

Inferring Proto-Neutron Star Parameters from Simulated Supernova Neutrino Data with Realistic Detector Background

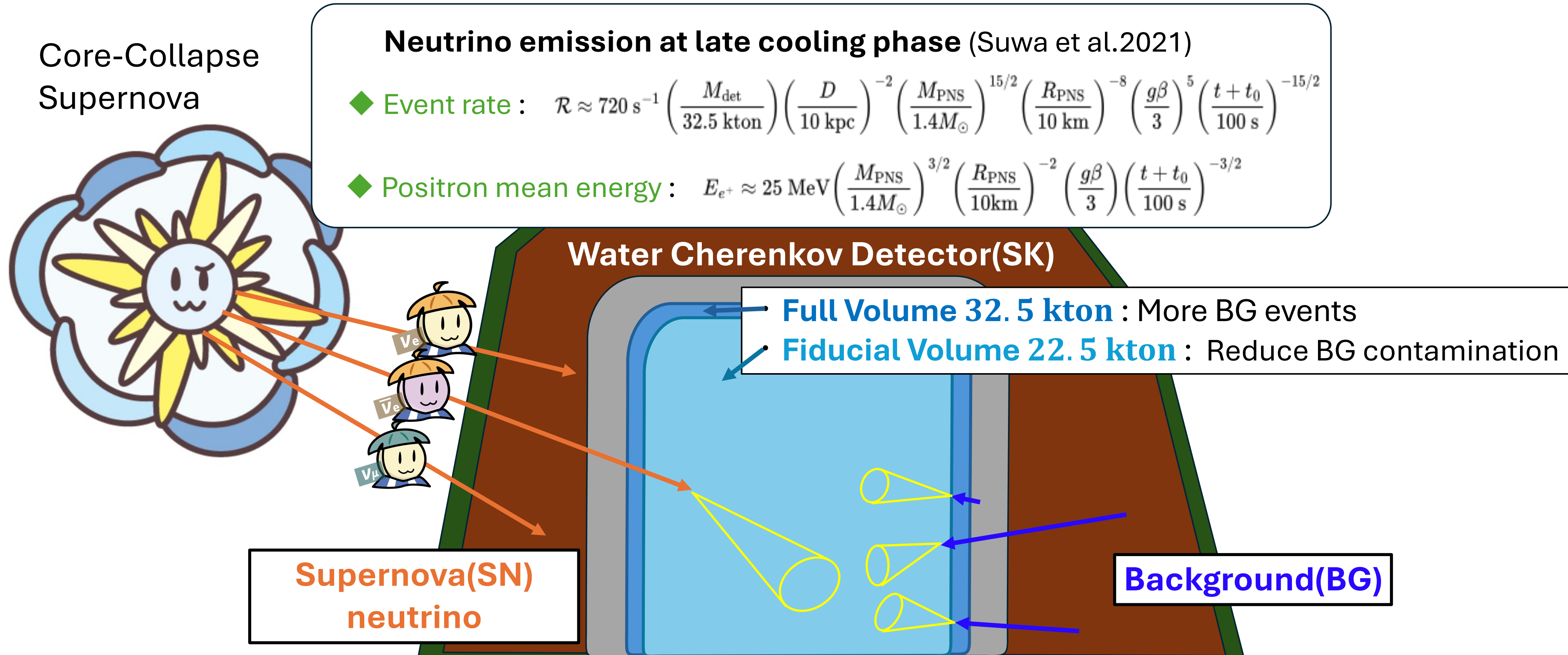
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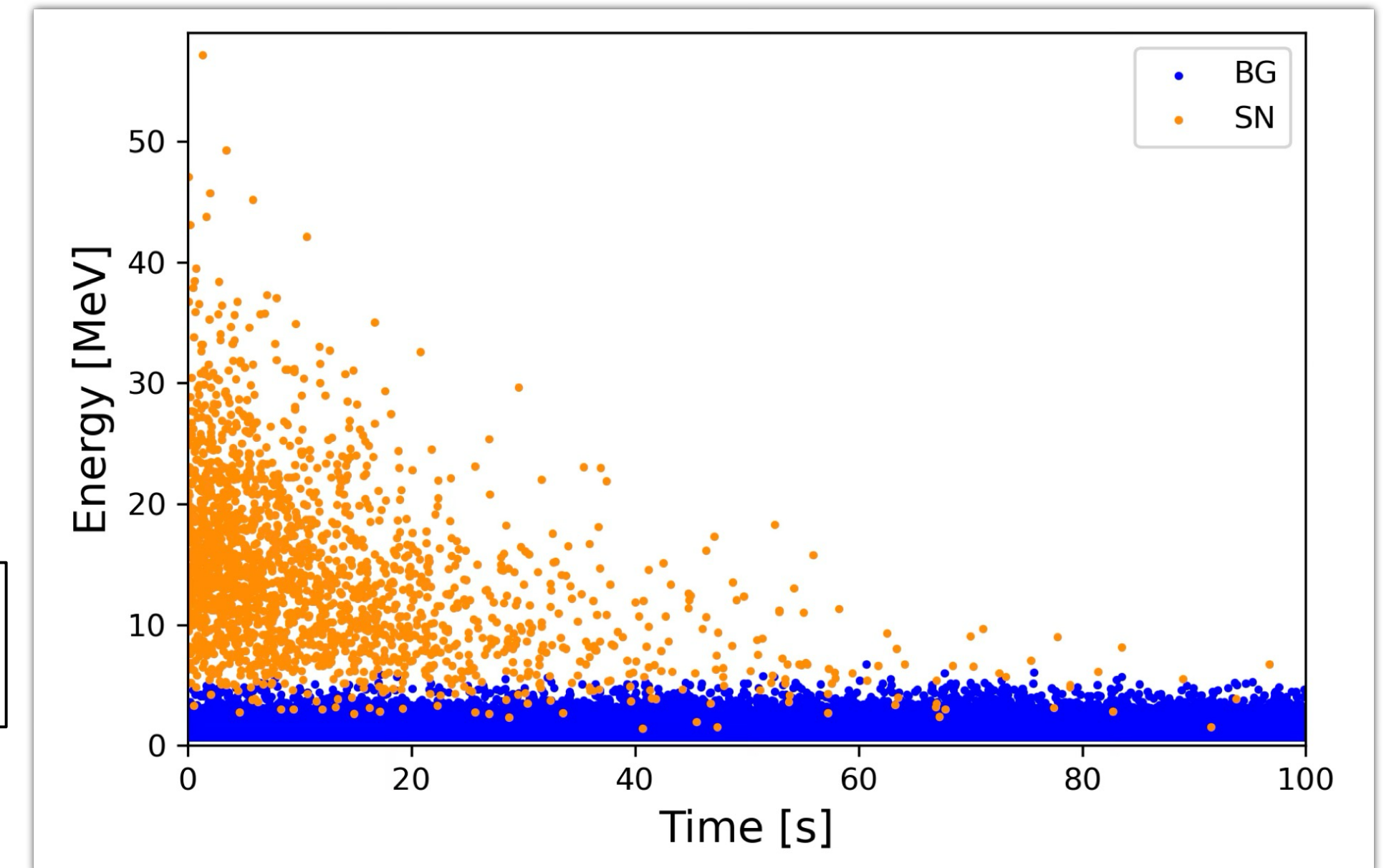
Abstract

