Measuring the neutrino mass

J.J. Gómez Cadenas

IFIC (CSIC & UV)

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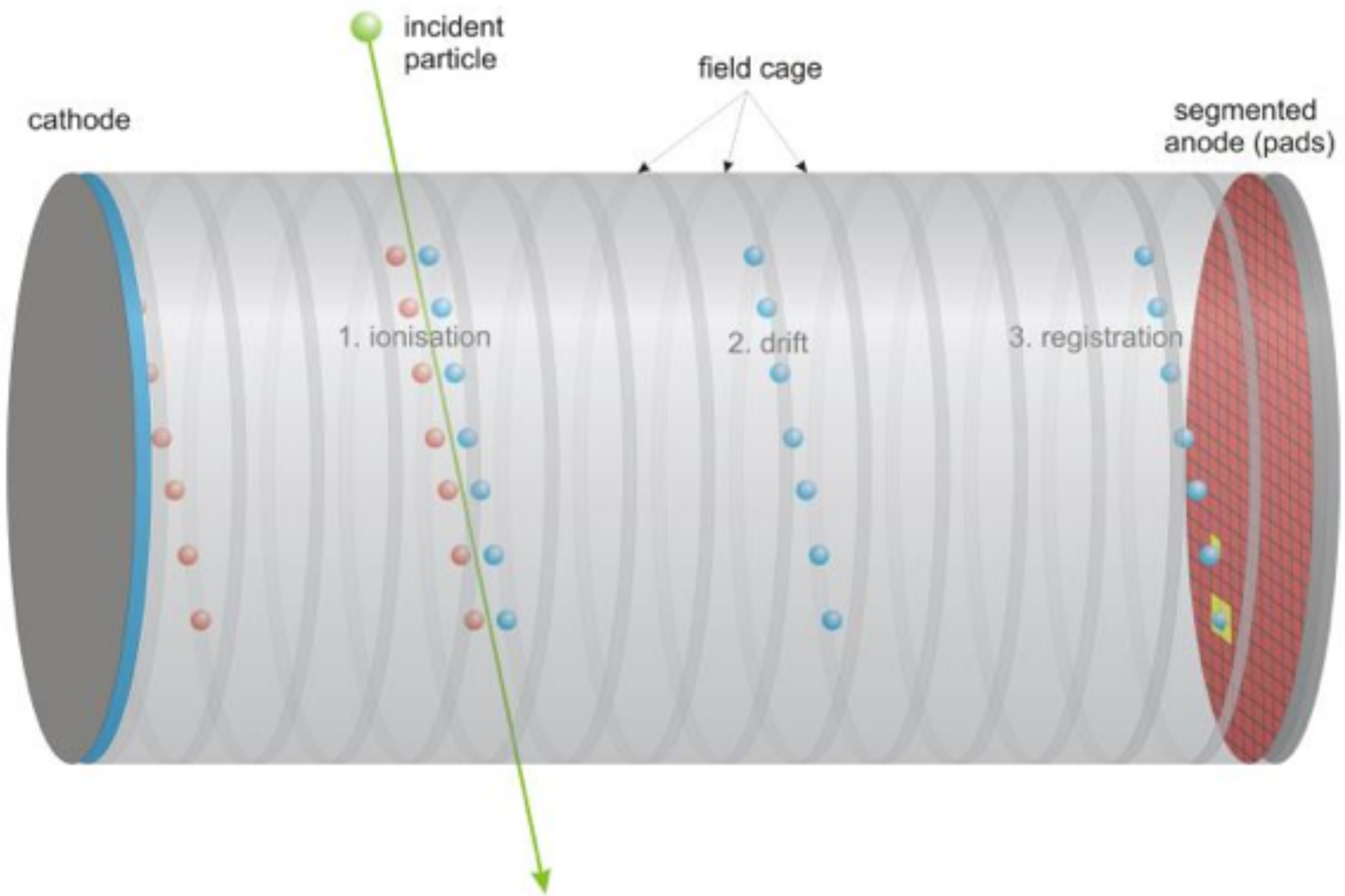
Lecture 5

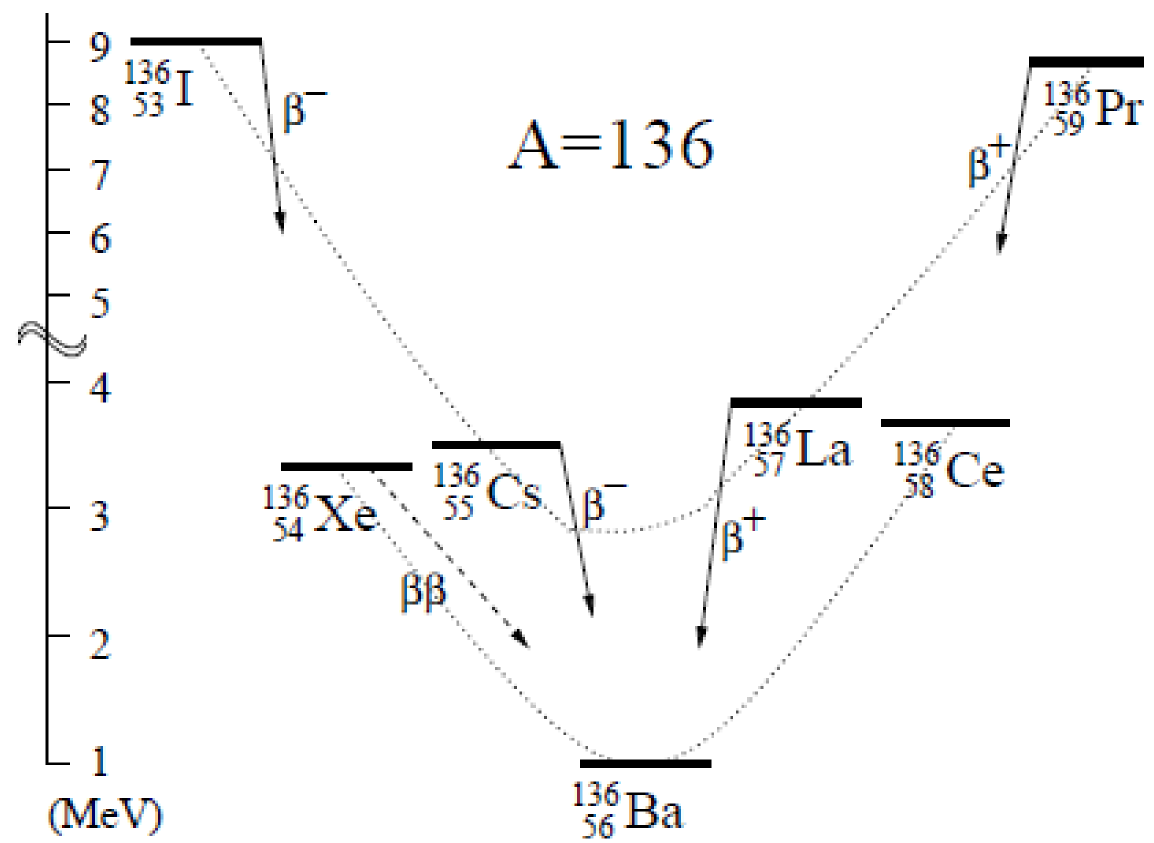
Xenon TPCs



- **The Time Projection Chamber (TPC). Invented by Dave Nygren, is one of the most successful detectors in nuclear and particle physics.**
- **It provides 3D image of tracks and if track contained also energy by calorimetric measurement.**

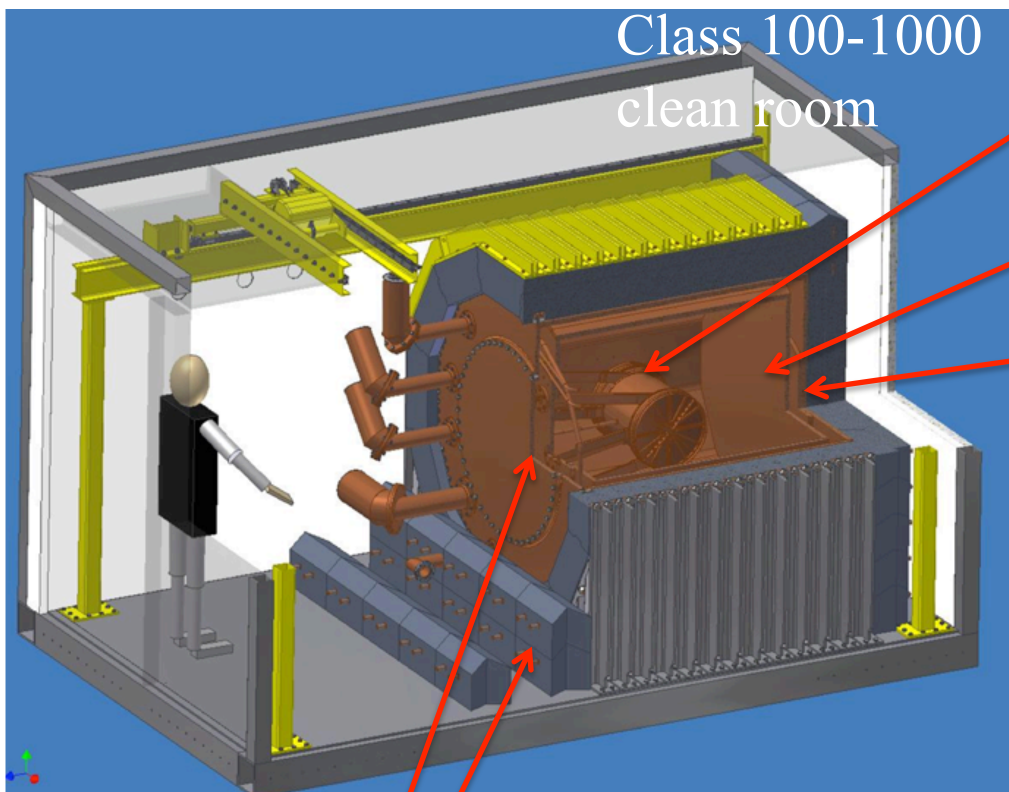
Xenon is a noble gas: one can build at Xenon TPC

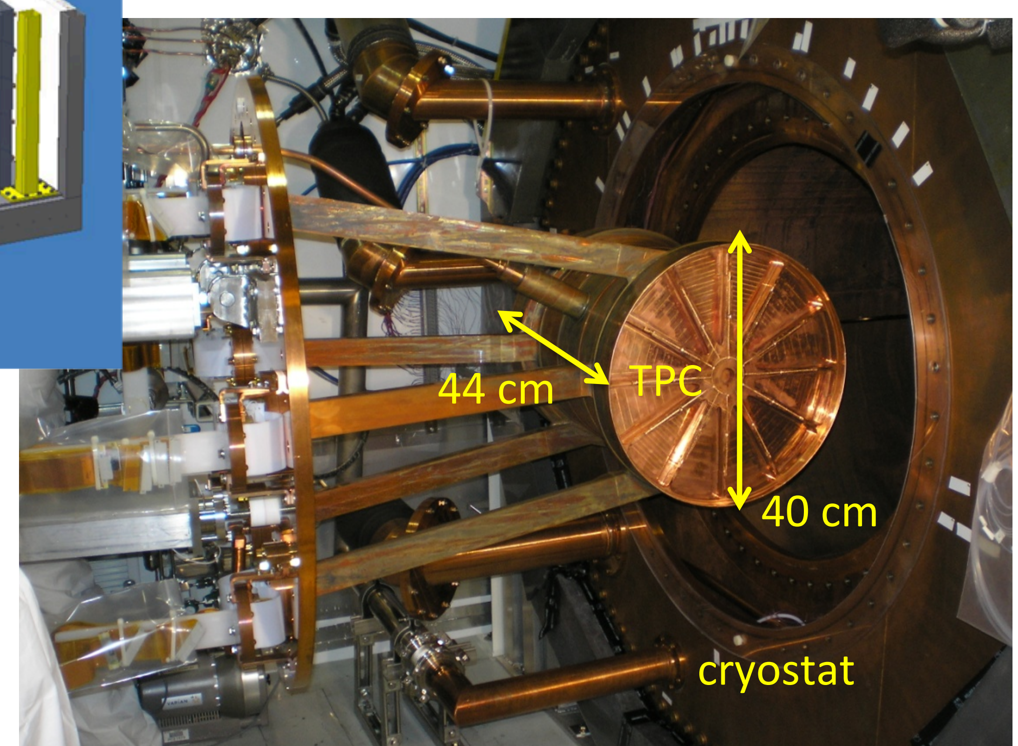
- Xenon is a good candidate for bb0n search
  - Q-value larger than energy of gammas from most natural radionuclides
  - Relatively easy to enrich in Xe-136 isotope
    - (no chemistry, centrifuge eff ~ dm=4.7 a.m.u.)
  - No need to grow high-purity crystals, continuous purification is possible (and relatively easy for a noble gas), more easily scalable
  - No long-lived cosmogenically activated isotopes
  - Final state (Ba-136 ion) can, in principle, be tagged, greatly reducing backgrounds



EXO

- 200 kg of Xe enriched to 80.6% Xe-136 total procured
  - 175 kg in liquid phase inside a cylindrical Time Projection Chamber
  - ~100 kg current fiducial mass

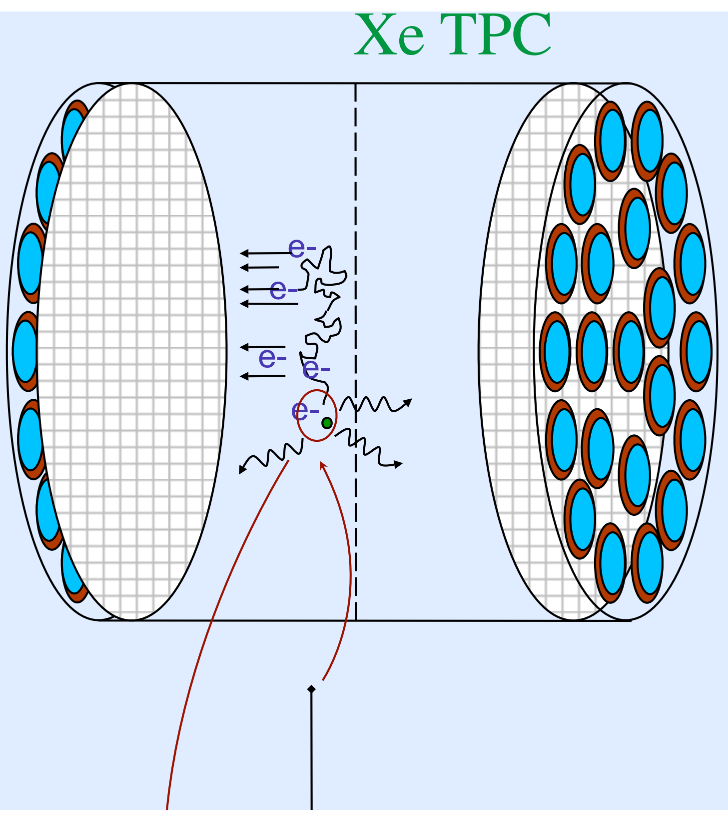




EXO detection strategy

detect the 2 electrons
(ionization + scintillation in xenon TPC)

$$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-} \; (+\, 2\nu_e)$$



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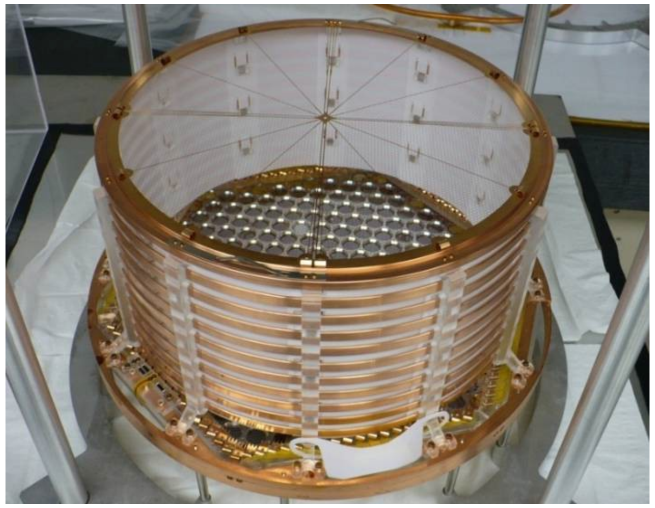
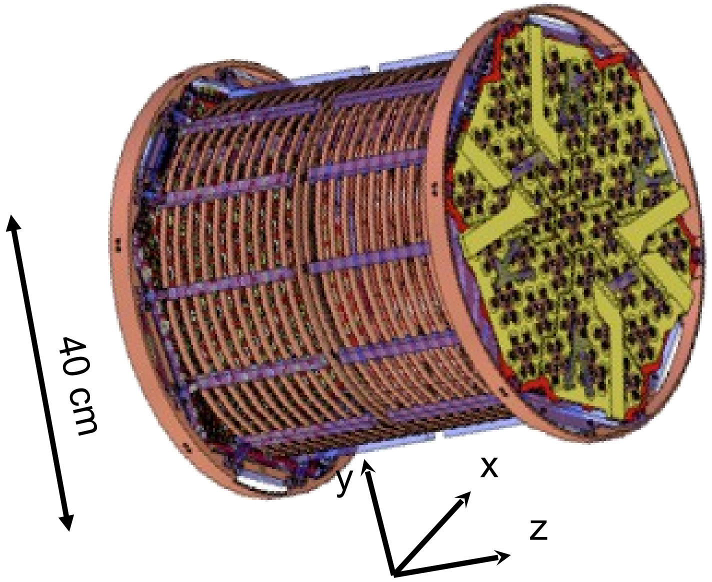


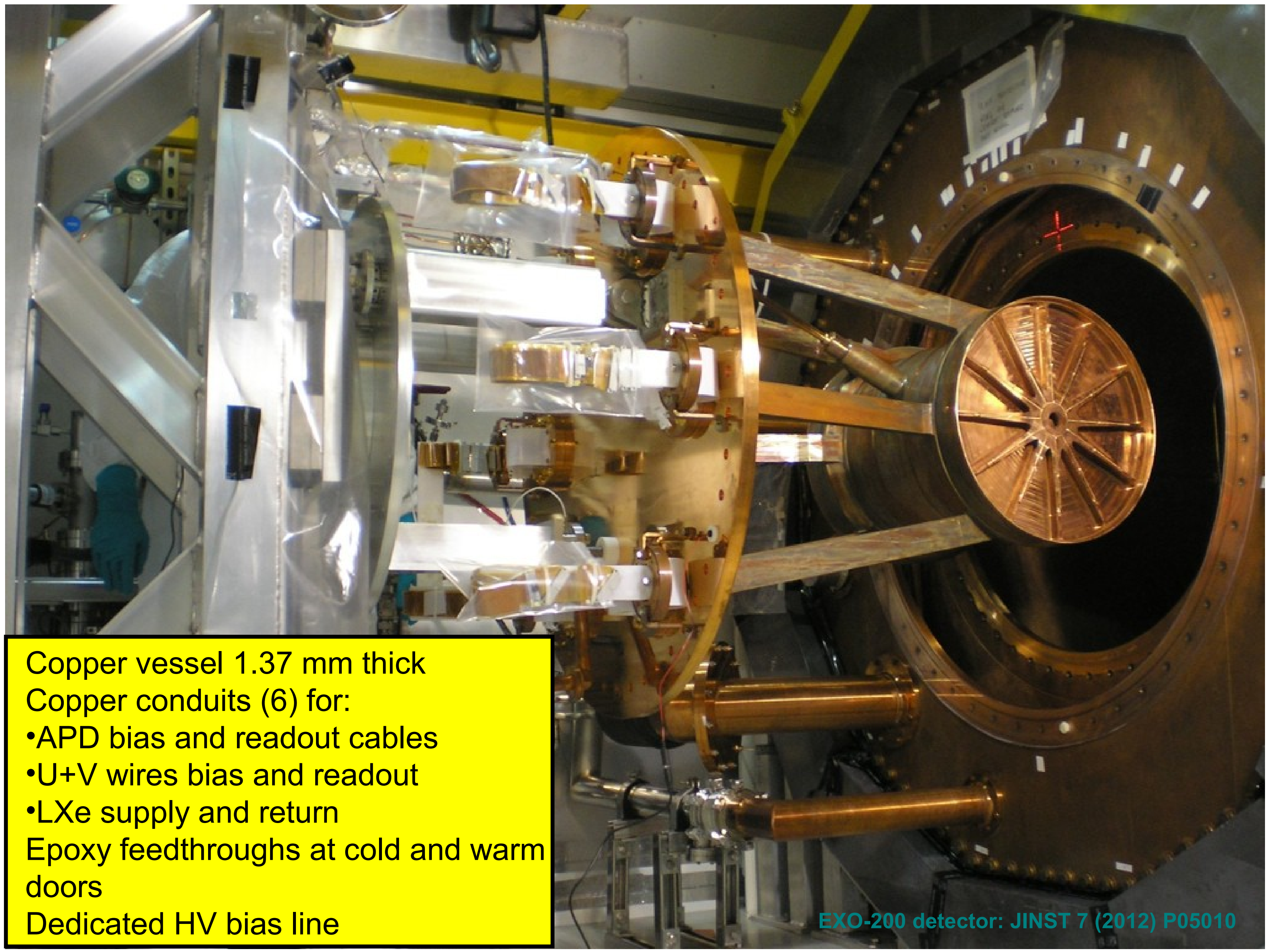


- Common cathode + Two Anodes
  - 376 V/cm drift field
- Each half records both charge and scintillation information with
  - 38 U (charge collection) + 38 V (charge induction) triplet wire channels, crossed at 60 degrees
    - Wire pitch 3 mm (9 mm / channel)
    - Photo-etched Phosphor bronze
  - 234 large area avalanche photo-diodes, in groups of 7 (178 nm Xe light)

