Xe^{136} TPCs for $\beta\beta0\nu$ searches

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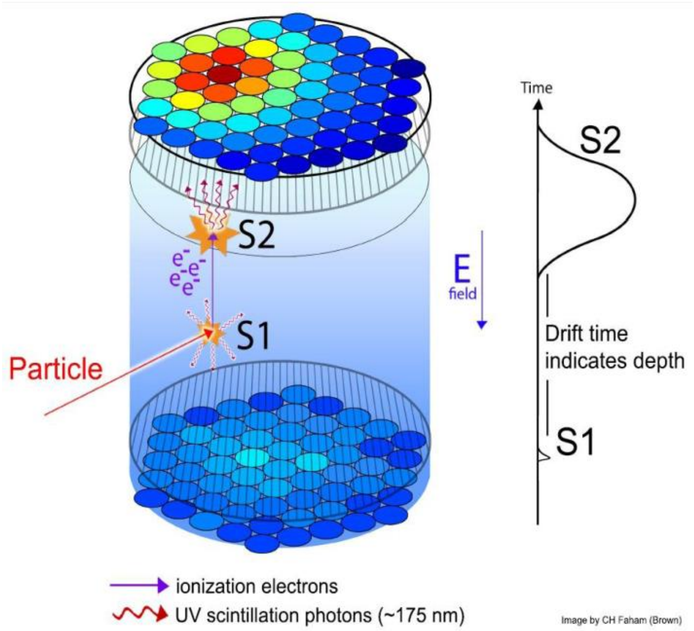
XXIX International Conference on Neutrino Physics, July 2020, in Cyberspace

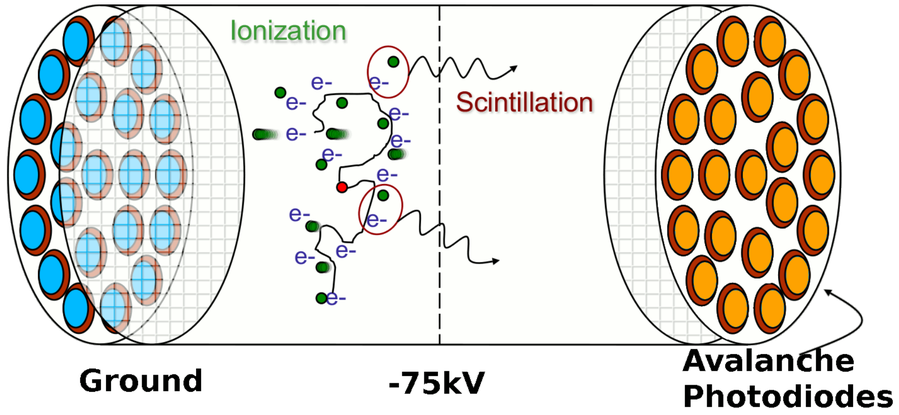
Outlook

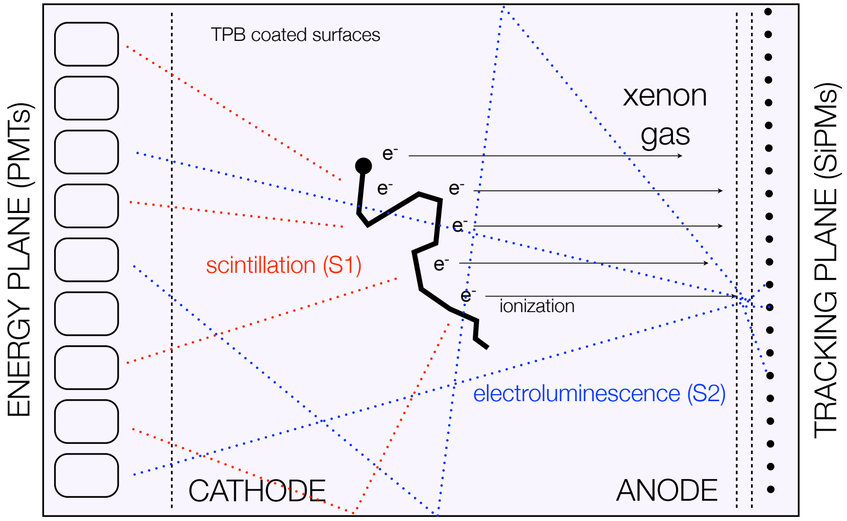
- Xenon TPCs
- LXe TPCs
- HPXe TPCs
- BOLD

Xenon TPCs

- Detection exploits scintillation (S1) and ionisation (S2) signals in xenon.
- S1 provides t_0, essential for fiducial definition.
- EL TPCs (NEXT/AXEL, XENON, LZ, LUX, DARWIN) detect only light (S2 converted via electroluminescence in photons)
- EXO/nEXO/PANDA-X-III: detect charge (without/with) amplification

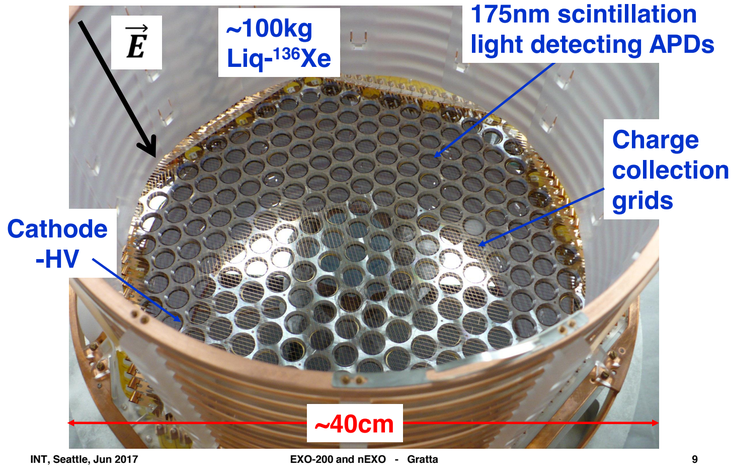


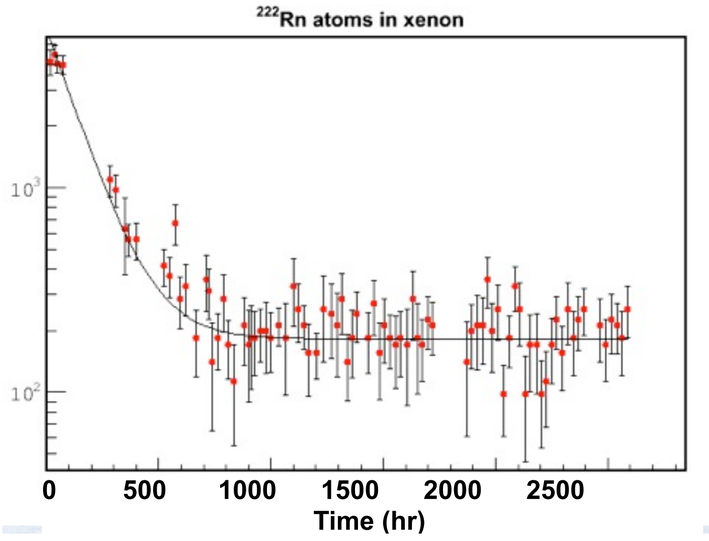


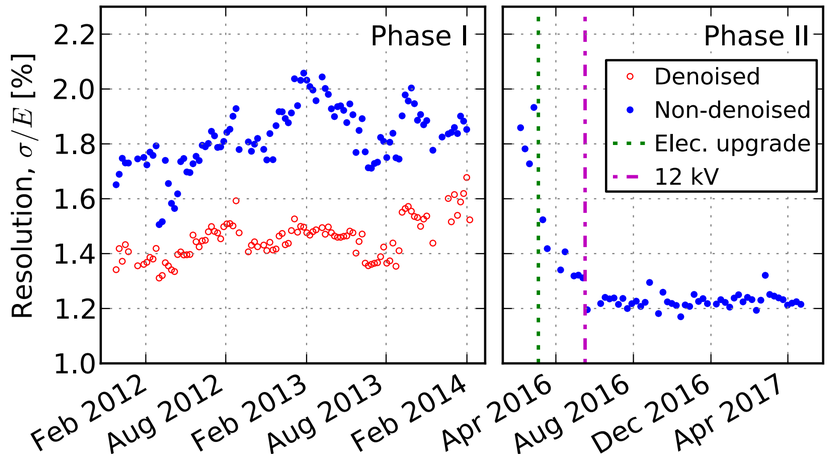


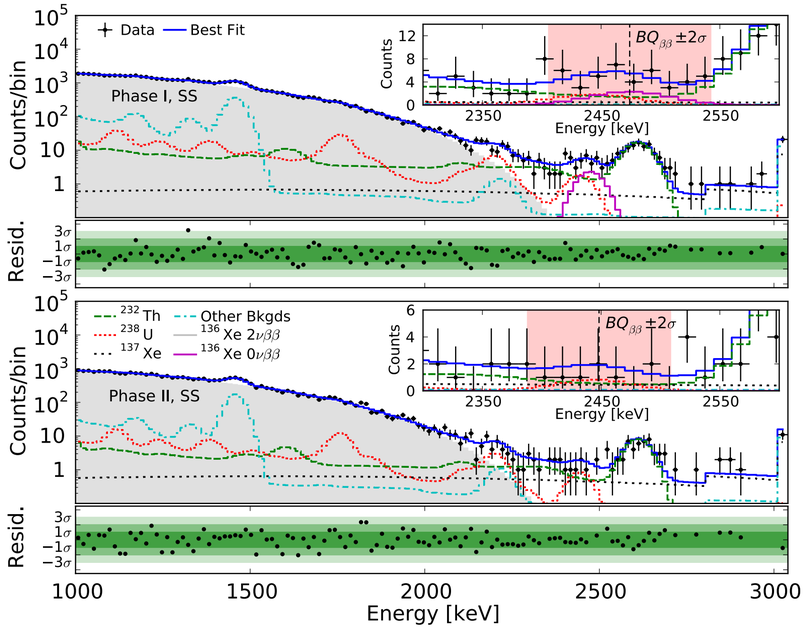
EXO-200

• *Phys.Rev.Lett.* 123 (2019) 16, 161802





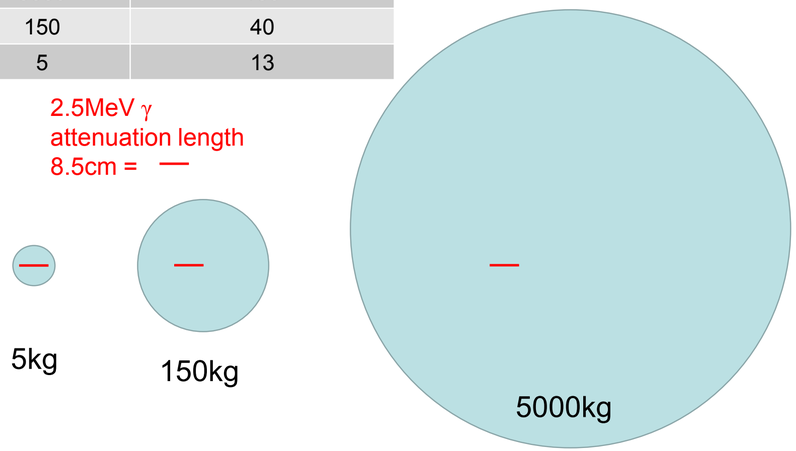




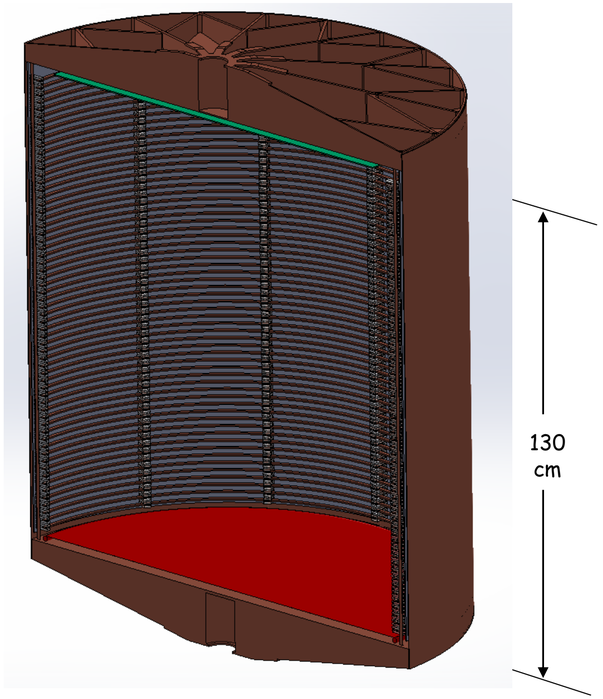
- Demonstrated single phase LXe TPC technology. Energy measured using scintillation (APDs) and ionisation (wires). Anticorrelation allows a measurement with a resolution of 2.8 % FWHM at $Q_{\beta\beta}$
- Searched for $\beta\beta0\nu$: sensitivity T ~3.7 10^{25} y. Limit T >5 10^{25} y at 90 % CL.
- Background Index (B): $(1.5 \pm 0.3) \times 10^{-3}\ \mathrm{kg}^{-1}\ \mathrm{yr}^{-1}\ \mathrm{kev}^{-1}$

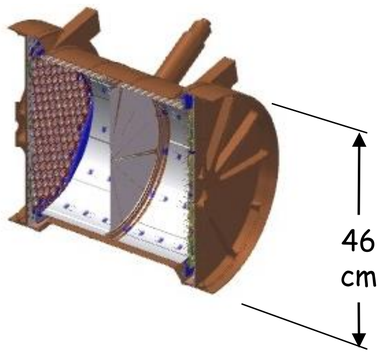
nEXO

LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13



This works best for a monolithic detector

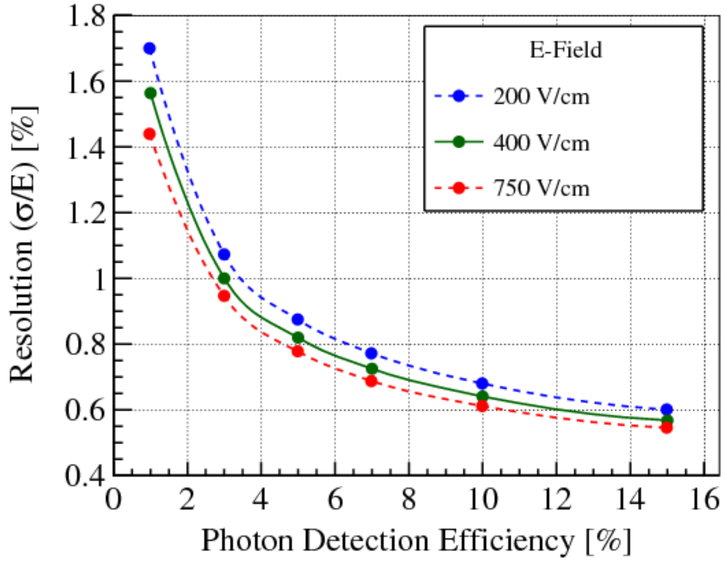


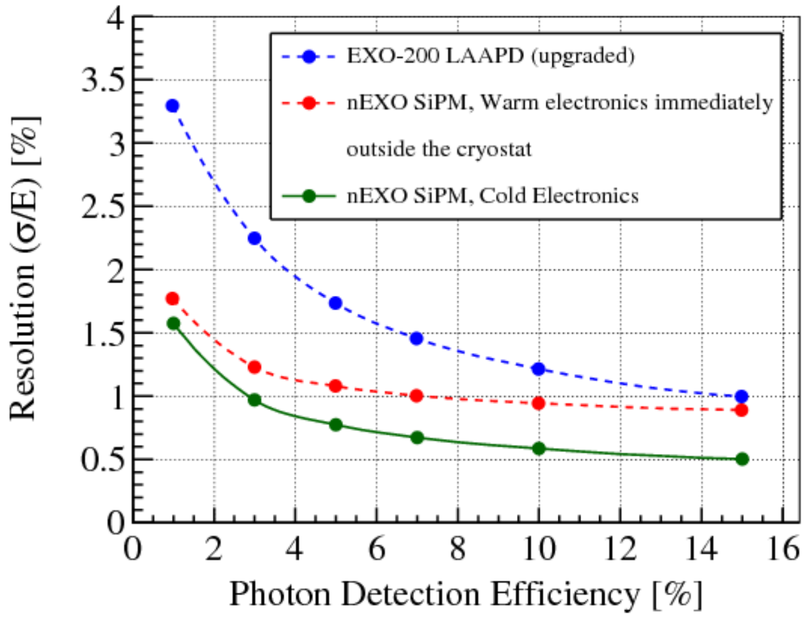


- Monolithic single phase detector with 5 ton enriched xenon total mass (~4 ton fiducial mass). Principle of operation like EXO-200, but asymmetric TPC to minimise impact of Rn-222 daughters. Underground must be deep to minimise Xe^{137} background (SNOLAB assumed)
- S2 measured from charge (no amplification, silica tiles patterned with crossed metal strips at the anode).
- S1 measured covering the barrel with VUV SiPMs (4.5 m^2 of them).
- Combines low background budget, self-shielding, good energy resolution.

