# EXO-200: Results, Plans for Phase-II, and Beyond

*Igor Ostrovskiy*

# Origin of Neutrino mass

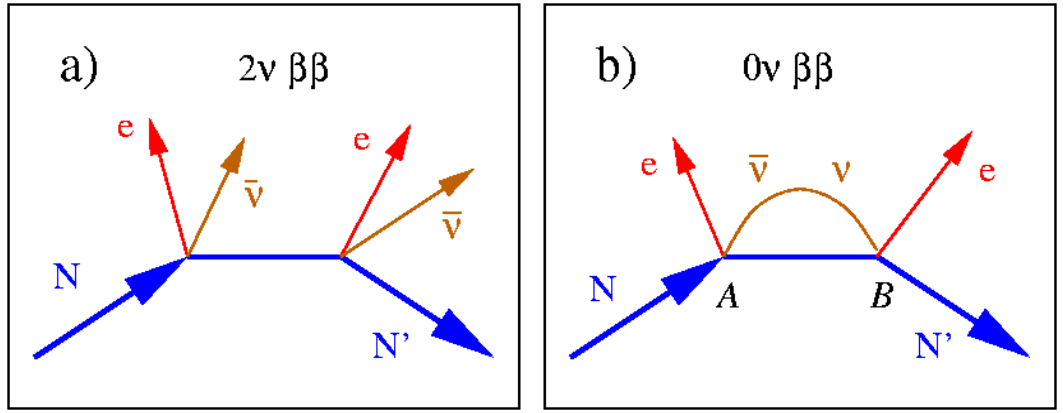
- From neutrino oscillation experiments we know that neutrino has a **non-zero mass**. We have measured relative mass-squared differences of different states
  - But what about **absolute mass values**?
  - How do masses of the different states align (***normal, inverted*** **hierarchy**)?
  - What is the origin of the mass term (***Dirac, Majorana***)?
- One of the most promising ways to answer these questions is to study a peculiar type of radioactive decay, **forbidden in the SM**!

| | |
|---|---|
| Composition | Elementary particle |
| Statistics | Fermionic |
| Generation | First, second and third |
| Interactions | Weak interaction and gravitation |
| Symbol | $\nu_e$, $\nu_\mu$, $\nu_\tau$, $\bar{\nu}_e$, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$ |
| Antiparticle | Antineutrinos are possibly identical to the neutrino (see *Majorana fermion*). |
| Theorized | $\nu_e$ (Electron neutrino): Wolfgang Pauli (1930)<br>$\nu_\mu$ (Muon neutrino): Late 1940s<br>$\nu_\tau$ (Tau neutrino): Mid 1970s |
| Discovered | $\nu_e$: Clyde Cowan, Frederick Reines (1956)<br>$\nu_\mu$: Leon Lederman, Melvin Schwartz and Jack Steinberger (1962)<br>$\nu_\tau$: DONUT collaboration (2000) |
| Types | 3 – electron neutrino, muon neutrino and tau neutrino |
| Mass | Small, but non-zero. See the *mass* section. |
| Electric charge | 0 e |
| Spin | $\frac{1}{2}$ |
| Weak hypercharge | −1 |
| $B - L$ | −1 |
| $X$ | −3 |

From Wikipedia

# Double beta decay

- ***Two-neutrino*** mode is a Standard model process observed for several isotopes, but is extremely rare
- ***Neutrinoless*** mode violates lepton number conservation
  - can only happen if neutrinos are **massive Majorana** particles
  - provides information about **absolute mass** scale
  - has never been observed*
- Main goal of EXO-200 is to search for the neutrinoless mode




* a controversial discovery claim exists by a sub-group of Heidelberg-Moscow collaboration [H.V. Klapdor-Kleingrothaus and I.V. Krivosheina Mod. Phys. Lett., A21 (2006) 1547]

# Detecting double-beta decay

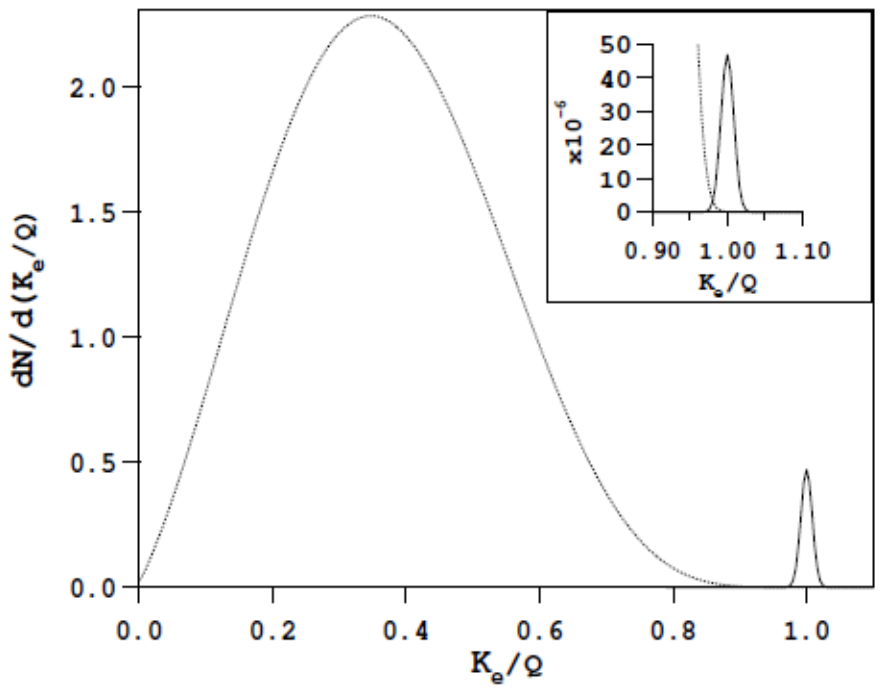


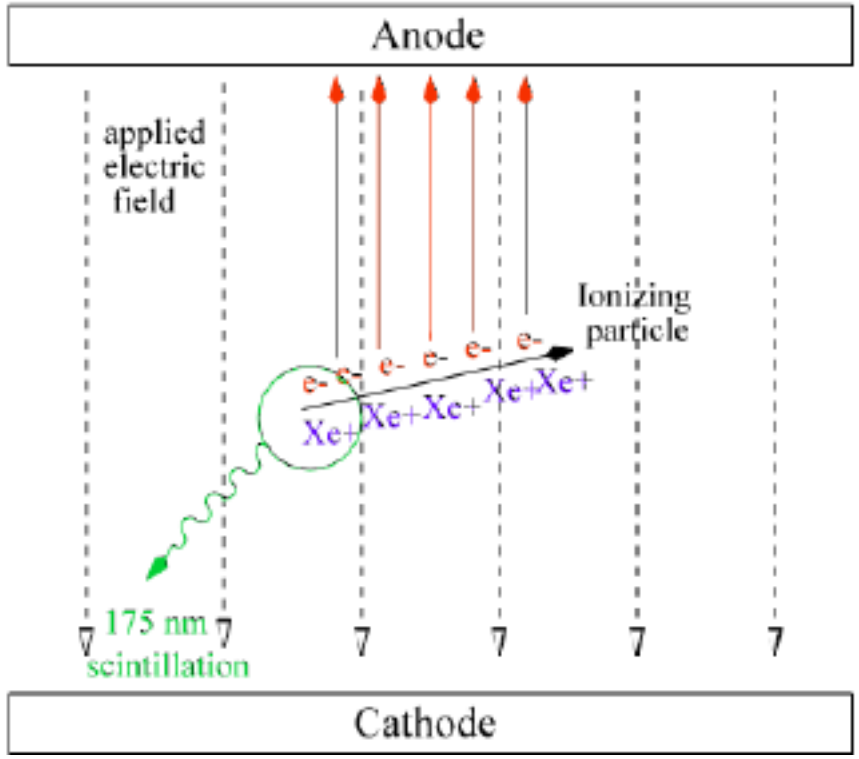

Illustration from P.Vogel, arXiv:hep-ph/0611243,
Assumes 2% resolution and 1e2 (1e6 in insert) ratio of 2nu/0nu

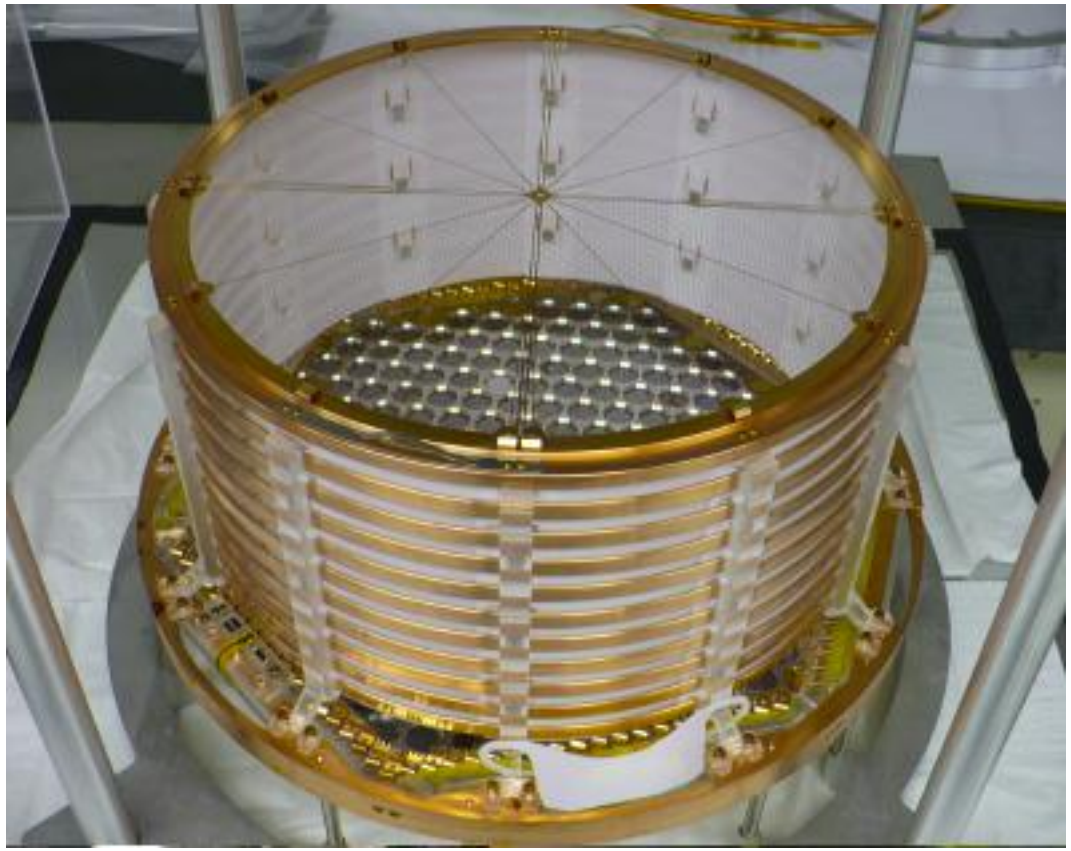
- In the two-neutrino mode electrons have to share energy with undetectable neutrinos
  - A calculable, but broad and featureless spectrum
- In the neutrinoless mode, a mono-energetic peak is expected at Q-value
  - Good energy resolution is essential
  - Large Q-value is preferred

