Probabilistic modelling of space object controlled reentry and ground risk estimation

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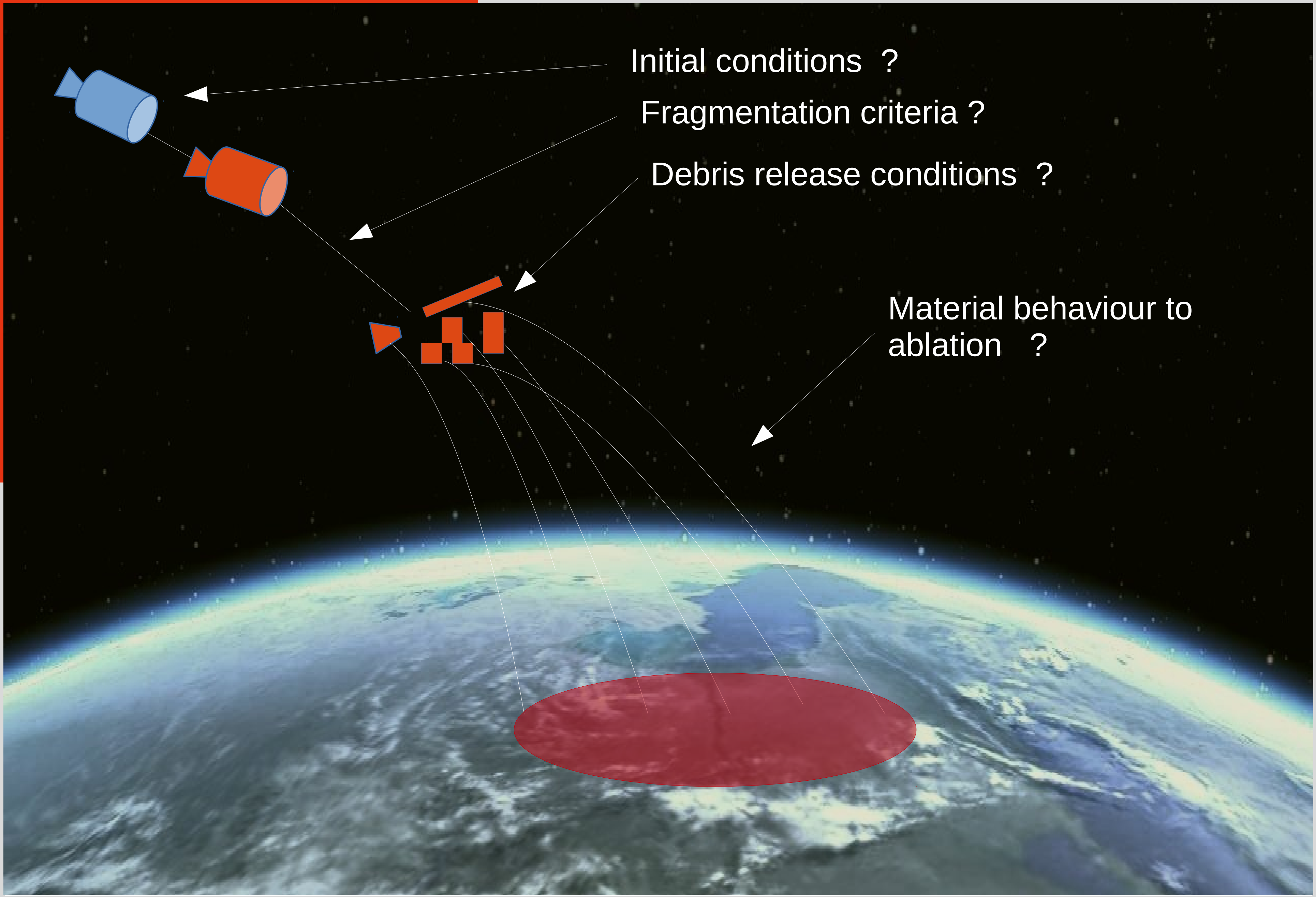
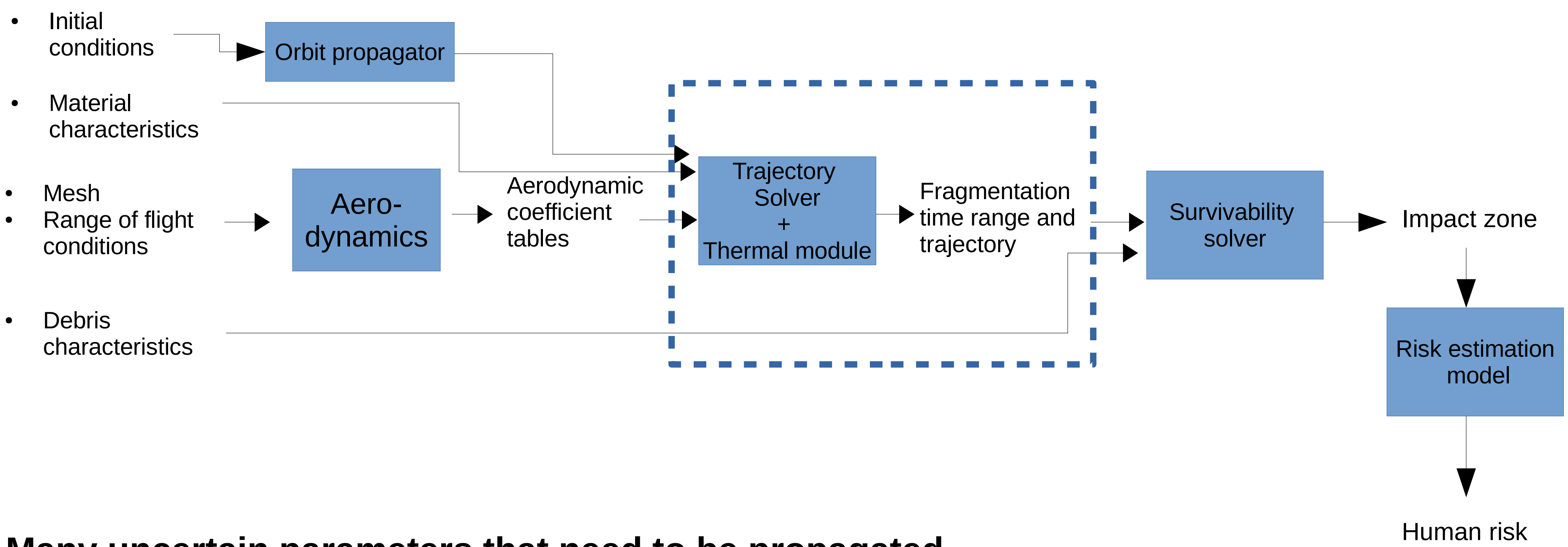


Initial conditions ?
Fragmentation criteria ?
Debris release conditions ?
Material behaviour to ablation ?

