

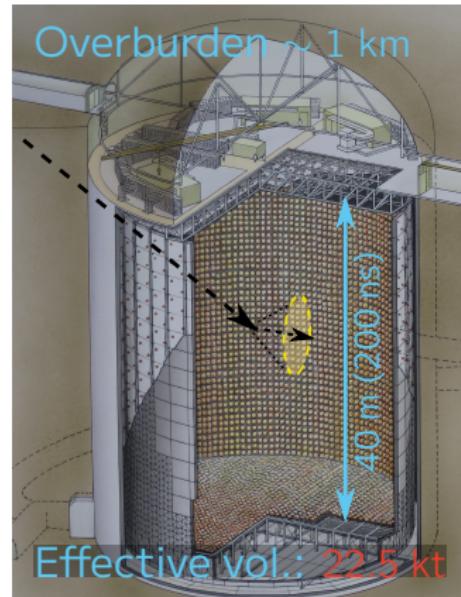


Lower Energy Extension for Anti-Electron-Neutrino Search in the Super-Kamiokande

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for Super-Kamiokande Collaboration
TAUP 2023 (Vienna),
31 Aug. 2023



- Water Cherenkov detector
 - Effective volume: 22.5 kt
 - Physics targets
 - ▶ ν oscillation meas. w/ atmospheric- and solar- ν
 - ▶ Search for nucleon-decay
 - ▶ ν astronomy:
supernova, solar
- Gd-loaded phase (2020–)
 - Higher efficiency of neutron tagging
⇒ **Better sensitivity in supernova- ν**

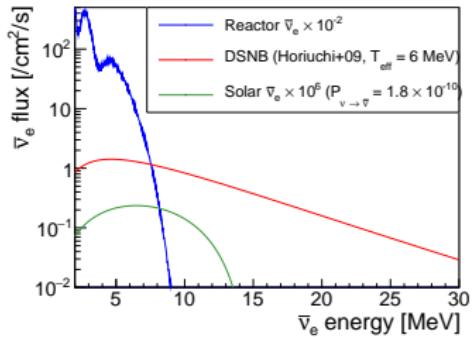
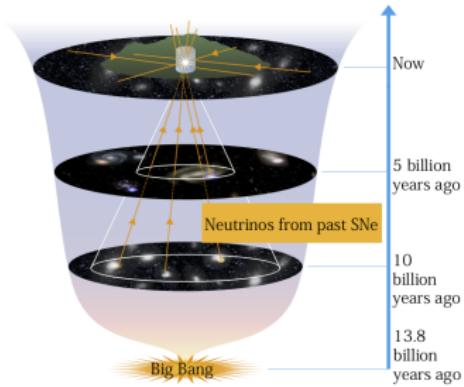


Phase	Period	Gd
SK-I-V	'96 Apr.–'20 Aug.	0%
SK-VI	'20 Aug.–'22 Jun.	0.011%
SK-VII	'22 Jun.–	0.033%

