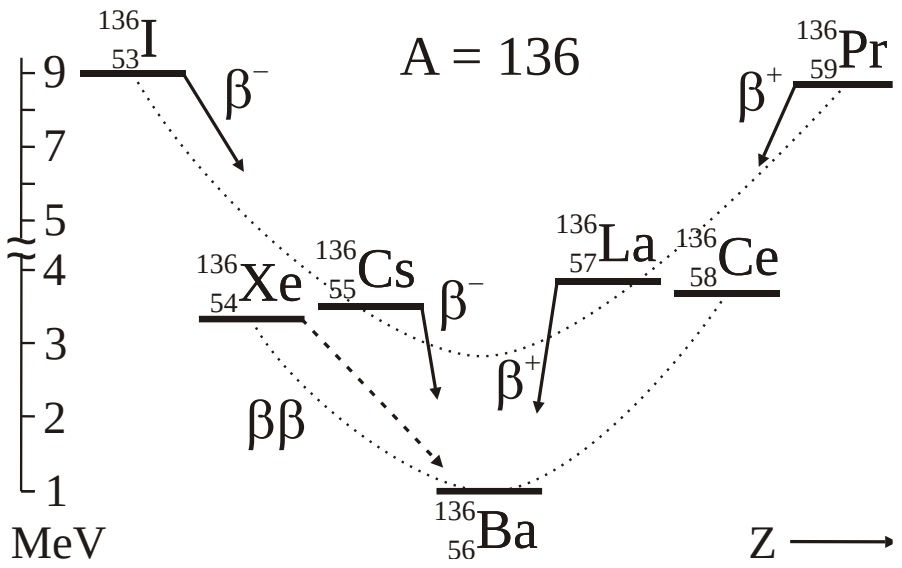
Latest Results from EXO-200

Mike Jewell
Stanford University

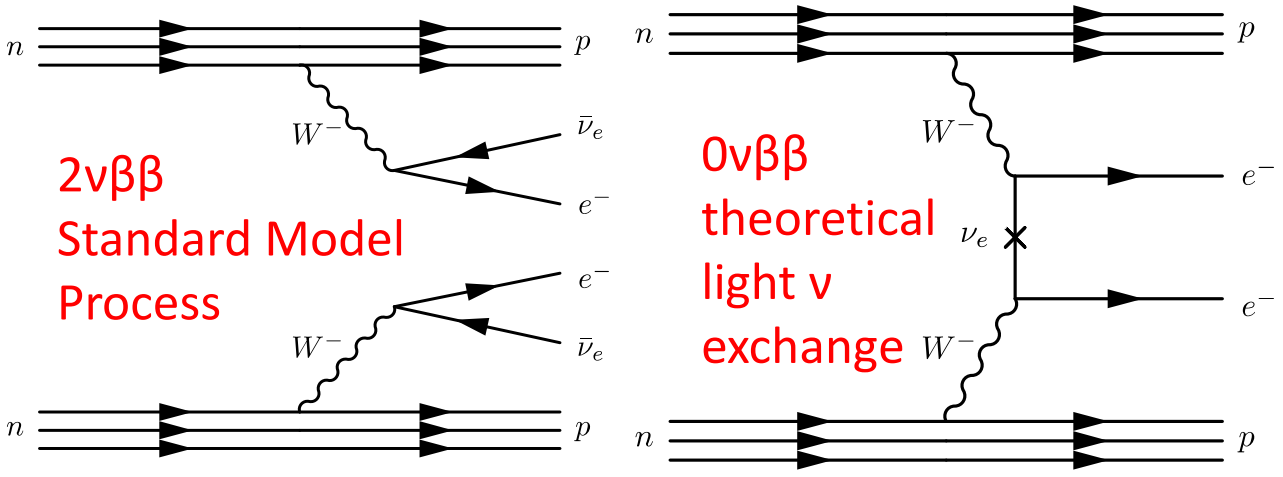
NorCal HEP-EXchange

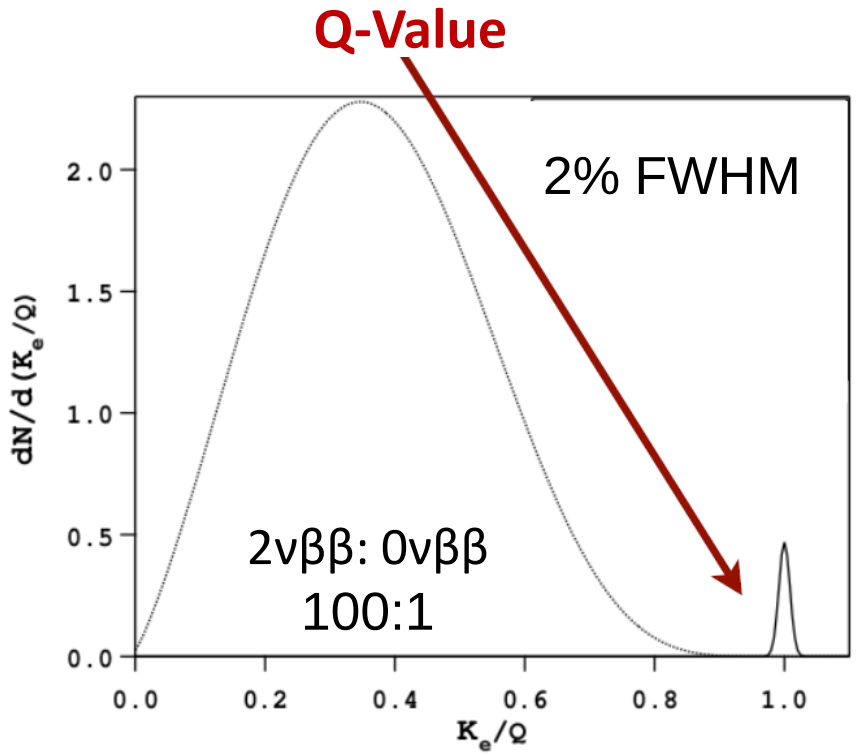
December 2nd, 2017

Neutrinoless Double Beta Decay (0νββ)



- Massive Majorana Neutrinos
- Lepton Number Violating Process
- Absolute Neutrino Mass Scale



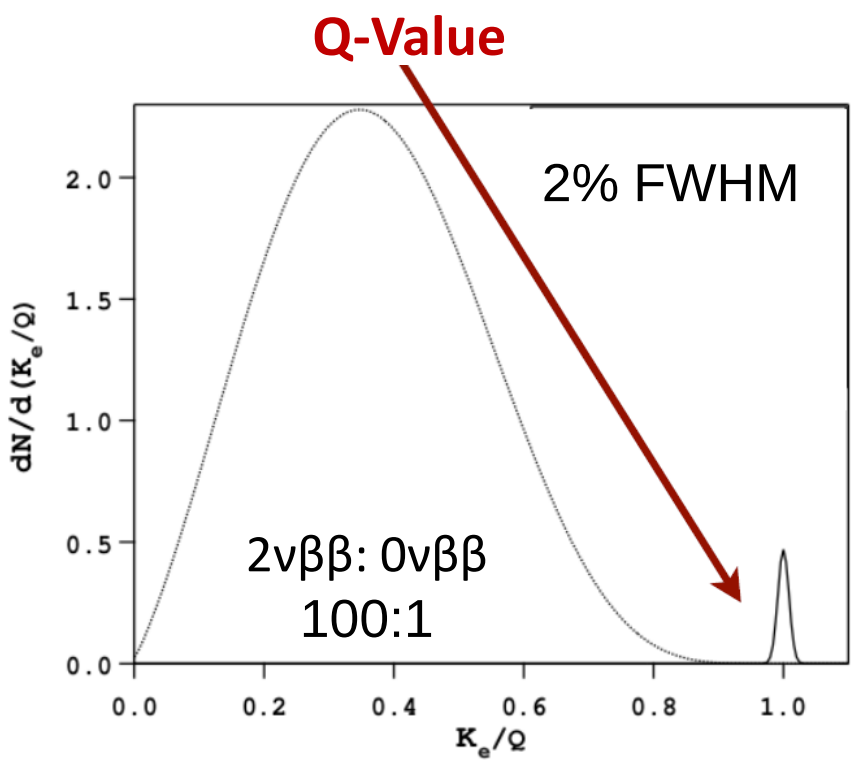


Searching For 0νββ

- 0νββ in ^{136}Xe
  - Decays to ^{136}Ba
  - 2νββ observed in ^{136}Xe ($T_{1/2} = 2.165 \pm 0.016 \pm 0.059 \text{ x } 10^{21}\ yrs$) [1]
  - Q-Value of 2458 keV
  - Previous EXO-200 limit on 0νββ $T_{1/2}^{0\nu\beta\beta} > 1.1 \text{ x } 10^{25}$ yrs [2]
- ^{136}Xe as Detector
  - Xenon produces ionization and light signals
  - Also use Xenon as the detection medium

$^{136}Xe \rightarrow {}^{136}Ba + 2e^- + 2\bar{\nu}$

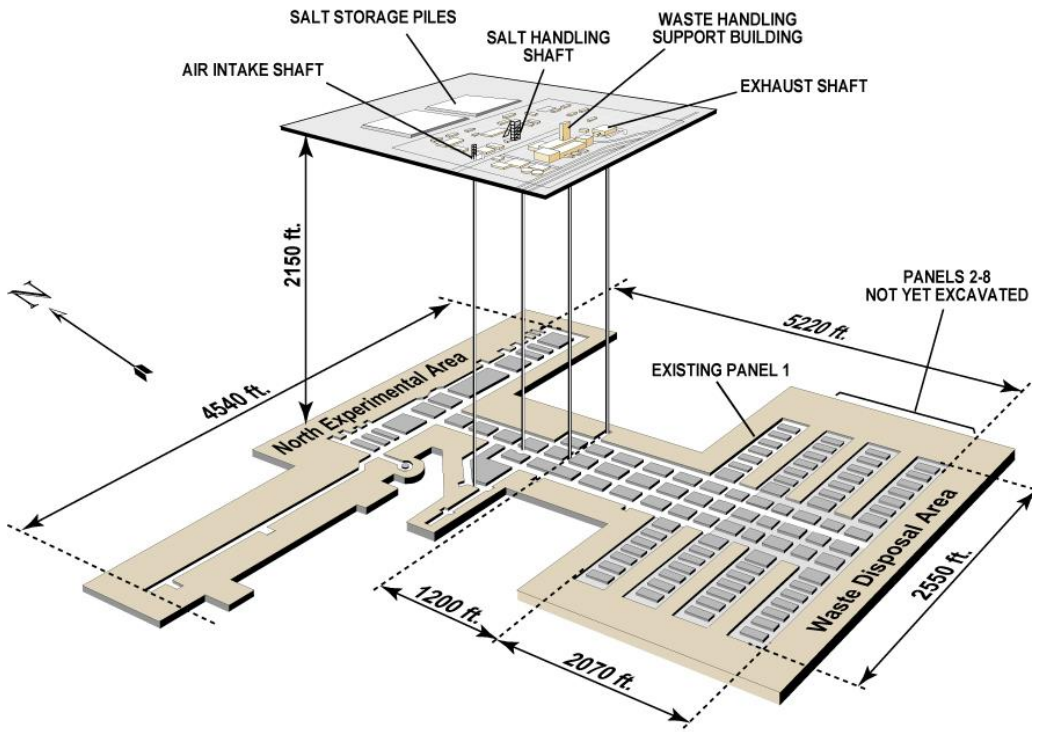
$^{136}Xe \rightarrow {}^{136}Ba + 2e^-$