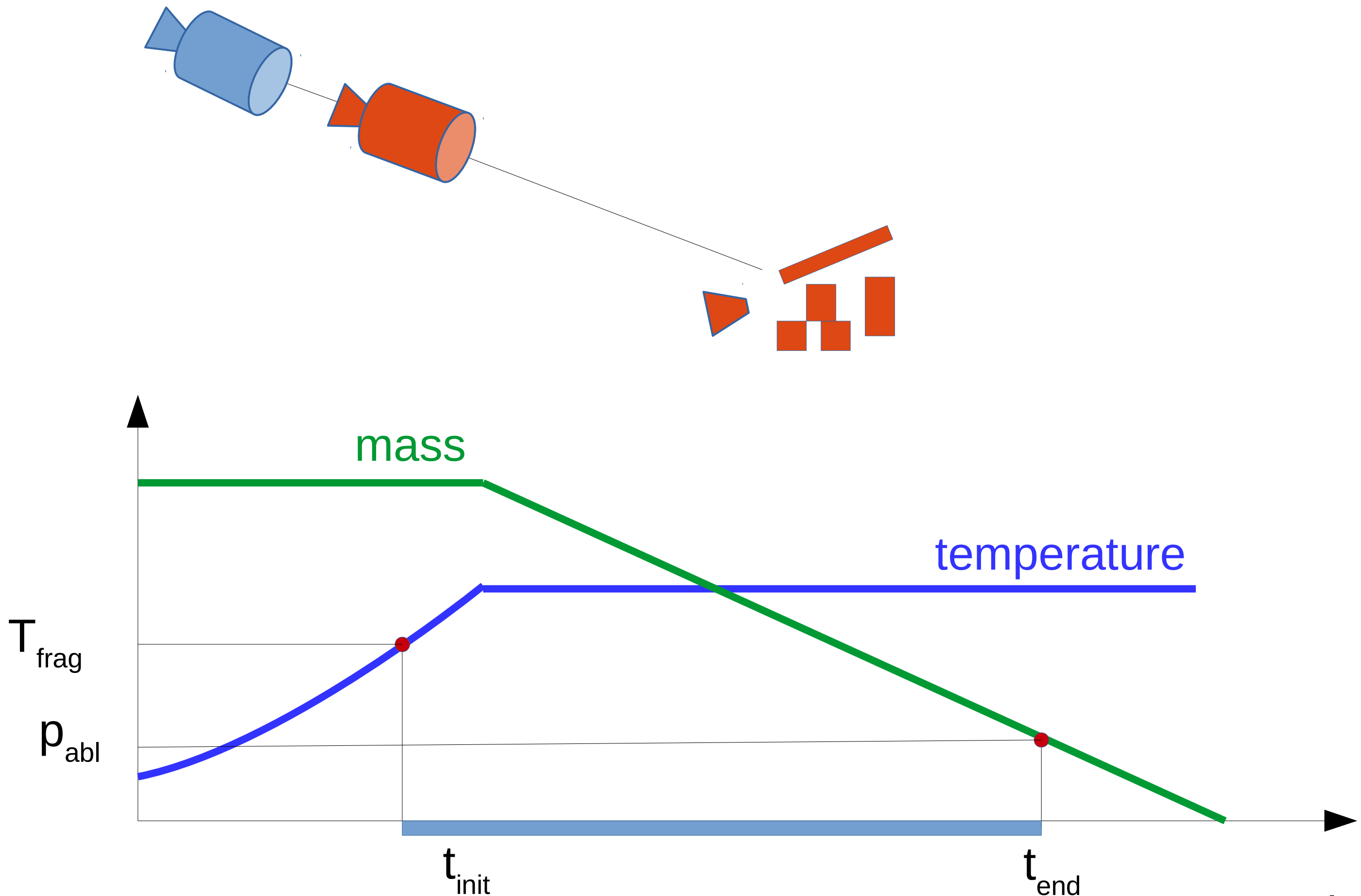
System of solvers for reentry trajectory predictions



Many uncertain parameters that need to be propagated

Brute force Monte Carlo propagation is out of reach

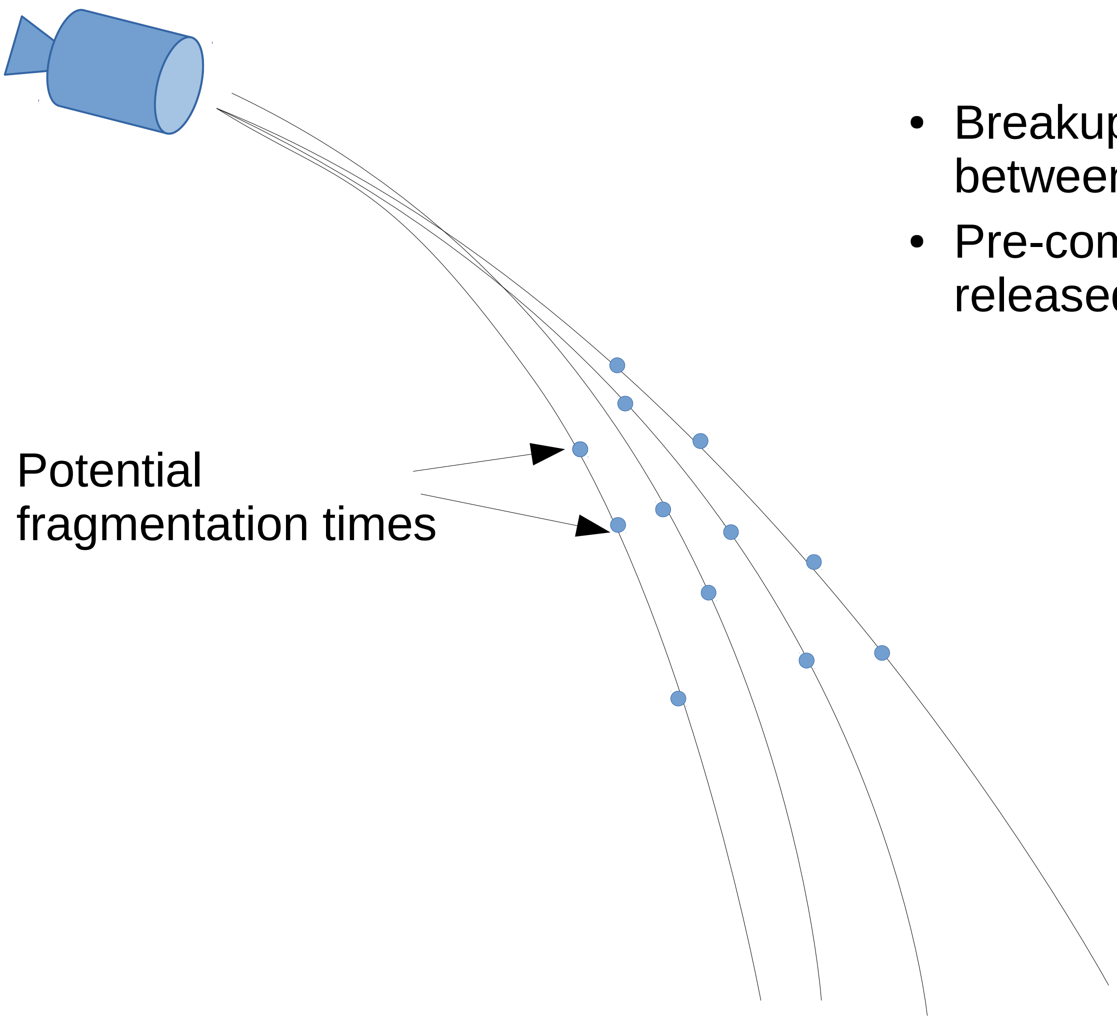
Probabilistic modeling of breakup



fragmentation range

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

- Breakup occurs at random between t_{init} and t_{end}
- Pre-computed fragments are released at breakup



Cases under investigation

GTO Reentry :

