Enriched Xenon Observatory

EXO

for double beta decay

Status and Prospects for the EXO-200 and nEXO Experiments

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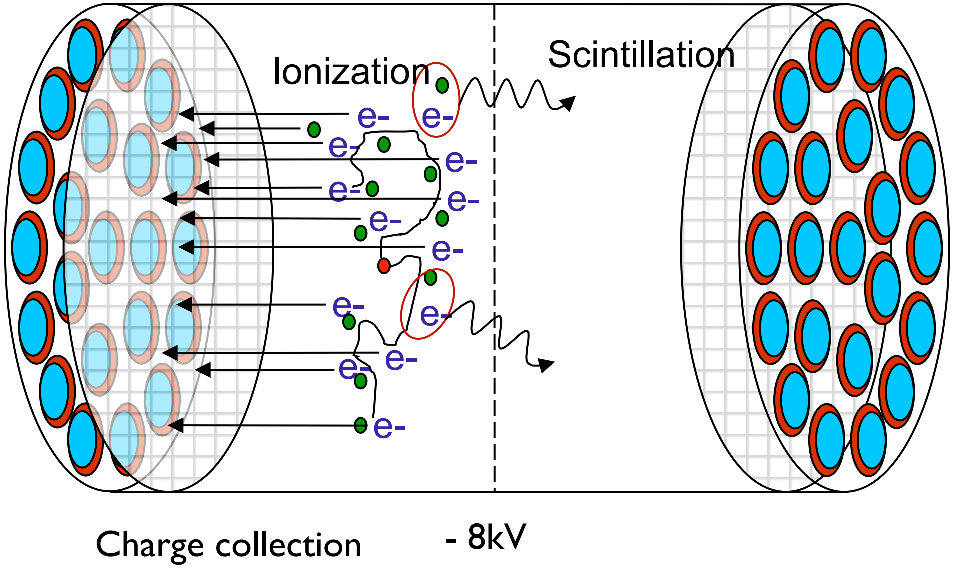
On behalf of the EXO-200 and nEXO Collaborations

Neutrino'16, Imperial College, London

July 8, 2016

Use Liquid Xenon Time Projection Chambers (TPC) to Search for 0νββ Decay

- Xe is used both as the source and detection medium.
- Simultaneous collection of both ionization and scintillation signals.
- Full 3-D reconstruction of all energy depositions in LXe.
- Monolithic detector structure, excellent background rejection capabilities.

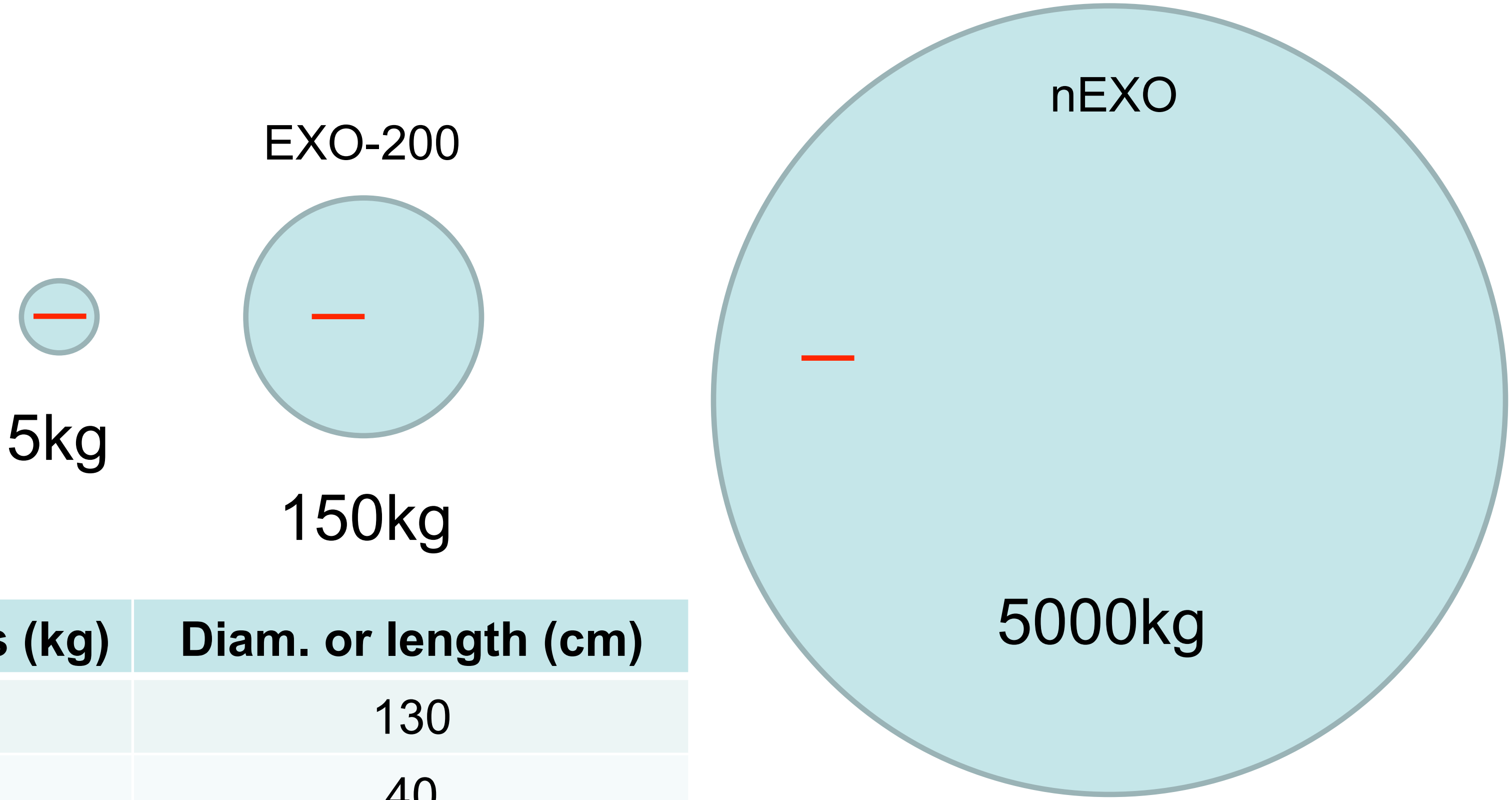


Example of TPC schematics (EXO-200)

EXO-200 is a running LXe detector with ~110 kg active volume. It has demonstrated key performance parameters for 0νββ search, and can reach 0νββ half-life sensitivity of 5.7 x10^{25} yrs after Phase-II operation.

nEXO is a proposed ~ 5 tonne detector. Its design will be optimized to take full advantage of the LXe TPC concept and can reach 0νββ half-life sensitivity of ~ 10^{28} yrs

Monolithic Detectors



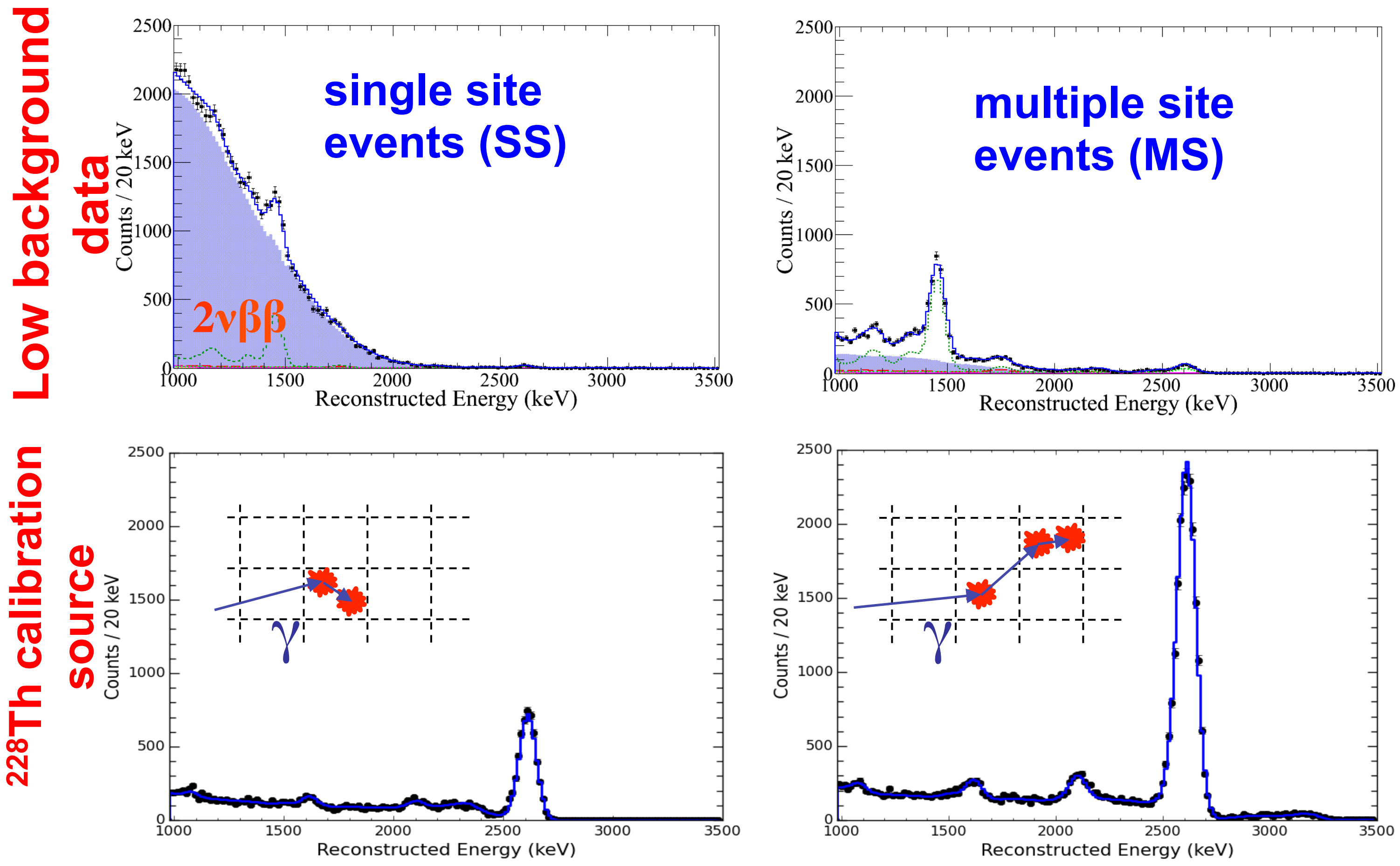
LXe mass (kg)	Diam. or length (cm)
5000	130
150	40
5	13

2.5MeV gamma ray attenuation length 8.5 cm = —

Monolithic detector is essential for background rejection:

