Gravitational Wave Coincidence Neutrino Search at KamLAND

S.Obara, and for KamLAND collaboration
(Frontier Research Institute for Interdisciplinary Sciences, Tohoku Univ.)

supported by …

TOHOKU UNIVERSITY

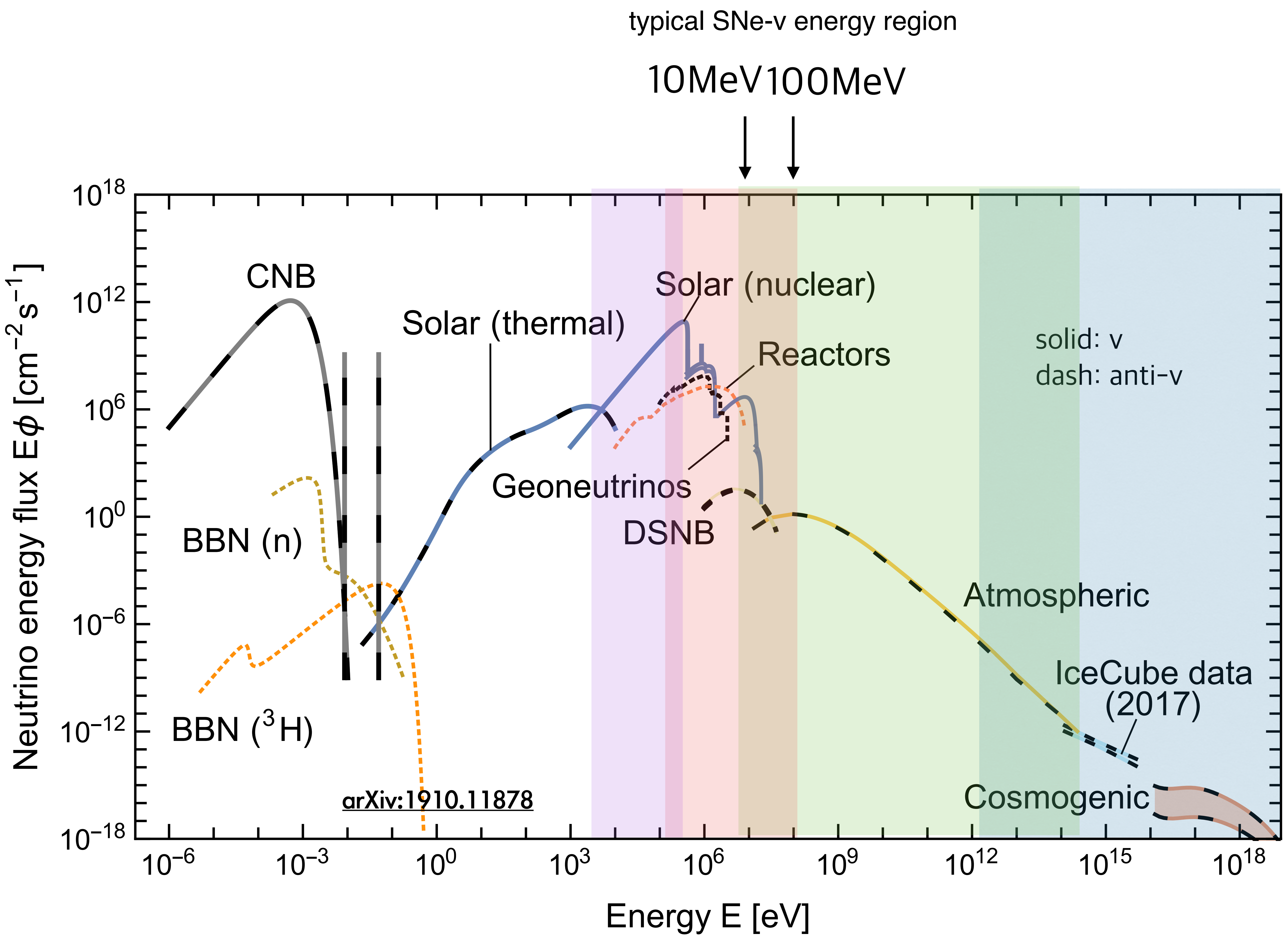
FRIS

GPPU

科研費 KAKENHI

地下から解き明かす宇宙の歴史と物質の進化
Unraveling the History of the Universe and Matter Evolution with Underground Physics