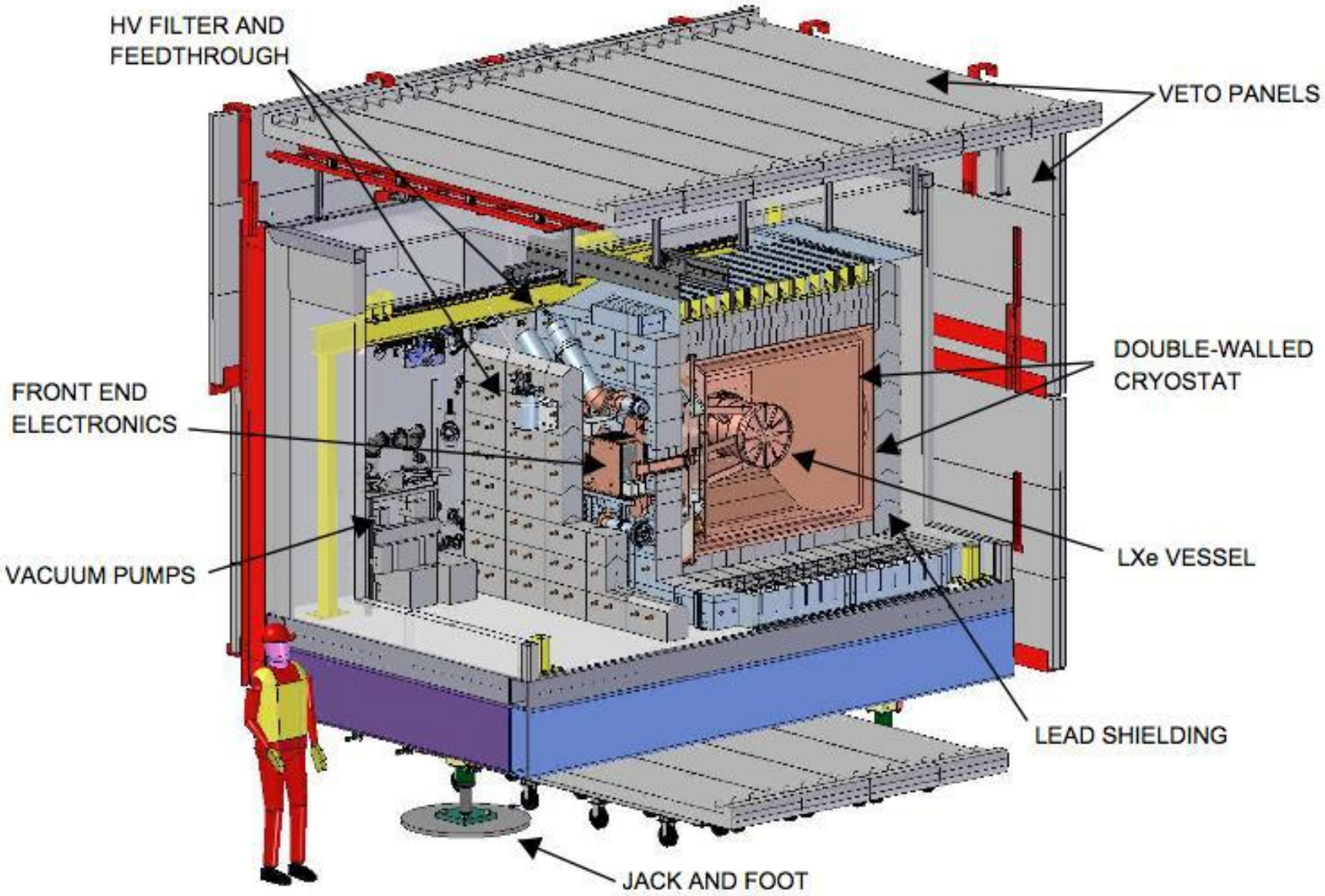
# EXO-200

- ~200 kg of Xe enriched to 80.6% in $^{136}$Xe
  - ~175 kg in liquid phase inside a cylindrical Time Projection Chamber
  - ~100 kg current fiducial mass
- Located at 1585 m.w.e. in the Waste Isolation Plant near Carlsbad, NM
  - Muon rate reduced to the order of $10^{-7}$ Hz /cm$^2$ /sr
  - Salt has inherently lower levels of U/Th (<100 ppb), compared to rock
  - Low levels of Rn (~20 Bq/m$^3$ )
- Carefully selected radioactively clean materials, rigorous cleaning procedures, detector installation inside class 1000 clean room
  - Goal of **40 counts/2 yrs** in 2$\sigma$ 0nu energy window (assuming 140 kg LXe, 1.6% resolution)
  - M. Auger et al., **JINST 7 (2012)** P05010 and D.S. Leonard et al., **NIM A 591 (2008)** 490

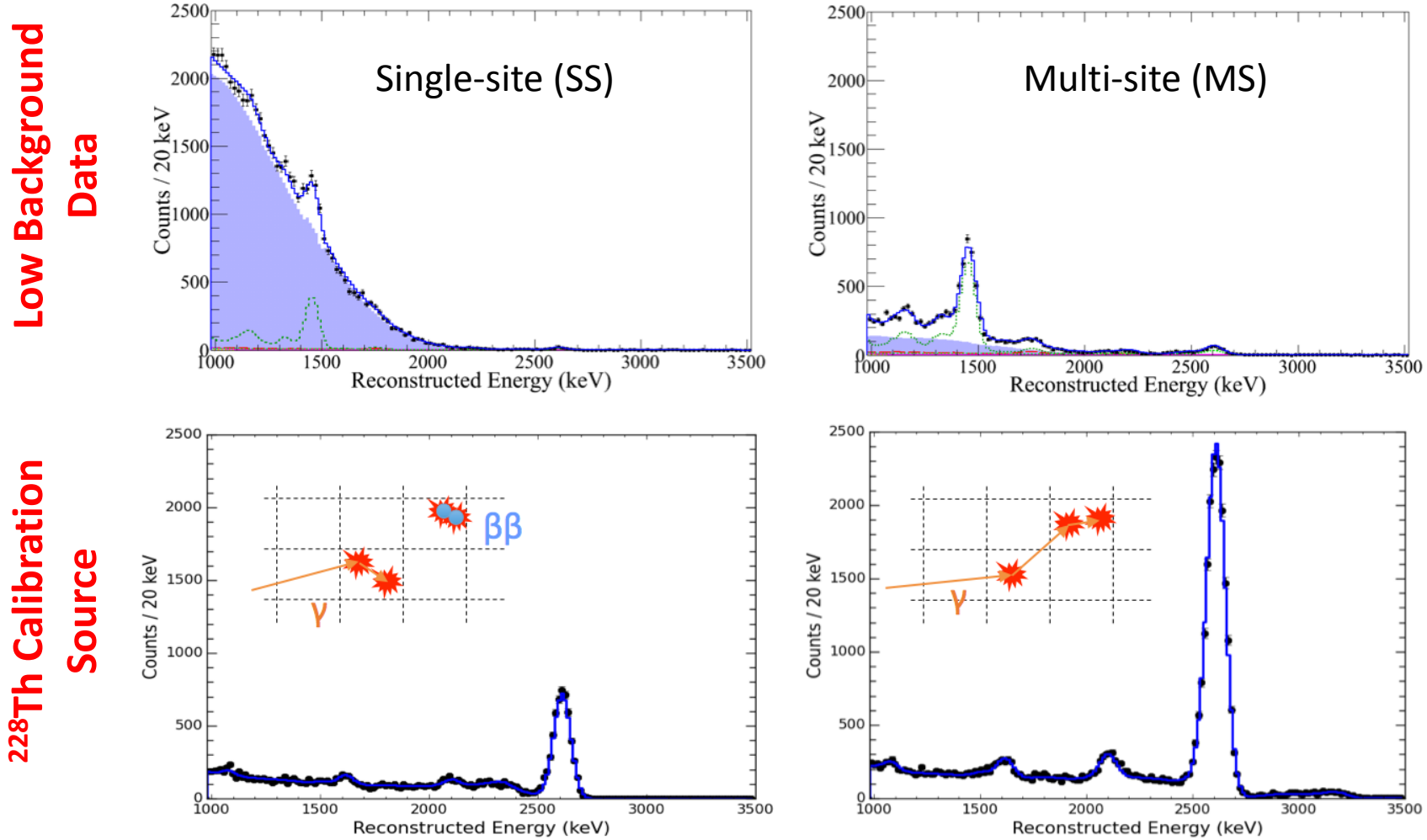
# EXO-200 time projection chamber (TPC)



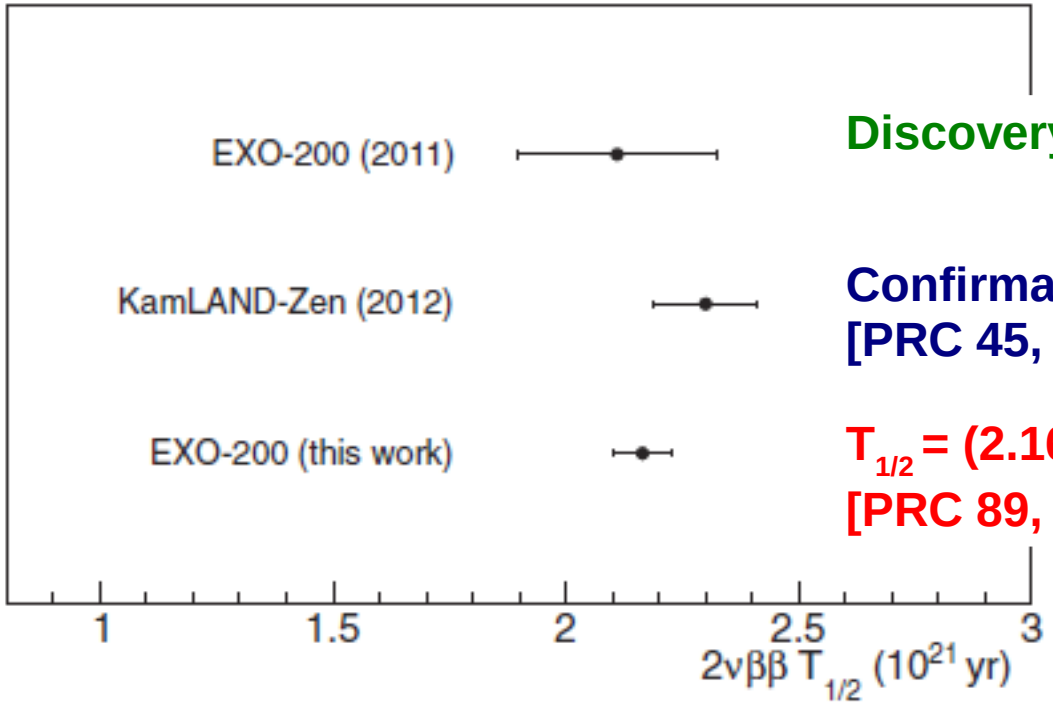

HV FILTER AND
FEEDTHROUGH
VETO PANELS
DOUBLE-WALLED
CRYOSTAT
FRONT END
ELECTRONICS
LXe VESSEL
VACUUM PUMPS
LEAD SHIELDING
JACK AND FOOT

# Single- vs. Multi-site events




Very useful in identifying gamma backgrounds!

# Two-neutrino result




**Discovery [PRL 107, 212501 (2011)]**

**Confirmation by KamLAND-Zen [PRC 45, 045504 (2012)]**

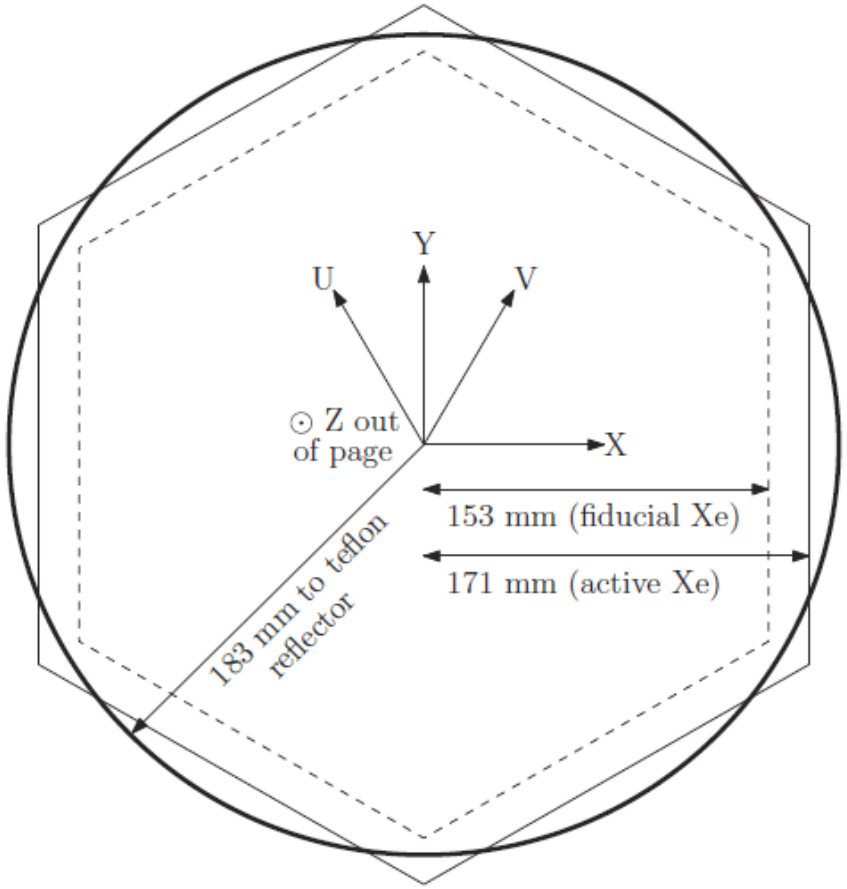
**$T_{1/2} = (2.165 \pm 0.016^{stat} \pm 0.059^{sys}) \cdot 10^{21}$ yr [PRC 89, 015502 (2014)]**

