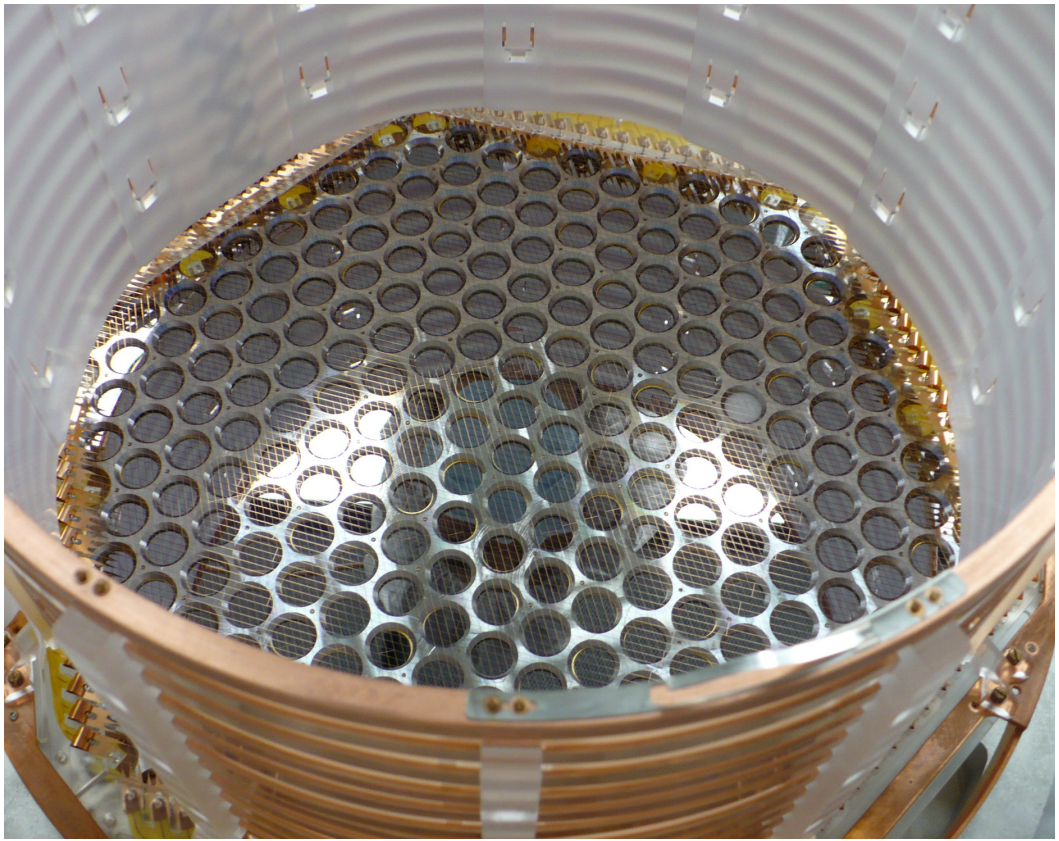
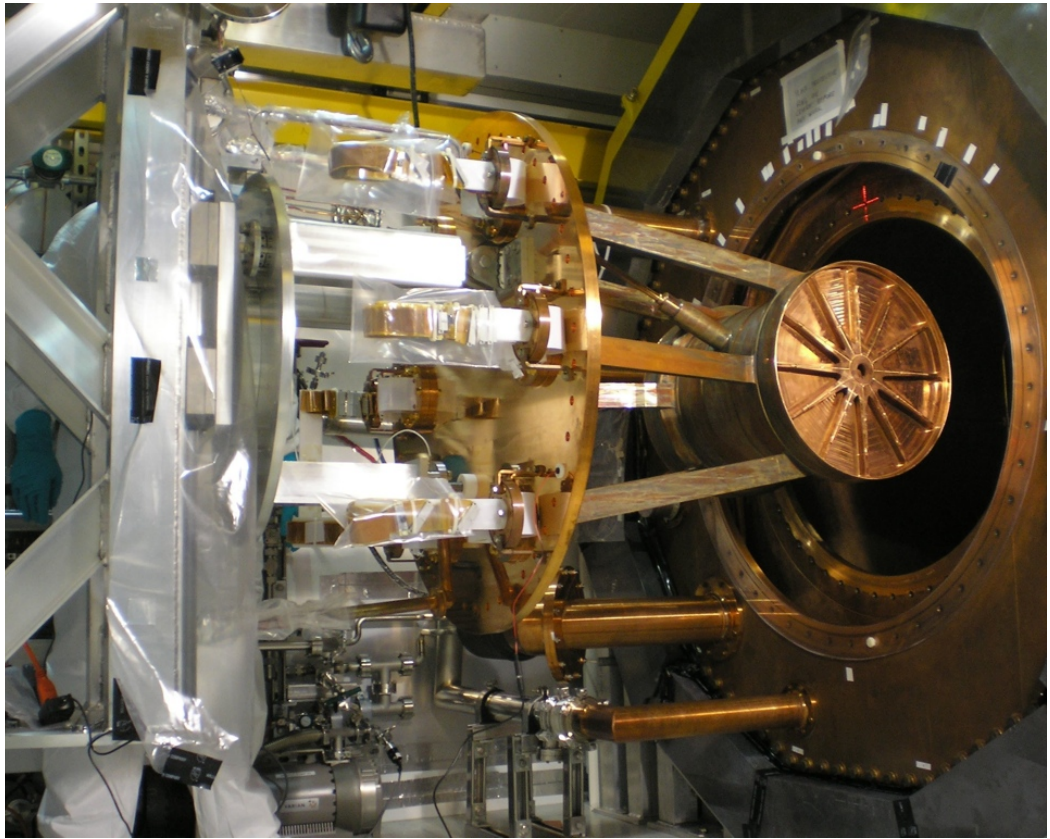
Searching for neutrinoless double beta decay with EXO

David Moore, Yale University

Neutrino Seminar Series, Fermilab
October 19, 2017





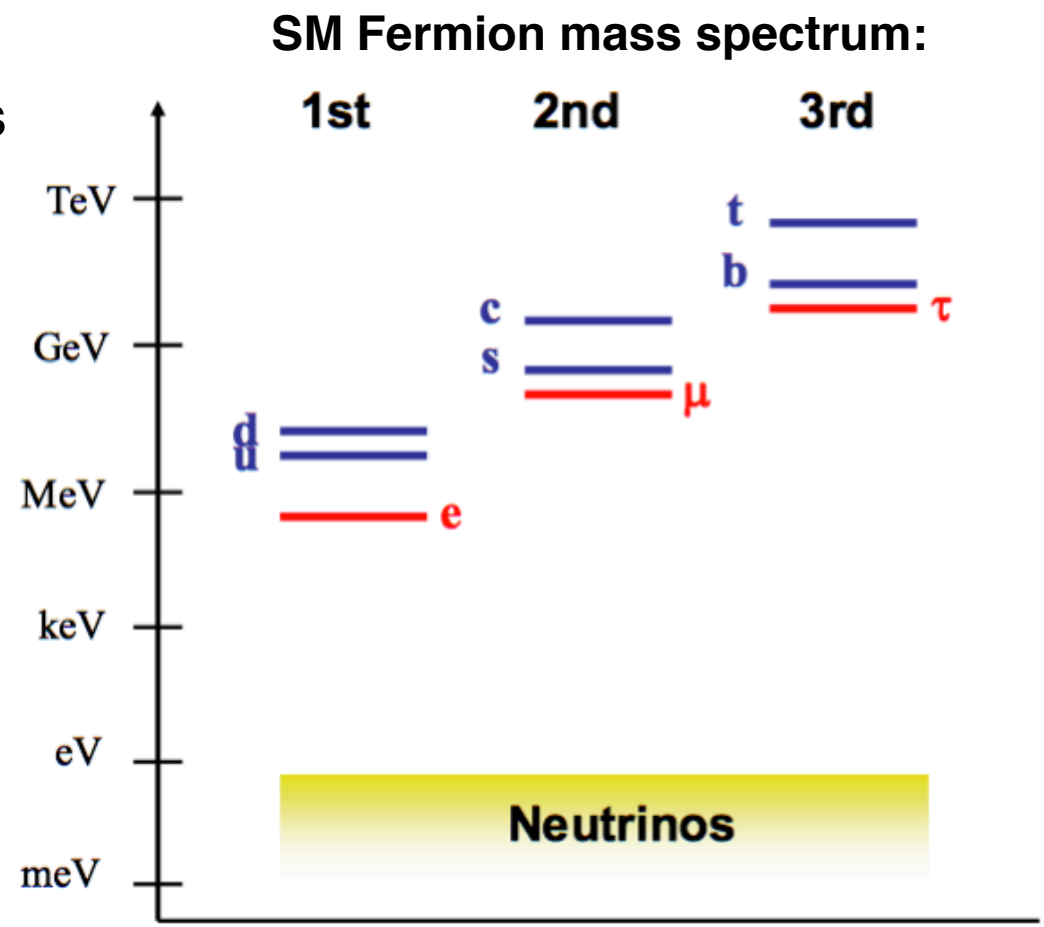
Neutrino masses

- Oscillation experiments show that neutrinos have small, non-zero mass

- "See-saw" models provide a natural way to obtain small m_ν:

$$m_\nu \approx \frac{m_{q,l}^2}{m_R} \quad \Rightarrow \quad m_R \gtrsim 10^{14}\ \mathrm{GeV}$$

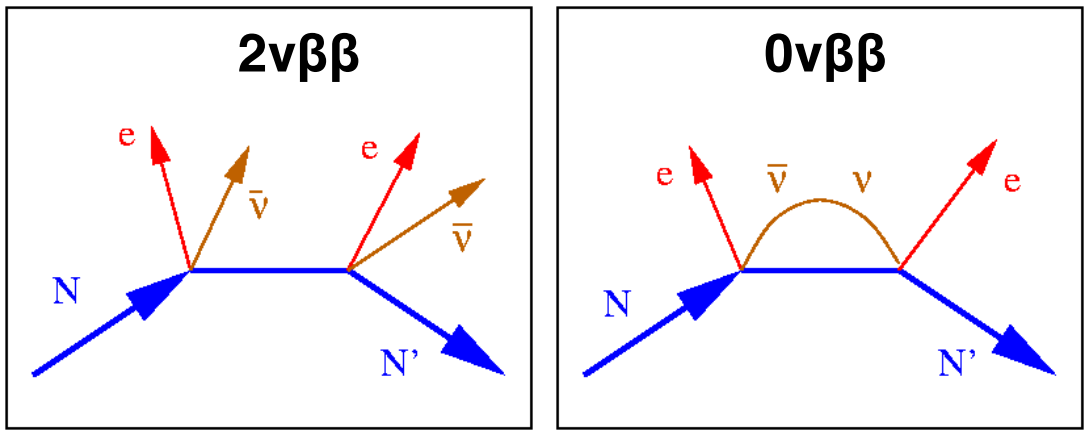
- A key test is whether neutrinos are Majorana (i.e., $\nu = \bar{\nu}$)



- Lepton number violation present in certain see-saw models could also be related to mechanism for leptogenesis in early universe

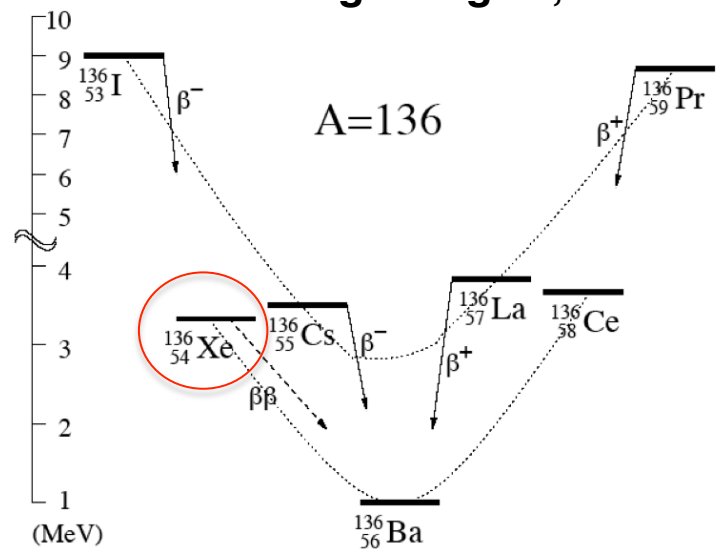
0νββ

- Double beta decay is the most sensitive probe of the Majorana nature of the neutrino
- If neutrinos are Majorana particles, decay can proceed with no emitted neutrinos (0νββ)

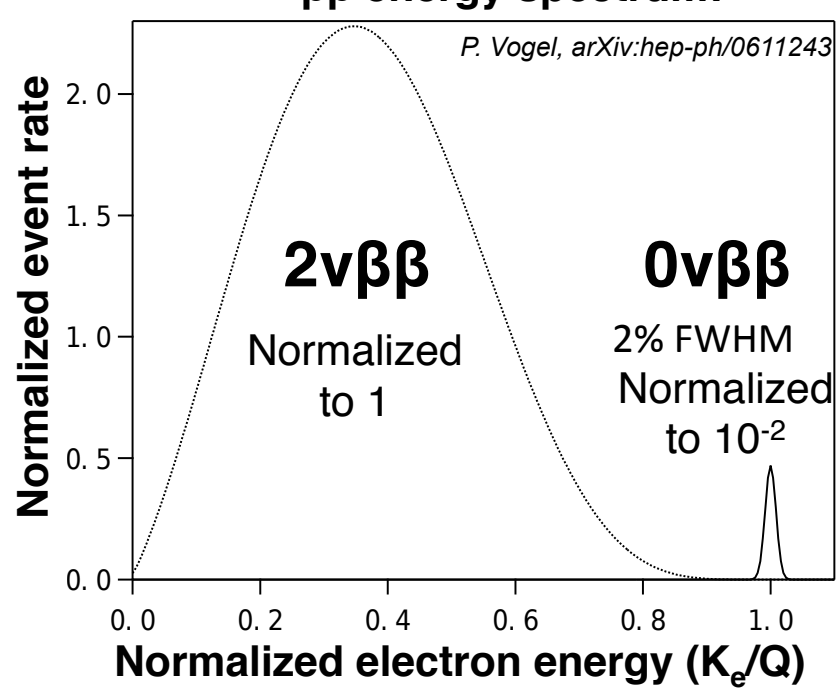


- Observation of 0νββ would provide:
  - A beyond the Standard Model, lepton-number violating process
  - Demonstrate that neutrinos are Majorana particles
  - Constrain absolute neutrino mass scale

Nuclear binding energies, A = 136:



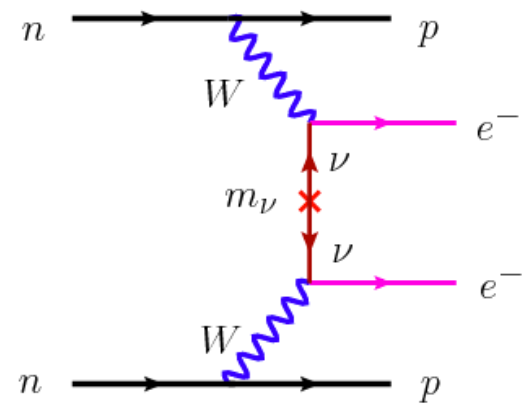
ββ energy spectrum:



Majorana mass

- For the "standard mechanism":

$$\left(T^{0\nu}_{1/2}\right)^{-1} = g_A^4\, G^{0\nu}\, \left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$



g_A - *effective axial coupling (~1.27)*

$G^{0\nu}$ - *phase space factor*

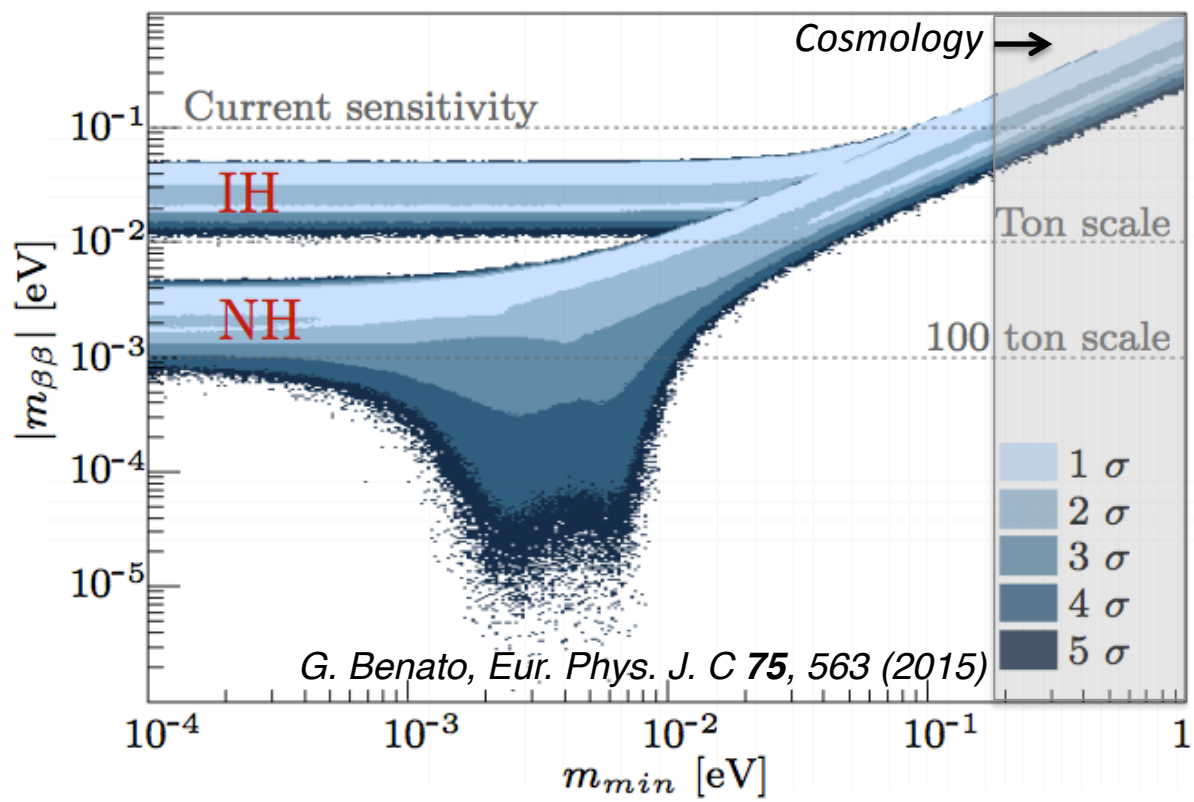
$M^{0\nu}$ - *Nuclear matrix element (NME)*

"Effective" Majorana mass:

$$\langle m_{\beta\beta}\rangle = \left|\sum_i U_{ei}^2 m_i\right|$$

Other mechanisms can substantially enhance rate!