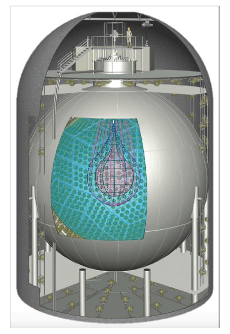
Various Neutrino Energies & Detectors



XENON

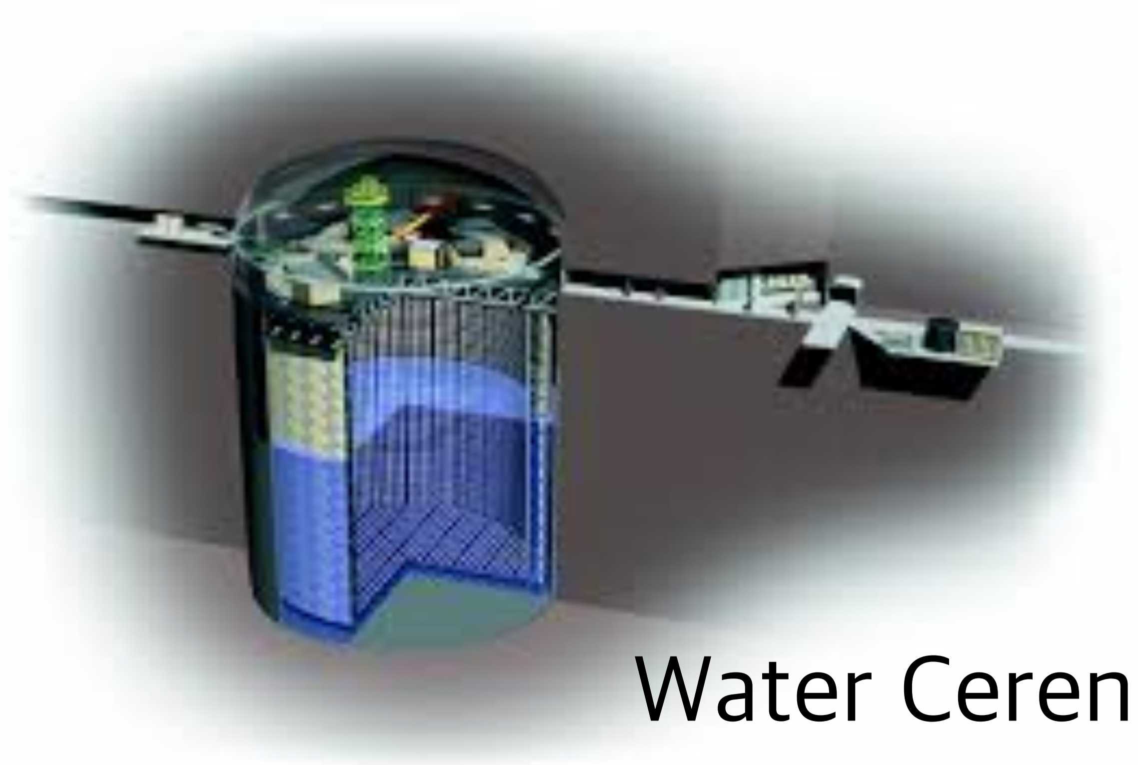
Dual-phase TPC
sub-keV

KamLAND



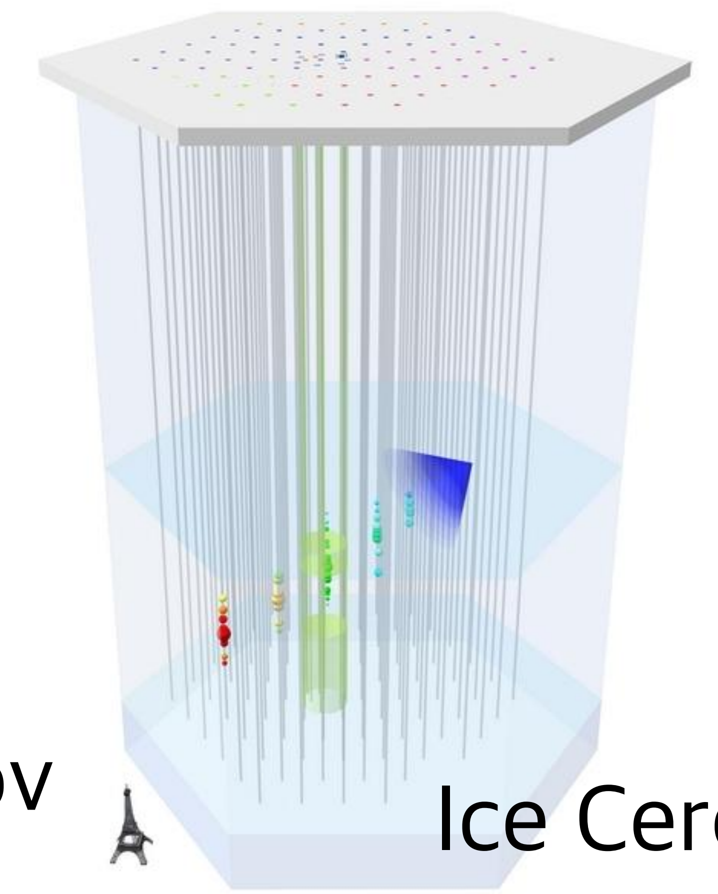
Liquid Scintillator
a few MeV

Super-Kamiokande



Water Cerenkov
sub-GeV

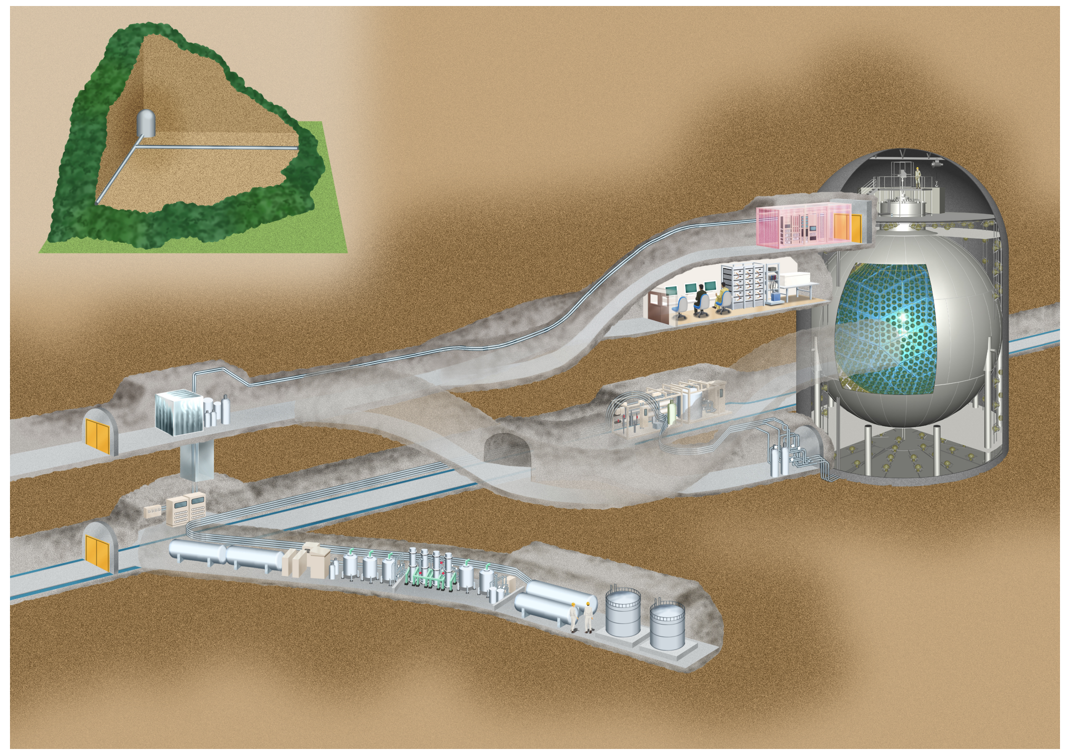
Ice Cube

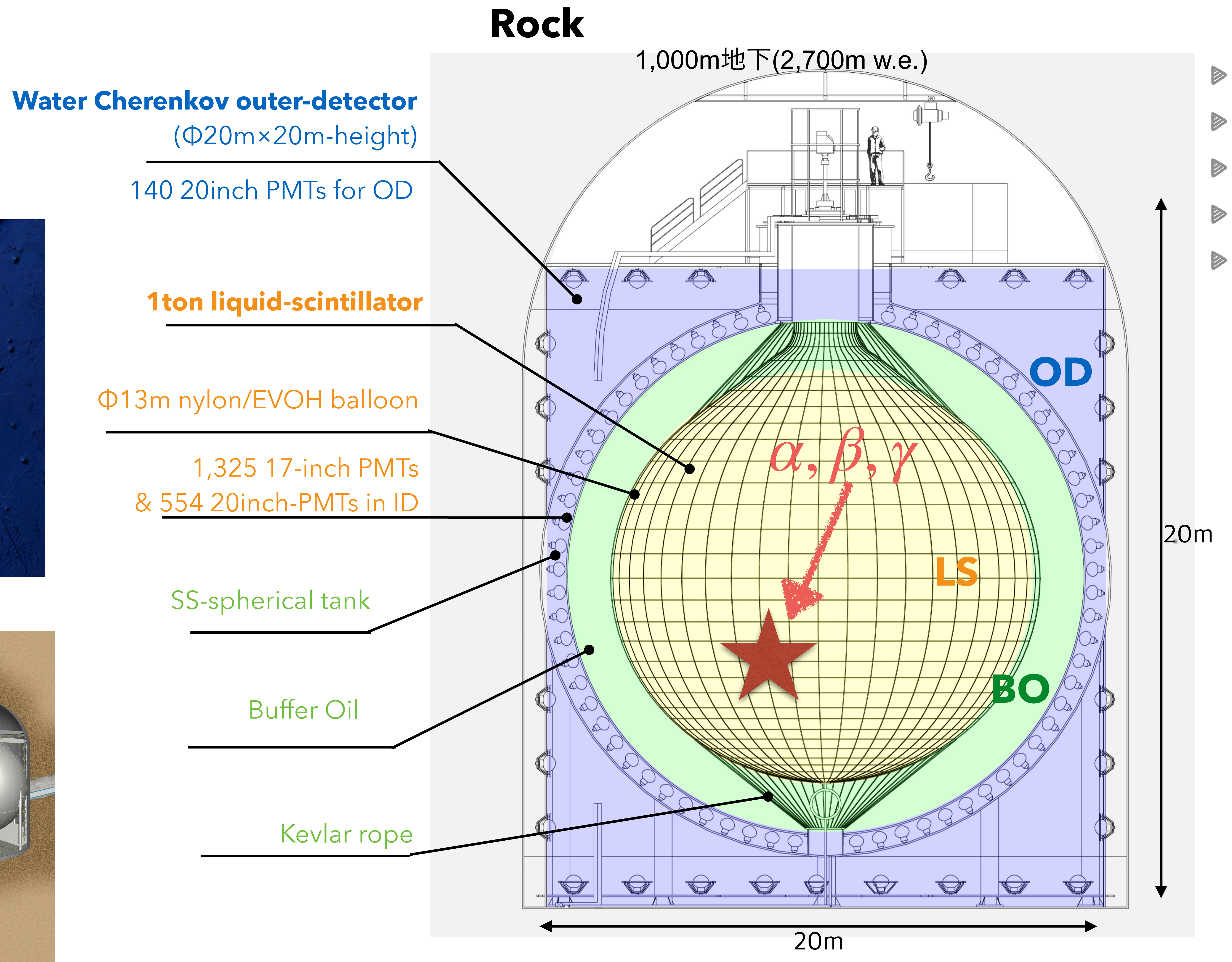


Ice Cerenkov
> TeV

KamLAND Detector

Kamioka **L**iquid-scintillator **A**nti-**N**eutrino **D**etector





LS=Liquid-Scintillator, BO=Buffer-Oil, OD=OuterDetector, ID=InnerDetector(LS+BO)

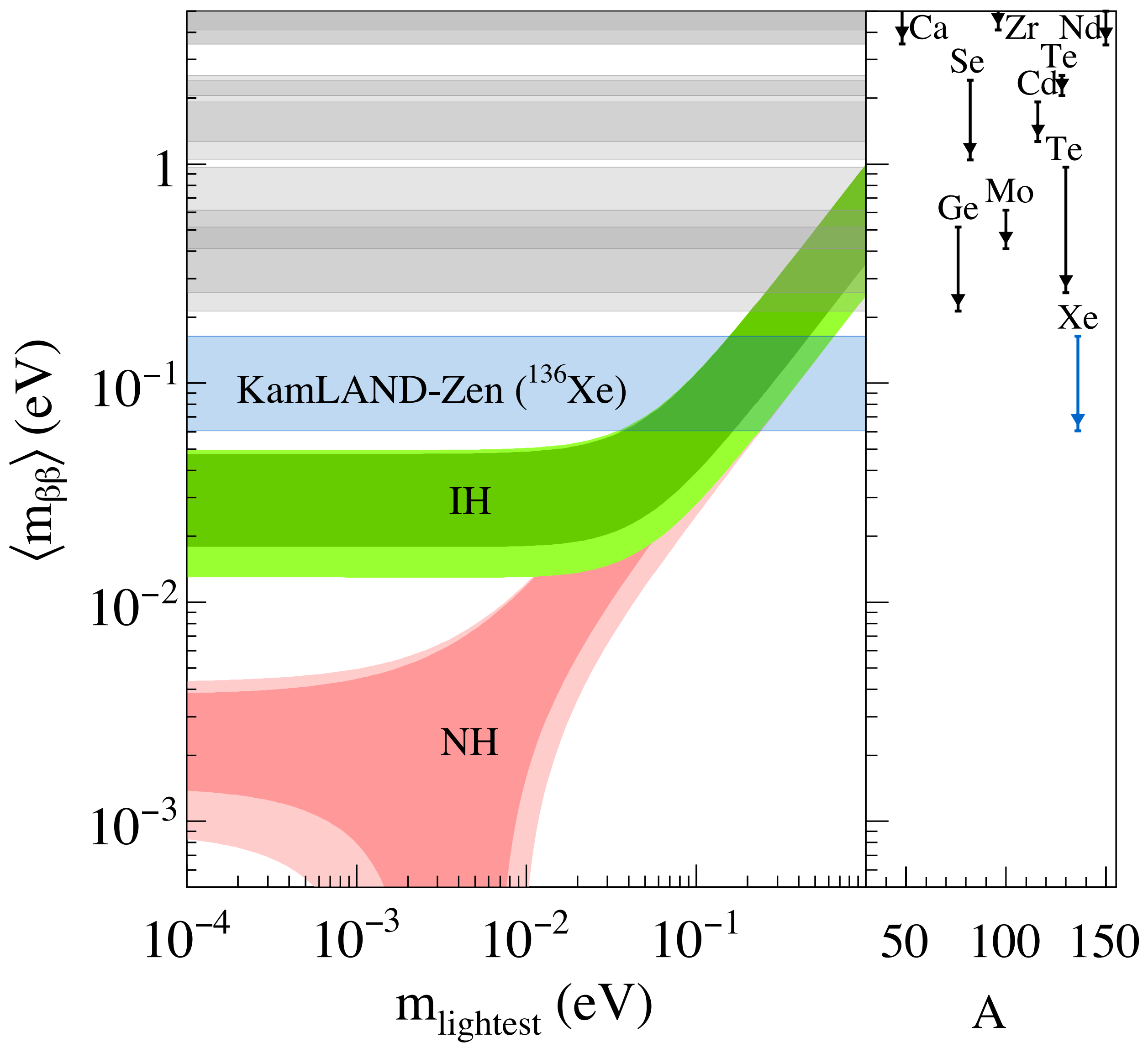
- 1 km underground from Mt. Ikenoyama
- former place of old KamiokaNDE
- next-door to the Super-Kamiokande
- Observe scintillation light by PMT
- Event reconstruction is performed by the hit timing and charges

KamLAND-Zen experiment

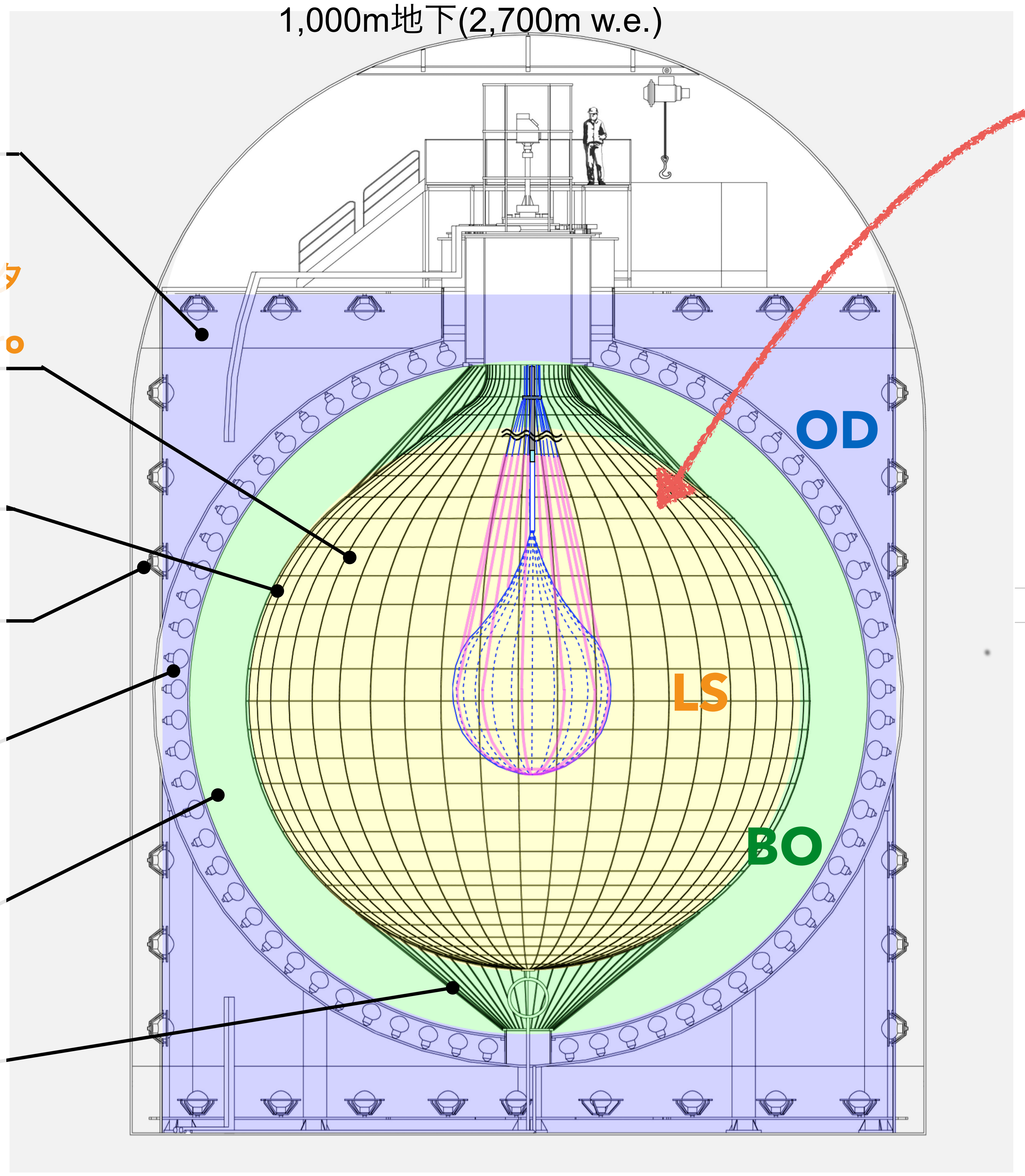
KamLAND Zero-**N**eutrino double-beta decay search experiment

- Search “neutrino less double-beta decay” using ^{136}Xe isotope in liquid-scintillator
- Now running with 780kg of ^{136}Xe
-

