Search for 0νββ decay with EXO-200 and nEXO

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On behalf of the EXO-200 and nEXO Collaborations

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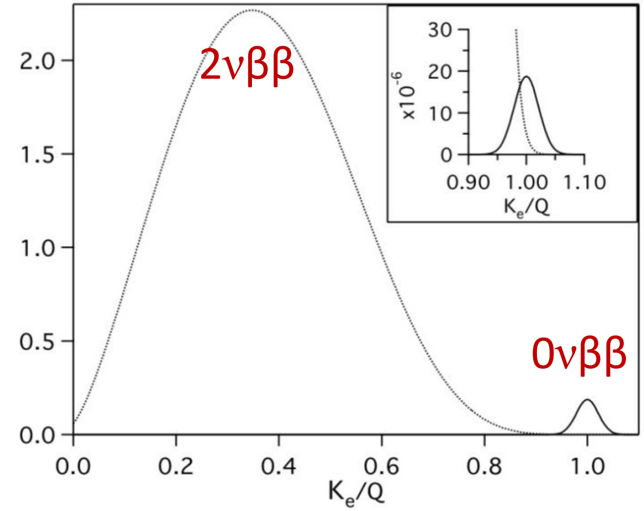
0ν2β: detection? how? when will we be able to know if Dirac and Majorana? complementarity of different planned experiments

from WG5 conveners

0νββ requirements



N_B = number of background counts in the ROI along the measure time

- t_{meas} measuring time [y]
- ☆ **M** detector mass [kg]
- **ε** detector efficiency
- ☆ **i.a.** isotopic abundance
- **A** atomic number
- ★ **ΔE** energy resolution [keV]
- ★★ **bkg** background [c/keV/y/kg]

$N_B \gg 1$

$$S_{1/2}^{0\nu} \propto \epsilon \frac{i.a.}{A} \sqrt{\frac{M \cdot t_{meas}}{bkg \cdot \Delta E}}$$

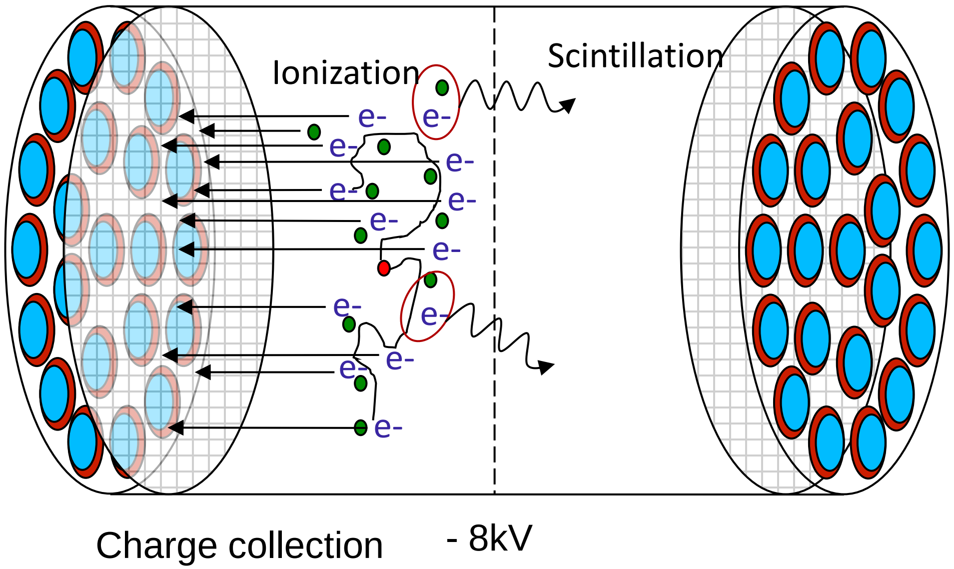
$N_B \leq O(1)$ → "zero"

$$S_{1/2}^{0\nu} \propto \epsilon \frac{i.a.}{A} M \cdot t_{meas}$$

Use liquid Xenon TPC to search for $0\nu\beta\beta$

Advantage of Xenon:

- Xenon is used both as the source and detection medium.
- ^{136}Xe enrichment is easier and safer.
- Easily scale to tonne scale.
- Low background -- No long lived radioactive isotopes and can be continuously purified.



Example of TPC schematics (EXO-200)

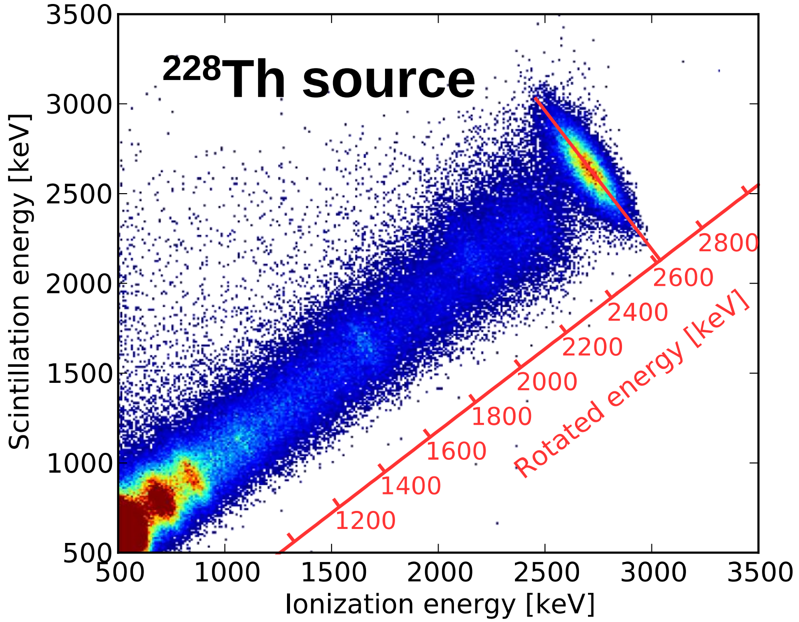
Advantage of liquid Xenon TPC:

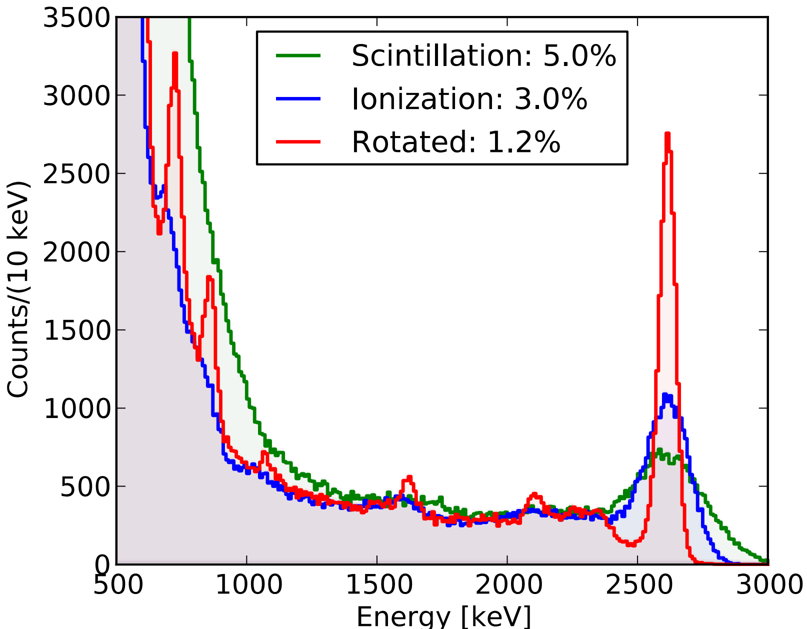
- Simultaneous collection of both ionization and scintillation signals.
- Full 3D reconstruction of all energy depositions in LXe.
- Monolithic detector structure with excellent background rejection capabilities.
- Background free measurements – Ba tagging.

- **Combine light and ionization to enhance energy resolution**

(E.Conti et al. Phys Rev B 68 (2003) 054201)

- **EXO-200 has achieved ~1.28% energy resolution at the Q value.**
- **nEXO will reach resolution < 1%, sufficient to suppress background from 2νββ.**





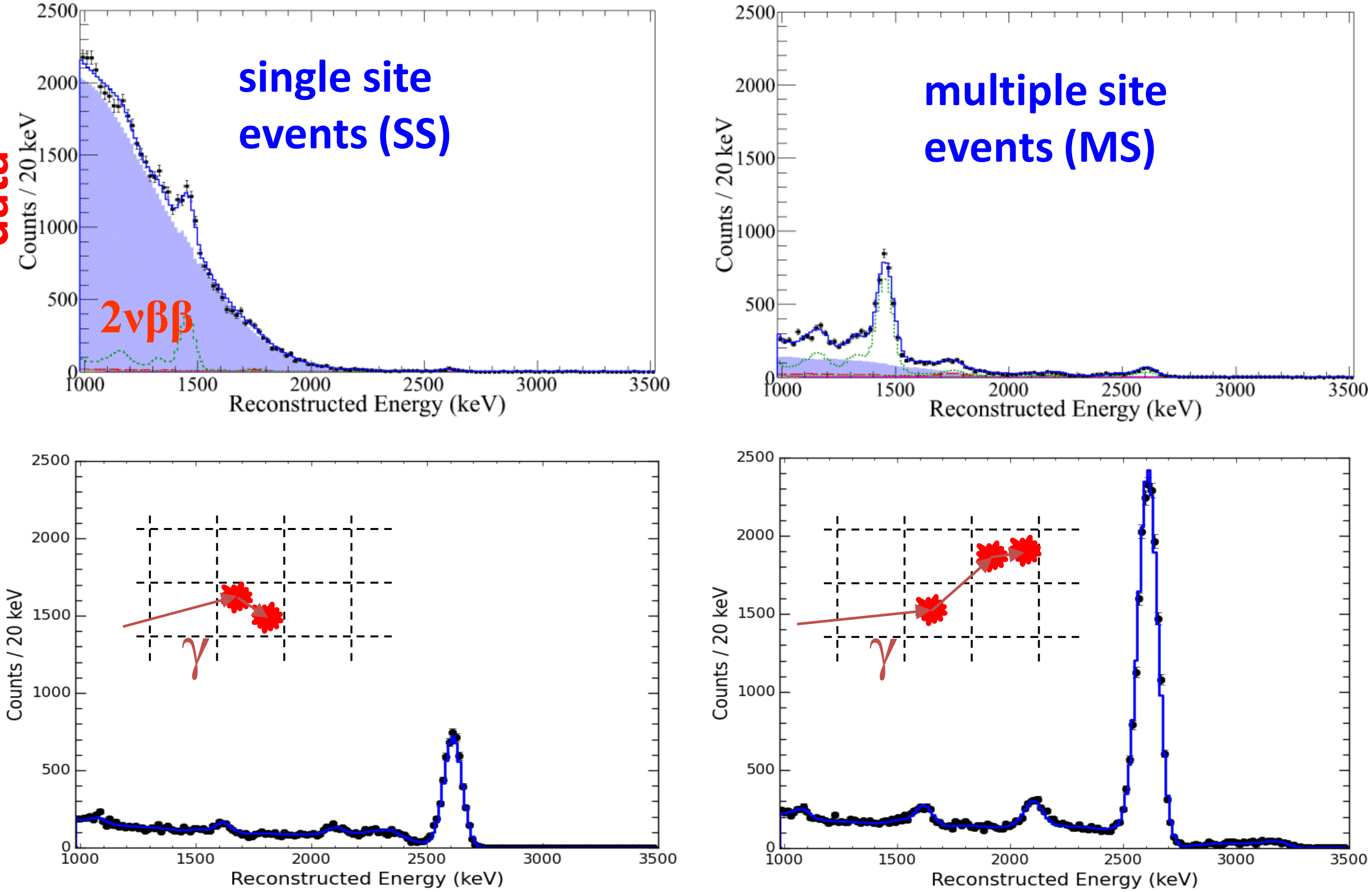
However, LXe TPC IS NOT A PURE CALORIMETER, it can use optimally more than just the energy.

