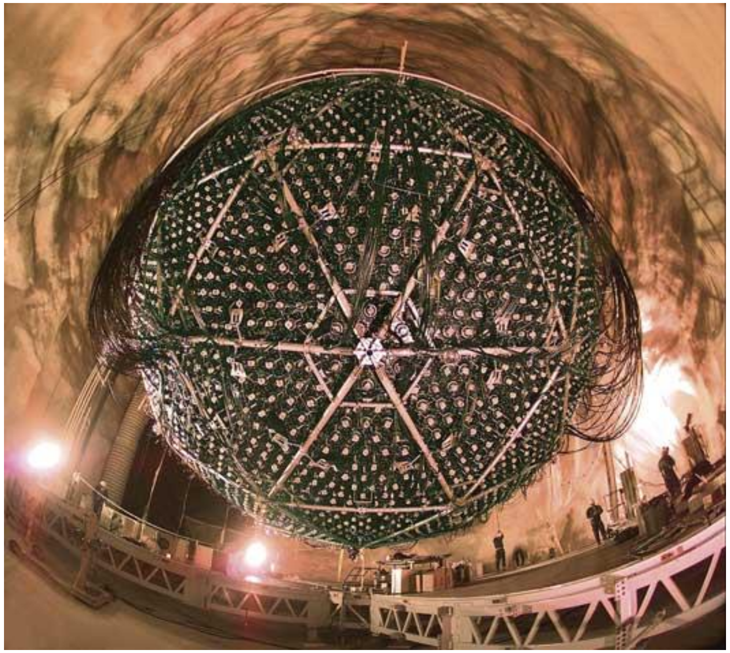
Searching for 0νββ with EXO-200 and nEXO

- Motivation for ββ search
- The EXO-200 and nEXO experiments

Thomas Brunner for the nEXO collaboration
CAP2016 – June 13, 2016

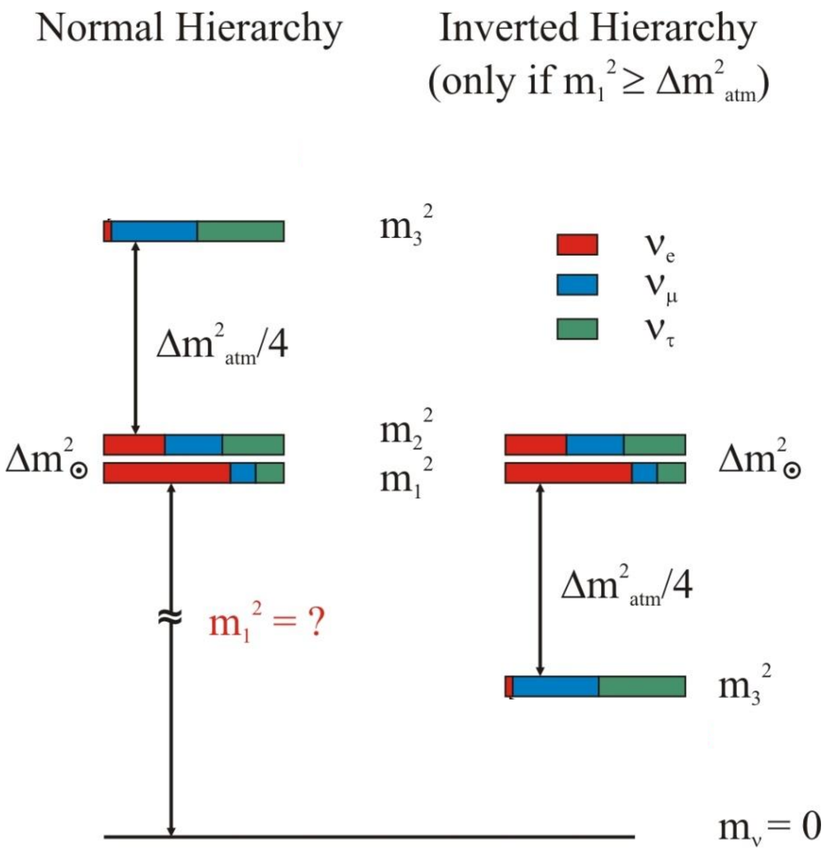
Neutrino oscillations



SNO, picture taken from http://www.oit.on.ca

Pontecorvo–Maki–Nakagawa–Sakata matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{m1} \\ \nu_{m2} \\ \nu_{m3} \end{pmatrix}$$



Relative mass scale

- Indicate a neutrino mass
- Determination of mixing angle θ_{ij}
- Indicate mass hierarchy
- Determination of δm^2

Neutrino oscillations

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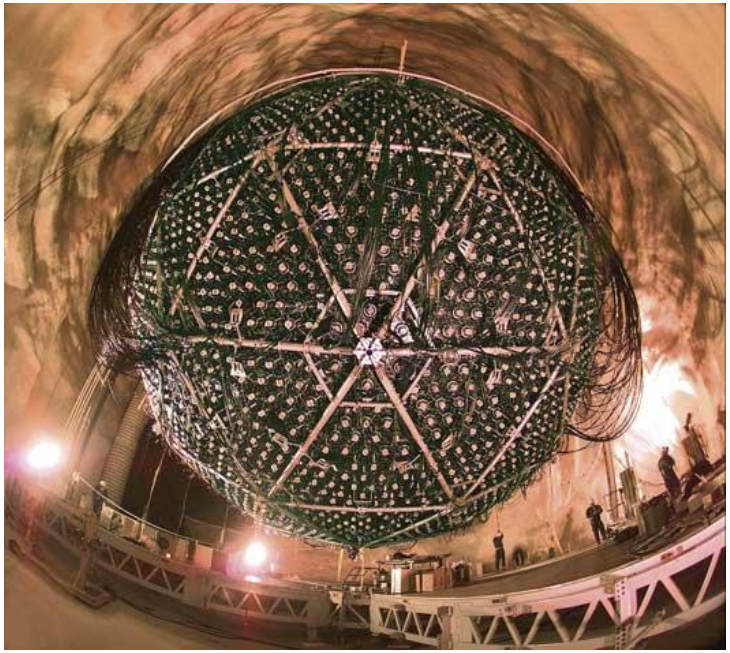

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What oscillation experiments cannot tell us about ν's

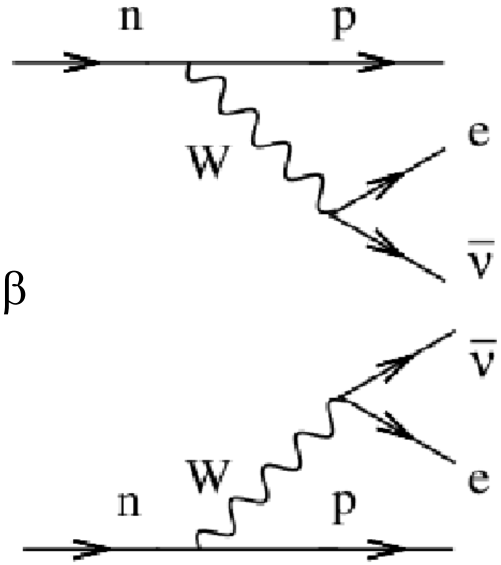
- What is the absolute mass scale
- Why is the neutrino mass so small?
- What is the nature of the ν: Dirac or Majorana?

→Search for 0νββ decay

Double beta decay

M.Goeppert-Mayer, Phys. Rev. 48 (1935) 512

2νββ

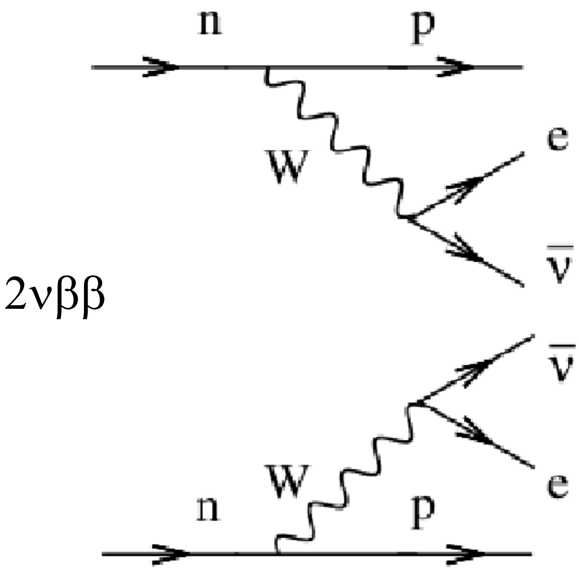


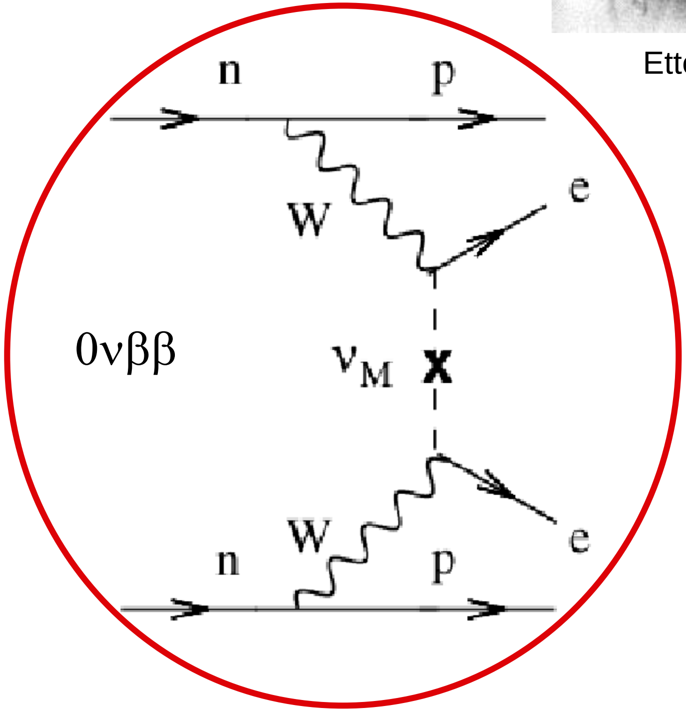
Double beta decay

M.Goeppert-Mayer, Phys. Rev. 48 (1935) 512

The most promising approach to determine the nature of the neutrino!
Lepton number is violated in this decay!

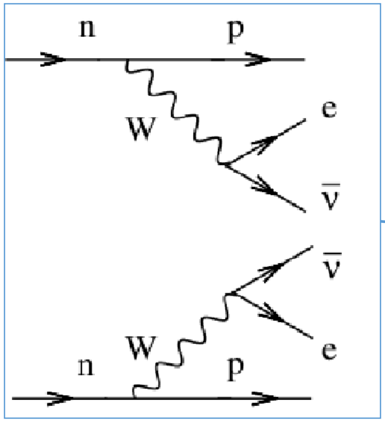
Ettore Majorana

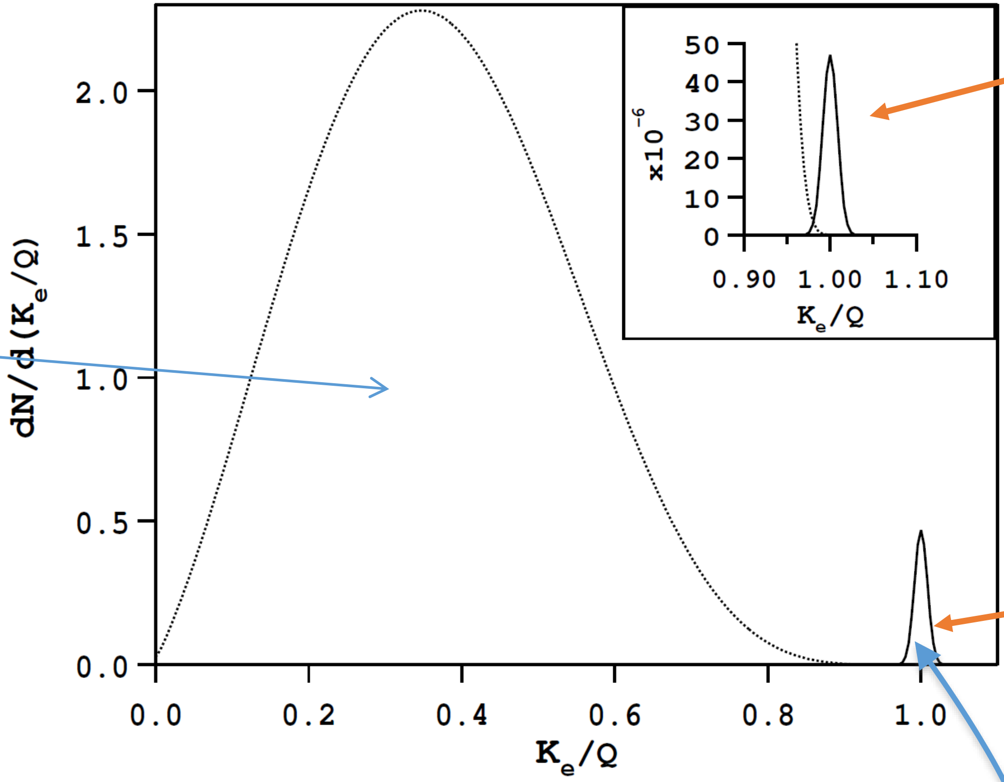




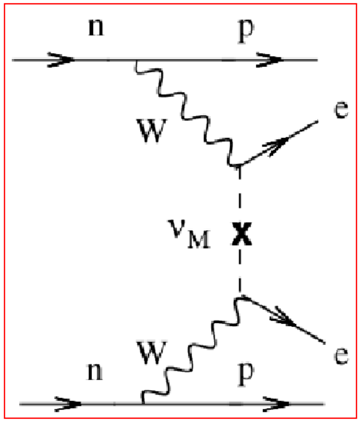
This process can only occur for a Majorana neutrino!

