JUNO COSMOGENIC BACKGROUND

# Cosmogenic background estimation for JUNO's oscillation measurement

## with reactor antineutrinos

**Cailian Jiang**, on behalf of the JUNO Collaboration | Nanjing University

*Results correspond to one of three methods used to perform oscillation analysis*

NANJING UNIVERSITY

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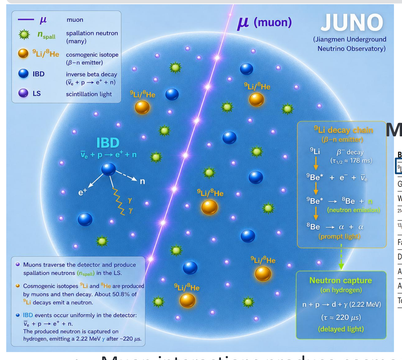
UCI Department of Physics & Astronomy

## Physics Motivation



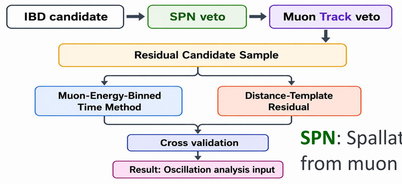

**Most dominant background**

| Backgrounds (cpd) | Pre-fit | Best fit |
|---|---|---|
| $^9$Li/$^8$He | 4.3±1.4 | 3.9±0.6 |
| Geoneutrinos | 1.2±0.5 | 1.4±0.4 |
| World reactors | 0.88±0.09 | 0.88±0.09 |
| $^{210}$Bi-$^{210}$Po | 0.18±0.10 | 0.20±0.10 |
| $^{13}$C(α,n)$^{16}$O | 0.04±0.02 | 0.04±0.02 |
| Fast neutrons | 0.02±0.02 | 0.02±0.02 |
| Double neutrons | 0.05±0.05 | 0.07±0.05 |
| Atmospheric neutrinos | 0.08±0.04 | 0.07±0.04 |
| Accidentals (×10$^{-3}$) | 4.9±0.3 | 4.9±0.3 |
| Total | 6.80±1.49 | 6.63±0.74 |

*Nature 654, 343-352 (2026).*

- Muon interactions produce cosmogenic isotopes.
- **Li9/He8 beta-n** decays **mimic IBD signals**.
- Residual background must be quantified.

### Analysis Strategy

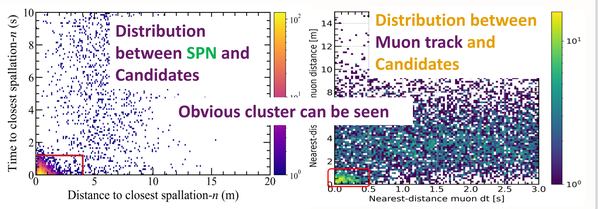



**SPN**: Spallation Neutron from muon

### Selection Criteria

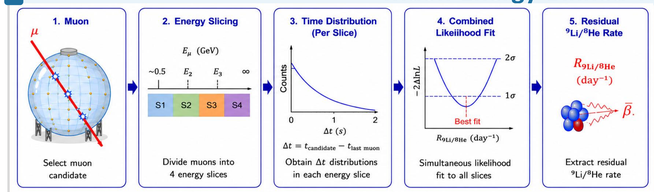
| IBD Selection | | Muon-induced Background Rejection | |
|---|---|---|---|
| Fiducial Volume | R < 17.2 m | Water Pool Muon Veto | 2 ms |
| Prompt Energy | 0.7 < Ep < 12 MeV | Central Detector Muon Veto | 5 ms |
| Delayed Energy | 2.0 < Ed < 2.5 MeV or 4.5 < Ed < 5.5 MeV | Spallation Neutron Veto | Δr < 4 m, Δt < 1.2 s |
| Coincidence Time | 5 < Δt < 1000 μs | Track Veto | $\frac{\Delta r_\mu}{2.5\text{ m}} + \frac{\Delta t_\mu}{0.5\text{ s}} < 1$ |
| Coincidence Distance | Δr < 1.5 m | | |

