XVI International Workshop on Neutrino Telescopes

2-6 March 2015, Palazzo Franchetti, Istituto Veneto di Scienze, Lettere ed Arti, Venezia, Italy

From EXO-200

to nEXO

Andrea Pocar

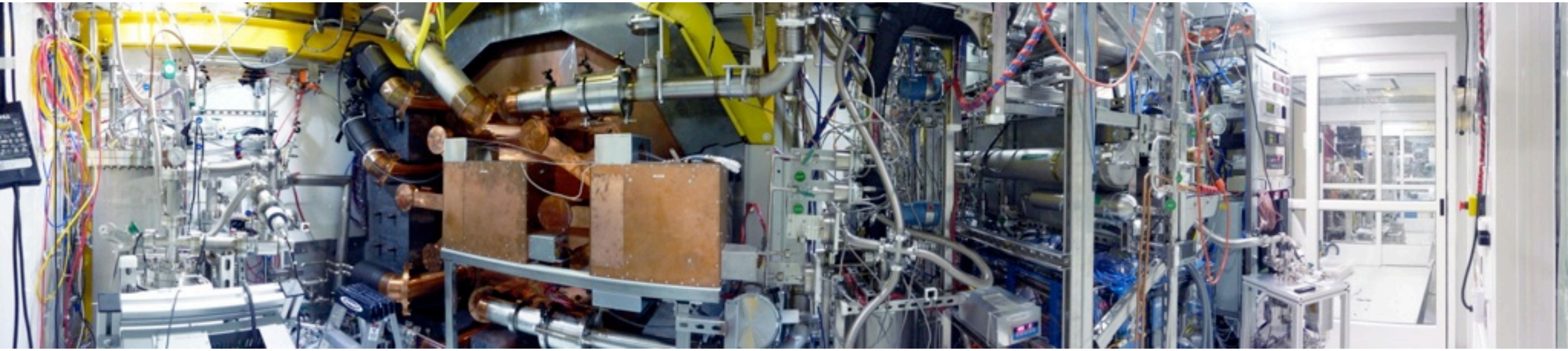
University of Massachusetts, Amherst

Lawrence Livermore National Laboratory

on behalf of the
EXO-200 and nEXO collaborations

Outline

- The Enriched Xenon Observatory (EXO) Program
- The EXO-200 experience
- From EXO-200 to nEXO
- nEXO R&D
- Status and future of EXO-200
- Outlook



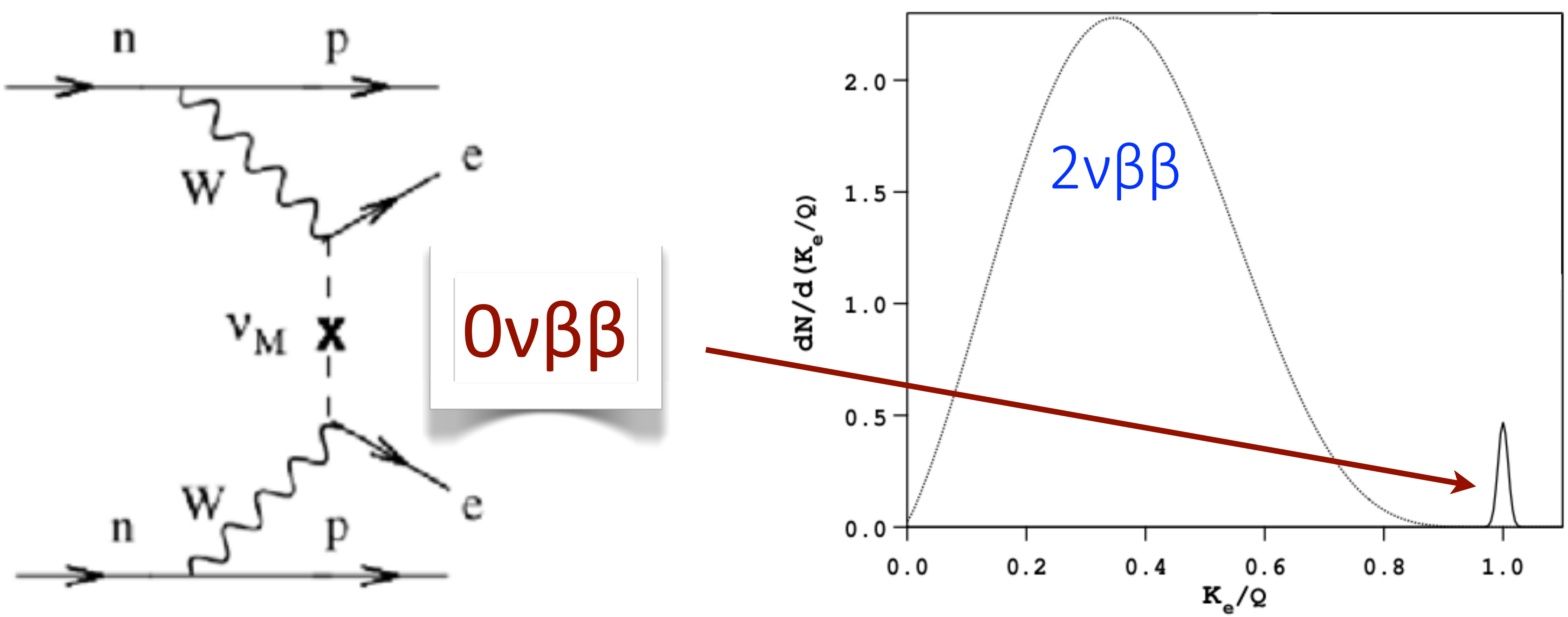
Why 0νββ double beta decay

observation of 0νββ decay:

- massive, Majorana neutrinos
- lepton number violation

0νββ rate

- absolute neutrino mass (model dependent)



The Enriched Xenon Observatory

Search for $0\nu\beta\beta$ decay of ^{136}Xe (Q=2458 keV) with enriched xenon TPC's (with scintillation readout) of increasing sensitivity and size

Enrichment is relatively simpler and less expensive

- 10% --> 80-90% proven on the 100's kg scale

Continuous re-purification possible

- form electronegative and radioactive contaminants

Xenon is reusable

- could be transferred between experiments

Monolithic detector, remarkable self-shielding

Good (enough) energy resolution

- with combined scintillation + ionization

$\beta\beta/\gamma$ discrimination

- event topology

Limited cosmogenic activation

- longest-lived 4 minutes

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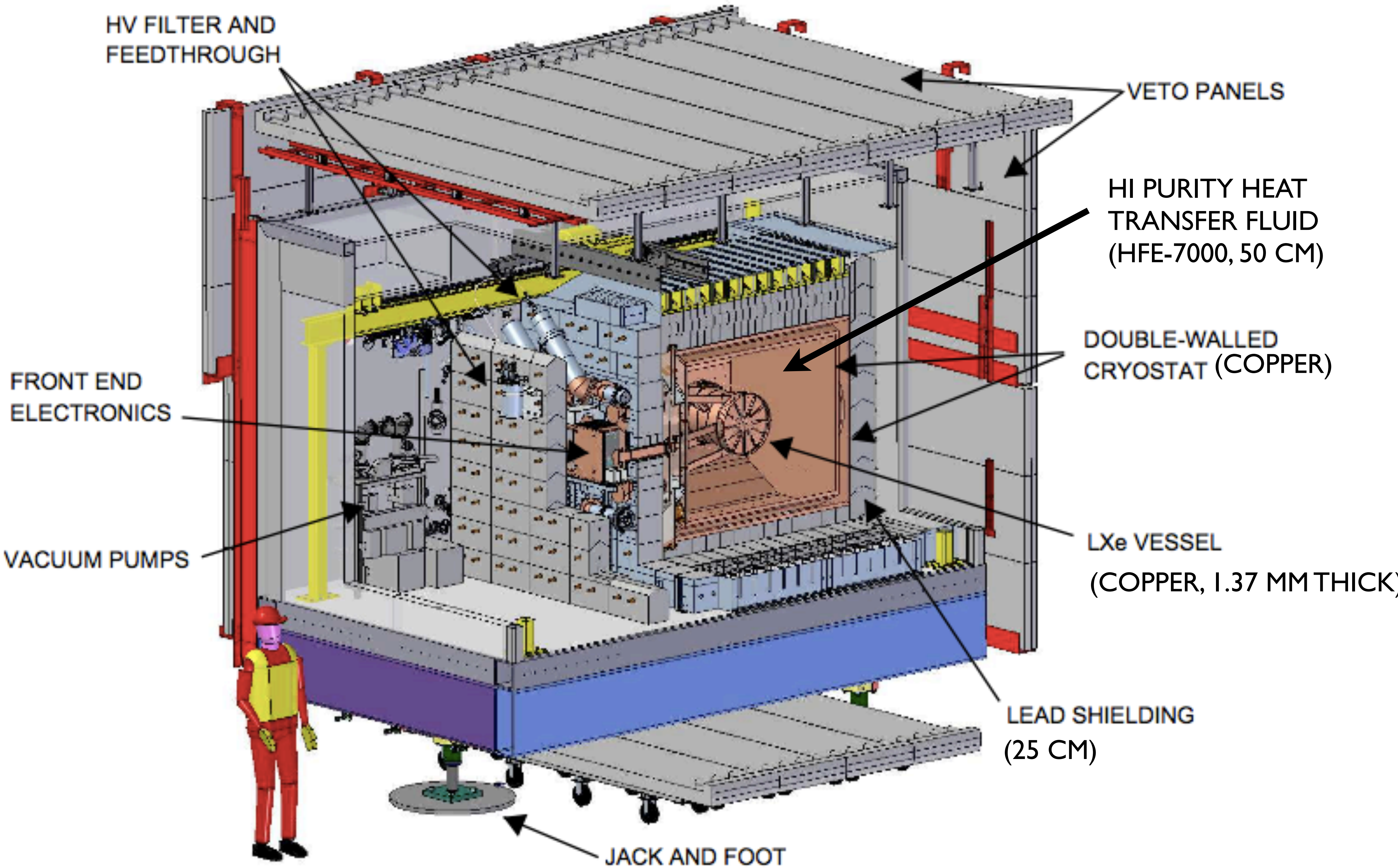
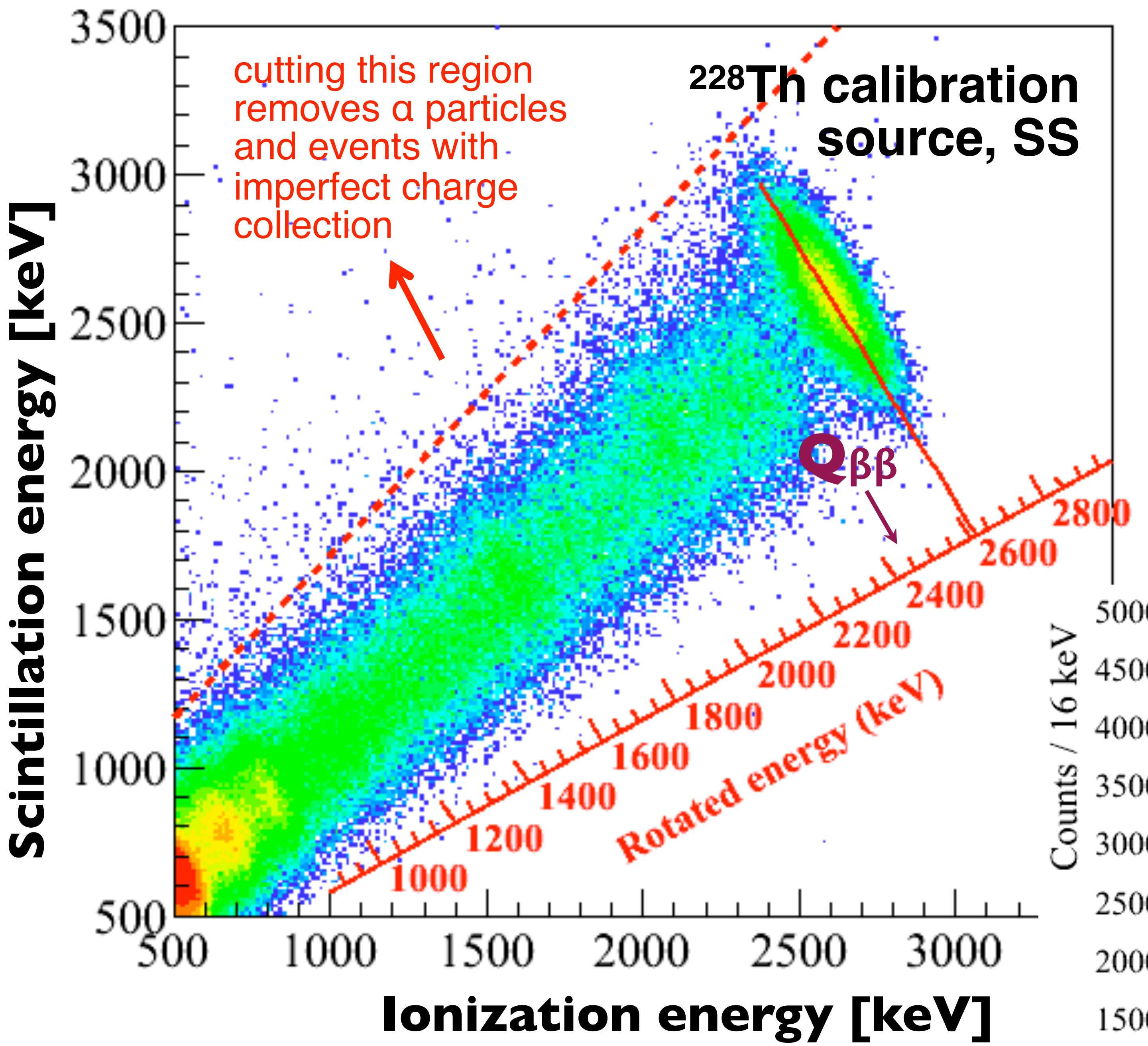
Xenon admits a novel coincidence technique
- Ba daughter tagging

M. Moe, PRC 44, R931 (1991)

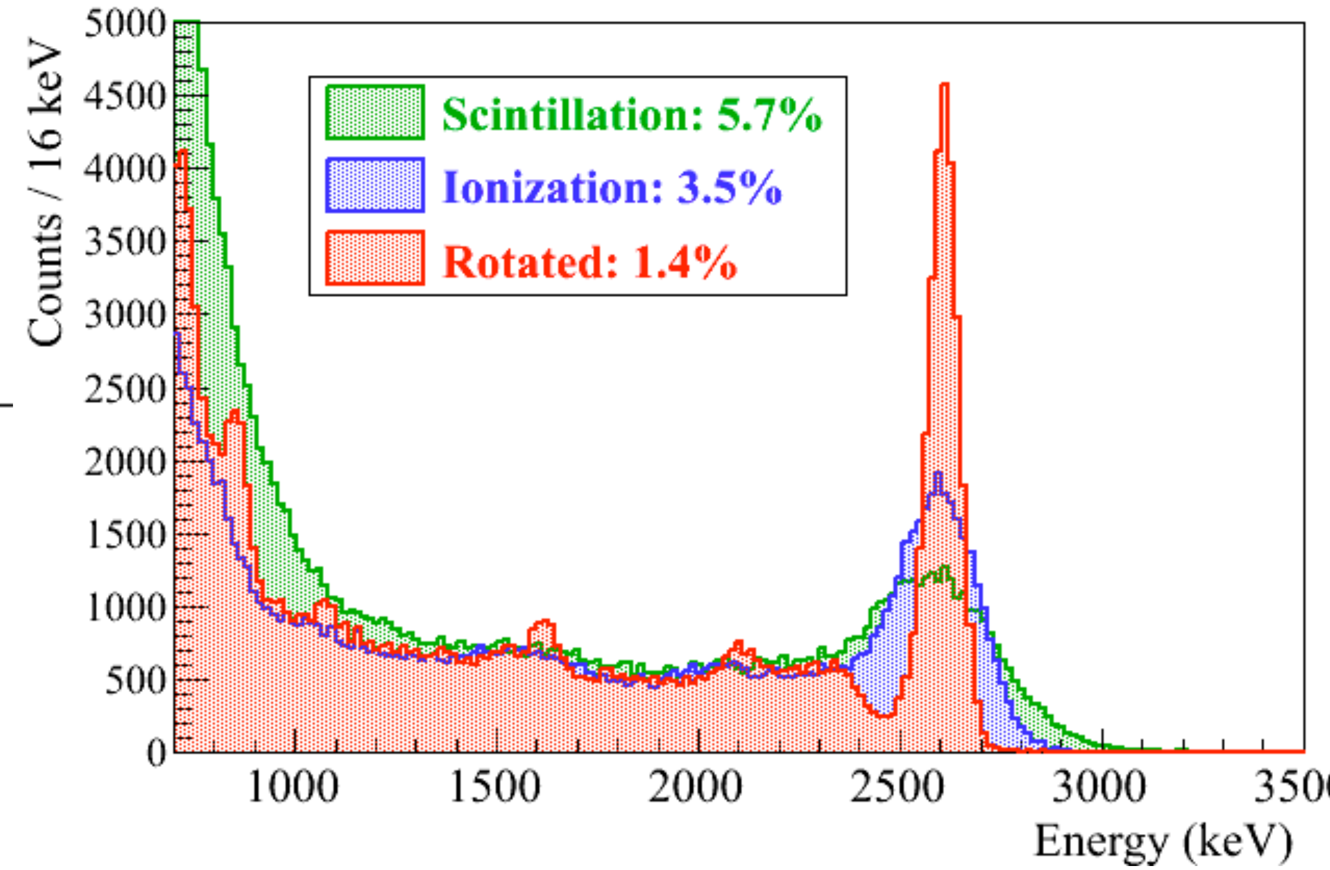
The EXO-200 detector at WIPP (~1,500 m.w.e.)



Energy reconstruction



- Reconstruct "rotated" energy measured in scintillation versus ionization plane
- Takes into account anti-correlation of charge and scintillation response to improve energy resolution
- Calibration performed with ^{60}Co, ^{137}Cs, ^{226}Ra, and ^{228}Th
- Denoised LAAPD signals

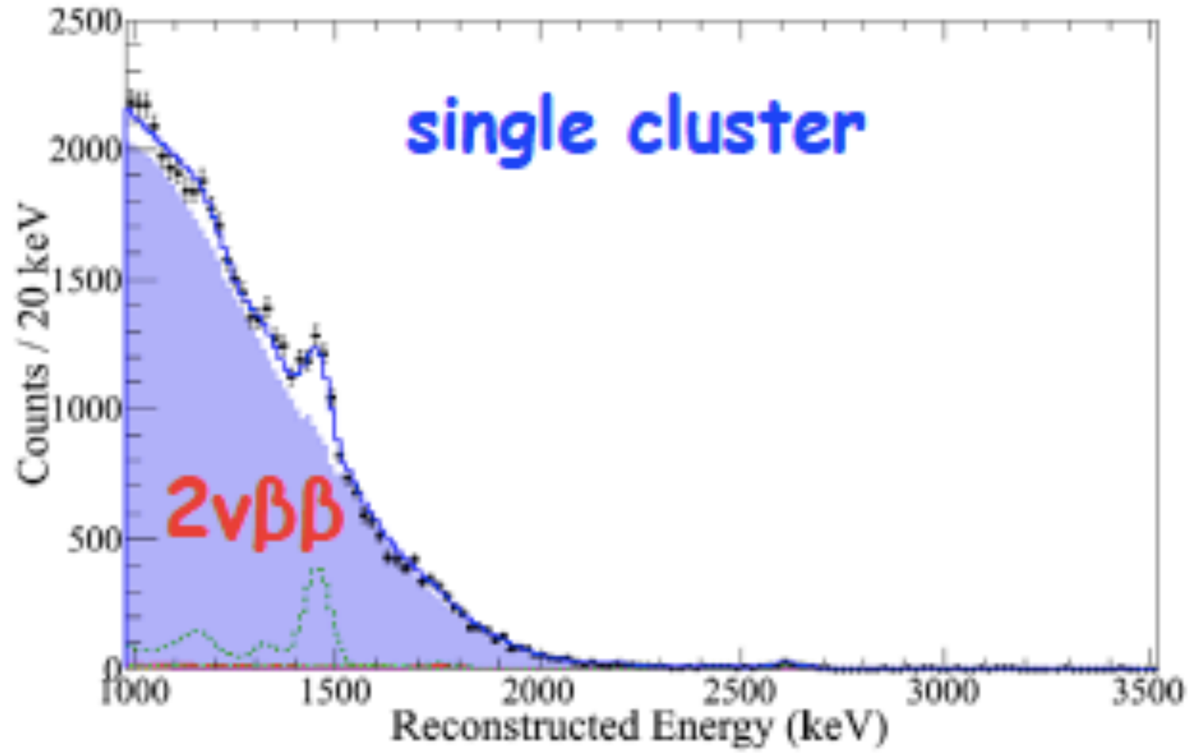


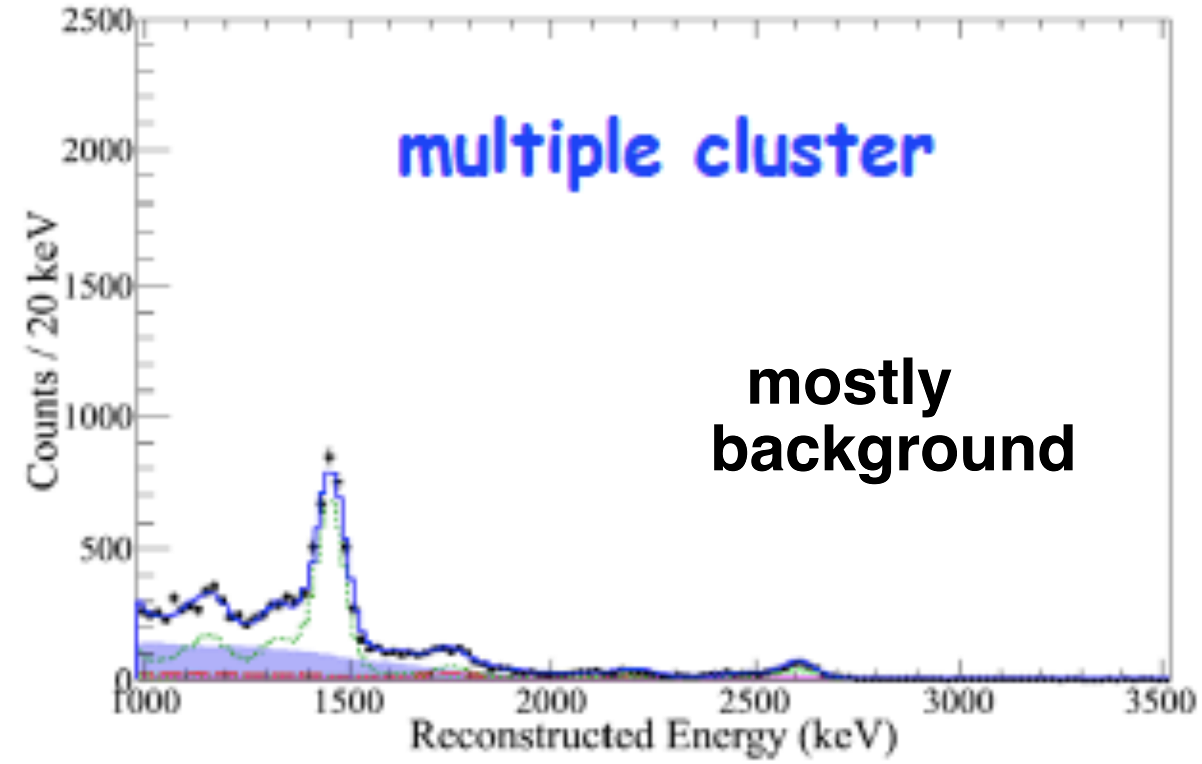
Molecular properties of xenon cause increased scintillation to be associated with decreased ionization (and vice-versa)