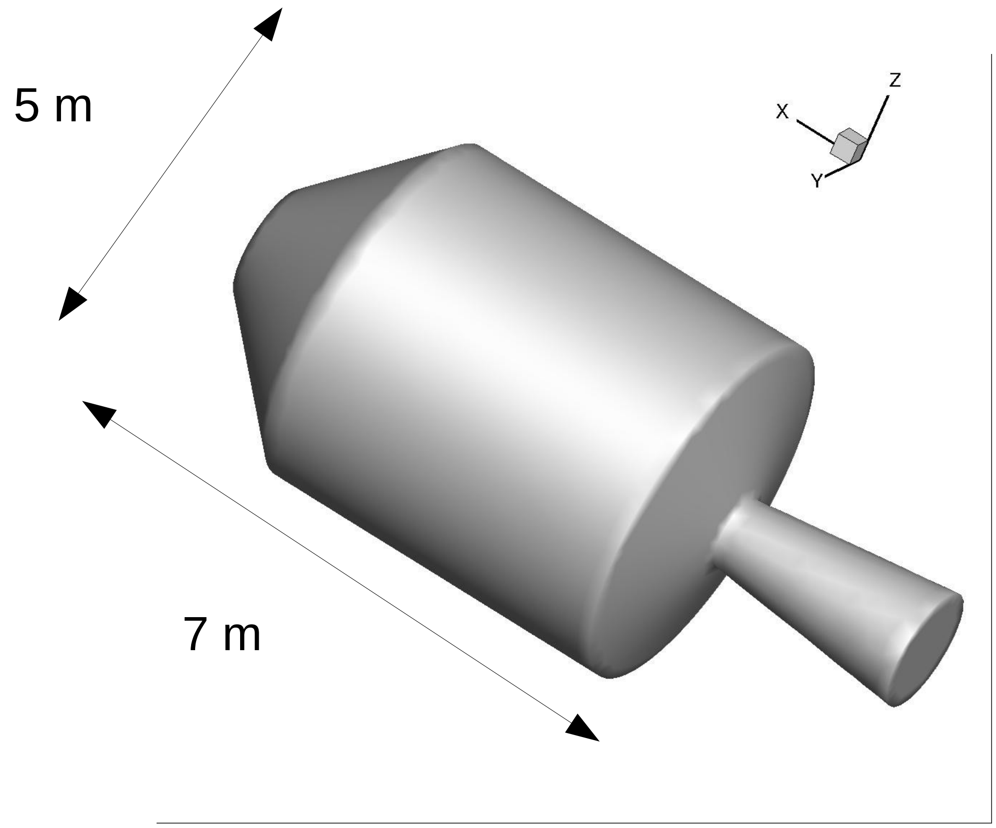
- Slope : -9 degrees
- Velocity : 9600 m/s
- Equatorial orbit

Object characteristics :

- Mass : 7000 kg
- Material : aluminium

Scenario :

- Controlled reentry



Uncertainties characterization :

Initial conditions :

- Boost time
- Boost orientation
- Orbital elements
- Upper Stage orientation : uniform

Material uncertainties : for Aluminium, Steel, Inconel, Titanium

- Density
- Emissivity
- Tfusion
- Hfusion

Atmosphere conditions :

- Solar flux : [65:240]
- Magnetic index : [2:75]
- Time : [0:365]

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

Fragmentation model parameters :

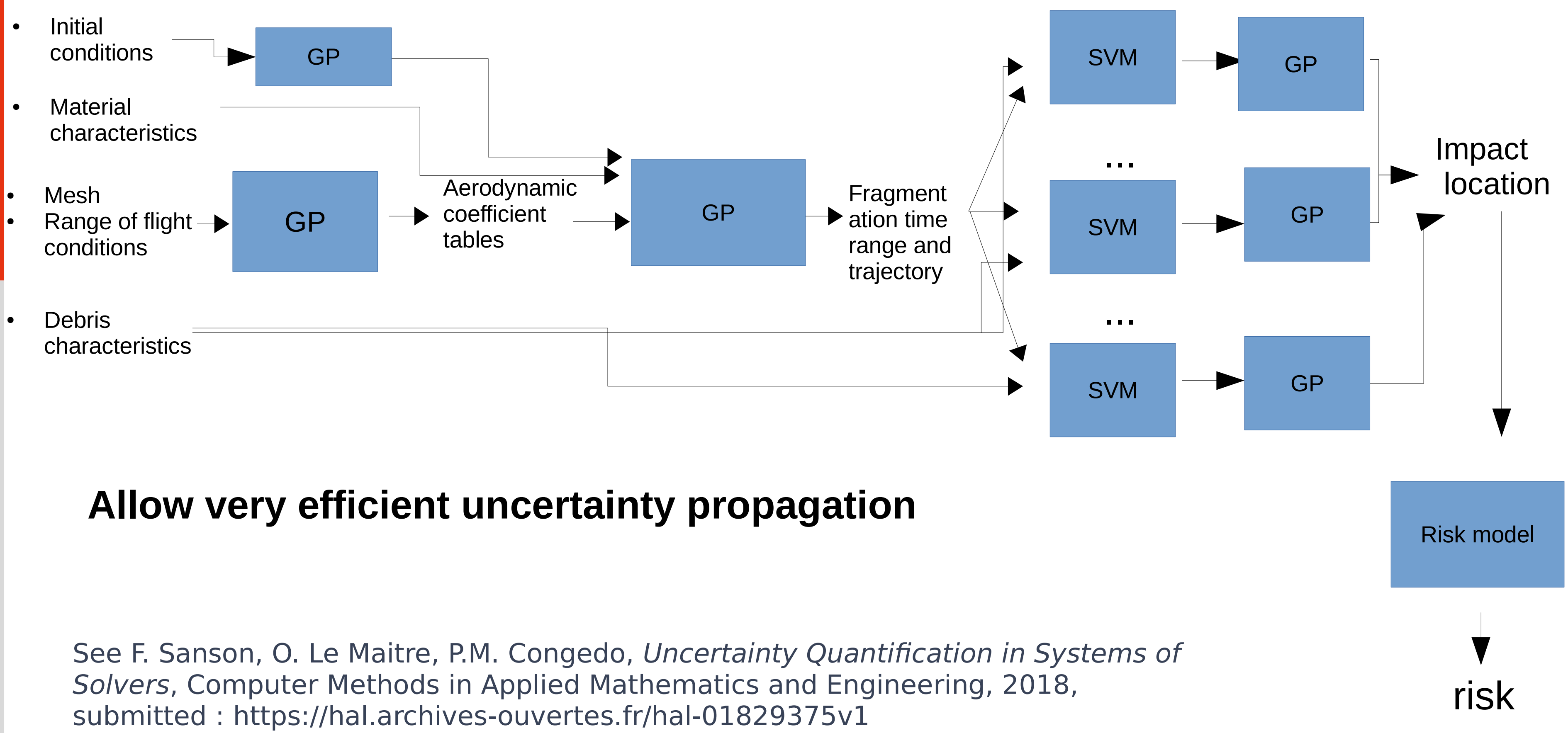
- T_{frag} : [400,700] K
- P_{abl} : [0.7, 0.9]

Total 38 uncertainties

Challenges with Uncertainty Quantification and probabilistic modelling

- Explore the potential outputs of a given probabilistic scenario → requires a lot of simulations
- Sensitivity Analysis : quantify the variation in the output due to variations in the inputs → requires a lot of simulations

