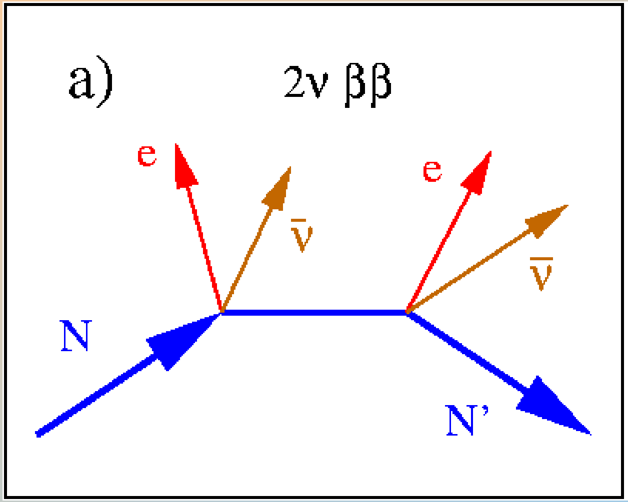
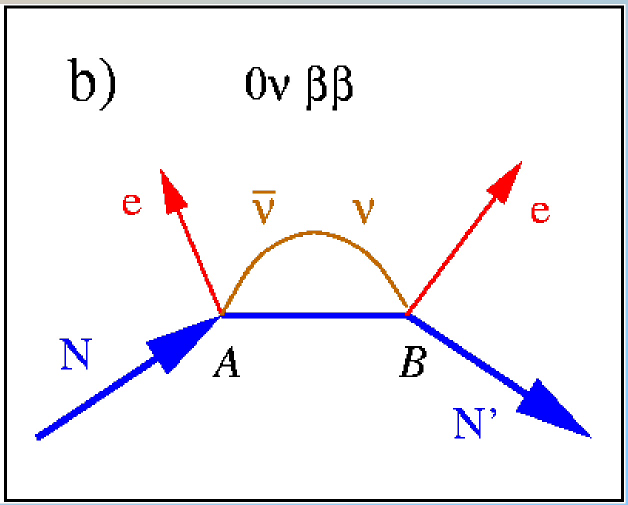
From EXO-200 to nEXO

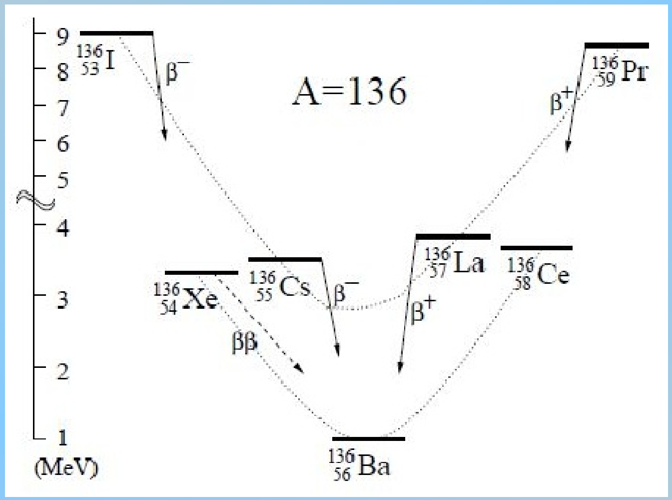
Vladimir Belov, ITEP
for EXO-200 and nEXO
collaborations

The 3rd international conference on particle physics and
astrophysics, Moscow, 4 October 2017

Double beta decay



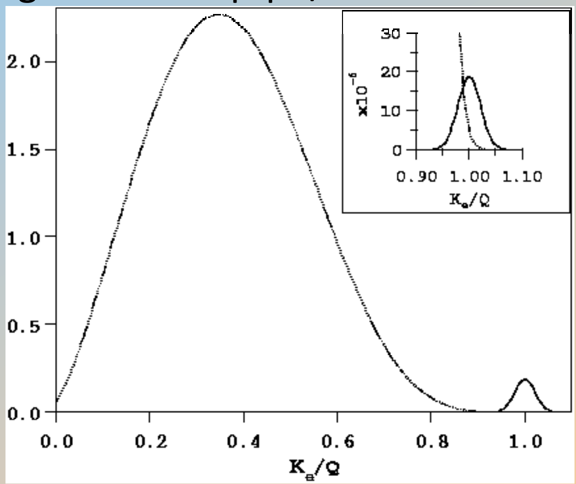




2ν mode
is a conventional 2nd order process in Standard Model discovered for many isotopes

0ν mode
is a hypothetical process always means New Physics.
This is search for:
Lepton Number Violation
Majorana fermions

Simulated double beta decay spectrum
P.Vogel. arXiv:hep-ph/0611243



To reach high measurement sensitivity for 0ν mode one requires,

- High energy resolution
- Large Isotope mass
- Low background

Why xenon

Energy resolution is poorer than the crystalline devices (~ factor 10), but...

Monolithic detector. Xenon can form detection medium, allow self shielding, surface contamination minimized. Very good for large scale detectors.

Has high Q value. Located in a region relatively free from natural radioactivity.

Isotopic enrichment is easier. Xe is already a gas & ^{136}Xe is the heaviest isotope.

Xenon is "reusable". Can be purified & recycled into new detector (no crystal growth).

Minimal cosmogenic activation. No long lived radioactive isotopes of Xe.

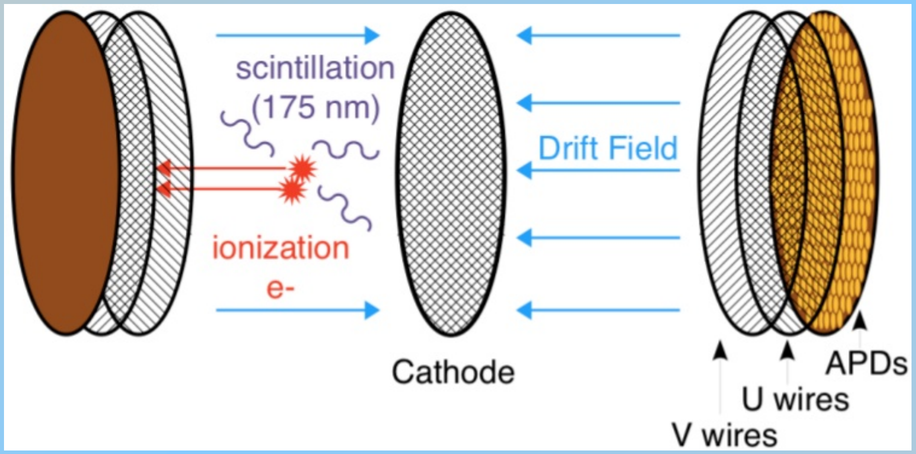
Energy resolution can be improved. Using scintillation light/ionization correlation.

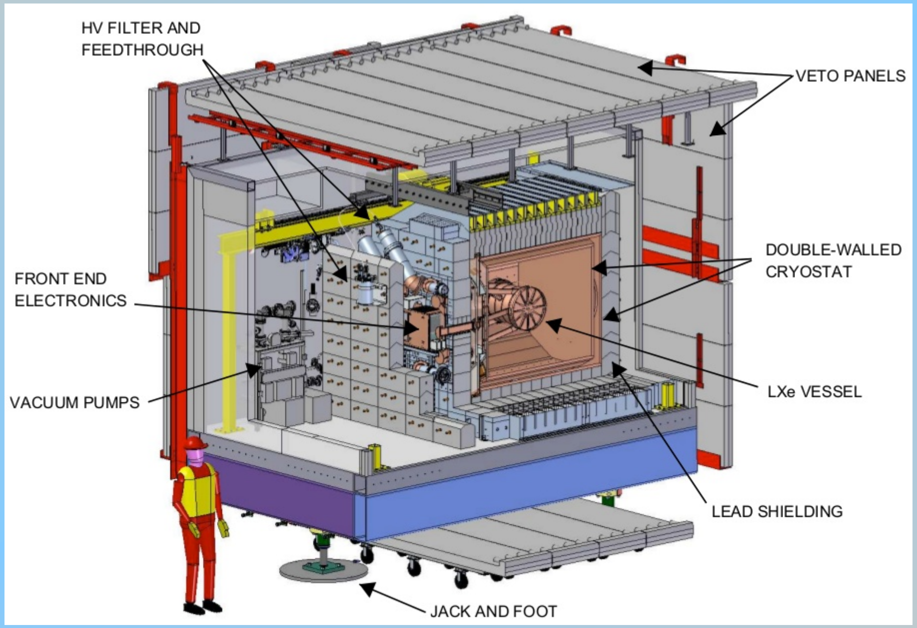
Particle identification. Slightly limited, but can be used to tag alphas from Rn chain.

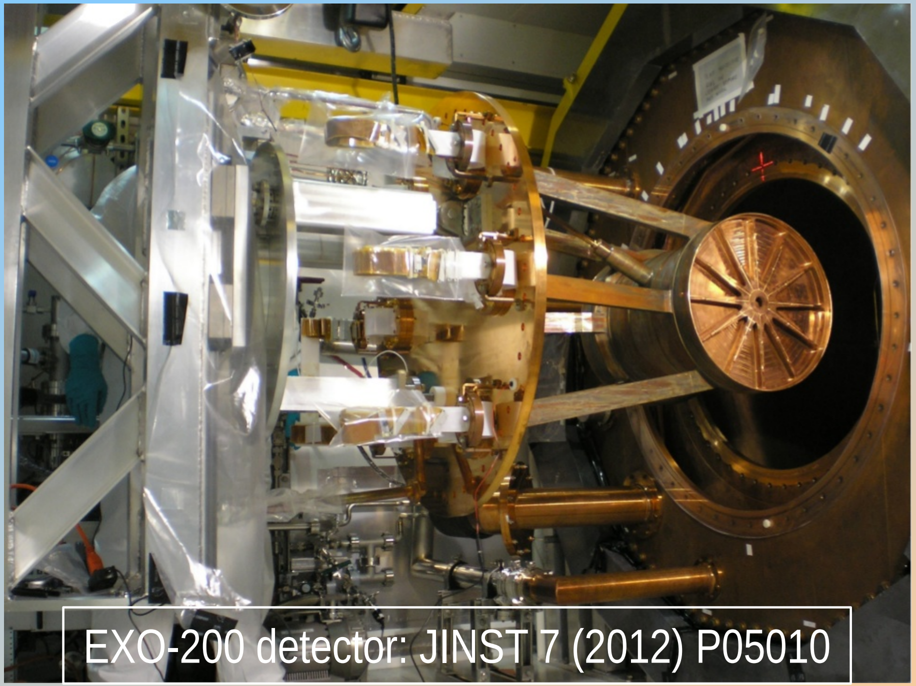
… admits a novel coincidence technique. Background reduction by Ba daughter tagging (M.Moe PRC 44, R931, 1991).

EXO-200 detector

- Double Time Projection Chamber (TPC)
- 110 kg of liquid xenon in active volume enriched to 80.6 in ^{136}Xe
- Reading both ionization and scintillation
- Drift field 564 V/cm
- Comprehensive material screening program
- Massive background shielding (> 50 cm of HFE, 5 cm of copper, 25 cm of lead)
- Located in salt mine at 1600 m.w.e.

