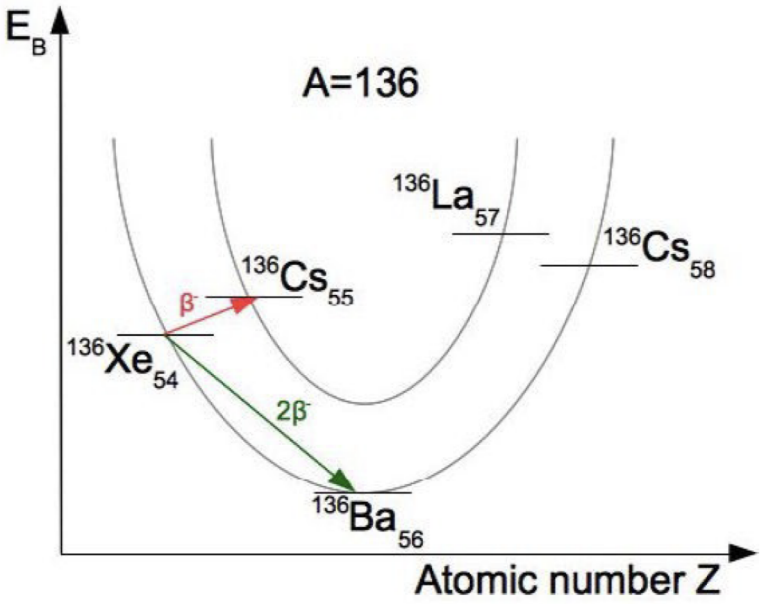
Searching for 0νββ with the EXO-200 Experiment -- Results and Prospects

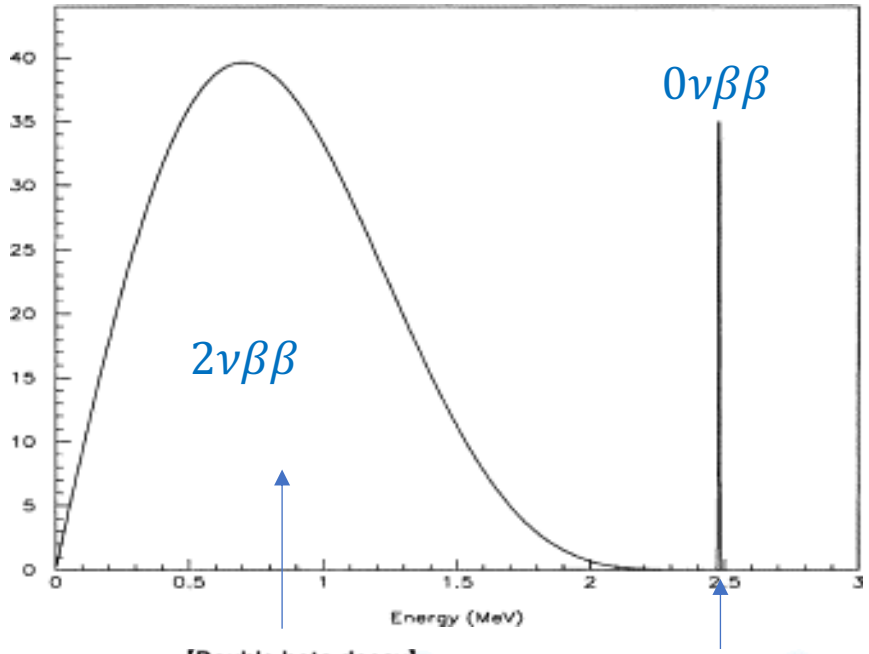
Yale University

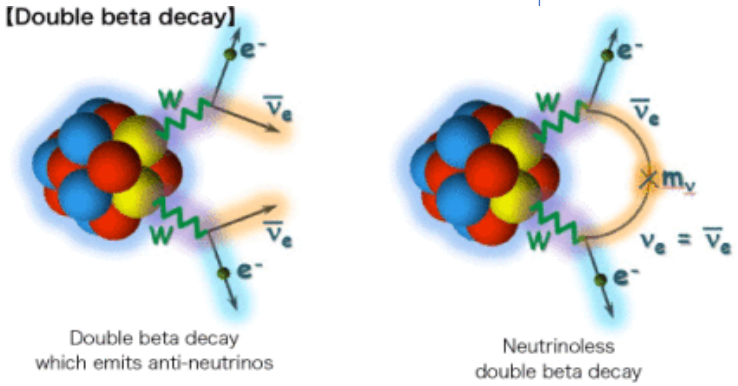
Qing (Shilo) Xia

On behalf of the EXO-200 Collaboration

^{136}Xe double beta decay spectrum







$^{136}Xe\ 2\nu\beta\beta\ \ decay\ half\ life$:
Ref: *Phys. Rev. C 89, 015502* (2014)

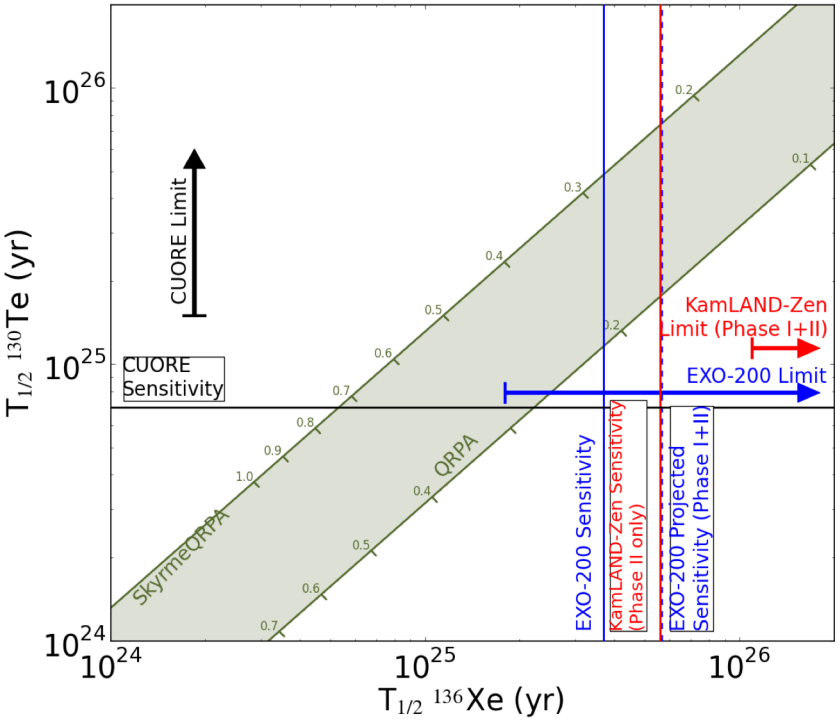
$T_{1/2}(2\nu\beta\beta) = (2.165 \pm 0.016_{stat} \pm 0.059_{sys}) \cdot 10^{21} yr$

$T_{1/2}(0\nu\beta\beta) = ?$

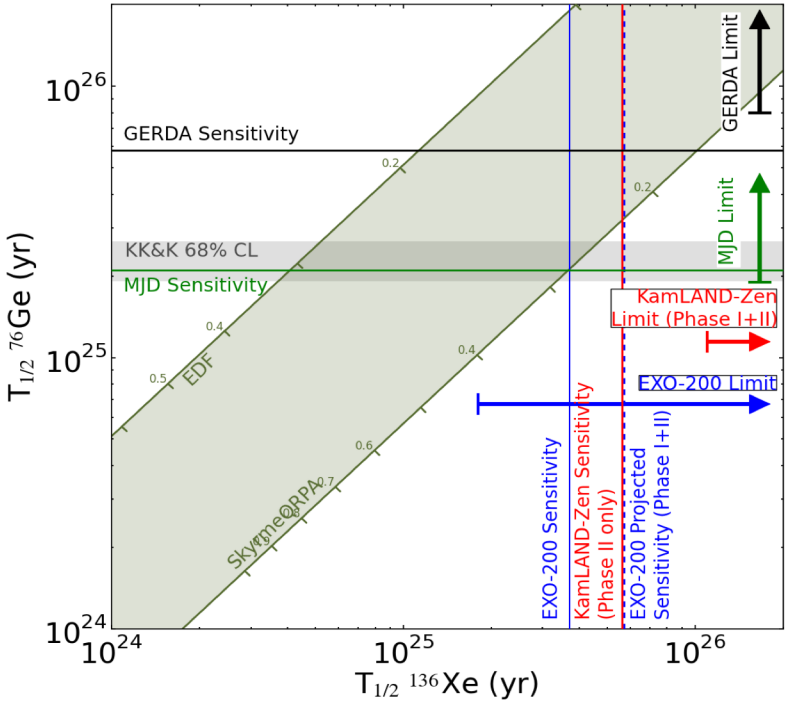
$0\nu\beta\beta$ decay rate $\Gamma = (T_{1/2}^{0\nu})^{-1} = G^{0\nu}|M^{0\nu}|^2|\frac{\langle m_{\beta\beta}\rangle}{m_e}|^2$