- **Event multiplicity (SS/MS in EXO-200)**
- **Distance from the TPC surface**
- **Particle ID (α-electron)**

Event multiplicity information

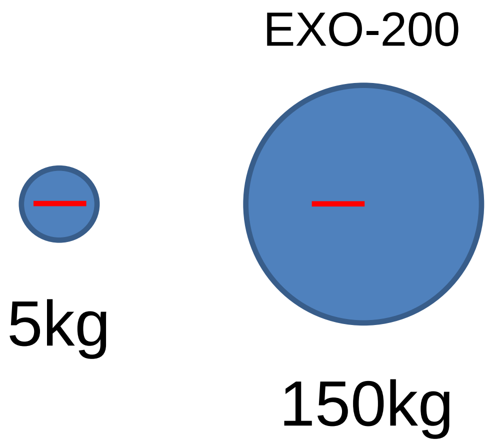
Low background data

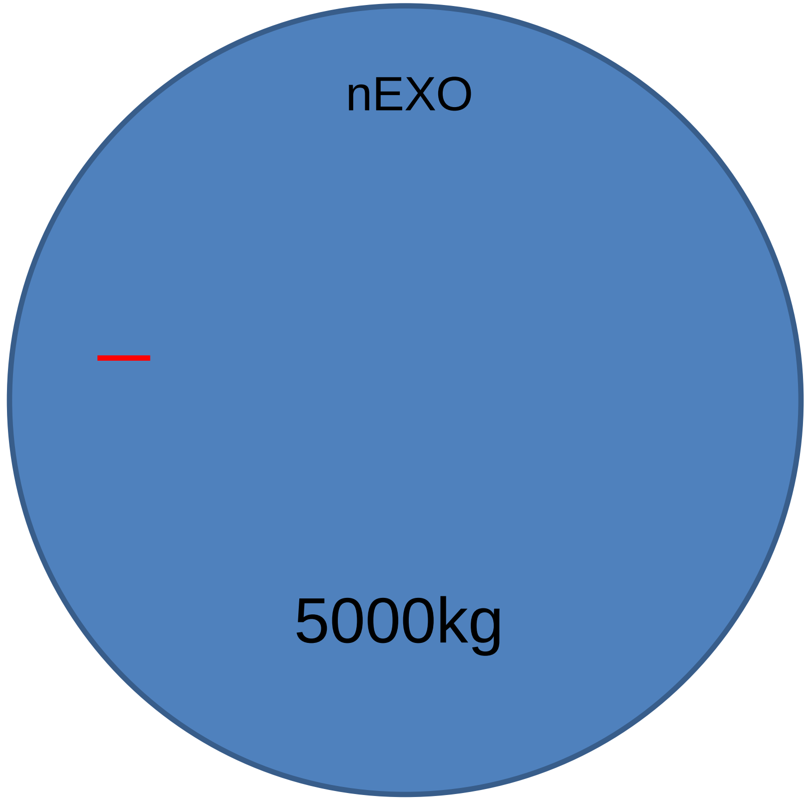
^{228}Th calibration source



SS/MS discrimination is a very powerful tool to reject gamma backgrounds, because Compton scattering results in multiple energy deposits. This is well demonstrated in EXO-200.

Monolithic Detectors





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

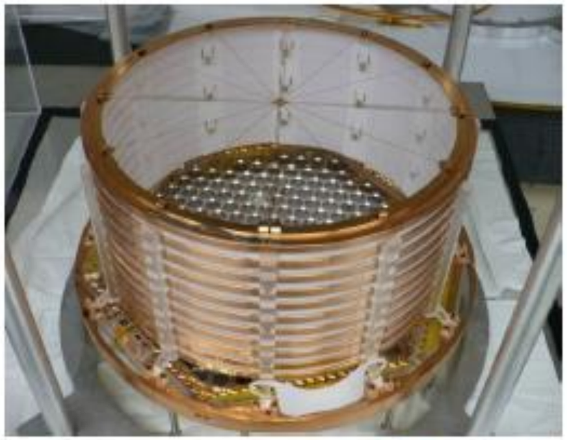
2.5MeV gamma ray attenuation length 8.5 cm = —

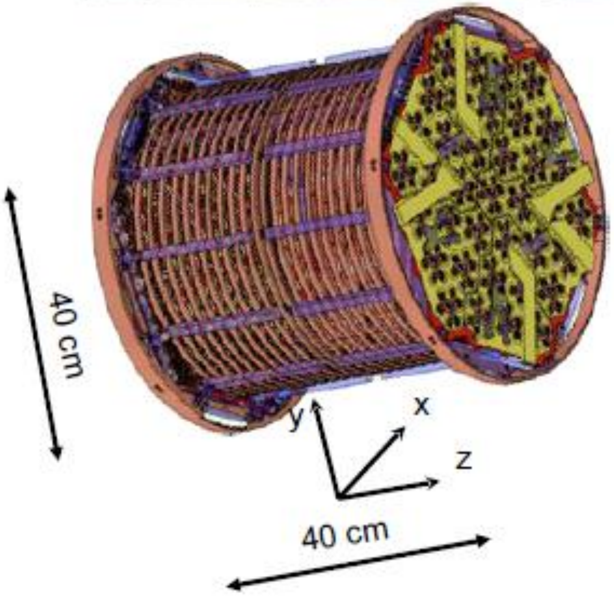
Monolithic detector is essential for background rejection:

- **Rejection of surface background**
- **Self-shielding, containment of Compton scattering**
- **Inner fiducial volume extremely clean**

The EXO-200 TPC

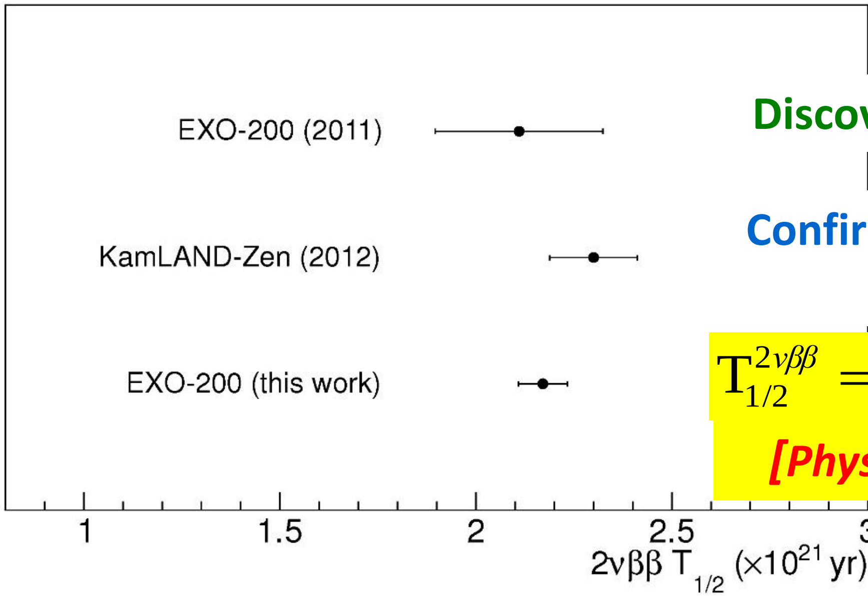
200kg of Xe enriched to 80.6% Xe-136 and 175kg LXe inside TPC





- A common cathode + two anodes
  - ✓ 376V/cm drift field
- Each half reading ionization and 178nm scintillation with:
  - ✓ 38 U triplet wire channels (charge)
  - ✓ 38 V triplet wire channels, crossed at 60 degrees (induction)
  - ✓ 234 large area avalanche photodiodes (APDs, light in groups of 7)
  - ✓ All signals digitized at 1 MHz, ±1024 μs around trigger (2 ms total)
- Teflon reflectors
- Copper field shaping rings
- Acrylic supports
- Flexible bias/readout cables: copper on kapton, no glue