Architecture of the system of surrogate models

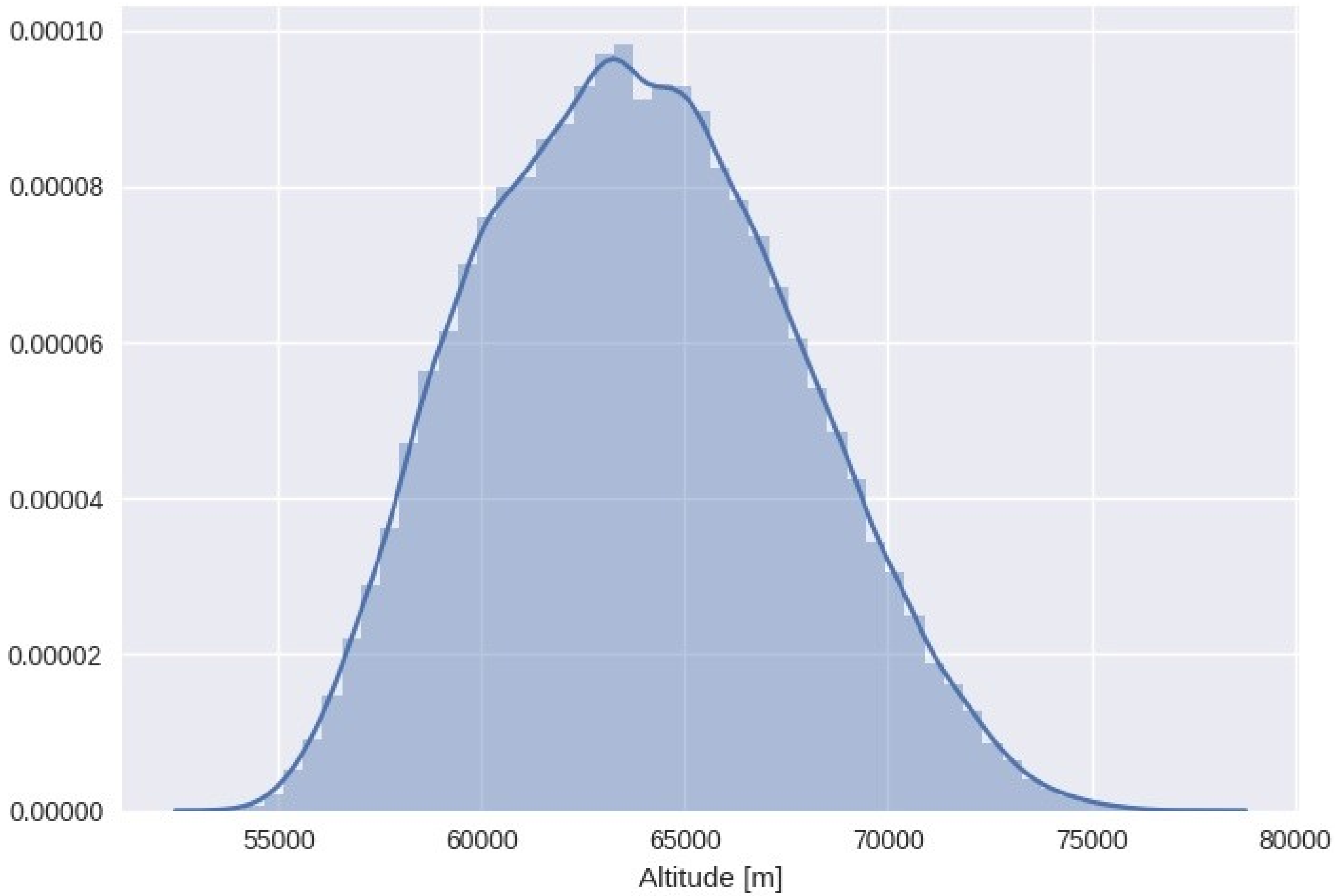


Allow very efficient uncertainty propagation

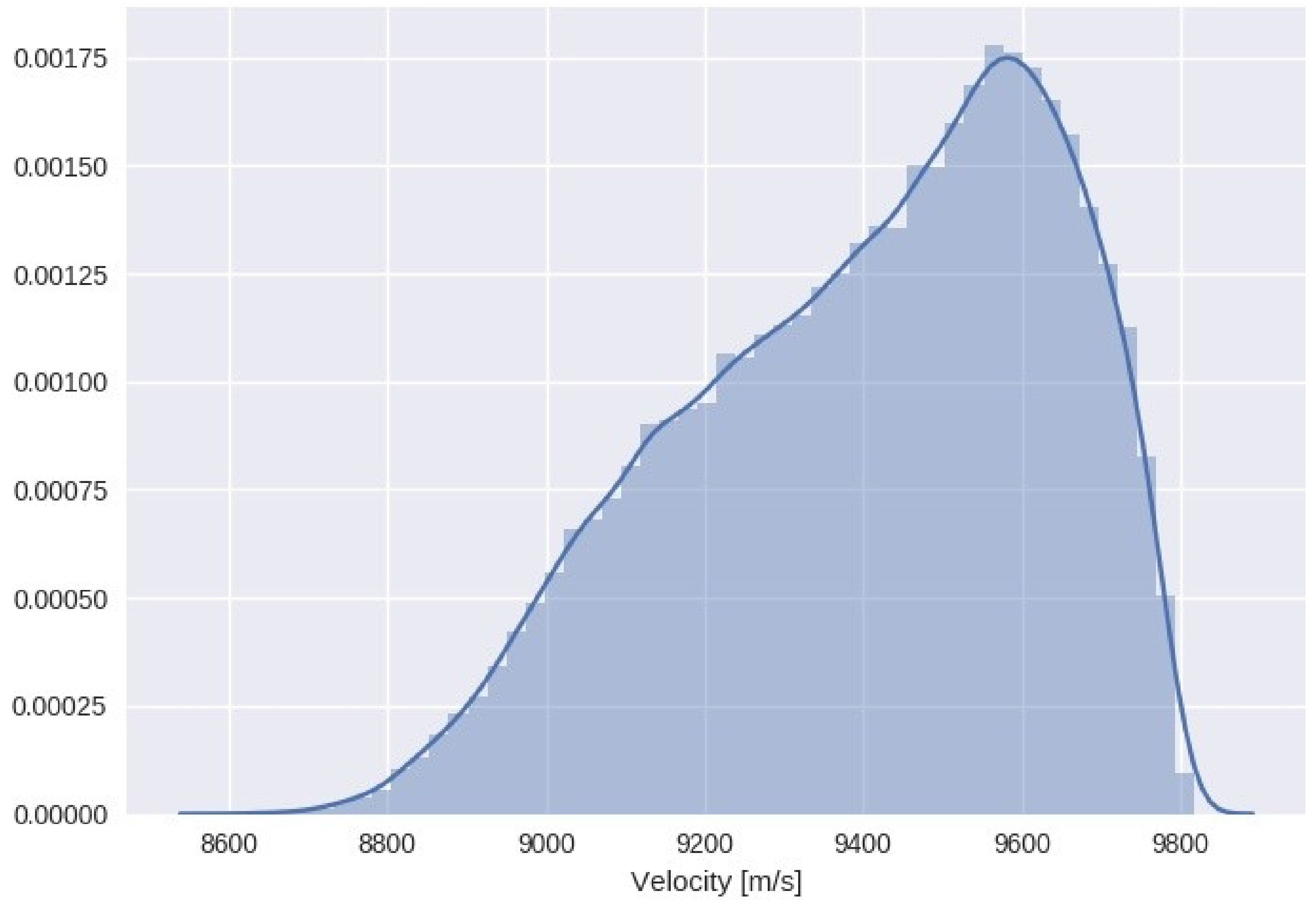
See F. Sanson, O. Le Maitre, P.M. Congedo, *Uncertainty Quantification in Systems of Solvers*, Computer Methods in Applied Mathematics and Engineering, 2018, submitted : https://hal.archives-ouvertes.fr/hal-01829375v1