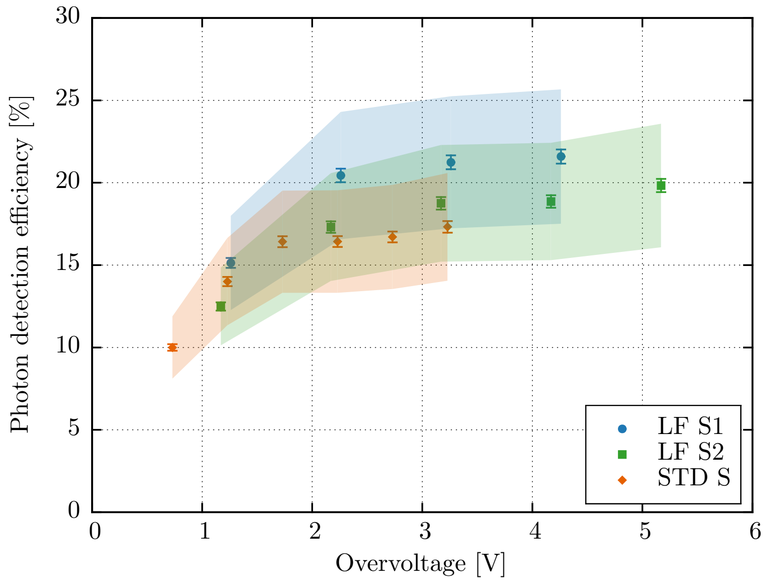
nEXO SiPMs

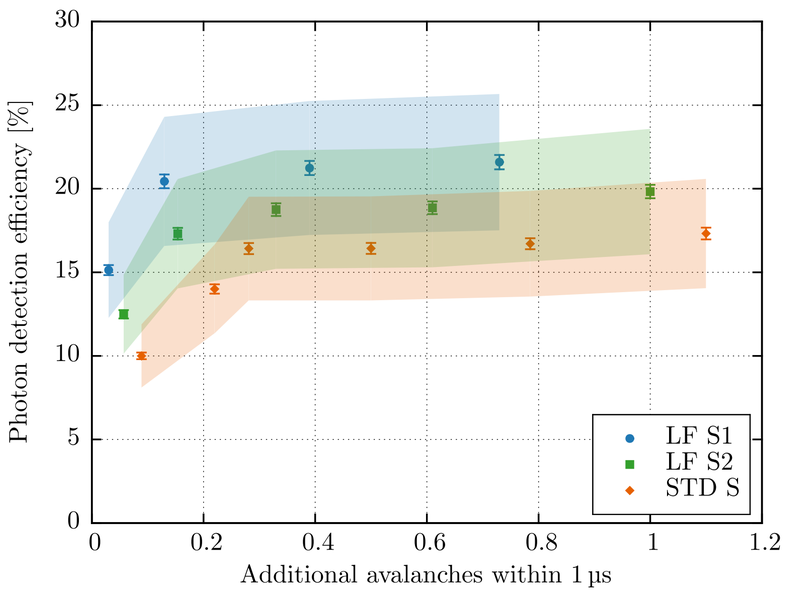
https://arxiv.org/pdf/1806.02220.pdf





- Photon detection efficiency of 3%, cold electronics: Energy resolution = 2.3 % FWHM at $Q_{\beta\beta}$
- 0.1 pe rms electronic noise/SiPM



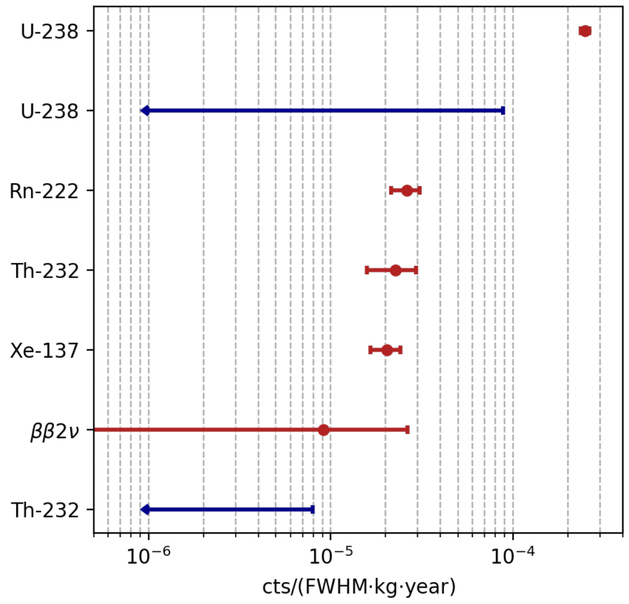


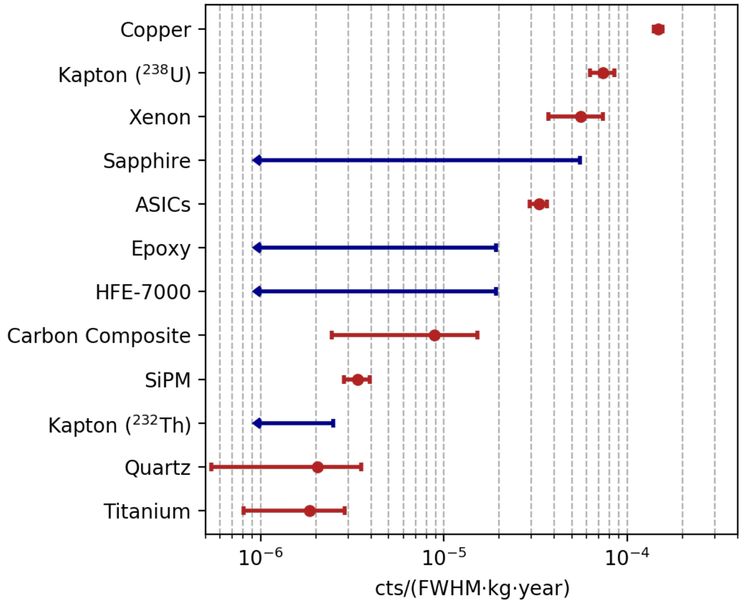
Parameter	Value
Total instrumented area	$\simeq 4.5\ \mathrm{m}^2$
Overall light detection efficiency	$\epsilon_o > 3\ \%$
SiPM PDE (175 nm, normal incidence)	$\epsilon_{PD} > 15\ \%$
Overvoltage	$> 3\ \mathrm{V}$
Dark noise rate	$< 50\ \mathrm{Hz/mm}^2$
Correlated avalanche rate	< 0.2

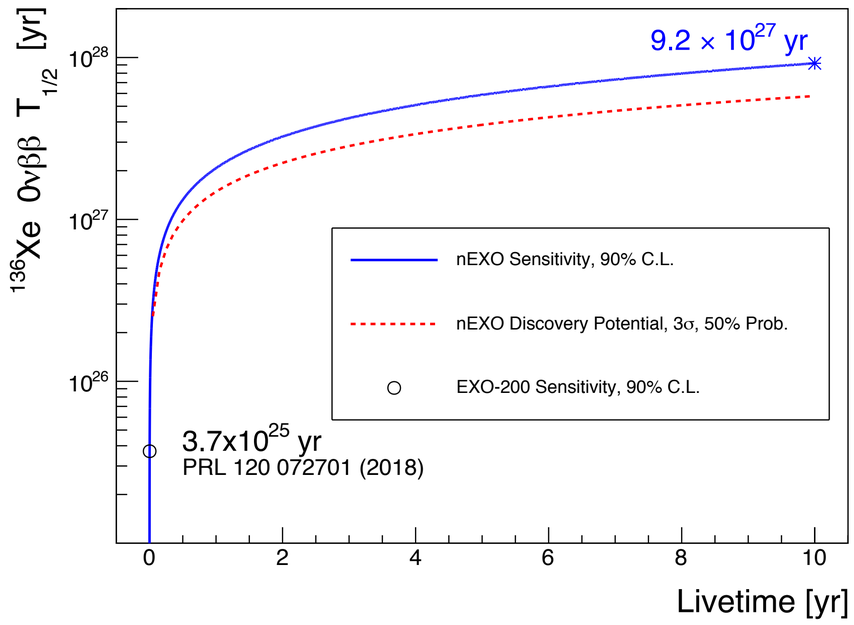
nEXO performance

https://arxiv.org/ftp/arxiv/papers/1805/1805.11142.pdf

Lifetime required for good ionisation measurement: 10 ms (EXO 3ms)







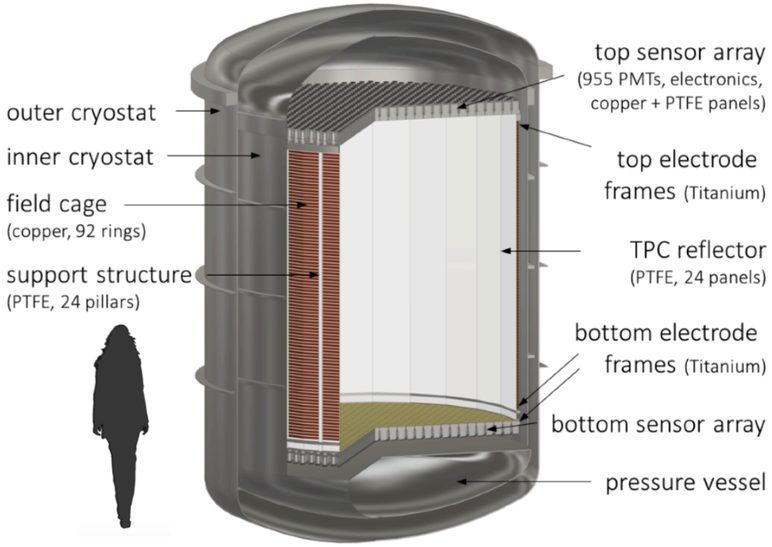
In inner 2 ton: $\mathrm{B(nEXO)} \sim 3.6 \times 10^{-4}/(\mathrm{FWHM} \cdot \mathrm{kg} \cdot \mathrm{year}) = 5.3 \times 10^{-6}/(\mathrm{keV} \cdot \mathrm{kg} \cdot \mathrm{year})$

$\mathrm{B(EXO)} \sim = 1.5 \times 10^{-3}/(\mathrm{keV} \cdot \mathrm{kg} \cdot \mathrm{year})$

Reach: T $\sim 10^{28}$ year for 50 ton · year

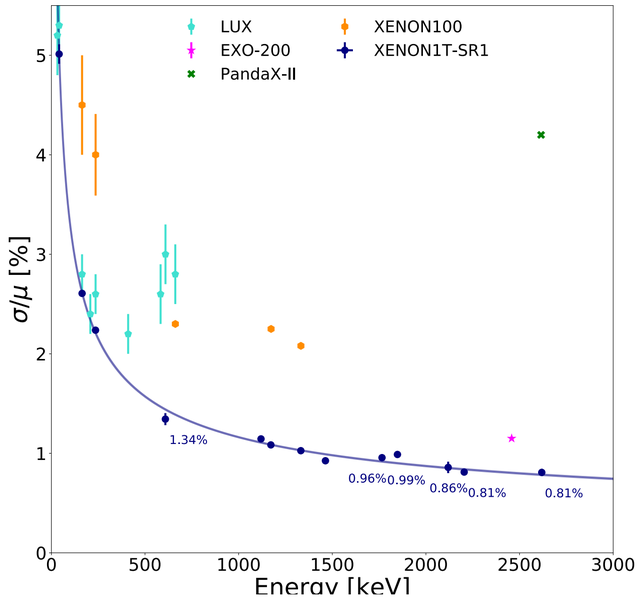
Darwin

- Two-phase TPC: 2.6 m ø, 2.6 m height
- 50 t (40 t) LXe in total (in the TPC)
- Two arrays of photosensors (e.g. 1800 3-inch PMTs)
- PTFE reflectors and copper field shaping rings
- Low-background, double-walled titanium cryostat
- Shield: Gd-doped water, for μ and n



DARWIN collaboration, JCAP 1611 (2016) 017

Figure from XENON1T

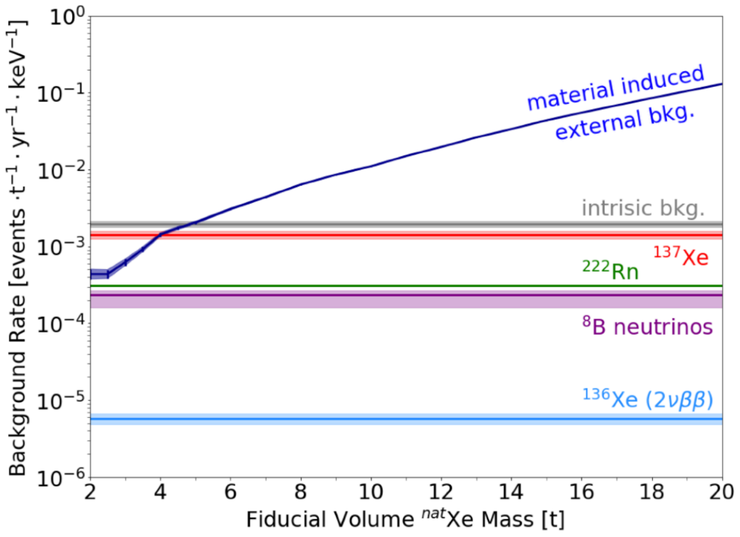


- Dual phase (EL amplification of S2) allows low threshold (needed for DM searches). Energy resolution 1.8 % FWHM at $Q_{\beta\beta}$
- Natural xenon (9 % ~3.5 tons of Xe^{136})

https://arxiv.org/abs/2003.13407

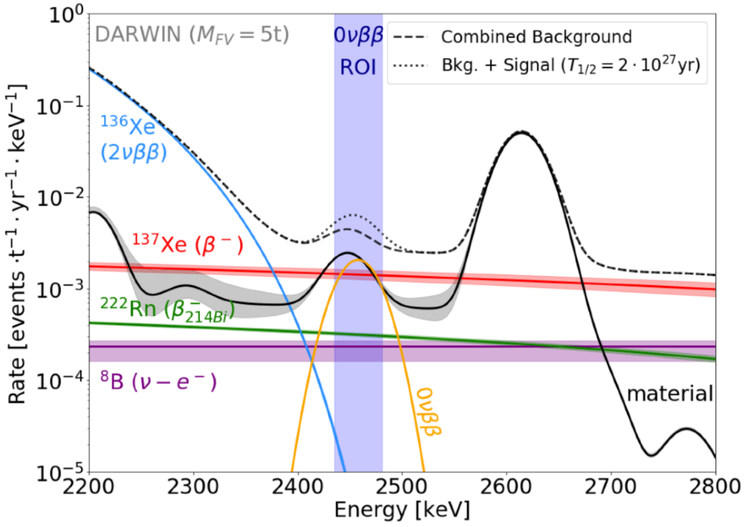
Darwin

- 2.4 x 10^{27} y for 5 t x 10 y exposure (90% CL)



