XMASS

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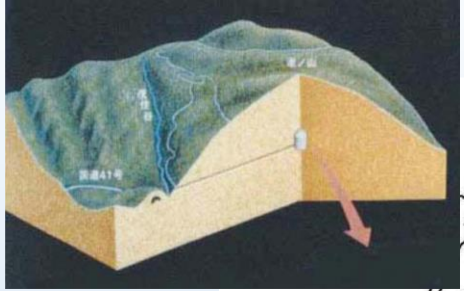
第4回超新星ニュートリノ研究会@箱根

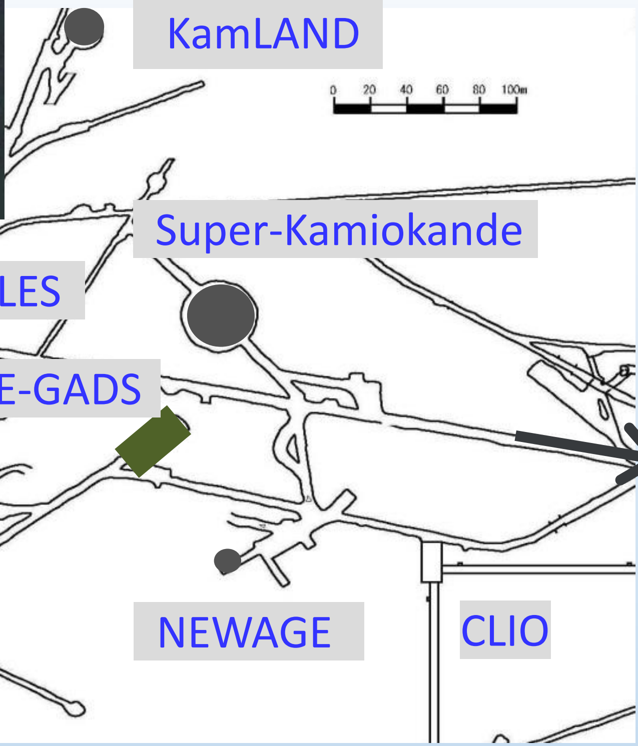
Outline

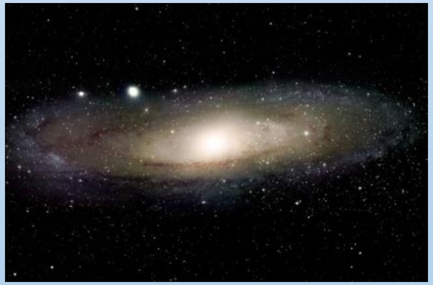
- XMASS experiment
- Supernova neutrino observation via coherent elastic neutrino-nucleus scattering (CEvNS)
  - K. Abe et al. (XMASS Collaboration), Astropart. Phys. 89 (2017) 51-59
- Other searches for low-energy events originated from astronomical sources
  - Search for solar Kaluza-Klein axions
    - K. Abe et al. (XMASS Collaboration), PTEP 2017, 103C01 (2017)
  - Search for event bursts associated with gravitational-wave events

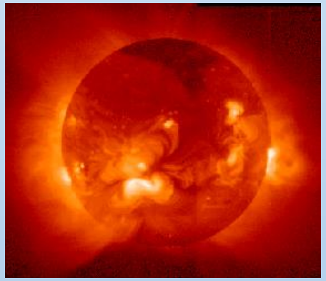
The XMASS project

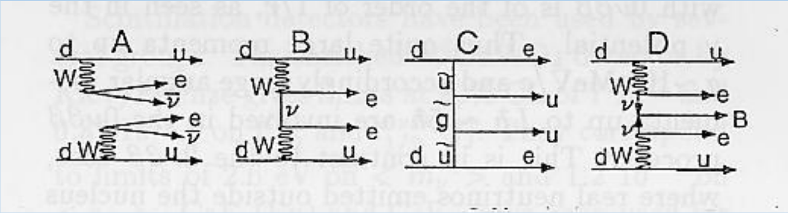
- XMASS: a multi purpose experiment with liquid xenon
- Located 1,000 m underground (2,700 m.w.e.)
  at the Kamioka Observatory in Japan
- Aiming for
  - Direct detection of dark matter
  - Observation of low energy solar neutrinos (*pp*/^{7}Be)
  - Search for neutrino-less double beta decay
- Features
  - ➢ Low energy threshold (~0.5keVee)
  - ➢ Sensitive to e/γ events as well as nuclear recoil
  - ➢ Large target mass and its scalability



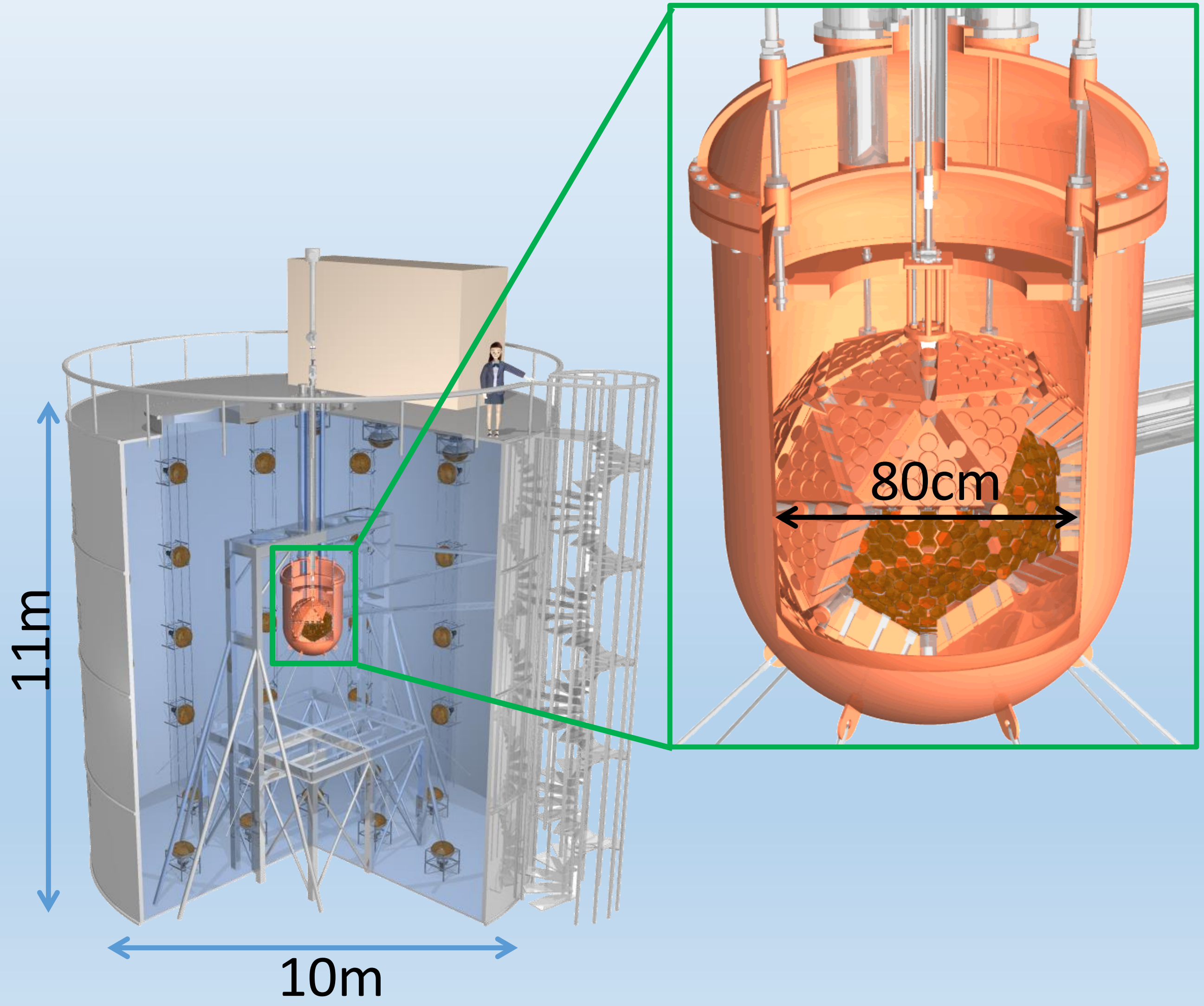






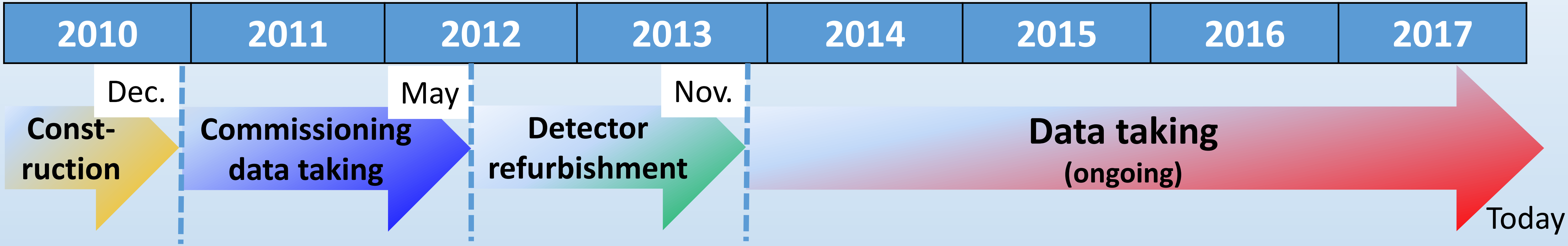


Single-phase liquid Xenon detector: XMASS-I



- Liquid xenon detector
  - 832 kg of liquid xenon (-100 ^{o}C)
  - 642 2-inch PMTs (Photocathode coverage >62%)
  - Each PMT signal is recorded by 10-bit 1GS/s waveform digitizers
- Water Cherenkov detector
  - 10m diameter, 11m high
  - 72 20-inch PMTs
  - Active shield for cosmic-ray muons
  - Passive shield for n/γ

