Recent Results from KamLAND-Zen and Future Prospects

Dr. Ömer Penek

on behalf of the KamLAND-Zen Collaboration

15th Conference on the Intersections of Particle and Nuclear Physics CIPANP
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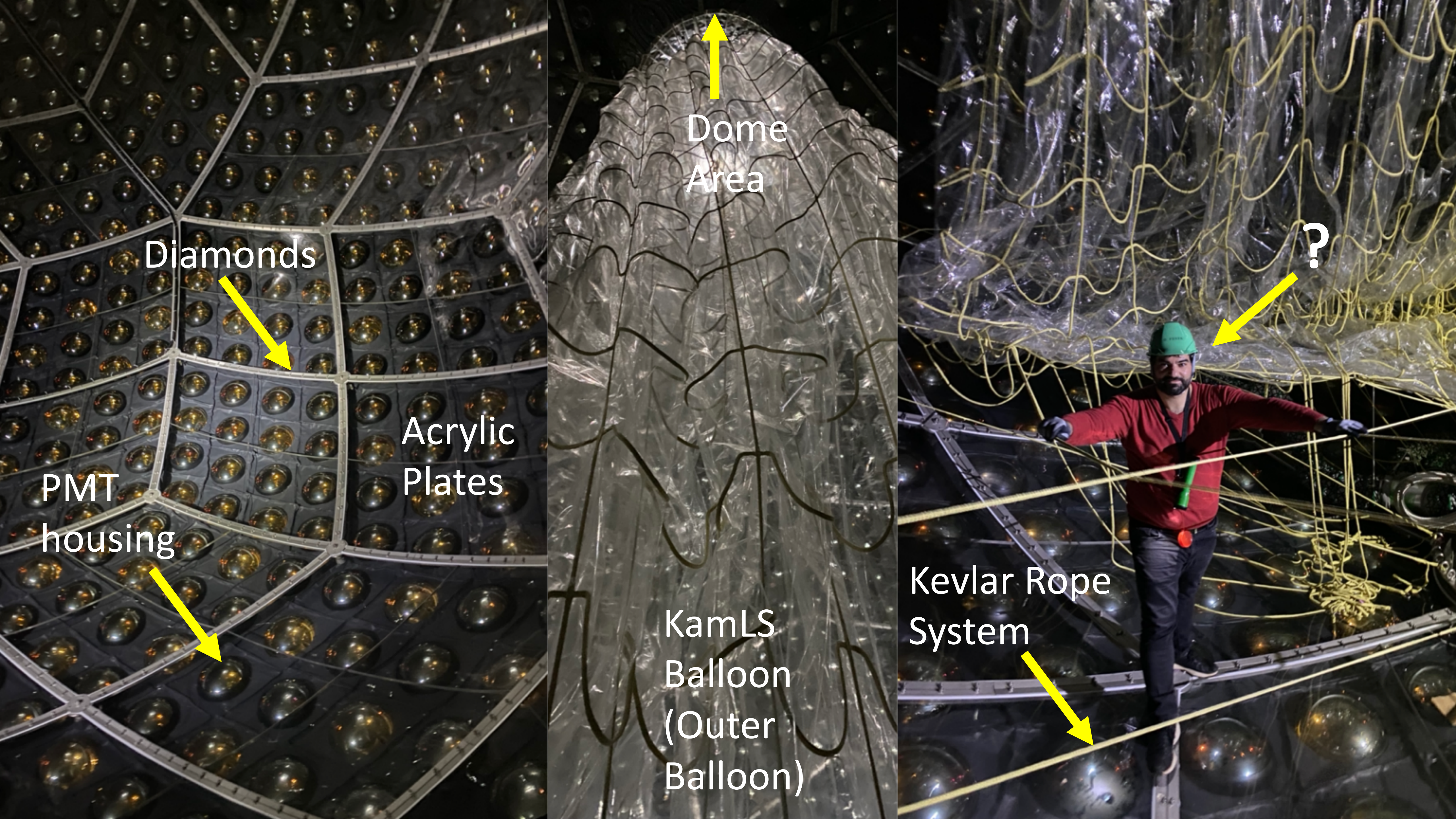

Diamonds
Acrylic Plates
PMT housing
Dome Area
KamLS Balloon (Outer Balloon)
?
Kevlar Rope System

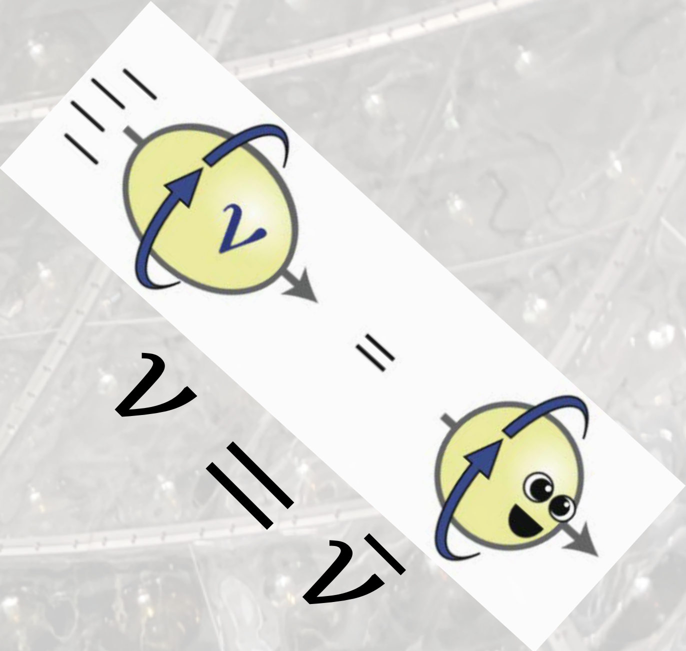
Contents

- Motivation: $0\nu\beta\beta$ and KamLAND-Zen
- From Event Selection to Spectral Analysis
- KamLAND2-Zen
- Summary / Outlook

$0\nu\beta\beta$

Ettore Majorana
Teoria simmetrica dell'elettrone e del positrone
(A symmetric theory of electrons and positrons) **.**
Il Nuo vo Cimento, 14 : 17 –184, 1937.

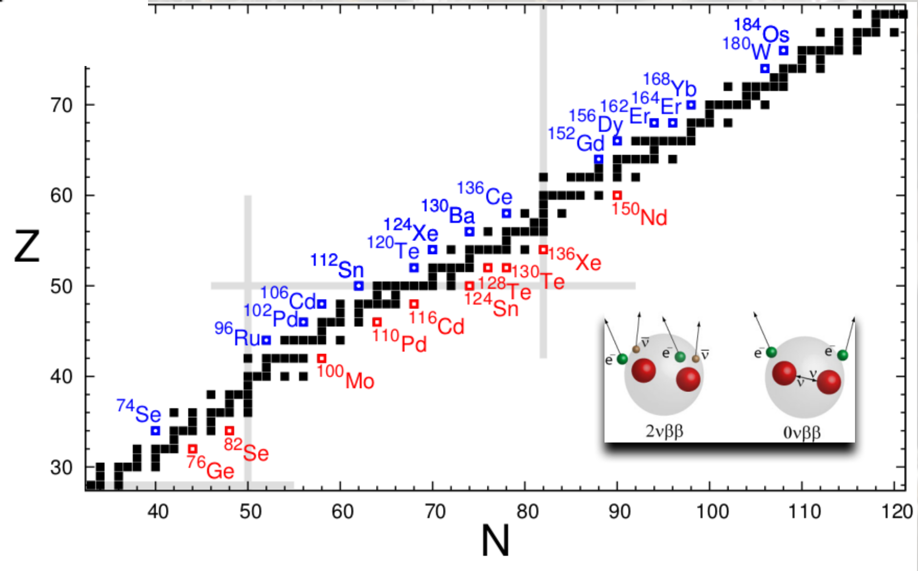
It follows from the above assumptions that in vacuum a neutrino can be transformed into an antineutrino and vice versa. This means that the neutrino and antineutrino are "mixed" particles, i.e., a symmetric and antisymmetric combination of two truly neutral Majorana particles ν_1 and ν_2 of different combined parity.[5]



From F. Šimkovic Neutrino2022

Bruno Pontocorvo Majorana
Inverse beta processes and nonconservation of lepton charge Zhur. **Eksptl'. I Teoret. Fiz. 34, 247 (1958)**
➔ Lepton Number Violation

Candidates ➔



$0\nu\beta\beta$

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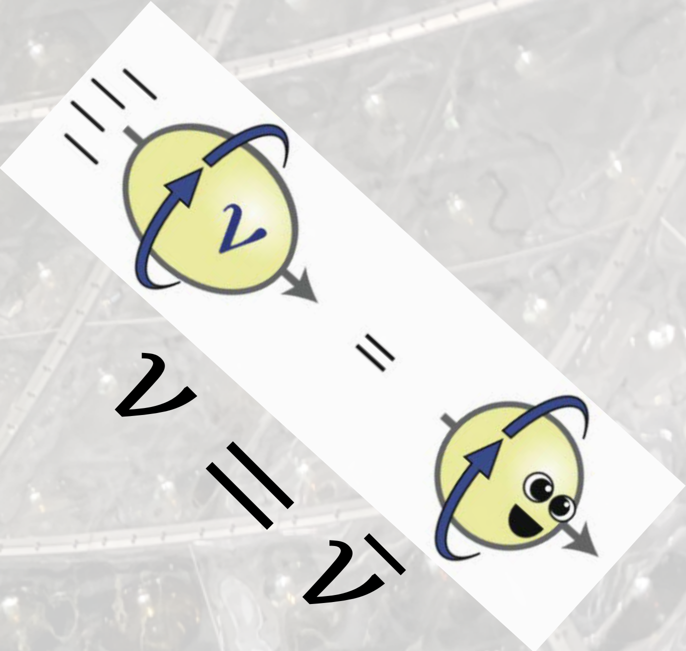

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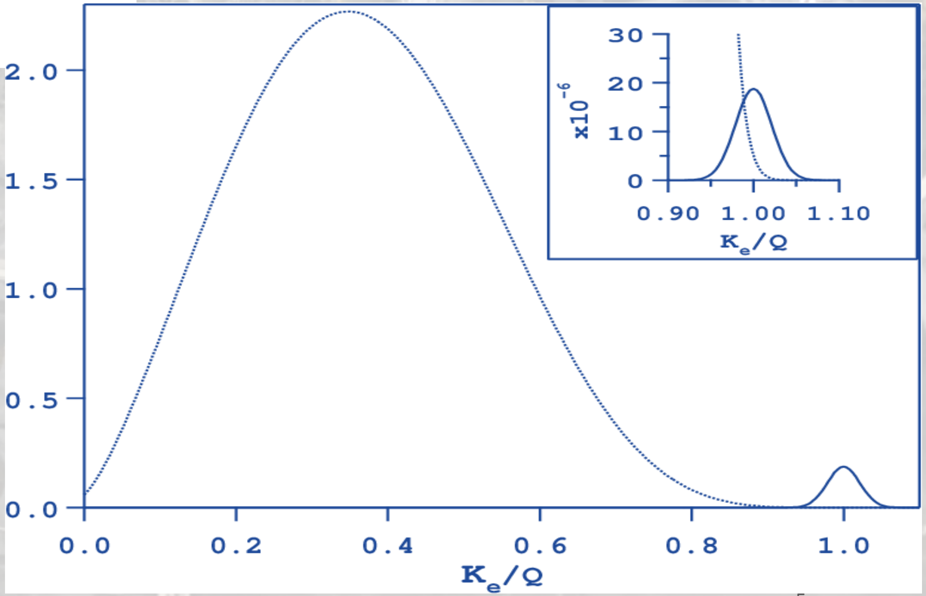
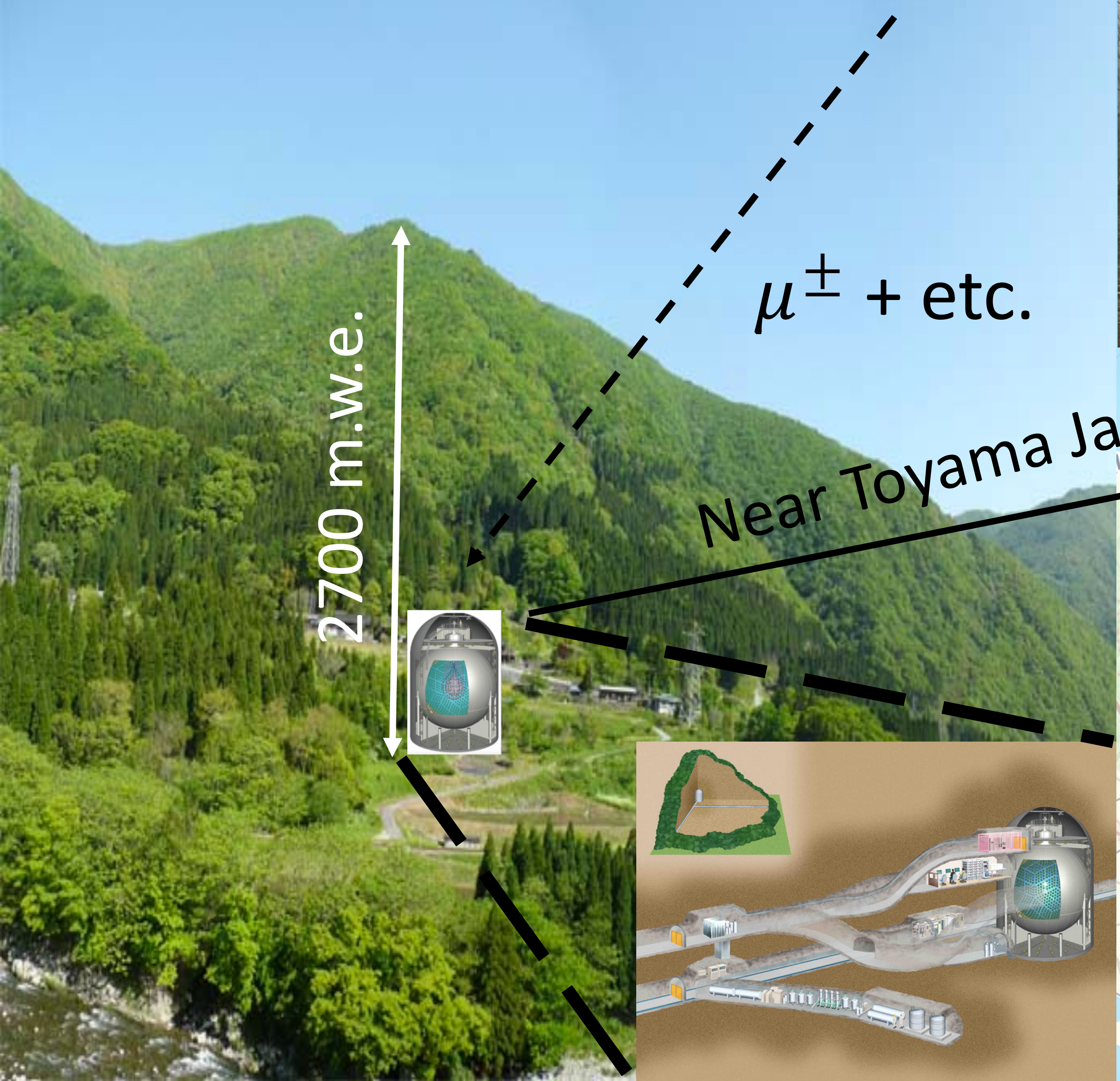
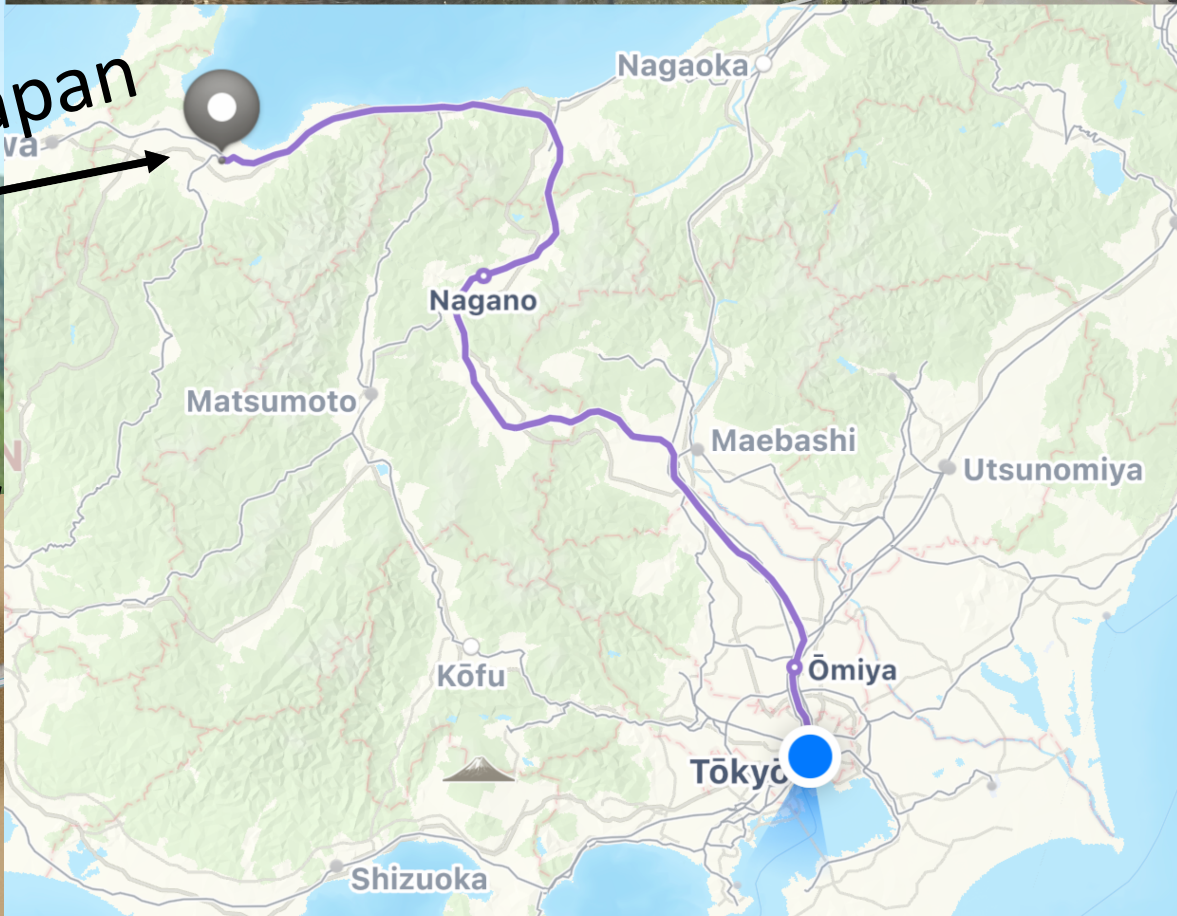
Spectra ➔



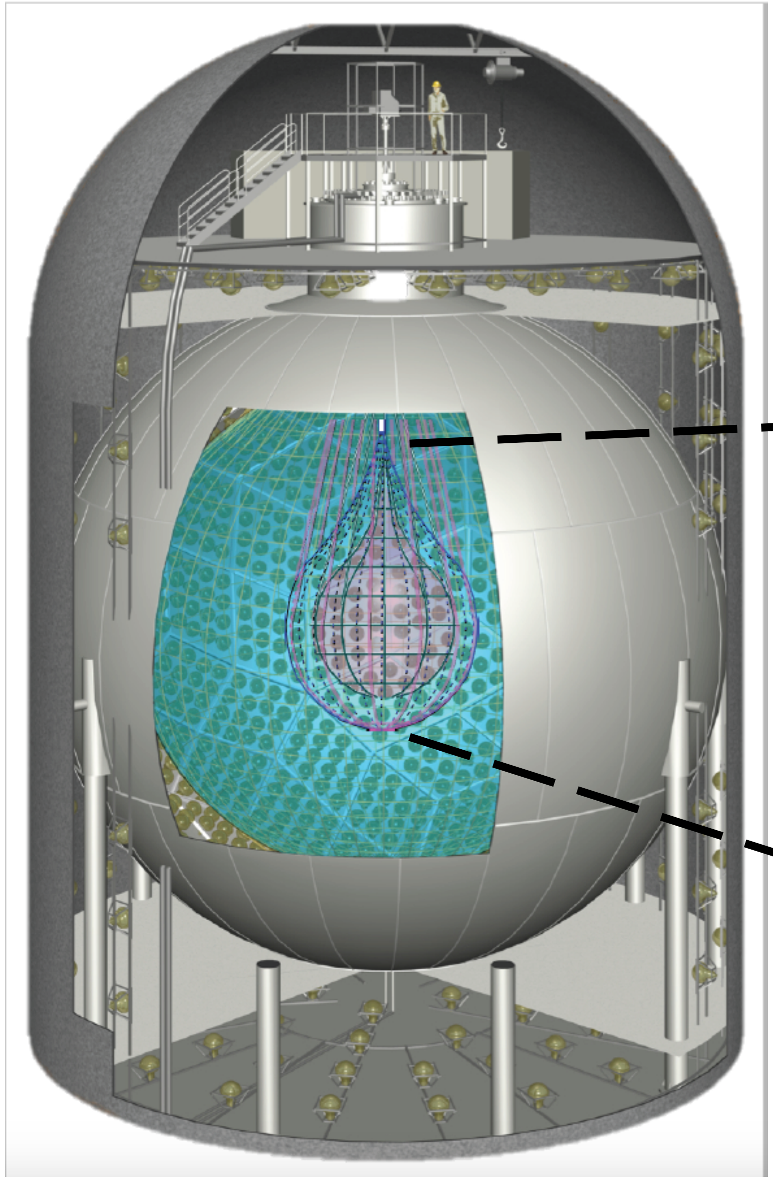
KamLAND-Zen…

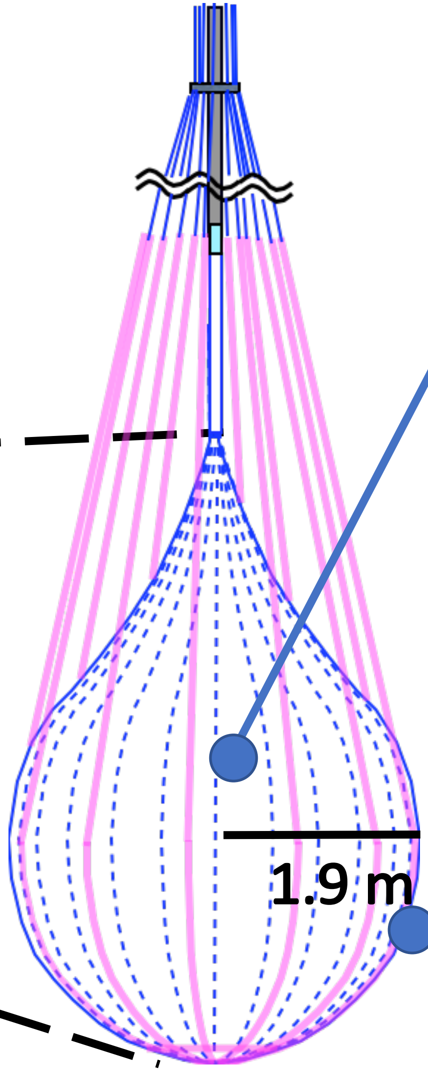
KamLAND (Kamioka Liquid Scintillator $\bar{\nu}$ Detector)





KamLAND-Zen Detector Short Cut





KL-Zen Inner Balloon (IB) filled with Xenon-LS

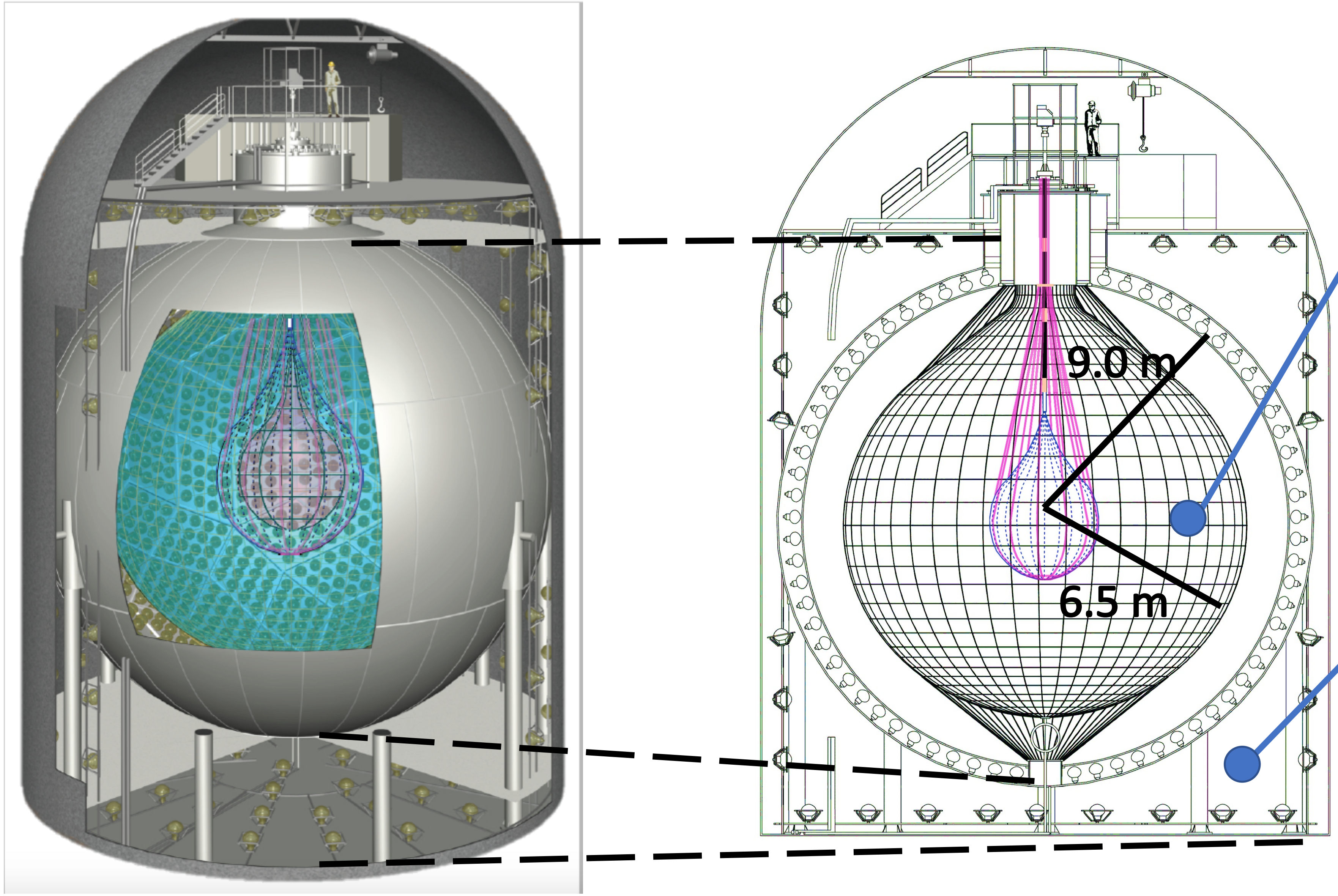
82% decane,
18% pseudocumene (1,2,4-trimethylbenzene), 2.4g/l fluor PPO (2,5-diphenyloxazole)