Precision ^{136}Xe 2νββ Measurement



EXO-200 start data taking in June 2011

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

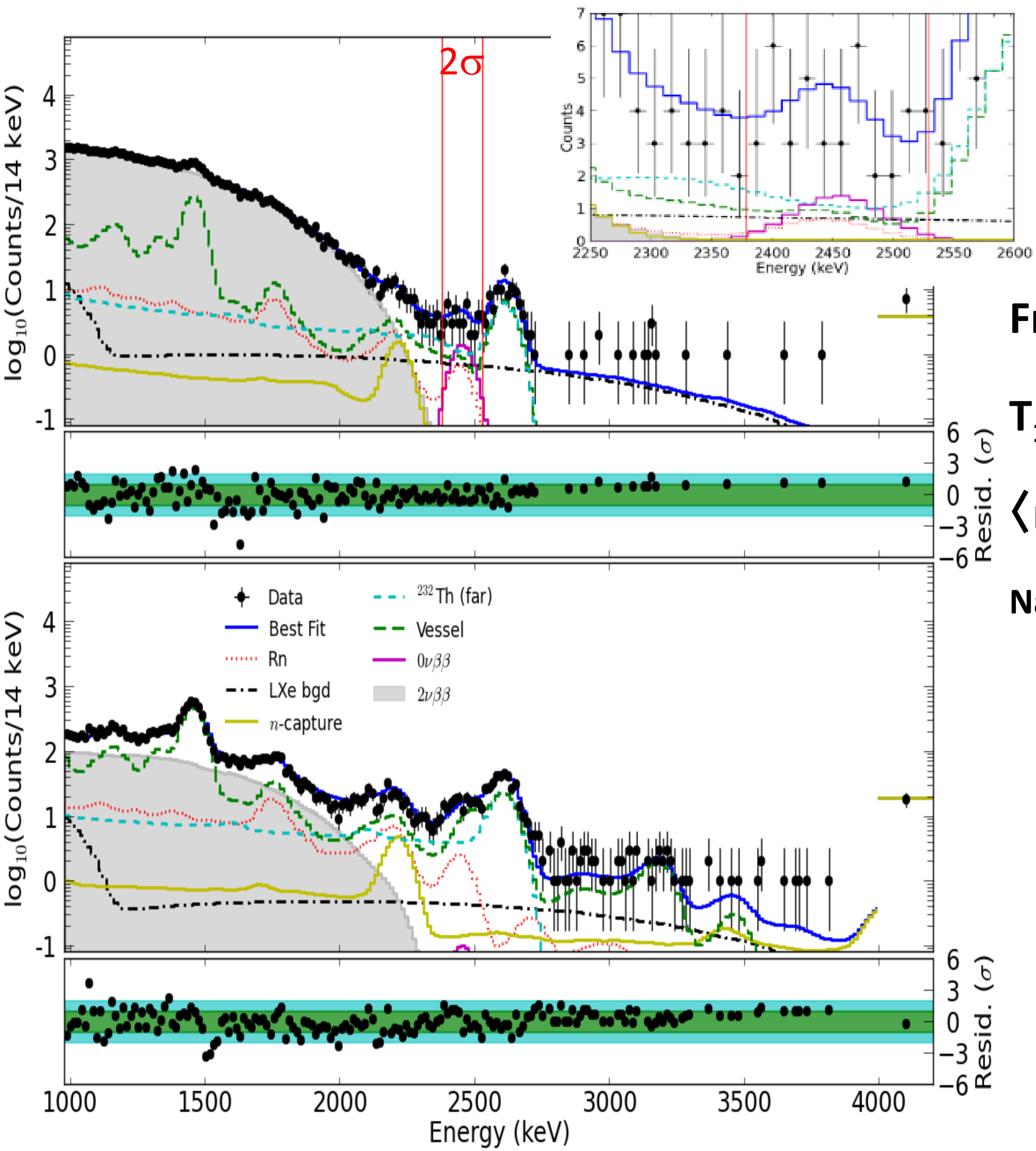
Confirmation by KamLAND-Zen *[PRC 85, 045504 (2012)]*

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

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

Longest and most precisely measured 2νββ half-life

EXO-200 Phase-I results



^{136}Xe 0νββ search with 100 kg·yr exposure

From profile likelihood:

$T_{1/2}^{0\nu\beta\beta} > 1.1\cdot10^{25}$ yr

$\langle m_{\beta\beta}\rangle <$ 190 – 450 meV (90% C.L.)

Nature (2014) doi:10.1038/nature13432

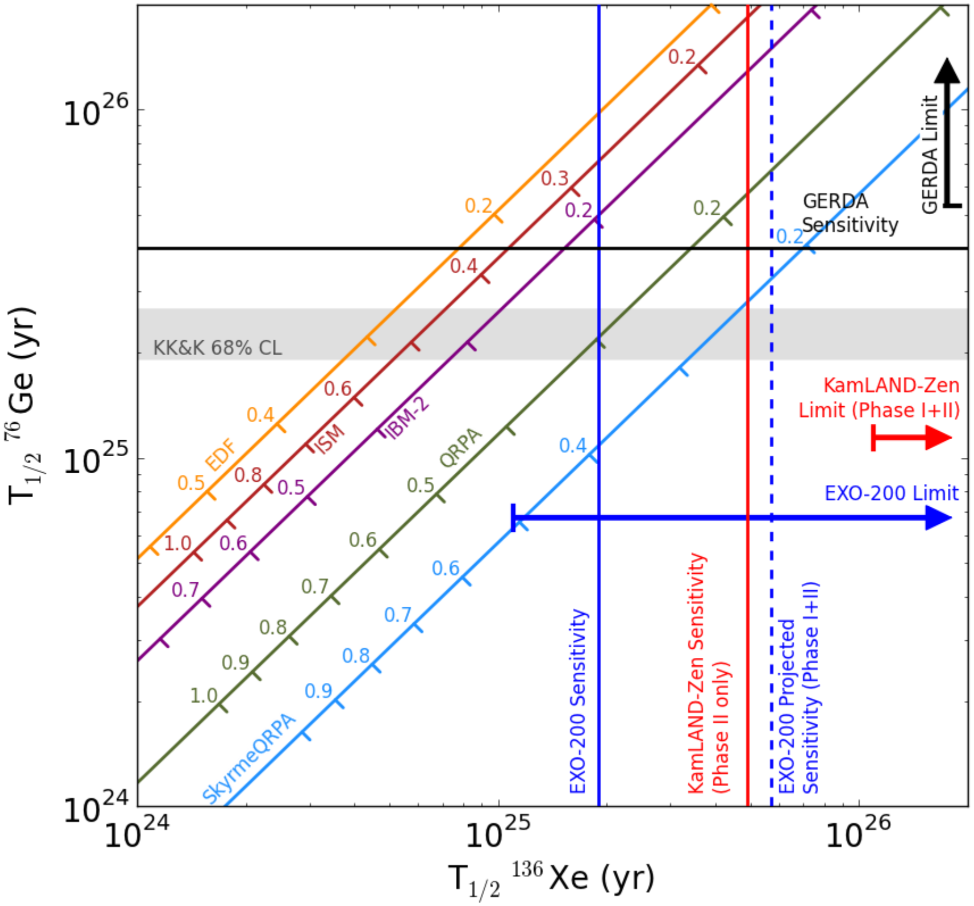
Background in the 0ν ROI: (1.7±0.2)·keV^{-1} ton^{-1} yr^{-1}

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

EXO-200 Phase II Sensitivity

Upgrades made in Phase II:

- **APD electronics upgrade improved energy resolution from 1.58% to 1.28% at Q of 0νββ, and might be better with improved data processing.**
- **Deradonator reduced Rn level by a factor of ~10, sufficient to suppress this background for 0νββ.**



EXO-200 can reach $0\nu\beta\beta$ half-life sensitivity of 5.7×10^{25} ys.

With lower threshold, EXO-200 can improve measurement of ^{136}Xe 2νββ and searches in other physics channels.

EXO-200:
Nature (2014),
doi:10.1038/nature13432

GERDA Phase 2:
Public released result. June, 2016
(frequentist limit)

KamLAND-Zen:
arXiv:1605.02889 (2016)

From EXO-200 to nEXO

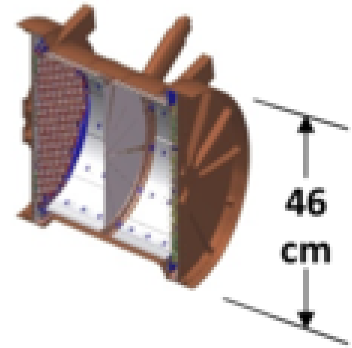
❄ What did we learn from EXO-200?

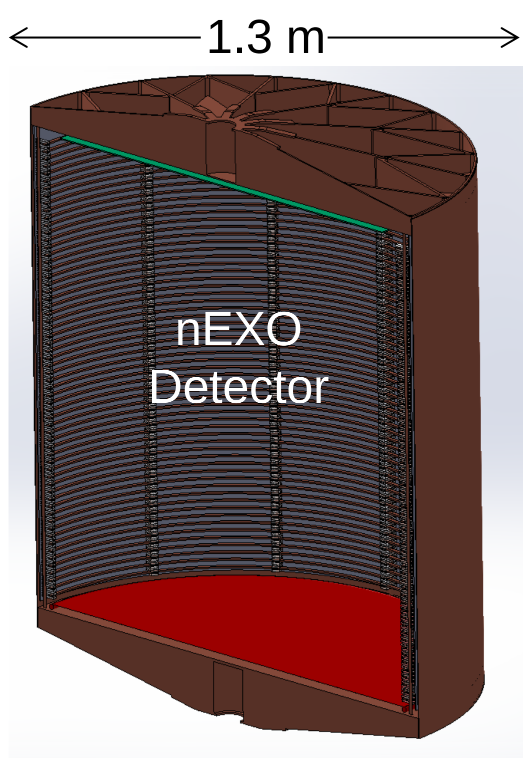
- Measured residual backgrounds **consistent with radio-assays** and surpassed the design background goal.
- Energy resolution is better than design, **σ/E(Q)=1.28%.**
- Demonstrated power of **standoff distance** in monolithic detector.
- Demonstrated power of **SS/MS b/g discrimination**.

❄ nEXO

- **5 tones** of enriched Xe (90% or higher), < **1.0% (σ/E)** energy resolution.
- Enhanced **self shielding**.
- Possible later upgrade to **Ba tagging** to increase sensitivity.
- Many **optimizations** from EXO-200 are made to improve a successful design.