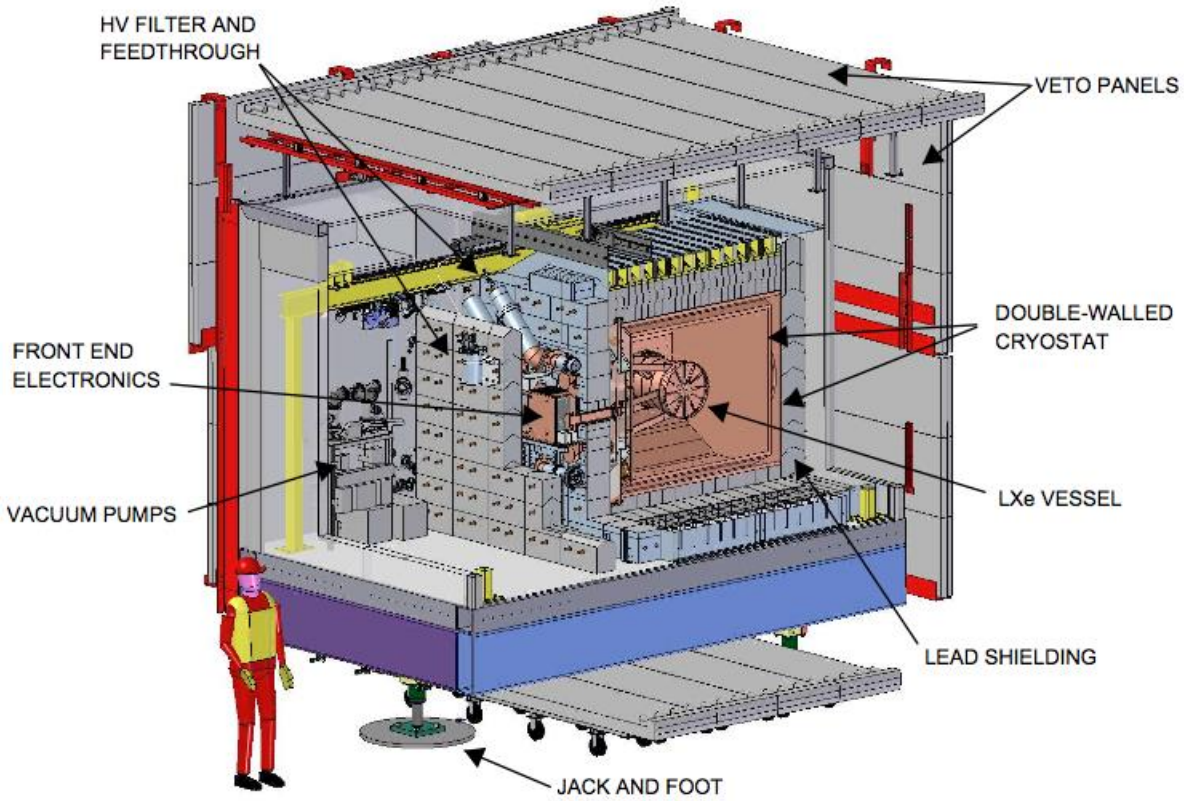


*[1] Phys. Rev. C **89**, 015502 (2013)*
*[2] Nature **510**, 229 (2014)*

EXO-200

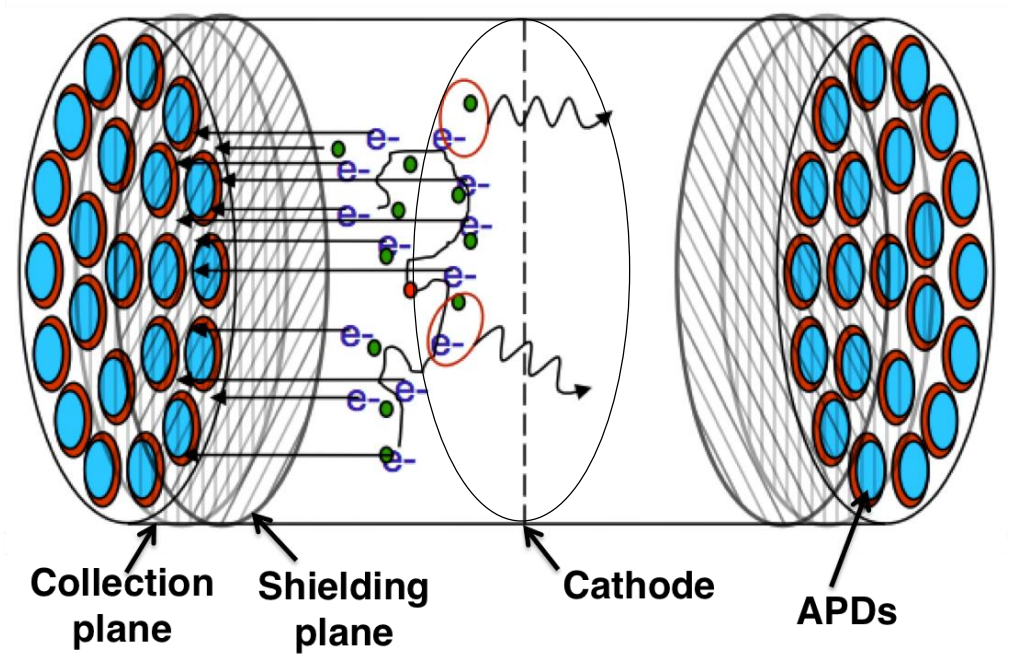
- EXO-200 uses a Liquid Xenon (LXe) Time Projection Chamber (TPC) to search for 0νββ Decay
- Uses 110 kg active volume of Xe^{136}
- Located in a Salt Mine at the Waste Isolation Pilot Plant (WIPP) near Carlsbad NM

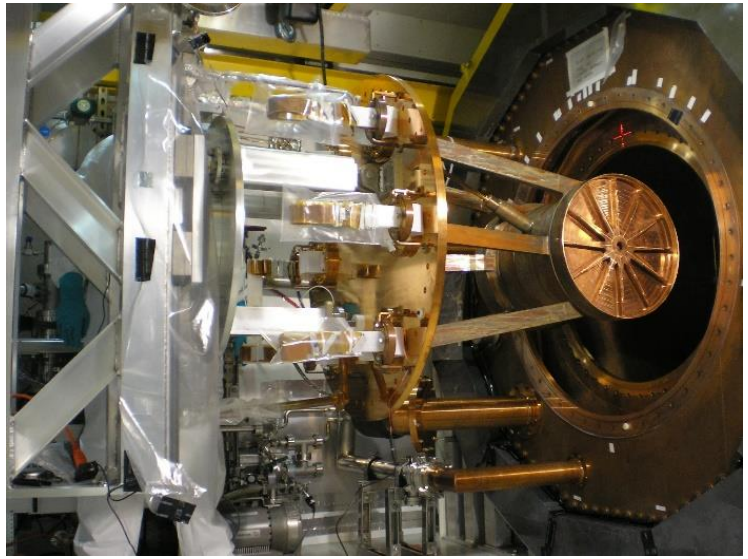


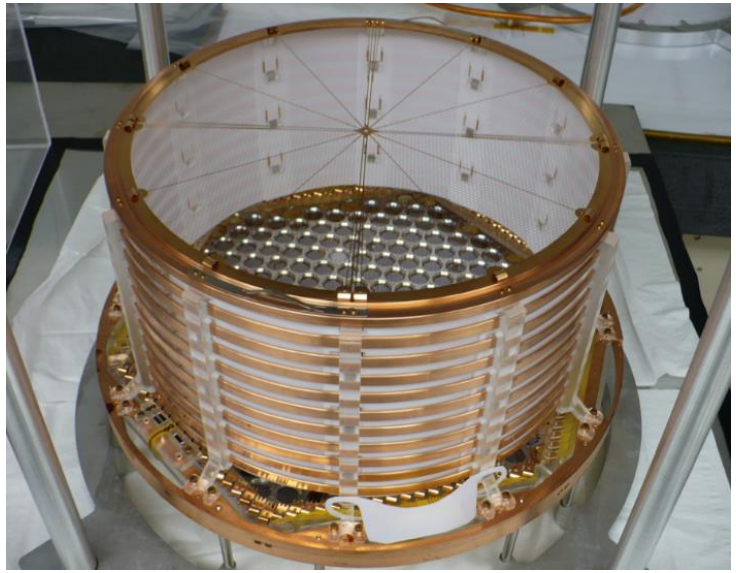


EXO-200 TPC

- Two identical back to back TPCs
- Full 3D Reconstruction
- Ionization signal readout by crossed wire planes
- Scintillation (175nm) collected by APDs



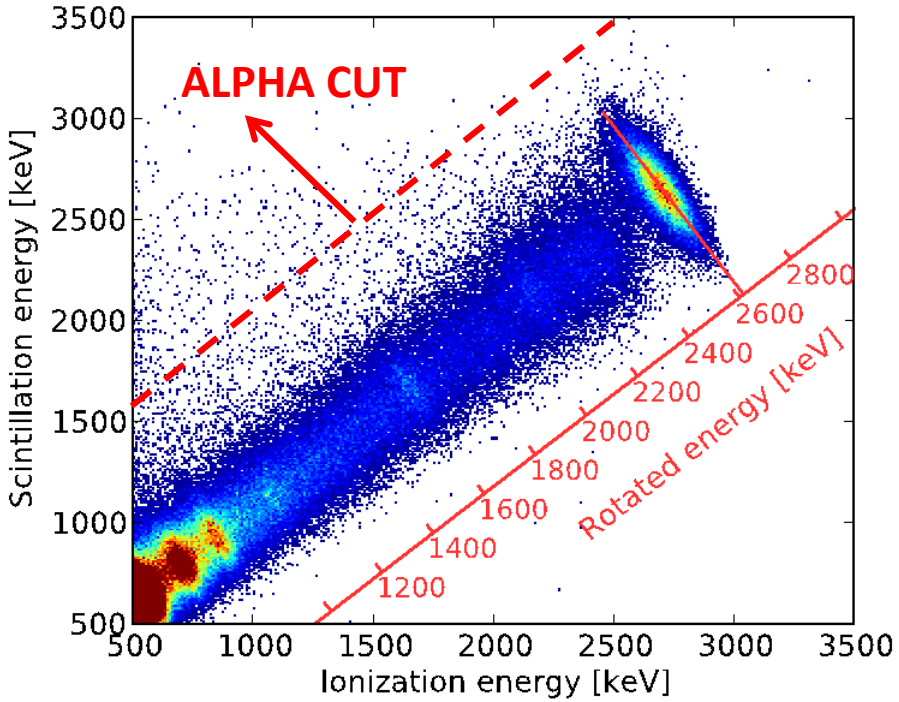




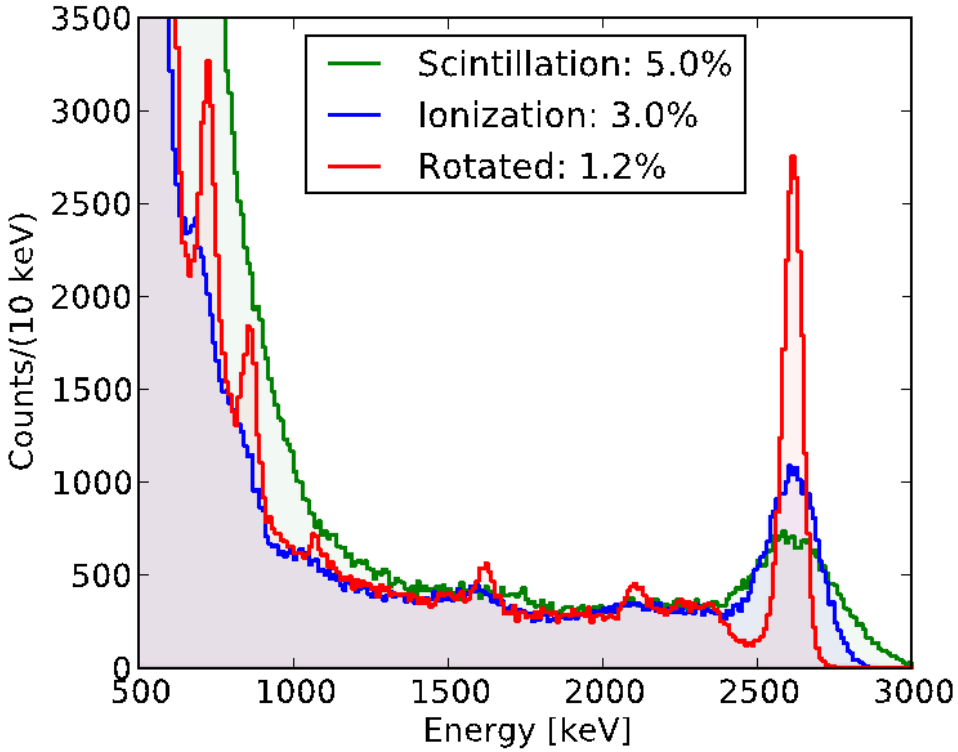
Energy Measurement

- Resolution improvement by combining Anti-Correlated Charge and Light Signals
- Alphas Rejected using Light to Charge Ratio

