The KamLAND-Zen experiment

The first neutrinoless double beta decay search in the Inverted Ordering mass region

33e Rencontres de Blois 05/24/2022

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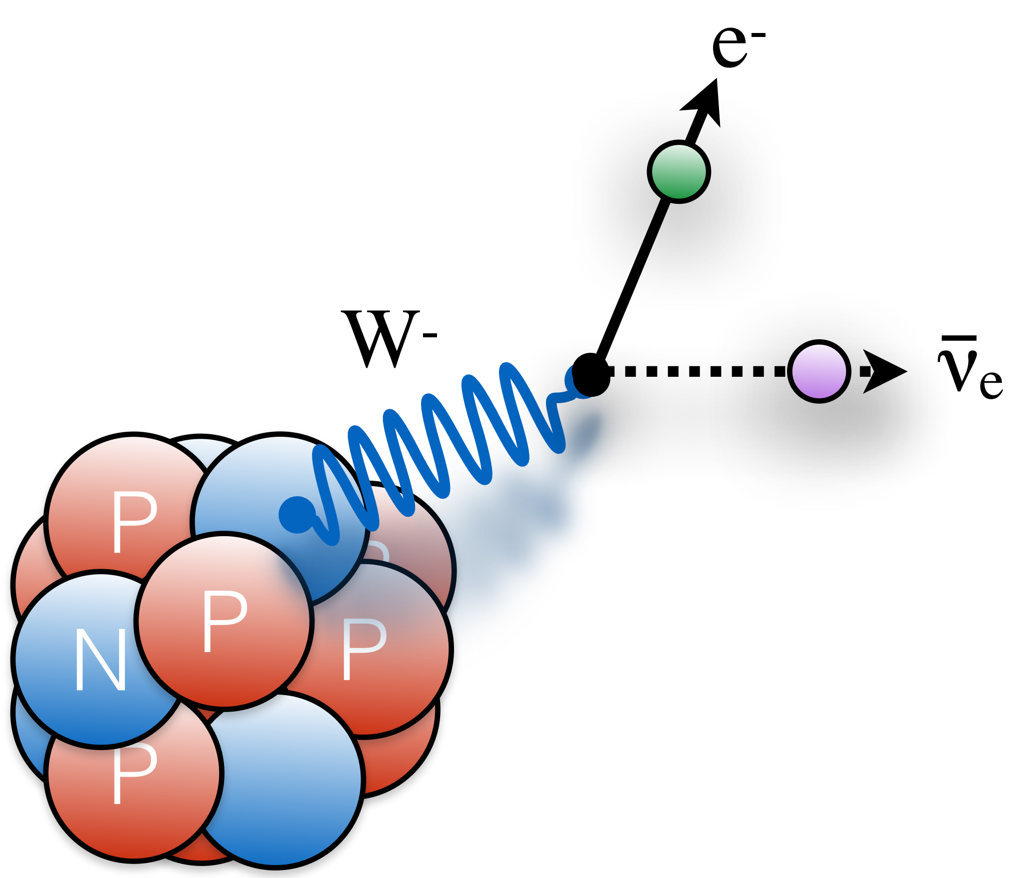
PRL: First Search for the Majorana Nature of the Neutrino in the inverted Mass Ordering Region with KamLAND-Zen
Based on Preprint: arXiv.2203.02139
See also Machine Learning paper, PRC: arXiv:2203.01870



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(Discovered 1899)

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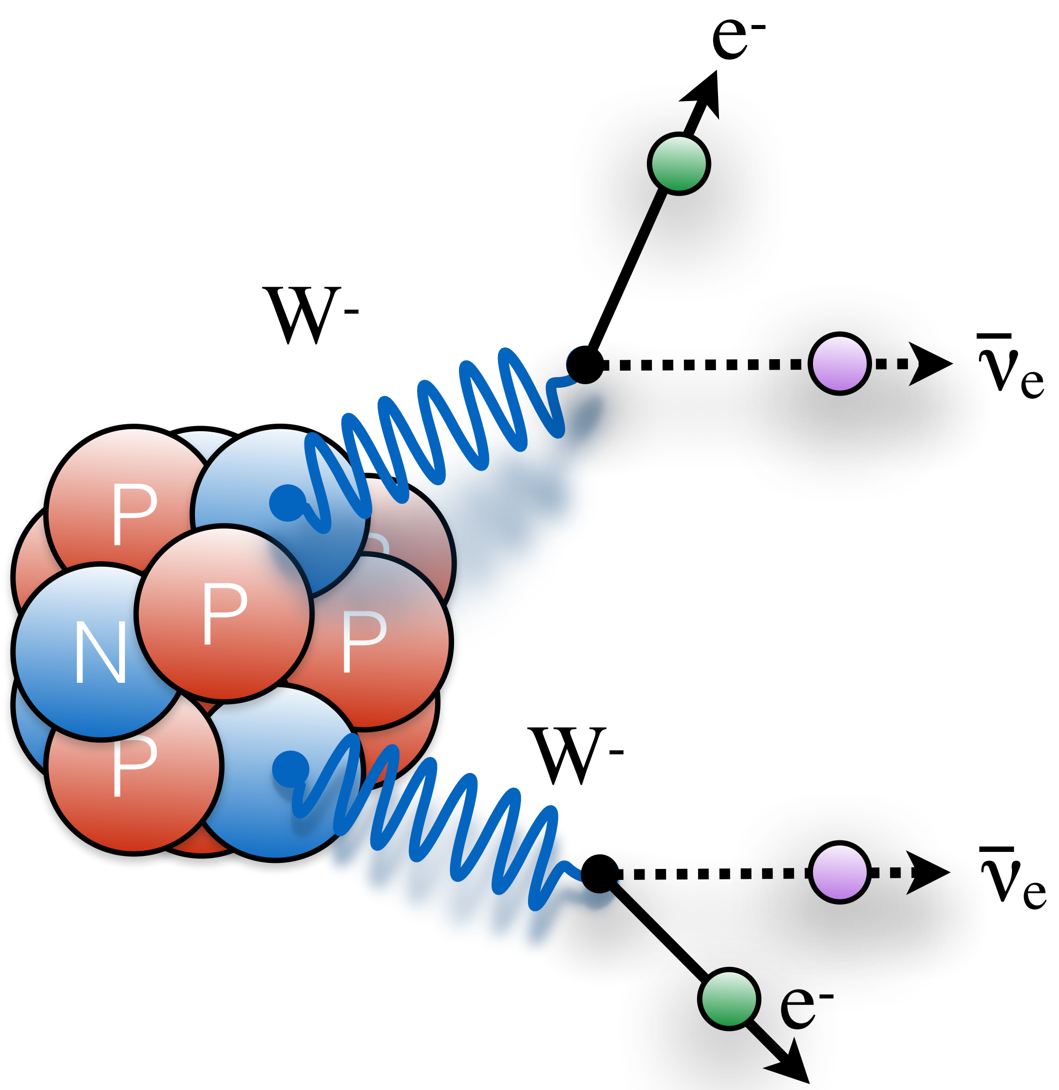

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Half life ~ 10^{19-24} years

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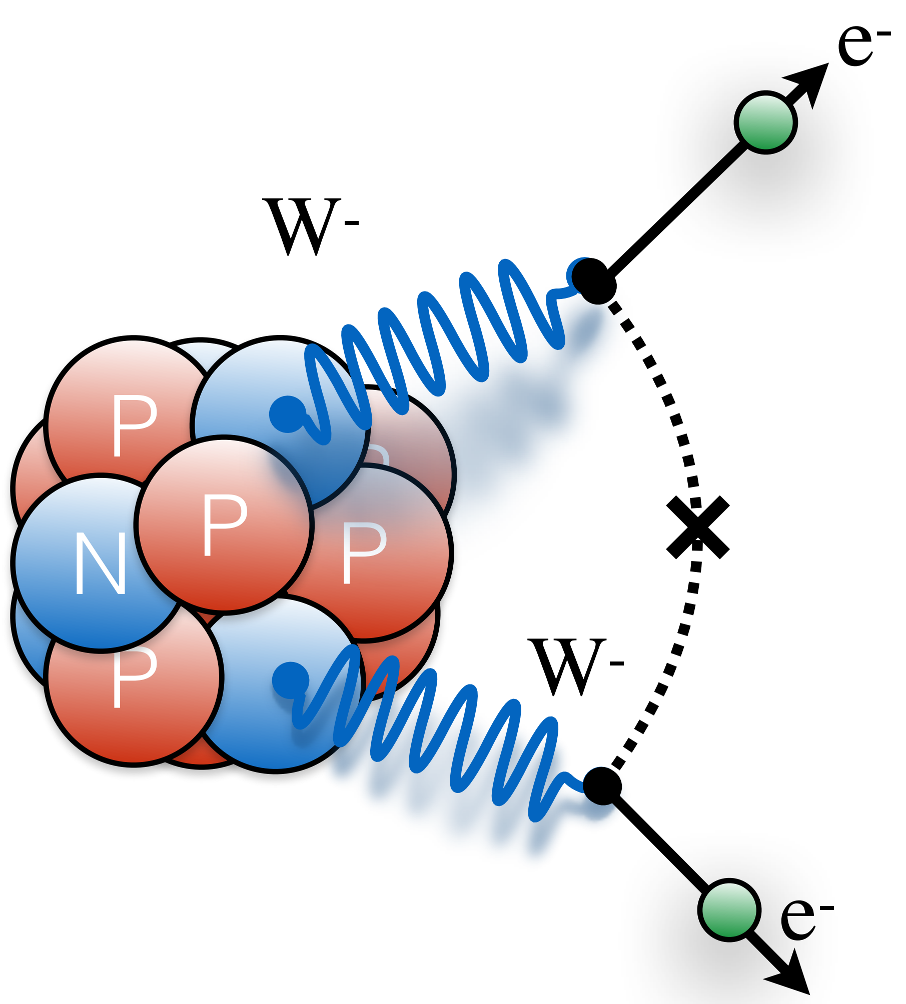

Neutrinoless Double Beta Decay (0νββ)
(large experimental program underway)

Expected Half life > 10^{26} years

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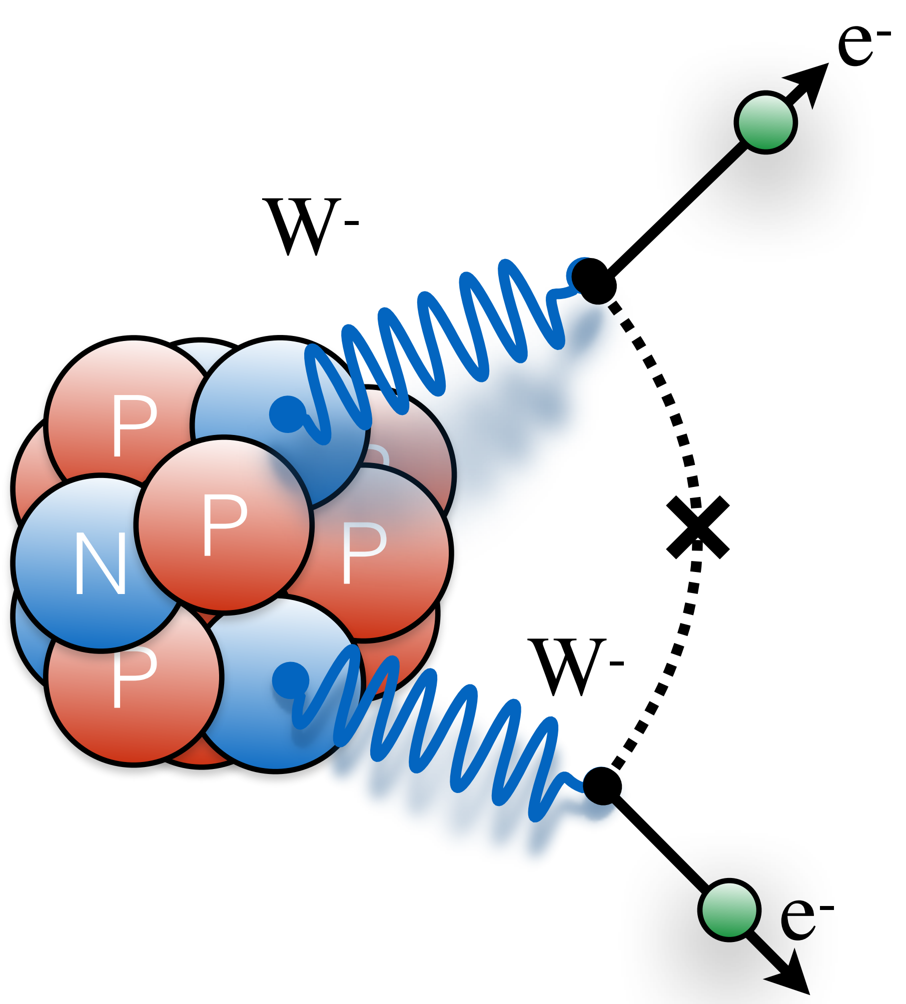

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The search for 0νββ is one of the most pressing and important modern-day questions in particle physics.

The search for $0\nu\beta\beta$ is a search for physics beyond the Standard Model.

If observed:

The neutrino is a Majorana particle. $\nu = \bar{\nu}$

Lepton number is violated. $\Delta L \neq 0$

Neutrinos acquire mass through a new mechanism.

Other potential implications of $0\nu\beta\beta$

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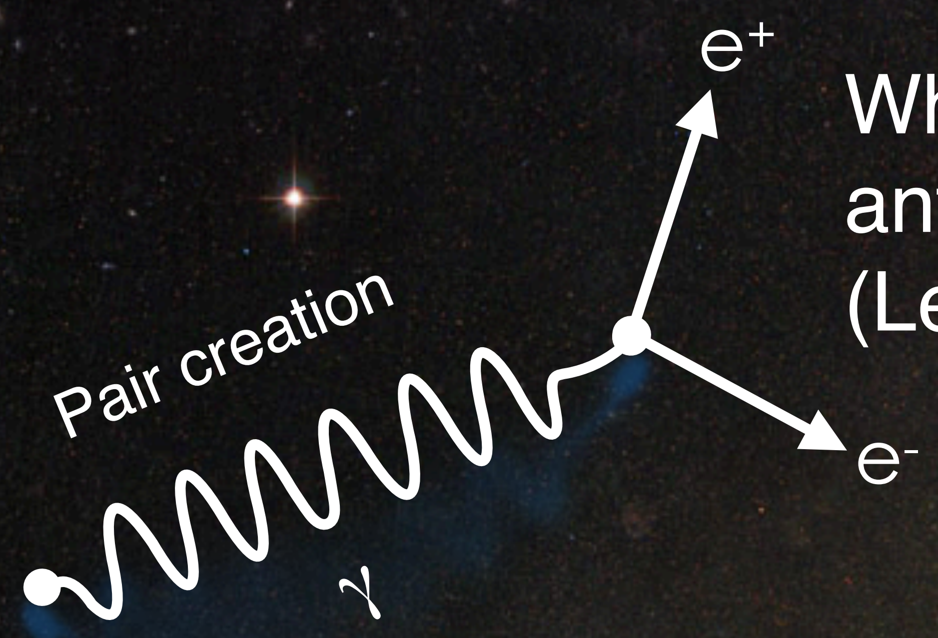
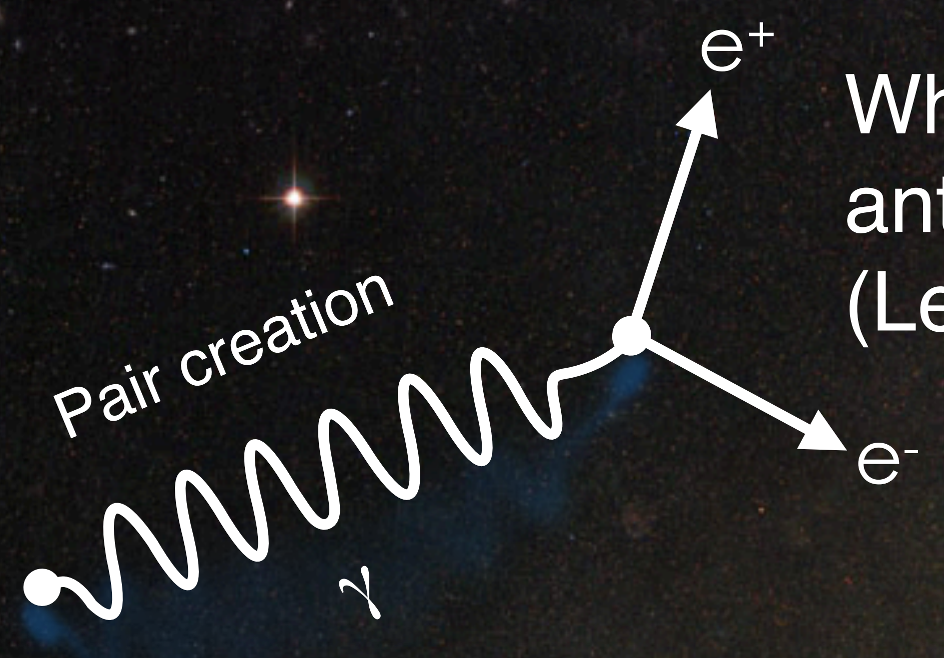


Why is there an imbalance of matter to antimatter in the Universe?
(Leptogenesis, Baryogenesis)

Other potential implications of $0\nu\beta\beta$



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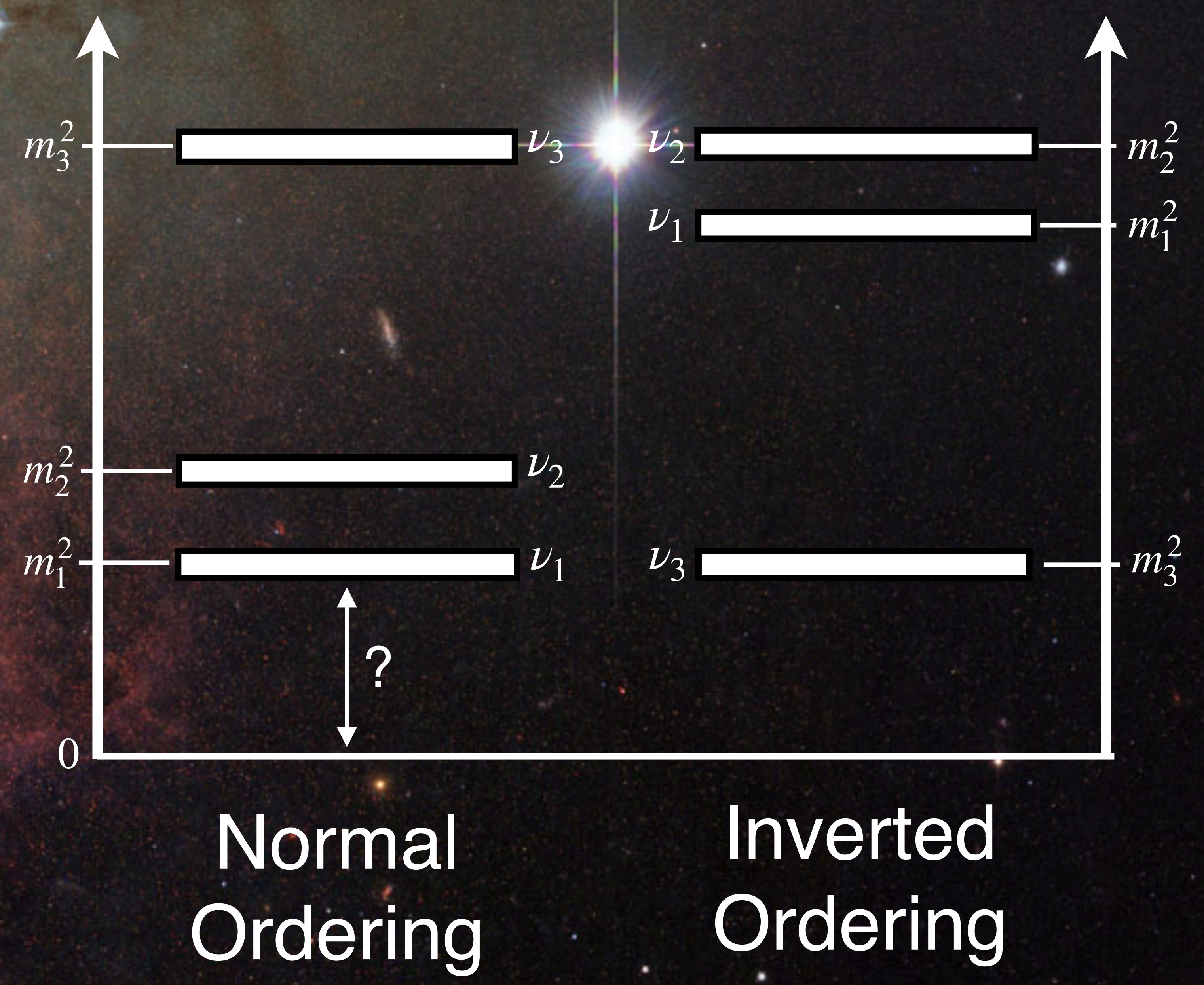
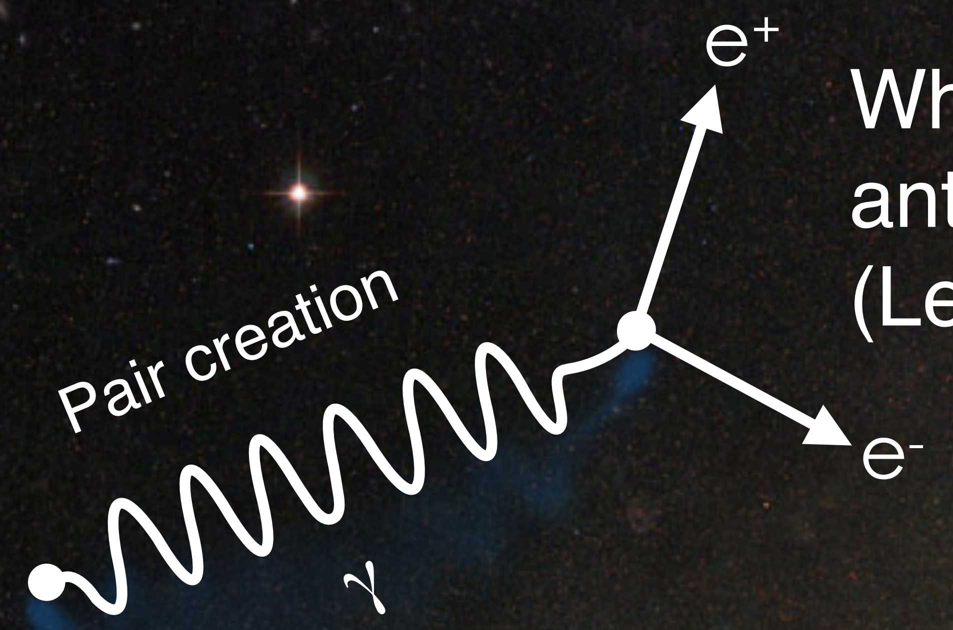
What is the neutrino mass ordering?

What is the lightest state?



Other potential implications of 0νββ



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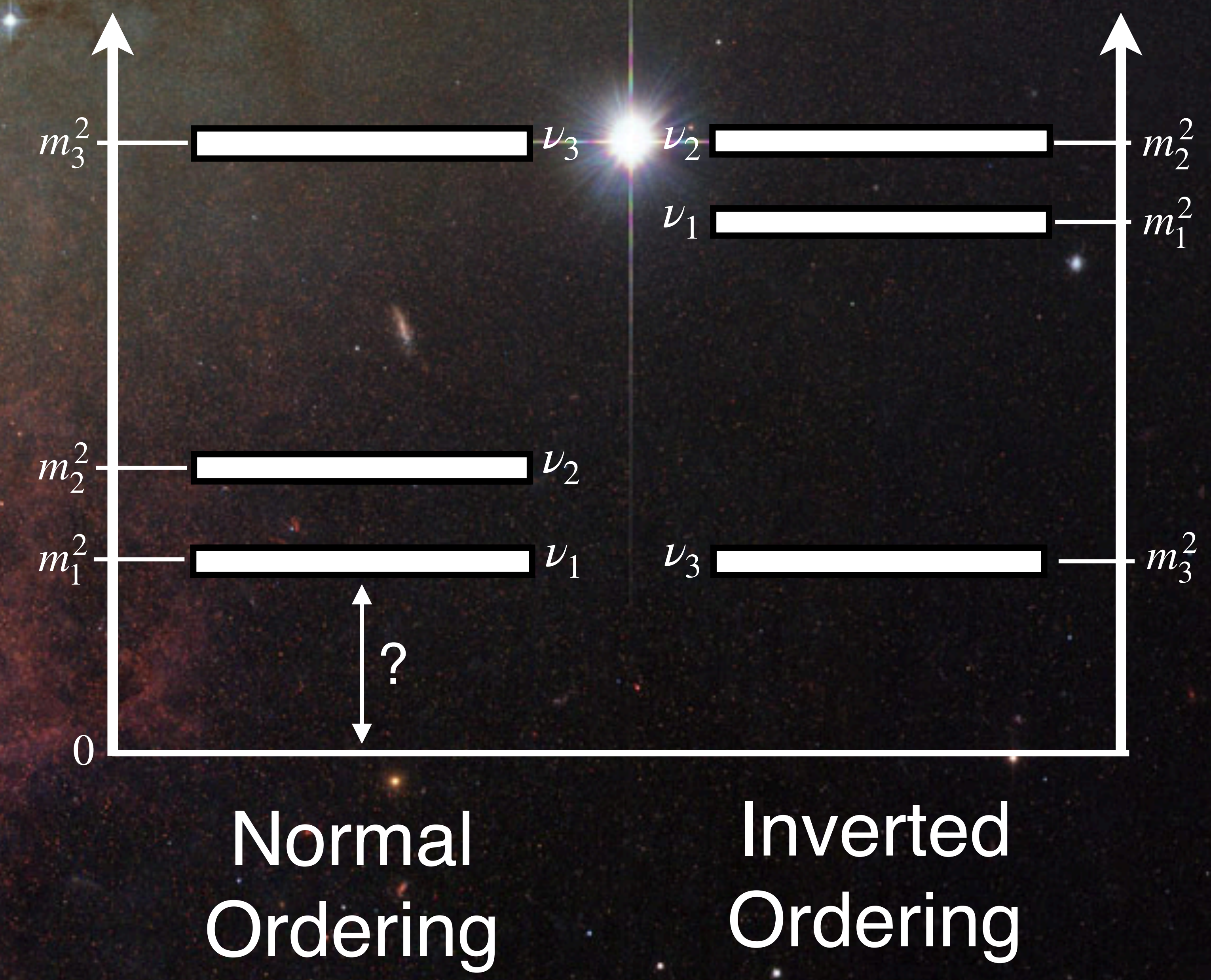
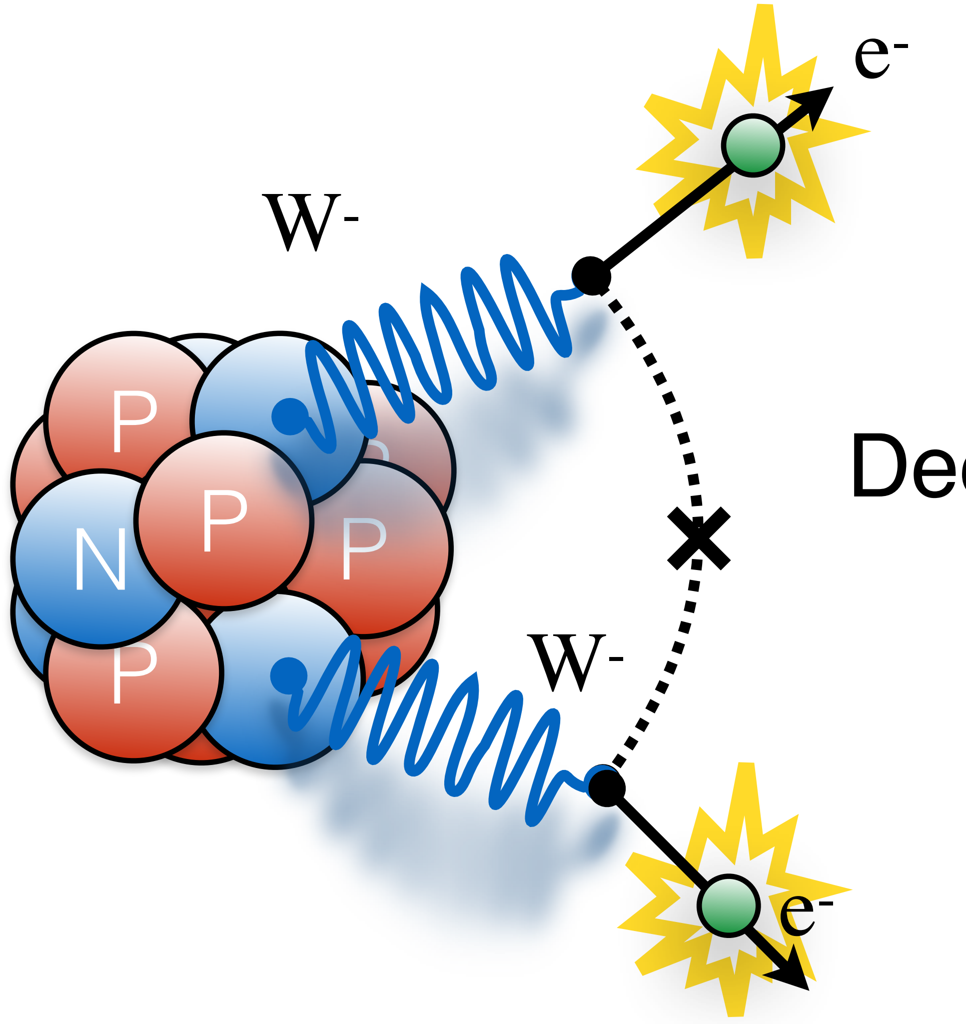


What is the lightest state?

Are there other processes that drive 0νββ? Other beyond the Standard Model physics?

Observable signature of 0νββ

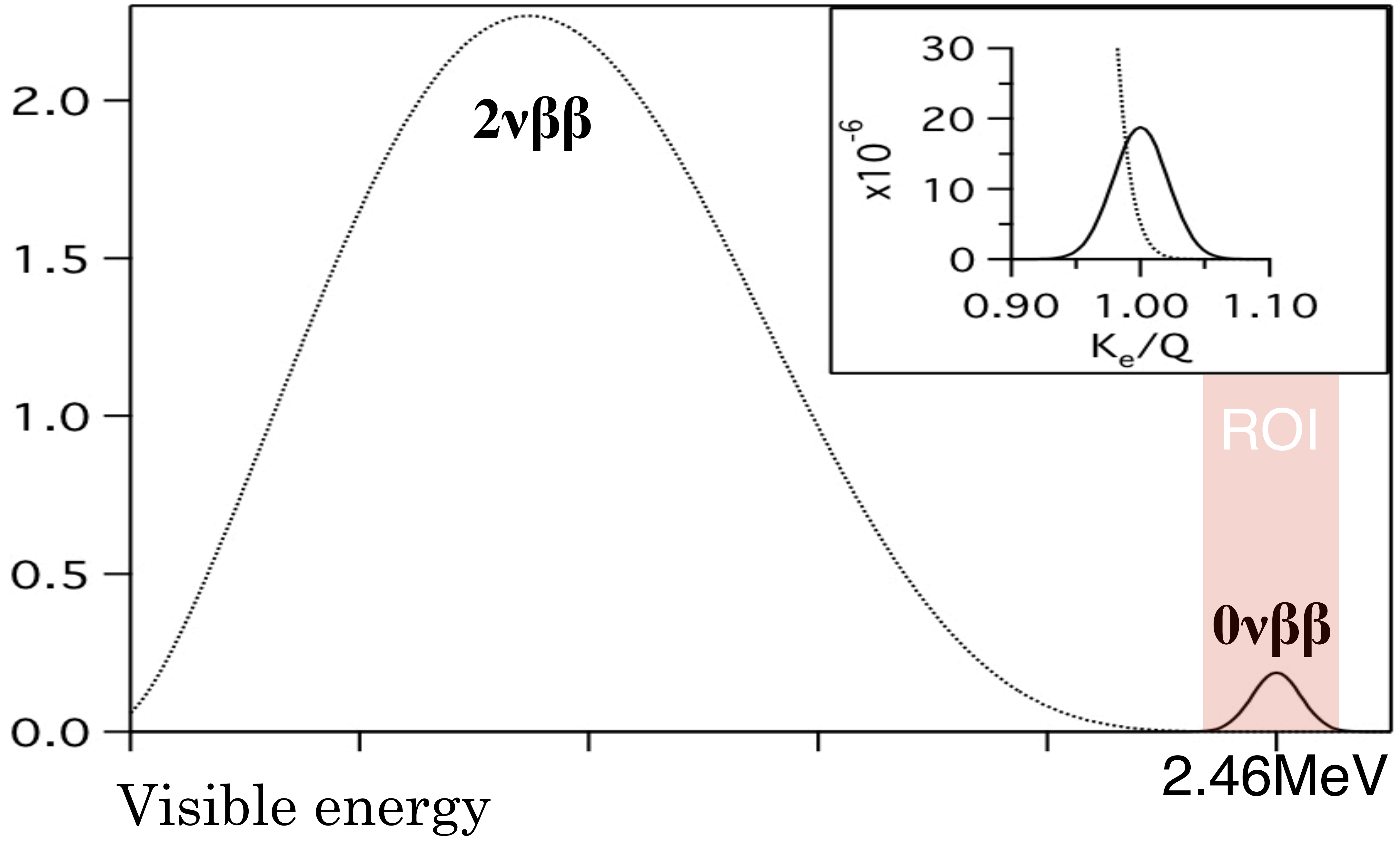


Decay energy ($Q_{\beta\beta}$) is shared by electrons.

Neutrinoless Double Beta Decay (0νββ)

$$(A, Z) \rightarrow (A, Z+2) + 2e^{-}$$

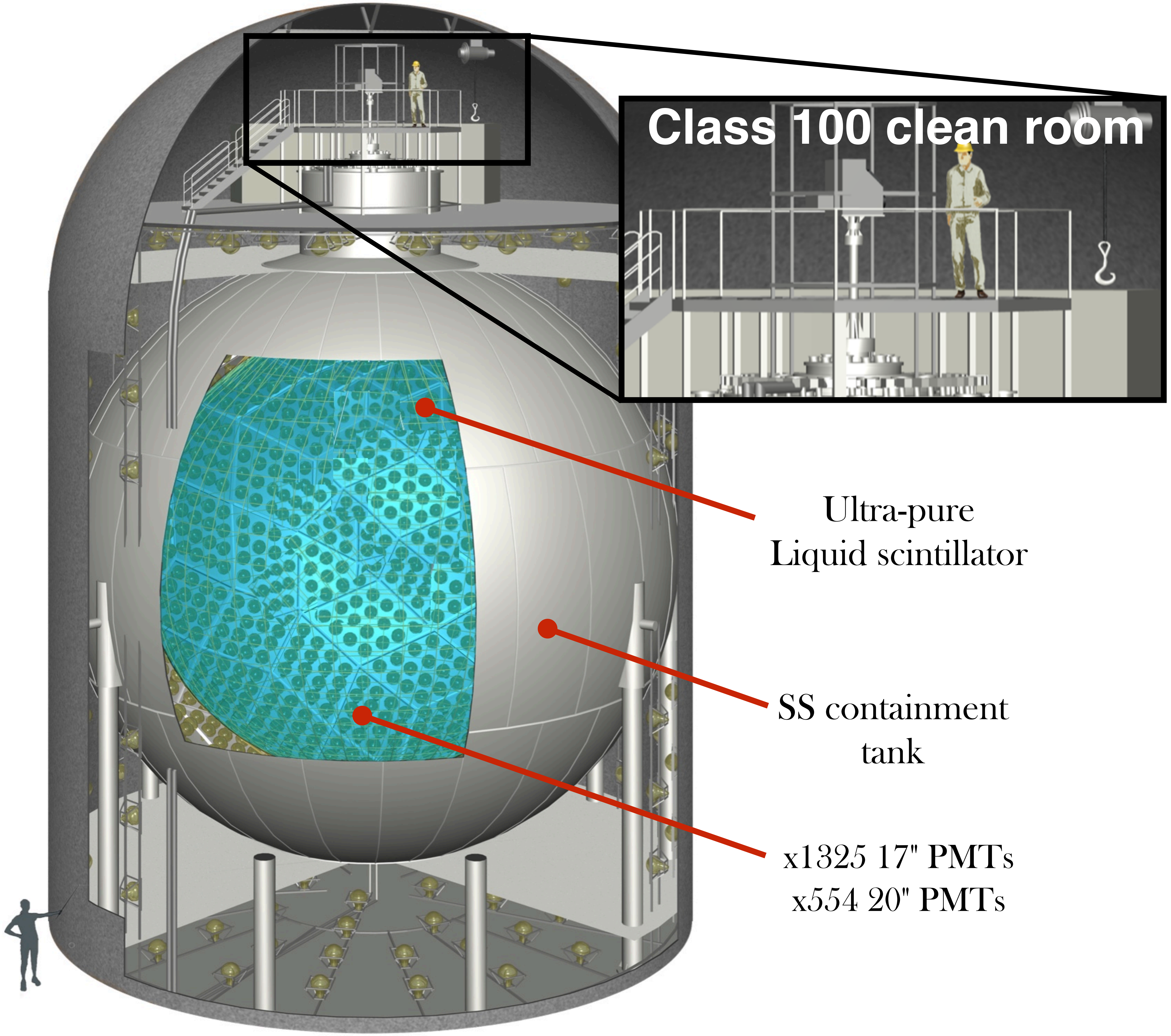
Isotope	Natural abundance (%)	$Q_{\beta\beta}$ (MeV)
^{136}Xe	8.9	2.46



The observable is a **0νββ event rate** (equivalently, a half-life $T_{1/2}$).
Region of interest (ROI) := [2.35 - 2.70 MeV]

KamLAND (the Kamioka Liquid Scintillator Antineutrino Detector)

The KamLAND detector



1,200m³ liquid scintillator.
(contained in a 13-m transparent balloon)

PMTs are suspended in buffer oil provide 34% photocathode coverage.

Ultra low radioactivity.

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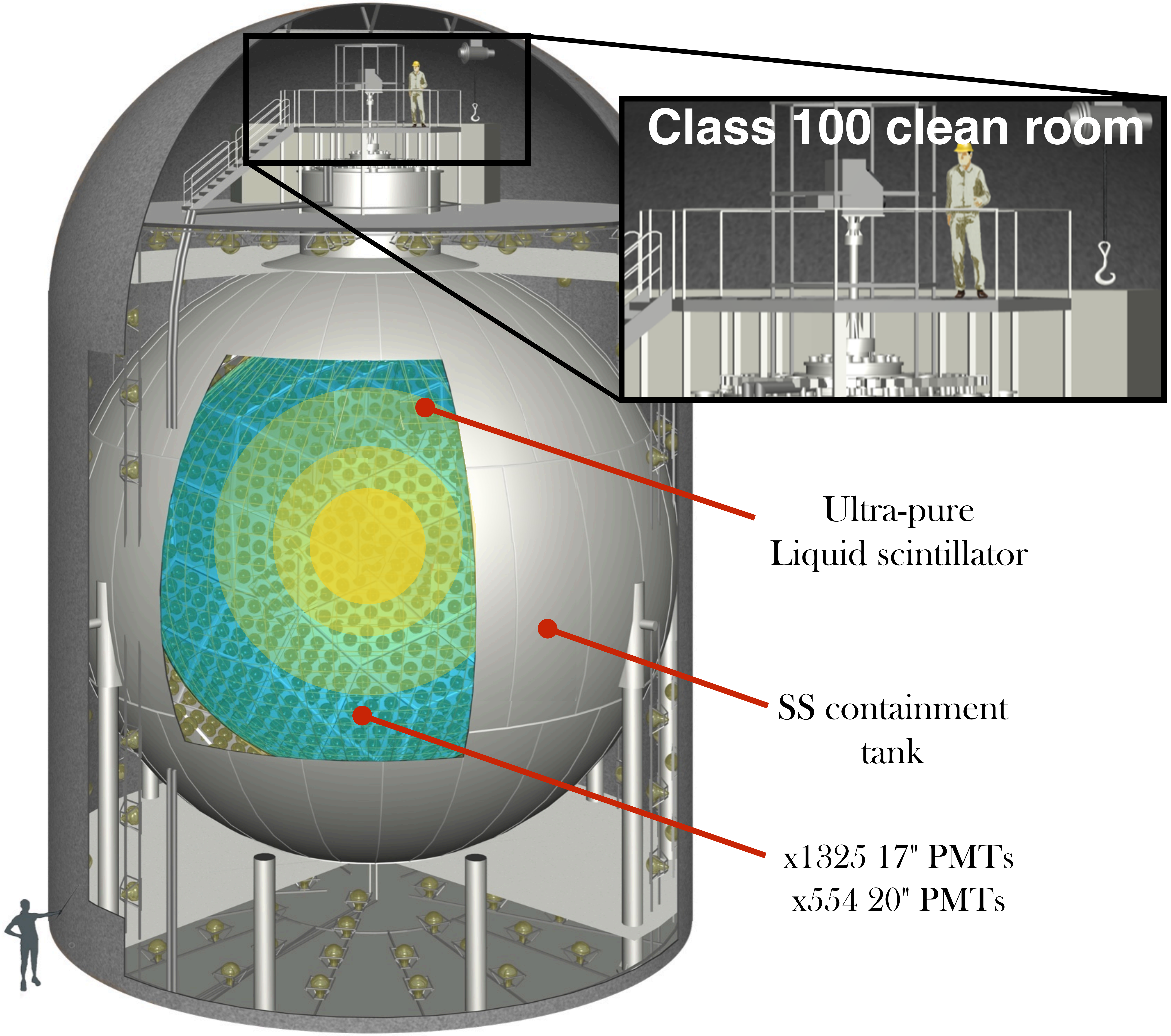

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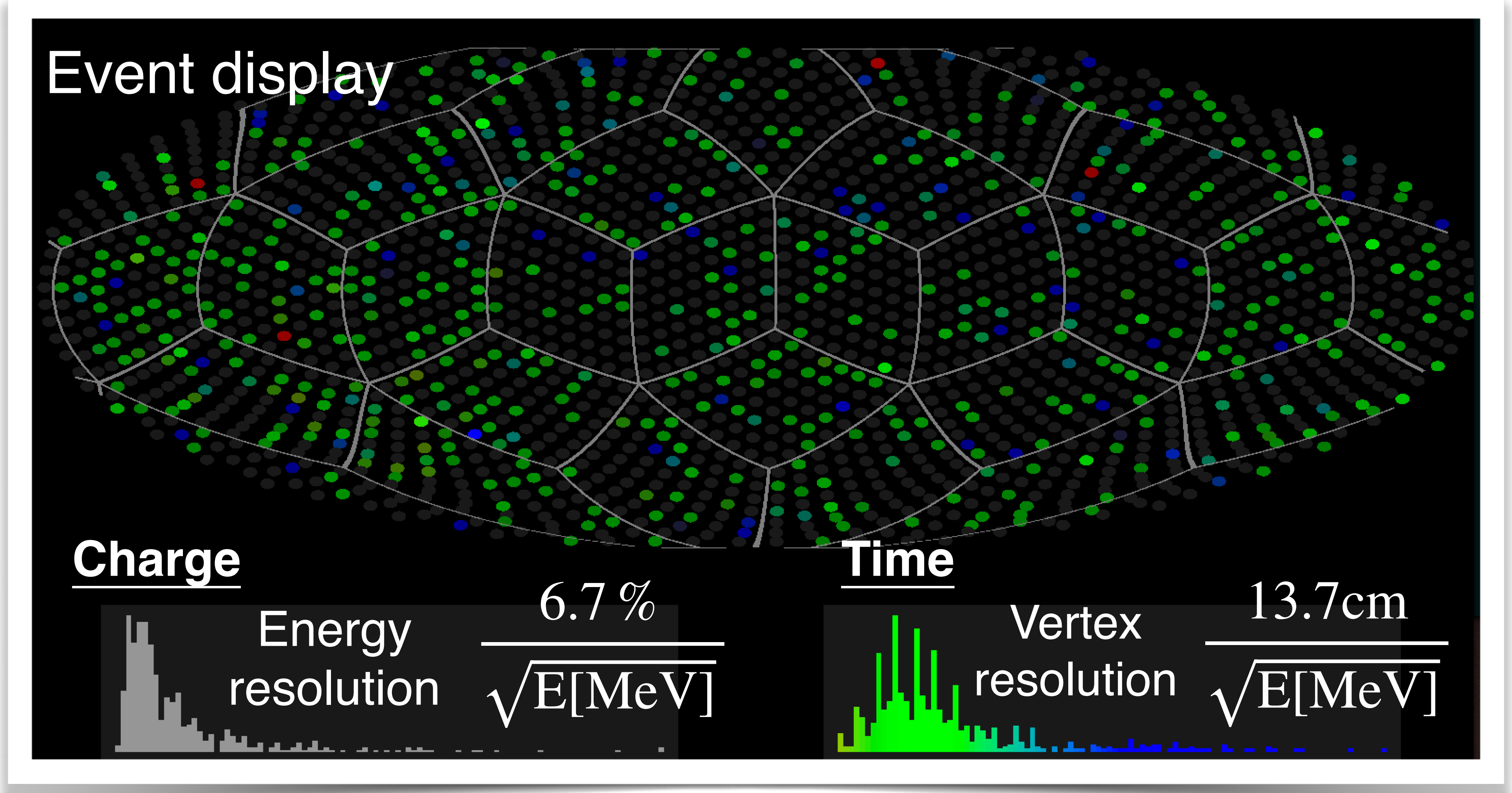
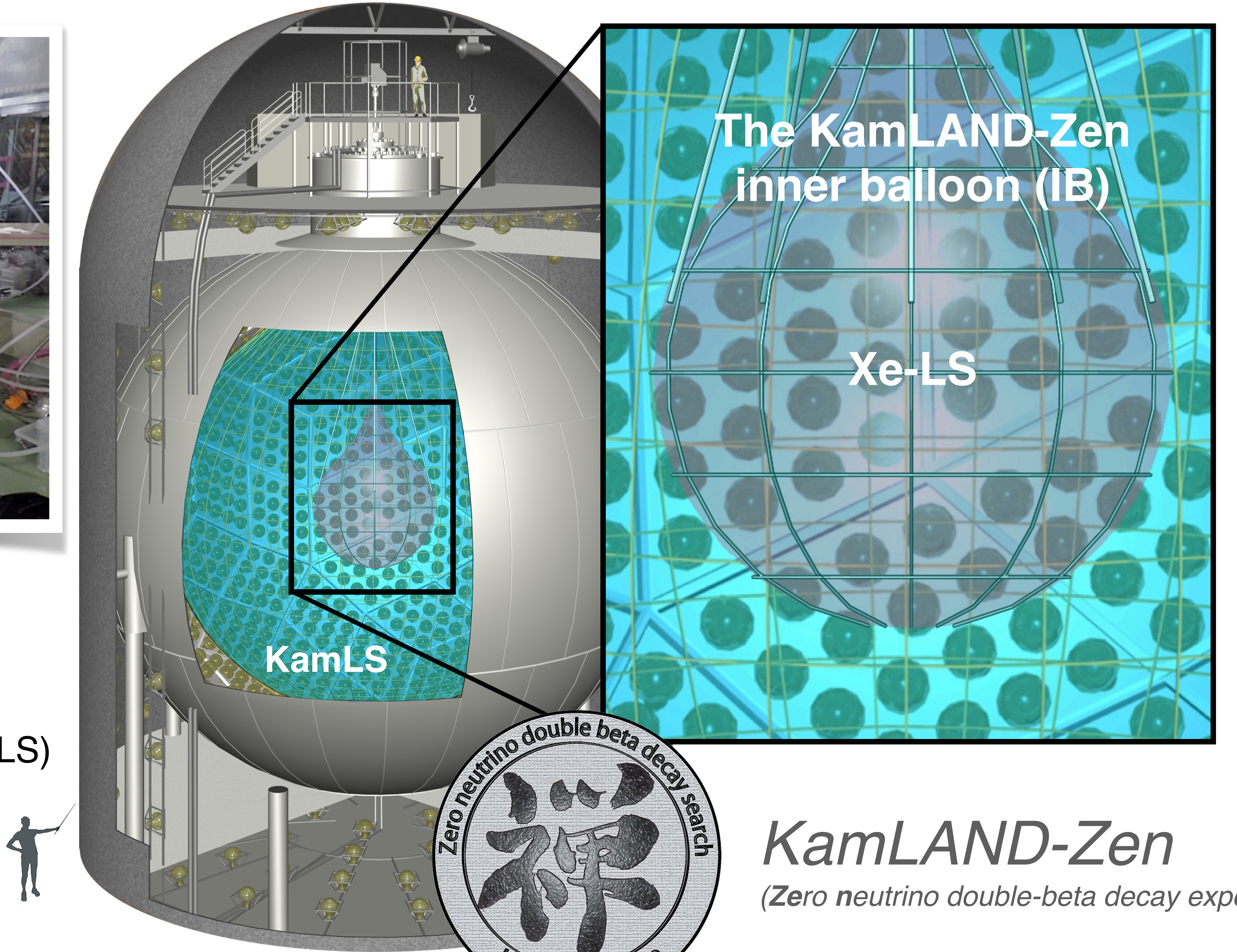


