POLITECNICO MILANO 1863 | DEPARTMENT OF AEROSPACE SCIENCE AND TECHNOLOGY

COMPASS

2nd Space Capacity Allocation For The Sustainability of Space Activities Workshop

ESMILE: An Ensemble-Driven Particle-in-a-Box Model for Efficient Space Debris Scenario Exploration

03.06.2026 I Francesco De Bortoli, Elisa Boccolari, Camilla Colombo, Andrea Nava, Luca Spazzacampagna, Patryk Niczke, Marcin Miklewski, Jan Kowalski, Francisco Simarro, Emma Stevenson, Stijn Lemmens

Background: the space debris domain

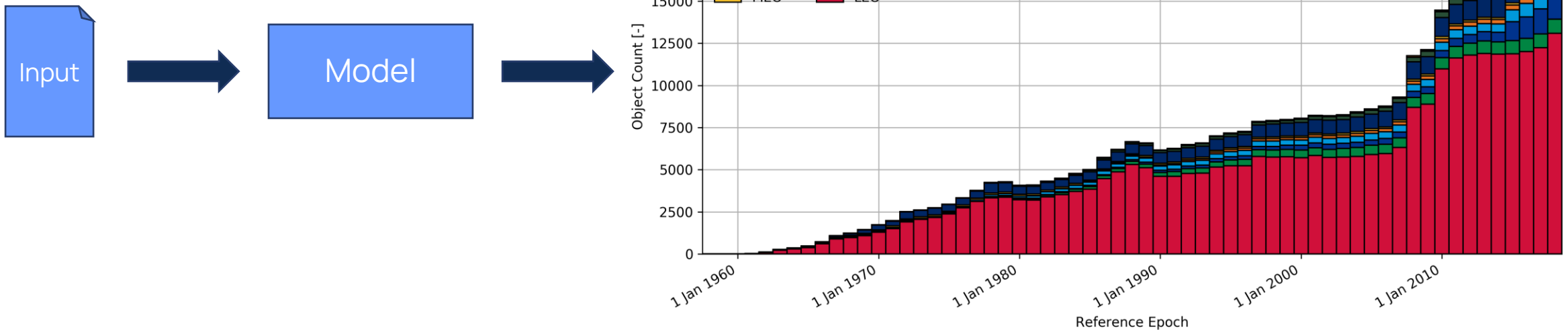
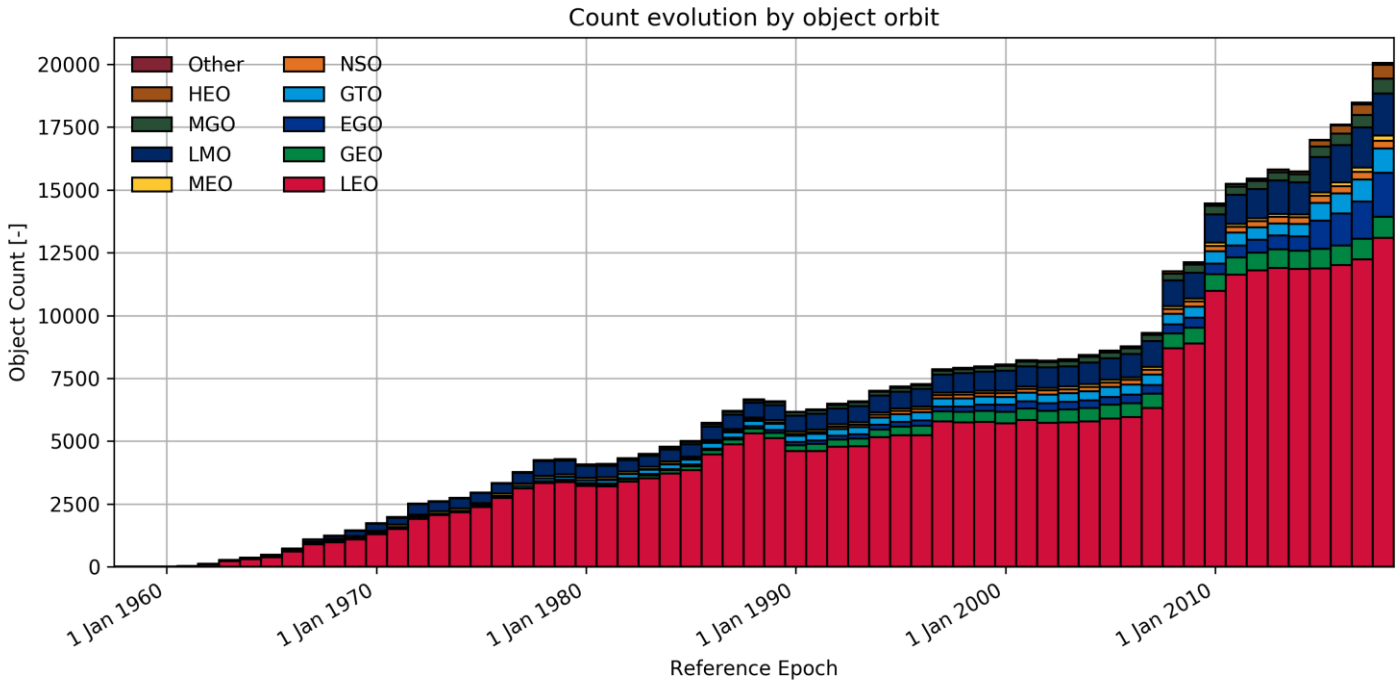


Image source: European Space Agency, Analysis and prediction, available at esa.int/Space_Safety/Space_Debris/Analysis_and_prediction (Accessed: May 2026)

Background: the space debris domain

Input → Model →



COMETA DELTA LEGEND LUCA MEDEE SDM

Image source: European Space Agency, Analysis and prediction, available at esa.int/Space_Safety/Space_Debris/Analysis_and_prediction (Accessed: May 2026)

Background: the space weather domain

Multi-Models

Perturbed-Physics

Background: the space weather domain

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Perturbed-Physics

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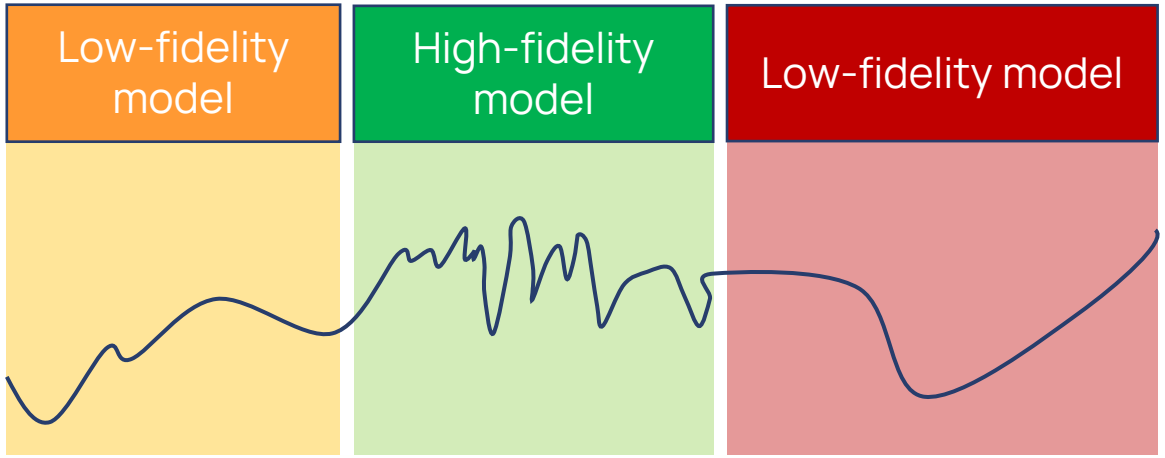
(Laplace, 1818)