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

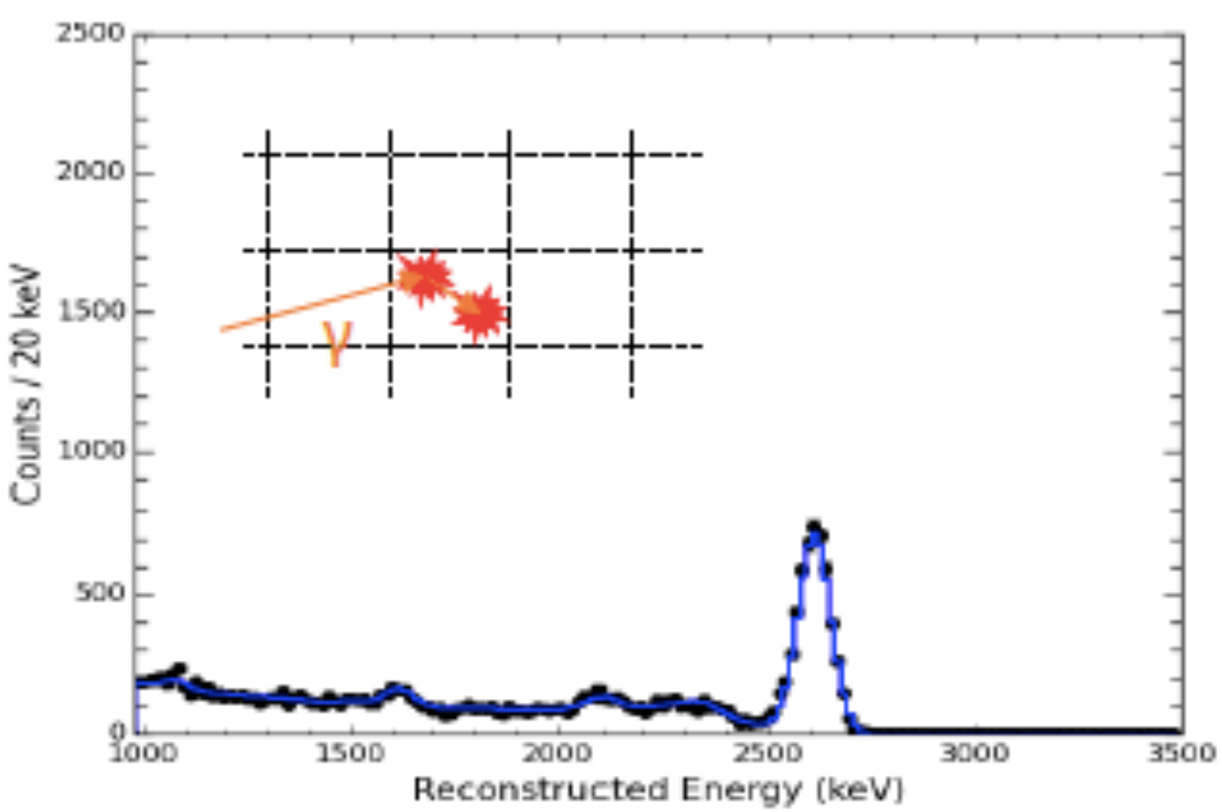
Background discrimination and tracking

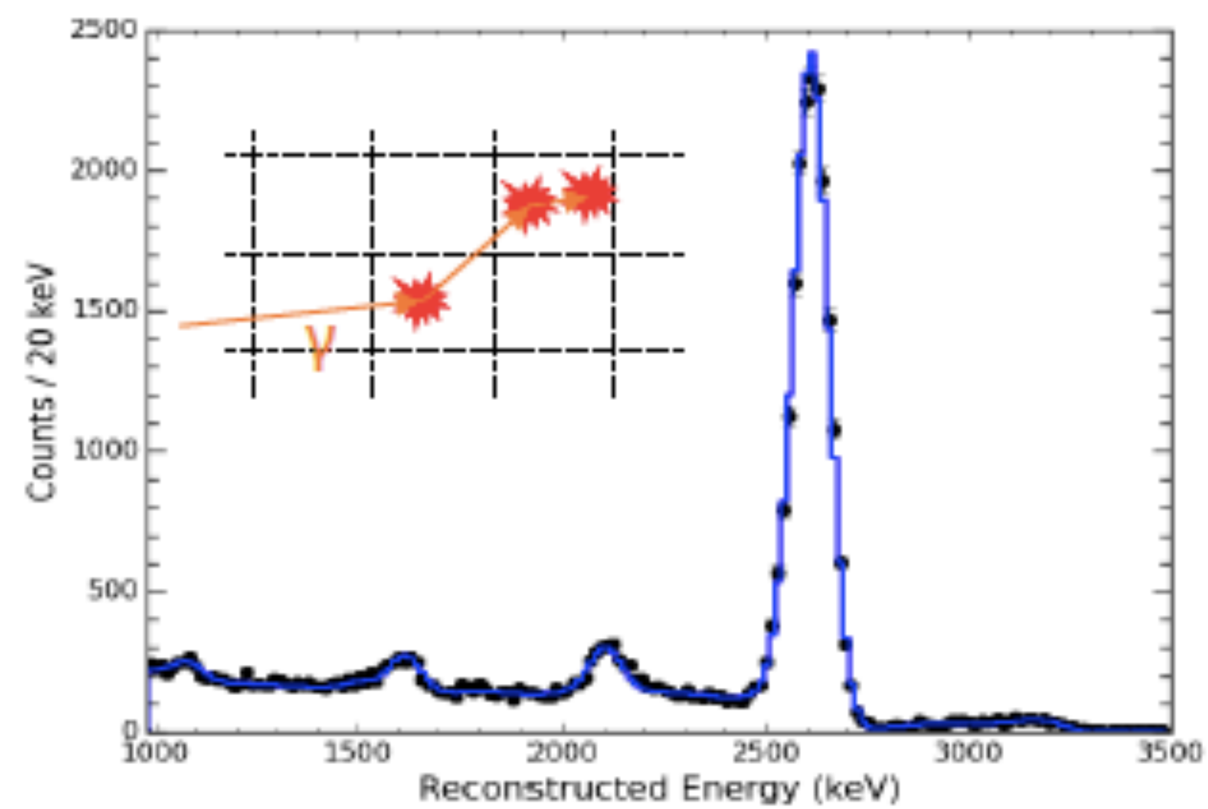
Low background data



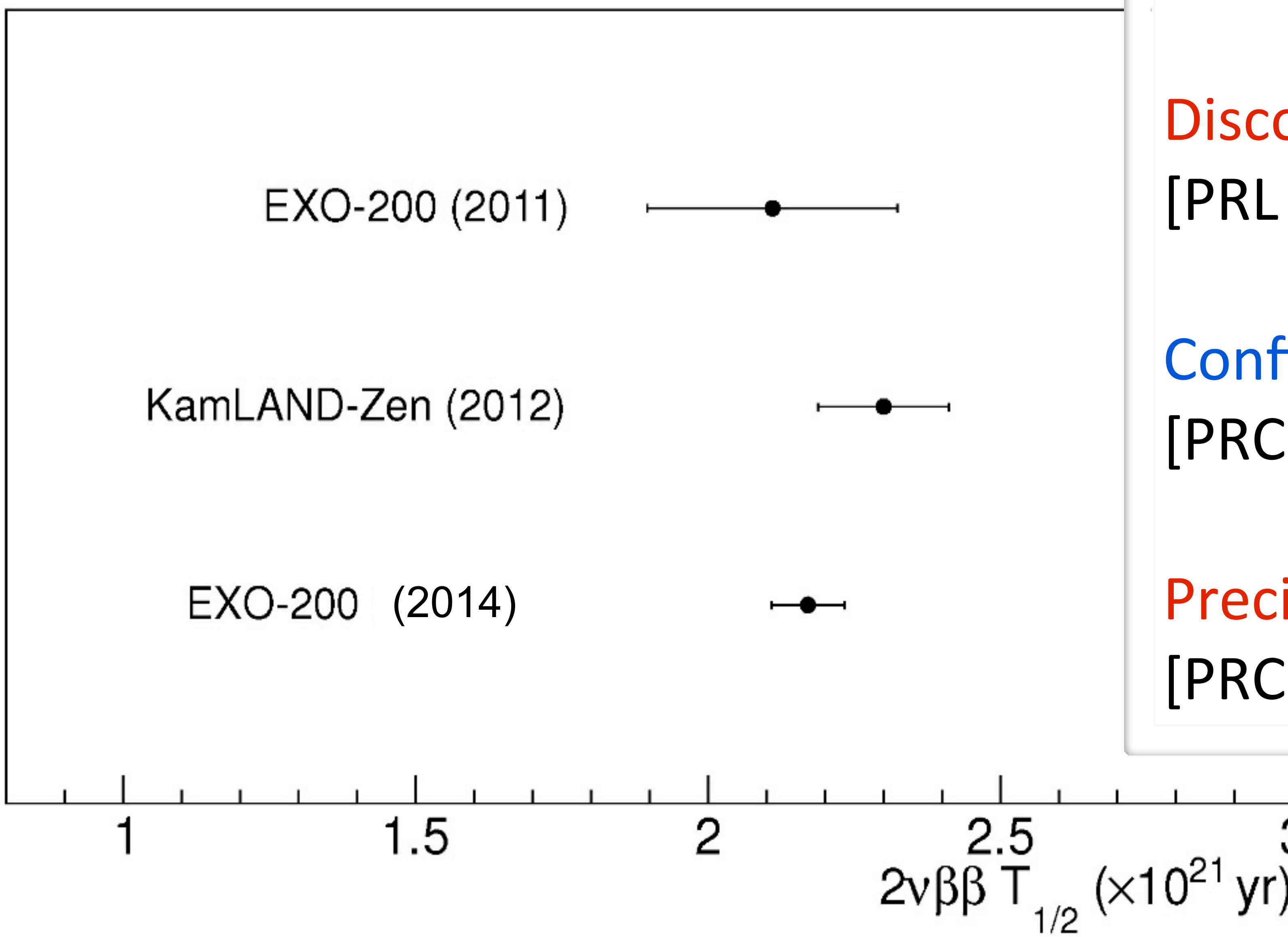


^{228}Th calibration source





EXO-200: precision measurement of 2νββ decay of ^{136}Xe



Start data taking in June 2011

Discovery of 2νββ decay of 136Xe
[PRL 107, 212501 (2011)]

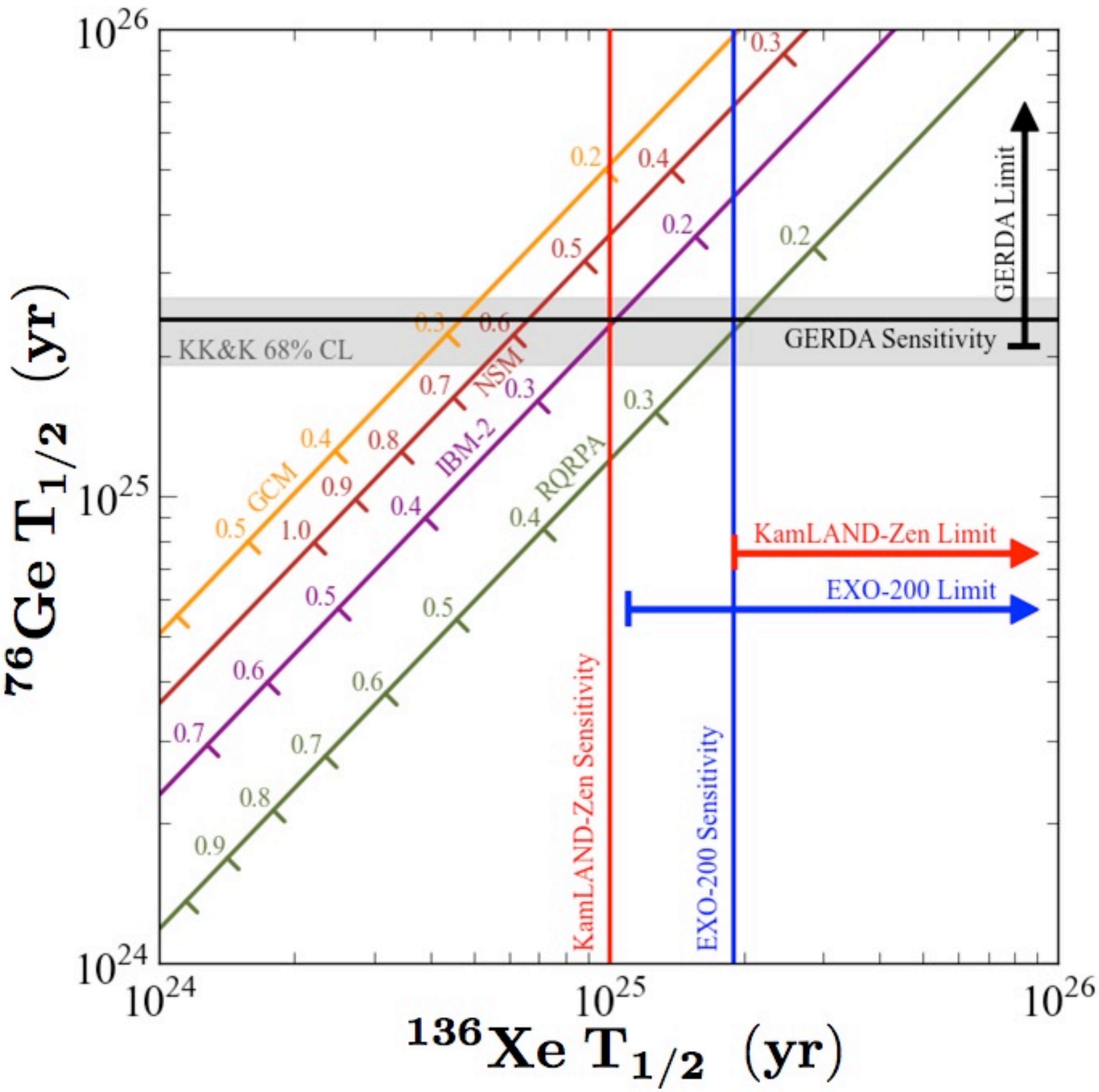
Confirmation by KamLAND-Zen
[PRC 85, 045504 (2012)]

Precision measurement (~3%)
[PRC 89, 015502 (2014)]

$$\mathbf{T^{2\nu\beta\beta}_{1/2} = (2.165 \pm 0.016(stat) \pm 0.059(syst)) \times 10^{21} yr}$$

(longest, yet most precisely measured 2νββ decay of all 'practical' isotopes)

EXO-200: search for 0νββ decay of ^{136}Xe



EXO-200 limit:

$$T^{0\nu\beta\beta}_{1/2} > 1.1 \times 10^{25}\ \text{yr}\ \ (90\%\ \text{C.L.})$$

$$< m_{\beta\beta} >= 190 - 450\ \text{meV}$$

EXO-200 sensitivity:

$$T^{0\nu\beta\beta}_{1/2} = 1.9 \times 10^{25}\ \text{yr}$$

[Nature, 510, 229-234 (2014)]

[GERDA: PRL 111, 122503 (2013)]

[KL-Zen: PRL 110, 062502 (2013)]

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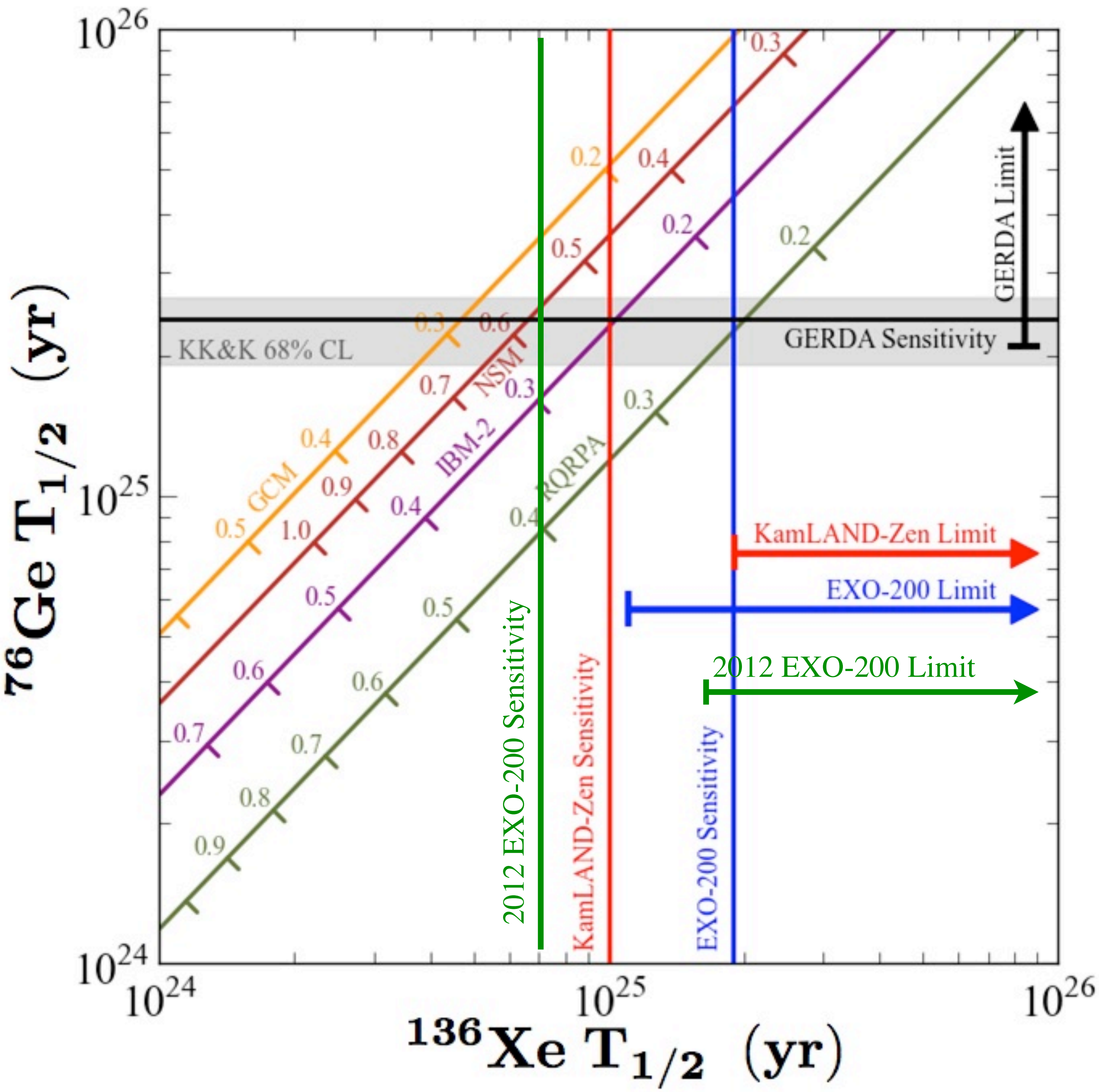

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[PRL 109, 032505 (2012)]

What have we learnt from EXO-200?

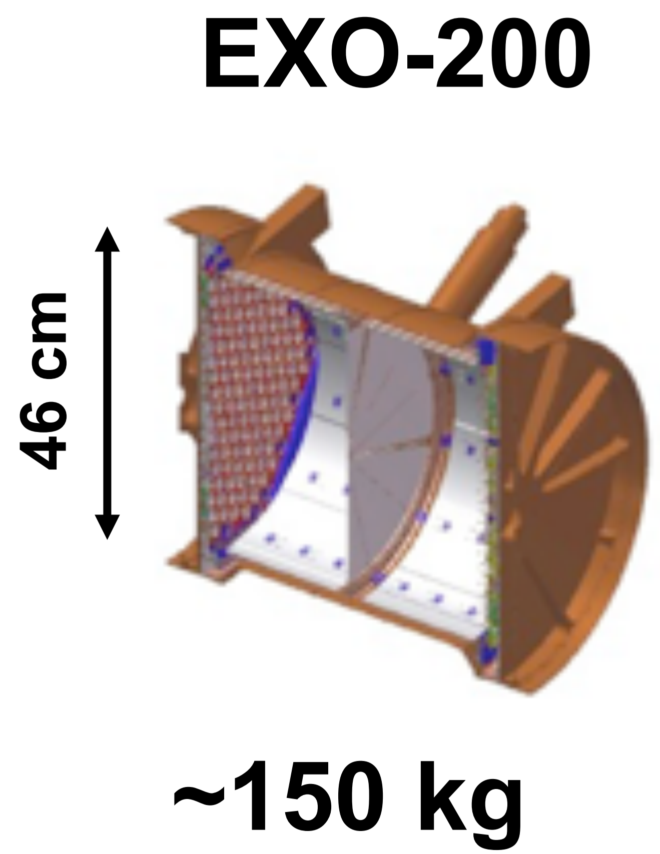
- Operated a 100 kg scale enriched-LXe TPC for 2 years
    - Measured residual **backgrounds consistent with radio-assays**
    - Reached design (anti-correlated) **energy resolution, σ/E(Q)=1.5%**
    - Stable **electron drift time of ~3 ms** or better
    - Demonstrated power of **standoff distance in monolithic detector**
    - Demonstrated power of **single-/multi-site β/γ discrimination**

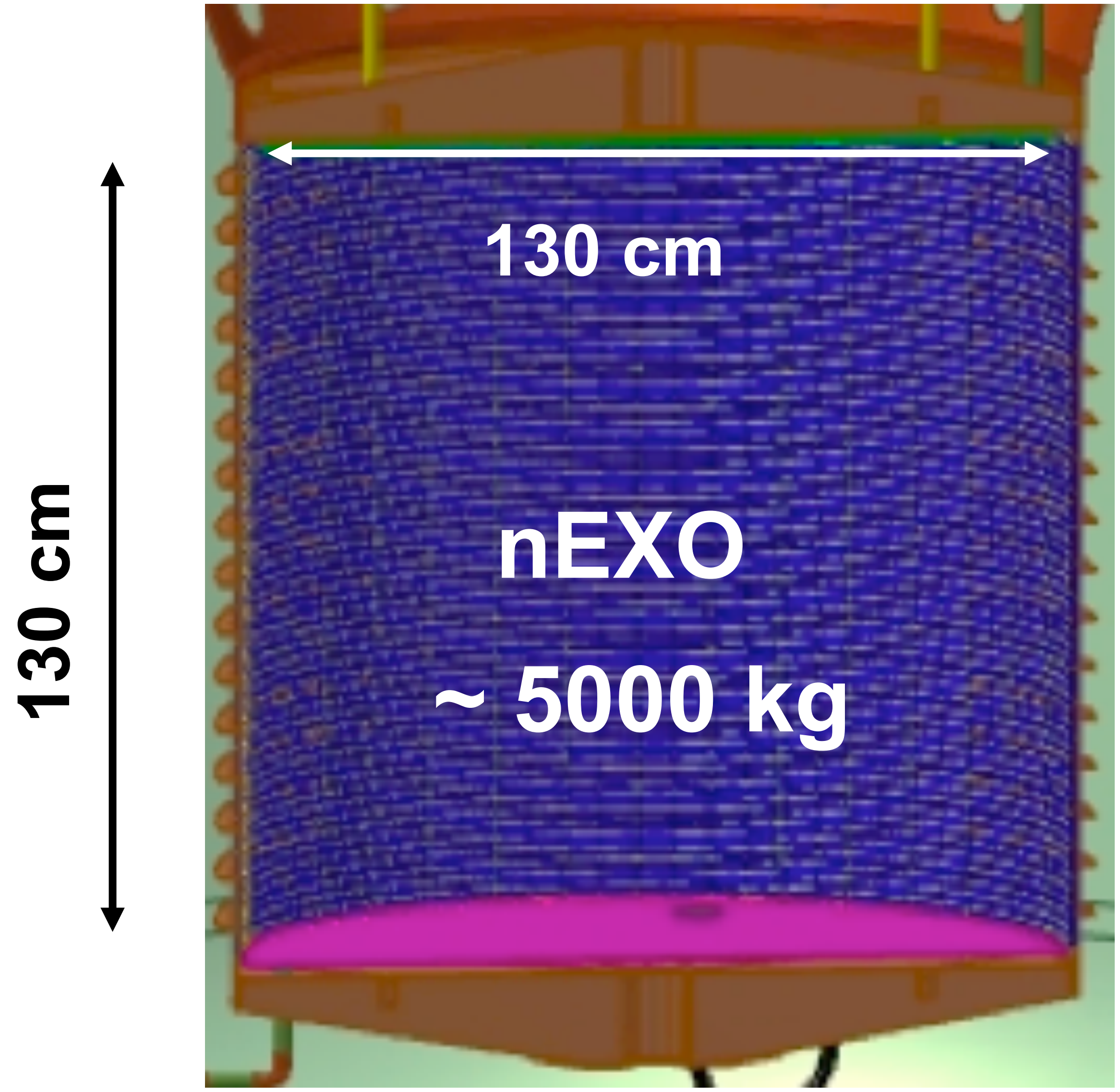
- Implemented novel detector solutions
    - 500x LAAPDs for VUV (175 nm) scintillation detection
    - Photo-etched, charge collection wires, cathode, and fasteners
    - Epoxy-potted, kapton flat cable feedthroughs
    - HFE-7000 thermal bath and radiation shield
    - Ultra-light design, no solder joints, no electrical connectors

From EXO-200 to nEXO

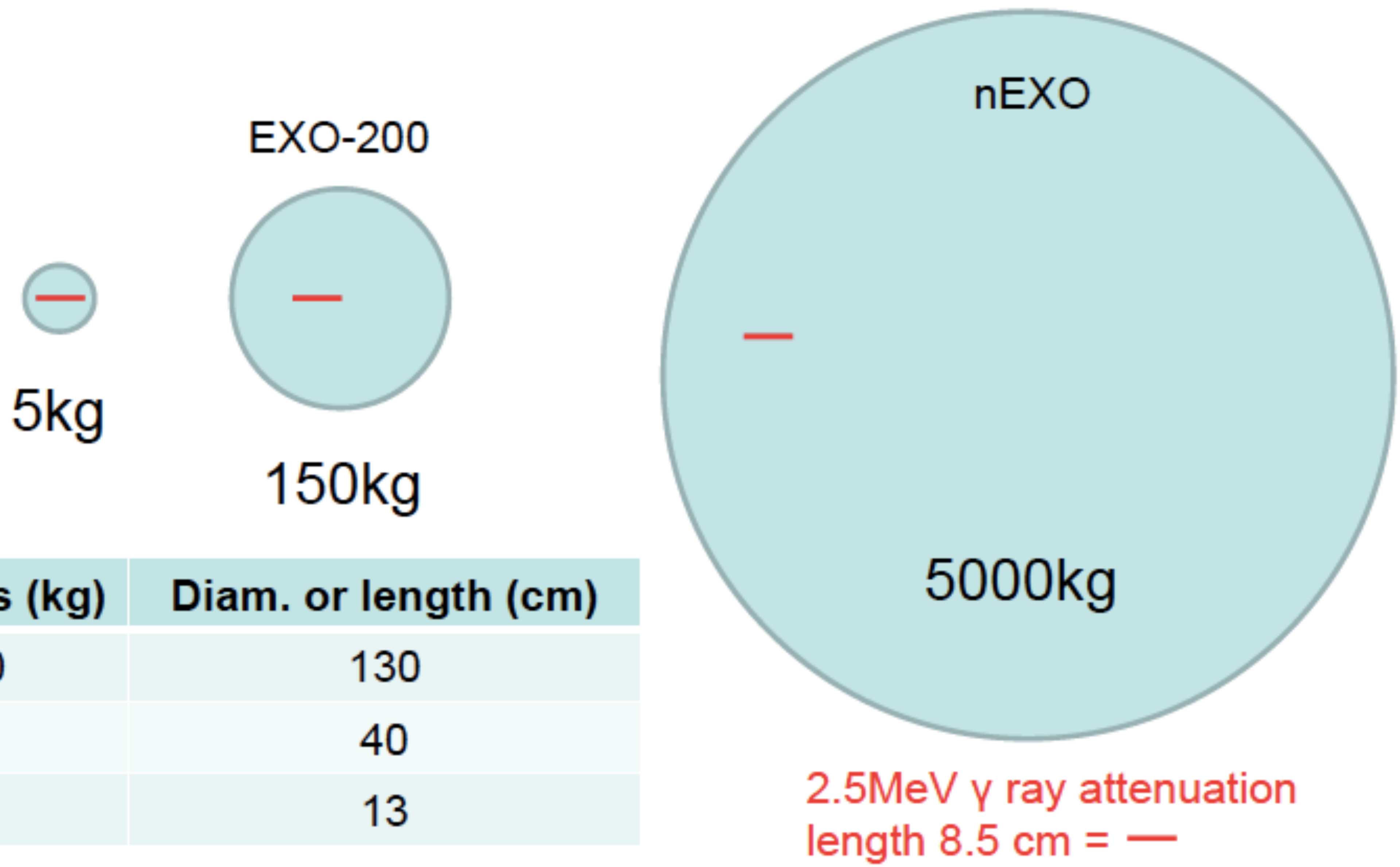
- 5 tonnes of enriched LXe
- enhanced self-shielding
- x100 better $T_{1/2}$ sensitivity

- < 1% energy resolution
- no central cathode
- *no* Ba tagging (initially)





