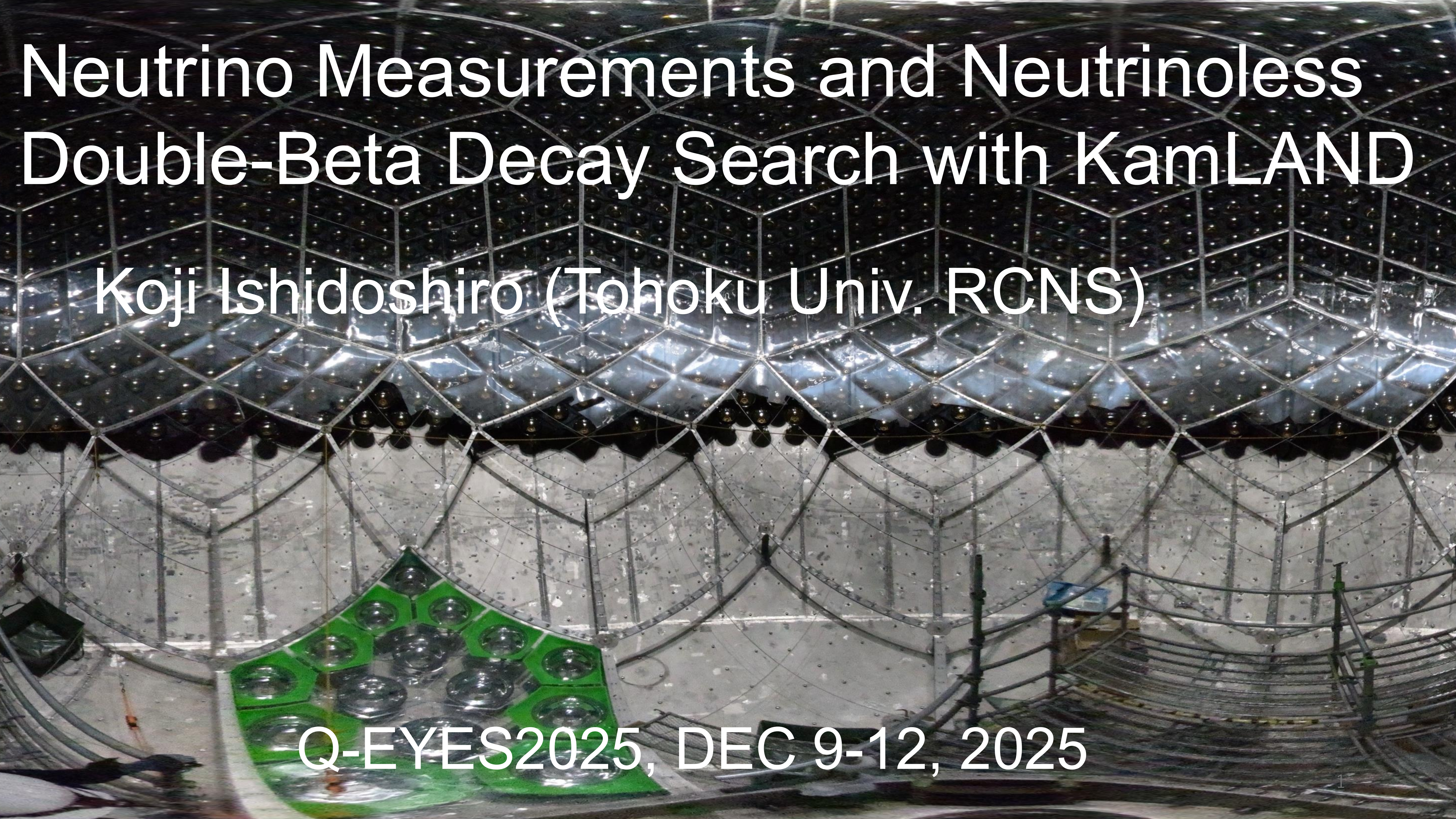
Neutrino Measurements and Neutrinoless Double-Beta Decay Search with KamLAND

Koji Ishidoshiro (Tohoku Univ. RCNS)



Q-EYES2025, DEC 9-12, 2025

Contents

KamLAND detector

Neutrino measurements

- Geological neutrinos
- Astrophysical neutrinos

Double-beta decay search

Future prospect

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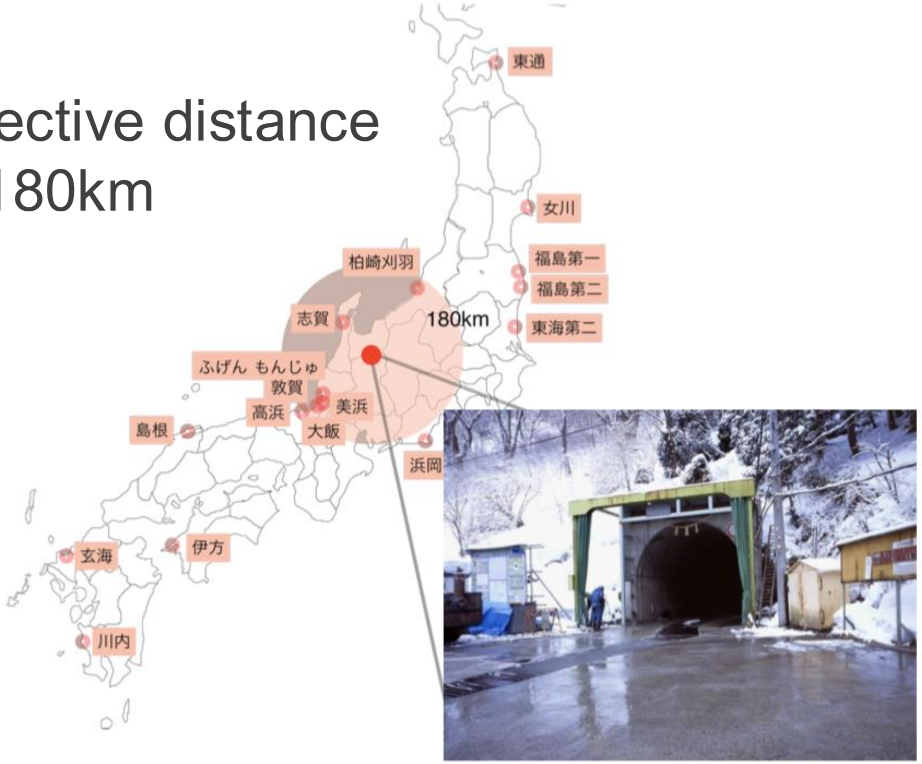
KamLAND

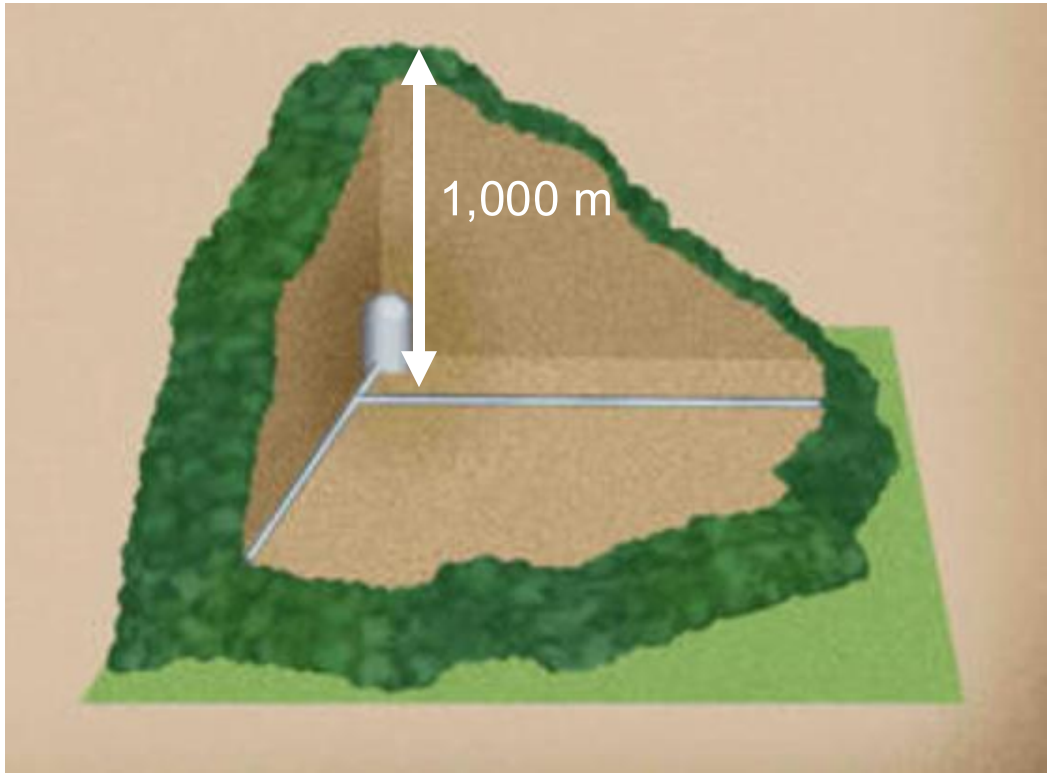
Kamioka Liquid Scintillator Anti-Neutrino Detector

located 1,000 m underground in Kamioka mine

Initial target: **reactor-ν measurements** with solar-ν problem

effective distance
~ 180km





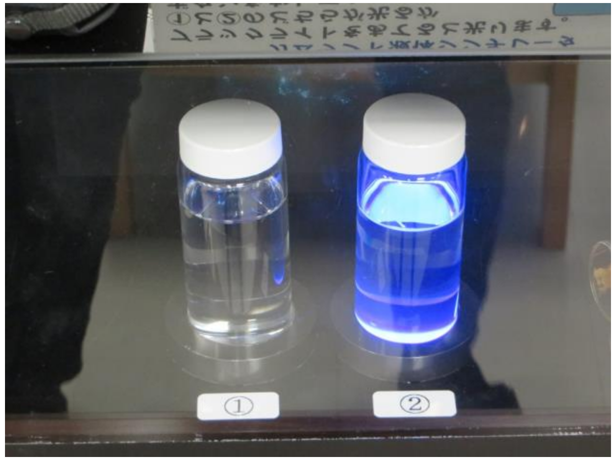
KamLAND

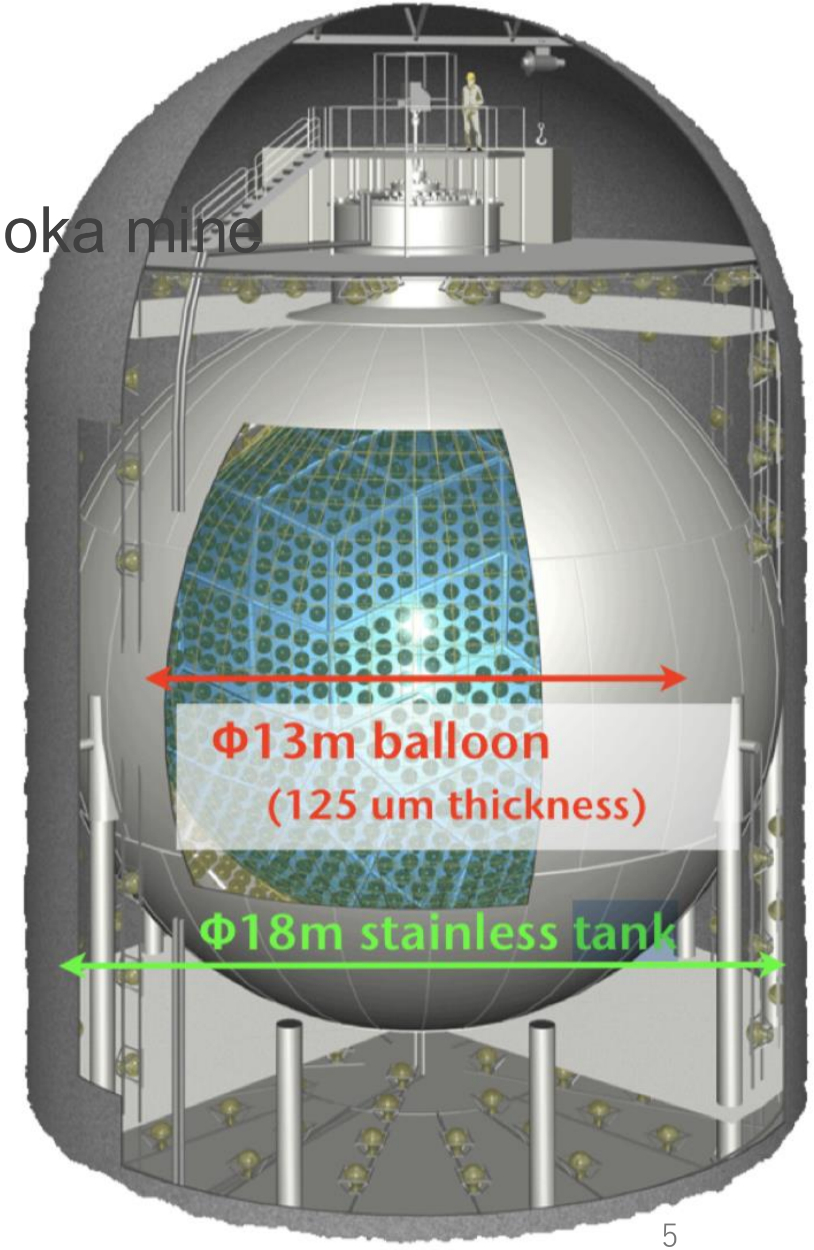
Kamioka Liquid Scintillator Anti-Neutrino Detector