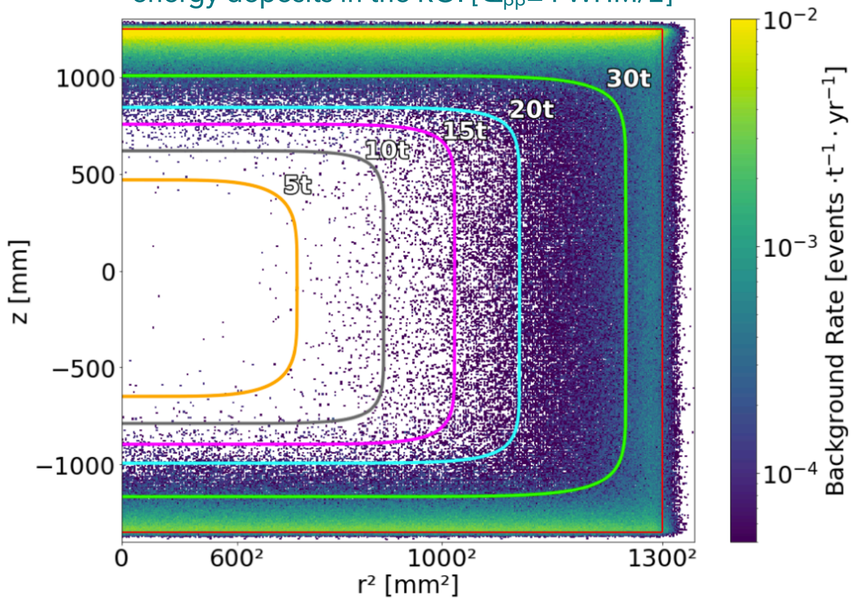
Rate versus fiducial mass

Signal: $T_{1/2}$ = 2 x 10^{27} y



Rate in 5 tonnes fiducial region (0.45 t ^{136}Xe)

100 y of DARWIN run time, event with energy deposits in the ROI [$Q_{\beta\beta}$± FWHM/2]

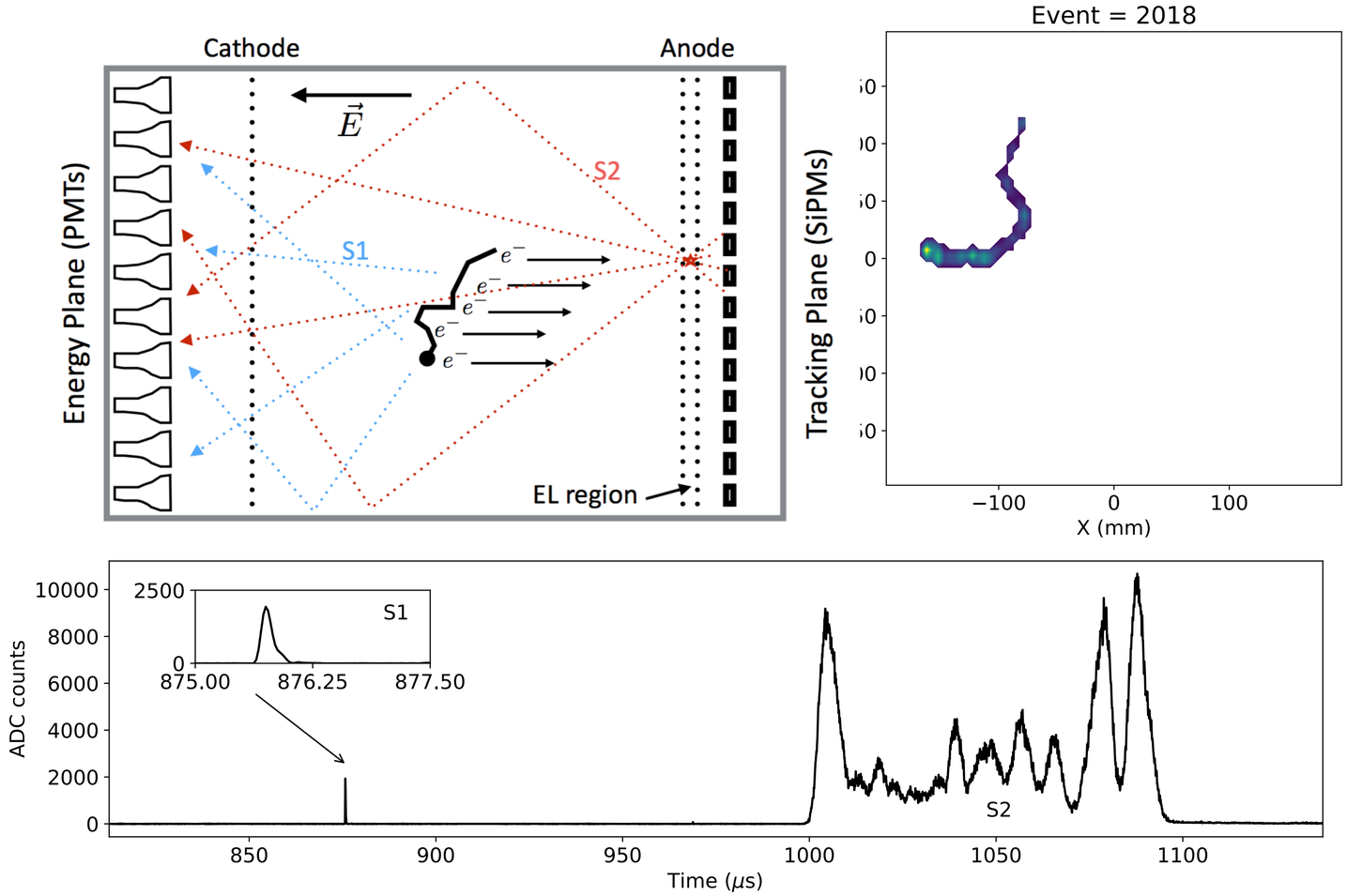


Lifetime: 10 ms (XENON-1t 1ms), Energy resolution = 1.8 % (XENON-1t 1.8%) FWHM at $Q_{\beta\beta}$

Reach: T $\sim 2.4 \times 10^{27}$ year for 5 ton · year of enriched xenon similar to nEXO

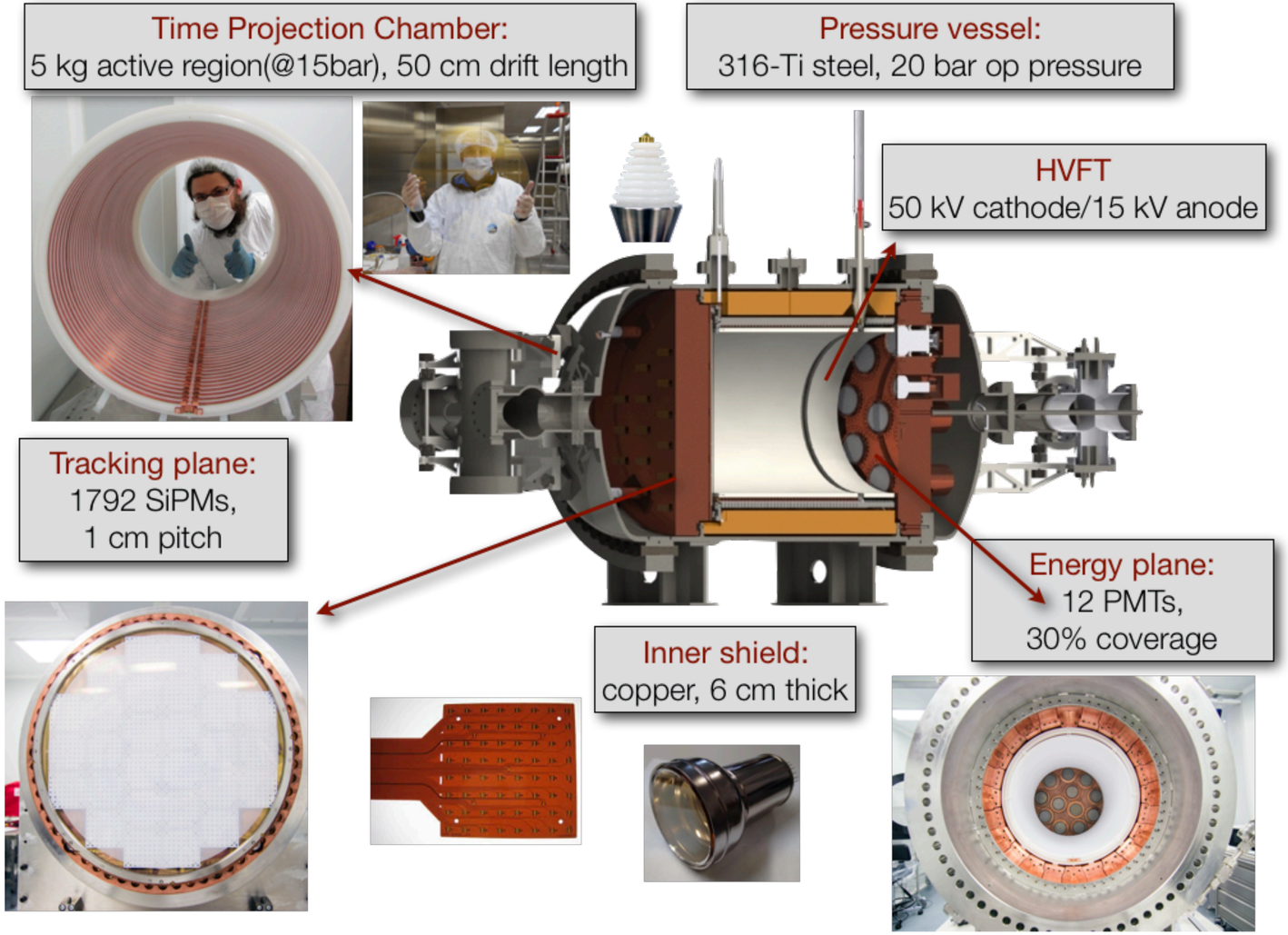
NEXT

https://arxiv.org/pdf/1906.01743.pdf



- HPXeEL TPC
- Good energy resolution (measured ~0.8 % FWHM, feasible 0.5-0.7 % FWHM).
- Topological signature (reconstruction of electrons in event). Measured 70 % efficiency for 95 % background suppression, expected 90-97 %
- Radiopure detector, along the lines of all other Xe TPCs
- Strong potential for barium tagging “in situ”.

NEXT-White and NEXT-100



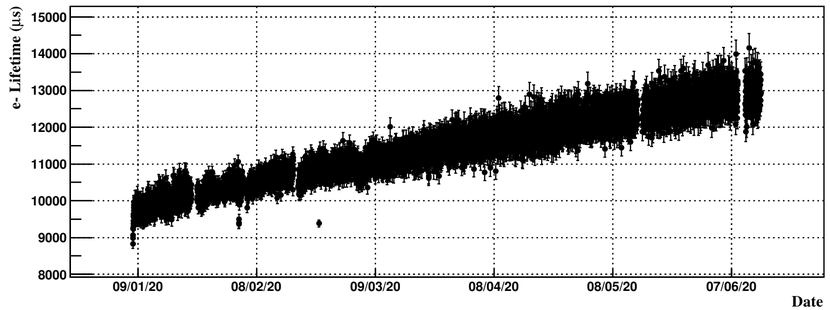
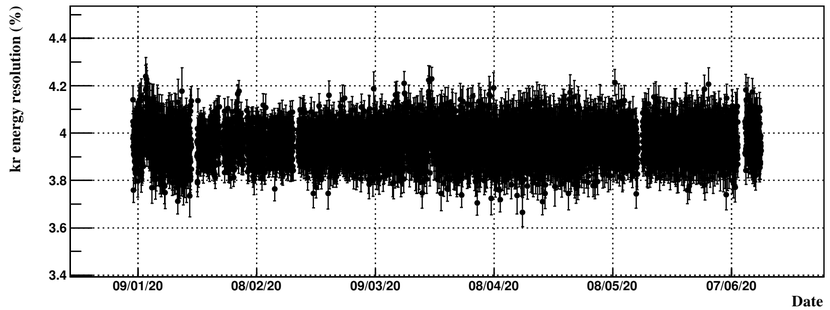
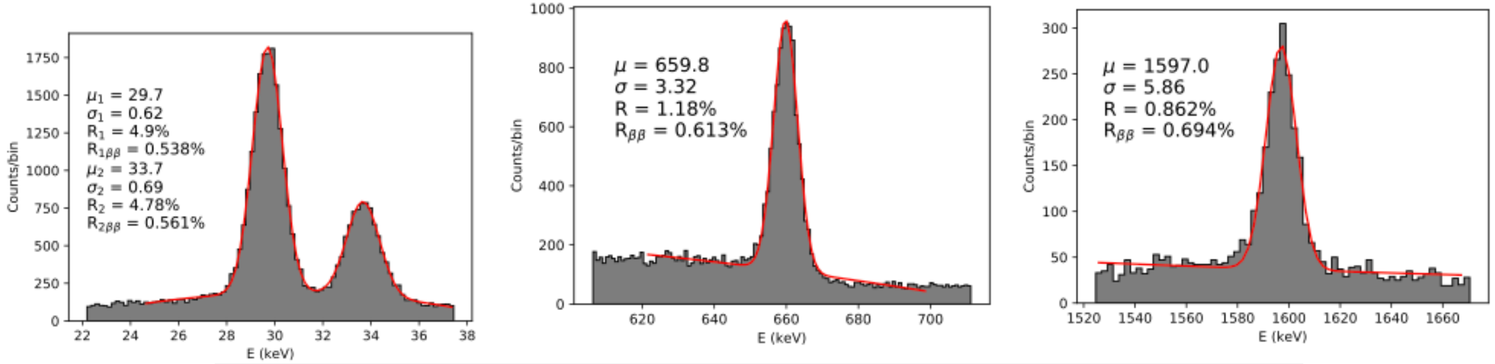


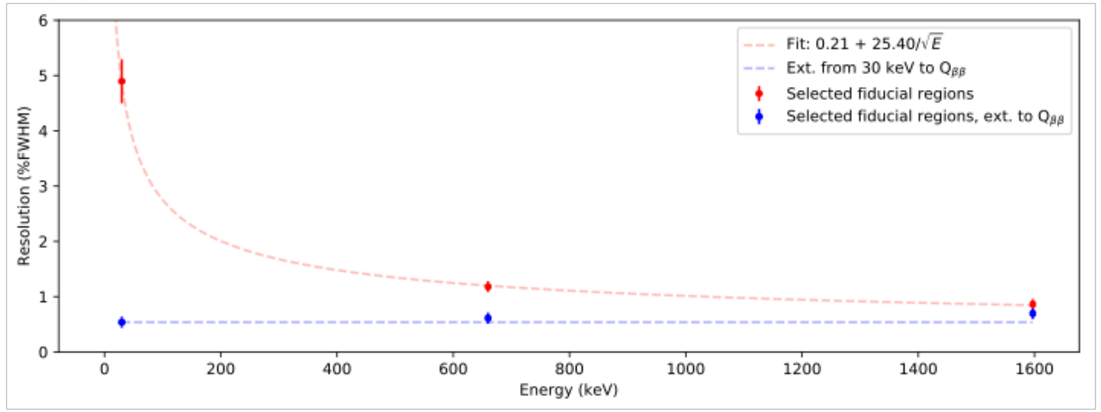
Figure 1. Electron lifetime during the low-background period of Run-Vc.



