# Spacecraft Collision Risk Assessment with Probabilistic Programming

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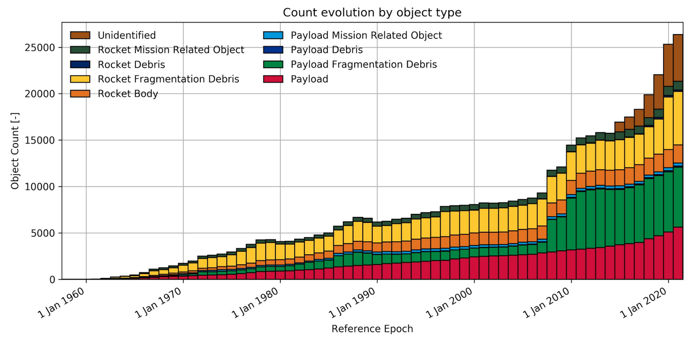
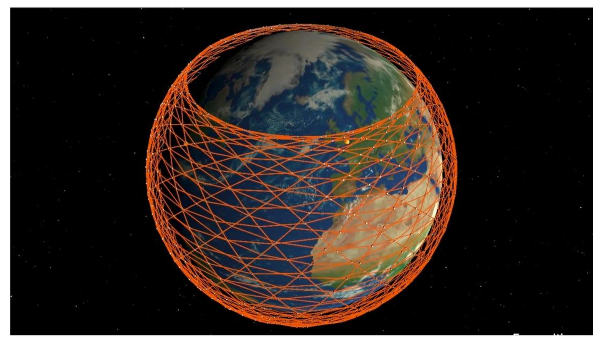
## Summary

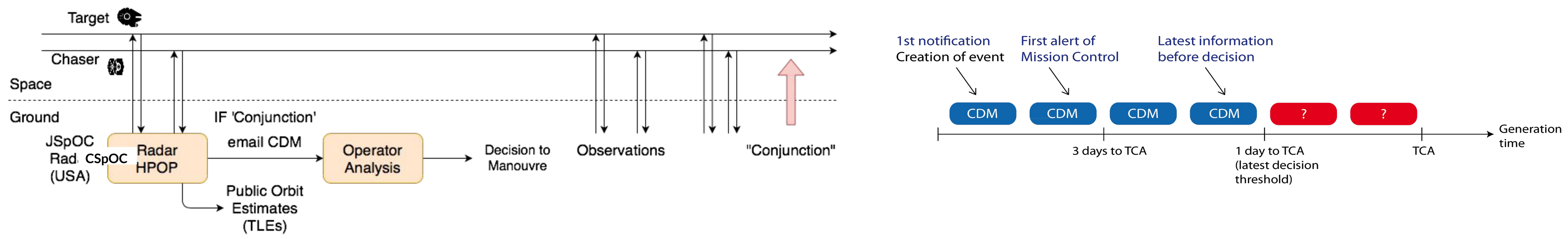
We build a novel physics-based probabilistic generative model for synthetically generating conjunction data messages, calibrated using real data. By conditioning on observations, we use the model to obtain posterior distributions via Bayesian inference. We show that the probabilistic programming approach to conjunction assessment can help in making predictions and in finding the parameters that explain the observed data in conjunction data messages, thus shedding more light on key variables and orbital characteristics that more likely lead to conjunction events. Moreover, our technique enables the generation of physically accurate synthetic datasets of collisions, answering a fundamental need of the space and machine learning communities working in this area.