Neutrinoless double beta decay





[arXiv:hep-ph/0611243]



$0\nu\beta\beta$ peak (normalized to 10^{-6})

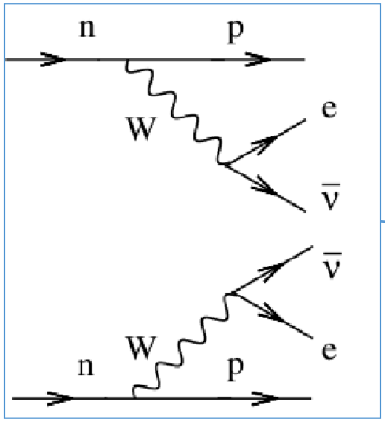
$0\nu\beta\beta$ peak (normalized to 10^{-2})

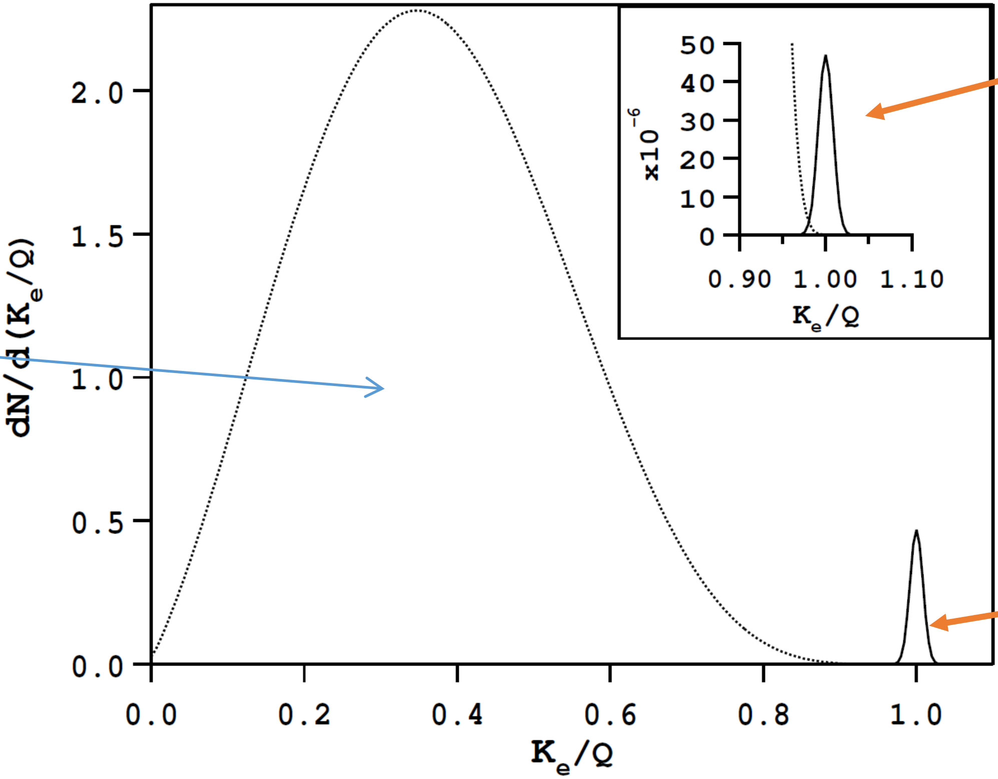
kinetic energy K_e of the two electrons in units of kinematic endpoint (Q)

Smeared by the energy resolution of the hypothetical detector

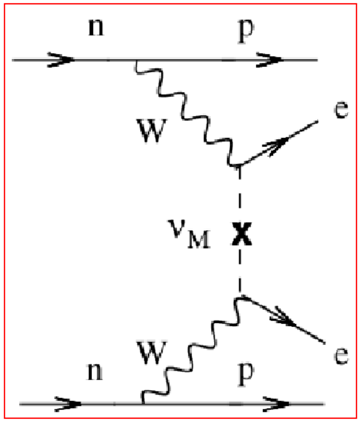
Neutrinoless double beta decay

[arXiv:hep-ph/0611243]





$0\nu\beta\beta$ peak (normalized to 10^{-6})



$0\nu\beta\beta$ peak (normalized to 10^{-2})

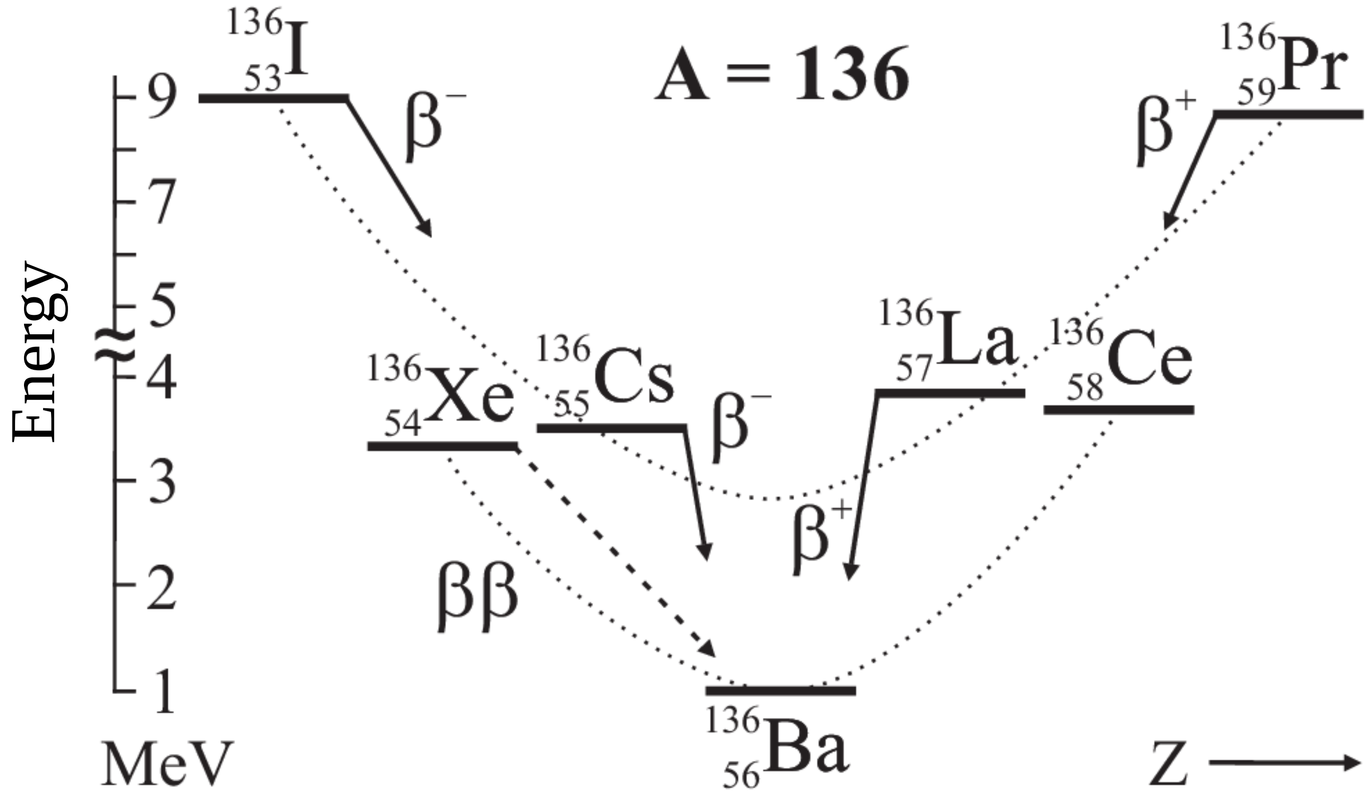
$$\left[T^{0\nu}_{1/2}\right]^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2\left\langle m_\nu\right\rangle^2$$

$G^{0\nu}$ is a phase space factor

$M^{0\nu}$ is the nuclear matrix element

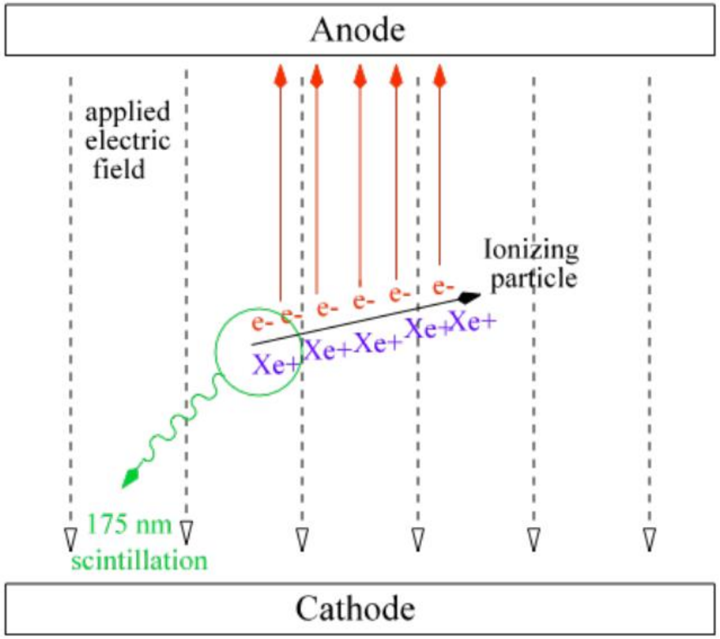
Effective Majorana mass: $\left\langle m_\nu\right\rangle = \left|\sum_i U_{ei}^2 m_i\,\varepsilon_i\right|$ (light neutrino exchange mechanism only)

Double Beta Decay



- If first-order beta decay is forbidden energetically or by spin, second-order double beta decay (a weak nuclear process) can be observed
- True for several isotopes such as: ^{48}Ca, ^{76}Ge, ^{130}Te, ^{136}Xe

Searching for 0νββ in ^{136}Xe with EXO



Liquid-Xe Time Projection Chamber

- Liquid Xe at 168K
- Cryogenic electronics in LXe
- Detection of scintillation light and secondary charges
- 2D read out of secondary charges at segmented anode
- Full 3D event reconstruction:
  1. Energy reconstruction
  2. Position reconstruction
  3. Event Multiplicity

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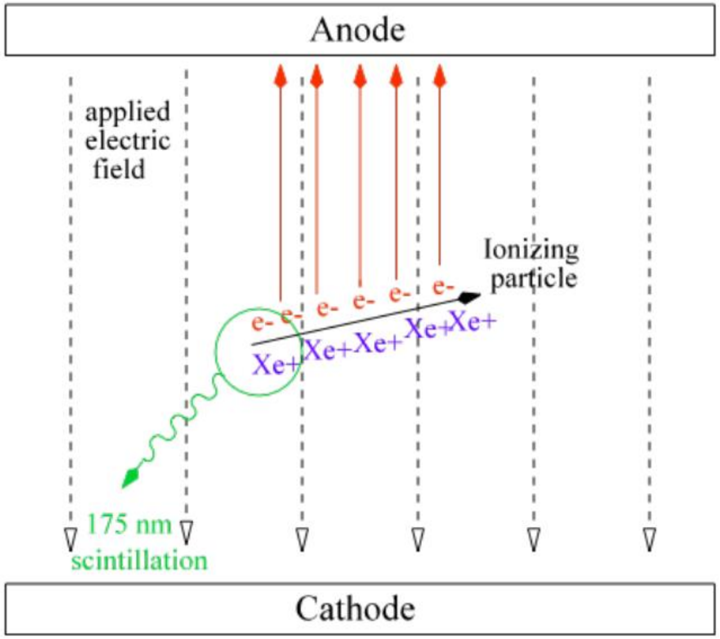

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$T_{1/2}^{0\nu} > 10^{25}$ years !!