- *JINST* 13 (2018) 12, P12010

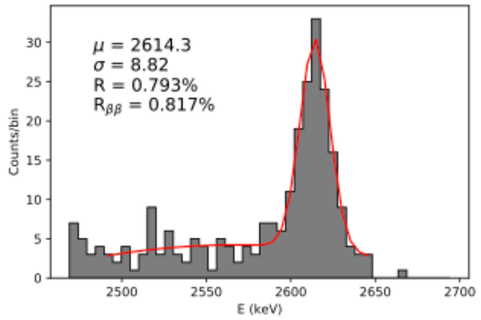
NEXT: Resolution





Energy resolution at $Q_{\beta\beta} \sim 0.8\,\%\,FWHM$ dominated by track corrections (0.5 % FWHM por point-like tracks). Room for improvement.

Energy resolution

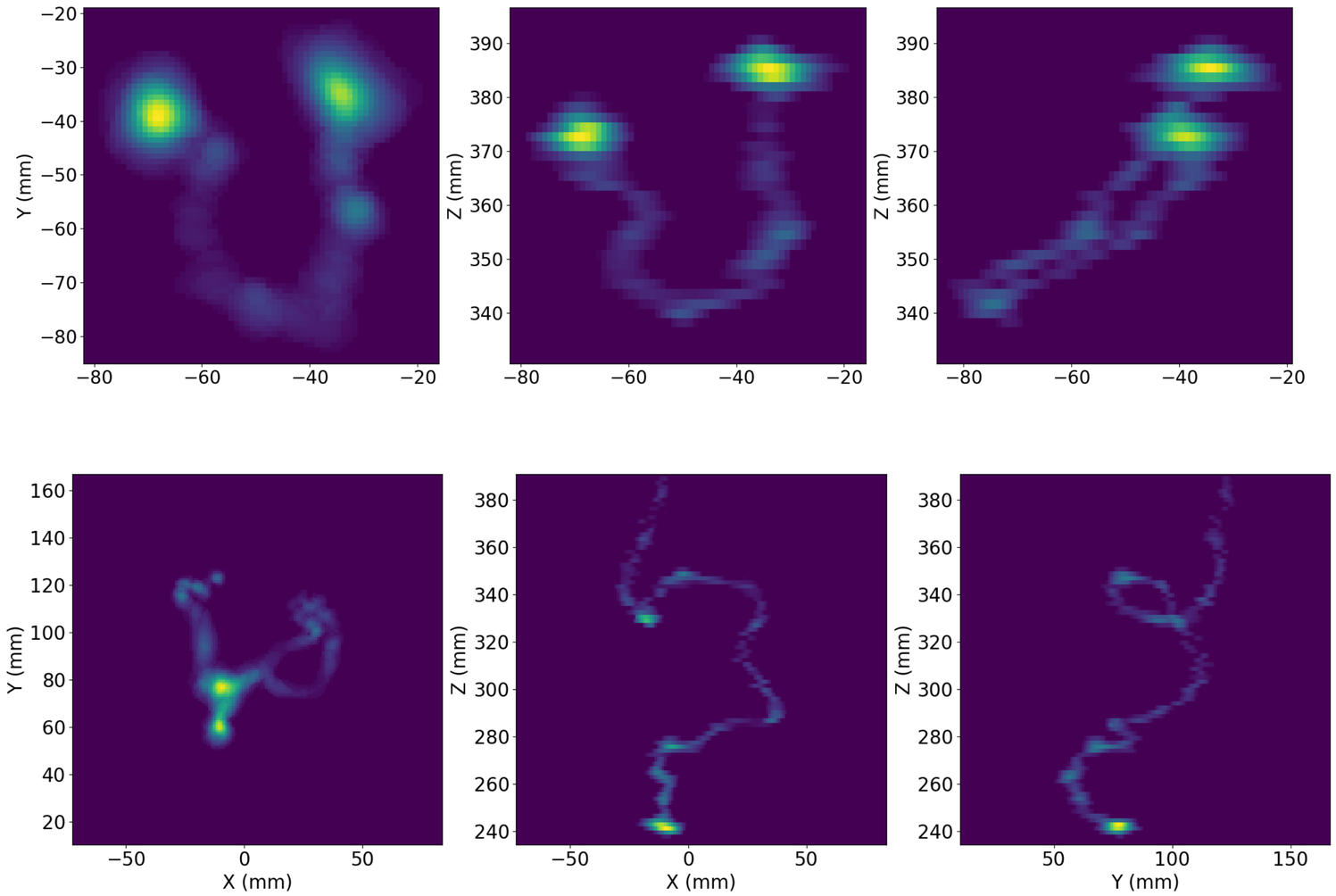


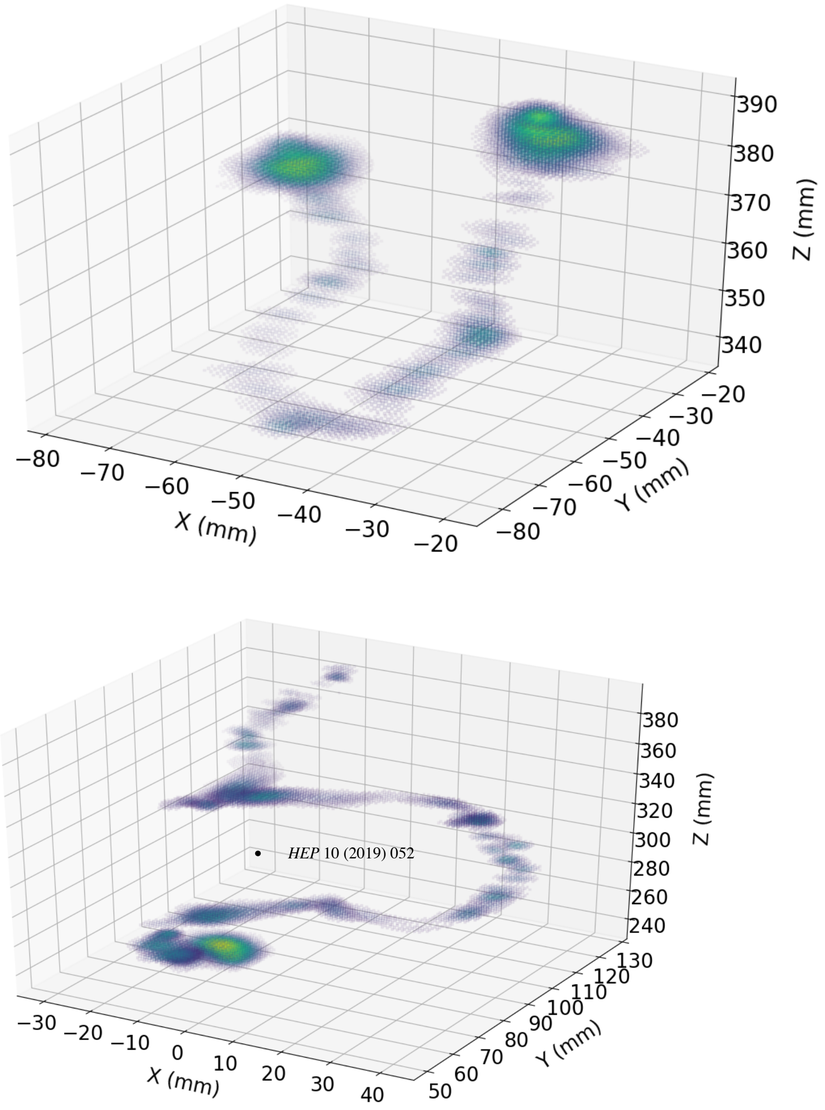
- *JHEP* 10 (2019) 230

Topological signature

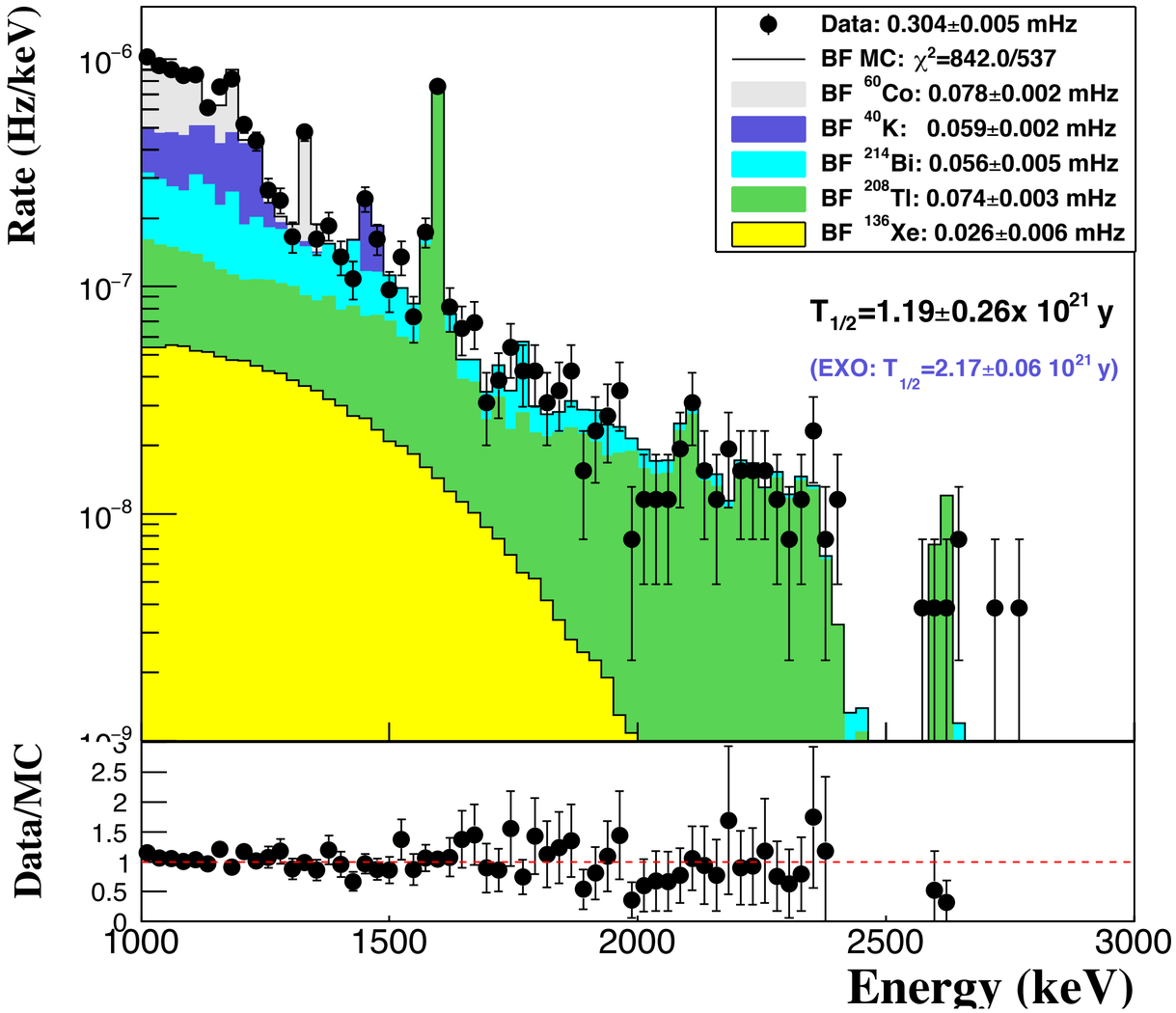
• *JHEP* 10 (2019) 052

Single and double electrons from $\beta\beta2\nu$ analysis with energies near $Q_{\beta\beta}$



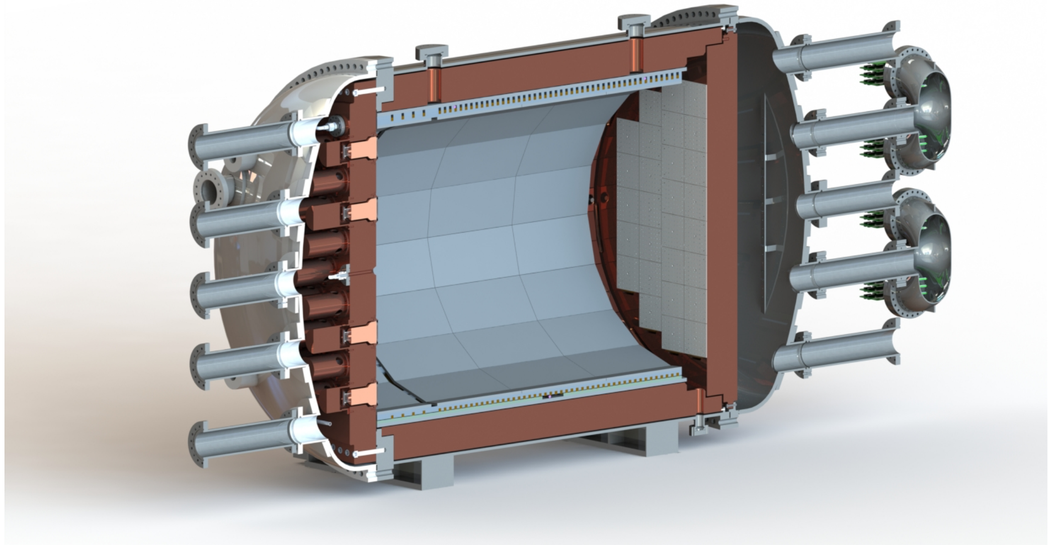


Measurement of $\beta\beta2\nu$ mode/NEXT-100



PRELIMINARY

$$B \sim 4 \times 10^{-4}\ \mathrm{kg}^{-1}\ \mathrm{yr}^{-1}\ \mathrm{kev}^{-1}$$



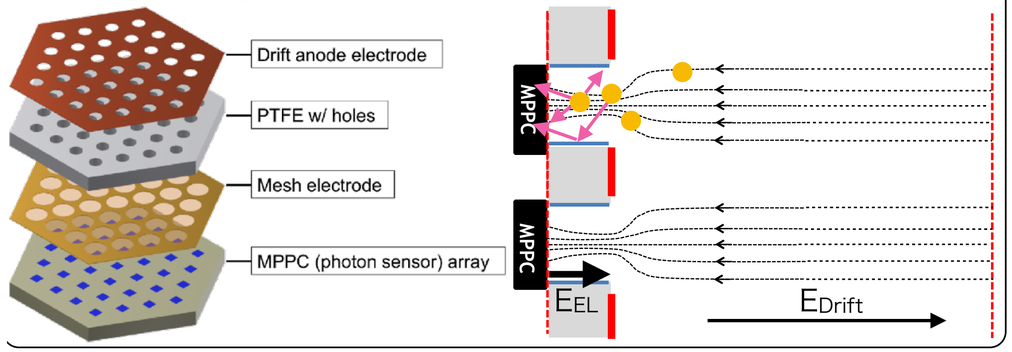
AXEL/PANDA-X-III

https://s3.cern.ch/inspire-prod-files-7/7491a380661a620b4239f88f64a9129b
arXiv:1610.08883

Electroluminescence Light Collection Cell (ELCC)

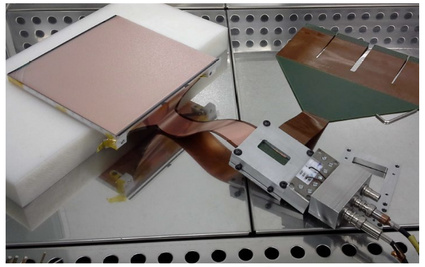
Ionization electrons are pulled into cells and EL lights are generated by the electric fields