EXO-200 **discovered** the 2ν mode in $^{136}$Xe and provided the **most accurate** measurement of a 2ν half-life among all isotopes

# Measurement of two-neutrino mode half-life

- 2ν measurement is not limited by statistics, so we used a strict fiducial cut to leave only the best-modeled core volume – 66.2 kg of $^{136}$Xe

| Component | Error (%) |
|---|---|
| Normalization | 2.6 |
| SS fraction | 0.77 |
| Backgrounds | 1.3 |
| Statistical | 0.76 |
| **Total** | **2.83** |



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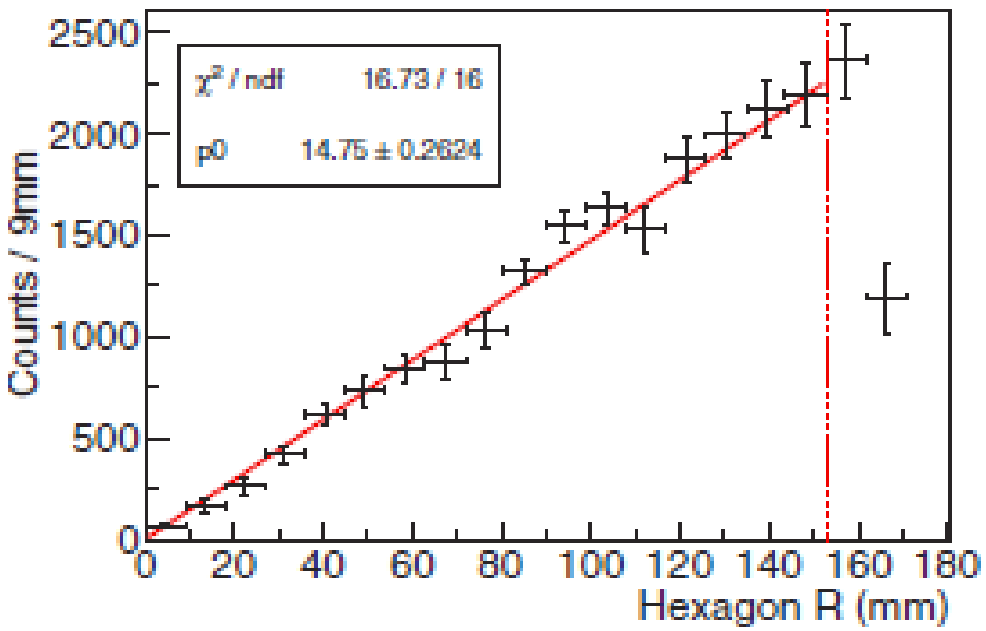
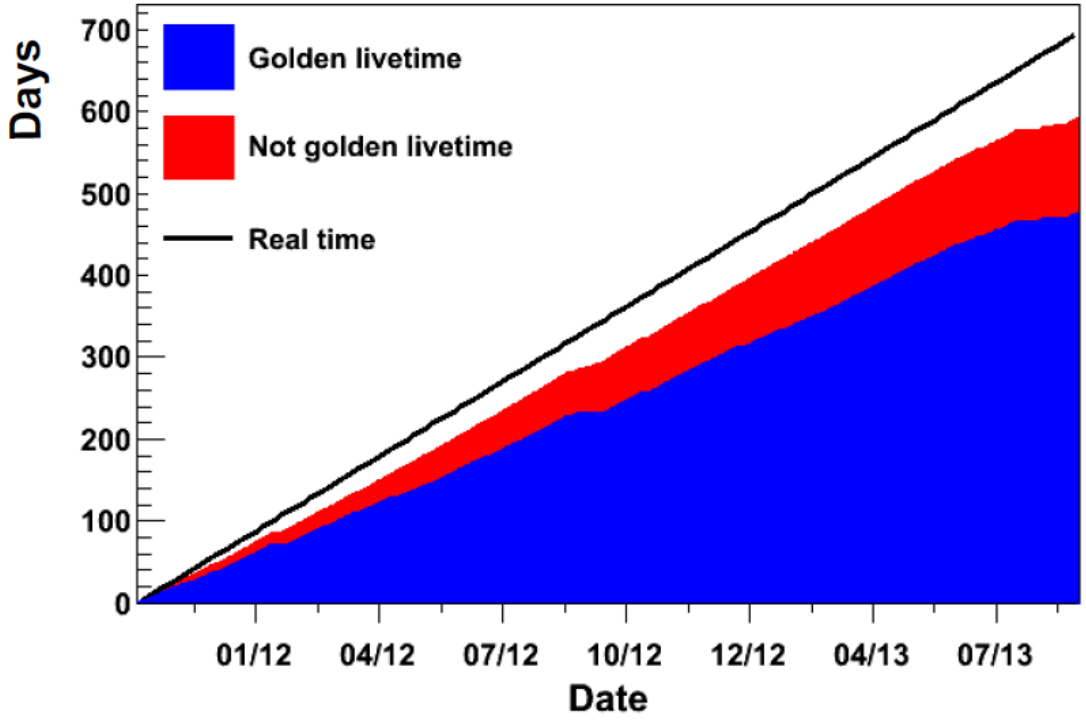



Rate of 2ν decay vs. apothem

# Dataset for neutrinoless analysis




- **477.60±0.01** live days collected between 10/2011 and 09/2013
- Larger fiducial volume to maximize exposure
- **100.0±3.4** kg·yr $^{136}$Xe

# Systematics budget

- Signal detection efficiency:

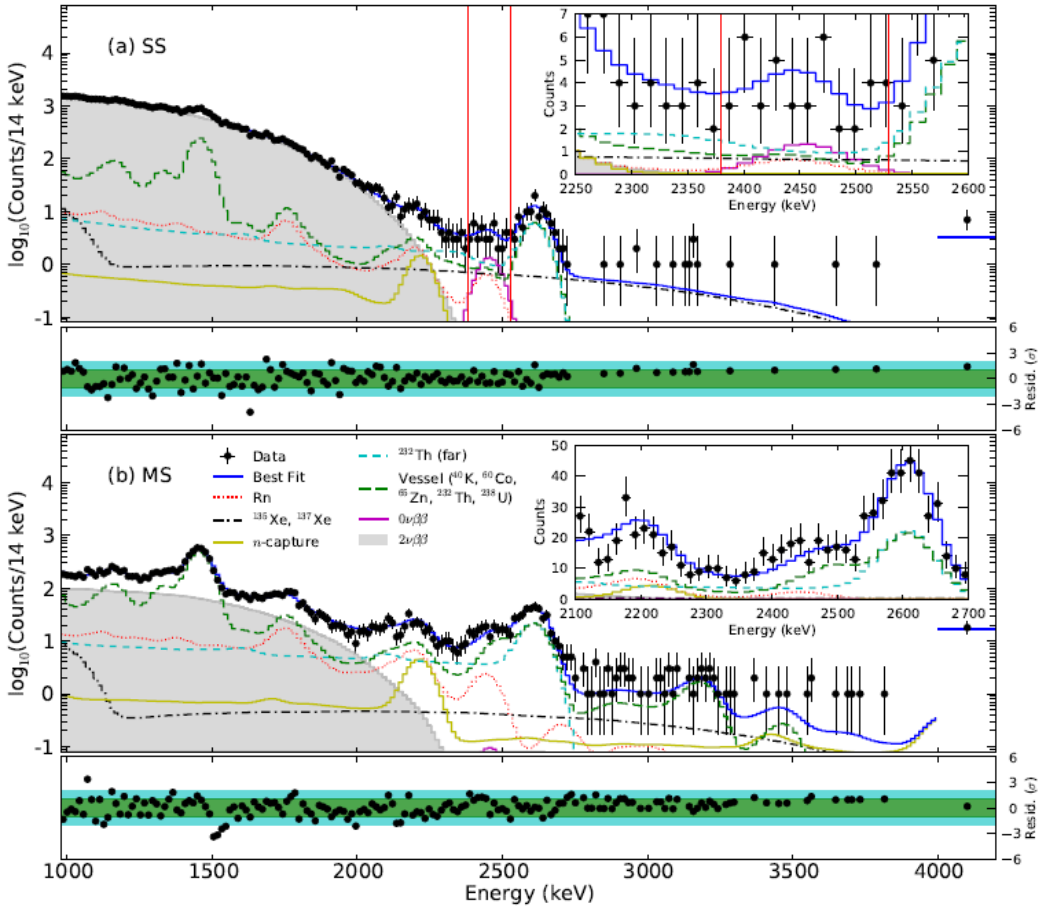
| Source: | Signal efficiency [%]: | Relative error [%]: |
|---|---|---|
| Summary from 2-nu | 93.1 | 0.9 |
| Partial reconstruction | 90.9 | 7.8 |
| Fiducial volume | | 3.4 |
| **Total:** | **84.6** | **8.6** |

- Region-of-interest (ROI) backgrounds:

| Source: | Relative error [%]: |
|---|---|
| Background shape distortion | 9.2 |
| Choice of background model components | 5.7 |
| Variation of energy resolution over time | 1.5 |
| **Total:** | **10.9** |

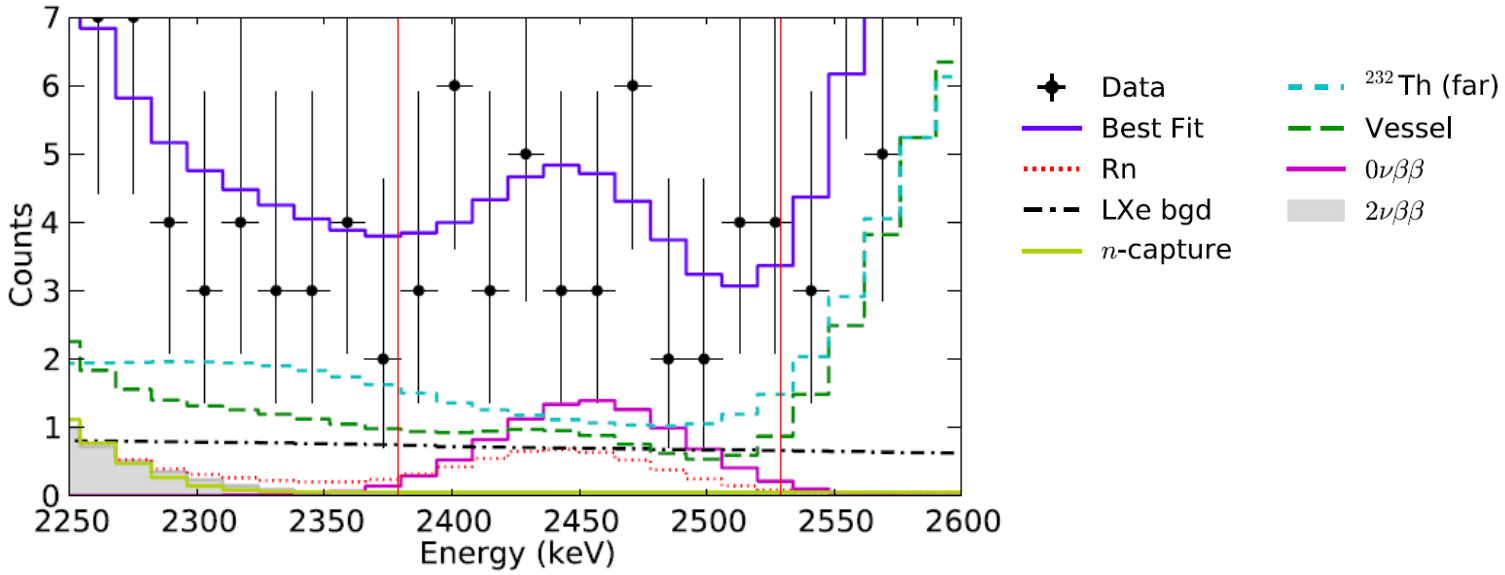
- Deviation between β and γ energy scale ($E_\beta = B \cdot E_\gamma$): ***B* = 0.999 ±0.002**
- Single-site fraction error*: **(Data – MC)/Data = 9.6%**