History of XMASS-1

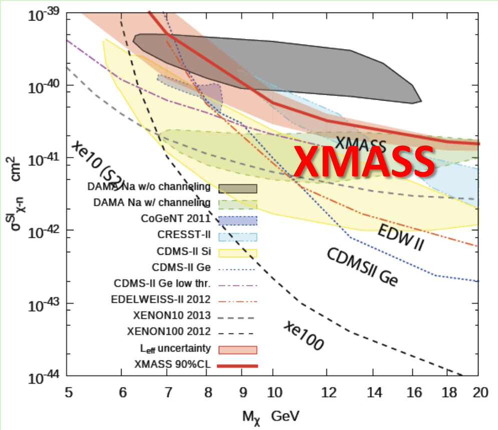


- ***Has been stably taking data for more than 4 years since November 2013.***
- ***Will continue data-taking until December 2018.***

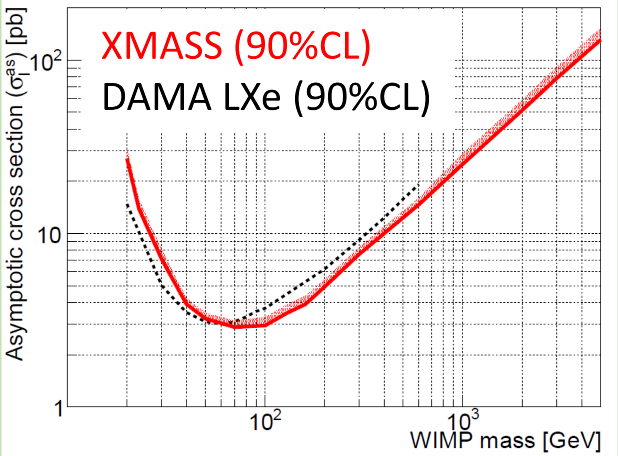
Diversity of physics target with XMASS

Dark matter searches

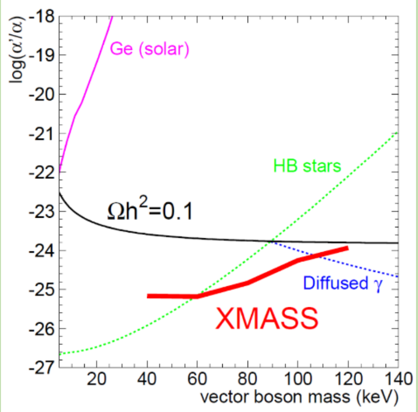
Low mass WIMP search
Phys. Lett. B719 (2013) 78



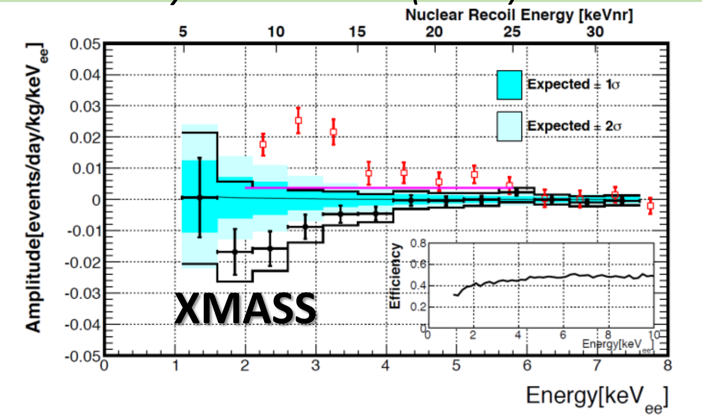
WIMP-^{129}Xe inelastic scattering
PTEP (2014) 063C01



Bosonic super-WIMPs search
Phys. Rev. Lett. 113 (2014) 121301

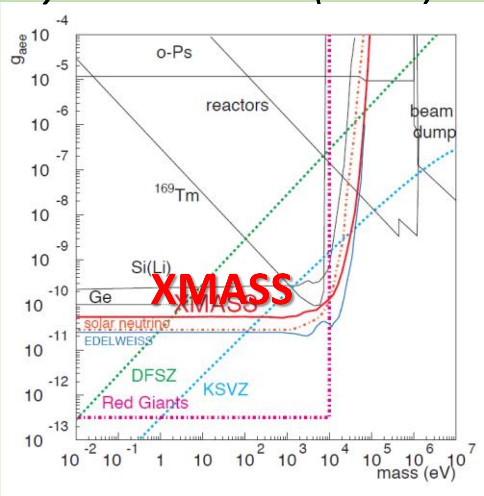


Annual modulation search
Phys. Lett. B759 (2016) 272



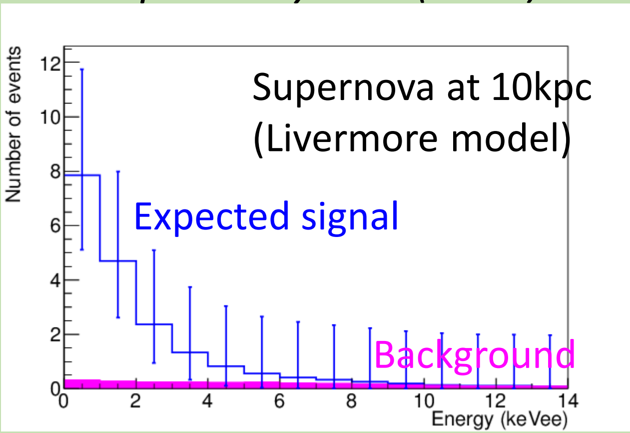
Solar axion search

Phys. Lett. B724 (2013) 46

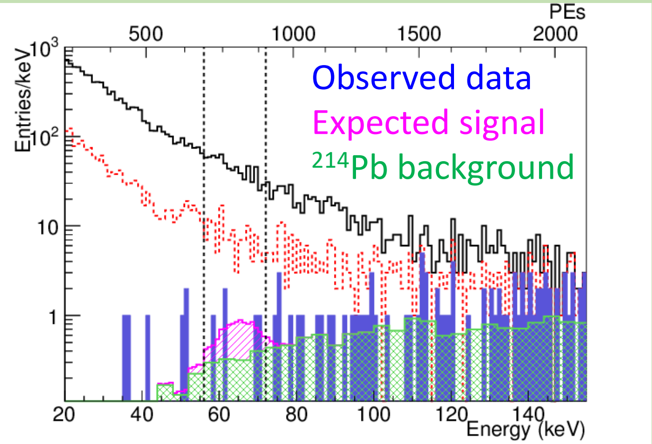


Possibility of supernova neutrino detection

Astropart. Phys. 89 (2017) 51



Search for 2ν double electron capture on ^{124}Xe, ^{126}Xe



Phys. Lett. B759 (2016) 64

Supernova neutrino observation via coherent elastic neutrino-nucleus scattering

Supernova neutrino observation in XMASS

■ **Coherent elastic neutrino-nucleus scattering**

$$\nu_x + (A, Z) \rightarrow \nu_x + (A, Z)$$

- Main channel of supernova neutrino events in XMASS.
- Sensitive to all neutrino flavors
- Nuclear recoil with energy below O(10keV)

■ **Charged current neutrino-nucleus reactions**

$$\nu_e + (A, Z) \rightarrow e^- + (A, Z+1)$$
$$\bar{\nu}_e + (A, Z) \rightarrow e^+ + (A, Z-1)$$

- Possibility of detection in case of nearby supernova
- Electron scattering with energy of O(MeV) → different from coherent scattering

Coherent elastic ν-nucleus scattering (CEvNS)

$$\nu + A \rightarrow \nu + A$$

- Neutrino is scattered off by all the nucleons in a nucleus coherently
  - Weak neutral current interaction
  - Cross section ~ N^2
  - Recoil energy ~ O(10) keV

$$\frac{d\sigma}{dE_{nr}}(E_\nu, E_{nr}) = \frac{G_F^2 M}{2\pi} G_V^2 \left[1 + \left(1 - \frac{E_{nr}}{E_\nu}\right)^2 - \frac{M E_{nr}}{E_\nu^2} \right]$$

$$G_V = [(\frac{1}{2} - 2\sin^2\theta_W)Z - \frac{1}{2}N]F(q^2)$$

- Main mechanism of trapping neutrinos in the core of a supernova

- Ultimate background for direct dark matter searches (solar ν, atm. ν, and DSNB ν)

- ~~Has not been observed yet~~

Coherent elastic ν-nucleus scattering (CEvNS)