➔ (3.13±0.01)% Xe gas
➔ 745 kg enriched Xenon = 91% ^{136}Xe + 9% ^{134}Xe
➔ Uranium 10^{-17} g/g
➔ Thorium 10^{-16} g/g

KL-Zen IB Film

25 µm transparent nylon film

KamLAND-Zen Detector Short Cut



KamLAND-LS

1 kton LS = 80V% of normal dodecane + 20V% pseudocumene + 1.36g/l PPO (2,5-diphenyloxazole) fluor

Cherenkov Detector

3.2 kton Water for Muon Veto

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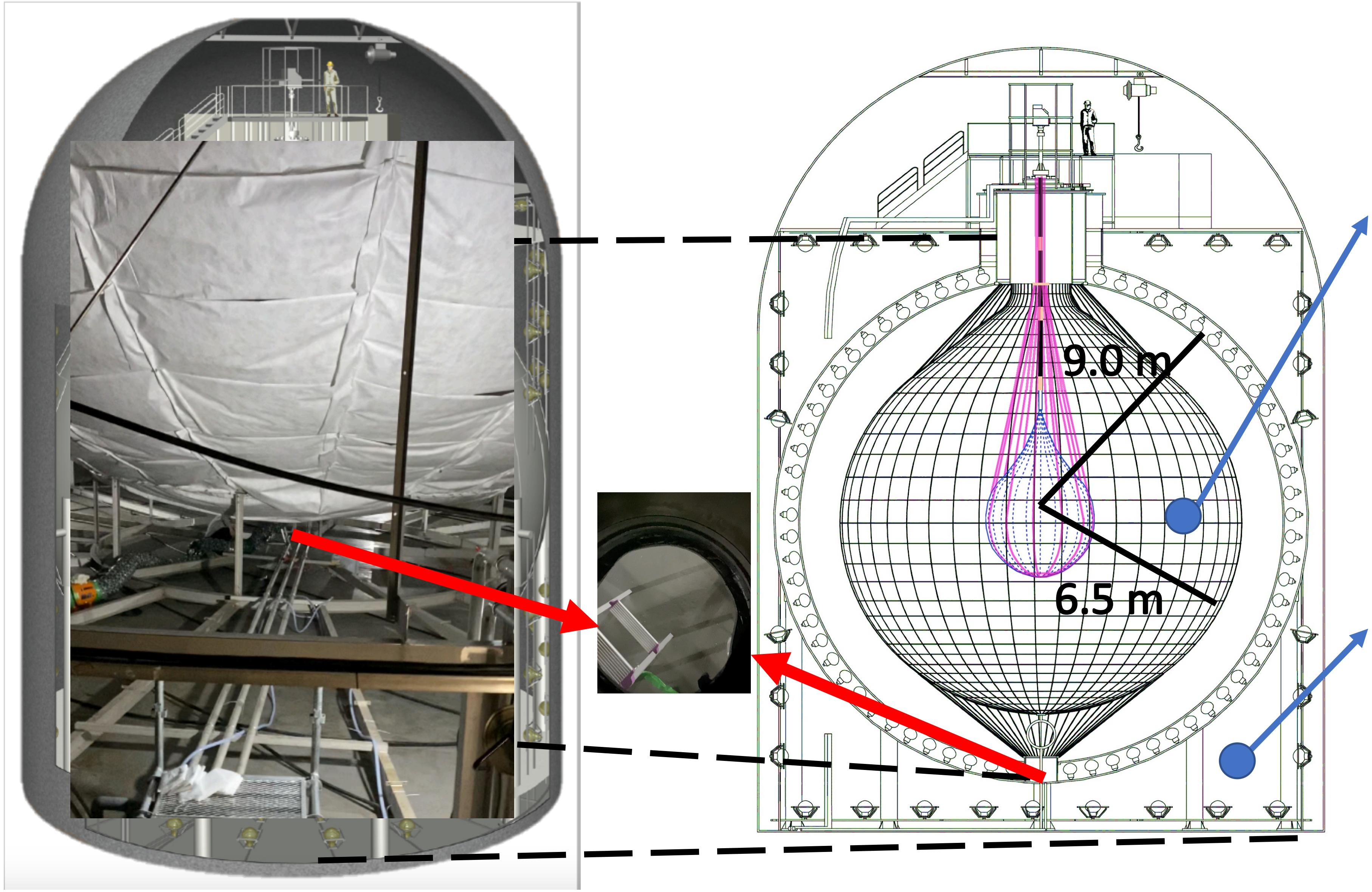

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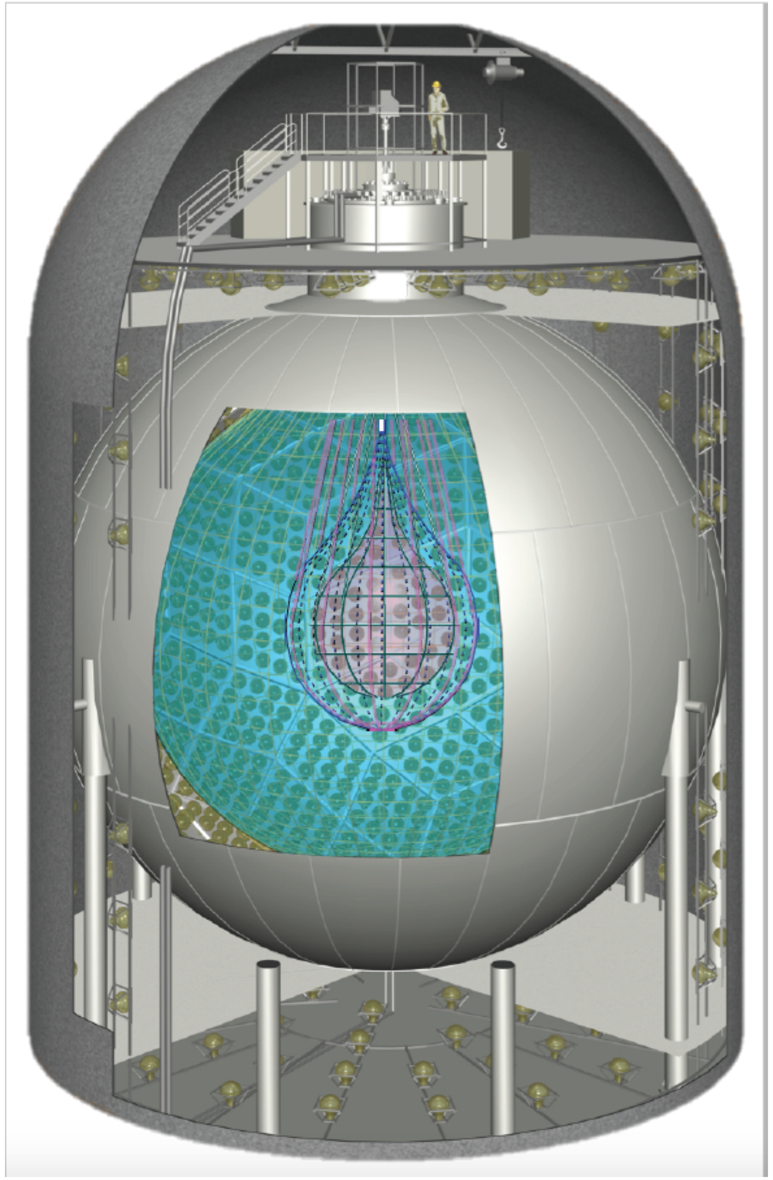


$\boldsymbol{Q_{\beta\beta}(^{136}\mathrm{Xe}) = 2.458\ \mathrm{MeV}}$

Net Light Yield = 250 p.e./MeV

PMTs = 1325 17-inch and
554 20-inch

Resolutions:

Energy $\sim 6.7\%/\sqrt{E[\mathrm{MeV}]}$,

Vertex $\sim 13.7\ \mathrm{cm}/\sqrt{E[\mathrm{MeV}]}$

Analysis Range = [0.5,4.8] MeV
and R<2.5 m (Fiducial Volume)

Publications + Phases

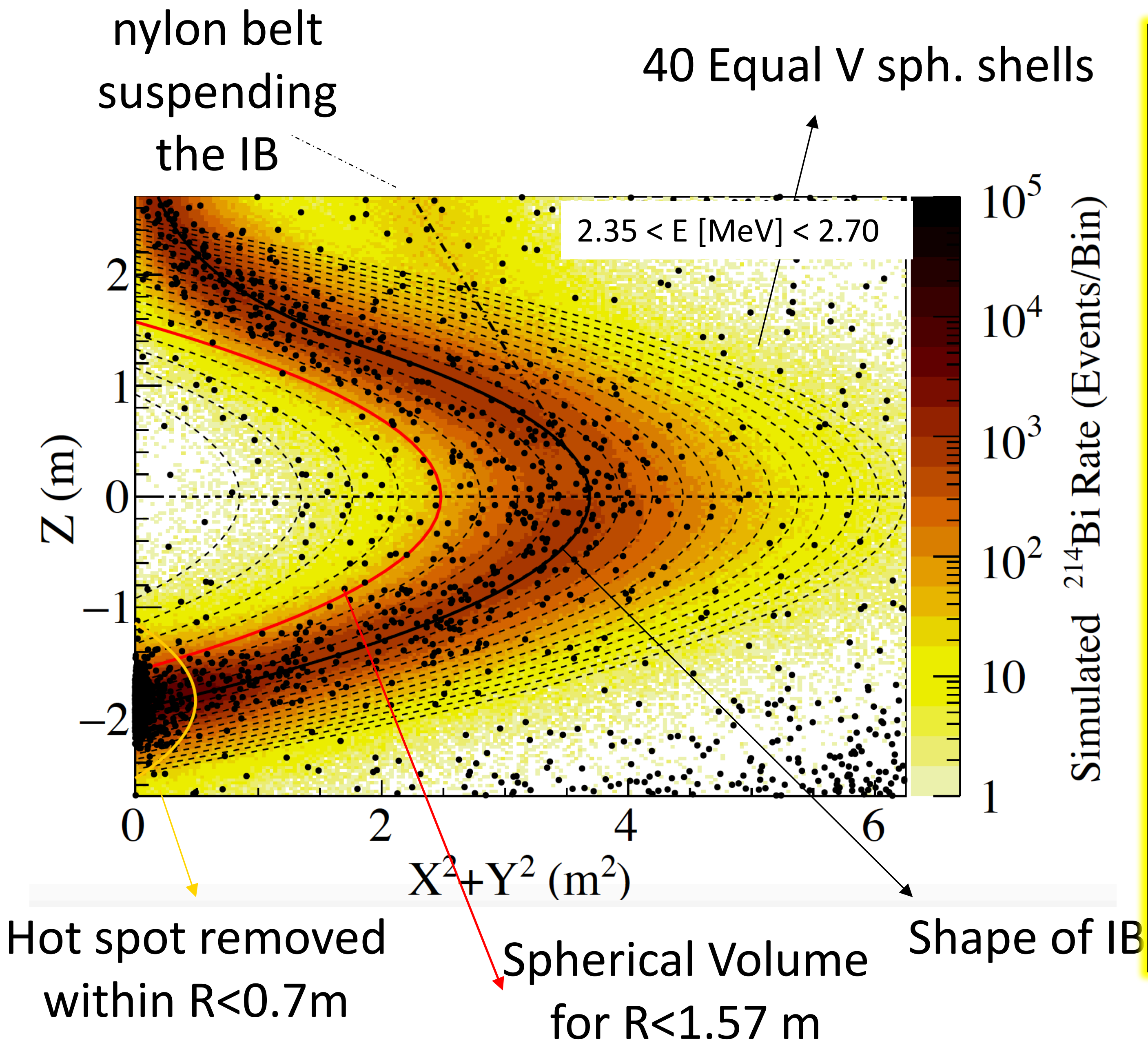
KamLAND-Zen 400: Oct. 12 2011 - Oct. 27 2015
Phase I: PRL 110,(2013) 062502
Phase II: PRL 117.8 (2016): 082503
Excited states: Nuc. Ph. A 946 (2016): 171-181

KamLAND-Zen 800: Feb. 5 2019 to Jan. 12 2024
Phys. Rev. Lett. 130.5 (2023): 051801

KamLAND-Zen 800 Final Physics Run:
Aug. 27th 2024

Complete KLZ 800 Dataset
arXiv:2406.11438v1 (2024)

KamLAND-Zen Event Selection Cuts



- FV R<2.5 m + hot spot + deadtime

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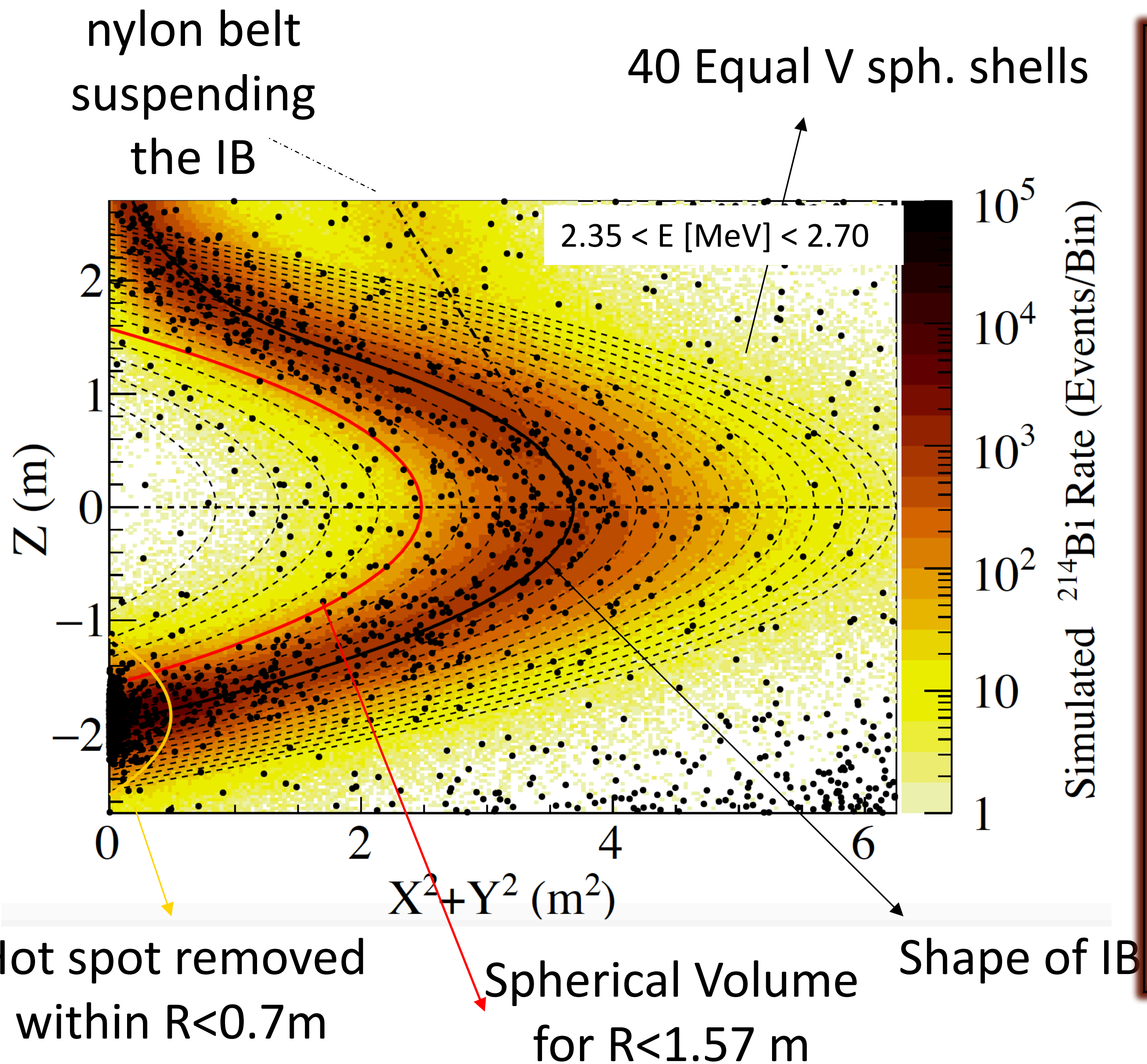

- FV R<2.5 m + hot spot + deadtime
- μs and μs + $\Delta t < 2$ ms

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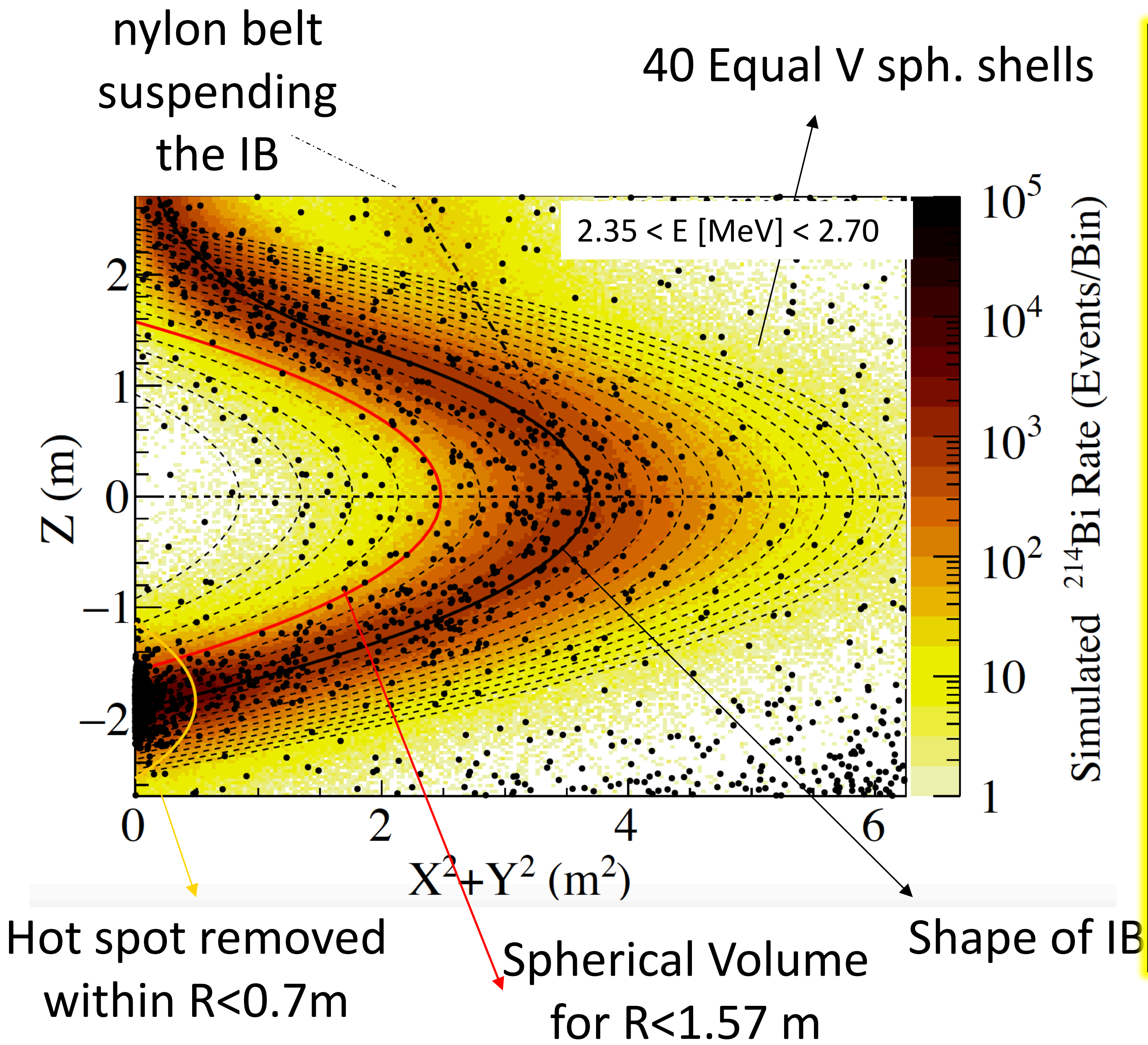

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- Bi-Po's by delayed coincidence tag (prompt Bi + delayed Po, double pulse) $(\Delta t, \Delta r) < (1.9\ \mathrm{ms}, 1.7\mathrm{m})$

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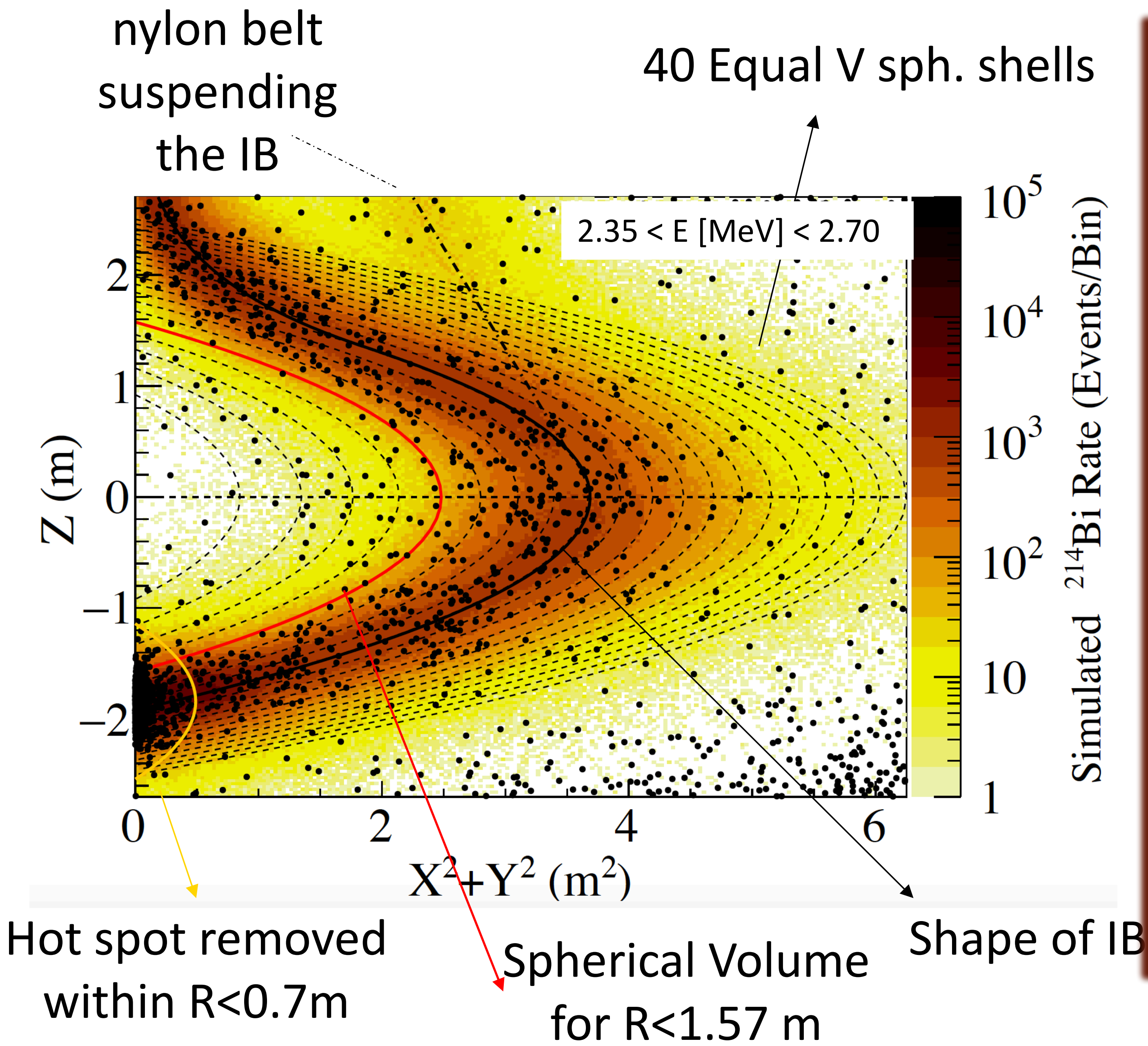

