Search for $0\nu\beta\beta$ with the Complete EXO-200 Dataset

Ako Jamil for the EXO-200 Collaboration

Yale University

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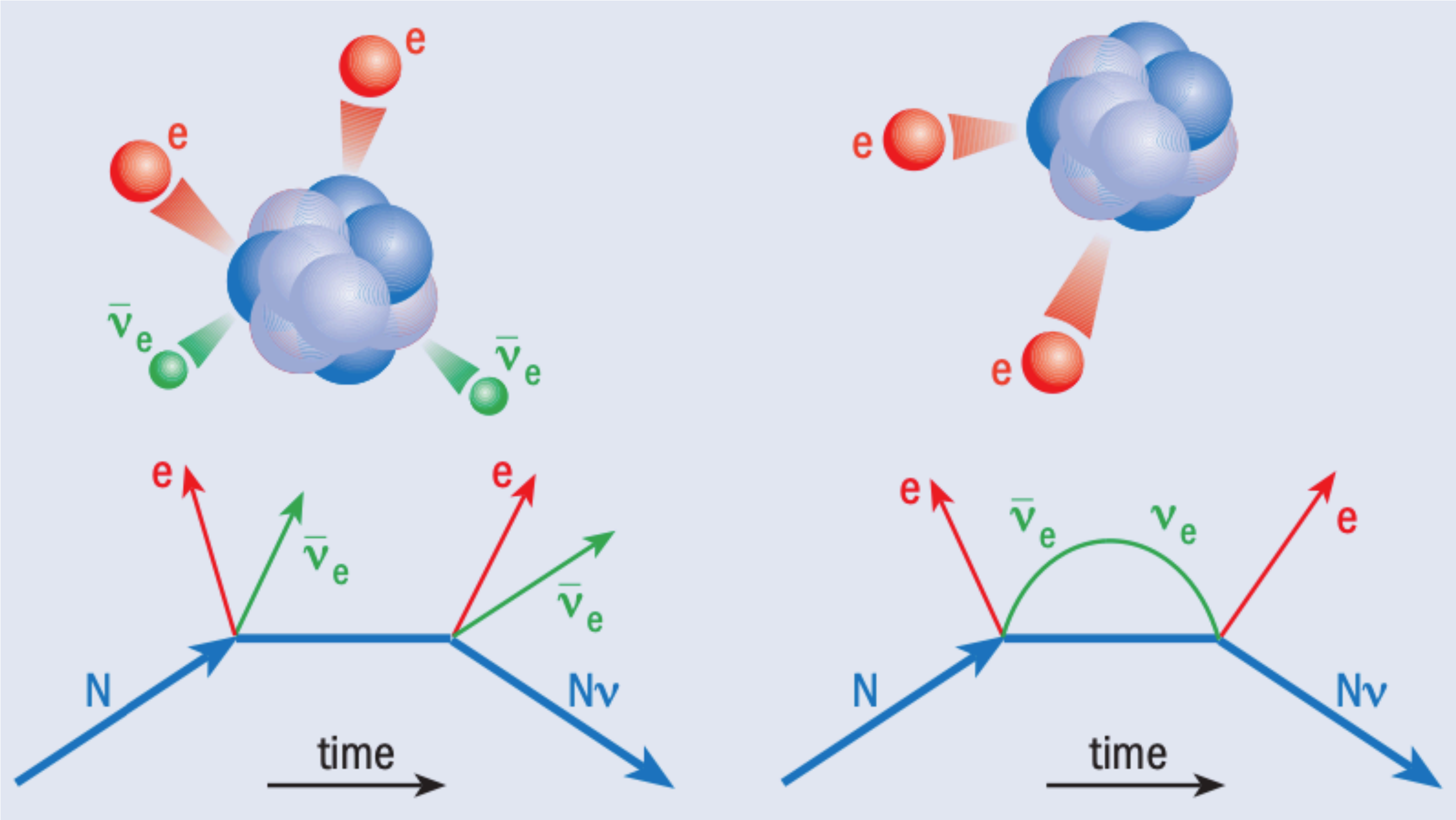
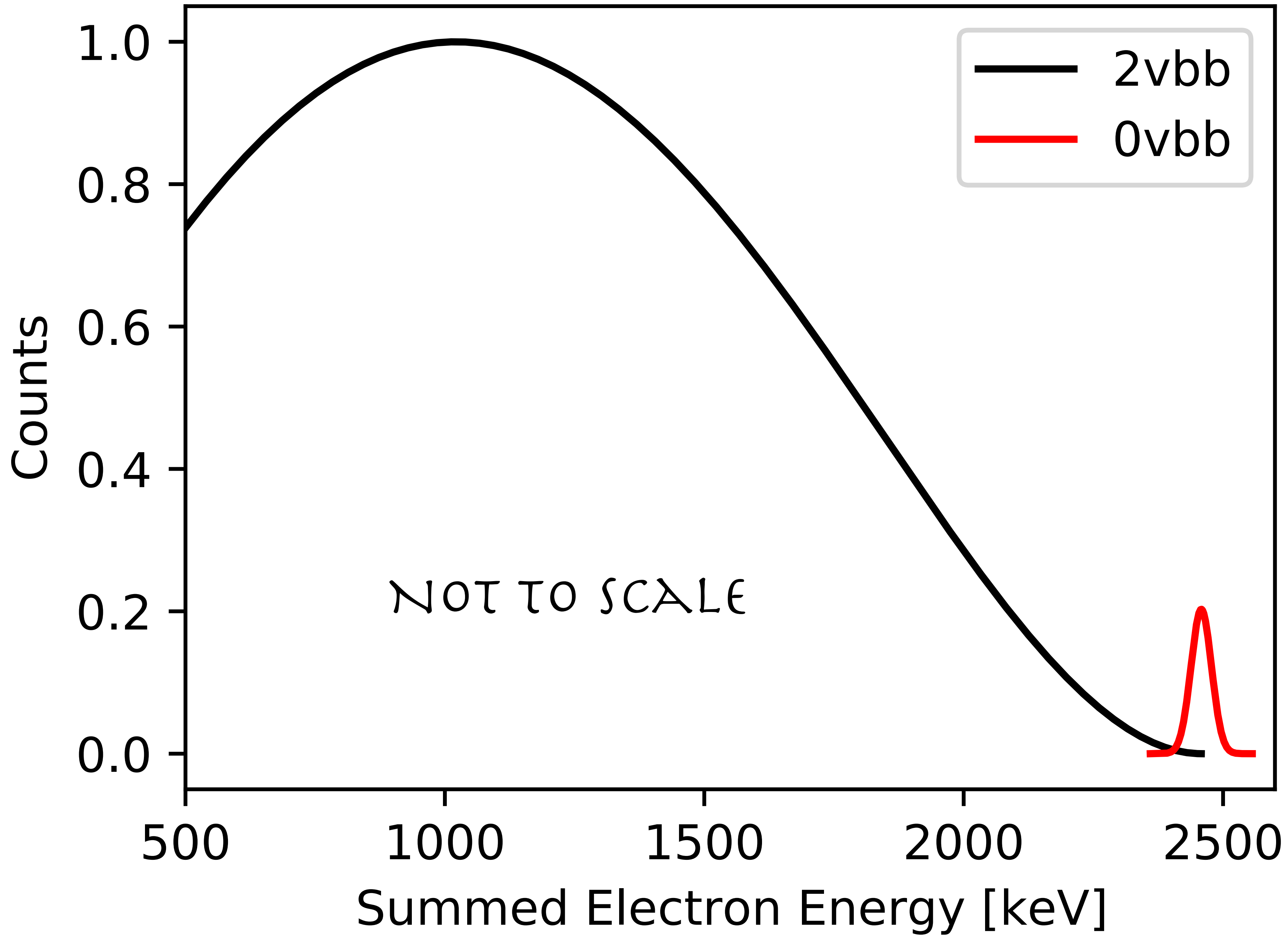
CoSSURF, Rapid City

Motivation for Neutrinoless Double Beta Decay

- Finding $0\nu\beta\beta$ always implies new physics
  - Lepton number violation
  - Neutrinos are Majorana fermions ($\nu \equiv \bar{\nu}$)
  - Origin of neutrinos masses
  - Insight into absolute neutrino mass scale
  - Possibly linked to matter and anti-matter asymmetry
- Experimental signature is a peak at the Q-value ($2458\,\mathrm{keV}$ for $^{136}\mathrm{Xe}$)

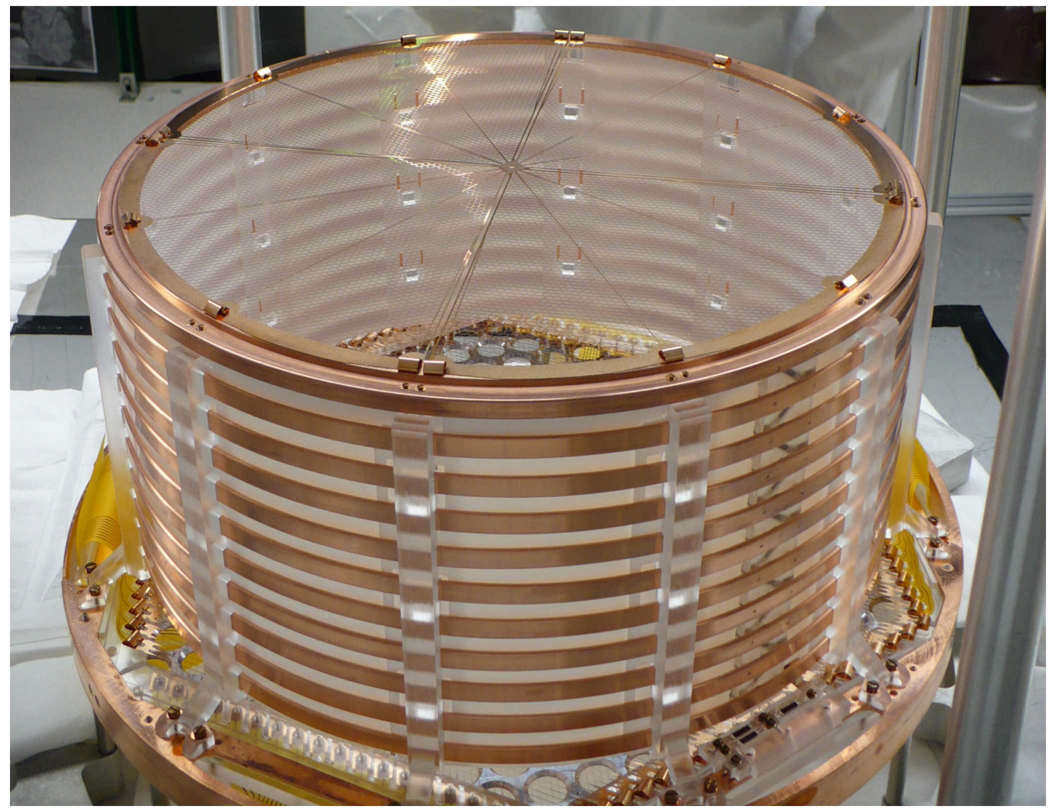




EXO-200 Collaboration Meeting December 2019

Liquid Xenon Detectors for $0\nu\beta\beta$

EXO-200

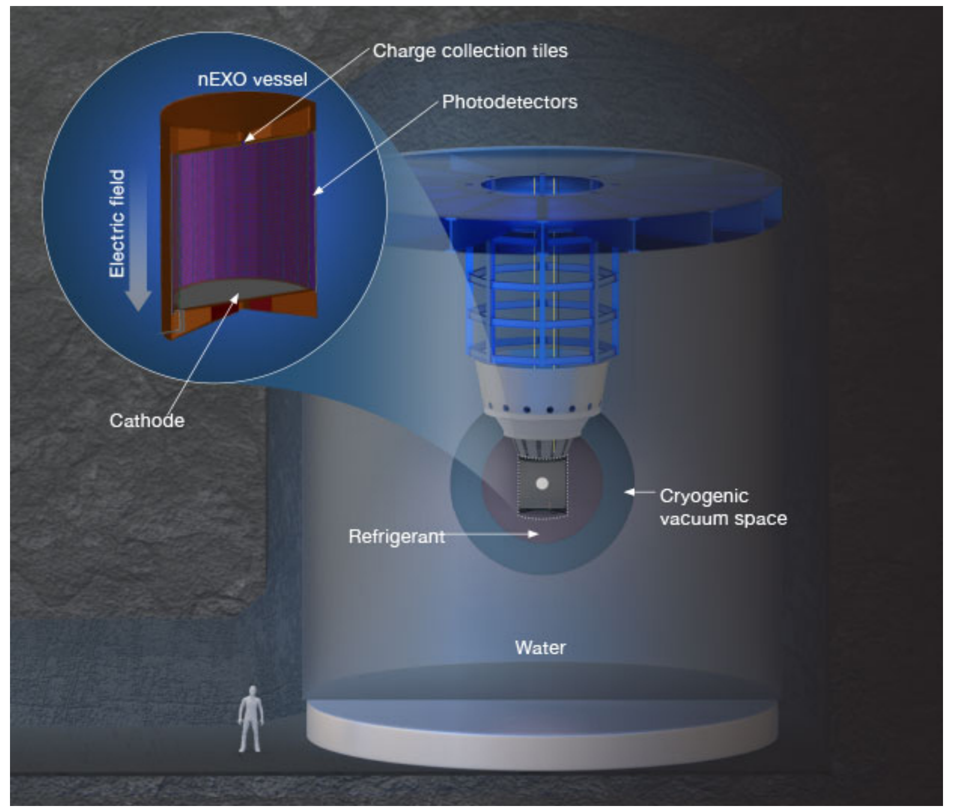


- First $100\,\mathrm{kg}$-class $0\nu\beta\beta$ search
- Discovered $2\nu\beta\beta$ in $^{136}\mathrm{Xe}$ in 2011
- Limit: $T_{1/2}^{0\nu} > 3.5 \times 10^{25}\,\mathrm{yr}$
- Sensitivity: $T_{1/2}^{0\nu} > 5.0 \times 10^{25}\,\mathrm{yr}$
- Pioneered ultra low-background LXe TPC technology

Phys. Rev. Lett. 123, 161802 (2019)

>2 ORDERS OF MAGNITUDE IMPROVEMENT IN HALF-LIFE SENSITIVITY

nEXO

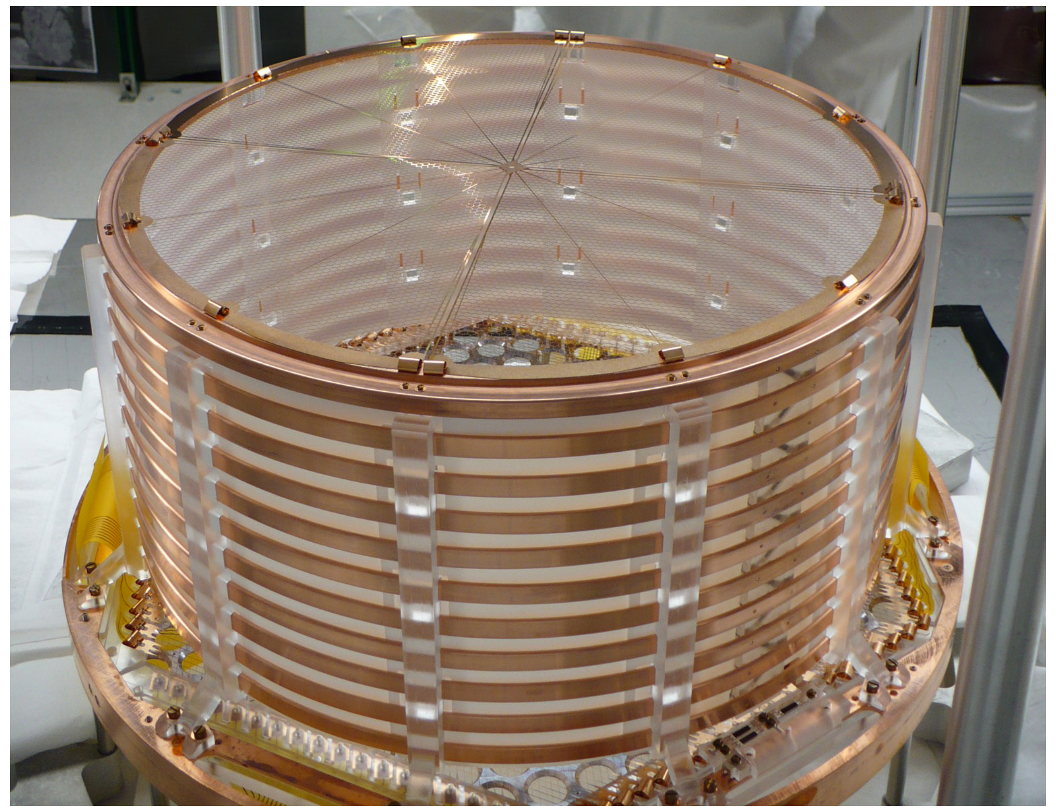


- 5 tonnes of liquid xenon
- Better self-shielding and external shielding
- Improved charge (tiles) and light (SiPM) readout
- Projected Sensitivity: $T_{1/2}^{0\nu} > 1.35 \times 10^{28}\,\mathrm{yr}$

J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022)

Liquid Xenon Detectors for $0\nu\beta\beta$

EXO-200



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nEXO

Search for $0\nu\beta\beta$ beyond $10^{28}\,\mathrm{yr}$ half-life sensitivity with nEXO

https://indico.sanfordlab.org/event/28/contributions/365/

shielding

- Improved charge (tiles) and light (SiPM) readout
- Projected Sensitivity: $T^{0\nu}_{1/2} > 1.35 \times 10^{28}\,\mathrm{yr}$

