nEXO 实验进展

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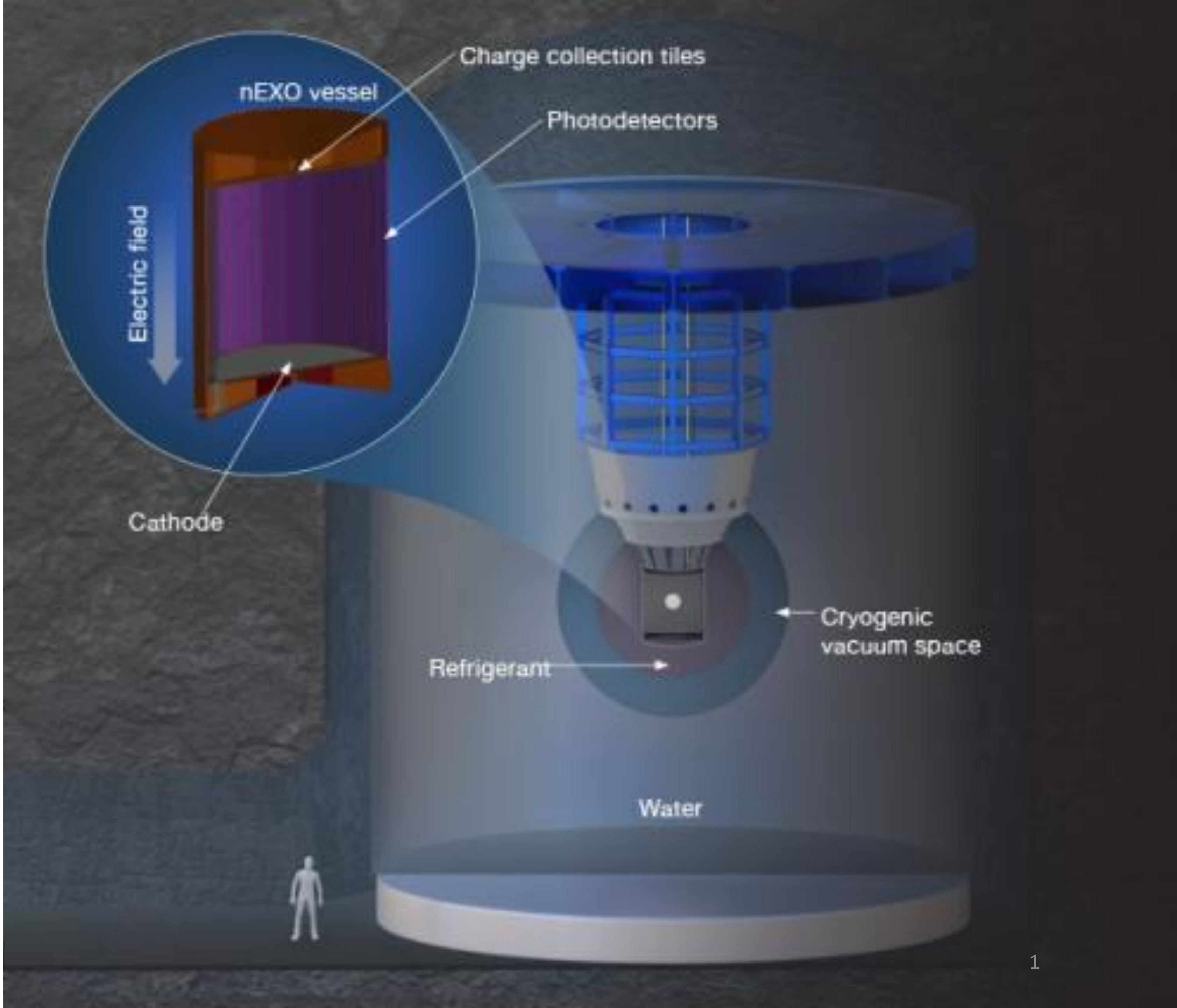
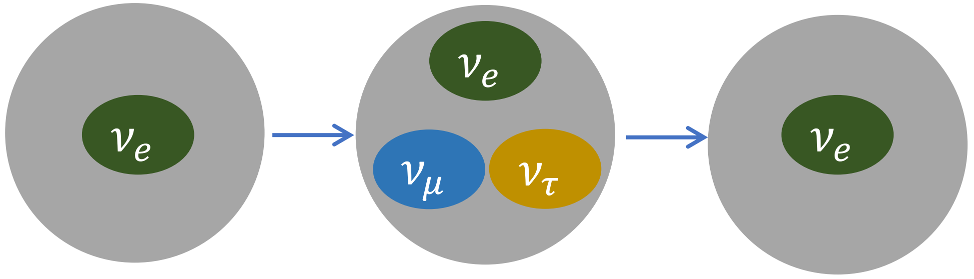
$0\nu\beta\beta$研讨会
中山大学，珠海
2021年5月22日



Outline

- $0\nu\beta\beta$ decay
- Liquid Xenon TPC technology
- EXO-200, prototype demonstration of nEXO
- nEXO design
- R&D and IHEP efforts
- Conclusion

Neutrino oscillation



Massive neutrinos!

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\theta_{23} & sin\theta_{23} \\ 0 & -sin\theta_{23} & cos\theta_{23} \end{pmatrix} \begin{pmatrix} cos\theta_{13} & 0 & e^{-i\delta} sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} sin\theta_{13} & 0 & cos\theta_{13} \end{pmatrix} \begin{pmatrix} cos\theta_{12} & sin\theta_{12} & 0 \\ -sin\theta_{12} & cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \approx 45^\circ$ — Accelerator + Atmospheric

$\theta_{13} \approx 10^\circ$ — Reactor + Accelerator

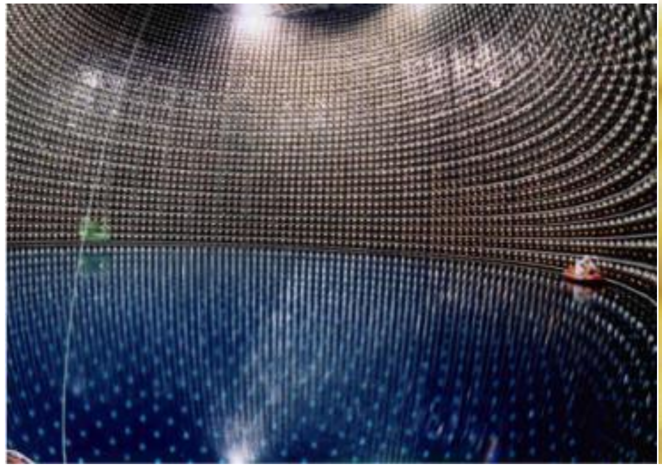
$\theta_{12} \approx 35^\circ$ — Solar + Reactor

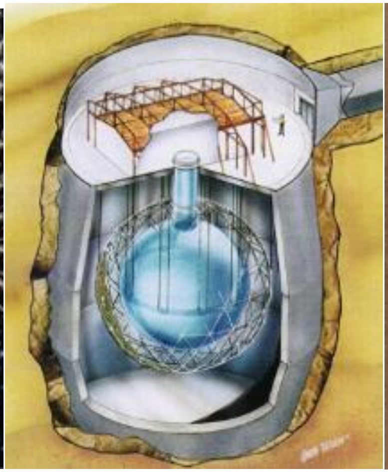
The Nobel Prize in Physics 2015

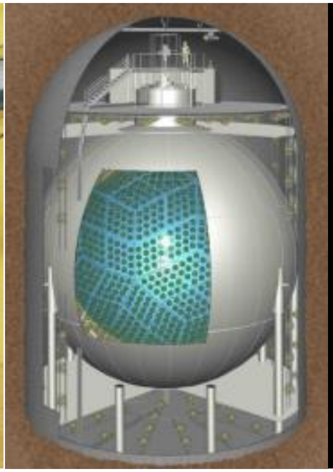
Photo: A. Mahmoud
Takaaki Kajita
Prize share: 1/2

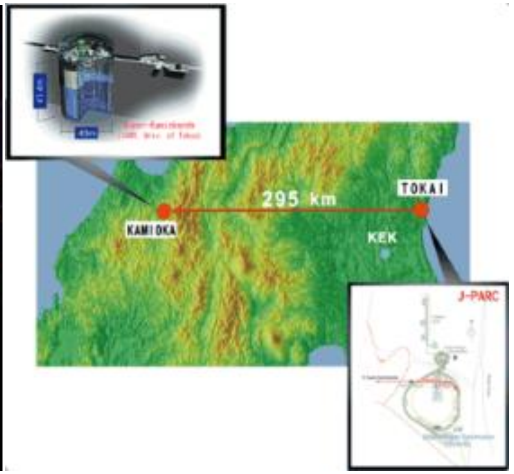
Photo: A. Mahmoud
Arthur B. McDonald
Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*



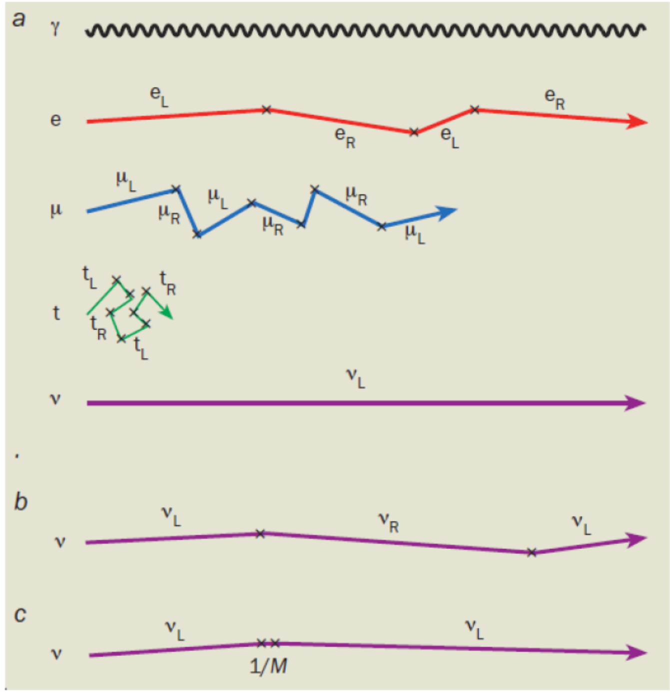


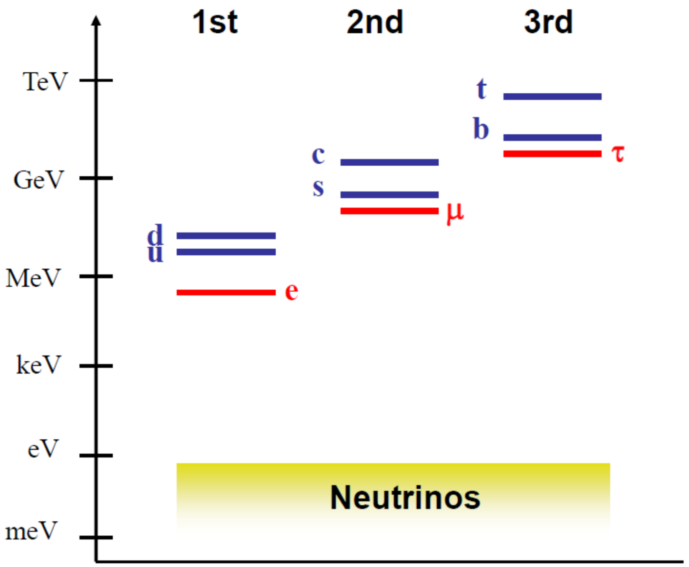




Neutrino mass generation mechanism

- Neutrino oscillation experiments demonstrate neutrinos have non-zero mass
- Neutrino mass is significantly smaller than other fermions
- **Majorana nature** of neutrinos allows a natural way to explain the small neutrino mass by see-saw mechanism

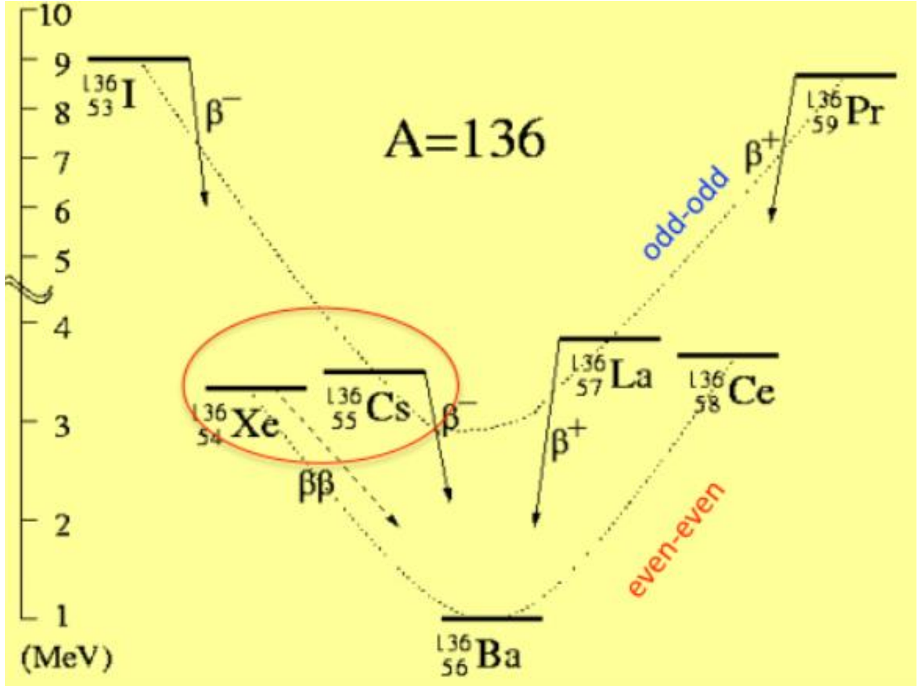




The search for $0\nu\beta\beta$ is the most sensitive probe of Majorana nature of neutrinos.

Double beta decay

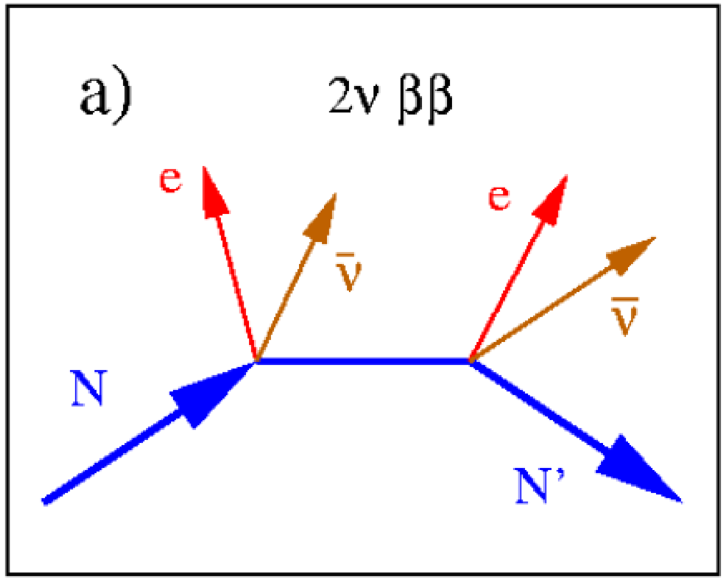
- Double beta decay is a second order process
- Only observable if first order beta decay is energetically forbidden

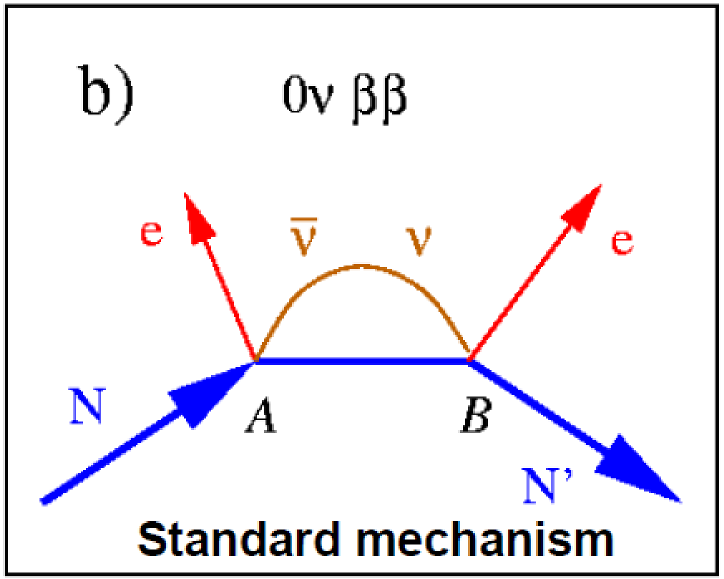


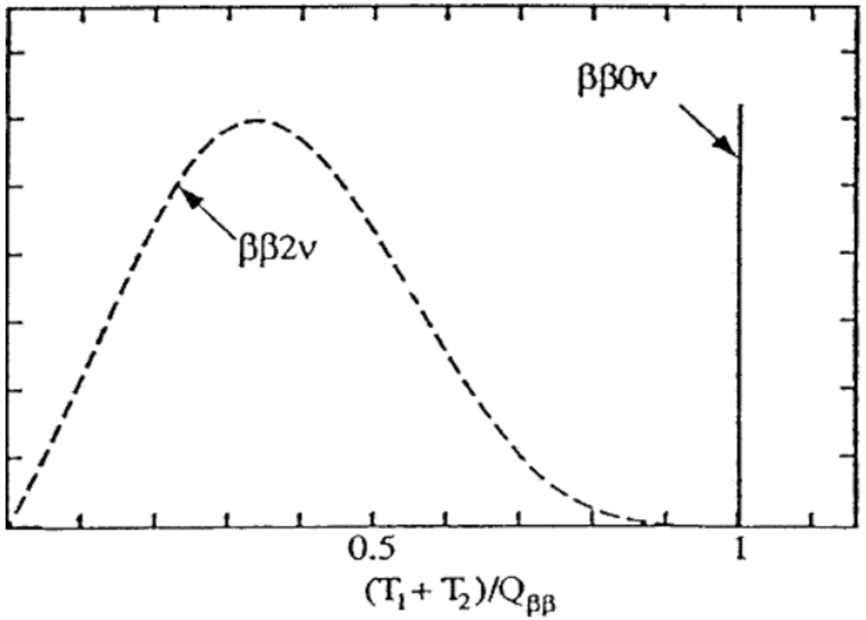
Candidate with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.458	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

Neutrinoless double beta decay ($0\nu\beta\beta$)







$2\nu\beta\beta$ decay

- Conventional process

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

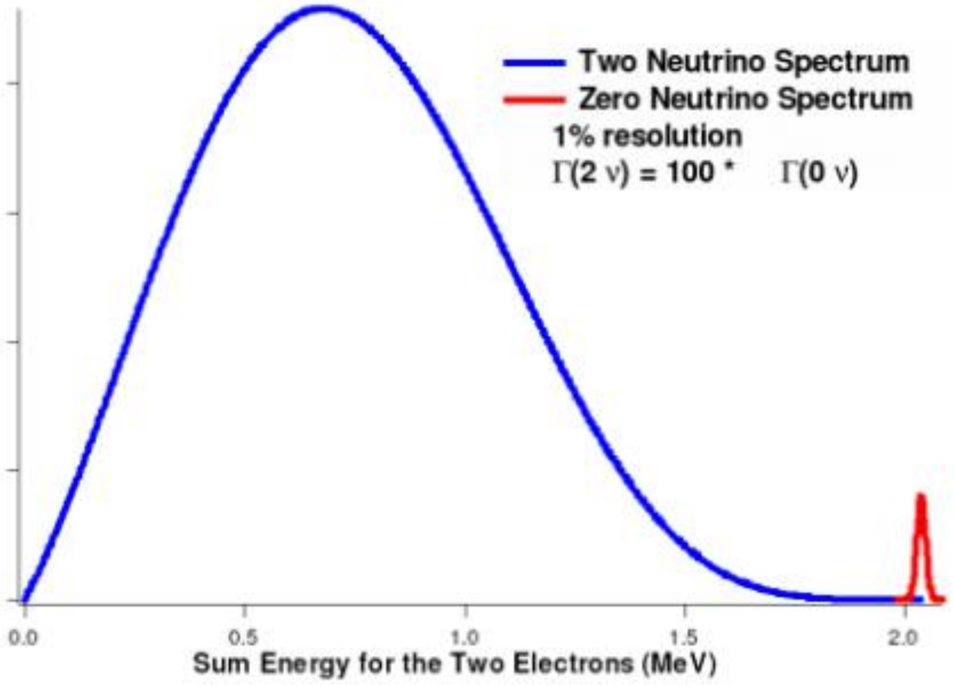
- **Majorana neutrino**
- **Lepton number violation**
- **Absolute neutrino mass scale**

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

Experimental sensitivity

$$t_{1/2} \sim \sqrt{\frac{MT}{\mathrm{B} \times \Delta E}}$$

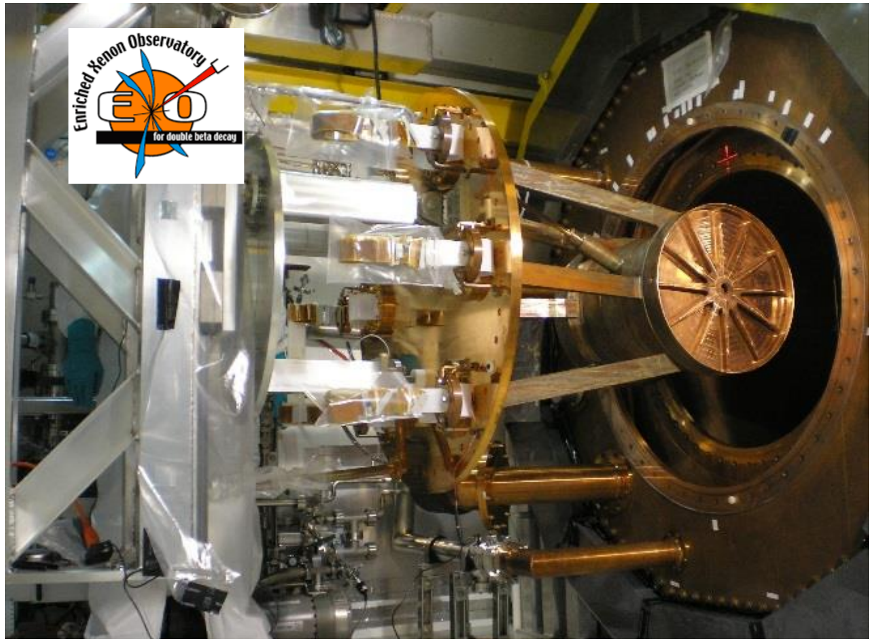
- large detector mass
- low background level
  - low radioactivity detector
  - powerful background rejection
- high energy resolution



Searching for $0\nu\beta\beta$ in ^{136}Xe, a phased approach

EXO-200:

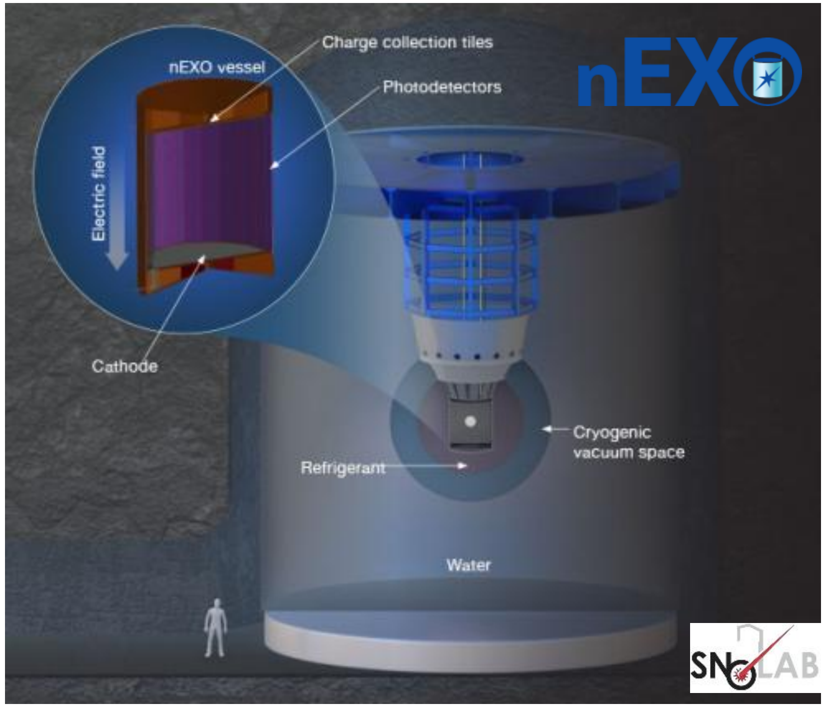
- EXO-200 first 100-kg class ββ experiment
- Discovery of $2\nu\beta\beta$ in Xe-136
- 200 kg liquid-Xe TPC with ~80% Xe-136
- Located at the WIPP mine in NM, USA
- Decommissioned in Dec. 2018
- End-of-run calibration campaign data will inform the detailed design of nEXO



https://www-project.slac.stanford.edu/exo/

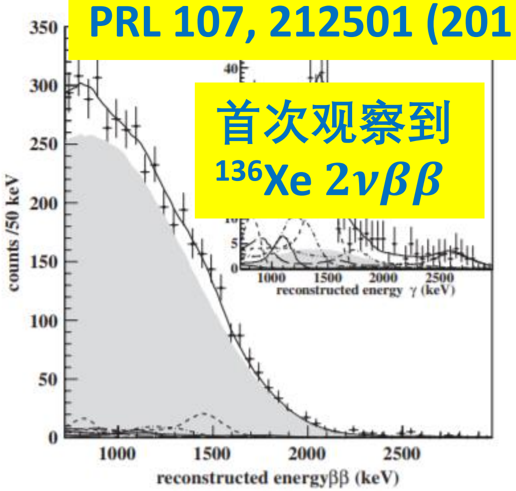
nEXO:

- Next-generation 5-tonne liquid Xe TPC
- Enriched in Xe-136 at ~90%
- Designed to go to beyond ~10^{28} years.
- SNOLAB cryopit preferred location by collaboration
- Decision on funding of nEXO anticipated this summer!



https://nexo.llnl.gov/

PRL 107, 212501 (2011)



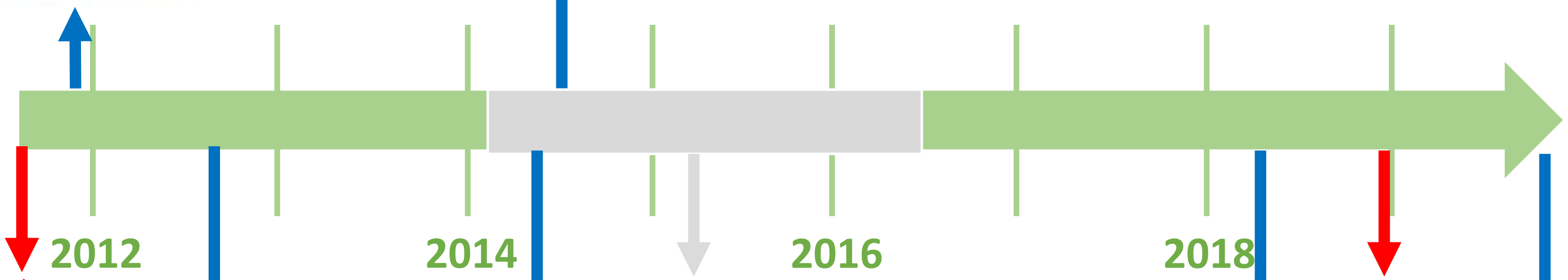
首次观察到
^{136}Xe $2\nu\beta\beta$

ARTICLE

Nature 510 229-234 (2014)