→Need:

- high target mass
- high exposure
- low background rate
- good energy resolution

Natural radiation decay rates

A banana	~10 decays/s
A bicycle tire	~0.3 decays/s
1 l outdoor air	~1 decay/min
100 kg of ^{136}Xe (2ν)	~1 decay/10 min

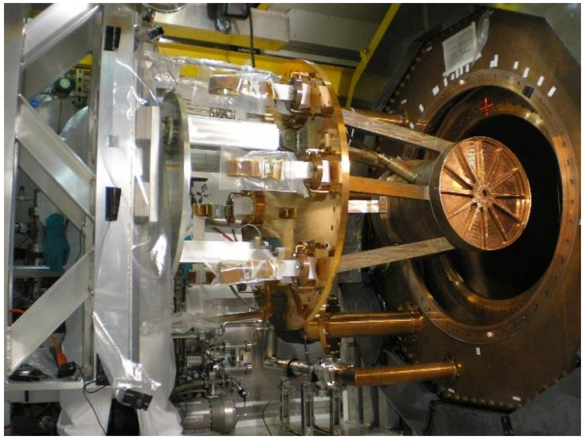
0νββ decay	>1000 x rarer than 2νββ
Age of universe	1.4 x 10^{10} years

Advantages of ^{136}Xe

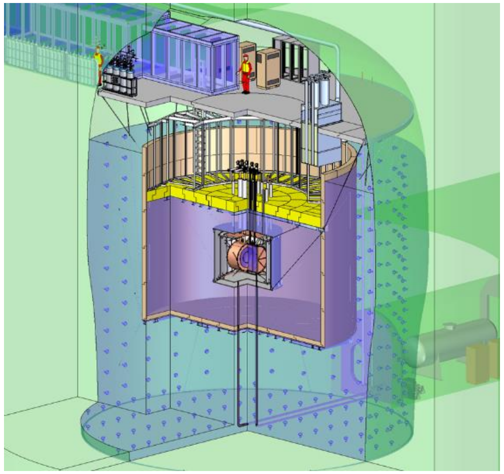
- Easy to enrich: 8.9% natural abundance but can be enriched relatively easily (better than growing crystals)
- Can be purified continuously, and reused
- High $Q_{\beta\beta}$ (2458 keV): higher than most naturally occurring backgrounds
- Minimal cosmogenic activation: no long-life radioactive isotopes
- Energy resolution: improves using scintillation and charge anti-correlation
- LXe self shielding
- Background can be potentially reduced by Ba^{++} tagging

Phased approach:

1. EXO-200: 200kg liquid-Xe TPC



2. nEXO: 5-ton liquid Xe TPC with Ba tagging option (SNO lab cryopit)



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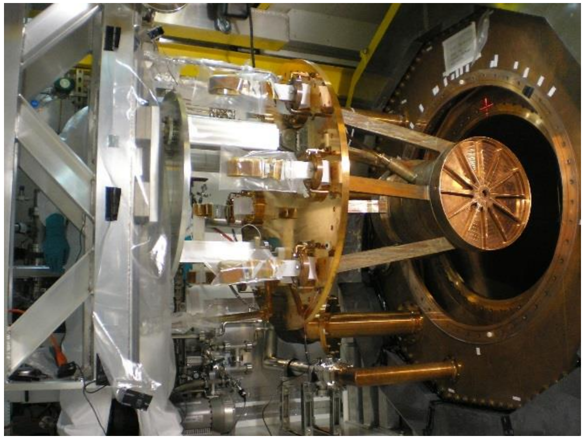

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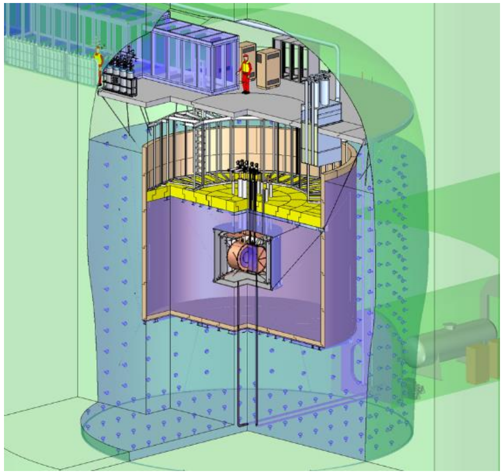
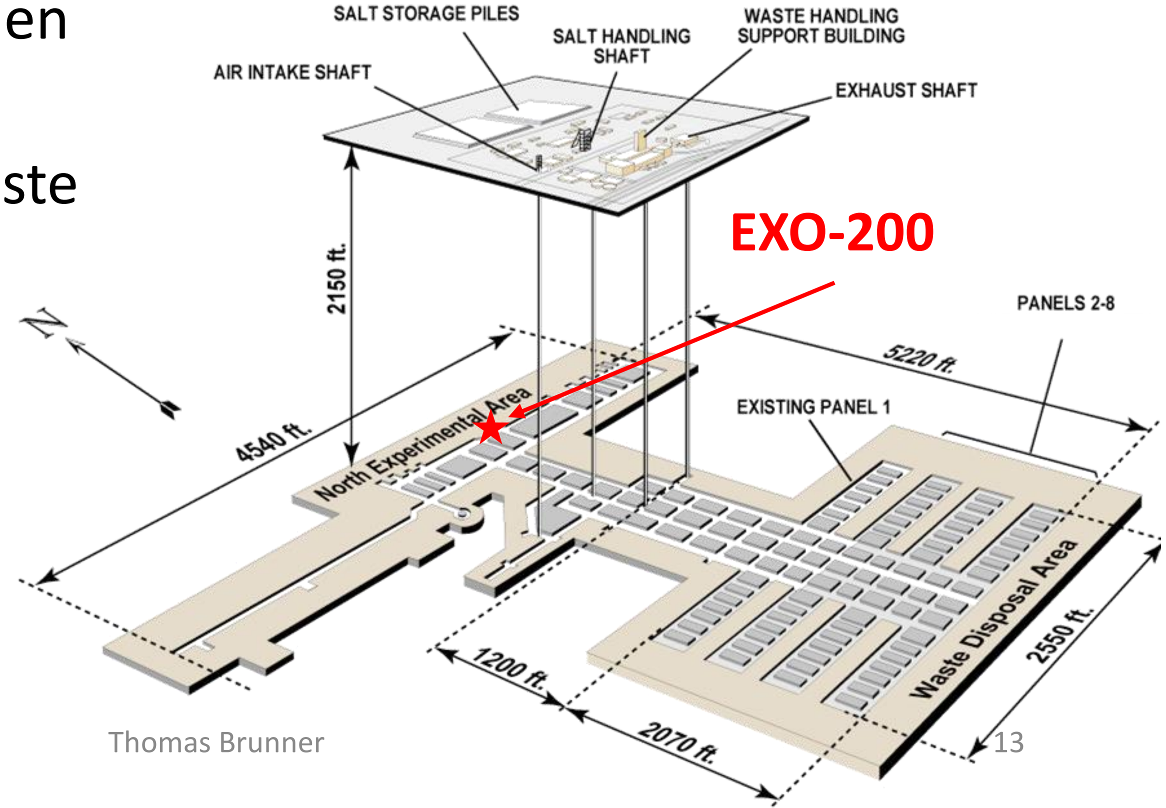


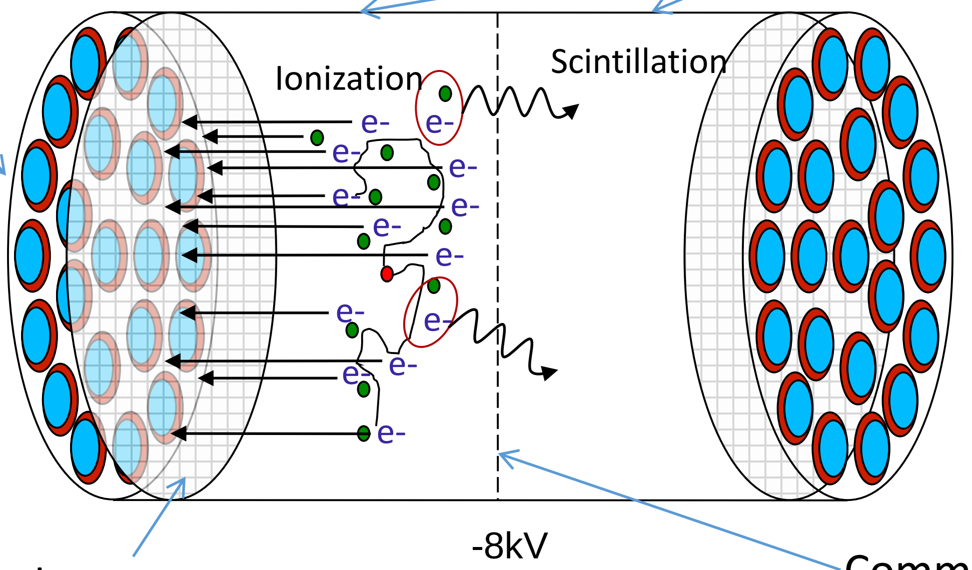
See talks by
- Y. Lan M1-4
- R. Gornea T1-5

EXO-200

- Located at the Waste Isolation Pilot Plant at 32°22’30”N 103°47’34”W (Carlsbad, NM).
- 2150 feet depth (~655m), ≈1585 mwe flat overburden
- U.S. DOE permanent repository for nuclear waste
- Low radioactivity levels:
  - U, Th <100ppb
  - Radon background < 10 Bq/m^3



EXO-200 Time Projection Chamber (TPC) Basics



TPC modules

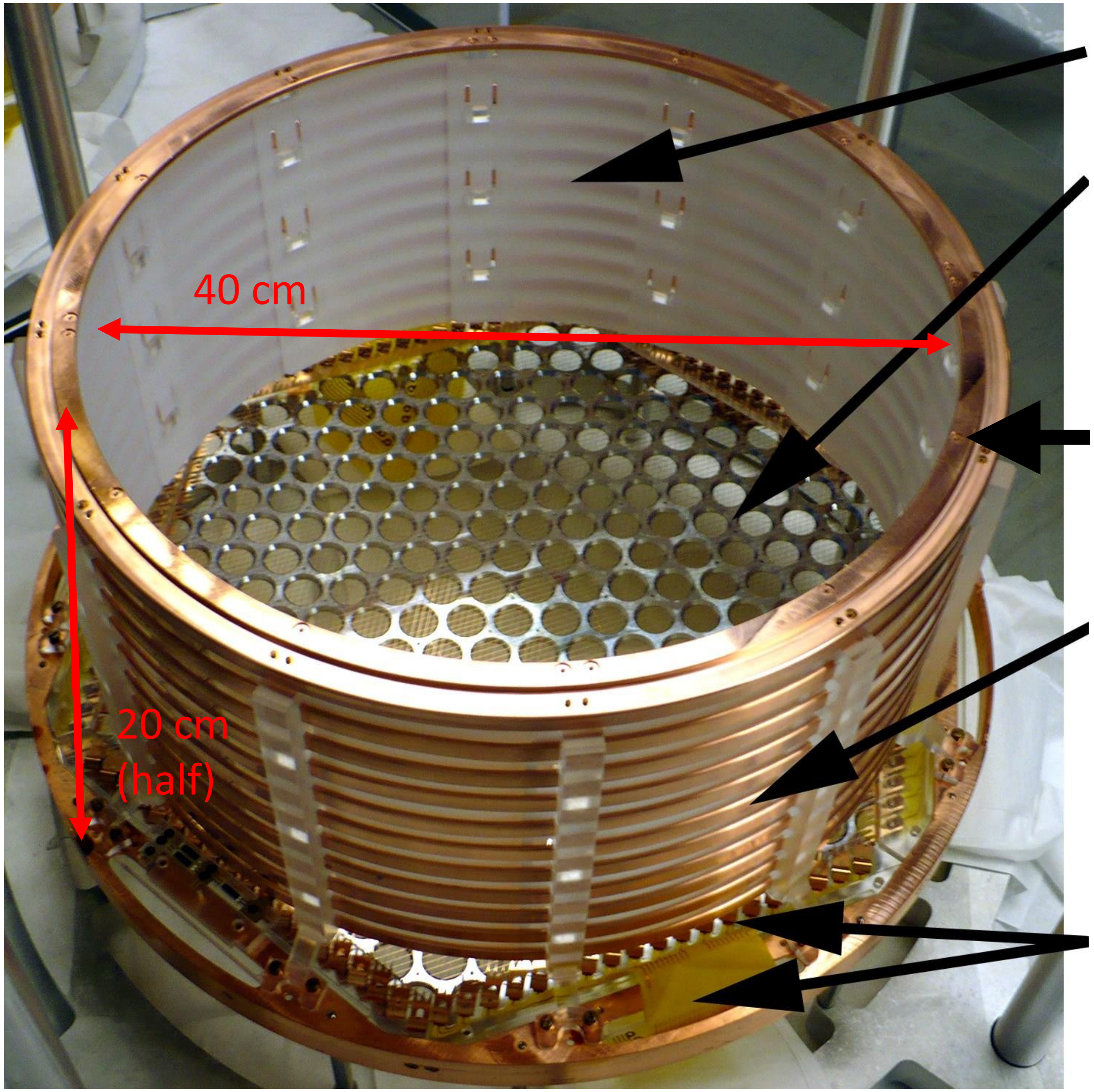
Avalanche photodiode (APD) array observes prompt scintillation

Crossed shielding and charge collection grids give give x,y position

Common cathode

- Z-position from the time difference between scintillation and ionization
- Event energy from the combination of ionization and scintillation
- TPC allows rejection of some gamma backgrounds because Compton scattering results in multiple energy deposits