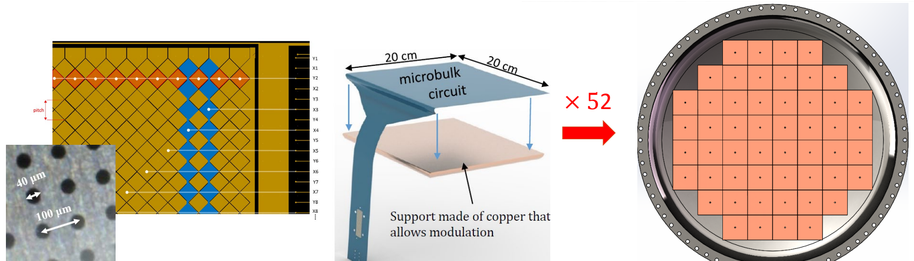
[Merit] - Less position dependence
- Track reconstruction
- Rigid structure

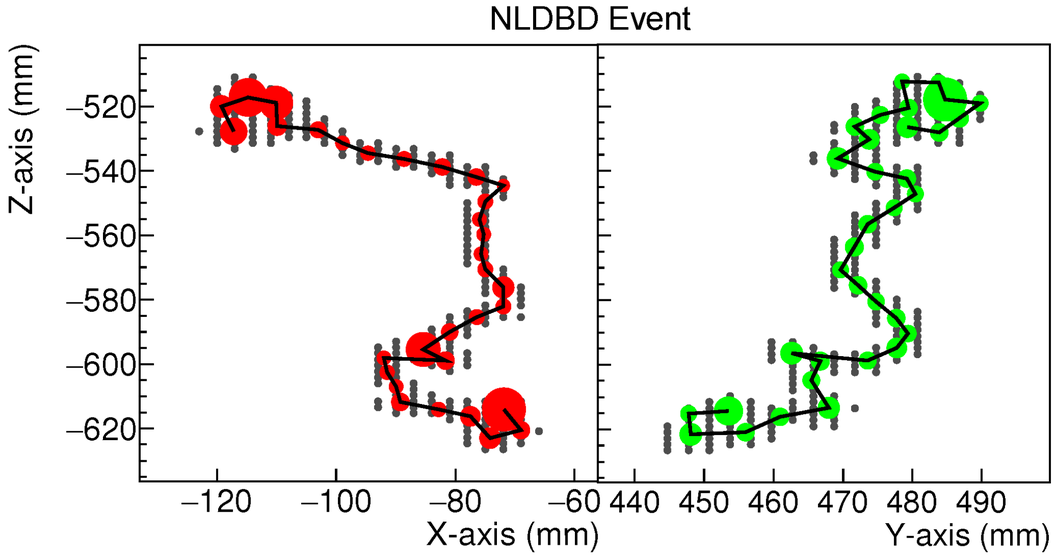


- AXEL: ELCC concept very well suited for ton-scale . VUV SiPMs.
- PANDA-X-III: optimal topology reconstruction. Resolution ~3 % FWHM. T_0?
- Convergence HPXe projects for ton-scale appears as a must.

- MicroMegas films with OFHC copper backing
  - 20 by 20 cm each
  - 3 mm pitch size, 128 strip readouts
- 52 pieces: Mosaic layout to cover readout planes
- Readout plane design near final.

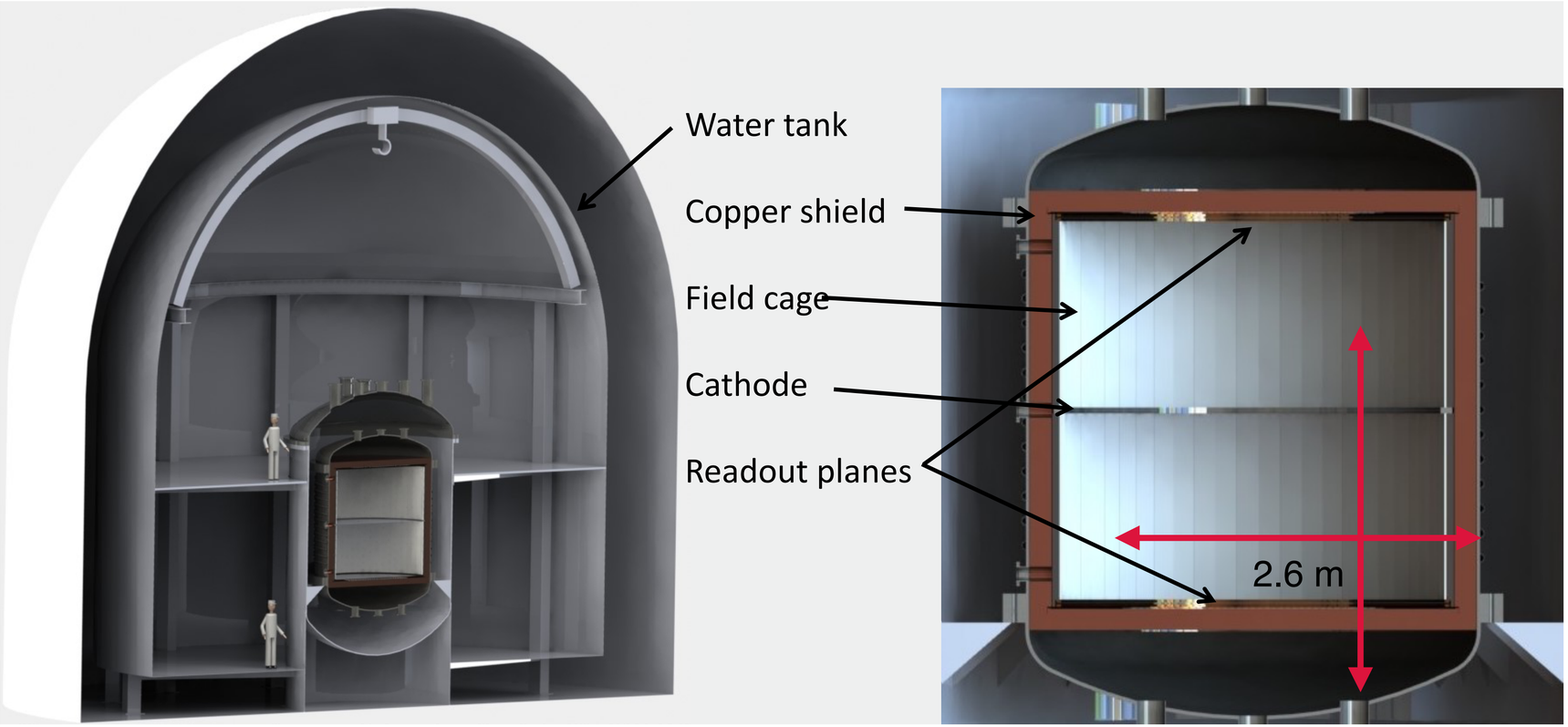






NEXT-HD

https://arxiv.org/pdf/2005.06467.pdf



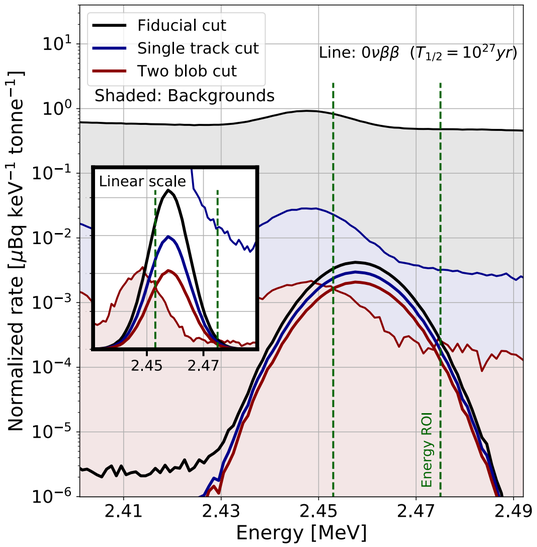
- A NEXT detector with ~1 tonne of xenon at 15 bar.
  Symmetric design with a central cathode and two readout planes with SiPMs.

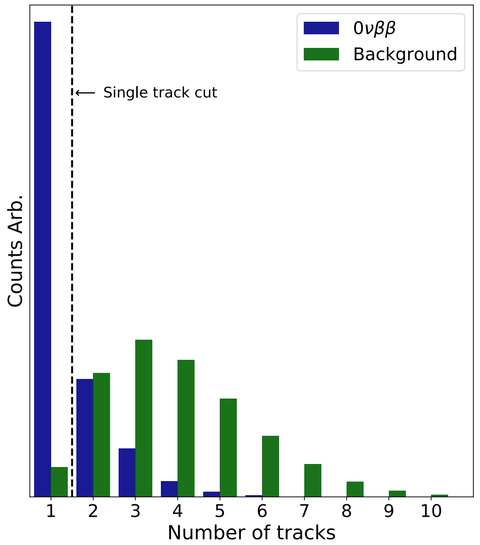
- Energy readout in a Barrel Energy Detector (double-clad fibres readout by SiPMs)

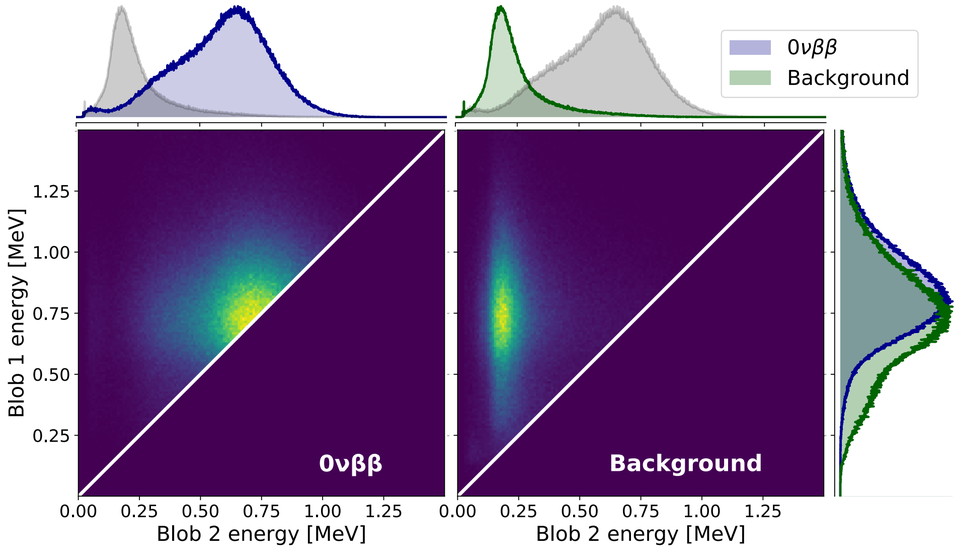
NEXT-HD

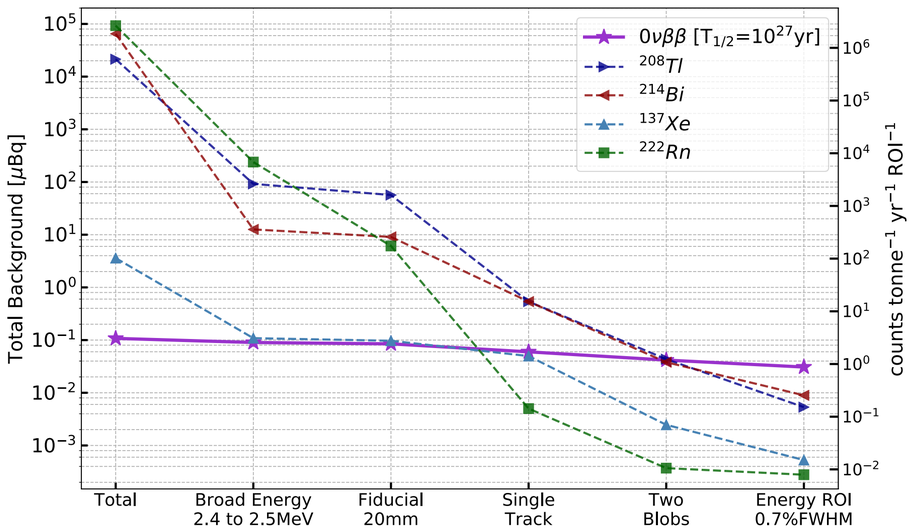
1 module 5 years: T $\sim 10^{27}$ year for 5 ton · year

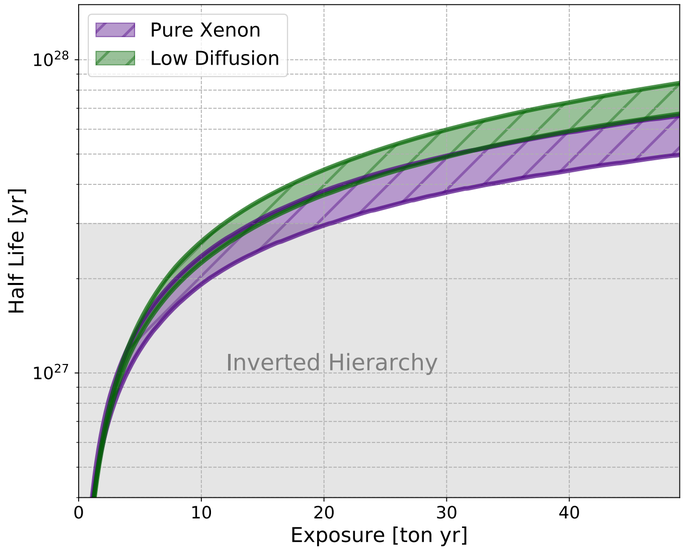
5 module 10 years: T $\sim 10^{28}$ year for 50 ton · year

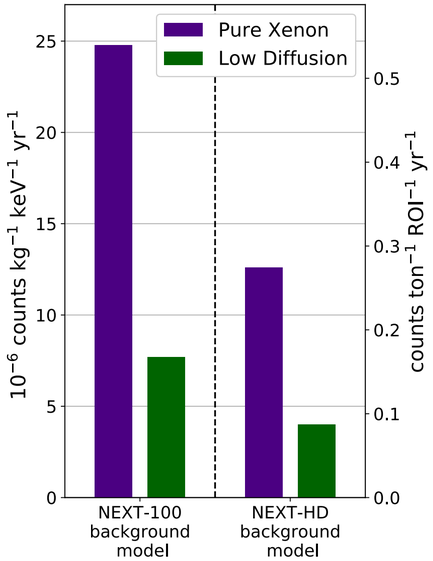












BOLD

Show stoppers?

- Enriched xenon is expensive and production of tens of tons appears prohibitive. At the highest peak even 5 ton of enriched xenon may cost well in excess of 100 M$
- HPXe are “small” (1 ton per module). Several modules are needed to achieve 50 ton x year exposure. In exchange, cost per module is modest and there is the possibility of improving the technology from one module to the next
- Conversely, for a LXe TPC one needs to pay upfront all the xenon before building the apparatus, leaving less room for retro-fitting detector. In exchange a single detector does the job.
- Dark Matter detectors such Darwin would be competitive if only they would have more enriched xenon. Fiducial cut limits Darwin to 0.5 tons.
- Internal backgrounds such as those associated to Xe^{137} and Rn^{222} may become very difficult to control once we get to the level of less than one count per ton of target

BOLD1: Enriched xenon from NPPs

- Xenon from nuclear waste is naturally enriched almost at 50 %.
- R&D program on recycling nuclear waste under way at LSC (Spain) in collaboration with ORANO (France) and ENUSA (Spain).
- ORANO @La Hague: Possible up to 3 tons/yr ^{136}Xe production at a lower cost than processing natural xenon.
- Gross Numbers: ~6 10^4 metric tons Uranium consumed a year
- ~ 6 kg ^{136}Xe / metric ton U : ~360 tons ^{136}Xe /yr
- Extraction: recycling (~50%) or gas escape by pinching bars (1-2%).
- A energy program with NPPs may lead to acquiring ~50 tons of xenon enriched at 50 % in ^{136}Xe.

