Low-energy astrophysics with KamLAND

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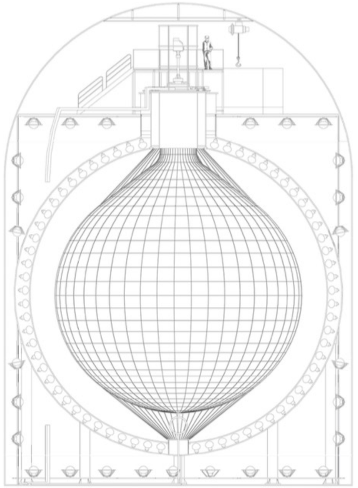
Strategy of This Study

1. MeV-scale neutrino profile



- KamLAND detector

2. Gravitational wave / solar flare time profile

- LIGO/Virgo-O2/O3 for gravitational waves
- *GOES* flare catalogue for solar flares

3. Coincidence analysis

The KamLAND detector

Kamioka **L**iquid-scintillator
Anti-**N**eutrino **D**etector

Inner detector (ID)

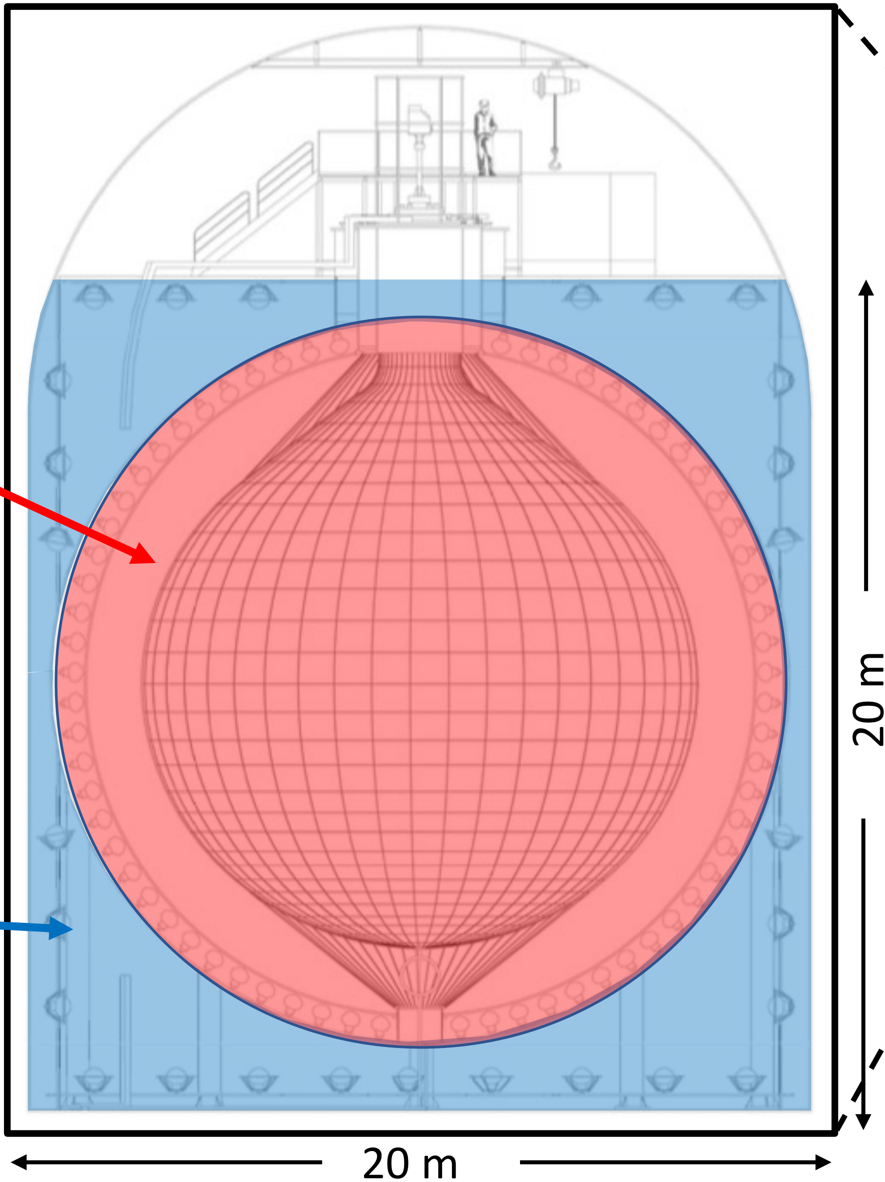
- 17inch PMT x1325
- 20inch PMT x554
- Liquid scintillator 1 kt

