Next-generation neutrinoless double beta decay search with LXe

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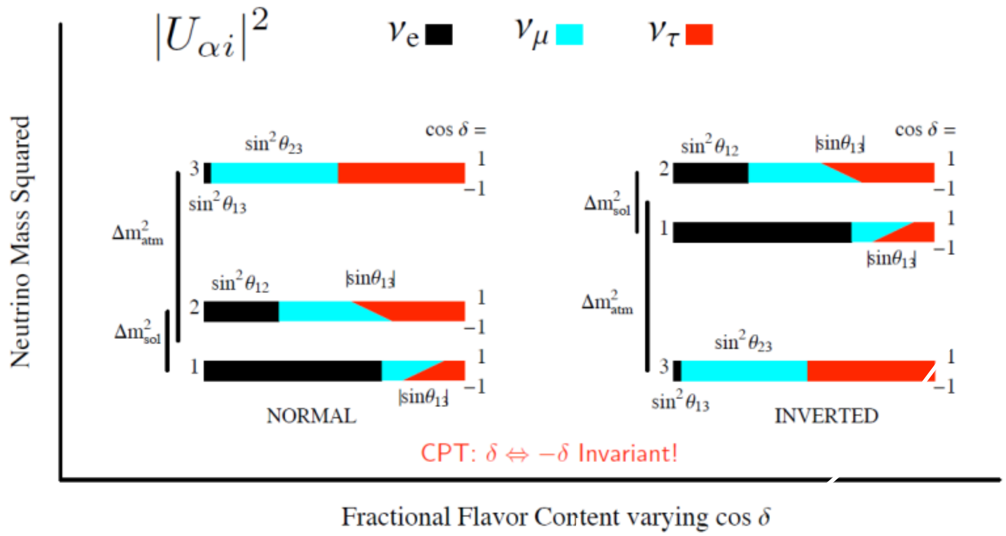
Neutrinos in the standard model

<u>Neutrinos have non-vanishing masses</u>

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$



$$\left|\sum_i m_i U_{ei}^2 e^{j\alpha_i}\right| < 150\,\text{meV}$$

0νββ searches

$$\sum_i m_i < 250\,\text{meV}$$

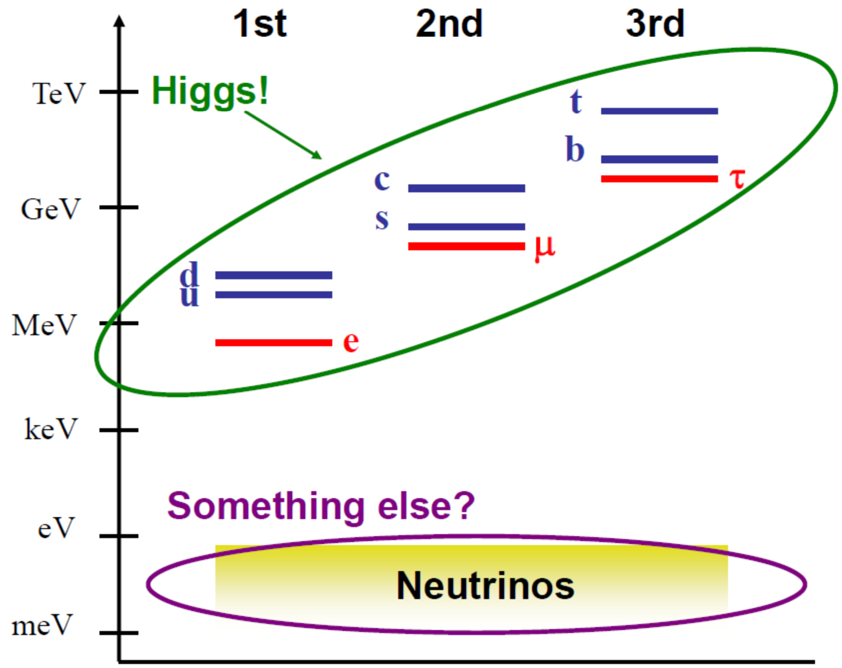
Cosmology

$$\sqrt{\sum_i (m_i U_{ei})^2} < 2.3\,\text{eV}$$

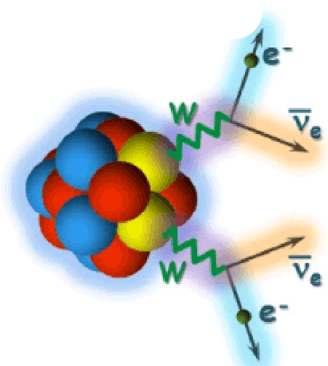
β-decay end-point of energy spectrum

Neutrinos in the standard model

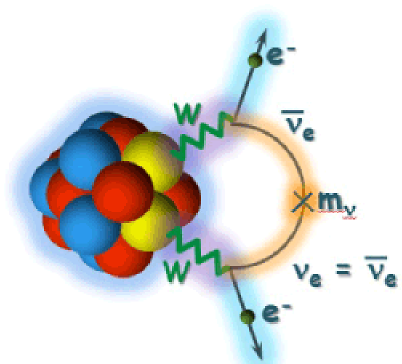
Neutrinos masses stand apart from that of the charged fermions



Neutrinoless double beta decay

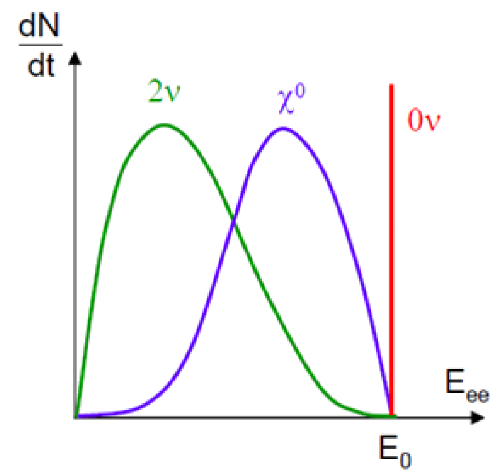


Double beta decay
which emits anti-neutrinos



Neutrinoless
double beta decay

total Lepton Number Violating process

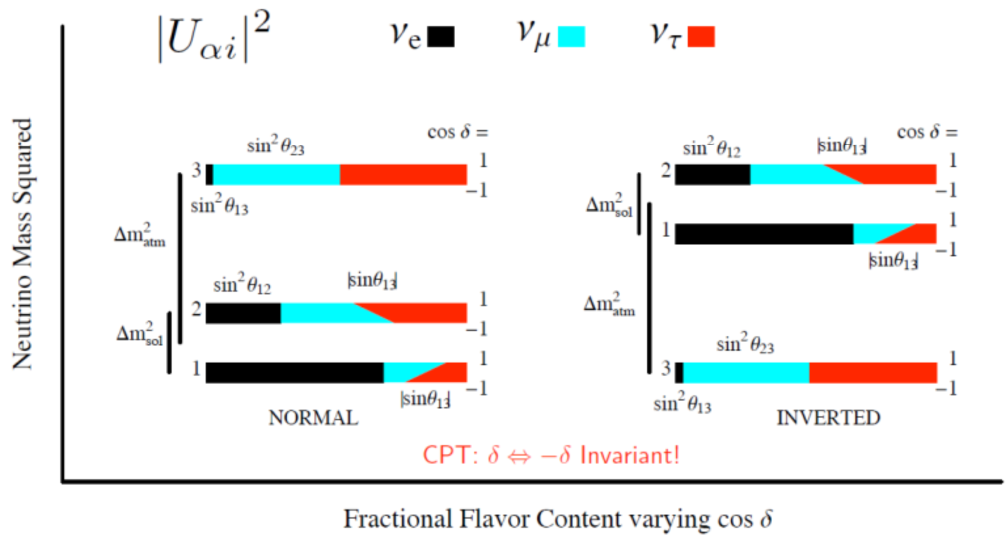


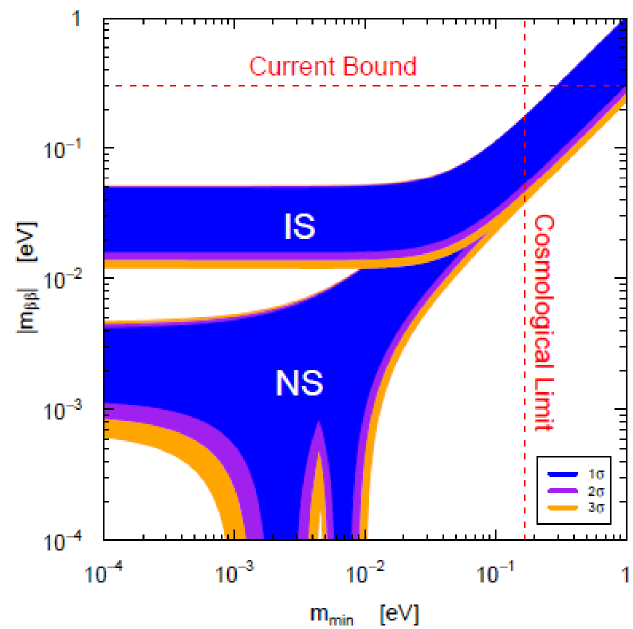
$$\left[T_{1/2}^{0\nu}(0^+ \rightarrow 0^+)\right]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\left|M^{0\nu}\right|^2 \left\langle m_{\beta\beta} \right\rangle^2$$

$$\left\langle m_{\beta\beta} \right\rangle = \left| \sum_{k=1}^{3} m_k \left|U_{ek}\right|^2 e^{i\alpha_k} \right|$$

