New Results from the EXO-200 experiment

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On behalf of the EXO-200 Collaboration

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FLASY 2019@ USTC

Massive Neutrinos: Dirac vs. Majorana

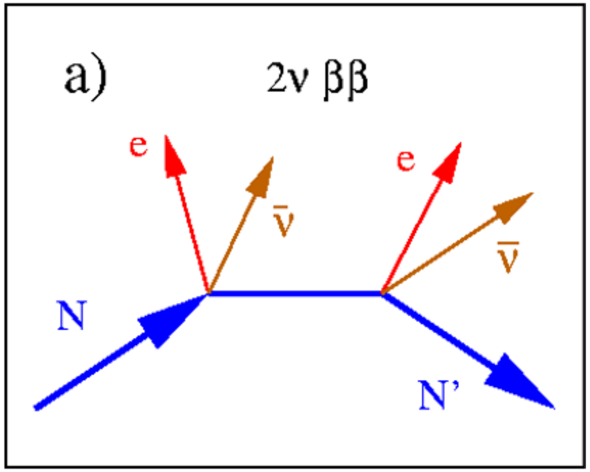
Neutrinos are massive particles, either Dirac or Majorana

Paul Dirac

Massive Dirac neutrinos

Lepton number conservation

Difficult to verify



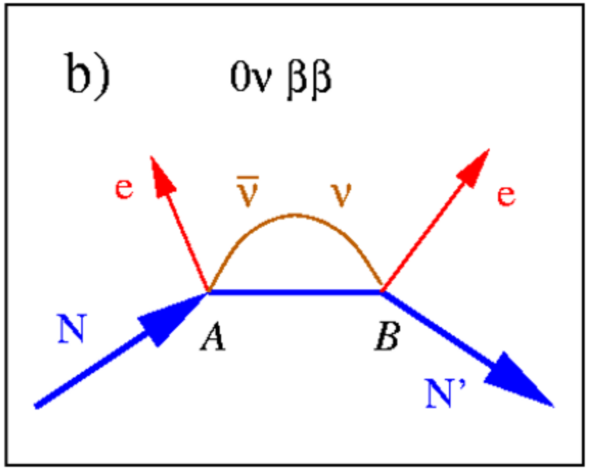
Ettore Majorana

Massive Majorana neutrinos

Lepton number violation

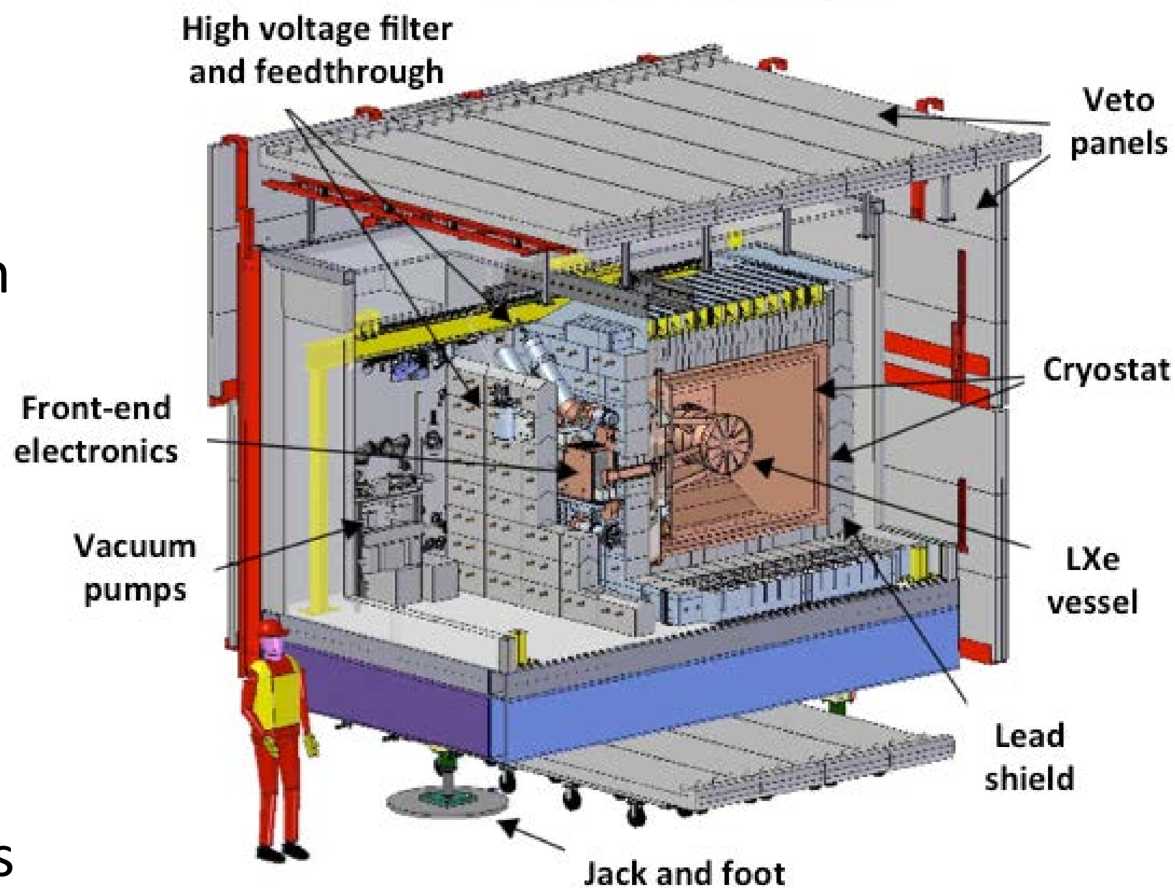
- Theoretical aspect: a natural way to understand tiny ν masses (See-Saw mechanism)