→ Event detection

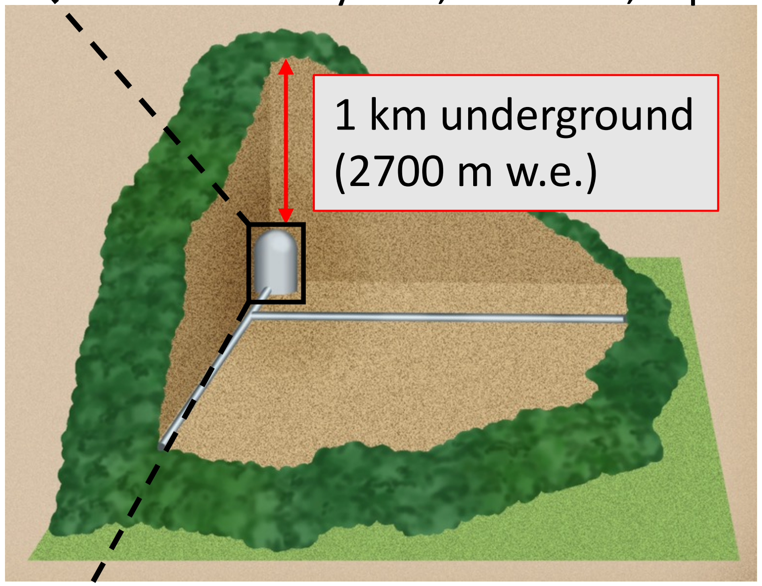
Outer detector (OD)

- 20inch PMT x140
- Purified water 3.2 kt

→ Shield + Active veto

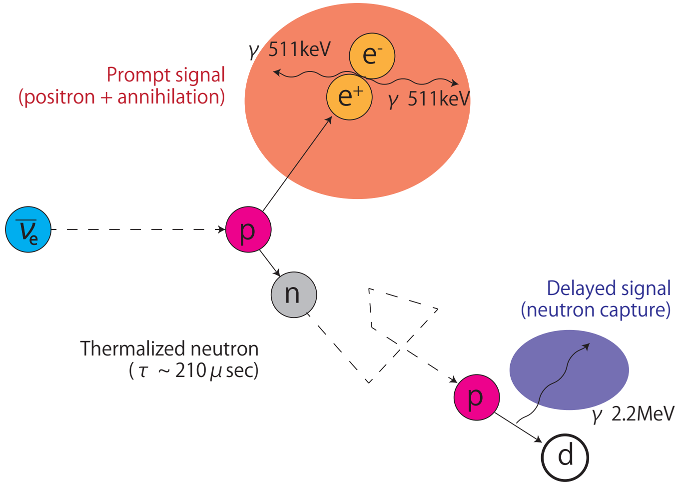


Mt. Ikenoyama, Kamioka, Japan



The cosmic-ray muon flux is attenuated by the rock.

