KamLAND-Zen 0ν2β Results and Status

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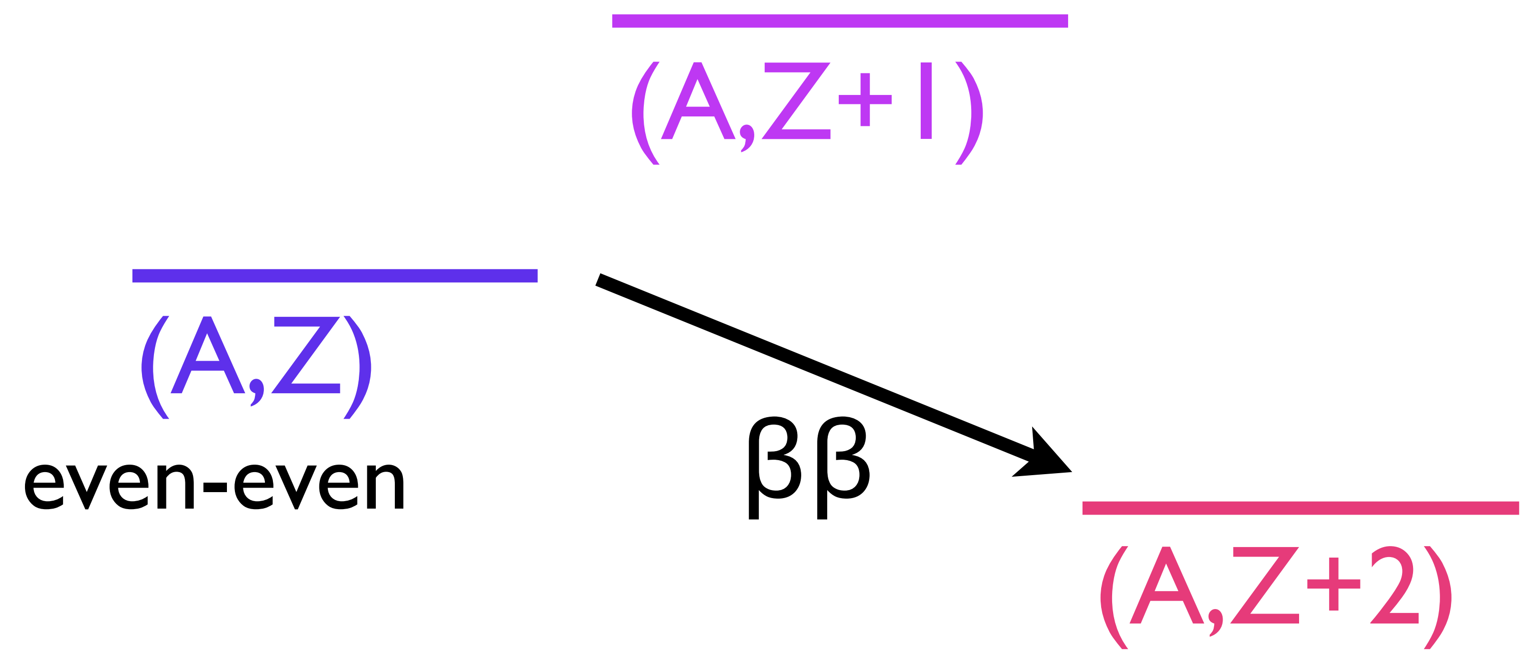
Double Beta Decay



A second-order process only detectable if first-order beta decay is energetically forbidden

Rare, but Standard Model Process:

$$2\nu2\beta : (A, Z) \rightarrow (A, Z+2) + e^- + e^- + \overline{\nu}_e + \overline{\nu}_e$$

^{136}Xe

^{76}Ge

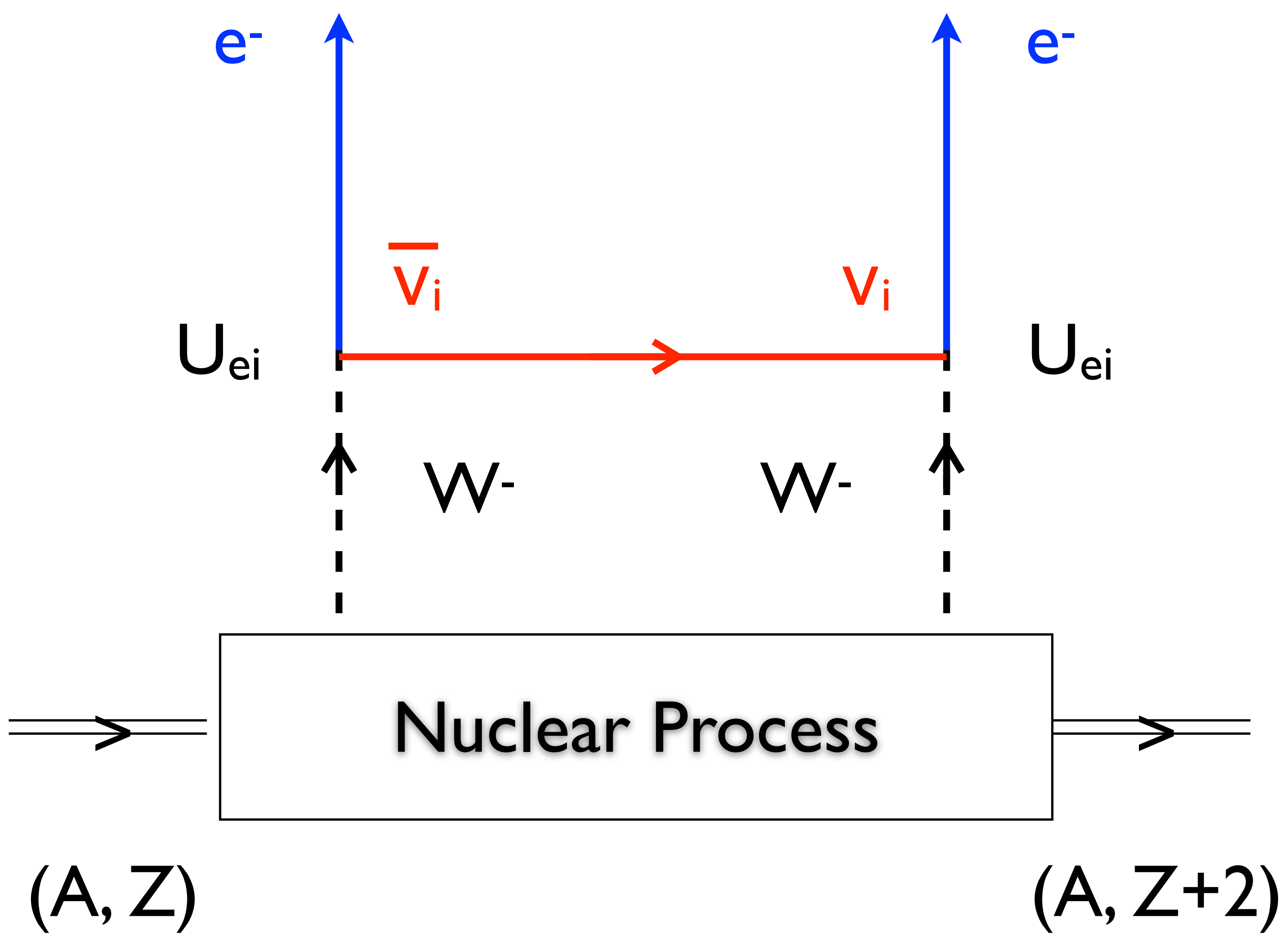
^{82}Se

^{100}Mo

^{130}Te

…

Neutrinoless Double Beta Decay



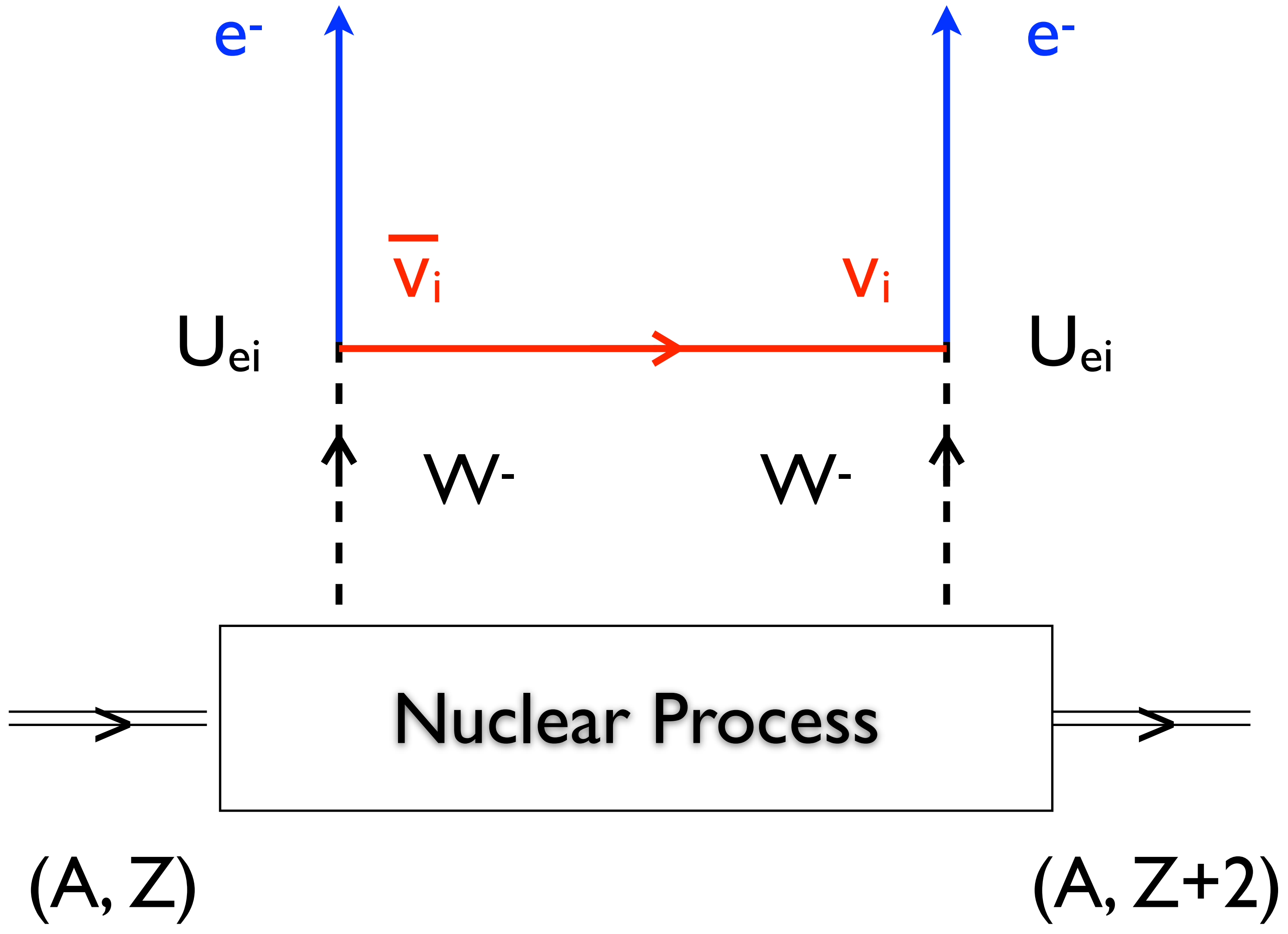
But what if ν is Majorana?

$$M_\nu \neq 0$$
$$|\Delta L| = 2$$

$$0\nu 2\beta : (A,Z) \rightarrow (A, Z+2) + e^- + e^-$$

- Extremely rare process [W.H. Furry (1939): $T_{1/2} > 10^{16}$ yr]
- Requires massive Majorana neutrino
- Lepton Number Violation
  - Model dependent - Standard interpretation: light Majorana ν + SM interactions

Neutrinoless Double Beta Decay



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$$0\nu2\beta: (A, Z) \rightarrow (A, Z+2) + e^- + e^-$$

PHYSICAL REVIEW D VOLUME 25, NUMBER 11 1 JUNE 1982

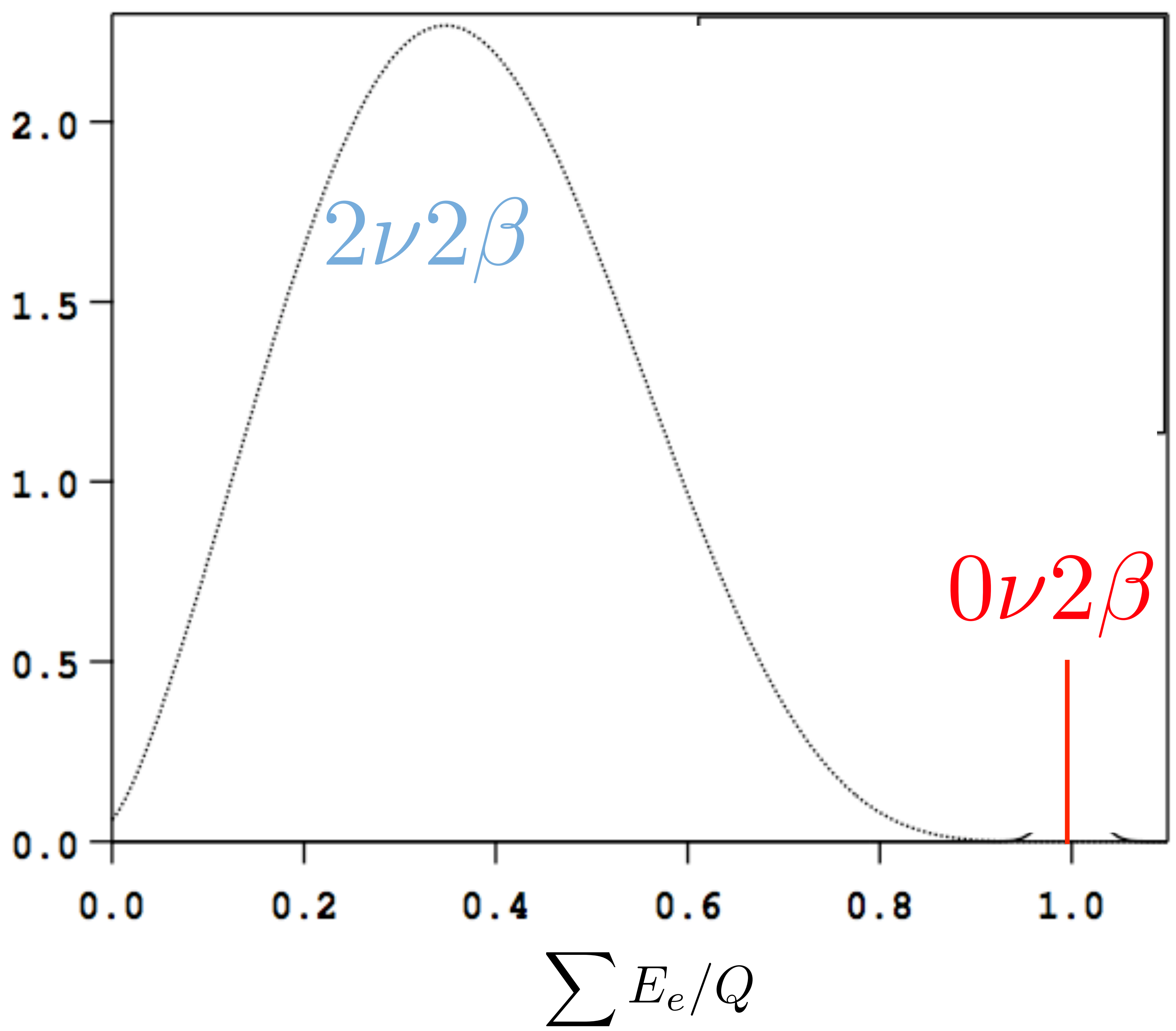
Neutrinoless double-β decay in SU(2)×U(1) theories

J. Schechter and J. W. F. Valle
Department of Physics, Syracuse University, Syracuse, New York 13210
(Received 14 December 1981)

It is shown that gauge theories give contributions to neutrinoless double-β decay [$(\beta\beta)_{0\nu}$] which are not covered by the standard parametrizations. While probably small, their existence raises the question of whether the observation of $(\beta\beta)_{0\nu}$ implies the existence of a Majorana mass term for the neutrino. For a "natural" gauge theory we argue that this is indeed the case.

