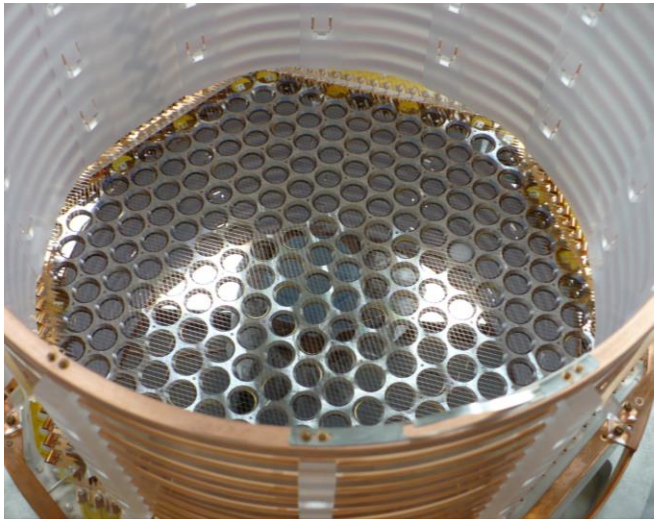
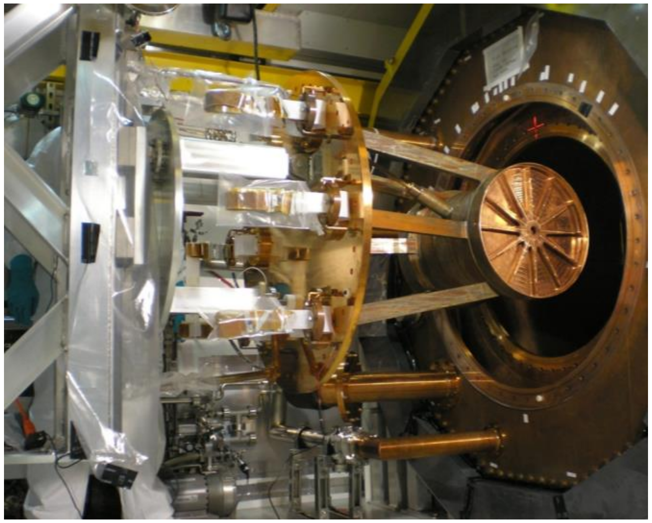
Latest EXO-200 Results

Caio Licciardi for the EXO-200 Collaboration
Carleton University
TAUP 2017, Sudbury





^{136}Xe $0\nu\beta\beta$

- $0\nu\beta\beta$ in ^{136}Xe
  - $^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}$, Q-value 2457.83±0.37 keV

M. Redshaw et al, PRL 98, 053003 (2007)

- Xenon is used both as the source and the detection medium
- Liquid xenon (LXe) time projection chamber (TPC)
  - Full 3D reconstruction of energy depositions
- Monolithic detector provides excellent background rejection capabilities
- Promising future for nEXO, tonne-scale LXe TPC
  - nEXO: a tonne-scale next-generation double-beta decay experiment, R. MacLellan
  - Progress in Barium tagging at the single atom/ion level for nEXO, C. Chambers
  - Results of nEXO detector development, T. Brunner
  - Background modeling for the nEXO neutrinoless double beta decay experiment, J. Orrell (poster)
  - The nEXO radioassay program, R. MacLellan (poster)

- *This talk: new results from EXO-200!*

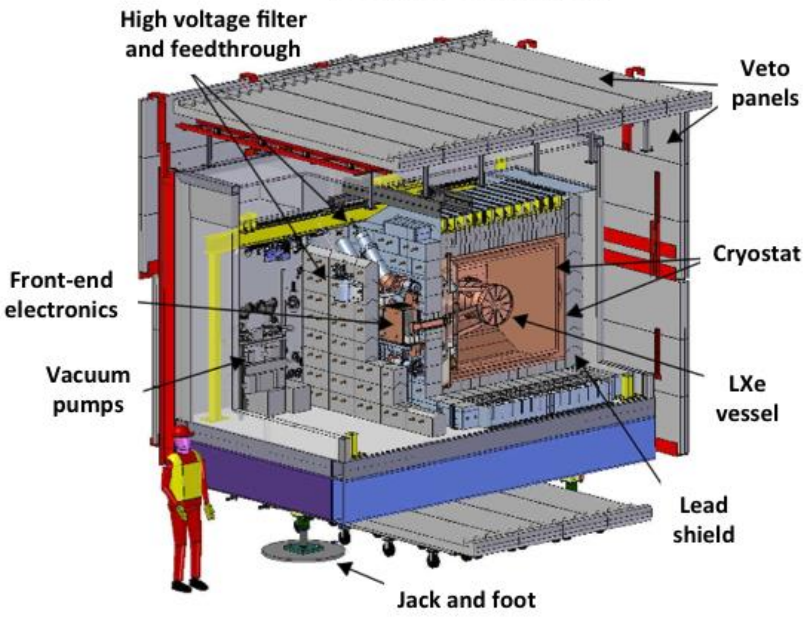
University of Alabama, Tuscaloosa AL, USA — M Hughes, I Ostrovskiy, A Piepke, AK Soma, V Veeraraghavan
University of Bern, Switzerland — J-L Vuilleumier
University of California, Irvine, Irvine CA, USA — M Moe
California Institute of Technology, Pasadena CA, USA — P Vogel
Carleton University, Ottawa 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

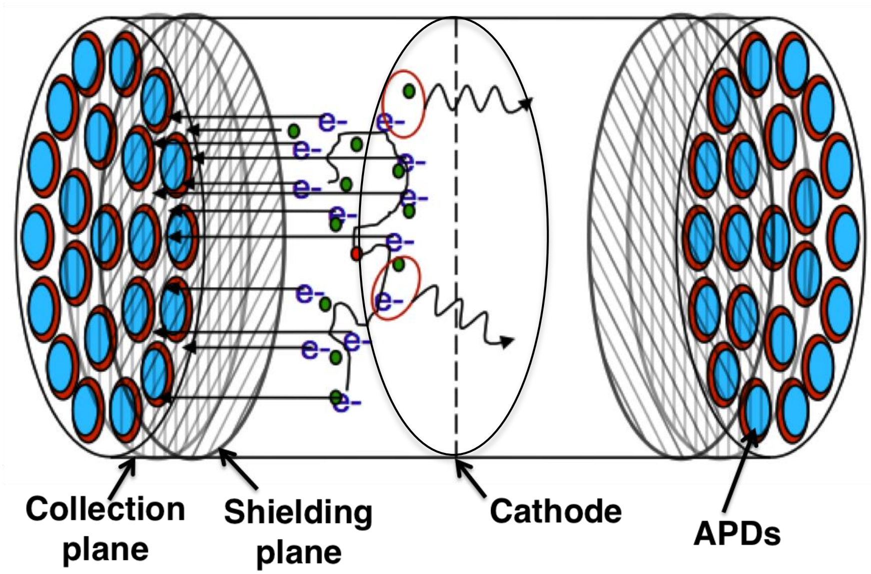
SLAC National Accelerator Laboratory, Menlo Park CA, USA — M Breidenbach, R Conley, T Daniels, J Davis, S Delaquis, A Johnson, LJ Kaufman, B Mong, A Odian, CY Prescott, PC Rowson, JJ Russell, K Skarpaas, A Waite, M Wittgen
University of South Dakota, Vermillion SD, USA — J Daughhetee, R MacLellan
Friedrich-Alexander-University 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

TPC

- EXO-200 consists of a radiopure TPC filled with enriched LXe (80.6%)
- Located at Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM, USA
- High-voltage applied between cathode and anodes (opposite ends)
- Two measurements of energy deposited in event
  - Scintillation light (178 nm), by large avalanche photo-diodes (APDs)
  - Ionization charge, by 2 wire grids (induction and collection)

Detector schematic:



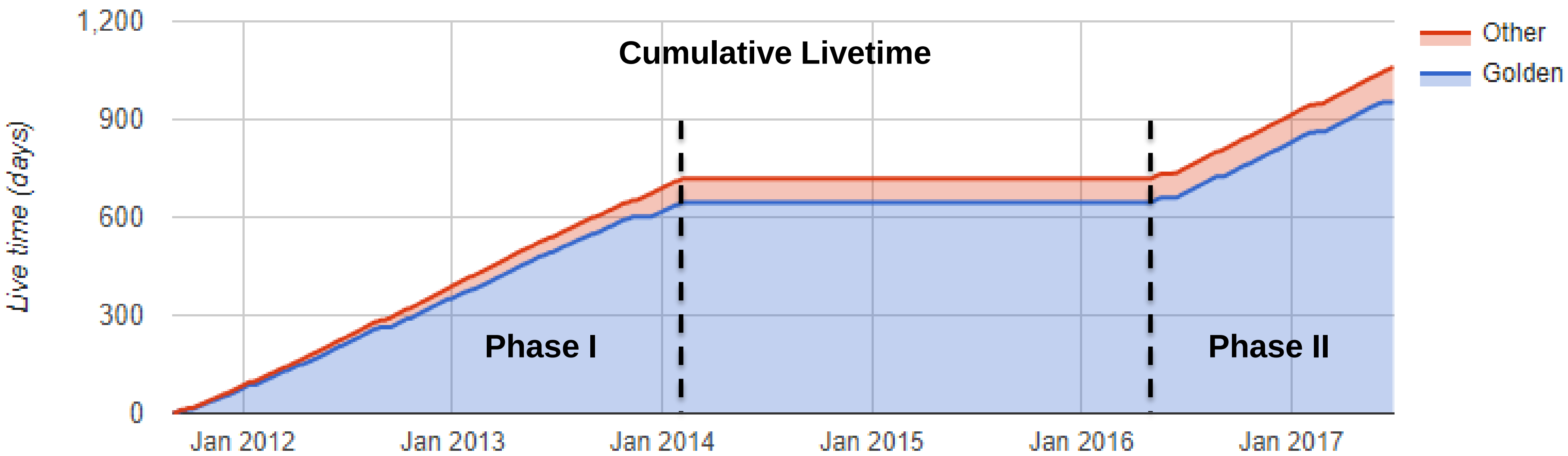


Phase-I

- 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)