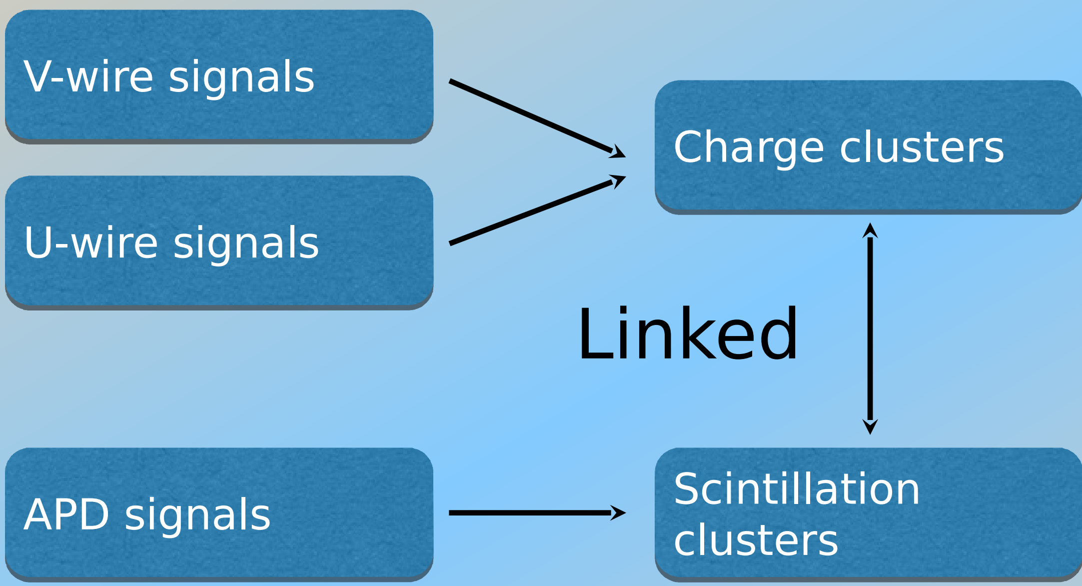


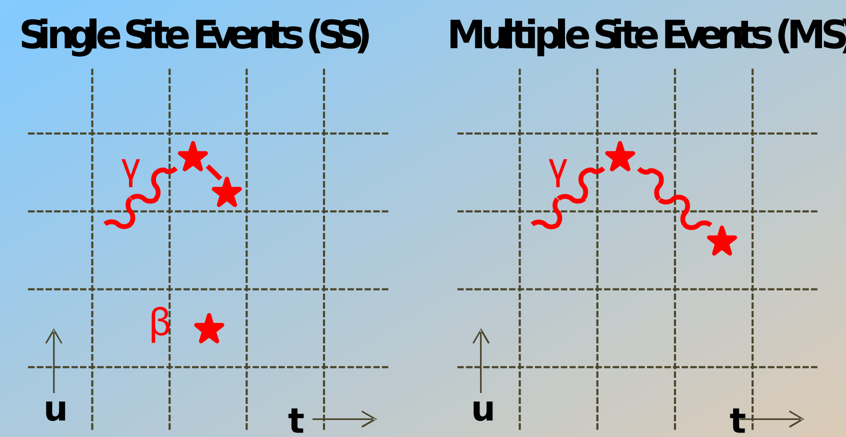




Event reconstruction

- Signal finding. Digital filters are used on waveforms from U,V wires and APDs
- Parameters of pulses (t, E) are estimated for both charge and light
- Pulses are combined into clusters producing position and energy
- Size of cluster is estimated from rise time and number of wires affected
- Position is used in form of Standof Distance (SD) that is distance from any cluster to the nearest wall

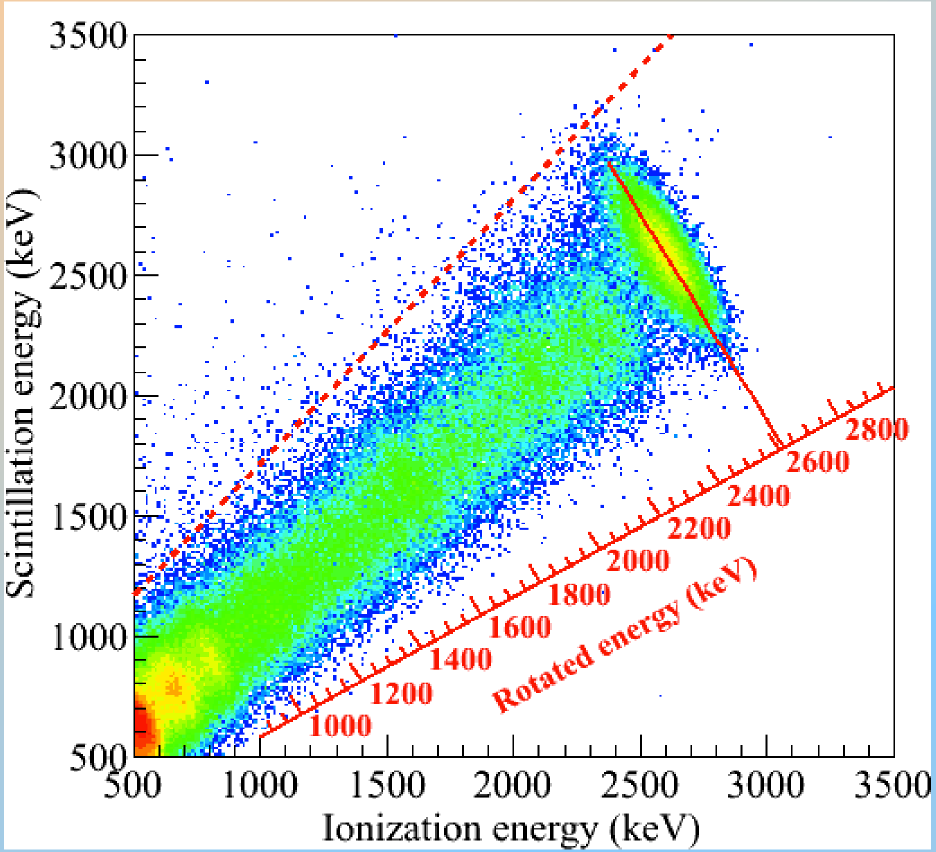




Efficiency to get into SS: $2\beta0\nu$ ~90%
γ 2.5MeV ~30%

But we don't throw MS events away! We use them in the fit to help predict background

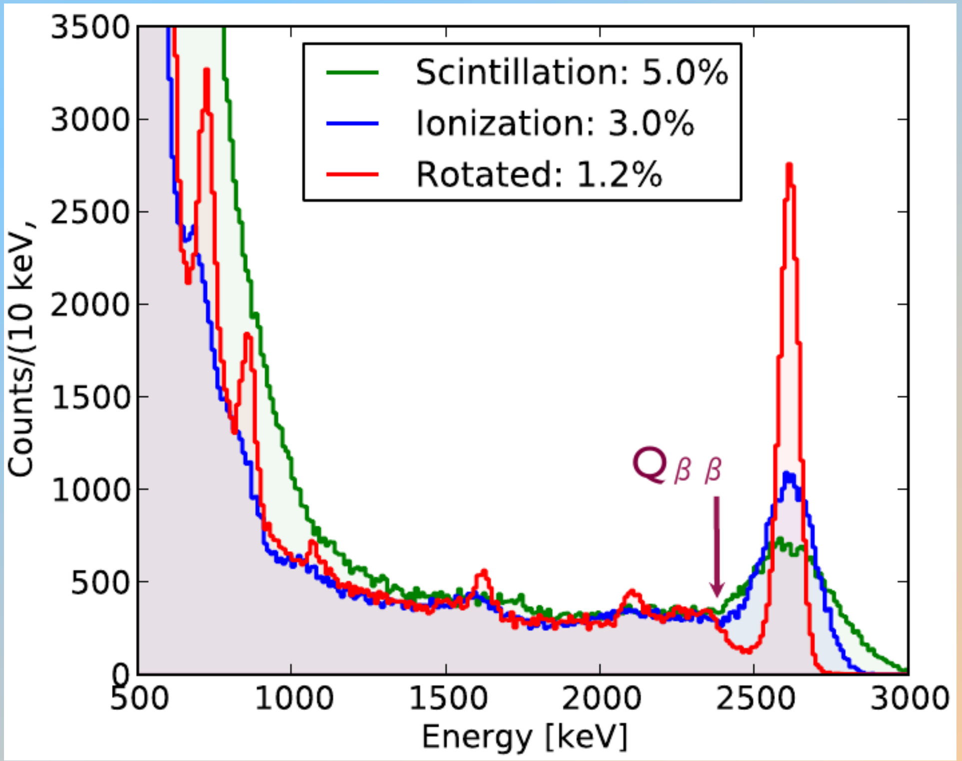
Combining ionization and scintillation



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

Mixing angle is chosen to optimize energy resolution at 2615 keV line.

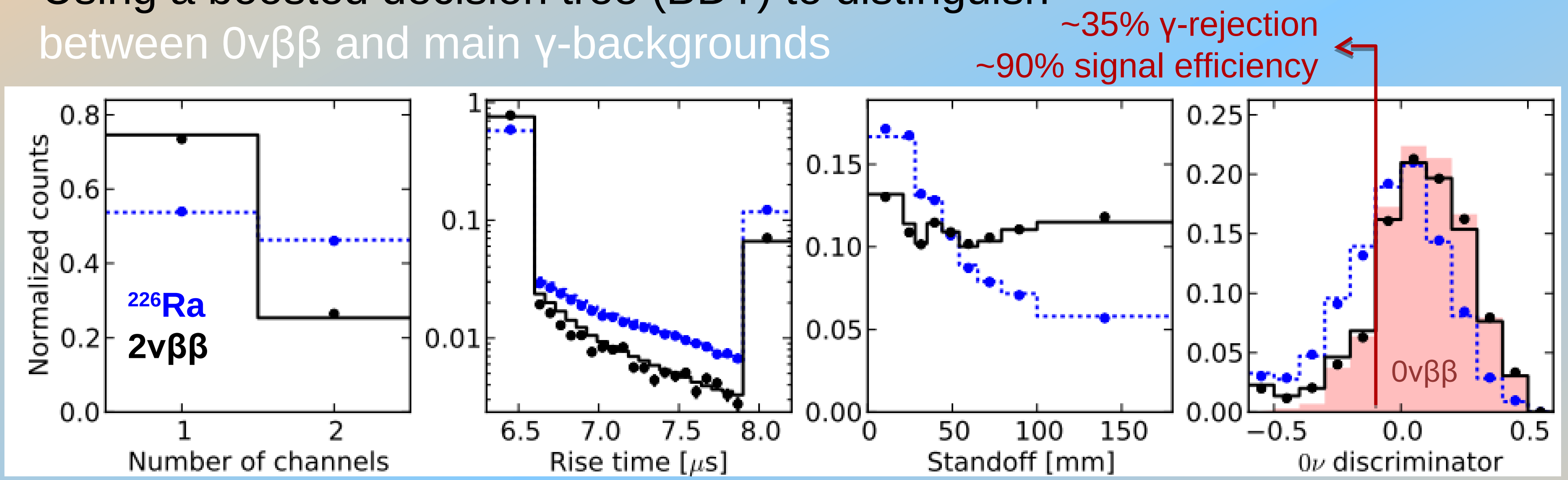


EXO-200 has achieved ~ 1.2% energy resolution at the Q value.
nEXO will reach resolution < 1%, sufficient to suppress background from 2νββ.