EXO-200 Detector



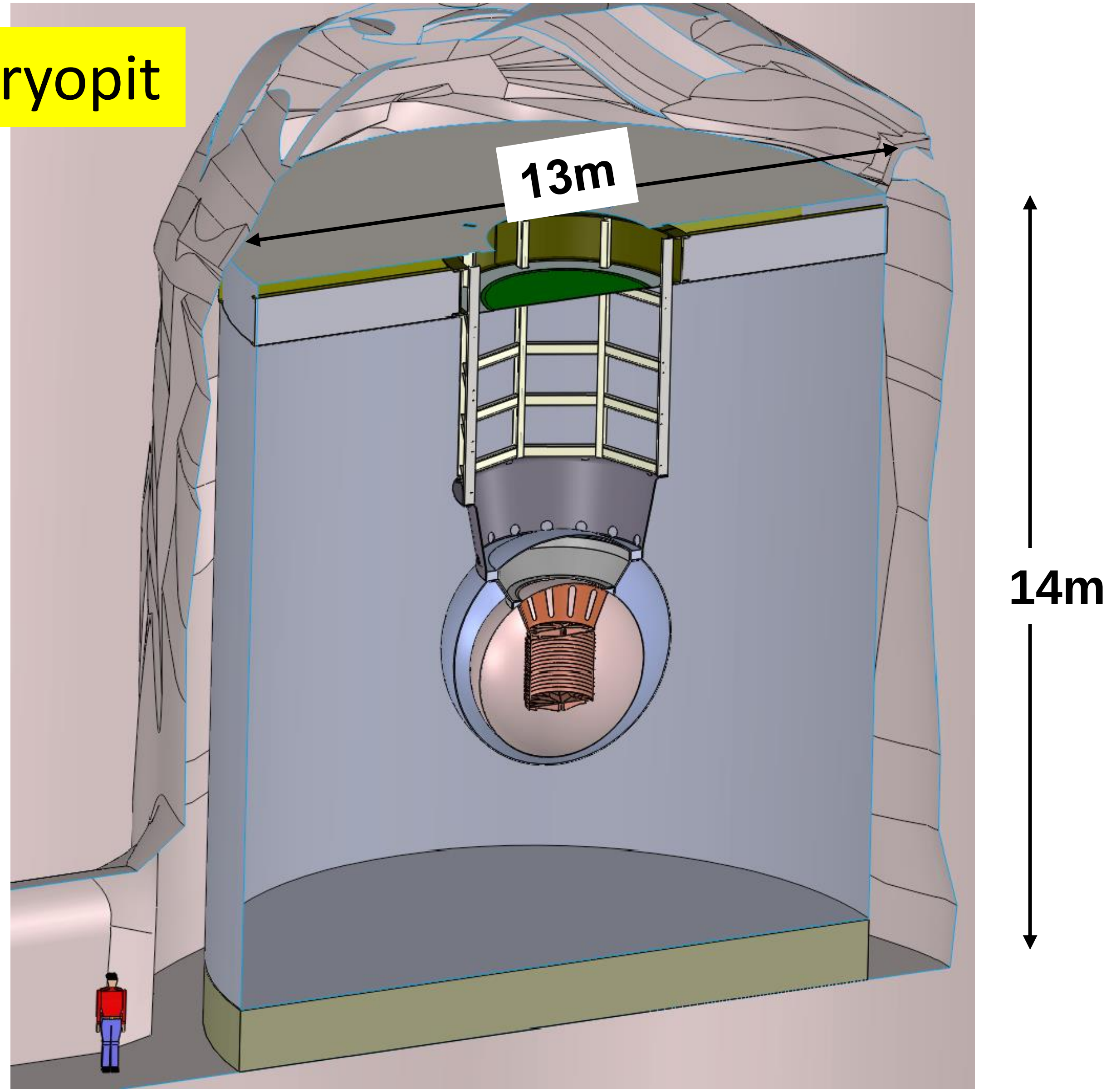


Optimizations from EXO-200 to nEXO

Optimization	Reason
Up to 40 × volume/mass	Inverted hierarchy sensitivity
Move cathode to end	Remove all internal sources of background
6× high voltage	Longer drift length
> 3 × electron lifetime	Longer drift length
Increased photo-coverage	Energy resolution (to 1% σ/E), scintillation threshold
SiPMs over LAAPDs	Higher gain, lower bias, less material, energy resolution, lower scintillation threshold
In LXe front end electronics	Lower noise/lower threshold to ID Compton
Low outgassing materials	Longer electron lifetime
New calibration methods	To calibrate 'deep' detector (by design)
Deeper site	Reduced cosmic activation
Charge tiles over wires	3mm position resolution, simpler/smaller mechanical supports, lower radioactivity

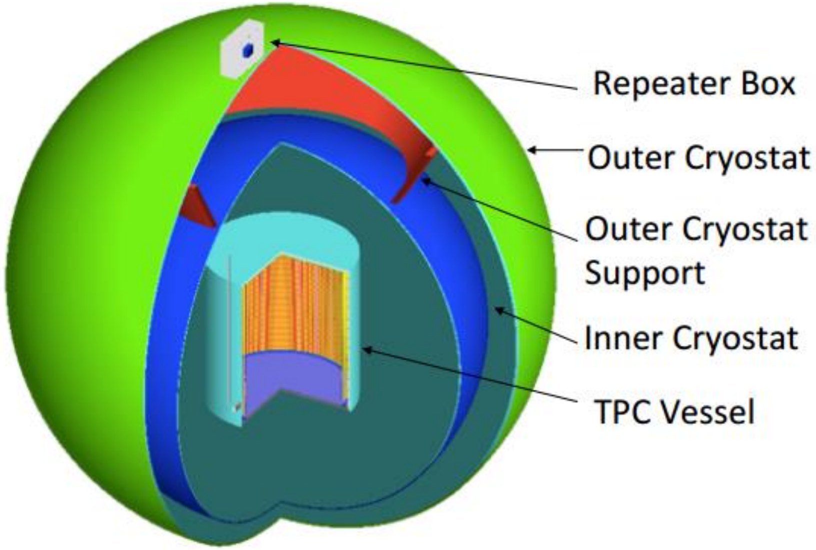
View of conceptual design of nEXO

SNOLAB's cryopit

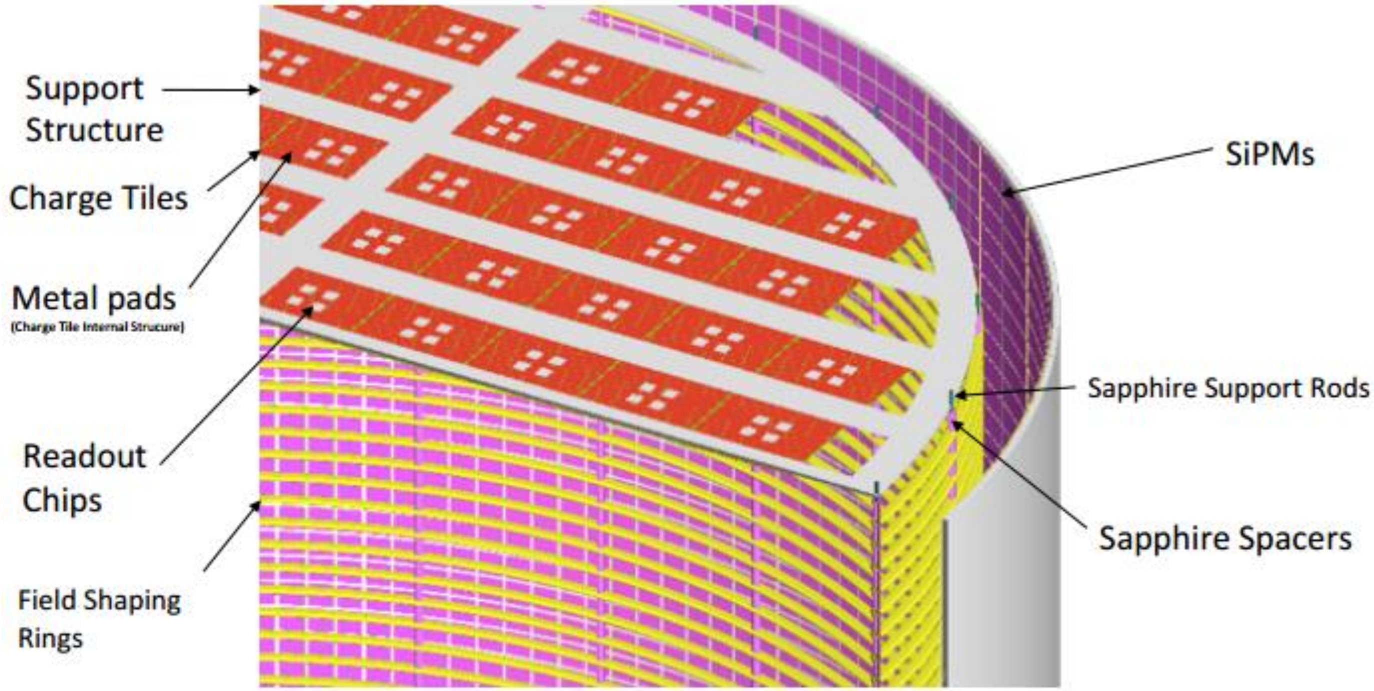


6,000 m.w.e. depth sufficient to shield cosmogenic background.

nEXO TPC Conceptual Design



- Cathode is located at the bottom of TPC.
- A pad-like charge readout tile is on top of TPC.
- Photo-sensors are behind the field shaping rings and will operate in a high field region.



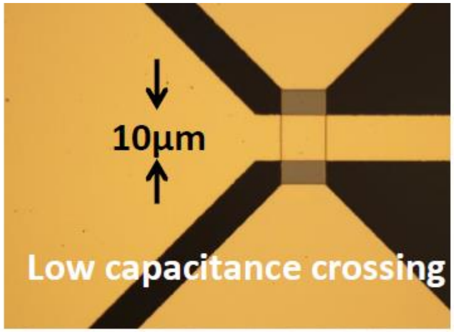
Ongoing research for nEXO

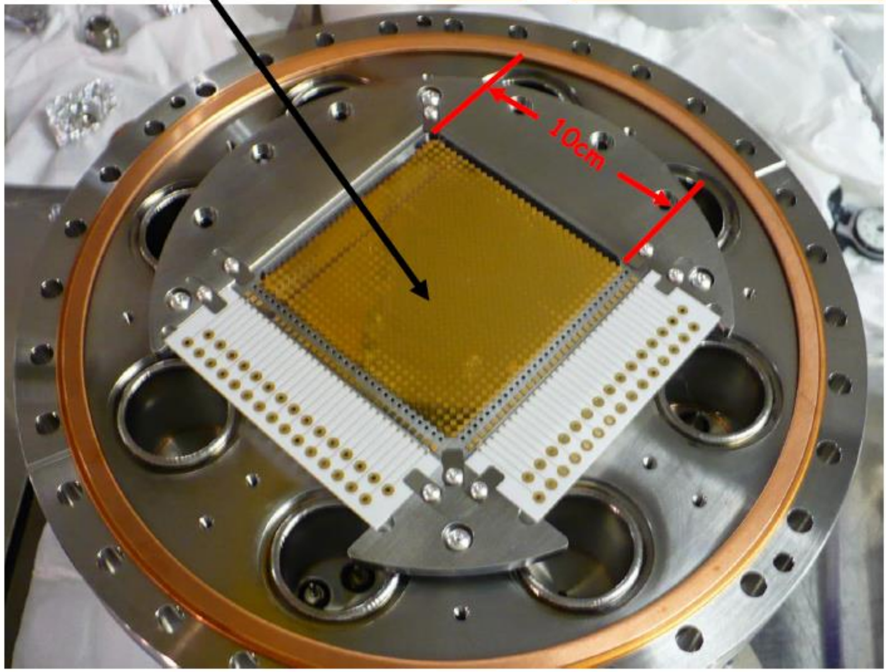
- **Charge readout tile**
- **Photo-detector**
- **High voltage**
- **Radio-assay**
- **Low Background, Cryogenic Electronics**
- **Calibration**
- **Low background Cryostat**
- **Simulation**
- **Ba-tagging**

Charge readout tile

- EXO-200 used wires for charge readout.
- In nEXO, a modular and pad-like charge collection scheme is under study.
- A 10cm x 10cm prototype has been made by IHEP/IME in China.
- Metallized pads on fused silica substrate.
- Intersections between X and Y are isolated with SiO2 layer.
- 3mm pad pitch, 60 orthogonal channels (30 x 30).
- Currently functional testing in LXe is processing in US.

