Detection prospects for the double-beta decays of ^{124}Xe

Workshop on Xenon Detector $0\nu\beta\beta$ Searches:
Steps Towards the Kilotonne Scale

SLAC | 25 – 27 October 2023

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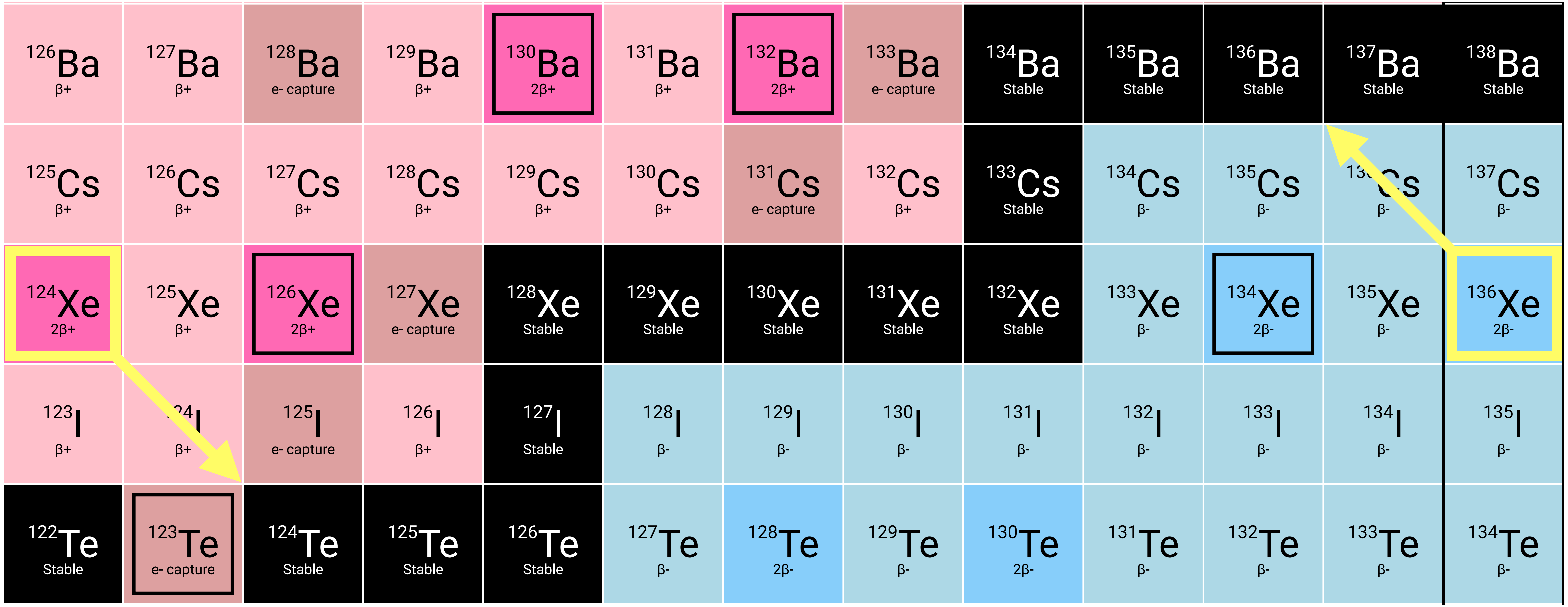
Double-beta decays in xenon

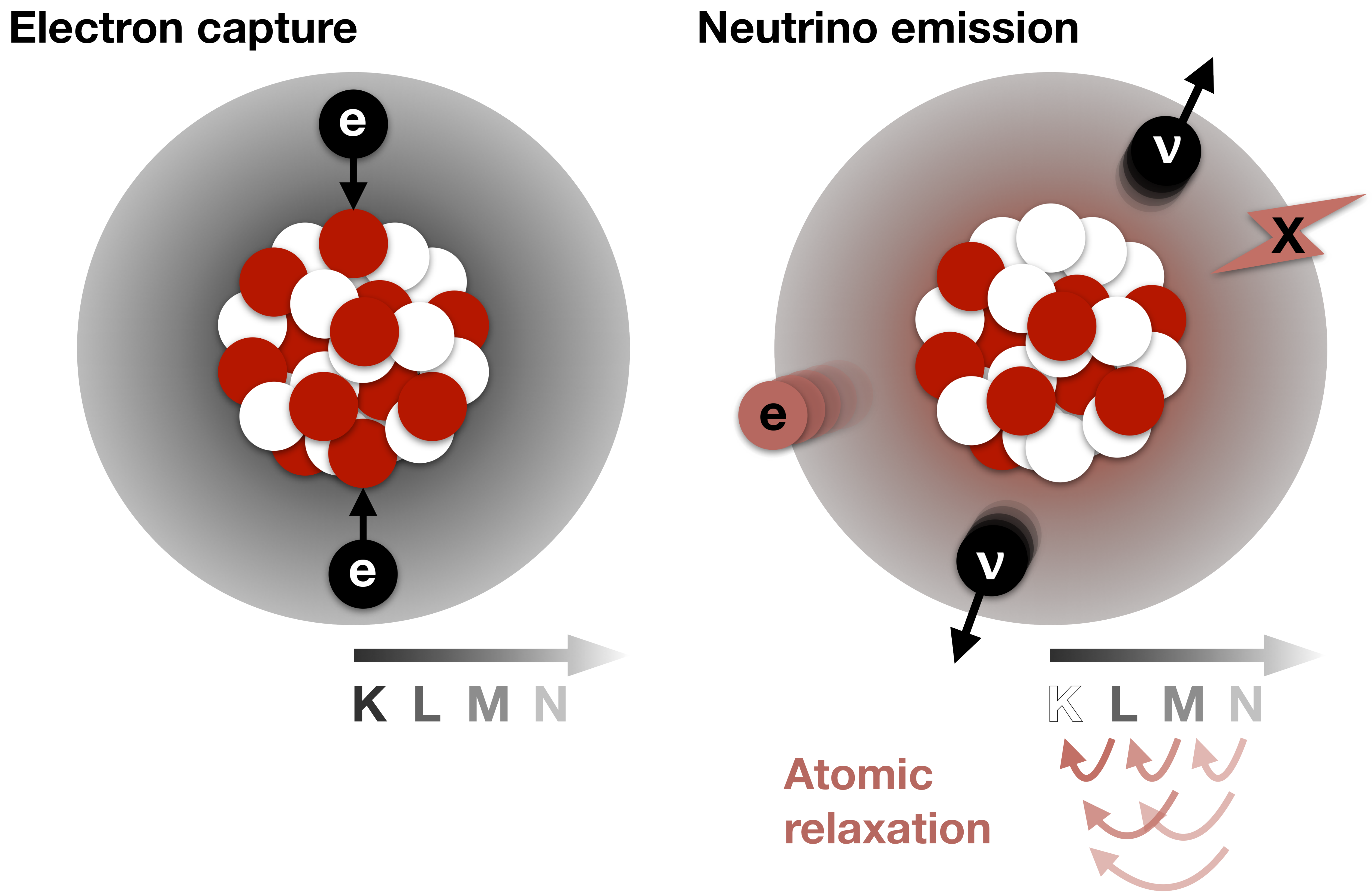
~0.1 %
$^{124}Xe/^{nat}Xe$



~8.9 %
$^{136}Xe/^{nat}Xe$

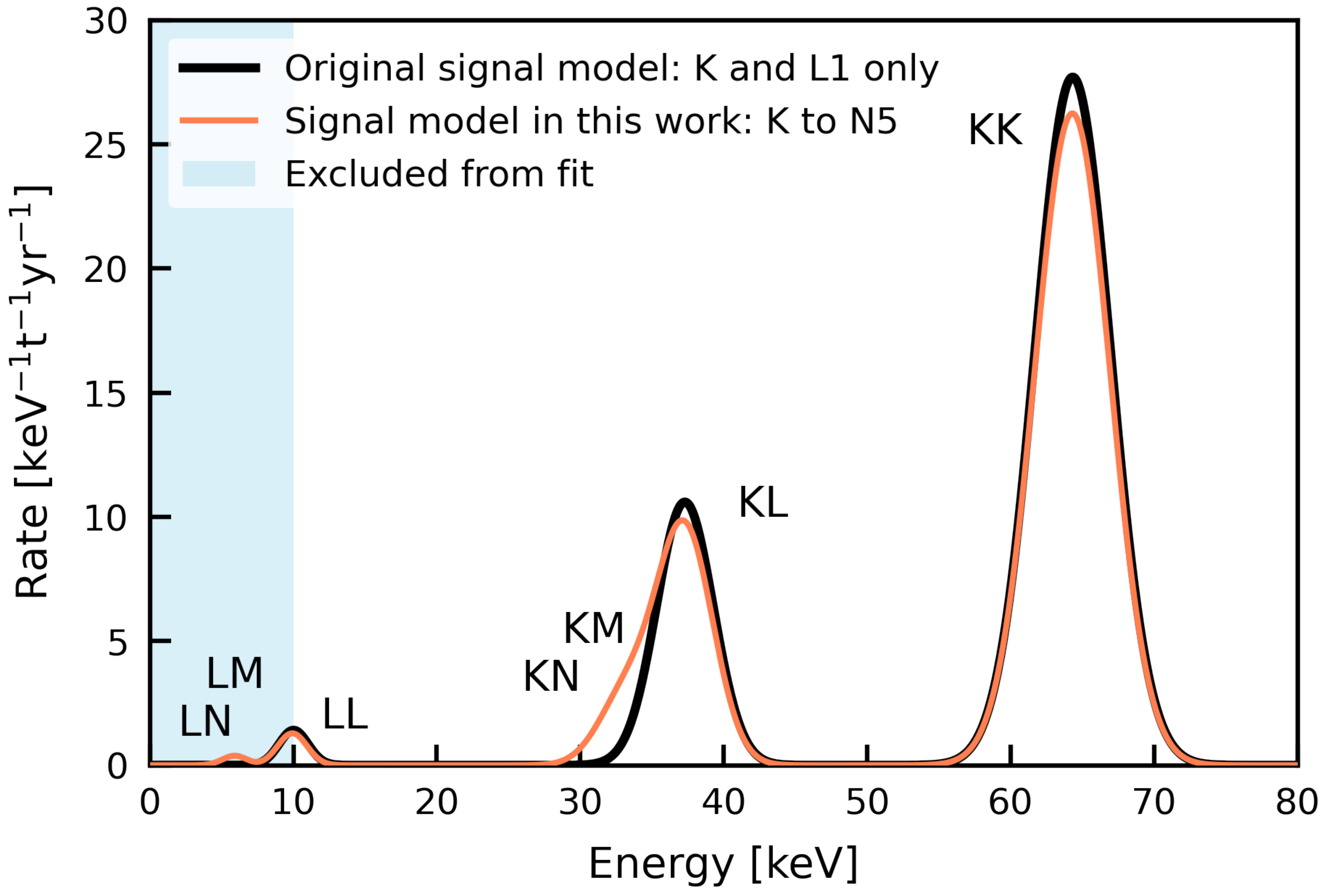
The Colourful Nuclide Chart, https://people.physics.anu.edu.au/~ecs103/chart/

Two-neutrino double-electron capture



$$^{124}\mathrm{Xe} + 2e^- \rightarrow {}^{124}\mathrm{Te} + 2\nu_e$$

Phys. Rev. C 106, 024328 (2022)



Q = 2856.7 keV

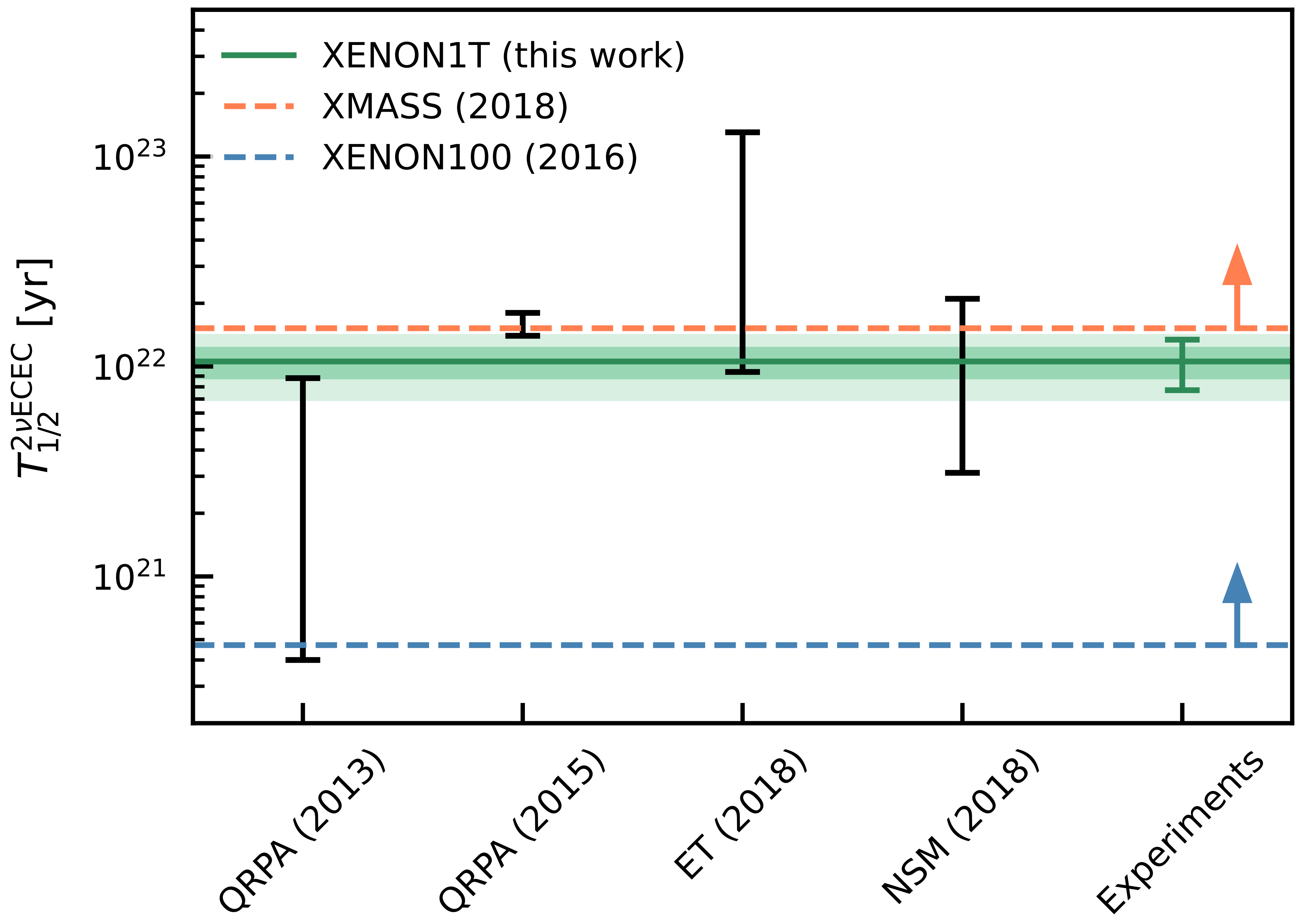
$E_{KK, measured}$ = 64.3 keV

Measurements by XENON1T and XENONnT

XENON1T (2016 – 2018)