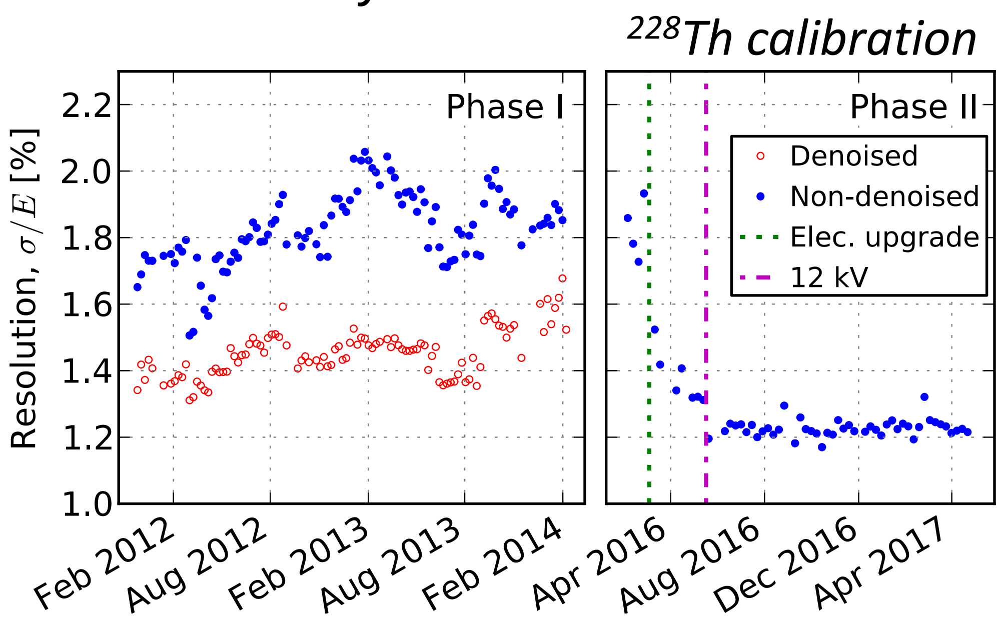
Phase-II

- 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: this talk!

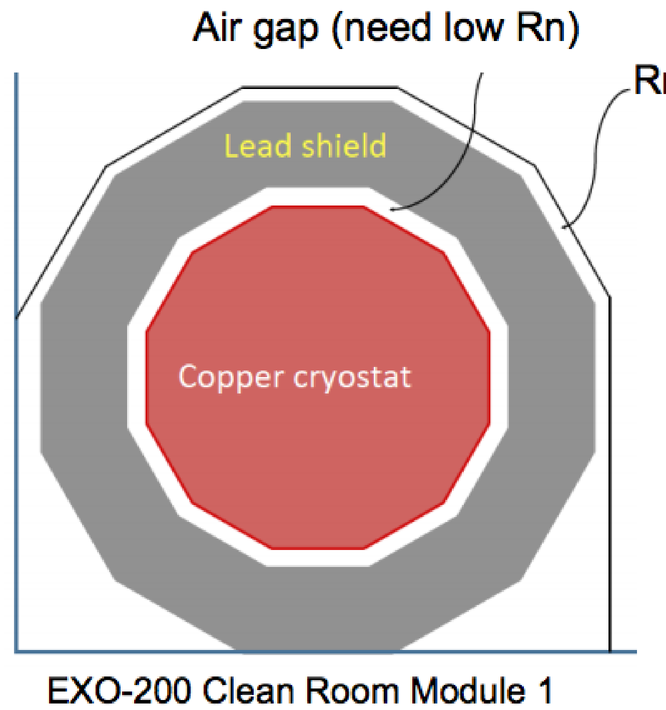


Detector Upgrades

- Front end readout electronics
  - *Reduce APD read-out noise*
- Increase of HV
  - *-8kV → -12 kV*
- Effect in energy resolution:
  - Phase-I: σ/E(Q) = 1.38%
  - Phase-II: σ/E(Q) = 1.23%, steady



- System to suppress radon in air gap

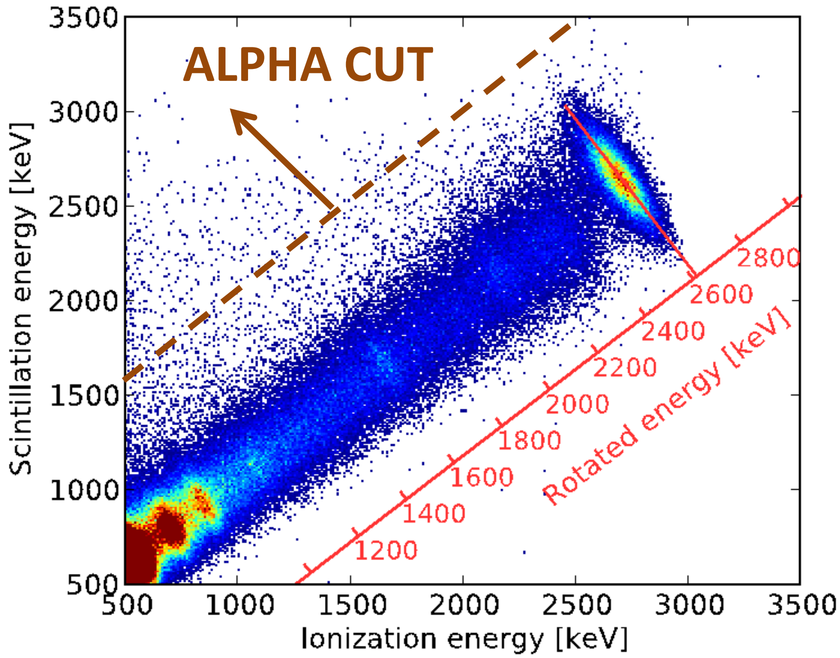


- Direct air sampling shows radon levels reduced in the gap by >10x

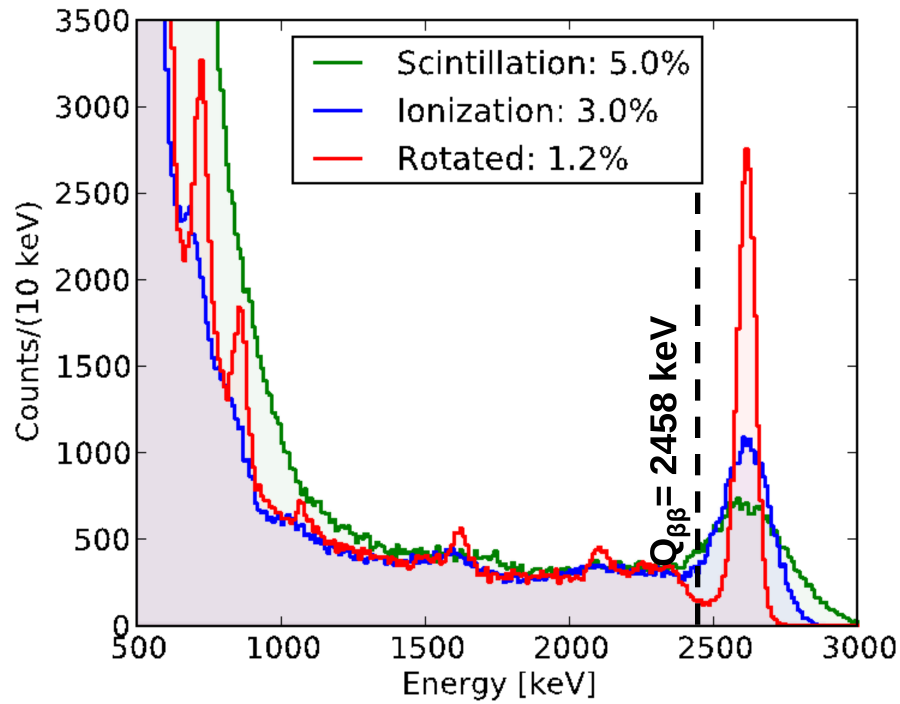
Energy

- Rejection of α particles (vs β/γ) using light/charge ratio
- Using anti-correlation between charge and scintillation response
  - "Rotated" energy provides optimal resolution in the energy of interest

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

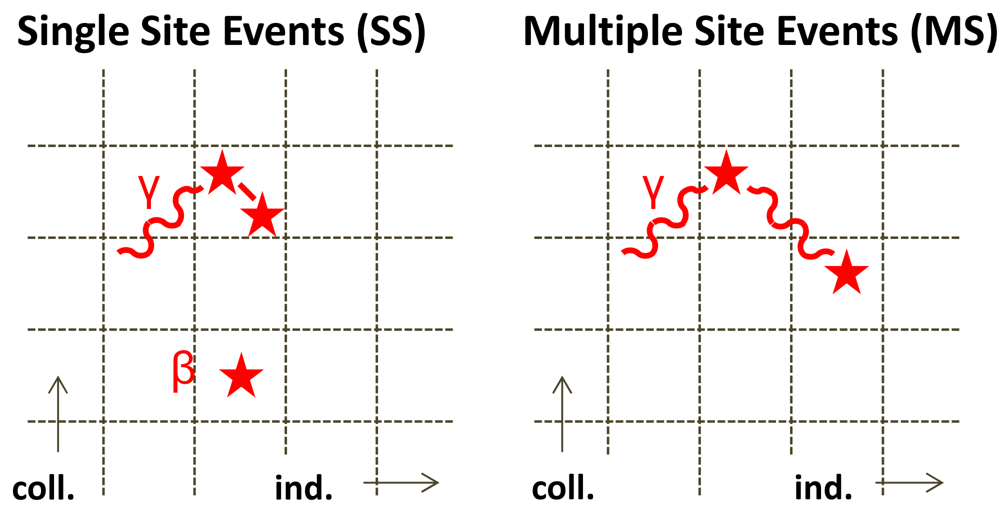


Reconstructed energy, ^{228}Th calibration:

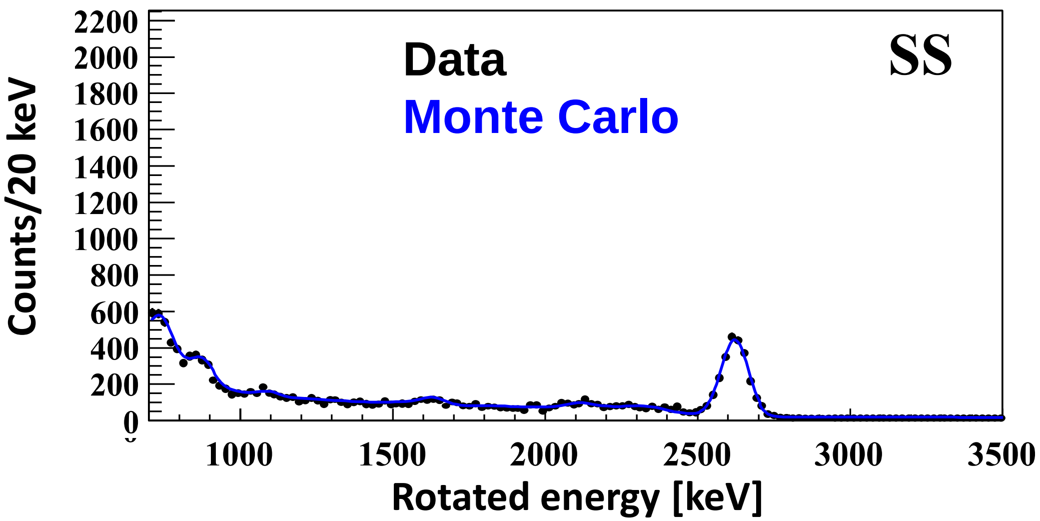


Position Discrimination

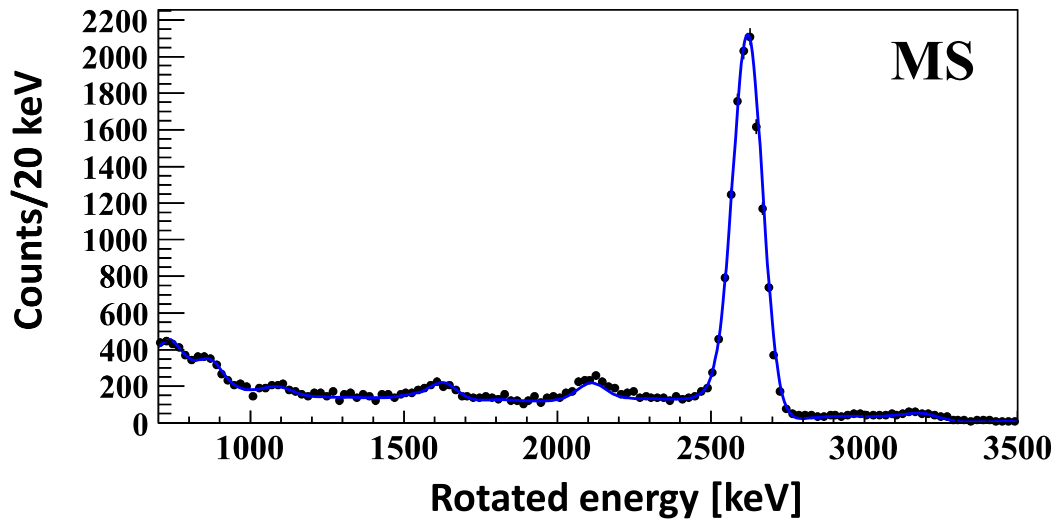
- ββ deposits energy at single location
- Channel pitch is 9 mm in X/Y, Z (time) resolution is ~6 mm
- SS fraction is ~20% in the energy region of interest



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



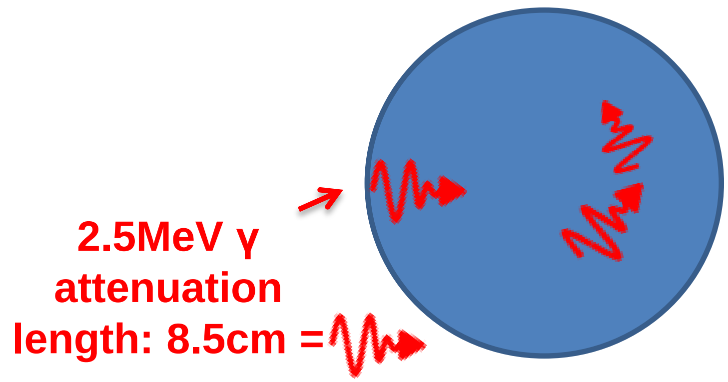
Energy spectrum, ^{228}Th calibration data, MS:



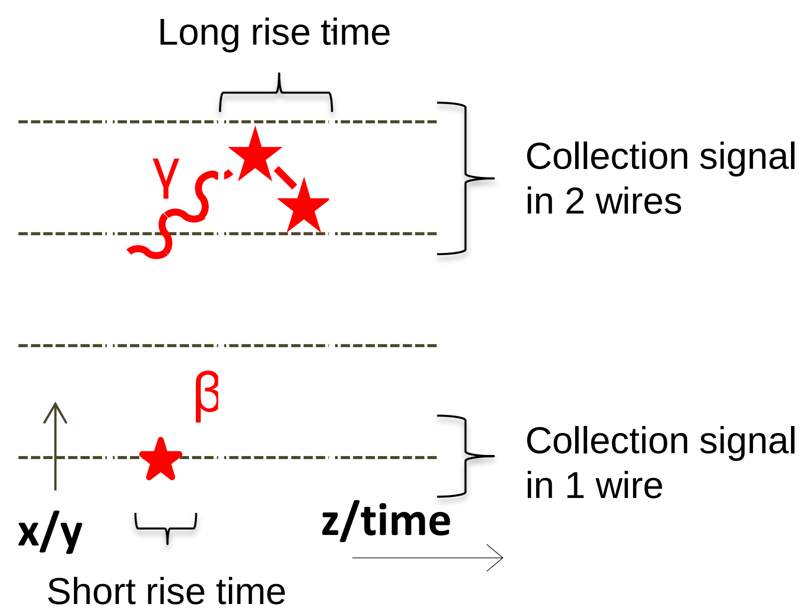
Improved γ-background Rejection

- Additional discrimination in SS using *spatial distribution* and *cluster size*

LXe self-shielding:



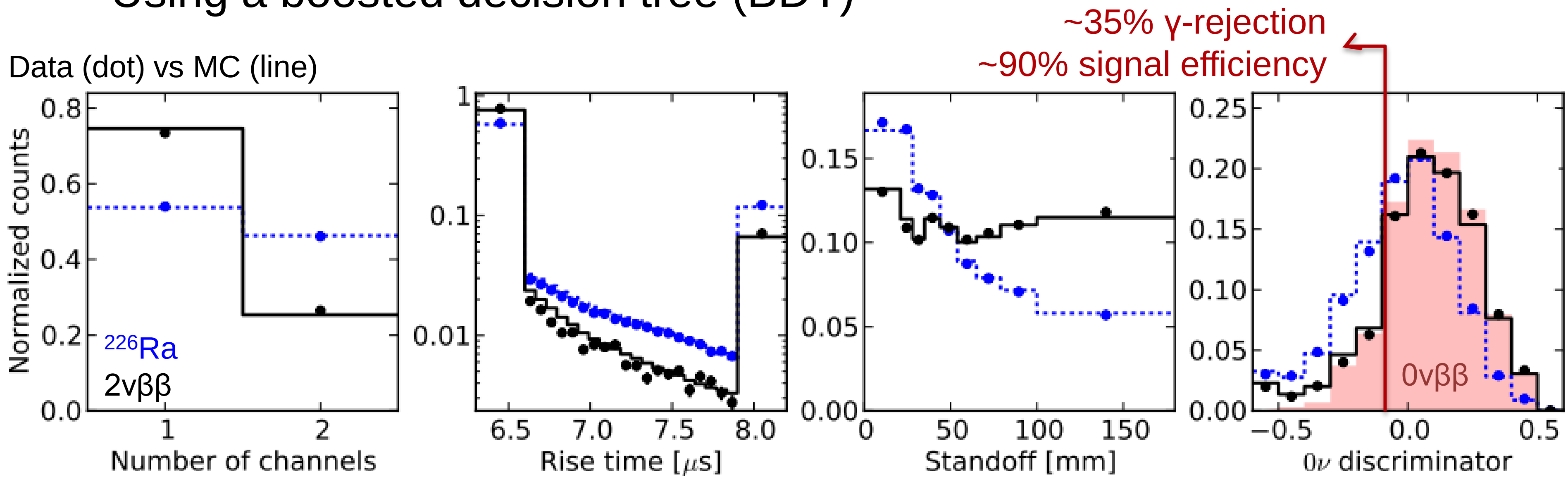
- Entering γ-rays rate is exponentially reduced by LXe self-shielding, provides independent measurement of γ-backgrounds
  - standoff-distance



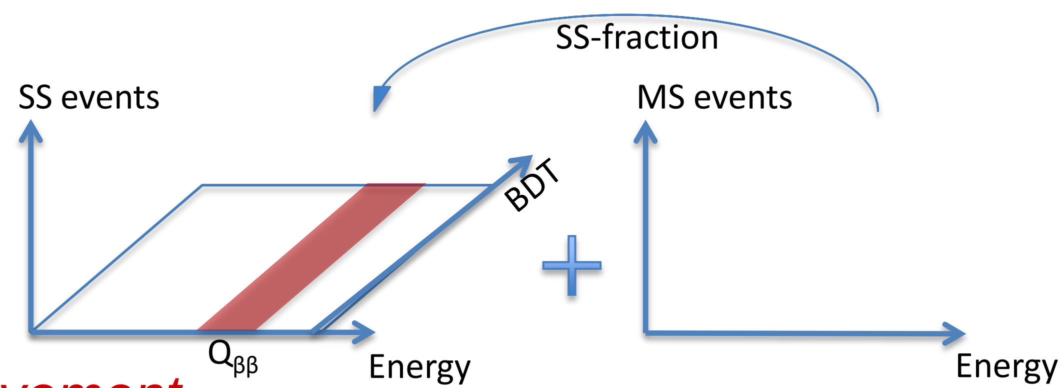
- Size of individual cluster estimated from:
  - pulse rise time (longitudinal direction)
  - number of wires with collection signal (transverse)

Optimal 0νββ Discrimination

- Optimize SS discriminators into a more powerful one
  - Using a boosted decision tree (BDT)



- Fitting 0νββ discriminators
  - Energy
  - SS/MS
  - *BDT → ~15% sensitivity improvement*