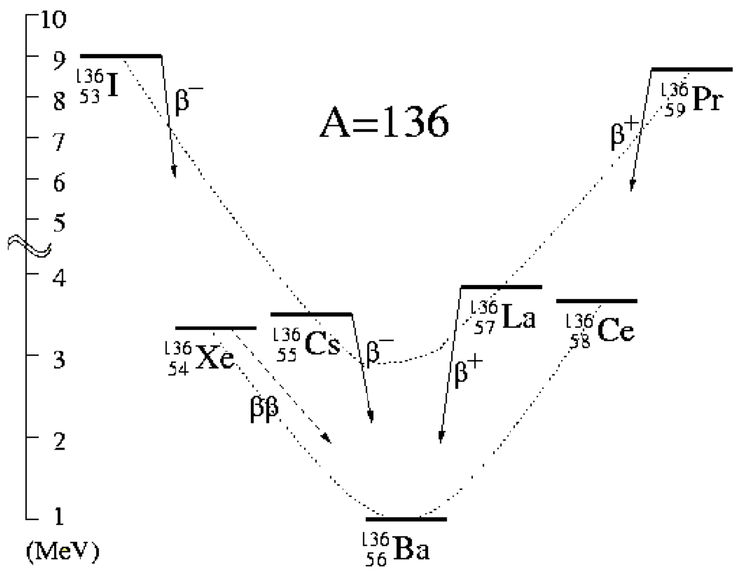
Neutrinoless double beta decay

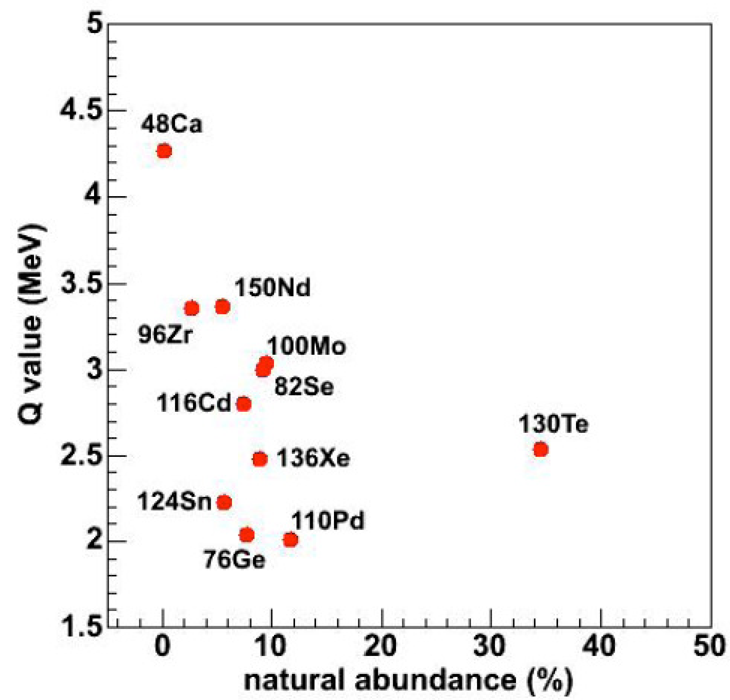
$$\langle m_{\beta\beta} \rangle = \left| \sum_{k=1}^{3} m_k |U_{ek}|^2 e^{i\alpha_k} \right|$$



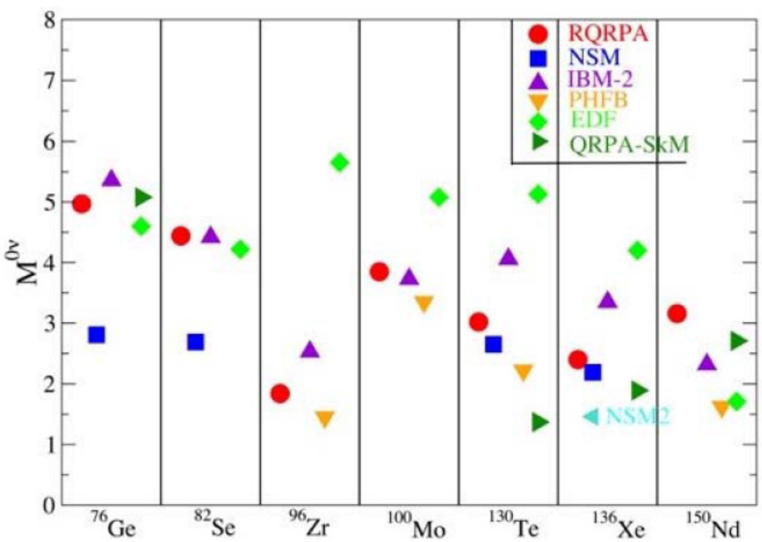


Isotope selection

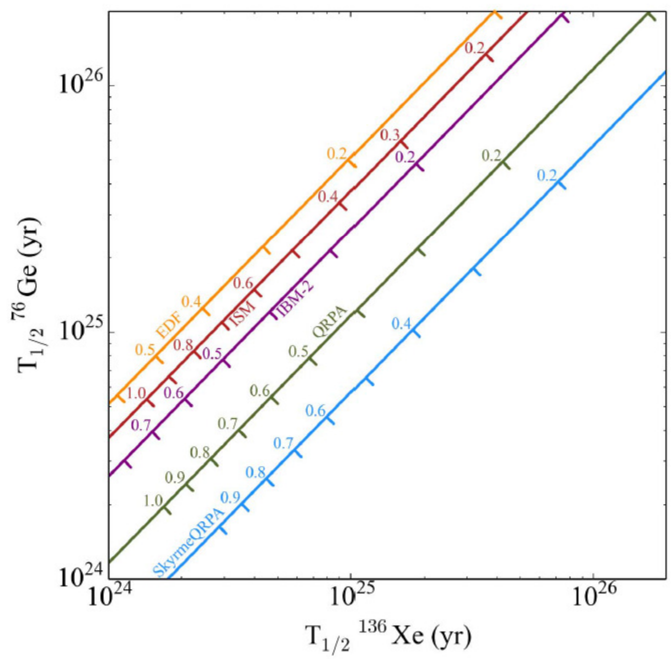




Nuclear Matrix Elements



Petr Vogel, 2014

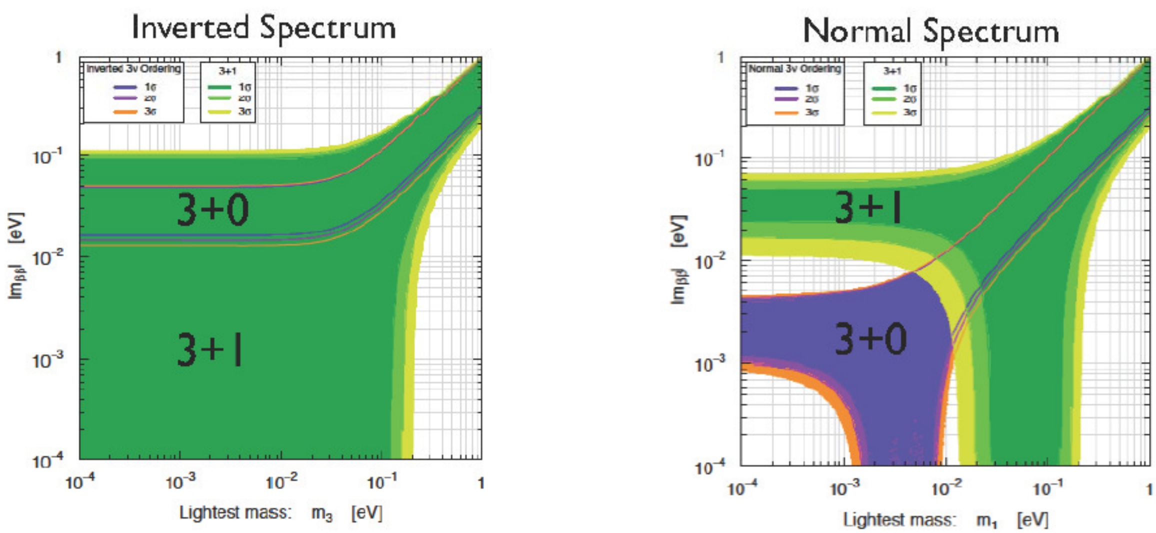


EDF: T.R. Rodriguez and G. Martinez-Pinedo, PRL 105, 252503 (2010)
ISM: J. Menendez et al., Nucl Phys A 818, 139 (2009)
IBM-2: J. Barea, J. Kotila, and F. Iachello, PRC 91, 034304 (2015)
QRPA: F. Šimkovic et al., PRC 87 045501 (2013)
SkyrmeQRPA: M.T. Mustonen and J. Engel PRC 87 064302 (2013)

Other LNV processes

- Low scale seesaw: intriguing example with one light sterile ν_R with mass (~eV) and mixing (~0.1) to fit short baseline anomalies
- Extra contribution to effective mass $m_{\beta\beta} = m_{\beta\beta}|_{\text{active}} + |U_{e4}|^2 \, e^{2i\Phi} \, m_4$

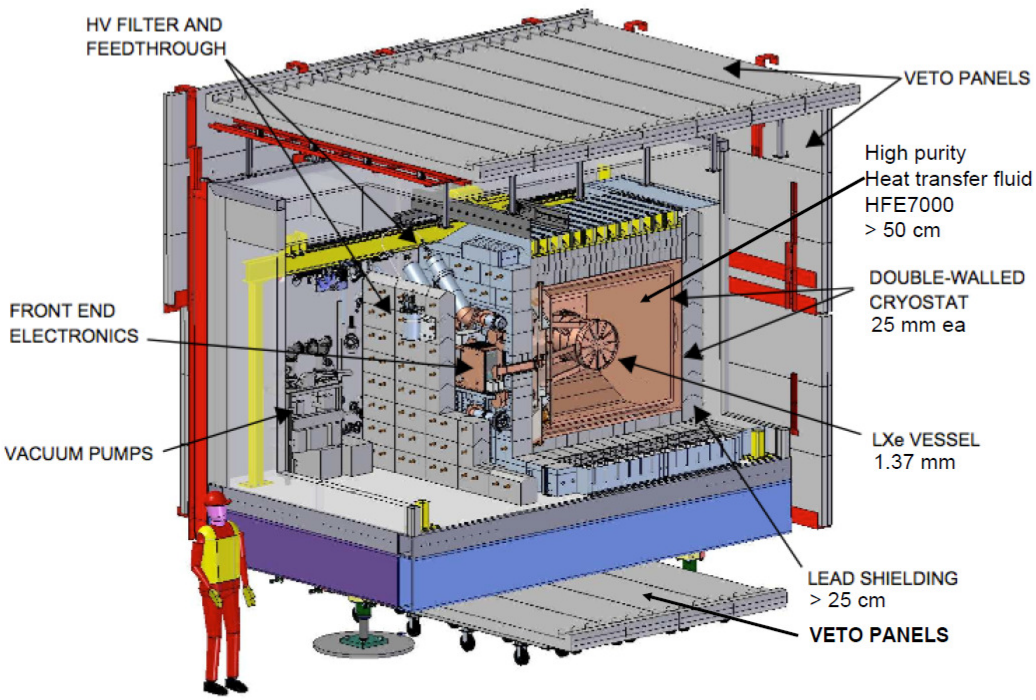
Stolen from V.Cirigliano, NSAC Oct 2016

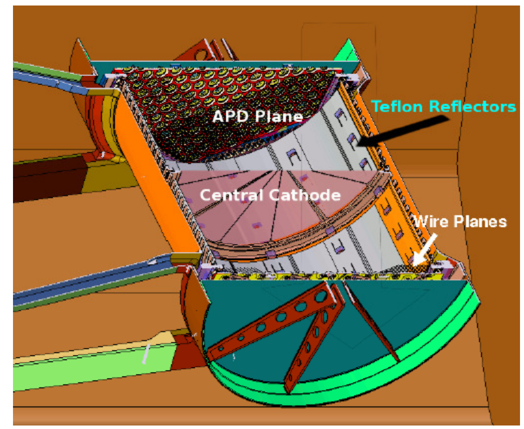


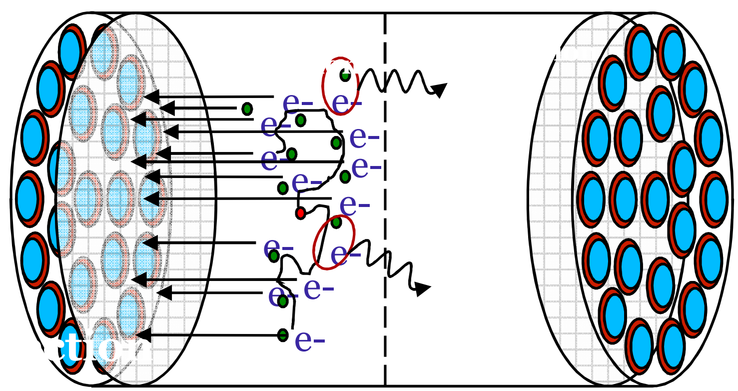
Giunti-Zavanin 1505.00978

Usual phenomenology turned around !