Optimal discrimination

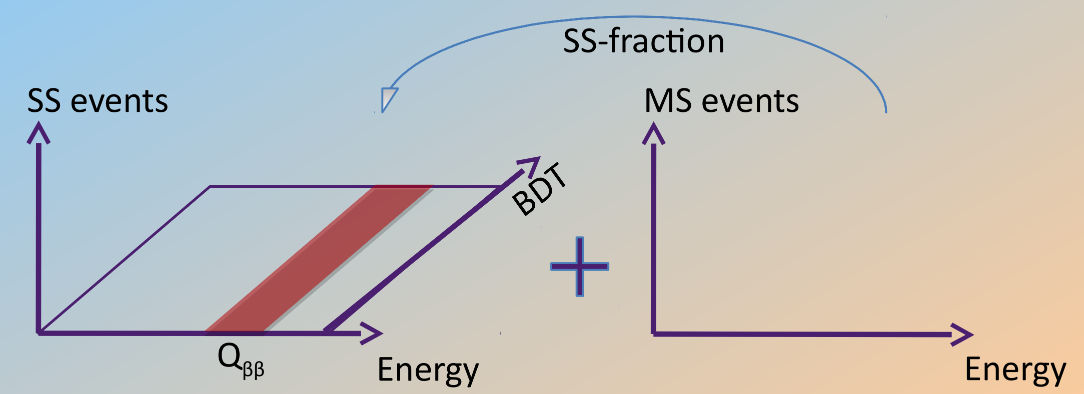
Optimize SS discriminators into a more powerful one

- Using a boosted decision tree (BDT) to distinguish between 0νββ and main γ-backgrounds



Fitting 0νββ discriminators

- Energy
- SS/MS
- BDT

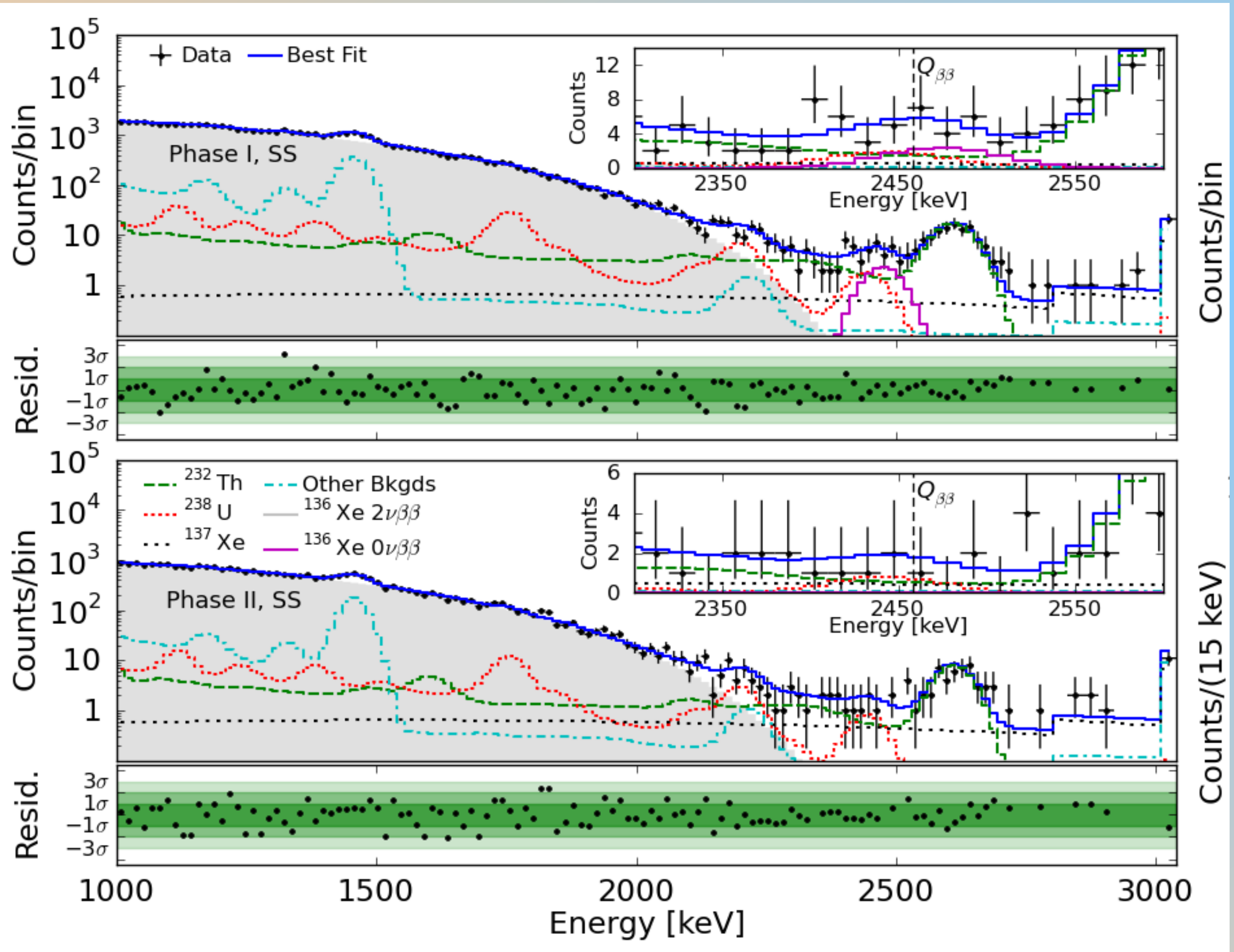


⇒ ~15% sensitivity improvement

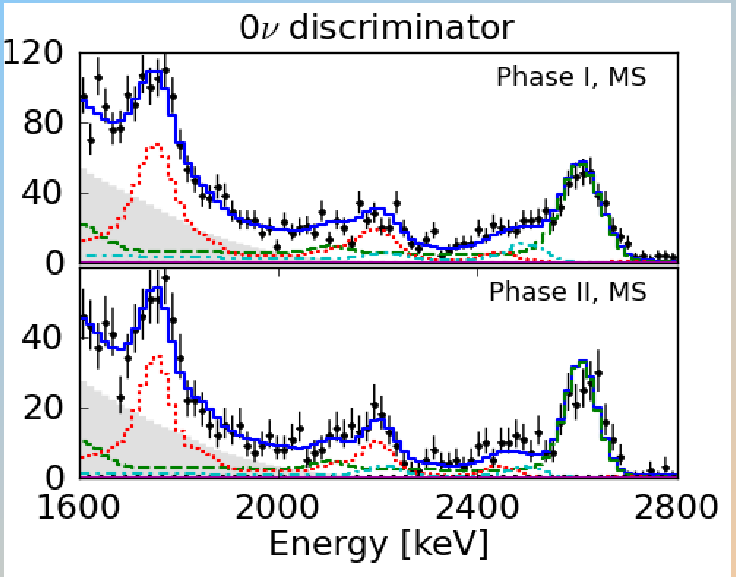
Results

Background model + data ⇒ maximum likelihood fit

Combine Phase I + Phase II profiles

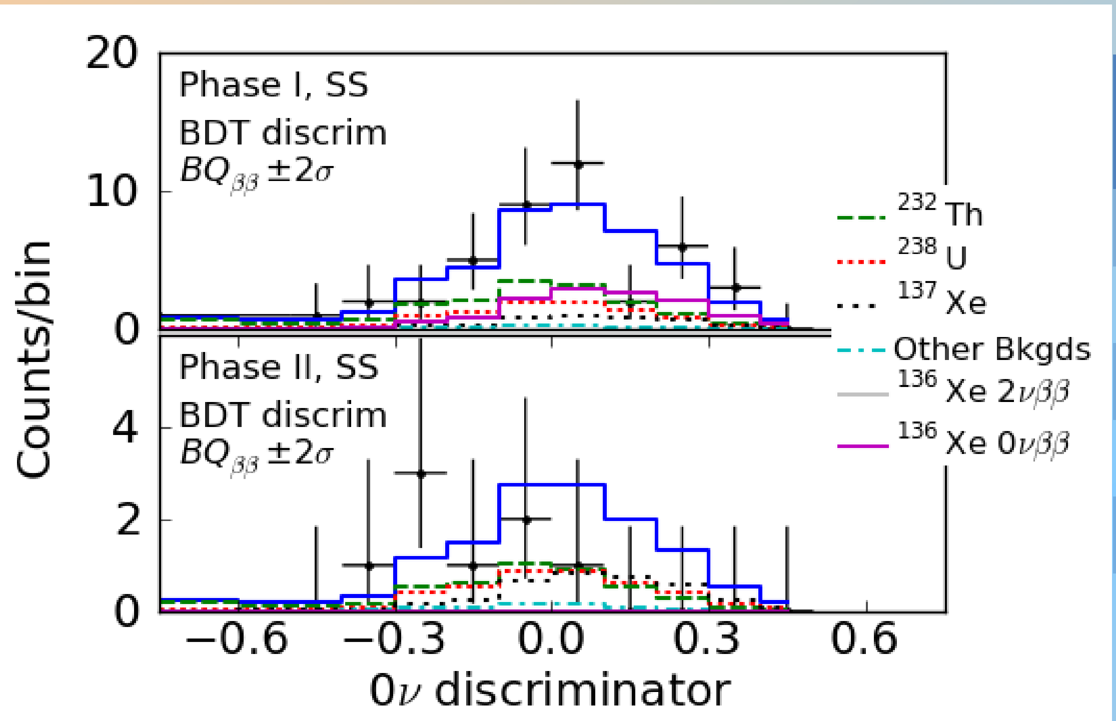


Systematics	Phase I (%)	Phase II (%)
Detection efficiency	82.4 ± 3.0	80.8 ± 2.9
Shape differences	±6.2	±6.2
SS fraction	±5.0	±8.8