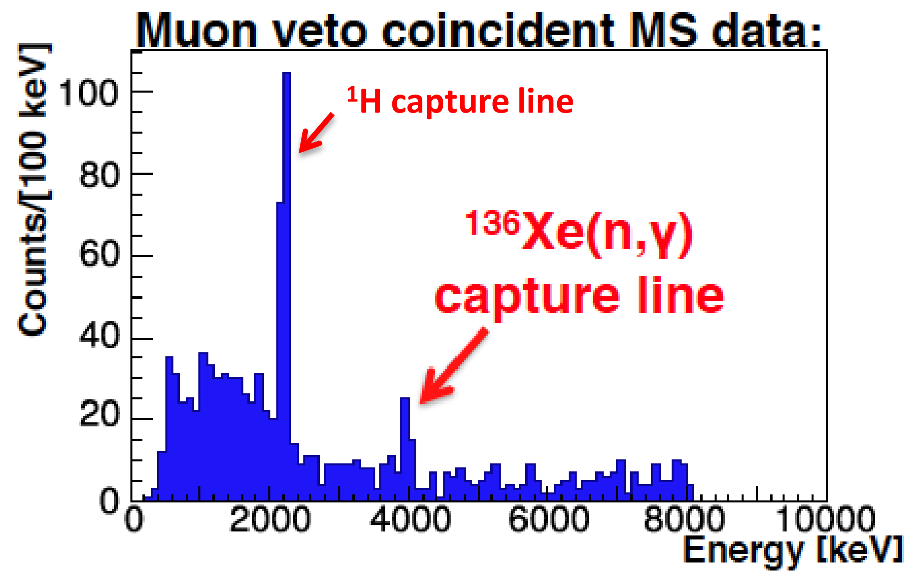


^{137}Xe β-decay Veto

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

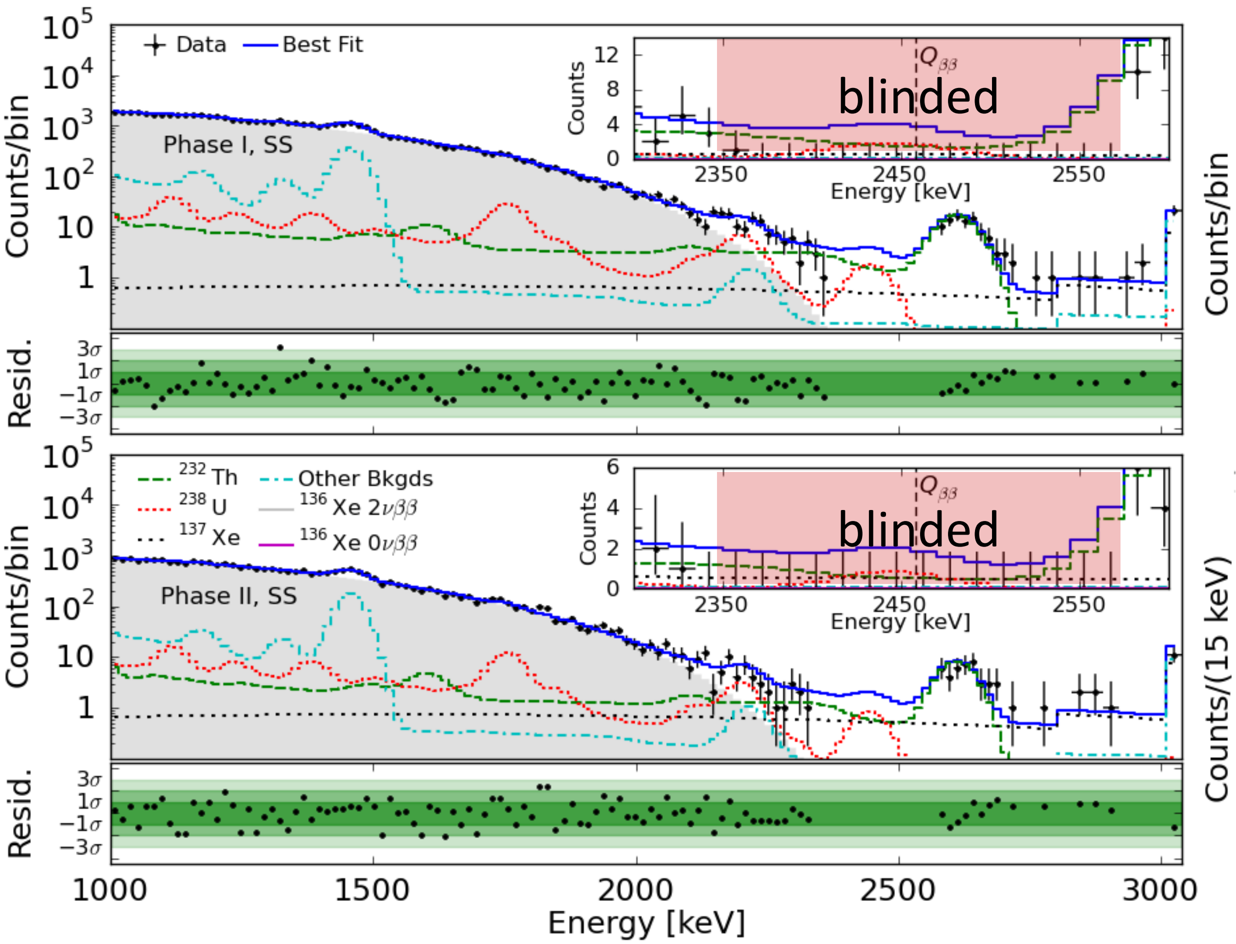
JCAP ***1604****, 029 (2016)*



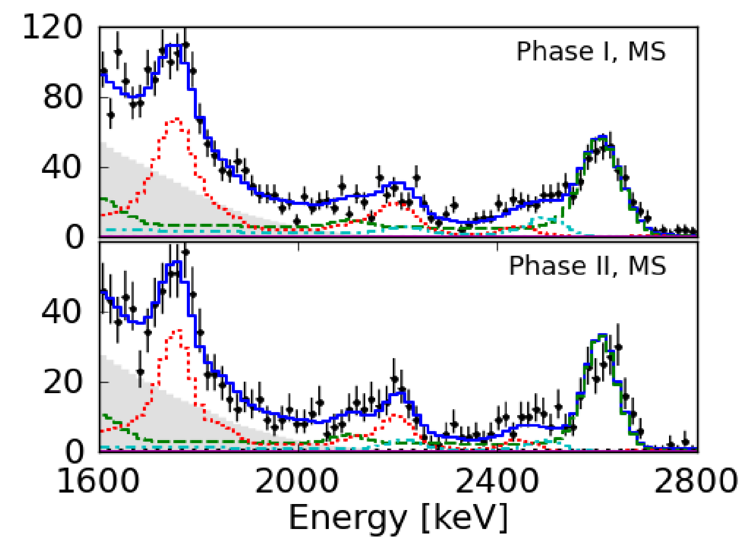
- Tag neutron capture on ^{136}Xe events using both veto panel and de-excitation prompt γs information to suppress ^{137}Xe β-decays
- Veto same TPC half of the γ signal for $5xT_{1/2}$ = 19.1 min
  - ~25% rejection
    - *Phase-I: 7.0 cts → 4.4 cts*
  - Exposure loss ~3%

Analysis Approach

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

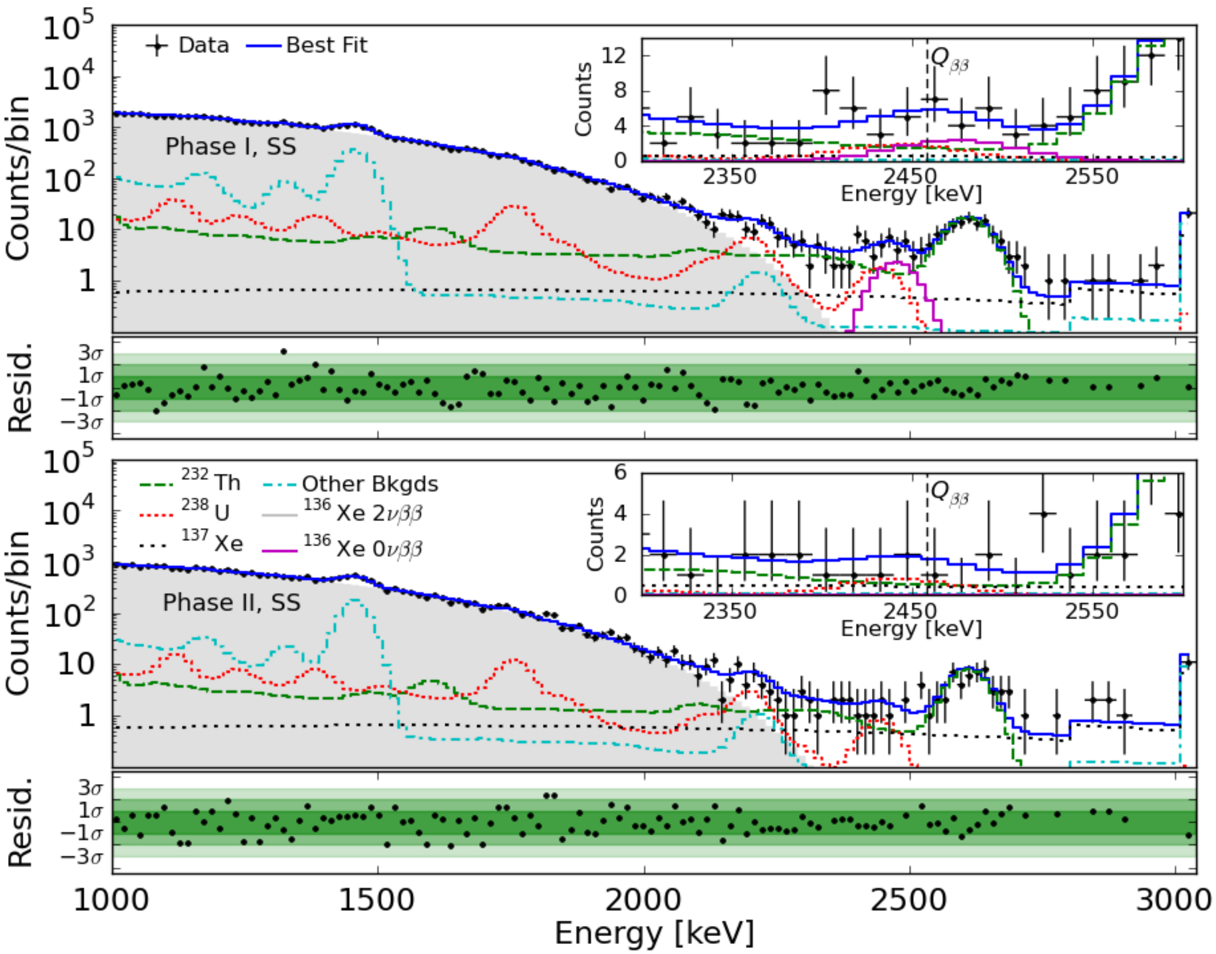


Systematics	Phase I (%)	Phase II (%)
Detection efficiency	82.4 ± 3.0	80.8 ± 2.9
Shape differences	±6.2	±6.2
SS fraction	±5.0	±8.8