Introducing KamLAND-Zen



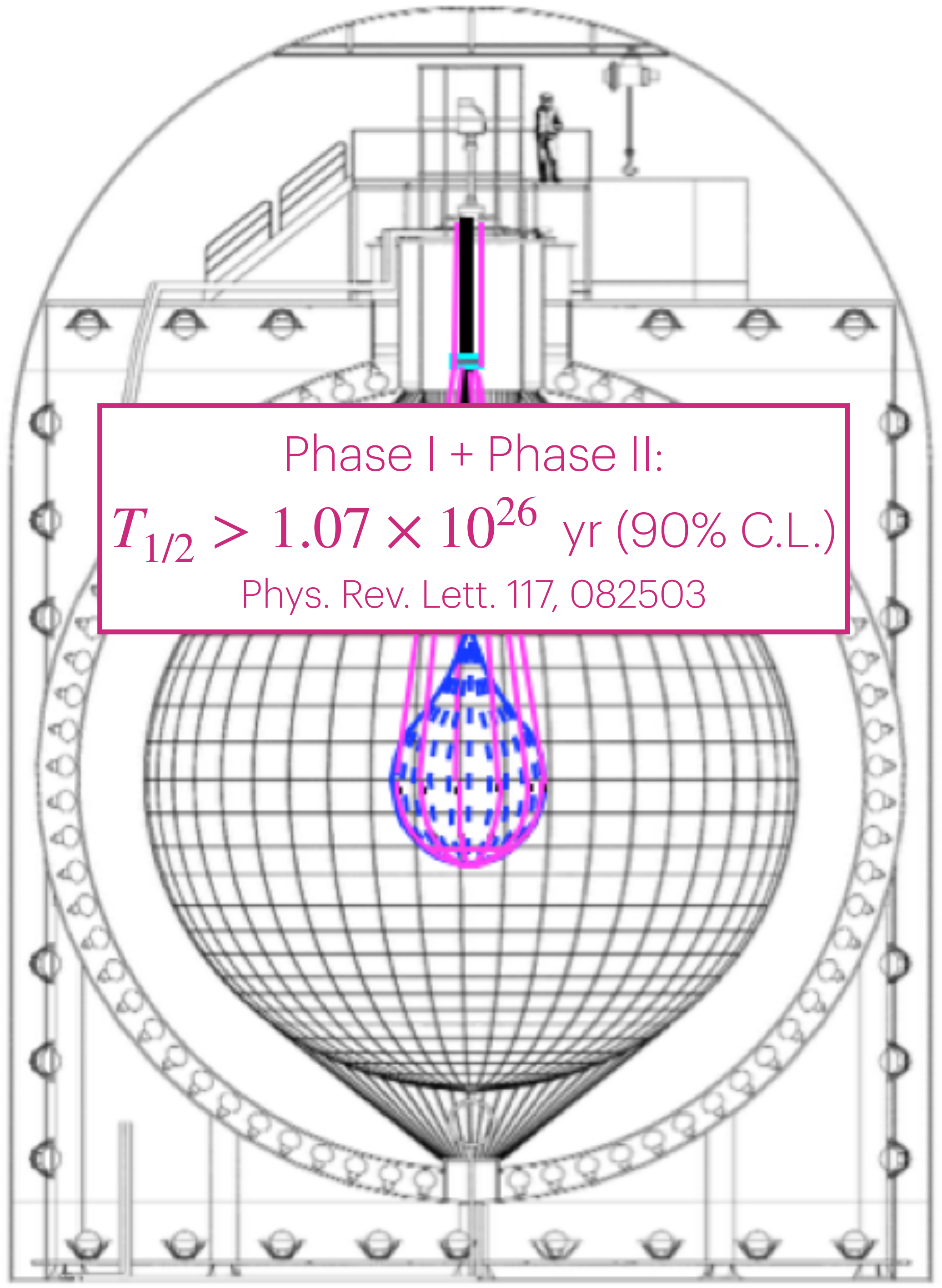
<u>Xenon 136</u>
Natural abundance = 8.9%
Isotopic enrichment = 90.86%
3% wt soluble in Liquid Scintillator (XeLS)

KamLAND-Zen

*(**Ze**ro **n**eutrino double-beta decay experiment)*

The evolution of KamLAND-Zen

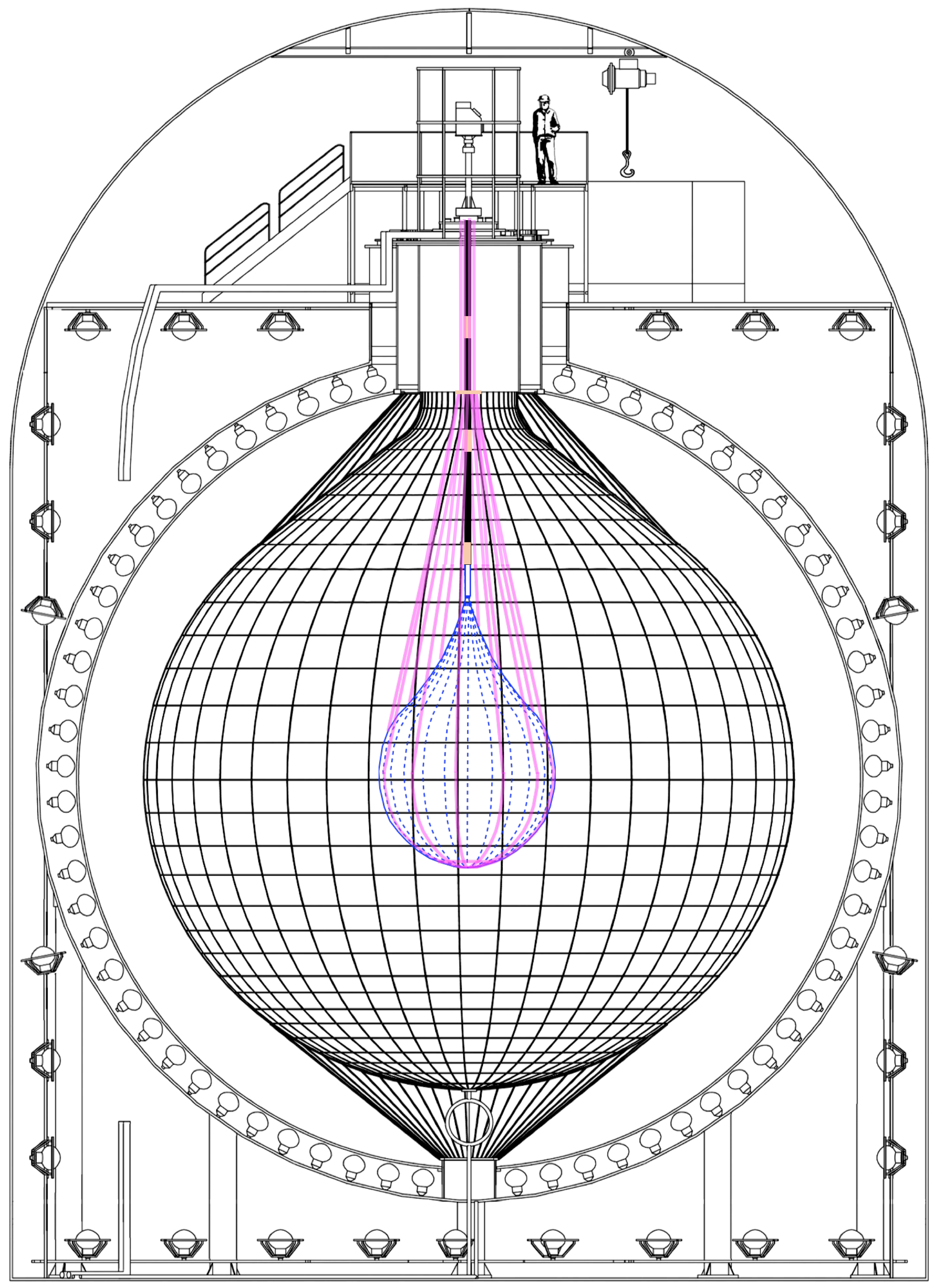
Past



KamLAND-Zen 400:

- Duration: 2011 ~ 2015
- Inner-balloon radius = 1.54 m
- Xenon mass = 320 ~ 381 kg

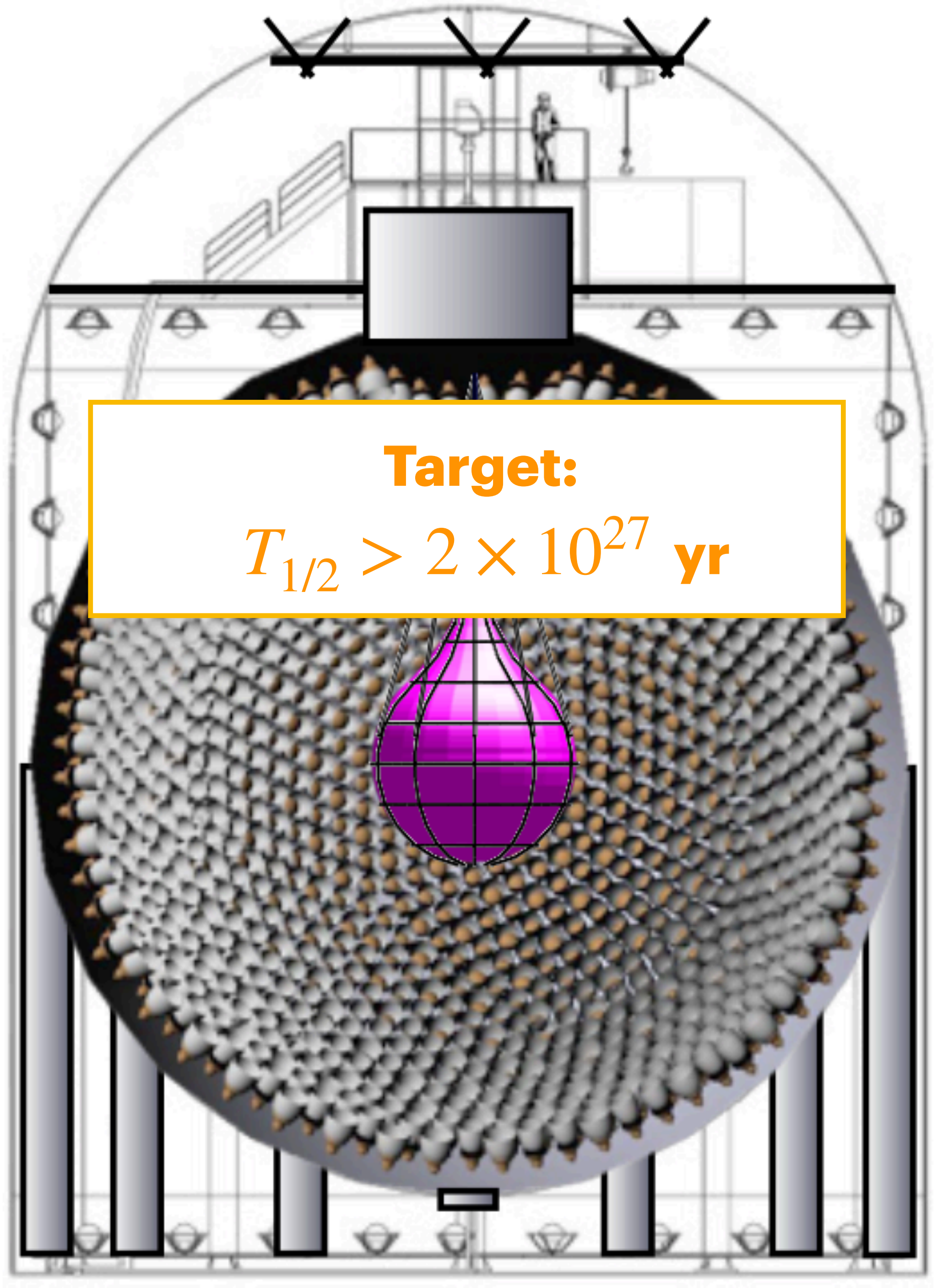
Present



KamLAND-Zen 800:

- Data taking starts Jan. 2019
- Inner-balloon radius = 1.90 m
- Xenon mass = 745 ± 3 kg

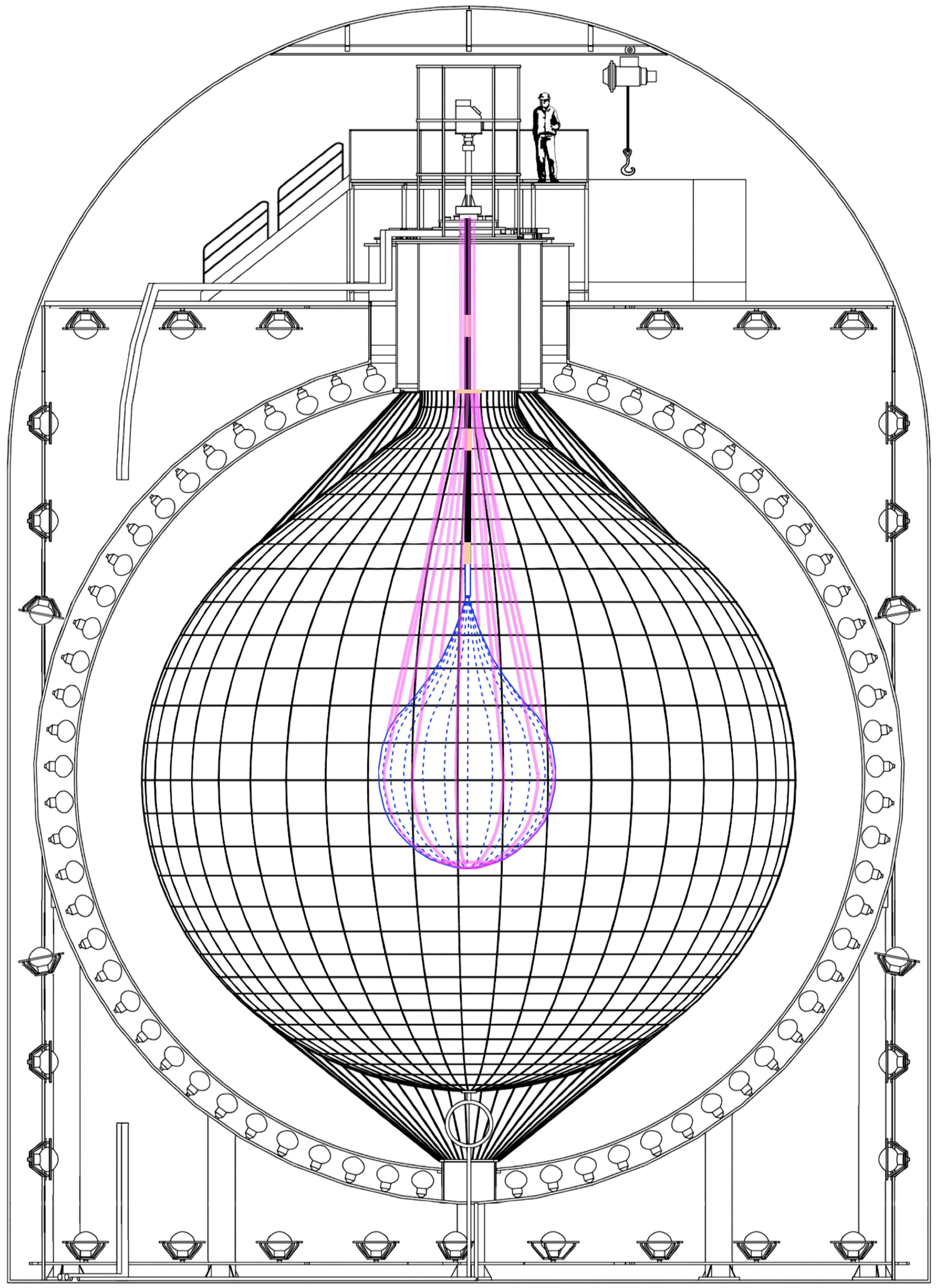
Future



KamLAND2-Zen:

- Xenon mass ~ 1ton
- Aiming at 100% Photocoverage
- PEN scintillation balloon film
- Updated readout electronics

Conceptual overview of primary backgrounds



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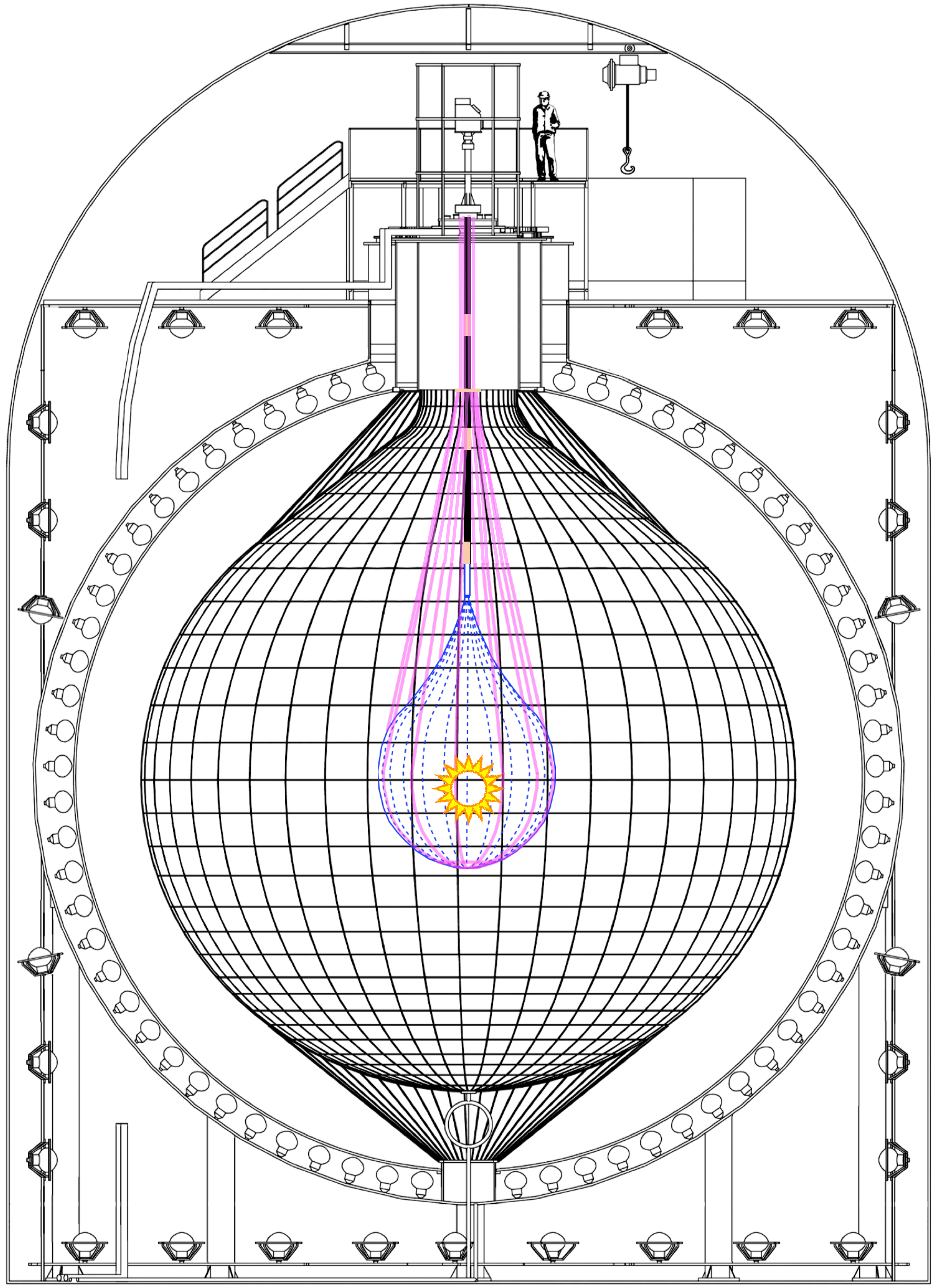
<u>Internal Radioactive Impurities:</u>
The Xe-LS radioactive impurities.
(Uranium and Thorium)



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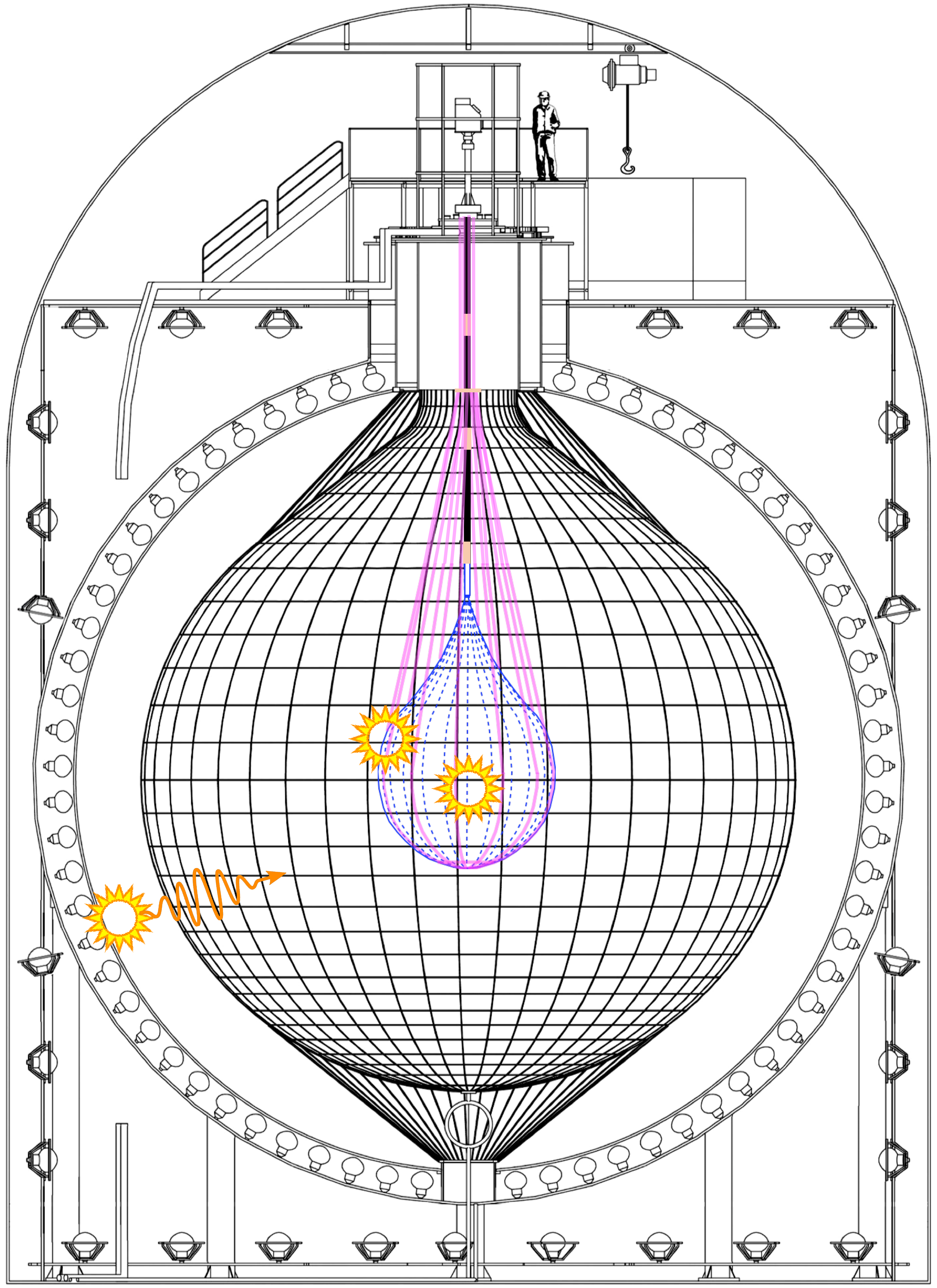

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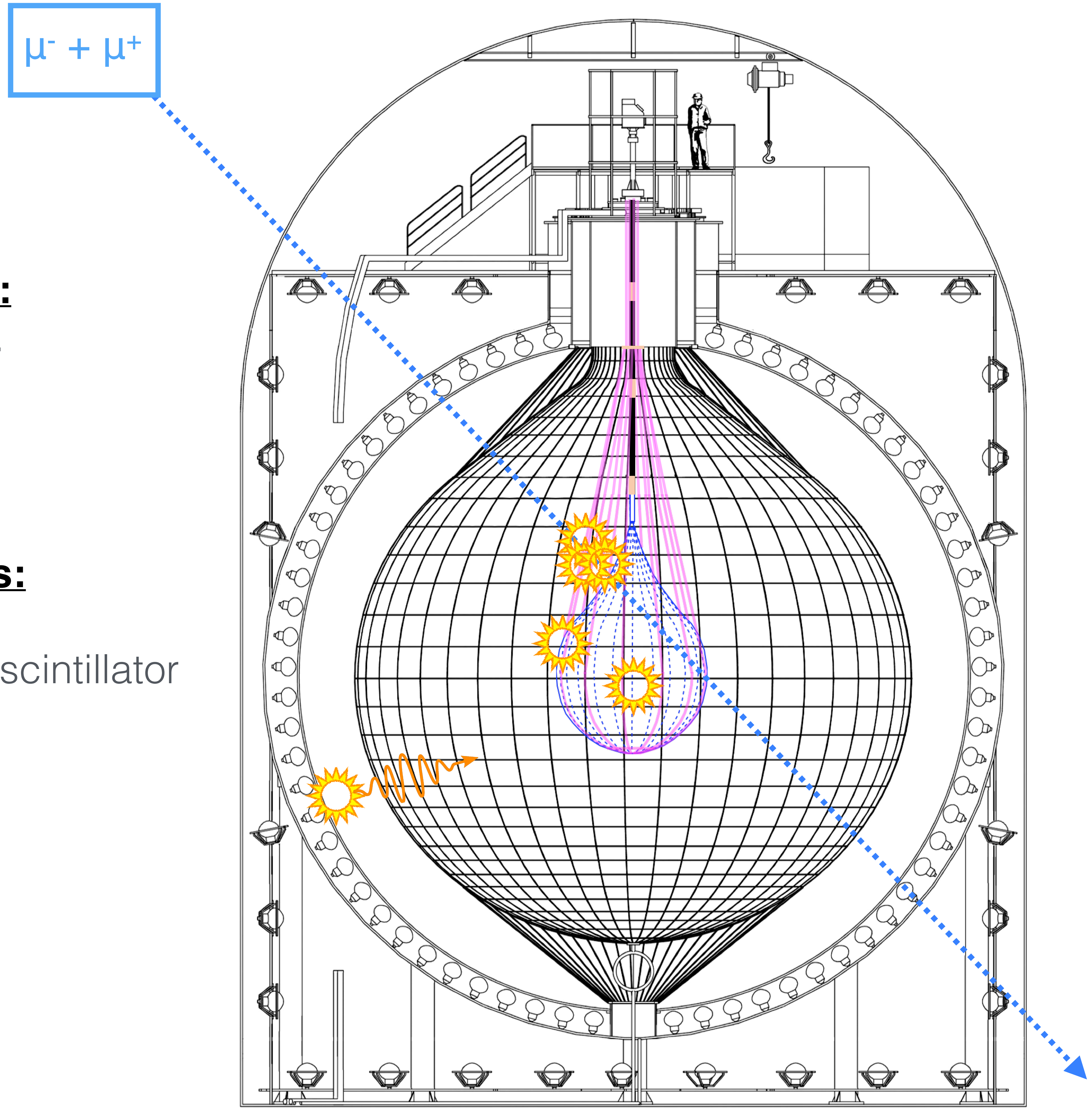

Cosmogenic spallation products:
Dominant background.
Cosmic ray muon spallation on carbon (short-lived) and xenon (long-lived).

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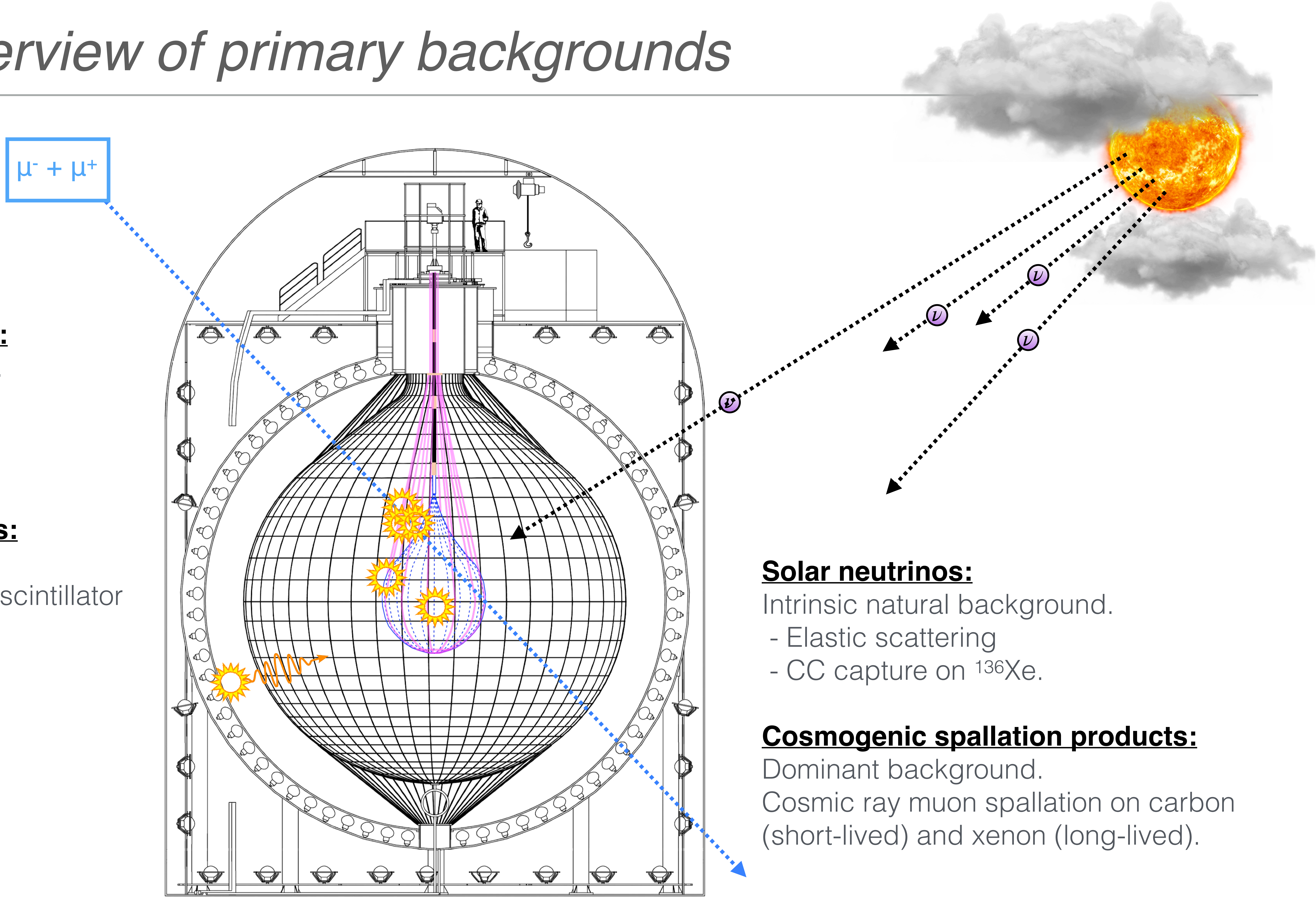

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- Elastic scattering
- CC capture on ^{136}Xe.

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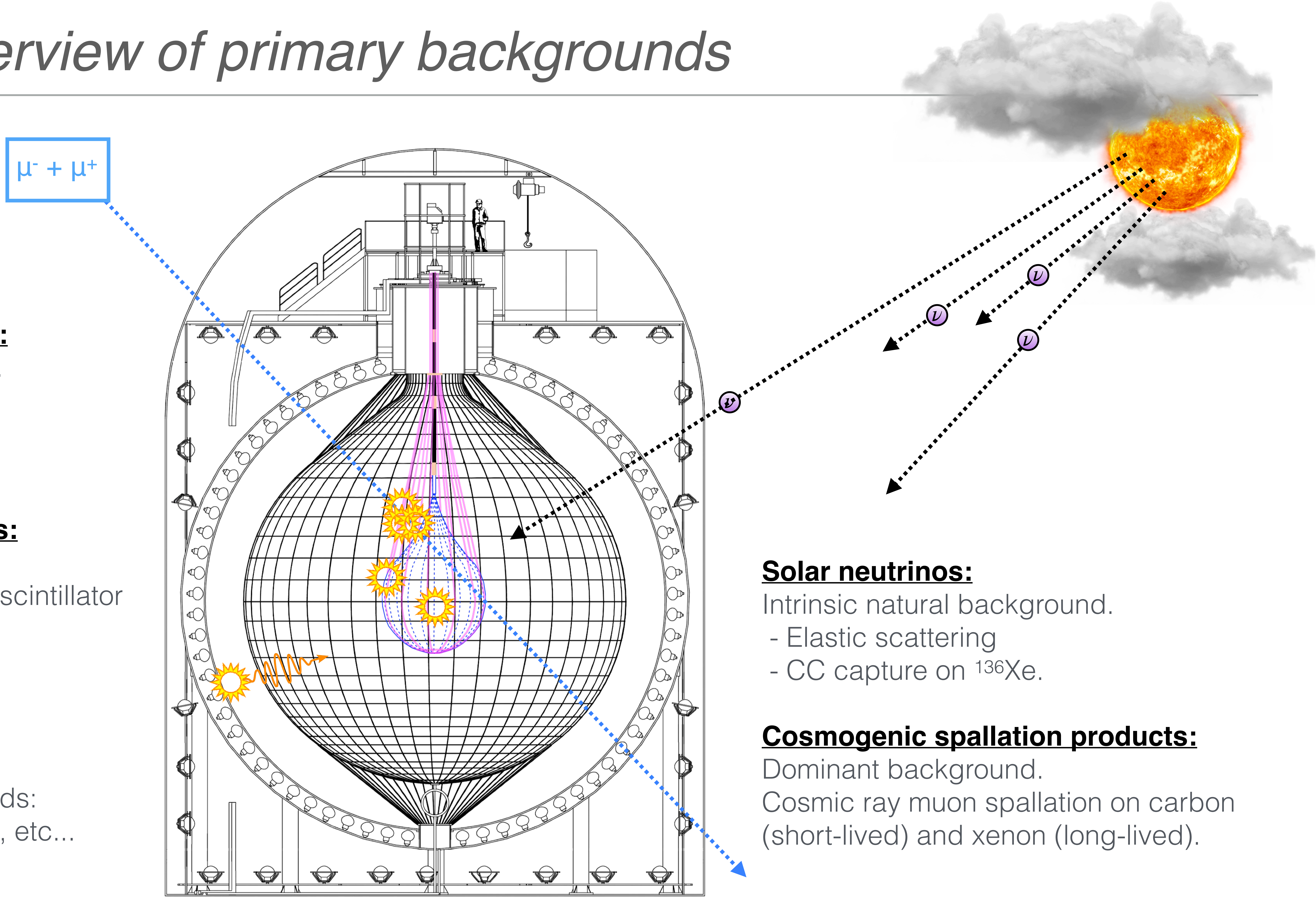
Others:
There are many other backgrounds:
^{40}k, ^{85}Kr, ^{134}Xe, Fukushima fallout, etc...



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Analysis method overview

40 equal-volume bins:

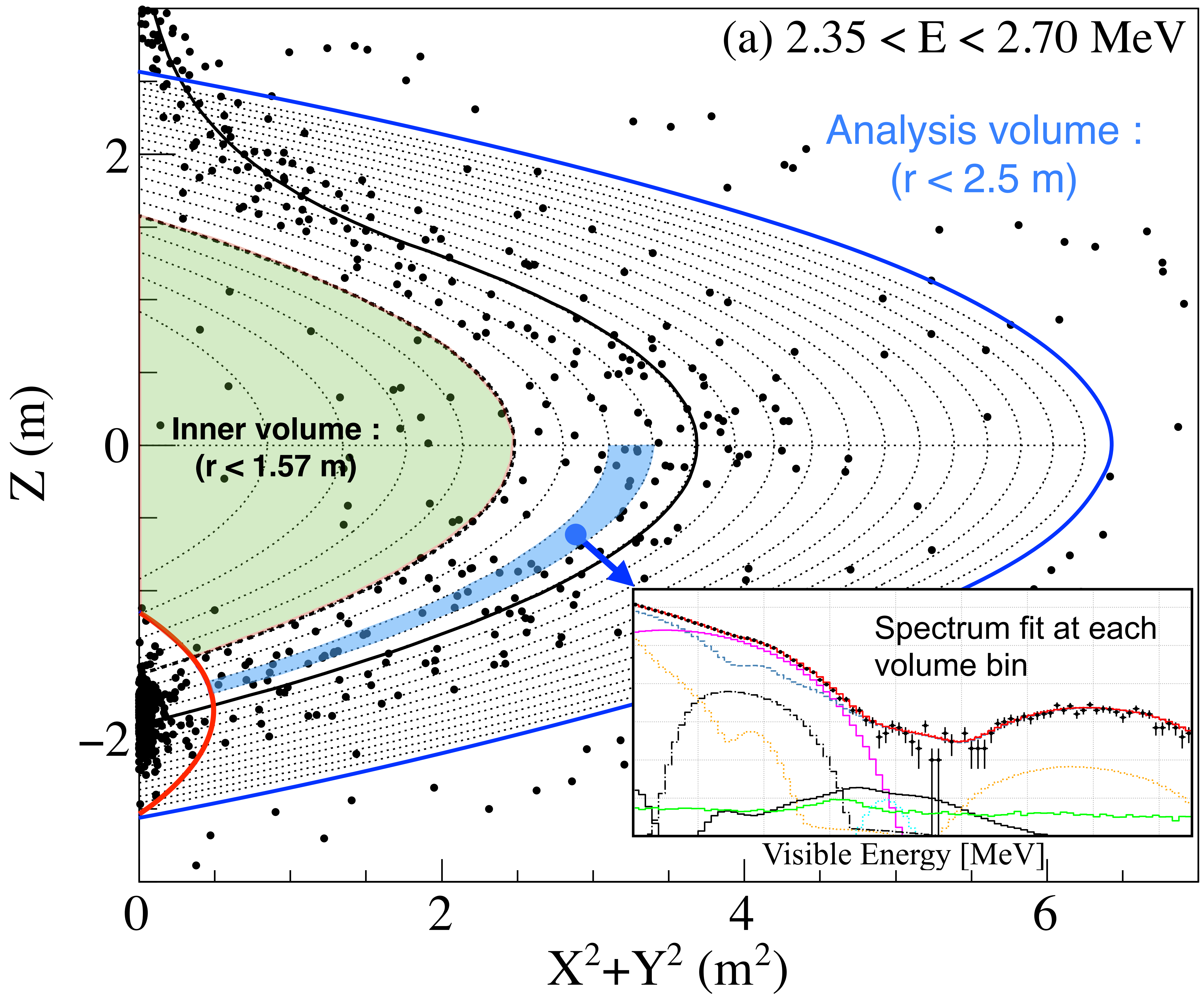
- radius 20 × {upper sphere, lower sphere}

3 distinct time bins:

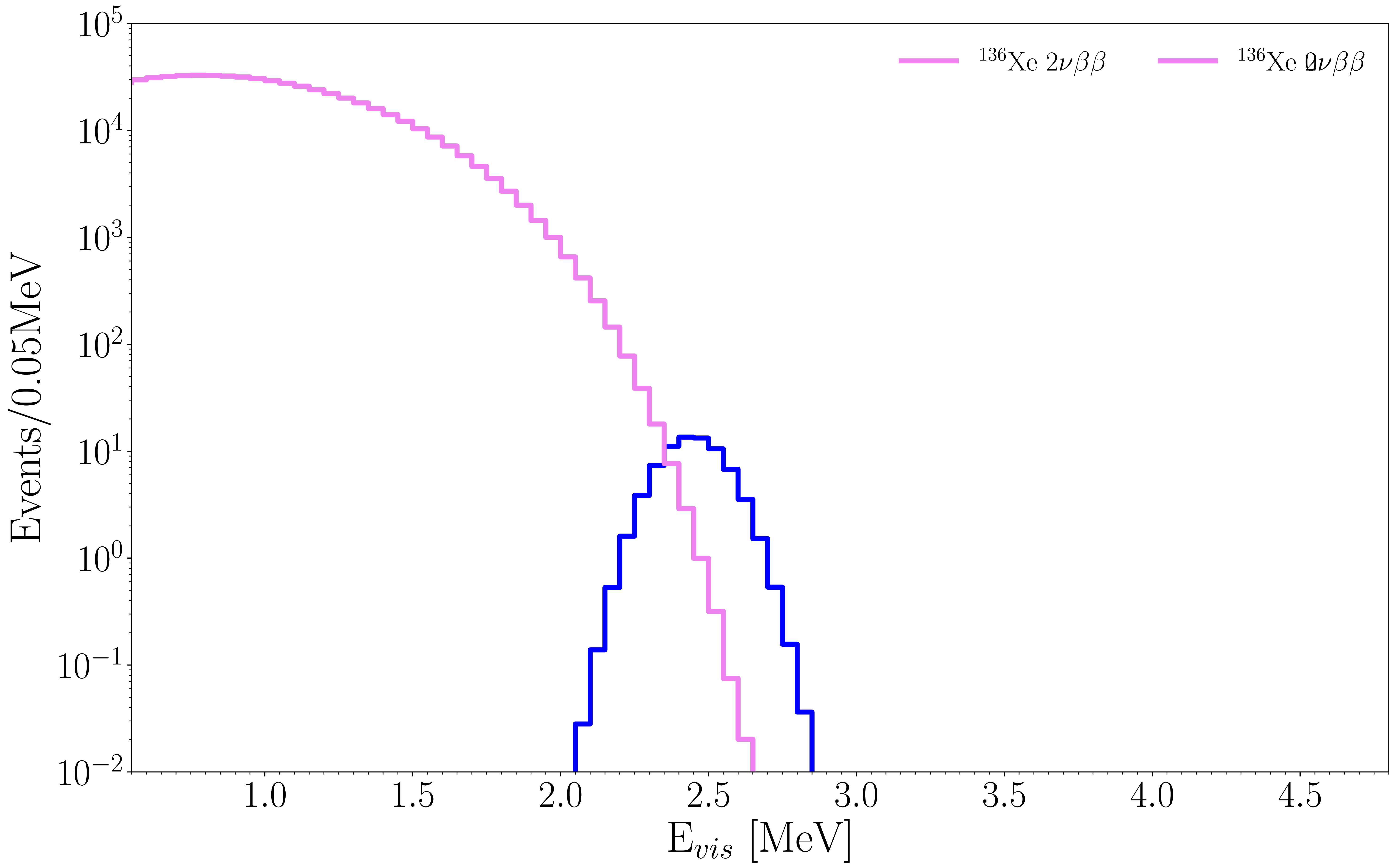
- Independent MC expectation
- Fitted simultaneously with same parameters

86 energy bins:

- spanning from 0.5MeV to 4.8MeV



KamLAND-Zen 800, what did we see?



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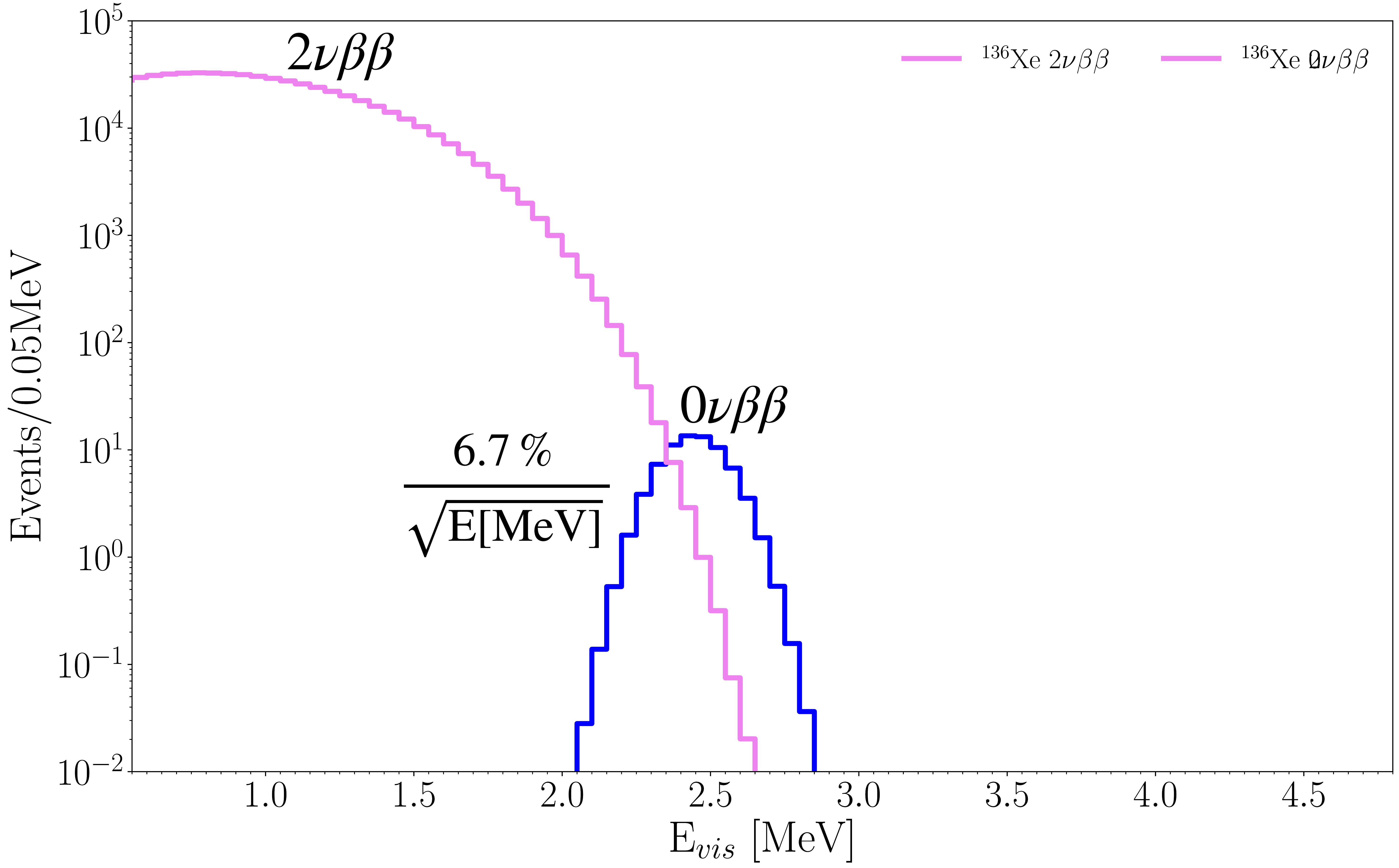

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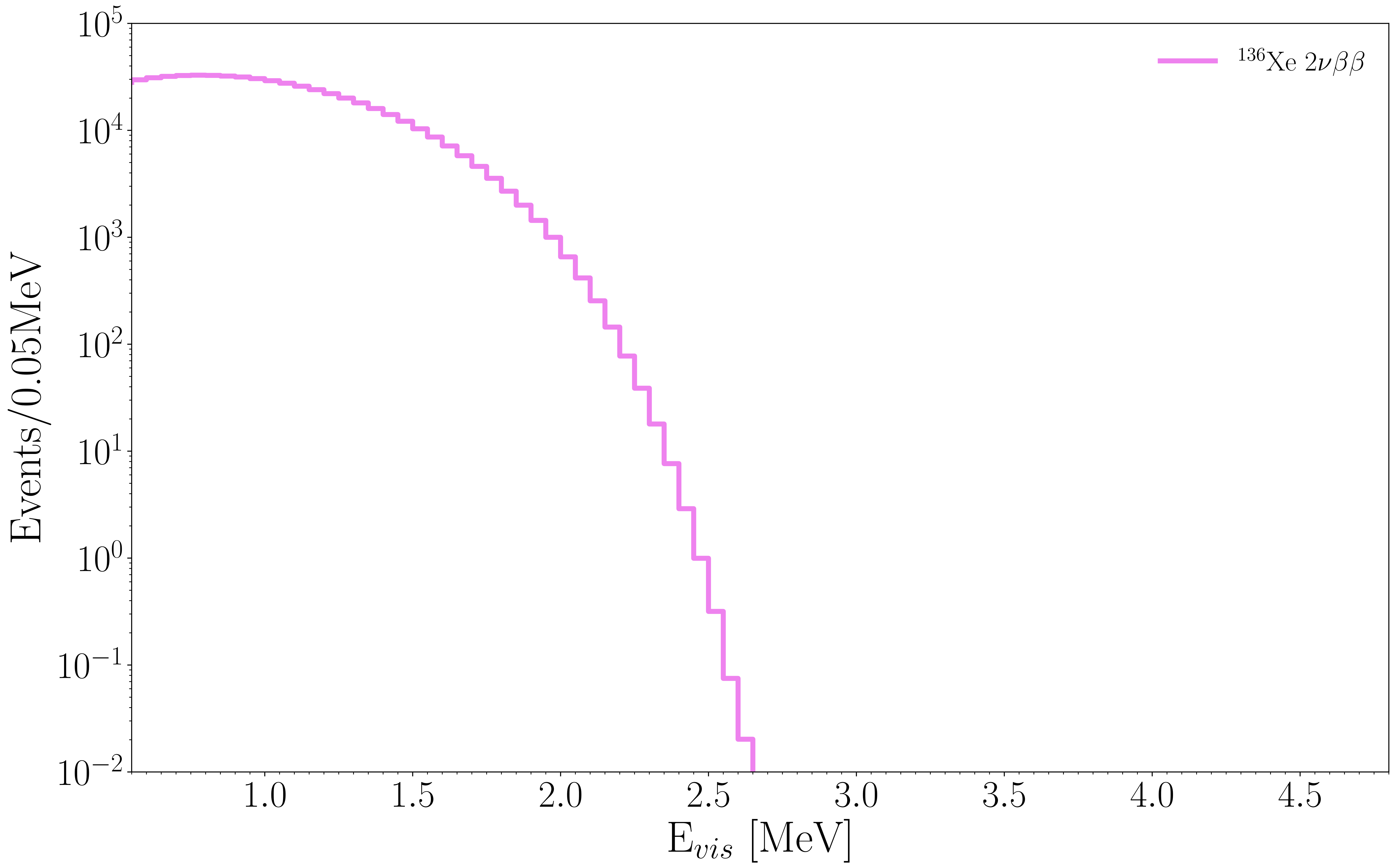

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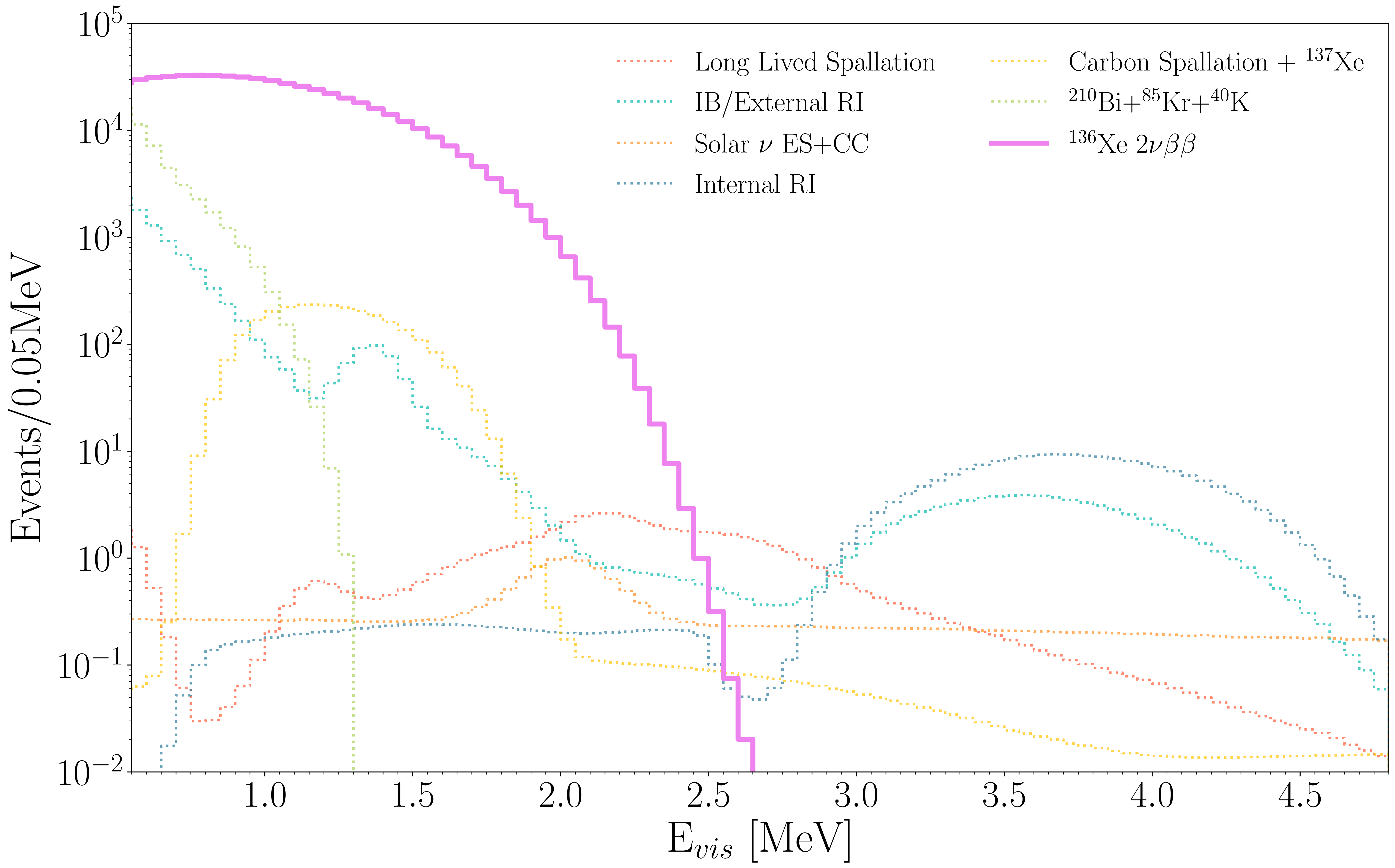