0νββ searches: a feasible and sensitive probe to the Majorana nature of ν

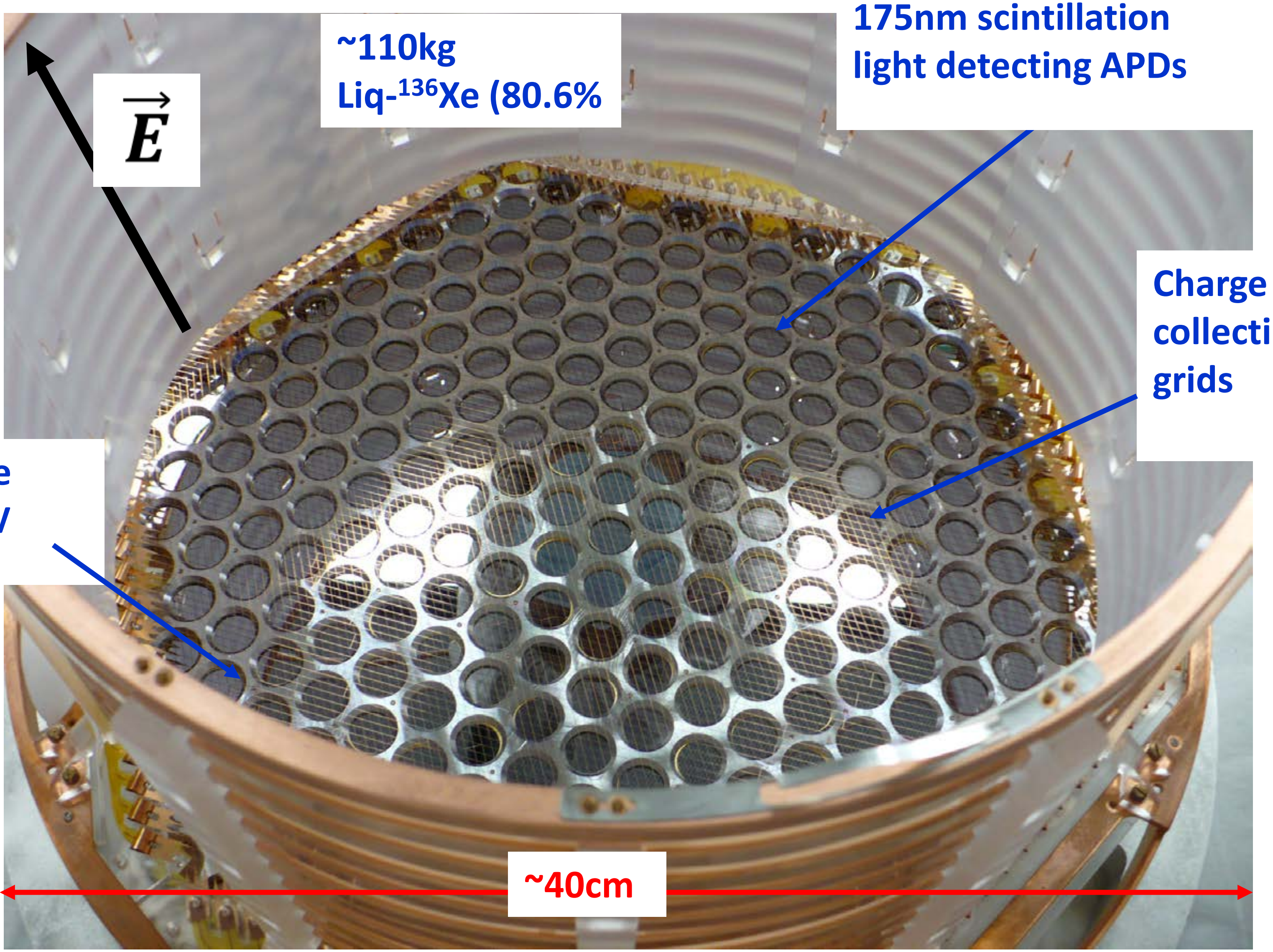


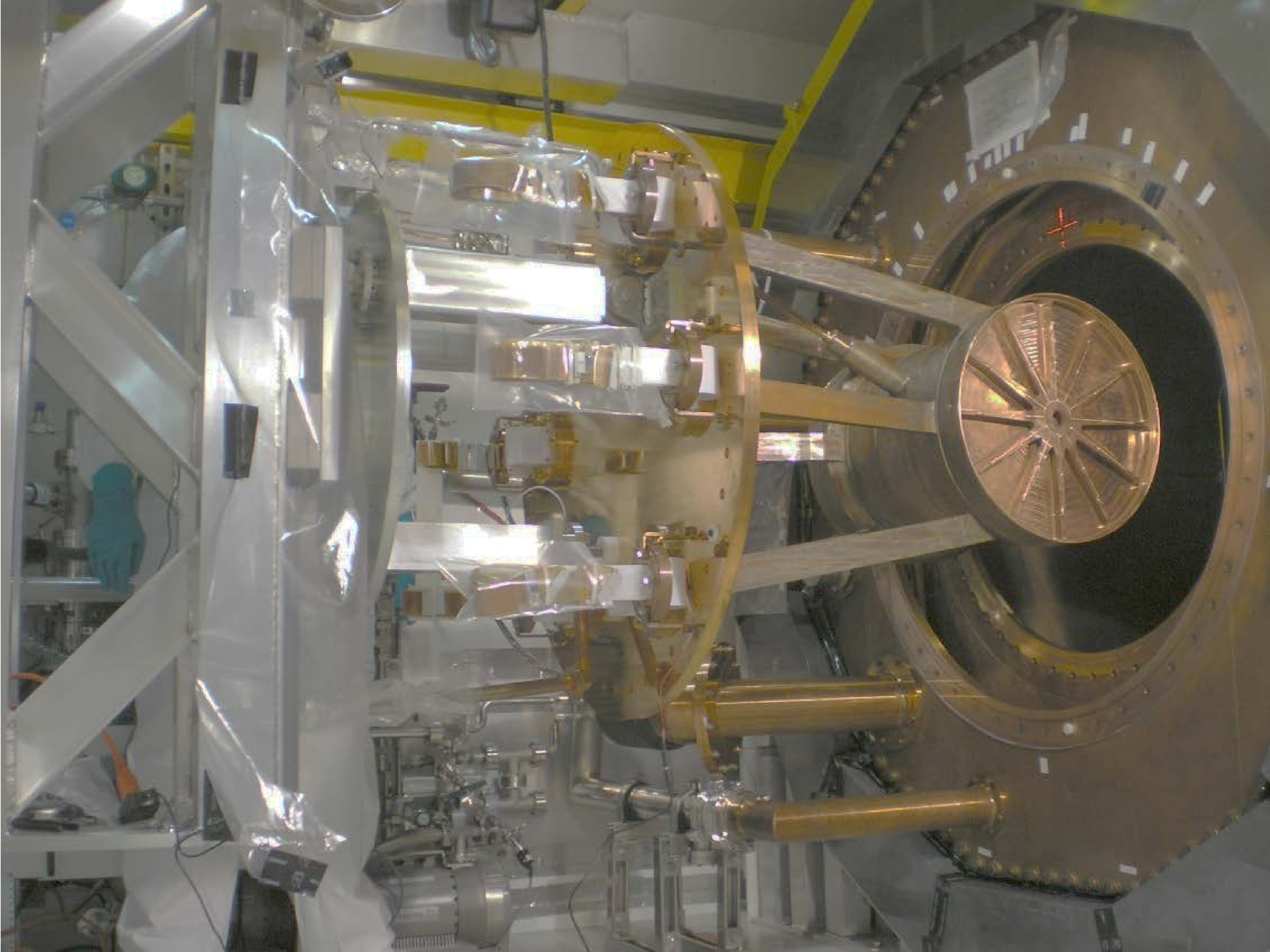
- Located at Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM, USA
- 1624 m.w.e. overburden
- LXe vessel surrounded by ~50 cm HFE-7000 cryofluid, housed in a double-wall cryostat
- ~25 cm passive lead shield in all directions
- Plastic scintillator panels for muon veto

Detector schematic:

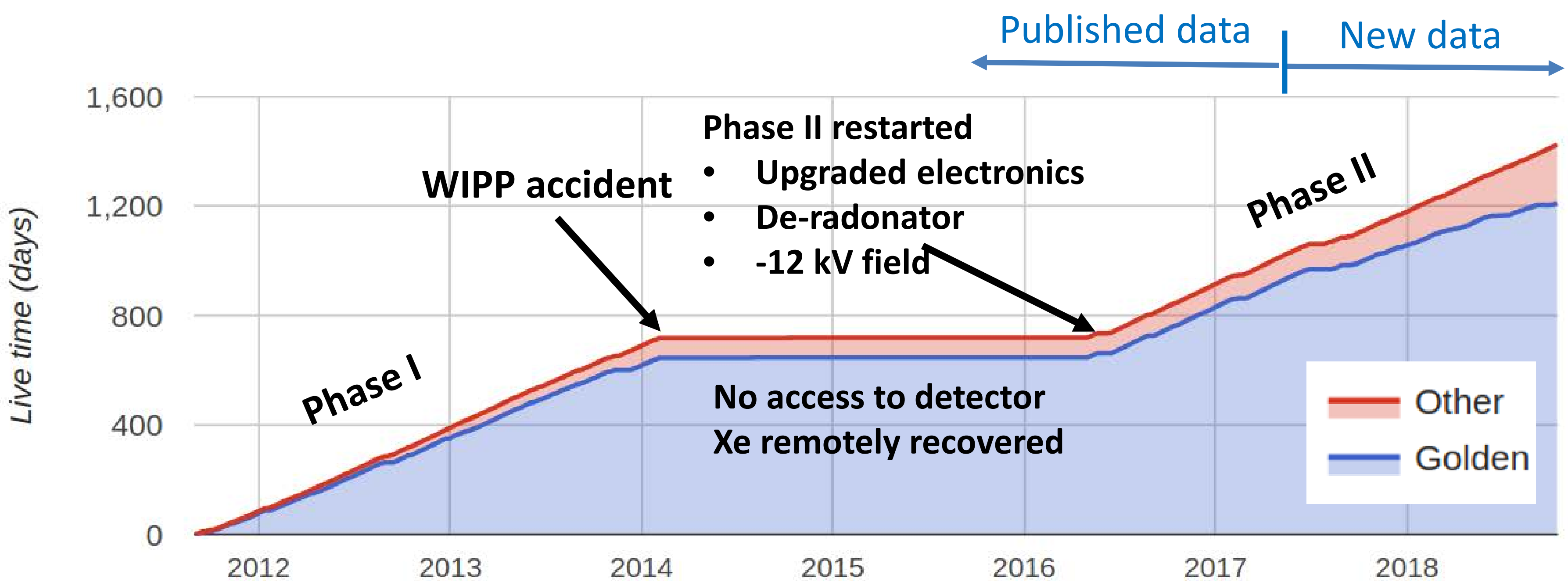


The EXO-200 liquid ^{136}Xe Time Projection Chamber





EXO-200 timeline



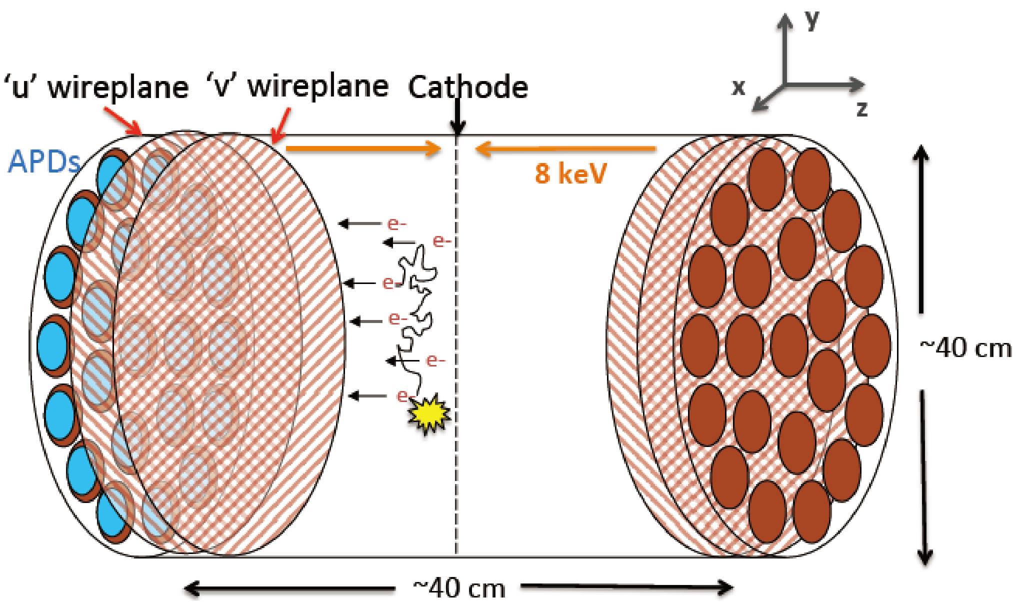
- Operation concluded in Dec 2018, with 1181.3 days of live-time
- **Phase I** from Sep 2011 to Feb 2014
  - Most precise $2\nu\beta\beta$ measurement, *Phys. Rev. C* ***89****, 015502 (2013)*
  - Stringent limit for $0\nu\beta\beta$ search, *Nature* ***510****, 229 (2014)*

- **Phase II** operation begins on Jan 31, 2016 with system upgrades
  - First results with Phase II data, *Phys. Rev. Lett.* ***120****, 072701 (2018)*
  - This talk, new results with complete dataset!

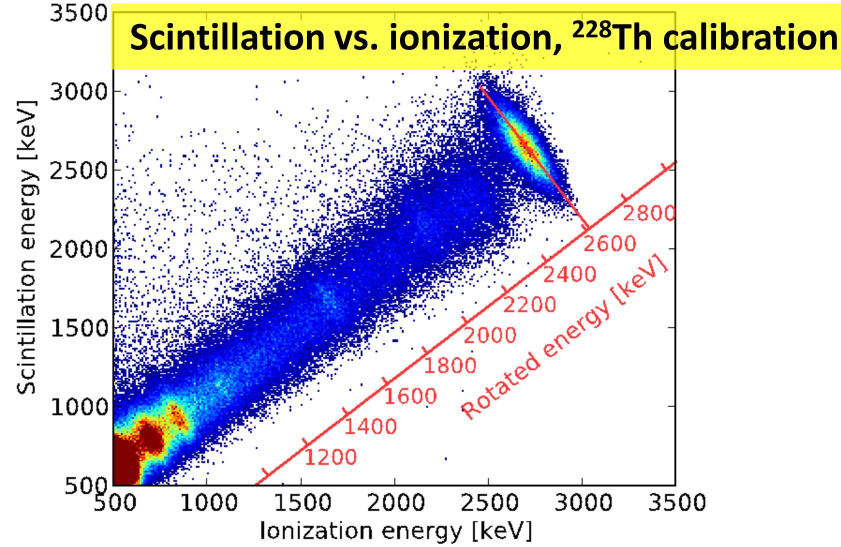
Energy Resolution

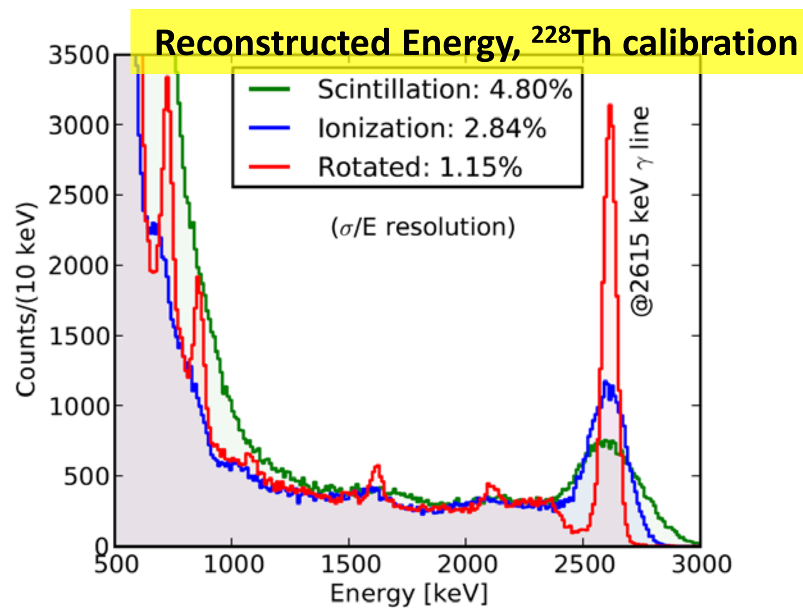
- **Energy meas.** → Combine Light and Ionization

*E. Conti et al. Phys. Rev. B 68 (2003) 054201



Schematic plot of **EXO-200** Time Drift Chamber

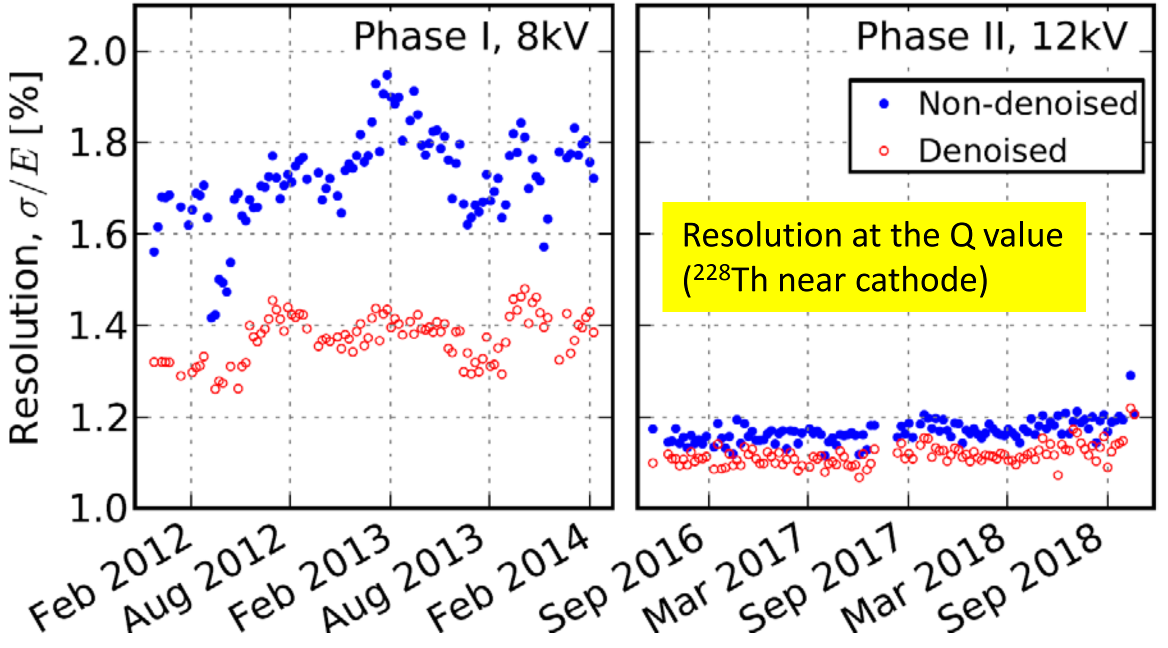




While no one really understands the energy resolution in LXe, scintillation and ionization are anti-correlated and this can be exploited to improve the energy resolution

Improved Resolution in Phase-II

- 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%)