Detecting 0ν2β Decay

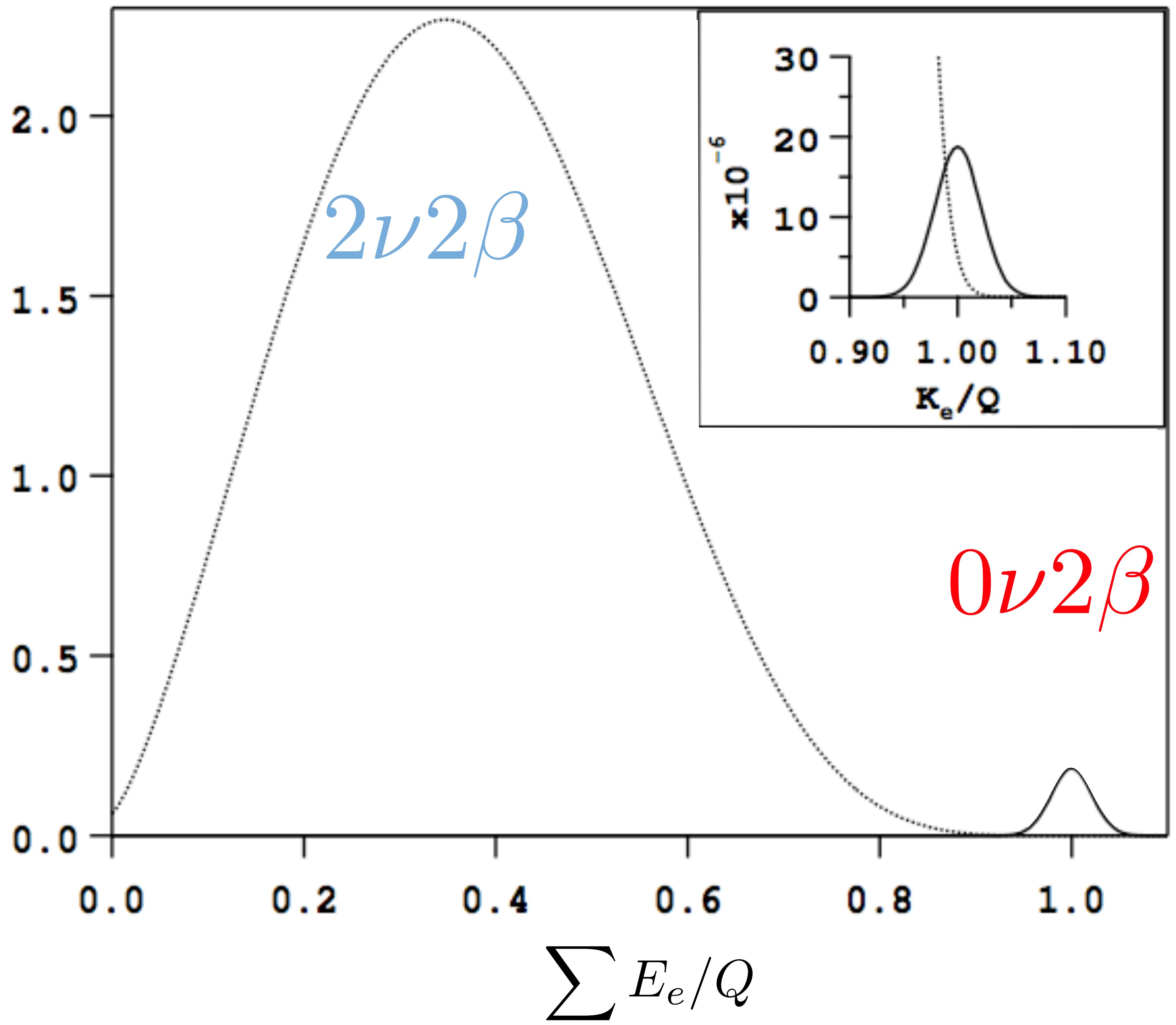
Without energy resolution



In ^{136}Xe:
$Q_{\beta\beta}$=2.458 MeV

Detecting 0ν2β Decay

With energy resolution



In ^{136}Xe:

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

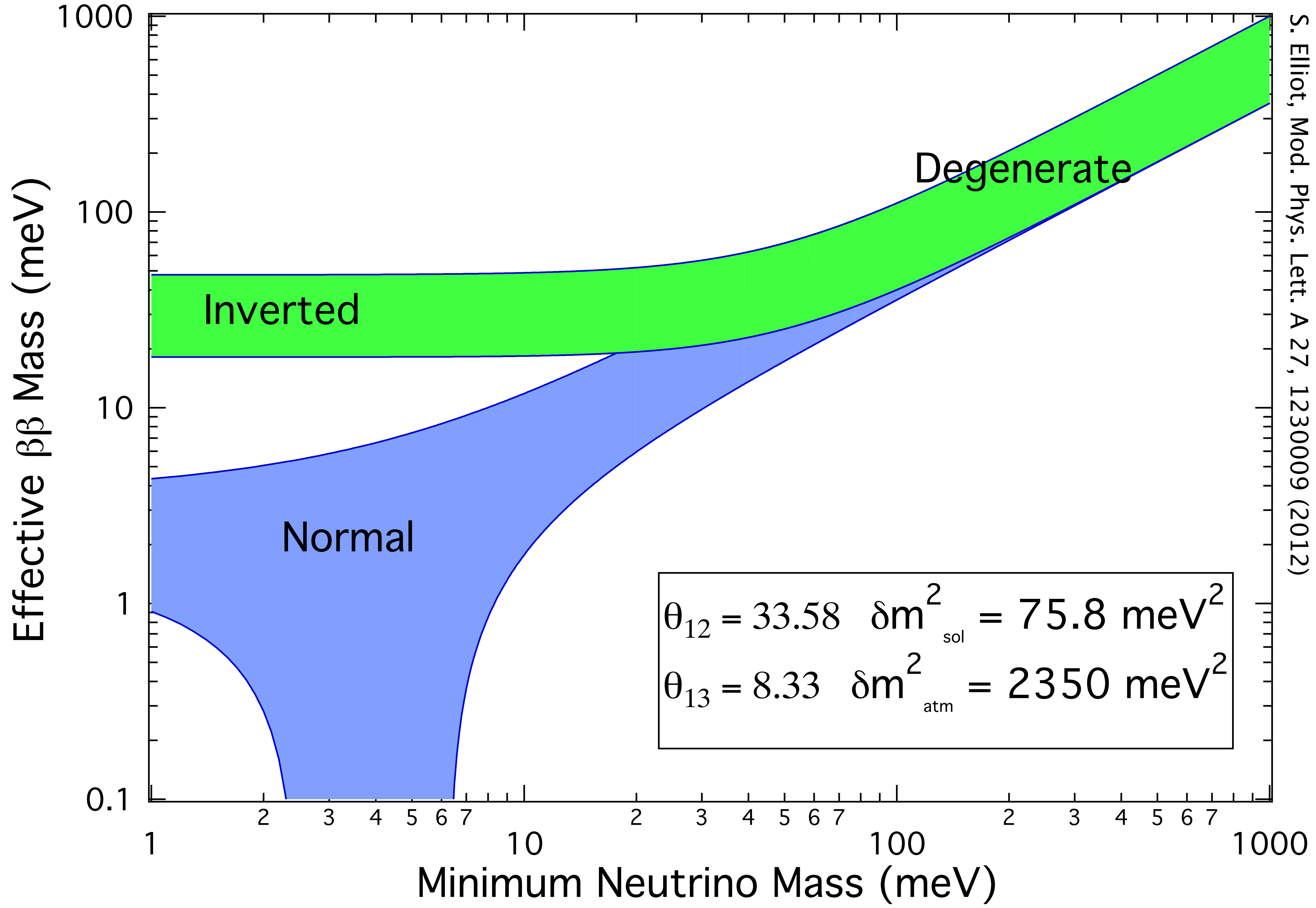
What mass does 0ν2β measure?

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q,Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

Phase Space factor: Calculable

Nuclear Matrix Element: Hard to calculate

Effective Majorana mass: $\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$ [coherent sum]



S. Elliot, Mod. Phys. Lett. A 27, 1230009 (2012)

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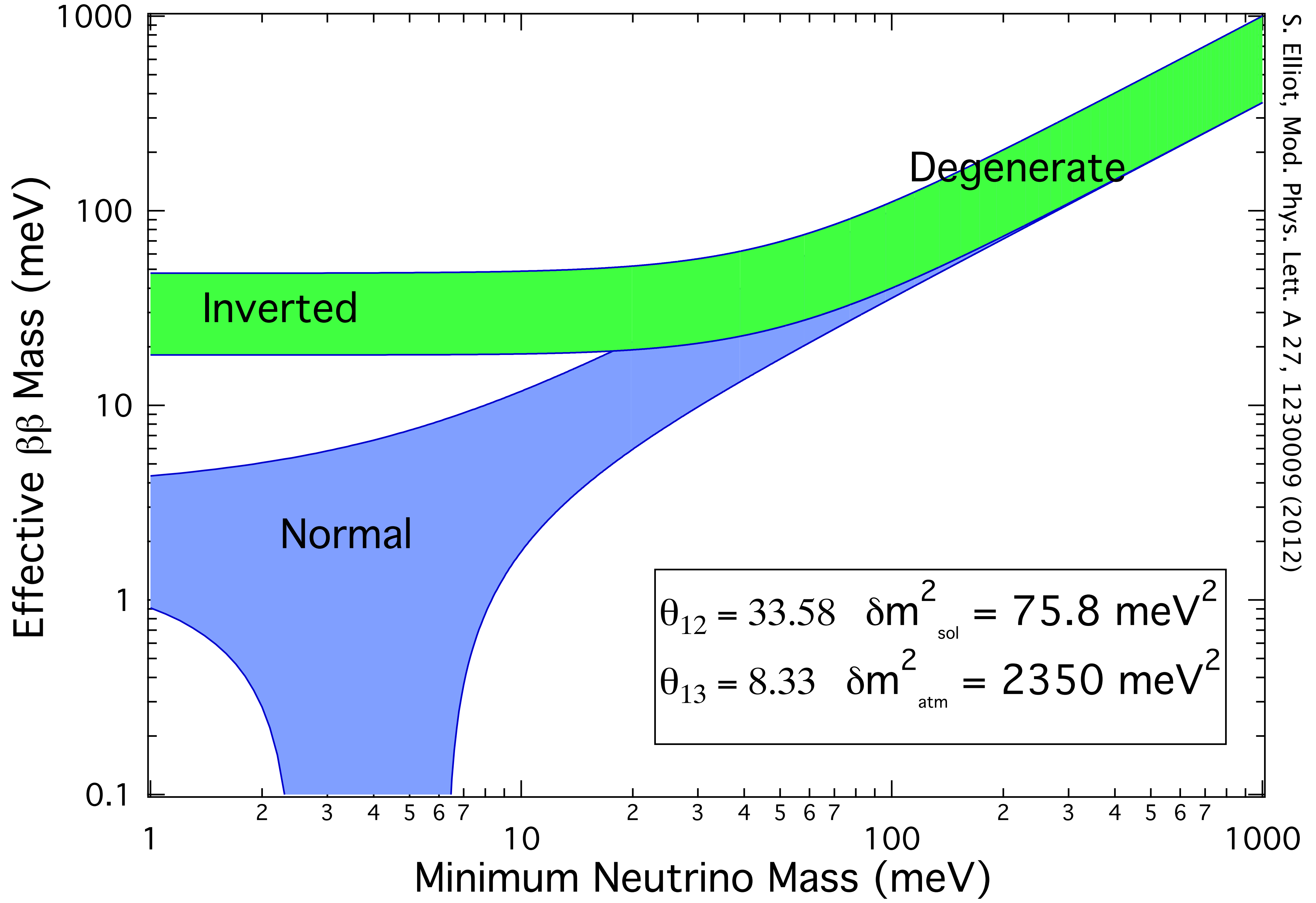
Phase Space factor: Calculable

Nuclear Matrix Element: Hard to calculate

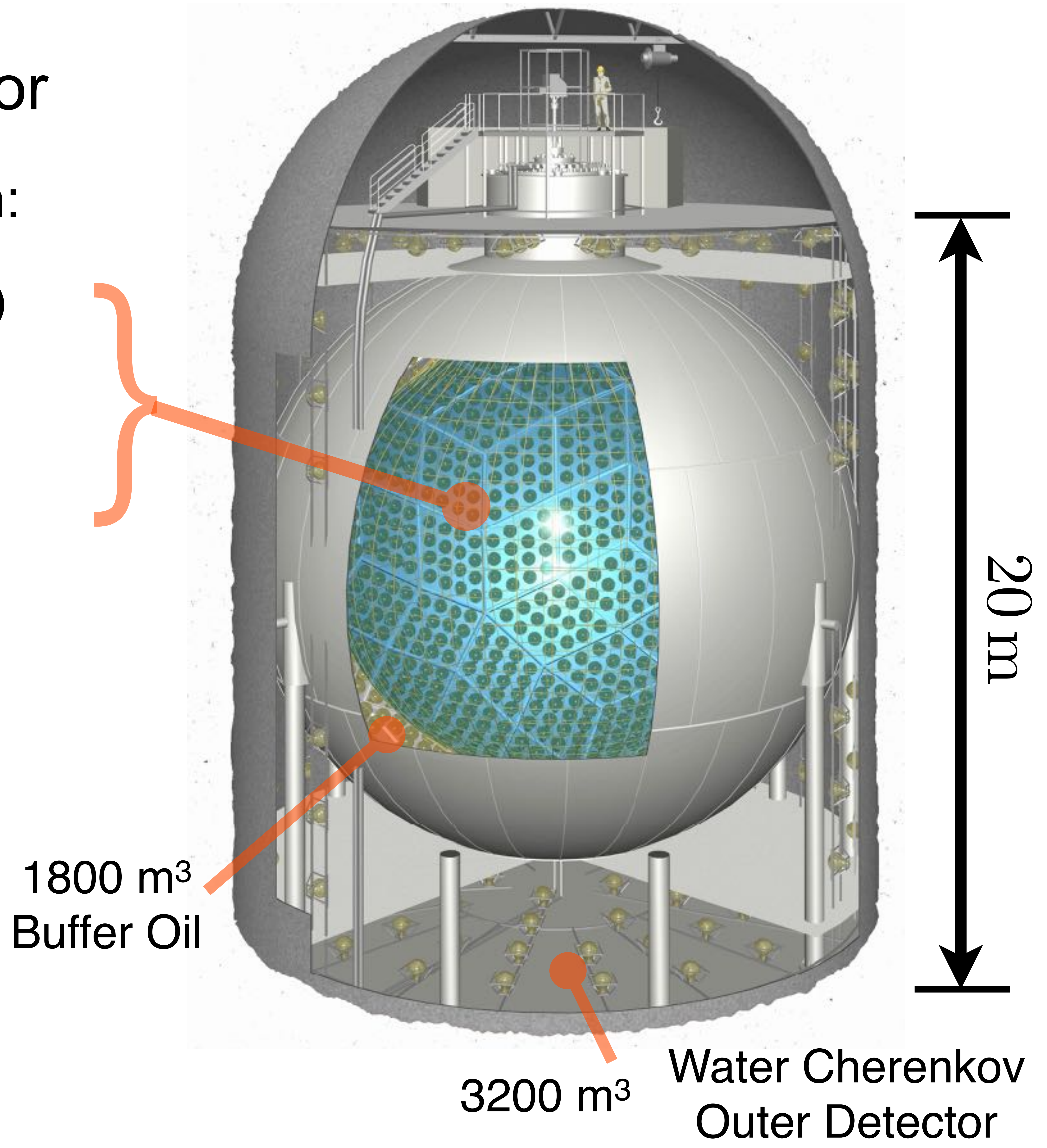
Interesting physics

Effective Majorana mass: $\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$ [coherent sum]



KamLAND(-Zen) detector

- 1 kton Scintillation Detector
  - 6.5m radius balloon filled with:
    - 20% Pseudocumene (scintillator)
    - 80% Dodecane (oil)
    - PPO
- 34% PMT coverage
  - ~1300 17" fast PMTs
  - ~550 20" large PMTs
- Water Cherenkov veto



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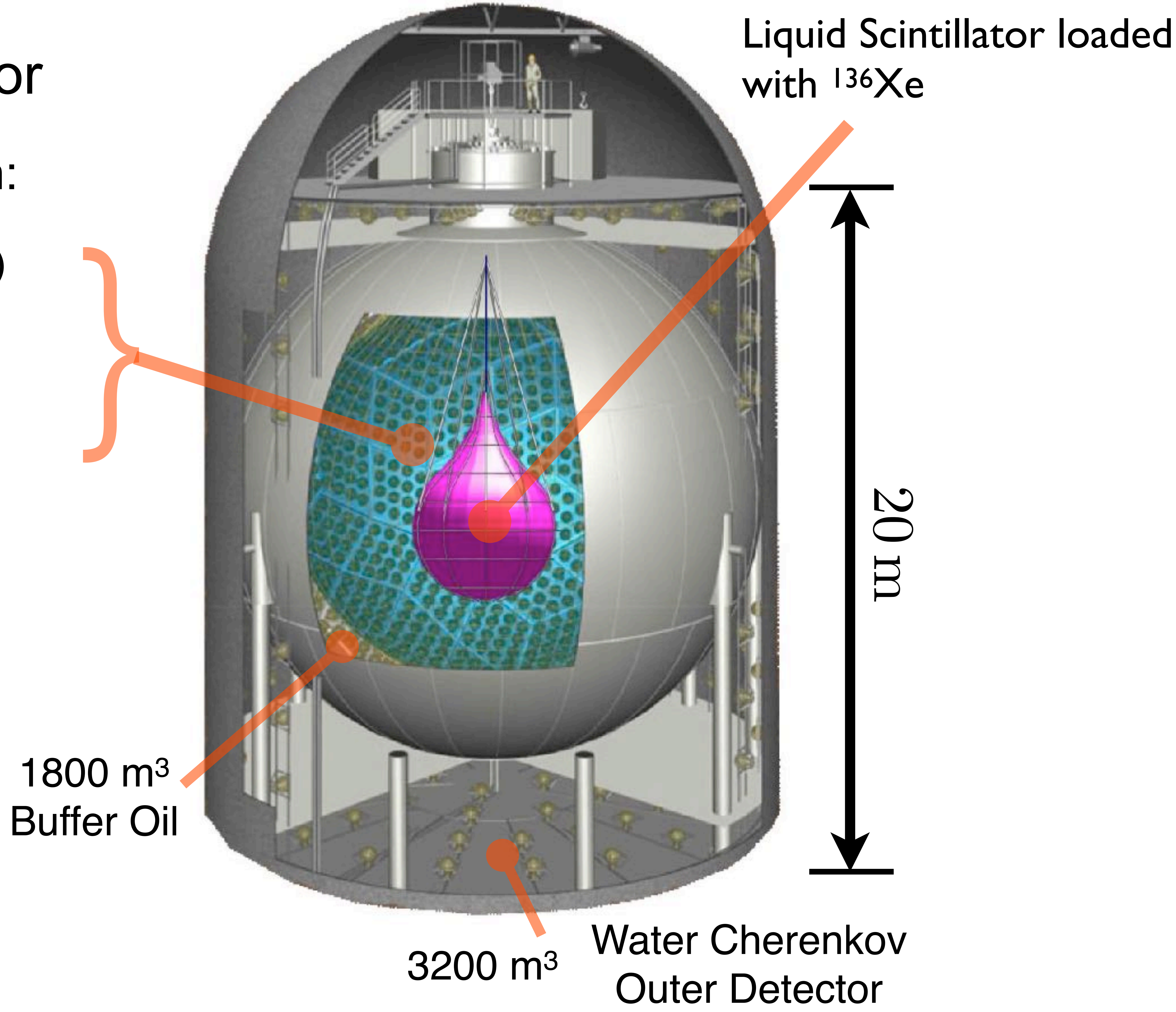
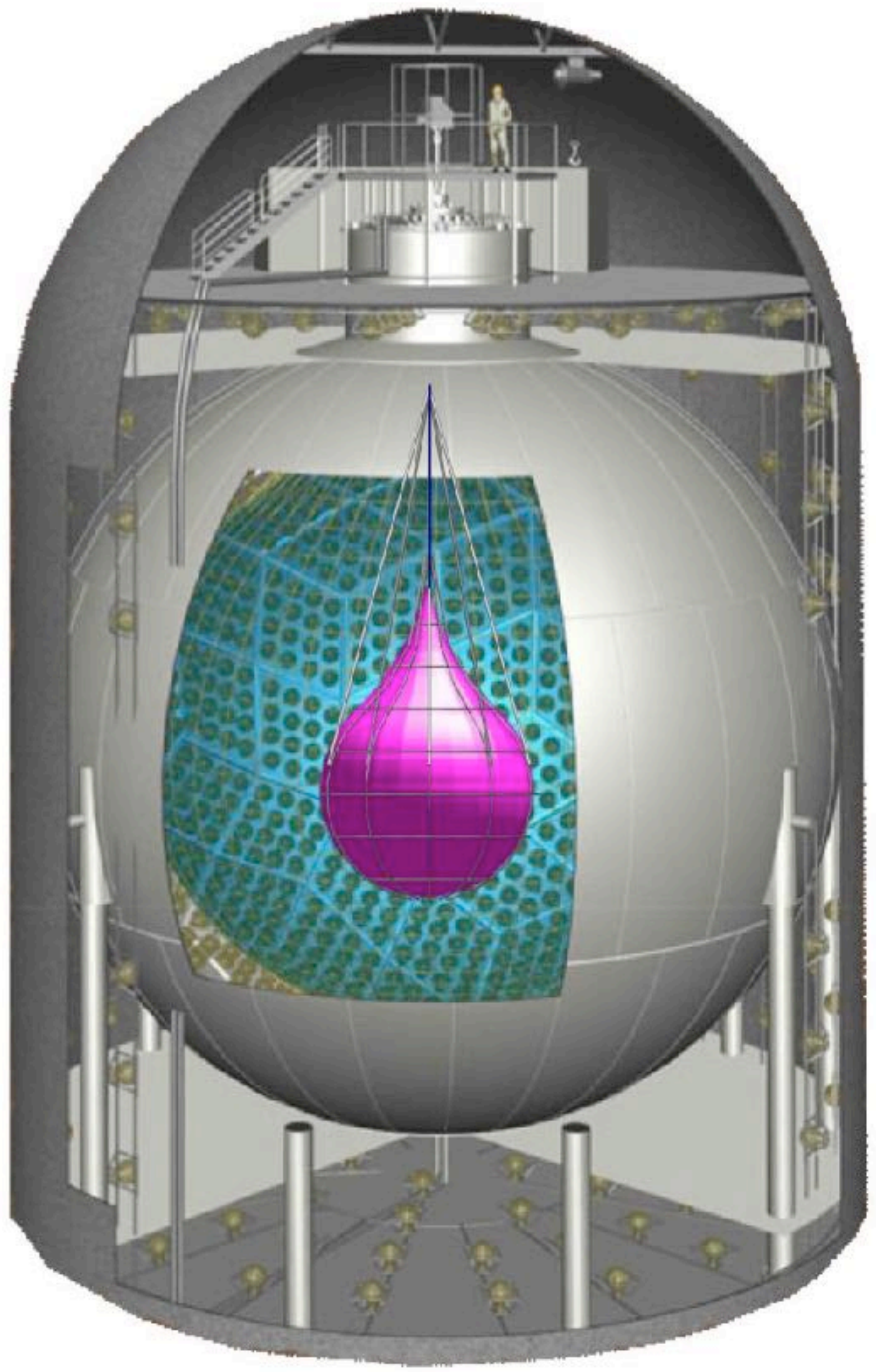