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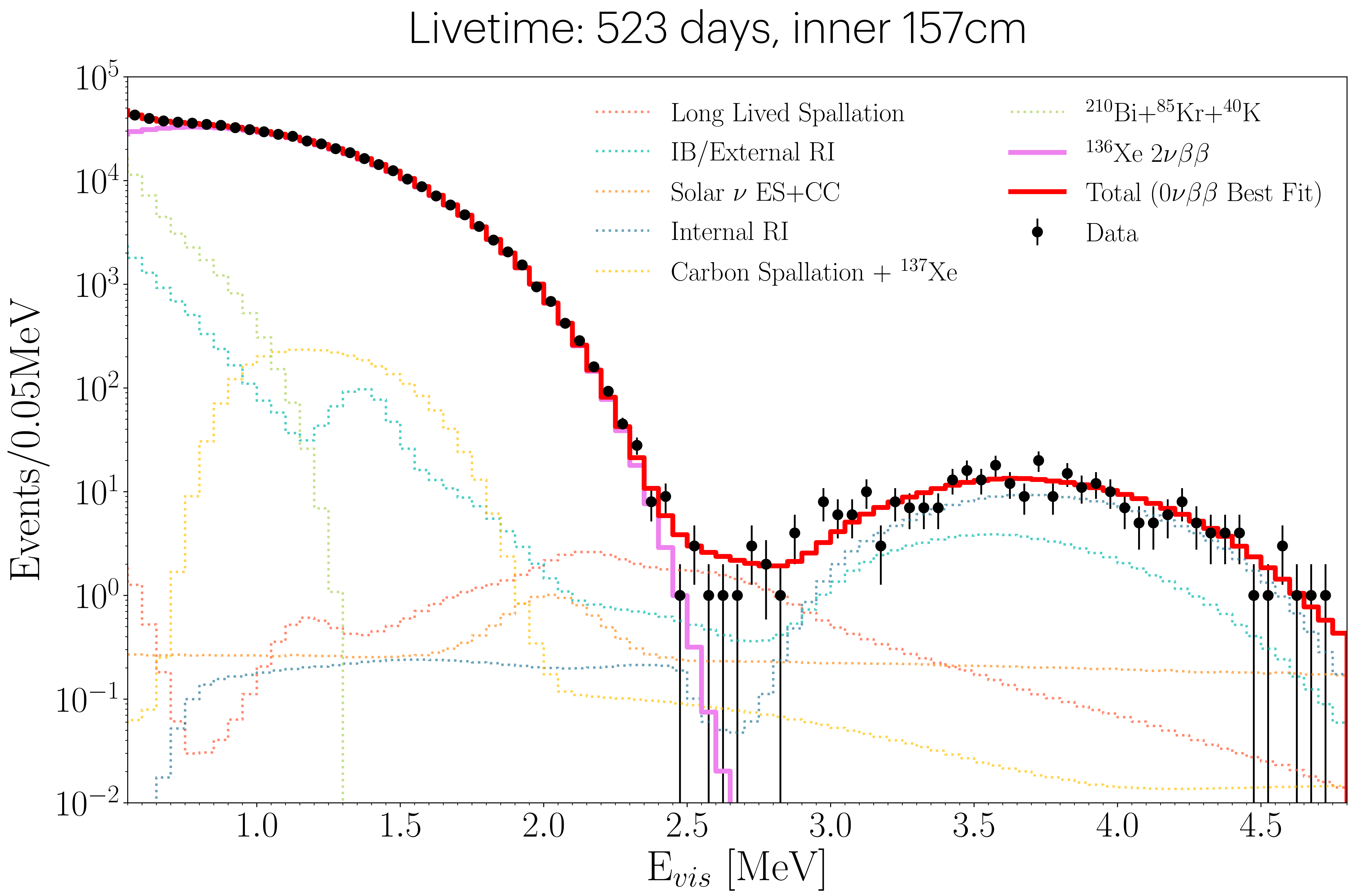

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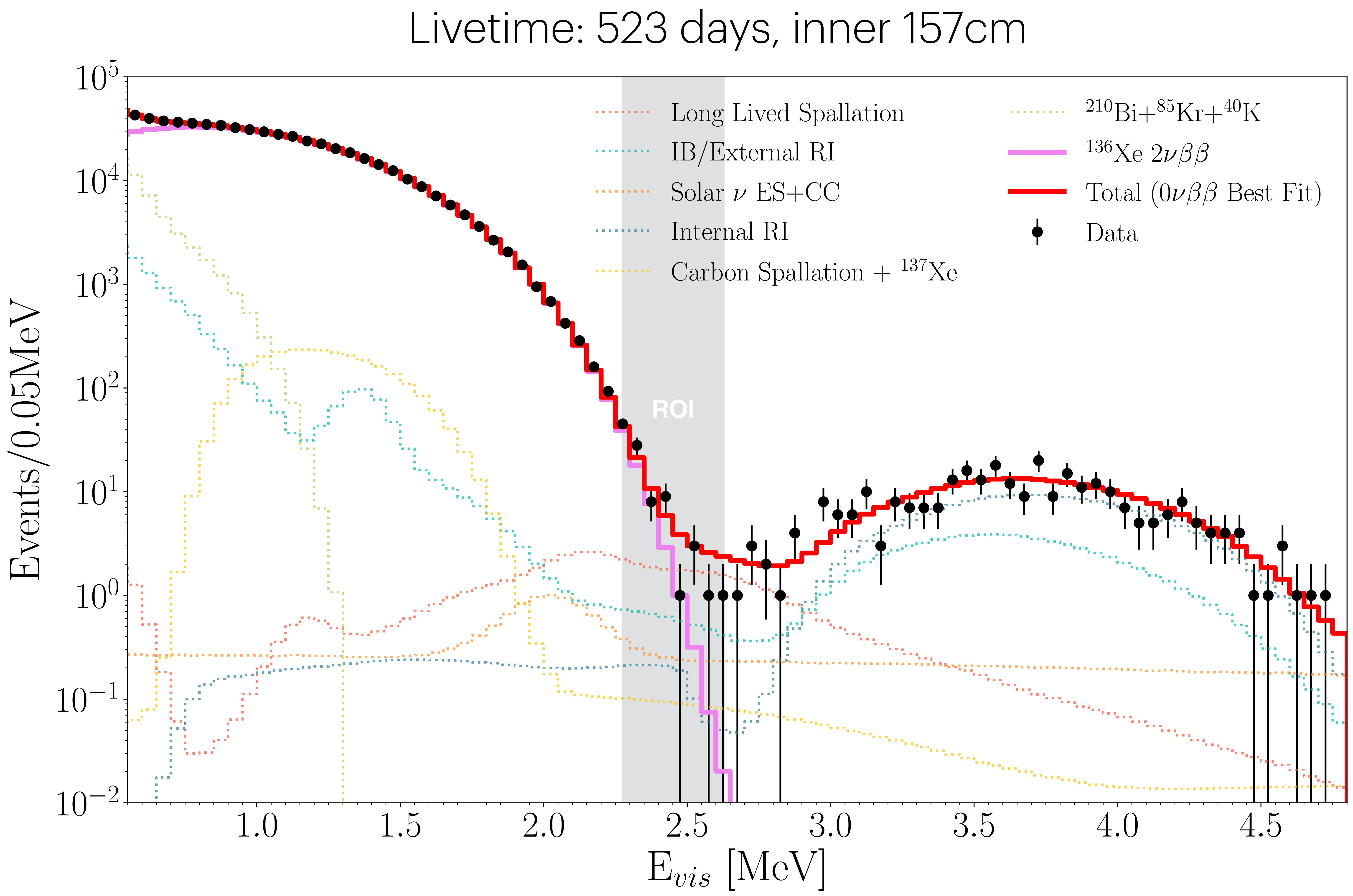

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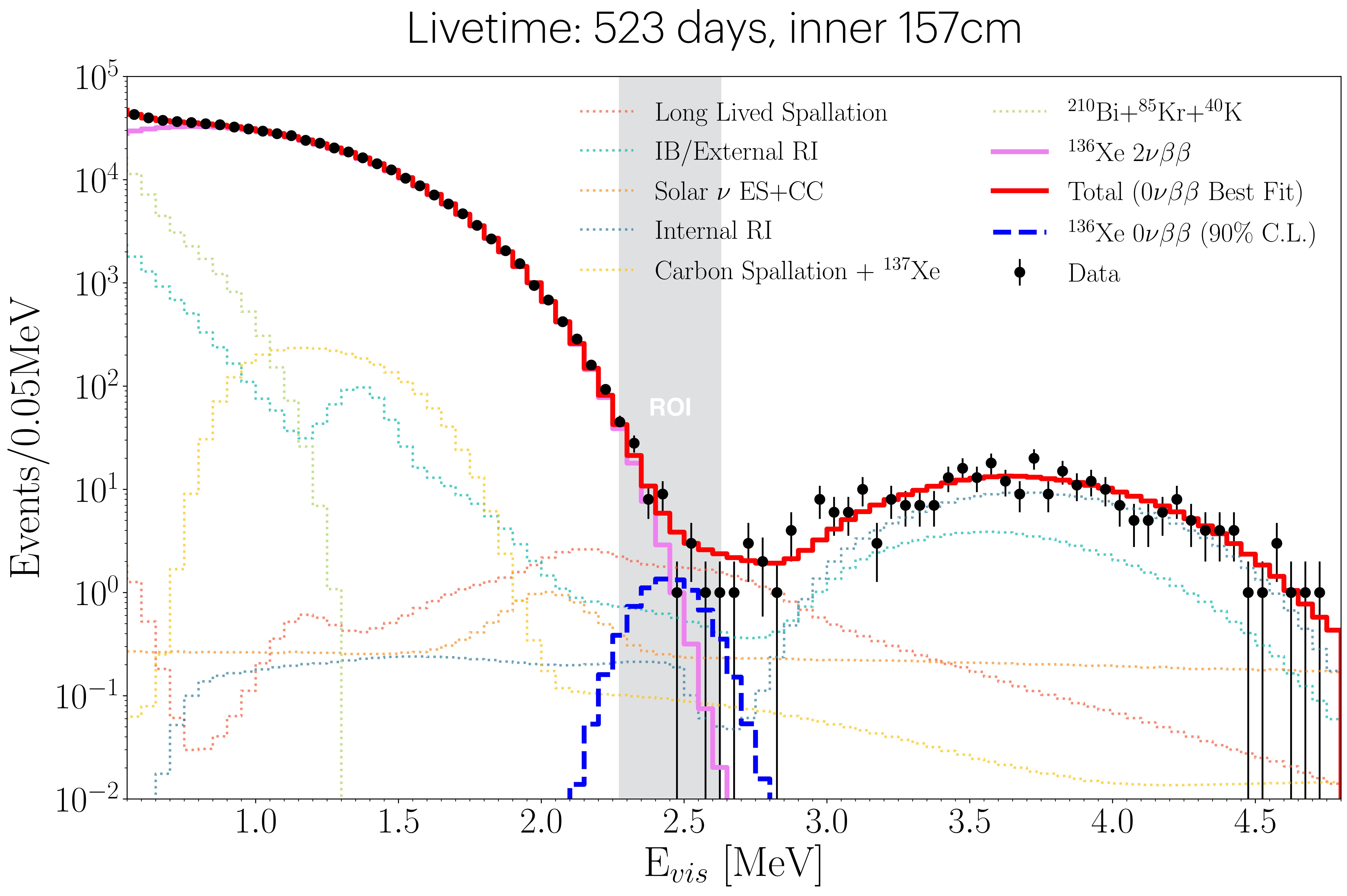

The results

Background	Best-fit	
	Frequentist	Bayesian
^{136}Xe $2\nu\beta\beta$	11.98	11.95
Residual radioactivity in Xe-LS		
^{238}U series	0.14	0.09
^{232}Th series	0.84	0.87
External (Radioactivity in IB)		
^{238}U series	3.05	3.46
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Neutrino interactions		
^{8}B solar ν e^- ES	1.65	1.65
Spallation products		
Long-lived	12.52	11.80
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Apply KamNet to entire dataset result:

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What limits our sensitivity?

2νββ energy tail
Most dominant &
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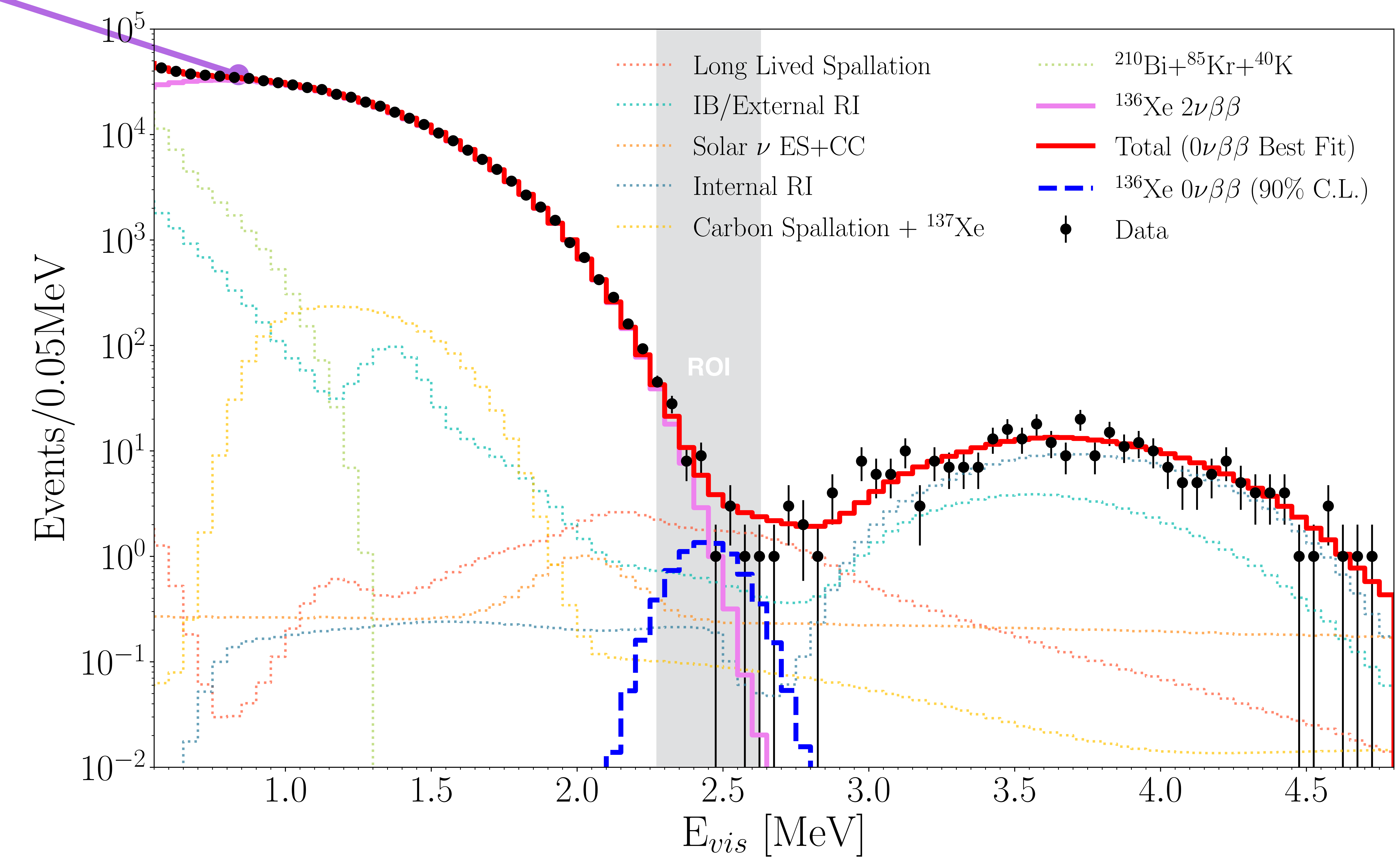
~ 12 events/ROI



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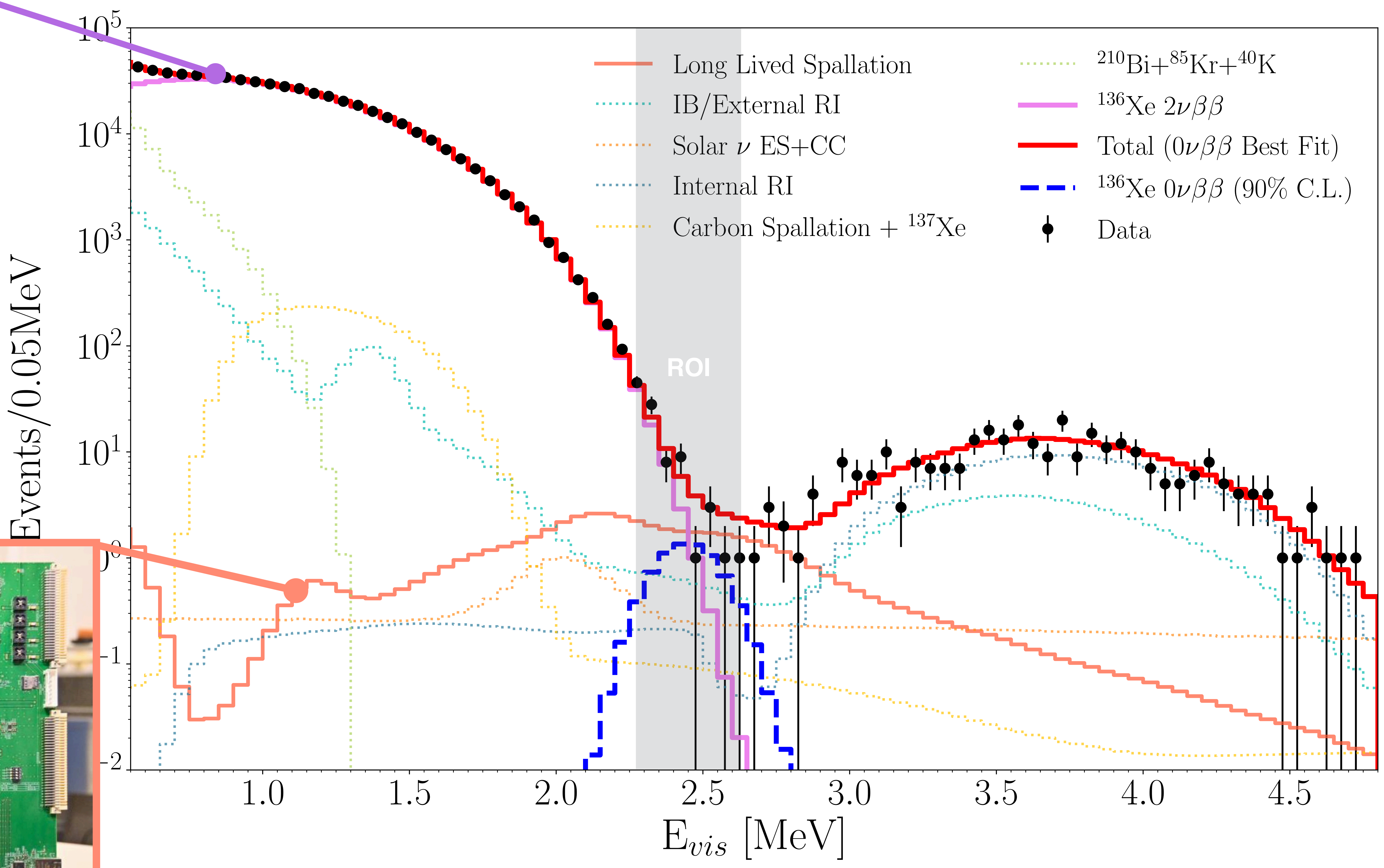

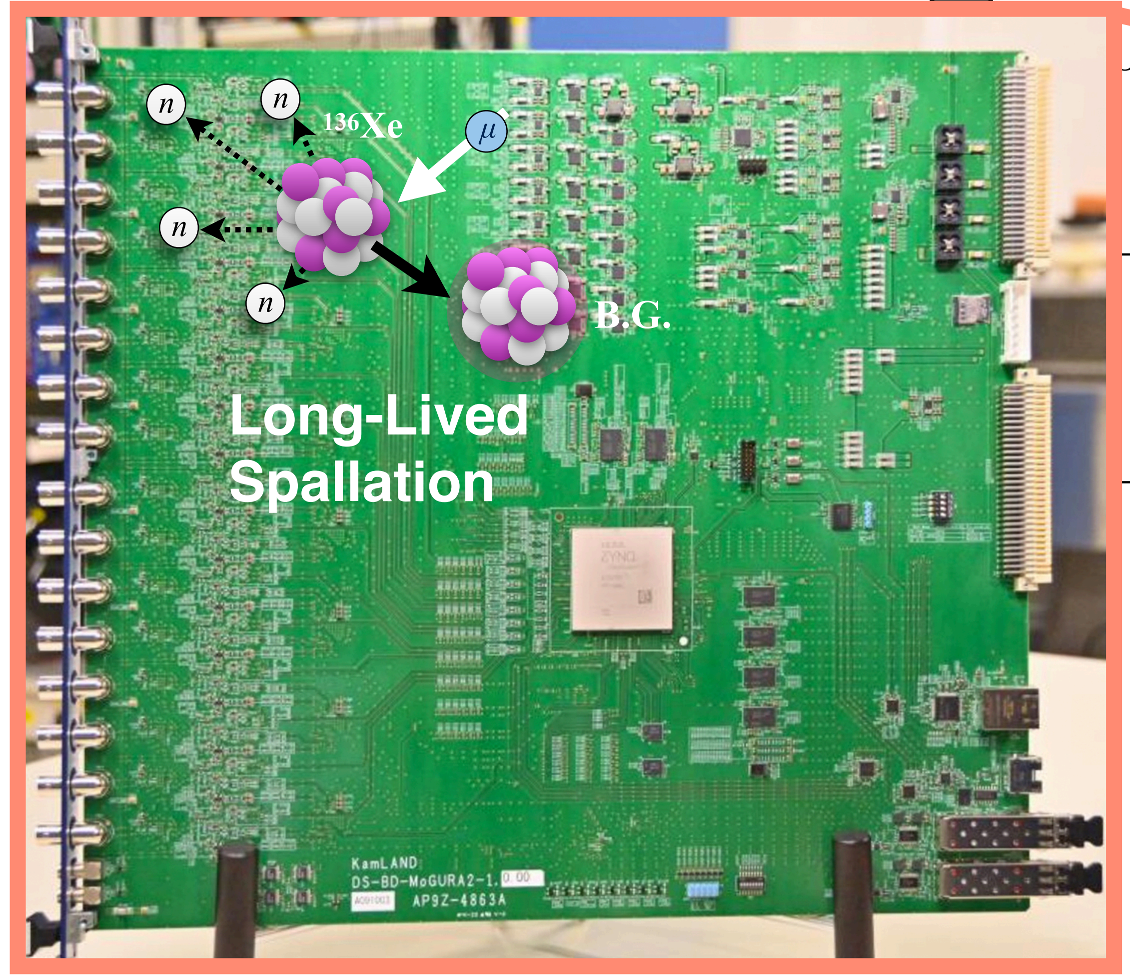

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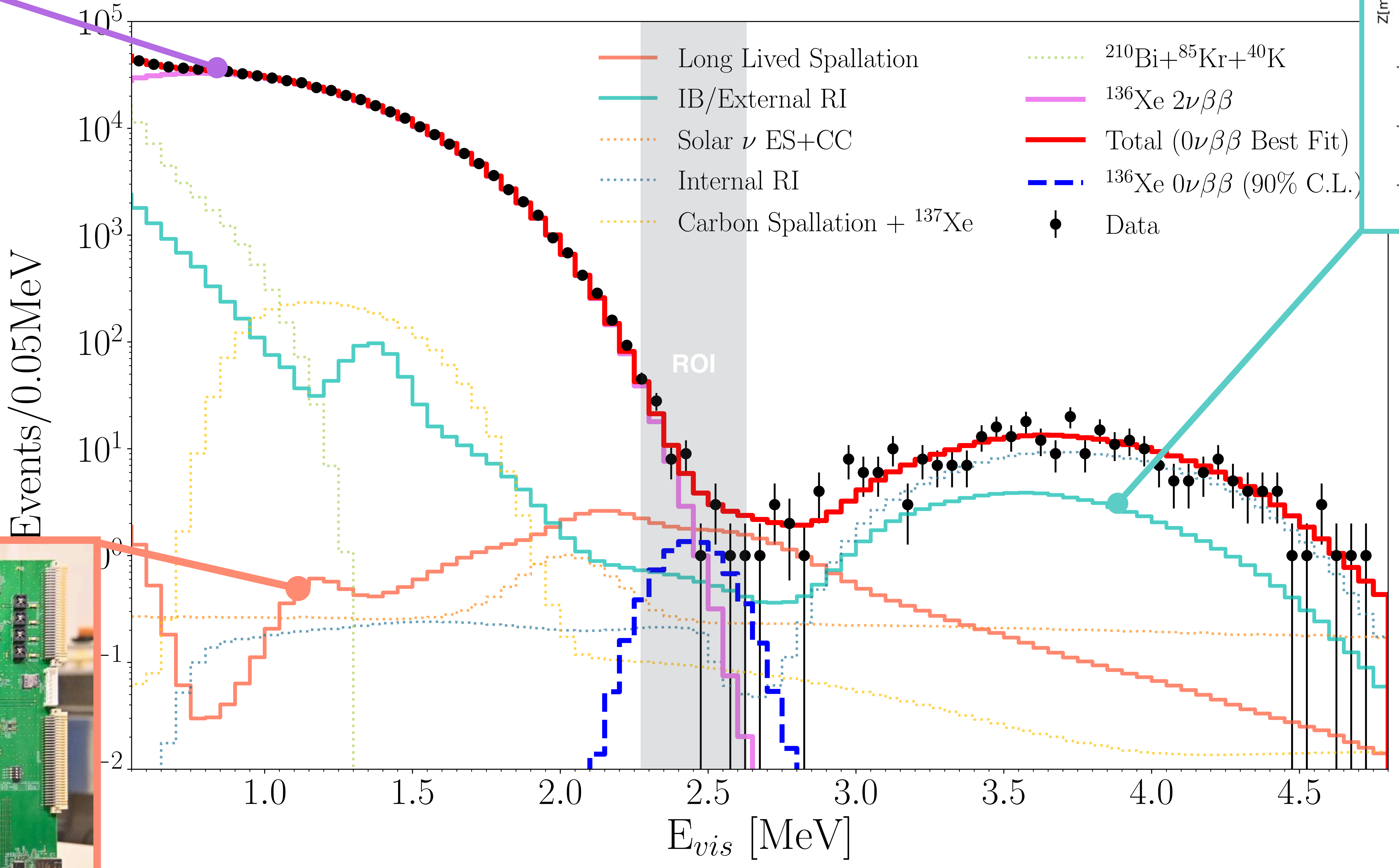

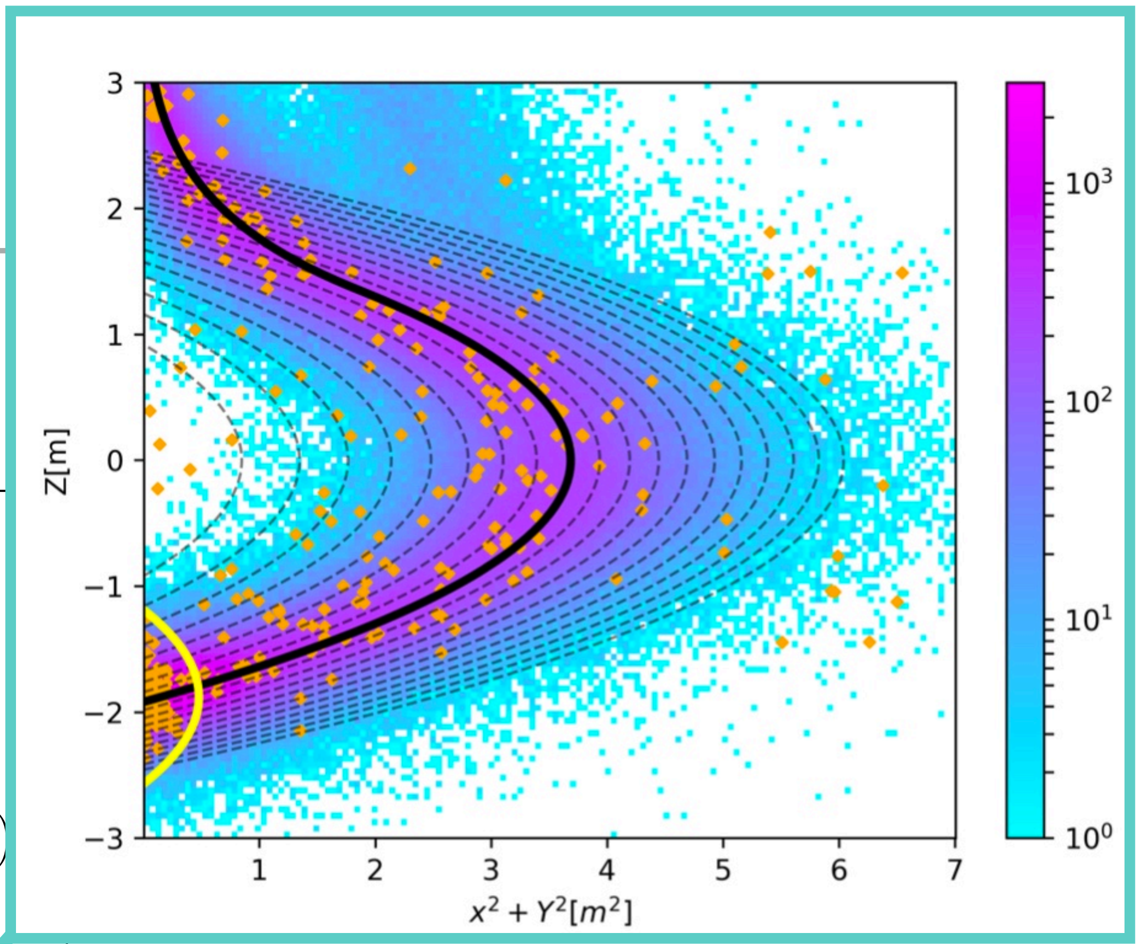

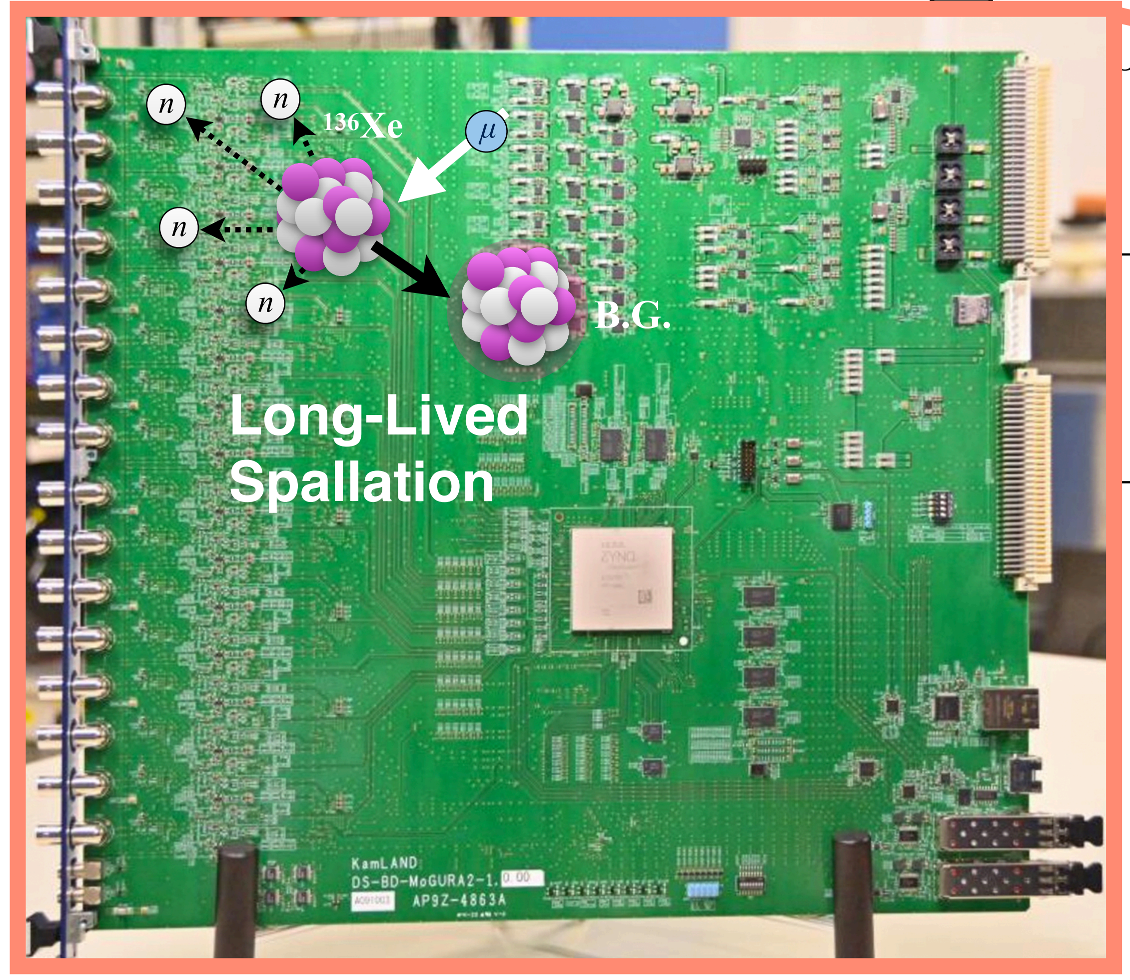

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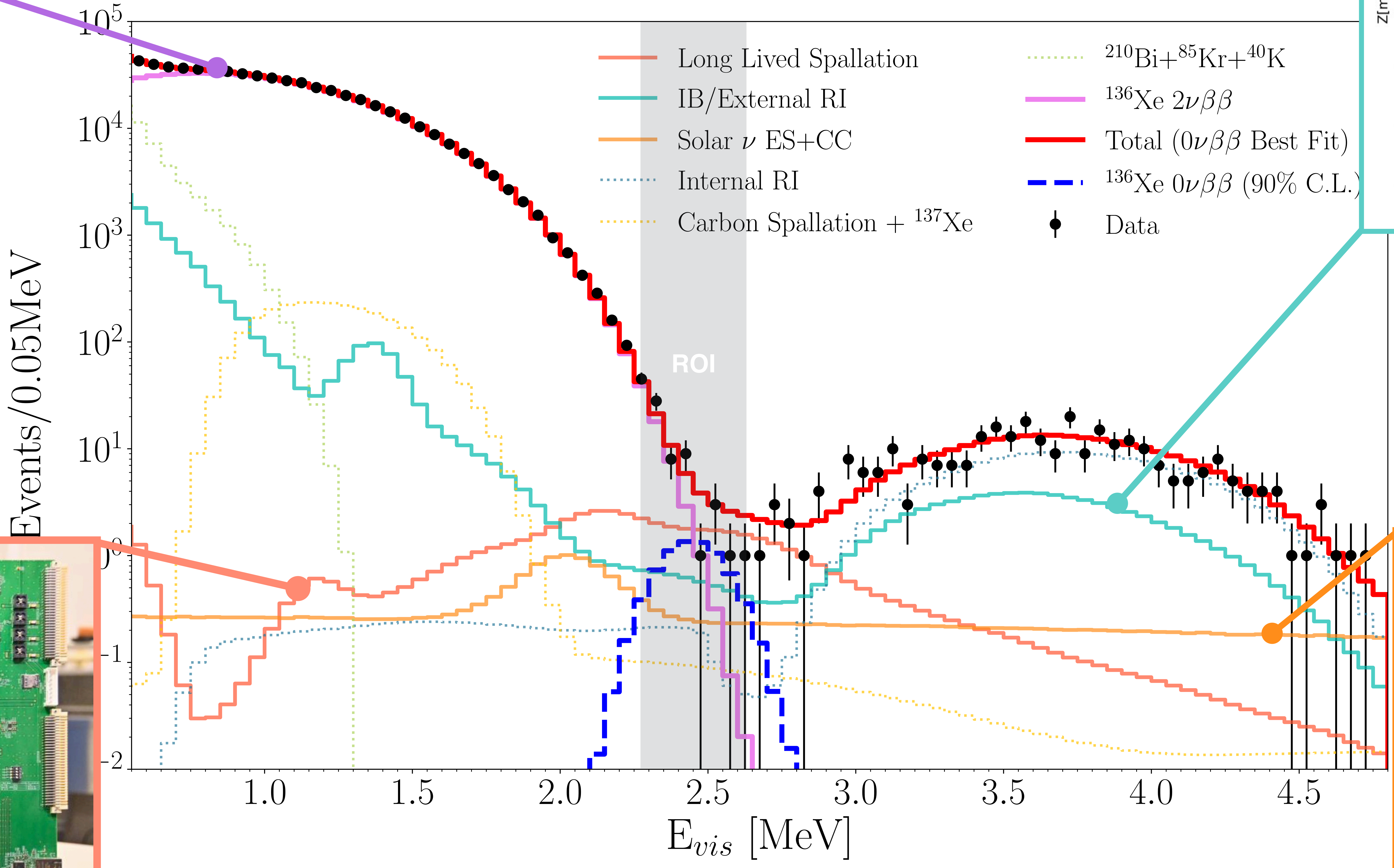

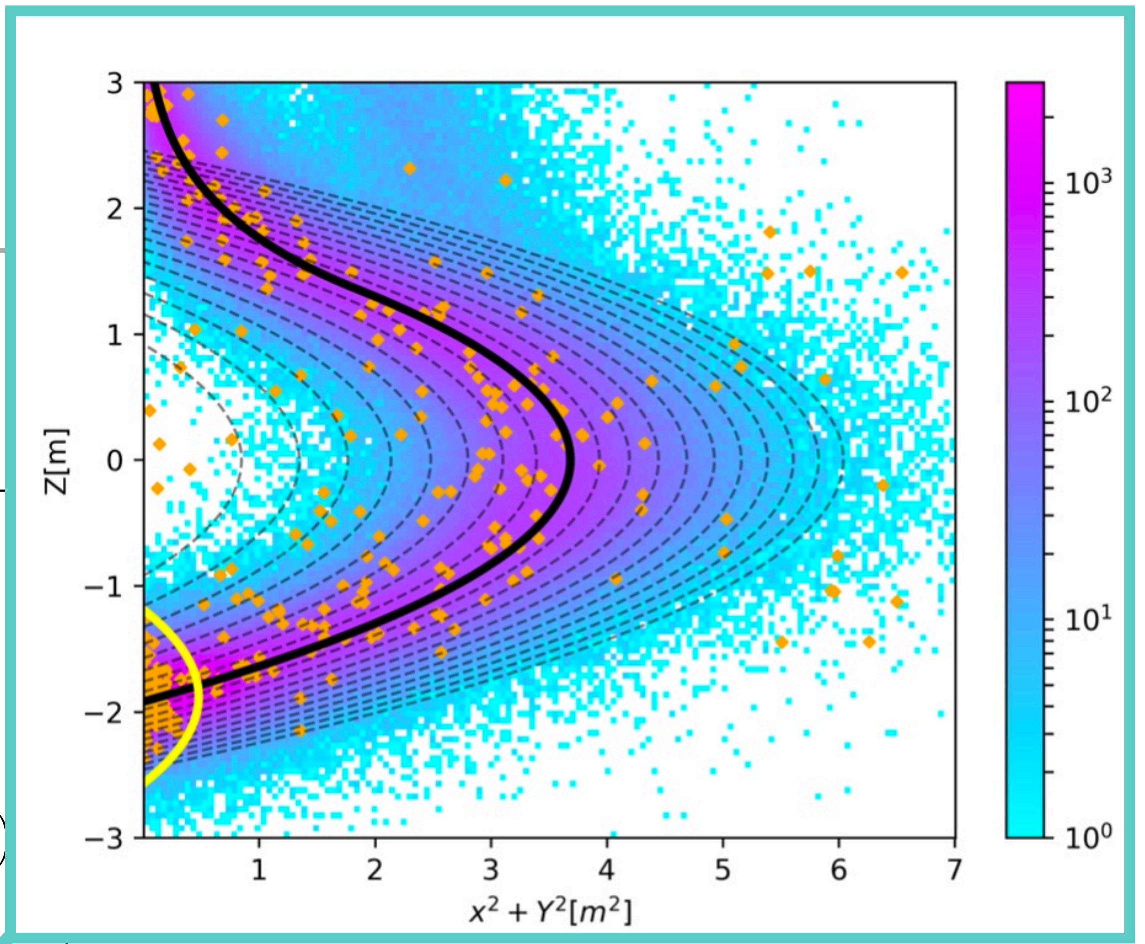

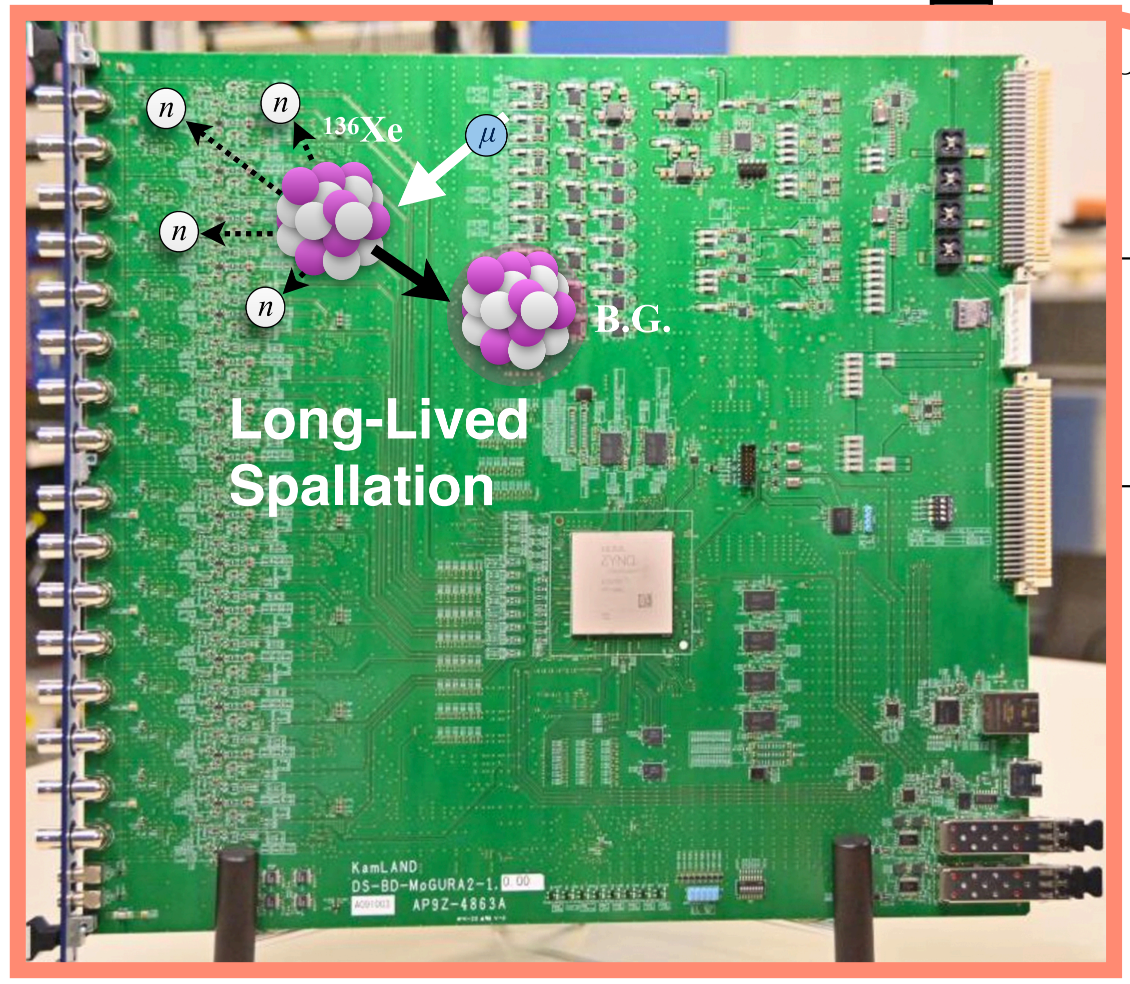

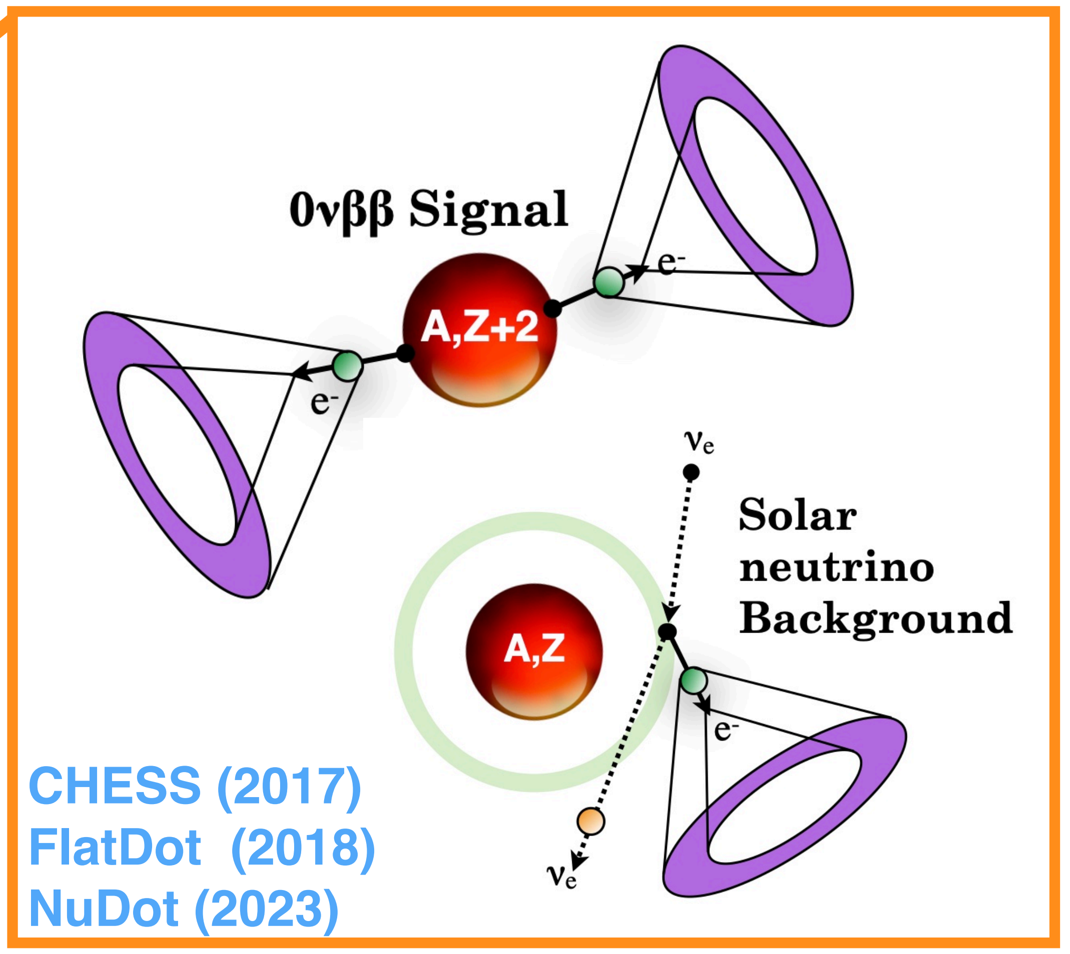

Connecting the limit on the half-life to fundamental physics

The observable

The effective Majorana mass

Made up of Standard Model fundamental numbers

(The particle physics)

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}|M^{0\nu}|^2 m_{\beta\beta}^2$$

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Nuclear Matrix Element (for ^{136}Xe):

$$|M^{0\nu}| = 1.5 - 4.5$$

Nuclear structure effects.

Large uncertainty.