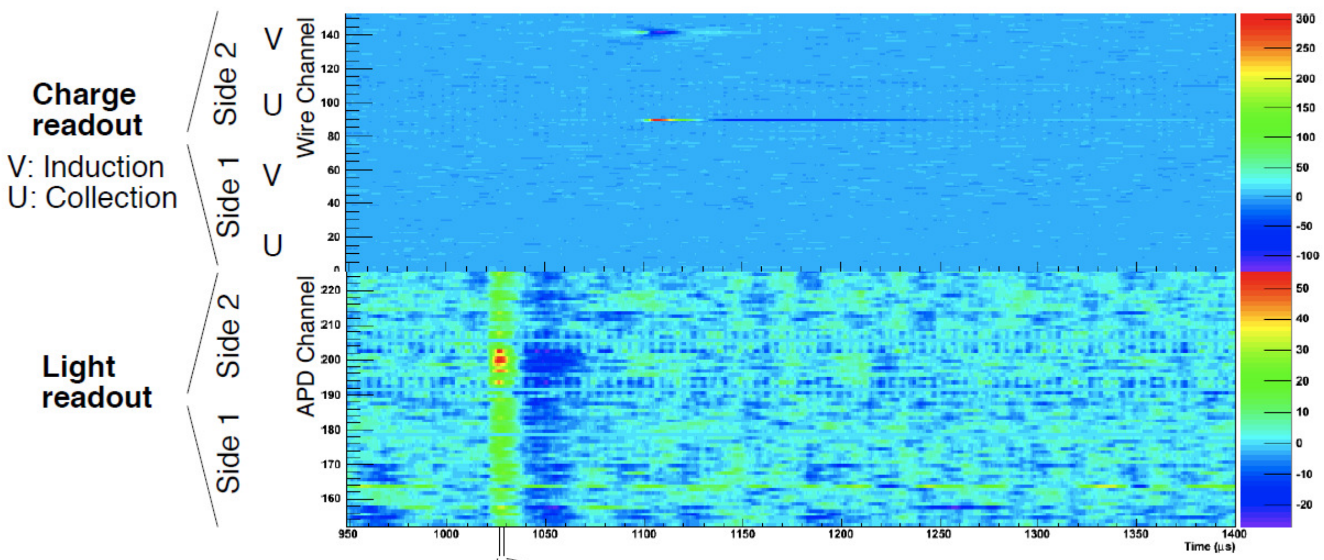
EXO-200 prototype

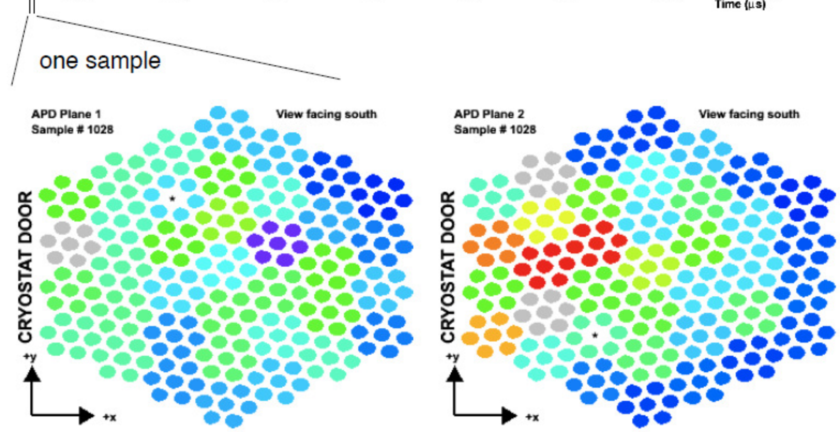






Data collection



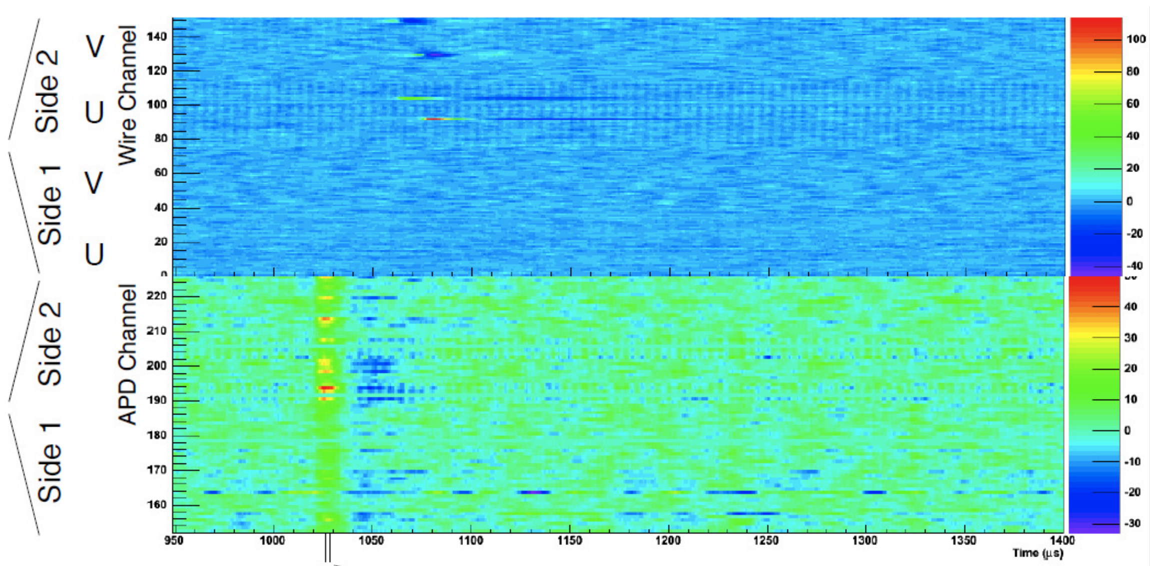


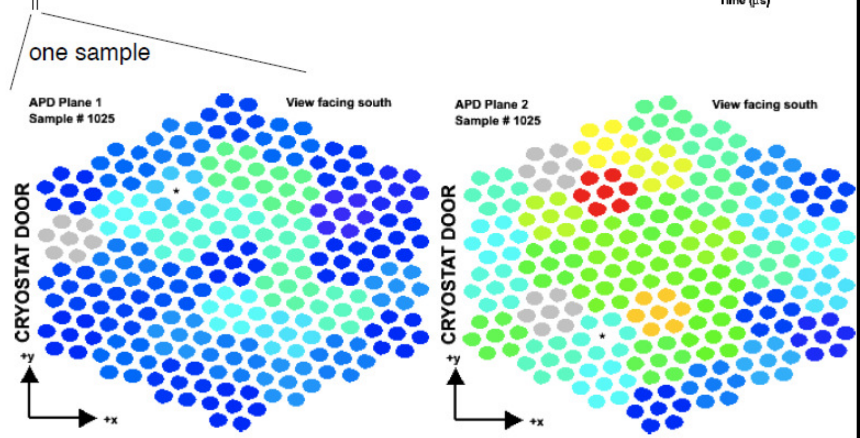
A single-site energy deposition in EXO-200

Scintillation light is seen at both sides. The light is more diffuse on side 1 and more localized on side 2, where the event occurred.

The light signal always precedes both charge signals. The induction (V) signal precedes the collection (U) signal.

Data collection





A two-site Compton scattering event

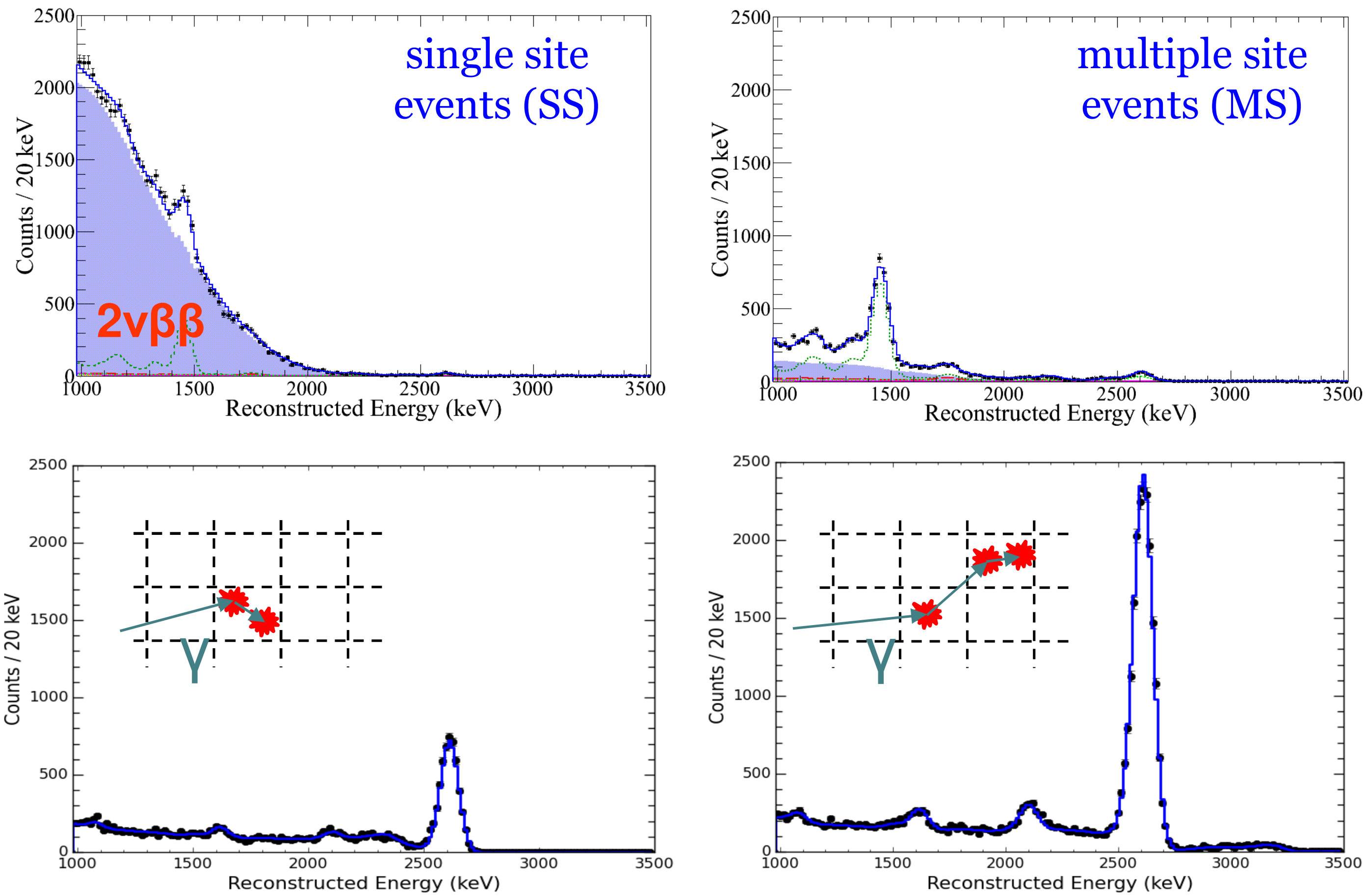
All scintillation light arrives at the same time, indicating that the two energy depositions are simultaneous.