EXO-200 TPC



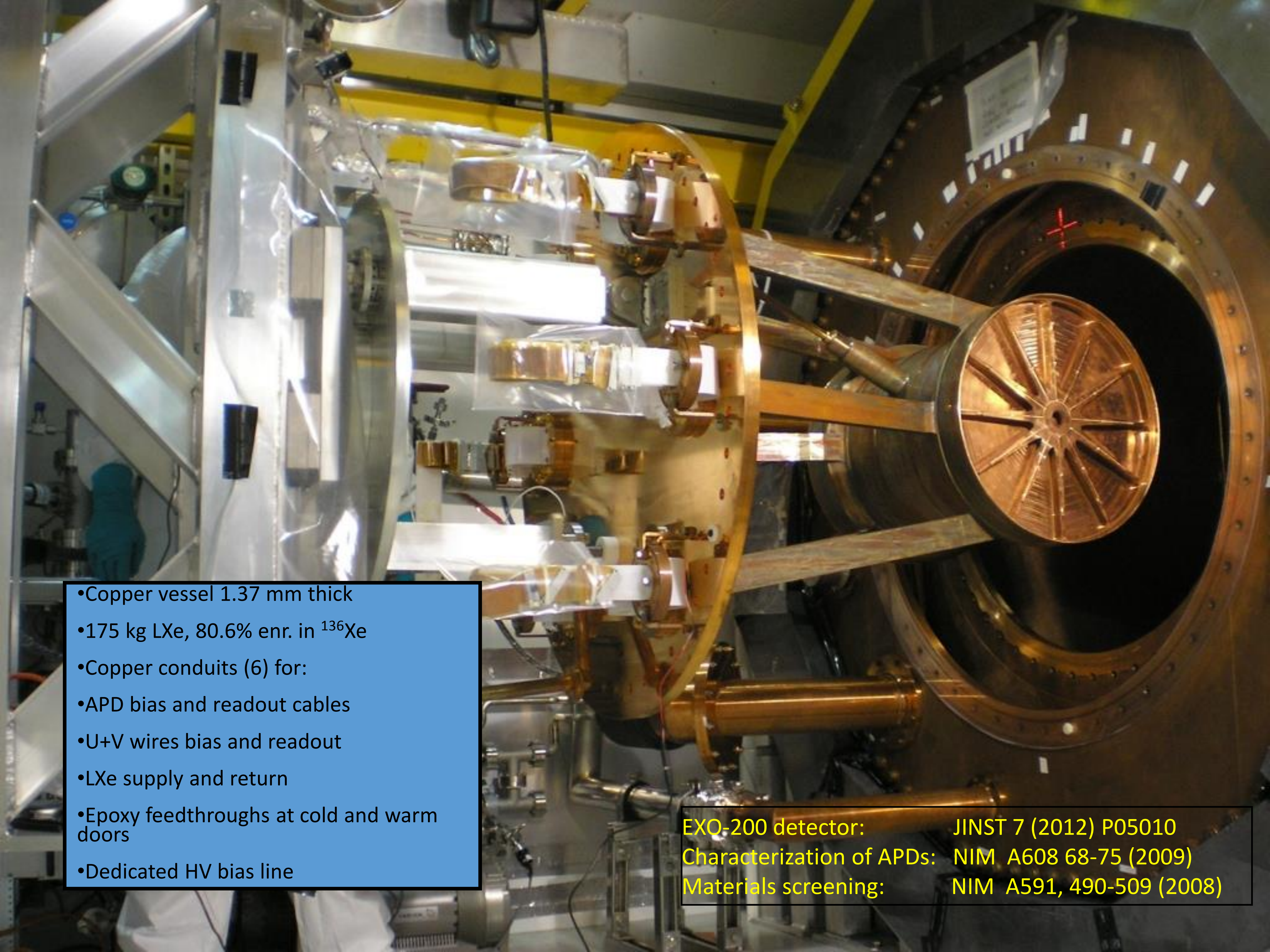
Teflon Reflectors
(increase light collection)

APD plane and wire planes
(wires are photo-etched)

Central HV plane
(photo-etched phosphor bronze)

Acrylic supports
and field shaping
rings

Kapton flex cables
(spring connections
eliminate solder joints
and glue)

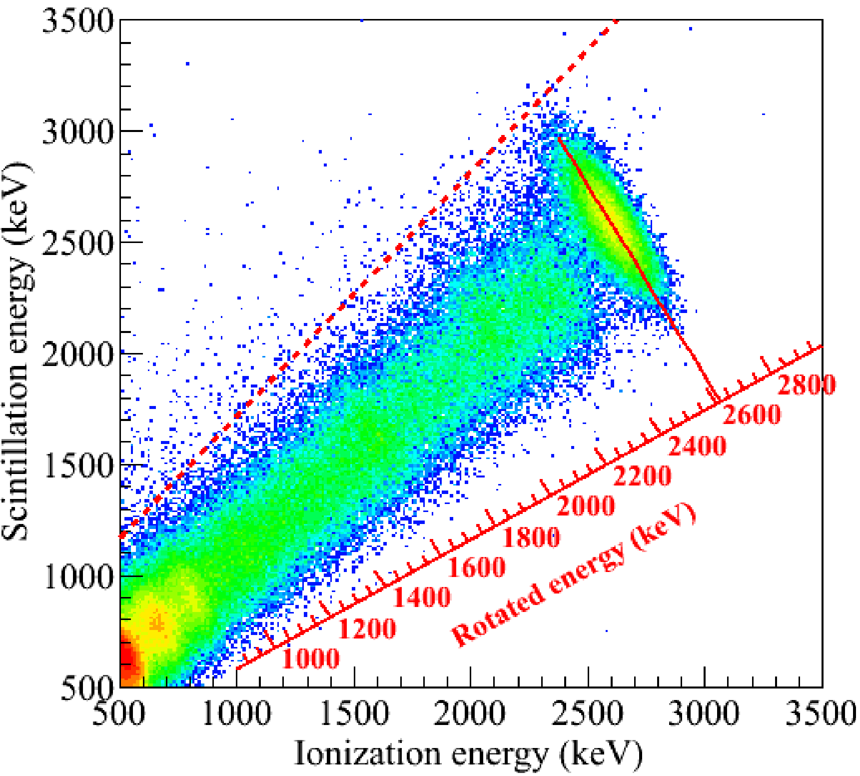


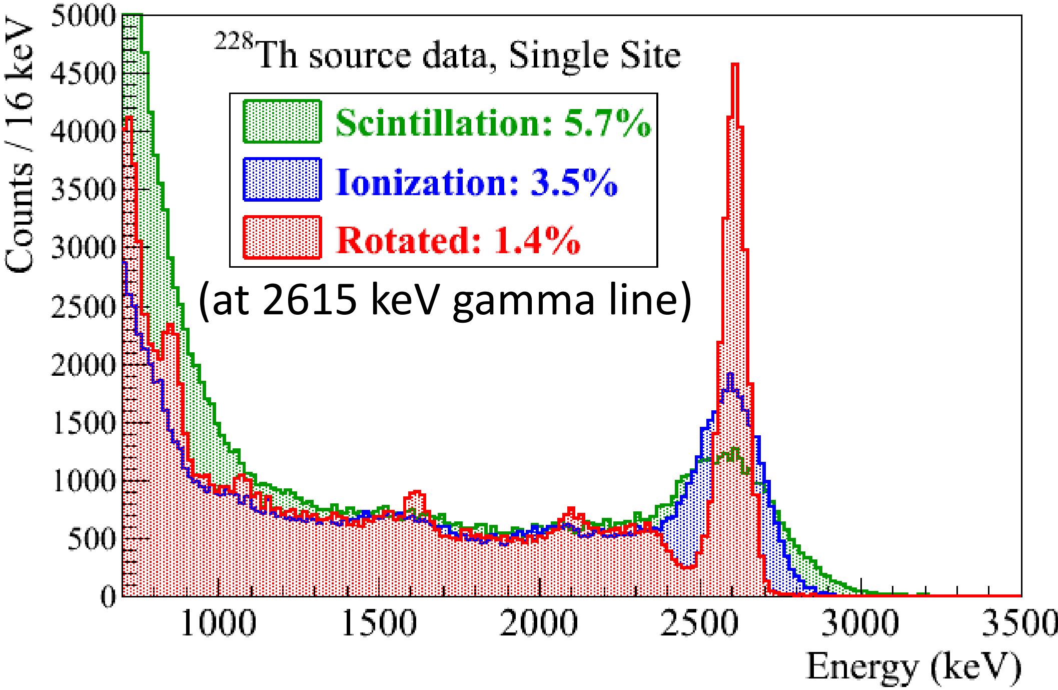
- Copper vessel 1.37 mm thick
- 175 kg LXe, 80.6% enr. in ^{136}Xe
- Copper conduits (6) for:
- APD bias and readout cables
- U+V wires bias and readout
- LXe supply and return
- Epoxy feedthroughs at cold and warm doors
- Dedicated HV bias line

EXO-200 detector:	JINST 7 (2012) P05010
Characterization of APDs:	NIM A608 68-75 (2009)
Materials screening:	NIM A591, 490-509 (2008)

Energy measurement

Combination of charge and light





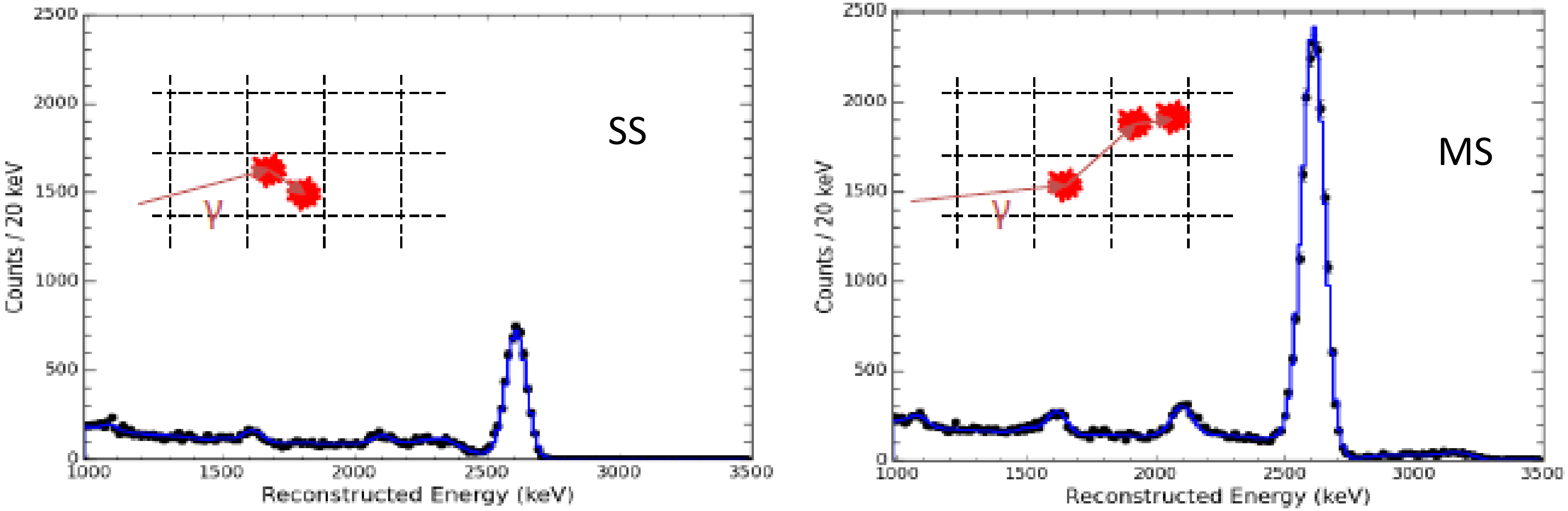
‘Rotation angle’ determined weekly using ^{228}Th source data, defined as angle which gives best ‘rotated’ resolution