Search for Majorana neutrinos with the first two years of EXO-200 data

The EXO-200 Collaboration*



开始运行

运行中断

运行结束

Most precise $2\nu\beta\beta$ half-life of ^{136}Xe
PRC 89 1, 015502 (2014)

Search for $0\nu\beta\beta$ with Phase-II
PRL 120, 072701 (2018)
PRL 123, 161802 (2019)

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Search for Neutrinoless Double-Beta Decay in ^{136}Xe with EXO-200

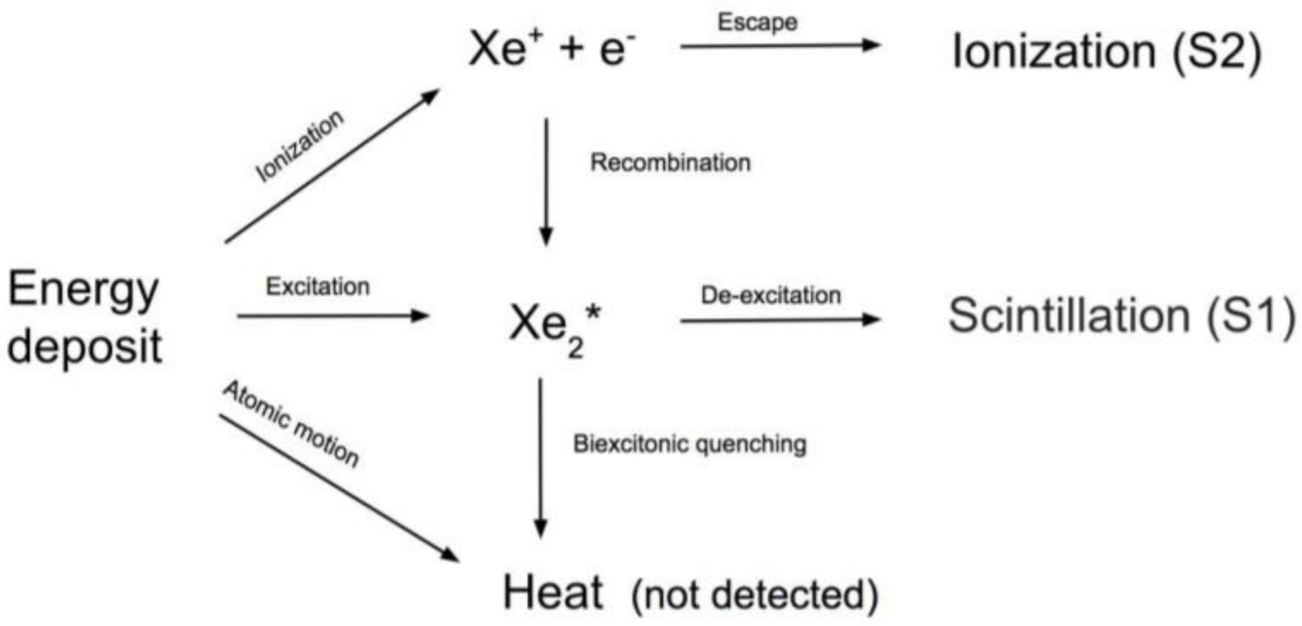
M. Auger *et al.* (EXO Collaboration)
Phys. Rev. Lett. **109**, 032505 – Published 19 July 2012

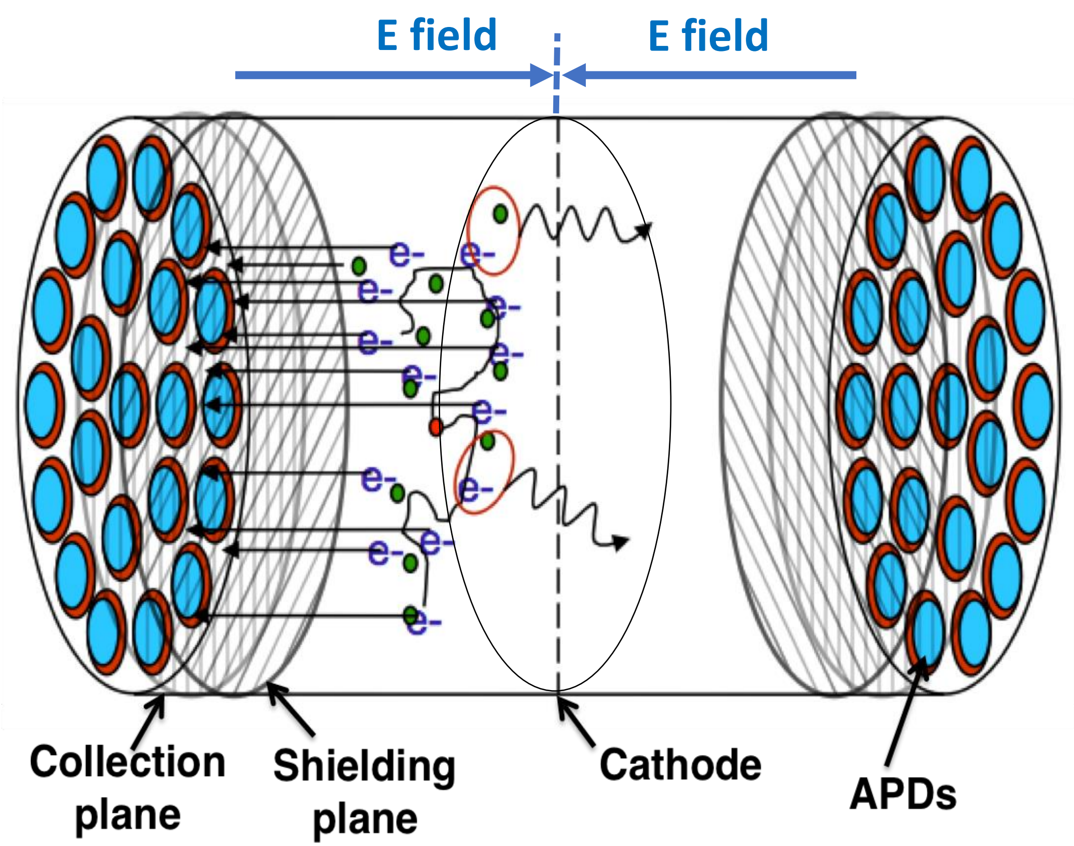
PRL 109, 032505 (2012)

Physics See Synopsis: Looking for No Neutrinos

Time Projection Chamber

- Energy deposit in liquid xenon induced two types of signals
  - Xe atoms are ionized → electrons drift to the anode and being collected
  - Xe atoms are excited → de-excitation gives VUV photons

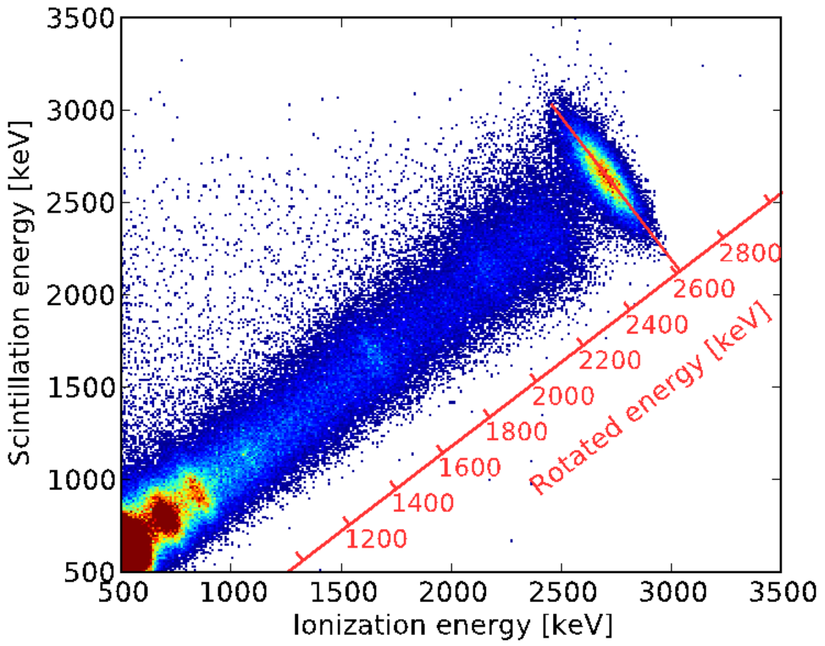




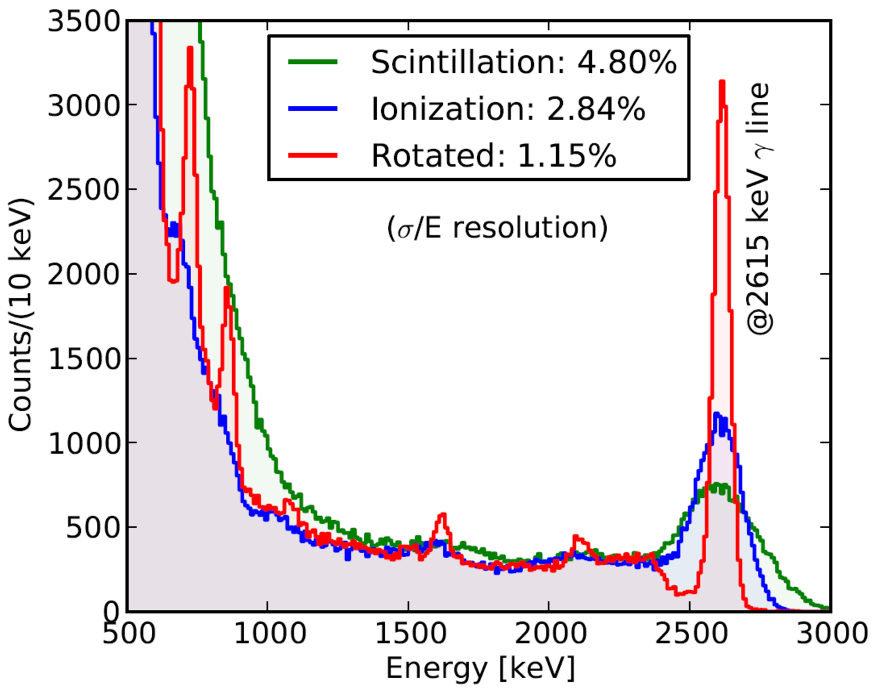
Energy

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

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

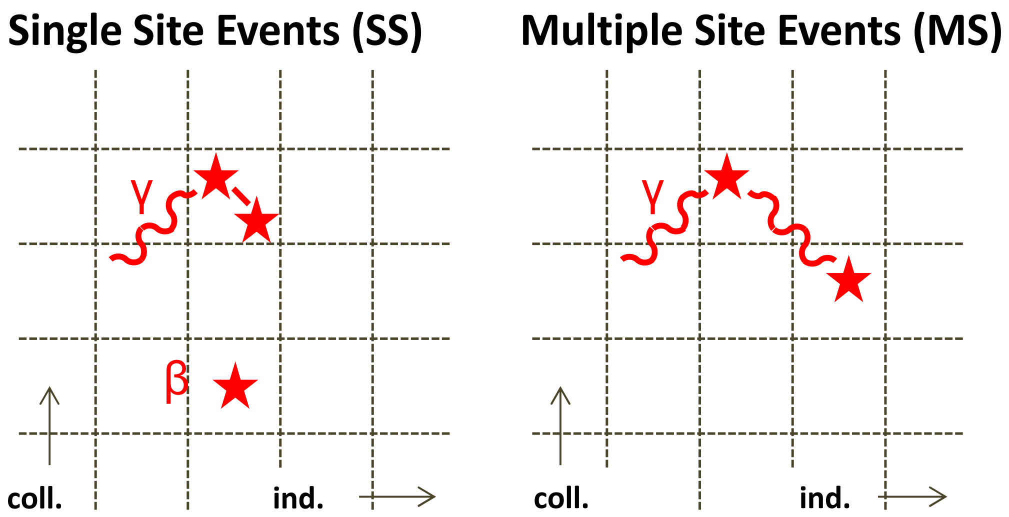


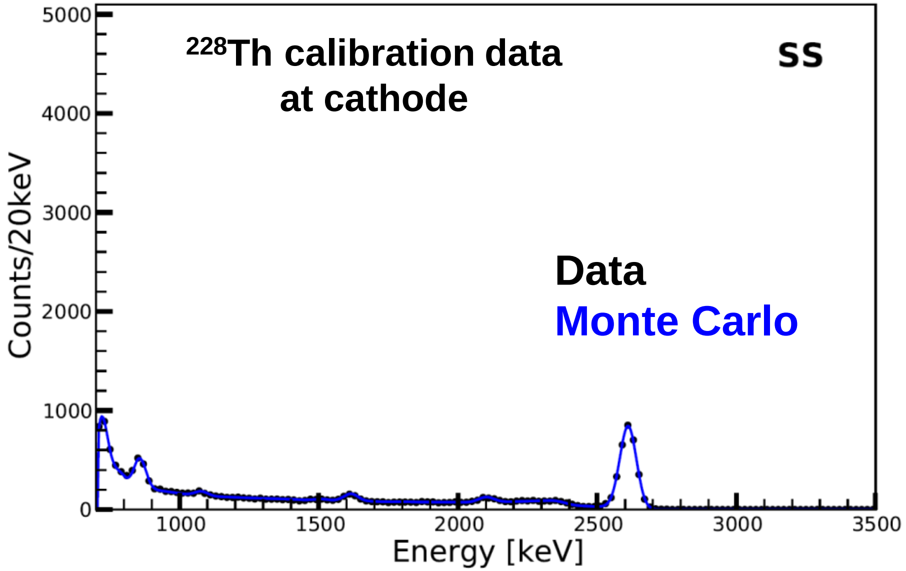
Reconstructed energy, ^{228}Th calibration:

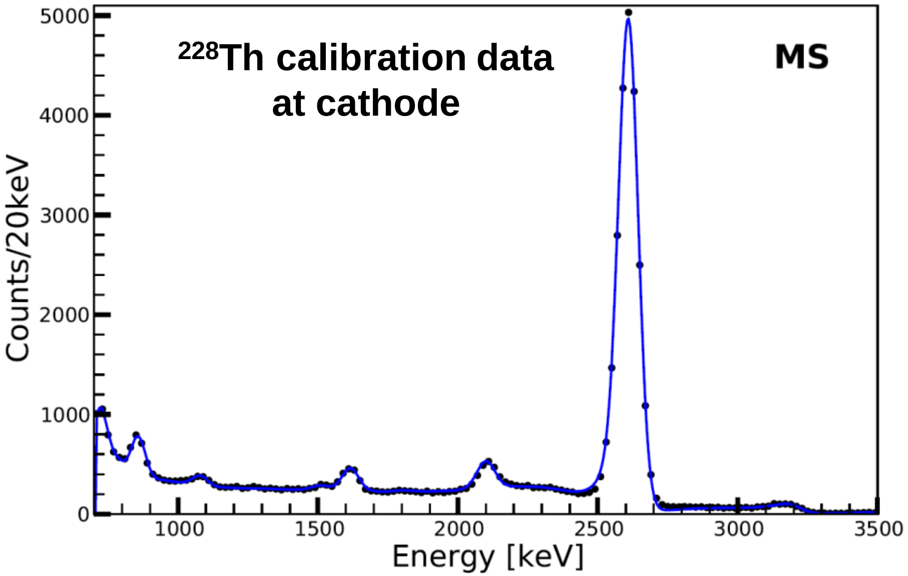


3D vertex and SS/MS classification

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







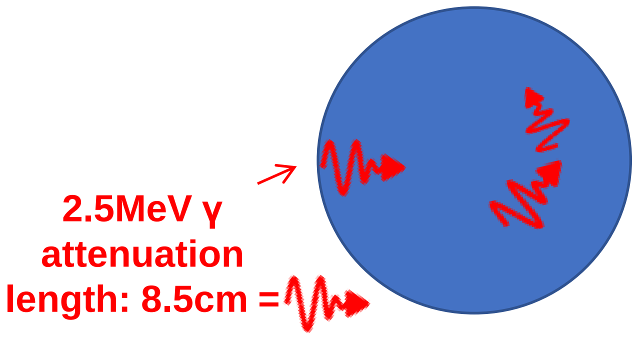
Background Suppression: Event topology SS

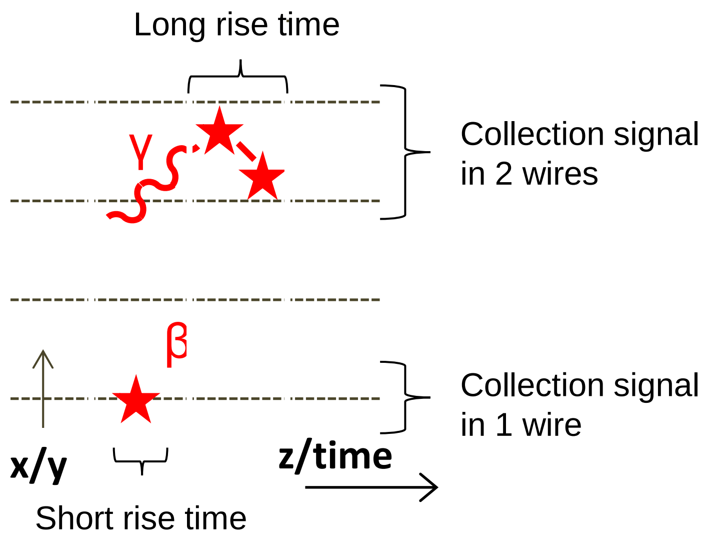
- Additional discrimination in SS using *spatial distribution* and *cluster size*

- 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)

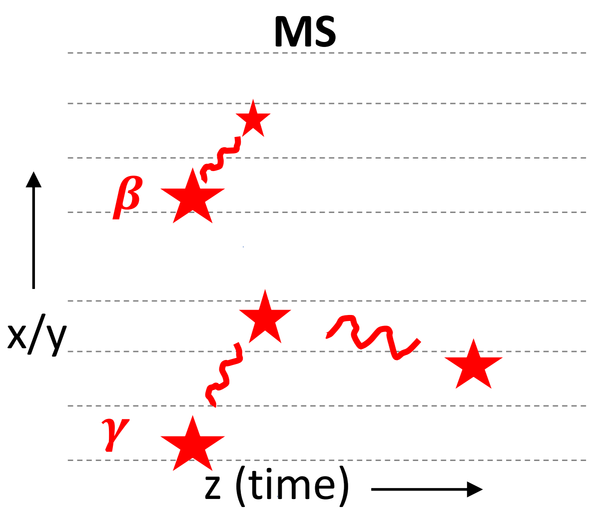
LXe self-shielding:

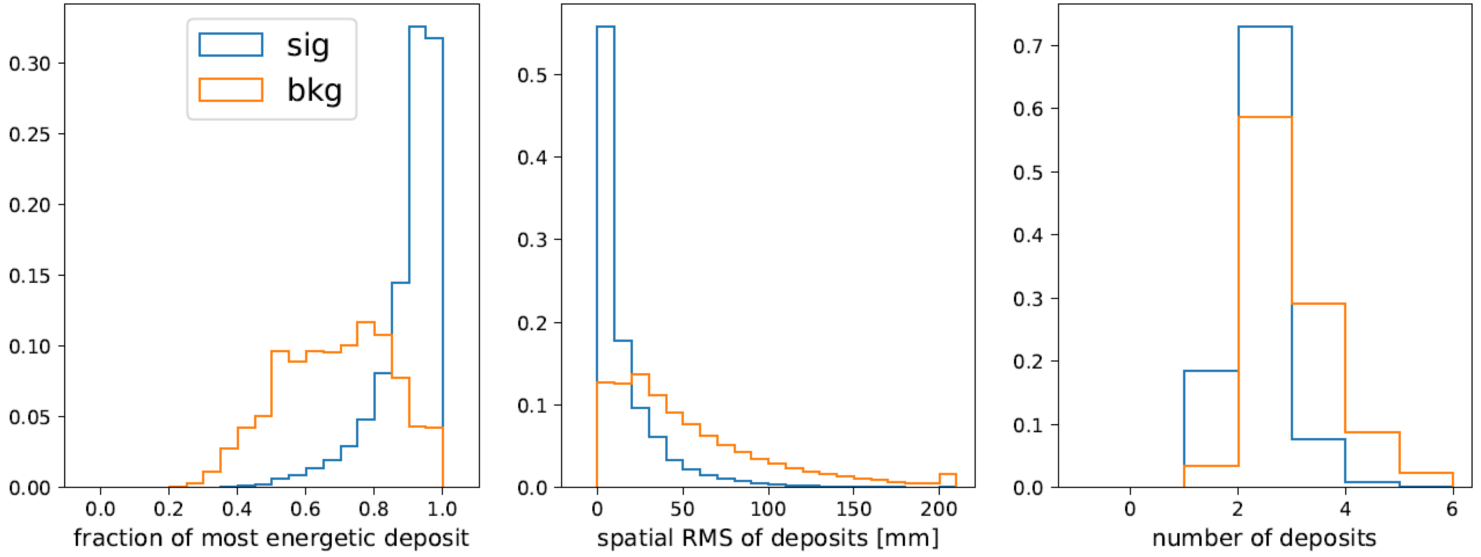




Background Suppression: Event topology MS

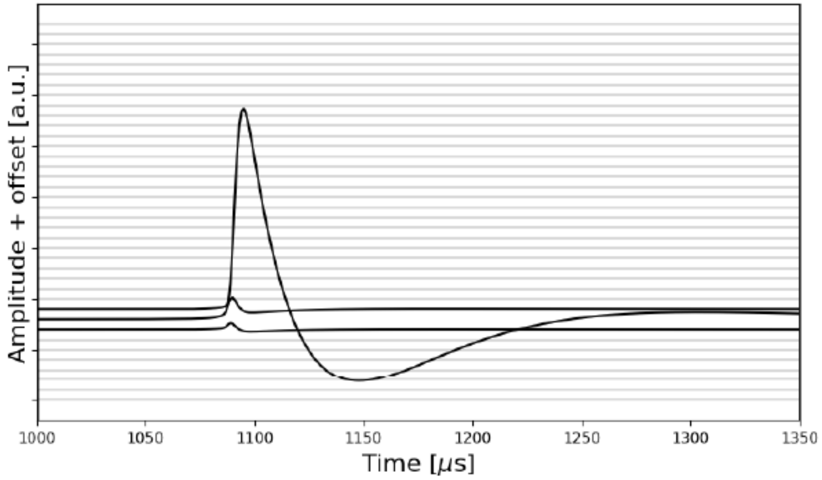
- $0\nu\beta\beta$ in MS arising from small energy deposits due to bremsstrahlung, while γ Compton scatters
- Distinct features in number of energy deposits, energy distribution and spatial spread among deposits
- High background rejection than in SS to compensate the fact that MS is dominated by backgrounds