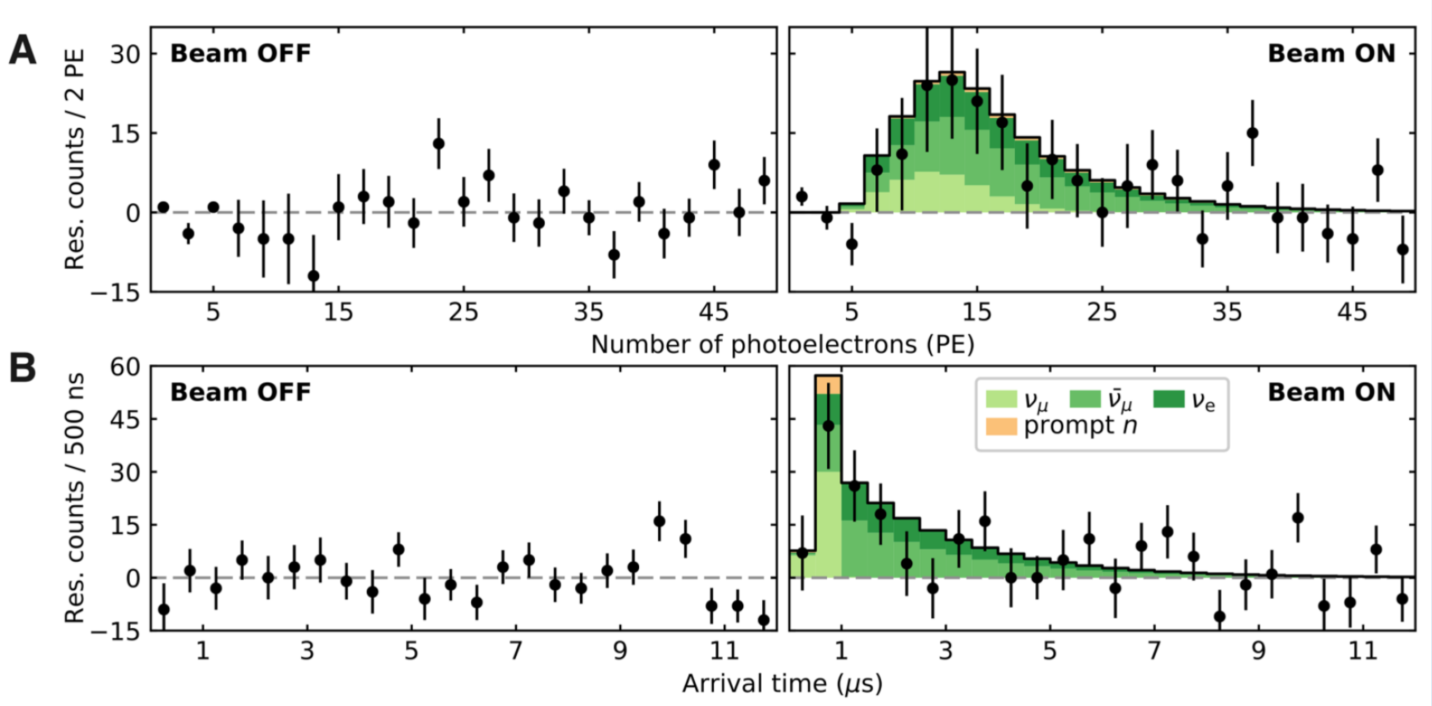
Science

REPORTS

Cite as: D. Akimov *et al.*, *Science* 10.1126/science.aao0990 (2017).

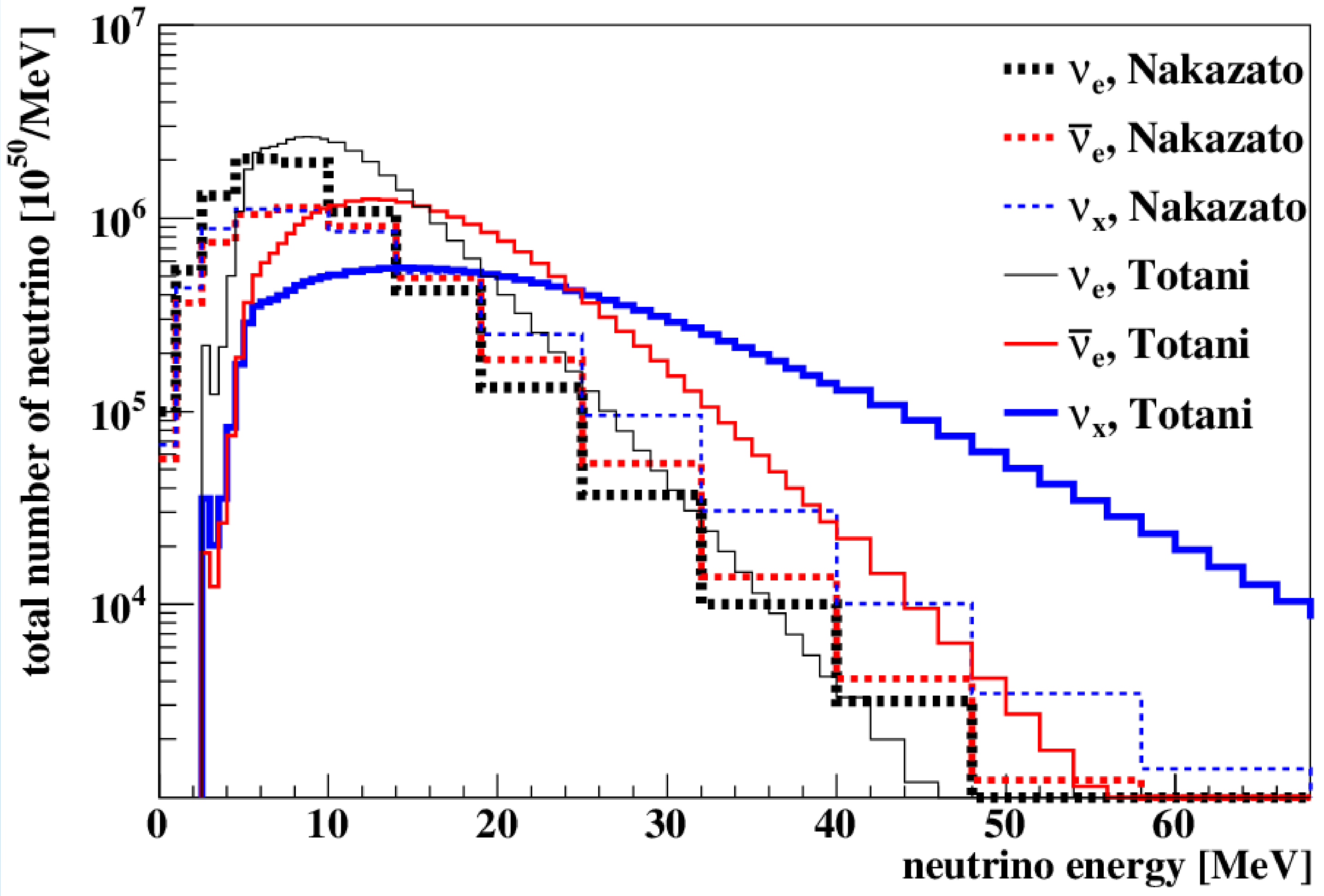
Observation of coherent elastic neutrino-nucleus scattering

D. Akimov,[1,2] J. B. Albert,[3] P. An,[4] C. Awe,[4,5] P. S. Barbeau,[4,5] B. Becker,[6] V. Belov,[1,2] A. Brown,[4,7] A. Bolozdynya,[2] B. Cabrera-Palmer,[8] M. Cervantes,[5] J. I. Collar,[9*] R. J. Cooper,[10] R. L. Cooper,[11,12] C. Cuesta,[13†] D. J. Dean,[14] J. A. Detwiler,[13] A. Eberhardt,[13] Y. Efremenko,[6,14] S. R. Elliott,[12] E. M. Erkela,[13] L. Fabris,[14] M. Febbraro,[14] N. E. Fields,[9‡] W. Fox,[3] Z. Fu,[13] A. Galindo-Uribarri,[14] M. P. Green,[4,14,15] M. Hai,[9§] M. R. Heath,[3] S. Hedges,[4,5] D. Hornback,[14] T. W. Hossbach,[16] E. B. Iverson,[14] L. J. Kaufman,[3||] S. Ki,[4,5] S. R. Klein,[10] A. Khromov,[2] A. Konovalov,[1,2,17] M. Kremer,[4] A. Kumpan,[2] C. Leadbetter,[4] L. Li,[4,5] W. Lu,[14] K. Mann,[4,15] D. M. Markoff,[4,7] K. Miller,[4,5] H. Moreno,[11] P. E. Mueller,[14] J. Newby,[14] J. L. Orrell,[16] C. T. Overman,[16] D. S. Parno,[13¶] S. Penttila,[14] G. Perumpilly,[9] H. Ray,[18] J. Raybern,[5] D. Reyna,[8] G. C. Rich,[4,14,19] D. Rimal,[18] D. Rudik,[1,2] K. Scholberg,[5] B. J. Scholz,[9] G. Sinev,[5] W. M. Snow,[3] V. Sosnovtsev,[2] A. Shakirov,[2] S. Suchyta,[10] B. Suh,[4,5,14] R. Tayloe,[3] R. T. Thornton,[3] I. Tolstukhin,[3] J. Vanderwerp,[3] R. L. Varner,[14] C. J. Virtue,[20] Z. Wan,[4] J. Yoo,[21] C.-H. Yu,[14] A. Zawada,[4] J. Zettlemoyer,[3] A. M. Zderic,[13] COHERENT Collaboration#



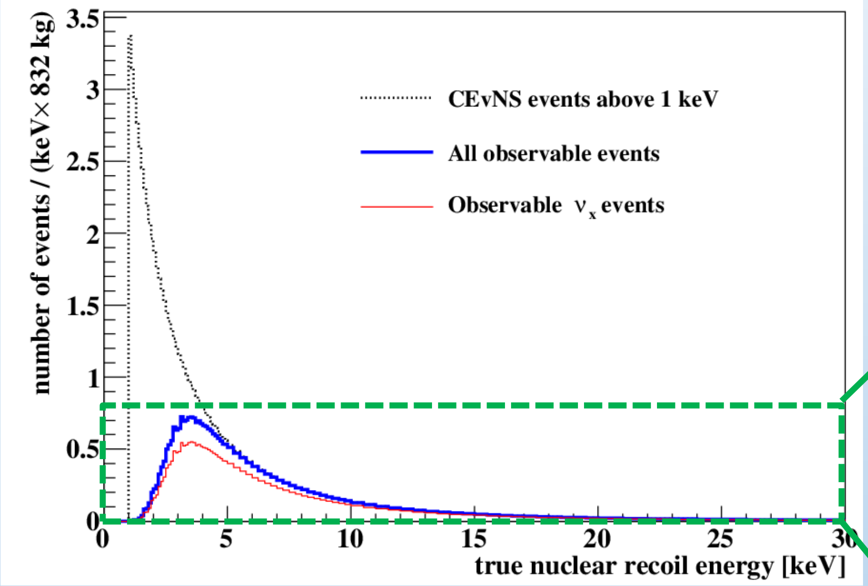
Coherent elastic neutrino-nucleus scattering was now observed !!