Energy resolution is dominated by APD noise

Position/multiplicity reconstruction

Background measurement/reduction

^{228}Th calibration source in EXO-200 detector



Events with > 1 charge cluster: multi-site (MS) events

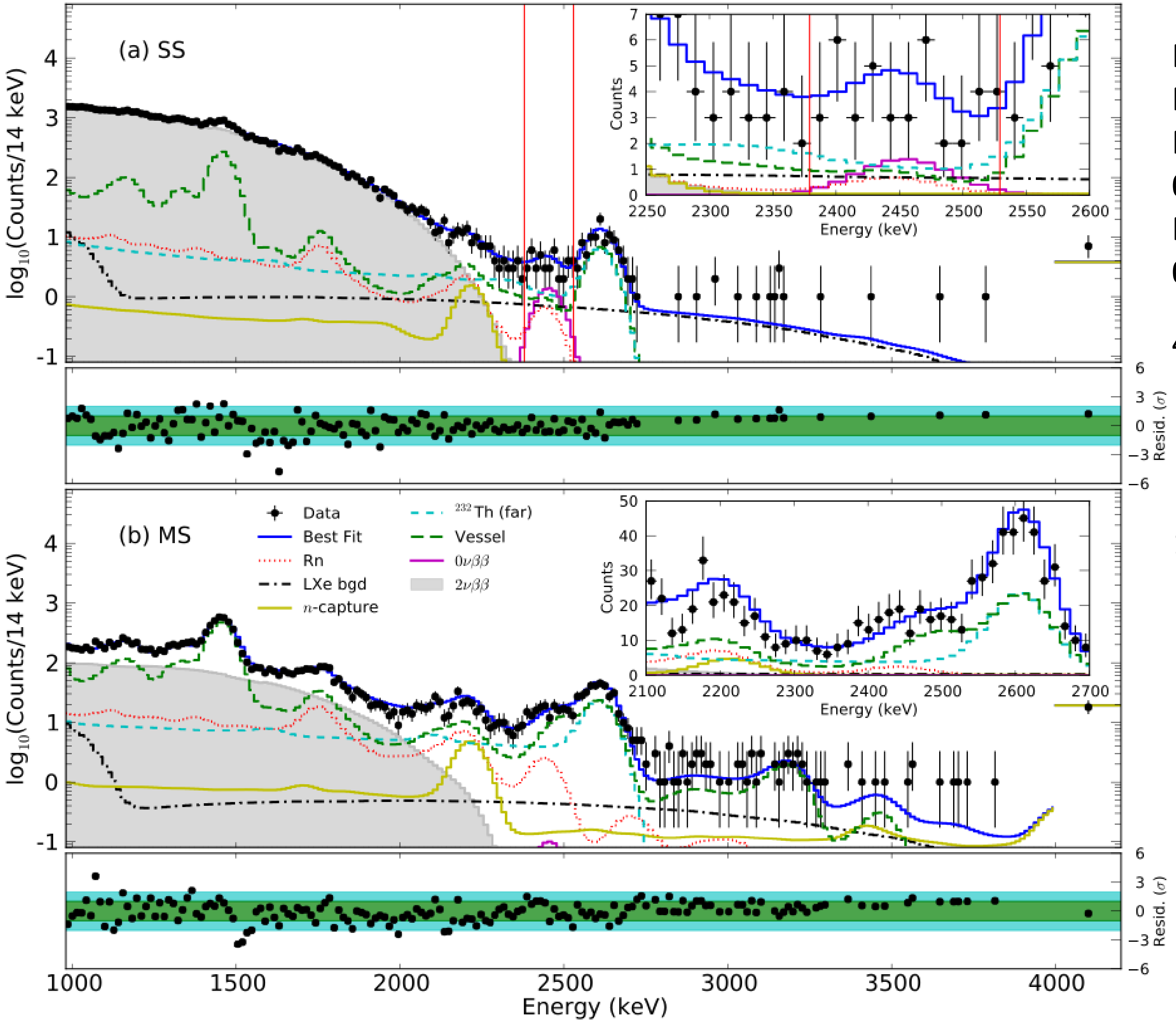
Event with 1 charge cluster: single-site (SS) events

0νββ: ~90% SS

γs: ~30% SS at 0νββ energy

MS events used to constrain background models

Recent 0νββ decay result



Run 2 data consists of:
Run 2a already used for
PRC 2014 and PRL 2012
09/22/2011 – 04/15/2012
Runs 2b and 2c
04/16/2012 – 09/01/2013

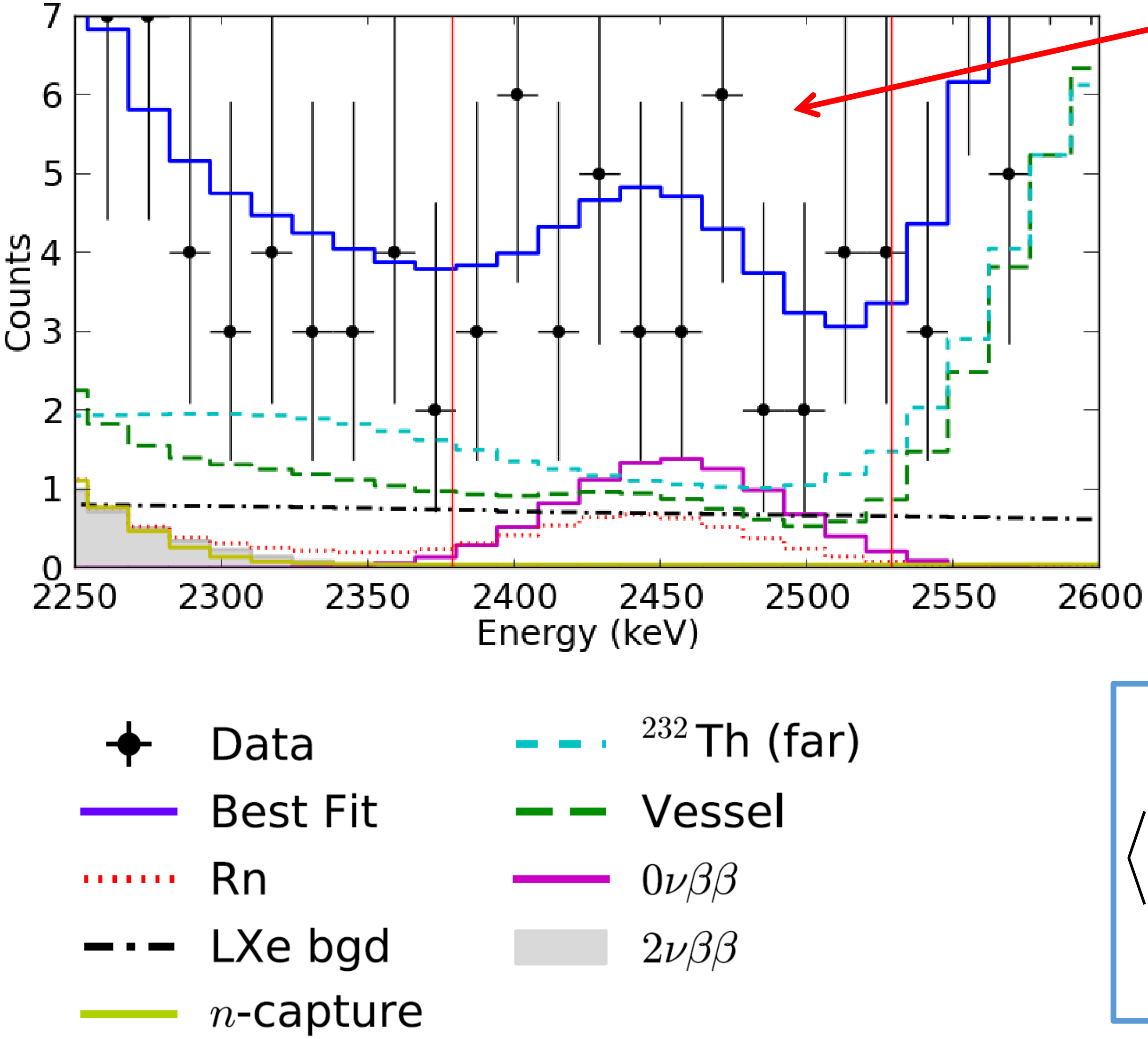
477.60+/-0.01 days of data

^{136}Xe exposure:
99.8 kg yr

Simultaneous fit to
energy and standoff
distance for SS and MS

Nature 510, 229 (2014)

Recent 0νββ decay result



39 counts in ±2σ ROI

Background fit in ±2σ ROI	
^{232}Th	16.0
^{238}U	8.1
^{137}Xe	7.0
Total	**31.1 ± 3.8**

From profile likelihood:

$$T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25}\ yr$$

$$\langle m_{\beta\beta} \rangle < 190 - 450\ meV$$

$$(90\%\ C.L.)$$

Nature 510, 229 (2014)

Phys. Rev. Lett. 109, 032505 (2012)

EXO-200 (0ν)ββ search

2011 First measurement of 2νββ in ^{136}Xe [PRL 107, 212501 (2011)]

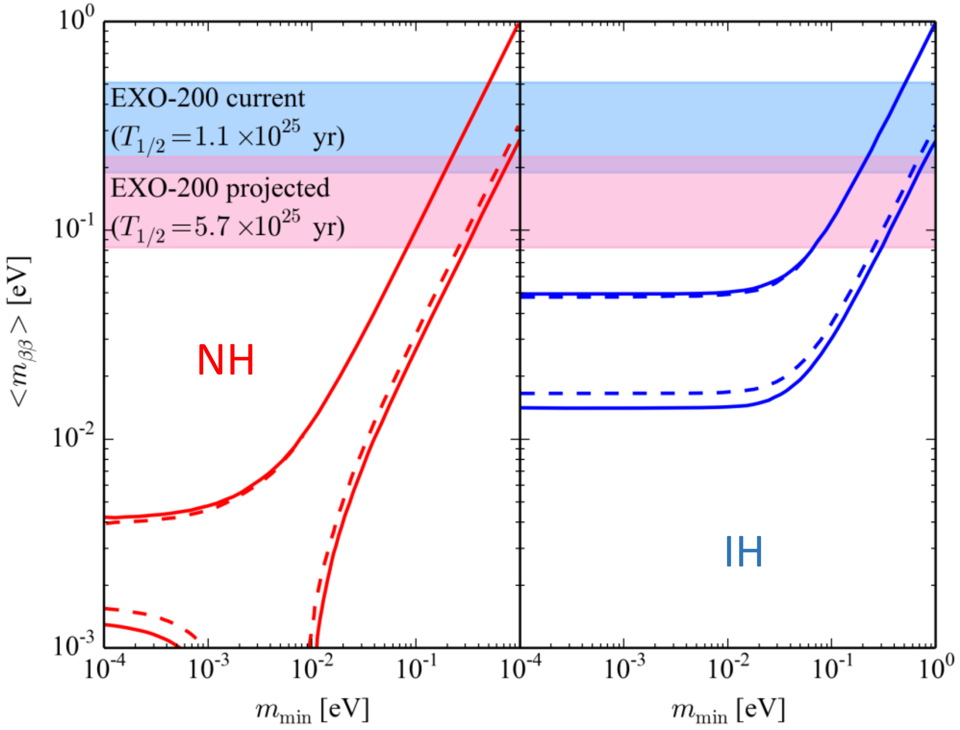
2012 First 0νββ result, best $m_{\beta\beta}$ limit [PRL 109, 032505 (2012)]

2013 Most precisely measured 2νββ rate — and the lowest
→slowest process ever directly measured in nature! [PRC 89, 015502 (2014)]

2014 Improved sensitivity to $m_{\beta\beta}$ [Nature 510, 229 (2014)]

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

$T_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{25}\ yr\ @\ 90\%\ C.L.$



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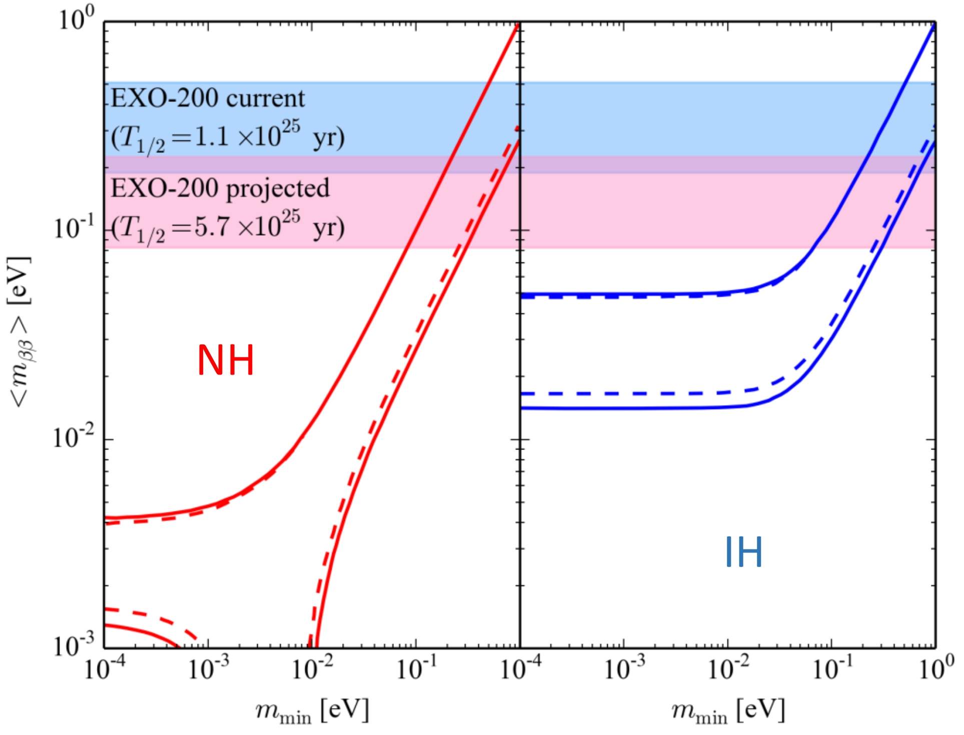
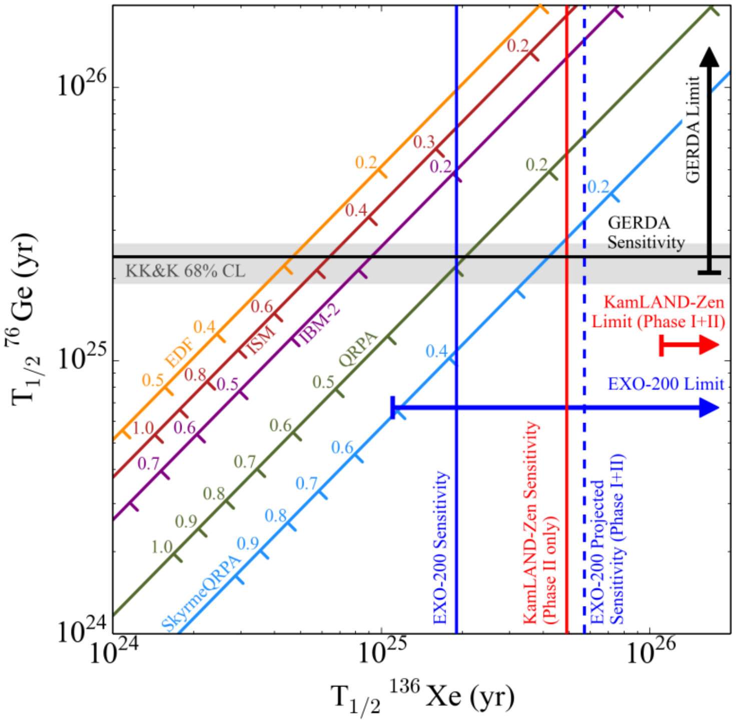
$T_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{25}$ *yr @ 90% C.L.*