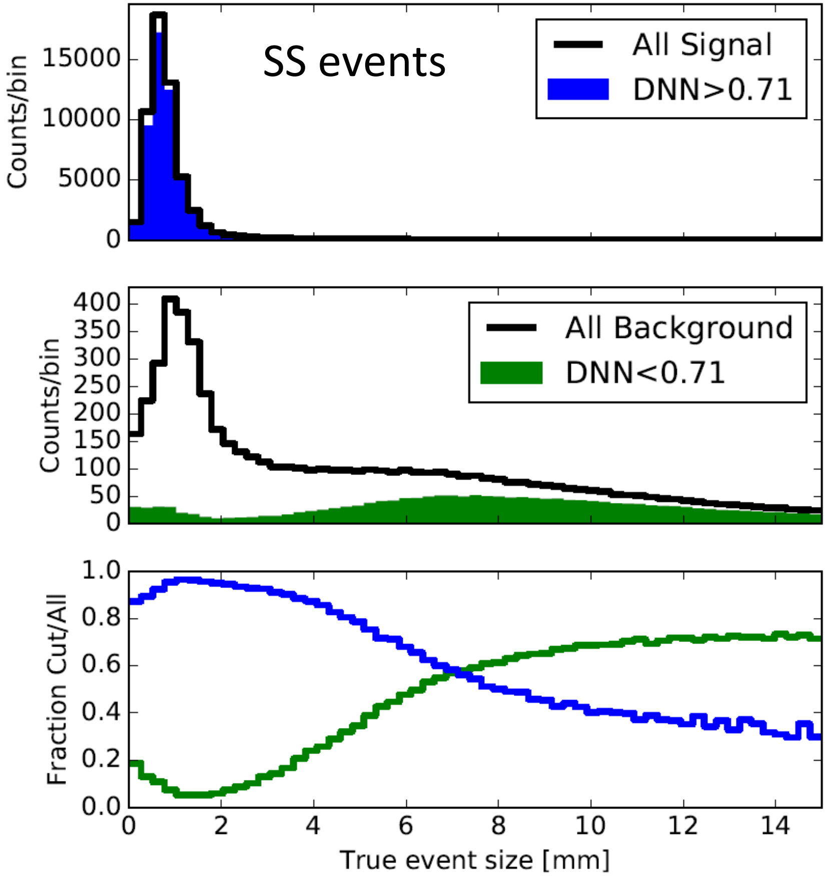




All in DNN

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

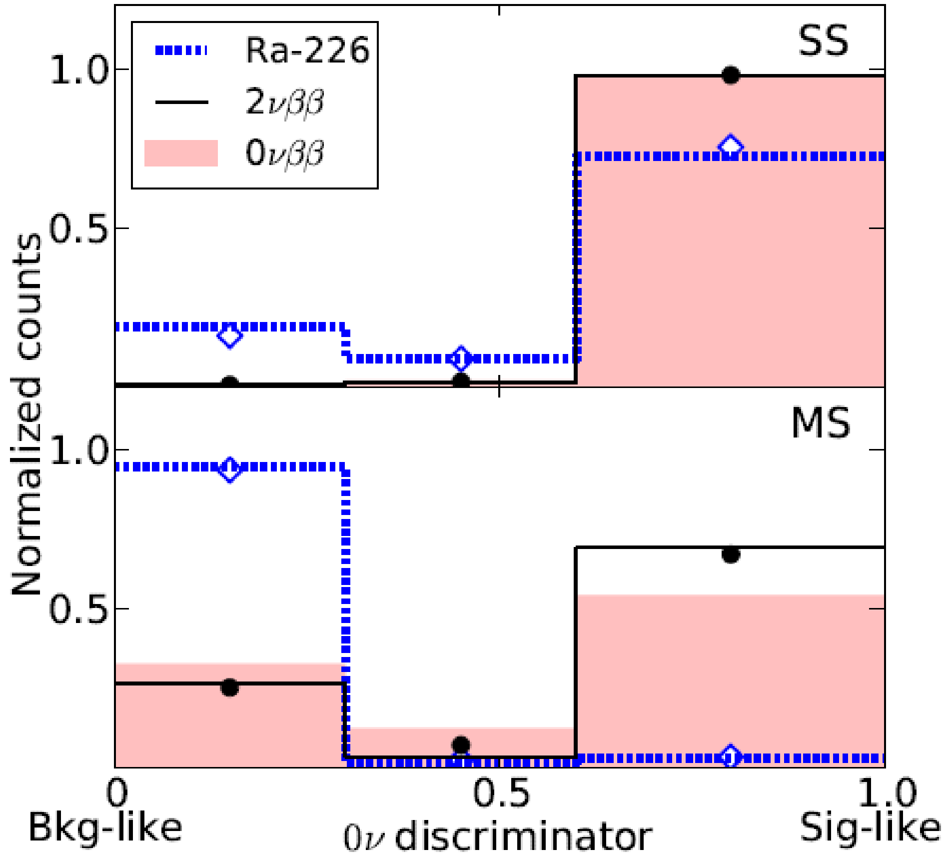




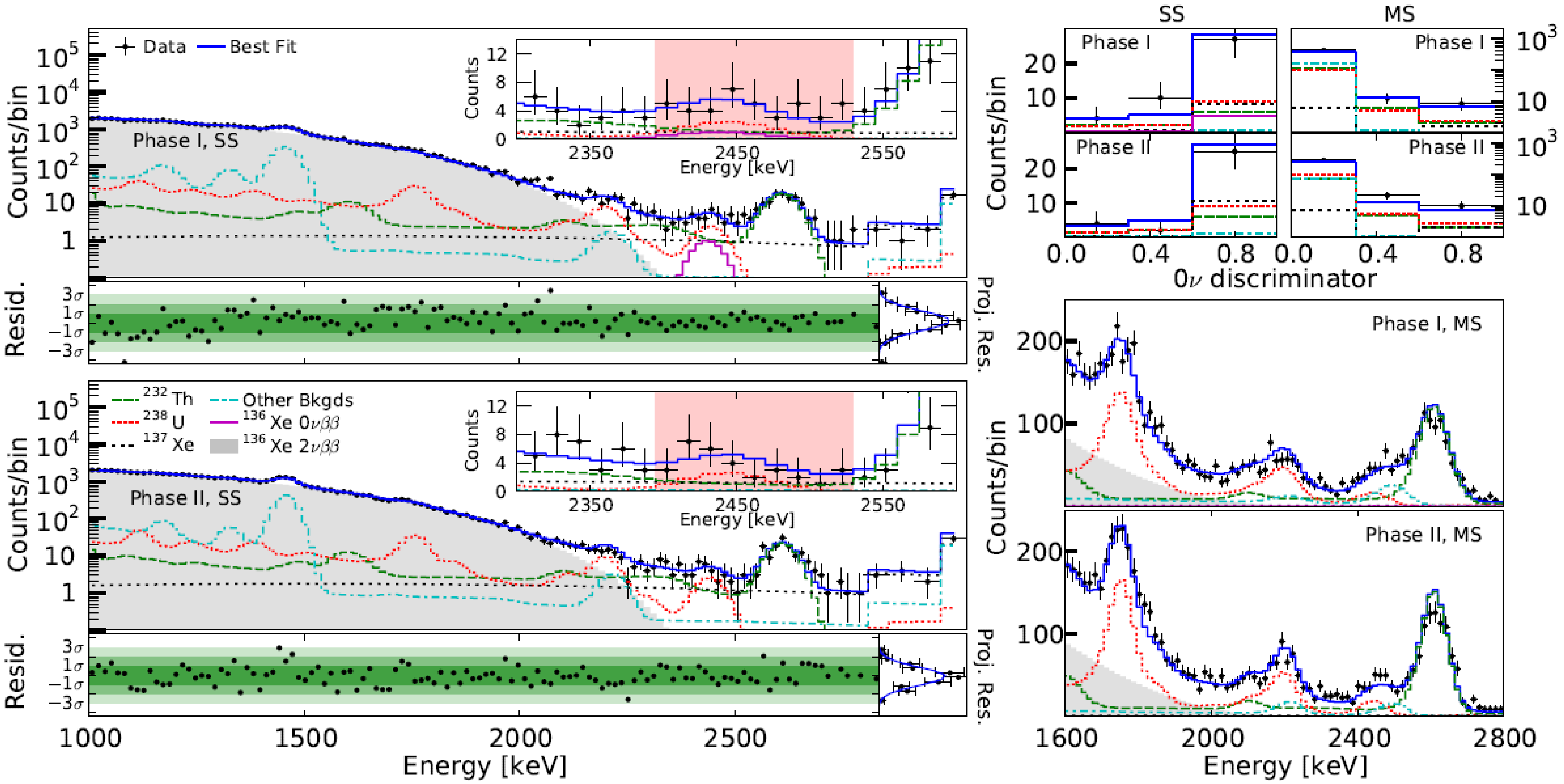
- Signal/background identification efficiency correlates with the true event size based on truth information in simulation
- Indicates the network can pick up correct features on the waveform to reconstruct event, (find wire signals, cluster signals into energy deposits), thus to discriminate signal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

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 $Q_{\beta\beta} \pm 2\sigma$



Multi-dimensional fit



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 x 10^{25} yr (90% C.L.)

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

Sensitivity 5.0x10^{25} yr

PHYSICAL REVIEW LETTERS 123, 161802 (2019)

Editors' Suggestion

Search for Neutrinoless Double-β Decay with the Complete EXO-200 Dataset

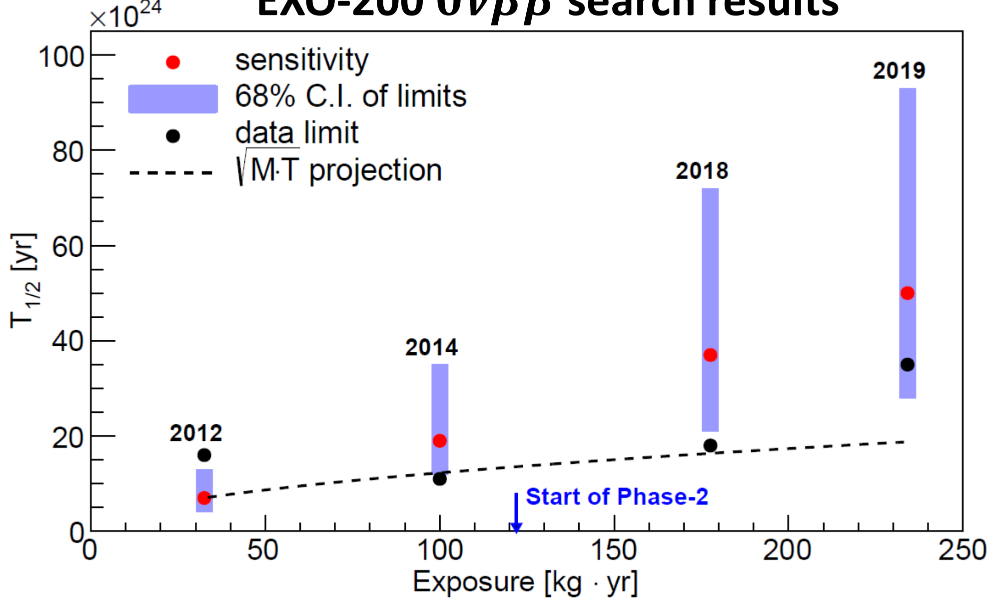
G. Anton,[1] I. Badhrees,[2,a] P. S. Barbeau,[3] D. Beck,[4] V. Belov,[5] T. Bhatta,[6] M. Breidenbach,[7] T. Brunner,[8,9] G. F. Cao,[10] W. R. Cen,[10] C. Chambers,[11,b] B. Cleveland,[12,c] M. Coon,[4] A. Craycraft,[11] T. Daniels,[13] M. Danilov,[5,d] L. Darroch,[8] S. J. Daugherty,[14] J. Davis,[7] S. Delaquis,[7,*] A. Der Mesrobian-Kabakian,[12] R. DeVoe,[15] J. Dilling,[9] A. Dolgolenko,[5] M. J. Dolinski,[16] J. Echevers,[4] W. Fairbank, Jr.,[11] D. Fairbank,[11] J. Farine,[12] S. Feyzbakhsh,[17] P. Fierlinger,[18] D. Fudenberg,[15] P. Gautam,[16] R. Gornea,[2,9] G. Gratta,[15] C. Hall,[19] E. V. Hansen,[16] J. Hoessl,[1] P. Hufschmidt,[1] M. Hughes,[20] A. Iverson,[11] A. Jamil,[21] C. Jessiman,[2] M. J. Jewell,[15] A. Johnson,[7] A. Karelin,[5] L. J. Kaufman,[7,e] T. Koffas,[2] R. Krücken,[9] A. Kuchenkov,[5] K. S. Kumar,[22,f] Y. Lan,[9] A. Larson,[6] B. G. Lenardo,[15] D. S. Leonard,[23] G. S. Li,[15,†] S. Li,[4] Z. Li,[21] C. Licciardi,[12] Y. H. Lin,[16] R. MacLellan,[6] T. McElroy,[8] T. Michel,[1] B. Mong,[7] D. C. Moore,[21] K. Murray,[8] O. Njoya,[22] O. Nusair,[20] A. Odian,[7] I. Ostrovskiy,[20] A. Piepke,[20] A. Pocar,[17] F. Retière,[9] A. L. Robinson,[12] P. C. Rowson,[7] D. Ruddell,[13] J. Runge,[3] S. Schmidt,[1] D. Sinclair,[2,9] A. K. Soma,[20] V. Stekhanov,[5] M. Tarka,[17] J. Todd,[11] T. Tolba,[10] T. I. Totev,[8] B. Veenstra,[2] V. Veeraraghavan,[20] P. Vogel,[24] J.-L. Vuilleumier,[25] M. Wagenpfeil,[1] J. Watkins,[2] M. Weber,[15] L. J. Wen,[10] U. Wichoski,[12] G. Wrede,[1] S. X. Wu,[15] Q. Xia,[21] D. R. Yahne,[11] L. Yang,[4] Y.-R. Yen,[16] O. Ya. Zeldovich,[5] and T. Ziegler[1]

(EXO-200 Collaboration)

Background contribution to Q ± 2σ

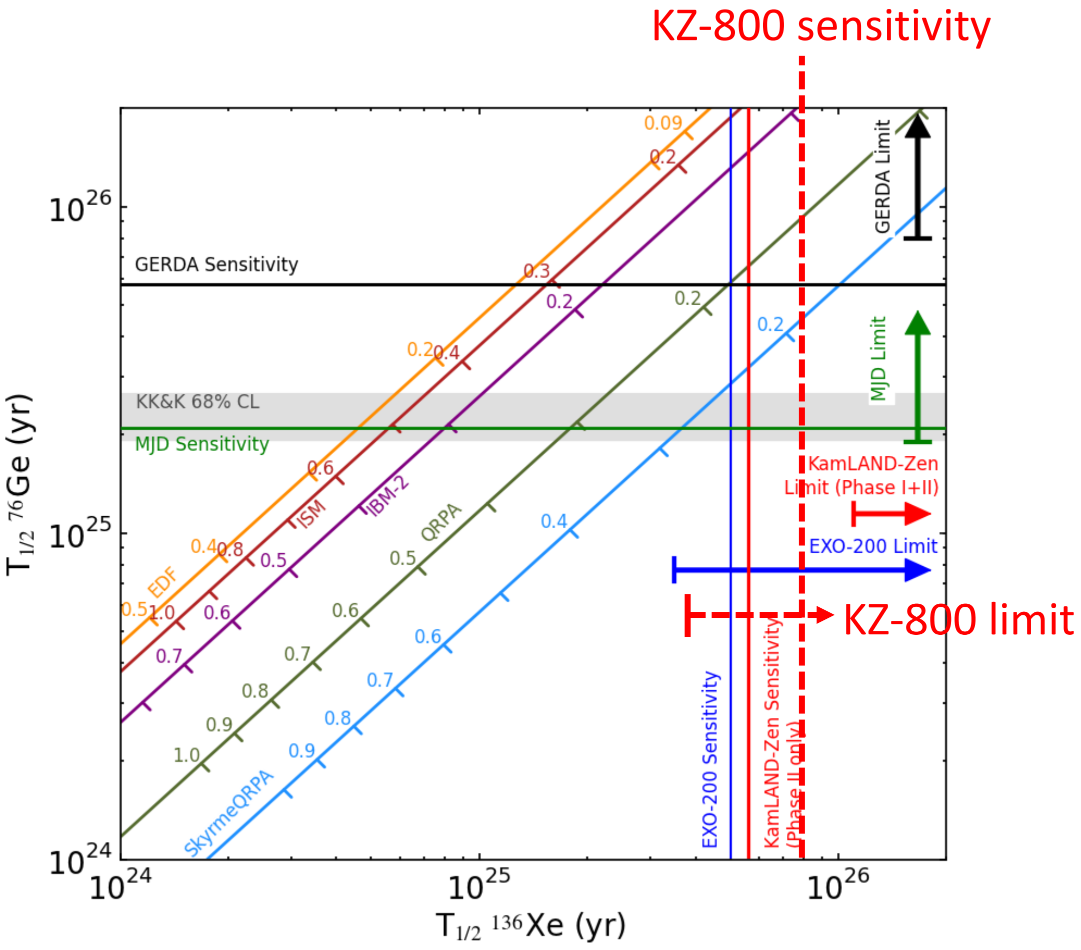
(counts)	^{238}U	^{232}Th	^{137}Xe	Total	Data
Phase I	12.6	10.0	8.7	32.3±2.3	39
Phase II	12.0	8.2	9.3	30.9±2.4	26

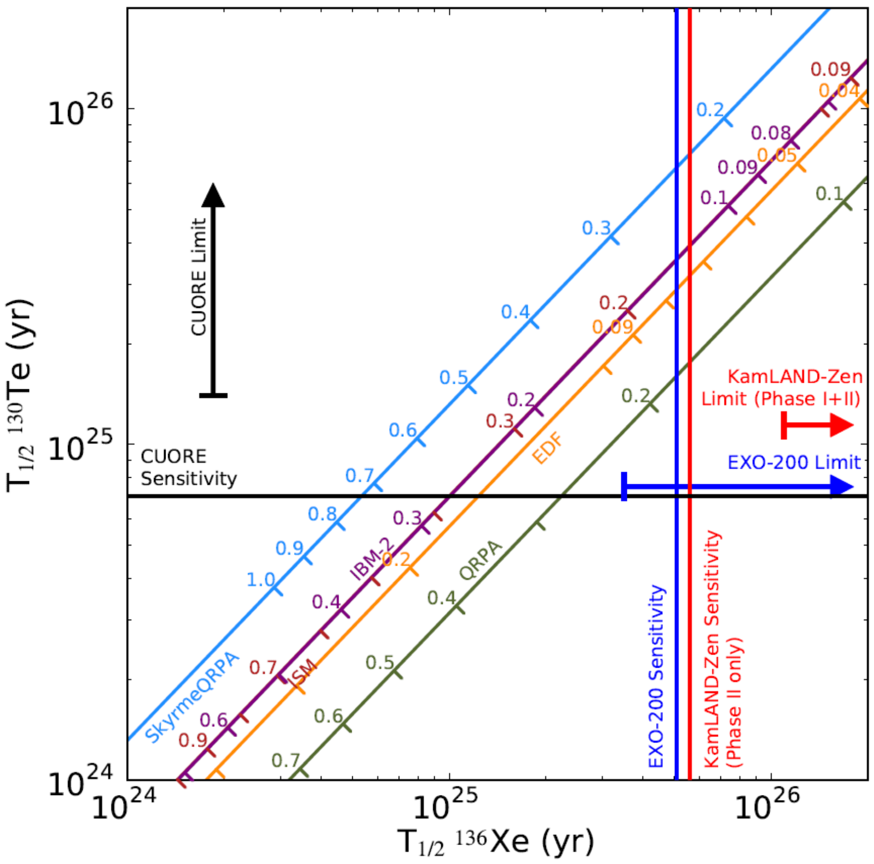
EXO-200 $0\nu\beta\beta$ search results



2012: Phys.Rev.Lett. 109 (2012) 032505
2014: Nature 510 (2014) 229-234
2018: Phys. Rev. Lett. 120, 072701 (2018)
2019: Phys.Rev.Lett. 123 (2019) no.16, 161802

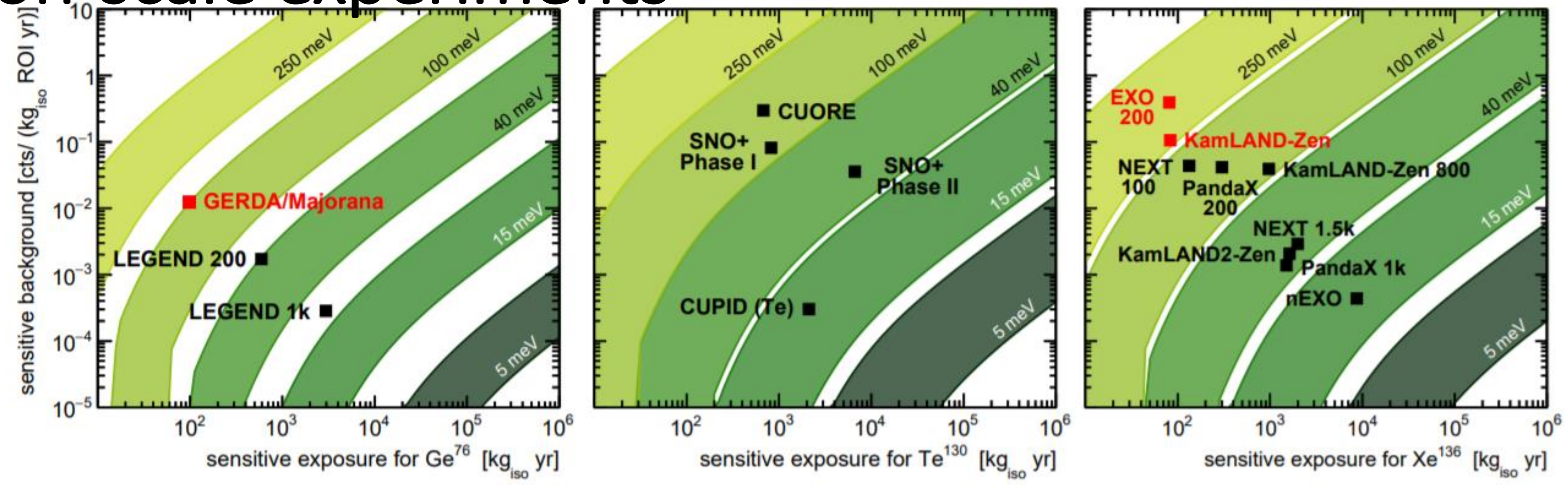
Neutrino mass limits



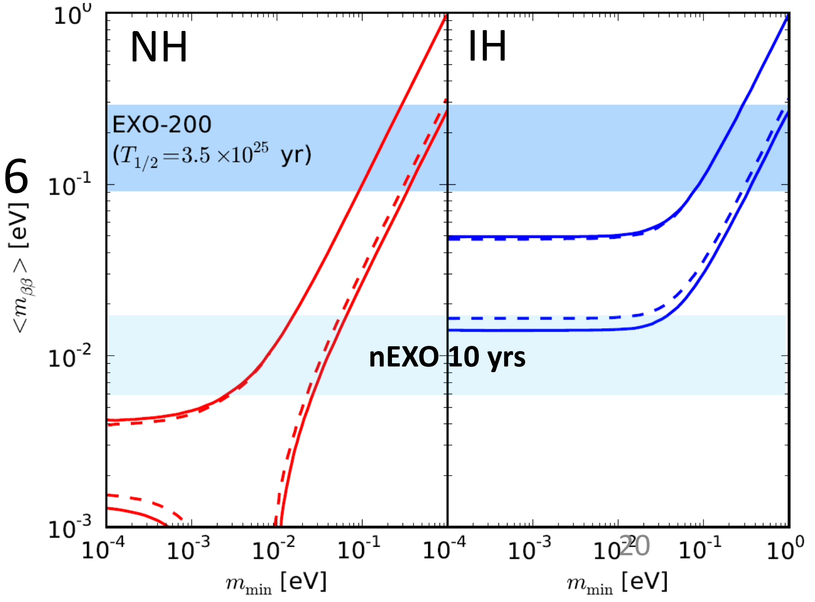


Ton-scale experiments

Phys.Rev. D96 (2017) no.5, 053001

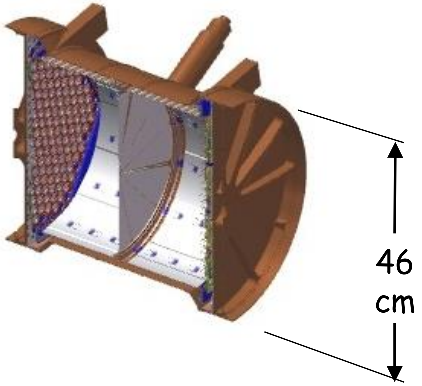


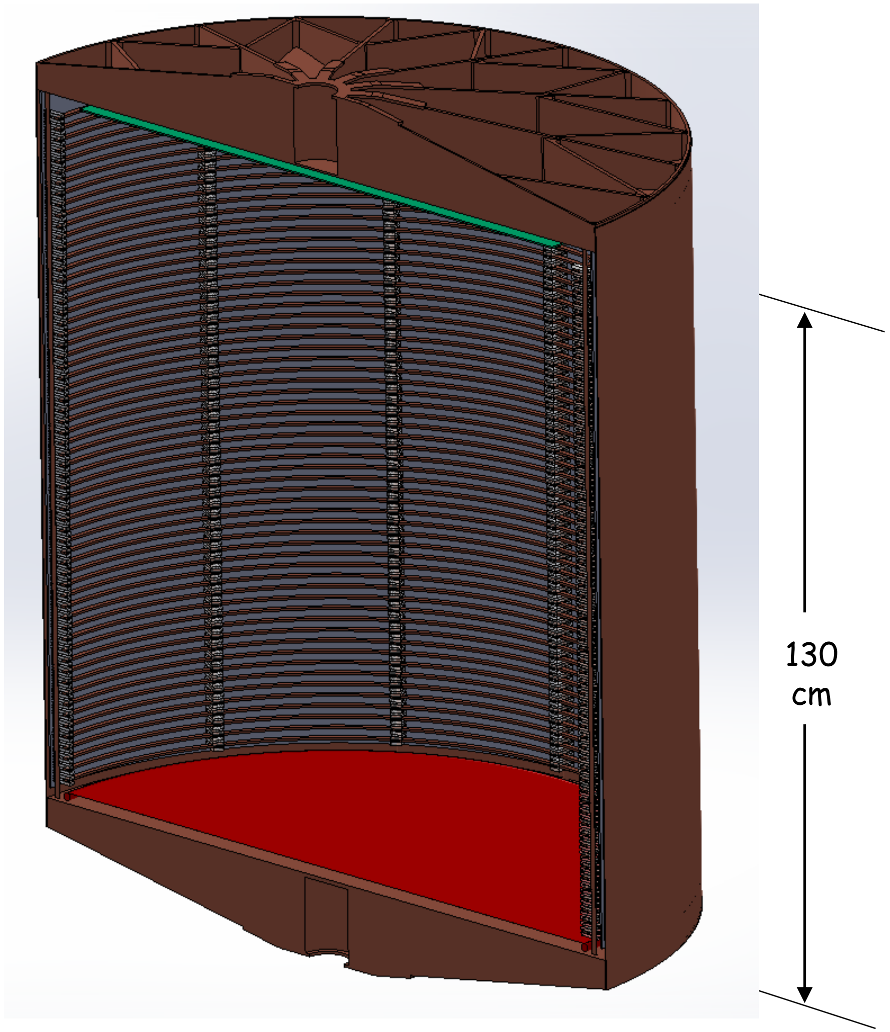
- Next generation tonne-scale experiments approaching bottom of IH or cover the entire IH
- Planned successor of EXO-200 with 5-tonne liquid xenon enriched in Xe136
- ~10^{28} yr sensitivity to 0vbb half-life, cover the entire inverted hierarchy