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



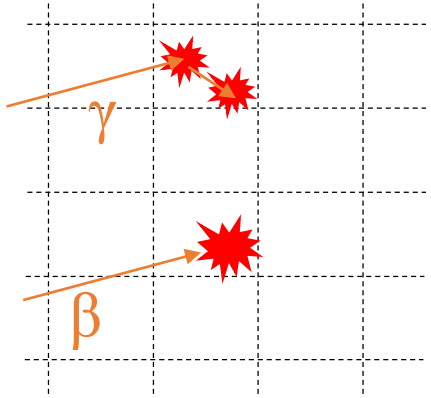
Reconstructed energy, ^{228}Th calibration:



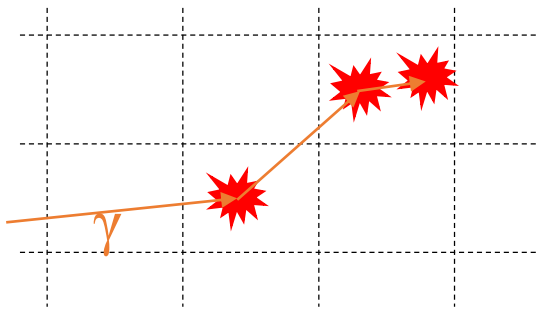
Background Discrimination

- 0νββ signals produce single energy deposits
- Many backgrounds deposit energy in multiple locations from Compton Scattering
- Classify events as Single-Site (SS) or Multi-Site (MS)
- SS Fraction for gammas in ROI is ~20%

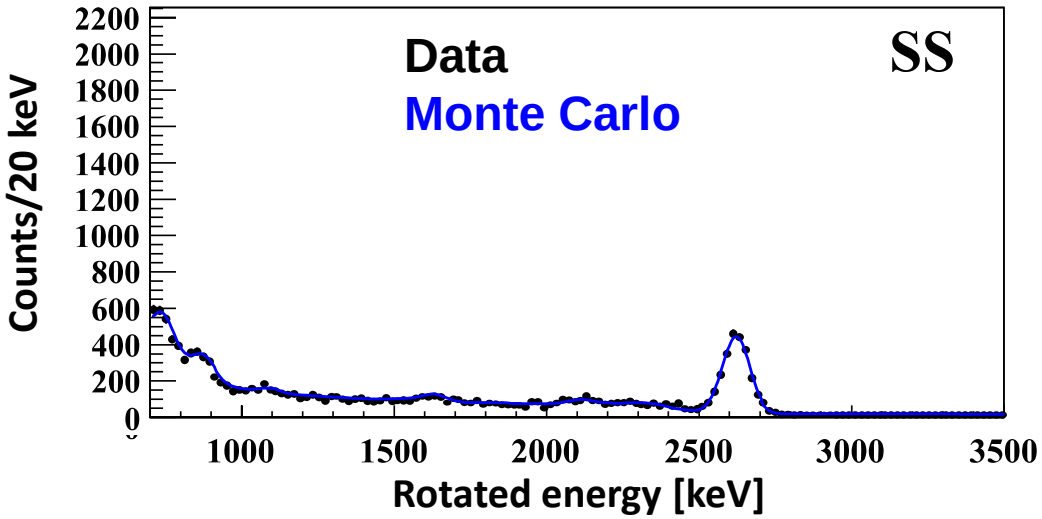
Single-Site (SS)



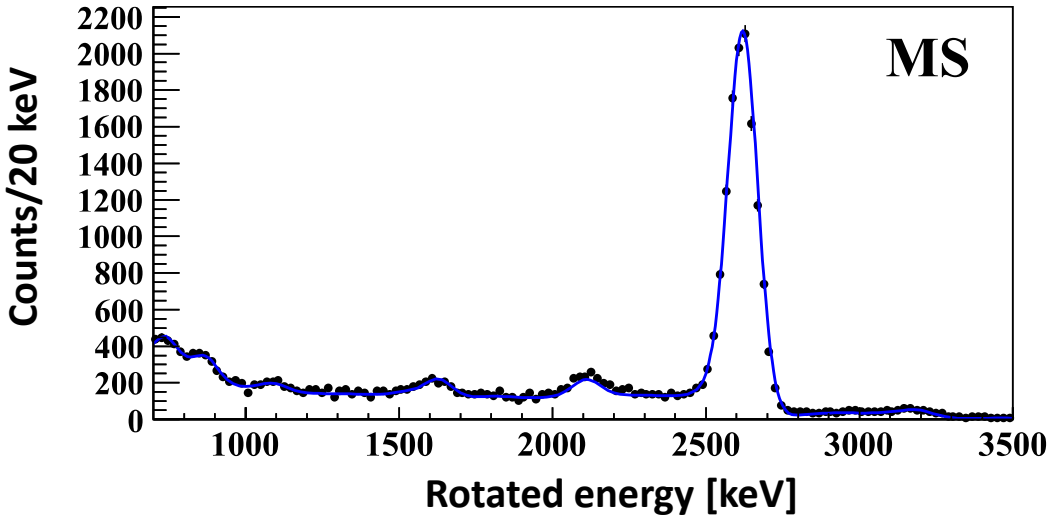
Multiple-Site (MS)



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

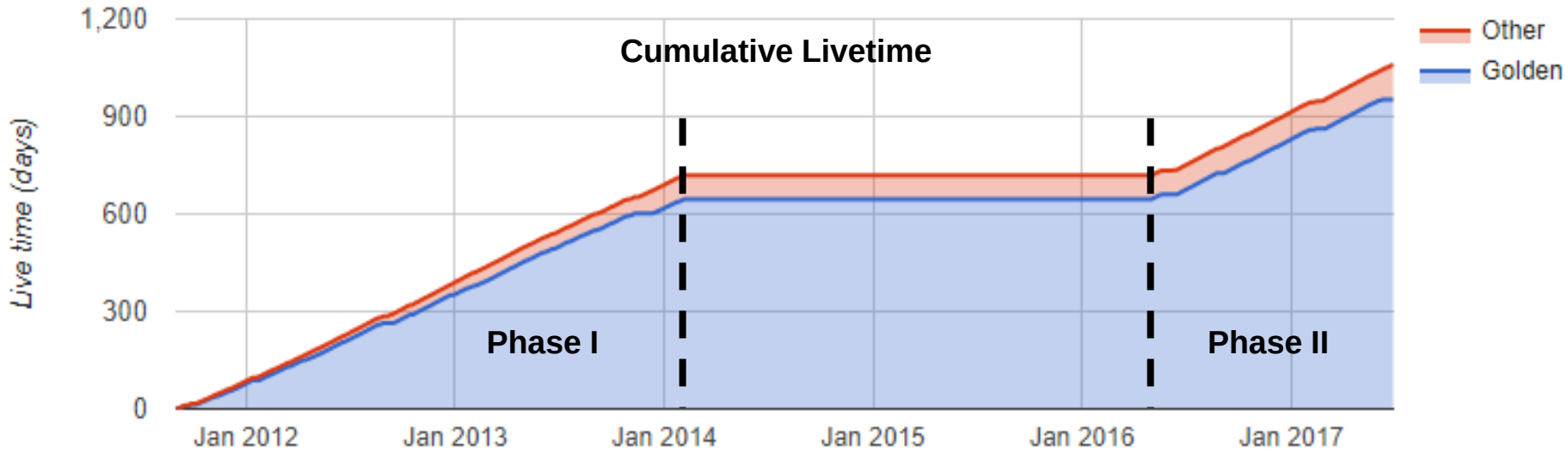


Energy spectrum, ^{228}Th calibration data, MS:



Timeline of EXO-200 Data Taking

- Phase-1
  - Sep 2011 to Feb 2014 (596.7 days of livetime)
  - Feb 2014 WIPP incident closed access
- Phase-2
  - Regained access in 2015
  - Hardware Upgrades and Raised Cathode Bias
  - Restarted Data Taking

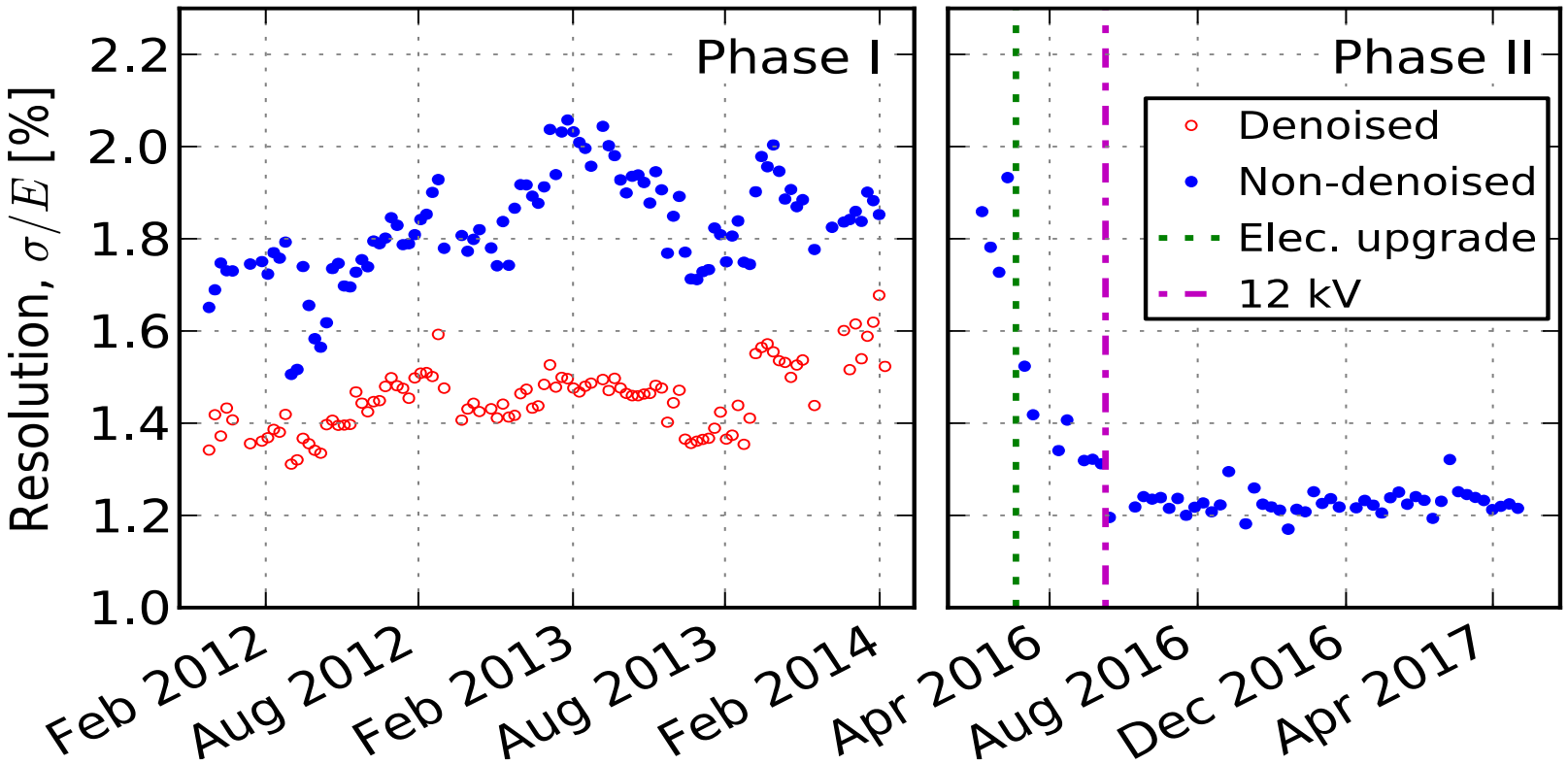


Detector Upgrades

- Front End Electronics Upgrade
  - Reduced APD Noise
- Increased the Cathode Bias
  - -8kV → -12 kV