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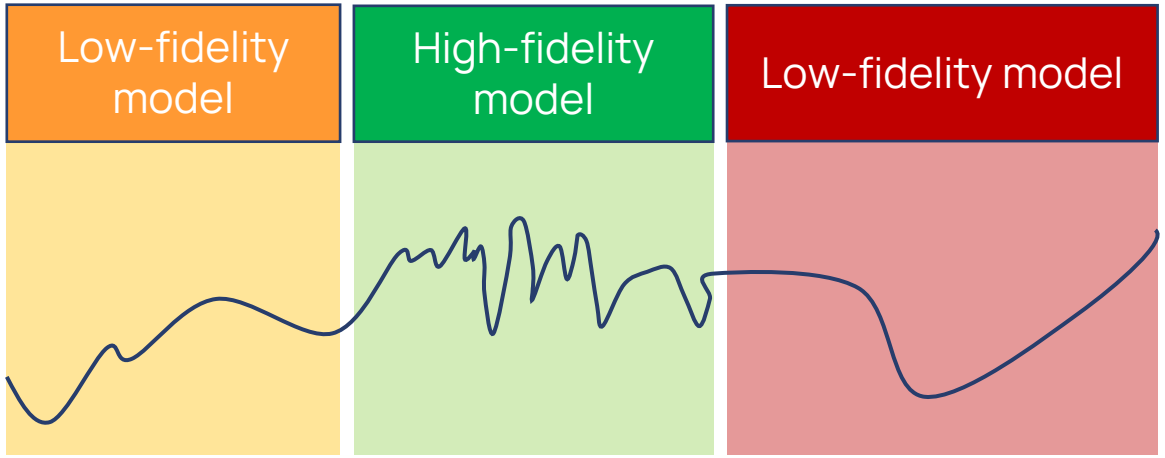
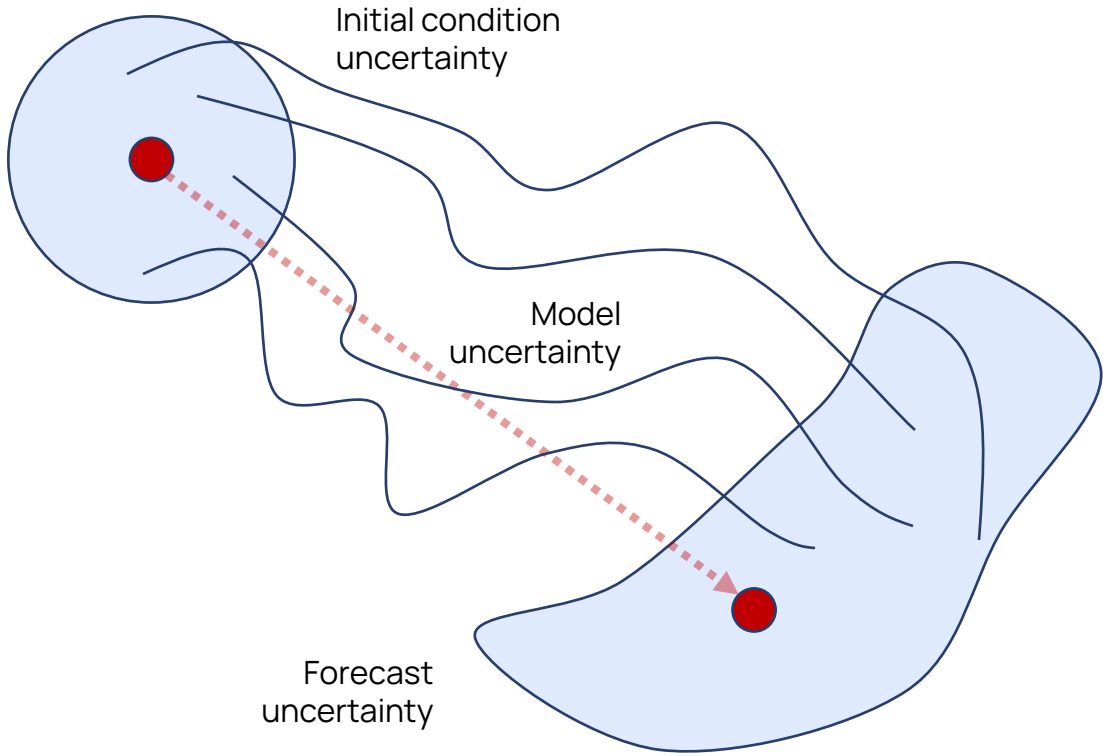


Perturbed-Physics



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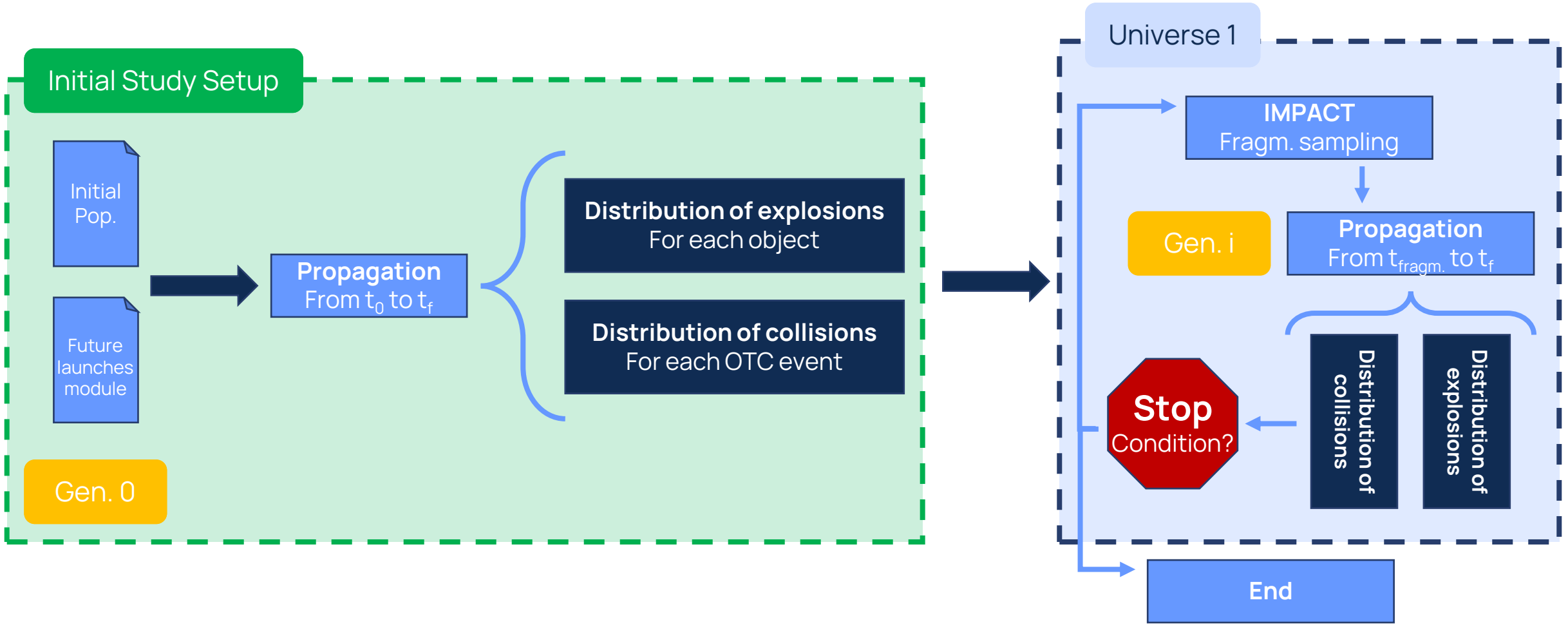
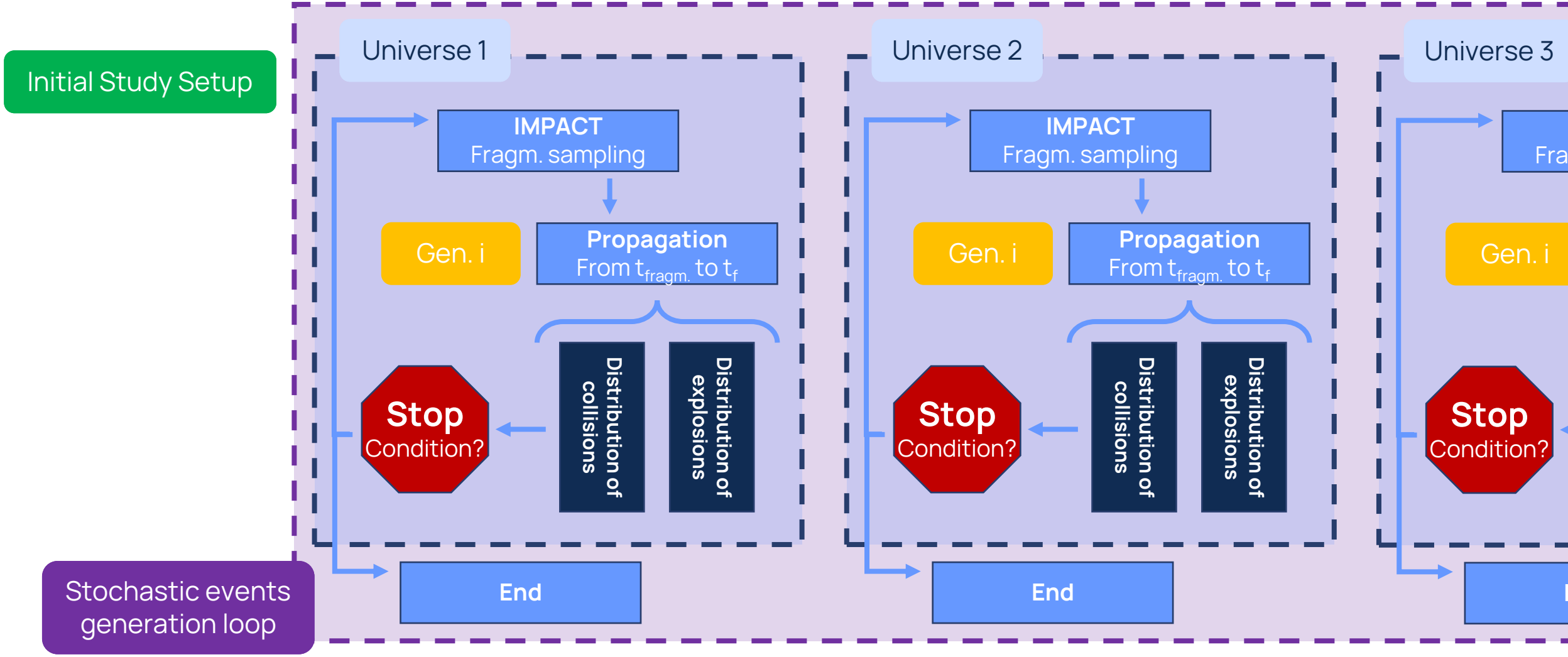
Perturbed-Physics scheme: adapted from S. A. Murray, 'The Importance of Ensemble Techniques for Operational Space Weather Forecasting', *Space Weather*, vol. 16, no. 7, pp. 777–783, Jul. 2018, doi: 10.1029/2018SW001861.

Background: the Aerospace Debris Environment Project Tool



Scheme re-adapted from G. Henning *et al.*, 'ADEPT: Calculating the Infinite Multiverse of Future Space Environments', in *Second International Orbital Debris Conference*, 2023.

Background: the Aerospace Debris Environment Project Tool



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Background: the Aerospace Debris Environment Project Tool

Initial Study Setup

Stochastic events generation loop

Universe 1

Universe 2

Universe 3

....