In this case, the gamma ray occurred on side 2. The light hitting side 2 is more localized, while the light hitting side 1 is more diffuse across the plane.

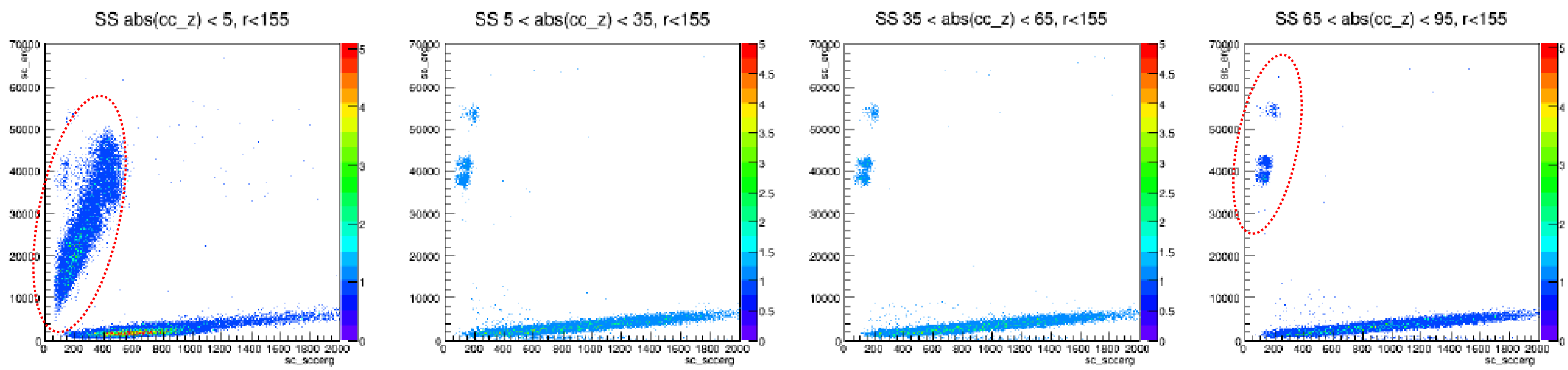
Event topology

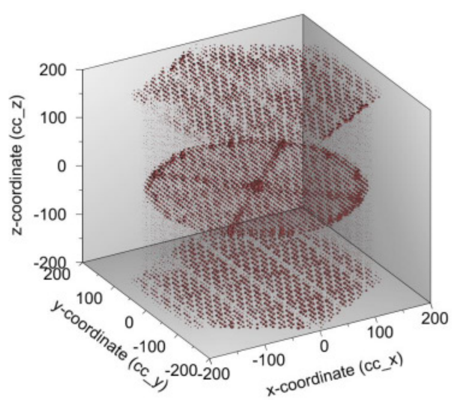
Low background data

^{228}Th calibration source

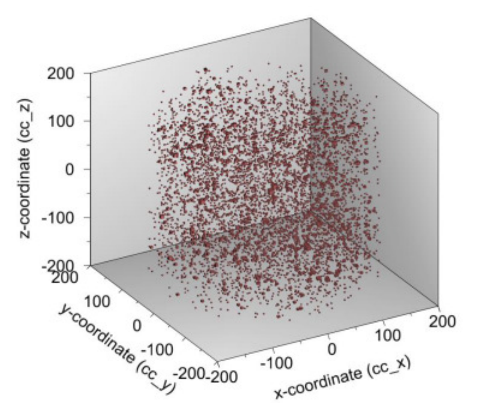


Particle ID & fiducial volume



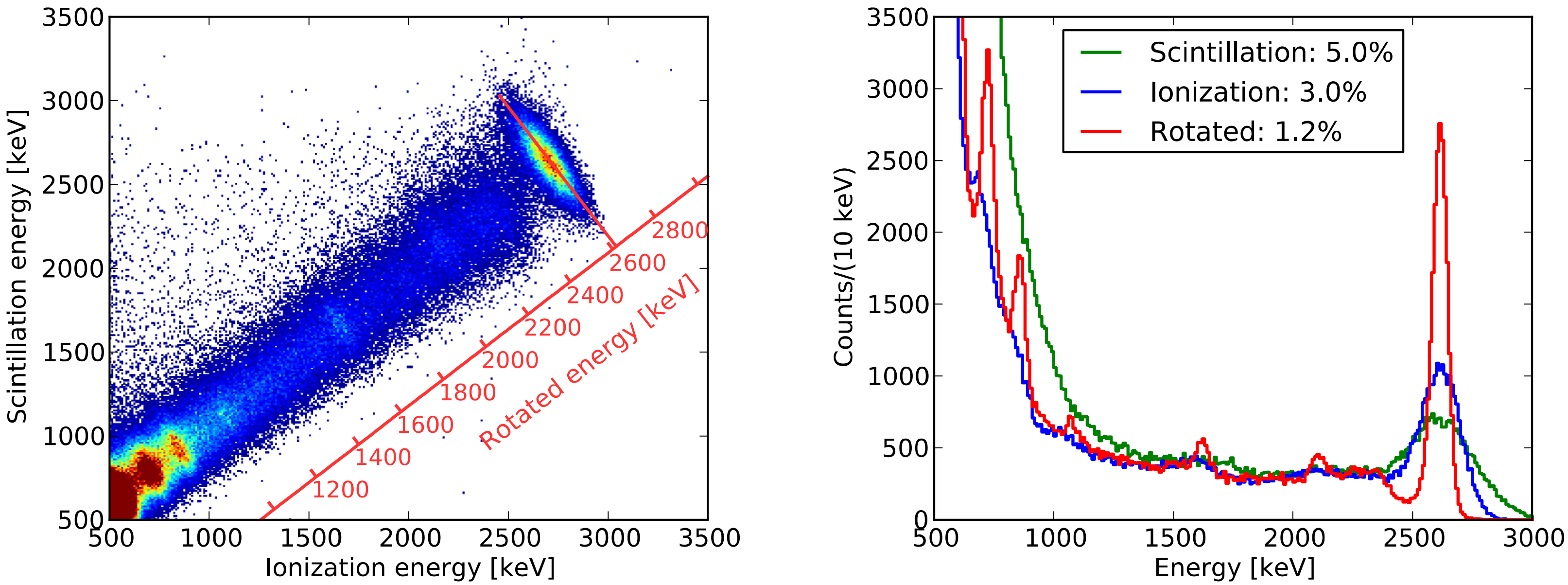


Events from the cathode and anodes



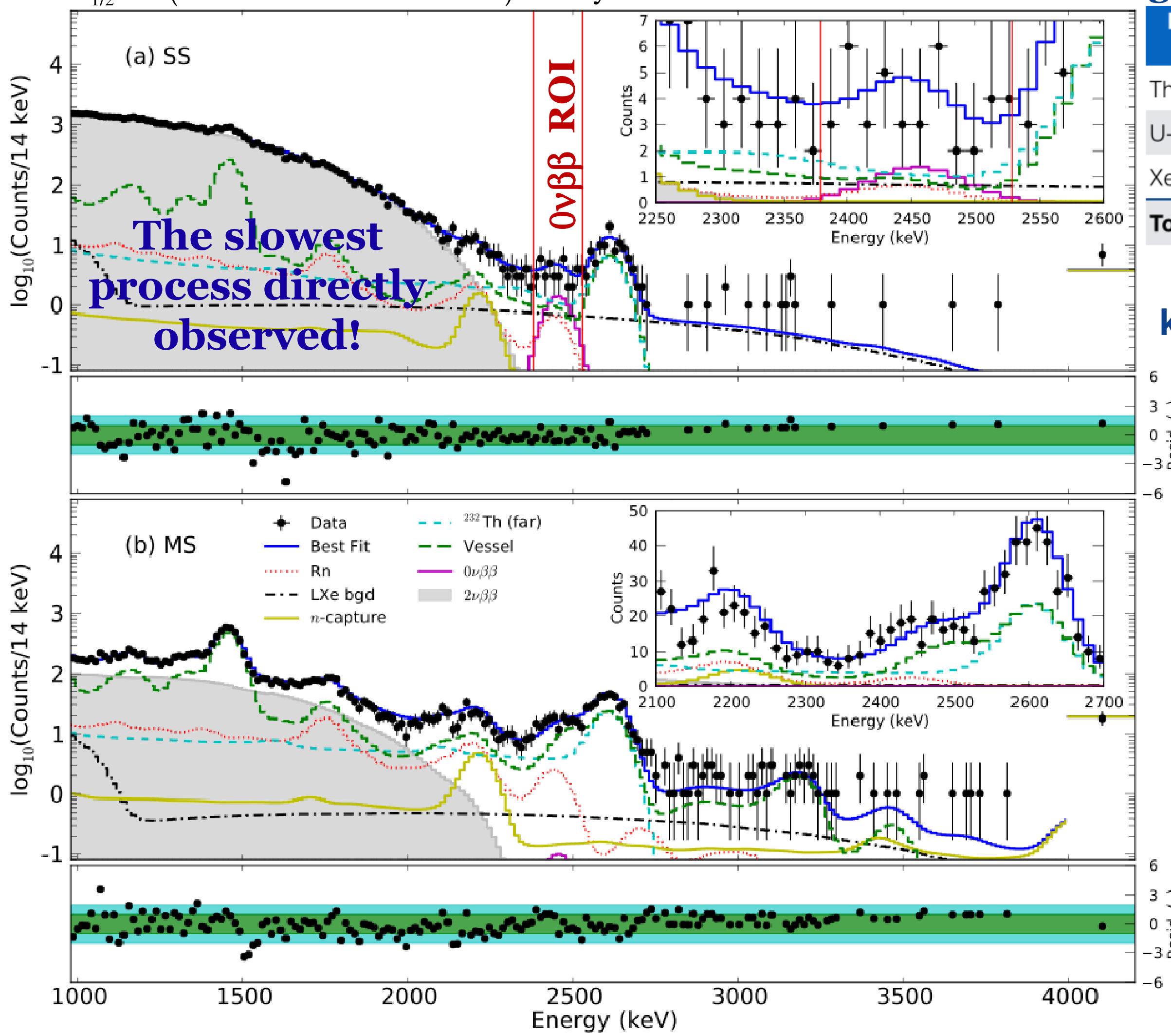
Events from the LXe bulk

Energy measurement



EXO-200 backgrounds

$$T_{1/2}^{2\nu\beta\beta} = \left(2.165 \pm 0.016^{stat} \pm 0.059^{syst}\right) \times 10^{21}\ \text{yr}$$