Supernova neutrino energy spectra used in the calculation

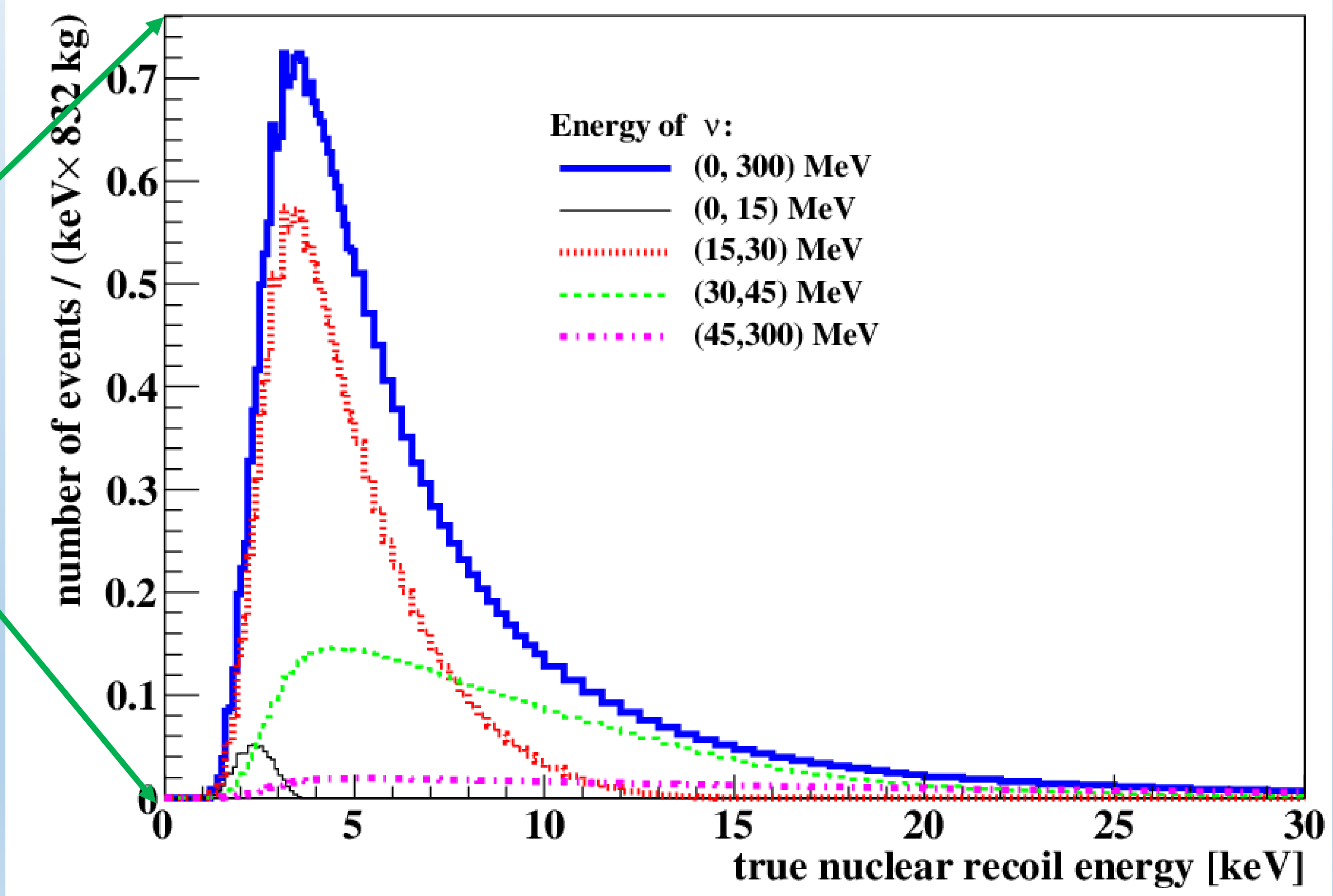


($20M_{solar}$, Z=0.02, t_{rev}=200ms)

Nuclear recoil energy spectrum by supernova neutrinos

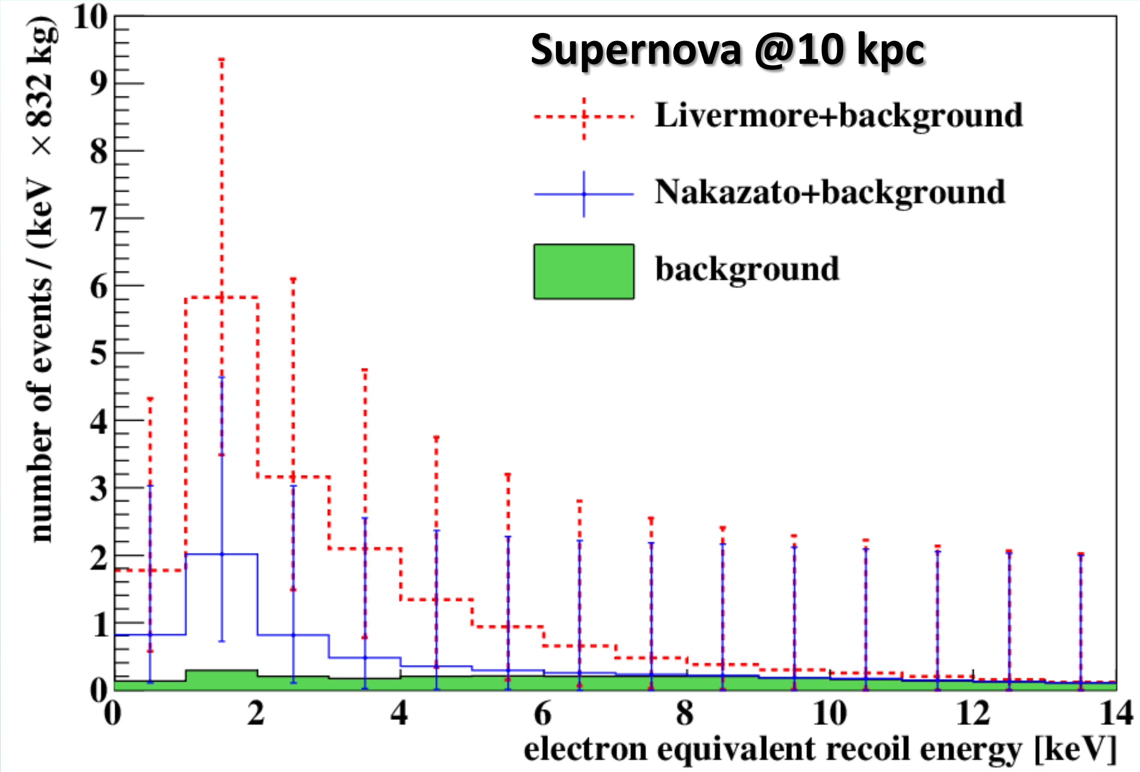


True nuclear recoil energy spectra for each neutrino energy



- XMASS can detect mainly ν_x
- Sensitive to neutrinos with Eν>15MeV

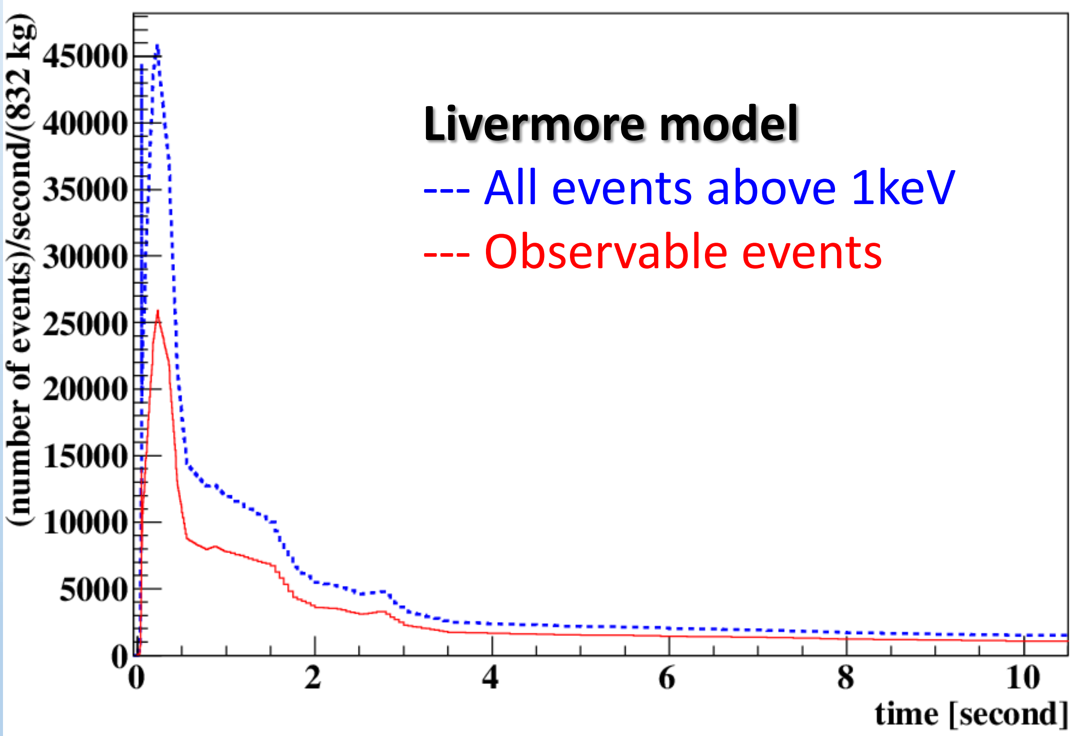
Expected supernova neutrino signal in XMASS