Nature 568, 532–535 (2019)

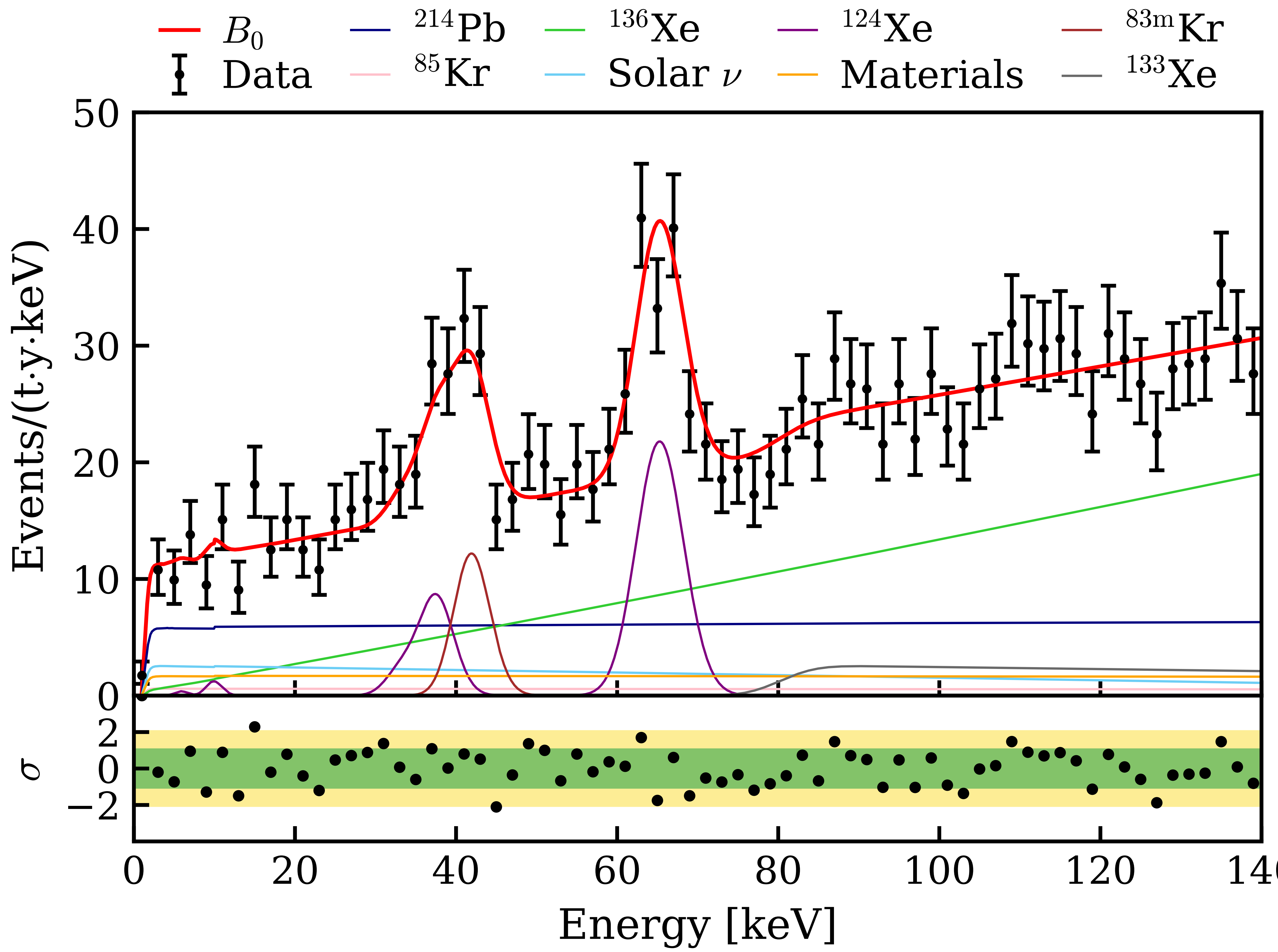
Phys. Rev. C 106, 024328 (2022)



$$T_{1/2}^{2\nu\mathrm{ECEC}} = (1.1 \pm 0.2_{\mathrm{stat}} \pm 0.1_{\mathrm{sys}}) \cdot 10^{22}\ \mathrm{yr}$$

XENONnT (since 2021)

Phys. Rev. Lett. 129, 161805 (2022)

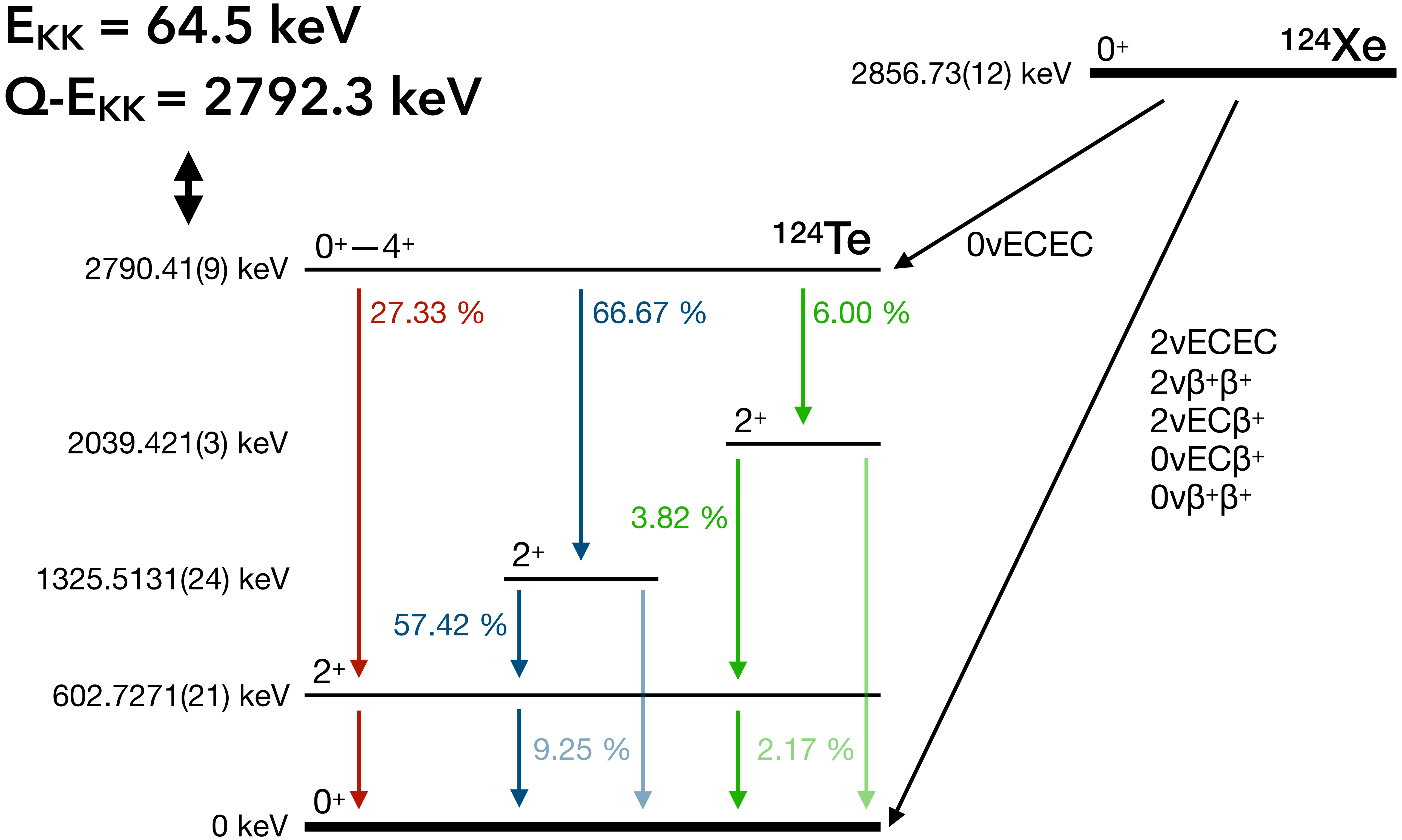


$$T_{1/2}^{2\nu\mathrm{ECEC}} = (1.18 \pm 0.13_{\mathrm{stat}} \pm 0.14_{\mathrm{sys}}) \cdot 10^{22}\ \mathrm{yr}$$

Neutrinoless double-electron capture

A. Fieguth, B. Lenardo, C. Weinheimer and C. Wittweg, Eur. Phys. J. C 80 (2020) 12, 1161

Q = 2856.7 keV
E_{KK} = 64.5 keV
Q-E_{KK} = 2792.3 keV

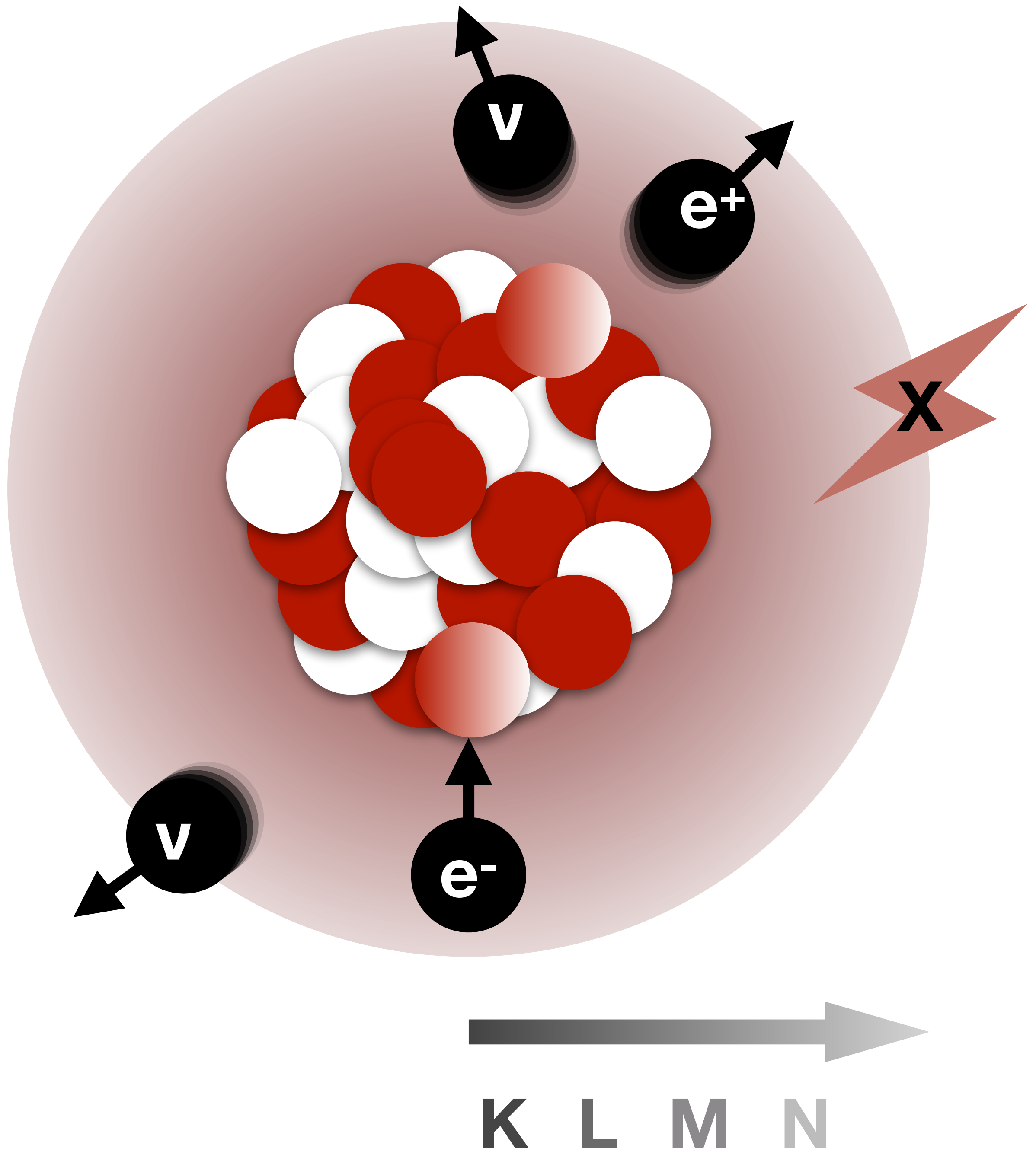


- Resonant decay needed in order to conserve energy and momentum
- ^{124}Te state at 2790.41 keV is 1.9 keV off resonance and J^P unknown

$$(T_{1/2}^{0\nu \mathrm{ECEC}})^{-1} = G_{0\nu}\,|M_{0\nu}|^2\,|f(m_\mathrm{i}, U_\mathrm{ei})|^2 R$$

