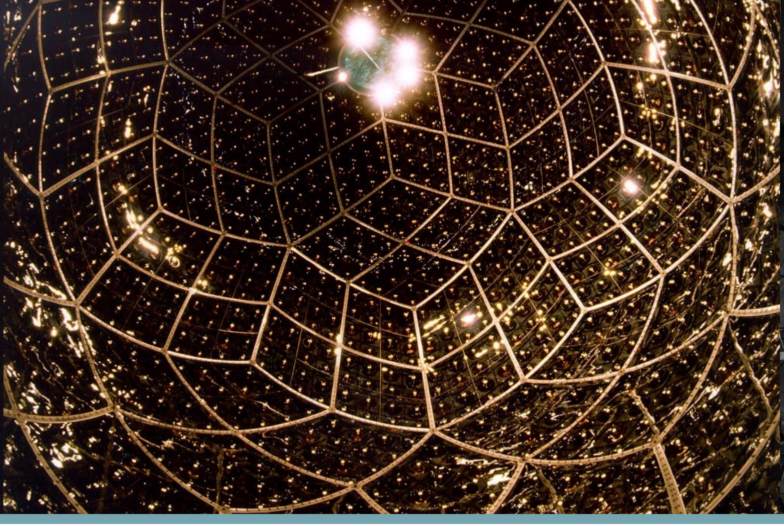


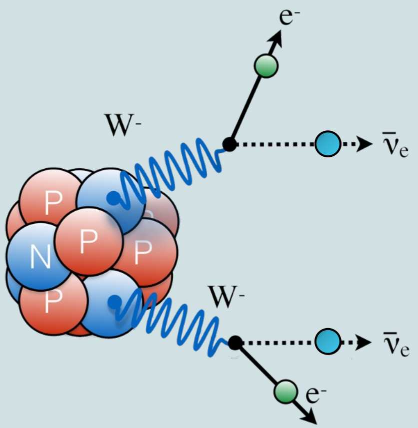

LATEST KAMLAND-ZEN RESULTS AND THE IMPACT OF MUON SPALLATION ON THE $0\nu\beta\beta$ SEARCH

Kelly Weerman (Nikhef, Amsterdam, Netherlands)
On behalf of the KamLAND collaboration

TAUP2025 | Xichang, China | Aug. 24th – 30th 2025

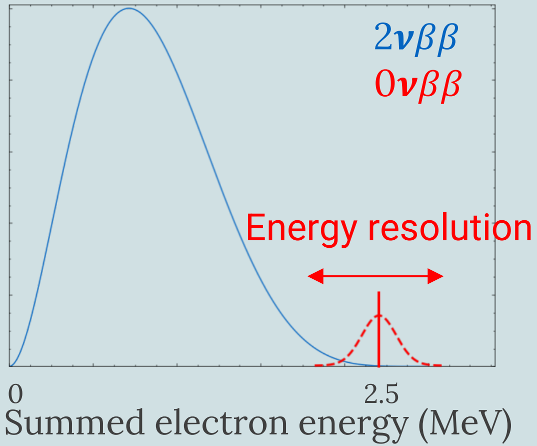
Observable signature of neutrinoless double beta decay

Double β-decay



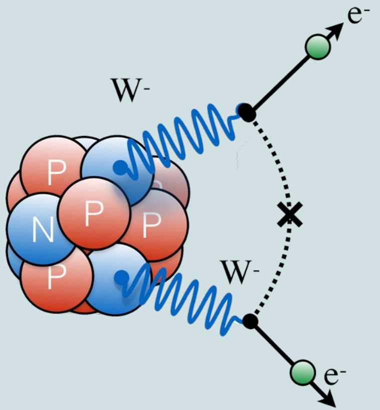
$T_{1/2} \sim 10^{18\text{-}24}$ years

Energy distribution of electrons



$$^{136}_{54}\mathrm{Xe} \rightarrow {}^{136}_{56}\mathrm{Ba} + 2e^-$$

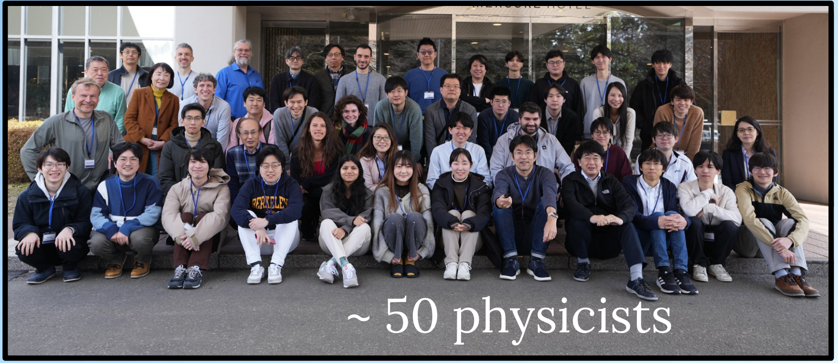
Neutrinoless double β

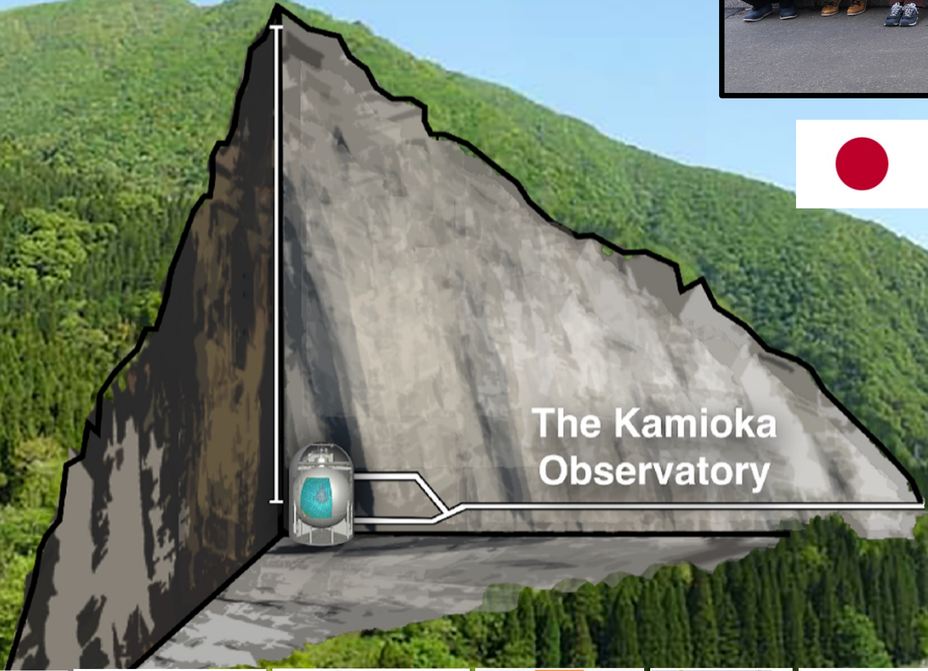


$T_{1/2} > 10^{26}$ years

Most stringent limit on $0\nu\beta\beta$ in **xenon** from KamLAND-Zen: $T_{1/2} > 3.8 \times 10^{26}$ years

KamLAND Collaboration





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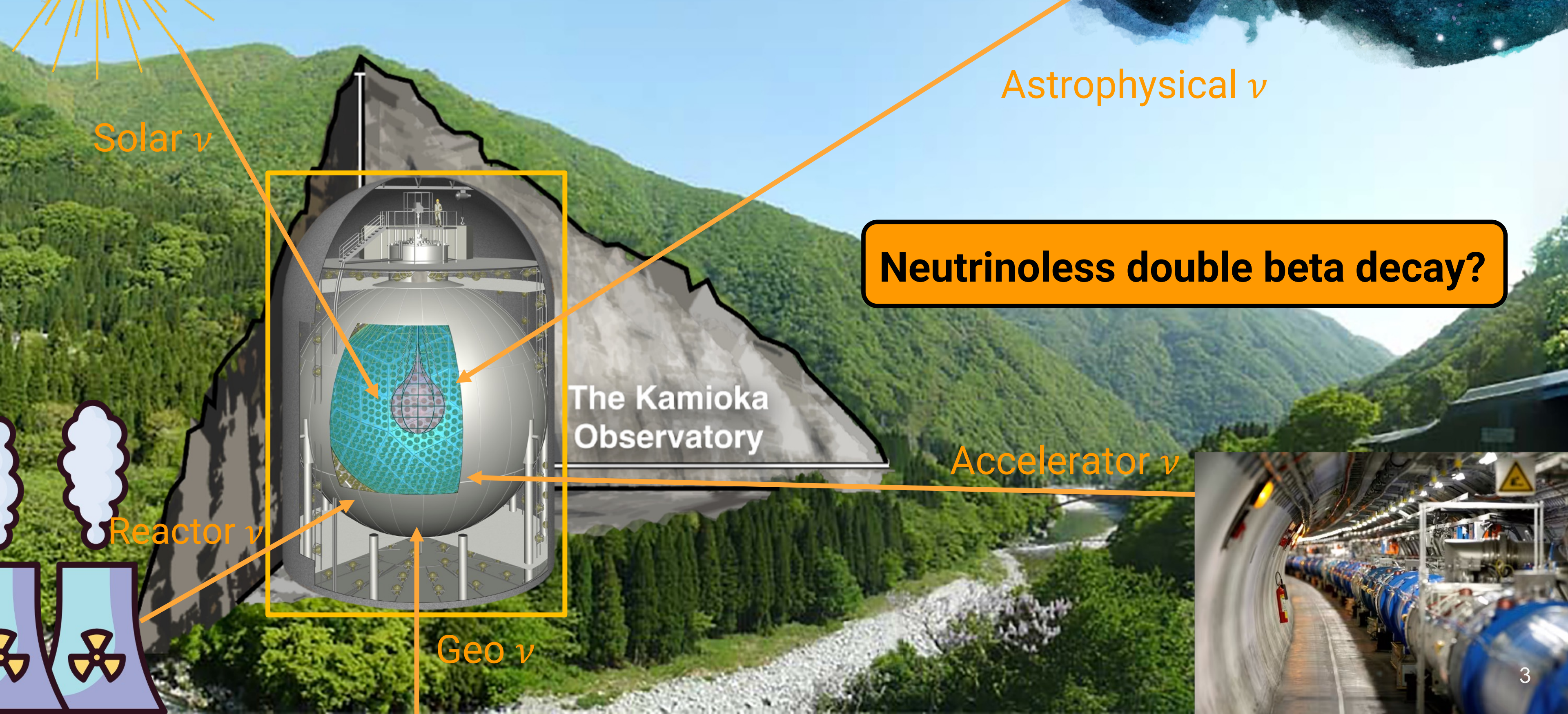
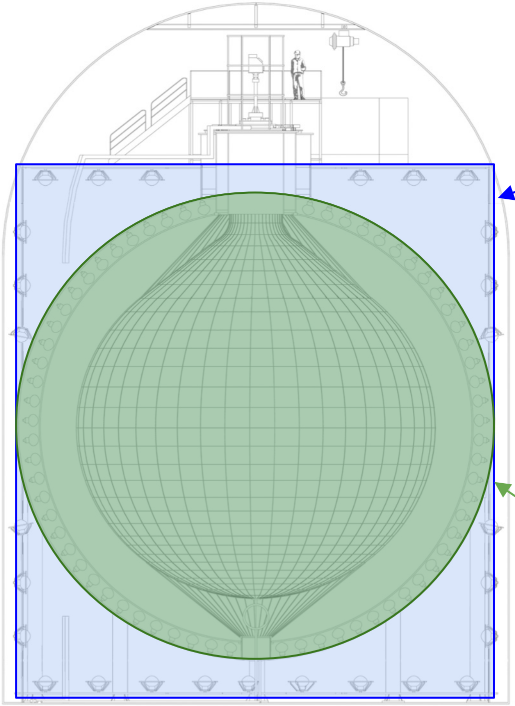
BERKELEY LAB
THE UNIVERSITY OF TENNESSEE KNOXVILLE
TUNL
UNIVERSITY of HAWAI'I
VIRGINIA TECH
BOSTON UNIVERSITY
Nikhef
IPMU