## Collision Avoidance and the Kessler Syndrome

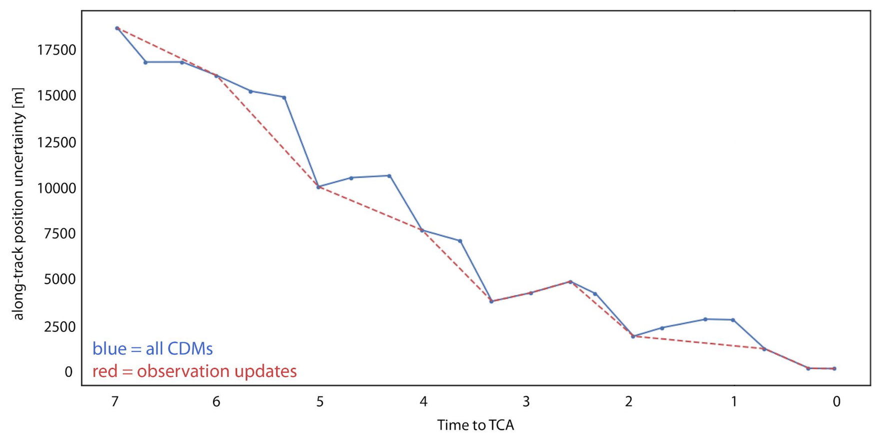
- In 60 years of human spaceflight, **low Earth orbit** has become a junkyard of thousands of pieces of Space Debris
- Collisions cause more collisions: "**Kessler Syndrome**" can cause the object population to grow exponentially
- Not only the population of passive objects is growing: companies plan **mega constellations** of thousands of satellites





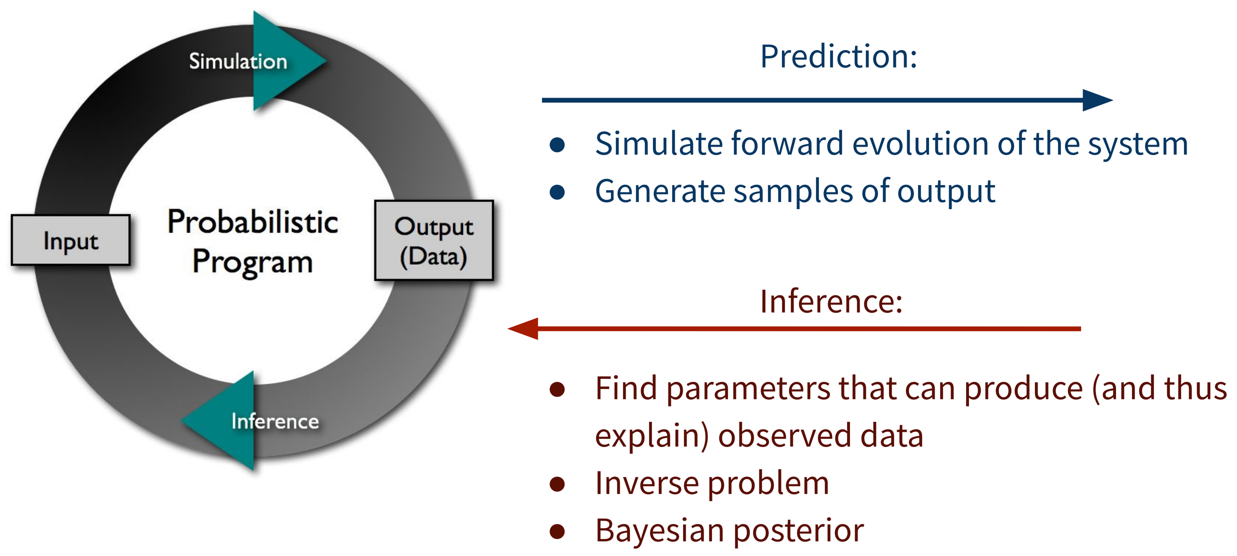

- Active satellites (**targets**) are observed and screened against catalogue population of known resident space objects (**chasers**) for close approaches (**conjunctions**), corresponding collision warnings (**CDMs**) issued to the owner/operator
- CDMs are not received on a regular basis and the creation process is not transparent. This makes the dynamic evolution of the event **hard to assess.**
- Currently, **risk assessment** is performed **manually** and a case-by-case analysis of the event evolution might become unfeasible in the future
- During **Kelvins Collision Avoidance Challenge**, ESA Space Debris Office published anonymised dataset of 4 years of CDMs
- Can **machine learning** methods assist the risk assessment process?