IHEP/IME tile anode, mounted to underside of cell lid





Prototype charge readout tile

R&D of photo-detector in nEXO

Good energy resolution requires efficient readout of the 175nm scintillation light to be combined with the ionization signal.

Besides high photon detection efficiency (PDE), a desirable photo-detector should also have low noise, reasonable cost, ultra-low radioactivity and availability in m^2 mount.

VUV sensitive SiPMs

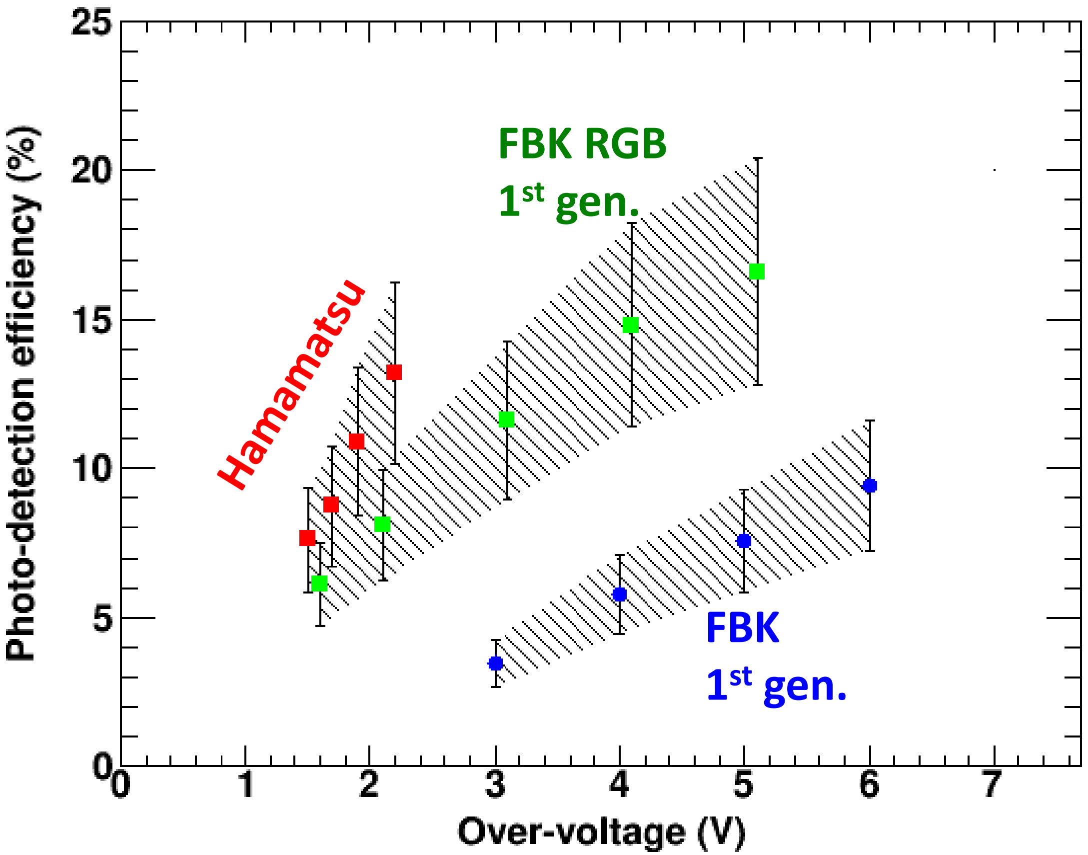
Working with a number of SiPM companies.
We have facilities to

- **Measure SiPM characterization – PDE, dark noise, cross talk, …**
- **Measure Radio-purity of SiPMs**
- **Study SiPM performance in high field.**
- **Measure reflectivity on SiPM surface.**

Other R&D items related to SiPM:
Readout schemes; 3D SiPM; Supporting and connections.

Hamamatsu produces devices with PDE= ~12% @ 175nm (encapsulated devices).

First nEXO-specific run at FBK (Italy) provided ~10% QE *[I.Ostrovskiy et al. IEEE TNS 62 (2015) 1.]*
New "RGB" devices reach PDE = ~15% @175nm.



A new run at FBK was made based on a new technology (NUV-HD).
The new generation devices (NUV) have reached PDE > QE>15% @175nm, with 1x1cm^2 devices.

Radio assay results of the FBK devices are very encouraging.

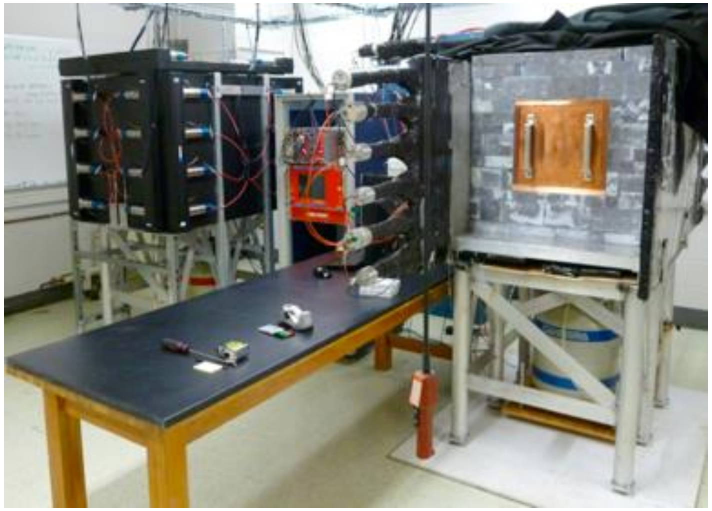
Other testing results are coming, stay tuned.

Radio-assay programs for nEXO

- **To achieve nEXO designed sensitivity, backgrounds from different sources must be well controlled.**
  - **Cosmogenic background**
  - **Environmental radioactivity**
  - **Natural and man-made radioactivity**

- **Various techniques have been used for the material radioactivity measurements.**
  - **Above ground and underground Ge γ-spectroscopy**
  - **Neutron Activation Analysis (NAA) -– 10^{-9} g/g for K, 10^{-12}-10^{-13} g/g for U/Th**
  - **Inductively Coupled Plasma Mass Spectrometry (ICP-MS, China, Korea, PNNL) – sub ppt**
  - **Glow Discharge Mass Spectrometry (GD-MS) (NRC, Canada)**
  - **Radon emanation counting – 60 decays/day**

ICP-MS at IHEP, Beijing



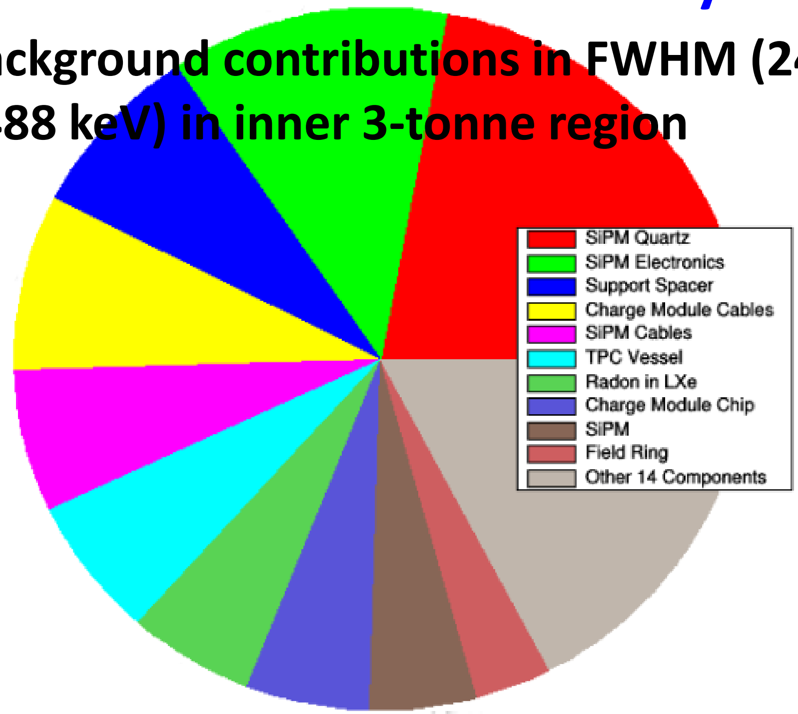
Ge detector lab at U. of Alabama

Detector simulation

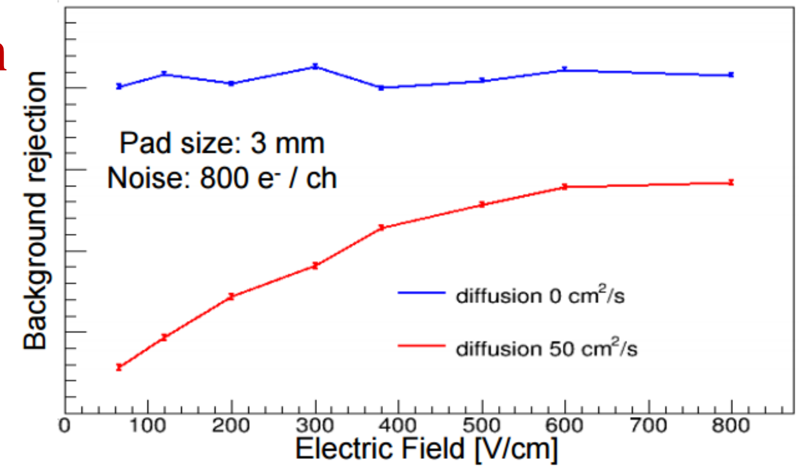
- Simulations plays an important role in detector design optimization and sensitivity prediction.
- A Geant4-based detector simulation software has been developed.