General Purpose Detector



Neutrinoless double beta decay?

Kamioka Liquid Scintillator Antineutrino Detector



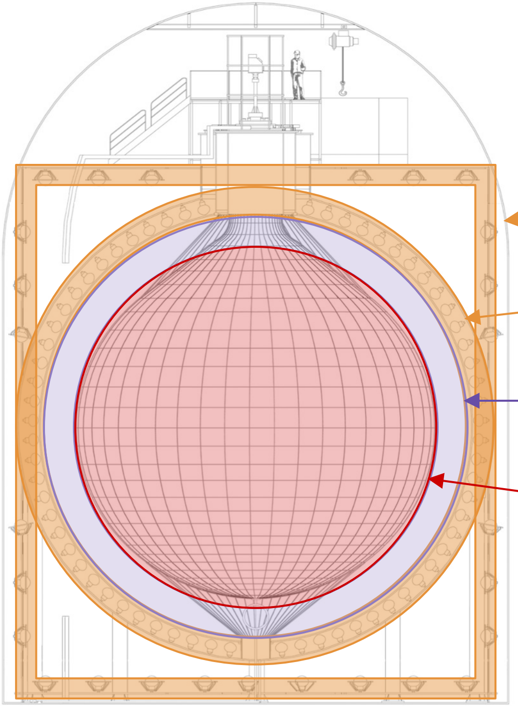
Outer Cherenkov detector

Inner Scintillation detector

Cylindrical tank, ⌀18m

- 3.2kt pure water

Kamioka Liquid Scintillator Antineutrino Detector



Outer Cherenkov detector

Outer PMTs

Inner PMTs

Buffer oil

Liquid Scintillator balloon

Inner Scintillation detector

Cylindrical tank, ⌀18m

- 3.2kt pure water

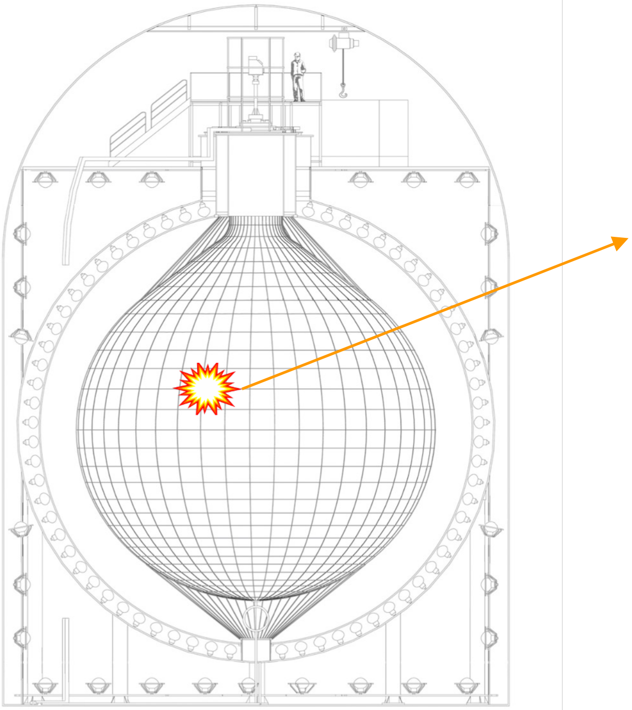
~1800 17- & 20-inch PMTs

Non-scintillation oil 1.4kt

KamLAND-LS, ⌀13m, 1kt

- Dodecane 80.2%
- Pseudocumene 19.8%
- PPO 1.36g/L

Kamioka Liquid Scintillator Antineutrino Detector



Charge & Timing

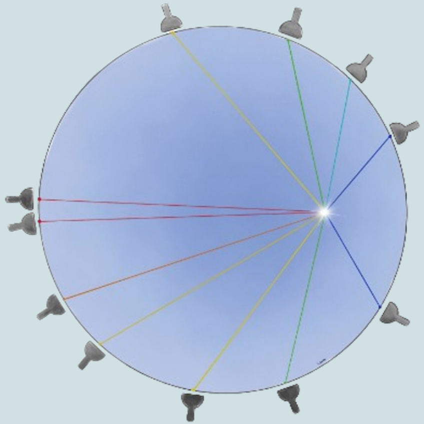
↓

Energy & Vertex

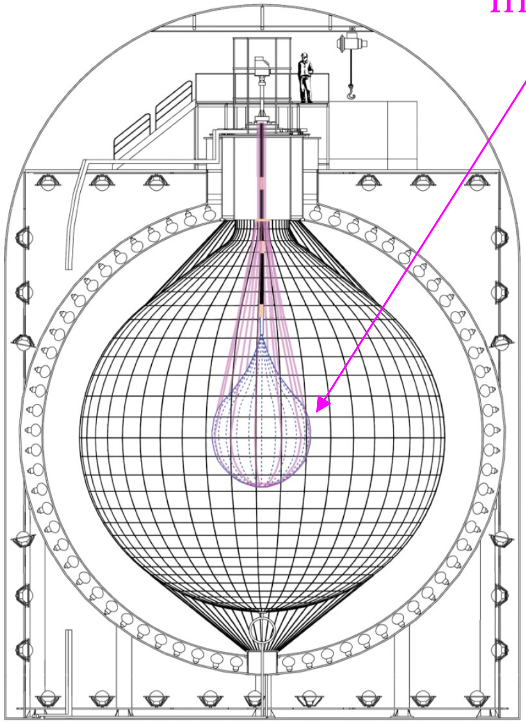
$$\frac{6.7\%}{\sqrt{E(\mathrm{MeV})}} \qquad \frac{13.7\mathrm{cm}}{\sqrt{E(\mathrm{MeV})}}$$

Inner detector

- ~ 1300 17-inch PMTs
- ~ 550 20-inch PMTs



KamLAND-Zen: Zero Neutrino Double Beta



Zen 400 (Oct. 2011 – Oct. 2015)

Phase I: PRL 110 (2013): 0625023

→ 320 kg Xe

Phase II: PRL 117.8 (2016): 082503

→ 383 kg Xe

Zen 800 (Feb. 2019 – Jan. 2024)