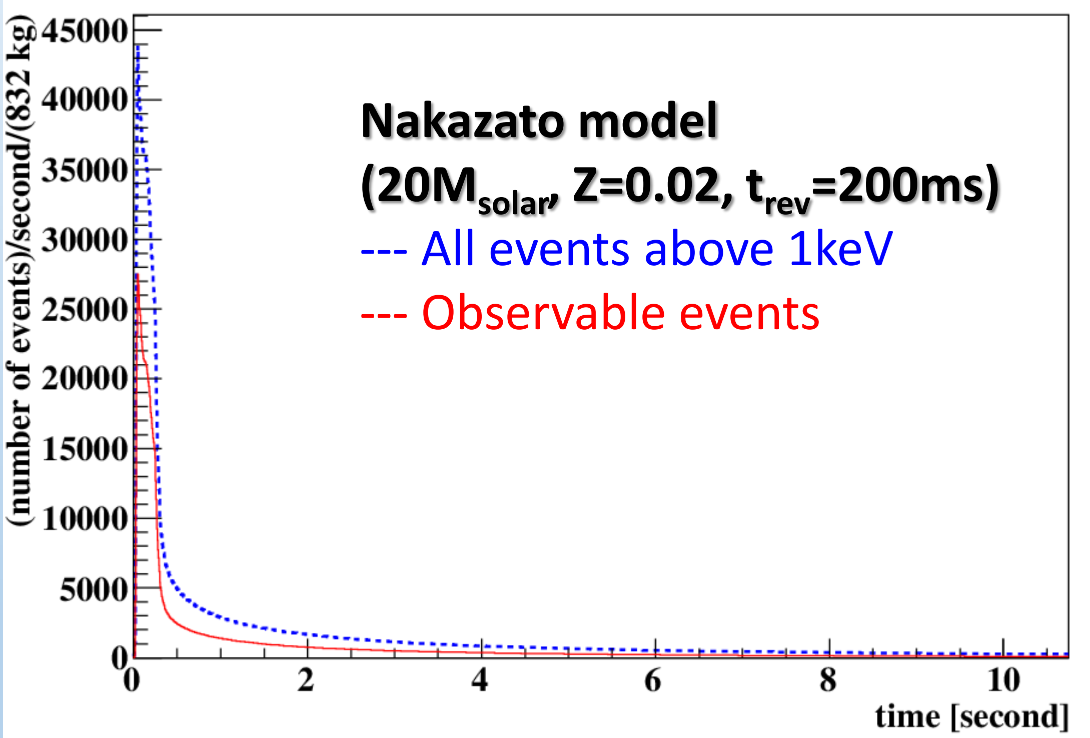


Supernova model	d=10 kpc	d=196 pc
Livermore	15	3.9×10^4
Nakazato ($20M_{solar}$, Z=0.02, t_{rev}=100ms)	3.5	0.9×10^4
Nakazato ($30M_{solar}$, Z=0.02, t_{rev}=300ms)	8.7	2.3×10^4
Nakazato (black hole)	21	5.5×10^4

- In the case of supernova at 10 kpc, 3.5-21 events are expected in 18 sec depending on the supernova models.
- For Betelgeuse (196 pc), ~10^4 events are expected.

Expected time profile of supernova neutrino events in XMASS





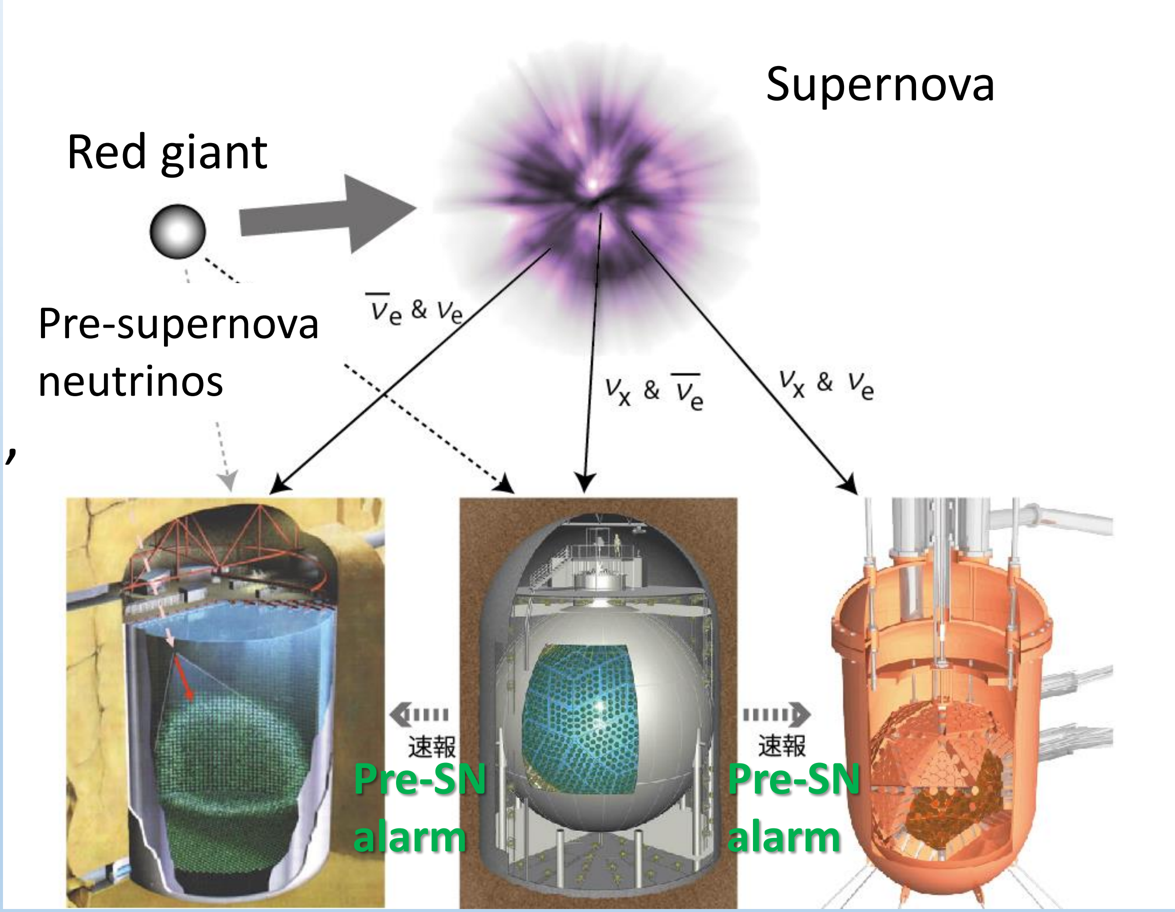
Can discriminate models using time profile
in the case of nearby supernova (~200pc)

Comprehensive observation network in Kamioka

- To compare the XMASS event timings with other detectors' events,
  - GPS time synchronization was introduced in the XMASS DAQ system.

- In the case of nearby supernovae (e.g. Betelgeuse), KamLAND has possibility to detect "pre-supernova neutrinos" a few days before explosion.
  - XMASS is monitoring the semi-realtime pre-supernova alarm provided by KamLAND.

- XMASS is also waiting for a next supernova !!



Super-Kamiokande KamLAND XMASS

Other searches for low-energy events originated from astronomical sources

Search for solar Kaluza-Klein axions

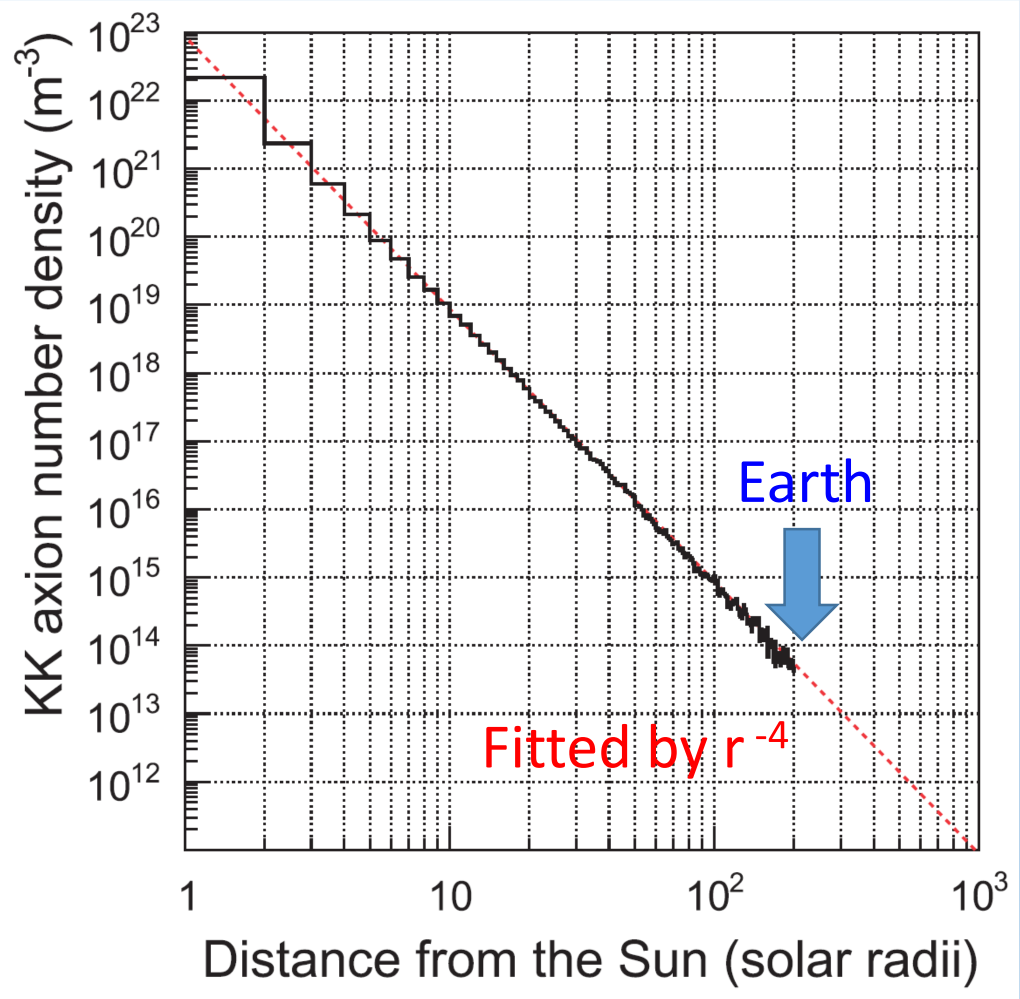
- In theories of large extra dimensions, axions could propagate in extra dimensions and acquire infinite number of mass levels.
  ➔ Kaluza-Klein (KK) axions

- KK axions would be produced in the Sun via the Primakoff effect (γ+Ze→Ze+a) and photon coalescence (γ+γ→a).

