New results from the EXO-200 experiment

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On behalf of the EXO-200 collaboration
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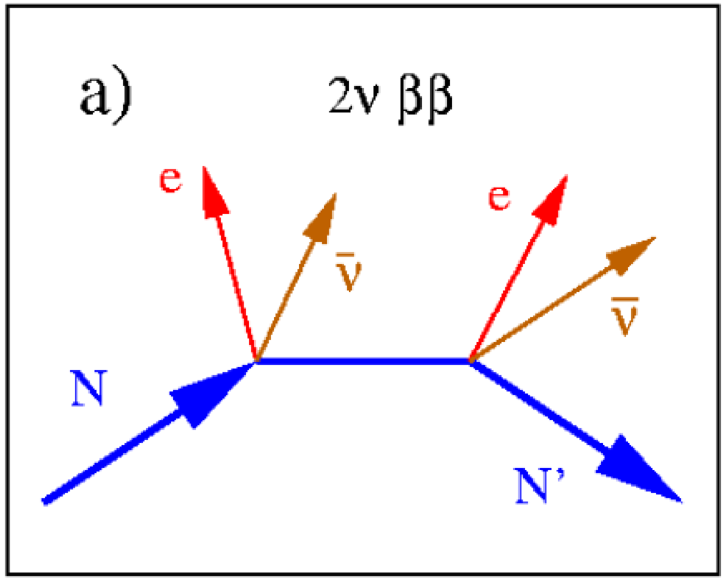
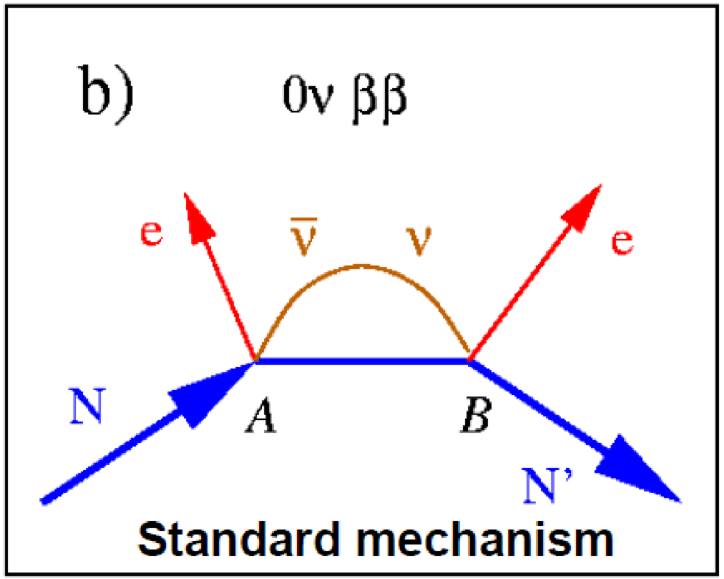
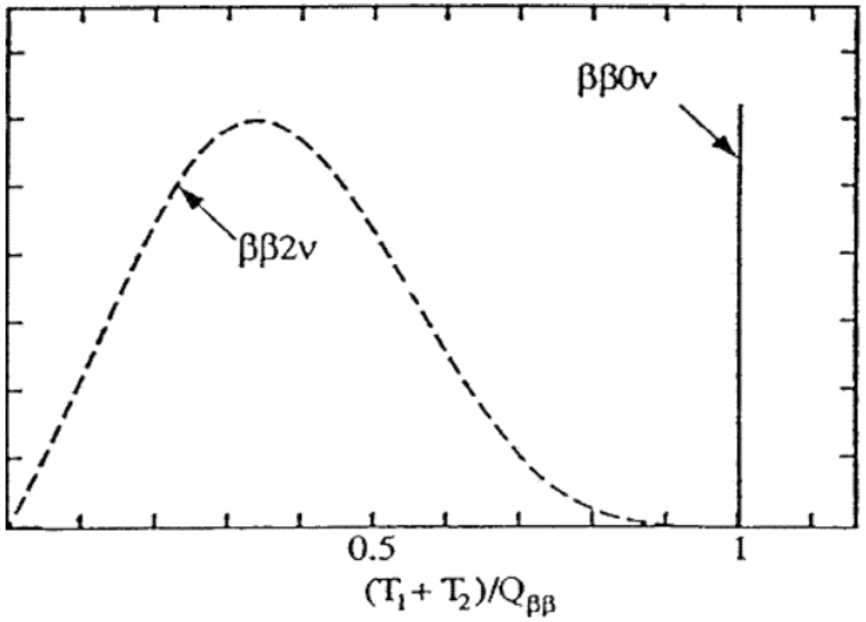
Neutrinoless double beta decay ($0\nu\beta\beta$)







$2\nu\beta\beta$ decay

- Conventional process

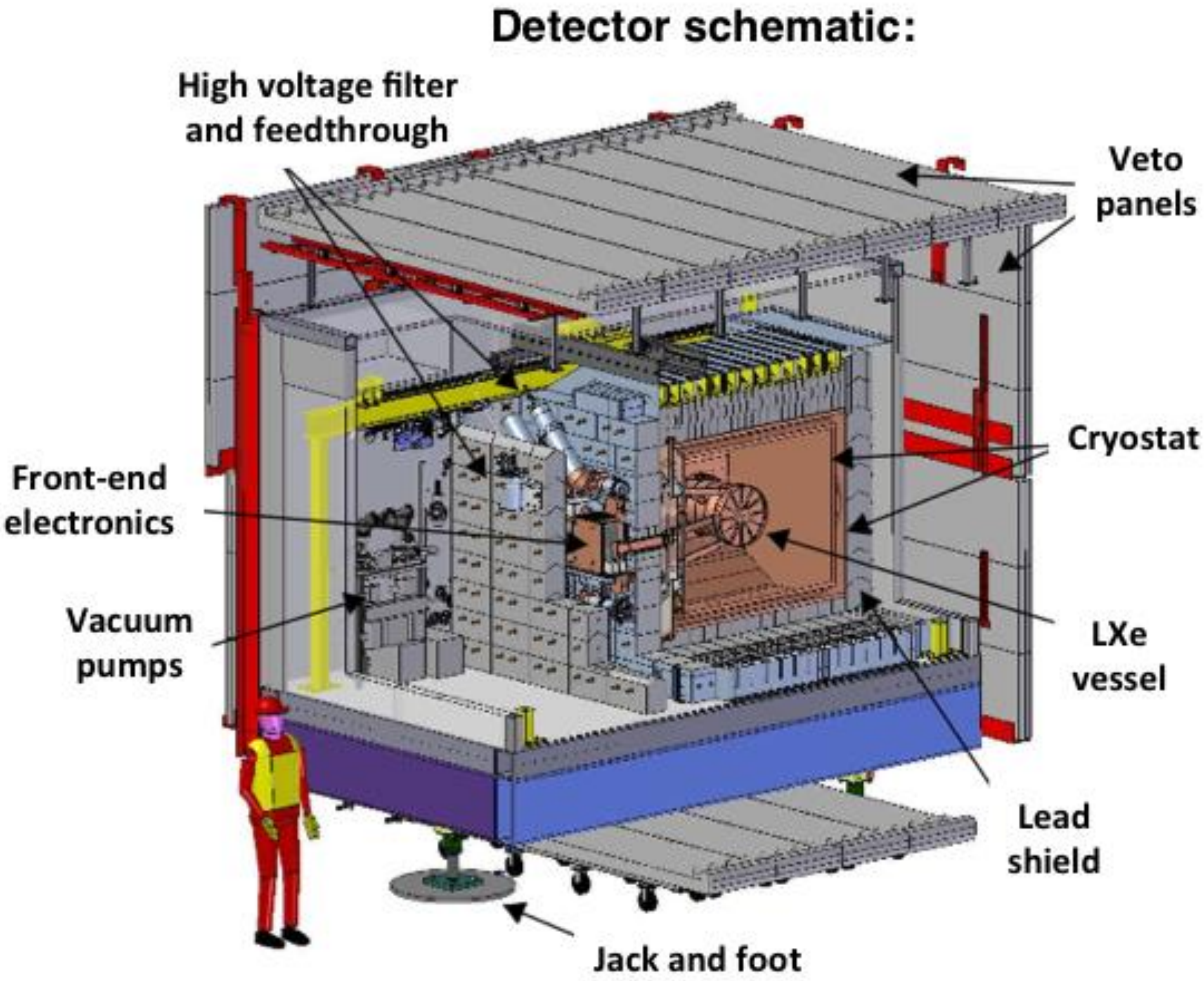
$0\nu\beta\beta$ has rich physics implications:

- **Majorana neutrino**
- **Lepton number violation**
- **Absolute neutrino mass scale**

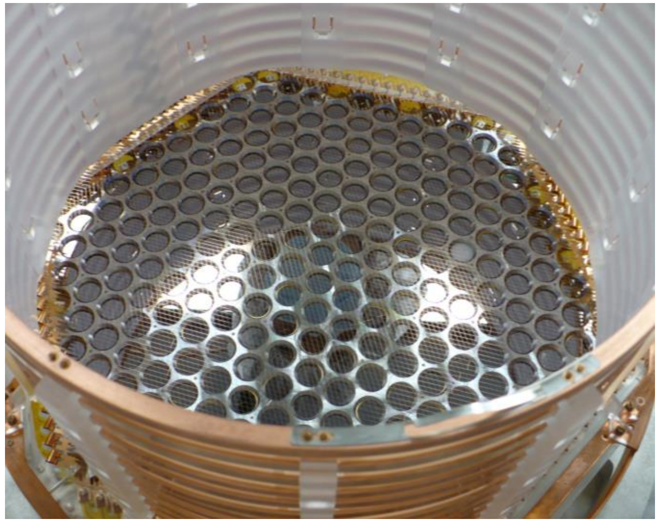
- 2ν VS 0ν spectrum: continuum vs peak
- Good energy resolution required to separate 0ν from 2ν