Universe 100

Post-Processing

Layers visualisation

Scheme re-adapted from G. Henning *et al.*, 'ADEPT: Calculating the Infinite Multiverse of Future Space Environments', in *Second International Orbital Debris Conference*, 2023.

Ensemble and Surrogate Modelling for Debris Environment Long-Term Simulation

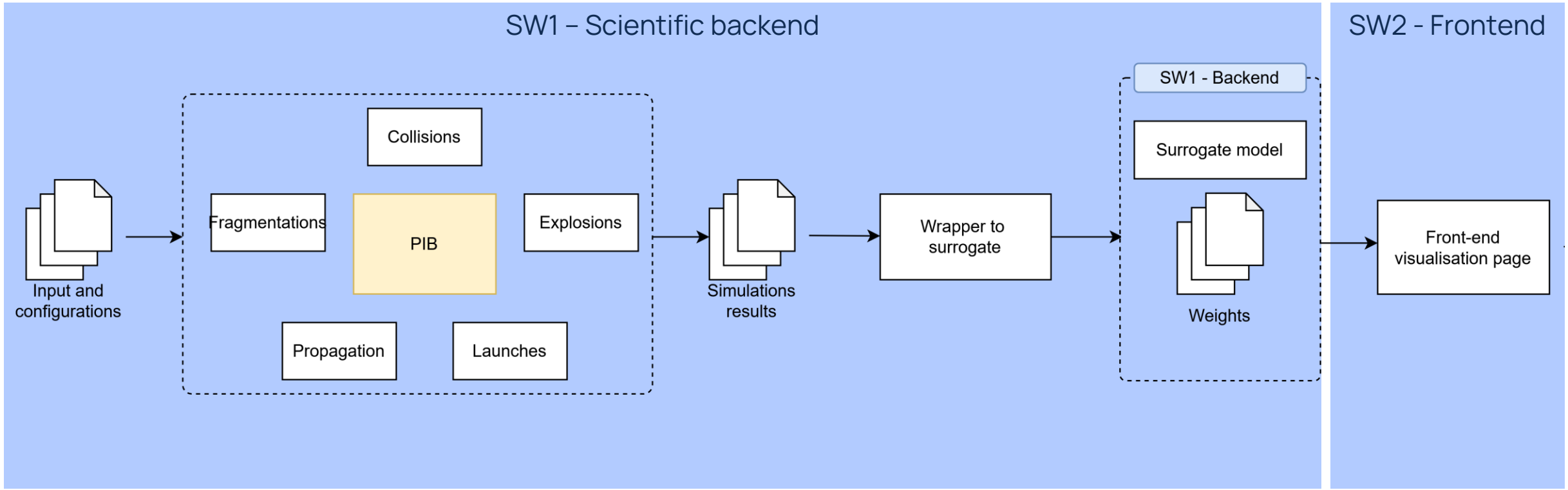
European Space Agency

Politecnico di Milano

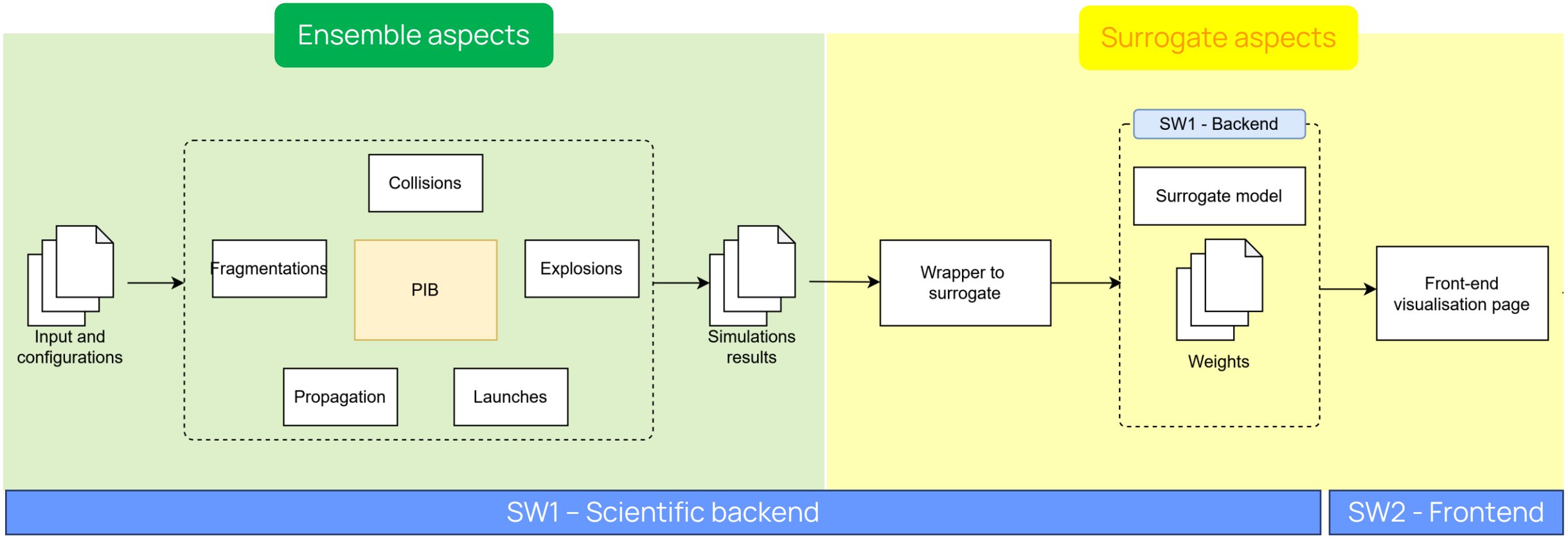
GMV

Telespazio

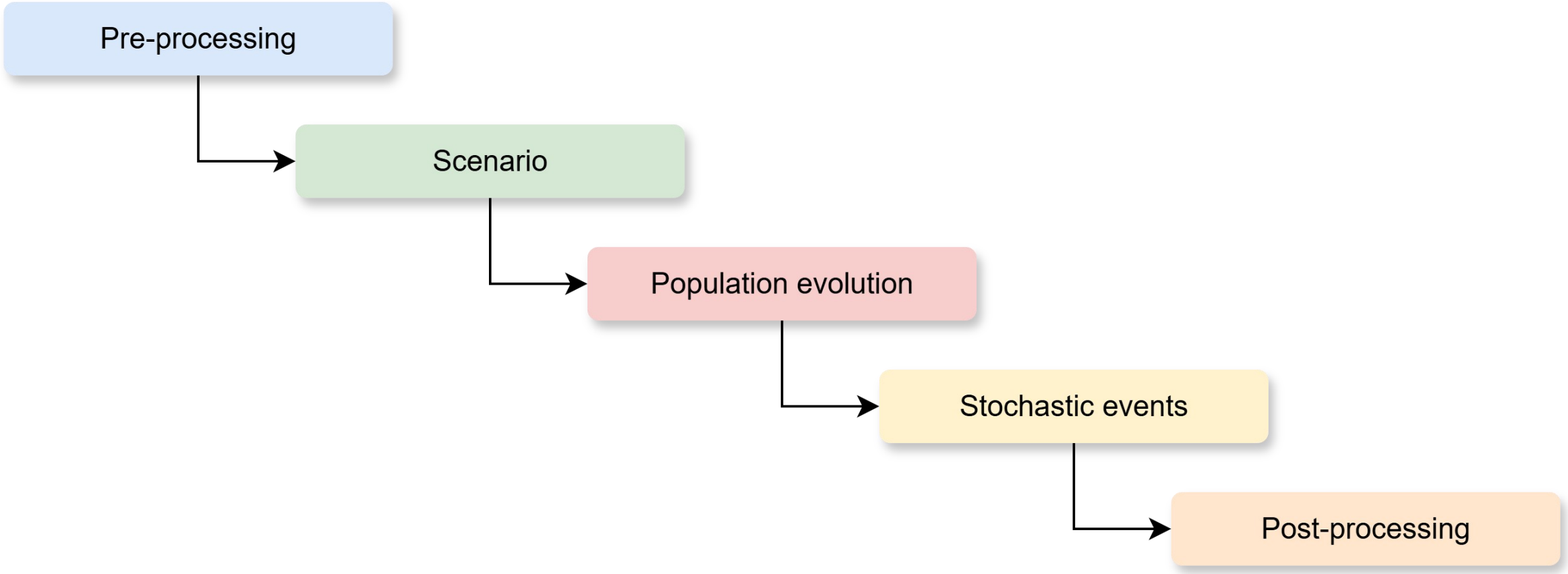
Products of the Project



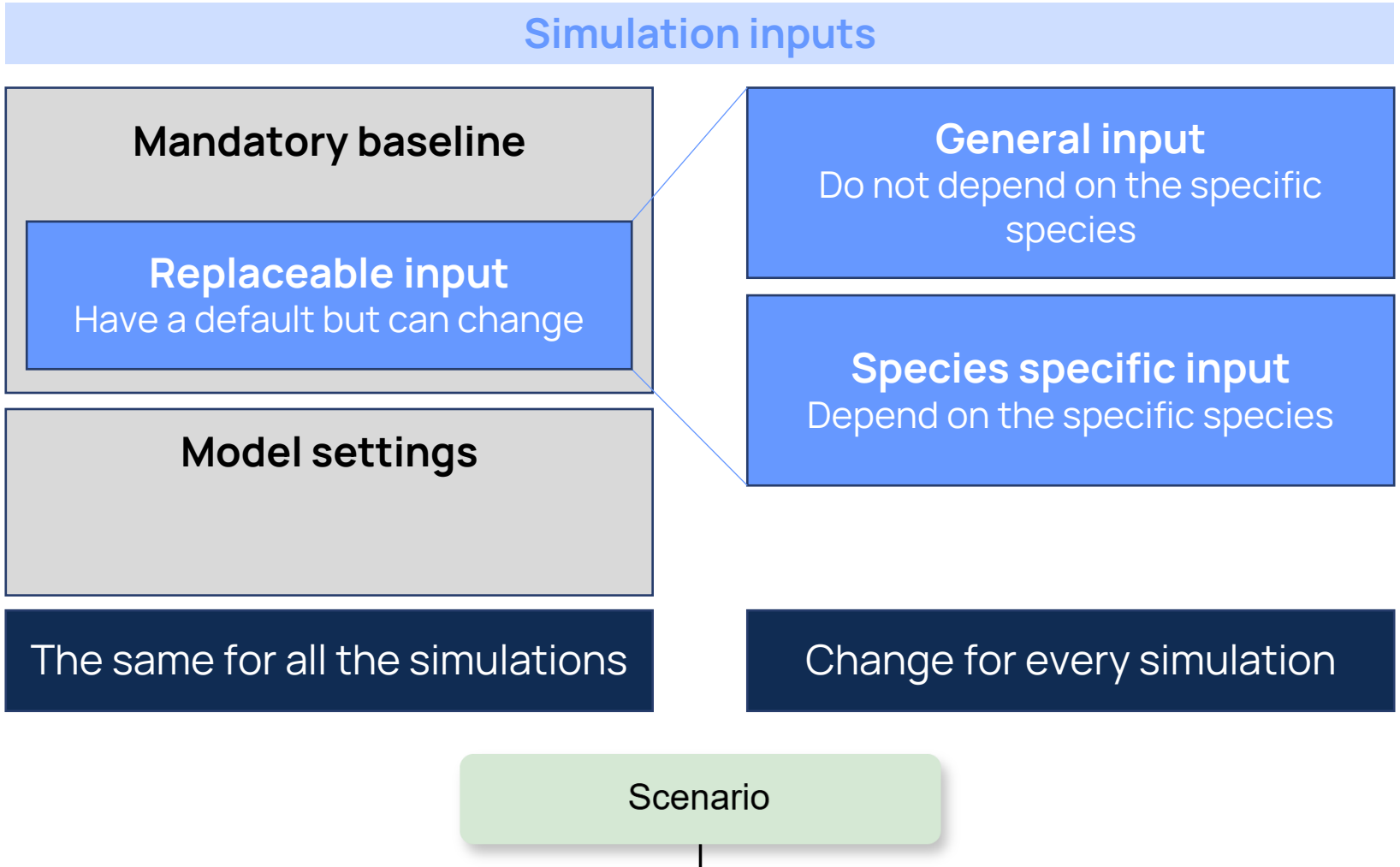
Products of the Project