- $G^{0\nu}$: phase space factor; $M^{0\nu}$: nuclear matrix element
- $\langle m_{\beta\beta}\rangle = \sum_i U_{ei}^2 m_i$: effective majorana mass

Current limits on $0\nu\beta\beta$ half-life of various isotopes



EXO-200: *Phys.Rev.Lett.120,072701(2018)*
KamLAND-Zen: *PRL 117 (2016) 082503*
CUORE: Phys. Rev. Lett. 120, 132501
Skyrme QRPA: PRC 87, 064302 (2013)
QRPA: PRC 89, 064308 (2014)



EXO-200: *Phys.Rev.Lett.120,072701(2018)*
GERDA: *Phys. Rev. Lett. 120, 132503*
Majorana: *Phys. Rev. Lett.* ***120****, 132502*
KamLAND-Zen: *PRL 117 (2016) 082503*
KK&K Claim: *Mod. Phys. Lett., A21 (2006) 1547*
EDF: PRL 105, 252503 (2010)

The EXO-200 Collaboration

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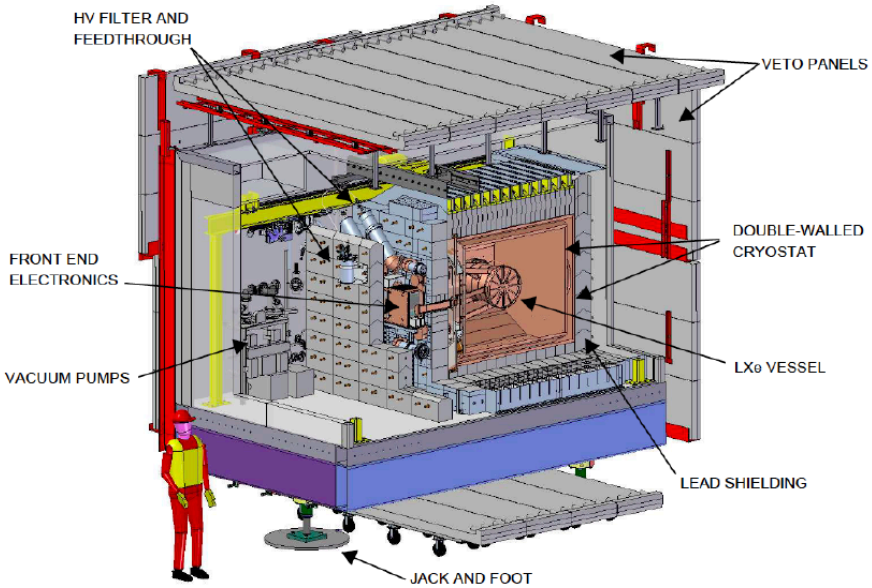
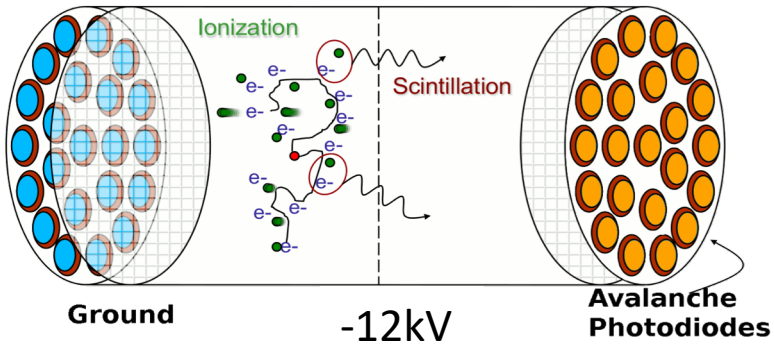
Yale University, New Haven CT, USA — A Jamil, Z Li, D Moore, Q Xia

EXO-200 at WIPP

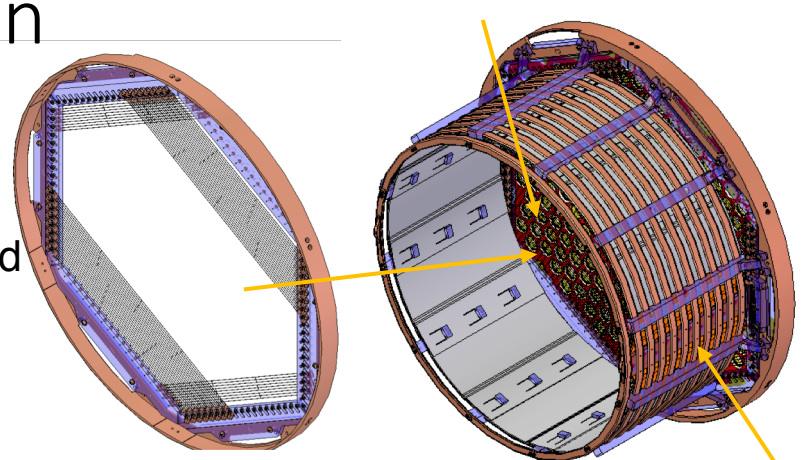
Design of the EXO-200 detector



Charge and light energy deposit in the TPC



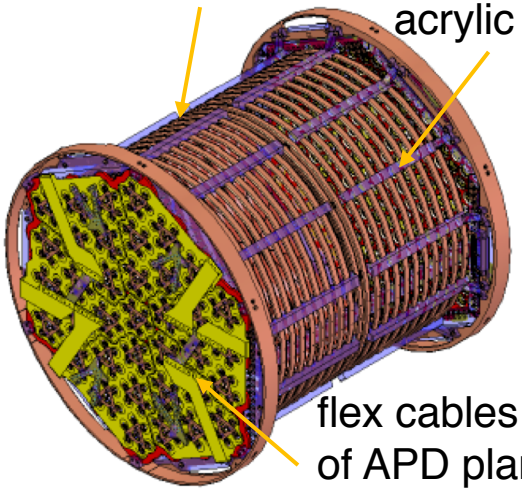
TPC design



crossed charge wires (photo-etched phosphor bronze)

APD plane

field shaping rings (copper)



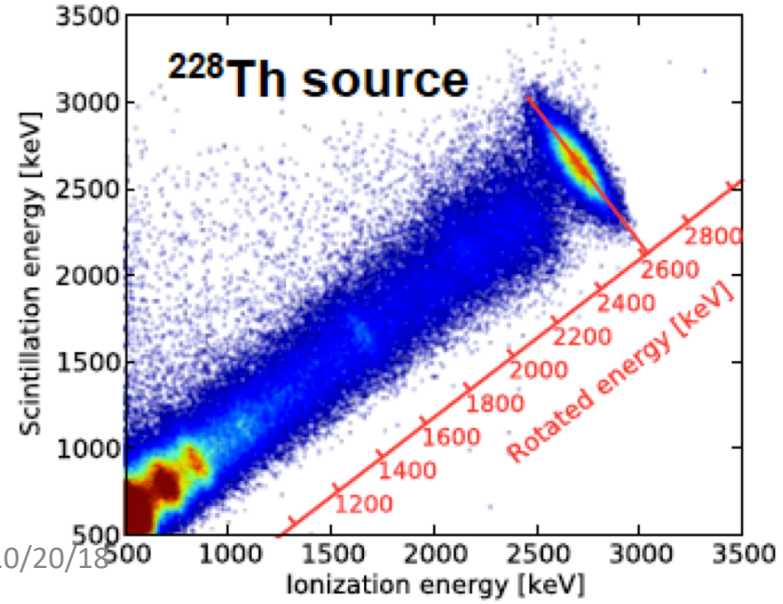
Central HV plane

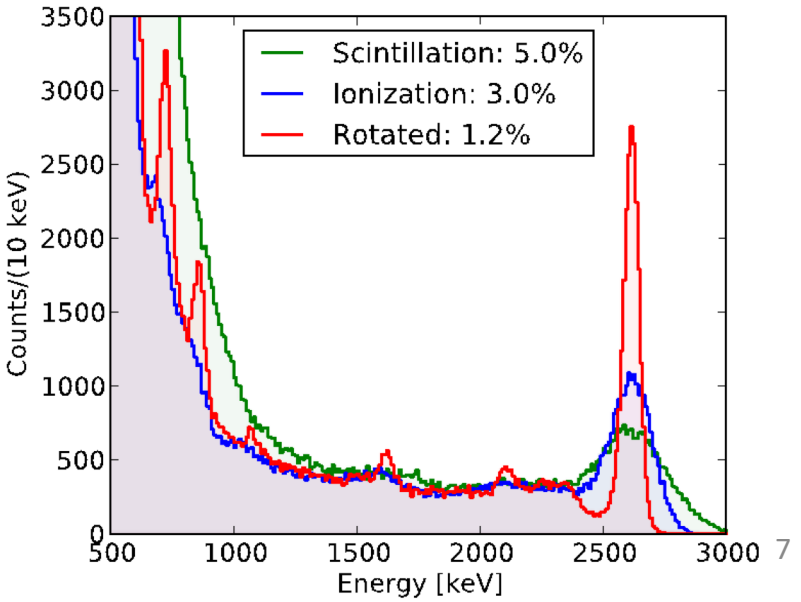
acrylic supports

flex cables on back of APD plane (copper on kapton)

