Robust Ground Footprint Estimation of Reentering Space Objects

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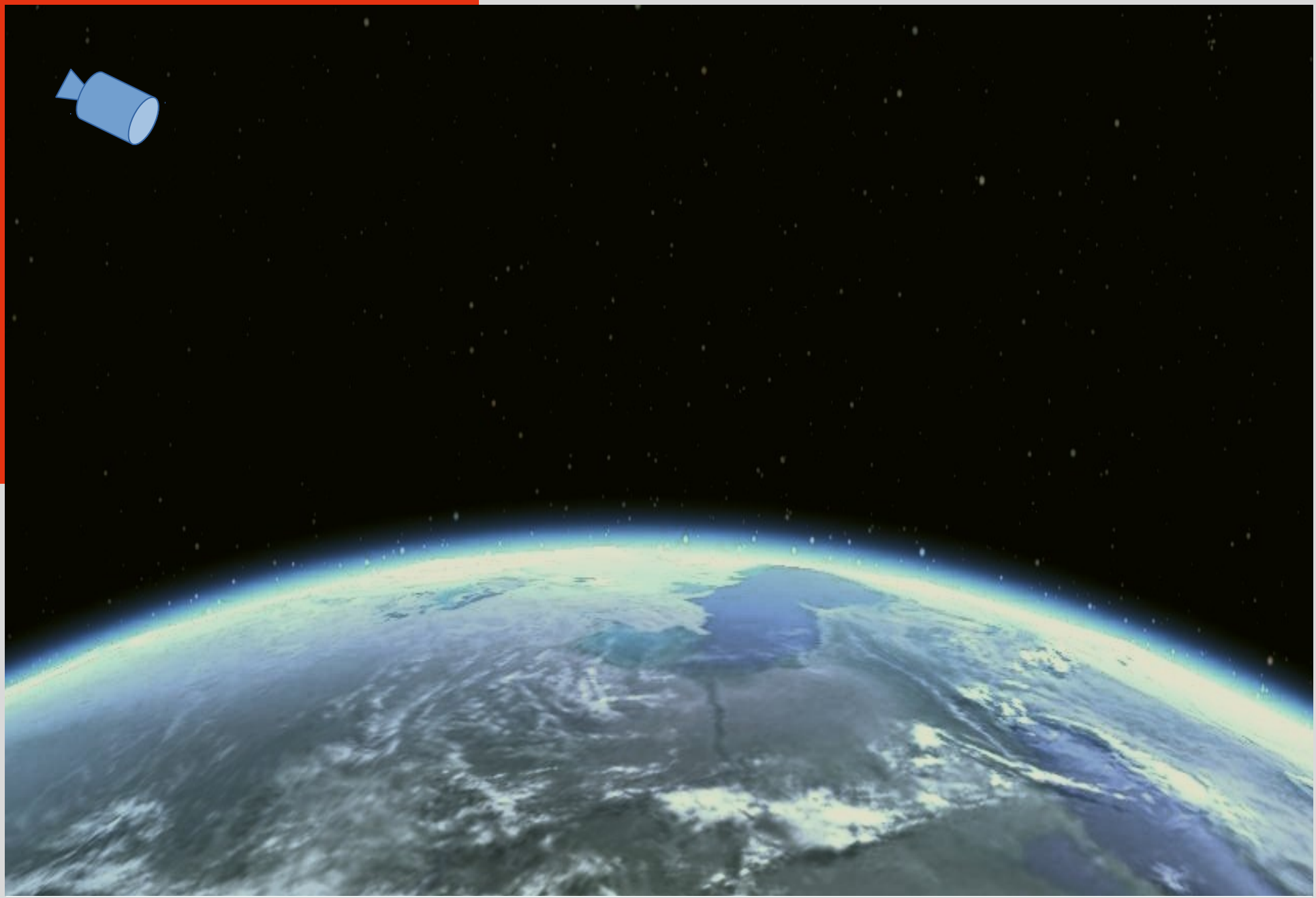
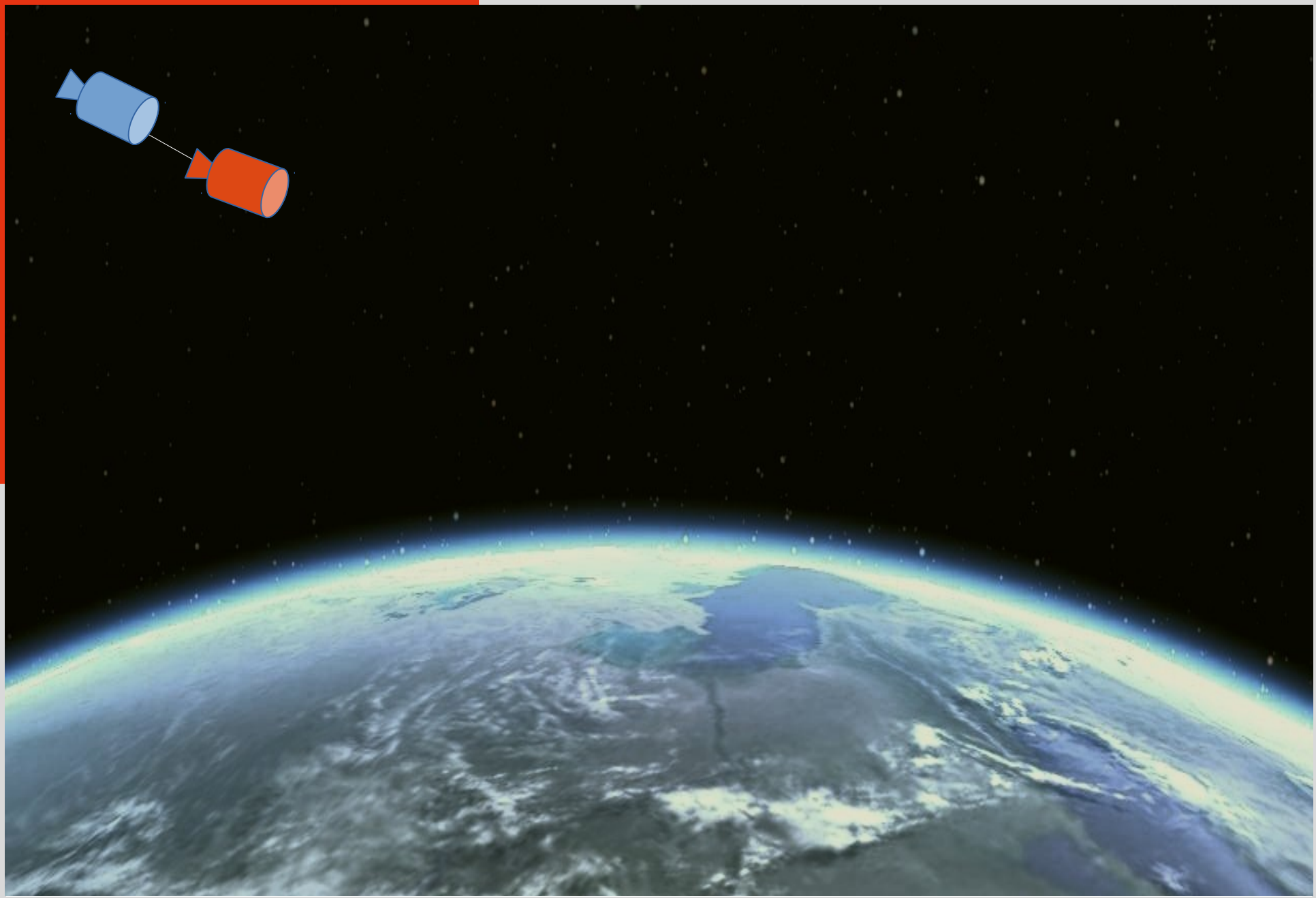
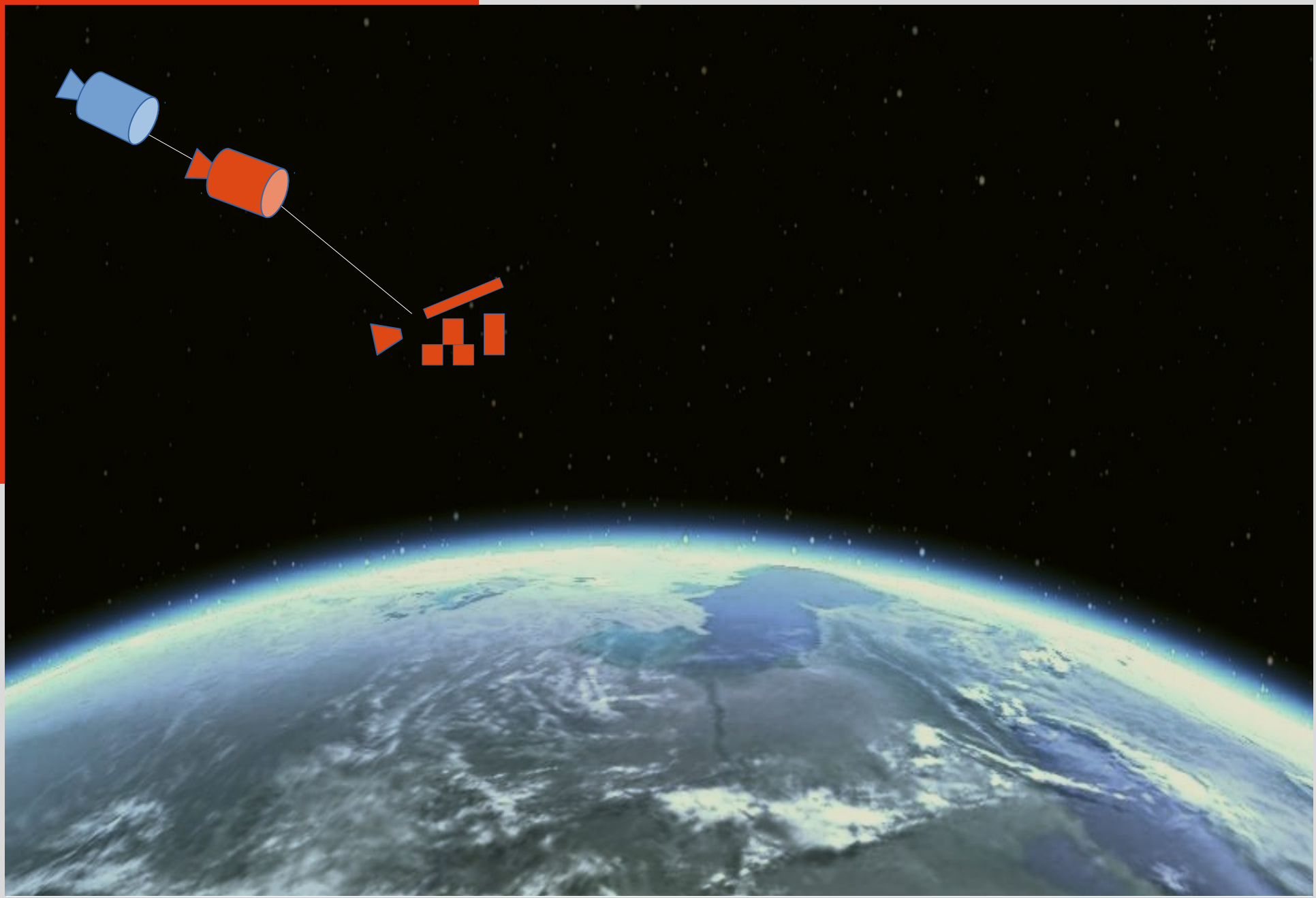
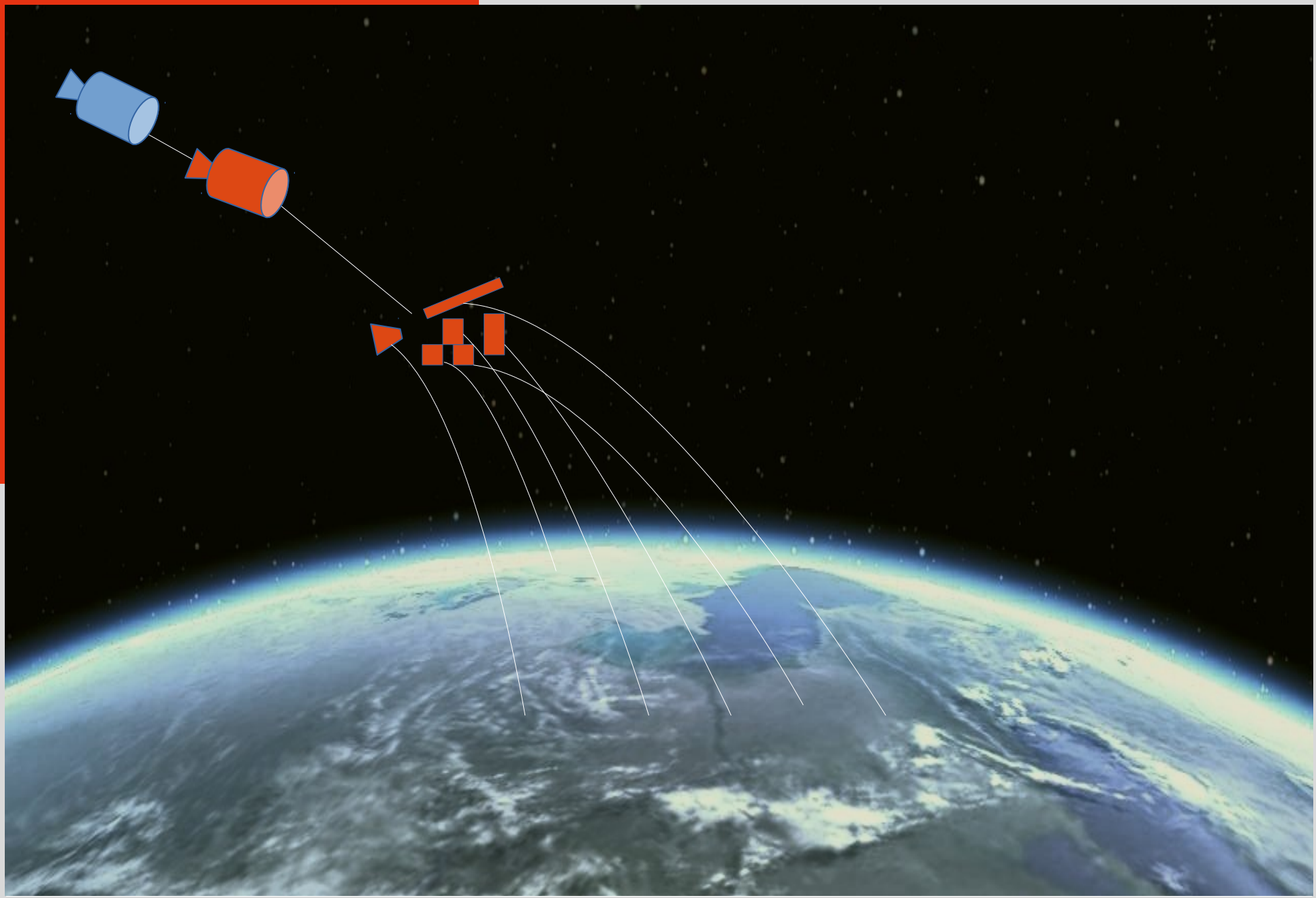
Outline