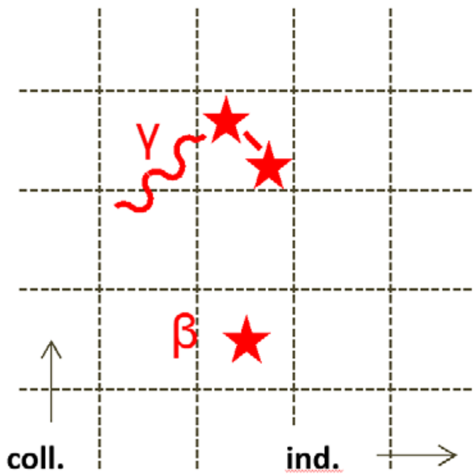
Phase I: 1.35+-0.09%

Phase II: 1.15+-0.02%

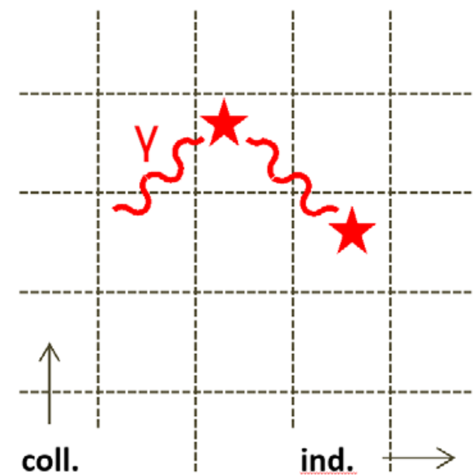
Vertex reconstruction and SS/MS classification

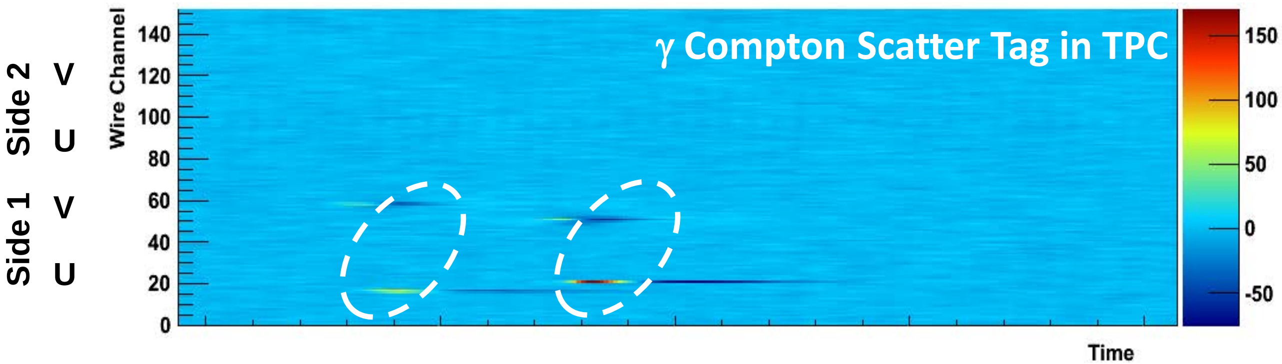
- X/Y (U/V) position determined by the signals in cross wire planes with 9 mm pitch
- Z position determined by the time delay between light signal and collection signals in wires with ~ 6 mm resolution
- ββ mostly deposits energy at single location (SS)
- γ backgrounds deposits at multiple locations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

Single Site Events (SS)



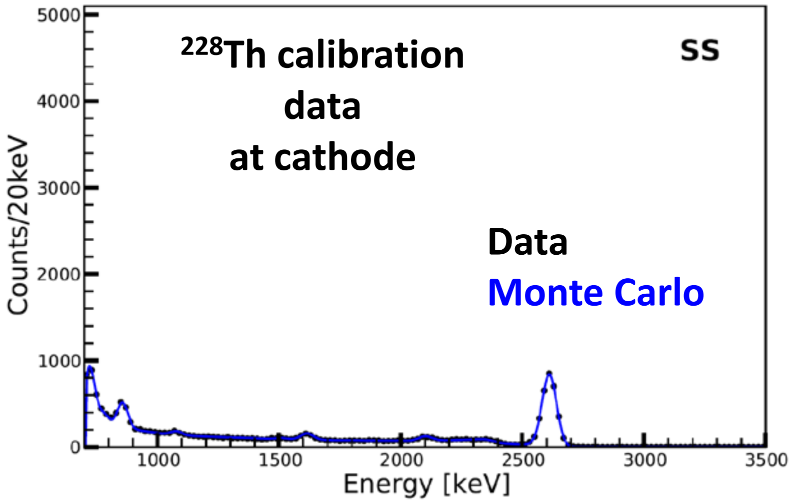
Multiple Site Events (MS)

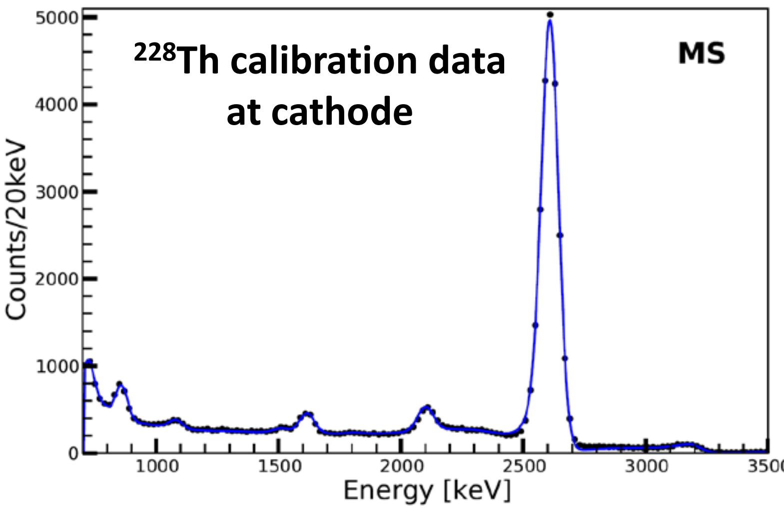




Relaxed 3D cut

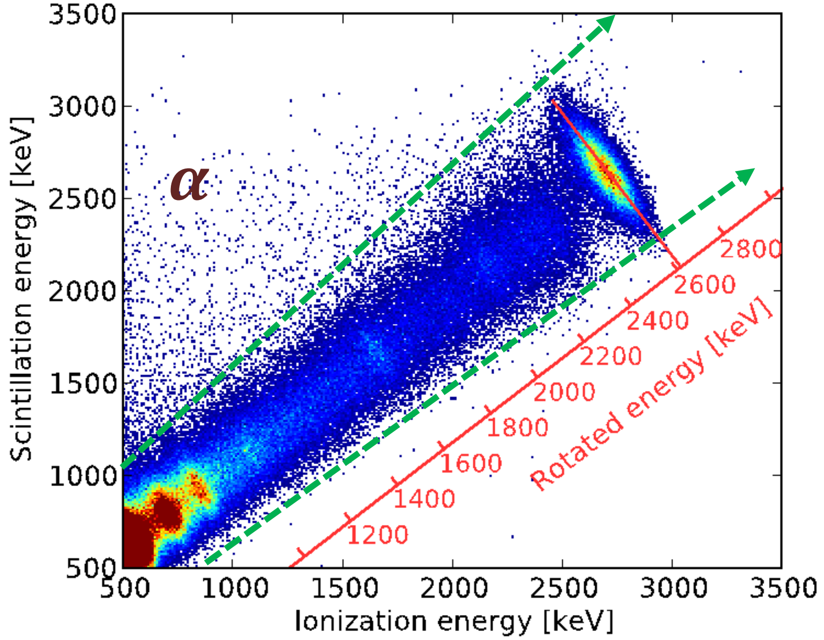
- Previous analyses
  - Require all events having full 3D position
  - Partial 3D events are due to small energy deposit having complete collection on U-wire, but having no V signals because of higher threshold
- This new analysis
  - Require >60% of energy deposits having 3D position, only recovering 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 $Q_{\beta\beta} \pm 2\sigma$ for ^{228}Th source deployed near the cathode





Light/charge Diagonal cut

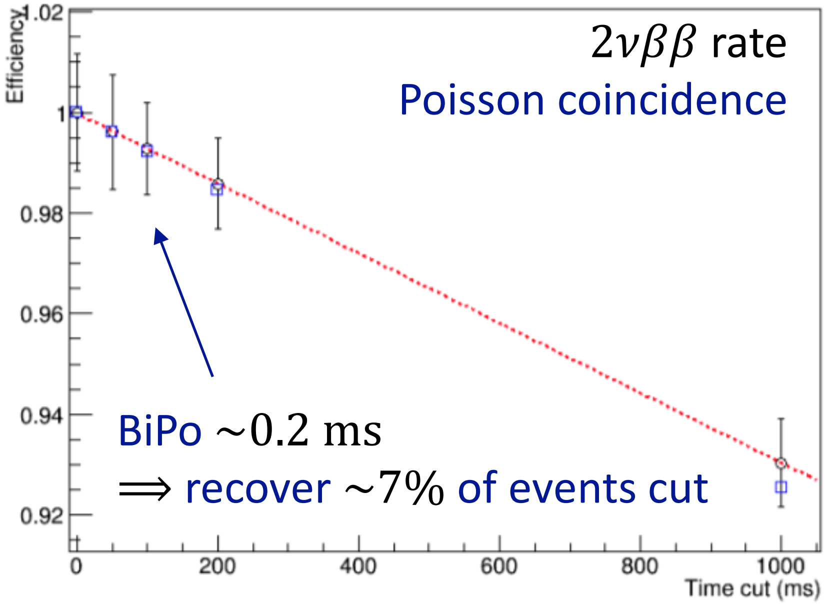
- Powerful to reject α, as well as poorly reconstructed β/γ with anomalous light/charge ratio
- Requires 2D light/charge energy calibration and good understanding of detector
- Light/charge ratio distributions validated by data/MC comparison using source and $2\nu\beta\beta$ data