Position uncertainty evolution for an example event

## Probabilistic Programming and Collision Avoidance

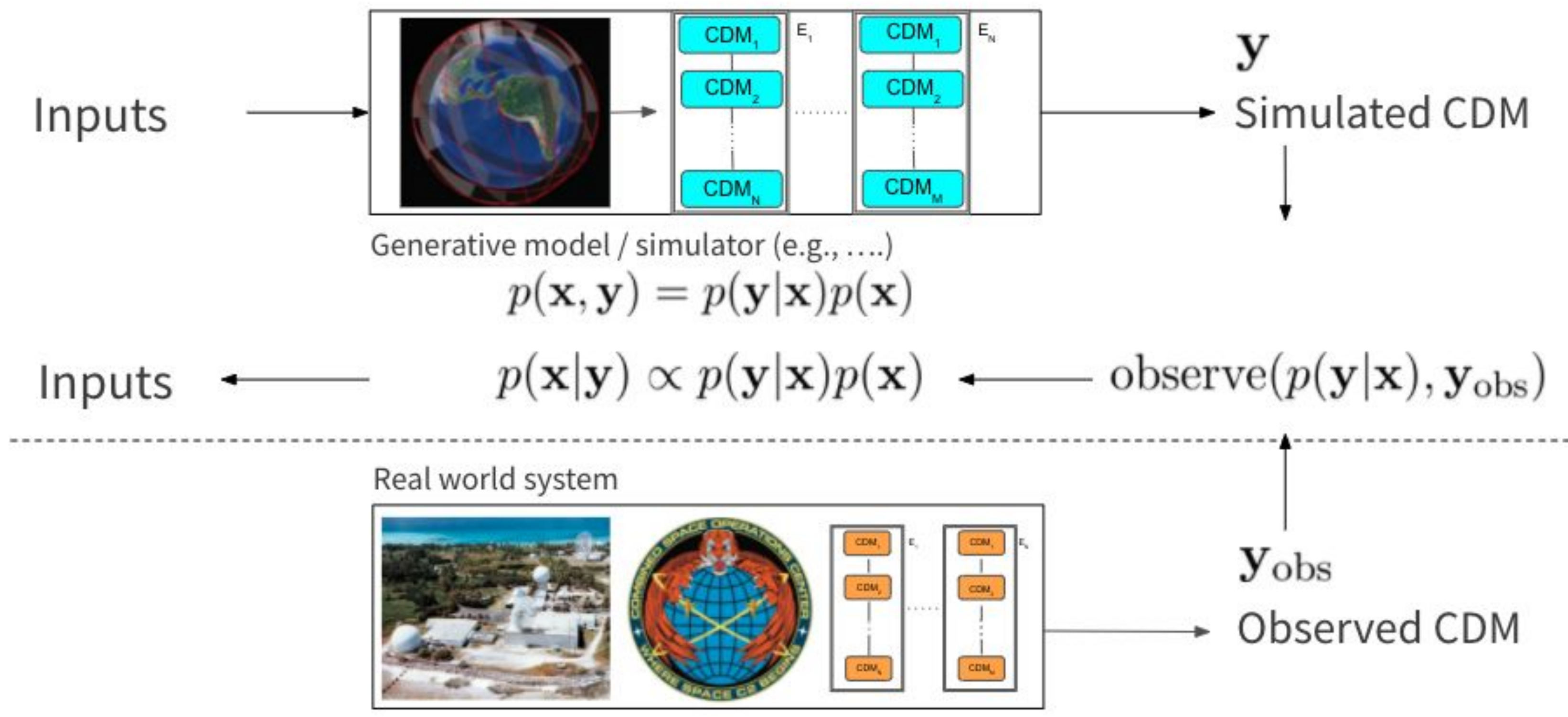
- **Probabilistic programming** allows to specify probabilistic models for data generation and to perform inference in the model conditioned on observed data
- A probabilistic program specifies the prior probability distribution over latent variables, an **interpretable procedure** that computes the observations given the latent variables (i.e., probabilistic model), and a **likelihood** distribution
- The probabilistic model can be run **forward** (data generation), or **backwards** (given some observed data, infer posterior distributions over latent variables conditioned on observations)
- **Pyprob** was used as probabilistic programming system




PyProb

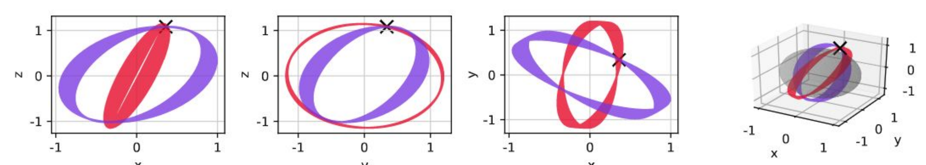
## Probabilistic Model of Orbits, Conjunctions, and CDM generation