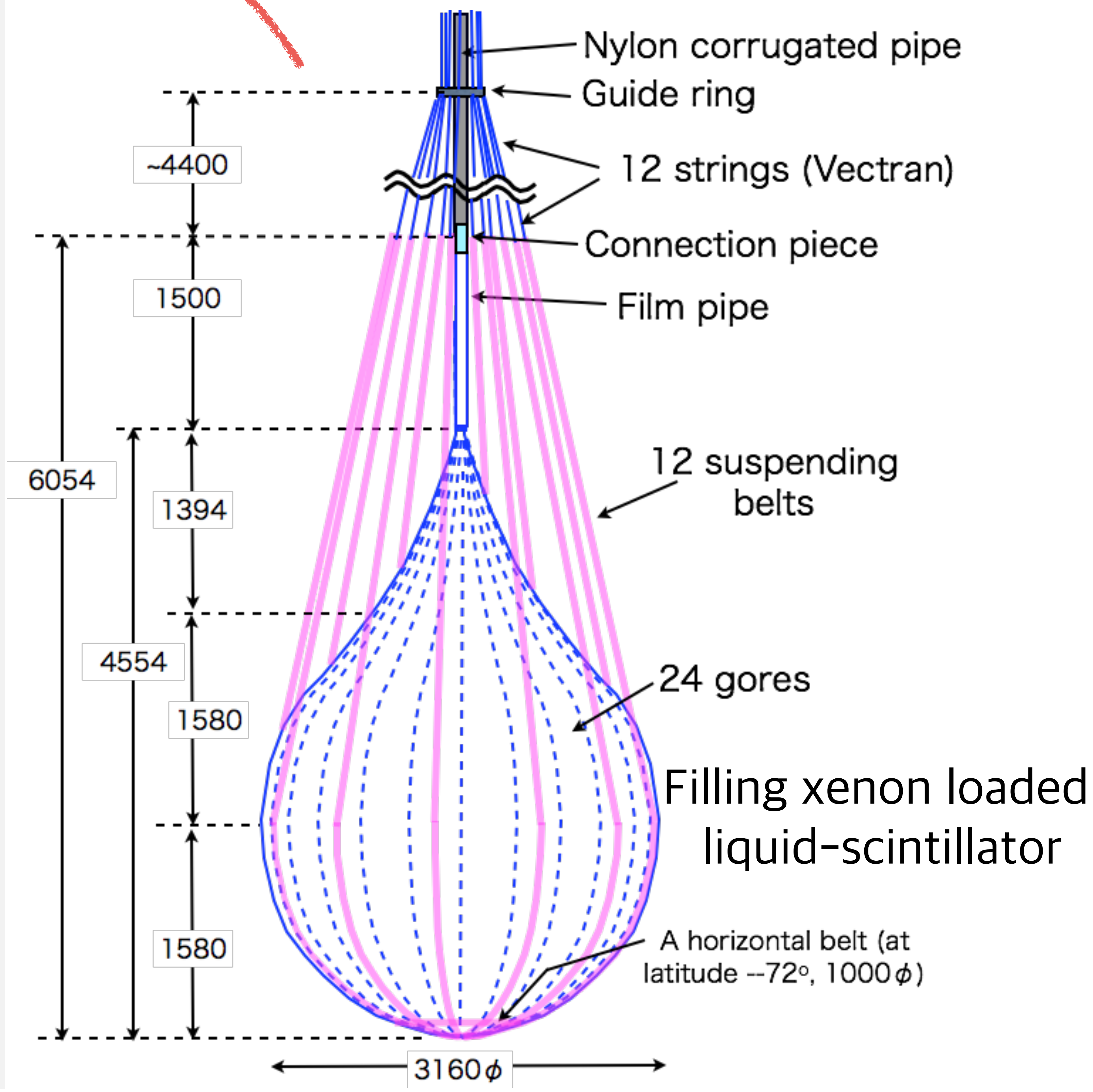
Phys. Rev. Lett. 117, 082503 (2016)



Rock



Installing a smaller nylon-made balloon at the center of the KamLAND



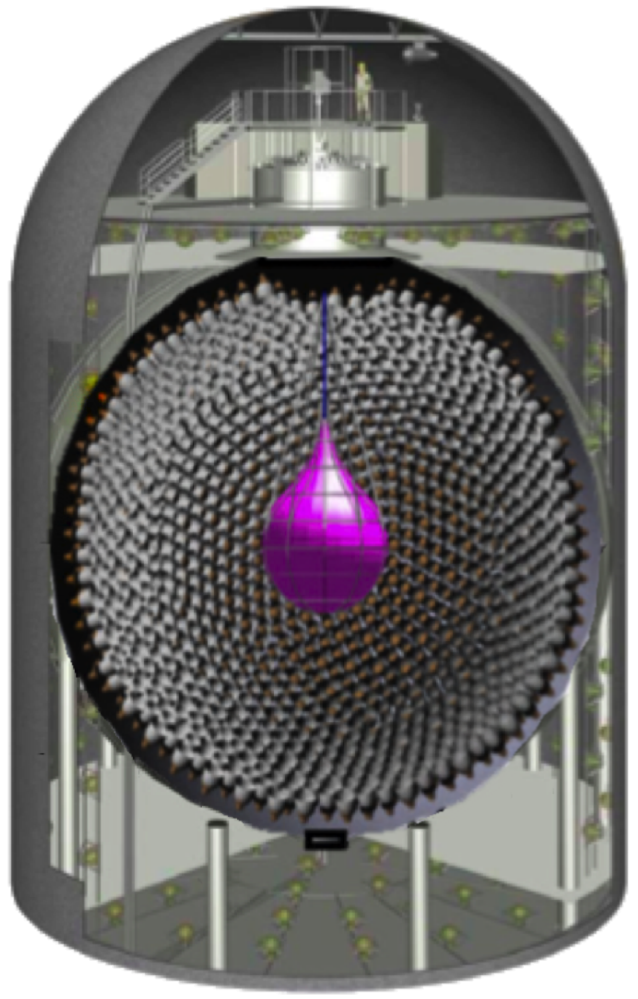
LS=Liquid-Scintillator, BO=Buffer-Oil, OD=OuterDetector, ID=InnerDetector(LS+BO)

This nylon-made balloon construction is summarized in paper (now preparing…)

KamLAND2(-Zen), OceanBottomDetector

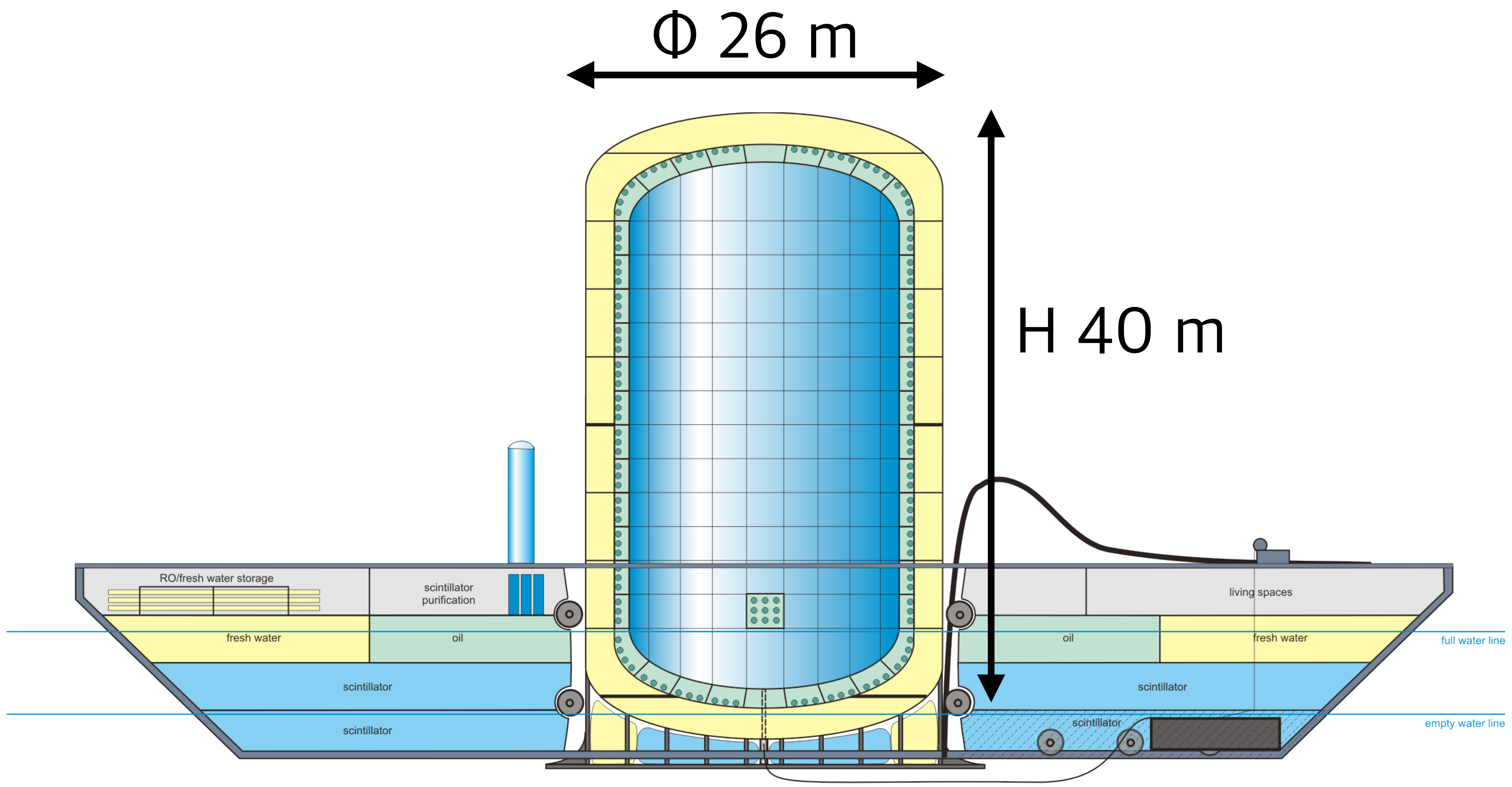
KamLAND2-Zen

- Upgrade program of KamLAND (AIP Conference Proceedings 1666, 170003 (2015))
- New electronics for ^{10}C tagging (過去の超新星研究会など)
- New LAB-based LS (brighter than now)
- Winstone-cone-shape light collecting mirror
- High-Q.E. PMTs
- Scintillating Balloon (PTEP (2019) 073H01)



Ocean Bottom Detector

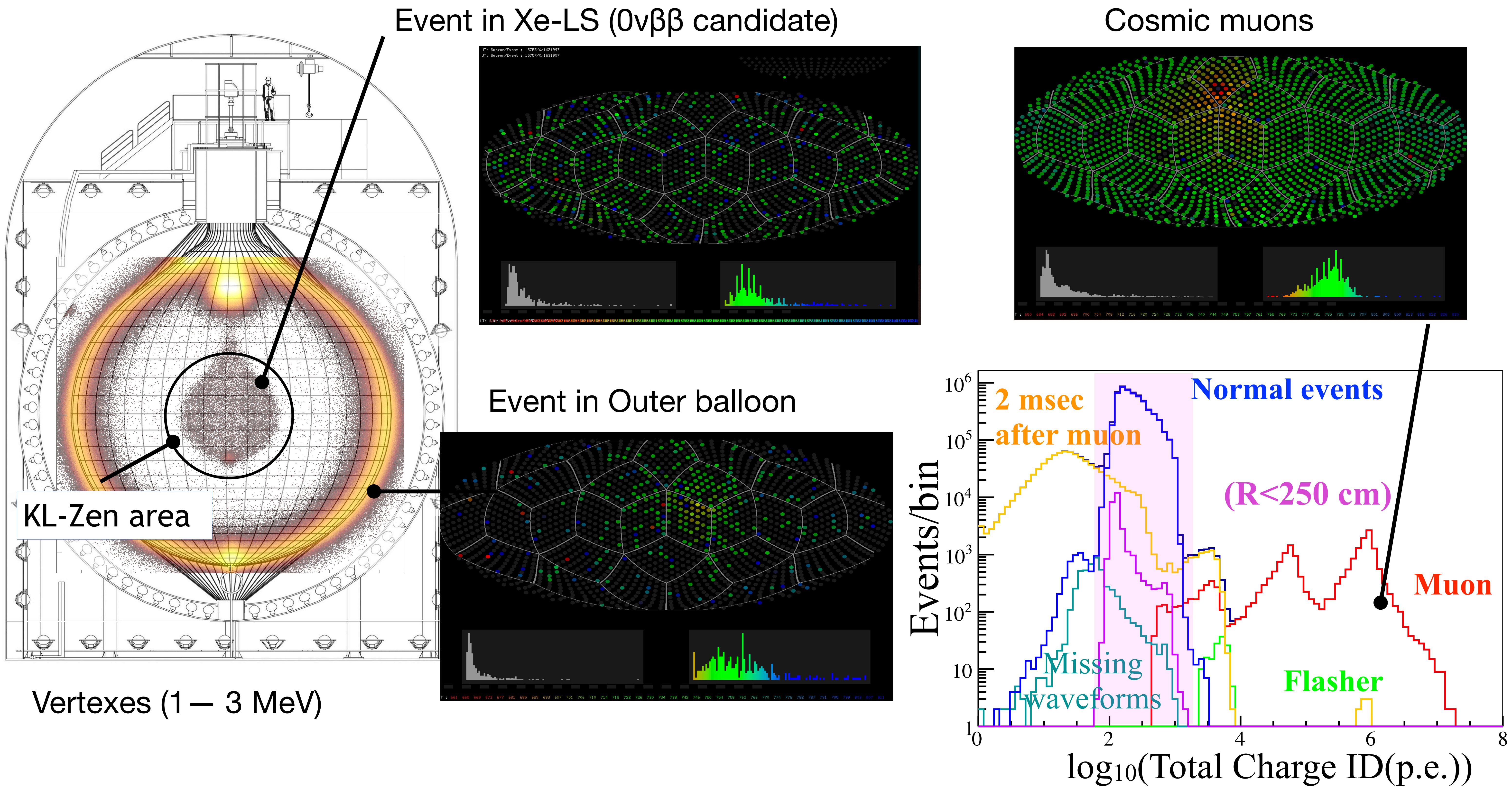
- Main purpose => geo-neutrino precise measurement
- A large liquid-scintillator detector
- → Tomorrow talk by Sakai