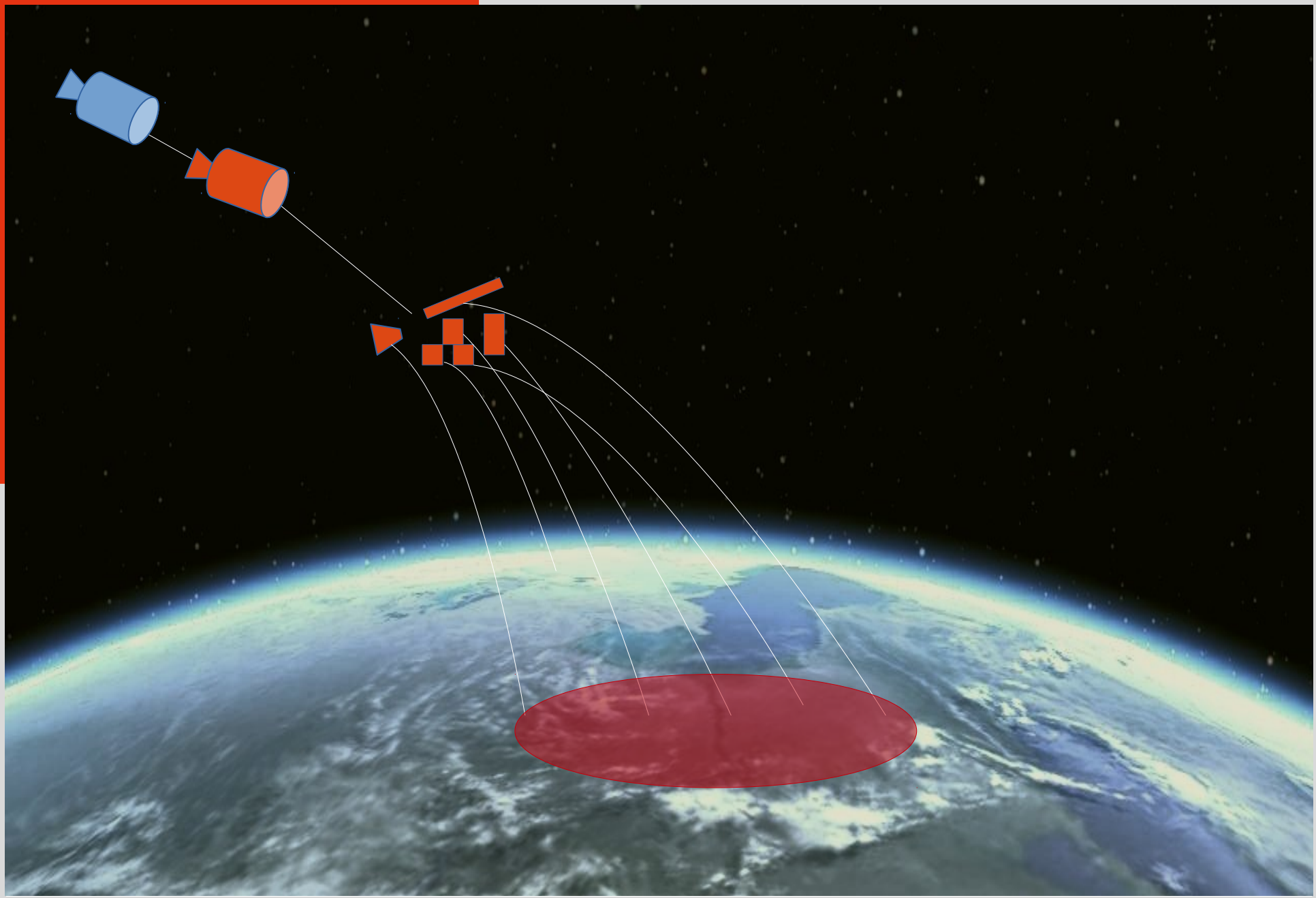
- Numerical tools
- Results for fragmentation predictor
- Results for impact zone estimations