Majorana mass parameter space:



*G. Benato, Eur. Phys. J. C **75**, 563 (2015)*

Double beta decay in ^{136}Xe

- Require ~ ton-yr exposures while minimizing backgrounds
- Liquid Xe offers several advantages for a large experiment:
  - **Easy to enrich** (noble gas, ^{136}Xe heaviest "stable" isotope)
  - **Reusable** (can be repurified and recycled)
  - **Self-shielding** (large, monolithic detectors reduce surface backgrounds)
  - **Minimal cosmogenic activation** (no long-lived radioactive isotopes)
  - **Energy resolution ~1%** (obtained by measuring charge and scintillation)

Candidate nuclides with Q > 2 MeV:

Candidate:	Q: [MeV]	Abundance: [%]
^{48}Ca → ^{48}Ti	4.271	0.187
^{76}Ge → ^{76}Se	2.040	7.8
^{82}Se → ^{82}Kr	2.995	9.2
^{96}Zr → ^{96}Mo	3.350	2.8
^{100}Mo → ^{100}Ru	3.034	9.6
^{110}Pd → ^{110}Cd	2.013	11.8
^{116}Cd → ^{116}Sn	2.802	7.5
^{124}Sn → ^{124}Te	2.228	5.64
^{130}Te → ^{130}Xe	2.533	34.5
^{136}Xe → ^{136}Ba	2.479	8.9
^{150}Nd → ^{150}Sm	3.367	5.6

LXe-based detectors may also allow **identification of Ba daughter** nucleus, eliminating all non-ββ backgrounds *see, e.g., M.K. Moe,* Phys. Rev. C. 44, R931 (1991)

The EXO-200 Collaboration

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University of Bern, Switzerland — J-L Vuilleumier
University of California, Irvine, Irvine CA, USA — M Moe
California Institute of Technology, Pasadena CA, USA — P Vogel
Carleton University, Ottawa ON, Canada — I Badhrees, W Cree, R Gornea, K Graham, T Koffas, C Licciardi, D Sinclair
Colorado State University, Fort Collins CO, USA — C Chambers, A Craycraft, W Fairbank Jr, D Harris, A Iverson, J Todd, T Walton
Drexel University, Philadelphia PA, USA — MJ Dolinski, EV Hansen, YH Lin, Y-R Yen
Duke University, Durham NC, USA — PS Barbeau
Indiana University, Bloomington IN, USA — JB Albert, S Daugherty
Laurentian University, Sudbury ON, Canada — B Cleveland, A Der Mesrobian-Kabakian, J Farine, A Robinson, U Wichoski
University of Maryland, College Park MD, USA — C Hall
University of Massachusetts, Amherst MA, USA — S Feyzbakhsh, S Johnston, A Pocar
McGill University, Montreal QC, Canada — T Brunner, Y Ito, K Murray

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Friedrich-Alexander-University Erlangen, Nuremberg, Germany G Anton, R Bayerlein, J Hoessl, P Hufschmidt, A Jamil, T Michel, M Wagenpfeil, G Wrede, T Ziegler
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Stony Brook University, SUNY, Stony Brook, NY, USA — K Kumar, O Njoya, M Tarka
Technical University of Munich, Garching, Germany — W Feldmeier, P Fierlinger, M Marino
TRIUMF, Vancouver BC, Canada — J Dilling, R Krücken, Y Lan, F Retière, V Strickland
Yale University, New Haven CT, USA — Z Li, D Moore, Q Xia

EXO-200 TPC

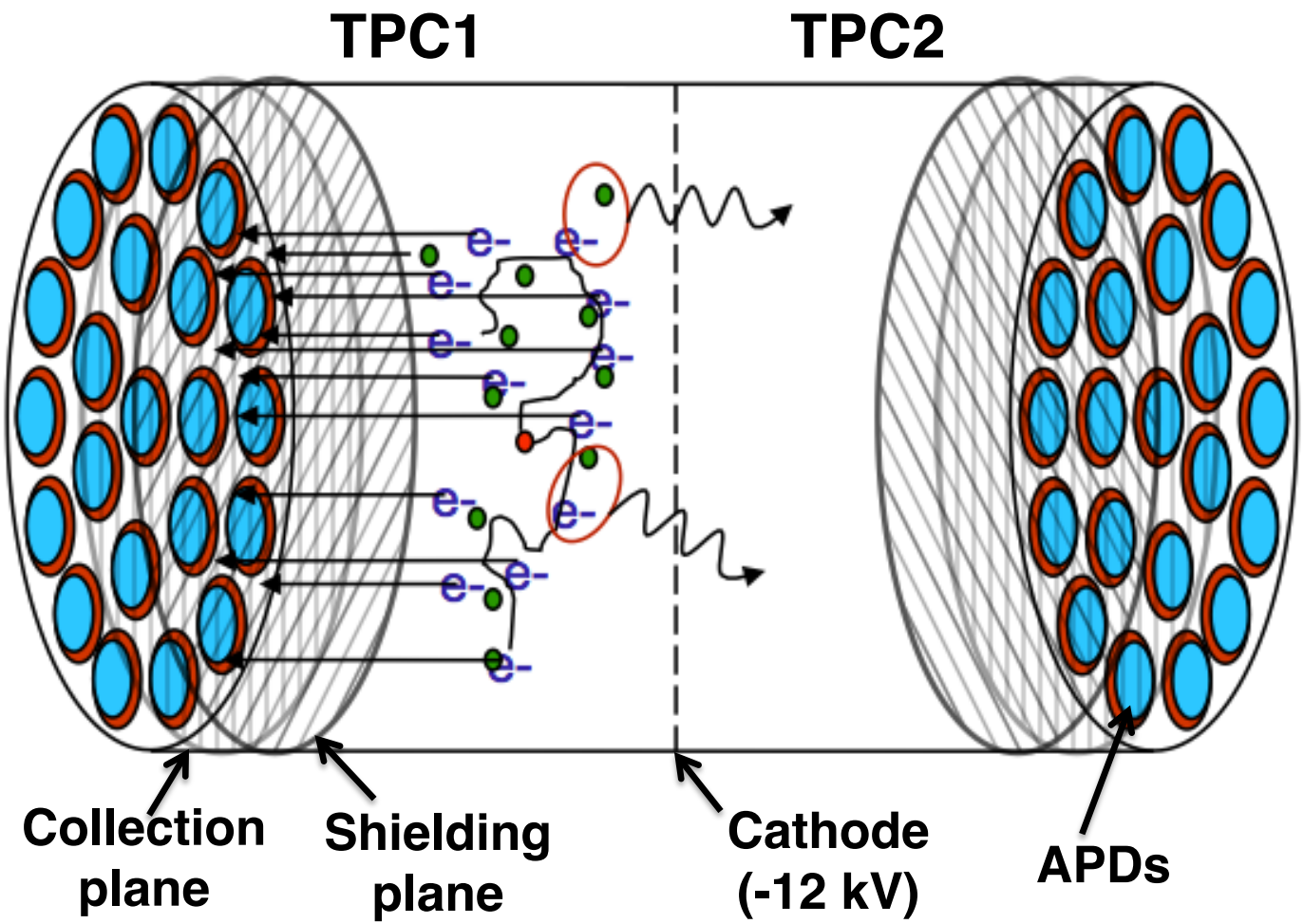
- The EXO experimental program is searching for the 0νββ of ^{136}Xe
- EXO-200 consists of a radiopure time projection chamber (TPC) filled with ~175 kg liquid Xe, enriched to 80.6% ^{136}Xe

Wire channel pitch = 9mm

Pulse rise time ~ 3 μs

Drift field = 580 V/cm

Light collection eff ~ 8%



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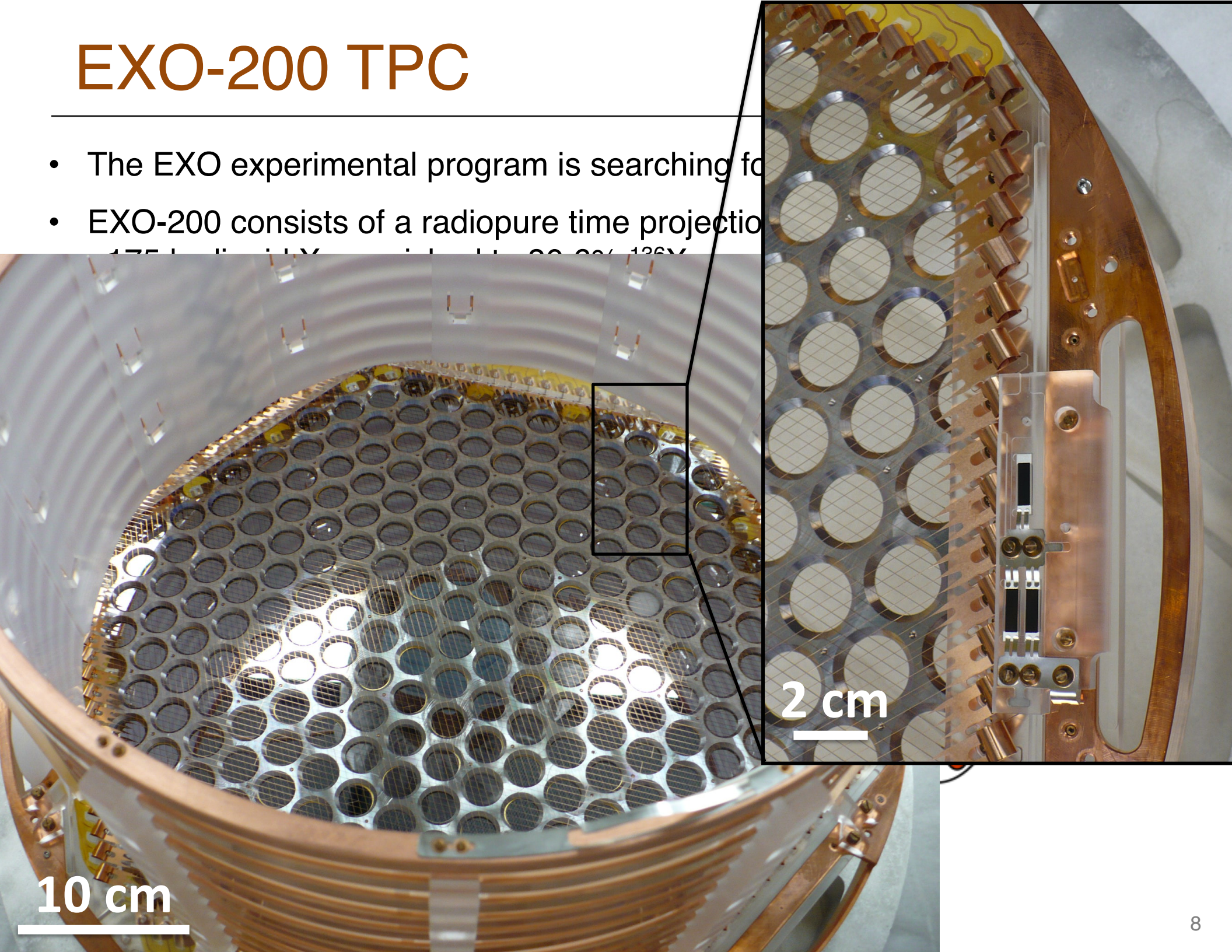
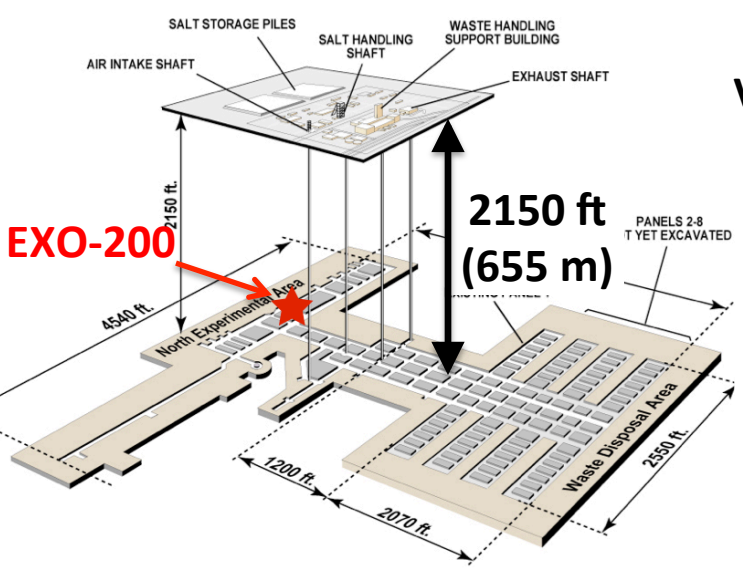


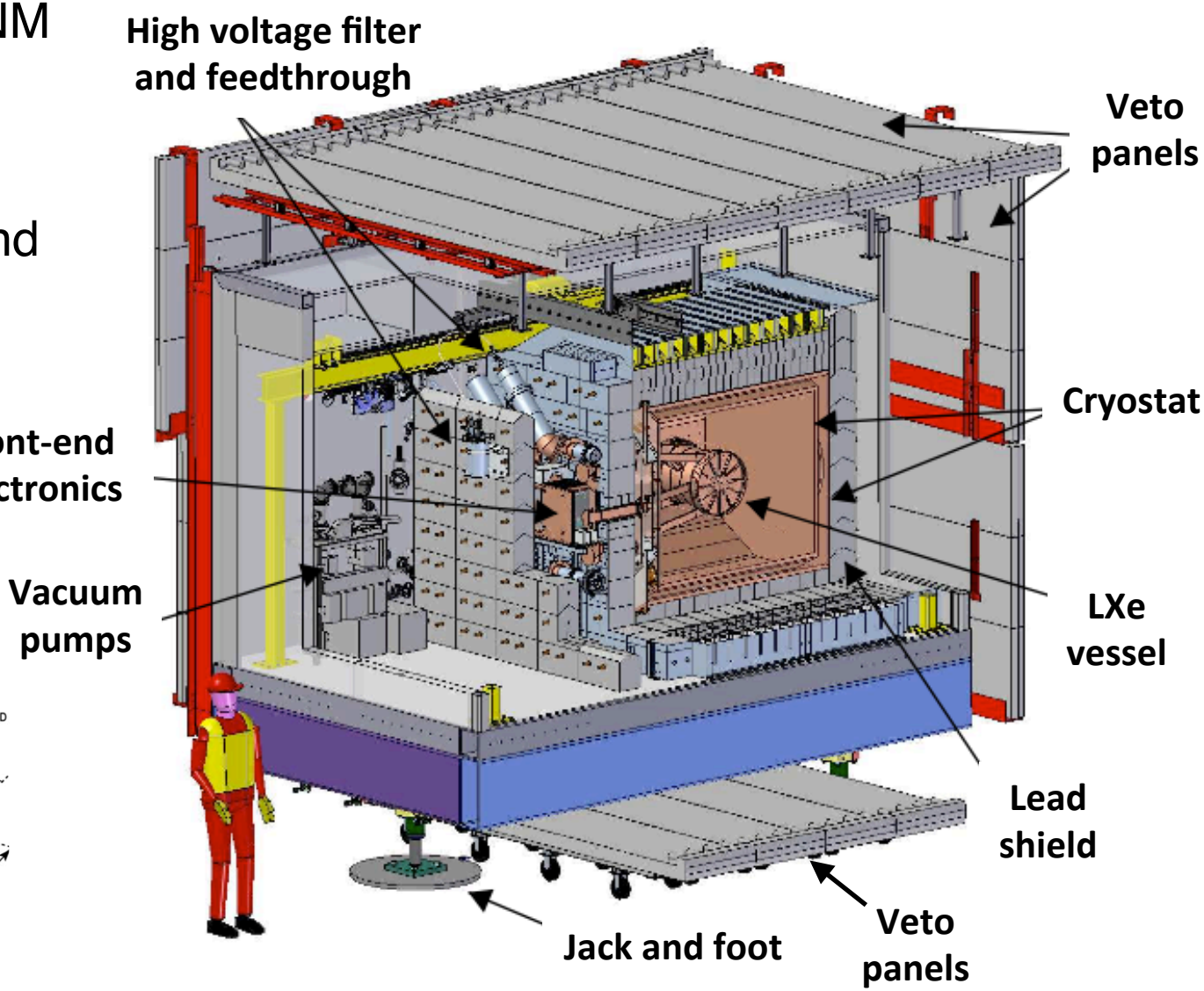
EXO-200 detector

- Detector installed at WIPP facility near Carlsbad, NM (~1600 mwe)
- TPC additionally surrounded by active and passive shielding

WIPP site:



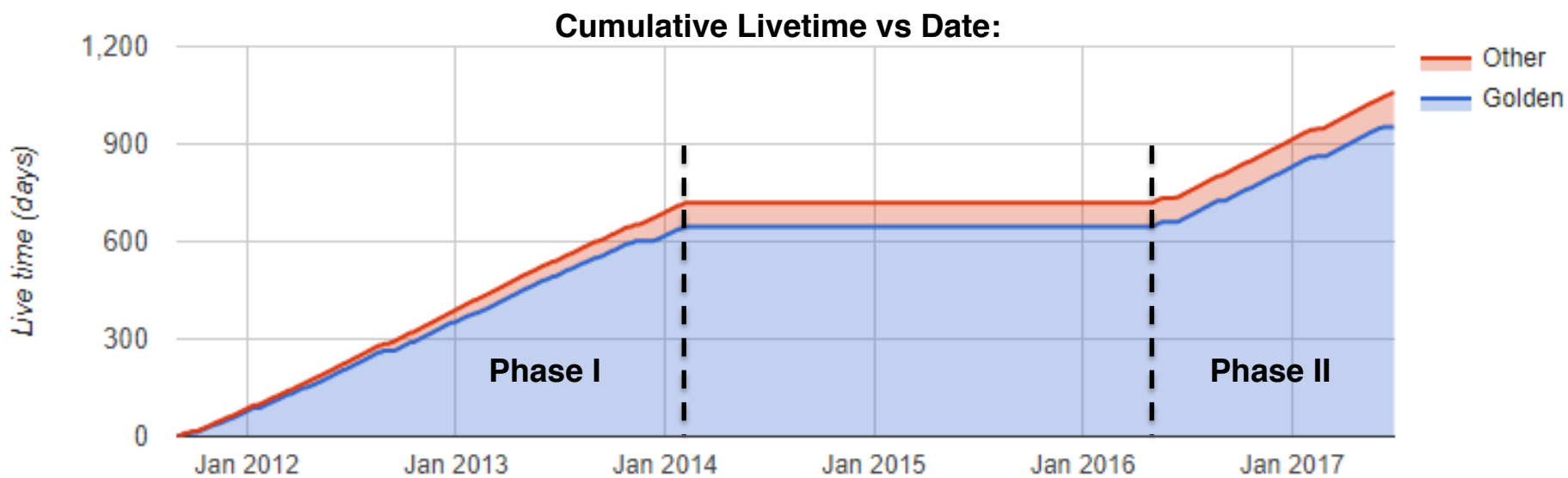
Detector schematic:



EXO-200 operation

- **Sep 2011 to Feb 2014**
  - Total live time 596.7 days
- Selected physics results
  - Most precise 2νββ measure
    - *Phys. Rev. C **89**, 015502 (2013)*
  - High-sensitivity search for 0νββ
    - *Nature **510**, 229 (2014)*
    - Sensitivity $T_{1/2}^{0\nu\beta\beta} > 1.9\times10^{25}$ yr (90%CL)

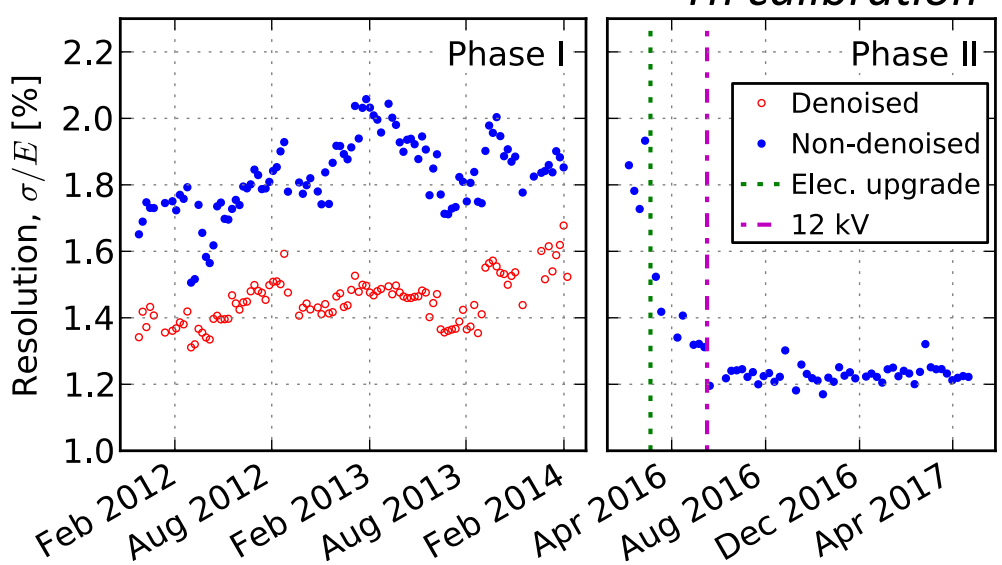
- **2016 to Present:**
  - Access regained after stop imposed by WIPP accidents
  - Jan to May 2016
    - Hardware upgrades
  - HV raised by 50% in May 2016
  - Live time 271.8 days



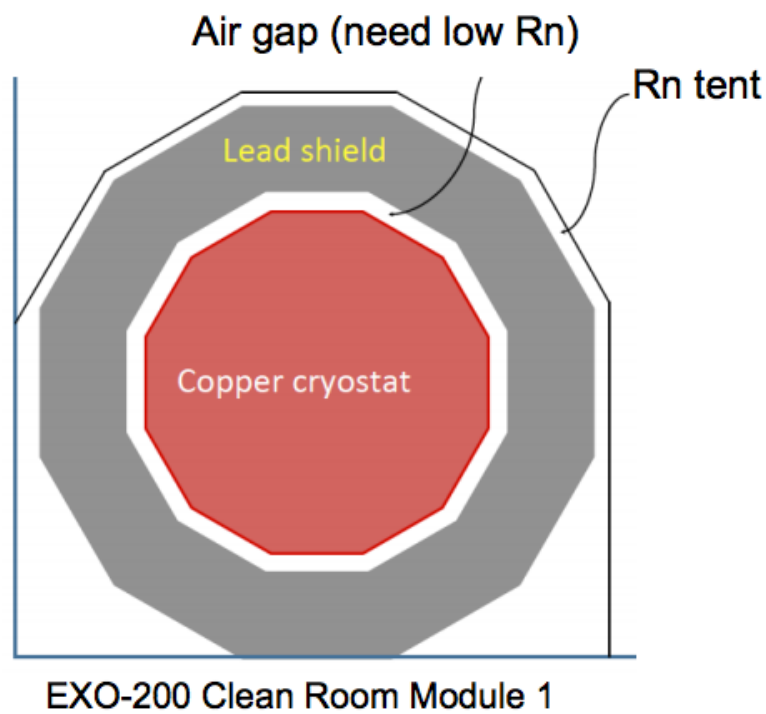
Detector Upgrades

- Front end readout electronics
  - *Reduce APD read-out noise*
- Increase of HV
  - *-8kV → -12 kV*
- Effect in energy resolution:
  - Phase-I: σ/E(Q) ~ 1.4-1.6%
  - Phase-II: σ/E(Q) = 1.2%, steady

^{228}Th calibration



- System to suppress radon in air gap

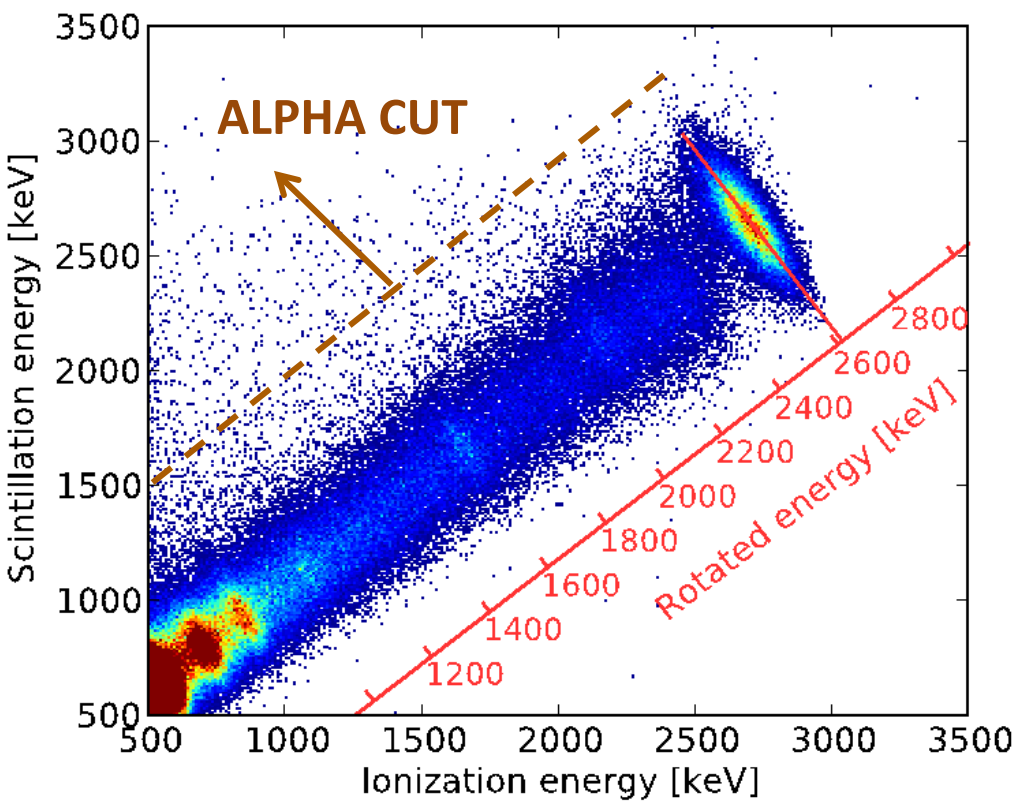


- Direct air sampling shows radon levels reduced in the gap by >10x

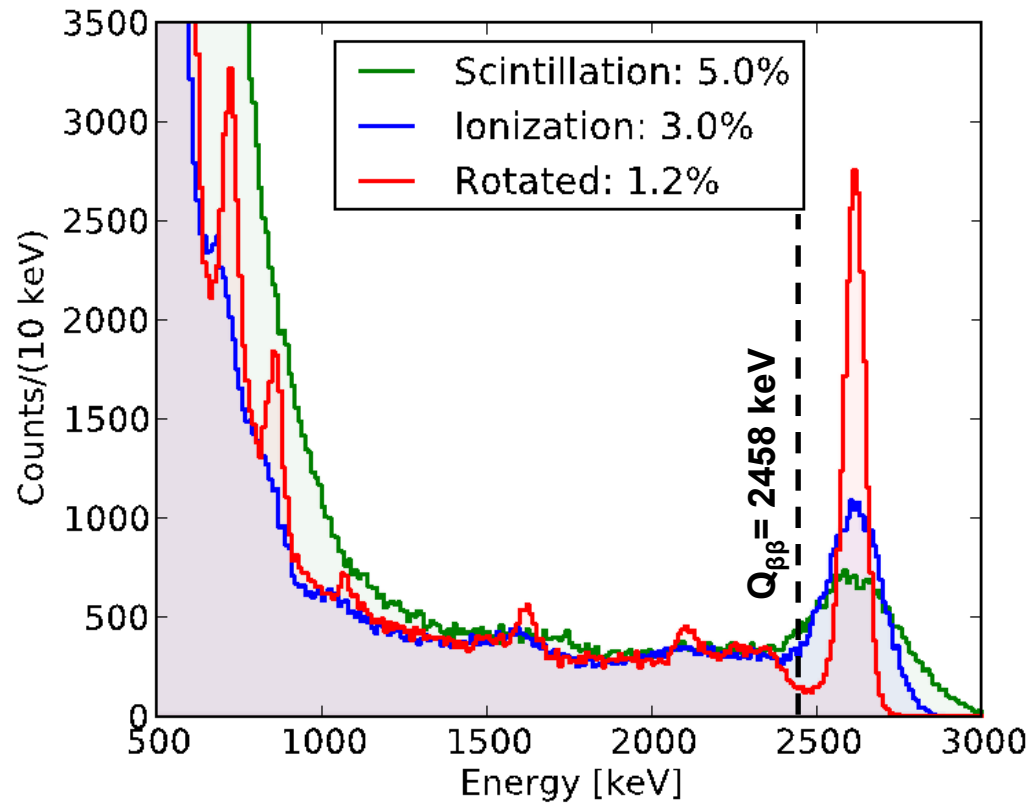
Energy resolution

- Reconstruct “rotated” energy measured in scintillation versus ionization plane
- Takes into account anti-correlation of charge and scintillation response to improve energy resolution

Scintillation vs. ionization, ^{228}Th calibration:

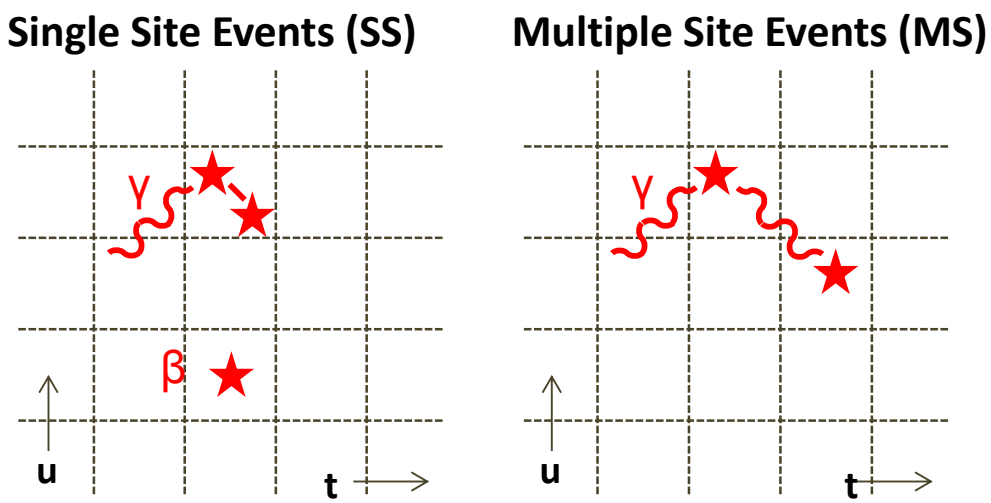


Reconstructed energy, ^{228}Th calibration:

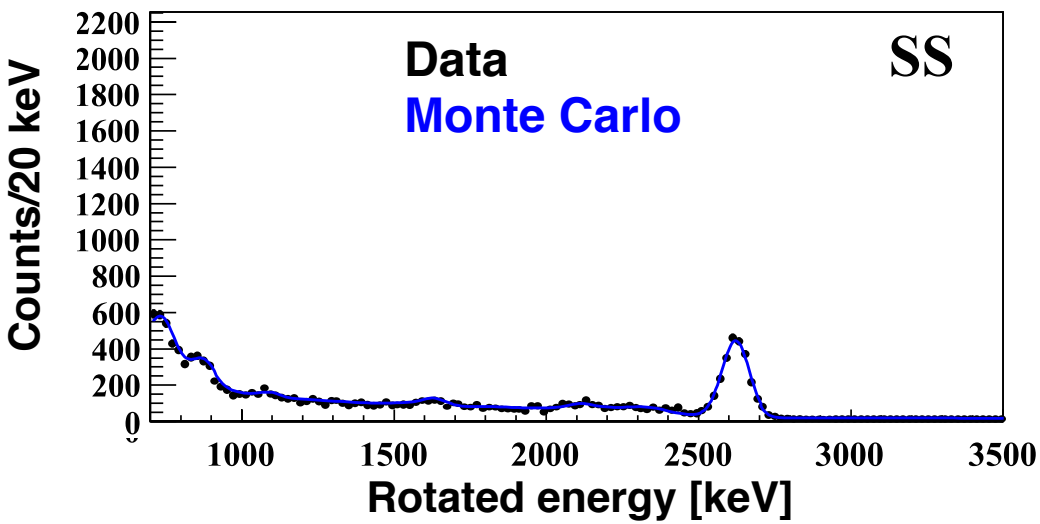


Background discrimination

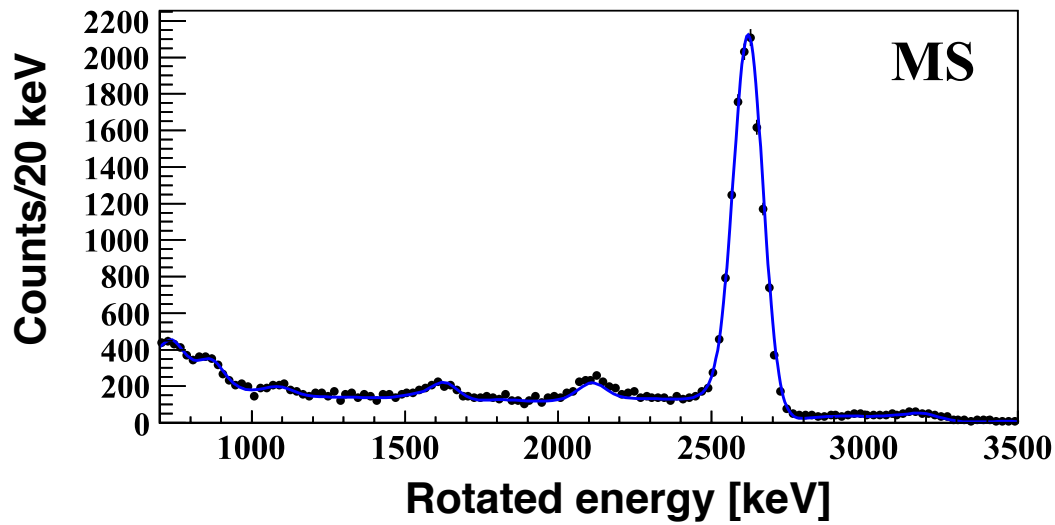
- ββ signal deposits energy at single location, backgrounds are multi-site
- Channel pitch is 9 mm in X/Y, Z resolution is ~6 mm
- SS fraction is ~20% in 0νββ region of interest



Energy spectrum, ^{228}Th calibration data, SS:



Energy spectrum, ^{228}Th calibration data, MS:

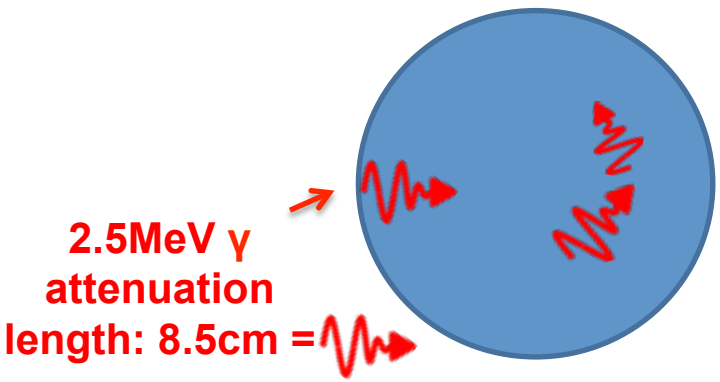


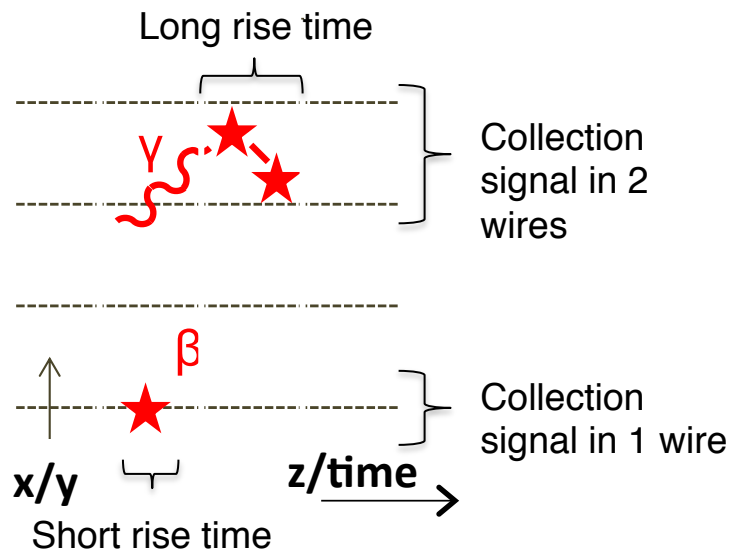
*Phys. Rev. C **89**, 015502, arXiv:1306.6106 (2013)*