# Final fit




**Projections on energy axes (fit also includes position information)**

# Single-site zoom-in



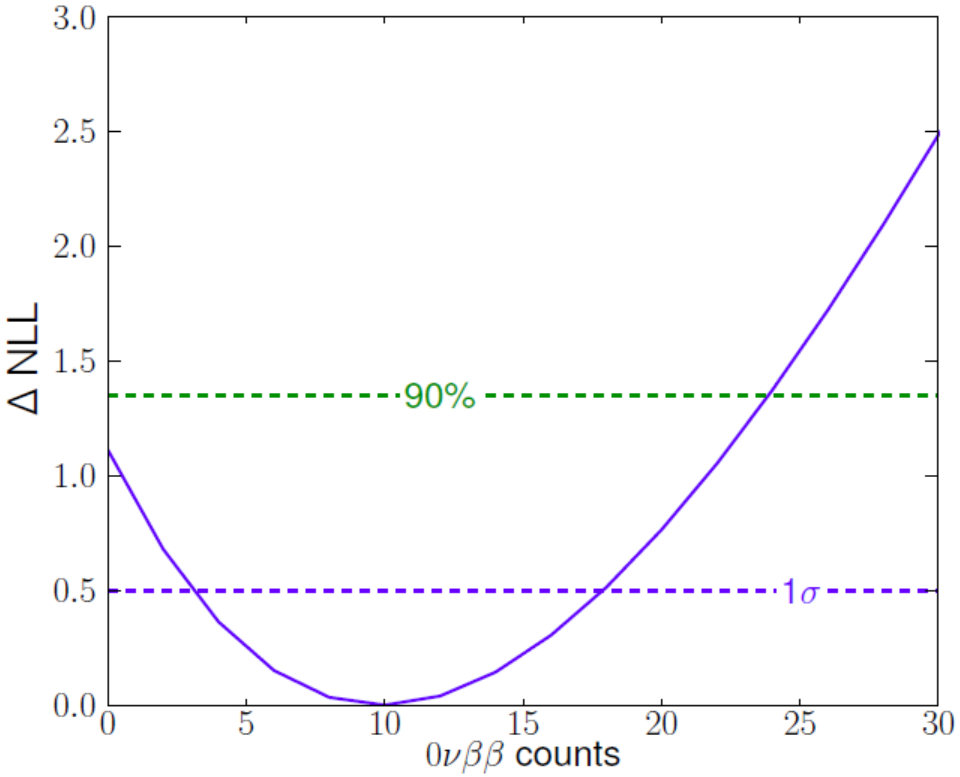

**2σ ROI breakdown for major backgrounds**

| | 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 |

*normalized to total exposure (124 kg*yr).
$^{136}$Xe exposure is 100 kg·yr

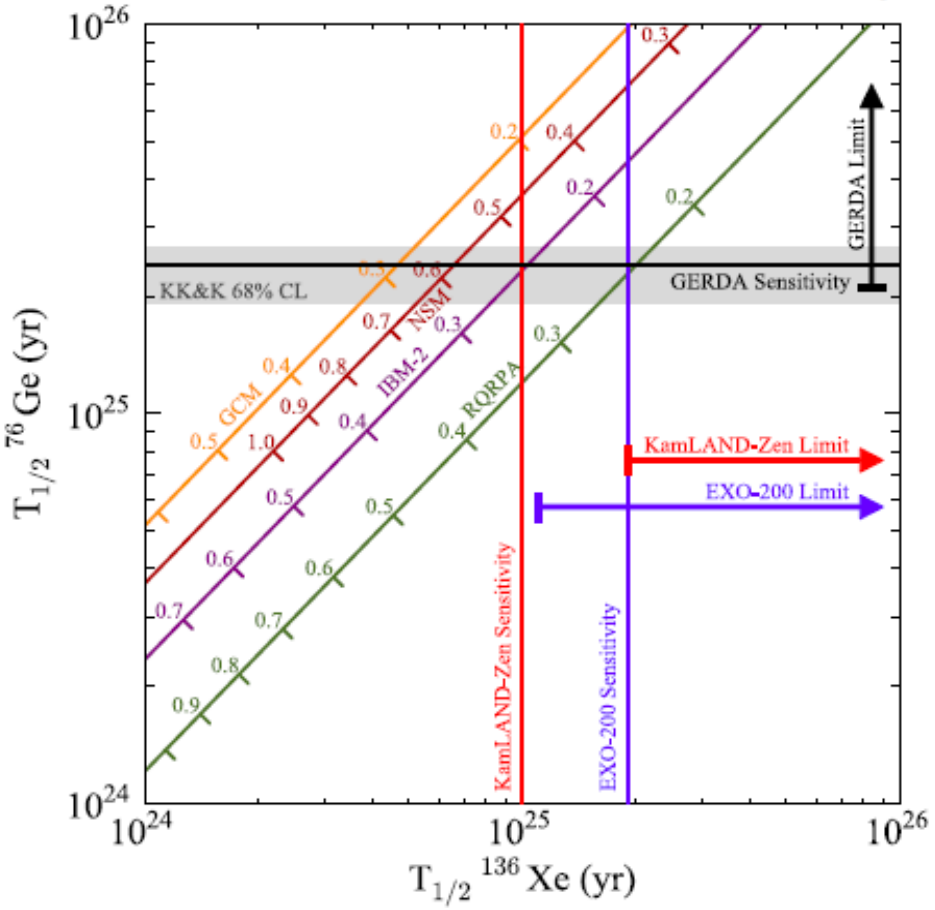
Compare to p.5

# 90% C.L. Limit




- The event excess is compatible with background fluctuation at **~1.2σ**
- 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**
- ~1.5 "σ" away from the median
  - 14% of signal-free toys have limits worse than this

# Context




**EXO-200:**
**Nature 510 (2014) 229**

GERDA Phase 1:
PRL 111 (2013) 122503

KamLAND-Zen:
PRL 110 (2013) 062502

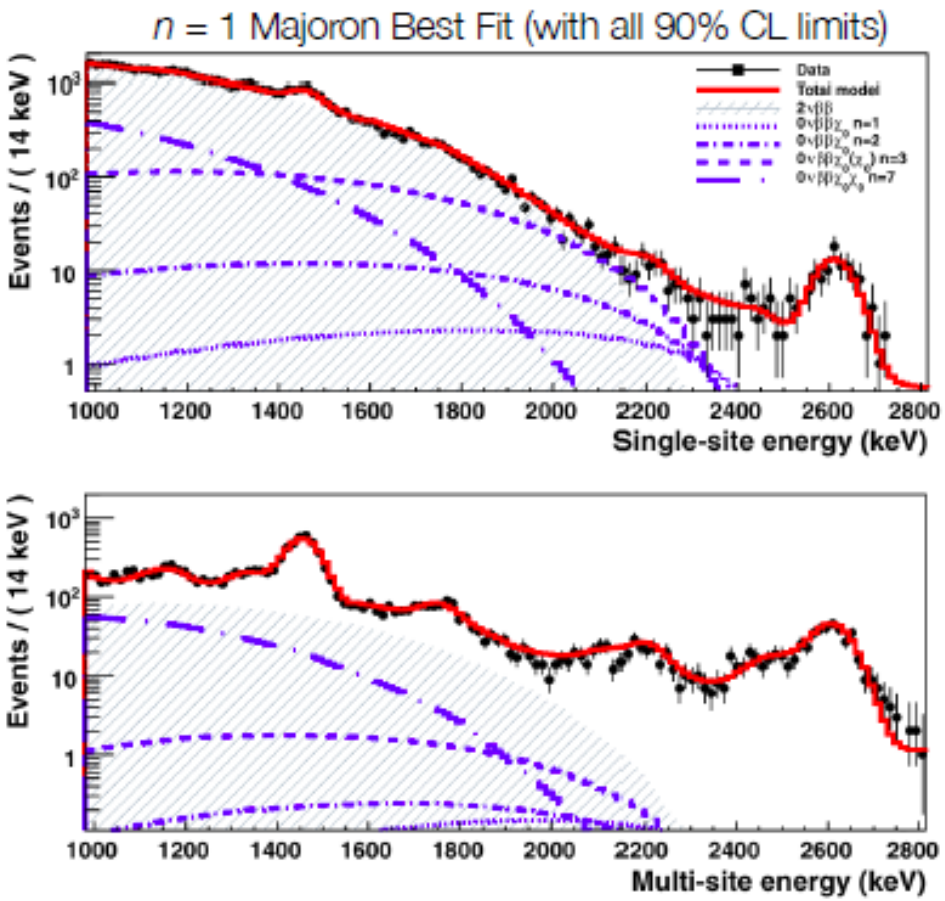
KK&K Claim:
Mod. Phys. Lett., A21
(2006) 1547

# Other BSM physics: 0ν Majoron-mediated decays

$$(A, Z) \rightarrow (A, Z+2) + 2e^- + \chi_0$$
$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\chi_0$$

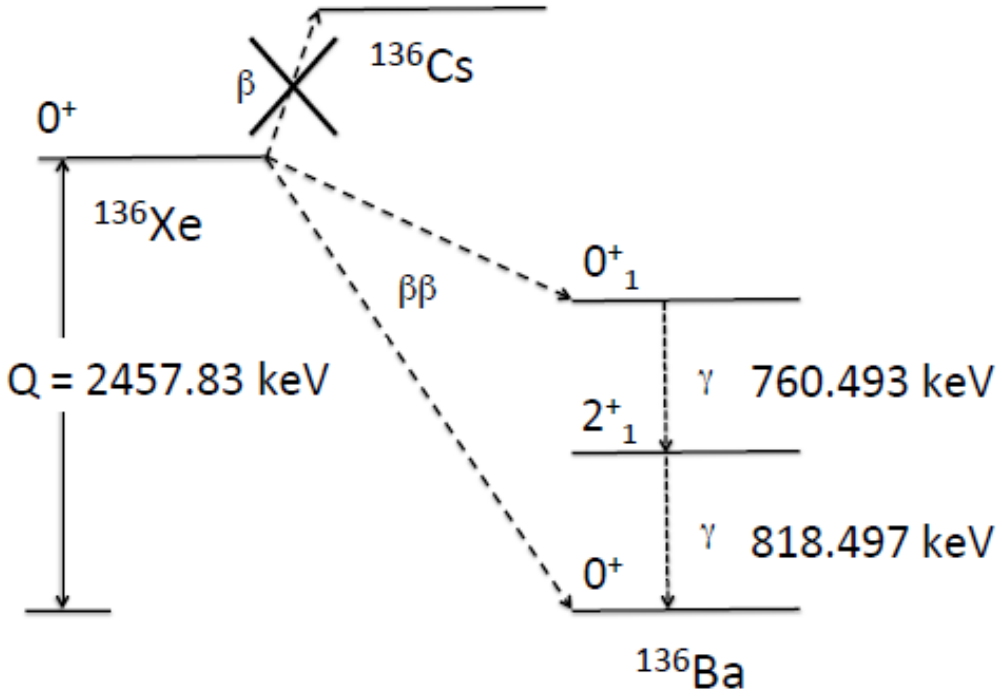
← Massless or light boson ("Majoron")

- Originally described as Goldstone boson of lepton number symmetry breaking
- Possible dark matter candidates; speculated to be involved in other astrophysical processes
- Characteristic spectral shape that can be searched for in EXO-200
- No stat. significant evidence was found. Limits on coupling constants among strongest to date
- **PRD 90, 092004 (2014)**



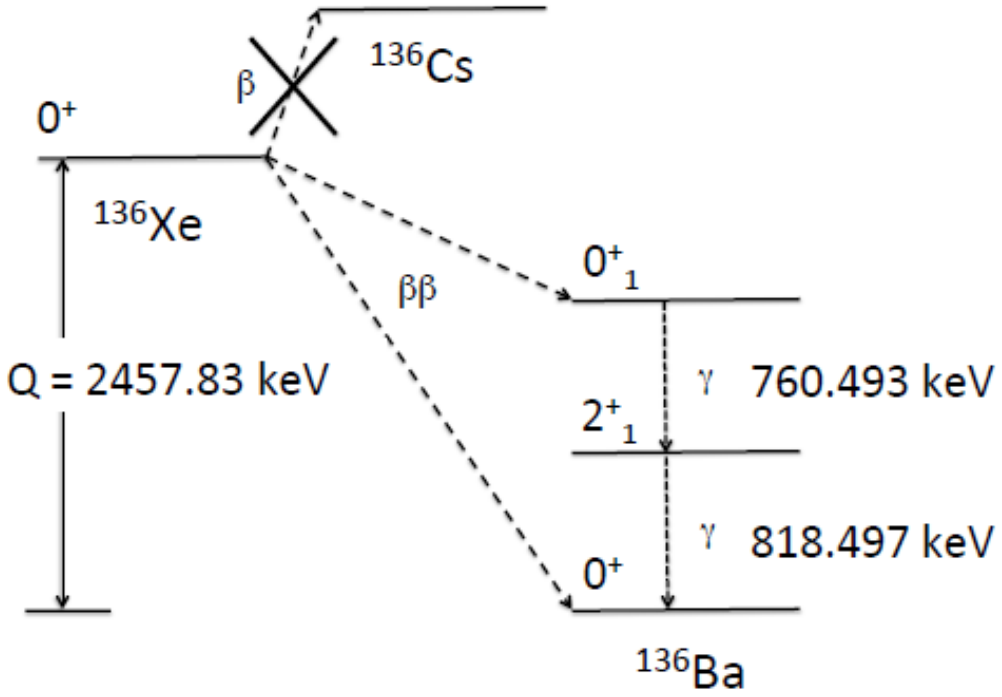
# Other SM physics: 2ν decay to excited states