Improved $0\nu\beta\beta$ detection efficiency

- Event coincidence cut
  - Originally designed to remove time-correlated events, e.g. Bi-Po cascade, potential muon induced long-lived decay products …
  - Later, no evidence of contributions from such cosmogenic isotopes was found (*JCAP 1604 (2016) no.04, 029*)
  - Reducing time cut window from 1s to 0.1 s is still sufficient for rejecting Bi-Po

D. Fudenberg, PhD thesis (2017)



- $0\nu\beta\beta$ detection efficiency increases from ~80% to 97.8±3.0% (96.4±3.0%) for Phase I (II)

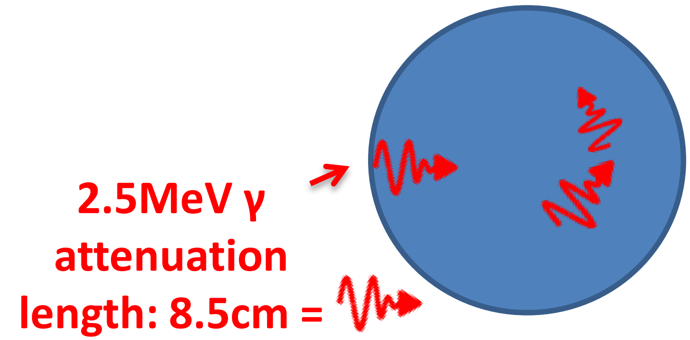
Improved background rejection for SS

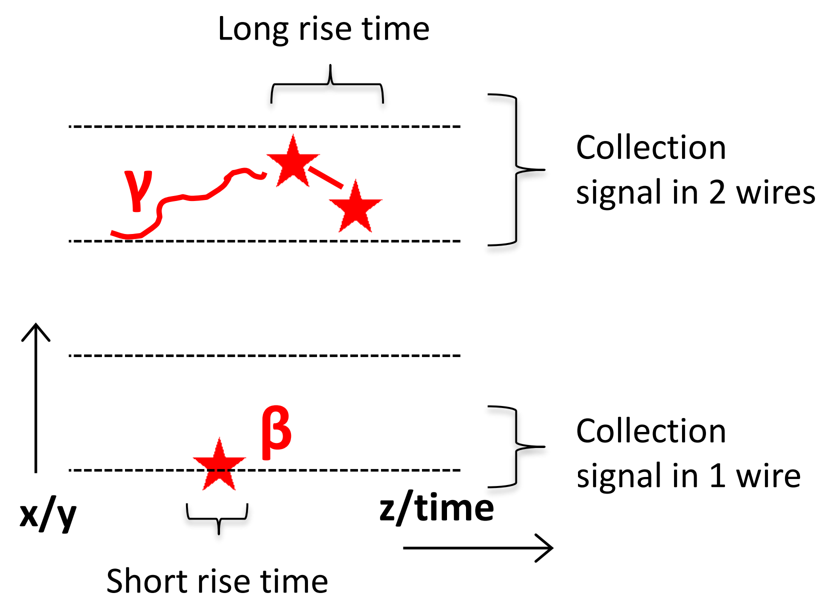
- Additional discrimination in SS: *spatial distribution* and *cluster size*

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

- **Size of individual cluster**
  - pulse rise time (longitudinal)
  - number of wires with collection signal (transverse)

LXe self-shielding:

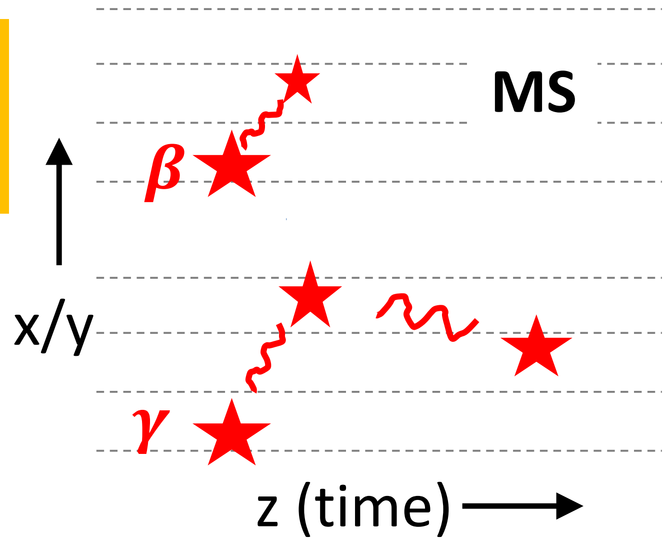




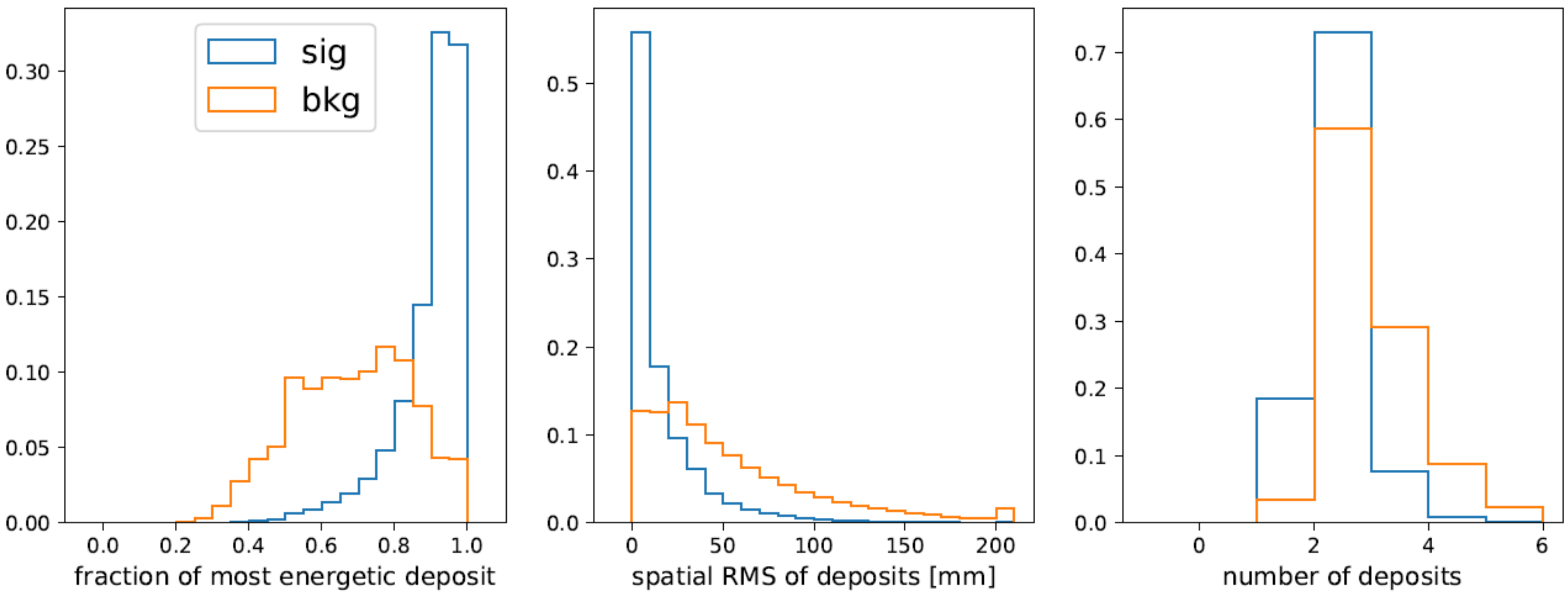
*Techniques already used in Phys. Rev. Lett. **120**, 072701 (2018)*