located 1,000 m underground in Kamioka mine

Inner detector
- 1kt liquid scintillator
- 1,325 17inch
  + 554 20inch PMTs

Outer detector
- 3.2kt Cherenkov detector
- 140 20inchPMTs





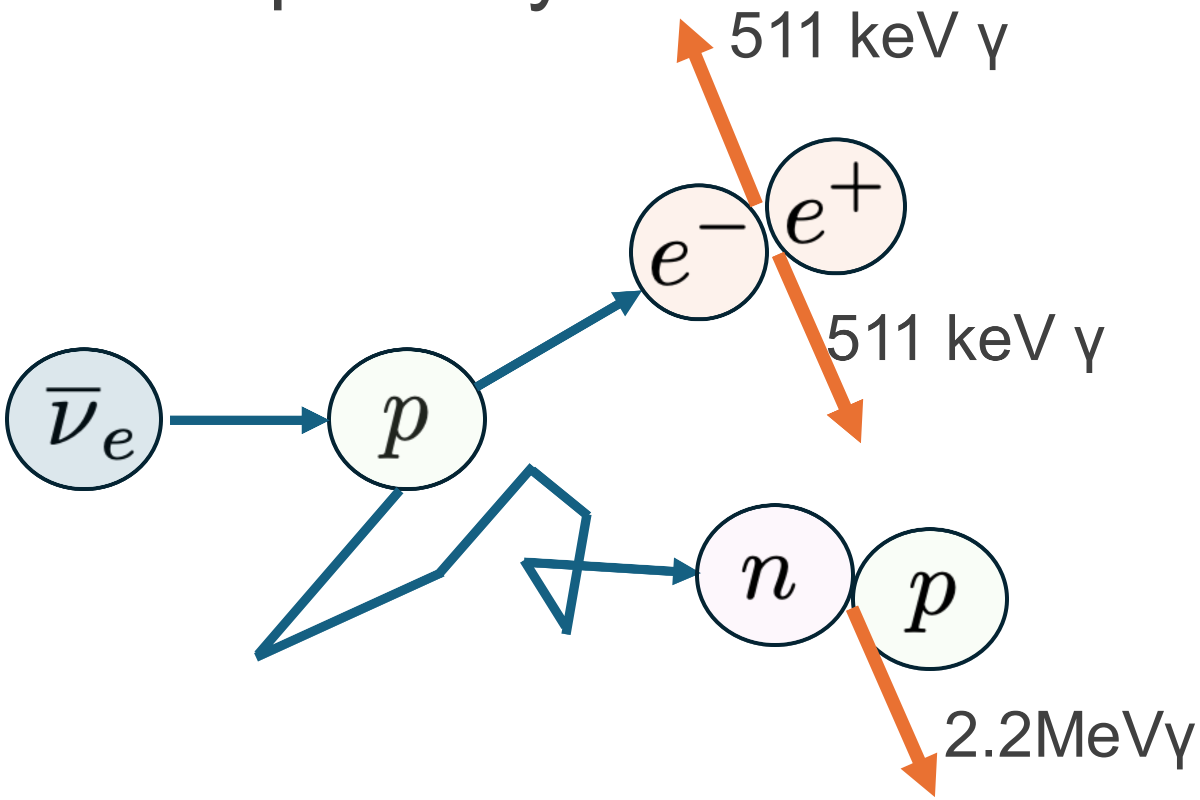
Material		Density	Volume ratio
Dodecane (N-12)	$C_{12}H_{26}$	0.749 g/cm^3	80%
Pseudocumene (1,2,4-Trimethylbenzene)	C_9H_{12}	0.875 g/cm^3	20%
PPO (2,5-Diphenyloxazole)	$C_{15}H_{11}NO$		1.36g/l
KamLAND-LS		0.77721 g/cm^3	

KamLAND collaboration

Around 50 members from Japan, the United States, the Netherlands, and Spain

Neutrino detection

Inverse-β decay



- Low-background measurements using spatial and temporal correlations
- 1.8 MeV energy threshold

Comparison with **SK**

Pros:

Better energy/vertex resolution

Lower threshold

due to the higher light yield of LS

Cons

Smaller volume

due to the difficulty of handling LS

A key feature of KL is its sensitivity to low-energy ν

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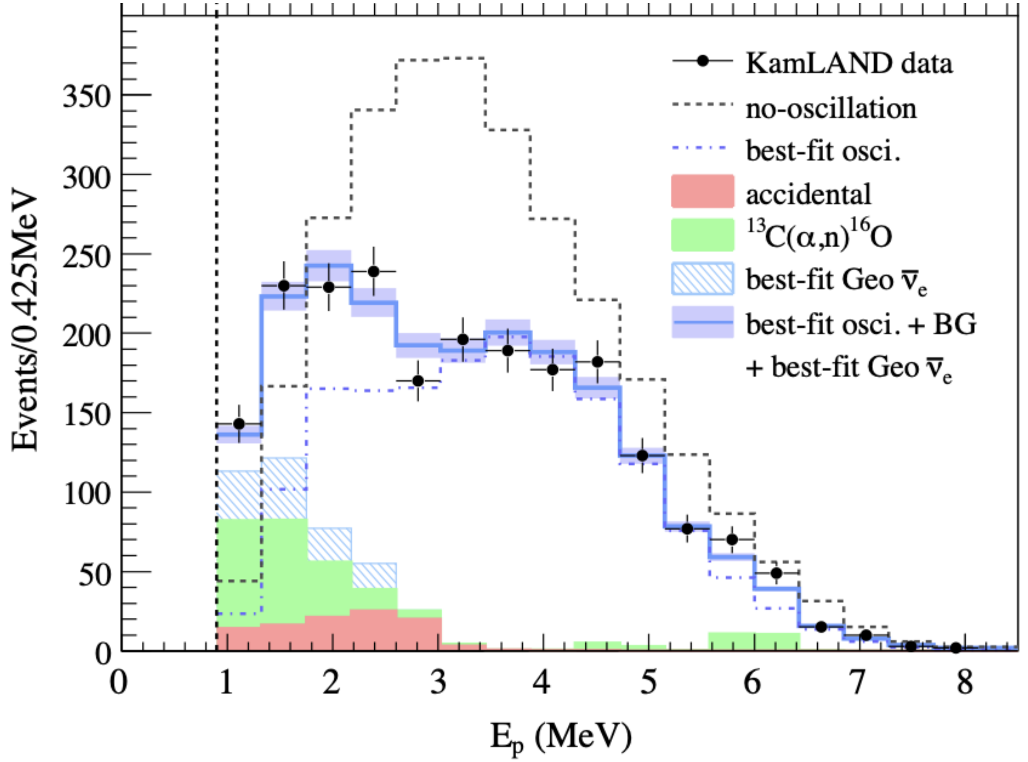
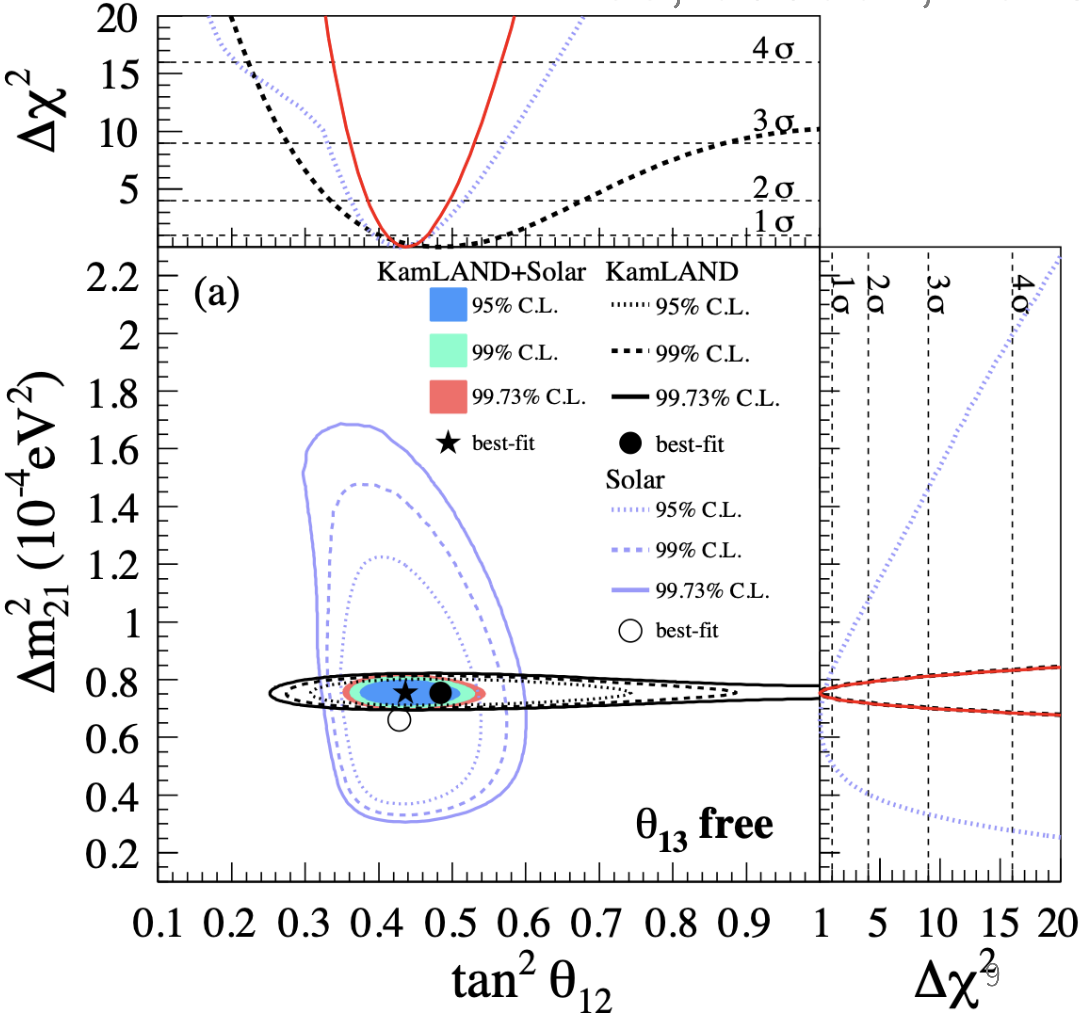
Reactor-ν measurements

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq 1 - \sin^2 2\theta \, \sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