Results

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



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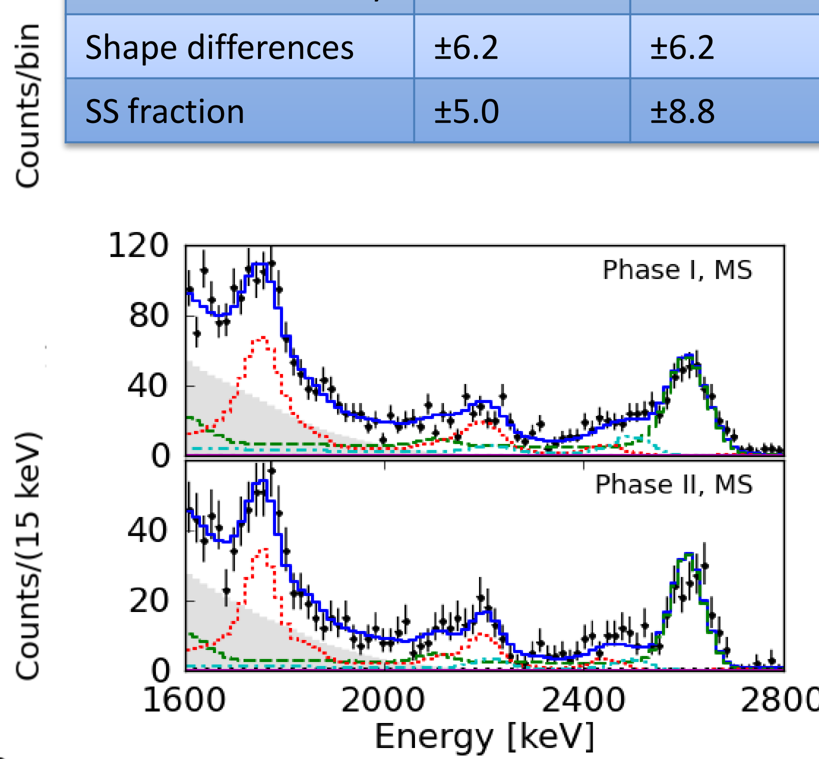
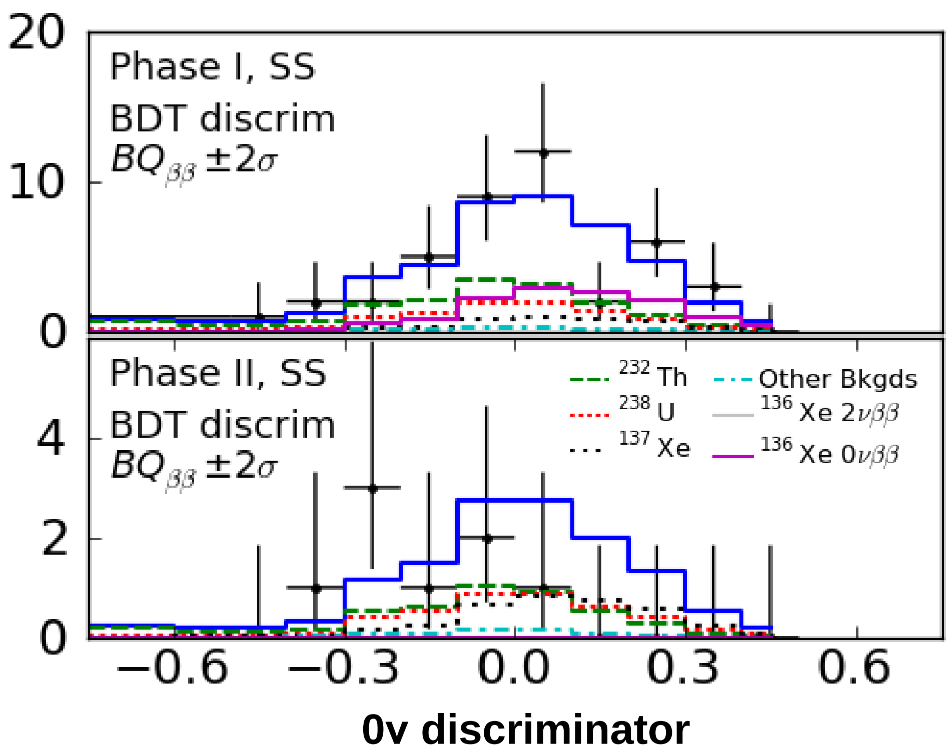


- No statistically significant excess: combined p-value ~1.5σ

Energy of Interest



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%

Sensitivity & Limits

- Combined analysis:
  - Total exposure = 177.6 kg.yr

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.)

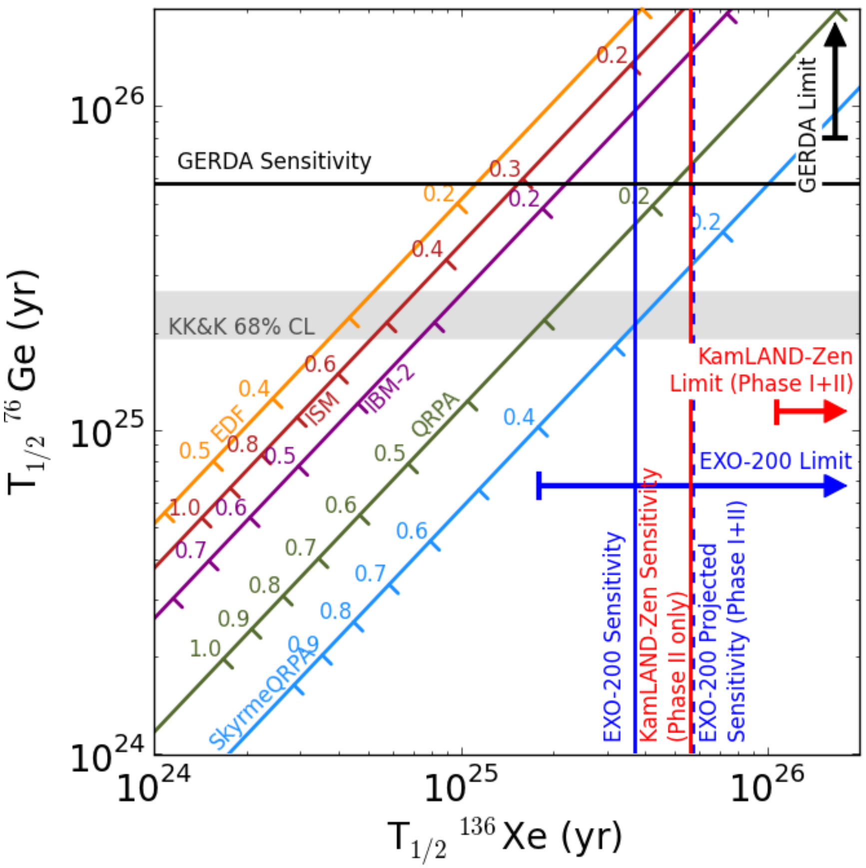
arXiv: 1707.08707

- Individual phase limits

	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

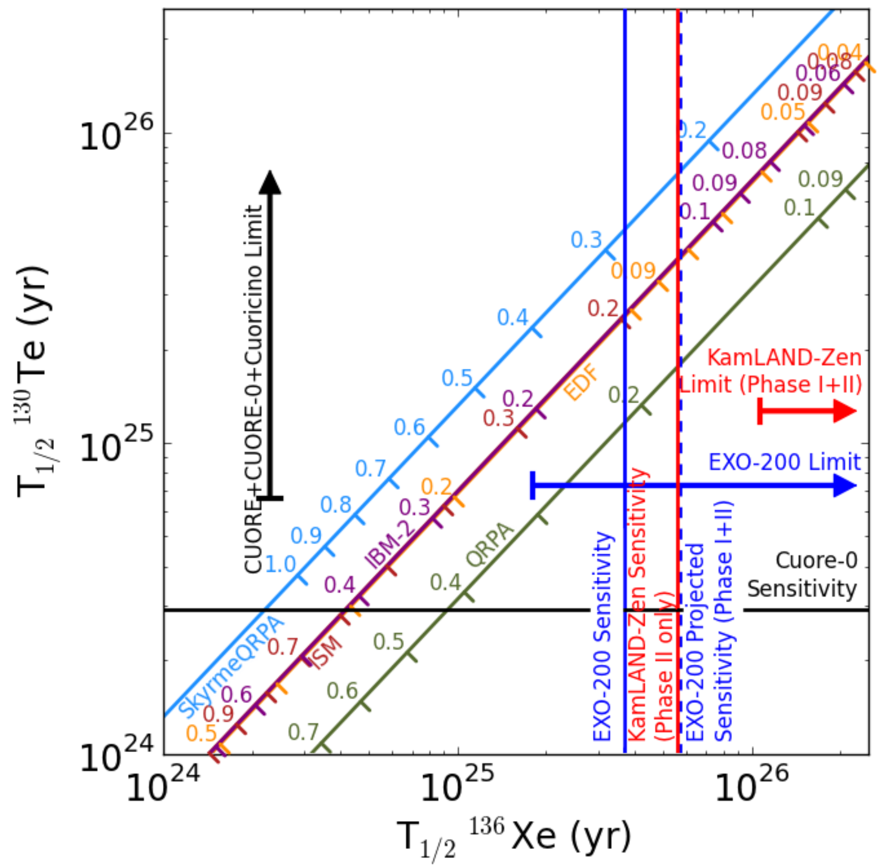
Outlook

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*

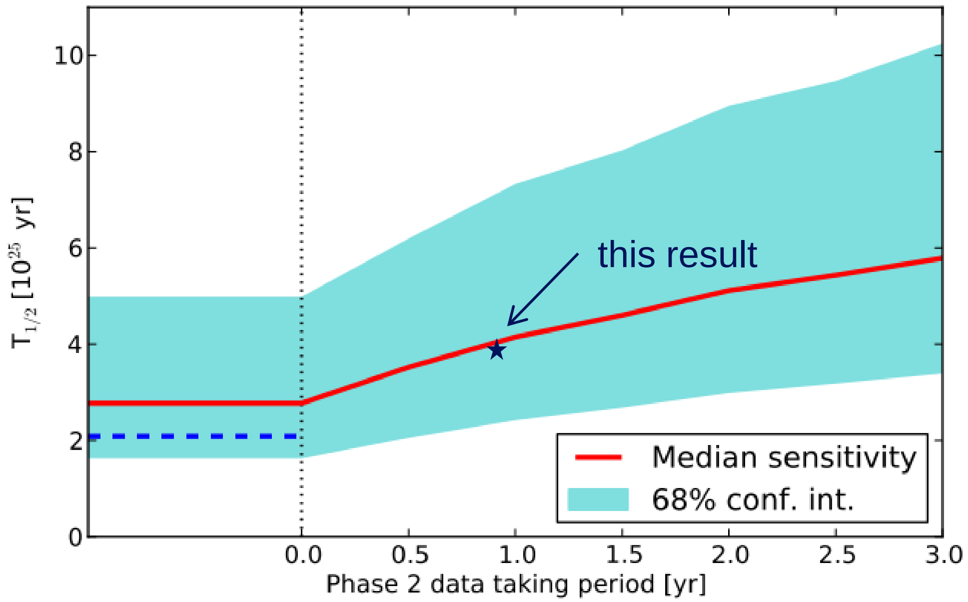
Current limits, ^{130}Te vs. ^{136}Xe:



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

Summary

- New EXO-200 data results show no statistically significant 0νββ excess
  - $T_{1/2}^{0\nu\beta\beta}$ > 1.8x10^{25} yr (90% CL)
  - $\langle m_{\beta\beta} \rangle$ < 147 – 398 meV
- EXO-200 sensitivity to 0νββ of 3.7x10^{25} yr, improved by 2x



- On-going EXO-200 Phase-II running will continue to improve sensitivity

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Yale University, New Haven CT, USA — Z Li, D Moore, Q Xia

Thank you!

NMEs

For phase space I take the values of Kotila and Iachello (PRC85,034316)
24.81×10^{-15} for Ca48, 2.363×10^{-15} (Ge), 14.22×10^{-15} (Te) and 14.58×10^{-15} for Xe136.

To convert it into the formula $1/T_{1/2} = G^{0nu} |M|^2 <m_{nu}>^2$ where $<m_{nu}>$ is in eV one needs to divide this by m_e^2 and multiply by g_A^4. This gives $(G^{0nu})^{-1} = 4.05 \times 10^{24}$ (Ca), 4.24×10^{25} (Ge), 7.056×10^{24}(Te) and 6.88×10^{24}(Xe).

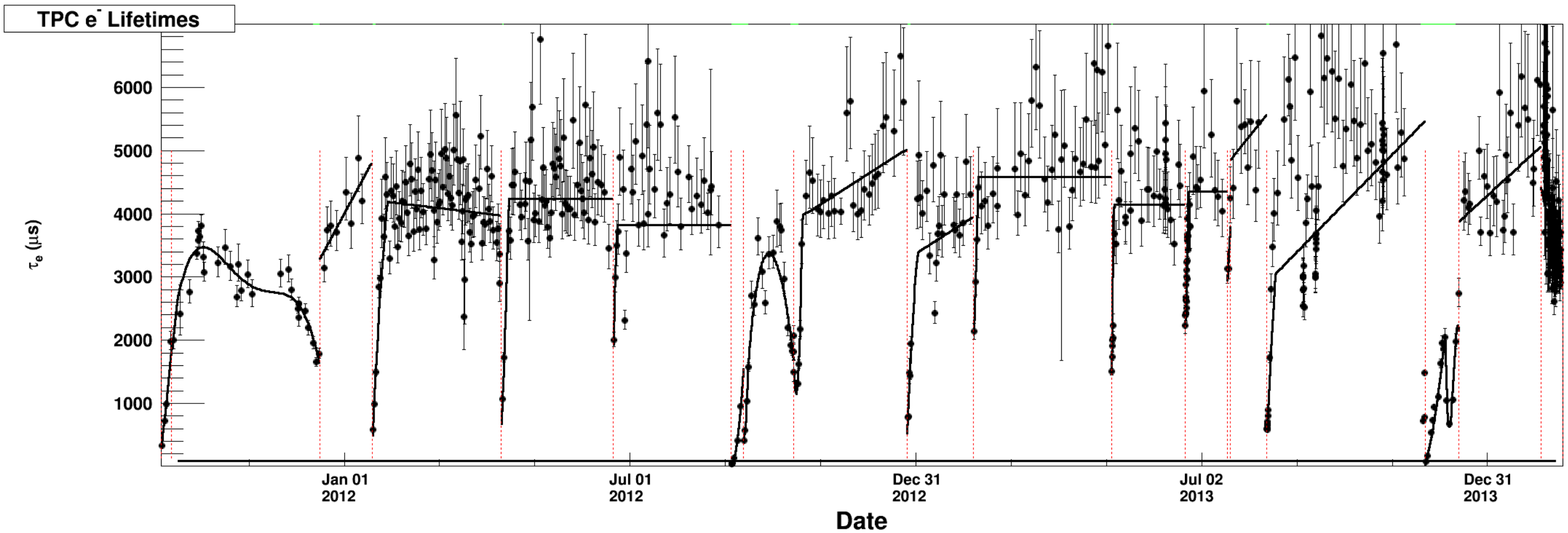
For matrix elements I take the following sources:
IBM, Barnea, Kotila, Iachello, PRC87, 014315: 2.33 (Ca), 6.07(Ge), 4.54(Te), 3.73(Xe)
EDF, Rodriguez, Martinez-Pinedo, PRL105, 252503: 2.37(Ca), 4.60(Ge), 5.13(Te),4.20(Xe)
QRPA, Engel, Simkovic, Vogel, PRC89, 064308 : 0.61(Ca), 4.64(Ge), 3.65(Te),2.02(Xe)
NSM, Menendez et al., NPA818, 139: 0.85(Ca), 2.81(Ge), 2.65(Te), 2.19(Xe)

$<m_{nu}> = 1/M_{Xe} \times 1/(G_{Xe})^{1/2} \times 1/(T_{1/2}^{Xe})^{1/2}$
where $1/G_{Xe}$ and $T_{1/2}$ are in 10^{24} units and $<m_{nu}>$ is in eV

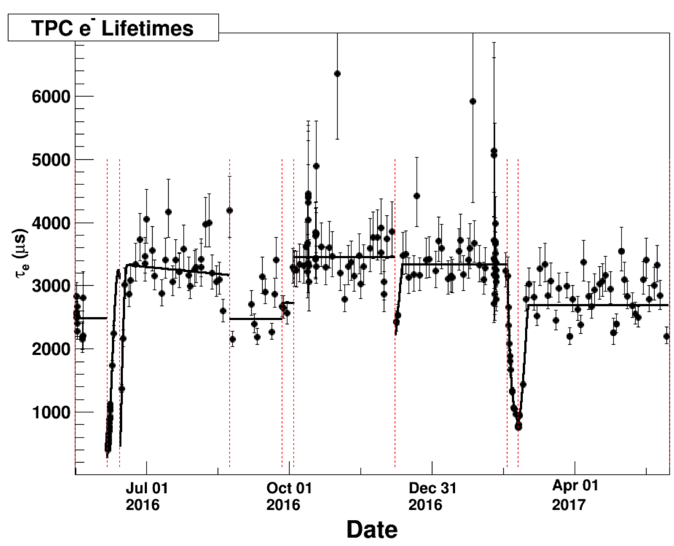
Thus $<m_{nu}>$ (eV)$\times(T_{1/2}^{Xe})^{1/2}$ = 0.703(IBM), 0.625(EDF), 1.29 (QRPA), 1.20(NSM)

Purity

- Phase I



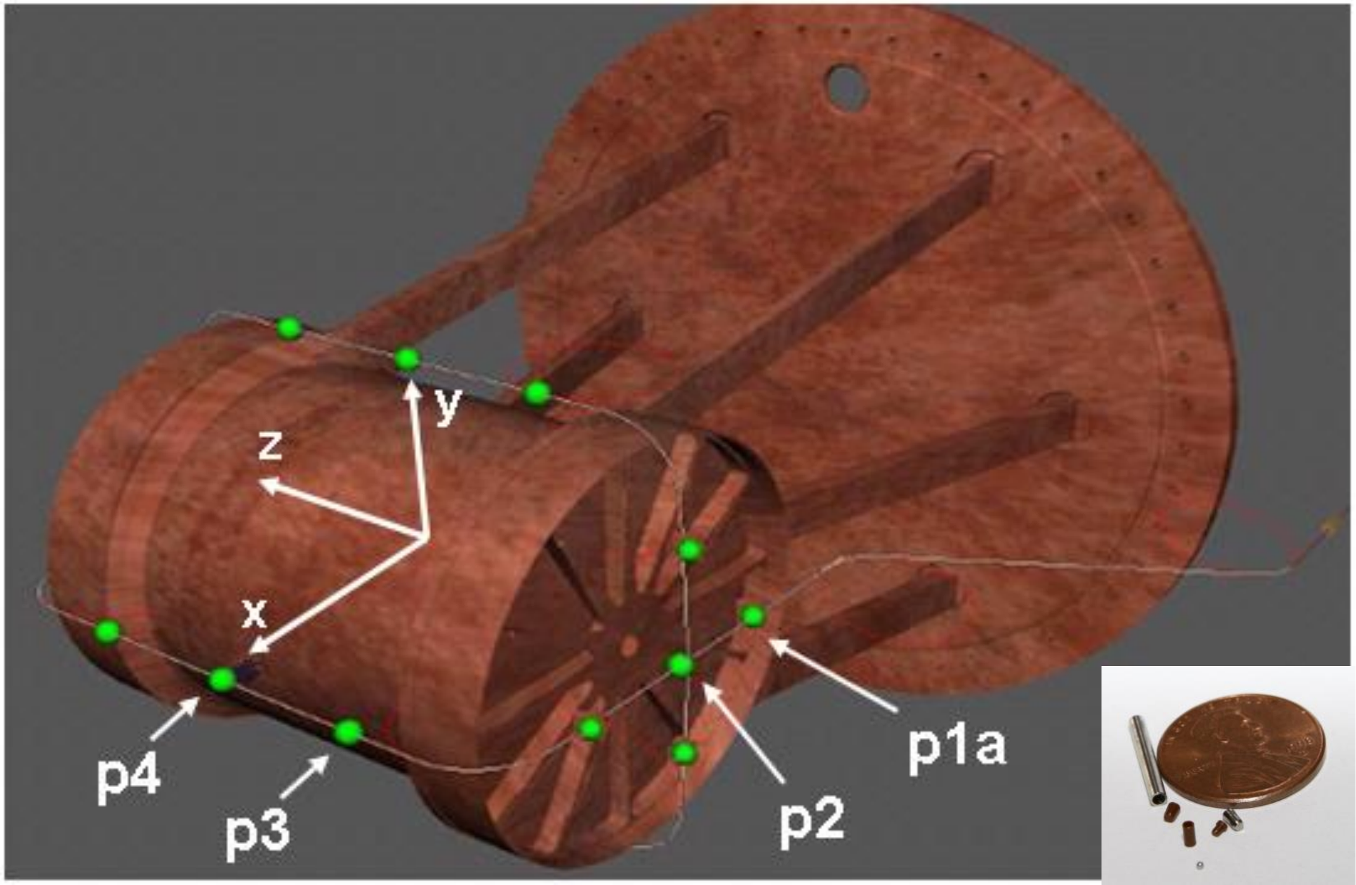
- Phase II (new purifiers)



