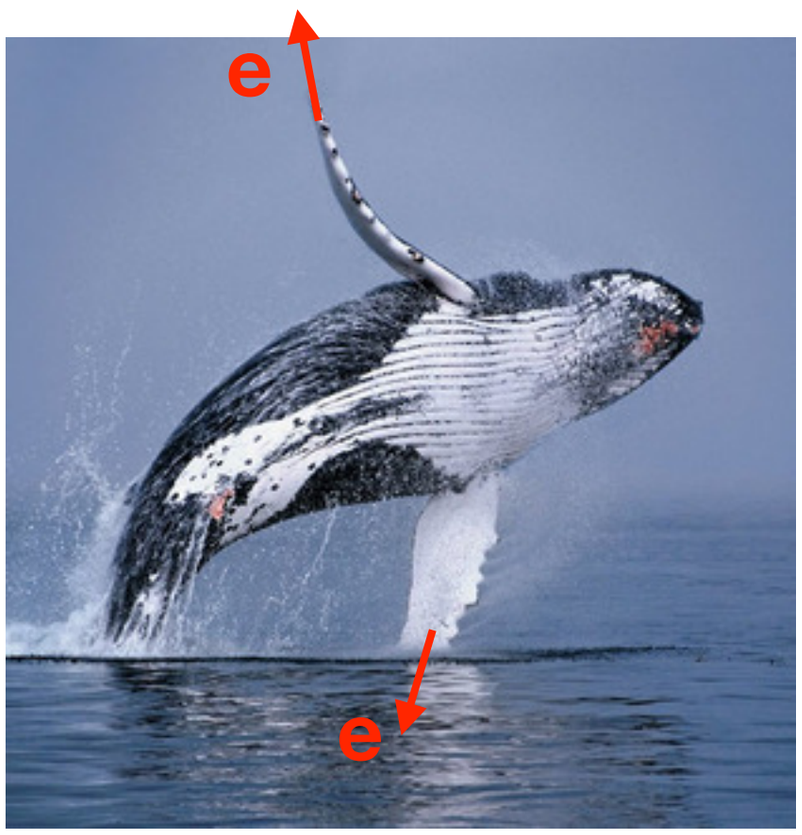
2019 Meeting of the Division of Particles and Fields of the American Physical Society

29 July — 2 August

Northeastern University Boston, MA, USA



The search for neutrinoless double beta decay with EXO-200

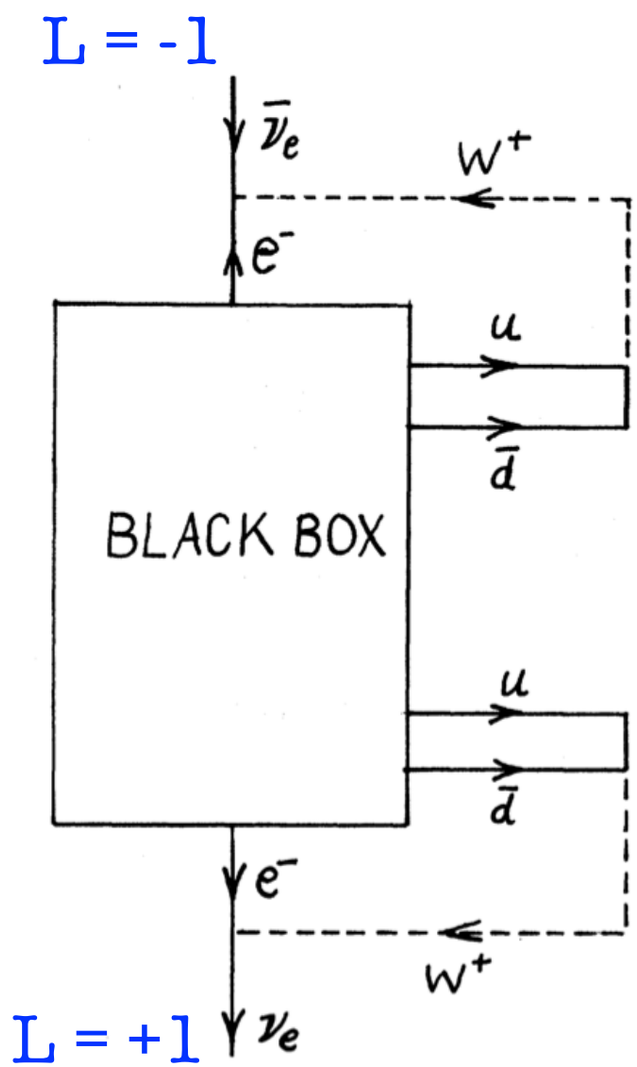
Andrea Pocar

University of Massachusetts, Amherst

Outline

- *Neutrinoless double beta decay*
- *EXO-200*
  - *Detector*
  - *Recent results*
- *Outlook*

0νββ decay = new physics



[Schechter and Valle, 1982]

observation of 0νββ decay

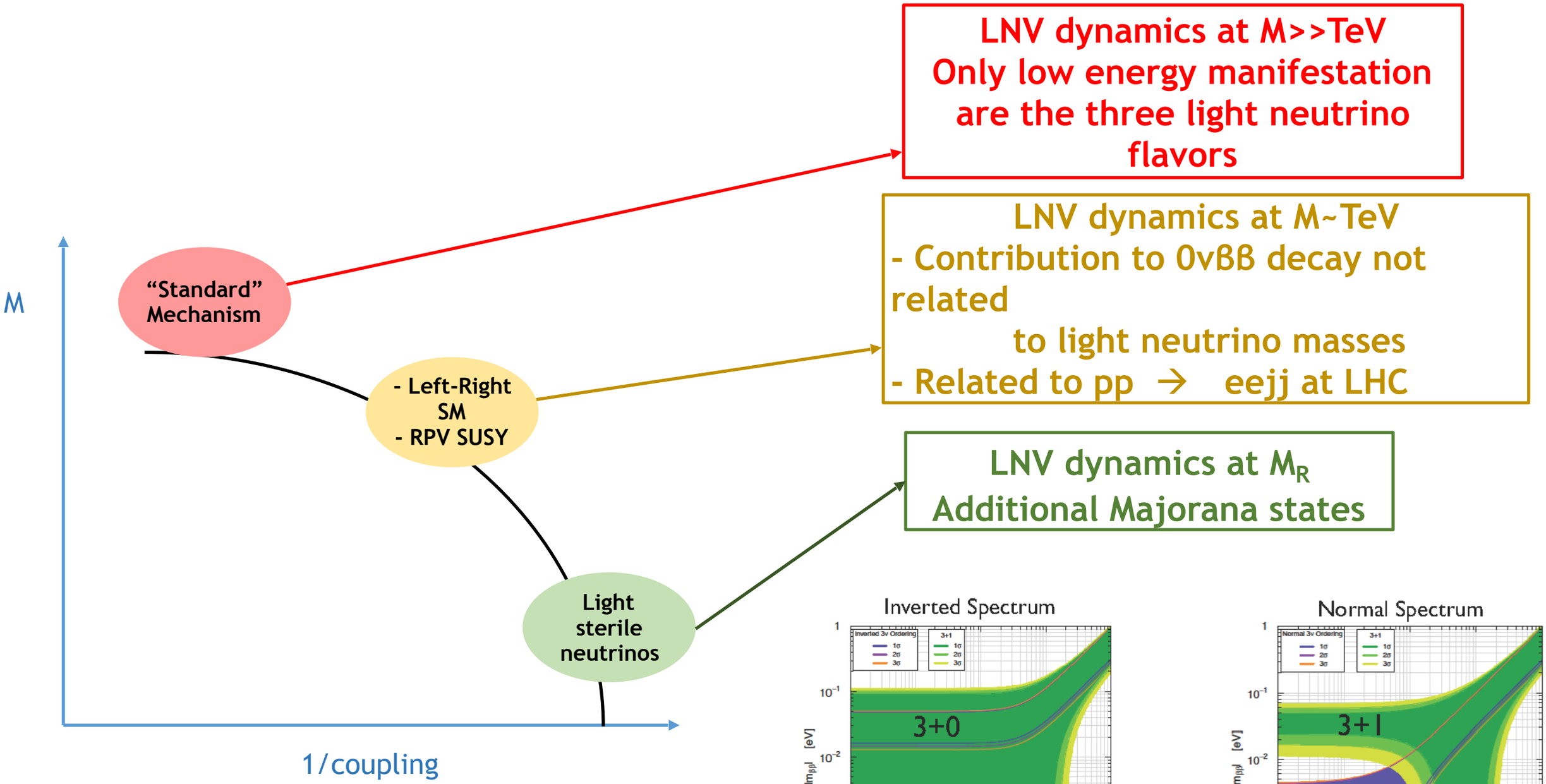
- massive, Majorana neutrinos
- **lepton number violation (ΔL = 2)**
- new mass scale of nature

0νββ rate

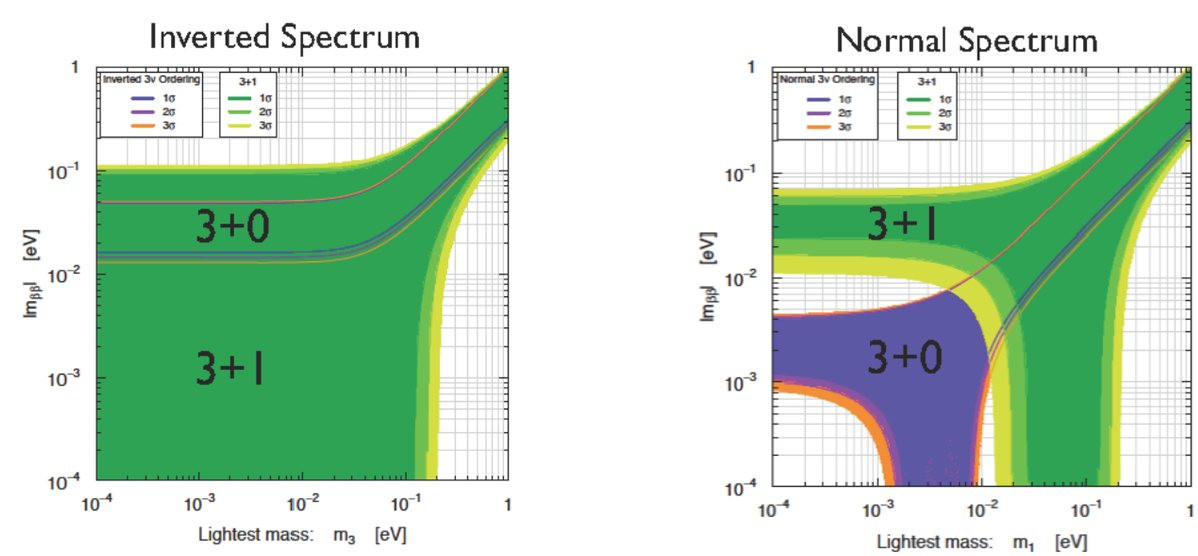
- absolute neutrino mass (model dependent)

possible probe for understanding the matter dominance in the universe through leptogenesis (via Δ(B-L))

Different physics can contribute to the decay



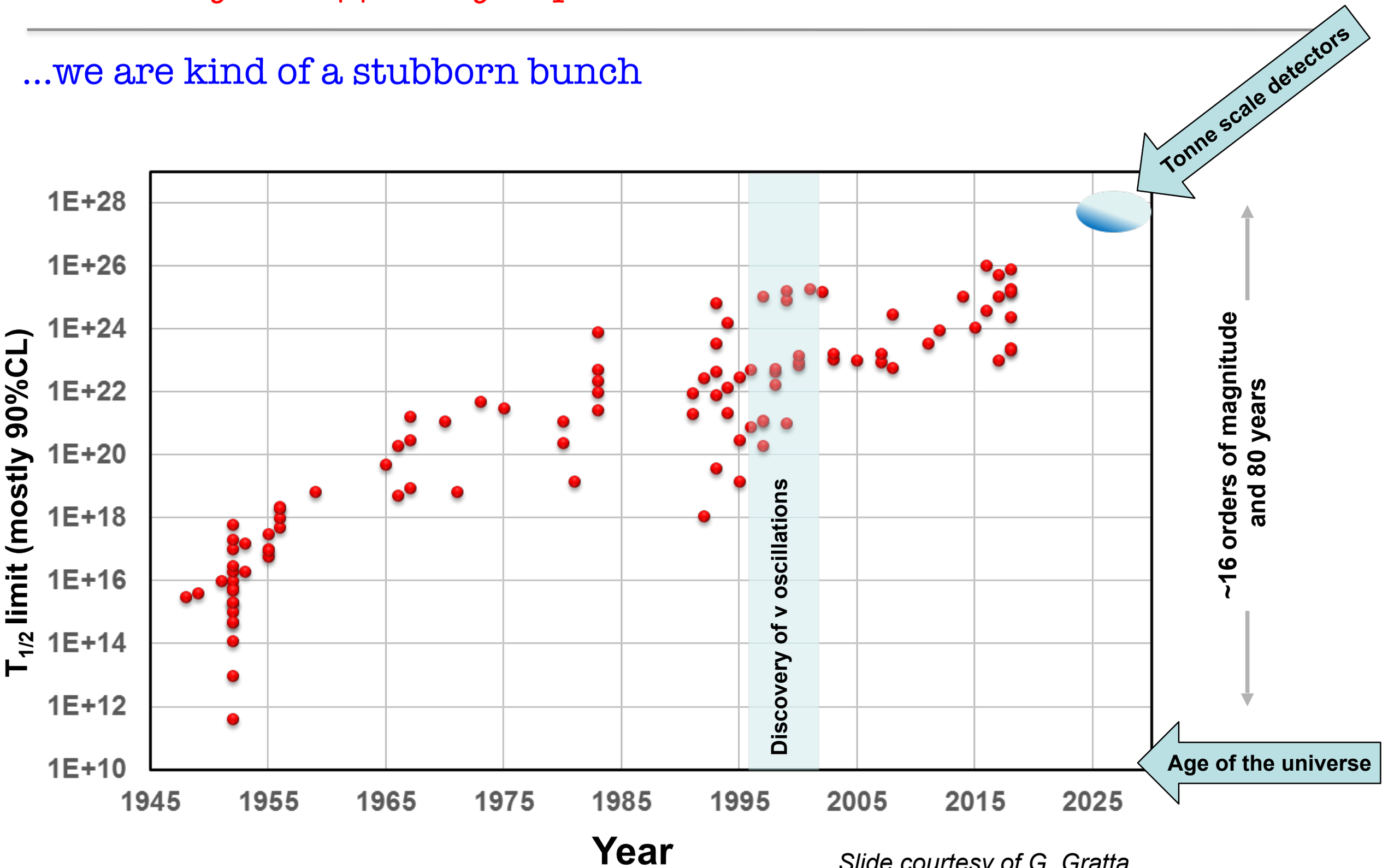
After V. Cirigliano



Giunti-Zavanin 1505.00978, JHEP07(2015)171

The history of 0νββ decay experiments in one slide

...we are kind of a stubborn bunch



Slide courtesy of G. Gratta
Data courtesy of S.Elliott and the PDG.
Not all results are necessarily shown.

why Xenon?