KamLAND-Zen advantages & disadvantages

- +Well-understood detector
- +Highly pure, self-shielding environment
- +Large ββ source mass, scalable
- -Relatively poor energy resolution
- -No particle identification

$$T^{0\nu}_{1/2} \propto \epsilon \frac{a}{A}\sqrt{\frac{Mt}{b\Delta E}}$$

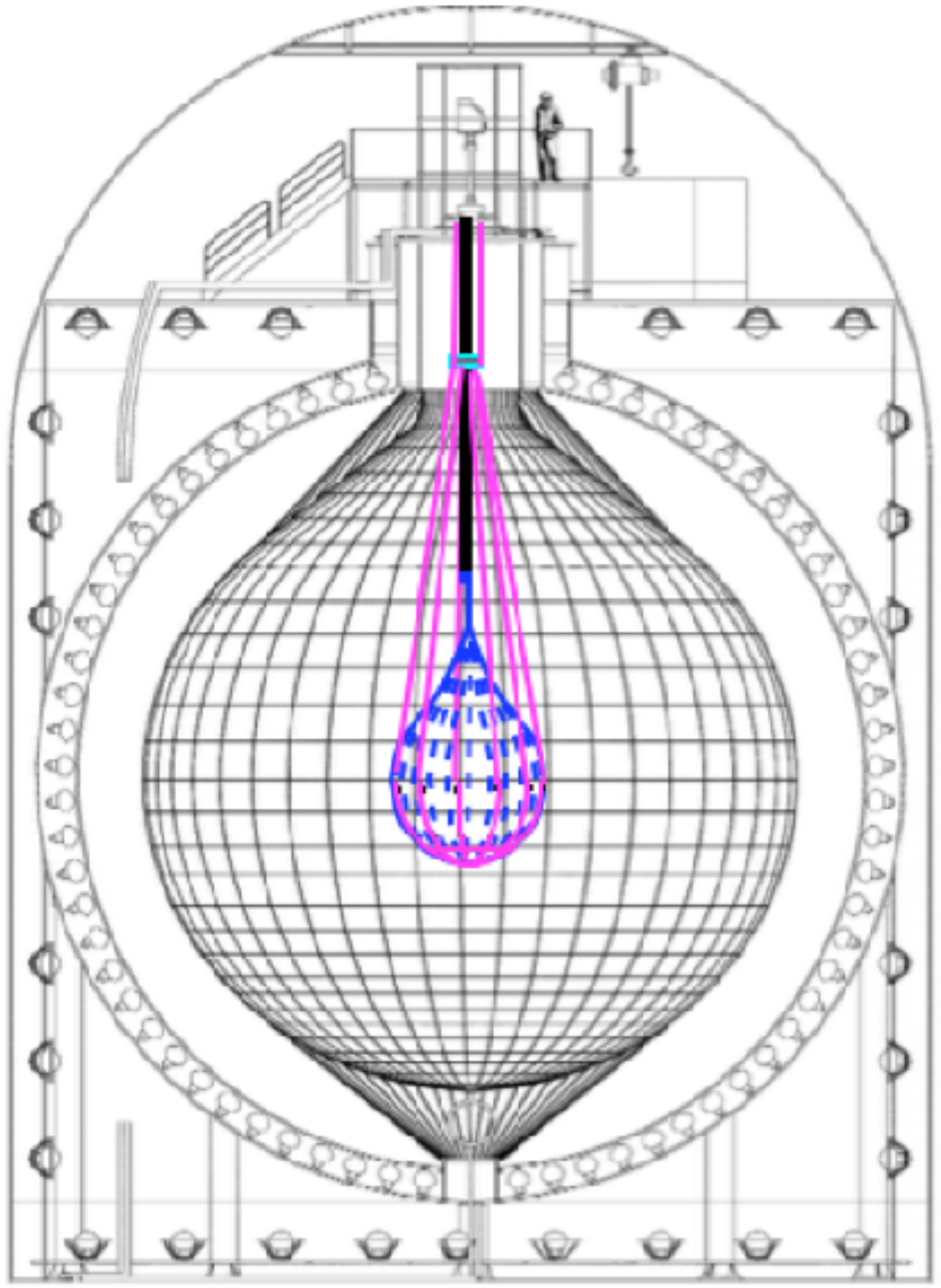


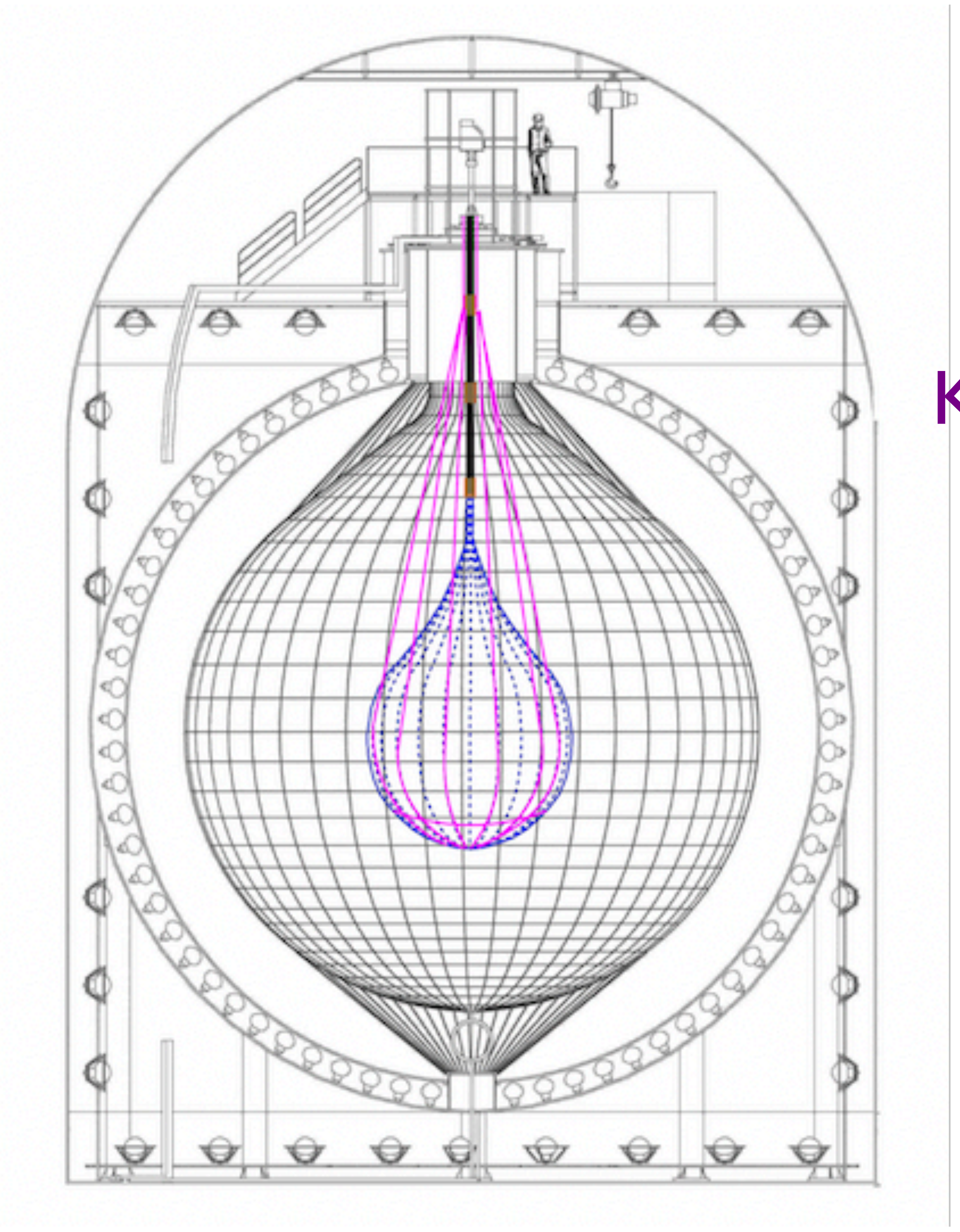
KLZ 400 & KLZ 800

2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021

Phase I | No Xe | KLZ 400 - Phase II | No Xe | ~~New balloon~~ | No Xe | New balloon | KLZ 800

90 kg-yr





KamLAND-Zen 400

- Mini-balloon radius 1.54m
- 320 - 380kg ^{136}Xe
- 2011 - 2015

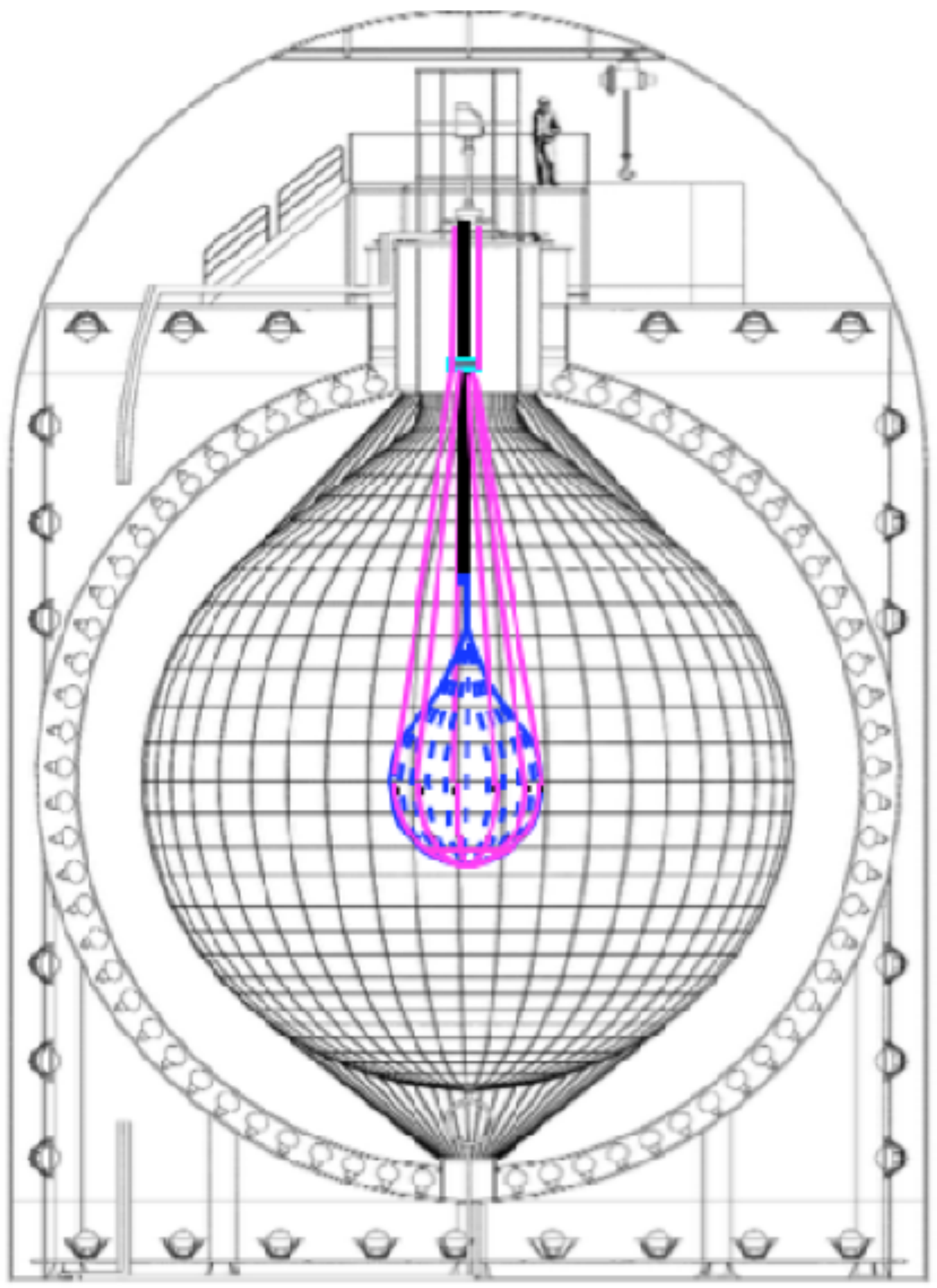
KamLAND-Zen 800

- Mini-balloon radius 1.90m
- 745kg ^{136}Xe
- Start Jan'19

KLZ 400 & KLZ 800

2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021

Phase I	No Xe	KLZ 400 - Phase II	No Xe	~~New balloon~~	No Xe	New balloon	KLZ 800
90 kg-yr	purification	504 kg-yr					Start Jan'19