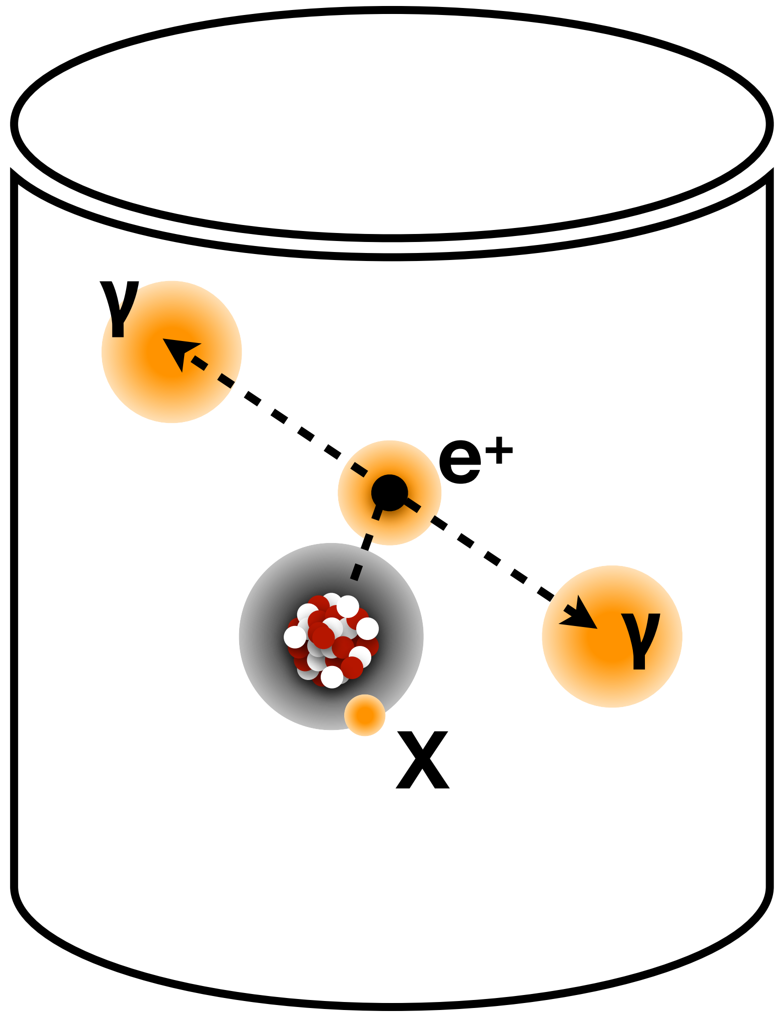
$$R = \frac{m_\mathrm{e}c^2\Gamma}{\Delta^2 + \Gamma^2/4} = 2.92 \pm 0.47$$

Electron capture with positron emission



- Single electron capture.
- Atomic relaxation by X-rays and Auger electrons.
- Emission of positron.
- Positron will thermalize, annihilate with e^- and create back-to-back γ-rays.
- Neutrinos leave detector.

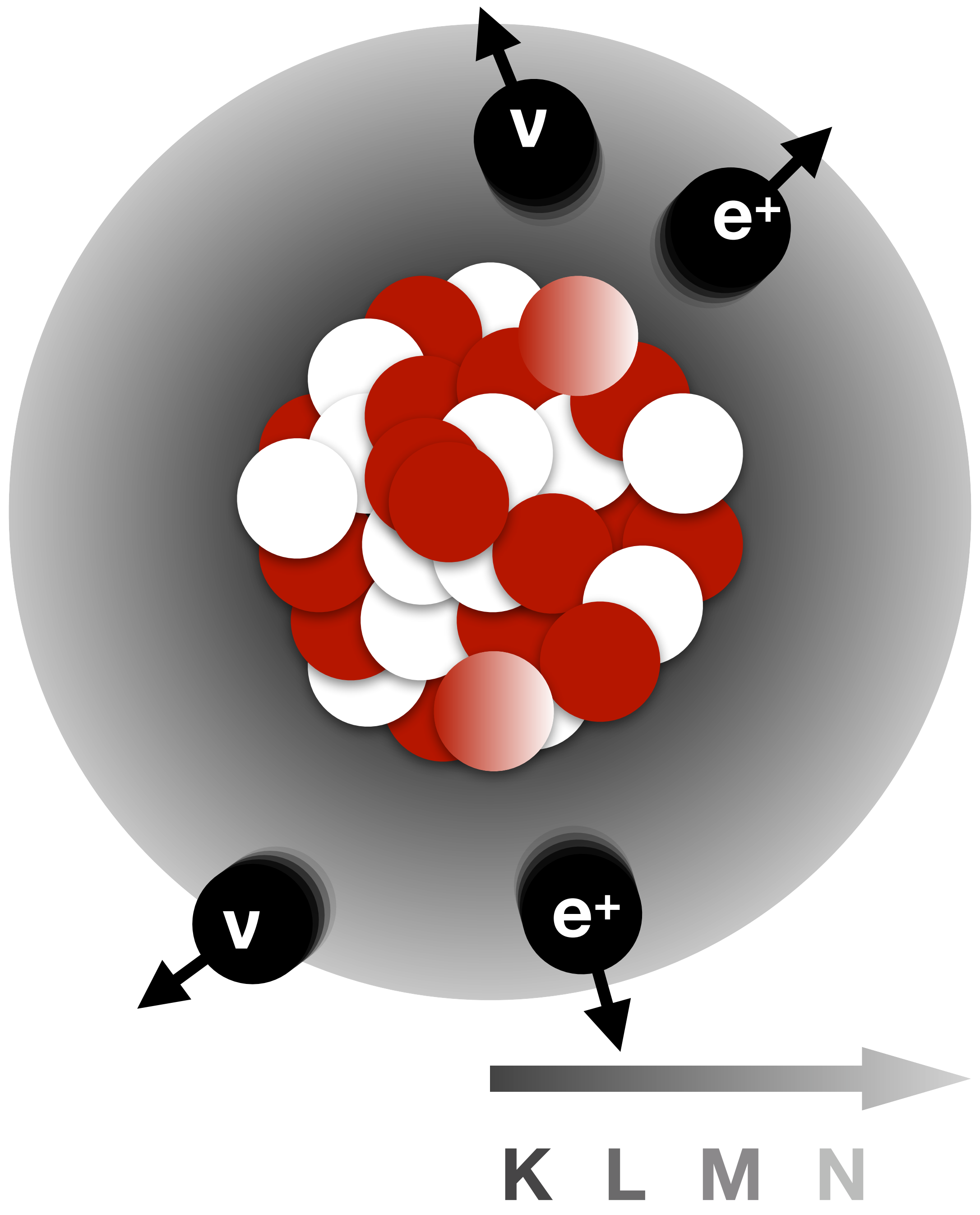
Look for a 2-γ coincidence, the thermalization of the positrons and the atomic relaxation.



$$E_\mathrm{k} = 31.8\,\mathrm{keV}$$

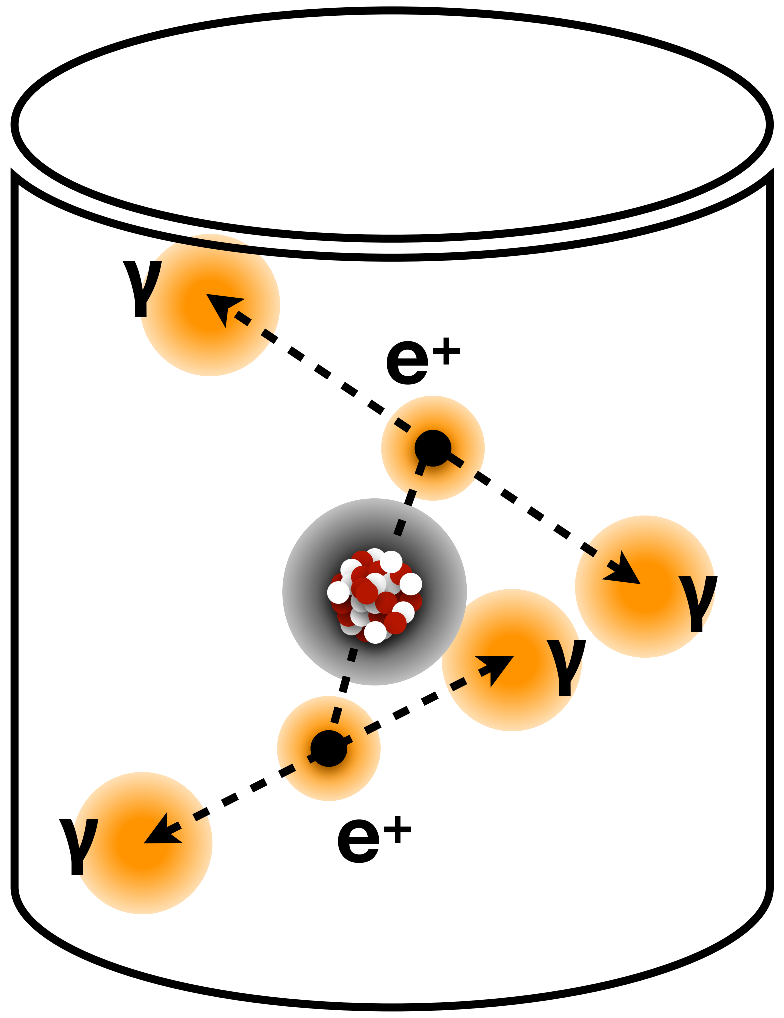
$$E_{\mathrm{e}^+}(+E_{2\nu}) = Q - 2m_\mathrm{e}c^2 - E_\mathrm{k} \leq 1802.9\,\mathrm{keV}$$

Double-positron emission



- Emission of two positrons.
- No excitation of the atomic shell.
- Positrons will thermalize, annihilate with e- and create two pairs of back-to-back γ-rays.
- Neutrinos leave detector.

$$E_{2e^+}(+E_{2\nu}) = Q - 4m_e c^2 \leq 812.7\,\mathrm{keV}$$



Look for a 4-γ coincidence and the thermalization of the positrons.

Half-life estimates for unobserved decays

Literature value

XENON1T 2vECEC half-life

$$(T^{2\nu}_{1/2})^{-1} = G_{2\nu}\,|M_{2\nu}|^2$$

Literature values, range for NME

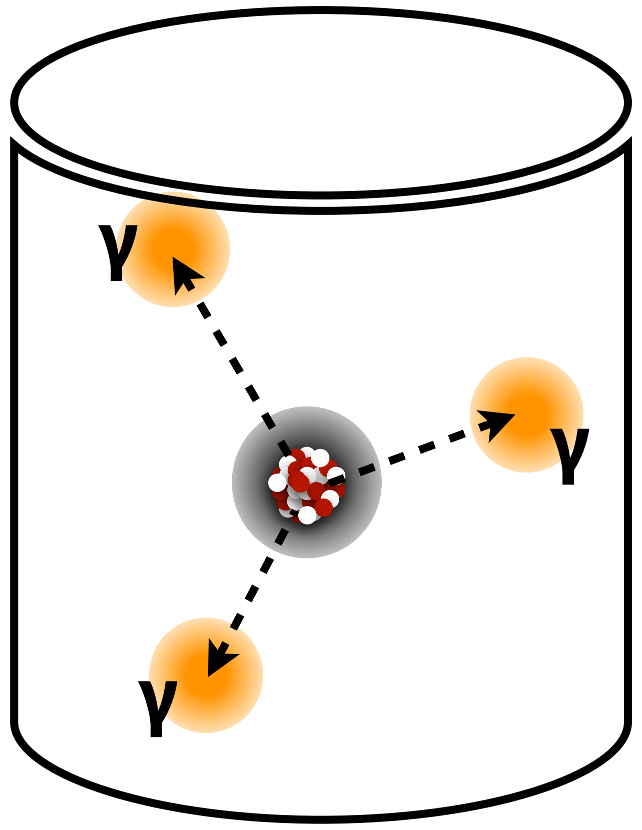
$$(T^{0\nu}_{1/2})^{-1} = R \cdot G_{0\nu}\,|M_{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

$$\langle m_{\beta\beta}\rangle^2 = |\sum_{\mathrm{i}} U^2_{\mathrm{ei}} m_{\mathrm{i}}|^2$$

KATRIN and Kamland-Zen upper limits from 2020

ECEC

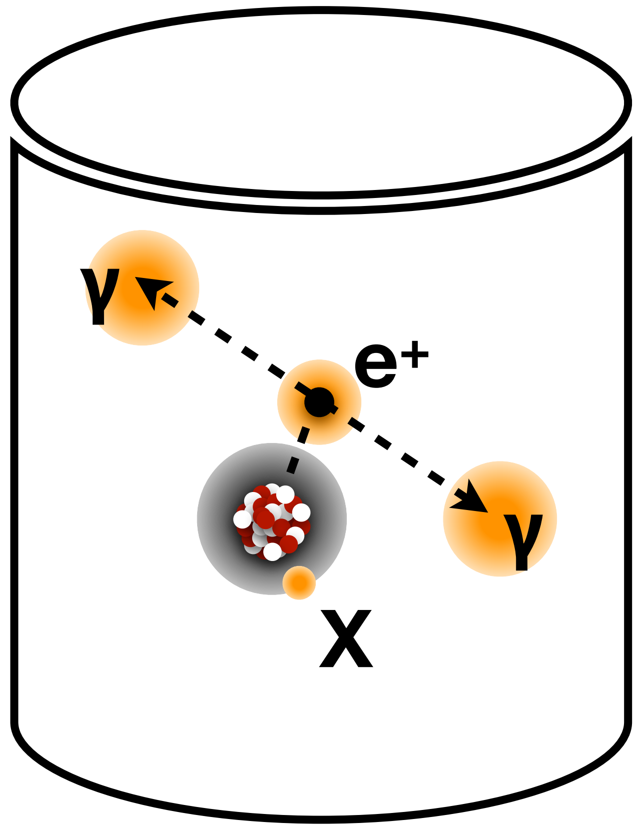
$T^{0\nu}_{1/2} > 1.8 \cdot 10^{29}$ yr – $3.9 \cdot 10^{32}$ yr