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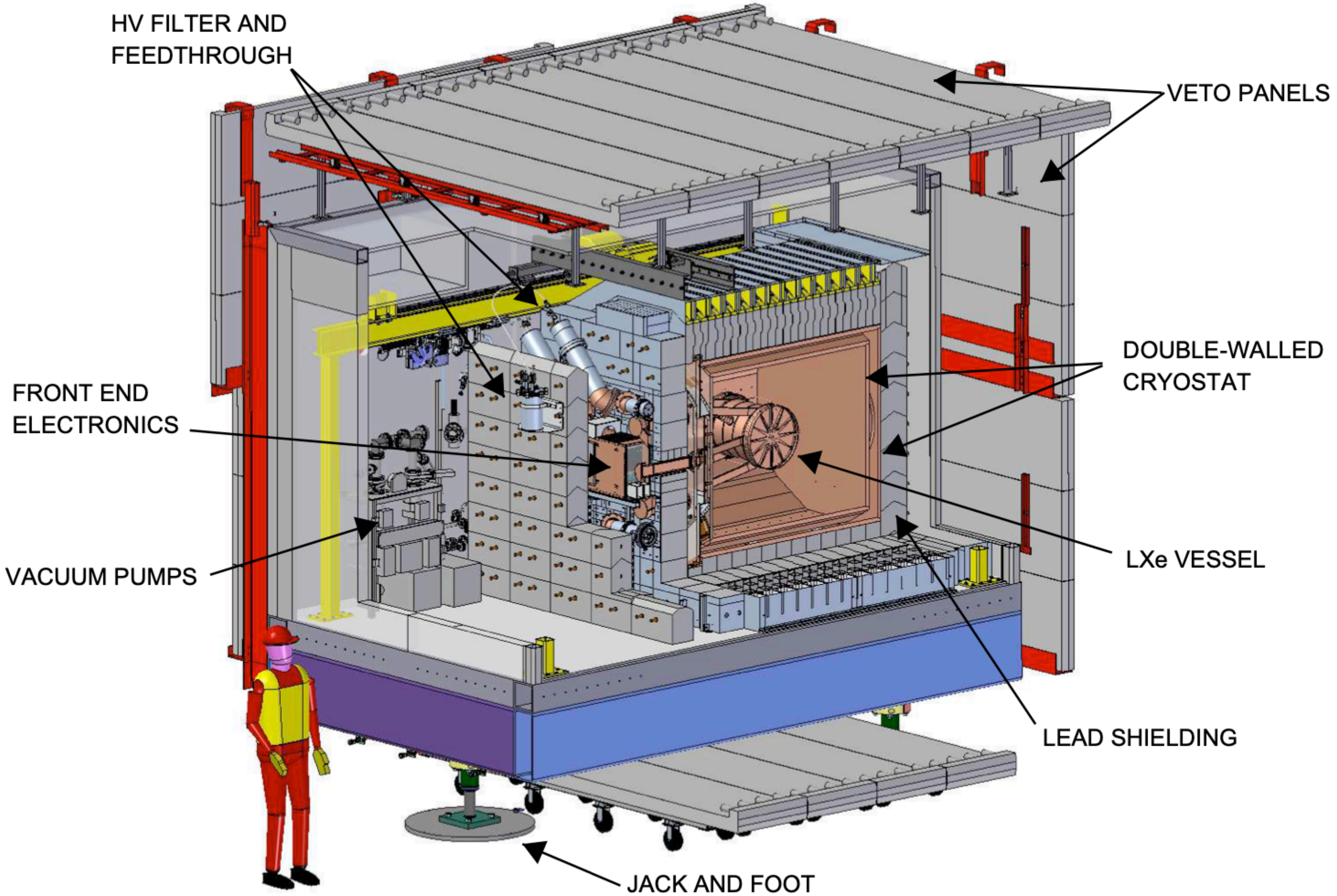
The EXO-200 Experiment

- Primary physics goal: $0\nu\beta\beta$
- TPC with $175\,\mathrm{kg}$ of LXe enriched to $80\,\%$ in $^{136}\mathrm{Xe}$
- Two identical back to back TPCs made from radio-pure copper
- Located at Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM, USA
- Data taking from Sept. 2011 to Dec. 2018



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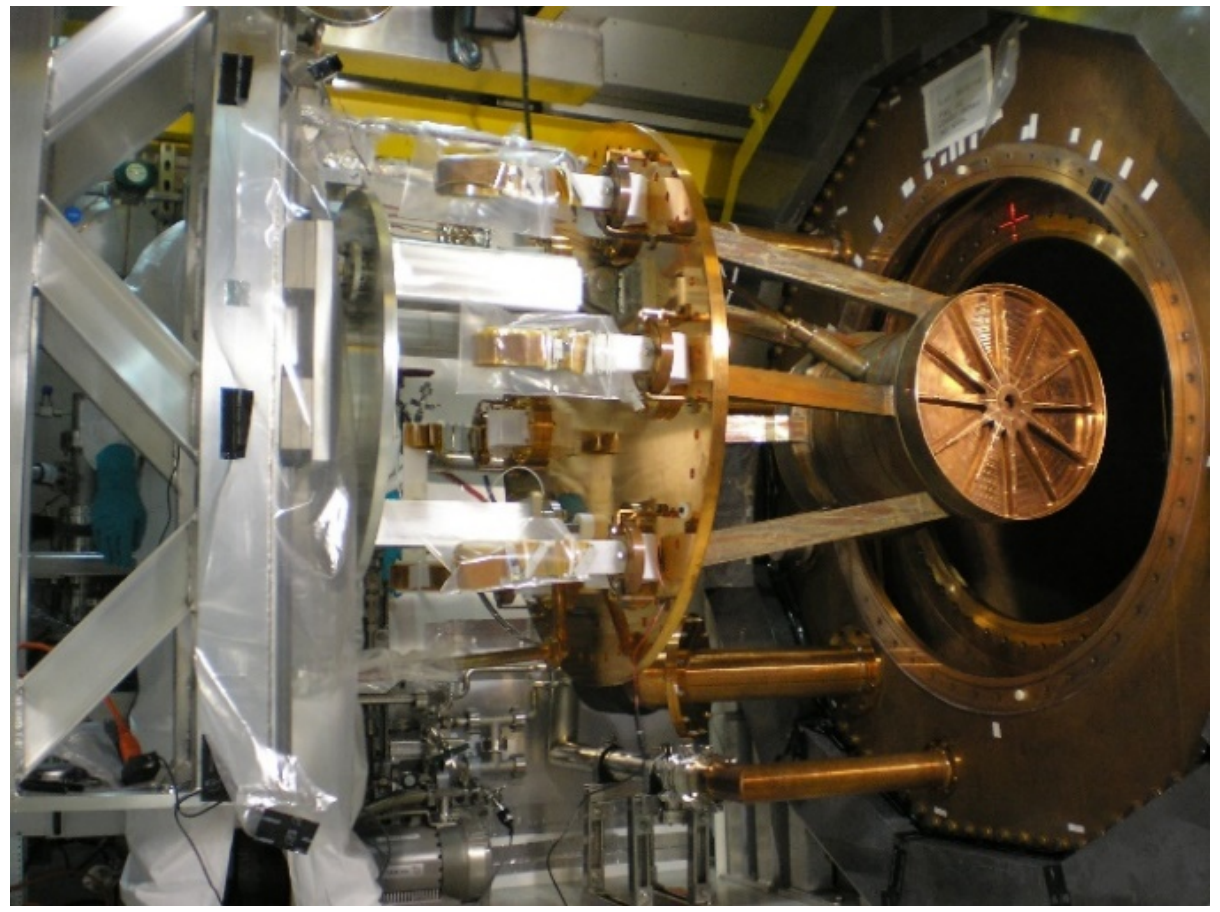
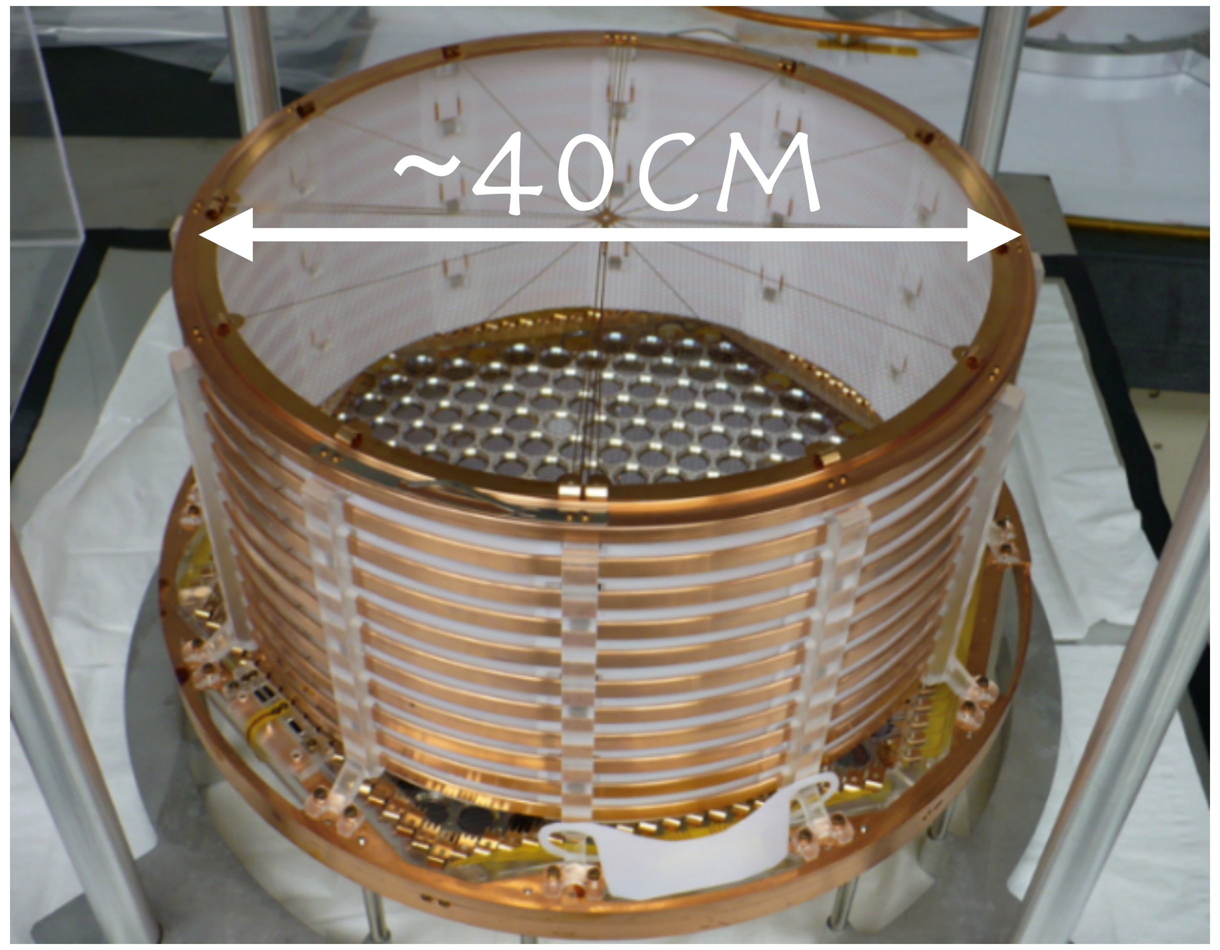
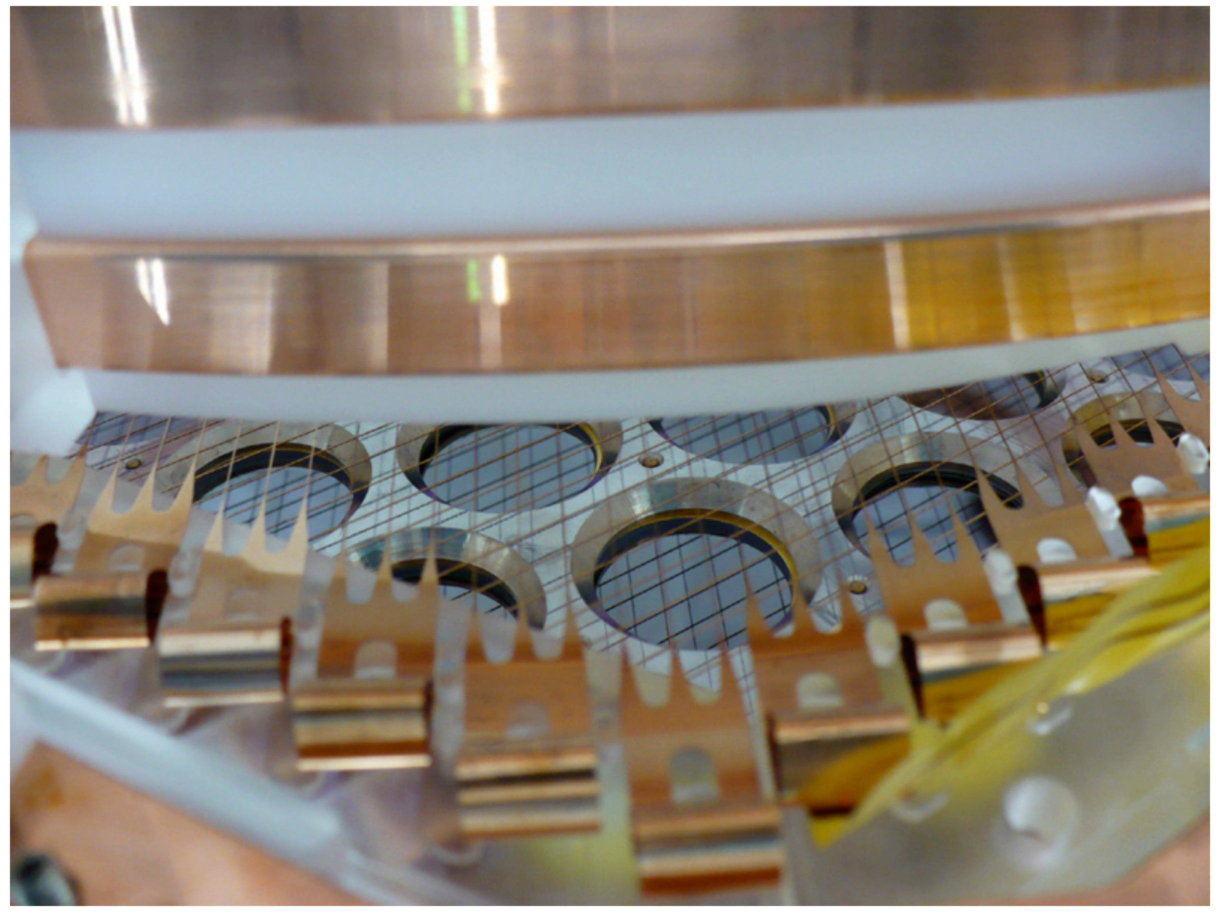
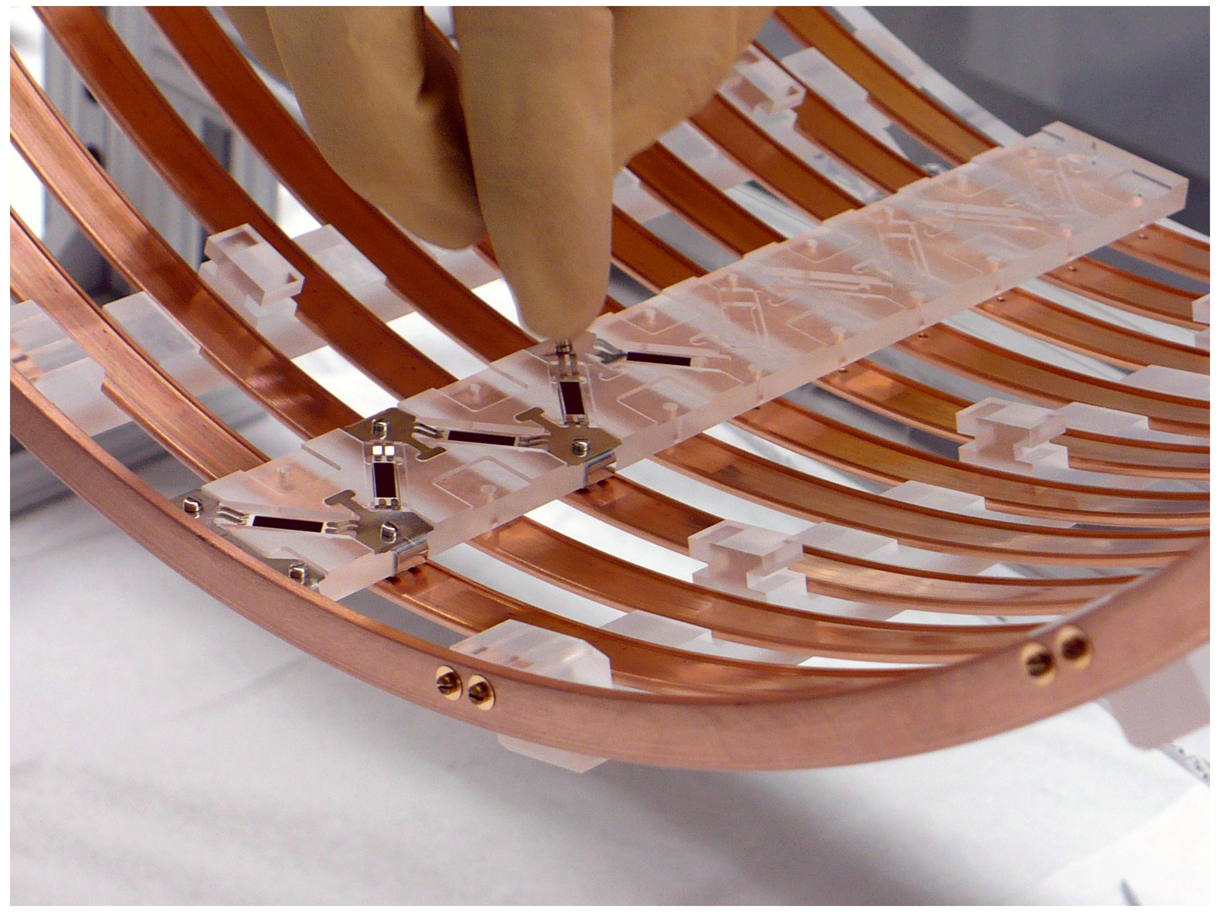
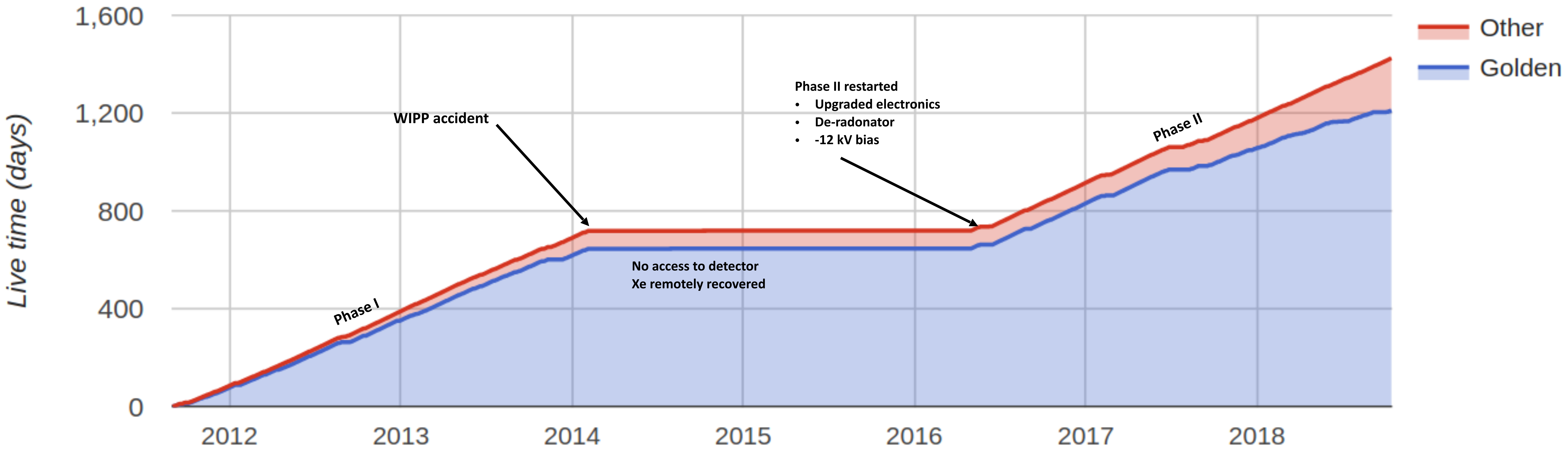