EXO-200

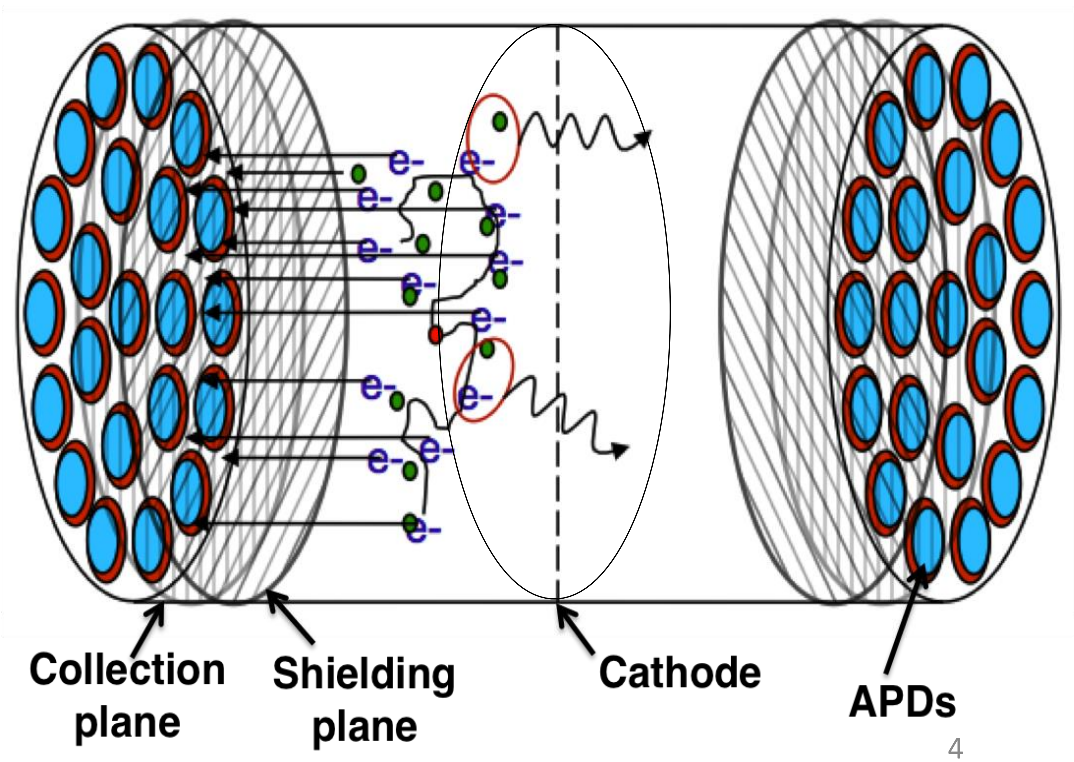
- Located at Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM, USA
- 1624 m.w.e. overburden
- LXe vessel surrounded by ~50 cm HFE-7000 cryofluid, housed in a double-wall cryostat
- ~25 cm passive lead shield in all directions
- Plastic scintillator panels for muon veto



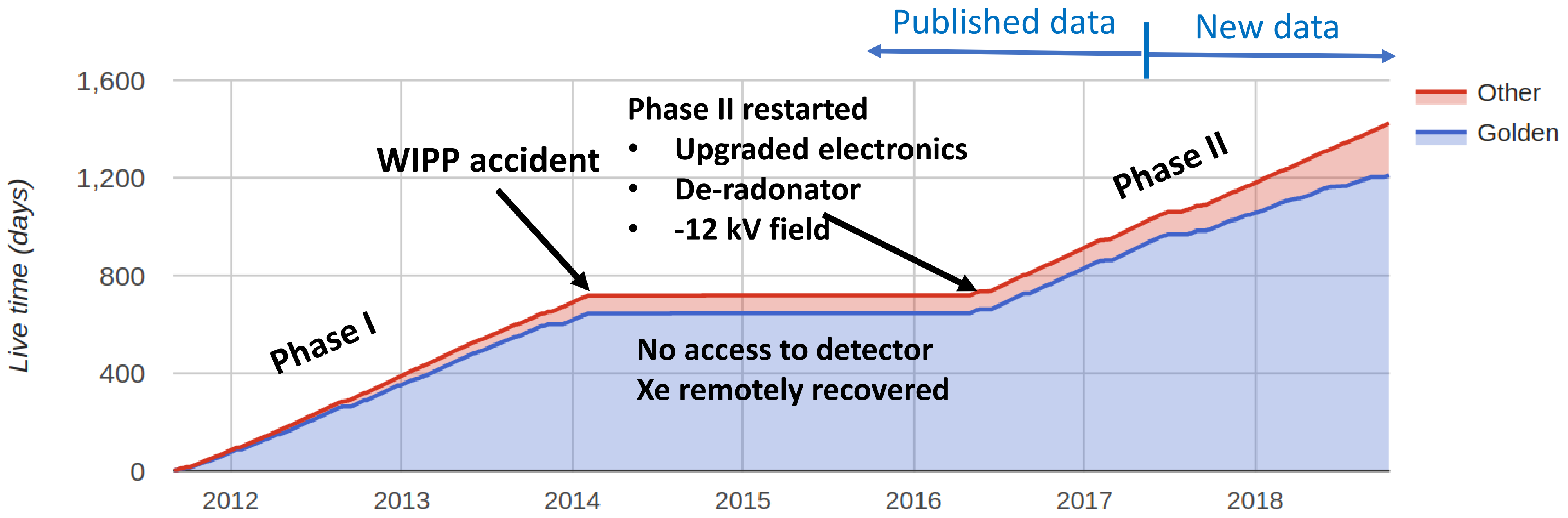
Time Projection Chamber (TPC)



- Single phase liquid xenon TPC with ^{enr}Xe (80.6%)
- ~110 kg active volume
- Two back-to-back TPCs with cathode in the middle
- Scintillation light readout by arrays of large area avalanche photodiodes (LAAPDs)
- Ionization detected by two wire grids crossing at 60 degree
  - Collection plane (U-wires)
  - Shielding plane (V-wires)



EXO-200 timeline

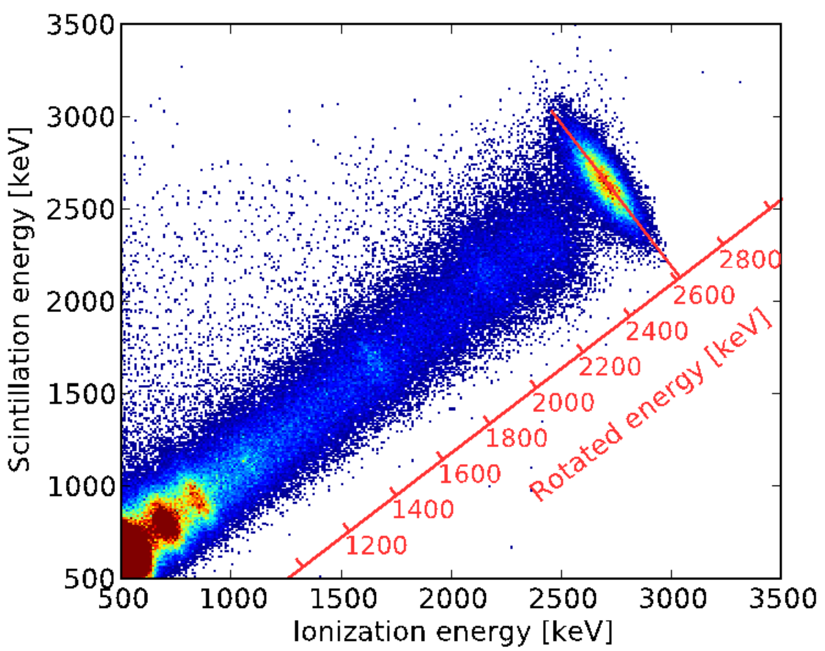


- Operation concluded in Dec 2018, with 1181.3 days of livetime
- Phase I from Sep 2011 to Feb 2014
  - Most precise $2\nu\beta\beta$ measurement, *Phys. Rev. C* ***89****, 015502 (2013)*
  - Stringent limit for $0\nu\beta\beta$ search, *Nature* ***510****, 229 (2014)*
- Phase II operation begins on Jan 31, 2016 with system upgrades
  - First results with Phase II data from upgraded detector, *Phys. Rev. Lett.* ***120****, 072701 (2018)*
  - **This talk, new results with complete dataset!**

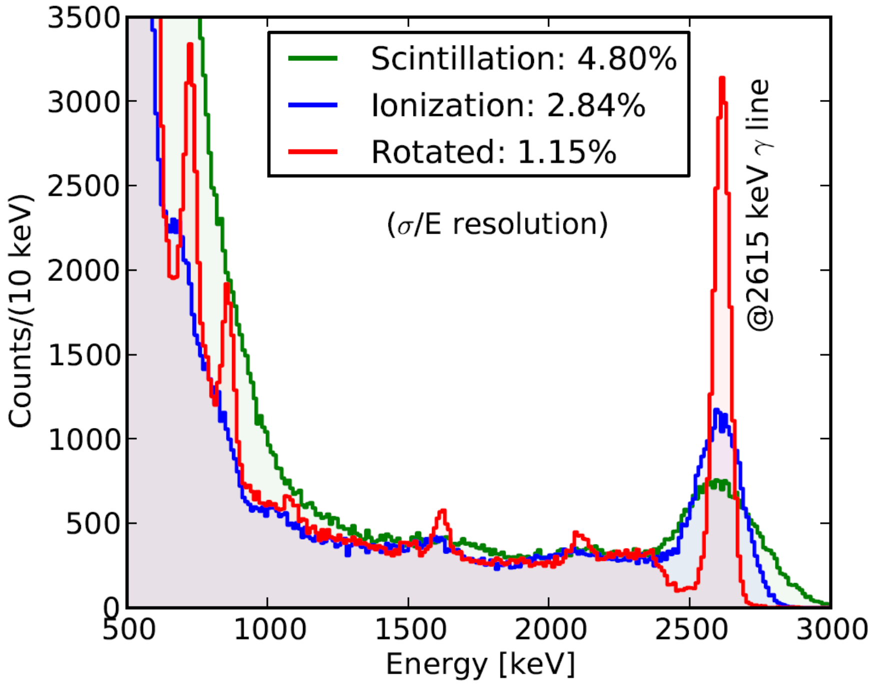
Energy

- Using anti-correlation between charge and scintillation response
  - “Rotated” energy provides optimal resolution in the energy of interest