Improved background rejection for MS

0νββ in MS:
Small energy deposits due to bremsstrahlung

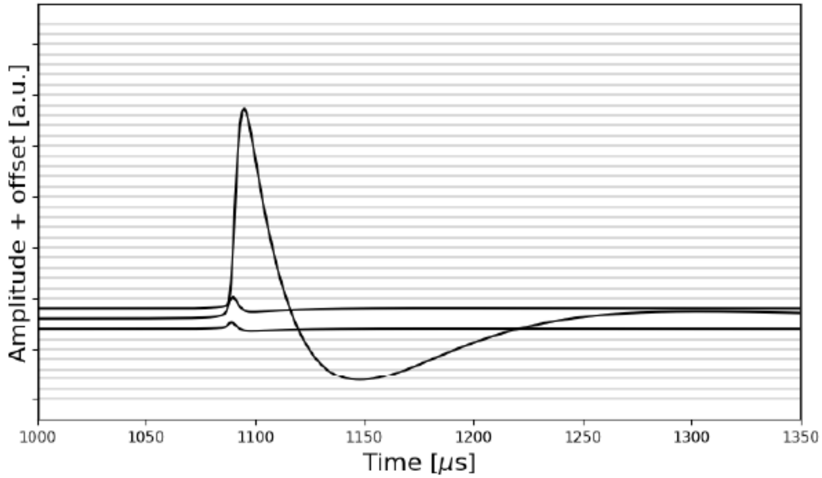


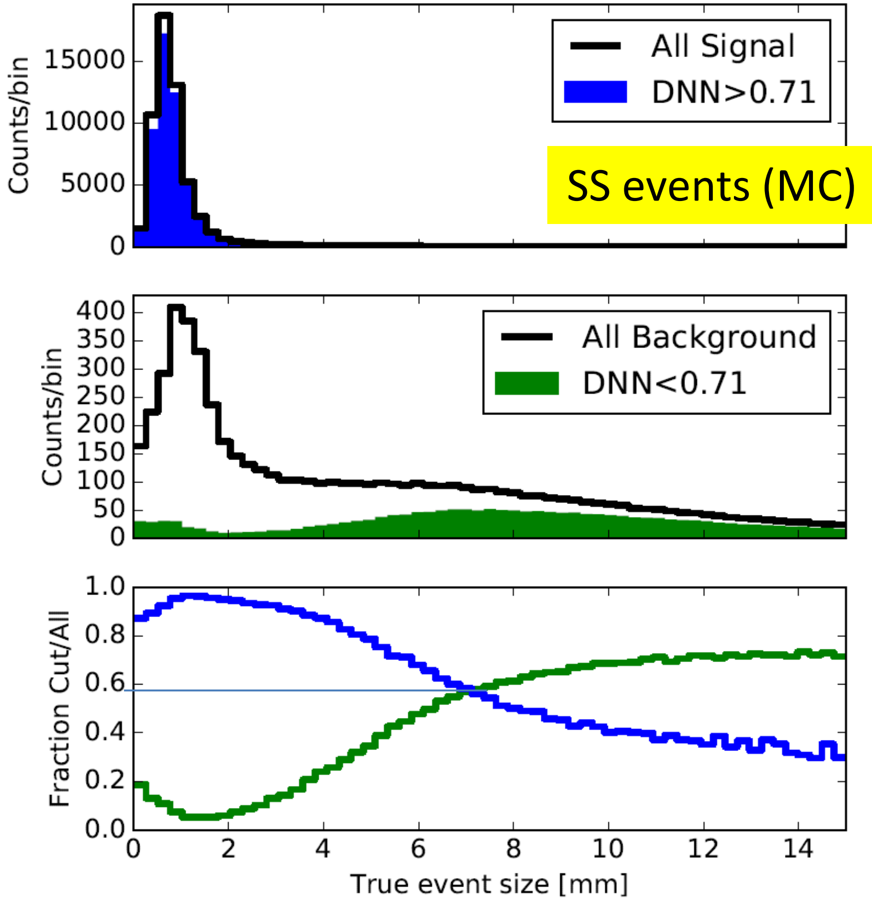
Distinct features allow higher background rejection than in Single-Site, to compensate the fact that Multi-Site is dominated by backgrounds.



Improved background discrimination with DNN

- Deep neural network (DNN) training:
  images built from U-wire waveforms





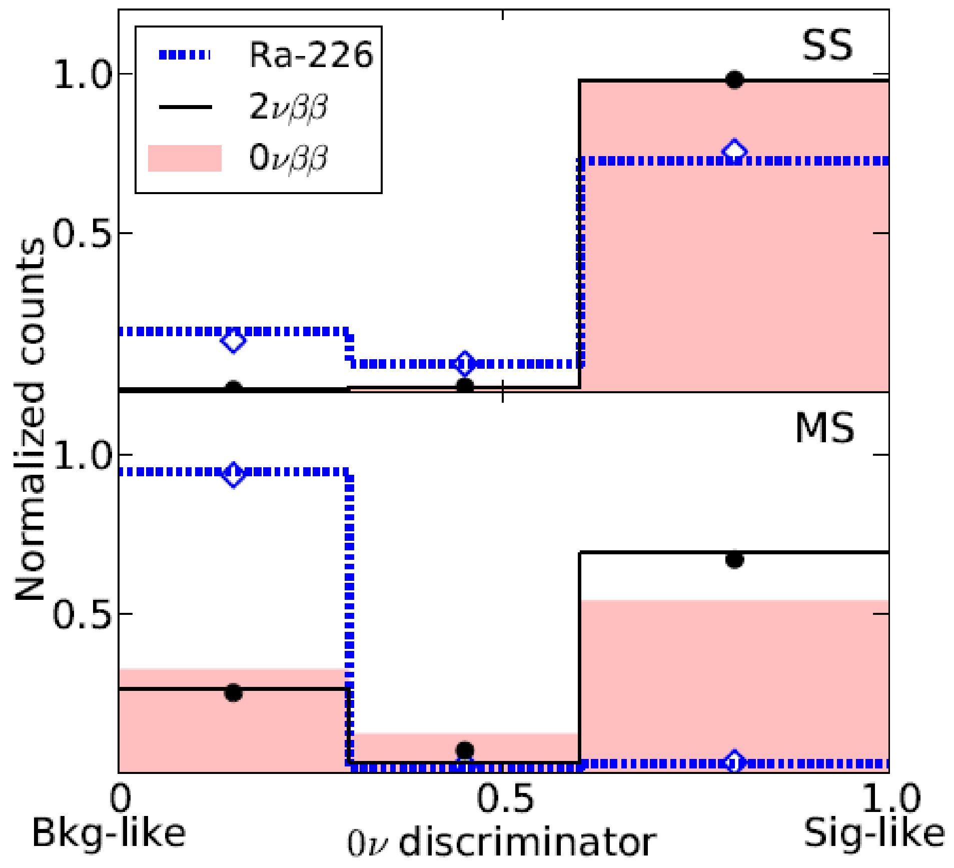
- Using MC data to train DNN, S/B discrimination power correlates with the true event size

  → DNN can pick up correct features on the waveforms for reconstruction

Data/MC agreement for DNN

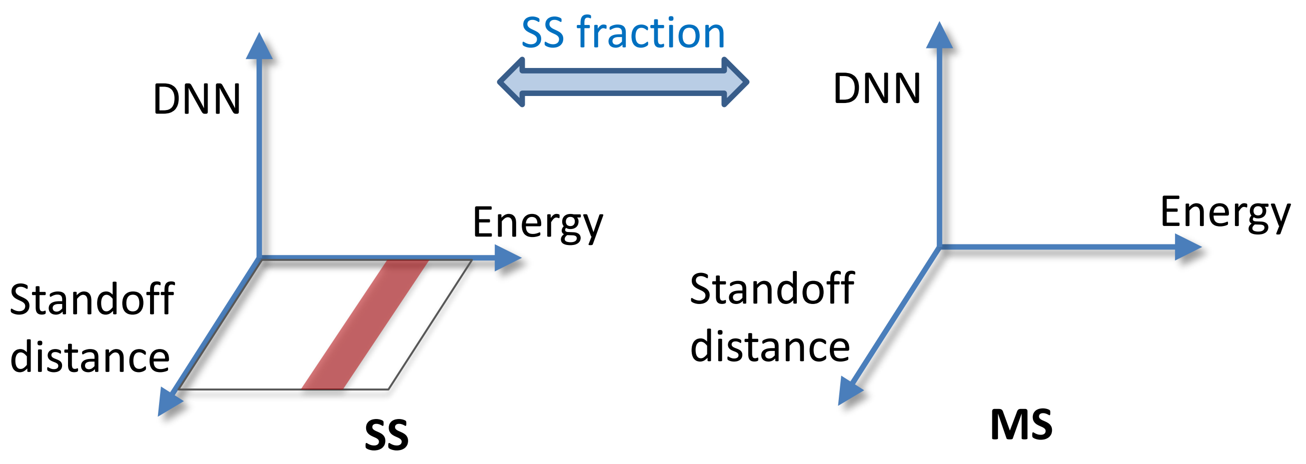
- Data/MC agreement validated with different data
  - **γ:** Ra-226, Th-228, Co-60 calibration sources
  - **β:** $2\nu\beta\beta$ data