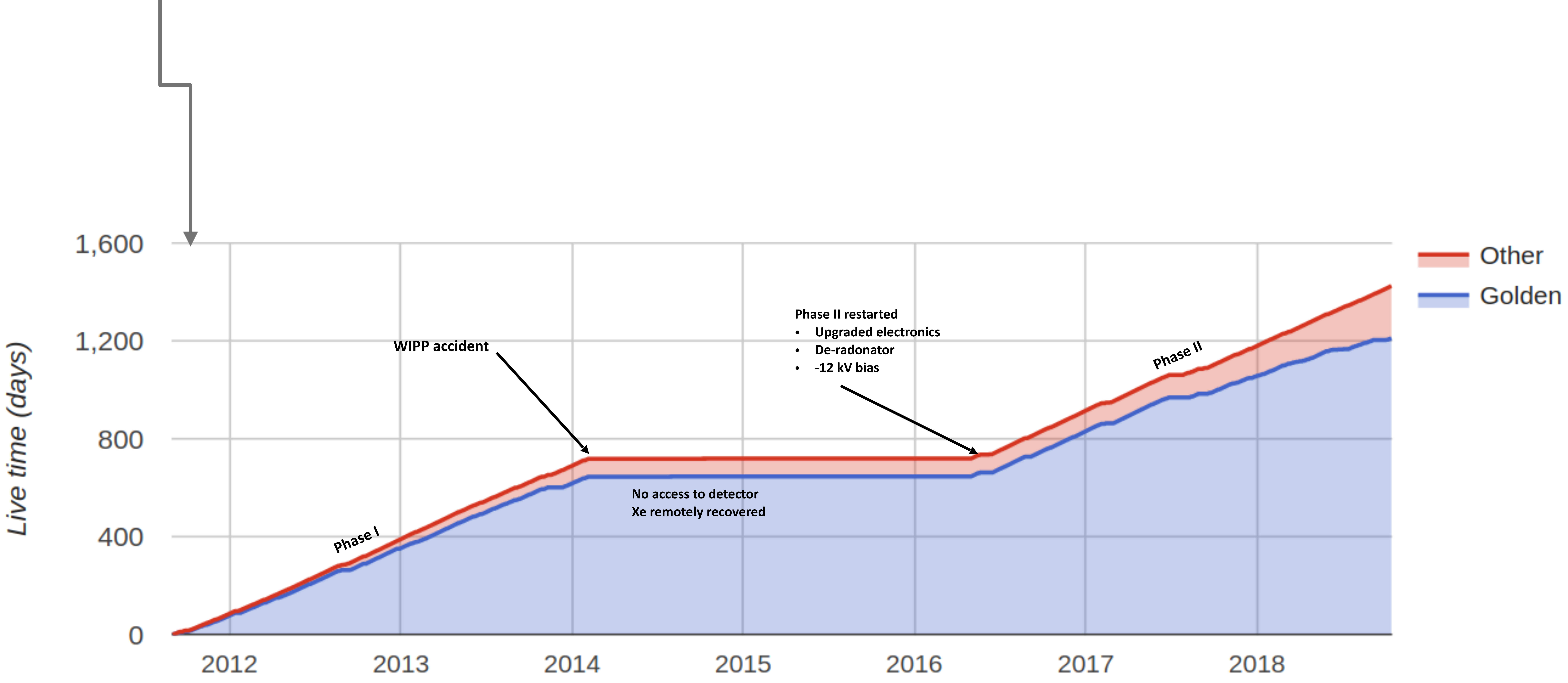
Timeline and Data Taking



Timeline and Data Taking

Observation of Two-Neutrino Double-Beta Decay in 136Xe with the EXO-200 Detector

Phys. Rev. Lett. 107, 212501 (2011)



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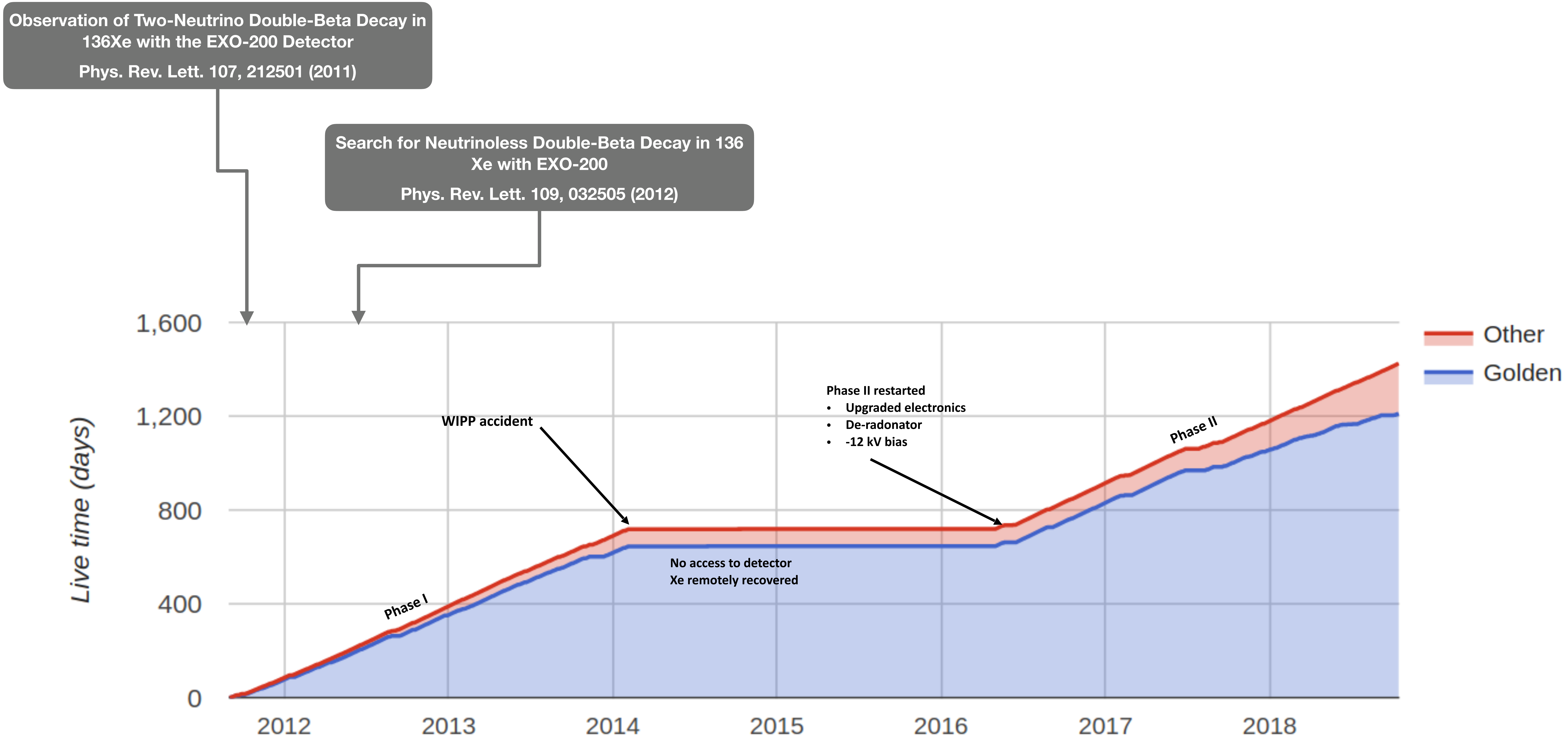

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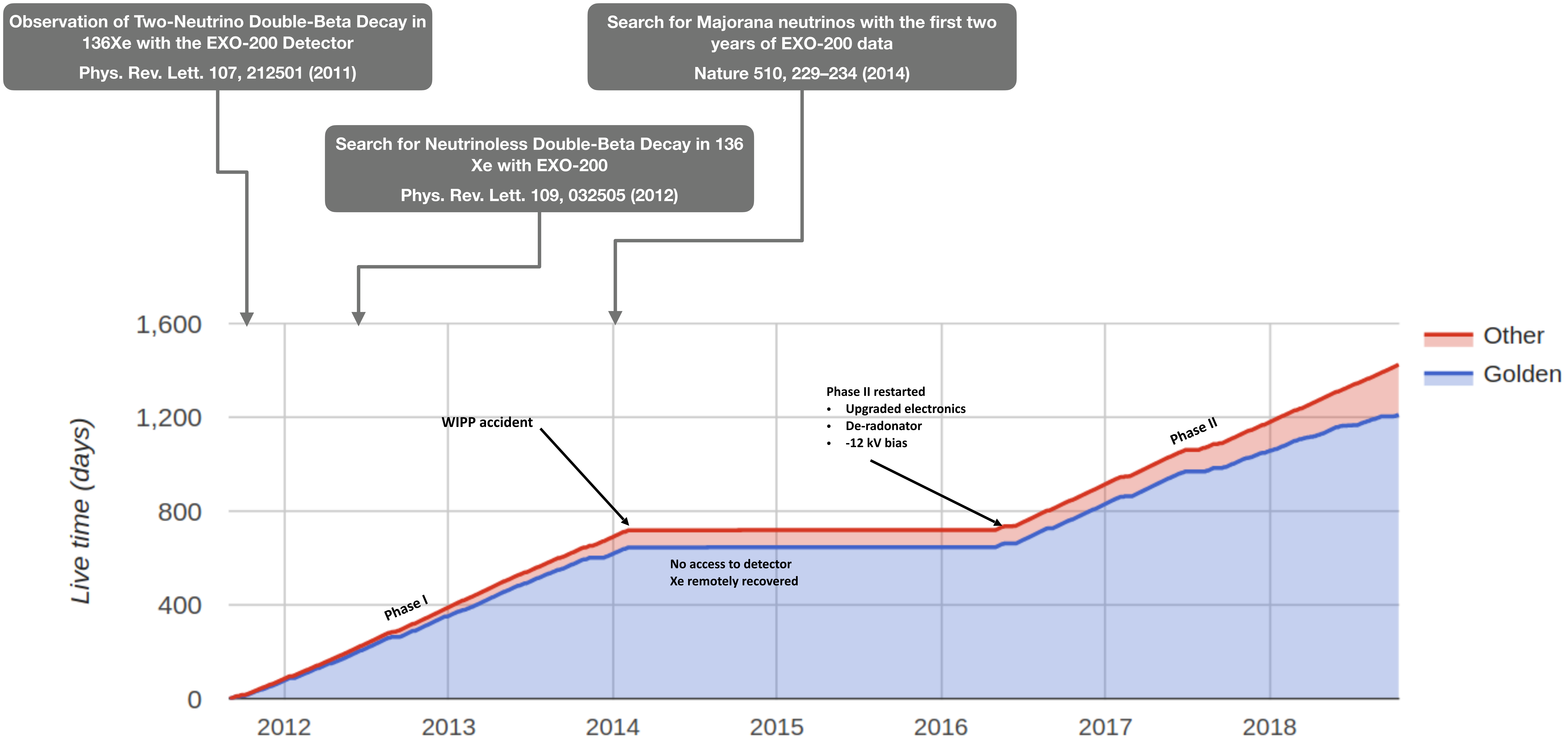

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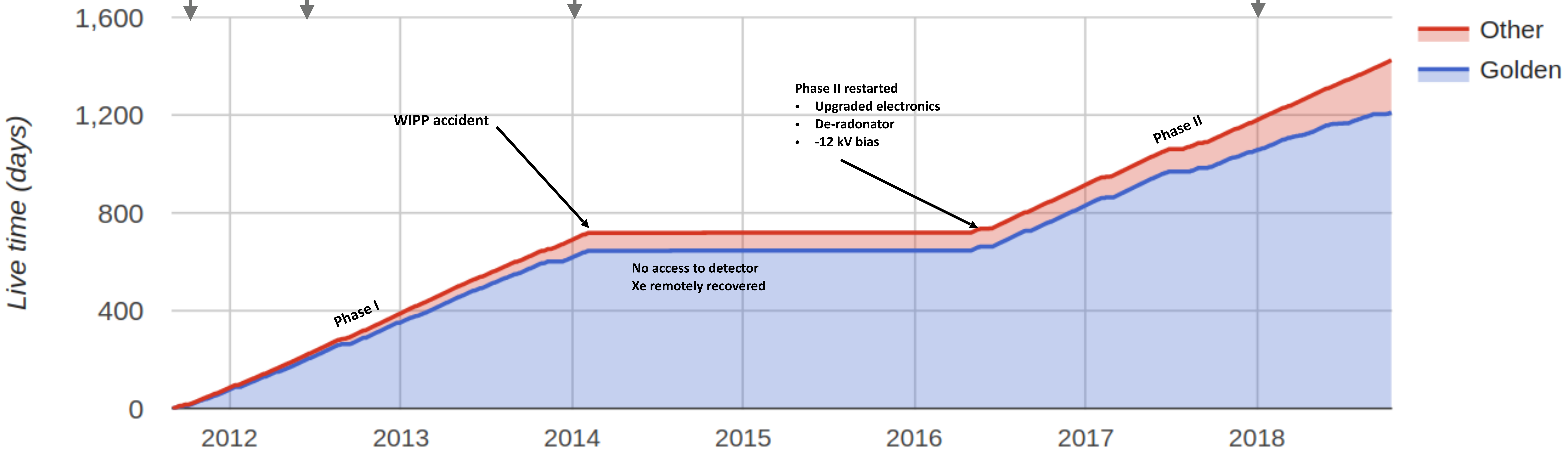

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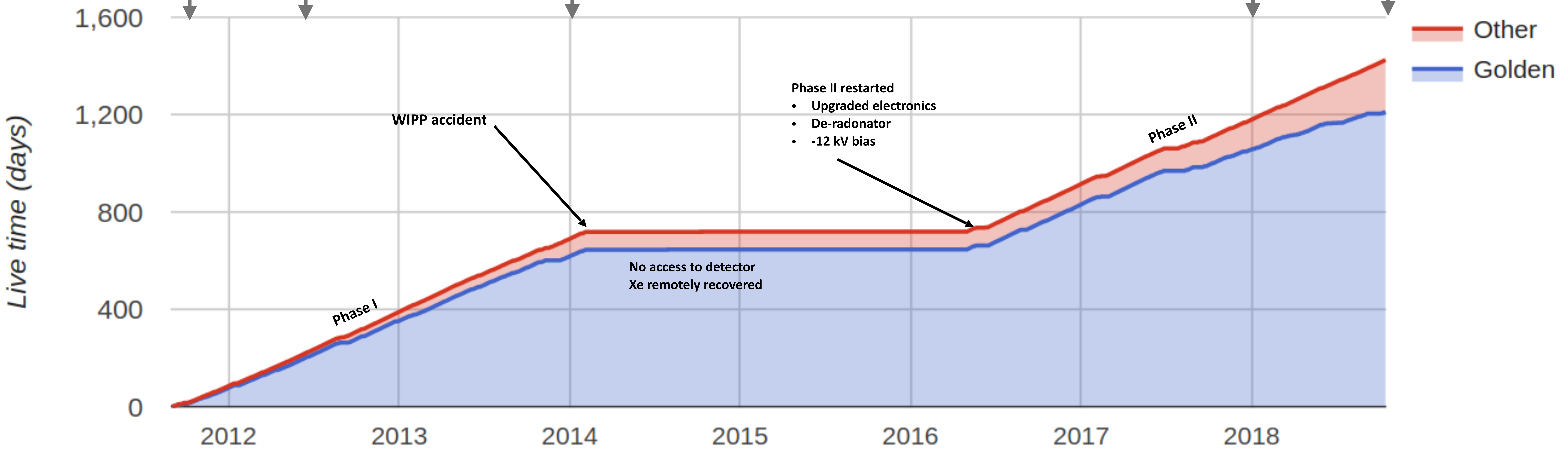
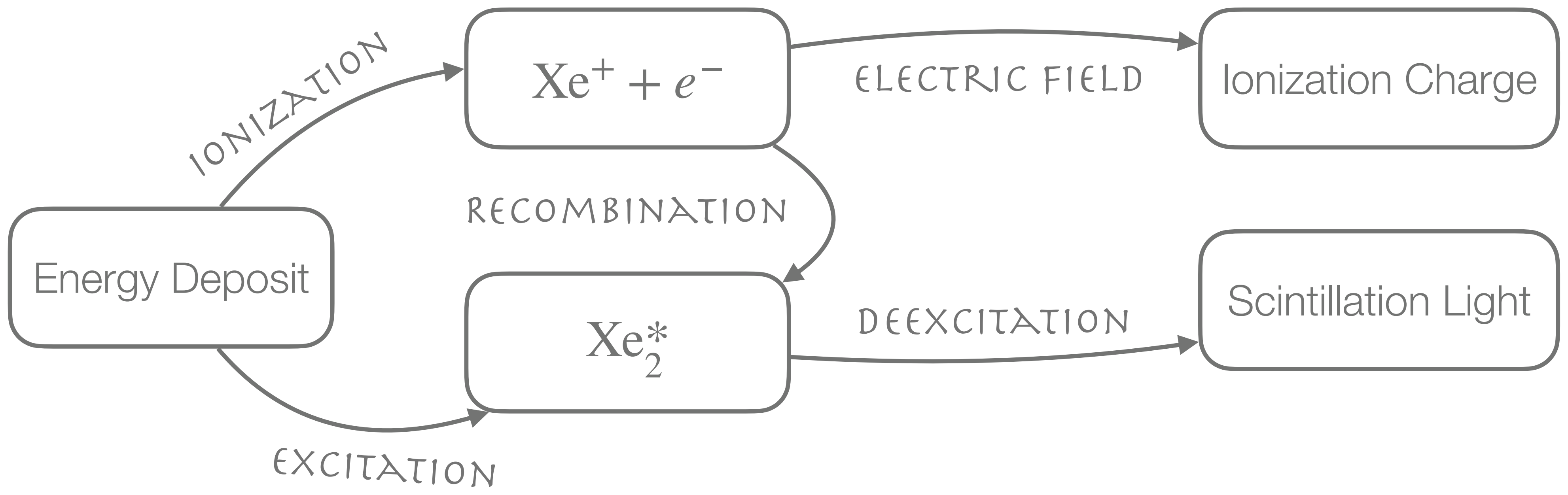
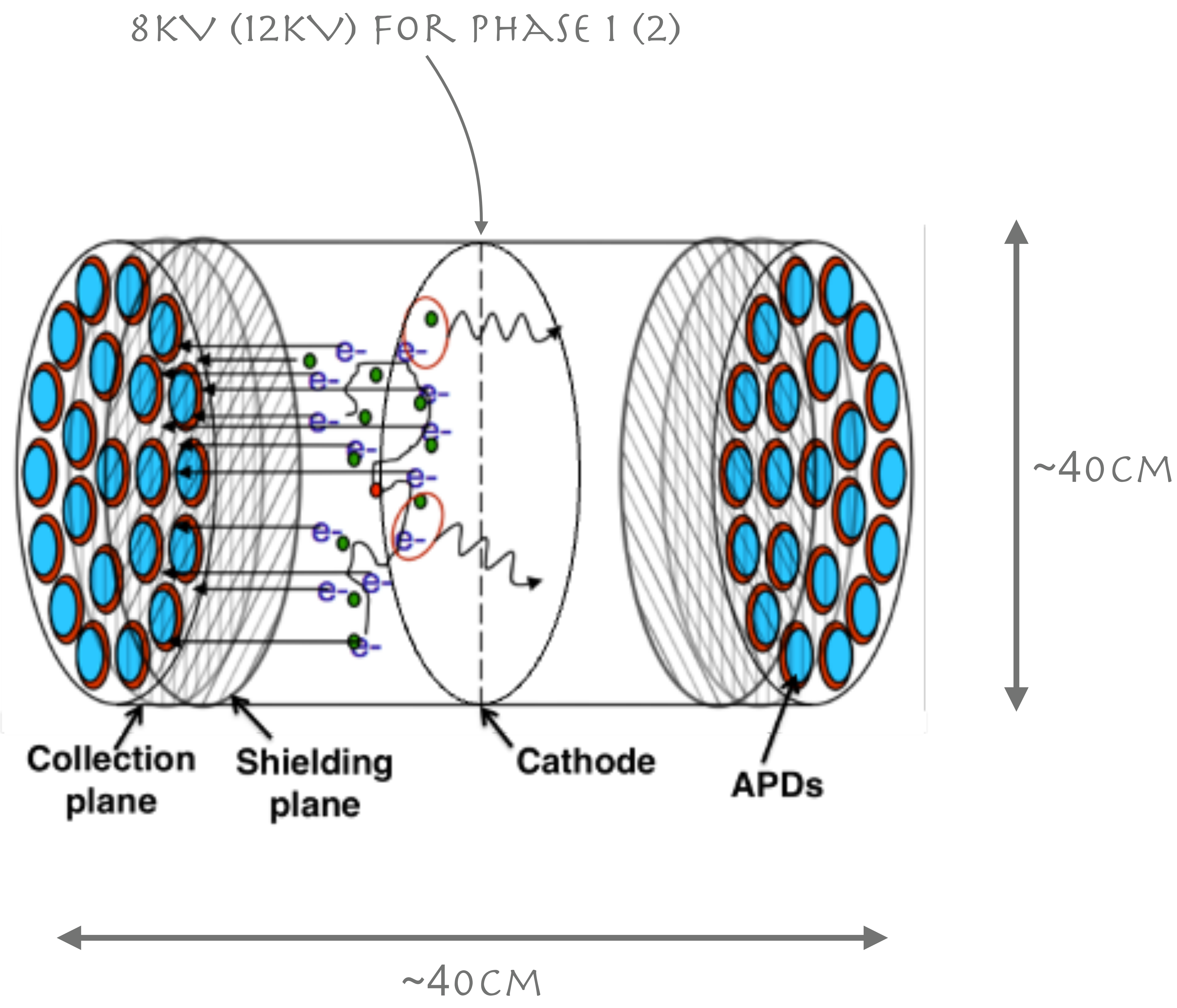