First dataset: PRL 130.5 (2023): 051801

Complete: arXiv 2406.11438

→ 745 kg Xe

First → Complete dataset

Livetime 523 → **1131** days

Exposure 1.0 → **2.1** ton yr ^{136}Xe

$$^{136}_{54}\mathrm{Xe} \rightarrow\ ^{136}_{56}\mathrm{Ba} + 2e^{-}$$

Xe-LS balloon, ⌀3.8m, 24t

- 3% enriched xenon

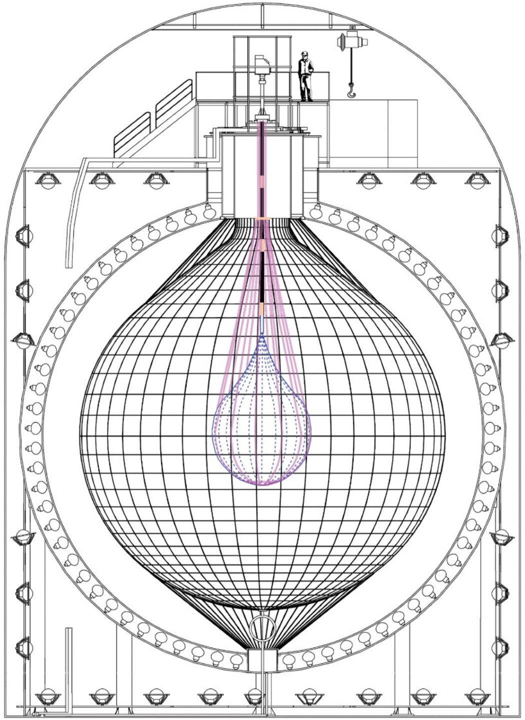
→ 745 kg Xe

↳ 91% ^{136}Xe

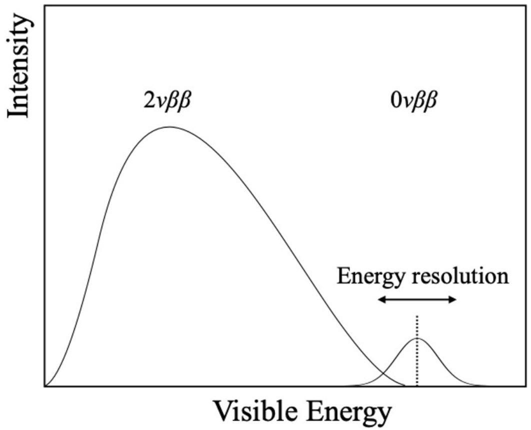
$Q_{\beta\beta}$ = 2.458 MeV

Nikhef UNIVERSITY OF AMSTERDAM

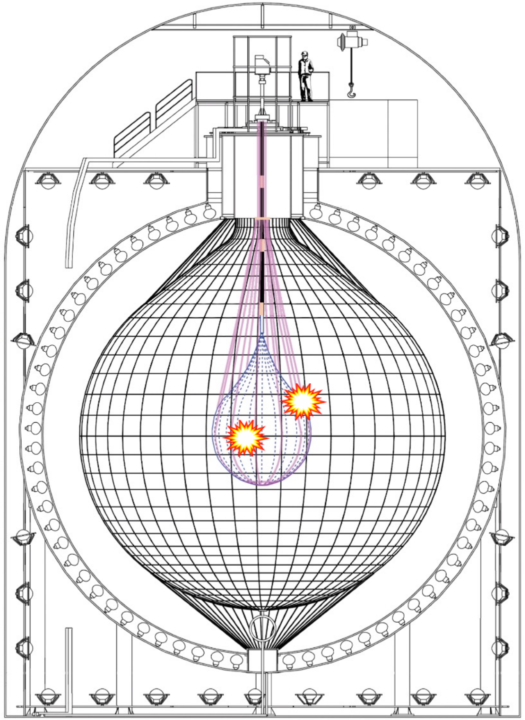
Dominant backgrounds for the $0\nu\beta\beta$ search



- $2\boldsymbol{\nu}\beta\beta$ decay

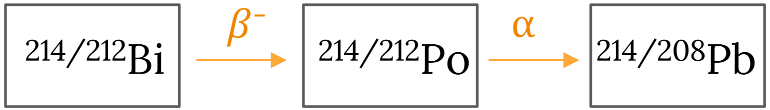


Dominant backgrounds for the $0\nu\beta\beta$ search

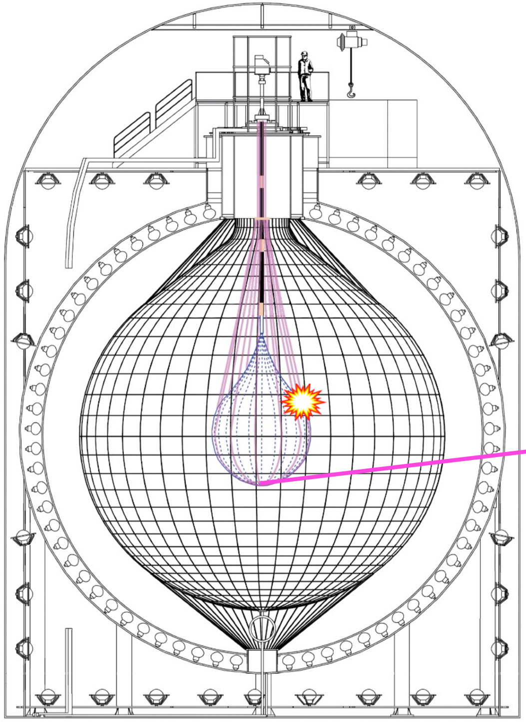


- $2\nu\beta\beta$ decay
- Radioactive Impurities (RI)
  - ➔ **In** Xe-LS: ^{232}Th & ^{238}U >97% tagging effiency
  - ➔ **External**

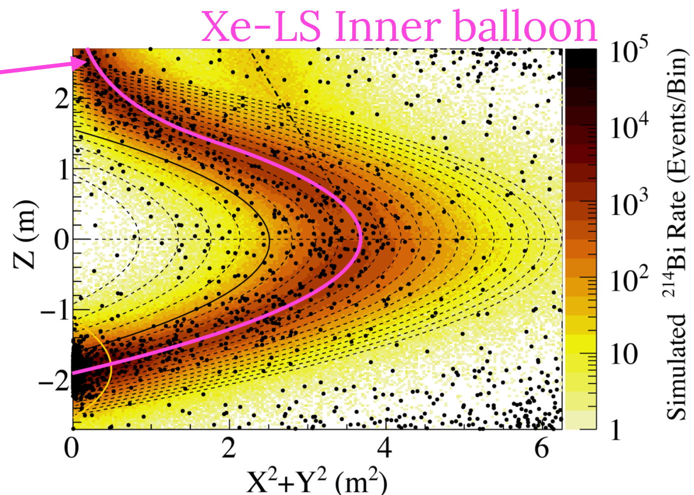
    Dominated by ^{238}U because delayed coincidence ^{214}Bi(β) - ^{214}Po(α) efficiency ~50% due to absorption of α on non-scintillating IB



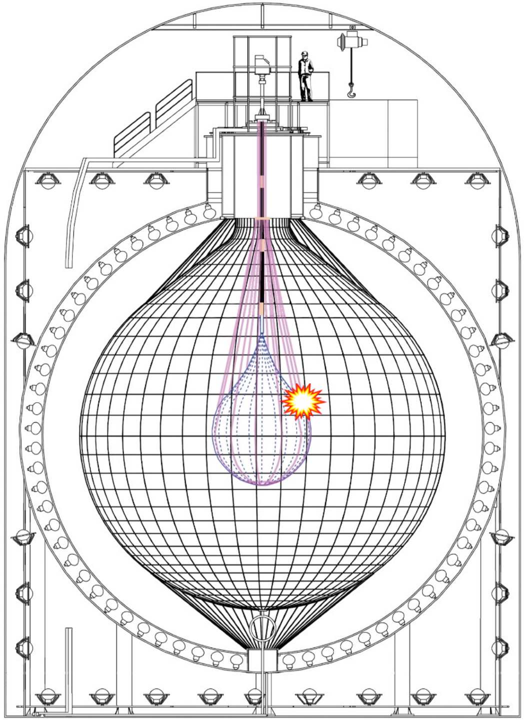
Dominant backgrounds for the $0\nu\beta\beta$ search



- $2\nu\beta\beta$ decay
- Radioactive Impurities (RI)
  - ➔ **In** Xe-LS: ^{232}Th & ^{238}U >97% tagging effiency
  - ➔ **External:** inner balloon material

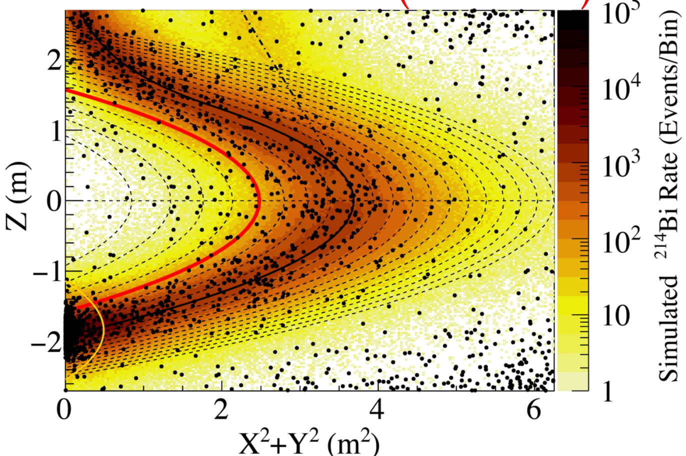


Dominant backgrounds for the $0\nu\beta\beta$ search

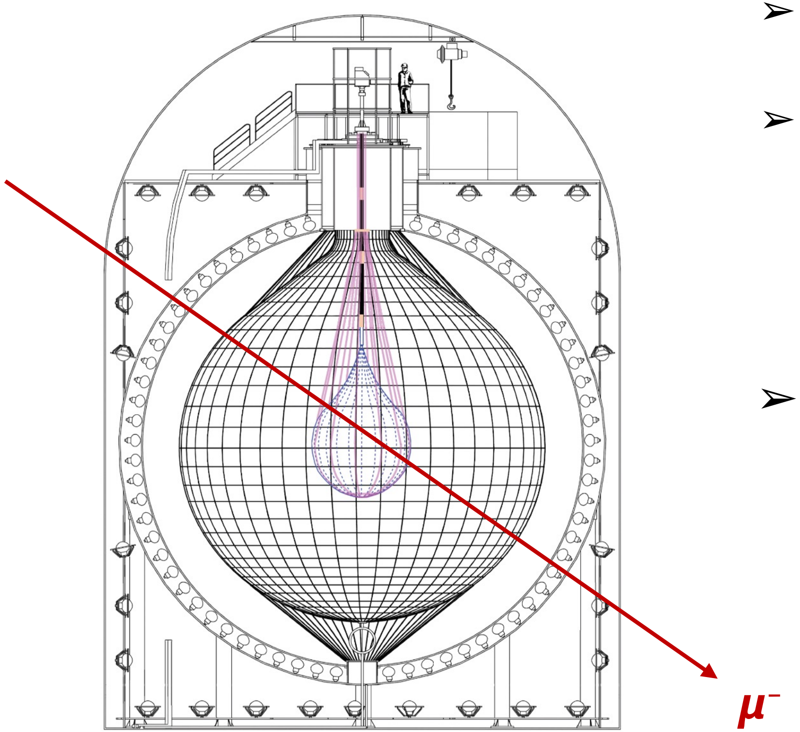


- $2\nu\beta\beta$ decay
- Radioactive Impurities (RI)
  - ➔ **In** Xe-LS: ^{232}Th & ^{238}U >97% tagging effiency
  - ➔ **External:** inner balloon material