### Muon-Candidate Correlation




## Two Complementary Estimators

### Muon-Energy-Binned-Time Estimator



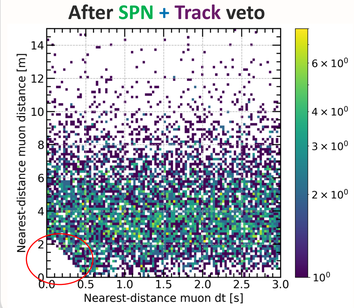

$$N_k(t) = \sum_{iso} N_{iso}^{(k)} \lambda_{iso}^{(k)} e^{-\lambda_{iso}^{(k)} t} + N_{\text{uncorr}}^{(k)} R_\mu^{(k)} e^{-R_\mu^{(k)} t} \qquad iso \in \{^9\text{Li}, {}^8\text{He}\},\ \lambda_{iso}^{(k)} = R_\mu^{(k)} + \frac{1}{\tau_{iso}},$$

$$N_{\text{uncorr}}^{(k)} = N_{\text{IBD+Acc}} + \sum_{j \neq k} \sum_{iso} N_{iso}^{(j)}.$$

- $k = 1, \ldots, 4$ labels the four muon-energy regions;
- $N_{iso}^{(k)}$ are the correlated $^9$Li/$^8$He yields in the $k$-th muon-energy region;
- $N_{\text{IBD+Acc}}$ is a global parameter shared across all regions;
- $N_{\text{uncorr}}^{(k)}$ contains IBD, accidental events, and $^9$Li/$^8$He contributions from the other muon-energy regions, which are uncorrelated with the current muon sample.

*Nucl.Instrum.Meth.A* 564 (2006)

**After SPN + Track veto**




**After SPN veto**

$$N_{\text{remain}}(t) = N_{\text{far}} e^{-t/\tau} + N_{\text{near}} e^{-t/\tau} \Theta(t - 1.2\text{ s}) \qquad \tau \approx 257.2\text{ ms}$$

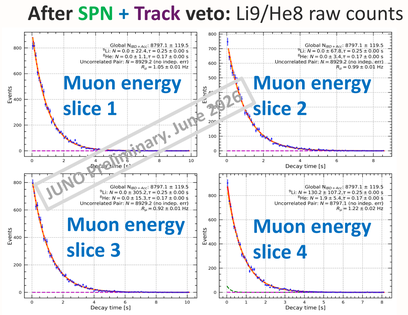
$$N_{\text{remain}}(t) \simeq N_{\text{far}} e^{-t/\tau}$$ **neglected**

**After SPN + Track veto**: The **time distribution** should be

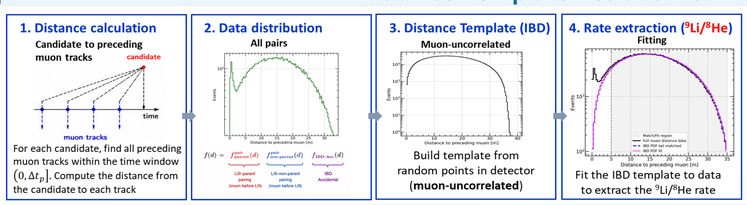
$$N_{\text{remain}}(t) = N_{\text{far}} e^{-t/\tau} + N_{\text{near}} e^{-t/\tau} \Theta(t - 0.5\text{ s}) \quad \bigstar$$

The **modified time structure** and **limited statistics** lead to **unstable fits** and **large uncertainties.**

**After SPN + Track veto:** Li9/He8 raw counts




### Distance-Template Residual Estimator

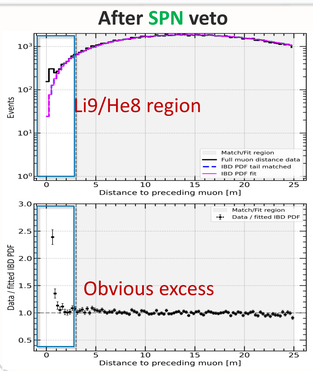



$$N_{\text{tail}}^{\text{data}}(d) = N_{\text{fit}}^{\text{tail}} P_{\text{template}}(d), \qquad f_{\text{tail}} = \int_{\text{tail}} P_{\text{template}}(d)\, \mathrm{d}d$$