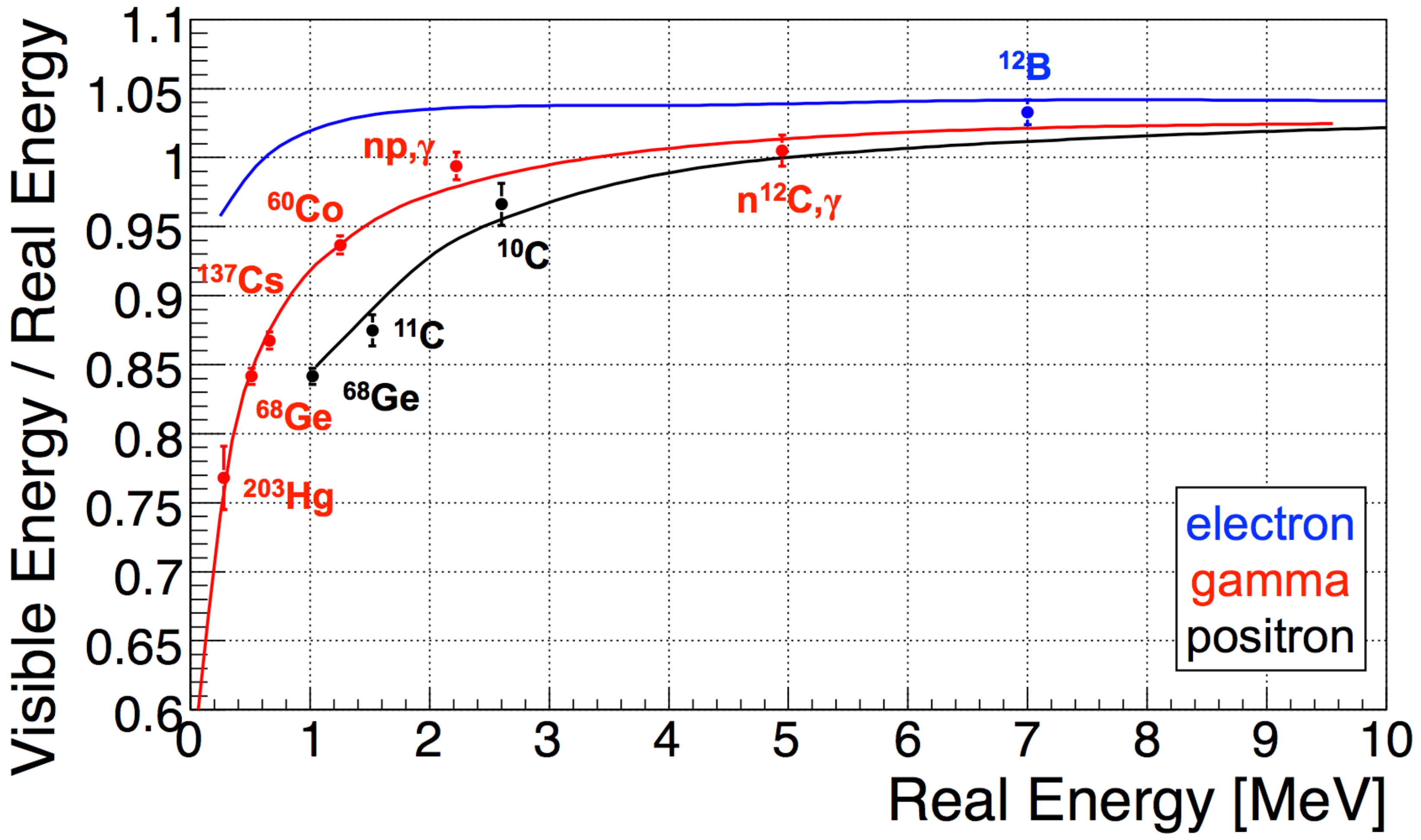


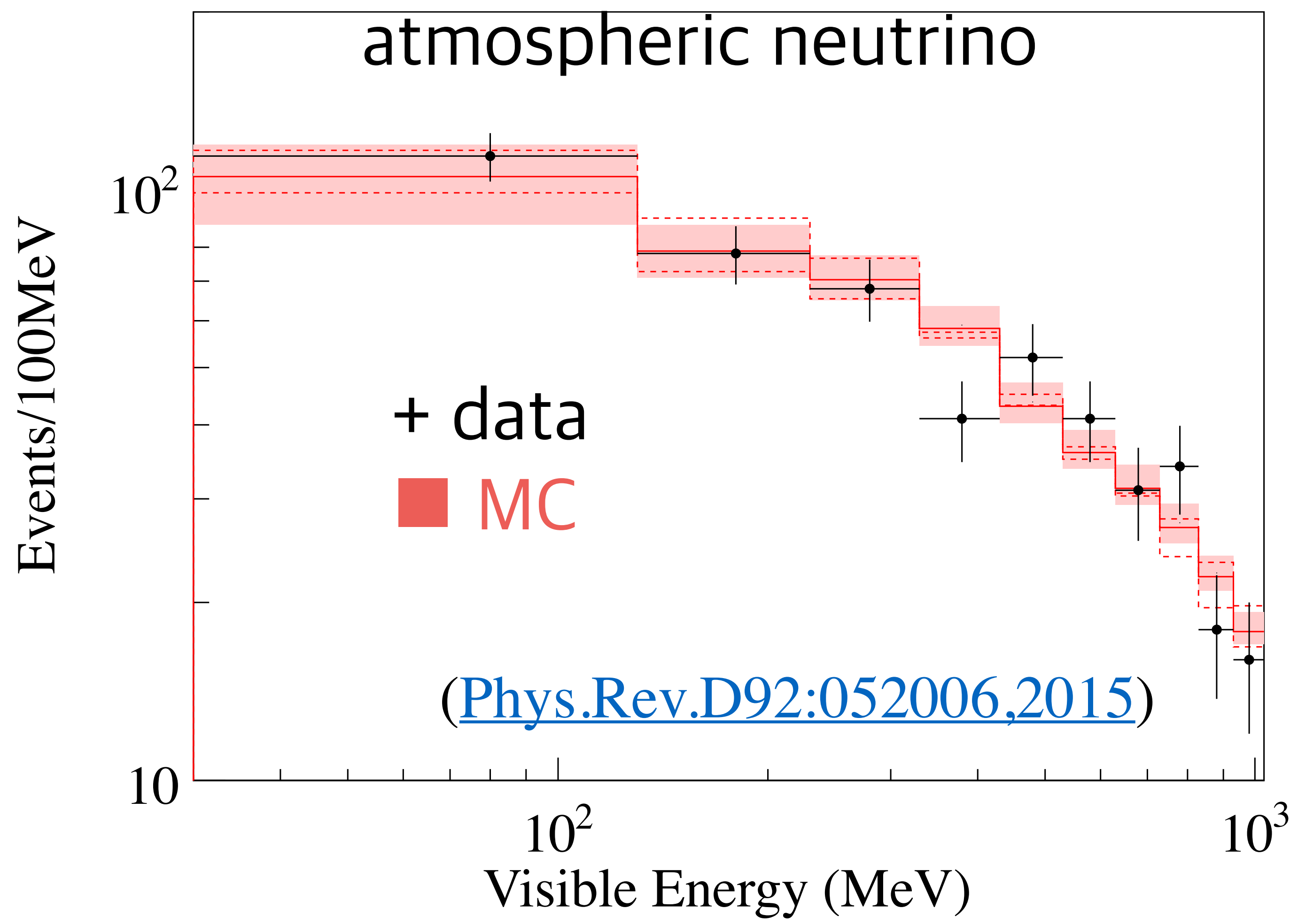
(cf; JUNO Φ~35m)

Scintillation Photons & Event Reconstruction

- Energy and vertex are reconstructed from the hit-timings and charges
- Various radioactive sources are useful for calibration
- Also spallation products, and atmospheric neutrinos

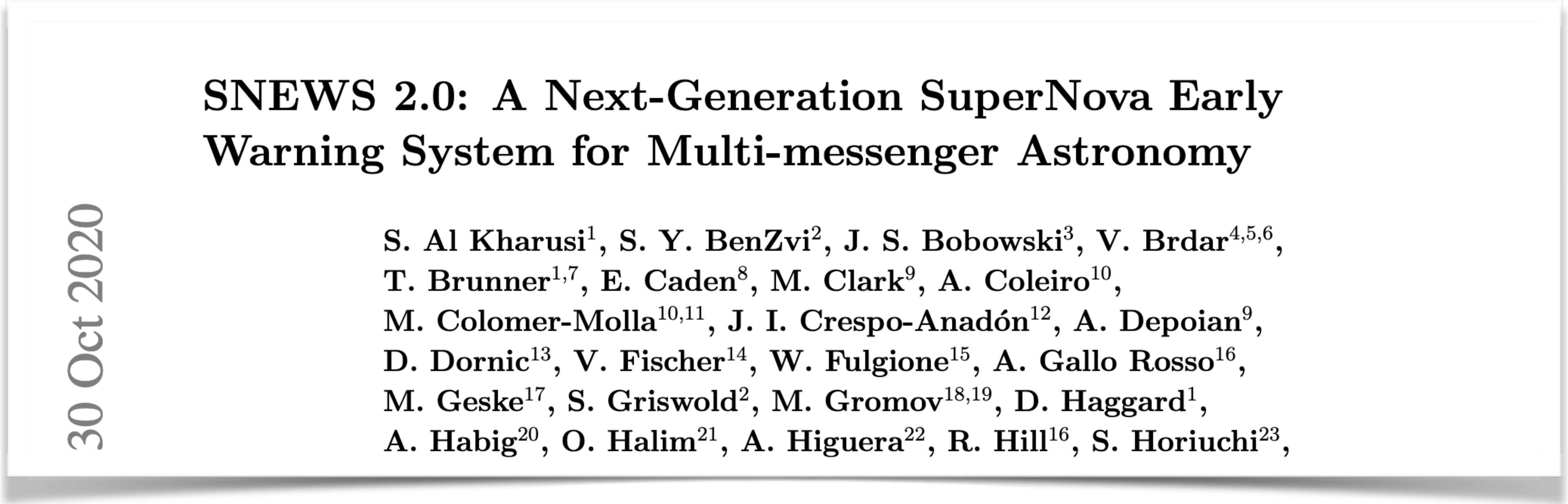






Astrophysical Neutrinos @ KamLAND

- SNEWS
  - (Pietro Antonioli et al 2004 New J. Phys. 6 114)
  - SNEWS2.0 white paper (arXiv:2011.00035)



30 Oct 2020

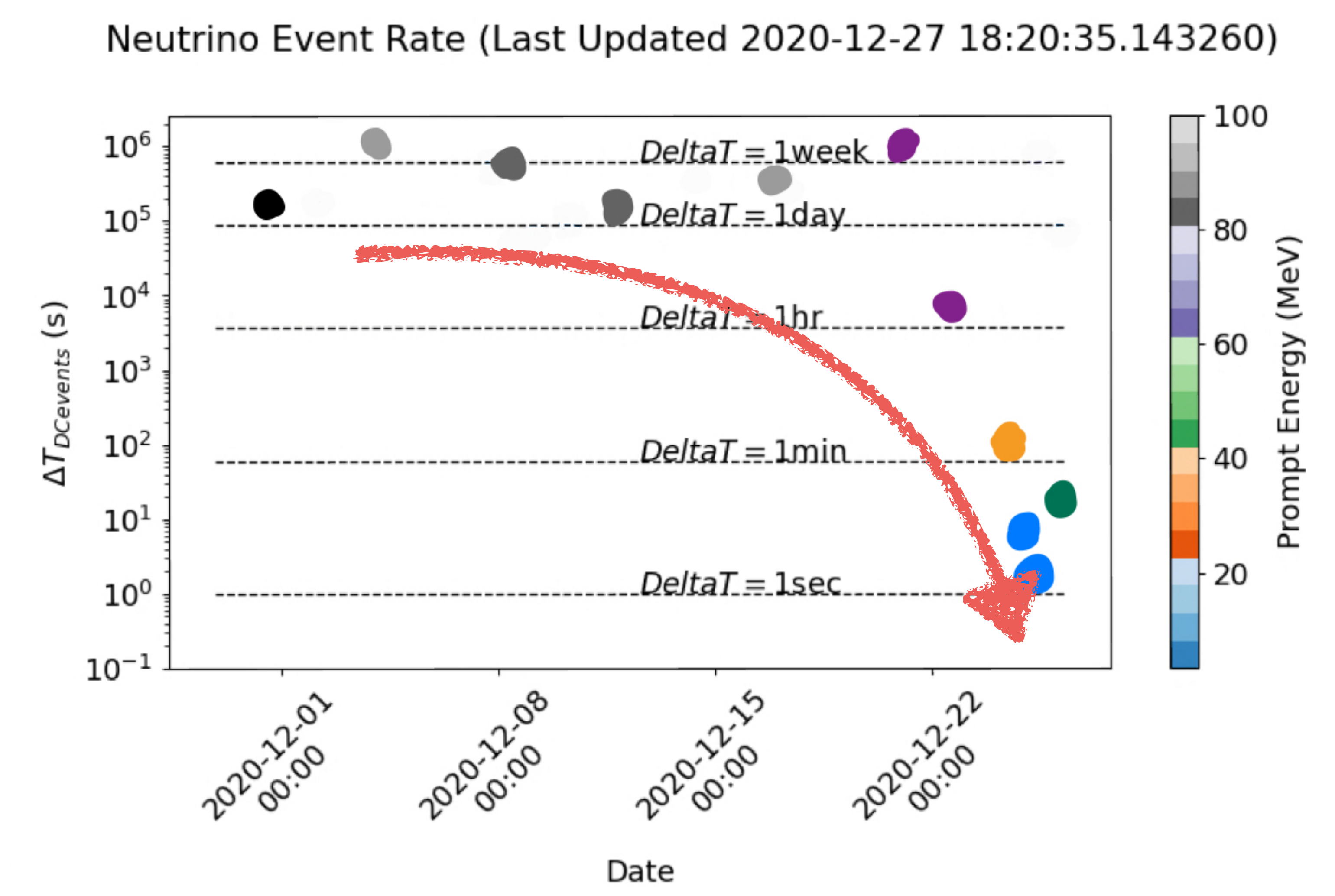
SNEWS 2.0: A Next-Generation SuperNova Early Warning System for Multi-messenger Astronomy