APDs

APDs are very clean and light, highly sensitive to VUV
Gain is set to ~200 with V~1.5kV
Characterization of APDs: NIM A608 68-75 (2009)

Apparatus at WIPP

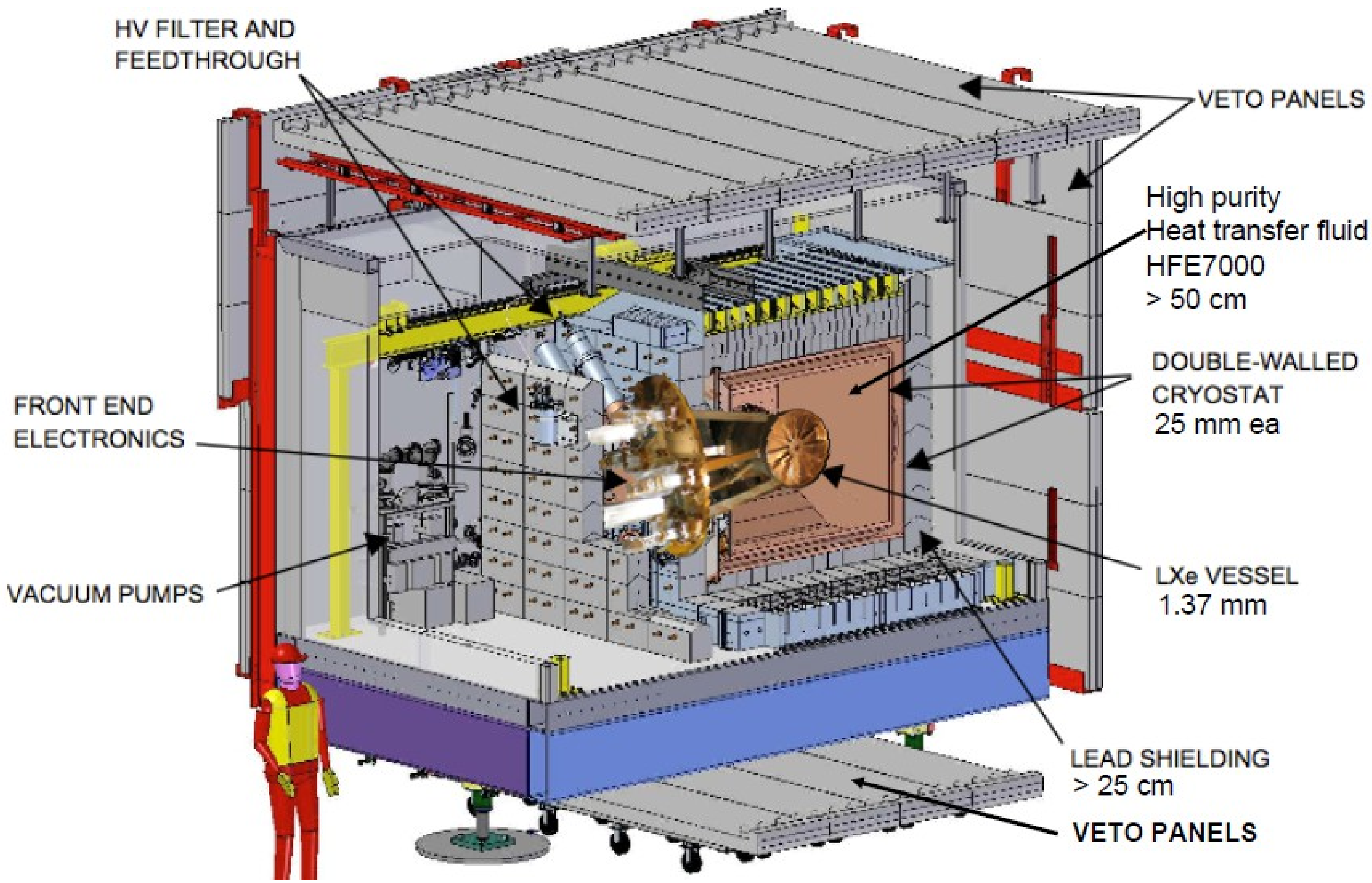


Copper vessel 1.37 mm thick
Copper conduits (6) for:
- APD bias and readout cables
- U+V wires bias and readout
- LXe supply and return

Epoxy feedthroughs at cold and warm doors
Dedicated HV bias line

EXO-200 detector: JINST 7 (2012) P05010

Apparatus at WIPP

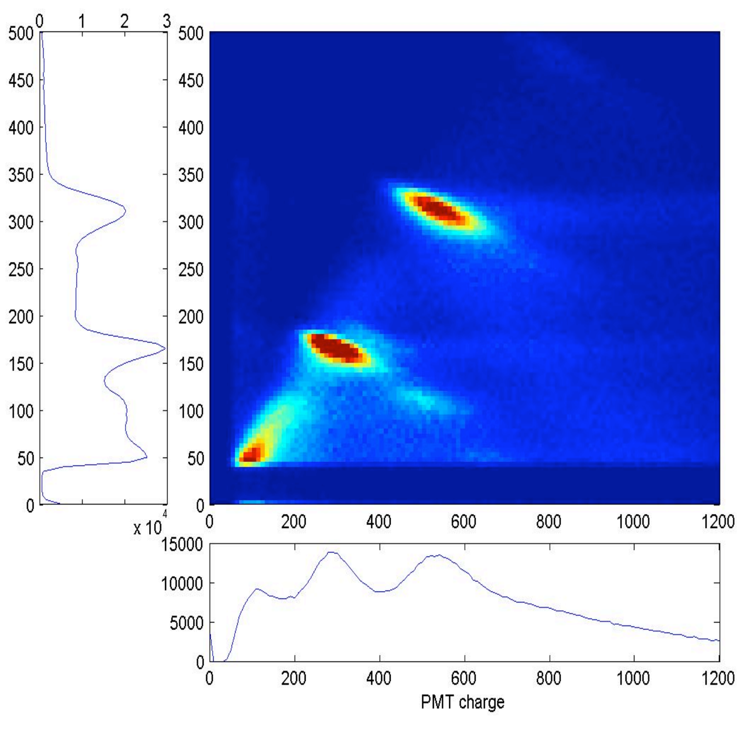


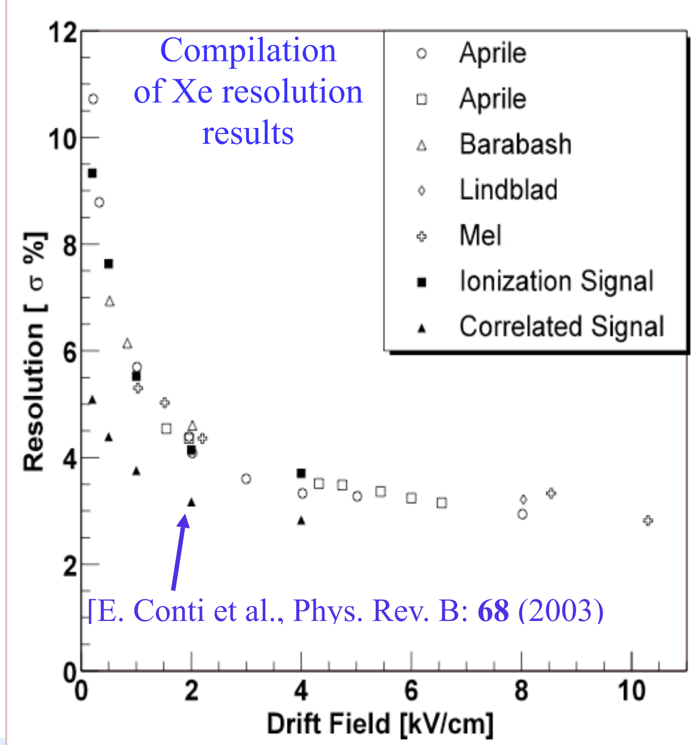
Energy resolution

Anti-correlated ionization and scintillation improves the energy resolution in LXe

Ionization alone:
$\sigma(E)/E = 3.8\%$ @ 570 keV
or 1.8% @ $Q_{\beta\beta}$

Ionization + Scintillation:
$\sigma(E)/E = 3.0\%$ @ 570 keV
or 1.4% @ $Q_{\beta\beta}$



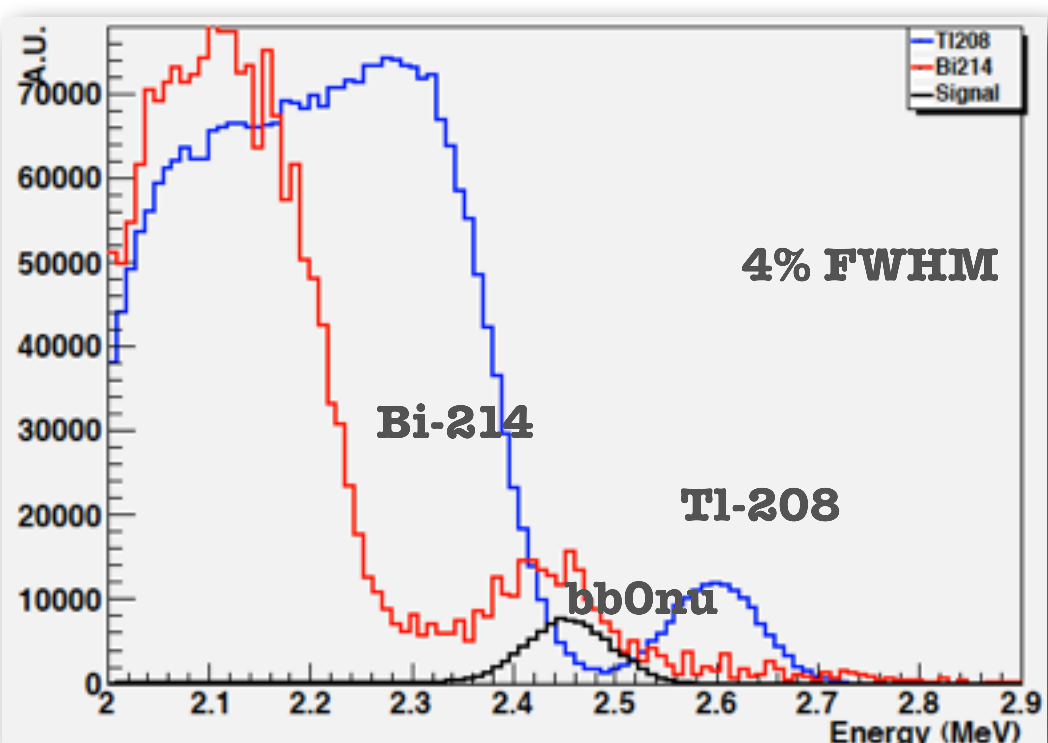


$$\frac{\Delta E}{E}(FWHM) = 2.4 \times \frac{\Delta E}{E}(rms) = 3.6\%$$

EXO main backgrounds

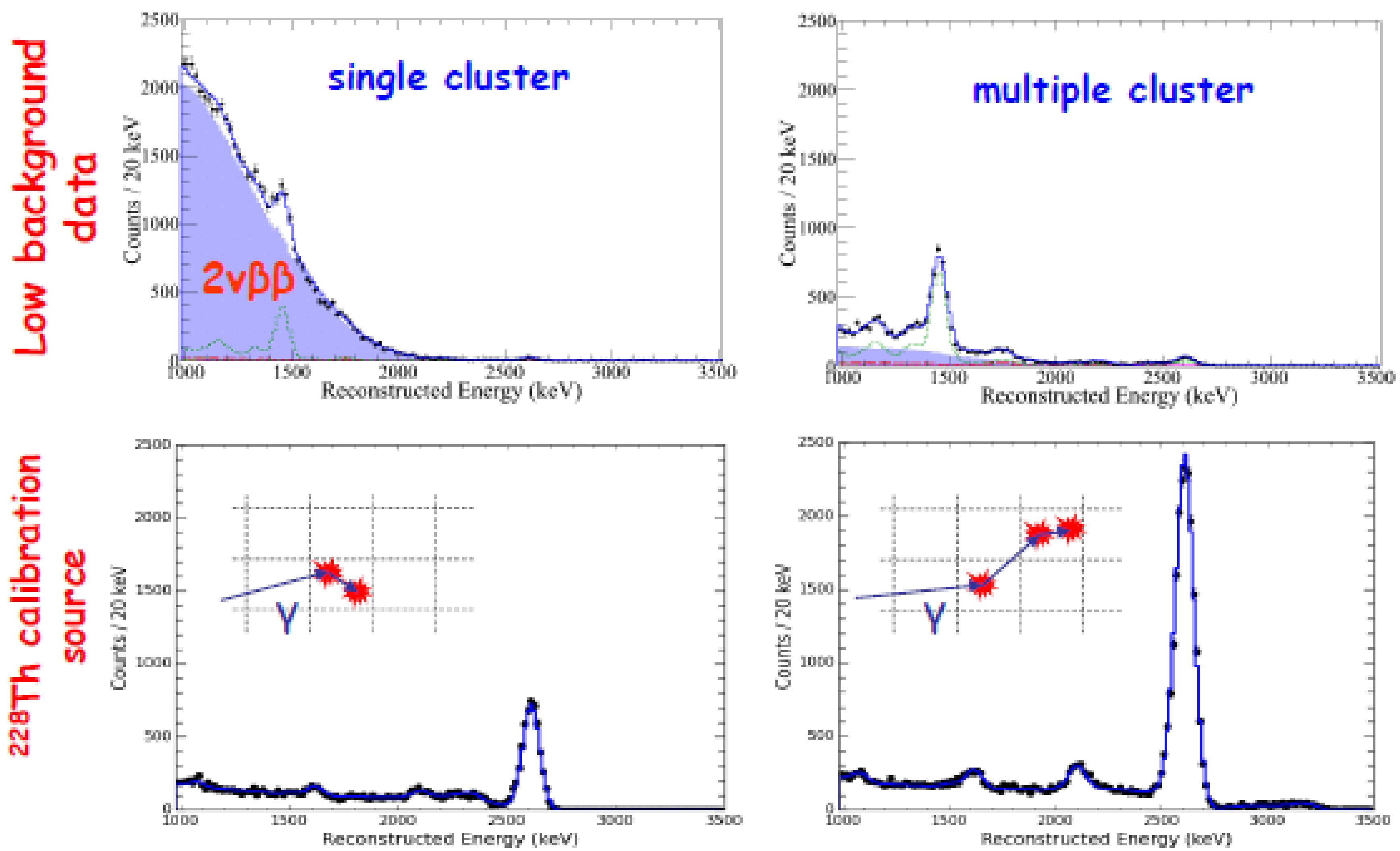
- γ (2449 keV) from ^{214}Bi decay (from ^{238}U and ^{222}Rn decay chains)
- γ (2615 keV) from ^{208}Tl decay (from ^{232}Th decay chain)
- γ (1.4 MeV) from ^{40}K (a concern for the $2\nu\beta\beta$)
- ^{60}Co: 1173 + 1333 keV simultaneous γ's (from ^{63}Cu(α,n)^{60}Co)
- other γ's in ^{238}U and ^{232}Th chains
- other cosmogenics of Cu (a concern for the $2\nu\beta\beta$)
- in situ cosmogenics in Xe, neutron capture de-excitations, ...

- ^{222}Rn anywhere (Xe, HFE, air gaps inside lead shield)



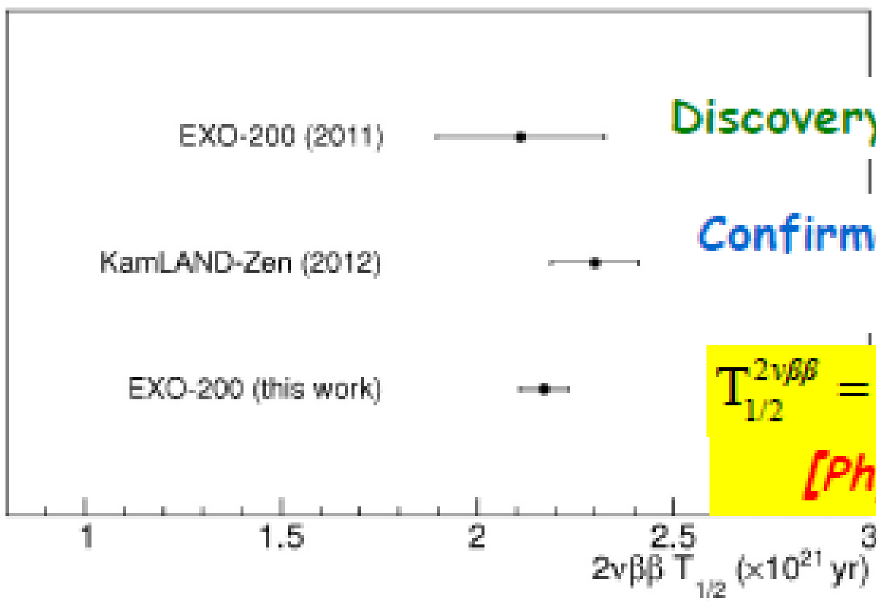
- **TPC fiducialization (only events in the fiducial volume, away from surfaces), and good 3D location eliminates all alpha background (a concern for Ge, bolometers) leaving only high energy gammas.**
- **However ~4% FWHM energy resolution does not allow to separate signal peak from leading Bi-214 and Tl-208 peaks**

Single site vs multiple site: separate signal from backgrounds



Very useful to identify gamma backgrounds!