Fiducial Volume (r < 1.57m)

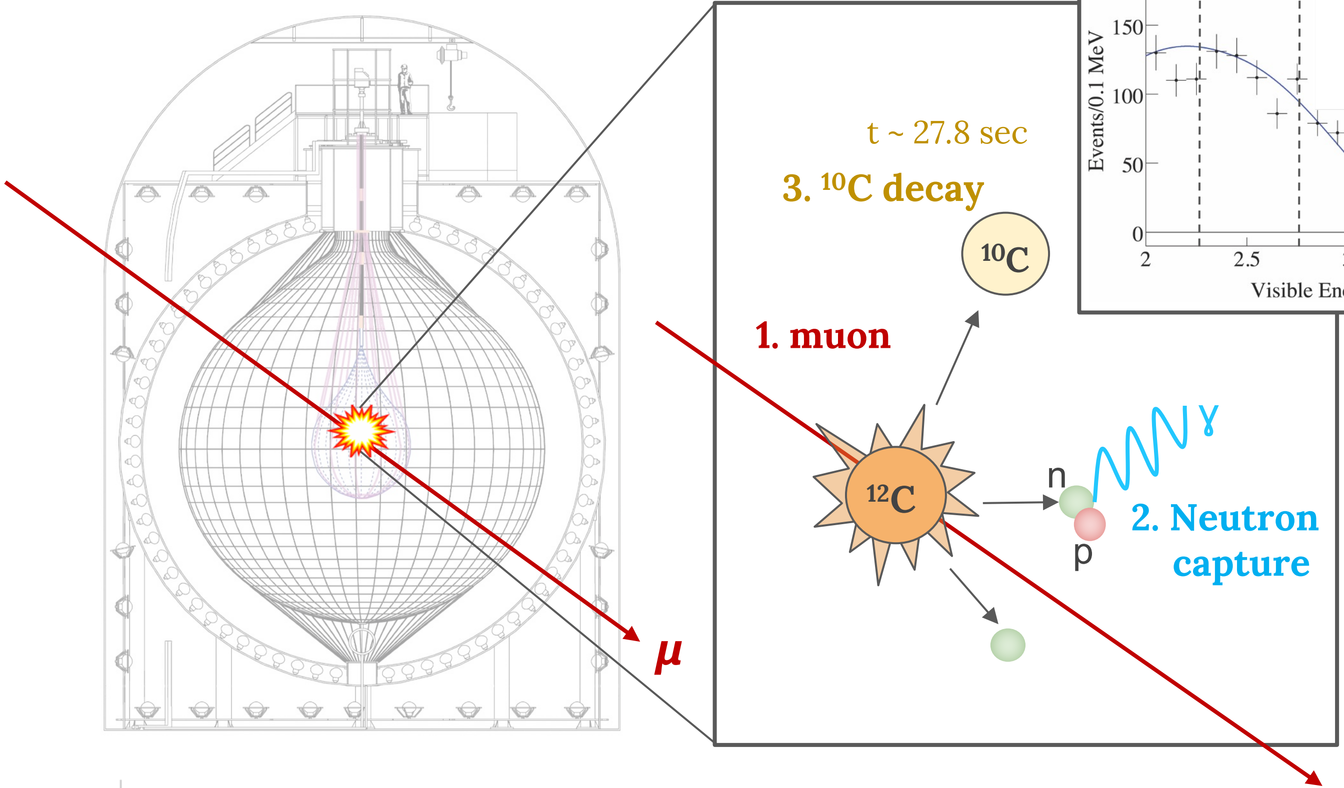


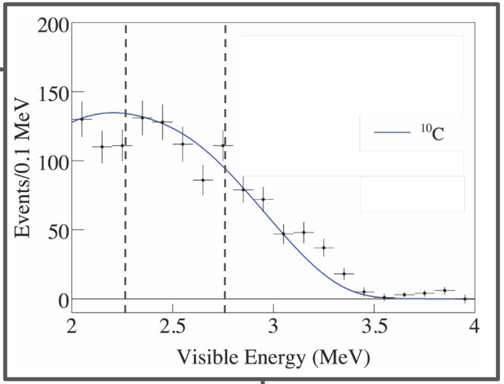
Dominant backgrounds for the $0\nu\beta\beta$ search



- $2\nu\beta\beta$ decay
- Radioactive Impurities (RI)
  - **In** Xe-LS: ^{232}Th & ^{238}U >97% tagging effiency
  - **External:** inner balloon material
- Muon spallation products
  - Short-lived: carbon spallation products dominated by ^{6}He, ^{8}Li, ^{10}C, ^{12}B
  - **Long-lived: xenon spallation**

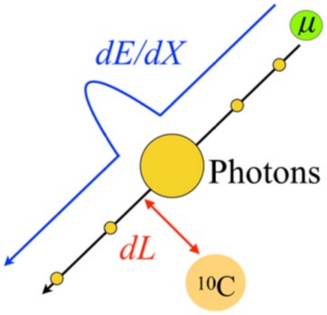
Short-lived isotope production from carbon spallation





Triple coincidence tagging

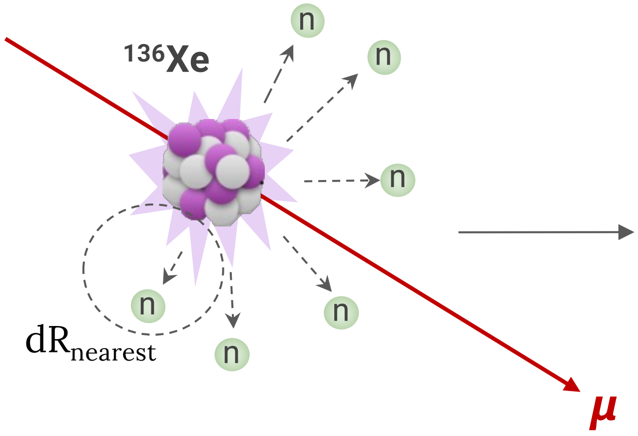
+ shower likelihood



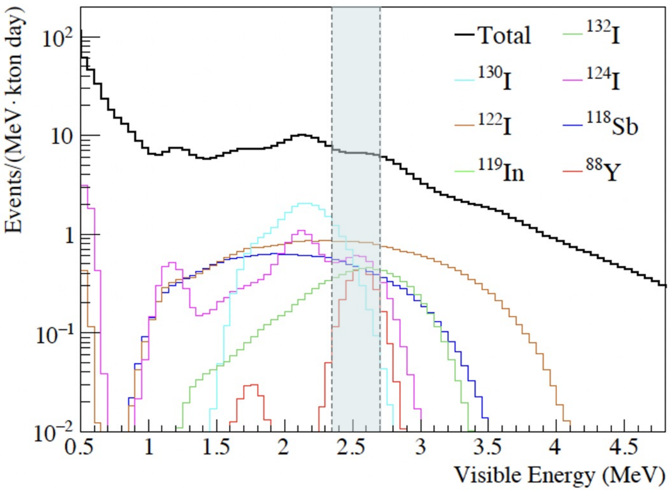
> 95% carbon spallation rejection efficiency

Long-lived isotope production from xenon spallation

- Muon spallation on xenon results in long-lived isotopes $T_{1/2}$ ~ (sec - months)



Phys. Rev. C 107.5 (2023): 054612



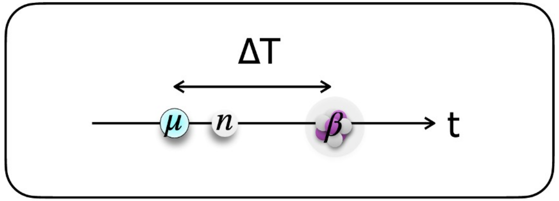
Neutron tagging

74.5 ± 0.4%

LL tagging

47.1 ± 8.7%

Deadtime **9%**

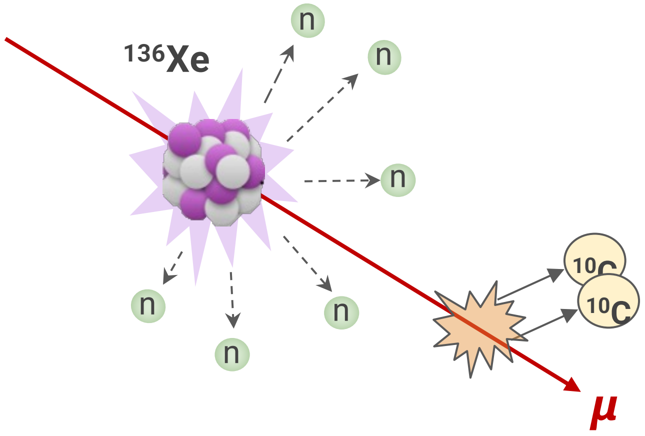


Likelihood based on number of neutrons (ENN), distance ($dR_{nearest}$) and time ($dT < 4.6$ days)

Long-lived isotope production from xenon spallation

- Many features with correlations over long time windows and variable length input