S. Al Kharusi[1], S. Y. BenZvi[2], J. S. Bobowski[3], V. Brdar[4,5,6], T. Brunner[1,7], E. Caden[8], M. Clark[9], A. Coleiro[10], M. Colomer-Molla[10,11], J. I. Crespo-Anadón[12], A. Depoian[9], D. Dornic[13], V. Fischer[14], W. Fulgione[15], A. Gallo Rosso[16], M. Geske[17], S. Griswold[2], M. Gromov[18,19], D. Haggard[1], A. Habig[20], O. Halim[21], A. Higuera[22], R. Hill[16], S. Horiuchi[23],

- Galactic Supernovae (cf; 過去の研究会)
- Pre Supernova (cf; K. Asakura et al 2016 ApJ 818 91)
- Supernova Relic Neutrinos (cf; Astrophys.J.745:193,2012)
- Neutrino searches associated wtih
  - Gamma-Ray-Bursts (cf; K. Asakura et al 2015 ApJ 806 87)
  - Gravitational Wave event (cf; Astrophys.J.829, L34, 2016) <— only the first BH-BH merger
- Burst Supernovae (on-going)
- Besides, other coincidence searches for transient events, such as IceCube’s event (on-going)

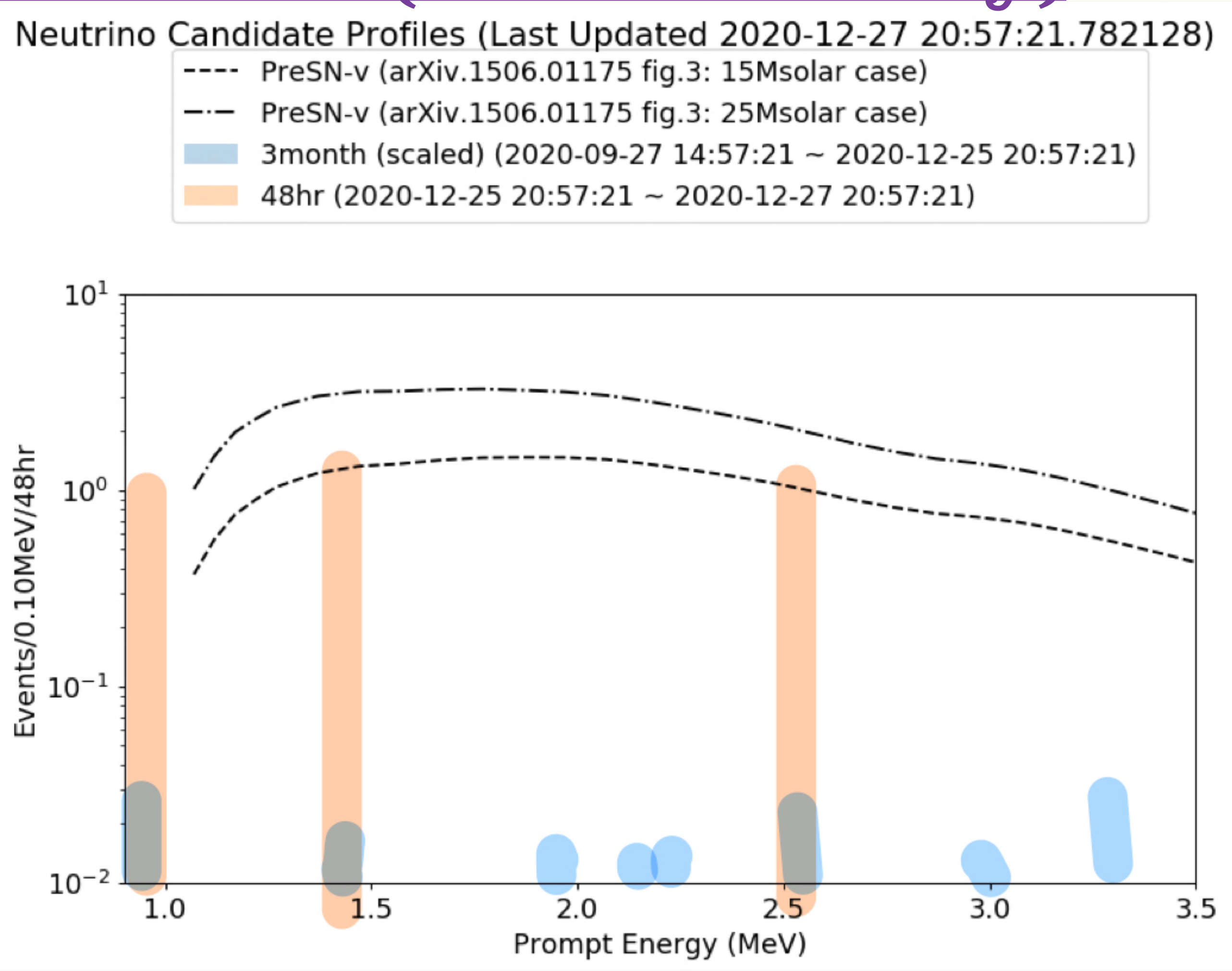
Online Supernova Analyses Updated

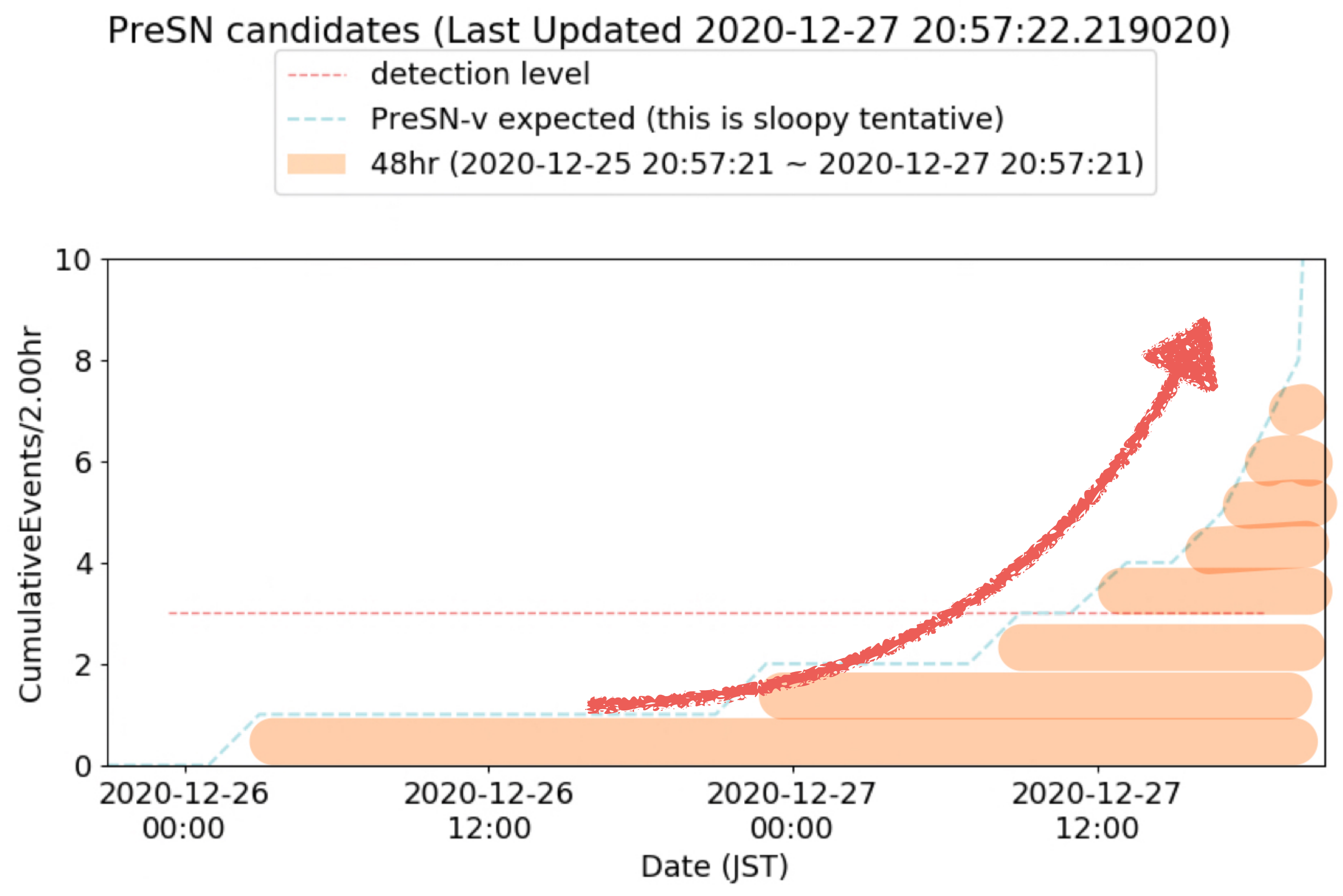
- Completely debug & update
  - baseline scan, waveform integration
  - event reconstruction, energy correction
  - event selection, likelihood based selection
  - online webpage
- Old one needs ~20hr for temporary offline-analysis file processing for more precise checking → now the online-analysis file is the same as offline one
- Useful for other physics online analysis



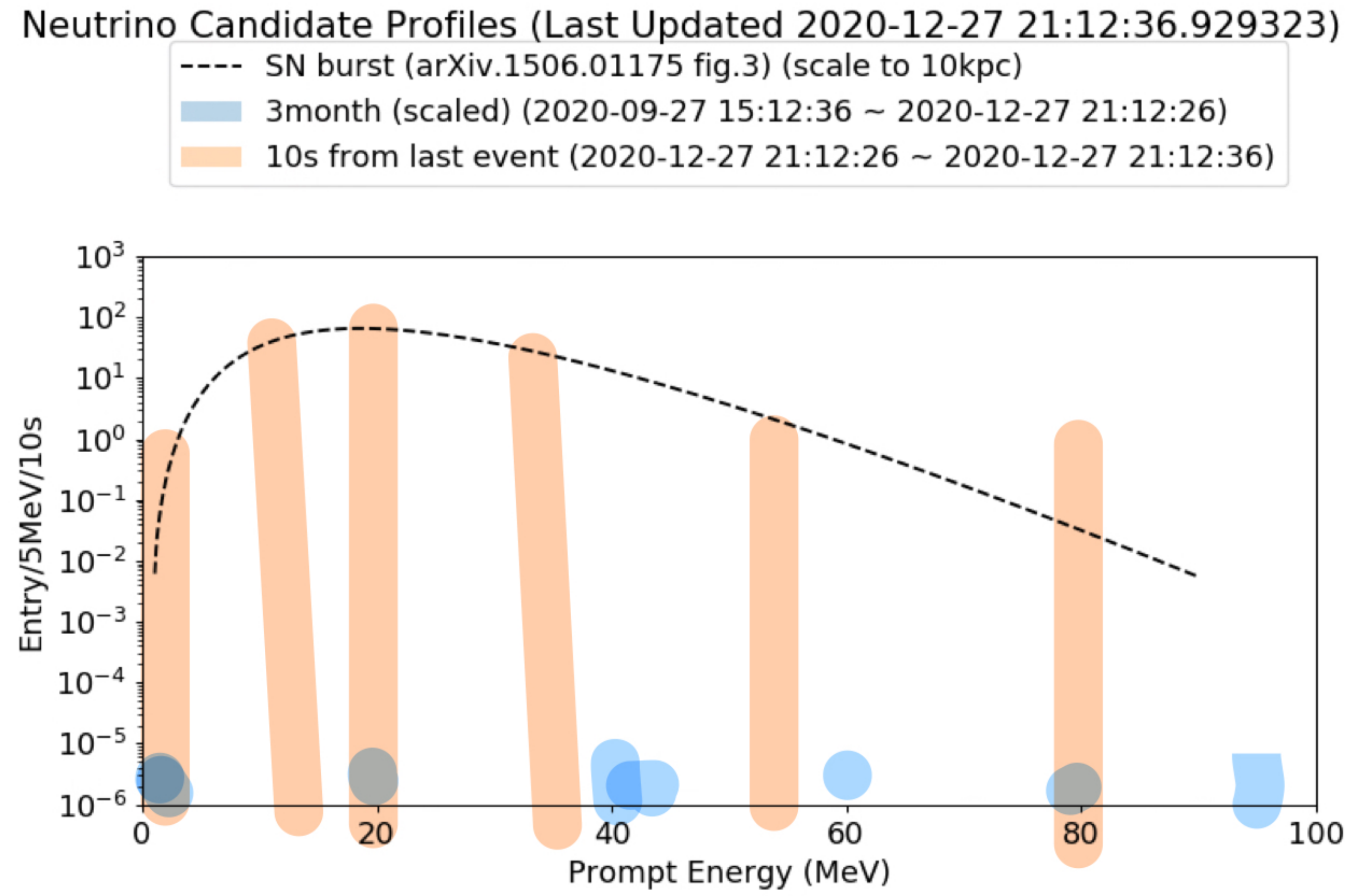
※ プロットは僕がiPadで適当に描いたやつです

PreSNmon (Internal Only)