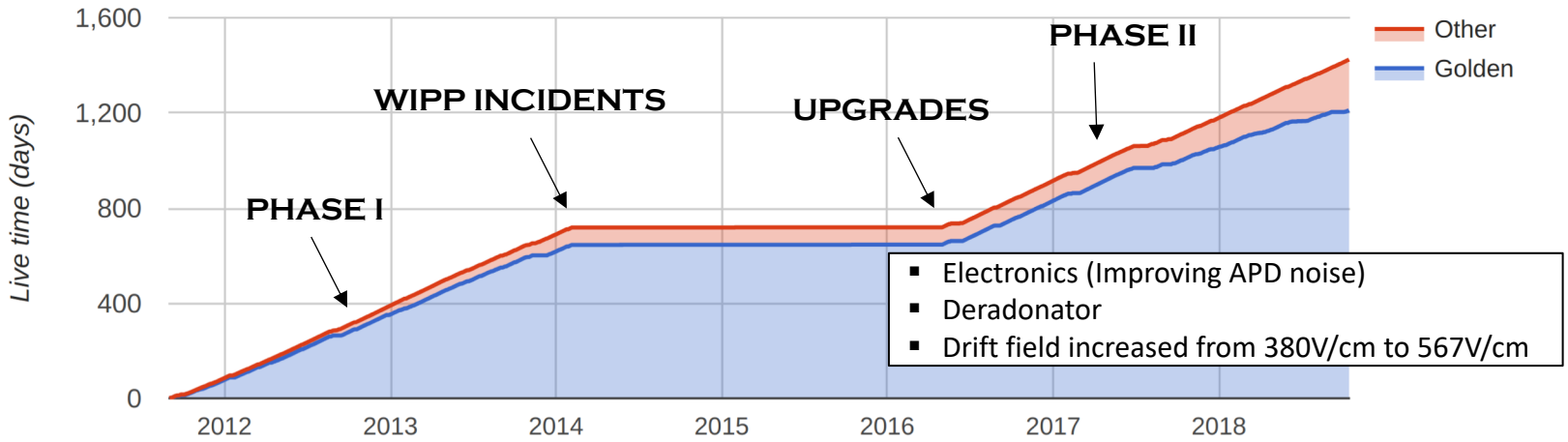
Energy resolution of the detector

- An incident particle generates both charge and light signals the detector
- The elliptical island in the 2D energy histogram below demonstrates the anti-correlation between charge and light energy deposition
- To optimize the energy resolution, we introduce a rotated energy $E_r=E_s\sin\theta+E_c\cos\theta$ (E_s is scintillation energy, E_c is ionization energy)

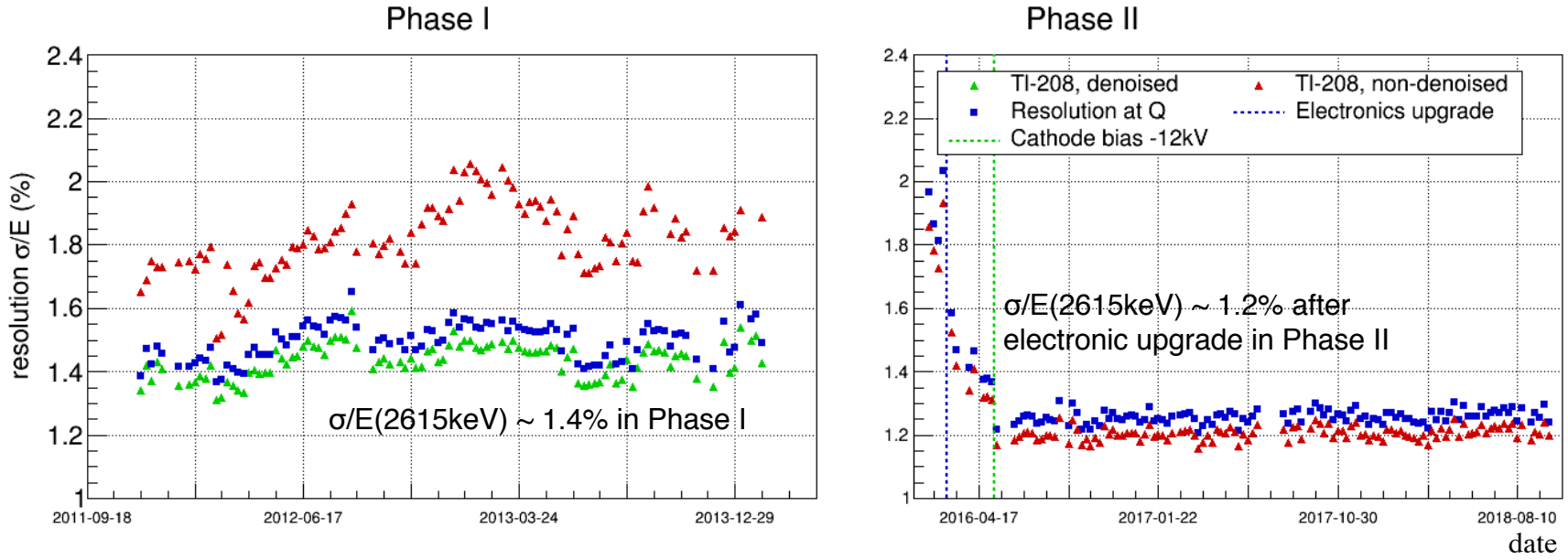




EXO-200 operation



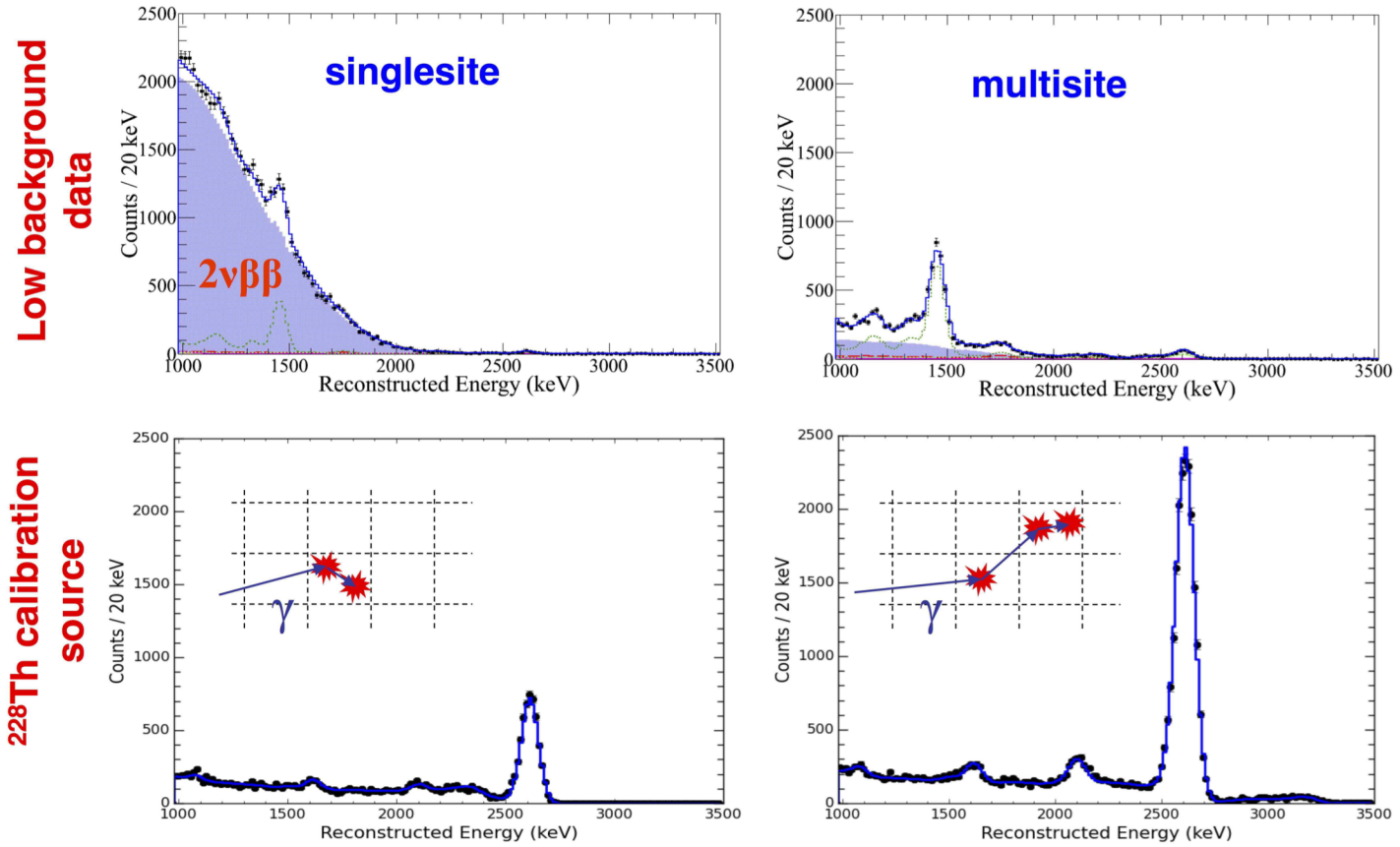
Energy resolution vs. time



- Energy resolution is improved from 1.4% to 1.2% after electronic upgrade

EXO-200 signal/background discrimination

- Topological classification provides good signal/background discrimination
- Electron-like signal events (e.g.$2\upsilon\beta\beta$) are predominantly single-sited, while gamma-like background events are mostly multi-sited