Supernova (SN) neutrinos are key messengers for exploring the interior of an SN, especially the properties of the Proto-Neutron Star (PNS). SPECIAL BLEND (Harada +23) is a framework developed to estimate PNS parameters from SN neutrino data. It can estimate PNS radius, mass, and total emitted neutrino energy. However, in realistic observations, low-energy background events overlap in energy with SN neutrino events and degrade the estimation accuracy. To address this issue, we updated the estimation method by introducing an energy threshold. By excluding events below the threshold, background contamination can be reduced. We found that, for the SK fiducial volume, the energy threshold of 5.5 MeV allows the 1σ credible intervals to capture the true values for an SN up to 100 kpc away.

Supernova neutrino and background events



Mock data at Super-Kamiokande



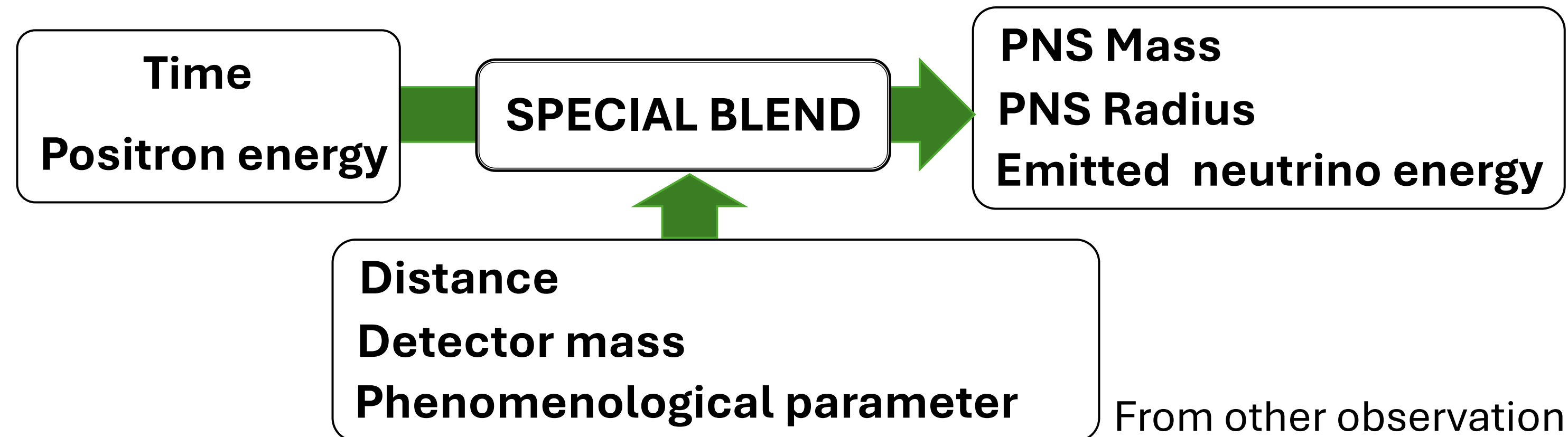
Low-energy BG events contaminate SN neutrino data; therefore, we need to **reduce the effect of BG events**.

Method

Supernova Parameter Estimation Code based on Insight on Analytic Late-time Burst Light curve at Earth Neutrino Detector

SPECIAL BLEND (Harada et al. 2023)

Estimate PNS parameters from observed SN neutrino data



Likelihood functions

◆ Binned likelihood (BLH)