- ✓ known purification technology
- ✓ simplest enrichment (~1 tonne of ^{enr}Xe already available for science)
- ✓ scalable technology (also demonstrated by dark matter searches)
- ✓ can be re-purified and transferred between detectors

- ✓ allows for particle ID, event topology (α/β, multiplicity for β/γ, standoff)
- ✓ LXe provides superior self-shielding
- ✓ standard 2νββ is the slowest (among practical isotopes)
  ($T^{0\nu}_{1/2} \sim 2 \times 10^{21}$ y)

- ✳ energy resolution:
  Ge/bolometers > GXe > LXe > liquid scintillator
- ✓ might allow for daughter (barium) tagging

The EXO-200 Collaboration

University of Alabama, Tuscaloosa AL, USA — M Hughes, O Nusair, 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, R Gornea, C Jessiman, T Koffas, D Sinclair, B Veenstra, J Watkins
Colorado State University, Fort Collins CO, USA — C Chambers, A Craycraft, D Fairbank, W Fairbank Jr, A Iverson, J Todd
Drexel University, Philadelphia PA, USA — MJ Dolinski, P Gautam, EV Hansen, YH Lin, Y-R Yen
Duke University, Durham NC, USA — PS Barbeau
Friedrich-Alexander-University Erlangen, Nuremberg, Germany — G Anton, J Hoessl, P Hufschmidt, T Michel, M Wagenpfeil, S Schmidt, G Wrede, T Ziegler
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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
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Laurentian University, Sudbury ON, Canada — B Cleveland, A Der Mesrobian-Kabakian, J Farine, C Licciardi, A Robinson, U Wichoski
University of Maryland, College Park MD, USA — C Hall
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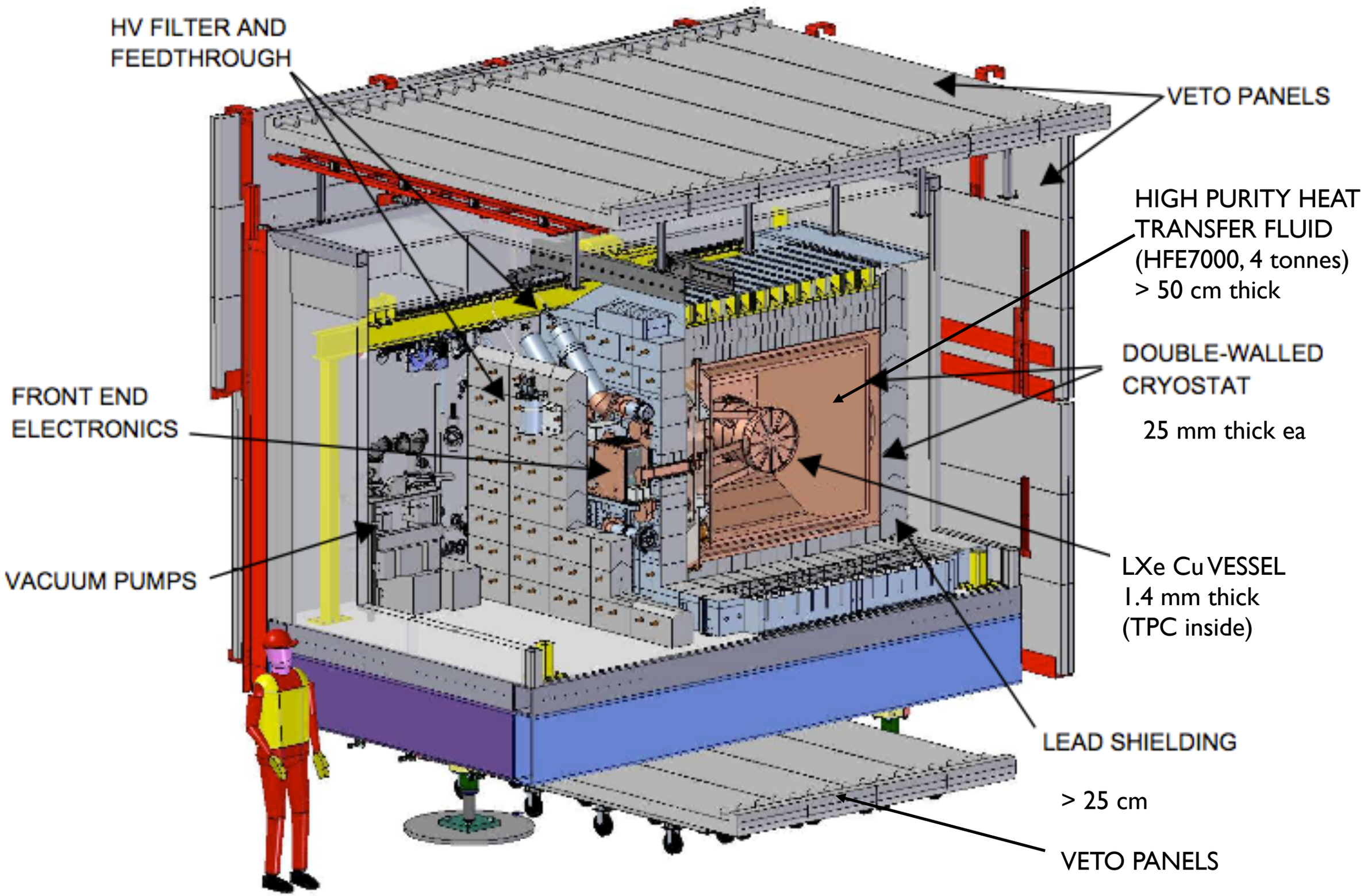
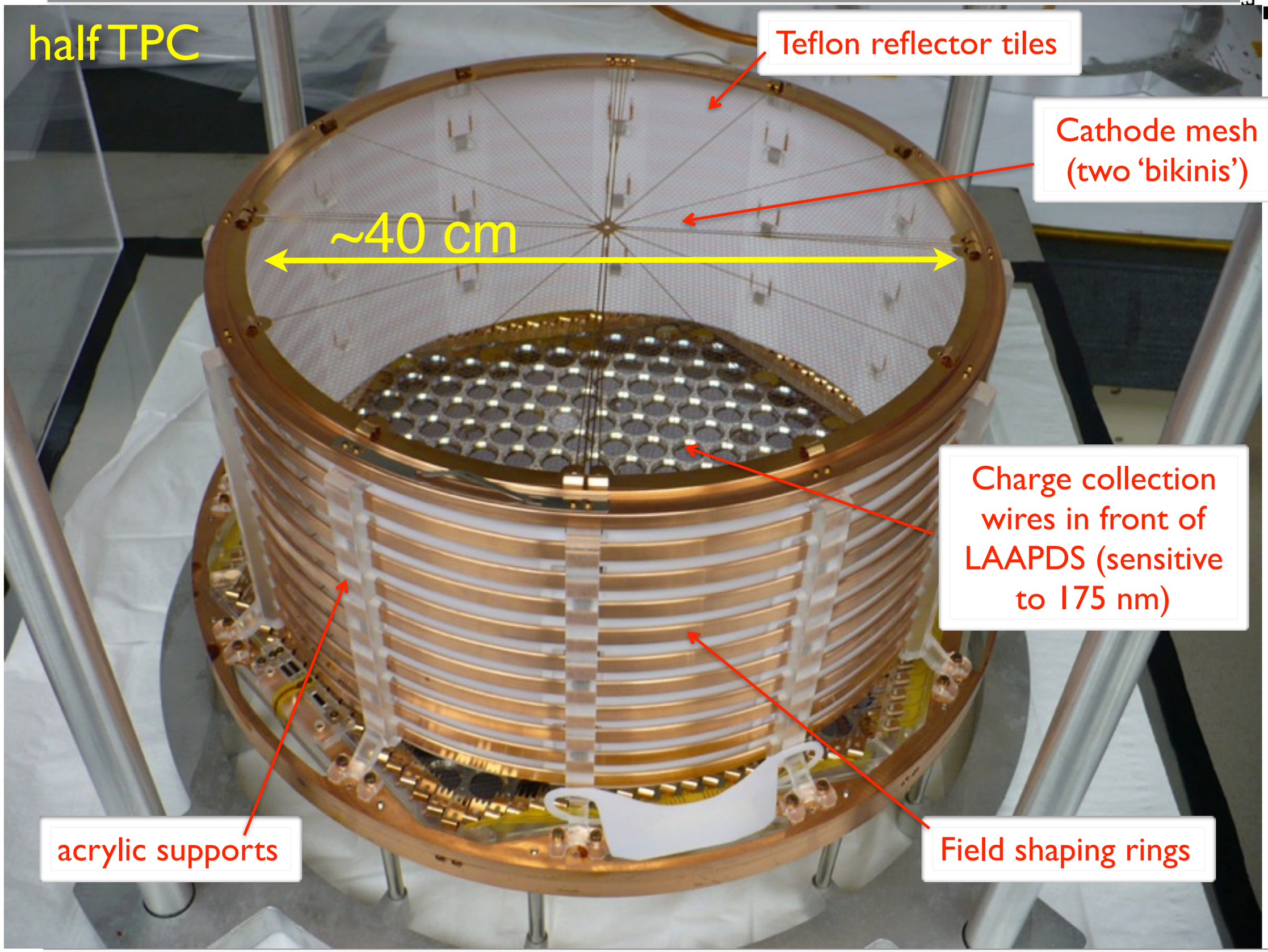
University of South Dakota, Vermillion SD, USA — A Larson, R MacLellan
Stanford University, Stanford CA, USA — J Dalmasson, R DeVoe, D Fudenberg, G Gratta, M Jewell, S Kravitz, G Li, A Schubert, M Weber, S Wu
Stony Brook University, SUNY, Stony Brook, NY, USA — K Kumar, O Njoya
Technical University of 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 — A Jamil, Z Li, D Moore, Q Xia