(The nuclear physics)

Connecting the limit on the half-life to fundamental physics

The observable

Calculable constants with ~3x uncertainty

The effective Majorana mass

Made up of Standard Model fundamental numbers

(The particle physics)

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M^{0\nu}|^2 m^2_{\beta\beta}$$

Connecting the limit on the half-life to fundamental physics

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$$|m_{\beta\beta}| = |c^2_{12}c^2_{13}m_1 + s^2_{12}c^2_{13}e^{i\alpha 1}m_2 + s^2_{13}e^{i\alpha 2}m_3|$$

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+/-2% +/-2% +/-1.5%

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[0,2π] [0,2π]

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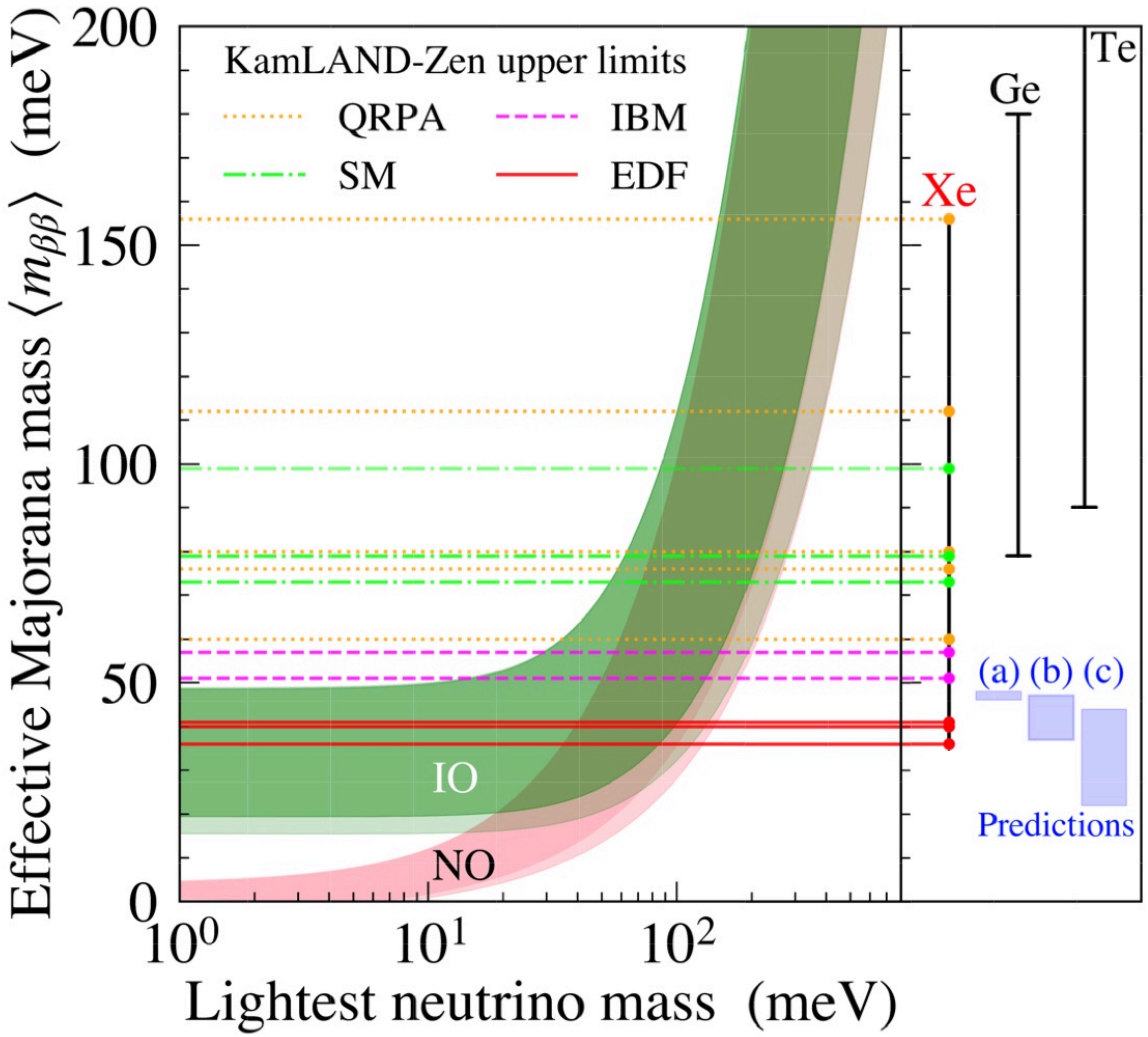
Placing limits on the Majorana nature of the neutrino



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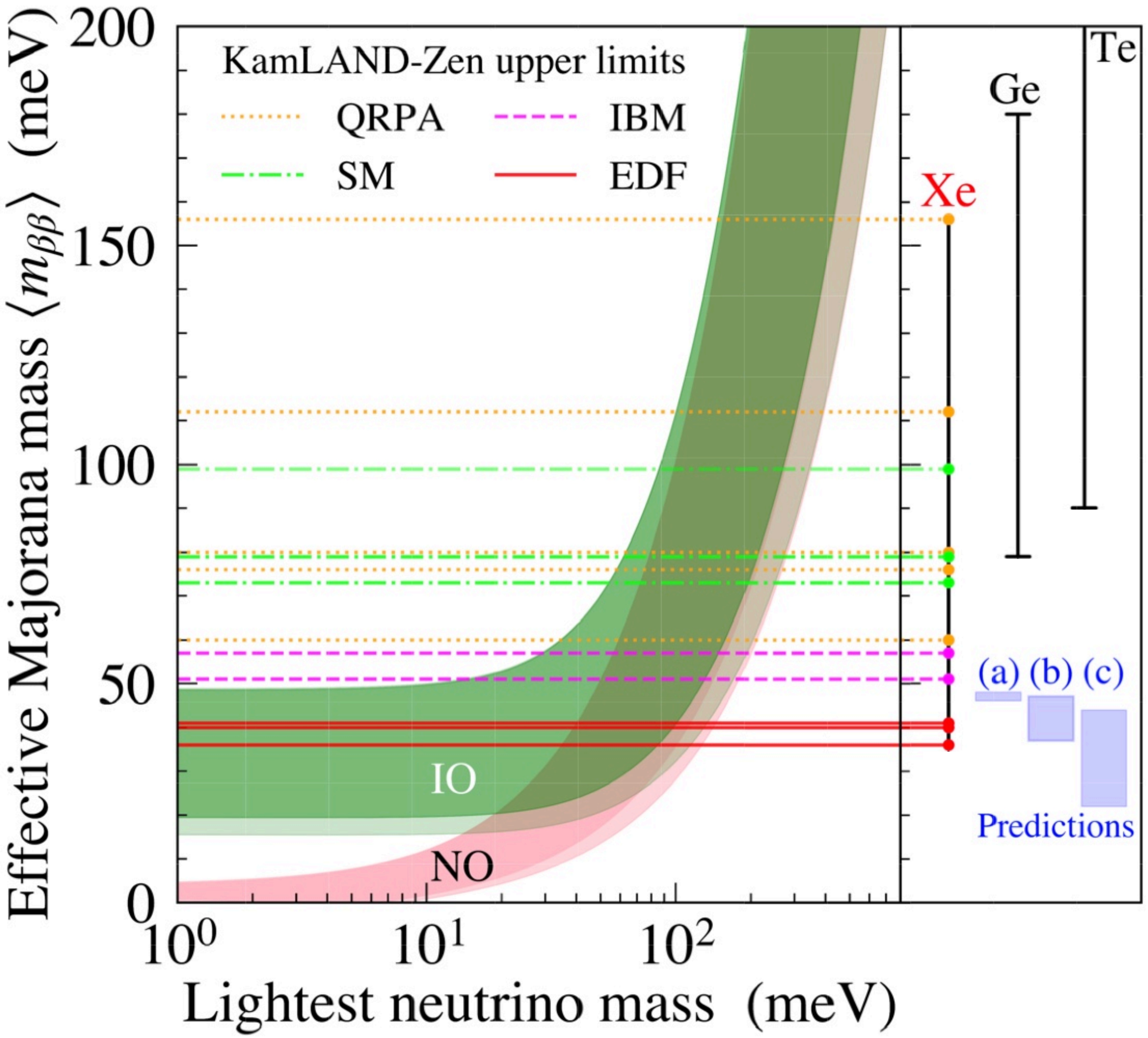

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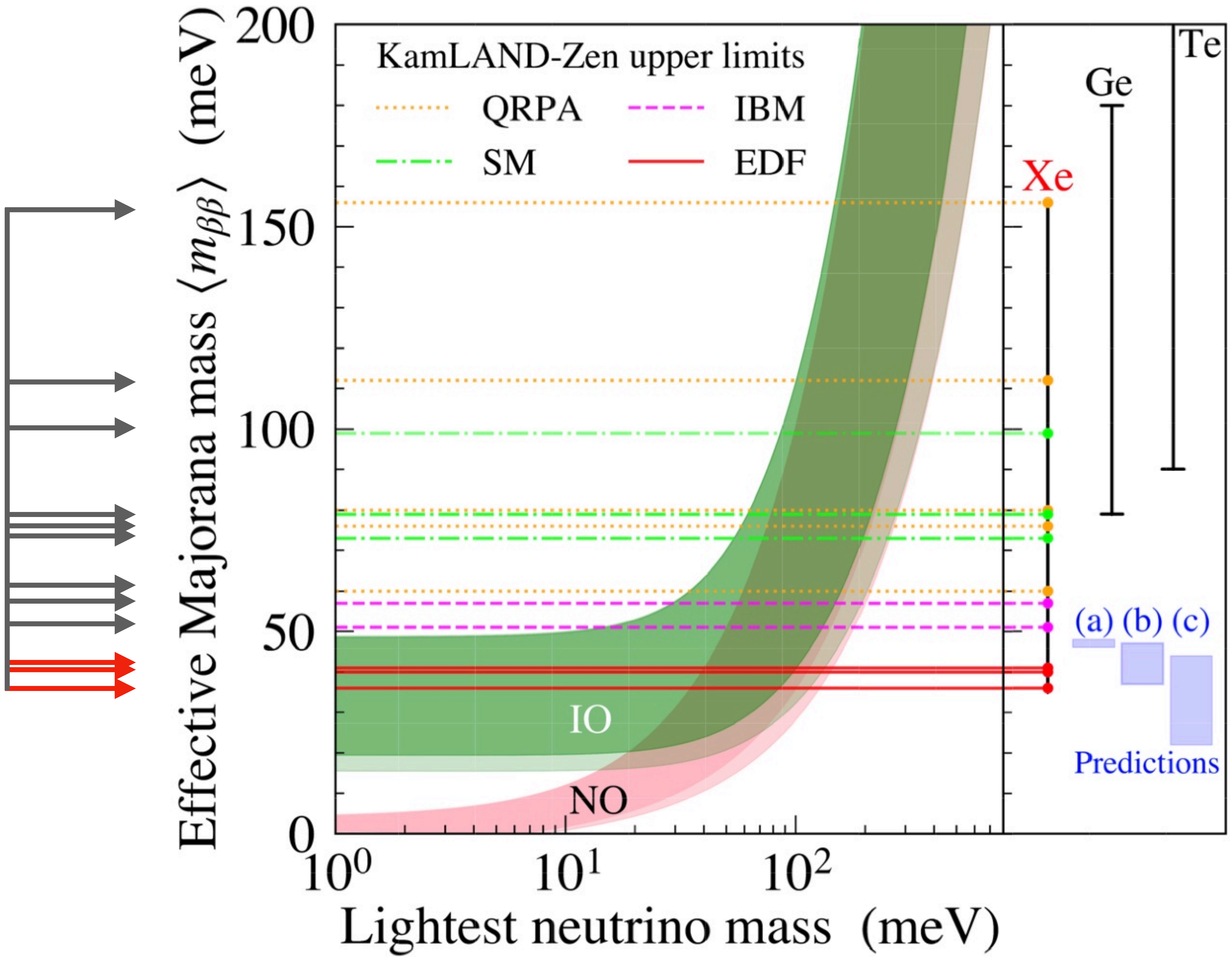

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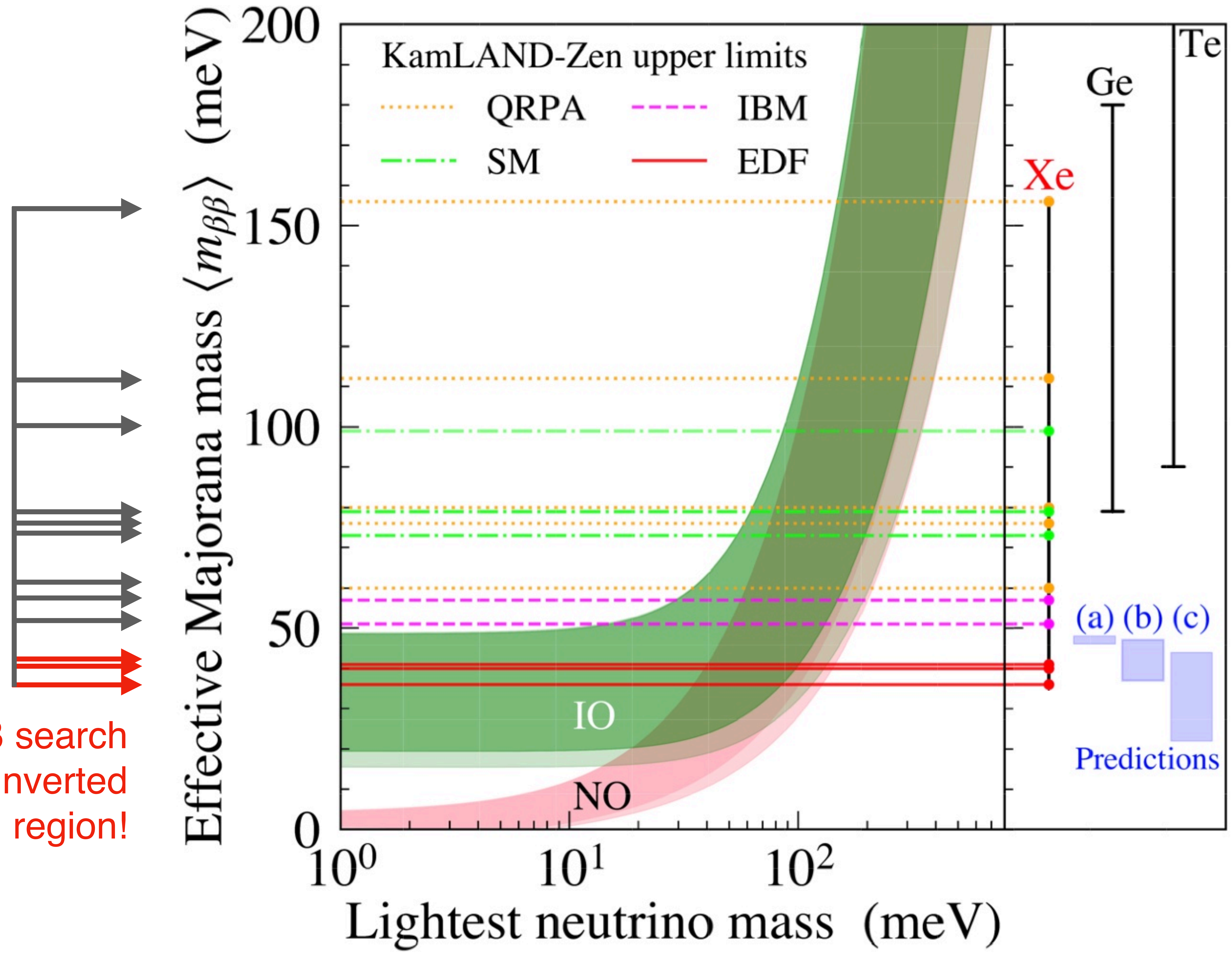

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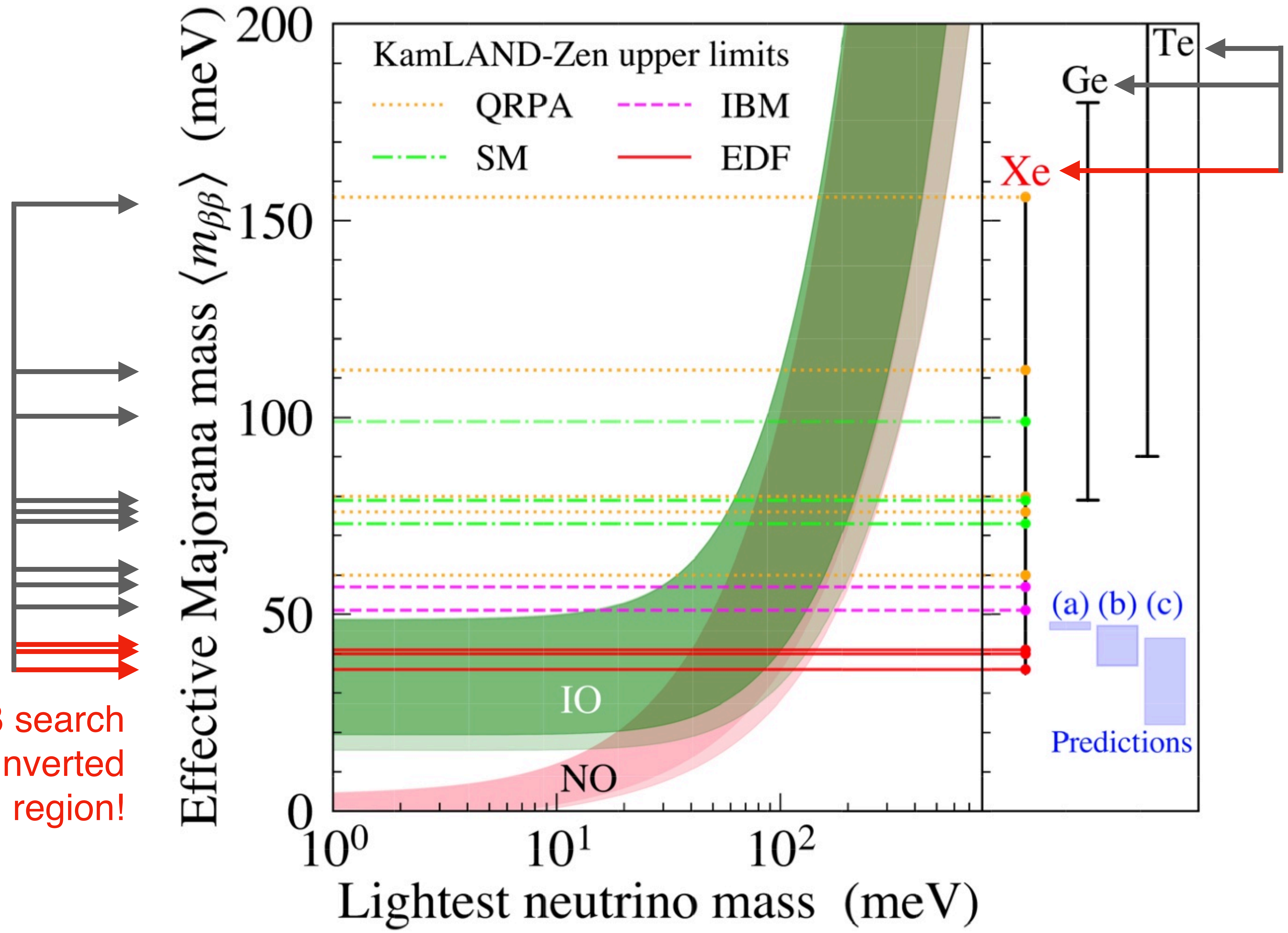

This Xe 0νββ search represents the **worlds most stringent limit** on the effective Majorana mass

(Ge) GERDA: Phys.Lett. **125** 252502
(Te) CUORE: arXiv: 2104.06906v1

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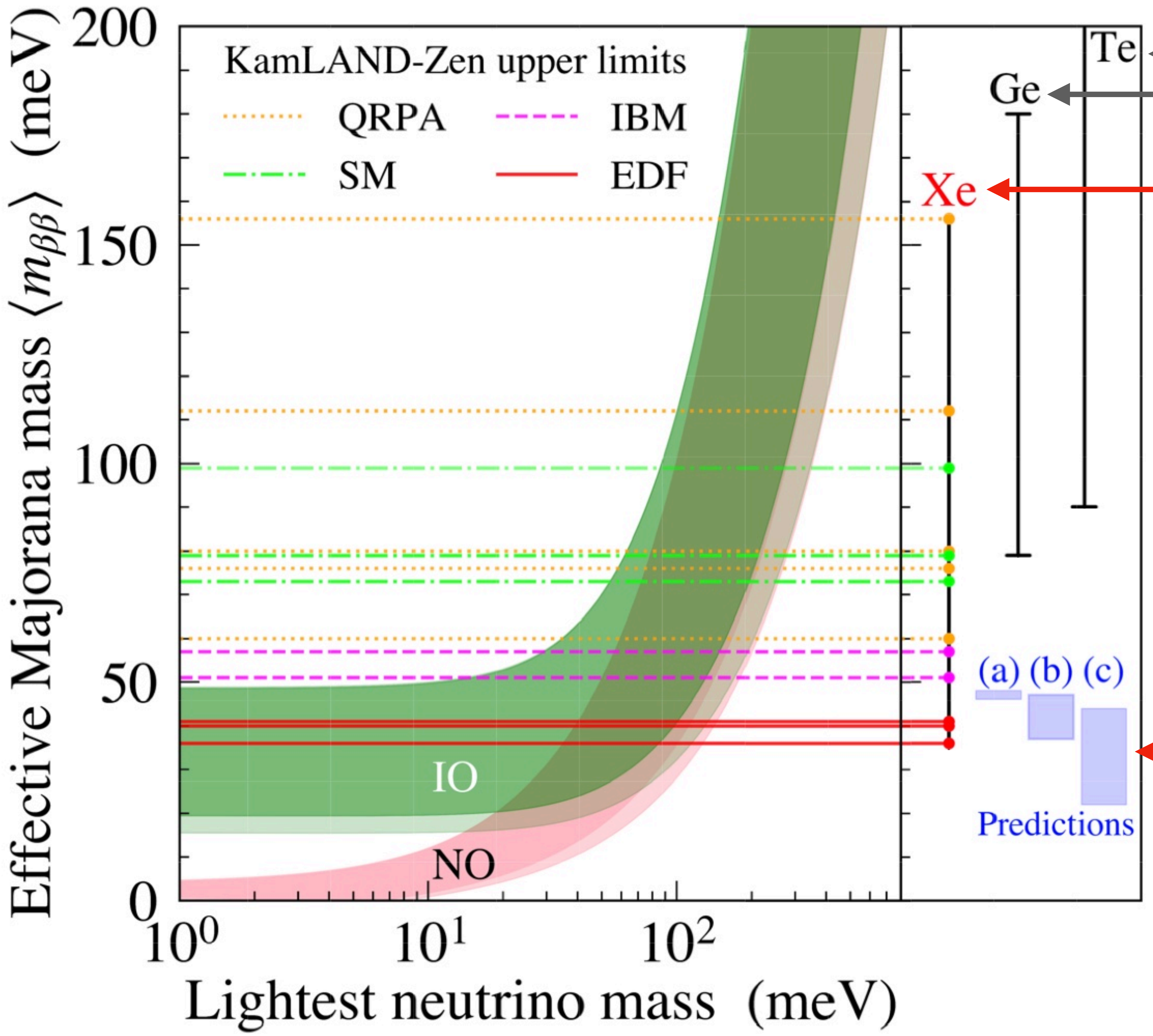

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With this result, we are now starting to tests of theoretical predictions.

(a) Phys. Rev. D 86, 013002
(b) Phys. Lett.B 811 , 135956
(c) Euro.Phys.J.C 80, 76

Conclusion

Major technical milestone for liquid scintillator technology:

- scalability at low cost
- machine learning algorithms (KamNet) and new background rejection techniques

Future plan:

- State-of-the-art electronics upgrade (MoGURA2)
- Improved light yield, improved light collection, and increased Xe loading in scintillating balloon (KamLAND2-Zen)

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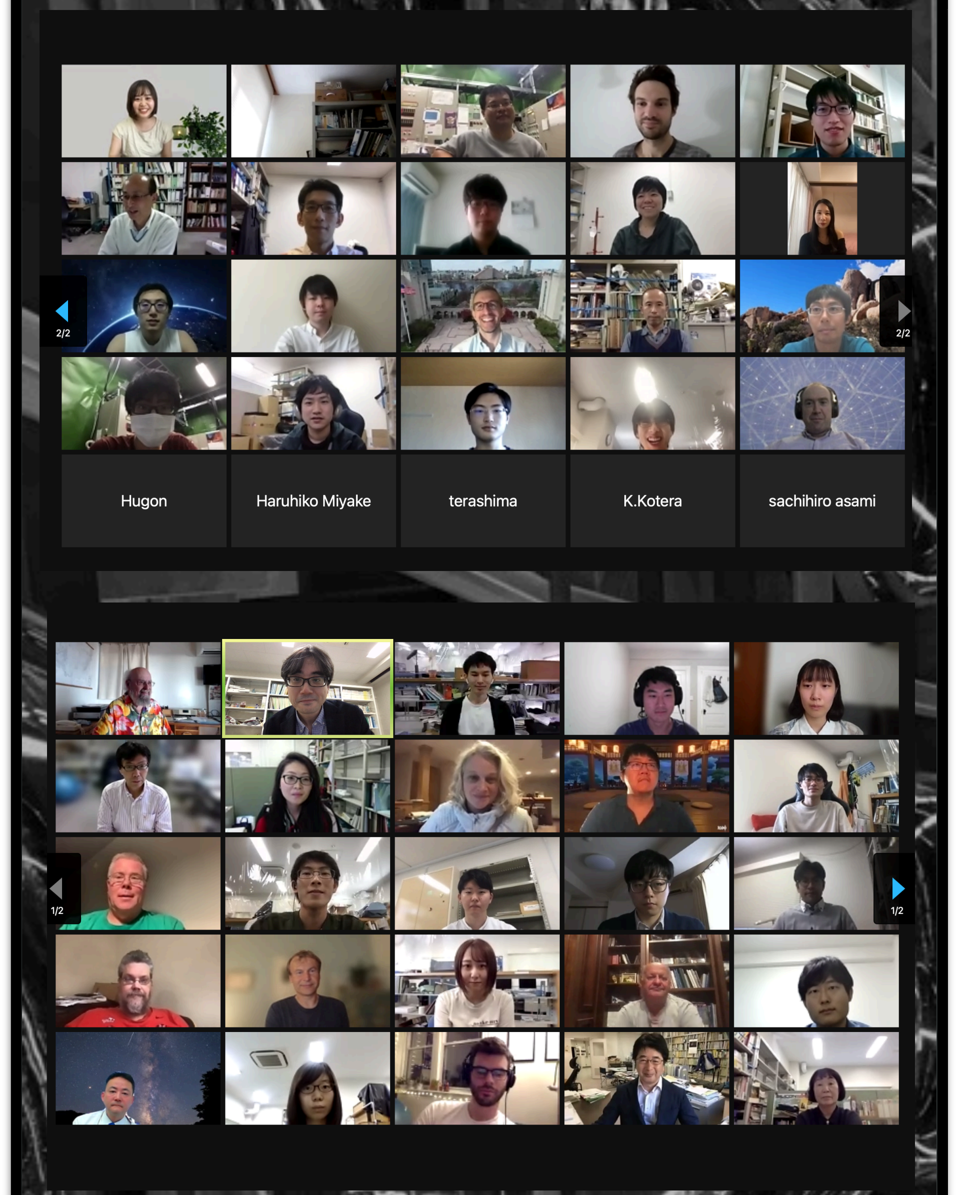
With nearly a 1-ton-year exposure, we are now starting to search for the Majorana neutrinos in the IO region!

KLZ-400 + KLZ-800 combined result (90% C.L.):

$$T_{1/2}^{0\nu\beta\beta} > 2.3 \times 10^{26}\ \mathrm{yr},\ \ \langle m_{\beta\beta} \rangle < 36 - 156\ \mathrm{meV}$$



HEISING-SIMONS FOUNDATION

Massachusetts Institute of Technology

MERCI POUR VOTRE ATTENTION!

SPENCER N. AXANI
SAXANI@MIT.EDU

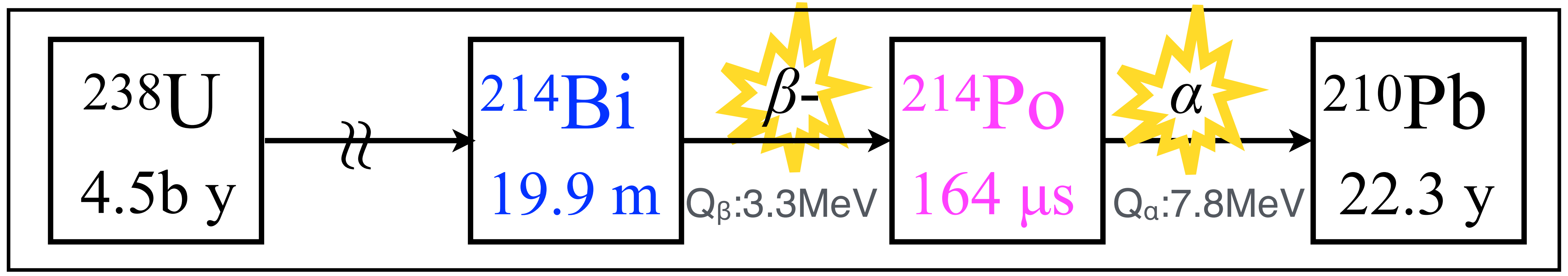
STAY TUNED FOR THE PUBLICATION:
PHYSICAL REVIEW LETTERS:

"FIRST SEARCH FOR THE MAJORANA NATURE OF THE NEUTRINO IN THE INVERTED MASS ORDERING REGION WITH KAMLAND-ZEN"

BIG THANKS:
LINDLEY WINSLOW, CHRIS GRANT, BRUCE BERGER, AOBO LI, ZHENGHAO FU, JOE SMOLSKY, HASUNG SONG, KATARZYNA FRANKIEWICZ, JITRAPON LERTPRASERTPONG, CARRIE LABOR-SMITH, & THE KAMLAND COLLABORATION

Radioactive backgrounds: The uranium series: ^{214}BiPo

^{238}U is all around us.
The **^{214}Bismuth** → **^{214}Polonium** chain extends in the energy region of interest (2.35 < E < 2.70 MeV).



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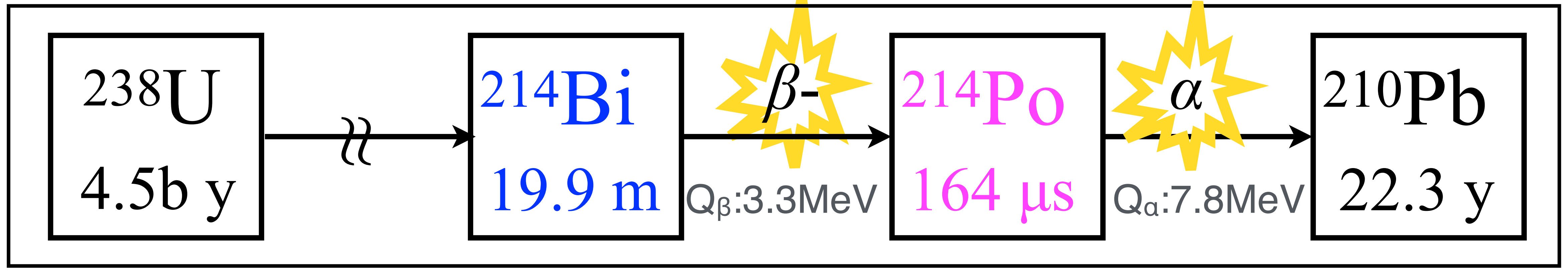

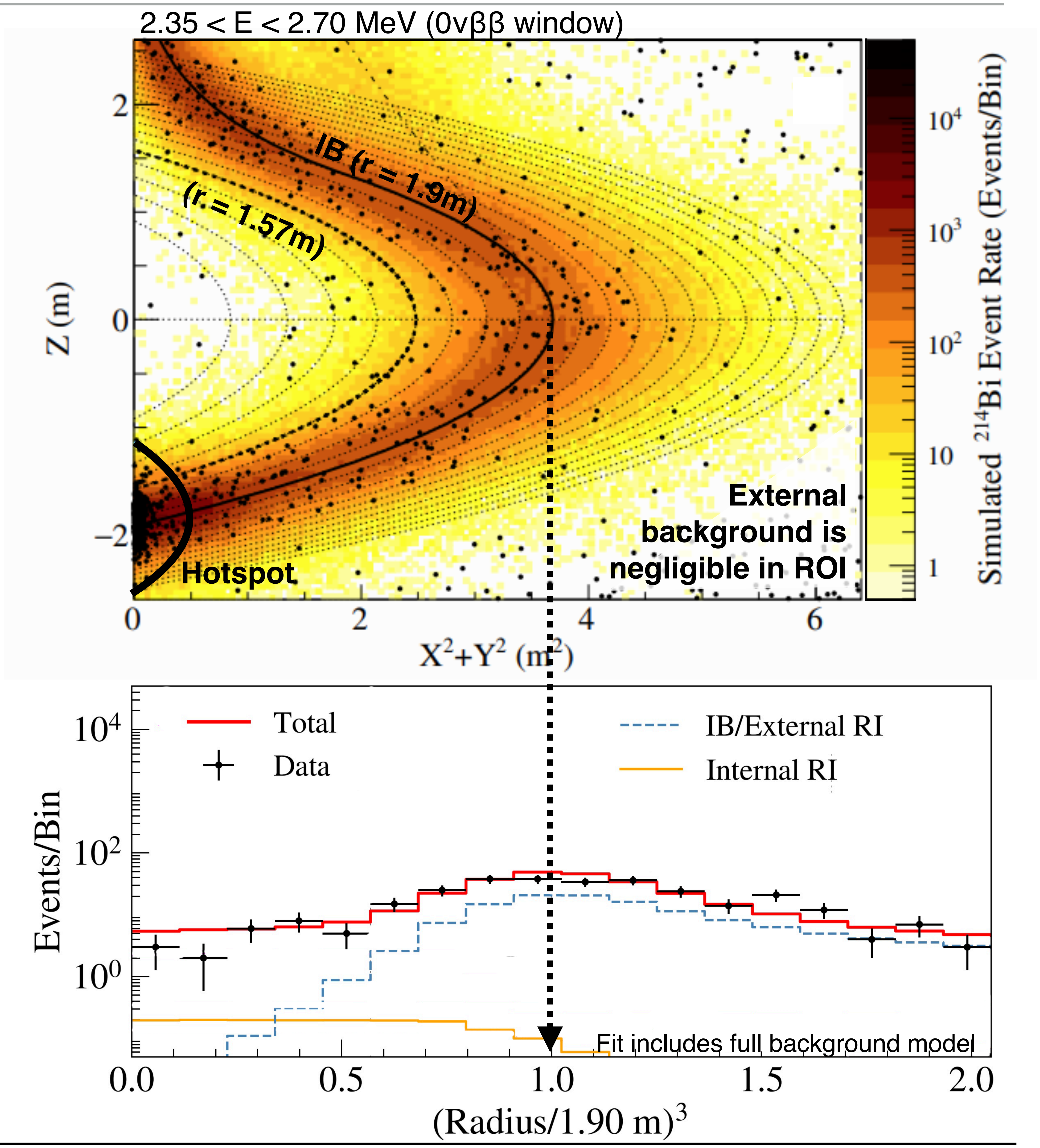

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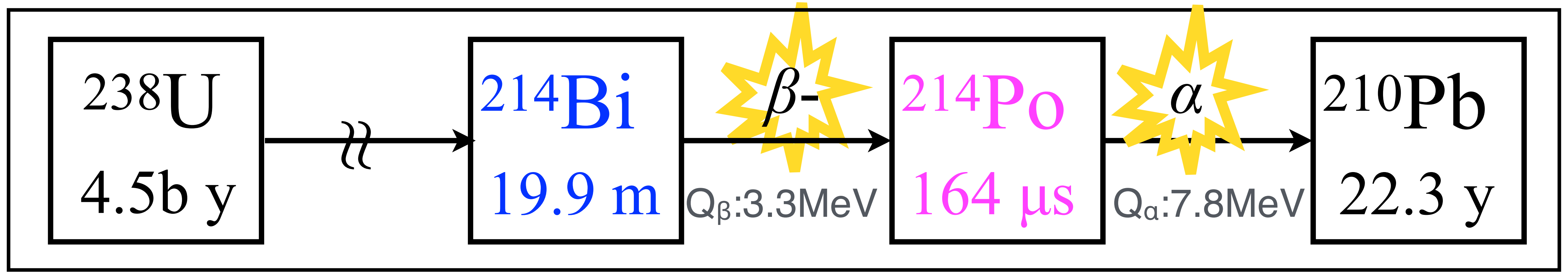
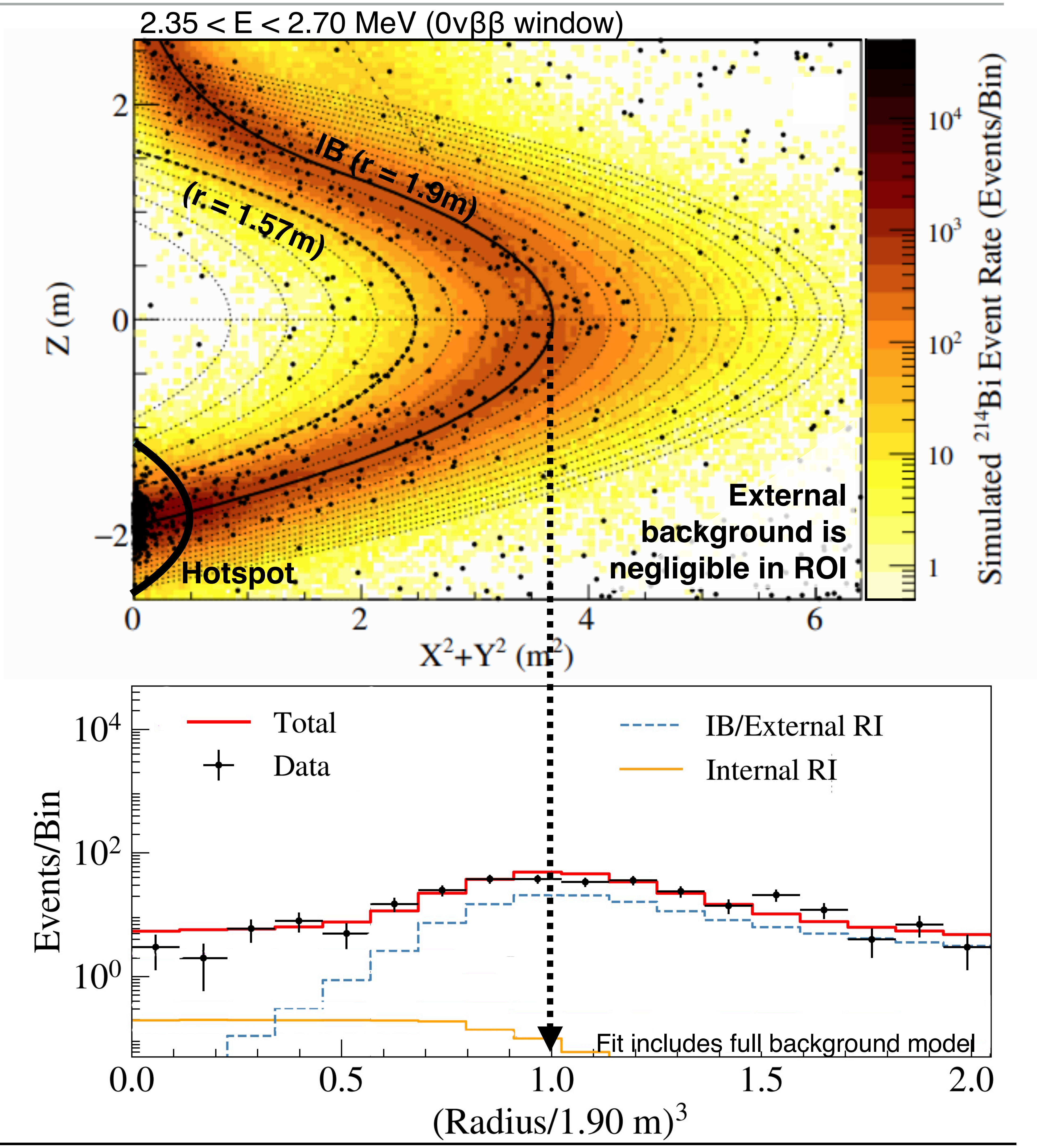


Rejection efficiency:

99.9% tagging efficiency in liquid scintillator
~50% in the balloon material (IB absorbs α)



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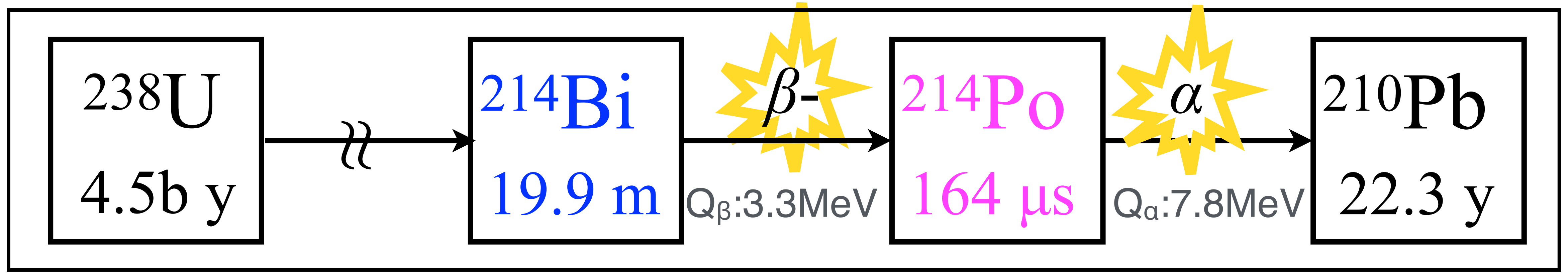

Delayed coincidence tag: β- followed by α emission

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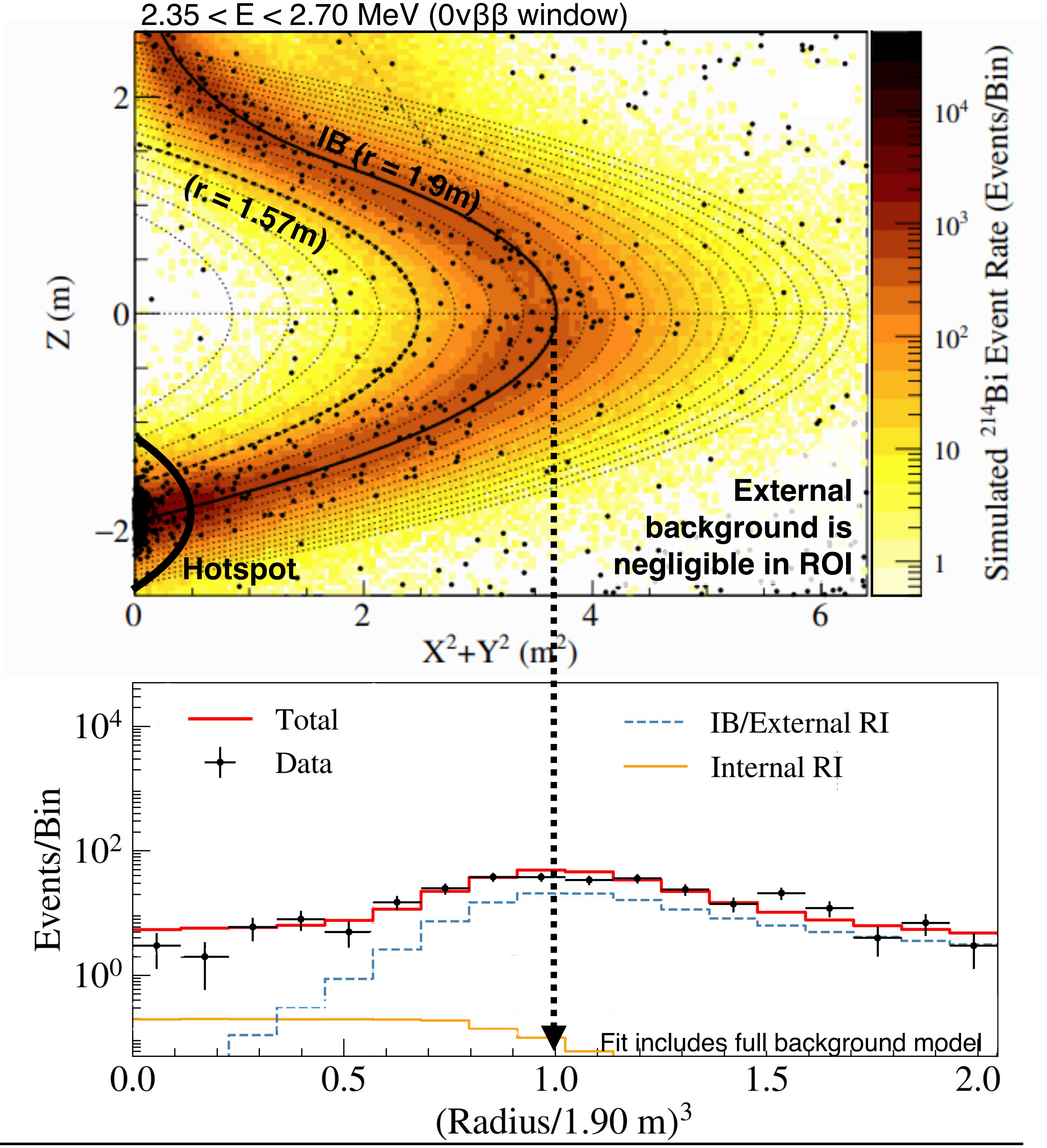

Radioactive backgrounds: The thorium series: ^{212}BiPo

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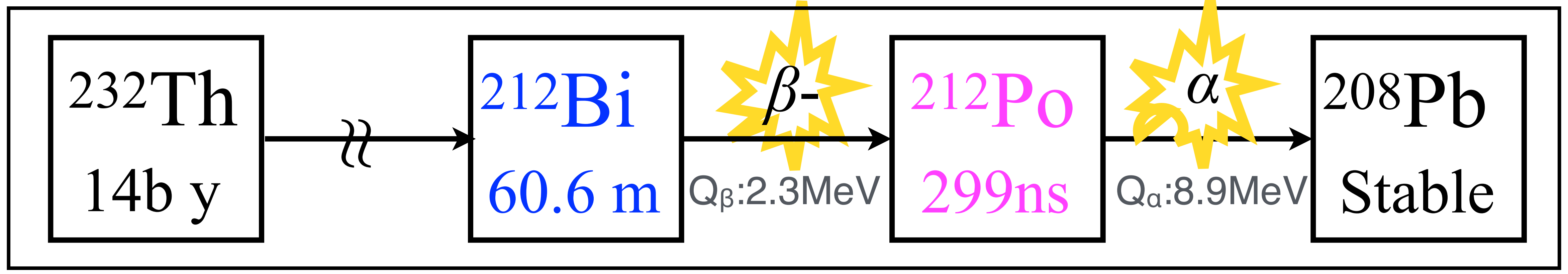
The **^{212}Bismuth** → **^{212}Polonium** pileup can extend into our ROI (2.35 < E < 2.70 MeV).