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

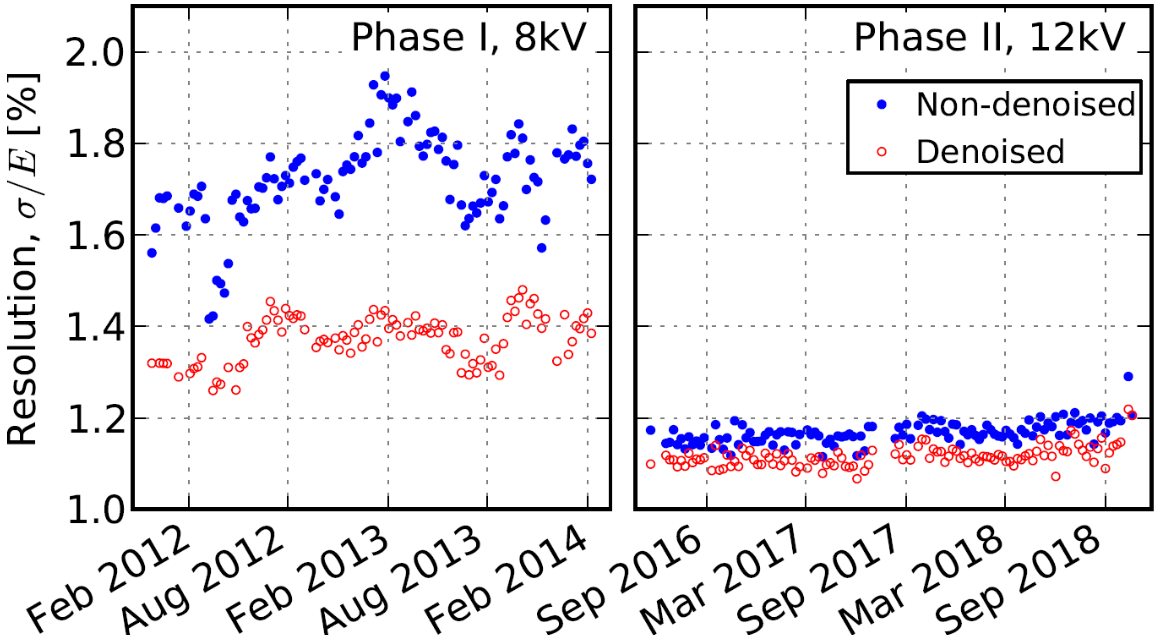


Reconstructed energy, ^{228}Th calibration:



Resolution improvement

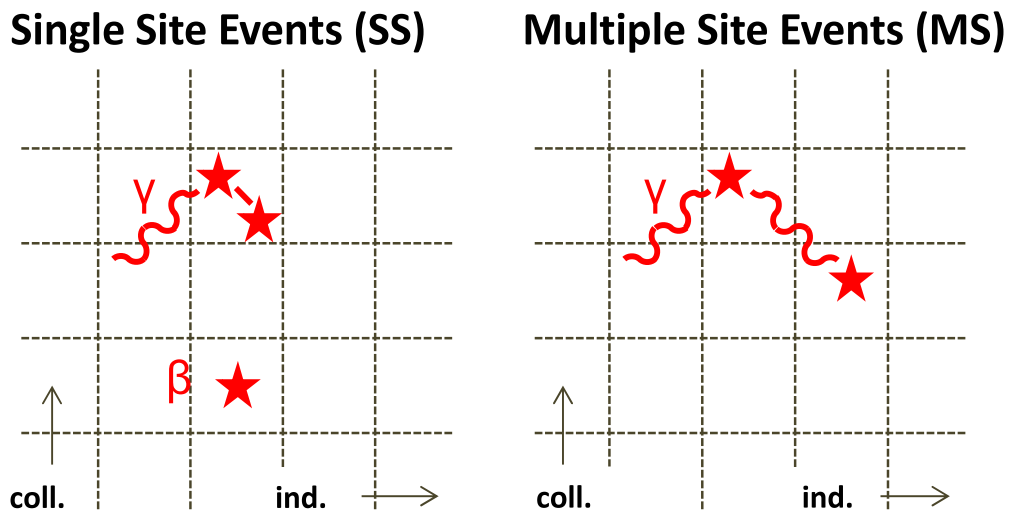
Resolution at the Q value (^{228}Th near cathode)



- Front end readout electronics
  - Reduce APD readout excess noise
- Cathode HV increased from -8 kV to -12 kV
- Software De-noising to optimize energy calibration
- De-noising adapted for Phase II as well in new analysis
- Proper Modeling of mixed collection/induction wire signals
- Energy resolution (σ/E) at $Q_{\beta\beta}$ value (design goal 1.6%)
  - Phase I: 1.35+-0.09%
  - Phase II: 1.15+-0.02%

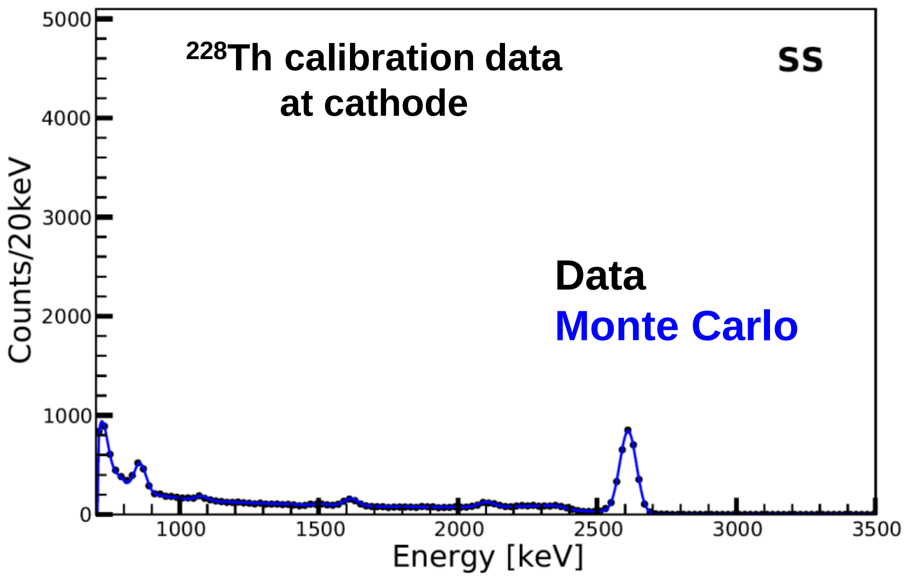
Vertex reconstruction and SS/MS classification

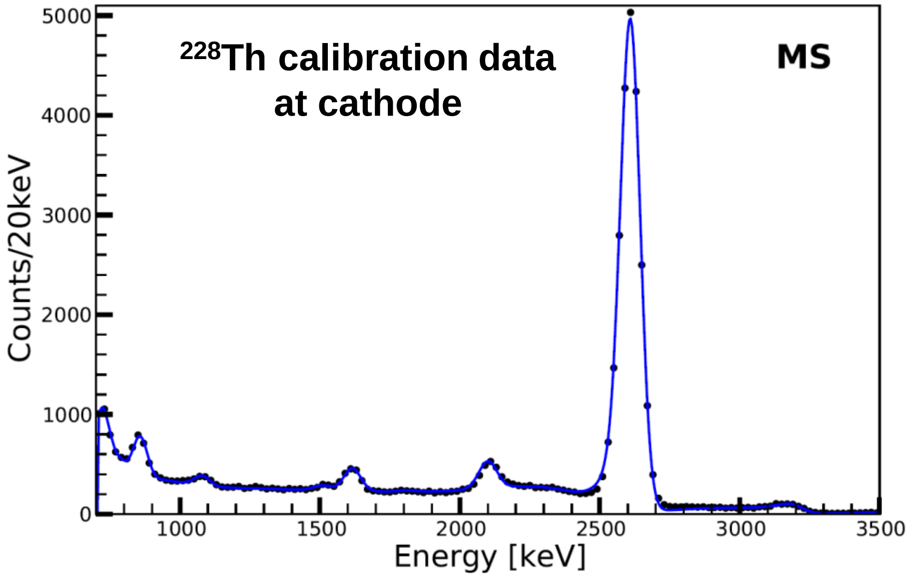
- X/Y (U/V) position determined by the signals in cross wire planes with 9 mm pitch
- Z position determined by the time delay between light signal and collection signals in wires with ~ 6 mm resolution
- ββ mostly deposits energy at single location (SS)
- γ backgrounds deposits at multiple locations (MS)
- SS/MS classification is very powerful in background rejection