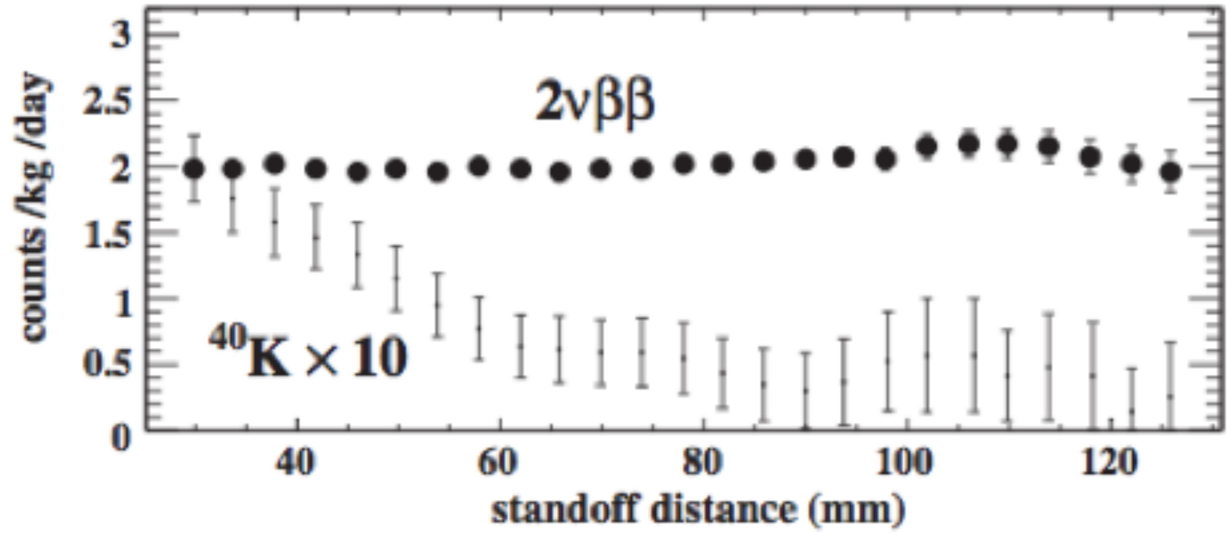
From EXO-200 to nEXO

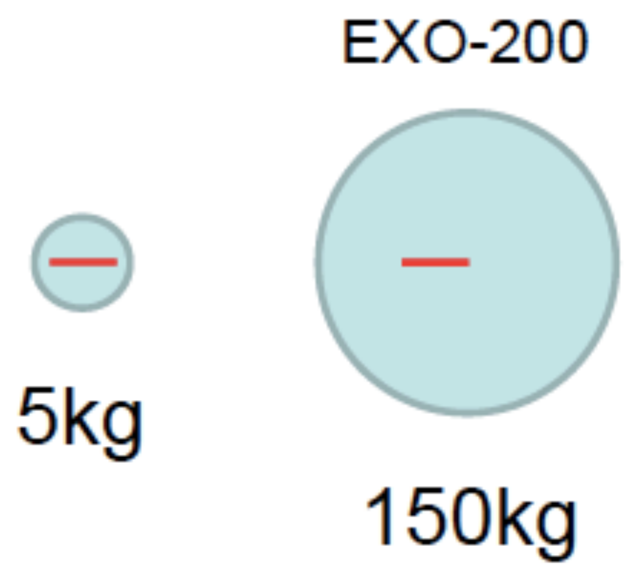


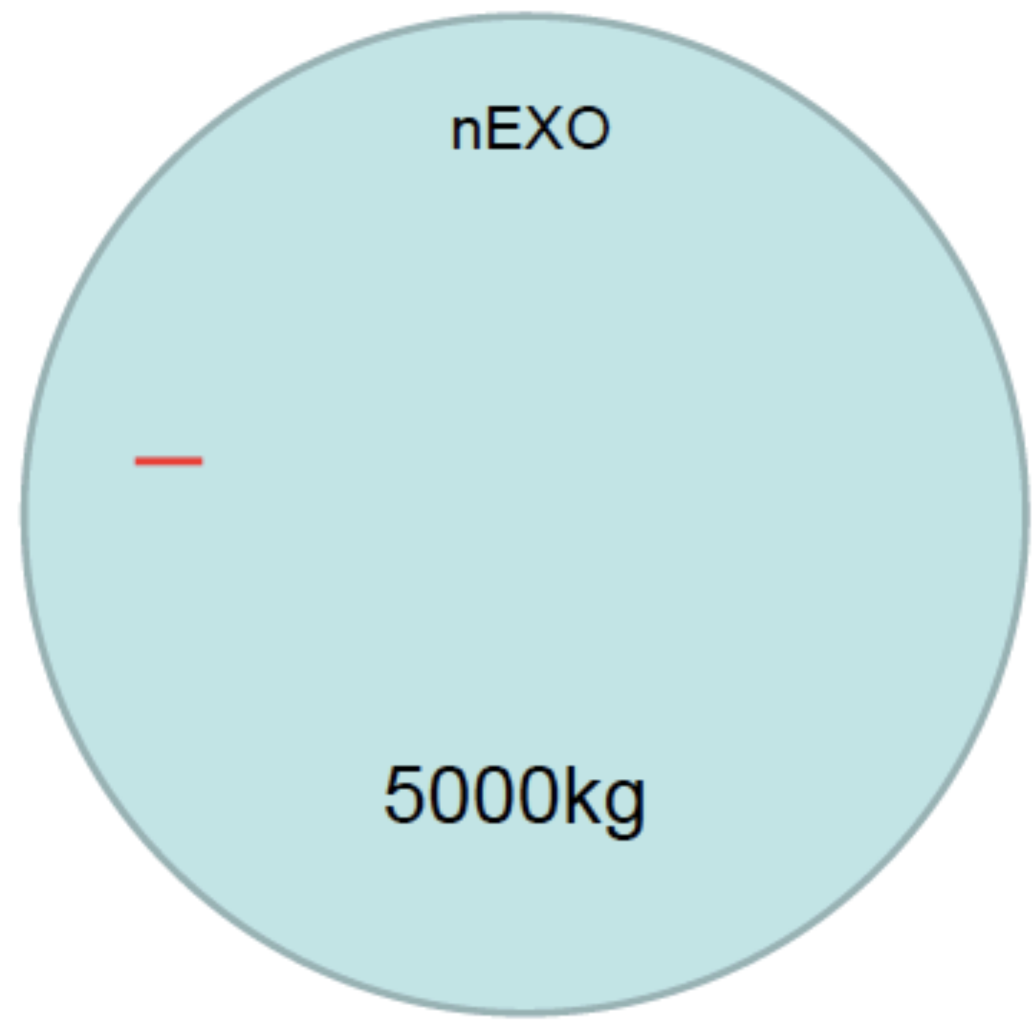
LXe mass (kg)	Diam. or length (cm)
5000	130
150	40
5	13

Monolithic design is dramatically improves performance with size

From EXO-200 to nEXO





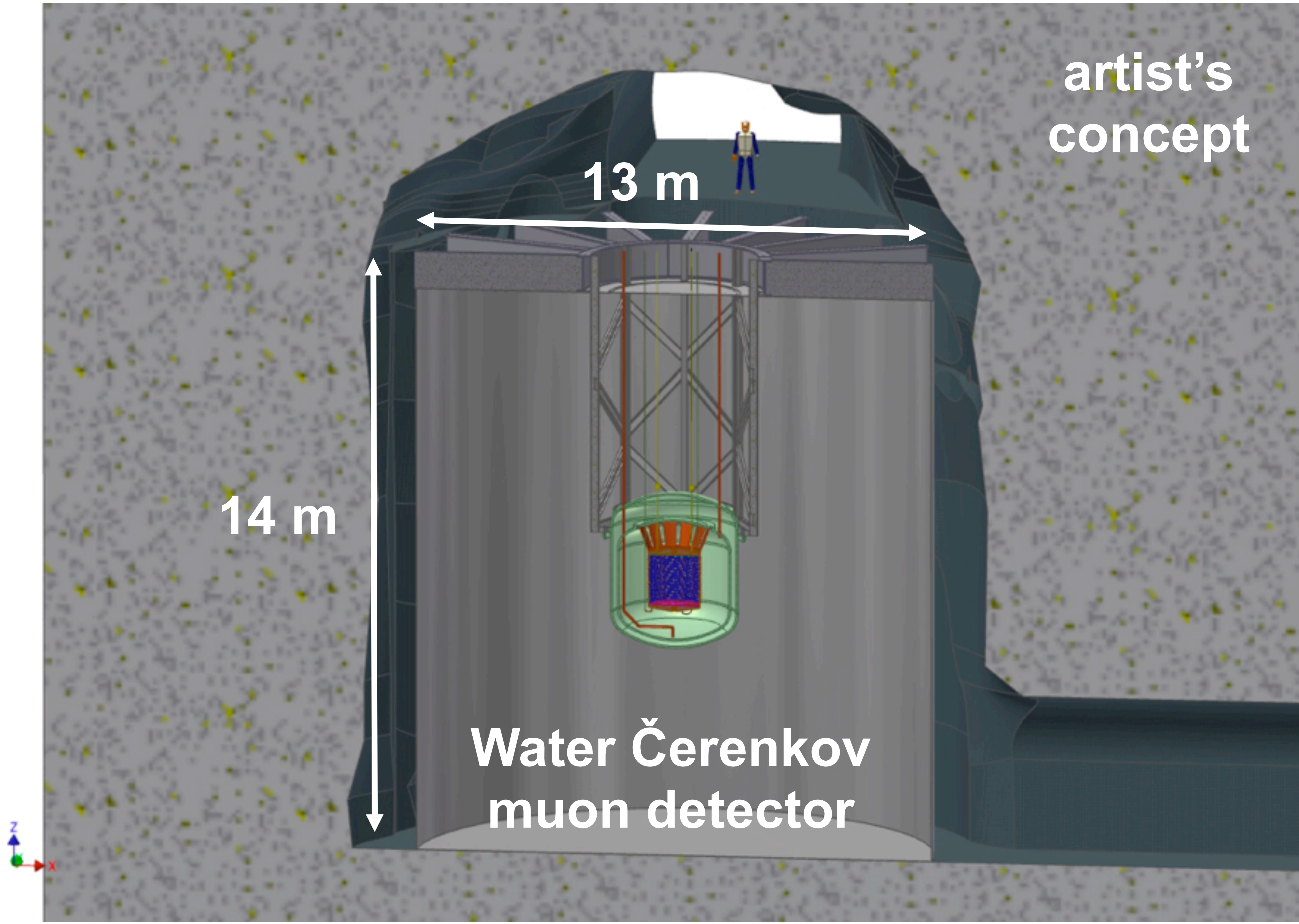


LXe mass (kg)	Diam. or length (cm)
5000	130
150	40
5	13

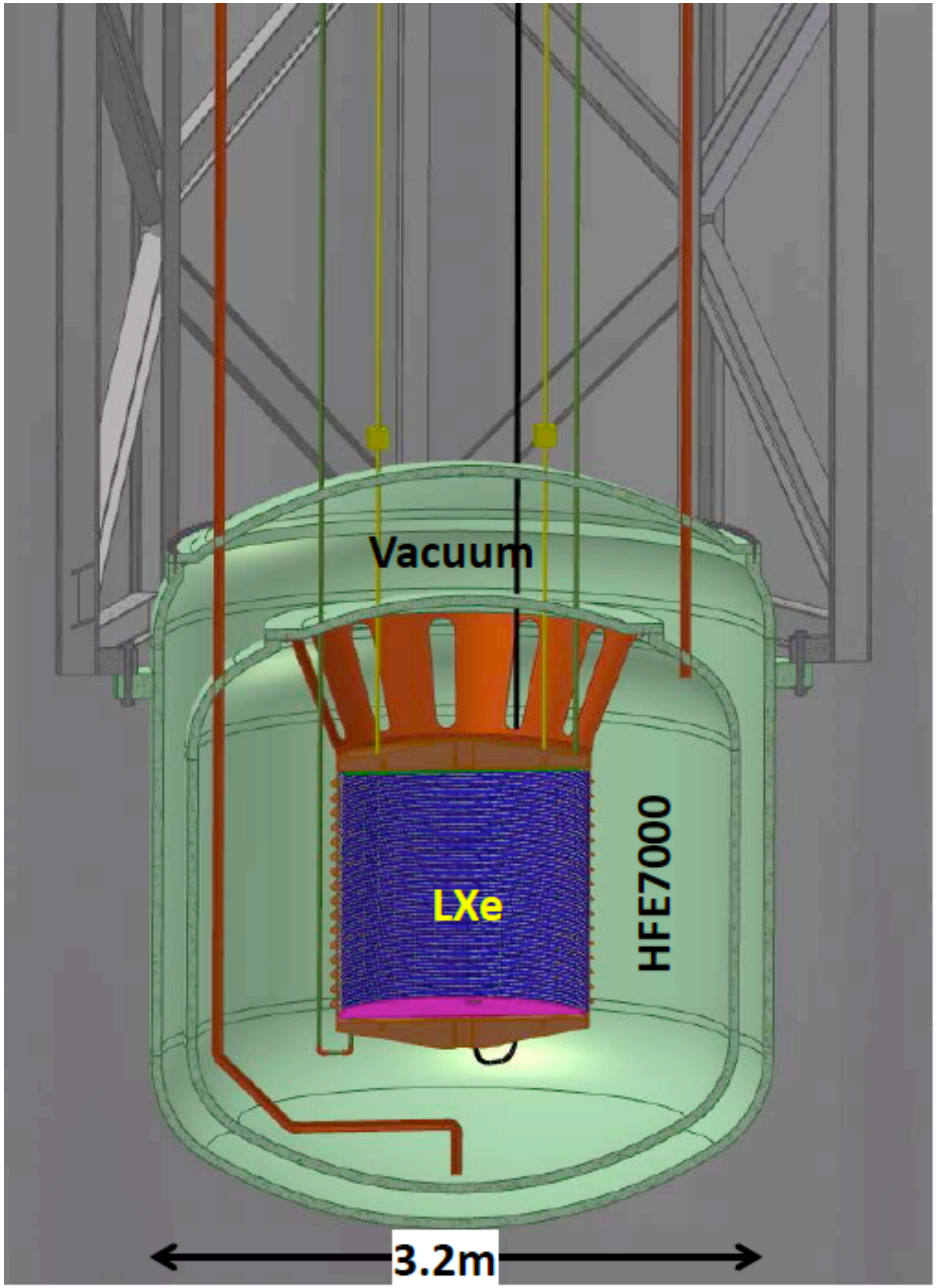
2.5MeV γ ray attenuation length 8.5 cm = —

Monolithic design is dramatically improves performance with size

nEXO (inside SNOLab's Cryopit)



nEXO Cryostat



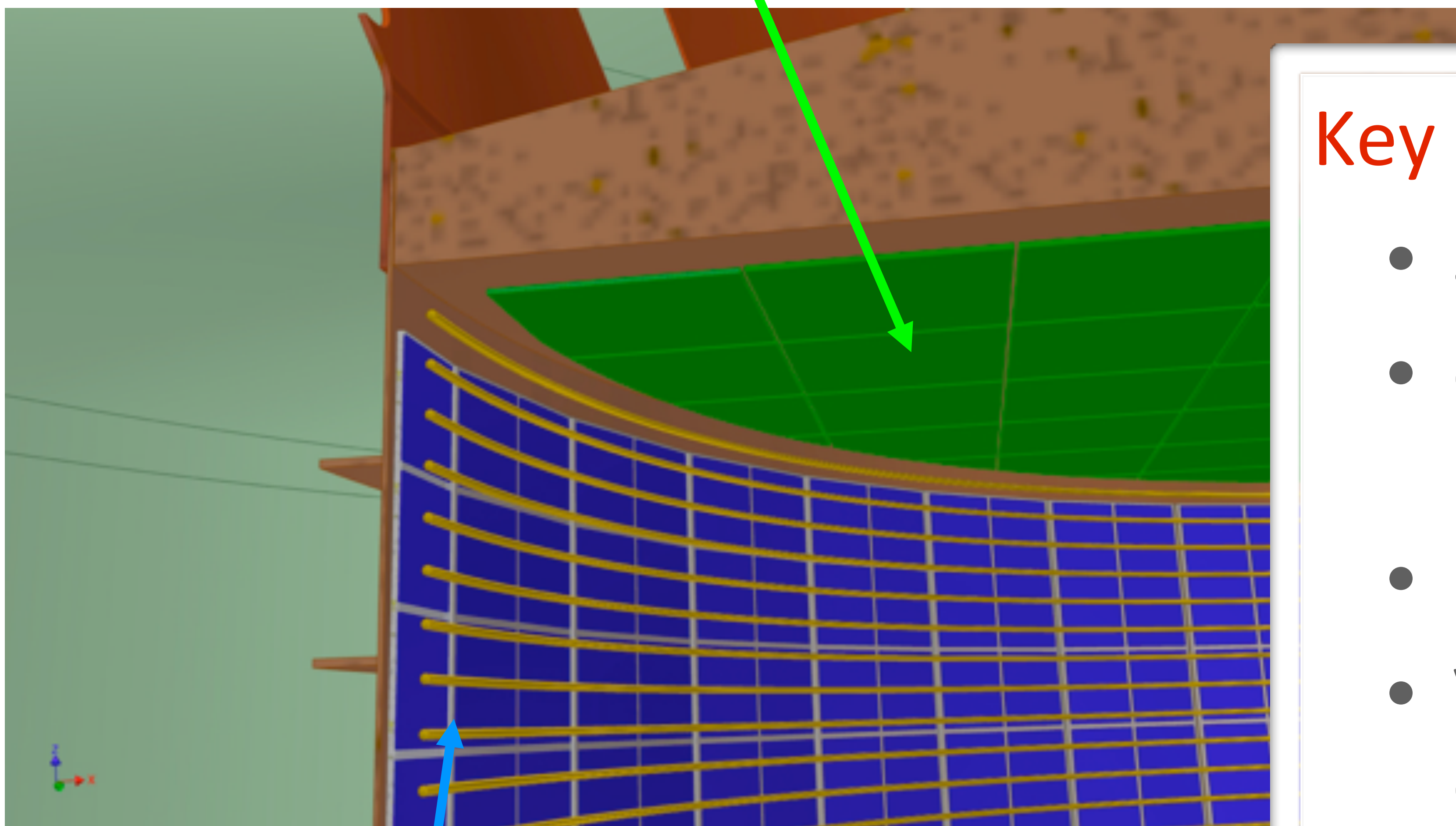
Researching the feasibility of a carbon fiber composite cryostat

- construction underground
- low background

R&D:

- feedthroughs
- material selection
- low temperature performance

nEXO TPC



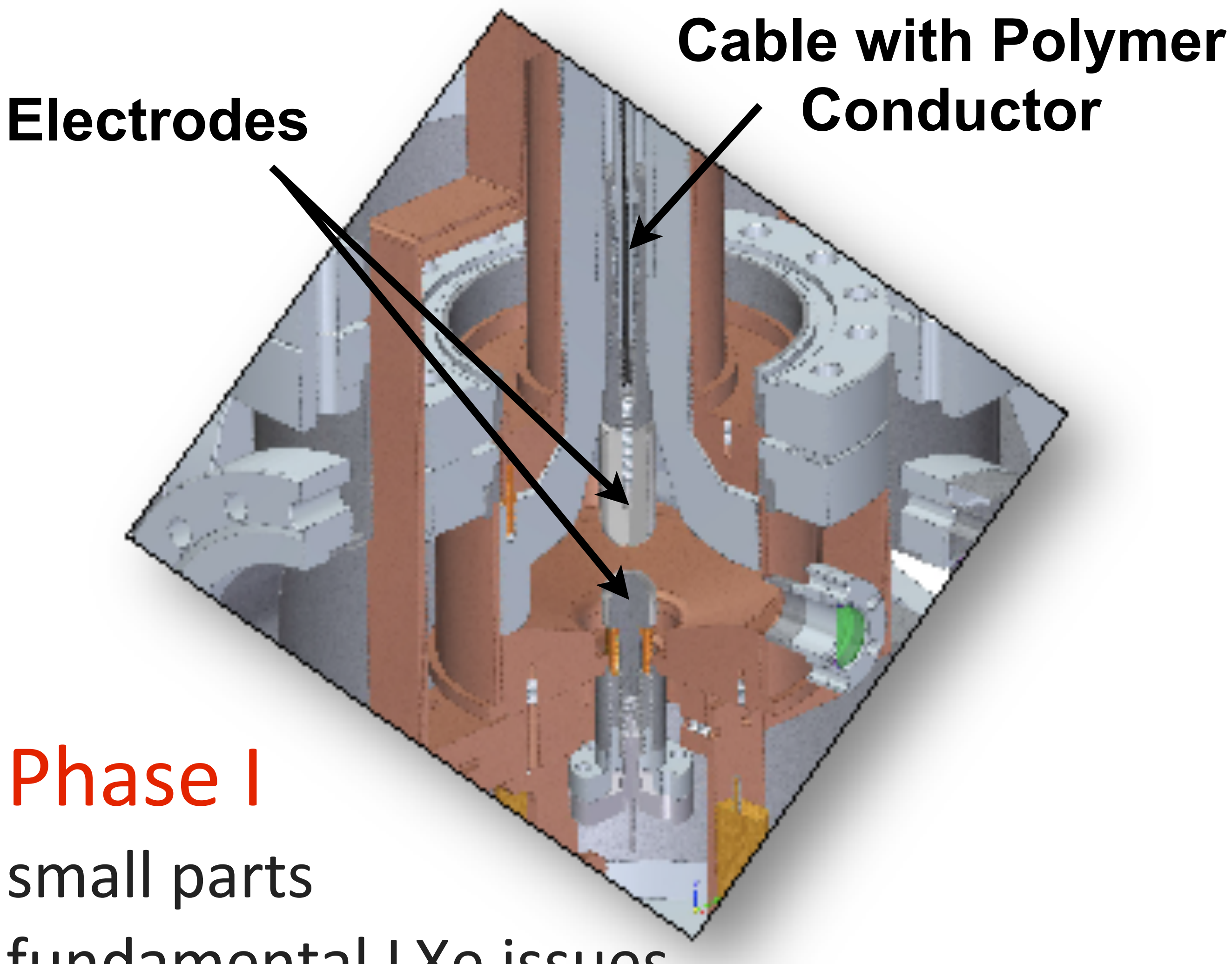
TPC: ~ 1.3 m x 1.3 m

Key features

- single drift volume
- charge collected on pads
- 'no' plastics
- VUV scintillation collected on SIPMs behind the field cage
- thin Cu vessel