GalacticSNmon (Internal Only)



GW coincident neutrino search

- There are some Gravitational Wave (GW) events observed by LIGO-O2
  - Super-K, Borexino, DayaBay, IceCube, XMASS reported the coincidence search
- There are a lot of GW candidates listed by LIGO-O3
  - NOvA reported the coincidence event search for their GCN alert

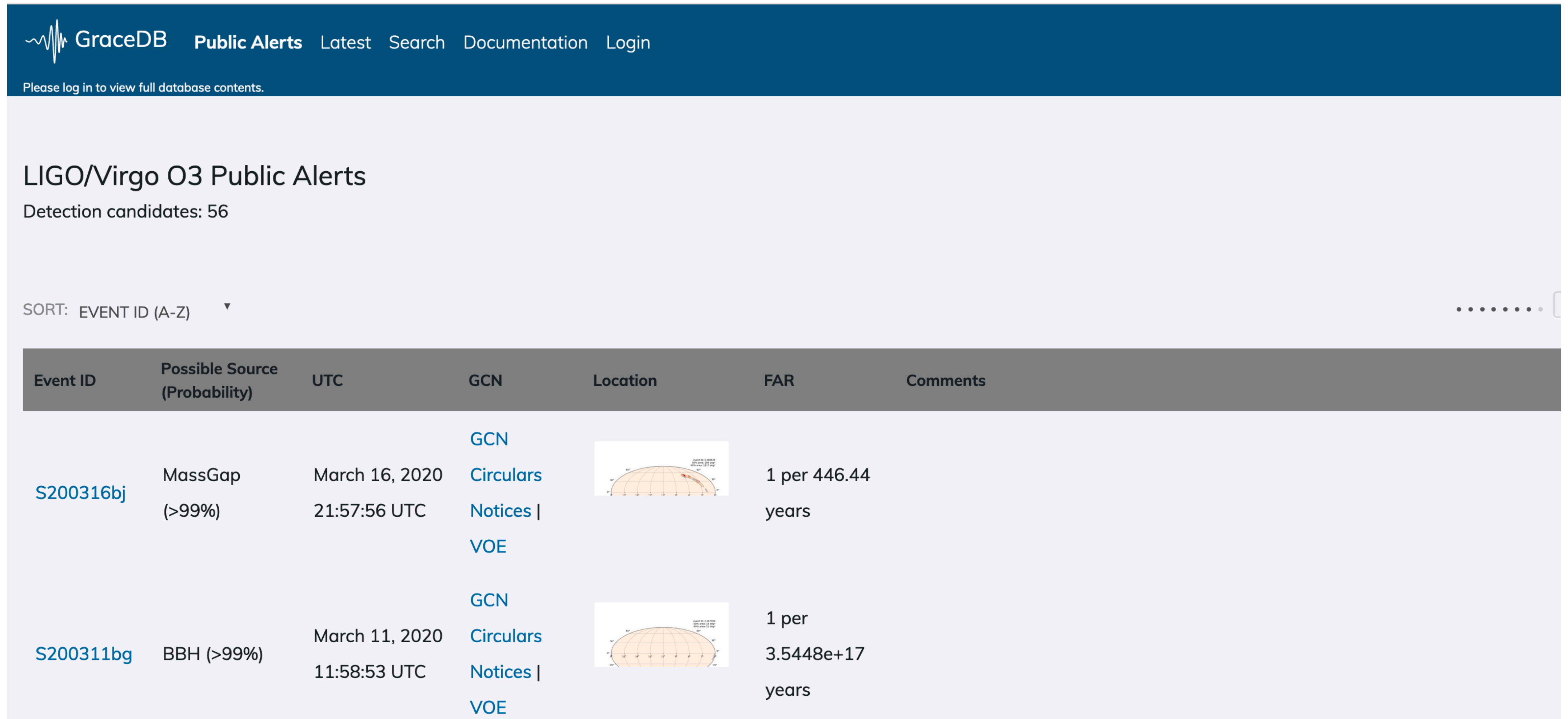
- We follow GW events observed by LIGO-O2 and check GW candidates listed by LIGO-O3
  - ※ here, LIGO-O3 candidates are not officially confirmed events, just candidates

- In contrast to IceCube and Super-K, KamLAND has a role as low-energy counter part

TABLE I. Search results for the 11 GW events. We report a false-alarm rate for each search that found a given event; otherwise, we display ⋯. The network SNR for the two matched-filter searches is that of the template ranked highest by that search, which is not necessarily the template with the highest SNR. Moreover, the network SNR is the quadrature sum of the detectors coincident in the highest-ranked trigger; in some cases, only two detectors contribute, even if all three are operating nominally at the time of that event.

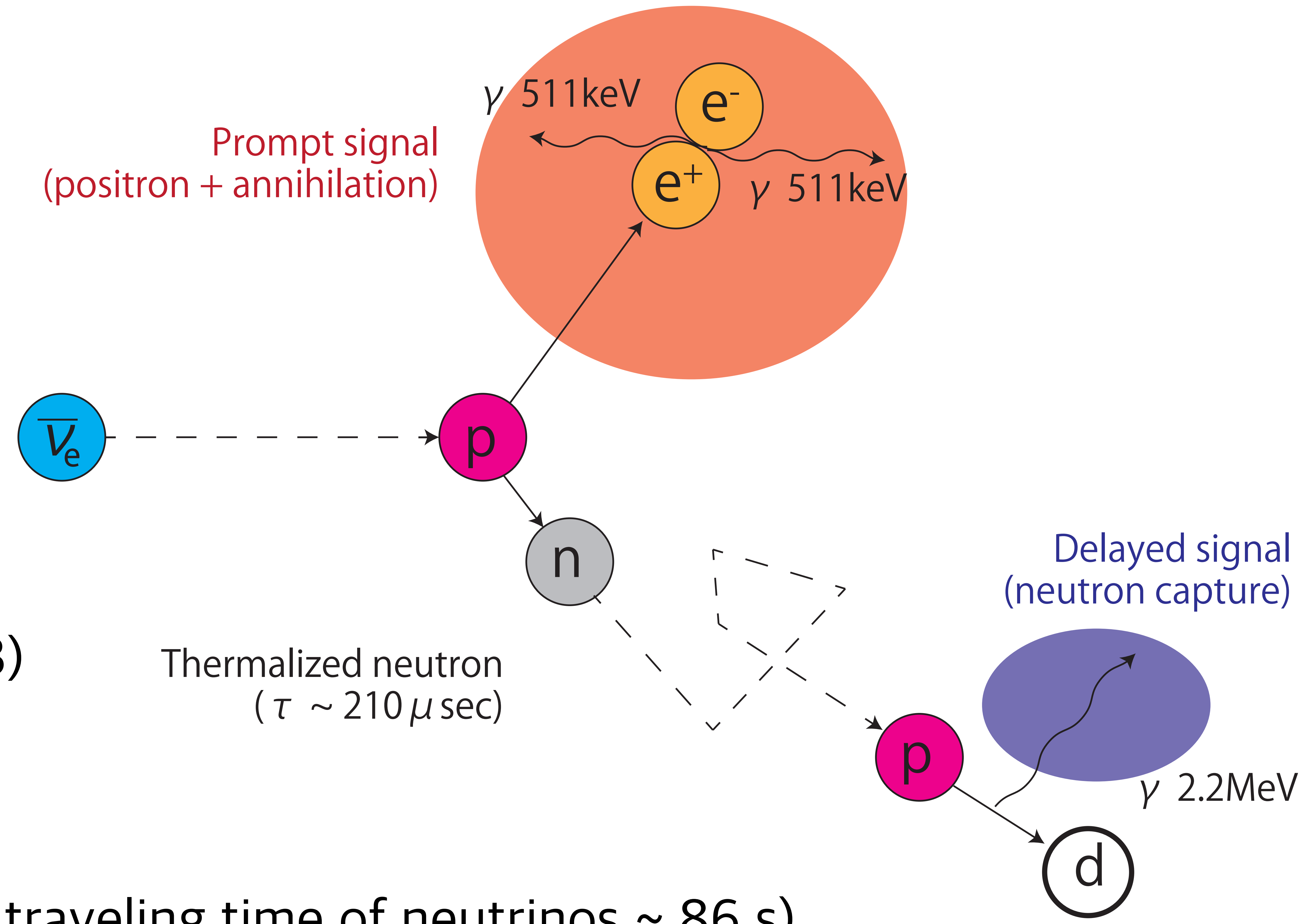
		FAR $[y^{-1}]$			Network SNR		
Event	UTC time	PyCBC	GstLAL	cWB	PyCBC	GstLAL	cWB
GW150914	09:50:45.4	$<1.53 \times 10^{-5}$	$<1.00 \times 10^{-7}$	$<1.63 \times 10^{-4}$	23.6	24.4	25.2
GW151012	09:54:43.4	0.17	7.92×10^{-3}	⋯	9.5	10.0	⋯
GW151226	03:38:53.6	$<1.69 \times 10^{-5}$	$<1.00 \times 10^{-7}$	0.02	13.1	13.1	11.9
GW170104	10:11:58.6	$<1.37 \times 10^{-5}$	$<1.00 \times 10^{-7}$	2.91×10^{-4}	13.0	13.0	13.0
GW170608	02:01:16.5	$<3.09 \times 10^{-4}$	$<1.00 \times 10^{-7}$	1.44×10^{-4}	15.4	14.9	14.1
GW170729	18:56:29.3	1.36	0.18	0.02	9.8	10.8	10.2
GW170809	08:28:21.8	1.45×10^{-4}	$<1.00 \times 10^{-7}$	⋯	12.2	12.4	⋯
GW170814	10:30:43.5	$<1.25 \times 10^{-5}$	$<1.00 \times 10^{-7}$	$<2.08 \times 10^{-4}$	16.3	15.9	17.2
GW170817	12:41:04.4	$<1.25 \times 10^{-5}$	$<1.00 \times 10^{-7}$	⋯	30.9	33.0	⋯
GW170818	02:25:09.1	⋯	4.20×10^{-5}	⋯	⋯	11.3	⋯
GW170823	13:13:58.5	$<3.29 \times 10^{-5}$	$<1.00 \times 10^{-7}$	2.14×10^{-3}	11.1	11.5	10.8

Phys. Rev. X 9, 031040 (2019)



$\bar{\nu}_e$ Selection Criteria; InverseBetaDecay(IBD)

- **<u>Delayed-Coincidence (DC) event</u>**
    - Basically follows the usual selection
        - ([Nature Geoscience vol.4, p.647-651 (2011)](#))
        - ([A. Gando et al 2012 ApJ 745 193](#))
    - 0.9 < Ep < 100 MeV
    - 1.8 < Ed < 2.6 or 4.4 < Ed < 5.6 MeV
    - ΔR < 200 cm
    - 0.5 < ΔT < 1000 μs
    - FiducialR < 600 cm
    - muon vetos
    - Likelihood Selection
    - Inner-balloon cut for delayed event (for LIGO-O3)