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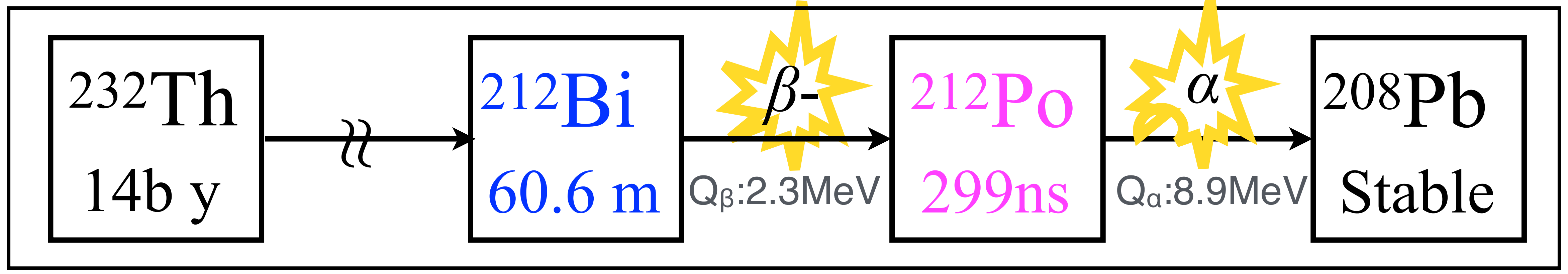

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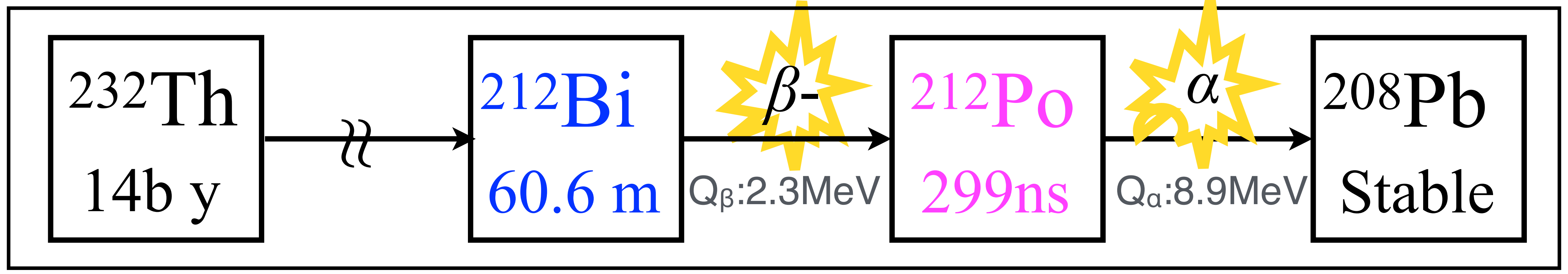

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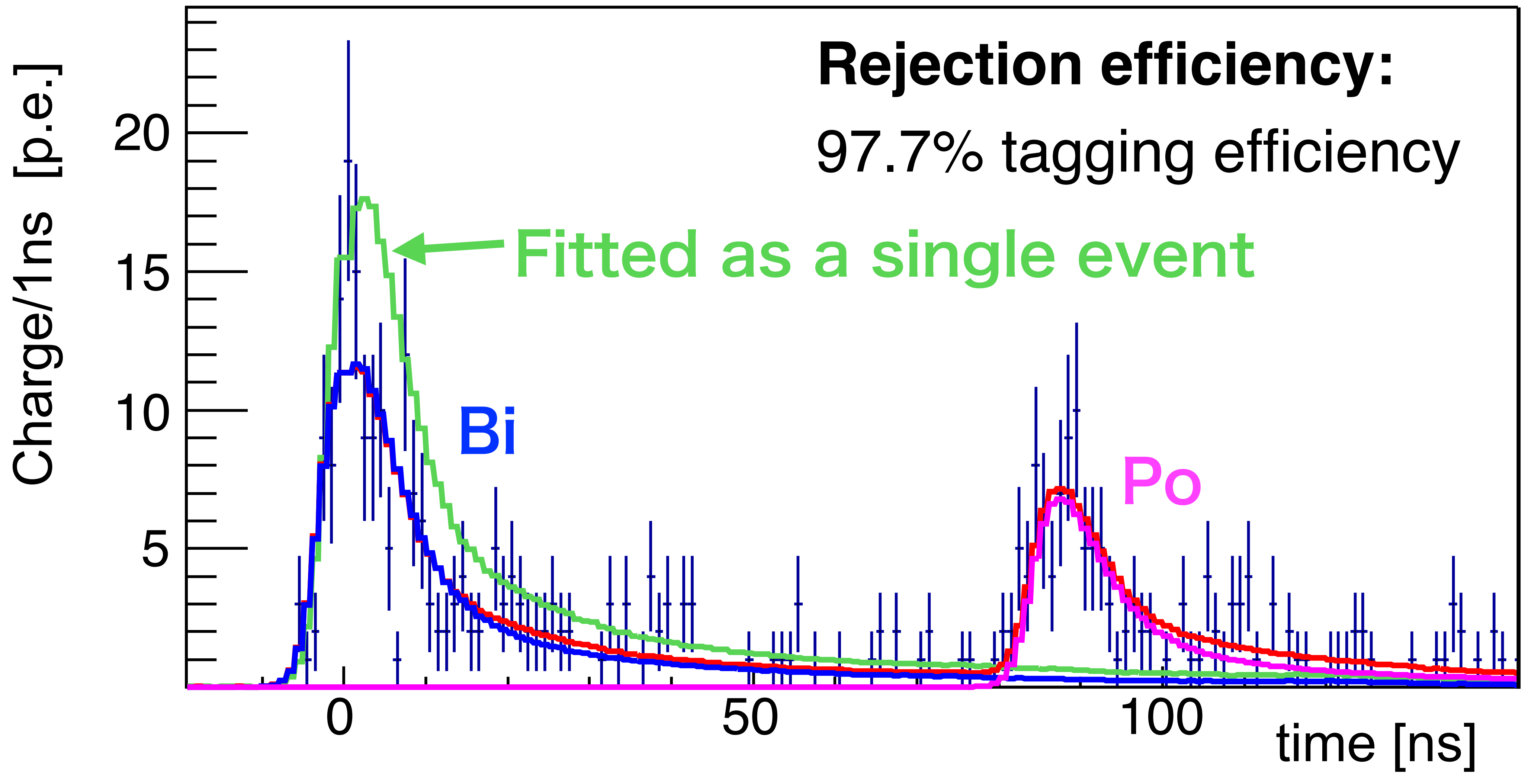

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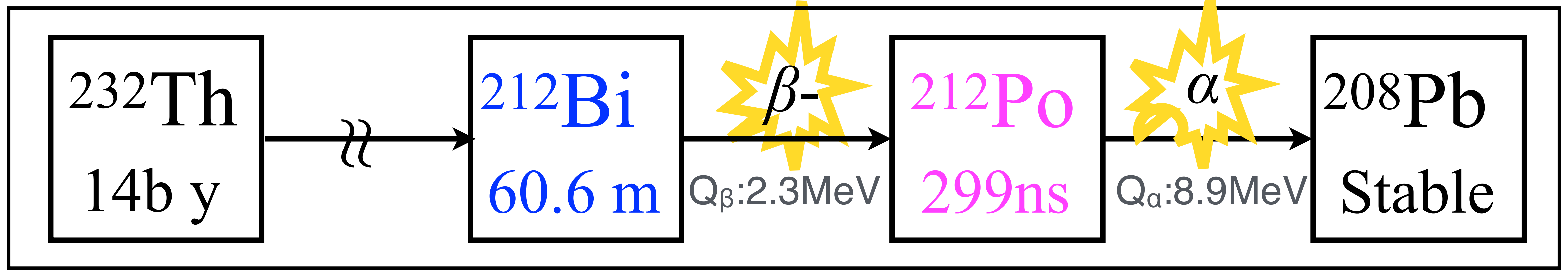

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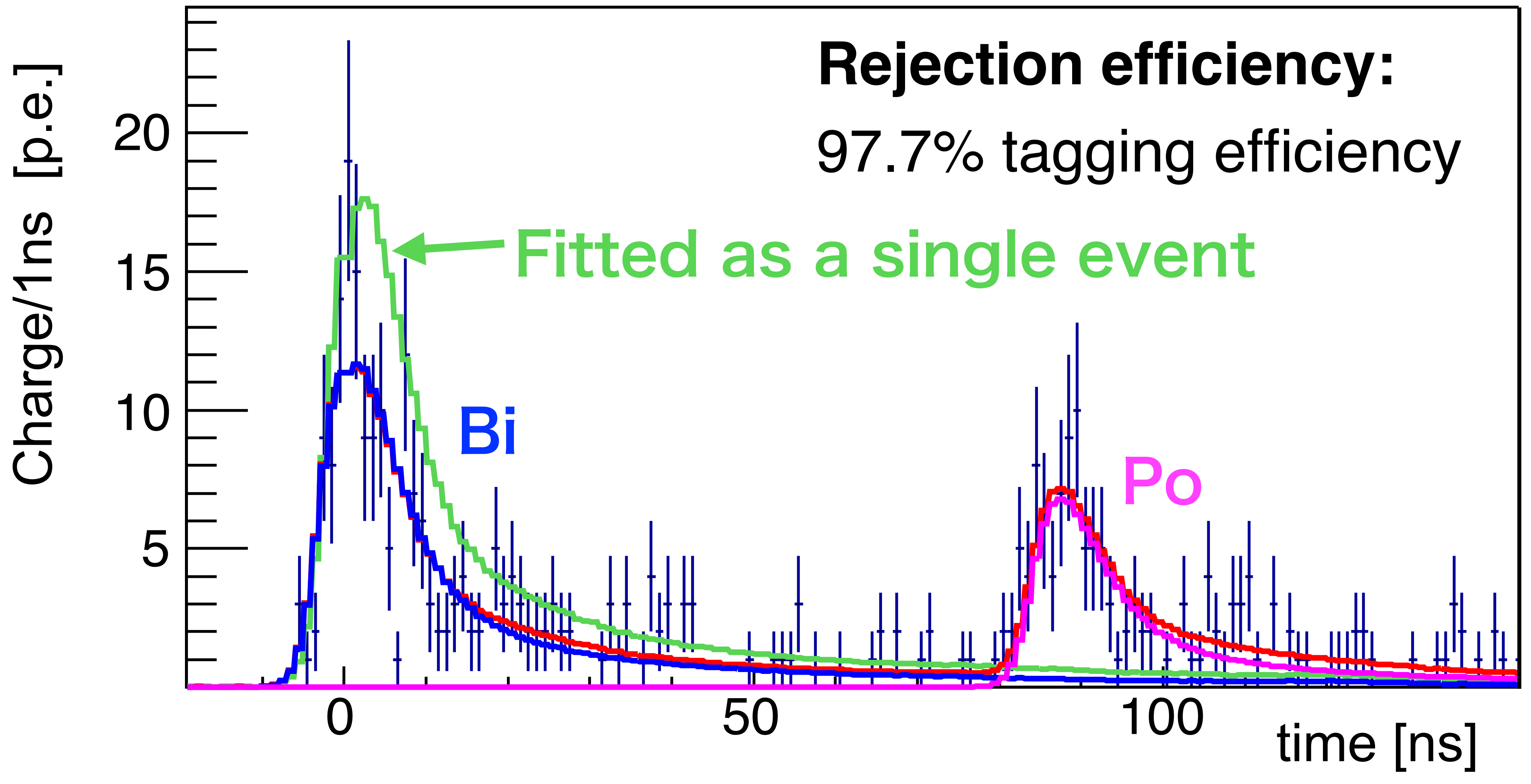

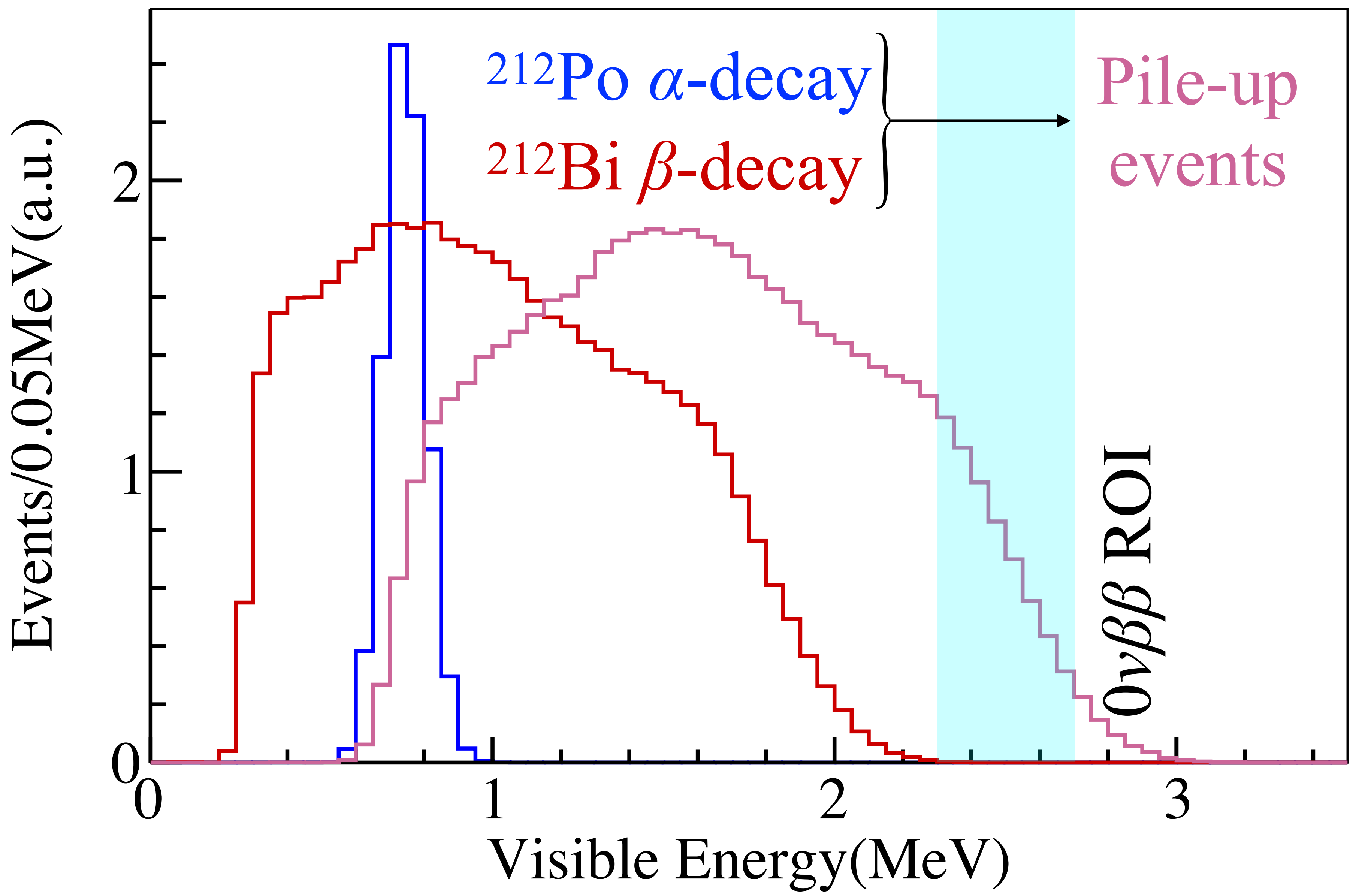


k+/-
π+/-
...
n
p
e+/-
μ+/-
2,700 m.w.e.
x10⁵ rate reduction under
muon Rate: 0.198+/-0.03Hz
Triple coincidence tag for carbon spallation
1
μ
12C
n
n
10C
10B
2.2MeV
p
p
2
γ
d
d
γ
e+
e-
νe
γ
3
Rejection efficiency ~95%

Cosmic-ray muon backgrounds: Carbon spallation

Carbon (scintillator) spallation products:

- ^{6}He, ^{8}Li, **^{10}C,** ^{12}B
- Isotopes have short half-lives

Mitigation strategy

- Triple coincidence:

1 muon 2 neutron capture 3 Decay

H (2.2MeV),
^{12}C (4.9MeV),
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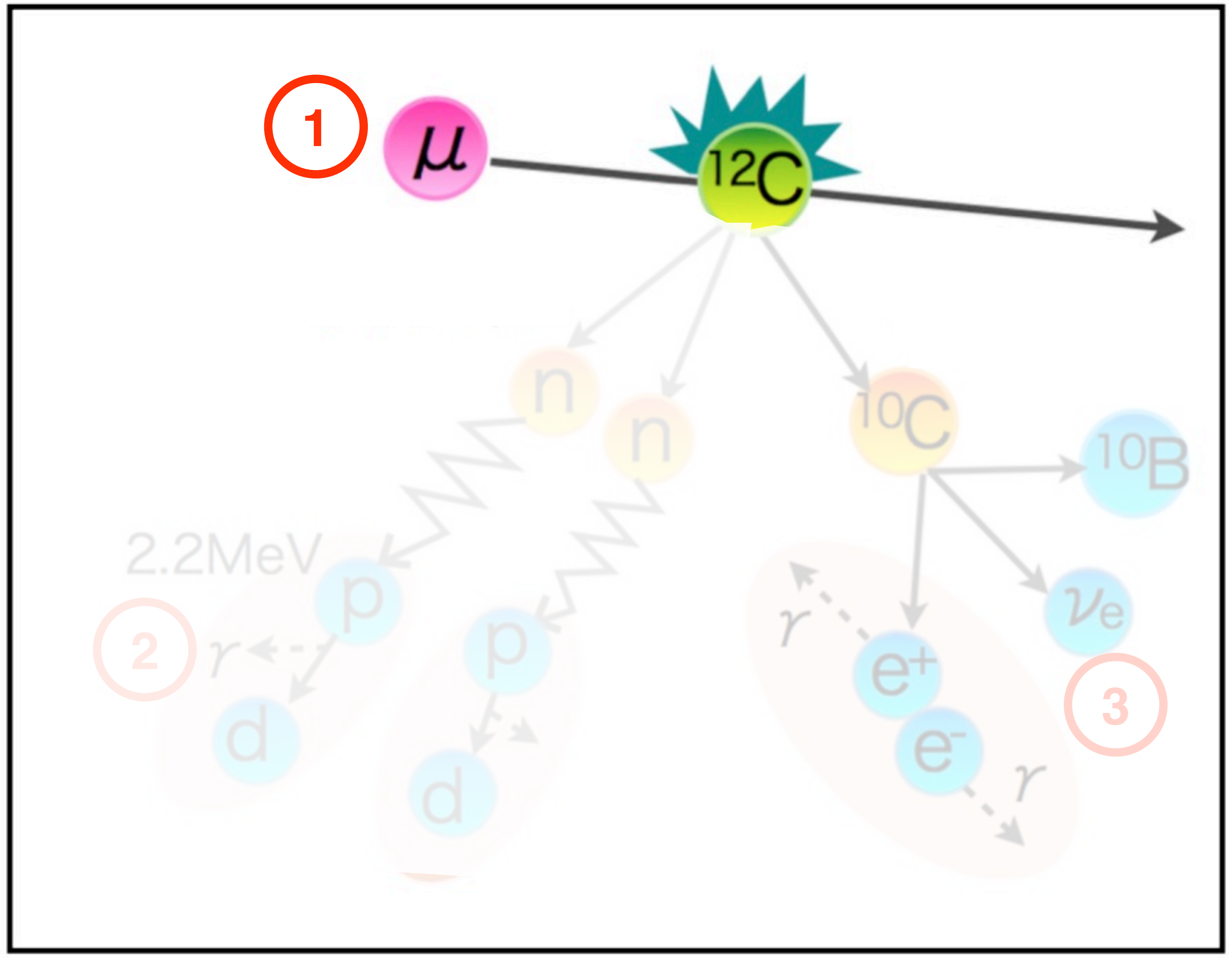

- A new likelihood method based on muon energy deposition (dE/dx), and space/time correlations is used.

Rejection efficiency: 99.3% on ^{10}C.
This is one of our largest reducible backgrounds.

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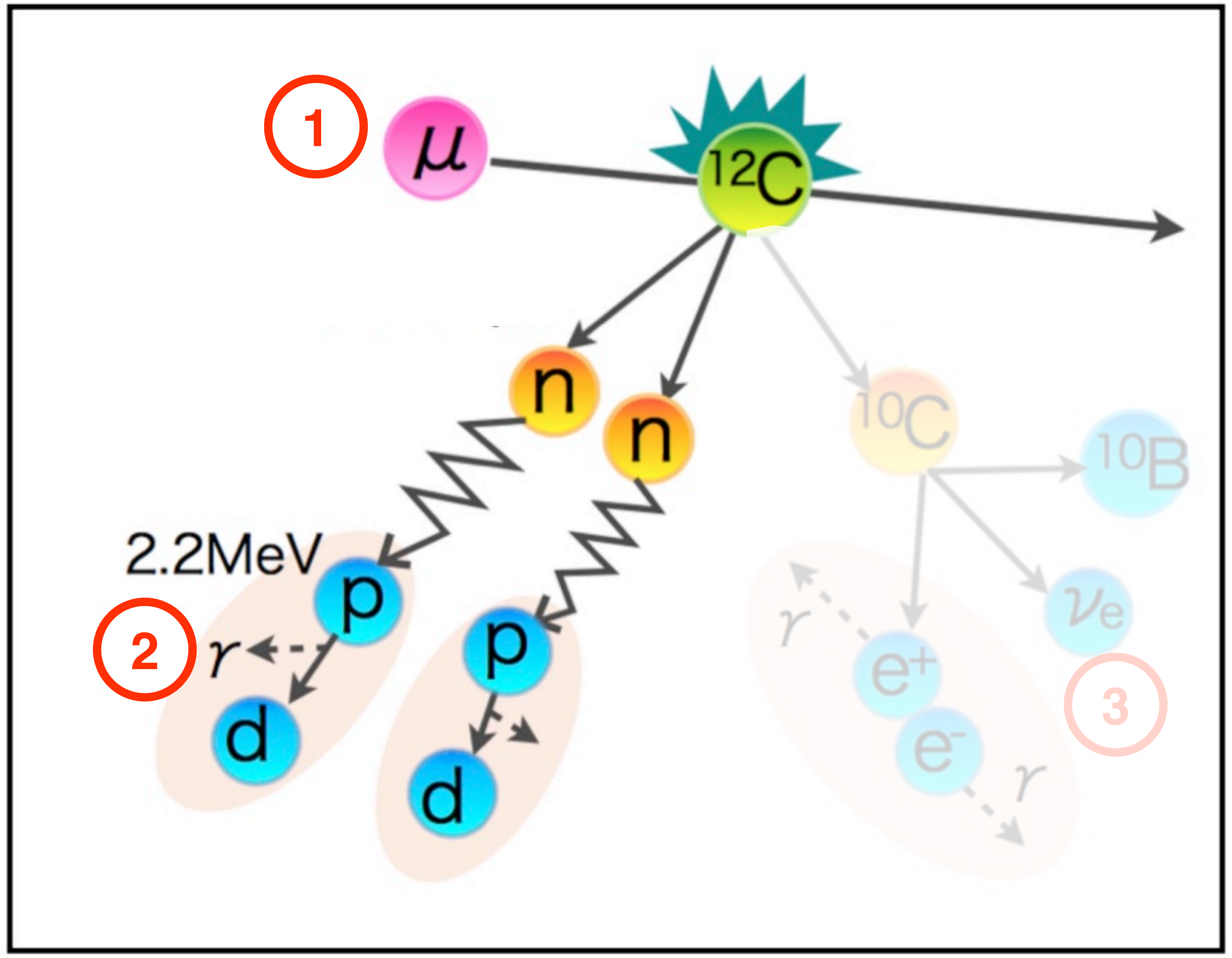

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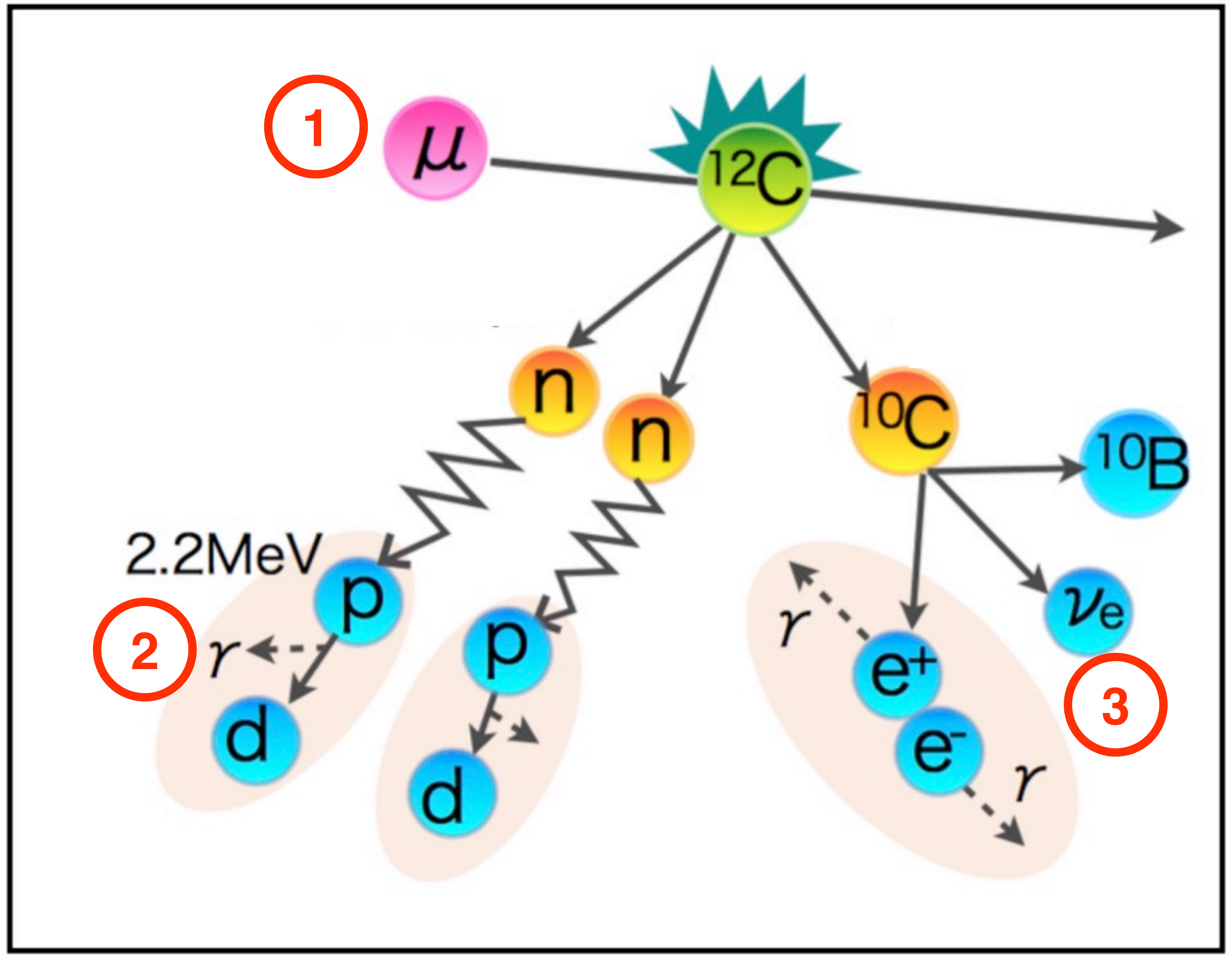

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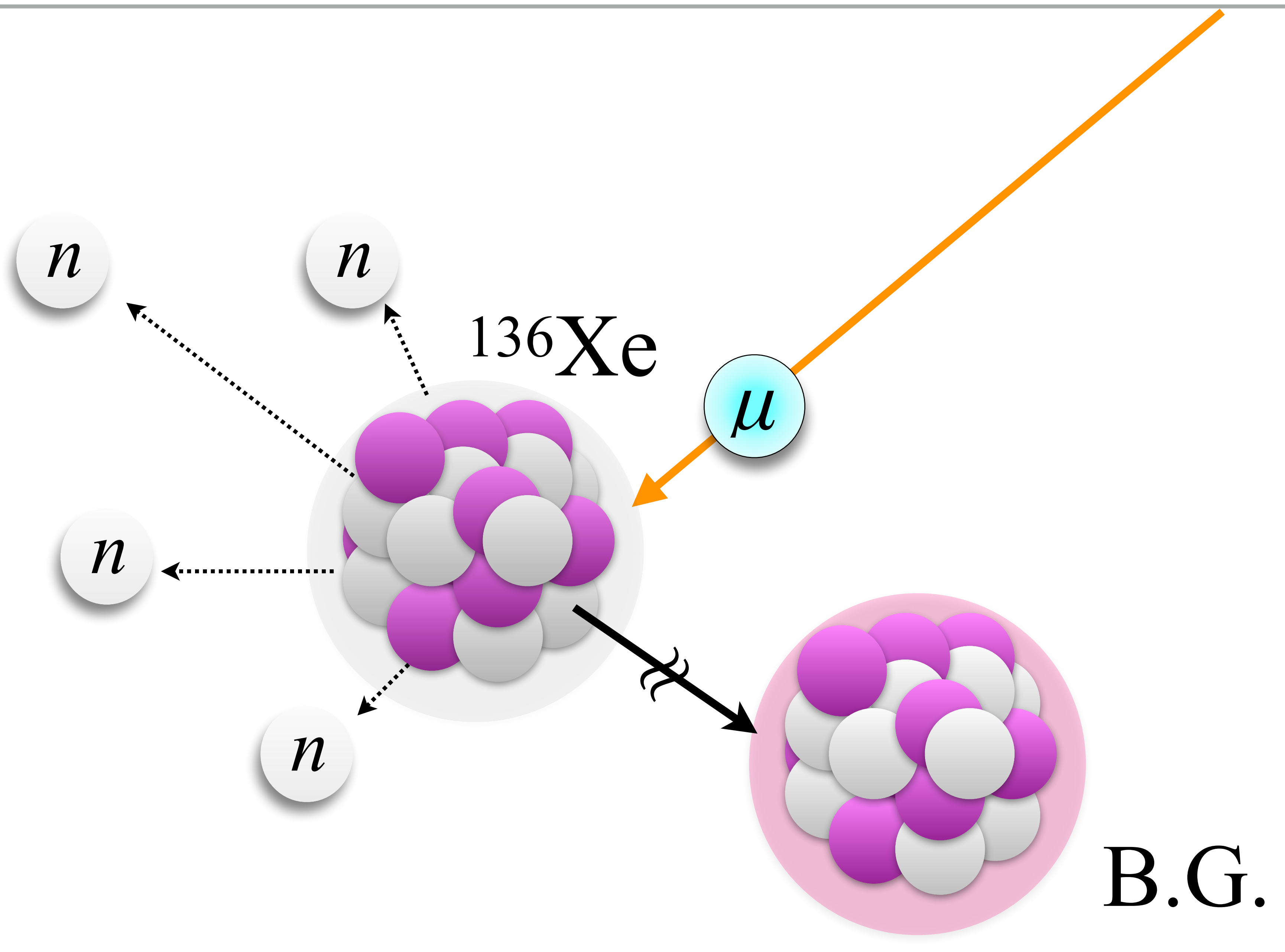
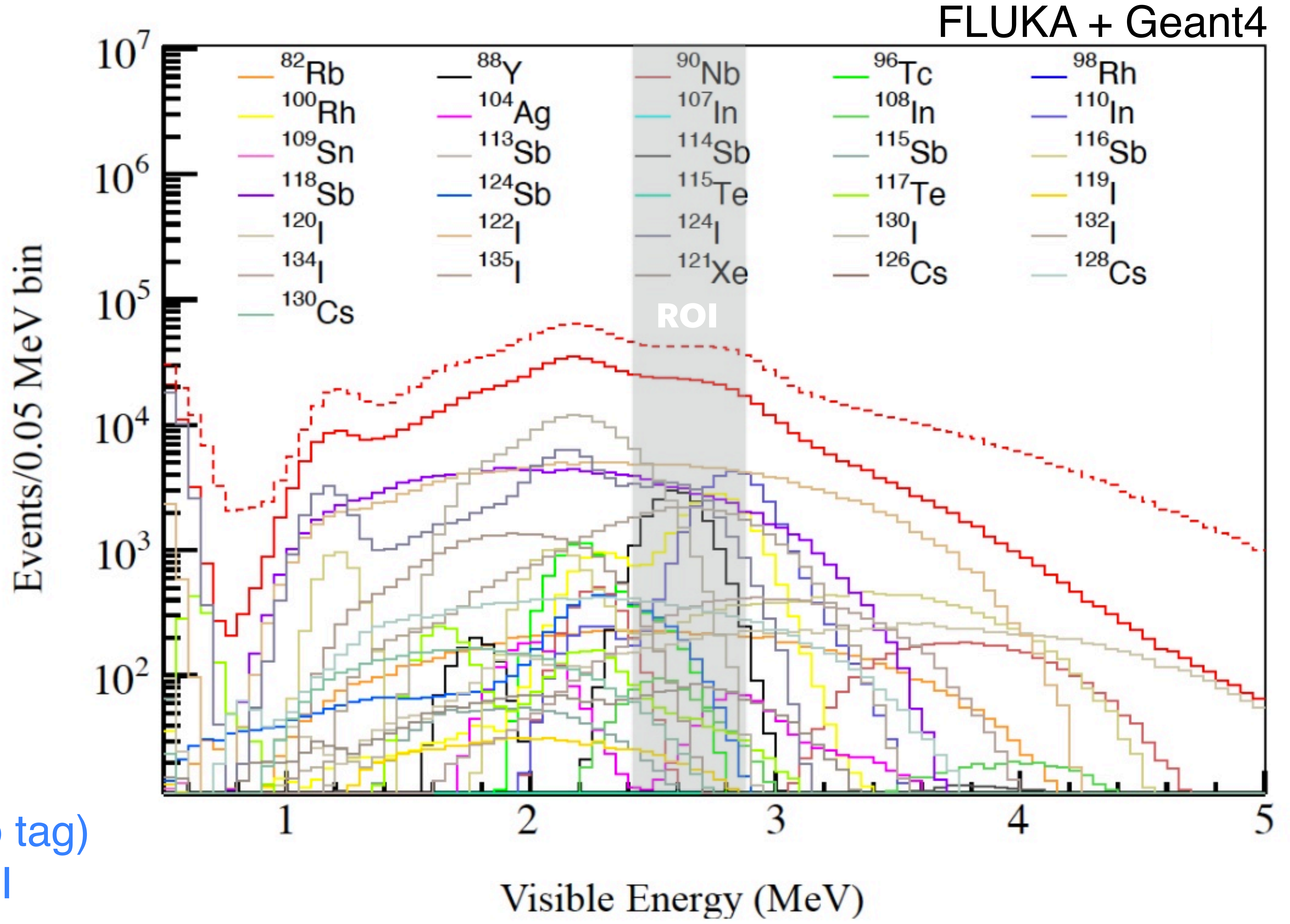
Cosmic-ray muon backgrounds: Xenon spallation





Long-Lived ^{136}Xe spallation backgrounds:

- Dominant background in KLZ
- Possess half-lives of hours or days (hard to tag)
- Some of these isotopes extend into our ROI

Rejection efficiency = 42.0 ± 8.0%

KamNet: A Spatiotemporal Neural Network

The Essence of KamNet

- Allow LS detector to perform PID based on tracking and topology
- Coincidence-free, independent background tagging channel

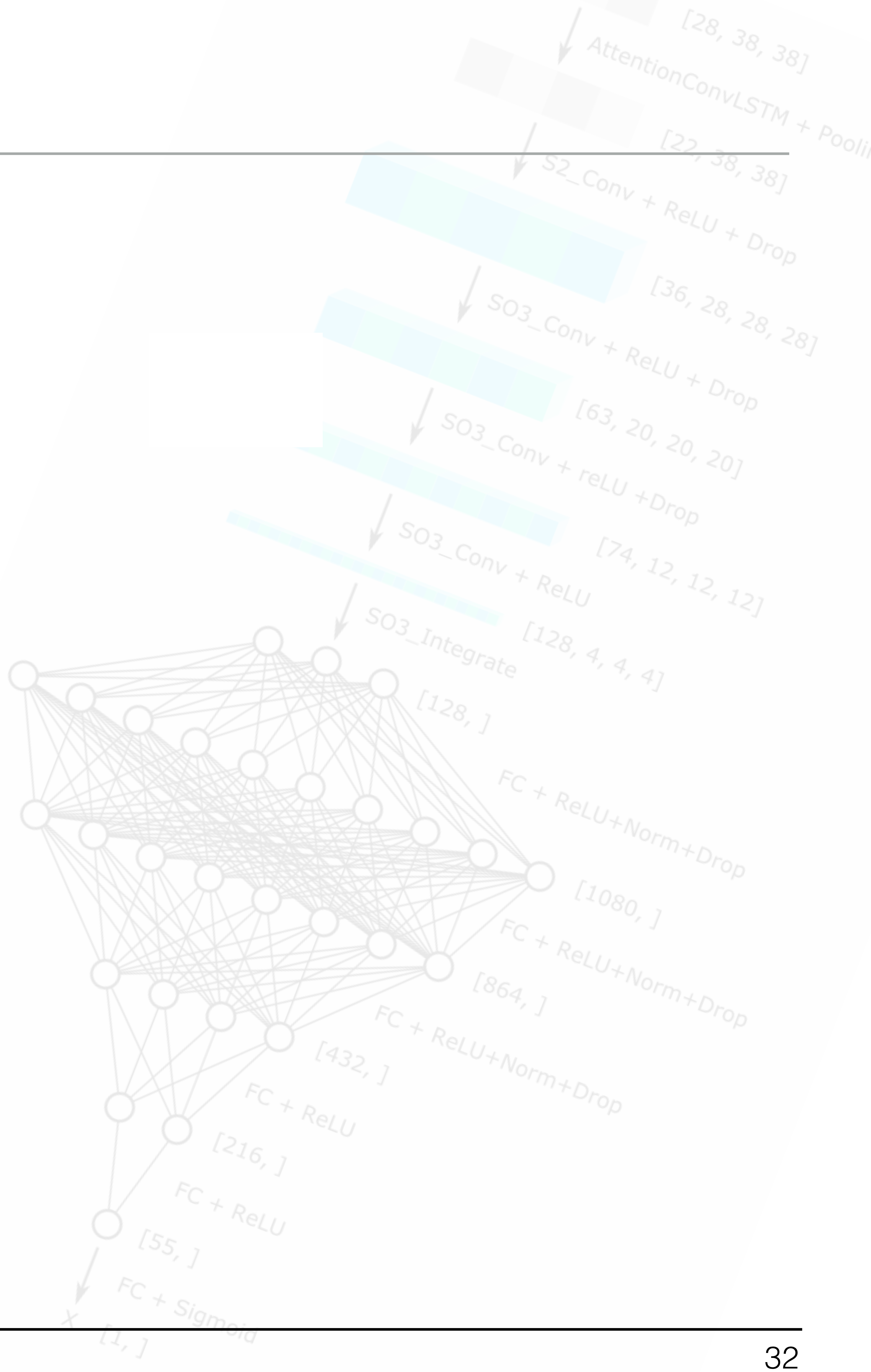
The Power of KamNet

- Reject 27% of XeLS backgrounds and 59% of film backgrounds
  - Leads to 17.7% exposure gain without hardware upgrade

The Future of KamNet

- Has potential to further improve the KamLAND-Zen 800 limit
- Applicable to all spherical LS detectors! Source code available soon.

KamNet paper submitted to Phys. Rev. C
Preprints available at **arXiv:2203.01870**



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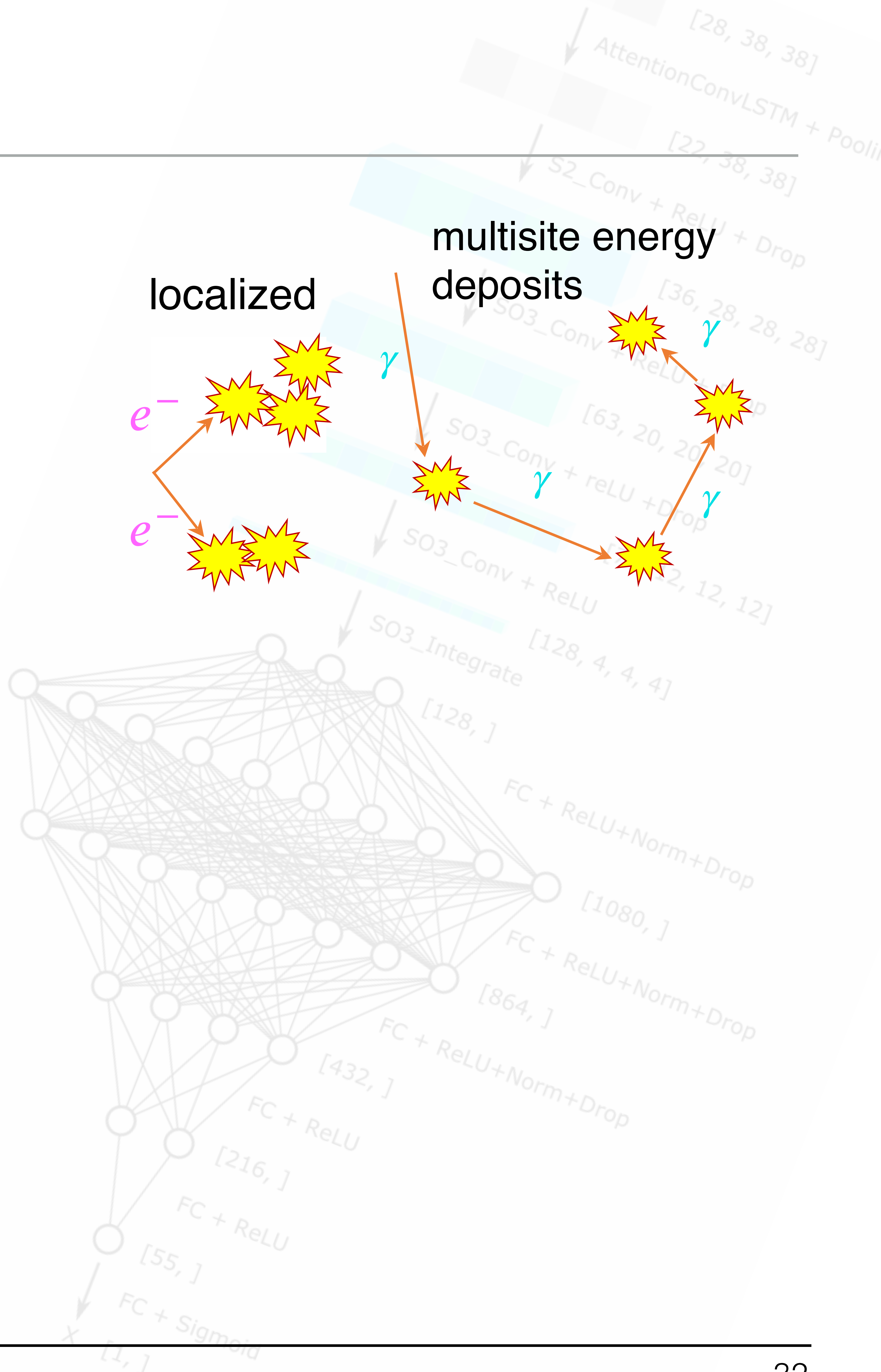

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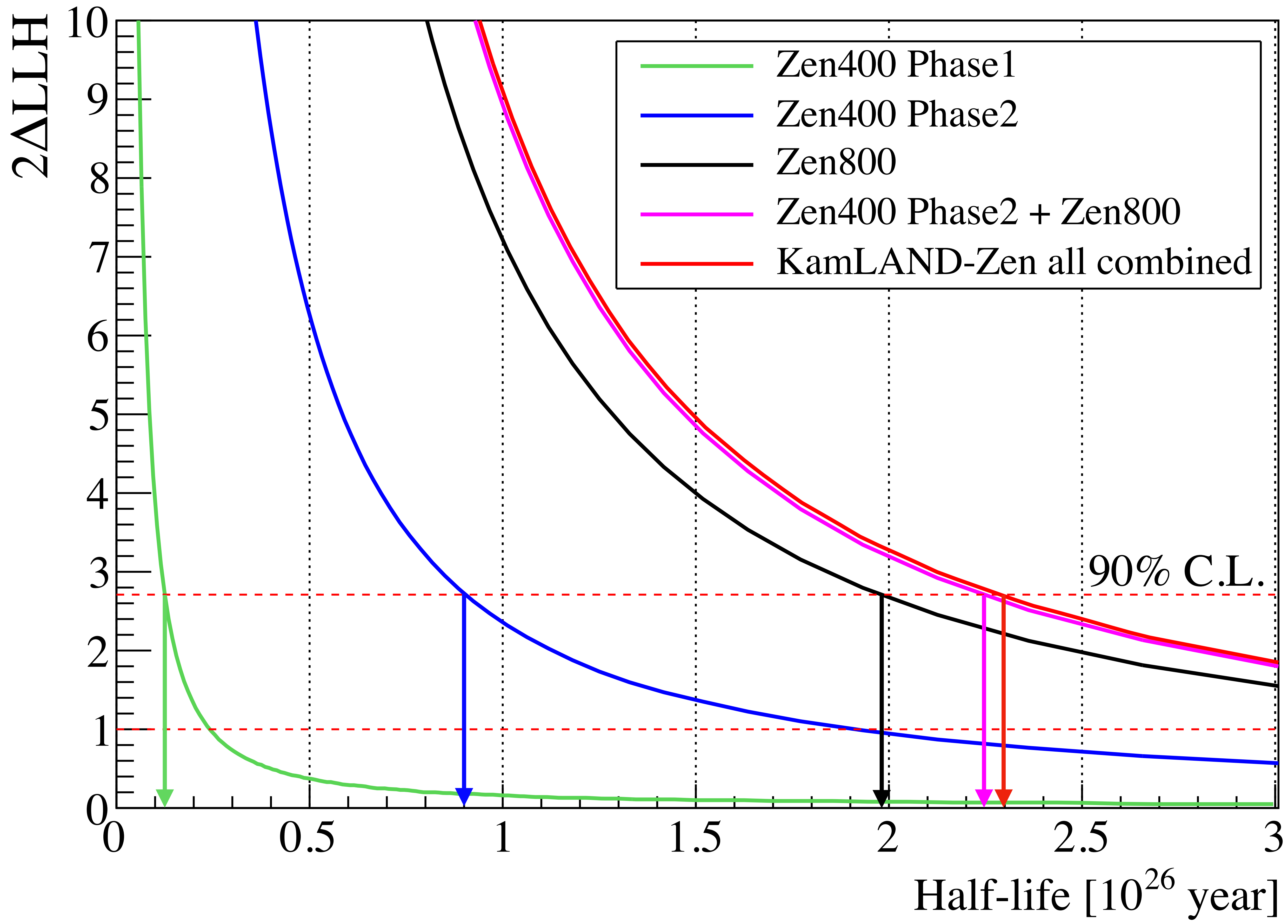
The combined frequentist result

The combined fit is performed in a frequentist framework.
Re-analyze the KamLAND-Zen 400 data with **updated background rejection techniques** and **long-lived spallation** consideration.



Combined limit (90% C.L):

$$T_{1/2}^{0\nu\beta\beta} > 2.3 \times 10^{26}\text{yr}$$

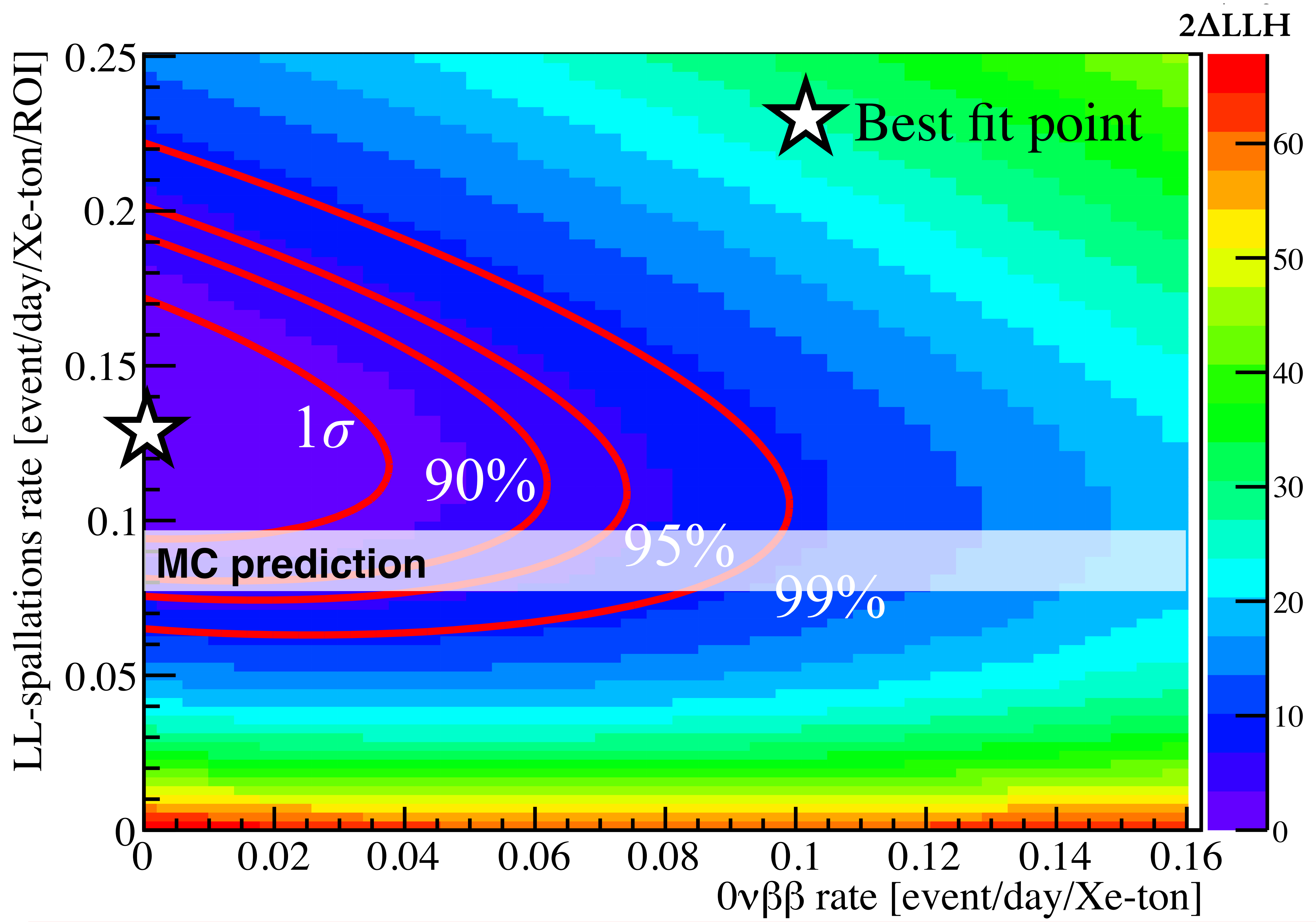
Sensitivity :

$$T_{1/2}^{0\nu\beta\beta} > 1.5 \times 10^{26}\text{yr}$$

Result (assuming Wilks' at the 90% C.L.)