nEXO R&D in full swing

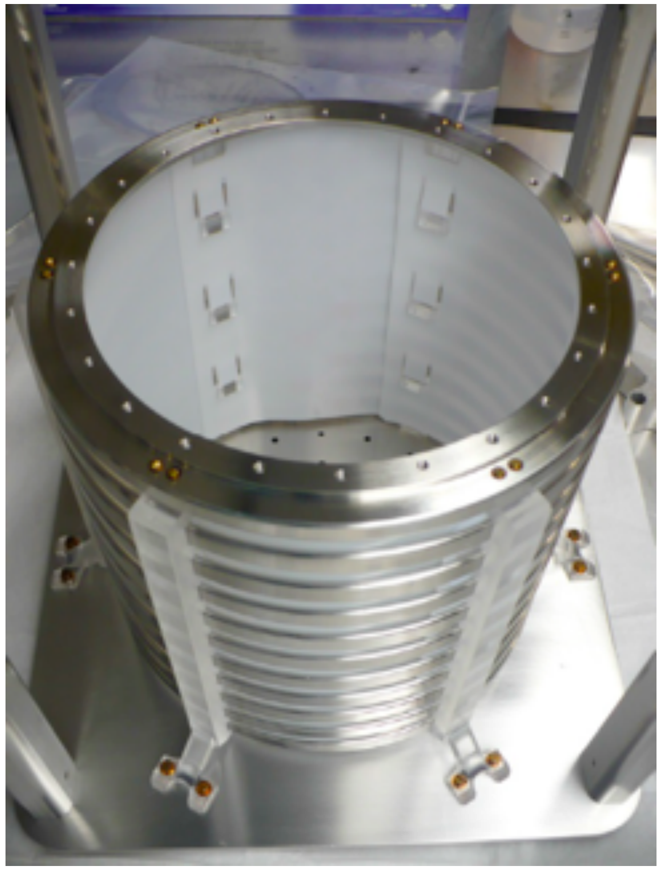
nEXO R&D: High Voltage



Phase I

small parts

fundamental LXe issues



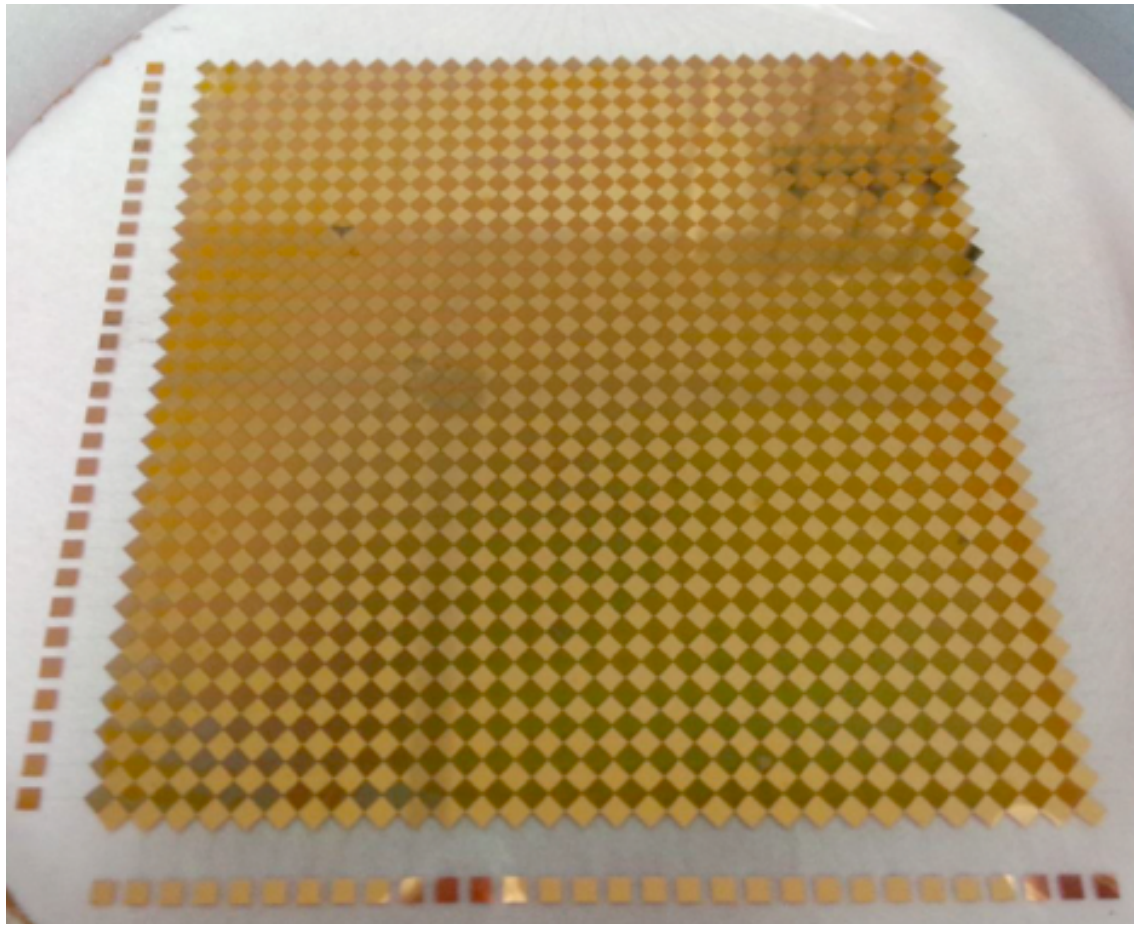
Phase II -- long-term effects,

investigate EXO-200 parts

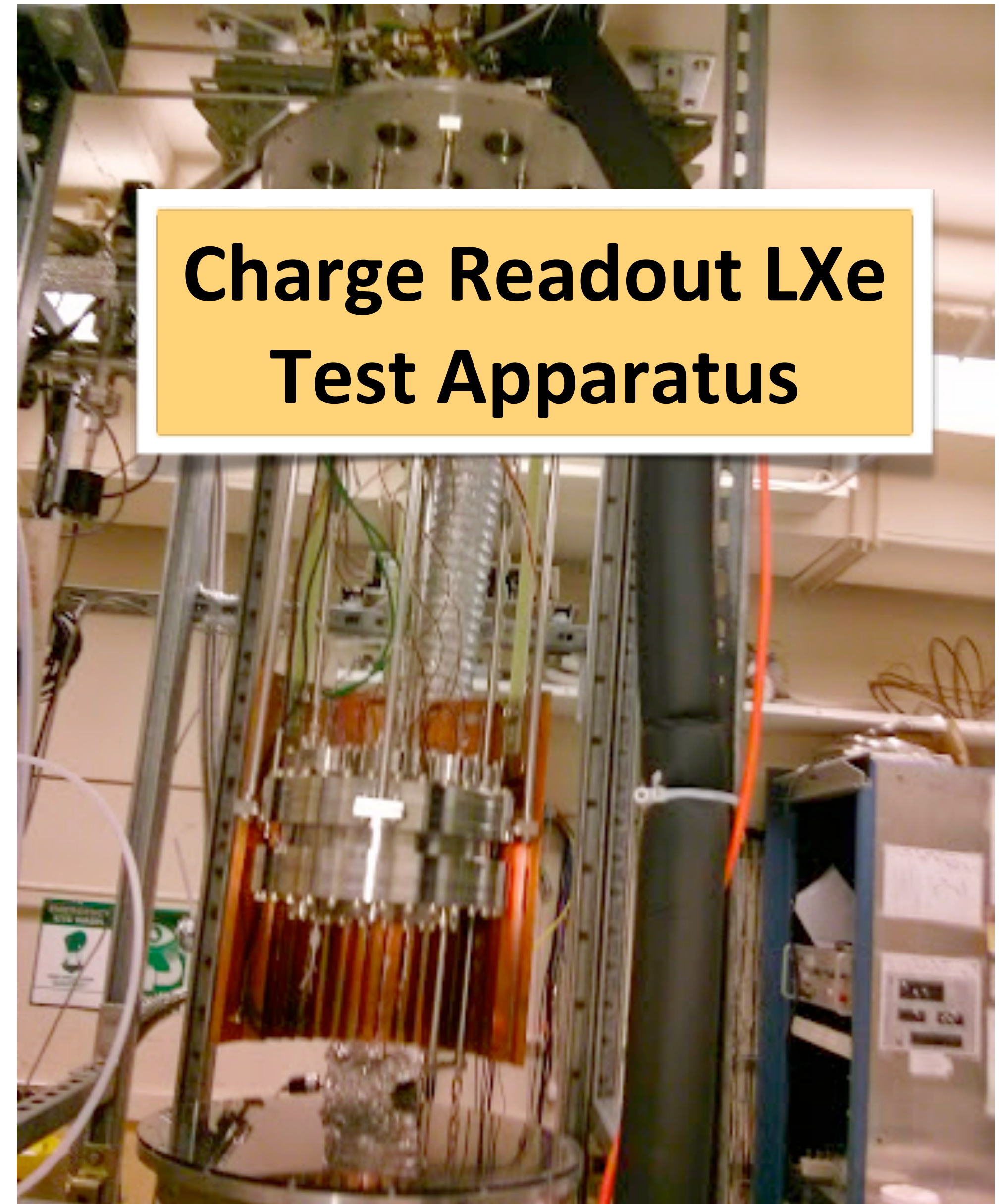
R&D goals:

- small scale tests to inform design
- LXe purity issues
- test full-scale parts (Phase III)

nEXO R&D: Charge Collection Tiles



Prototype Charge Readout Quartz Tile



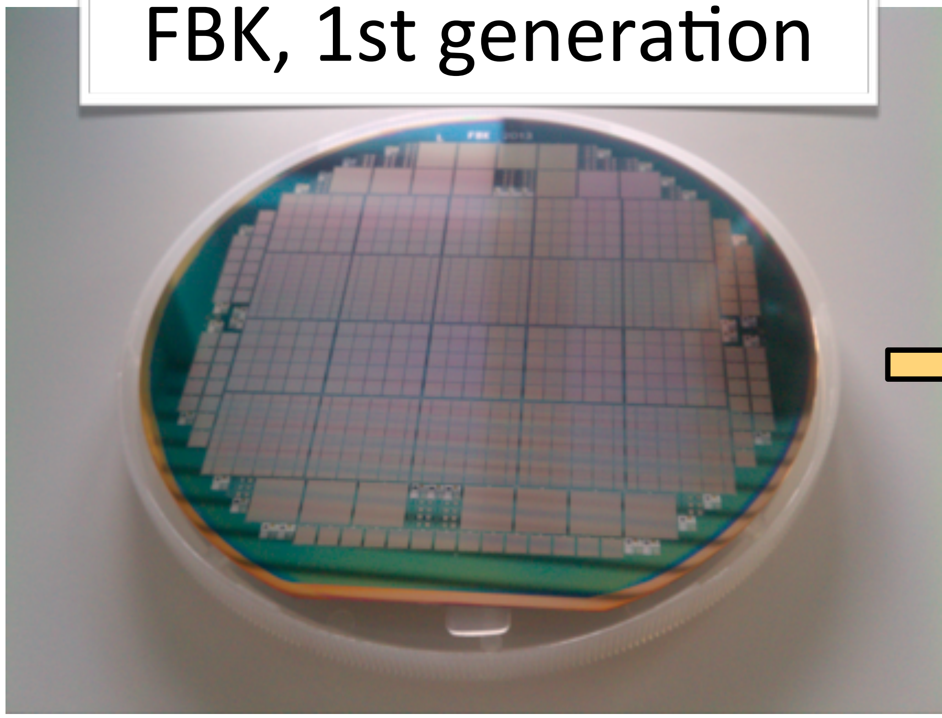
Charge Readout LXe Test Apparatus

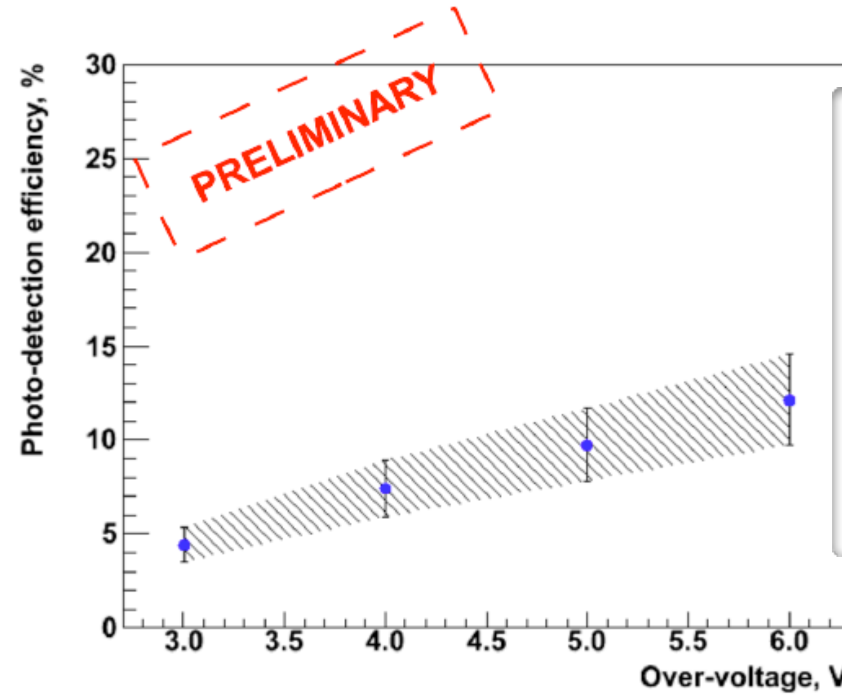
R&D goals and program:

- Charge readout structures on low background substrates
- SS/MS discrimination (readout pitch, comparison with simulations

nEXO R&D: VUV sensitive SiPMs

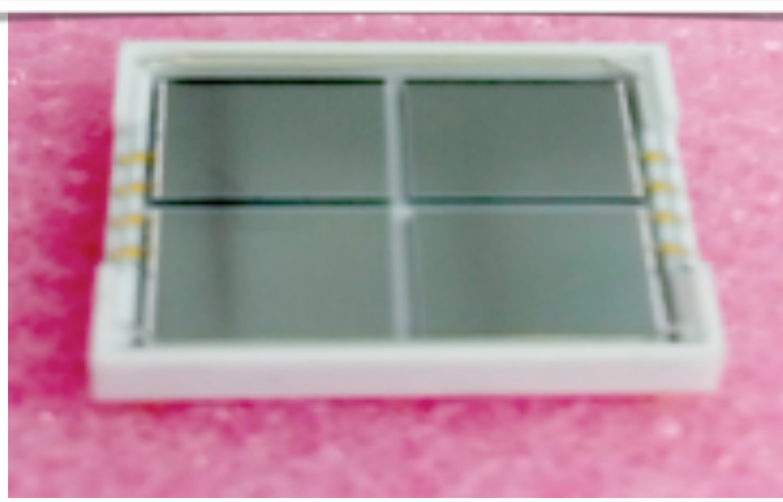
FBK, 1st generation

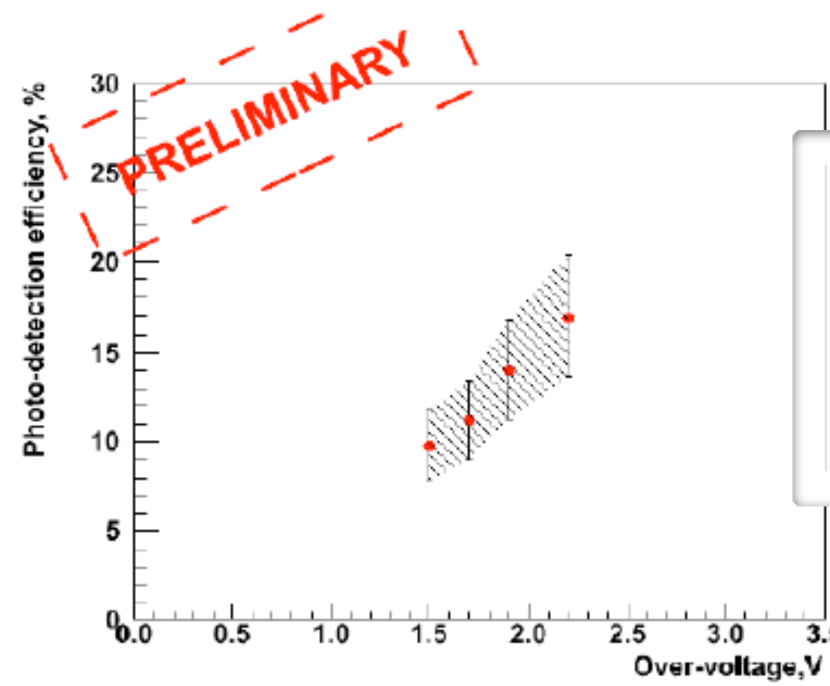




2nd generation FBK has improved performance

Hamamatsu, MEG device





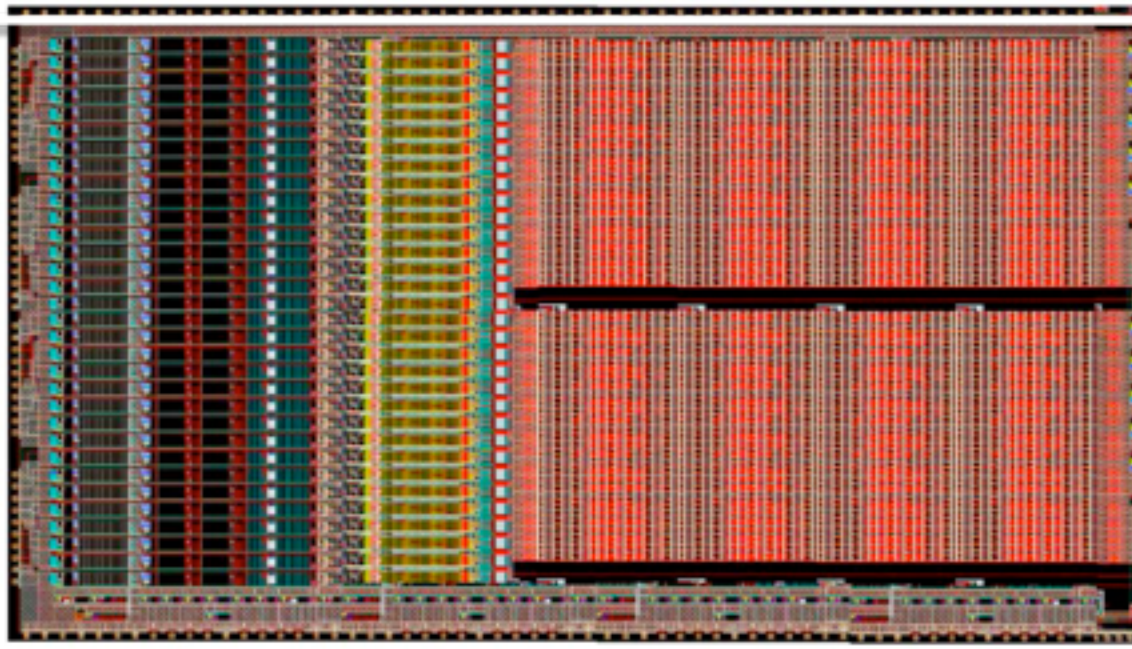
need low background packaging

R&D goals:

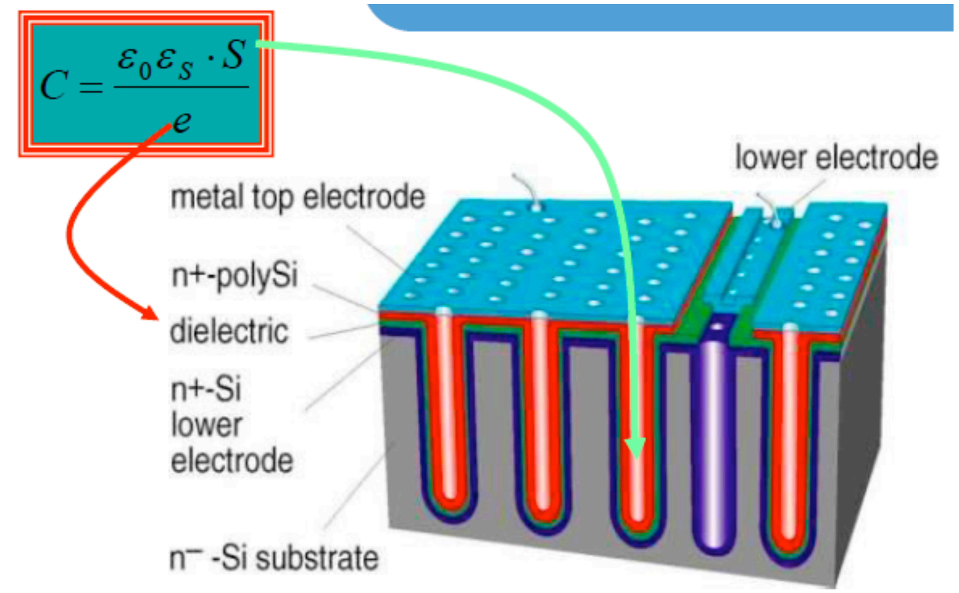
- high light collection efficiency (>15% at 175 nm)
- ultra-low background (~ppt levels Th-232, U-238)

nEXO R&D: Cold Front-End Electronics

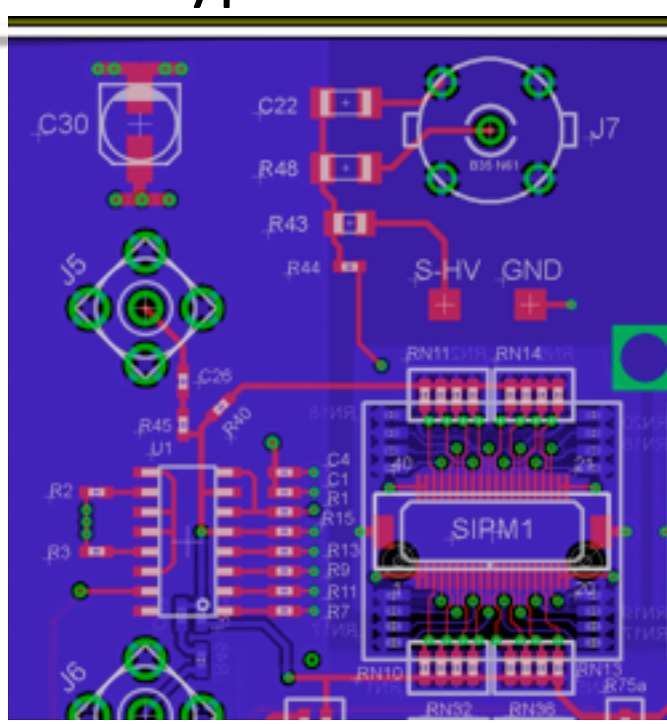
Concept of Cold Charge Readout ASIC



Si Miniature Capacitors



Prototype Circuit for SiPMs



R&D program:

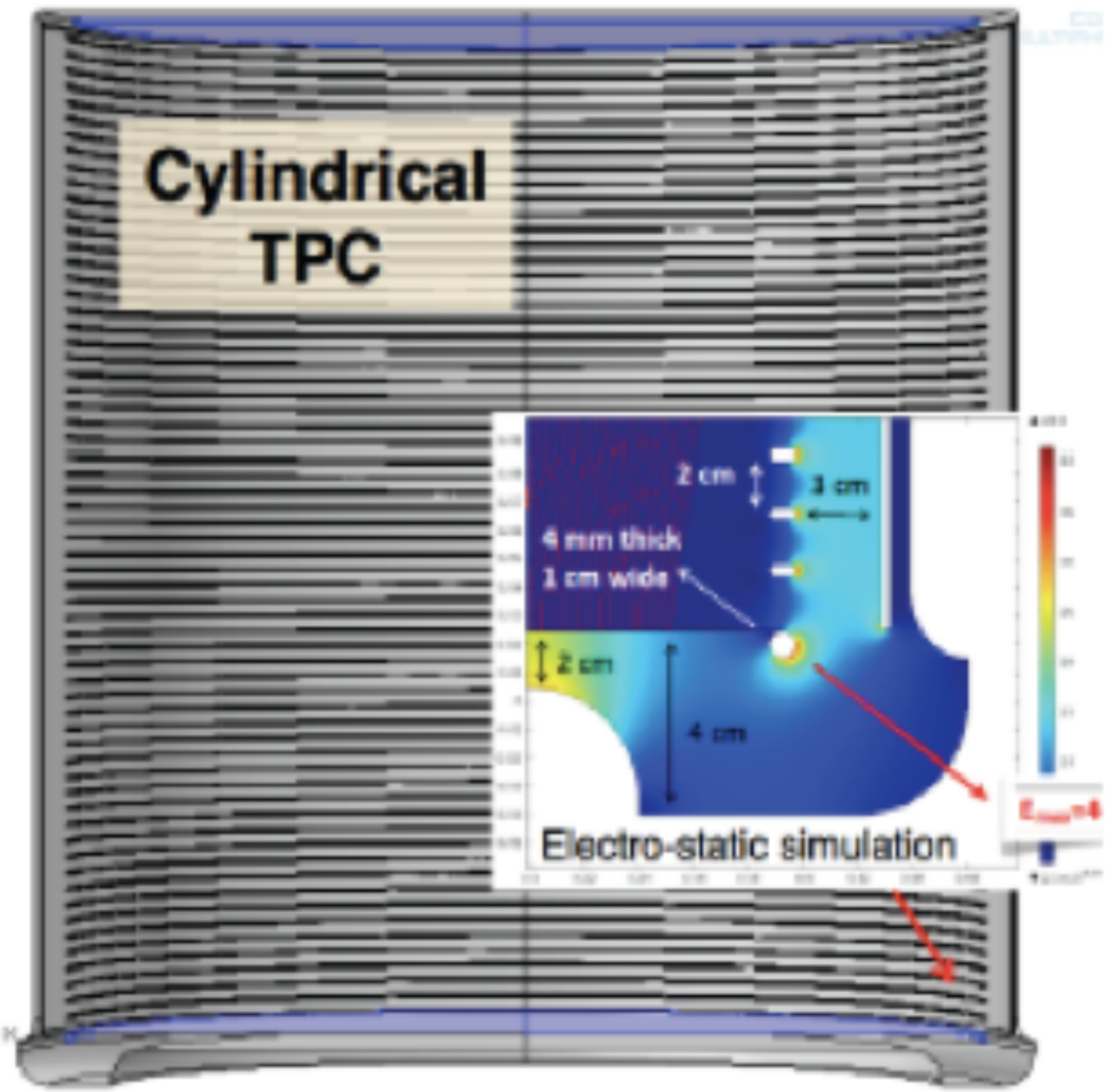
- improve energy resolution
- low background, low noise
- keep required power low enough
- multiplexing to reduce cabling/feedthroughs
- critical components (cables, capacitors, etc)

nEXO R&D: TPC design

R&D program:

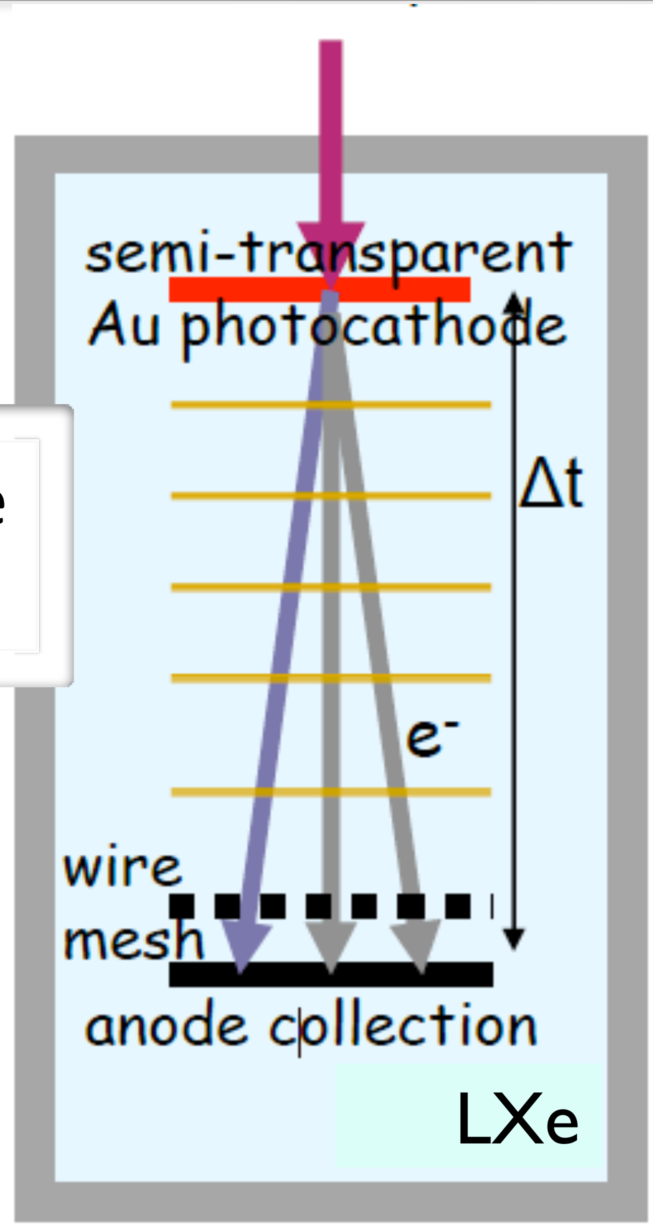
- optimization of TPC layout and fiducial volume
- plastic-less design
- cathode design
- 10 ms electron lifetime
- VUV mirrors (Al + fluoride coatings)
- integration with Xe vessel

TPC E-field simulations:

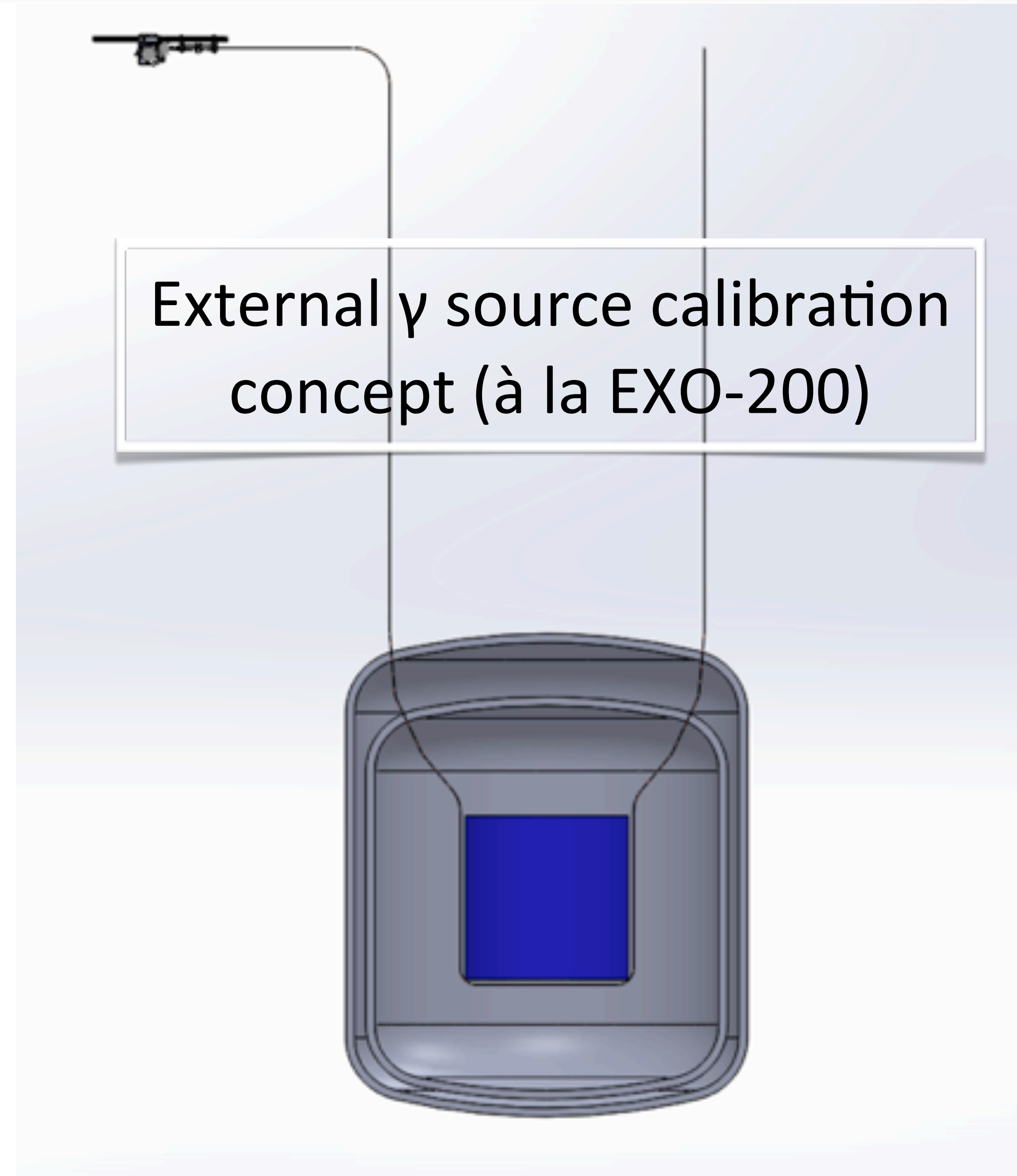


nEXO R&D: Calibrations

Photocathode in LXe tests



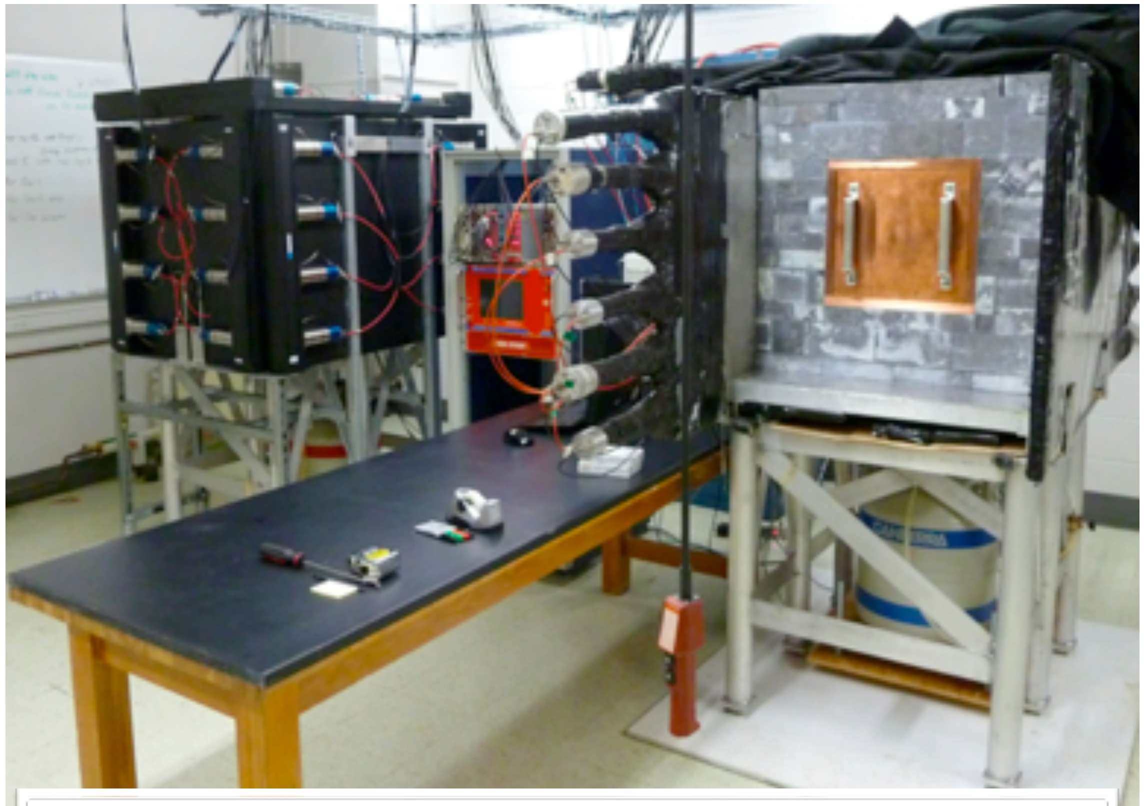
External γ source calibration concept (à la EXO-200)



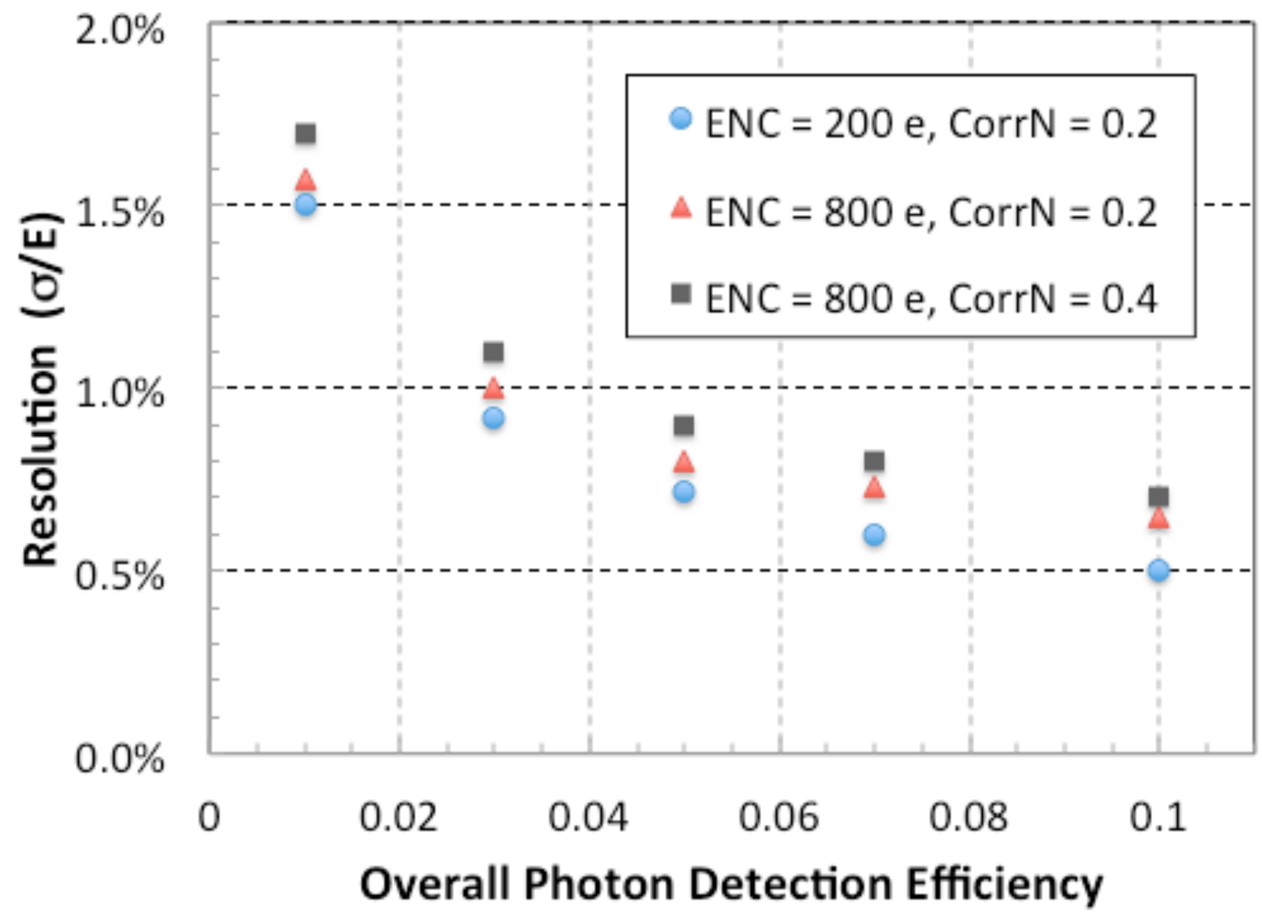
R&D program:

- calibrations for energy scale, Xe purity, detector stability
- external and internal sources
- Laser excited photocathode or Xe *in situ* photo-ionization

nEXO R&D: Radio-Assay and Detector Simulations



Ge detector lab at U. of Alabama



Energy Resolution vs Light Collection

R&D program:

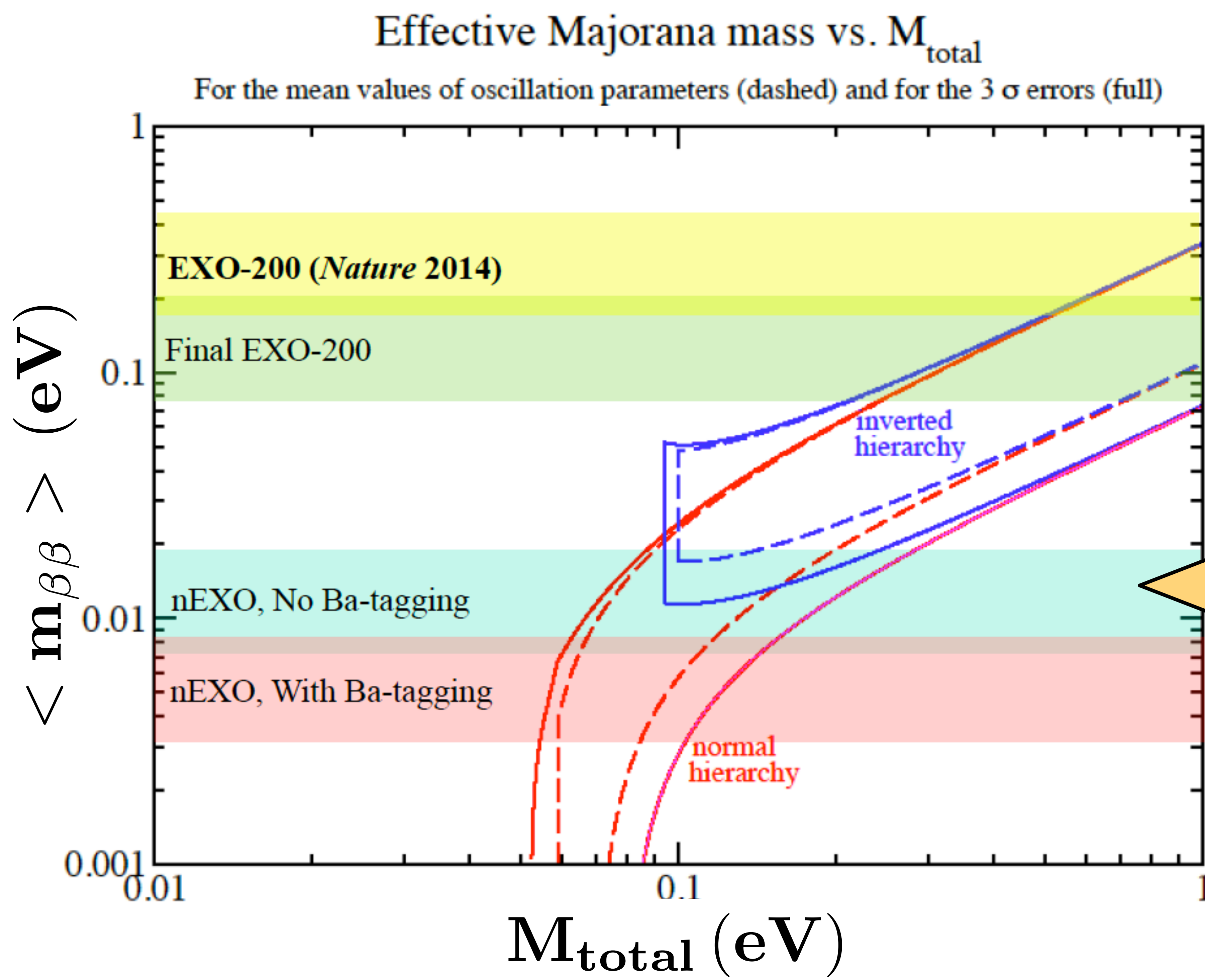
- radio-assays: NAA, GE counting, Rn counting, ICPMS
- multi faceted detector optimization
- optimal site determination and shielding requirements

What else from EXO-200?

Following 2 accidents at the WIPP mine, EXO-200 personnel is now granted regular access to the site and recovery operations are ongoing

- EXO-200 can still contribute to the leading set of experiments
- Upgrades had bee installed before the accident:
  - Radon suppression system for air around the detector
  - Upgraded electronics (could get to 1% energy resolution)
- Approx. 2 years of data are still being worked on:
  - cosmogenics
  - gamma, beta, and alpha backgrounds

nEXO Physics Sensitivity



$T_{1/2} = 6 \times 10^{27}$ yr in 5 years of counting

Majorana neutrino mass $\langle m_{\beta\beta} \rangle$ sensitivity of 7-18 meV

125 researchers
25 institutions
7 countries

University of Alabama, Tuscaloosa AL, USA - D. Auty, T. Didberidze, M. Hughes, A. Piepke, R. Tsang
University of Bern, Switzerland - S. Delaquis, R. Gornea, T. Tolba, J-L. Vuilleumier
Brookhaven National Laboratory, Upton NY, USA – M. Chiu, G. De Geronimo, S. Li, V. Radeka, T. Rao, G. Smith, T. Tsang, B. Yu
California Institute of Technology, Pasadena CA, USA - P. Vogel
Carleton University, Ottawa ON, Canada - Y. Baribeau, V. Basque, M. Bowcock, M. Dunford, K. Graham, P. Gravelle, R. Killick, T. Koffas, C. Licciardi, E. Mane, K. McFarlane, R. Schnarr, D. Sinclair
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IHEP Beijing, People's Republic of China - G. Cao, X. Jiang, H. Li, Z. Ning, X. Sun, N. Wang, W. Wei, L. Wen, W. Wu
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University of Massachusetts, Amherst MA, USA - J. Dalmasson, S. Johnston, A. Pocar
Oak Ridge National Laboratory, Oak Ridge TN, USA – L. Fabris, D. Hornback, R.J. Newby, K. Ziock
IBS Center for Underground Physics, Daejeon, South Korea - D.S. Leonard
SLAC National Accelerator Laboratory, Menlo Park CA, USA - T. Daniels, K. Fouts, G. Haller, R. Herbst, K. Nishimura, A. Odian, P.C. Rowson, K. Skarpaas
University of South Dakota, Vermillion SD, USA – R. MacLellan
Stanford University, Stanford CA, USA - T. Brunner, J. Chaves, R. DeVoe, D. Fudenberg, G. Gratta, M. Jewell, S.Kravitz, D. Moore, I. Ostrovskiy, A. Schubert, K. Twelker, M. Weber
Stony Brook University, SUNY, Stony Brook, NY, USA – K. Kumar, O. Njoya, M. Tarka
Technical University of Munich, Garching, Germany - P. Fierlinger, M. Marino
TRIUMF, Vancouver BC, Canada – J. Dilling, P. Gumplinger, R. Krücken, F. Retière, V. Strickland

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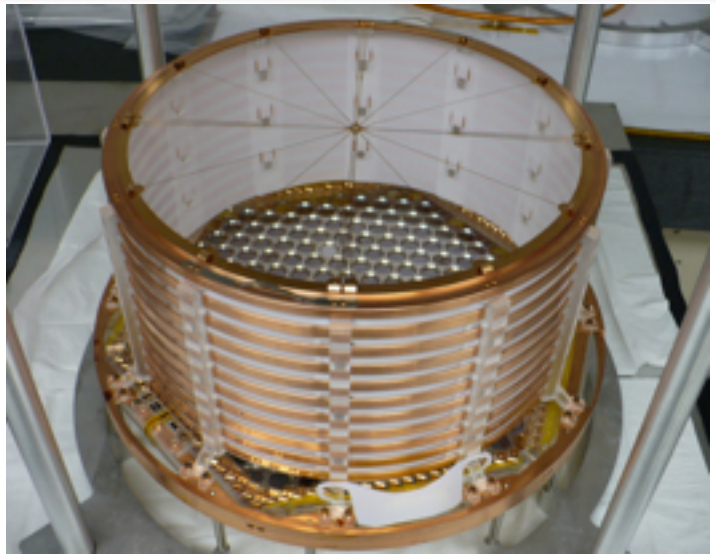
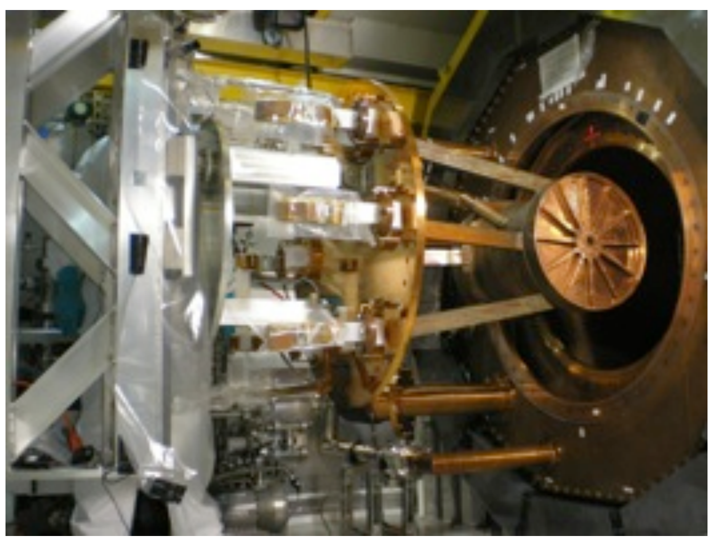
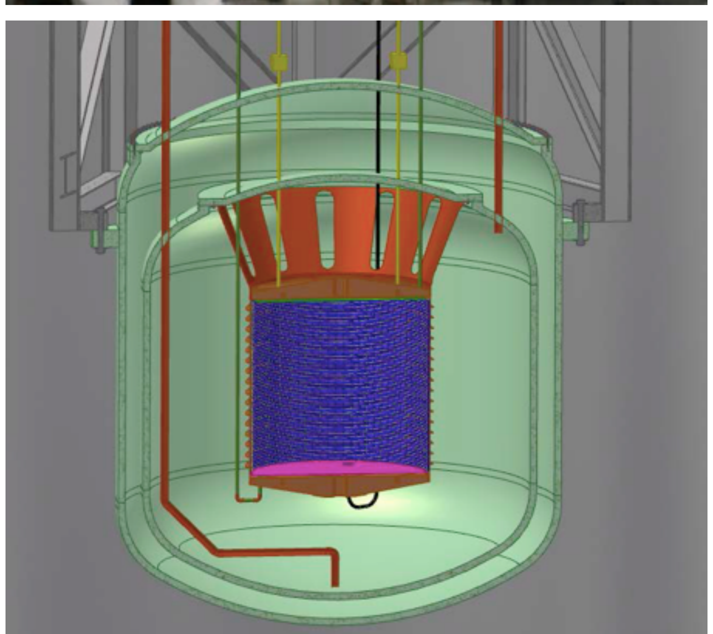
Summary

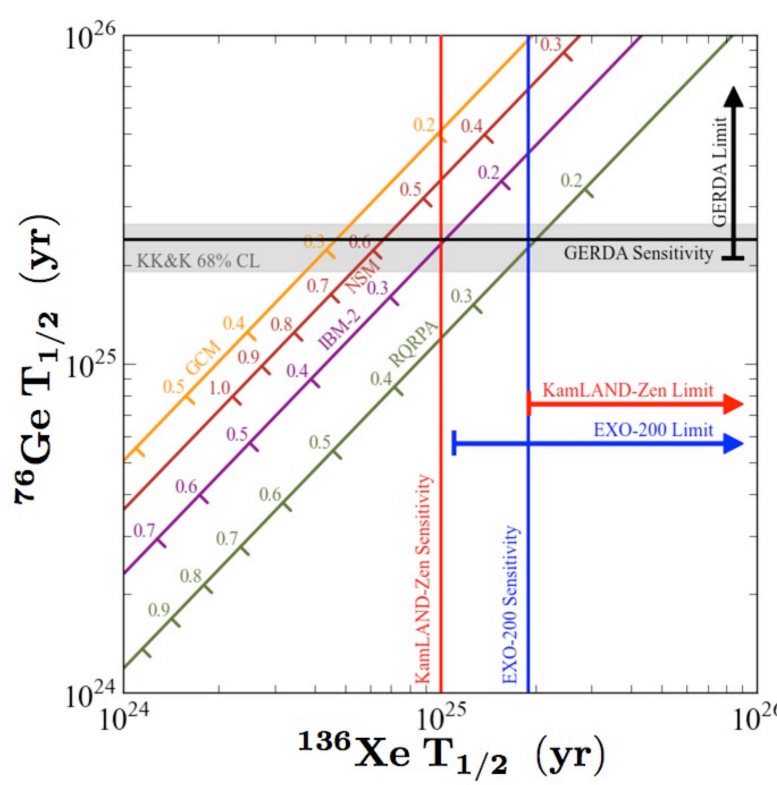
stay hungry, my friend

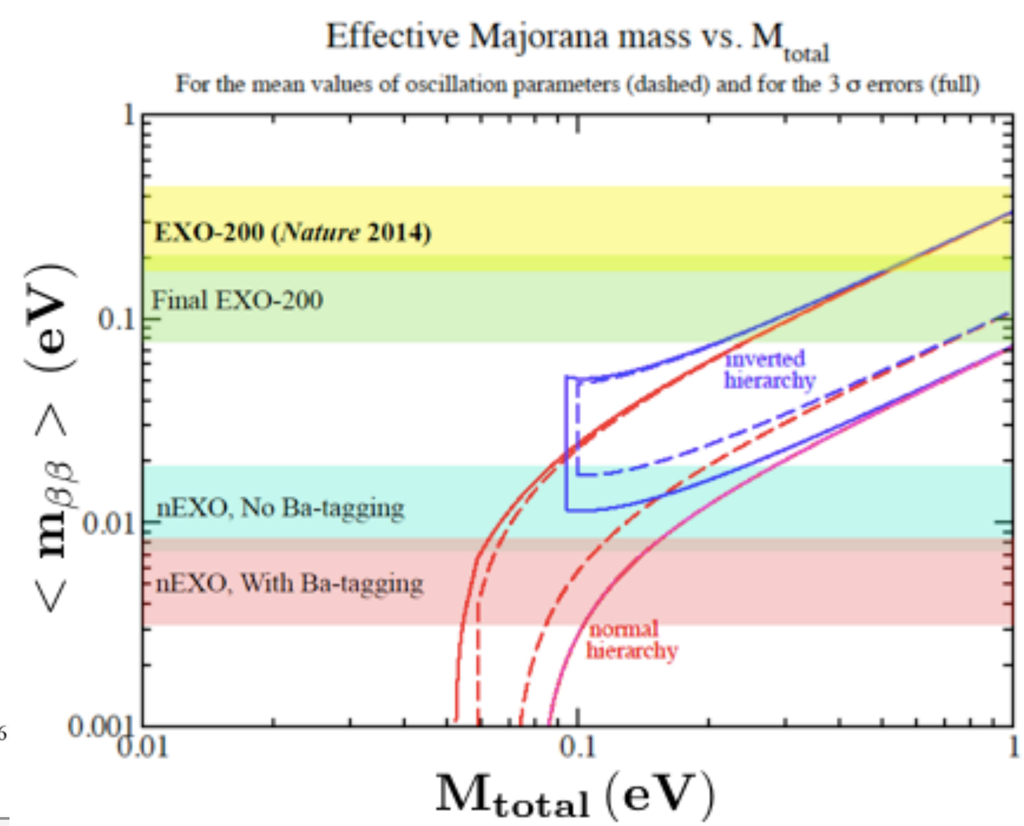






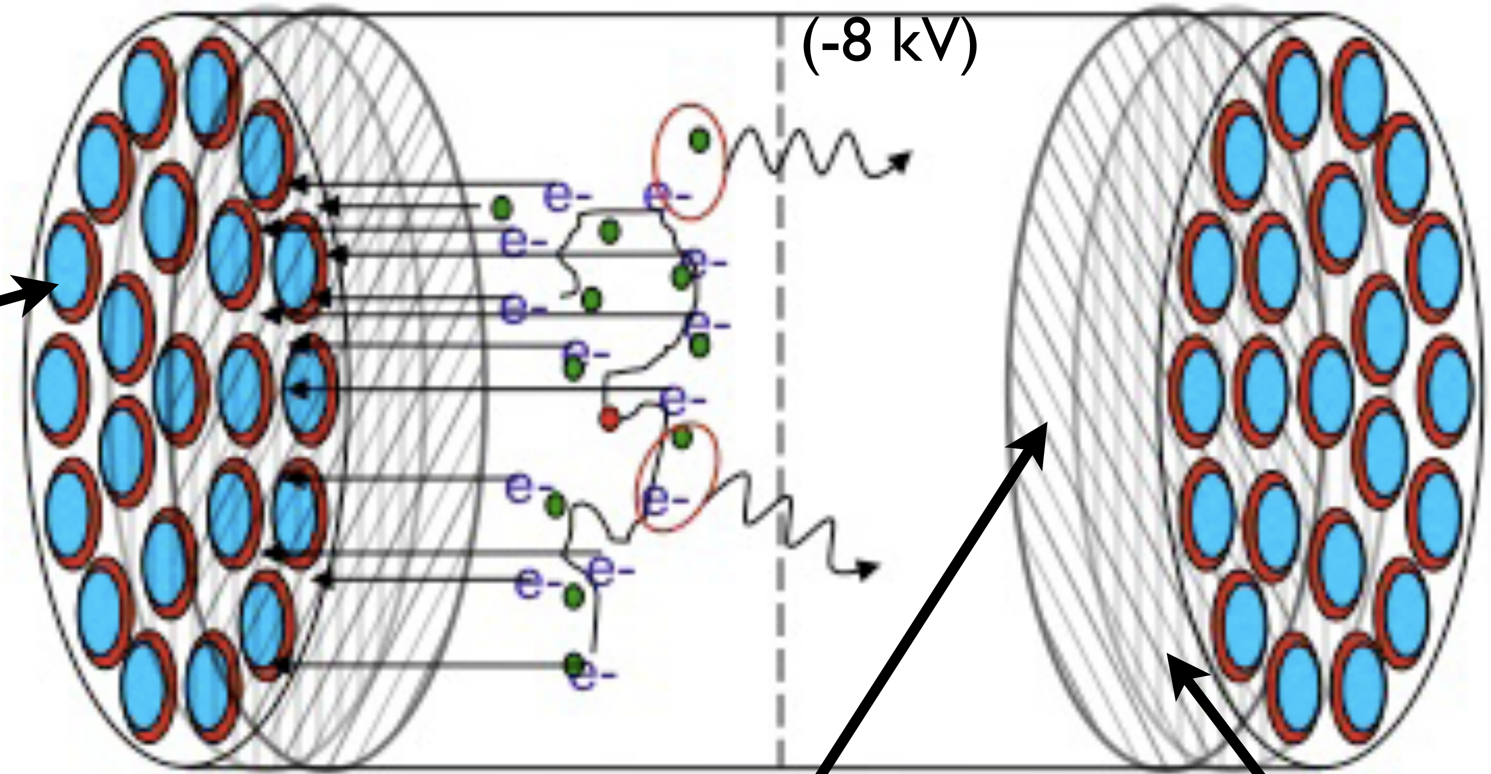
- EXO-200 has demonstrated the LXe TPC technology at the ~100 kg scale and has indicated a plausible way towards a leading tonne-scale experiment (nEXO)
- nEXO has an active international R&D program for a LXe DBD experiment with x100 the sensitivity of EXO-200
- The nEXO R&D can be very well synchronized with that of other large noble liquid detectors (SiPMs, HV, purity, cryogenics, ...)