No statistically significant excess: combined p-value ~1.5σ

Results

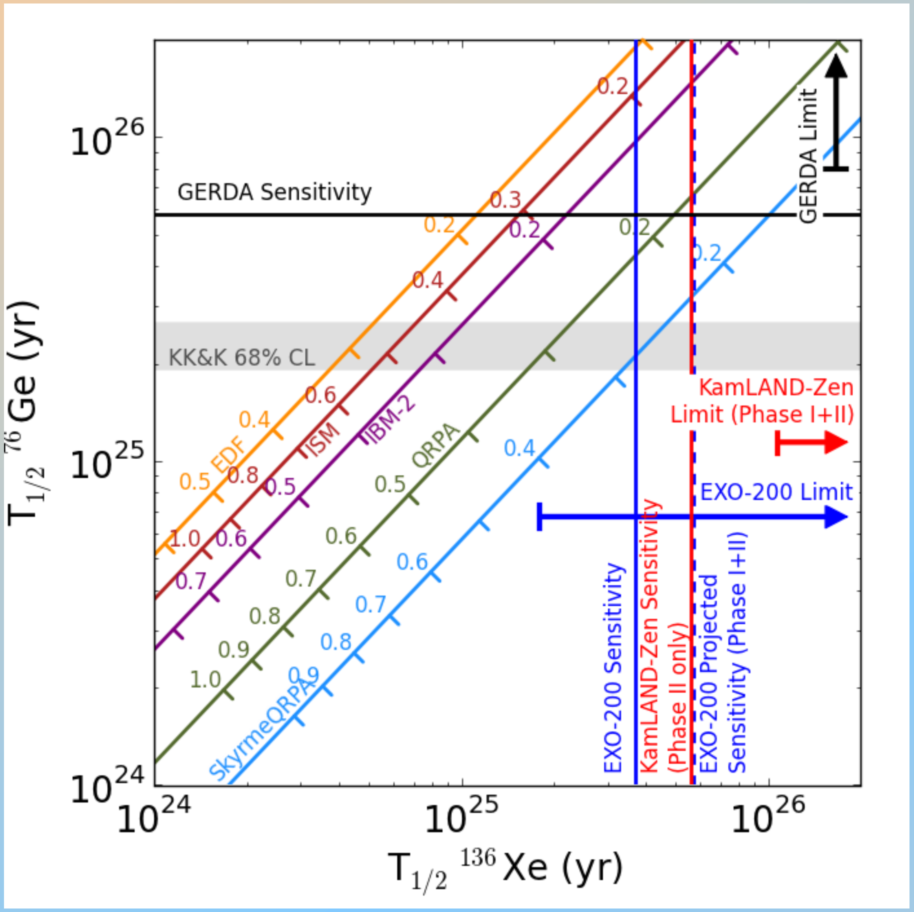


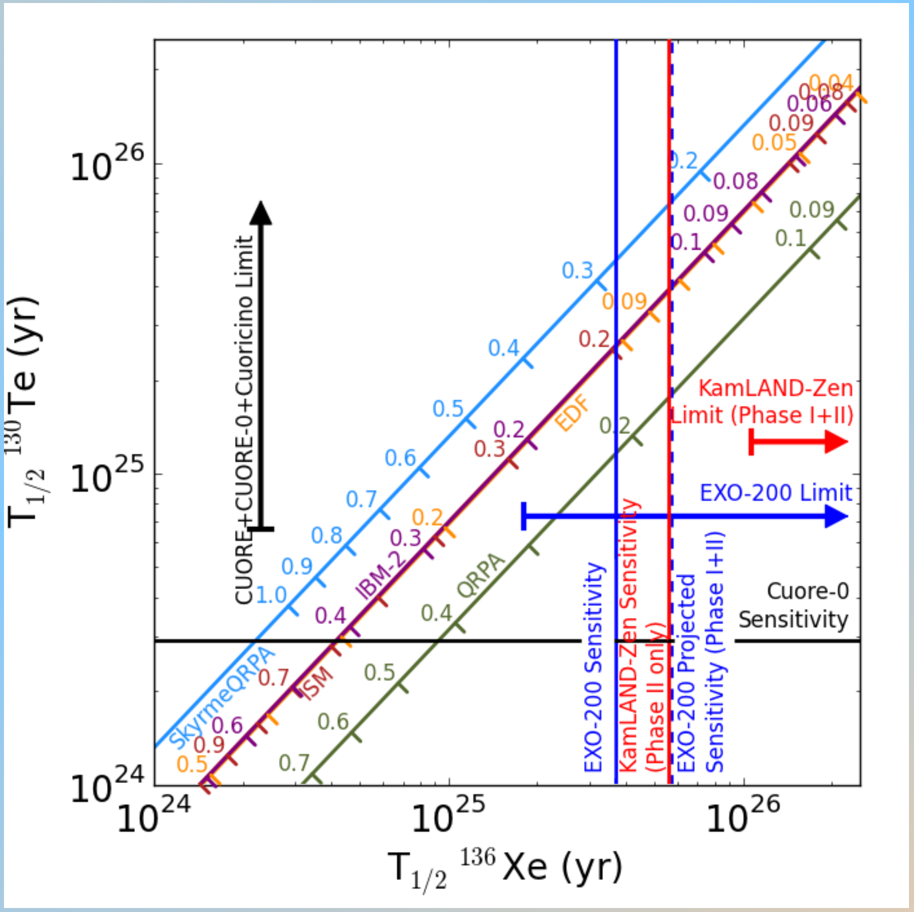
Contributions to BQ±2σ	Phase I (cts)	Phase II (cts)
^{232}Th	15.8	4.8
^{238}U	9.4	4.2
^{137}Xe	4.4	3.6
Total	**30.7±6.0**	**13.2±1.4**
Data	***43***	***8***

- Total exposure 177.6 kg·y
- Background index ~ 1.5 ± 0.2 x10^{-3} / (kg·yr·keV)
- **Sensitivity 3.7·10^{25} yr (90% CL)**
- $T_{1/2}$(0vββ) > 1.8·10^{25} yr
- 〈 $m_{\beta\beta}$ 〉 < 147–398 meV (90% CL)

ArXiv: 1707.08707

Comparison





EXO-200: *this result, arXiv: 1707.08707*
GERDA: *talk by L. Pandola @ TAUP-2017*
KamLAND-Zen: *PRL 117 (2016) 082503*
KK&K Claim: *Mod. Phys. Lett., A21 (2006) 1547*

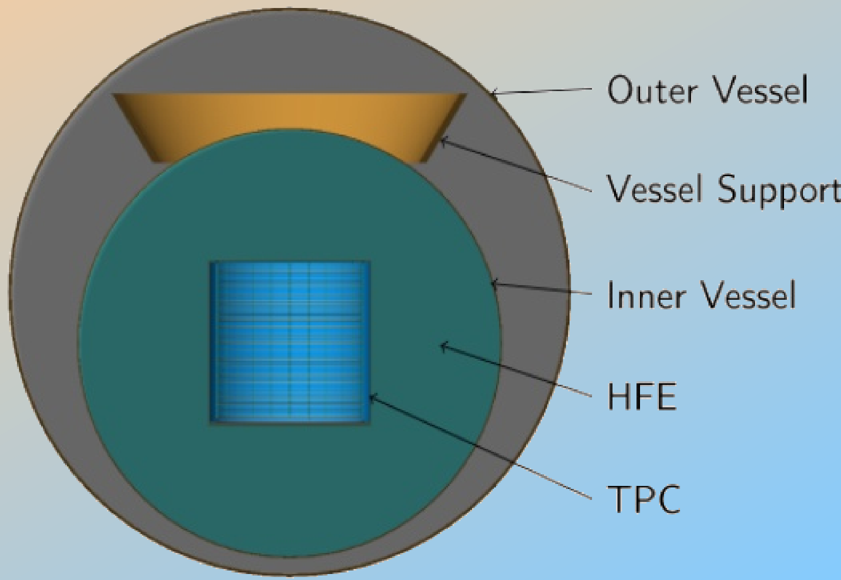
EXO-200: *this result, arXiv: 1707.08707*
CUORE: *talk by O. Cremonesi @ TAUP-2017*
Sensitivity in PRL 115 (2015) 102502

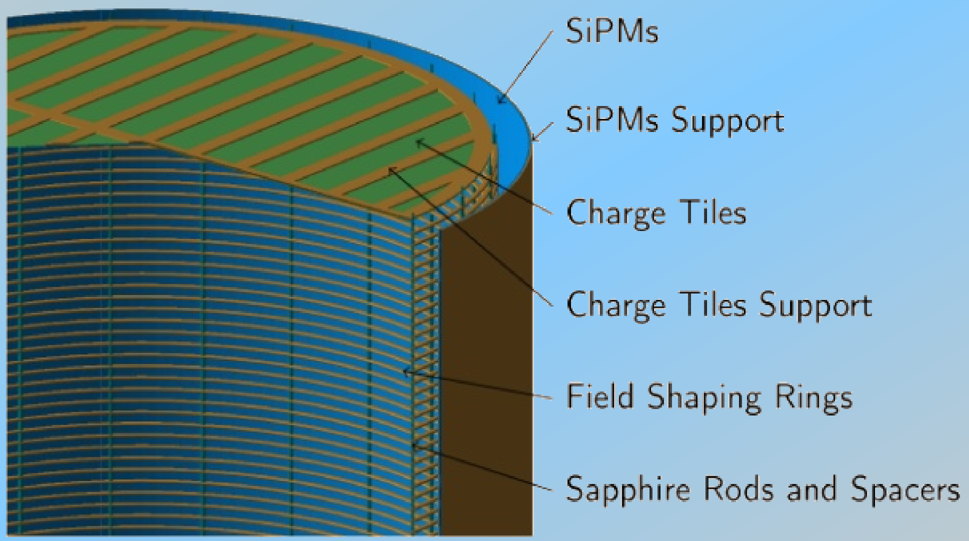
EXO-200 and beyond

- Operated a 200 kg scale LXe TPC for 5 years
- Made the **most precise** measurement of ^{136}Xe halflife
- Measured **residual backgrounds are very low**
- Achieved stable **electron lifetime of ~3 ms** or better
- Utilized **self-shielding in monolithic detector**
- Demonstrated power of **β/γ discrimination** (SS/MS)
- Upgraded electronics (get to **1.2% energy resolution !**)

- It's time to think about tonne-scale experiment!
- We are entering the "golden era" of ββ decay experiments as detector sizes exceed interaction length
- 5000 kg homogenious liquid xenon detector nEXO
- It isn't just 30 EXO-200 experiments
- Our aim is to reach more than ×100 sensitivity