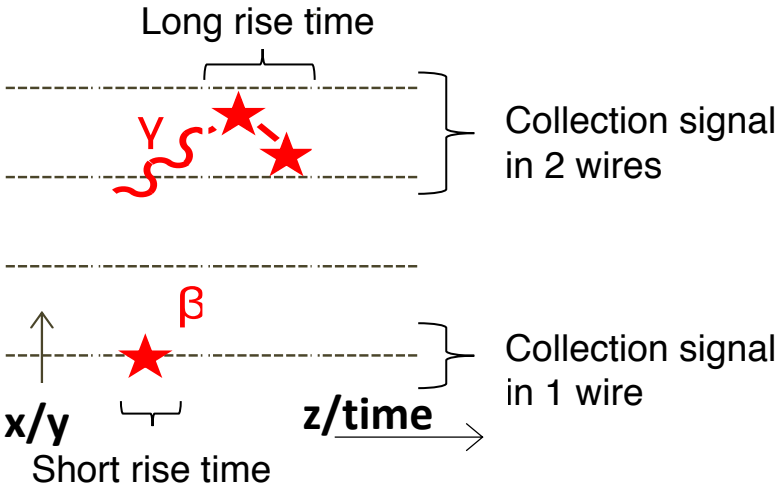


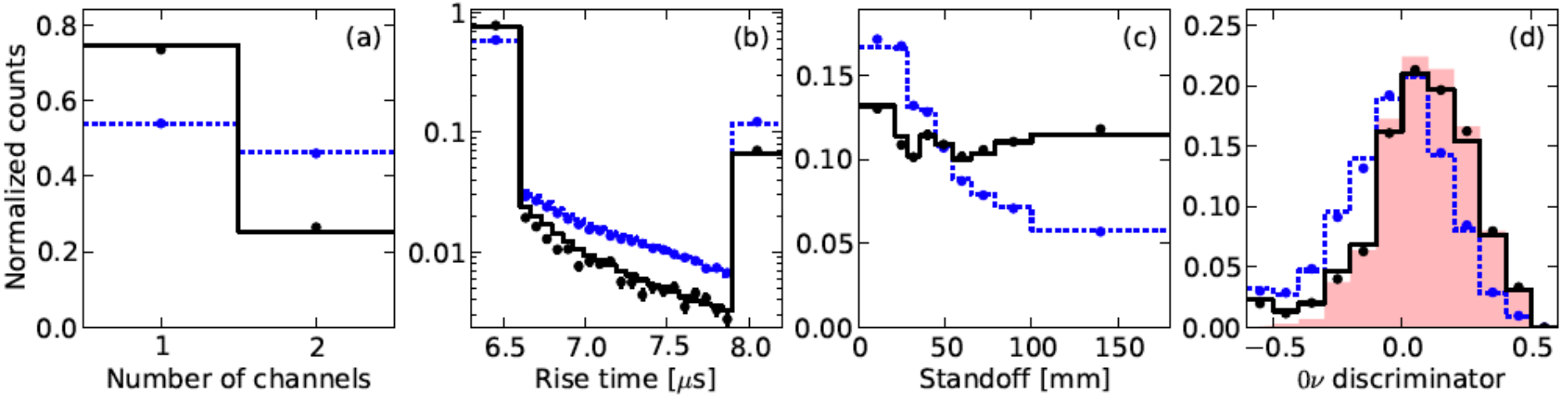
Improved analysis for Phase II

Multi-variate discriminator improves signal/background separation:

- Number of channels hit by the charge cluster
- Rise time of the charge pulse
- Standoff distance

Improved sensitivity by ~15%

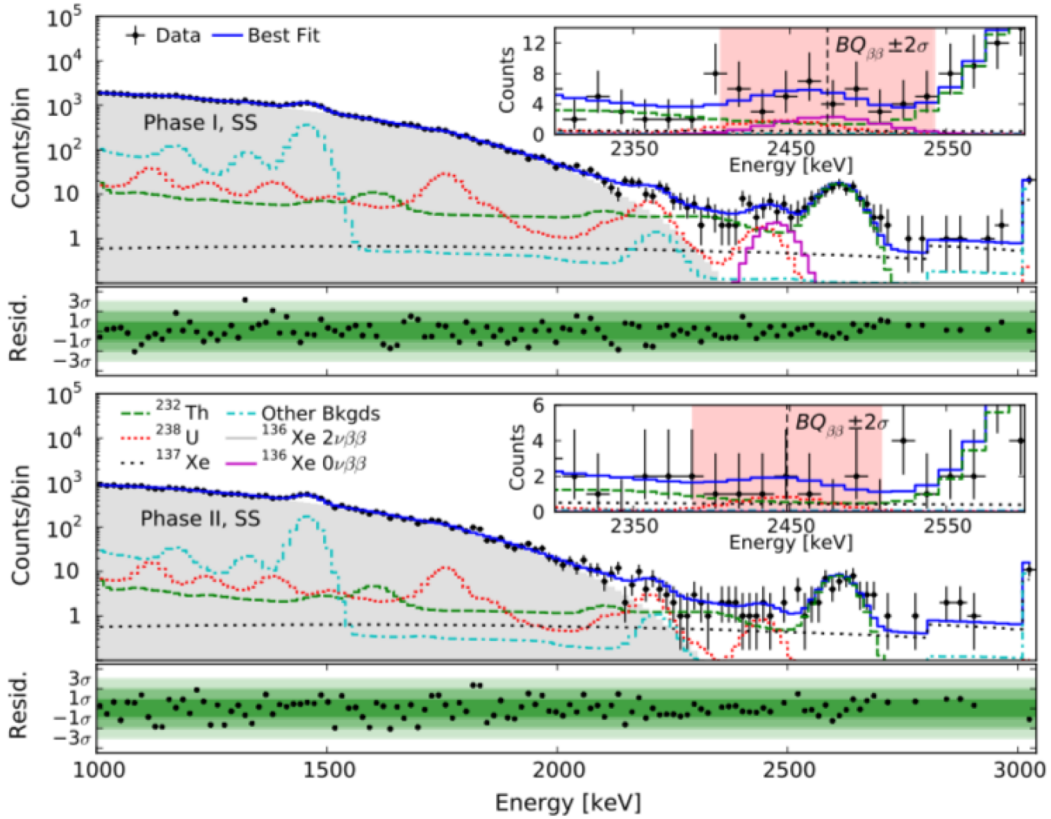


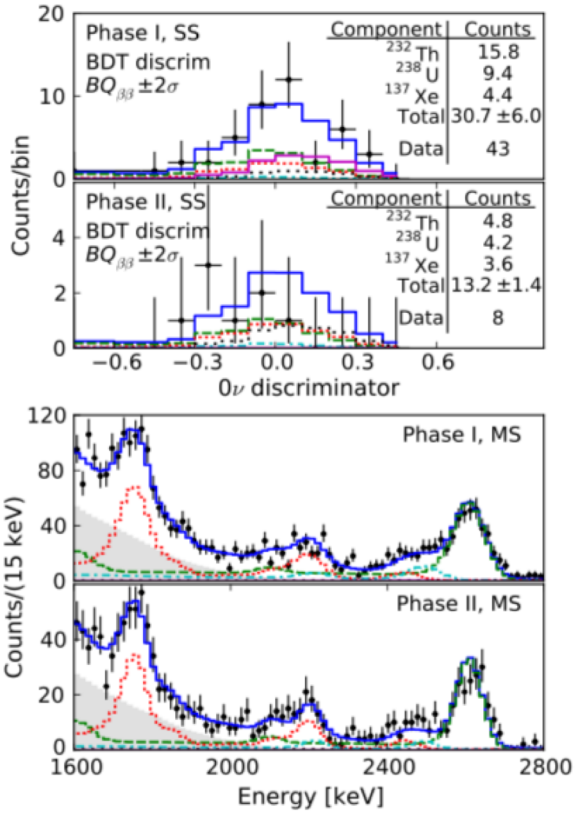


Black dots—$2\upsilon\beta\beta$ data; Black lines—$2\upsilon\beta\beta$ MC;
Blue dots – ^{226}Ra data; Blue lines – ^{226}Ra MC.
Red region – MC of the expected BDT discriminator distribution for a $0\upsilon\beta\beta$ signal