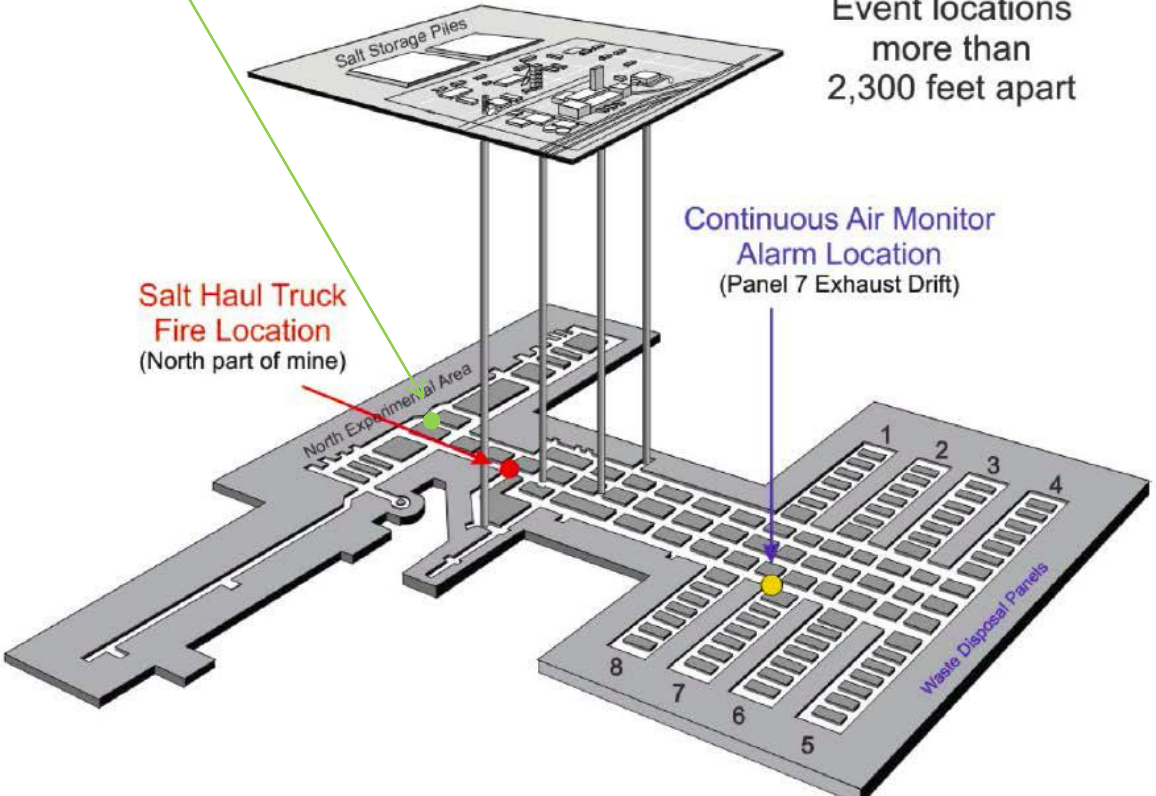


KamLAND ZEN [arXiv:1605.02889]
GERDA [PRL 111, 122503 (2013)]

The future of EXO-200

EXO-200 is about 1.2 km from the radiation event


EXO-200 note pad


Event locations more than 2,300 feet apart

Salt Haul Truck Fire Location
(North part of mine)

Continuous Air Monitor Alarm Location
(Panel 7 Exhaust Drift)

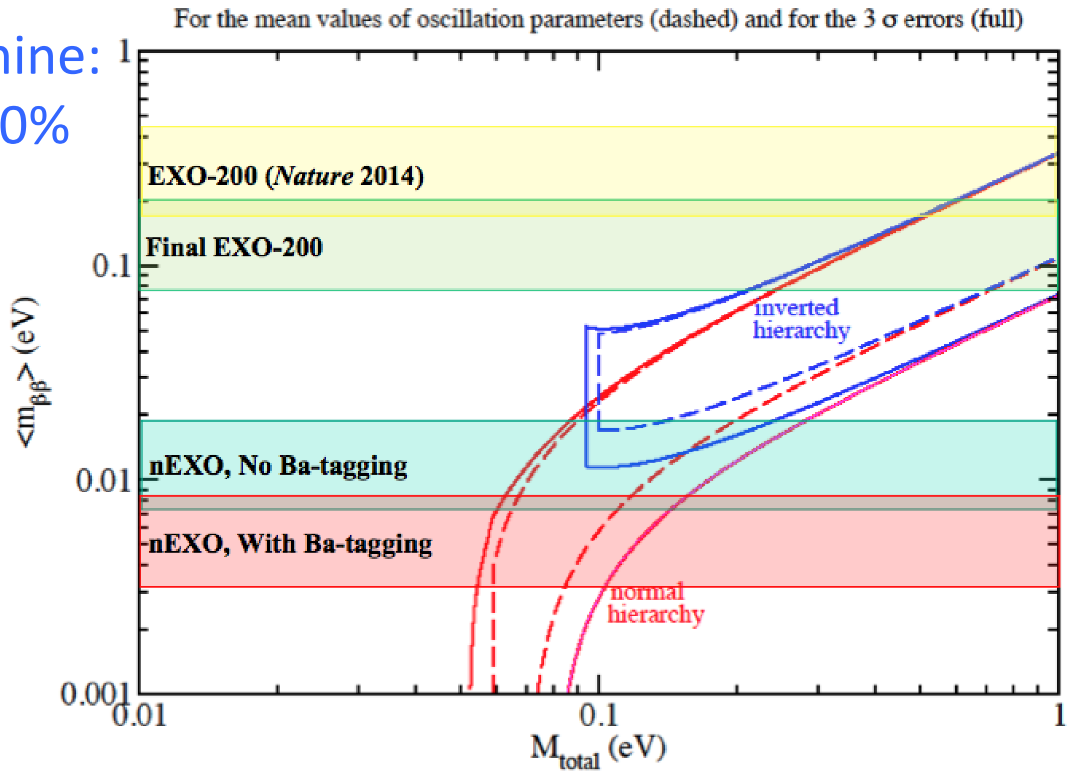
- **Feb. 5 2014:** Fire in WIPP underground
- **Feb. 14, 2014:** Radiation release event
- So far no radioactivity has been measured at EXO-200
- EXO clean up finished
- Low background data taking resumed in early 2016
- Stay tuned for new results

$0\nu\beta\beta$ search with EXO

Multi-phase program :

- **EXO-200** – operational at WIPP mine:
  - ~175kg xenon enriched at ~80%
  - Current limit on $0\nu\beta\beta$: 1.1 x 10^{25} years (EXO-200)
  - Continue data taking for 2 more years
  - Sensitivity: 100-200 meV

- **nEXO** - R&D underway:
  - 5T xenon enriched at ~90%
  - Sensitivity: 5-30 meV
  - Improved techniques for background suppression and possibly Ba tagging



→ Development of nEXO is well advanced

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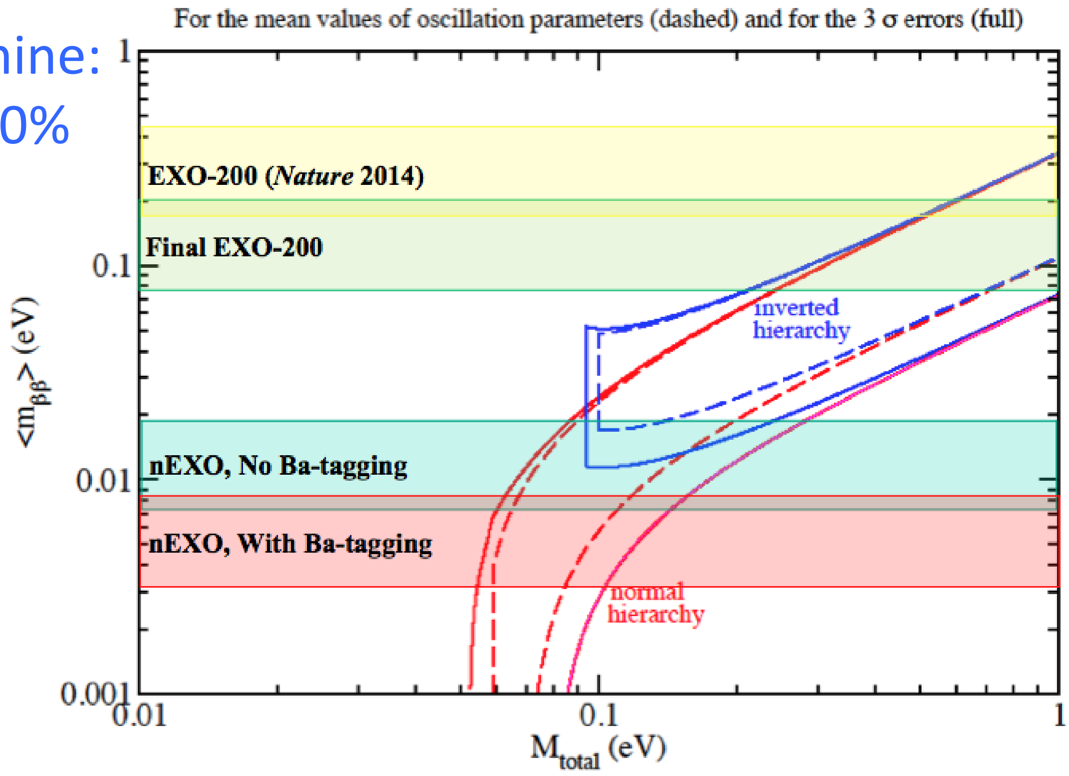

For more information on Ba tagging:
- Y. Lan M1-4
- R. Gornea T1-5

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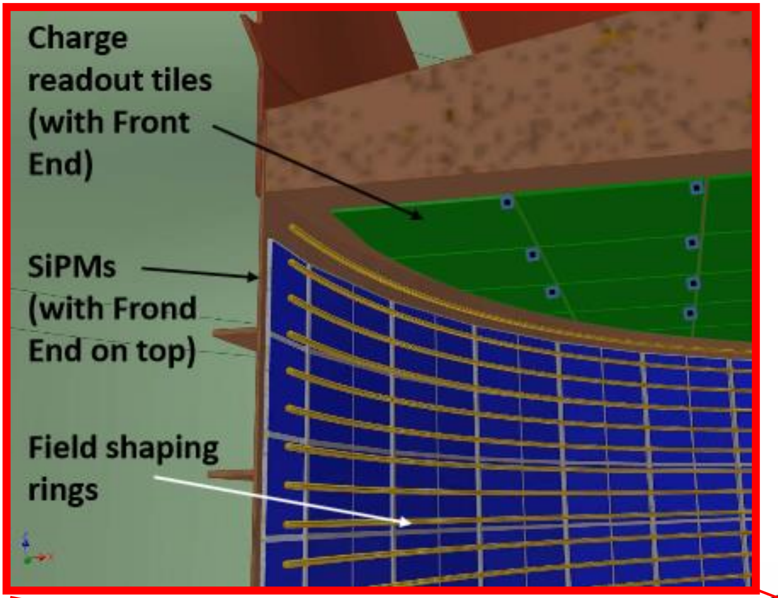
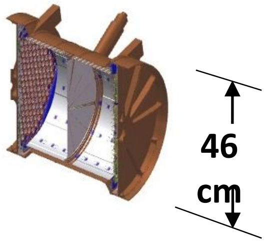
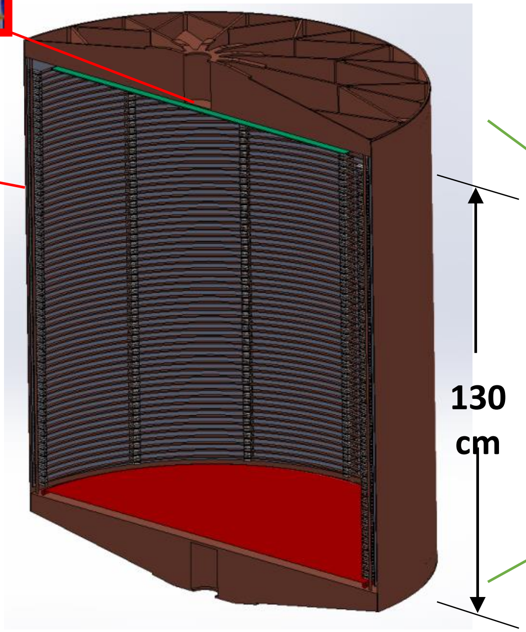