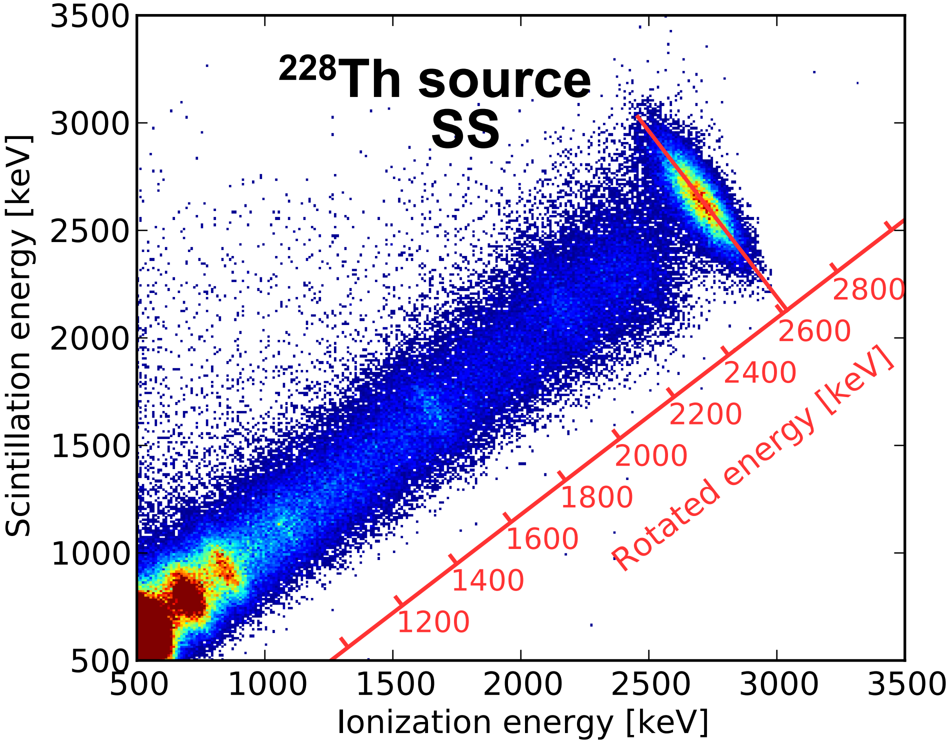
- **Rejection of surface background**
- **Self-shielding, containment of Compton scattering**
- **Inner fiducial volume extremely clean**

Topological Event Information



- **TPC allows the rejection of gamma backgrounds because Compton scattering results in multiple energy deposits.**
- **SS/MS discrimination is a powerful tool not only for background rejection, but also for signal discovery.**

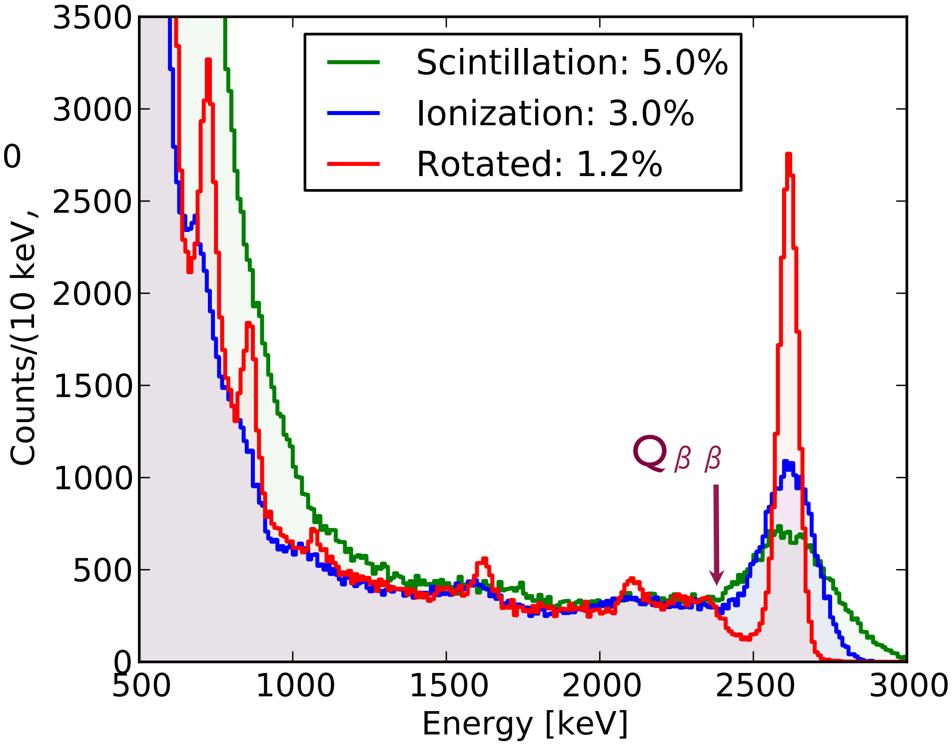
Detector Energy Resolution



Combining Ionization and Scintillation energy to enhance energy resolution

Anticorrelation between scintillation and ionization in LXe known since early EXO R&D

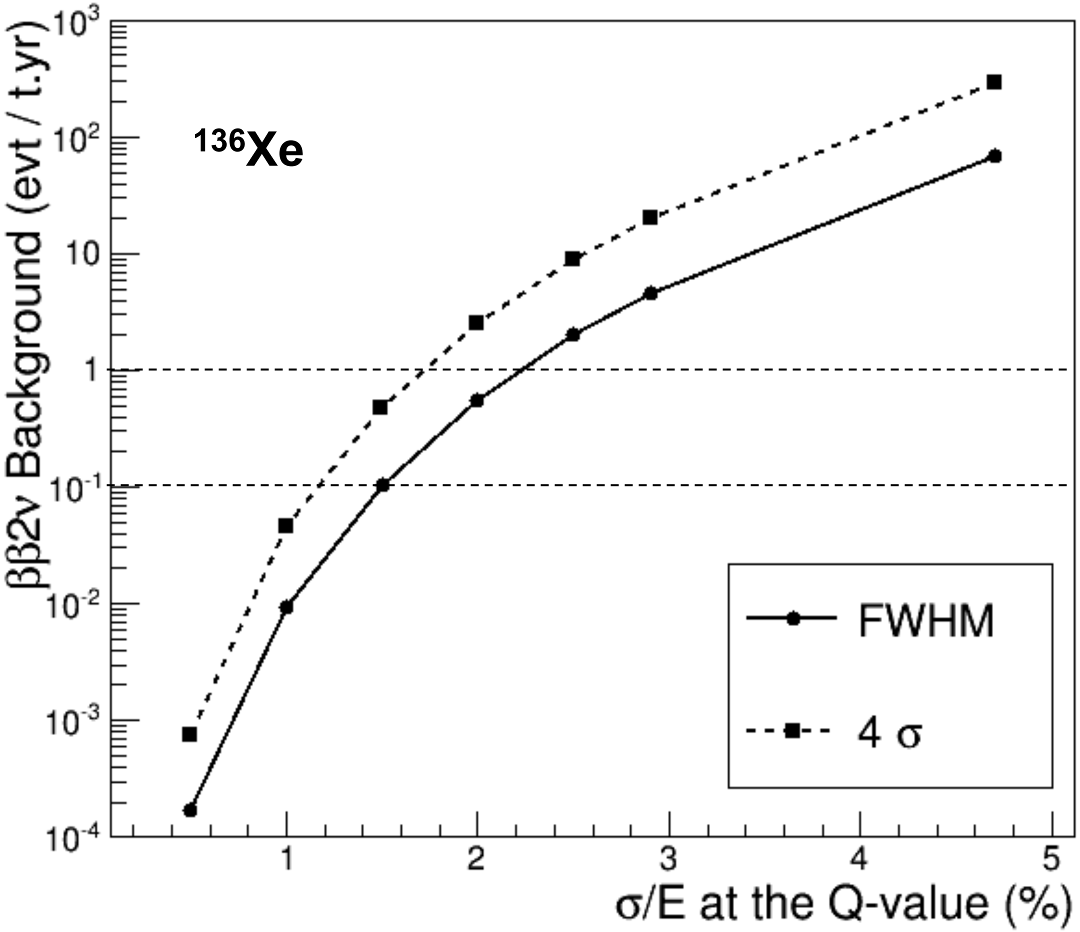
(E.Conti et al. Phys Rev B 68 (2003) 054201)



EXO-200 has achieved ~ 1.25% energy resolution at the Q value.

nEXO will reach resolution < 1%, sufficient to suppress background from 2νββ.