EXO milestones



Discovery of 2ν mode [PRL 107, 212501 (2011)]

Confirmation by KamLAND-Zen [PRC 85, 045504 (2012)]

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

[Phys. Rev. C 89 (2014) 015502]

- **First 0-nu analysis**
  - 09/11 – 04/12 “Run 2a”. ***PRL 109 (2012) 032505***, 26.3 kg*yr Xe-136
  - **Median expected 90% C.L. U.L.: 0.7e25 yrs.** Realized limit: 1.6e25 yrs
- **Second 0nu-analysis**
  - Incorporates several analysis improvements tested in 2nu analysis, more than thrice as much data. Massive effort to assess systematics affecting 0nu search
  - 09/11 – 09/13 “Run2abc”. ***Nature 510 (2014) 229***, 100.0 kr*yr Xe-136

Systematic errors

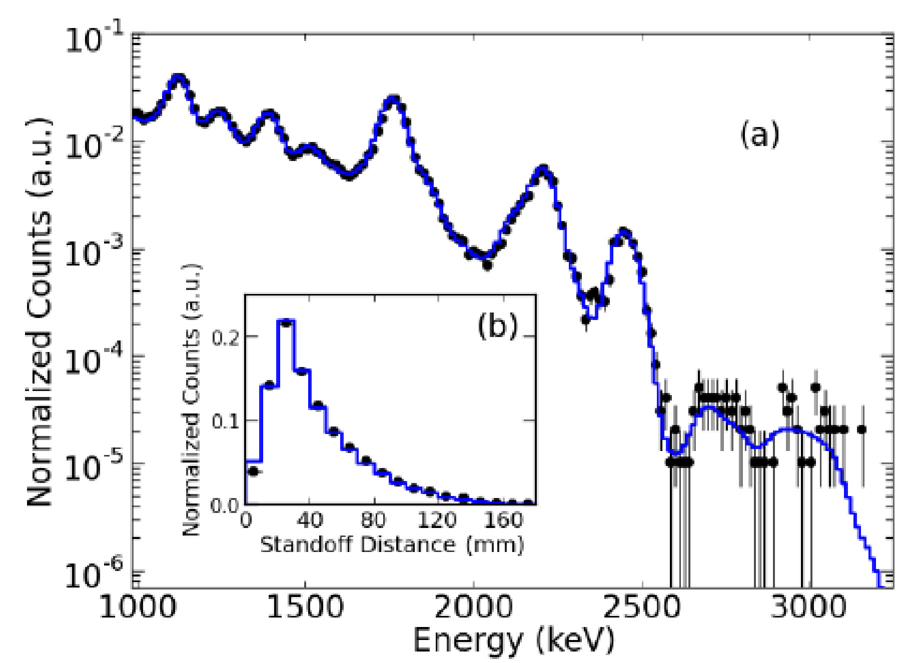
Source	Signal eff. (%)	Error (%)
Event selections		
Summary from [9]	93.1	0.9
Partial reconstruction	90.9	7.8
Fiducial Volume/Rate agreement	-	3.4
Total	84.6	8.6

TABLE I. **$0\nu\beta\beta$ signal efficiency and associated systematic errors.** 'Partial reconstruction' refers to the requirement that all events be fully reconstructed in X,Y and Z. The summary for event selection from [9] includes all efficiencies and related errors except fiducial volume and partial reconstruction, which have been recalculated in this work for $0\nu\beta\beta$.

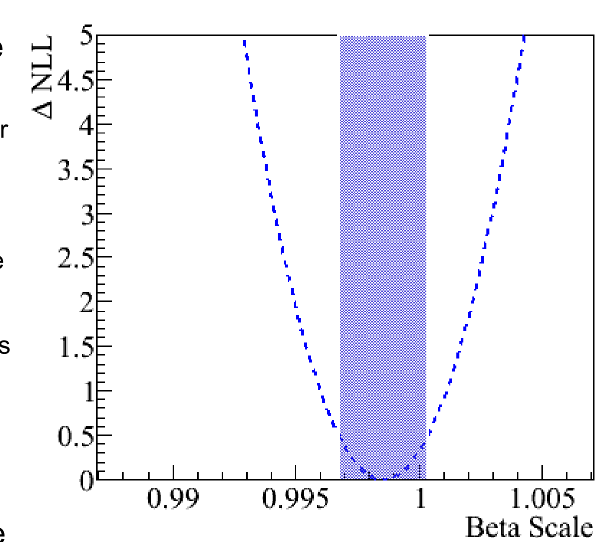
Source	Error (%)
Background shape distortion	9.2
Background model	5.7
Energy resolution variation	1.5
Total	10.9

TABLE II. **Systematic errors on the determination of background in the ROI.** These arise from incorrect modeling of the background shape (Background shape distortion), incorrect or incomplete background model (Background model), and the residual variation of the energy resolution over time (Energy resolution variation, see e.g. Figure 1).

Ra-226 source shape agreement

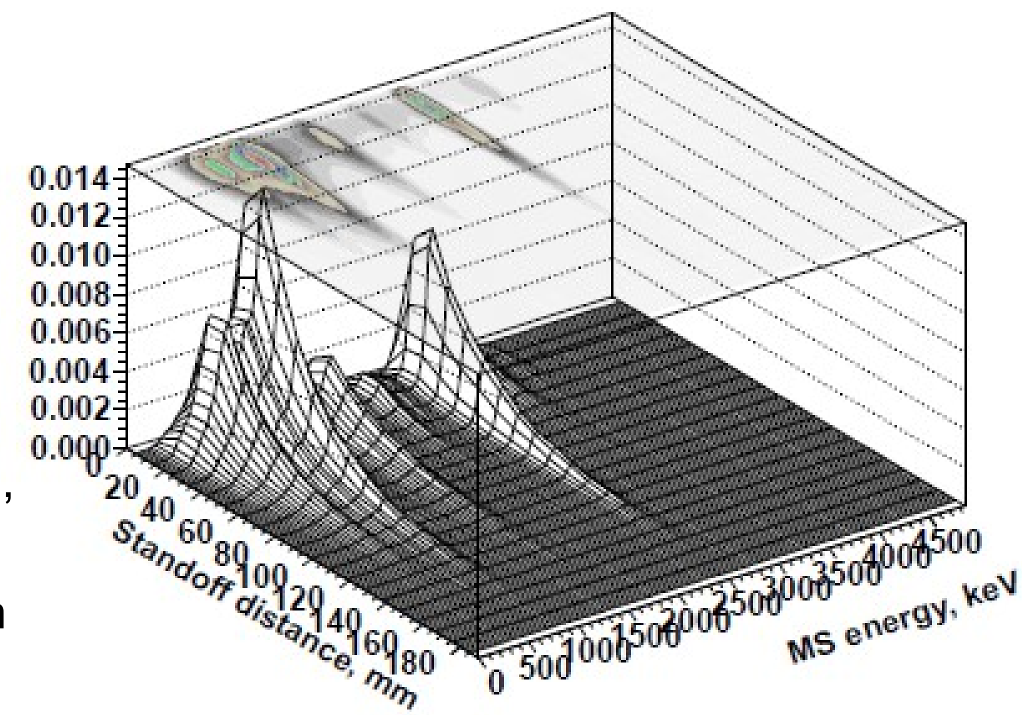


- Energy scales for beta and gammas may not exactly coincide
  - gamma of 1 a.u. of energy deposits energy as several electrons of smaller amount of energy – hence different dE/dX, light/charge ratio, IR/recoil losses
  - even after combining light and charge channels, the effect may not vanish completely due to imperfections of detector response/instrumental effects
  - knowing beta-scale (defined as multiplicative factor B, Eb = B*Eg) is important to accurately define ROI
- Our data is a relatively clean source of beta events - use profile NLL scan to determine the beta-scale



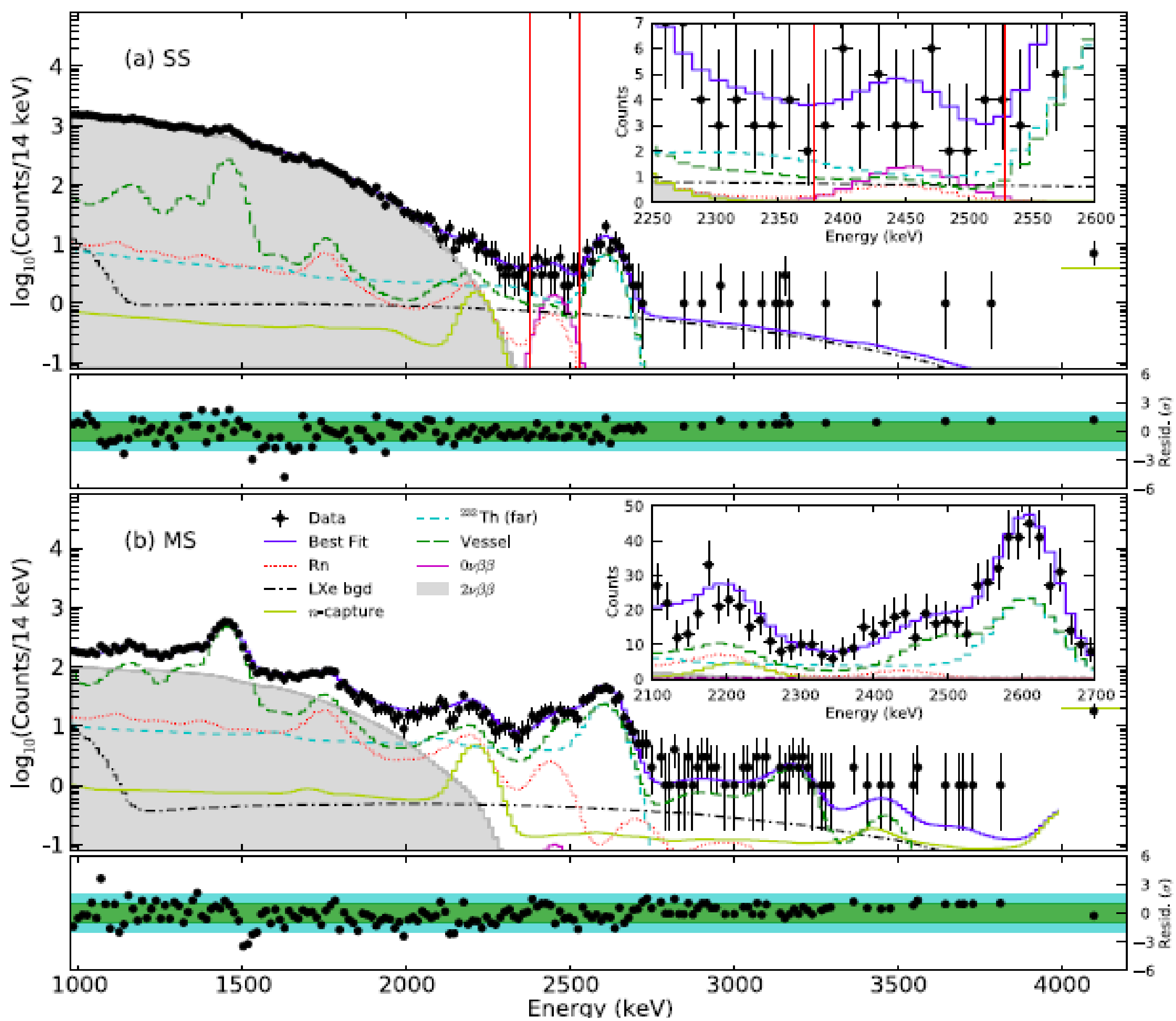
Fitting the data

- 3 observables
  - SS and MS energies
  - Standoff distance
- couple dozens parameters
  - Number of events and SS fractions (+ univariate variables for common and ROI specific normalization)
    - Signals: bb2n, bb0n
    - TPC vessel backgrounds: Co-60, K-40, U-238, Th-232, Mn-54, Zn-65
    - LXe backgrounds: Xe-135, Xe-137, Rn
    - Remote backgrounds: Rn in the air gap, Th in cryostat
    - Neutron captures: H in HFE, Cu in cryostat, Xe136 in LXe
- Constraints
  - Normalizations, Rn in LXe, SS fraction (correlated for gammas)



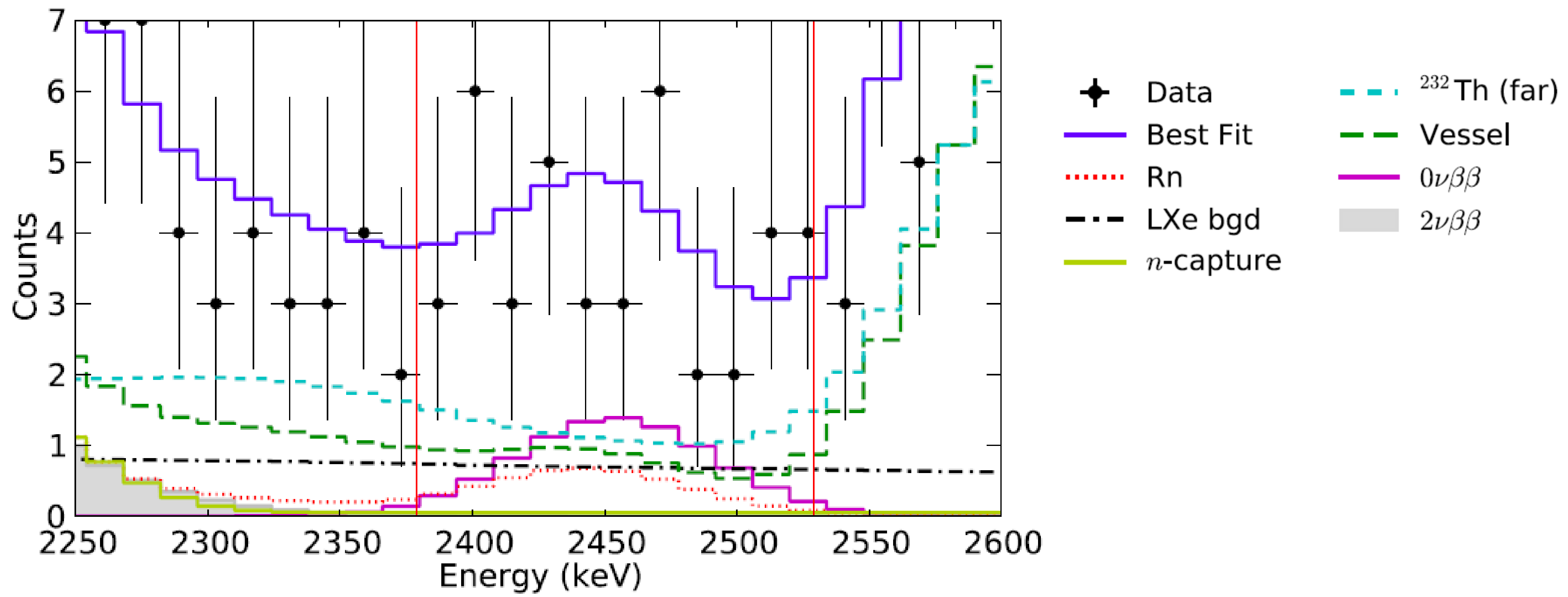
Th232 PDF. True Geant4 energy spectrum was smeared by resolution curve measured from the data

Fit results



- **Notice that EXO spectrum is in-between that KamLAND-ZEN (pekas not resolved) and that of GERDA (every peak resolved). Here the landscape presents broad peaks corresponding to**
- **~4% FWHM energy resolution.**

Fit results close up

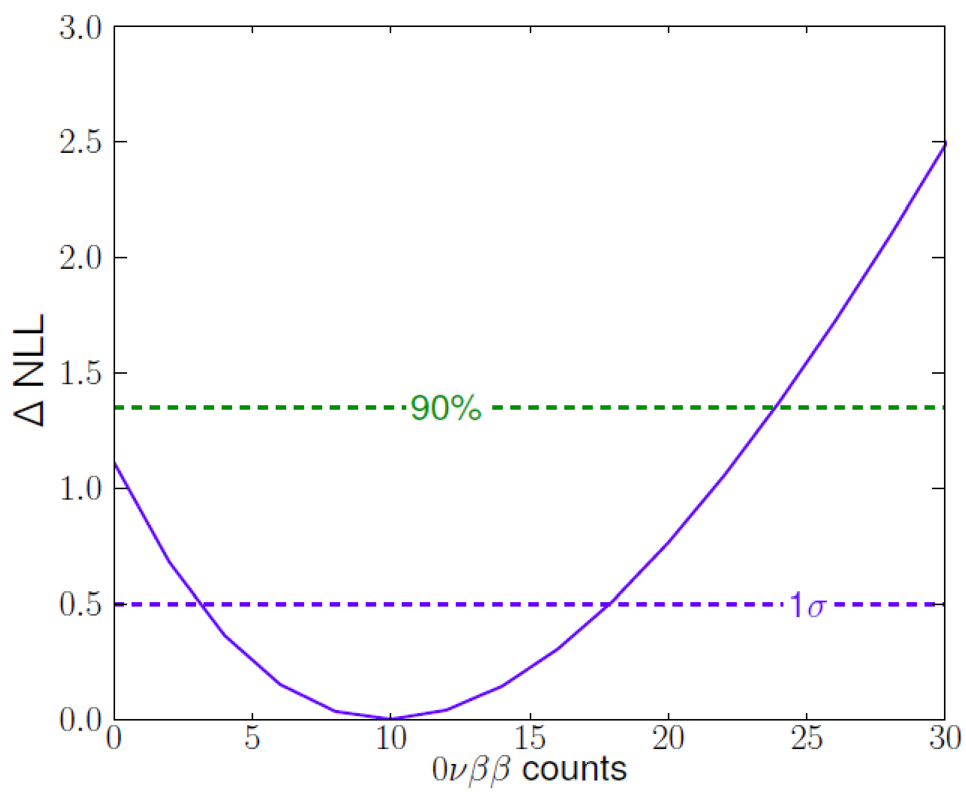


2 sigma ROI breakdown for major backgrounds

	Events	BI, 1e-3 /kg/yr/keV*
Th-232	**16.0**	
U-238	**8.1**	
Xe-137	**7.0**	
Total	**31.1±1.89(stat)±3.3(syst)**	**1.7±0.2**

- **BI ~4 x 10^{-3} ckky**

Fit results



Fit in 2 sigma ROI

Background	31.1
0nu	9.9
Total	41.0

Data in 2 sigma ROI

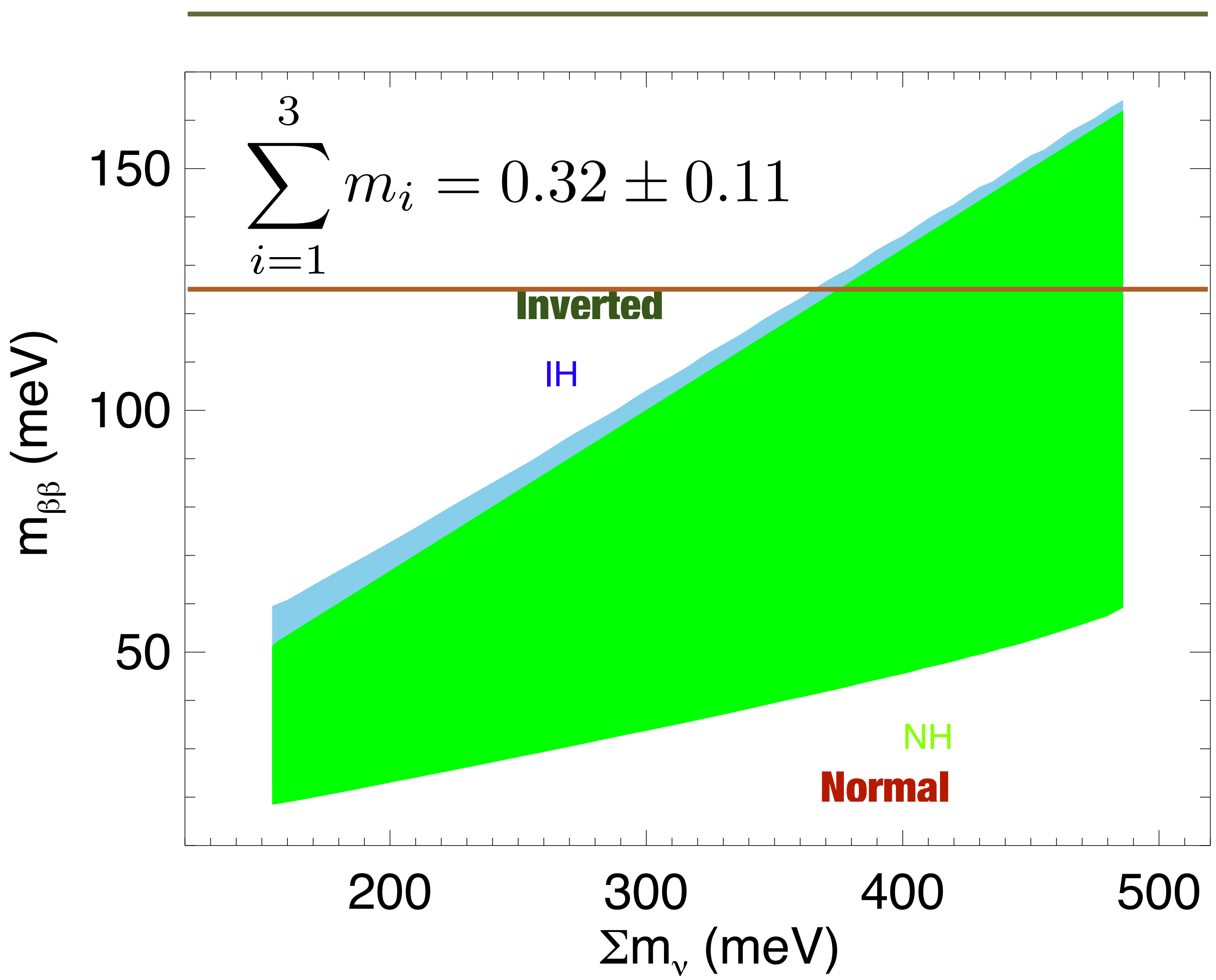
Total	39

Result is consistent with “background only” hypothesis at ~1.2 sigma

Median 90% C.L. U.L. limit assuming adequate “background-only” model: **>1.9e25 yrs**
Limit from the fit to the actual data: **>1.1e25 yrs**