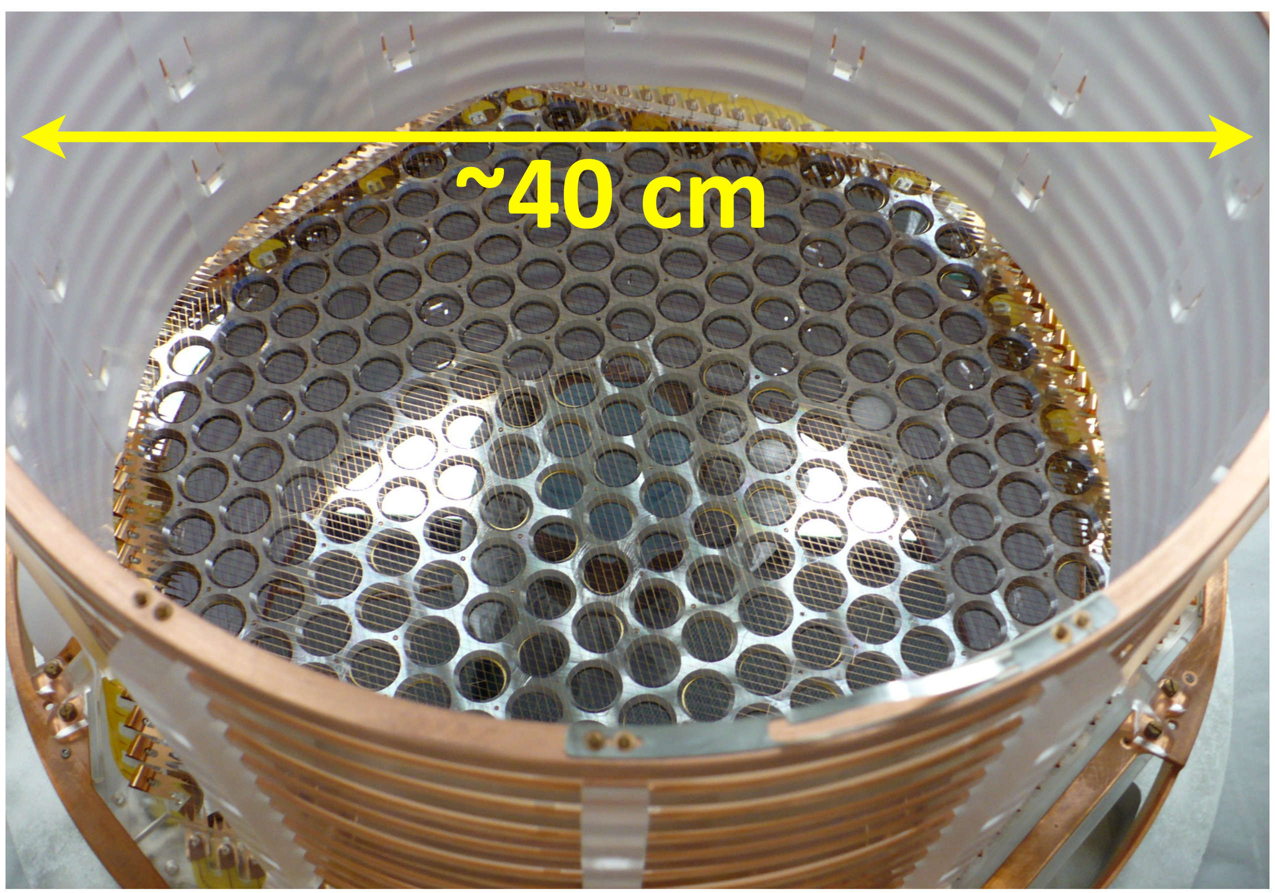




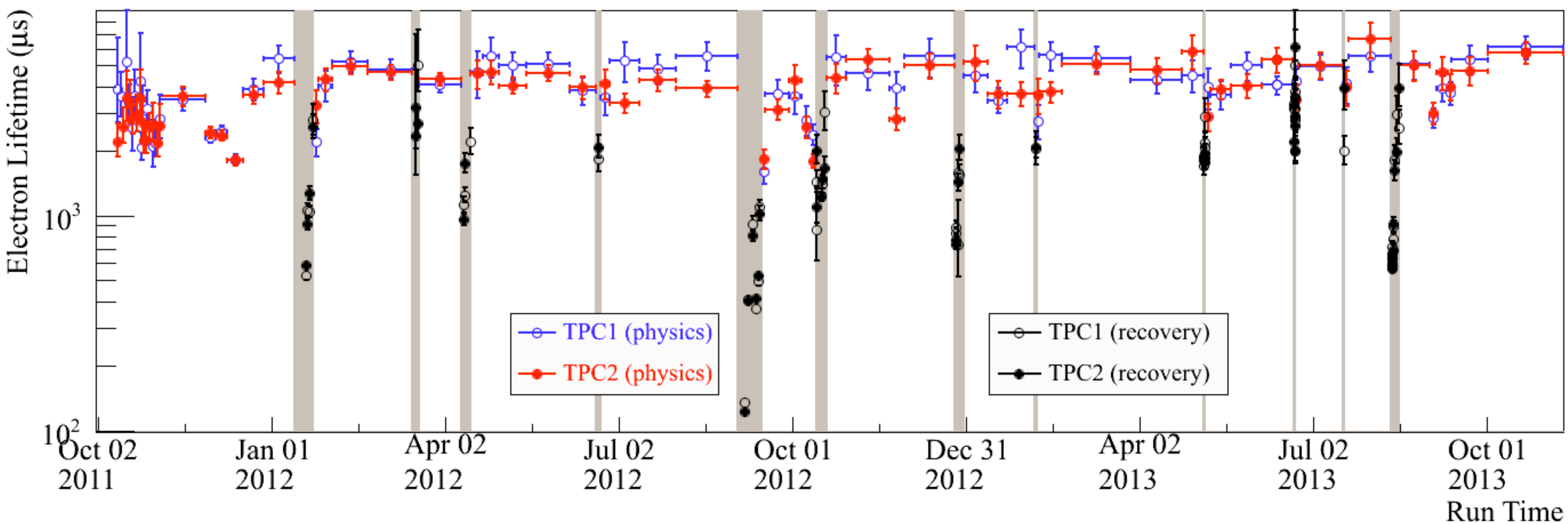
EXO-200 Time Projection Chamber

- Radio-pure, dual TPC (shared center cathode), filled with ~150 kg LXe, 80.6% ^{136}Xe)
- Scintillation detected by APDs at interaction time
- Rotated charge collection and shielding planes give x/y, z from electron drift time





Xenon purity from electronegative species



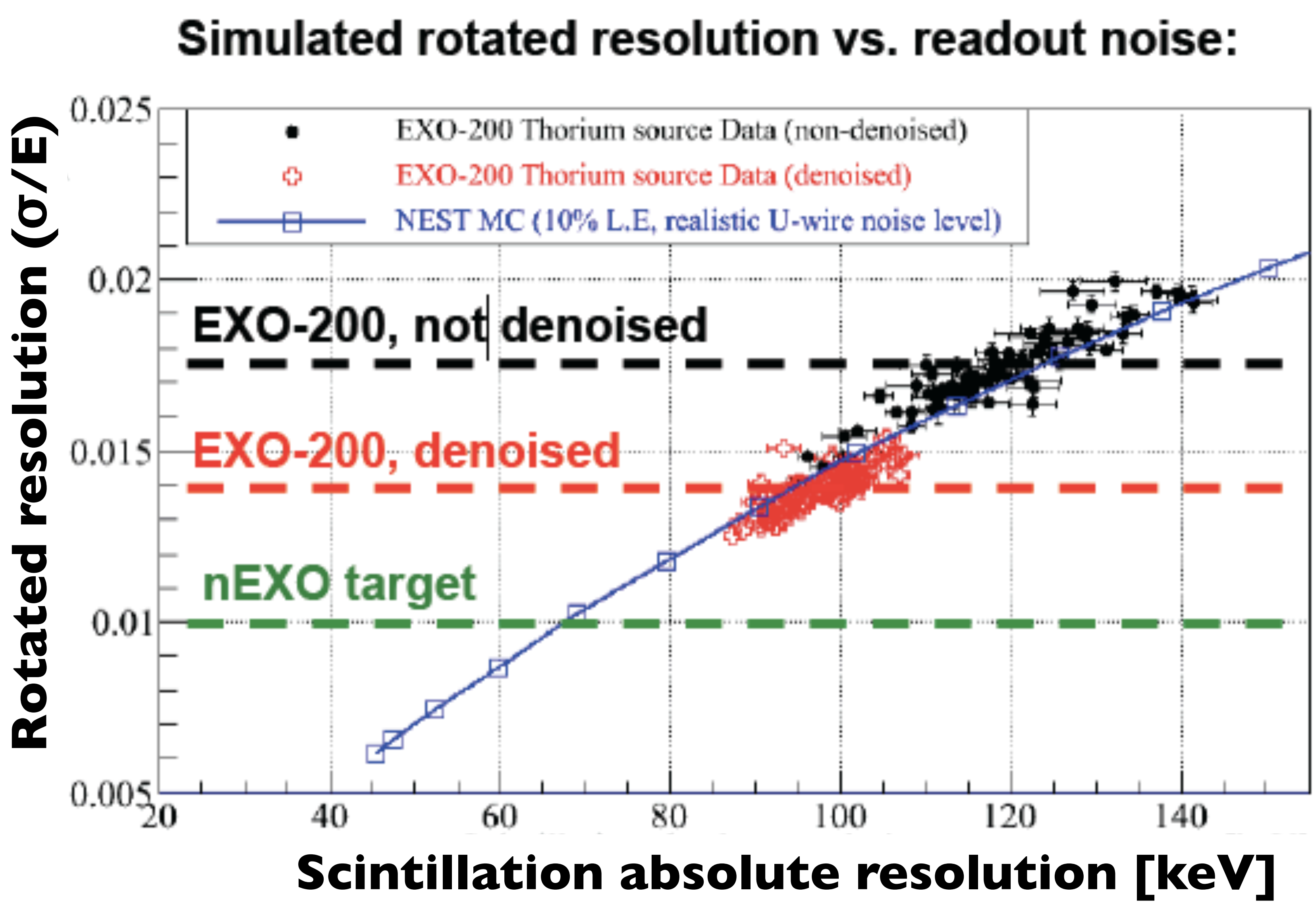
Xenon gas is forced through heated Zr getter by a custom ultraclean pump.

At τ_e = 3 ms:
- drift time <110 µs
- loss of charge: 3.6% at full drift length

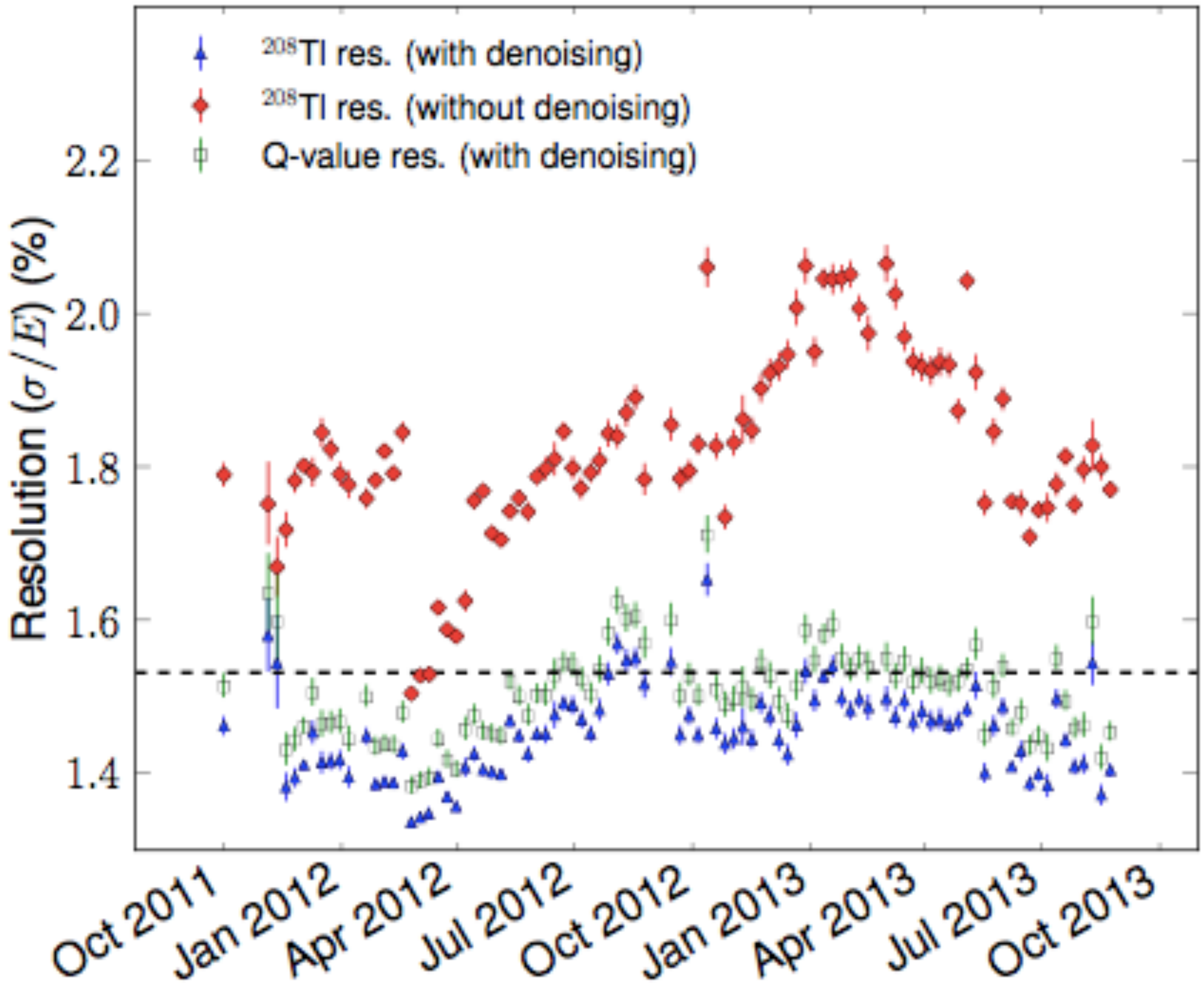
Ultraclean pump: *Rev SciInstr. 82 (10) 105114*
Xenon purity with mass spec: *NIM A675 (2012) 40*
Gas purity monitors: *NIM A659 (2011) 215*

Understanding energy resolution

- $\sigma/Q_{\beta\beta}$ = 1% requires minimal readout noise in scintillation and charge readout
- Have demonstrated 1.4% resolution in EXO-200; simulations indicate that 1% resolution is attainable with improved readout electronics for light channels
- This will be tested with EXO-200 upgrades

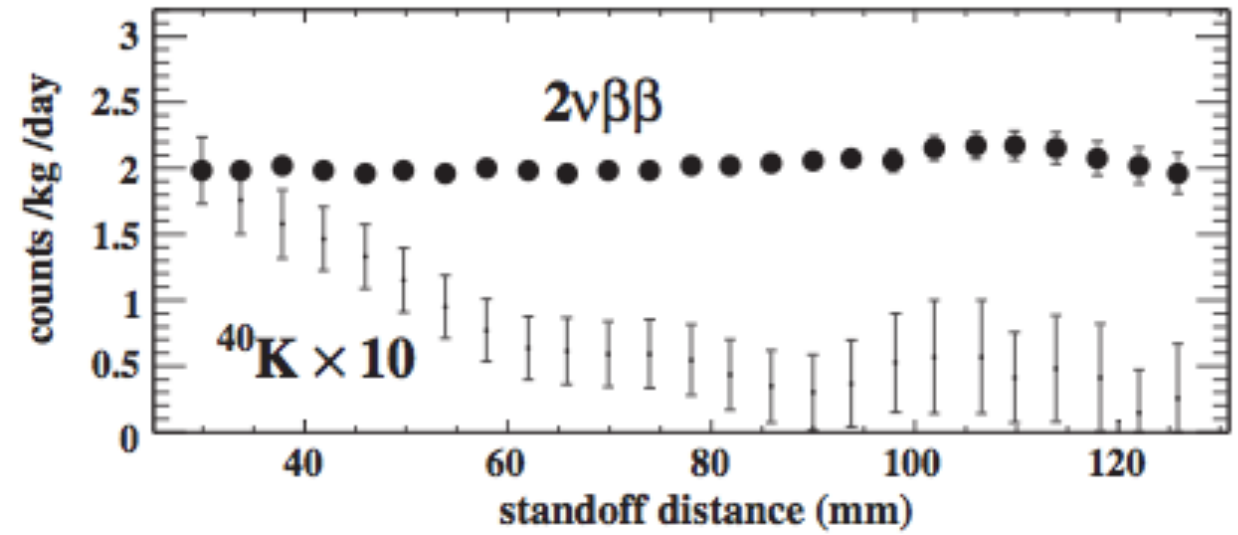


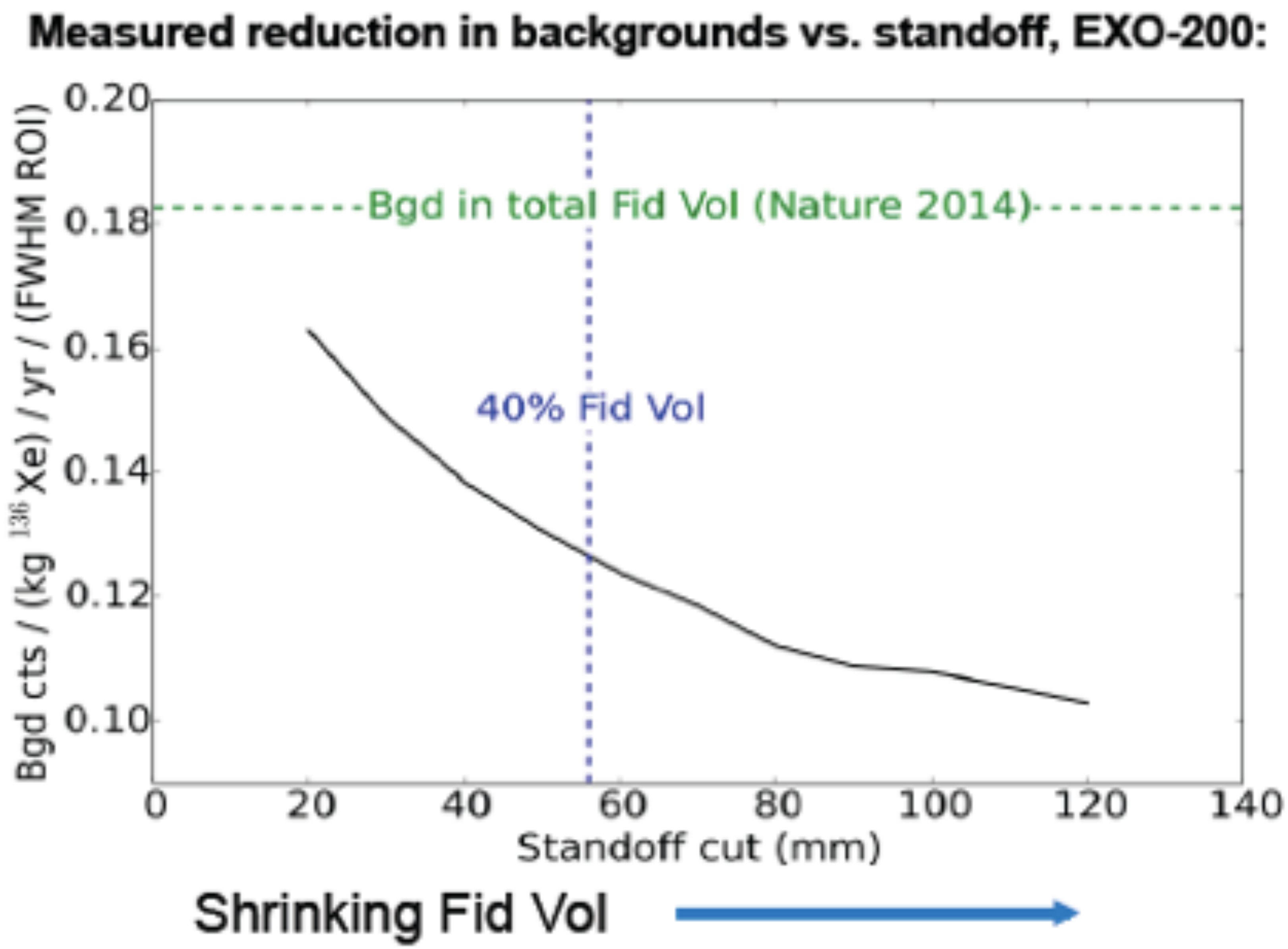
LAAPD denoising



1.53 % in SS at 0νββ Q-value

Self shielding (EXO-200)



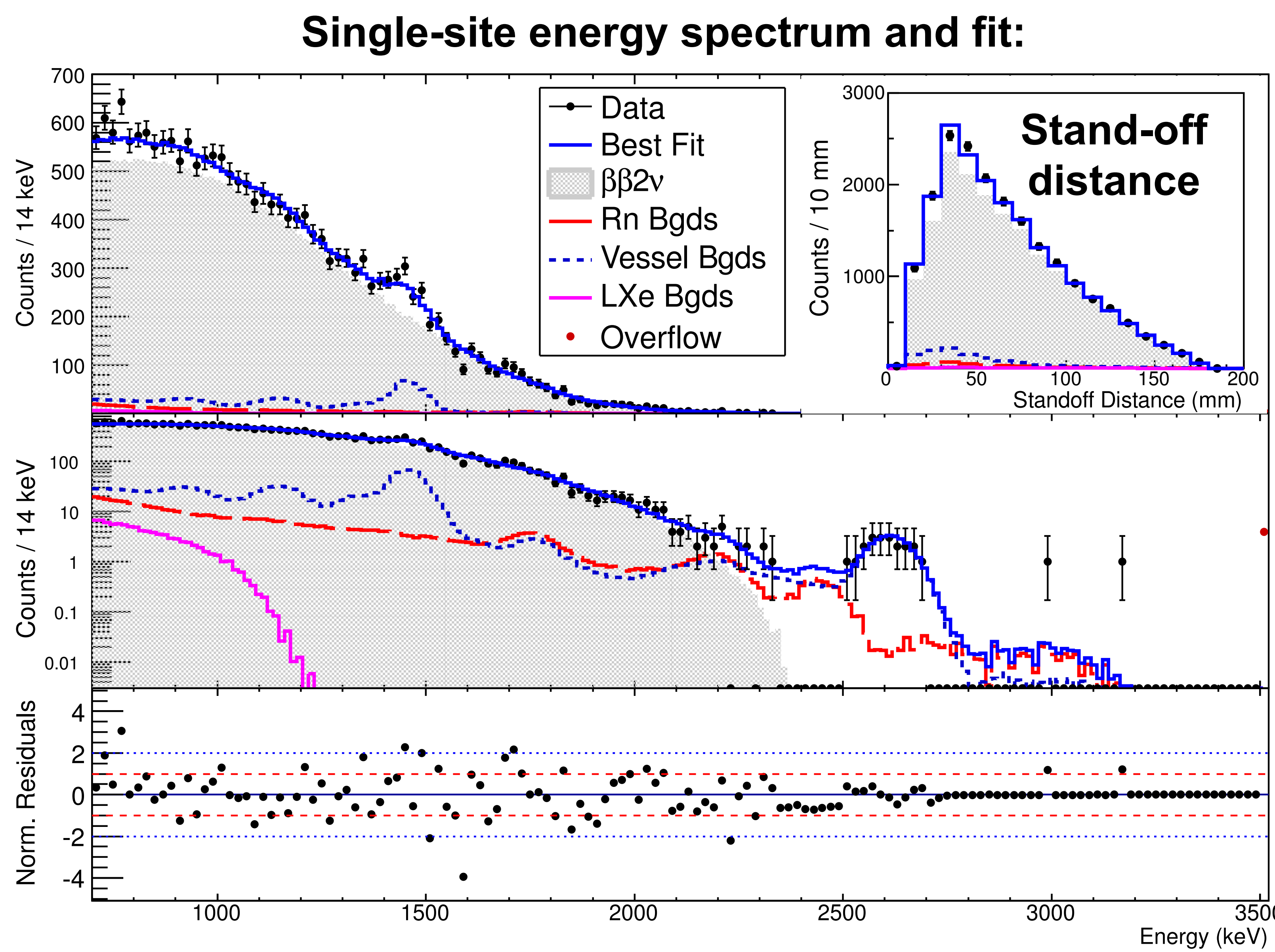


precision measurement of $T_{1/2}^{2\nu\beta\beta}$ (PRC 2013)

Run 2a data set (previously analyzed in PRL **109**, 032505 [2012]) reanalyzed with improvements to event reconstruction and reduced fiducial volume uncertainty

$T_{1/2}^{2\nu\beta\beta}$ measured with total relative uncertainty of 2.85 %

Most precisely measured 2νββ half life of any isotope to date

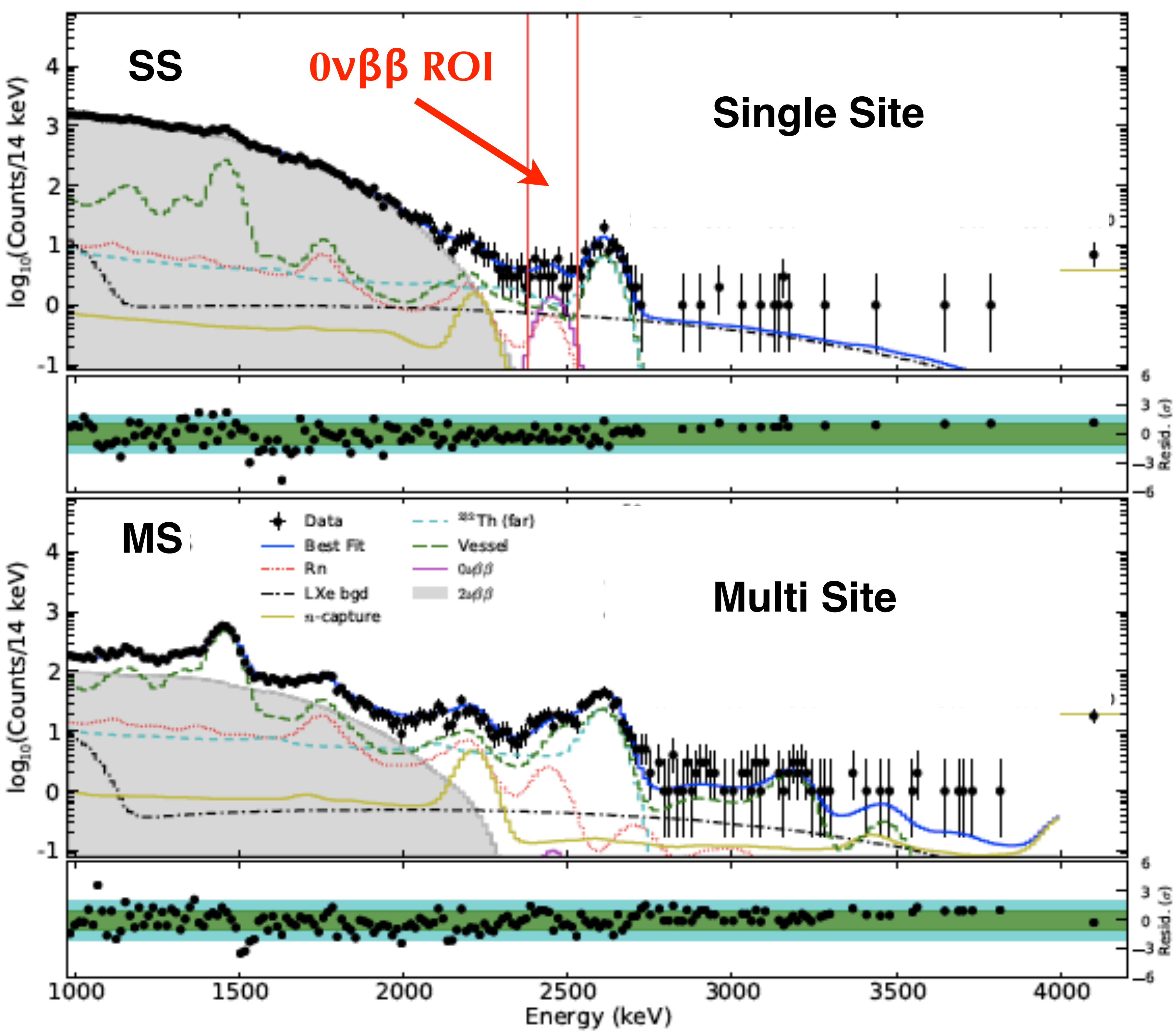


PRC 89 (2014) 015502

$$T_{1/2}^{2\nu\beta\beta} = (2.165 \pm 0.016 \pm 0.059) \times 10^{21}\ \text{yr}$$

(stat..) (syst.)