Calibration

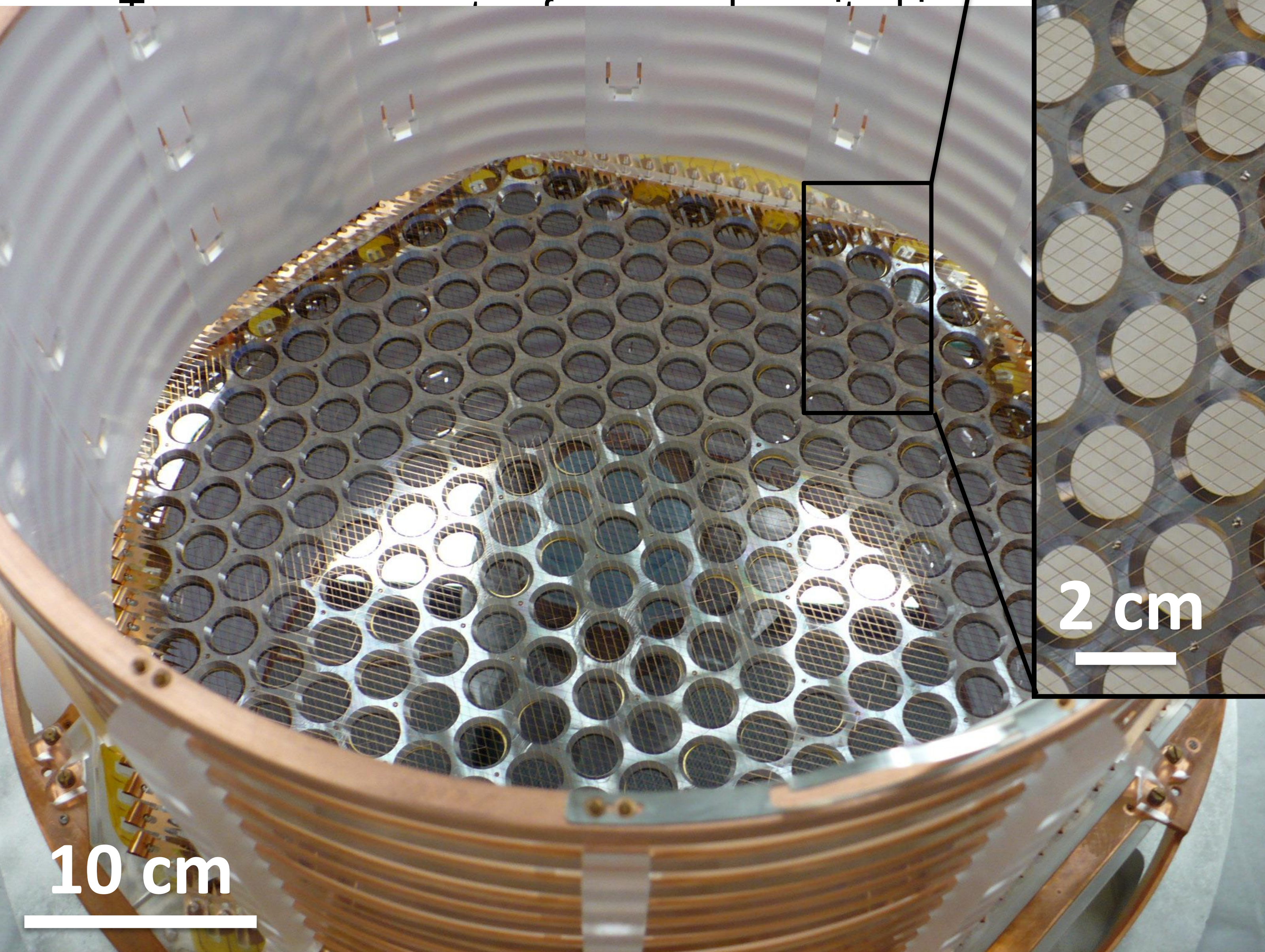
- Primary calibration from ^{228}Th source (2615 keV ^{208}Tl γ-line)

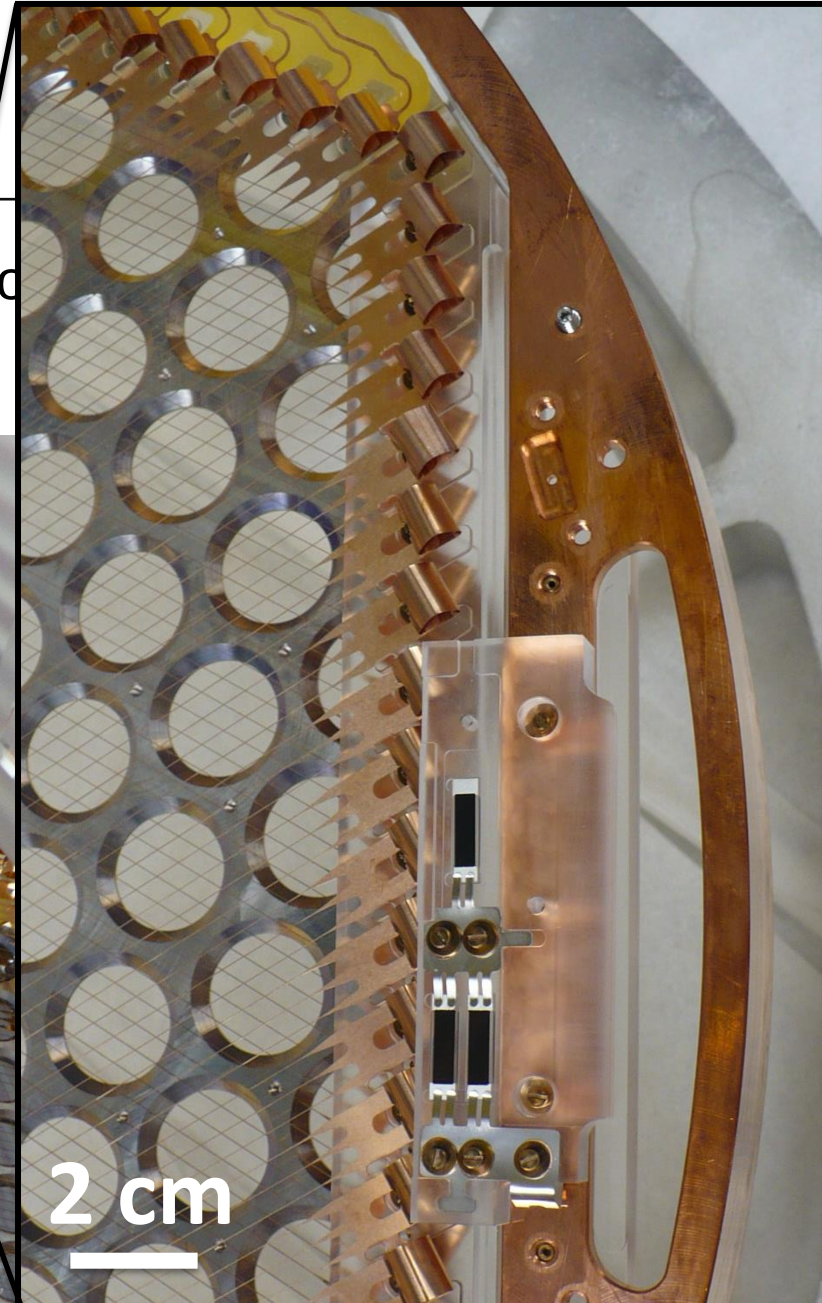
- Periodic (~3 months) campaigns using other γ sources
  - ^{60}Co, ^{226}Ra and ^{137}Cs