- **Bad luck or hint of a discovery?**

Expected: NEXT-100



- **100 kg yr**
- **ΔE=3.6 % FWHM at $Q_{\beta\beta}$**
- **B=5 x 10^{-3} ckky ⇒**
  - **$T^{0\nu}$=2 x 10^{25}⇒**
  - **$m_{\beta\beta}$ = 125-352 meV**

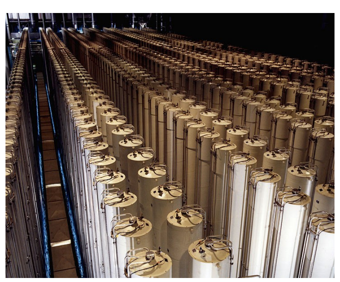
- **Similar result to that of KamLAND-ZEN.**

Comming soon to an underground lab near you

Why NEXT? — Advantages of HPXe technology

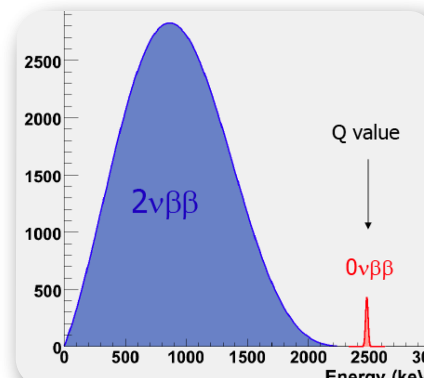
$$T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}}$$

Cost



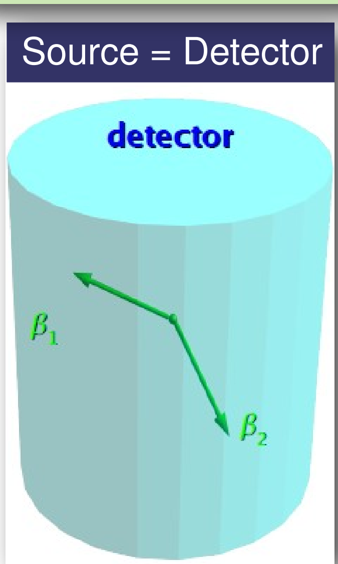
Xenon is the cheapest and easiest to enrich of all ββ isotopes. No long lived radioactive isotopes. There is already 1 ton of enriched xenon in the World.

ΔE



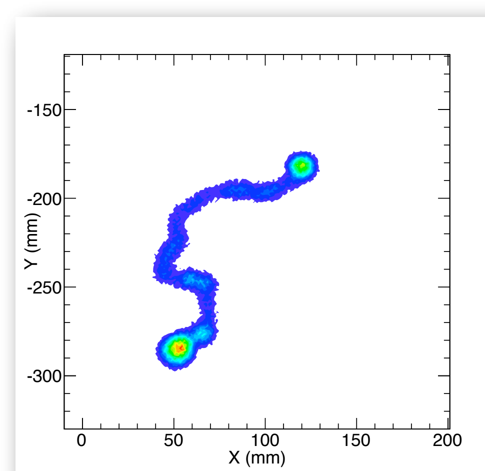
HPXe TPC is the only xenon detector that provides good energy resolution (better 1% FWHM at Qbb)

Scalability



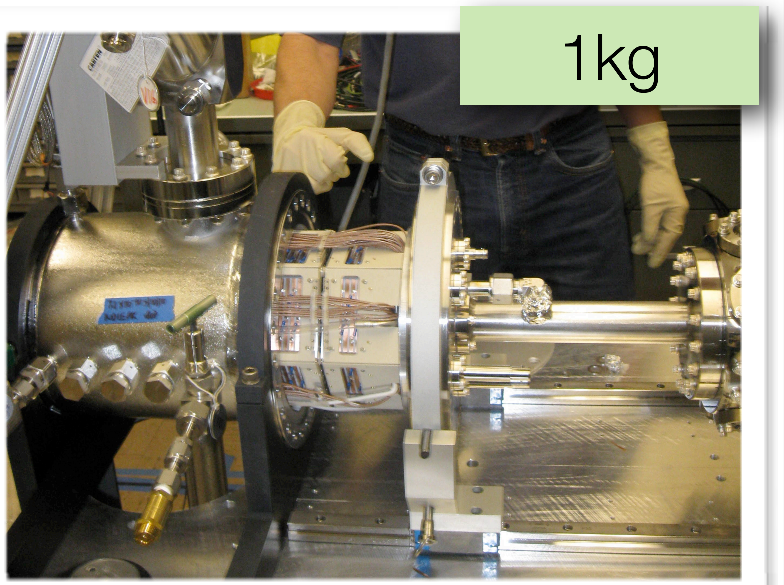
Xenon is a noble gas suitable to build a TPC. No dead areas, S/N improves with L

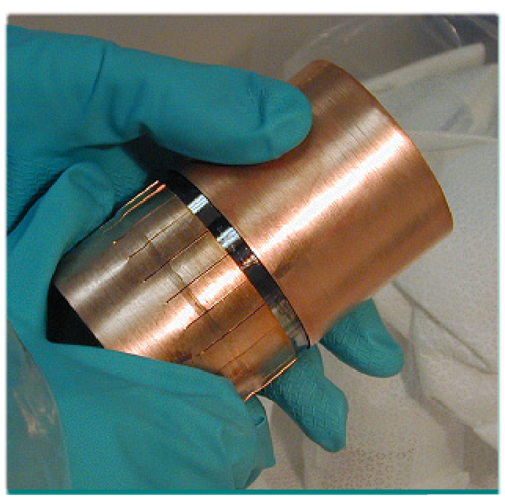
Background

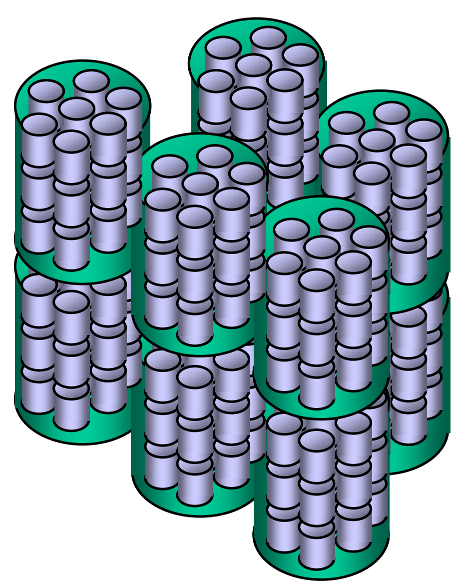


HPXe TPC is the only xenon detector that provides topological signal

Scalability





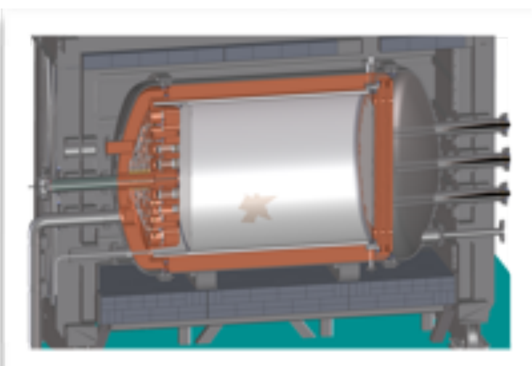


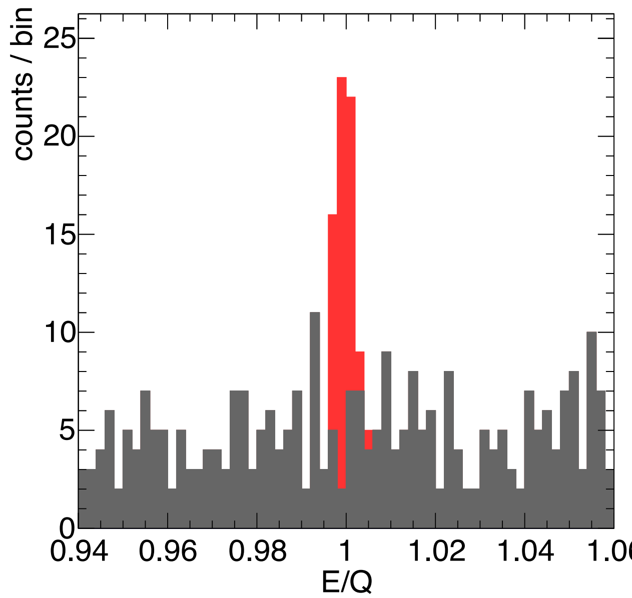
210 2.35 kg crystals

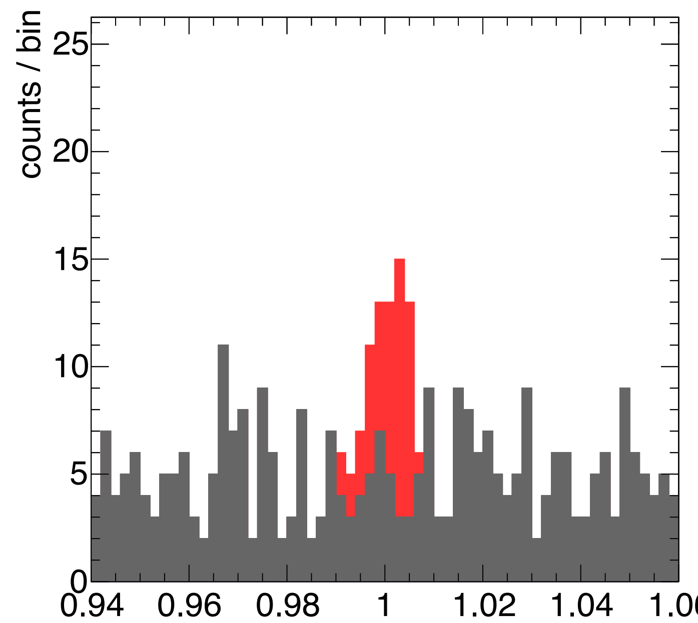
Economy of scale: Double L, signal increases 8 (L^3), background increases 4 (L^2), S/N improves by a factor 2

Energy resolution makes a difference

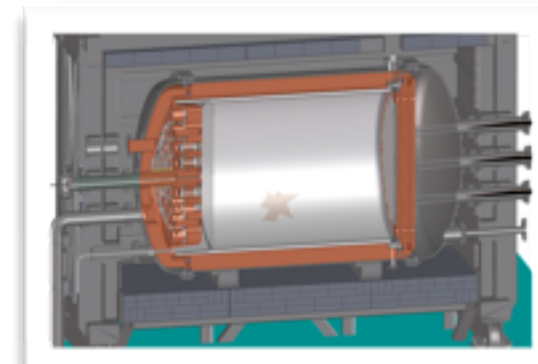
0,5 % FWHM



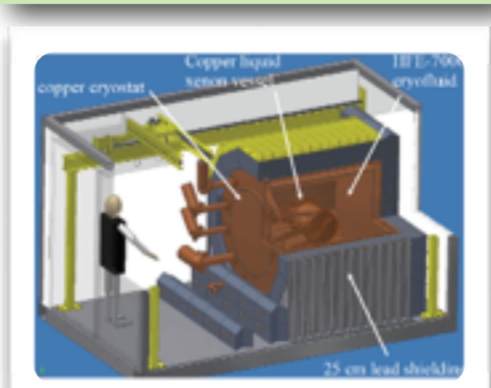


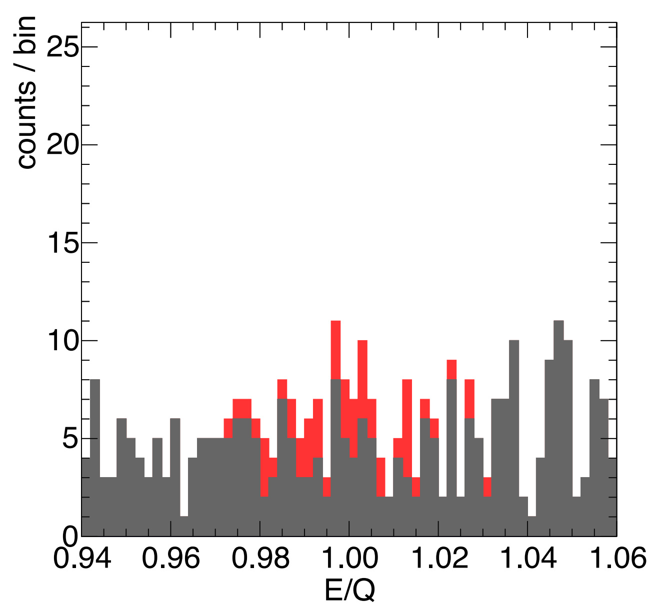


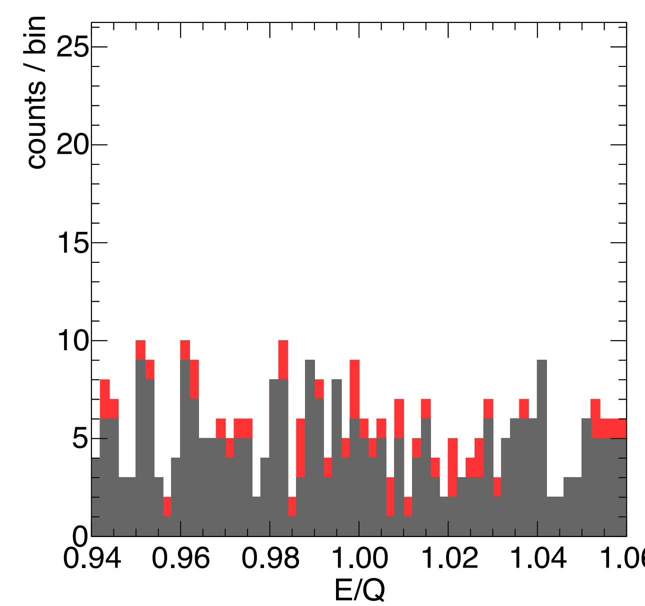
1,0 % FWHM



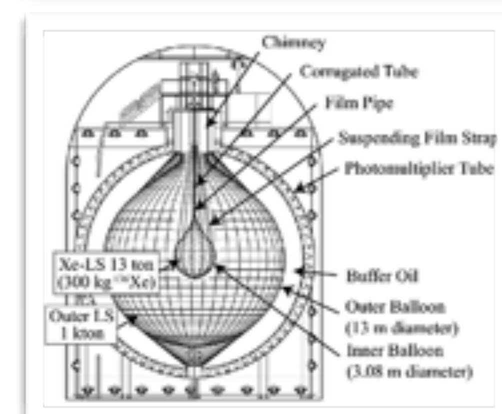
3.5 % FWHM







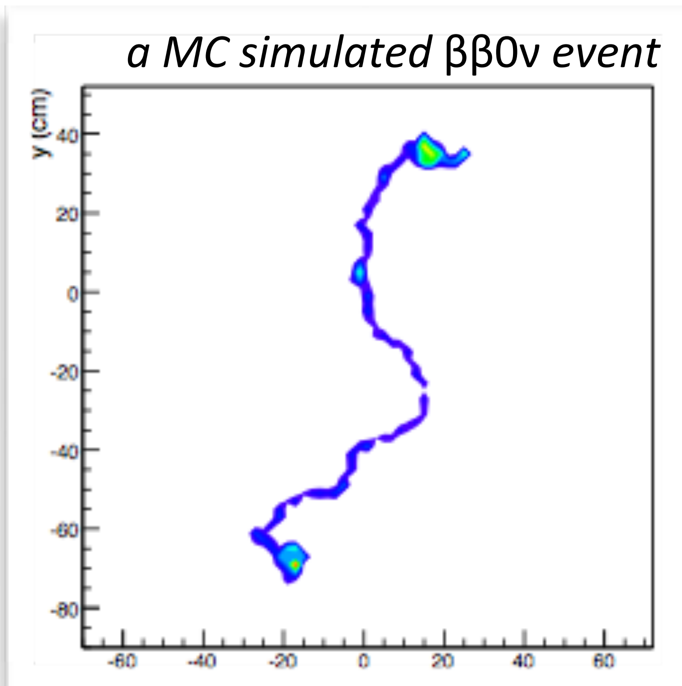
10 % FWHM

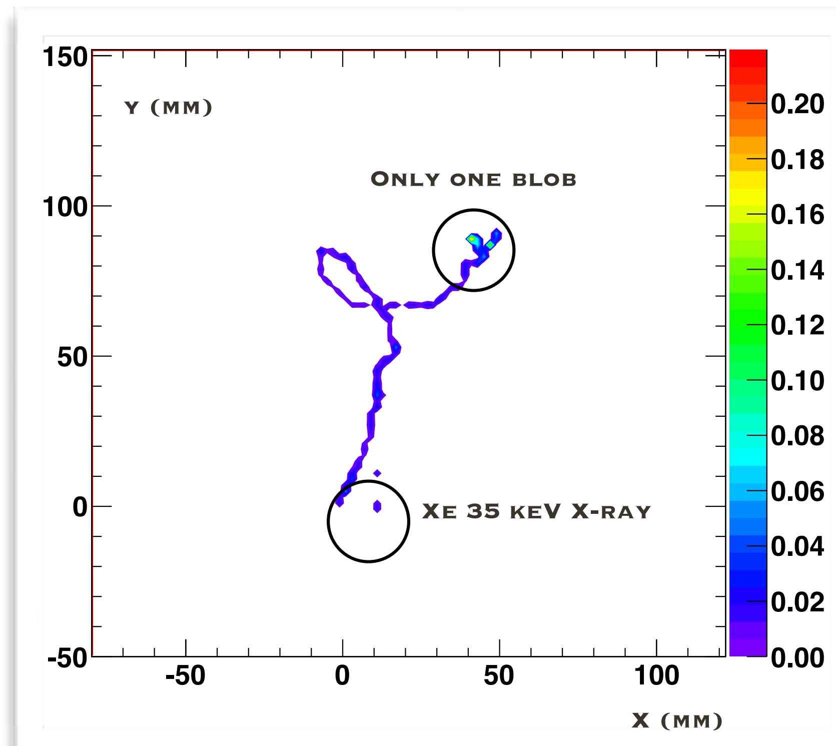


Signal and backg

- Signal: 50 events, $T^{0\nu} = 5\ 10^{25}$ y and an exposure of 1 ton year.
- Background 1 count/keV/ton/year.