DSNB and MeV $\bar{\nu}_e$ Physics

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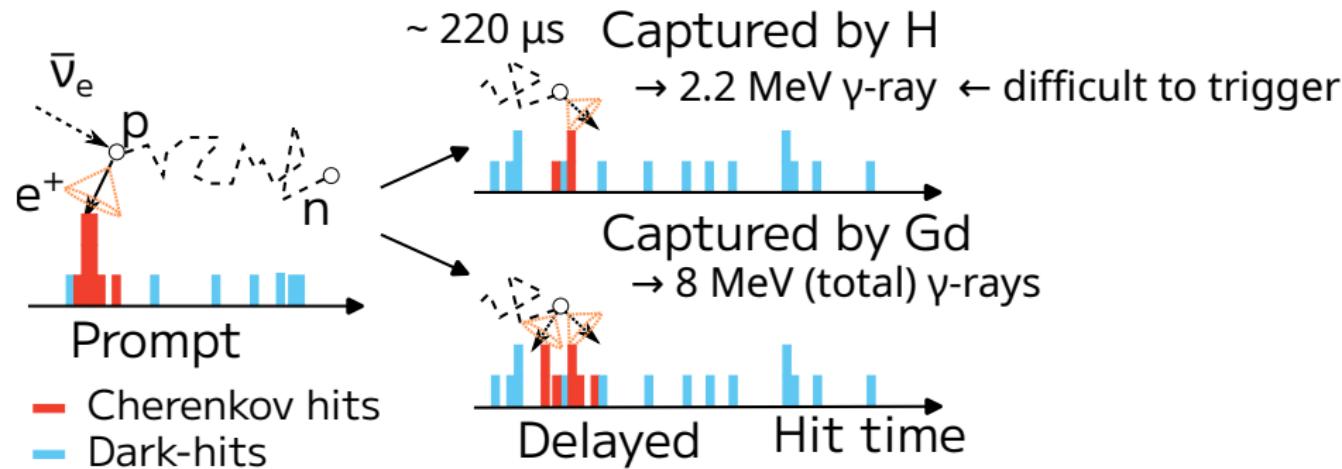
- $\bar{\nu}_e$ of ~ 10 MeV
 - Diffuse Supernova Neutrino Background (DSNB)
 - ▶ Collective neutrinos from core-collapse supernova (CCSN)
 - ▶ Probe of CCSN mechanism, star formation rate, etc.
 - ▶ Latest result from SK-Gd (prev. talk)
 - Reactor $\bar{\nu}_e$
 - Beyond standard model
 - ▶ Solar $\bar{\nu}_e$
 - ▶ Dark matter



$\bar{\nu}_e$ Signal in Water

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- Inverse Beta Decay (IBD) $\bar{\nu}_e + p \longrightarrow e^+ + n$
 - Largest cross section @ $E_\nu \sim 10$ MeV in water
 - ⇒ Delayed coincidence

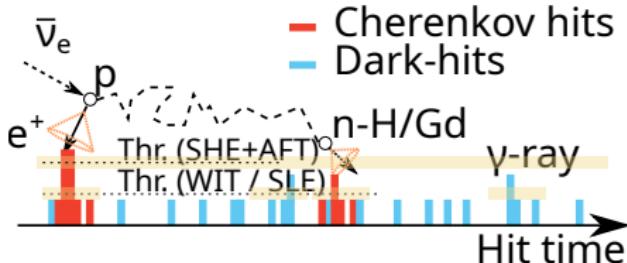


⇒ Saving all hits for 540 μs (SHE+AFT trigger)

Extension of Lower Energy Region 5/13

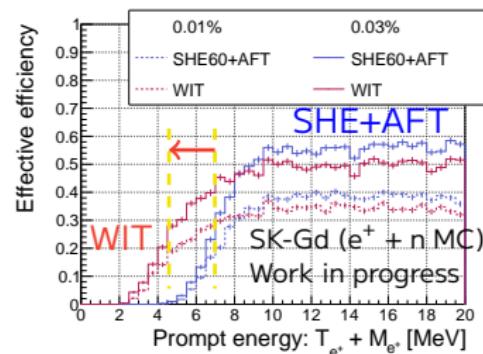
- Conventional analysis:

- Delayed signal from raw hit info. of 540 μ s
 $\Rightarrow E_{\text{thr}, \bar{\nu}_e} \sim 7 \text{ MeV}$



- Lower energy extension:

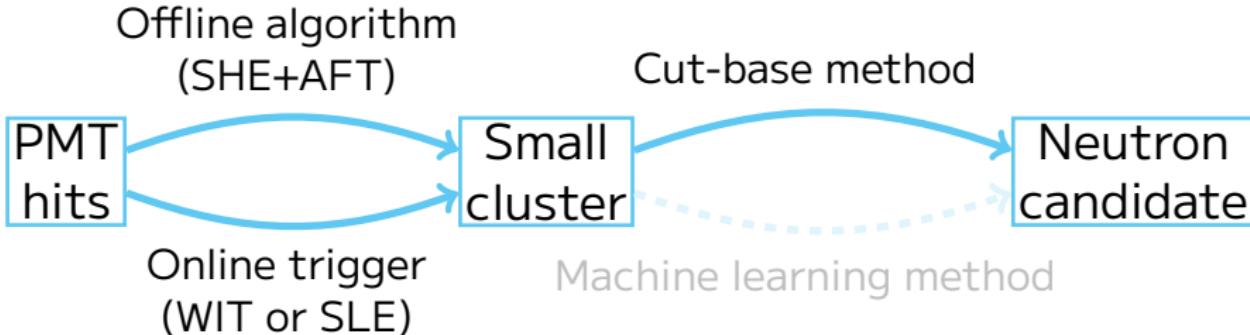
- Delayed signal from low energy triggers
 - SLE (N_{hits} base)
or WIT (online builder) $\Rightarrow E_{\text{thr}, \bar{\nu}_e} \sim 4.5 \text{ MeV}$



Trigger	Threshold	Gate width	n-H	n-Gd
SHE+AFT (N_{hits})	7 MeV	540 μ s	○	○
WIT or SLE	4.5 MeV	$\sim 1 \mu\text{s}$	△	○

Neutron Tagging

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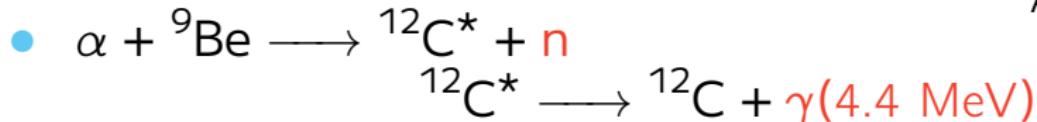


1. Hit cluster search in timing
2. Multi-variable analysis
 - Features of Cherenkov event
 - ▶ Hit timing, ring shape, photo-yield, distance from prompt event, etc.
 - Cut-base method
 - ▶ Efficiency $\sim 30\%$ and miss-tagging $\sim 0.01\%$

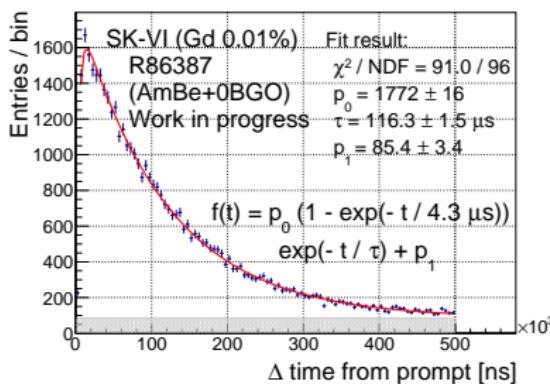
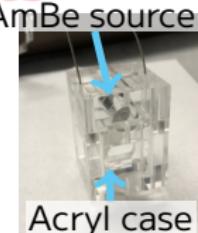
Feasibility Check with AmBe

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⇒ AmBe source (γ -n pair): **IBD-like events**



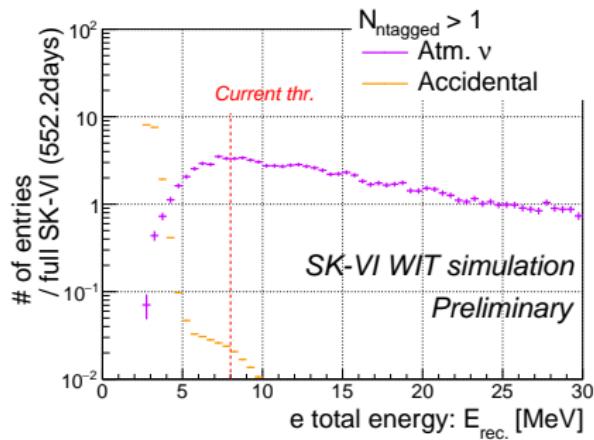
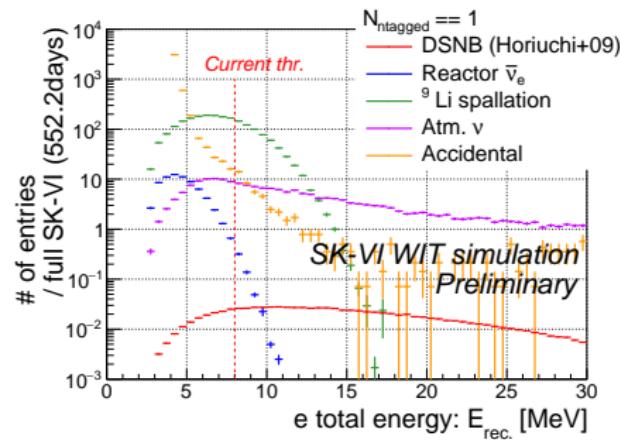
⇒ $E_\gamma < E_{\text{threshold}}$ of SHE+AFT trigger $\sim 8 \text{ MeV}$