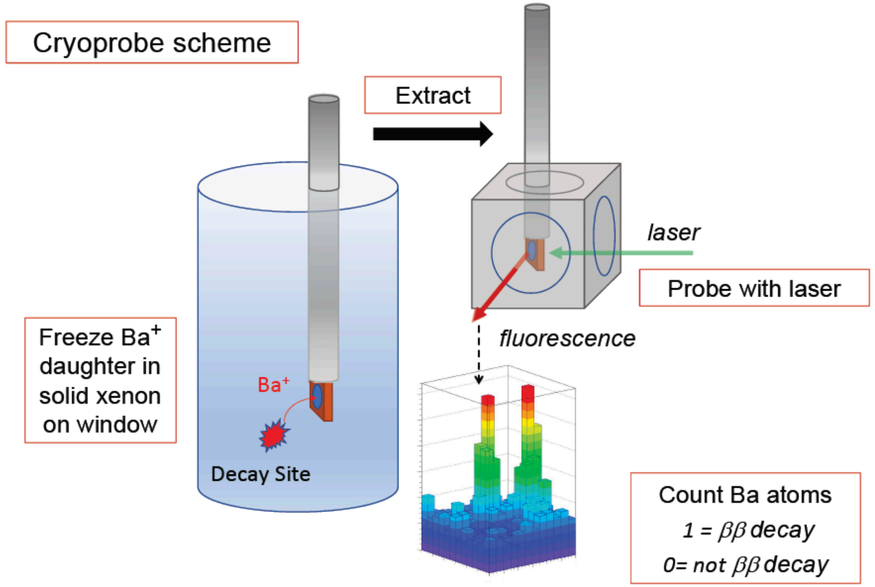
BOLD2: Barium Tagging can change the game

Imaging of single Ba atoms and ions in solid xenon for barium tagging in nEXO

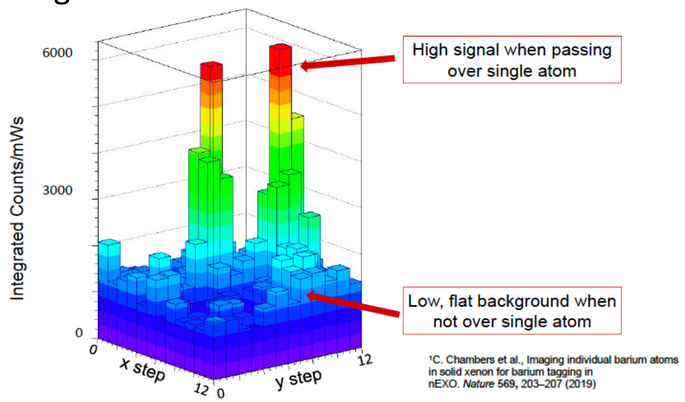
James Todd, David Fairbank, and William Fairbank
Colorado State University and the nEXO Collaboration

$$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}$$

Barium tagging gives potential to eliminate all but 2νββ backgrounds in neutrinoless double beta decay experiments.

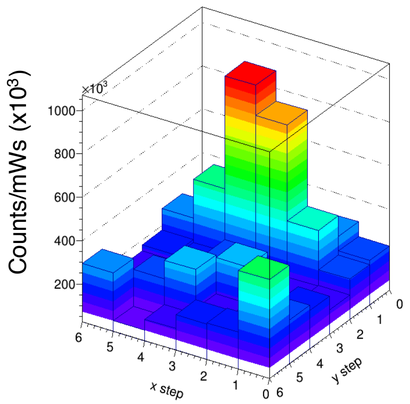


Images of Ba atoms and Ba^{+} ions at few atom level

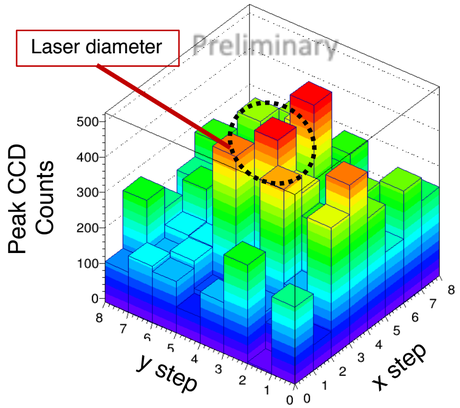


[1]C. Chambers et al., Imaging individual barium atoms in solid xenon for barium tagging in nEXO. *Nature* 569, 203–207 (2019)

Image of two barium atoms in the single vacancy matrix site.[1]



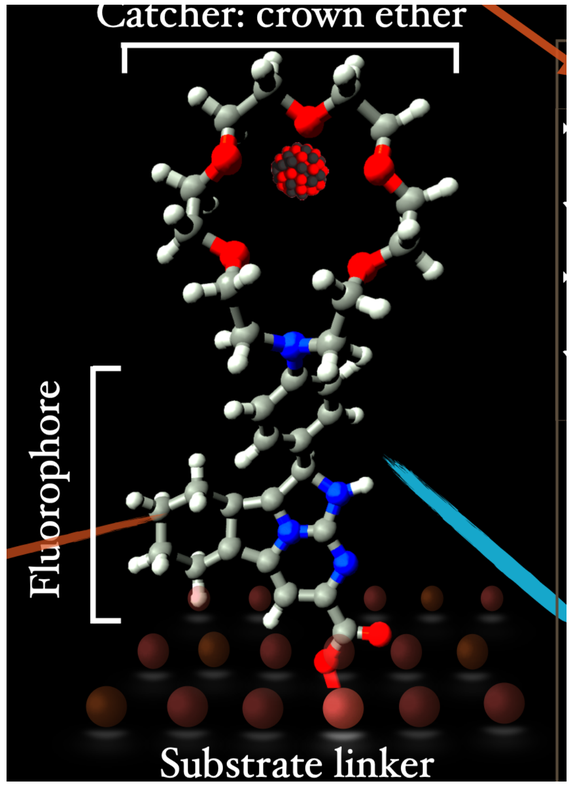
Step size: 4μm
Single Ba image in 7-vacancy site



Scan image of Ba^{+} deposit looking at 530 nm Ba^{+} emission, with ~4 Ba^{+} ions deposited in entire scan area.

https://www.nature.com/articles/s41586-019-1169-4

Barium Tagging can change the game



The **NEXT** Collaboration's Big Idea:

Exploit *single molecule fluorescent imaging (SMFI)* to visualize a single barium ion as it arrives at the TPC cathode.

For ^{136}Xe, in gas phase, the daughter is ~100% $^{136}Ba^{++}$, perfect for using SMFI techniques.

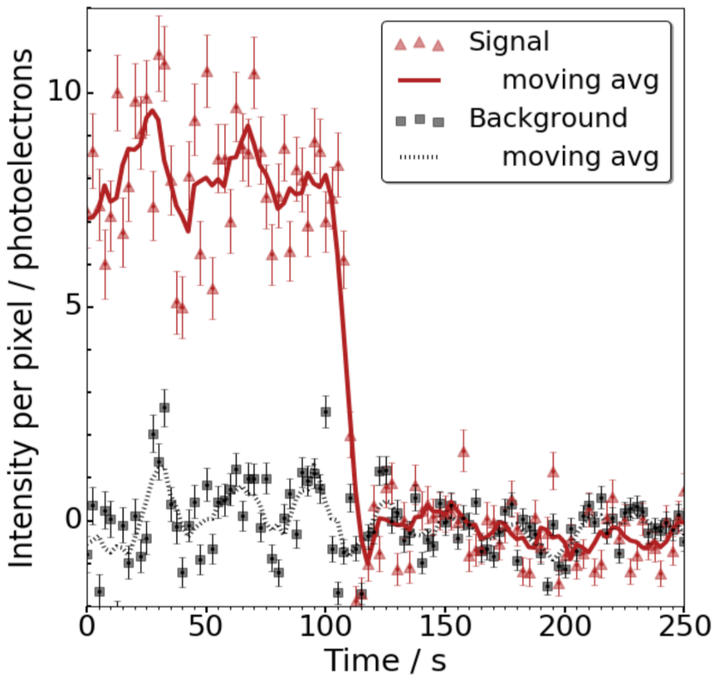
Goal: develop custom molecules that change luminous response after chelating Ba dications.

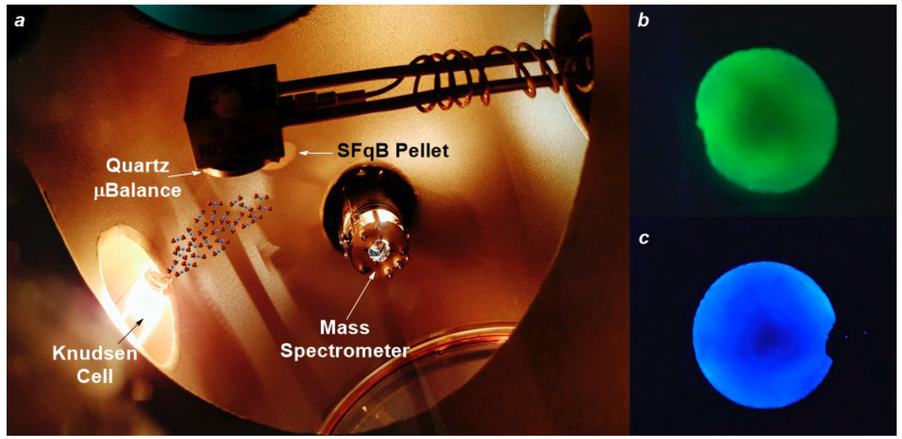
Molecules must (and do!) display high specificity to Ba^{++}

Common elements: crown ether + fluorophore + linker

Complementary approaches explored in US and Spain
Spain: molecule changes color strongly: green → blue
Texas: molecule changes from non-luminous to luminous

Molecular engineering: predictive computations too!

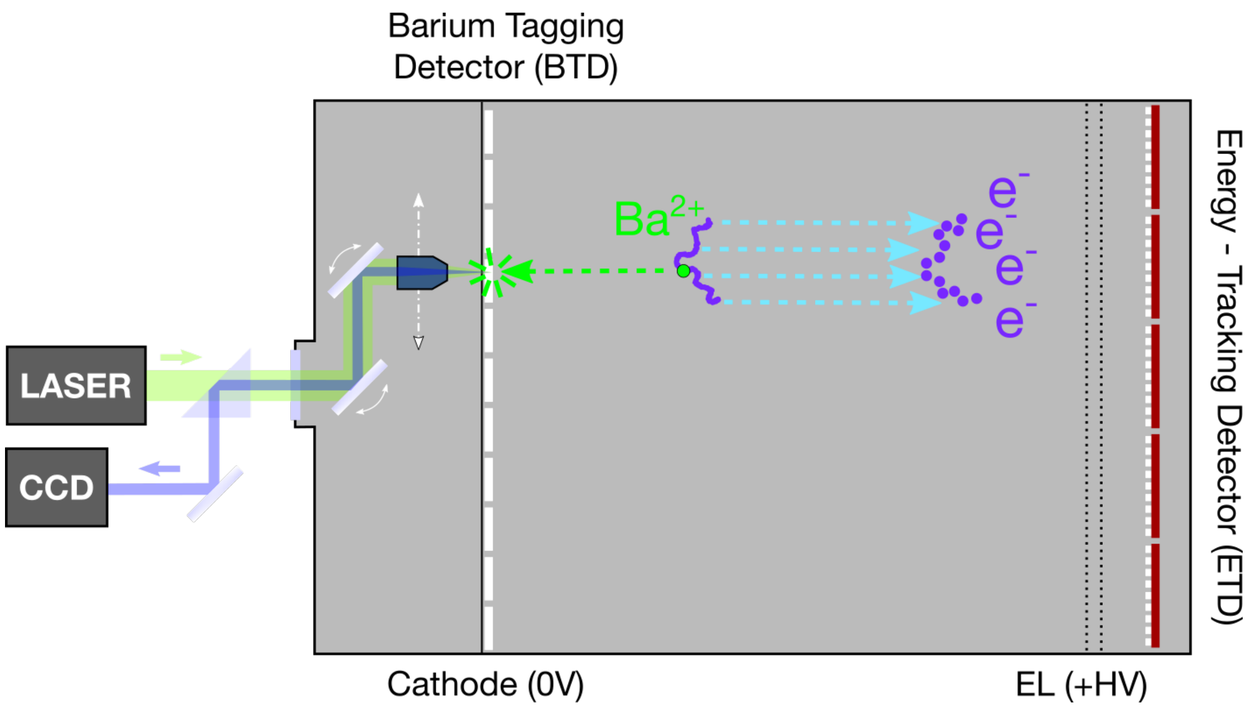


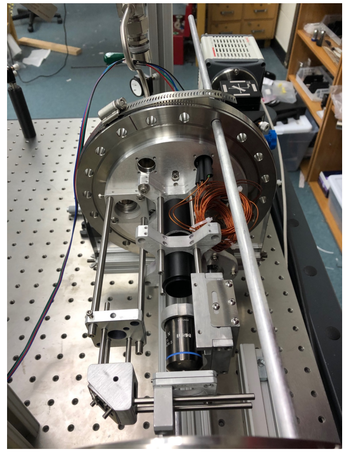


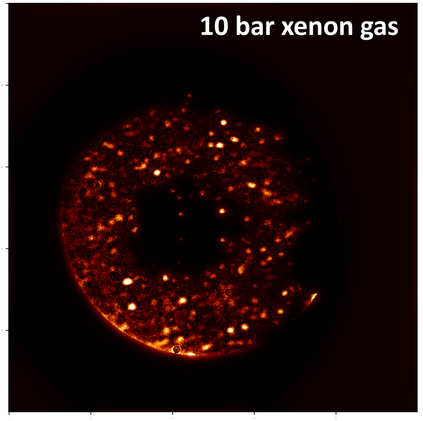
https://www.nature.com/articles/s41586-020-2431-5

https://journals.aps.org/prl/abstract/10.110 /PhysRevLett.120.132504

Barium Observation Light Detector (NEXT-BOLD)







- Predict arrival position of Ba2+ with windows of 1 cm/1ms
- Instrument full cathode or implement RF carpet
- Open gate to let Ba^{2+} pass just when it arrives to cathode. Thus coincidence between topology, energy and Ba^{2+} signal
- Unambiguous B^{a2+} signature from color shift, photobleaching or both.

https://www.nature.com/articles/s41586-020-2431-5

https://arxiv.org/abs/2006.09494

A unique opportunity

- Finding if the neutrino is its own antiparticle (e.g, a Marihuana Particle as defined by Dave Nygren) is one of the major questions sill unanswered in particle physics. There is great motivation to fully cover the IH and beyond.

- Several isotopes are needed (no one would built the LHC with a single detector in the ring). Xenon is an obvious candidate and xenon experiments have shown tremendous potential.