EXO-200 Time Projection Chamber

- Ionizing radiation will either ionize or excite Xe atoms



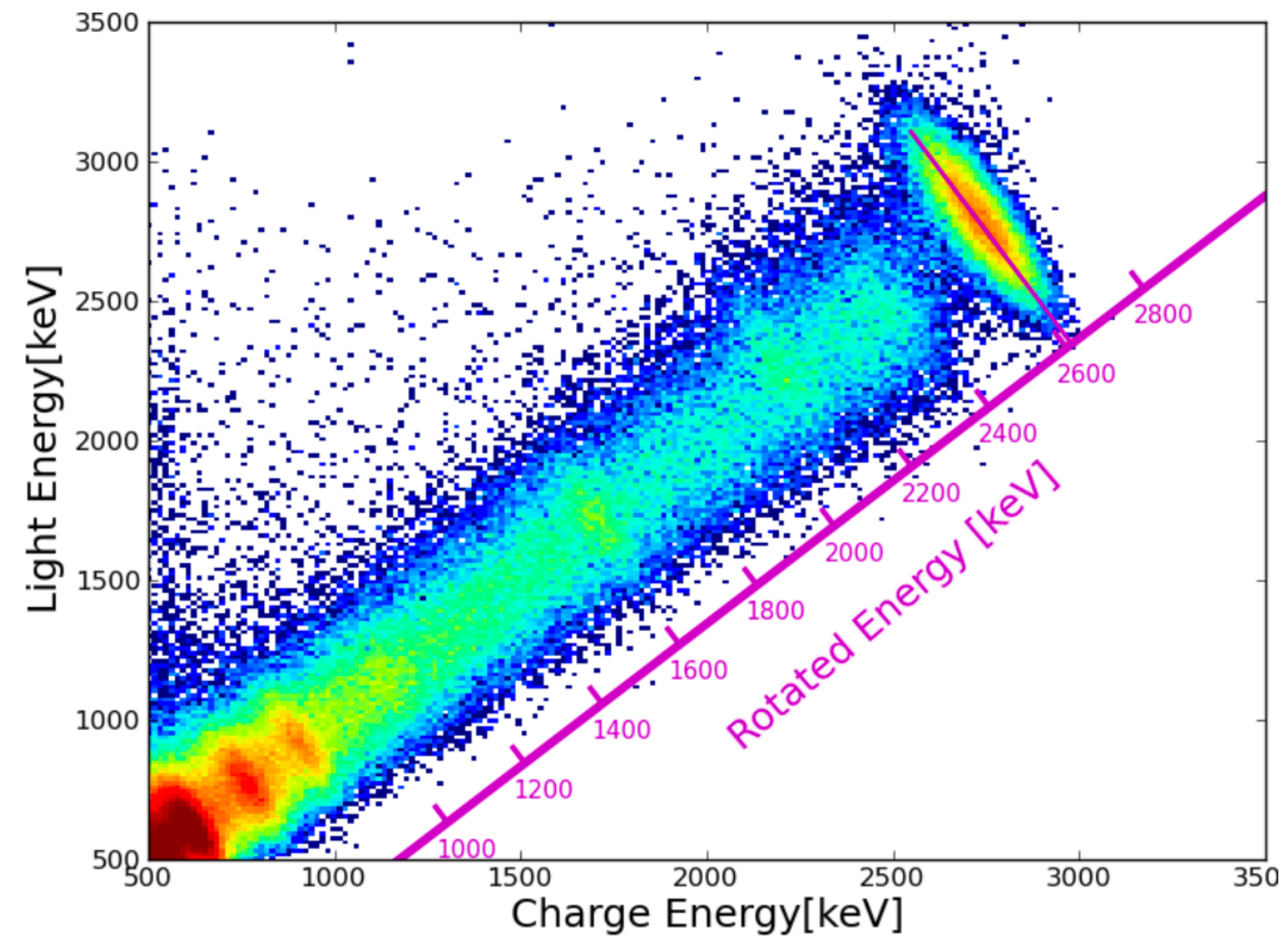


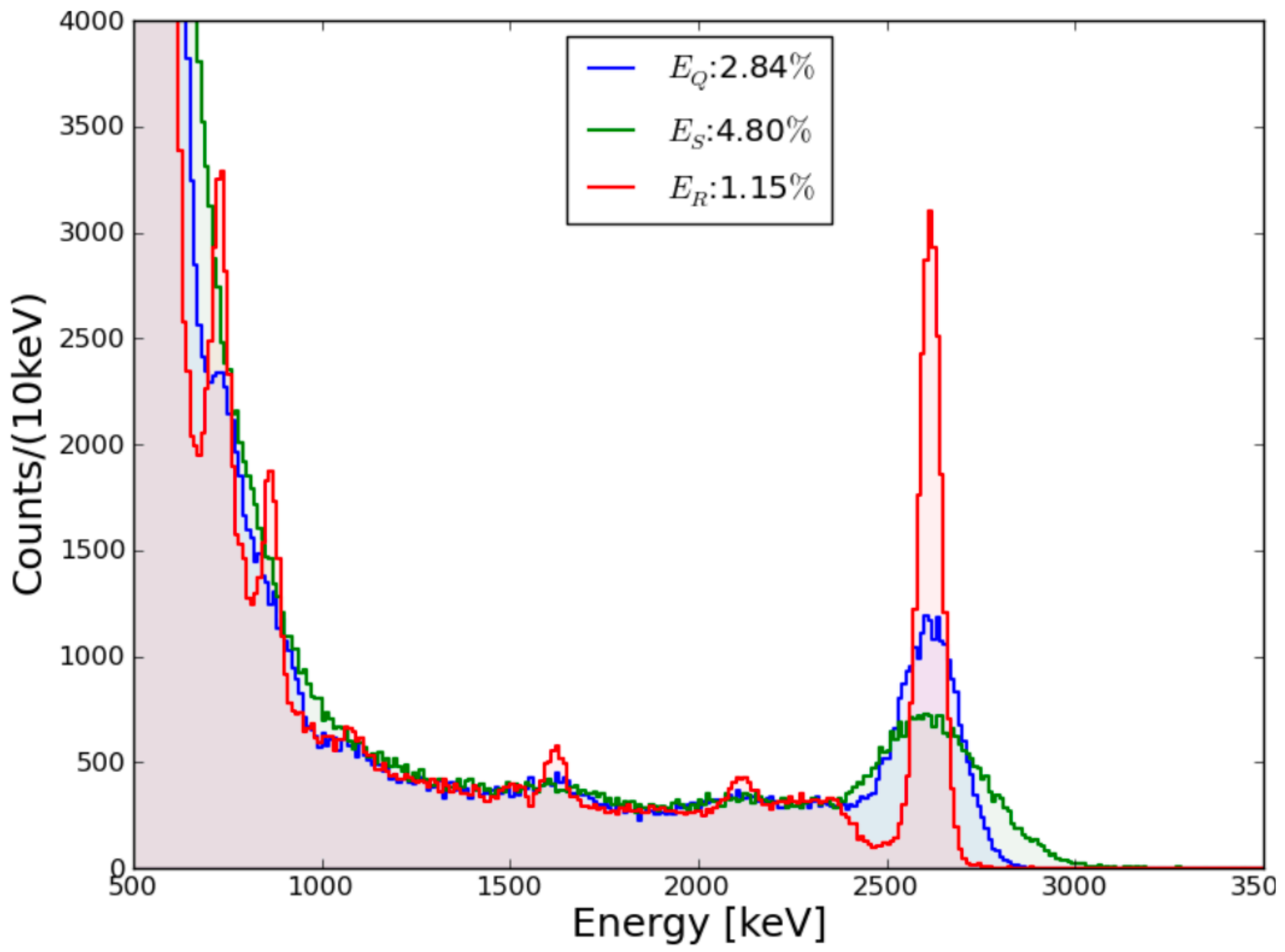
- Scintillation light (175nm) are immediately detected by Large Area Avalanche Photo-diodes
- Ionization charge is drifted to cross-wired planes (U and V-wires)
- TPC technologies allows for 3D reconstruction of individual energy deposits
- In EXO-200 we use a multi-dimensional analysis with: Energy | Standoff | Topology

Energy Measurement in EXO-200

- Anti-correlation between number of light and charge quanta can be exploited for improved energy resolution
  - Phase I: $(1.35 \pm 0.09)\,\%$
  - Phase II: $(1.15 \pm 0.02)\,\%$
- Main improvement comes from
  - Increased high voltage (more charge than light)
  - Improved front-end electronics and software-based de-noising of the light channel
- Energy resolution makes $2\nu\beta\beta$ background in the ROI negligible