Level-based structure



Scenario Definition Level: Input parameter space exploration



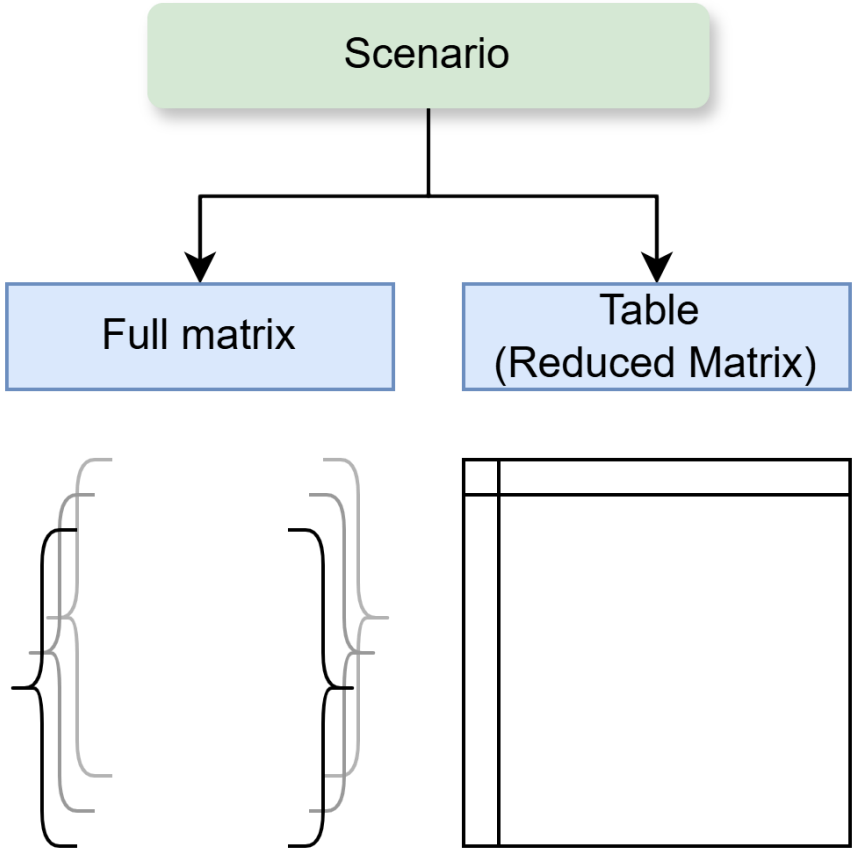
Scenario Definition Level: Input parameter space exploration

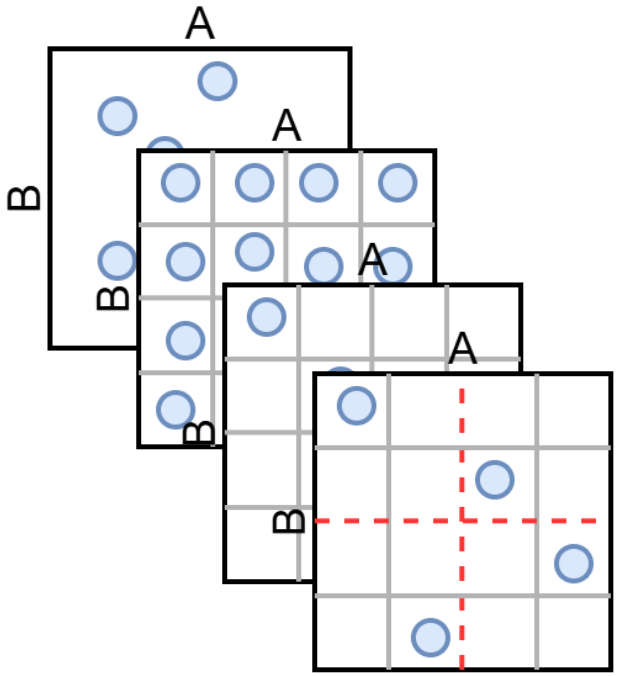
Simulation inputs

General input
Do not depend on the specific species

Species specific input
Depend on the specific species

Change for every simulation





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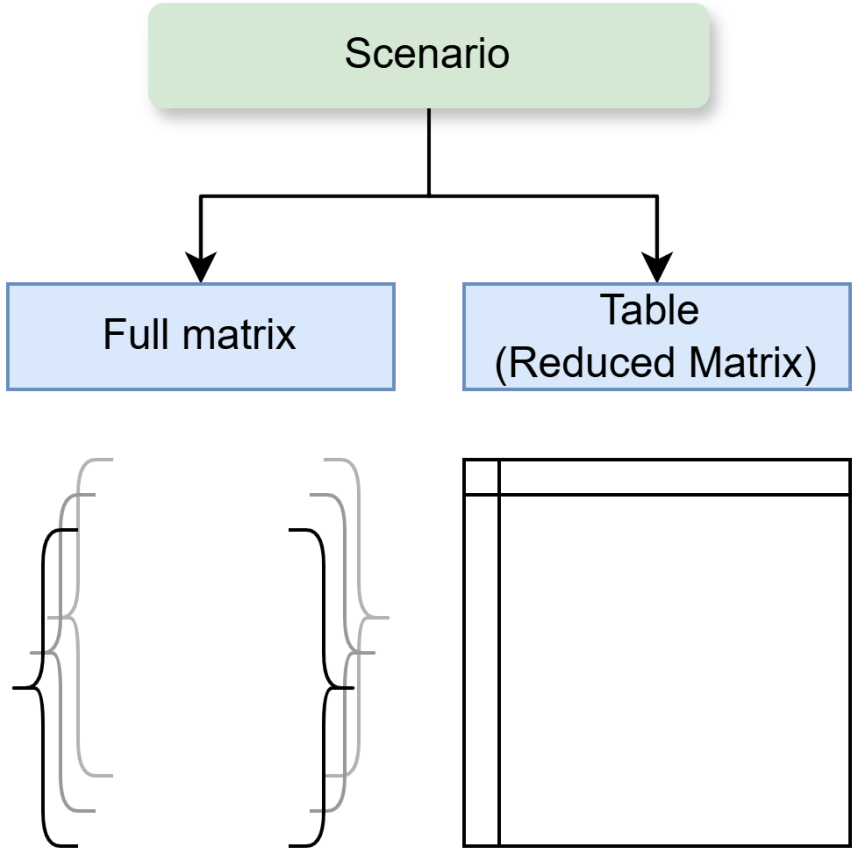
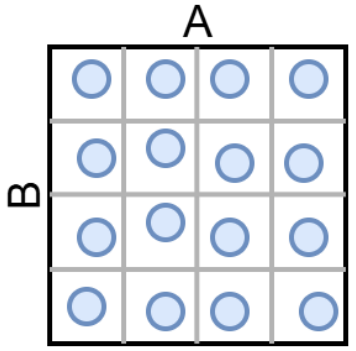
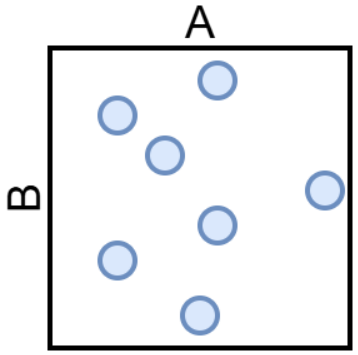
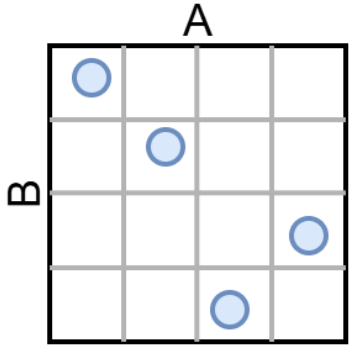