nEXO detector design

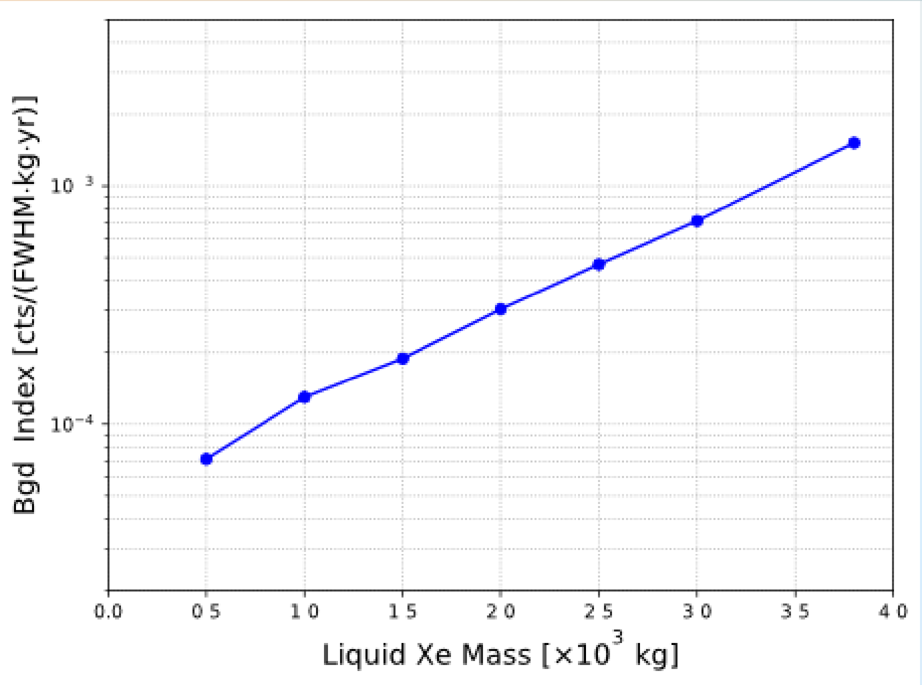


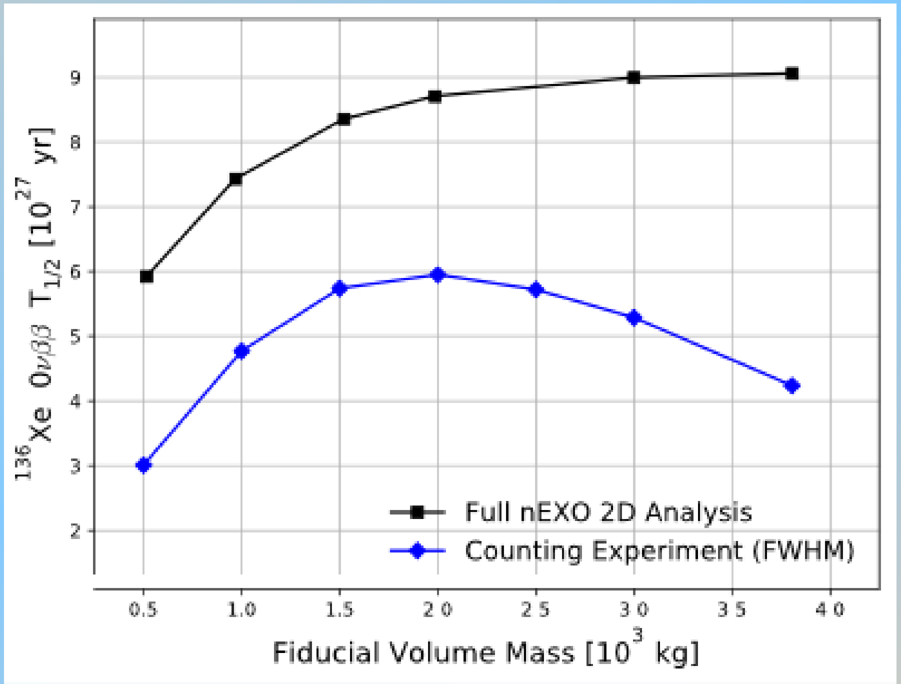


- 1.3 × 1.3 m cylinder TPC
- About 30× active xenon mass
- Thin copper TPC vessel
- Single drift zone
- Cathode on bottom
- HFE as coolant and shield
- Deeper location site

- Charge tiles instead of wires
- ... reading 2D position
- SiPMs on the barrel
- ... naturally sensitive to VUV
- Good reflection everywhere
- Cold front-end electronics
- Better than 1% energy resolution

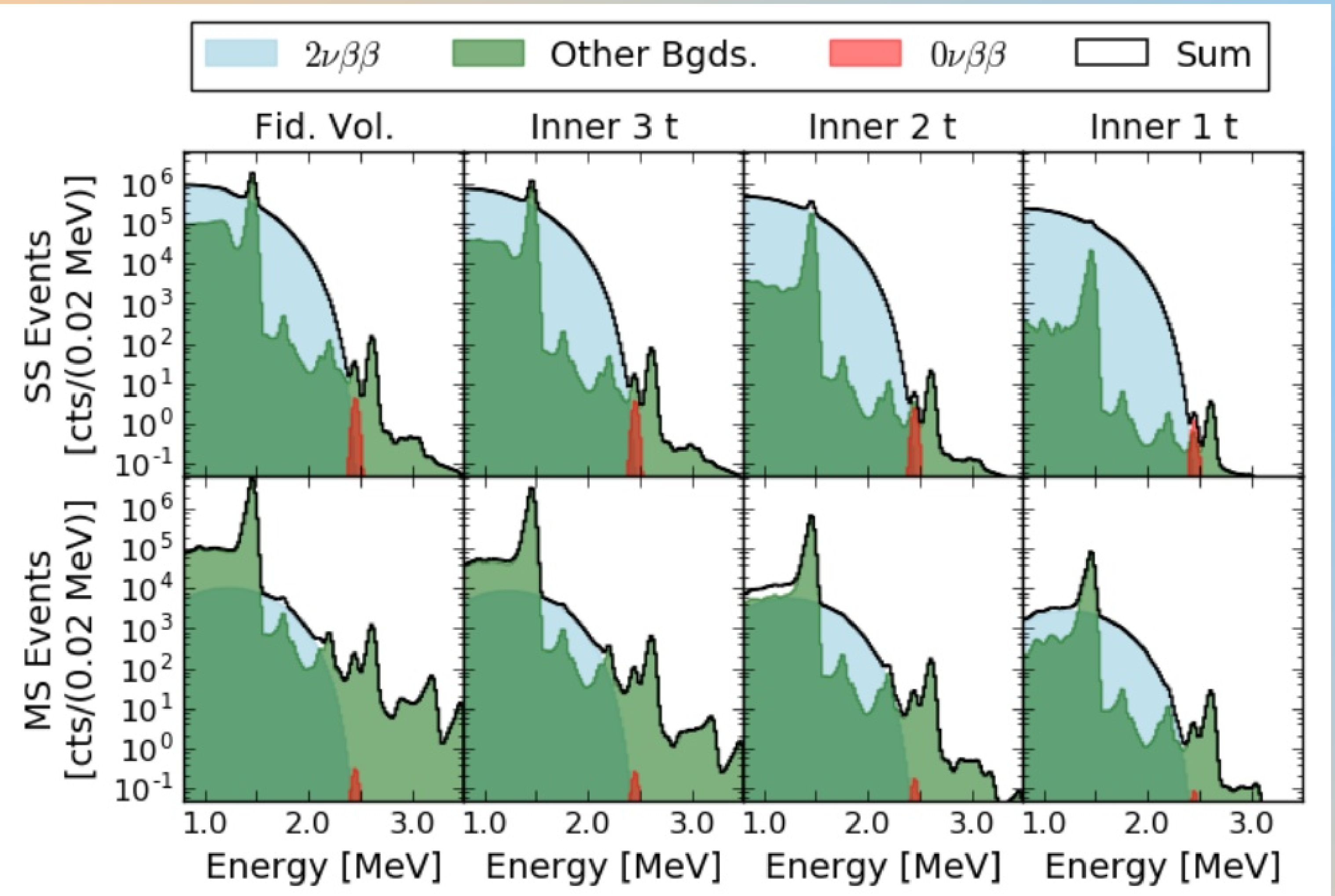
Fiducial Volume dependence





- Background index is a function of a fiducial volume size
- Global fit analysis optimally exploits all xenon volume, because accounts for both signal and background
- ~95% of sensitivity is reached within 2000 kg FV
- This is achieved with all measured materials, no extrapolation

Signal and Background

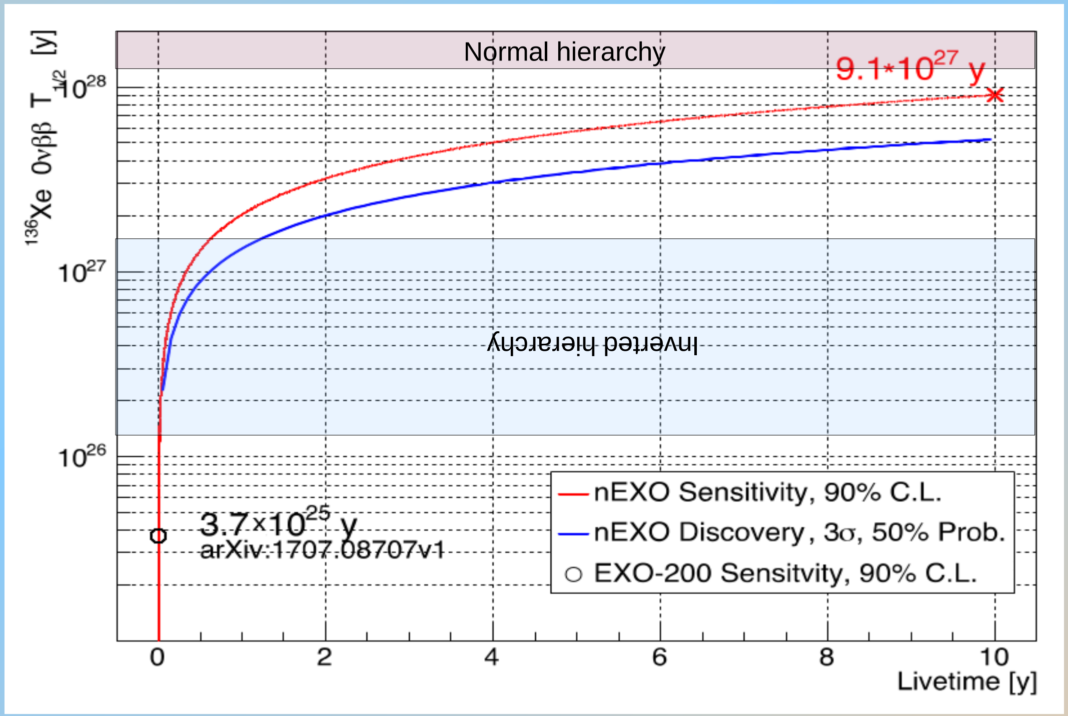


Background contribution	
^{238}U	78%
^{232}Th	14%
^{222}Rn	5,7%
^{137}Xe	2,0%
2β2v	0,2%

- 90% C.L. sensitivity with 10-year exposure is 9.1×10^{27} yr
- Current background estimate: 3×10^{-4} counts/FWHM/kg/yr assuming a 2 tonne fiducial volume.

nEXO prospects

- nEXO is a next generation $2\beta0\nu$ experiment with ongoing R&D.
- Will have discovery potential in the IH region.
- Estimated to have a sensitivity of 9.1×10^{27} yr at 90% C.L. to the ^{136}Xe $2\beta0\nu$ half-life with a 10-year exposure.



Using the best case NME (GCM)
Rodriguez, Martinez-Pinedo, Phys.Rev.Lett. 105 (2010) 252503

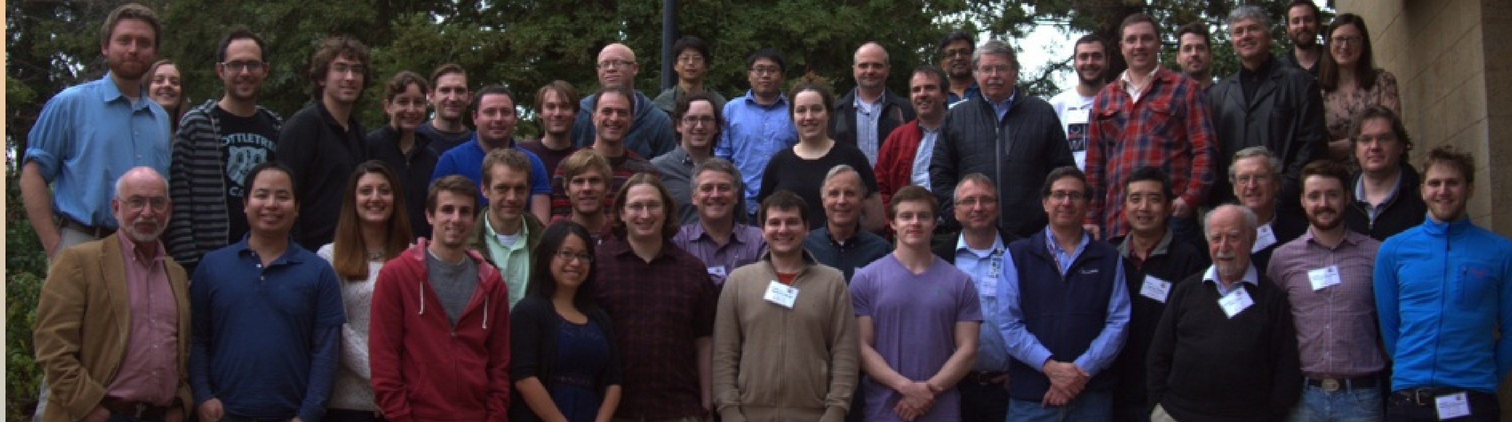
Conclusion

- $0\nu\beta\beta$ searches are for discovery of new physics, with connections to many areas of modern physics
- Looking at more than one isotope is important
- Results from 100 kg yr searches are here, with no discovery yet
- EXO-200 has successfully validated the suitability of nEXO approach
- Substantial R&D is in progress to fine-tune the design of nEXO, a 5000 kg detector that will drastically advance the field
- The 10 meV region is within our reach!