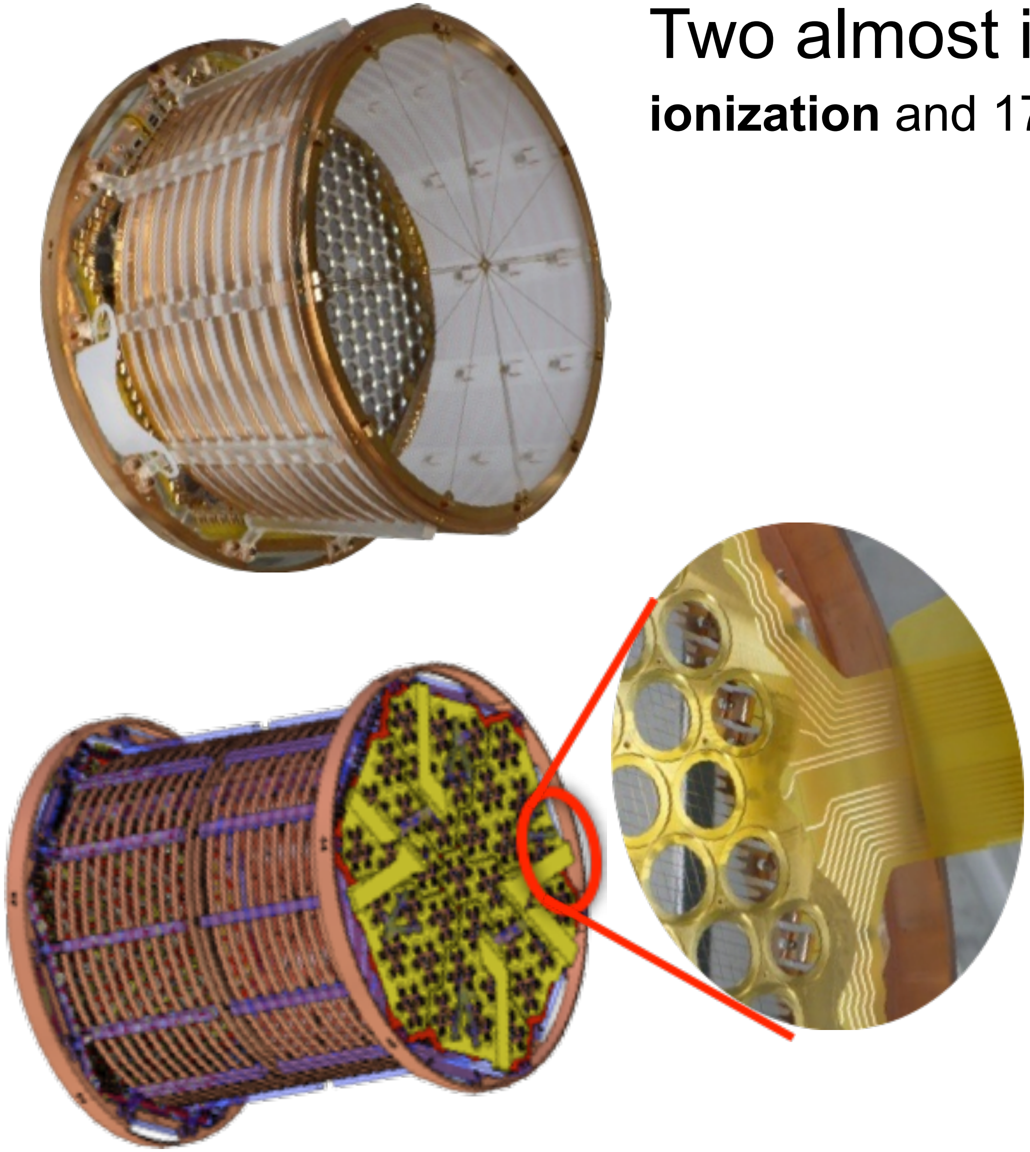
Energy Resolution and 2νββ Background



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.**

The EXO-200 TPC



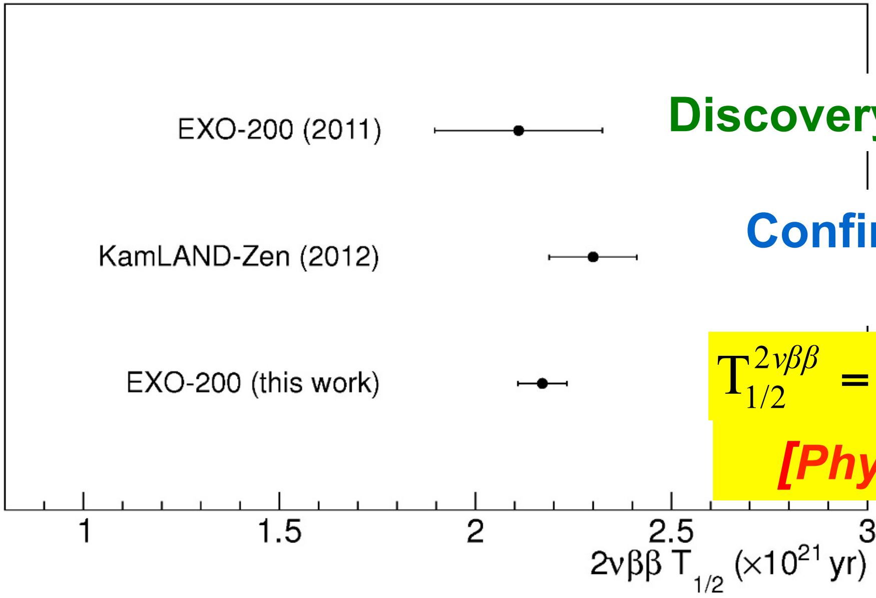
Two almost identical halves reading

ionization and 178 nm **scintillation**, each with:

- 38 U triplet wire channels (charge)
- 38 V triplet wire channels, crossed at 60° (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)
- Drift field 376 V/cm
- TPC housed in a copper vessel with 1.37 mm wall thickness

EXO-200 Phase-I Results

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)]*

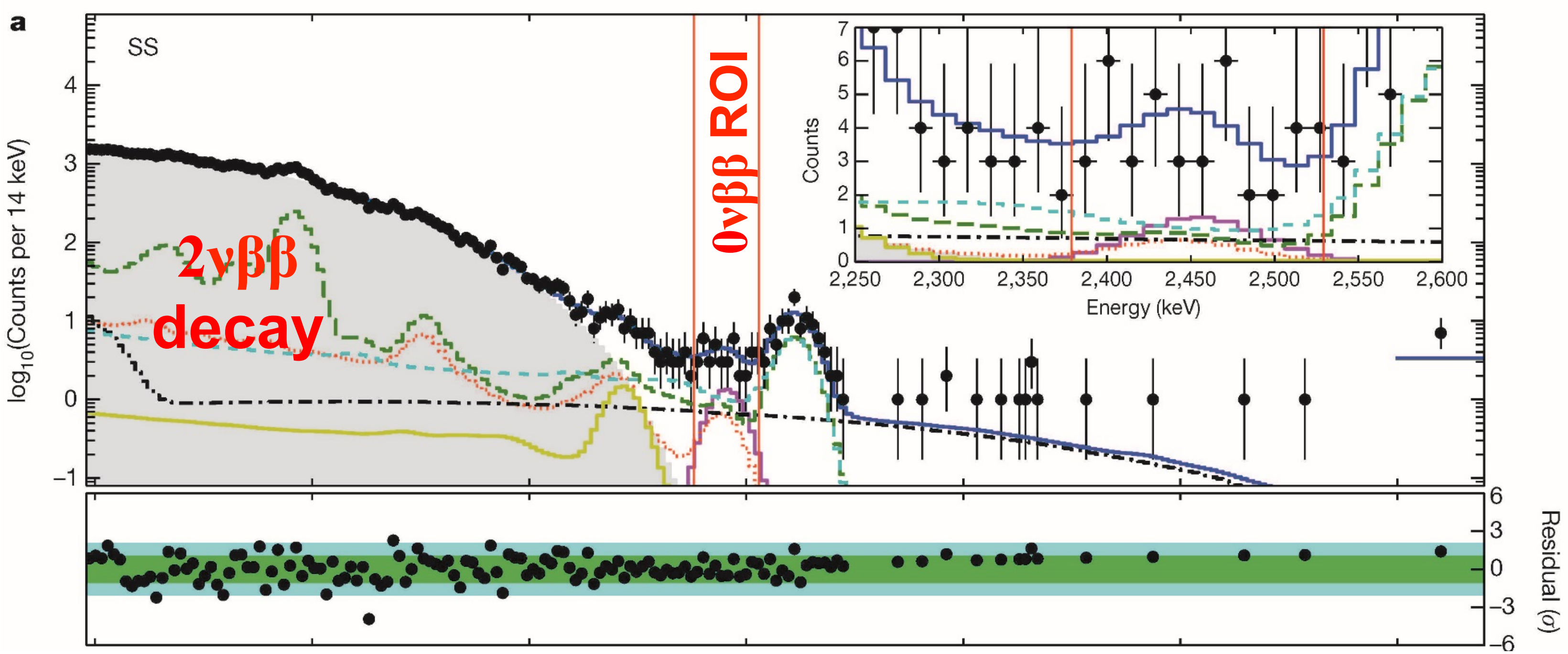
$$T_{1/2}^{2\nu\beta\beta} = \left(2.165 \pm 0.016^{\mathrm{stat}} \pm 0.059^{\mathrm{syst}}\right) \cdot 10^{21}\ \mathrm{yr}$$

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

Longest and most precisely measured 2νββ half-life

EXO-200 Phase-I Results

^{136}Xe $0\nu\beta\beta$ search with100 kg·yr exposure



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

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

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

Recovery from Underground Incidents


DOE Accident Inv. Rep., Mar 2014

WIPP Events:

- 5 Feb. 2014 - Fire in WIPP underground
- 14 Feb. 2014, ~23:00 – Unrelated airborne radiological event

Recovery:

- 18 Feb 2014, remote recovery of enriched xenon
- Sept. 2014 – June 2015, drift and clean room cleanup and TPC health diagnostics (no measureable radioactive contamination inside or outside the cleanrooms.
- June – Oct. 2015, equipment repair and Infrastructure maintenance

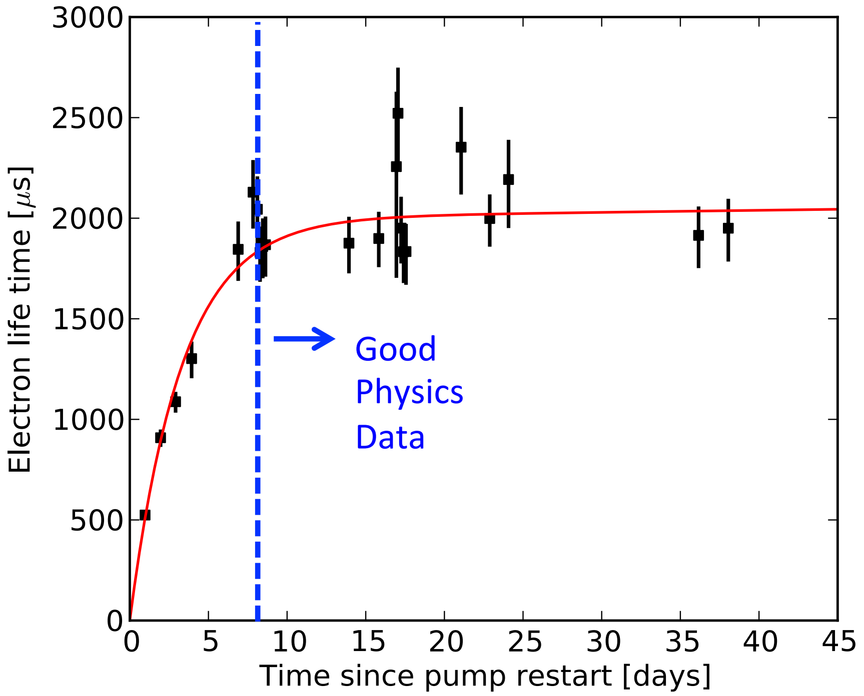
(EXO-200 detector and control systems worked well despite trying circumstances.)

Phase-II Restart:

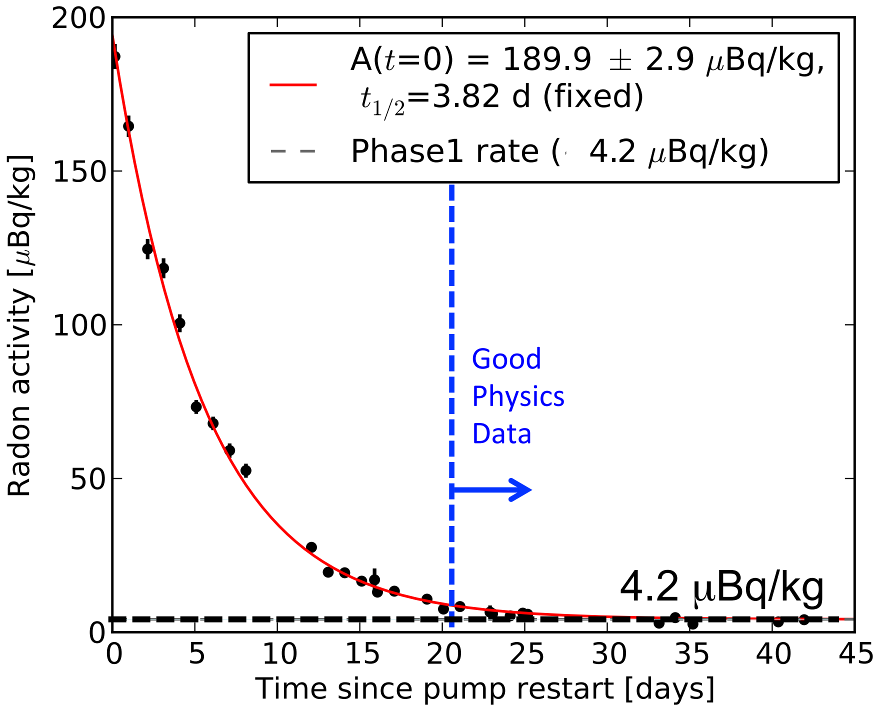
- Oct. 2015 – Jan. 2016, system cooldown, gas purification and liquid xenon filling
- Feb. – April 2016, detector upgrades (electronics and derandonator)
- April 2016, Phase-II Physics data taking begins

EXO-200 Phase-II Operation

- EXO-200 Phase-II operation begins on 1/31/2016, after enriched liquid xenon fill.
- Data shows that the detector reached excellent xenon purity and ultra-low internal Rn level shortly after restart.