Phys. Rev. Lett. 120, 072701 (2018)

Comparison between energy spectrum for Phase I and Phase II



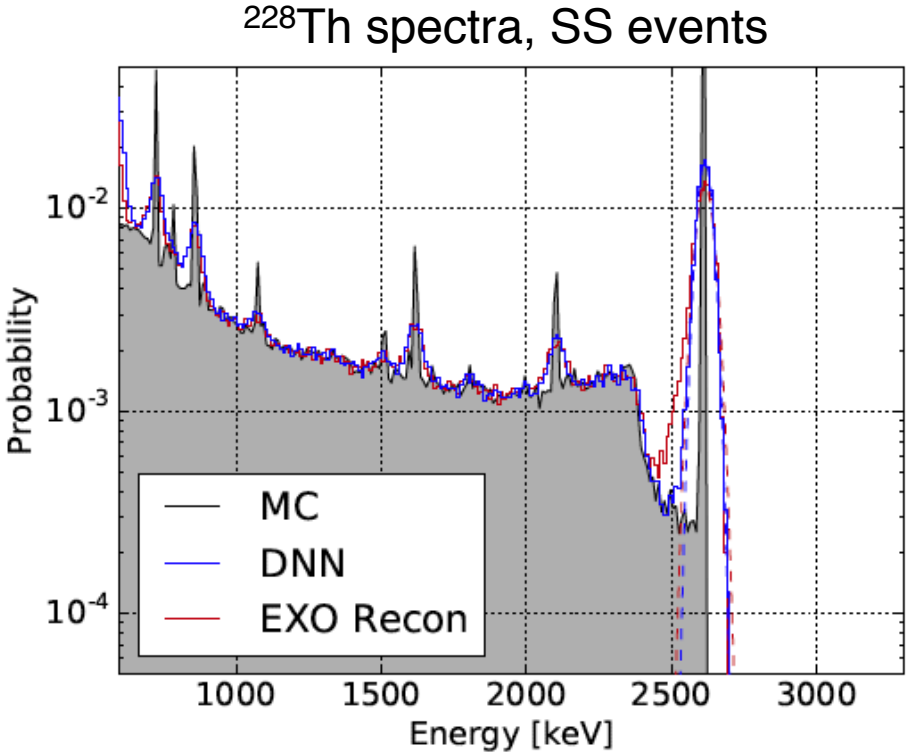


EXO-200	Sensitivity	Limit, 90%CL
2012	0.7×10^{25} yr	1.6×10^{25} yr
2014	1.9×10^{25} yr	1.1×10^{25} yr
2018	3.7×10^{25} yr	1.8×10^{25} yr

Phys. Rev. Lett. 120, 072701 (2018)

Deep Neural Networks (DNN) for Charge Energy Reconstruction

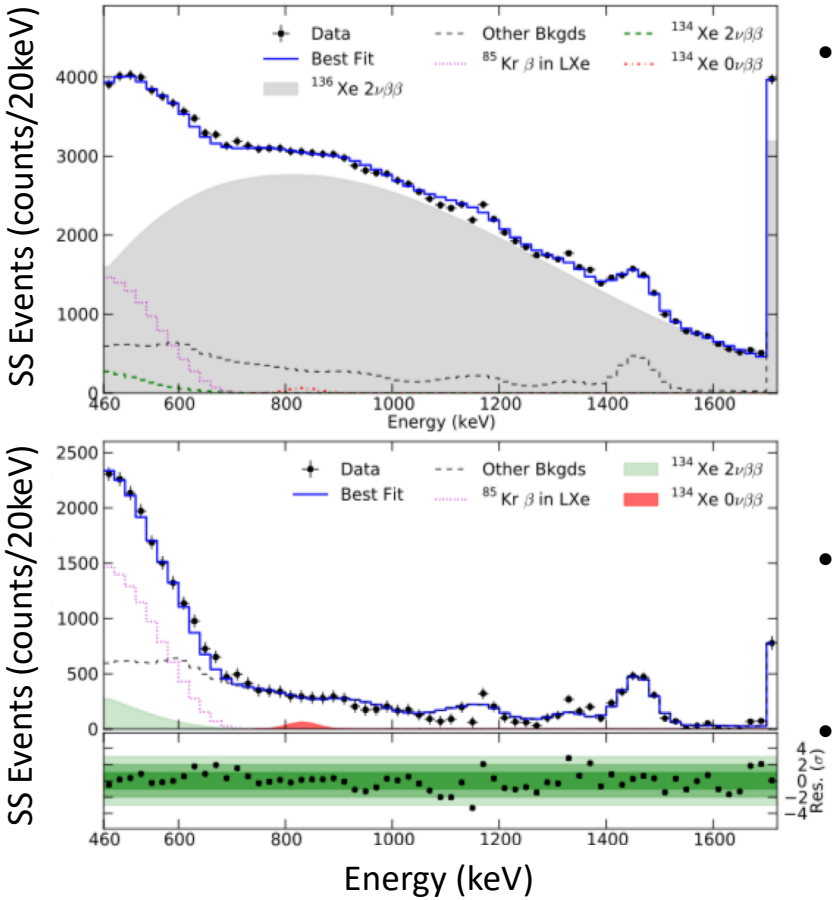
- Monte Carlo simulation generates a large number of events for which the “true charge energy” is known.
- DNN extracts energy directly from 76 charge readout channels’ waveform patterns.
- DNN reconstructs a better charge energy resolution than the standard EXO reconstruction method.



2018 JINST 13 P08023

Search for double beta decay of ^{134}Xe

$$^{134}Xe \rightarrow 134Ba^{++} + 2e^{-}(+2\bar{\nu}_e) \qquad \text{Q value} = 825.8 \pm 0.9keV$$



- Results from EXO-200 measurement (*Phys. Rev. D 96, 092001, 2017*):

  $T_{1/2}^{2\nu\beta\beta} > 8.7\times10^{20}\ yr$ at 90% C.L.
  (Theoretical value: $\sim10^{24} - 10^{25} yr$)

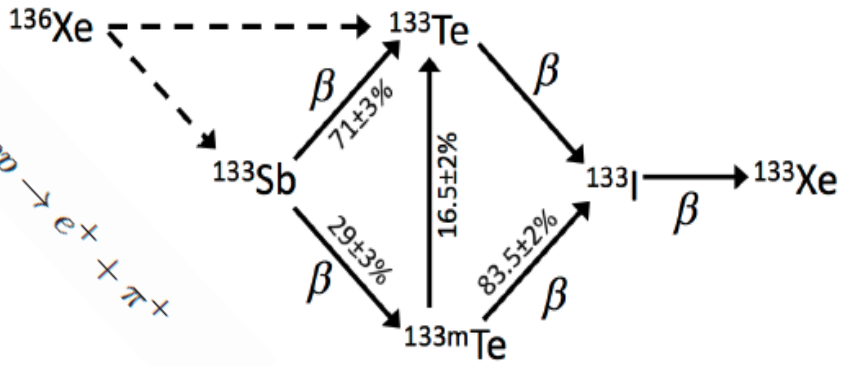
  $T_{1/2}^{0\nu\beta\beta} > 1.1\times10^{23}\ yr$ at 90% C.L.

- Improved by factors of 10^5 and 2 respectively compared to previous measurements.
- Lower scintillation noise and reduced ^{85}Kr in Phase II will improve search sensitivity