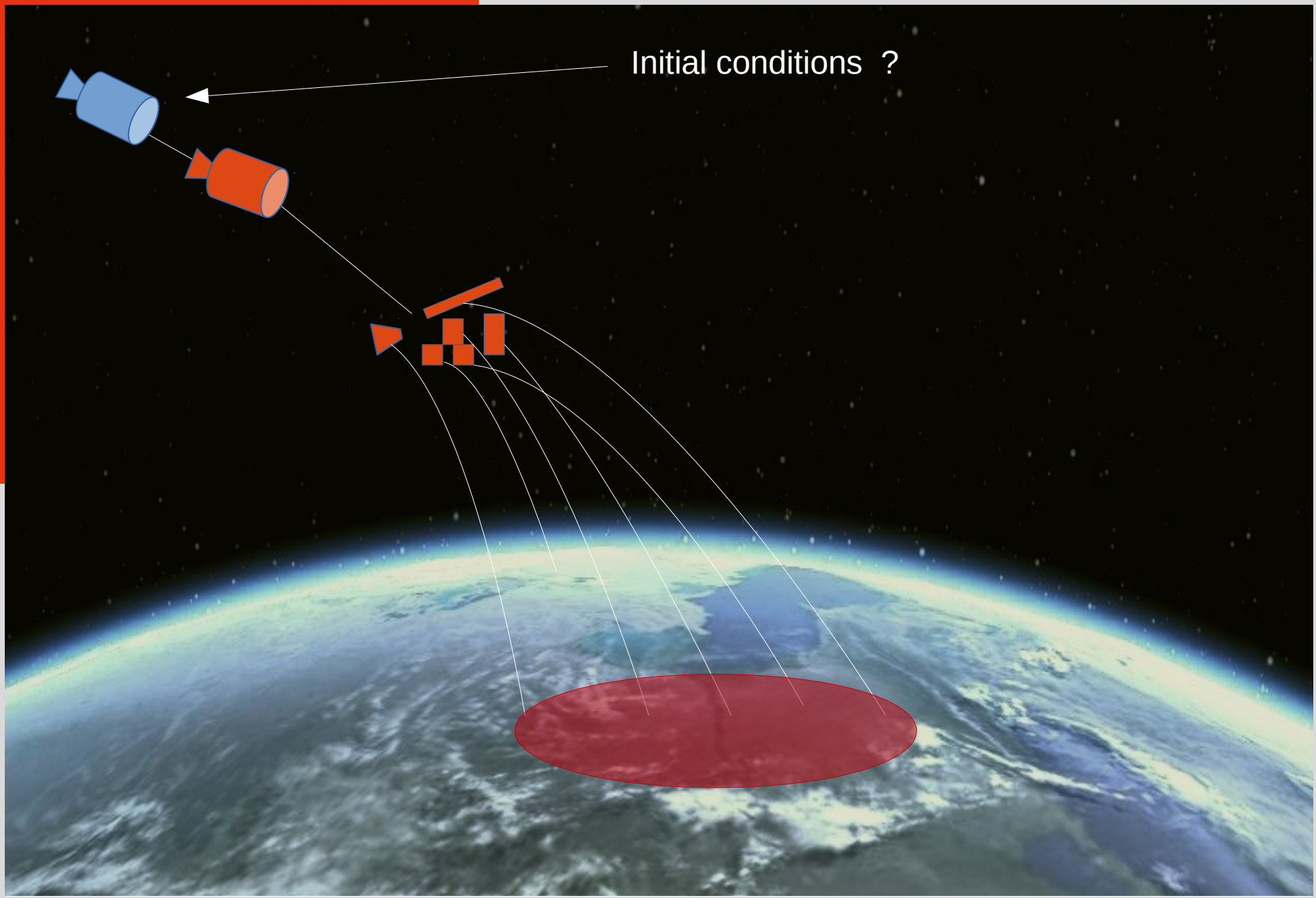


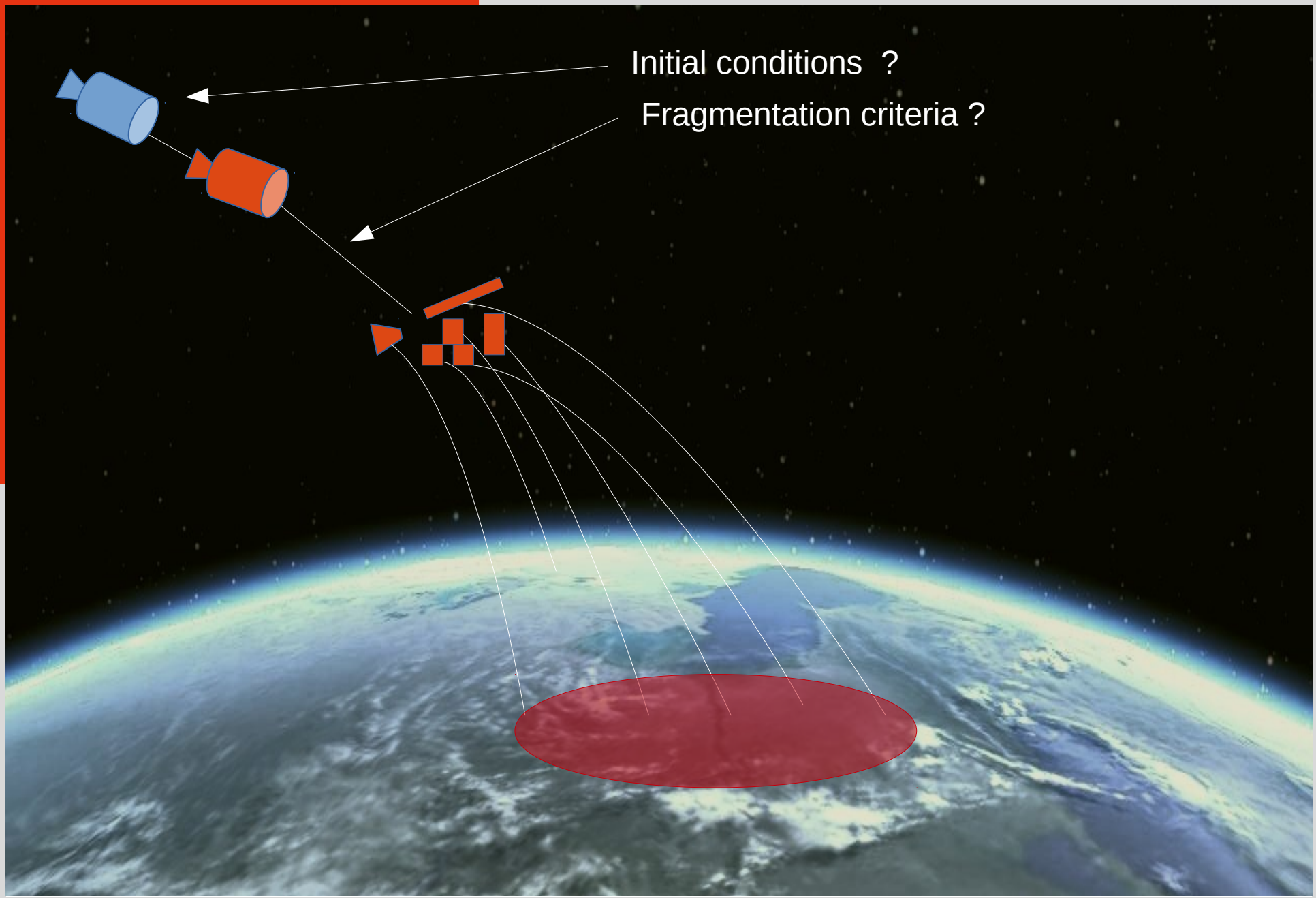


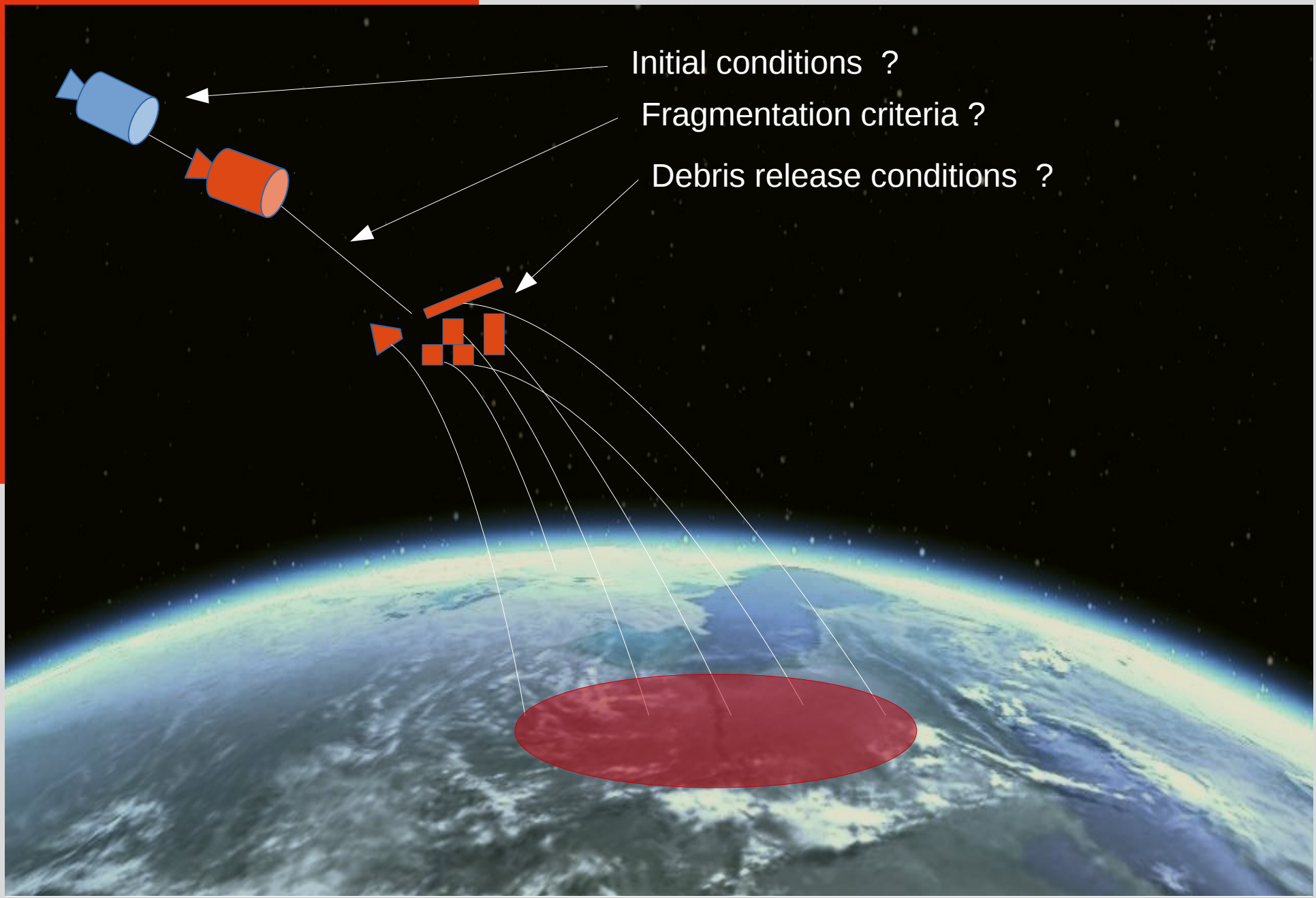


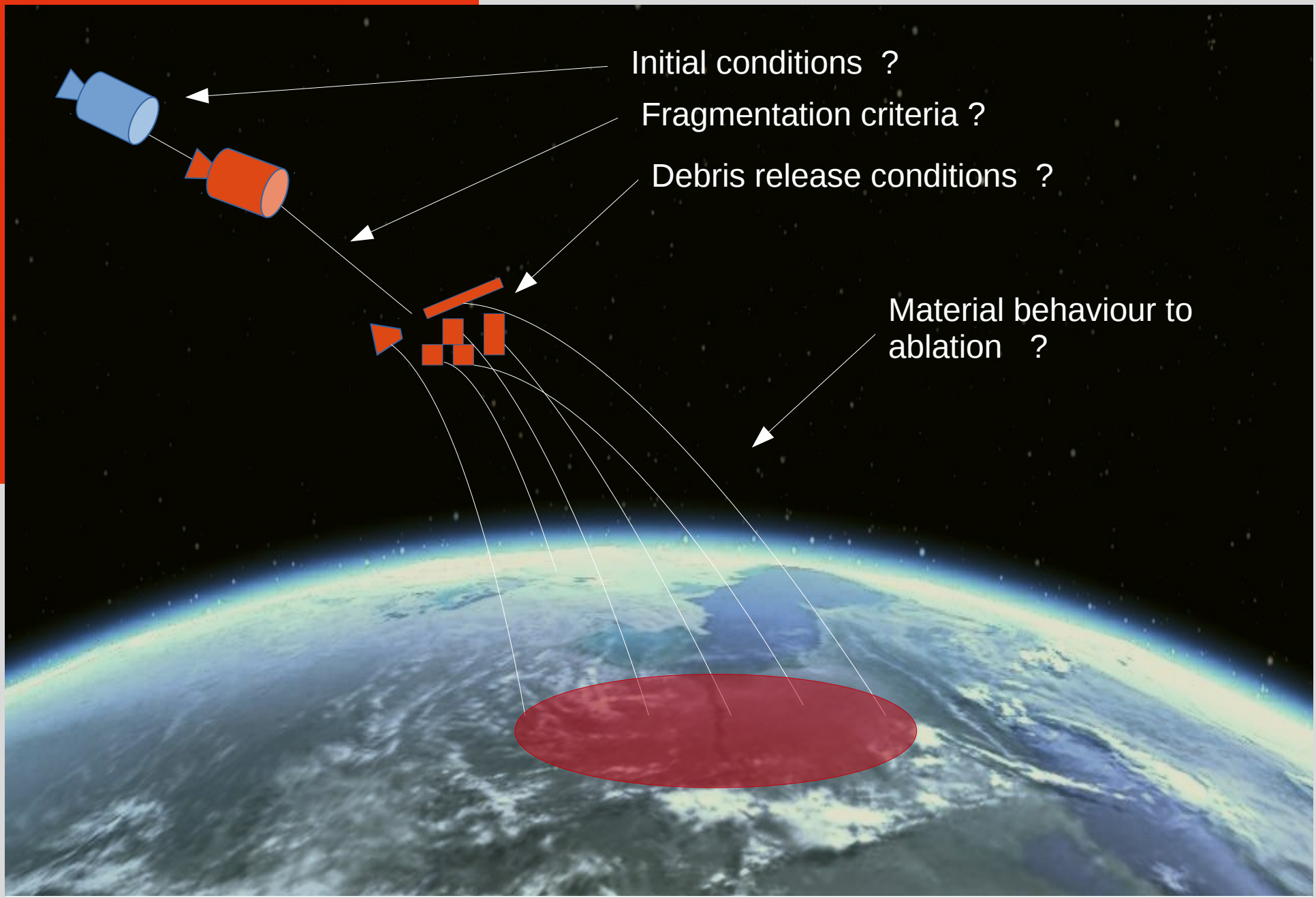





Initial conditions ?


Initial conditions ?
Fragmentation criteria ?

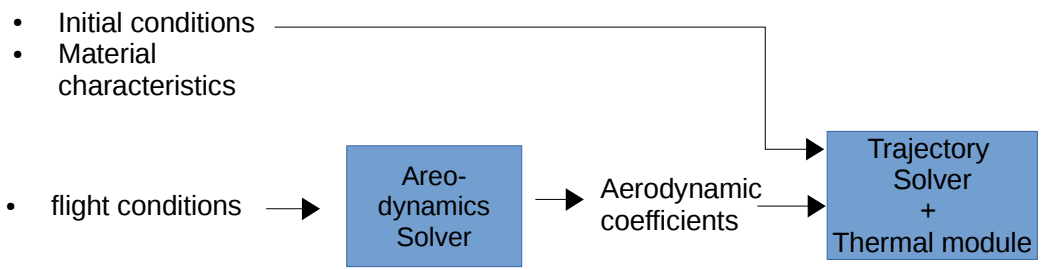

Initial conditions ?
Fragmentation criteria ?
Debris release conditions ?


Initial conditions ?
Fragmentation criteria ?
Debris release conditions ?
Material behaviour to ablation ?