Breakup predictions

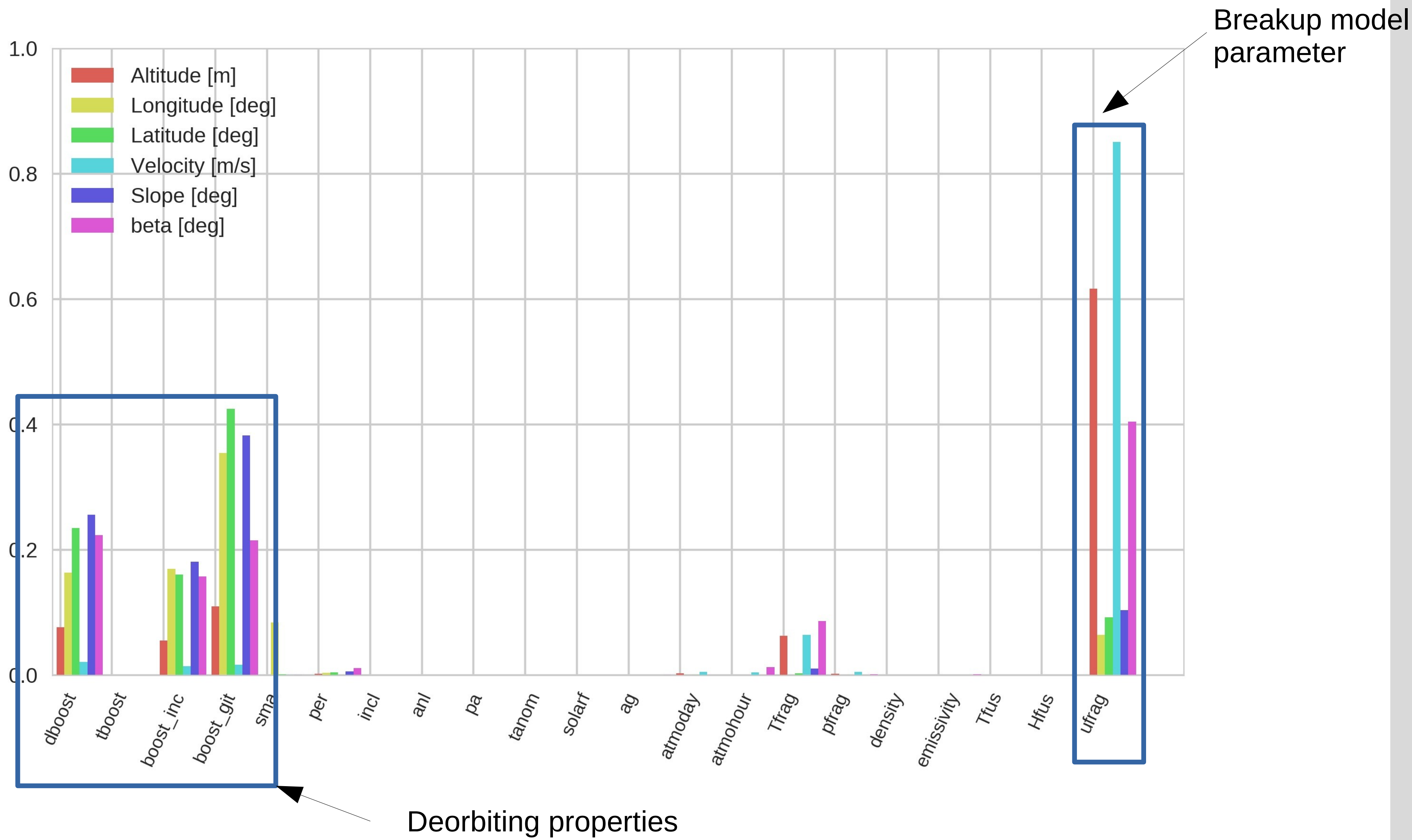
Altitude and velocity at breakup :



Altitude and velocity at breakup :



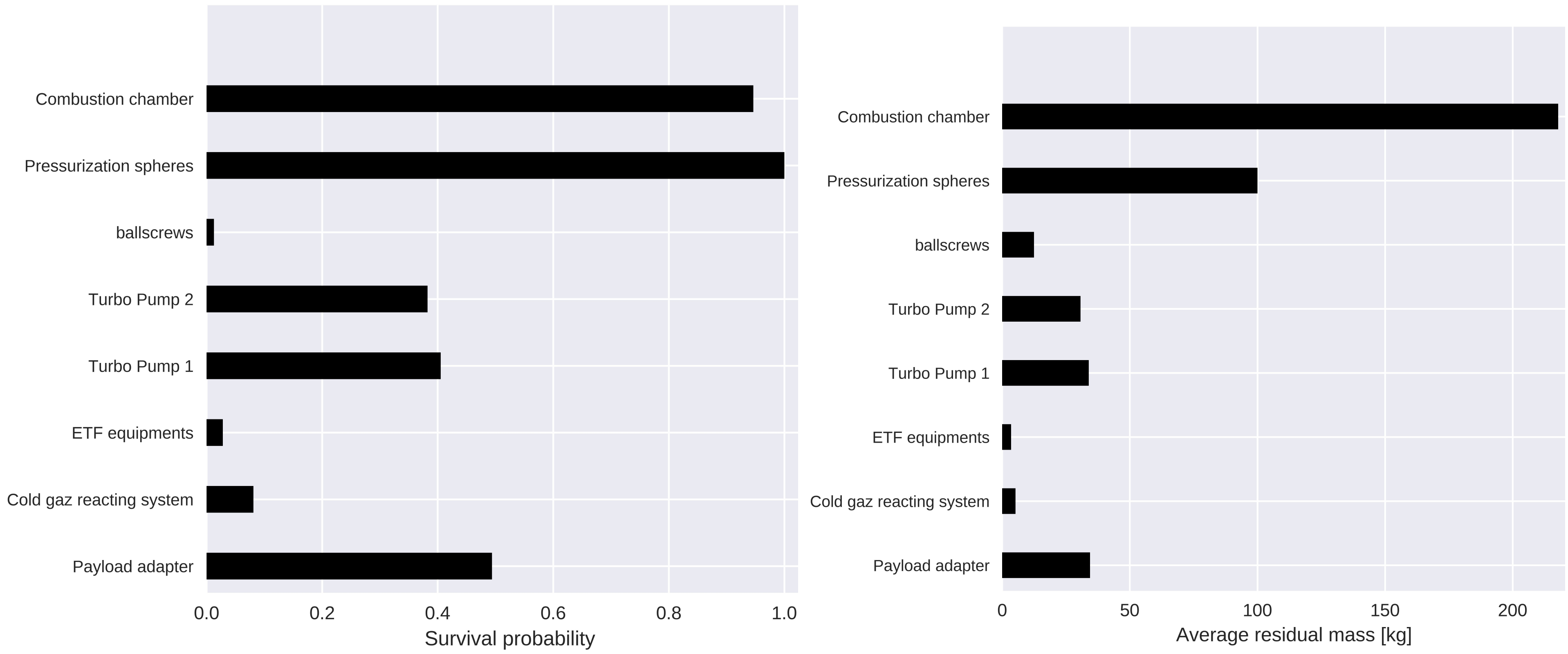
Identifying sources of uncertainties :