Relaxed 3D cut

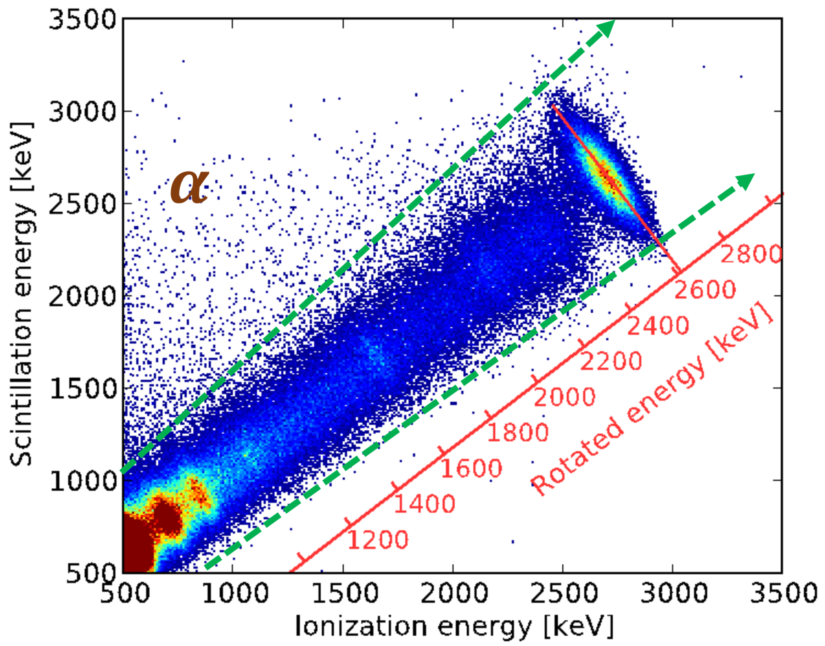
- Previous analyses require all events having full 3D position
- Partial 3D events are due to small energy deposit having complete collection on U-wire, but usually having no V signals because of higher threshold
- Now require >60% of energy deposits having 3D position, only recovering MS events
- Recovers almost all previously cut $0\nu\beta\beta$ events (10%) in MS due to small bremsstrahlung deposit
- Average SS fraction is **12%** in the energy range $Q_{\beta\beta} \pm 2\sigma$ for Th-228 source deployed near the cathode





Light/charge Diagonal cut

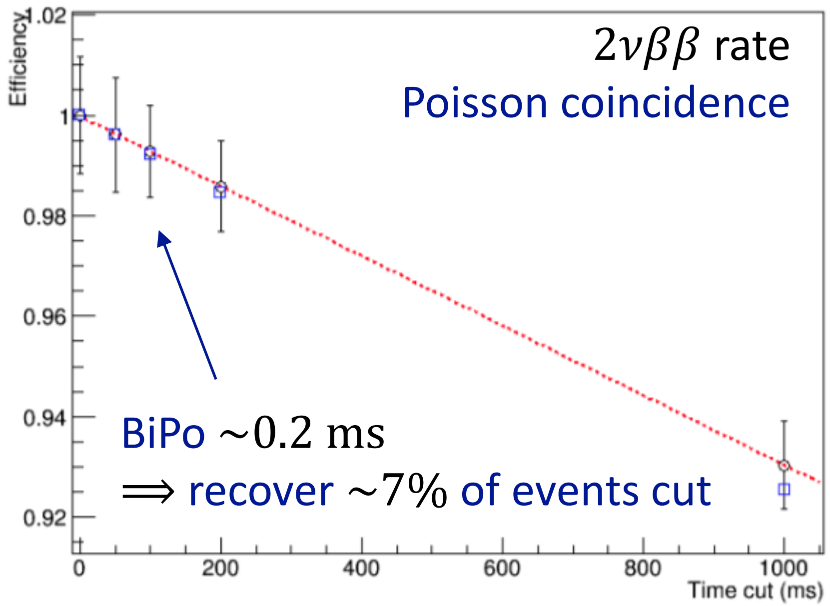
- Requires 2D light/charge energy calibration and good understanding of detector
- Light/charge ratio distributions validated by comparison between data/simulation using source and $2\nu\beta\beta$ data
- Powerful to reject α, as well as poorly reconstructed β/γ with anomalous light/charge ratio



Increasing $0\nu\beta\beta$ detection efficiency

- Another major signal efficiency loss in previous analyses has been improved in addition to the 3D cut
- Event coincidence cut
  - Originally designed to remove time-correlated events, e.g. Bi-Po event, potential muon induced long-lived decay products …
  - Comprehensive cosmogenic background studies (*JCAP 1604 (2016) no.04, 029*) later found no evidence of contributions from such muon-induced isotopes
  - Reducing time cut window from 1s to 0.1 s is still sufficient for rejecting Bi-Po
- $0\nu\beta\beta$ detection efficiency increases from ~80% to 97.8±3.0% (96.4±3.0%) for Phase I (II)

D. Fudenberg, PhD thesis (2017)



Improved background rejection for SS

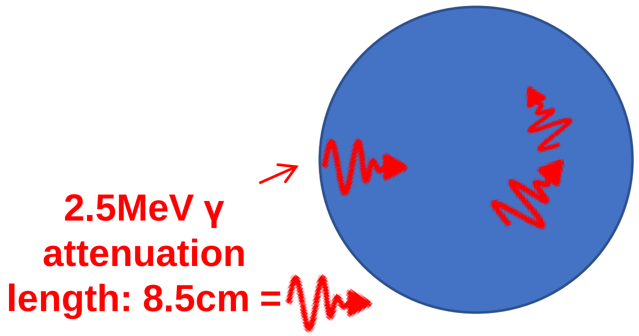
- Additional discrimination in SS using *spatial distribution* and *cluster size*

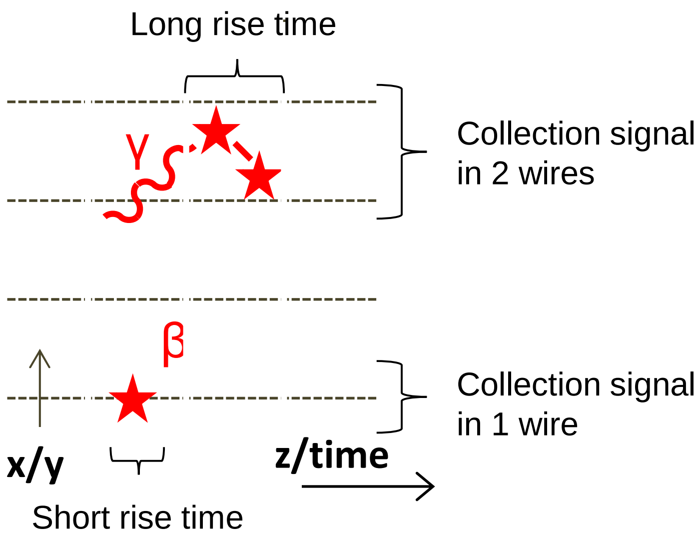
- Entering γ-rays rate is exponentially reduced by LXe self-shielding, provides independent measurement of γ-backgrounds
  - standoff-distance

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

Techniques already used in Phys. Rev. Lett. ***120****, 072701 (2018)*

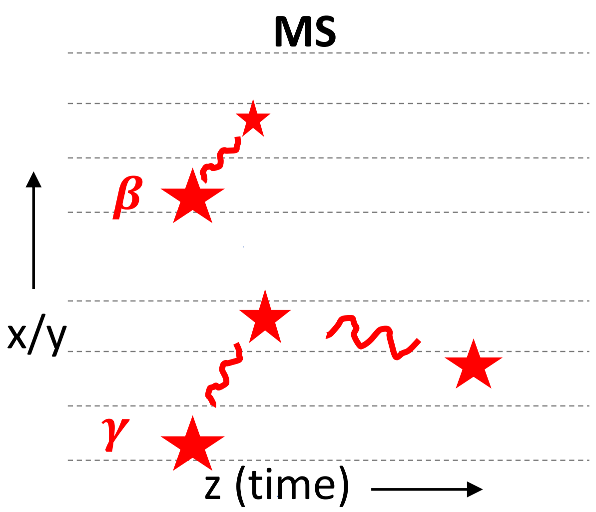
LXe self-shielding:

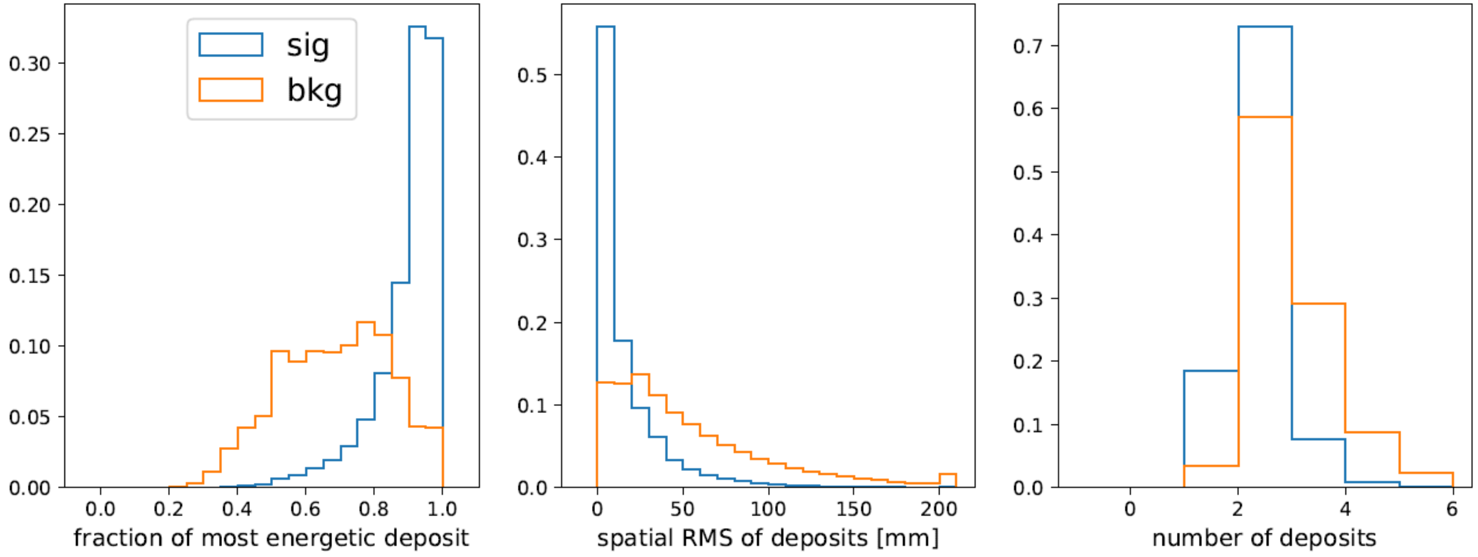




Improved background rejection for MS

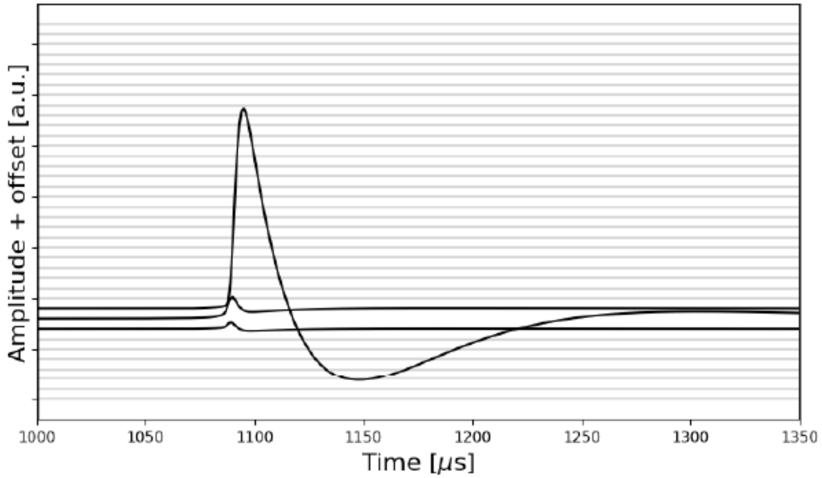
- $0\nu\beta\beta$ in MS arising from small energy deposits due to bremsstrahlung, while γ Compton scatters
- Distinct features in number of energy deposits, energy distribution and spatial spread among deposits
- High background rejection than in SS to compensate the fact that MS is dominated by backgrounds



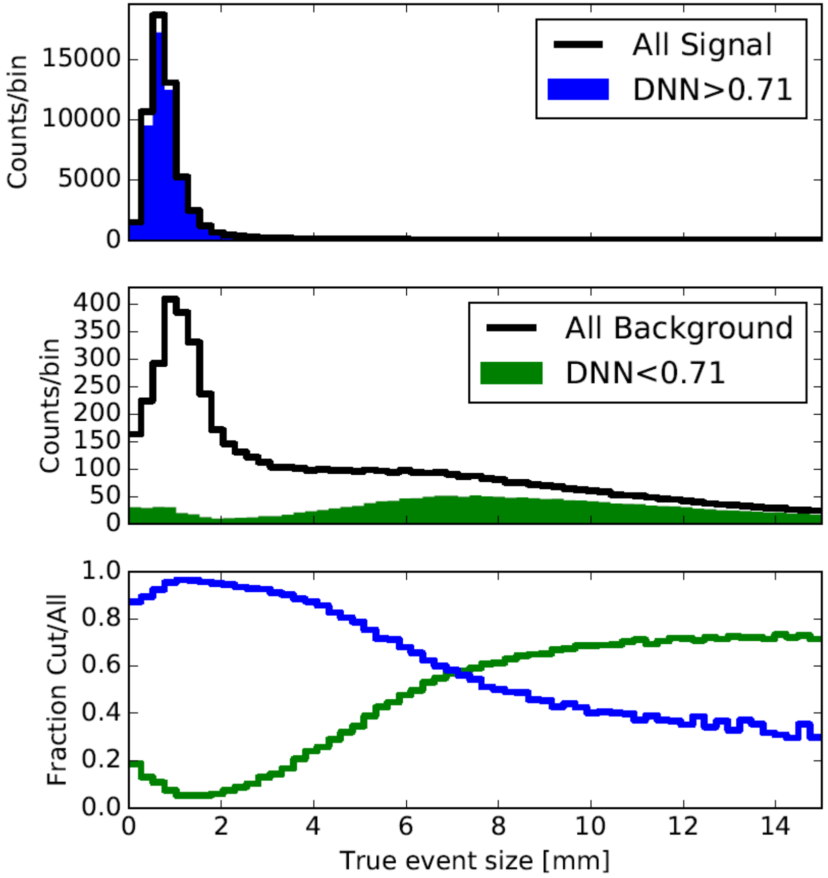


Improved background discrimination with DNN

- Deep neural network (DNN) based $0\nu\beta\beta$ discriminator
- DNN trained on images built from U-wire waveforms



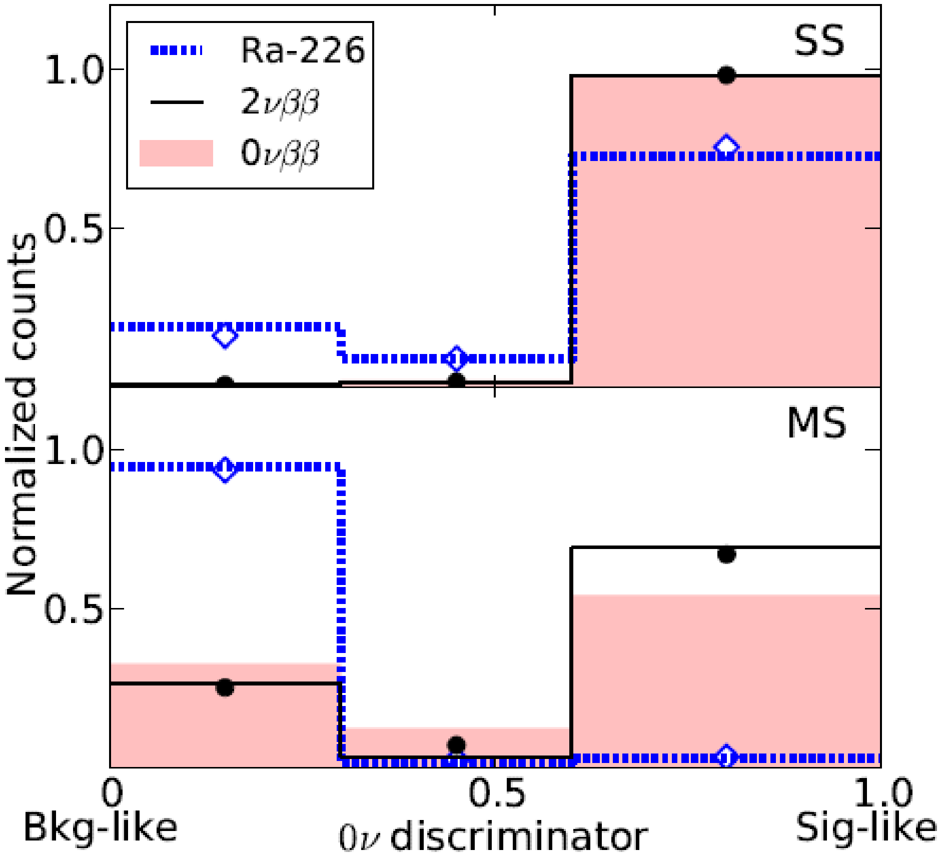
SS events



- Signal/background identification efficiency correlates with the true event size based on truth information in simulation
- Indicates the network can pick up correct features on the waveform to reconstruct event, (find wire signals, cluster signals into energy deposits), thus to discriminate signal and background

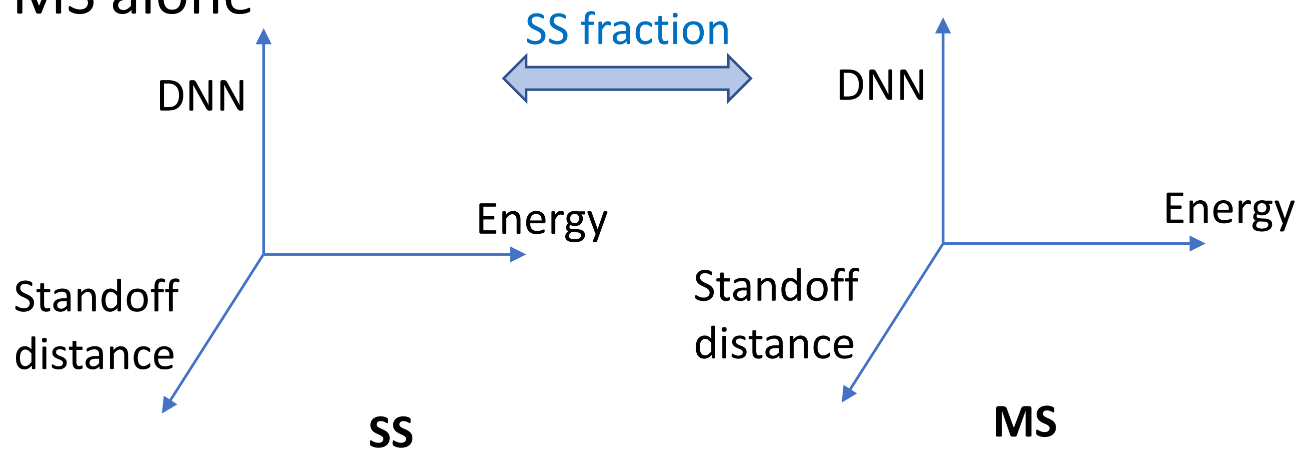
Data/MC agreement for DNN

- Data/MC agreement validated with different data
  - γ: Ra-226, Th-228, Co-60 calibration sources
  - β: $2\nu\beta\beta$ data
- Showed consistent and reasonable agreement
- Any differences in data/MC are taken into account as systematic uncertainties on normalization of backgrounds within $Q_{\beta\beta} \pm 2\sigma$