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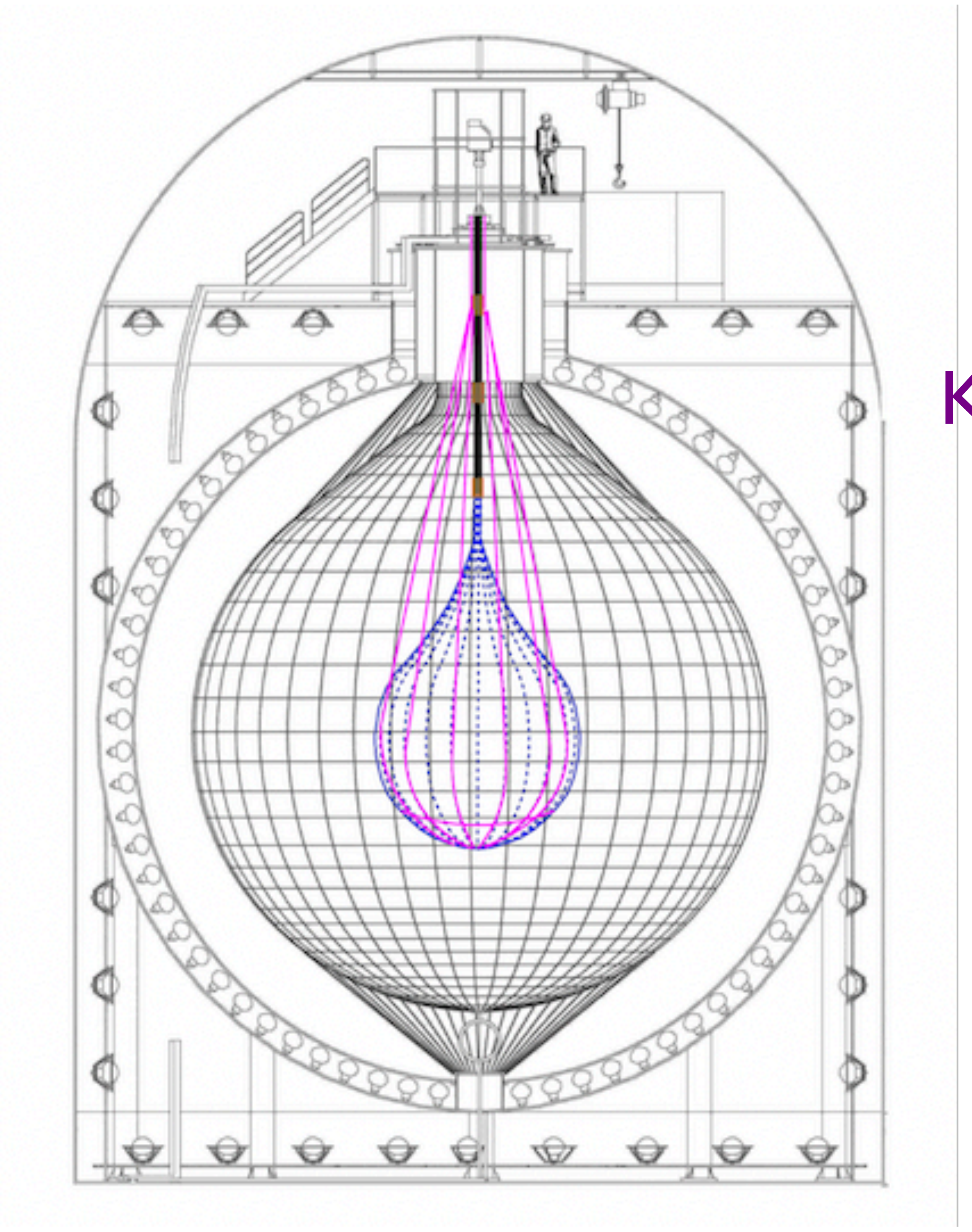
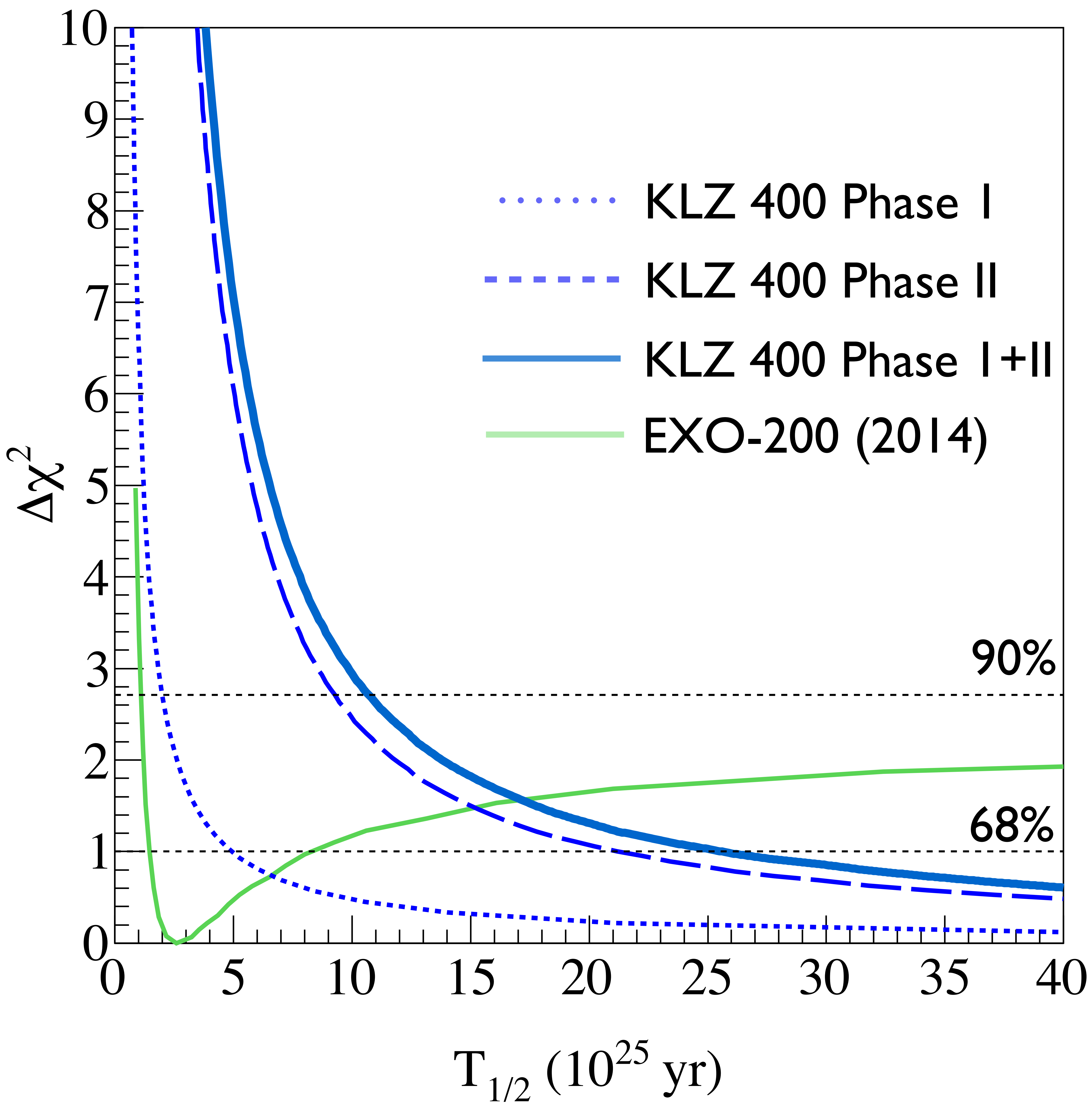


KamLAND-Zen 800

- Mini-balloon radius 1.90m
- 745kg ^{136}Xe
- Start Jan'19

^{136}Xe 0ν2β Decay Half-life



KLZ Phase I:

$T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr — 90 kg-yr

KLZ Phase II:

$T^{0\nu}_{1/2} > 9.2 \times 10^{25}$ yr — 504 kg-yr

[Sens: > 5.6×10^{25} yr]

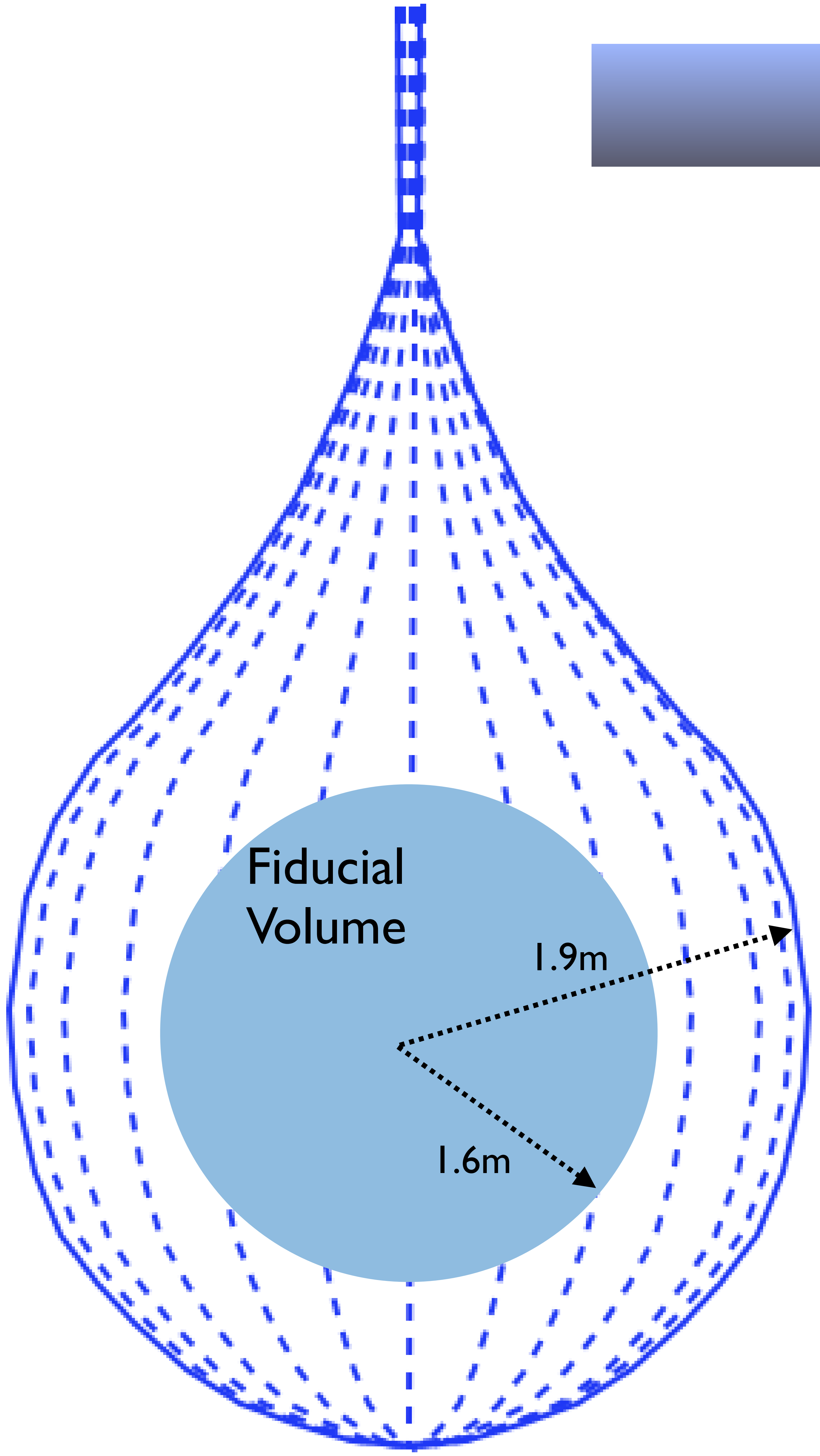
KLZ Phase I+II:

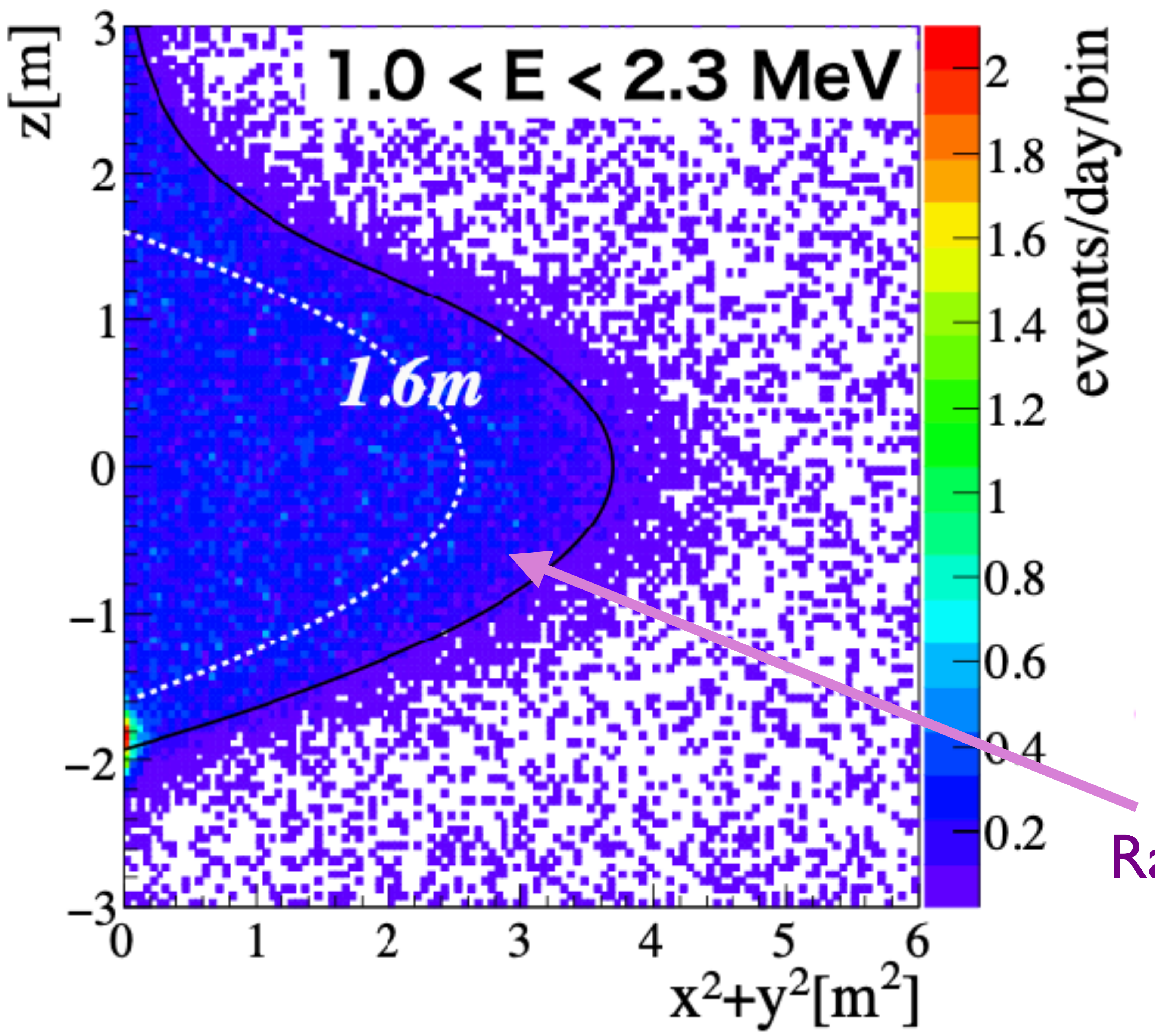
$T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ yr

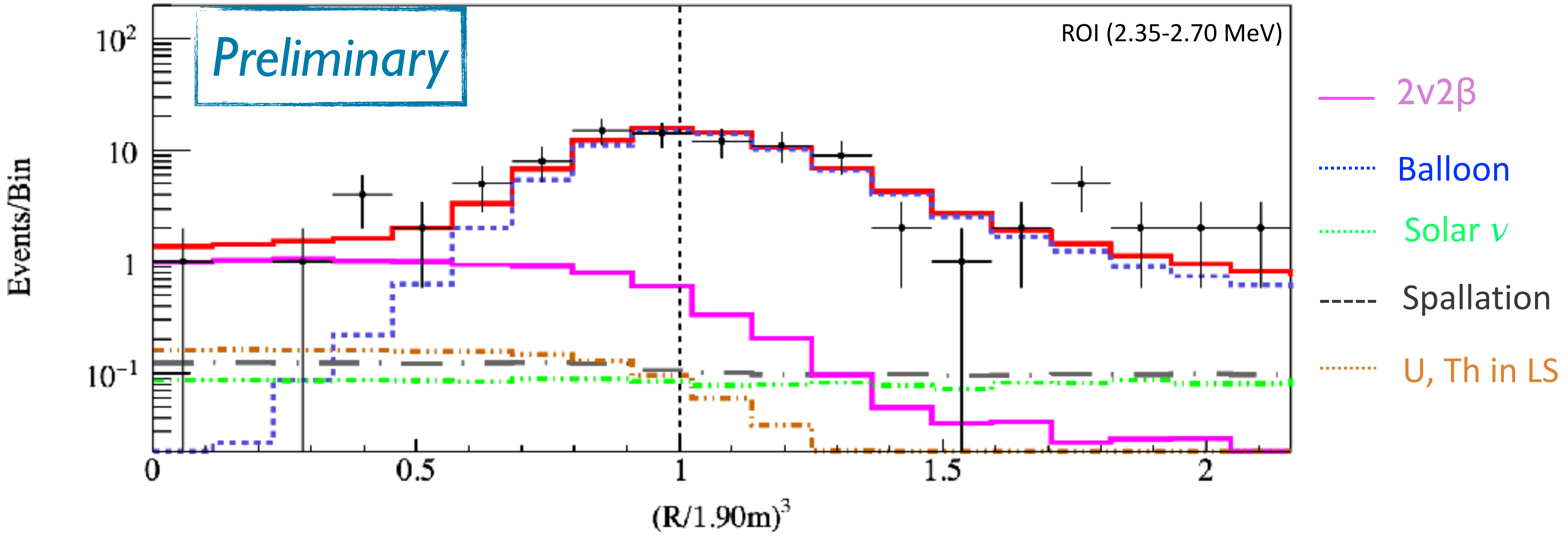
(all @ 90% C.L.)