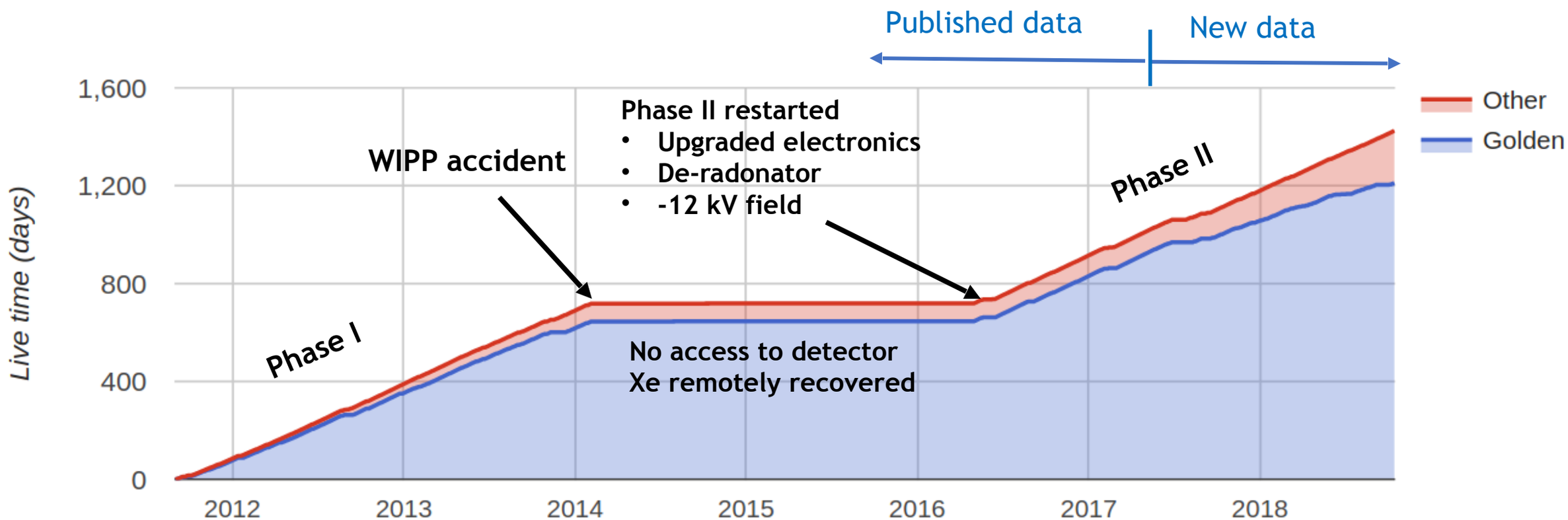
The EXO-200 detector

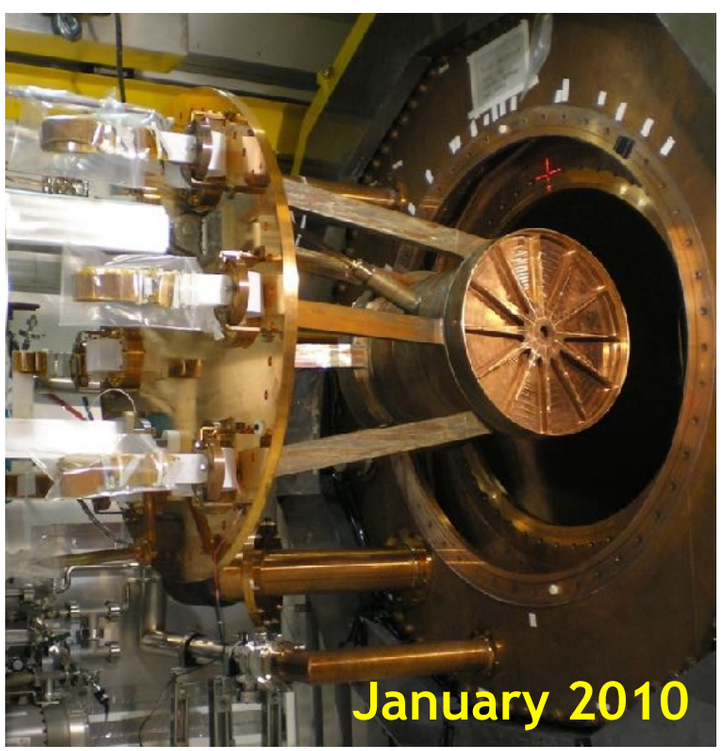


the EXO-200 TPC



EXO-200 timeline



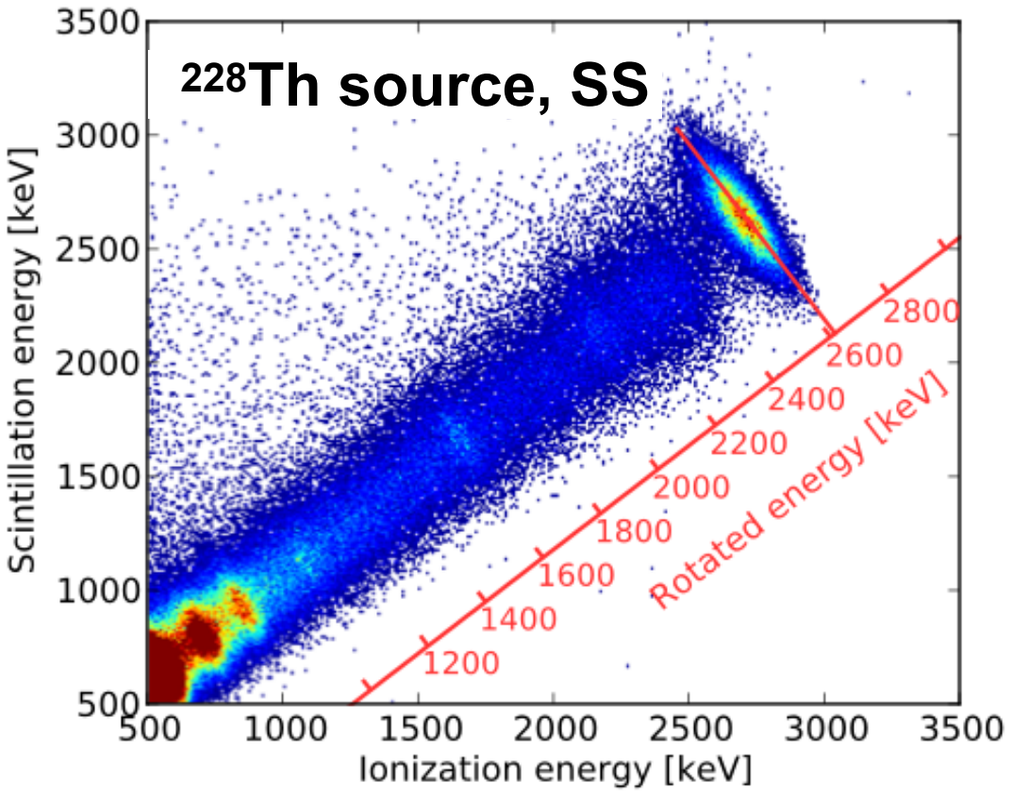


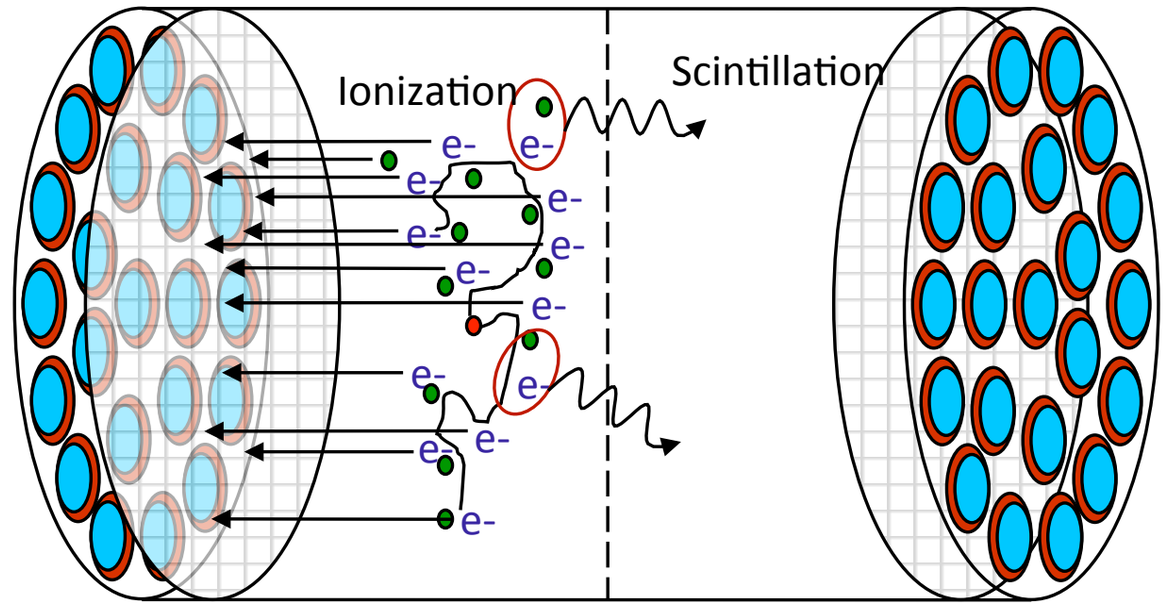
- Operation concluded in Dec 2018, with 1181.3 days of live time

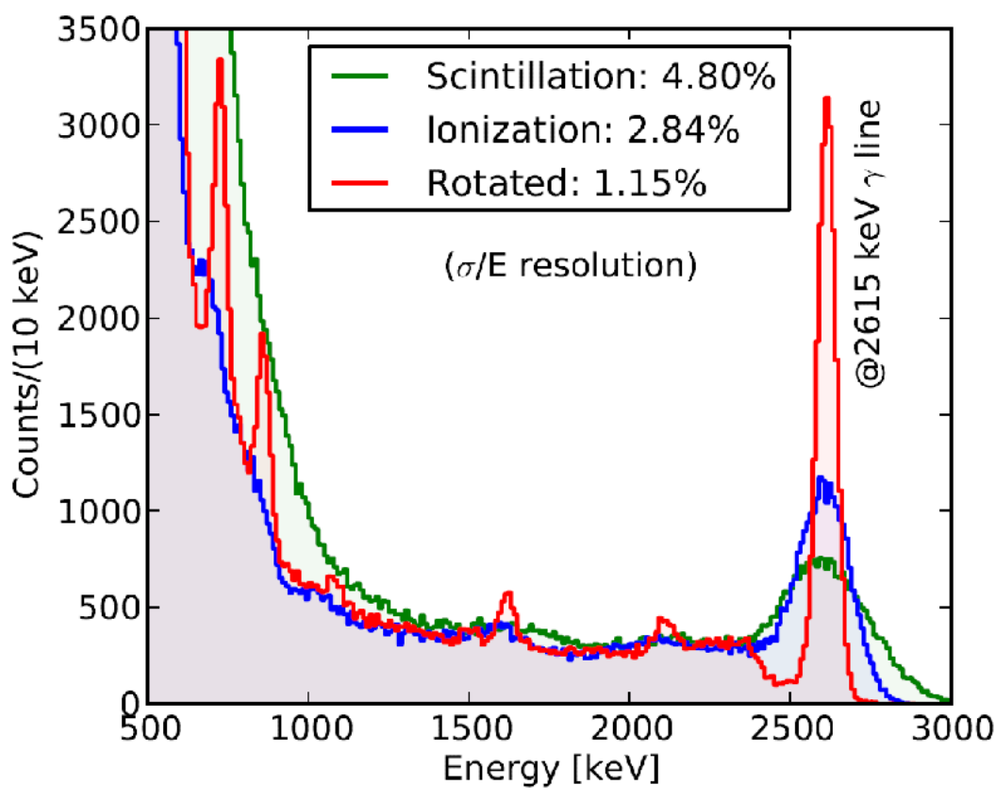
- Phase I from Sep 2011 to Feb 2014
  - Most precise $2\nu\beta\beta$ measurement, *Phys. Rev. C* ***89***, *015502 (2013)*
  - Stringent limit for $0\nu\beta\beta$ search, *Nature* ***510***, *229 (2014)*
- Phase II operation begins on Jan 31, 2016 with system upgrades
  - First results with Phase II data from upgraded detector, *Phys. Rev. Lett.* ***120***, *072701 (2018)*

  - **This talk, new results with complete dataset!**

Detector energy resolution





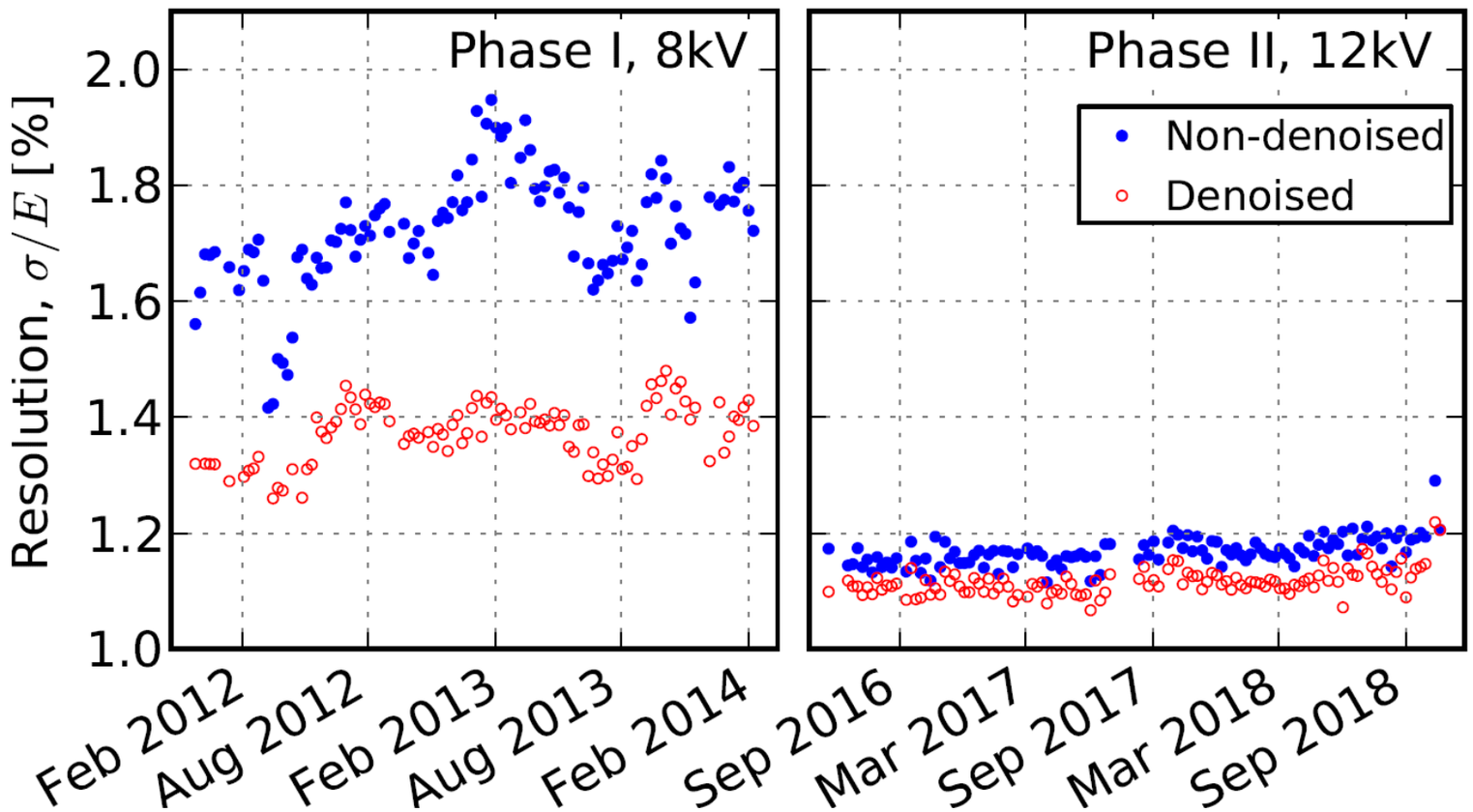


Combining Ionization and Scintillation energy to enhance energy resolution

Anti-correlation between scintillation and ionization in LXe known since early EXO R&D