PRD 83, 052002,2011



PRD 88, 033001, 2013

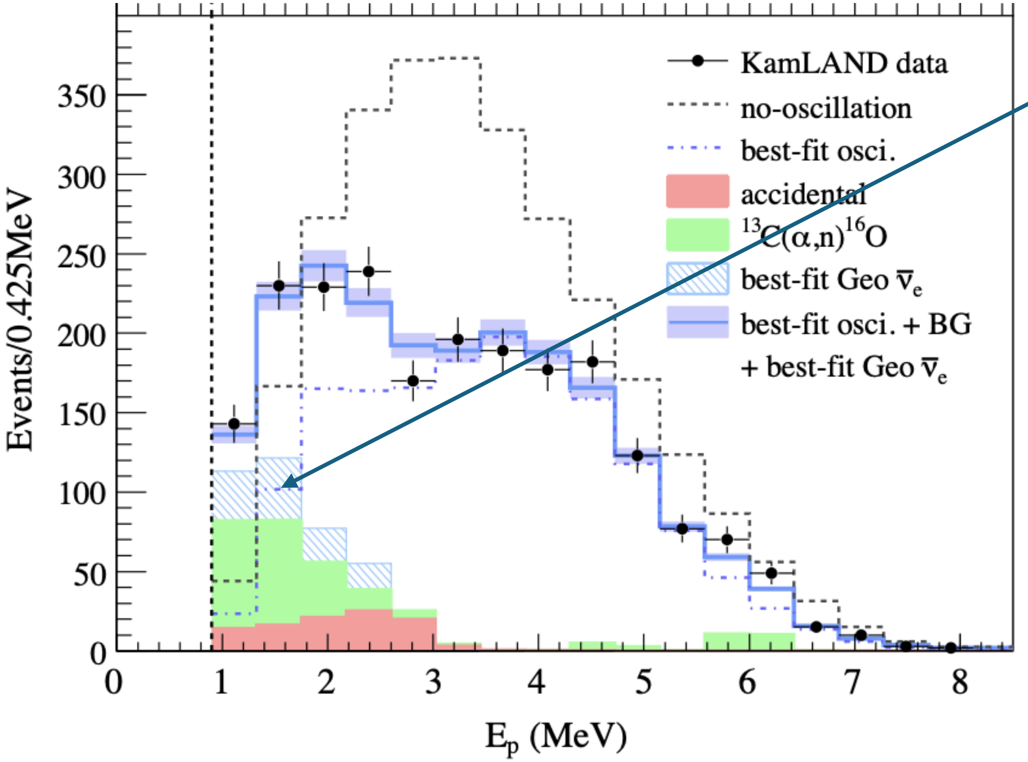


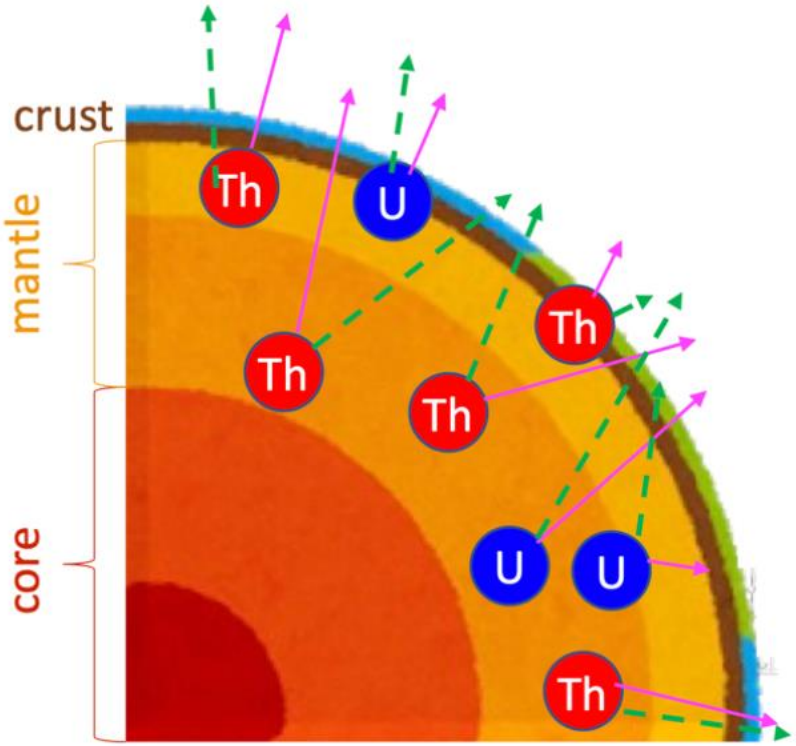
World-leading measurements of Δm_{21}^2 and θ_{12}

Geo-ν

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq 1 - \sin^2 2\theta \, \sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

PRD 83, 052002,2011





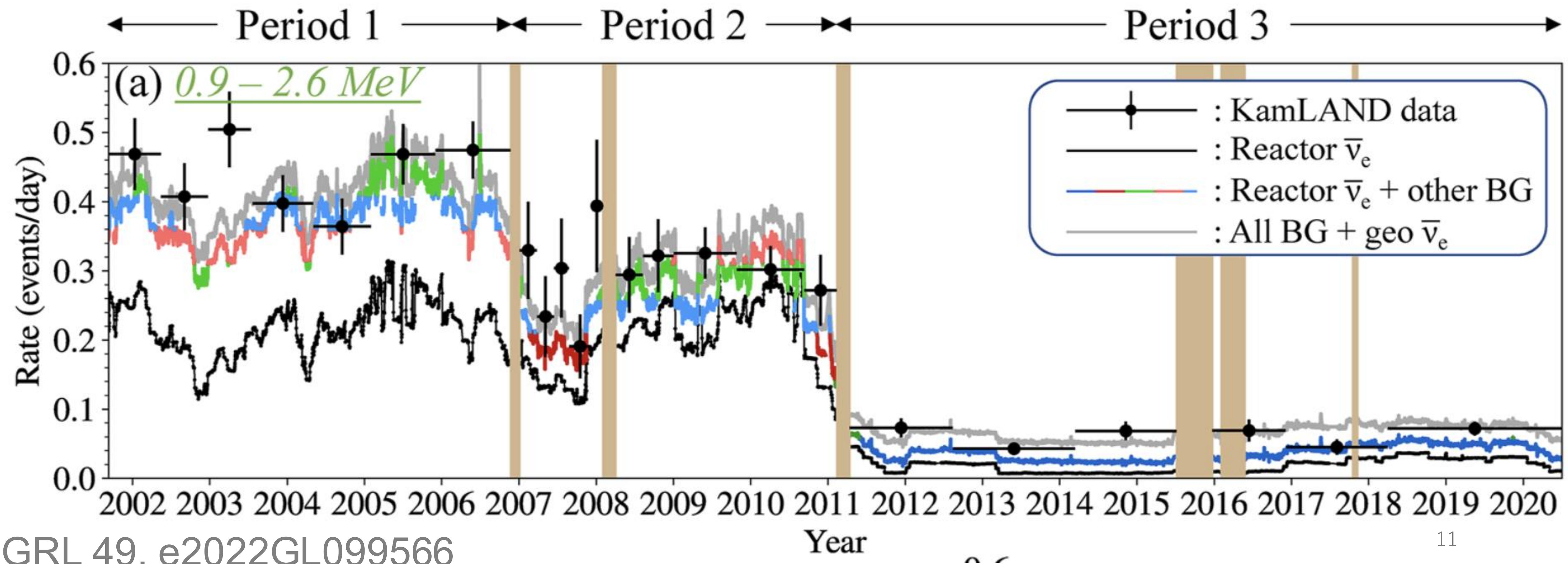
$$^{238}\mathrm{U} \to {}^{206}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.7\ \mathrm{MeV}$$

$$^{232}\mathrm{Th} \to {}^{208}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.7\ \mathrm{MeV}$$

$$^{40}\mathrm{K} \to {}^{40}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.311\ \mathrm{MeV}$$

Time trend of ν rate

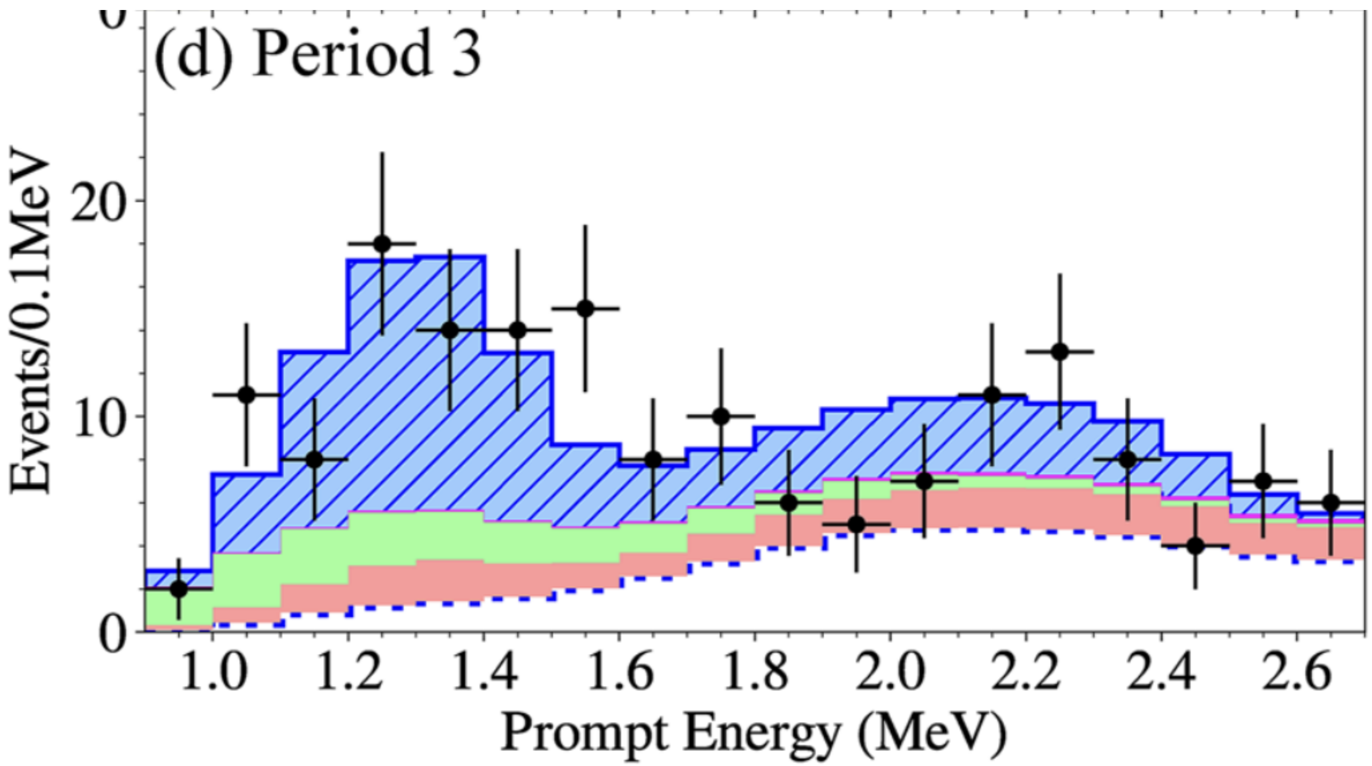
Today's signal (reactor-ν) is tomorrow's background