KamLAND-Zen 800: the frequentist result

Maximum likelihood calculation with raster scan of **LL spallation rate** and **0νββ rate**.
Roughly 38 nuisance parameters included in the fit (floated, constrained, and fixed).



$$T_{1/2}^{0\nu\beta\beta} > 2.0 \times 10^{26} \mathrm{yr}\ 90\,\%\,\mathrm{C.L.}\,(\mathrm{Wilks'})$$

$$T_{1/2}^{0\nu\beta\beta} > 2.3 \times 10^{26} \mathrm{yr}\ 90\,\%\,\mathrm{C.L.}\,(\mathrm{Feldman-Cousins})$$

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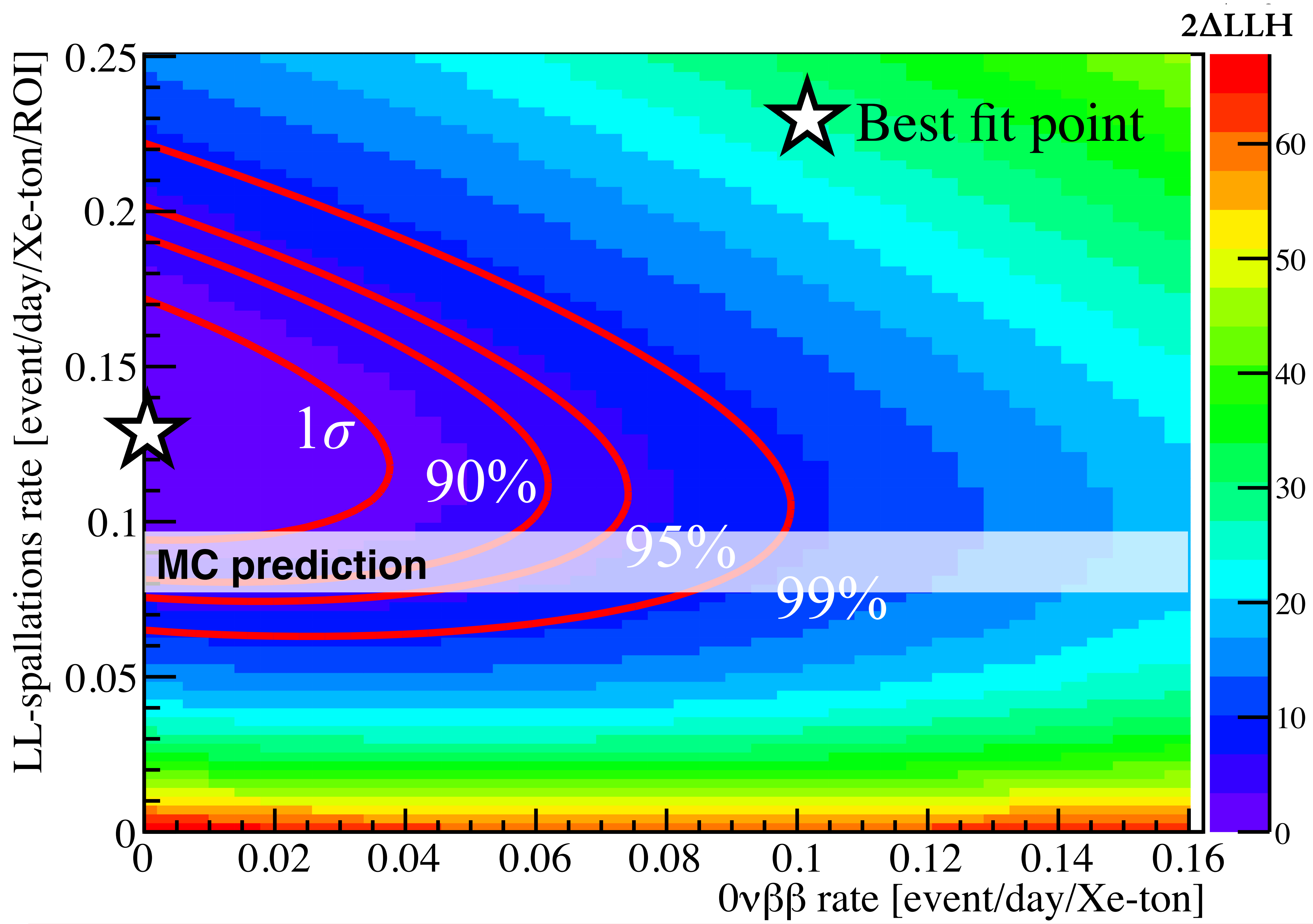

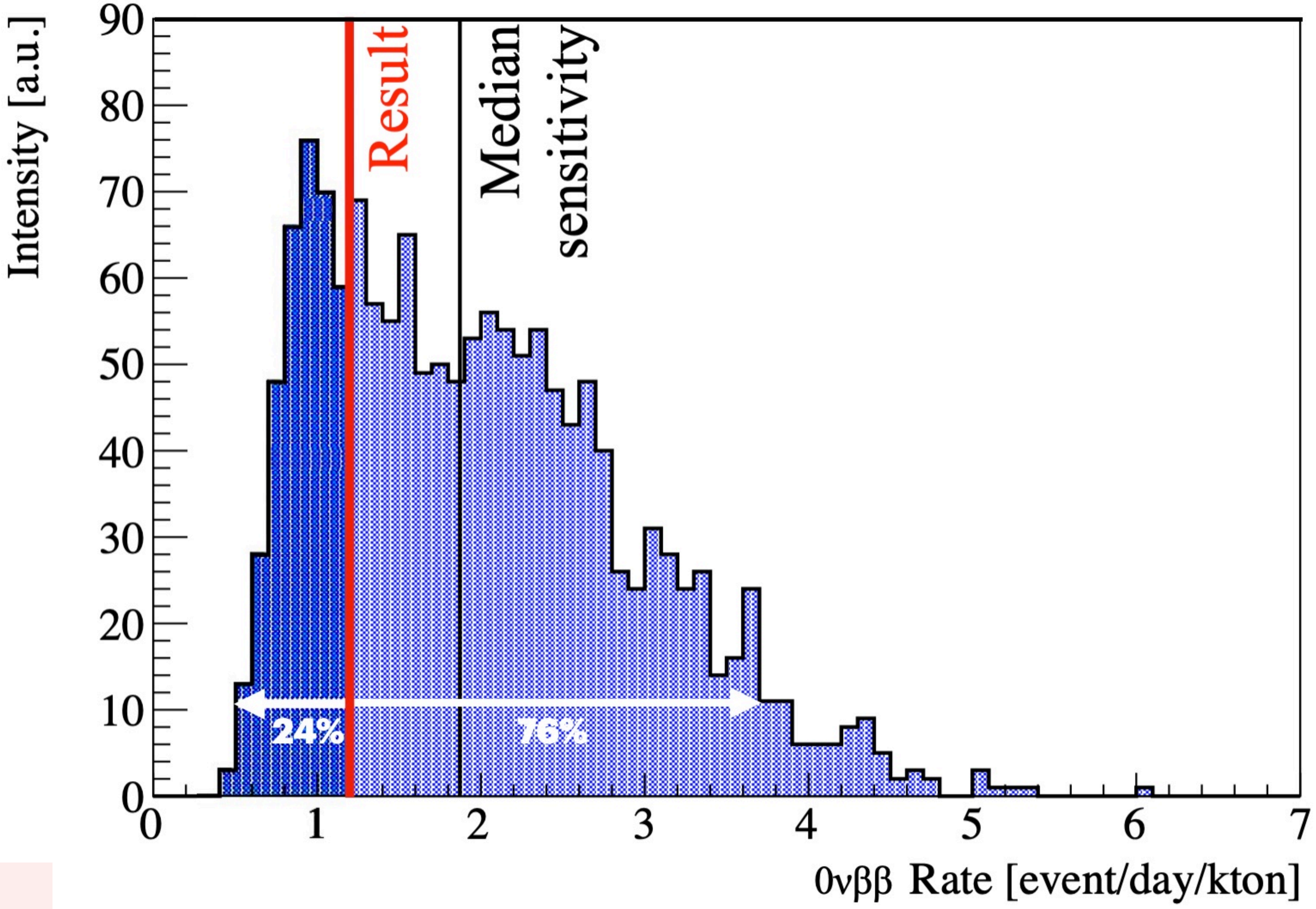

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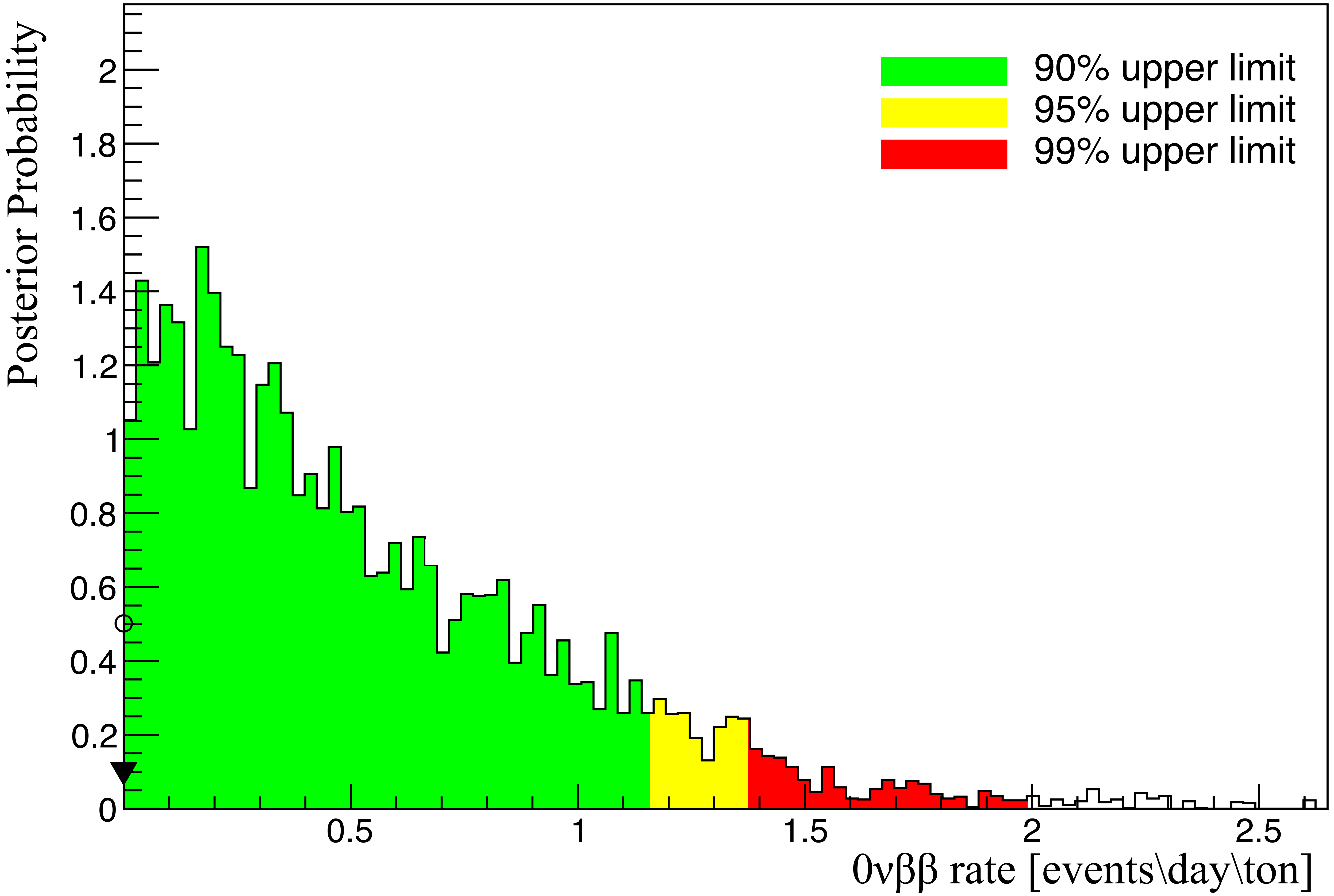
$$T_{1/2}^{0\nu\beta\beta} > 2.3 \times 10^{26} \mathrm{yr}\ 90\,\%\ \mathrm{C.L.}\ (\mathrm{Feldman-Cousins})$$

KamLAND-Zen 800: the Bayesian result

Bayesian Analysis Toolkit: BAT based on a Markov Chain Monte Carlo
https://github.com/bat/bat

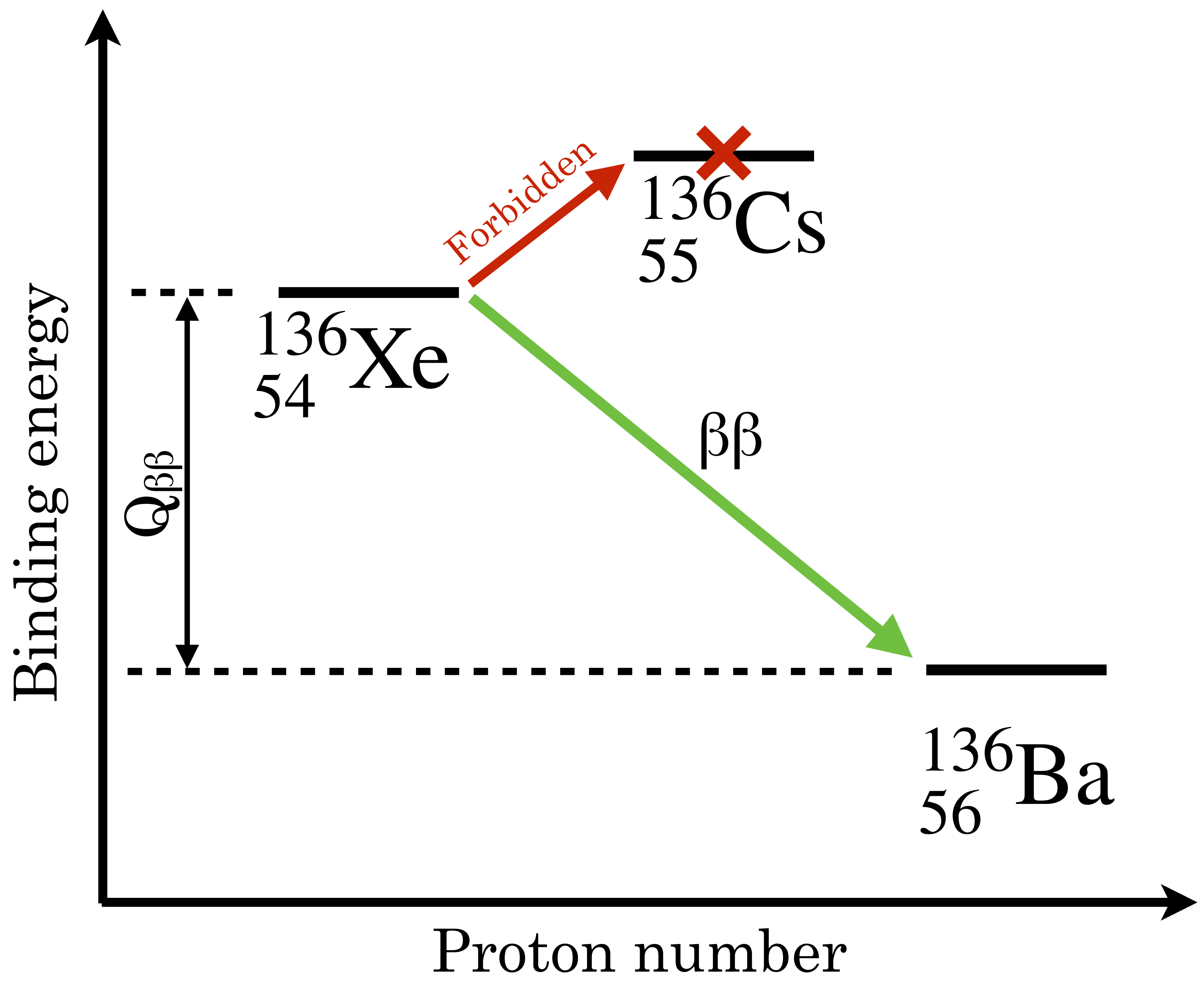
- Best-fit result:
  $0\nu\beta\beta$ rate $= 0.0$ event/day/kton
- Decay rate upper limit (90% C.I.):
  $0\nu\beta\beta$ rate < 1.2 event/day/kton
- Half-life lower limit (90% C.I.):
  $T_{1/2}^{0\nu\beta\beta} > 2.1 \times 10^{26}\text{yr } (90\,\%\,\text{C.I.})$
- Asimov sensitivity (90% C.I.):
  $T_{1/2}^{0\nu\beta\beta} > 2.0 \times 10^{26}\text{yr } (90\,\%\,\text{C.I.})$



Which elements can undergo this process?

We want single β-decay to be forbidden.
We want something stable.

Look for Even (P) - Even (N) nuclei.



Commonly used 2νββ isotopes

Isotope	Natural abundance (%)	$Q_{\beta\beta}$ (MeV)
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	8.7	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.8	3.035
^{116}Cd	7.5	2.813
^{130}Te	34.08	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371

- Observed for 14 elements.
- Capable in ~44 elements ~beta-stable isotopes.

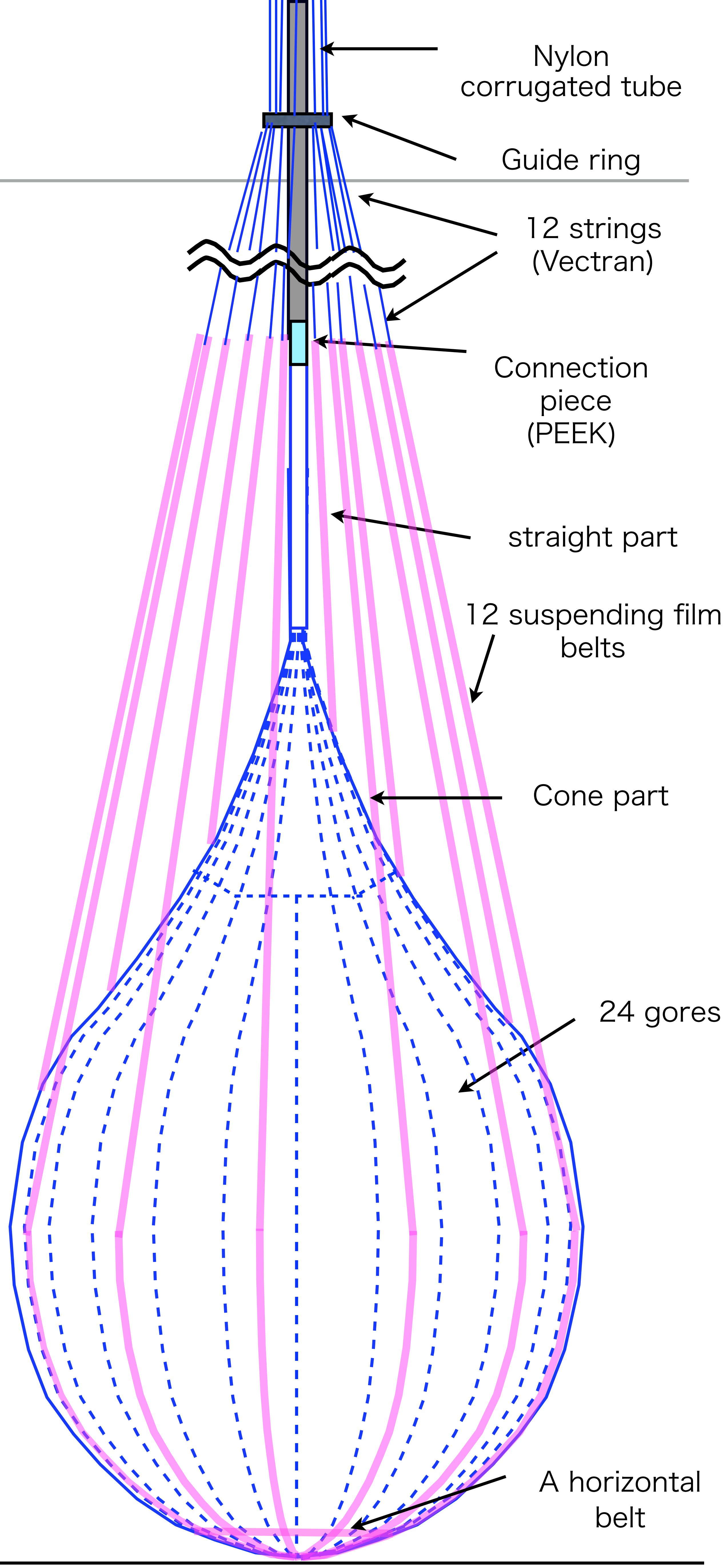
The new inner balloon construction

A cleaner and larger inner balloon allows for higher sensitivity.

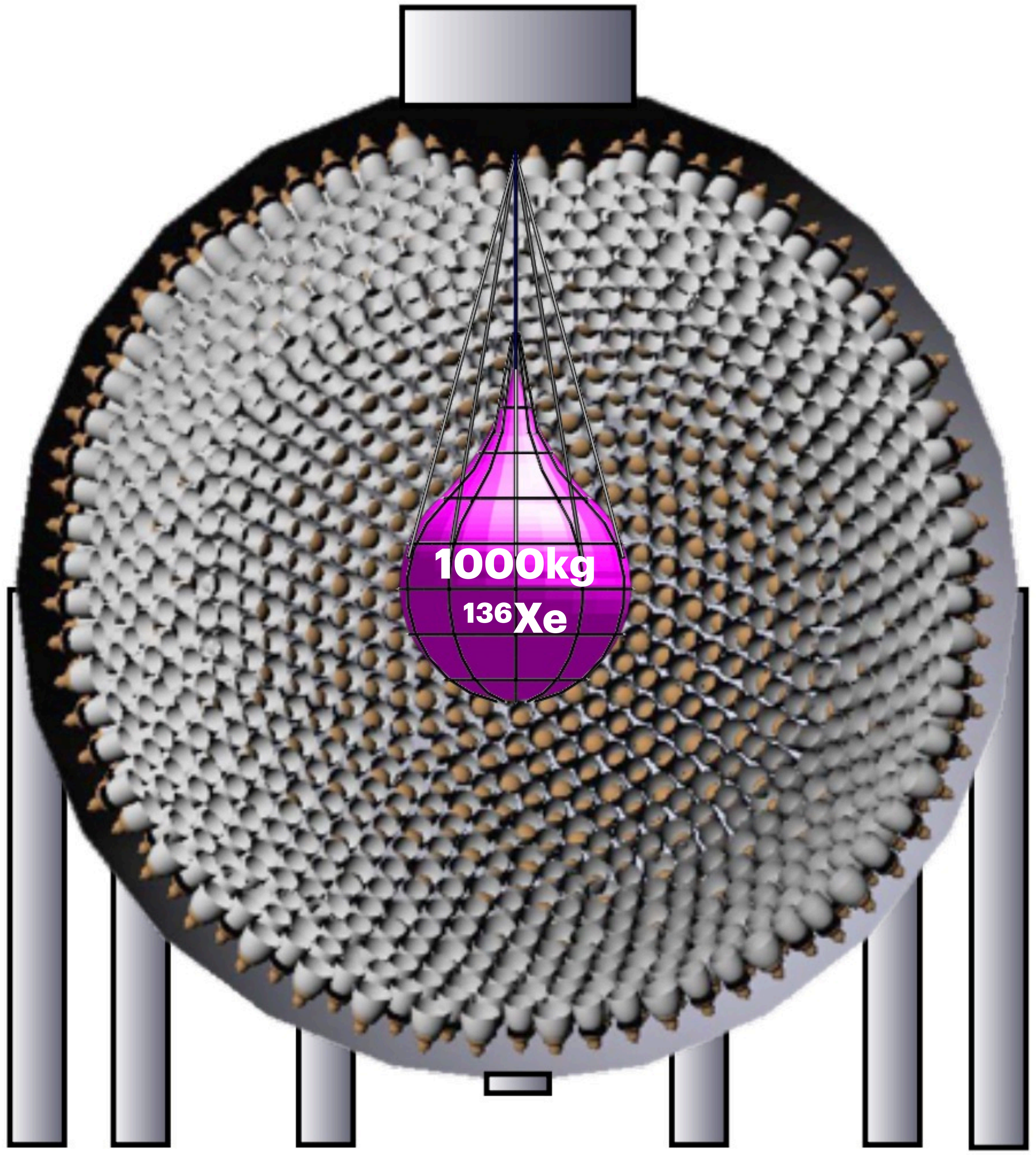
- Fabricated in class 1 clean room.
- 25 µm nylon film components are welded.

	KamLAND-Zen 400		KamLAND-Zen 800
Radius [m]	1.54		1.90
^{238}U [g/g]	4.6×10^{-11}	1/10	3×10^{-12}
^{232}Th [g/g]	3.4×10^{-10}		3.8×10^{-11}

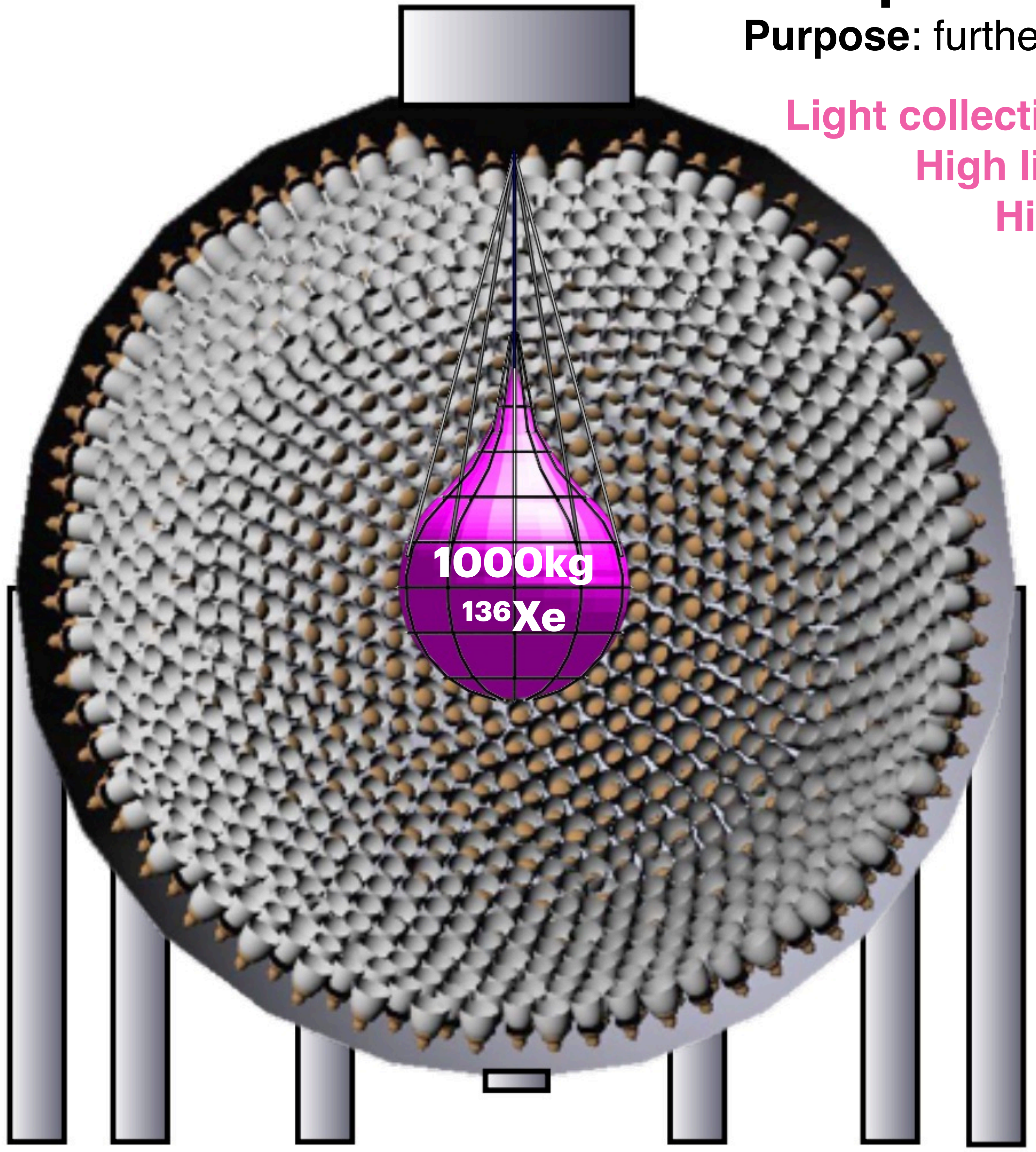
Larger balloon and significant reduction in background contamination



KamLAND2-Zen aims to cover the Inverted Ordering region.



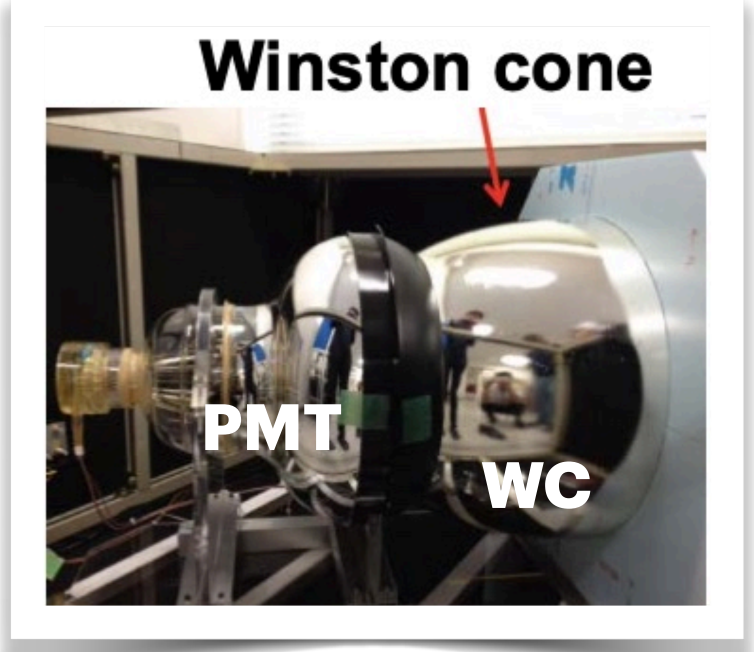
KamLAND2-Zen aims to cover the Inverted Ordering region.



1. Improved energy resolution

Purpose: further separate **2νββ** from the **0νββ**.

Light collection with Winston Cones (x1.8)
High light yield scintillator (x1.4)
High QE 20" PMTs (x1.9)



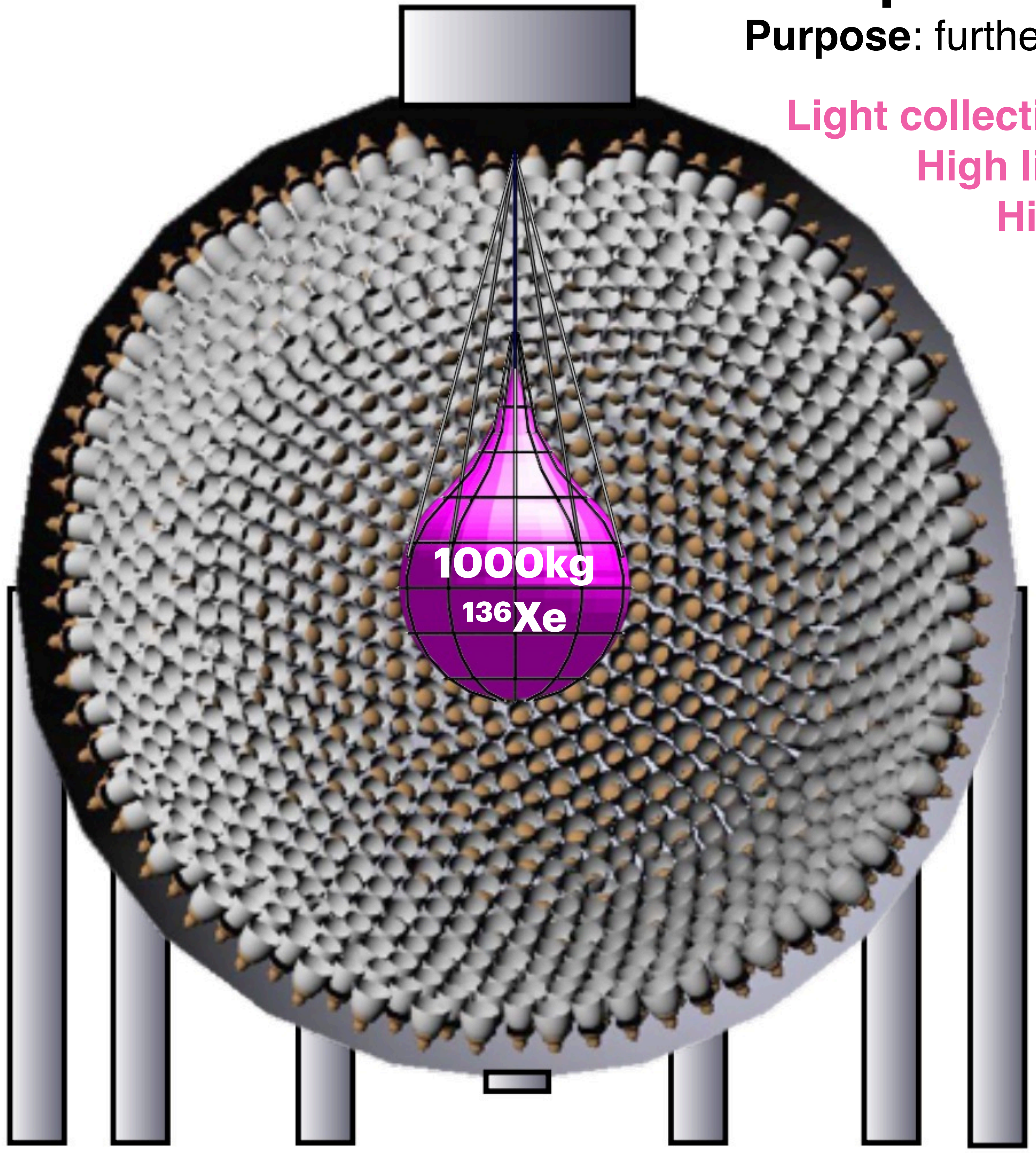
4% → 2% energy resolution

x100 reduction in 2νββ background rate.

KamLAND2-Zen aims to cover the Inverted Ordering region.

2. State-of-the-art electronics

Purpose: Improve background suppression. Tagging long lived isotope from cosmic ray spallation.



1. Improved energy resolution

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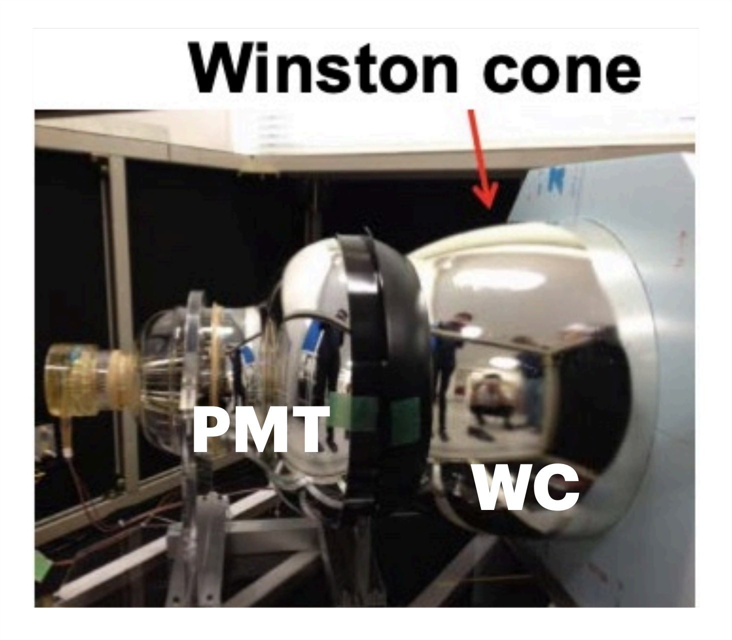
Light collection with Winston Cones (x1.8)
High light yield scintillator (x1.4)
High QE 20" PMTs (x1.9)



4% → 2% energy resolution

x100 reduction in 2νββ background rate.

Towards KamLAND2-Zen

KamLAND2-Zen aims to cover the Inverted Ordering region.

2. State-of-the-art electronics

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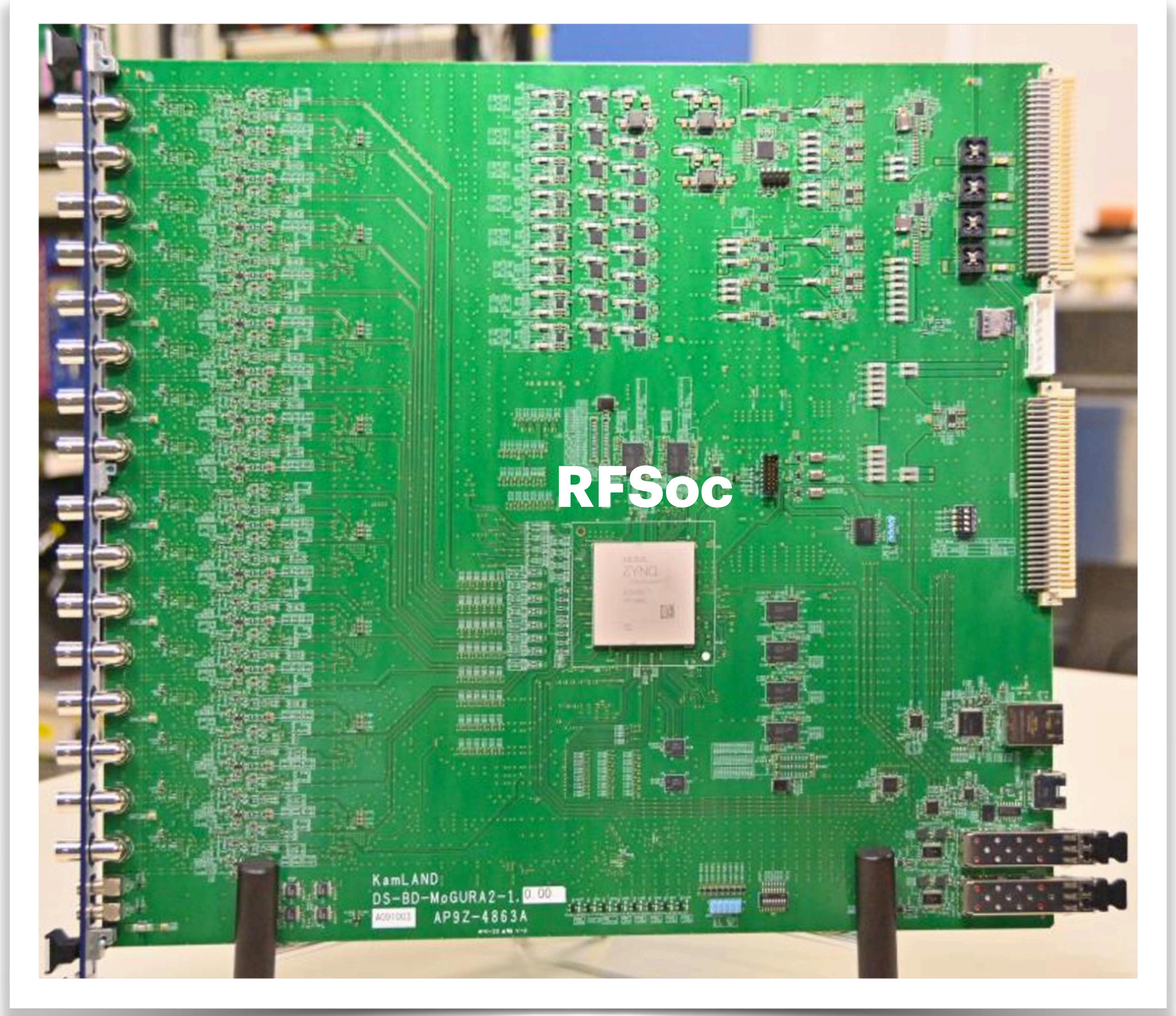

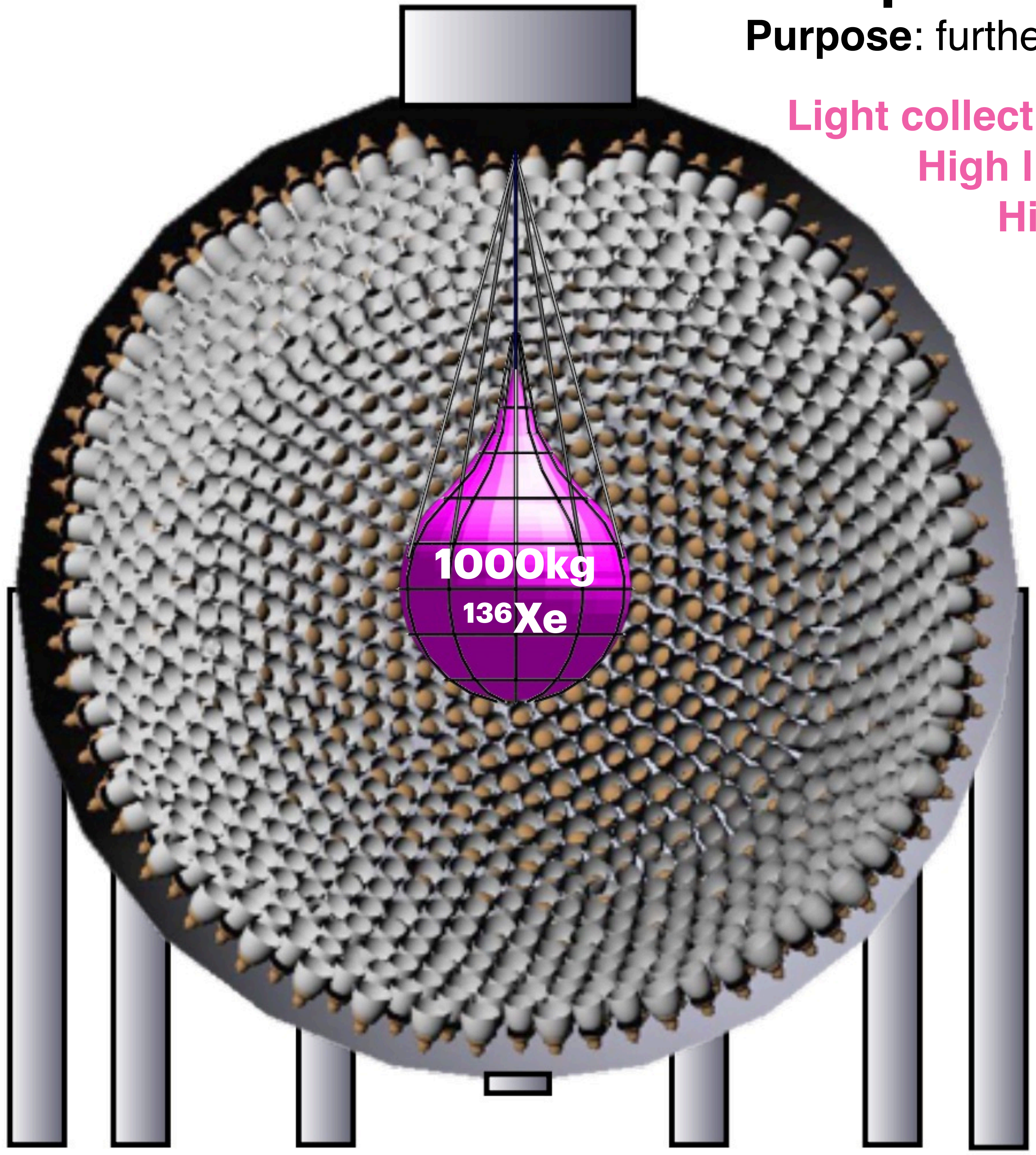

1. Improved energy resolution

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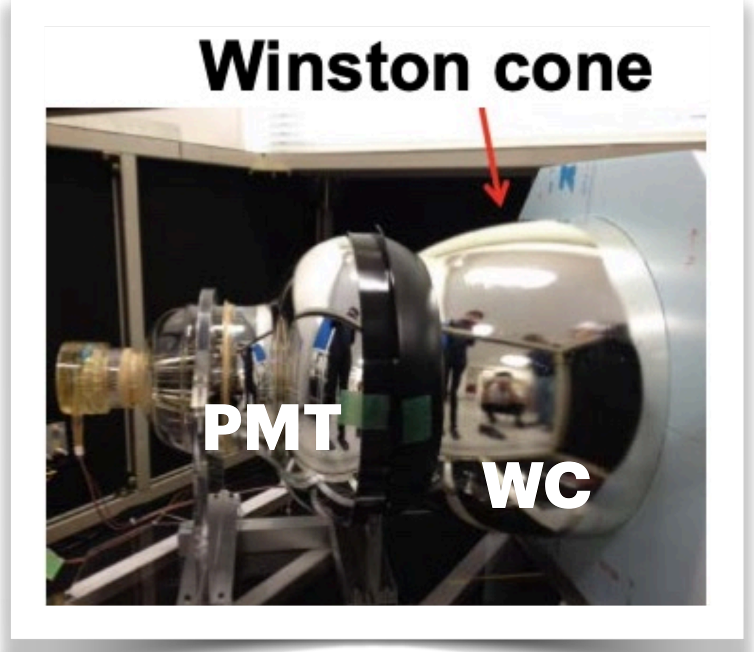
Light collection with Winston Cones (x1.8)
High light yield scintillator (x1.4)
High QE 20" PMTs (x1.9)

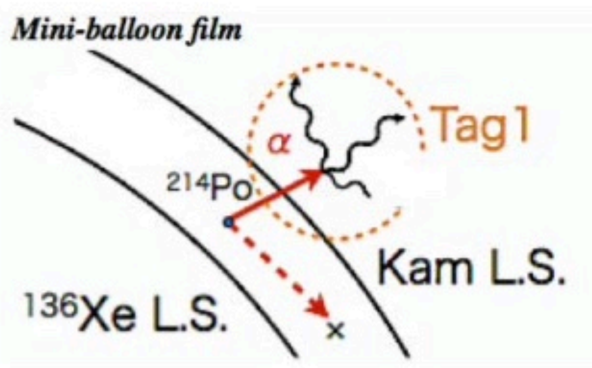


4% → 2% energy resolution

x100 reduction in 2νββ background rate.

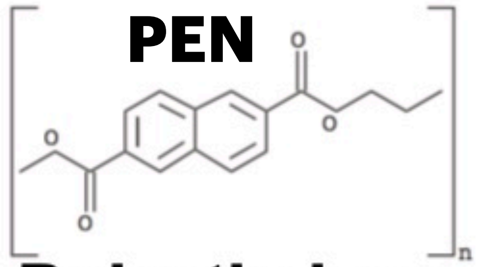
3. Improved inner balloon

Purpose: reduce backgrounds originating from balloon.



Tag ^{214}Bi decays.

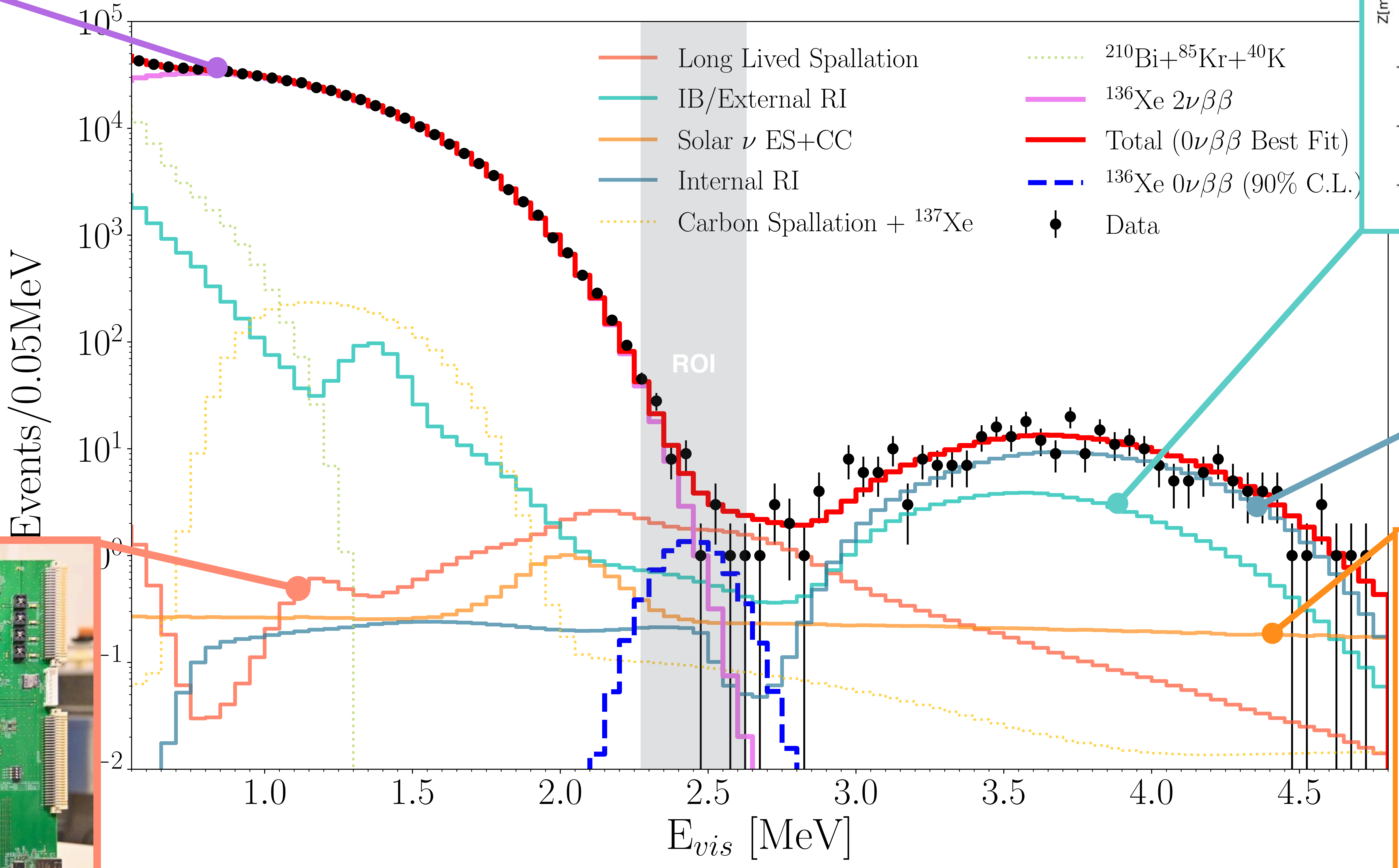
PEN

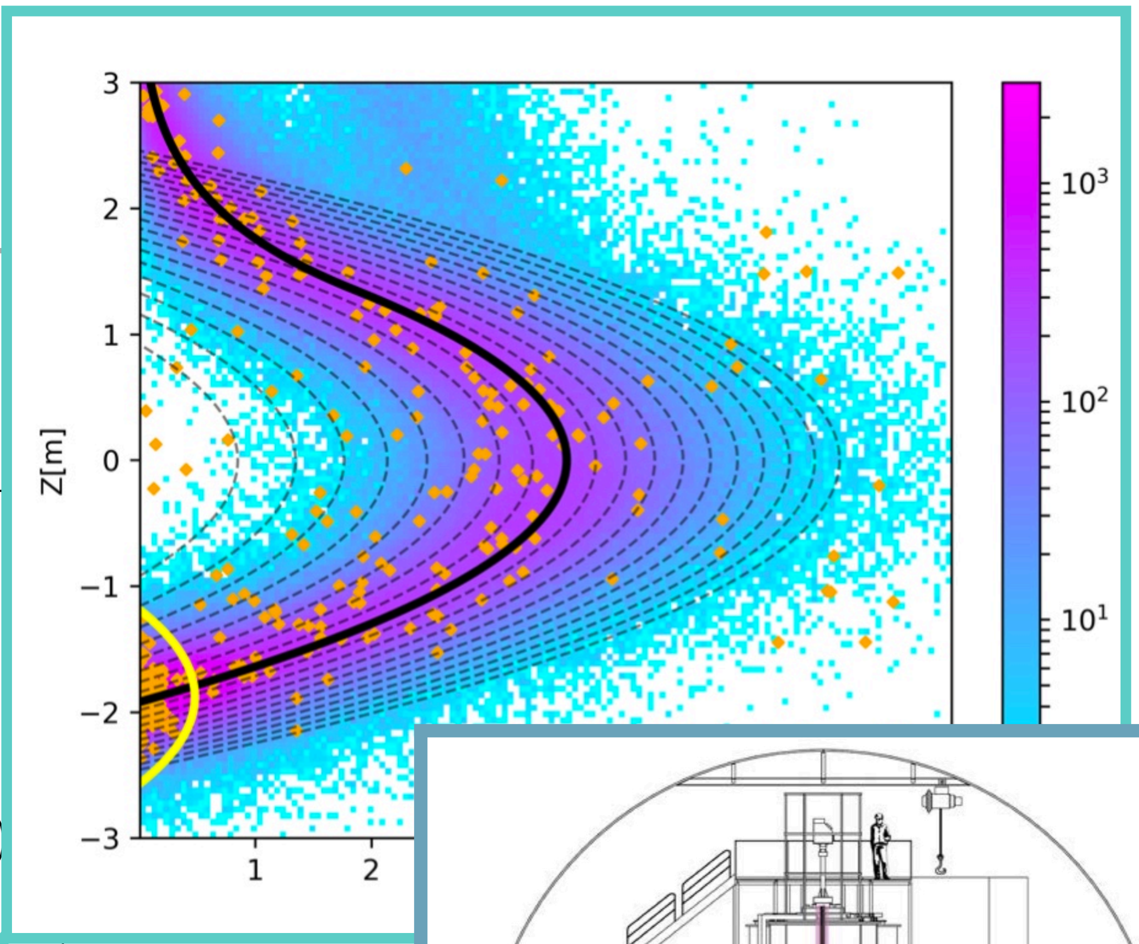


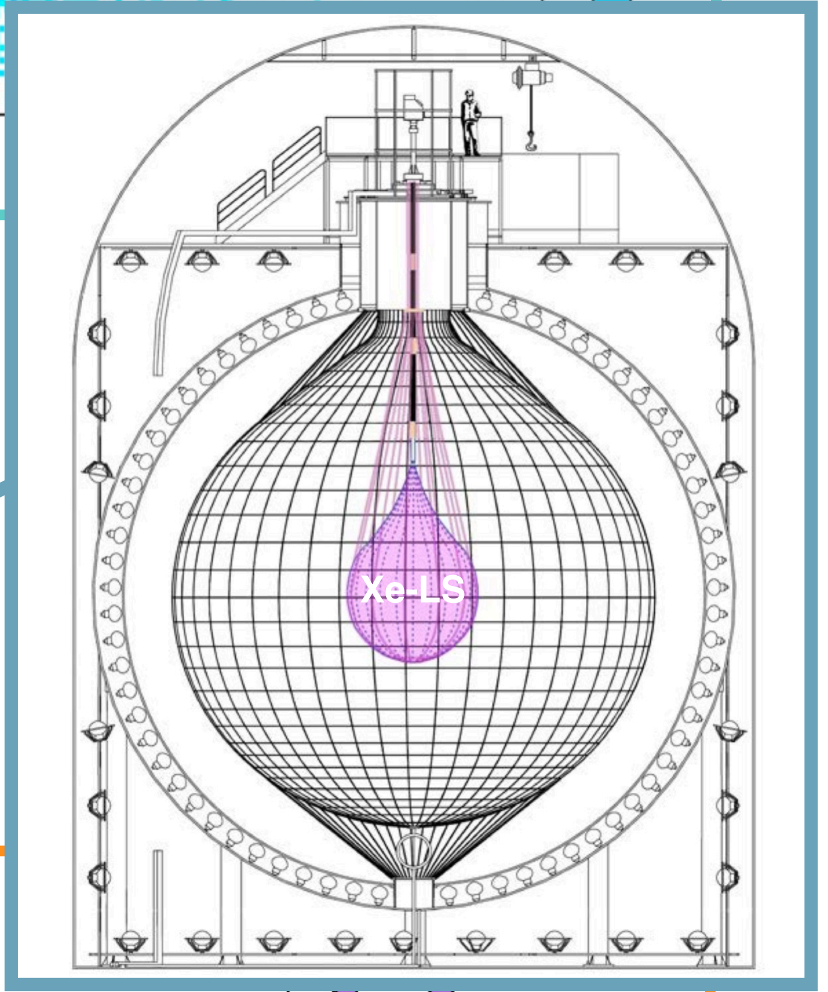
Polyethylene naphthalate

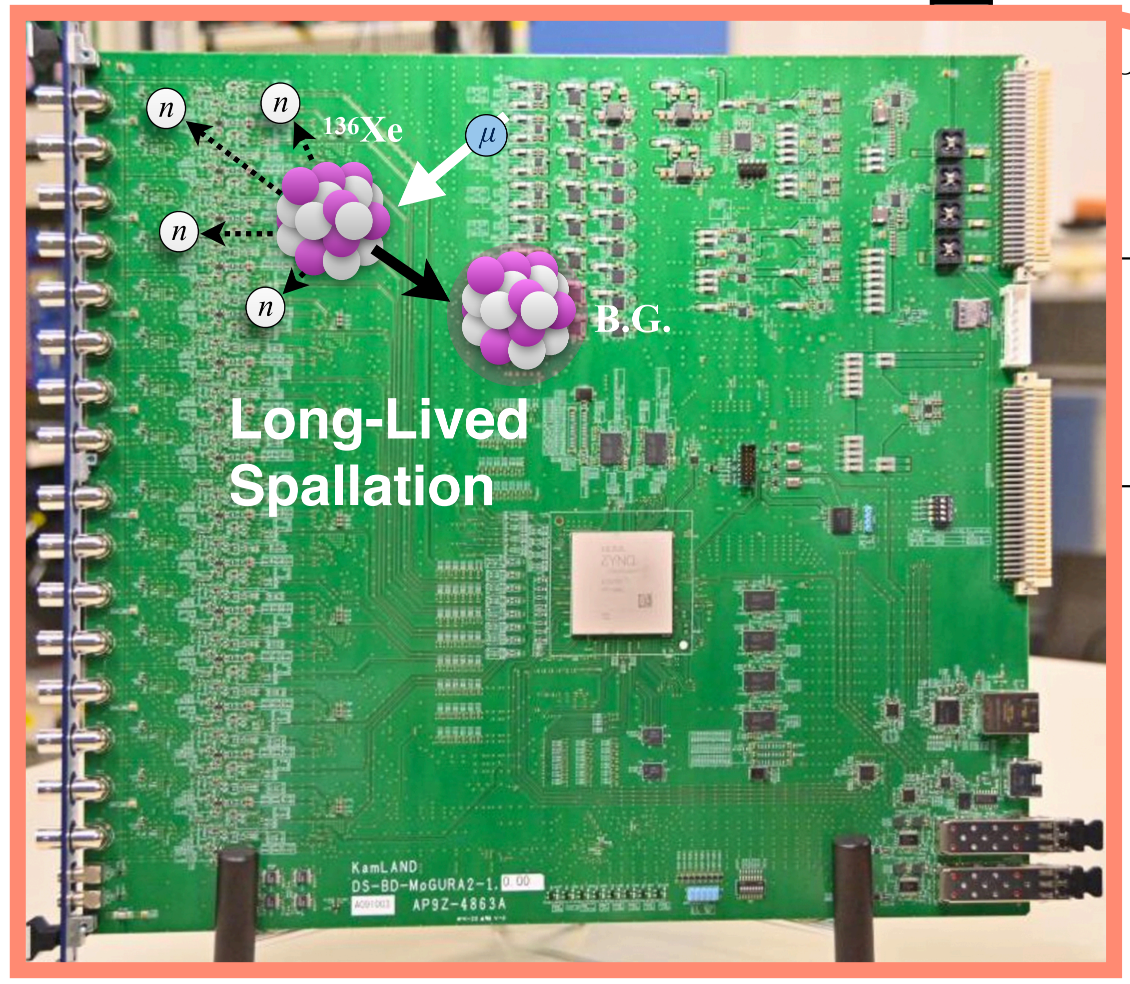
What limits our sensitivity?