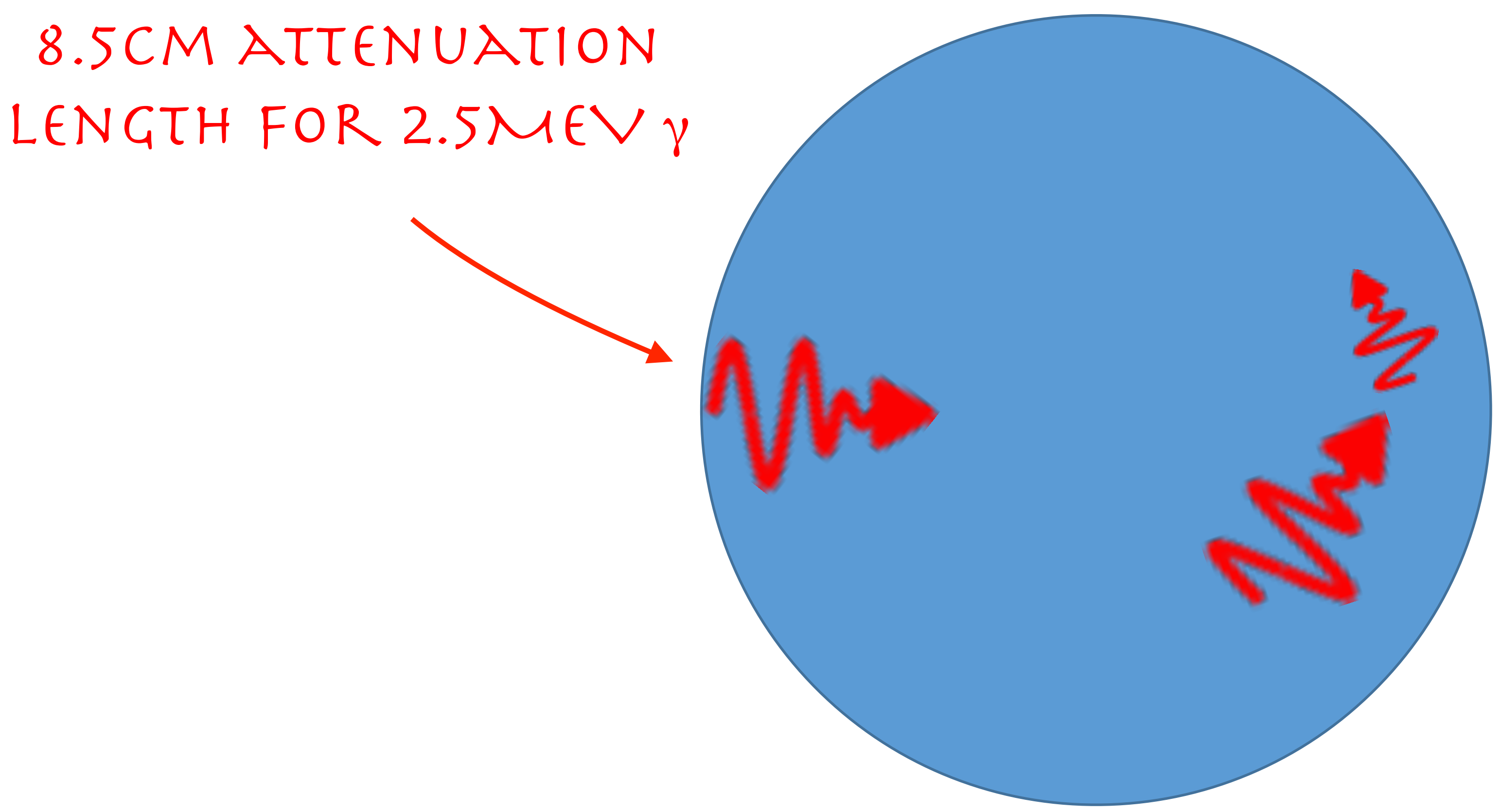
TH-228 CALIBRATION SOURCE

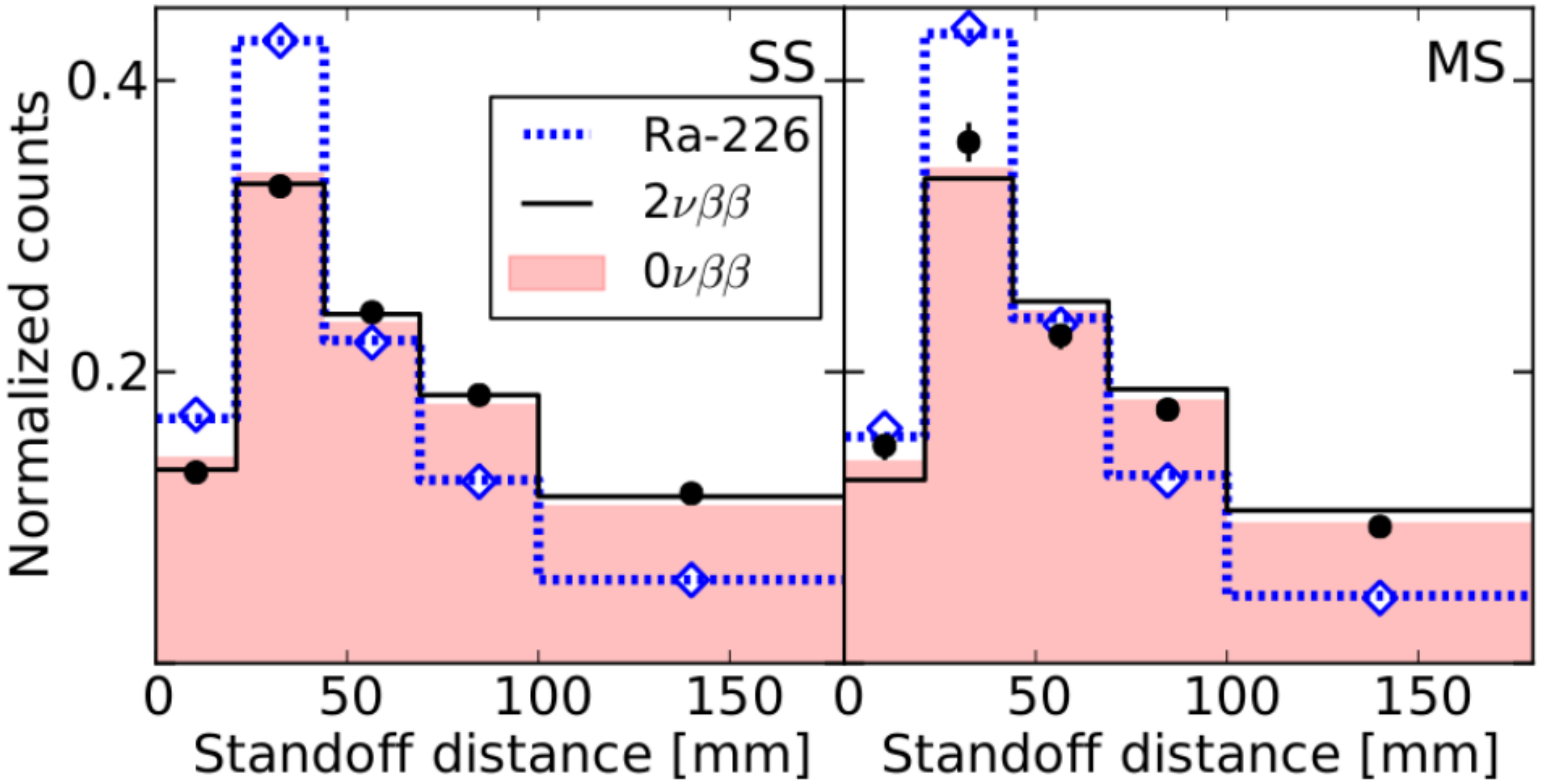




Spatial Distribution of Events

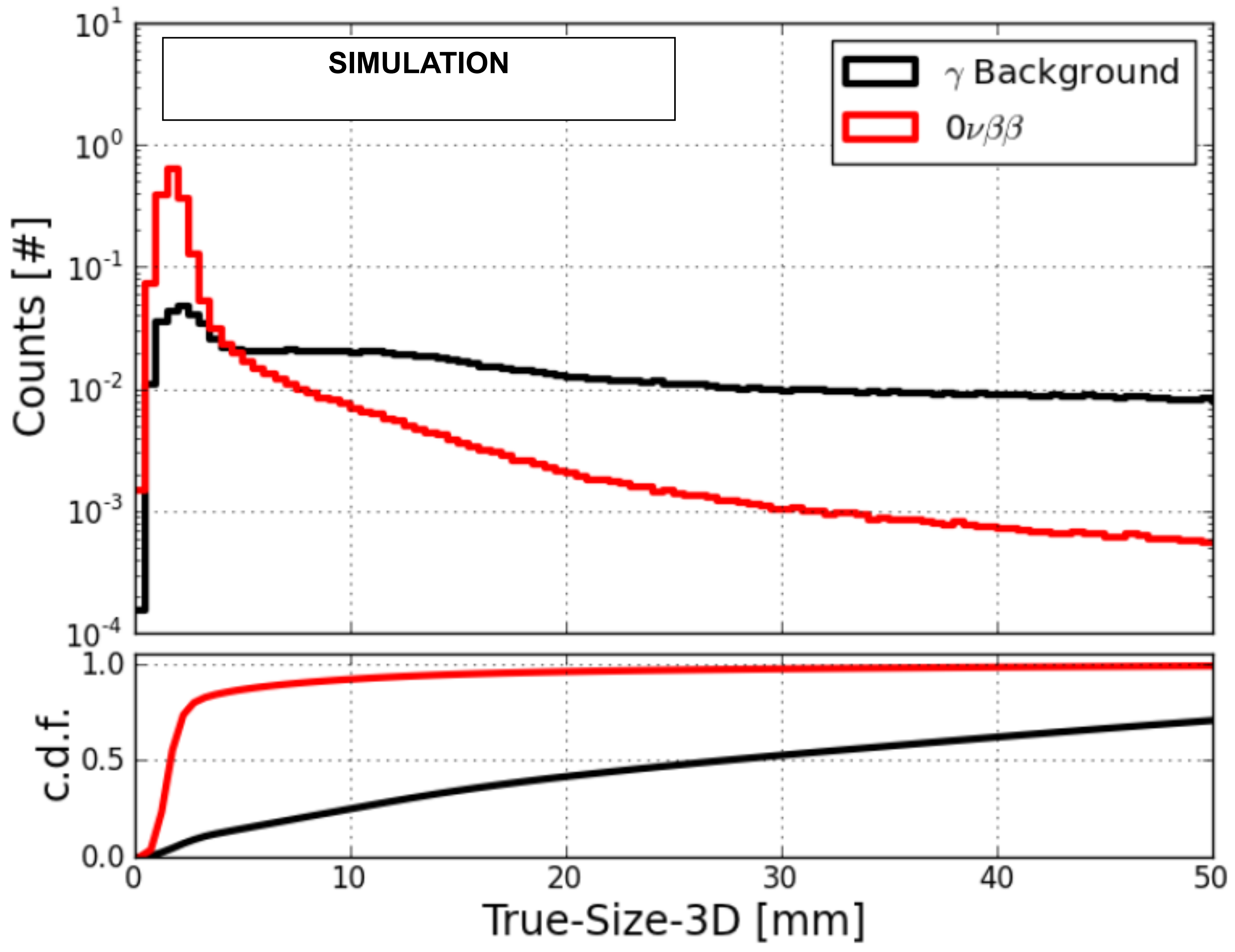
- The distance to the closest detector (standoff) edge helps discriminate between
  - External γ-backgrounds originating from the detector material
  - Uniformly distributed $0\nu\beta\beta$
- Self-shielding of LXe provides
  - Careful measurement of backgrounds in the outer parts
  - A more radio-pure inner region

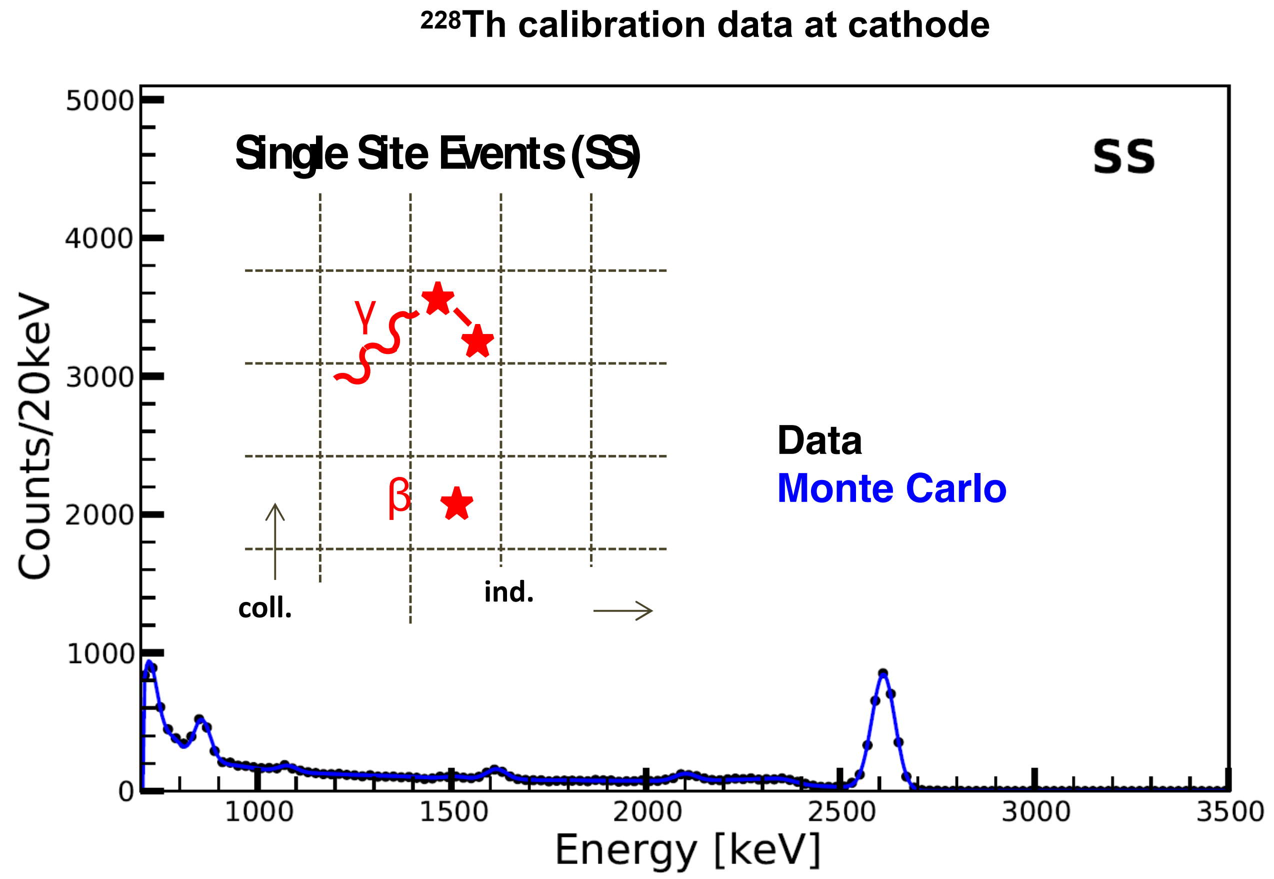


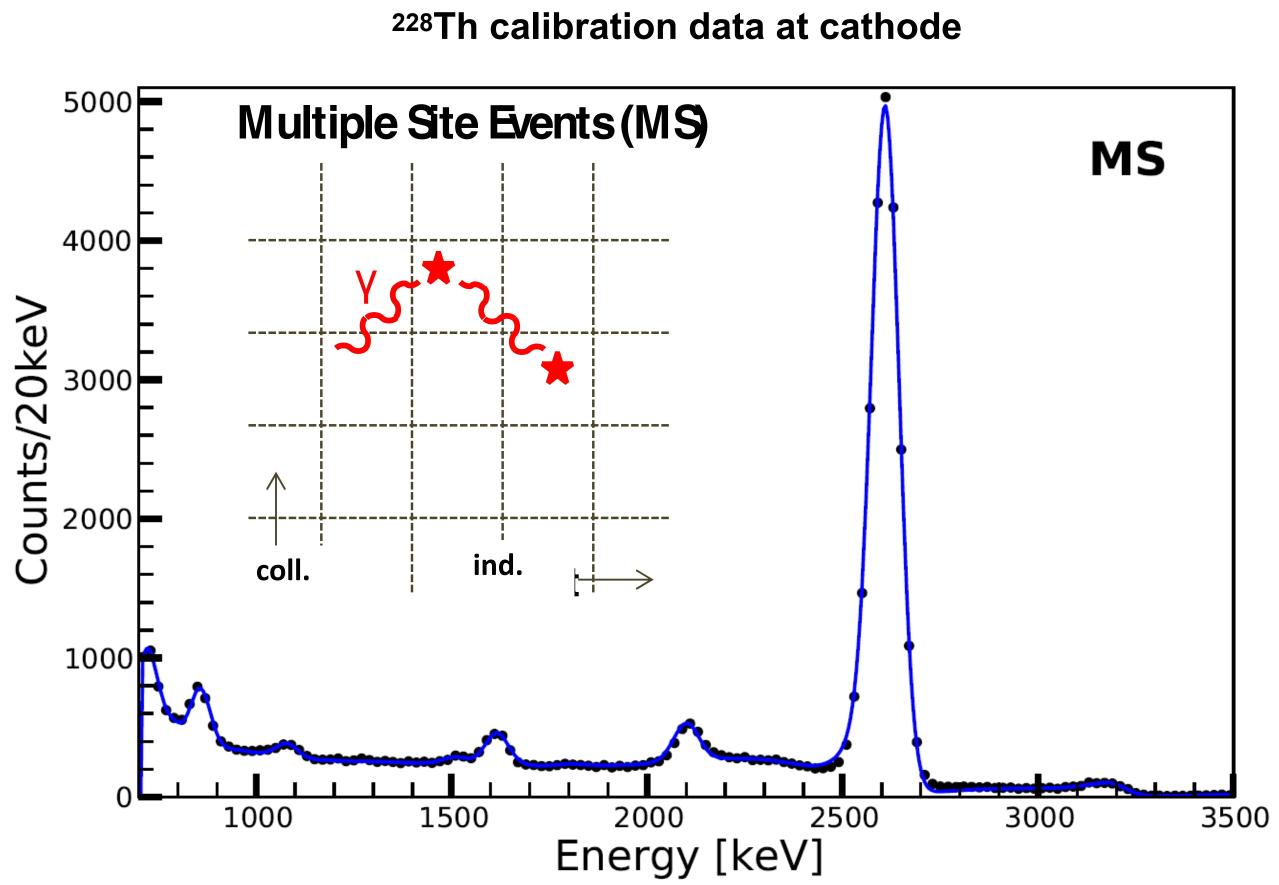


Topological Discrimination

- Event topology can be used to separate signal from background
  - $0\nu\beta\beta$ are spatially contained (single-site)
  - γ-backgrounds at the same energy predominantly undergo Compton-scattering (multi-site)
- Fraction of single-sited γ -background at the Q-value is ~15%





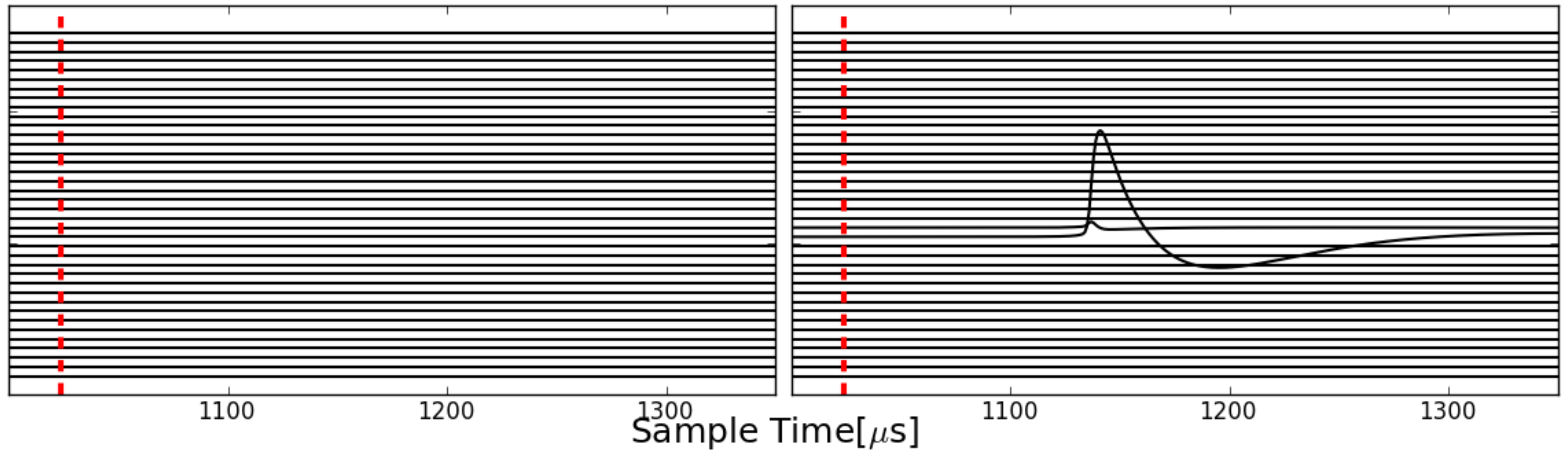


Deep Neural Network Based Discriminator

- Demonstrated improved energy reconstruction with DNN: JINST 13 (2018) no.08, P08023

- Use waveform images of U-wire signals

- DNN scores "signal-likeness" of each event



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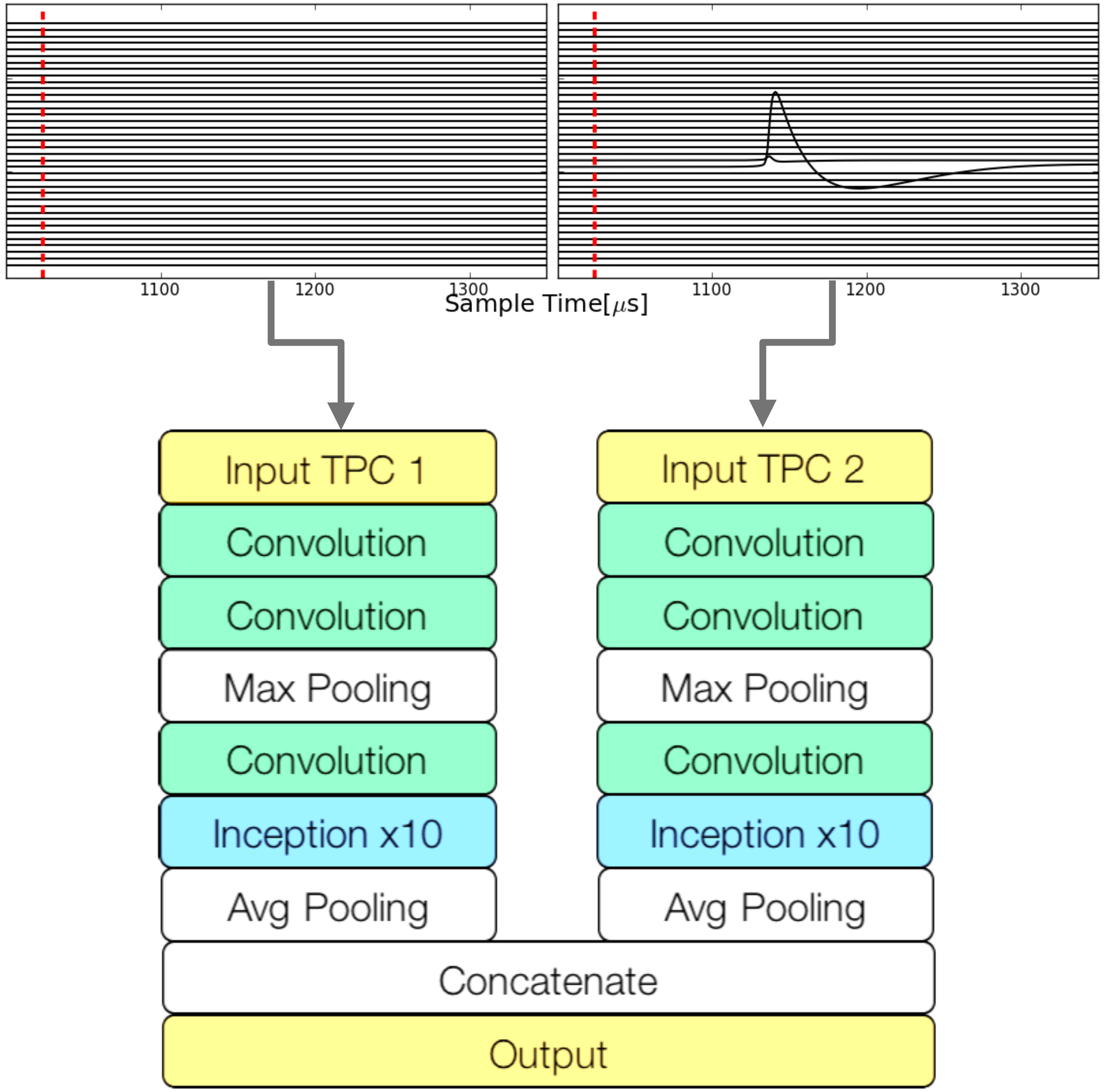