ECβ+

$T^{2\nu}_{1/2} = (1.7 \pm 0.6) \cdot 10^{23}$ yr

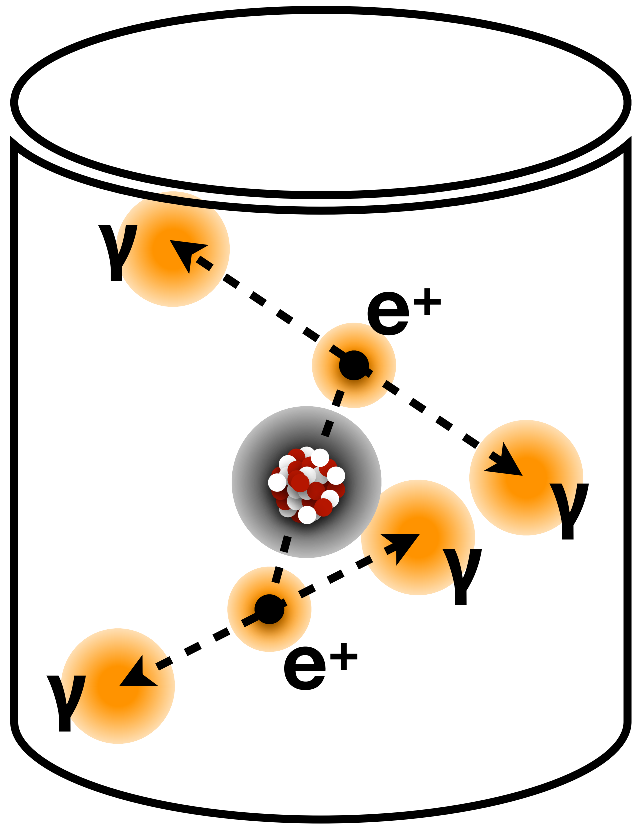
$T^{0\nu}_{1/2} > 4.8 \cdot 10^{25}$ yr – $5.3 \cdot 10^{28}$ yr



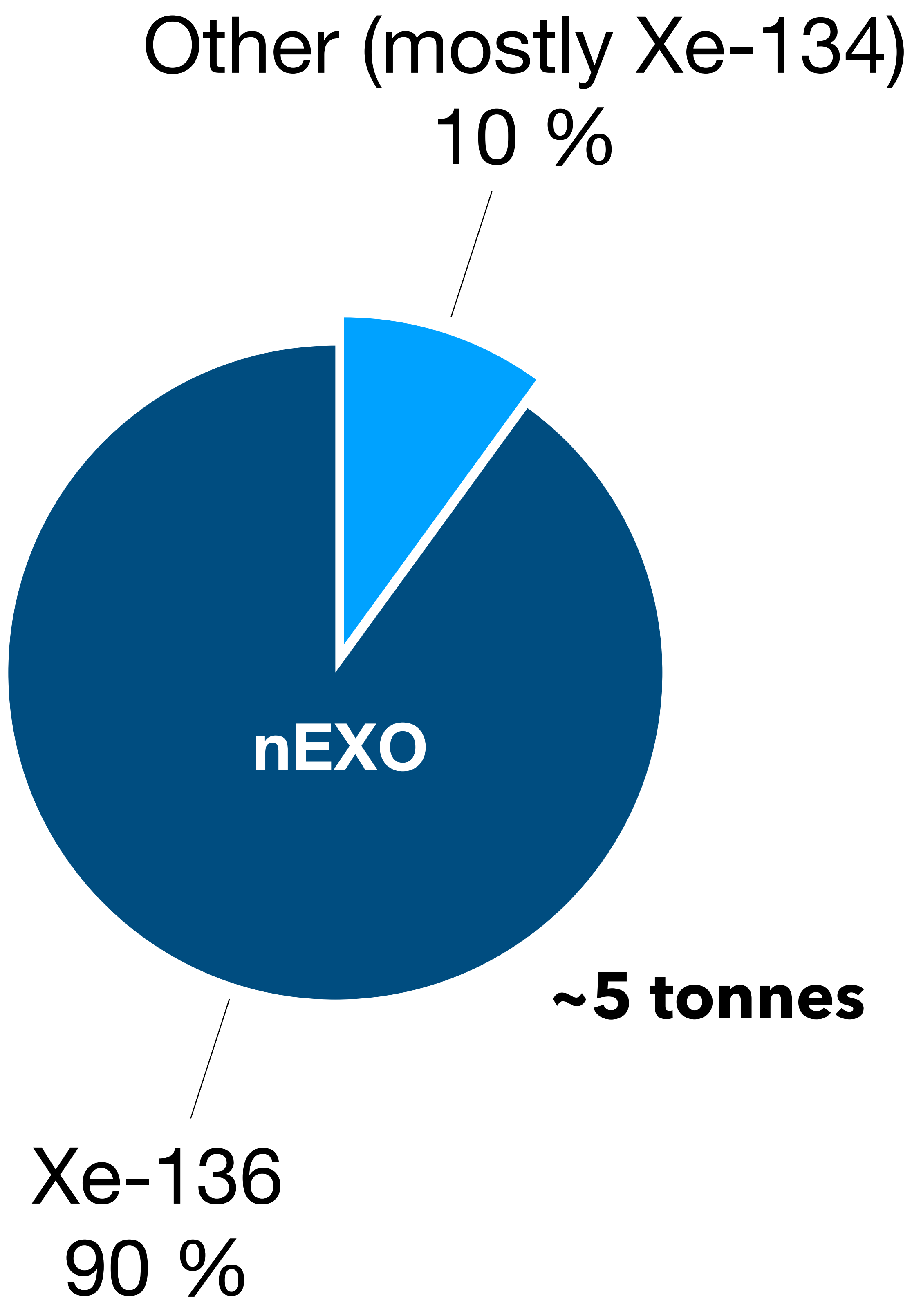
β+β+

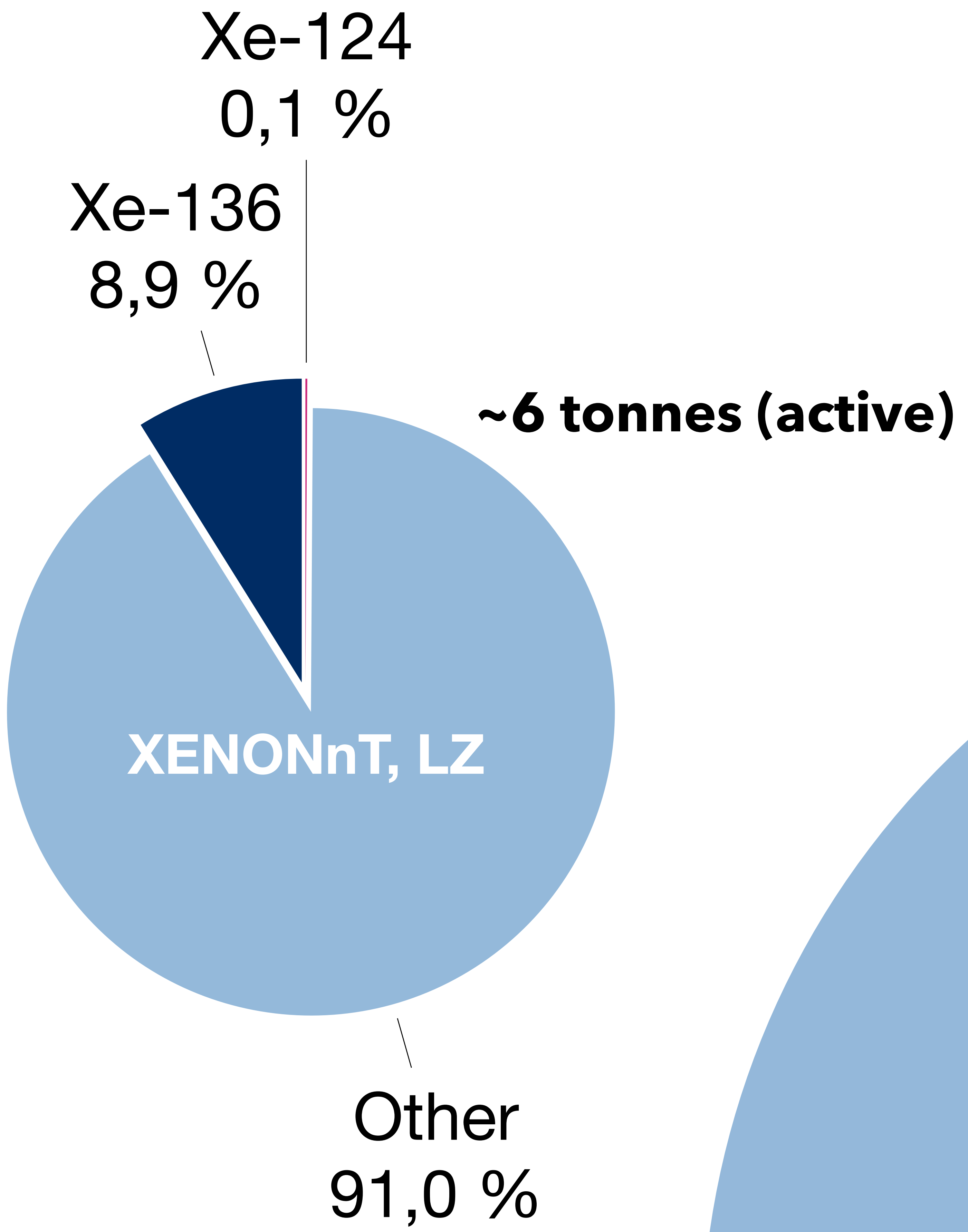
$T^{2\nu}_{1/2} = (2.2 \pm 0.7) \cdot 10^{28}$ yr

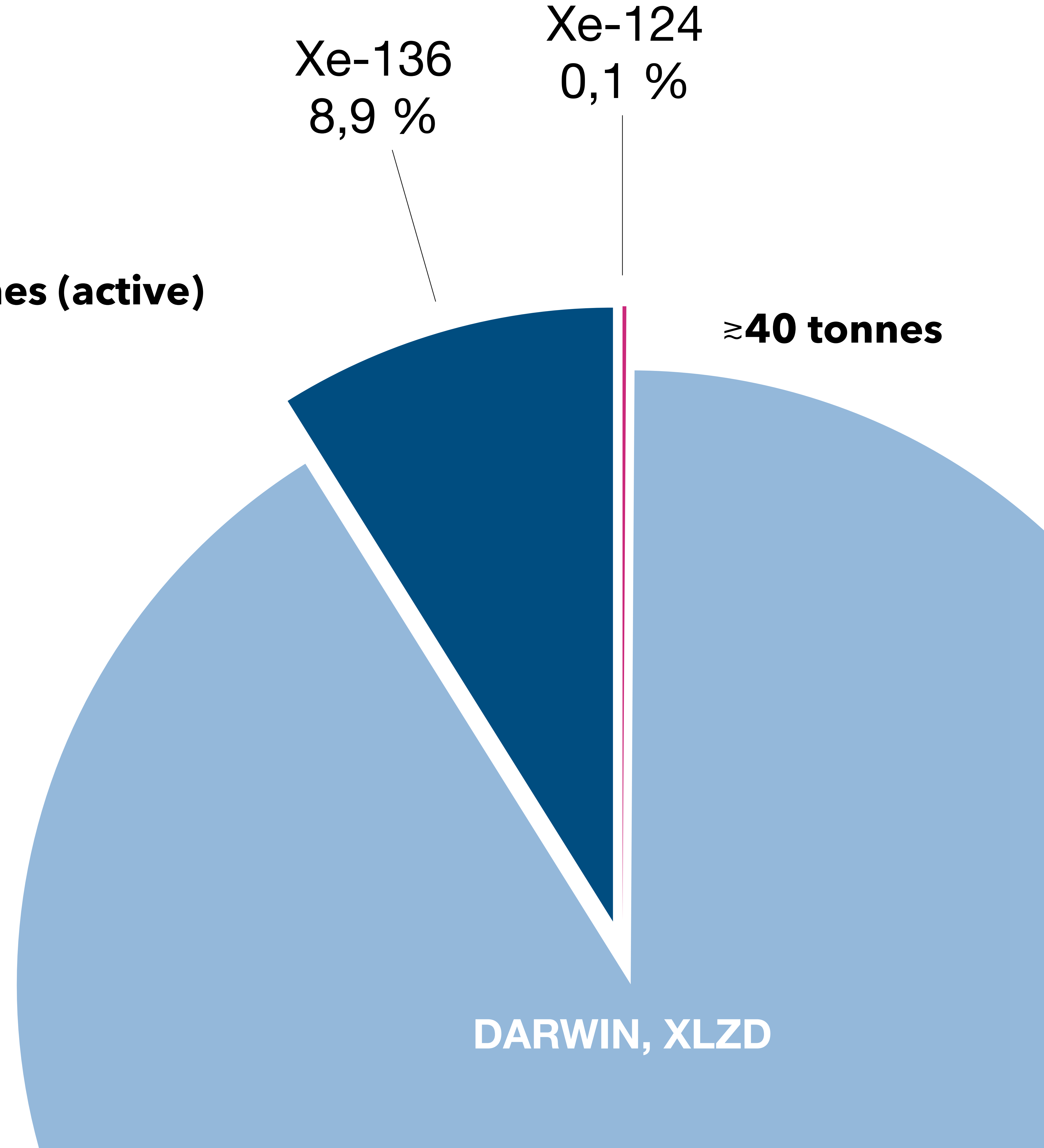
$T^{0\nu}_{1/2} > 8.6 \cdot 10^{26}$ yr – $9.3 \cdot 10^{29}$ yr