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

EXO-200 Phase-II: energy resolution

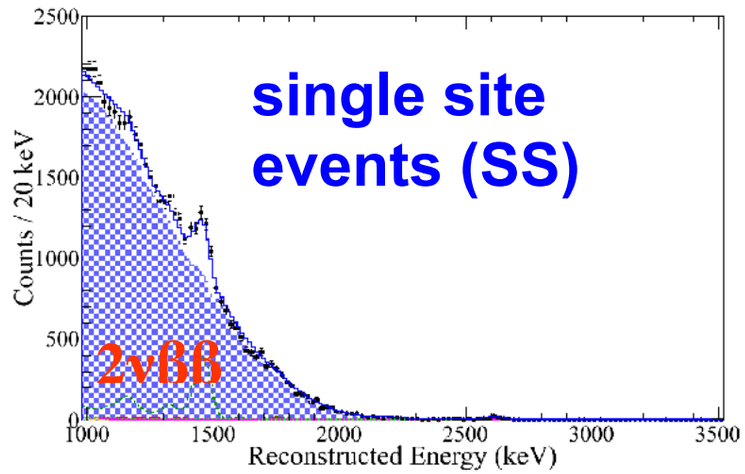


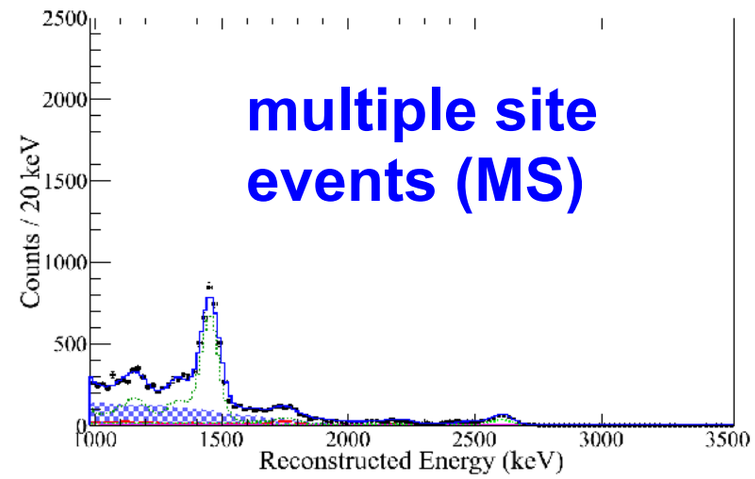
- Front end readout electronics
  - Reduce APD readout excess noise
- Cathode HV increased from -8 kV to -12 kV
- Software De-noising to optimize energy calibration

- 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%

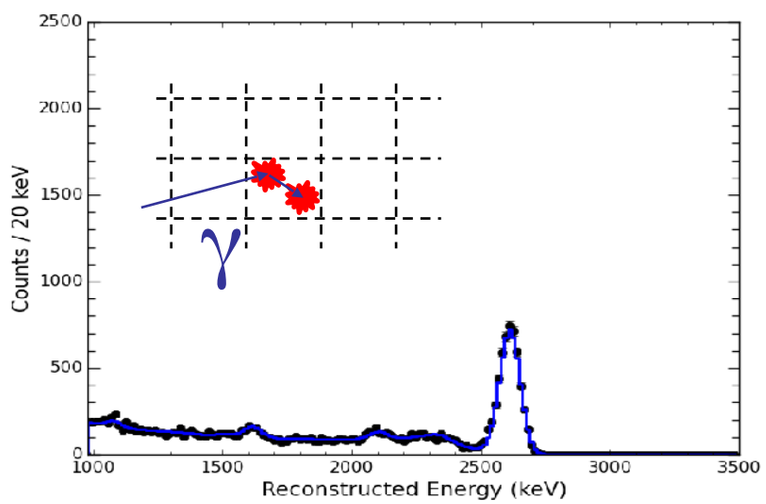
Topological event reconstruction

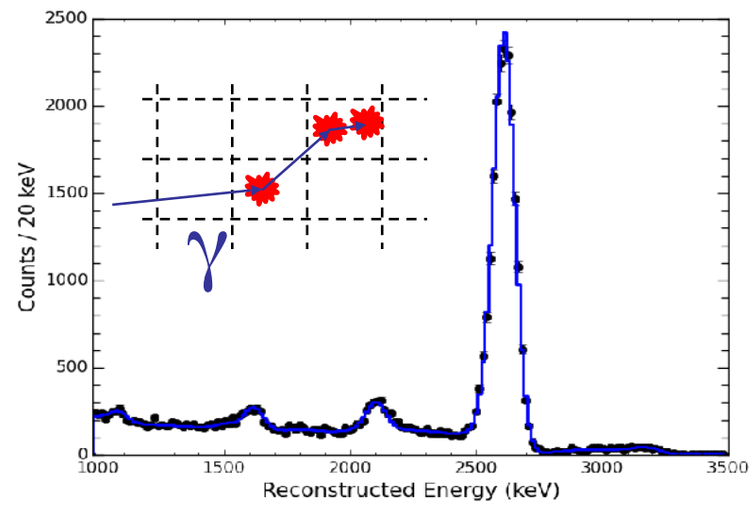
Low bg data



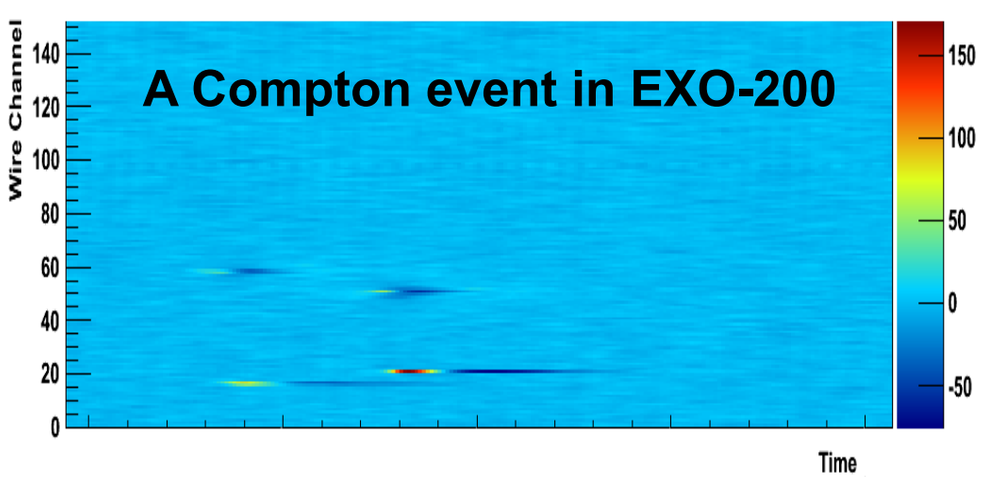


^{228}Th calibration source





- X/Y (U/V) position from charge signals on crossed-wire planes (9 mm pitch)
- Z position from ionization charge drift time (1 MHz sampling, ~6 mm resolution)
- Software De-noising to optimize energy calibration



- TPC allows the rejection of gamma backgrounds because Compton scattering results in multiple energy deposits.
- SS/MS discrimination is a powerful tool for background rejection as well as for signal discovery.

EXO-200 papers

S. Delaquis et al. "Deep Neural Networks for Energy and Position Reconstruction in EXO-200" JINST 13 (2018) P08023

J.B. Albert et al. "Search for nucleon decays with EXO-200"PRD97(2018) 072007

J.B. Albert et al. "Search for 0νββDecay with the Upgraded EXO-200 Detector" PRL120(2018) 072701

D.S. Leonard et al. "Trace radioactive impurities in final construction materials for EXO-200" NIMA 871 (2017) 169

J.B. Albert et al. "Searches for Double Beta Decay of134Xe with EXO-200" PRD96 (2017) 092001

J.B. Albert et al. "Measurement of the Drift Velocity and Transverse Diffusion of Electrons in Liquid Xenon with the EXO-200 Detector"PRC95 (2017) 025502

C.G. Davis et al. "An Optimal Energy Estimator to Reduce Correlated Noise for the EXO-200 Light Readout" JINST11(2016) P07015

J.B. Albert et al. "Cosmogenic Backgrounds to 0νββ in EXO-200" J. Cosmol. Astropart. Phys. 4 (2016) 029

J.B. Albert et al. "First Search for Lorentz and CPT Violation in ββ Decay with EXO-200" PRD 93 (2016) 072001

J.B. Albert et al. "Search for 2νββ decay of 136Xe to the 01+ excited state of 136Ba with EXO-200" PRC 93 (2016) 035501

J.B. Albert et al. "Measurements of the ion fraction and mobility of alpha and beta decay products in LXe using EXO-200" PRC 92 (2015) 045504.

J.B. Albert et al. "Investigation of radioactivity-induced backgrounds in EXO-200" PRC 92 (2015) 015503

J.B. Albert, et al. "Search for Majoron-emitting modes of ββ decay of136Xe with EXO-200" PRD 90 (2014) 092004

J.B. Albert, et al. "Search for Majorana neutrinos with the first two years of EXO-200 data" Nature 510 (2014) 229

J.B. Albert, et al. "An improved measurement of the 2νββhalf-life of 136Xe with EXO-200" PRC 89 (2014) 015502

M. Auger, et al. "Search for Neutrinoless ββ Decay in136Xe with EXO-200" PRL 109 (2012) 032505

M. Auger, et al. "The EXO-200 detector, part I: Detector design and construction" J. Inst7(2012) P05010

A. Dobi, et al. "Xenon purity analysis for EXO-200 via mass spectrometry" NIM A675(2012) 40

N. Ackerman, et al. "Observation of Two-Neutrino ββ Decay in Xe-136 with EXO-200" PRL 107 (2011) 212501

A. Dobi, et al. "A Xenon Gas Purity Monitor for EXO" NIM A 659 (2011) 215

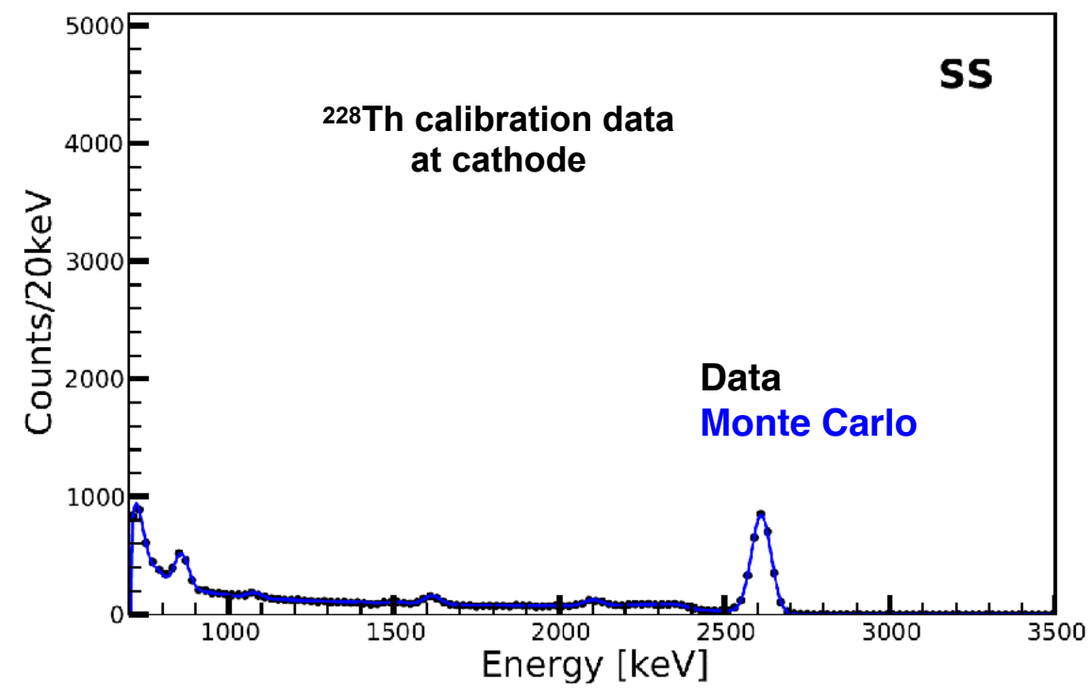
F. LePort, et al. "A magnetically-driven piston pump for ultra-clean applications" Rev. Sci. Inst. 82 (2011) 105114