- The development of the ton scale will keep us busy for a decade. We are in the infancy of the field, with (at least) two more order of magnitude to go in T_0

- Reaching 10^{27} year appears feasible by incremental improvement but…

Bold ideas are needed

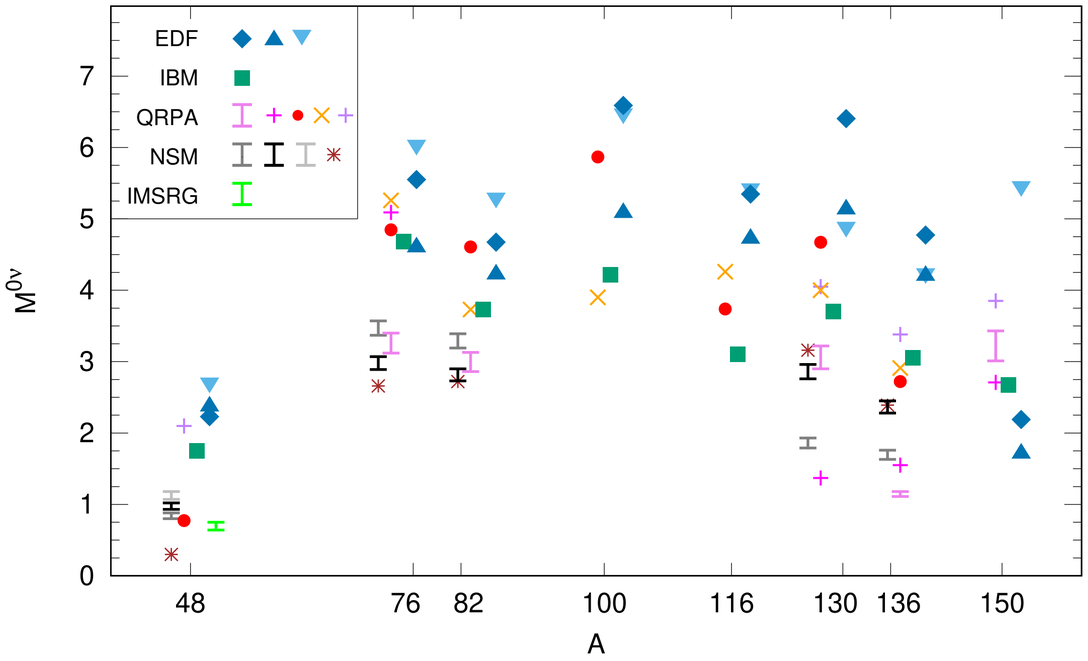
- Reaching 10^{28} and beyond may need bold ideas.
- nEXO & NEXT with Barium tagging
- Darwin with xenon enriched at 50% in Xe^{136} thus 20 tons of enriched xenon.
- A future experiment with Xe^{136} (and barium tagging) deploying O(20) tons of target mass (1 x LXe, n x VHPXe), may reach an exposure of 200 ton x year, “background free”, thus approaching T_0 ~10^{29} y and further exploring Majorana’s landscape.

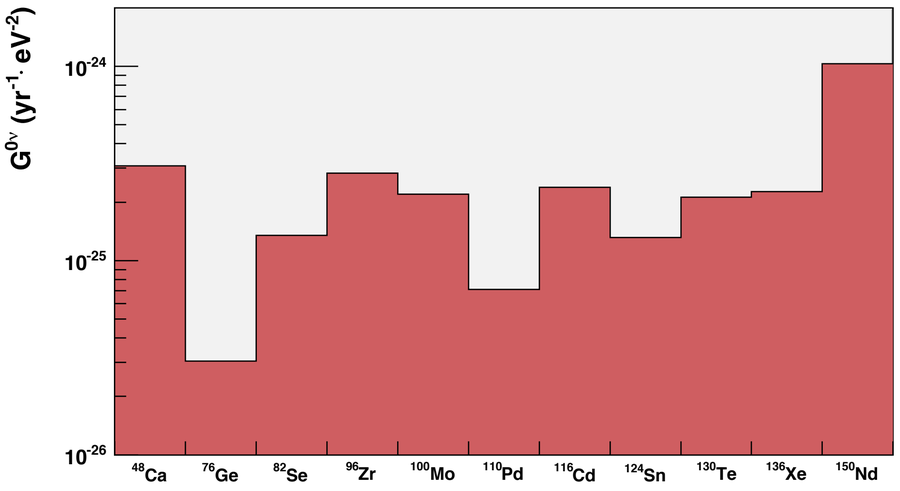
Thanks for your attention

Backup

Why Xenon?

Relative atomic mass	135.907219(8) [24]
Q value ^{136}Xe $\rightarrow$ ^{136}Ba	2457.83(37) keV [25] 2458.7(6) keV [26] 2458.1(3) keV (average)
$G^{0\nu}$ (10^{-15} year^{-1})	14.58 [27] 14.54 [28]
$0\nu\beta\beta$ decay NME	2.19 (ISM) [29] 3.05 (IBM-2) [30] 2.46 (QRPA) [31] 2.91 (QRPA) [32] 4.12 (EDF) [33] 4.32 (EDF) [34]





Xenon production

- Xenon and krypton are produced as by-products o cryogenic oxygen and nitrogen production.

- It is not economical to operate a plan to collect just neon, krypton or xenon. Collection of these gases is only economical at large ASUS which produce typically 2000+ tons per day of oxygen

LOX incl.

2000 ppm

Kr/Xe

Large Air Separation Unit (ASU)
with rare gases column
Air intake > 150,000 m^3/h or
oxygen capacity > 30,000 m3/h

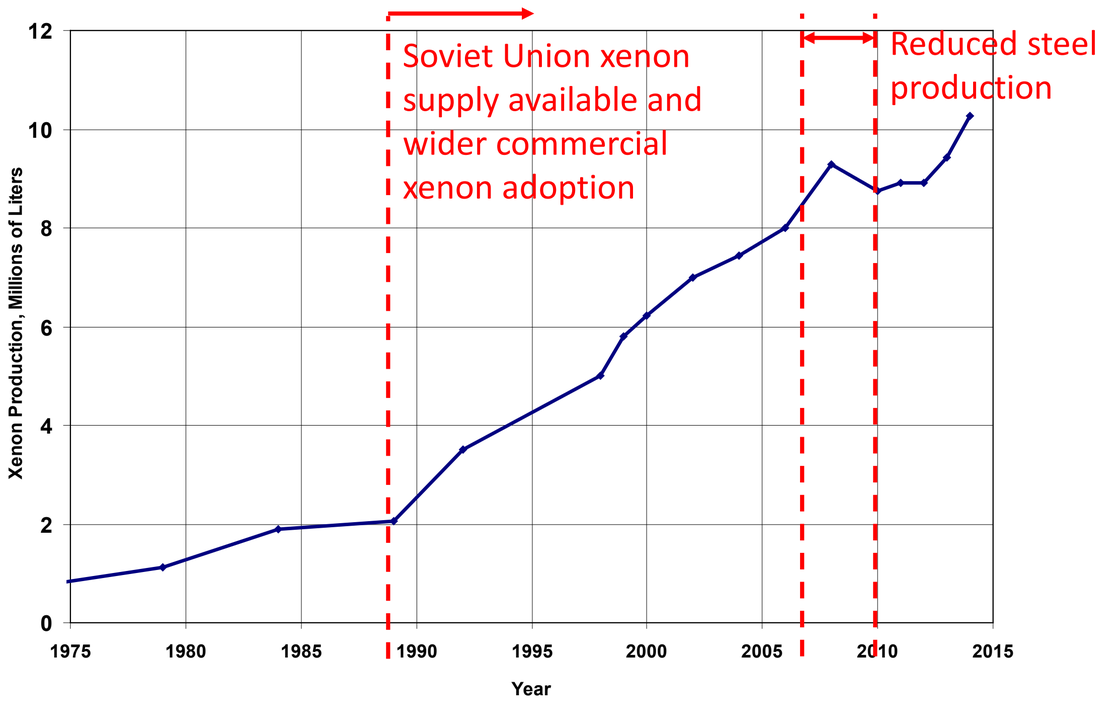
Kr/Xe Enrichment
99%

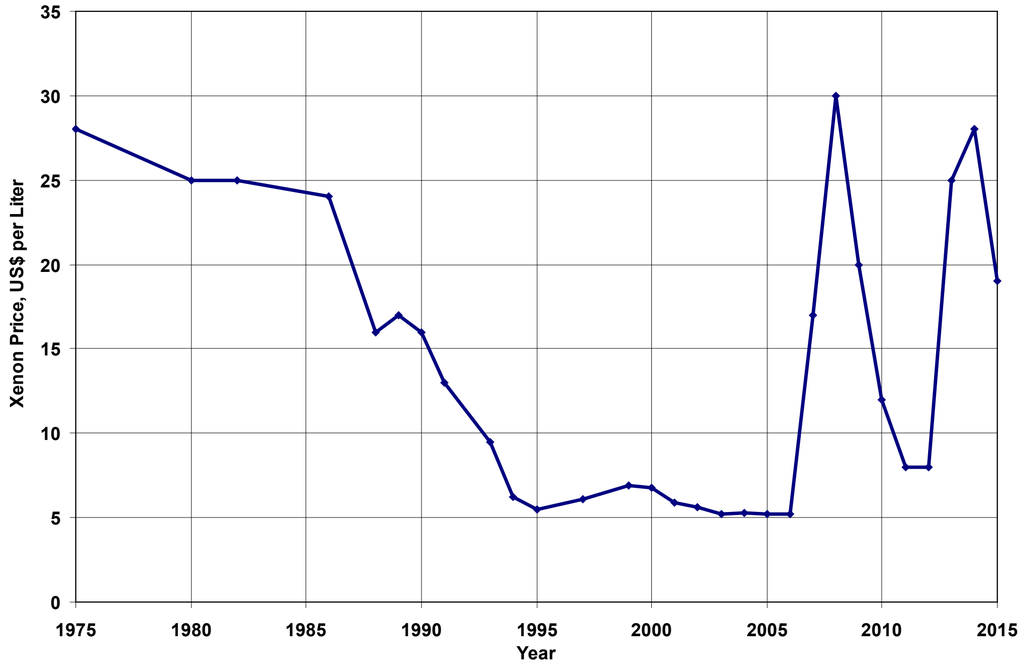
Kr/Xe
Separation

Pure
Kr / Xe

Xenon production and cost

- In 2019 global market reached 17.9 Ml or ~100 tons.
- Cost per ton varies wildly, range between 1-5 M$/ton for natural xenon. Enriching multiplies cost by typically x 10.

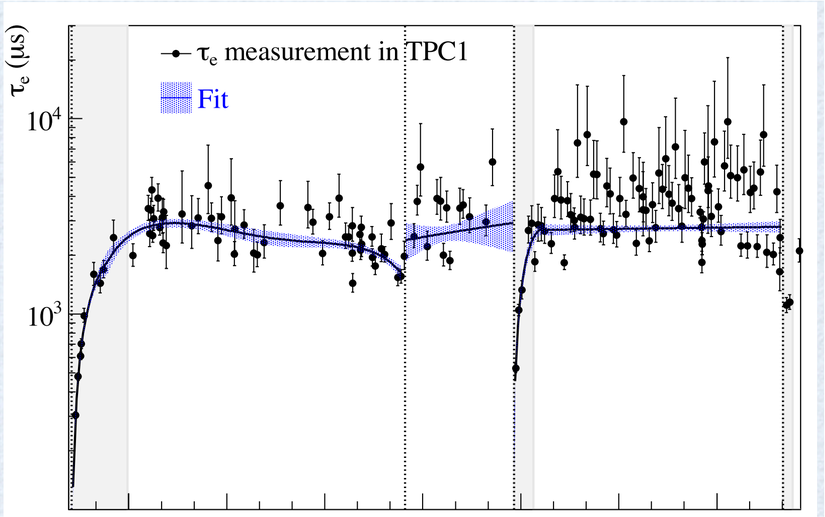


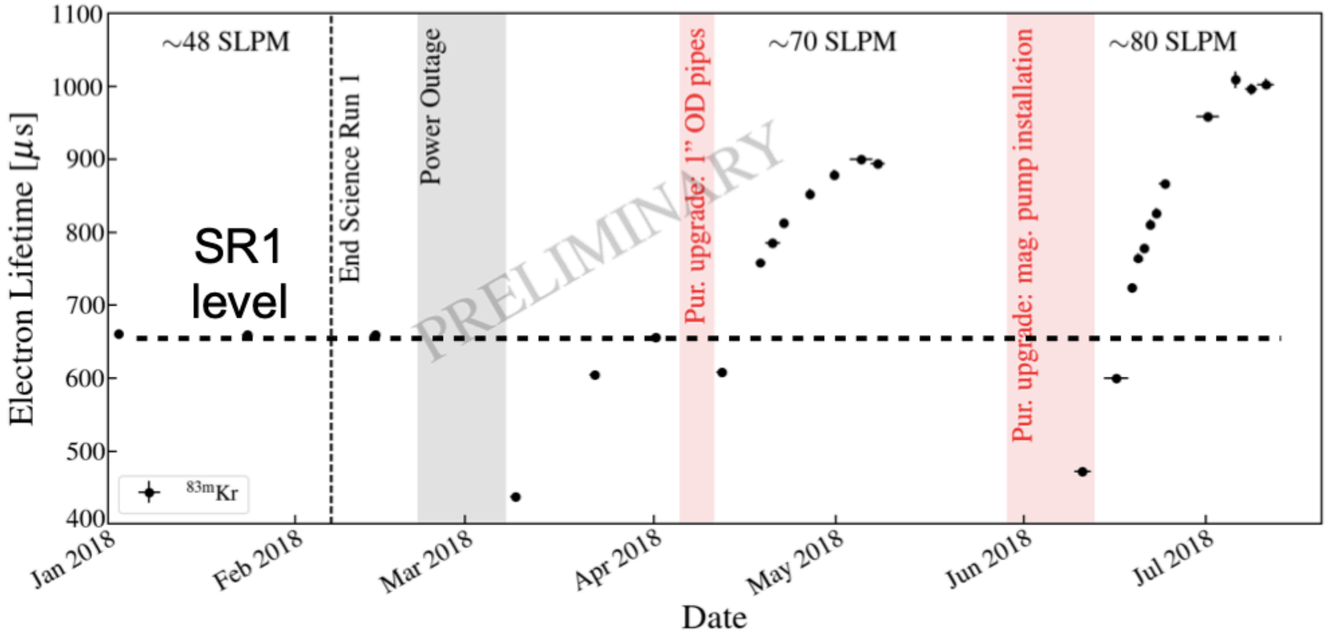


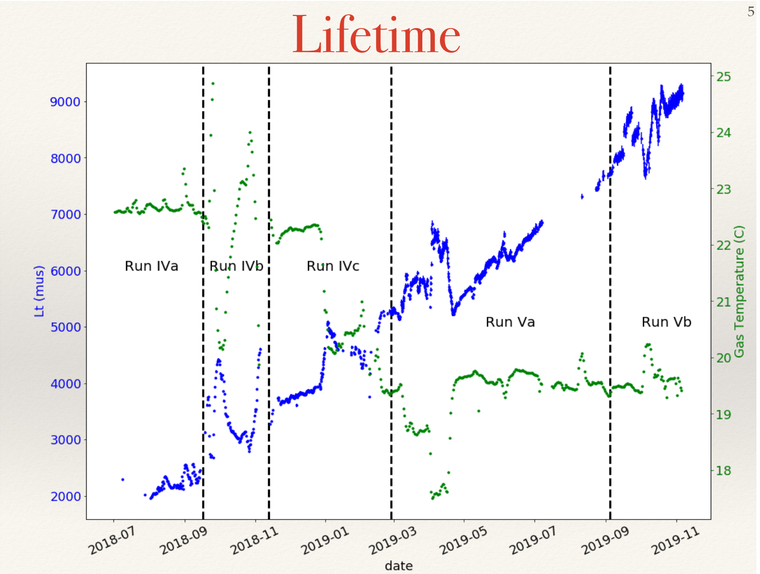
- **Global annual production estimated at 53,000 kg**