Experiments

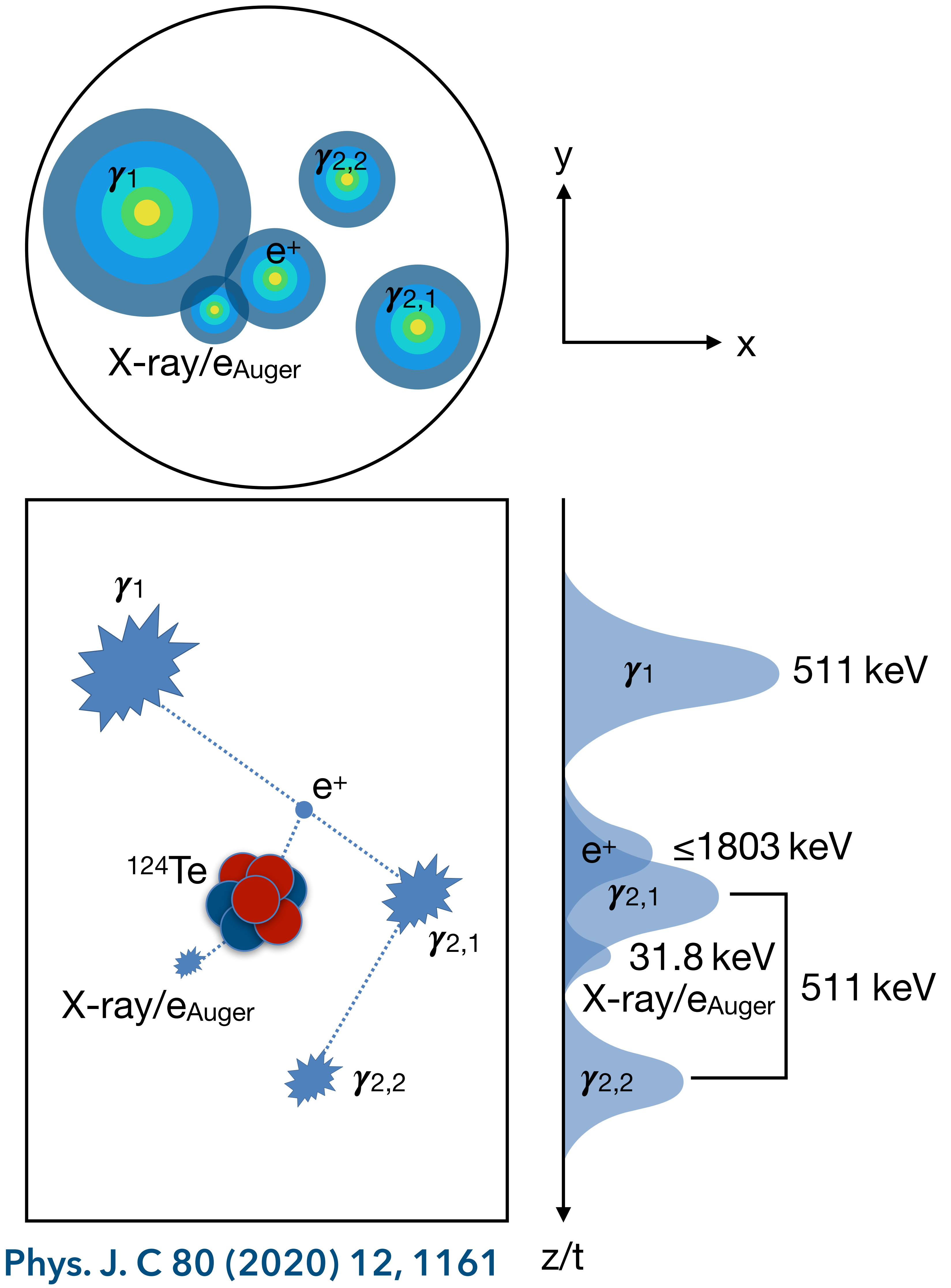






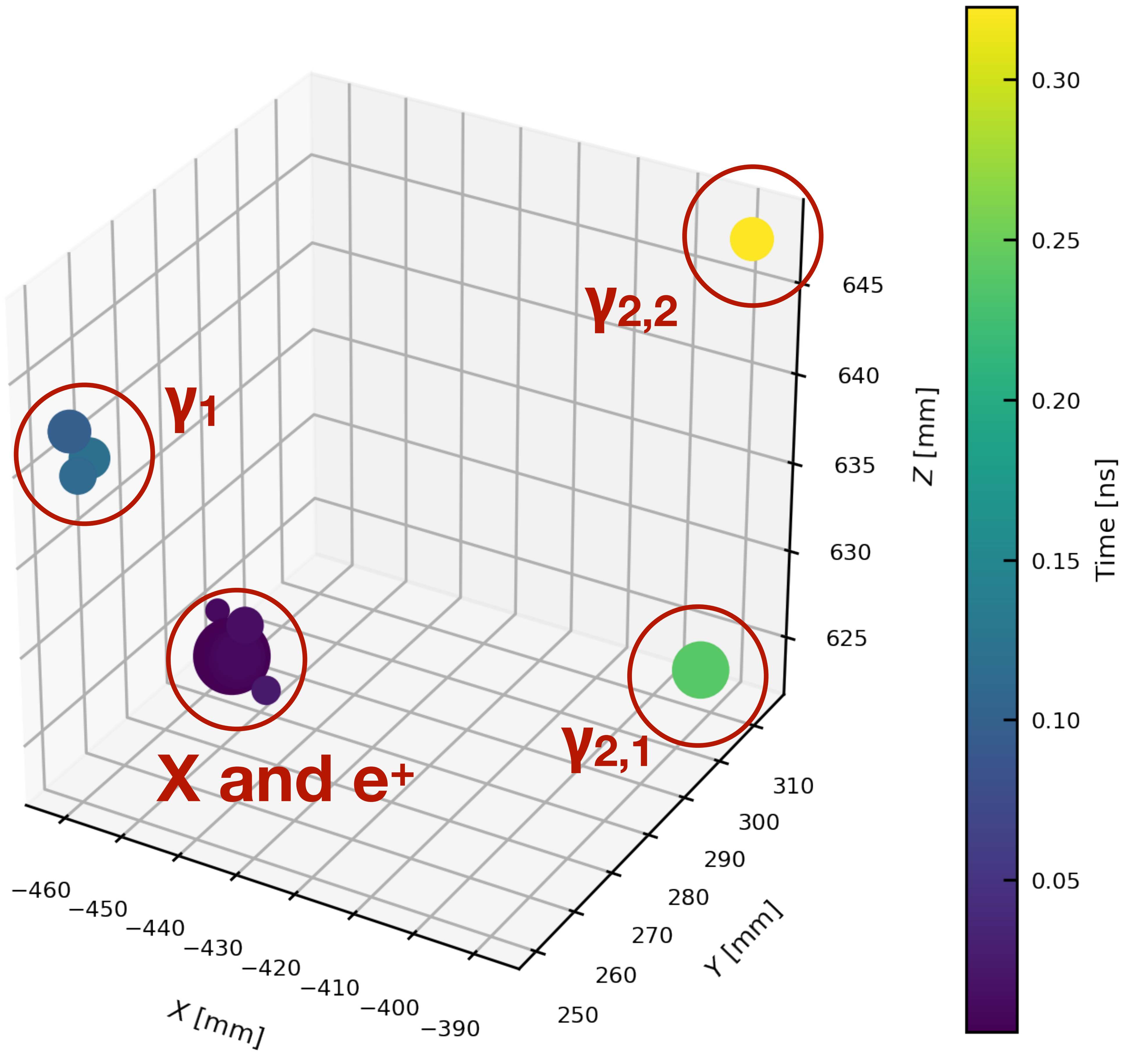
- Natural xenon with ~1 kg ^{124}Xe per tonne
- Detectors feature dual-signal readout of light and charge for calorimetry and position reconstruction

Simulation of event signatures



Eur. Phys. J. C 80 (2020) 12, 1161

- Light signal and delayed charge signal give ***x***, ***y***, ***z***, ***E***
- Simulate decays in simplified geometries
- Reconstruct distinct decay signatures
- Determine efficiency and background suppression



Simulated 0νECβ+ event

Reconstruction efficiency

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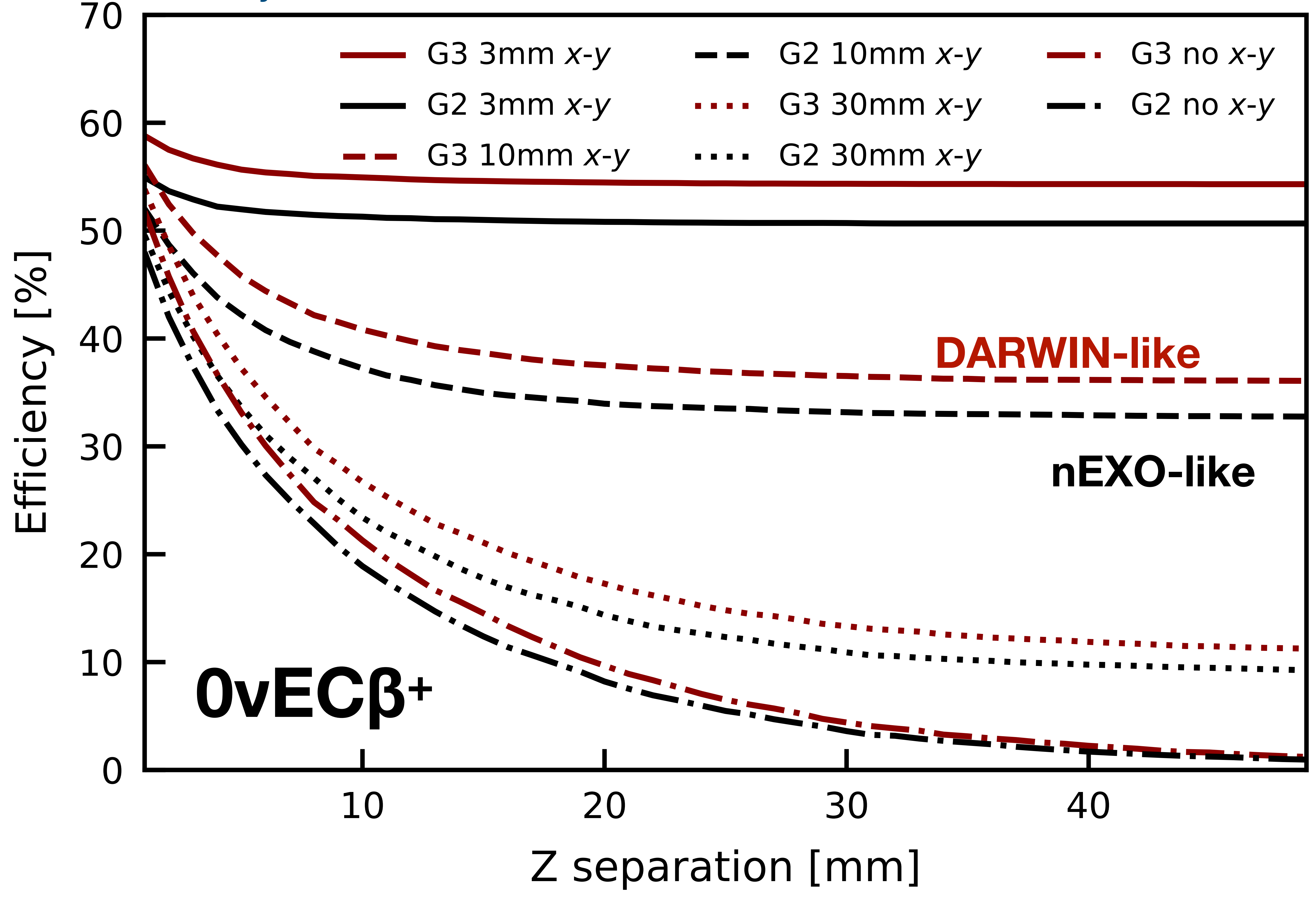
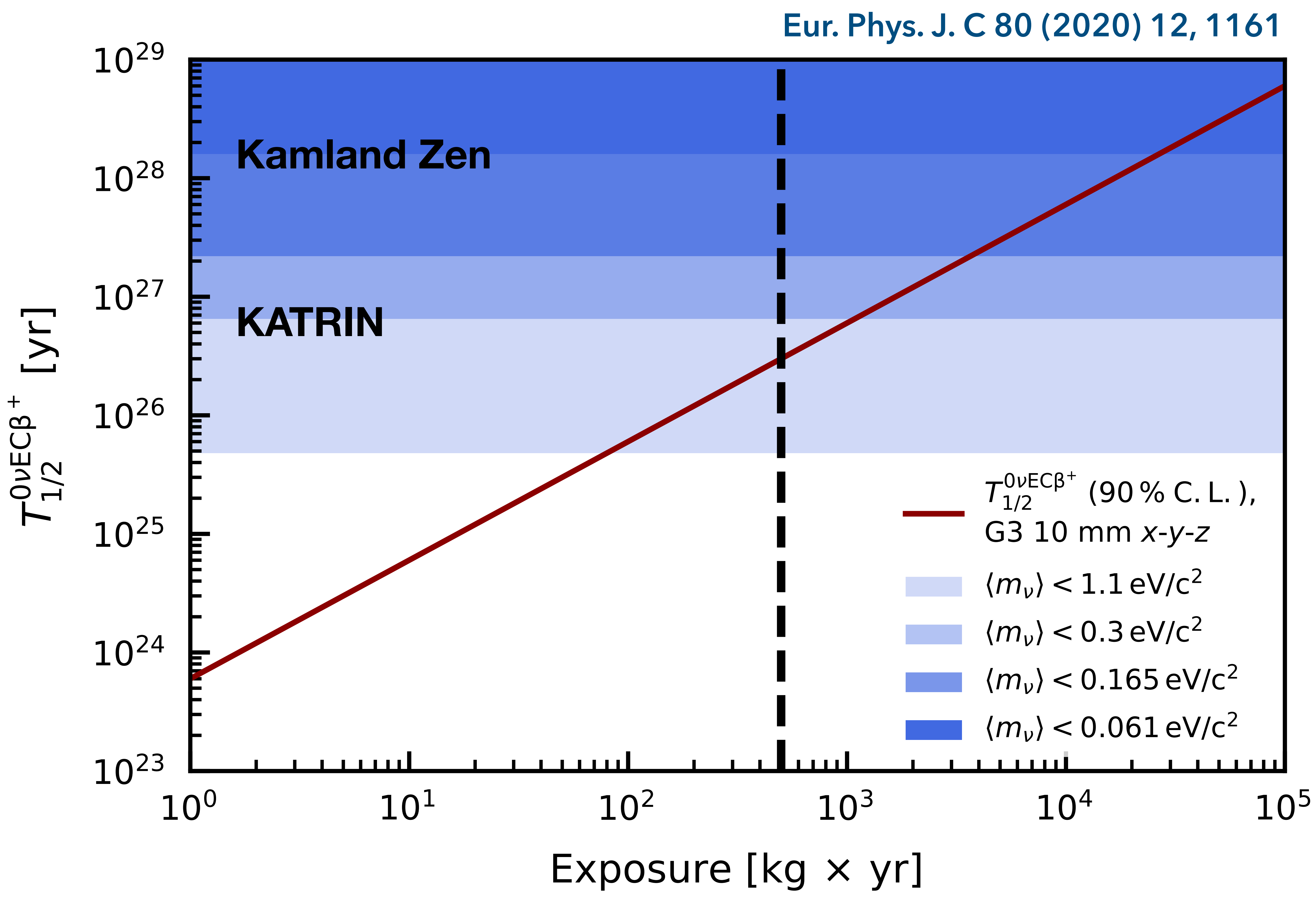


