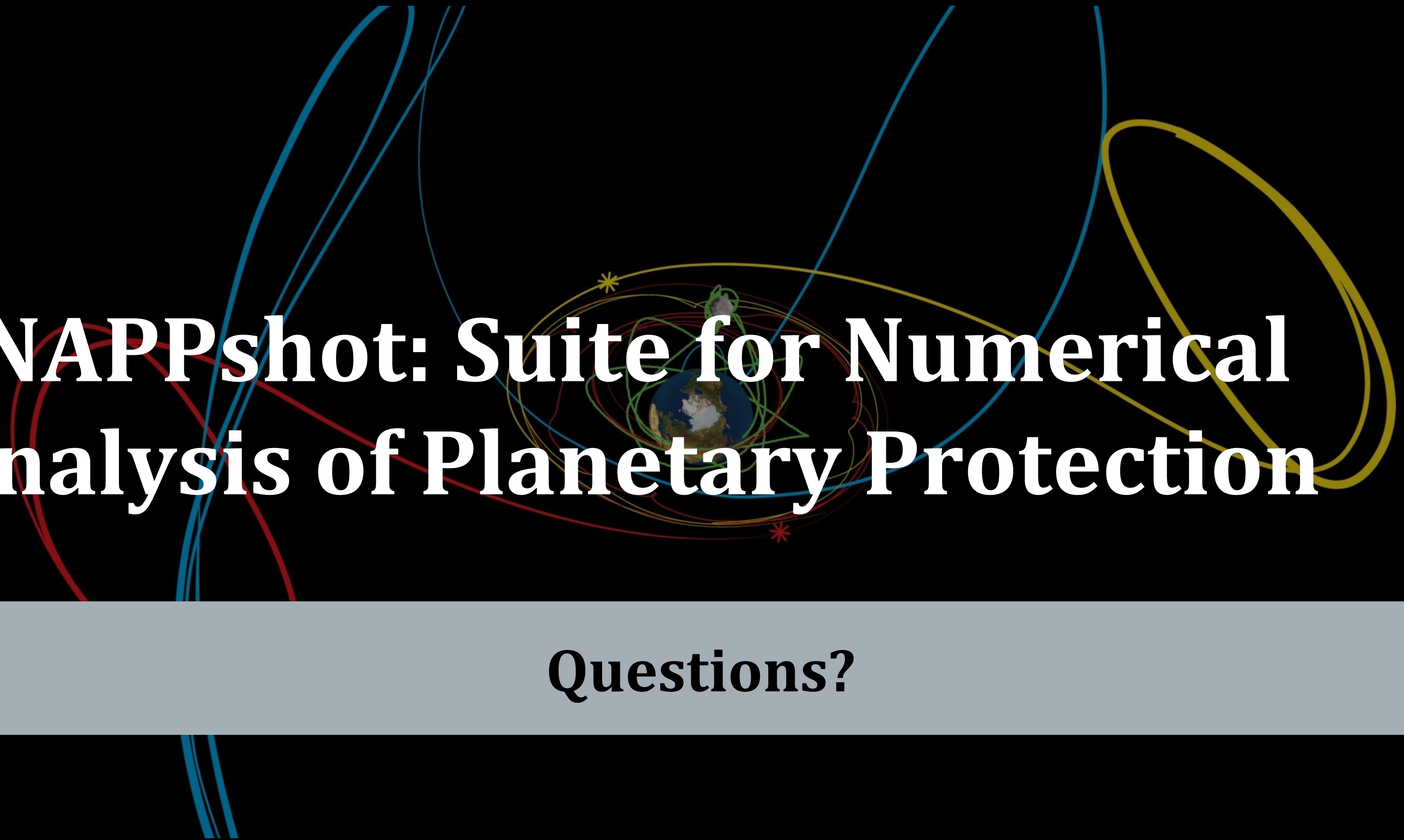
A new tool, **SNAPPshot**, was developed for this purpose. A **Monte Carlo** analysis is performed considering the dispersion of the initial condition and of other parameters.

Each run is characterised by studying the close approaches through the **b-plane** representation to detect conditions of **impacts** and **resonances**.

The method was applied to study the dispersion of the **launcher** of **Solo** and the failure of the **propulsion system** of **BepiColombo**.

Flexible tool: applicability can be extended to the **robust design** of manoeuvres or to the study of **asteroid deflection missions**.

The present study was funded by the European Space Agency through the contract 4000115299/15/D/MB, *Planetary Protection Compliance Verification Software.* Technical Responsible University of Southampton: Camilla Colombo, c.colombo@soton.ac.uk



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Questions?

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