Multivariate discriminator

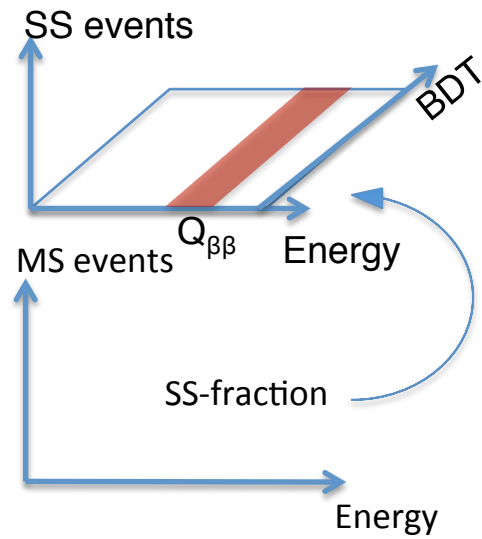
- Add BDT-based discriminator to further identify γ backgrounds passing discrete SS/MS classification

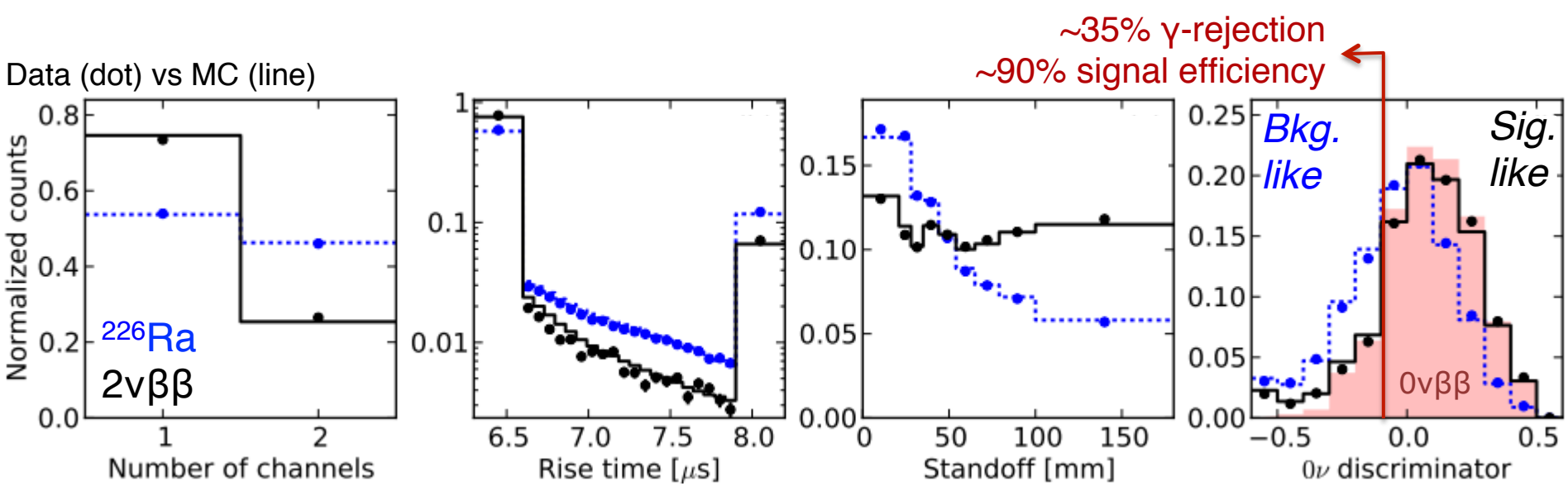
LXe self-shielding:





Multi-dimensional fit:

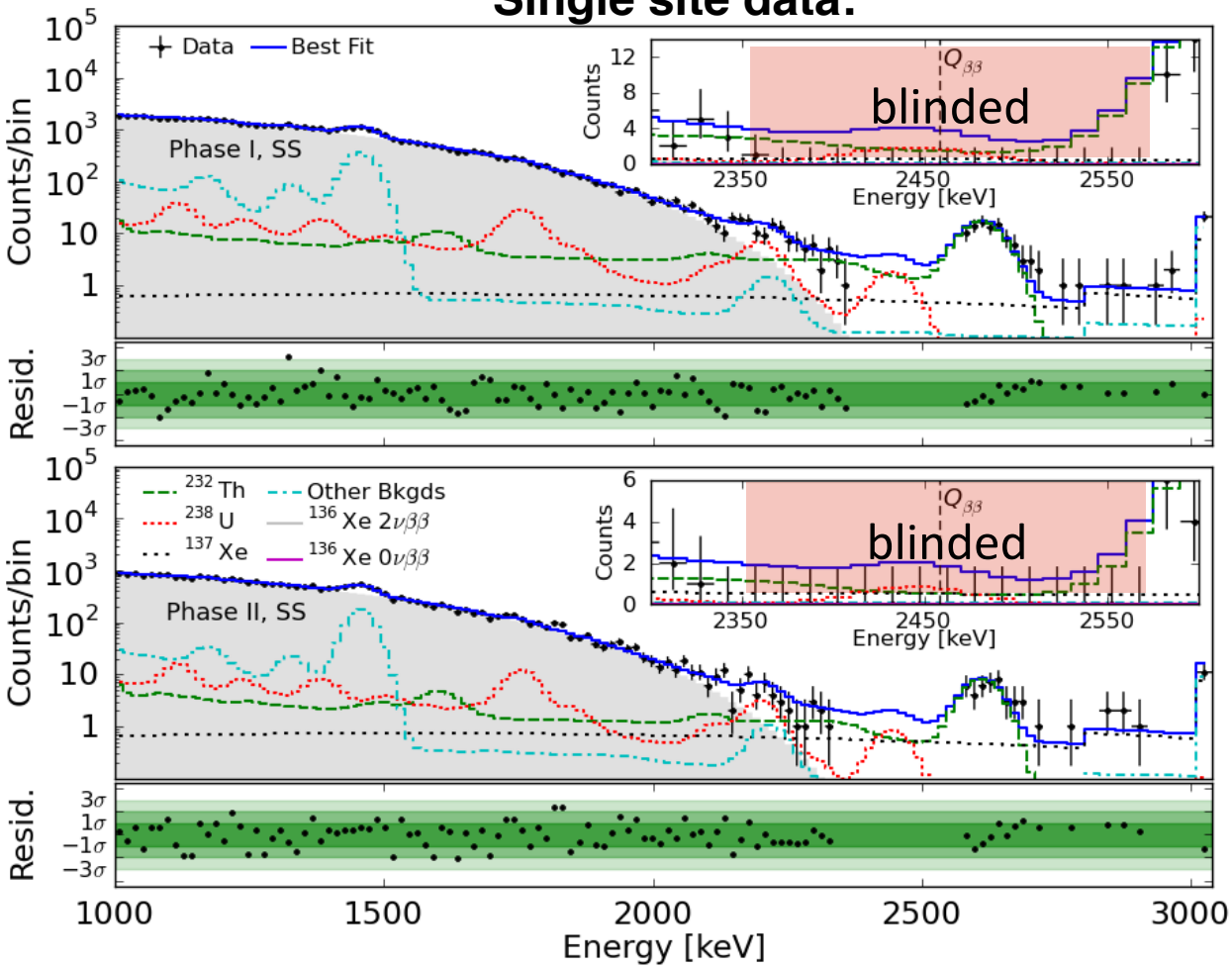




Phase 2 results (2017)

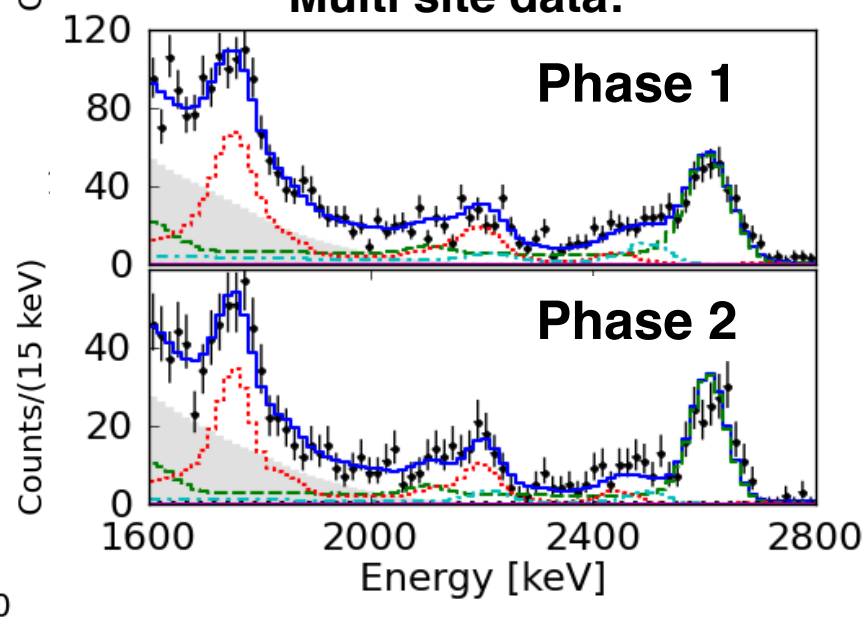
- "Blind" analysis
- Background model + data → maximum likelihood fit
- Combine Phase I + Phase II profiles

Single site data:



Systematics	Phase I (%)	Phase II (%)
Detection efficiency	82.4 ± 3.0	80.8 ± 2.9
Shape differences	±6.2	±6.2
SS fraction	±5.0	±8.8

Multi site data:

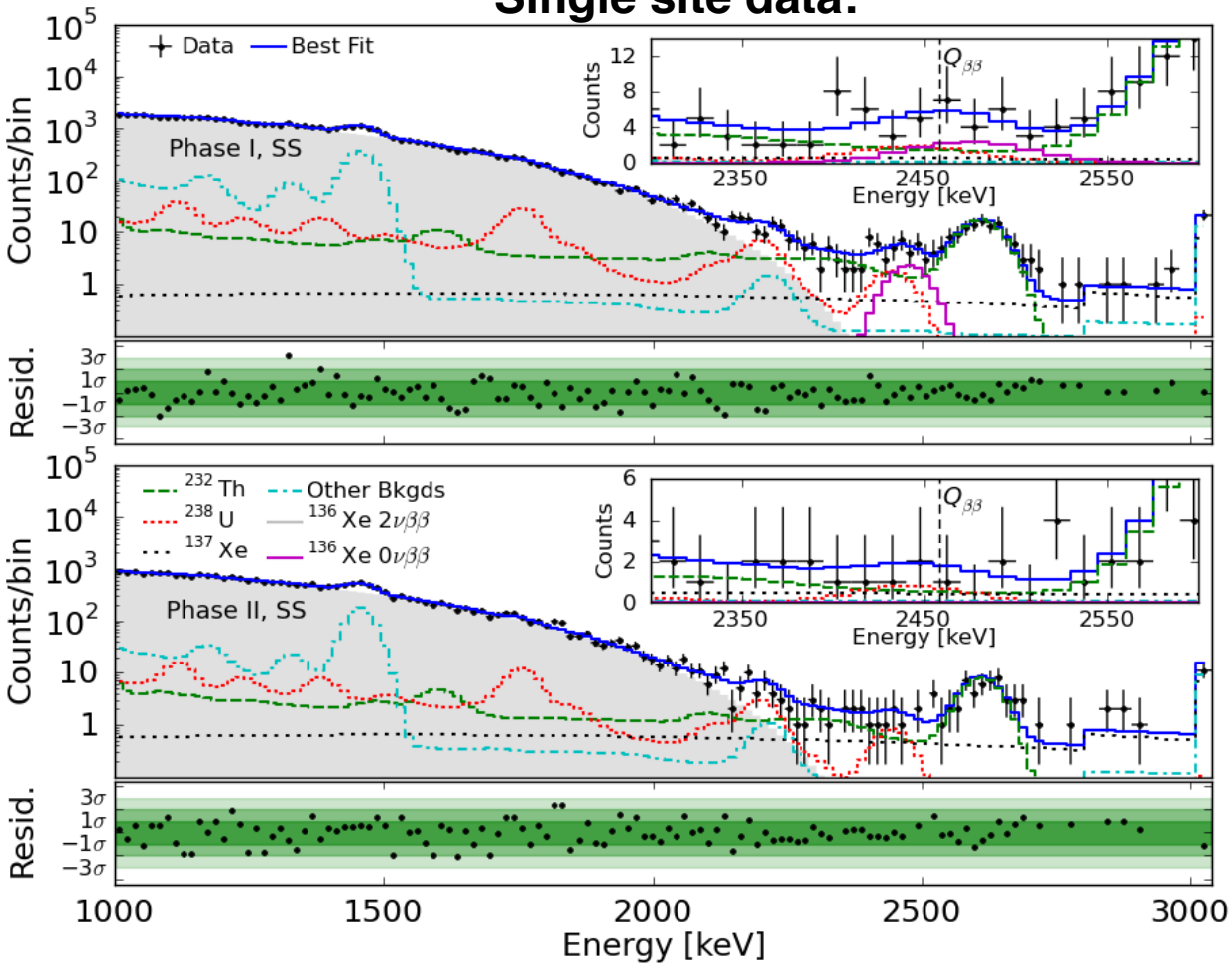


arXiv: 1707.08707

Phase 2 results (2017)

- Background model + data → maximum likelihood fit
- Combine Phase I + Phase II profile likelihood
- No statistically significant excess: combined p-value ~1.5σ

Single site data:



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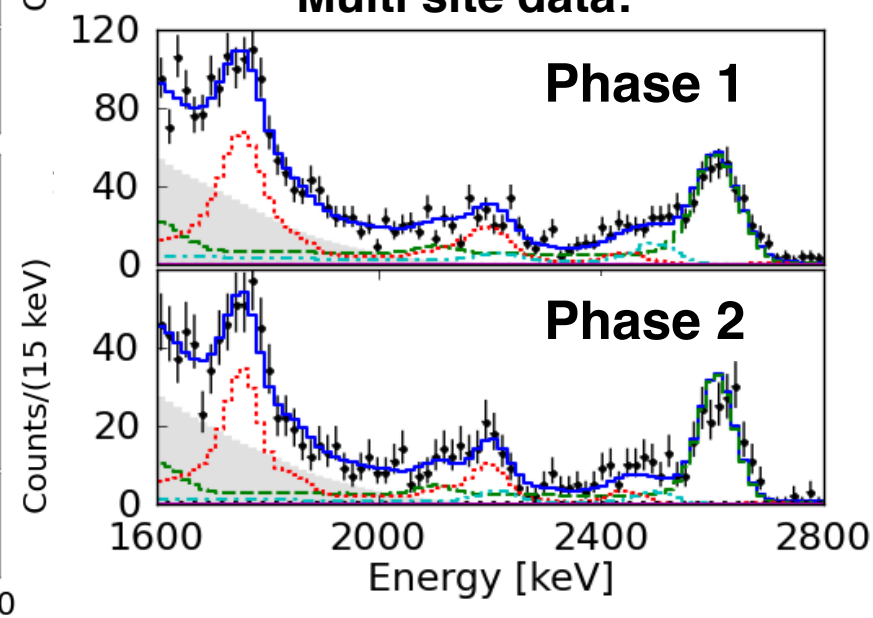

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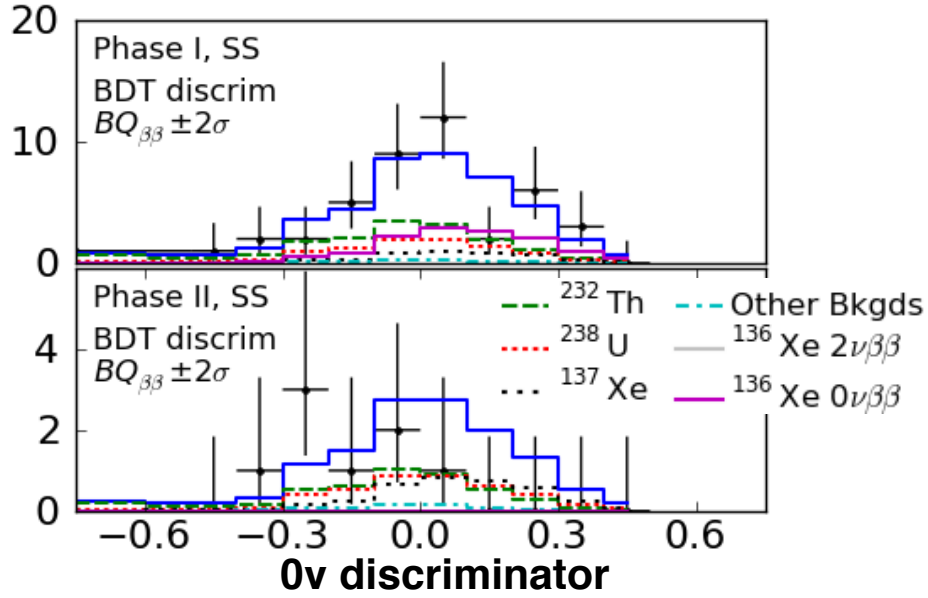


Contributions to BQ±2σ	Phase I (cts)	Phase II (cts)
^{232}Th	15.8	4.8
^{238}U	9.4	4.2
^{137}Xe	4.4	3.6
Total bkg:	**30.7±6.0**	**13.2±1.4**
Data cts:	***43***	***8***