- Improvement to Energy Resolution:
  - Phase-I: σ/E(Q) = 1.38%
  - Phase-II: σ/E(Q) = 1.23%, steady

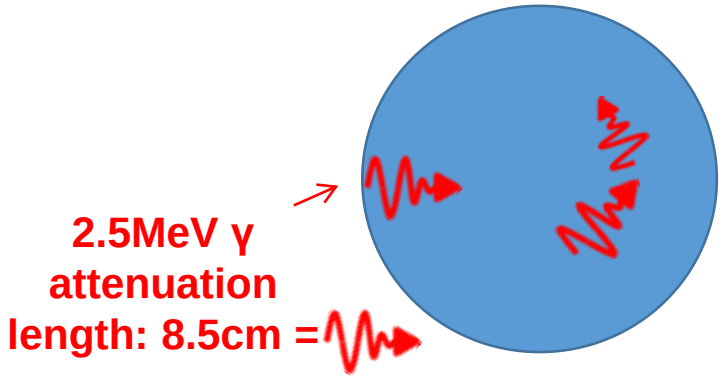
^{228}Th Calibration Data

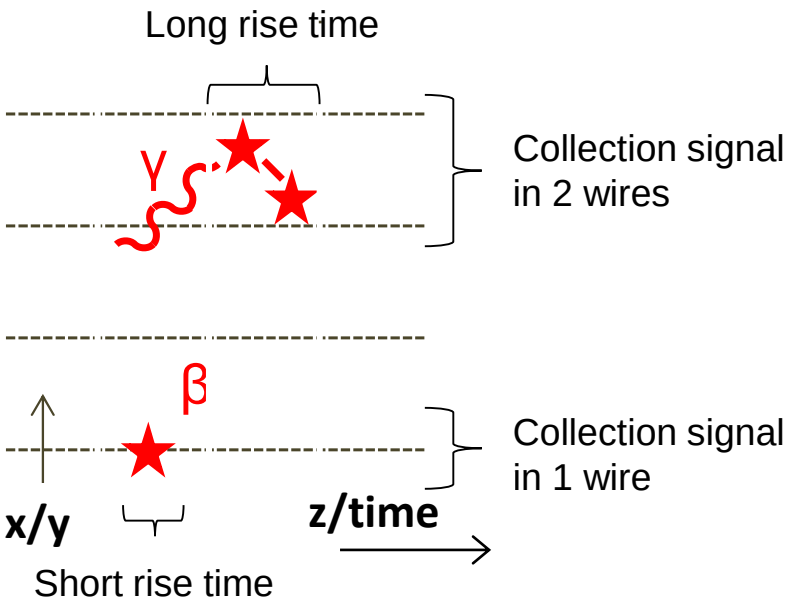


Improved Background Discrimination

- Spatial and size information can also be used to further improve discrimination
- **Standoff Distance**
  - Rate of gammas entering detector are exponentially reduced by LXe self shielding
  - Gives independent measure of Gamma Backgrounds
- **Rise Time**
  - Estimate of longitudal size of cluster
- **Number of Channels Hit**
  - Estimate of transverse size of clusters

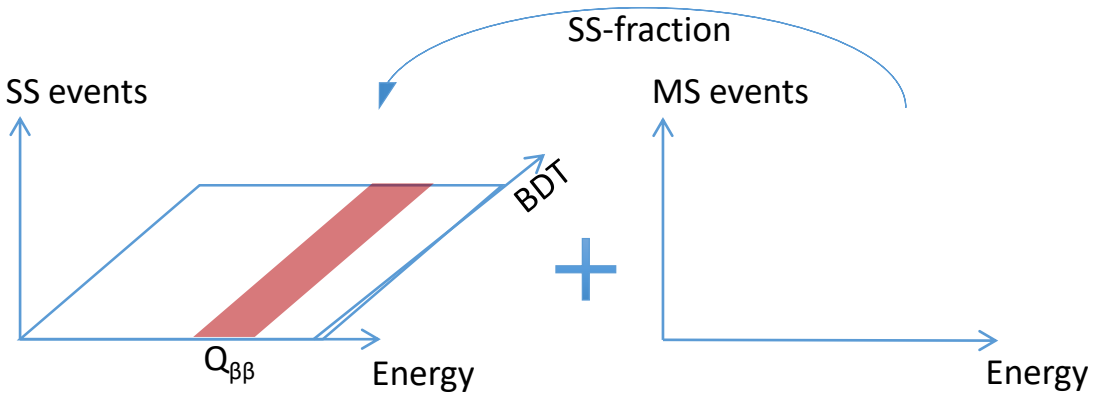
LXe self-shielding:

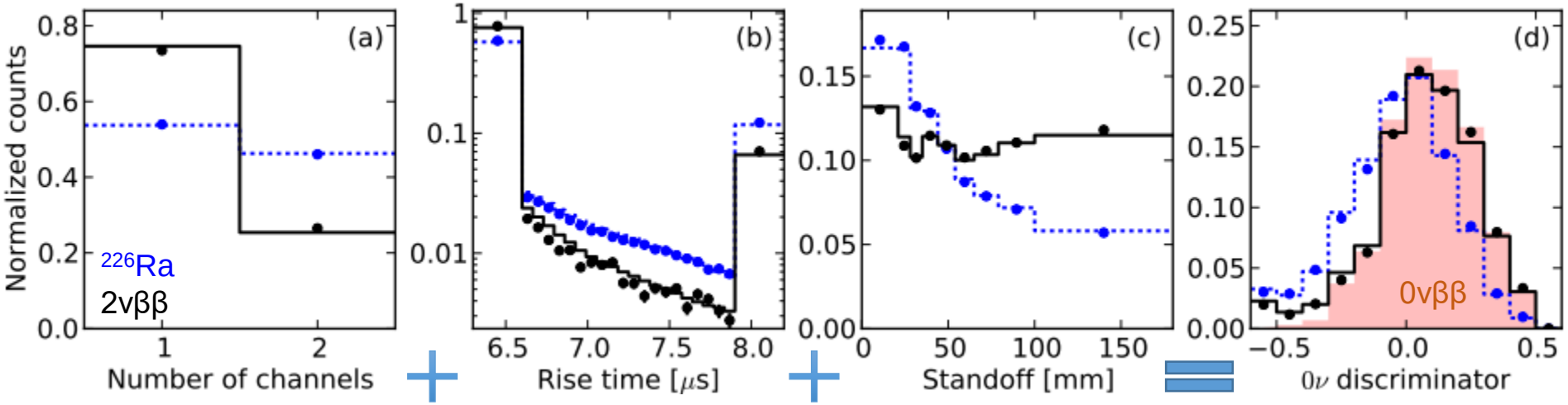




Improved Background Discrimination

- Additional Discrimination using event size and position
- Combine using a Boosted Decision Tree (BDT) to determine new 0v discriminator
- BDT → ~15% sensitivity improvement
- Fit using 3 discriminators (Energy, Multiplicity, BDT)

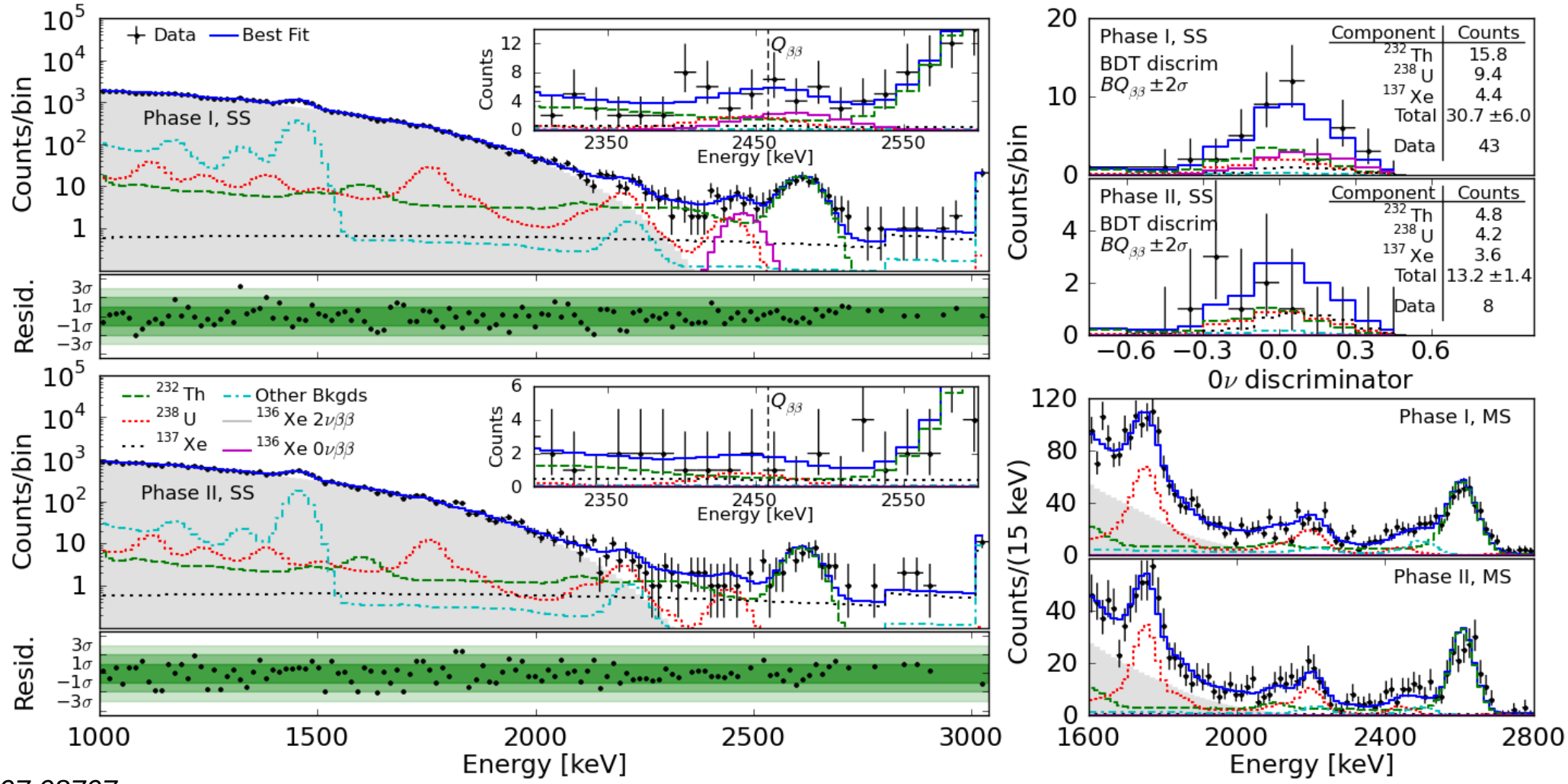




Fit Results

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

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



arXiv: 1707.08707

New EXO-200 Results

Sensitivity of 3.7×10^{25} yr (90% CL)