Neutrino Detection Channels in KamLAND



Inverse-beta decay (IBD)

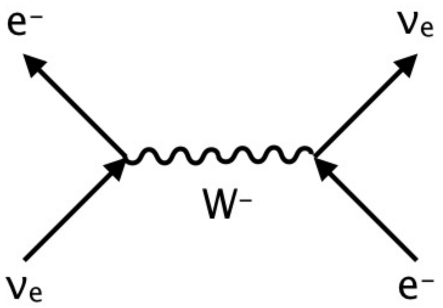
Reactor neutrino measurement
Geo neutrino measurement
(Phys. Rev. D. **88**, 033001)

- $\overline{\nu}_e$ only
- Ethreshold = 1.806 MeV
- Large cross section
- Ultra-low BG observation by delayed coincidence
  - Prompt : Positron + annihilation
  - Delayed : neutron capture on ^{1}H(^{12}C)

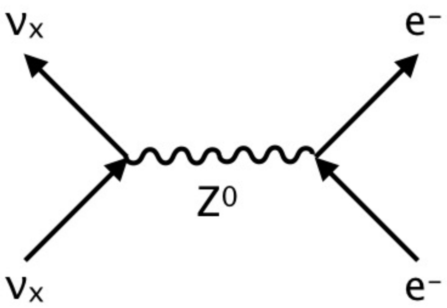
Electron scattering (ES)

- Higher background rate
- ν_e, $\overline{\nu}_e$, ν_μ, $\overline{\nu}_\mu$, ν_τ, $\overline{\nu}_\tau$
- No reaction threshold

solar neutrino measurement
(Phyis. Rev. C **92**, 055808)



CC



NC

Neutrinos from Gravitational Burst Events

- Gravitational wave (GW) experiment LIGO/Virgo collaboratiom found a lot of burst events.
- Thermal neutrino emission from the GW source is theoretically predicted.
  (Phys. Rev. D **93**, 044019, Phys. Rev. Lett. **107**, 051102, Phys. Rev. D **97**, 103001)

- Some coincident neutrino searches were reported by IceCube, SK, Borexino and other detectors.
- In contrast to IceCube and SK, KamLAND provides **low-energy (MeV-scale) extension**.

- In this analysis, we searched for $\overline{\nu}_e$ associated with GW events in LIGO-O2 and -O3.
- We focused on $\overline{\nu}_e$ with energy from 1.8 MeV to 111 MeV via IBD channel.
- A list of GWs in LIGO-O2 and -O3 was taken from the published article (PRX **9** (2019) 031040) and their online GW candidate database (GraceDB), respectively. → 60 GWs
- The neutrino event time window was set as ±500 sec for each GWs.

Results : Gravitational Wave Neutrinos

- The number of background IBD events was estimated from offtime windows of each GWs.

N_{BG} = 4.08 × 10^{-3} events within ±500 sec (LIGO-O2)
N_{BG} = 4.27 × 10^{-3} events within ±500 sec (LIGO-O3)