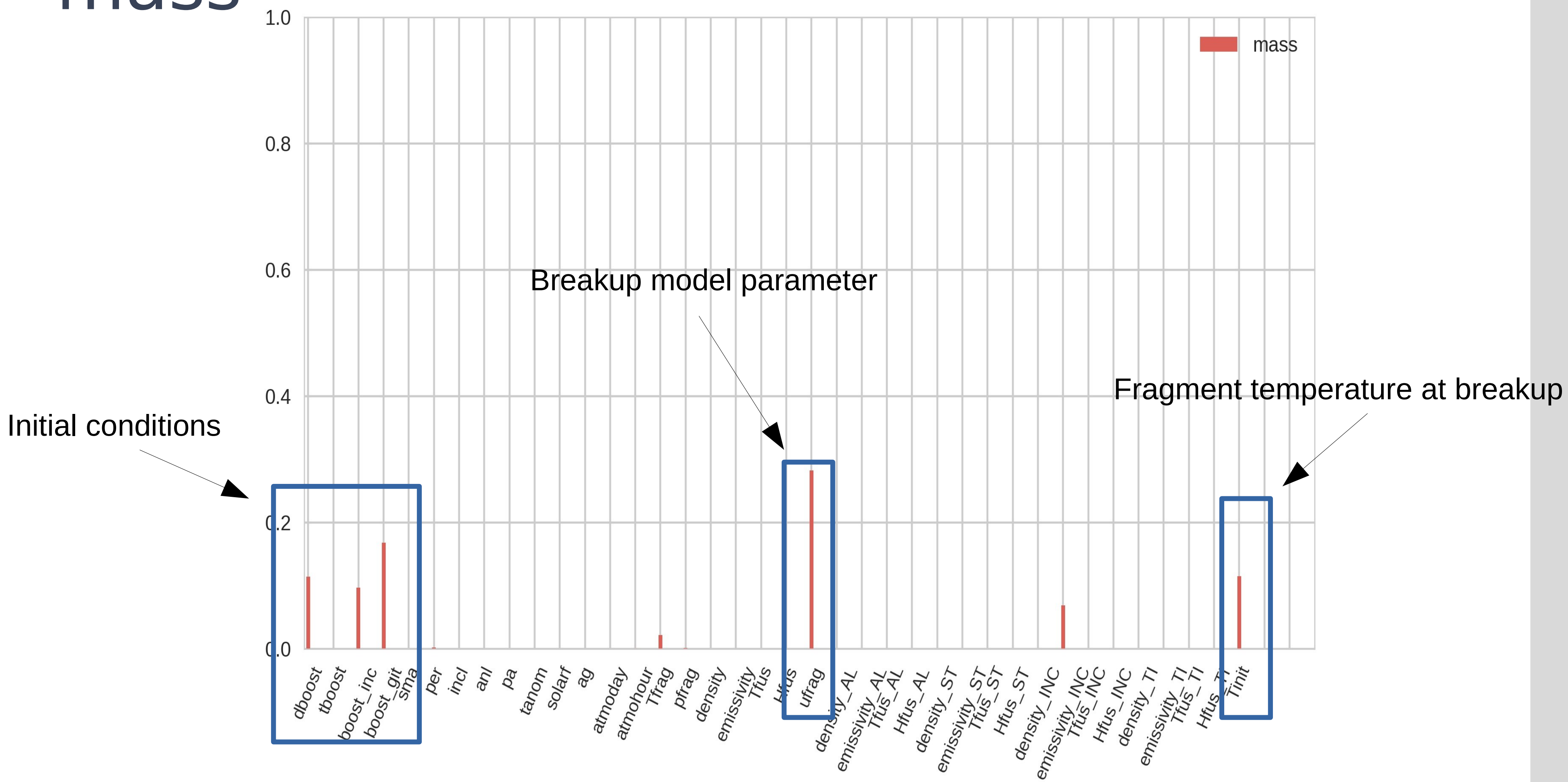
Survivability predictions

Survivability probability

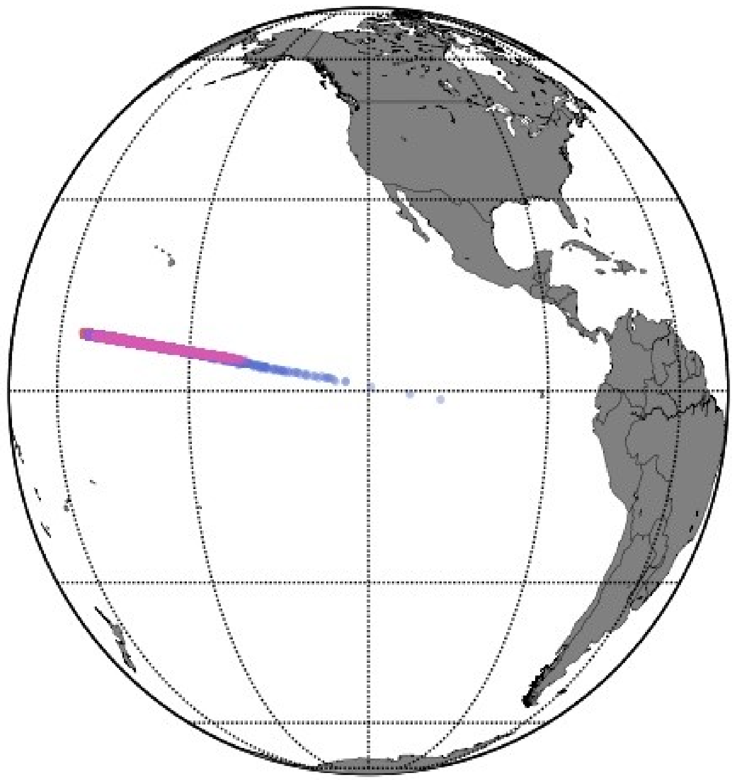
What is the probability for a given object to reach the ground ?