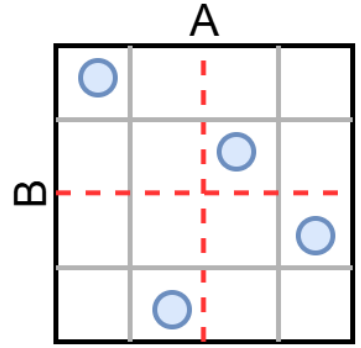
Full Matrix



Random Sampling



Latin Hypercube Sampling



Orthogonal Latin Hypercube Sampling

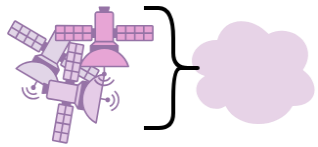
Population Evolution Level: Efficient and re-usable orbital displacement

Different propagation techniques

Timestep dynamic

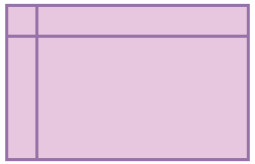
Densities are propagated with the continuity equation

Partial object-level



Propagate single distinct objects separately and convert to densities when needed

Precomputed propagation



Use lookup tables to compute the propagation process of the different elements

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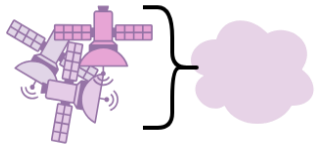

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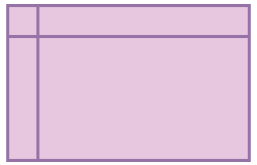


Use lookup tables to compute the propagation process of the different elements

Different models exploitation

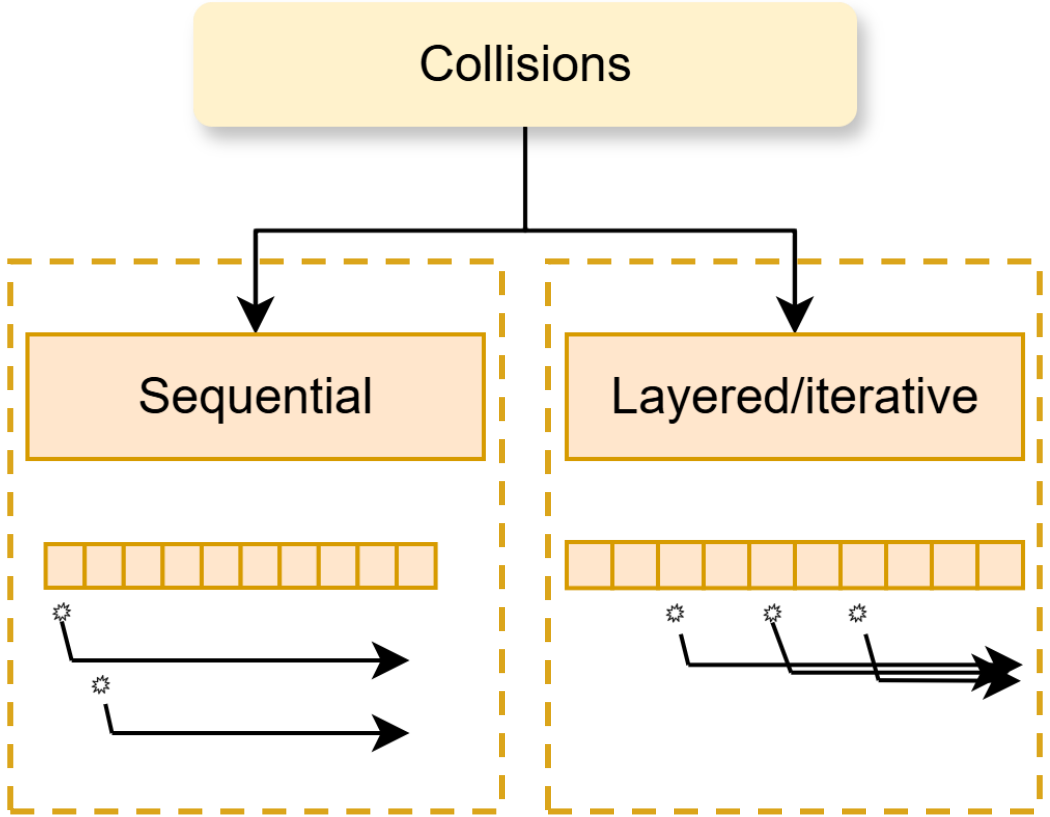
Multi-model philosophy: combine different modelling assumptions to enhance precision or computational speed. This could include:

- Solar activity models
- Atmosphere models
- Perturbation complexity

Stochastic Events Level: explosions and collisions effects

Sequential approach

Legacy option, requires several Monte Carlo simulations to become statistically relevant



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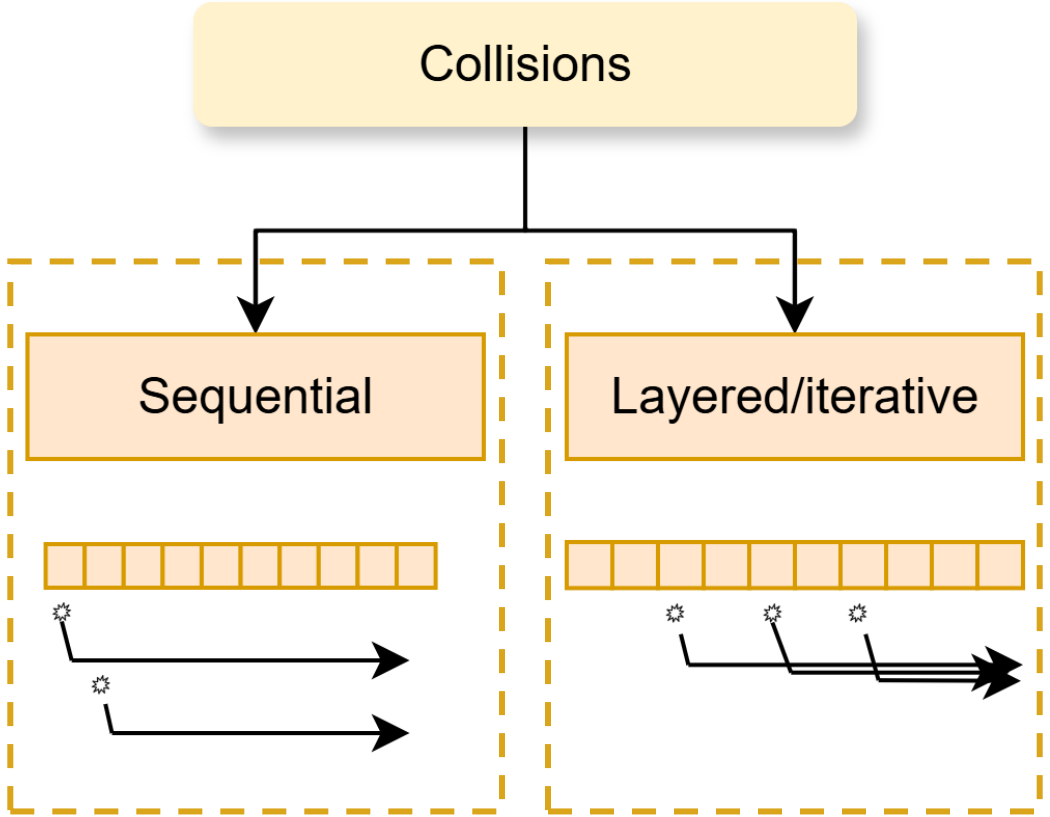
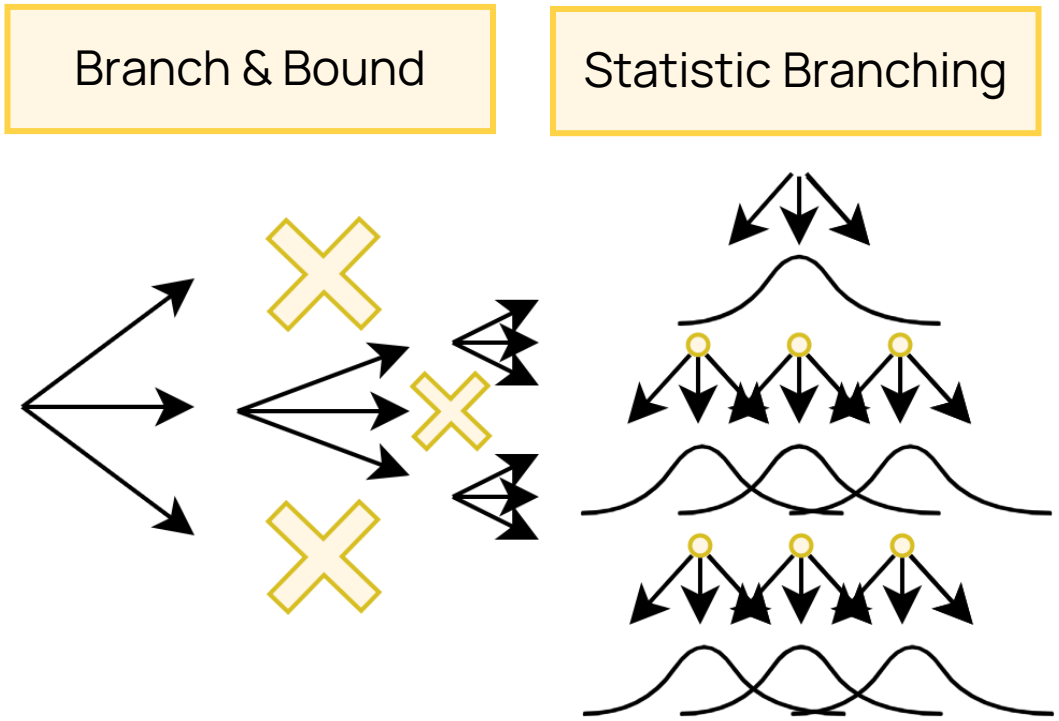


