Observation of distant reactor neutrino in Super-Kamiokande with gadolinium-loaded water

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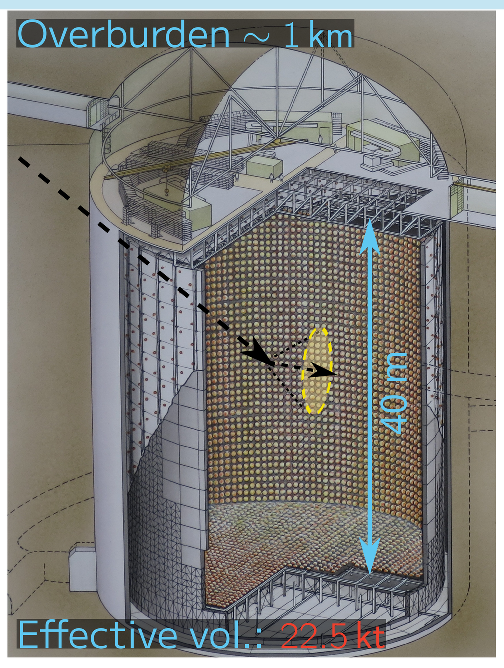
1. Super-Kamiokande experiment

Large Water Cherenkov detector

- Location: underground (1 km), Kamioka
- Physics targets along 28 year operation
  - ν oscillation measurements: atmospheric-ν, solar-ν, accelerator-ν (T2K exp.)
  - ν astronomy: solar, supernovae (burst and relic)
  - Dark matter
  - GUT via proton decay search
  - ⇒ Various ν sources and so on...



SK-Gd (Summer of 2020–) [1]

- Gadolinium Gd: enhancement of neutron tagging efficiency
  - Large neutron capture cross section
  - Higher energy (8 MeV) in neutron capture than hydrogen (2.2 MeV)

⇒ Better efficiency for $\bar{\nu}_e$ in 10 MeV region

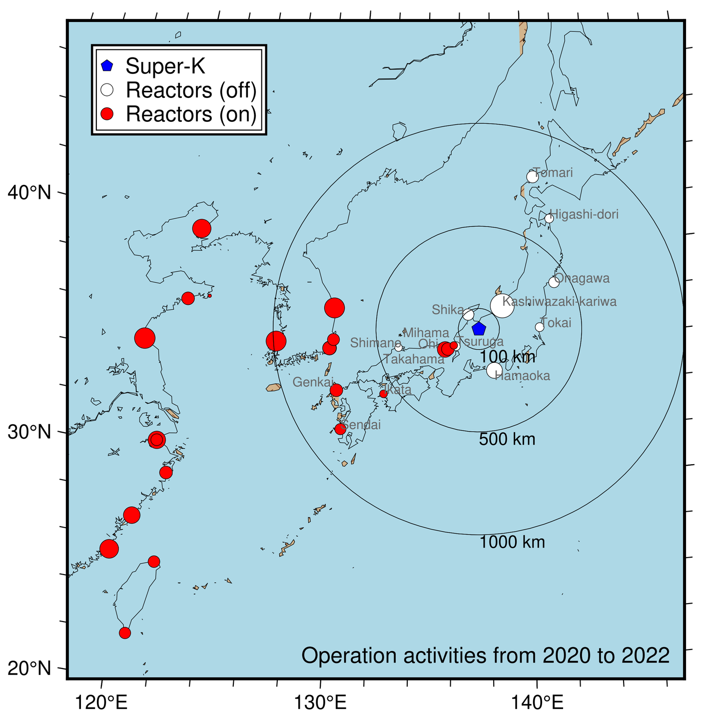
- Inverse Beta Decay (IBD): $\bar{\nu}_e + p \longrightarrow e^+ + n$

- Two phases of SK-Gd: SK-VI and SK-VII

Phase	Gd-concentration	Date (livetime)	
SK-VI	0.01 %	Jun. 2020 – (536.6 d)	⟵ today's result
SK-VII	0.03 %	Jun. 2022 –	