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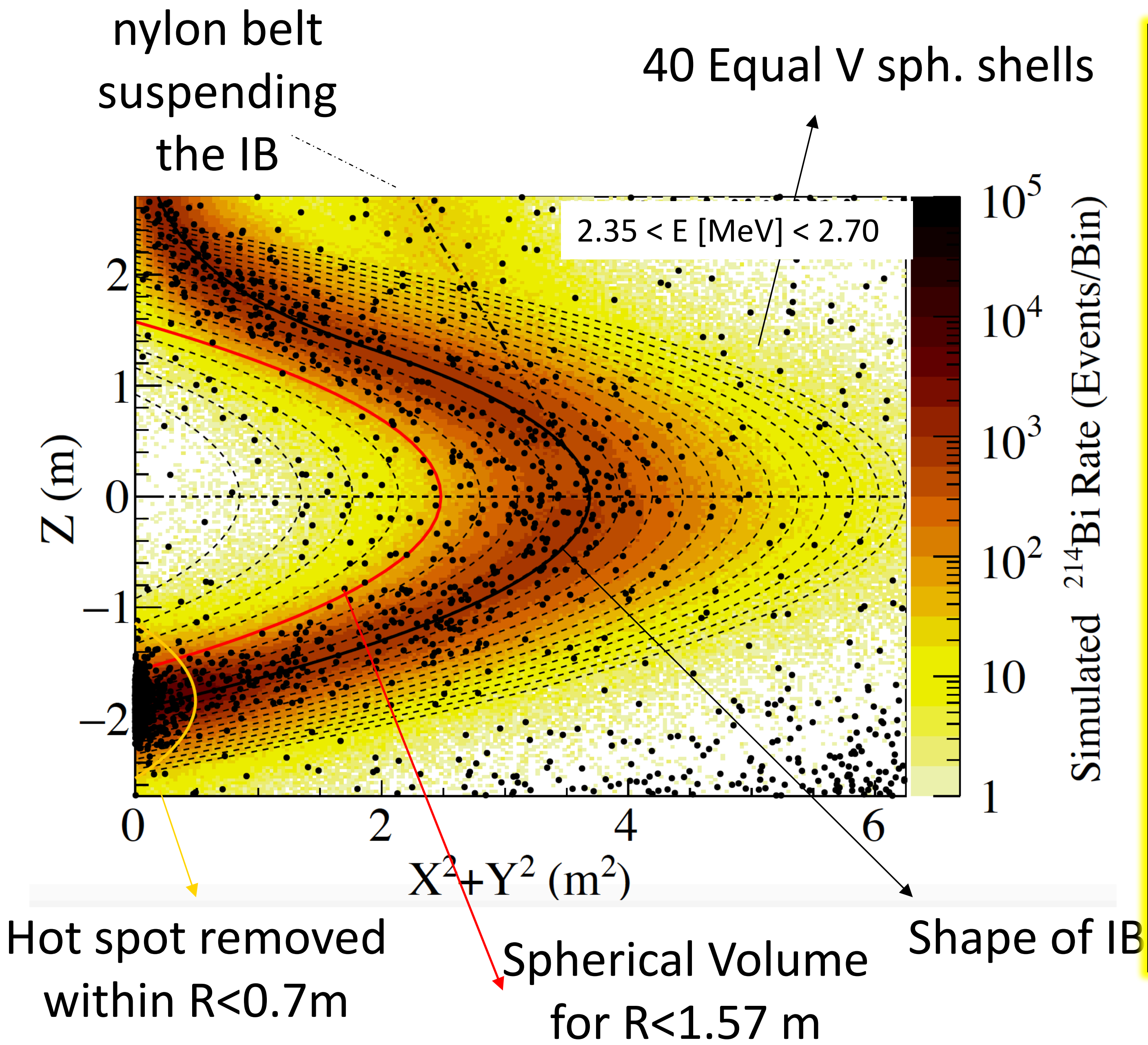

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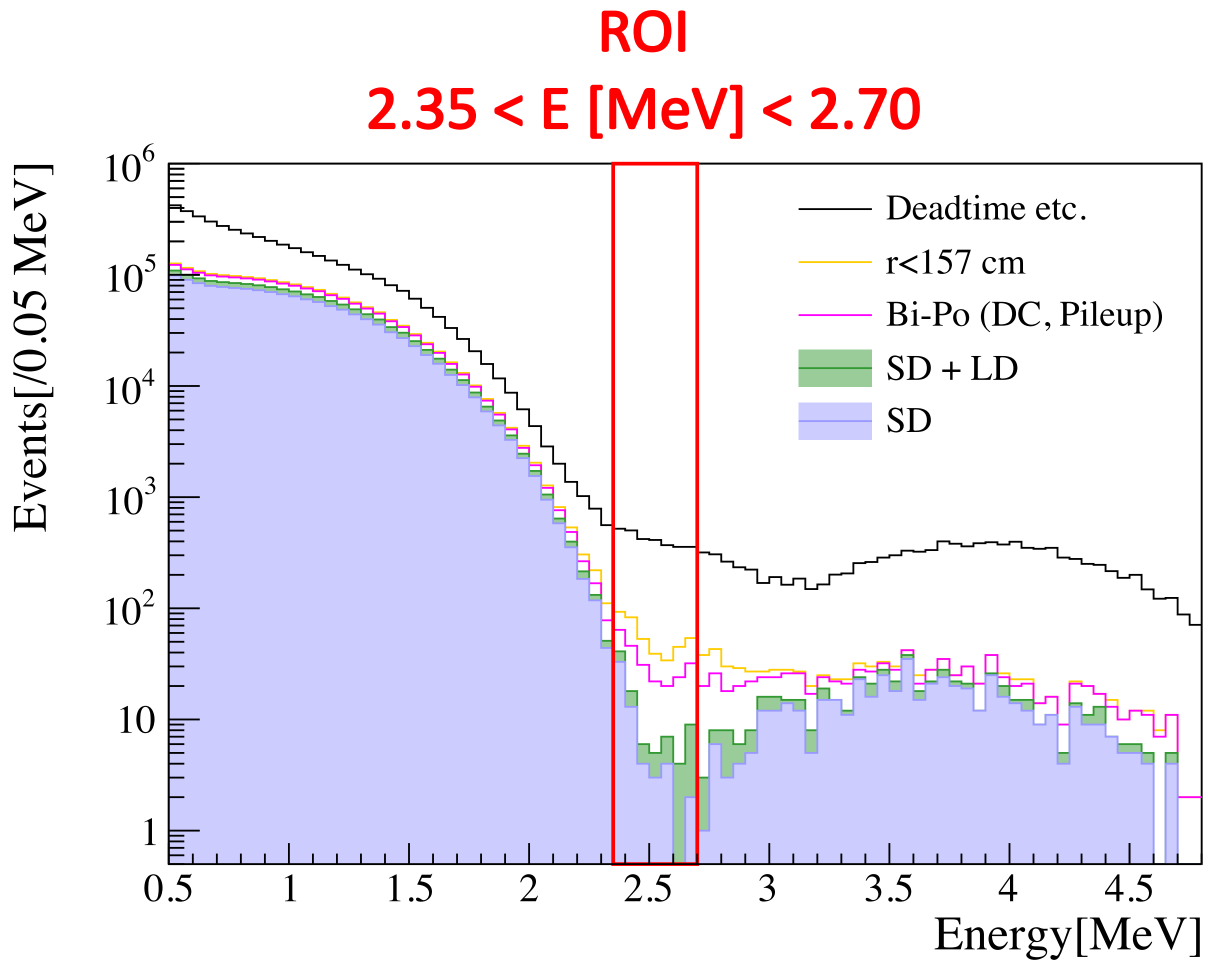
- Bad reco events are removed (vertex-time-charge discrimination with inefficiency <0.1%)

KamLAND-Zen Event Selection Cuts



Exposure and Long-Lived (LL) Sep.

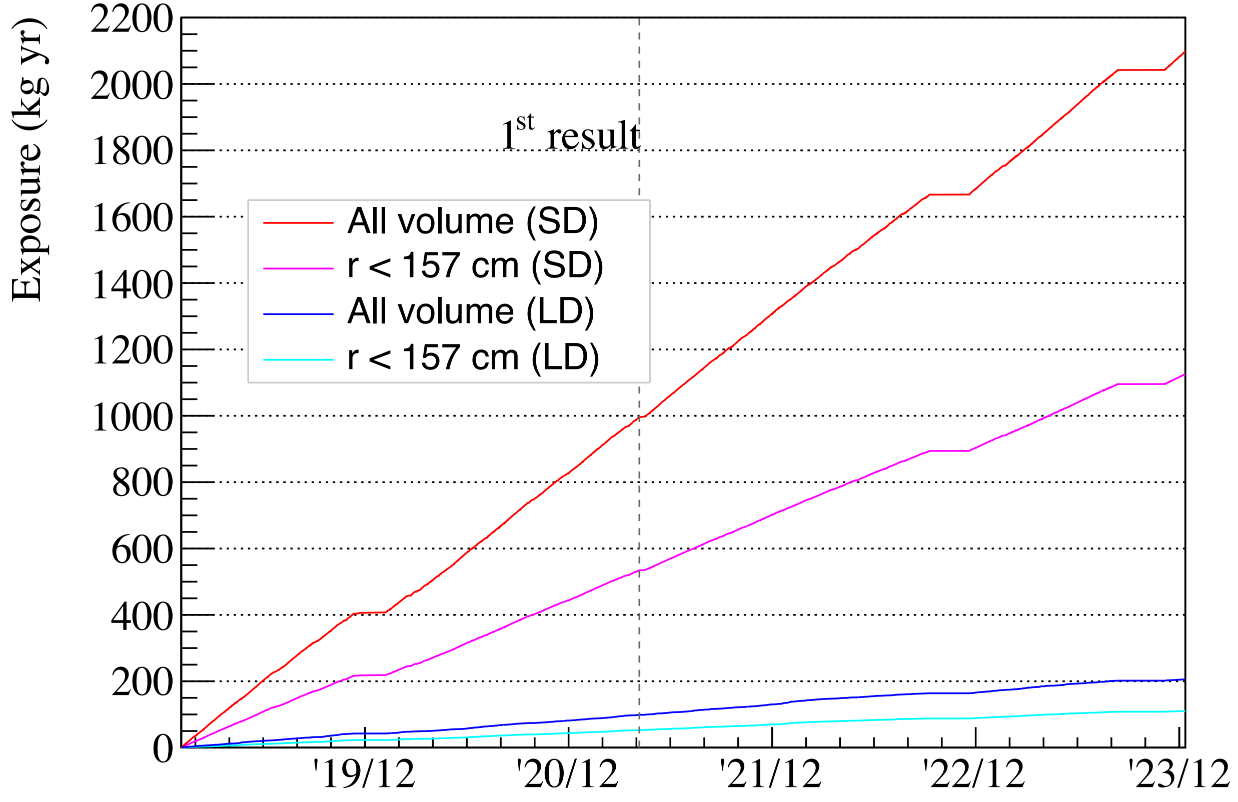
- **Long-Lived Data (LD):** classified as LL bkgs i.e. muon spallation products with $\tau \geq O(100s)$, $\varepsilon_{LD} \sim 10\%$ ⇔ 111 Days

- **Singles Data (SD):** not classified as long-lived bkgs, $\varepsilon_{SD} \sim 90\%$ ⇔ 1131 Days

➢ Data is divided into two exposure fractions optimized wrt Long Lived Spallation Backgrounds

➢ Simultaneous Spectral Fit is done on these Datasets

KamLAND-Zen Event Selection Cuts Exposure



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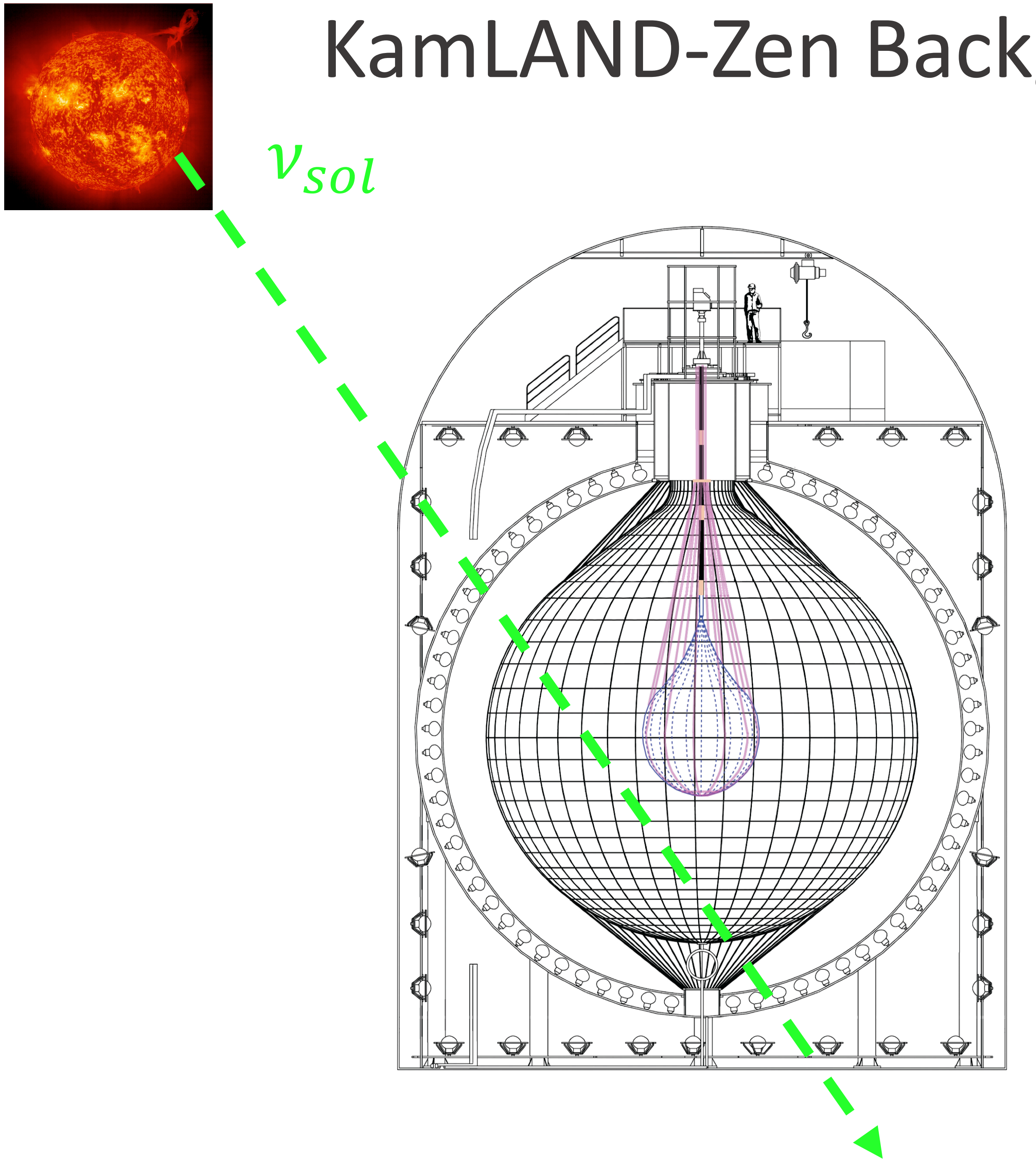
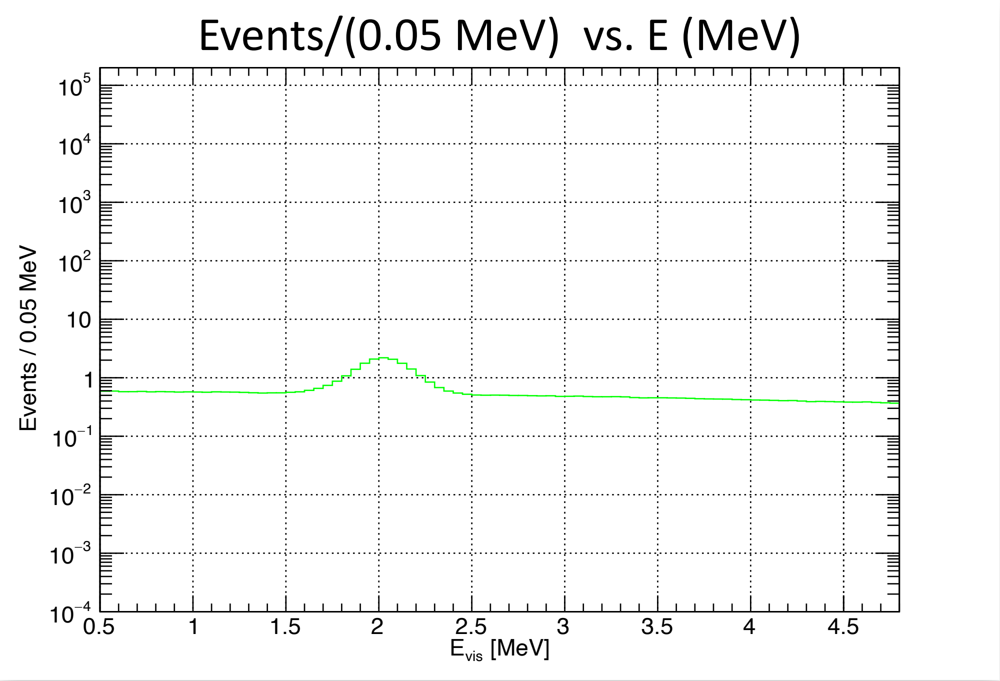
Total Xe Exposure in KLZ-800 reached 2.097 ton x year

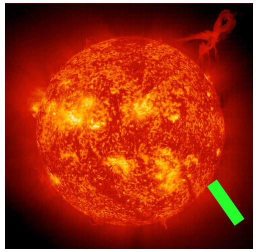
KamLAND-Zen Backgrounds after Event Selection

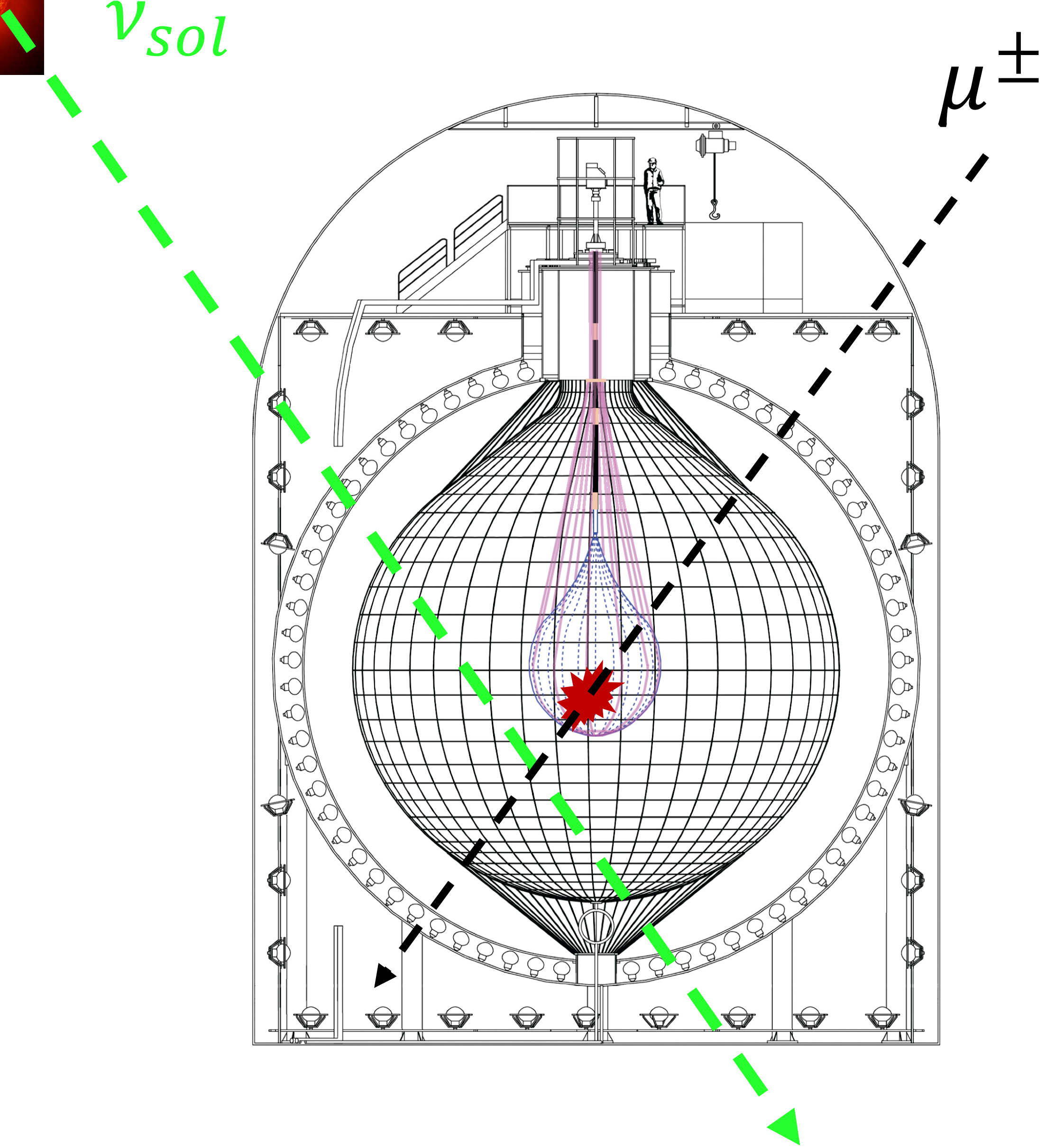


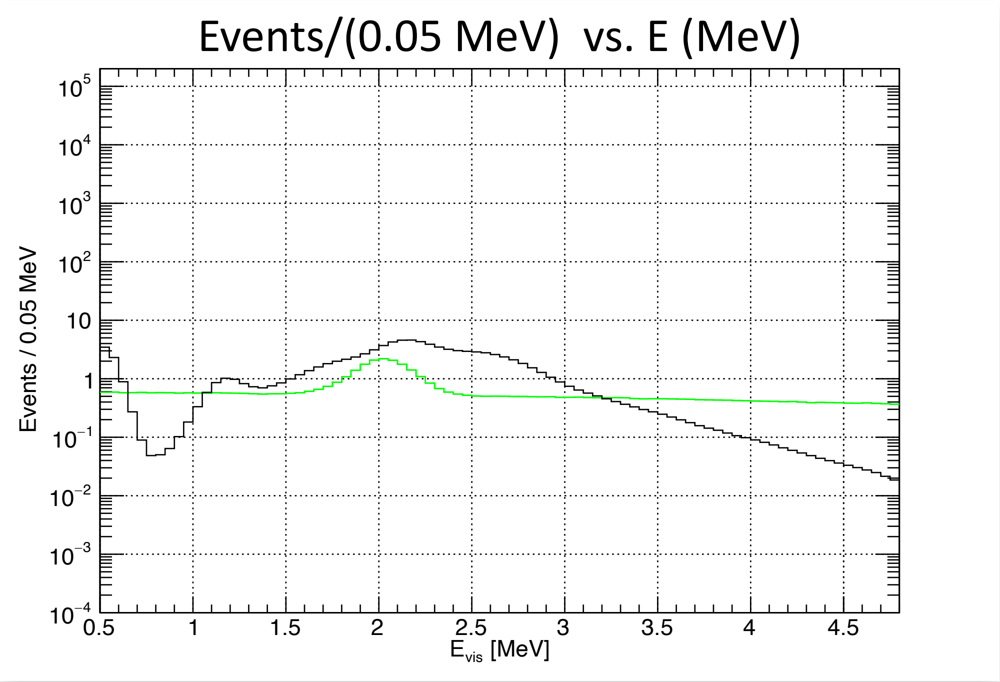


- Solar Neutrino Interactions (ES+CC)

KamLAND-Zen Backgrounds after Event Selection

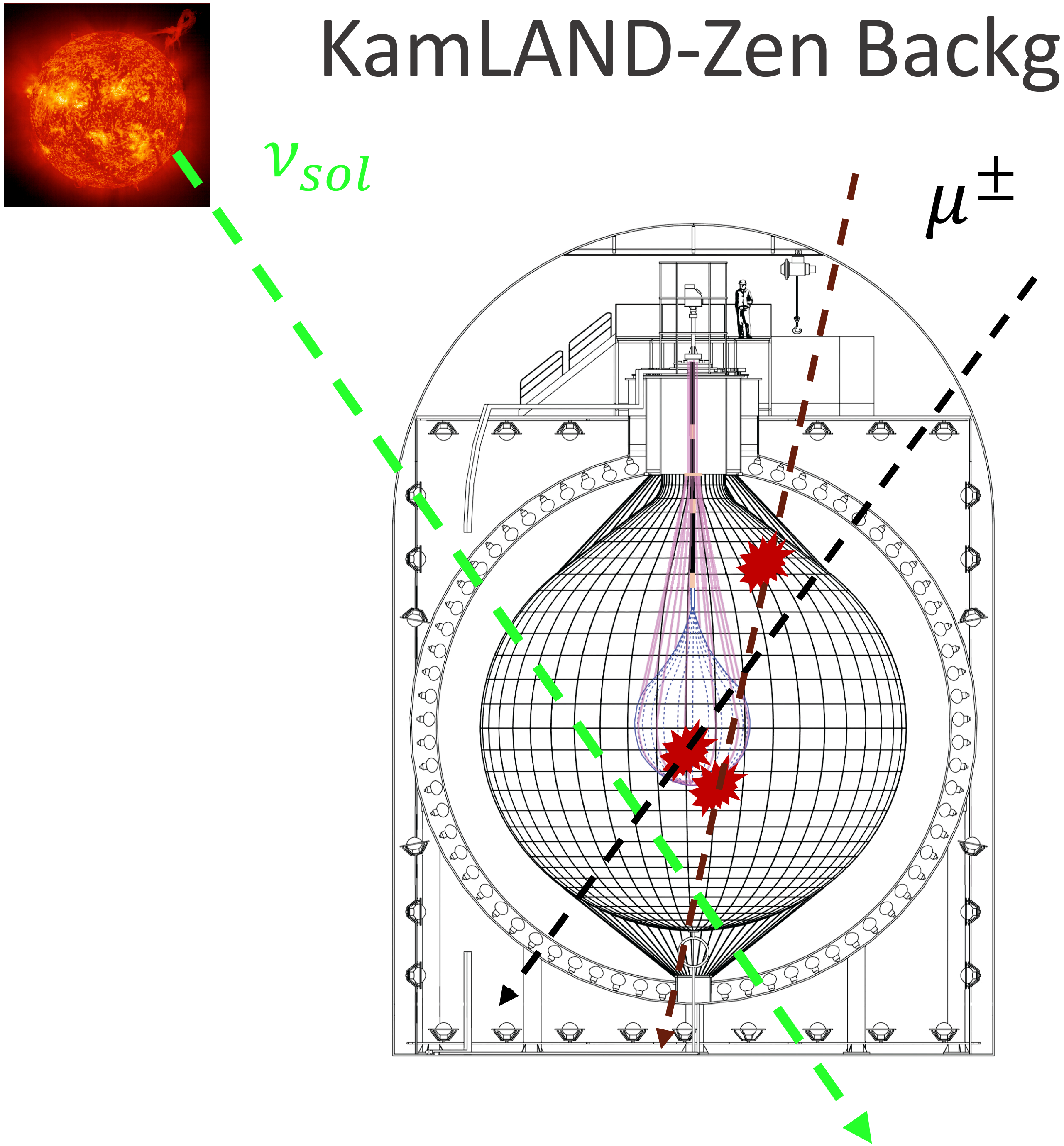


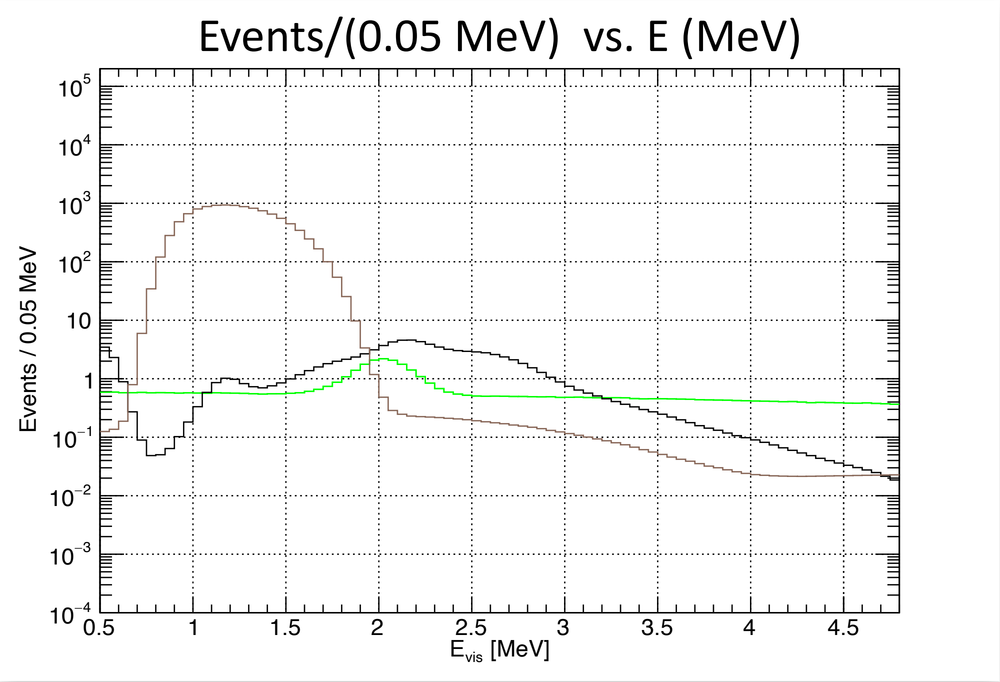




- Solar Neutrino Interactions (ES+CC)
- Cosmogenics Xenon Spallation Products

KamLAND-Zen Backgrounds after Event Selection





- Solar Neutrino Interactions (ES+CC)
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- Cosmogenics Carbon spallation Products