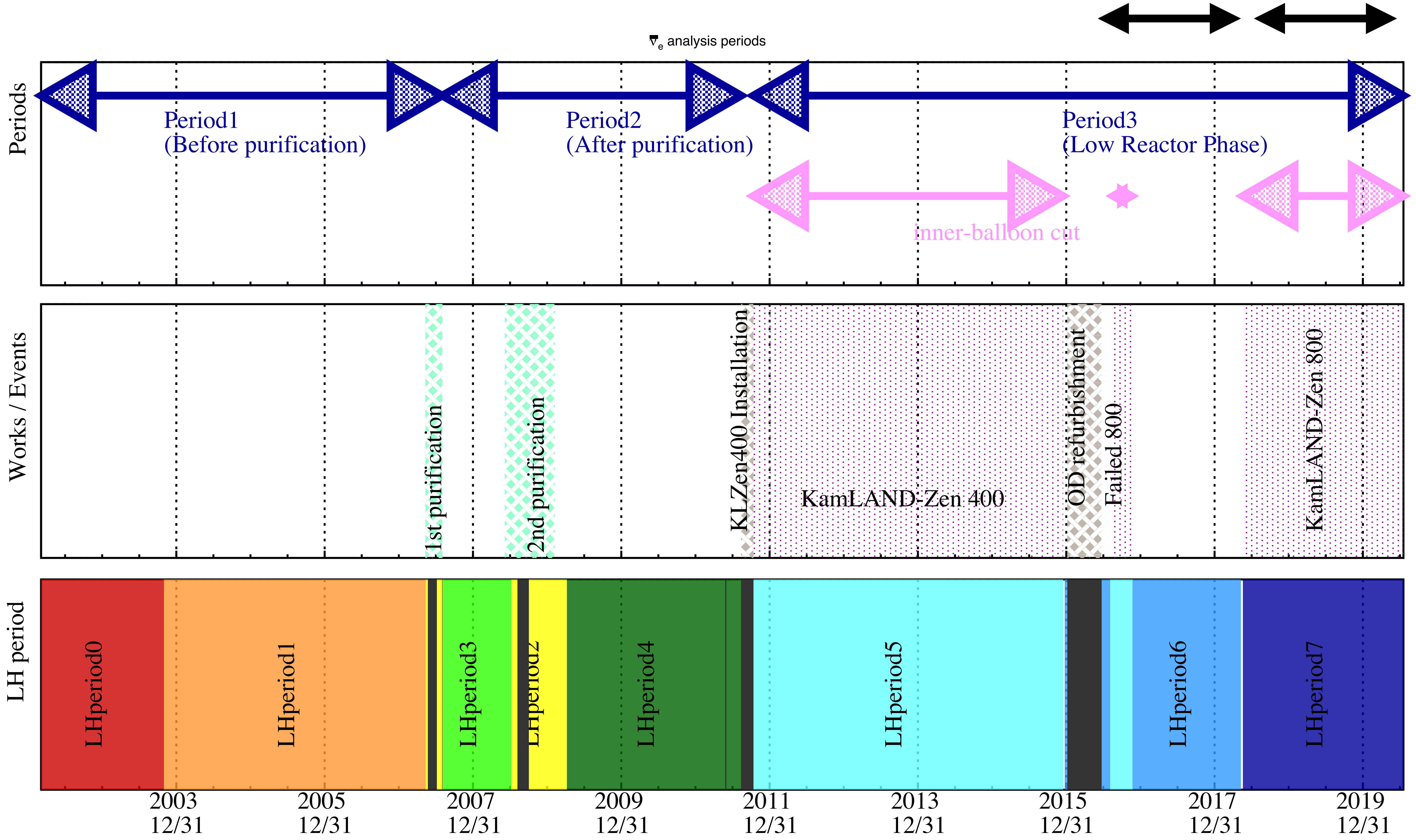


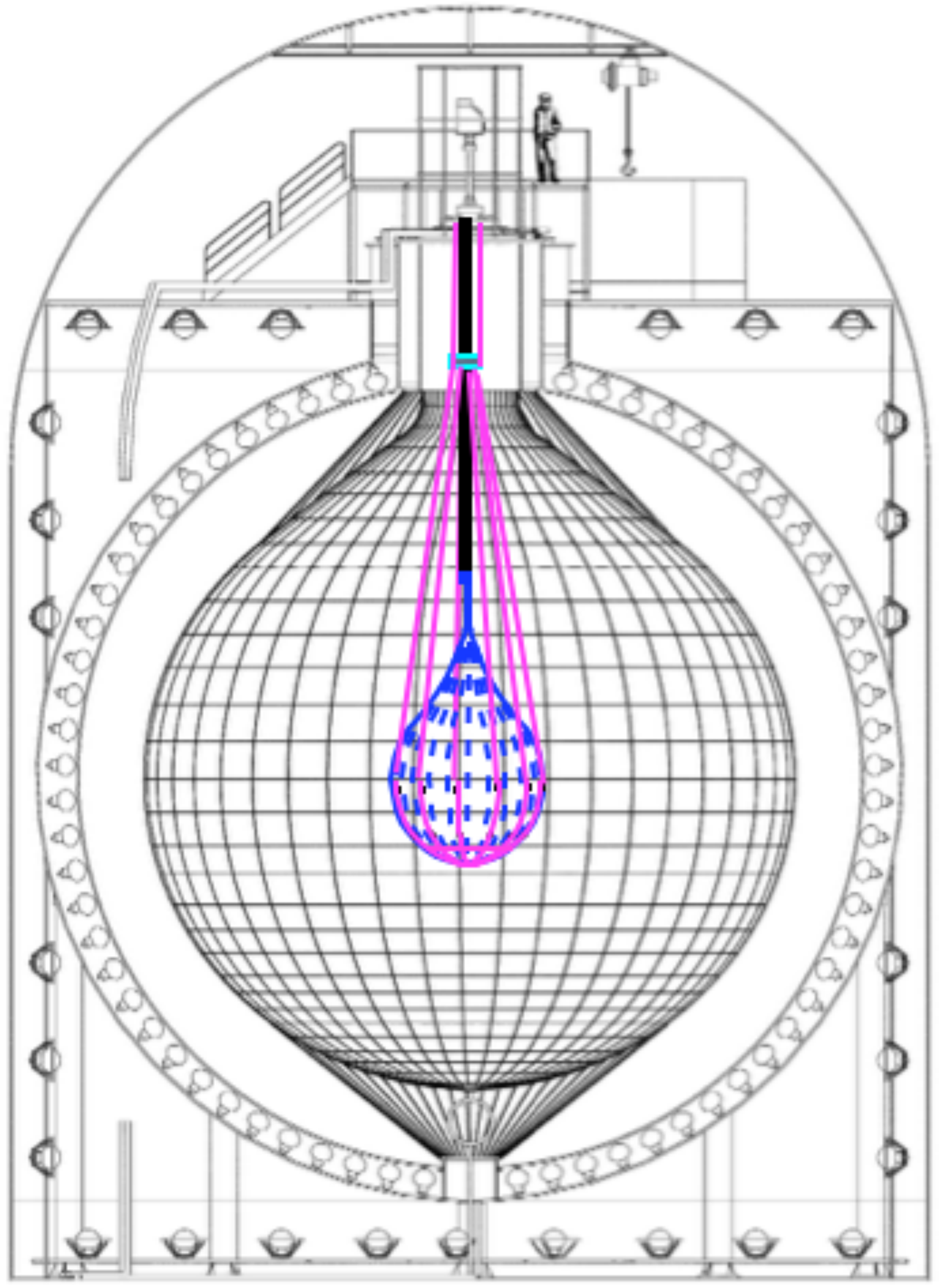
- **<u>Coincidence Search Window</u>**
    - ±500 s from GW events ([Baret et al. 2011](#))
    - (※ In the most distant GW case (2840 Mpc), the traveling time of neutrinos ~ 86 s)

Data Set

LIGO-O2 events == LH6
(without inner-balloon cut)

LIGO-O3 candidates == LH7
(with inner-balloon cut for KLZen800)

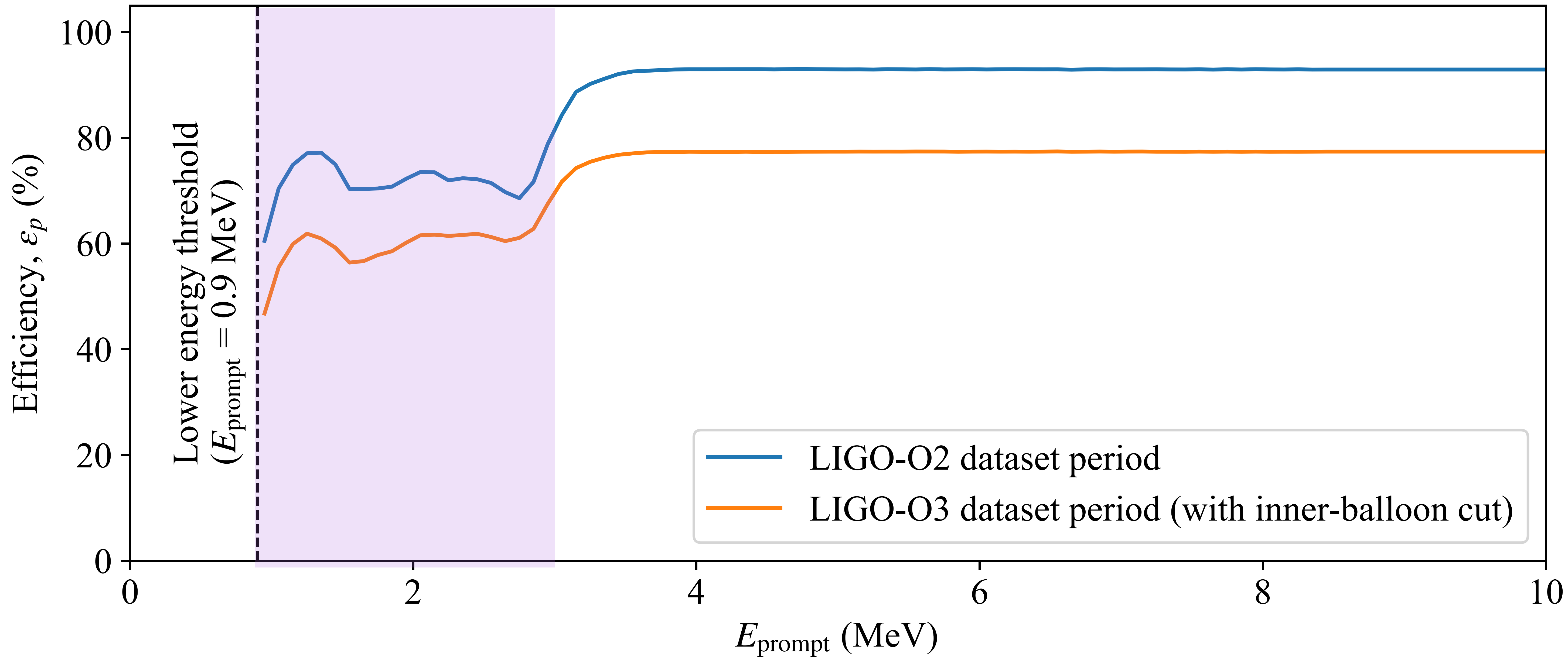




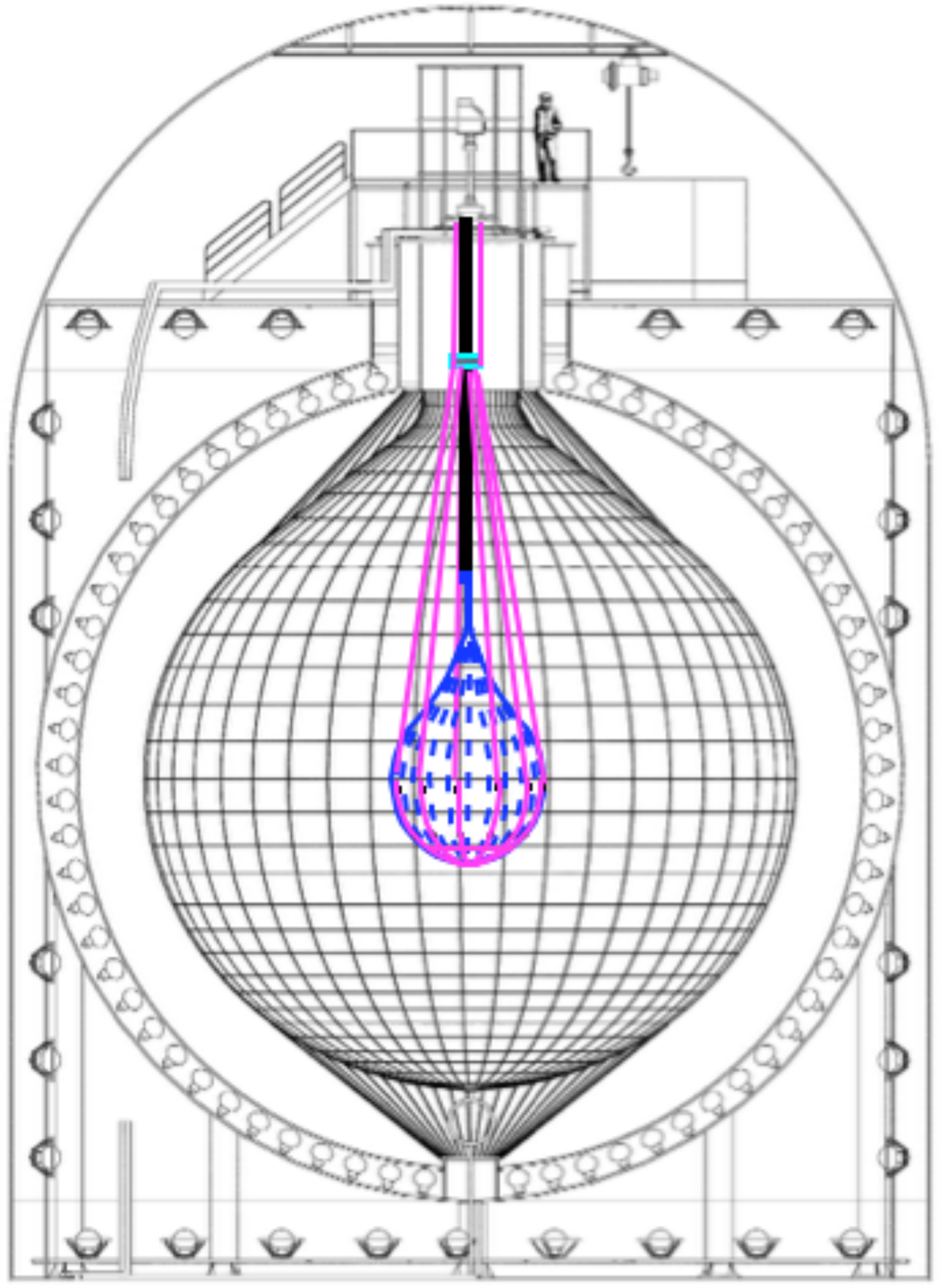
Selection Efficiency and other parameters