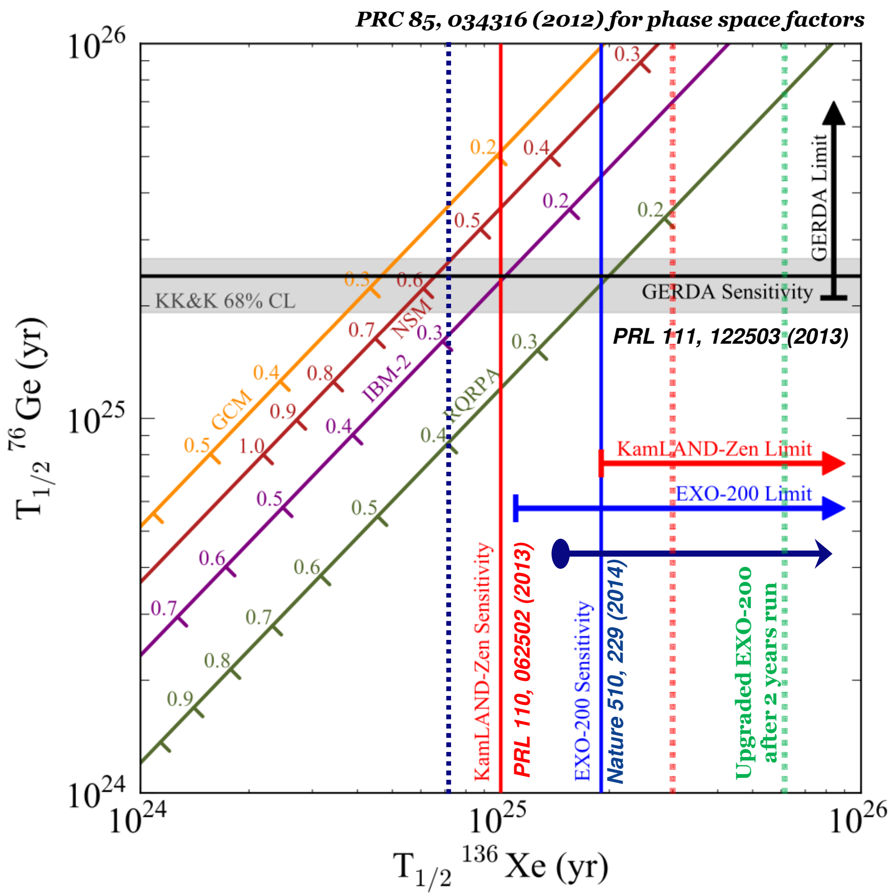


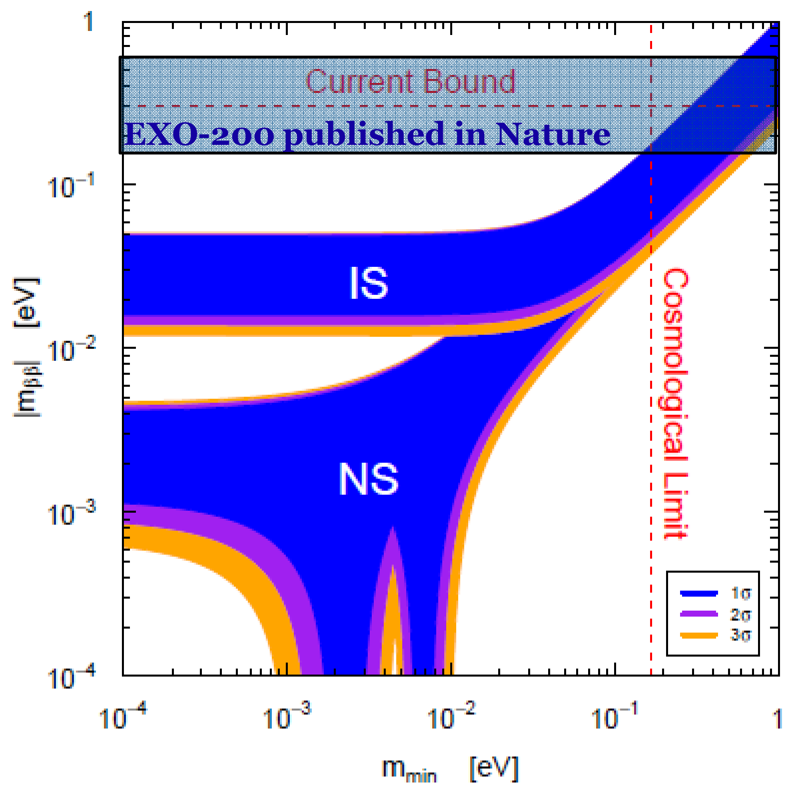
100 kg.yr exposure

Backgrounds in ± 2σ ROI	
Th-228 chain	16.0
U-232 chain	8.1
Xe-137	7.0
Total	**31.1 ± 3.8**

(1.7 ± 0.2) $keV^{-1}\ ton^{-1}\ yr^{-1}$

EXO-200 results





Future experiments

Arguments in favour of a rich and diversified $0\nu\beta\beta$ search program

- *There could be unknown gamma transitions and a line observed at the "end point" in one isotope does not necessarily imply the $0\nu\beta\beta$ decay discovery*
- *Nuclear matrix elements are not very well known and any given isotope could come with unknown liabilities*
- *Different isotopes correspond to vastly different experimental techniques*
- *2 neutrino background is different for various isotopes*
- *The elucidation of the mechanism producing the decay requires the analysis of more than one isotope*

Low density trackers
- NEXT, PandaX (^{136}Xe gas TPC)
- SuperNEMO (foils and gas tracking, ^{82}Se)

Pros: Superb topological information
Cons: Very large size

Liquid (organic) scintillators
- KamLAND-ZEN (^{136}Xe)
- SNO+ (^{130}Te)

Pros: "simple", large detectors exist, self-shielding
Cons: Not very specific, 2ν background

Crystals
- GERDA, Majorana (^{76}Ge)
- CUORE, CUPID (^{130}Te)

Pros: Superb energy resolution, possibly 2-parameter measurement
Cons: Intrinsically fragmented

Liquid TPC
- nEXO (^{136}Xe)

Pros: Homogeneous with good E resolution and topology
Cons: Does not excel in any single parameter

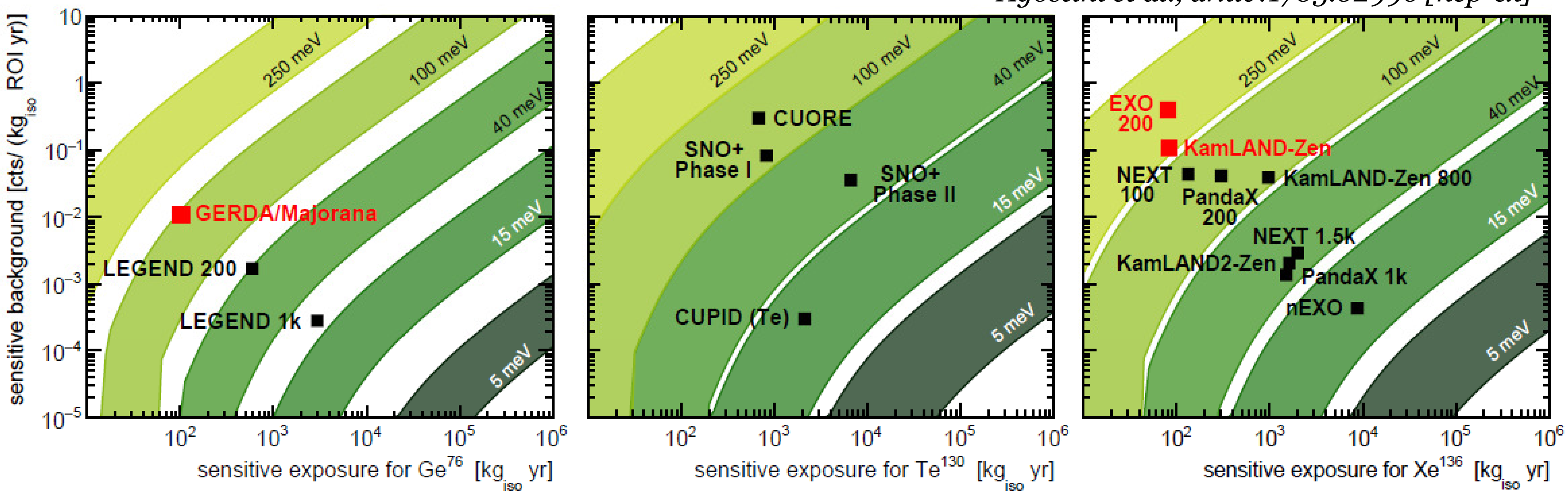
Future experiments

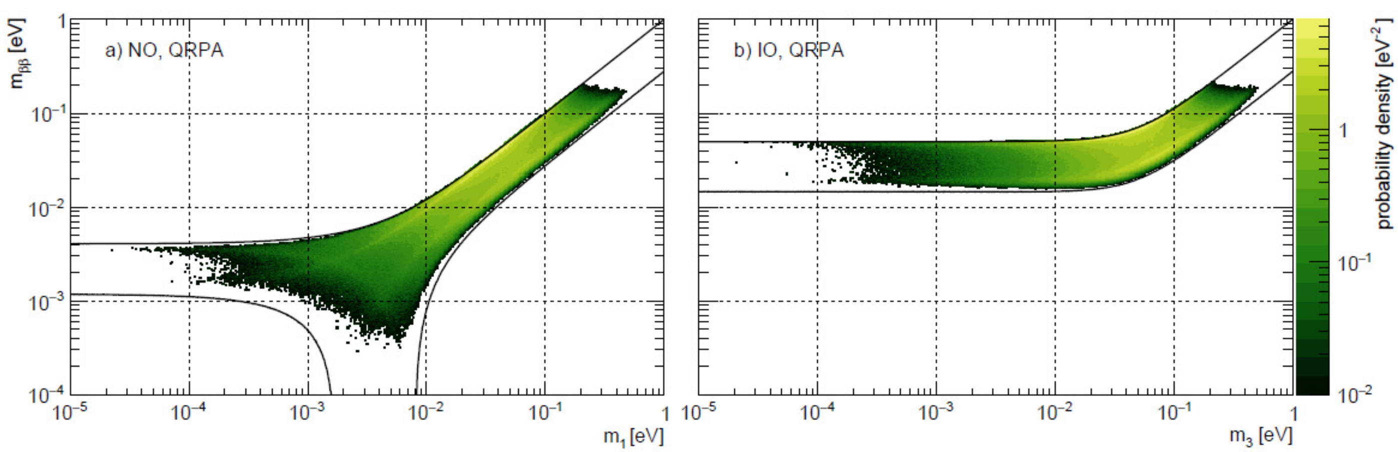
Agostini et al., arxiv:1705.02996 [hep-ex]