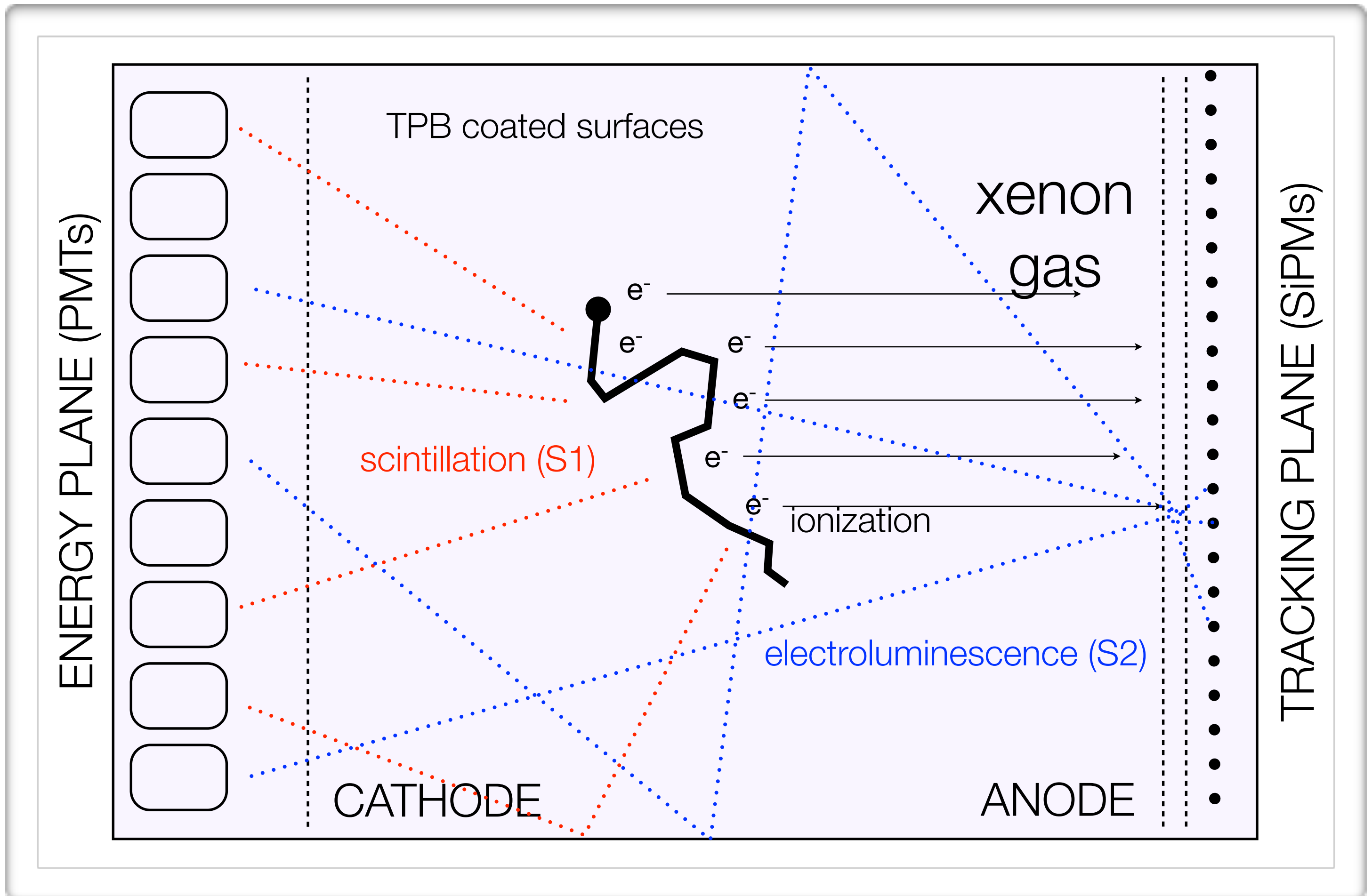
Topological background reduction





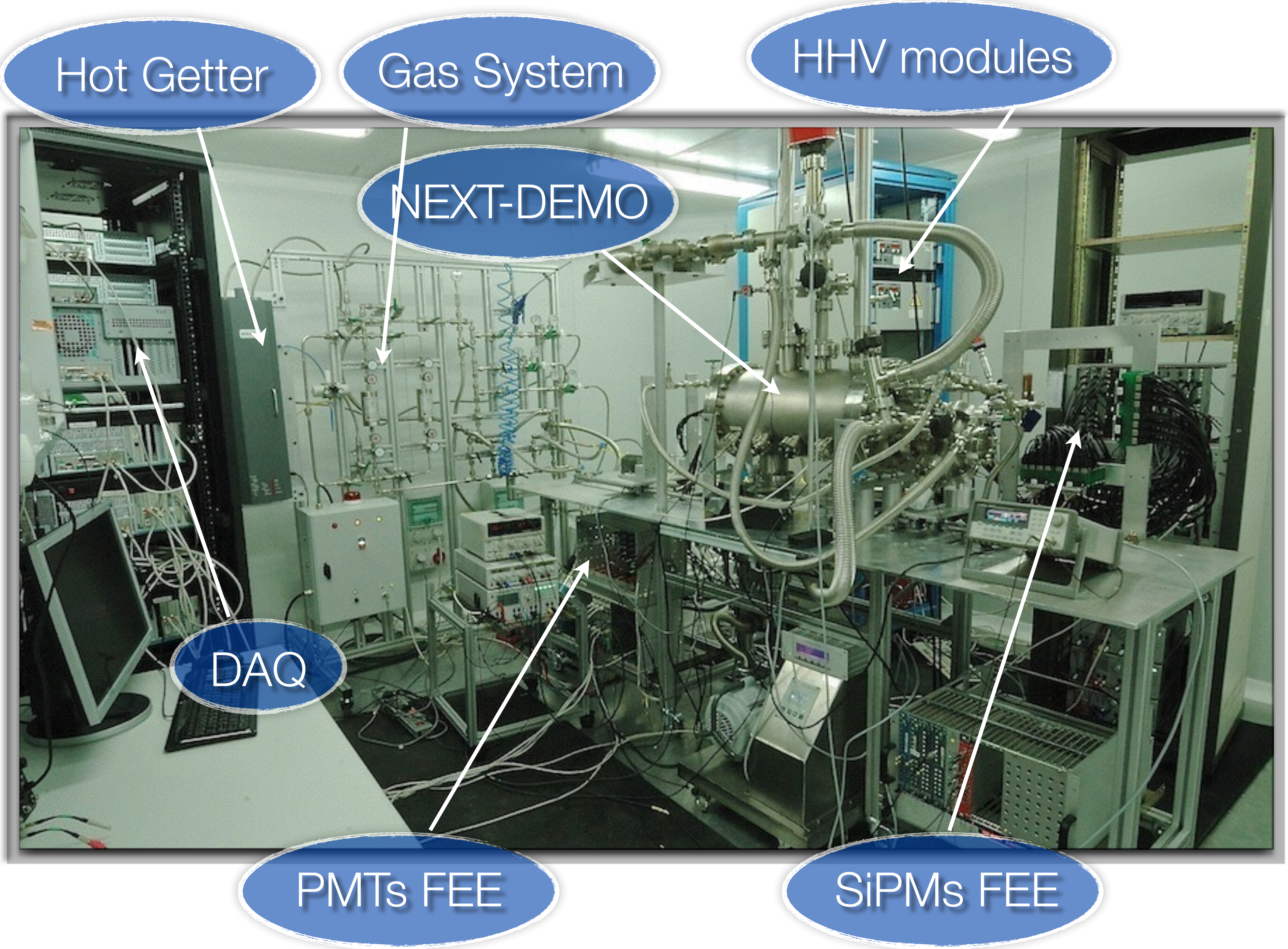
- In xenon gas at 15 bar, a ββ event is a twisted track, 10 cm long, with two energy blobs at the two ends and no additional floating clusters.
- Instead the backgrounds are single electrons, accompanied 85% of the time by X-rays (Xenon de-excitation).
- HPXe TPC offers a signal that looks like a signal: two identified electrons with an energy within 10 keV of Qbb

NEXT: A light TPC

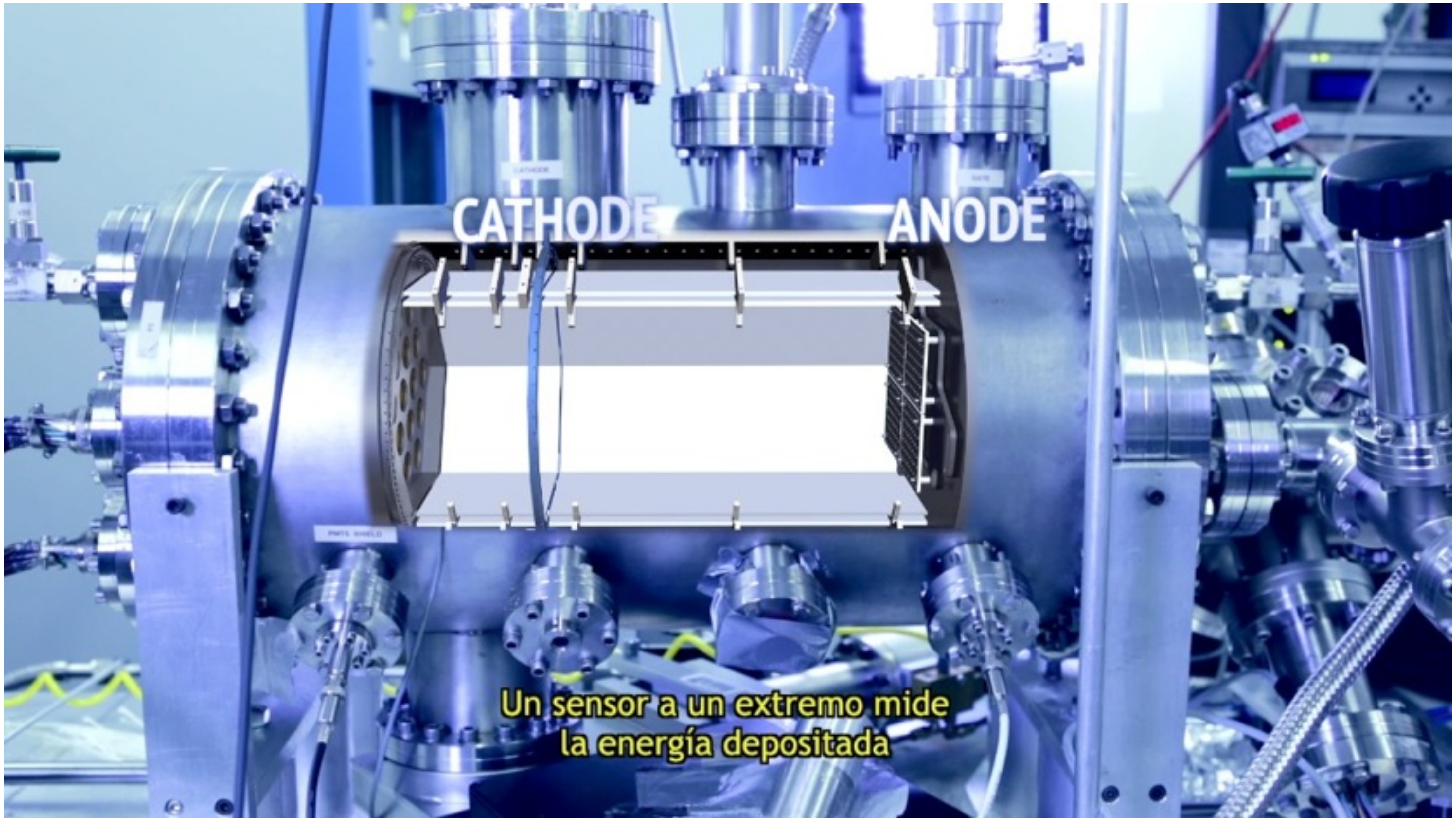


EL mode is essential to get lineal gain, therefore avoiding avalanche fluctuations and fully exploiting the excellent Fano factor in gas

- It is a High Pressure Xenon (HPXe) TPC operating in EL mode.
- It is filled with 100 kg of Xenon enriched at 90% in Xe-136 (in stock) at a pressure of 15 bar.
- The event energy is integrated by a plane of radiopure PMTs located behind a transparent cathode (energy plane), which also provide t0.
- The event topology is reconstructed by a plane of radiopure silicon pixels (MPPCs) (tracking plane).


Hot Getter
Gas System
HHV modules
NEXT-DEMO
DAQ
PMTs FEE
SiPMs FEE

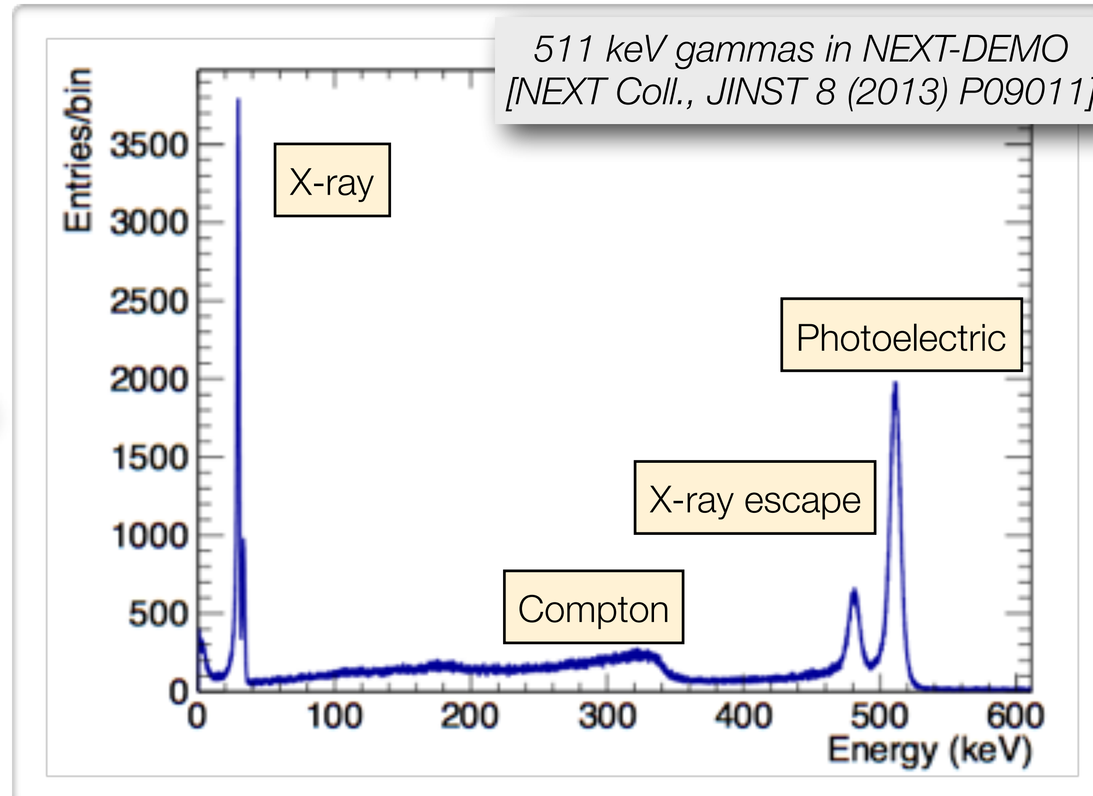
Anatomy of NEXT-DEMO



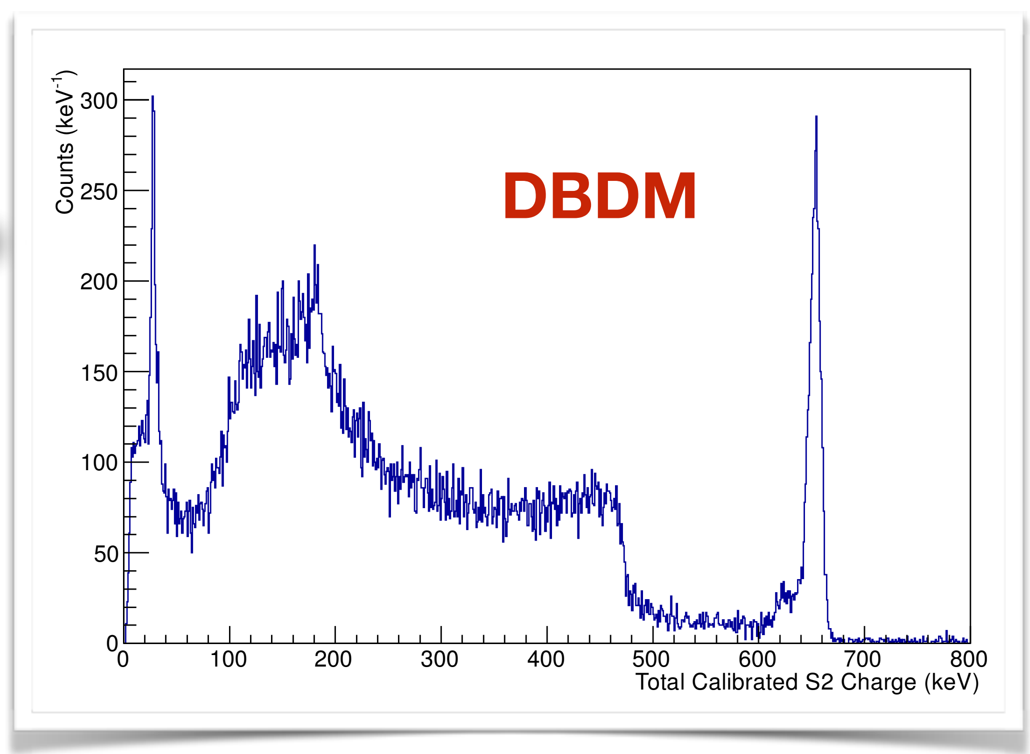
NEXT R&D: detector performance achievements

- 1.8% FWHM energy resolution for 511 keV electrons over large fiducial volume

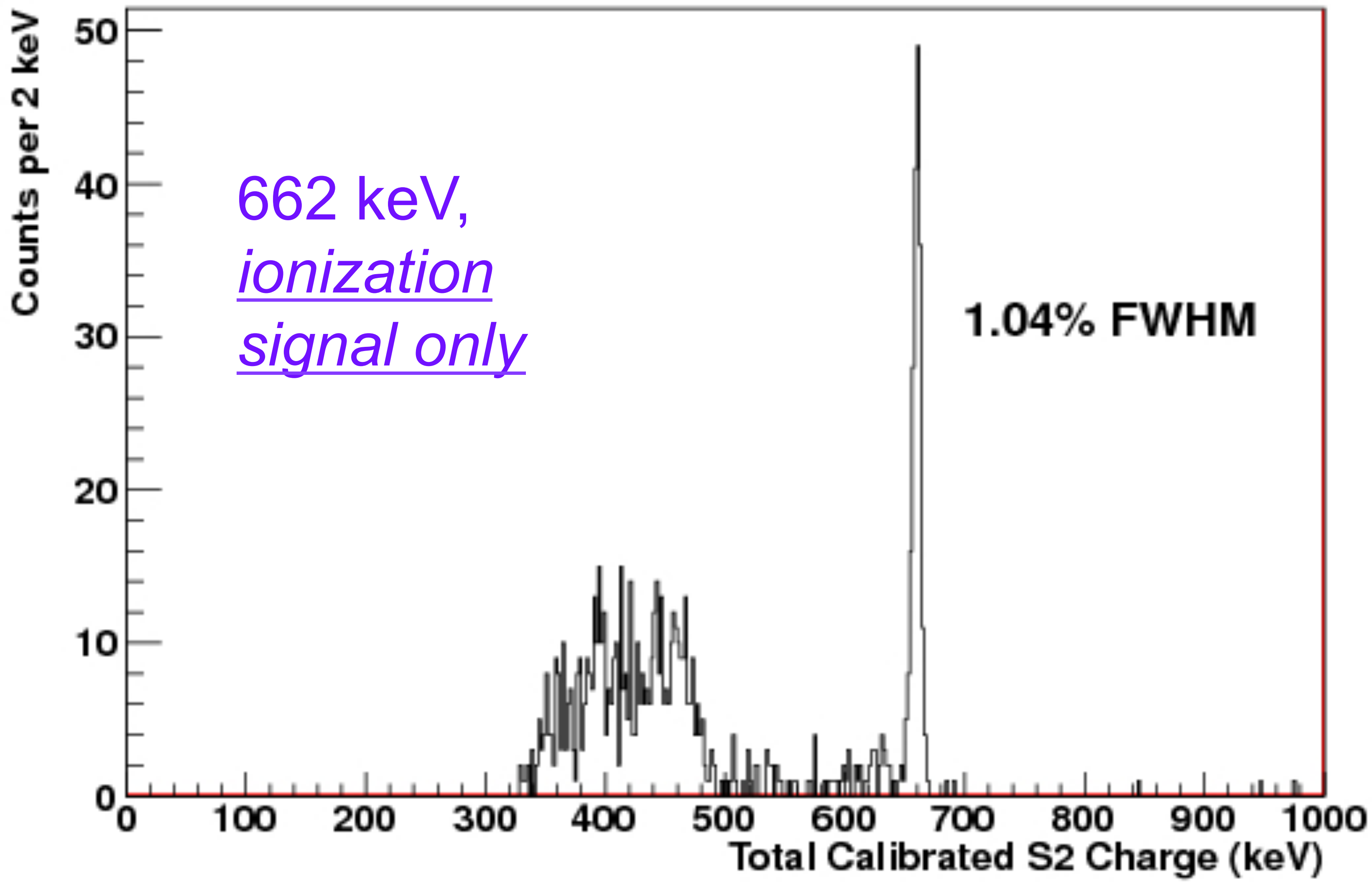
- Extrapolates to 0.75% FWHM at $Q_{\beta\beta}$ energy of 136Xe decay