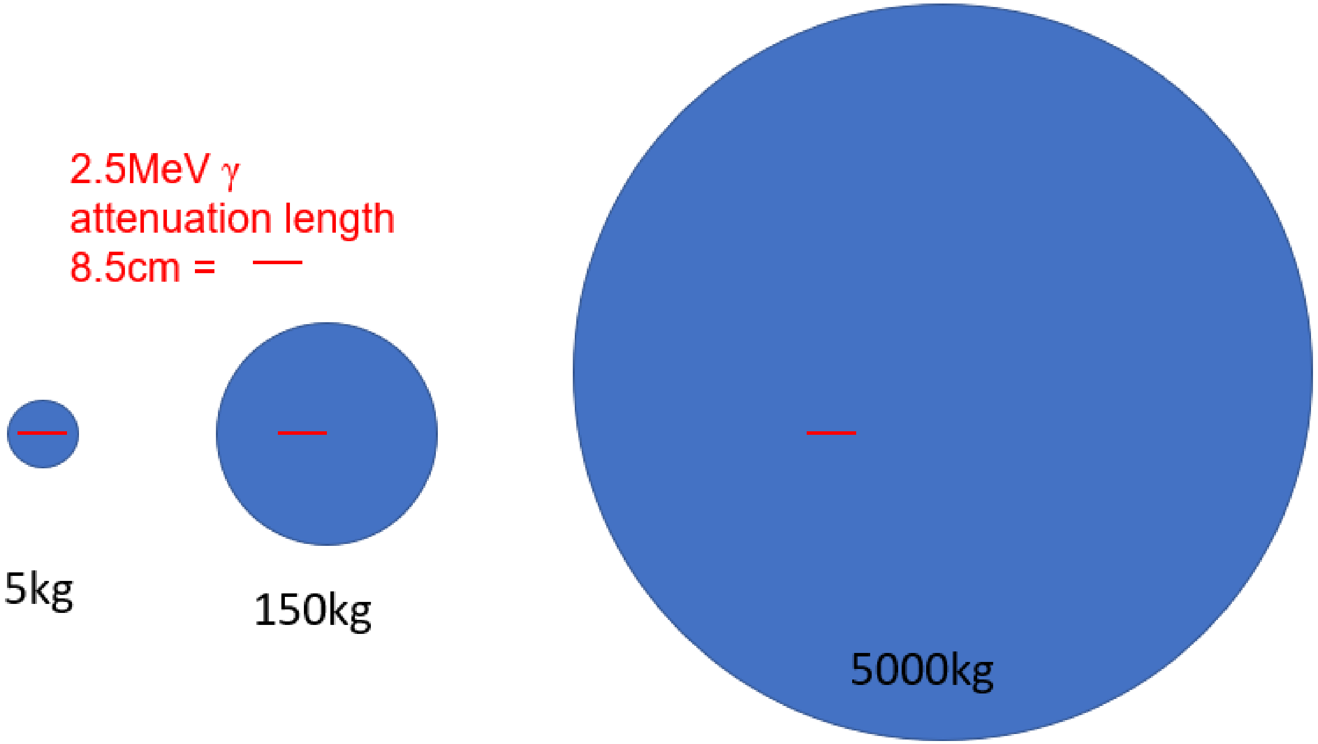
From EXO-200 to nEXO

LXe mass (kg)	Diameter or length (cm)
5000	130
150	40

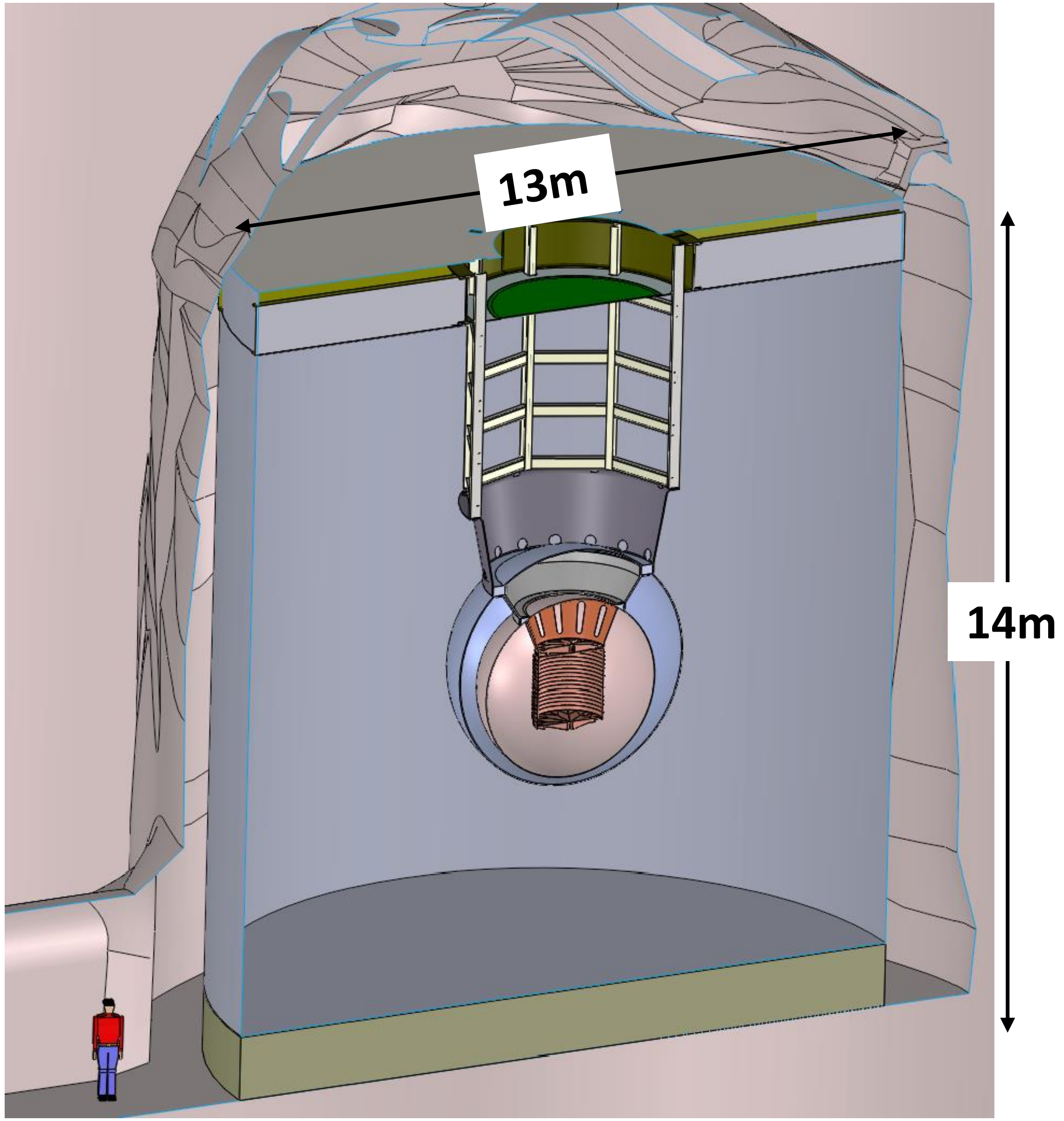




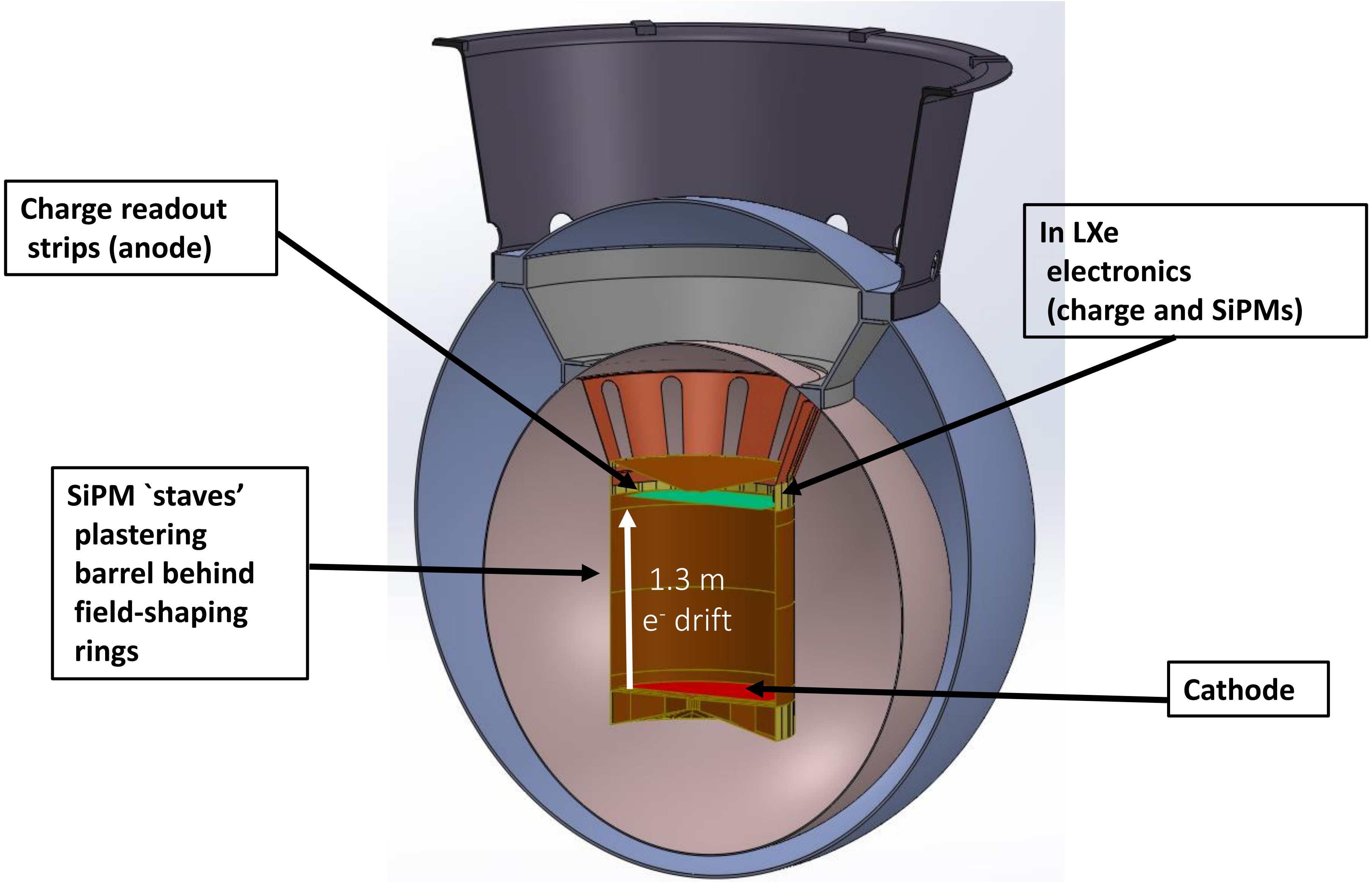
2.5MeV γ
attenuation length
8.5cm = —



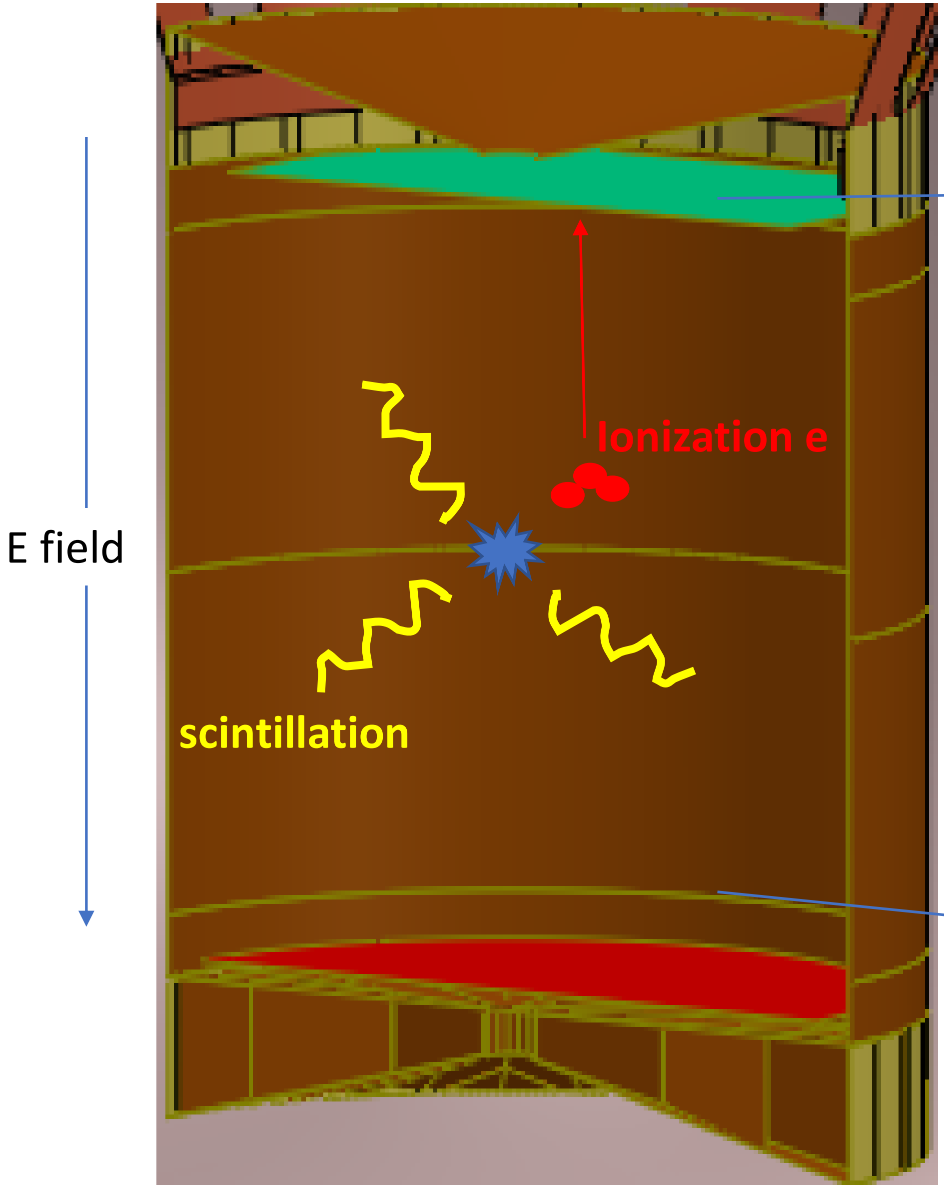
Artist view of nEXO in SNOLab cryopit



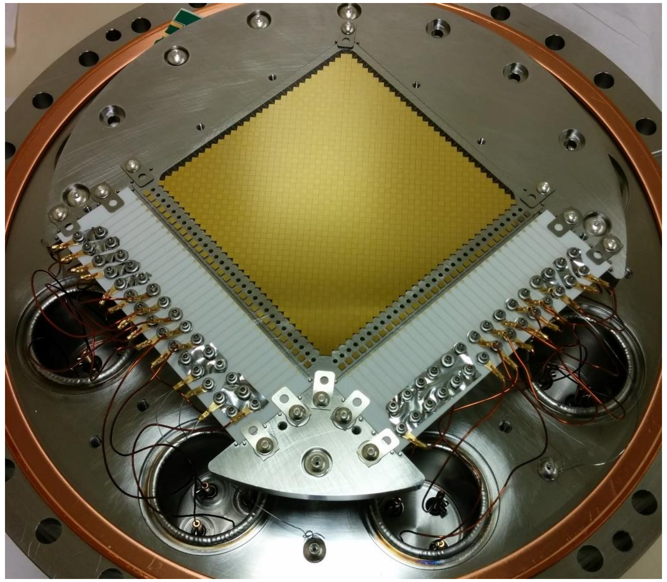
nEXO TPC baseline design

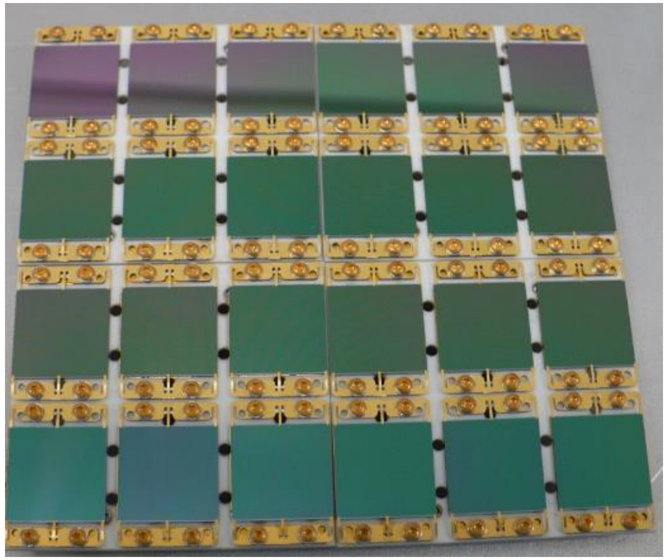


~5 tonne single phase **TPC with enriched Xe136**



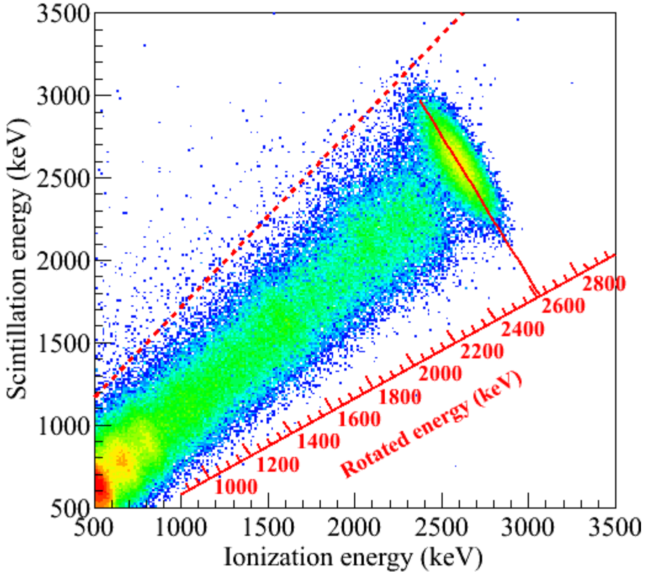
Charge tile anode for ionization charge collection





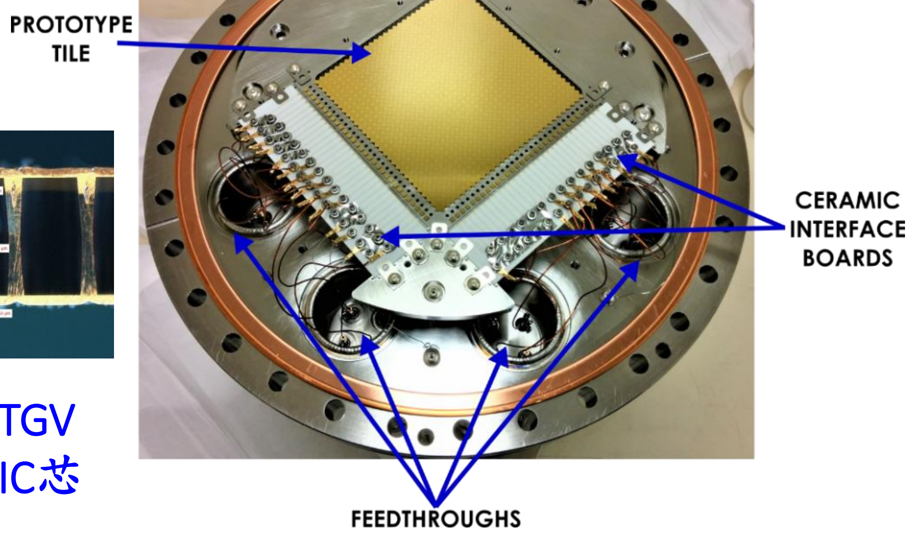
SiPM covered barrel (4 m^2) for scintillation light detection

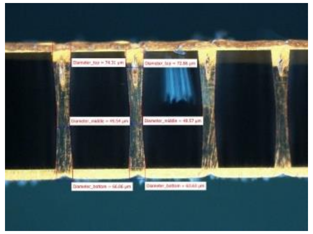
Energy anti-correlation



R&D highlights at IHEP

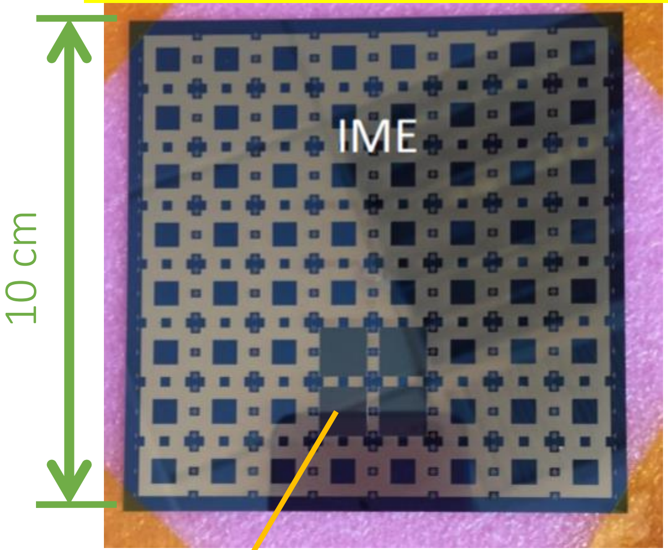
晶圆测试：JINST 13 P01006 (2018)

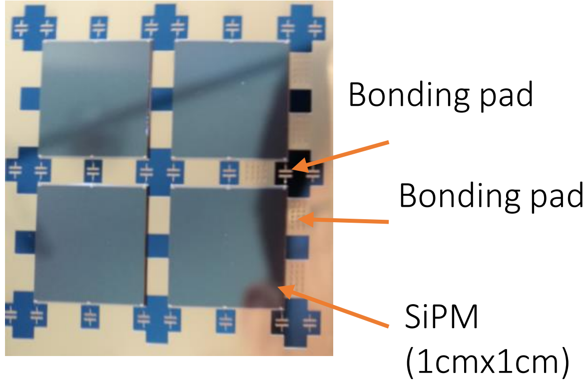


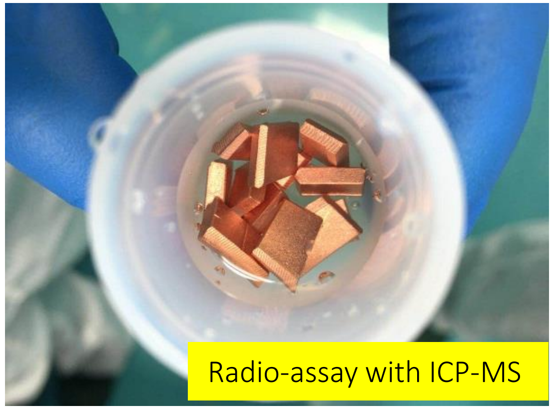


正在解决TGV工艺、ASIC芯片3D集成

合作组第一块SiPM Interposer样品







Radio-assay with ICP-MS

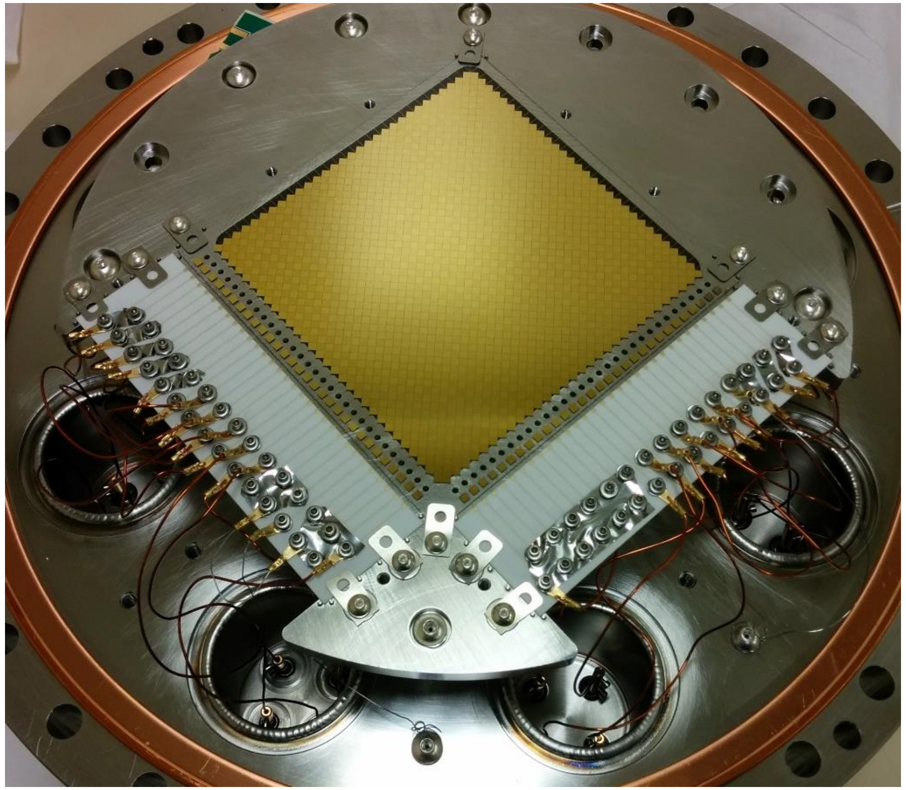
IHEP ASIC v2测试板

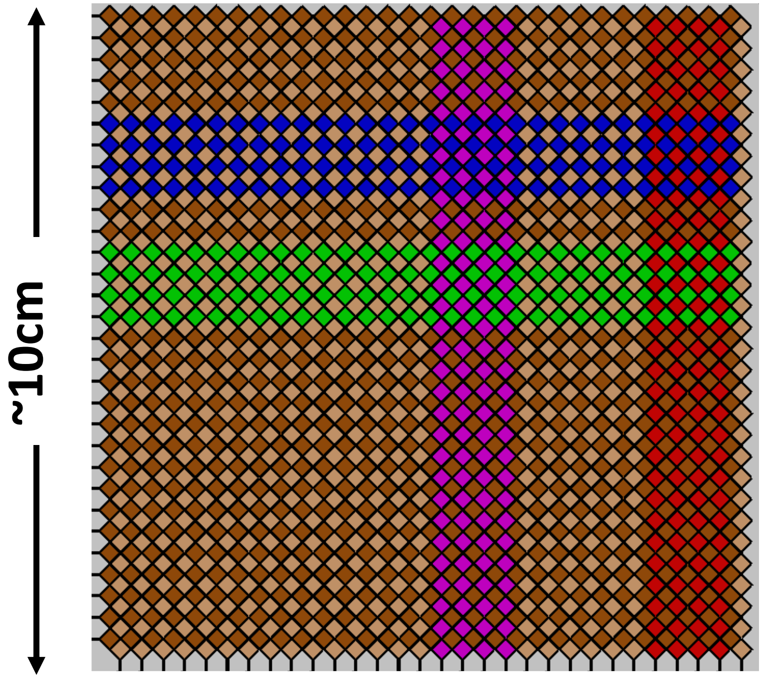
nEXO：Cu中U含量检出限达到0.18 ppt

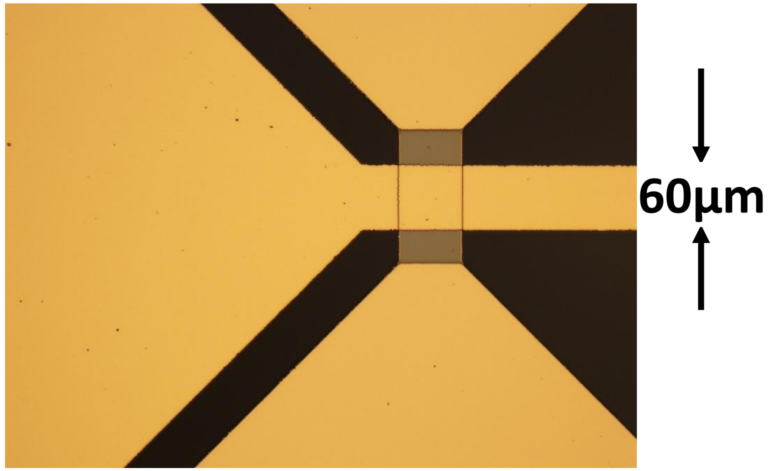
JUNO：PPO放射性控制，精度可到0.2~0.4 ppt

Charge tile

- Developed by IHEP and IME
- Charge will be collected on arrays of strips fabricated onto low background dielectric wafers (baseline is silica)
  - Self-supporting/no tension
  - Built-on electronics (on back)
  - Far fewer cables
  - Ultimately more reliable, lower noise, lower activity