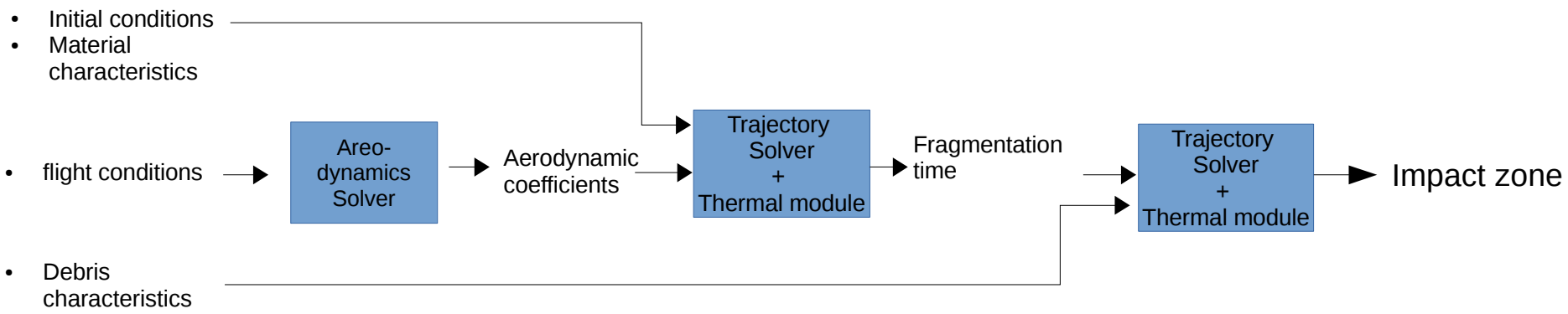
Architecture of the system

- flight conditions → Areo-dynamics Solver → Aerodynamic coefficients

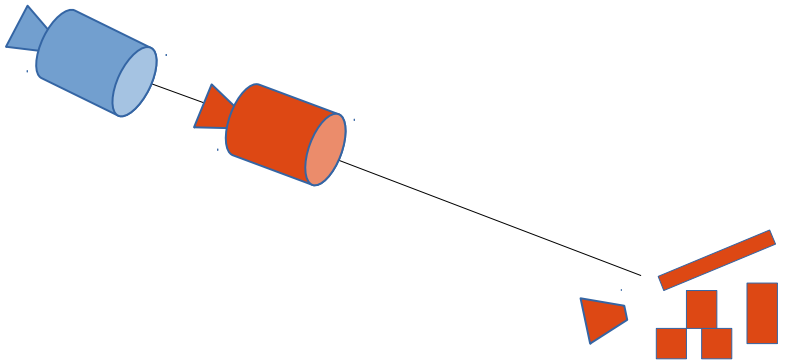
Architecture of the system

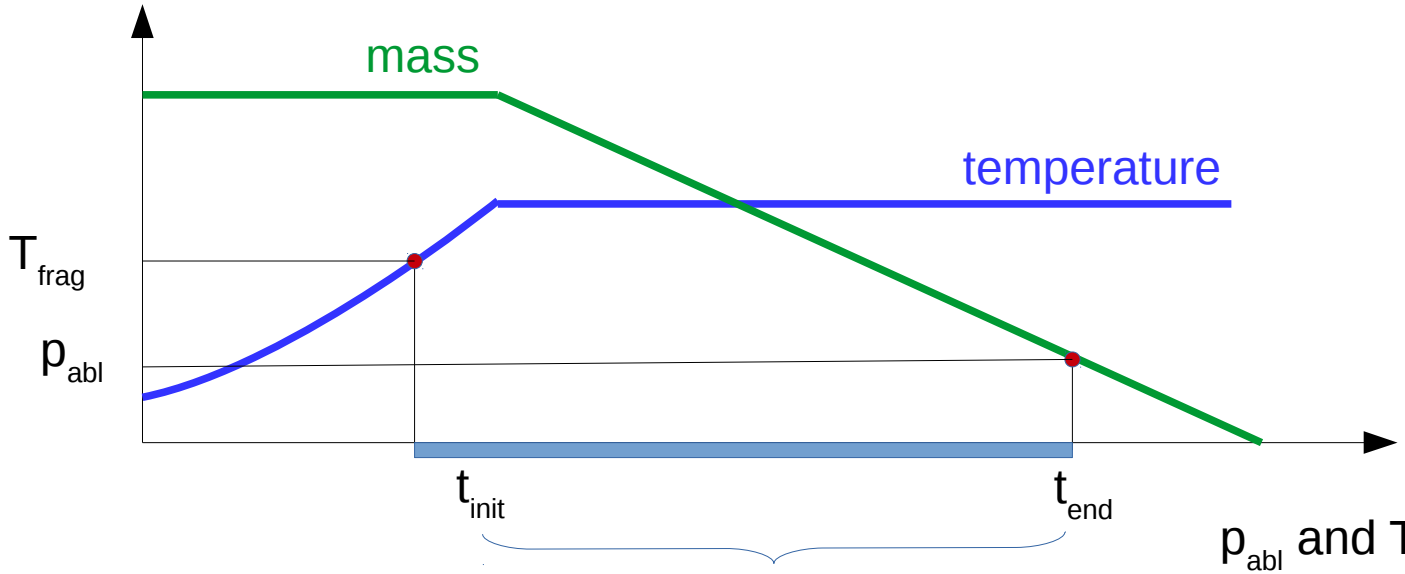


Architecture of the system

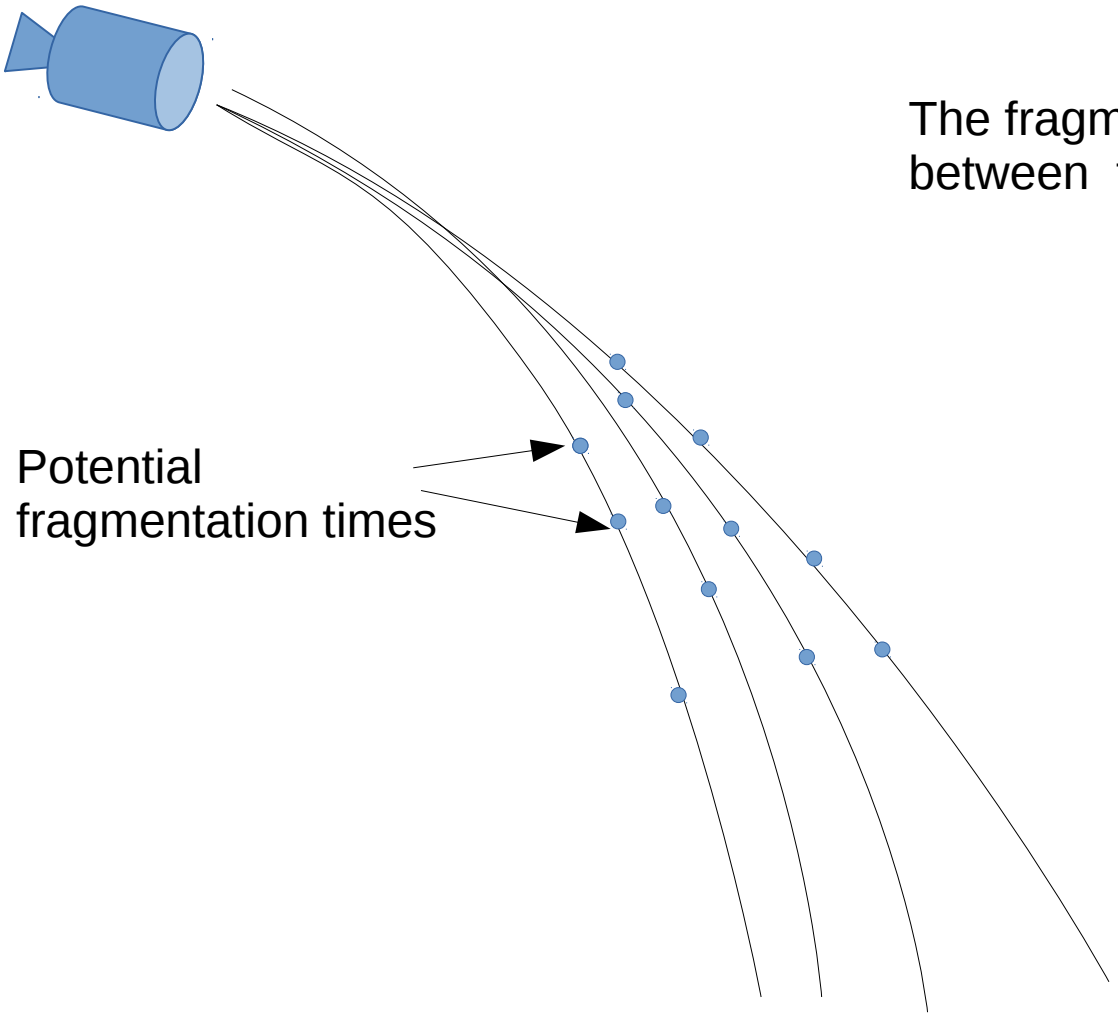


Probabilistic modeling of fragmentation



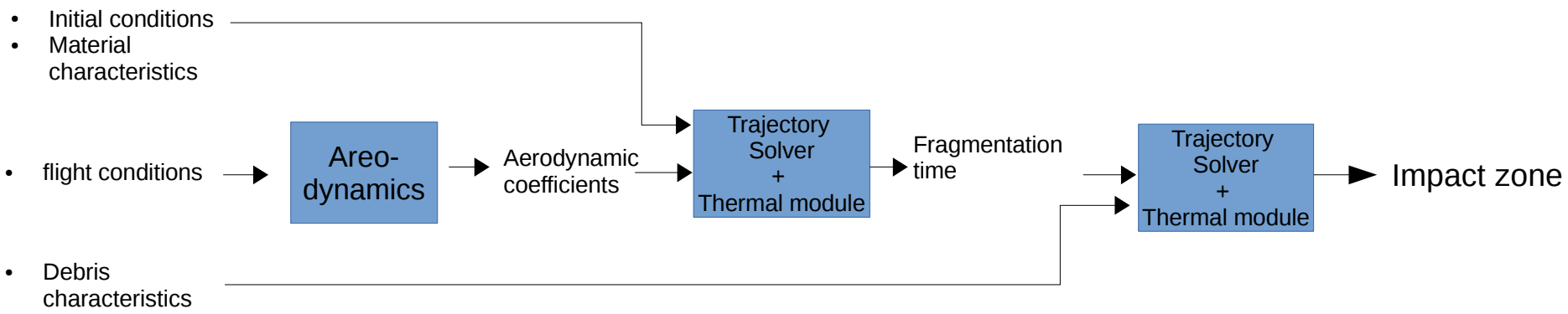


p_{abl} and T_{frag} are additional uncertainties

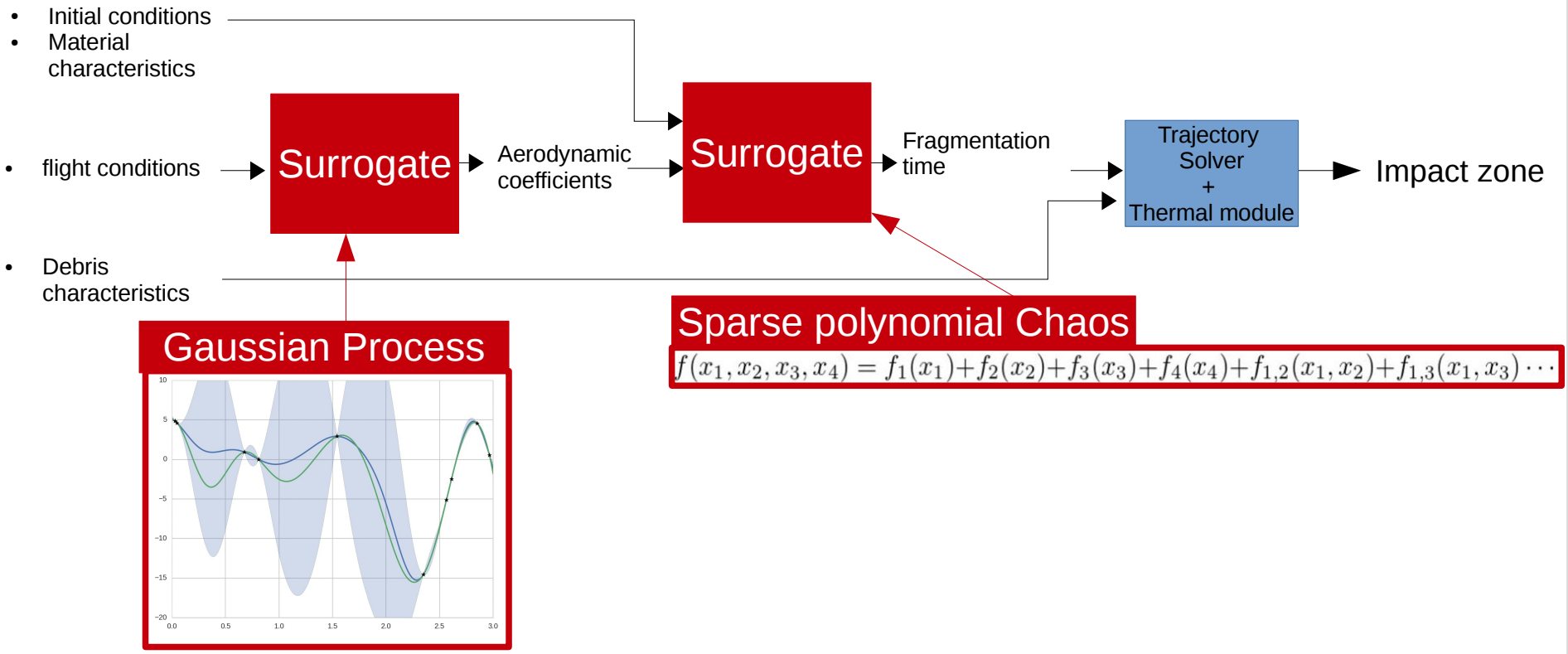


The fragmentation occurs at random between t_{init} and t_{end}

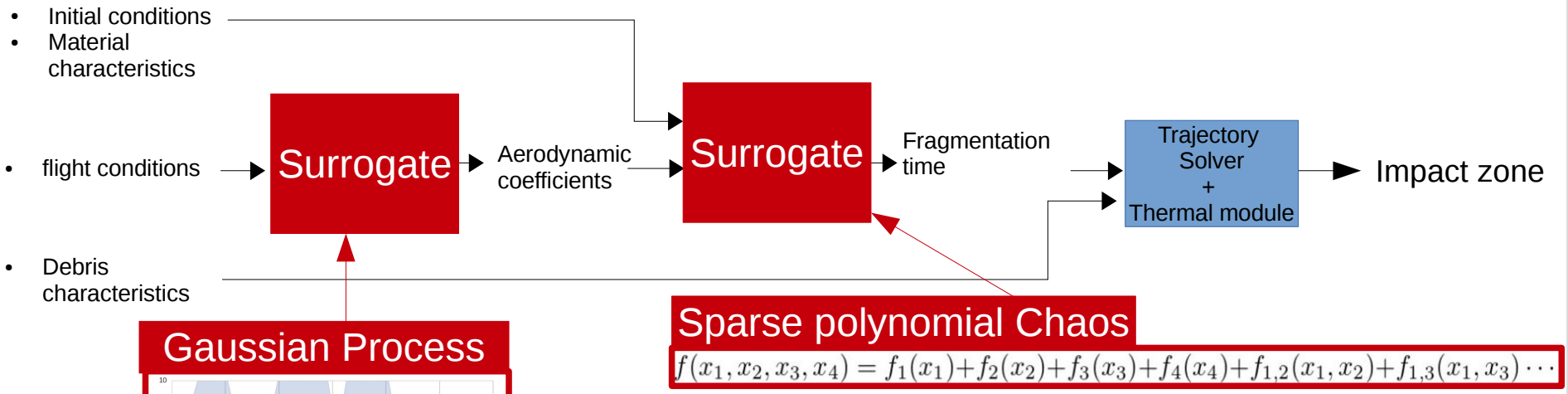
Efficient trajectory sampling



Efficient trajectory sampling



Efficient trajectory sampling



Computational cost cut down by orders of magnitude

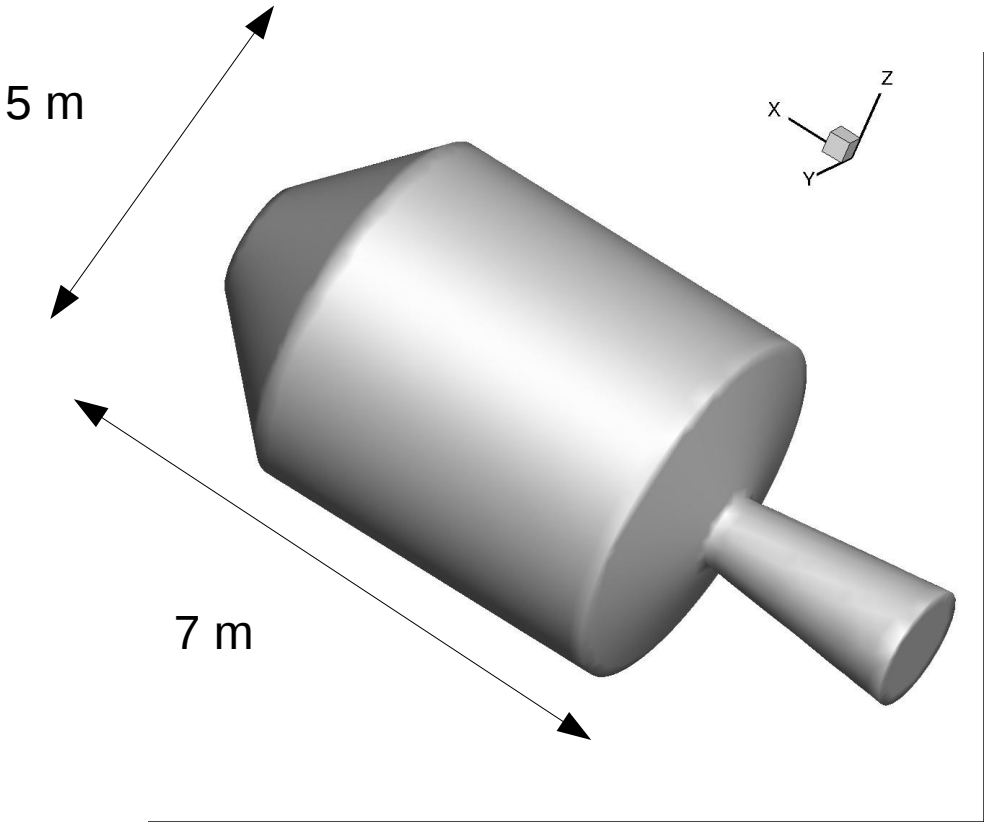