KamLAND-Zen Coll, Phys. Rev. Lett. 117, 082503 (2016); arXiv:1605.02889

KLZ 800 Mini-Ballon Backgrounds







Balloon film backgrounds:

$^{238}U \sim 3 \times 10^{-12}$ g/g

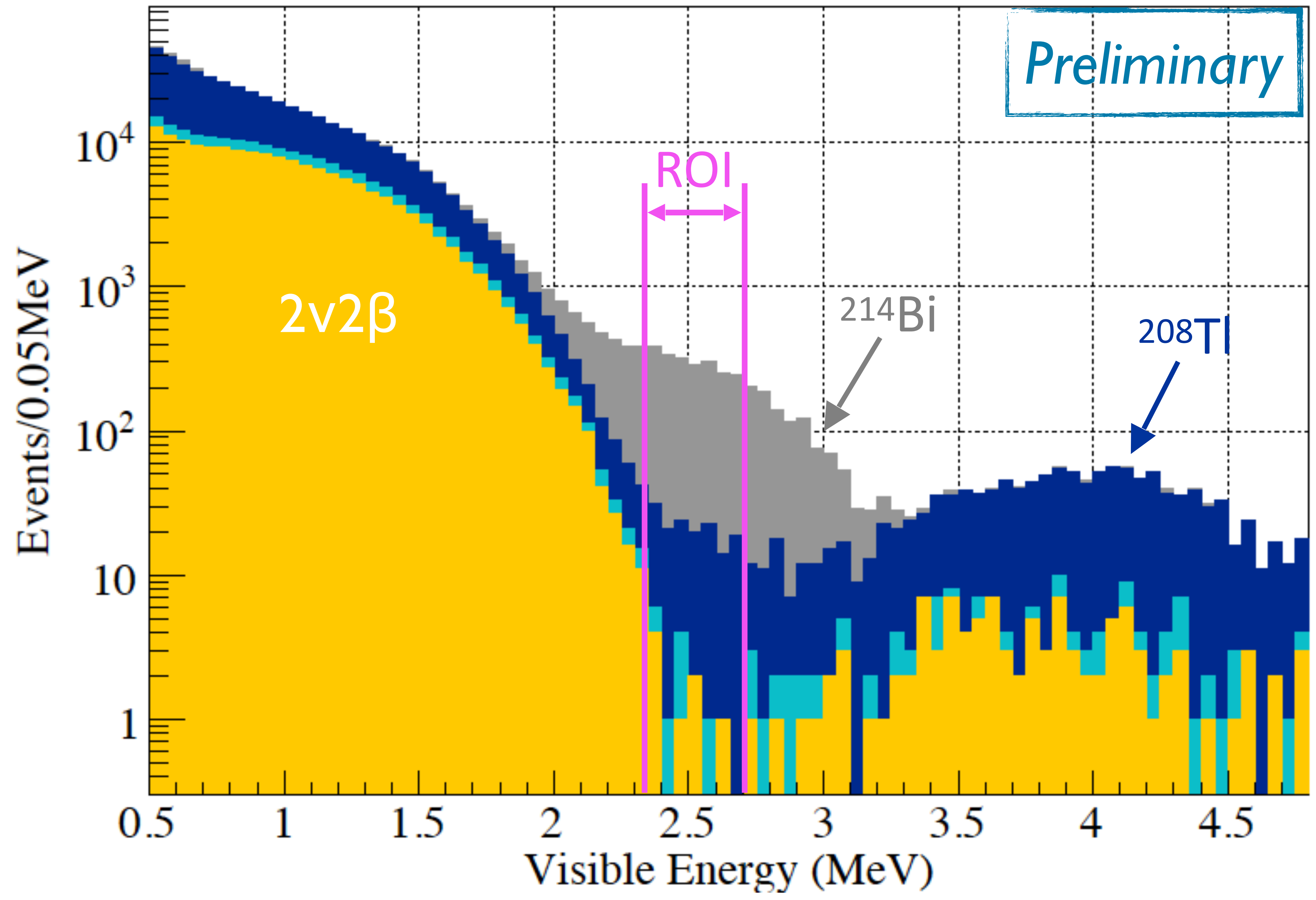
$^{232}Th \sim 4 \times 10^{-11}$ g/g

x10 reduction compared to KLZ 400 IB

Event Selection

Preliminary

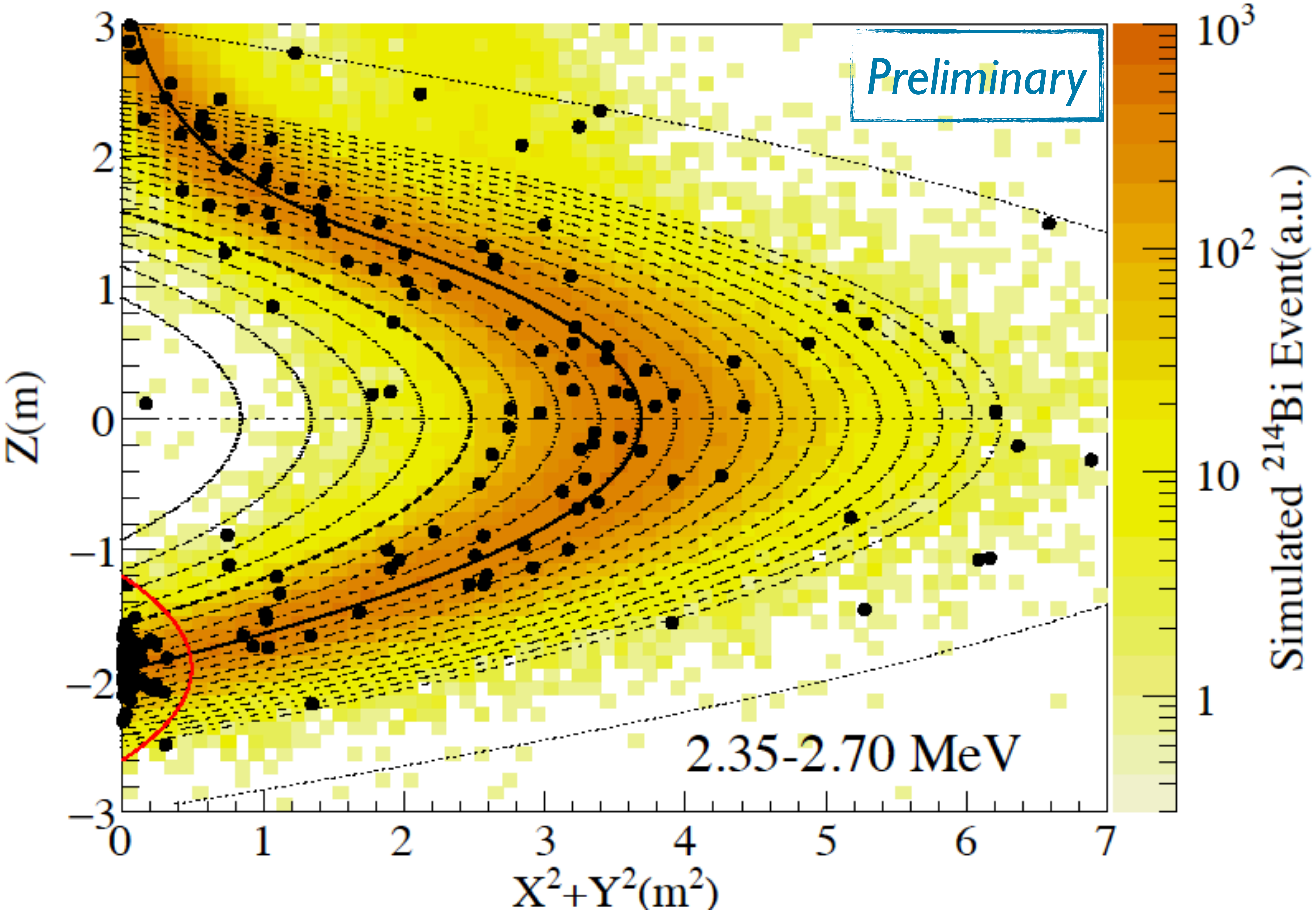
Total lifetime of 132.7 days



- Progression of cuts:
  - R < 240cm: Select events inside and just outside the mini-balloon
  - Rn cut: Delayed coincidence cut for ^{214}Bi - ^{214}Po and ^{212}Bi - ^{212}Po
  - Fiducial volume: Further reduce backgrounds by selecting R < 157cm
  - Spallation cut: Remove events correlated with muons

Fitting the Data in Equal Volume Bins

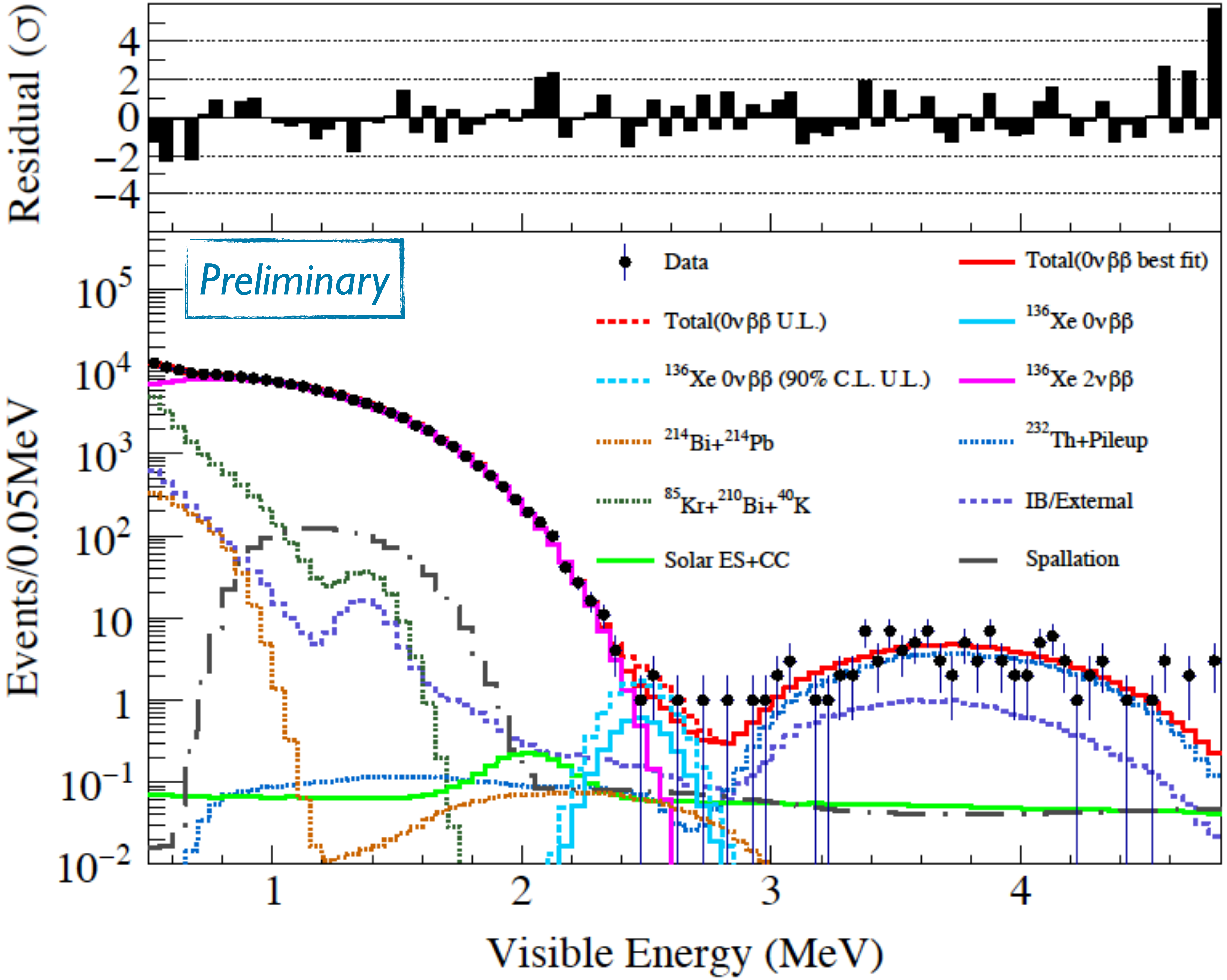
Vertex distribution in the ROI overlaid on ^{214}Bi MC



- Simultaneously fit 40 equal volume bins inside of r < 2.5 m
  - Outer region → more sensitive to backgrounds on mini-balloon film
  - Inner region → more sensitive to 0ν2β decay

Preliminary Results

Data with R<1.57m



246 kg-yr of ^{136}Xe exposure

- 8 events observed in the ROI
- 0ν2β decay best-fit value: 2.8 events
- Total ROI background best-fit: 7.9 events
- 90% C.L. upper limits:

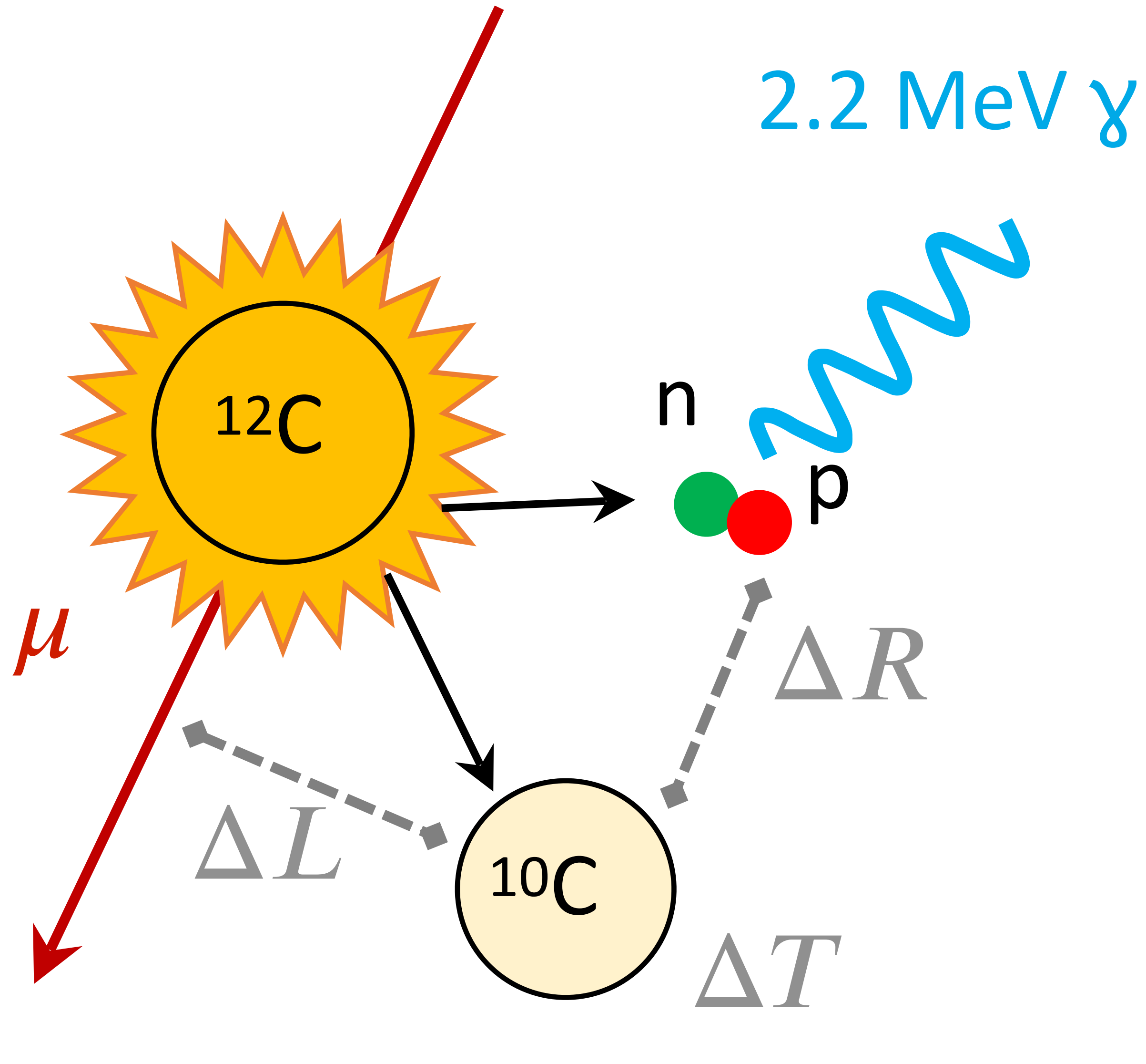
$T^{0\nu}_{1/2} > 4 \times 10^{25}$ yr

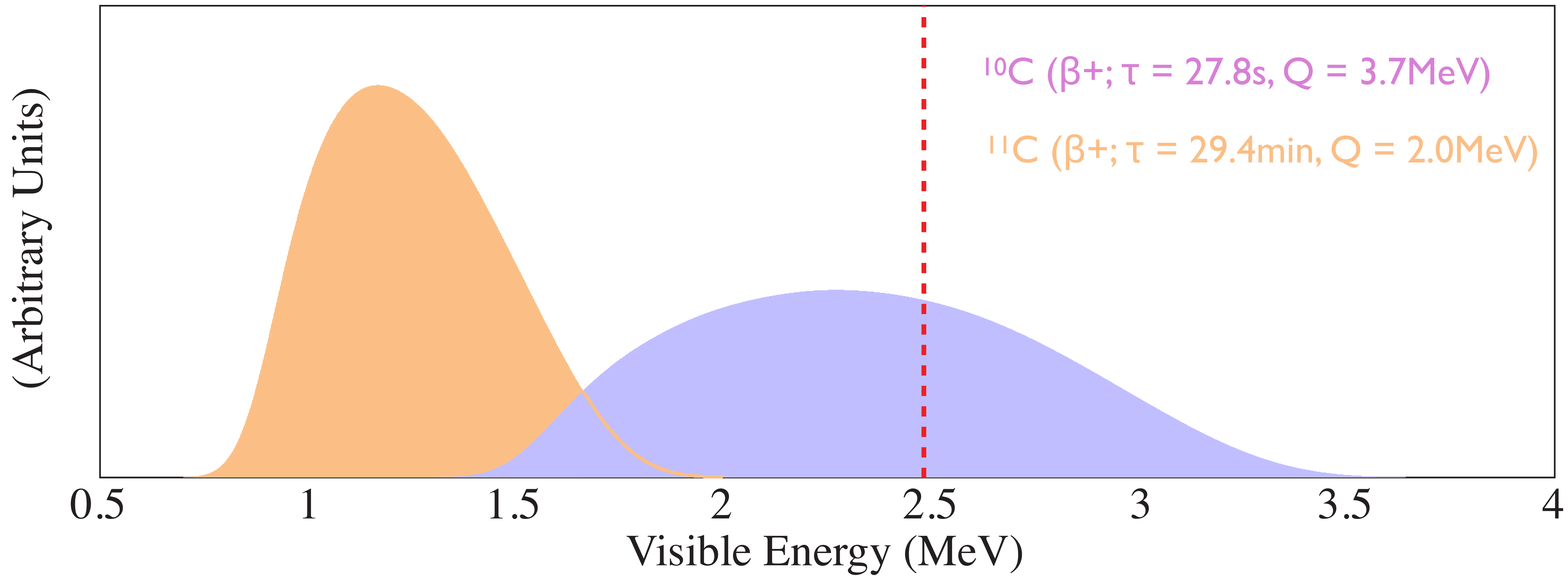
[Sens: > 8 x 10^{25} yr]