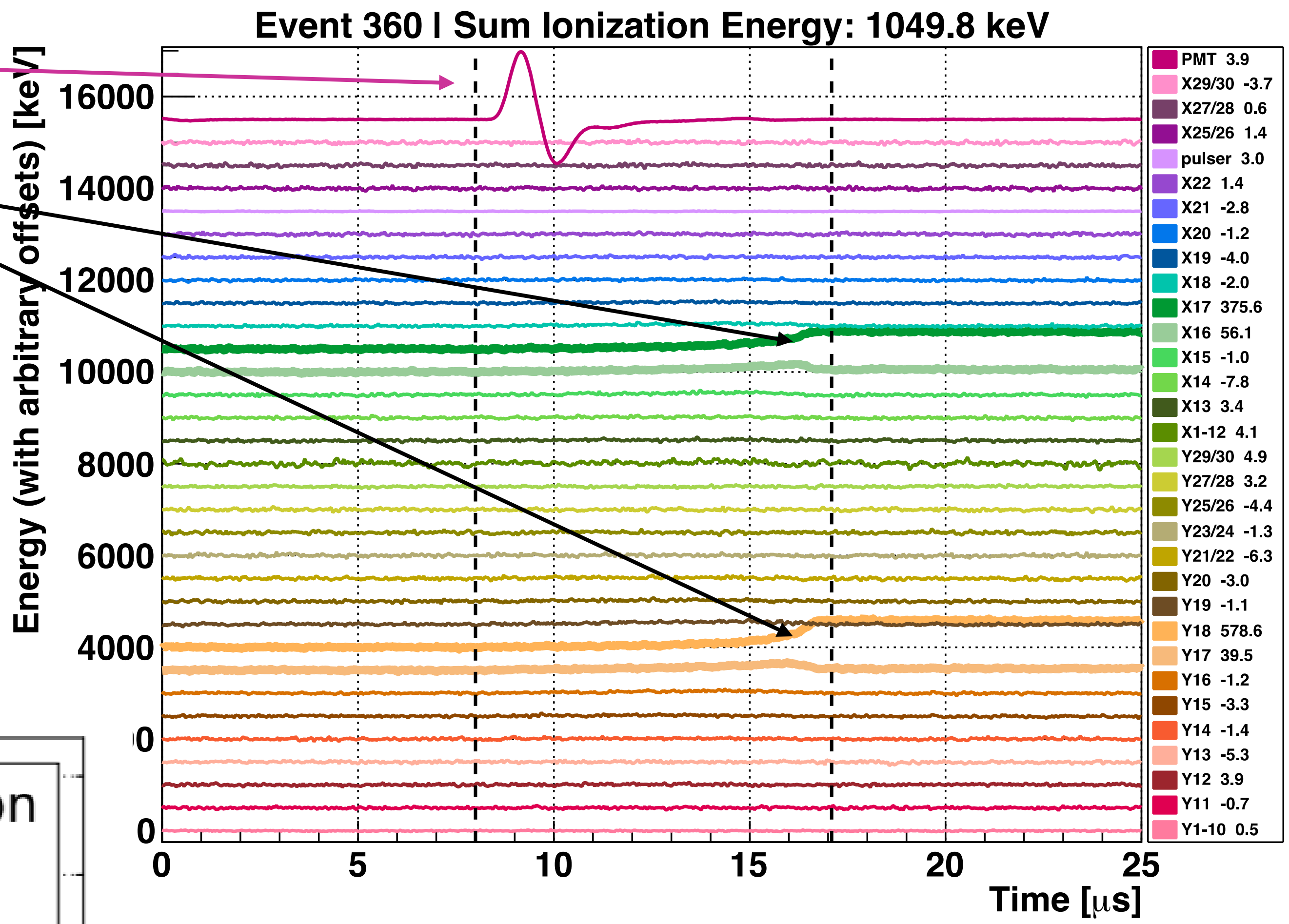




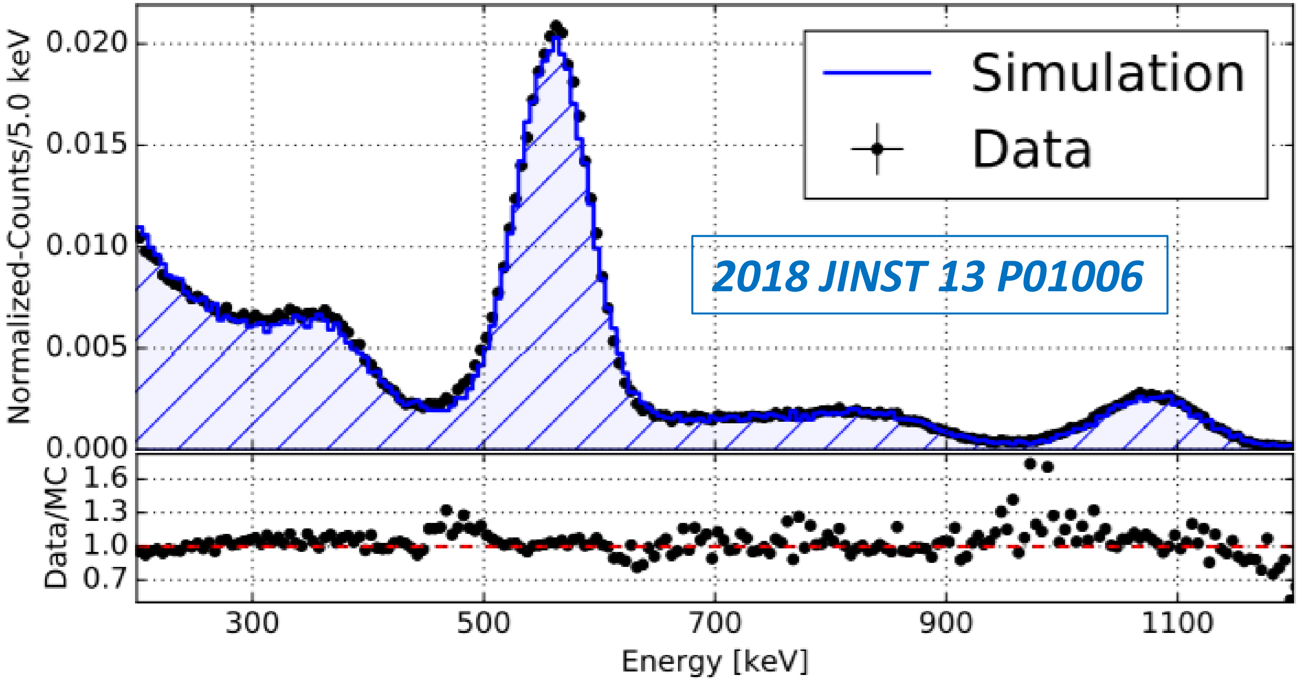
Max metallization cover with min capacitance

PMT (trigger)

Charge collection

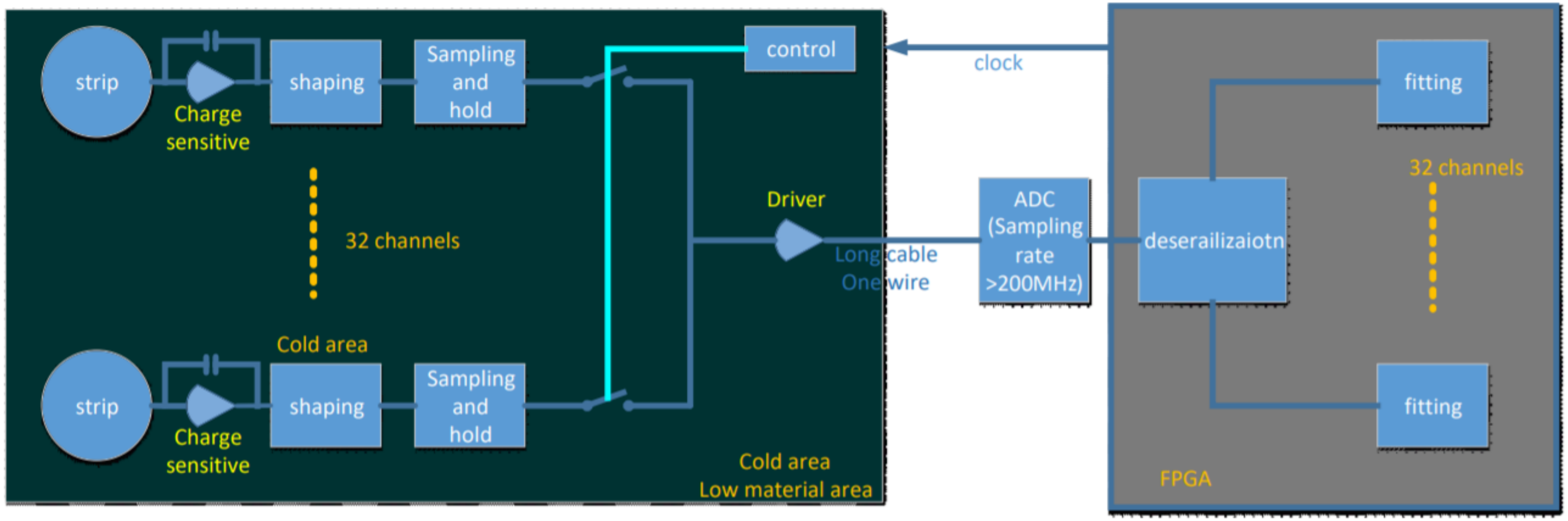


Stanford LXe test setup



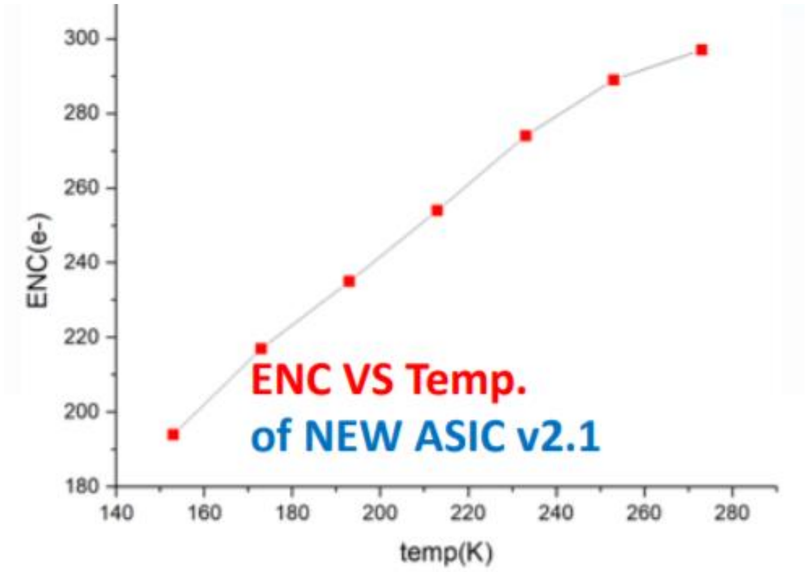
- Charge only resolution at 570 keV: 5.5%
- Consistent with the intrinsic resolution of liquid xenon

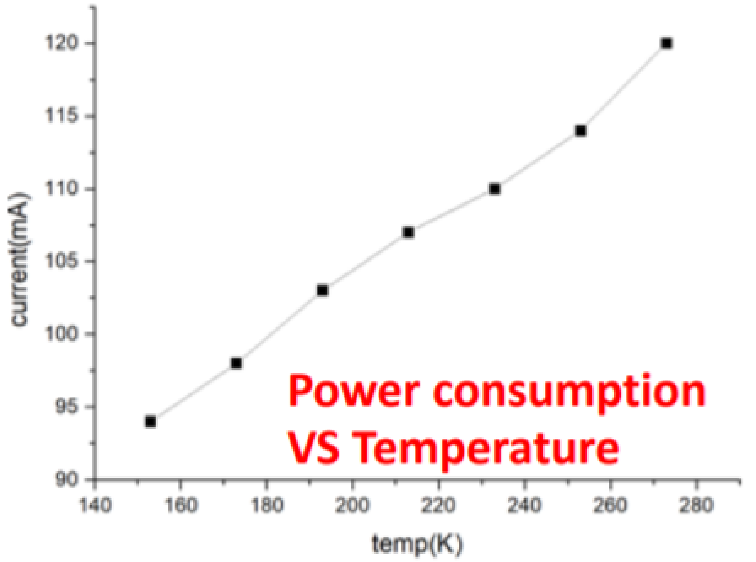
Charge readout ASIC at IHEP



IHEP ASIC readout design for nEXO

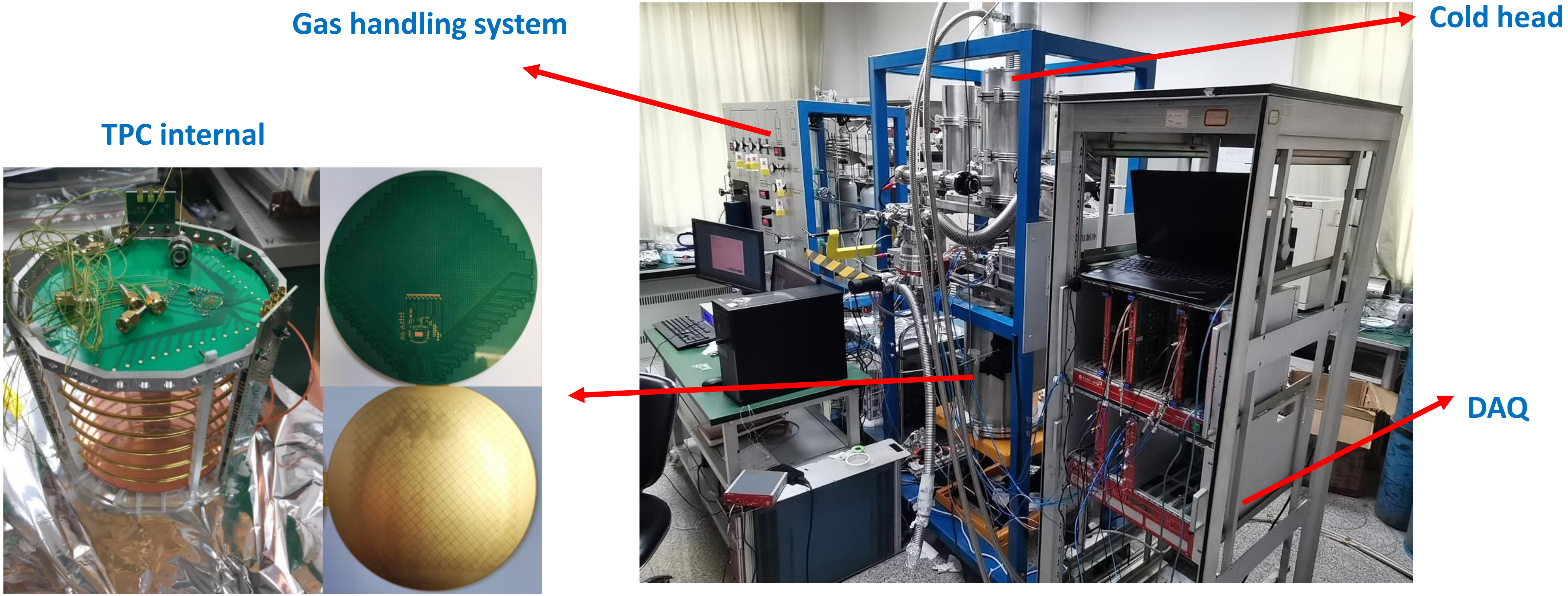
- **Analog serial readout ASIC**
- **32 channels per chip**
- **Low background: no extra decoupling capacitors on the board**





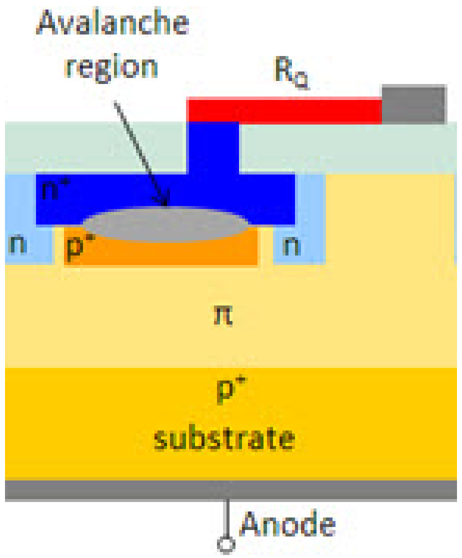
ENC down to 190 e- at 160 K

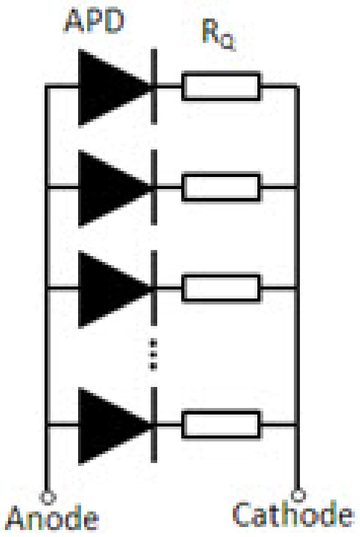
IHEP LXe Test Setup for Charge Tile & ASIC Readout

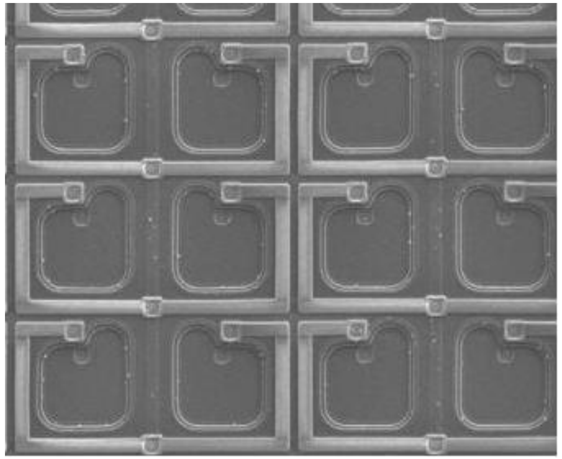


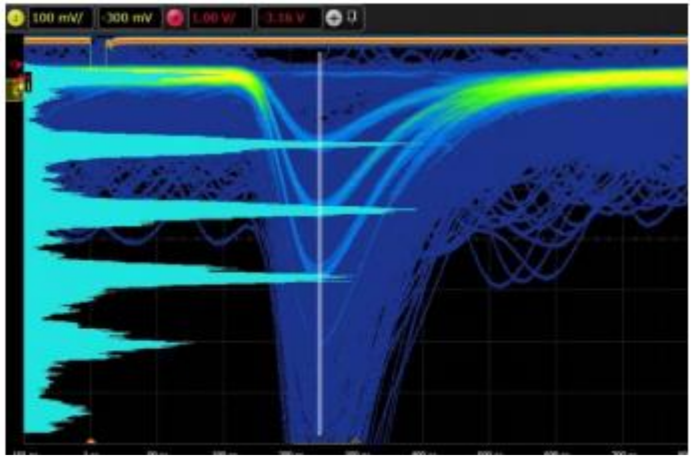
- Major upgrades in both charge and light readout ongoing in the past several month
- Test charge tile and understand the signal shape
- Characterize ASIC performance in LXe

Silicon photomultiplier (SiPM) for light readout









- Parallel connected arrays of SPADs operated in Geiger mode
- Passive quenching resistor stops avalanche
- “Binary” output from each pixel
- Final output is the summation of all fired pixels

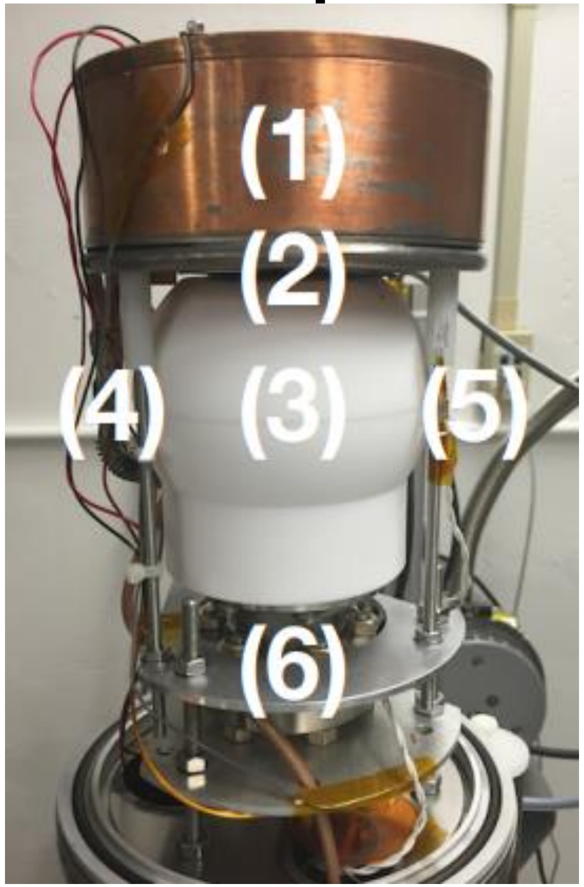
Pros

- High gain (~1e6)
- Low radioactivity
- Immune to magnetic field
- compact

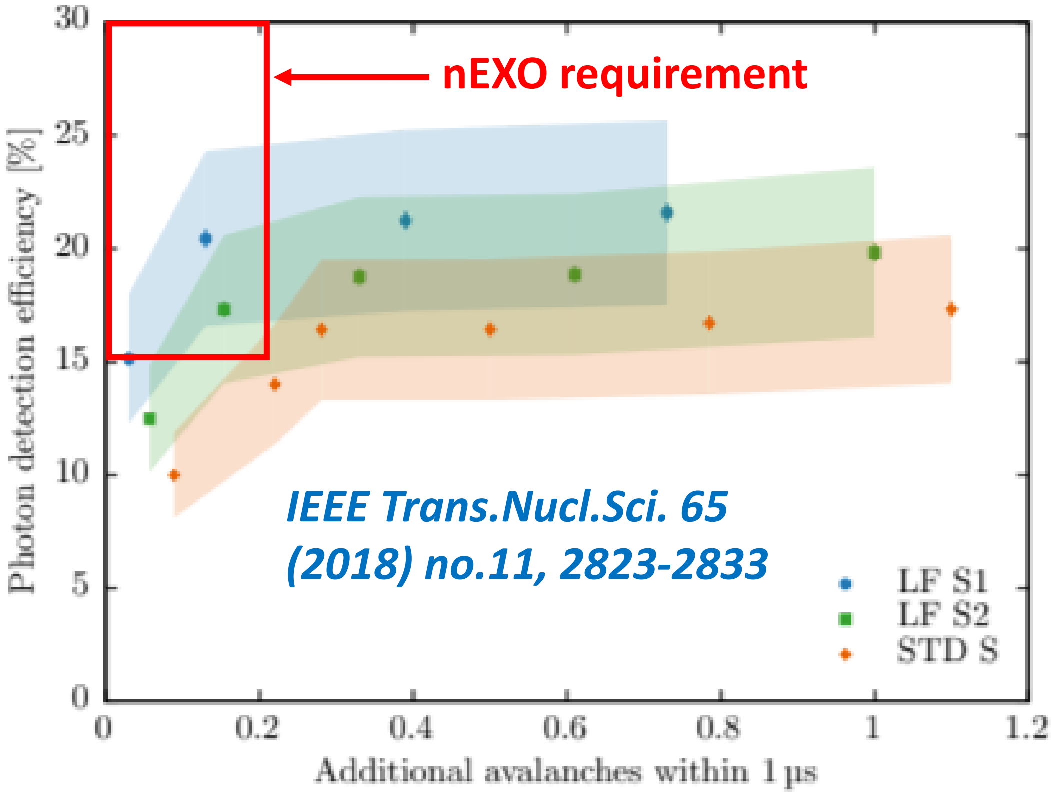
Cons

- High dark rate (drastically reduced at cryogenic temperature though)
- After pulse and cross talk
- Large capacitance per unit area

SiPM performance characterization



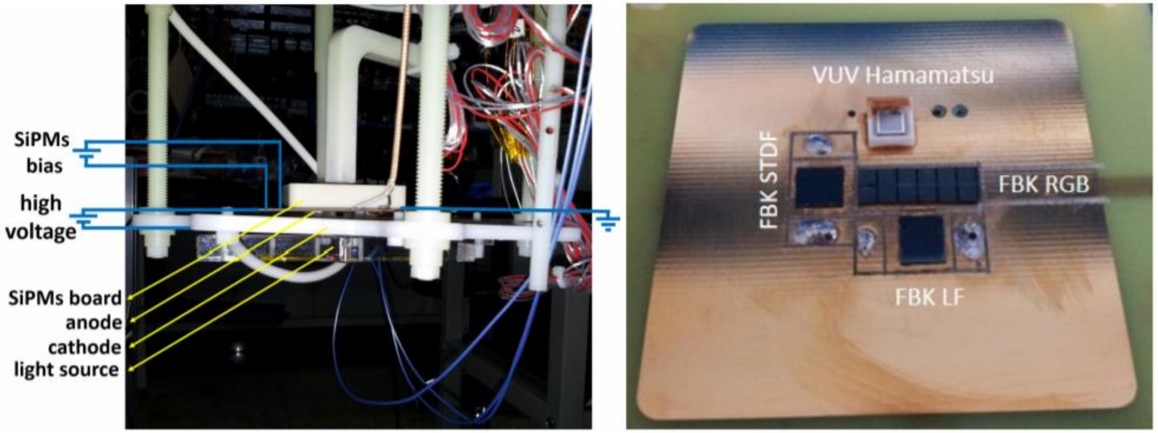
1. Detector chamber
2. Bandwidth filter
3. Reflector
4. cooling gas tube
5. LED
6. Xe scintillation light source

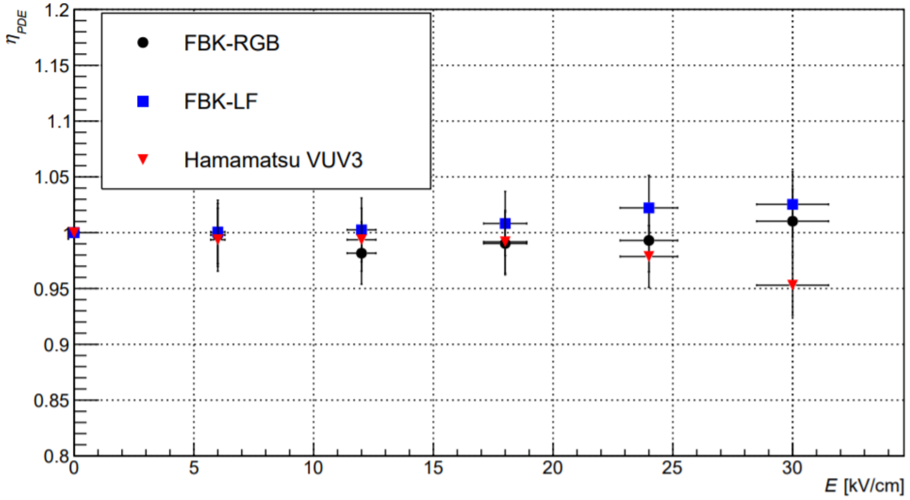


- Work closely with FBK to develop SiPM satisfying nEXO specifications
- Already found one candidate satisfying the minimum requirement