Simulation + radio-assay

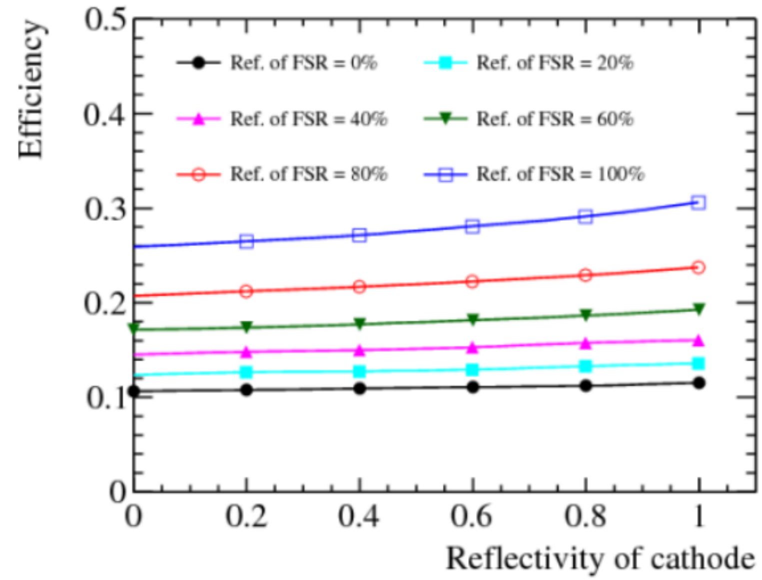
Background contributions in FWHM (2428-2488 keV) in inner 3-tonne region



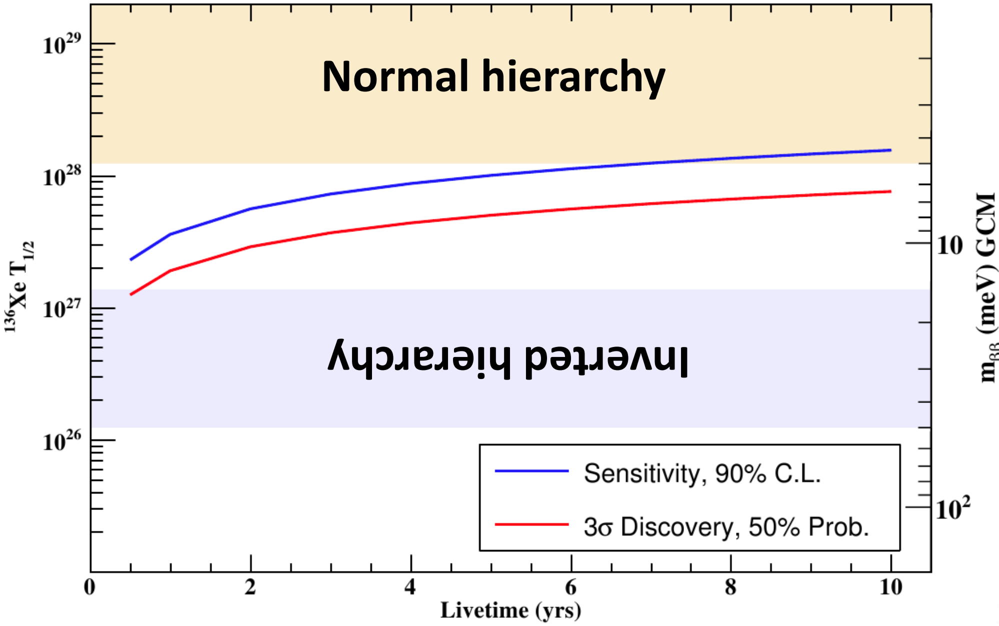
Drift field vs Background Rejection



Light Collection Efficiency vs Cathode and Field Rings Reflectivity



Summary

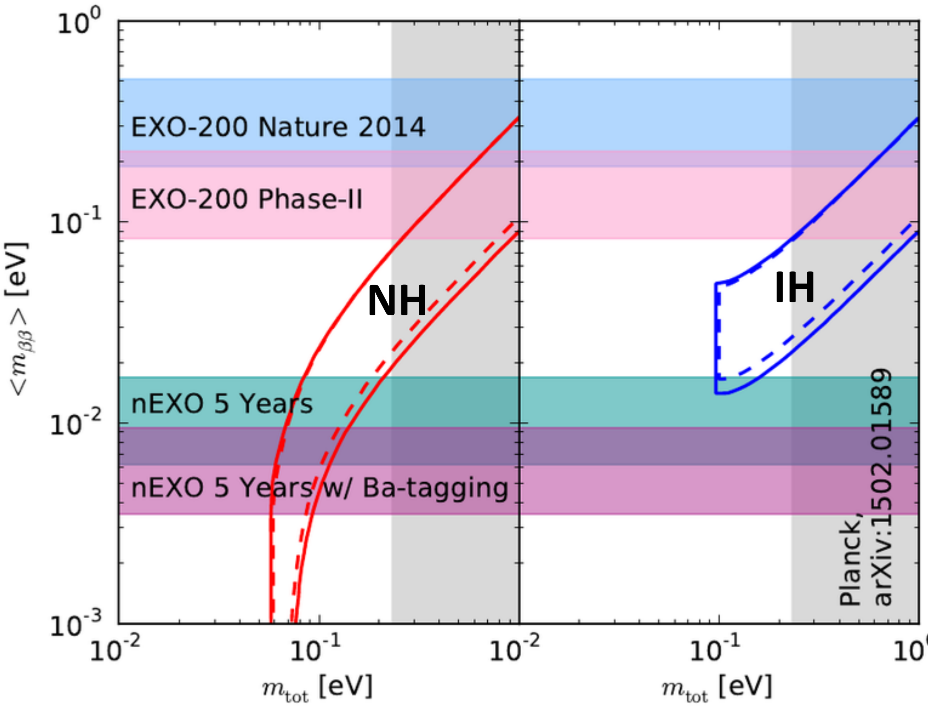


nEXO goal:

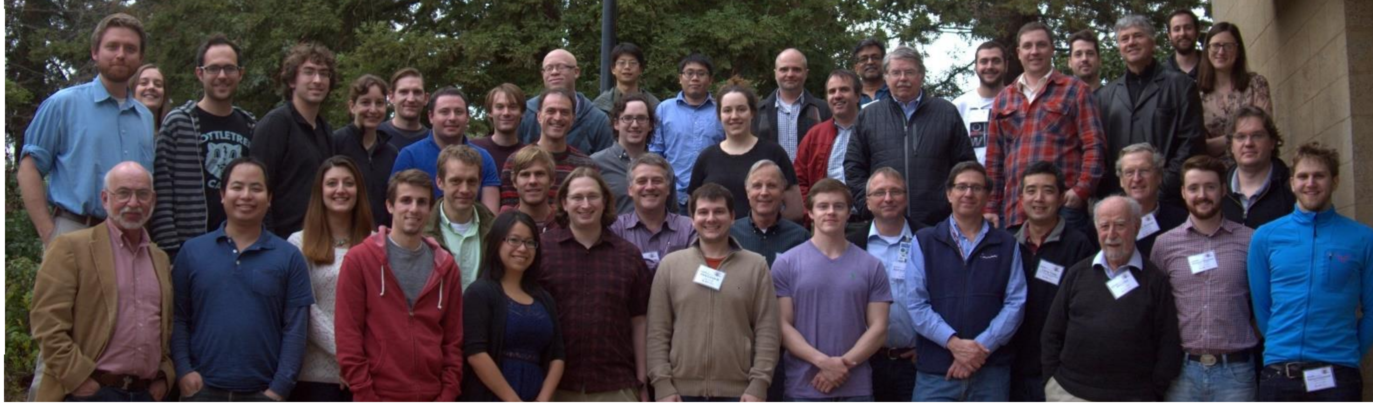
$T_{1/2}$ ($\beta\beta0\nu$ ^{136}Xe) > 10^{28} y at 90% C.L. at 5 years' exposure

With the best-case nuclear matrix element (GCM)

90% C.L. sensitivity for a range of matrix elements



Enriched Xenon Observatory
EXO
for double beta decay



The EXO-200 Collaboration

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Enriched Xenon Observatory

EXO

for double beta decay

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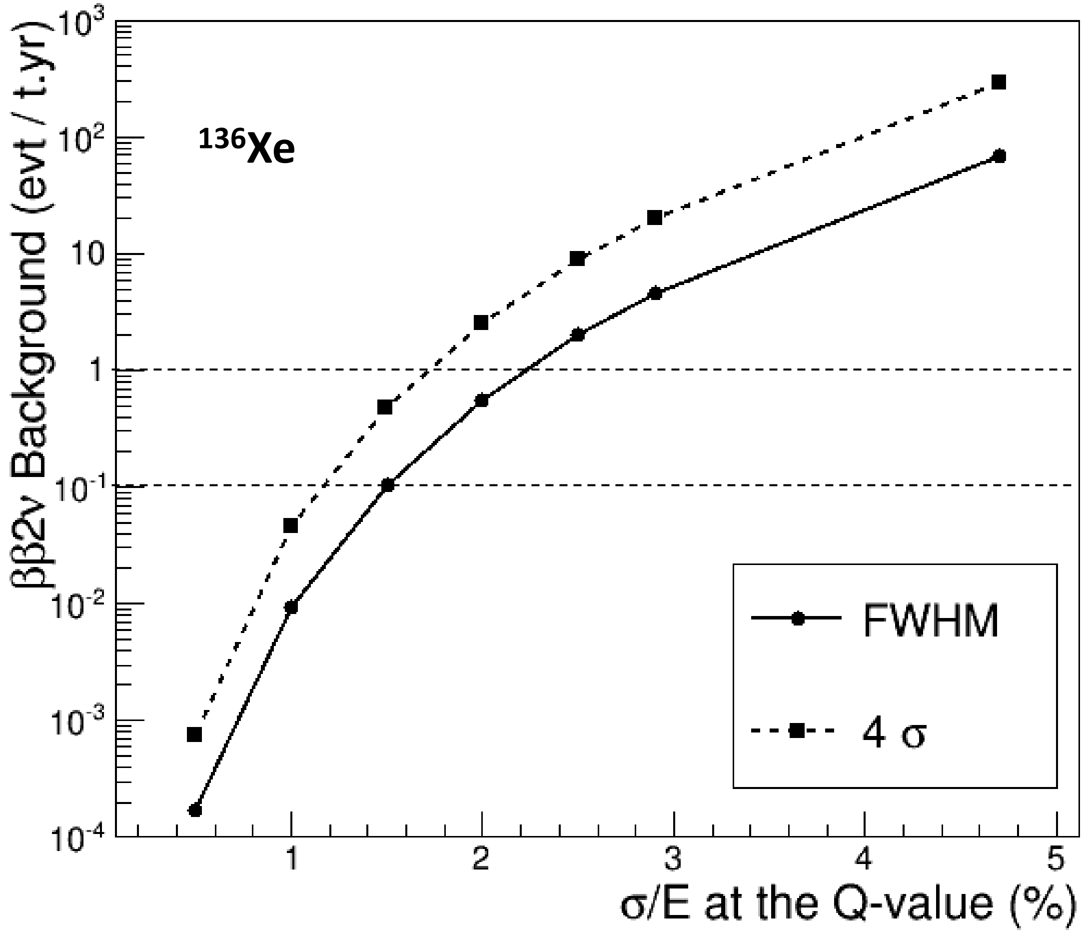
Backup slides



The 2νββ background is smallest for ^{136}Xe, as it has the longest 2νββ half-life.