- A small fraction are gravitationally trapped and accumulated in the solar system, and then decay into two photons (a→γ+γ).

- They might explain the solar corona problem.

Expected number density of trapped KK axions

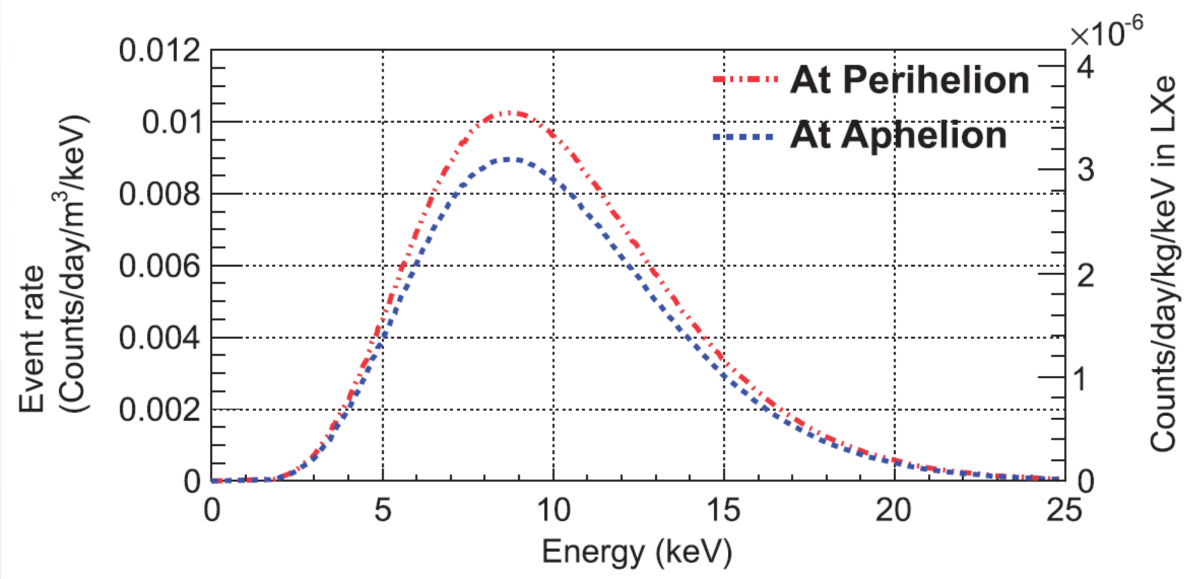


Search for solar Kaluza-Klein axions

- In the terrestrial detectors, these KK axions can be detected through their decay (a→γ+γ) in the detector volume.
  - Total energy deposit ~9 keV

- The event rate modulates annually due to the change of distance between the Sun and the Earth.
  - ~14% change between max. and min.

Expected energy spectra of the KK axion decay

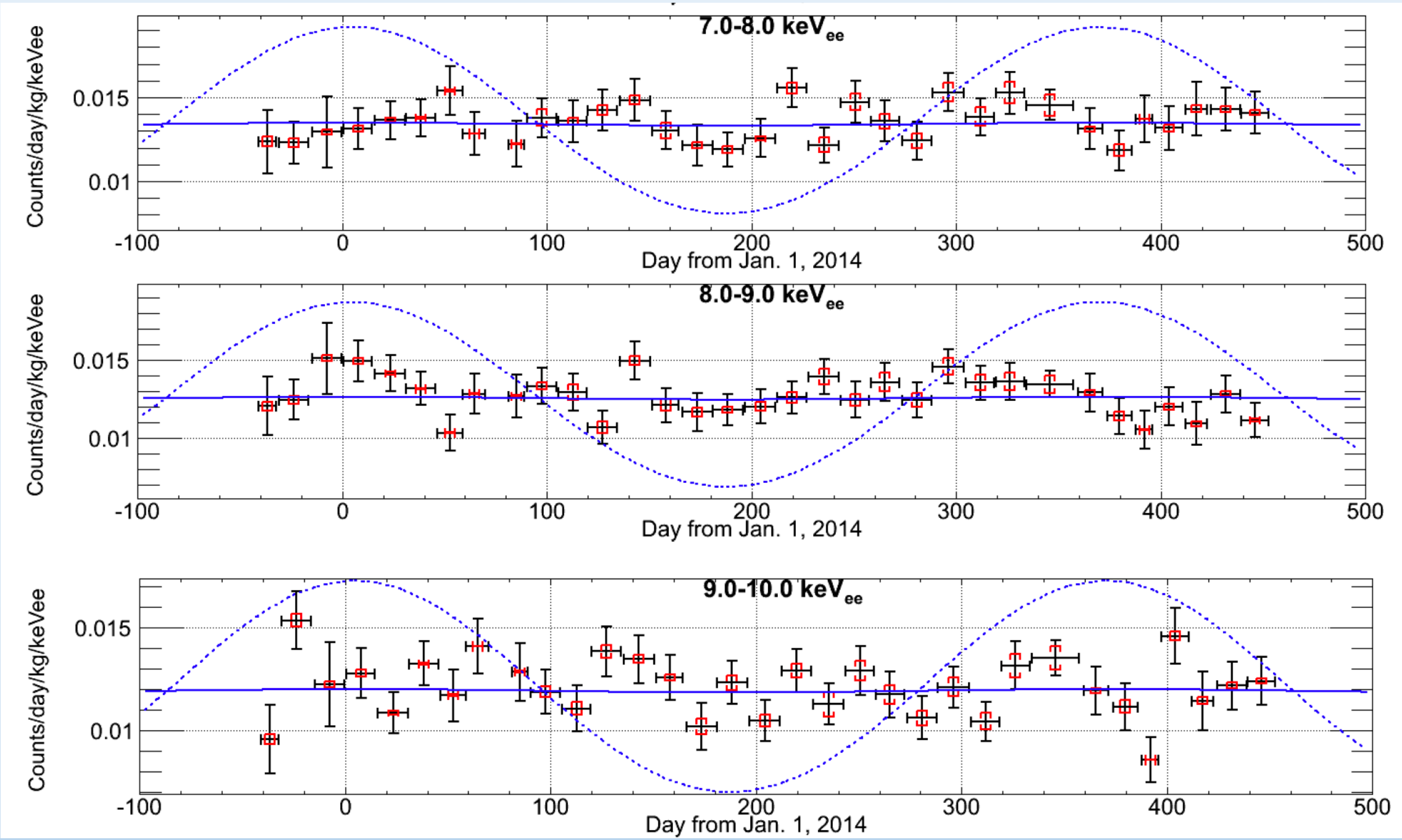


Expected KK axion number density on Earth

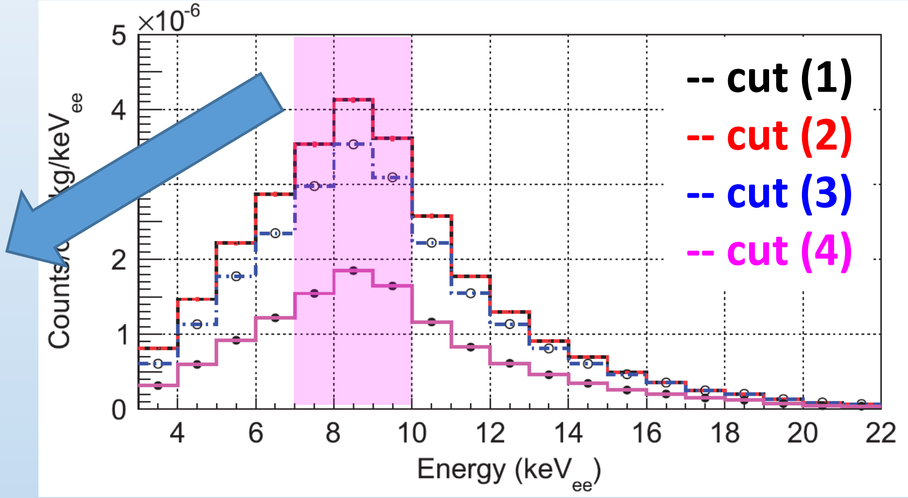
$$n_a(t) = \bar{n}_a \left(1 - e\cos\frac{2\pi(t-t_0)}{T}\right)^{-4}$$
$$\approx \bar{n}_a \left[1 + 4e\left(\cos\frac{2\pi(t-t_0)}{T} + \frac{5}{2}e\cos^2\frac{2\pi(t-t_0)}{T}\right)\right]$$

Solar Kaluza-Klein axion results (1)