Electron lifetime

- NEXT-White: >10 ms
- XENON1T: 1 ms
- EXO-200: 3 ms

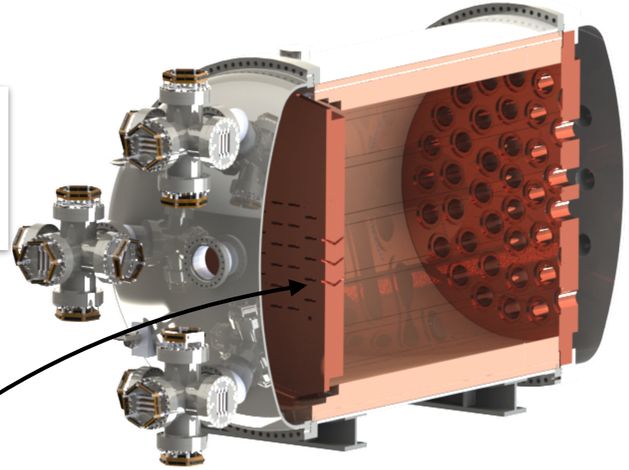


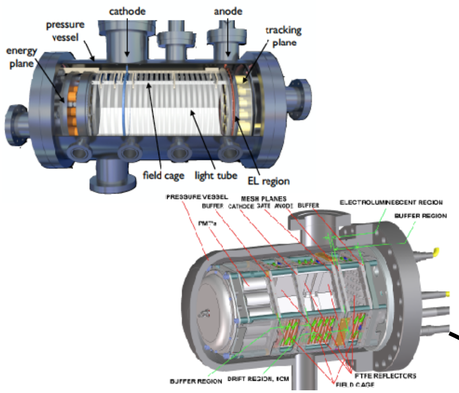




The NEXT program

NEXT-100 (~100 kg)
[2020 - 2020's]



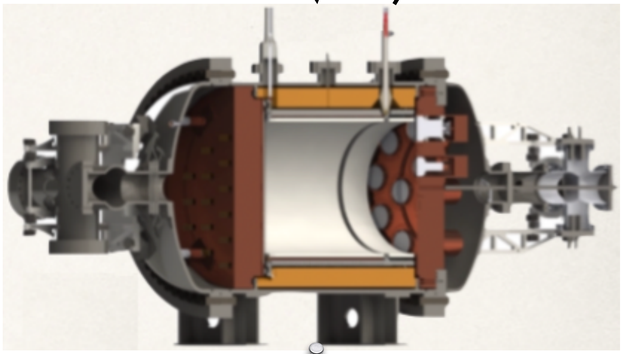


ββ0ν searches (10^{26} y)
Show extrapolation to ton scale

Prototypes (~1 kg)
[2009 - 2014]

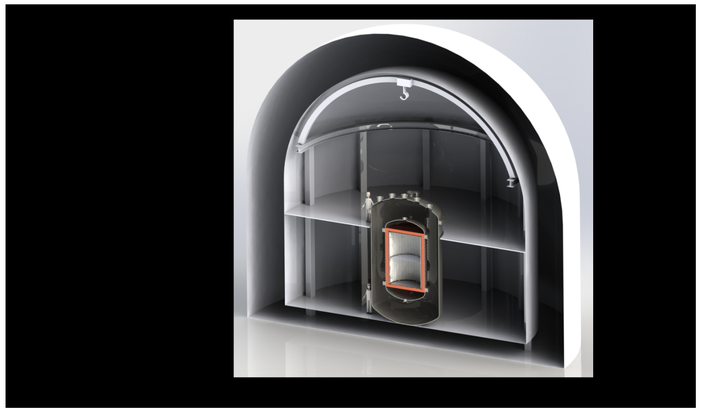
Demonstration of detector concept

NEXT-White (~5 kg)
[2015 - 2018]

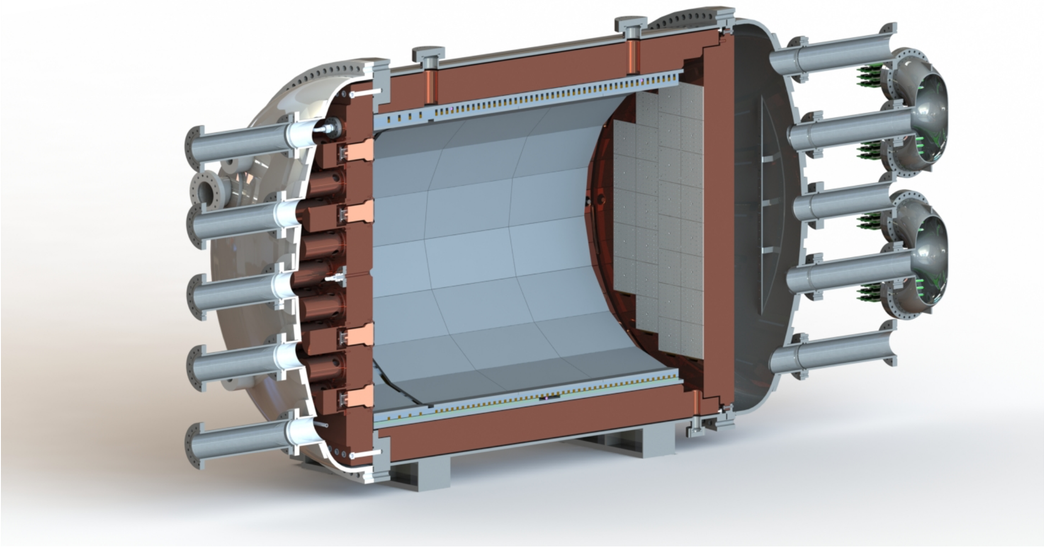


Underground and radio-pure operations, background, ββ2ν

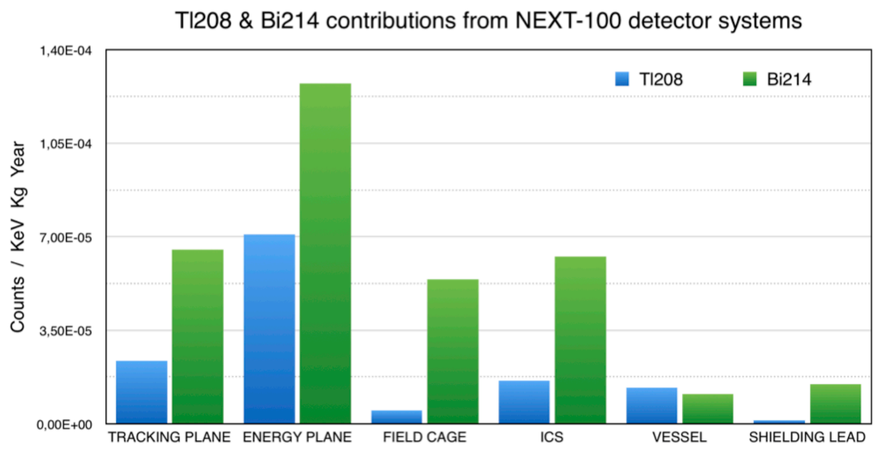
NEXT-HD/BOLD
[2020's]

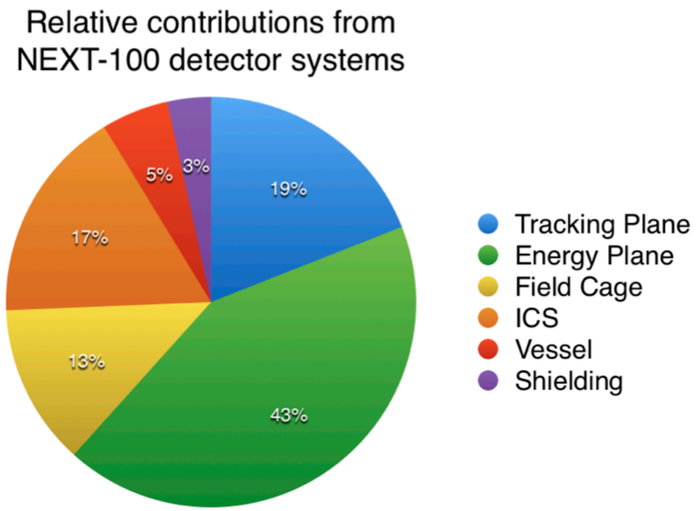


NEXT-100 (commissioning in 2021)



$$BQ \sim 4 \times 10^{-3}\ \mathrm{kg}^{-1}\ \mathrm{yr}^{-1}\ \mathrm{kev}^{-1}$$



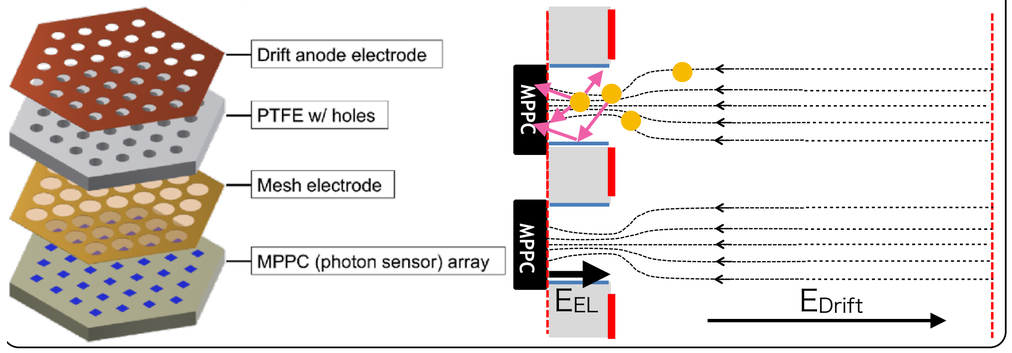


AXEL

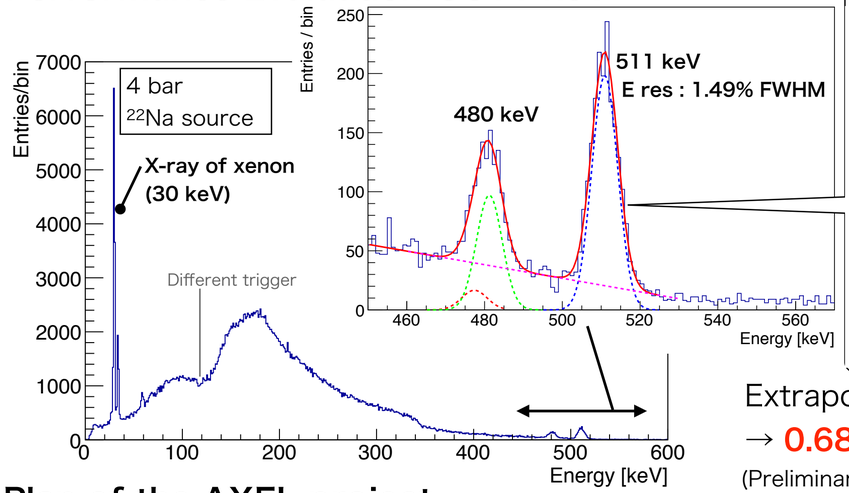
Electroluminescence Light Collection Cell (ELCC)

Ionization electrons are pulled into cells and EL lights are generated by the electric fields

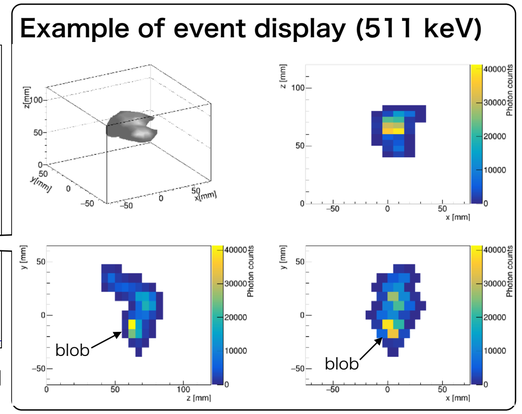
[Merit] - Less position dependence
- Track reconstruction
- Rigid structure



Performance Evaluation @511 keV



Example of event display (511 keV)



Extrapolate to the Q-value (2458 keV)

→ **0.68—1.18% FWHM**

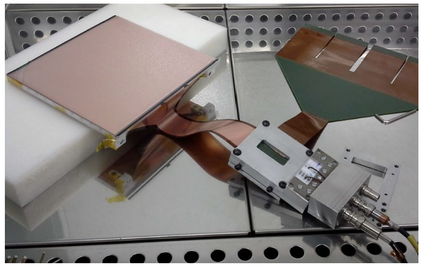
(Preliminary, improved from PTEP, 2020 Issue 3, 033H01)

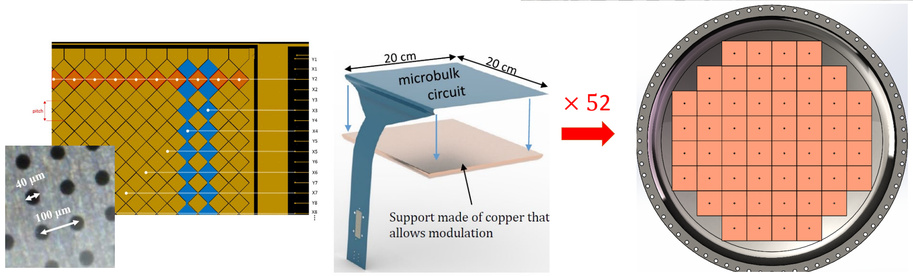
Plan of the AXEL project

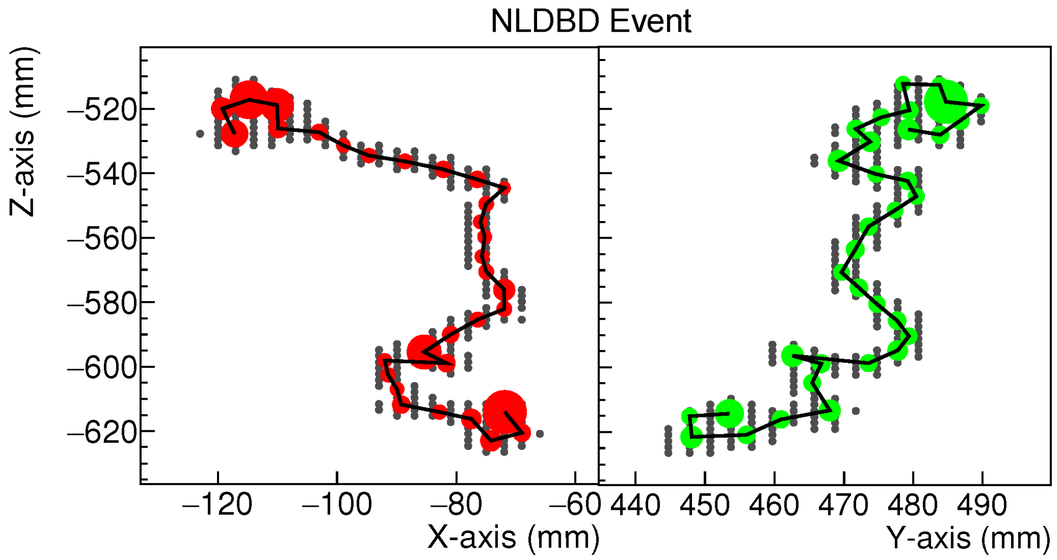
- AXEL project (led by Kyoto University) adds several ideas to the HPXeEL technology:
- Use of ELCC. Sharper definition of tracks and possibility to build very large structures (for ton scale detector)
- VUV SiPMs used both for tracking and energy resolution with good results
- Future ton-scale HPXe most likely will include one or more AXEL solutions

PANDAS-X-III

- MicroMegas films with OFHC copper backing
  - 20 by 20 cm each
  - 3 mm pitch size, 128 strip readouts
- 52 pieces: Mosaic layout to cover readout planes
- Readout plane design near final.







- Use or MicroMegas with charge multiplications as alternative to HPXeEL
- Use of true 2D pads for charge collection best for topology reconstruction
- Energy resolution ~3 % FWHM with Xe-TMA.
- XE-TMA: very low diffusion (further enhancement of topological signature) but no t_0 (no fiducial volume in Z). This appears as no-go for ton-scale searches.