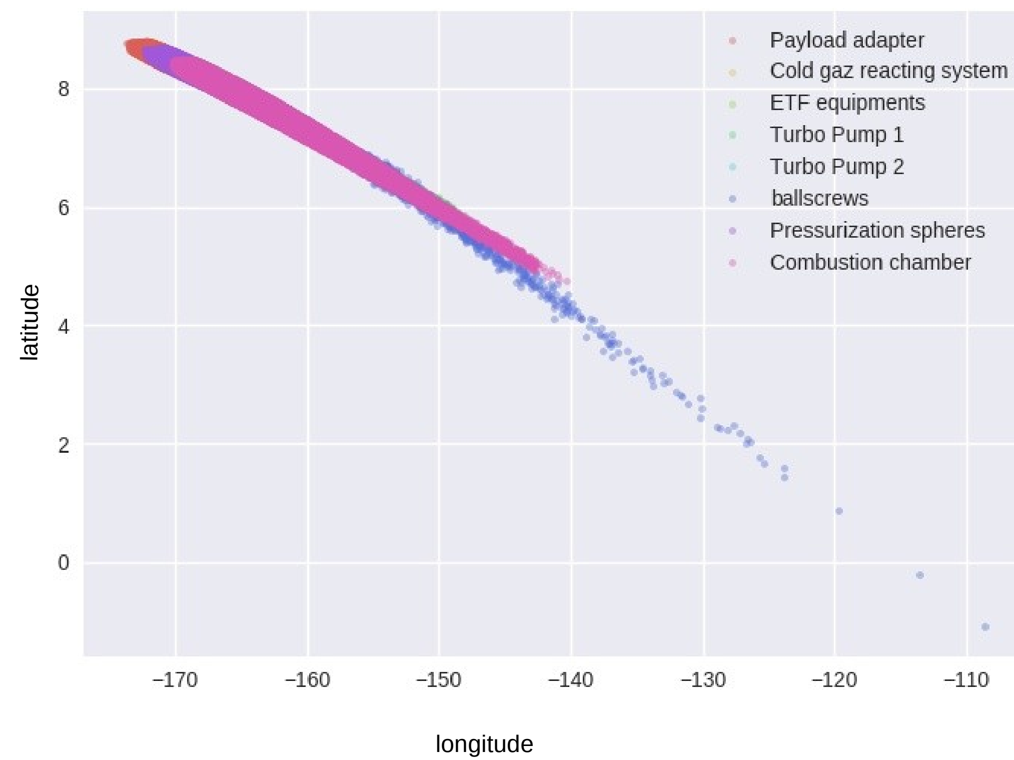


Sensitivity Analysis on the residual mass



Impact location



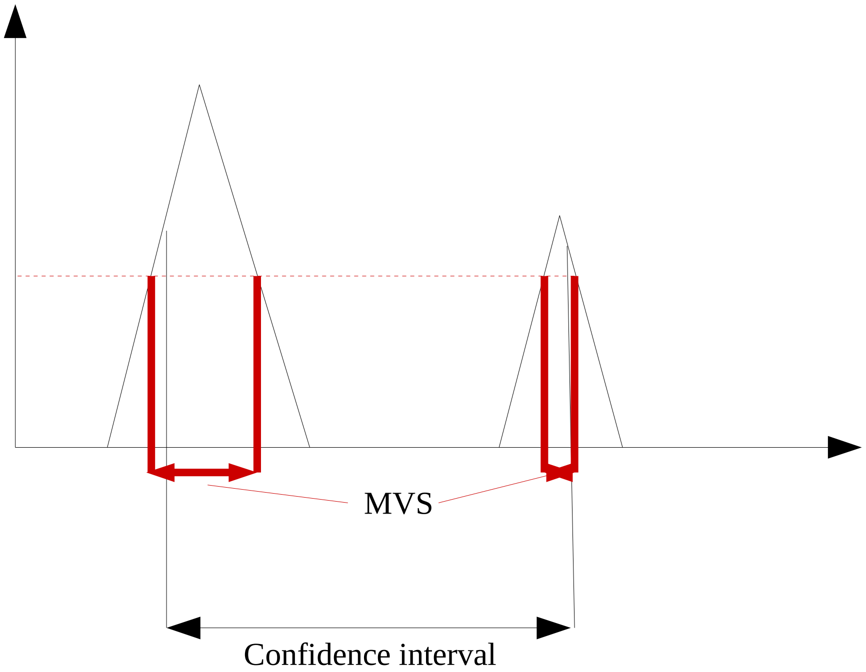


Impact zone using Minimum Volume Sets

- Generalization of confidence intervals

$$\min_{\Omega} \quad \mathrm{Vol}(\Omega) \text{ subject to } P(X \in \Omega) \geq 1 - \epsilon$$

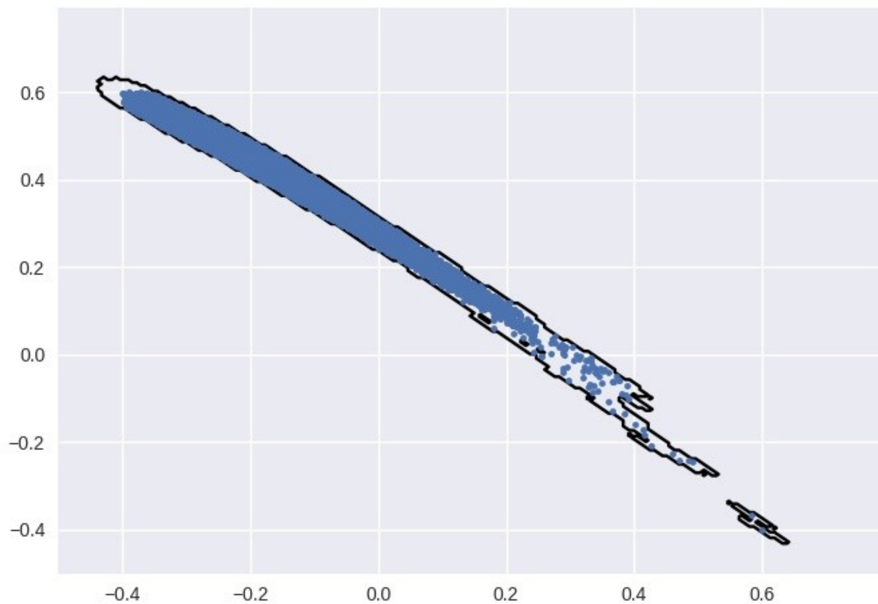
- Also defined in multivariate case
  - Confidence intervals do not generalize easily in 2D
  - They do not seem optimal for disjoint distributions



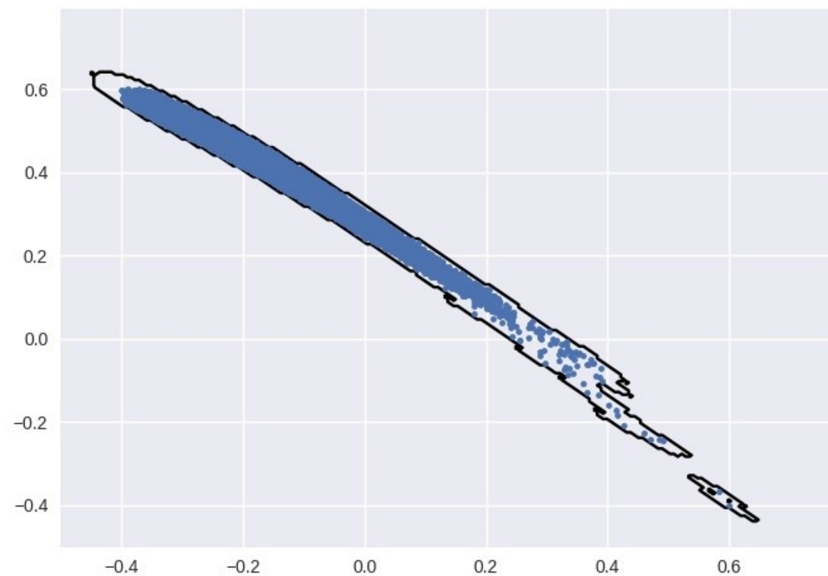
- Under mild assumptions it is a level set of the pdf

Impact zone using Minimum Volume Sets

$$\min_{\Omega} \quad \text{Vol}(\Omega) \text{ subject to } P(X \in \Omega) \geq 1 - \epsilon$$



Impact zone at 99.99 %



Impact zone at 99.998 % [99.9985;99.9975] %
(using 3.3e6 samples, 3 sigmas)

Algorithm adapted from R. Pastel : *Estimation of rare event probabilities and extreme quantiles : applications in the aerospace domain,* PhD thesis 2012

Conclusions :

- Developed a robust reentry predictor using simple models
- The use of advanced uncertainty quantification tools cut down computational cost (millions of samples generated in a 2 hours on single core)
- Mathematical definition of impact zone
- More advanced probabilistic models are under developement
- Uncertainty Quantification can provide quick and robust answers to complex problems

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Related work :