Experiment	Iso.	Iso. Mass	σ	ROI	ϵ_{FV}	ϵ_{sig}	$\mathcal{E}$	$\mathcal{B}$	3σ disc. sens. $\hat{T}_{1/2}$	3σ disc. sens. $\hat{m}_{\beta\beta}$	Required Improvement: Bkg	Required Improvement: σ	Required Improvement: Iso. Mass
		$[\mathrm{kg}_{iso}]$	[keV]	$[\sigma]$	[%]	[%]	$\left[\frac{\mathrm{kg}_{iso}\,\mathrm{yr}}{\mathrm{yr}}\right]$	$\left[\frac{\mathrm{cts}}{\mathrm{kg}_{iso}\,\mathrm{ROI\,yr}}\right]$	[yr]	[meV]			
LEGEND 200 [61, 62]	^{76}Ge	175	1.3	[-2, 2]	93	77	119	$1.7 \cdot 10^{-3}$	$8.4 \cdot 10^{26}$	40–73	3	1	5.7
LEGEND 1k [61, 62]	^{76}Ge	873	1.3	[-2, 2]	93	77	593	$2.8 \cdot 10^{-4}$	$4.5 \cdot 10^{27}$	17–31	18	1	29
SuperNEMO [68, 69]	^{82}Se	100	51	[-4, 2]	100	16	16.5	$4.9 \cdot 10^{-2}$	$6.1 \cdot 10^{25}$	82–138	49	2	14
CUPID [58, 59, 70]	^{82}Se	336	2.1	[-2, 2]	100	69	221	$5.2 \cdot 10^{-4}$	$1.8 \cdot 10^{27}$	15–25	n/a	6	n/a
CUORE [52, 53]	^{130}Te	206	2.1	[-1.4, 1.4]	100	81	141	$3.1 \cdot 10^{-1}$	$5.4 \cdot 10^{25}$	66–164	6	1	19
CUPID [58, 59, 70]	^{130}Te	543	2.1	[-2, 2]	100	81	422	$3.0 \cdot 10^{-4}$	$2.1 \cdot 10^{27}$	11–26	3000	1	50
SNO+ Phase I [66, 71]	^{130}Te	1357	82	[-0.5, 1.5]	20	97	164	$8.2 \cdot 10^{-2}$	$1.1 \cdot 10^{26}$	46–115	n/a	n/a	n/a
SNO+ Phase II [67]	^{130}Te	7960	57	[-0.5, 1.5]	28	97	1326	$3.6 \cdot 10^{-2}$	$4.8 \cdot 10^{26}$	22–54	n/a	n/a	n/a
KamLAND-Zen 800 [60]	^{136}Xe	750	114	[0, 1.4]	64	97	194	$3.9 \cdot 10^{-2}$	$1.6 \cdot 10^{26}$	47–108	1.5	1	2.1
KamLAND2-Zen [60]	^{136}Xe	1000	60	[0, 1.4]	80	97	325	$2.1 \cdot 10^{-3}$	$8.0 \cdot 10^{26}$	21–49	15	2	2.9
nEXO [72]	^{136}Xe	4507	25	[-1.2, 1.2]	60	85	1741	$4.4 \cdot 10^{-4}$	$4.1 \cdot 10^{27}$	9–22	400	1.2	30
NEXT 100 [64, 73]	^{136}Xe	91	7.8	[-1.3, 2.4]	88	37	26.5	$4.4 \cdot 10^{-2}$	$5.3 \cdot 10^{25}$	82–189	n/a	1	20
NEXT 1.5k [74]	^{136}Xe	1367	5.2	[-1.3, 2.4]	88	37	398	$2.9 \cdot 10^{-3}$	$7.9 \cdot 10^{26}$	21–49	n/a	1	300
PandaX-III 200 [65]	^{136}Xe	180	31	[-2, 2]	100	35	60.2	$4.2 \cdot 10^{-2}$	$8.3 \cdot 10^{25}$	65–150	n/a	n/a	n/a
PandaX-III 1k [65]	^{136}Xe	901	10	[-2, 2]	100	35	301	$1.4 \cdot 10^{-3}$	$9.0 \cdot 10^{26}$	20–46	n/a	n/a	n/a

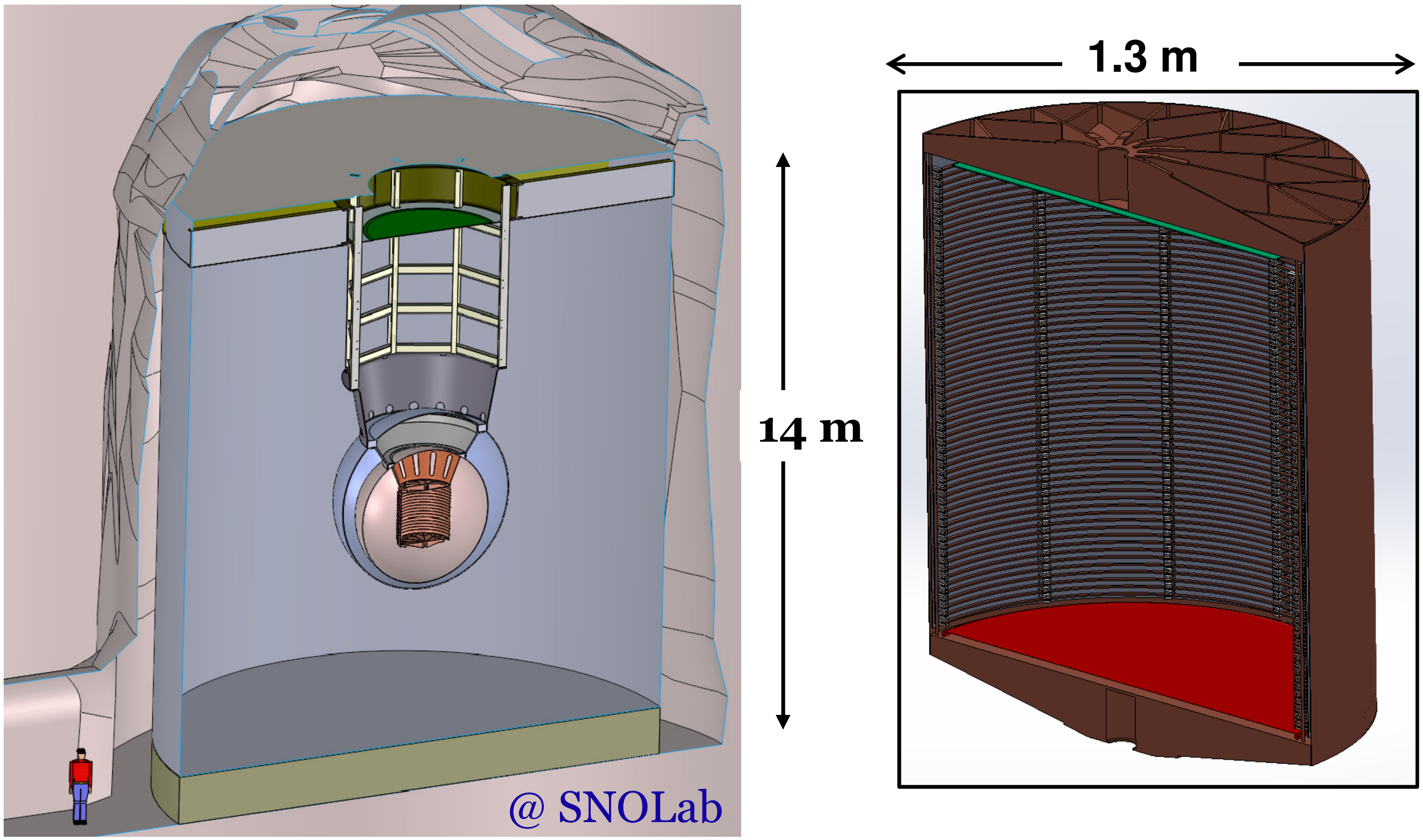
Future experiments

Agostini et al., arxiv:1705.02996 [hep-ex]