- Total exposure = 177.6 kg.yr
- Background index ~ 1.5±0.2 x10^{-3} / (kg.yr.keV)

90% CL Sensitivity: **3.7x10^{25} yr**

$T_{1/2}^{0\nu\beta\beta} > 1.8 \times 10^{25}$ yr

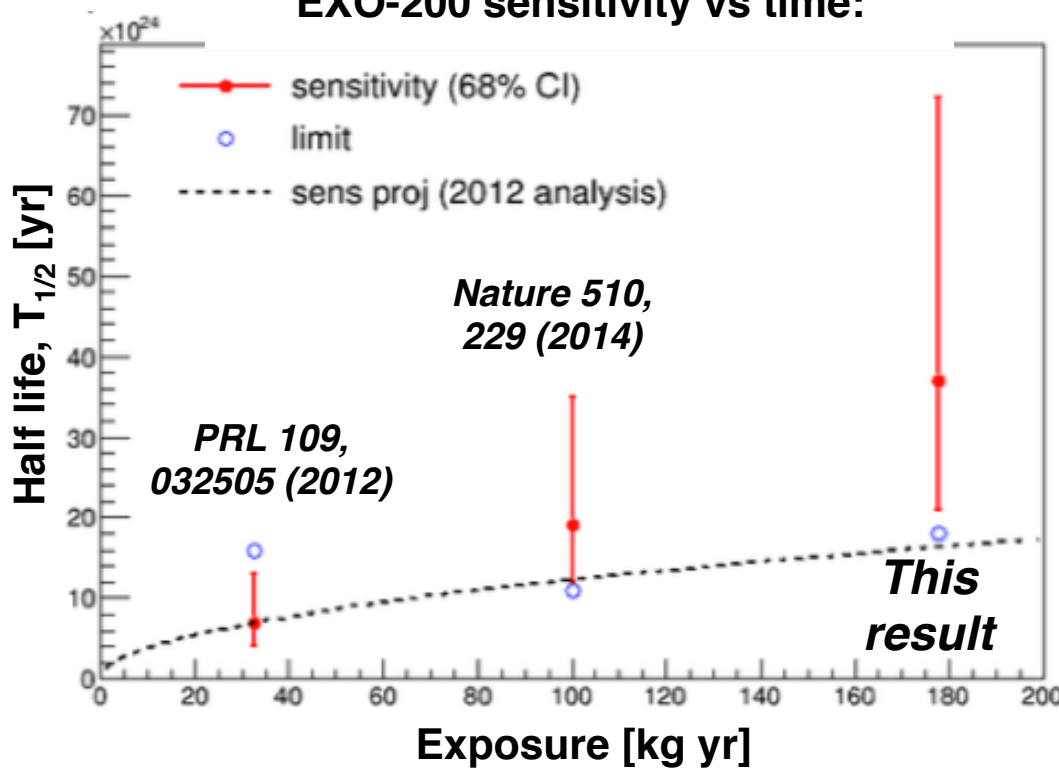
$\langle m_{\beta\beta} \rangle < 147 - 398$ meV

(90% C.L.)

	Livetime	Exposure	Limit (90% CL)
Phase I	596.7 d	122.0 kg.yr	$T_{1/2}^{0\nu\beta\beta} > 1.0\times10^{25}$ yr
Phase II	271.8 d	55.6 kg.yr	$T_{1/2}^{0\nu\beta\beta} > 4.4\times10^{25}$ yr

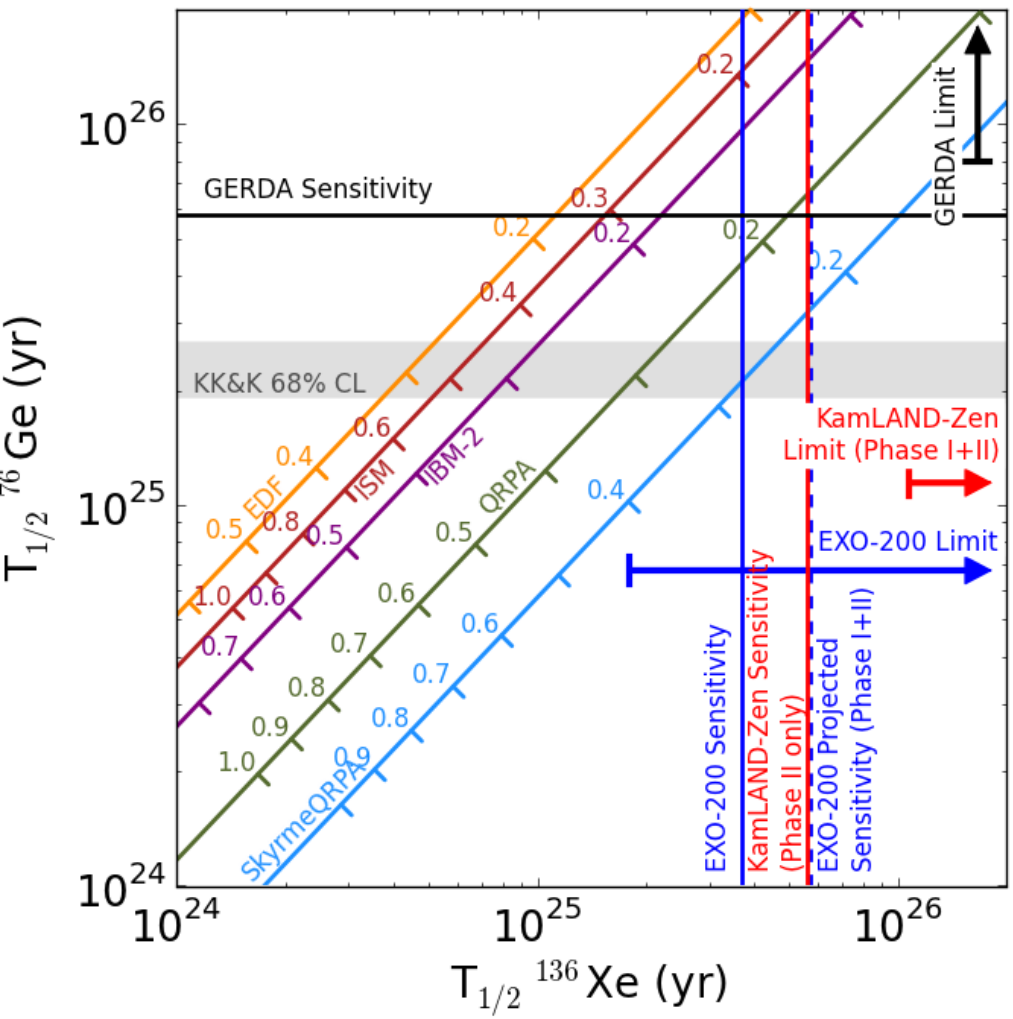
arXiv: 1707.08707

EXO-200 sensitivity vs time:



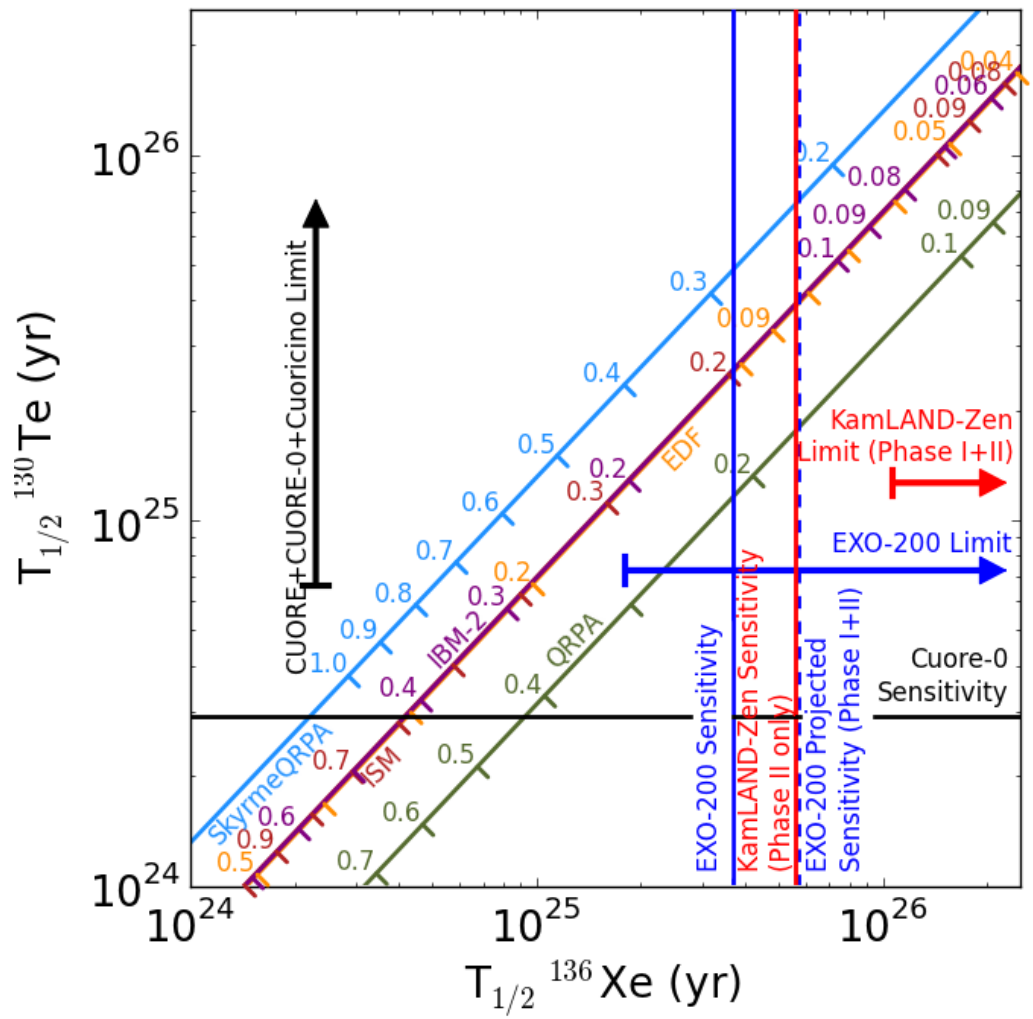
Current status

Current limits, ^{76}Ge vs. ^{136}Xe:



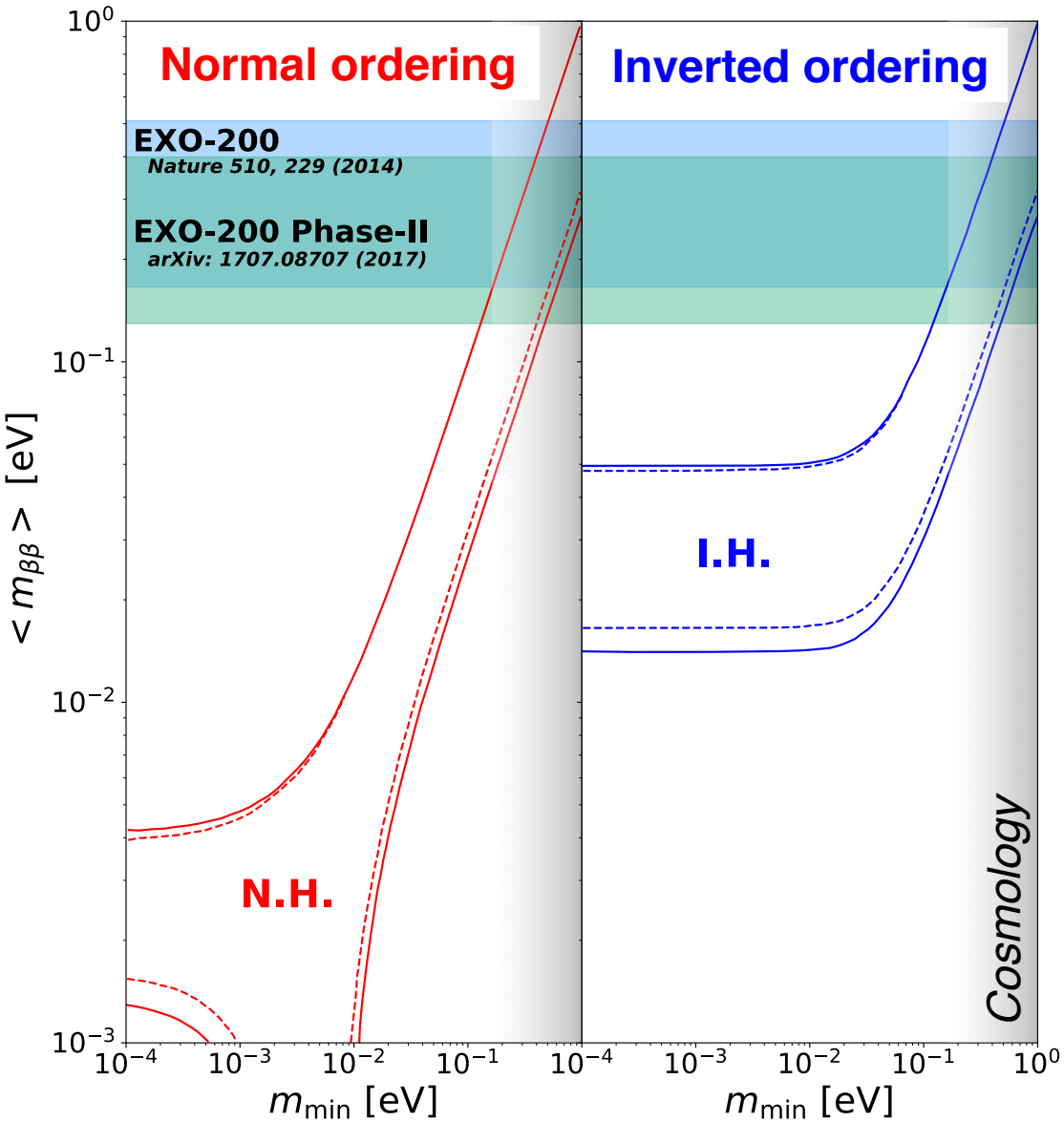
EXO-200: *this result, arXiv: 1707.08707*
TAUP2017 results from GERDA
KamLAND-Zen: *PRL 117 (2016) 082503*
KK&K Claim: *Mod. Phys. Lett., A21 (2006) 1547*

Current limits, ^{130}Te vs. ^{136}Xe:



EXO-200: *this result, arXiv: 1707.08707*
TAUP2017 results from CUORE
Cuore-0 Sensitivity in PRL 115 (2015) 102502

Future sensitivity (nEXO)



90% CL NO and IO allowed regions from:
Forero et al., PRD 90 (2014) 093006
Forero et al., Private Comm.

- EXO-200 will continue to run for ~1 year
- Ultimate expected sensitivity: $T_{1/2} \sim 5 \times 10^{25}$ yr

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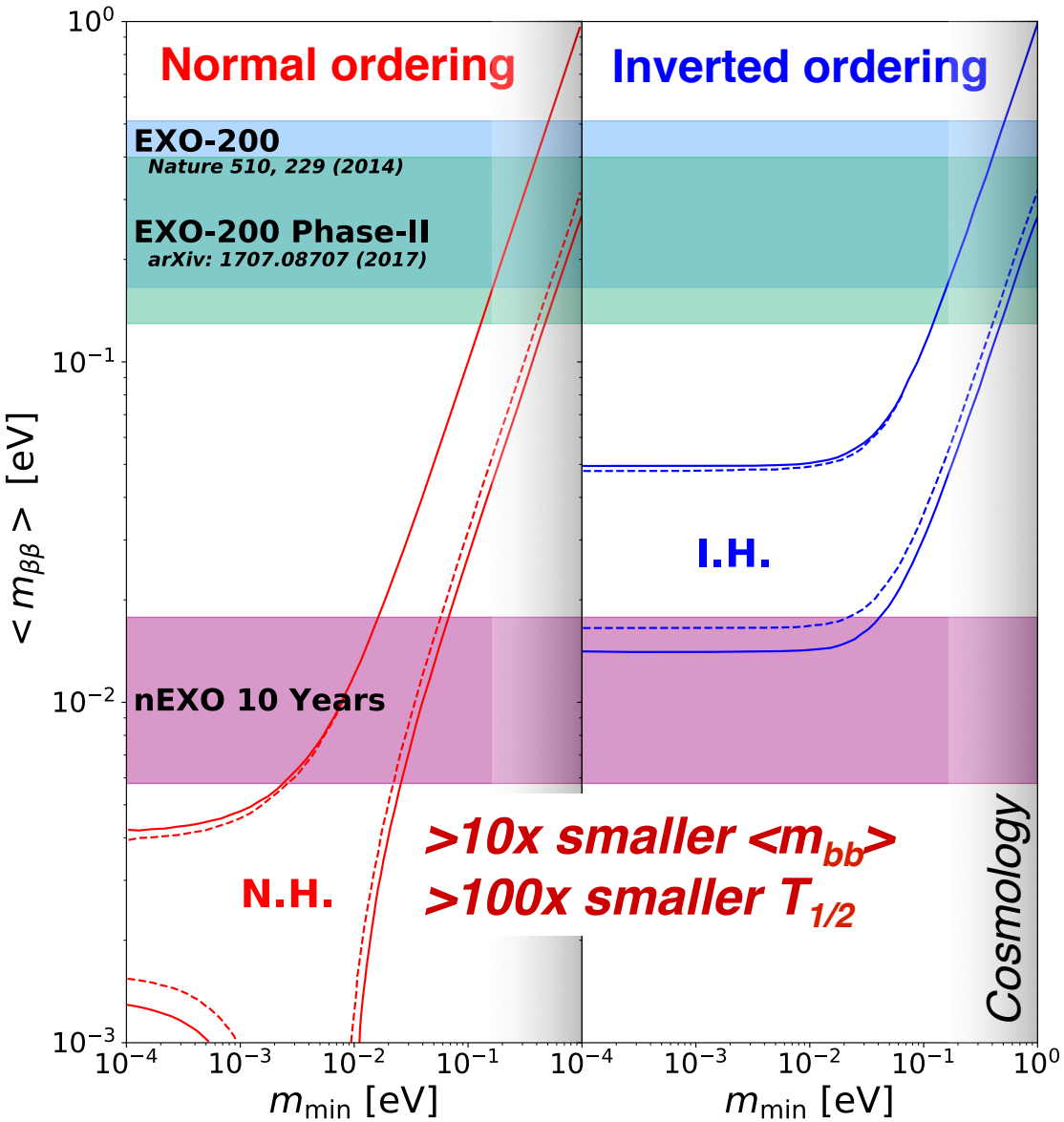


90% CL NO and IO allowed regions from:
Forero et al., PRD 90 (2014) 093006
Forero et al., Private Comm.