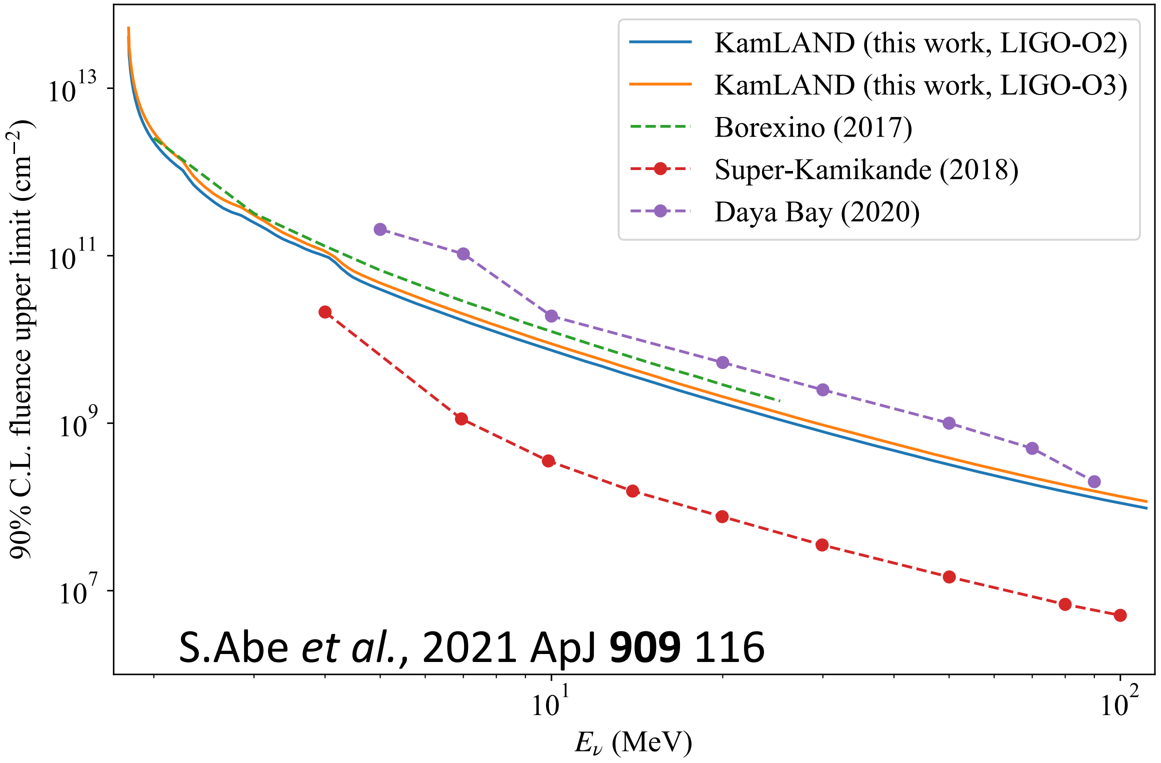
← This difference comes from difference of effective volume in each periods.

- No significant events were found for 60 GWs.
- Using Feldman-Cousins method, the upper limits on the number of GW-related events with 90% C.L. were obtained as;

N_{90} = 2.435 for a GW event (LIGO-O2)
N_{90} = 2.435 for a GW event (LIGO-O3)

- Assuming monochromatic neutrino spectrum, the upper limit on fluence was given by

$$\Phi^{\mathrm{IBD}}(E_\nu) = \frac{N_{90}}{\mathrm{N_p}\epsilon_{\mathrm{live}}\epsilon(E_\nu)\sigma(E_\nu)}$$



S.Abe *et al.*, 2021 ApJ **909** 116

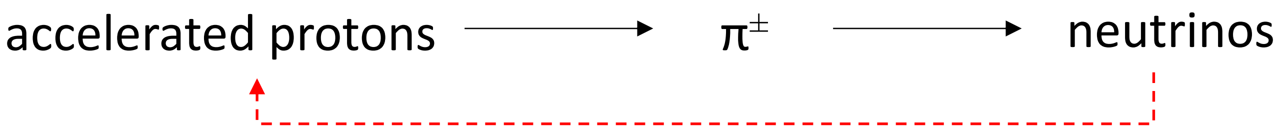
Solar Flare and Neutrino Emission

What is solar flare

- Solar flares are the largest explosive events in the solar system.
- UV, X-ray and γ-ray observation have contributed to the understanding of its mechanism.

Solar flare neutrino

- Cause of solar flare is described as magnetic reconnection leading to charged particle accelaration.
- Neutrinos are expected to be emitted from solar flares.