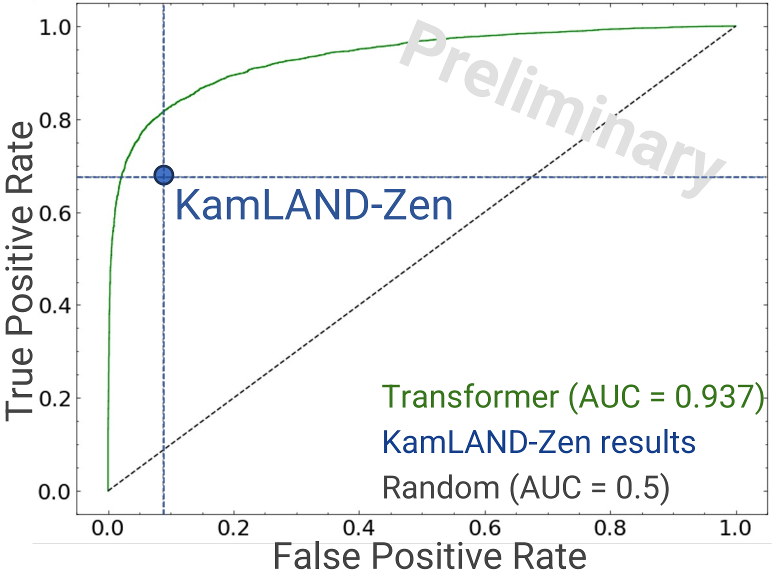
→ Machine Learning Transformer Model fits the data well



✓ Neutrons in a cloud around the LL-event

✓ Short-lived isotopes along the ***μ*** track

Simulation-based results



First results from FLUKA trained ML model

Spectrum construction and fit method

Events selected within analysis volume (r < 2.5m)

↓

Rn rejected with **FV** (r < 1.57m) ← *Visualize fit* / **BiPo coincidence**

↓

Short-lived spallation cut (^{10}C, ^{6}He, ^{12}B etc.)

↓

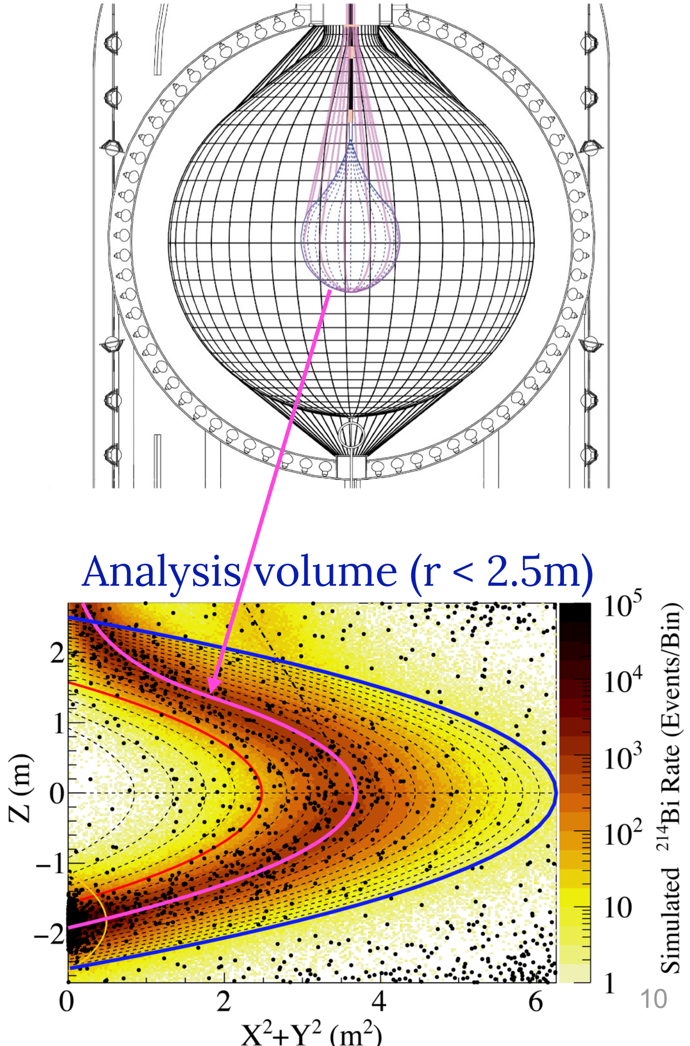
Long-lived spallation cut

Untagged (1131 days) → **$0\nu\beta\beta$ candidate (SD)**

Tagged (111 days) → **Long-lived events (LD)**

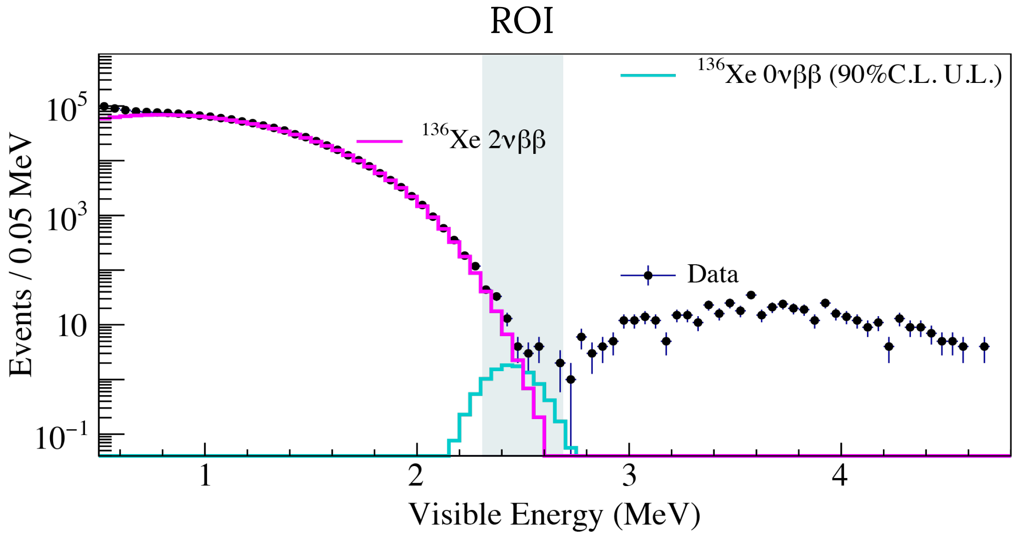
! Simultaneous fit to constrain the long-lived rate !

- 40 equal volume bins within r < 2.5m
- Energy bins ∈ (0.5–4.8) MeV | ROI (2.35–2.70) MeV



Improved $0\nu\beta\beta$ half-life limit with full KamLAND-Zen dataset

→ Livetime 1131 days | Exposure 2.1 ton yr ^{136}Xe



- ➢ $2\nu\beta\beta$ decay
- ➢ Radioactive contamination
- ➢ Cosmogenic spallation products

Improved $0\nu\beta\beta$ half-life limit with full KamLAND-Zen dataset

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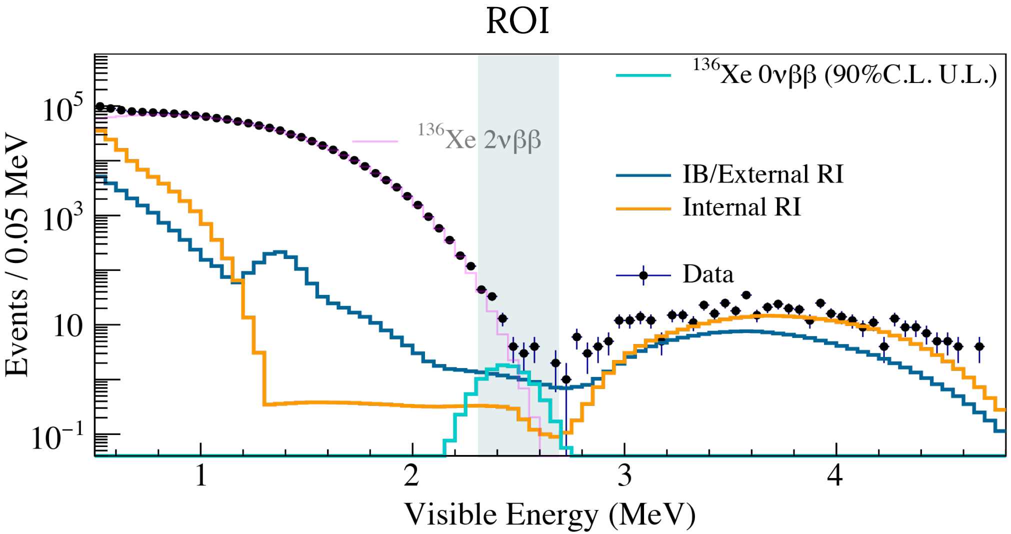