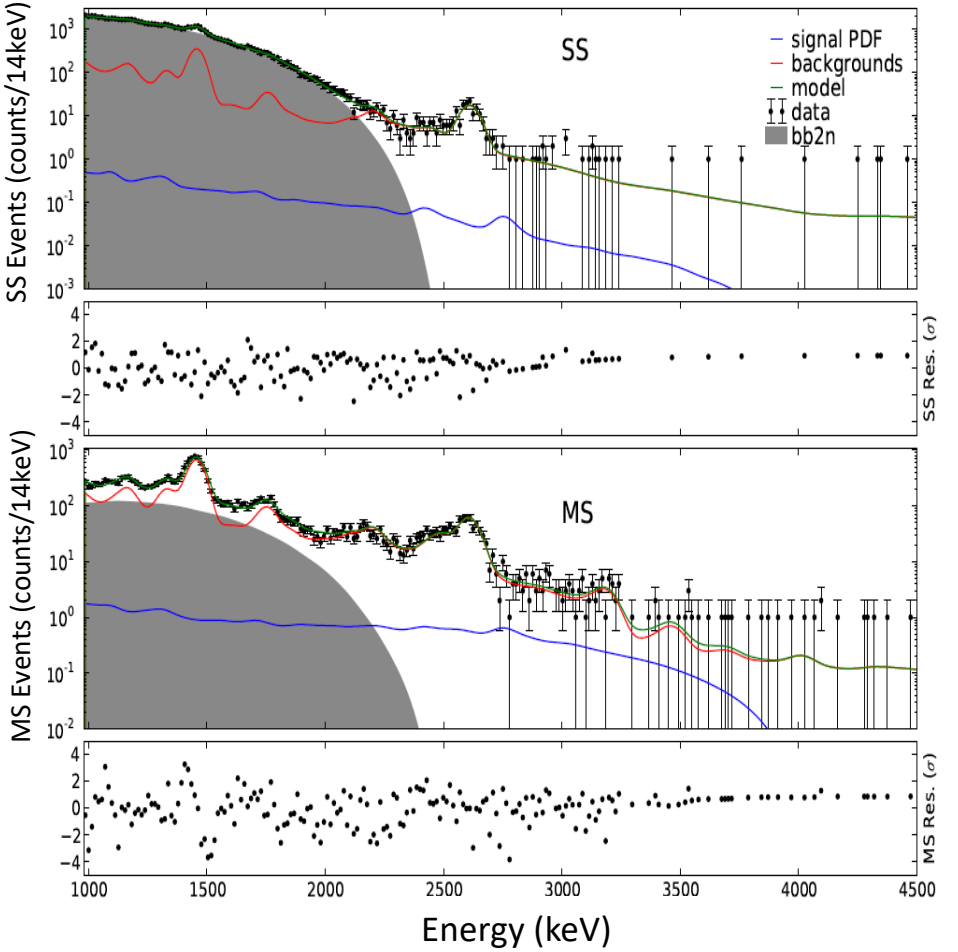
Search for nucleon decay using EXO-200

- Searched for exotic nucleon decay with ΔB =3
- Tested at $\Lambda \sim 10^2$ GeV energy scale

$$ppp \rightarrow e^+ + \pi^+ + \pi^+$$



Best-fit model for decay to ^{133}Sb:

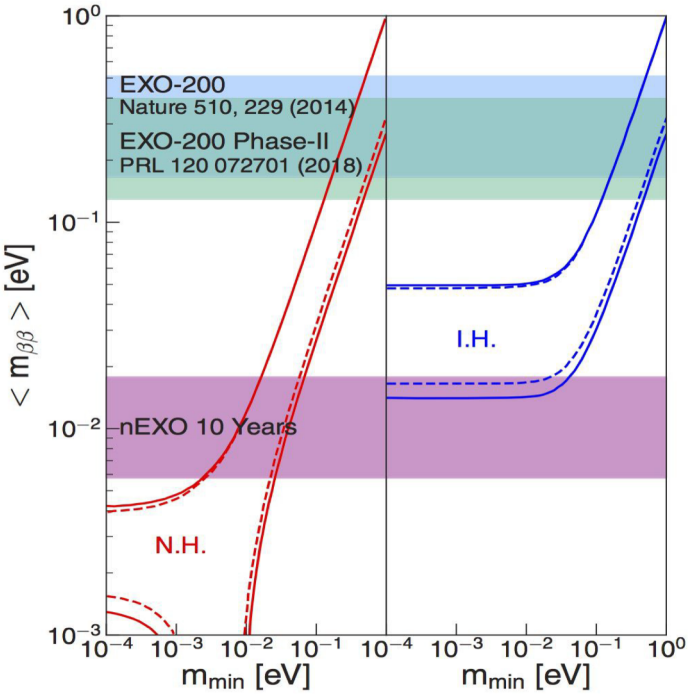


- Lifetime limits for ^{133}Sb: 3.3×10^{23} yr
- Lifetime limits for ^{133}Te: 1.9×10^{23} yr
- Exceeding the prior decay limits by a factor of 9 and 7, respectively

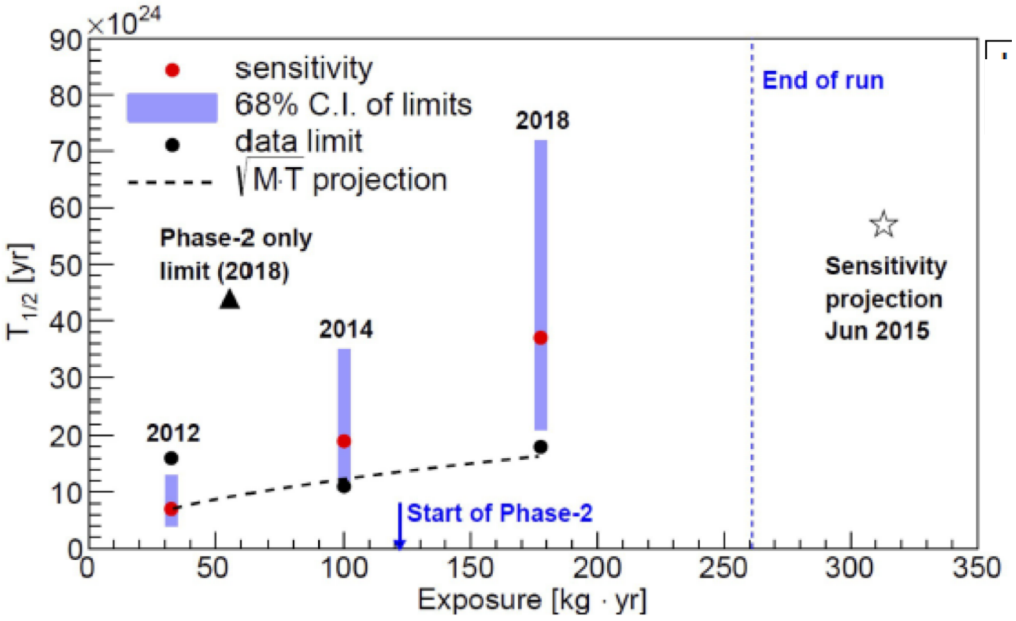
Phys. Rev. D 97, 072007 (2018)

Conclusion

- EXO-200 demonstrated the potential of monolithic / homogenous LXe detectors
- Detector sensitivity improved by a factor two ($1.9 \cdot 10^{25}$ yr in 2014, $3.7 \cdot 10^{25}$ yr in 2018)



EXO-200 detector sensitivity



- $T_{1/2}^{0\nu\beta\beta}(^{136}Xe) > 1.8\times10^{25}$ yr, $\langle m_{\beta\beta} \rangle < (147 - 398) meV$
- Significant improvement in the measurement of triple nucleon decay half-life
- Final results will follow after the end of Phase II at the end of year
- R&D towards a tonne-scale detector nEXO on the way, will reach a sensitivity of 10^{28} yr

Mahalo for your attention!

Backup slides

Experimental backgrounds and the importance of the detector's resolution

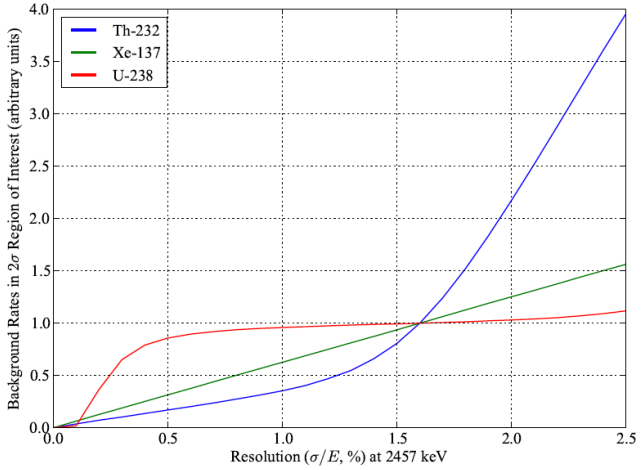
- Signal: ^{136}Xe $0\upsilon\beta\beta$'s signature mono-energetic peak at Q=2458 keV
- Main backgrounds :

  ^{137}Xe β decay with an endpoint energy of 4173 keV.

  ^{208}Tl from ^{232}Th decay chain--gamma peak 2615 keV; Compton edge at 2382 keV.

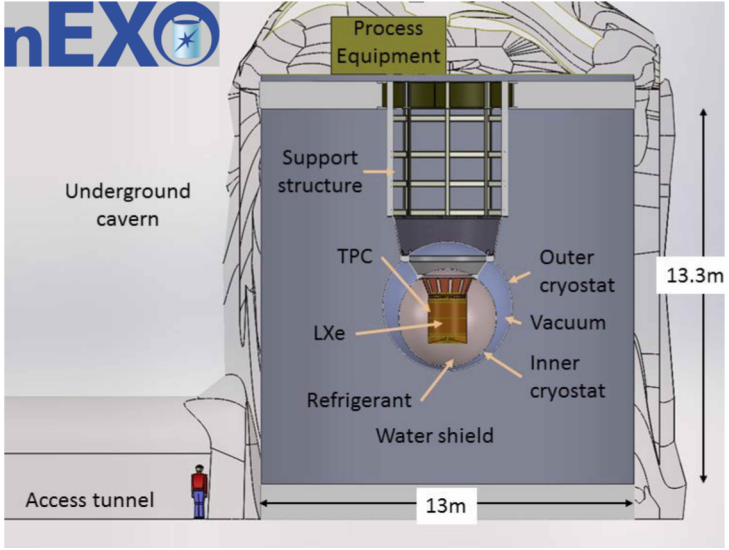
  ^{214}Bi from ^{238}U decay chain-- gamma at 2448 keV