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

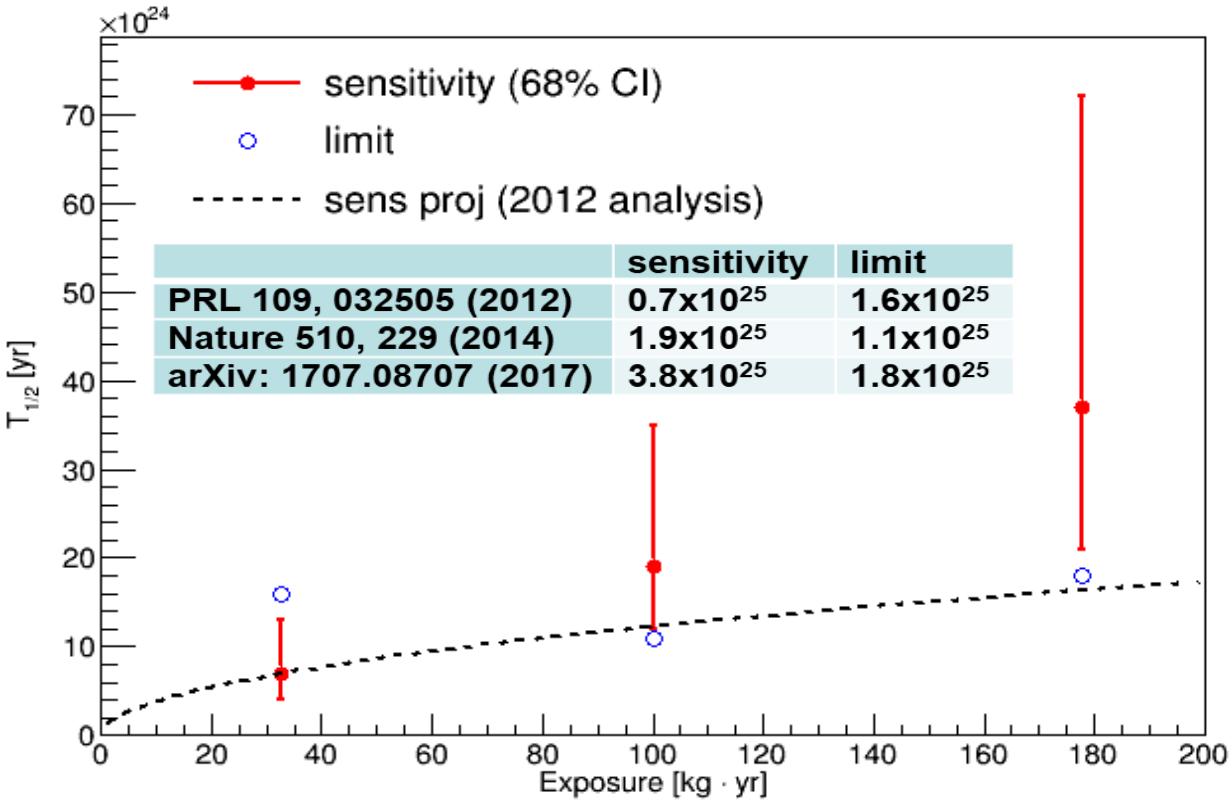
$\langle m_{\beta\beta} \rangle < 147 - 398$ meV

(90% C.L.)

arXiv: 1707.08707

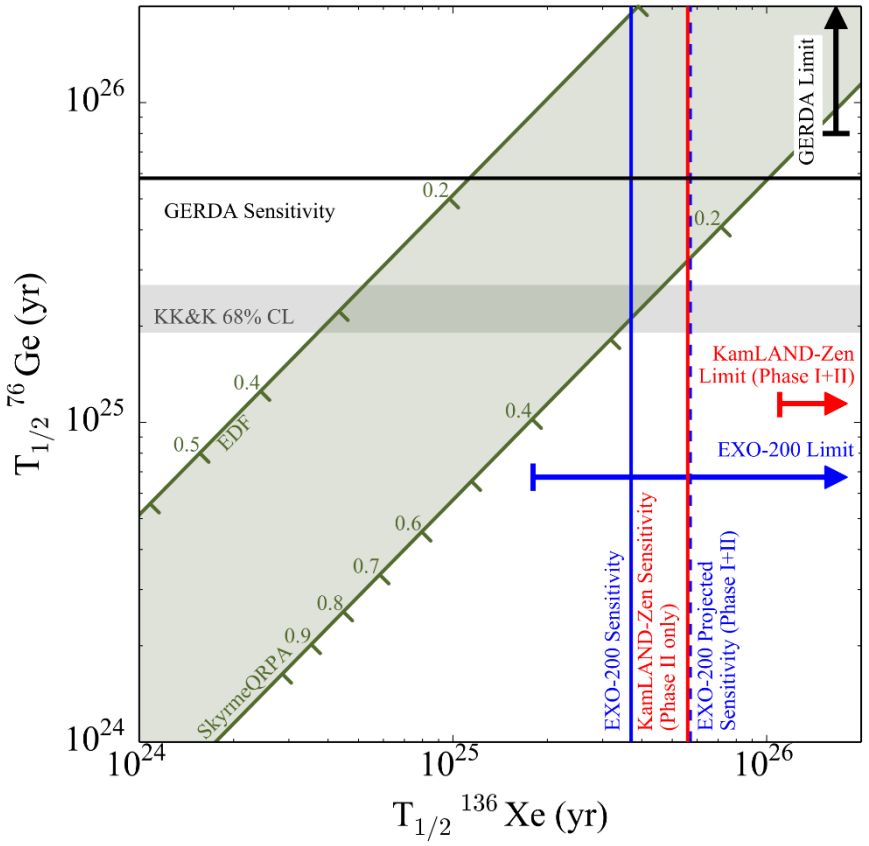
	Livetime	Exposure	Limit (90% CL)
Phase I	596.7 d	122.0 kg.yr	$T_{1/2}^{0\nu\beta\beta} > 1.0 \times 10^{25}$ yr
Phase II	271.8 d	55.6 kg.yr	$T_{1/2}^{0\nu\beta\beta} > 4.4 \times 10^{25}$ yr

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***



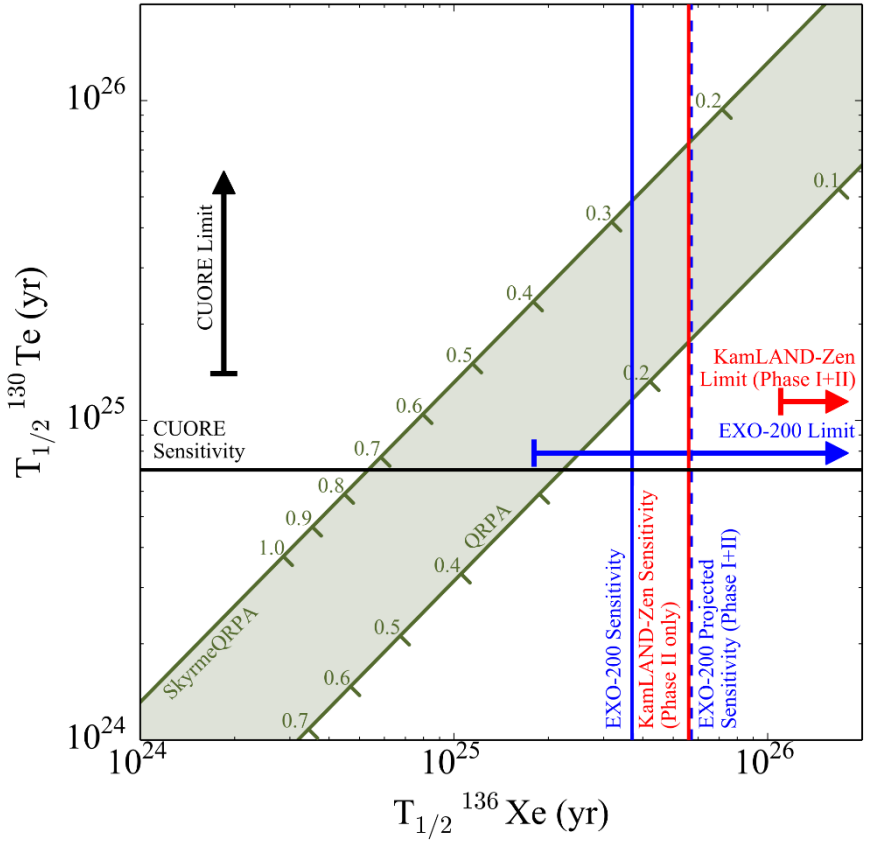
Current Progress

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



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

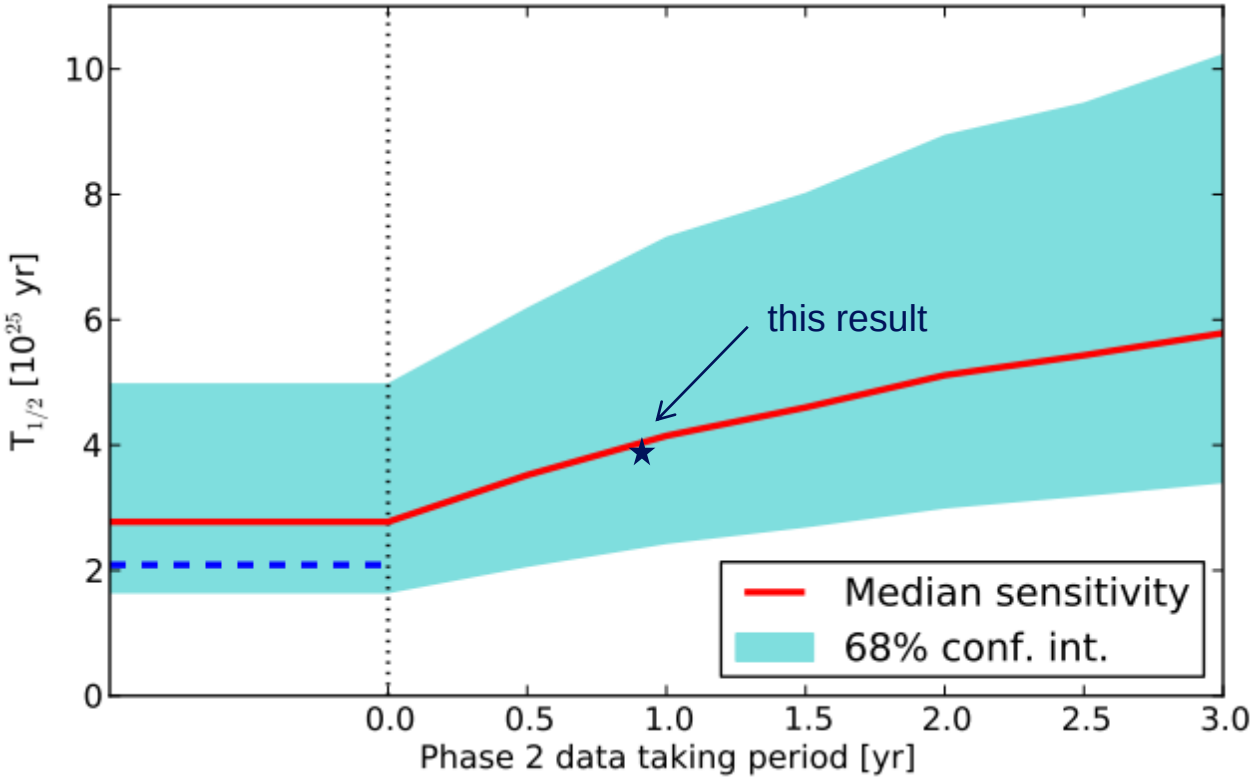
Current limits, ^{130}Te vs. ^{136}Xe:



EXO-200: this result, arXiv: 1707.08707
New Results from CUORE: talk by O. Cremonesi
Sensitivity in PRL 115 (2015) 102502

Conclusions

- Newest EXO-200 results combine Phase 1 and Phase 2 Data
  - No statistically significant 0νββ excess
  - Improved Limit: **$T_{1/2}^{0\nu\beta\beta} > 1.8\times10^{25}$ yr (90% CL)**
  - Improved Majorana Mass Limit: **$\langle m_{\beta\beta} \rangle < 147 - 398$ meV**
- Sensitivity to 0νββ improved by 2x
  - **Current Sensitivity 3.7×10^{25} yr**
- EXO-200 is Continuing to Run

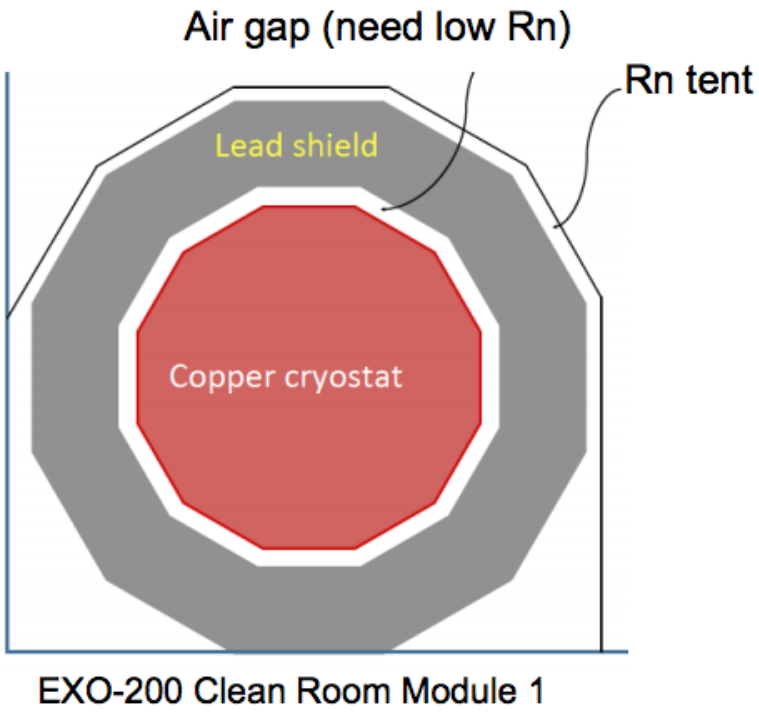


The EXO-200 Collaboration

University of Alabama, Tuscaloosa AL, USA — M Hughes, I Ostrovskiy, A Piepke, AK Soma, V Veeraraghavan
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

SLAC National Accelerator Laboratory, Menlo Park CA, USA — M Breidenbach, R Conley, T Daniels, J Davis, S Delaquis, A Johnson, LJ Kaufman, 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
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
Stanford University, Stanford CA, USA — R DeVoe, D Fudenberg, G Gratta, M Jewell, S Kravitz, G Li, A Schubert, M Weber, S Wu
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

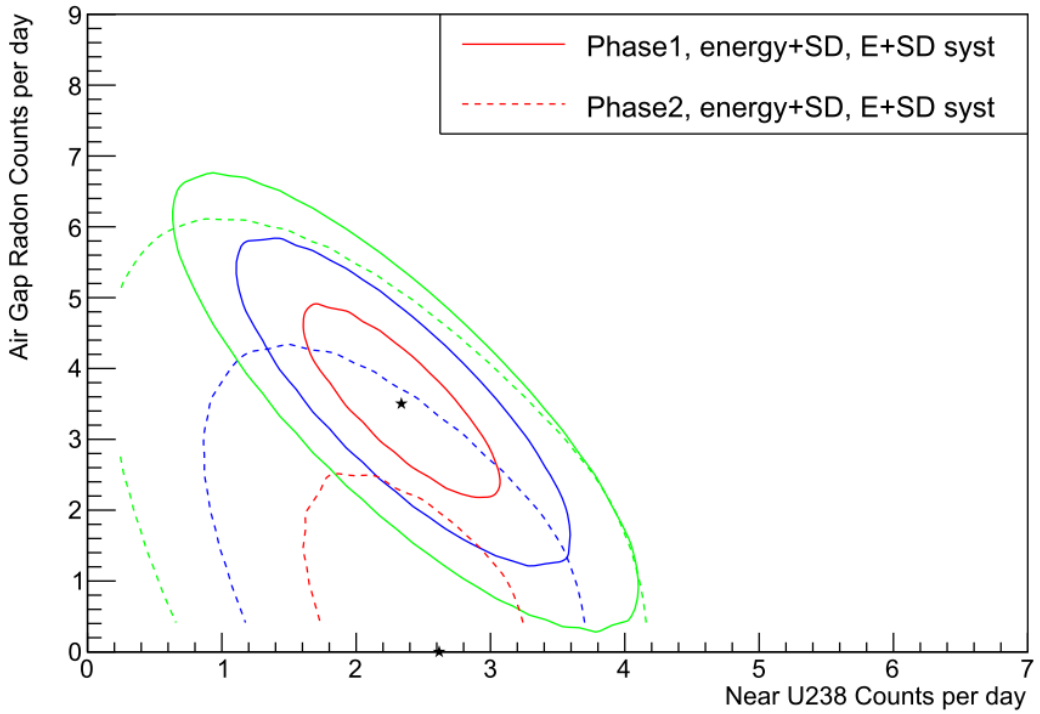
- System to suppress radon in air gap



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

De-radonator – Physics Profile

- Profile of near (vessel) and far (air gap) U components
- Small reduction between phaes within 1.2-sigma

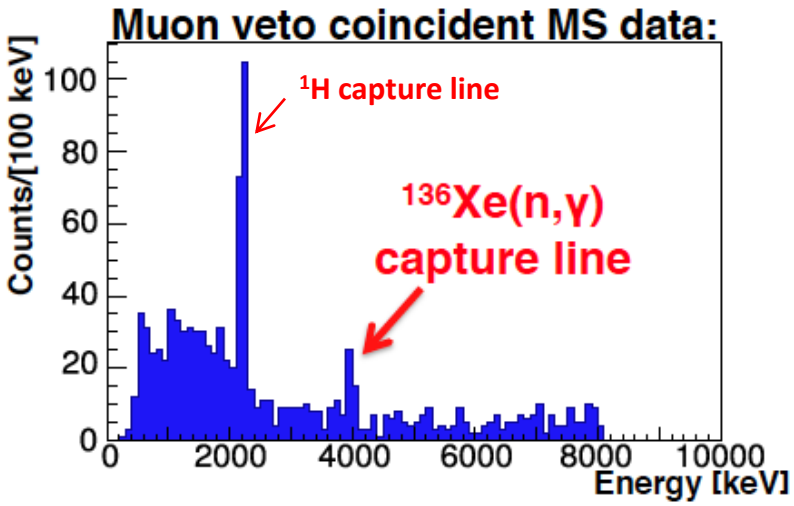


^{137}Xe β-decay Veto

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

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

JCAP ***1604***, *029 (2016)*



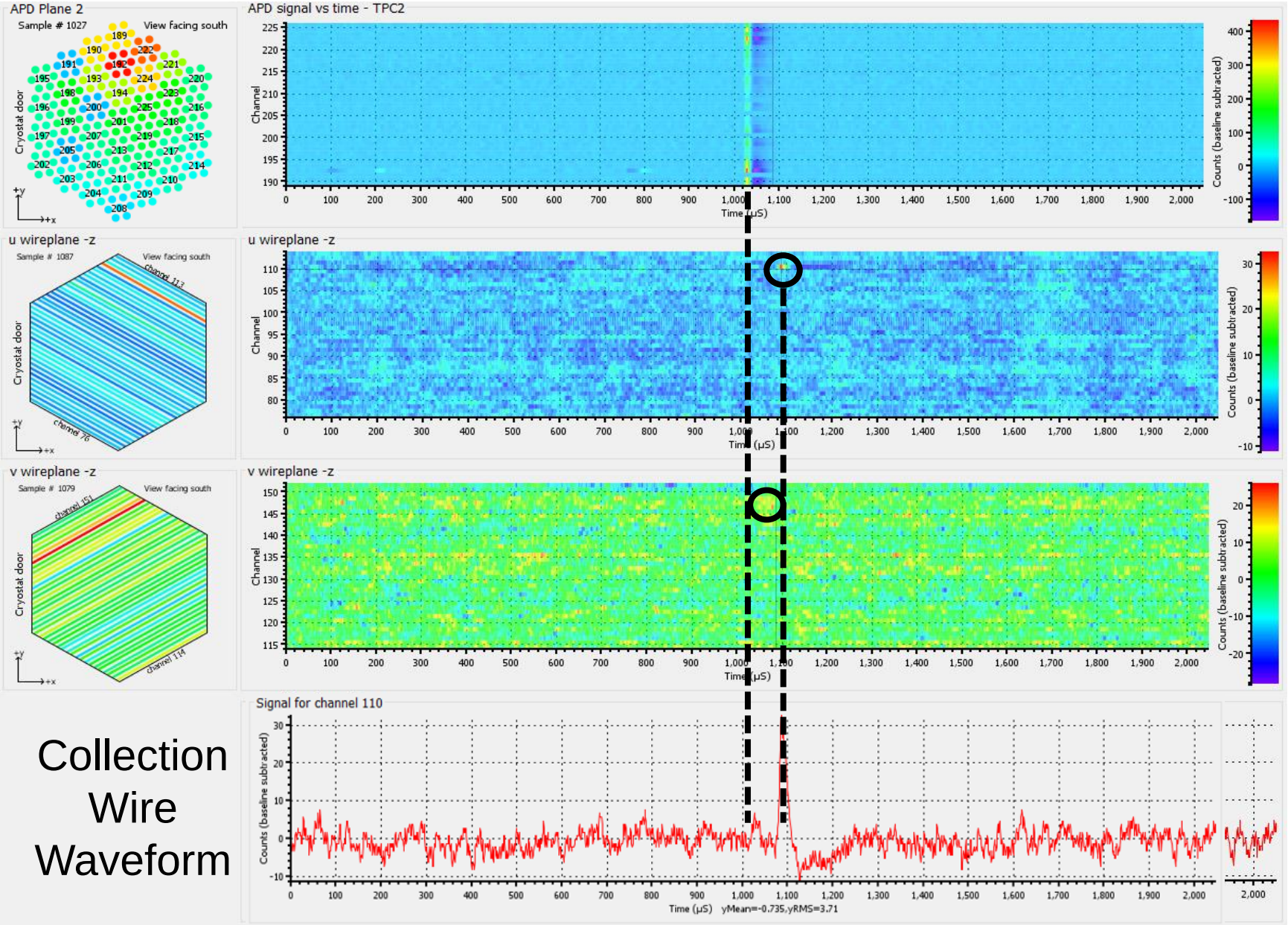
- Tag neutron capture on ^{136}Xe events using both veto panel and de-excitation prompt γs information to suppress ^{137}Xe β-decays
- Veto same TPC half of the γ signal for $5xT_{1/2}$ = 19.1 min
  - ~25% rejection
    - *Phase-I: 7.0 cts → 4.4 cts*
  - Exposure loss ~3%