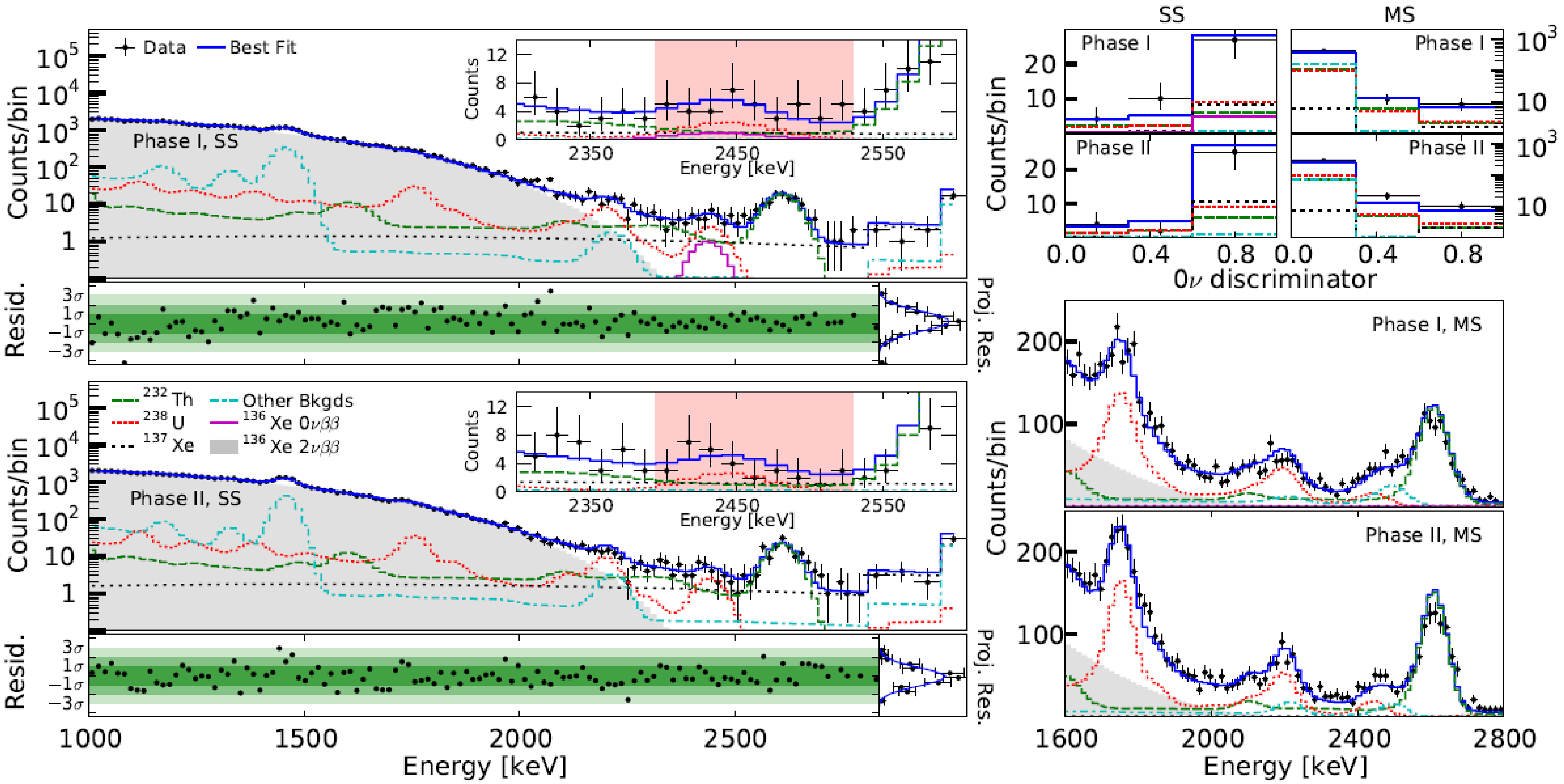


Analysis strategy

- Blinded analysis performed
- SS/MS classification
- 3-dimension fit in both SS and MS: E + DNN + standoff distance
  - Energy, event topology and spatial information
  - Make the most use of multi-parameters for background rejection
  - SS, MS relative contributions constrained by SS fraction
- Improvement of ~25% in $0\nu\beta\beta$ half-life sensitivity compared with using energy spectra + SS/MS alone



Best fit



Data
Best Fit
Phase I, SS
Counts/bin
Resid.
Proj. Res.
Counts
Energy [keV]
232 Th
238 U
137 Xe
Other Bkgds
136 Xe 0νββ
136 Xe 2νββ
Phase II, SS
Energy [keV]
SS
MS
Phase I
Phase II
0ν discriminator
Phase I, MS
Phase II, MS
Energy [keV]

Results

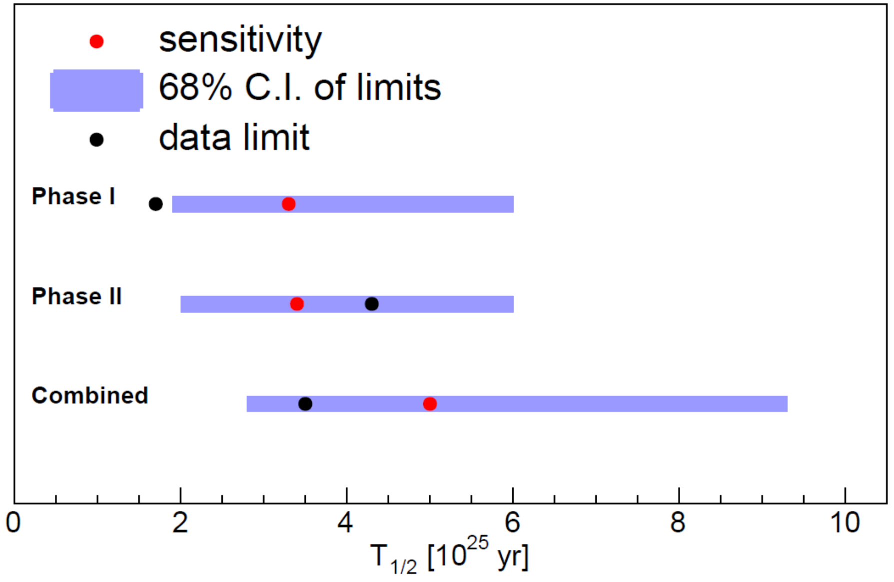
No statistical significant signal observed

Phase I+II: 234.1 kg·yr ^{136}Xe exposure

Limit $T_{1/2}^{0\nu\beta\beta} > 3.5 \times 10^{25}$ yr (90% C.L.)