TPC

- High-voltage applied between cathode and an

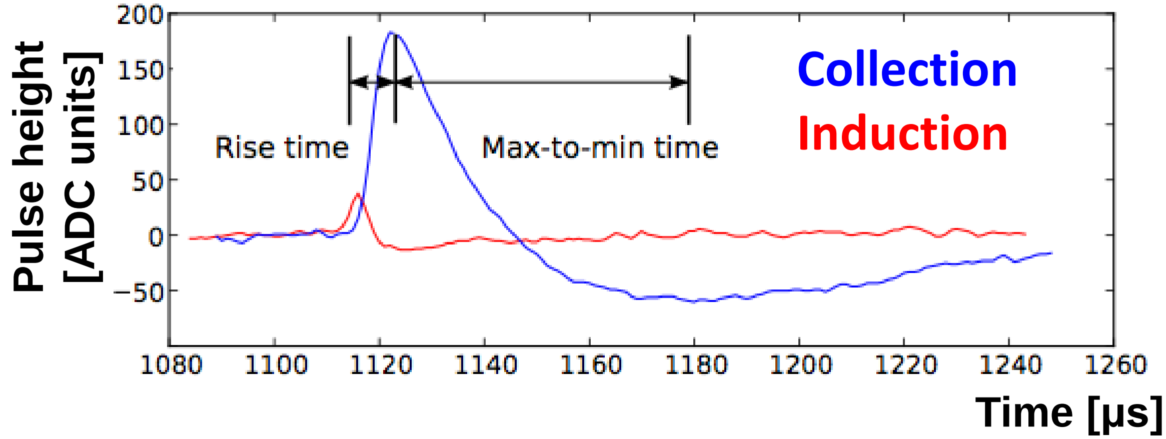




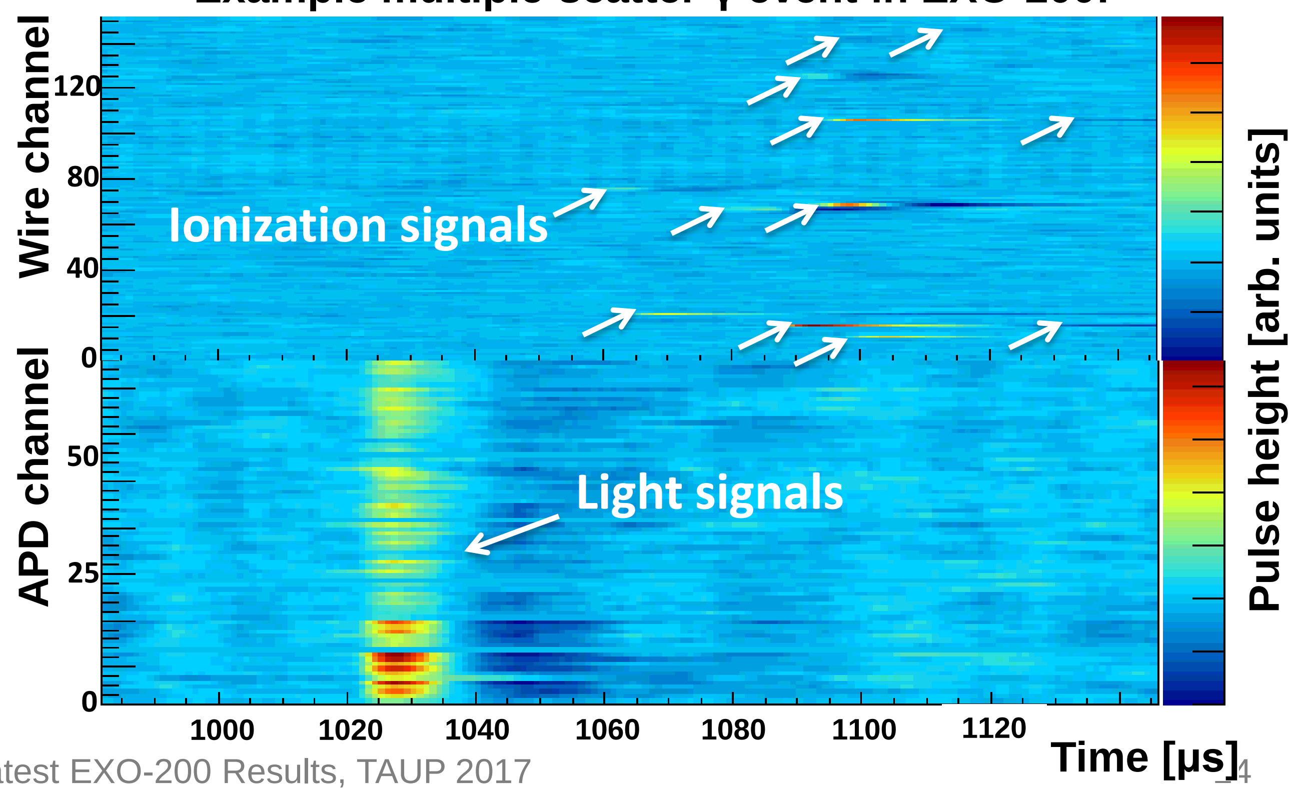
Event reconstruction

- Reconstruct energy and position of all interactions
- ββ signal is simple, but background events more complex
- Differentiate between induction and multiple scatters by pulse shape
- Likelihood-based algorithm "clusters" signals into energy deposits

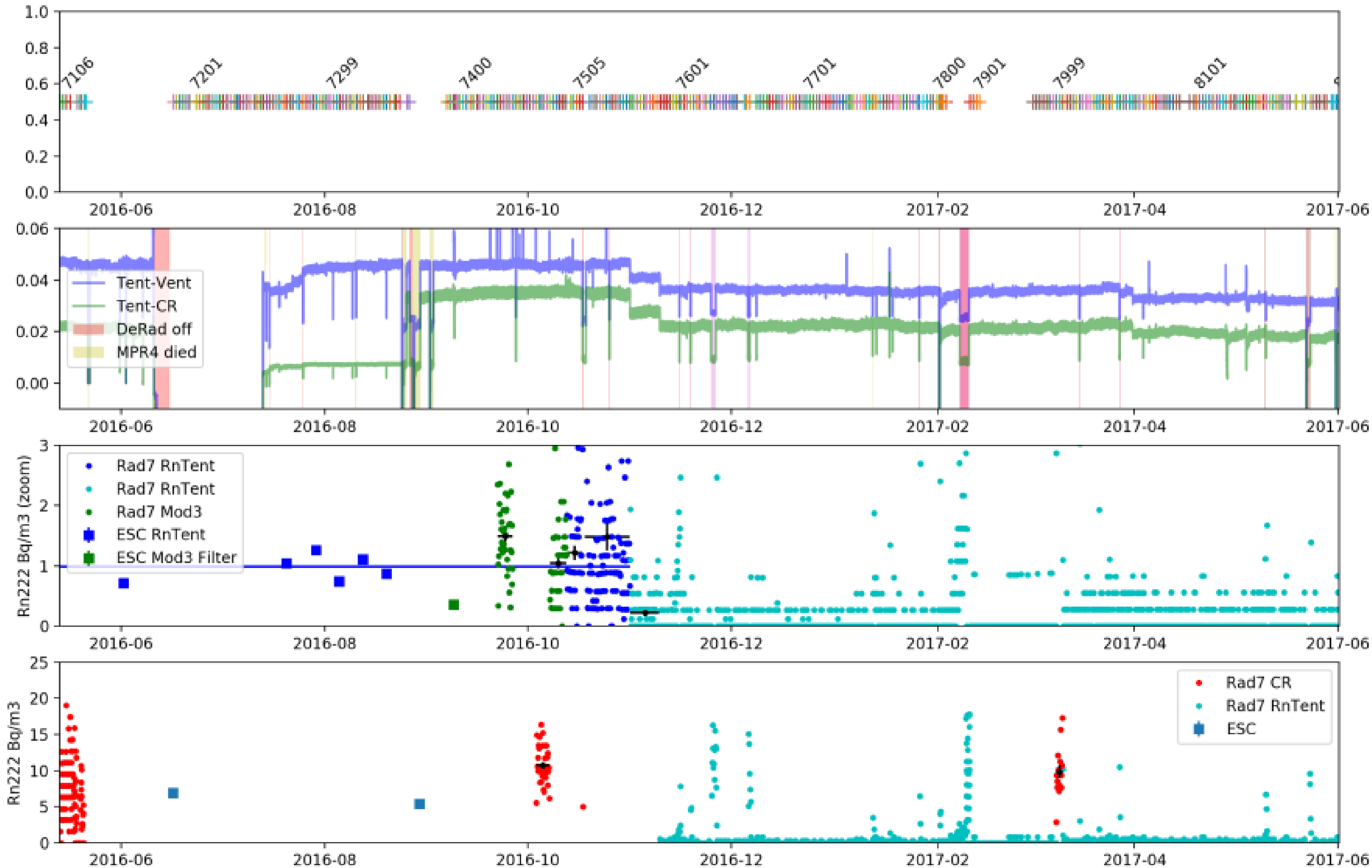
Pulse shapes for collection and induction signals:



Example multiple-scatter γ event in EXO-200:



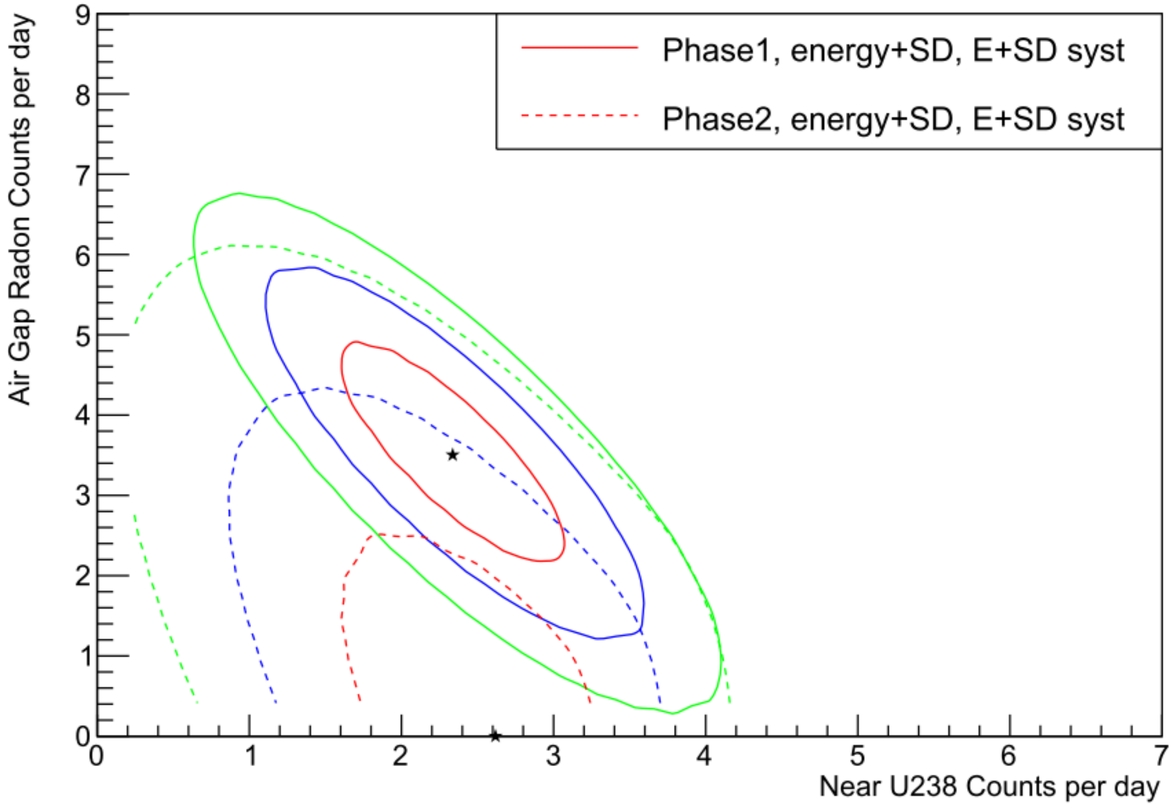
De-radonator - Direct Air Sampling



- Rn tent average in Phase II 0.55 Bq/m^3
- Clean room level ~10 Bq/m^3

De-radonator – Physics Profile

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



Innermost volume 1.39 kg.yr exposure