2. Reactor neutrinos

- Reactor: intense $\bar{\nu}_e$ source
  - Peak energy ~ 4 MeV
  - Widely used in ν physics
    - ▸ Short baseline: sterile ν search
    - ▸ Middle baseline: θ_{13} measurement
    - ▸ Long baseline: solar mixing (KamLAND)
- No measurement in water Cherenkov det.
  - Exception: evidence in SNO+ exp. [2]
- Interaction rate in SK: ~ 5 event/d
  - Nearest reactor from SK: 150 km
  - Total flux ~ 1/10 of before earthquake
- Modeling in analysis: SKReact [3] + SKSNSim [4]
  - Reactor spectrum: Huber-Mueller
  - Oscillation: PDG2022 value
  - Reactor activities: PRIS (INFN)
  - IBD: Ricciardi-Vignaroli-Vissani

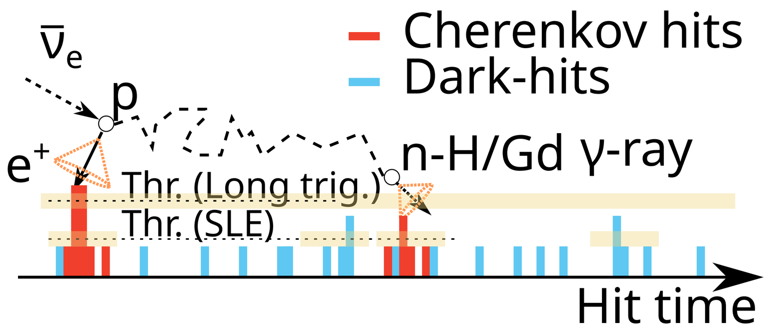


3. New analysis w/ low energy trigger

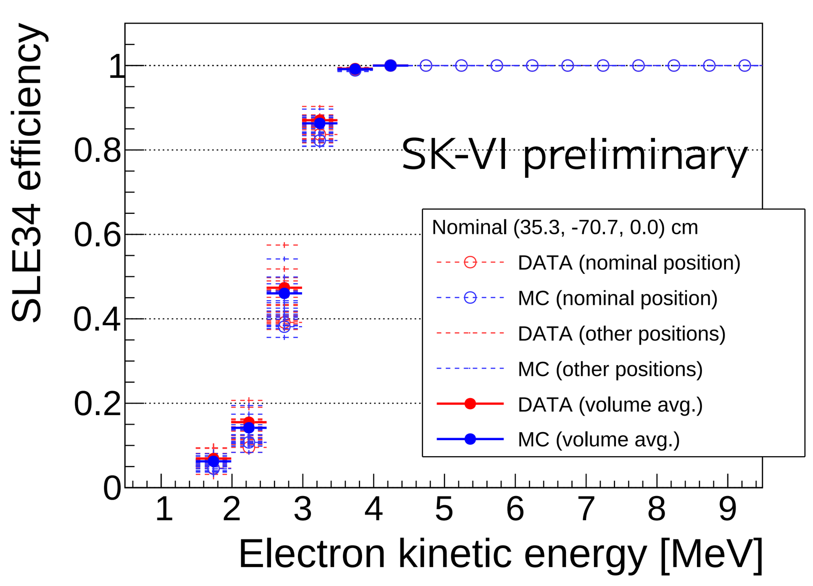
Requirement	Strategy in SK-Gd
Low energy threshold	Gd and low energy trigger ⇒ New analysis method
BG suppression	Water/air system, event quality, etc. ⇒ Similar to solar analysis

New analysis

- Pure-water phase: neutron signal is only 2.2 MeV γ-ray in hydrogen capture
  - Handled by only long gate trigger
  - Limited energy threshold.
- Gd-water phase: super low energy (SLE) trigger works for Gd-cap.
  - Evaluated w/ Ni/Cf γ-ray source



Analysis	Thr.	Gate width
Conventional	8 MeV	535 µs
New	3 MeV	1.5 µs



BG suppression

- Typical trigger rate ~ 20 kHz
- Reduction
  - Timing spread, topology of Cherenkov photons
  - Masking wall region