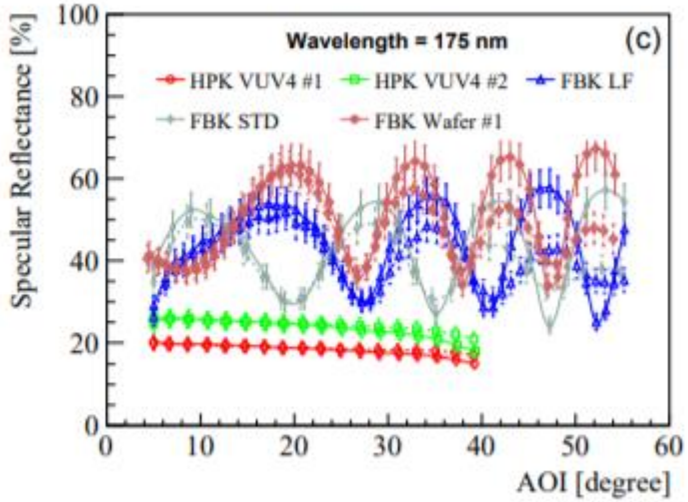
SiPM R&D

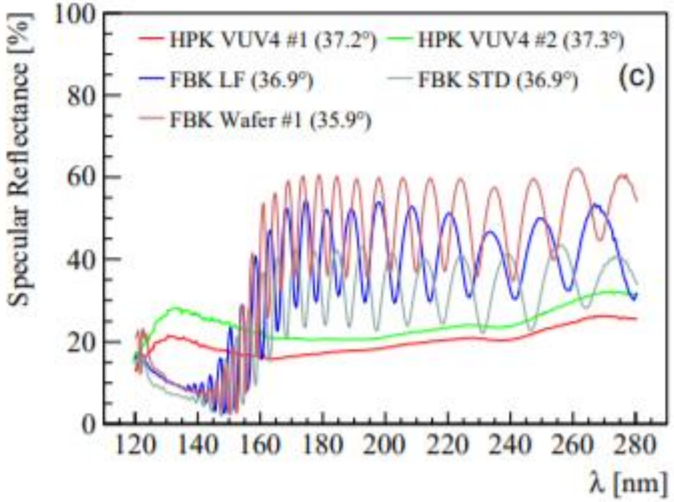
JINST 13 (2018) 09, T09006





IEEE Trans.Nucl.Sci. 67 (2020) 12, 2501-2510





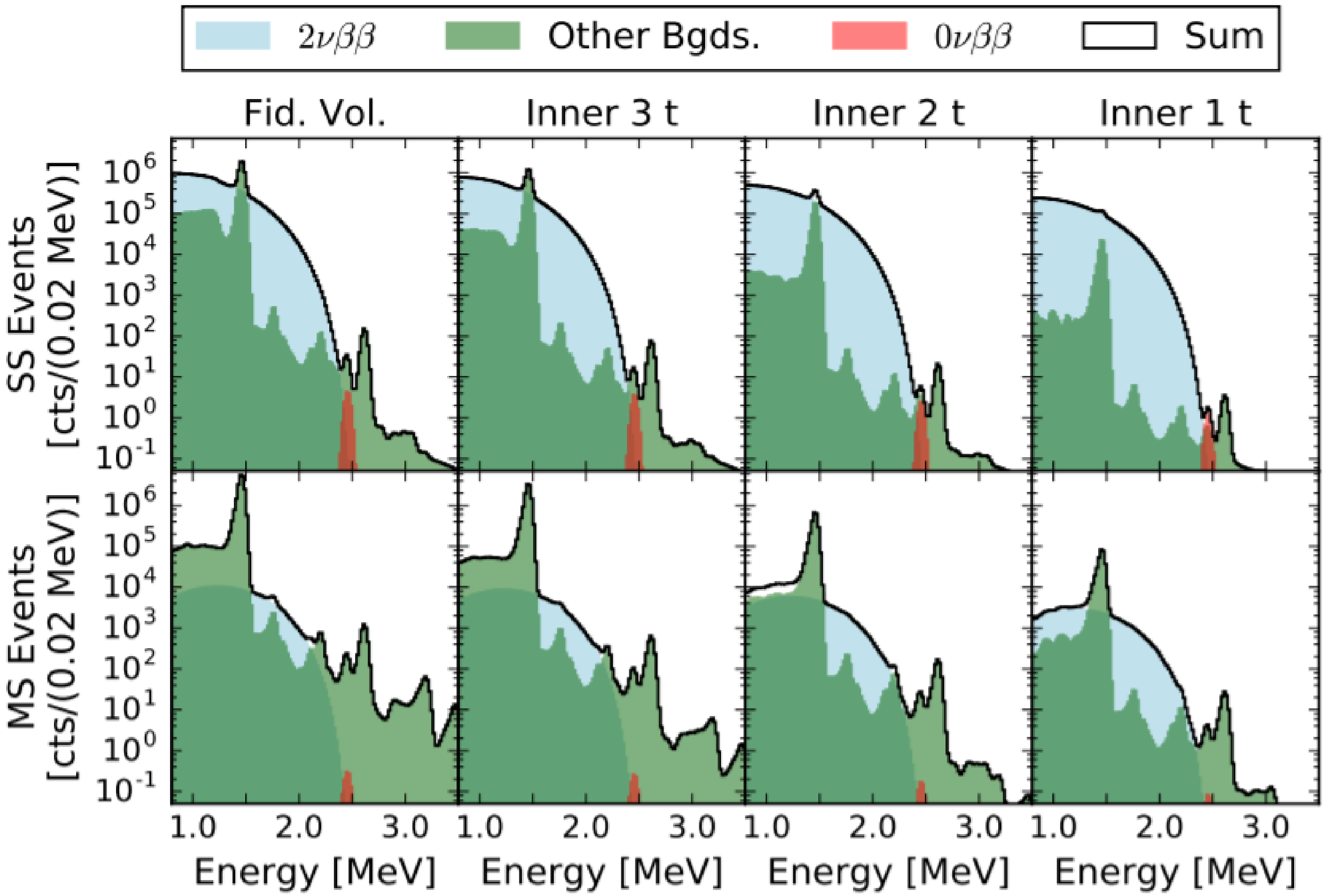
Material assay and background model

Material	Supplier	Method	K [ppb]	Th [ppt]	U U [ppt]	^{60}Co [μBq/kg]
Copper	Aurubis	ICPMS/Ge/GDMS	<0.7	0.13±0.06	0.26±0.01	<3.2
Sapphire	GTAT	NAA	9.5±2.0	6.0±1.0	<8.9	-
Quartz	Heraeus	NAA	0.55±0.04	<0.23	<1.5	-
SiPM	FBK	ICPMS/NAA	<8.7	0.45±0.12	0.86±0.05	-
Epoxy*	Epoxies Etc.	NAA	<20	<23	<44	-
Kapton*	Nippon Steel Cables	ICPMS	-	<2.3 pg/cm^2	4.7±0.7 pg/cm^2	-
HFE*	3M HFE-7000	NAA	<0.6	<0.015	<0.015	-
Carbon Fiber	Mitsubishi Grafil	Ge	550±51	58±19	19±8	-
ASICs	BNL	ICPMS	-	25.7±0.7	13.2±0.1	
Titanium	TIMET	Ge	<3.3	57±5	<7.3	-
Water	SNOLAB	Assumed	<1000	<1	<1	-

Component	Nuclides Simulated	Material	Mass or Surface Area
Outer Cryostat	^{238}U, ^{232}Th, ^{40}K	Carbon Fiber	1774 kg
Inner Cryostat	^{238}U, ^{232}Th, ^{40}K	Carbon Fiber	338 kg
Inner Cryostat Liner	^{238}U, ^{232}Th	Titanium	161.4 kg
HFE	^{238}U, ^{232}Th	HFE-7000	32700 kg
TPC Vessel	^{238}U, ^{232}Th	Copper	553.4 kg
Cathode	^{238}U, ^{232}Th	Copper	13.02 kg
Field Rings (FR)	^{238}U, ^{232}Th	Copper	73.2 kg
FR Support Leg	^{238}U, ^{232}Th, ^{40}K	Sapphire	0.94 kg
FR Support Spacer	^{238}U, ^{232}Th, ^{40}K	Sapphire	2.21 kg
SiPM	^{238}U, ^{232}Th, ^{40}K	SiPM	4.69 kg
SiPM Support	^{238}U, ^{232}Th	Copper	136.4 kg
SiPM Module Backing	^{238}U, ^{232}Th	Quartz	3.2 kg
SiPM Electronics	^{238}U, ^{232}Th	ASICs	2.04 kg
SiPM Glue	^{238}U, ^{232}Th, ^{40}K	Epoxy	0.12 kg
SiPM Cables	^{238}U, ^{232}Th	Kapton	1×10^4 cm^2
Charge Module Cables	^{238}U, ^{232}Th	Kapton	1×10^4 cm^2
Charge Module Electronics	^{238}U, ^{232}Th	ASICs	1.0 kg
Charge Module Glue	^{238}U, ^{232}Th, ^{40}K	Epoxy	0.35 kg
Charge Module Support	^{238}U, ^{232}Th	Copper	11.7 kg
Charge Module Backing	^{238}U, ^{232}Th	Quartz	0.94 kg
TPC LXe Volume	^{137}Xe, ^{222}Rn, $2\nu\beta\beta$, $0\nu\beta\beta$	Xenon	4038 kg
Outer LXe Volume	^{137}Xe, ^{222}Rn, $2\nu\beta\beta$, $0\nu\beta\beta$	Xenon	1071 kg

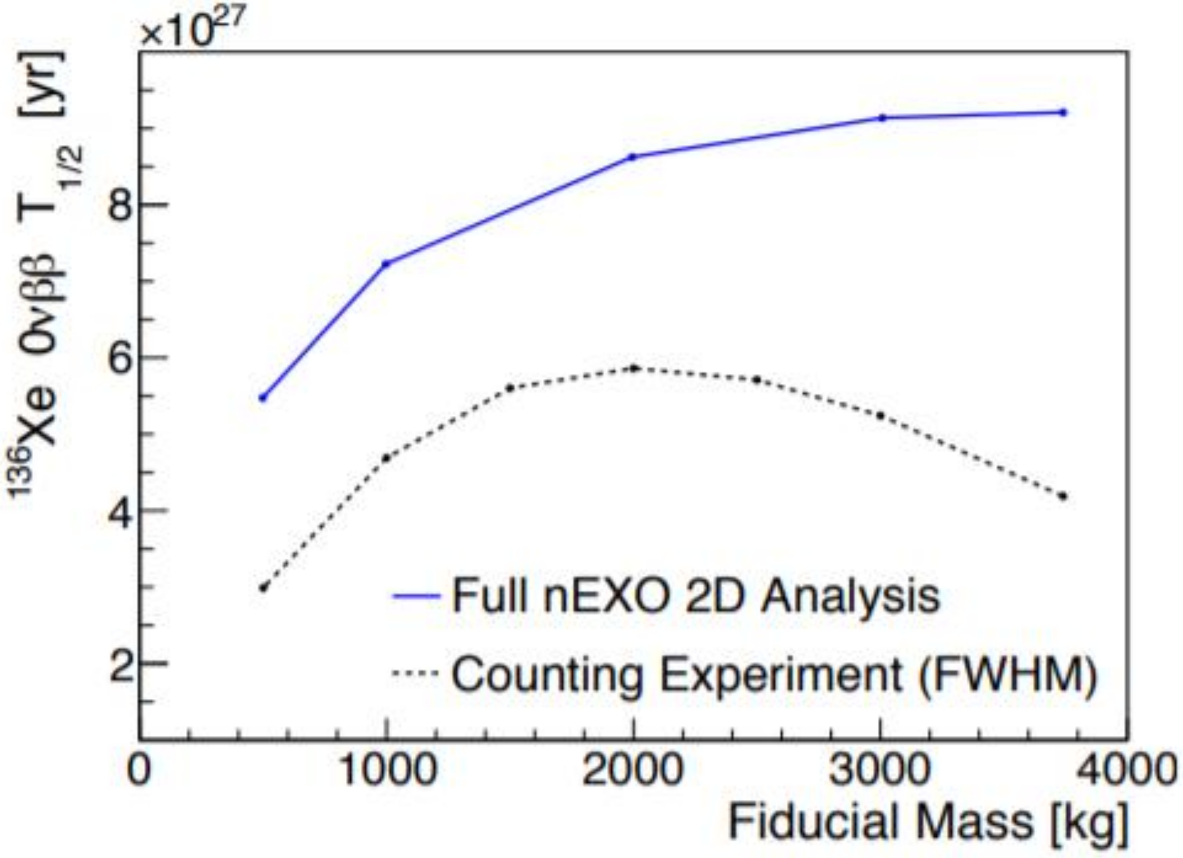
- Extensive radio-assay and background control program
- Comprehensive background modeling for sensitivity evaluation

Phys.Rev.C 97 (2018) 6, 065503



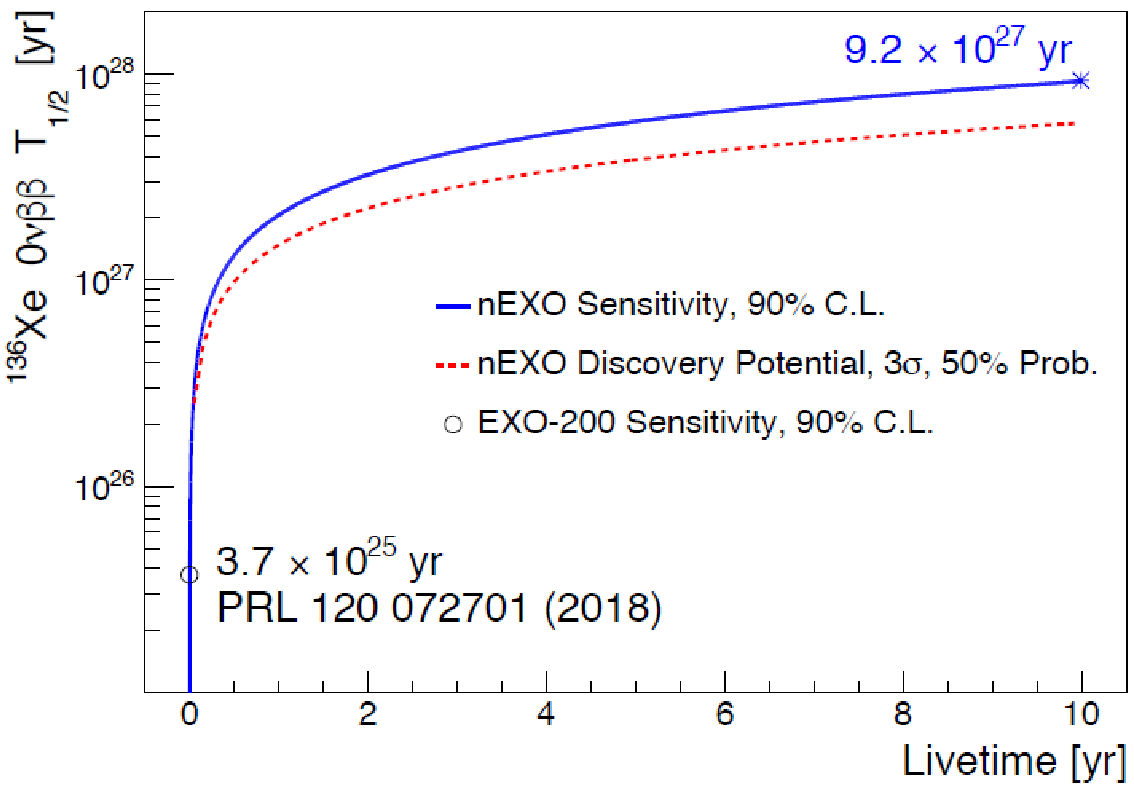
Assumed 0vbb half-life 5.7e27 yr

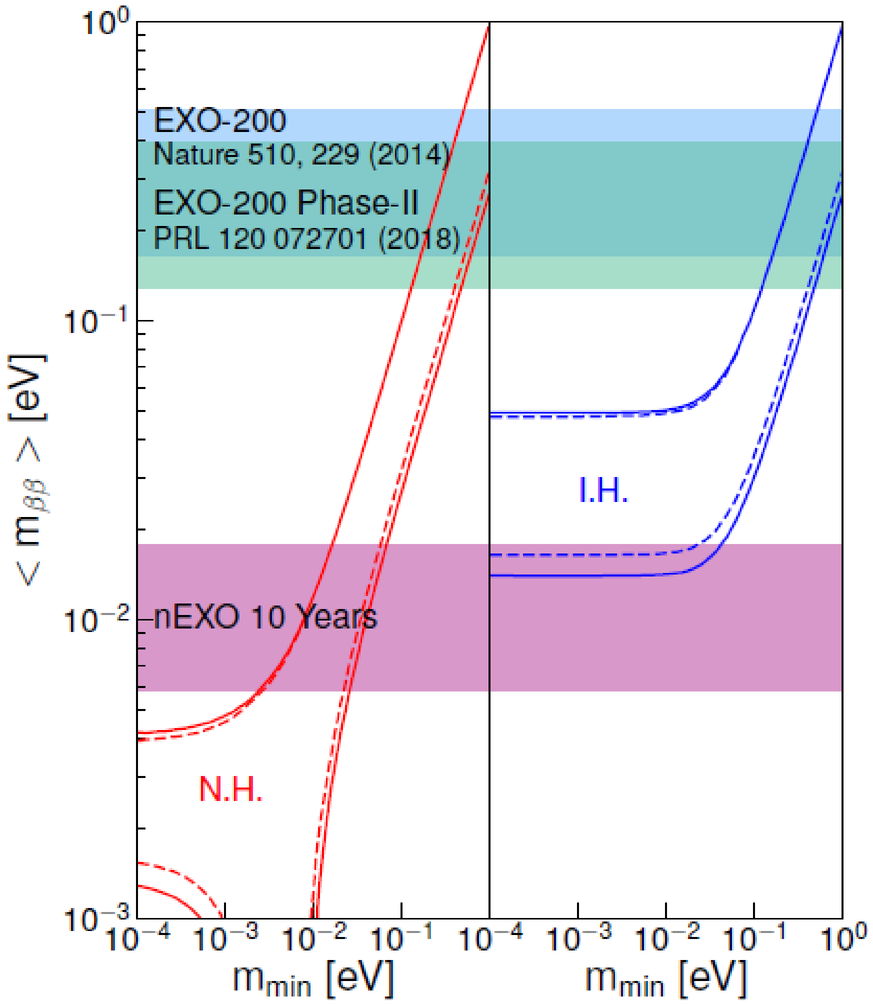
Multi-dimensional Fit vs Counting Experiment



Multi-variate analysis maximize the sensitivity to 0vbb than simple counting experiment.

Ultimate sensitivity





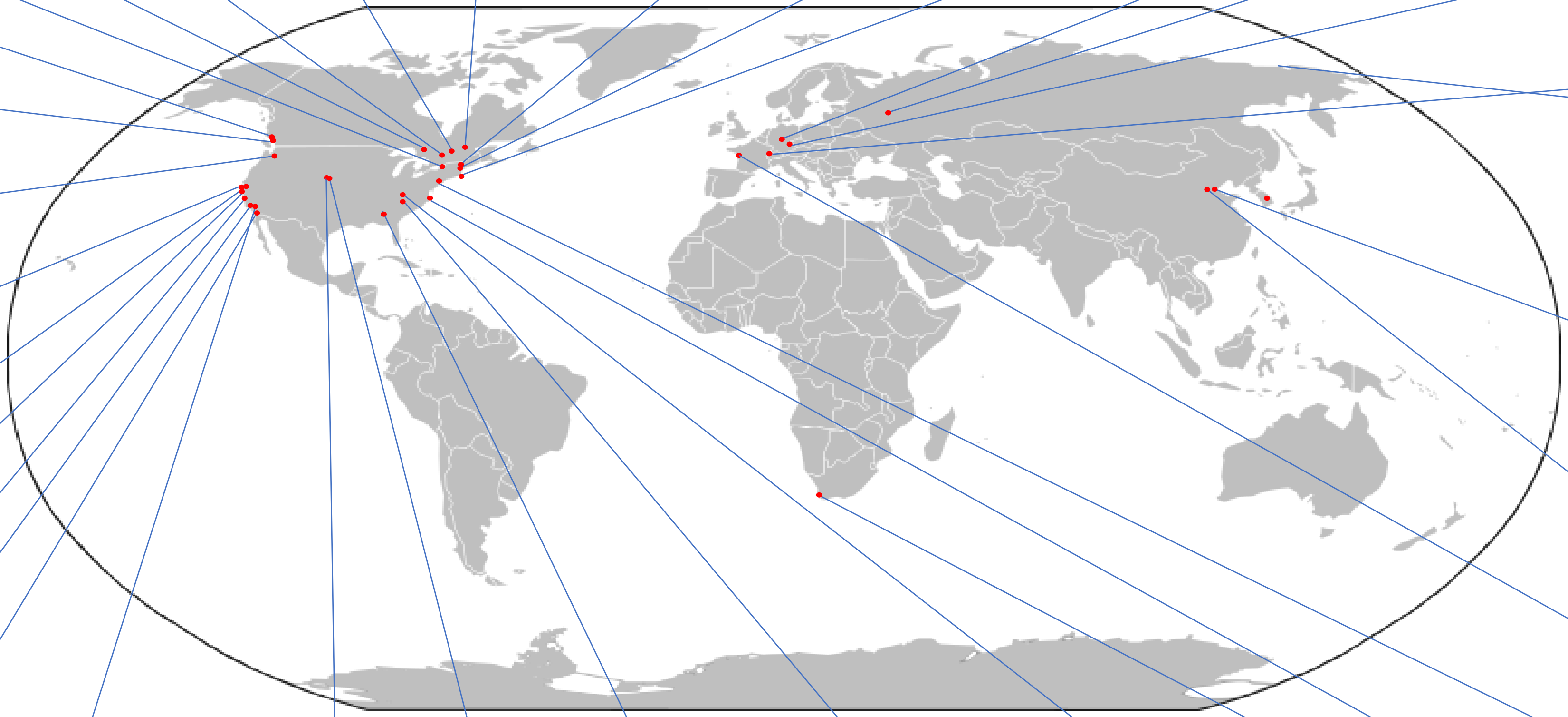
* **20-30% additional improvement with machine learning discriminator *JINST* 14 (2019) 09, P09020**
* **New sensitivity evaluation with improved radio-assay data, detector design and analysis will be released soon!**

nEXO publications (since 2018)

- **Reflectivity of VUV-sensitive Silicon Photomultipliers in Liquid Xenon,** M. Wagenpfeil, et al, arXiv:2104.07997 (2021)
- **Event Reconstruction in a Liquid Xenon Time Projection Chamber with an Optically-Open Field Cage,** T. Stiegler, et al (nEXO), NIMA 1000, 165239 (2021)
- **Reflectance of Silicon Photomultipliers at Vacuum Ultraviolet Wavelengths,** P. Lv, et al (nEXO) IEEE Trans. Nucl. Sci. 67, 2501 (2020)
- **Reflectivity and PDE of VUV4 Hamamatsu SiPMs in liquid xenon,** P. Nakarim, et al (nEXO), JINST 15, P01019 (2020)
- **Measurements of electron transport in liquid and gas Xenon using a laser-driven photocathode,** O. Njoya, et al., (nEXO), NIM A 972, 163965 (2020)
- **Characterization of the Hamamatsu VUV4 MPPCs for nEXO**, G. Gallina, et al. (nEXO), NIMA 940, 371 (2019)
- **Simulation of charge readout with segmented tiles in nEXO,** Z. Li, et al., (nEXO), JINST 14, P09020 (2019)
- **Study of Silicon Photomultiplier Performance in External Electric Fields, X.L. Sun,** et al., (nEXO), JINST 13, T09006 (2018) (arXiv:1807.03007) (nEXO Collaboration)
- **VUV-sensitive Silicon Photomultipliers for Xenon Scintillation Light Detection in nEXO,** IEEE Transactions on Nuclear Science 1 (2018) (arXiv:1806.02220)(nEXO Collaboration)
- **nEXO Pre-Conceptual Design Report,** arXiv:1805.11142v2 (nEXO Collaboration)
- **Characterization of an Ionization Readout Tile for nEXO,** JINST 13, P01006 (2018) (arXiv: arXiv:1710.05109v1)(nEXO Collaboration)
- **Sensitivity and Discovery Potential of nEXO to Neutrinoless Double Beta Decay,** Physical Review C 97, 065503 (2018) (arXiv: arXiv:1710.05075v1)(nEXO Collaboration)
- **Imaging individual Ba atoms in solid xenon for barium tagging in nEXO,** Nature 569, 203 (2019) (arXiv:1806.10694)(nEXO Collaboration)