Layered approach

New approach, allow the exploration of relevant cases and their effects based on the creation of layers that could possibly be combined with branching strategy

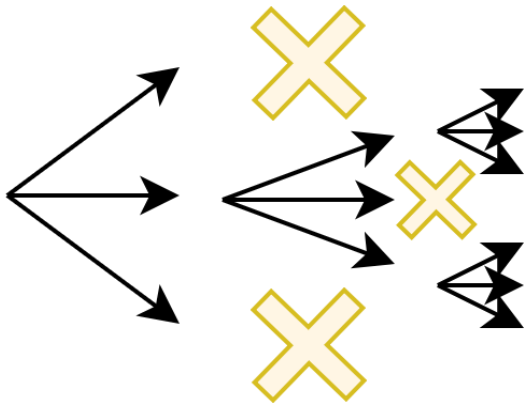
Stochastic Events Level: explosions and collisions effects



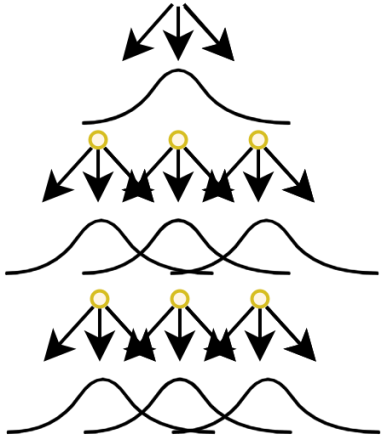
Stochastic Events Level: explosions and collisions effects

Branch & Bound

- A wide set of scenarios is explored.
- The **father-child processes relationship** is maintained so it is always possible to link the cause and the effect.
- Requires a **strict bounding condition** to avoid the combinatory explosion of the number of cases.



Statistic Branching



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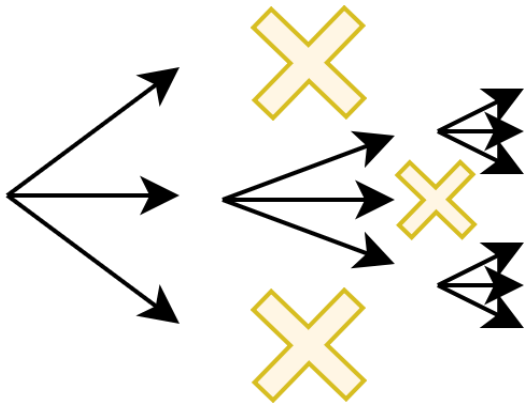
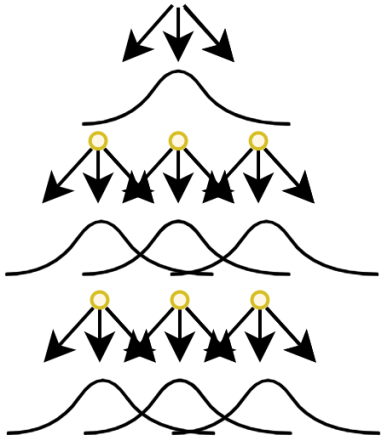
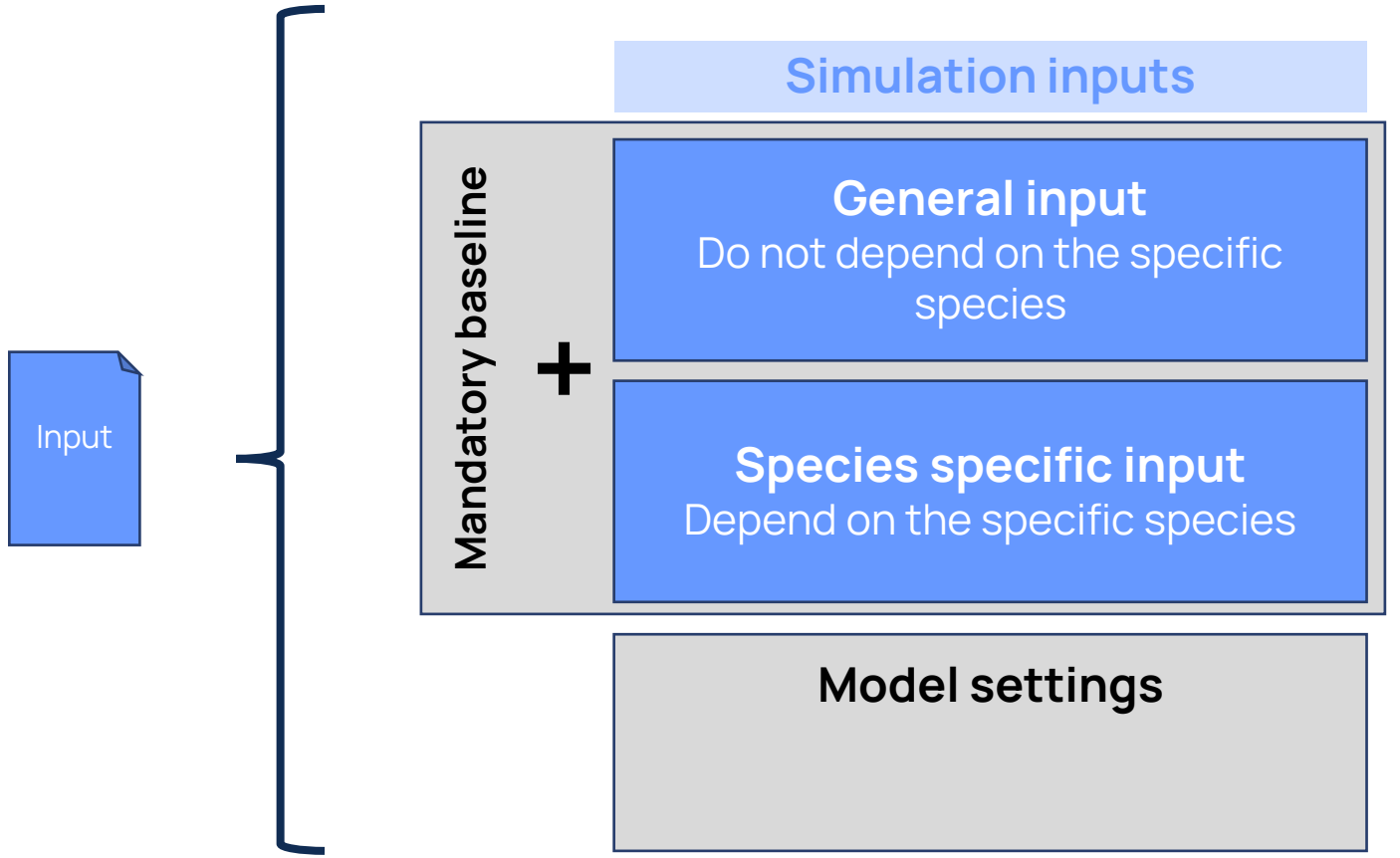


Statistic Branching

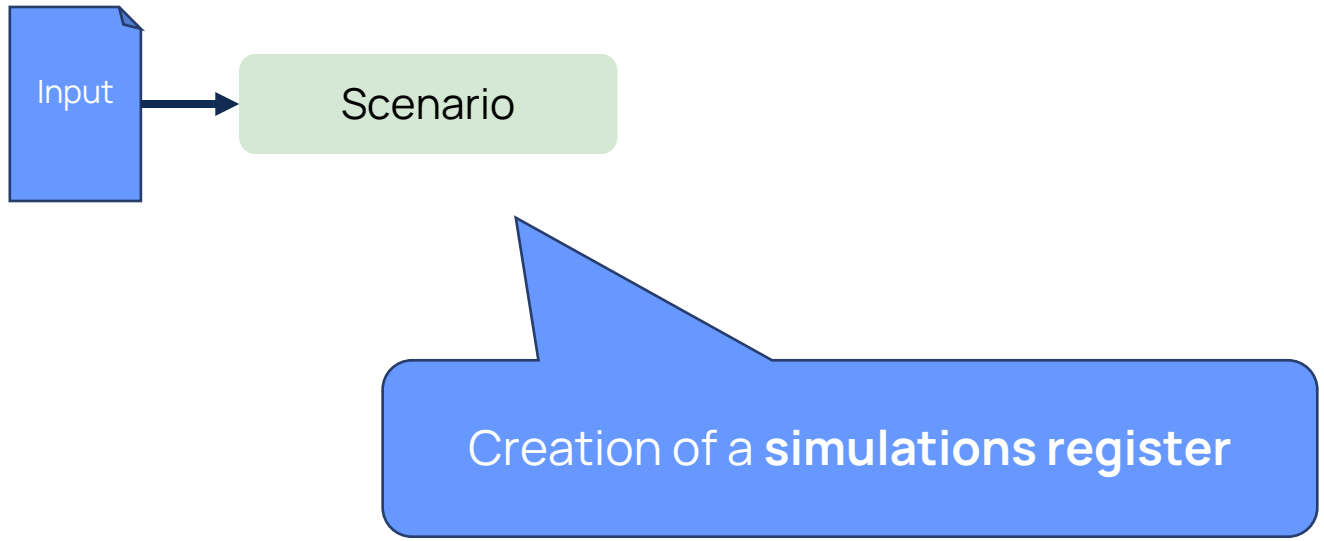
- Designed to fight the **curse of dimensionality**: from the number of performed simulations, only three cases are kept (average and standard deviations).
- **Statistical relevance** of the kept cases.
- Loss of information on the relations between the effects.