- Differences in data/MC are used to evaluate systematic uncertainties on normalization of backgrounds within $Q_{\beta\beta} \pm 2\sigma$



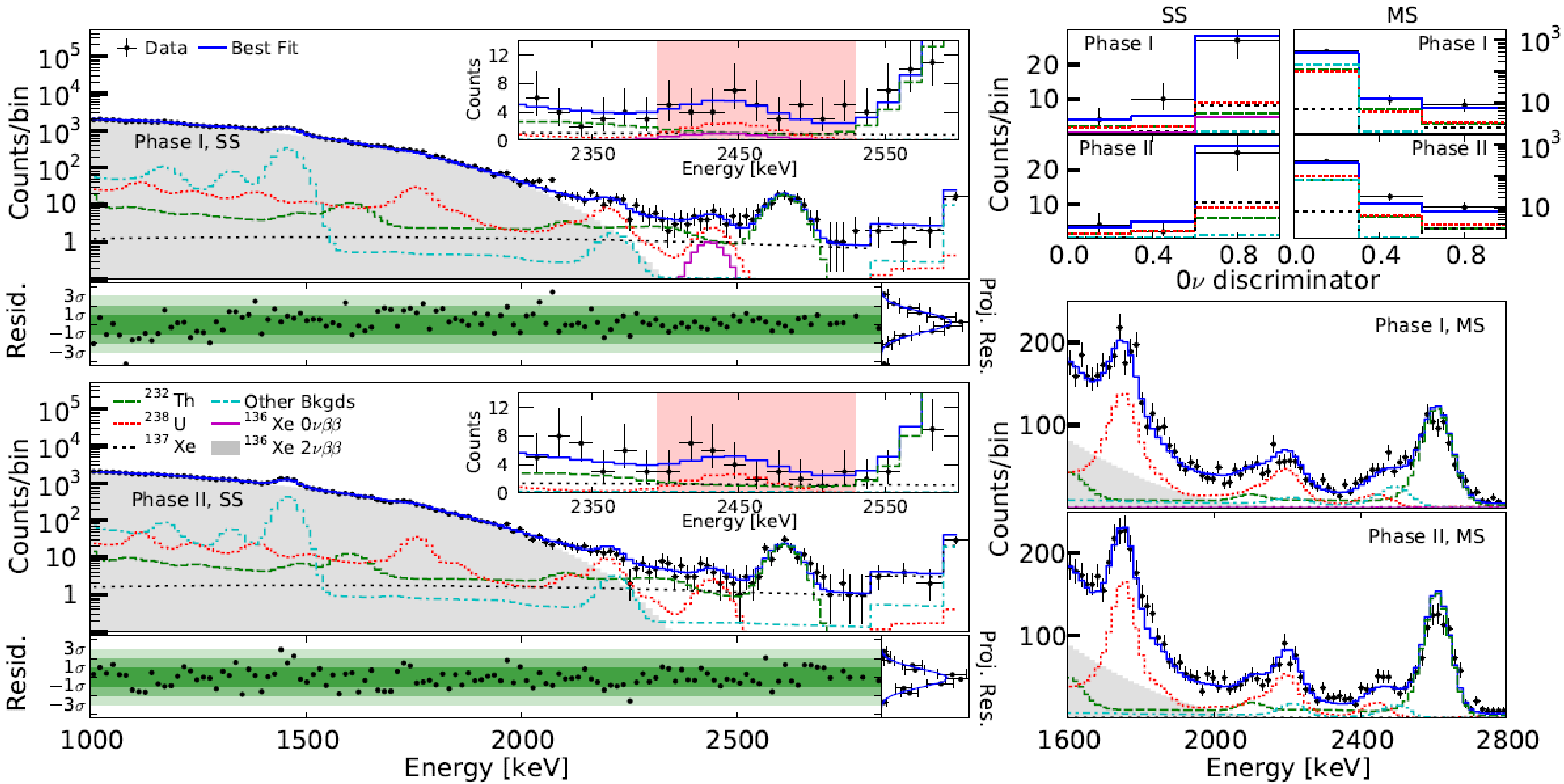
Analysis Strategy

- Blinded analysis performed
- 3-Dimension fit in both SS and MS



  - 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 Spectra



Results

No statistical significant signal observed

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

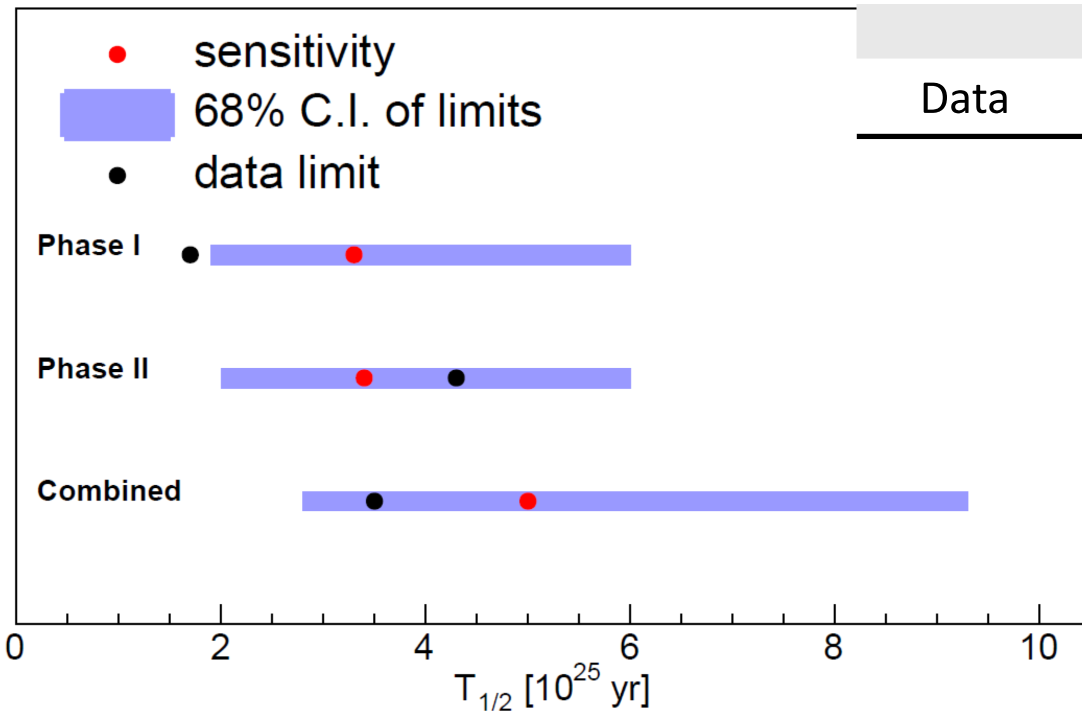
Limit : $T_{1/2}^{0\nu\beta\beta} > 3.5 \times 10^{25}$ yr (90% C.L.)

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

Sensitivity : 5.0×10^{25} yr (90% C.L.)