accelerated protons → $\pi^{\pm}$ → neutrinos

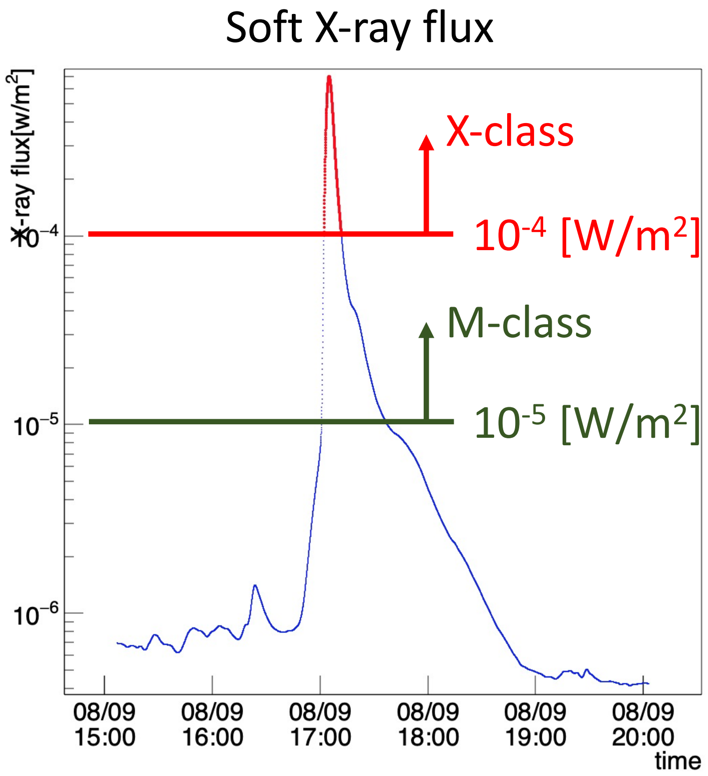
Solar flare neutrinos may play a key role in the understanding of initial particle acceleration by solar flare.

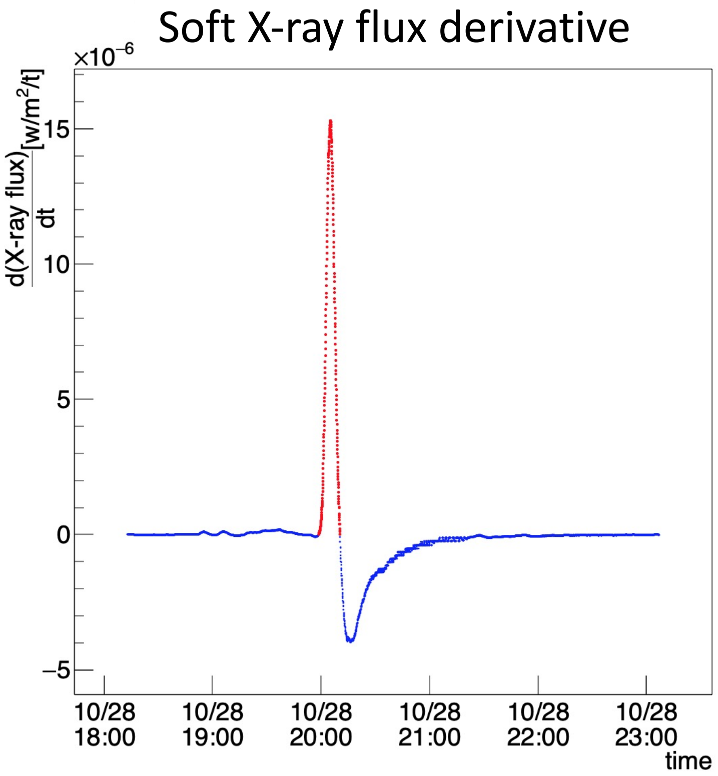
Detection of solar flare neutrino

- Expected fluence of solar flare neutrino : 398 – 770 cm^{-2} per flare in 10 – 100 MeV (IceCube, 2016)
- Detection of solar flare neutrino from single flare is feasible by current neutrino detectors.
- Populational study using a number of flare is important.

This study applied the method described in Okamoto et al. (2020)

Flare Selection and Time Window


Soft X-ray flux


Soft X-ray flux derivative

Flare selection:

- CIDAS database@Nagoya-u.
- X- or M- class flares from *GOES* data.