Enriched Xenon Observatory

EXO

for double beta decay



The EXO-200 Collaboration

University of Alabama, Tuscaloosa AL, USA — T Didberidze, M Hughes, A Piepke, R Tsang
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 — M Dunford, R Gornea, K Graham, R Killick, T Koffas, C Licciardi, D Sinclair
Colorado State University, Fort Collins CO, USA — C Chambers, A Craycraft, W Fairbank Jr., T Walton
Drexel University, Philadelphia PA, USA — E Callaghan, MJ Dolinski, YH Lin, E Smith, Y-R Yen
Duke University, Durham NC, USA — PS Barbeau
Friedrich-Alexander-University Erlangen, Nuremberg, Germany — G. Anton, R. Bayerlein, J. Hoessl, P. Hufschmidt, A. Jamil, T. Michel, M. Wagenpfeil, G. Wrede, T. Ziegler
IBS Center for Underground Physics, Daejeon, South Korea — DS Leonard
IHEP Beijing, People's Republic of China — G Cao, W Cen, T Tolba, L Wen, J Zhao
ITEP Moscow, Russia — V Belov, A Burenkov, M Danilov, A Dolgolenko, A Karelin, A Kuchenkov, V Stekhanov, O Zeldovich
University of Illinois, Urbana-Champaign IL, USA — D Beck, M Coon, S Li, L Yang
Indiana University, Bloomington IN, USA — JB Albert, S Daugherty, TN Johnson, LJ Kaufman, J Zettlemoyer
Laurentian University, Sudbury ON, Canada — B Cleveland, A DerMesrobian-Kabakian, J Farine, U Wichoski
University of Maryland, College Park MD, USA — C Hall
University of Massachusetts, Amherst MA, USA — S Feyzbakhsh, S Johnston, J King, A Pocar
McGill University, Montreal QC, Canada — T Brunner, K Murray
SLAC National Accelerator Laboratory, Menlo Park CA, USA — M Breidenbach, R Conley, T Daniels, J Davis, S Delaquis, R Herbst, A Johnson, M Kwiatkowski, B Mong, A Odian, CY Prescott, PC Rowson, JJ Russell, K Skarpaas, A Waite, M Wittgen
University of South Dakota, Vermillion SD, USA — J Daughhetee, R MacLellan
Stanford University, Stanford CA, USA — R DeVoe, D Fudenberg, G Gratta, M Jewell, S Kravitz, D Moore, I Ostrovskiy, A Schubert, M Weber
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, F Retière, V Strickland

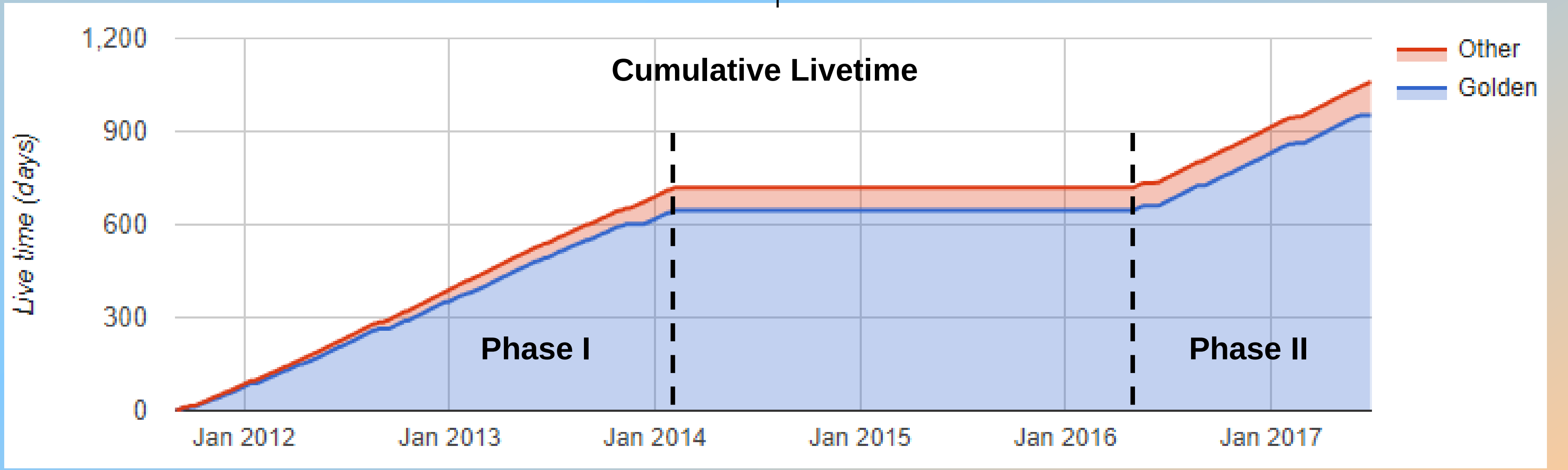
Data collection

Phase-I

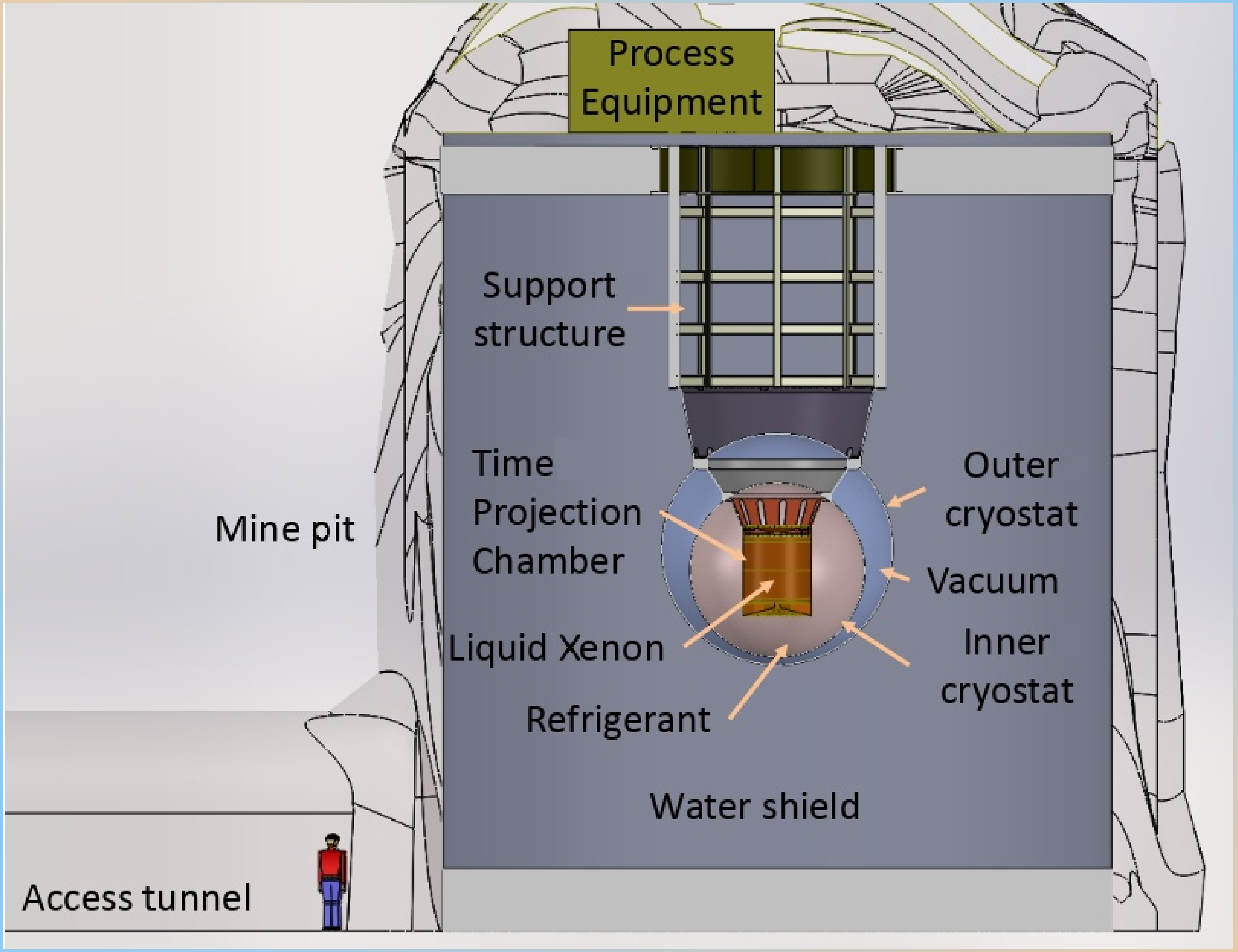
- Sep 2011 to Feb 2014
  - Total live time 596.7 days
- Selected physics results
  - Most precise 2νββ measure
    - *Phys. Rev. C **89**, 015502 (2013)*
  - Stringent 0νββ searches
    - *Nature **510**, 229 (2014)*
    - Sensitivity $T_{1/2}^{0\nu\beta\beta} > 1.9\times10^{25}$ yr (90%CL)

Phase-II

- Access regained in 2015 after stop imposed by WIPP accidents
- Jan to May 2016
  - Hardware upgrades
- HV raised by 50% in May 2016
  - Live time 271.8 days
- Physics results shown TAUP-2017
  - *ArXiv: 1707.08707*



nEXO @ SNOlab



Process Equipment
Support structure
Time Projection Chamber
Outer cryostat
Vacuum
Mine pit
Liquid Xenon
Inner cryostat
Refrigerant
Water shield
Access tunnel