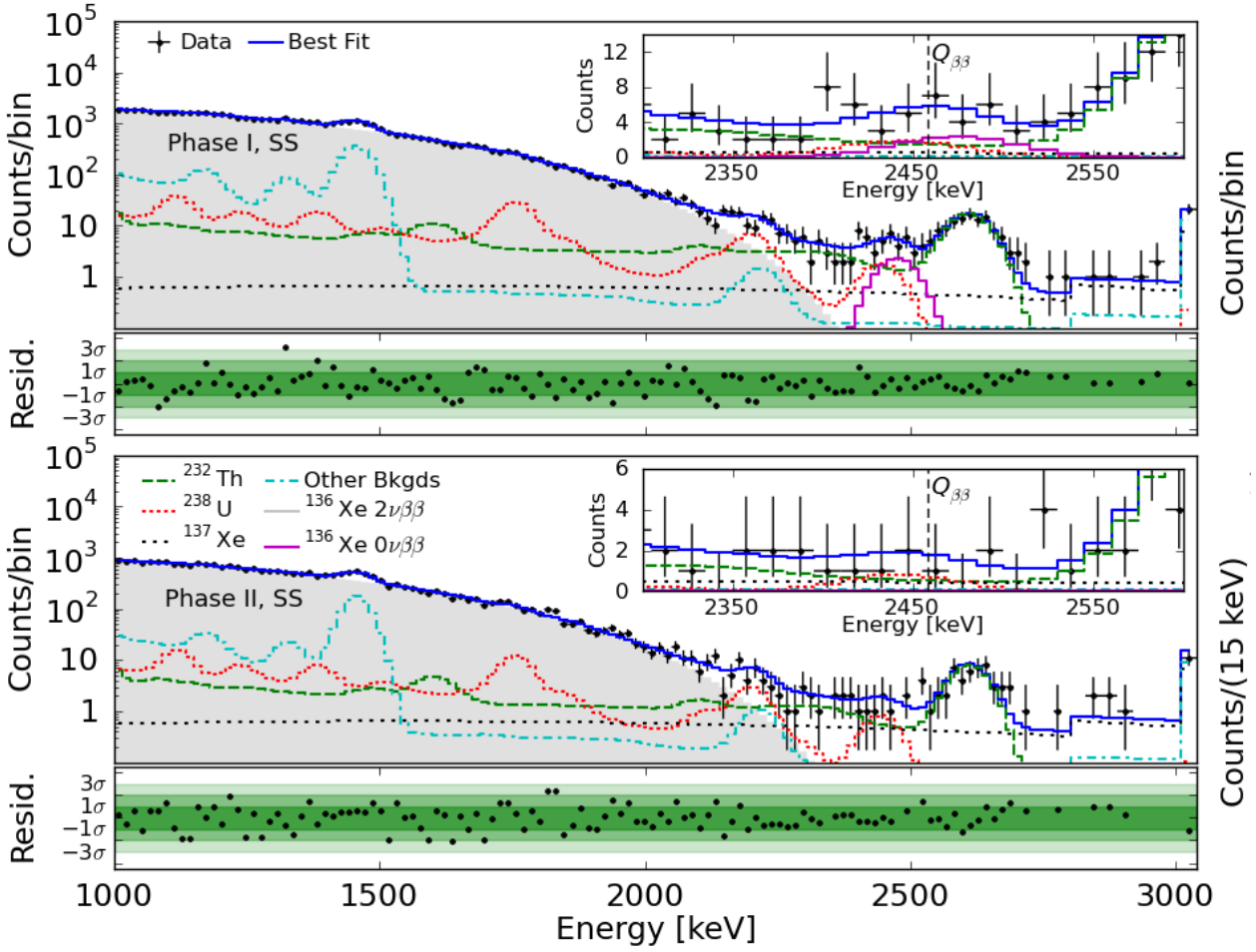
APD Plane

Collection Plane

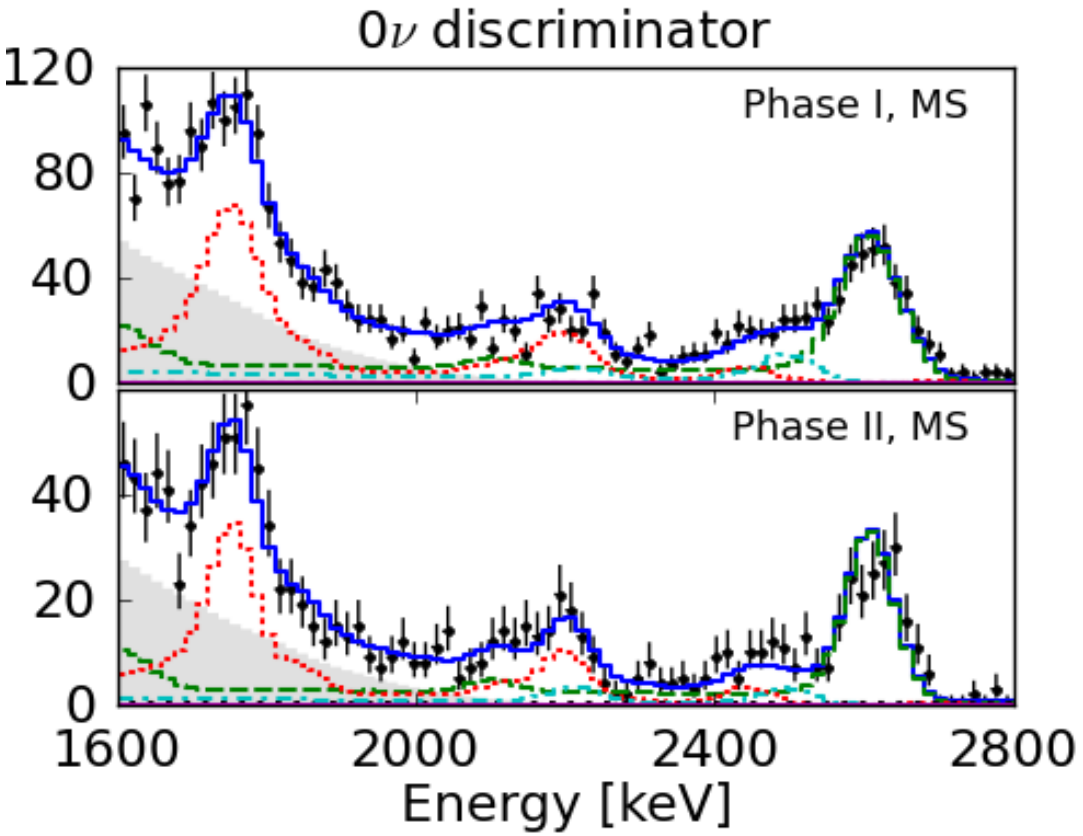
Induction Plane

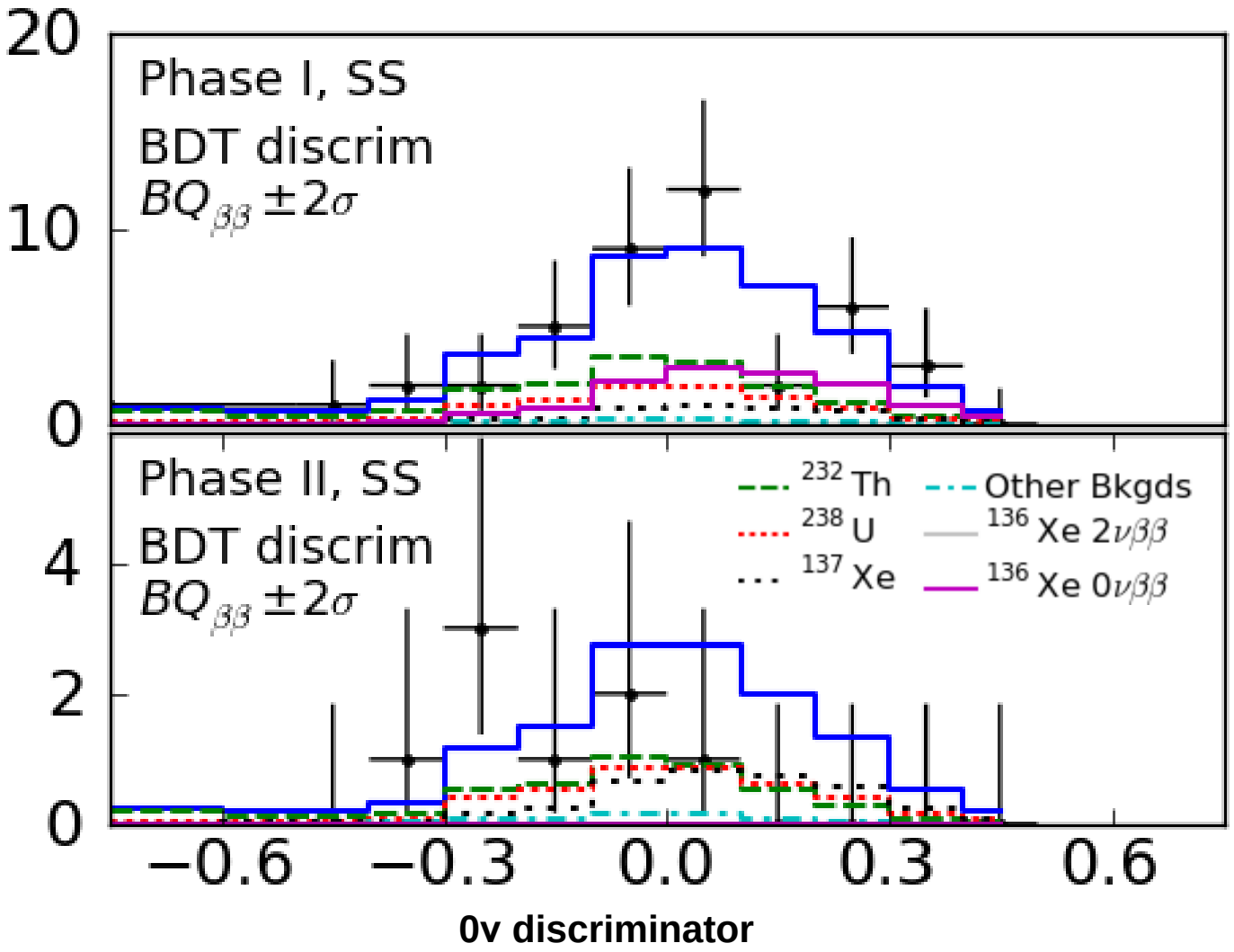
Collection Wire Waveform





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

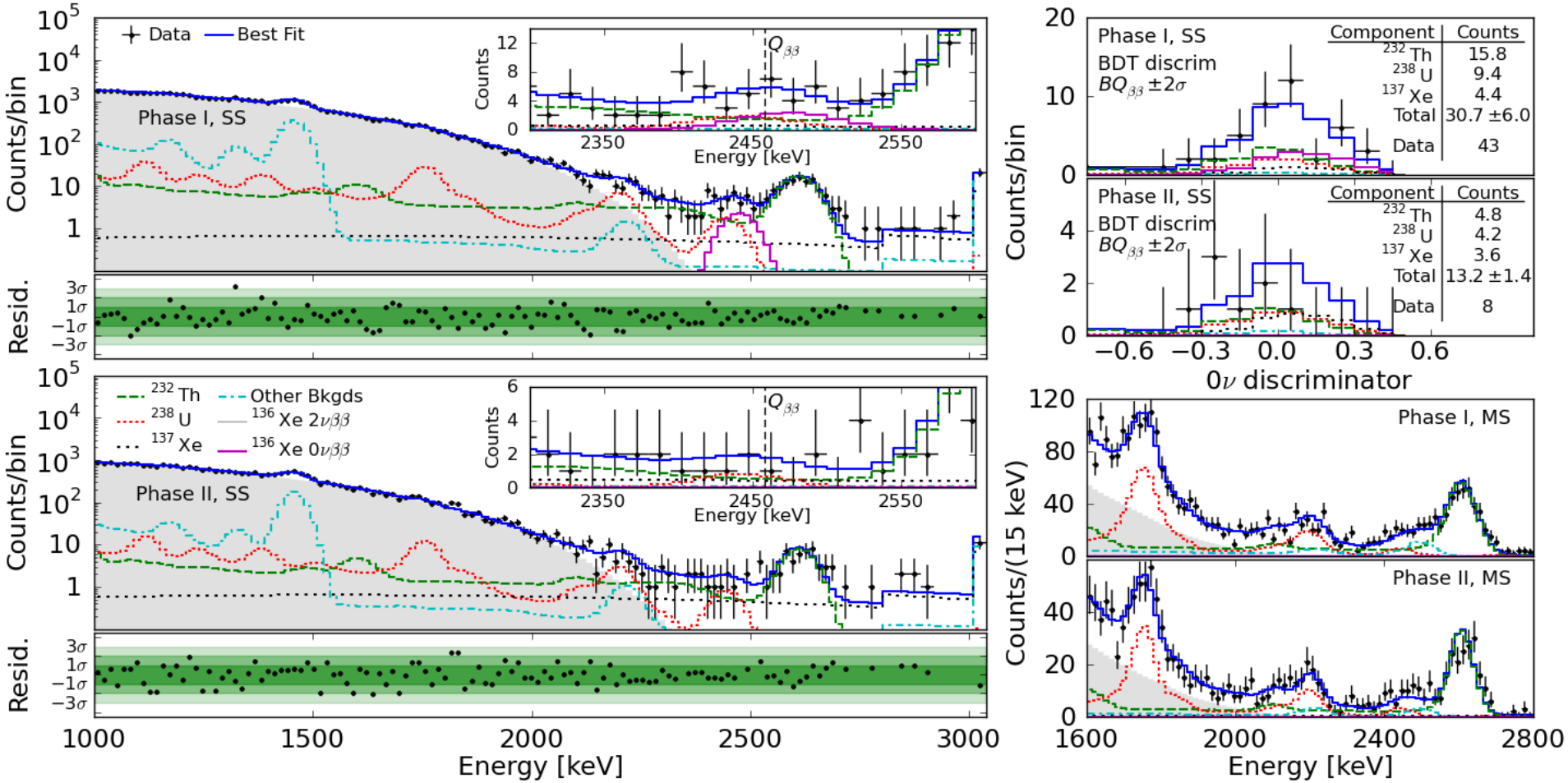




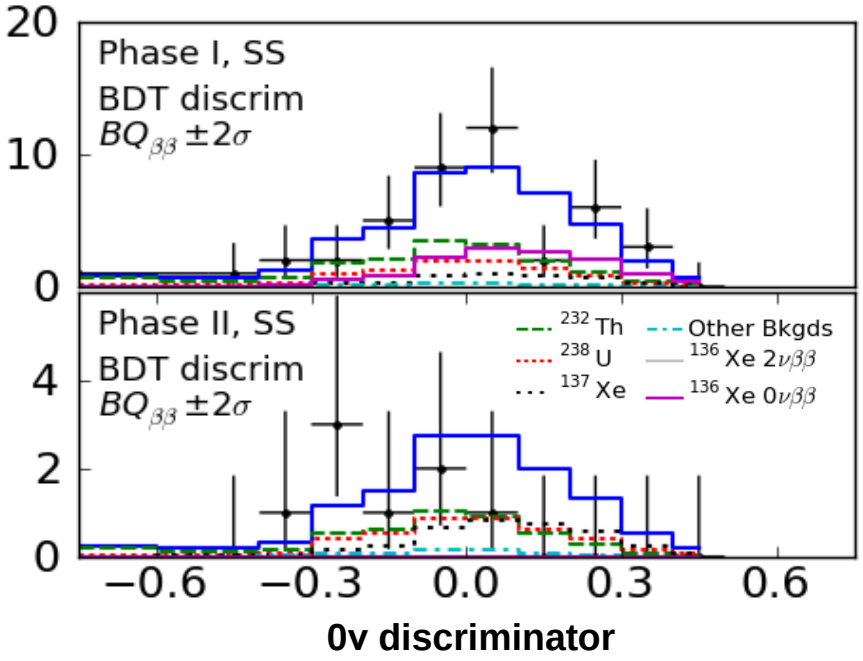
Contributions to BQ±2σ	Phase I (cts)	Phase II (cts)
^{232}Th	15.8	4.8
^{238}U	9.4	4.2
^{137}Xe	4.4	3.6
Total	**30.7±6.0**	**13.2±1.4**
Data	***43***	***8***

Fit Results

- Background Model + Data → Maximum Likelihood Fit
- No statistically significant excess: combined p-value ~1.5σ