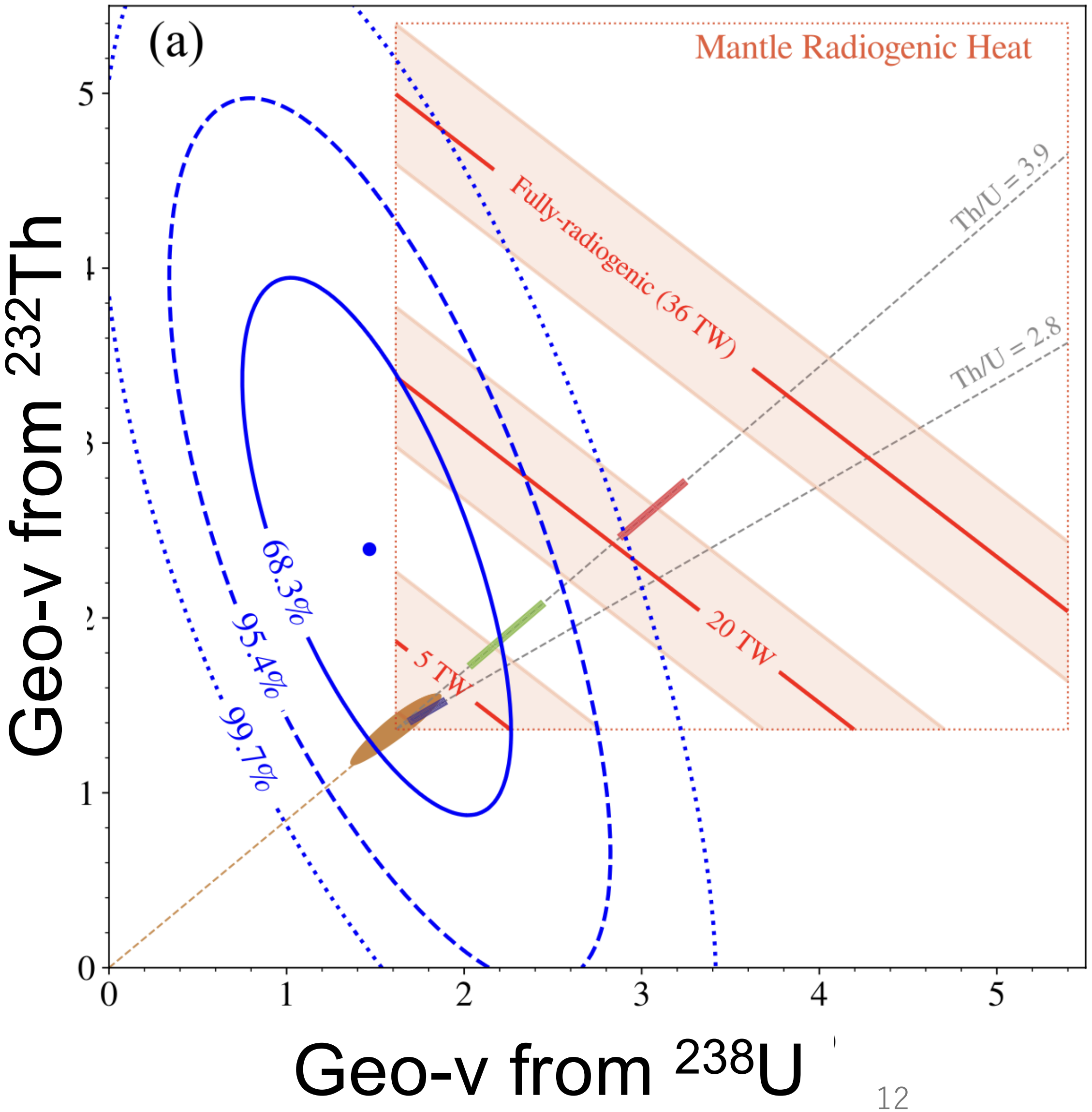
GRL 49, e2022GL099566

Geo-ν measurements

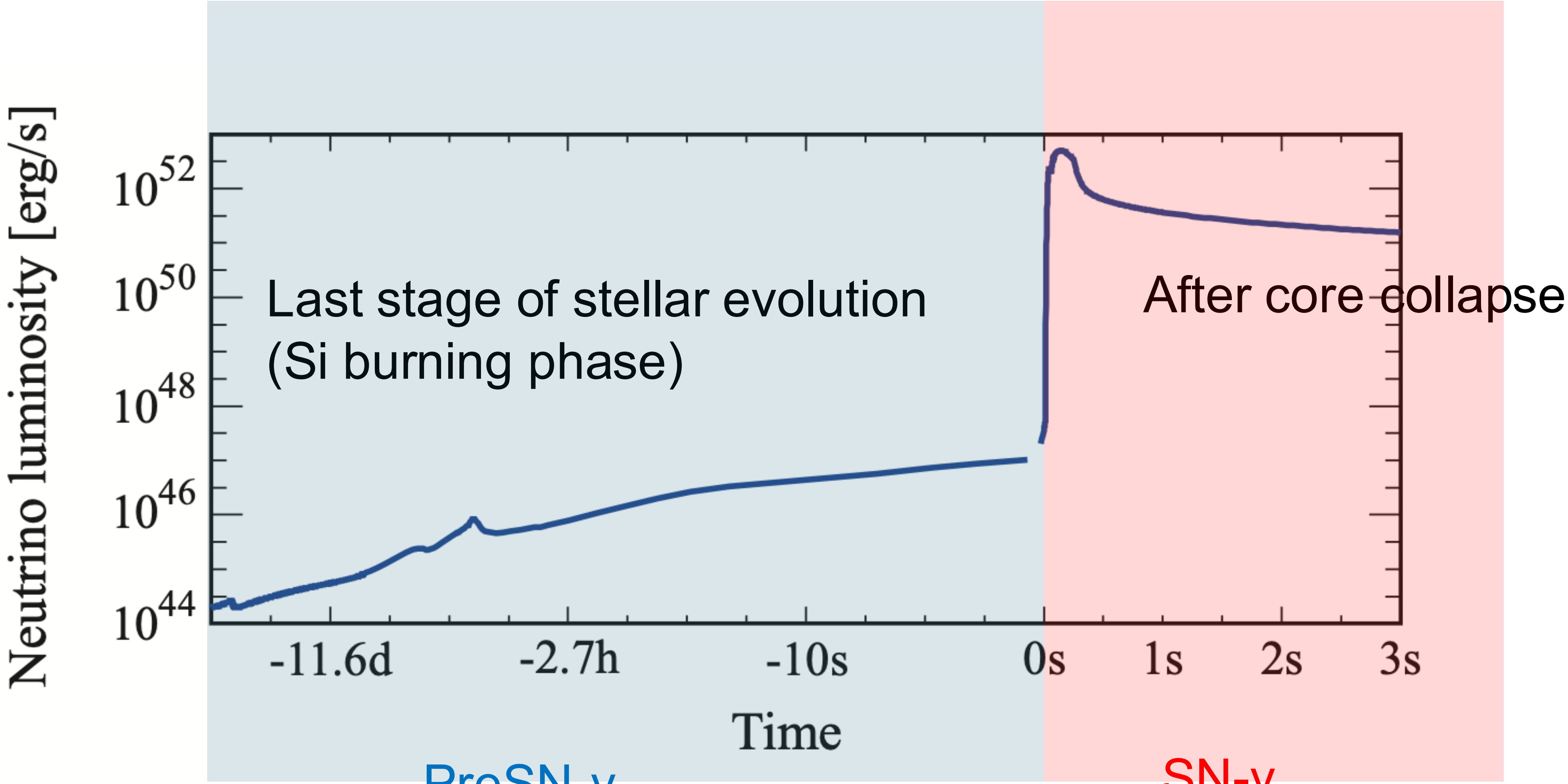
First observation of geo-ν (2005)
First constraint on both U and Th heat contributions (2022)



GRL 49, e2022GL099566



Astro-ν measurements



PreSN-ν

O(1MeV)

SN-ν

10sec. burst

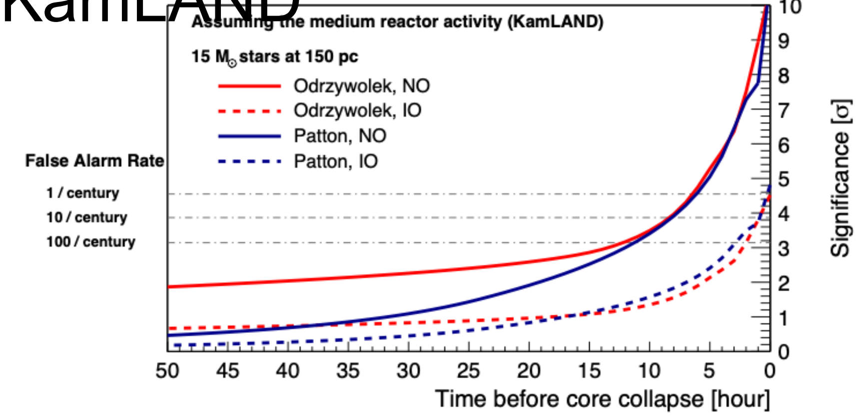
O(10MeV)