Muon Spallation

Carbon-based liquid scintillator produces muon spallation products

Spallation on ^{12}C



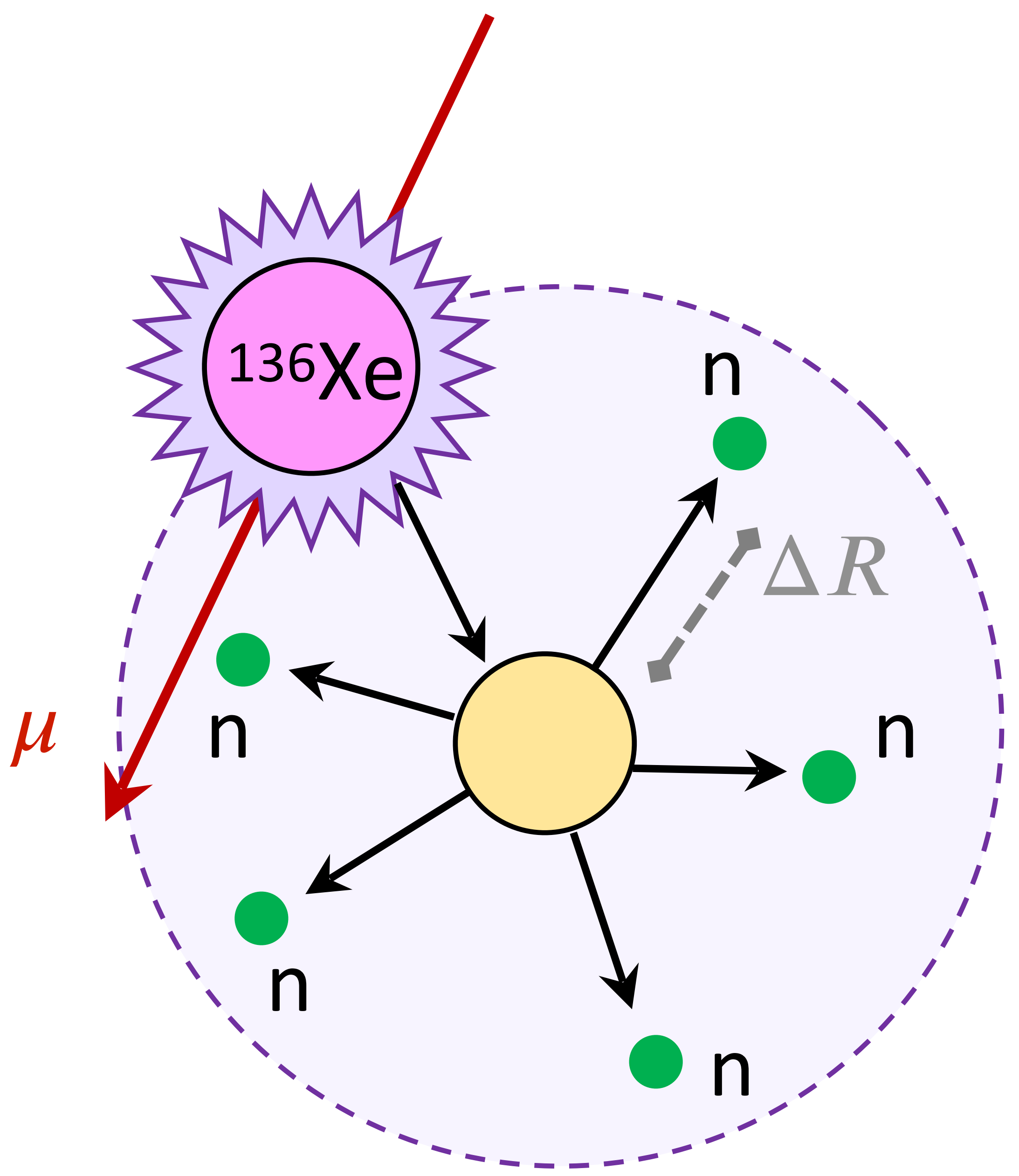


Triple coincidence cut (muon, neutron capture, subsequent ^{10}C decay) effective veto

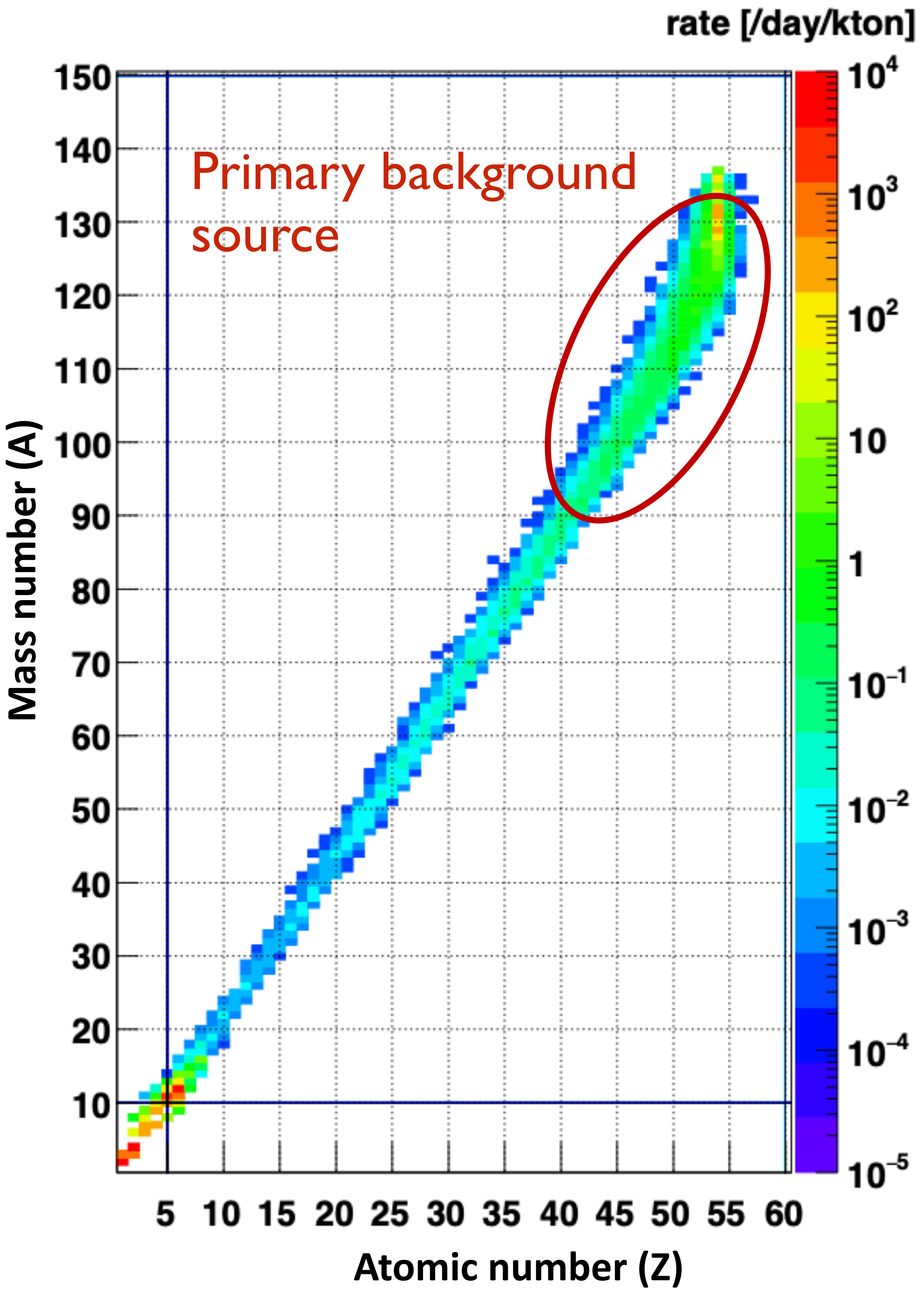
Muon Spallation

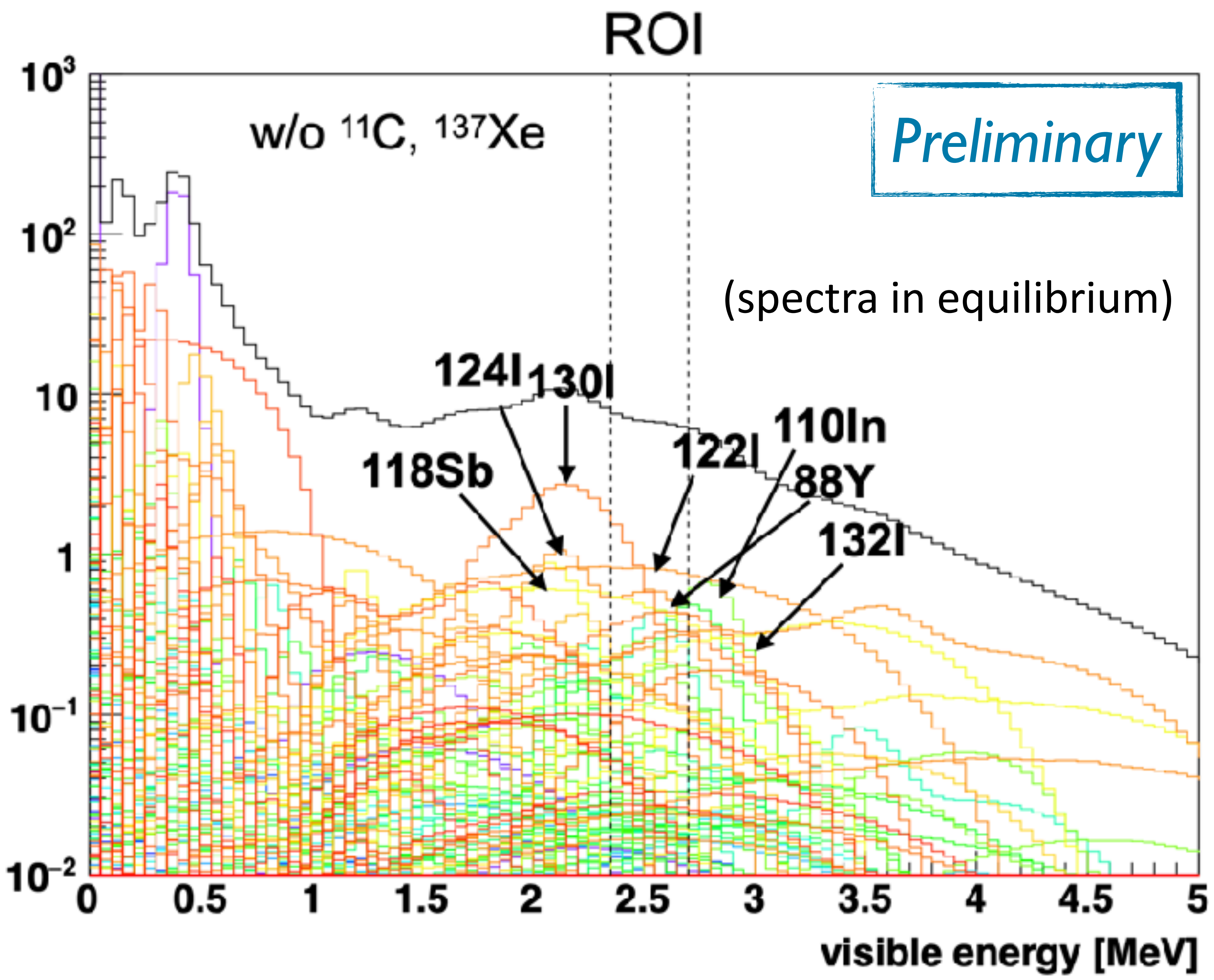
μ + ^{136}Xe spallation byproducts from FLUKA simulation

(NEW) Spallation on ^{136}Xe



Use a similar technique for high A isotopes with many neutrons



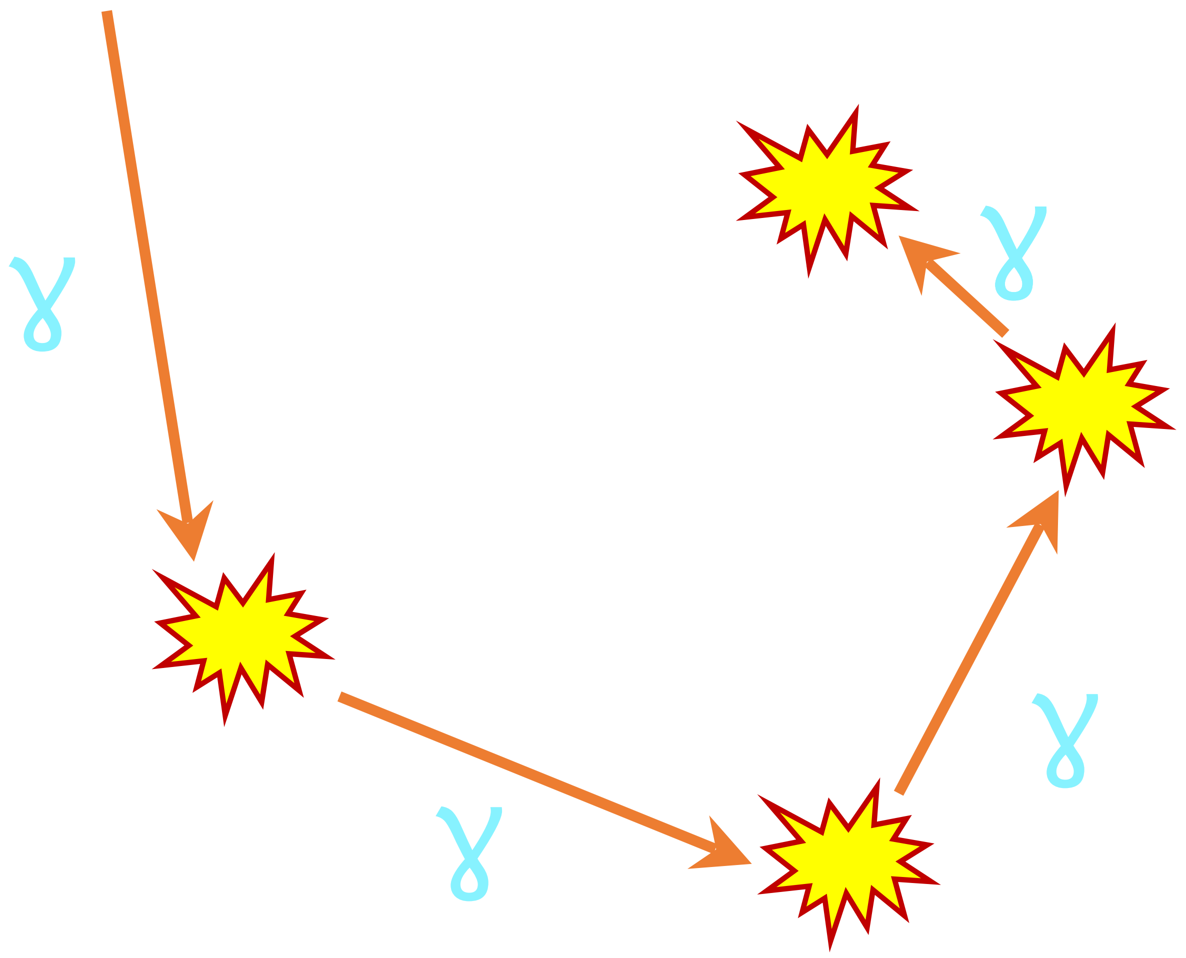


Long-lived spallation products in the ROI

$T_{1/2}$: **several hours to several days**

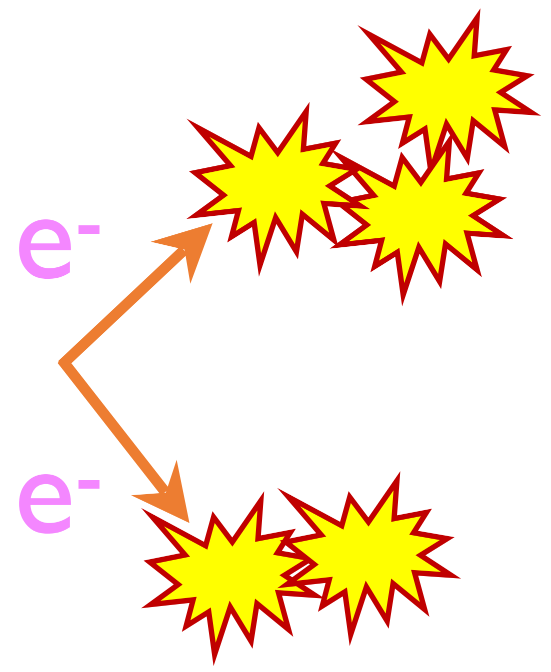
Very low rate!

Background Decays with Deep Learning



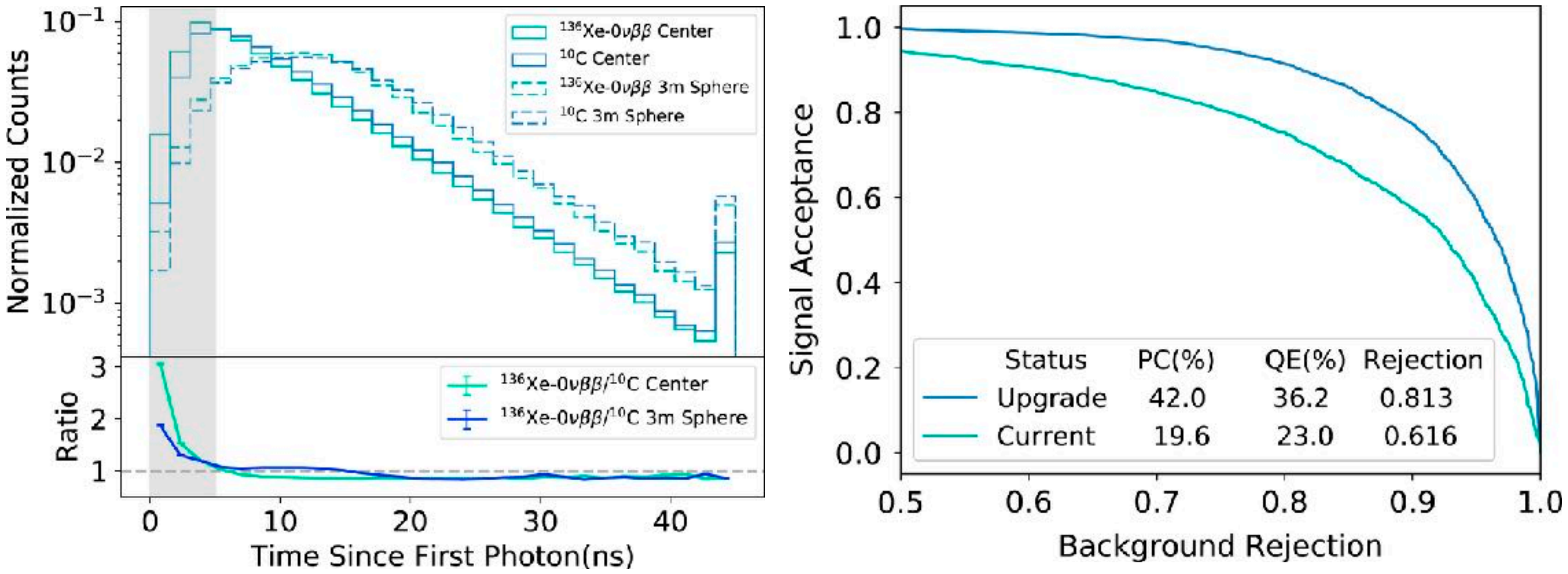
Background decays with ~MeV gamma-rays typically have energy deposits (Compton scatters) spread over distances of tens of centimeters.