Time window determination:

1. Take derivative of X-ray flux data
2. Find peak
3. Find leading and trailing zero point

Why derivative ??

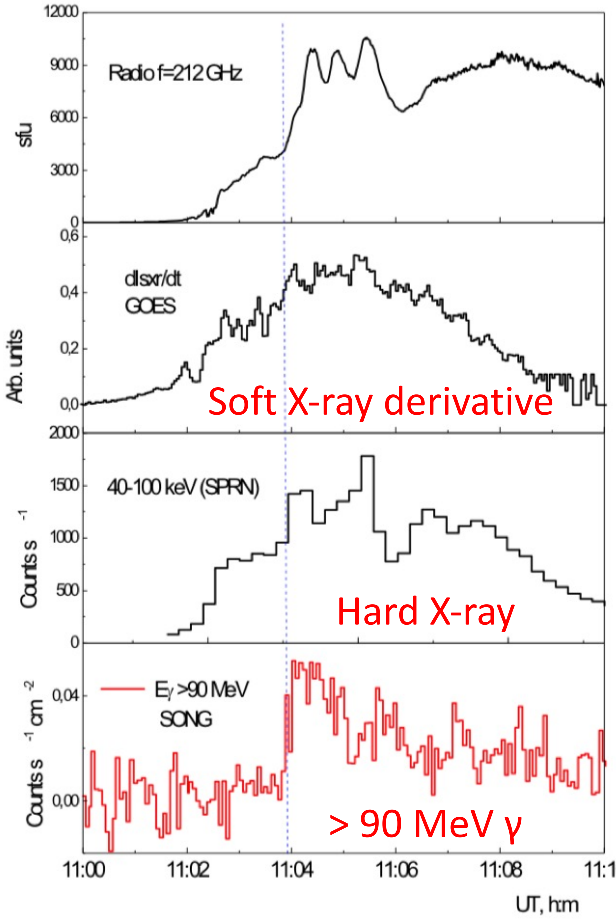


Figure 3. 28 October 2003 event.

V. Kurt, B. Yushkov, V. Grechnev, The Onset Time of the Pion-Decay Gamma-Ray Emission of Major Solar Flares, in: Proceedings of the 32nd International Cosmic Ray Conference, Vol. V10, 2011, pp. 6–9.

Solar Flare Dataset Summary

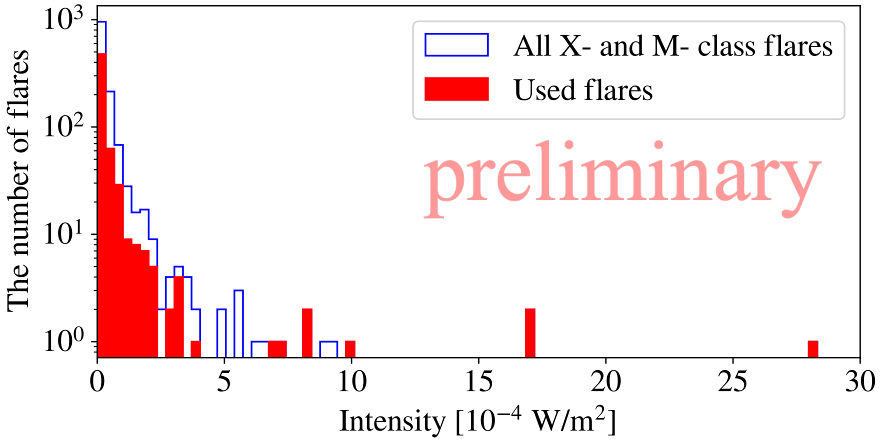
Flare selection from *GOES* data:

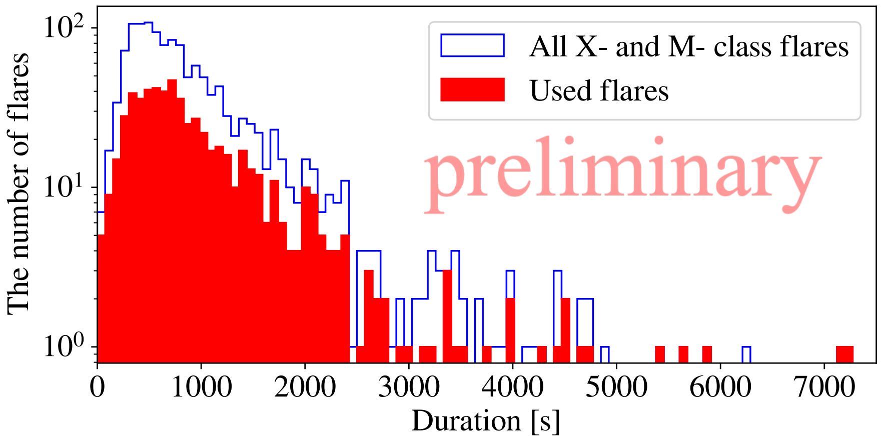
- 2002 March – 2019 September
- X- or M- class

→ **1342 flares**

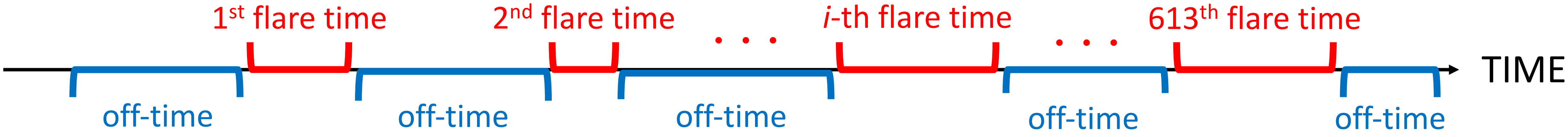
KamLAND livetime selection
(livetime ratio > 95%)

614 flares were used in this study.





On-off Analysis



#{extected} in *i*-th flare time window:

$$k_i = \underbrace{\eta_i \alpha I_i}_{\text{Signal term}} + \underbrace{N_i^{\mathrm{BG}}}_{\text{\#\{BG\} in i-th flare time window}}$$

Assuming the solar flare neutrino fluence is propotional to flare's intensity !!