- The two-neutrino mode of double beta decay is allowed in the SM
- The decay may also proceed to the first excited state ($0_1^+$), if energetically accessible
- It is interesting to try and measure this process, because it may provide additional constraints on NME
  - Some NME uncertainties are common for both decays, so cancelations are possible, potentially leading to more accurate extraction of Majorana mass from neutrinoless decay
- It may also test exotic alternative mechanisms for double beta decays

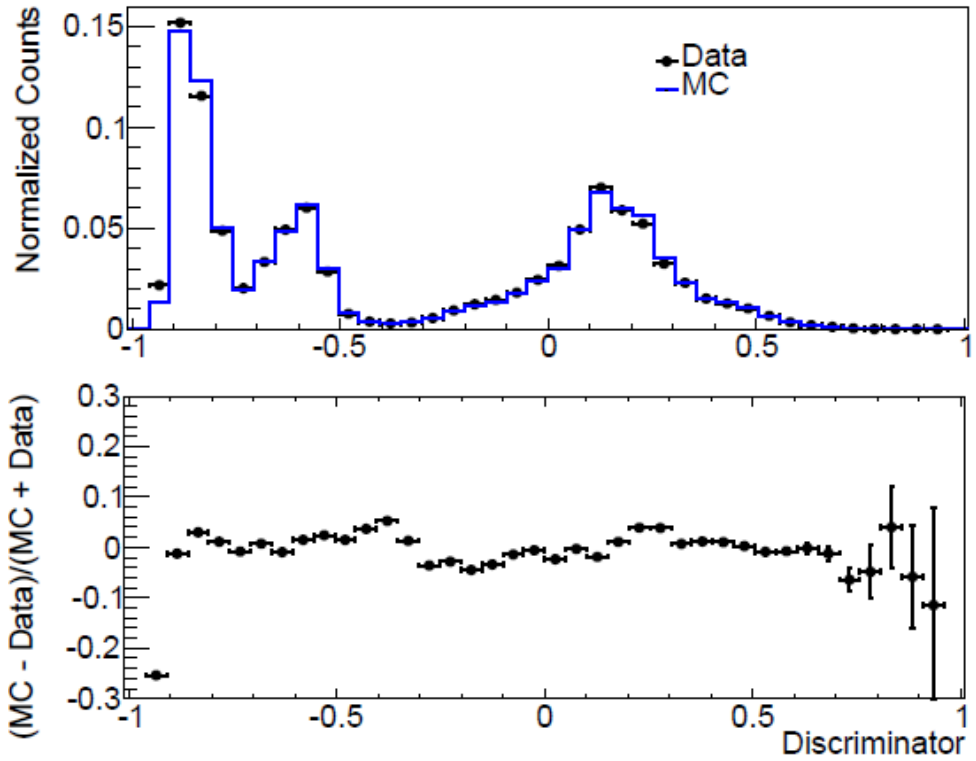


# Other SM physics: 2ν decay to excited states

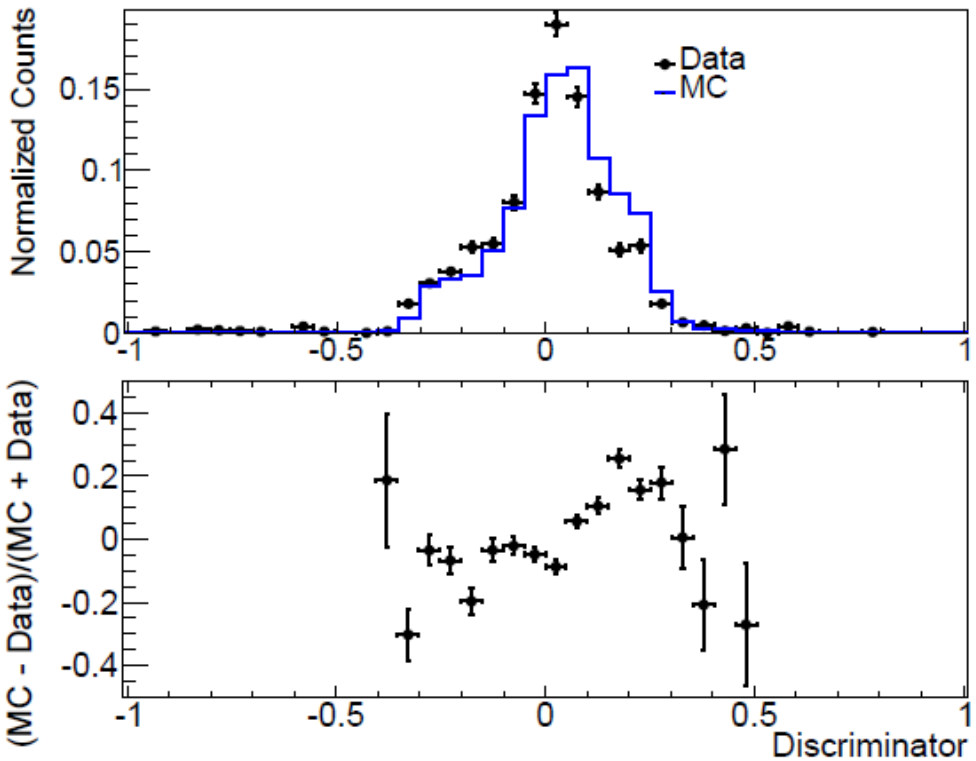
- Decay to $2_1^+$ state from the ground state of $^{136}$Xe has larger Q-value, but is highly suppressed due to angular momentum
- The primary interest for us is thus decay to $0_1^+$ state, which results in subsequent emission of **760.5 keV** and **818.5 keV** gammas
- The expected rate is calculated to be smaller than to the ground state by a factor of 3915 due to PSF, and by additional factor of 2.9 due to NME
  - **Expected half-life is thus 2.5e25 yrs**, higher than expected sensitivity of EXO-200
  - But NME uncertainties could lead to over-estimation, as was the case of $^{100}$Mo and $^{150}$Nd



# Final discriminator. Validating agreement of training and real events

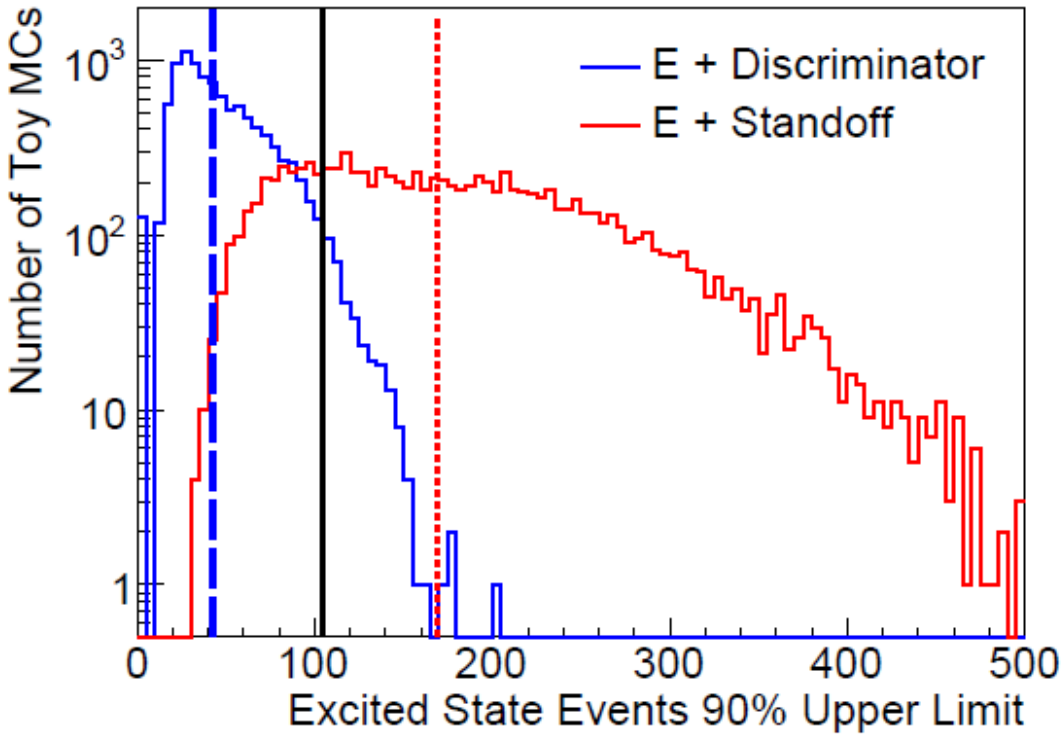



Data and MC event distribution of discriminator variable for $^{228}$Th calibration source




Data and MC event distribution of discriminator variable for 2νββ decays to ground state

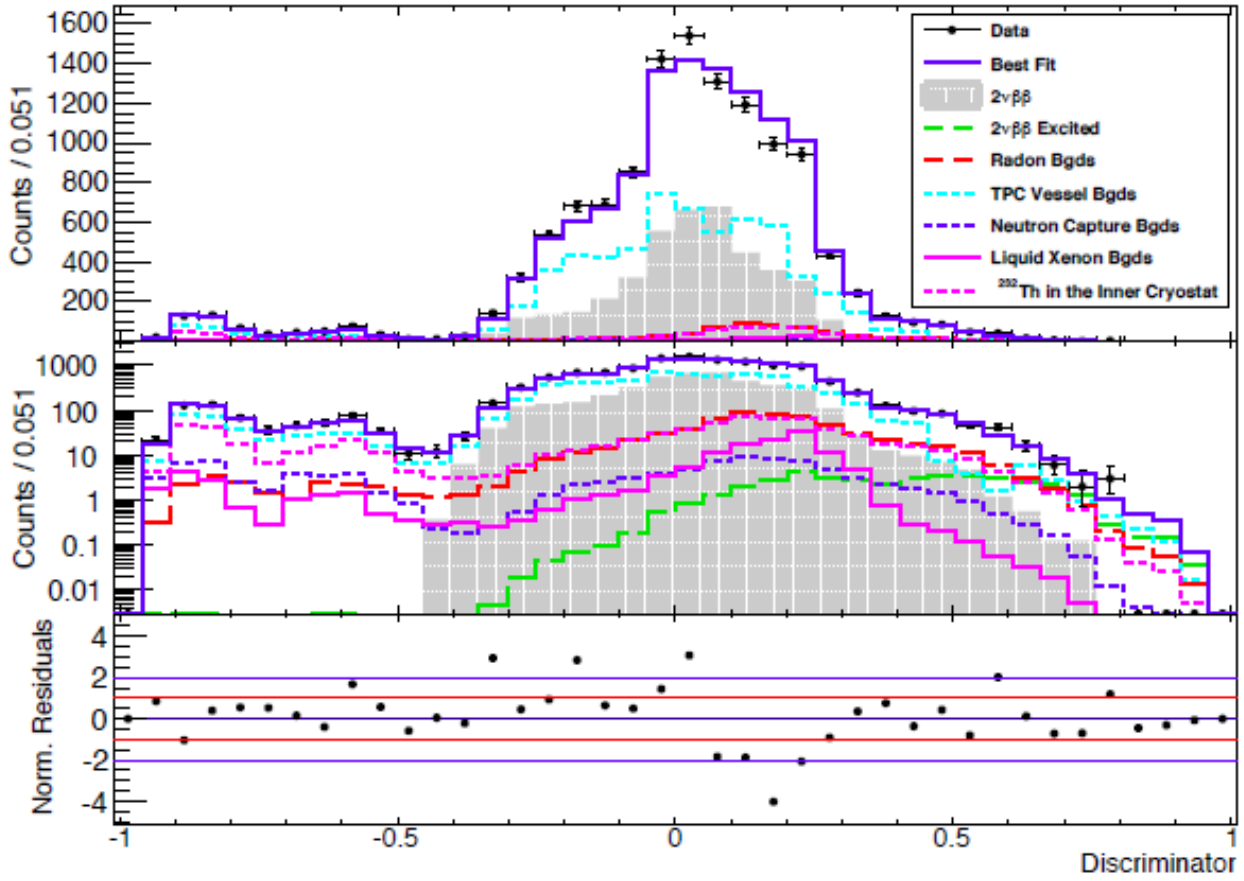
# Sensitivity improvement




- Using the BDT-based discriminator **variable increases median sensitivity by a factor of 3-4**, compared to the usual EXO analysis approach
- Expected median sensitivity: **$T_{1/2}$ > 1.7e24 yr @90% C.L.**