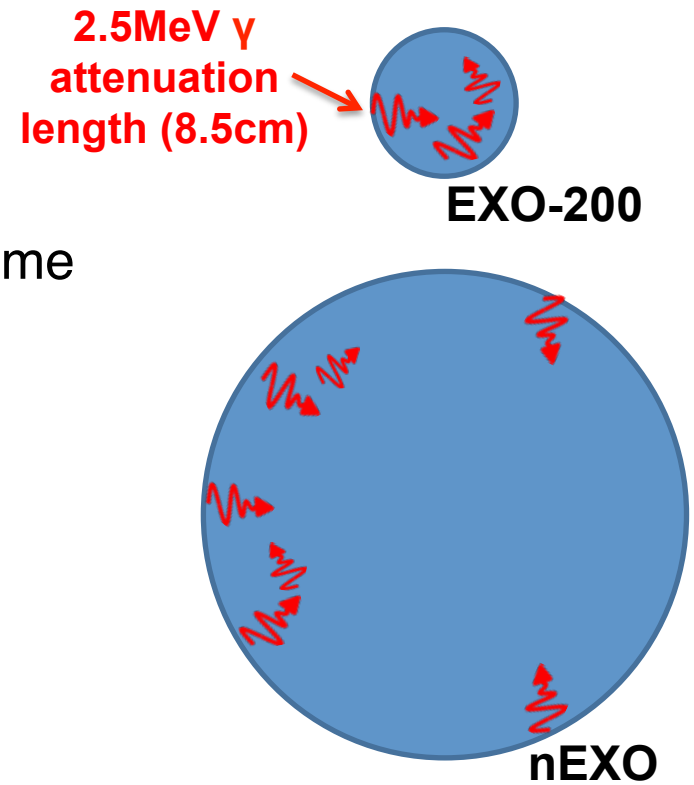
arXiv:1710.05075

- EXO-200 will continue to run for ~1 year
- Ultimate expected sensitivity: $T_{1/2} \sim 5 \times 10^{25}$ yr
- Next-generation being designed to reach $T_{1/2} \sim 10^{28}$ yr
- "US-led ton, scale experiment" highly recommend by 2015 LRP for nuclear science
- Broad, world-wide program with several isotopes/technologies is optimal

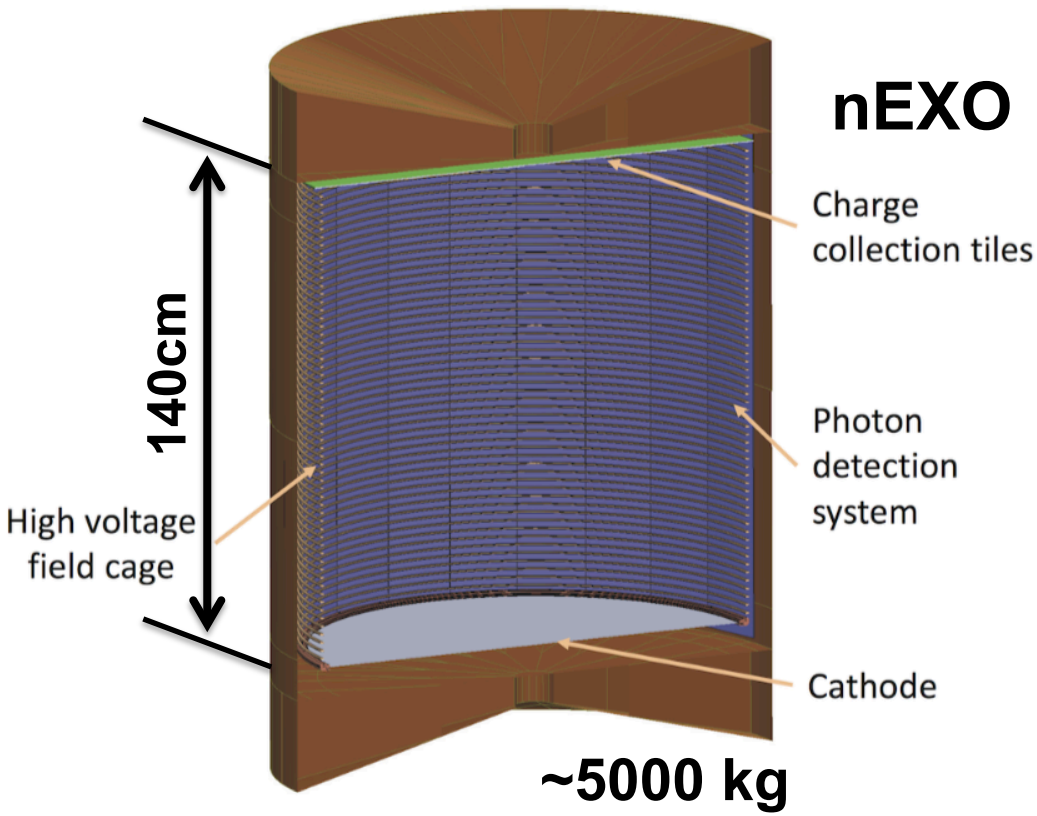
nEXO design concept

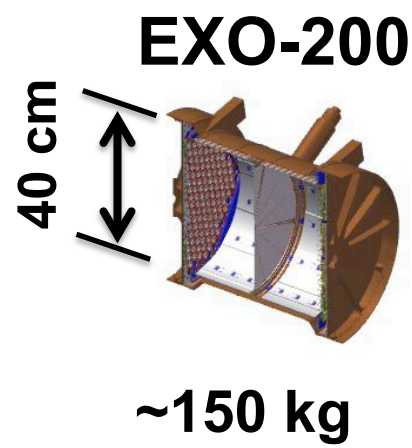
- Large LXe TPC can enable the exposure and low background needed at the multi-ton scale
- Multi-parameter detector allows measurement of background and signal in single, homogeneous volume

Self-shielding:



nEXO detector conceptual design:





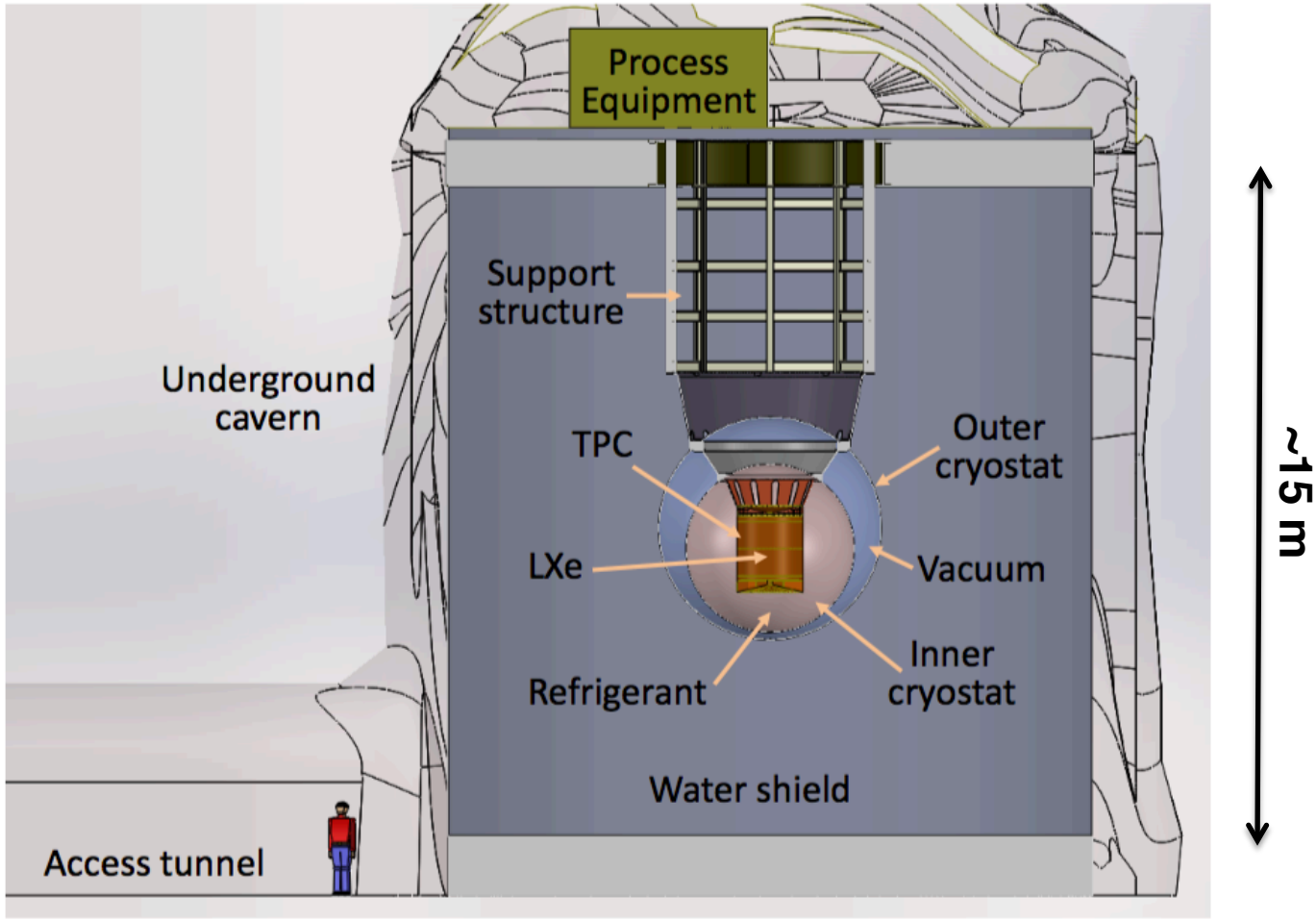
Experimental site

- Require deeper site (e.g., SNOLAB) to reduce cosmogenic ^{137}Xe
- Cosmogenic background simulations validated with EXO-200 data

J. Albert et al., arXiv:1512.06835 [2015]

arXiv:1710.05075

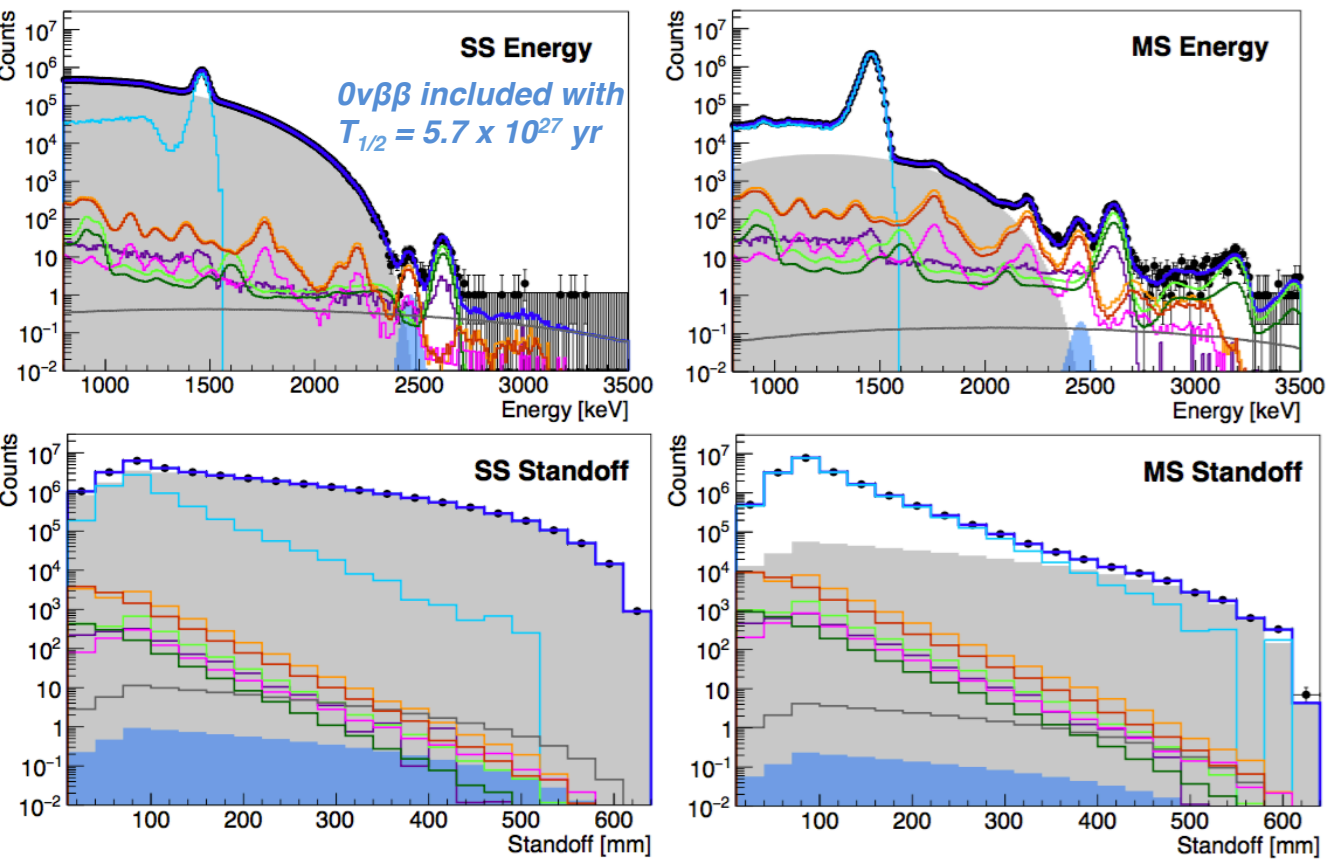
Conceptual design in SNOlab Cryopit:

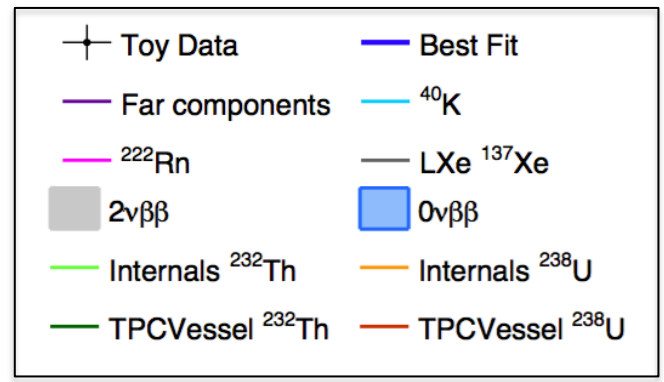


Sensitivity projections

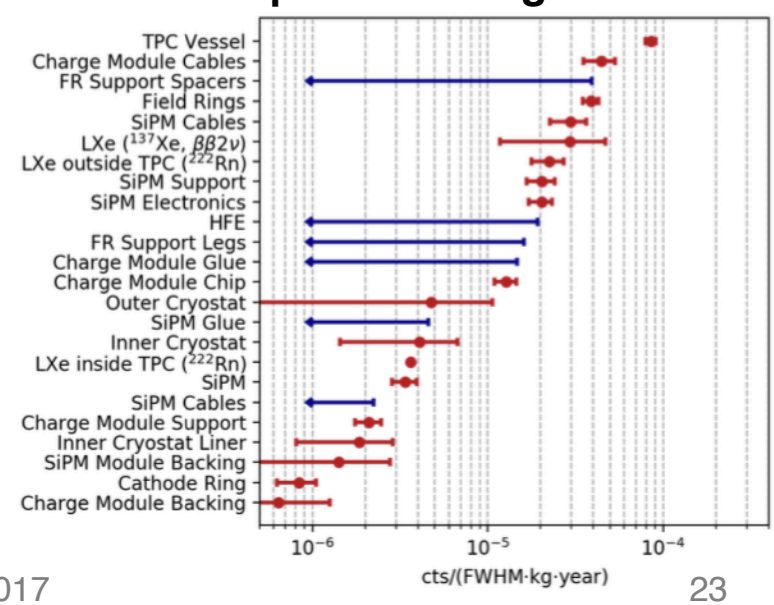
- Sensitivity projections for nEXO design based on direct measurements of material radiopurity and detailed detector simulation
- New paper posted describing baseline design and sensitivity: *arXiv:1710.05075*

Simulated nEXO spectra (full detector volume):





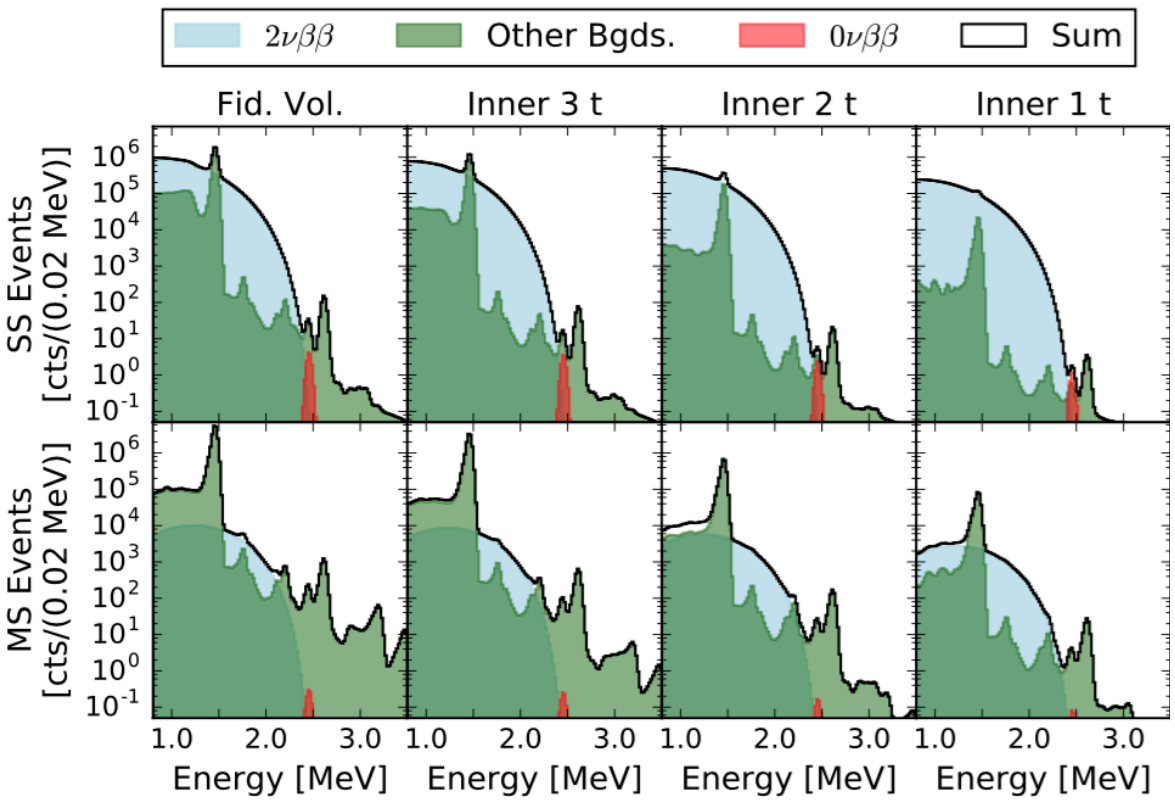
Component backgrounds:



Sensitivity projections

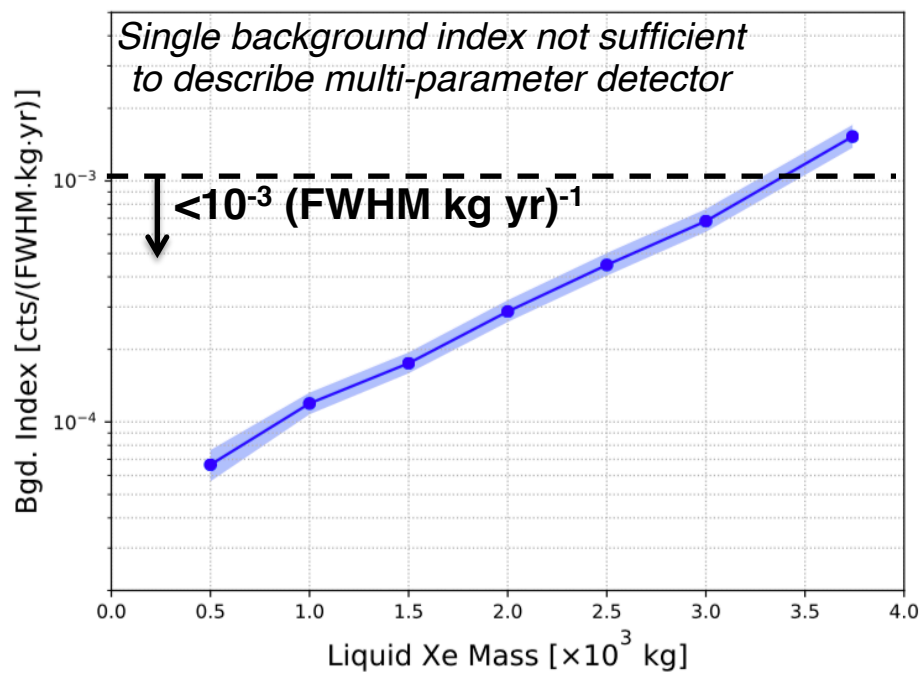
- nEXO sensitivity driven by multi-parameter fit simultaneously constraining both signal and background
- Backgrounds characterized in outer region of the detector and MS data, signal is most prominent in central region, SS

Simulated background and signal spectra:



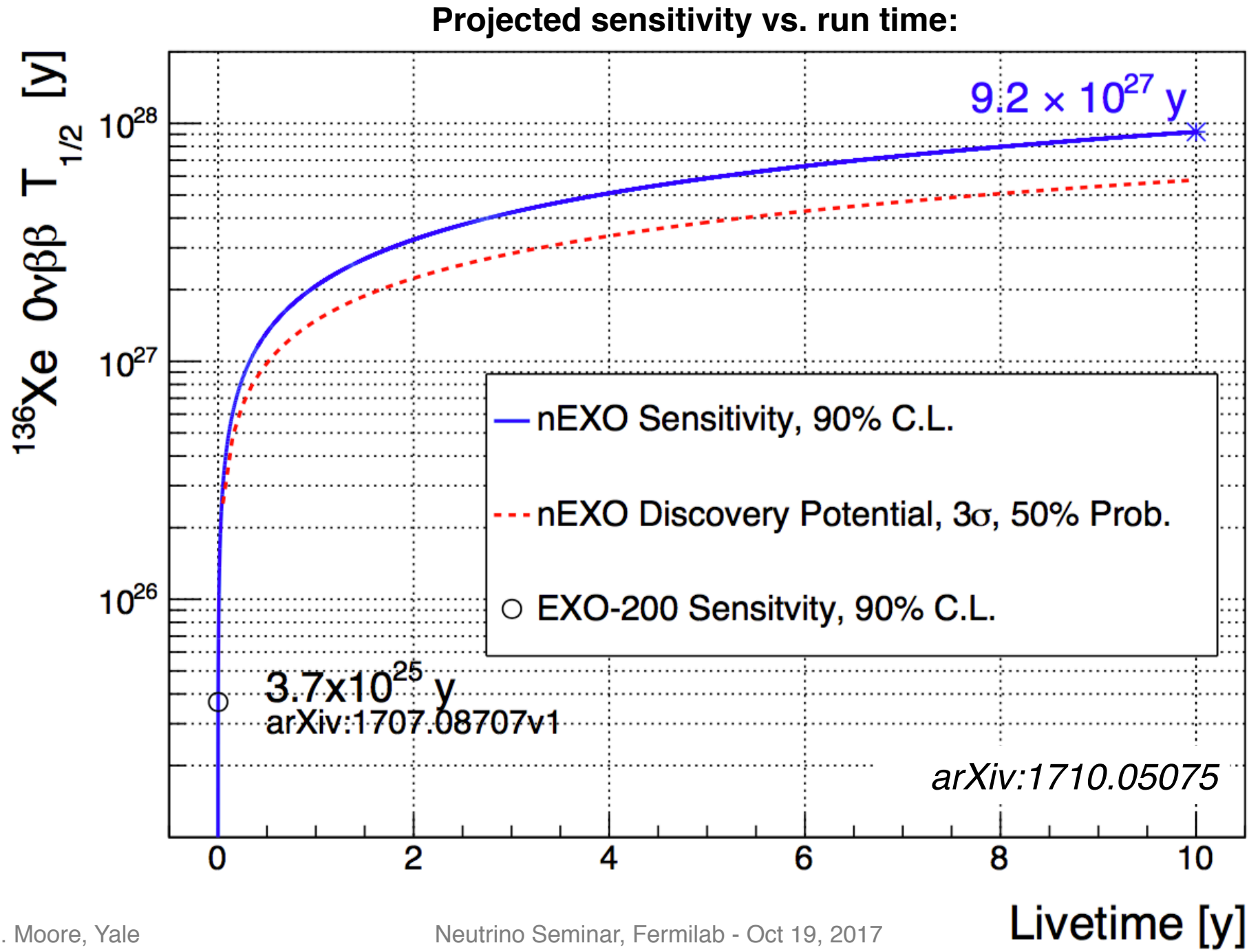
Includes 0νββ with $T_{1/2}$ = 5.7 x 10^{27} yr

Background index vs. central mass:

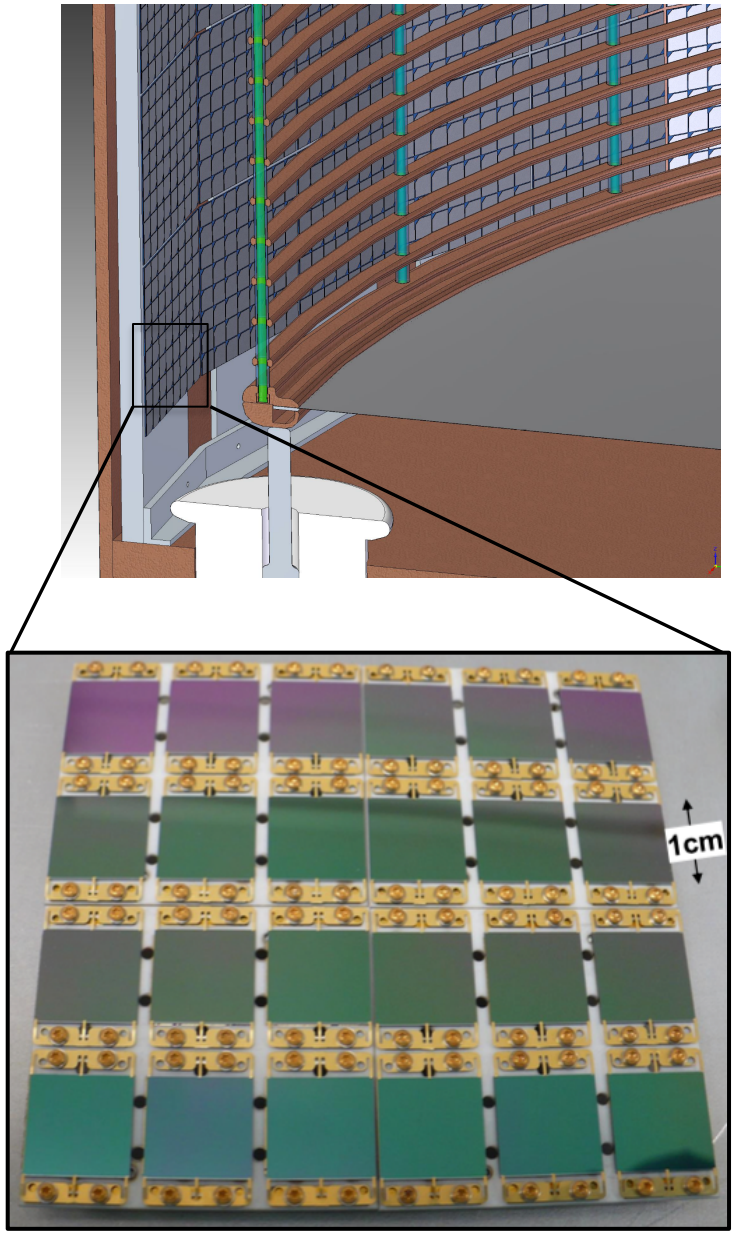


arXiv:1710.05075

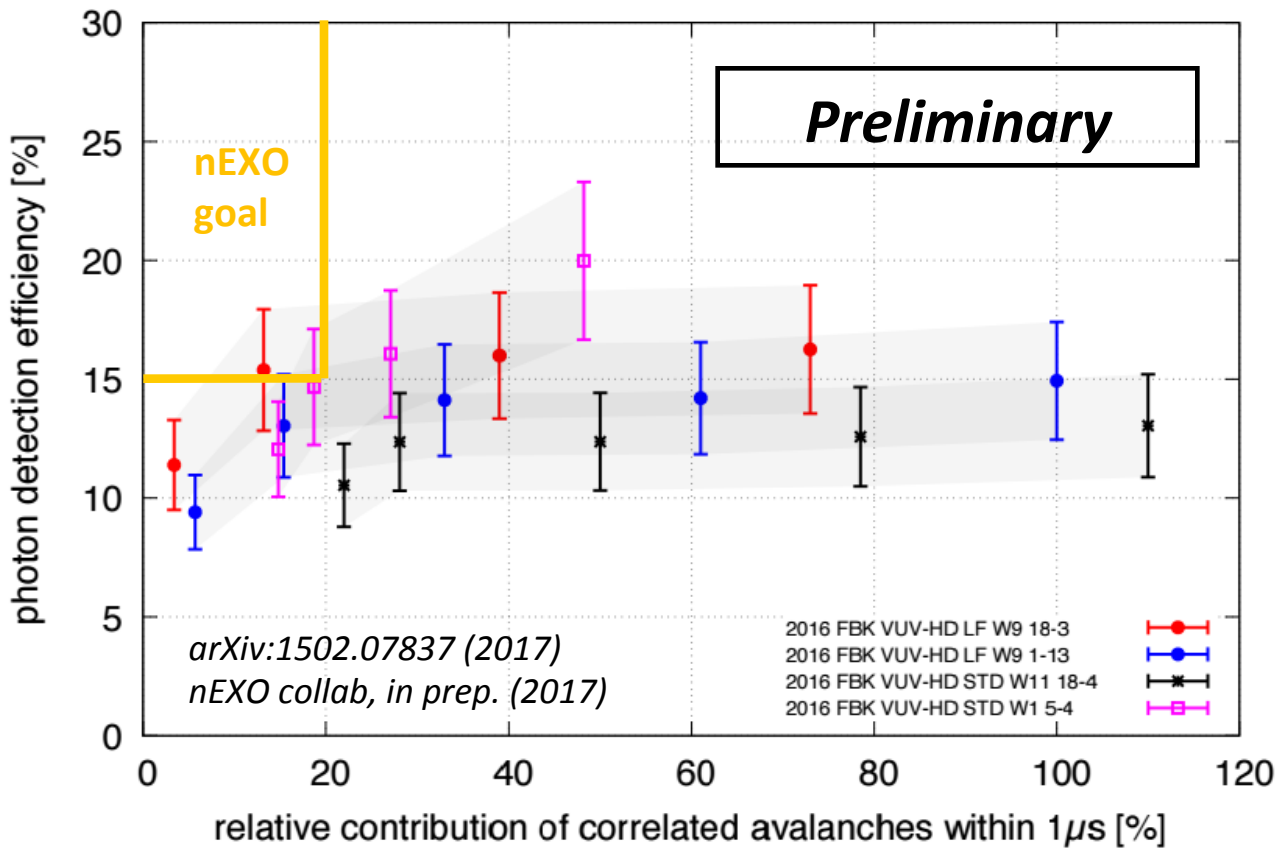
Sensitivity projections



Hardware R&D (SiPMs)

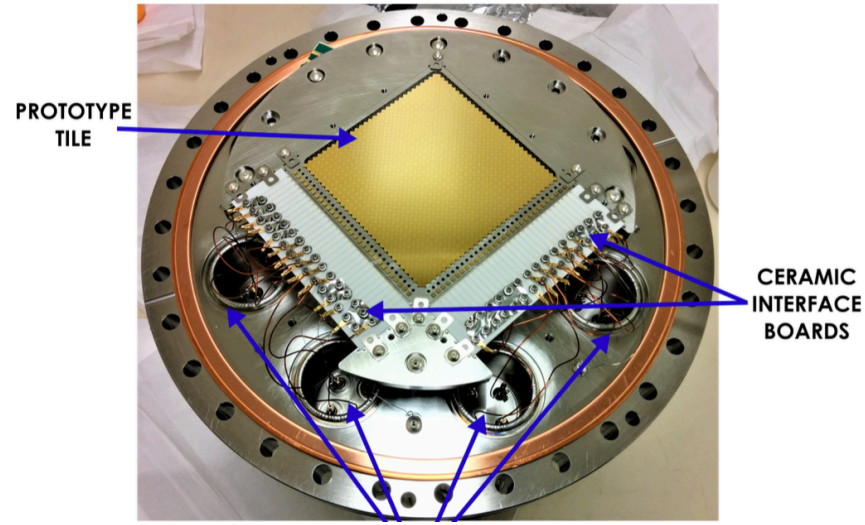


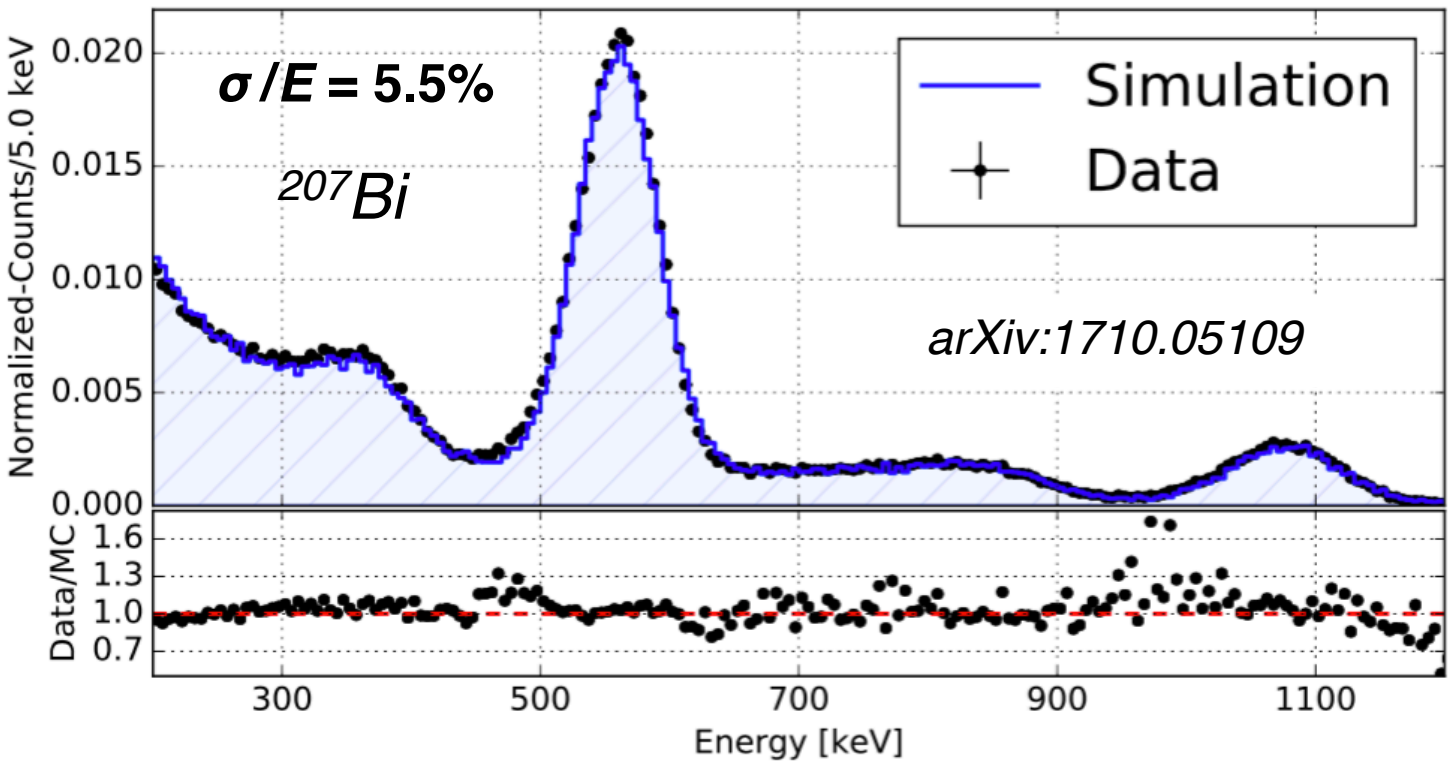
- Need ~4 m^2 of VUV-sensitive light detectors
- Have demonstrated at least one type of 1cm^2 SiPM that meets requirements
- R&D ongoing to further improve PDE