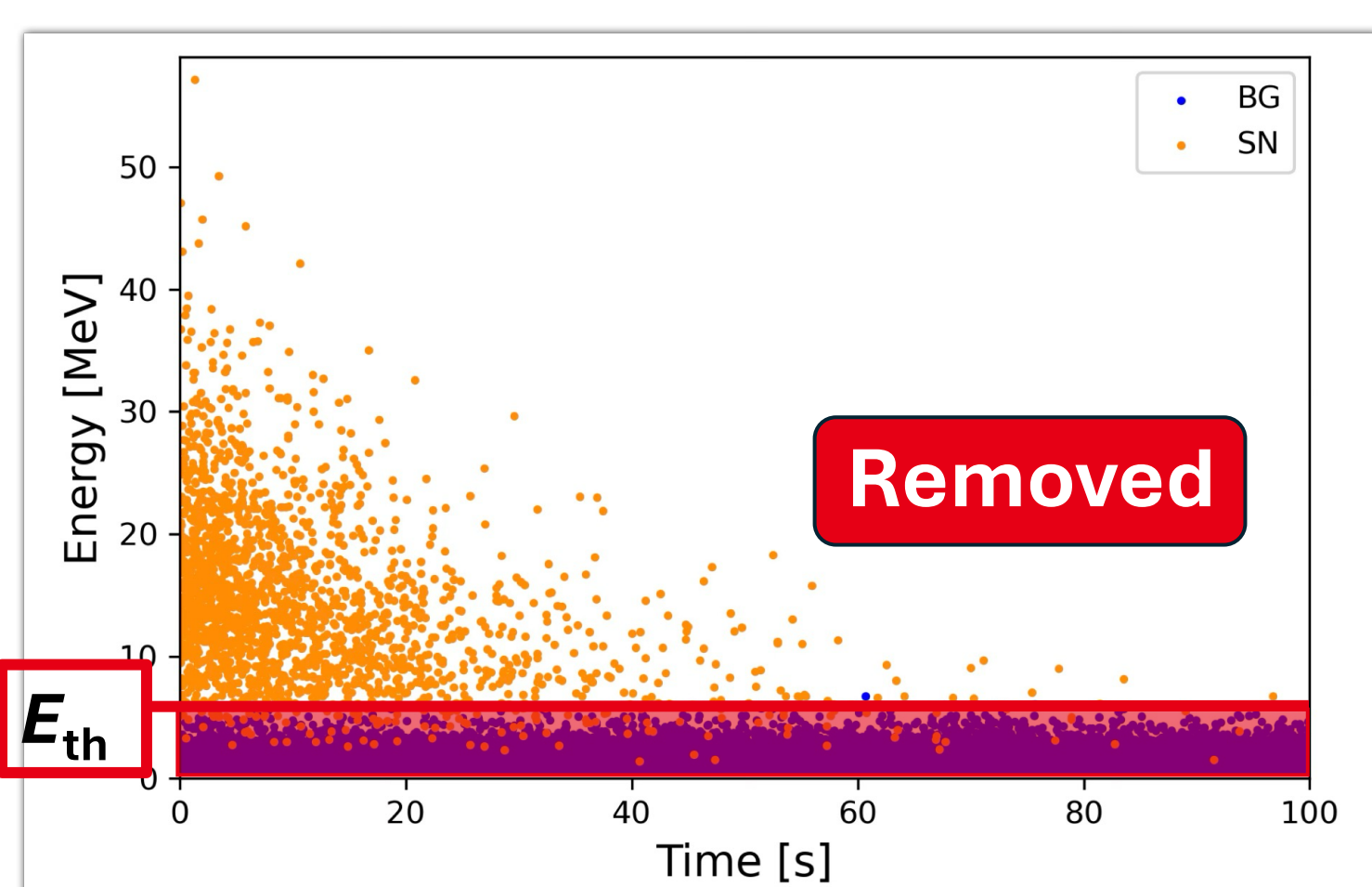
$$\mathcal{L}_{\text{BL}}(\theta | \{n_i\}_{2\text{D bin}}) \propto \prod_{i \in 2\text{D bin}} \exp(-\mathcal{R}(t_i, \theta) p(t_i, \epsilon_i, \theta) \Delta t_i \Delta \epsilon_i) \times \frac{(\mathcal{R}(t_i, \theta) p(t_i, \epsilon_i, \theta) \Delta t_i \Delta \epsilon_i)^{n_i}}{n_i!}$$

◆ Unbinned likelihood (UBLH)

$$\mathcal{L}_{\text{UBL}}(\theta | \{t_i, \langle \epsilon \rangle_i\}_{\text{event}}) \propto \exp\left(-\int \mathcal{R}(t, \theta) dt\right) \prod_{i \in \text{events}} \mathcal{R}(t_i, \theta) p(t_i, \epsilon_i, \theta)$$

Updated estimation method

We introduce an **energy threshold** treatment for low-energy BG into both the mock data and SPECIAL BLEND.