$\langle m_{\beta\beta} \rangle < (93 - 286)$ meV

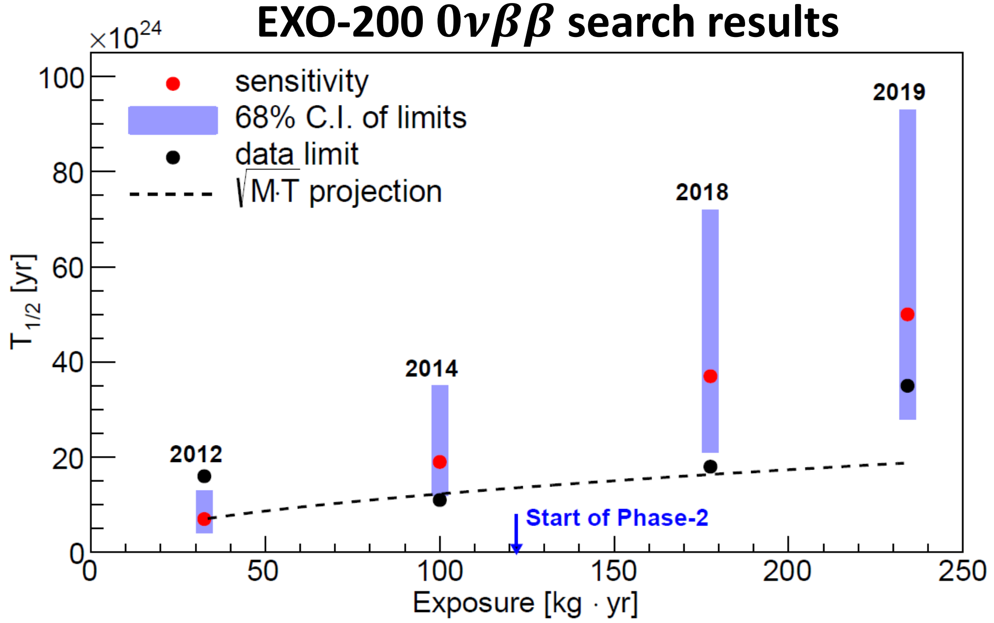
Sensitivity 5.0×10^{25} yr



Background contribution to $Q \pm 2\sigma$

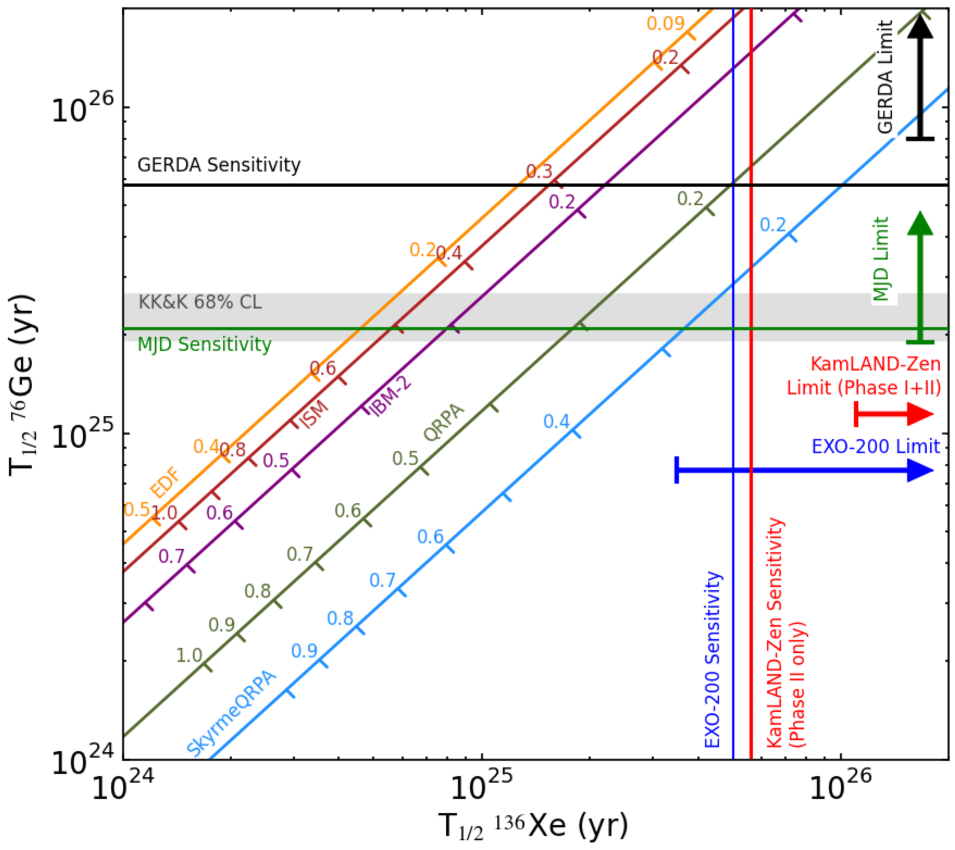
(counts)	^{238}U	^{232}Th	^{137}Xe	Total	Data
Phase I	12.6	10.0	8.7	32.3±2.3	39
Phase II	12.0	8.2	9.3	30.9±2.4	26

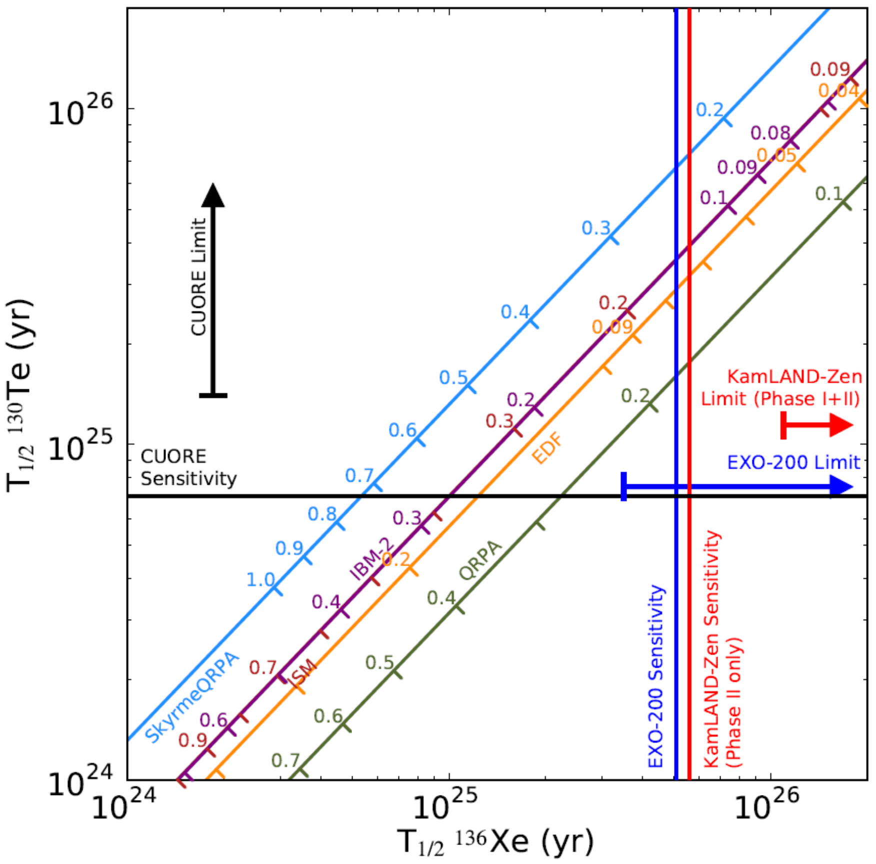
EXO-200 $0\nu\beta\beta$ search results



2012: Phys.Rev.Lett. 109 (2012) 032505
2014: Nature 510 (2014) 229-234
2018: Phys. Rev. Lett. 120, 072701 (2018)
2019: arXiv 1906.02723

Neutrino mass limits





Conclusion

- EXO-200 was the first 100-kg class experiment searching for $0\nu\beta\beta$, and successfully concluded after 7 years of stable operation
- EXO-200 produced a lot of important physics results
  - One of the most sensitive searches for $0\nu\beta\beta$, with full dataset giving a half-life limit of 3.5×10^{25} yr and a sensitivity of 5.0×10^{25} yr at 90% C.L. for ^{136}Xe $0\nu\beta\beta$
  - The first to observe the $2\nu\beta\beta$ decay from ^{136}Xe and made the most precise measurement on its half-life
  - Many other searches/tests of exotic models
  - Expecting more analyses on other physics topics with full EXO-200 dataset
- The planned 5-ton next generation experiment (nEXO) will have a $0\nu\beta\beta$ half-life sensitivity reaching $\sim 10^{28}$ yr half-life