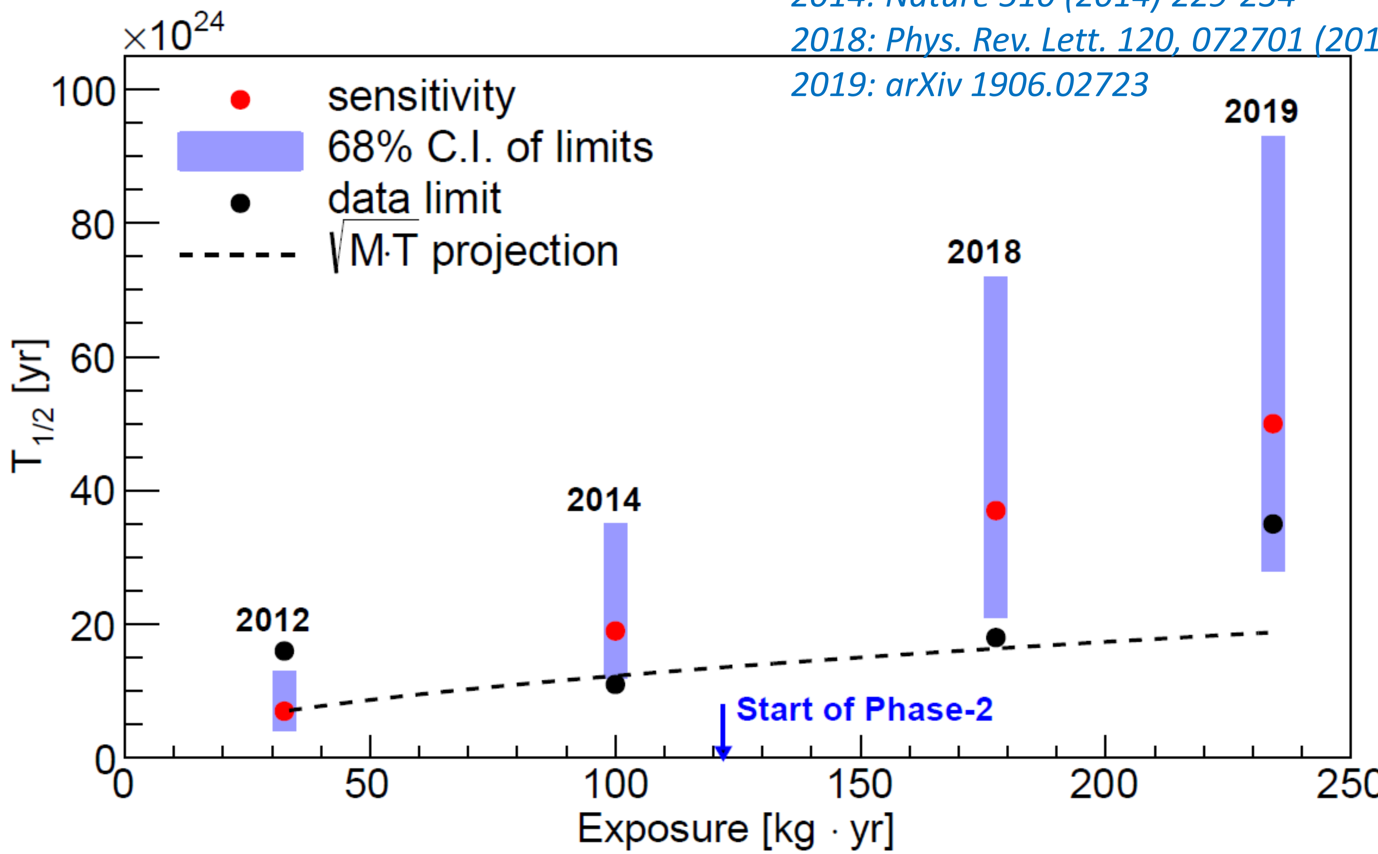
Background contribution to $\mathbf{Q \pm 2\sigma}$

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



A history of EXO-200 Results

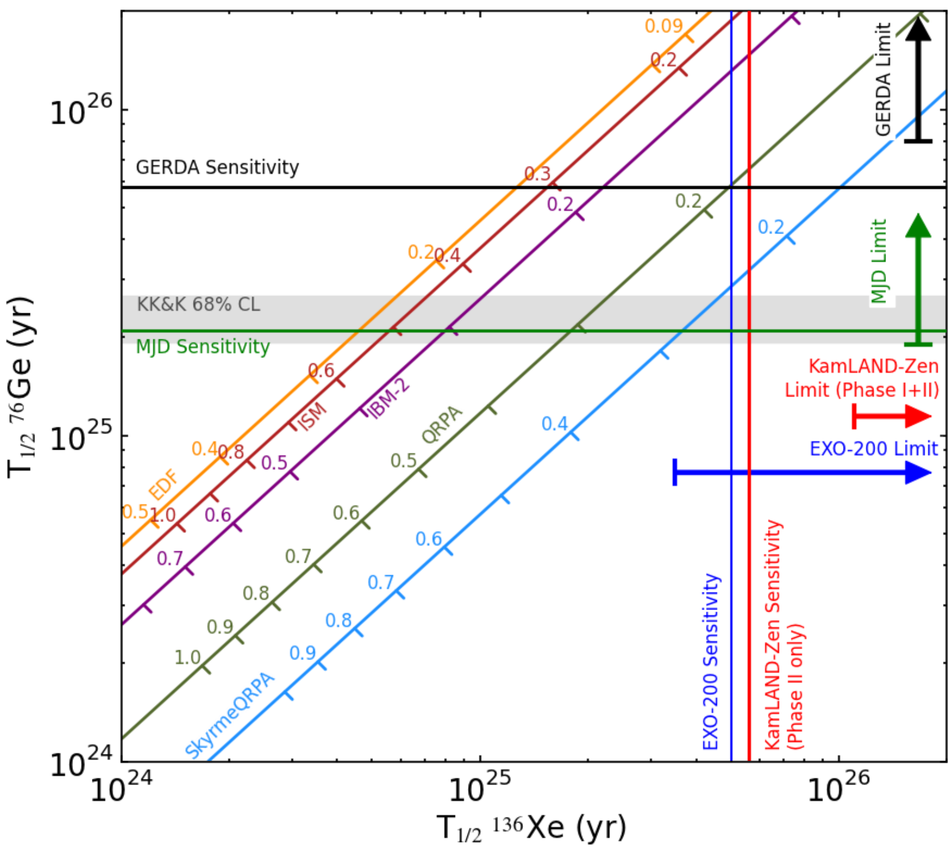
2012: Phys.Rev.Lett. 109 (2012) 032505
2014: Nature 510 (2014) 229-234
2018: Phys. Rev. Lett. 120, 072701 (2018)
2019: arXiv 1906.02723

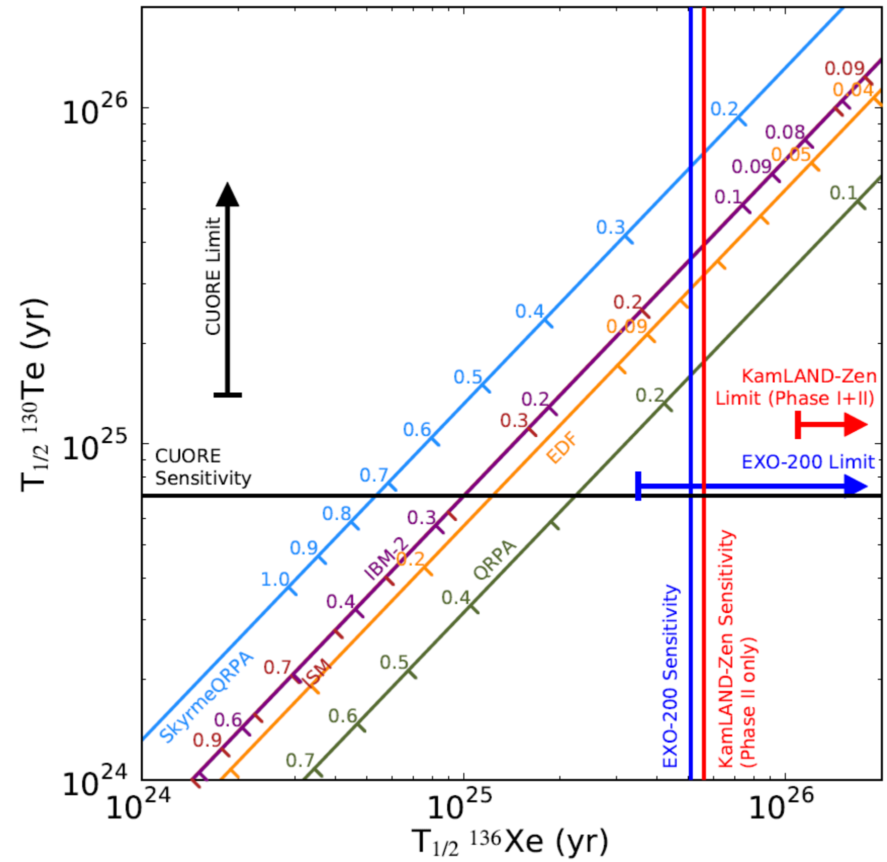


The sensitivity is the correct way to estimate the capability of an experiment, because it contains all the information that can be / is used.

If one wants to use the incomplete picture of a single parameter, then the "background index" is ~ (0.113 ± 0.008)*10^{-3} / (kg·yr·FWHM)

Limits on 0νββ half-life





Because of the uncertainties in the 0νββ decay mechanism and the NME, accurate comparisons between different isotopes are non-trivial.

Example using ^{136}Xe, ^{76}Ge and ^{130}Te (and assuming standard See-Saw)

Summary

- 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 x 10^{25} yr and a sensitivity of 5.0 x 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 ~10^{28} yr half-life

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Thanks!