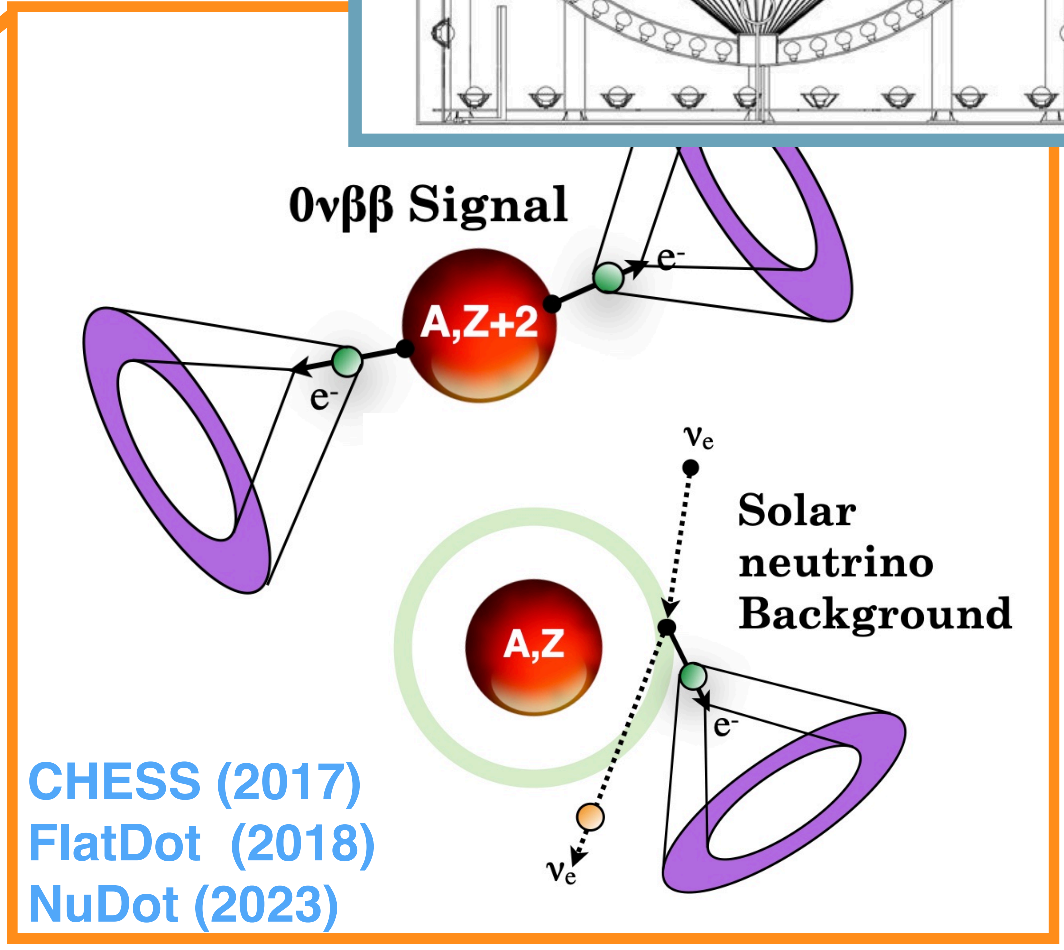
2νββ energy tail
Most dominant &
inevitable bkg.
~ 12 events/ROI







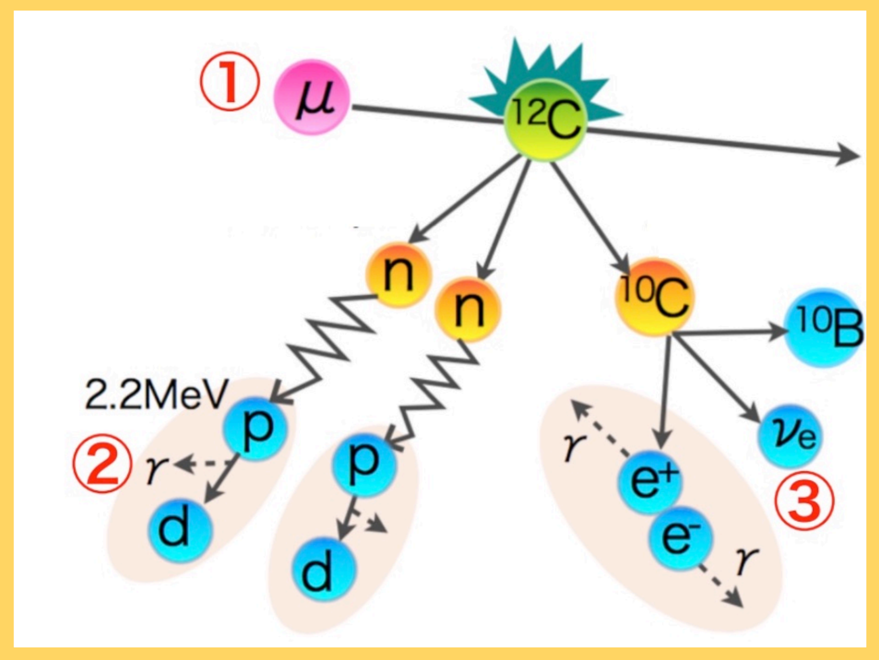


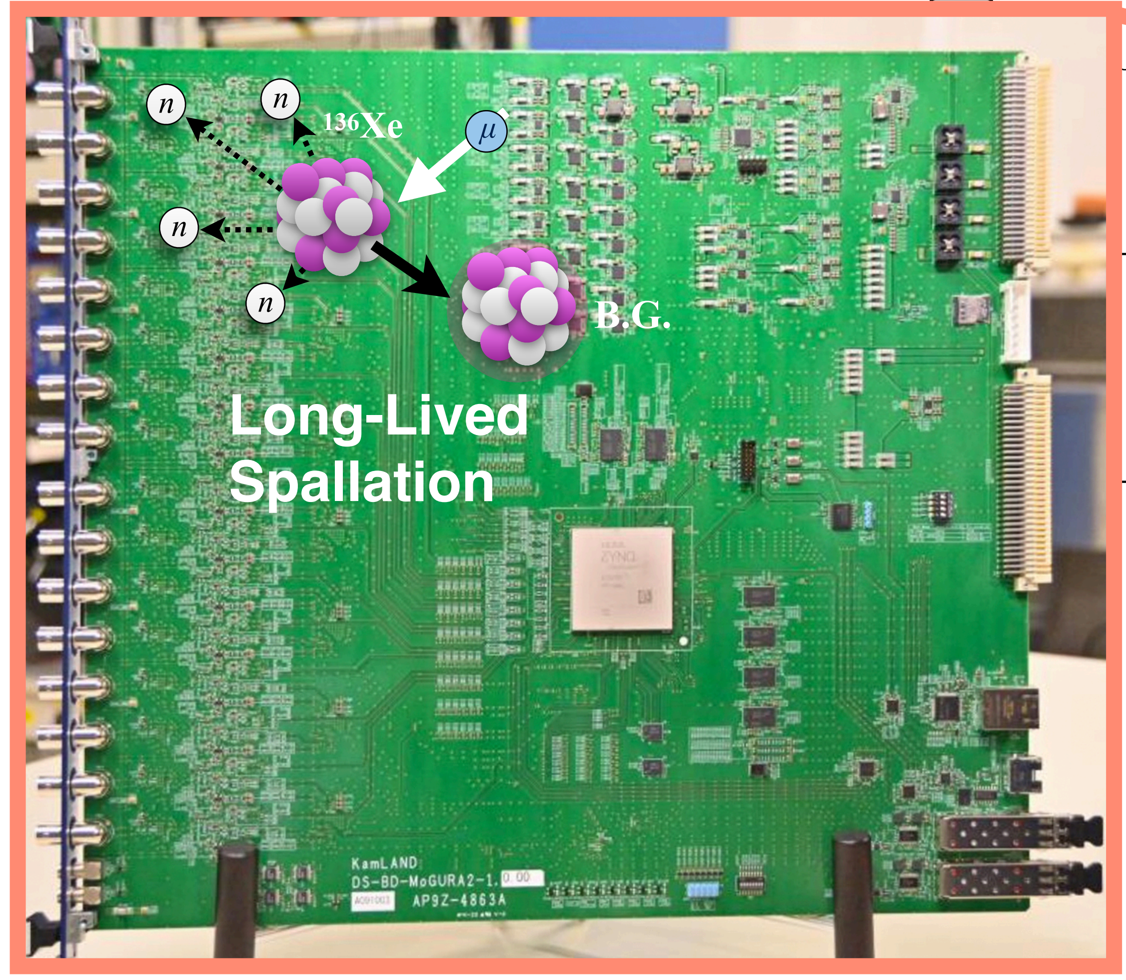


$$T^{0\nu\beta\beta}_{1/2} > 2.0 \times 10^{26} \text{yr (90 \% CL)}$$

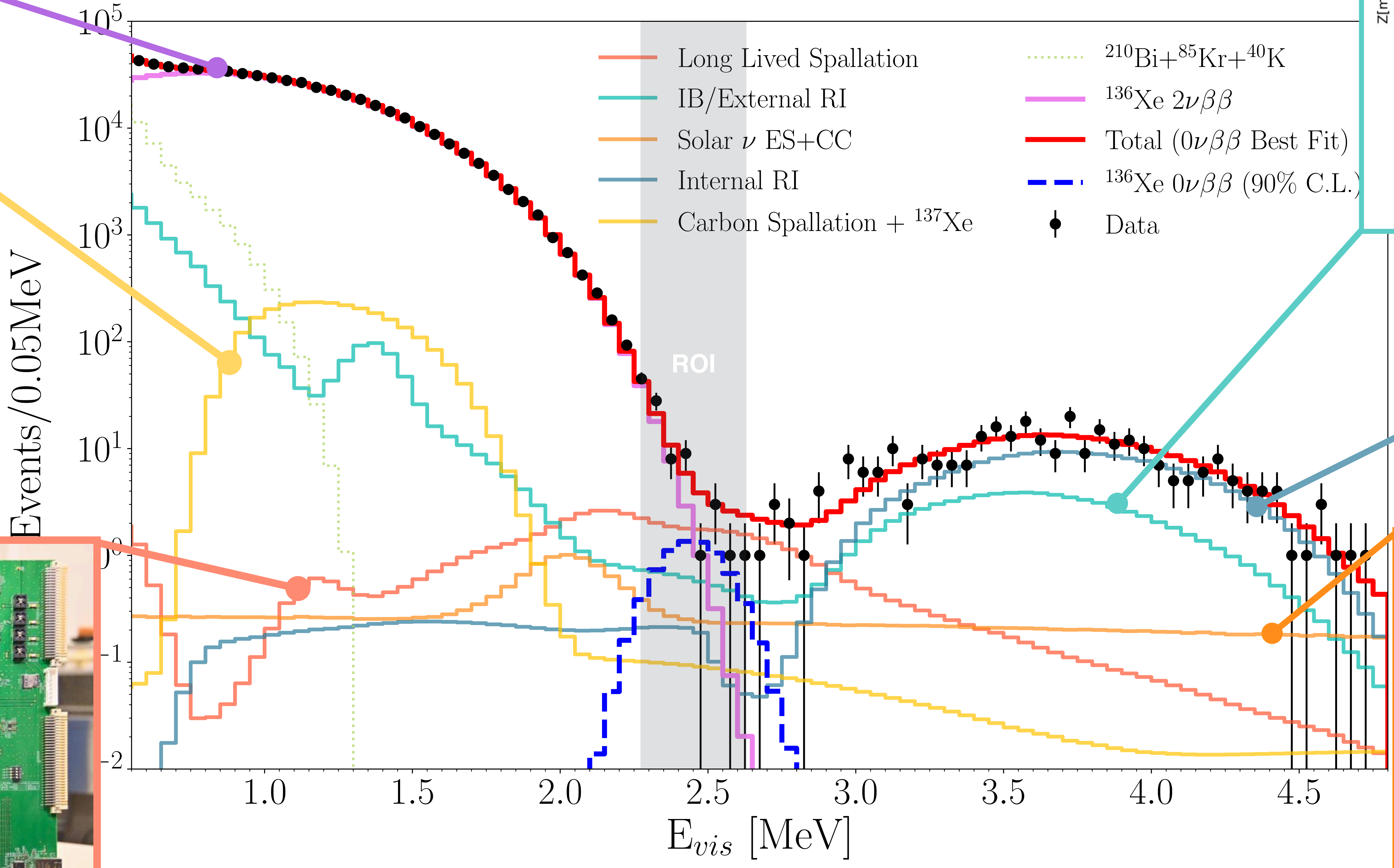
What limits our sensitivity?

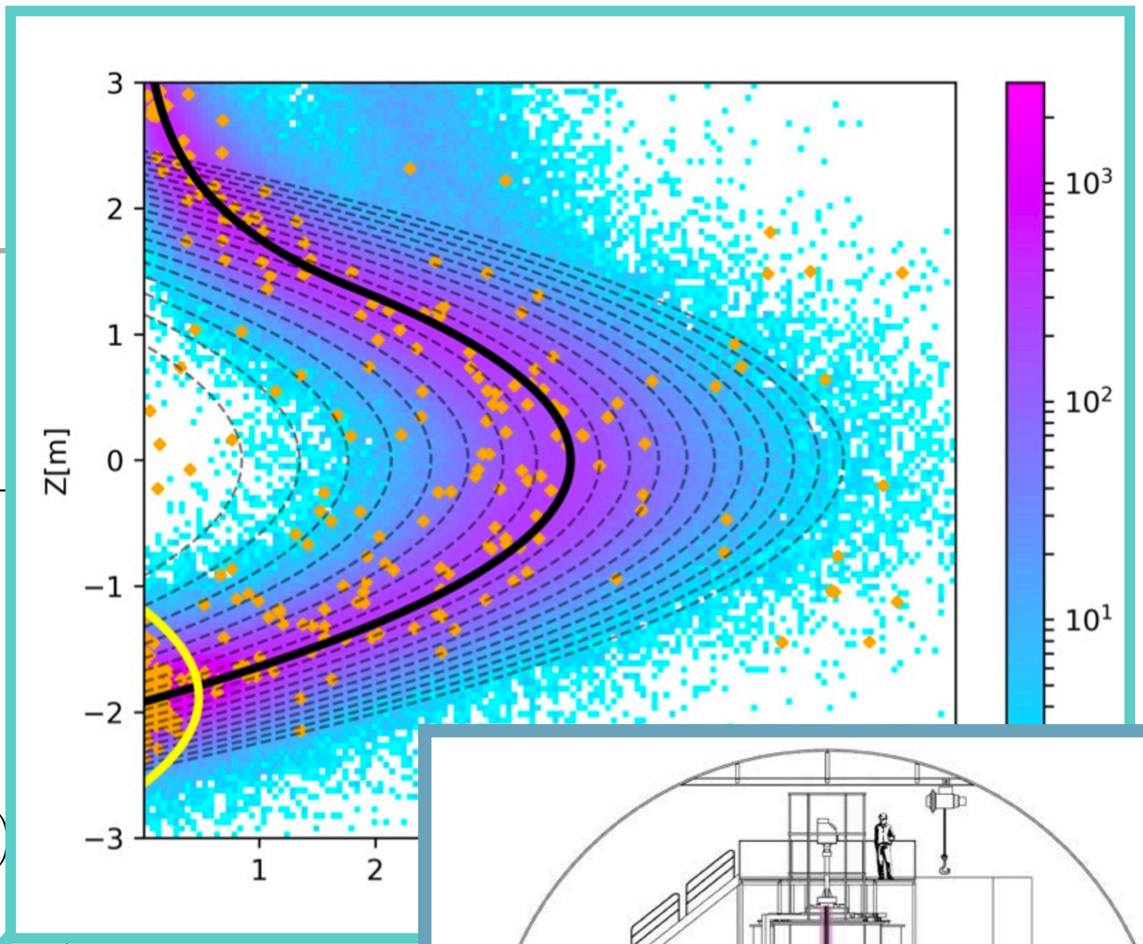
2νββ energy tail
Most dominant &
inevitable bkg.
~ 12 events/ROI

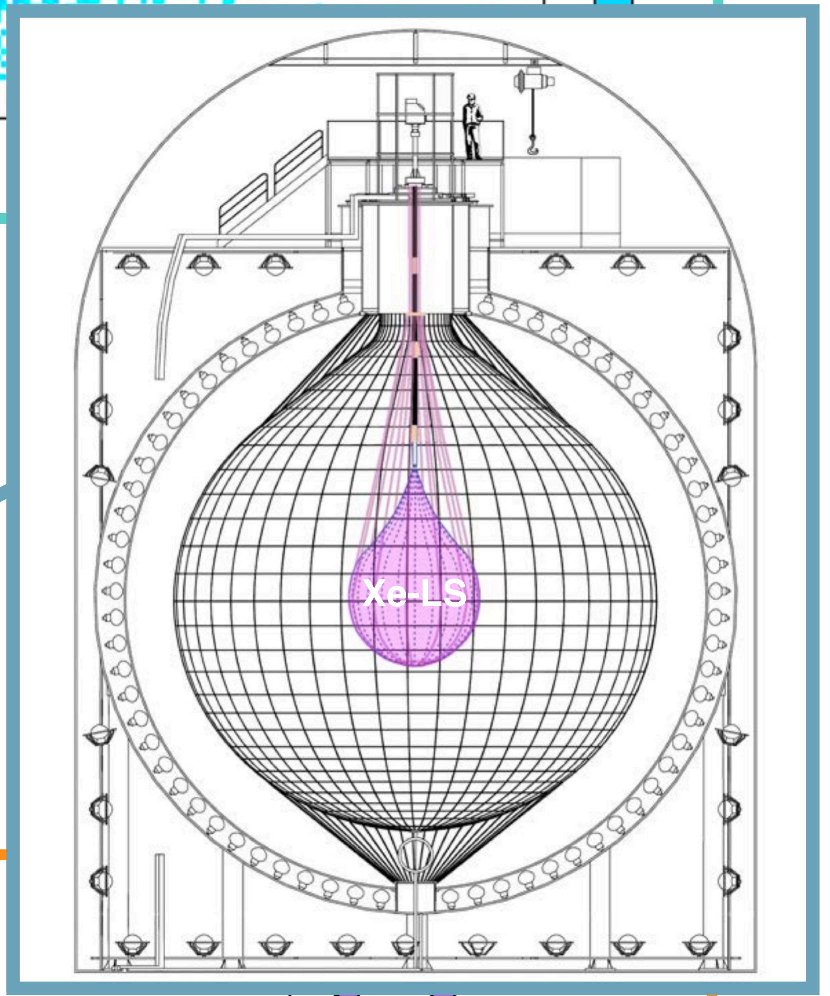


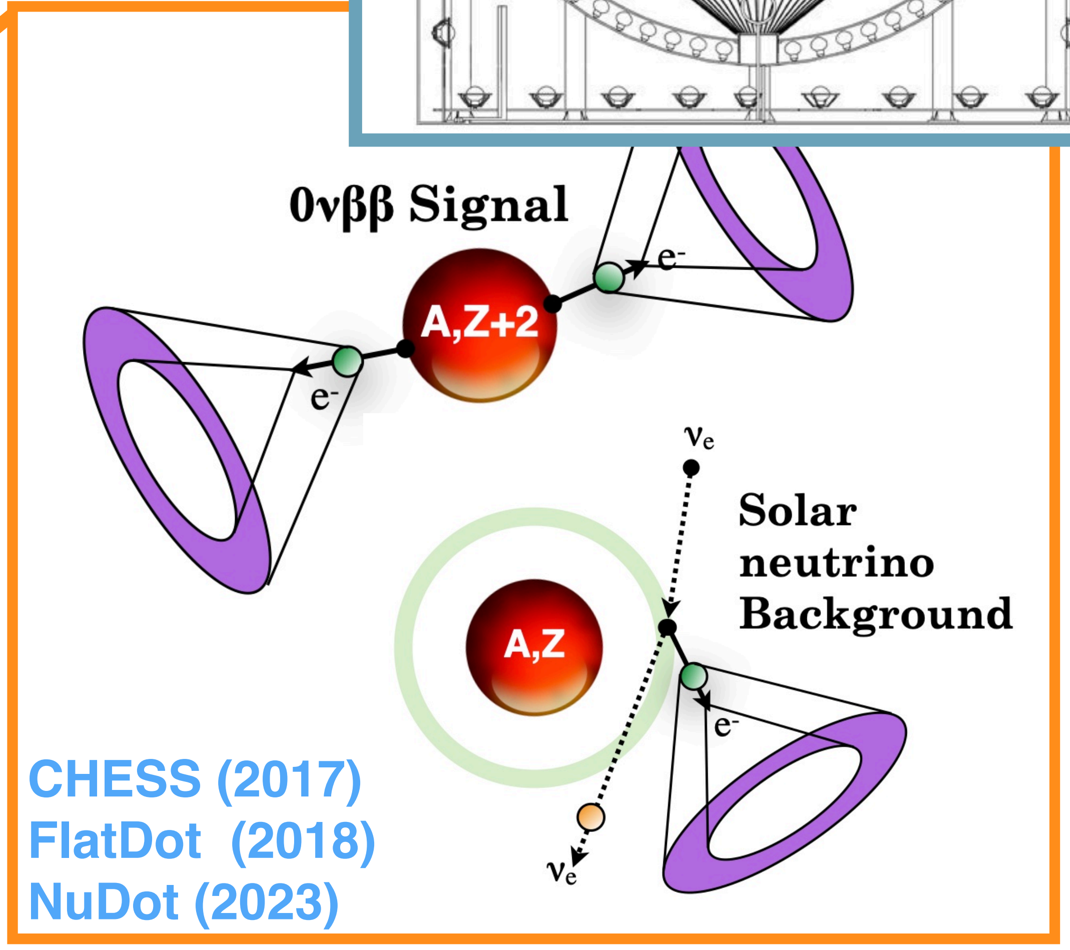


Livetime: 523 days, inner 157cm









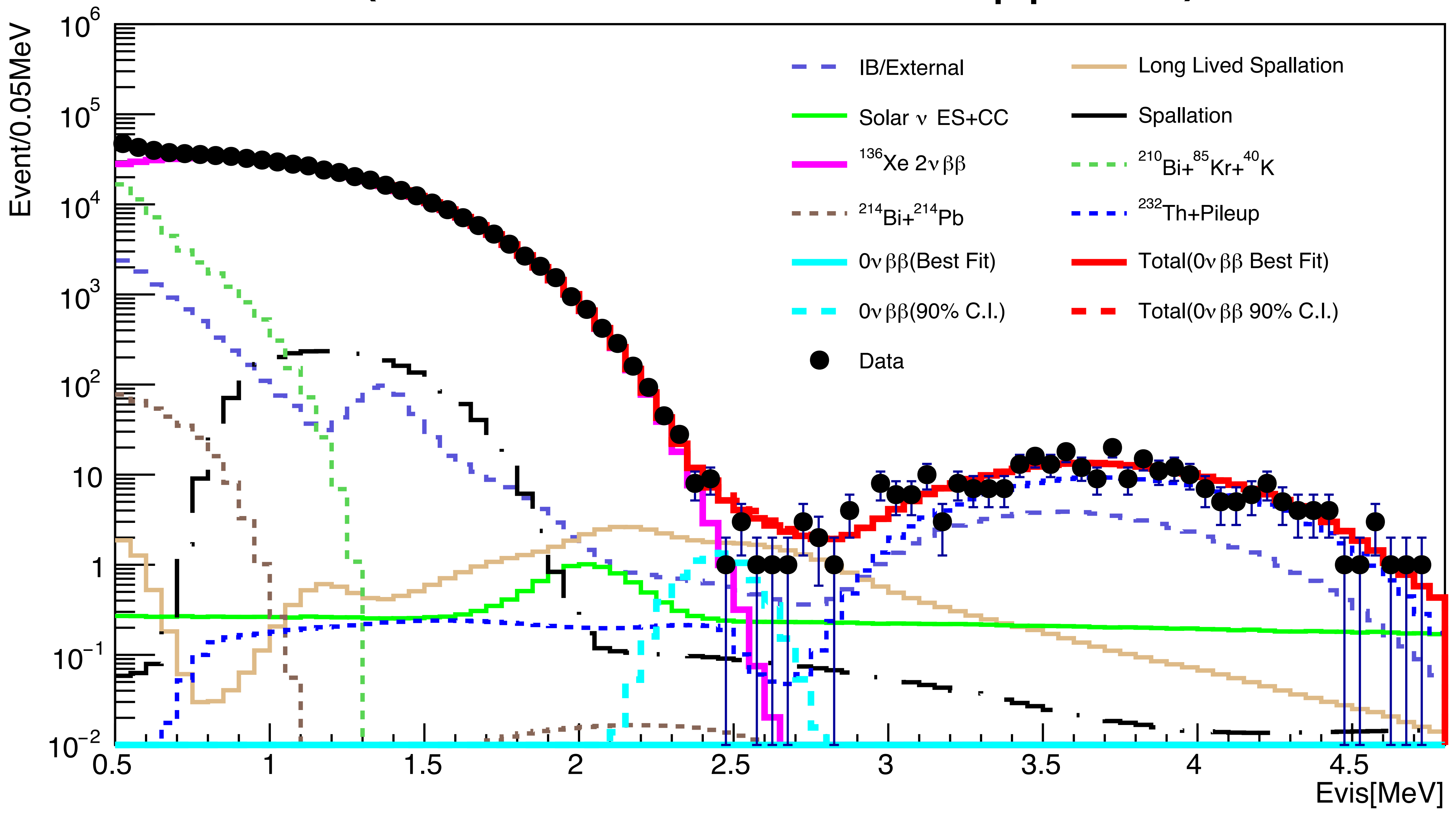
$$T^{0\nu\beta\beta}_{1/2} > 2.0 \times 10^{26}\text{yr (90 \% CL)}$$

Singles and LL datasets

- Simultaneous fit the 0νββ spectrum and a long lived spectrum to constrain backgrounds.

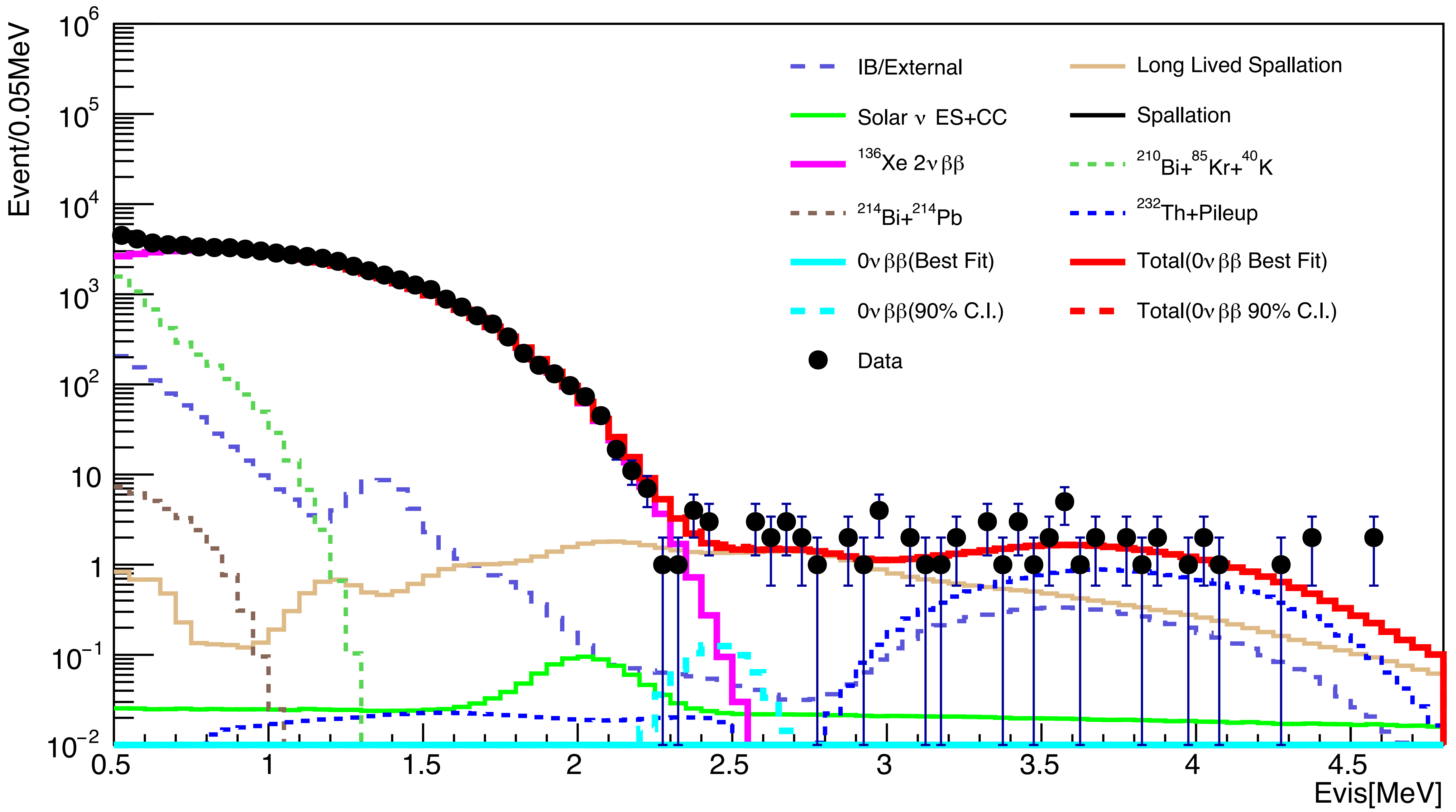
$0\nu\beta\beta$ candidate data set (singles dataset)

(dataset sensitive to 0νββ rate)



Long-lived product data set (LL dataset)

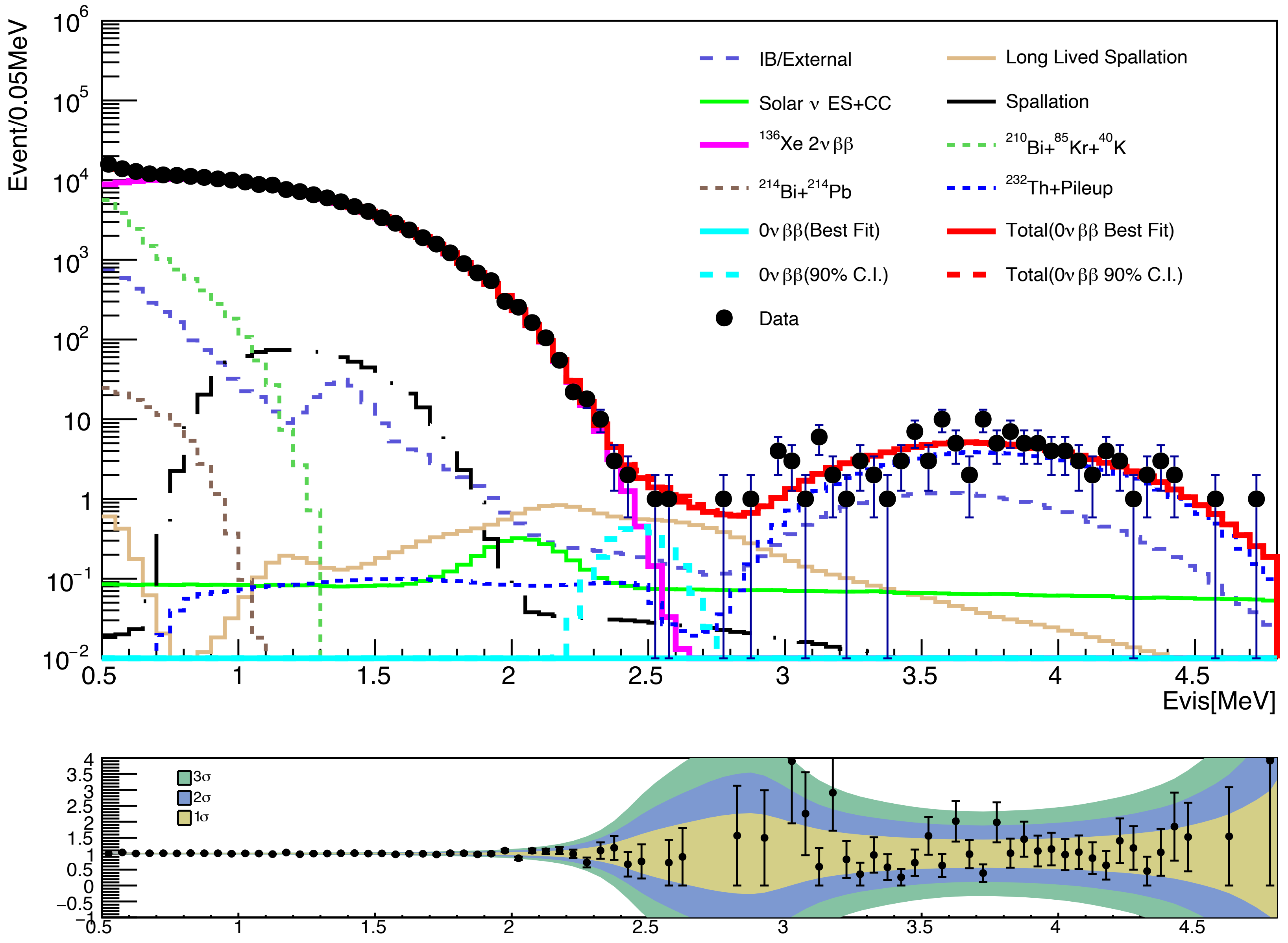
(used to constrain the LL rate)



KamLAND-Zen 800, what did we see?

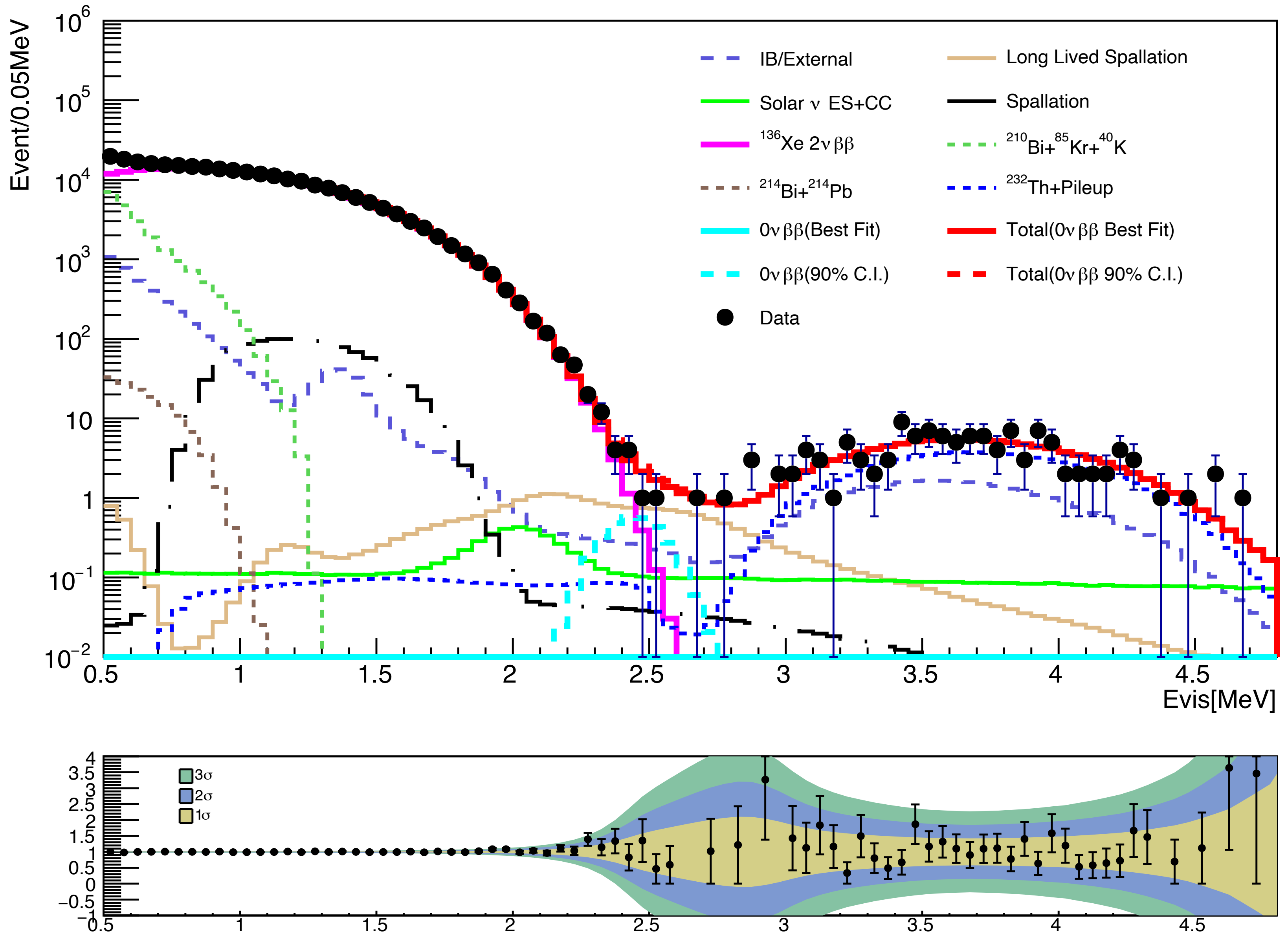
Exposure: 970 kg·yr
Total Livetime: 523.4 days

Time Bin 1



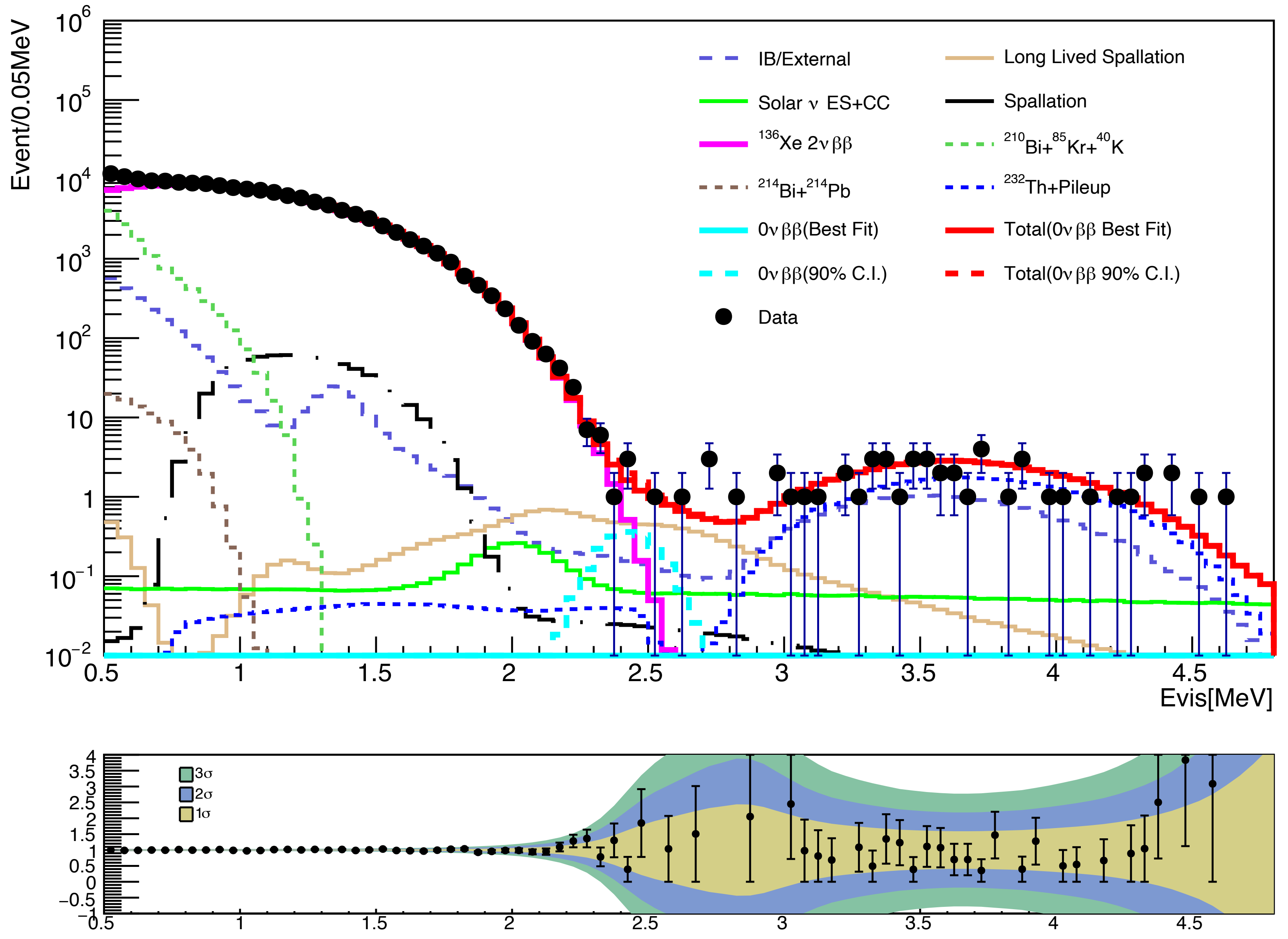
Total Livetime: **166.3 days**
02/05/2019 - 09/29/2019

Time Bin 2



Total LiveTime: **252.2 days**
09/30/2019 - 10/20/2020

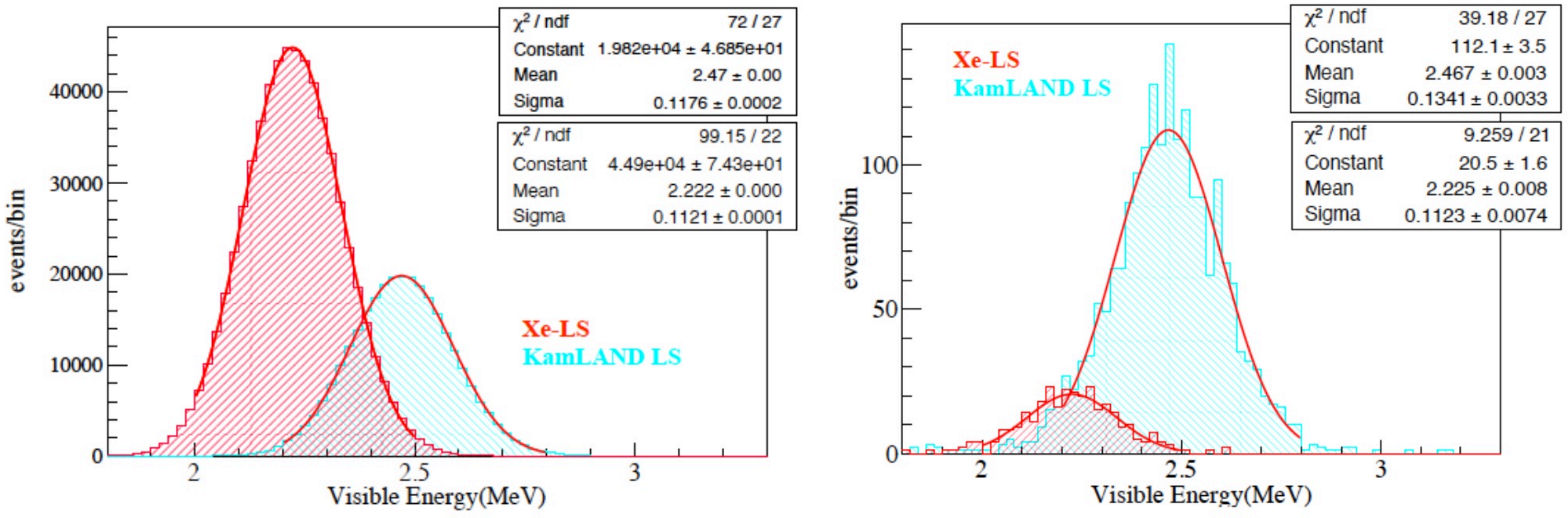
Time Bin 3



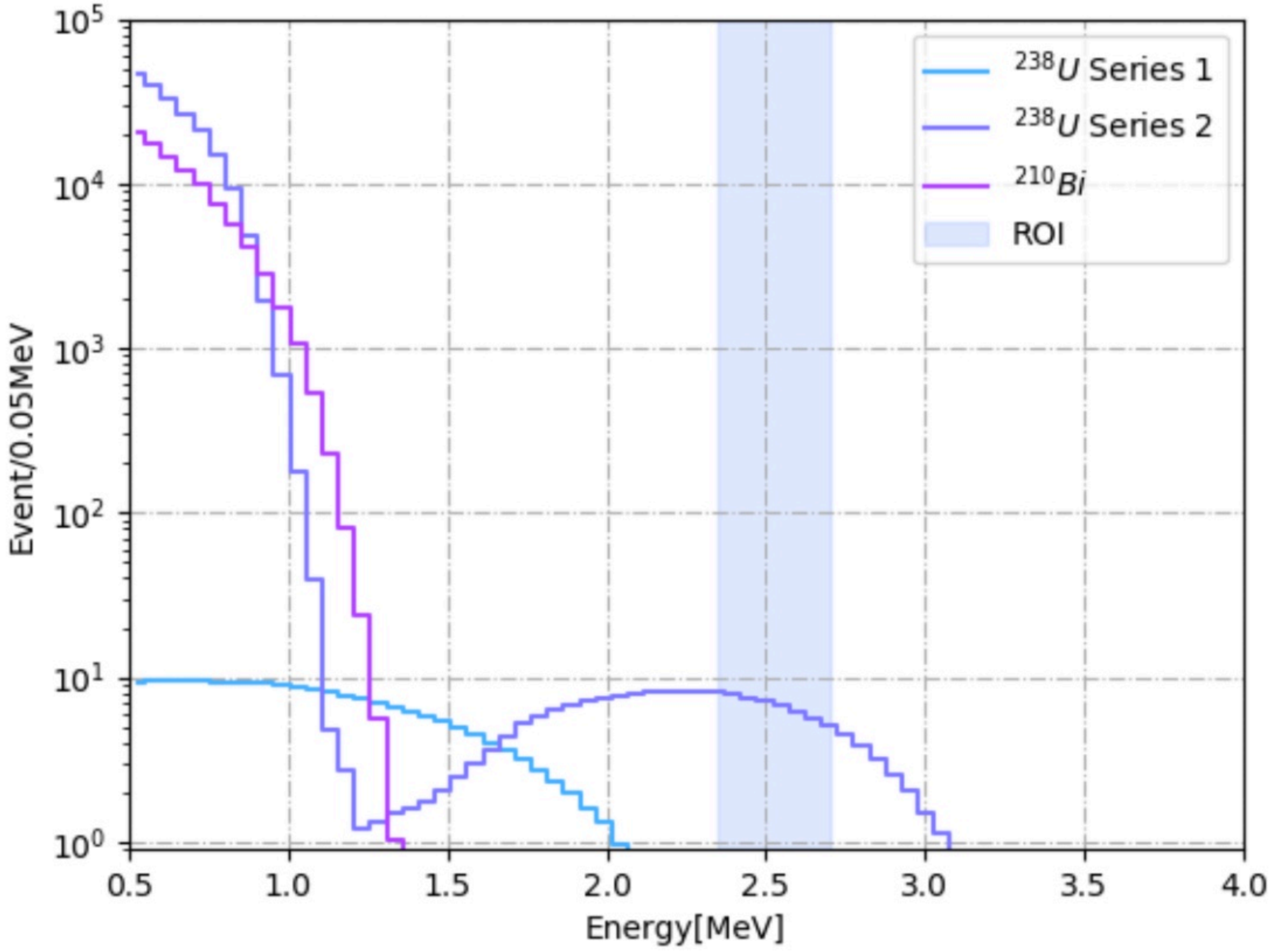
Total LiveTime: **135.1 days**
10/21/2020 - 05/08/2021

Energy calibration

Monoenergetic gamma peak from neutron capture.
Simulation/Data of XeLs and KamLS good agreement throughout detector volume.