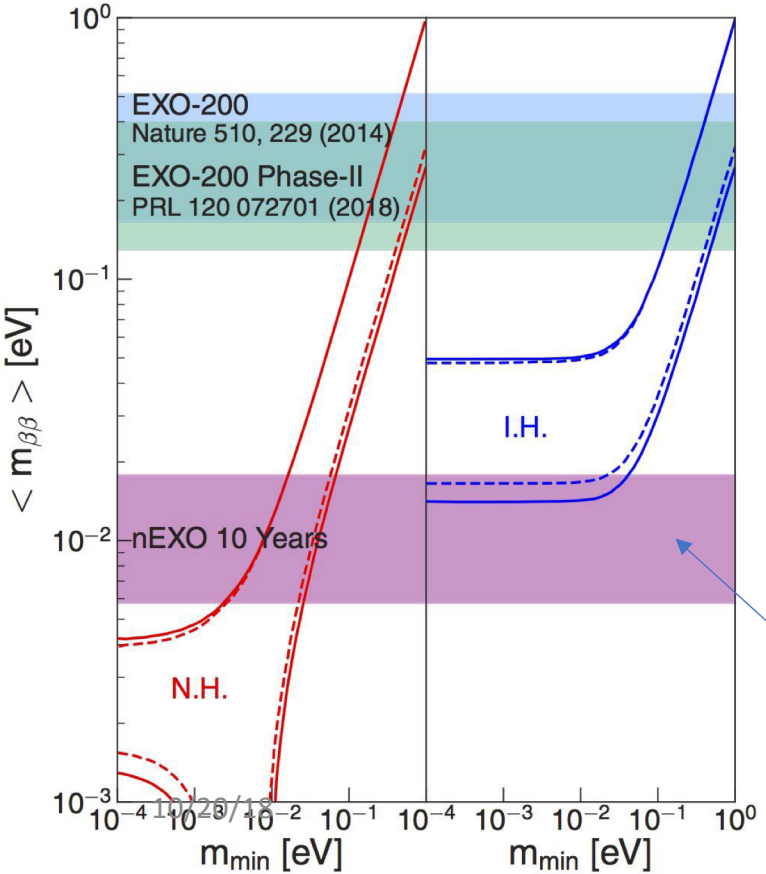
Relative change in background rates expected in our 2σ region of interest as a function of the energy resolution:

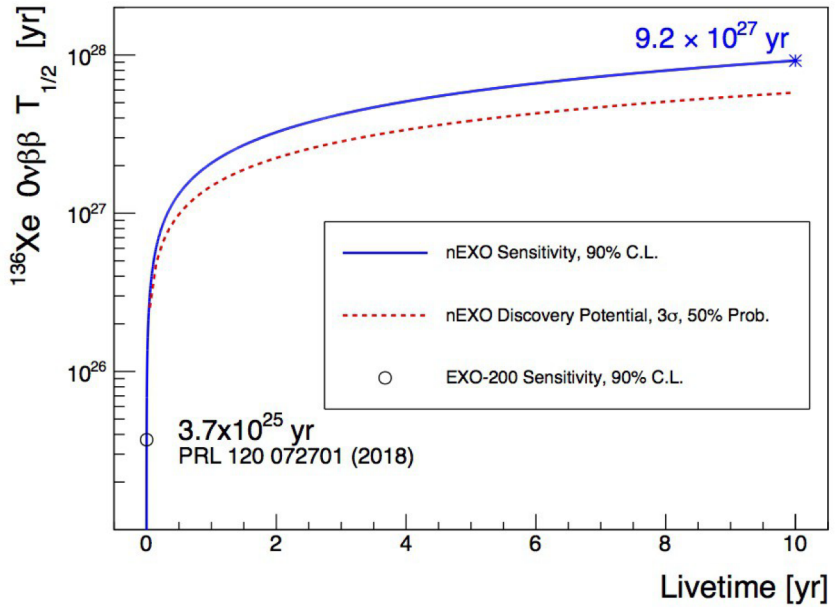


- The energy resolution near the region of Q value is of utmost importance for the sensitivity of the experiment.

nEXO – the next generation tonne-scale LXe detector





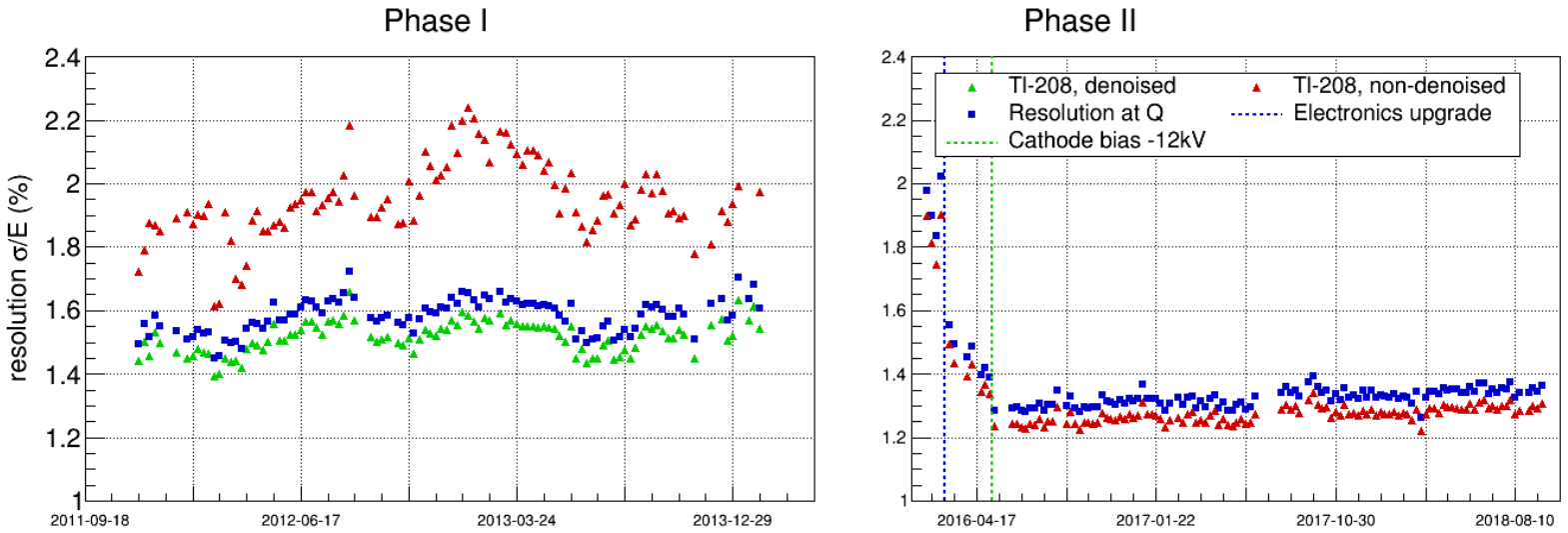


- Width of the bands represent the uncertainties in nuclear matrix elements
- Assumes axial vector constant $g_A = 1.27$

Advantages of LXe TPCs

- Xenon isotopic enrichment is relatively safe and easy
- Can be recycled and purified in to new detectors
- No long lived radioactive isotopes of Xe
- Background can be significantly reduced through daughter Ba tagging
- Fair energy resolution

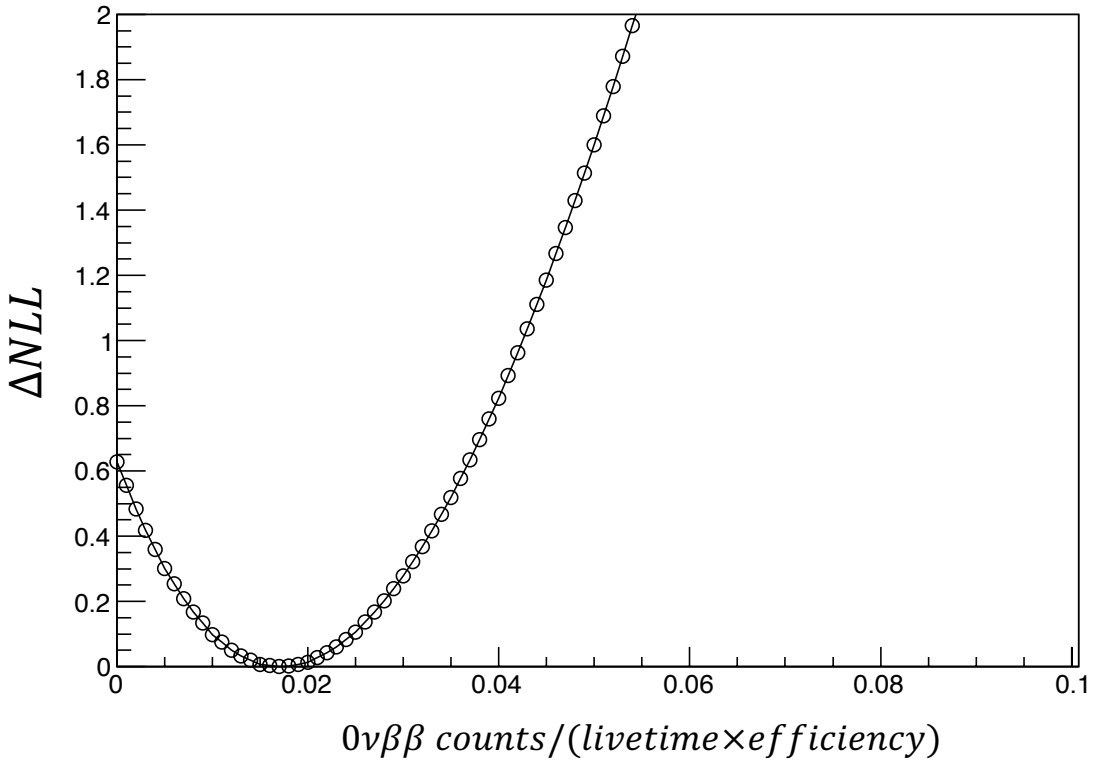
Resolution vs. time (multi-site events)