nEXO

>150 scientists, 34 institutions in 8 countries on 4 continents



Laurentian University
Université Laurentienne

Carleton University

McGill

Université de Sherbrooke

UMass Amherst

Yale University

Brookhaven National Laboratory

FAU
Friedrich-Alexander Universität Erlangen-Nürnberg

ИТЭФ

Rensselaer

The University of British Columbia

TRIUMF

Pacific Northwest National Laboratory

Technical University of Munich
TUM

u b
Universität Bern

ibs Institute for Basic Science

Skyline College
Achieve

IHEP

Lawrence Livermore National Laboratory

IMECAS

SLAC National Accelerator Laboratory

Subatech

Stanford University

Drexel University

Caltech

UC San Diego

The University of California Irvine
Let there be light

Colorado School of Mines

Colorado State University

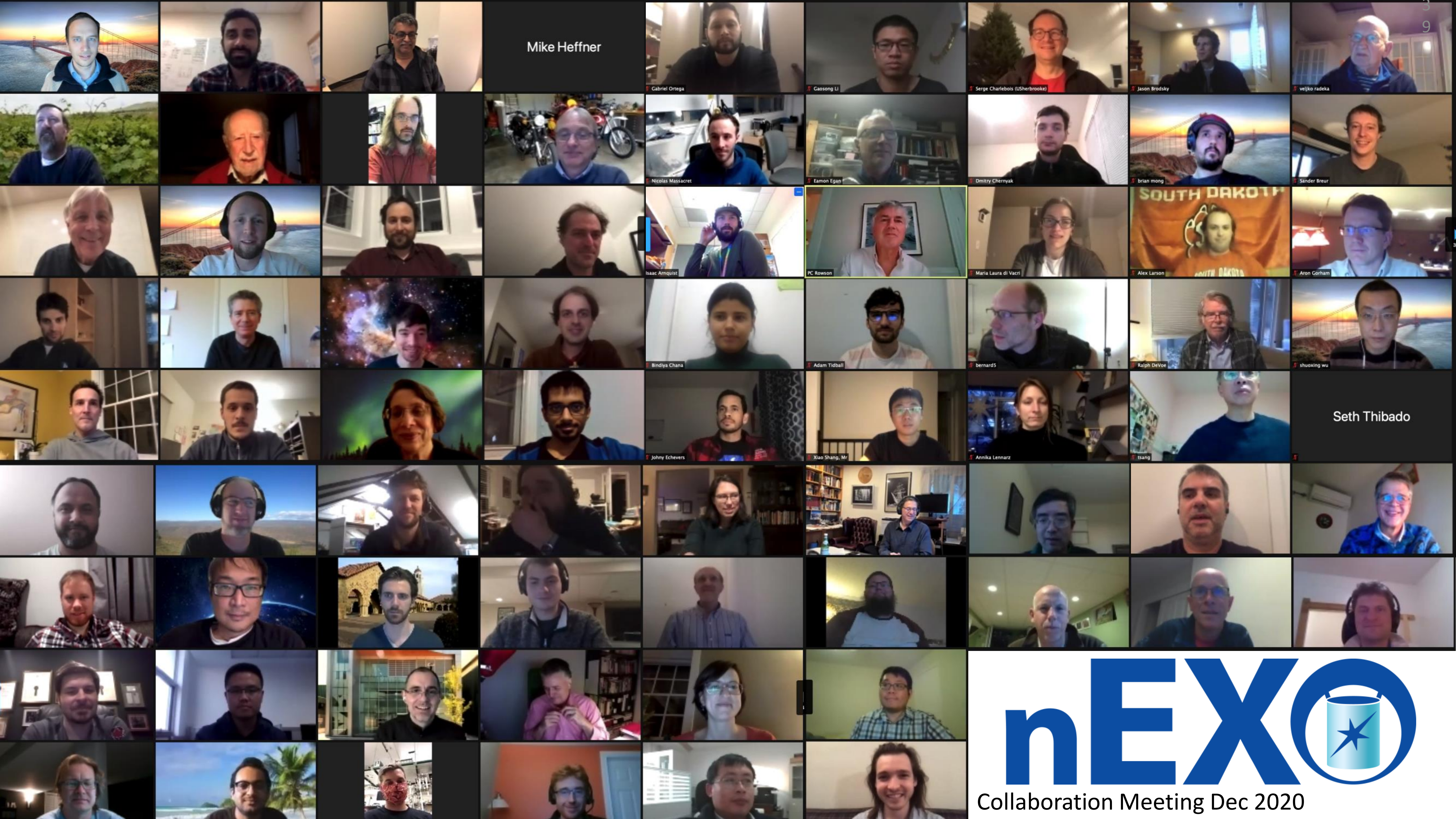
The University of Alabama
1831

Oak Ridge National Laboratory

University of Kentucky

University of the Western Cape
Respice Prospice

UNCW
University of North Carolina Wilmington



nEXO

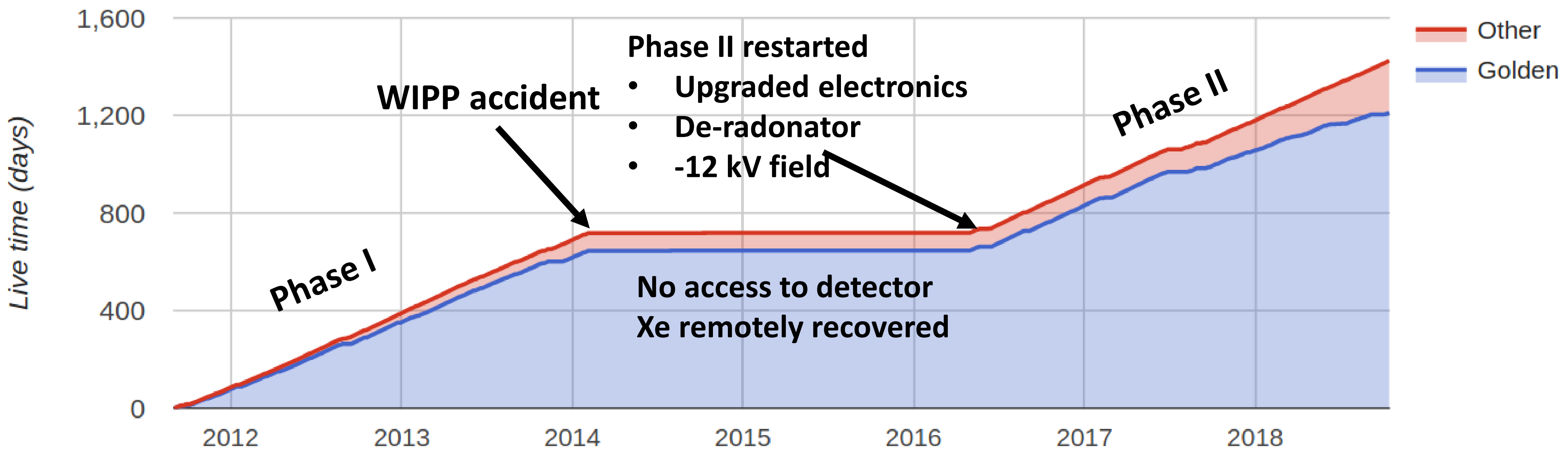
Collaboration Meeting Dec 2020

Summary

- EXO-200 demonstrated the liquid xenon TPC technology for $0\nu\beta\beta$ search
- nEXO is a discovery focused 0νββ experiment, designed to reach a sensitivity beyond ~10^{28} years, based on extensive R&D work
- US DOE has scheduled a DBD portfolio review in July 2021
- Observation of 0νββ always implies new physics!

Backup

EXO-200 timeline

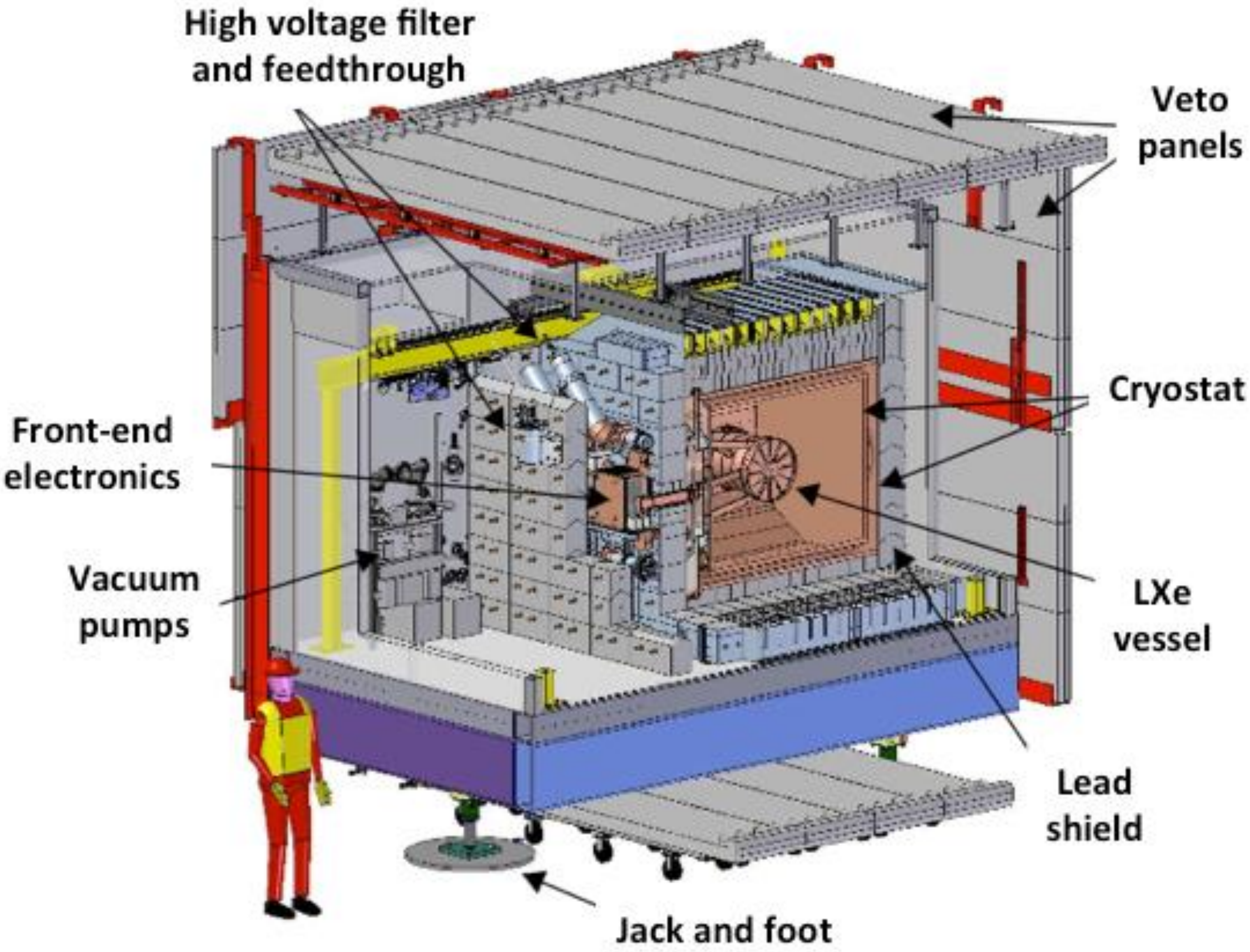


- Operation concluded in Dec 2018, with 1181.3 days of livetime
- Phase I from Sep 2011 to Feb 2014
  - Precise $2\nu\beta\beta$ measurement, *Phys. Rev. C* ***89****, 015502 (2013)*
  - Stringent limit for $0\nu\beta\beta$ search, *Nature* ***510****, 229 (2014)*
- Phase II operation begins on Jan 31, 2016 with system upgrades
  - First results with Phase II data from upgraded detector, *Phys. Rev. Lett.* ***120****, 072701 (2018)*
  - Final results with all exposure, ***Phys.Rev.Lett. 123 (2019) no.16, 161802***

EXO-200

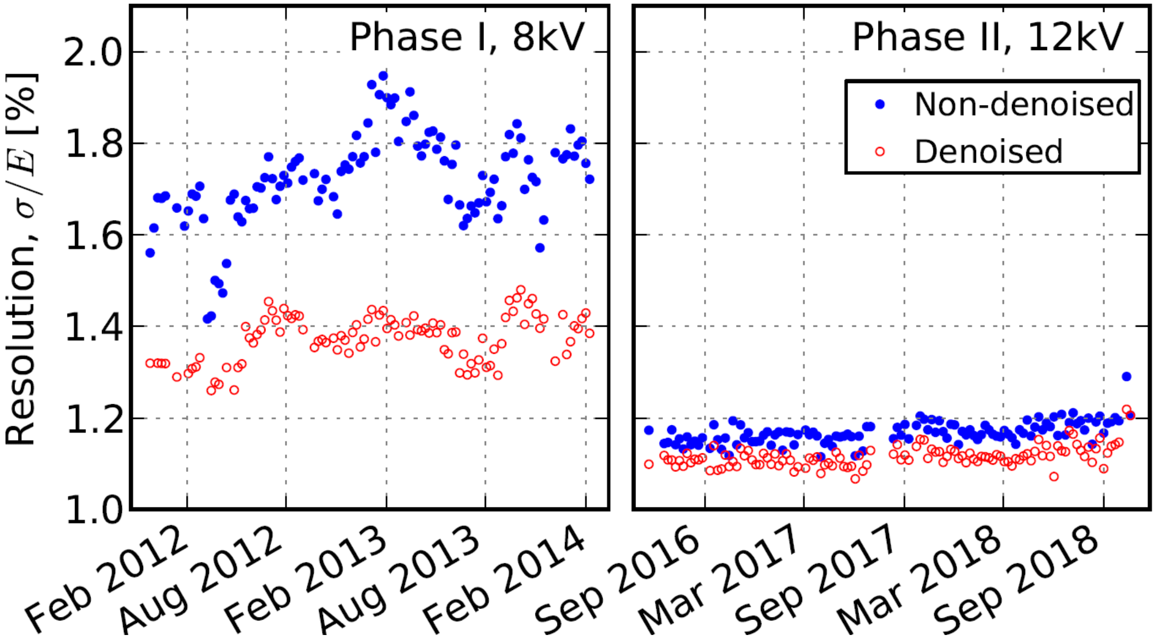
- Located at Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM, USA
- 1624 m.w.e. overburden
- LXe vessel surrounded by ~50 cm HFE-7000 cryofluid, housed in a double-wall cryostat
- ~25 cm passive lead shield in all directions
- Plastic scintillator panels for muon veto

Detector schematic:



Resolution improvement

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

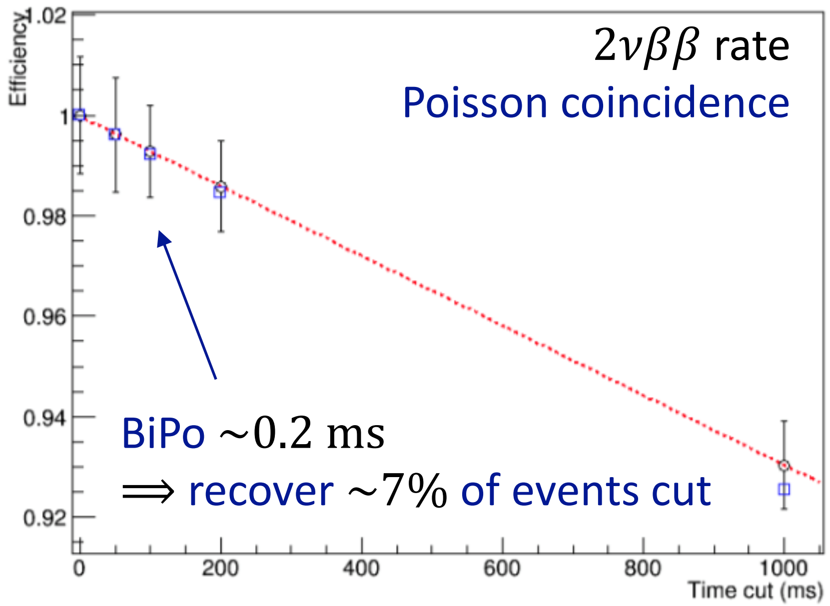


- Front end readout electronics
  - Reduce APD readout excess noise
- Cathode HV increased from -8 kV to -12 kV
- Software De-noising to optimize energy calibration
- De-noising adapted for Phase II as well in new analysis
- Proper Modeling of mixed collection/induction wire signals
- Energy resolution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

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

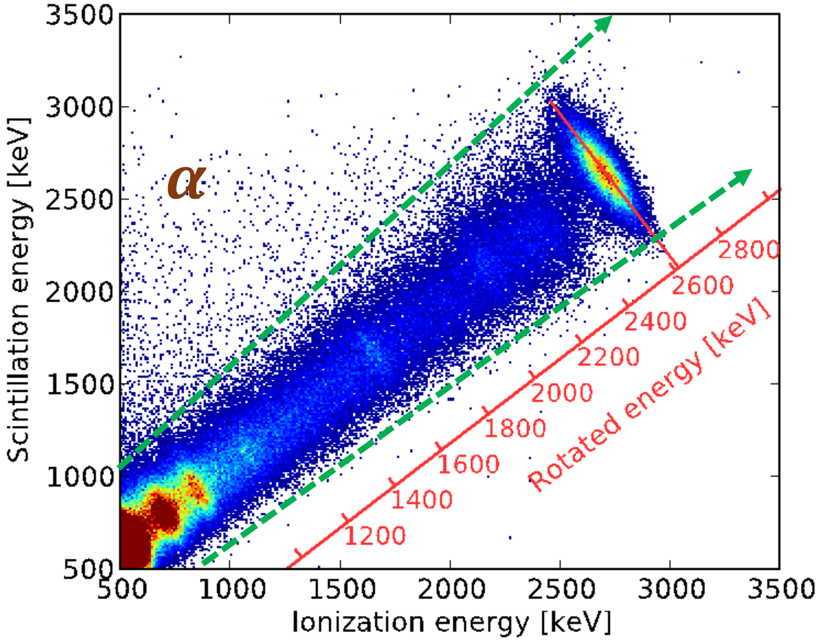
- Another major signal efficiency loss in previous analyses has been improved in addition to the 3D cut
- Event coincidence cut
  - Originally designed to remove time-correlated events, e.g. Bi-Po event, potential muon induced long-lived decay products …
  - Comprehensive cosmogenic background studies (*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)



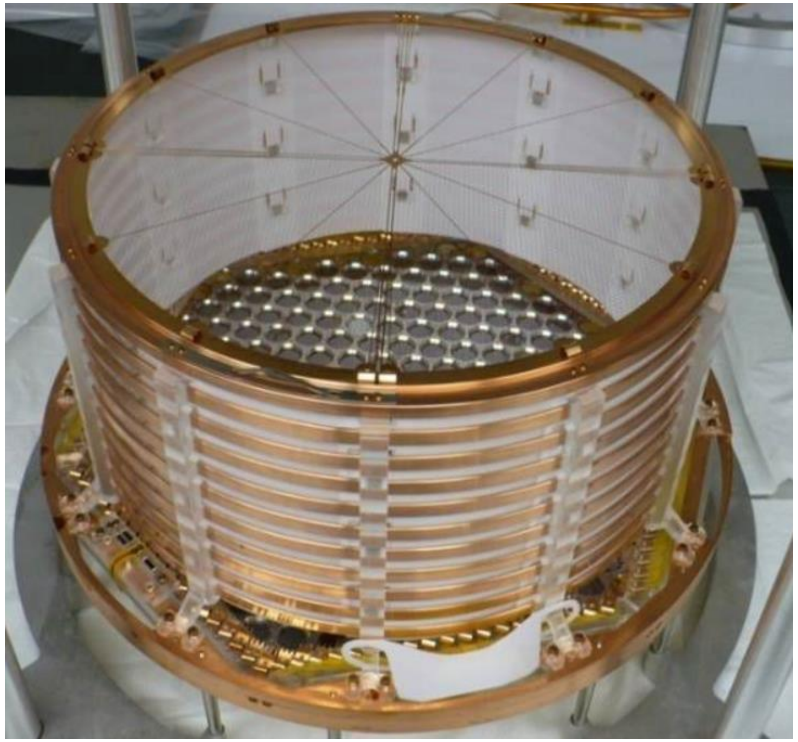
Light/charge Diagonal cut

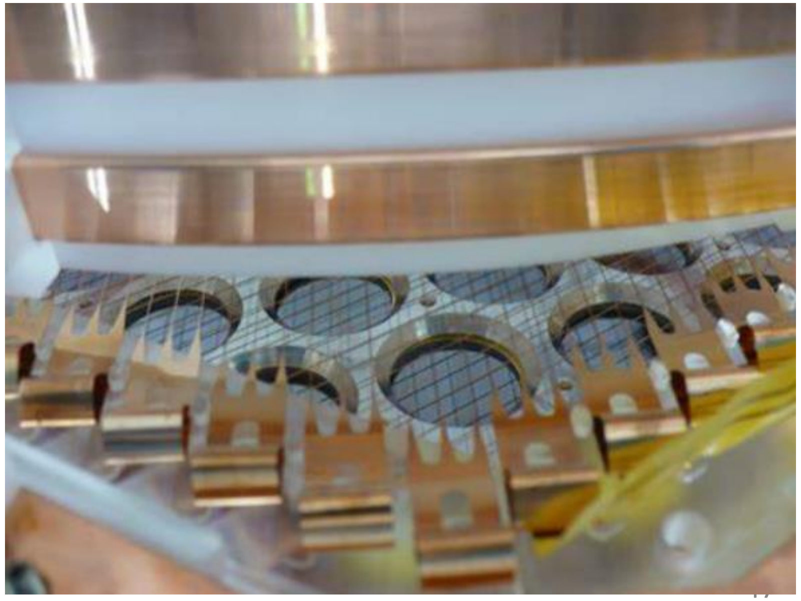
- Requires 2D light/charge energy calibration and good understanding of detector
- Light/charge ratio distributions validated by comparison between data/simulation using source and $2\nu\beta\beta$ data
- Powerful to reject α, as well as poorly reconstructed β/γ with anomalous light/charge ratio



Time Projection Chamber (TPC)

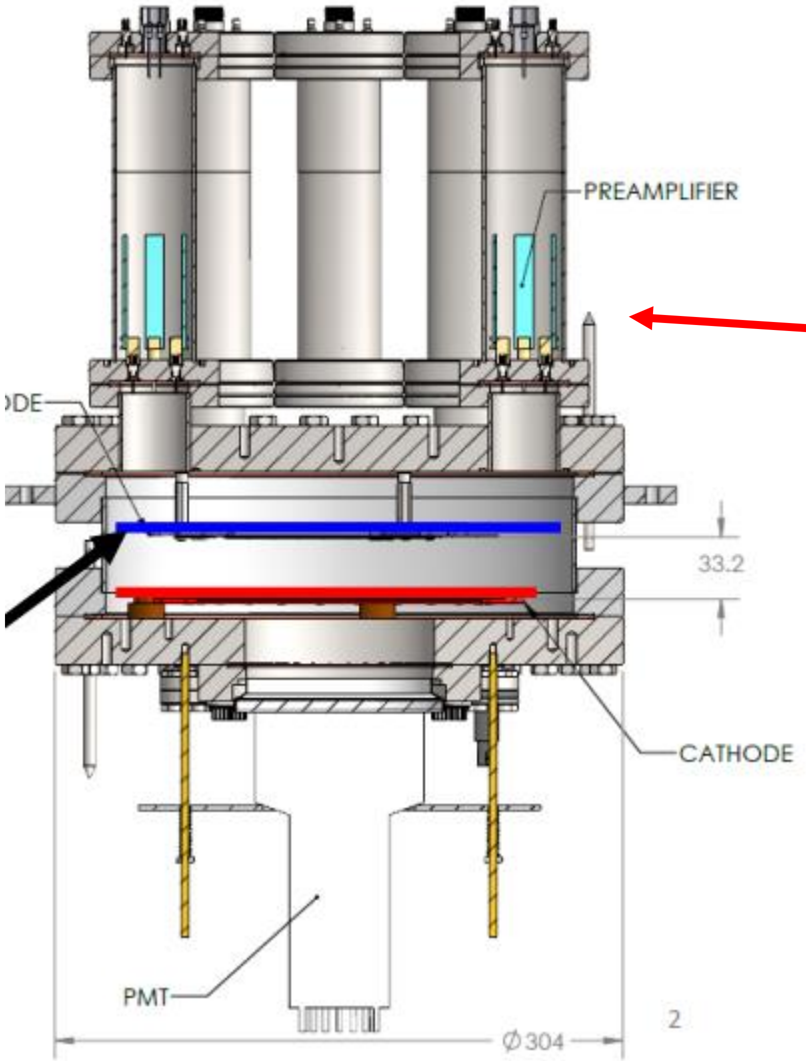
- Single phase liquid xenon TPC with ^{enr}Xe (80.6%)
- ~110 kg active volume
- Two back-to-back TPCs with cathode in the middle
- Scintillation light readout by APDs
- Ionization charge detected by two wire grids crossing at 60 degree
    - Collection plane (U-plane)
    - Induction (shielding) plane (V-plane)

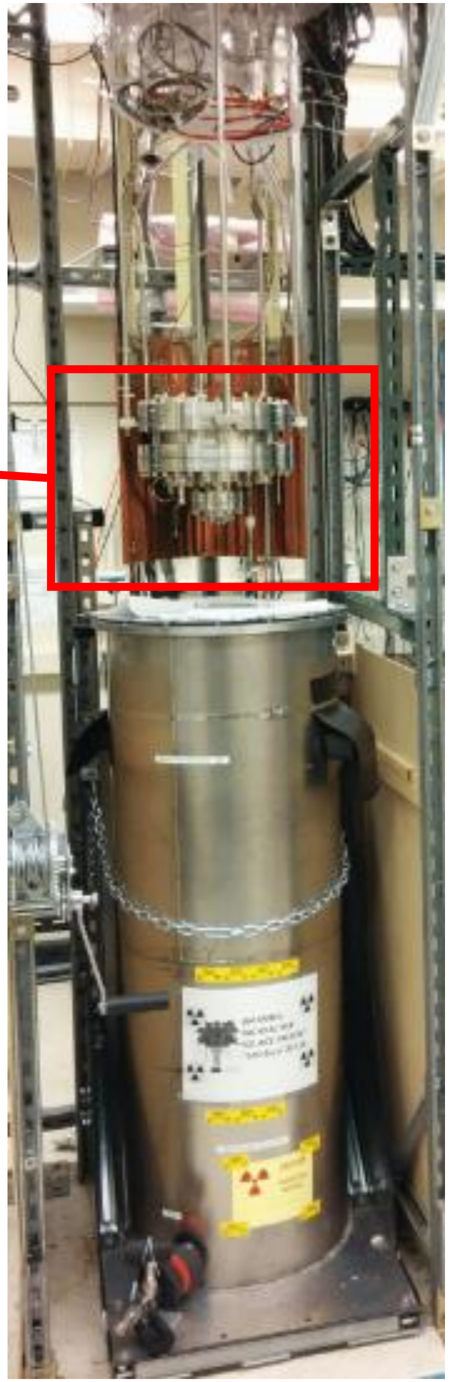




Test stand TPC

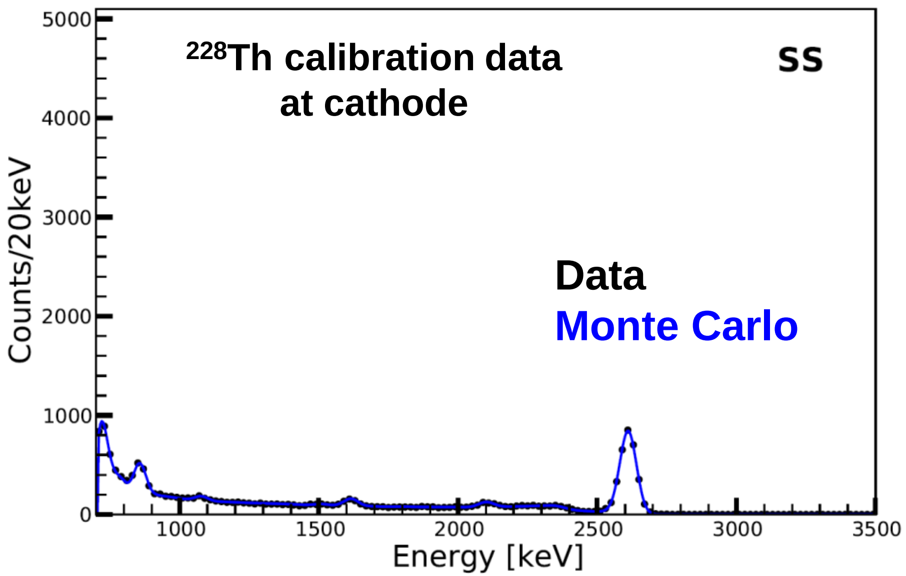
- 3.3 cm drift length
  - Operating at up to 1 kV/cm field
- Charge tile anode with
  - 30 X strips + 30 Y strips
- PMT for light detection
  - Low efficiency though
  - Used only for trigger