Cases under investigation

Object characteristics :

- Mass : 7000 kg
- Material : aluminium

Scenario :

- Controlled reentry from GTO orbit



Uncertainties characterization :

Initial conditions :

- Longitude : **179** ± 2.5 degrees
- Latitude : **5.65** ± 0.11 degrees
- Velocity : **9802** ± 4 m/s
- Slope : **-8.5** ± 1.5 degrees
- Bearing : **92.2** ± 0.3 degrees
- Orientation : uniform

Atmosphere conditions :

- Solar flux
- Magnetic index
- Time

from LS-TS-1-X-08-CNES-FR Ed5-R0

Material uncertainties :

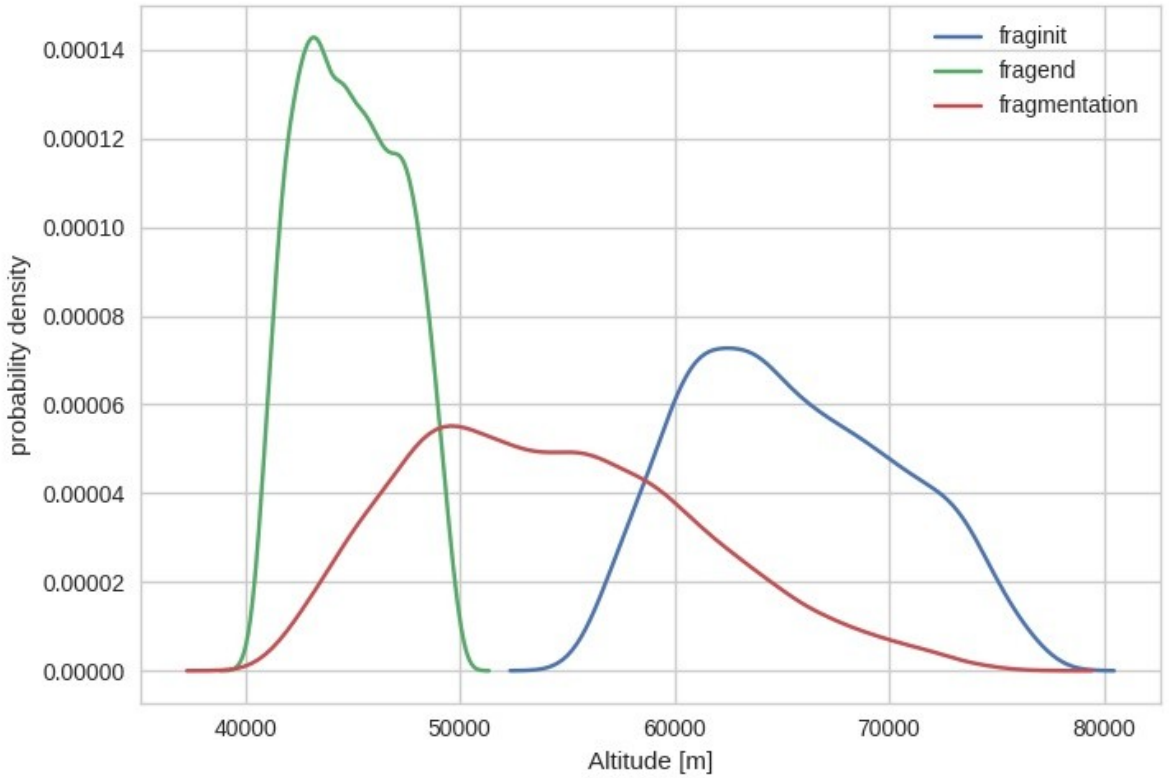
- Density
- Emissivity
- Tfusion
- Hfusion

Fragmentation model parameters :

- T_{frag} : [400,700] K
- P_{abl} : [0.5, 0.7]

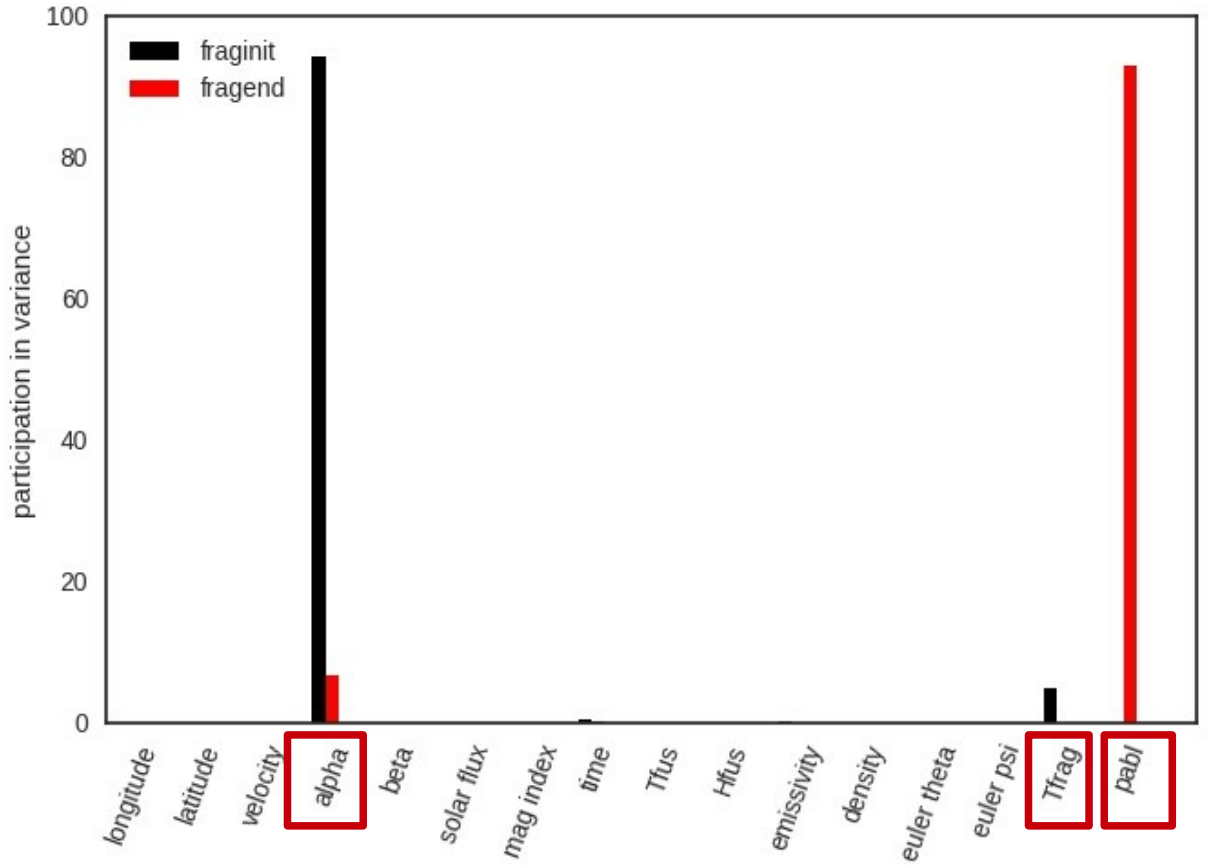
Fragmentation predictions

Fragmentation range :