# Final fit

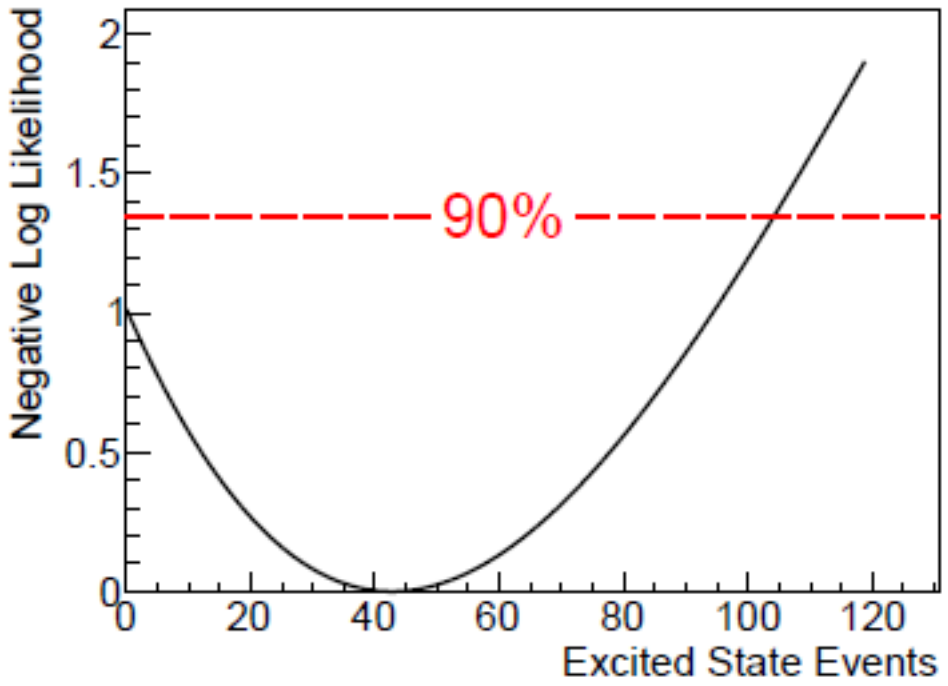
- 2-D ML fit in Energy and Discriminator observables
- Same dataset as in the last neutrinoless analysis (100 kg·yr $^{136}$Xe exposure)
- Same background components, plus excited decay signal component




Final fit results. Projection on Discriminator variable

# Result

- Best-fit value of 43 events
- Statistically insignificant
  - **Consistent with NULL at 1.6σ**
- Corresponding half-life limit: **$T_{1/2}$ > 6.9e23 yr @90% C.L.**
- Roughly a factor of two weaker than median sensitivity




**arXiv:1511.04770**

# Other recent EXO-200 papers

- **J.B. Albert et al. “Measurements of the ion fraction and mobility of alpha and beta decay products in liquid xenon using EXO-200”**
  - ***arXiv:1506.00317 (Jun 2015), submitted to Phys. Rev. C.***
- **J.B. Albert et al. "Investigation of radioactivity-induced backgrounds in EXO-200"**
  - ***Phys. Rev. C 92 (2015) 015503***

# EXO-200: Plans for Phase II

- Following the WIPP accidents on Feb 2014, access to the underground was discontinued and EXO-200 has stopped collecting data
- The access is largely restored by now and EXO-200 is making preparations to restart data-taking
- In May 2015, a panel of experts reviewed the case for continuation of EXO-200. Following the review, DOE has approved the restart and collection of 3 more years of data in June 2015
- Current plan is to restart by the end of the year

# Expected improvements in Phase-II

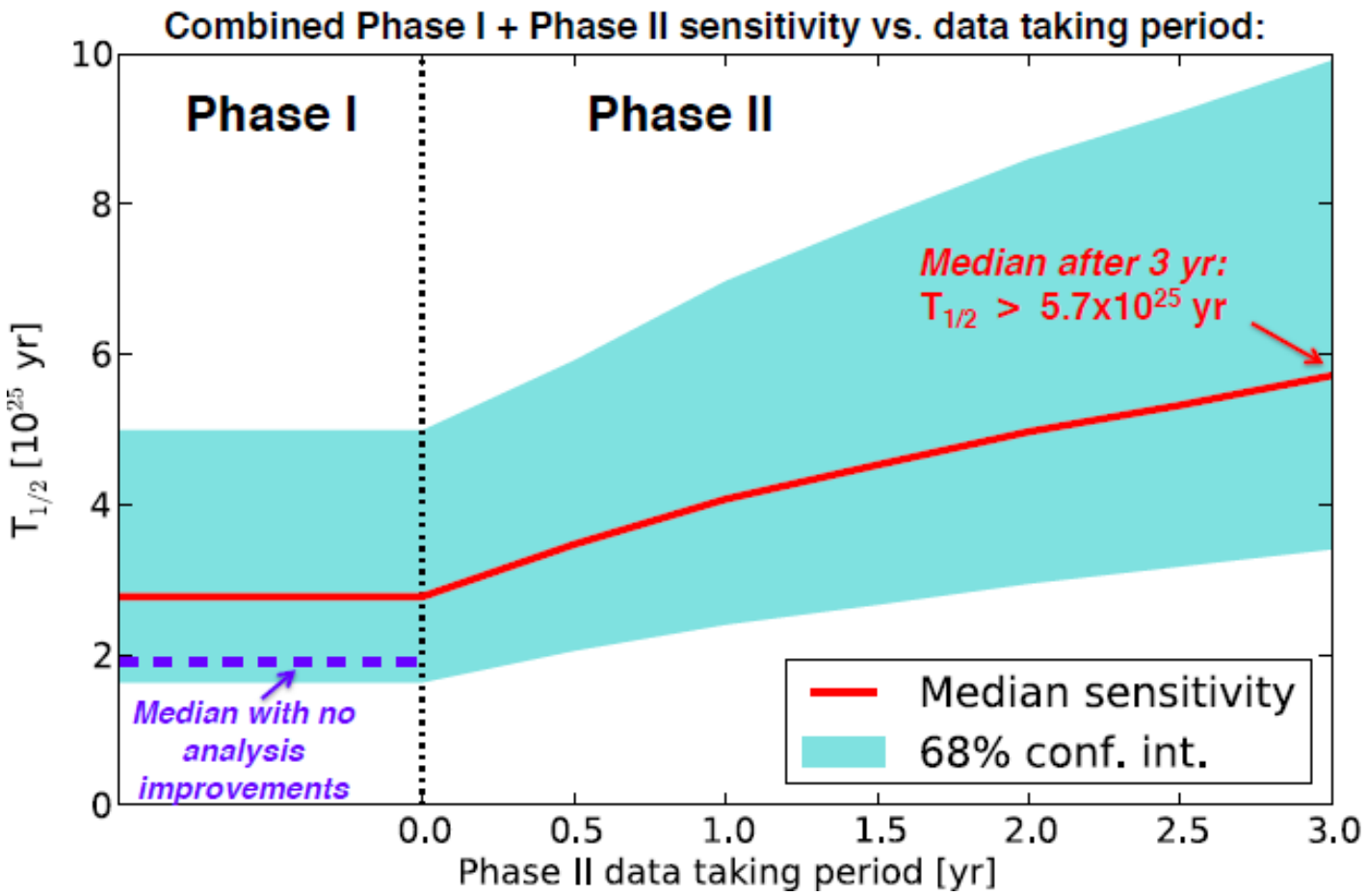
**Analysis**

- Reduce $^{137}$Xe background with a new veto cut for events consistent with $^{136}$Xe neutron capture $\gamma$s. **Up to ~40% expected reduction**
- Using pulse rise time and U-wire induction signals to improve SS/MS discrimination. Simple 1D cut already **moves 40% of $\gamma$s, while only 15% of signal, from SS to MS**. More could be possible with continuous variable

**Hardware**

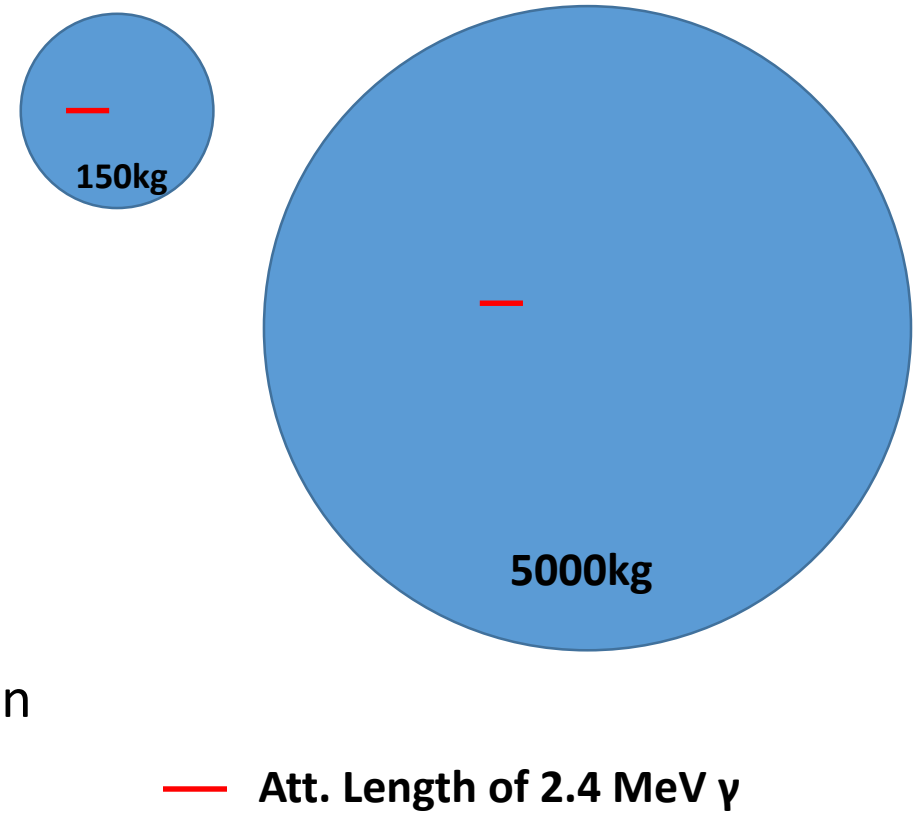
- Electronics upgrade to reduce noise in the light channel. Expected to decrease the **energy resolution at Q-value from ~1.5% to ~1%**
- "Deradonator" system to flush the air gap between cryostat and lead shield with Rn-suppressed air. Expected to **remove or reduce "remote" U background**