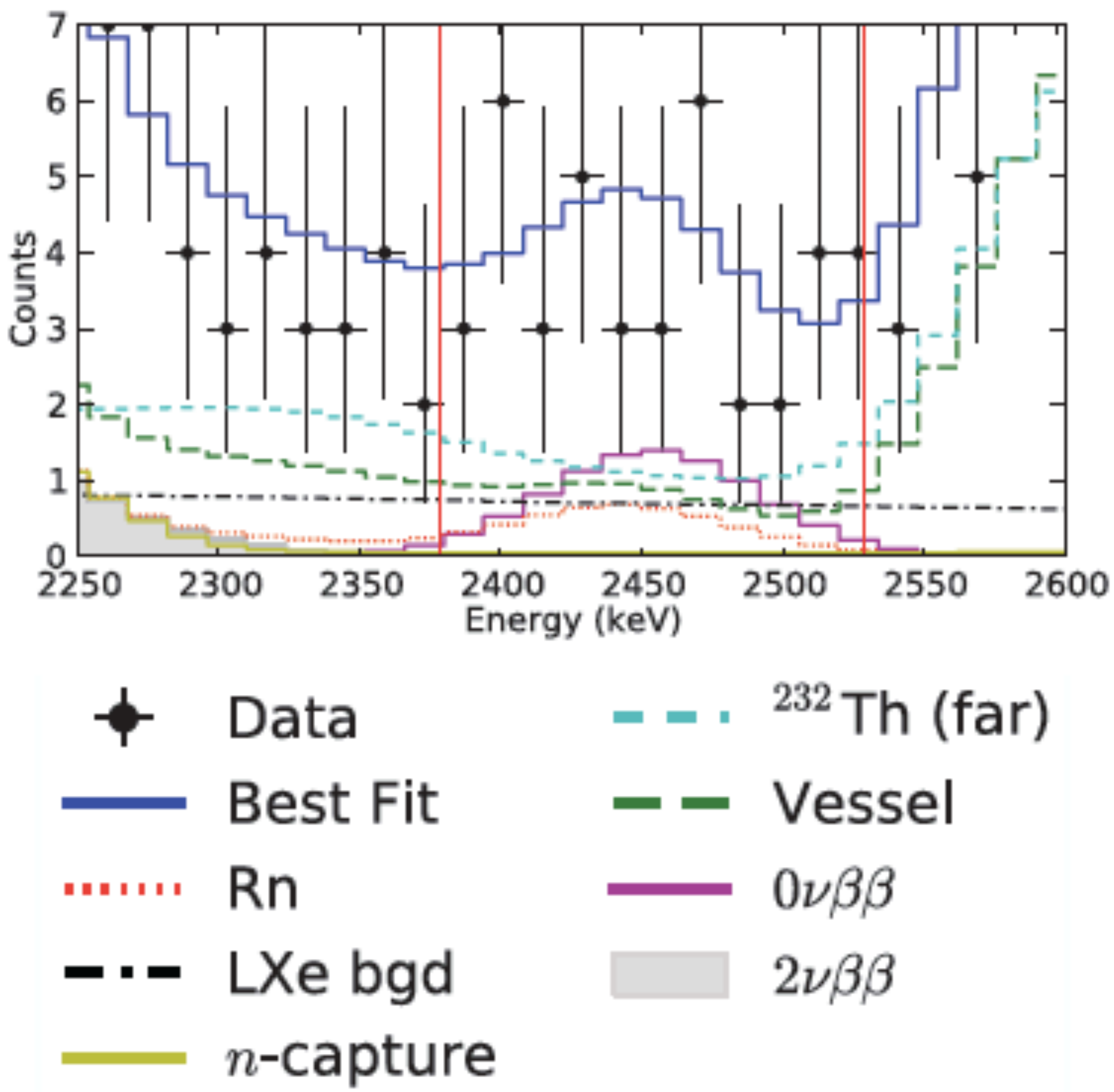
0νββ results - Nature 510, 9 (2014) (arXiv:1402.6956)



- Fit energy spectrum in 980-9800 keV range
- Multi-site (MS) data constrain backgrounds, while 0νββ ROI in in single site (SS) data.
- Fit also includes the "standoff distance" from nearest TPC surface to better constrain backgrounds (and identify signal)

0νββ results - Nature 510, 9 (2014) (arXiv:1402.6956)

Fit to single site spectrum near 0νββ ROI:



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

$T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25}$ yr

$\langle m_{\beta\beta} \rangle < 190 - 450$ meV

(90% C.L.)

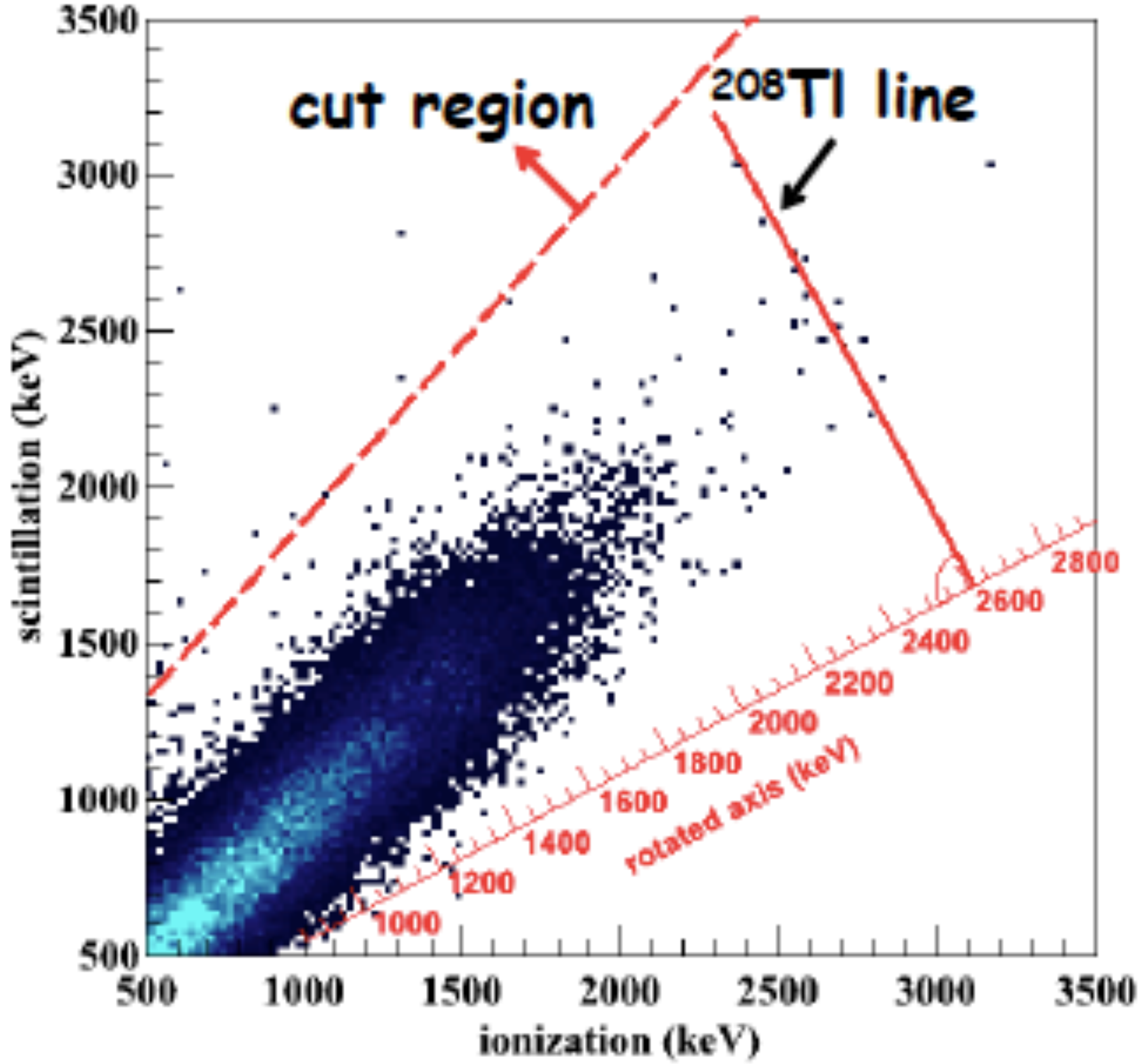
energy resolution

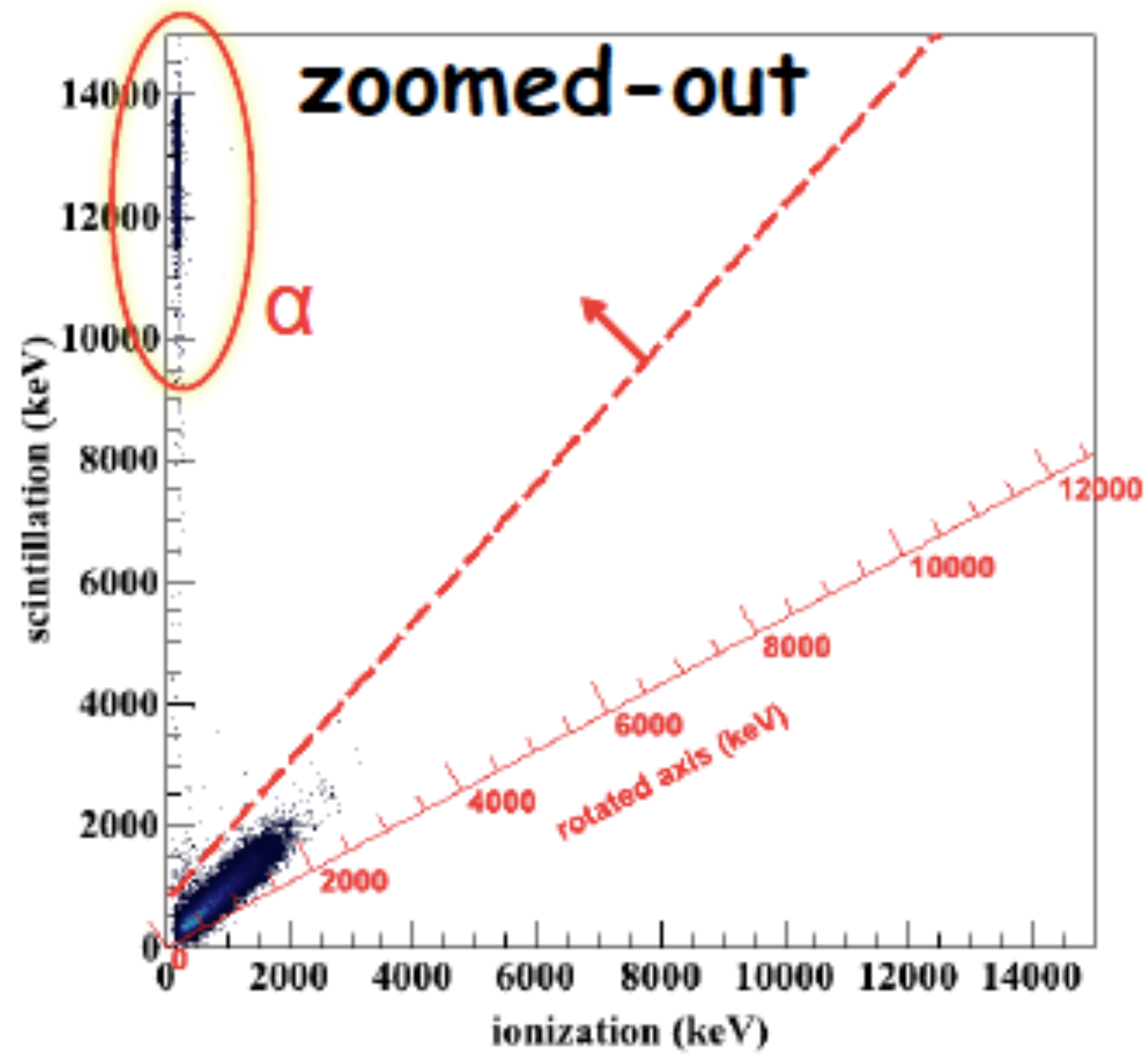
$$\frac{\sigma}{E}(Q) = 1.53$$

background index

$$(1.7 \pm 0.2) \times 10^{-3} \ \mathrm{cts/(keV \cdot kg \cdot y)}$$

alpha decay identification



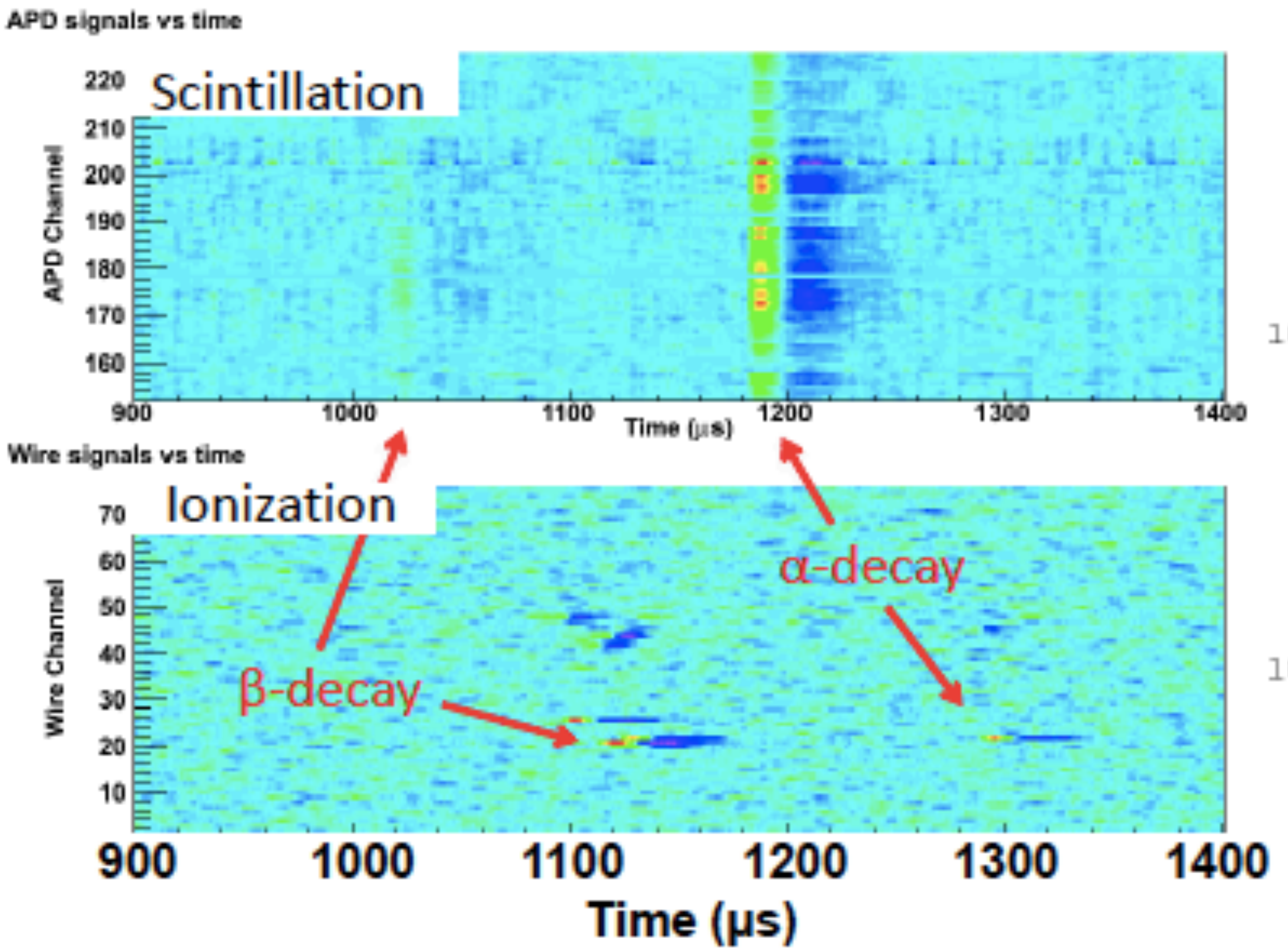


a diagonal cut (large scintillation, low charge) eliminates:

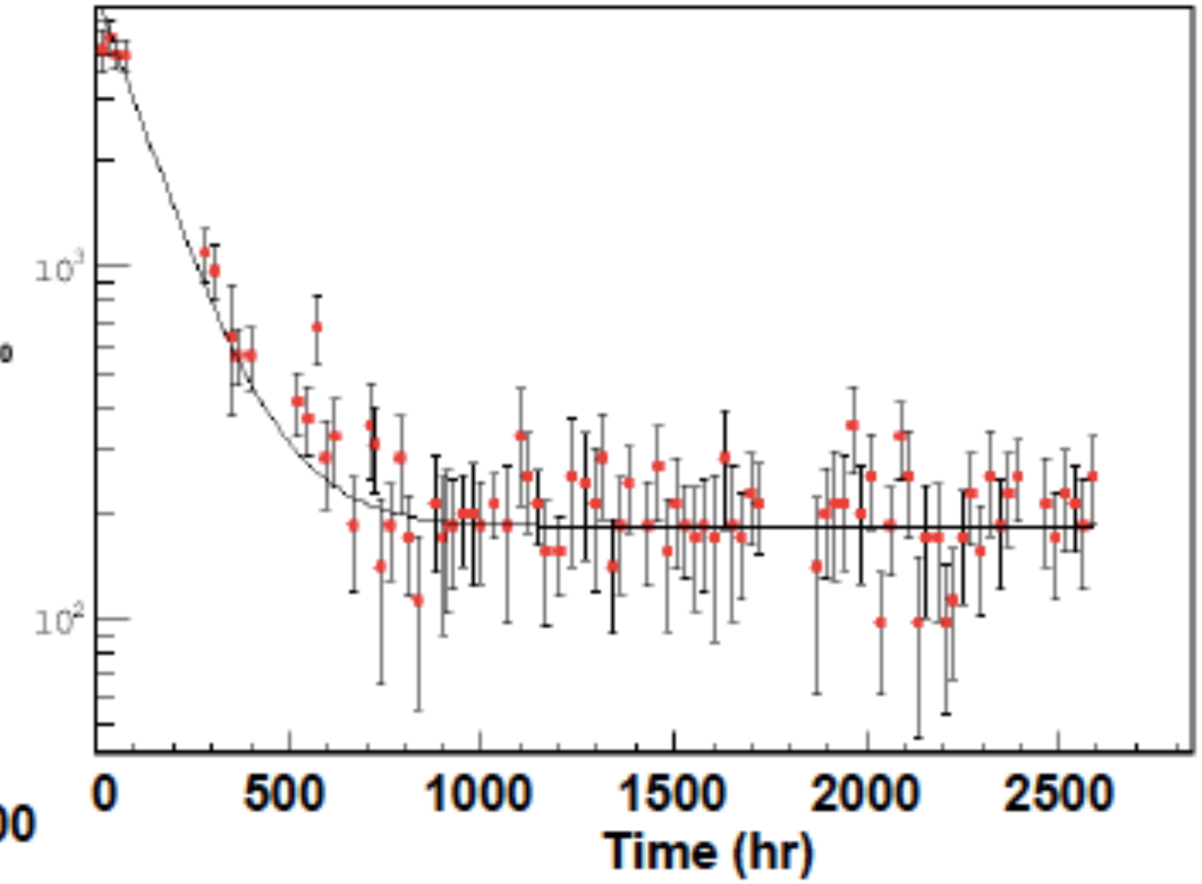
1) alphas

2) edge events (partial charge collection)

Radon in EXO-200



^{214}Bi – ^{214}Po correlations
in the EXO-200 detector



Total ^{222}Rn in LXe after initial fill

Long term study shows a constant source of
^{222}Rn dissolving in ^{enr}LXe: 360 ± 65 μBq (Fid. vol.)

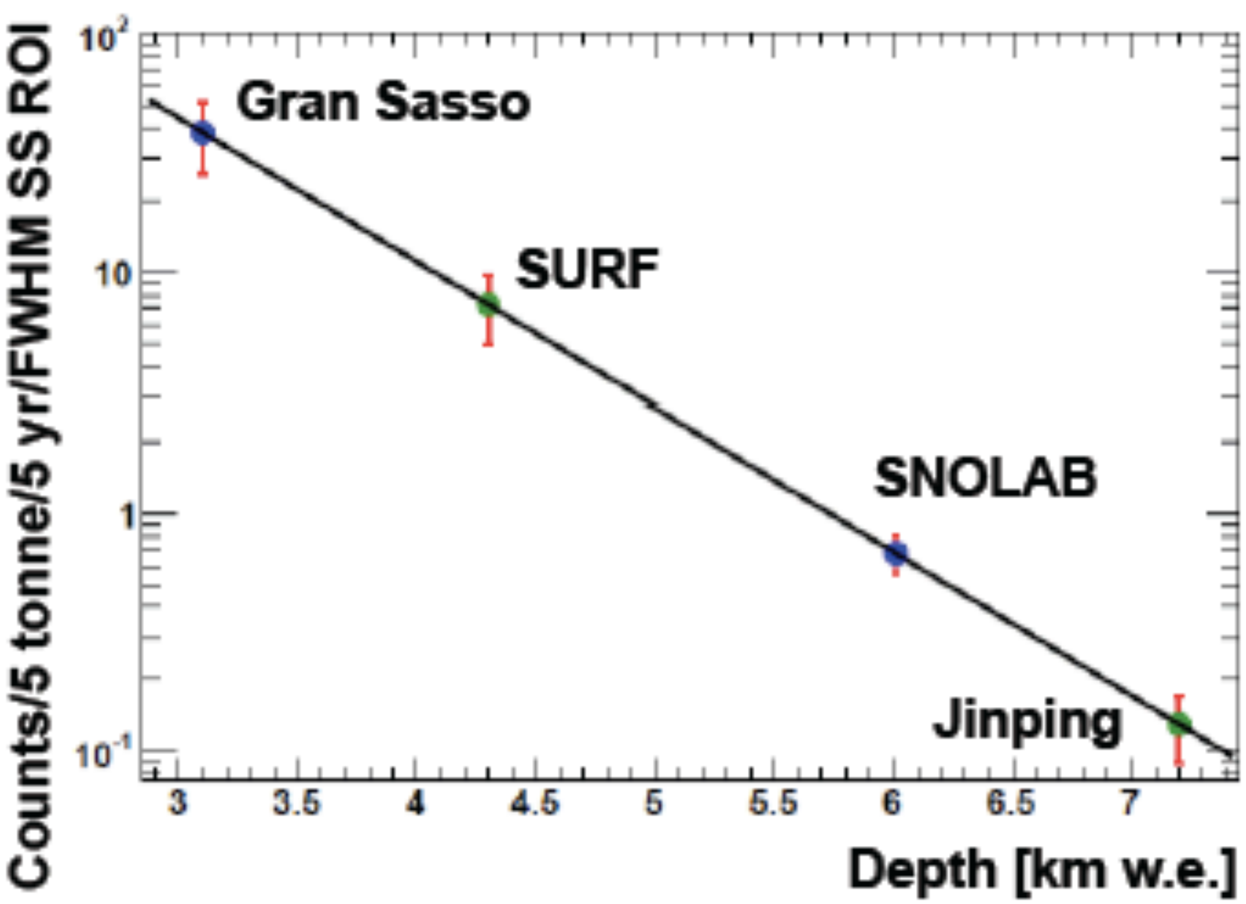
or 200 atoms of ^{222}Rn in our Xenon!