Gaussian shape for gammas, well reproduced by MC.

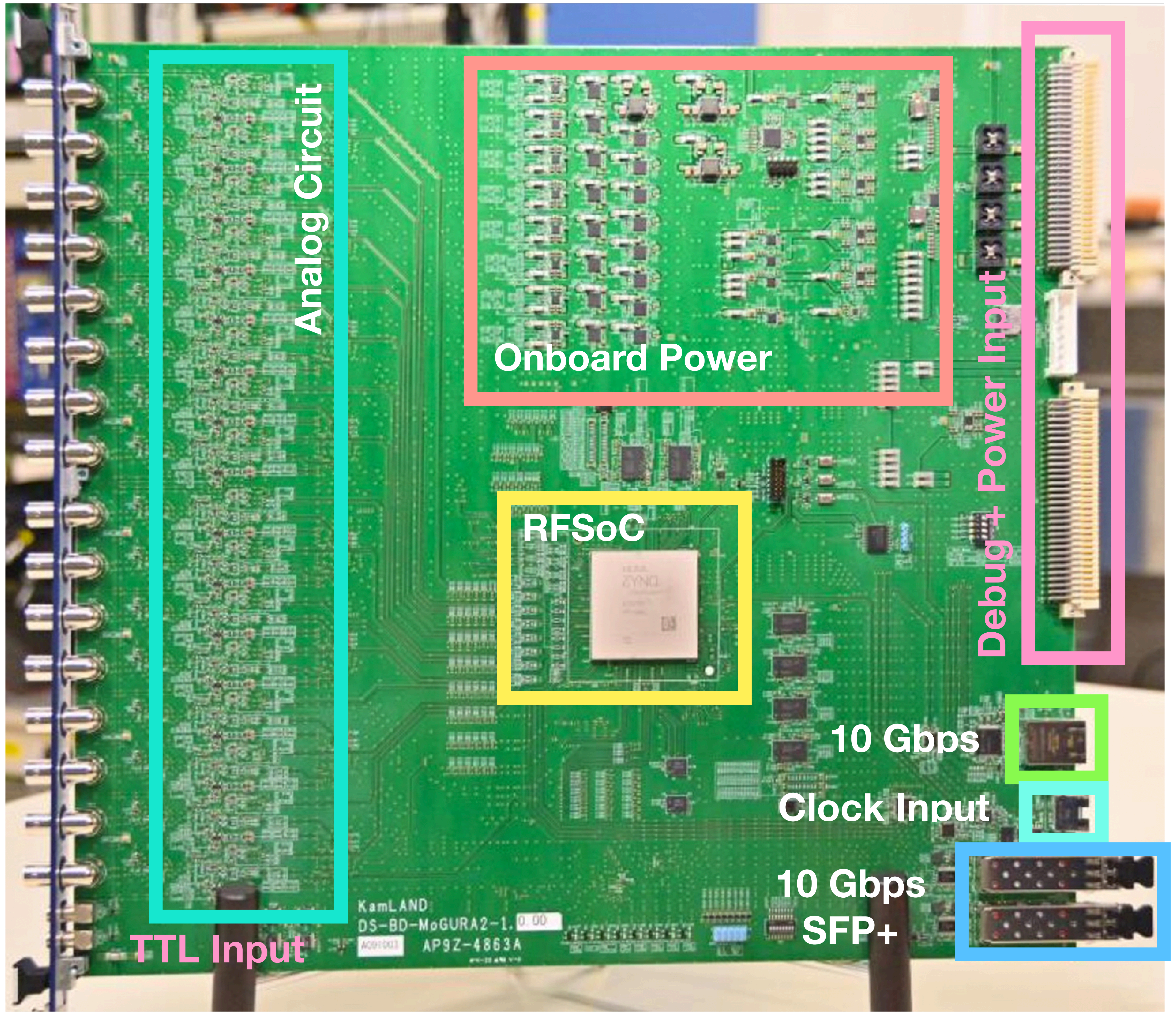


Beta decay spectrum from 214B. We monitor the high energy tail, with more statistics than the 2vBB spectrum, to search of energy scaling issues. None were observed. We'll reproduced with MC.

Results: The energy scaling uncertainty is <1%.

Electronics upgrade

16-channel prototype for KamLAND2-Zen



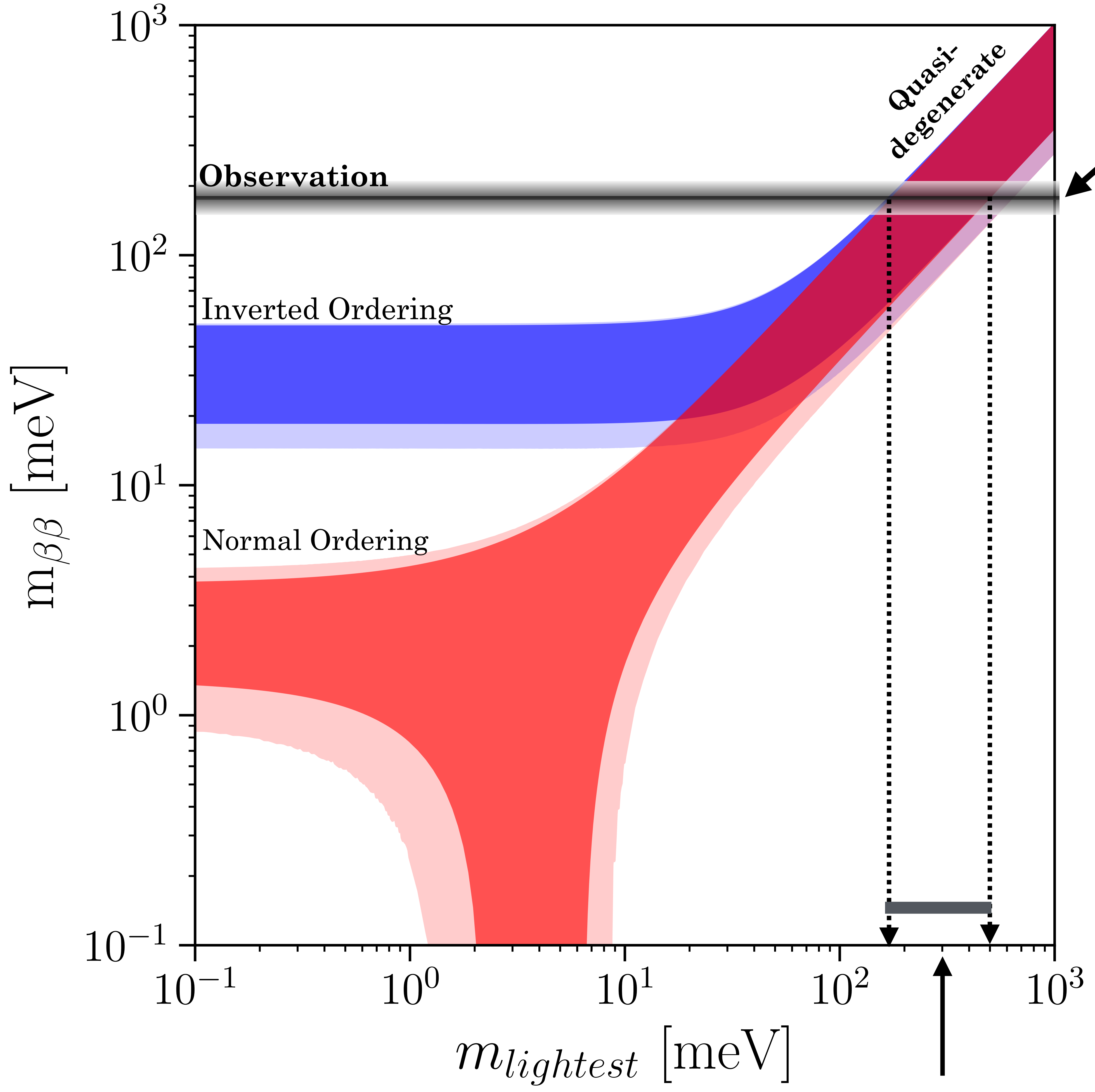
Primary Goals:

1. Digitize waveform during the chaotic period after a muon passes through the detector in order to record all neutrons, allowing us to reduce the Long-Lived spallation background.
2. Streaming data (deadtime free system), large data throughput.
3. Large memory buffers.

Reduction in PCB footprint	**Machine learning on FPGA**	***50% cost savings**	***30-40% power consumption savings**

* compared to standard RF signal chain

What to expect in the future

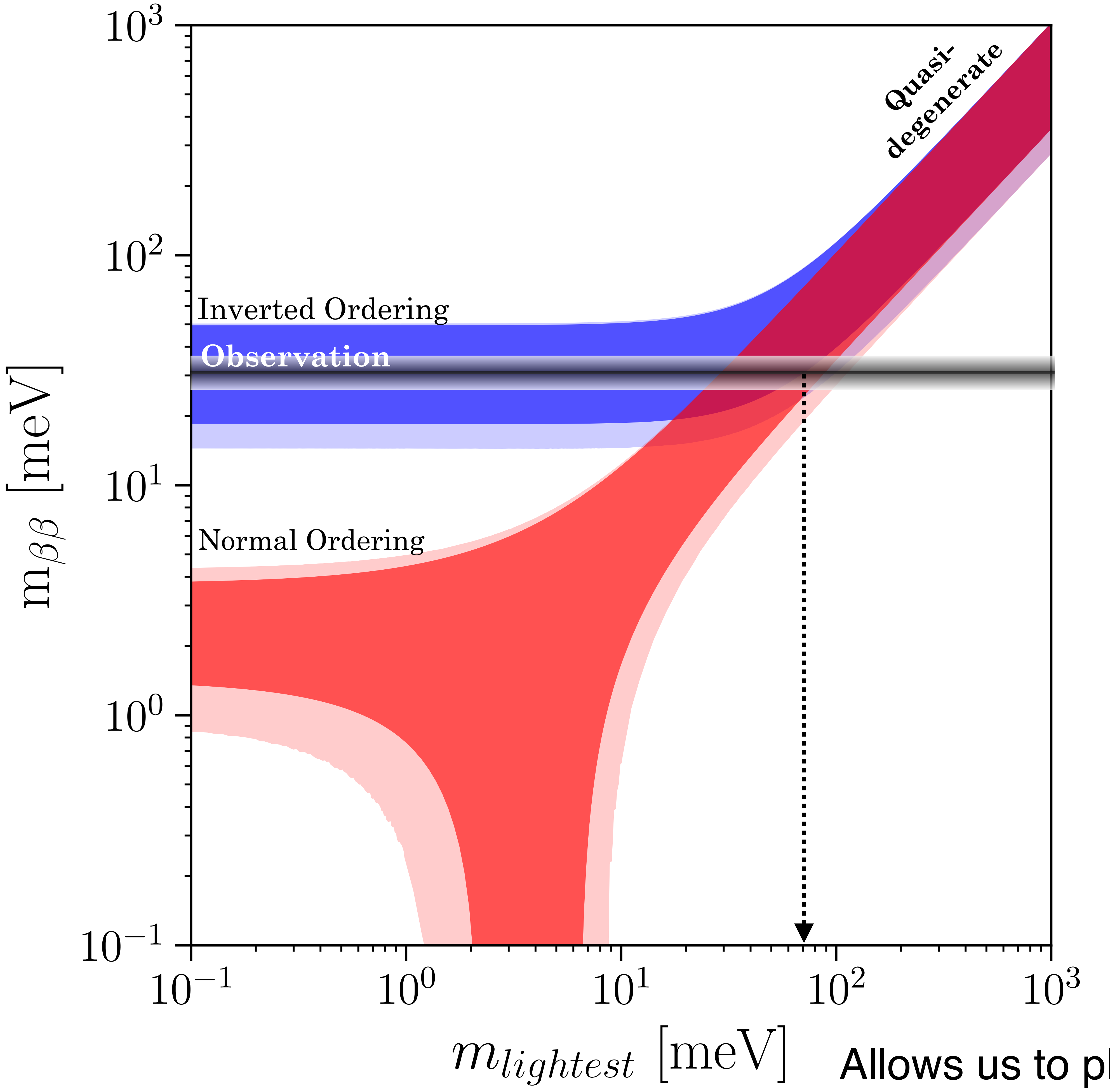


Largest uncertainty originates from the uncertainty in the nuclear structure of the isotope.

Discrepancy: would indicate other BSM physics.

Confirmation required from KATRIN; ECHo, HoLMES, Project 8, cosmology

What to expect in the future

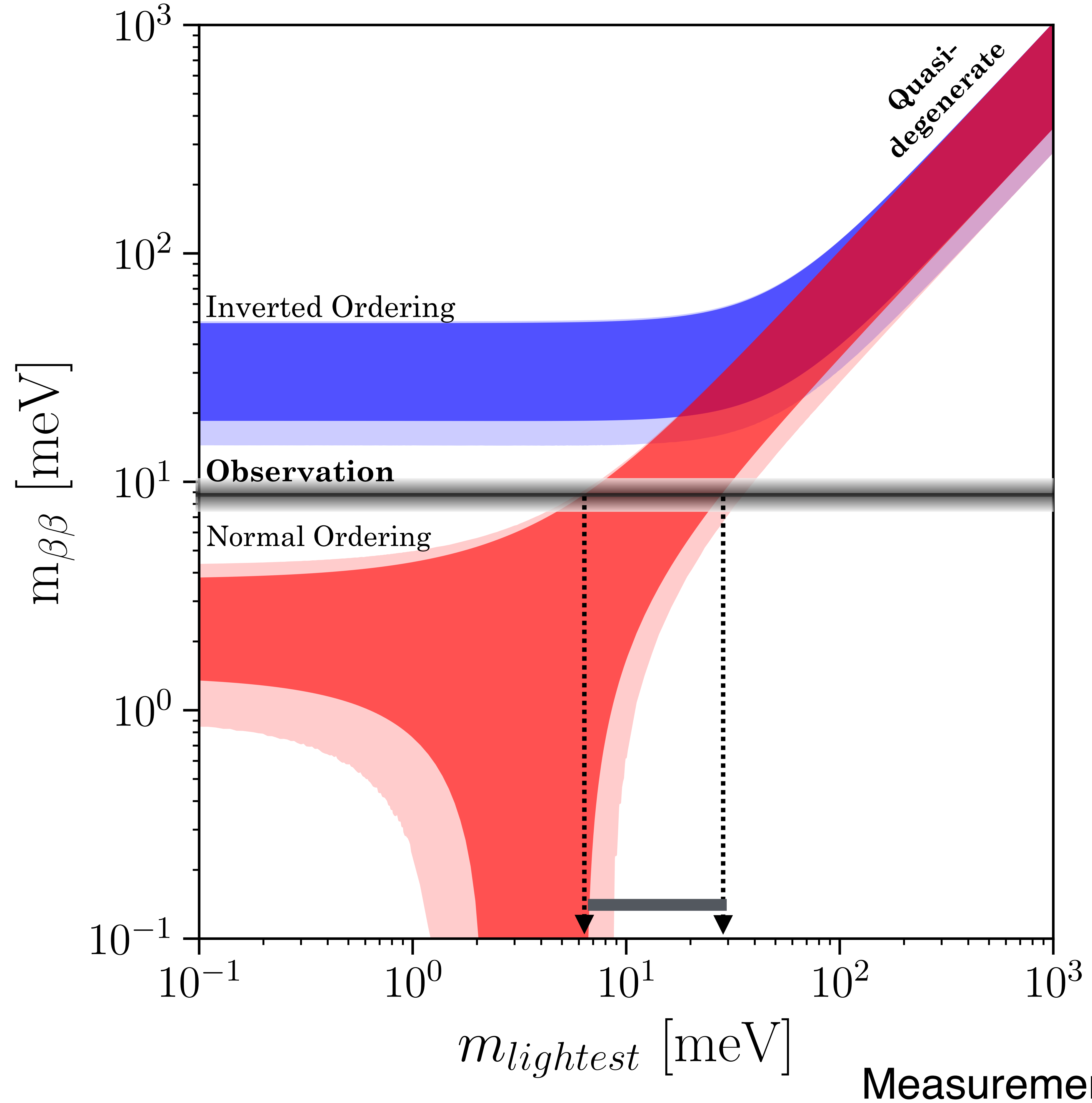


3.2σ favor for Normal Ordering (but waining)

Mass ordering from T2K + NOvA; JUNO; **PINGU**, ORCA; T2HKK, DUNE

Allows us to place a limit on the lightest neutrino mass and sum of neutrino mass.

What to expect in the future



Measurement of Mass hierarchy
Measurement of neutrino mass scale

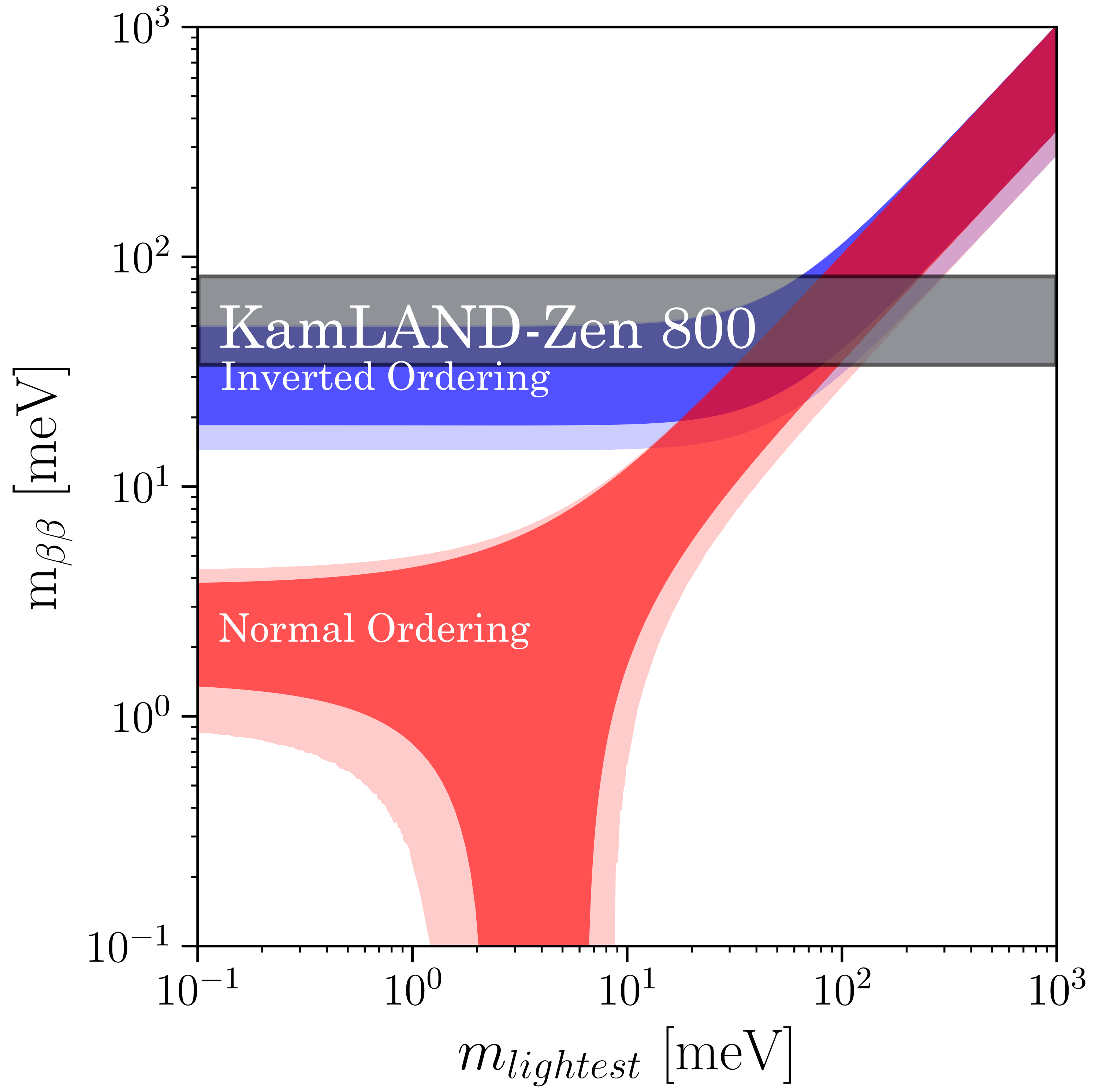
Sterile neutrinos?

Interpreting a discovery of 0νββ requires us to first solve another pressing question in neutrino physics:

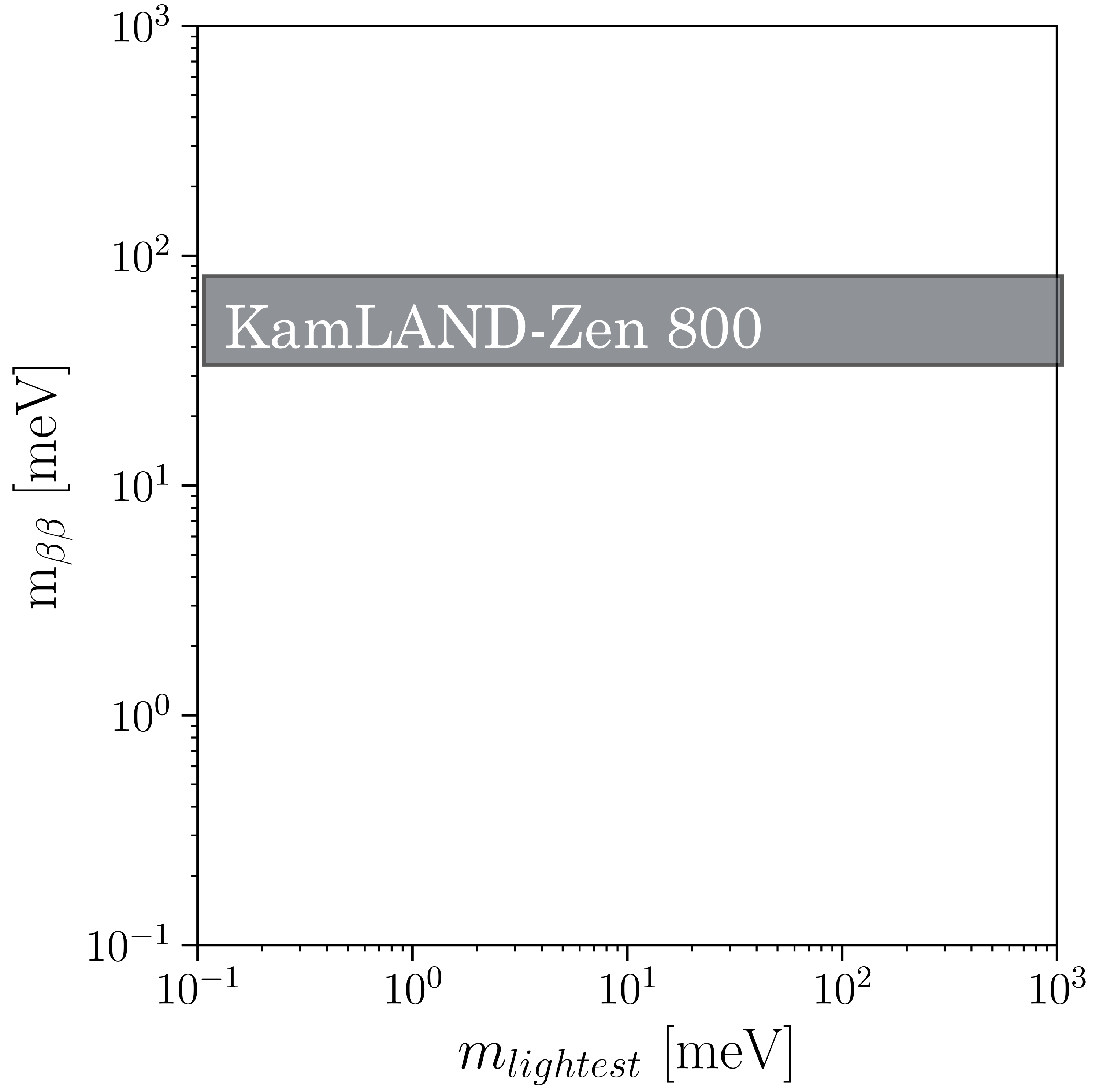
Are there additional neutrinos?

+1 Additional mass state

$$|m_{\beta\beta}^{eff}| = |U_{e1}^2 m_1 + U_{e2}^2 e^{i\alpha} m_2 + U_{e3}^2 e^{i(\alpha 2)} m_3 + U_{e4}^2 e^{i\gamma} m_4|$$

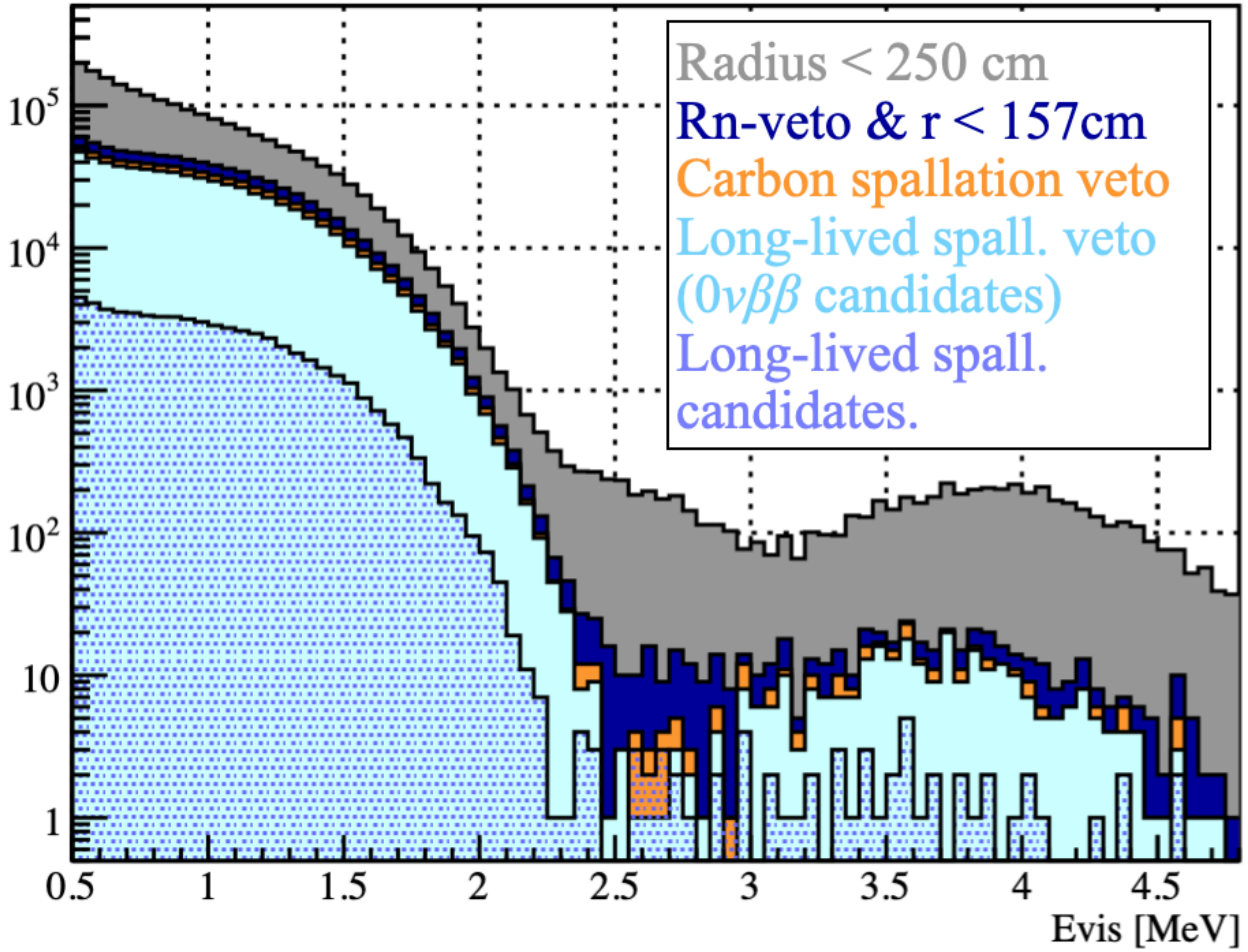


3+1 neutrinos



Fit configuration, detector uncertainties

- Xenon amount: 745±3 kg
- Xenon concentration: 3.13±0.01%
- Systematic Uncertainty in KLZ800:
  - Fiducial volume: 2.8%
  - Enrichment: 0.14%
  - Xe amount: 0.4%
  - Systematics introduced by energy response parameters during spectrum fitting



Allowable values of $m_{\beta\beta}$

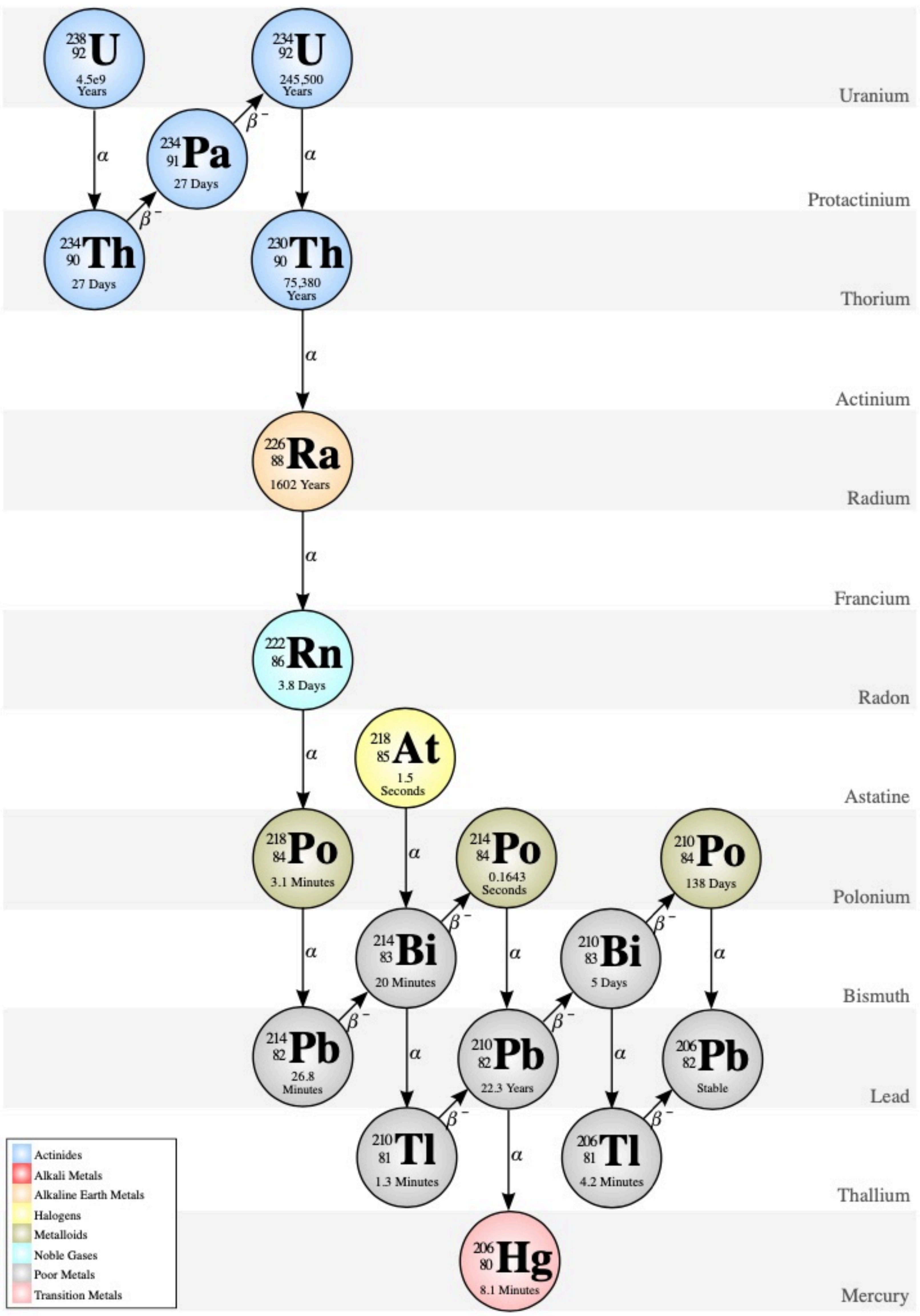
Table 9.4: Summary of the fit parameter handling
IB represents the inner-balloon, and Kam-LS is the KamLAND LS.

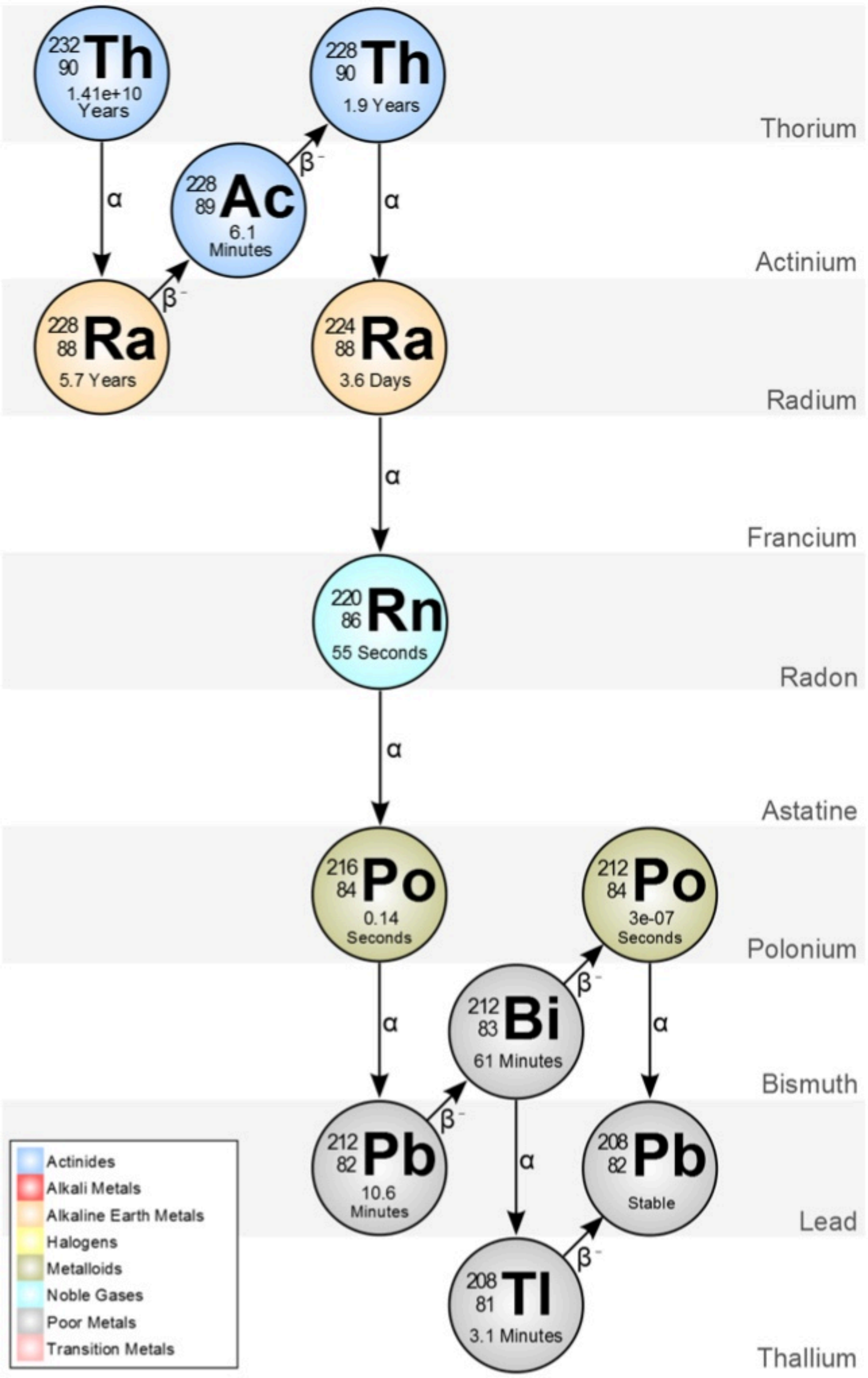
	Material source	condition(pre-fit)	condition ($0\nu\beta\beta$ scan)
^{136}Xe $0\nu\beta\beta$	Xe-LS	non	scanned
^{136}Xe $2\nu\beta\beta$	Xe-LS	floated	floated
^{238}U S1	IB	floated	fixed
^{238}U S2	Xe-LS	constrained	constrained
	IB,Kam-LS	floated	floated
^{232}Th S1	IB	floated	fixed
^{232}Th S2	Xe-LS,IB,Kam-LS	floated	fixed
^{212}Bi-^{212}Po pileup	Xe-LS,IB	floated	constrained
^{40}K	Xe-LS,IB,Kam-LS	floated	fixed
^{210}Bi	Xe-LS,IB,Kam-LS	floated	fixed
^{85}Kr	Xe-LS,Kam-LS	floated	fixed
Solar ν CC+NC	cosmogenic	fixed	fixed
^{10}C	spallation	fixed	constrained
^{11}C	spallation	constrained	constrained
^{6}He	spallation	fixed	fixed
^{8}Li	spallation	fixed	fixed
^{12}B	spallation	fixed	fixed
Long-lived	spallation	constrained	constrained
(Spectrum distortion)		constrained	constrained
^{137}Xe	^{136}Xe n-capture	fixed	constrained
Ext. γ	PMT, acrylic panel...	fixed	fixed
Energy scale(α)		constrained	constrained
Nonliniality(k_B, R)		constrained	constrained

Table 9.5: Summary of fitting results
The pre-fitting results with MIGRAD errors, best fit results, 90% C.L. results, and constraints on the parameters are shown.

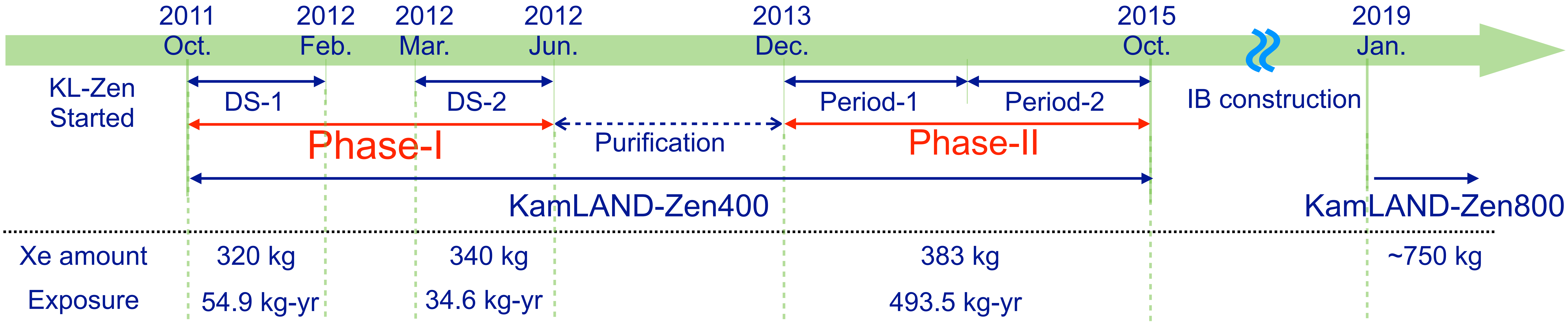
Parameter	Pre-fitting	Best fit	90% C.L.	Constraint
	Xe-LS [/day/kton]			
^{136}Xe $0\nu\beta\beta$	0(fix)	0.2	4.1	scanned
^{136}Xe $2\nu\beta\beta$	105571±338	105779	105901	free
^{238}U S2	223±38	222	222	222±38
^{232}Th S1	61±49			
^{232}Th S2	106±13	111	112	free
^{232}Th pileup	tagged to ^{232}Th S2	106	105	pre-fit±30%
^{40}K	139±179			
^{210}Bi	19517±811			
^{85}Kr	57963±1553			
Solar ν ES+CC	4.87+0.80(fixed)			
^{10}C	0.28(fixed)	0.26	0.25	$0.28^{+1.23}_{-0.33}$
^{11}C	480±80	539	541	463^{+113}_{-93}
^{6}He	0.72(fixed)			
^{8}Li	0.0(fixed)			
^{12}B	0.02(fixed)			
^{8}B	0.66(fixed)			
^{137}Xe	0.5(fixed)	0.49	0.49	0.50±0.33
Long-lived	10.0±4.0	8.04	2.50	18.2 ± 9.0
(Spectrum distortion)	0.15(σ)	0.02	-0.007	0±1
	IB [/day/IB]			
^{238}U S1	5.5±1.9			
^{238}U S2 ($z<0$, $z>0$)	4.8±0.7, 4.8±0.7	4.6, 4.7	4.5, 4.7	free
^{232}Th S1	23.3 ± 1.5			
^{232}Th S2 ($z<0$, $z>0$)	23.3±1.1, 33.5±1.9			
Pileup($z<0$, $z>0$)	tagged to ^{232}Th S2	24.3, 31.4	24.4, 31.5	pre-fit±30%
^{40}K	157±10, 122±9			
^{210}Bi	2627 ±24, 2591 ± 23			
	Kam-LS [/day/kton]			
^{238}U S2	1479.9±132			
^{232}Th S2	13.4±6.8			
^{40}K	1501±66			
^{210}Bi ($z<0$, $z>0$)	278±103, 9481±375			
^{85}Kr ($z<0$, $z>0$)	12816±544, 11723±672			
Solar ν ES	4.87(fixed)			
^{10}C	0.28(fixed)	0.40	0.41	$0.28^{+1.01}_{-0.33}$
^{11}C	568±28	561	561	463±93
^{6}He	0.72(fixed)			
^{8}Li	0.0(fixed)			
^{12}B	0.02(fixed)			
^{8}B	0.66(fixed)			
Ext. γ ($z<0$, $z>0$)	0.28, 0.69(fixed)			
α, k_B, R_C	0.991, 0.44,0.003	0.995, 0.32, 0.03	0.995, 0.31, 0.03	

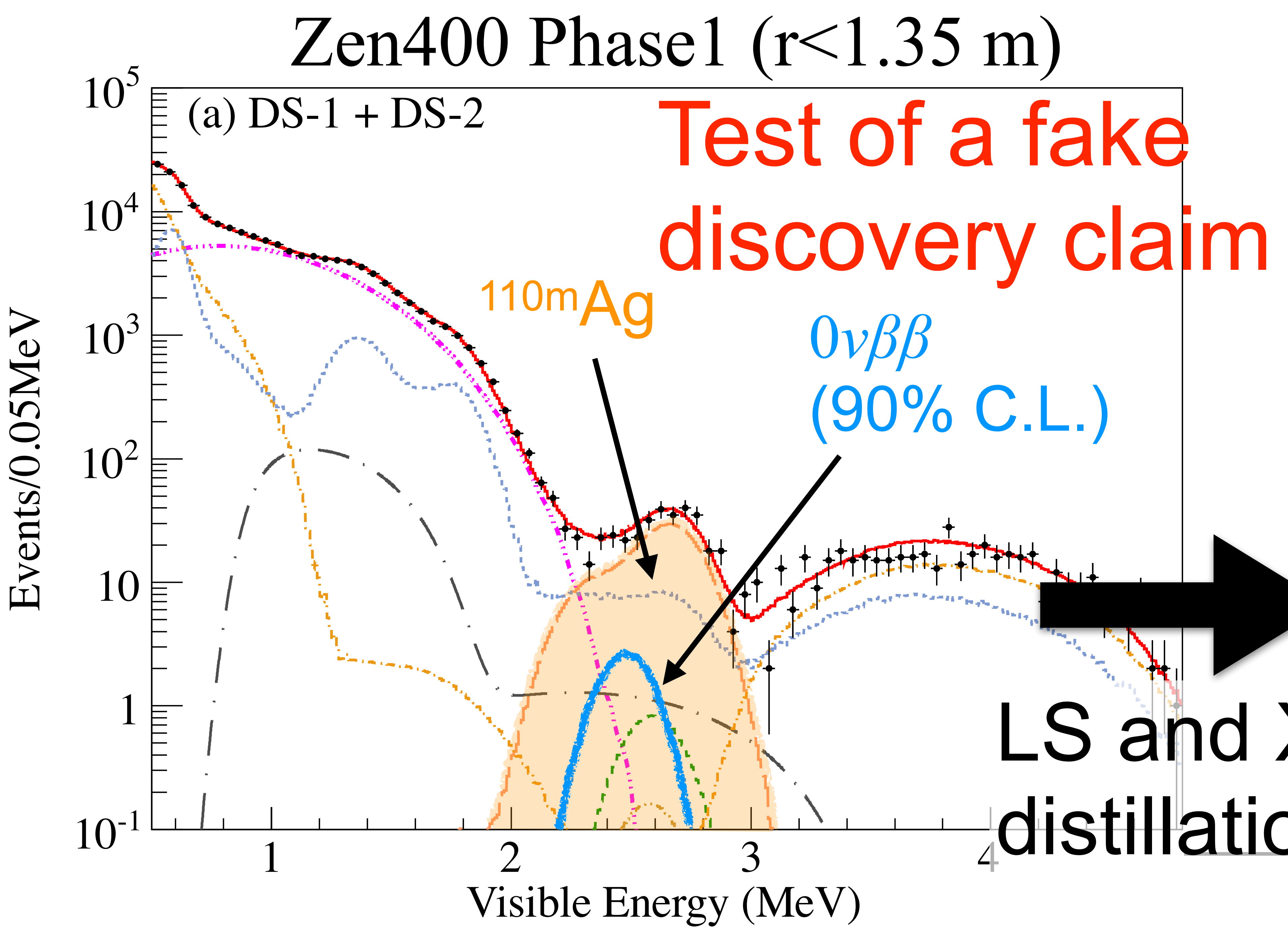
Uranium and Thorium chains



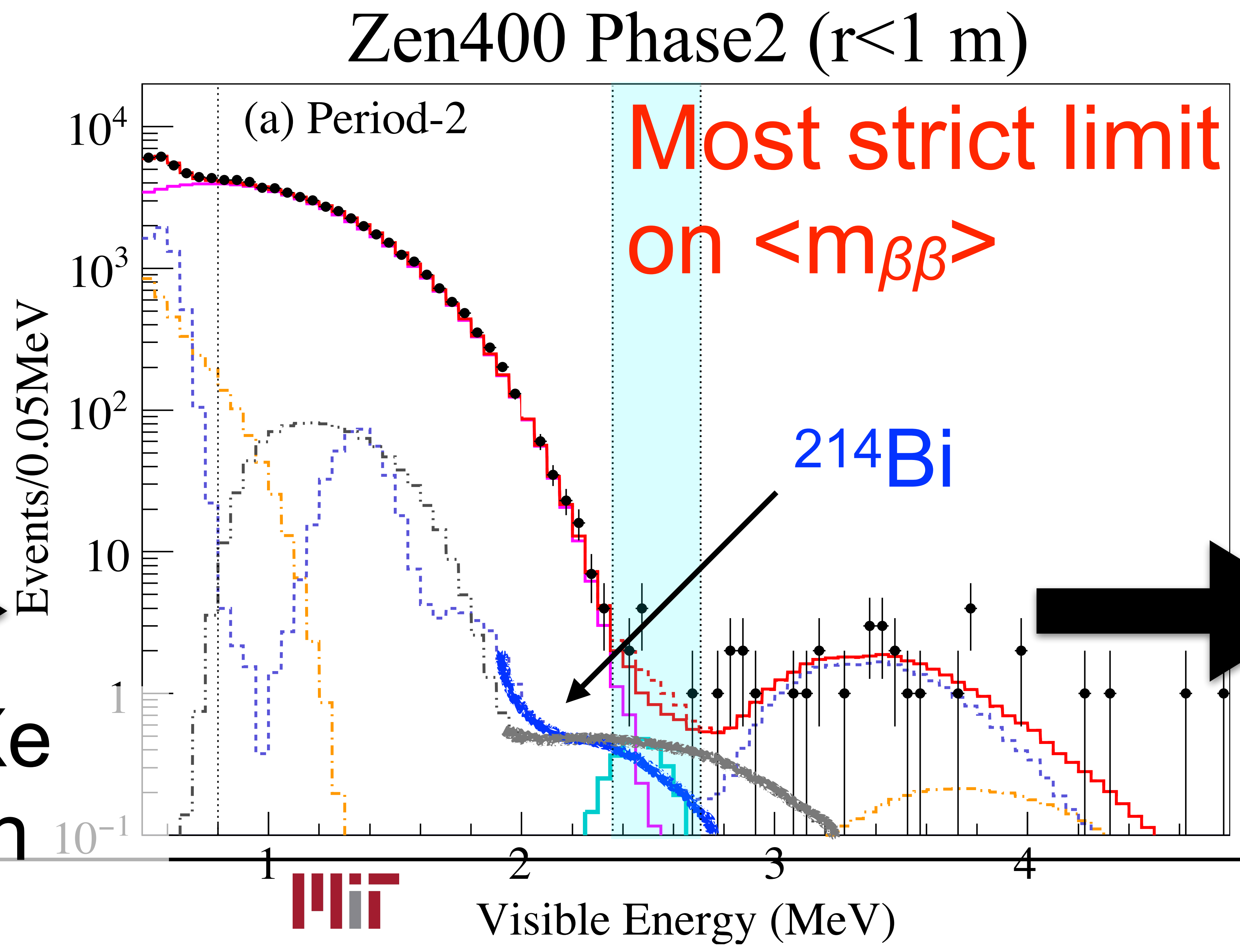


KamLAND-Zen history





LS and Xe distillation



Zen 800 :

Aim at the higher sensitivity

Discussion on Nuclear Matrix Elements

- Shell Model
  2.28, 2.45 -- J. Phys. G 45, 014003 (2018)
  1.63, 1.76 -- Phys. Rev. C 93, 024308 (2016)
  2.39 -- Phys. Rev. C 101, 044315 (2020)
- QRPA
  1.55 -- Phys. Rev. C 87, 064302 (2013)
  2.91 -- Phys. Rev. C 91, 024613 (2015)
  2.72 -- Phys. Rev. C 98, 064325 (2018)
  1.11, 1.18 -- Phys. Rev. C 97, 045503 (2018)
  3.38 -- Phys. Rev. C 102, 044303 (2020)
- EDF
  4.20 -- Phys. Rev. Lett. 105, 252503 (2010)
  4.77 -- Phys. Rev. Lett. 111, 142501 (2013)
  4.24 -- Phys. Rev. C 95, 024305 (2017)
- IBM
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