# EXO-200 Phase-II Estimated sensitivity

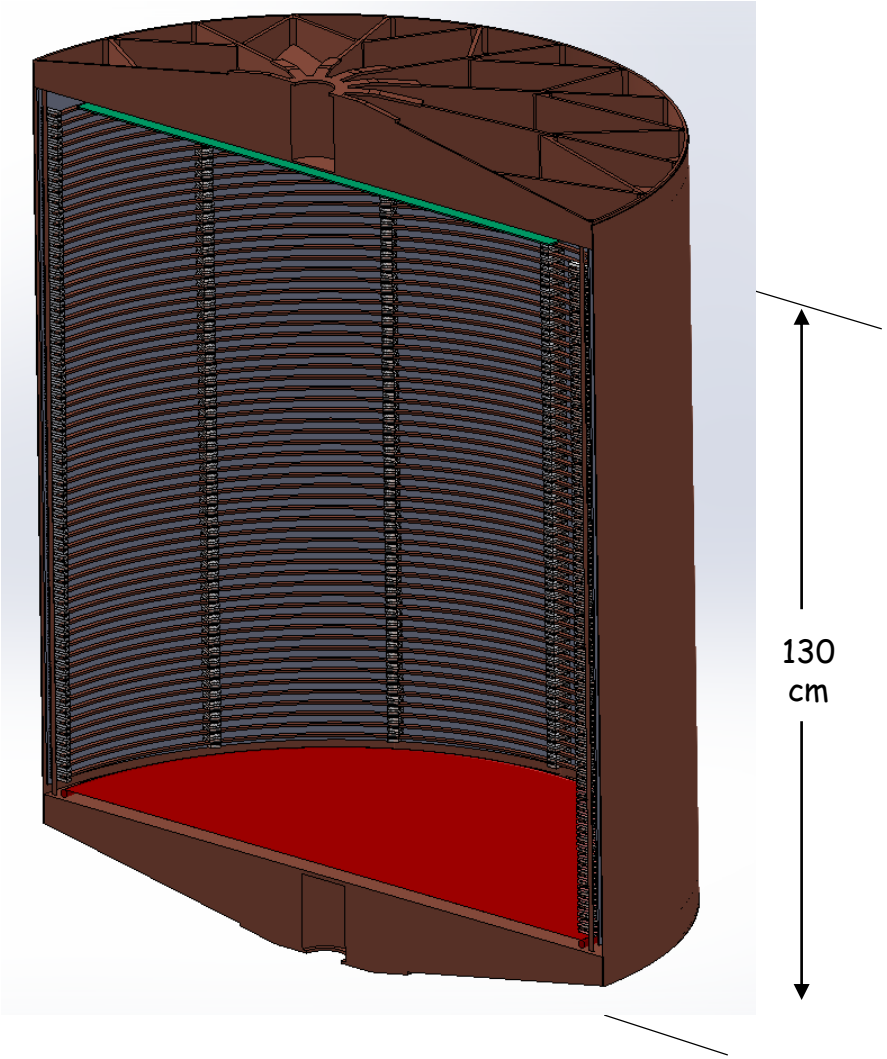


# From EXO-200 to nEXO

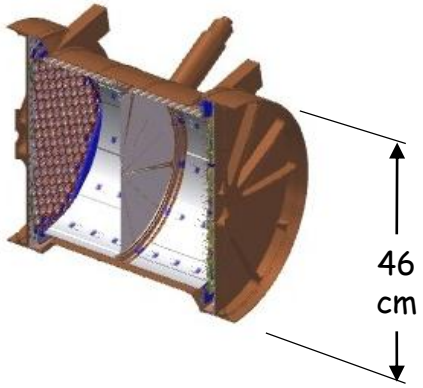
- EXO-200 demonstrated principle of a homogenous TPC capable of controlling backgrounds by a ***combination*** of **energy resolution**, **event topology**, and **event location**
- nEXO will take better advantage of all three (pending certain R&D):
  - Bigger detector w/o central cathode – better discrimination of external bkgs with position dependent fit
  - Better photodetection and new charge collection scheme with cold electronics – better energy resolution and multiplicity metrics



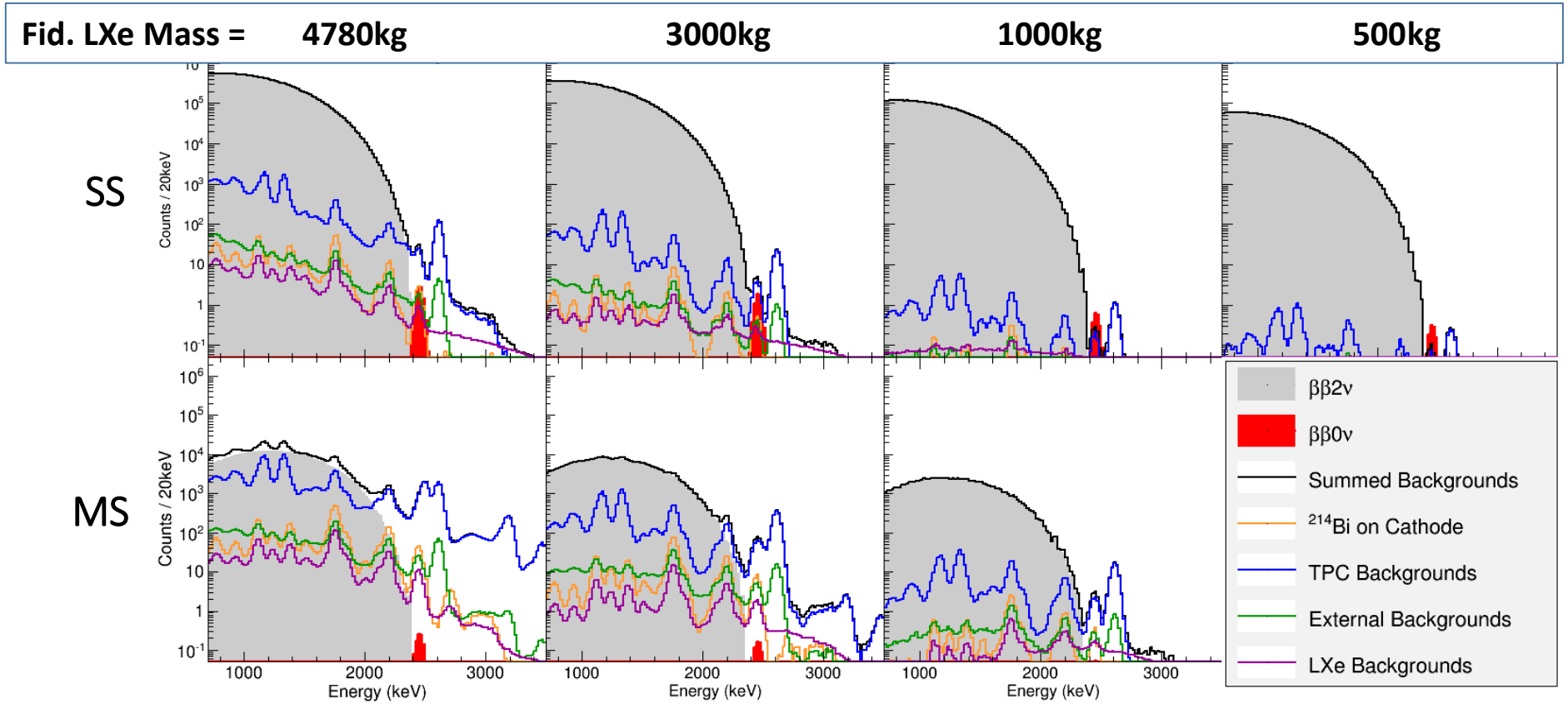
# From EXO-200 to nEXO: bigger, with cleaner core volume




- Based on EXO-200 experience, we plan to do standoff distance fit in **(almost) whole volume**
- No central cathode means **no source of Bi-214 gammas in the core volume**



# The role of standoff in background control of a big detector

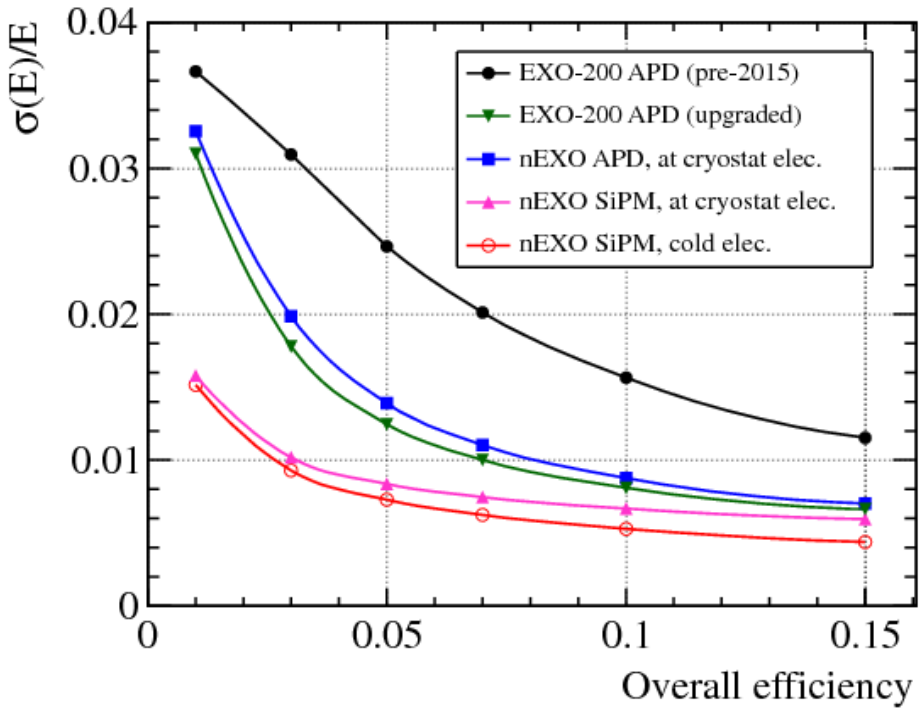


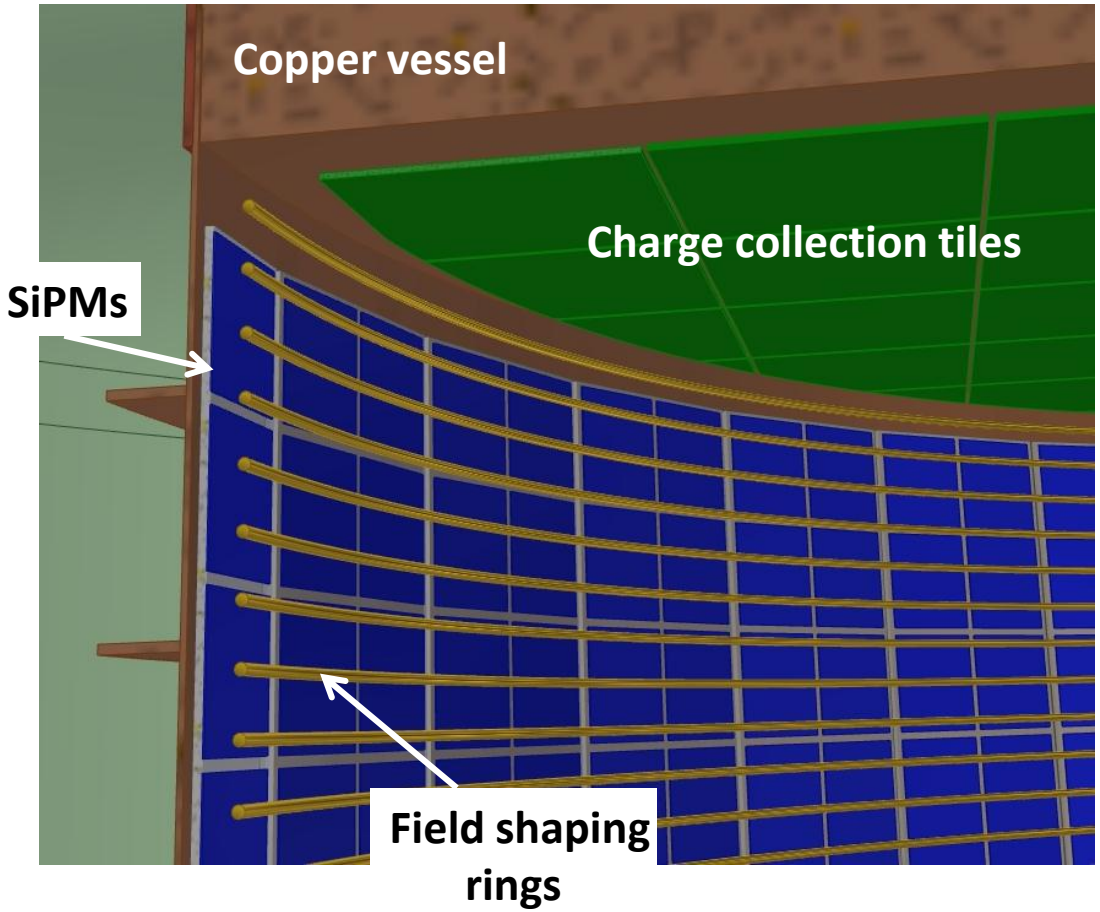

Example assumes:

- **5 yrs** of data
- Projected backgrounds
- $T^{0\nu}_{1/2}$=***6.6x10²⁷*** *yr*

Full volume **likelihood fit will always outperform simple fid. cut**, as long as one can model the shape of probability density functions adequately