Incomplete Fermi-Dirac integral

$$F_n(y) = \int_0^\infty \frac{x^n}{1 + \exp(x)} dx$$

$$\approx \exp(-y) P_{n,1}(y) C_n(y)$$

where $y \equiv E_{\text{th}}/k_B T$

◆ Updating analytic solution

$$\text{Event rate : } \mathcal{R}(0) \rightarrow \mathcal{R}(y) = \frac{F_4(y)}{F_4(0)} \mathcal{R}(0)$$

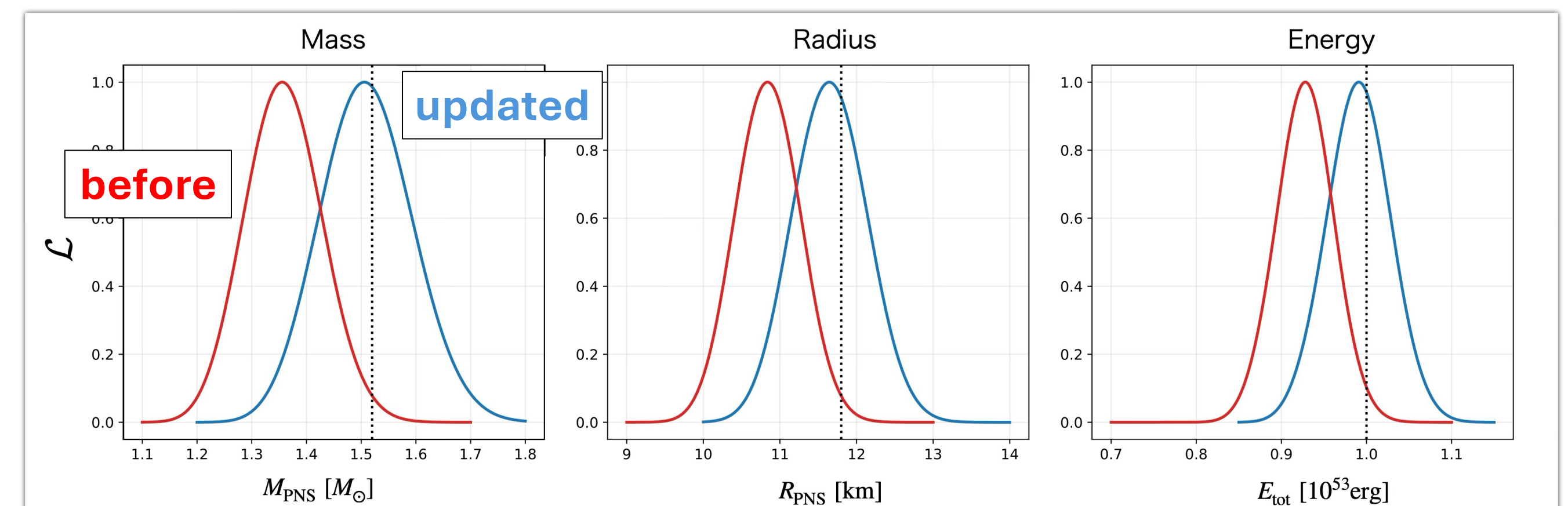
$$\text{Positron mean energy: } E_{e^+}(0) \rightarrow E_{e^+}(y) = \frac{F_5(y)/F_4(y)}{F_5(0)/F_4(0)} E_{e^+}(0)$$

We evaluate the accuracy of the updated SPECIAL BLEND and the impact of residual BG events on the parameter estimation.