- **While LXe TPCs provide many handles to discriminate backgrounds, energy resolution is the only handle to discriminate 2νββ background.**
- **Future very large scale detectors should have sufficient energy resolution to suppress the 2νββ mode.**

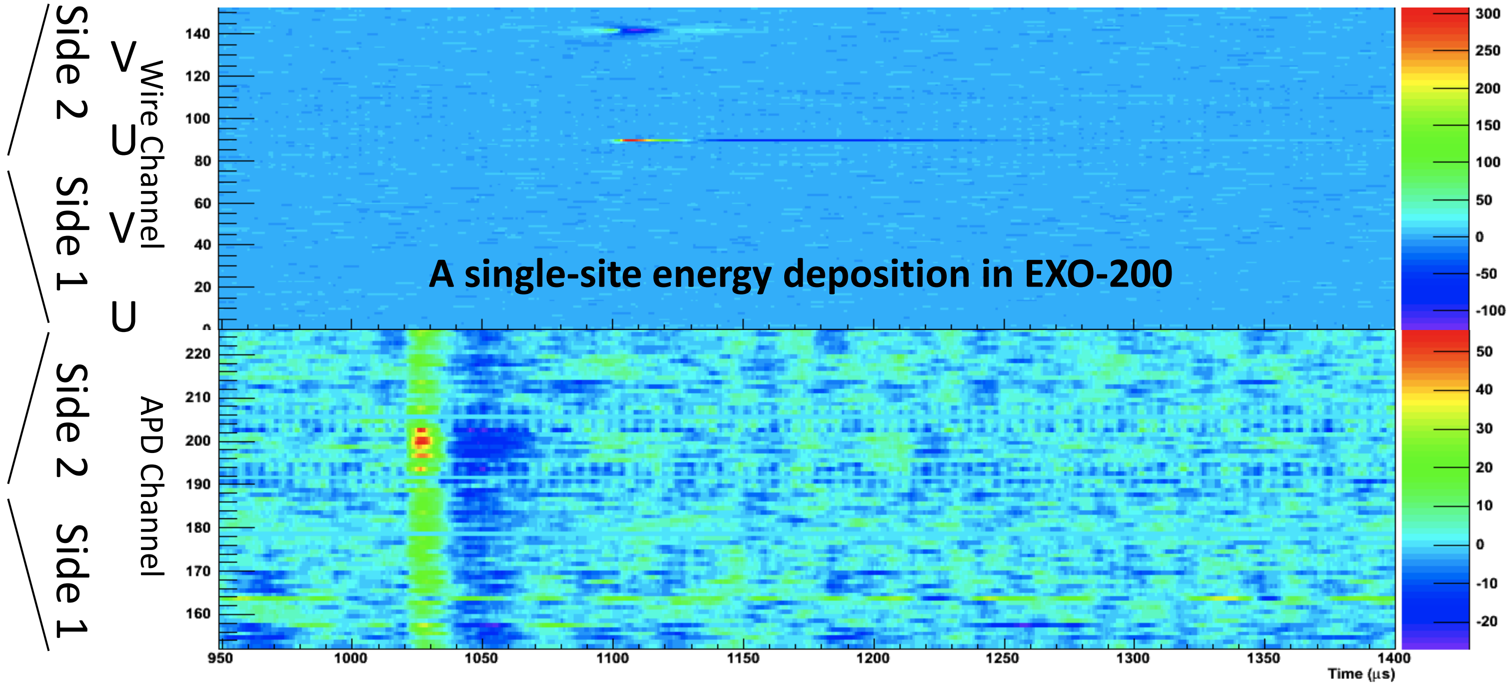
Events in EXO-200

Charge readout

V: Induction

U: Collection

Light readout



Charge readout

V: Induction

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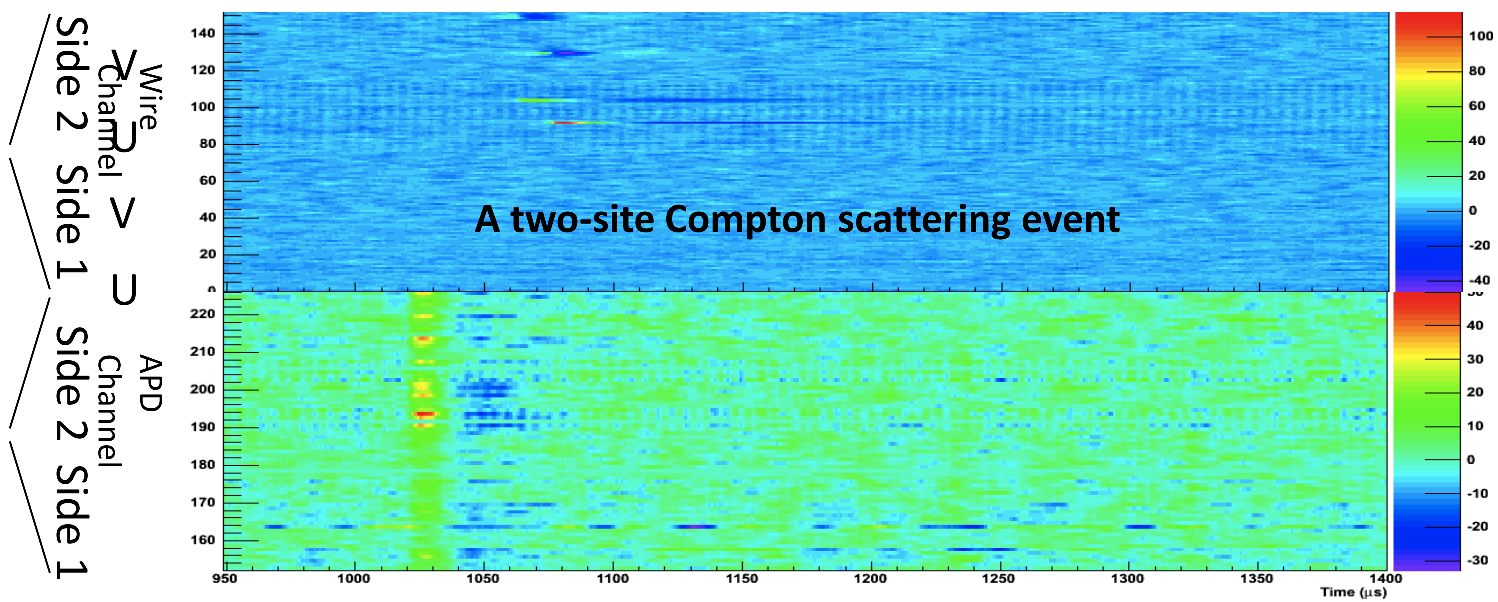
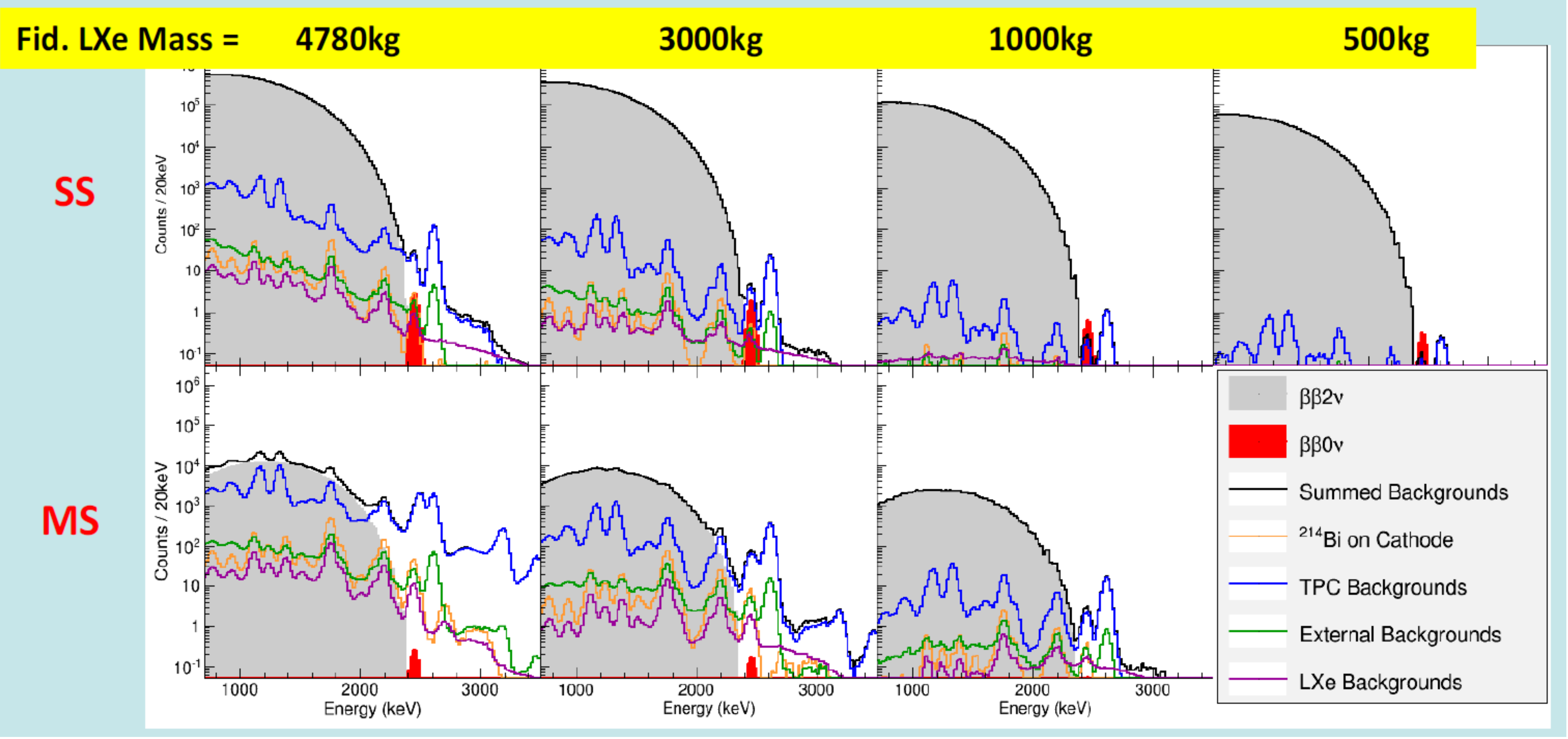
Light readout