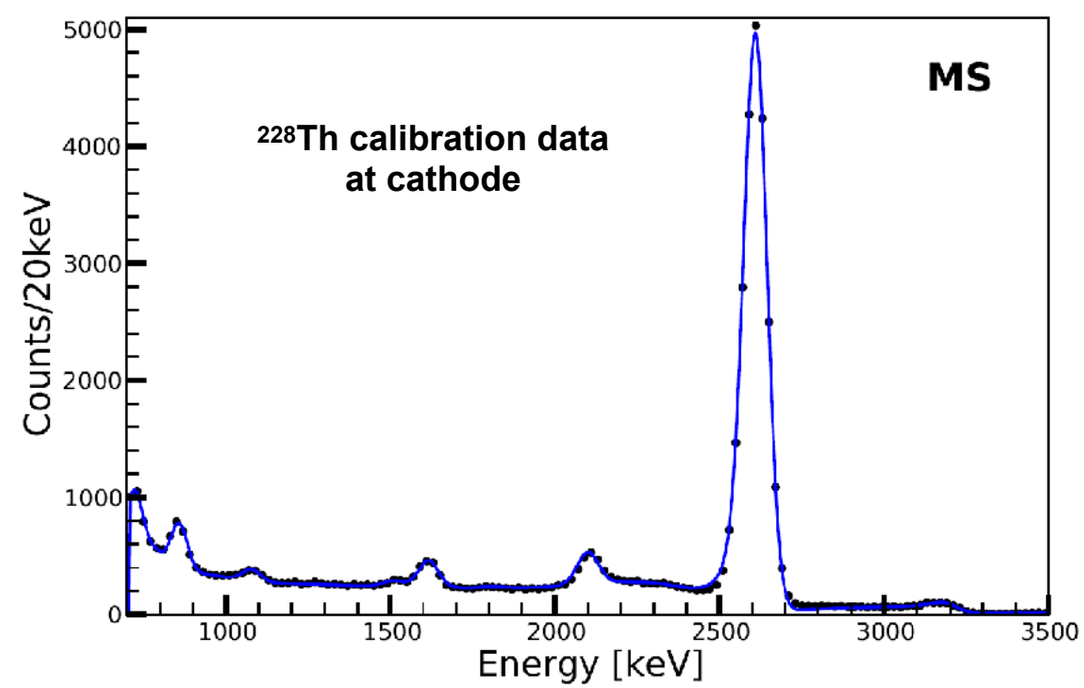
R. Neilson, et al. "Characterization of large area APDs for the EXO-200 detector" NIM A 608 (2009) 6875

D. Leonard, et al. "Systematic study of trace radioactive impurities in candidate construction materials for EXO-200" Nucl. Ins. Meth. A 591 (2008) 490

Position reconstruction

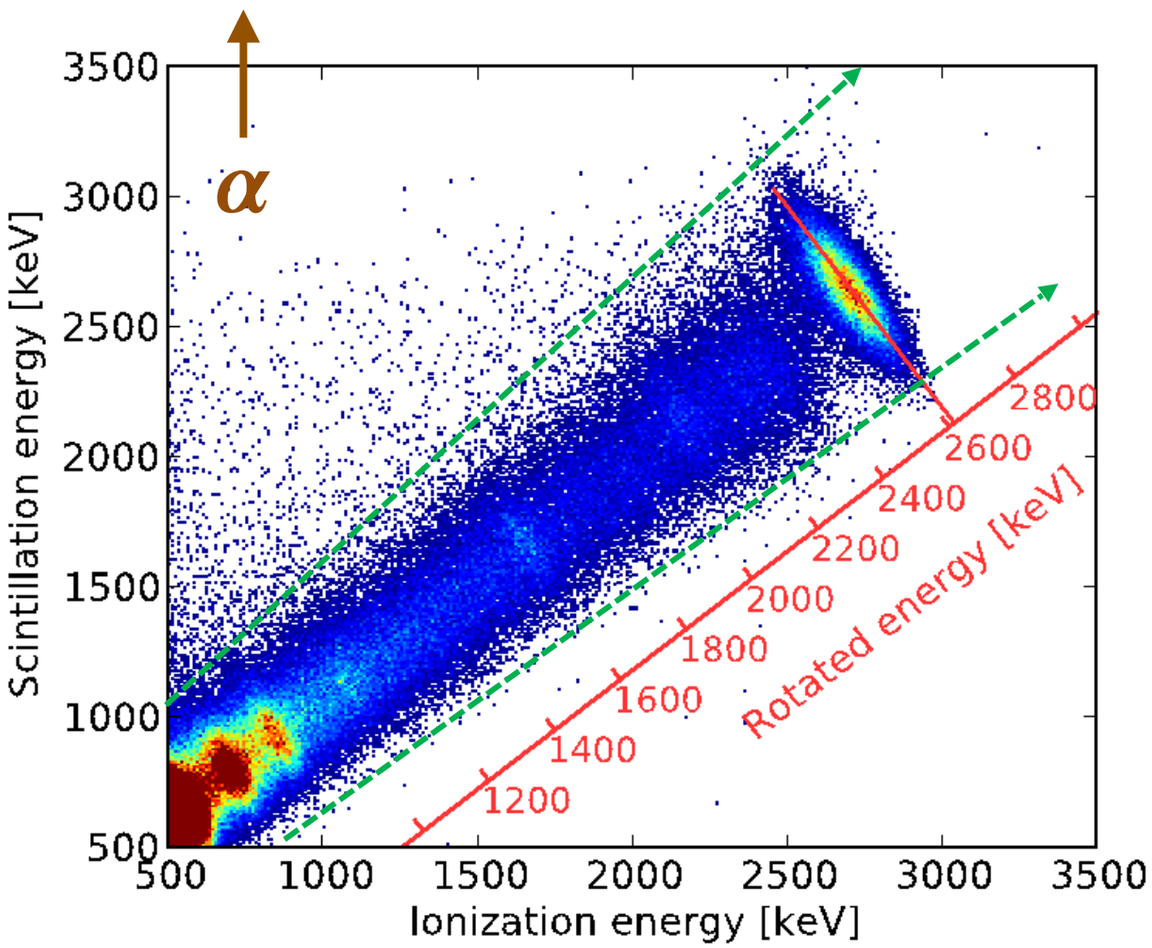
- Previous analyses require all events having full 3D position
- Some events have partial 3D reconstruction, i.e. small energy deposit having complete collection on U-wire, but no V signals (higher threshold, lower induction signal amplitude)
- Now require >60% of energy deposits having 3D position, only recovering MS events
- Recovers almost all previously cut 0νββ 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 ratio for particle ID

on this β-energy plot, bulk LXe α's appear at >10,000 keV_{scint}, <500 keV_{ioniz}



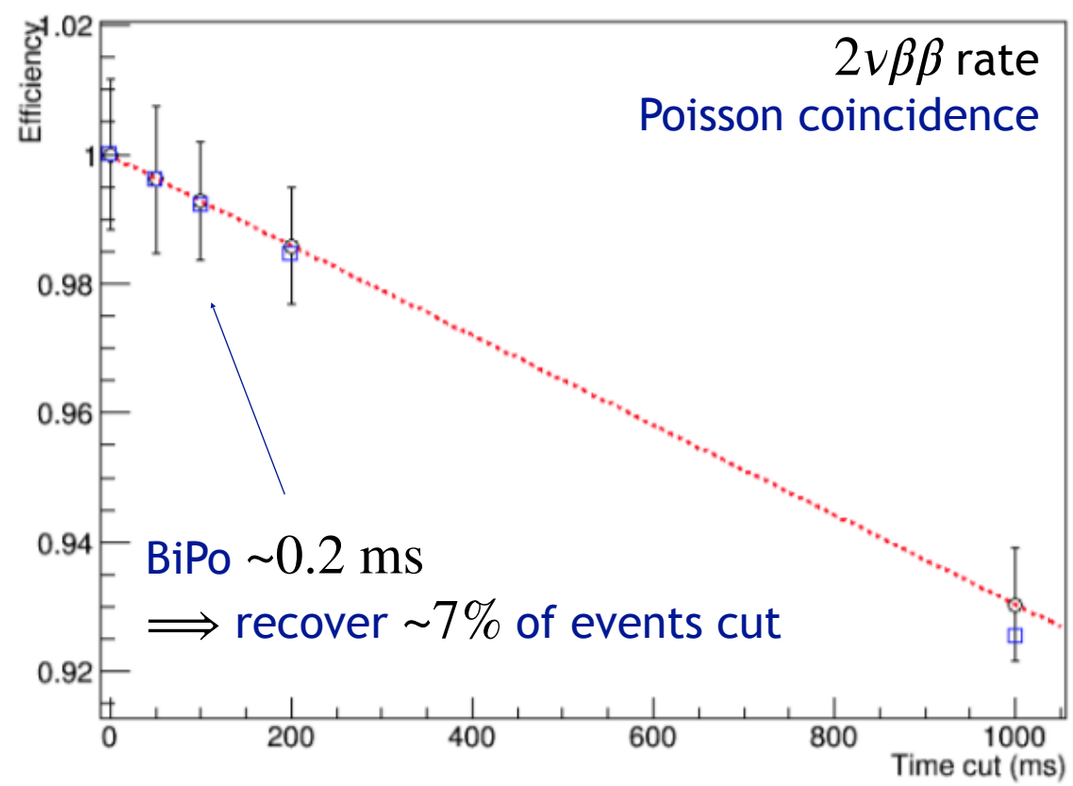
- Requires 2D light/charge energy calibration and good understanding of detector
- Light/charge ratio distributions validated by comparison between data/simulation using source and 2νββ data

- Powerful for α rejection, as well as poorly reconstructed β/γ with anomalous light/charge ratio (e.g. edge events)
- A similar approach was first used in our 'cosmogenics' paper, JCAP04(2016)029

0νββ detection efficiency imptrovement

- Tighter event coincidence 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

D. Fudenberg, PhD thesis (2017)

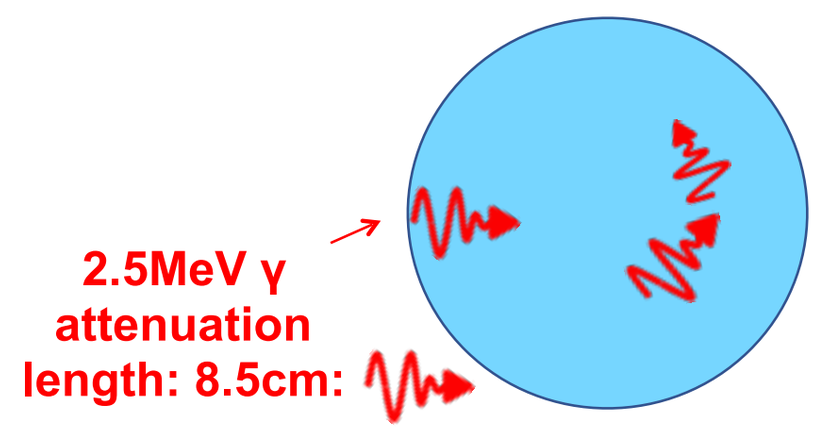


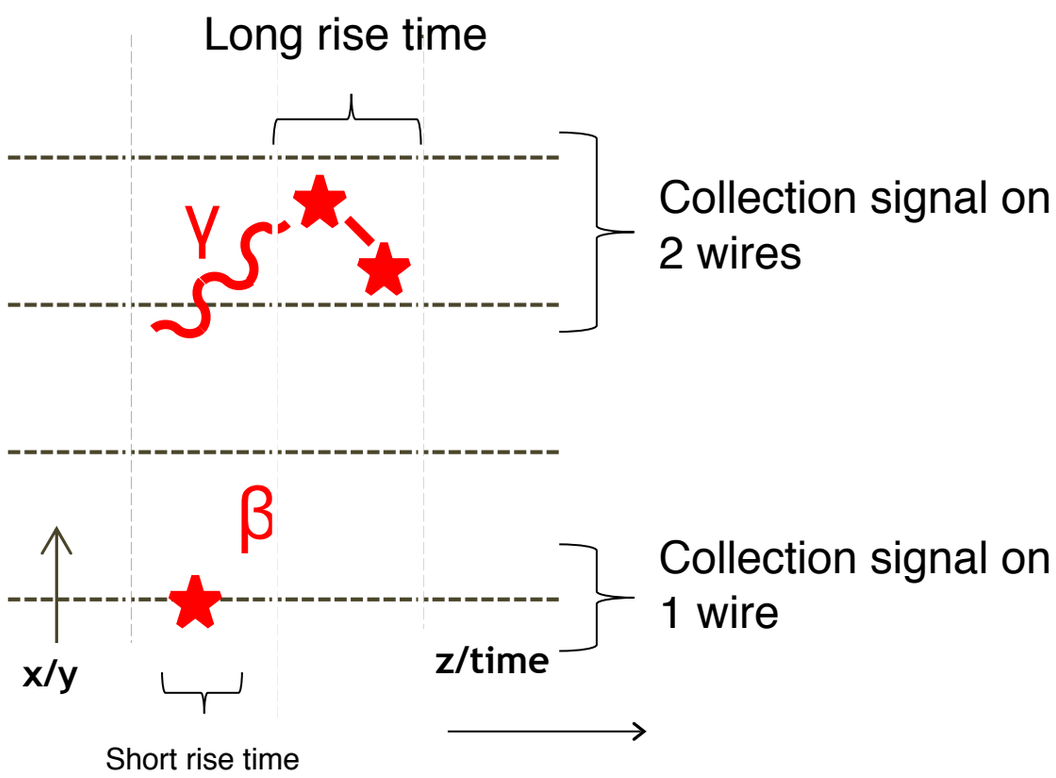
- 0νββ detection efficiency increased from ~80% to 97.8± 3.0% (96.4± 3.0%) for Phase I (II)

Background rejection for SS events

- Standoff distance:
  - γ-rays from the periphery of the detector are exponentially attenuated towards the center