⇒ Extended lower energy region w/ SLE

4. Event category

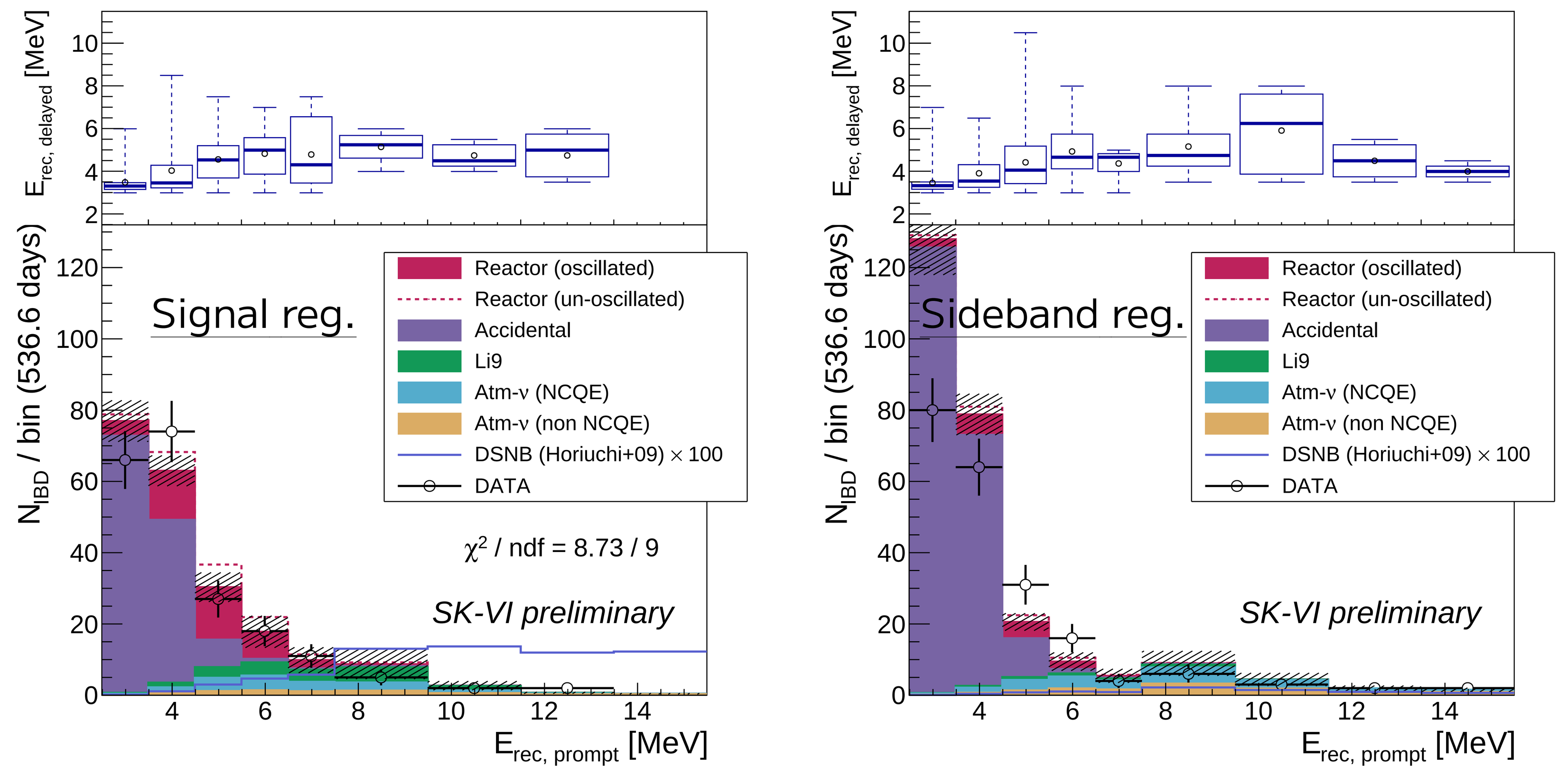
- BG sources: accidental coincidence of single event (^{214}Bi etc.), ^{9}Li of cosmic-ray spallation, atm. ν
  - Based on experience of conventional $\bar{\nu}_e$ analysis
- Signal and sideband regions: according to Cherenkov opening angle $\theta_{\text{Cherenkov}}$