Results

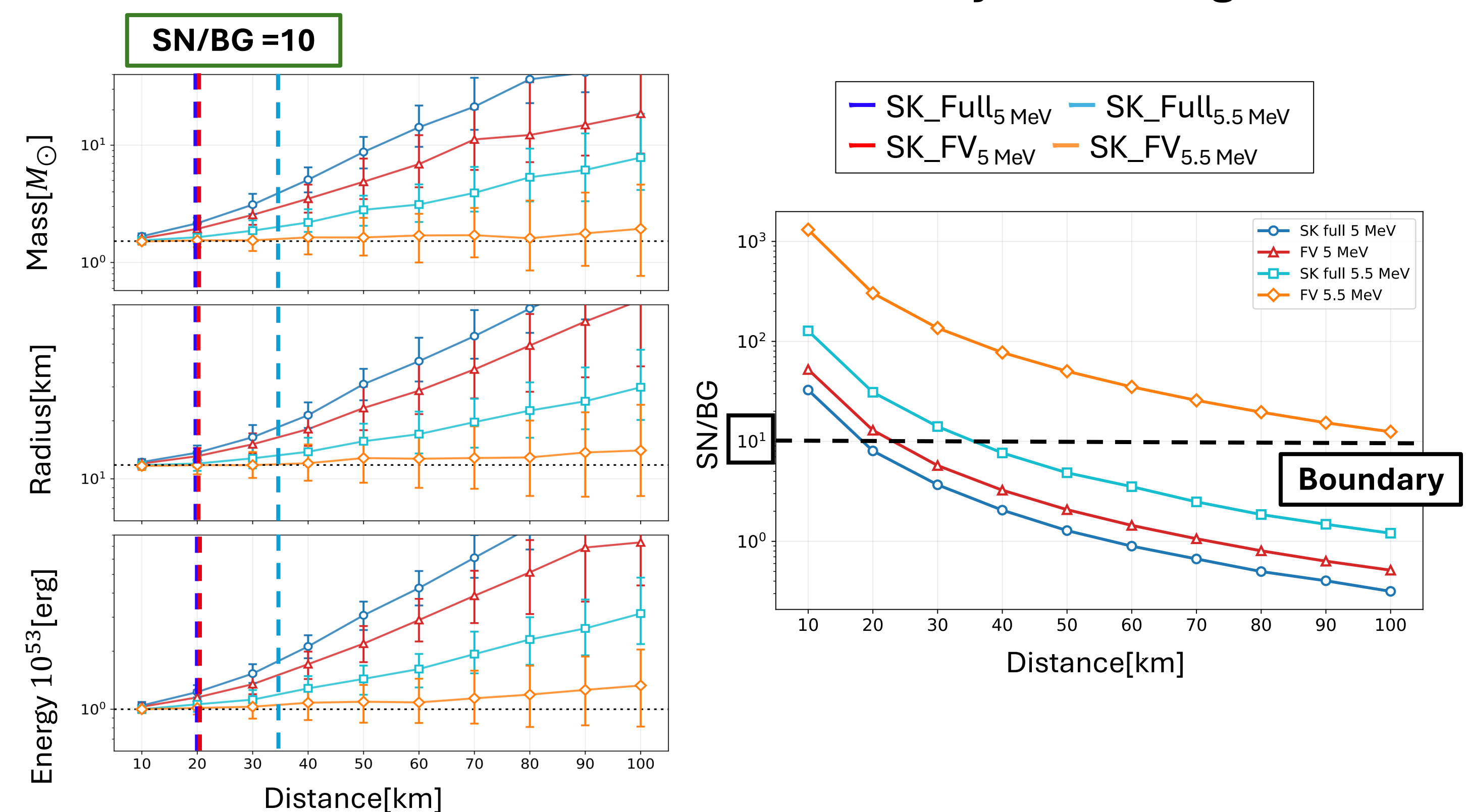
Accuracy of the updated SPECIAL BLEND for a SN at 10 kpc

- **without background (SK full volume $M_{\text{det}} = 32.5 \text{ kton}$)**



The updated SPECIAL BLEND improved the parameter estimation for event-cut data without BG, whereas residual BG degraded the estimation accuracy.

Distance dependence of estimation accuracy with background



For the SK fiducial volume with a 5.5 MeV threshold, the true values remained within 1σ credible intervals at 100 kpc. This might be related to the SN-to-BG event ratio. In our results, this boundary corresponds to **SN/BG ≈ 10**

Conclusion and future works

- Applying an energy threshold reduces the impact of the low-energy background events.
- In our current analysis, the boundary at which the true values remain within the 1σ credible intervals approximately correspond to **SN/BG ≈ 10**
- Based on this SK analysis, we will extend to a HK analysis strategy.