α : how many **neutrino interaction** (ES or IBD) happen in KamLAND by X1 flare

η_i : detection efficiency in *i*-th flare

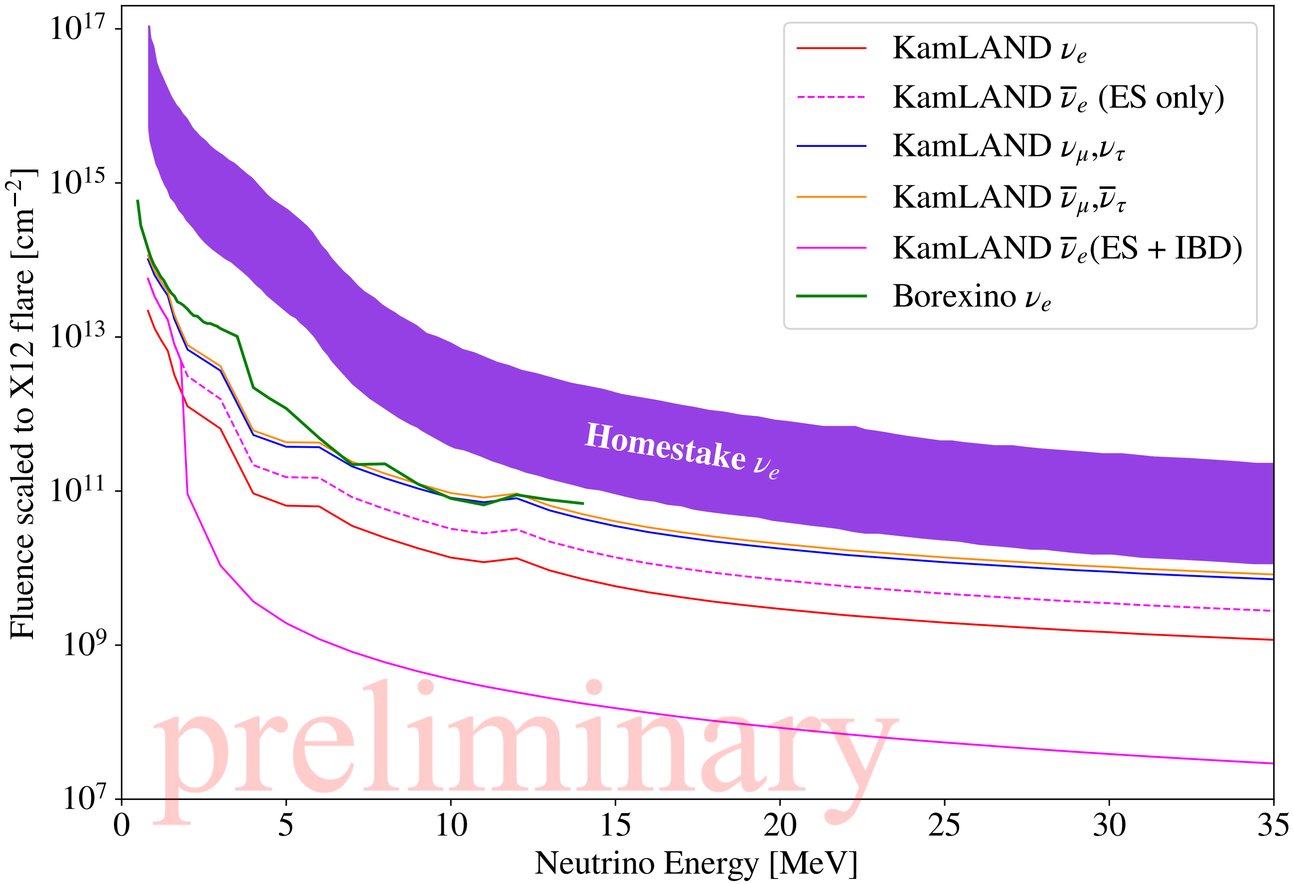
I_i : intensity of *i*-th flare

Likelihood $$L(\alpha) = \prod_{i \in \mathrm{Flare}} \frac{e^{-k_i} k_i^{N_i^{\mathrm{on}}}}{N_i^{\mathrm{on}}!}$$

N^{on}_i : #{observed} in *i*-th flare time window

Results : Solar Flare Neutrinos

Green’s function upper limit



Assuming monochromatic neutrino spectrum,

$$\Phi^{\mathrm{ES}}(E_\nu) = \frac{\alpha_{90}(E_\nu)}{\mathrm{N_e}\int_0^{\mathrm{T_{max}}}\sigma(E_\nu, E_\mathrm{e})dE_\mathrm{e}}$$

$$\Phi^{\mathrm{IBD}}(E_\nu) = \frac{\alpha_{90}}{\mathrm{N_p}\sigma(E_\nu)}$$

At 20 MeV,

$3.0 \times 10^9\,\mathrm{cm}^{-2}$ for ν_e

$1.5 \times 10^8\,\mathrm{cm}^{-2}$ for $\bar{\nu}_e$

Summary

- KamLAND is a large-volume liquid-scintillator detector sensitive to MeV-scale neutrinos.
- We performed analysis of coincidences between GW and solar flare events and neutrino events in KamLAND.
- We found no neutrino events correlerated with GW events observed by LIGO/Virgo and got 90% C.L. upper limits on the $\overline{\nu}_e$ fluence.
- We found no statistically significant excess of events in KamLAND related to solar flares and obtained the strongest 90% C.L. upper limit on fluence of solar flare neutrinos.