Astro-ν measurements

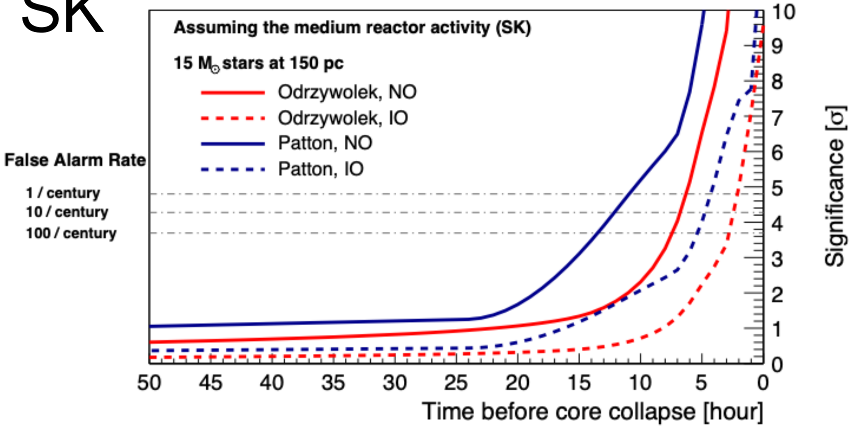
PreSN-ν

Combined alarm system with KL and SK

KamLAND

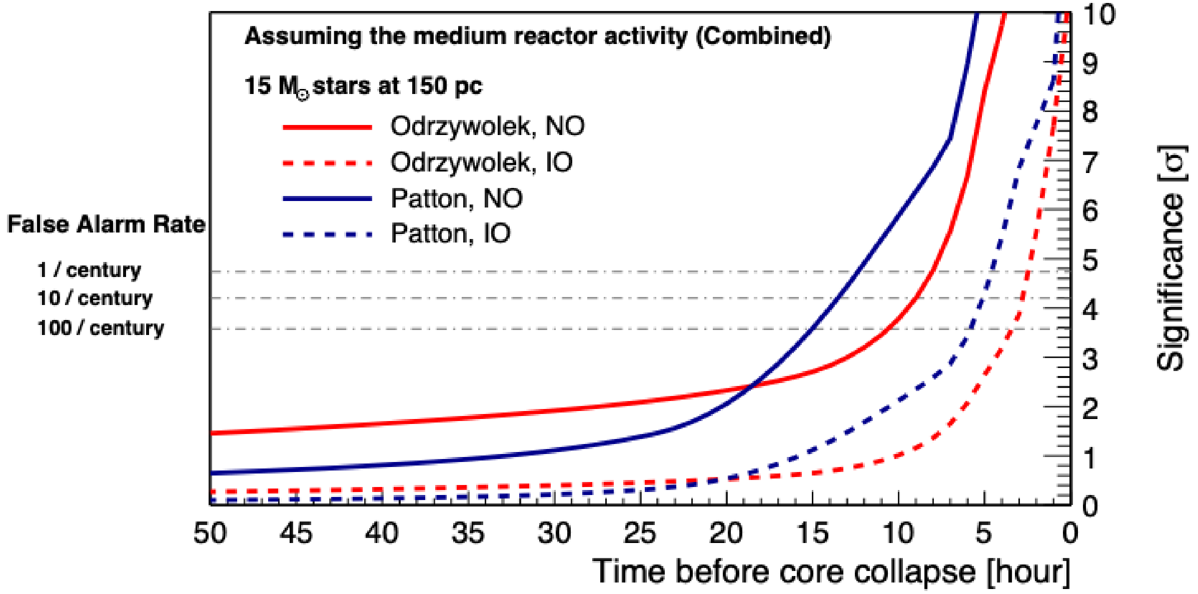


SK



Combined

S. Abe *et al* 2024 *ApJ* **973** 140



Astro-ν measurements

SN-ν

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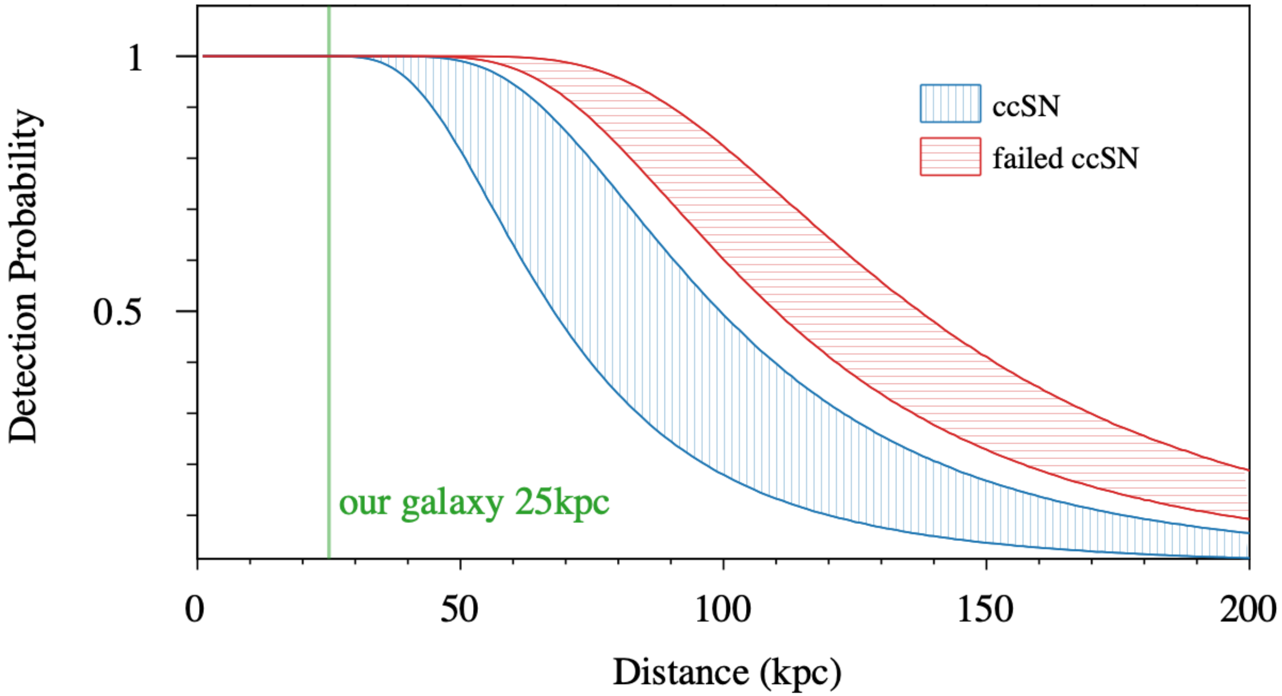
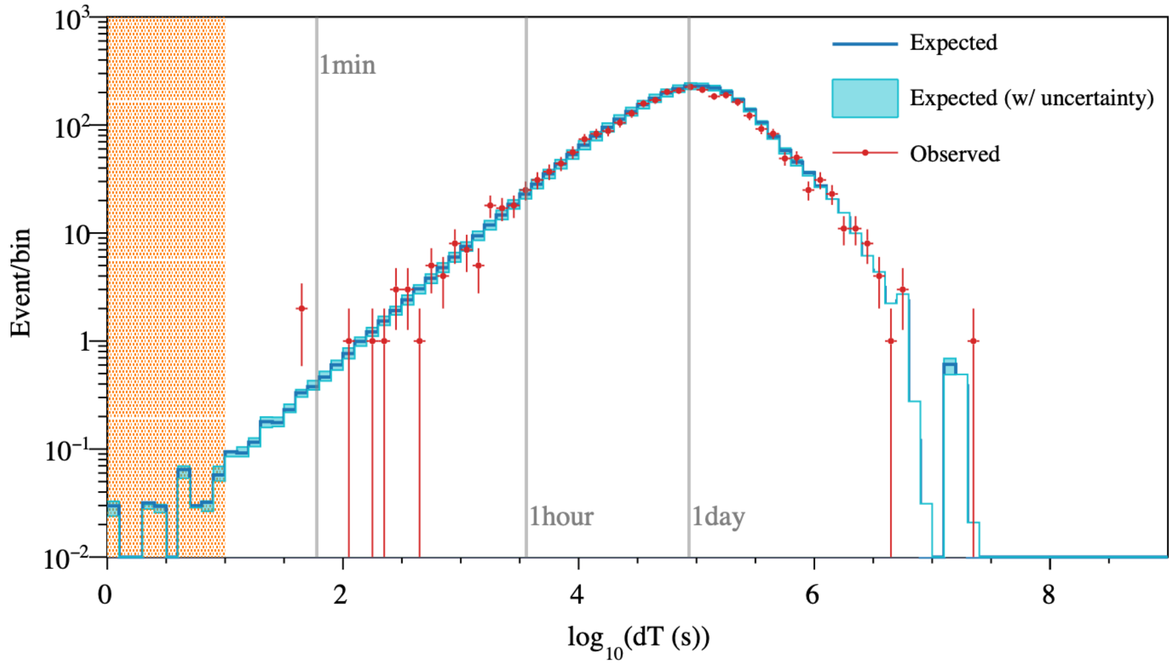


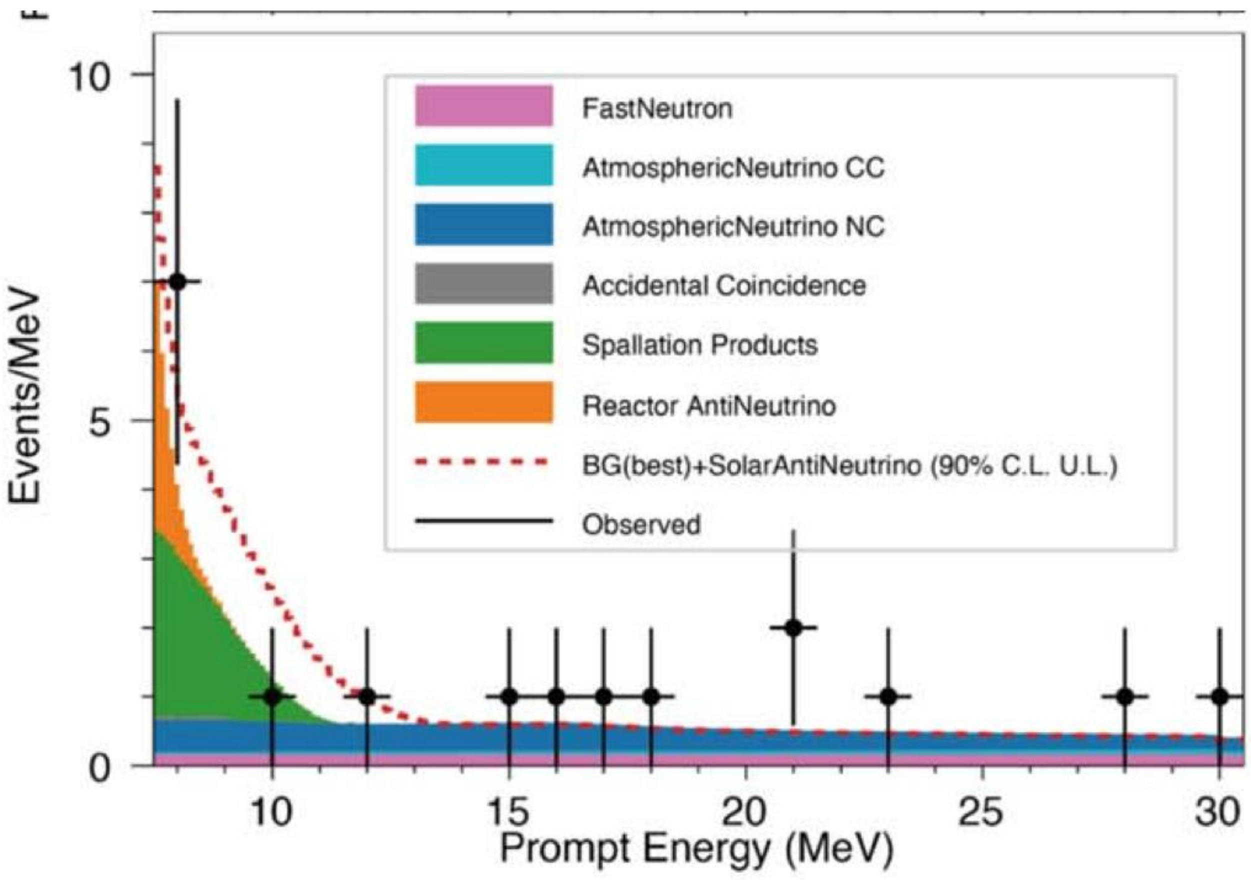


No detection → Star formation rate

$$<(17.5\text{–}22.7)\, M_\odot\, \mathrm{yr}^{-1}$$

Astro-ν measurements

Relic-ν



S. Abe *et al* 2022 *ApJ* **925** 14

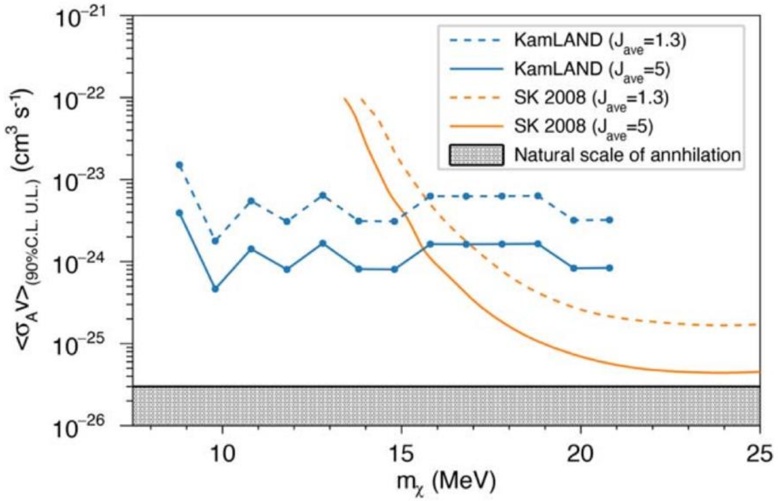
SNR-ν

Model	Expected Flux (cm^{-2}	F_{90} (cm^{-2} s^{-1})
Kaplinghat+00	19.9	74.5
Horiuchi+09 (6 M	5.8	61.6
Nakazato+15 (ma	5.1	108
Nakazato+15 (mi	2.2	105

Solar-$\bar{\nu}$

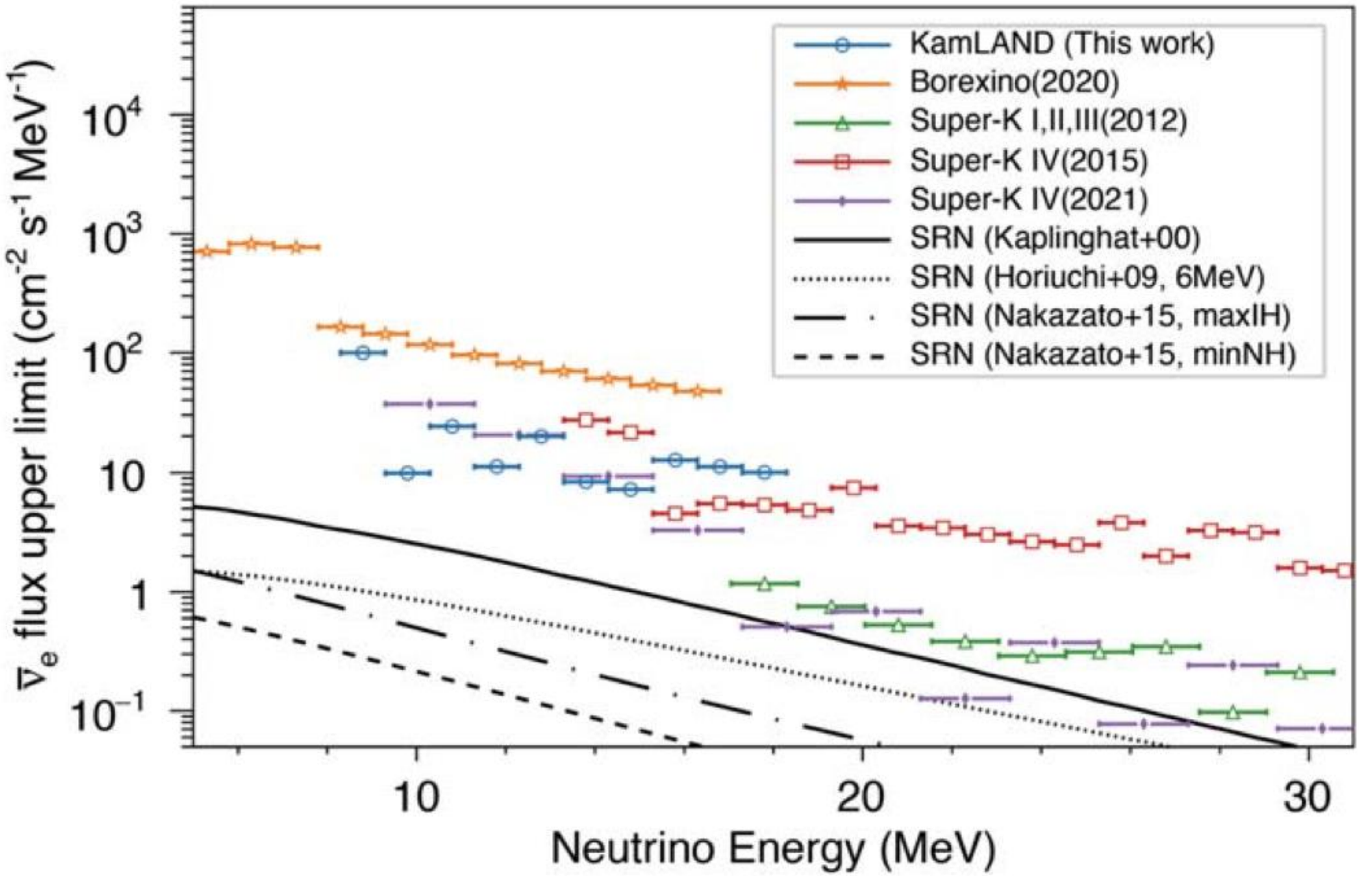
Conversion prob. < 3x 10^{-5}

Dark matter



Astro-ν measurements

Relic-ν



KamLAND provides unique for low-energy sensitivity for astro-ν

Ongoing works
- Analysis update with ML
- PBH analysis
- Joint constraints with SK
(not collaboration works)