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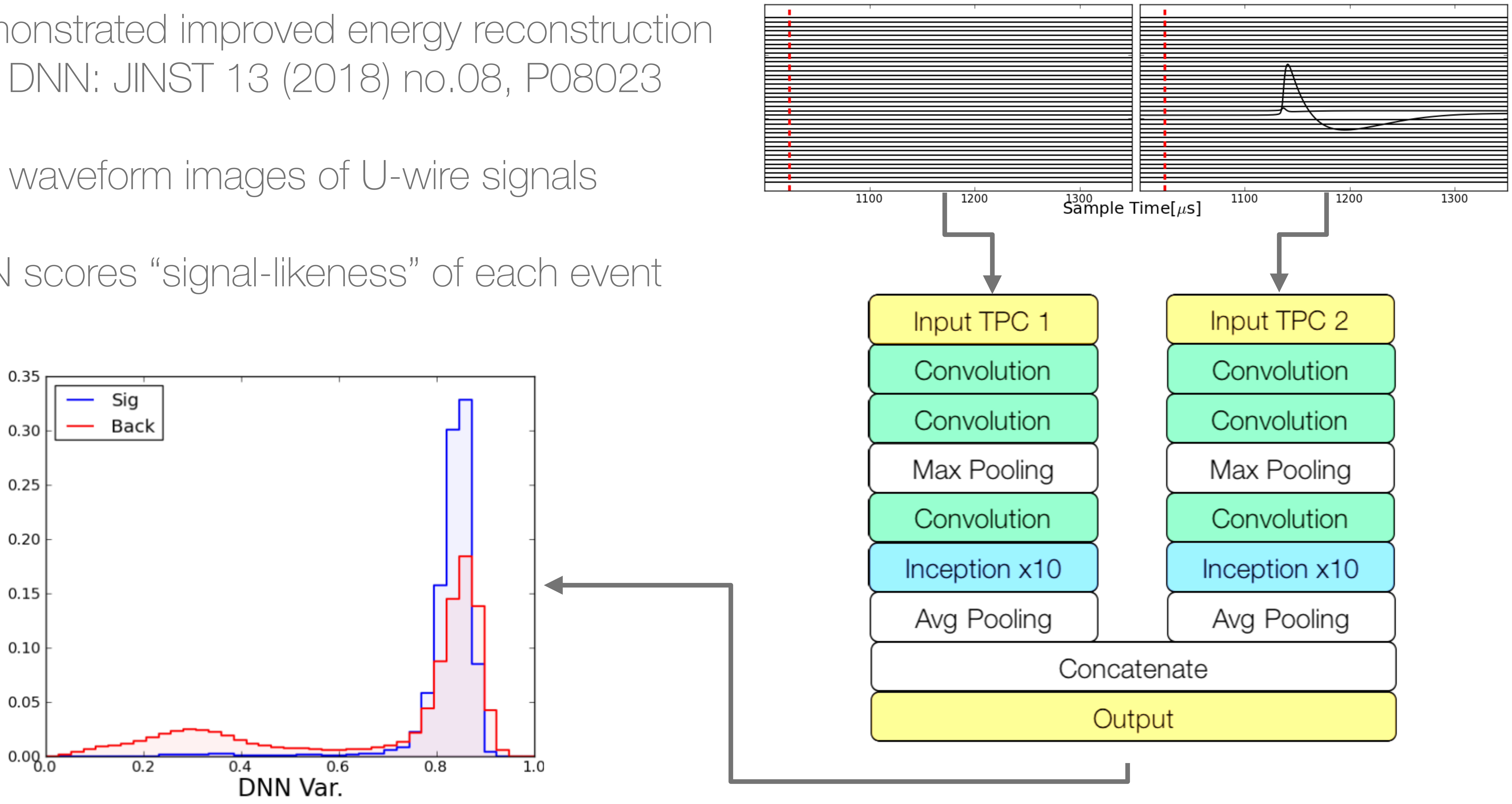
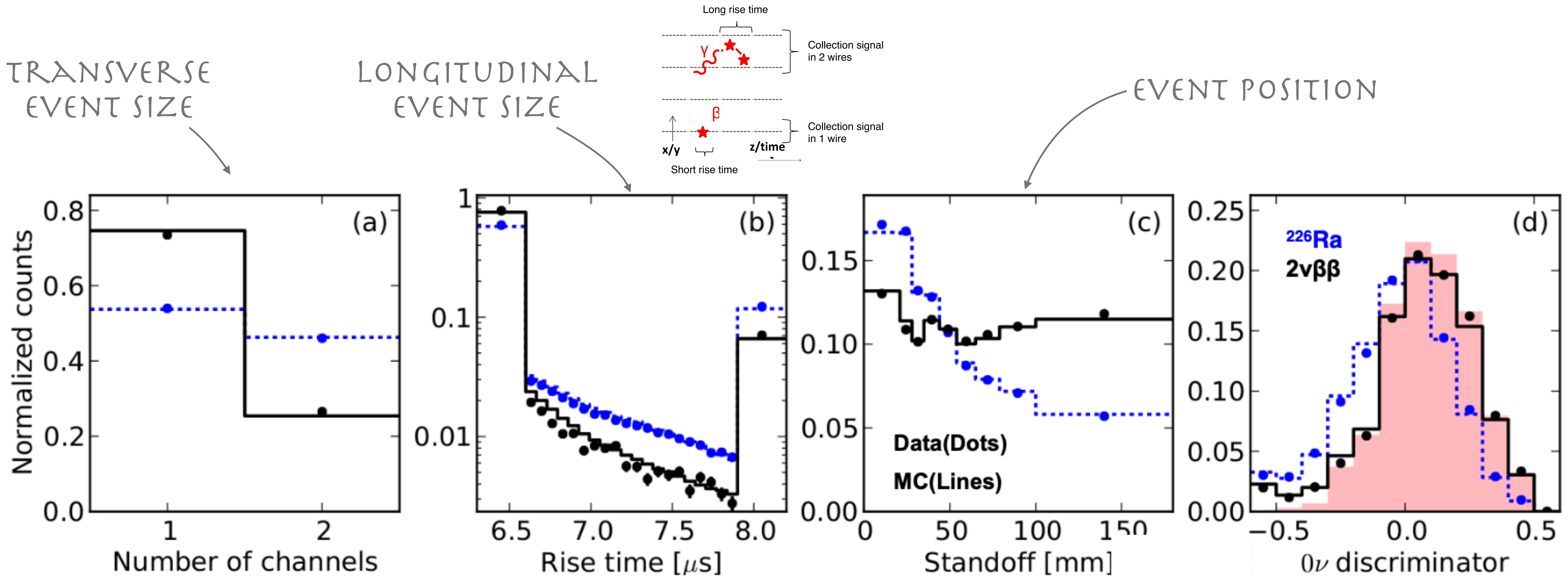


Boosted Decision Tree Discriminator (Single-Site)

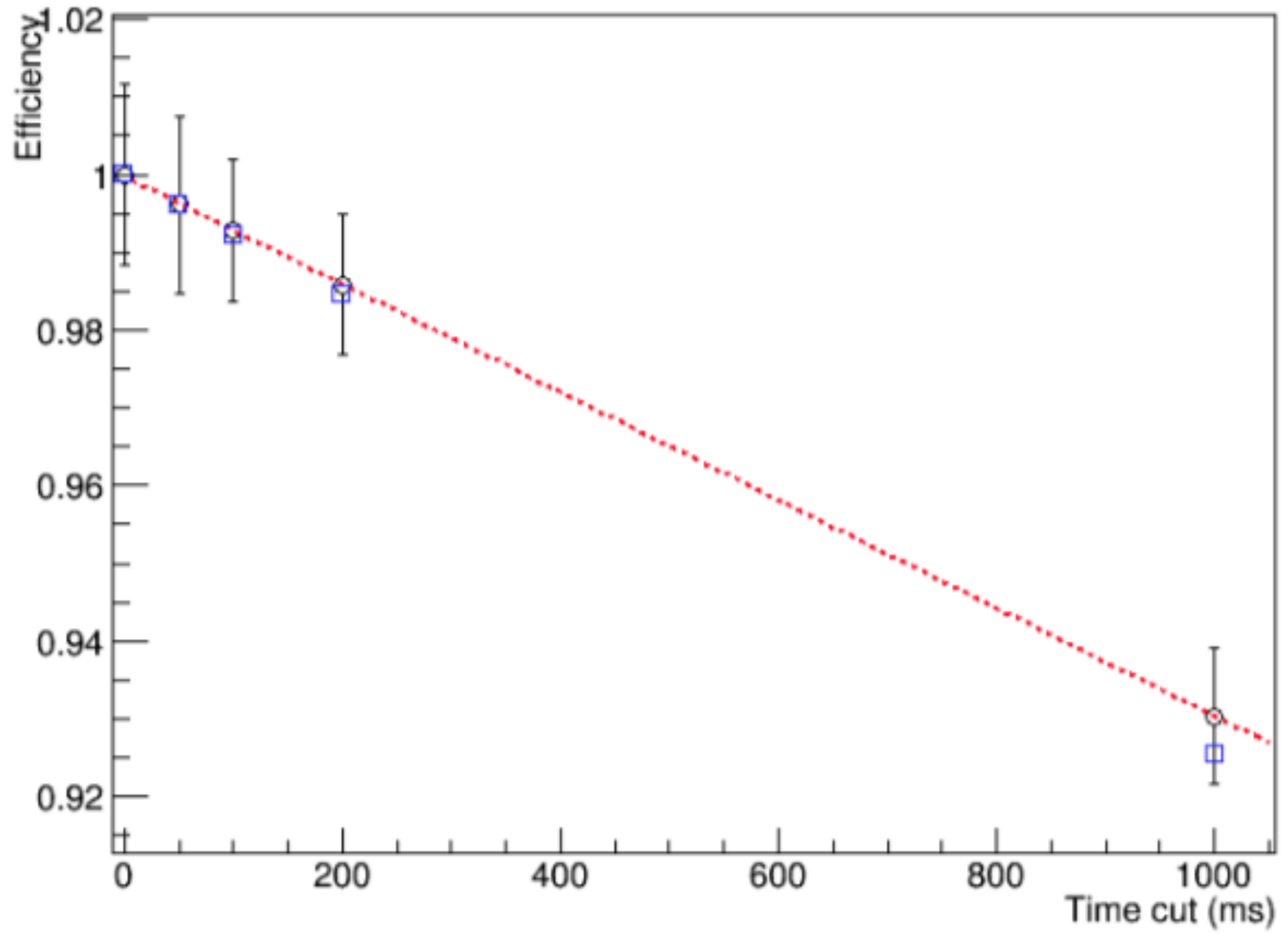
- Similar sensitivity to within ~3% with a more traditional BDT discriminator

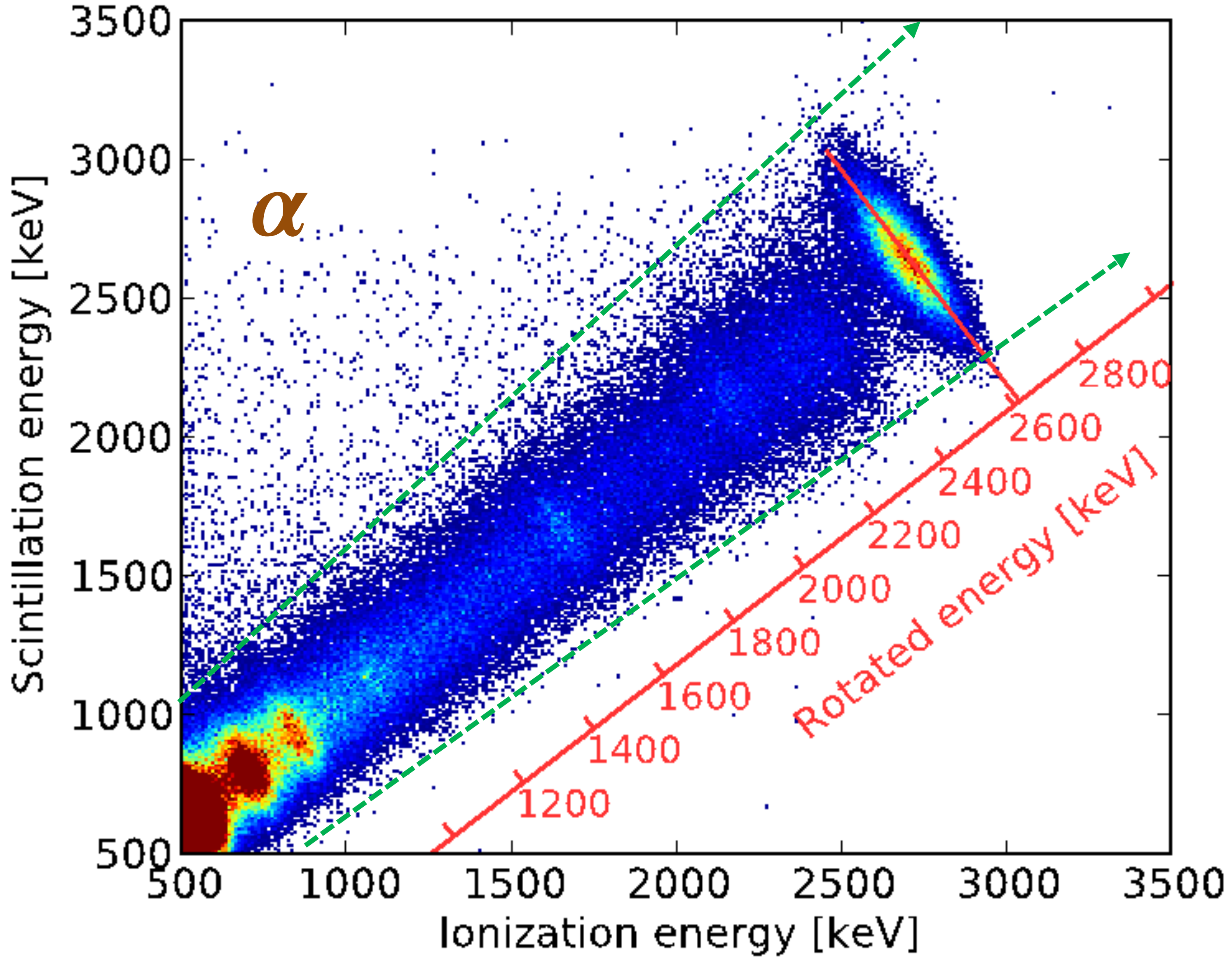
Separate BDT for MS:
- Number of Energy Deposits
- Energy Distribution
- Spatial Spread



Other Analysis Cuts

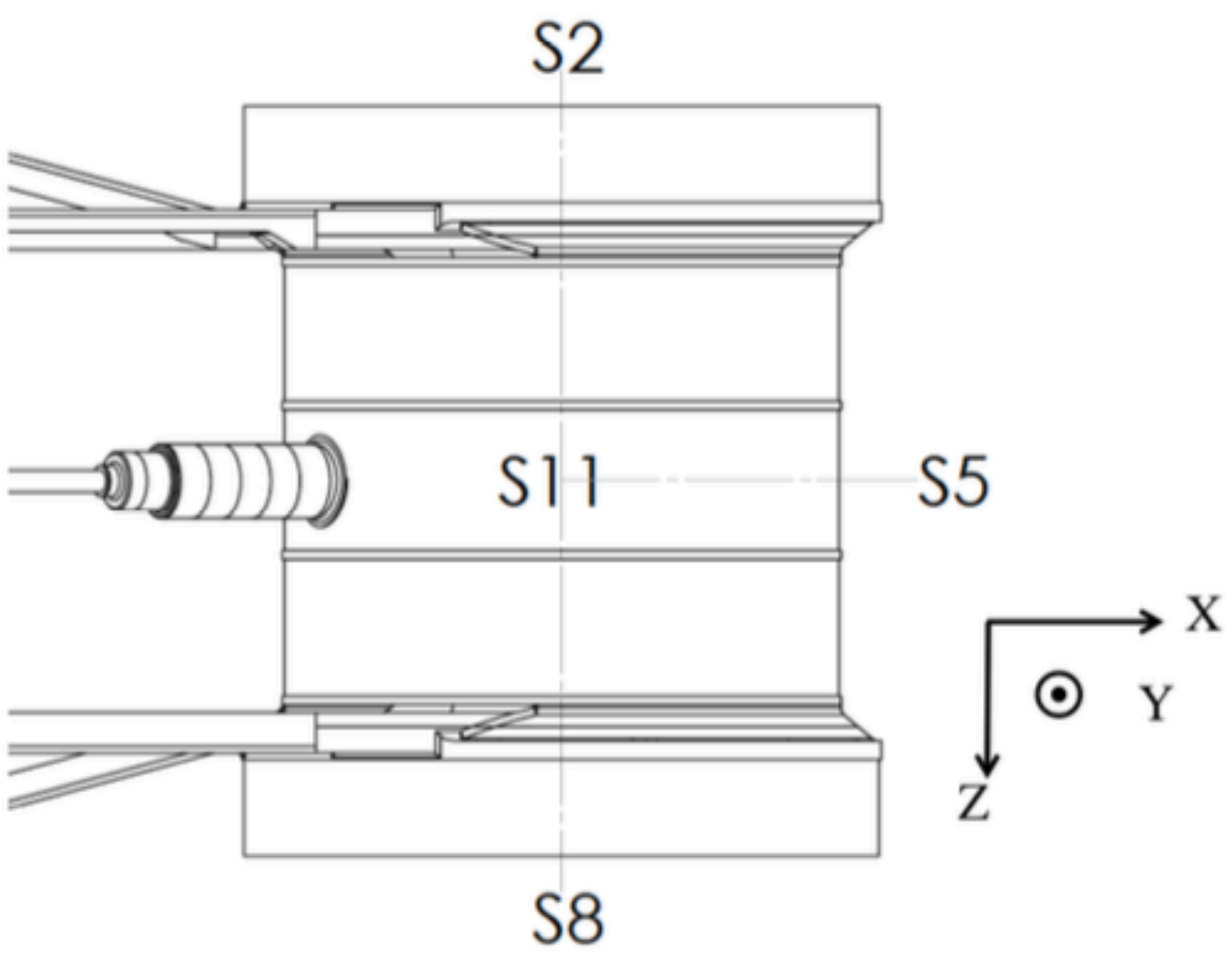
- Require $60\ \%$ of total energy to be fully 3D reconstructed (U,V and APD signal)
- Events within a $0.1\ \mathrm{s}$ coincidence window are discarded (BiPo)
- Cut on the ratio of light and charge removes
  - α-particle with nearly 100% efficiency
  - Poorly reconstructed β's and γ's
- Overall signal efficiency:
  - $\epsilon = (97.8 \pm 3.0)\ \%$ for Phase I
  - $\epsilon = (96.4 \pm 3.0)\ \%$ for Phase II