- Energy resolution (~ XENON1T)
- Energy threshold (~ keV for XENON1T)
- X-Y-Z separation of energy depositions

~ 40 % efficiency for 0vECβ^+

0vECβ^+ virtually background-free

Sensitivity

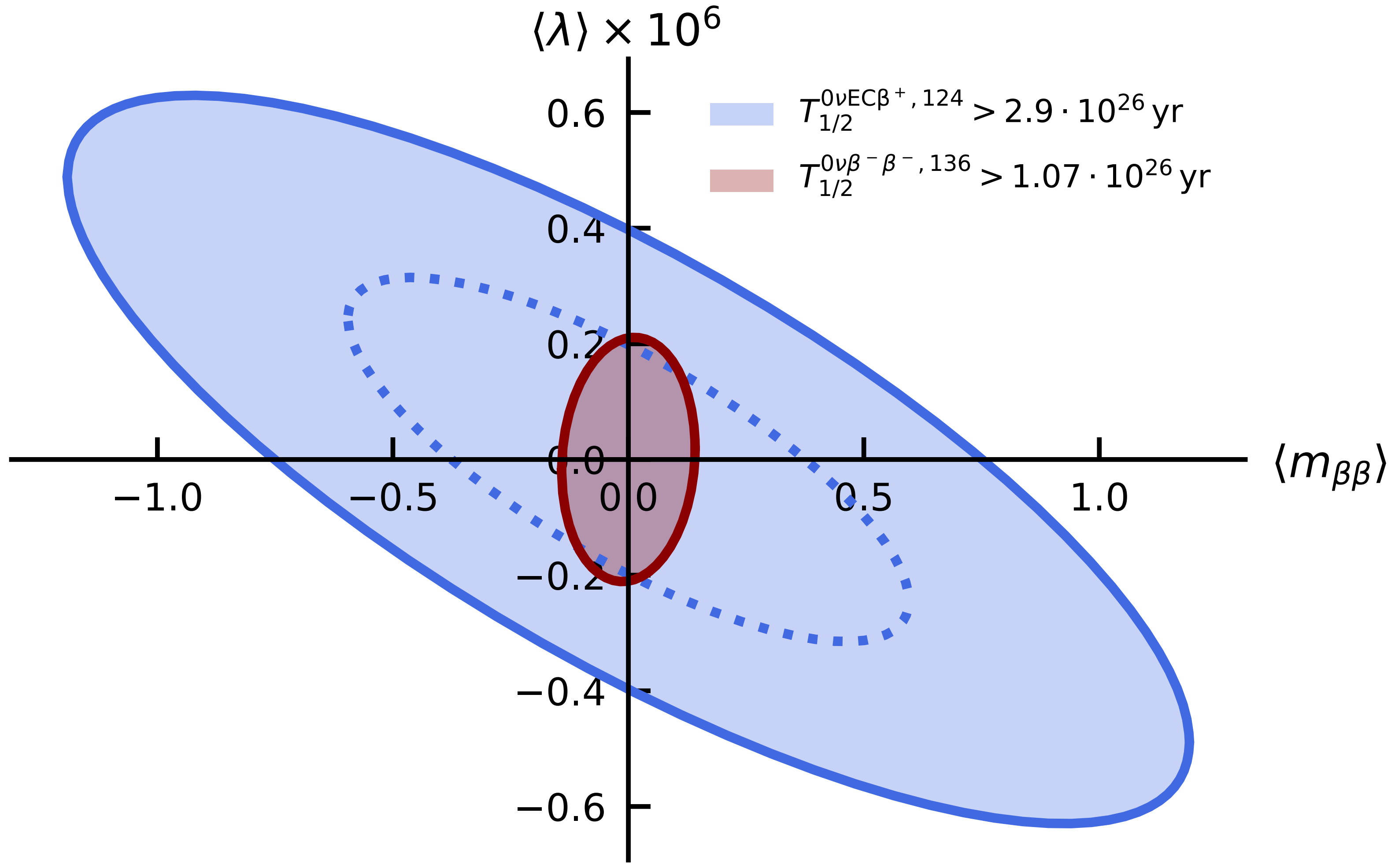


- Assume a background-free DARWIN-like experiment
- 90 % C.L. for observation of less than 2.3 events
- Sensitivity reaches most optimistic prediction
- Gain efficiency through improved reconstruction e.g. from machine learning algorithms

Need larger exposures and natural xenon (or enrichment tailings)!

What if it is not light neutrino exchange?

M. Hirsch et al.: Zeitschrift für Physik A Hadrons and Nuclei 347, 151 (1994)

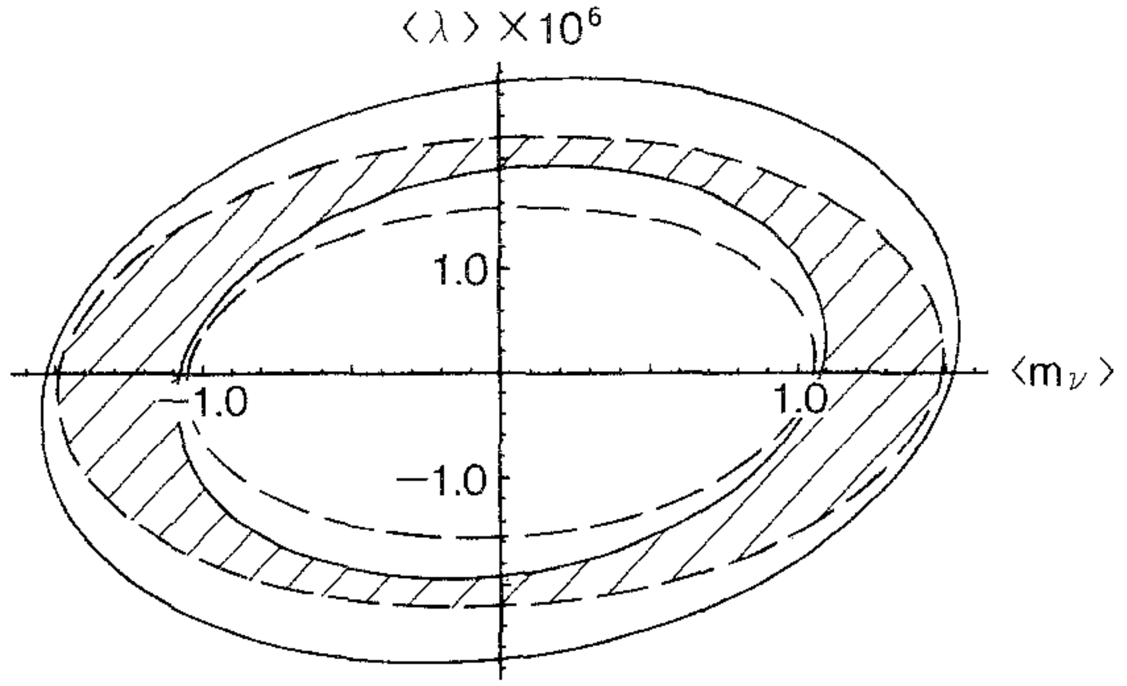


$$[T^{\alpha}_{1/2}(0^+_i \to 0^+_f)]^{-1} = C^{\alpha}_{mm}\left(\frac{\langle m_\nu\rangle}{m_e}\right)^2 + C^{\alpha}_{\eta\eta}\langle\eta\rangle^2 + C^{\alpha}_{\lambda\lambda}\langle\lambda\rangle^2 + C^{\alpha}_{m\eta}\frac{\langle m_\nu\rangle}{m_e}\langle\eta\rangle + C^{\alpha}_{m\lambda}\frac{\langle m_\nu\rangle}{m_e}\langle\lambda\rangle + C^{\alpha}_{\eta\lambda}\langle\eta\rangle\langle\lambda\rangle$$

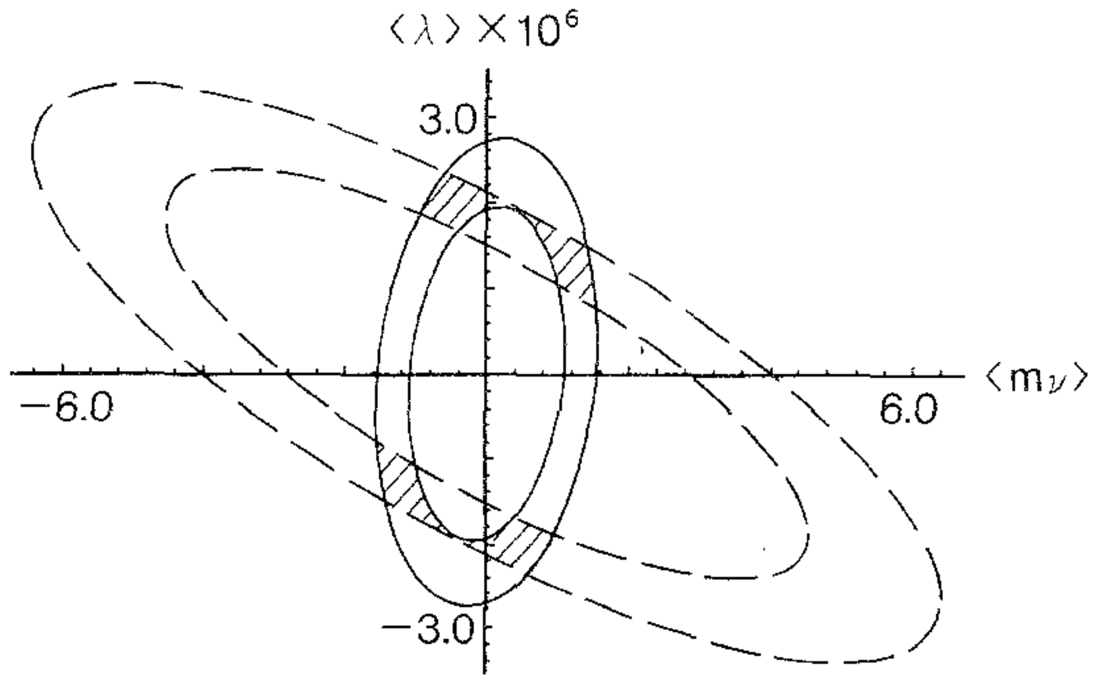
Matrix elements

Couplings and mixing

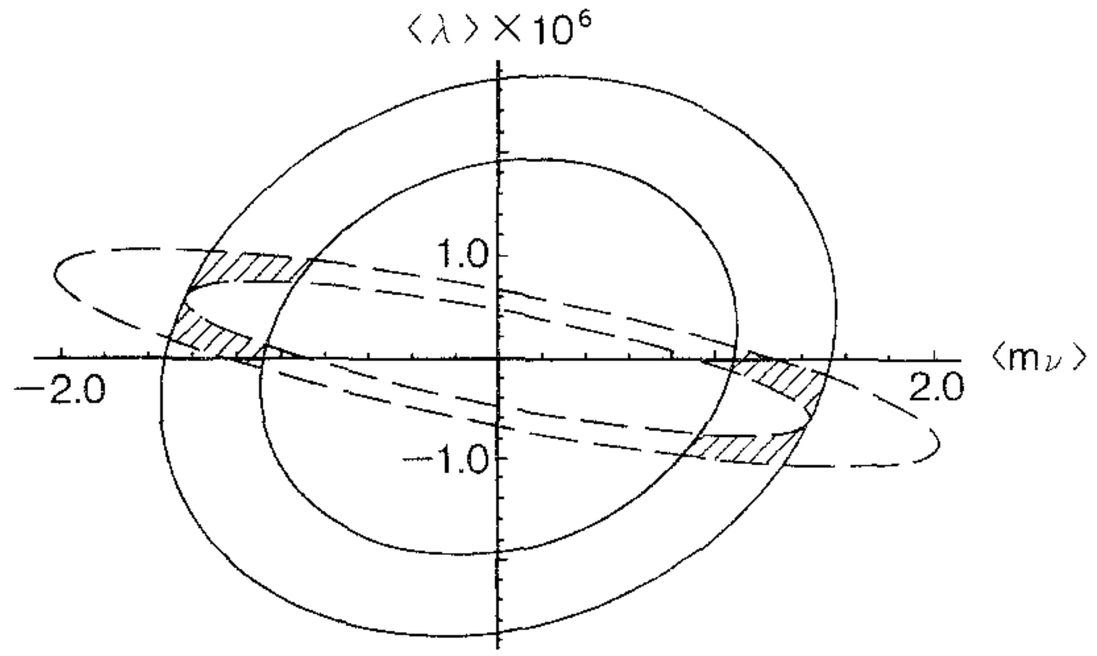
Observation of 0νβ⁻β⁻ in ^{76}Ge (full) and ^{136}Xe (dashed) with $T_{1/2} = (1.5 \pm 0.5) \times 10^{24}$ yr



Observation of 0νβ⁻β⁻ in ^{76}Ge and 0νECβ⁺ of ^{124}Xe with $T_{1/2} = (1.5 \pm 0.5) \times 10^{25}$ yr