- The DBDM prototype at LBNL extrapolates to **0.5 % FWHM** at $Q_{\beta\beta}$ using 660 Cs-137 electrons

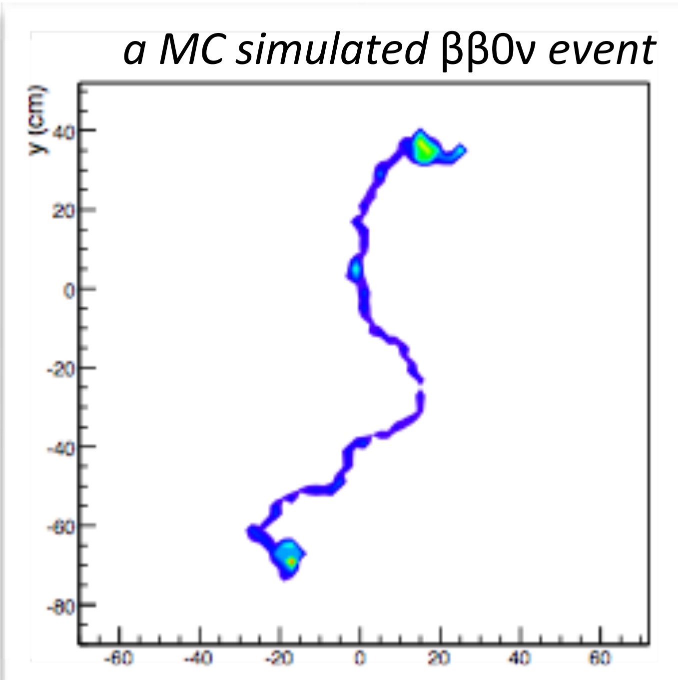


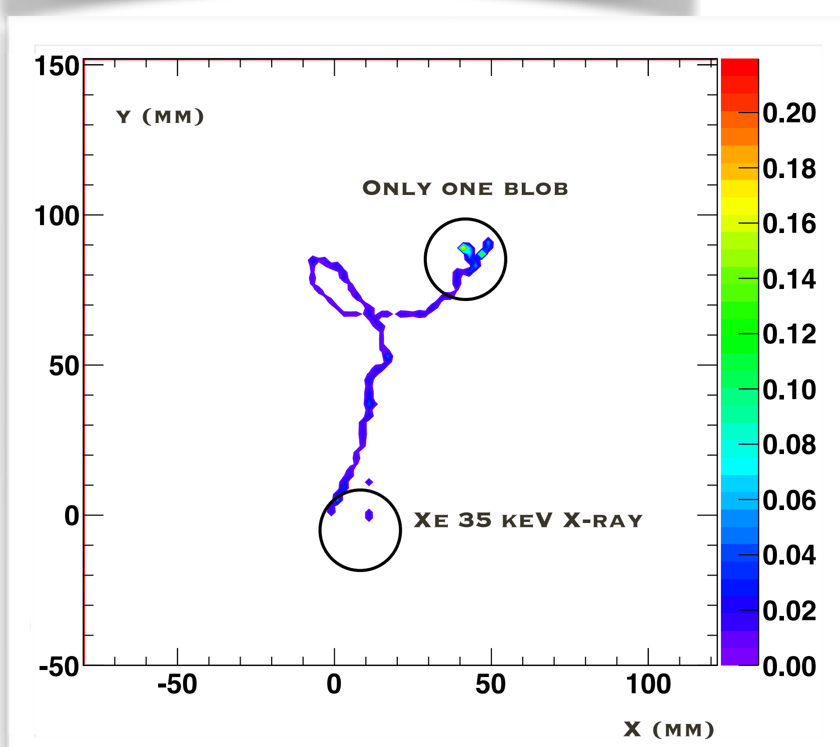
The beauty of resolution

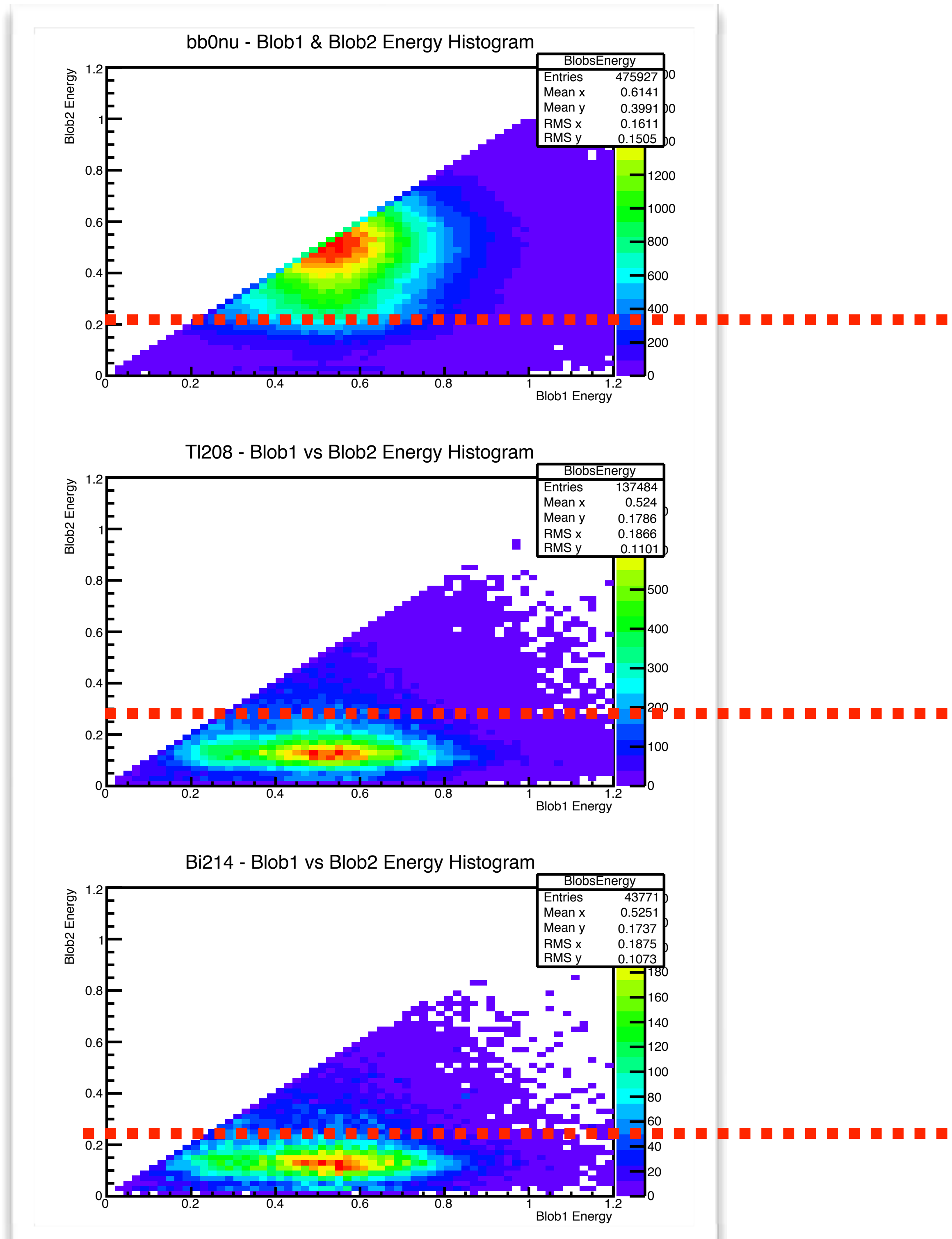


- **Extrapolates to 0.5 % at $Q_{\beta\beta}$**

Topological background reduction







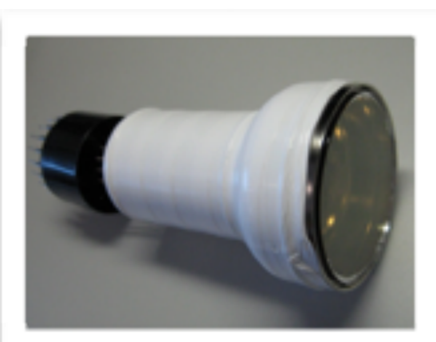
NEXT 100 kg detector at LSC: main features

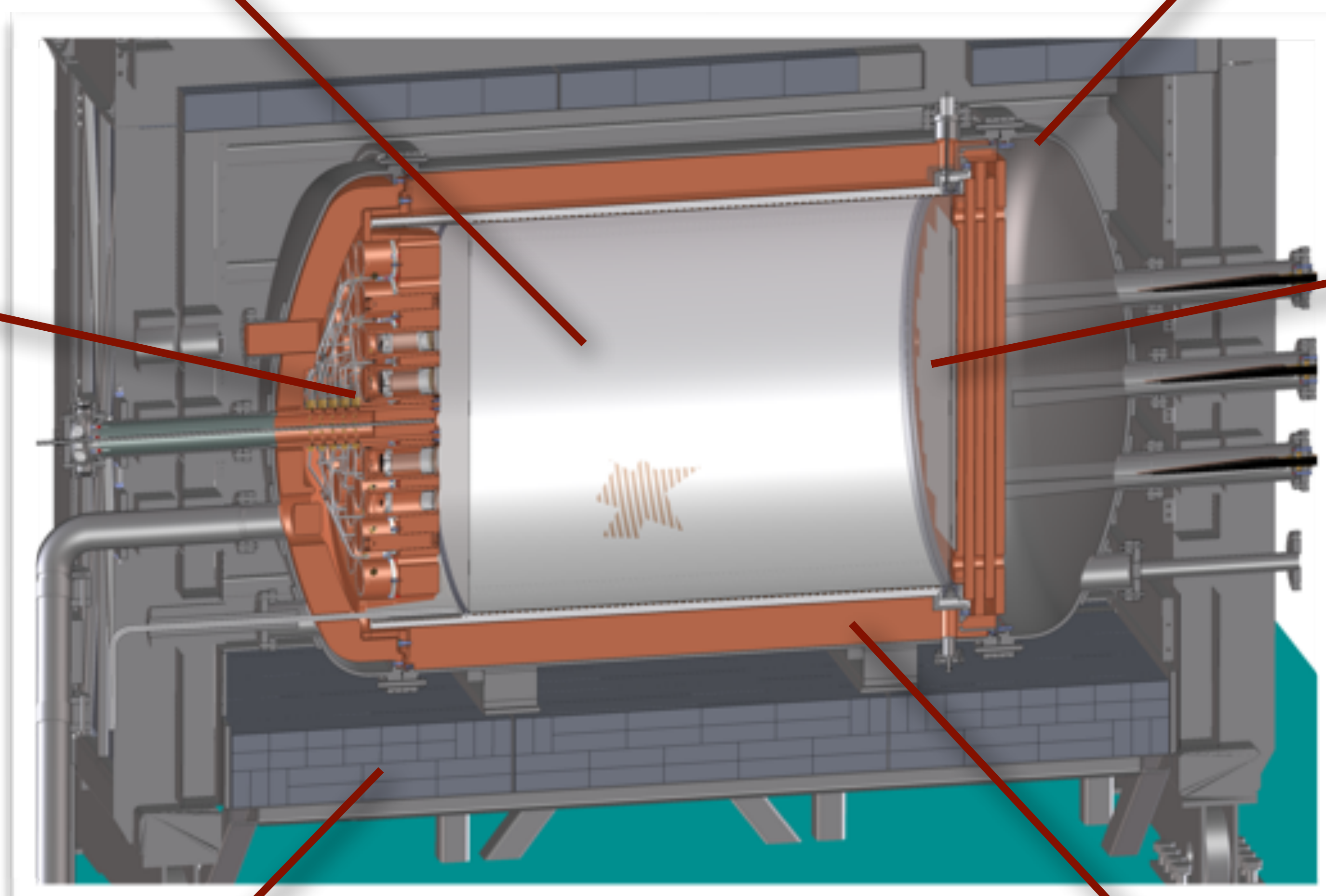
Time Projection Chamber:
100 kg active region, 130 cm drift length

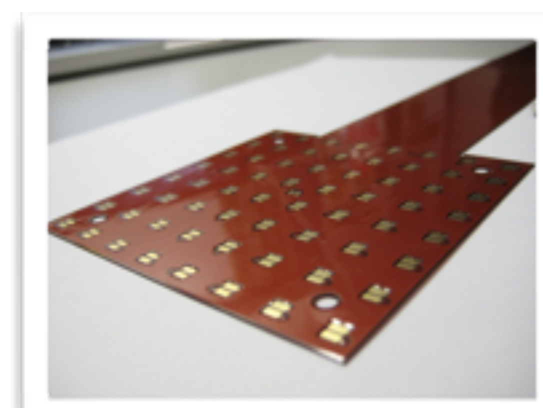
Pressure vessel:
stainless steel,15 bar max pressure

Energy plane:
60 PMTs,
30% coverage

Tracking plane:
7,000 SiPMs,
1 cm pitch







Outer shield:
lead, 20 cm thick

Inner shield:
copper, 12 cm thick

NEXT 100 kg radioactive budget

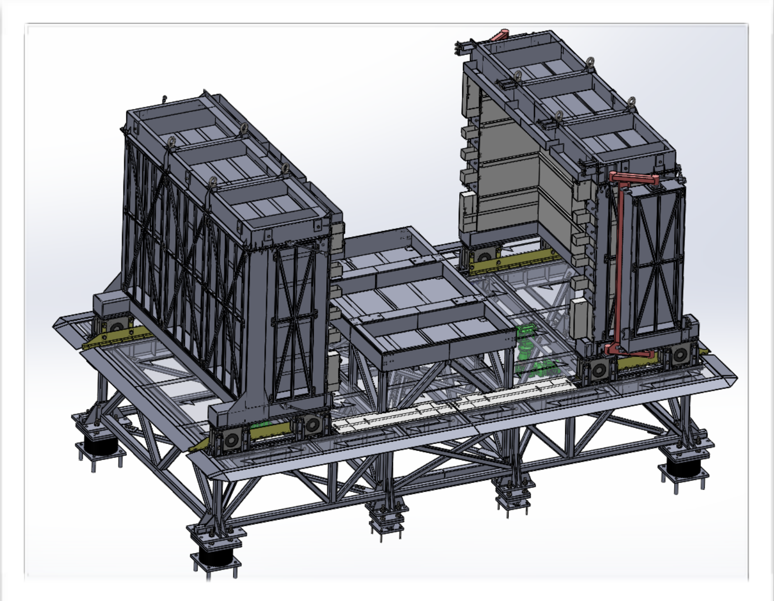
Activity shielded by ICS

Vessel

- Stainless steel 316Ti; 1121 kg
- Activity Tl-208: <0.150 mBq/kg
- Activity Bi-214: <0.460 mBq/kg

Shielding

- Lead; 13000 kg
- Activity Tl-208: <0.031 mBq/kg
- Activity Bi-214: <0.35 mBq/kg

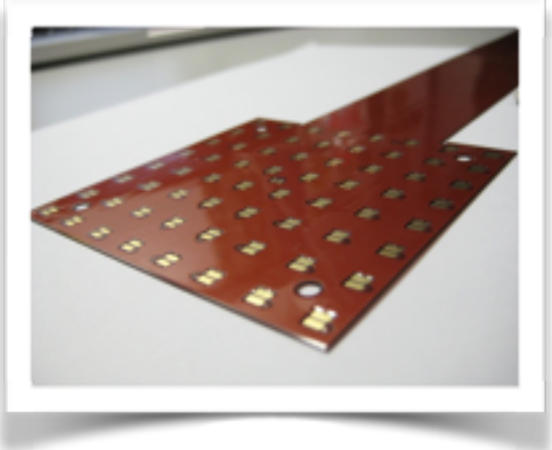


Lead Castle and Pressure Vessel:
Activity shielded by ICS.

NEXT 100 kg radioactive budget

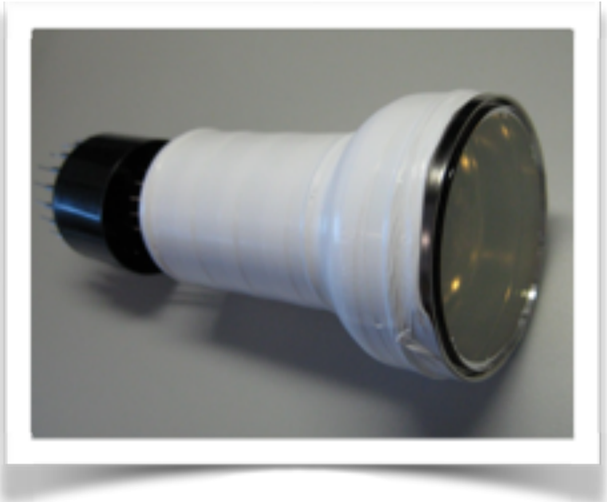
Kapton Dice boards

- Kapton and copper;107 units
- Activity Tl-208: —0.040 mBq/unit
- Activity Bi-214: —0.030 mBq/unit



PMTs

- Hamamatsu R11410-10; 60 units
- Activity Tl-208: —0.140 mBq/unit
- Activity Bi-214: —0.500 mBq/unit

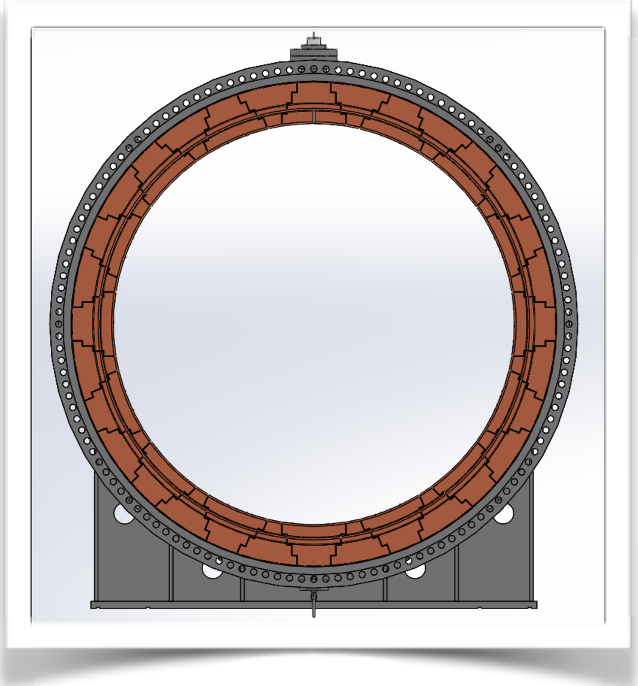


Sensors:
Activity level ~3 mBq per plane. Actual measurements. Not shielded.