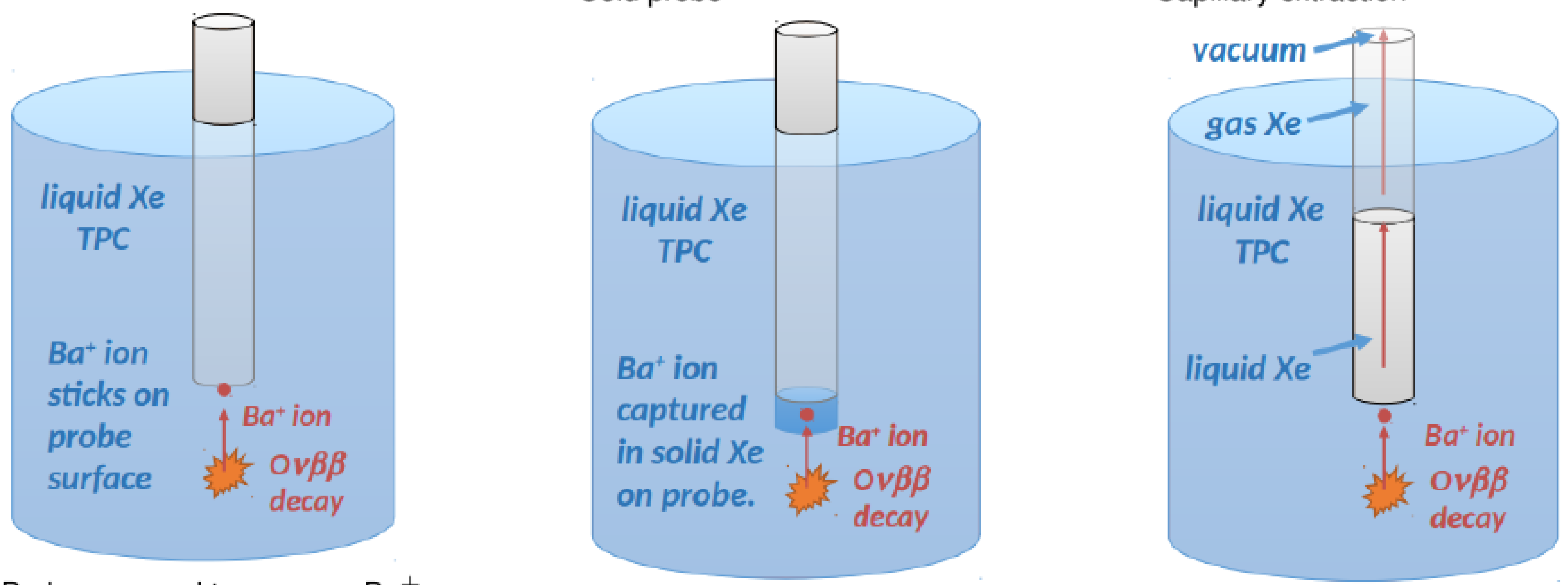
nEXO Barium tagging

Goal of barium tagging:

- Recover and identify xenon decay daughter barium if present
- Suppress background to almost background free

Several concepts are being investigated:

Conducting Probe | Cold probe [3] | Capillary extraction [4]



Probe removed to vacuum; Ba^+ identified by (1) laser ablation/resonance ionization or (2) thermal desorption/ionization

Probe removed to vacuum; Ba/Ba^+ identified laser fluorescence single atom imaging in SXe

Ba^+ "sucked" out of LXe through capillary into ion trap and identified laser fluorescence and MRTOF spectroscopy

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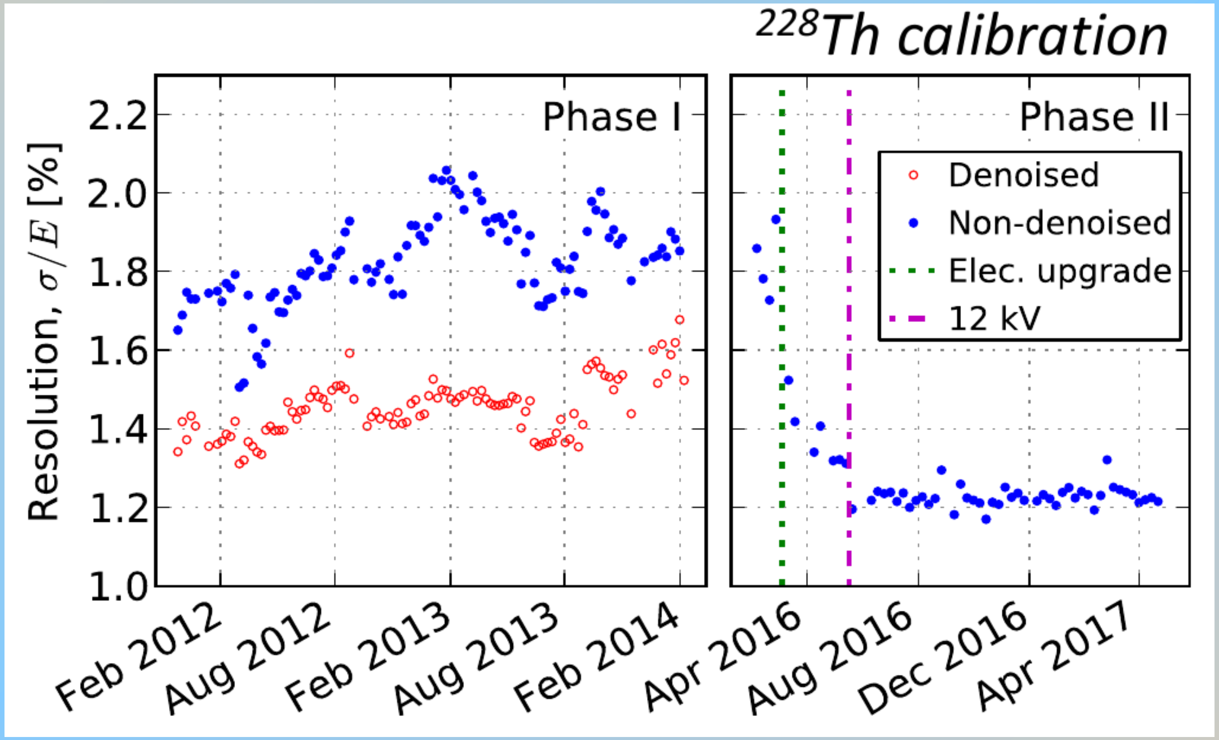
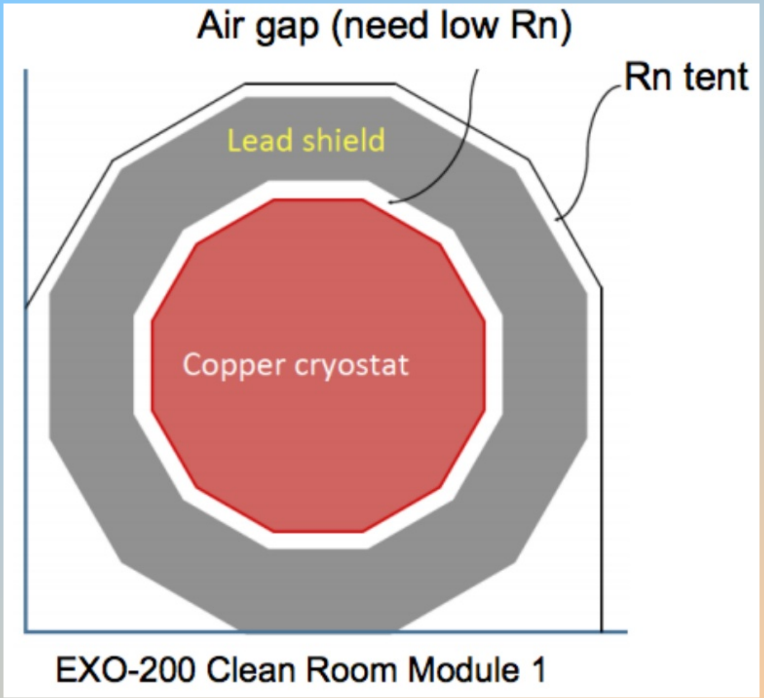
[3] B. Mong et al., "Spectroscopy of Ba and Ba^+ deposits in solid xenon for barium tagging in nEXO", Phys. Rev. A 91, (2015) 022505

[4] T. Brunner et al., "An RF-only ion-funnel for extraction from high-pressure gases", Int J. Mass Spec., 379, 110-120 (2015)

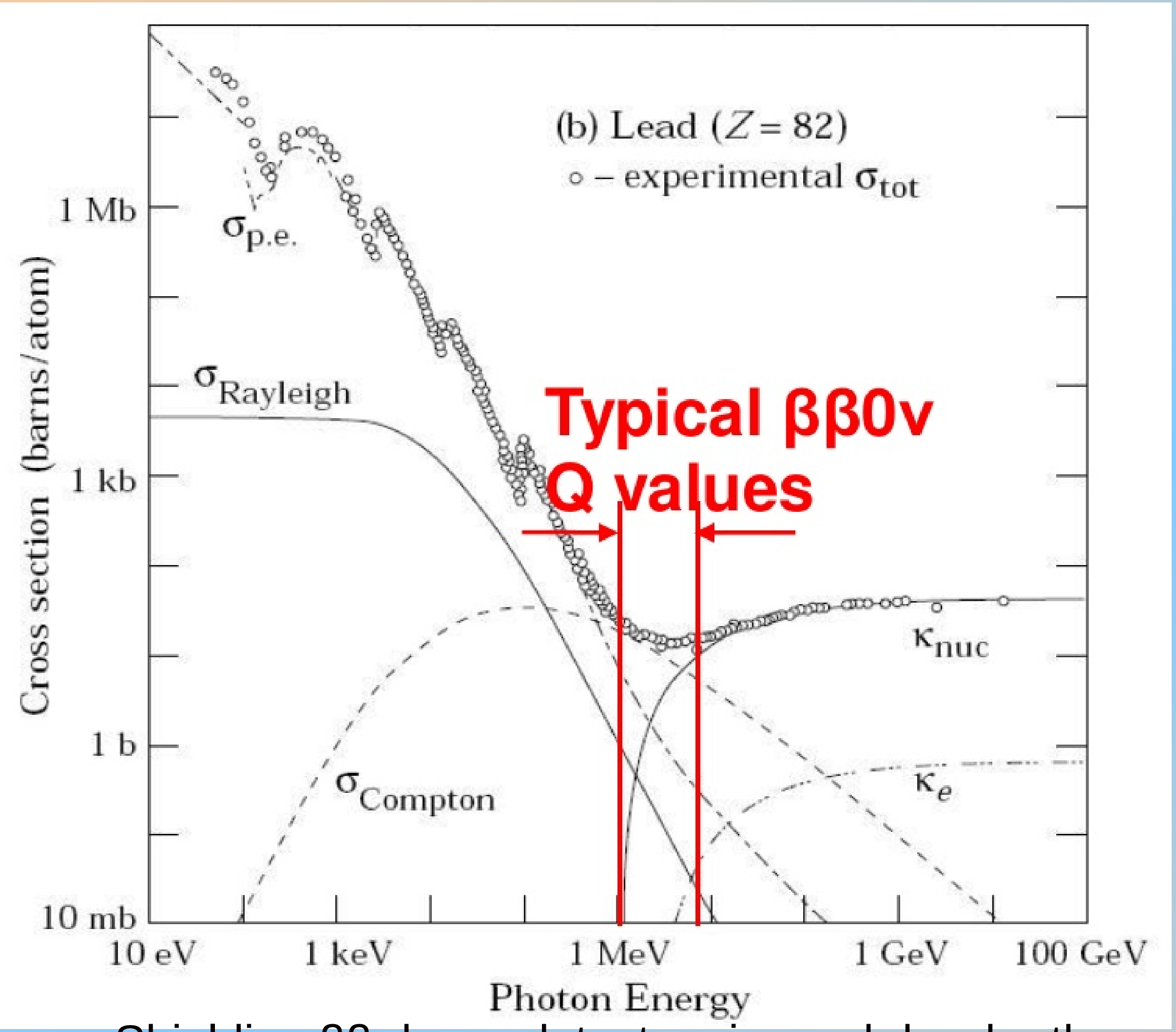
Detector upgrades

- Front end readout electronics (Reduce APD read-out noise)
- Increase of HV x1.5
- Effect in energy resolution: Phase-II: σ/E(Q) = 1.23%,
- System to suppress radon in air gap
- Direct air sampling shows radon levels reduced in the gap by >10