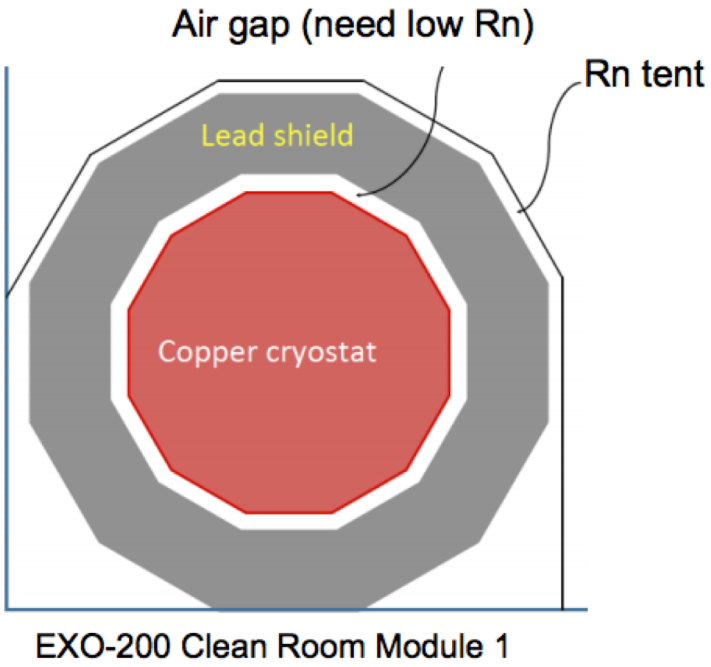
Phase I + Phase II likelihood profile

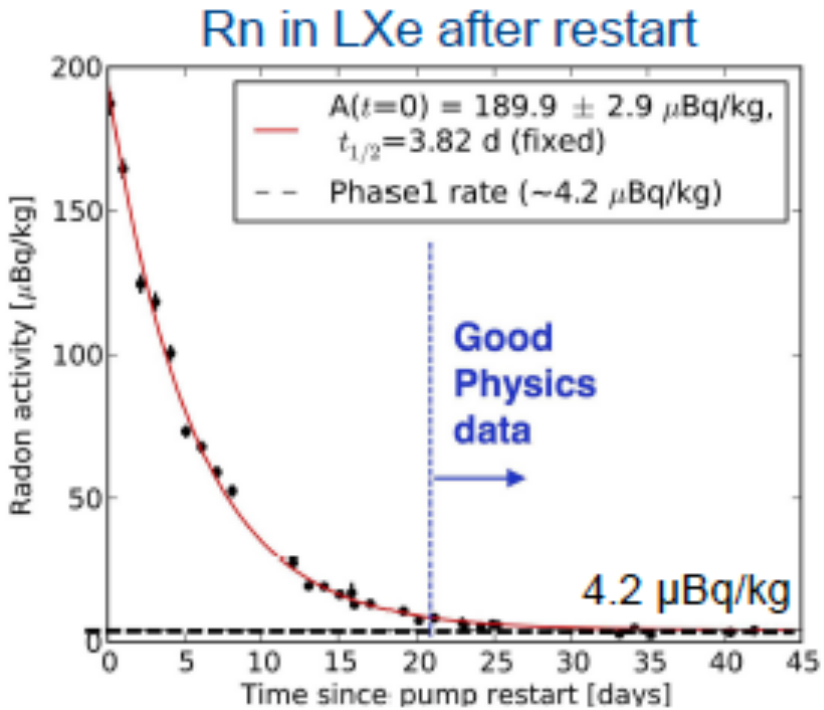
- The negative log likelihood function used in profile-likelihood

$$-\ln L = \sum_i \left[\left(\mu_i^{\mathrm{SS}} + \mu_i^{\mathrm{MS}} \right) - \left(k_{obs,i}^{\mathrm{SS}} \ln \mu_i^{\mathrm{SS}} + k_{obs,i}^{\mathrm{MS}} \ln \mu_i^{\mathrm{MS}} \right) \right] + G_{\mathrm{const}}$$



Radon activity



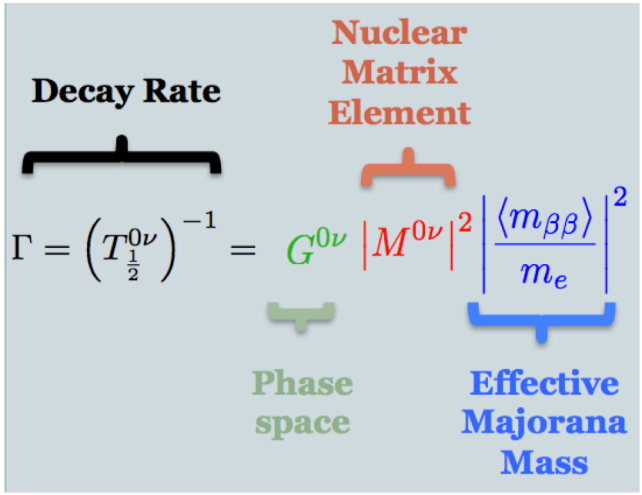


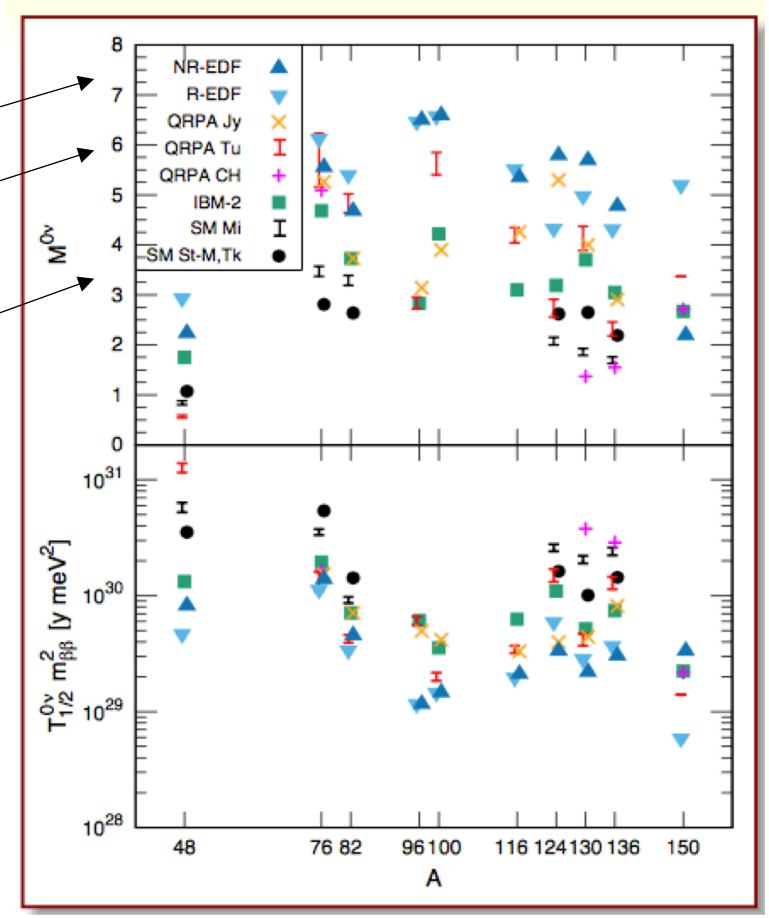
Uncertainties on nuclear matrix elements

Minimizing an energy functional with respect to local densities (but no n-p pairing)

QRPA involves small oscillations around a single determinant and quasi-particle states

Slater determinants restricted to a few single-particle shells





J.Engel and J. Menendez arXiv:1610.06548v2

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 $1/T_{1/2} = G^{0nu}\,|M|^2\,\langle m_{nu}\rangle^2$ where $\langle m_{nu}\rangle$ is in eV one needs to divide this by m_e^2 and multiply by g_A^4. This gives $(G^{0nu})^{-1} = 4.05\times10^{24}$ (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)

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

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