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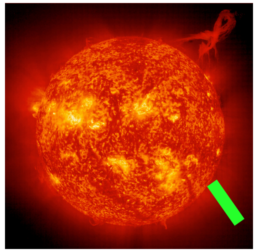
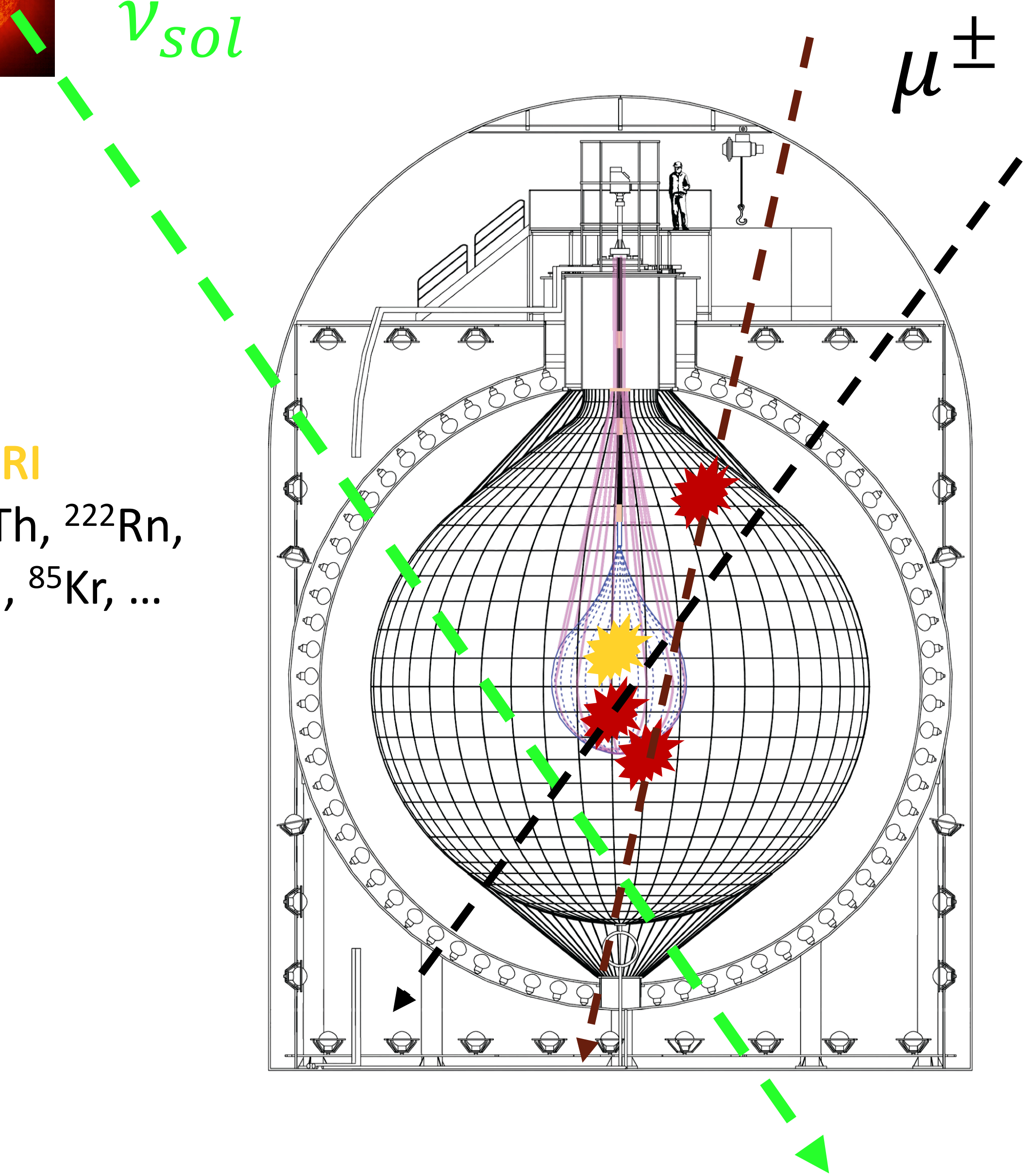
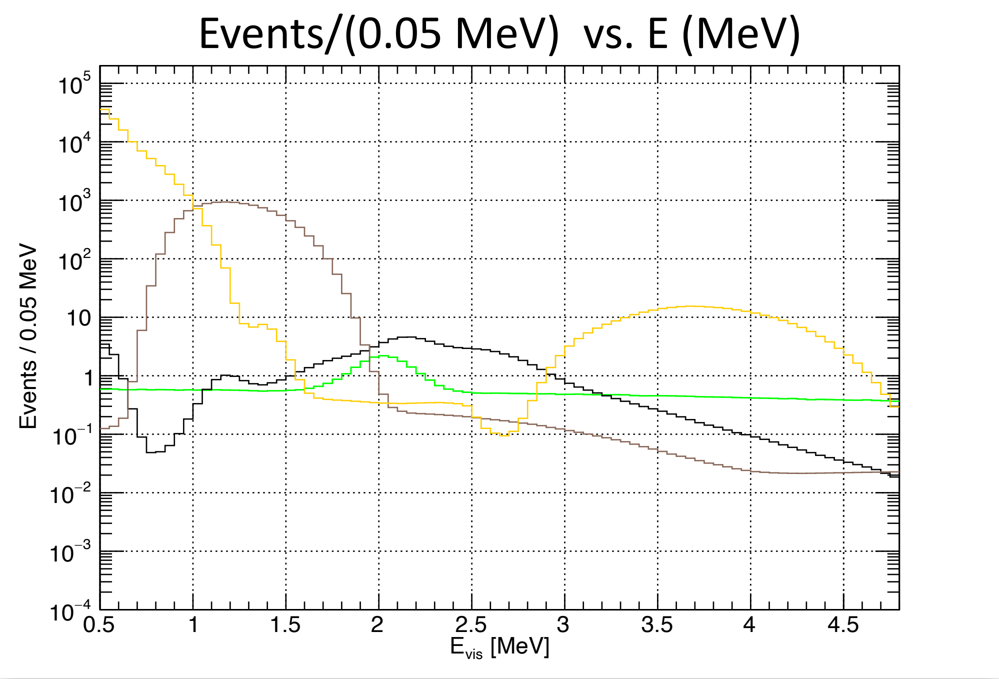




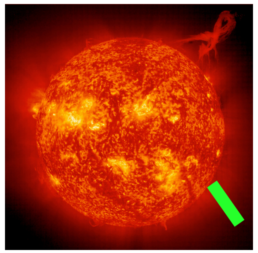
Internal RI

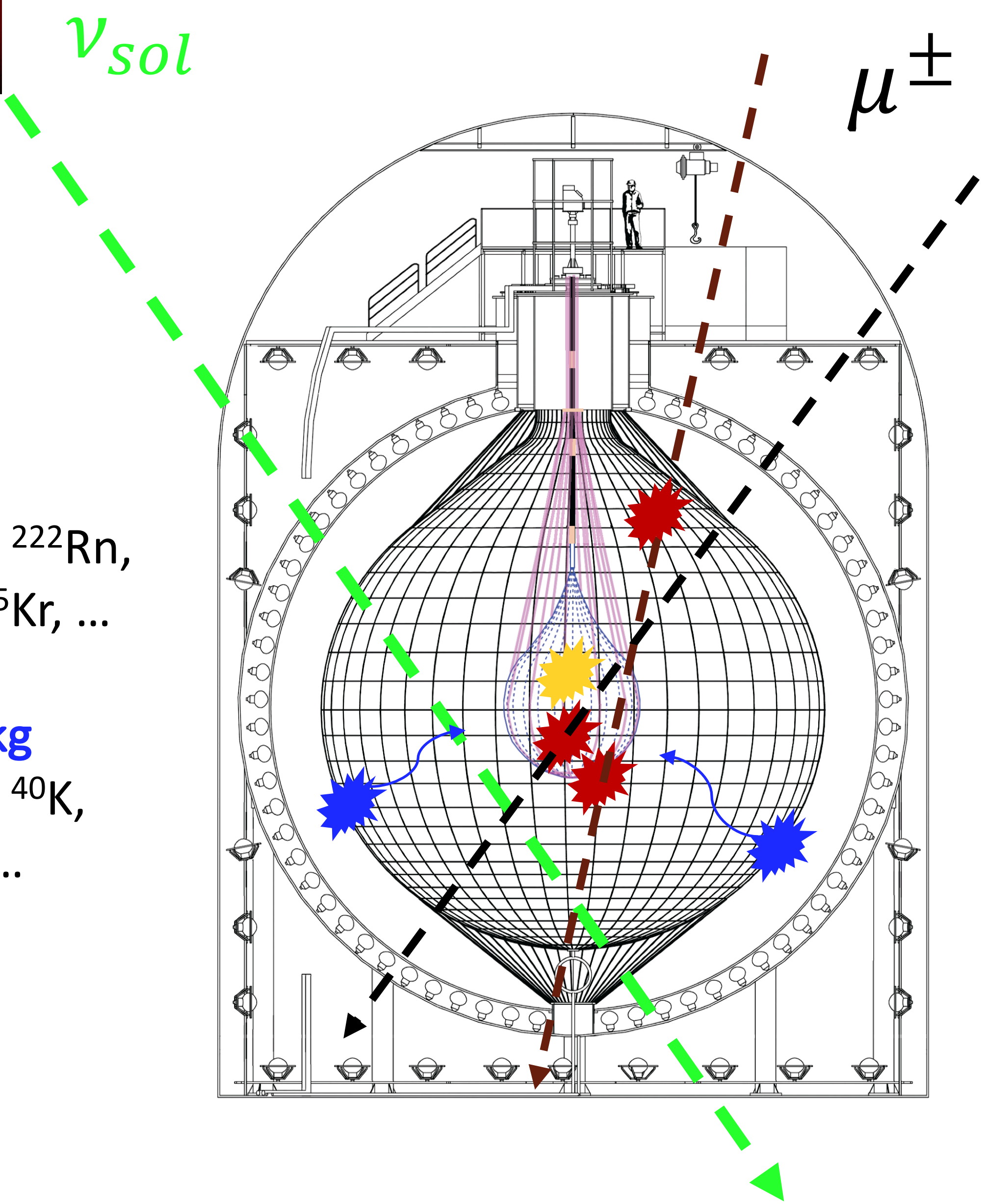
^{238}U, ^{232}Th, ^{222}Rn,
^{40}K, ^{210}Bi, ^{85}Kr, …



- Solar Neutrino Interactions (ES+CC)
- Cosmogenics Xenon Spallation Products
- Cosmogenics Carbon spallation Products
- Internal XeLS Radioactive Impurities (RI)

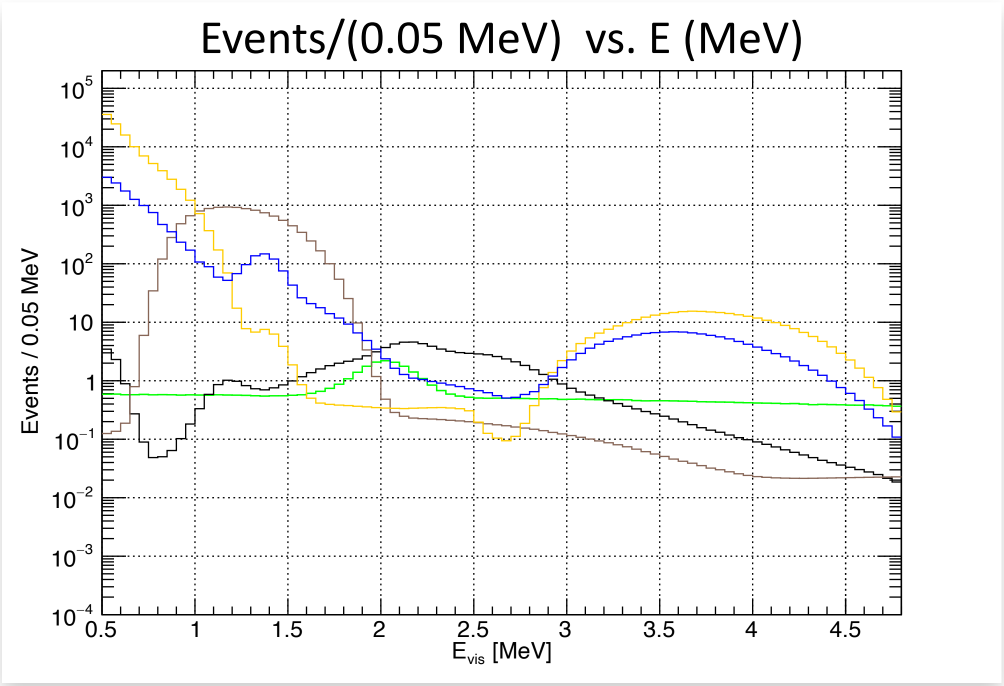
KamLAND-Zen Backgrounds after Event Selection





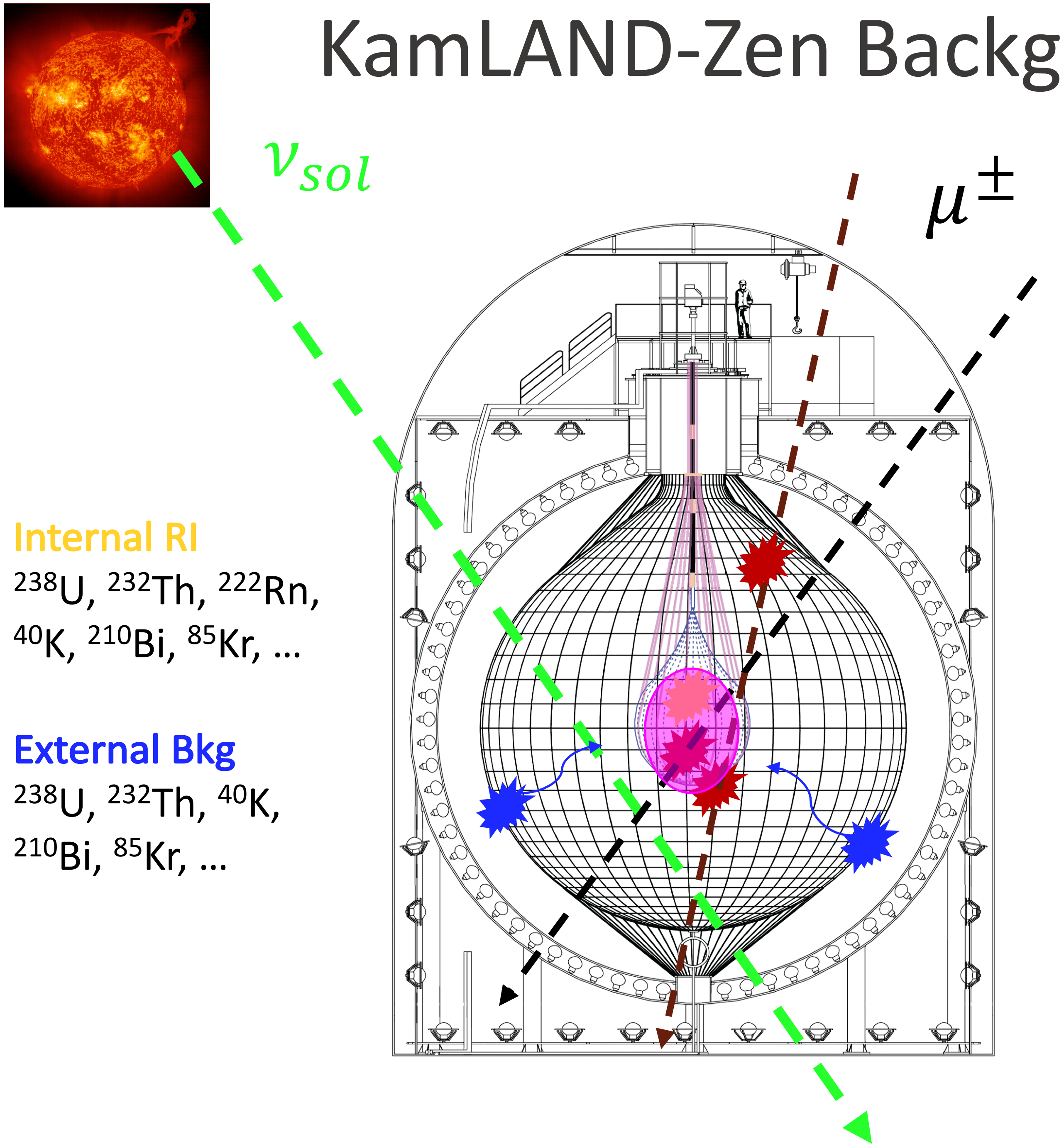
Internal RI
^{238}U, ^{232}Th, ^{222}Rn, ^{40}K, ^{210}Bi, ^{85}Kr, …

External Bkg
^{238}U, ^{232}Th, ^{40}K, ^{210}Bi, ^{85}Kr, …



- Solar Neutrino Interactions (ES+CC)
- Cosmogenics Xenon Spallation Products
- Cosmogenics Carbon spallation Products
- Internal XeLS Radioactive Impurities (RI)
- External to XeLS from IB + KamLAND-LS

KamLAND-Zen Backgrounds after Event Selection



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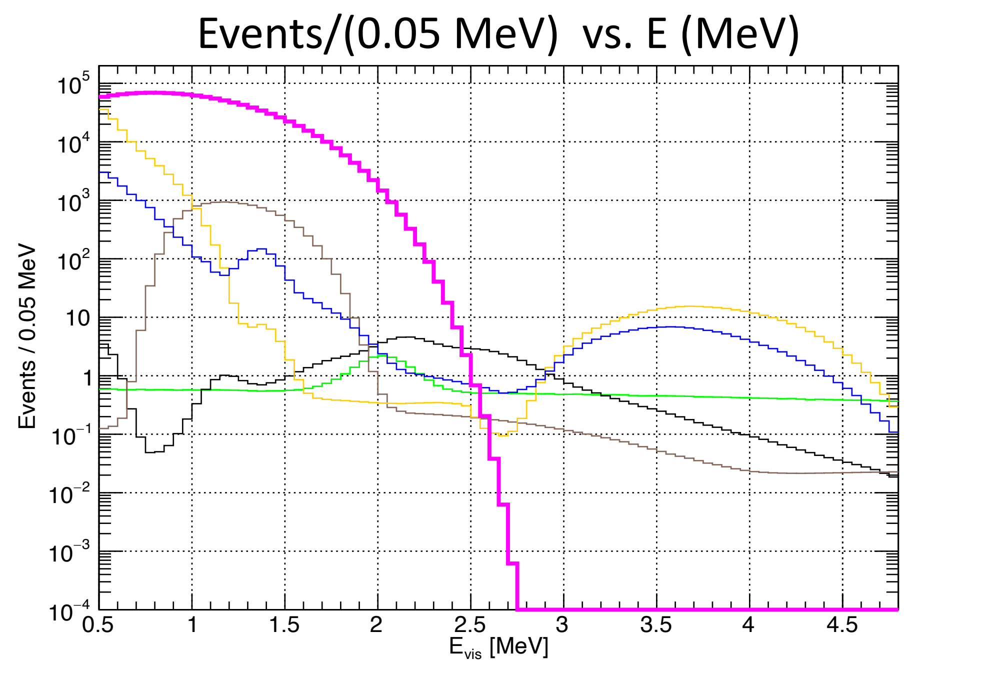

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- Cosmogenics Xenon Spallation Products
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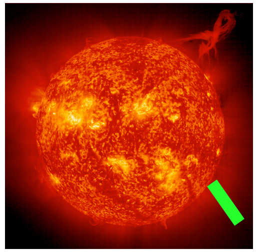
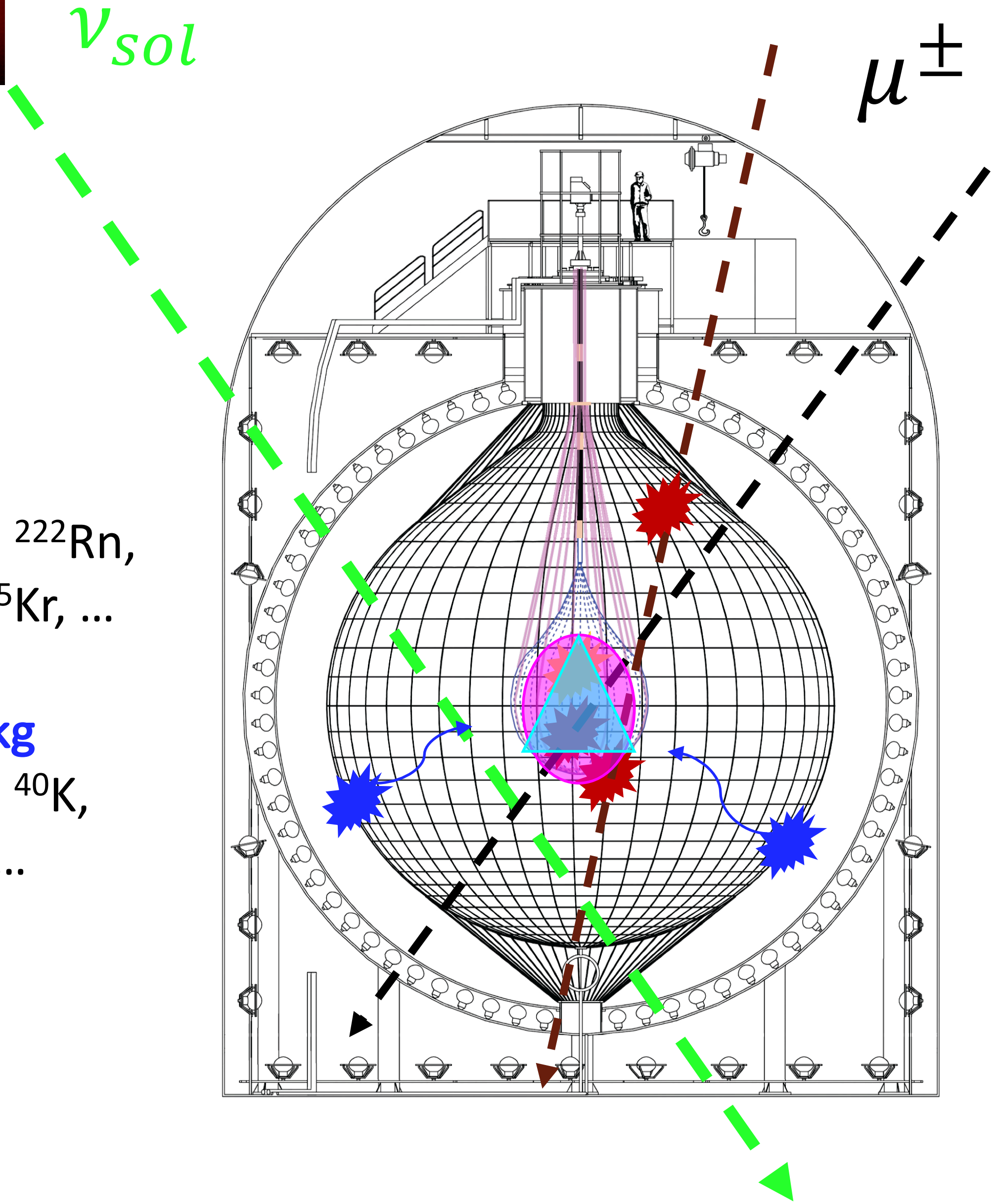
- Internal XeLS Radioactive Impurities (RI)
- External to XeLS from IB + KamLAND-LS
- $^{136}Xe\ 2\nu\beta\beta$ (source bkg)

KamLAND-Zen Backgrounds after Event Selection





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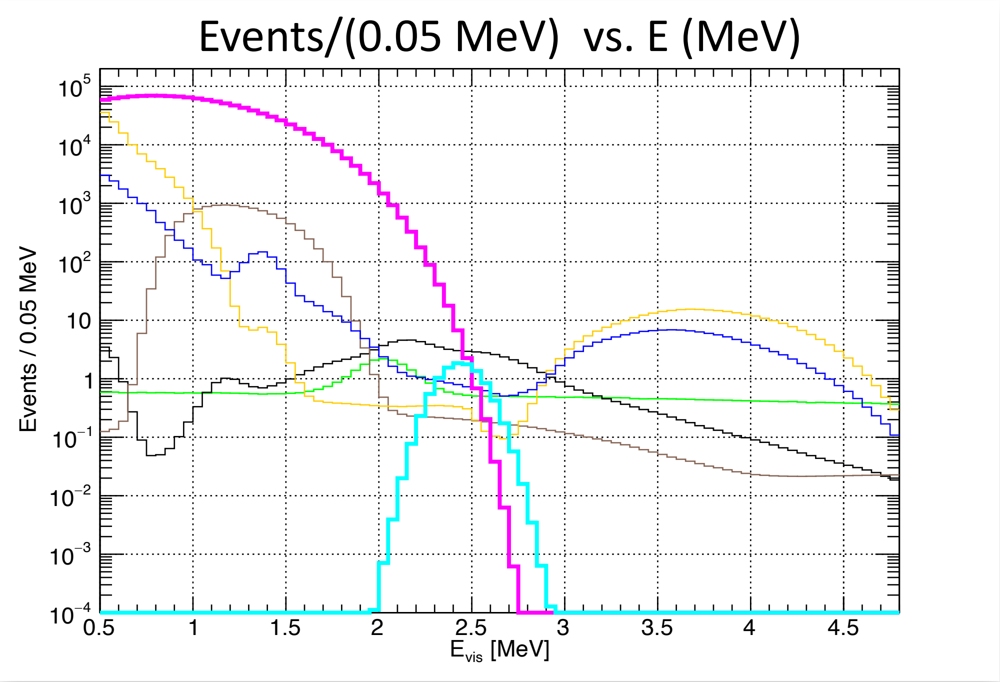