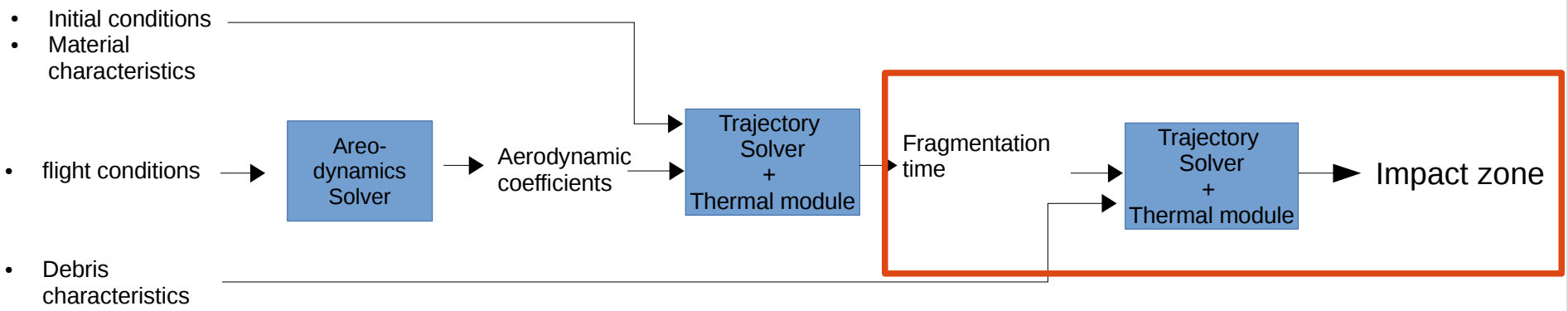
Sensitivity analysis :

Variance contribution of the uncertain inputs (Sobol indices)



Survivability predictions

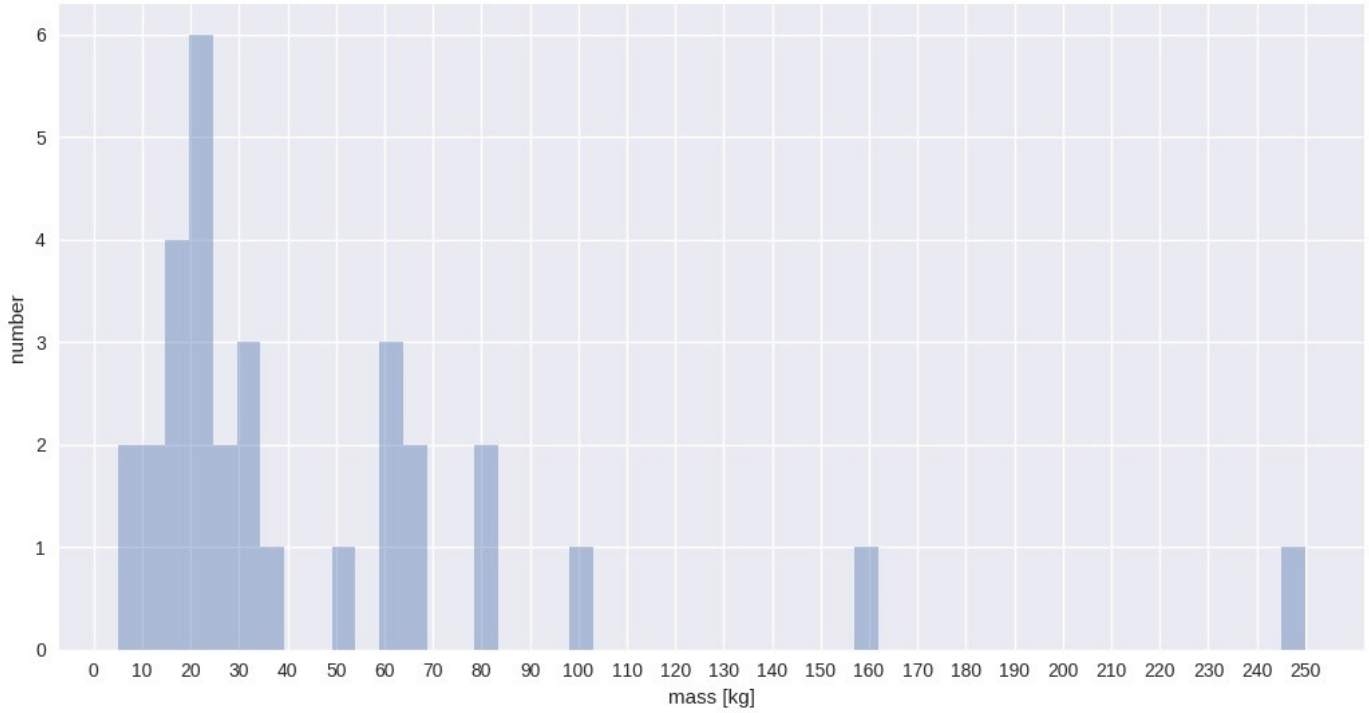
Architecture of the system



Debris properties

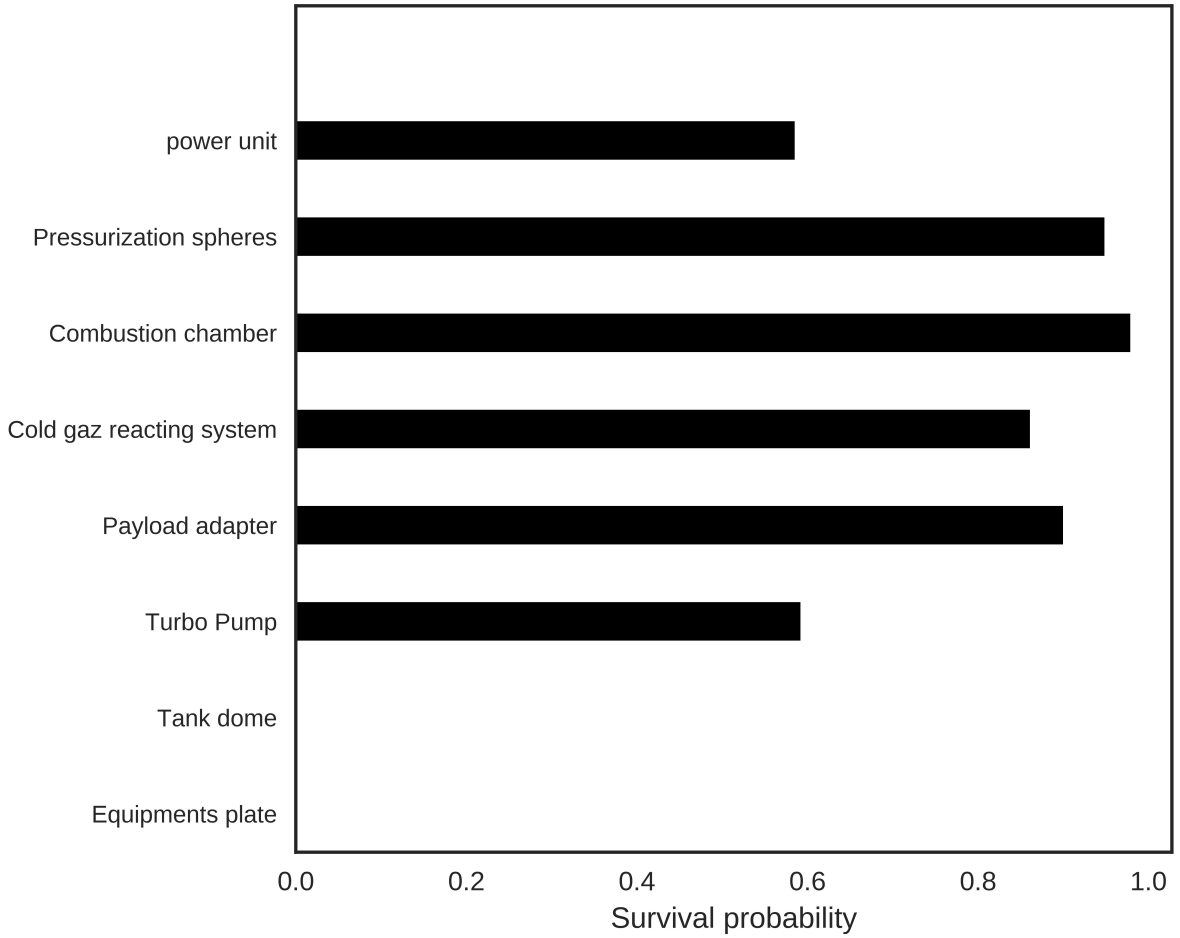
29 debris associated with a launcher upper stage:

- Boxes, flat plates, cylinders, spheres
- Total mass : 1417kg
- Material : Aluminium (58%), Inconel (26%), Titanium (8 %), Steel (7%)