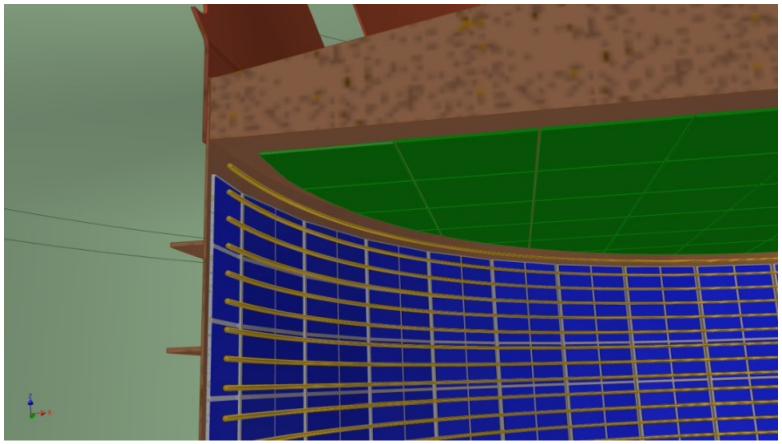


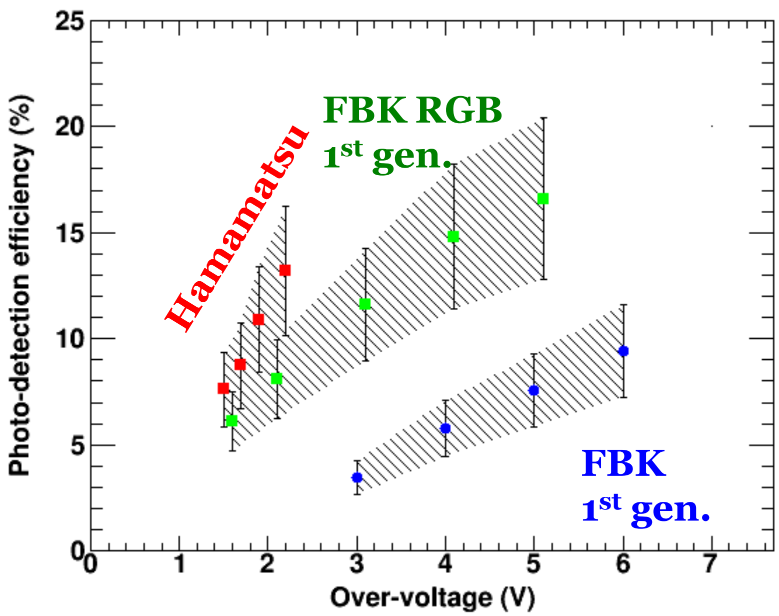


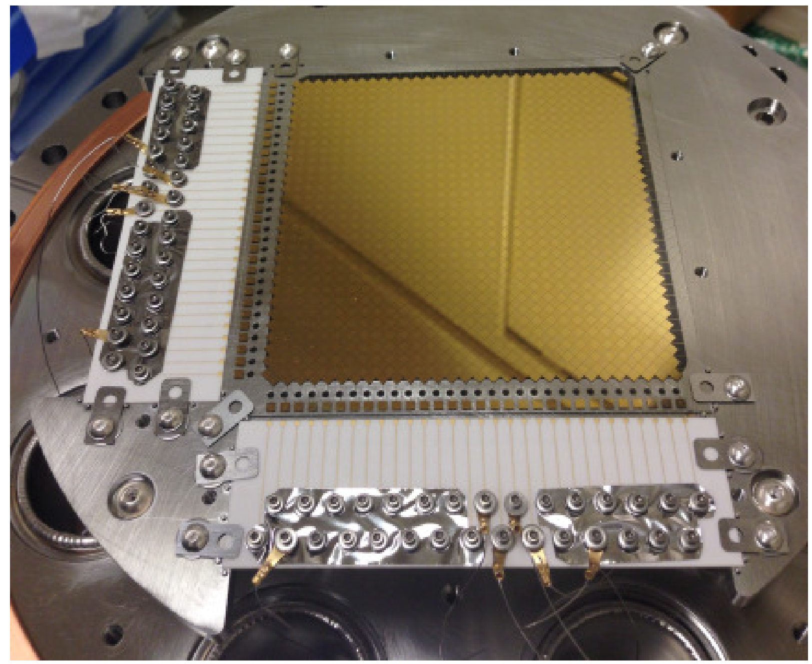
nEXO – 5 t LXe TPC



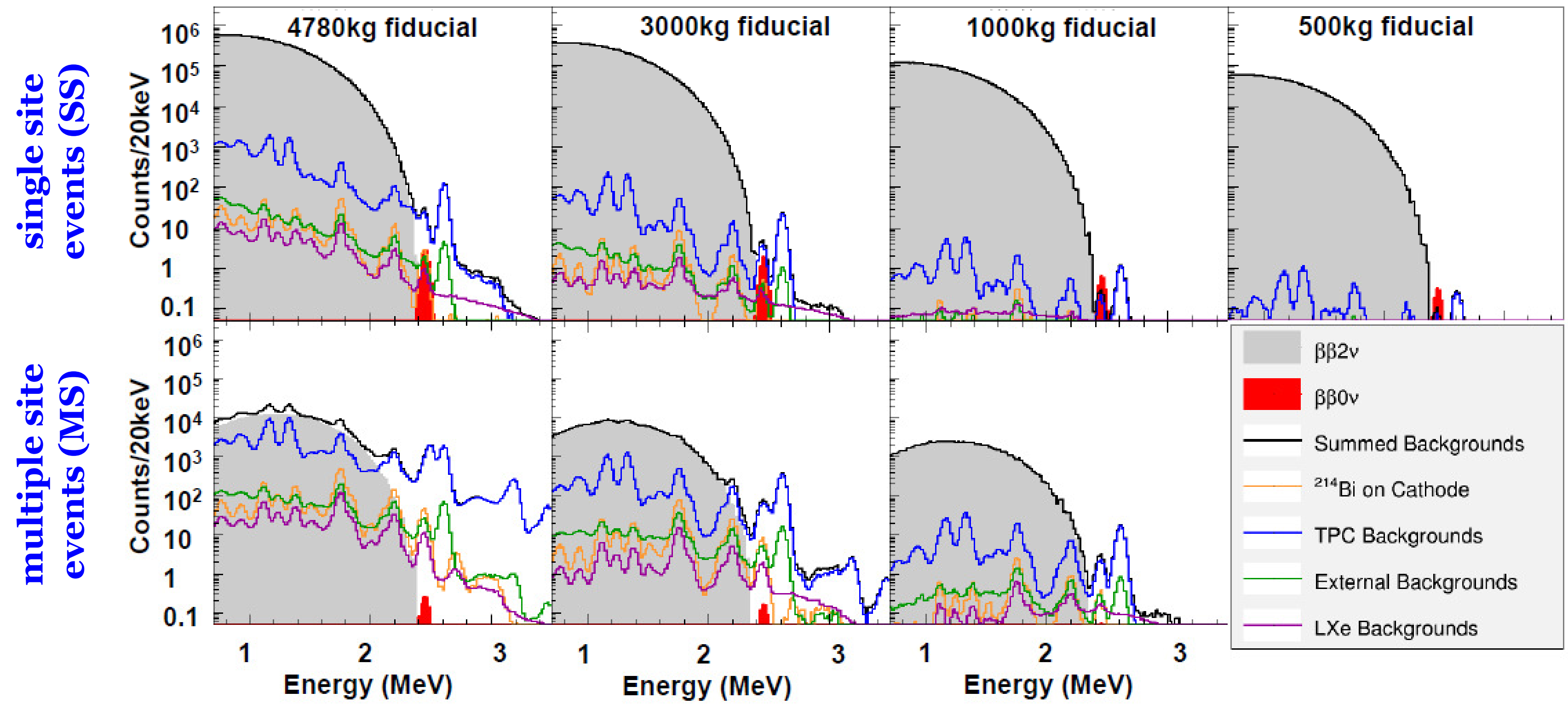
nEXO – 5 t LXe TPC





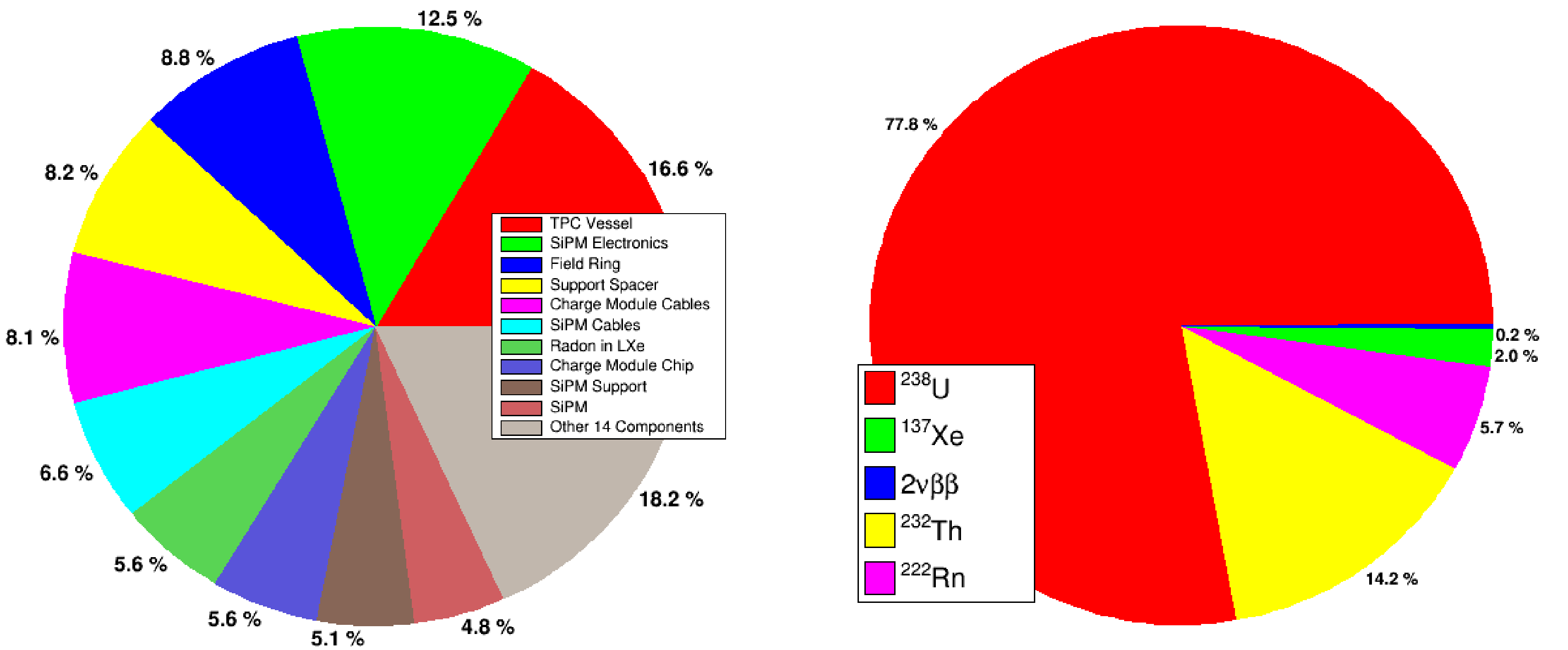


nEXO – 5 t LXe TPC

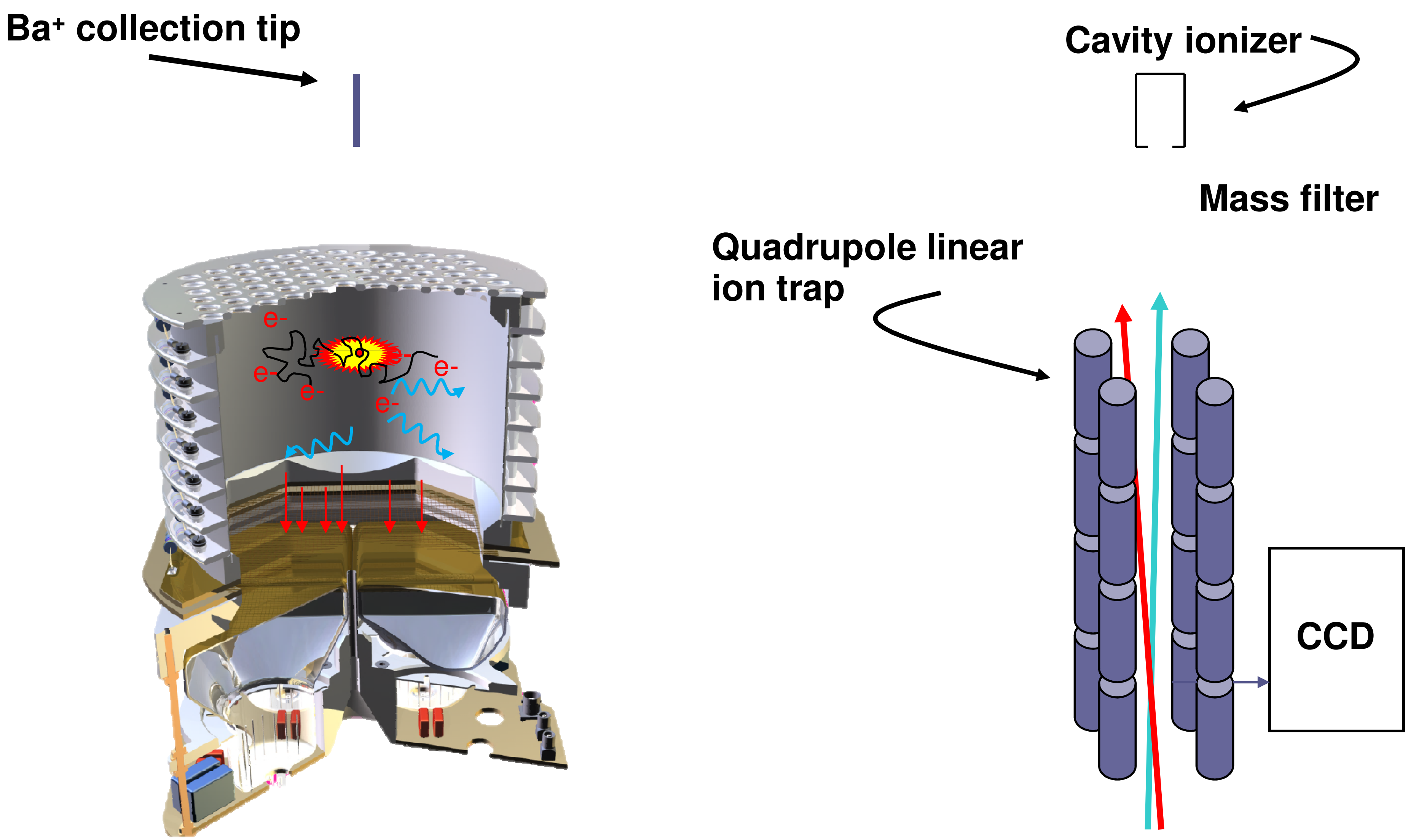


nEXO – 5 t LXe TPC

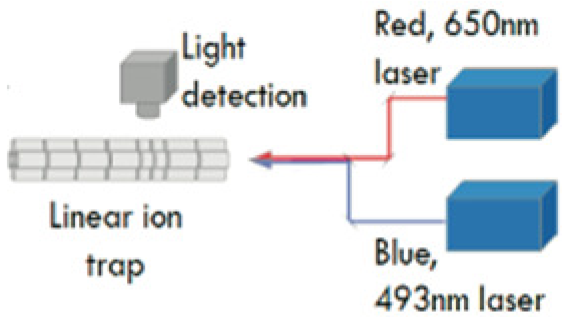
Background contributions in the ROI for the 3000 kg fiducial cut (2.1 events/year total rate)