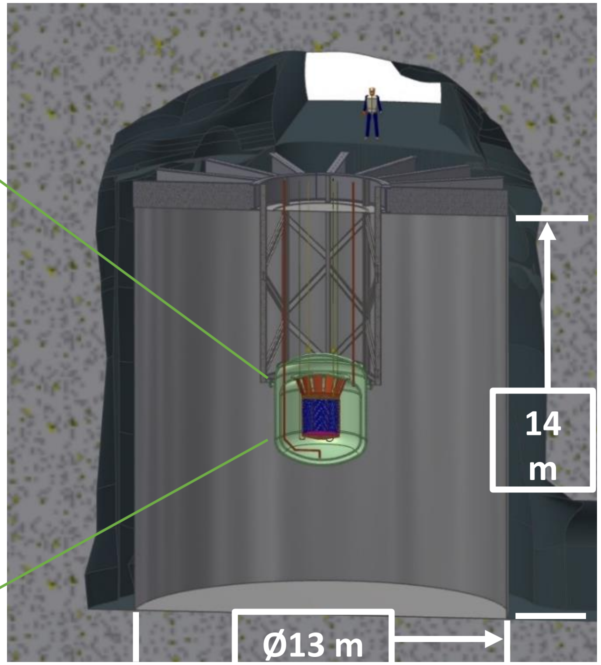
- Next-generation neutrinoless double beta decay detector
- 5 t liquid xenon TPC similar to EXO-200 (50x the size)
- Possible location in SNOLab Cryo Pit (6010 mwe)
- SiPM for light detection
- Tiles for charge read out
- 3D event reconstruction
- Expected σ/E of 1% at Q-value
- Possible addition of Ba-tagging after 5 years

EXO-200 for size comparison





nEXO TPC



nEXO at the SNOlab Cryopit

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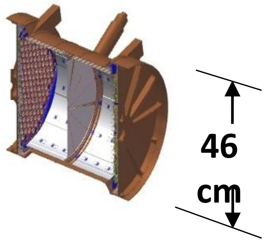
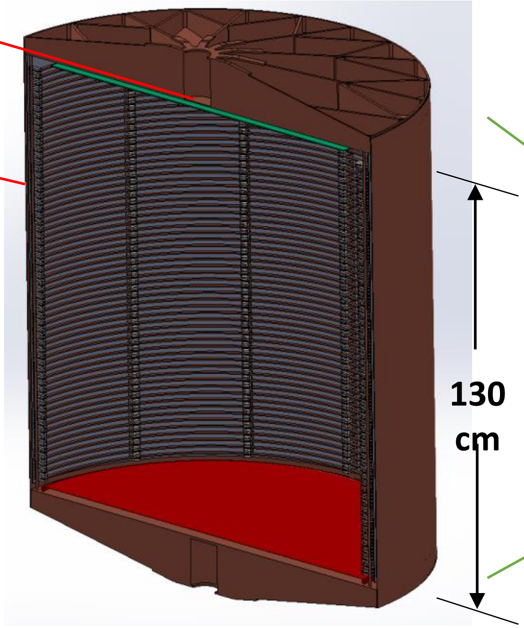
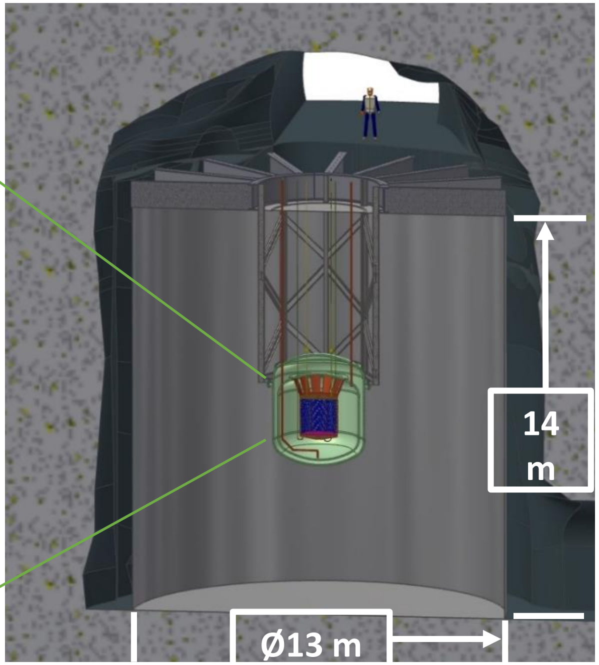




nEXO TPC

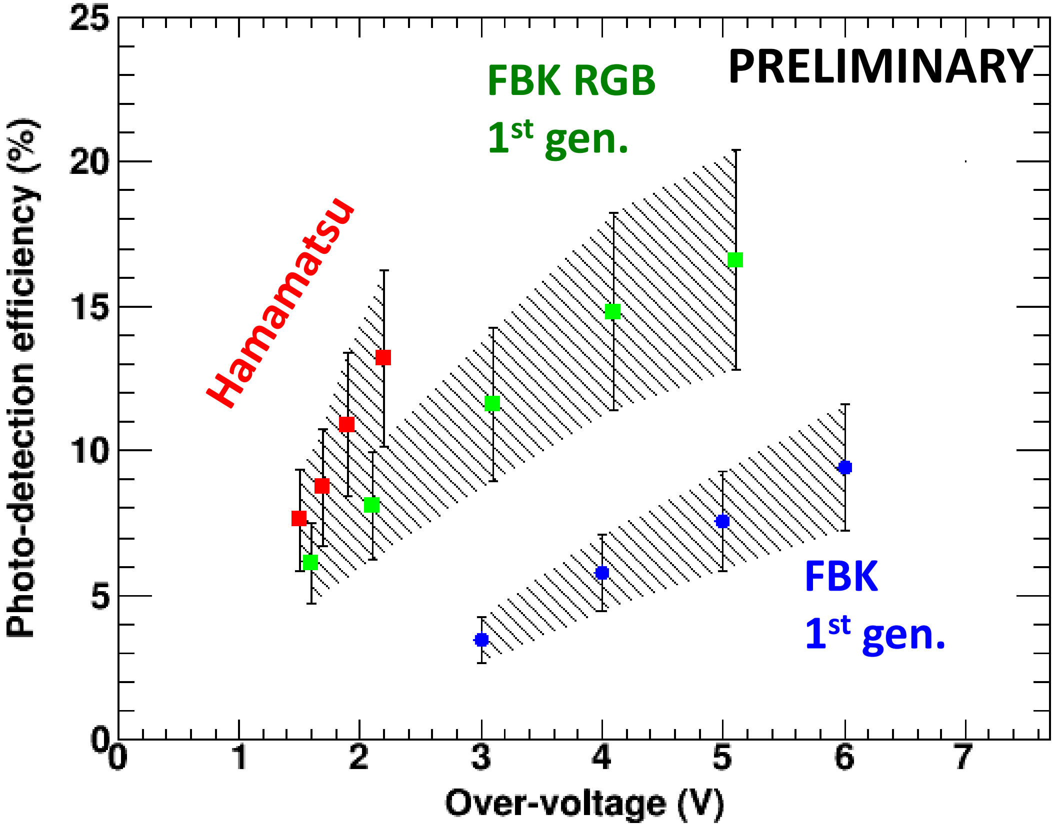


nEXO at the SNOlab Cryopit

SiPM Photodetector

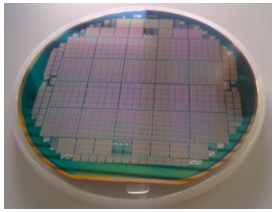
- Hamamatsu produces devices with QE= ~12% @ 175nm but encapsulation is too radioactive → trying to procure un-encapsulated devices

- First nEXO-specific run at FBK (Italy) provided ~10% QE *[I.Ostrovskiy et al. IEEE TNS 62 (2015) 1825.]*
- New FBK "RGB" devices reach 15% QE with 7.7x7.7mm^2.



- Working closely with manufacturers to develop SiPMs to reach >15% QE at 175nm
- Radioassay of SiPMs to determine radioactivity
- Development of integration of 1x1cm^2 SiPMs into 10x10cm^2 tiles
- Tests in liquid Xe planned

Hamamatsu MEG MPPC

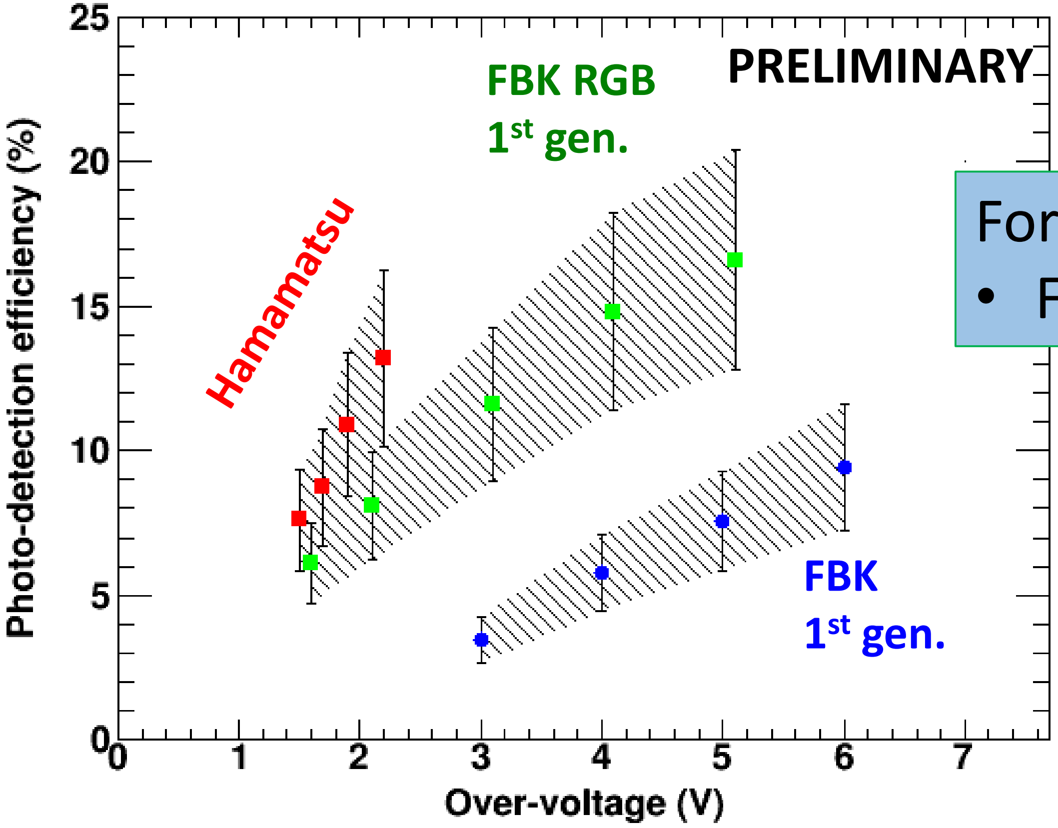


FBK SiPM

SiPM Photodetector

- Hamamatsu produces devices with QE= ~12% @ 175nm but encapsulation is too radioactive → trying to procure un-encapsulated devices

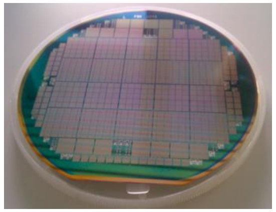
- First nEXO-specific run at FBK (Italy) provided ~10% QE *[I.Ostrovskiy et al. IEEE TNS 62 (2015) 1825.]*
- New FBK "RGB" devices reach 15% QE with 7.7x7.7mm^2.