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Motivation

Matter/anti-matter asymmetry in Universe

Sakharov conditions

- Baryon number violation (Baryogenesis)
- C and CP violation
- Departure from thermal equilibrim

Sakharov conditions: not satisfactorily fulfilled in SM

Beyond SM

Leptogenesis Strong candidates of Baryogenesis:

Decay of heavy right-handed neutrino: key in Leptogenesis

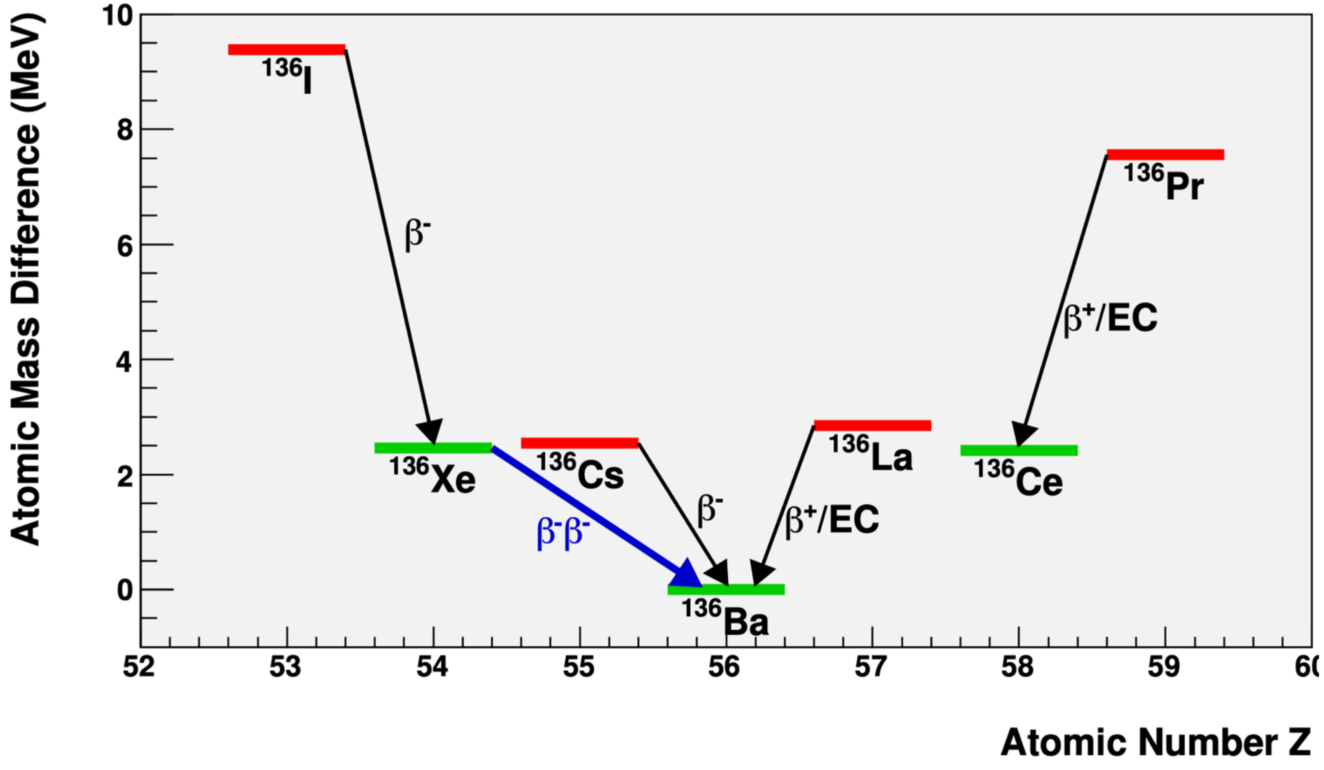
is predicted from the Majorana nature of neutrino

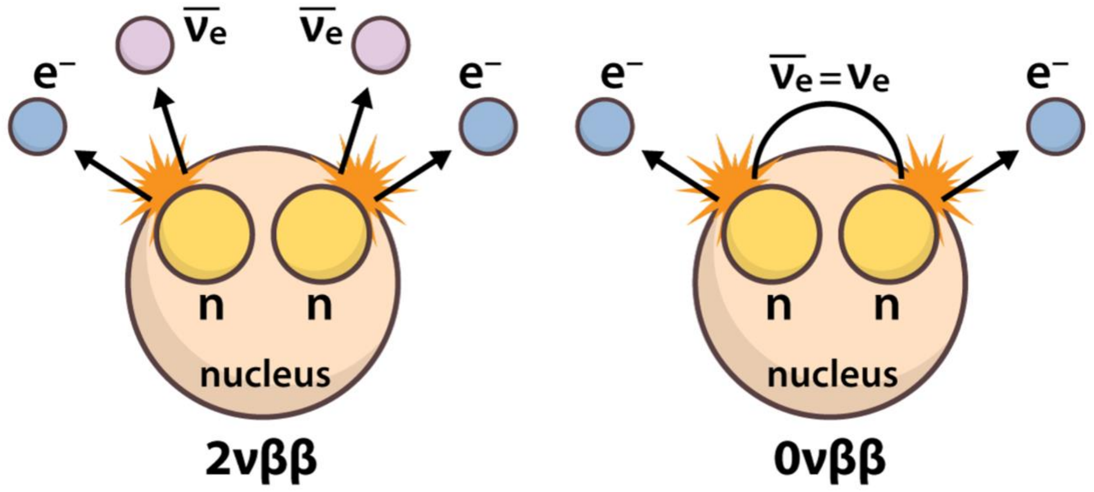
$$\nu_M \equiv \nu_L + (\nu_L)^c \qquad \nu_M^c = \nu_M$$