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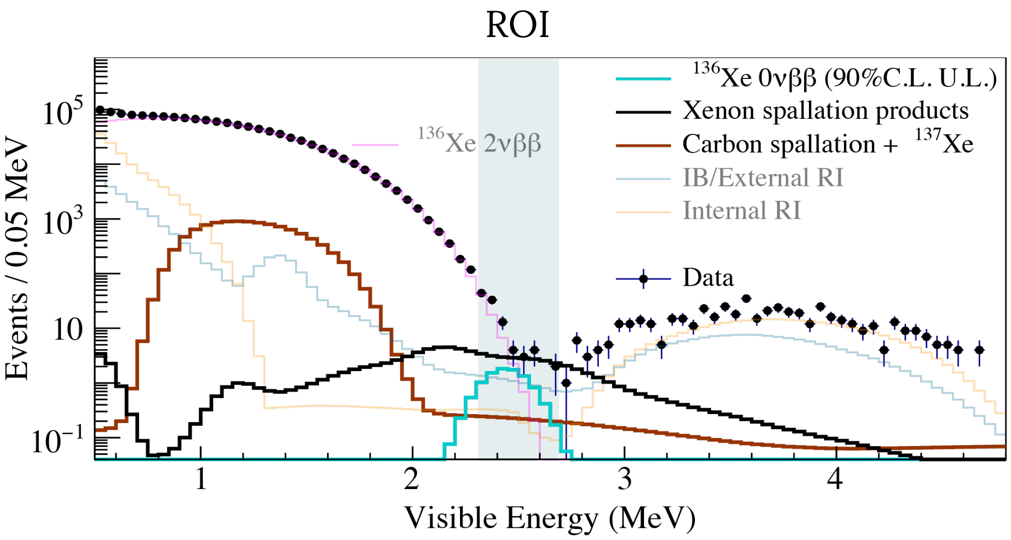
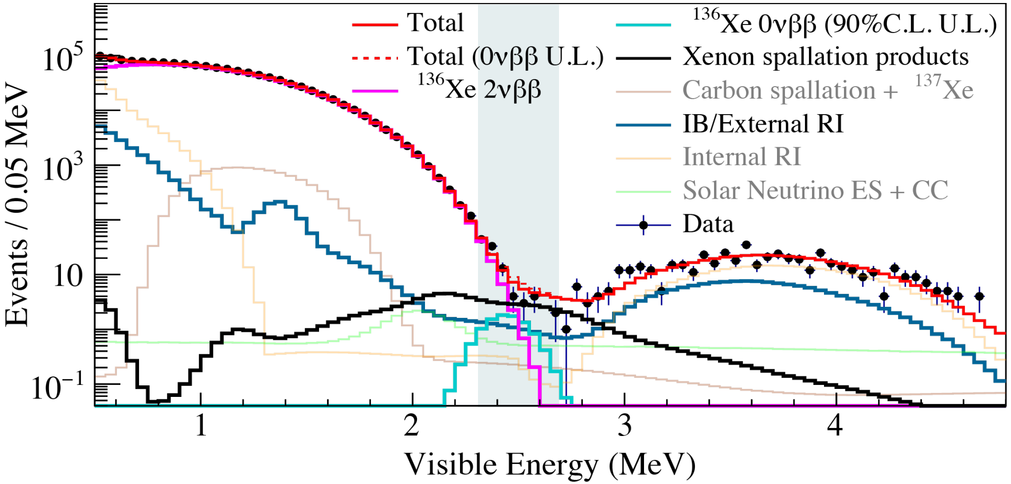


- ➢ $2\nu\beta\beta$ decay
- ➢ Radioactive contamination
- ➢ Cosmogenic spallation products

Improved $0\nu\beta\beta$ half-life limit with full KamLAND-Zen dataset

→ Livetime 1131 days | Exposure 2.1 ton yr ^{136}Xe

ROI



Fitting result (90% C.L.):

Before $T^{0\nu}_{1/2} > 2.0 \times 10^{26}$ yr → *Latest* $\mathbf{T^{0\nu}_{1/2} > 3.4 \times 10^{26}}$ **yr**

- ➢ $2\nu\beta\beta$ decay
- ➢ Radioactive contamination
- ➢ Cosmogenic spallation products

Combined KLZ 400 & 800 datasets:

Limit: $T^{0\nu}_{1/2} > 3.8 \times 10^{26}$ yr

Sensitivity: $T^{0\nu}_{1/2} > 2.6 \times 10^{26}$ yr

Implications for the neutrino mass ordering

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q,Z)\boxed{|M_{0\nu}|^2}\langle m_{\beta\beta}\rangle^2 \longrightarrow \langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

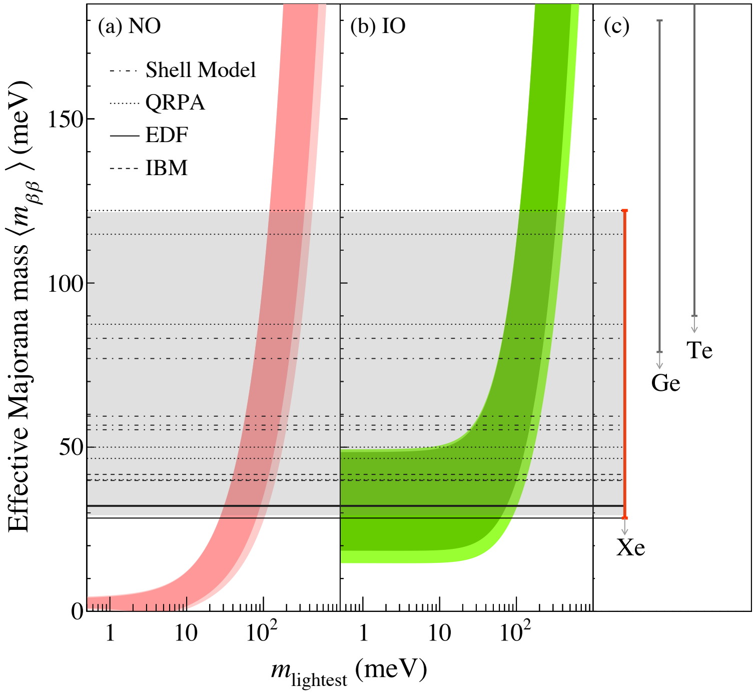
Nuclear Matrix Element

$T^{0\nu}_{1/2} > 3.8 \times 10^{26}$ yr

$\langle m_{\beta\beta}\rangle < (28 - 122)$ meV

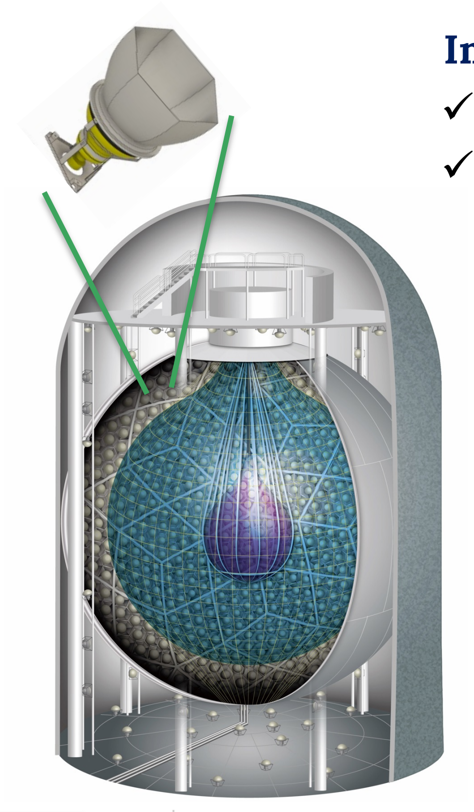
$m_{\nu 3} > m_{\nu 1}$

$m_{\nu 1} > m_{\nu 3}$



Upgrade to KamLAND2-Zen

Last physics run on August 27th 2024 → dismantling of detector ongoing



Improved energy resolution

✓ Mirrors around PMTs

✓ Higher QE PMTs

4% ⟶ 2% at 2.46 MeV

Scintillation inner balloon (PEN)

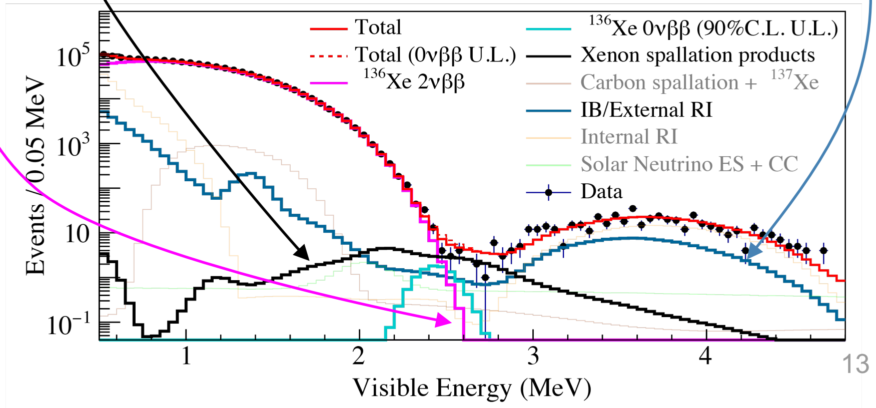
→ Larger fiducial volume

Dead-time free electronics

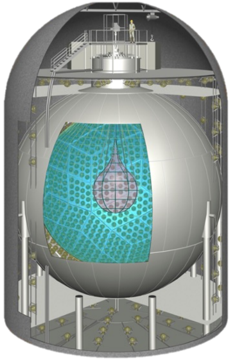
→ Higher neutron tagging efficiency

After 5 years:

$$T^{0\nu}_{1/2} > 2 \times 10^{27}\ \text{yr}$$



KamLAND2-Zen construction timeline



KamLAND dismantling — 2024

KamLAND2 construction

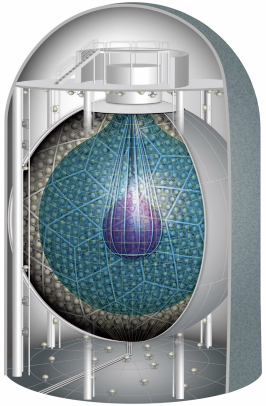
KamLAND2 begins — 2028

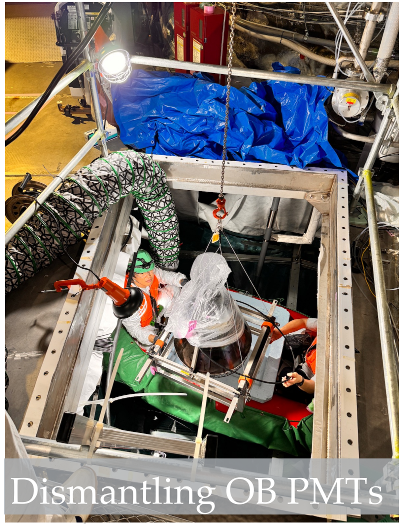
- ✓ Xe-LS & LS extraction
  - ✓ Outer Balloon dismantling
    - → PMT dismantling