- Solar Neutrino Interactions (ES+CC)
- Cosmogenics Xenon Spallation Products
- Cosmogenics Carbon spallation Products
- Internal XeLS Radioactive Impurities (RI)
- External to XeLS from IB + KamLAND-LS
- ^{136}Xe $2\nu\beta\beta$ (source bkg)
- ^{136}Xe $0\nu\beta\beta$ (90% Limit)

Statistical Approaches (Short Cut)

Frequentist Approach

Wilks Approximation

Feldman-Cousins

Bayesian Approach

Bayesian Evaluation

Statistical Approaches (Short Cut)

Frequentist Approach

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Bayesian Approach

Bayesian Evaluation

“Classical” Likelihood Profiling

$t \sim \Delta\chi^2 = -2\text{LLR}$

$\Leftrightarrow$ $\Delta\chi^2$ vs. Signal Rate

$\Leftrightarrow$ Asymptotic Case

Statistical Approaches (Short Cut)

Frequentist Approach

Wilks Approximation

Feldman-Cousins

"Classical" Likelihood Profiling
$t \sim \Delta\chi^2$= −2LLR
⇔ $\Delta\chi^2$ vs. Signal Rate
⇔ Asymptotic Case

"Profiling Likelihood Profile"
$t \sim \Delta\chi^2$= −2LLR
evaluated for different
hypotheses wrt null
⇔ Proper Confidence Interval
Evaluation

Bayesian Approach

Bayesian Evaluation

Statistical Approaches (Short Cut)

Frequentist Approach

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"Classical" Likelihood Profiling
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⬄ $\Delta\chi^2$ vs. Signal Rate
⬄ Asymptotic Case

Feldman-Cousins

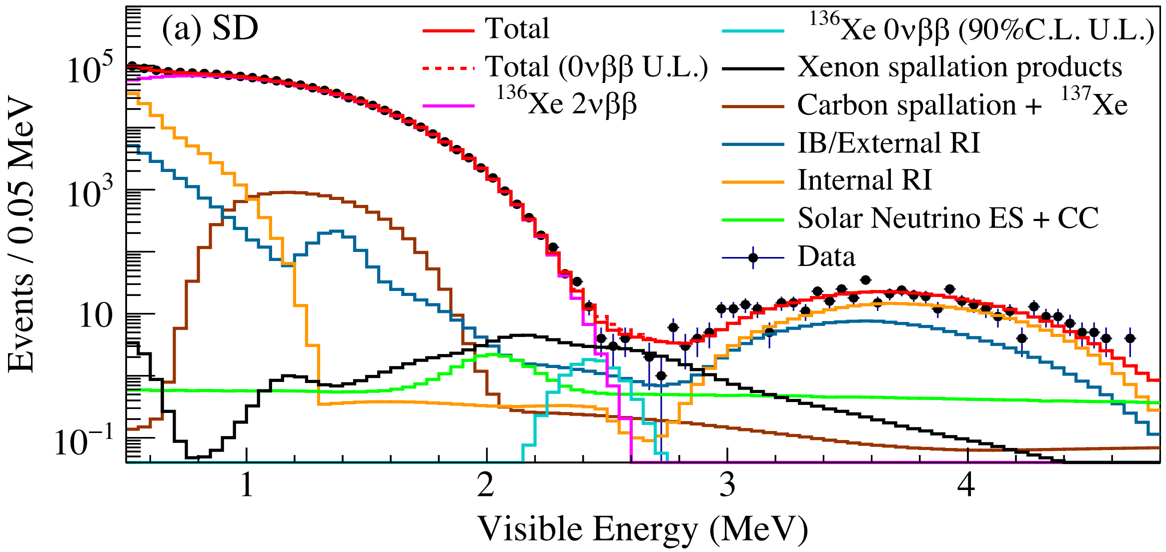
"Profiling Likelihood Profile"
$t \sim \Delta\chi^2 = -2\text{LLR}$
evaluated for different hypotheses wrt null
⬄ Proper Confidence Interval Evaluation

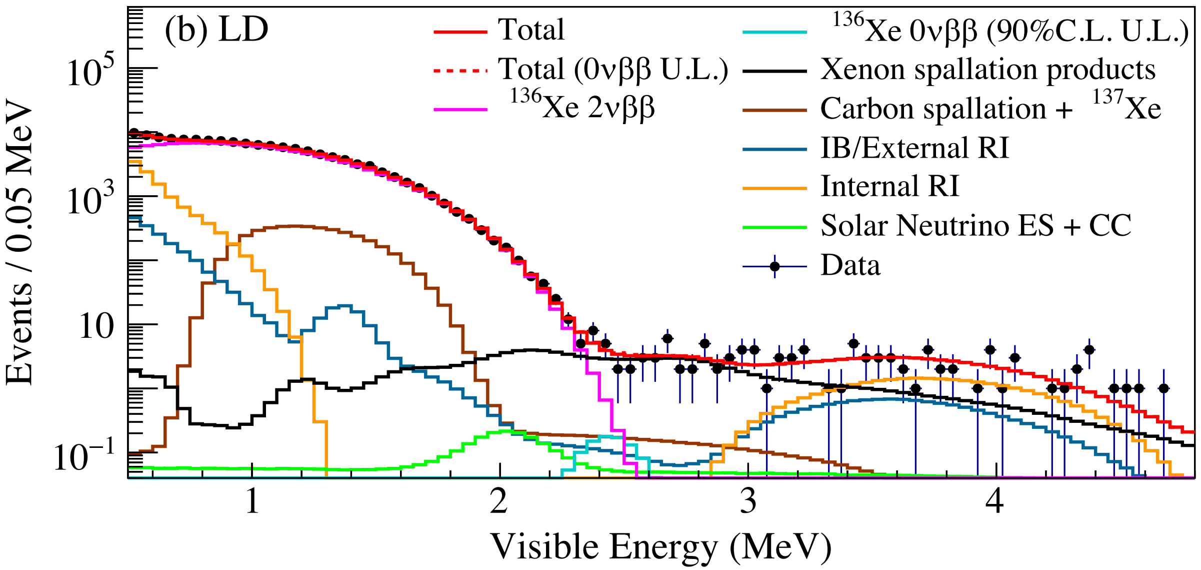
Bayesian Approach

Bayesian Evaluation

Bayes Theorem
$$p(M|D) = \frac{p(D|M)pr(M)}{p(D)}$$
⬄ "Credibility Interval"
Posterior $p(M|D)$
"probability of model given data" =
Likelihood $p(D|M)$ times **Prior** $pr(M)$
normalized by **Evidence** $p(D)$

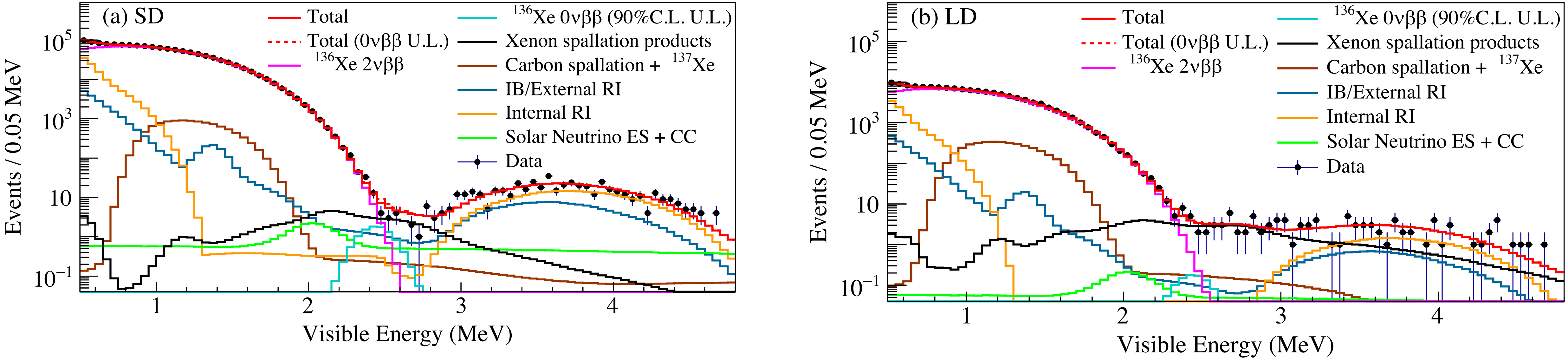
Multivariate Spectral Analysis





➔ No Signal Observed on Data ⇔ Calculate Limits based on toy Monte Carlo

Multivariate Spectral Analysis



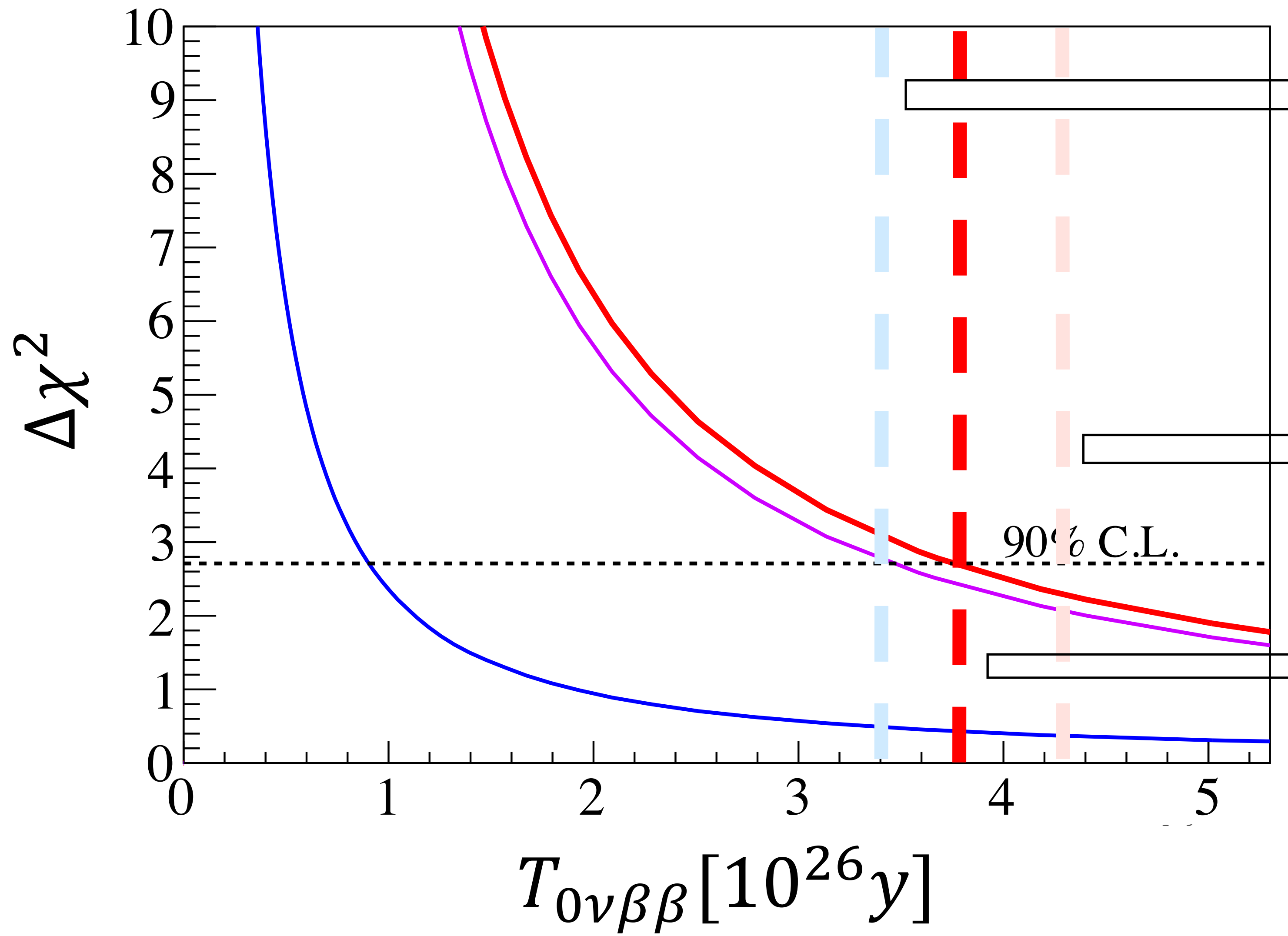
➔ **No Signal Observed on Data ⇔ Calculate Limits based on toy Monte Carlo**

Pseudo Dataset: Take Best Estimation of Backgrounds with Zero injected Signal (Null)

Frequentist	Bayesian
Evaluate Log-Likelihood-Ratio test statistics for different Hypothesis wrt Null and calculate 90 % limit (confidence)	Evaluate Posterior Distribution and calculate 90 % limit (credibility)

Results

Curves a la Wilks



Bayesian result:

$T_{1/2}^{0\nu\beta\beta} > 3.4 \times 10^{26}\text{yr (90 \% C.I.)}$

Here KLZ-800 only
(no combination with KLZ-400)

Frequentist Feldman-Cousins calculation result:

$T_{1/2}^{0\nu\beta\beta} > 4.3 \times 10^{26}\text{yr (90 \% C.L.)}$

Combined KLZ 400 + 800 Analysis (Wilks')

$T_{1/2}^{0\nu\beta\beta} > 3.8 \times 10^{26}\text{yr (90 \% C.L.)}$

Results

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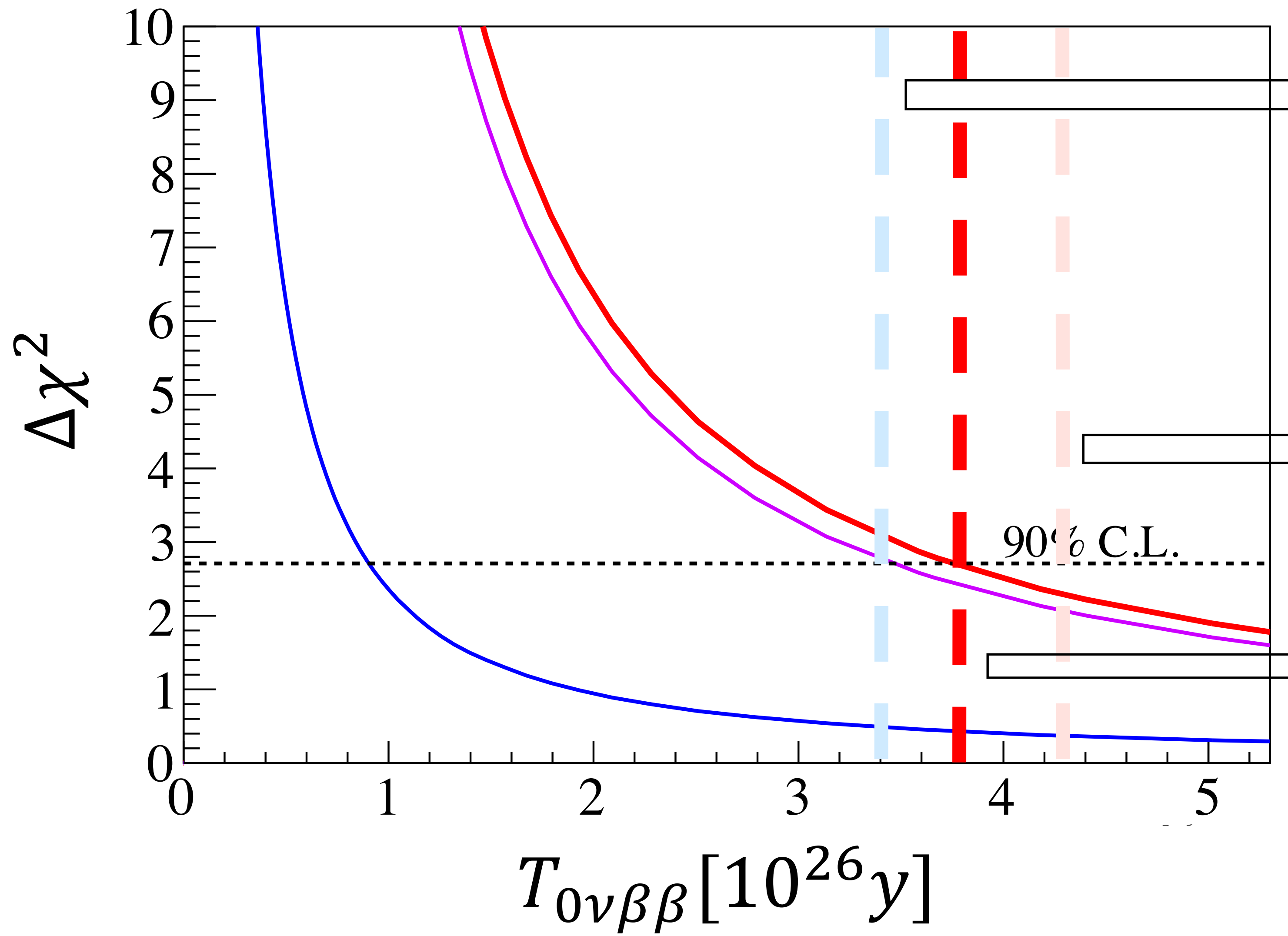

<u>Bayesian result:</u>

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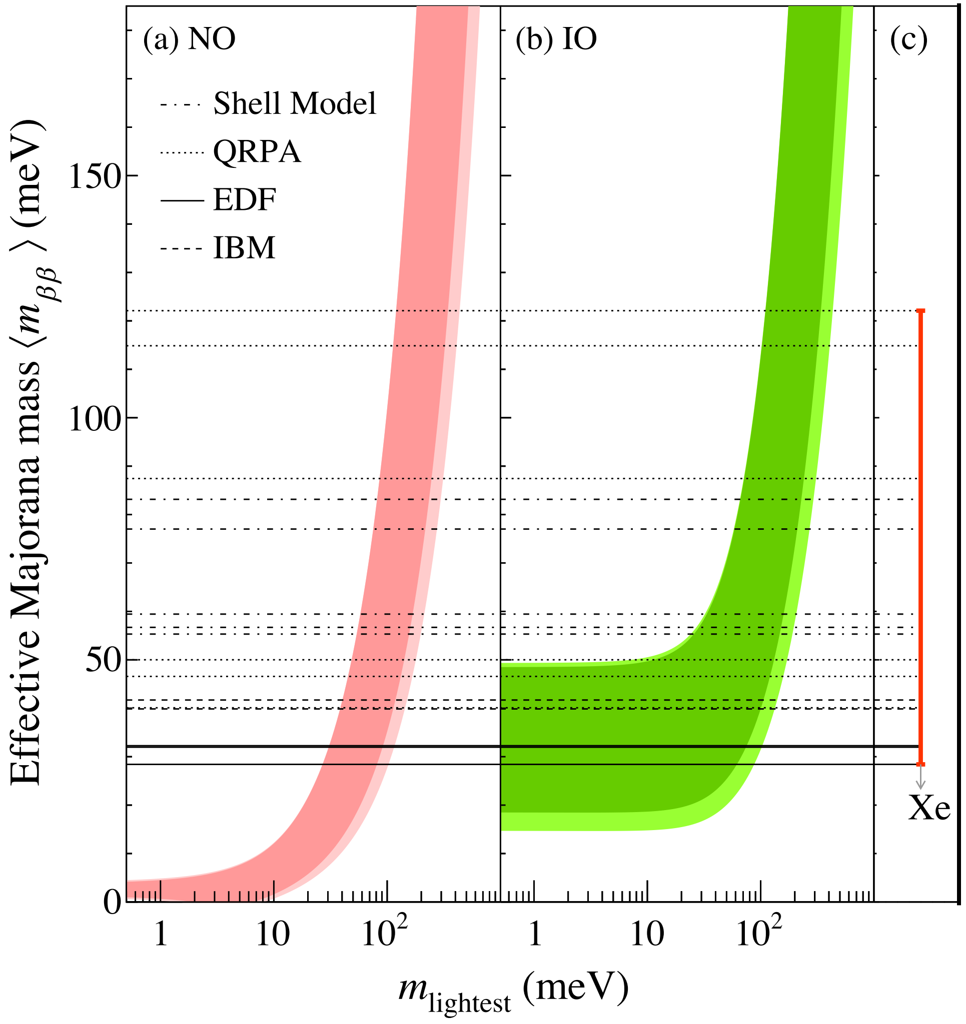
<u>Combined KLZ 400 + 800 Analysis (Wilks')</u>

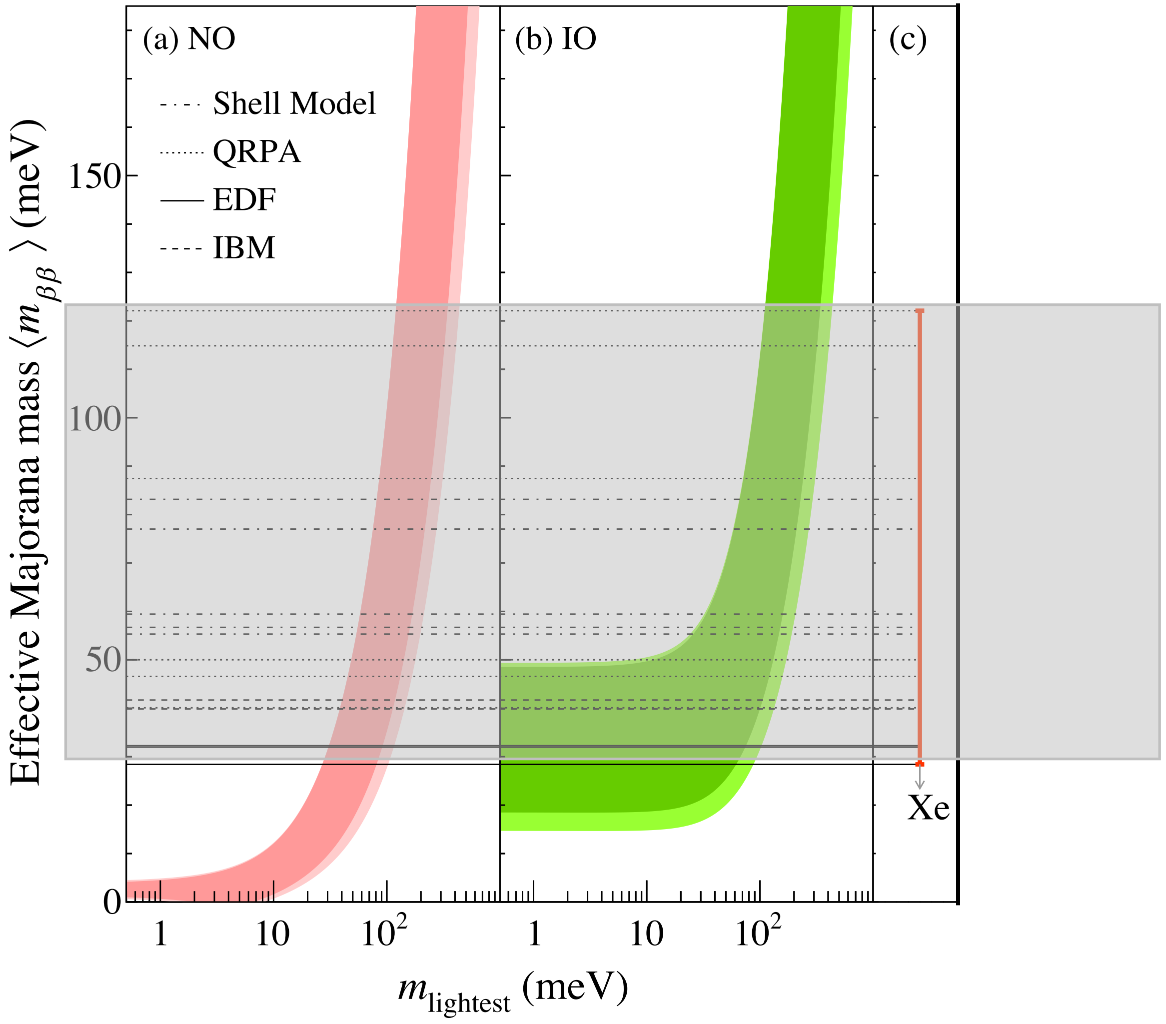
$$T_{1/2}^{0\nu\beta\beta} > 3.8 \times 10^{26}\text{yr (90 \% C.L.)}$$

$$T_{FC}(\mathbf{KLZ_{800}}) > T_{Wilks}(\mathbf{KLZ_{400+800}}) > T_{Wilks}(\mathbf{KLZ_{800}}) \approx T_{Bayes}(\mathbf{KLZ_{800}})$$

$$\left(T_{0.5}^{0\nu2\beta}\right)^{-1} = G^{0\nu}|M^{0\nu}|^2 m_{\beta\beta}^2$$



$$\left(T_{0.5}^{0\nu2\beta}\right)^{-1} = G^{0\nu}|M^{0\nu}|^2 m_{\beta\beta}^2$$



	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

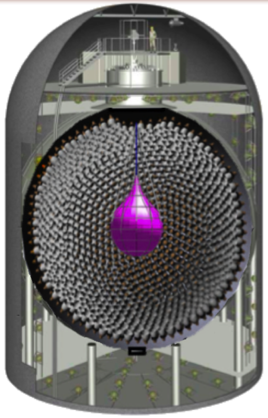
$$\boxed{\langle m_{\beta\beta}\rangle < 28 \ldots 122 \text{ meV}}$$