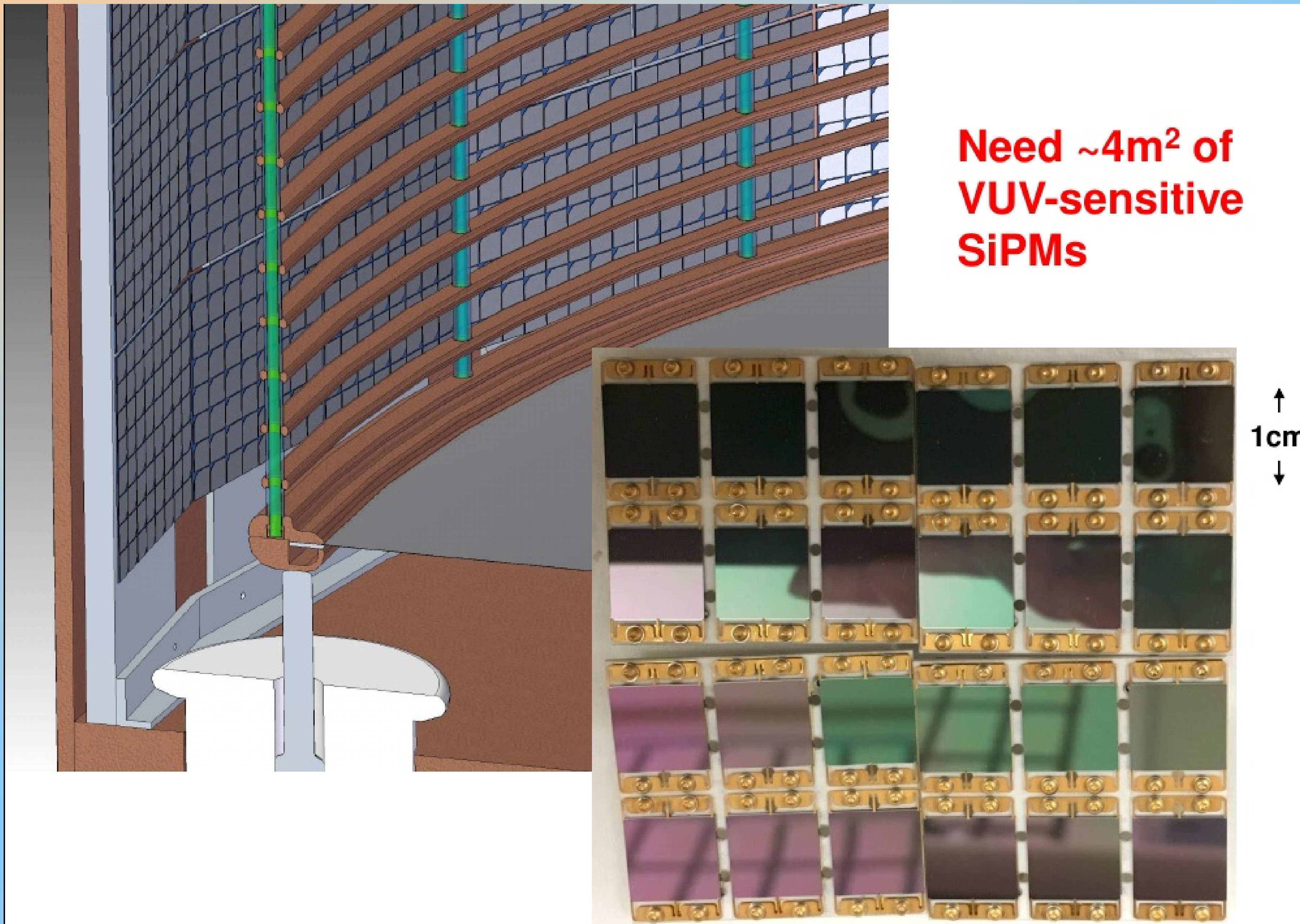


Shielding is difficult



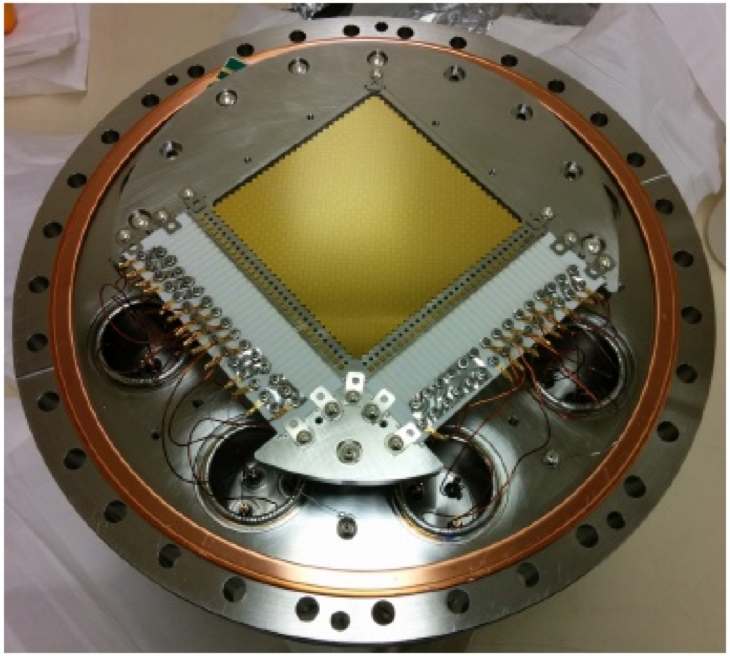
- Shielding ββ decay detectors is much harder than shielding Dark Matter ones
- We are entering the “golden era” of ββ decay experiments as detector sizes exceeds interaction length

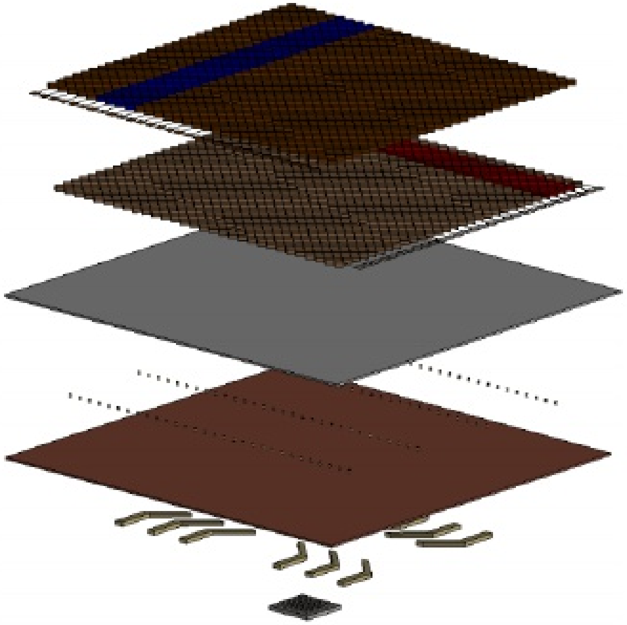
nEXO Photodetectors



nEXO Charge collection

- Orthogonal, noble-metal strips of 10 cm length on a quartz substrate
- Each strip consists of small metal pads linked diagonally, lying parallel to either the X- or the Y-axis.

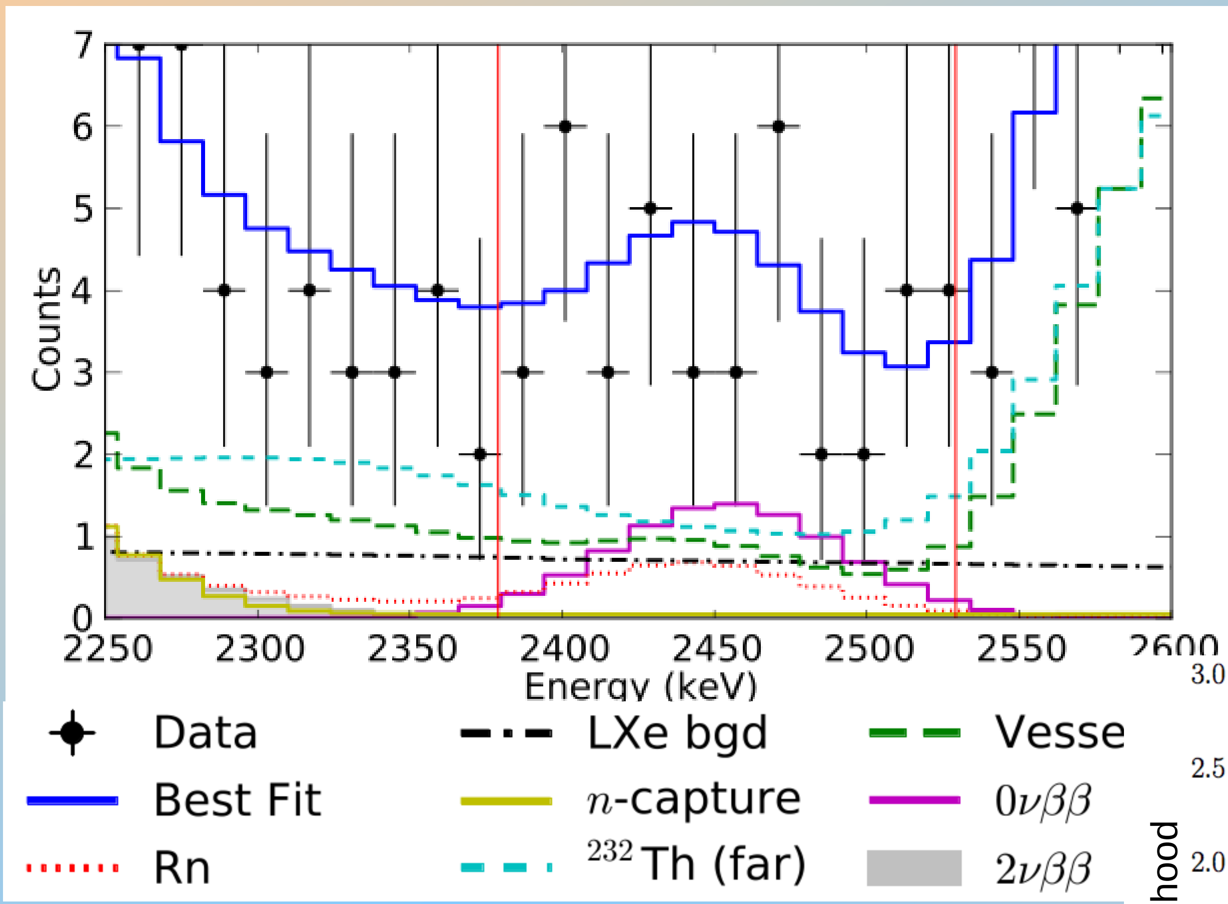




In going R&D:

- Improving fabrication process.
- Investigating different readout schemes.
- Integrating with cold electronics.

2β0ν measurement



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

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

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

(90% C.L.)

[*Nature* **510**, 229 (2014)]