PMT & mirror installation

Cleaner OB | LS | new electronics

Calibration system

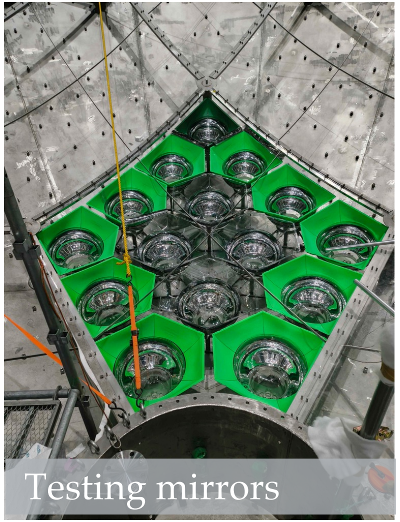




Dismantling OB PMTs

Inner Balloon removed

Inside KamLAND



Testing mirrors

Future prospects

KamLAND-Zen is searching for $0\nu\beta\beta$ with ^{136}Xe dissolved in liquid scintillator

- ➢ Current most stringent limit of is $T_{1/2} > 3.8 \times 10^{26}$ yr → $m_{\beta\beta} < (28 - 122)$meV

The detector upgrade of KamLAND to KamLAND2 has started

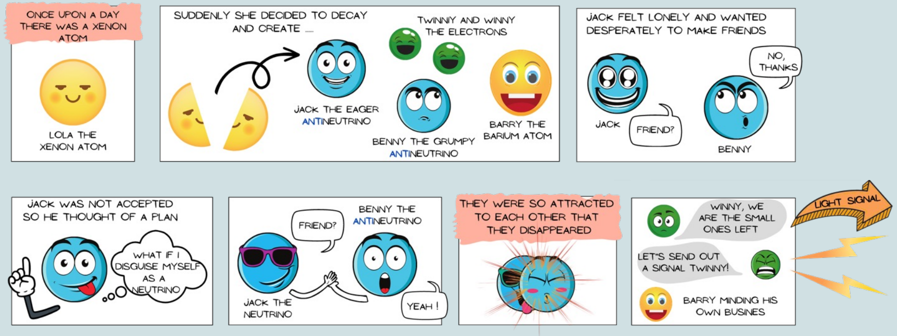
- ➢ Scintillating inner balloon
- ➢ Improved energy resolution
- ➢ New electronics for enhanced tagging efficiency

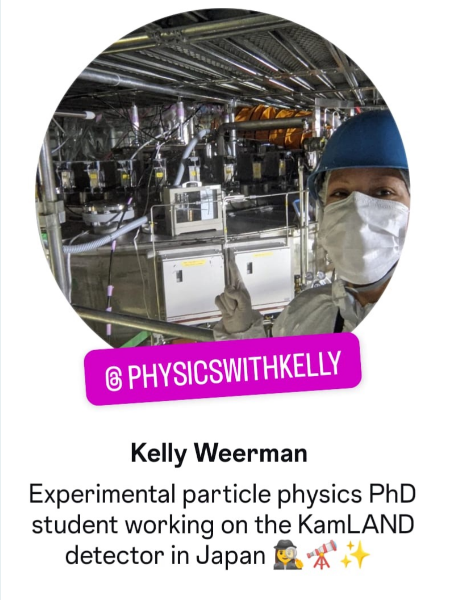
KamLAND2-Zen aims to cover the IO region | target sensitivity $\langle m_{\beta\beta} \rangle = 20$ meV

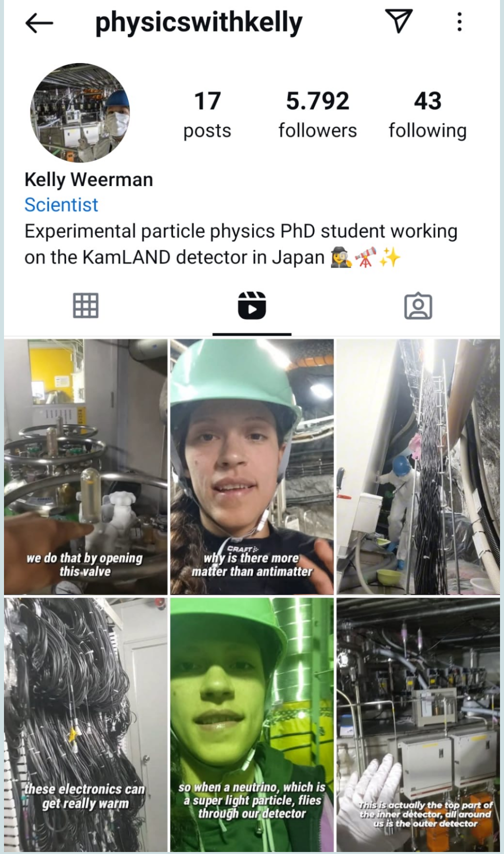
KamLAND2 dismantling & constrution ongoing → expected launch in 2028!

Thank you for your attention!

Follow me for fun videos & comics on KamLAND







Backup slides

KamLAND-Zen $0\nu\beta\beta$ half-life and mass limits

Majorana mass expectation from the KamLAND-Zen half-life limit using different nuclear matrix elements

	$M^{0\nu}$	$\langle m_{\beta\beta}\rangle$ (meV)
Shell model	2.28, 2.45	59.4, 55.3
	1.63, 1.76	83.1, 77.0
	2.39	56.7
QRPA	1.55	87.4
	2.91	46.6
	2.71	50.0
	1.11, 1.18	122, 115
	3.38	40.1
EDF theory	4.20	32.3
	4.77	28.4
	4.24	32.0
IBM	3.25	41.7
	3.40	39.9

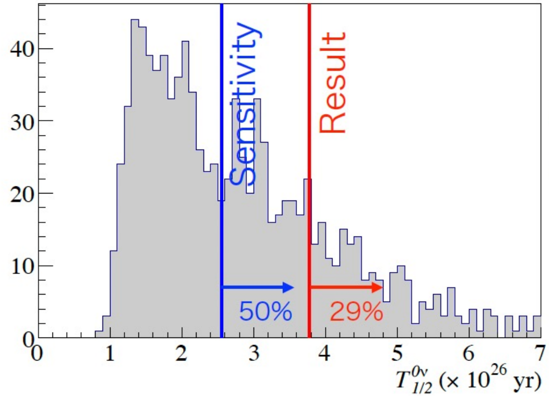
Confidence limits

KamLAND-Zen 800 only:

$T_{1/2} > 3.4 \times 10^{26}$ yr

Combined Zen 400 + 800:

$T_{1/2} > 3.8 \times 10^{26}$ yr



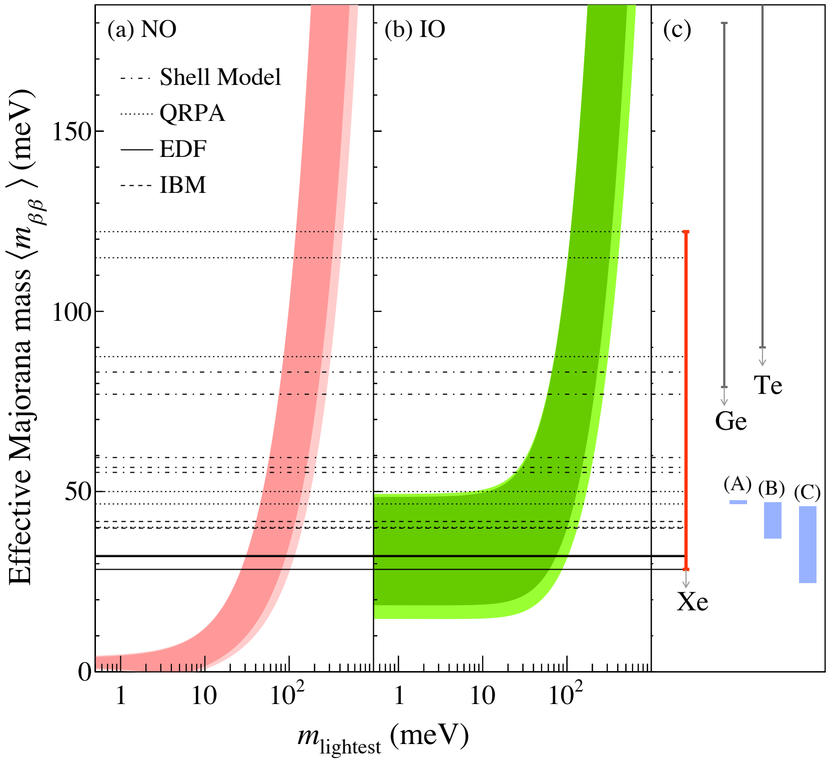
	Dataset	Exposure	$T_{1/2}$ (90% C.L.)
KamLAND-Zen 400	Phase I	85.9 kg yr	1.9×10^{25} yr
	+ Phase II	504 kg yr	1.07×10^{26} yr
KamLAND-Zen 800	First dataset	970 kg yr	2.3×10^{26} yr
	Complete dataset	2097 kg yr	3.8×10^{26} yr

Majorana neutrino mass prediction

Dark shaded regions: predictions based on best-fit values of neutrino oscillation parameters
Light shaded regions: 3σ ranges from oscillation parameter uncertainties.