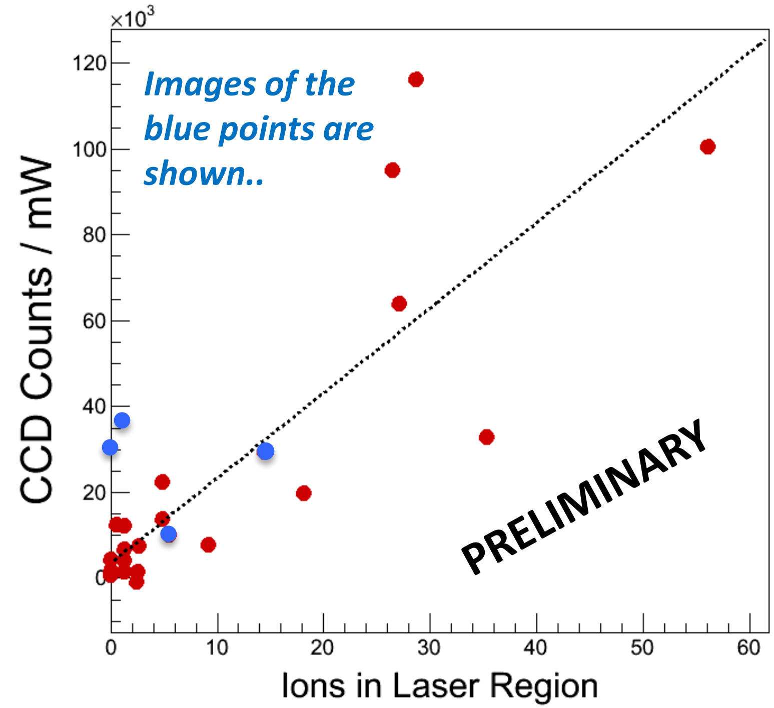


nEXO, 5 yr data, 0νββ @ $T_{1/2}$=6.6x10^{27} yr, projected backgrounds from subsets of the total volume

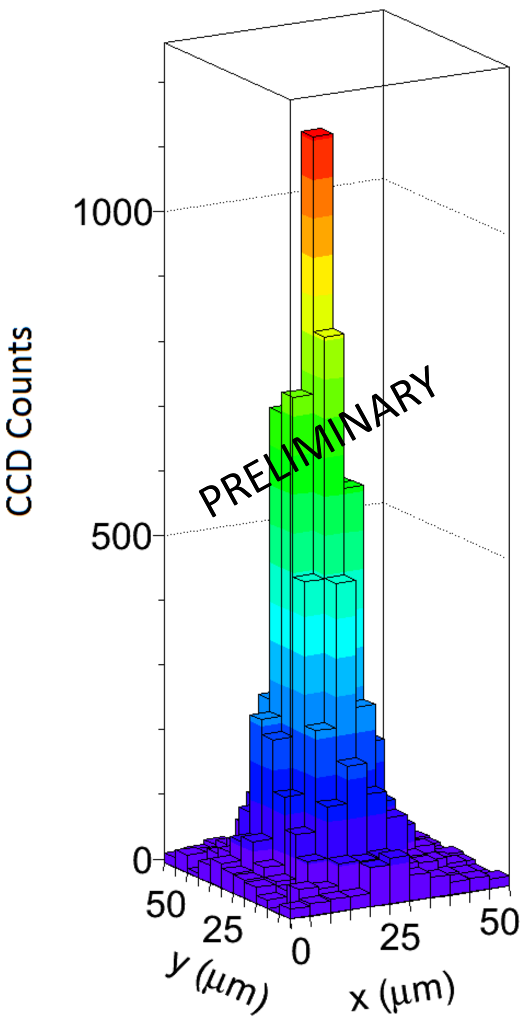


Ba-tagging

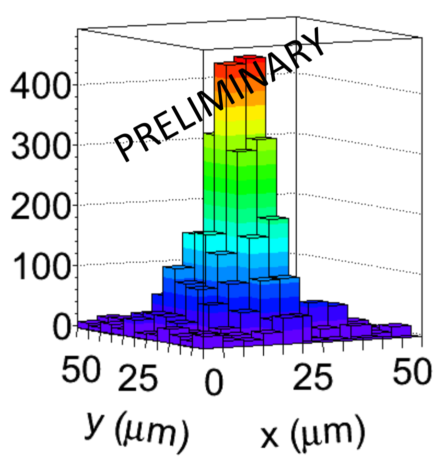
$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^{-} + 2\bar{\nu}_e$$



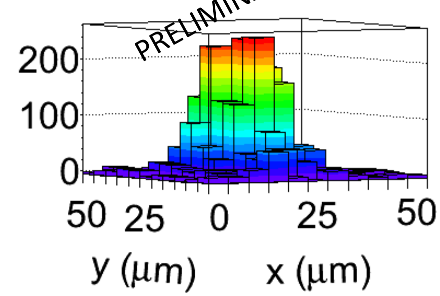
≤ 27 atoms



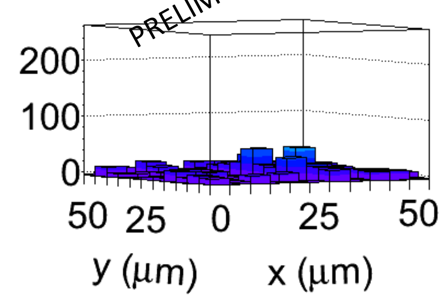
≤ 9 atoms



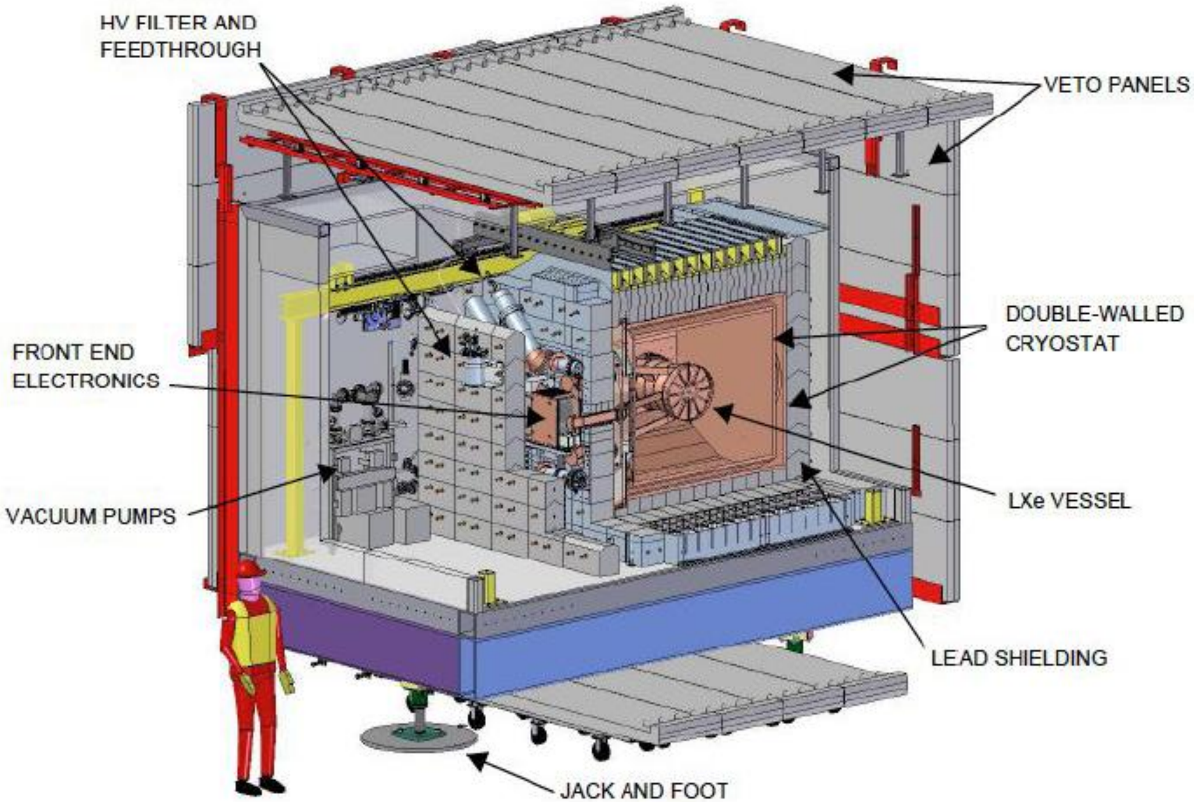
≤ 2.4 atoms



0 atoms



The EXO-200 detector



- 200kg of Xe enriched to 80.6% Xe-136 and 175kg LXe inside TPC
- Located at 1585 m.w.e. in the Waste Isolation Plant near Carlsbad, NM
  - ✓ – Muon rate is ~ 10^{-7} Hz /cm2 /sr
  - ✓ – Salt has inherently lower levels of U/Th, compared to rock
- EXO-200 start data taking in June 2011, and stopped on Feb. 5, 2014 due to WIPP incidents –-- Phase I data.
- April 2016, phase II data taking begins.