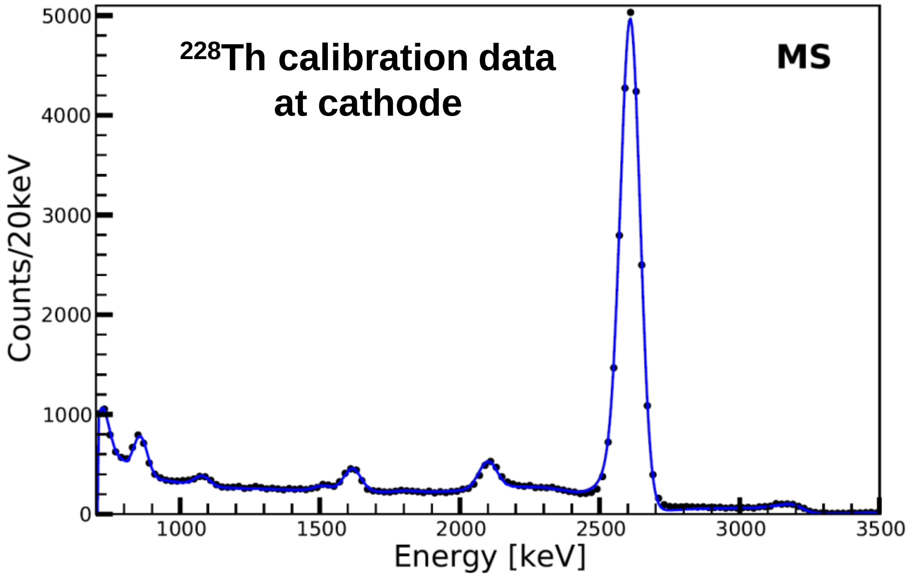




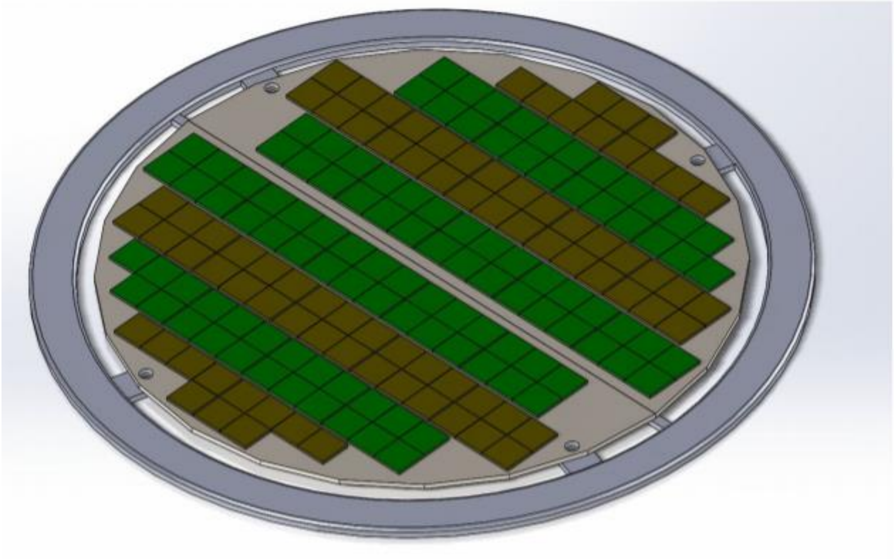
Relaxed 3D cut

- 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

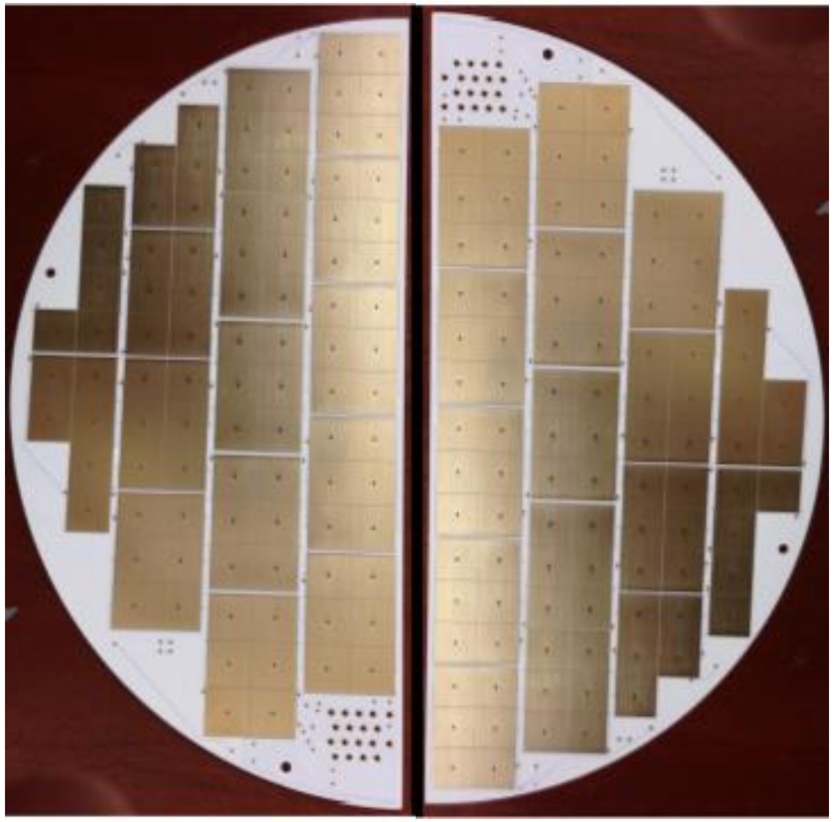




large area SiPM array Integration R&D



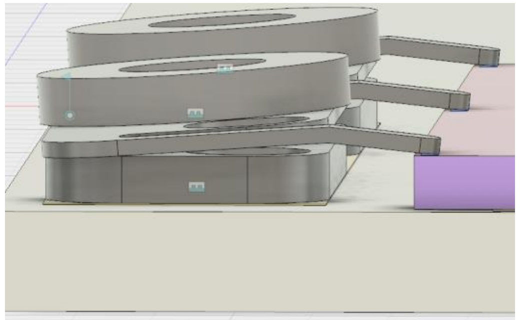
- A larger array with ~200 devices is being build
- New design optimized for light collection efficiency
- x10 increase in number of channels give rise to new technical difficulties
  - Individual DC bias for each channel with constraints in board size and low temperature
- Important to demonstrate 1% energy resolution goal with the nEXO-style charge-tile and SiPM readout
- Important R&D demonstration for DOE down selection!

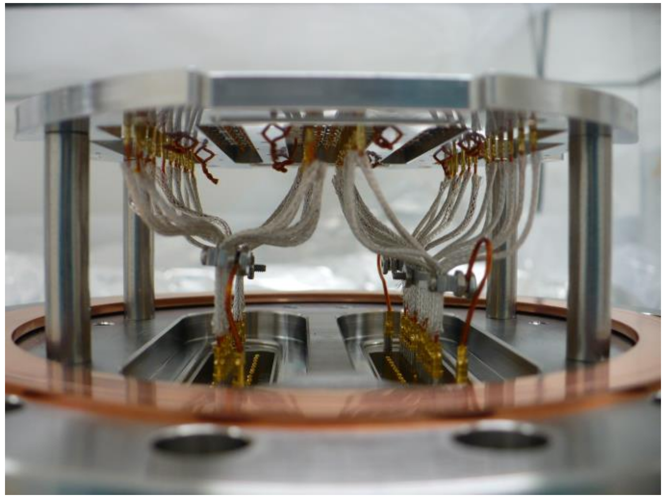


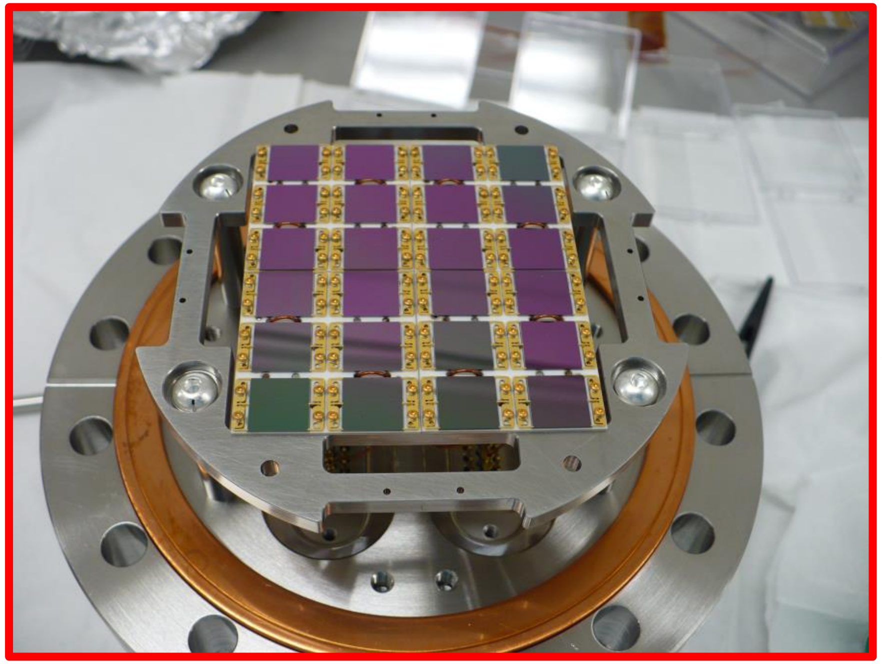
Ceramic carrier

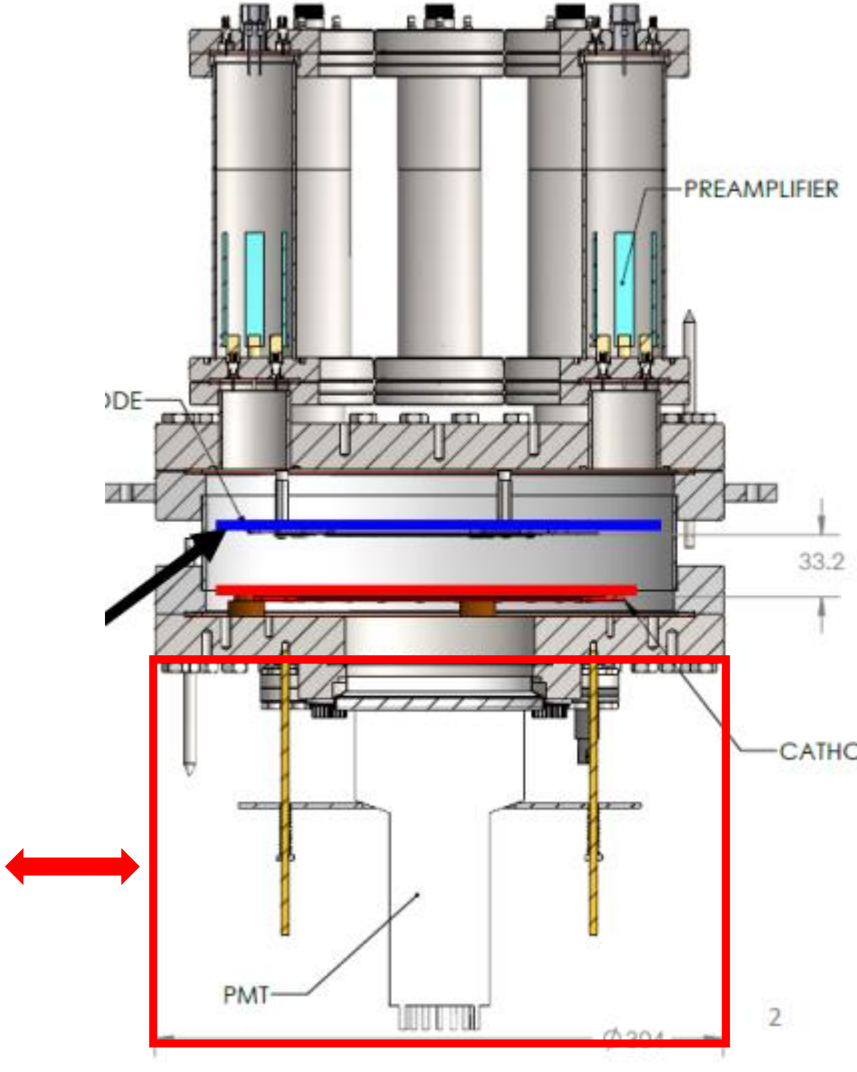
Integrate large area SiPM array to the test stand

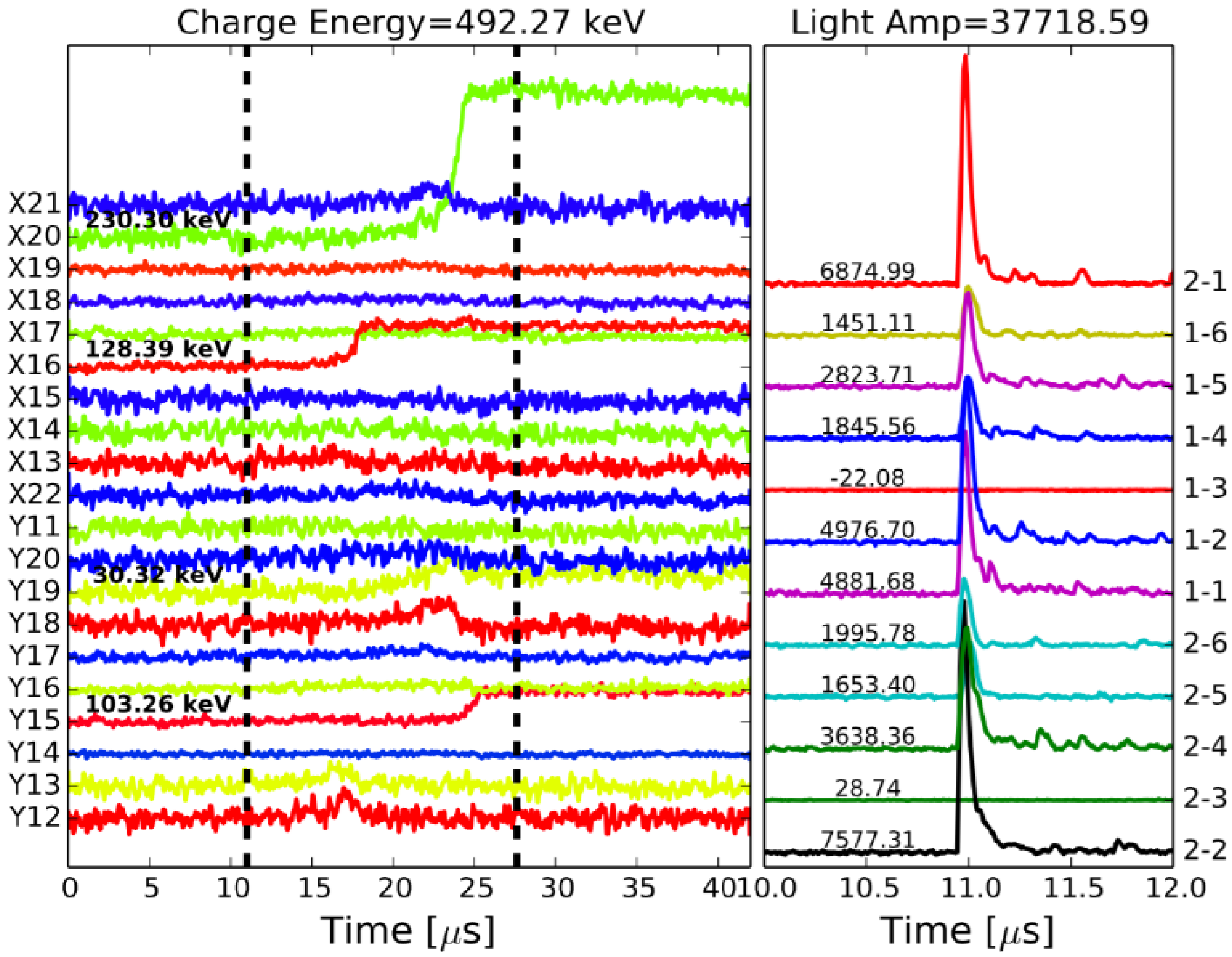
- Implemented an array of 24 SiPMs (24 cm^2) to replace the PMT in the test stand for light detection
  - The first close-to-nEXO-style detector
  - Improved light collection efficiency (5-10x)

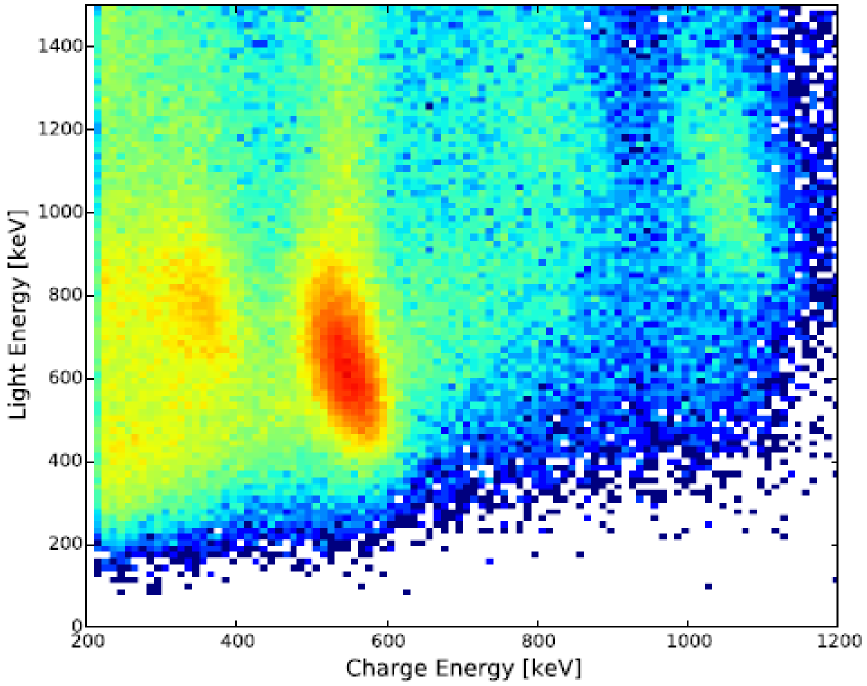


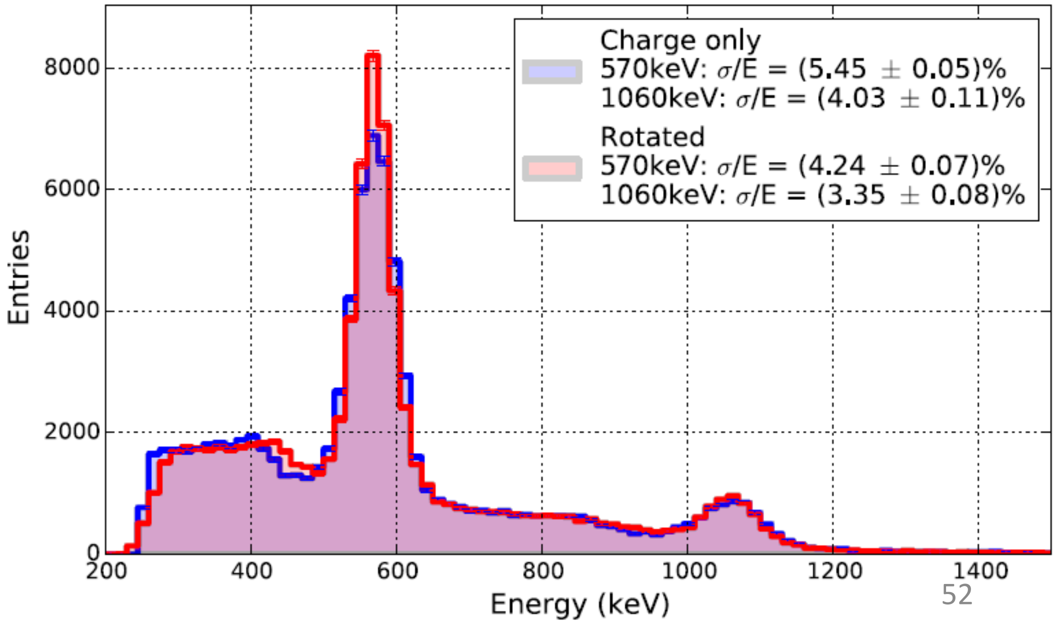






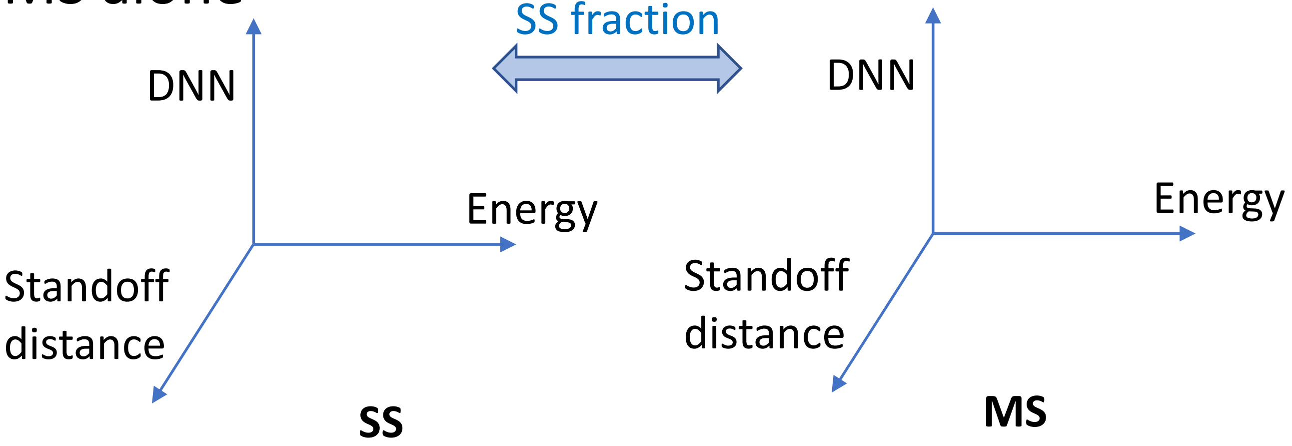

Charge Energy=492.27 keV
Light Amp=37718.59
X21
X20
X19
X18
X17
X16
X15
X14
X13
X22
Y11
Y20
Y19
Y18
Y17
Y16
Y15
Y14
Y13
Y12
230.30 keV
128.39 keV
30.32 keV
103.26 keV
6874.99
1451.11
2823.71
1845.56
-22.08
4976.70
4881.68
1995.78
1653.40
3638.36
28.74
7577.31
2-1
1-6
1-5
1-4
1-3
1-2
1-1
2-6
2-5
2-4
2-3
2-2
Time [μs]
Time [μs]


Light Energy [keV]
Charge Energy [keV]

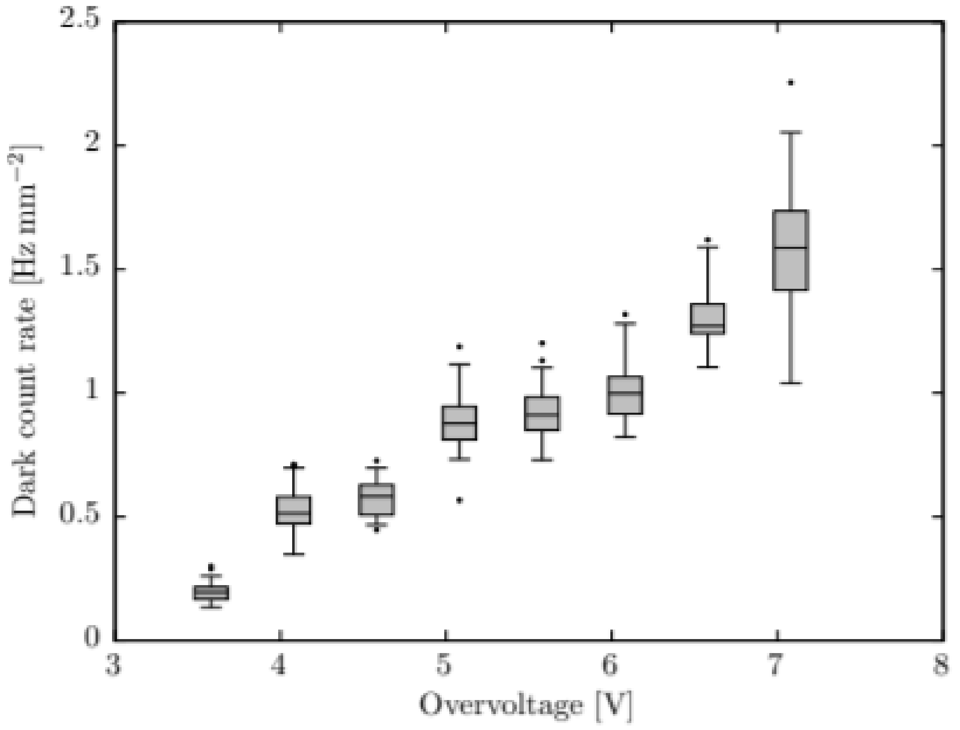

Charge only
570keV: σ/E = (5.45 ± 0.05)%
1060keV: σ/E = (4.03 ± 0.11)%
Rotated
570keV: σ/E = (4.24 ± 0.07)%
1060keV: σ/E = (3.35 ± 0.08)%
Entries
Energy (keV)

Analysis strategy

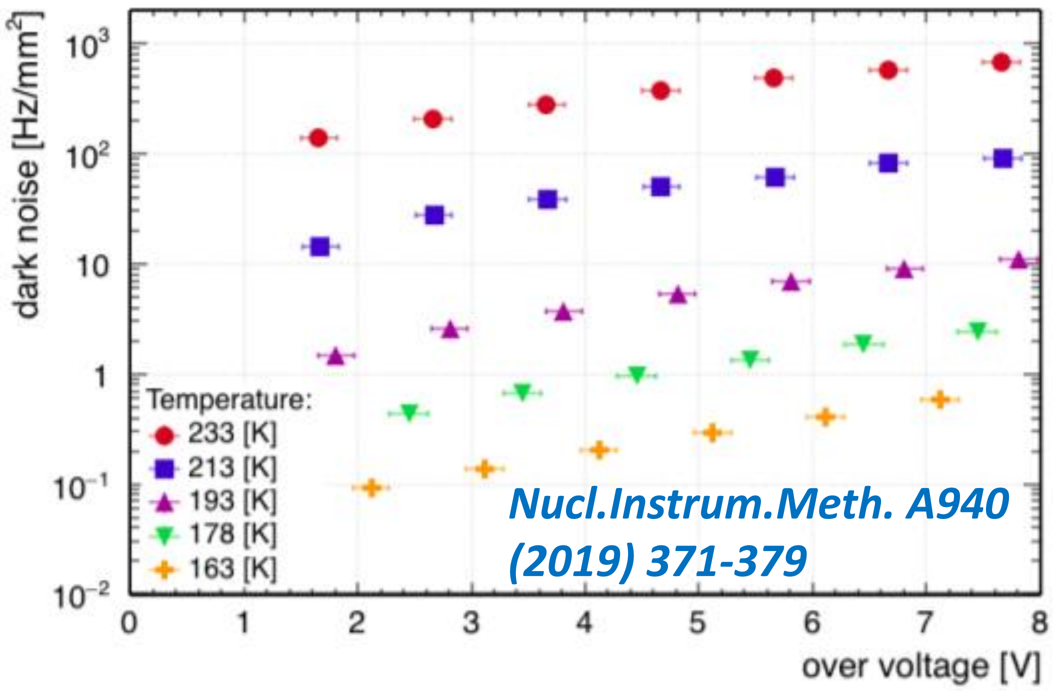
- Blinded analysis performed
- SS/MS classification
- 3-dimension fit in both SS and MS: E + DNN + standoff distance
    - Energy, event topology and spatial information
    - Make the most use of multi-parameters for background rejection
    - SS, MS relative contributions constrained by SS fraction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



FBK at -100C



Hamamatsu



- At 4V operation voltage and LXe temperature, dark count rate < 1Hz/mm^2
- Hamamatsu is better than FBK, achieves ~0.2 Hz/mm^2