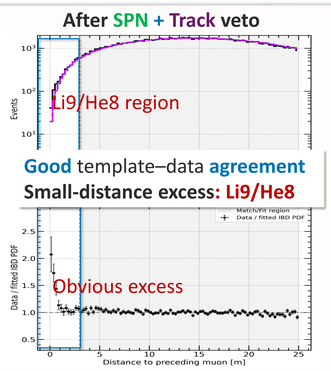
$$N_{\text{uncorr}} = \frac{N_{\text{fit}}^{\text{tail}}}{f_{\text{tail}}}, \qquad f_{\text{small}} = 1 - f_{\text{tail}}$$

$$N_{\text{Li9}} = N_{\text{small}}^{\text{data}} - N_{\text{uncorr}} f_{\text{small}}$$

**After SPN veto**



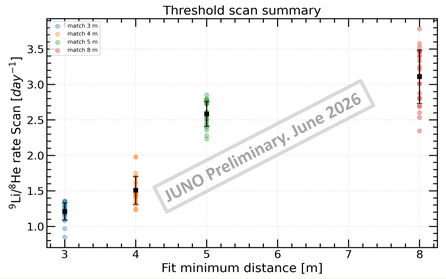

**After SPN + Track veto**




**Good** template–data **agreement**
**Small-distance excess: Li9/He8**

### Stability checks for Li9/He8 rate

- **Distance-template boundary (upper, lower)**
- **Distance PDF binning**

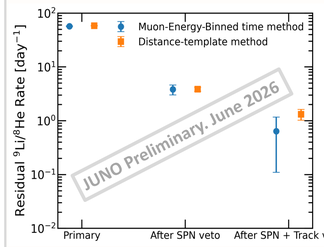



## Result: Validation + Combination

**Final residual $^9$Li/$^8$He rate**

**1.1 ± 0.3 (stat.) ± 0.3 (syst.) day$^{-1}$**

### Cross-check of Two Estimators




**Good agreement** is observed between **two estimators**
**Time method** gives **a larger statistic uncertainty**
Try to use **distance method** to **constrain result** from time method

### Constrained Combination

**Combine Time and Distance method**

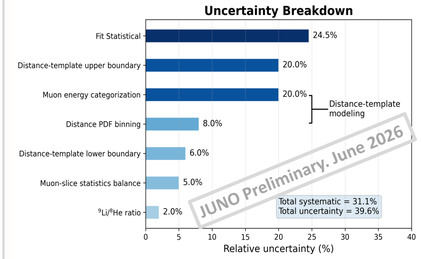
- **Decrease the statistic uncertainty of Time fitting result**
- **Distance-template result is used as an external Gaussian constraint in the time fit.**

$$\mathcal{L}_{\text{comb}} = \mathcal{L}_{\text{time}} \cdot \underbrace{\mathcal{G}\left(\hat{N}_{\text{Li9+He8}}^{\text{dist}} \,\middle|\, (1+r)\sum_{k=1}^{4} N_{\text{Li9},k}, \sigma_{\text{dist}}\right)}_{\text{Gaussian constraint from distance fit}} \qquad r = \frac{N_{\text{He8}}}{N_{\text{Li9}}} = 0.0143$$

$$\text{NLL}_{\text{comb}} = \text{NLL}_{\text{time}} + \frac{1}{2}\left(\frac{(1+r)\sum_k N_{\text{Li9},k} - \hat{N}_{\text{Li9+He8}}^{\text{dist}}}{\sigma_{\text{dist}}}\right)^2$$

| Selection Criteria | Constrained Rate ($day^{-1}$) |
|---|---|
| Primary | 58.0 ± 0.8 (stat.) |
| After SPN veto | 3.9 ± 0.3 (stat.) |
| After SPN + Track veto | 1.1 ± 0.3 (stat.) |

### Uncertainty Budget




- **Statistical uncertainty** is the **most dominant one**
- **Total systematic uncertainty ~ 25%**

**Results obtained by different methods are compatible**

## Summary

**1 Two estimators**
**Muon-energy-binned Time fit and Distance-Template residual fit are applied to the same sample.**

**2 Independent validation**
**Muon-Energy-Binned-Time Method and Distance-Template Residual Method give consistent residual estimates.**

**3 Strong suppression**
**Rate evolves from 58.0 (no veto) to 3.9 (SPN veto) to 1.1 (SPN + Muon Track veto) per day.**

**4 References**

[1] JUNO Collaboration, Nature 654, 343-352 (2026).
[2] JUNO Collaboration, Chin. Phys. C 50, 043001 (2026).
[3] L.J.Wen, *Nucl.Instrum.Meth.A* 564 (2006) 471-474.