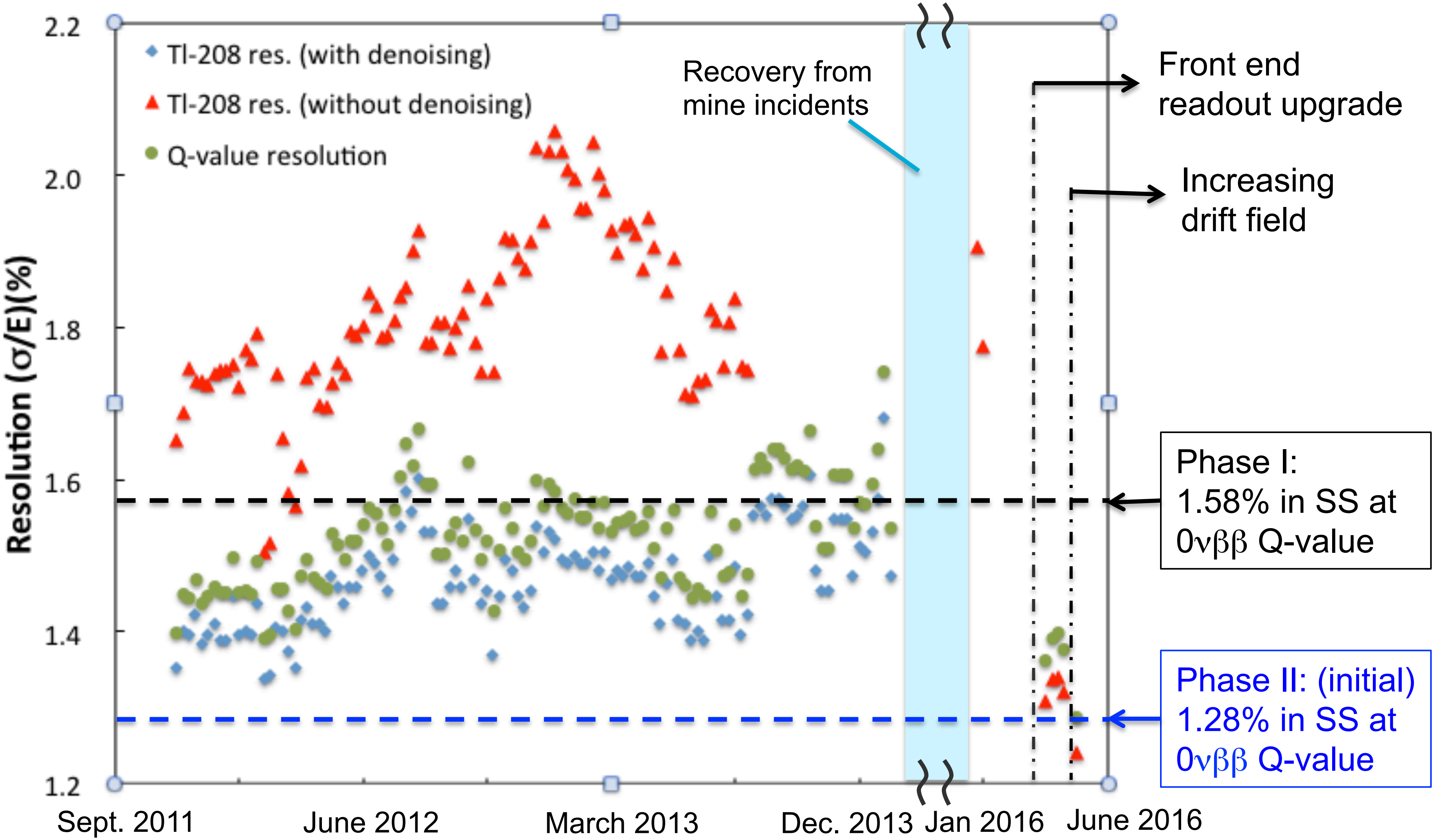


Xenon purity since Jan. 31, 2016



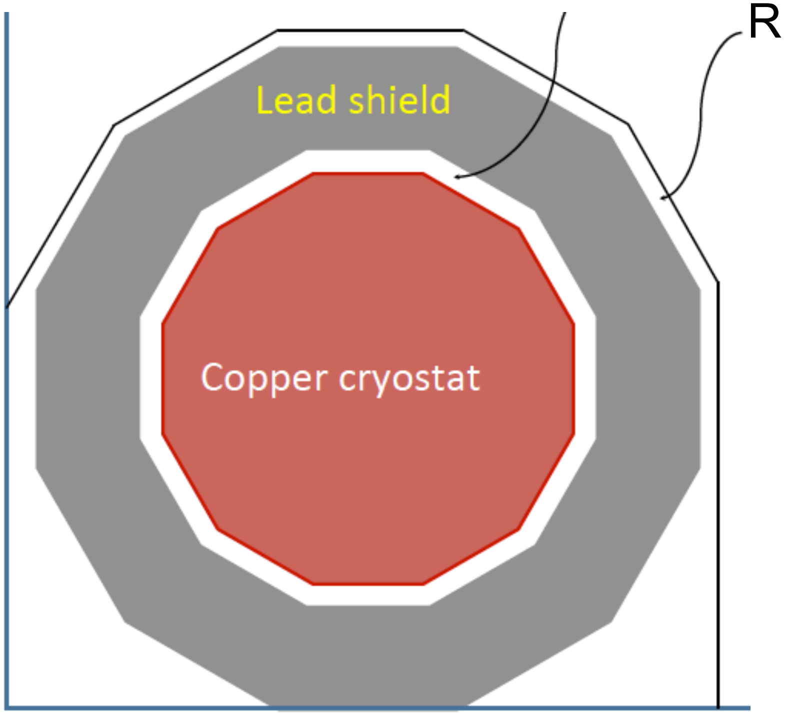
Rn level in TPC since Jan. 31, 2016

EXO-200 Phase II Upgrade Performance (Front End Readout Upgrade)



Further improvements in detector energy resolution may be possible with better signal reconstruction and detector non-uniformity corrections.

EXO-200 Phase II Upgrade Performance (Deradonator)



Air gap (need low Rn)

Rn tent

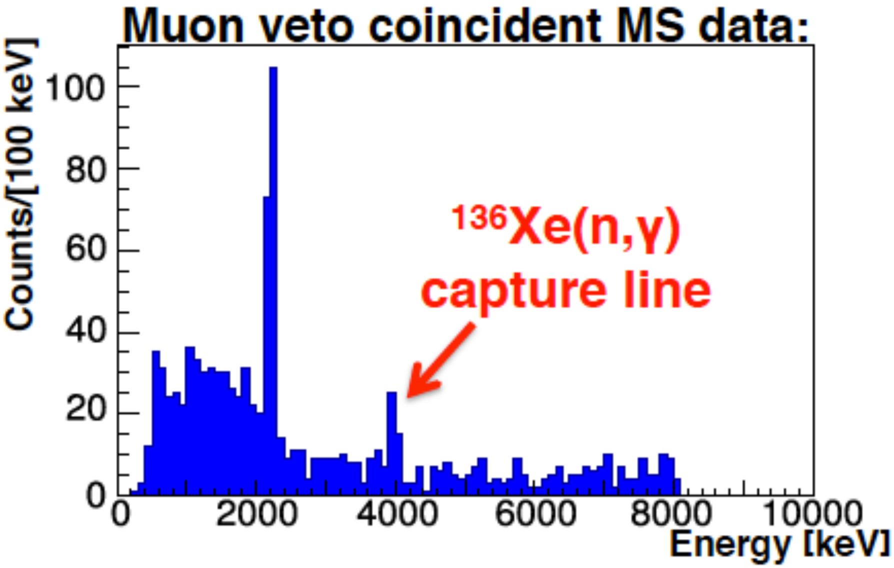
EXO-200 Clean Room Module 1

Deradnator can deliver 0.85 m^3/min of low Rn air

Measurements show that the Rn level in the air gap has been reduced by a factor ~ 10, sufficient to suppress this background for $0\nu\beta\beta$ search.

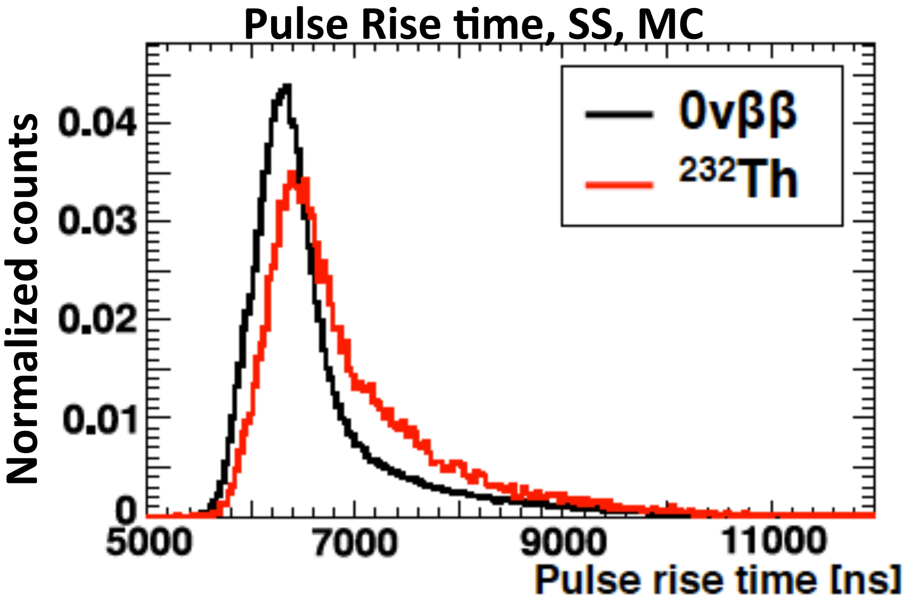
Phase-II Analysis Improvements

Xe-137 Veto



Tagging neutron capture events using both veto panel and prompt gamma information can suppress ^{137}Xe background.

Improved SS/MS discriminators



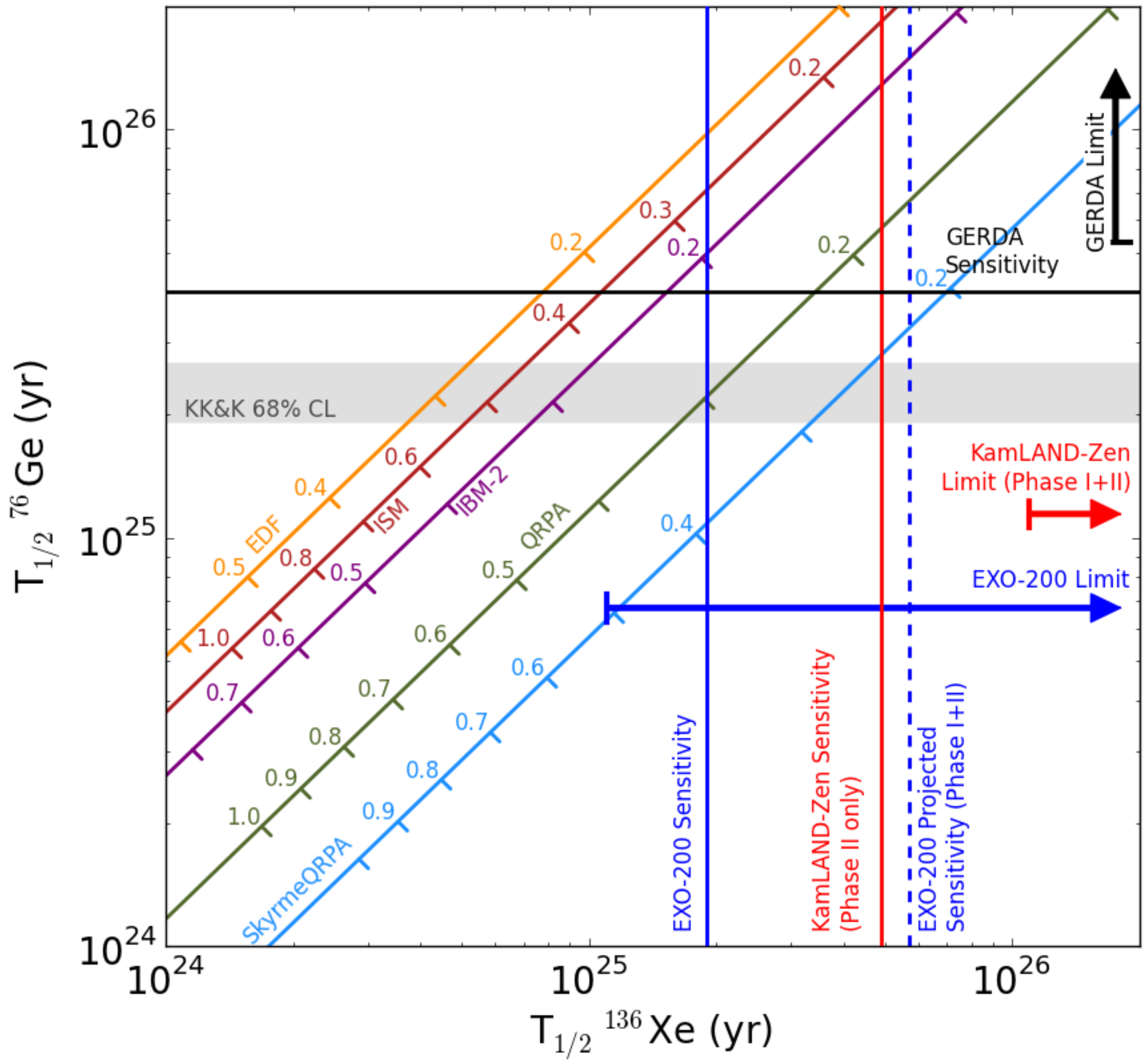
Discriminating gamma/beta events using the pulse rise time can suppress U and Th background.