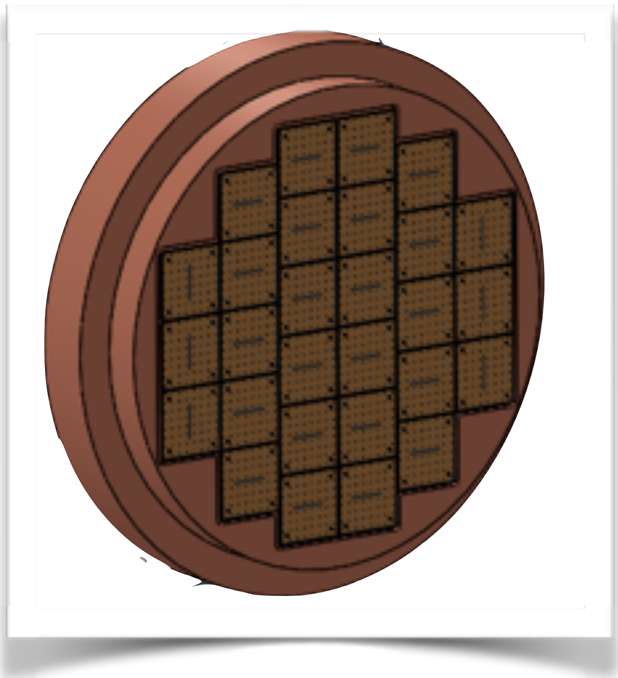
NEXT 100 kg radioactive budget

ICS, and support plates

- Copper (CuA1); ~9500 kg
- Activity Tl-208: <0.001 mBq/kg
- Activity Bi-214: <0.012 mBq/kg

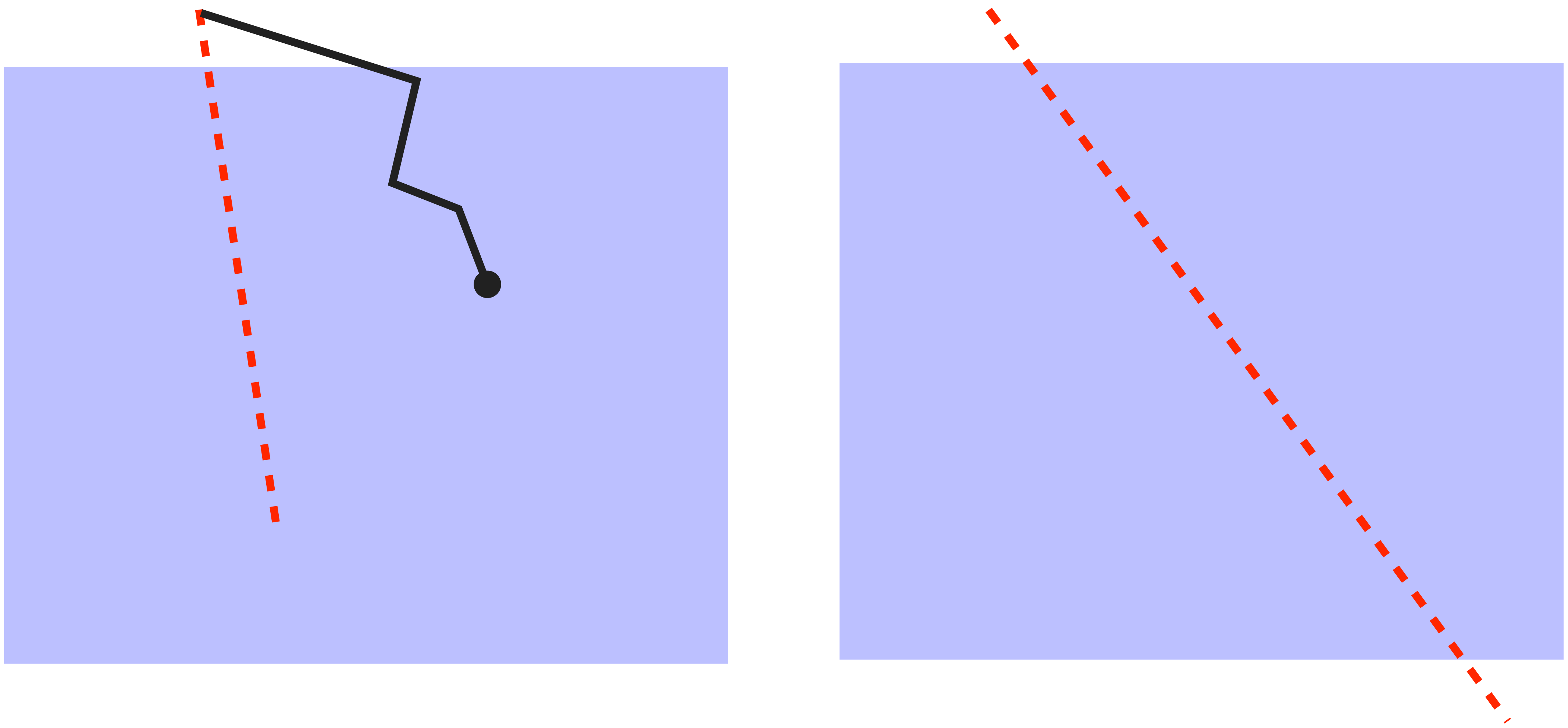


Copper
Electroformed commercial copper. Current measurements show our stock to be very radio pure, but only limits so far.



Residual radioactivity of ICS partially shielded (self-shielding)

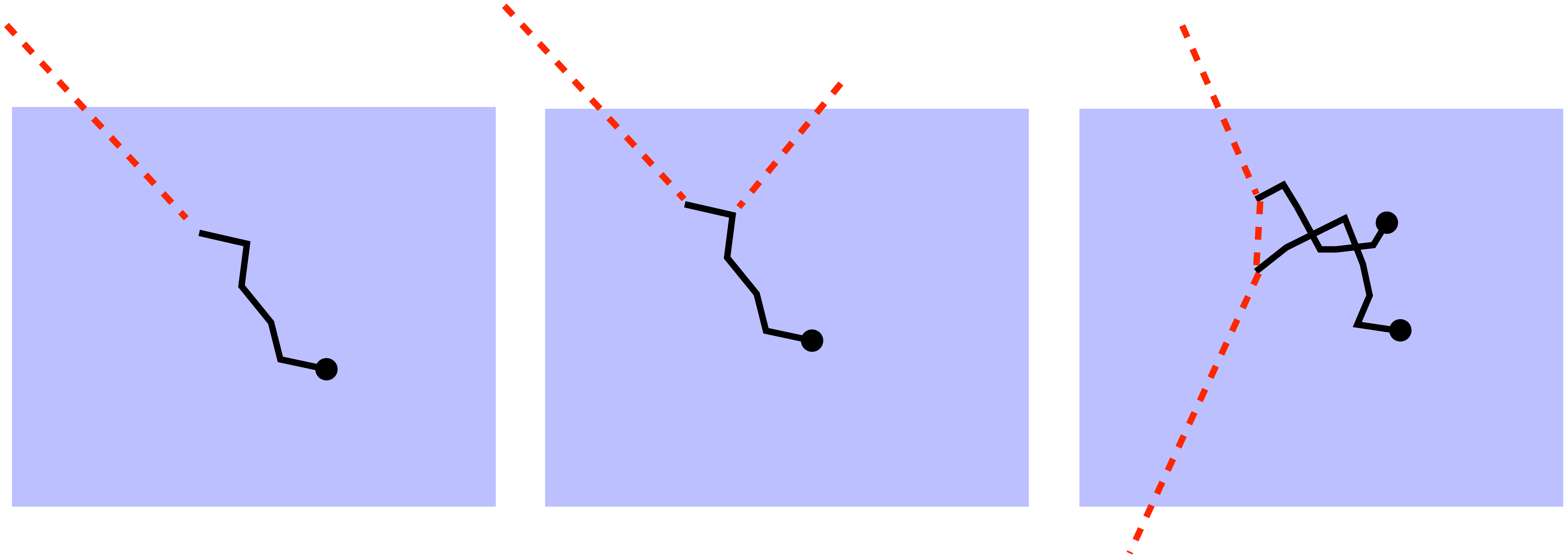
NEXT100 rejection of backgrounds



<u>A transparent target, away from surfaces</u>

- Veto of effectively all charged backgrounds entering the detector (left). High-energy gammas have a long interaction length (>3 m) in HPXe.

NEXT100 rejection of backgrounds



The 2-electron signature

- Interaction of high-energy gammas (from Tl-208 and Bi-214) in the HPXe can generate electron tracks with energies around the Q value of Xe-136. However, electron often accompanied of satellite clusters and single blob deposit

NEXT100 rejection of backgrounds

	$0\nu\beta\beta$	Tl-208	Bi-214
Fiducial E>2 MeV	67.86%	0.25%	0.01%
ROI	95.52%	8.99%	64.66%
1 track	74.60%	1.86%	12.54%
2 blobs	73.76%	9.60%	9.89%

The 2-electron analysis

- Effect of the filters (cuts) defining an event with 2 electrons and energy in a ROI of 2σ around $Q_{\beta\beta}$.
- Efficiency for signal ~35% for suppression factors 4-8 x 10^{-7}
- Topology rejection is the product of 1 track x 2 blobs conditions

NEXT 100 expected background

	Activity (Bq)		Rejection Factors		Final rate (ckky)	
	Tl-208	*Bi-214*	*Tl-208*	*Bi-214*	*Tl-208*	*Bi-214*
Dice Boards	4,28E-03	3,21E-03	7,90E-07	8,85E-07	3,047E-05	2,560E-05
PMTs	8,40E-03	3,00E-02	3,30E-07	2,68E-07	2,498E-05	7,244E-05
Field Cage	4,38E-03	1,53E-02	5,30E-07	8,02E-07	2,091E-05	1,107E-04
ICS	1,326E-02	1,105E-01	1,100E-07	8,400E-08	1,315E-05	8,365E-05
Vessel	1,66E-01	5,16E-01	1,10E-08	2,80E-09	1,644E-05	1,301E-05
Shielding Lead	6,266E-01	1,084E+00	2,000E-09	1,000E-10	1,129E-05	9,763E-07
SUBTOTAL	8,23E-01	1,76E+00			1,172E-04	3,063E-04
TOTAL BKGND	2,58E+00				**4,24E-04**	

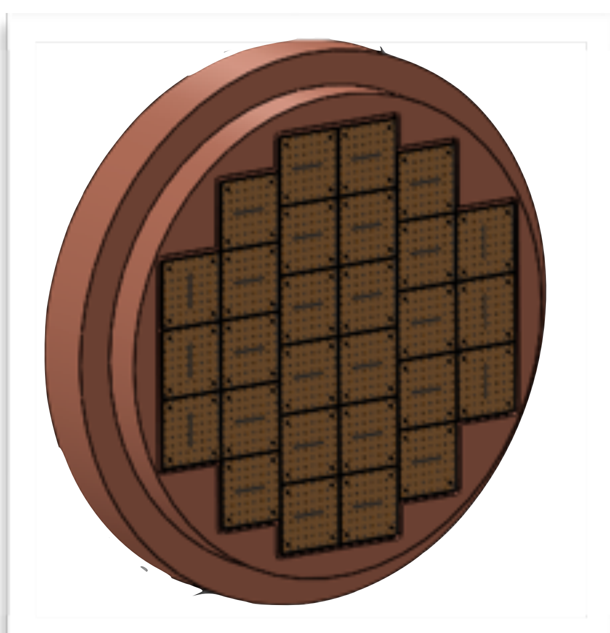
NEW (NEXT-WHITE) at glance

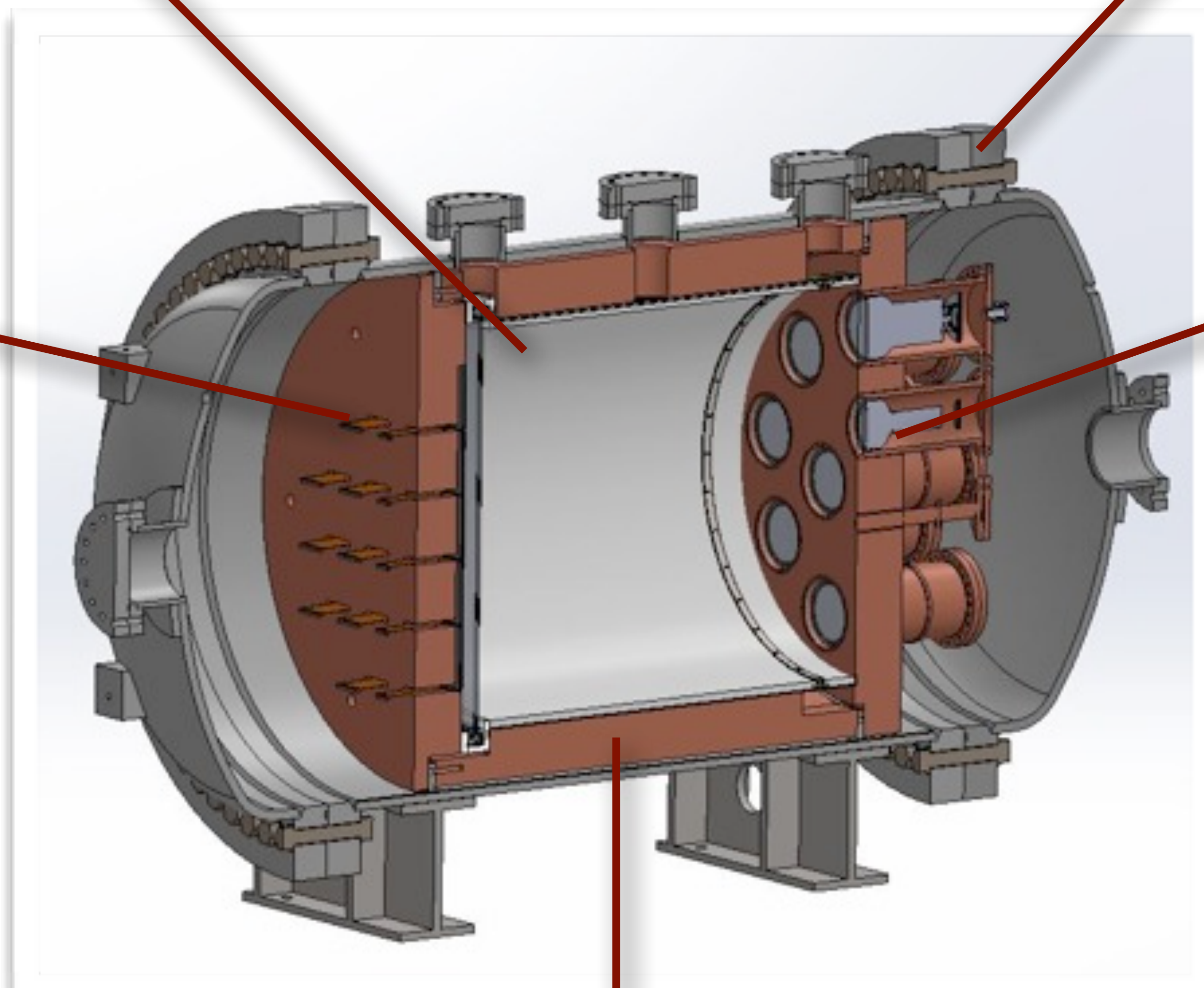
Time Projection Chamber:
10 kg active region, 50 cm drift length

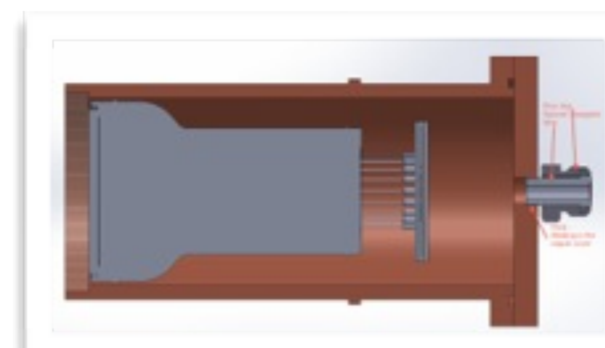
Pressure vessel:
316-Ti steel, 30 bar max pressure

