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A Differentiable Bayesian Anomaly Detection Framework for Robust SALT3 Parameter Estimation and Supernova Distance Calibration Using JAX

We present a novel Bayesian anomaly detection framework, applied to supernova analysis, that exploits a custom-built, differentiable, and highly parallelisable JAX implementation of the commonly used SNcosmo framework. In our framework, each supernova's flux is modelled via the SALT3 formalism, with the core computation—integrating the model flux over observational bandpasses—being fully differentiable and highly parallelisable.

We implement our Bayesian data cleaning strategy, where contaminated (or anomalous) data points are not simply excised but are instead managed by imposing an Occam penalty within the likelihood. This leads to a robust estimation of the SALT parameters (e.g., brightness scaling, stretch, and colour) even when subtle anomalies are present. In addition, we integrate a JAX-based Nested Sampling engine into our toolkit.

Following the methodology in Leeney et al. (2024), we compute a piecewise likelihood from:
$\mathrm{P(D}|\theta) = \prod_i \left([L_i(1-p_i)]^{\epsilon_{\max,i}} \left[\frac{p_i}{\Delta}\right]^{(1-\epsilon_{\max,i})} \right)$

which yields a masked chi-squared–like term that distinguishes between reliable and corrupted data. Notably, the condition $\log L_i + \log\Delta >$
$operatornamelogit(p)$
$relatesdirectlytothelogitfunction—acommonactivationfunctioninmachinelearningusedforbinaryclassification$

More robust modelling of the SALT parameters—particularly brightness scaling, stretch, and colour—directly translates to more precise distance measurements. By incorporating Bayesian anomaly detection, our framework not only flags but quantitatively down-weights anomalous data rather than discarding it outright. This comprehensive treatment minimises systematic biases in the fitted SALT parameters, reducing the scatter in the Hubble diagram. As a consequence, the inferred distance moduli are more accurate, which tightens the calibration of the SN Ia distance ladder. In turn, the improved precision in distance measurements can lead to significantly tighter constraints on the Hubble constant, potentially addressing current tensions in cosmological parameter estimation.

AI keywords

anomaly detection; differentiable algorithms; AI tooling

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Track Classification: Patterns & Anomalies