Category	Signal	Sideband
$\theta_{\text{Cherenkov}}$	around 42°	other
Event type	single e track	multiple tracks, μ/π track

5. Result: spectra, correlation w/ power trend

Signal and sideband spectra

- Signal region: excess of reactor $\bar{\nu}_e$
  ⇒ first positive observation of reactor $\bar{\nu}_e$ in SK(-Gd)
  - Inconsistency in sideband region (under investigation of details)
  - Plan to evaluate significance after this understanding
- Small stat. to discuss oscillation

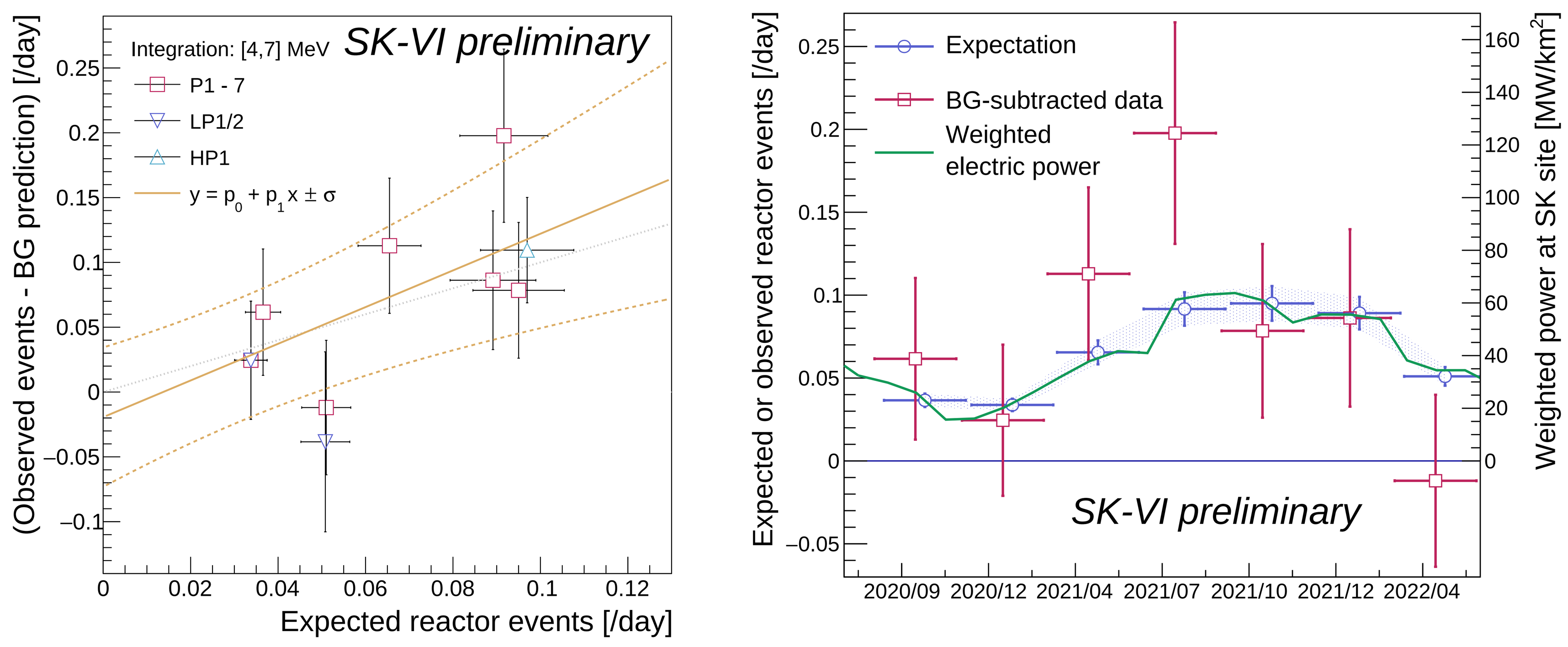


History and power correlation:

- Event rate: 3 months, signal: integrated 4–7 MeV bins
- ×2 variation in reactor $\bar{\nu}_e$ rate