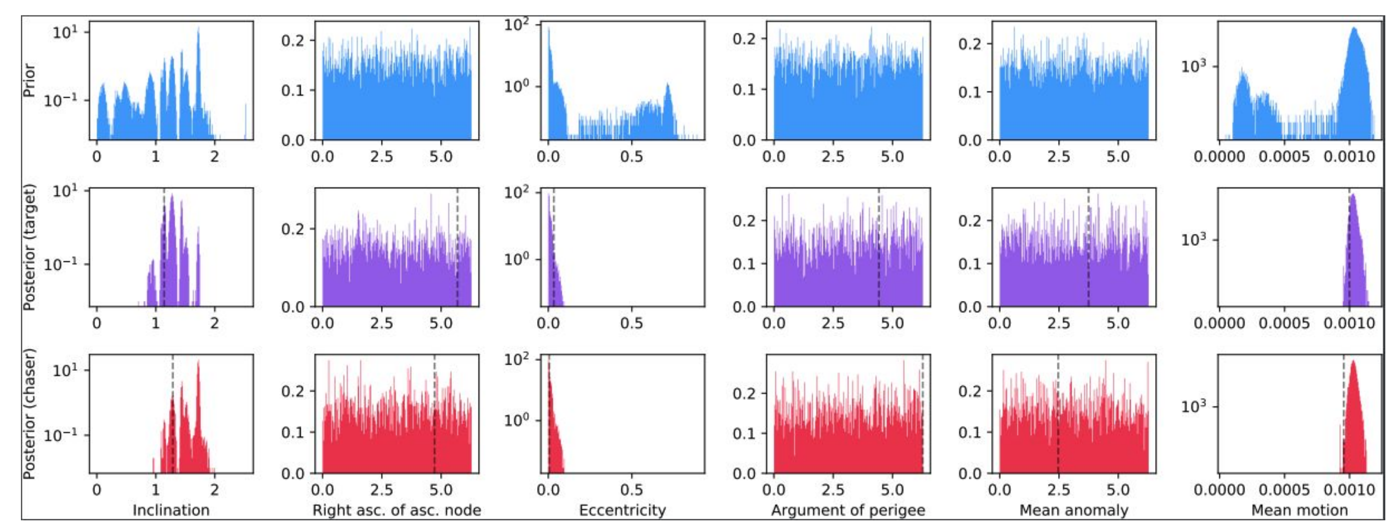
- We design a **novel probabilistic model** that can be used to synthetically generate CDM and perform inference over CDMs evolution
- Space simulation:
  - Target/chaser are **sampled** from priors
  - Their initial conditions are propagated through time using realistic **physical simulation of trajectories**, generating ground truth orbits
  - If a **conjunction event** is present, a ground simulation procedure is simulated
- Ground simulation:
  - **Observations** are simulated, with their associated **uncertainties**
  - **Monte Carlo propagation** is performed to propagate uncertainties
  - A series of CDMs is generated for that conjunction event
- The simulator was calibrated:
  - Priors were selected from **real datasets** (i.e., DISCOSweb, Kelvins, Space-Track)
  - **Observation noise** was **calibrated**




## Experiments

- **Importance sampling** was used as inference engine
- Top figure: physical orbits of **target** and **chaser** for the **ground truth observed event** that was used as test case
- Bottom figure: **prior** and **posterior** (for both target and chaser) distributions of a subset of latent variables (i.e., six orbital elements of both objects). The posterior is conditioned on the abovementioned ground truth test event, here highlighted with a dashed line.
- We see that some distributions are of **multimodal** nature, suggesting that the estimated posterior can provide insight into multiple different explanations of the observed values.






- The **right ascension of the ascending node**, **argument of perigee**, and **mean anomaly**, do not seem to play a relevant role in explaining the conjunction event. Meanwhile, the **mean motion**, **inclination**, and **eccentricity** have posterior distributions that differ significantly from the priors, underlying their pivotal roles in explaining the observed conjunction event. The less relevant role of the first three orbital elements is to be expected since these orbits are almost **circular**.

**Acknowledgments**

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