NME calculations:
Shell model → dot-dashed lines
QRPA→ dotted lines
EDF theory → solid lines
IBM → dashed lines

Three theoretical predictions in IO regio: A, B, C



KamLAND-Zen $0\nu\beta\beta$ confidence limits

Frequentist confidence limit (Wilks'):

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

Frequentist Feldman-Cousins calculation result:

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

Combined KLZ 400 + 800 Analysis (Wilks')

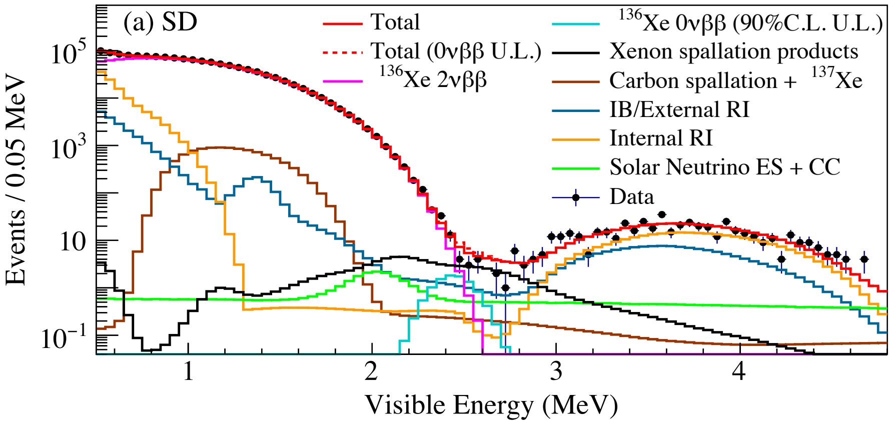
$$T_{1/2}^{0\nu\beta\beta} > 3.8 \times 10^{26}\text{yr}\ (90\,\%\,\text{C.L.})$$

Bayesian result:

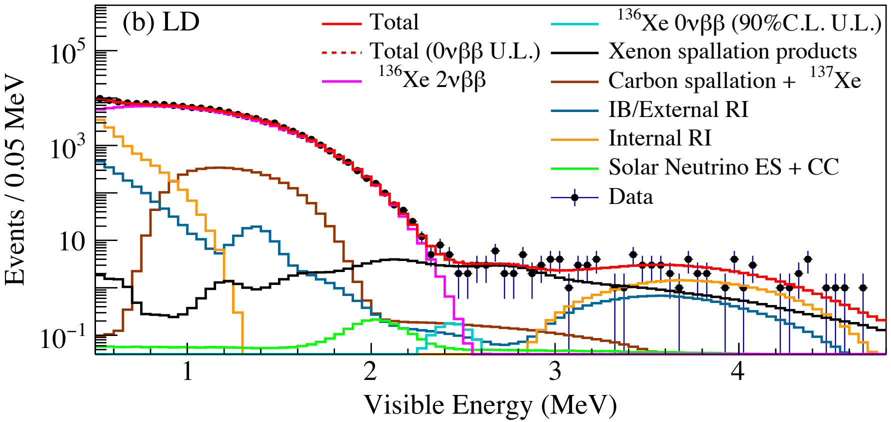
$$T_{1/2}^{0\nu\beta\beta} > 3.4 \times 10^{26}\text{yr}\ (90\,\%\,\text{C.I.})$$

KamLAND-Zen Singles- and LL-spectrum

Singles data: $0\nu\beta\beta$ candidates



Long-lived data: LL-candidates | 10% of SD

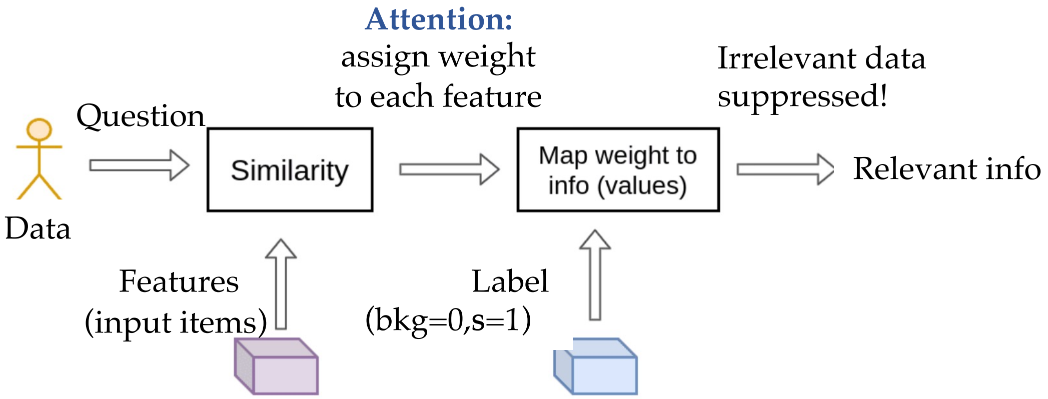


Why transformers are a good match for spallation

A deep learning model originally for Large Language Models like GPT and Copilot

→ **The output of muon spallation consists of many features (both from neutrons and SL isotopes) with correlations over long time windows (complex patterns) and variable-length (= number of n + SL) events**

So why does a Transformer fit so well for this type of data?



- ✓ Attention handles **long-range** (for example large dT) relationships → better for **complex patterns**
- ✓ Compare all input elements simultaneously → **efficient** for large datasets

- ✓ **It can handle variable-length input**

Transformers process input without fixed length constraints (unlike most ML models)

Pad and mask the data

Experimental design criteria for $0\nu\beta\beta$

Direct searches: kinematic parameters of the two electrons

➔ Total energy and individual electron paths

$$T_{1/2}^{0\nu} = \ln 2 \frac{N_A}{W} \left(\frac{a \cdot \epsilon \cdot M}{N_{\text{obs}}} \right) t \quad \propto \begin{cases} a\epsilon \cdot Mt \\ a\epsilon \sqrt{\dfrac{Mt}{N_{\text{bkg}} \cdot \Delta E}} \end{cases}$$

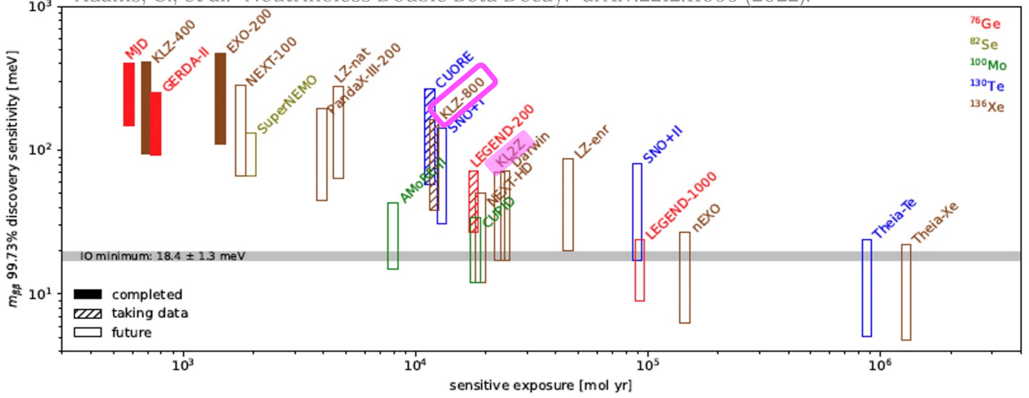
Detector and isotope choice depending on:

- High isotopic abundance — a
- Deployment in large quantity — M
- High-resolution detector — ΔE
- Low-background conditions — N_{bkg}

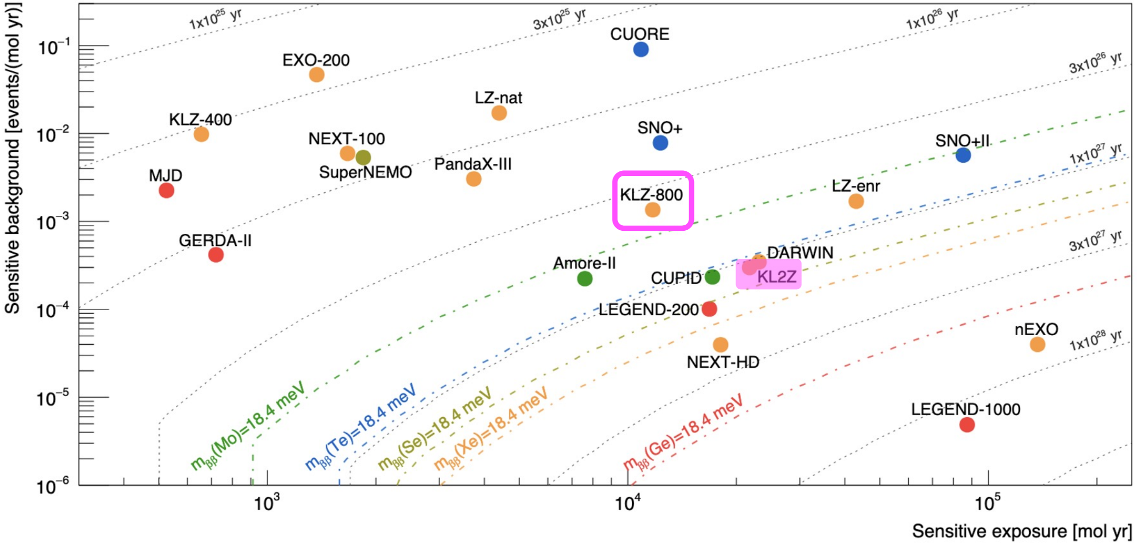
Sensitivity to $0\nu\beta\beta$

Limits
&
Discovery potential

Adams, C., et al. "Neutrinoless Double Beta Decay." arXiv:2212.11099 (2022).



Agostini, Matteo, et al. Rev. Mod. Phys. 95, 025002 (2023)



^{76}Ge
^{136}Xe
^{130}Te
^{100}Mo
^{82}Se