Time variation of event rate in each energy region



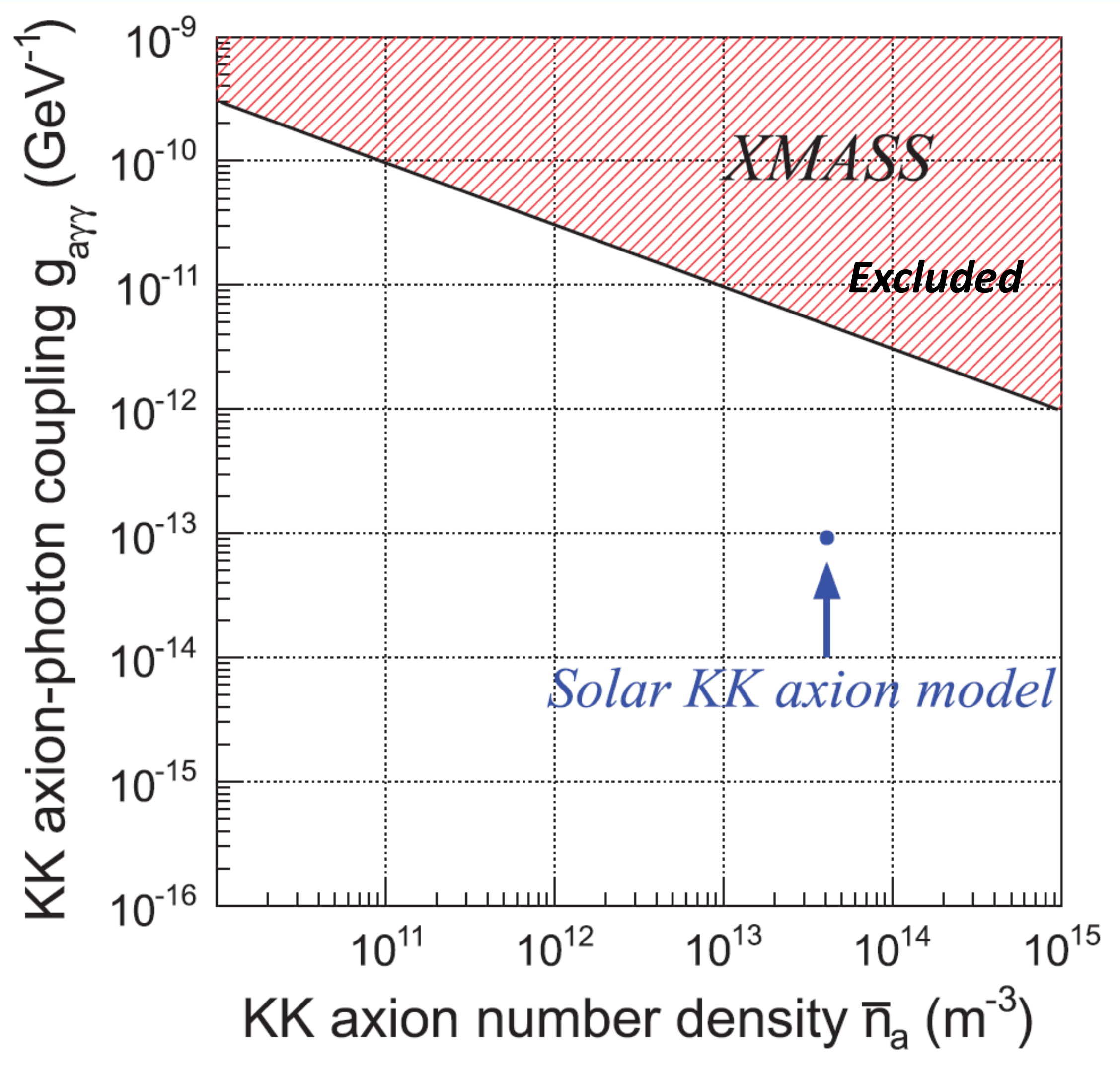
Expected KK axion signal spectra



No significant event rate modulation expected from solar KK axions was found

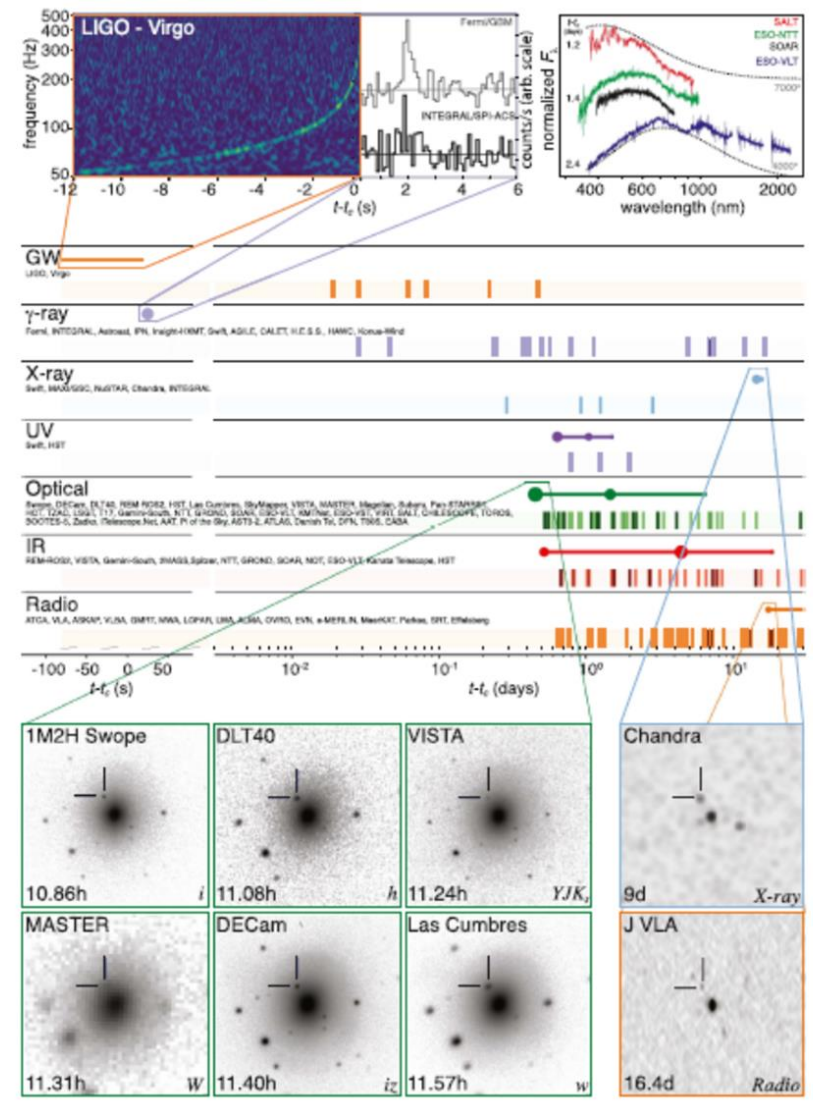
Black: the observed data w/ stat. error (red: sys. error)
Blue solid: the best fit result
Blue dash: the 90% CL upper limit (x20 enhanced)

Solar Kaluza-Klein axion results (2)



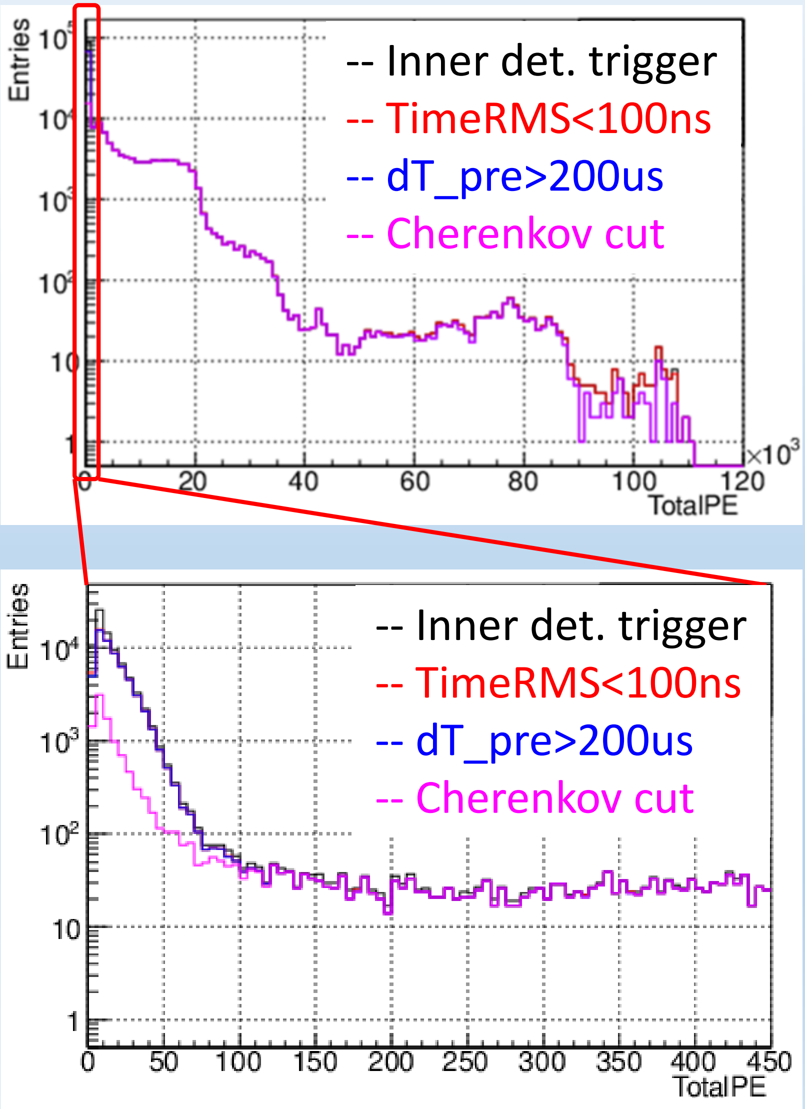
- ***The first experimental constraint on solar Kaluza-Klein axions.***
- ***$g_{a\gamma\gamma}$<4.8x10^{-12} GeV^{-1} (for n_a=4.07x10^{13} m^{-3})***
- ***Published in PTEP 2017, 103C01 (2017)***

Search for event burst associated with gravitational-wave (GW) events



- Several GW events reported by LIGO/Virgo since 2015.
- The 1st binary neutron star (NS-NS) merger was observed by LIGO/Virgo and also by multi-messengers.
- There are some theoretical predictions on neutrino emission from NS-NS mergers.
- XMASS was taking data continuously during these GW events.
  - ➢ has capability to detect neutrinos (via CEvNS), axions, axion-like particles etc.