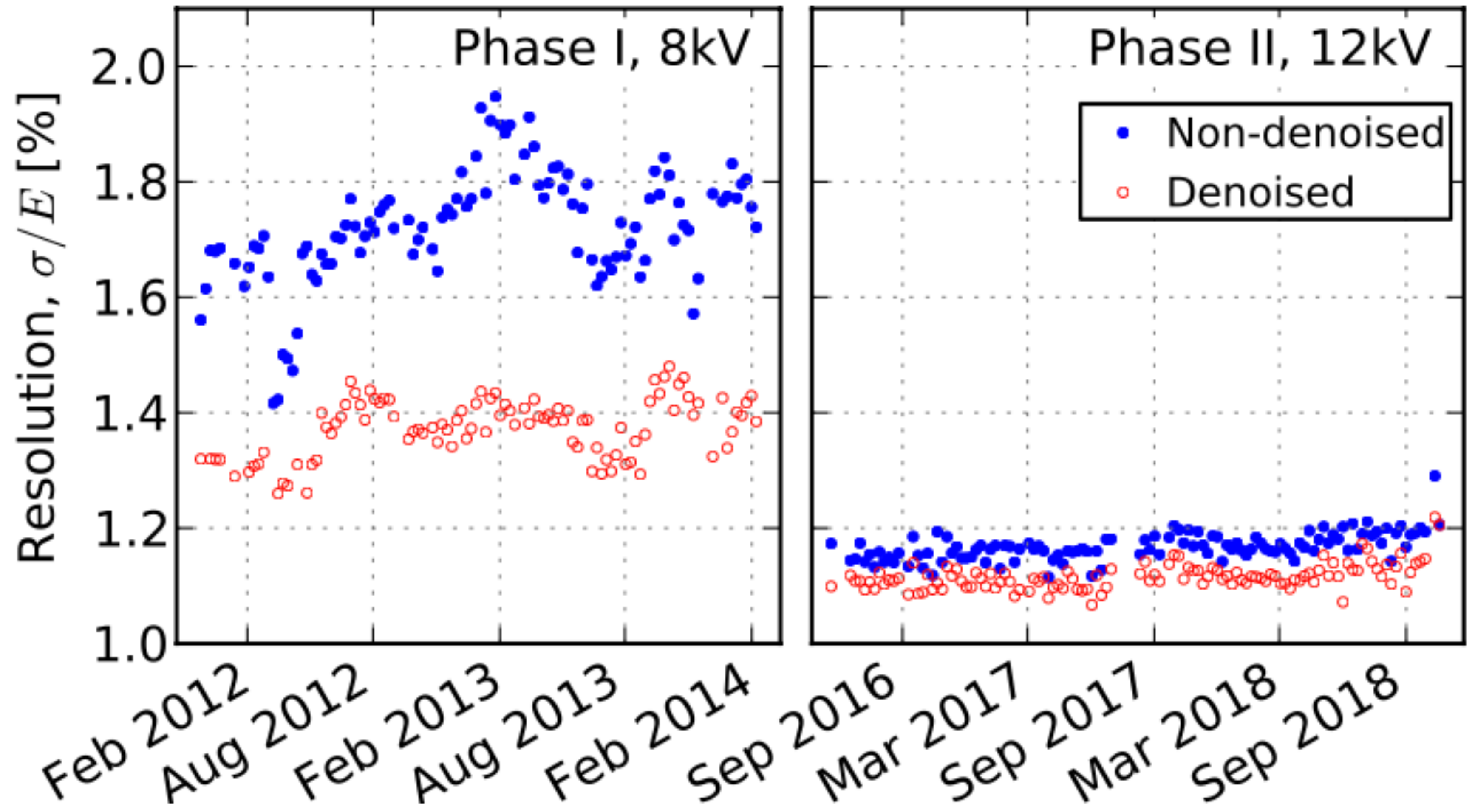




Detector Calibration

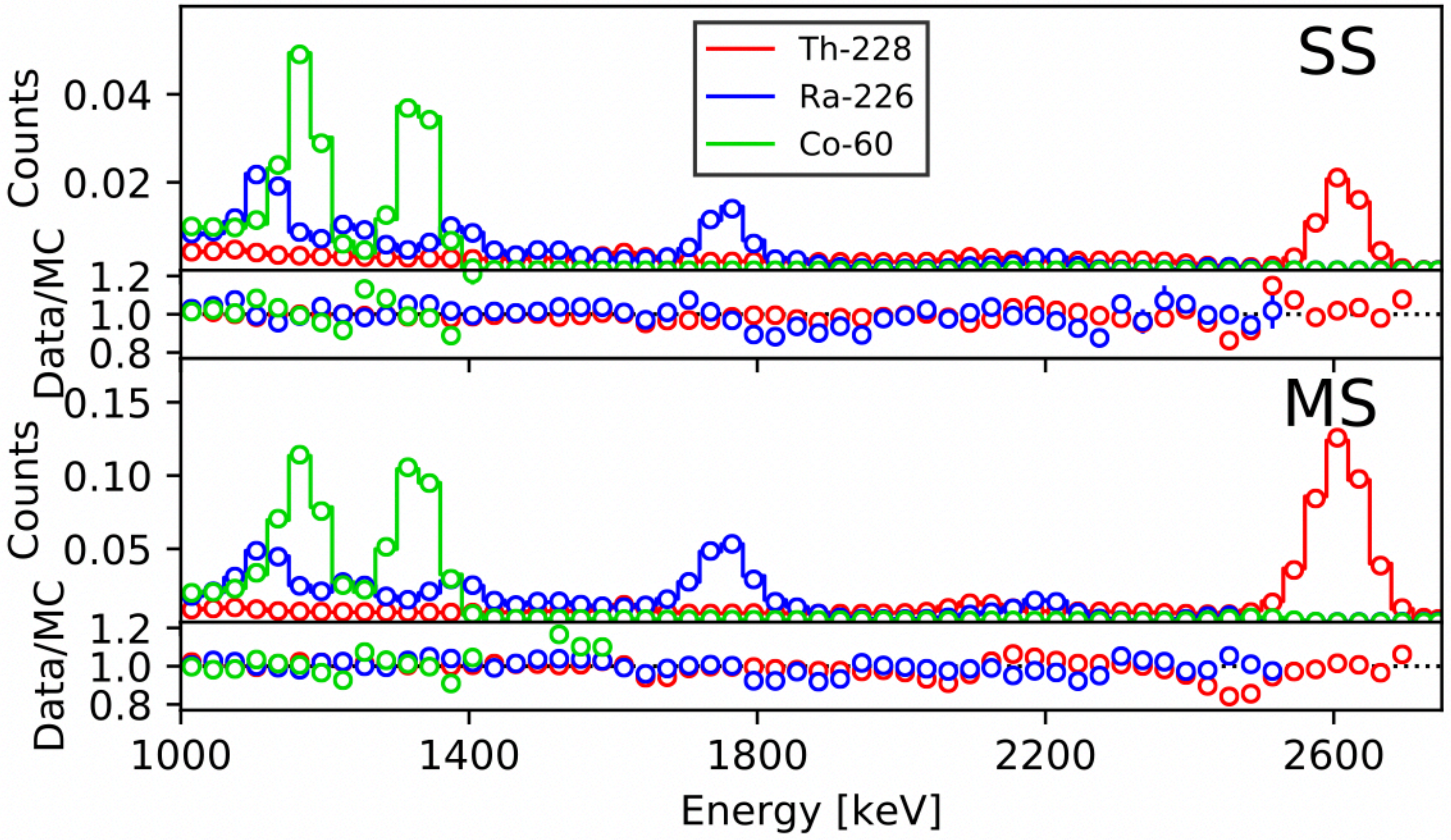
- Periodically position calibration sources near the detector using ^{137}Cs, ^{60}Co, ^{226}Ra, ^{228}Th
  - Monitor detector performance
  - Calibrate the energy scale
  - Calibrate the energy resolution
  - Measure the electron lifetime





Data/MC Agreement and Systematic Errors

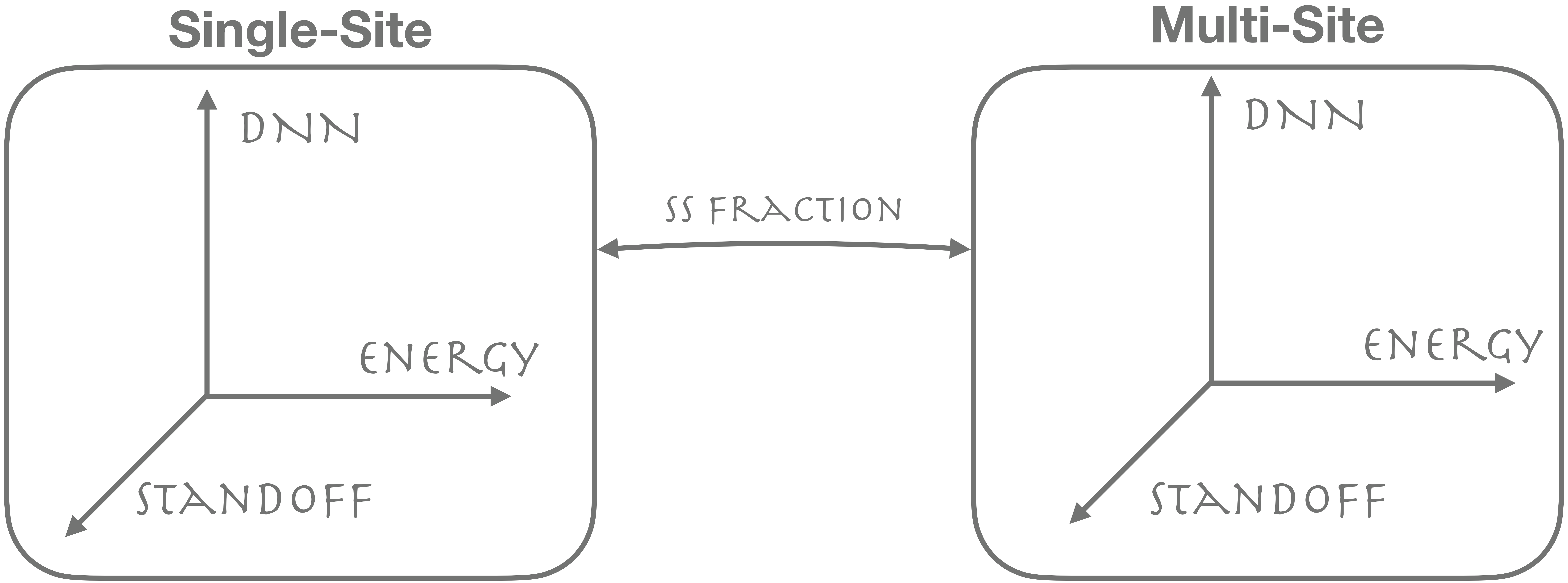
- We compare our MC prediction to the data from source calibration runs
  - Systematic from shape disagreements is propagated into our likelihood fit as a Gaussian constraints
  - Constrain SS-fraction
  - Energy scale error
- Error on signal detection efficiency estimated from comparison between MC and low background data



Source	Phase I	Phase II
Background errors		
Spectral shape agreement	5.8%	4.4%
Background model	4.0%	4.6%
Other [8]	1.5%	1.2%
Total error	7.1%	6.5%
Signal detection efficiency		
Fiducial volume	2.8%	2.6%
Partial 3D cut	< 0.4%	< 0.4%
Light-to-charge ratio	0.9%	0.9%
De-noising mis-rec	-	1.0%
Other [13]	< 1.0%	< 1.0%
Total error	3.1%	3.1%

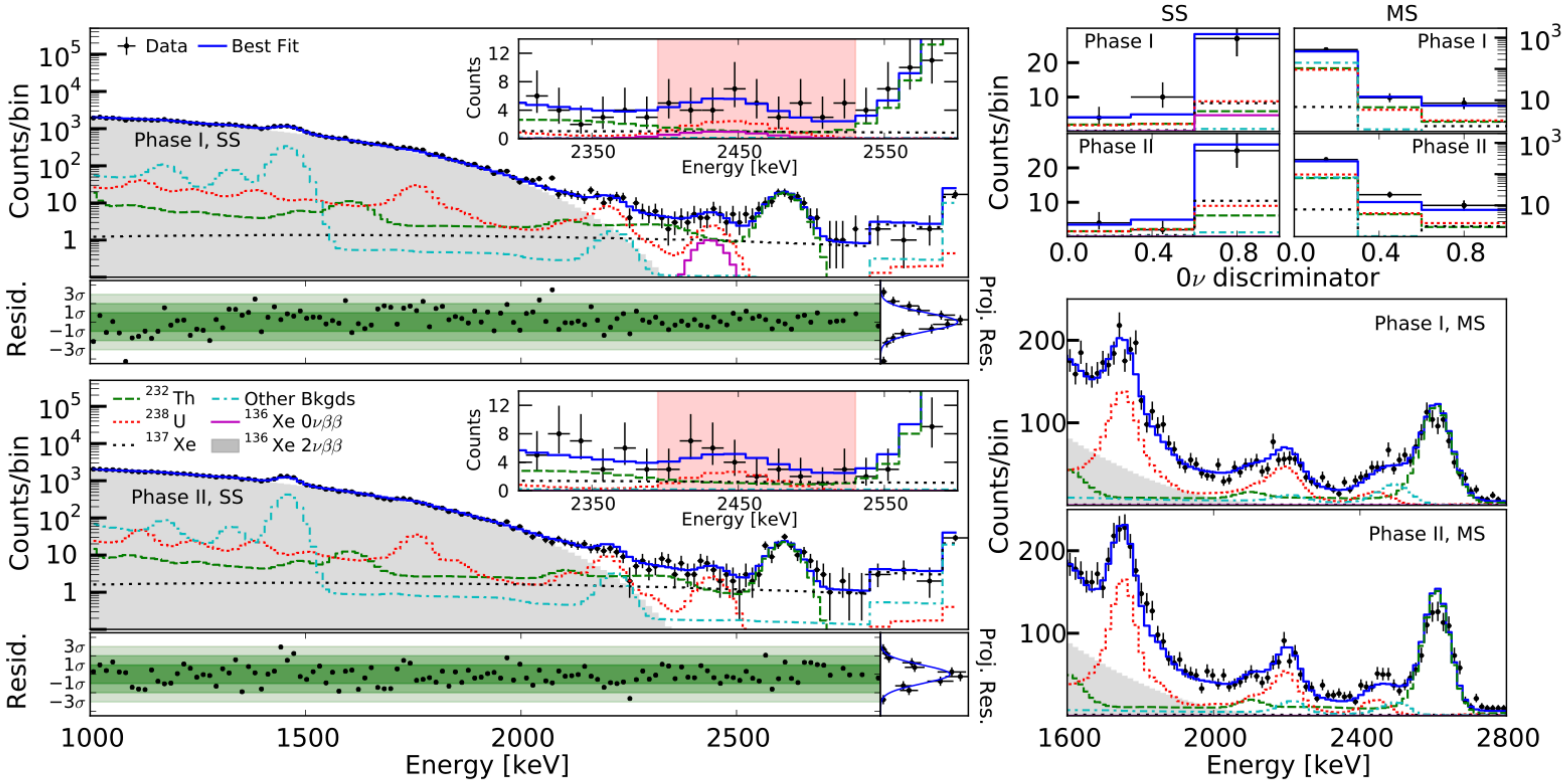
Multi-Dimensional Likelihood Analysis

- Perform a Frequentist analysis and minimize negative log-likelihood: $\mathscr{L} = -\ln L + G_{\mathrm{constr.}}$
- $\sim 25\,\%$ improvement in sensitivity over Energy + SS/MS only fit (mainly from DNN)