Observation of 0νβ⁻β⁻ in ^{76}Ge and 0νECβ⁺ of ^{124}Xe with $T_{1/2} = (1.5 \pm 0.5) \times 10^{26}$ yr



Summary and outlook

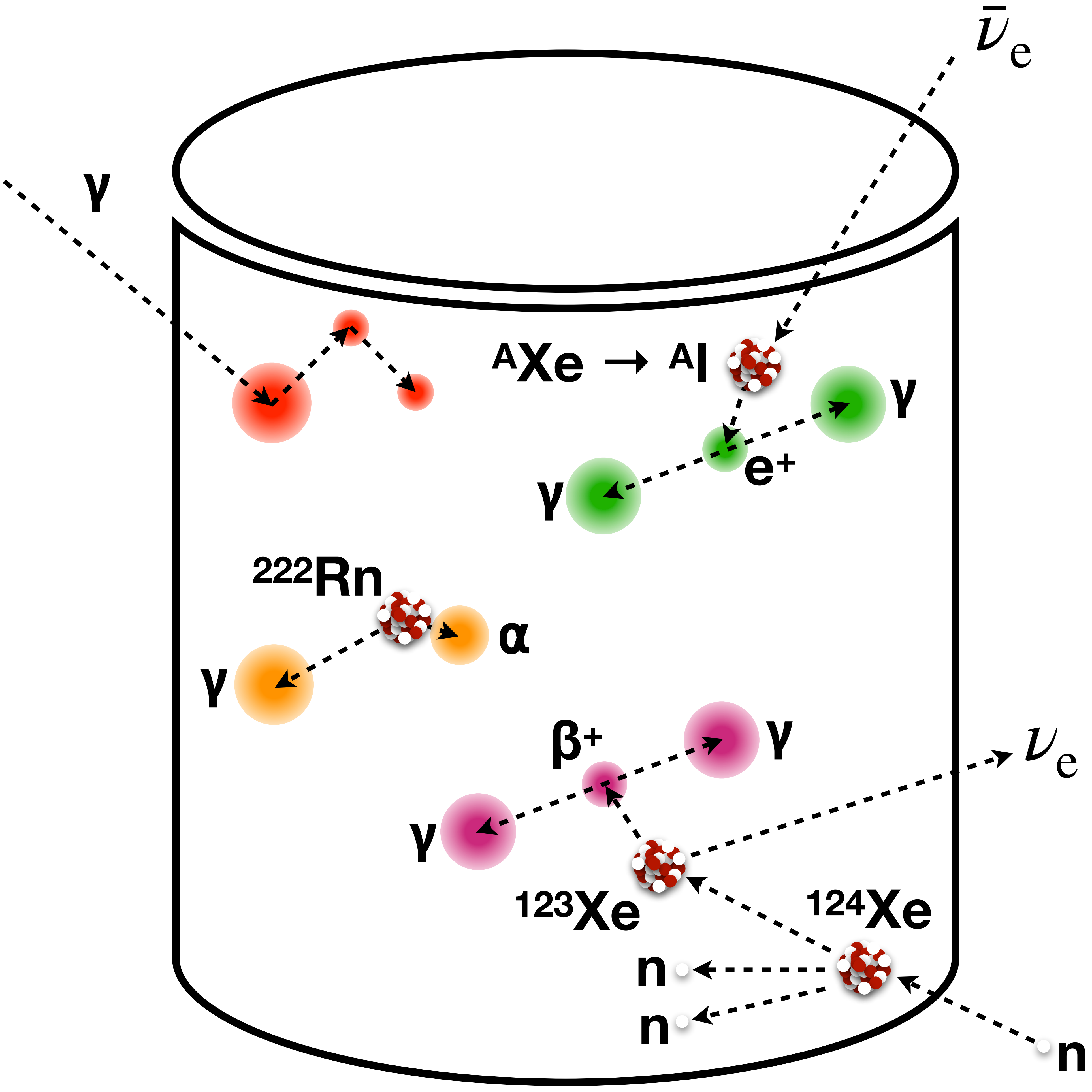
- ^{124}Xe supports three two-neutrino and three neutrinoless decay modes
- 2vECEC on the way of becoming a set of calibration lines.
- 2vECβ^{+} in reach for XENONnT and LZ
- 0vECβ^{+} is most promising for neutrinoless decay searches in ^{124}Xe and could provide complementary information to other isotopes
- Position resolution and background requirements met by current technology.
- 0vECβ^{+} requires kilotonne-year ^{nat}Xe exposures for realistic chance of observation

Backup slides

Double-beta emitters

Isotope	Q-value (keV)	Allowed decay modes	Natural abundance (%)
^{124}Xe	2857	ECEC, ECβ^+, $\beta^+\beta^+$	0.095
^{126}Xe	920	ECEC	0.089
^{134}Xe	826	$\beta^-\beta^-$	10.436
^{136}Xe	2458	$\beta^-\beta^-$	8.857

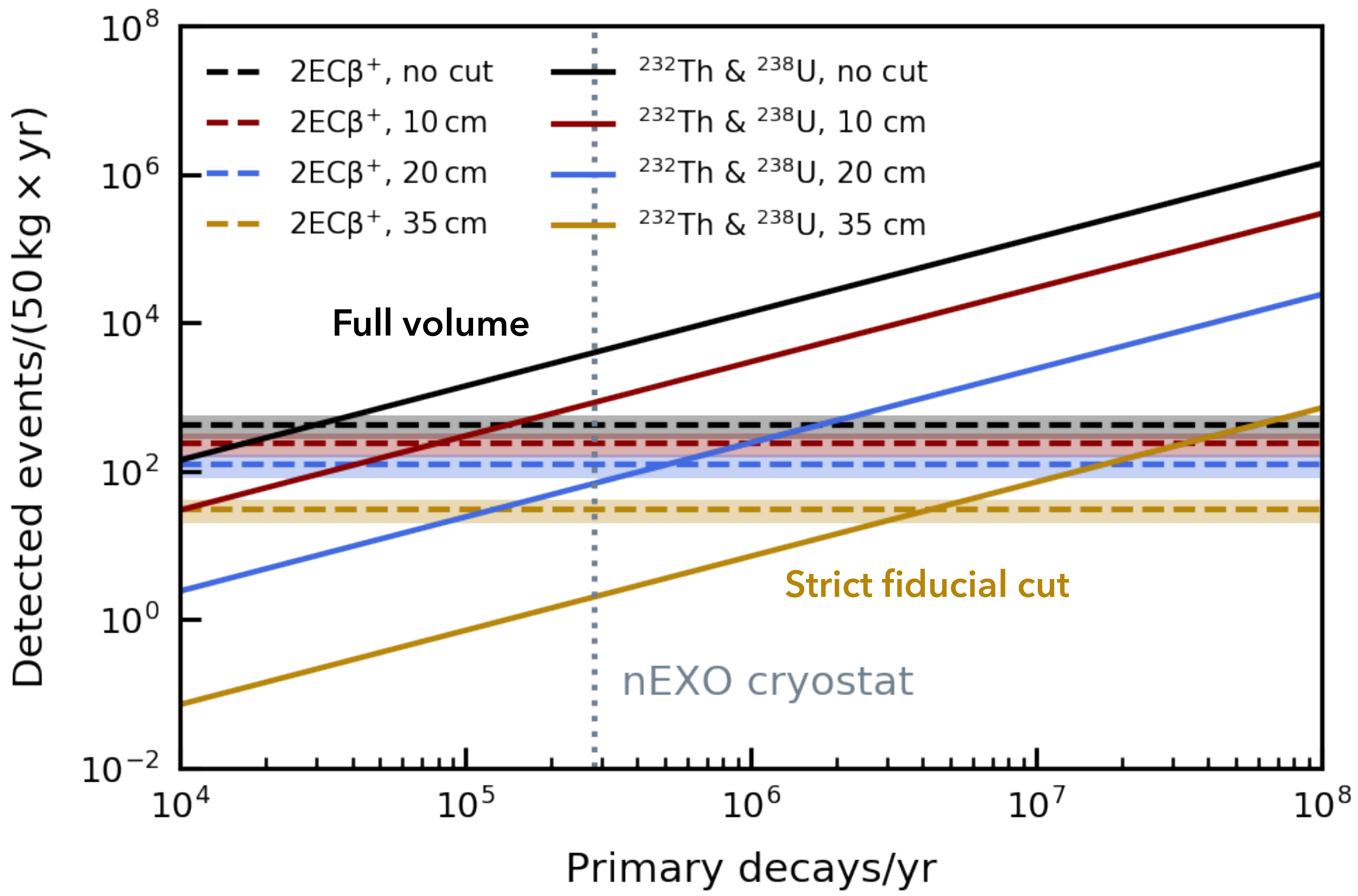
Background sources



^{222}Rn	CC scattering of (anti-)neutrinos	Neutron-induced backgrounds	External γ-rays
Intrinsic to the liquid xenon	Positrons from scattering of reactor- and geoneutrinos	^{124}Xe(n,2n)^{123}Xe	Radioactive contaminations of detector materials and external radiation
α removed by S2/S1 ratio, BiPo coincidence, β-decays do not pass selection criteria	Cannot be discriminated	Only muon-induced neutrons, β^+-BR, underground shielding, dependent on ^{124}Xe	Isotopes of interest vary depending on decay mode (mimic different signals)
-	< 1 event in 100,000 t-yr	< 10^{-3} - 10^{-2} events per t-yr	Depending on fiducialization