Search for event burst associated with GW events



- Apply simple event selections
  - Only inner detector trigger
  - PMT afterpulse rejection
  - Cherenkov event rejection

- Divide into 4 energy ranges
  - <~30 keV
  - 30-300 keV
  - 300-3000 keV
  - >~30000 keV

- Search for event burst by sliding coincidence windows with various time width (20 ms to 10 s)

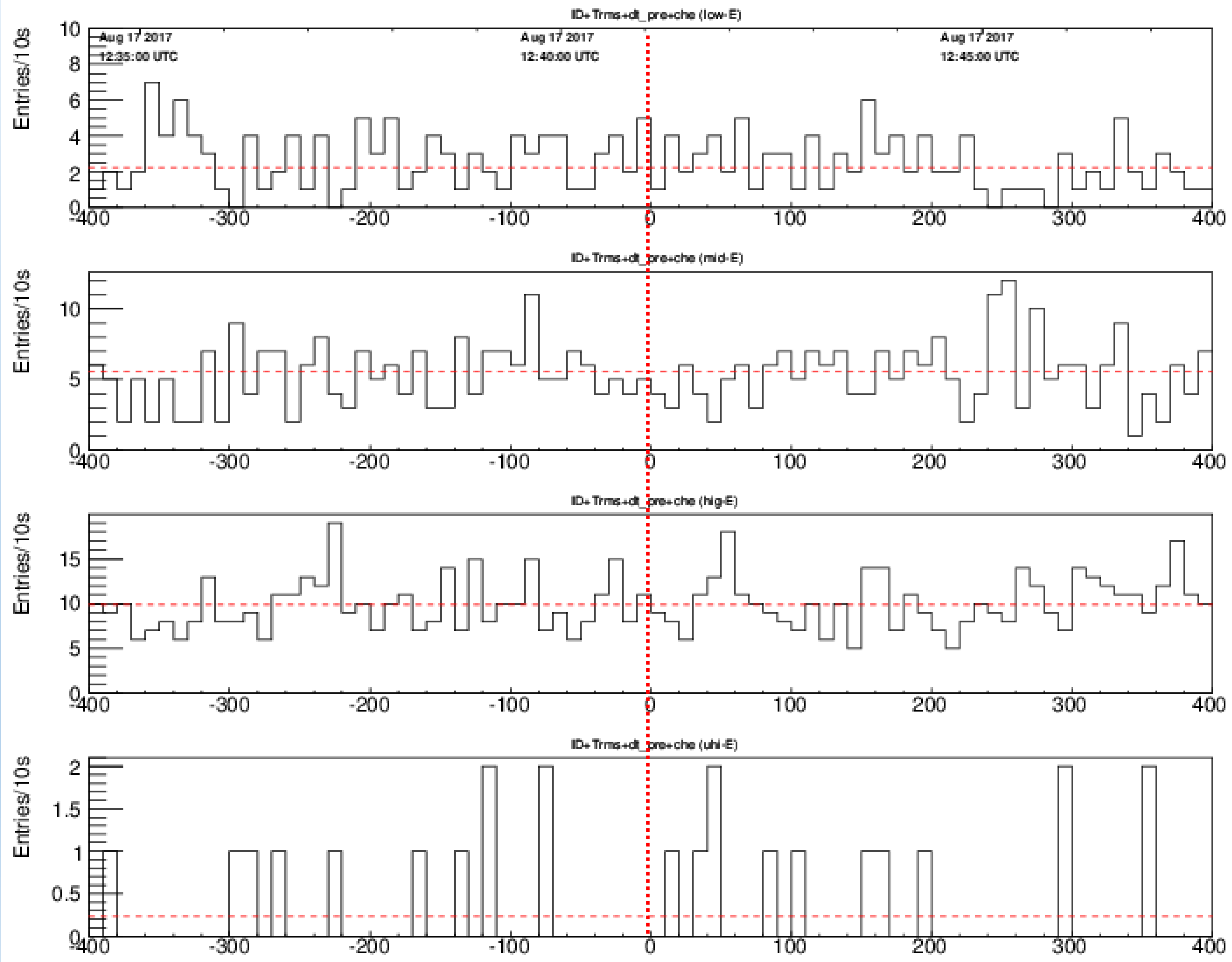
Event rate in the +/-400 sec window of GW170817 (NS-NS merger)

<~30keVee

30-300keVee

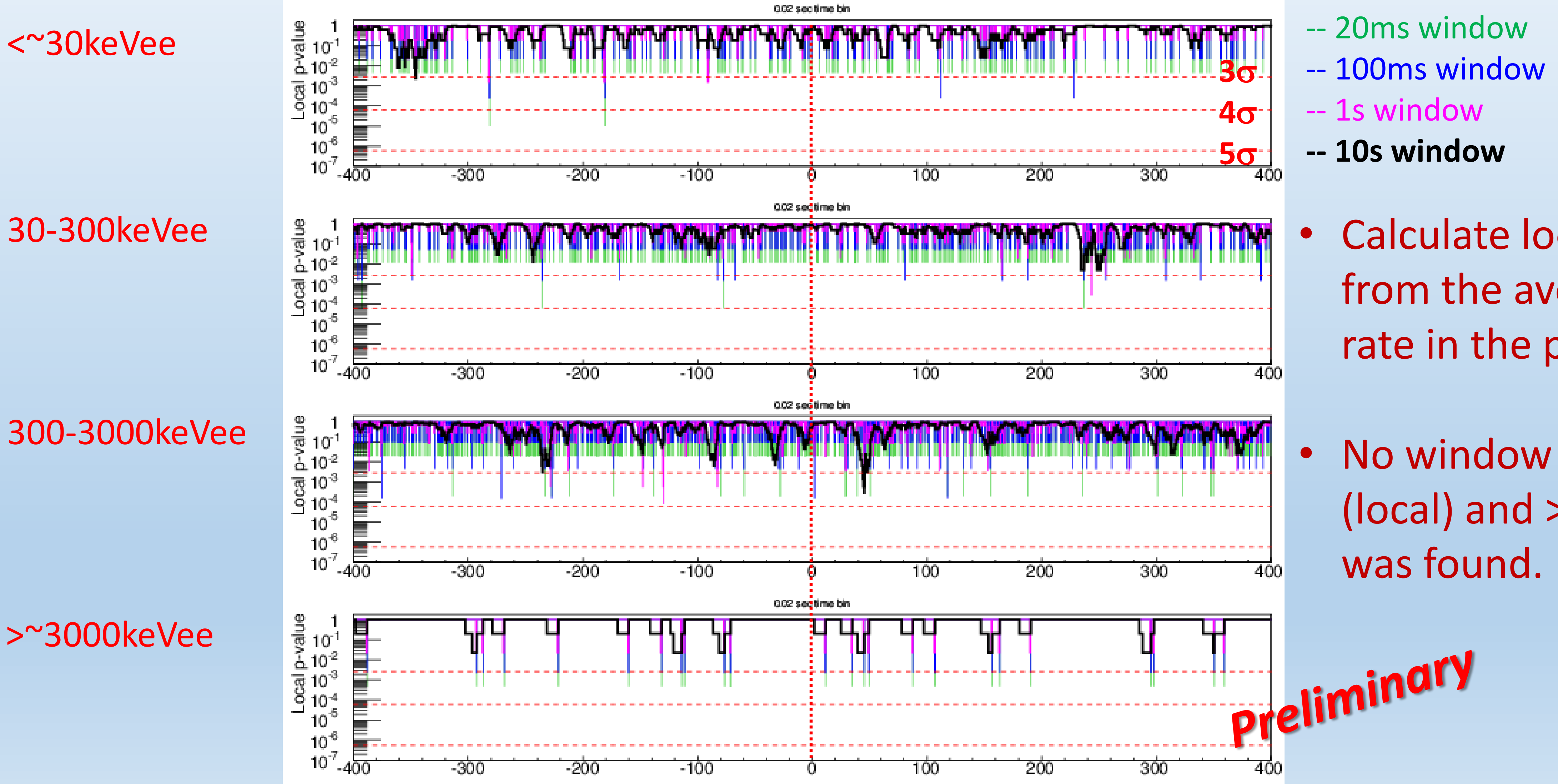
300-3000keVee

>~3000keVee



- Relative time since Aug. 17 2017 12:41:04 UTC (=21:41:04 JST)
- 1bin = 10s

Local p-value in the +/-400 sec window of GW170817 (NS-NS merger)



- Calculate local p-value from the average event rate in the pre-window.
- No window with >5σ (local) and >2σ (global) was found.

Summary

- Thanks to low energy threshold and large target mass, XMASS has possibility to detect galactic supernova neutrinos via coherent elastic neutrino-nucleus scattering.

- The XMASS-I detector has been stably taking data for more than 4 years, and will continue data-taking until December 2018.

- Other searches for low energy events originated from astronomical sources are also being conducted.
  - Search for solar Kaluza-Klein axions
  - Search for event bursts associated with gravitational-wave events