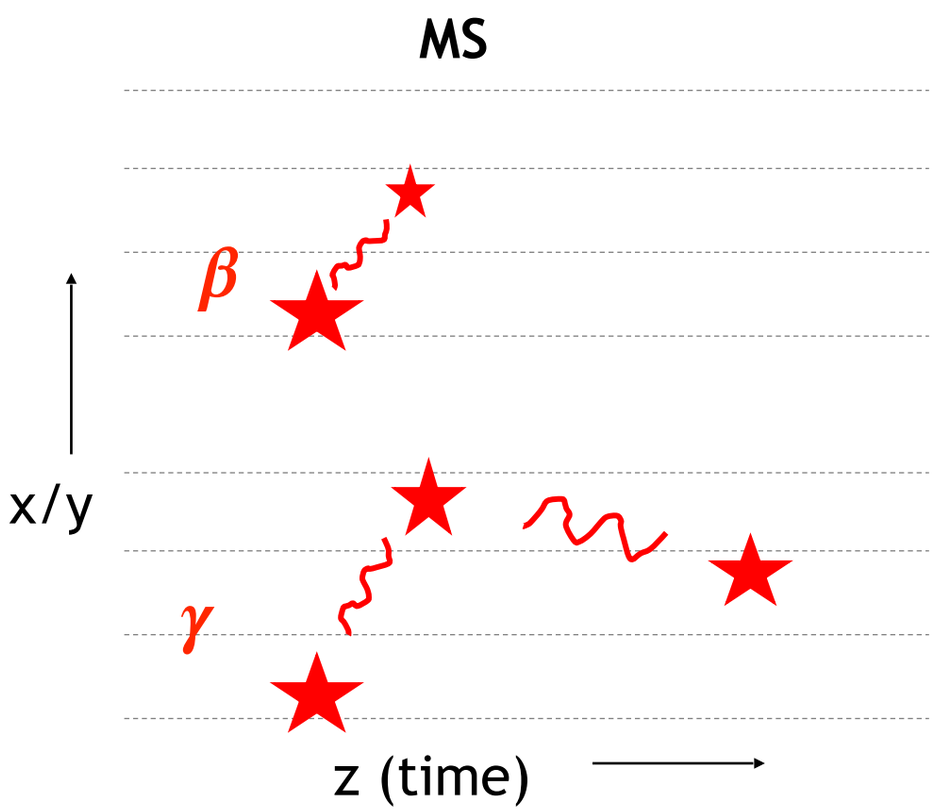
LXe self-shielding:



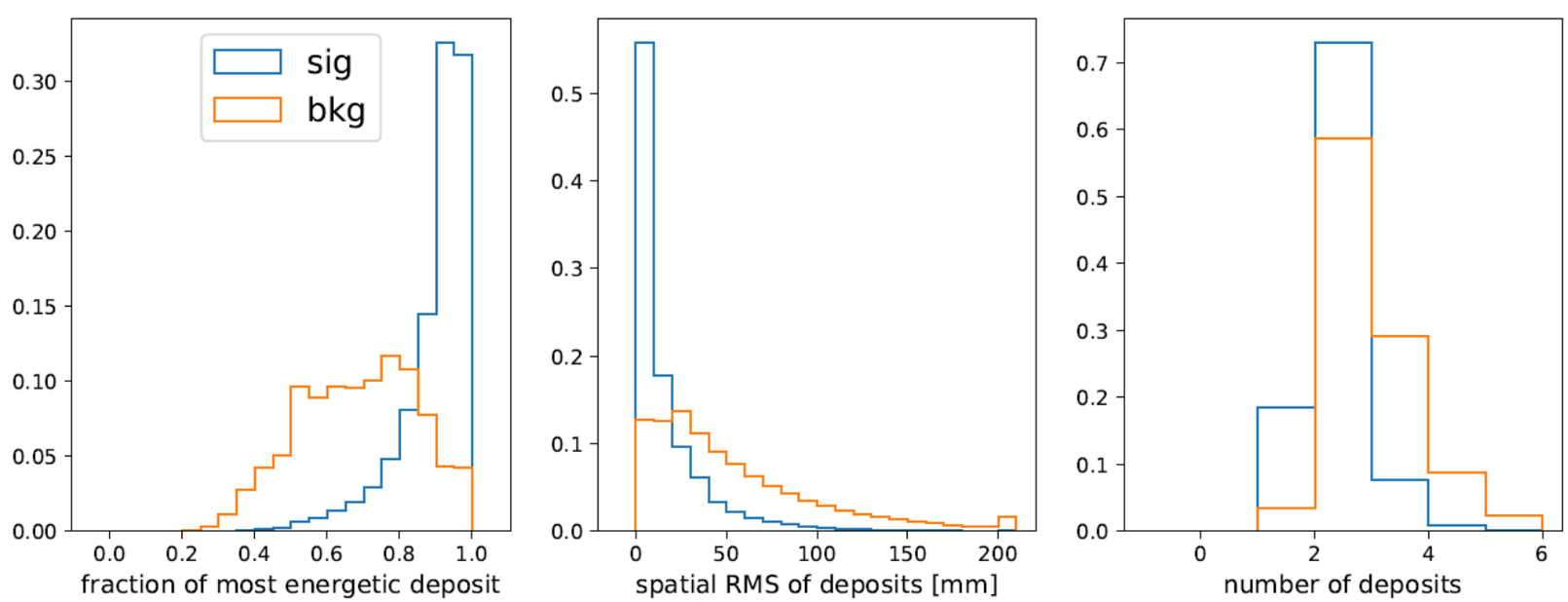


- SS cluster parameters:
  - number of wires with charge collection signals (transverse direction)
  - pulse rise time (longitudinal/drift direction)
  - already used in previous release, Phys. Rev. Lett. **120**, 072701 (2018)

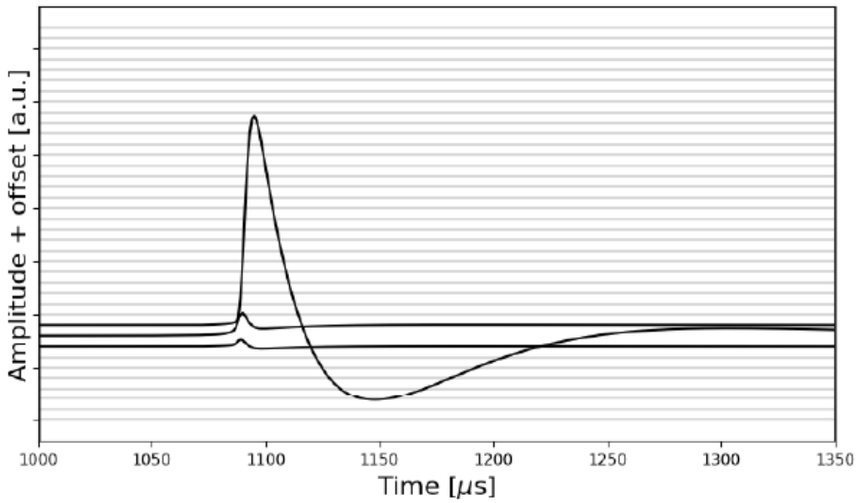
Background rejection for MS events



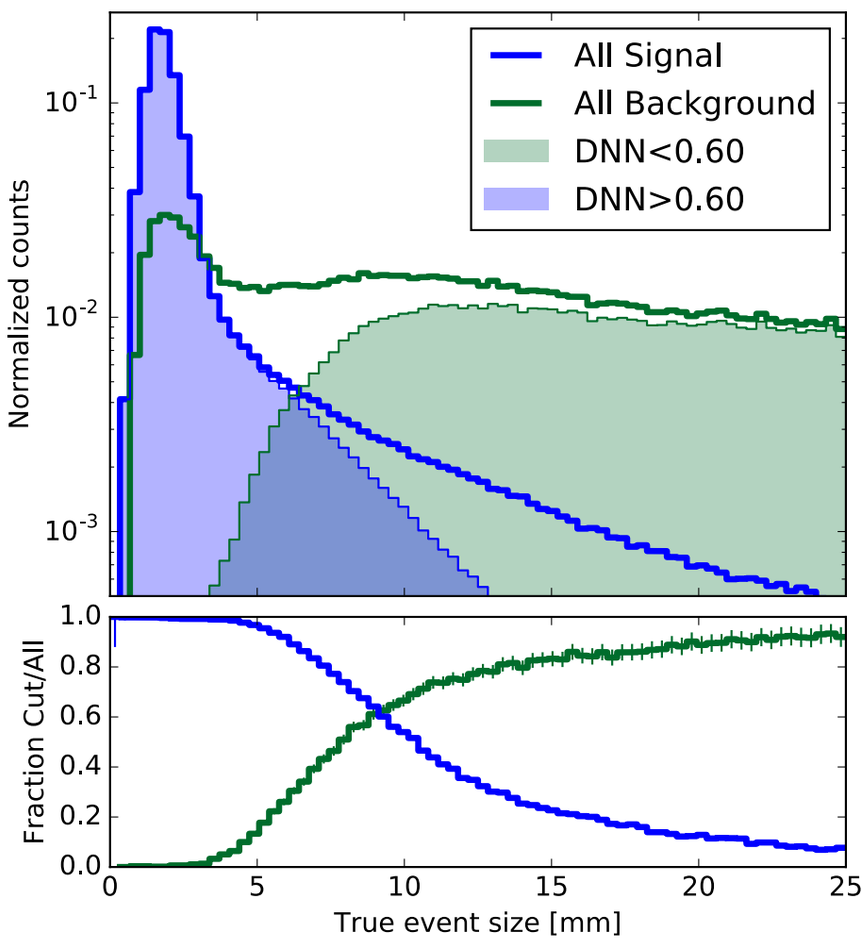
- 0νββ events in MS from small energy depositions due to bremsstrahlung (γ's Compton scatter)
- Distinct features in number, energy distribution and spatial spread of energy depositions
- Higher background rejection than in SS, MS is dominated by backgrounds



Background discrimination with DNN



- Discriminator built on a deep neural network (DNN)
- DNN trained on images built from U-wire waveforms

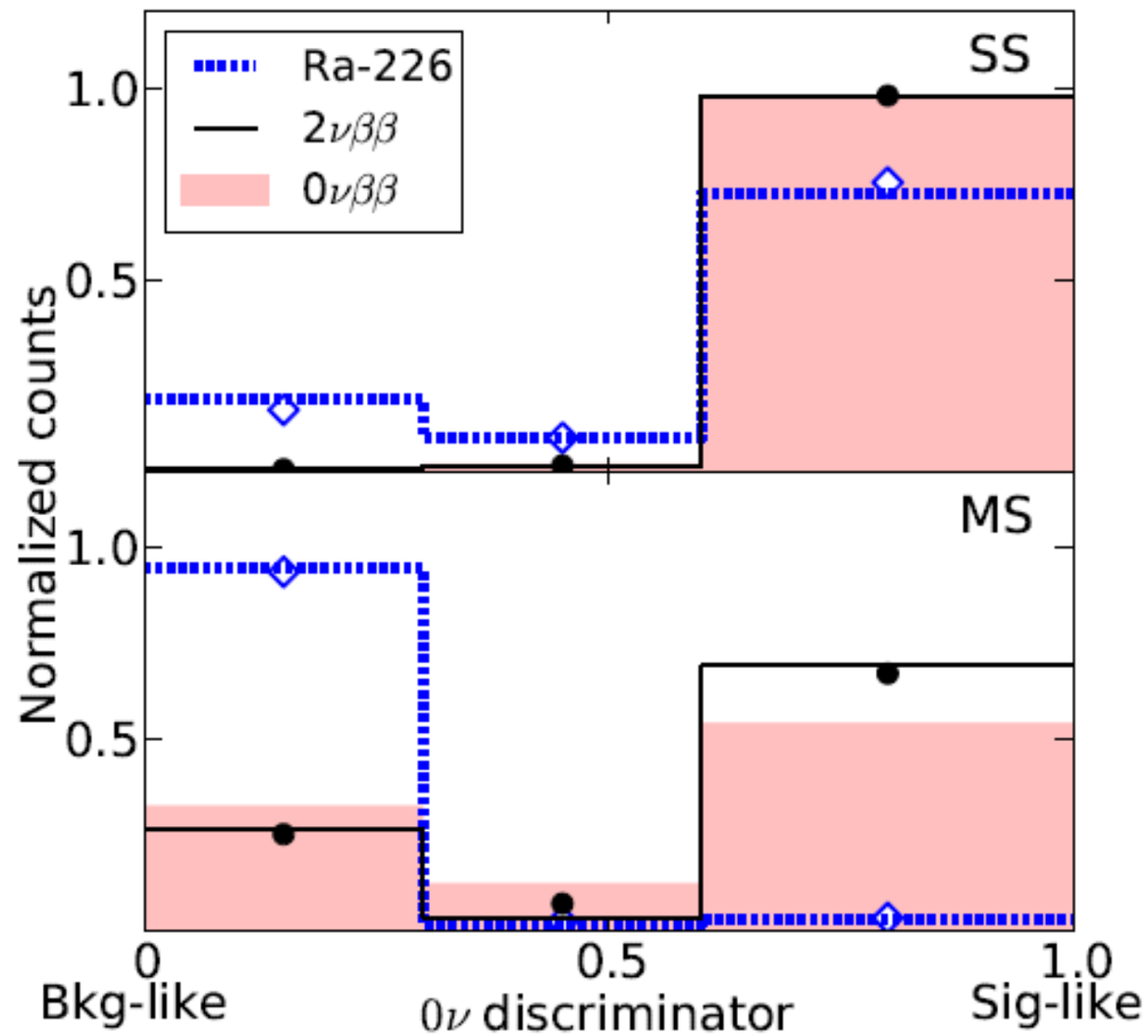


- Signal/background identification efficiency correlates with the true event size based on truth information in simulation
- Indicates the network can pick up correct features on the waveform to reconstruct event, (find wire signals, cluster signals into energy deposits), thus to discriminate signal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