…KamLAND2-Zen…

Upgrade → KamLAND2-Zen

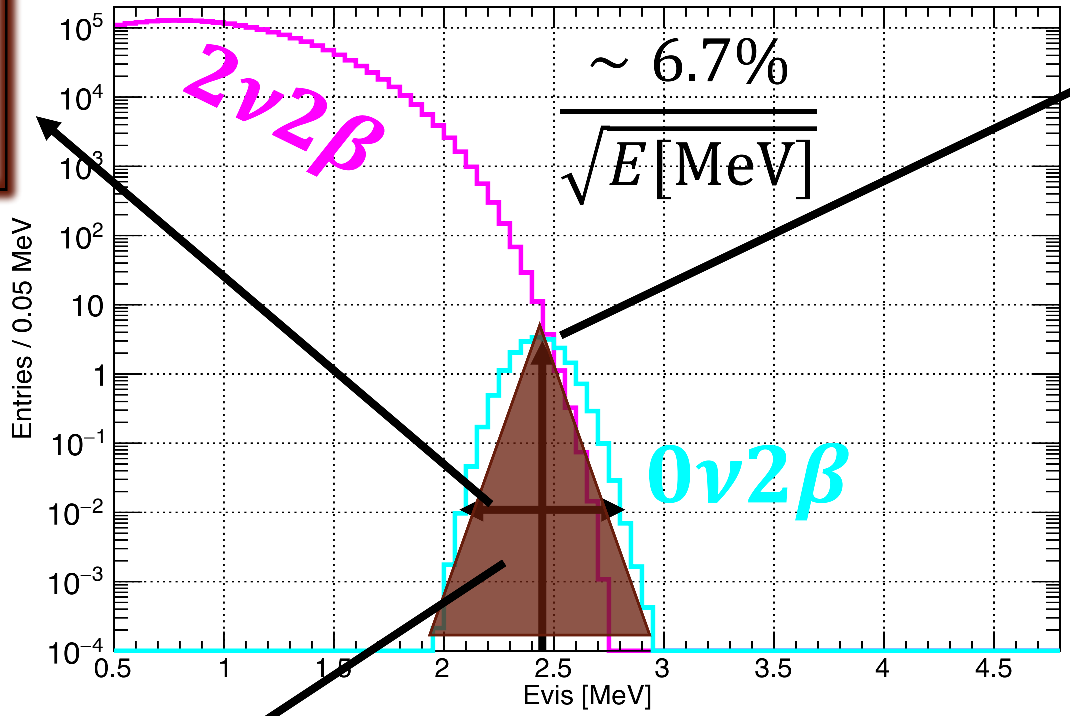
Energy Resolution

- More Light, More efficient



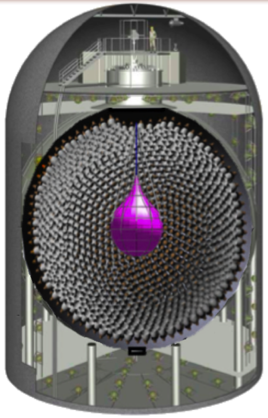
Electronics

- Efficient neutron + Spallation Tagging



Statistics

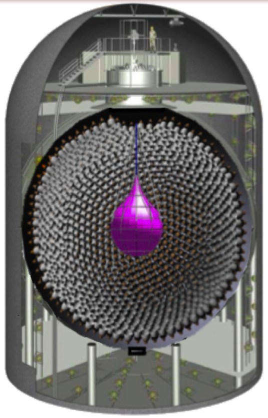
- More Xenon
- Lower Background



Upgrade → KamLAND2-Zen

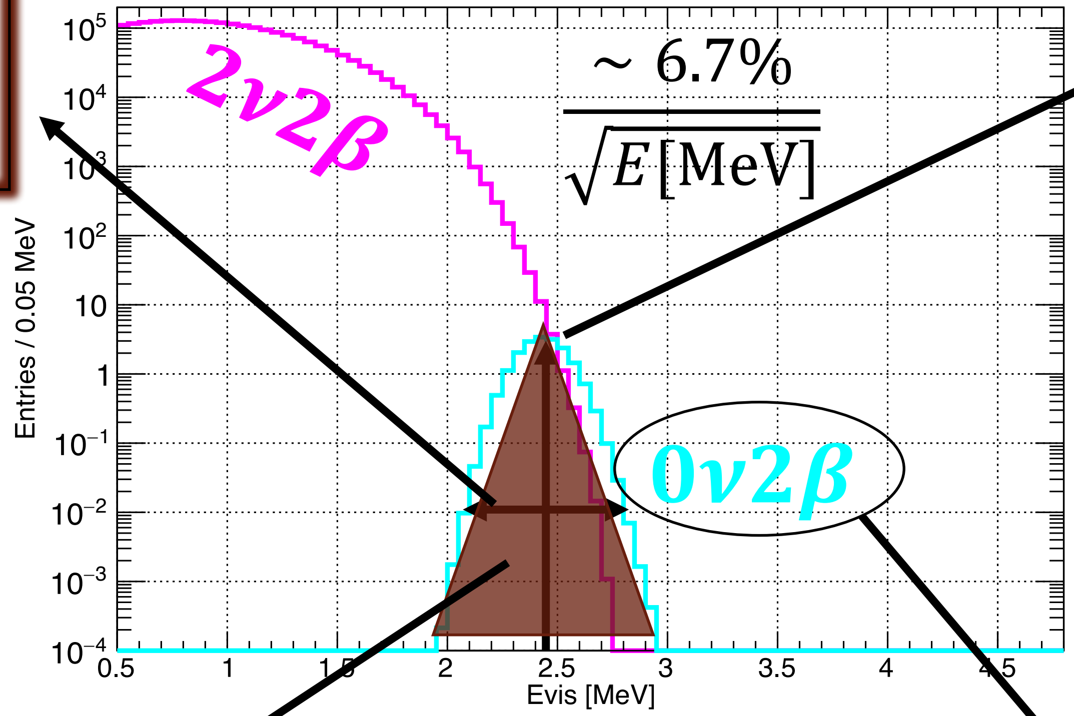
Energy Resolution

- More Light,
  More efficient



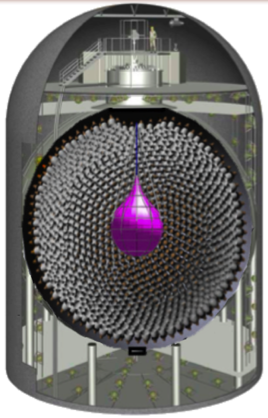
Electronics

- Efficient neutron + Spallation Tagging



Statistics

- More Xenon
- Lower Background

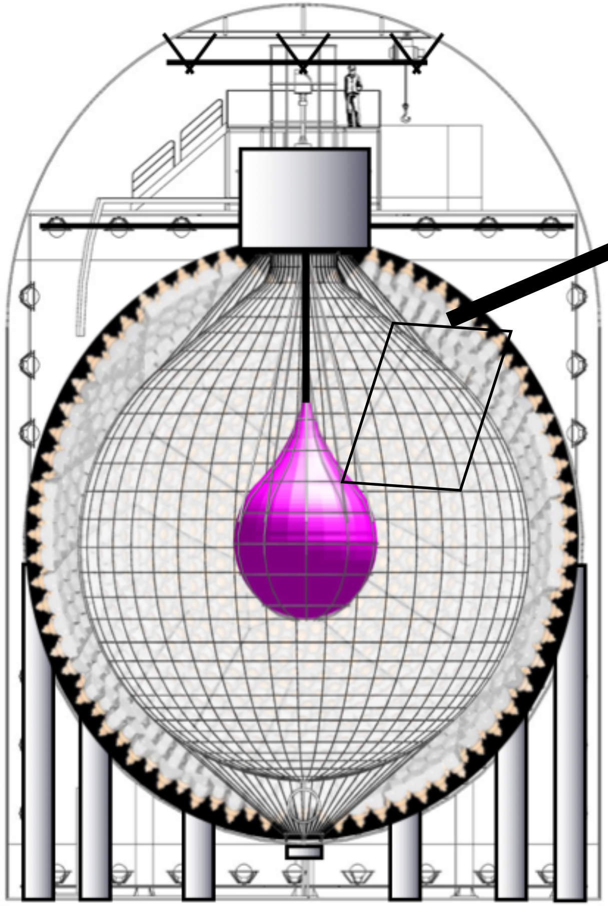


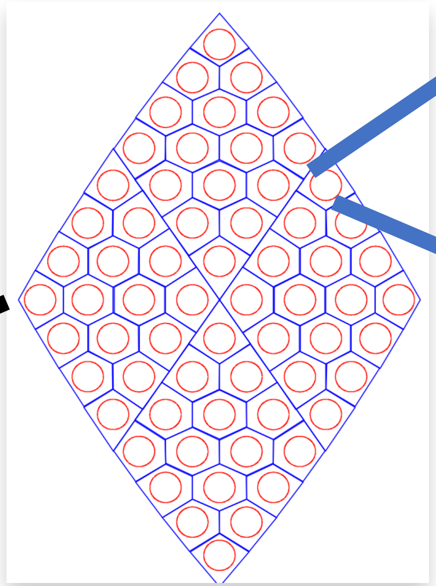
Sensitivity

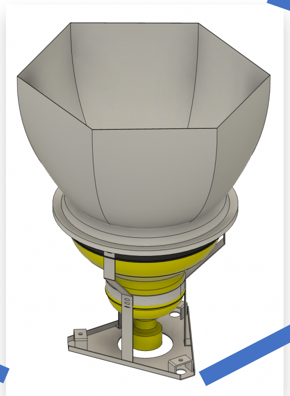
- Reach Normal Ordering

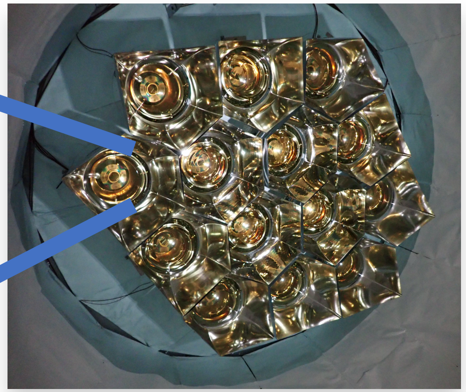
Resolution

Components	Formula	Density [g/cm^3]	Volume ratio
LAB	C_nH_{2n-6}	0.86	80%
PC	C_9H_{12}	0.875	20%
PPO	$C_{15}H_{11}NO$	–	2.00 g/L
Bis-MSB	$C_{24}H_{22}$	–	5 mg/L
LAB-LS	–	0.865	–



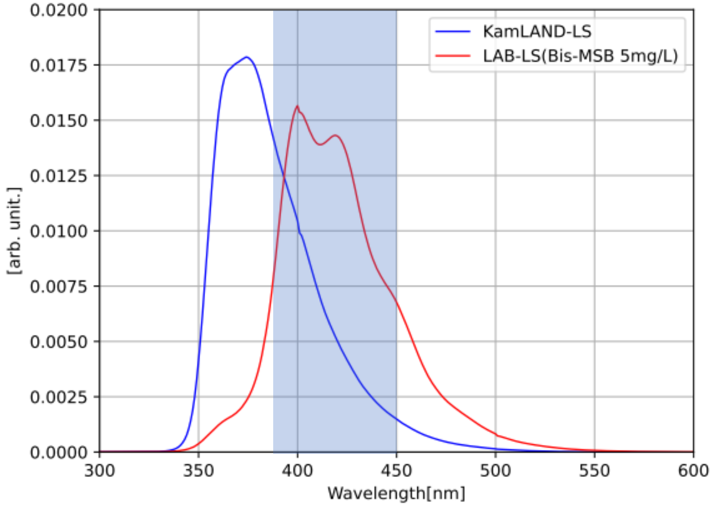


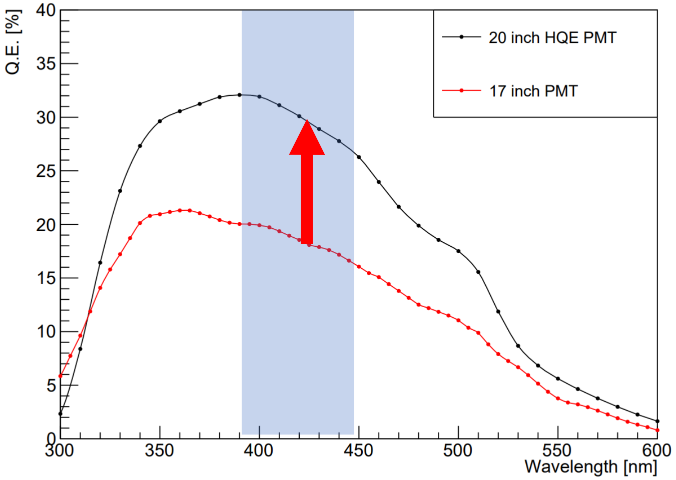




- High Quantum Efficiency PMT x1.9
- Light-collecting Winston cone mirrors x1.8
- New Scintillator Cocktail x1.4

$$@Q_{\beta\beta} = 2.458\ \mathrm{MeV}$$
$$4\% \rightarrow < 2.5\%$$



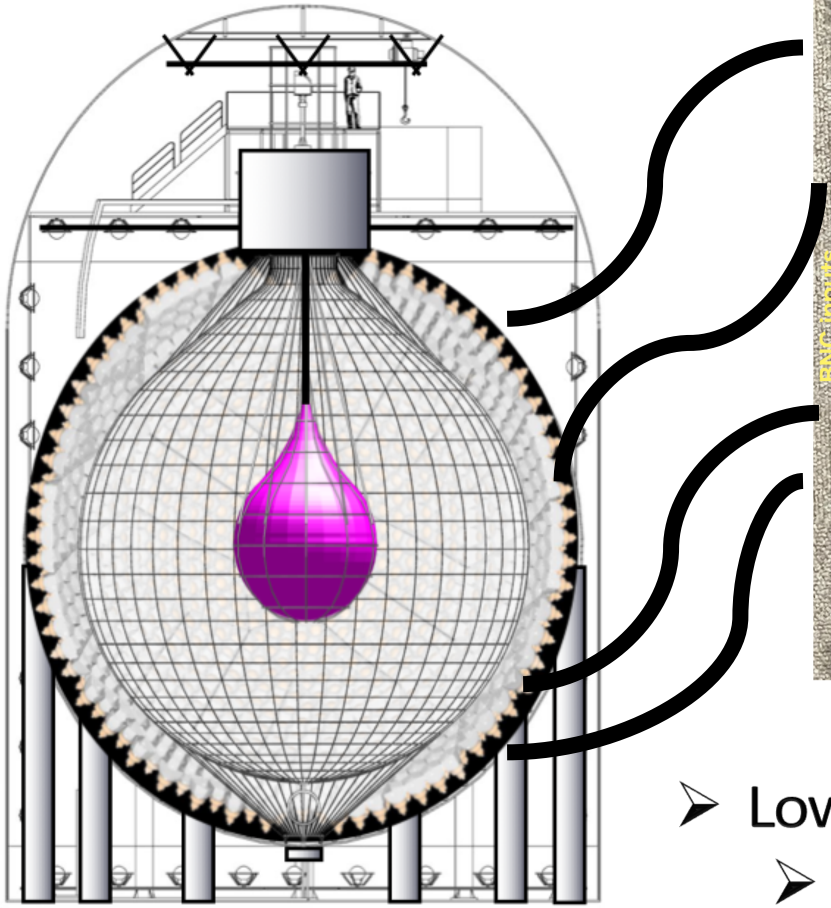


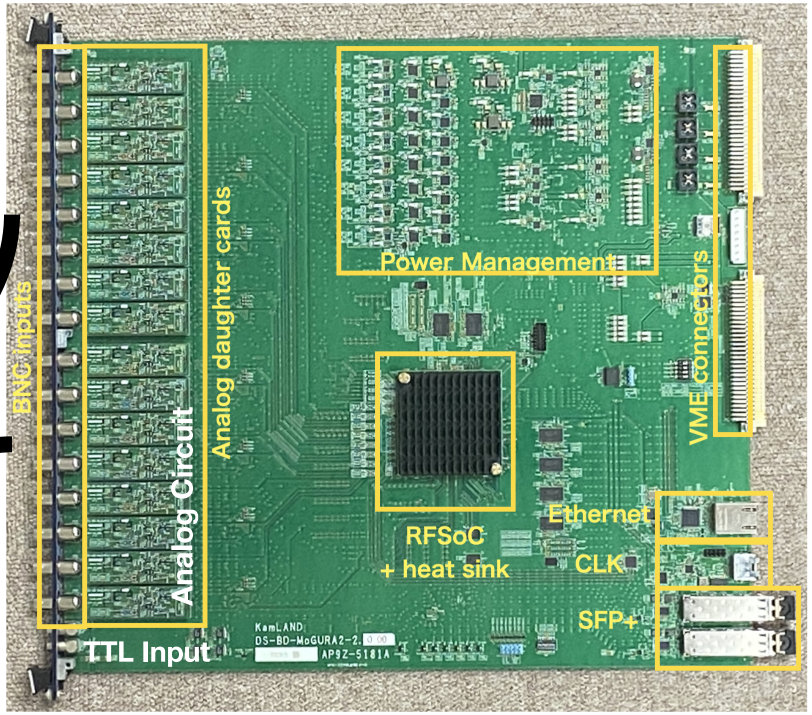
RND

Electronics Upgrade

- 16-channel prototype for KamLAND2-Zen

Goal





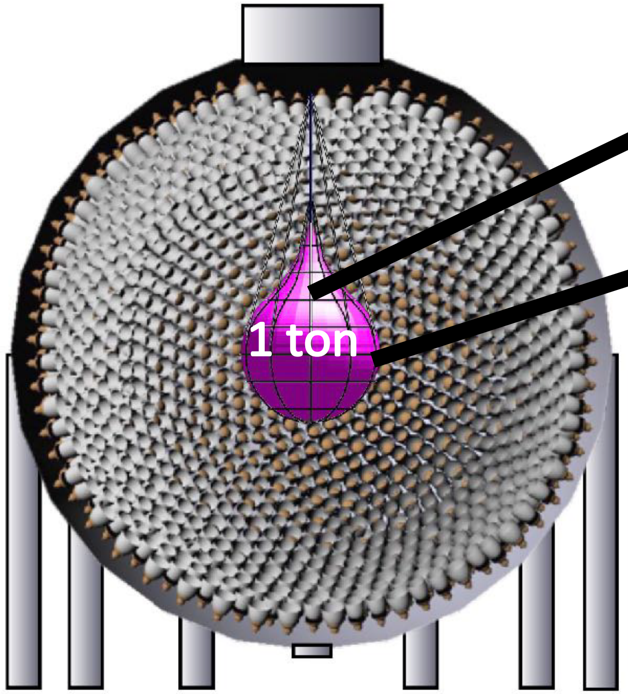
State of the Art Electronics MoGURA2 Boards
DAQ via RFSoC = Radio Frequency System-on-Chip

- Improve background suppression
- Tagging long lived isotopes from cosmic ray spallation
- Improve neutron ⇔ Long-Lived tagging efficiency

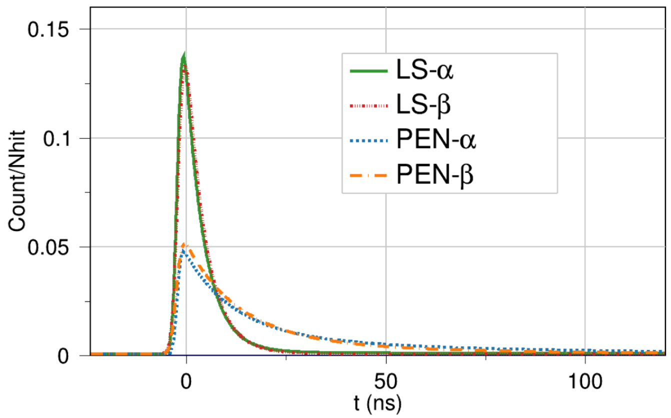
How

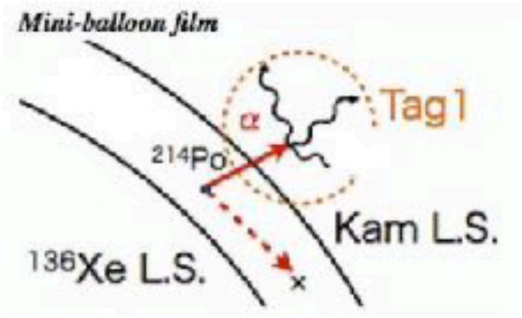
- ➢ Low noise front end to extract smaller pulses
  - ➢ Improve E resolution and extract fainter pulses (α near IB)
- ➢ Embedded AI for Advanced and Dynamic Triggering
  - ➢ Pulse extraction on-chip
  - ➢ Streaming DAQ (zero deadtime)

Other Upgrades

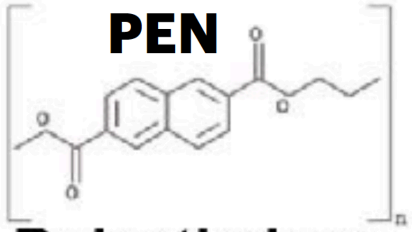


- Aiming for 1000 kg of Enriched Xenon → RND
- Improved Inner Balloon
  - ➢ Reduce Backgrounds originating from Balloon
  - ➢ Limited s/b ratio due to ^{214}Bi contamination



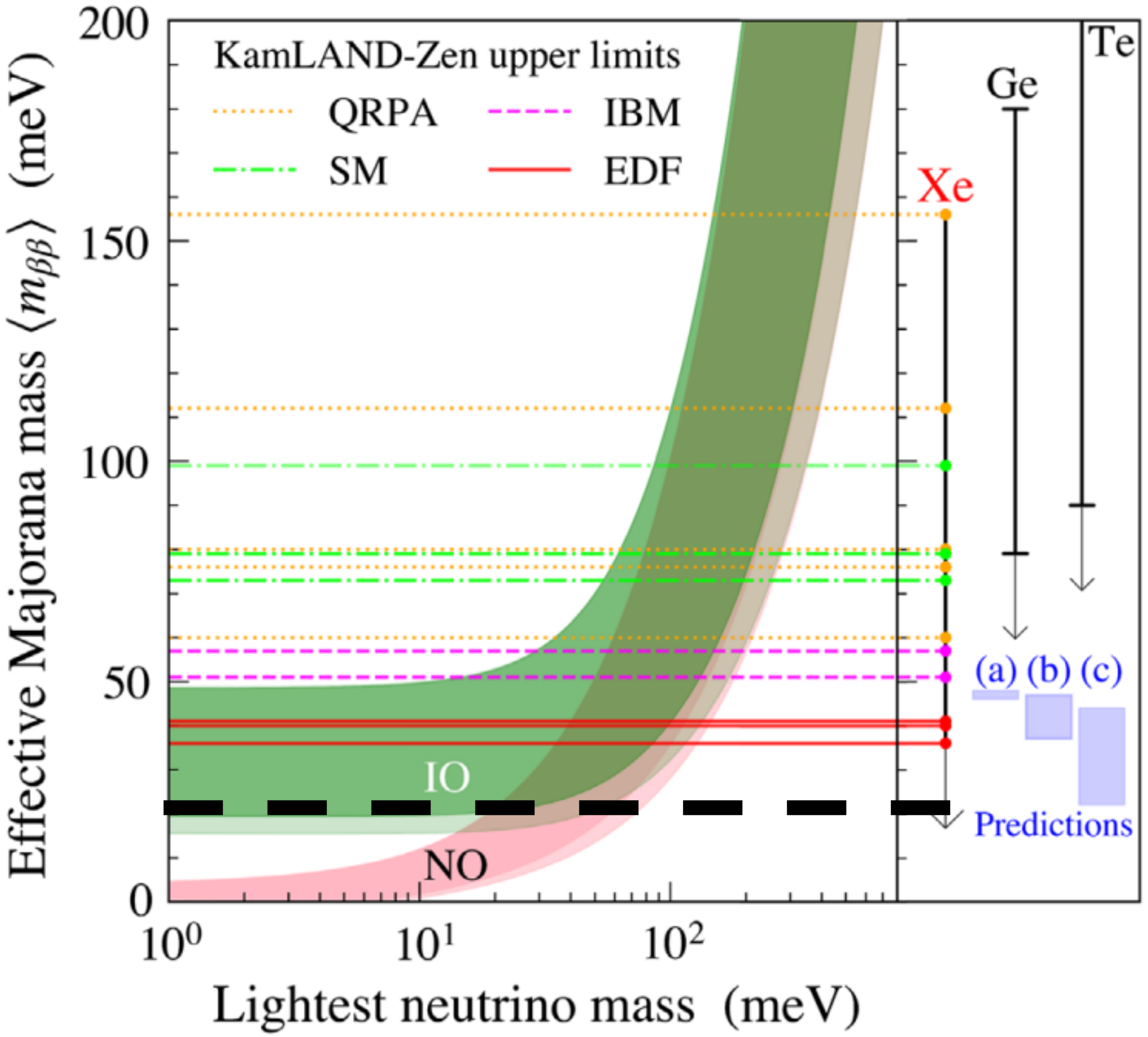


Tag ^{214}Bi decays.