Hardware R&D (Charge tiles)

- Modular 10cm x 10cm quartz charge collection tiles avoid tensioned wires
- Prototype tiles fabricated and charge collection in LXe demonstrated
- R&D ongoing to determine multiplicity rejection without Frisch grid

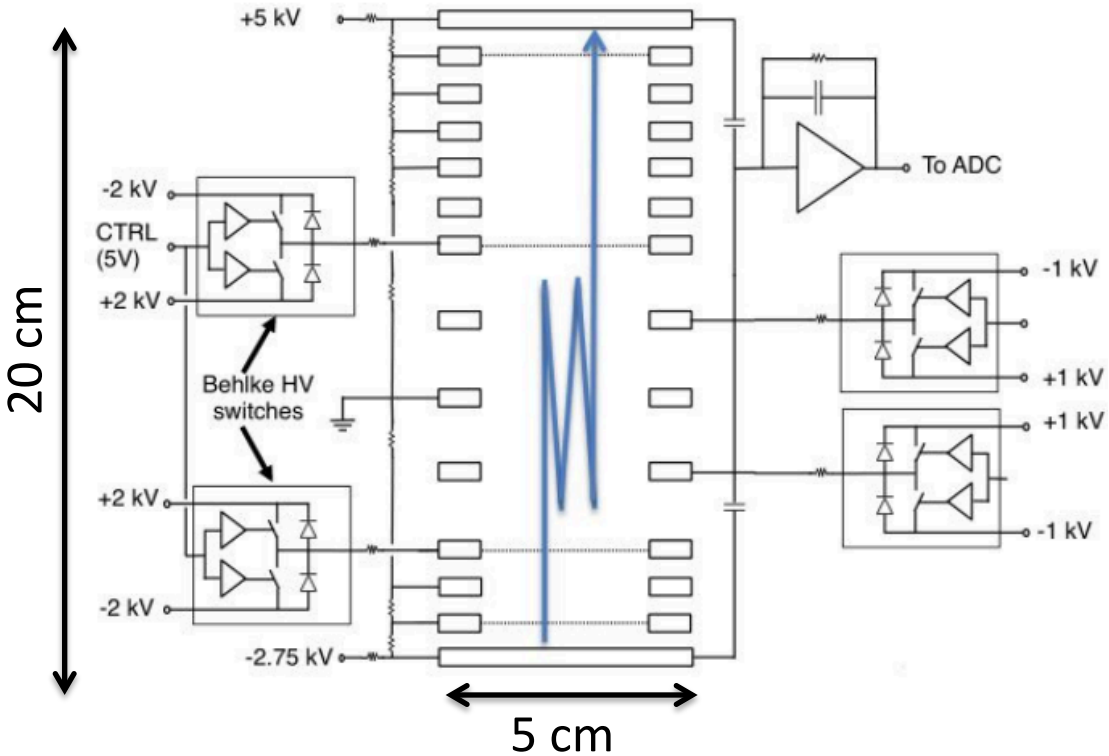




Hardware R&D (Charge collection)

- Large detectors (nEXO and beyond) require collection of charge over large drift distance
- Need to minimize loss of charge due to electronegative impurities
- At Yale, building switched HV chamber to study charge propagation over >>1 m distances

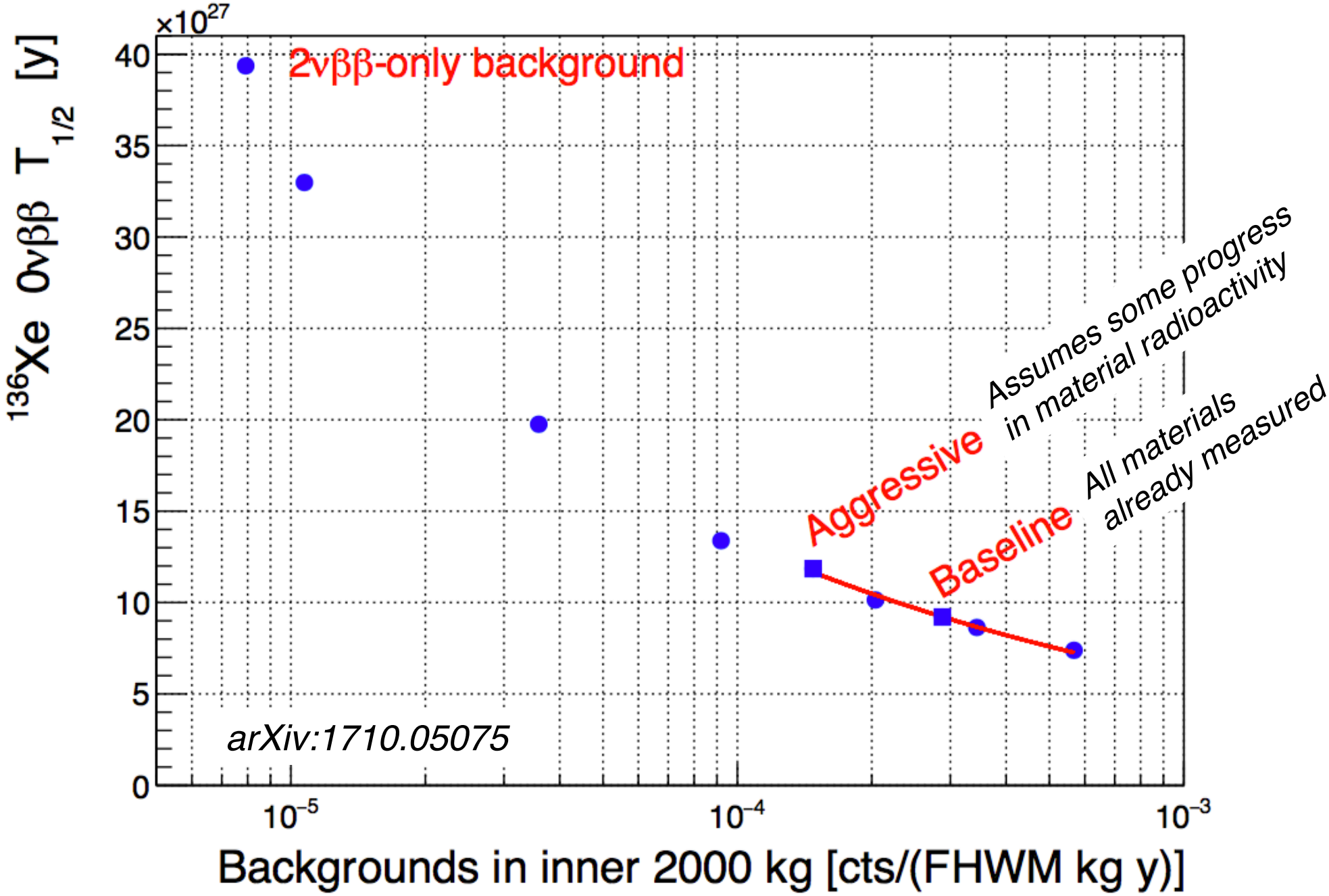
Switched HV drift chamber:



Switch +/-2 kV at 30 kHz for ~10 ms burst

LXe test stand at Yale:

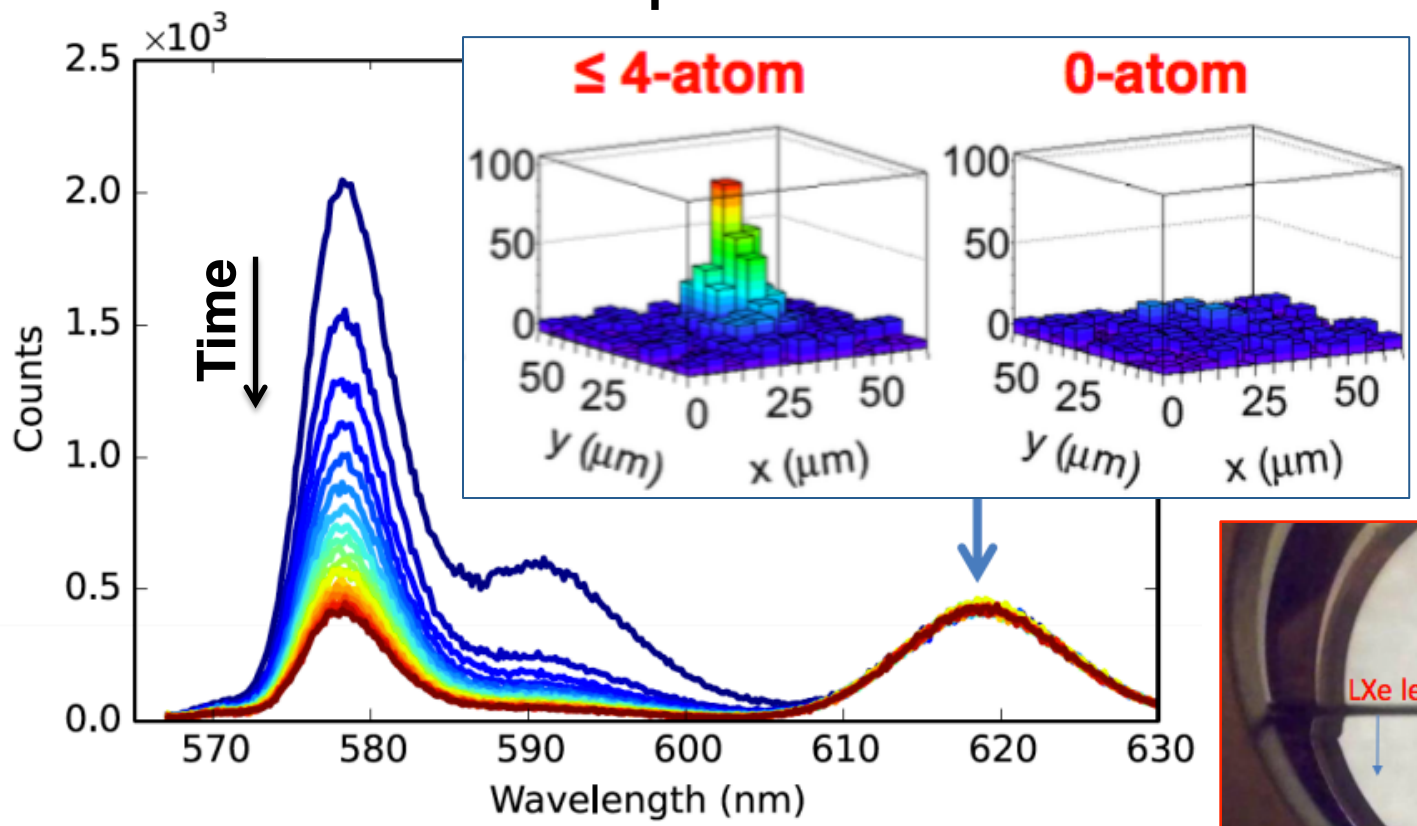
Sensitivity vs background



Ba "tagging"

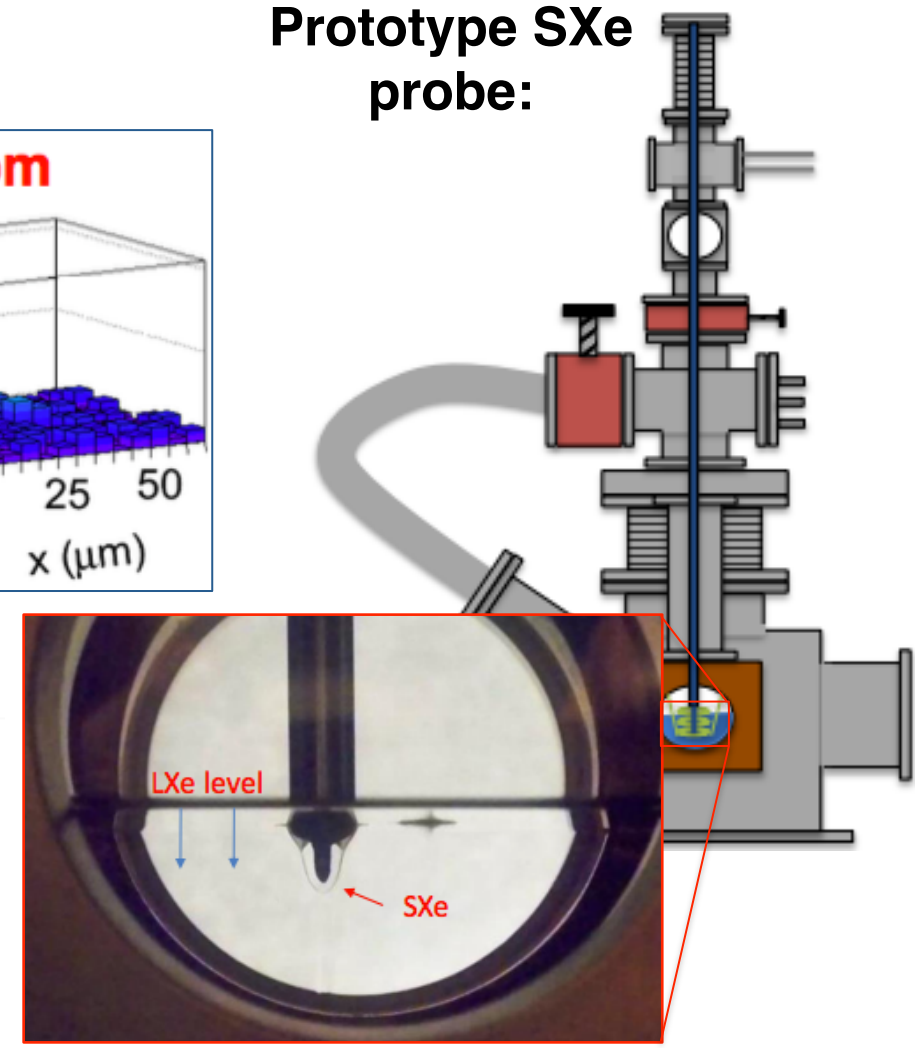
- Efficient identification of Ba daughter nucleus would eliminate all non-ββ backgrounds
- Recent progress on spectroscopy in solid Xe (SXe) has shown ~single atom sensitivity

Ba fluorescence spectrum in SXe:



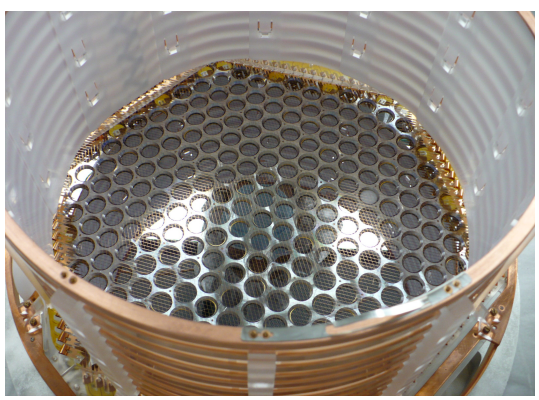
Spectroscopy details in B. Mong *et al.* (EXO Collaboration), Physical Review A **91**, 022505 (2015)

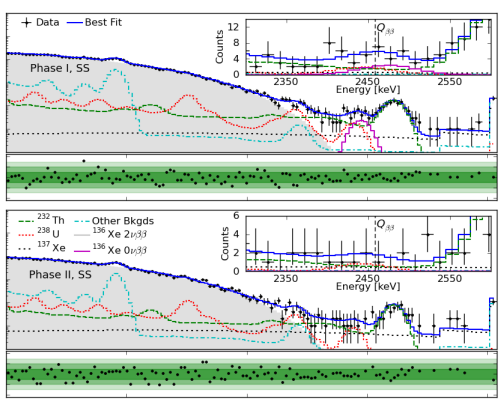
Prototype SXe probe:

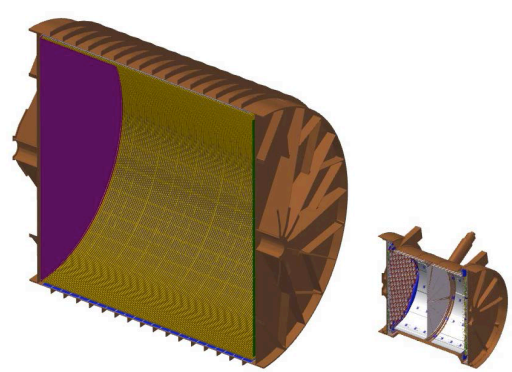


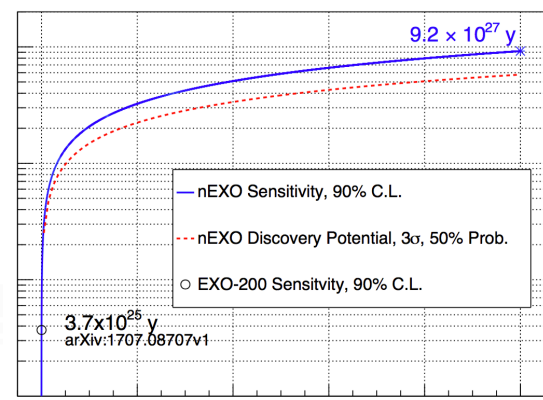
Summary

- Searches for 0νββ provide the most sensitive test of the Majorana nature of the neutrino
- EXO-200 has performed one of the most sensitive 0νββ searches to date
- We are now ready to build ton-scale experiments with negligible background, such as nEXO
- The 2015 US long range plan for NP recommended this effort as the top priority for the next new large project
- There is significant possibility to observe beyond the Standard Model physics by detecting 0νββ in the coming years!









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