- $\tau_{\text{capture time}} = 116 \pm 2 \mu\text{s}$
 - Consistent with usual analysis
- γ -n tagging efficiency:
⇒ $(\text{Eff.}) = 6.86 \pm 0.2\%$
(stat. only)

⇒ **Confirmed coincidence of γ and n**

- Expected spectrum before detailed cut



- Background sources, and how to reduce

Spallation ${}^9\text{Li}$

Accidental coincidence

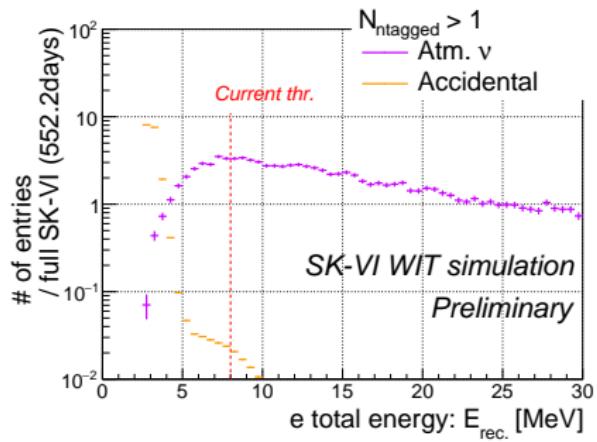
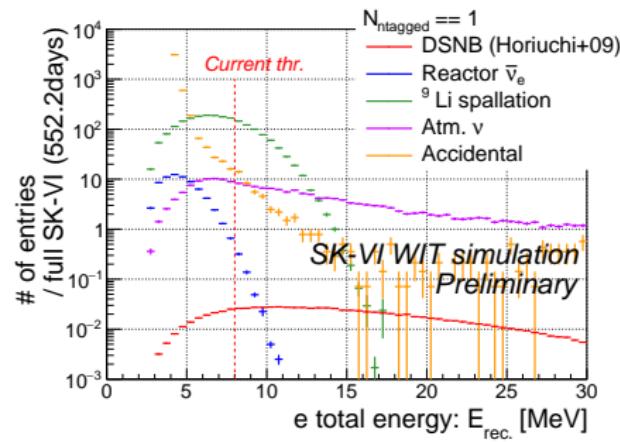
Atmospheric ν

Correlation with muon

Tuning of n-tag

Cherenkov ring pattern etc.

- Expected spectrum before detailed cut



- Background sources, and how to reduce

Spallation ${}^9\text{Li}$

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Atmospheric ν

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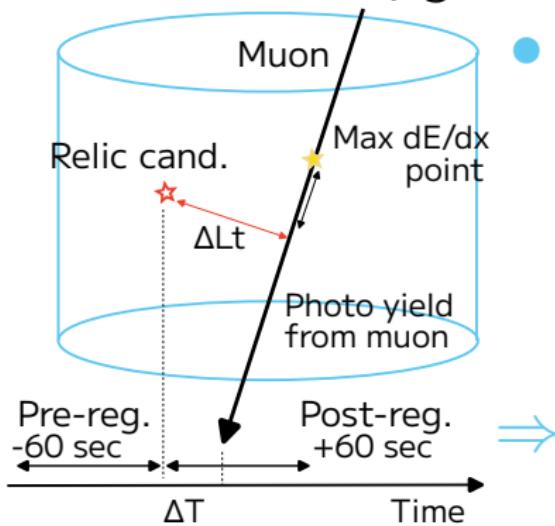
Tuning of n-tag

Cherenkov ring pattern etc.