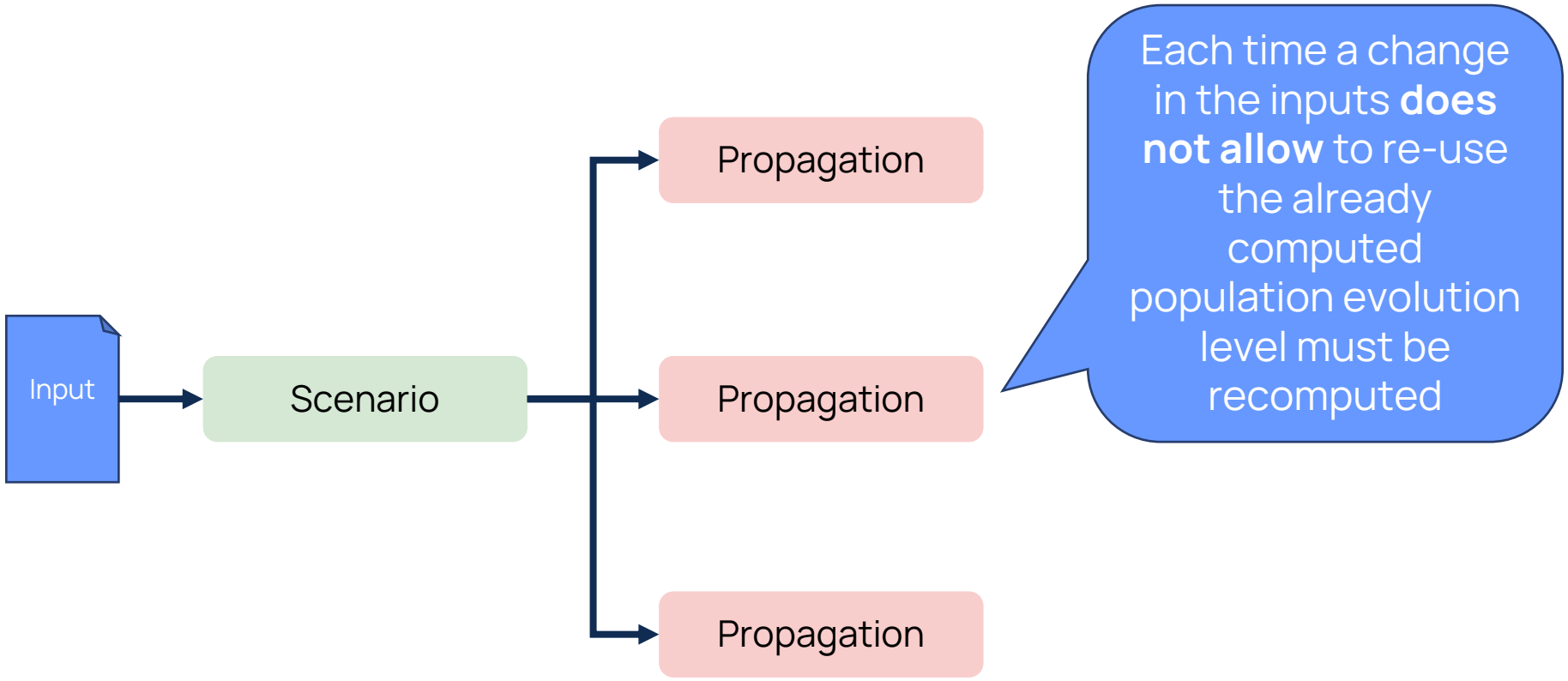
Summary


Input
Simulation inputs
Mandatory baseline
+
General input
Do not depend on the specific species
Species specific input
Depend on the specific species
Model settings