- Selection efficiencies are ε_s = 92.9% and ε_s = 77.4% for LIGO-O2 and LIGO-O3 dataset, respectively
- The difference btw two dataset derived from with or without the inner-balloon cut
- $N_T = (5.98 \pm 0.13) \times 10^{31}$ protons in R < 600 cm
- Livetime efficiencies in these datasets are ~ 87.8%

Suppressing accidental delayed-coincidence backgrounds
from radioactive impurities (^{40}K, ^{210}Bi, ^{208}Tl, on outer-balloon)



inner-balloon cut effect



Coincidence Event Search

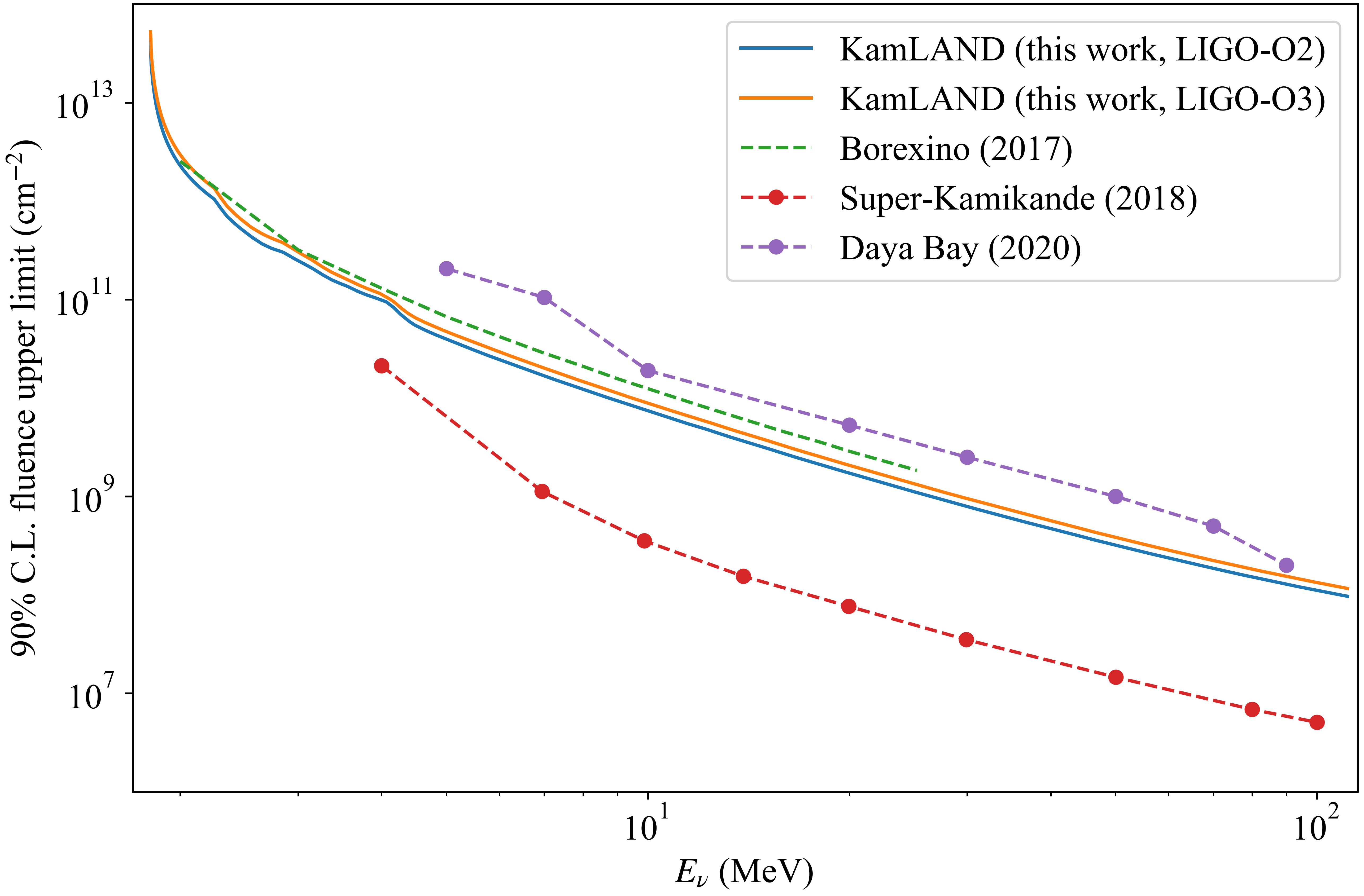
- Number of expected IBD events is estimated from offtime window from GWs
  - N_{exp} = 4.08e-3 events within ±500 s for LIGO-O2 period
  - N_{exp} = 4.27e-3 events within ±500 s for LIGO-O3 period

- No significant event is found for 60 GWs
  - 4 GWs are in bad run periods

- Using FeldmanCousins method (Phys. Rev. D 57, 3873, 1998), the number of upper limits with 90% C.L. are
  - N_{90} < 2.435 for a GW event (LIGO-O2)
  - N_{90} < 2.435 for a GW event (LIGO-O3)

- For monochromatic neutrino spectra, fluence upper limit is given as

$$F_{90}(E_\nu) = \frac{N_{90}}{N_T\,\epsilon_{\mathrm{live}}\,\epsilon_{\mathrm{s}}(E_\nu)\,\sigma(E_\nu)}$$



BinaryNeutronStar vs. BinaryBlackHole

- Discuss the difference btw BNS and BBH
  - Use only LIGO-O2 GW events
  - 1-BNS
  - 6-BBHs
  - cuz, LIGO-O3 GWs are just candidates
- Assuming Fermi-Dirac distribution,
  we can set upper limit on the neutrino fluence (all flavor) as
  - $\mathscr{F}_{90}^{\mathrm{BNS}} \leq 2.04 \times 10^{10}\,\mathrm{cm}^{-2}$
  - $\mathscr{F}_{90}^{\mathrm{BBH}} \leq 2.02 \times 10^{10}\,\mathrm{cm}^{-2}$

Table 1. The gravitational wave event list for LIGO-O2 (Abbott et al. 2019) and along with the KamLAND detector status. The three events in which KamLAND has already published the results for a coincidence search (Gando et al. 2016a) are not included in this table.

Gravitational wave	Date and time (UTC)	Distance (Mpc)	Source	KamLAND status
GW170104	2017 January 4, 10:11:58.6	990^{+440}_{-430}	BBH	running
GW170608	2017 June 8, 02:01:16.5	320^{+120}_{-110}	BBH	unusual data condition
GW170729	2017 July 29, 18:56:29.3	2840^{+1400}_{-1360}	BBH	running
GW170809	2017 August 9, 08:28:21.8	1030^{+320}_{-390}	BBH	running
GW170814	2017 August 14, 10:30:43.5	600^{+150}_{-220}	BBH	running
GW170817	2017 August 17, 12:41:04.4	40^{+7}_{-15}	BNS	running
GW170818	2017 August 18, 02:24:09.1	1060^{+420}_{-380}	BBH	running
GW170823	2017 August 23, 13:13:58.5	1940^{+970}_{-900}	BBH	running

$$\lambda_{\mathrm{FD}}(E_\nu) = \frac{1}{T^3 f_2(\eta)} \frac{E_\nu^2}{e^{E_\nu/T-\eta}+1}, \quad f_n(\eta) = \int_0^\infty \frac{x^n}{e^{x-\eta}+1} dx,$$

- Total energies from GW source are

$$\mathscr{L}_{90}^{\mathrm{BNS}} \leq 7.92 \times 10^{58} \left(\frac{D_{\mathrm{eff}}}{40\,\mathrm{Mpc}}\right)^2 \mathrm{erg}$$

$$\mathscr{L}_{90}^{\mathrm{BBH}} \leq 8.22 \times 10^{60} \left(\frac{D_{\mathrm{eff}}}{407.6\,\mathrm{Mpc}}\right)^2 \mathrm{erg}$$

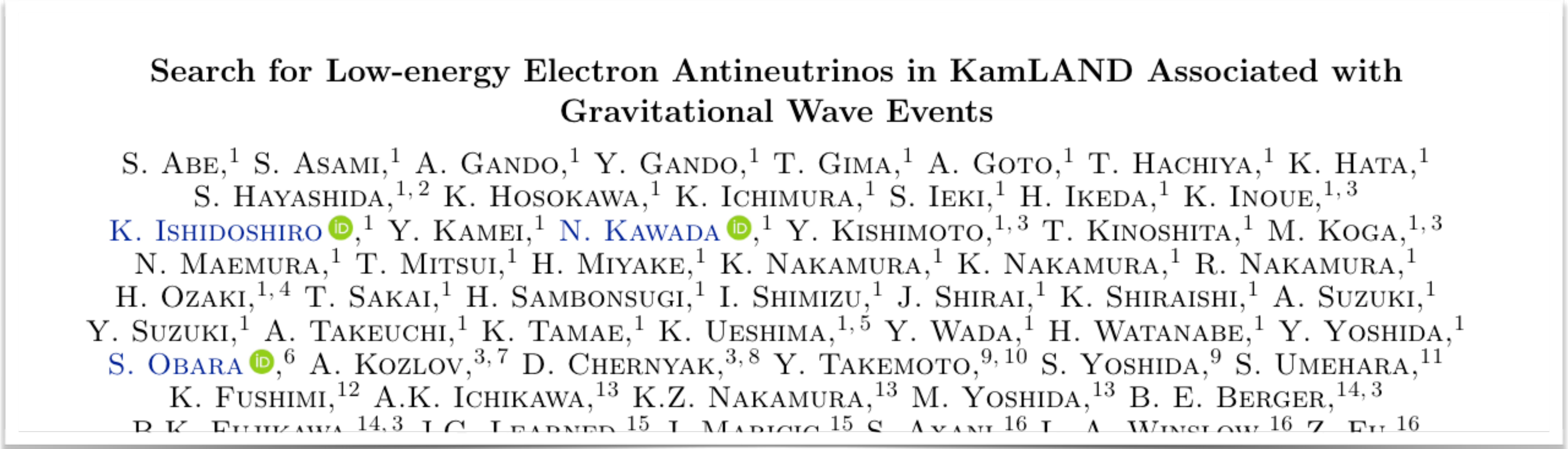
$$1/D_{\mathrm{eff}}^2 \equiv \sum_i 1/D_i^2$$

(cf; typical SN has $\mathscr{L} \sim \mathscr{O}(10^{53})$)

It seems to be the difference depends on the distance rather than the difference of GW source mechanism

Summary

- GW coincidence event search is updated
  - Last published paper included only the first 3-GWs
- Limits on fluence upper limit for 60 GWs (LIGO-O2 confirmed events and LIGO-O3 candidates)
  - Most strict upper limit for a few to several MeV neutrino energies (below SK's threshold)
  - The first limit for LIGO-O3 data
- Limits on total energies for BBH and BNS using only LIGO-O2
  - The upper limits still are still larger than the typical SNe ~O(10^{53})
- Above result is accepted in publication in ApJ (arXiv:2012.12053)
- We can smoothly search for transient astrophysical events via new online monitor



Search for Low-energy Electron Antineutrinos in KamLAND Associated with Gravitational Wave Events

S. Abe,[1] S. Asami,[1] A. Gando,[1] Y. Gando,[1] T. Gima,[1] A. Goto,[1] T. Hachiya,[1] K. Hata,[1] S. Hayashida,[1,2] K. Hosokawa,[1] K. Ichimura,[1] S. Ieki,[1] H. Ikeda,[1] K. Inoue,[1,3] K. Ishidoshiro,[1] Y. Kamei,[1] N. Kawada,[1] Y. Kishimoto,[1,3] T. Kinoshita,[1] M. Koga,[1,3] N. Maemura,[1] T. Mitsui,[1] H. Miyake,[1] K. Nakamura,[1] K. Nakamura,[1] R. Nakamura,[1] H. Ozaki,[1,4] T. Sakai,[1] H. Sambonsugi,[1] I. Shimizu,[1] J. Shirai,[1] K. Shiraishi,[1] A. Suzuki,[1] Y. Suzuki,[1] A. Takeuchi,[1] K. Tamae,[1] K. Ueshima,[1,5] Y. Wada,[1] H. Watanabe,[1] Y. Yoshida,[1] S. Obara,[6] A. Kozlov,[3,7] D. Chernyak,[3,8] Y. Takemoto,[9,10] S. Yoshida,[9] S. Umehara,[11] K. Fushimi,[12] A.K. Ichikawa,[13] K.Z. Nakamura,[13] M. Yoshida,[13] B. E. Berger,[14,3]

In Abst., $cm^2 \rightarrow cm^{-2}$

Backup