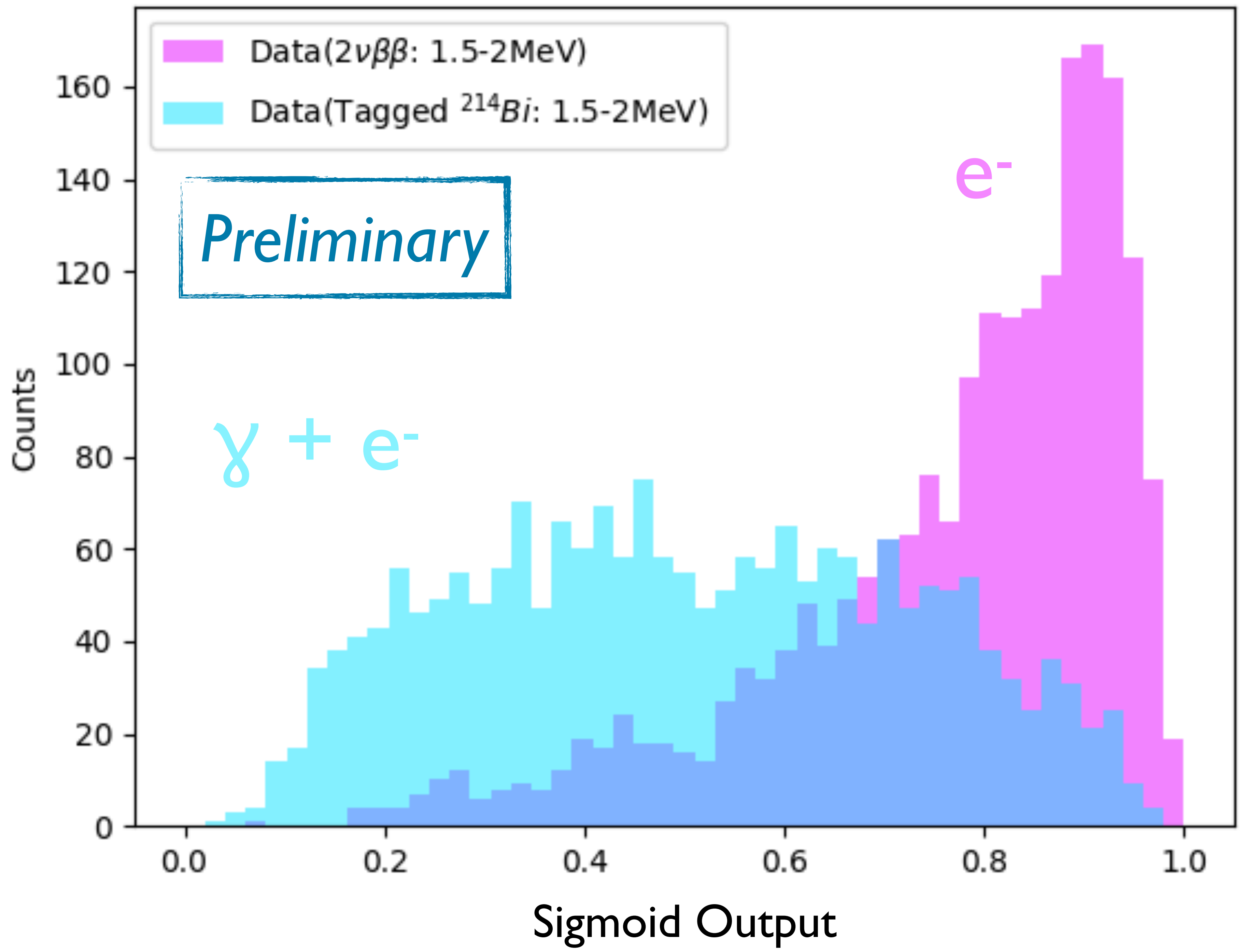
Decays only containing ~MeV electrons are more localized.



Spherical CNN applied to subset of KLZ data

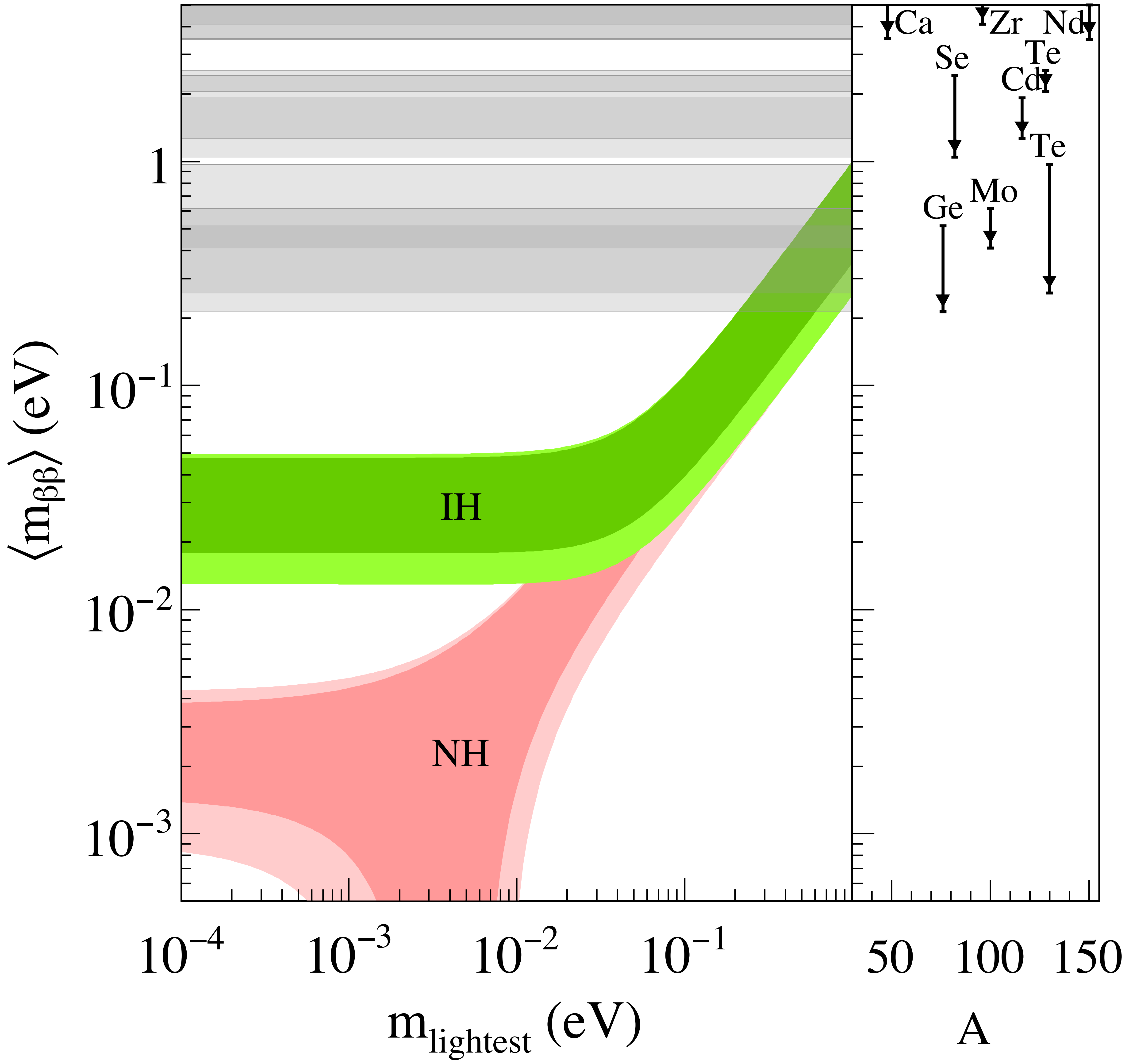
Spherical CNN applied to MC of ^{10}C and 0v2β events in KLZ-like detector





A. Li et al, NIM 947, 162604 (2019); arXiv:1812.02906

Effective Neutrino Mass



$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q,Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

KamLAND-Zen Coll, Phys. Rev. Lett. 117, 082503 (2016); arXiv:1605.02889

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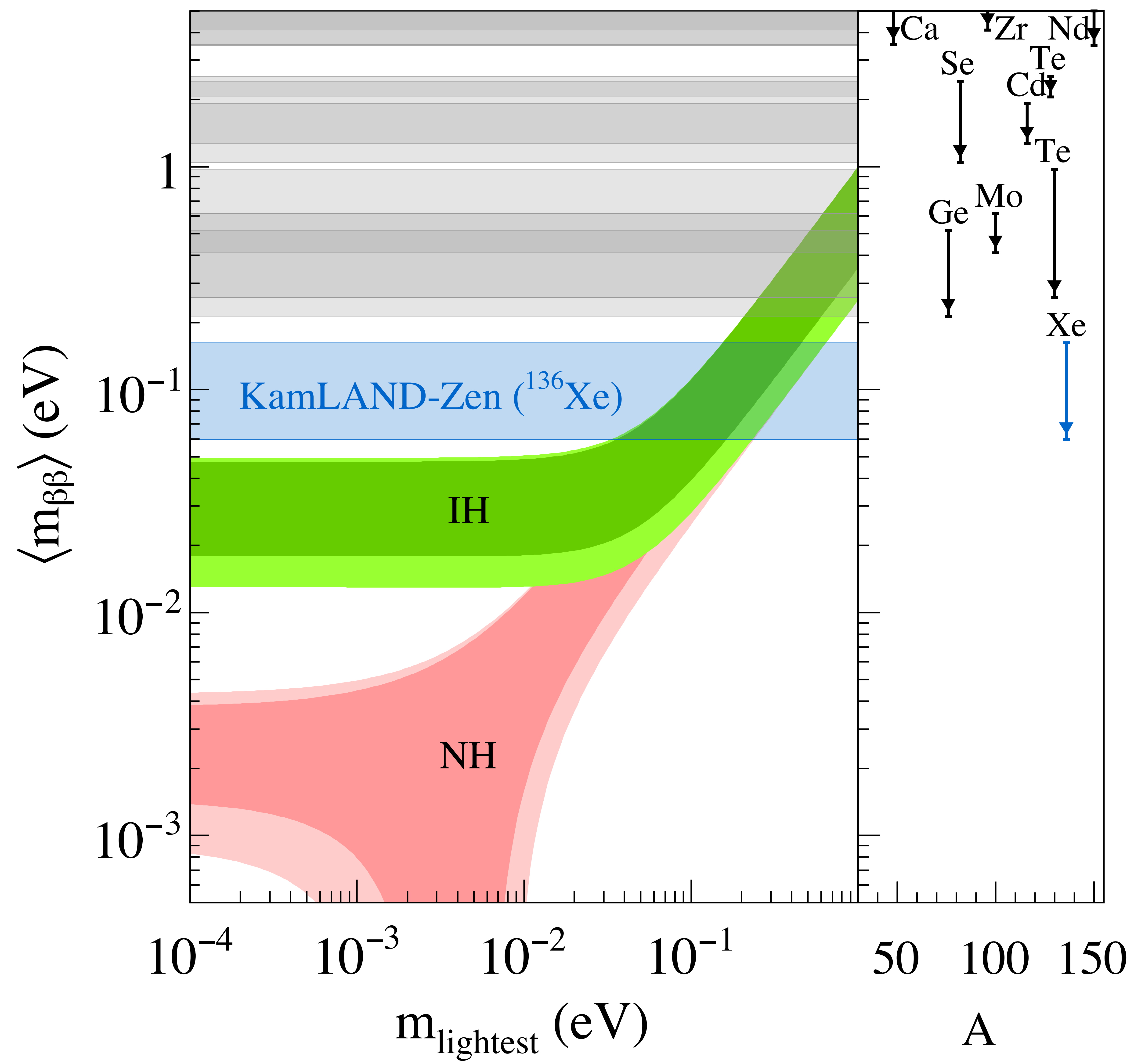


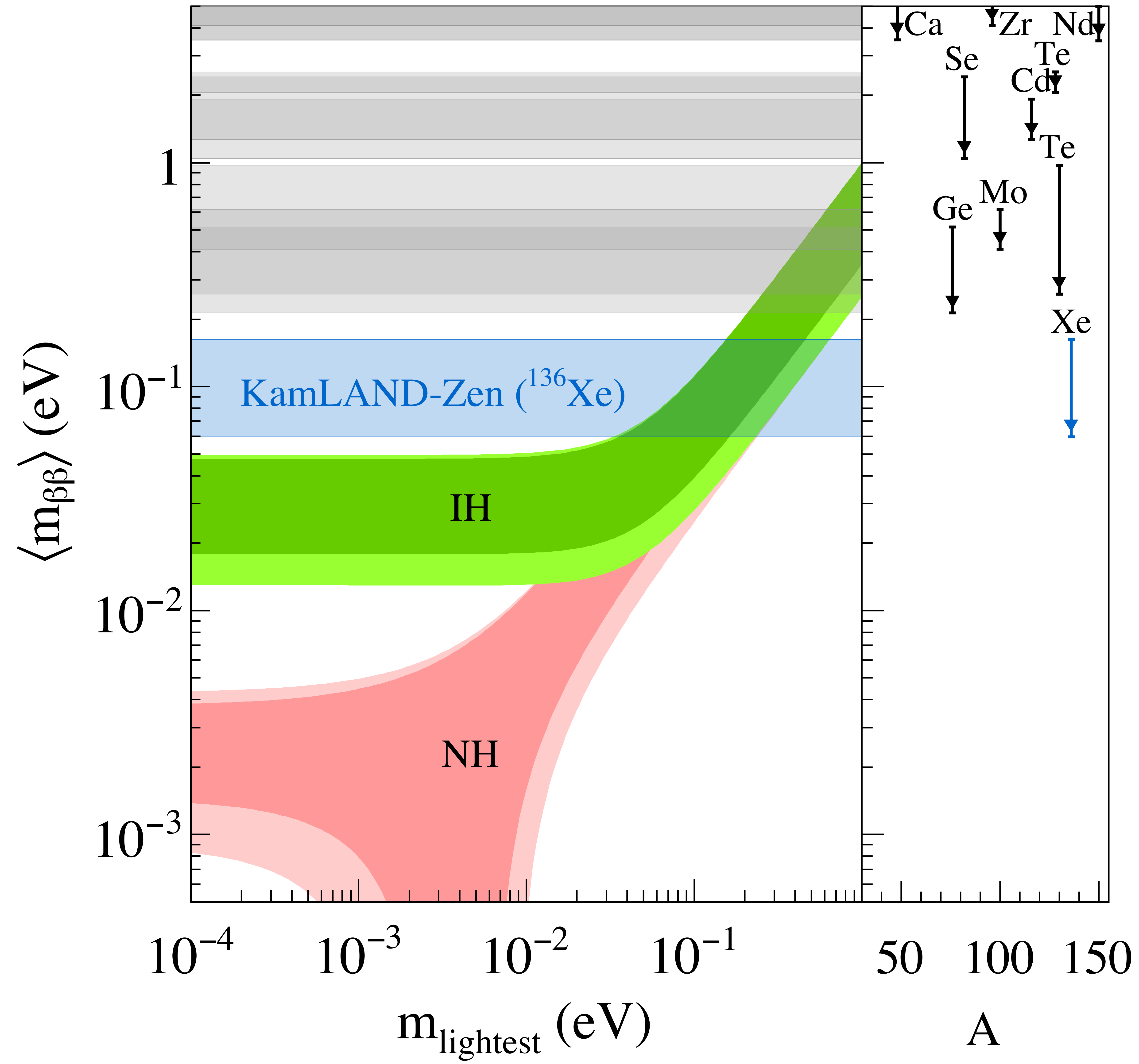
$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q, Z)|M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

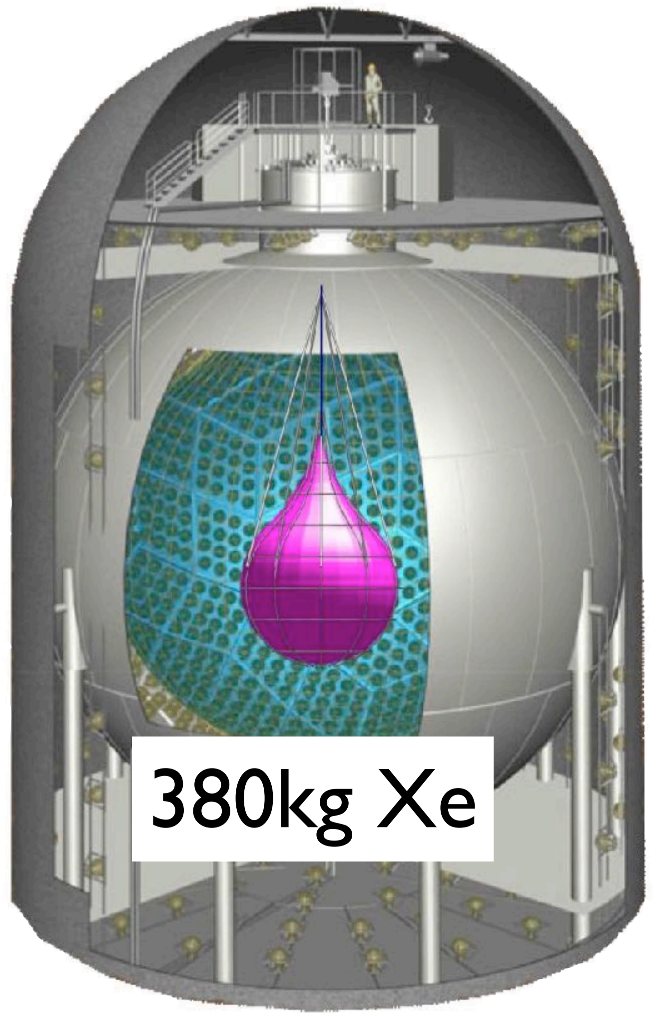
$\langle m_{\beta\beta} \rangle$ < 61 - 165 meV