Backgrounds from ^{238}U and ^{232}Th chains

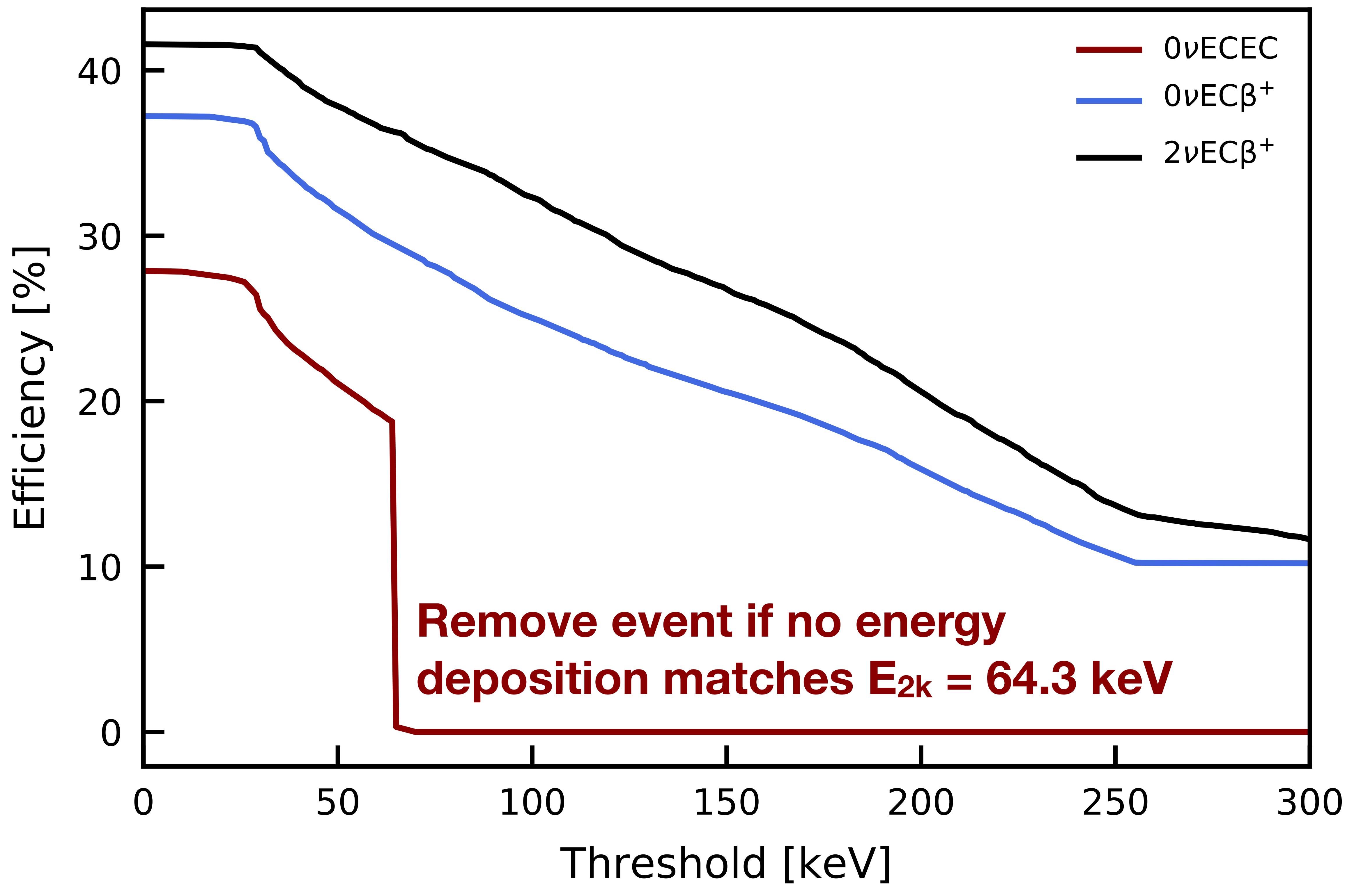
Events falsely detected as signal



Decreasing number of true signal events in FV

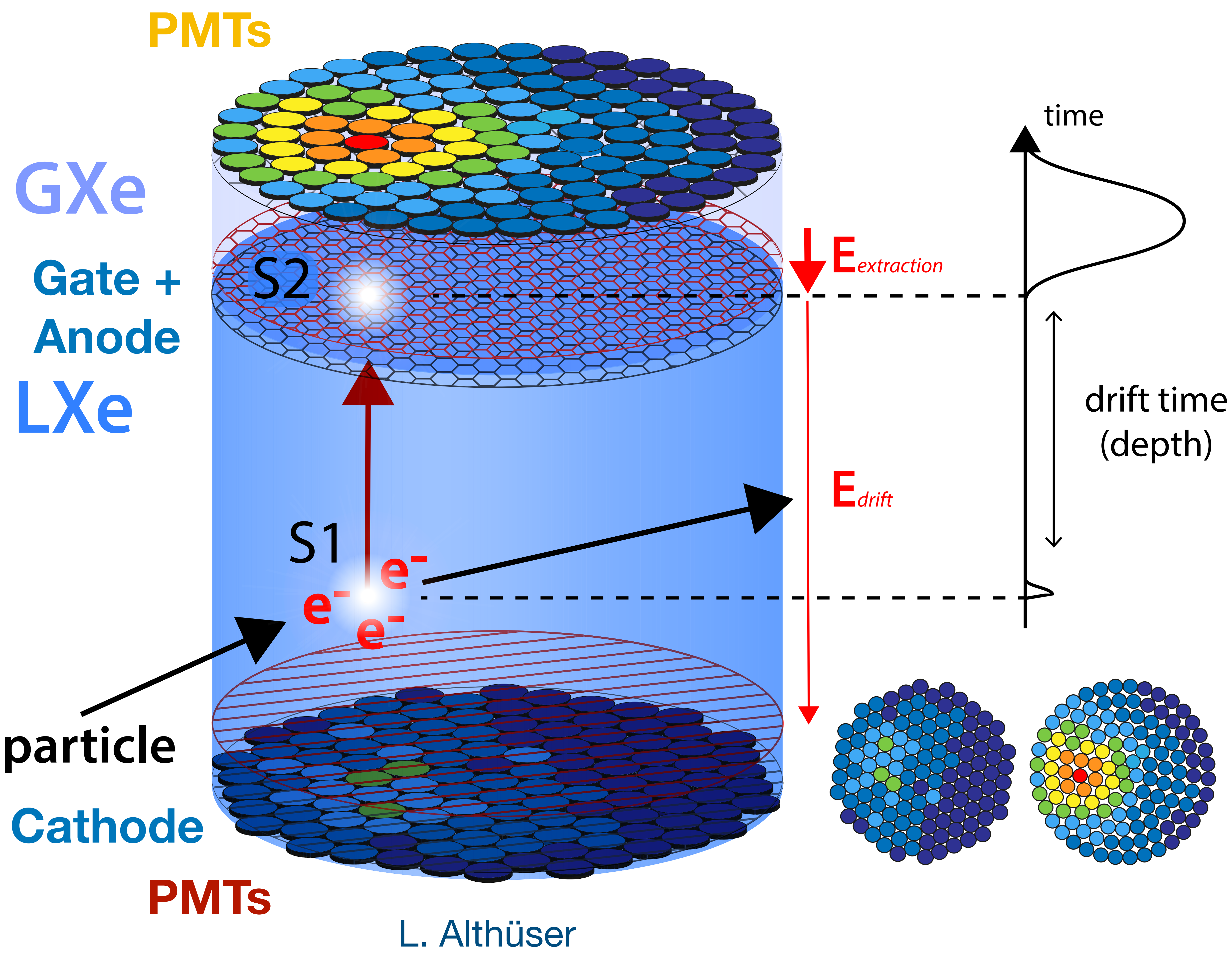
Number of primary ^{232}Th and ^{238}U decays expected from detector materials

Threshold and efficiency



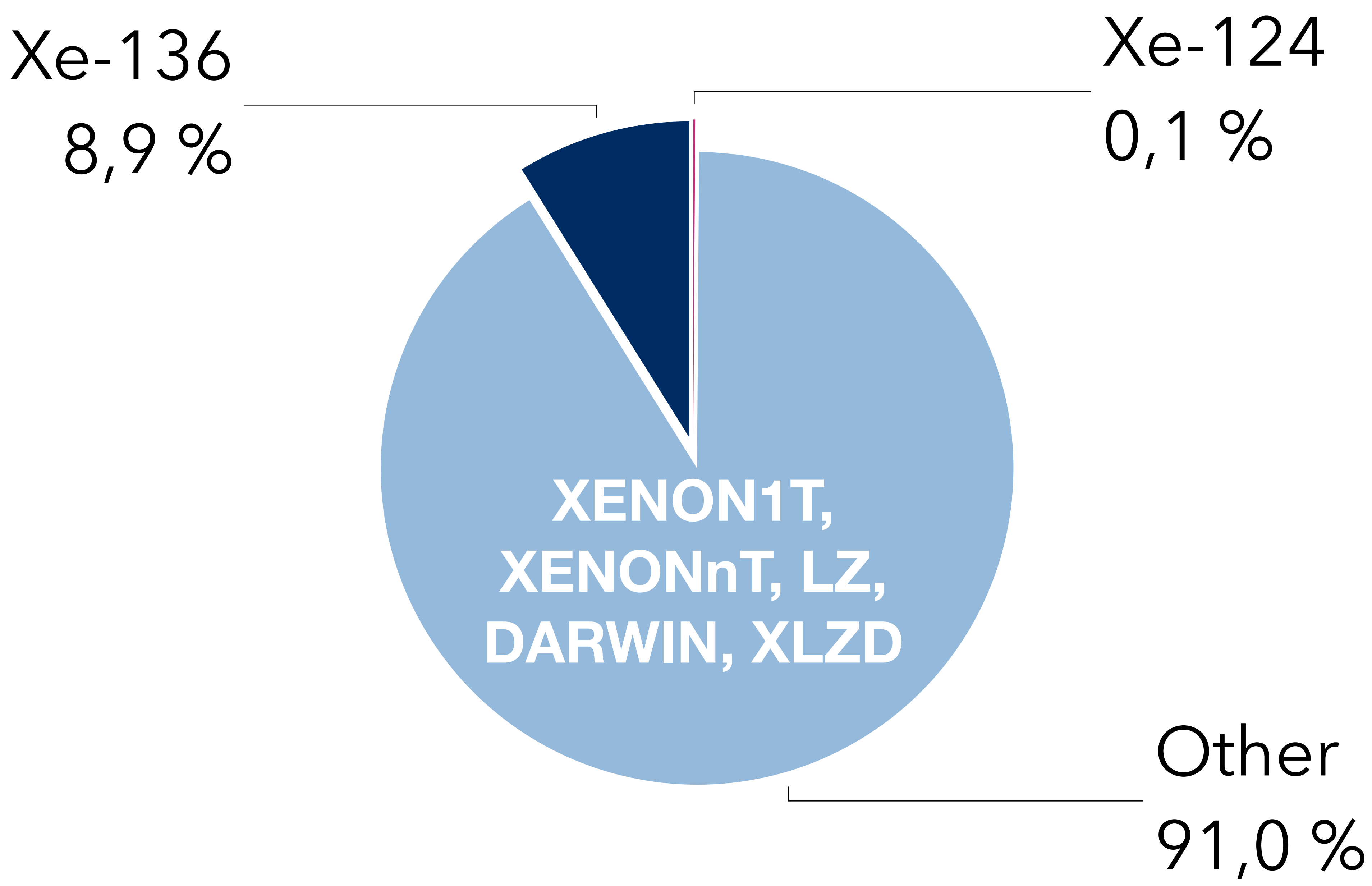
- Total energy deposition resolution still has room for improvement from signal readout (see as much light and charge as possible).
- Energy resolution for clusters by S2-only intrinsically limited by recombination fluctuations.
- Energy threshold can be tuned by signal readout.
- XENONnT/LZ and DARWIN have O(keV) threshold.
- EXO had ~ O(100 keV) threshold – likely similar for nEXO

Dual-phase TPC for dark matter

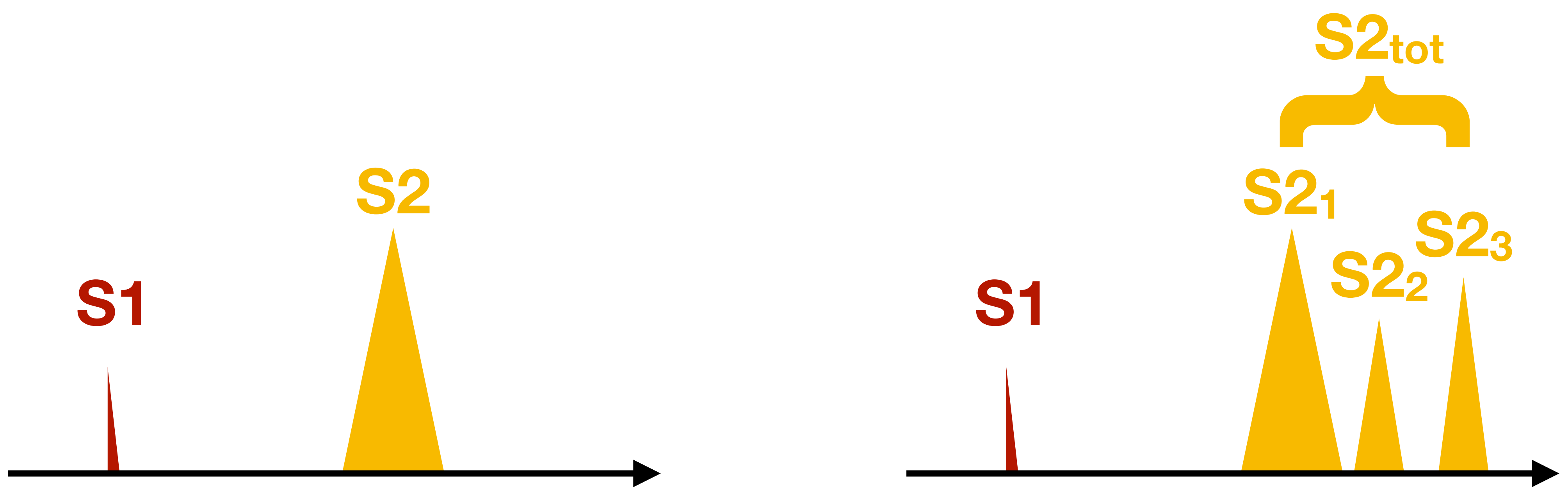


Scintillation and **ionisation:**

- Prompt light signal (**S1**).
- Secondary light in GXe from drifted charges (**S2**).
- Position reconstruction and calorimetry.

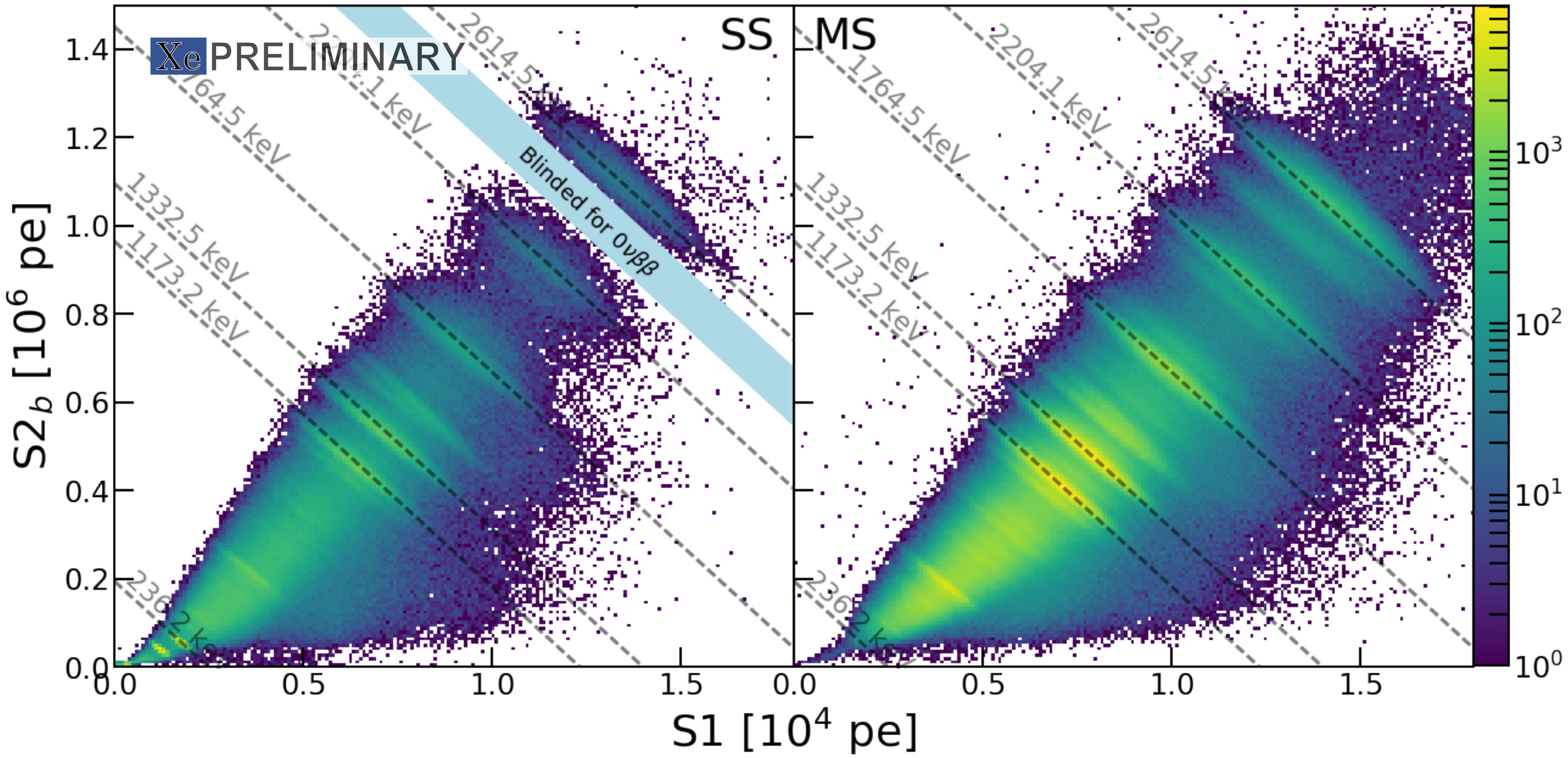


Event characteristics



WIMPs, **X-rays**, ɣ (E<200 keV), β-electrons

Neutrons, ɣ (E>200 keV)



$$E = W \cdot \left(\frac{S1}{g_1} + \frac{S2}{g_2} \right)$$

z from **S1**-**S2**-delay

x-y from **S2** hit pattern