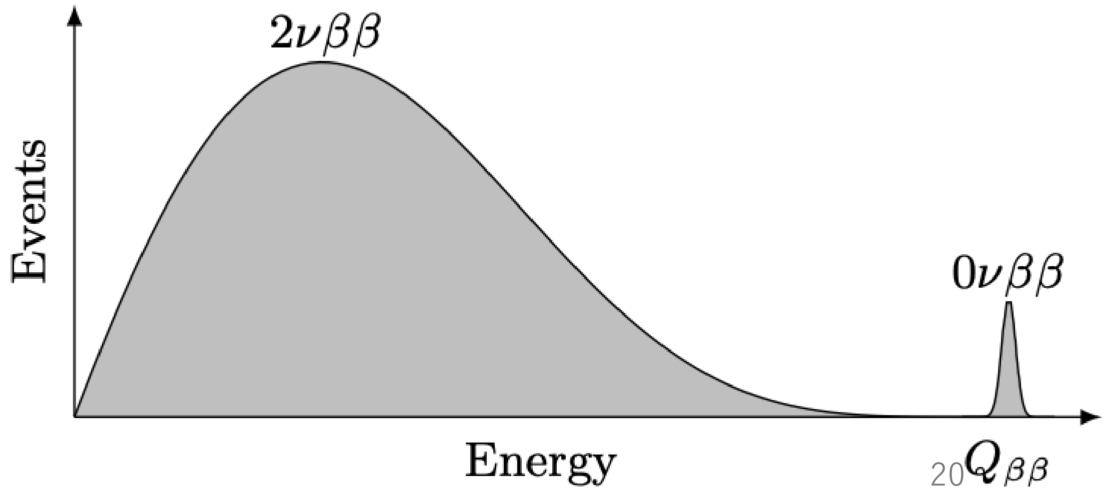
Double-β decay

Neutrinoless double-β (0ν2β) decay

: probe of the Majorana nature of neutrino





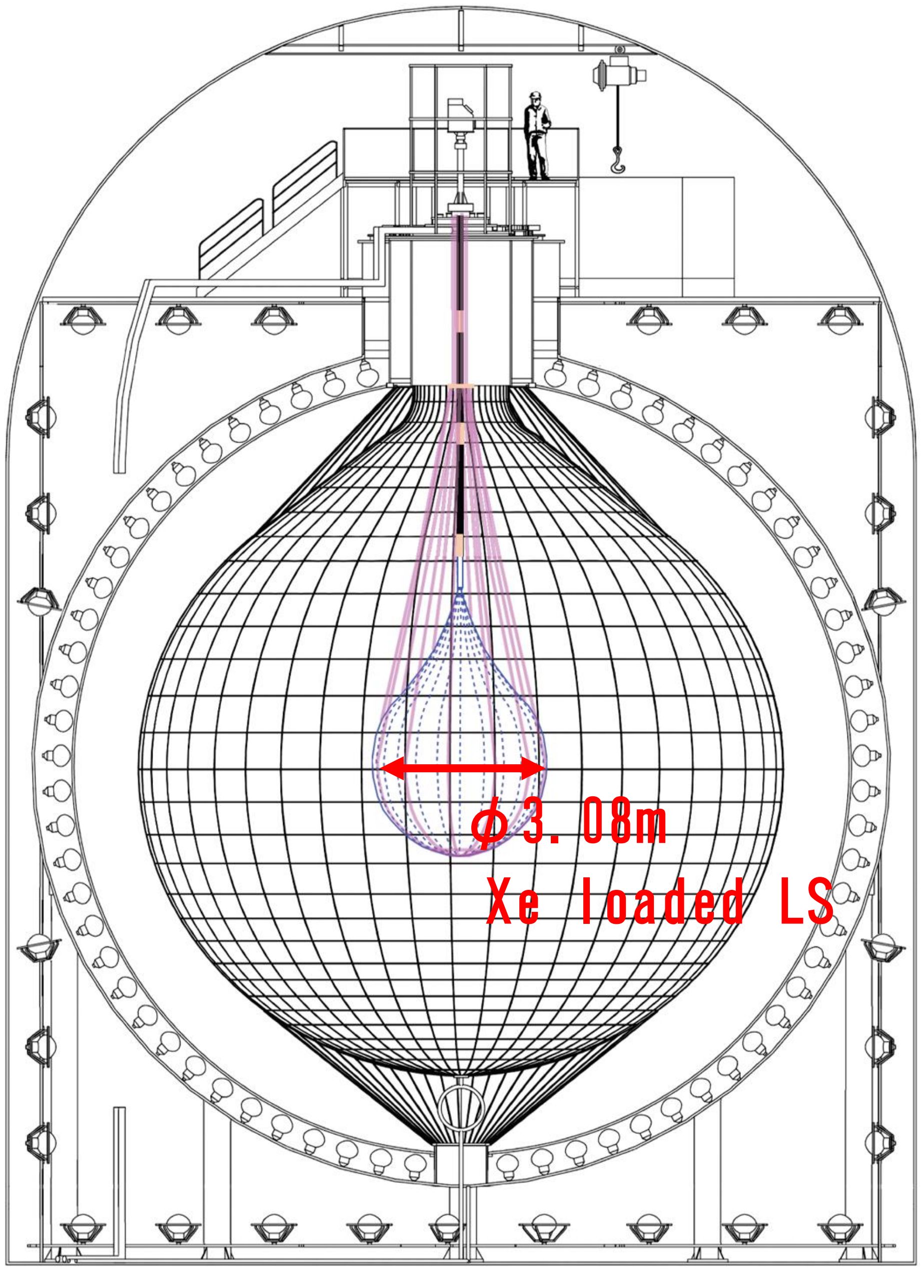


KamLAND-Zen

Target: 0ν2β decay of ^{136}Xe to probe the **Majorana nature of neutrinos**

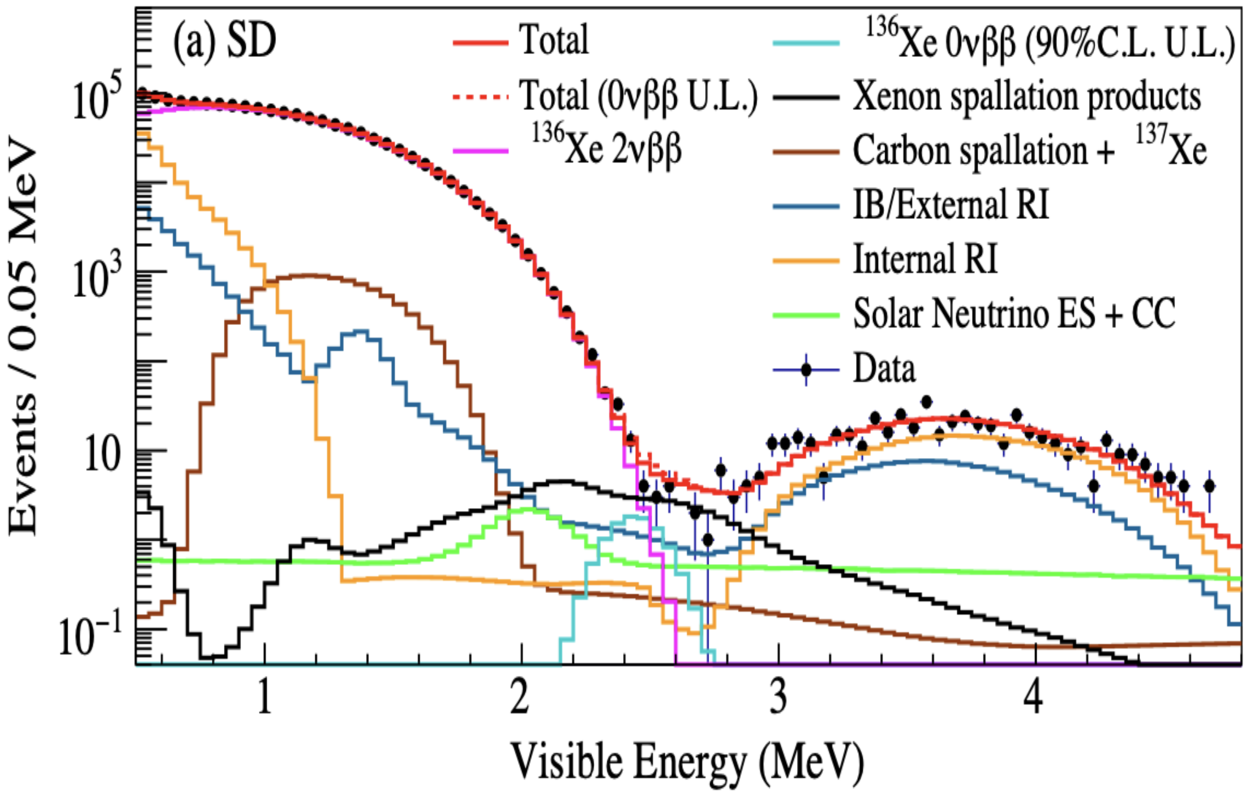
Features:

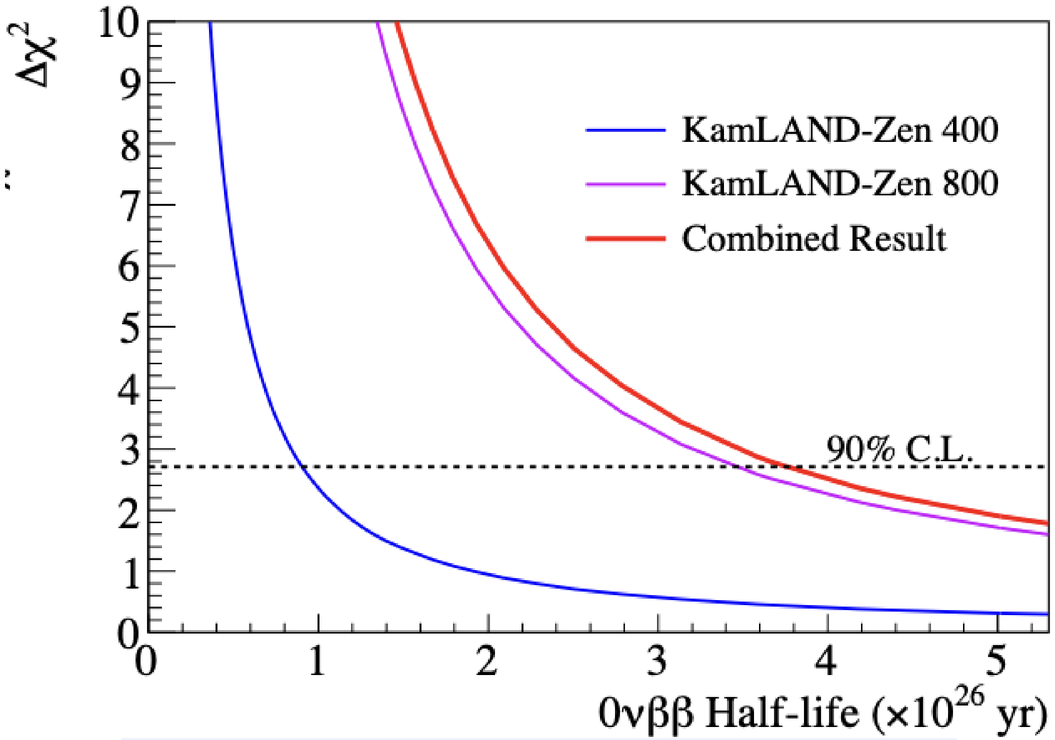
- Use of already **developed low-radioactive detector**
- High scalability
- Possibility of Xe purification
- On/off-measurements



Final result

Zen 800: Jan. 2019 – Jan. 2024 with enriched Xe 745 kg

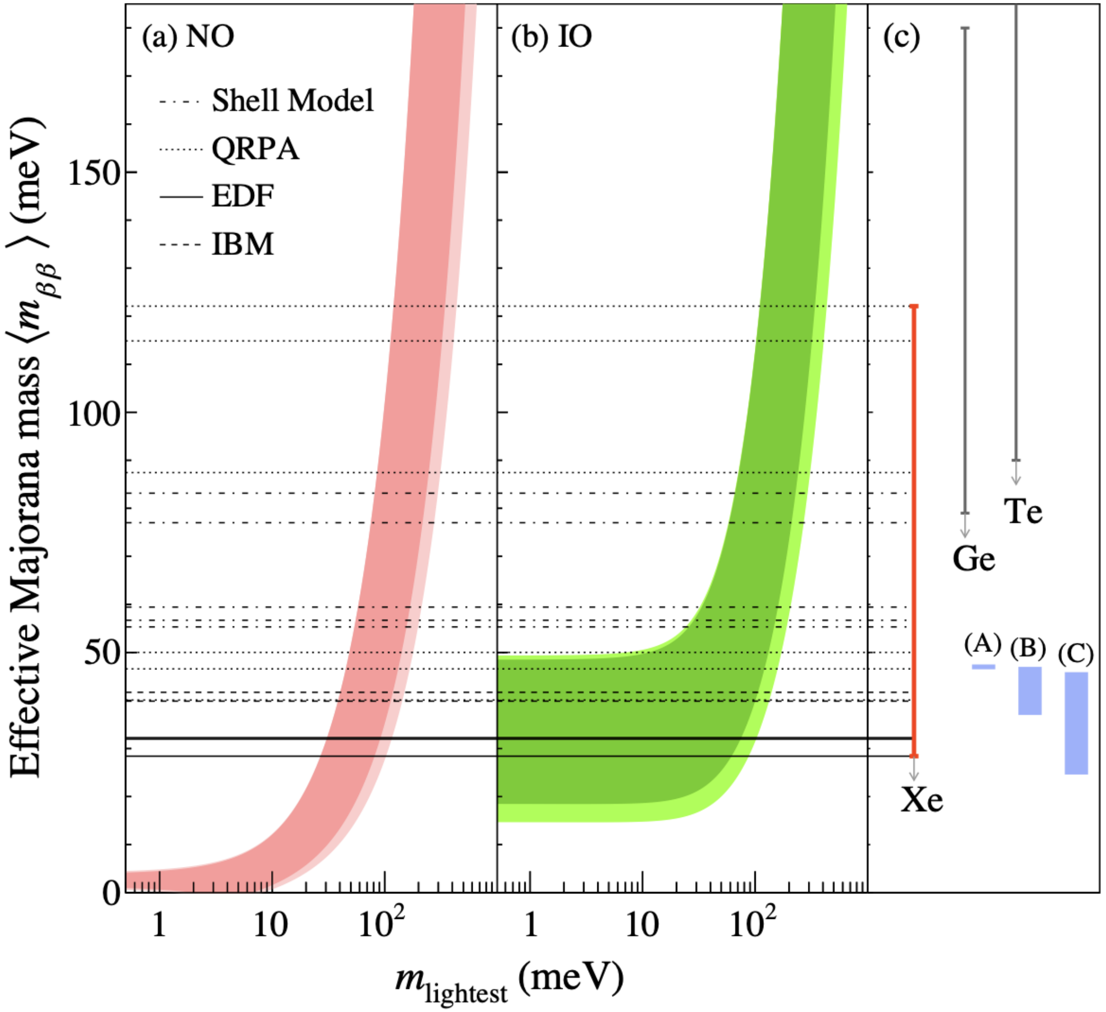




Zen 400	$T^{0\nu}_{1/2} > 0.9 \times 10^{26}$ yr
Zen 800	$T^{0\nu}_{1/2} > 3.4 \times 10^{26}$ yr
Combined	$\mathbf{T^{0\nu}_{1/2} > 3.8 \times 10^{26}}$ **yr**

Final result

Zen 800: Jan. 2019 – Jan. 2024 with enriched Xe 745 kg



	Ref.	$M^{0\nu}$	$\langle m_{\beta\beta} \rangle$ (meV)
Shell model	[34]	2.28, 2.45	59.4, 55.3
	[35]	1.63, 1.76	83.1, 77.0
	[36, 37]	2.39	56.7
QRPA	[38]	1.55	87.4
	[39]	2.91	46.6
	[40]	2.71	50.0
	[41]	1.11, 1.18	122, 115
	[42]	3.38	40.1
EDF theory	[43]	4.20	32.3
	[44]	4.77	28.4
	[45]	4.24	32.0
IBM	[46]	3.25	41.7
	[47]	3.40	39.9

$$\langle m_{\beta\beta} \rangle < (28 - 122)\,\text{meV} \quad (90\%\ \text{C.L.})$$