EXO-200 Final Result

No statistically significant evidence for $0\nu\beta\beta$ is observed



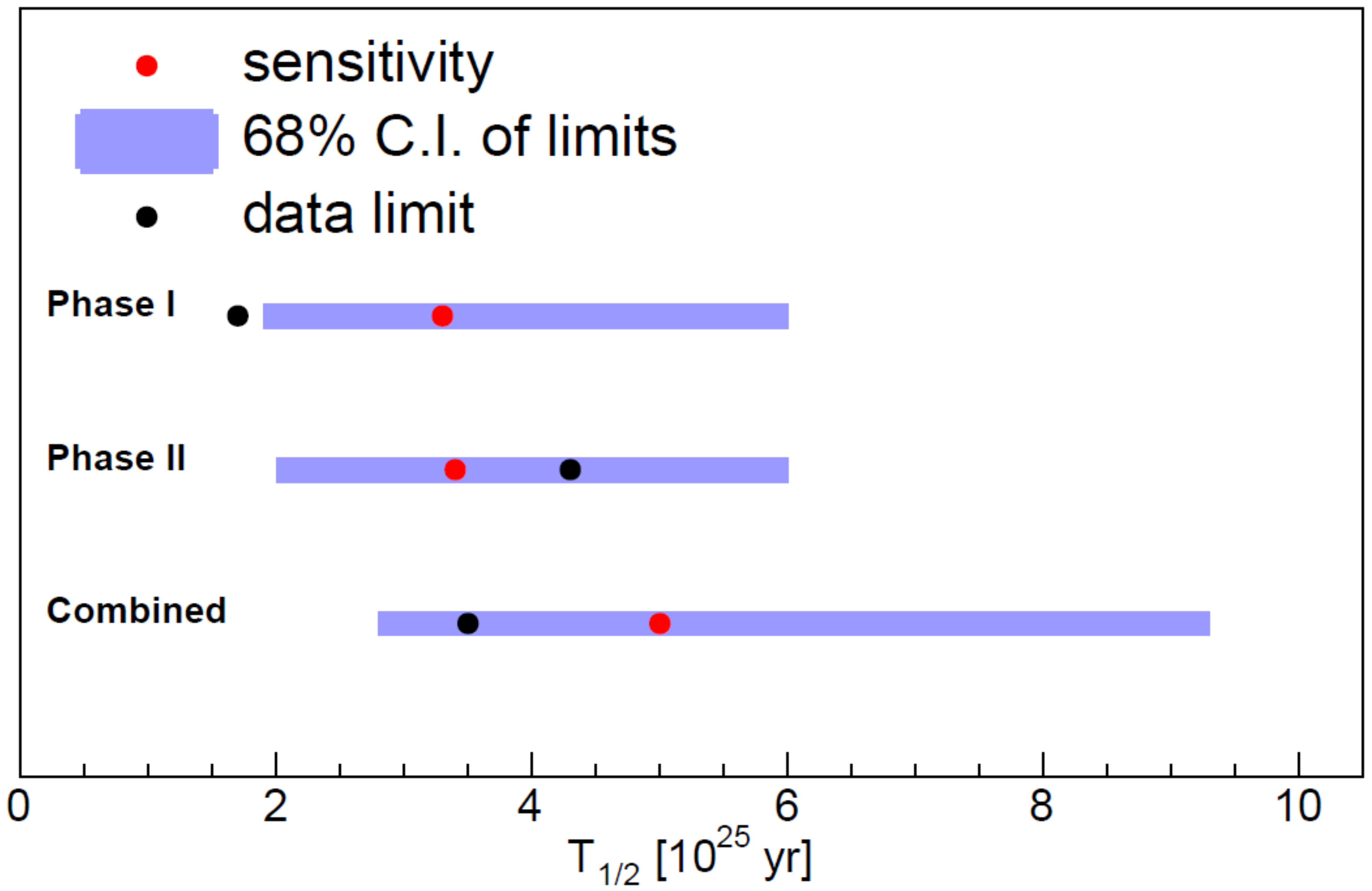
Summary of EXO-200 Results

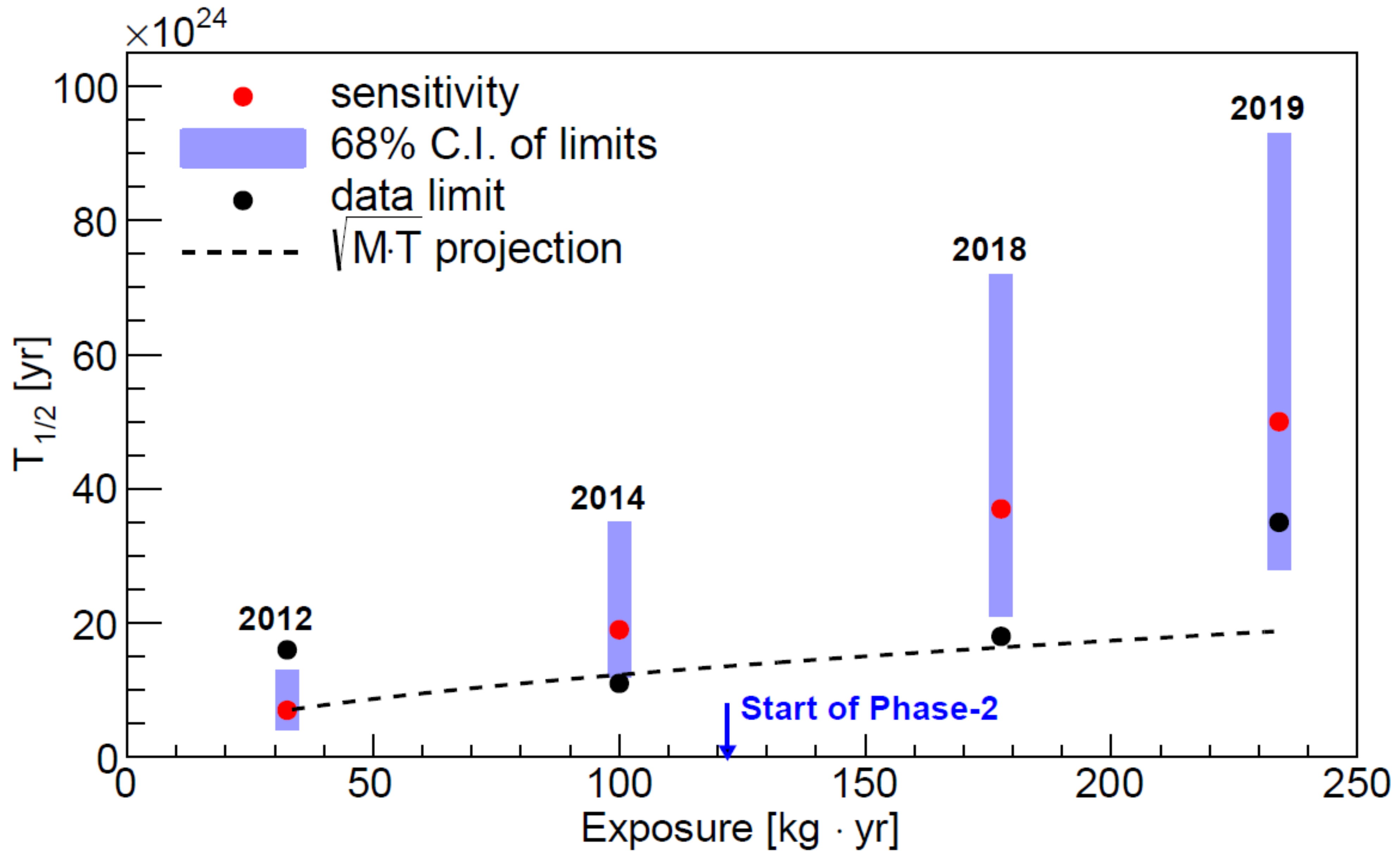
- Final exposure: $234.1\,\mathrm{kg}\cdot\mathrm{yr}$
- Expected sensitivity: $T_{1/2}^{0\nu} > 5.0 \times 10^{25}\,\mathrm{yr}$
- Lower limit:

$$T_{1/2}^{0\nu} > 3.5 \times 10^{25}\,\mathrm{yr}$$

$$m_{\beta\beta} < (93 - 286)\,\mathrm{meV}$$

- Major $0\nu\beta\beta$ results from EXO-200:
  - 2012: Phys. Rev. Lett. 109, 032505 (2012)
  - 2014: Nature 510, 229-234 (2014)
  - 2018: Phys. Rev. Lett. 120, 072701 (2018)
  - 2019: Phys. Rev. Lett. 123, 161802 (2019)





All EXO-200 Publications To Date

1. 2000: Phys. Lett. B 480, 12 (2000), Detection of very small Neutrino Masses in double-beta decay using laser tagging
2. **2003: Phys.Rev.B68:054201, Correlated Fluctuations between Luminescence and Ionization in Liquid Xenon**
3. 2005: Nucl.Instrum.Meth.A555 (2005), Mobility of thorium ions in liquid xenon
4. 2007: Phys. Rev. A 76, 023404 (2007), Observation of single collisionally cooled trapped ions in a buffer gas.
5. 2007: Nucl.Instrum.Meth.A578 (2007), A linear RFQ ion trap for the Enriched Xenon Observatory
6. 2007: Nucl.Instrum.Meth.A578 (2007), A liquid xenon ionization chamber in an all-fluoropolymer vessel
7. 2008: Nucl.Instrum.Meth.A591 (2008), Systematic study of trace radioactive impurities in candidate construction materials for EXO-200
8. 2008: Rev. Sci. Instrum. 79, 045101 (2008), A microfabricated sensor for thin dielectric layers
9. 2009: Nucl.Instrum.Meth.A608:68-75, Characterization of large area APDs for the EXO-200 detector
10. 2010: Rev. Sci. Instrum. 81 113301 (2010), A simple radionuclide-driven single-ion source
11. 2011: Rev. Sci. Instrum. 82 (2011) 105114, A magnetically-driven piston pump for ultra-clean applications
12. 2011: Nucl. Instrum. Meth. A659 (2011) 215-228, A xenon gas purity monitor for EXO
13. **2011: Phys. Rev. Lett. 107, 212501, Observation of Two-Neutrino Double-Beta Decay in 136Xe with the EXO-200 Detector**
14. 2012: Nucl .Instrum. Meth. A675 (2012) 40-46, Xenon purity analysis for EXO-200 via mass spectrometry
15. 2012: JINST 7 (2012) P05010, The EXO-200 detector, part I: Detector design and construction
16. **2012: Phys. Rev. Lett. 109, 032505, Search for Neutrinoless Double-Beta Decay in 136 Xe with EXO-200**
17. 2014: Phys. Rev. C 89, 015502, An improved measurement of the 2νββ half-life of Xe-136 with EXO-200
18. **2014: Nature 510 (2014) 229-234, Search for Majorana neutrinos with the first two years of EXO-200 data**
19. 2014: Phys. Rev. D 90, 092004, Search for Majoron-emitting modes of double-beta decay of 136Xe with EXO-200
20. 2015: Phys. Rev. C, 92, 015503 (2015), Investigation of radioactivity-induced backgrounds in EXO-200
21. 2015: Phys. Rev. C 92, 045504 (2015), Measurements of the ion fraction and mobility of alpha and beta decay products in liquid xenon using EXO-200
22. 2016: Phys. Rev. C 93, 035501 (2016), Search for 2νββ decay of 136Xe to the 0+1 excited state of 136Ba with EXO-200
23. 2016: J. Cosmol. Astropart. Phys. 04, 029 (2016), Cosmogenic Backgrounds to 0νββ decay in EXO-200
24. 2016: Phys. Rev. D 93, 072001 (2016), First Search for Lorentz and CPT Violation in Double Beta Decay with EXO-200
25. 2016: JINST 11 P07015 (2016), An optimal energy estimator to reduce correlated noise for the EXO-200 light readout
26. 2017: Phys. Rev. C 95, 025502 (2017), Measurement of the Drift Velocity and Transverse Diffusion of Electrons in Liquid Xenon with the EXO-200 Detector
27. 2017: Nucl. Inst. Meth. A871, 169 (2017), Trace radioactive impurities in final construction materials for EXO-200
28. 2017: Phys. Rev. D 96, 092001 (2017), Searches for Double Beta Decay of 134Xe with EXO-200
29. **2018: Phys.Rev.Lett. 120 (2018) 072701, Search for Neutrinoless Double-Beta Decay with the Upgraded EXO-200 Detector**
30. 2018: Phys. Rev. D 97, 072007 (2018), Search for nucleon decays with EXO-200
31. 2018: 2018 JINST 13 P08023, Deep Neural Networks for Energy and Position Reconstruction in EXO-200
32. **2019: Phys. Rev. Lett. 123, 161802, Search for Neutrinoless Double-Beta Decay with the Complete EXO-200 Dataset**
33. 2020: Phys. Rev. C 101, 065501 (2020), Measurement of the scintillation and ionization response of liquid xenon at MeV energies in the EXO-200 experiment
34. 2020: Phys. Rev. Lett. 124, 232502 (2020), Measurement of the Spectral Shape of the β-decay of Xe-136 to the Ground State of Cs-136 in EXO-200 and Comparison with Theory
35. 2021: Phys. Rev. D 104, 112002 (2021), Search for Majoron-emitting modes of 136-Xe double beta decay with the complete EXO-200 dataset
36. 2022: JINST 17 P02015 (2022), The EXO-200 detector, part II: auxiliary systems

Detector performance
Radio-purity
Discovery of $2\nu\beta\beta$
Search for $0\nu\beta\beta$
Detector physics
New Analysis Techniques
Other BSM physics

All EXO-200 Publications To Date

1. 2000: Phys. Lett. B 480, 12 (2000), Detection of very small Neutrino Masses in double-beta decay using laser tagging
2. 2003: Phys.Rev.B68:054201, Correlated Fluctuations between Luminescence and Ionization in Liquid Xenon
3. 2005: Nucl.Instrum.Meth.A555 (2005), Mobility of thorium ions in liquid xenon
4. 2007: Phys. Rev. A 76, 023404 (2007), Observation of single collisionally cooled trapped ions in a buffer gas.
5. 2007: Nucl.Instrum.Meth.A578 (2007), A linear RFQ ion trap for the Enriched Xenon Observatory
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7. 2008: Nucl.Instrum.Meth.A591 (2008), Systematic study of trace radioactive impurities in candidate construction materials for EXO-200
8. 2008: Rev. Sci. Instrum. 79, 045101 (2008), A microfabricated sensor for thin dielectric layers
9. 2009: Nucl.Instrum.Meth.A608:68-75, Characterization of large area APDs for the EXO-200 detector
10. 2010: Rev. Sci. Instrum. 81 113301 (2010), A simple radionuclide-driven single-ion source
11. 2011: Rev. Sci. Instrum. 82 (2011) 105114, A magnetically-driven piston pump for ultra-clean applications
12. 2011: Nucl. Instrum. Meth. A659 (2011) 215-228, A xenon gas purity monitor for EXO
13. 2011: Phys. Rev. Lett. 107, 212501, Observation of Two-Neutrino Double-Beta Decay in 136Xe with the EXO-200 Detector
14. 2012: Nucl .Instrum. Meth. A675 (2012) 40-46, Xenon purity analysis for EXO-200 via mass spectrometry
15. 2012: JINST 7 (2012) P05010, The EXO-200 detector, part I: Detector design and construction
16. 2012: Phys. Rev. Lett. 109, 032505, Search for Neutrinoless Double-Beta Decay in 136 Xe with EXO-200
17. 2014: Phys. Rev. C 89, 015502, An improved measurement of the 2νββ half-life of Xe-136 with EXO-200
18. 2014: Nature 510 (2014) 229-234, Search for Majorana neutrinos with the first two years of EXO-200 data
19. 2014: Phys. Rev. D 90, 092004, Search for Majoron-emitting modes of double-beta decay of 136Xe with EXO-200
20. 2015: Phys. Rev. C, 92, 015503 (2015), Investigation of radioactivity-induced backgrounds in EXO-200
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22. 2016: Phys. Rev. C 93, 035501 (2016), Search for 2νββ decay of 136Xe to the 0+1 excited state of 136Ba with EXO-200
23. 2016: J. Cosmol. Astropart. Phys. 04, 029 (2016), Cosmogenic Backgrounds to 0νββ decay in EXO-200
24. 2016: Phys. Rev. D 93, 072001 (2016), First Search for Lorentz and CPT Violation in Double Beta Decay with EXO-200
25. 2016: JINST 11 P07015 (2016), An optimal energy estimator to reduce correlated noise for the EXO-200 light readout
26. 2017: Phys. Rev. C 95, 025502 (2017), Measurement of the Drift Velocity and Transverse Diffusion of Electrons in Liquid Xenon with the EXO-200 Detector
27. 2017: Nucl. Inst. Meth. A871, 169 (2017), Trace radioactive impurities in final construction materials for EXO-200
28. 2017: Phys. Rev. D 96, 092001 (2017), Searches for Double Beta Decay of 134Xe with EXO-200
29. 2018: Phys.Rev.Lett. 120 (2018) 072701, Search for Neutrinoless Double-Beta Decay with the Upgraded EXO-200 Detector
30. 2018: Phys. Rev. D 97, 072007 (2018), Search for nucleon decays with EXO-200
31. 2018: 2018 JINST 13 P08023, Deep Neural Networks for Energy and Position Reconstruction in EXO-200
32. 2019: Phys. Rev. Lett. 123, 161802, Search for Neutrinoless Double-Beta Decay with the Complete EXO-200 Dataset
33. 2020: Phys. Rev. C 101, 065501 (2020), Measurement of the scintillation and ionization response of liquid xenon at MeV energies in the EXO-200 experiment
34. 2020: Phys. Rev. Lett. 124, 232502 (2020), Measurement of the Spectral Shape of the β-decay of Xe-136 to the Ground State of Cs-136 in EXO-200 and Comparison with Theory
35. 2021: Phys. Rev. D 104, 112002 (2021), Search for Majoron-emitting modes of 136-Xe double beta decay with the complete EXO-200 dataset
36. 2022: JINST 17 P02015 (2022), The EXO-200 detector, part II: auxiliary systems
37. **2022: Search for MeV Electron Recoil from Dark Matter in EXO-200**
38. **2022: Search for 2νββ decay of 136Xe to the 0+1 excited state with the Complete EXO-200 Dataset**

Upcoming publications:

Search for MeV Electron Recoil from Dark Matter in EXO-200

Search for 2νββ decay of 136Xe to the 0+1 excited state with the Complete EXO-200 Dataset

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Working on Updates to

Search for Two-Neutrinos Double Beta Decay of Xe-134

Lorentz and CPT Violation in Double Beta Decay

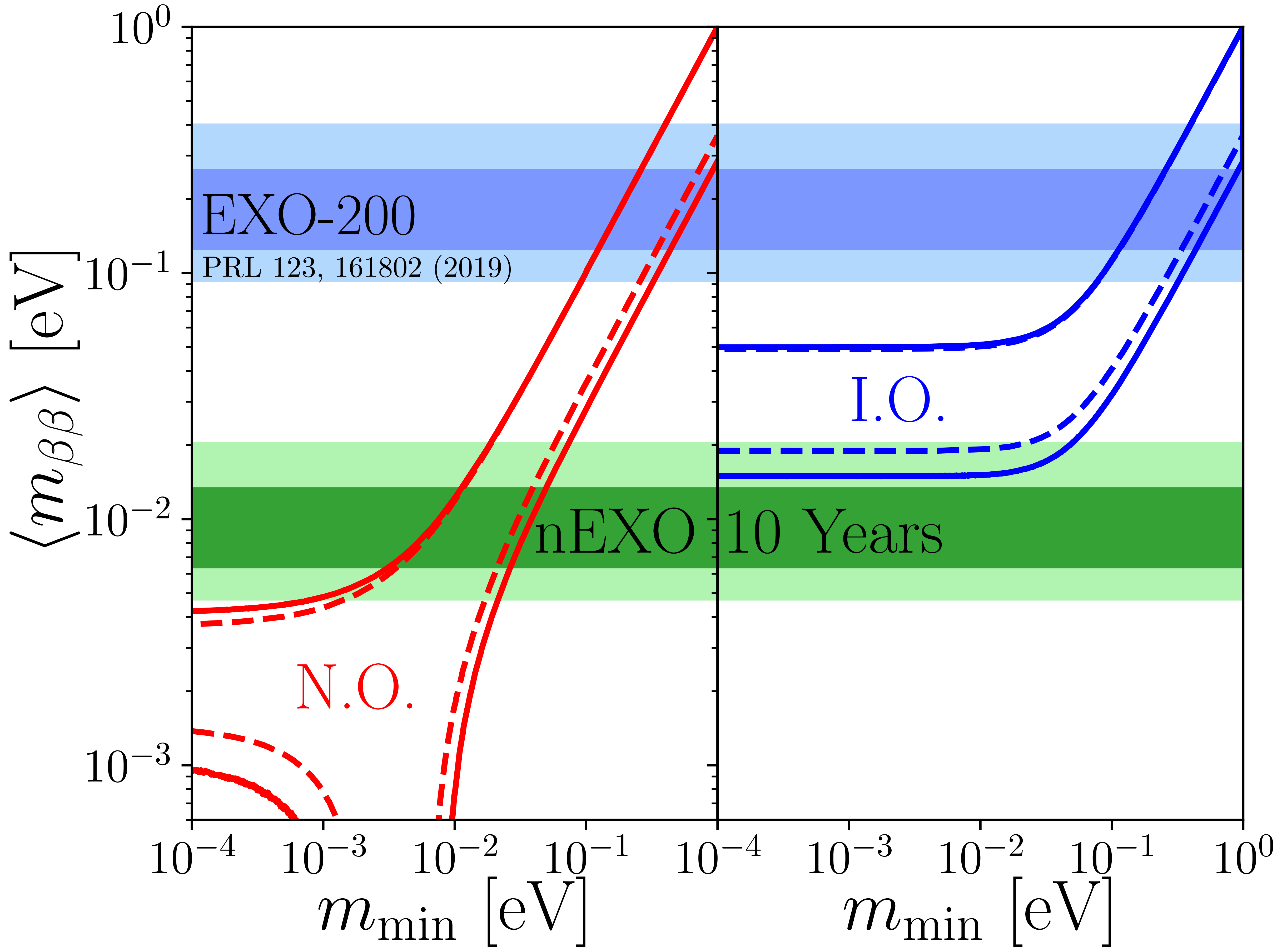
Search for the Excited States Decay of Xe-137

Summary

- EXO-200 has completed data taking as of December 2018
  - Accumulated 1181.3 days of livetime ($234.1\,\mathrm{kg\cdot yr}$ of $^{136}\mathrm{Xe}$ exposure)
- No statistically significant $0\nu\beta\beta$ signal observed
  - $T^{0\nu}_{1/2} > 3.5 \times 10^{25}\,\mathrm{yr}$
  - $m_{\beta\beta} < (93 - 286)\,\mathrm{meV}$
- While the main $0\nu\beta\beta$ search is complete more physics searches are underway
- Success of EXO-200 paves the way next generation experiment nEXO with projected half-life sensitivity $T^{0\nu}_{1/2} > 1.35 \times 10^{28}\,\mathrm{yr}$

$$\frac{1}{T^{0\nu}_{1/2}} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} G^{0\nu} \left| \mathcal{M}^{0\nu} \right|^2$$

Effective Majorana neutrino mass — Phase space factor — Nuclear matrix element



BACKUP SLIDES