Polyethylene naphthalate

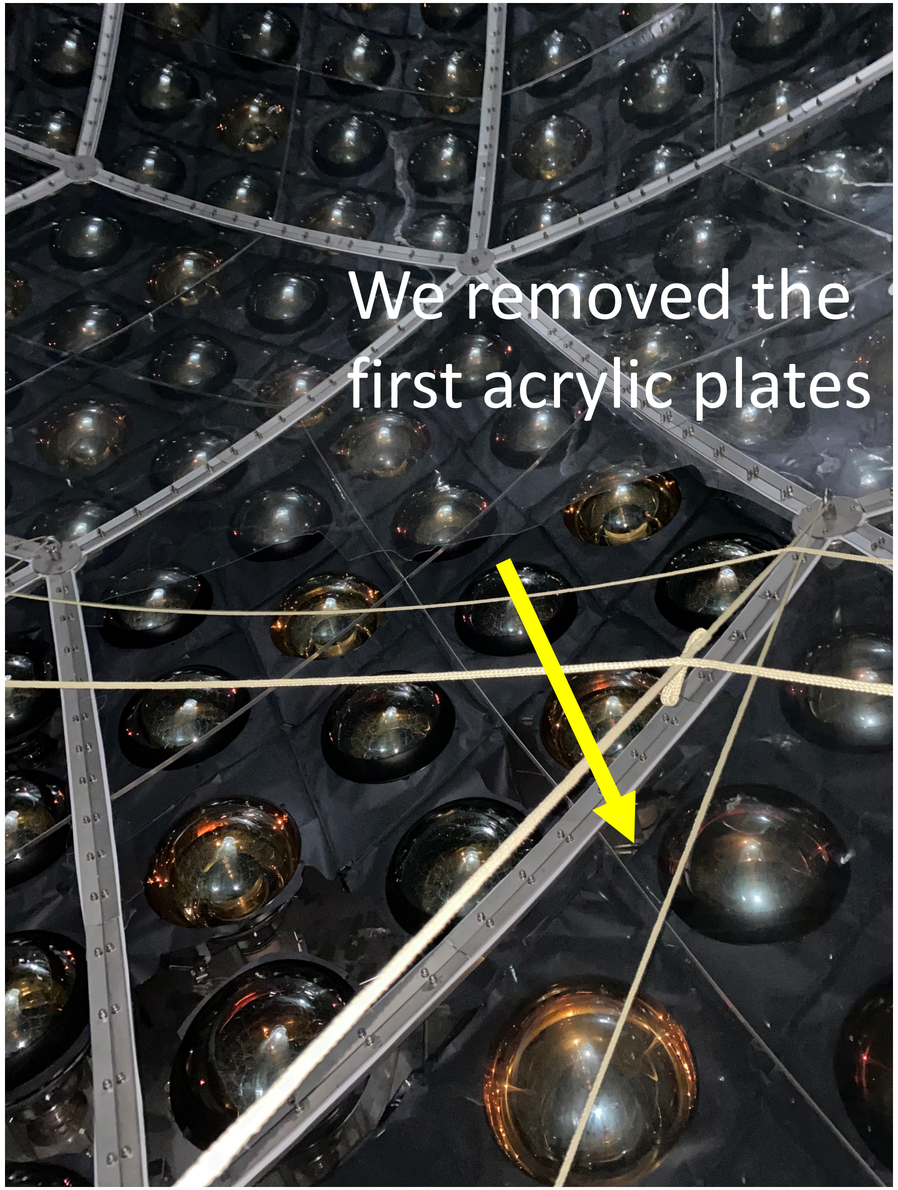
Sensitivity

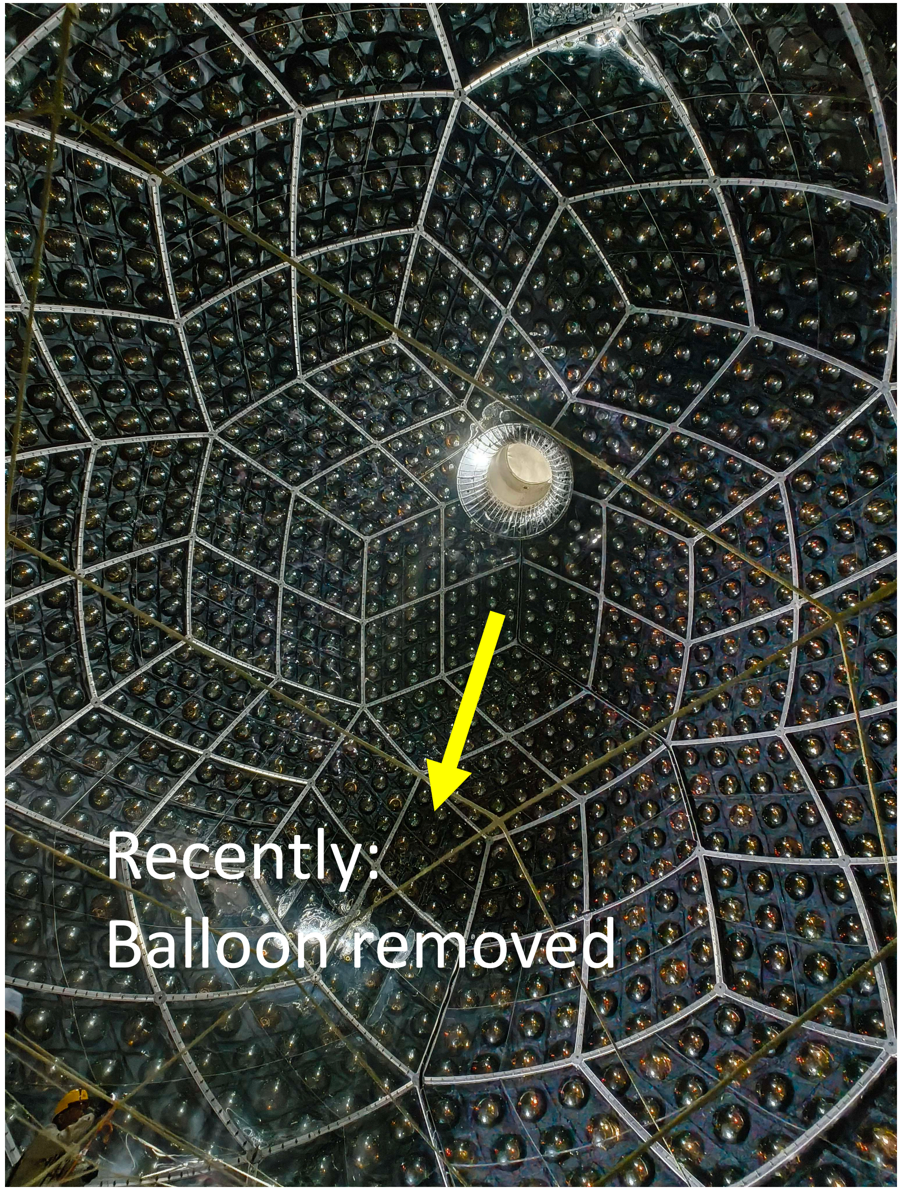


- Cover IO region
- Target Mass Sensitivity: $\langle \boldsymbol{m_{\beta\beta}} \rangle \sim \mathbf{20}$ meV / 5 years
- Half Life Sensitivity / 5 years: $\boldsymbol{T > 2 \times 10^{27}}$ **years**

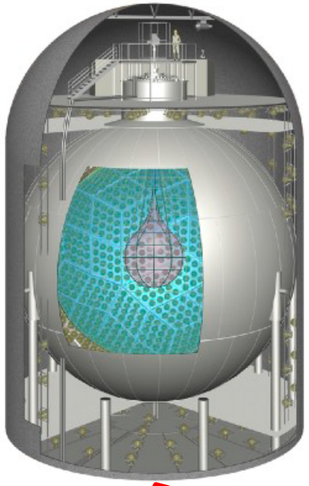
DAQ Start → 2028

Ongoing Constructions

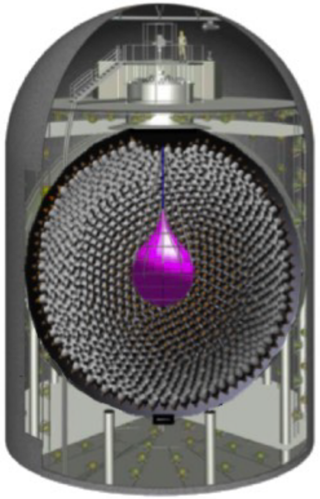




Ongoing Constructions → Timeline



2024 — 2025 — 2026 — 2027 — 2028



DONE — Xe + IB extraction

DONE — XeLS Extraction

DONE — KamLS Extraction

DONE — Outer Balloon Removal

PMT dismantling

Super Clean Facility KERNEL =
Kamioka Extremely Rare phenomena and NEutrino research Lab (IB construction etc.)

HQE PMT + Mirror Instal.

Cleaner Outer Balloon

High Light Yield LS

New electronics + Calibration

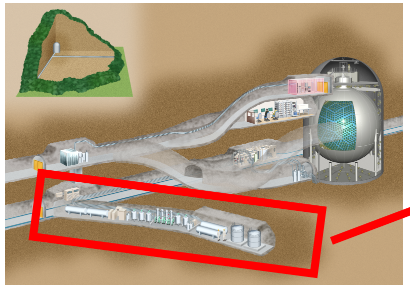
Scintillation Balloon

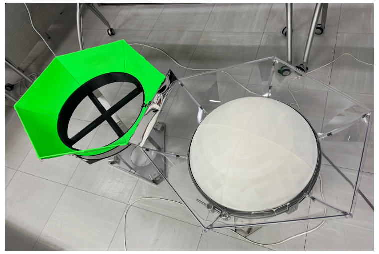
XeLS

Commissioning DAQ

Main DAQ

$0\nu2\beta$ → …





Mock-up

Outlook

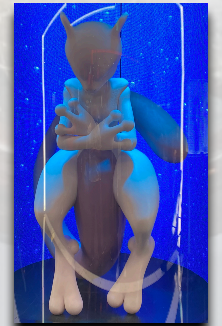
- KamLAND-Zen hunting for 10^{27} years

- Most stringent mass: $\langle m_{\beta\beta} \rangle < 28 \ldots 122$ meV

Outlook

- KamLAND-Zen hunting for 10^{27} years
- Most stringent mass: $\langle m_{\beta\beta} \rangle < 28 \ldots 122$ meV

Thank You



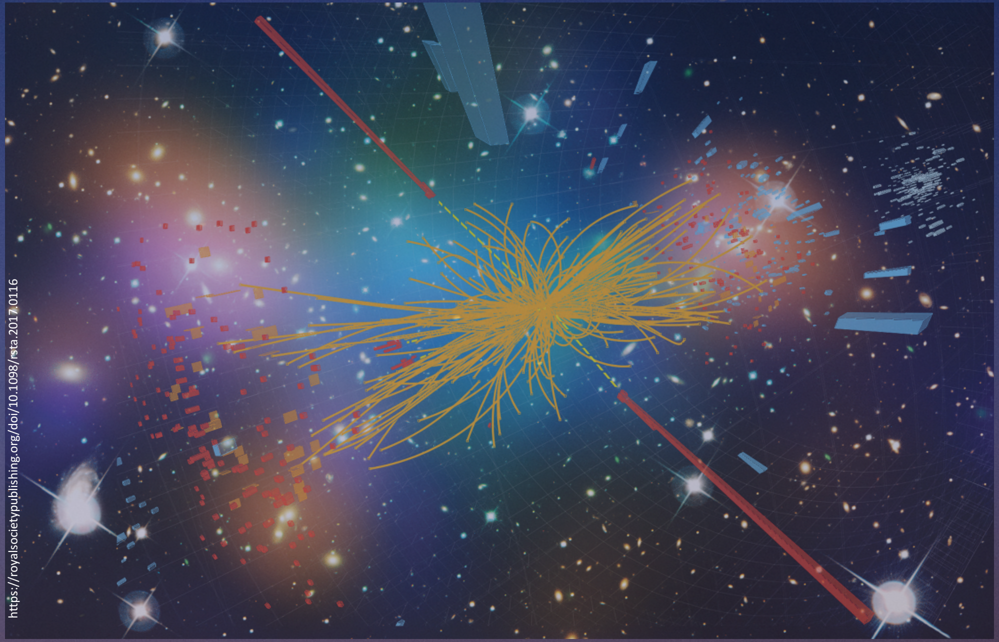
… will be unleashed soon

→ 2028

…Backup…

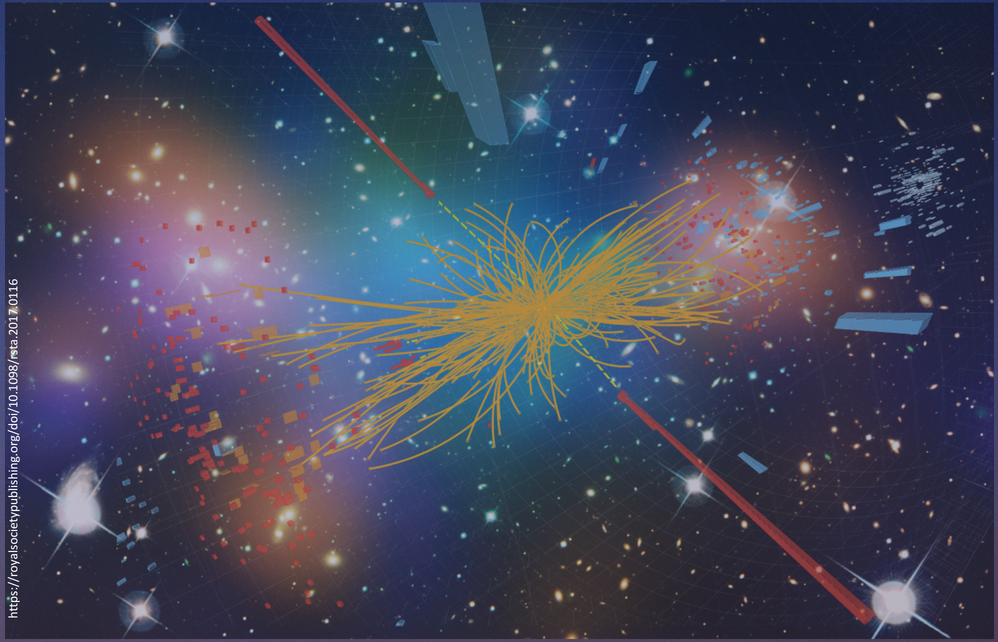
https://www.uni-kiel.de/fileadmin/user_upload/old_news_images/2015/2015-455-1.jpg

Matter-Antimatter-Asymmetry
Baryogenesis through Leptogenesis



https://www.uni-kiel.de/fileadmin/user_upload/old_news_images/2015/2015-455-1.jpg

Matter-Antimatter-Asymmetry
Baryogenesis through Leptogenesis



https://royalsocietypublishing.org/doi/10.1098/rsta.2017.0116

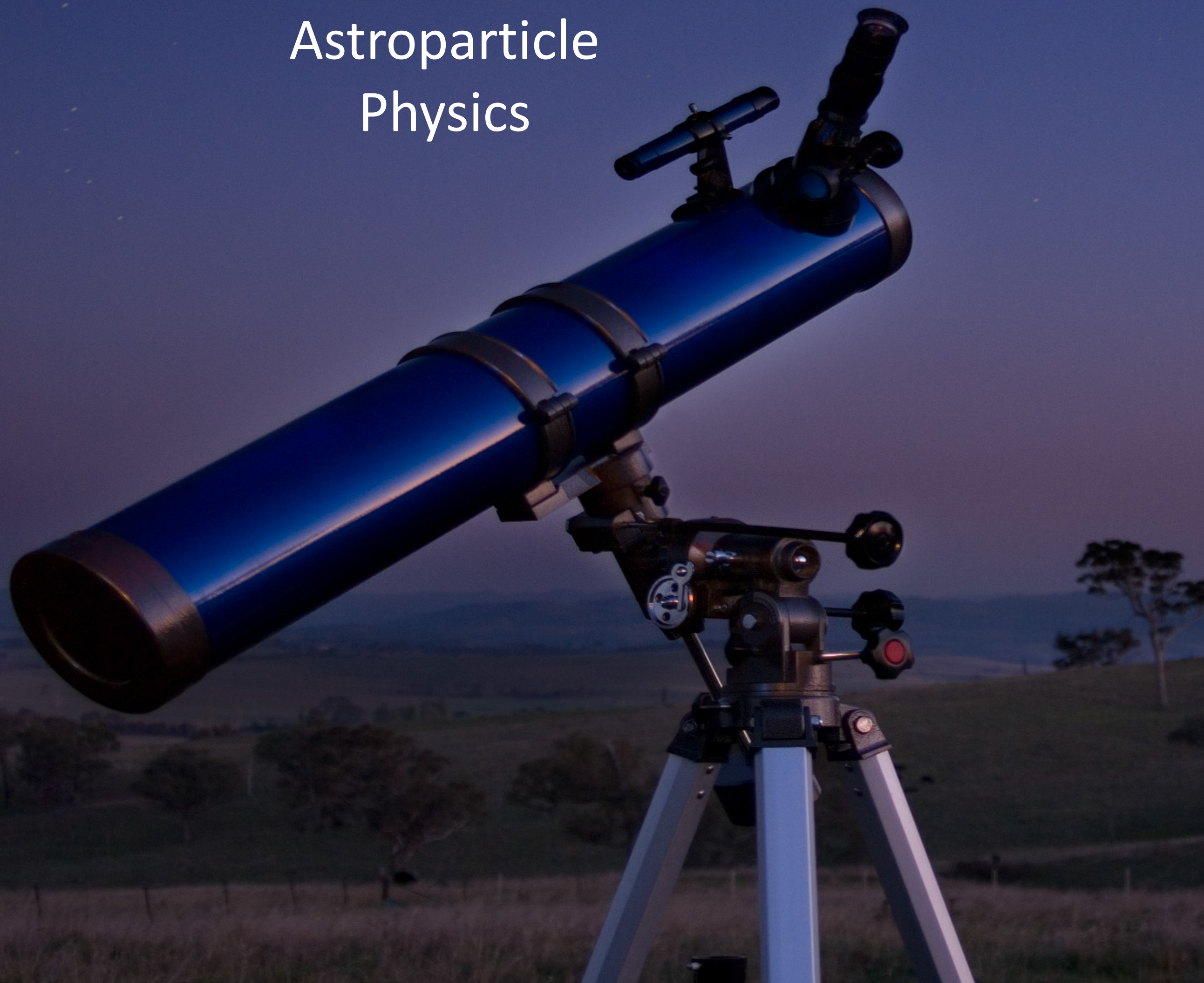
Why is m_ν light? (Seesaw)

https://www.symmetrymagazine.org/article/neutrinos-on-a-seesaw?language_content_entity=und

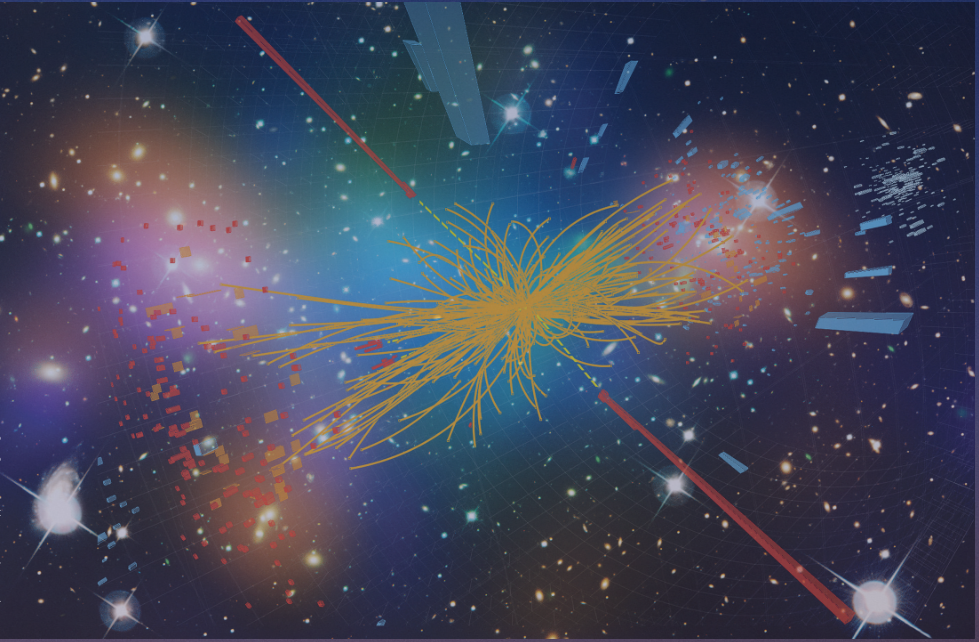
https://www.uni-kiel.de/fileadmin/user_upload/old_news_images/2015/2015-455-1.jpg


Pierre Auger Observatory (Argentinien)

Astroparticle Physics



Matter-Antimatter-Asymmetry
Baryogenesis through Leptogenesis

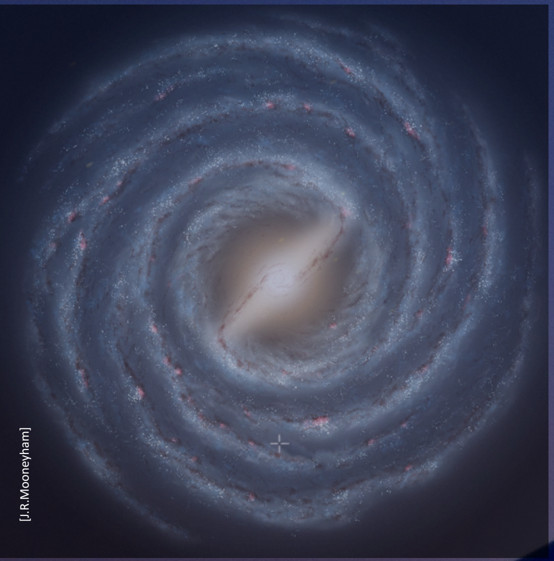

https://royalsocietypublishing.org/doi/10.1098/rsta.2017.0116

Why is m_ν light? (Seesaw)

https://www.symmetrymagazine.org/article/neutrinos-on-a-seesaw?language_content_entity=und

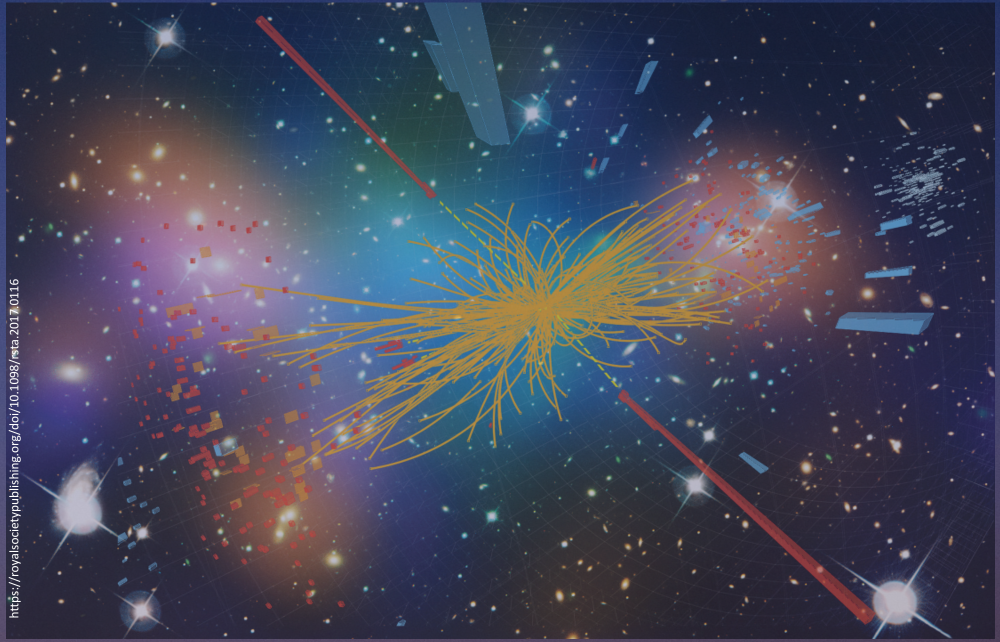
https://www.uni-kiel.de/fileadmin/user_upload/old_news_images/2015/2015-455-1.jpg

Standard Model
Cosmology
ν mass hierarchy



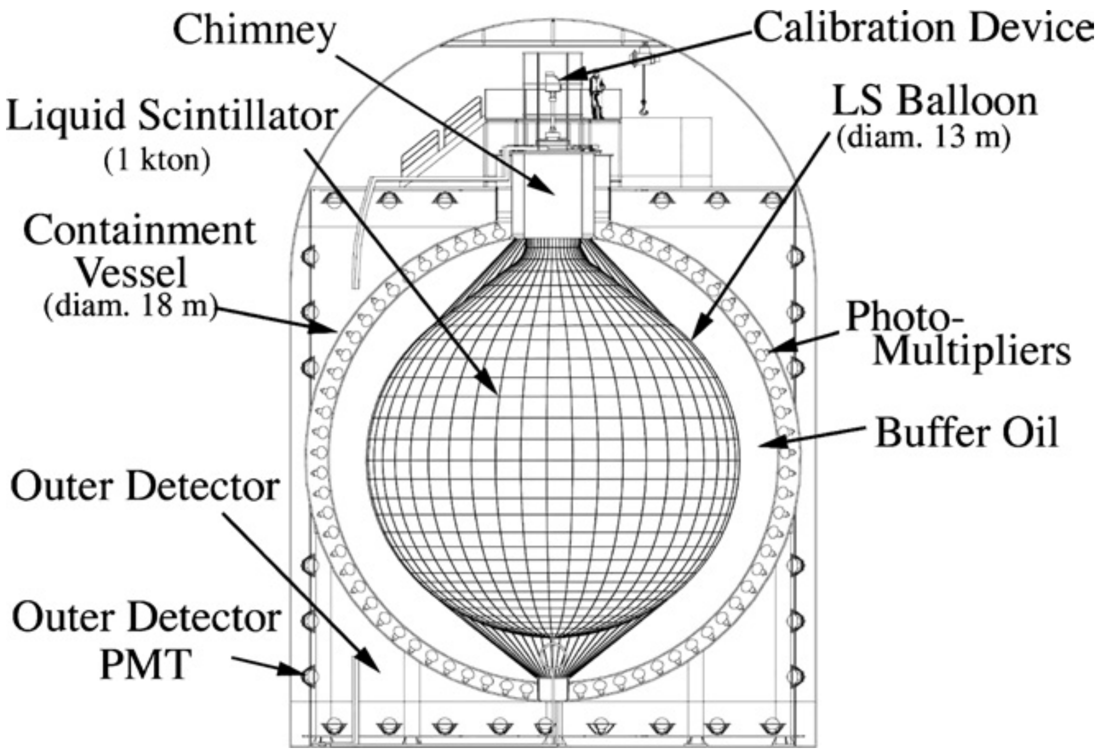
Astroparticle
Physics

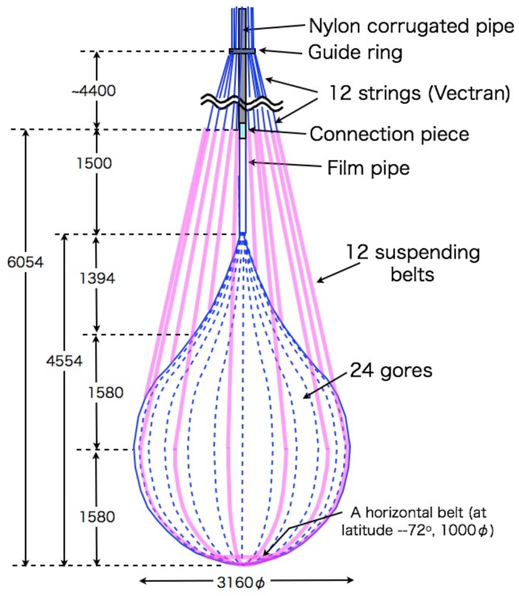
Matter-Antimatter-Asymmetry
Baryogenesis through Leptogenesis



Why is m_ν light? (Seesaw)

https://www.uni-kiel.de/fileadmin/user_upload/old_news_images/2015/2015-455-1.jpg