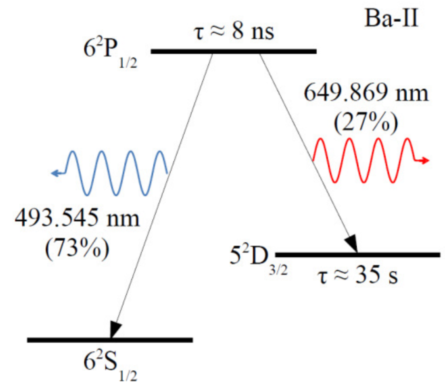
Ba ion tagging concept



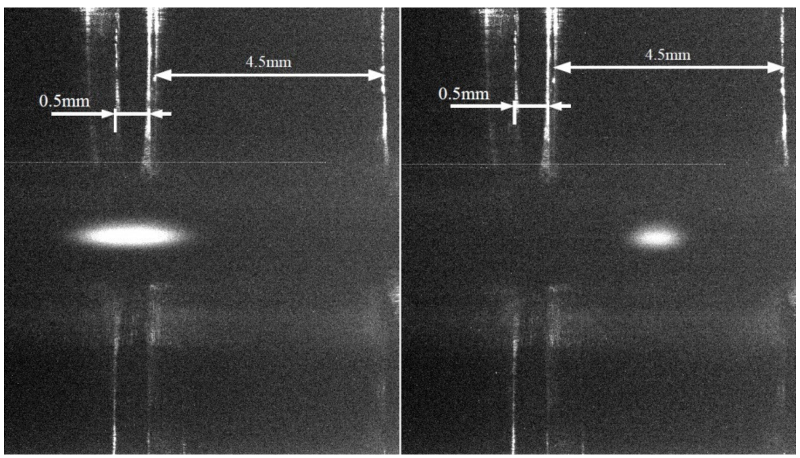
Ba ion detection



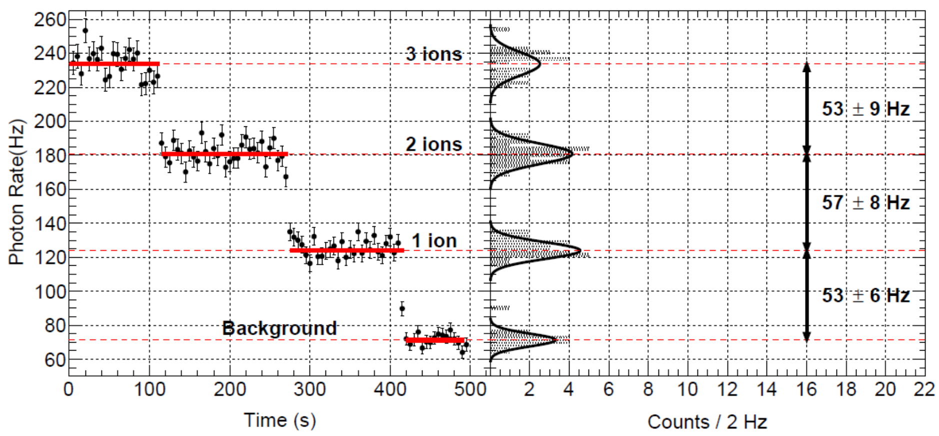
Using a relatively simple and well understood fluorescing system



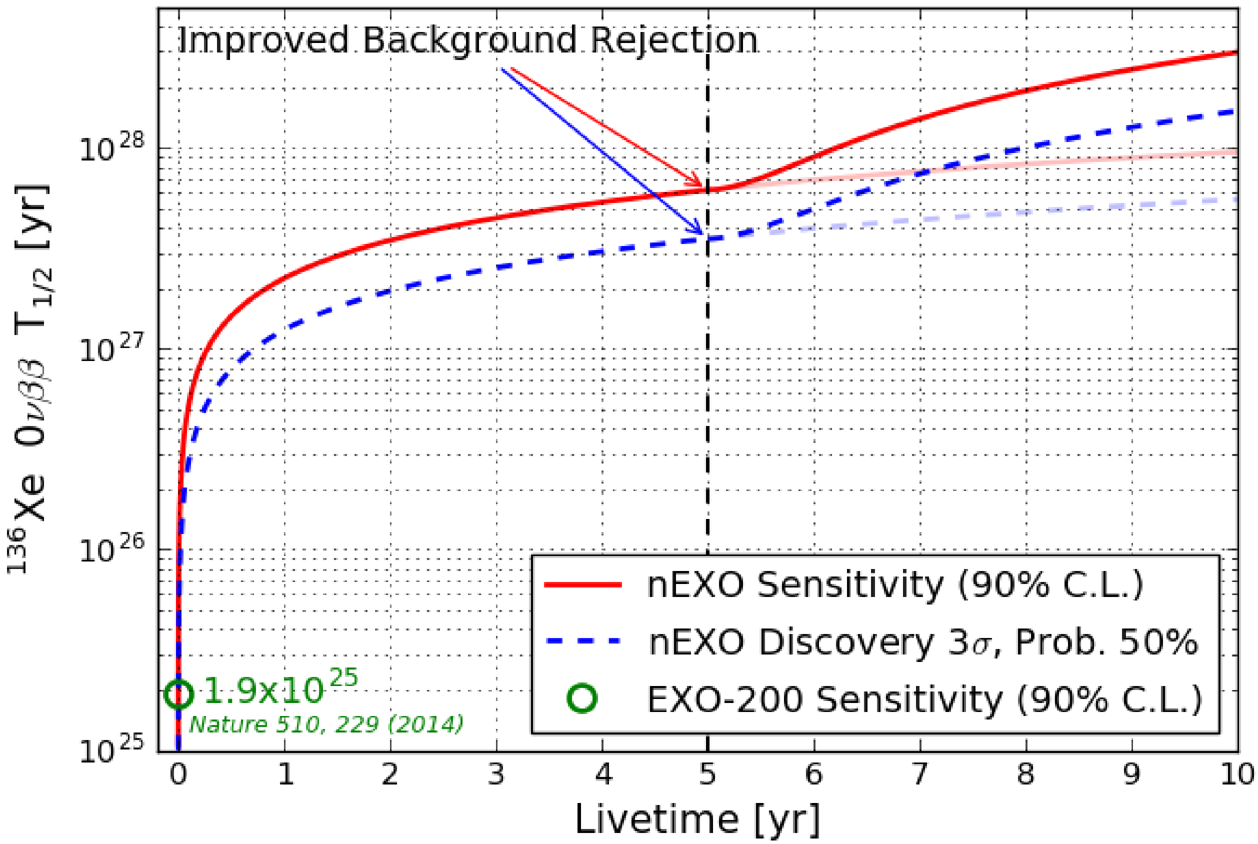
Demonstrated ion cloud imaging and accurate position control



Demonstrated single ion sensitivity using intermodulation technique (background control)



Expected performance



Expected performance