⇒ Linear correlation: 1.4 ± 0.8

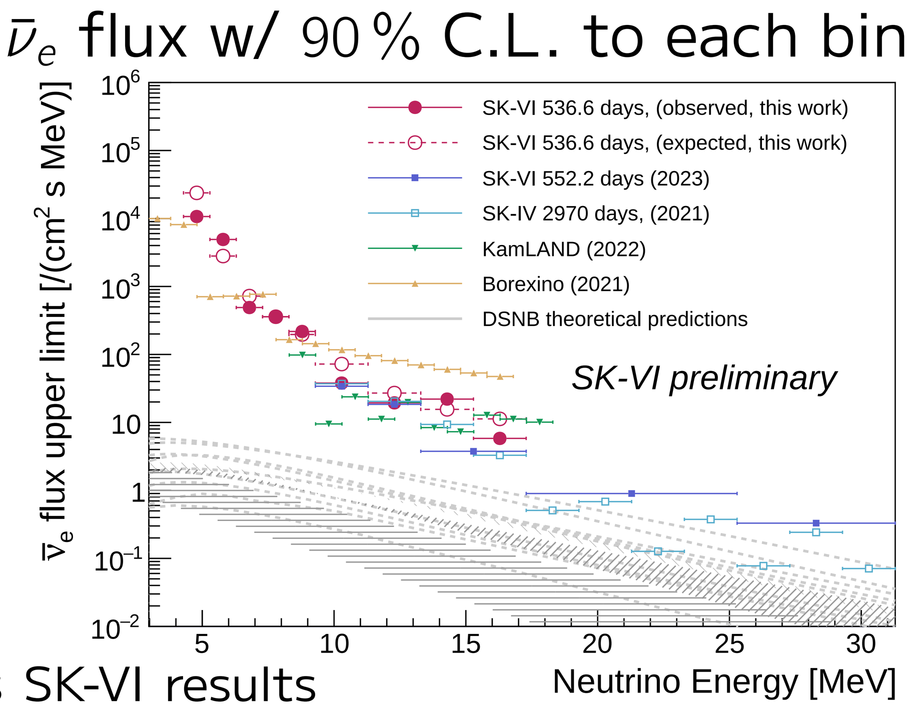
- No clear rejection of 0-slope due to low stat.



6. Upper limit on astrophysical $\bar{\nu}_e$ flux

⇒ Set upper limit on astro. $\bar{\nu}_e$ flux w/ 90 % C.L. to each bin

- No other excess of $\bar{\nu}_e$ events in signal region
  - Possible sources: solar $\bar{\nu}_e$, DM annihilation, diffuse supernova ν background, etc.
- Comparable sensitivities to large volume liquid scintillator exp. (KamLAND [5], Borexino [6])



- Note: overlapping w/ previous SK-VI results in 10–16 MeV bins: worse sensitivities due to tight criteria.

7. Summary and prospects

- SK-Gd: the largest Water Cherenkov detector for 10 MeV $\bar{\nu}_e$
- Extended lower energy region of $\bar{\nu}_e$ analysis
  - Development of new analysis method using SLE trigger for delayed coincidence search
- $\bar{\nu}_e$-analysis on SK-VI (2020–2022, 0.01 % Gd concentration, 536.6 d)

⇒ First observation of reactor $\bar{\nu}_e$ in SK

- Trend and correlation along reactor activities from 2020 to 2022.

⇒ Astrophysical $\bar{\nu}_e$ flux limit in new energy region in SK

- Prospect: new physics analysis in extended energy region
  - Dedicated $\bar{\nu}_e$-analysis: solar $\bar{\nu}_e$, DM annihilation, etc.
  - Oscillation study towards CPT-test

Reference: [1] K. Abe, et al. (SK), Nucl. Instrum. Methods Phys. Res. A 1027 (2022) 166248, [2] A. Allega, et al. (SNO+), Phys. Rev. Lett. 130 (2023) 091801, [3] A. Glodsack, DOI: 10.5281/zenodo.4395825, [4] F. Nakanishi, et al. , Astrophys. J. 965 (2024), 91, [5] S. Abe, et al. (KamLAND), Astrophys. J. 925 (2022), 14, [6] M. Agostini, et al. (Borexino), Astropart. Phys. 125 (2021), 102509.

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