Publications + Phases

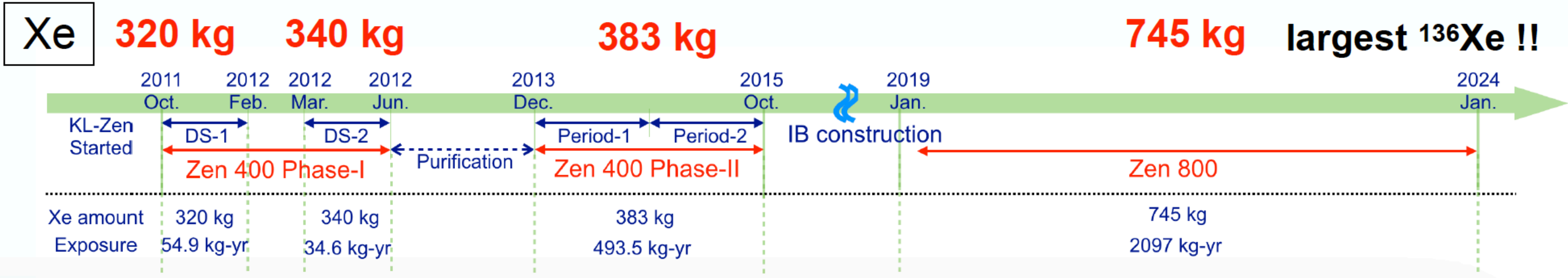
KamLAND-Zen 400: Oct. 12 2011 - Oct. 27 2015
Phase I: PRL 110,(2013) 062502
Phase II: PRL 117.8 (2016): 082503
Excited states: Nuc. Ph. A 946 (2016): 171-181

KamLAND-Zen 800: Feb. 5 2019 to Jan. 12 2024
Phys. Rev. Lett. 130.5 (2023): 051801

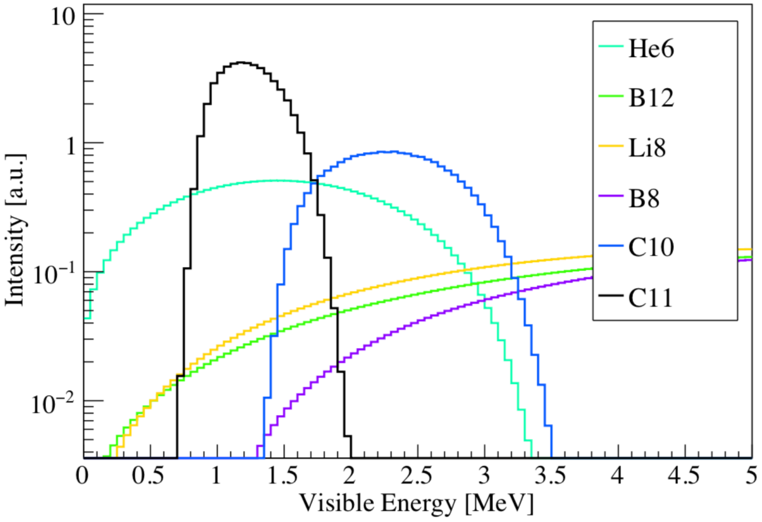
KamLAND-Zen 800 Final Physics Run:
Aug. 27th 2024

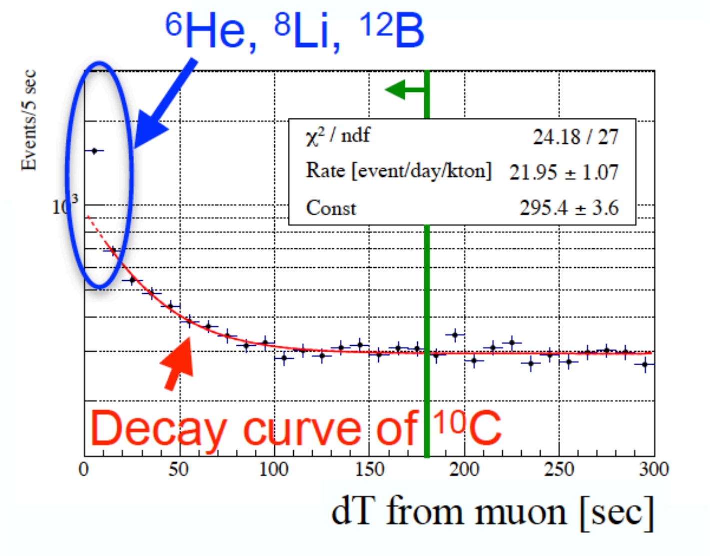
Complete KLZ 800 Dataset
arXiv:2406.11438v1 (2024)

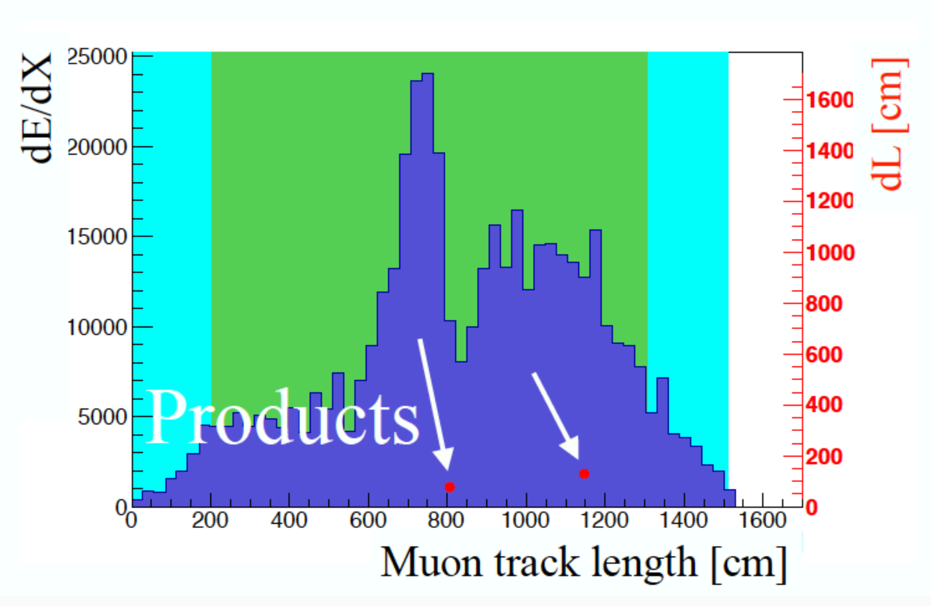
→ **high scalability**



Short-Lived Spallation Products







Energy Spectrum

➔ overlap with ROI

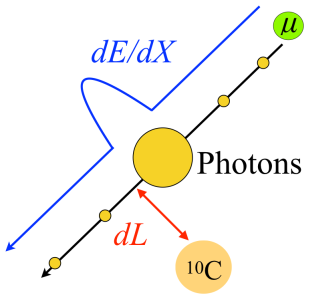
Triple Coincidence Tagging

$\mu + {}^{12}\mathrm{C} \rightarrow \mathrm{n} + X + \mu$ (X= ^{10}C, ..)

➔ (dT,dR) correlation with muons and neutrons (captured)

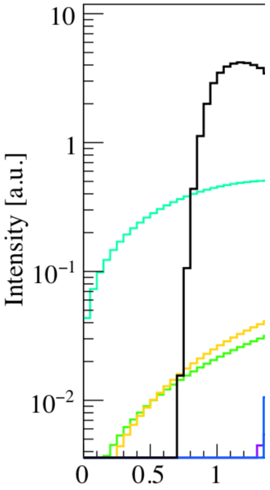
Shower Tagging

➔ (dE/dX,dL) space correlation with muon shower



Rejection Efficiency of short-lived Carbon Spallation products: > 95 %

Short-Lived Spallation Products

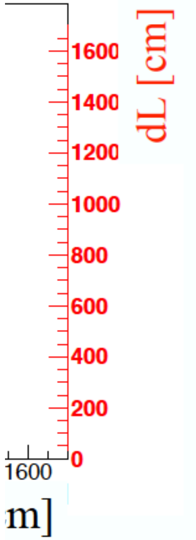


Energy

➔ ove

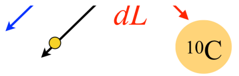
TABLE VIII. Summary of carbon spallation production rate and neutron capture rate in the KamLAND-LS. A unit conversion factor is provided as $(\text{kton day})^{-1} = 7.69 \times 10^{-8}\ \text{cm}^2/(\text{g}\ \mu)$. Spallation reactions were simulated for a KamLAND-LS cylinder and a Xe-LS cylinder, and the results are compared in the last column. For the precise estimation of ^{11}C β^+ decay, we require large statistics and the results from KamLAND is presented [34].

			Production rate $(\text{kton day})^{-1}$				
	$\tau_{1/2}$	Q (MeV)	$\mathcal{R}_{n\text{-tag}}$	$\mathcal{R}_{\text{isolated}}$	$\mathcal{R}^{\text{Data}}_{\text{Total}}$	$\mathcal{R}^{\text{FLUKA}}_{\text{KamLAND-LS}}$	$\mathcal{R}^{\text{FLUKA}}_{\text{Xe-LS}}/\mathcal{R}^{\text{FLUKA}}_{\text{KamLAND-LS}}$
^{8}He	119.1 ms	10.7 (β^-)	$0.5^{+1.1}_{-0.5}$	$0.3^{+0.5}_{-0.3}$	$0.8^{+1.2}_{-0.5}$	0.55 ± 0.04	0.96 ± 0.03
^{9}Li	178.3 ms	13.6 (β^-)	$2.5^{+0.3}_{-0.3}$	$0.1^{+0.2}_{-0.1}$	$2.7^{+0.3}_{-0.4}$	4.9 ± 0.4	1.00 ± 0.01
^{12}B	20.2 ms	13.4 (β^-)	43^{+3}_{-2}	$14.4^{+0.6}_{-0.08}$	58^{+3}_{-2}	42 ± 3	1.013 ± 0.003
^{12}N	11.0 ms	17.3 (β^+)	$0.8^{+0.9}_{-0.7}$	$0.07^{+0.2}_{-0.06}$	$0.9^{+0.9}_{-0.7}$	0.74 ± 0.06	1.02 ± 0.03
^{8}Li	839.9 ms	16.0 (β^-)	21^{+4}_{-3}	$0.9^{+1.6}_{-0.9}$	22^{+4}_{-4}	47 ± 3	1.021 ± 0.004
^{8}B	770 ms	18.0 (β^+)	3^{+4}_{-3}	$0.8^{+1.0}_{-0.6}$	4^{+4}_{-3}	11.0 ± 0.8	1.024 ± 0.008
^{9}C	126.5 ms	16.5 (β^+)	1^{+2}_{-1}	$0.2^{+0.5}_{-0.2}$	2^{+2}_{-1}	1.5 ± 0.1	1.02 ± 0.02
^{11}Be	13.8 s	11.5 (β^-)	$1.2^{+0.3}_{-0.2}$	$0^{+0.06}_{-0}$	$1.2^{+0.3}_{-0.2}$	1.09 ± 0.08	1.02 ± 0.02
^{10}C	19.29 s	3.65 (β^+)	19^{+2}_{-2}	$0.5^{+0.6}_{-0.5}$	19^{+2}_{-2}	23 ± 2	1.029 ± 0.005
^{6}He	806.7 ms	3.51 (β^-)	10^{+1}_{-1}	1^{+1}_{-1}	11^{+2}_{-1}	28 ± 2	1.022 ± 0.005
^{11}C	1221.8 s	1.98 (β^+)	–	–	973 ± 10 [34]	679 ± 49	1.012 ± 0.001
n	207.5 μs	2.223(cap.γ)	–	–	3781 ± 296	4046 ± 292	1.1485 ± 0.0004

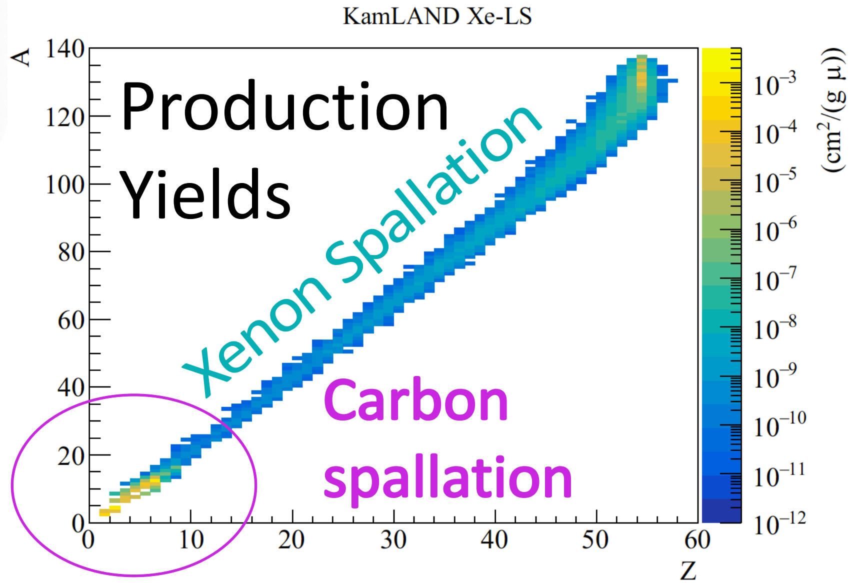


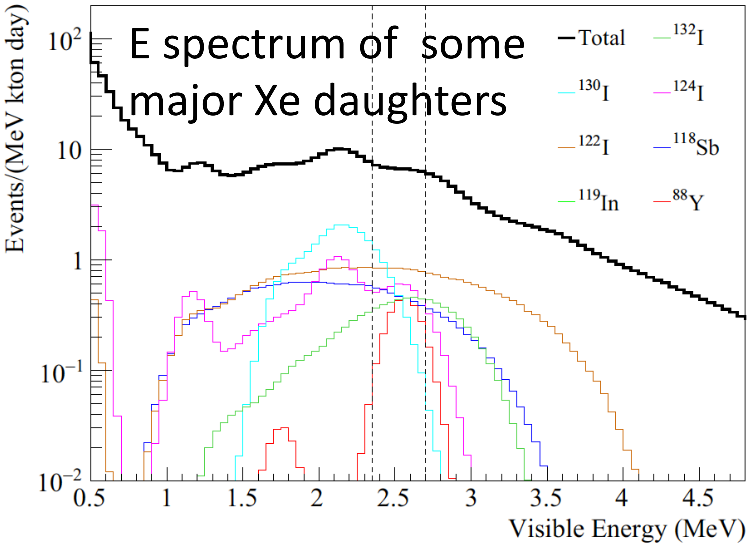
relation

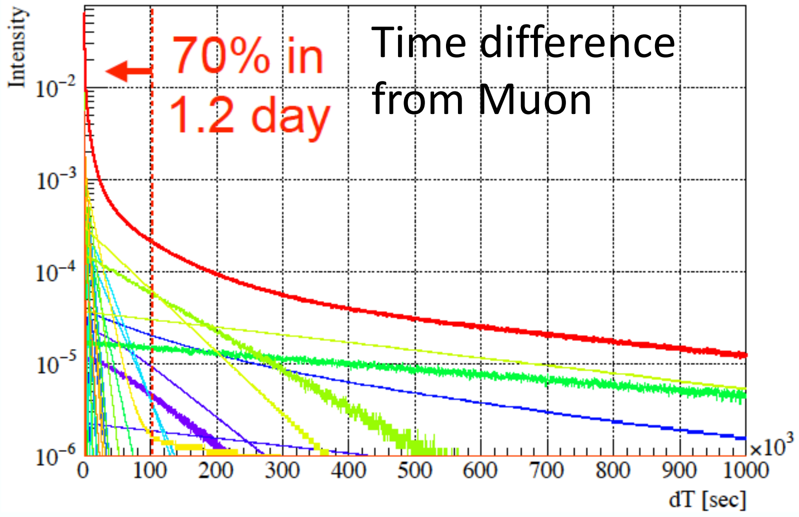
Spallation products: > 95 %



Long-lived Spallation Produts





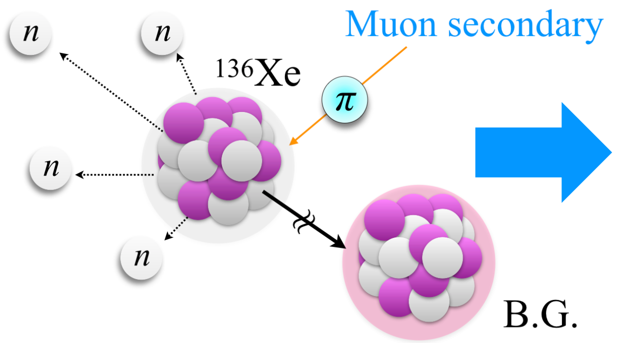


Based on Fluka simulation → A vs. Z

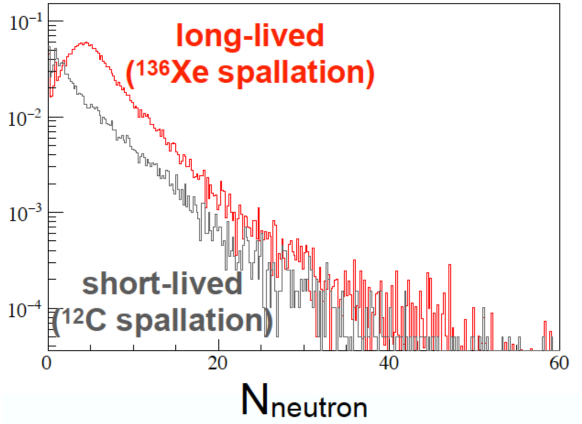
Expected Rate in ROI is ~ 30 events/Xe-ton/yr

Long time veto needed

Strategy → Likelihood-based tagging (N_n, dR, dT)



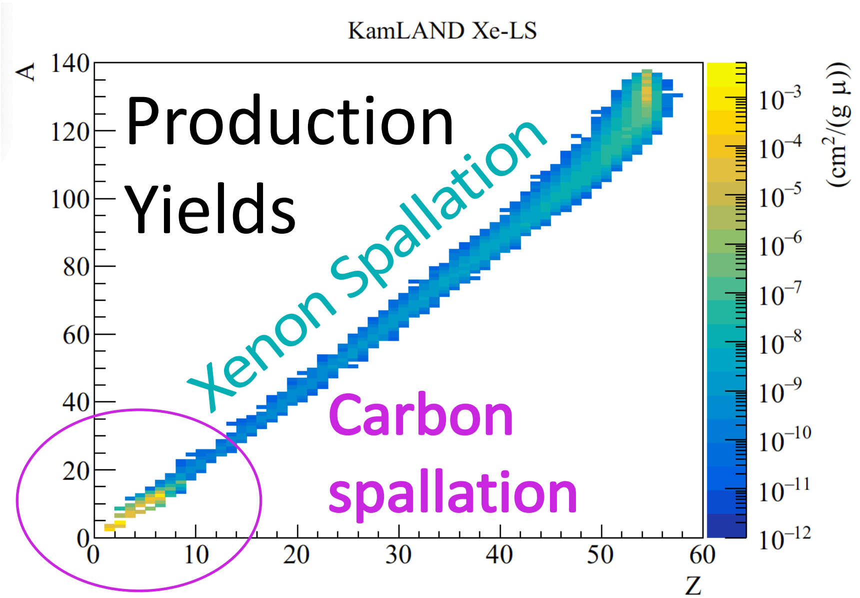
Dense neutron cluster
- ➔ Neutron Multiplicity
- ➔ Time and space correlation of muons and multiple neutrons



Rejection Efficiency for Xe Spallation Products

$\approx (\mathbf{47 \pm 9})\%$

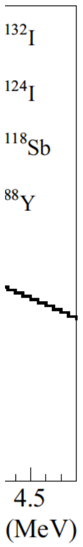
Long-li roduts



Based on Fluka simulation → A vs. Z

TABLE IX. Simulated production rate of dominant isotopes in $2.35 \leqslant E \leqslant 2.70$ MeV in Xe-LS.

	$\tau_{1/2}$ (s)	Q (MeV)	(kton day)$^{-1}$ ROI	Total
^{88}Y	9.212×10^{6}	3.62 (EC/$\beta^{+}\gamma$)	0.110	0.136
^{90m1}Zr	8.092×10^{-1}	2.31 (IT)	0.012	0.093
^{90}Nb	5.256×10^{4}	6.11 (EC/$\beta^{+}\gamma$)	0.024	0.095
^{96}Tc	3.698×10^{5}	2.97 (EC/$\beta^{+}\gamma$)	0.012	0.059
^{98}Rh	5.232×10^{2}	5.06 (EC/$\beta^{+}\gamma$)	0.011	0.076
^{100}Rh	7.488×10^{4}	3.63 (EC/$\beta^{+}\gamma$)	0.088	0.234
^{104}Ag	4.152×10^{3}	4.28 (EC/$\beta^{+}\gamma$)	0.012	0.160
^{104m1}Ag	2.010×10^{3}	4.28 (EC/$\beta^{+}\gamma$)	0.018	0.111
^{107}In	1.944×10^{3}	3.43 (EC/$\beta^{+}\gamma$)	0.019	0.135
^{108}In	3.480×10^{3}	5.16 (EC/$\beta^{+}\gamma$)	0.089	0.194
^{110}In	1.771×10^{4}	3.89 (EC/$\beta^{+}\gamma$)	0.053	0.236
^{110m1}In	4.146×10^{3}	3.89 (EC/$\beta^{+}\gamma$)	0.066	0.351
^{109}Sn	1.080×10^{3}	3.85 (EC/$\beta^{+}\gamma$)	0.027	0.122
^{113}Sb	4.002×10^{2}	3.92 (EC/$\beta^{+}\gamma$)	0.036	0.231
^{114}Sb	2.094×10^{2}	5.88 (EC/$\beta^{+}\gamma$)	0.020	0.297
^{115}Sb	1.926×10^{3}	3.03 (EC/$\beta^{+}\gamma$)	0.031	0.839
^{116}Sb	9.480×10^{2}	4.71 (EC/$\beta^{+}\gamma$)	0.071	0.939
^{118}Sb	2.160×10^{2}	3.66 (EC/$\beta^{+}\gamma$)	0.165	1.288
^{124}Sb	5.201×10^{6}	2.90 (EC/$\beta^{-}\gamma$)	0.016	0.054
^{115}Te	3.480×10^{2}	4.64 (EC/$\beta^{+}\gamma$)	0.012	0.124
^{117}Te	3.720×10^{3}	3.54 (EC/$\beta^{+}\gamma$)	0.052	0.594
^{119}I	1.146×10^{3}	3.51 (EC/$\beta^{+}\gamma$)	0.053	0.533
^{120}I	4.896×10^{3}	5.62 (EC/$\beta^{+}\gamma$)	0.091	0.953
^{122}I	2.178×10^{2}	4.23 (EC/$\beta^{+}\gamma$)	0.289	1.965
^{124}I	3.608×10^{5}	3.16 (EC/$\beta^{+}\gamma$)	0.190	1.654
^{130}I	4.450×10^{4}	2.95 ($\beta^{-}\gamma$)	0.195	1.188
^{132}I	8.262×10^{3}	3.58 ($\beta^{-}\gamma$)	0.148	0.427
^{134}I	3.150×10^{3}	4.18 ($\beta^{-}\gamma$)	0.043	0.183
^{121}Xe	2.406×10^{3}	3.75 (EC/$\beta^{+}\gamma$)	0.100	0.540
^{125}Cs	2.802×10^{3}	3.09 (EC/$\beta^{+}\gamma$)	0.012	0.266
^{126}Cs	9.840×10^{1}	4.82 (EC/$\beta^{+}\gamma$)	0.011	0.080
^{128}Cs	2.196×10^{2}	3.93 (EC/$\beta^{+}\gamma$)	0.031	0.229



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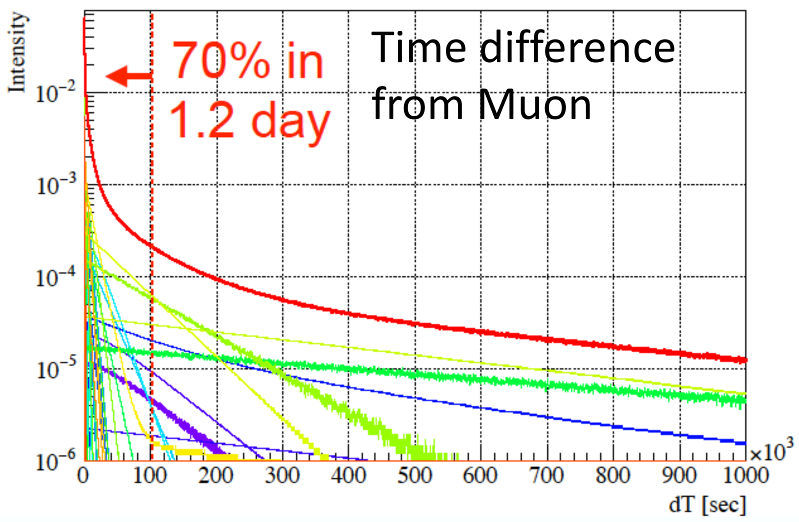
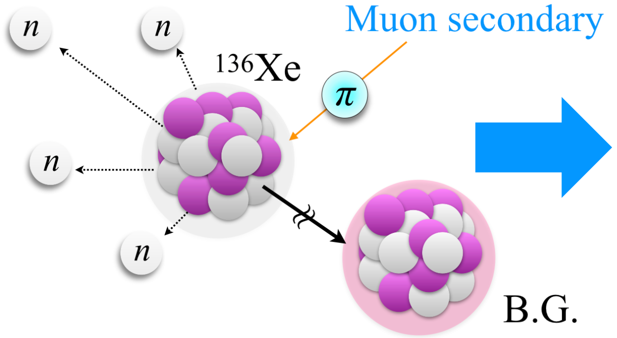


Long time veto needed

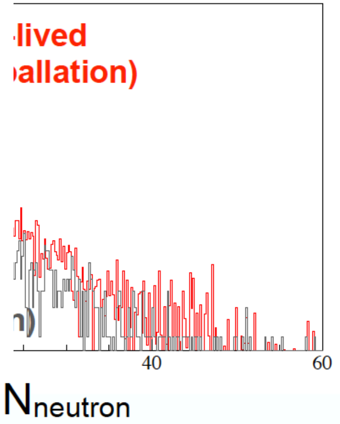
Strategy → Likelihood-based tagging (N_n, dR, d



Dense neut

➔ Neutron

➔ Time anc correlati and mult



Rejection Efficiency for Xe Spallation Products

$$\approx (\mathbf{47 \pm 9})\%$$