Many other analysis techniques under study:

- Enhance energy resolution through corrections of spatial and temporal non-uniformity
- Reduce systematics through detector simulation and calibration
- Implement continuous multiplicity metrics to improve event classification
- Develop multivariate discriminators and other machine learning algorithms

EXO-200 Phase II Sensitivity

P4.055 Status and improved detector performance of EXO-200, Y. Lin



EXO-200 can reach $0\nu\beta\beta$ half-life sensitivity of 5.7x10^{25} ys.

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

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

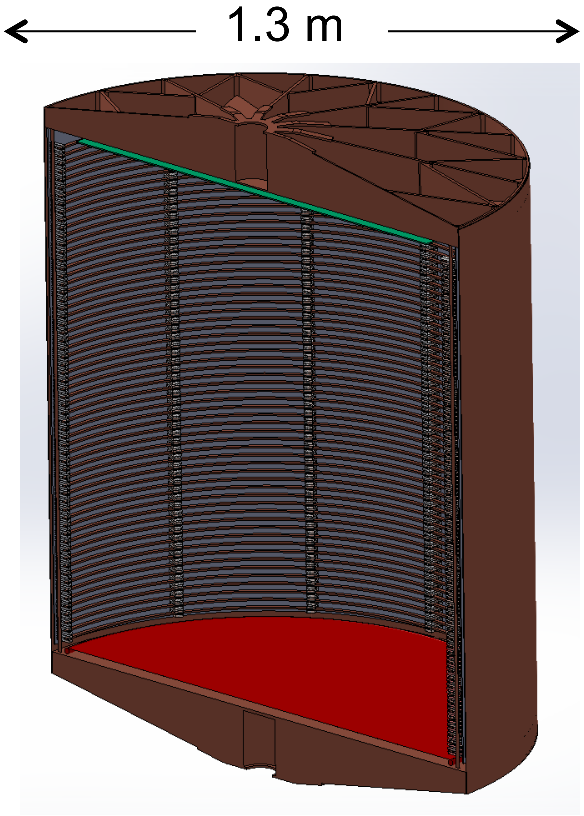
GERDA Phase 2:
Public released result. June, 2016
(frequentist limit)

KamLAND-Zen:
arXiv:1605.02889 (2016)

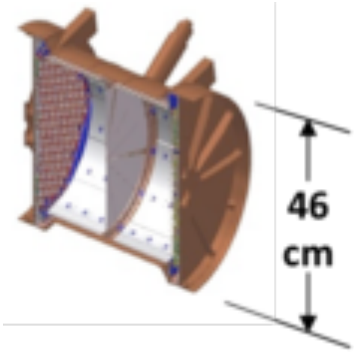
From EXO-200 to nEXO

- EXO-200 has surpassed design energy resolution and SS/MS rejection capability, and is expected to suppassed the design background goals.
- nEXO is a ~ 5 tonne LXe TPC with better detector performance
- 4.7 tonnes of active ^{enr}Xe (90% or higher), < 1.0% (σ/E) energy resolution.