Verification of DNN discrimination

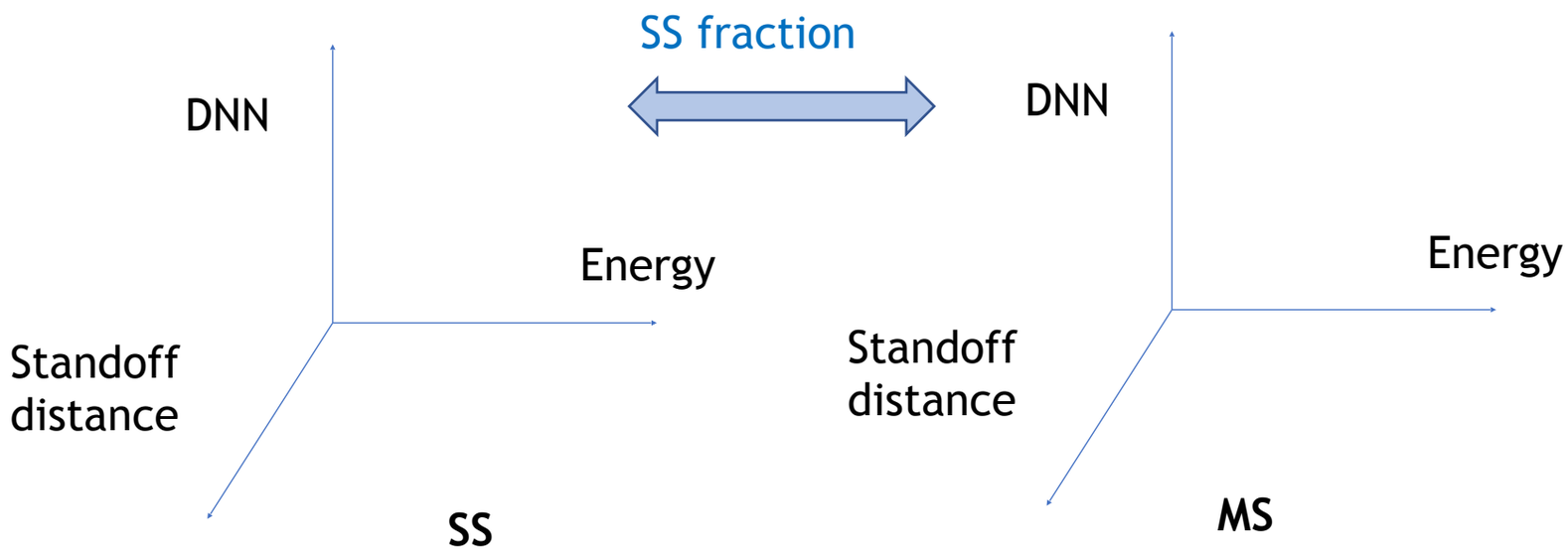
- Data/MC agreement validated with different data:
  - γ: Ra-226, Th-228, Co-60 calibration sources
  - β: 2νββ data

- Showed consistent and reasonable agreement
- Differences between data/MC are included as systematic uncertainties on the normalization of backgrounds within $Q_{\beta\beta} \pm 2\sigma$



arXiv:1906.02723

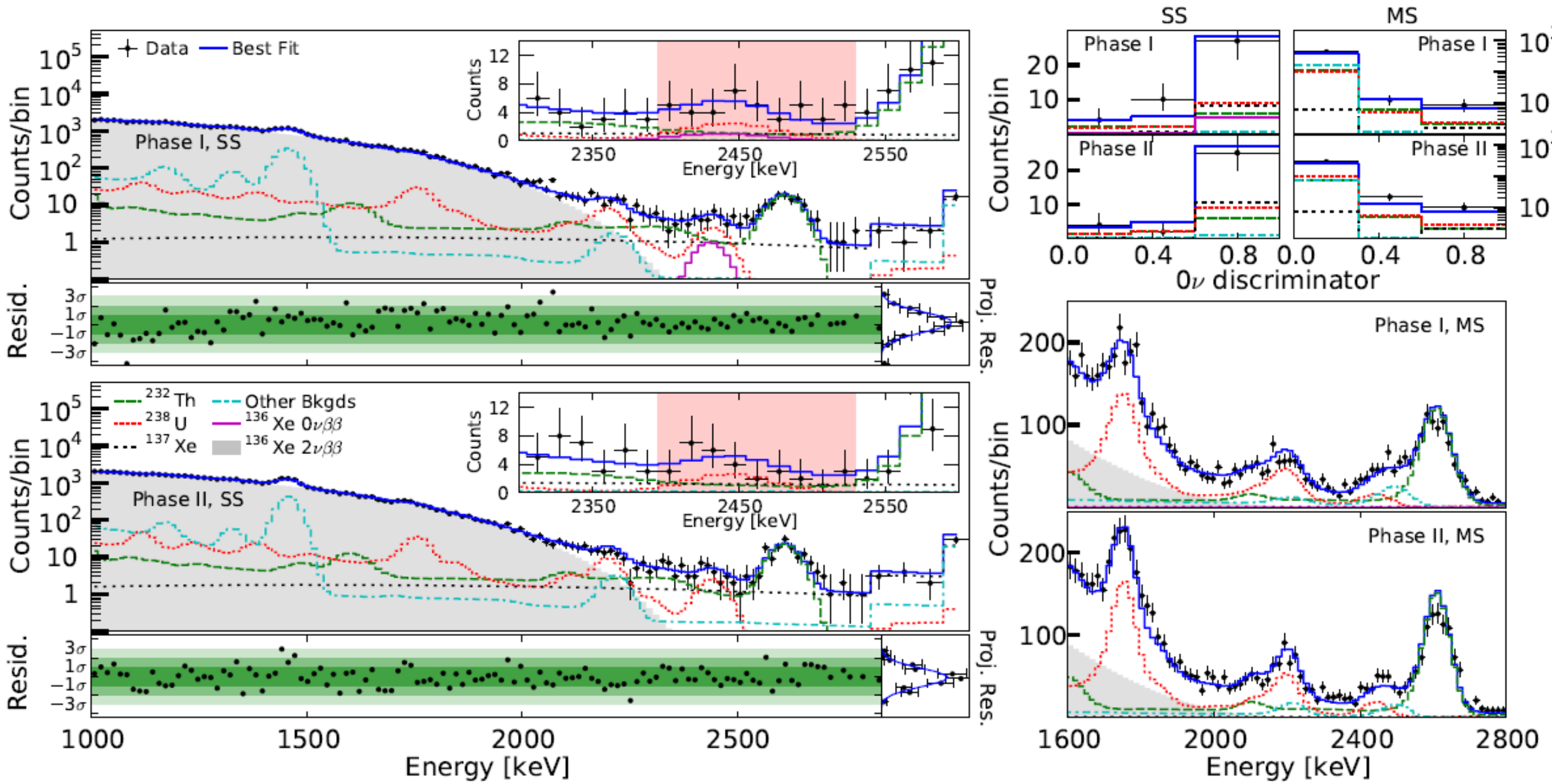
Analysis strategy on full Phase II data set



- Blind analysis
- SS/MS classification
- 3-dimensional fit for both SS and MS sets: Energy + 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% on the 0νββ half-life sensitivity compared with using energy spectra + SS/MS alone

the EXO-200 full Phase II results

arXiv:1906.02723



2019 release uses machine learning (DNN) for improved signal-to-background discrimination

EXO-200 results

arXiv:1906.02723

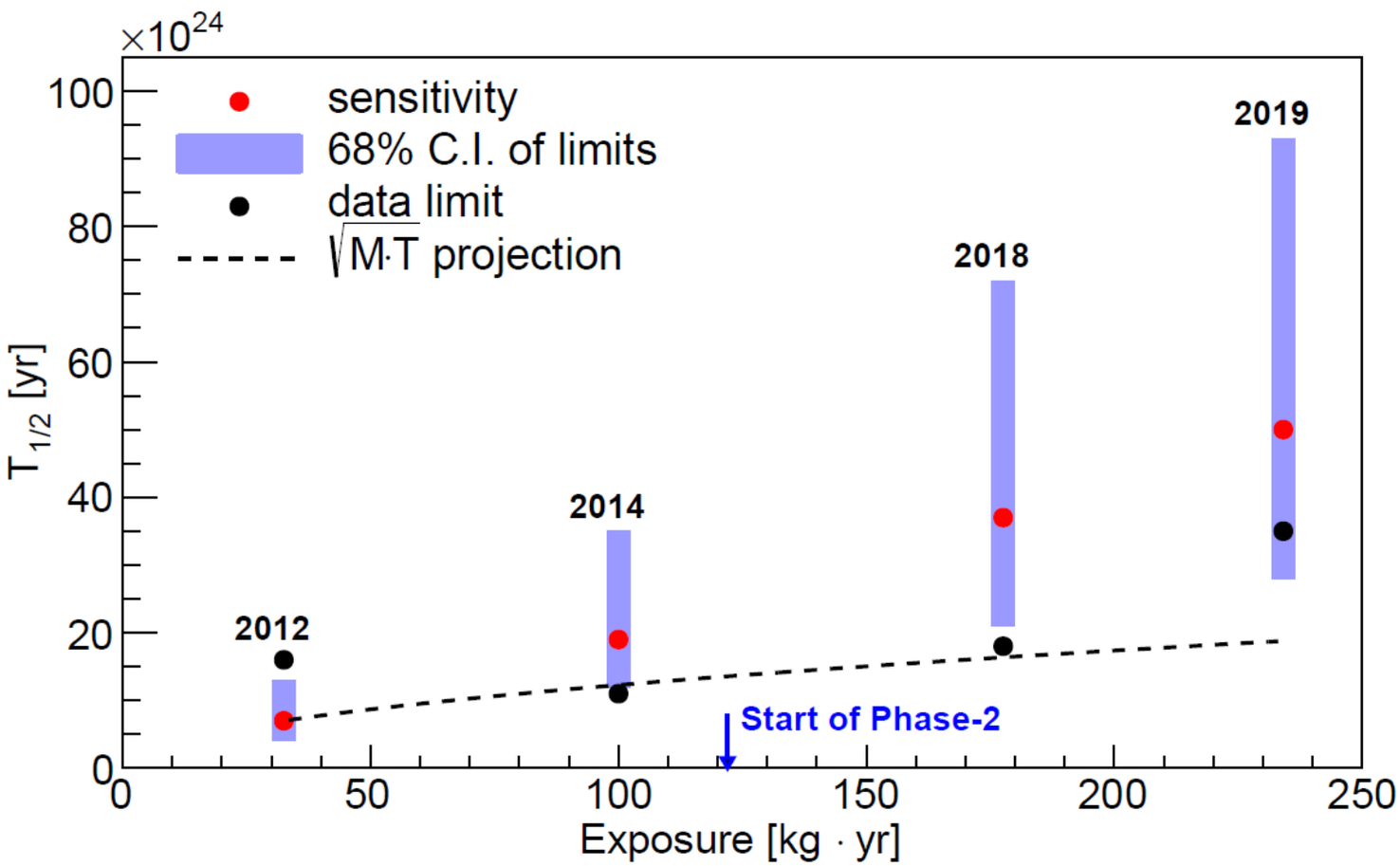
Phase I+II: 234.1 kg·yr ^{136}Xe exposure