Choice of experimental site

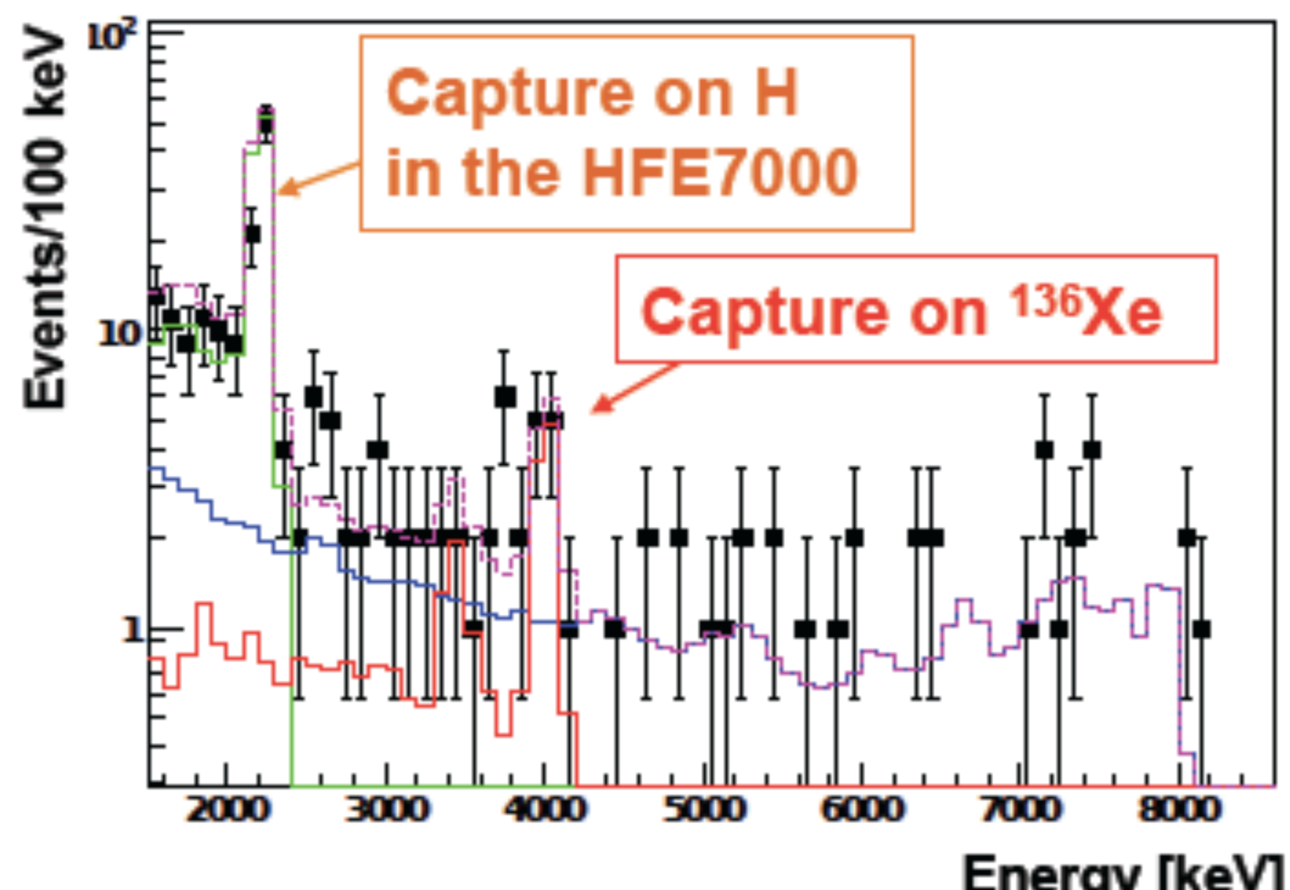
- Have simulated cosmogenic backgrounds for nEXO (cross-checked with EXO-200 data)
- Problematic backgrounds include β/γ emitters from n-capture (e.g. ^{137}Xe)

Site:	μ flux: [m^{-2} day]	Rock radioactivity: [Bq/kg] ^{232}Th:	^{238}U:
Gran Sasso (Italy)	22.3	0.25	5.18
SNOLAB (Canada)	**0.33**	**22.7**	**40.2**
Jinping (China)	~0.14	<0.27	1.8±0.2 (^{226}Ra)

Cosmogenic background rate vs. site:

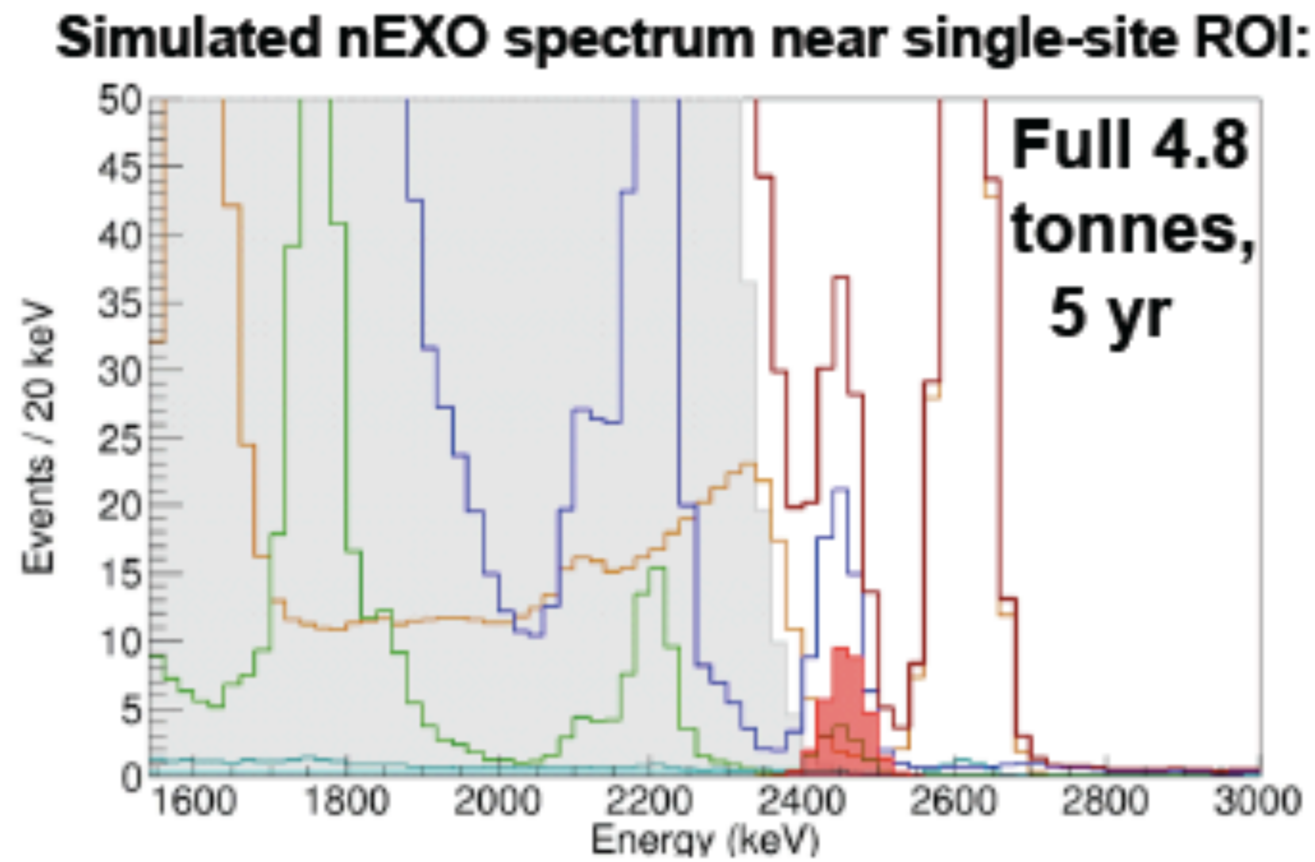


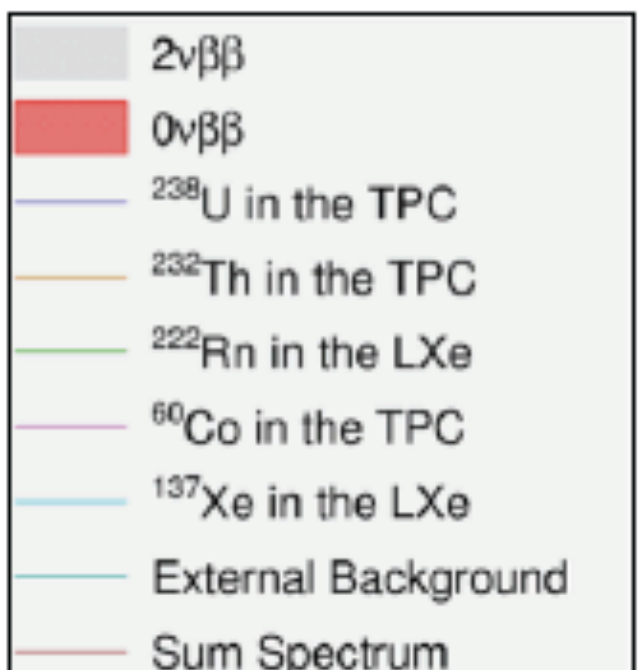
EXO-200 veto coincident spectrum:

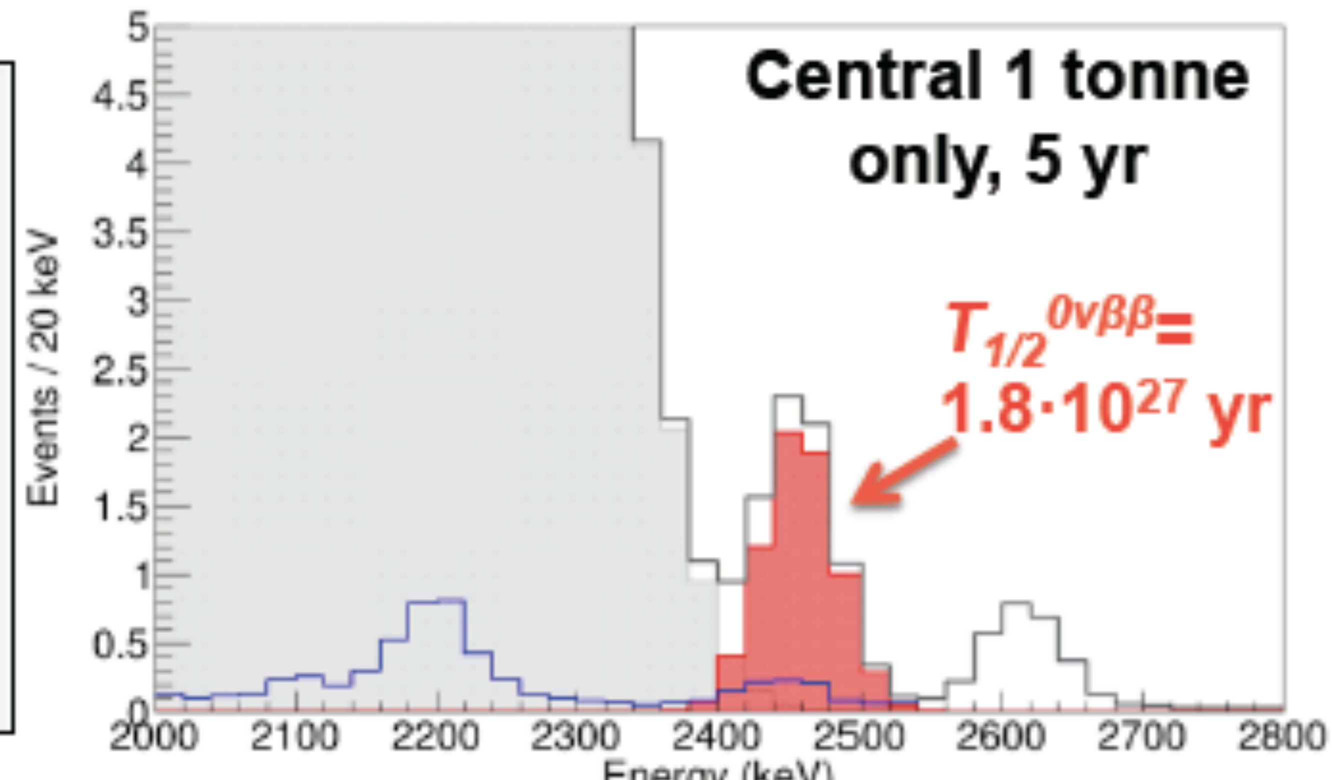


nEXO expected backgrounds and signals

- Have developed Geant4 simulation for nEXO, using experience gained from EXO-200
- Spectra on right show expected backgrounds in 5 yr exposure, and 0νββ at discovery threshold
- Background calculation assumes measured activity for detector materials
- This procedure was verified with EXO-200 data, and assumes several improvements for nEXO







nEXO background simulation

- nEXO backgrounds assume measured activities for all detector materials

from EXO-200:

- have compared with EXO-200 data to confirm validity of our assumptions
- Measured background rate from EXO-200 is ***$B_{EXO\text{-}200}$ = 151±19 counts/(ROI t yr)*** (ROI = $Q_{\beta\beta}$ ± 0.5 FWHM, Nature 510, 9 (2014))
- Agrees with predicted nEXO rate in outer 16.2 cm under the same assumptions

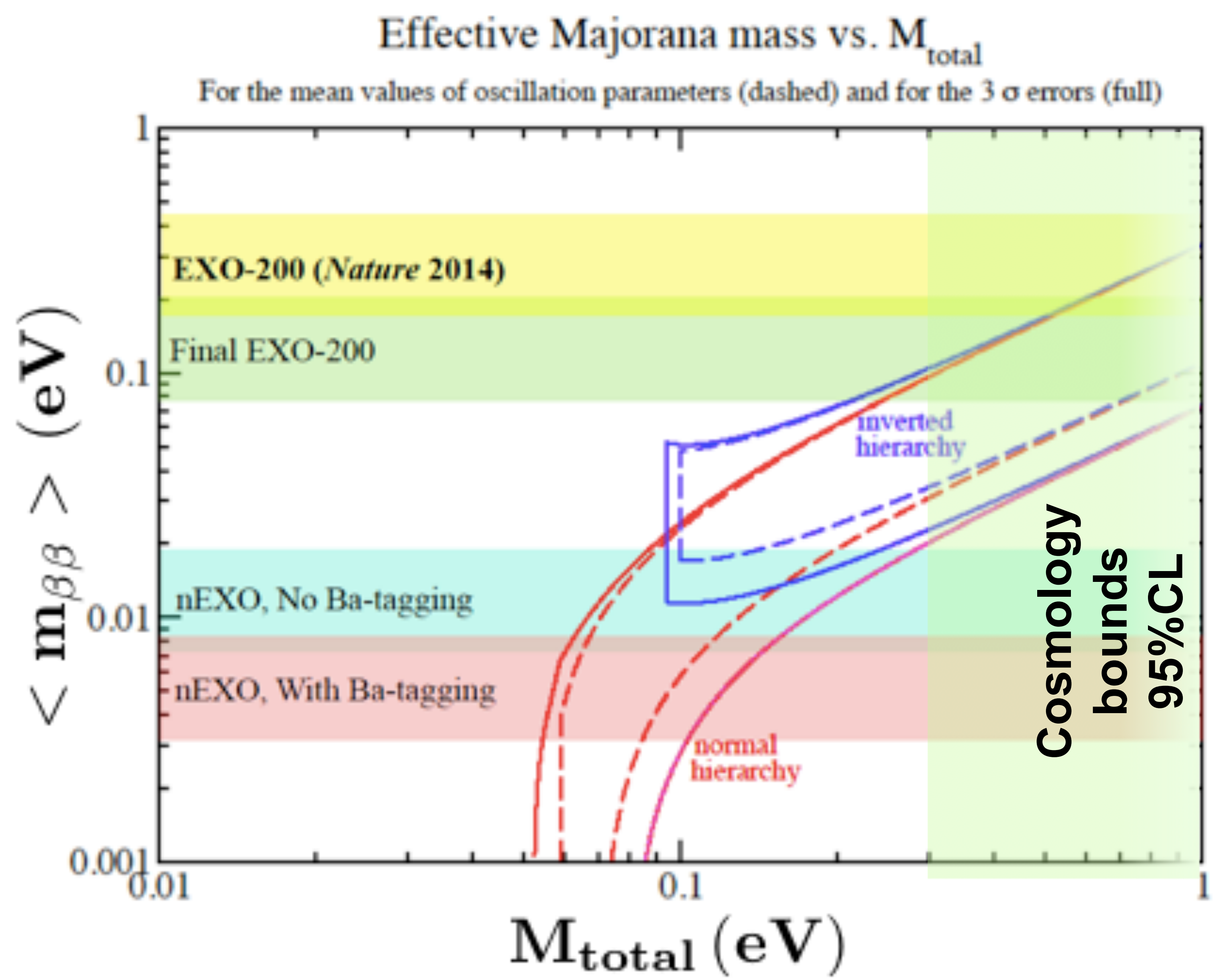
nEXO improvements:

  - improved energy resolution ($\sigma/Q_{\beta\beta}$ = 0.01)
  - improved SS/MS discrimination (wire pitch = 3mm)
  - reduced Cu activity from more sensitive radio assay (done)
  - lower 137Xe rate at SNOLab
  - reduced Rn density (lower surface/volume), longer 214BiPo cut
  - no kapton cables (cold electronics)
- total nEXO background prediction in outer 16.2 cm = ***Bn_{EXO} = 3.7 counts/(ROI t yr)***, a 40x background index improvement with respect to EXO-200

nEXO sensitivity

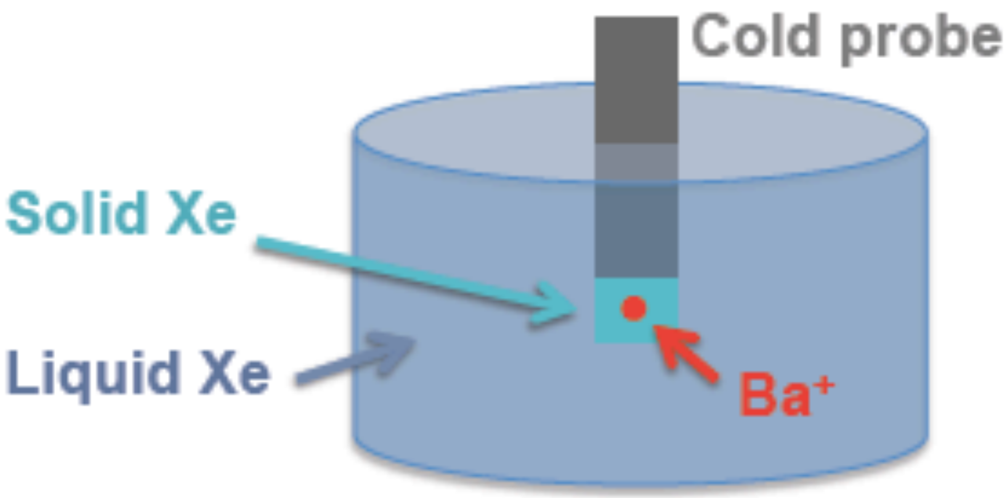
Parameter	nEXO	EXO-200
Fiducial Mass (kg)	4780	98.5
Enrichment (%)	90	80
Data taking time (yr)	5	5
Energy resolution @ $Q_{\beta\beta}$ (keV)	58	88 (58)
Background wthin FWHM of endpoint (evts/yr/mol_{136})	$6.1 \cdot 10^{-4}$	0.022 (0.0073)
Background within FWHM of endpoint inner 3000kg (evts/yr/mol_{136})	$1.6 \cdot 10^{-4}$	

- Sensitivity computed using background simulations
- Self shielding gives significantly lower backgrounds, especially in innermost volume
- Possible upgrade to include daughter Ba tagging

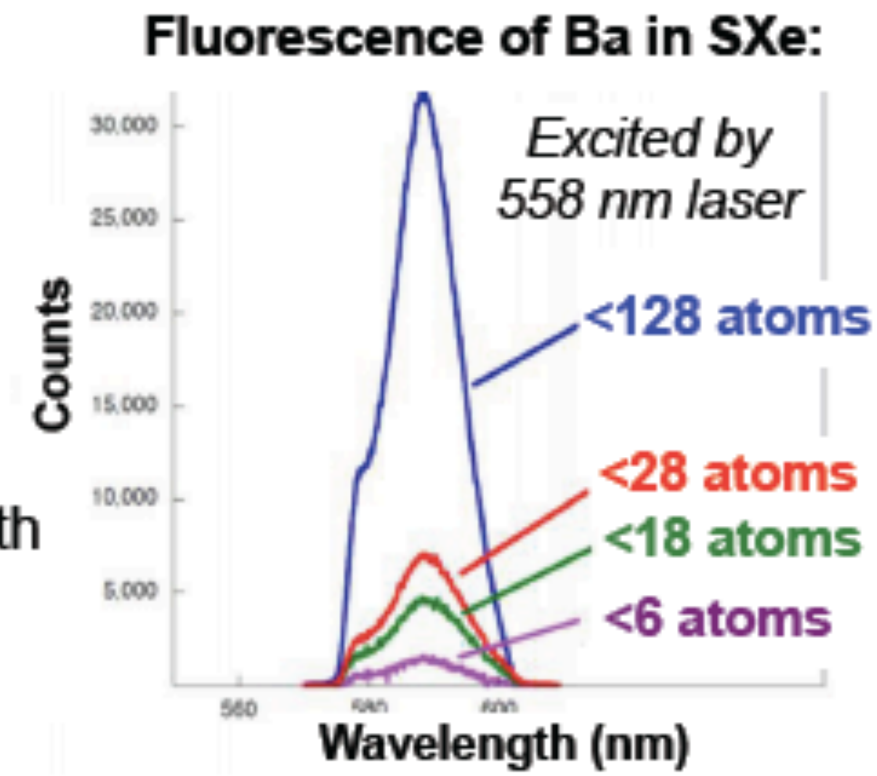


Ba tagging R&D

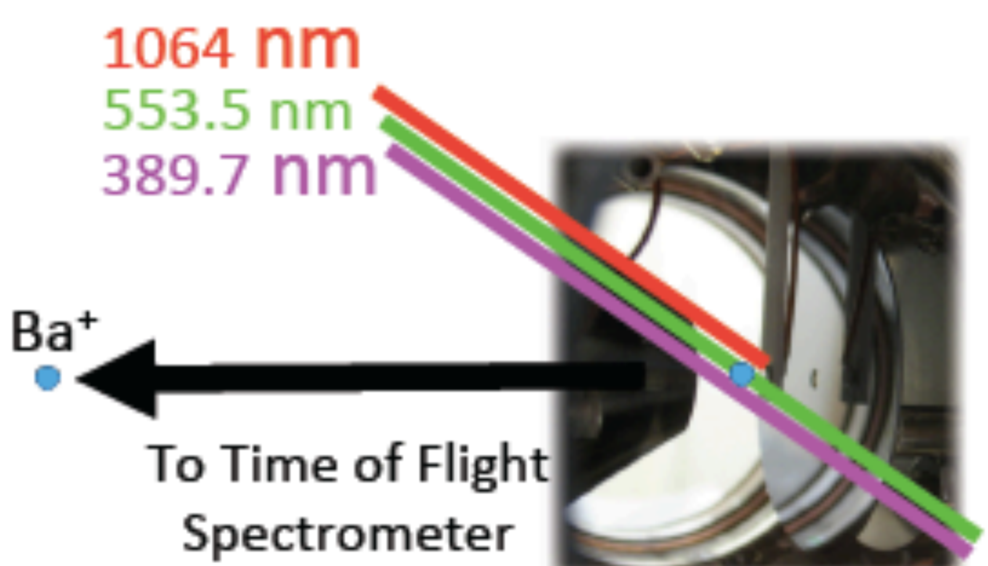
- Several techniques are currently being pursued:
  - Tagging from solid Xe by fluorescence spectrum

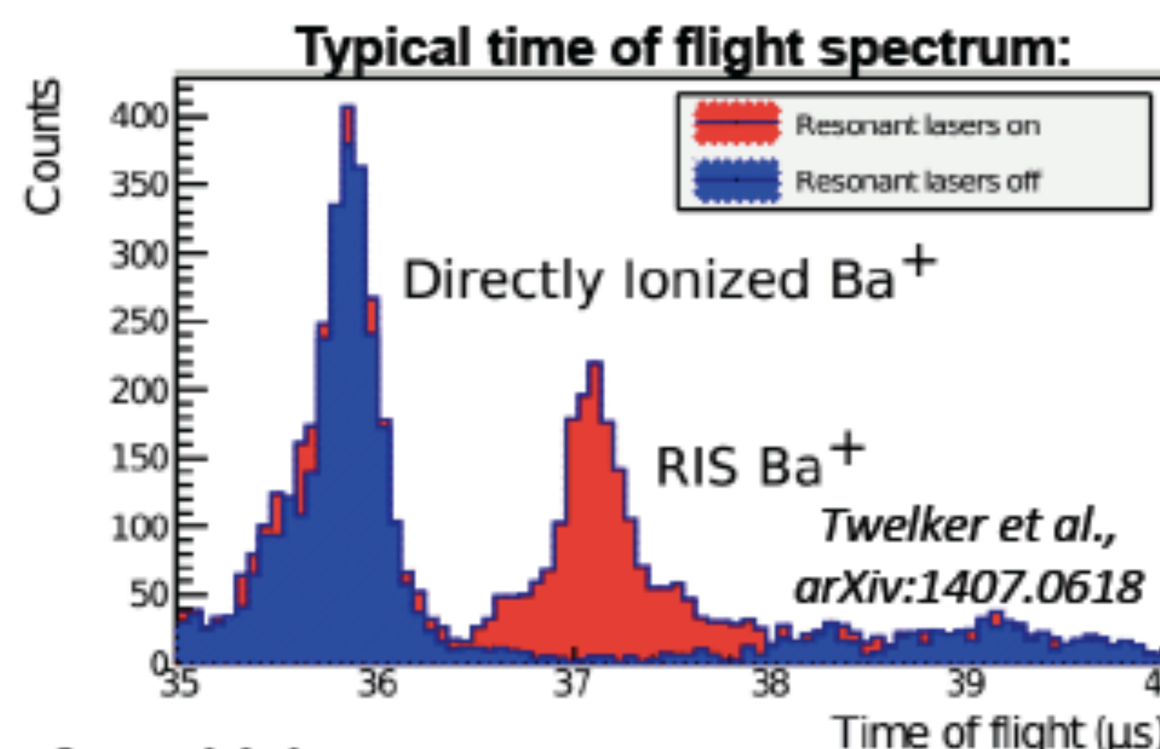


Detect single ion or atom on the probe with laser-induced fluorescence



  - Resonance ionization spectroscopy (RIS):





- Also studying ion extraction and tagging from high pressure Xe gas

nEXO sensitivity with Ba tagging

- In addition, R&D to develop techniques to identify Ba daughter nucleus of $0\nu\beta\beta$ decay ("Ba tagging") is continuing
- Candidate $0\nu\beta\beta$ events would be identified in real time and daughter Ba ion collected by probe inserted into the TPC at the decay location
- Identity of Ba daughter can be confirmed spectroscopically
- This technology would eliminate all non-$\beta\beta$ backgrounds near ROI
- Could extend ultimate reach of nEXO into the normal hierarchy since full 5 tonne mass would be background free