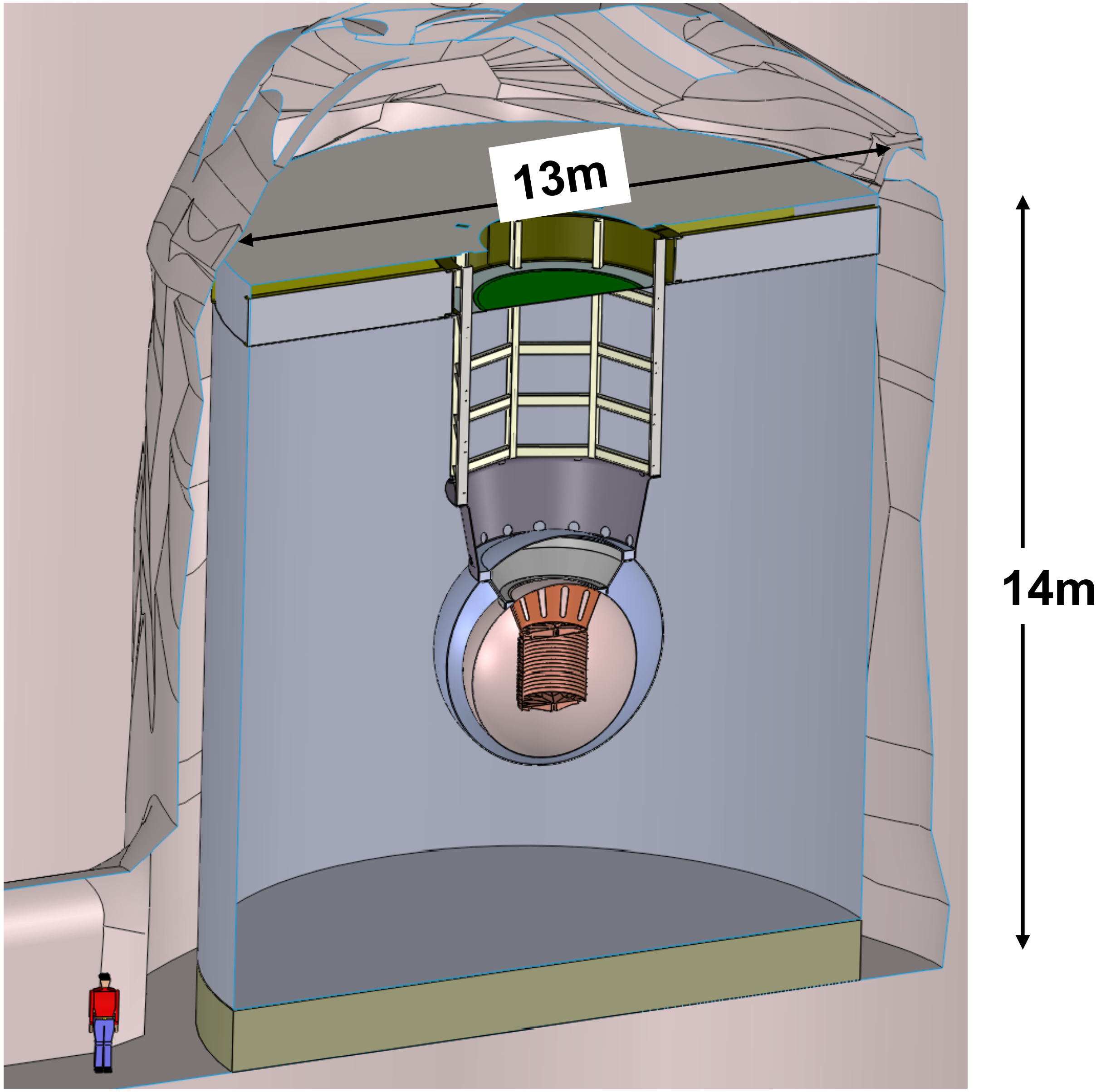
nEXO Detector



EXO-200 Detector

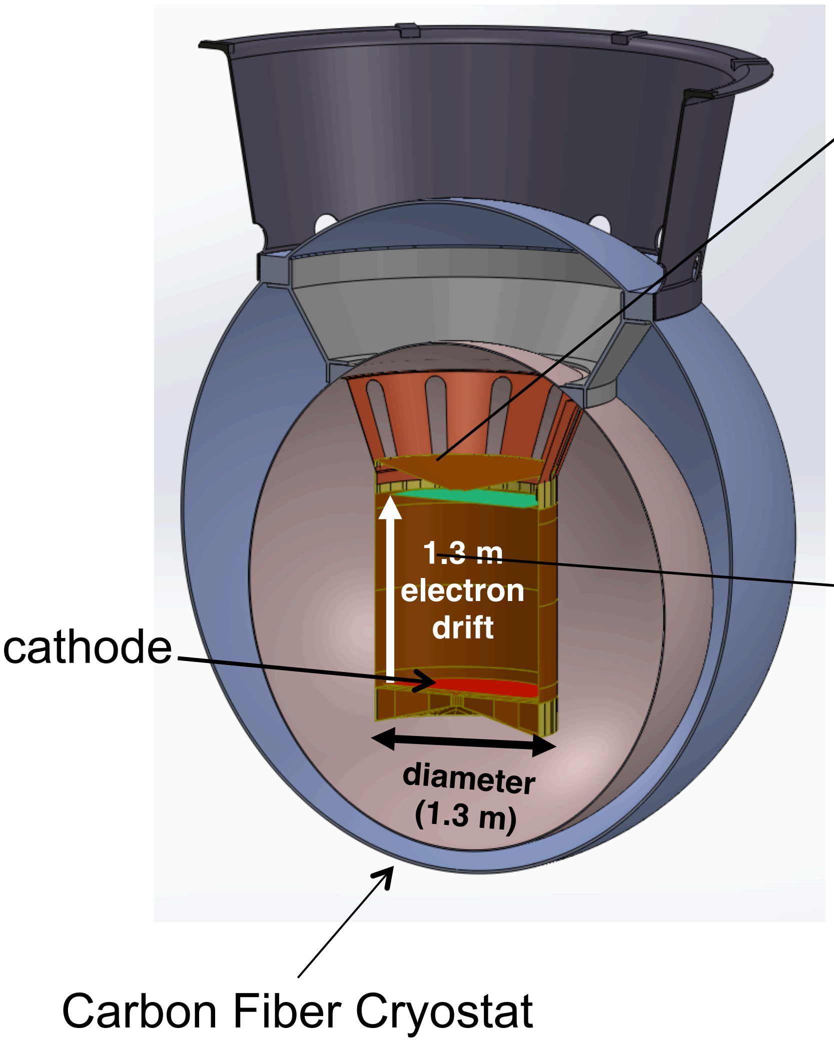


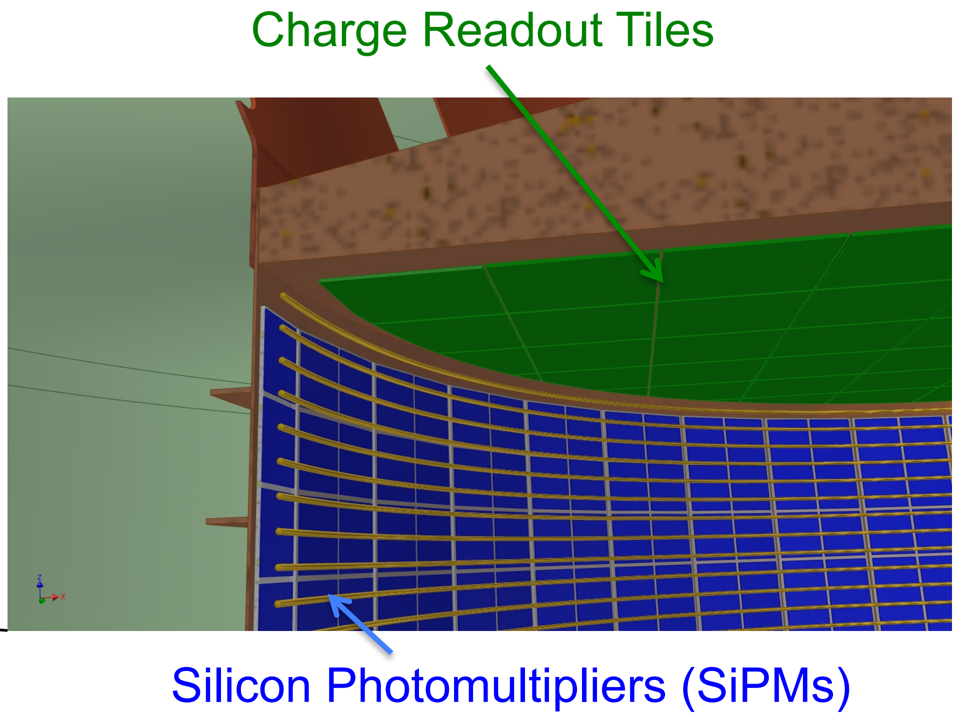
Preliminary artist view of nEXO in the SNOlab Cryopit



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

nEXO TPC Conceptual Design (artist's view)

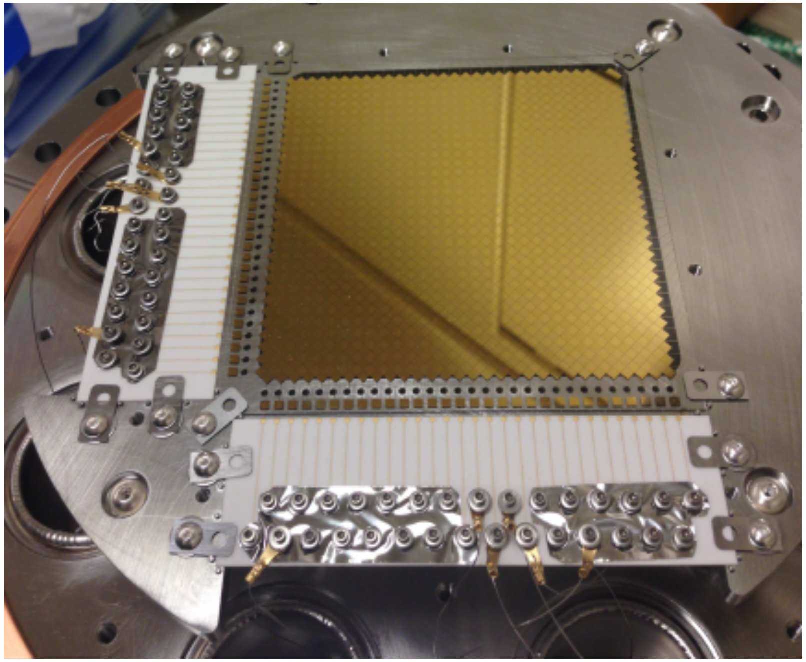




Baseline concept: (Improved TPC design).

- Single drift volume
- Charge collection on the anode plane
- Light collection on the barrel behind field shaping rings

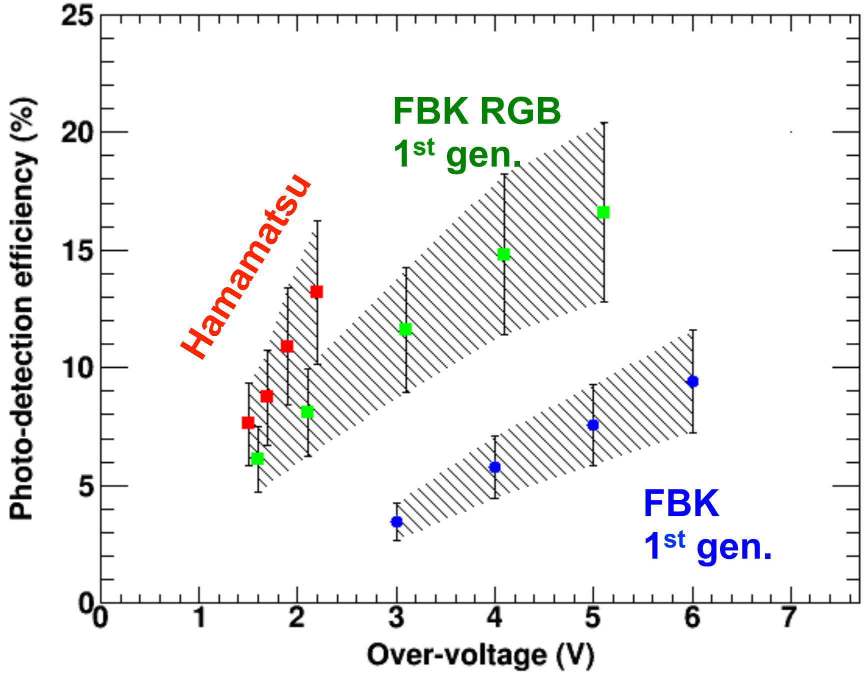
Prototype Charge Readout Tile



A modular and pad-like charge collection scheme is under study to replace a more traditional wire readout.

Prototype 3mm pitch, crossed strip quartz tile has been produced and tested in liquid xenon.

VUV sensitive SiPMs

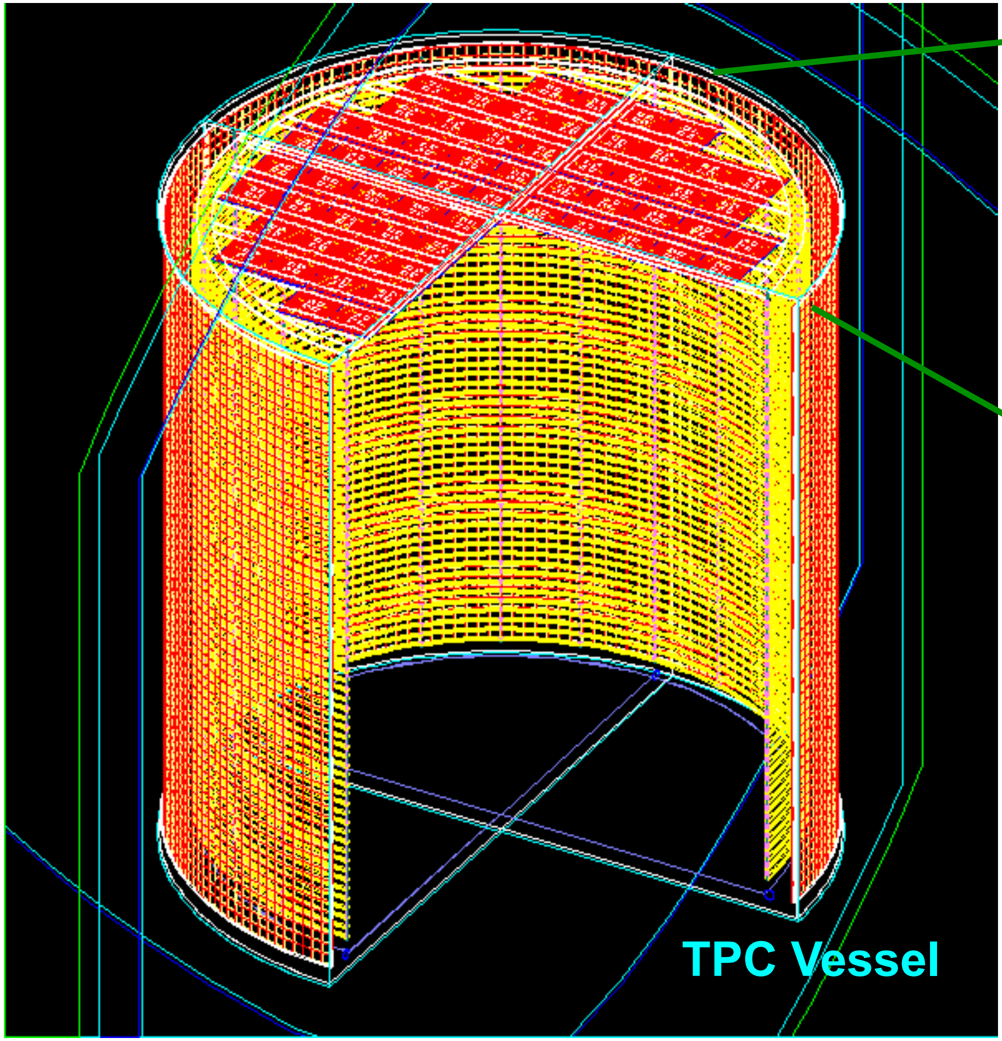


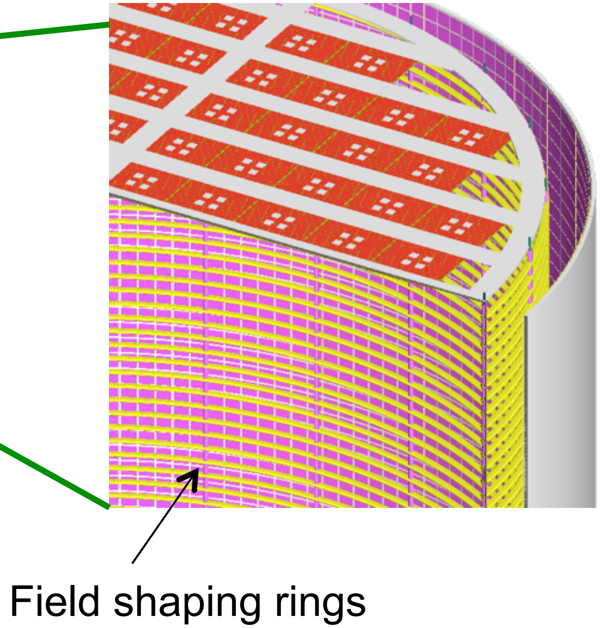
Adapted from I.Ostrovskiy et al. IEEE TNS 62 (2015) 1.

First nEXO-specific run at FBK (Italy) provided ~10% PDE. New generation devices have reached PDE > 15%@ 170nm. Radio assay results of the FBK devices are also very encouraging.