Spallation Event

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- Radioactive isotopes produced by cosmic- μ
- In DSNB analysis, cut by likelihood method
 - Time diff., geometrical correlation, photo-yield



- (spallation samples) = (pre) – (post)
random **μ -correlated**

	random	μ -correlated
pre-	○	○
post-	○	✗
⇒ sub.	✗	○

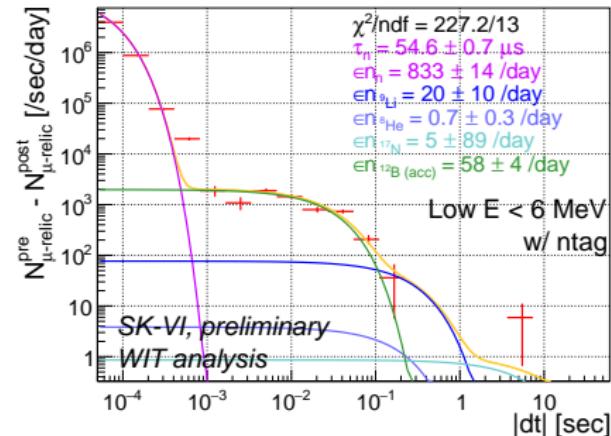
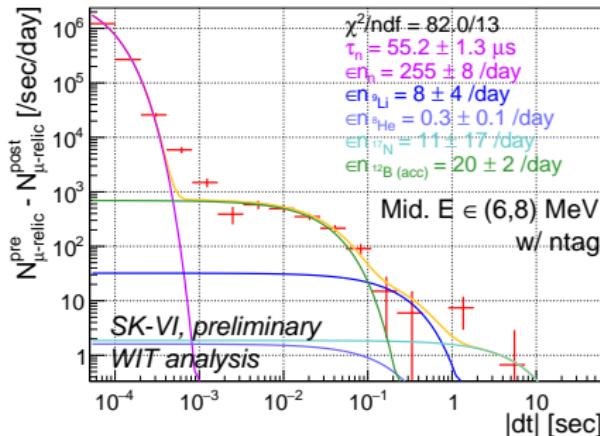
Checked Δt distribution

- Feasibility study to see lower energy events

Time Difference Distribution

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1 month data



- Confirmed IBD like component of spallation events in lower energy
 - Dominated by accidental ^{12}B
 - IBD-like tagging method is working well

Today

To establish BG reduction method

Tuning of each reduction step:
spallation, accidental, atmospheric- ν .

To open data

With improved analysis:

- Lower energy component
- Improvement neutron tagging method
- Model fitting

- SK-Gd: Gd-doped Water Cherenkov Detector
 - Improved $\bar{\nu}_e$ tagging \Rightarrow DSNB
- **Lowering energy threshold:** 8 MeV \rightarrow 4 MeV
 - Reactor $\bar{\nu}_e$
 - Better understanding of BG to DSNB
 - ▶ Spallation ${}^9\text{Li}$, atmospheric ν
- Developing analysis method with revisiting trigger system
 - Confirmed feasibility with real data:
AmBe neutron source, spallation events
- Prospect: **re-analysis of SK-VI
(first Gd-phase) with new energy window**

Appendix

Selection criteria for AmBe events

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Selected events in three steps:
based on DSNB analysis



1. Pairing: combination of prompt (1) –delayed (N)

- Distance $\Delta r < 3$ m and time difference $\Delta t < 500$ μs

2. Prompt-event:

- FV cut (distance from wall > 2 m)
- Quality of Cherenkov ring
- Distance from AmBe source < 5 m
- Number of delayed candidates $N_{\text{delayed evt.}} = 1$

3. Delayed-events:

- Time difference from prompt > 4 μs
- FV cut
- Quality of Cherenkov ring
- Total energy $E > 3.0$ MeV
- Distance from prompt $\Delta r < 3$ m