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

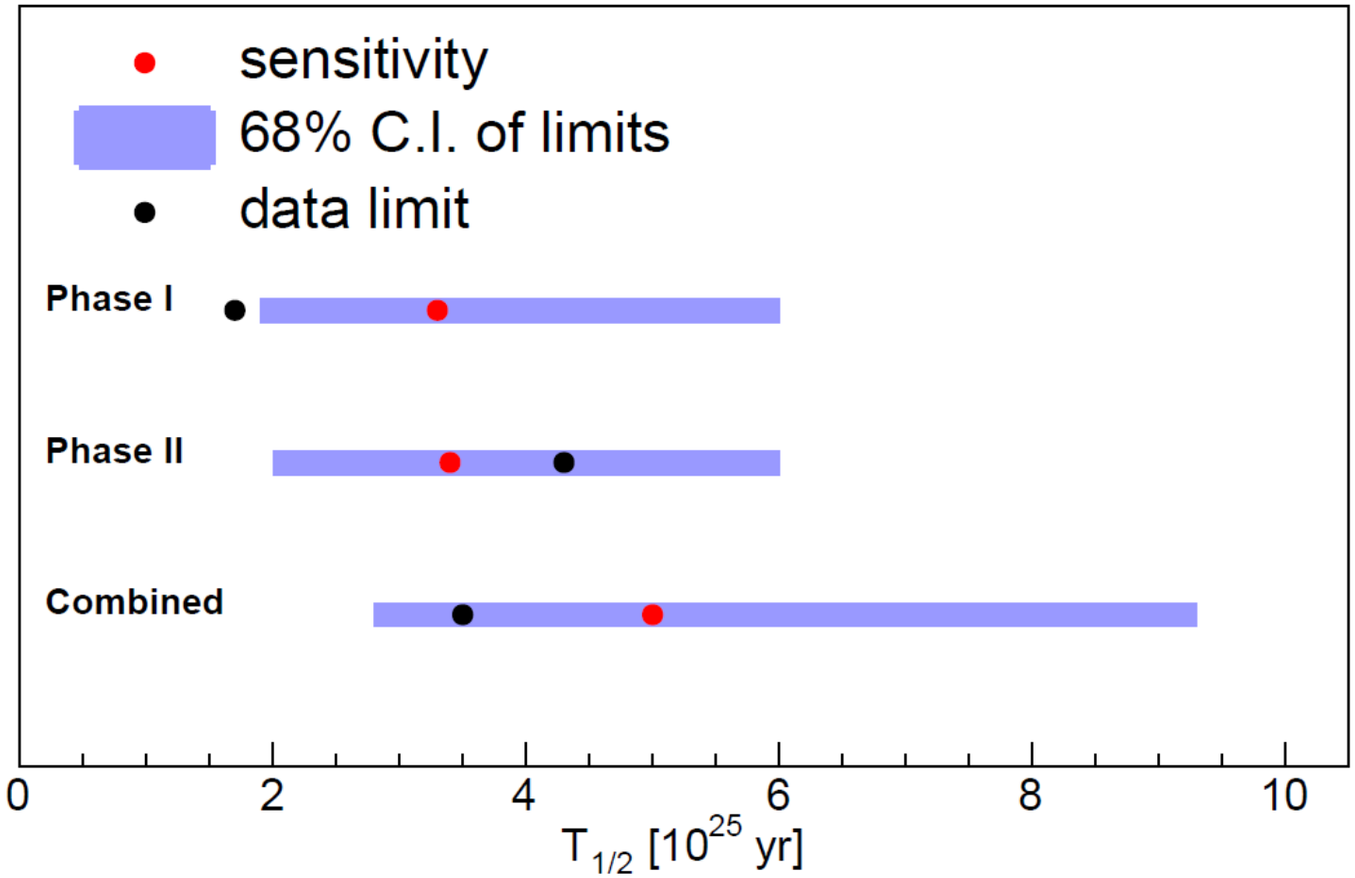
No statistically significant signal observed



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

EXO-200 results

arXiv:1906.02723



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

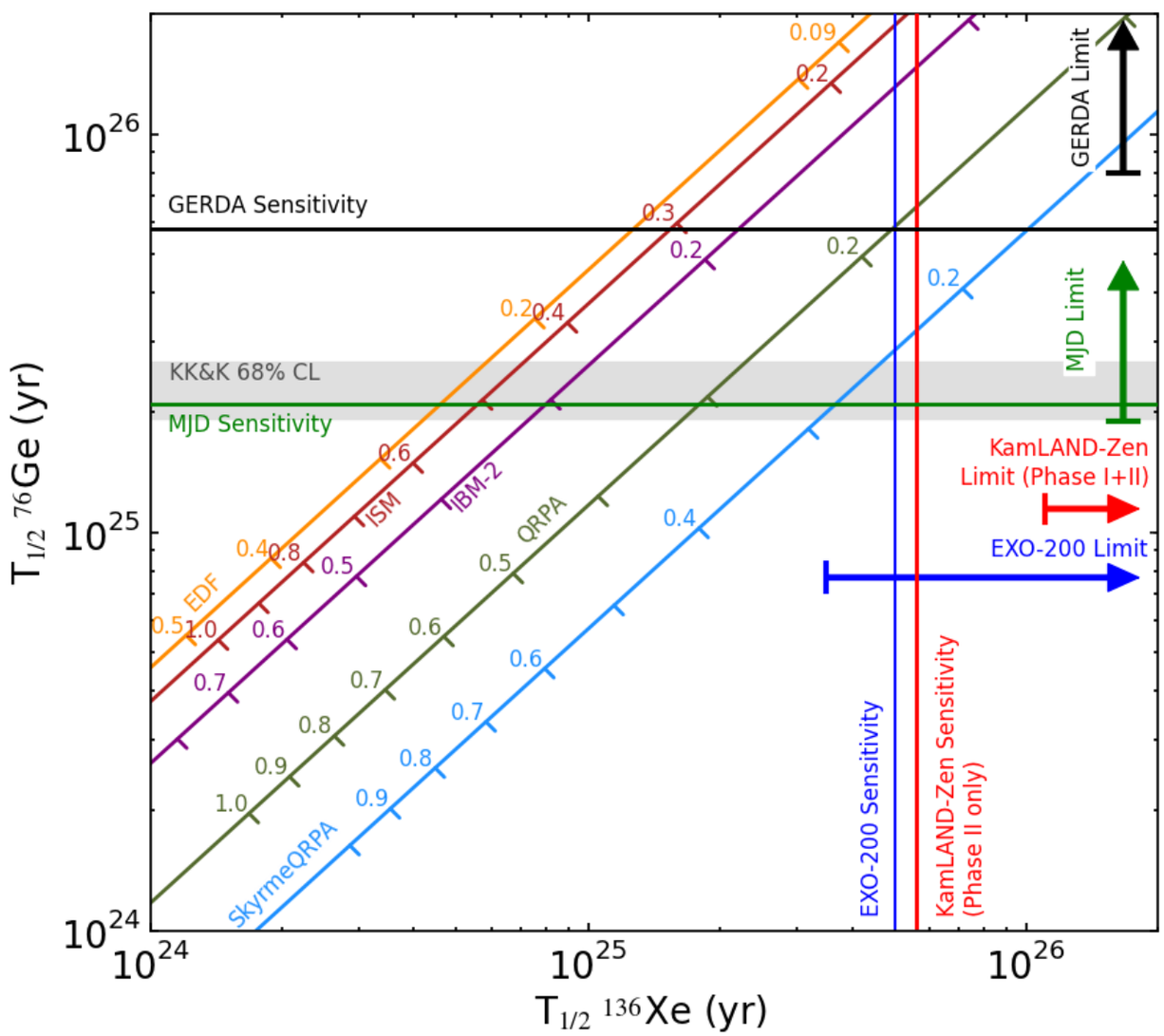
Sensitivity 5.0×10^{25} yr

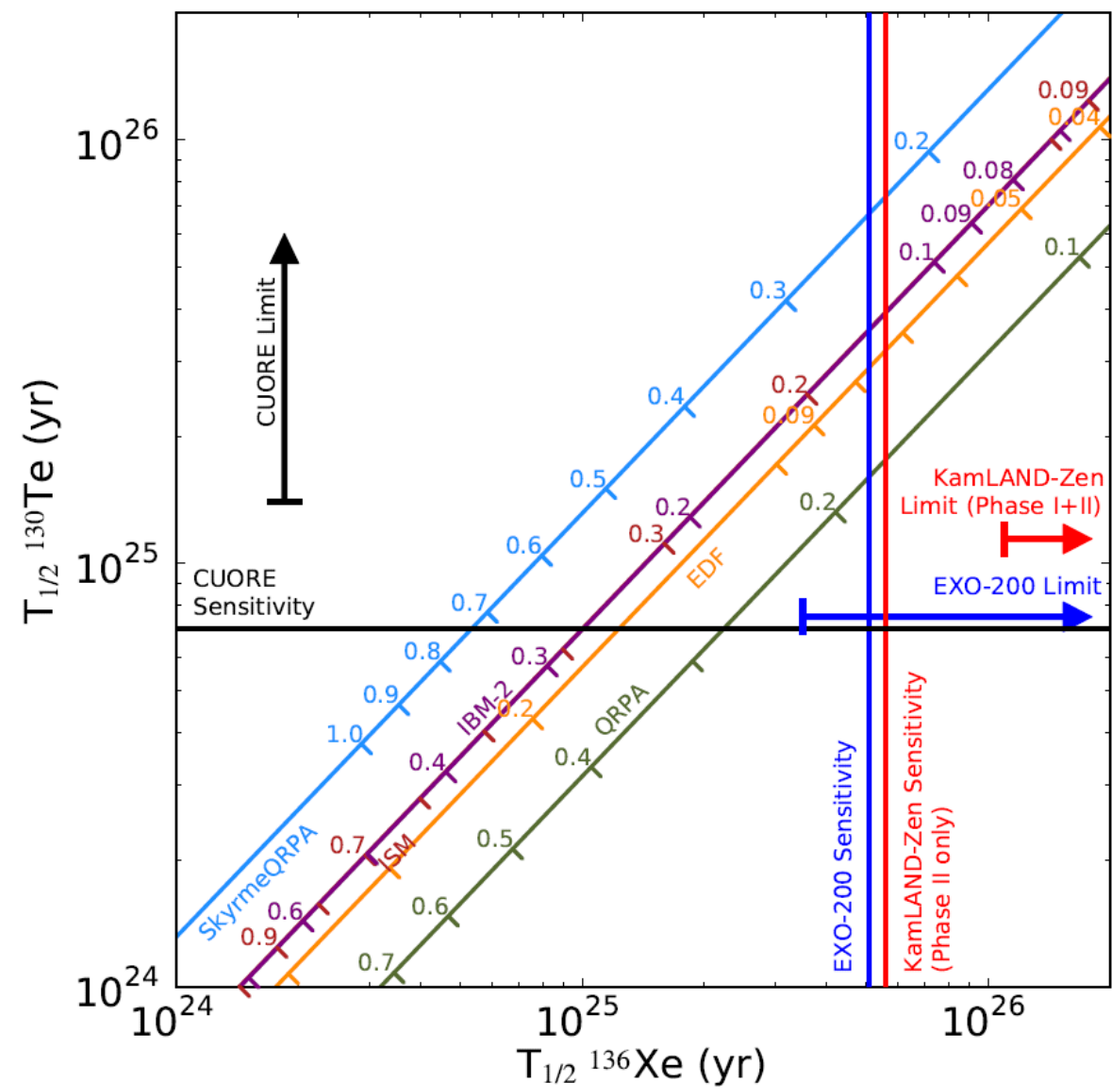
(counts)	^{238}U	^{232}Th	^{137}Xe	Total	Data
Phase I	12.6	10.0	8.7	32.3±2.3	39
Phase II	12.0	8.2	9.3	30.9±2.4	26

Background contribution to $Q \pm 2\sigma$

No statistically significant signal observed

Comparing isotopes



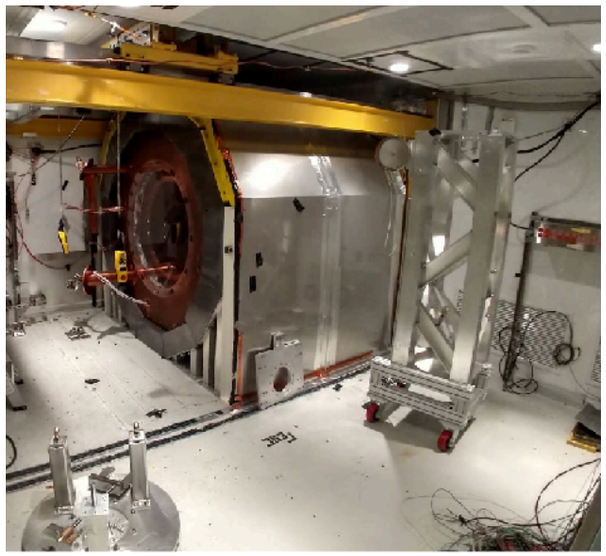


A comparison to experiments using other isotopes requires assumptions on the mass mechanism and the matrix elements

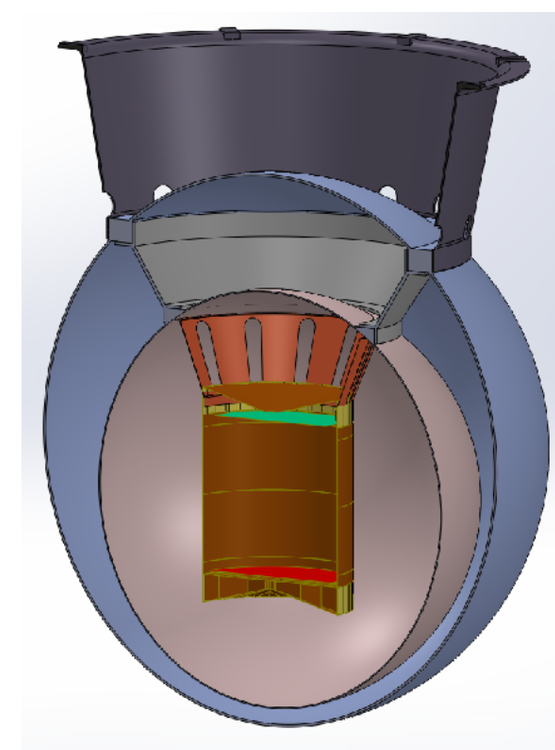
Summary, conclusions, outlook

stay hungry, my friend

- The search for neutrino-less double beta decay ($0\nu\beta\beta$) is one of the top scientific priorities in nuclear and particle physics
- Xenon is an excellent isotope for large double beta decay experiments. LXe TPC's, including EXO-200, have proven to be scalable (>100x), low background detectors for rare event searches over the past 1.5 decades.



- EXO-200 was the first 100-kg-scale (1 kmole) experiment to run, inspiring the 25-fold scale up, nEXO.
- EXO-200 ended operations in Dec. 2018



- EXO-200 has released the results of a search for $0\nu\beta\beta$ decay of Xe-136 with its full dataset with a sensitivity close to the best ones in the field ($T_{1/2} > 5 \times 10^{25}$ yr; lower half-life limit on the process: $> 3.5 \times 10^{25}$ yr).
- EXO-200 has paved the way to a 5-tonne LXe enriched Xe-136 TPC experiment, nEXO (next talk)