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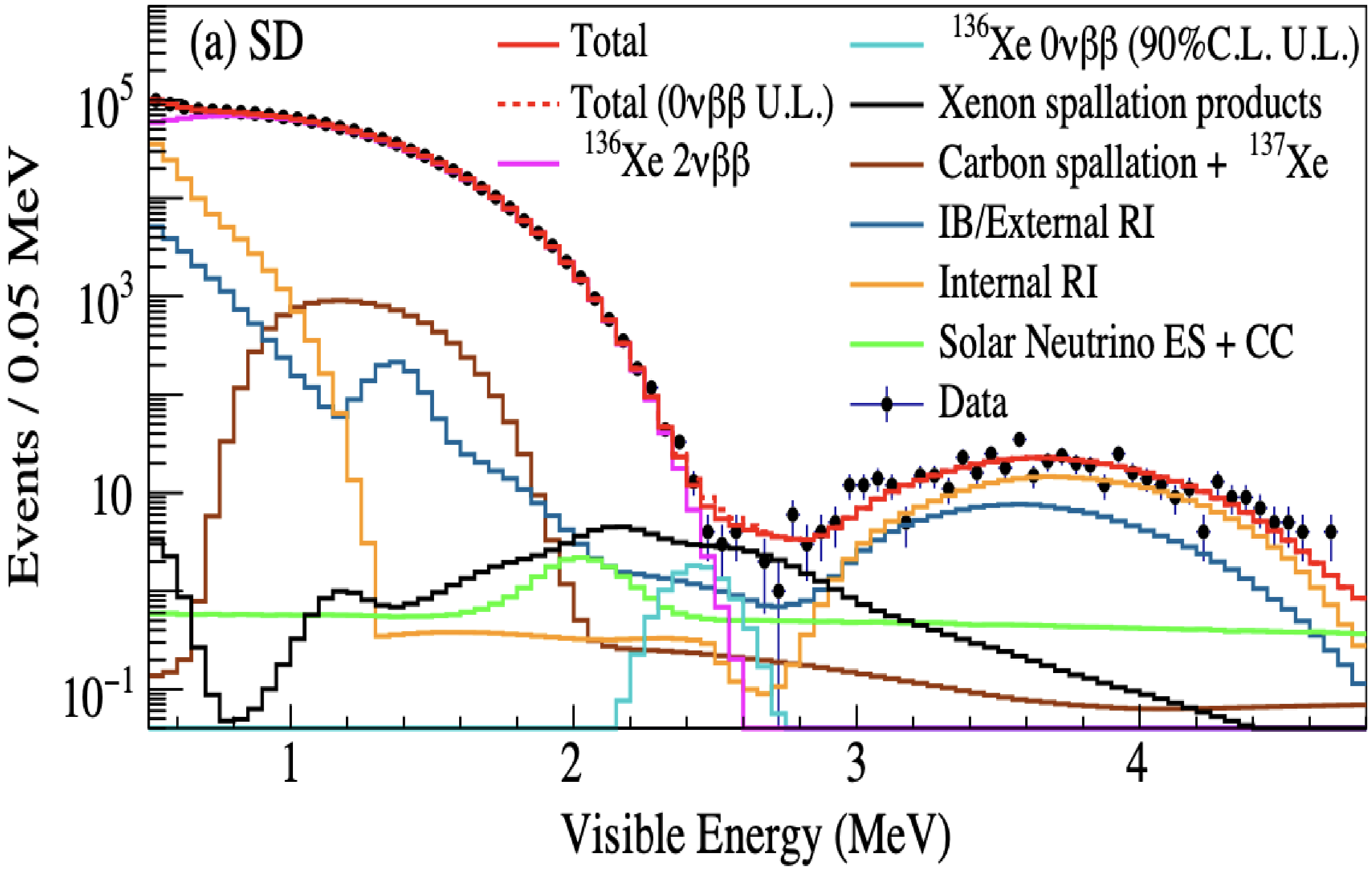

Background	Estimated	Best-fit
^{136}Xe $2\nu\beta\beta$	-	27.60
Residual radioactivity in Xe-LS		
^{238}U series	0.08 ± 0.01	0.08
^{232}Th series	-	1.35
External (Radioactivity in IB)		
^{238}U series	-	6.61
^{232}Th series	-	0.04
Neutrino interactions		
^{8}B solar ν e^- ES	3.57 ± 0.09	3.57
Spallation products		
Long-lived	17.82 ± 1.30 †	19.39
^{10}C	0.00 ± 0.05	0.00
^{6}He	0.54 ± 0.27	0.56
^{137}Xe	0.72 ± 0.60	0.72

KamLAND2-Zen

KamLAND2-Zen

Improvements of energy resolution (4% -> 2%)
(high-QE 20inch PMT, brighter LS, collecting mirrors)

Scintillating balloon
(214Bi tag)

New electronics, ML
(neutron detection, ML-based PID)

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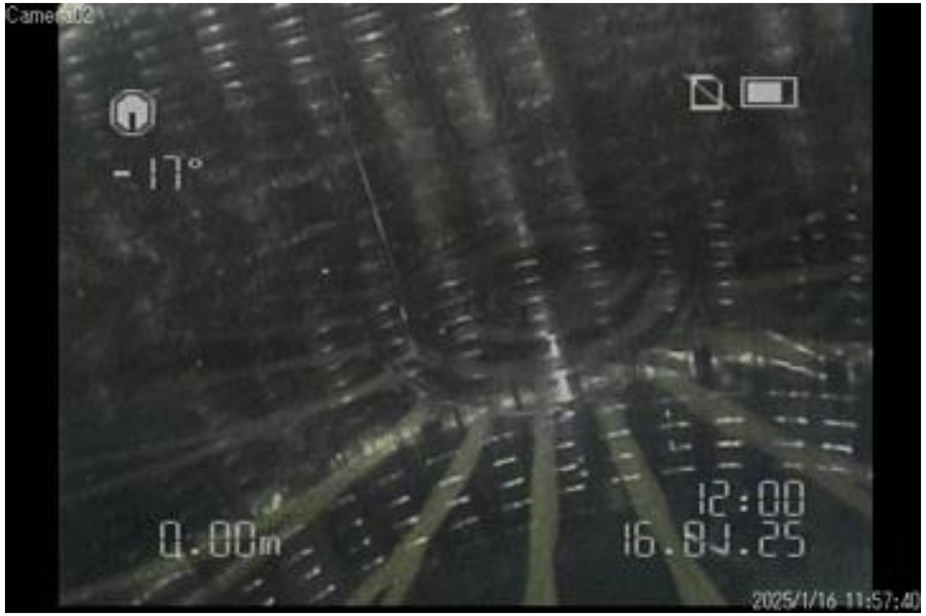
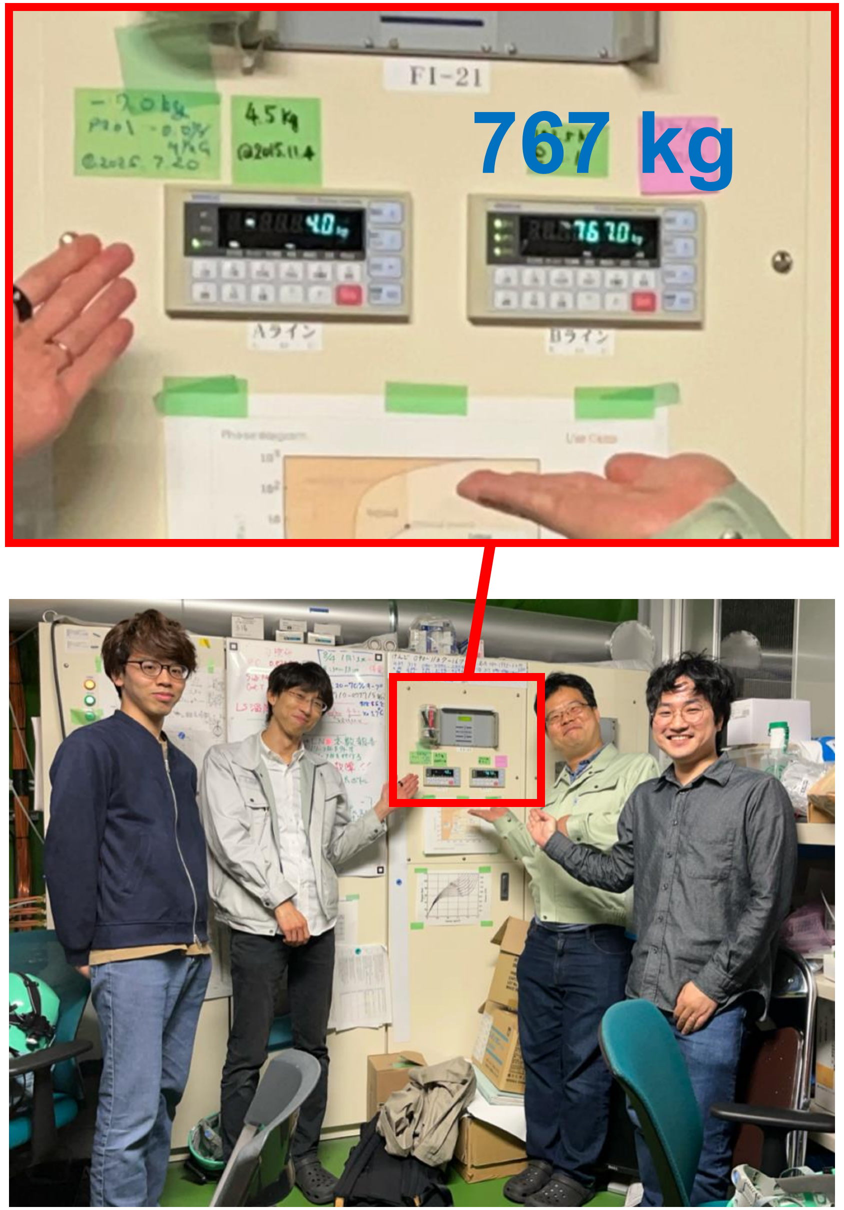
KamLAND2-Zen

Dismantling

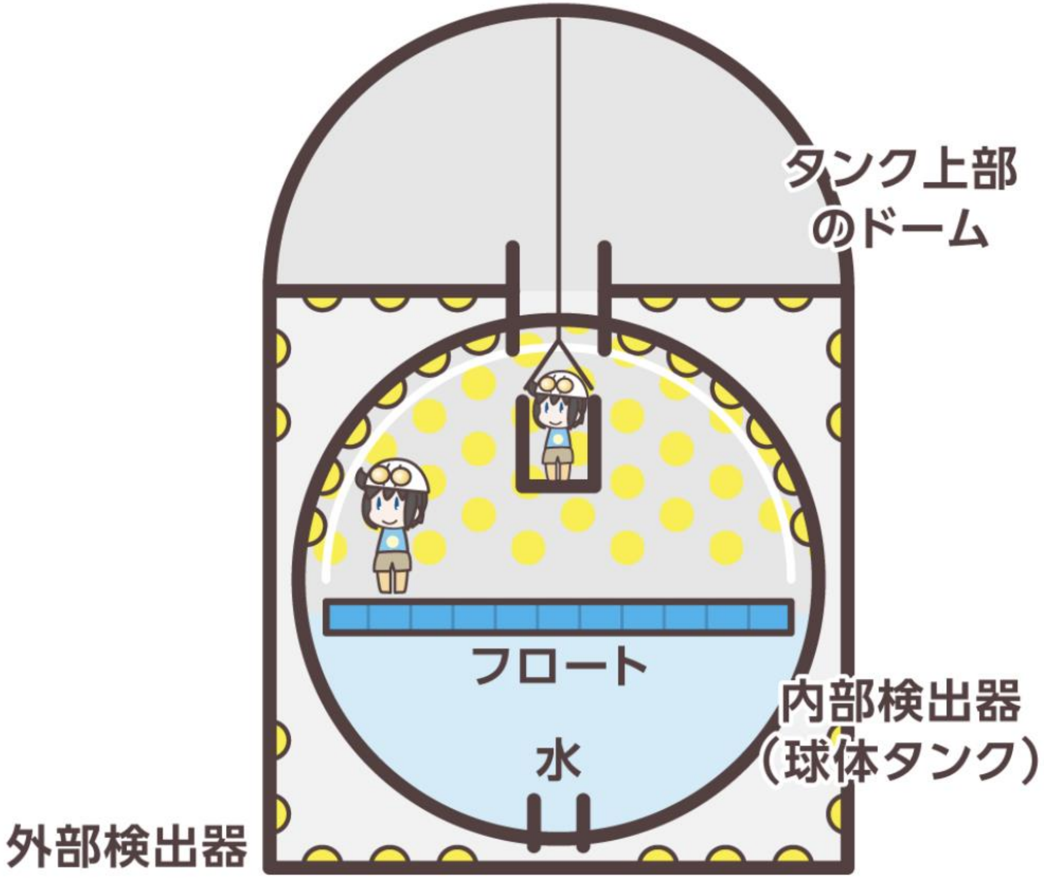
Stop KamLAND DAQ: Aug. 2024
(Enriched)Xe recovery and distillation: Jul. 2025
LS draining: Jan. 2025





Dismantling

Removal of PMT: Oct. 2025



Next

Installation of new PMTs starting in autumn 2026
Filling with LS starting in summer 2027
Restart of DAQ in spring 2028

KamLAND2 will start in FY2027

Installation XeLS and its housing 2028-2029

KamLAND2-Zen will start in FY2028-2029??

Summary

KamLAND: world-leading results

- low-energy neutrino measurements
- neutrino-less double β decay search

KamLAND2: will start in FY2027

Further possibilities

- muon puzzle
- Super-KamLAND??