KamLAND-Zen Coll, Phys. Rev. Lett. 117, 082503 (2016); arXiv:1605.02889

Future Goals

KamLAND-Zen 400





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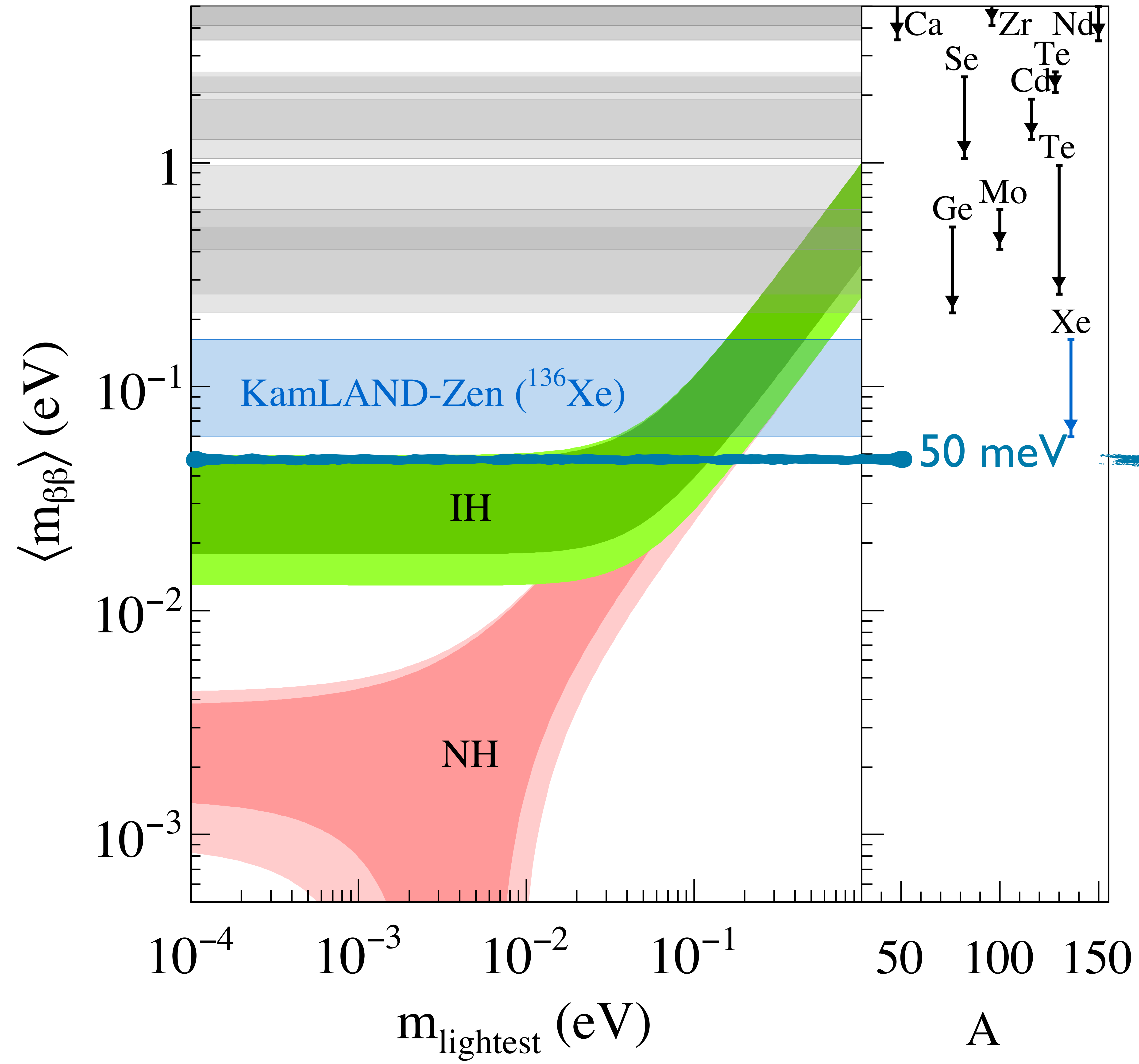

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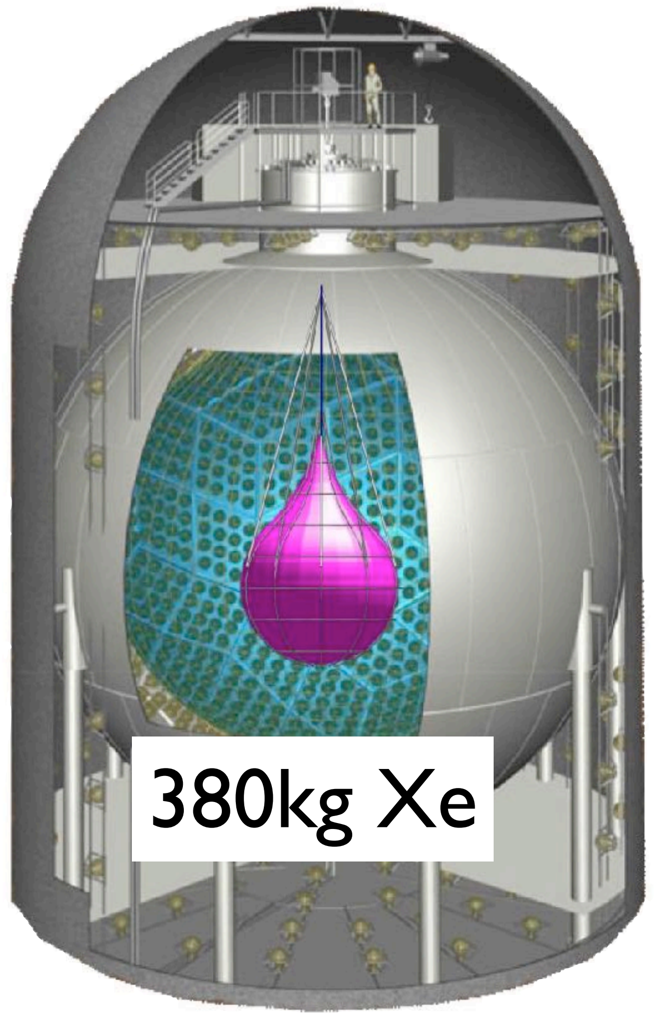
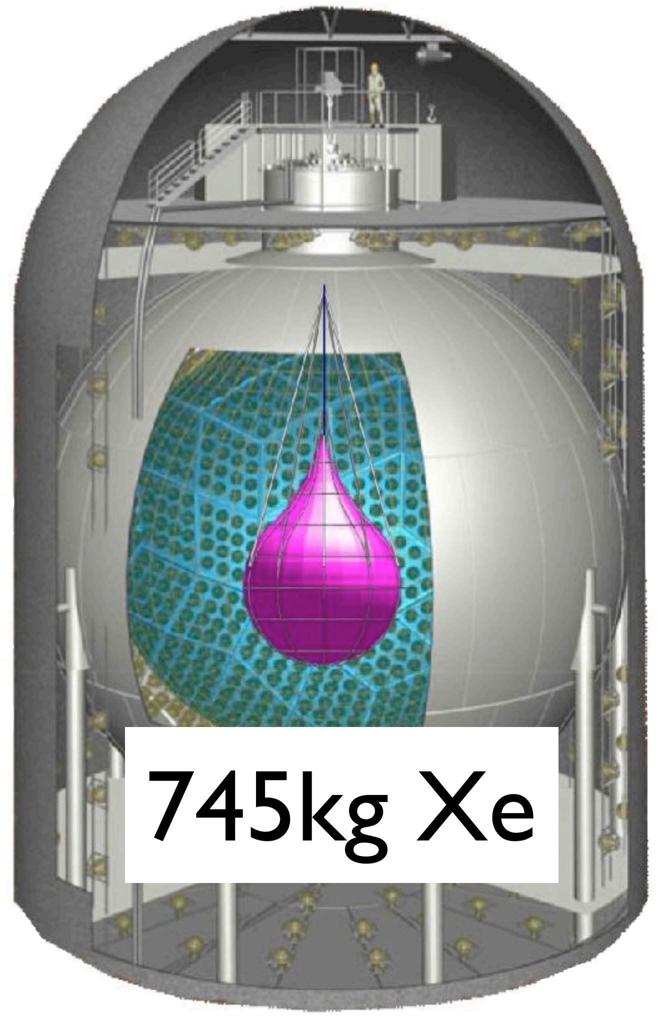
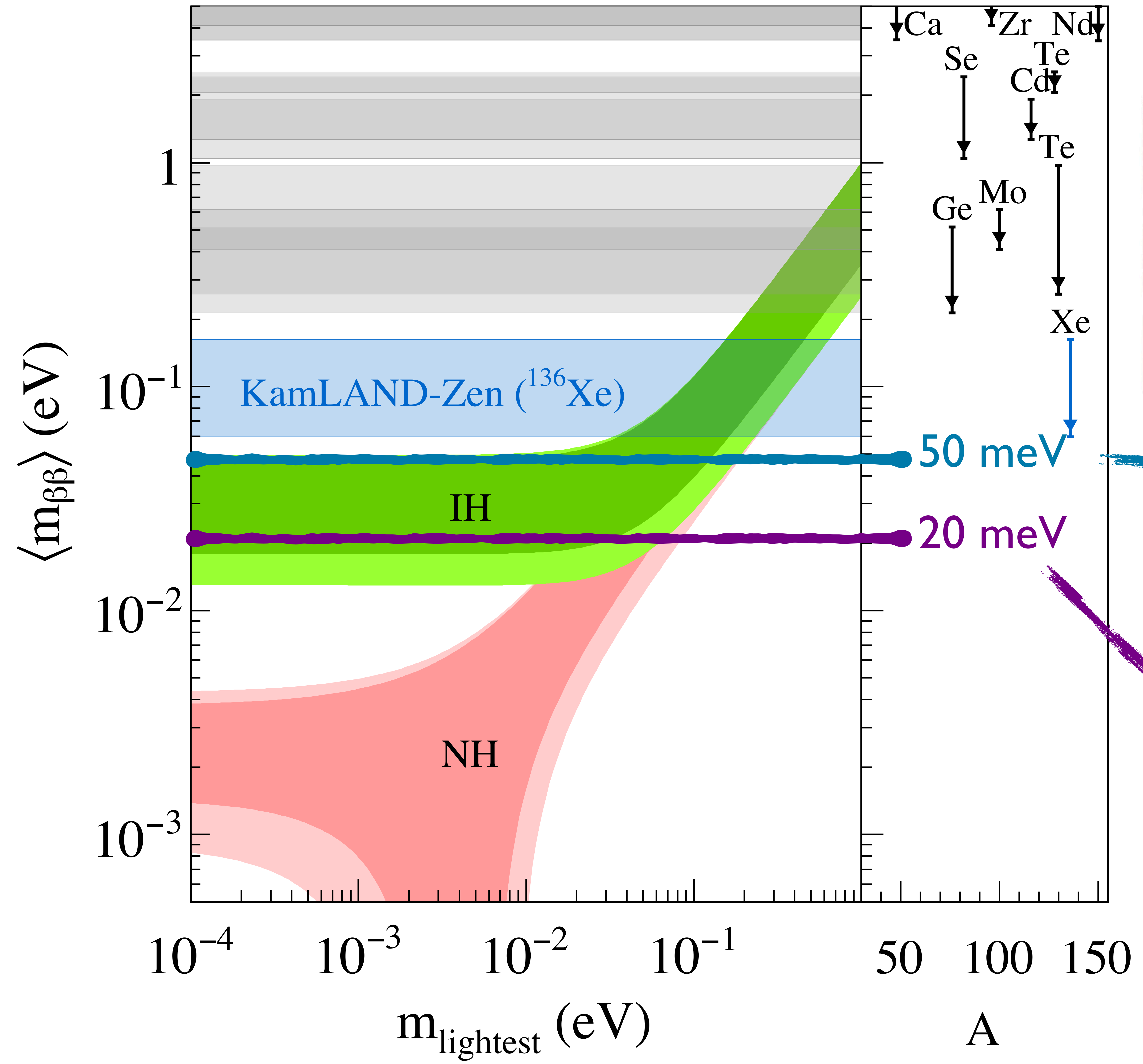


KamLAND-Zen 800

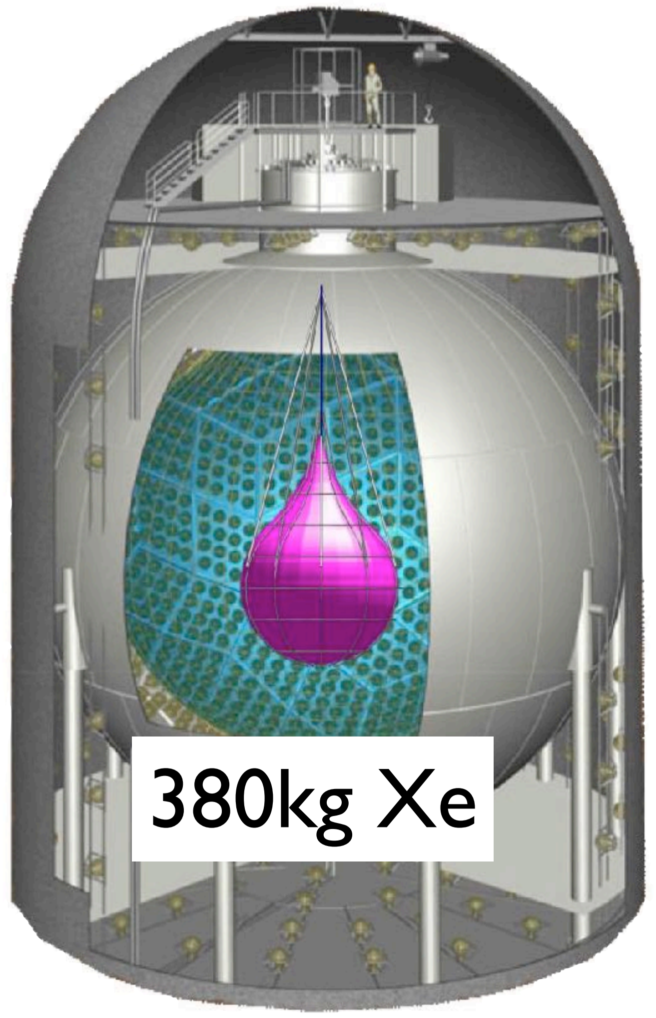


$T_{1/2} > 5 \times 10^{26}$yr

Future Goals



KamLAND-Zen 400



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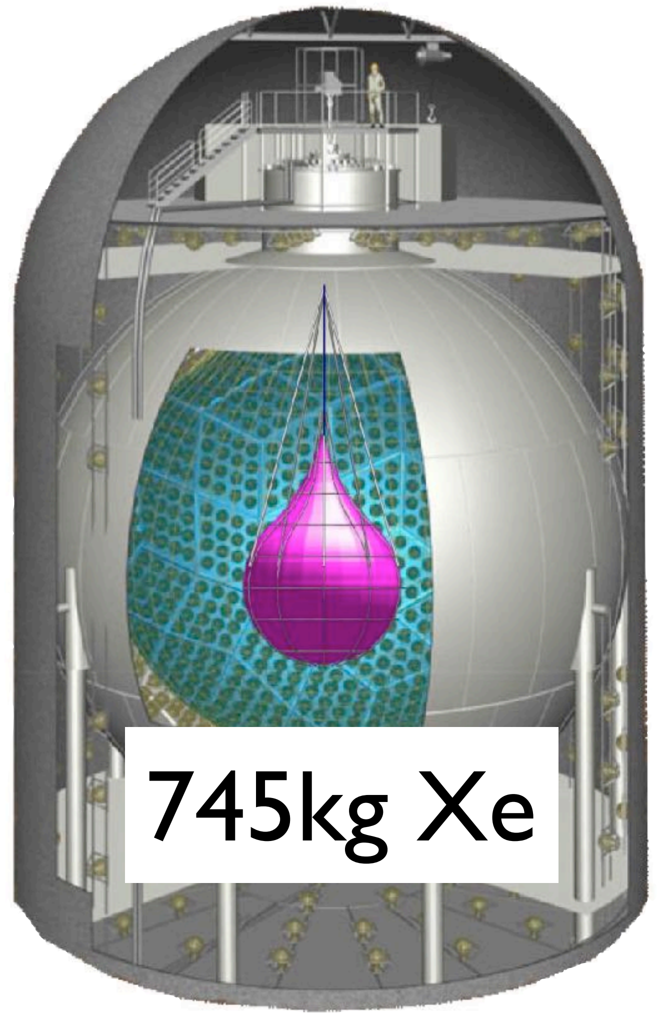
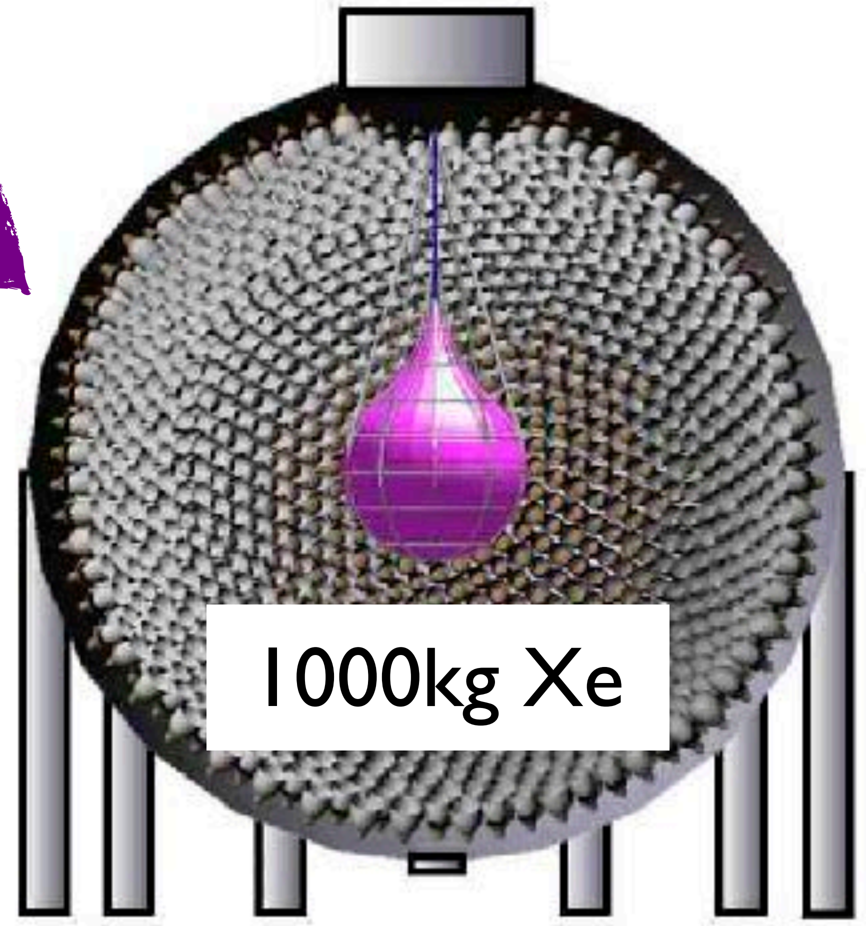


$T_{1/2} > 5 \times 10^{26}$yr

KamLAND2-Zen



$T_{1/2} > 2 \times 10^{27}$yr