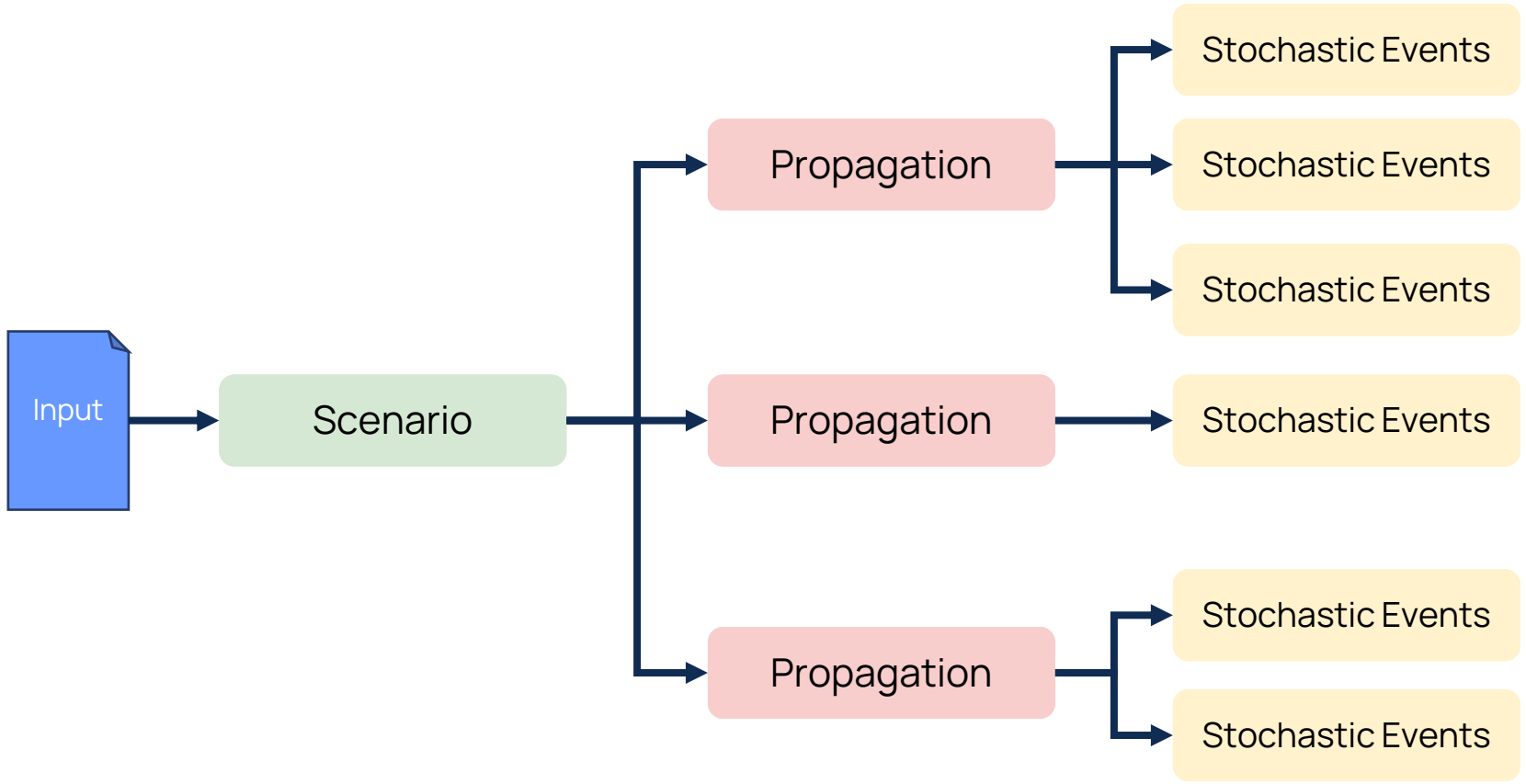
Summary



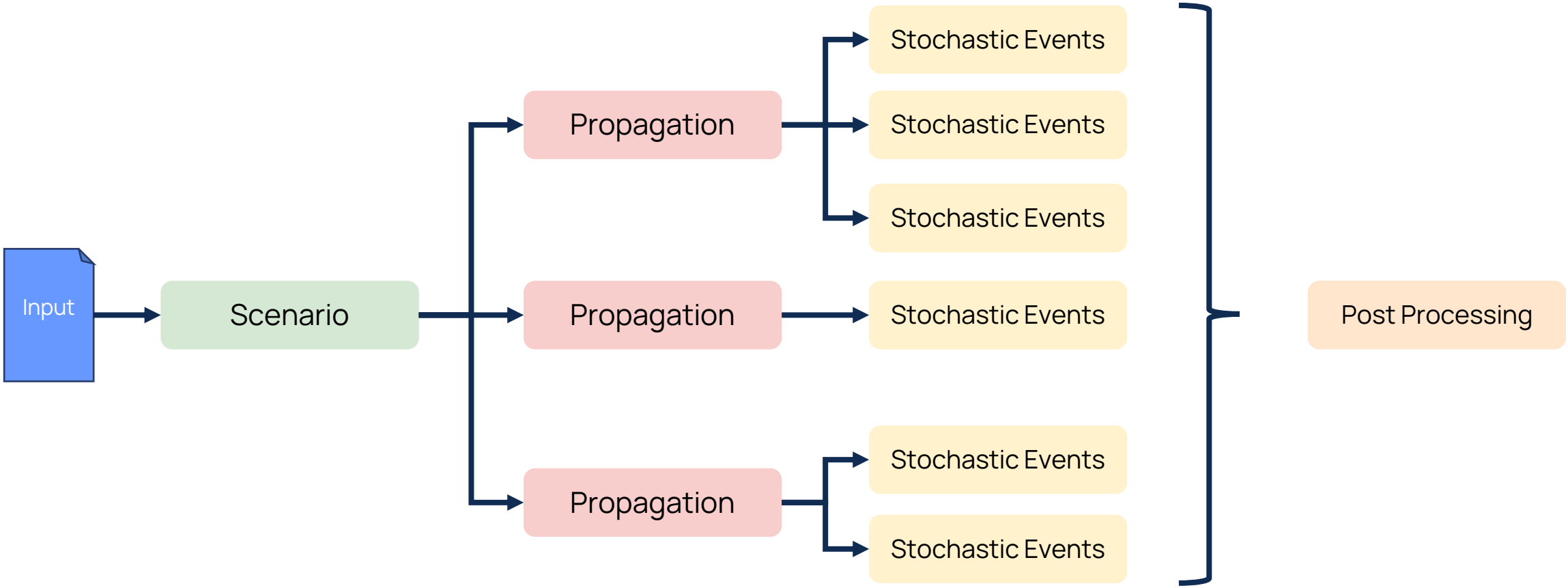
Summary


Input
Scenario
Propagation
Propagation
Propagation
Each time a change in the inputs **does not allow** to re-use the already computed population evolution level must be recomputed

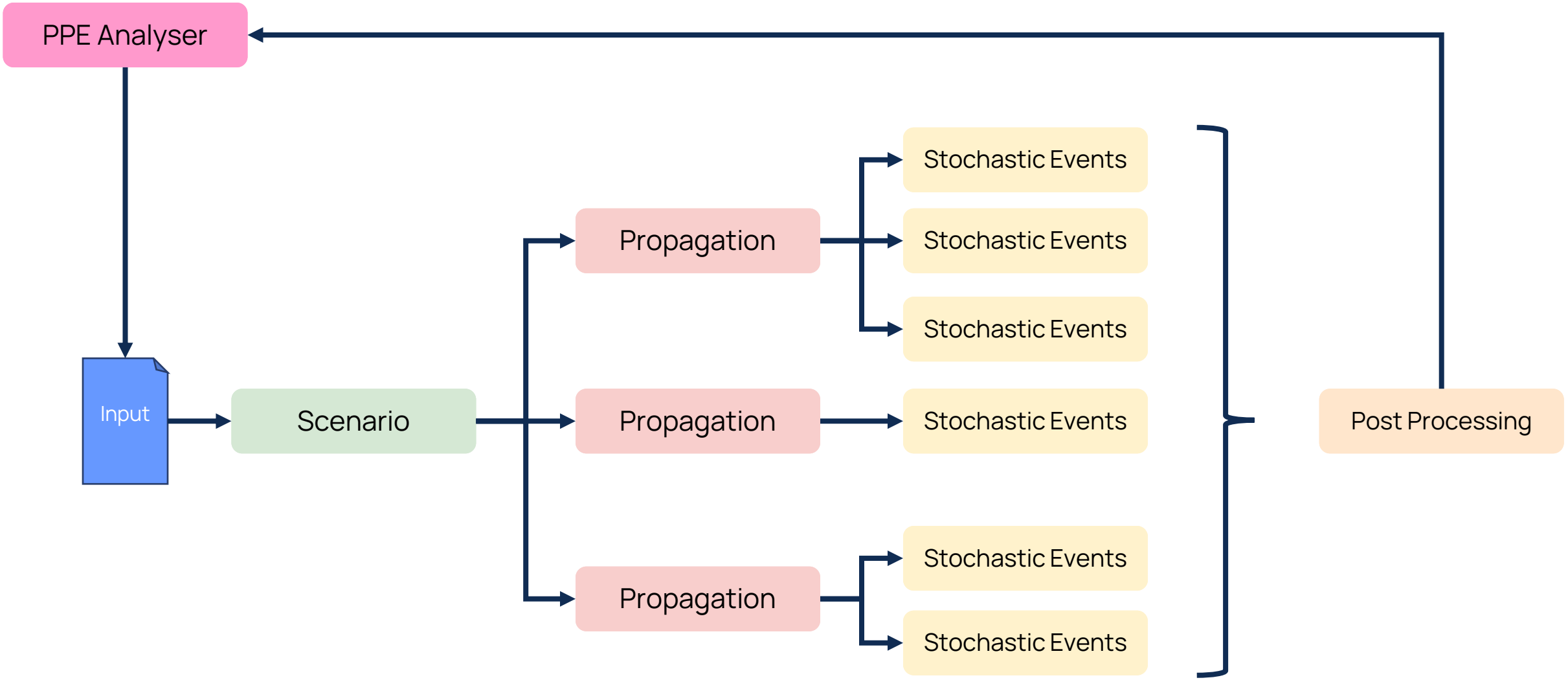
Summary


Input
Scenario
Propagation
Propagation
Propagation
Stochastic Events
Stochastic Events
Stochastic Events
Stochastic Events
Stochastic Events
Stochastic Events

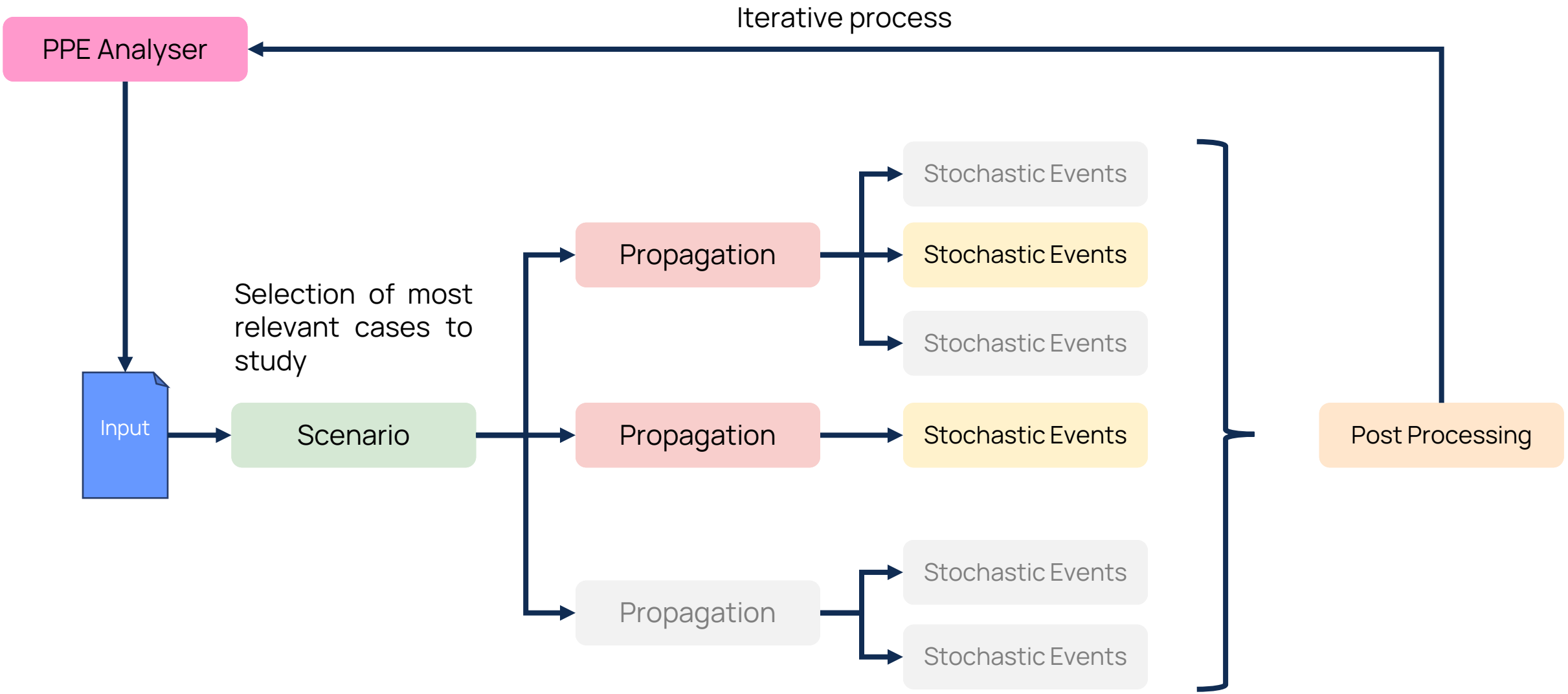
Summary


Input
Scenario
Propagation
Propagation
Propagation
Stochastic Events
Stochastic Events
Stochastic Events
Stochastic Events
Stochastic Events
Stochastic Events
Post Processing

Summary


PPE Analyser
Input
Scenario
Propagation
Propagation
Propagation
Stochastic Events
Stochastic Events
Stochastic Events
Stochastic Events
Stochastic Events
Stochastic Events
Post Processing

Summary


Iterative process
PPE Analyser
Input
Selection of most relevant cases to study
Scenario
Propagation
Propagation
Propagation
Stochastic Events
Stochastic Events
Stochastic Events
Stochastic Events
Stochastic Events
Stochastic Events
Post Processing

Objectives

Which inputs affect the long-term evolution the most?

Which is the confidence on the results we obtain?

How would the environment change if stricter policies are enabled?

How do constellations shape the evolution of the trends?

How long do we need to wait to see the effects of the changes?

Thank You for your attention

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