Tracking plane:
1,800 SiPMs,
1 cm pitch

Energy plane:
12 PMTs,
30% coverage

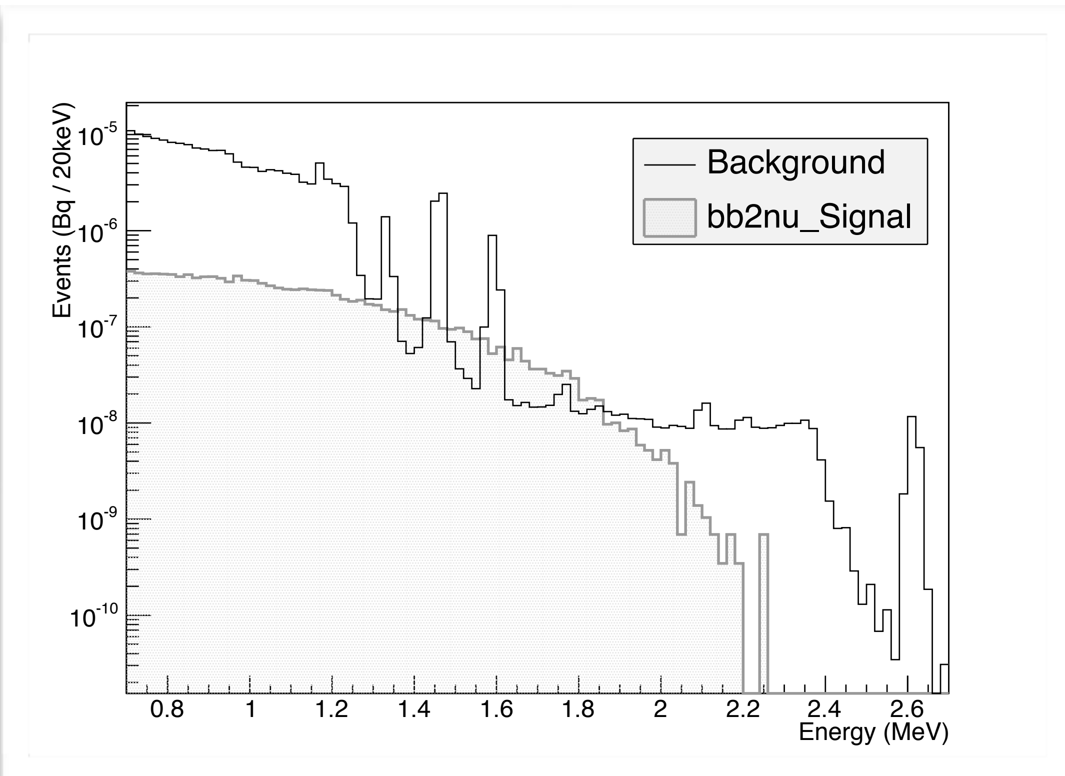


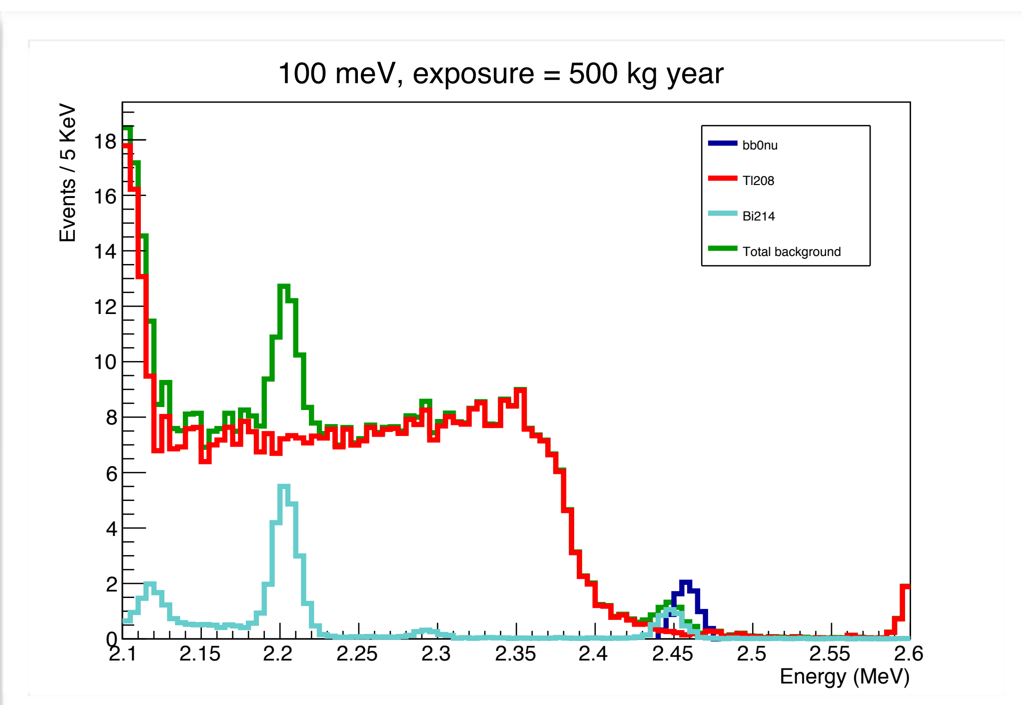




Inner shield:
copper, 6 cm thick

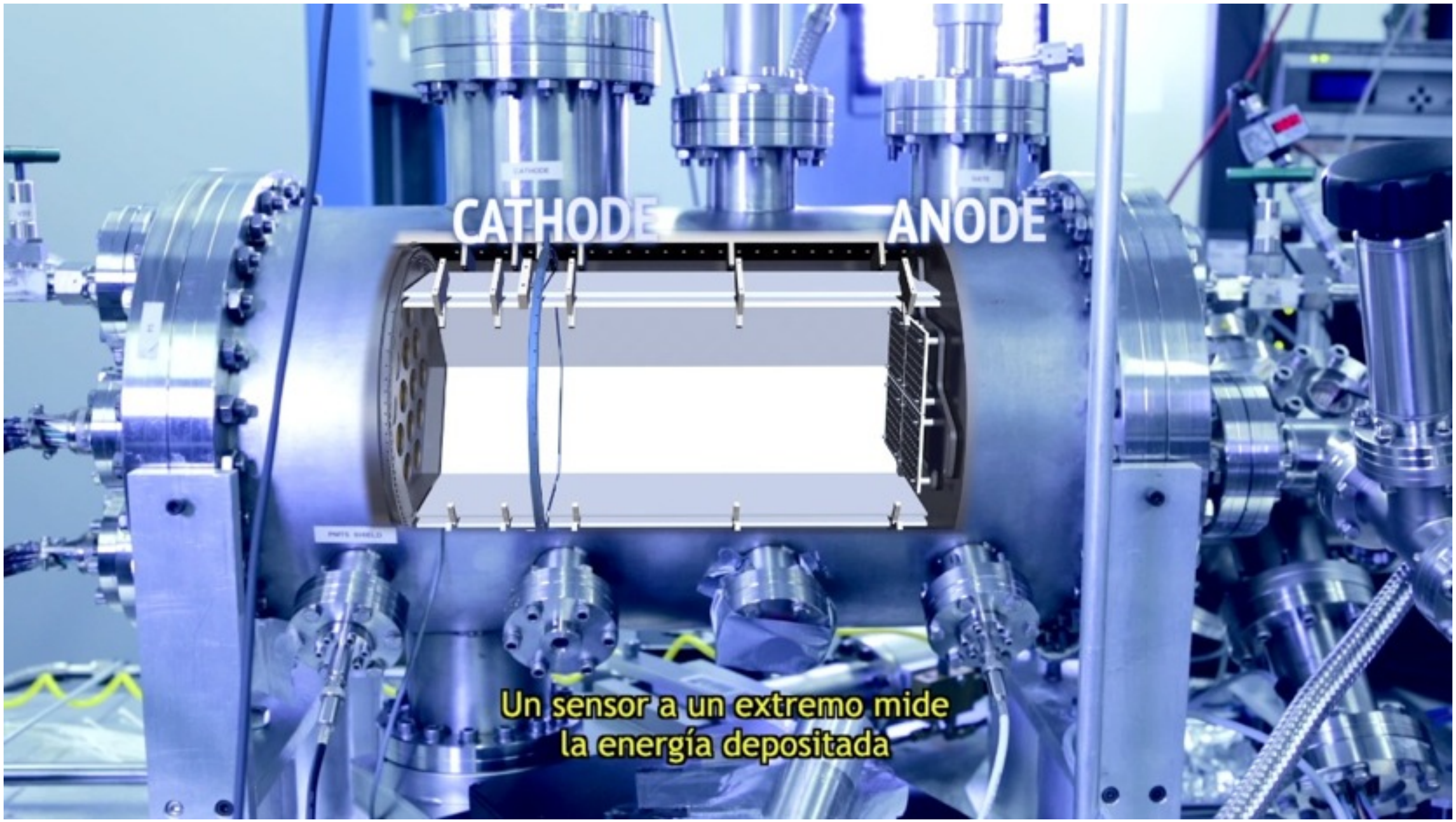
Goals of NEW



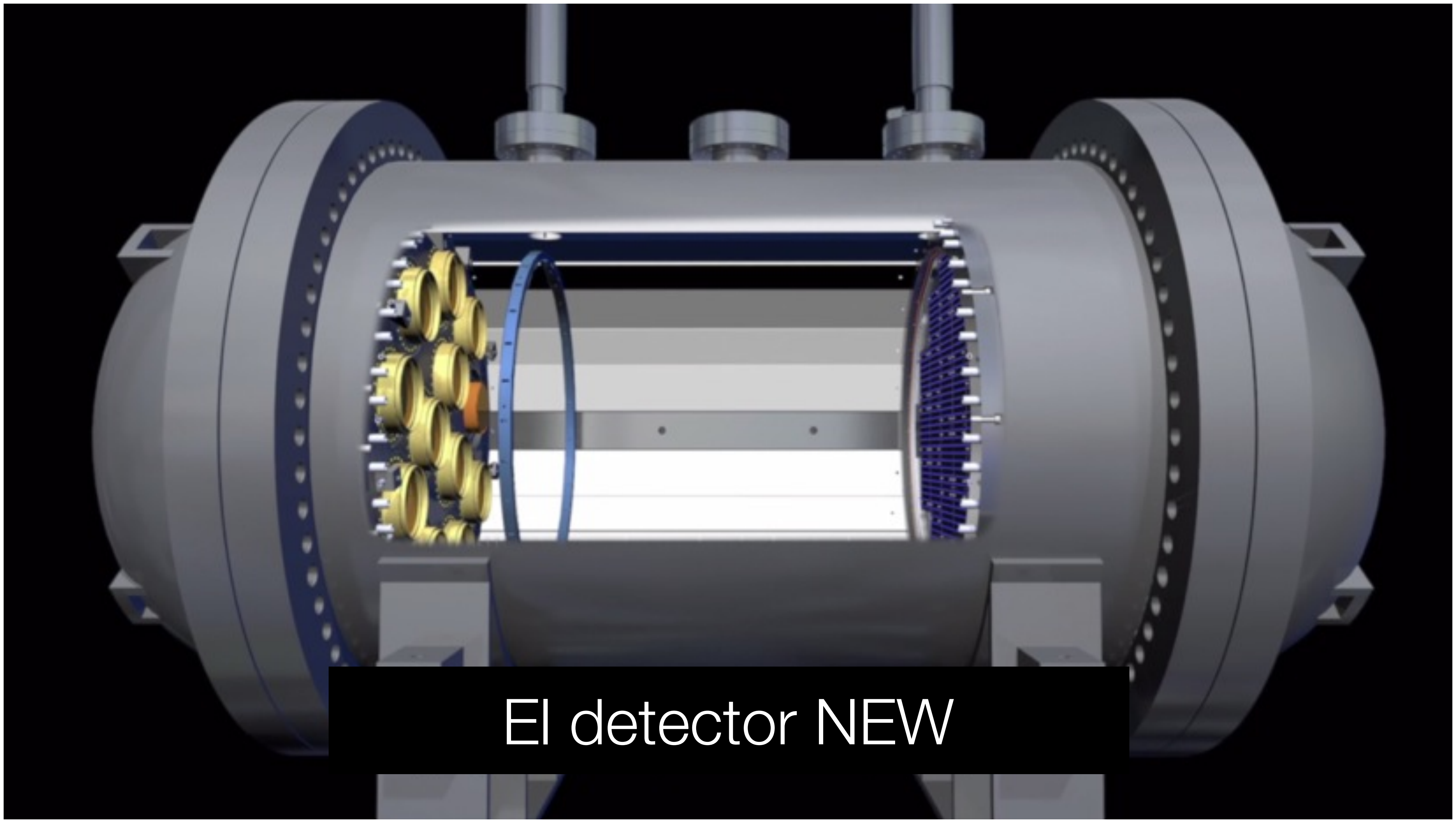


- Measure the expected backgrounds from the different isotopes, but specially Bi-214 and Tl-208.
- Validate NEXT background model using measurement.
- Identify any unexpected source of background (correct if needed)
- Observe ββ2v signal.
- Demonstrate energy resolution: our goal is to reach 0.5 % FWHM in the large detector.
- Demonstrate topological signature from data (ββ2v and Tl-208 double escape peak).
- Certify technology and underground operation with enriched xenon.

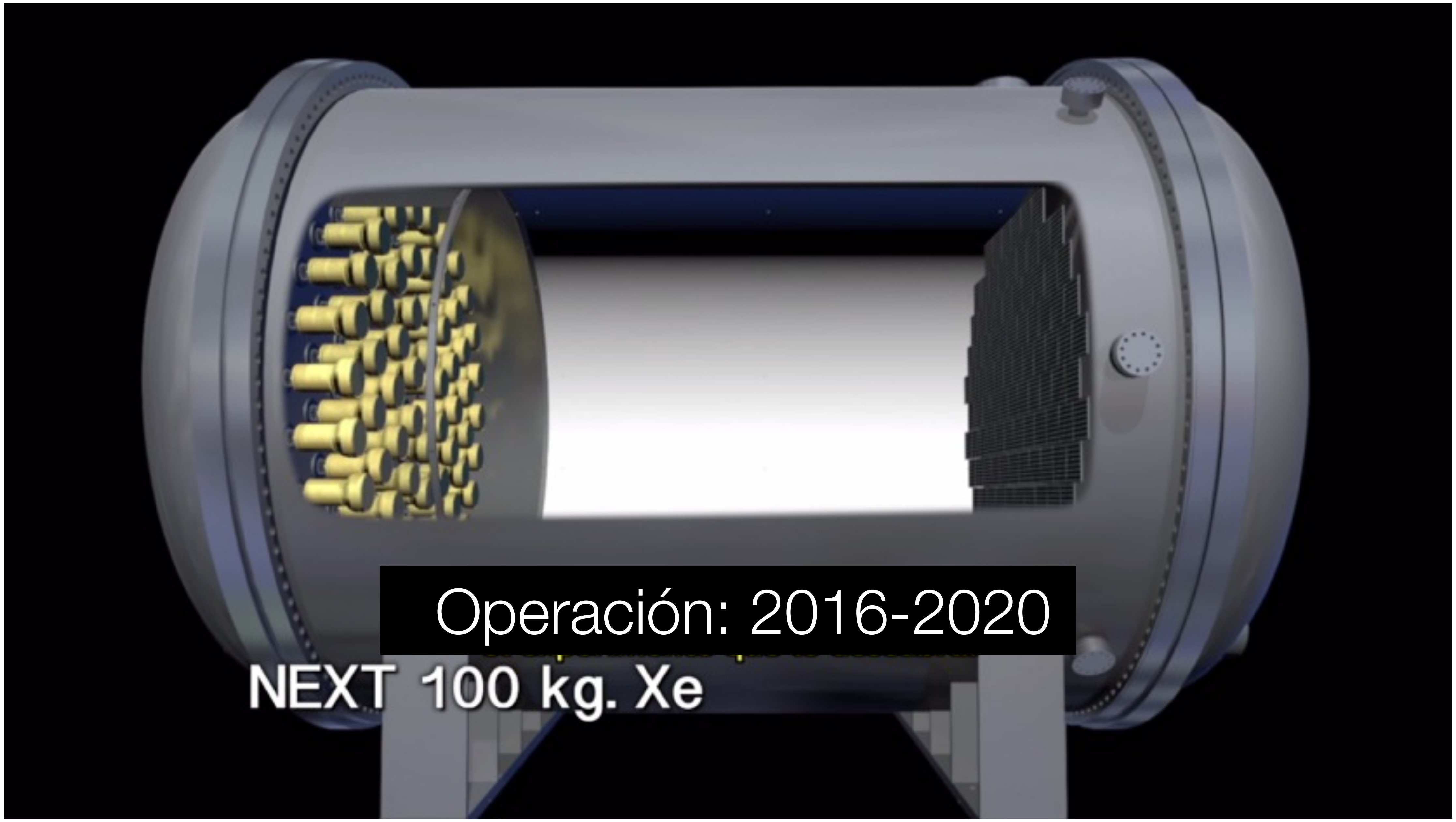
Anatomy of NEXT-DEMO



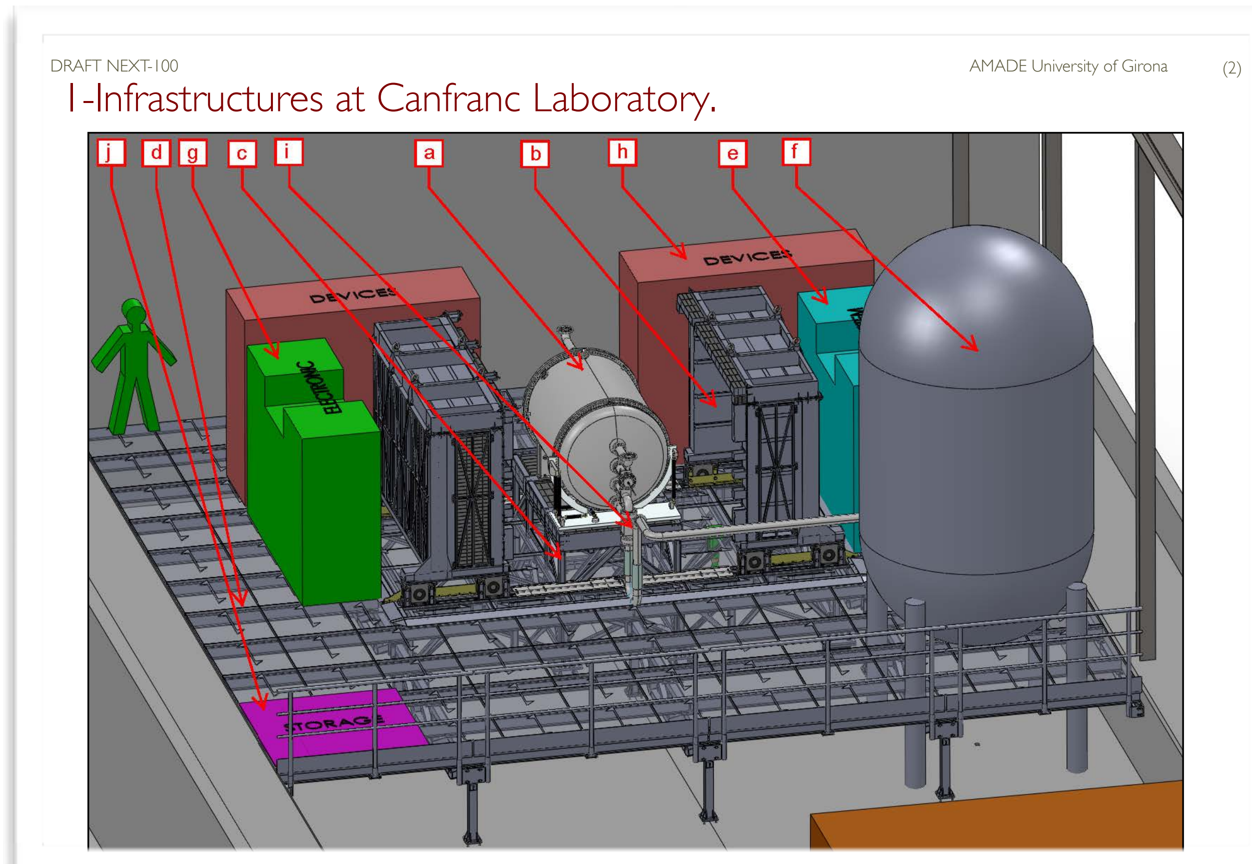
NEW



NEXT-100

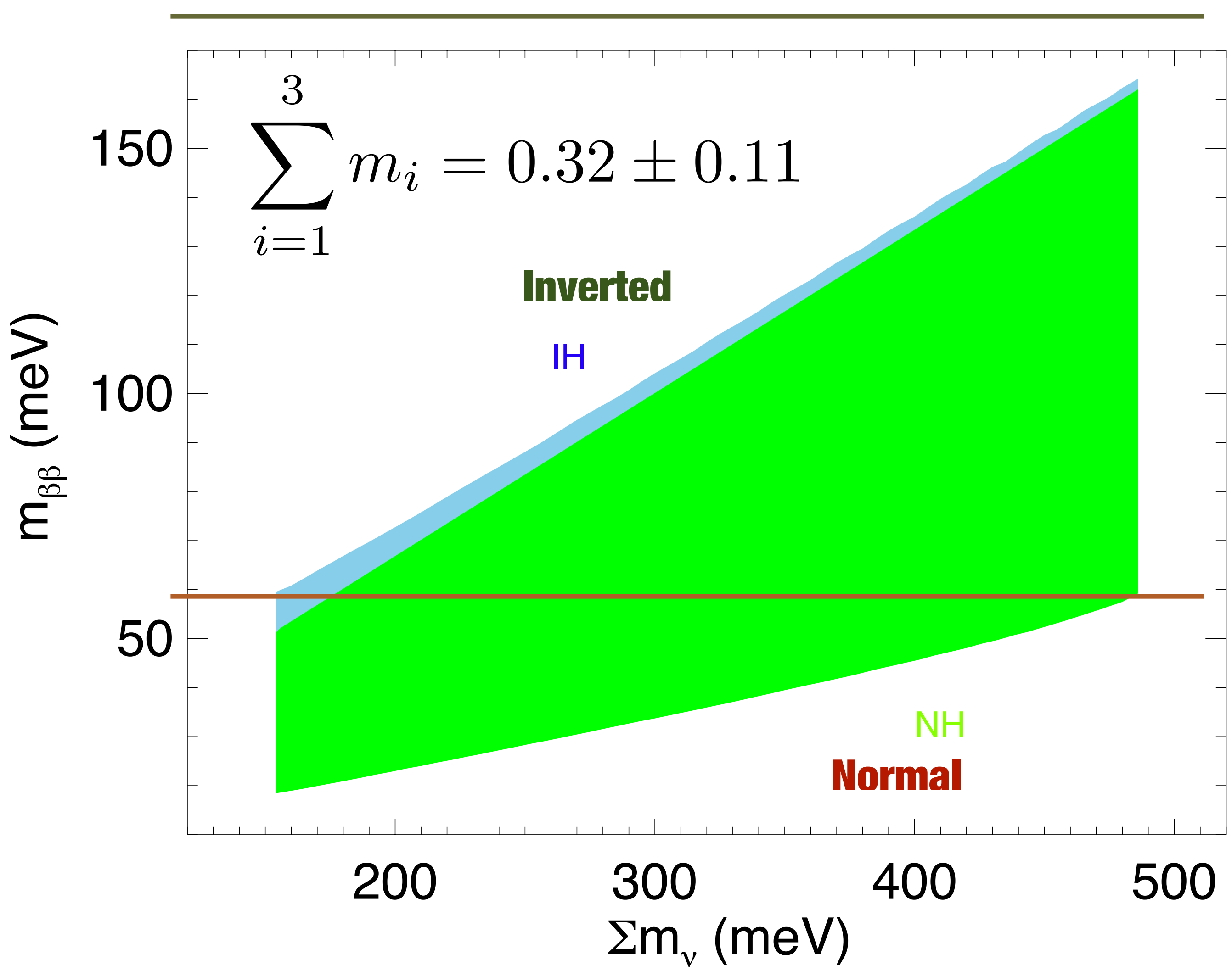


NEXT at LSC



Infrastructures: platform, lead castle, gas system, emergency recovery system, completed. First phase of experiment starts in 2015. In stock, 100 kg of enriched xenon and 100 kg of depleted xenon.

Second phase: the 600 kg run



- 300 kg yr in 5 years
- ΔE=0.7 % FWHM at $Q_{\beta\beta}$
- B=5 x 10^{-4} ckky ⇒
    - $T^{0\nu}$=6 x 10^{25}⇒
    - $m_{\beta\beta}$ = 70-196 meV

- Will Cover a significant fraction of cosmological region.