- F. Sanson, C. Bertorello, J-M. Bouilly, P.M. Congedo, *Breakup prediction under uncertainty : application to upper stage controlled reentries from GTO orbit*, Aerospace Science and Technology, 2018, submitted : https://hal.archives-ouvertes.fr/hal-01898010v1

- F. Sanson, O. Le Maitre, P.M. Congedo, *Uncertainty Quantification in Systems of Solvers*, Computer Methods in Applied Mathematics and Engineering, 2018, submitted : https://hal.archives-ouvertes.fr/hal-01829375v1

- F. Sanson, C. Bertorello, C. Finzi, J.M. Bouilly, P.M. Congedo, Robust Ground footprint estimation for reentering space objects, 4th International Space Debris Workshop, Darmstadt, Germany, April 2018

- F. Sanson, J.M. Bouilly, P.M. Congedo, Uncertainty Quantification in Orbital Debris Reentry for Reliable Ground Footprint Estimation, ESA Space Debris conference 2017 - 7th European Conference on Space Debris, Darmstadt, Germany, April 2017

Thank you

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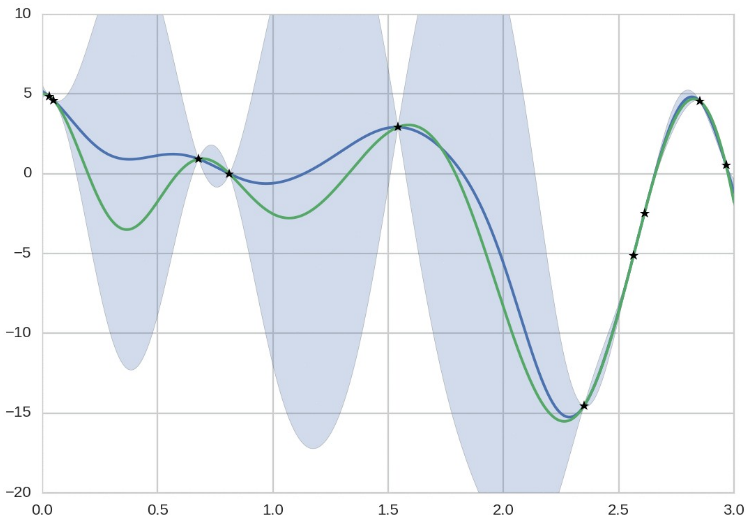
Uncertainty quantification tools :

Gaussian Processes

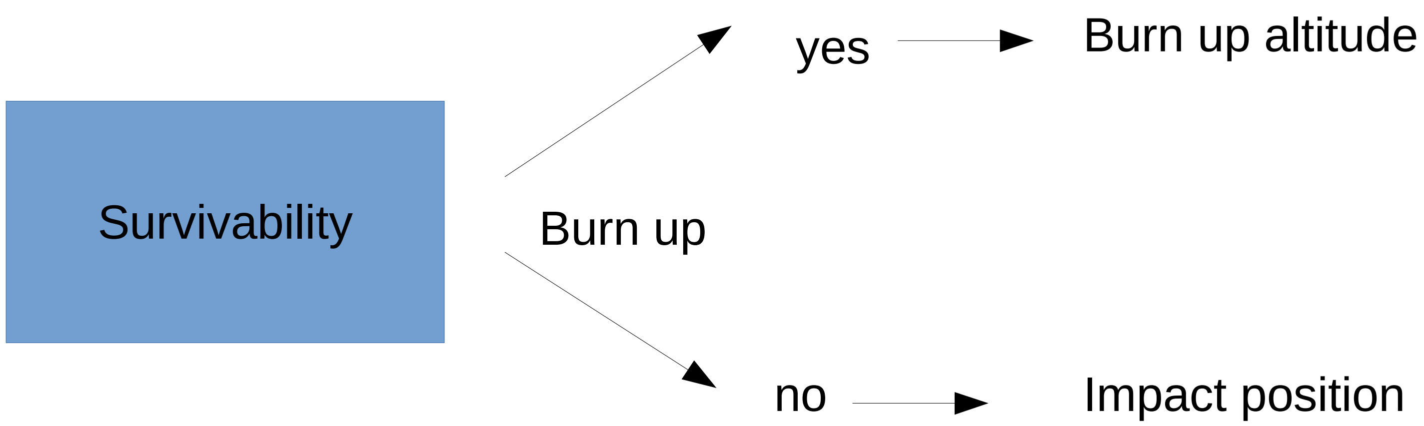
Surrogate model construction with predictive error estimation

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

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



Difficulty for survivability prediction : building a surrogate model on the discountinuity



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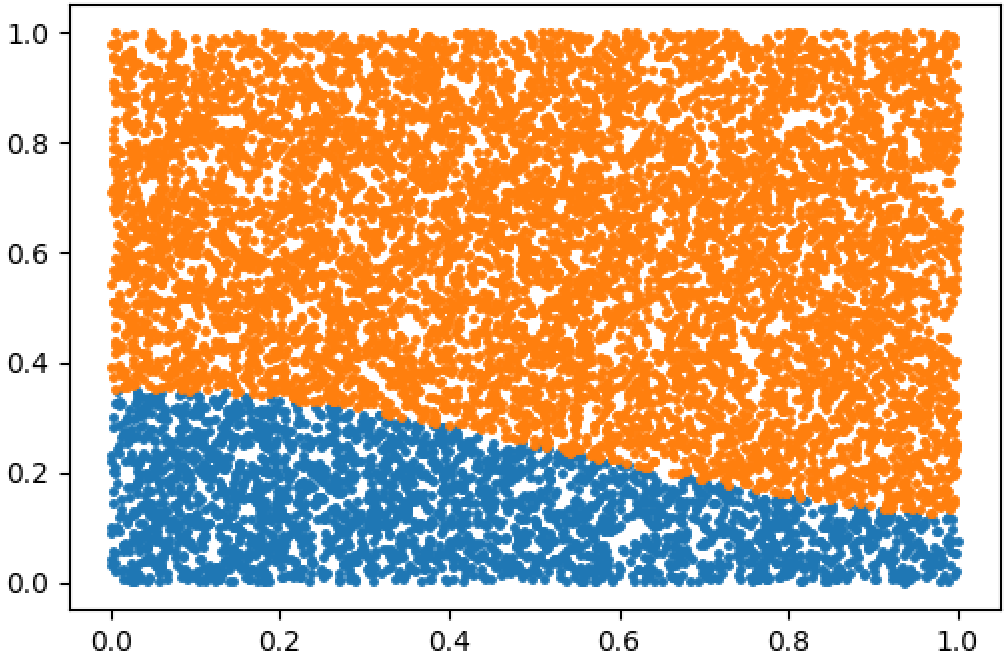
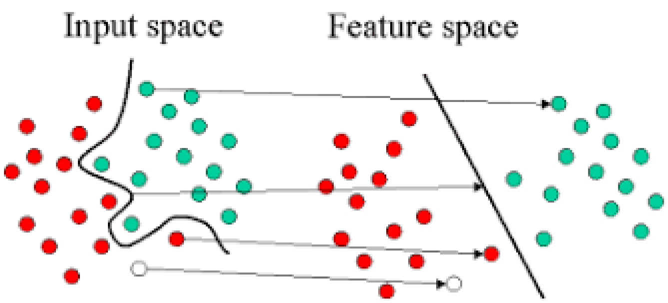
Approach : use a Support Vector Machine classifier





SVM separates the uncertainty space between objects that burn and objects that do not.