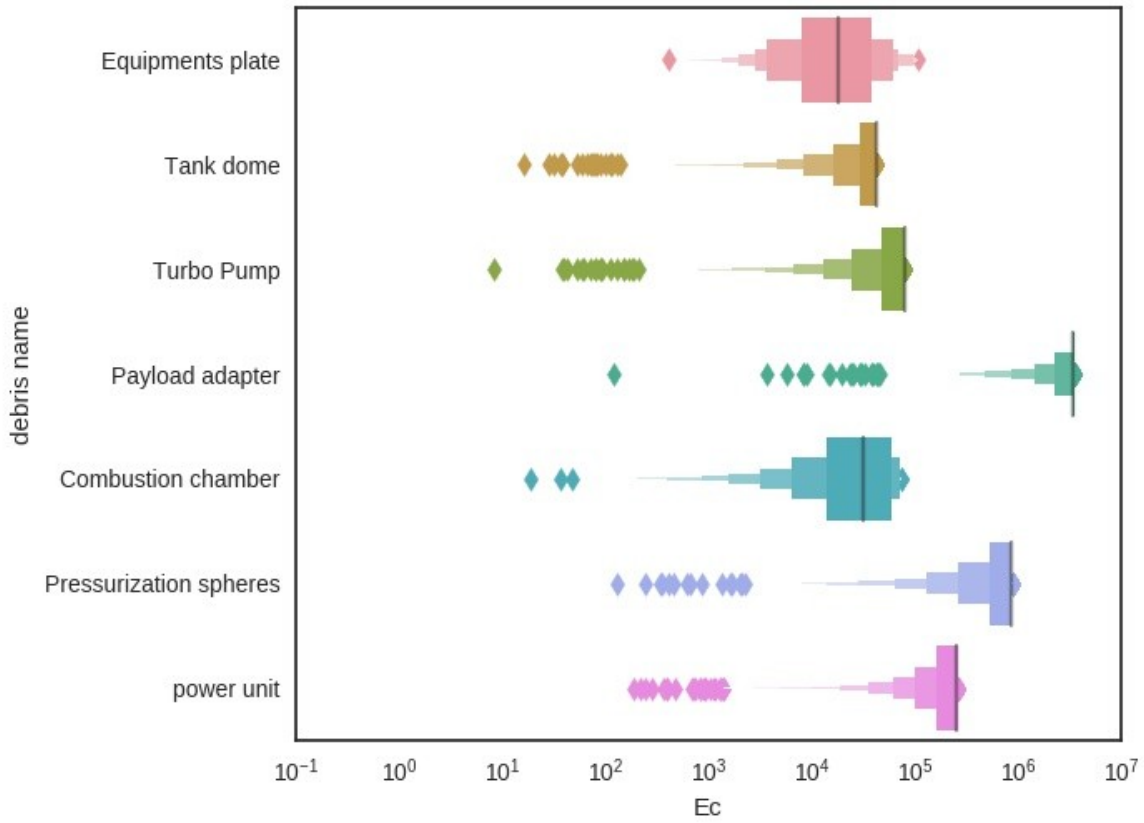


Survivability probability

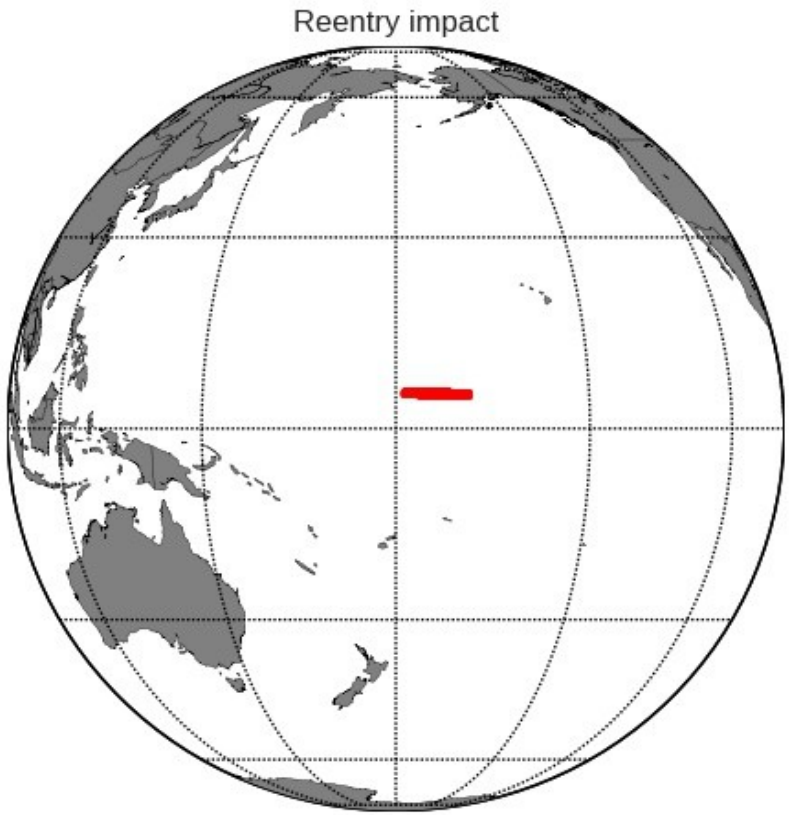
What is the probability for a given object to reach the ground ?



Impact energy of the surviving debris



Impact zone



Covered area : 44 396 km²

Conclusions :

- Developed a robust reentry predictor using simple models
- The use of advanced uncertainty quantification tools cut down computational cost
- Most of the uncertainties come from fragmentation model parameters
- More accurate models and methods for estimating the ground footprint are to be implemented

Thank you

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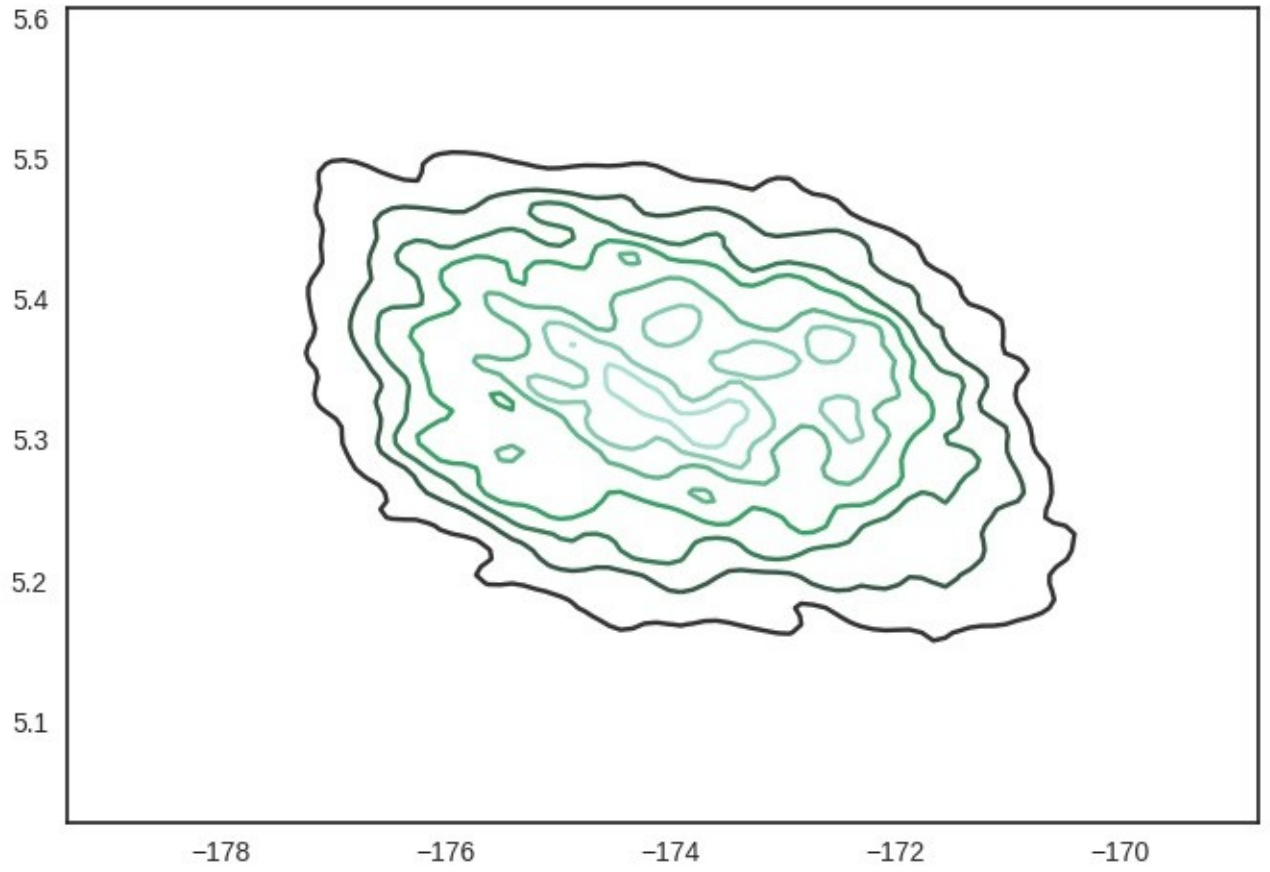
Impact zones



Uncertainty quantification tools :

Sparse Chaos Polynomial Decomposition

Use ANOVA decomposition coupled with sparse polynomial regression

$$f(x_1, x_2, x_3, x_4) = f_1(x_1) + f_2(x_2) + f_3(x_3) + f_4(x_4) + f_{1,2}(x_1, x_2) + f_{1,3}(x_1, x_3) \cdots$$

Sparse polynomial approximation of each terms

Efficient for computing Sobol indices or variance contribution of the inputs

$$S_i = \frac{Var[E[Y|X_i]]}{V[Y]}$$

variance due to X_i

Total variance

Computational cost **with surrogate : 5000**
Computational cost **without surrogate : several millions**

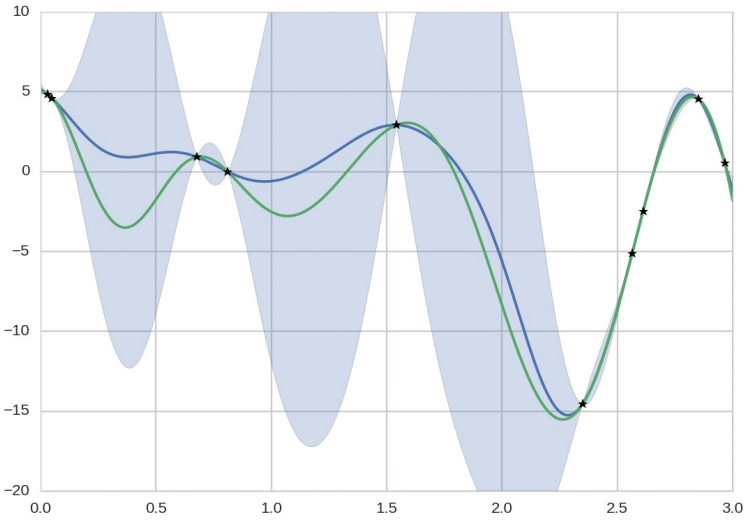
Uncertainty quantification tools :

Gaussian Processes

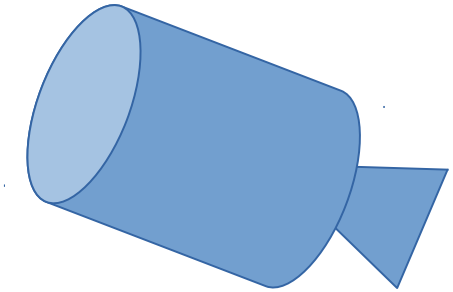
Surrogate model construction with predictive error estimation

Used to generate Aerodynamic table with less than 0.2% error :

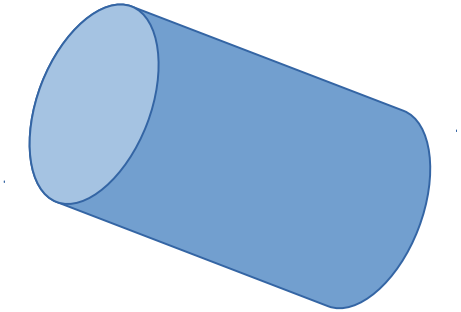
Computational cost **with surrogate : 1500**
Computational cost **without surrogate : 10 000**



Low fidelity approach for fragmentation



Aerodynamics



Thermal model

- Model the upper stage as a cylinder with same weight and volume
- Model heat flux with analytical formulae (Adryans 0D)
- Use 0D model for estimating time of fusion
- Fragmentation will occur at some (random) time during fusion