P1.069 Photon detection for nEXO
F. Retiere

nEXO Radio-assay and Detector Simulation





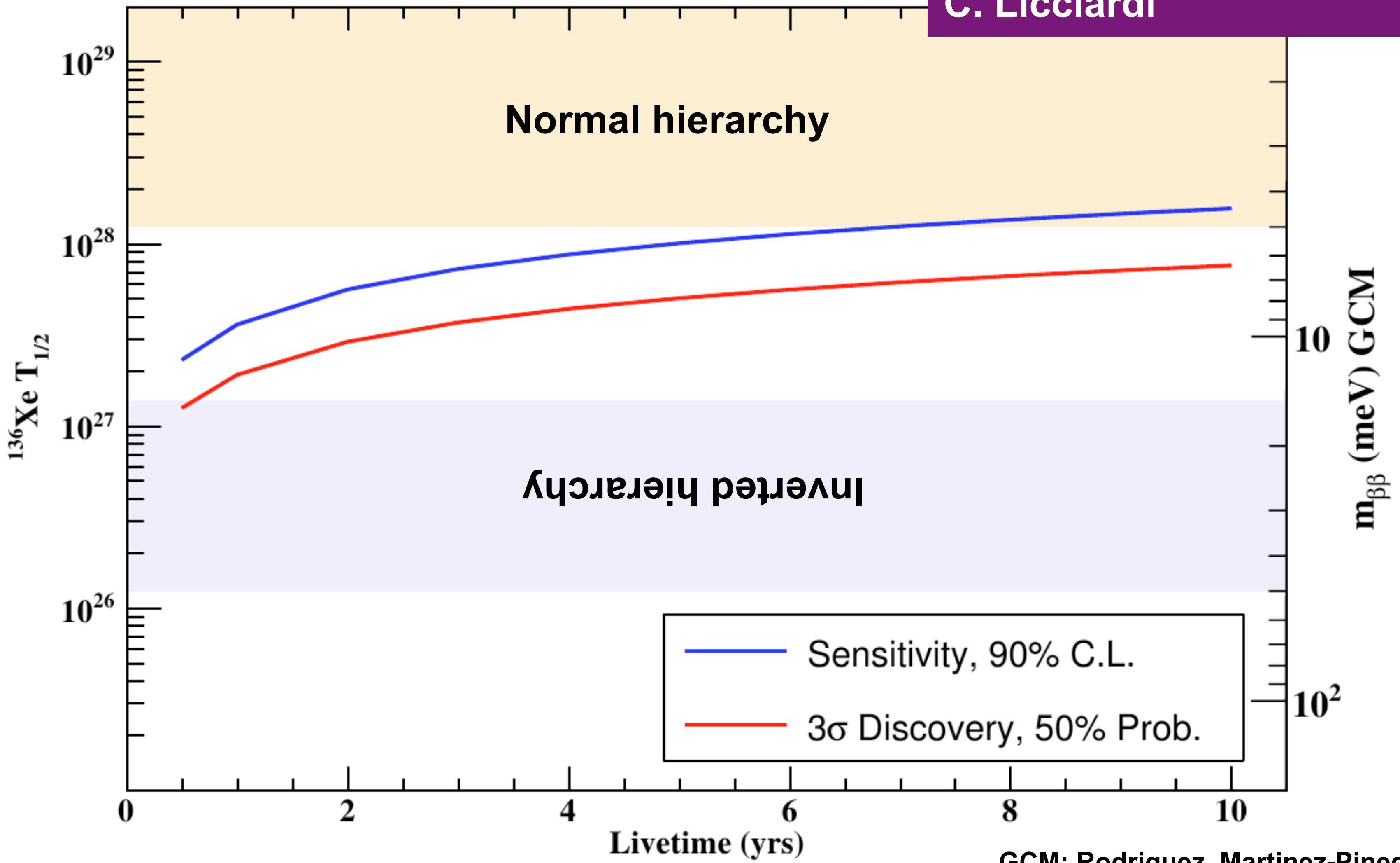
P1.067 nEXO Radio Assay Program, H. Tsang

P4.063 Informing nEXO R&D through simulations, S. Sangiorgio

Recent substantial progress in radio-assay and simulation assists the detector design optimization and provides more accurate predictions of $0\nu\beta\beta$ sensitivity.

nEXO Sensitivity

P4.056 The sensitivity of the nEXO experiment to majorana neutrinos
C. Licciardi



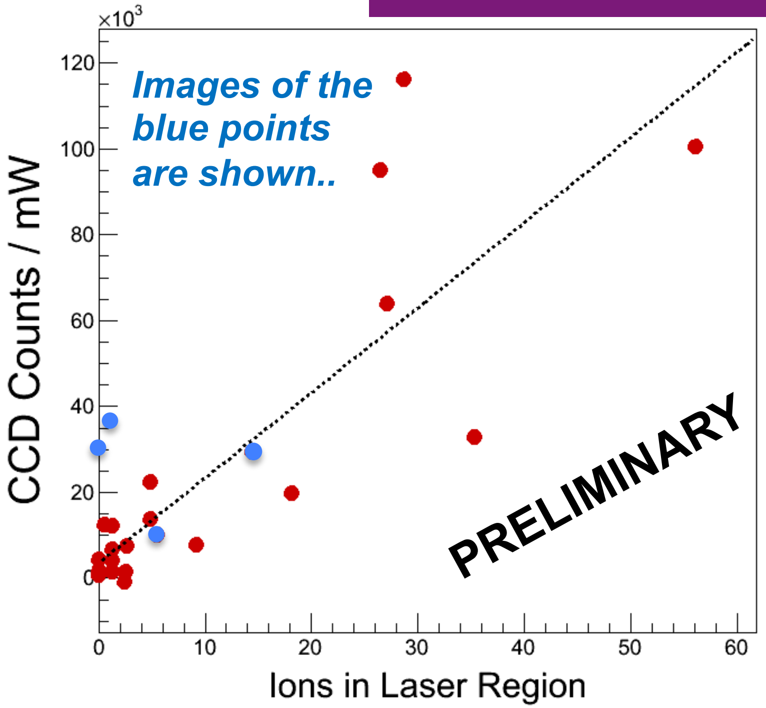
nEXO sensitivity as a function of time for the best-case nuclear matrix element (GCM).

GCM: Rodriguez, Martinez-Pinedo, Phys. Rev. Lett. 105 (2010) 252503

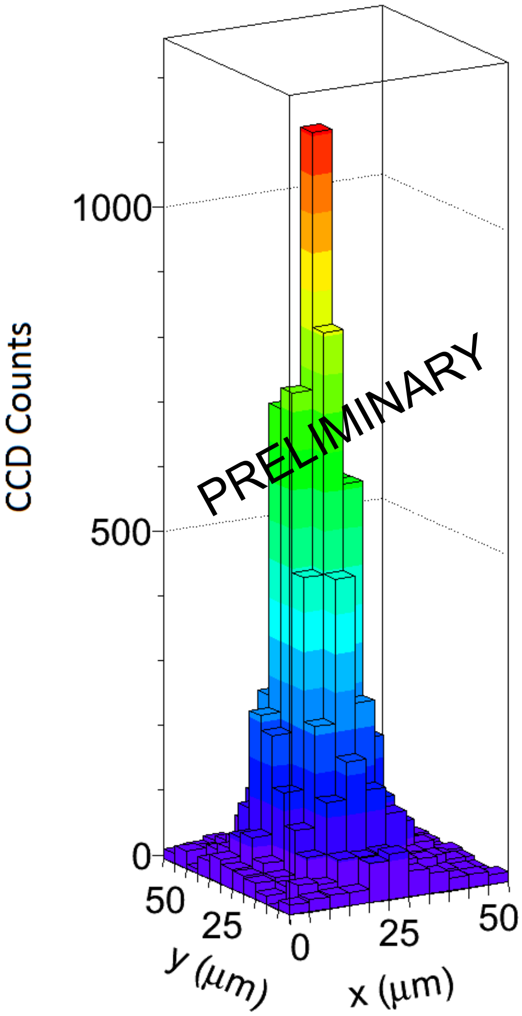
Tagging ββ decay daughter Ba

P1.068 Ba-tagging
T. Brunner

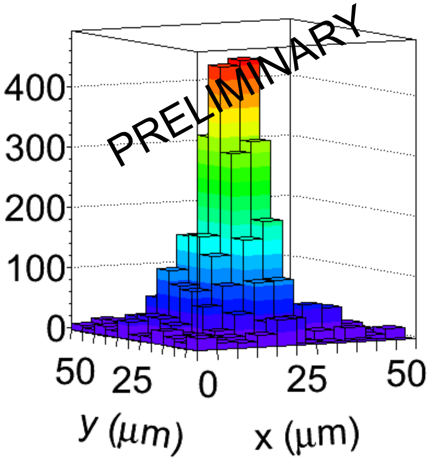
$$^{136}_{54}Xe \rightarrow {}^{136}_{56}Ba^{++} + 2e^{-} + 2\bar{\nu}_e$$


Images of the blue points are shown..