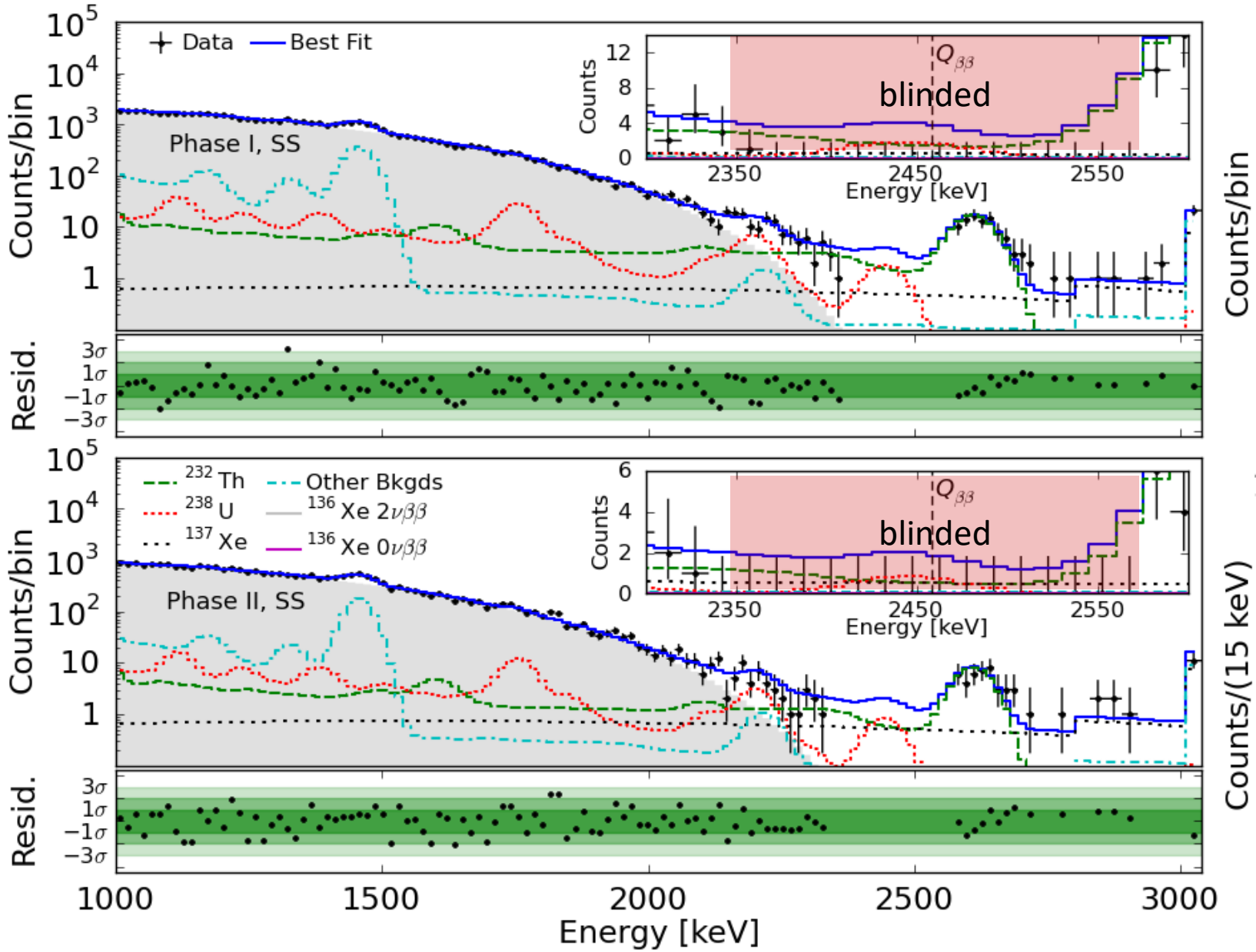
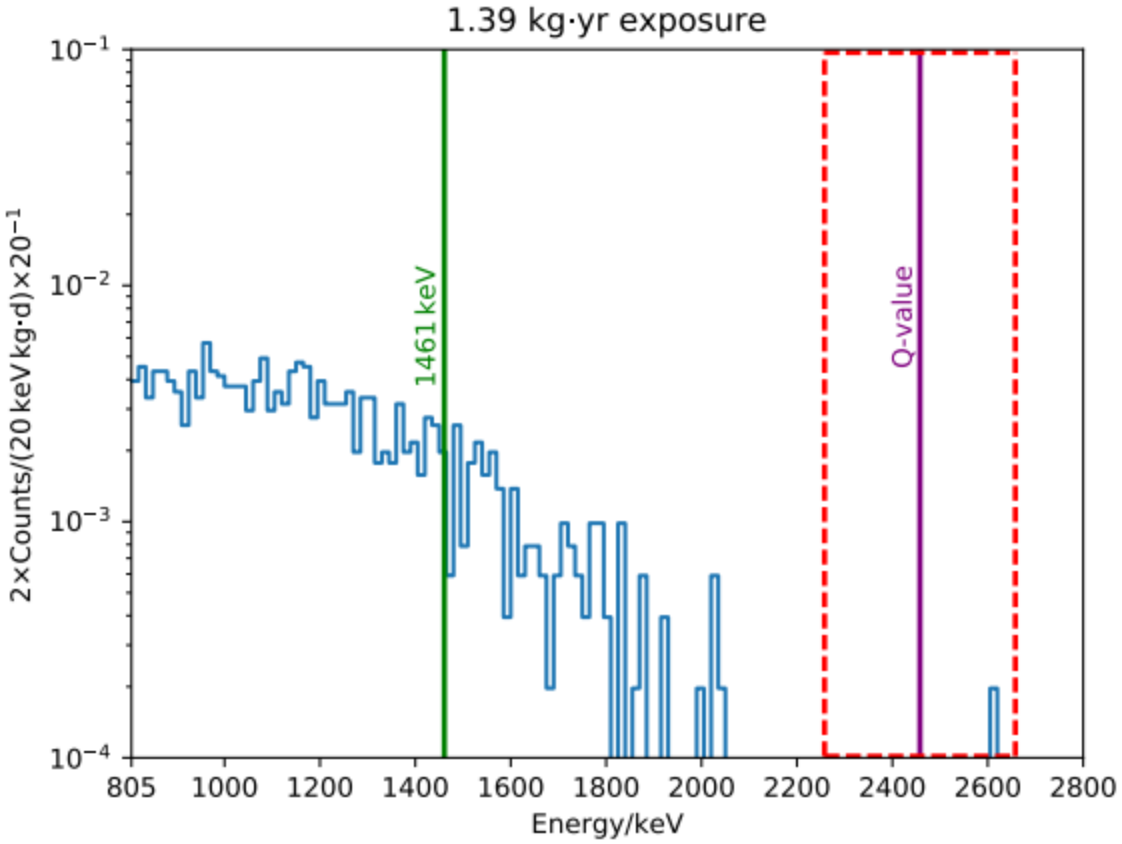
arXiv: 1707.08707



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***

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

- Component contributions
  - ^{232}Th reduction consistent with difference in resolution
  - ^{137}Xe rejection ~25%


Data
Best Fit
Phase I, SS
Counts/bin
Resid.
$Q_{\beta\beta}$
blinded
Counts
Energy [keV]
^{232}Th
^{238}U
^{137}Xe
Other Bkgds
^{136}Xe $2\nu\beta\beta$
^{136}Xe $0\nu\beta\beta$
Phase II, SS
Counts/(15 keV)
Energy [keV]

Innermost volume 1.39 kg.yr exposure