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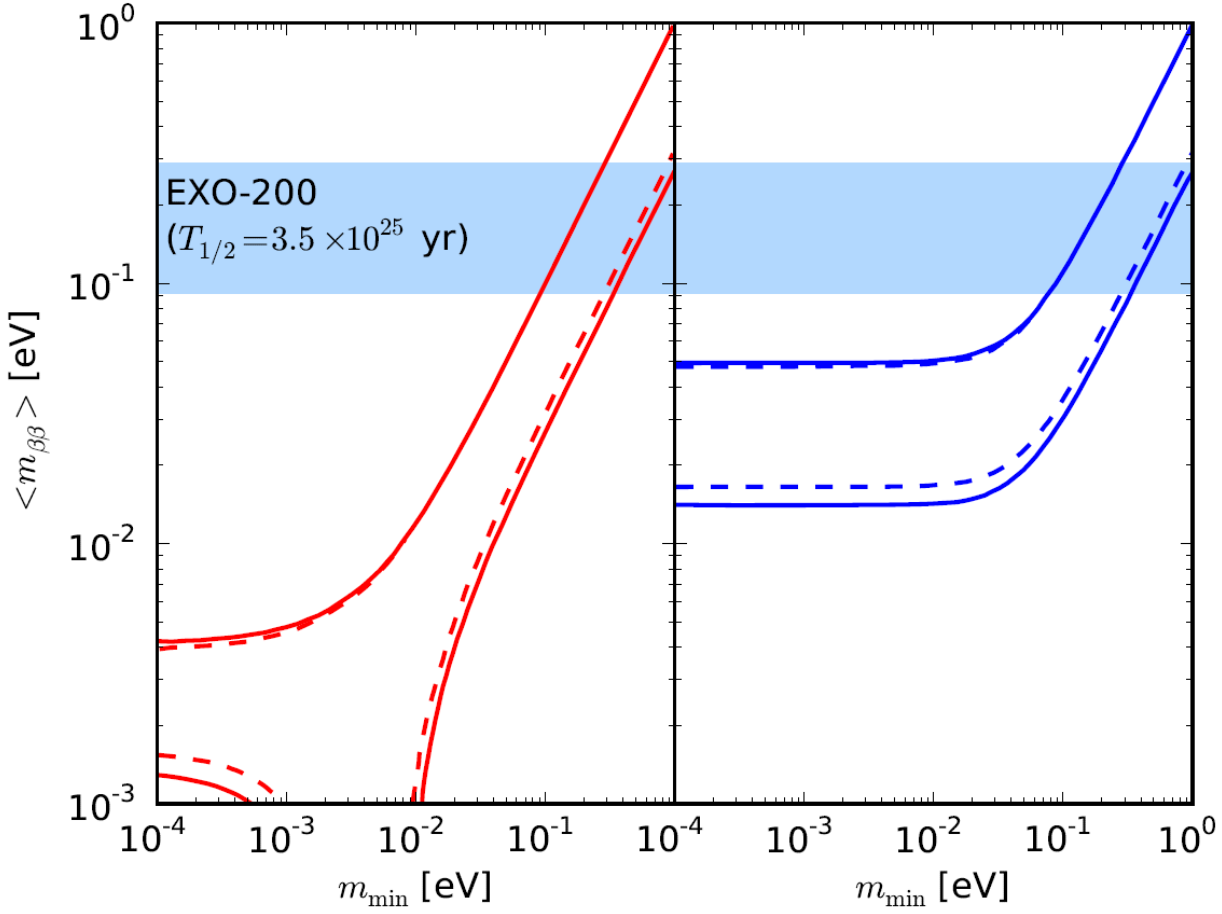
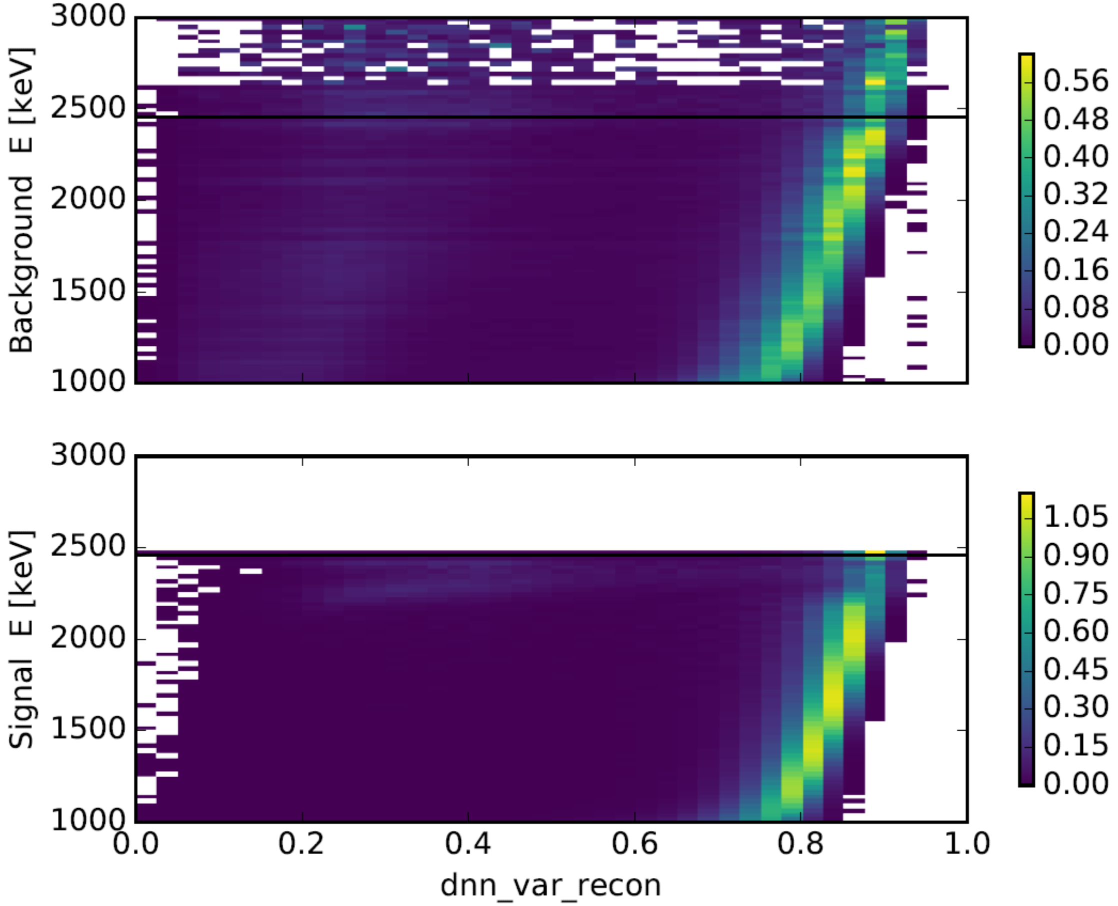
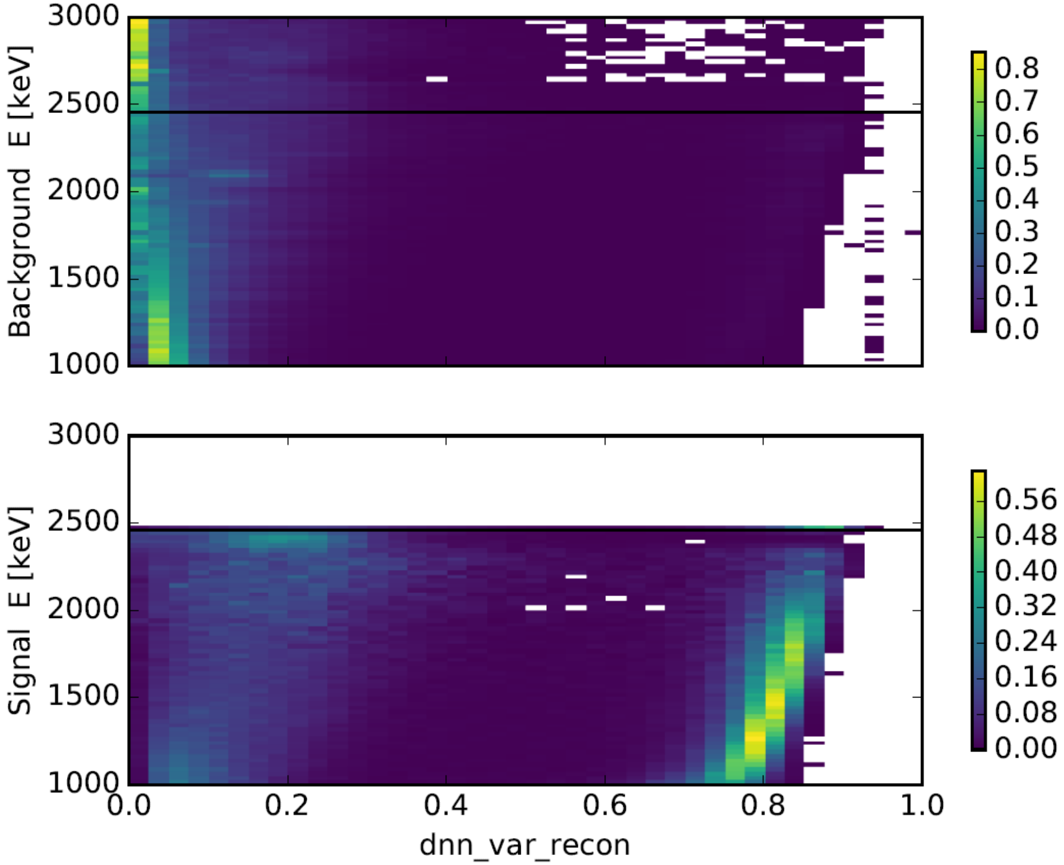
Backup



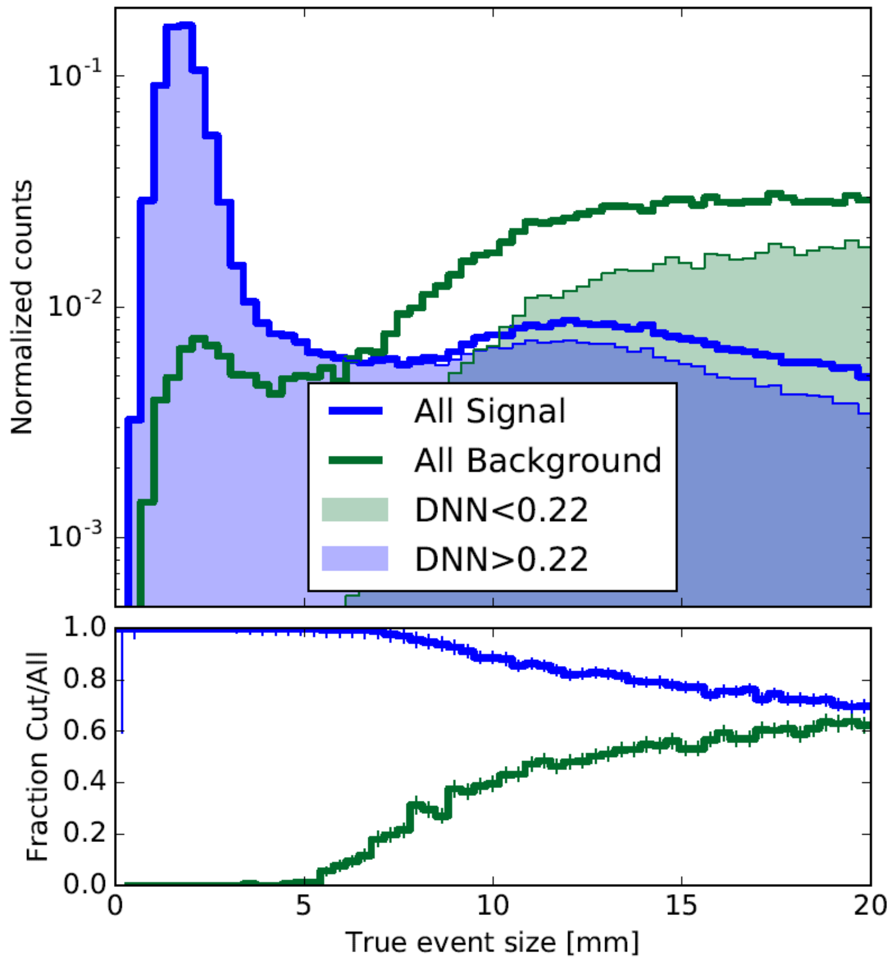
EXO-200
($T_{1/2}=3.5\times10^{25}$ yr)
$<m_{\beta\beta}>$ [eV]
$m_{\min}$ [eV]
$m_{\min}$ [eV]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}


Background E [keV]
3000
2500
2000
1500
1000
0.56
0.48
0.40
0.32
0.24
0.16
0.08
0.00
Signal E [keV]
3000
2500
2000
1500
1000
1.05
0.90
0.75
0.60
0.45
0.30
0.15
0.00
0.0
0.2
0.4
0.6
0.8
1.0
dnn_var_recon

SS


Background E [keV]
3000
2500
2000
1500
1000
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Signal E [keV]
3000
2500
2000
1500
1000
0.56
0.48
0.40
0.32
0.24
0.16
0.08
0.00
0.0
0.2
0.4
0.6
0.8
1.0
dnn_var_recon

MS



Normalized counts
10^{-1}
10^{-2}
10^{-3}
All Signal
All Background
DNN<0.22
DNN>0.22
Fraction Cut/All
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
True event size [mm]