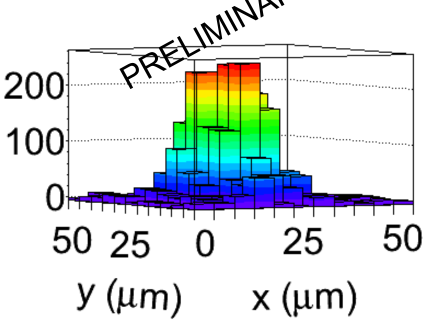
≤ 27 atoms



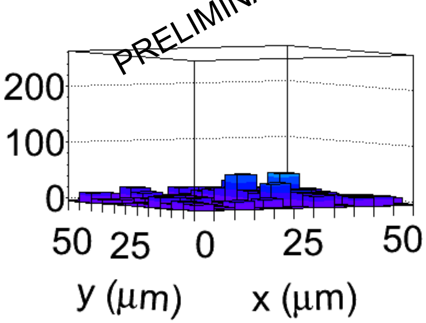
≤ 9 atoms



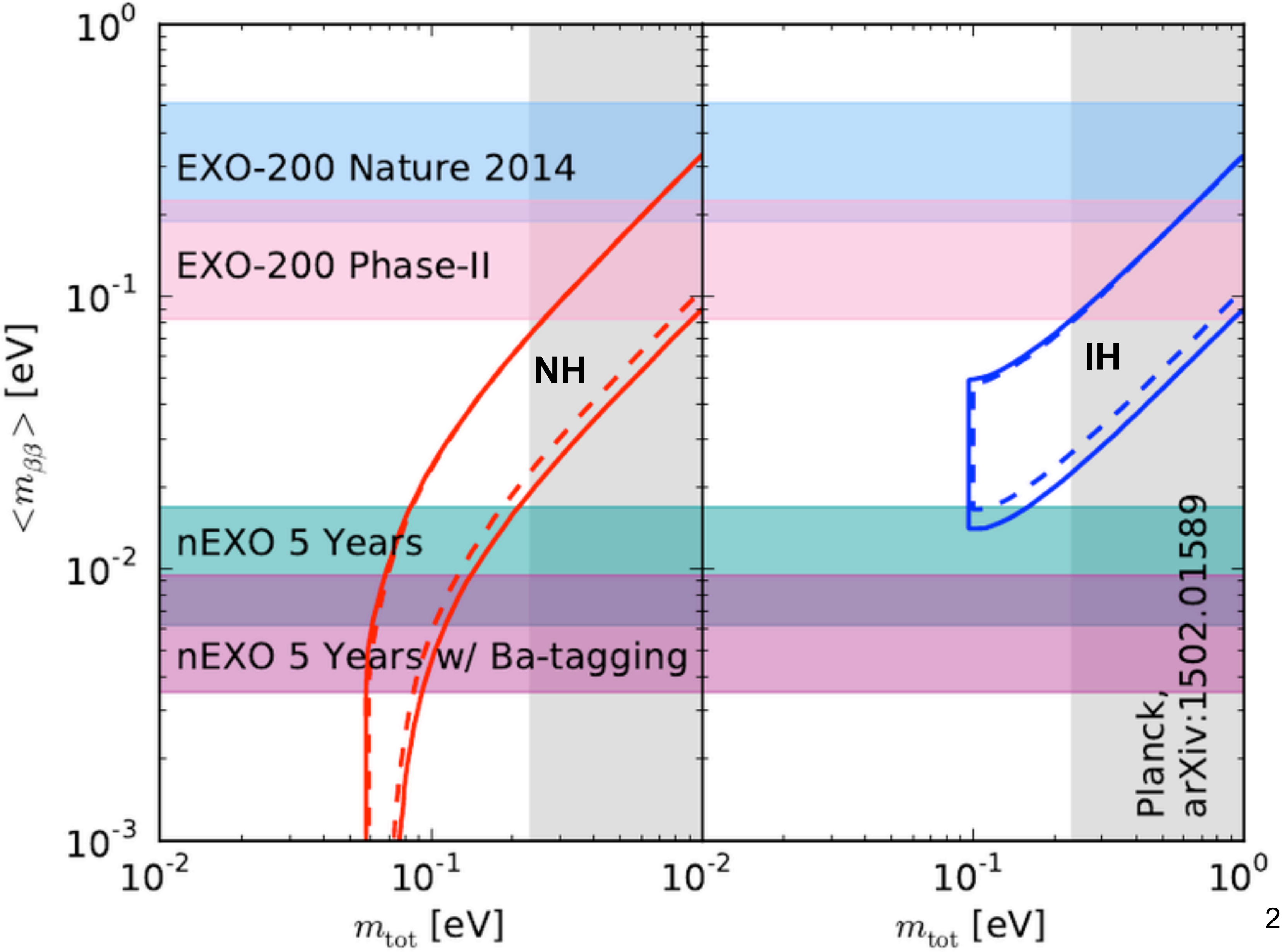
≤ 2.4 atoms



0 atoms

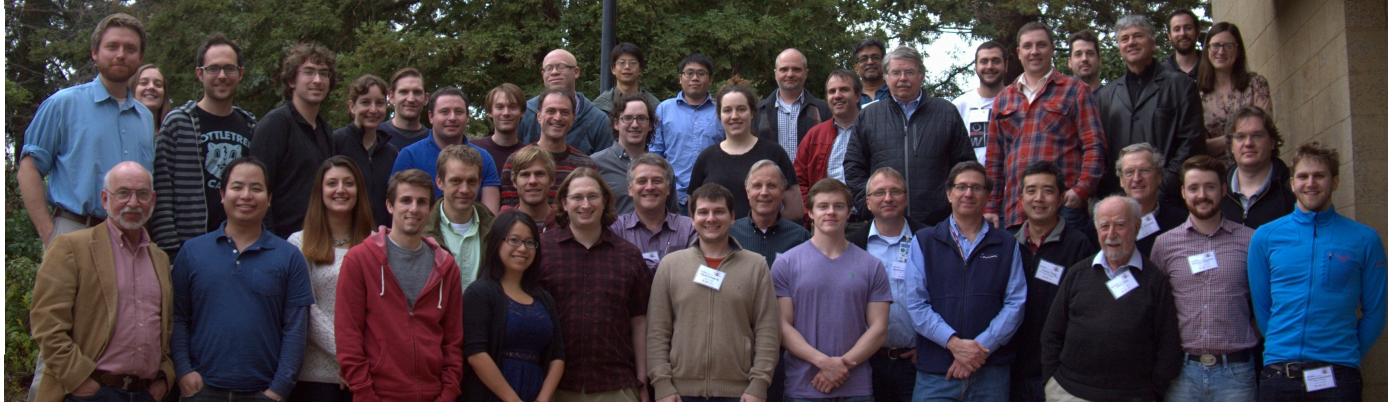


Summary


EXO-200 Nature 2014
EXO-200 Phase-II
nEXO 5 Years
nEXO 5 Years w/ Ba-tagging
NH
IH
Planck, arXiv:1502.01589
$<m_{\beta\beta}>$ [eV]
m_{tot} [eV]
m_{tot} [eV]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{-2}
10^{-1}
10^{0}

The EXO-200 Collaboration

Enriched Xenon Observatory
for double beta decay



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for double beta decay

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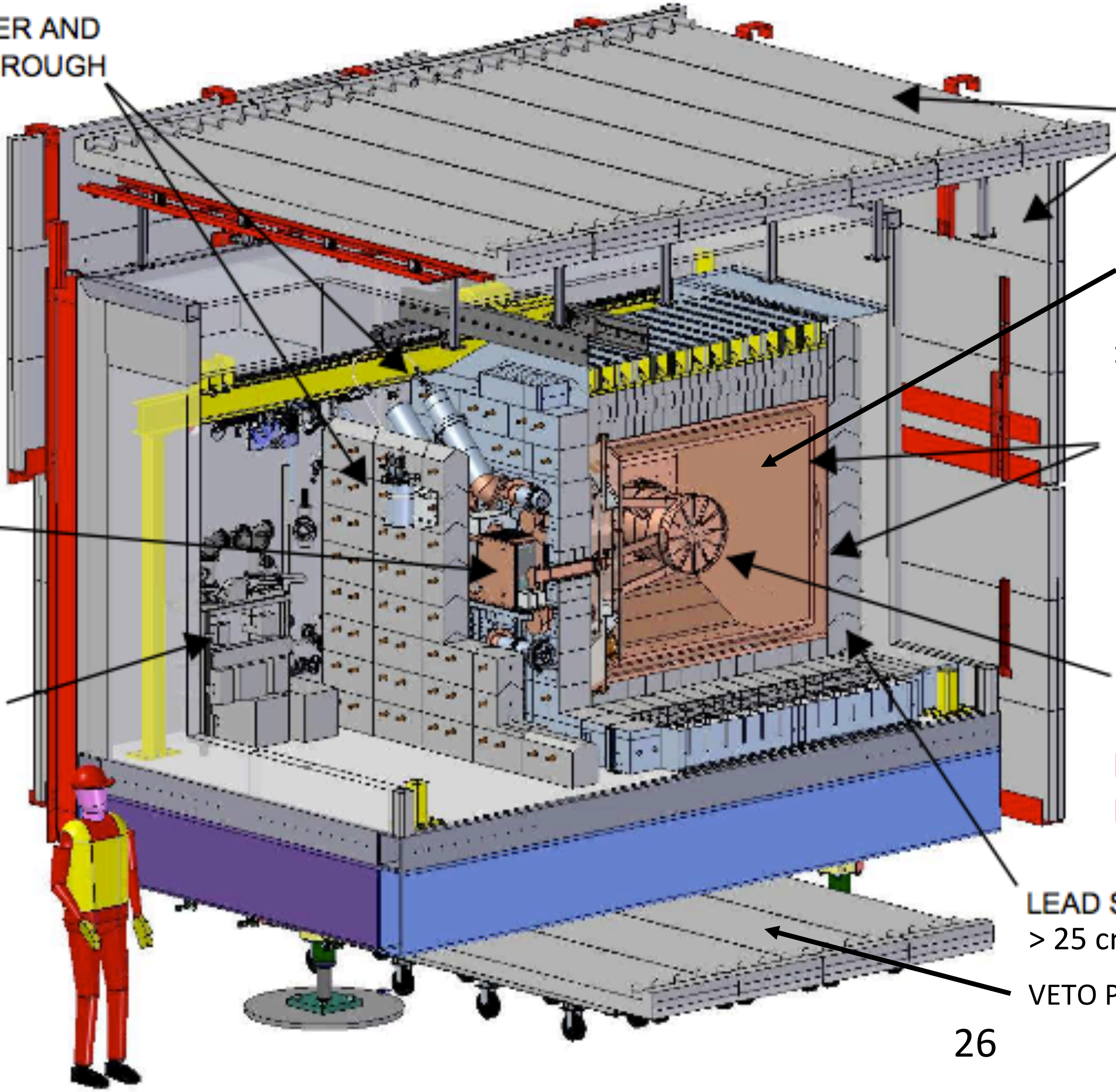
The EXO-200 Detector



HV FILTER AND FEEDTHROUGH

VETO PANELS

High purity
Heat transfer fluid
HFE7000
> 50 cm

DOUBLE-WALLED CRYOSTAT
25 mm ea

FRONT END ELECTRONICS

VACUUM PUMPS

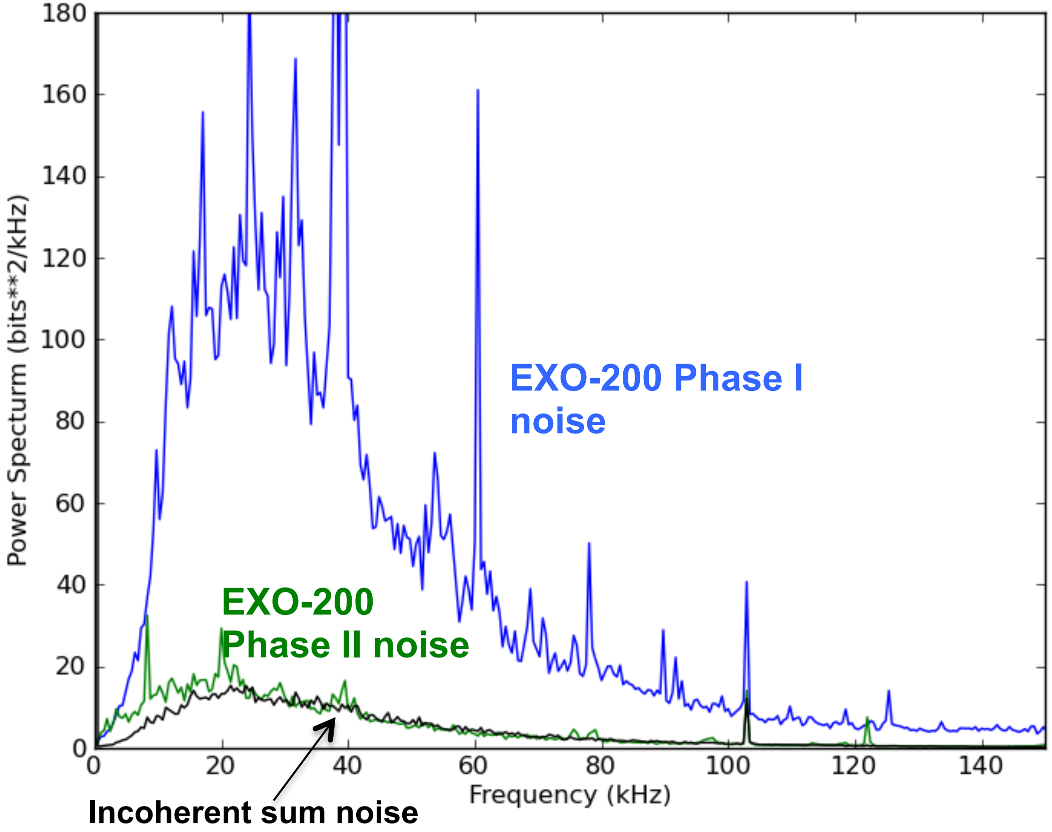
LXe VESSEL
1.37 mm Wall

Radio Quiet
Environment

LEAD SHIELDING
> 25 cm

VETO PANELS

EXO-200 Phase II Upgrade Performance (Front-End Electronics)



Sum APD Noise FFT power spectra

- **After electronics upgrade, the coherent sum noise of the APD channels is reduced by a factor 2.5.**
- **There is only 20% excessive coherent noise remaining.**