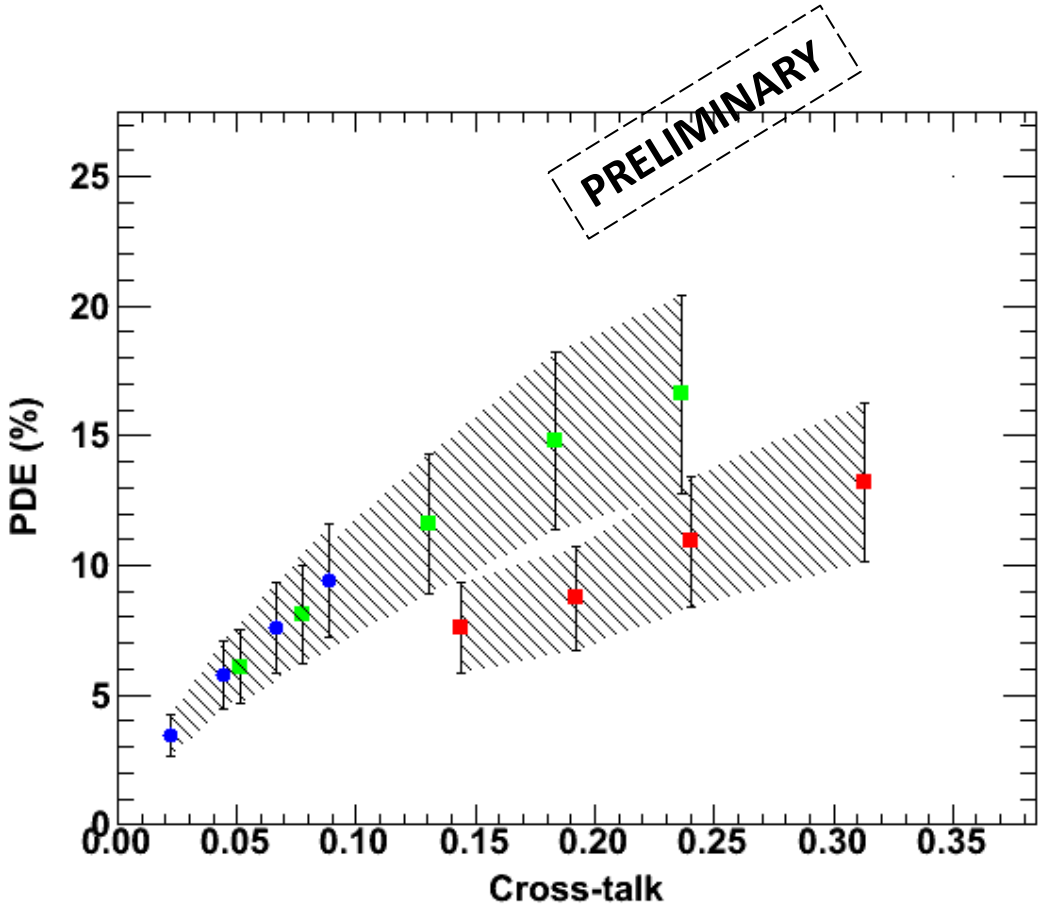
# From EXO-200 to nEXO: higher gain photodetectors, bigger coverage




- Combine light/charge for best resolution
- APD noise limits resolution in EXO-200
- With barrel placed SiPMs, assume 1% for nEXO (but even 0.5% not impossible)

# SiPM technology is almost there!




**Blue** – "FBK-2010", **Green** – "FBK-RGBHD", **Red** – "Hamamatsu-VUV2"

- Both Hamamatsu and FBK, basically, achieved min. PDE@175nm requirement (15 abs.%, **w/o wavelength-shifter**)
- Other parameters also improve from one production to another
- FBK readily provides bare devices for ultimate radiopurity

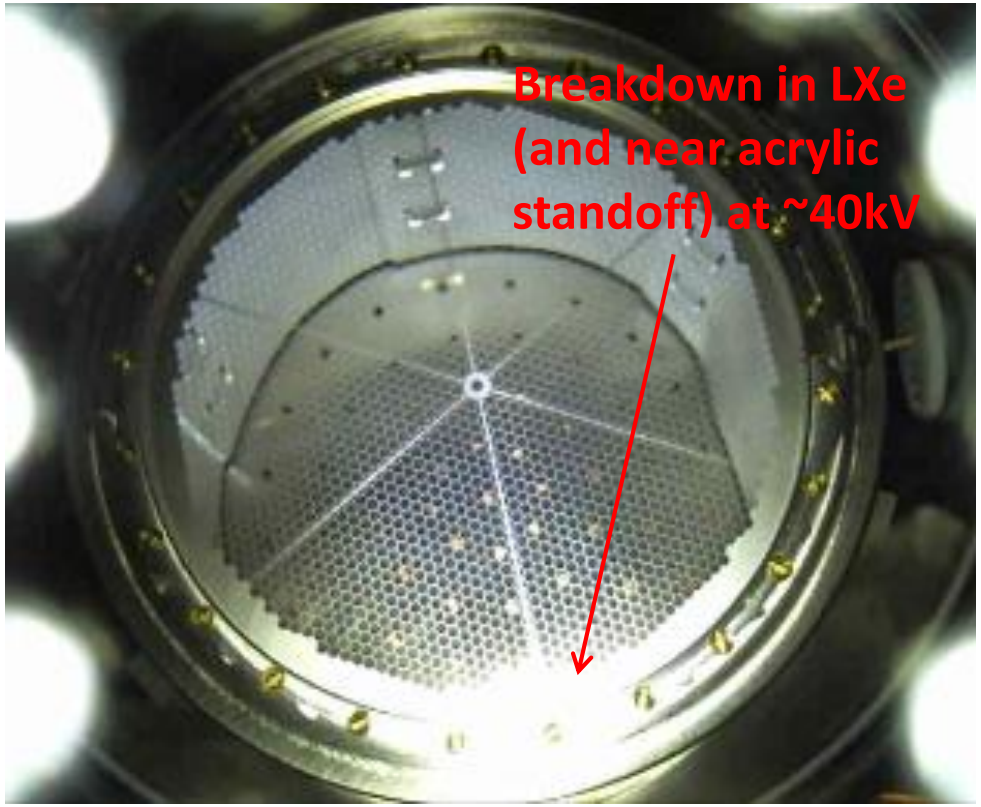
For recent results of nEXO R&D effort on SiPMs: *I.Ostrovskiy et al. IEEE TNS **62** (2015) 1825.*

# From EXO-200 to nEXO: Full list of advancements

| What | Why |
|---|---|
| ~30x volume/mass | To give sensitivity to the inverted hierarchy |
| No cathode in the middle | Larger low background volume/no $^{214}$Bi in the middle |
| 6x HV for the same field | Larger detector and one drift cell |
| >3x electron lifetime | Larger detector and one drift cell |
| Better photodetector coverage | Energy resolution |
| SiPM instead of APDs | Higher gain, lower bias, lighter, E resolution |
| In LXe electronics | Lower noise, more stable, fewer cables/feedthroughs, E resolution, lower threshold for Compton ID |
| Lower outgassing components | Longer electron lifetime |
| Different calibration methods | Very “deep” detector (by design) |
| Deeper site | Less cosmogenic activation |
| Larger vessels | 5 ton detector and more shielding |

# nEXO R&D is in full swing to address remaining challenges

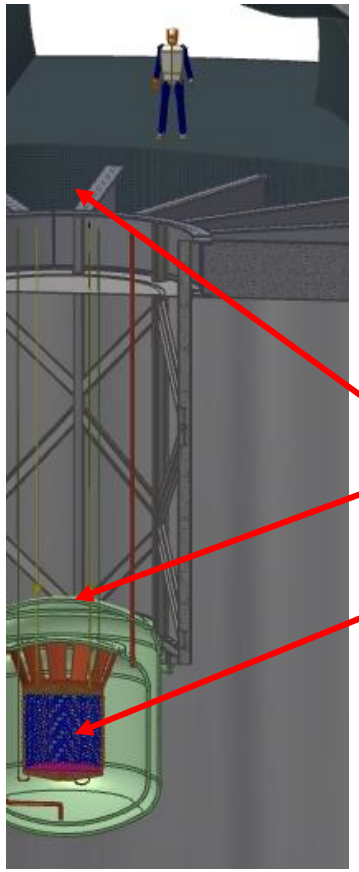
- High Voltage
  - Need 50 kV to maintain the same field as in EXO-200
  - Most LXe experiments had HV problems
  - Phase 1: <3kg setup confirms breakdown from well polished surfaces at ~300 kV/cm
  - Phase 2: 100kg “miniEXO” test setup in progress. Preliminary indication is that EXO-200 problems are specific to EXO-200
  - Phase 3: Planned full scale nEXO segment with final materials. Designed in coordination with LZ




“mini-EXO” test setup

# nEXO R&D is in full swing to address remaining challenges

- Cryogenic electronics
  - Cables are substantial contributor to background budget in EXO-200 and nEXO plans to further increase granularity of readout to improve topology discrimination
  - Fully integrated, ultra-low background cold electronics has not been built before
  - nEXO is working on a proof of principle chip for a 10x10 $cm^2$ tile, to be tested for radiopurity and in performance in LXe

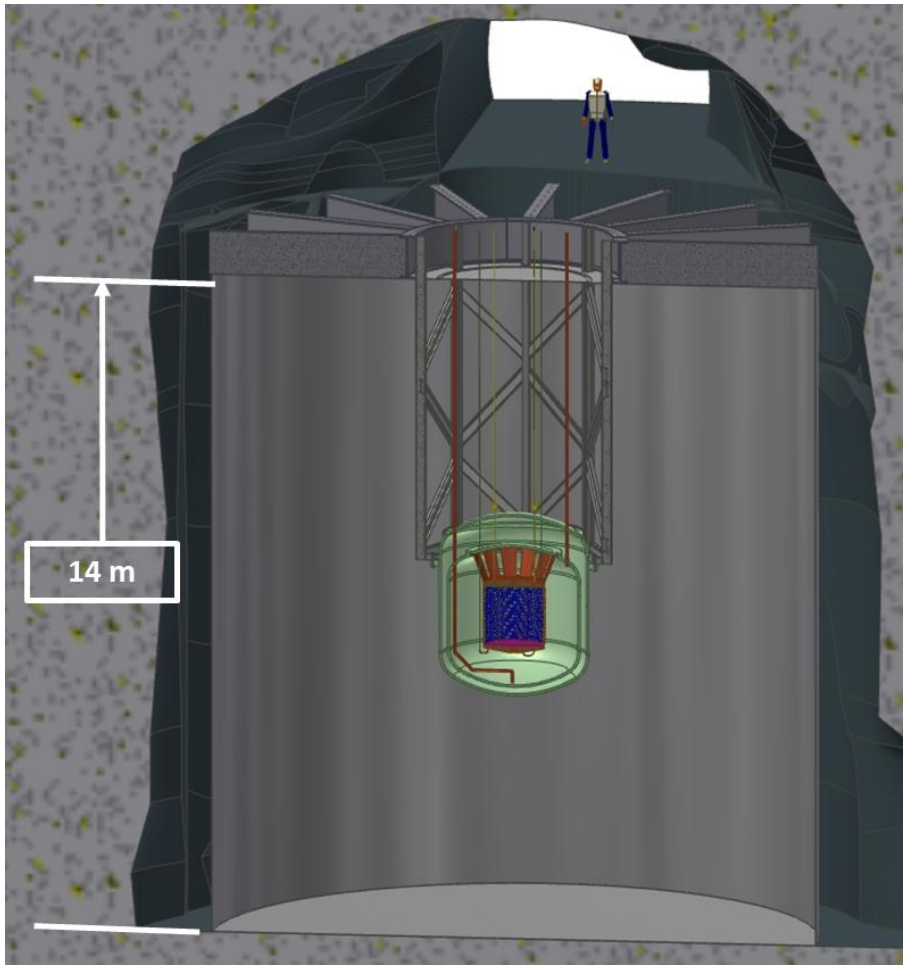


| Location | Cable length (m) | Total cap (pF) | Intrinsic RMS Noise (e) | RMS contribution to charge energy resolution | Charge cluster threshold (keV) |
|---|---|---|---|---|---|
| In lab (warm) | 8 | 800 | 3200 | 2.5% | 600 keV |
| At cryostat (warm/cold) | 2 | 200 | 800 | 0.6% | 150 keV |
| Inside TPC (cold) | ~0 | <40 | <200 | 0.2% | 40 keV |

Assumes simple tile charge collection system with interleaved strips and EXO-200 style cables for the remote location cases.

# nEXO R&D is in full swing to address remaining challenges

- Also working on material radiopurity tests, simulation, calibration ideas
- Limited work on mechanical design of the vessel and cryostat
  - TPC vessel is copper, as in EXO-200
  - Considering carbon-composite cryostat (easier to construct UG, potentially cleaner, would not need as much HFE)
- Cryopit (SNO lab) as primary choice of location
  - $^{137}$Xe background (~25% in EXO-200) is not an issue



# Summary

- EXO-200 has already produced one of the strongest results for neutrinoless, two-neutrino, and Majoron-mediated decays
  - The experiment is currently preparing for Phase-II
  - Phase-II is expected to improve sensitivity to neutrinoless decay by up to a factor of 3, compared to Phase-I (assuming 3 years of data-taking and stated hardware and analysis improvements)
- The next generation experiment, nEXO, is a planned 5-tonne scale-up
  - Because of its multi-parameter capabilities, nEXO has robust discovery potential
  - Its general configuration was validated by successful EXO-200
  - Homogeneity is a desirable feature. Required R&D is in full swing
  - This is a tested collaboration that is known to be capable of successfully executing every phase of an experiment
  - It is essential that this science is done in an effective and timely manner. *nEXO plans to be ready to start construction project in 2017*

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