- Working closely with manufacturers to develop SiPMs to reach >15% QE at
determine radioactivity
- Development of integration of 1x1cm^2 SiPMs into 10x10cm^2 tiles
- Tests in liquid Xe planned

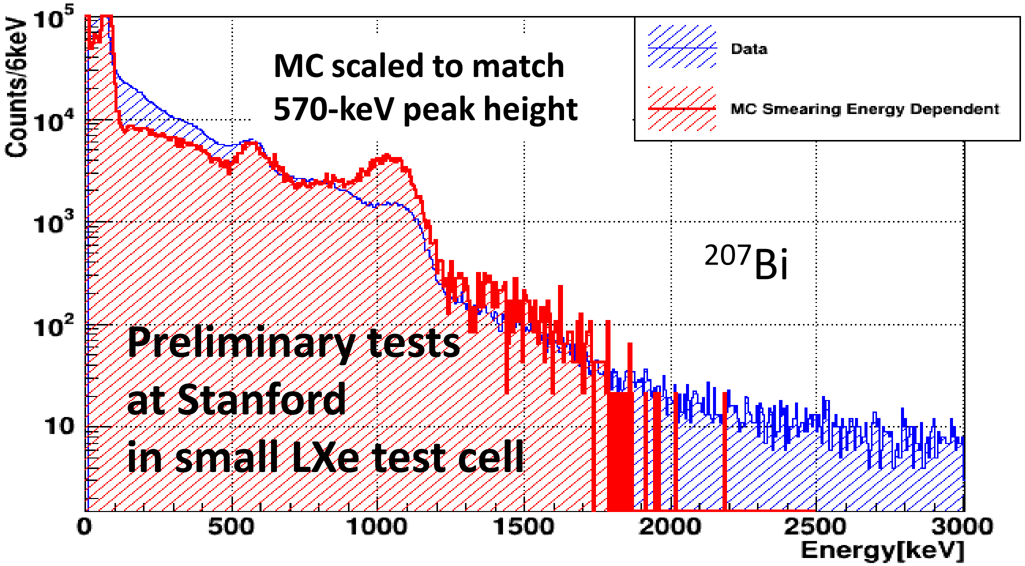
For more information on SiPM:
- F. Retiere W2-4


Hamamatsu MEG MPPC


FBK SiPM

Charge Readout Tiles

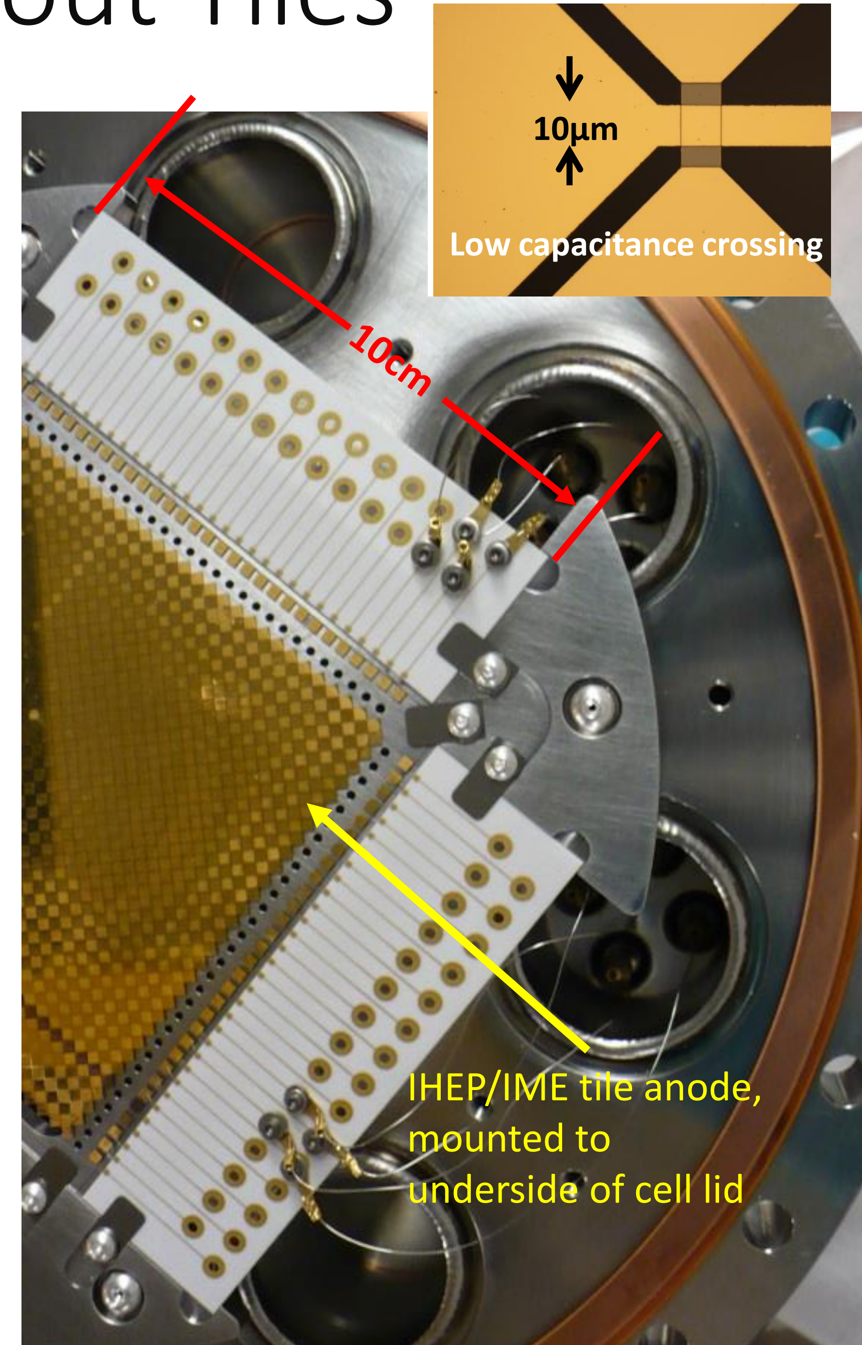
- EXO-200 used wires for charge-readout
- Produced by IHEP/IME; functional testing in LXe in the US.
- 10 x 10cm^2 Prototype Tile
- Metallized strips on fused silica substrate
- 60 orthogonal channels (30 x 30)
- 3mm strip pitch
- Strip intersections isolated with SiO$_2$ layer
- Currently testing in LXe with a ^{207}Bi source



MC scaled to match 570-keV peak height

^{207}Bi

Preliminary tests at Stanford in small LXe test cell

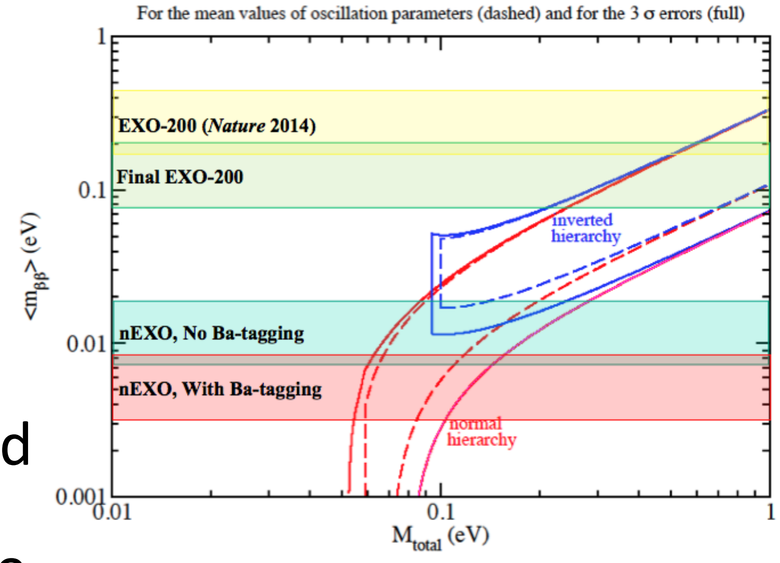


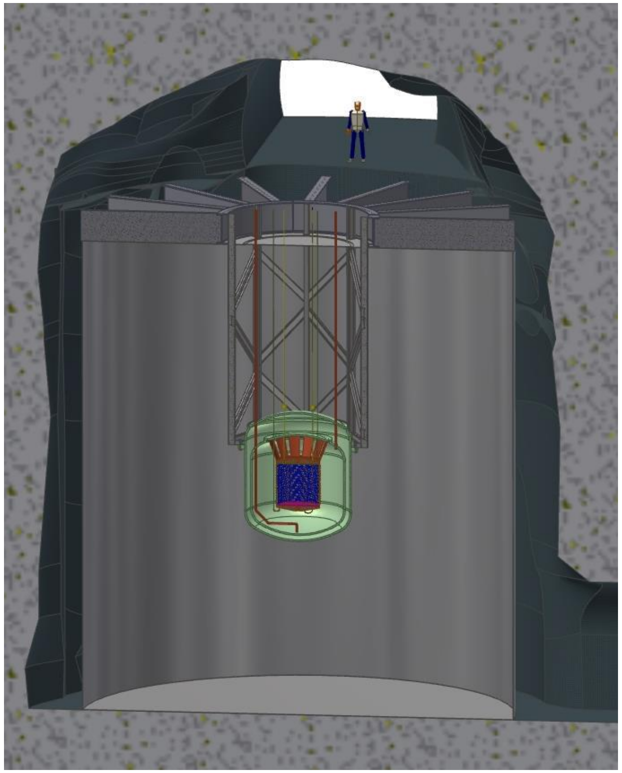
Low capacitance crossing

IHEP/IME tile anode, mounted to underside of cell lid

Summary & Plans

- EXO-200 is operational and taking low background data
- nEXO is the next generation $0\nu\beta\beta$ experiment with 5 T isotopically enriched LXe
- nEXO expands on the success of EXO-200 and improves performance via R&D efforts
- nEXO will have many handles on background
- nEXO has discovery potential in Inverted Hierarchy pushing the lower bound of $\langle m_{\beta\beta} \rangle$
- The 10meV region is within reach
- Strong Canadian contribution to EXO-200 and nEXO





Enriched Xenon Observatory
EXO
for double beta decay

The nEXO Collaboration

University of Alabama, Tuscaloosa AL, USA — T Didberidze, M Hughes, A Piepke, R Tsang
University of Bern, Switzerland — J-L Vuilleumier
Brookhaven National Laboratory, Upton NY, USA — M Chiu, G De Geronimo, S Li, V Radeka, T Rao, G Smith, T Tsang, B Yu
California Institute of Technology, Pasadena CA, USA — P Vogel
Carleton University, Ottawa ON, Canada — I Badhrees, Y Baribeau, M Bowcock, M Dunford, M Facina, R Gornea, K Graham, P Gravelle, R Killick, T Koffas, C Licciardi, K McFarlane, R Schnarr, D Sinclair
Colorado State University, Fort Collins CO, USA — C Chambers, A Craycraft, W Fairbank Jr, T Walton
Drexel University, Philadelphia PA, USA — E Callaghan, MJ Dolinski, YH Lin, E Smith, Y-R Yen
Duke University, Durham NC, USA — PS Barbeau, G Swift
University of Erlangen-Nuremberg, Erlangen, Germany — G Anton, R Bayerlein, J Hoessl, P Hufschmidt, A Jamil, T Michel, T Ziegler
IBS Center for Underground Physics, Daejeon, South Korea — DS Leonard
IHEP Beijing, People' s Republic of China — G Cao, W Cen, X Jiang, H Li, Z Ning, X Sun, T Tolba, W Wei, L Wen, W Wu, J Zhao
ITEP Moscow, Russia — V Belov, A Burenkov, A Karelin, A Kobyakin, A Kuchenkov, V Stekhanov, O Zeldovich
University of Illinois, Urbana-Champaign IL, USA — D Beck, M Coon, S Li, L Yang
Indiana University, Bloomington IN, USA — JB Albert, S Daugherty, TN Johnson, LJ Kaufman, G Visser, J Zettlemoyer
University of California, Irvine, Irvine CA, USA — M Moe
Laurentian University, Sudbury ON, Canada — B Cleveland, A Der Mesrobian-Kabakian, J Farine, U Wichoski
Lawrence Livermore National Laboratory, Livermore CA, USA — O Alford, J Brodsky, M Heffner, G Holtmeier, A House, M Johnson, S Sangiorgio
University of Massachusetts, Amherst MA, USA —S Feyzbakhsh, S Johnston, M Negus, A Pocar
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Pacific Northwest National Laboratory, Richland, WA, USA — EW Hoppe, JL Orrell
Rensselaer Polytechnic Institute, Troy NY, USA — E Brown, K Odgers
Université de Sherbrooke — S Charlebois, D Danovitch, R Fontaine, JF Pratte, J Sylvestre
SLAC National Accelerator Laboratory, Menlo Park CA, USA — J Dalmasson, T Daniels, S Delaquis, G Haller, R Herbst, M Kwiatkowski, A Odian, M Oriunno, B Mong, PC Rowson, K Skarpaas
University of South Dakota, Vermillion SD, USA — J Daughhetee, R MacLellan
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TRIUMF, Vancouver BC, Canada — J Dilling, P Gumplinger, R Krücken, Y. Lan, F Retière, V Strickland

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University of Erlangen-Nu
IBS Center for Undergroun
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ITEP Moscow, Russia — V
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Indiana University, Bloomi
University of California, Ir
Laurentian University, Sud
Lawrence Livermore Natio

University of Massachusett
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SLAC National Accelerator

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Thanks to my Canadian collaborators:

Carleton University

Laurentian University

McGill University

Universite de Sherbrooke

TRIUMF

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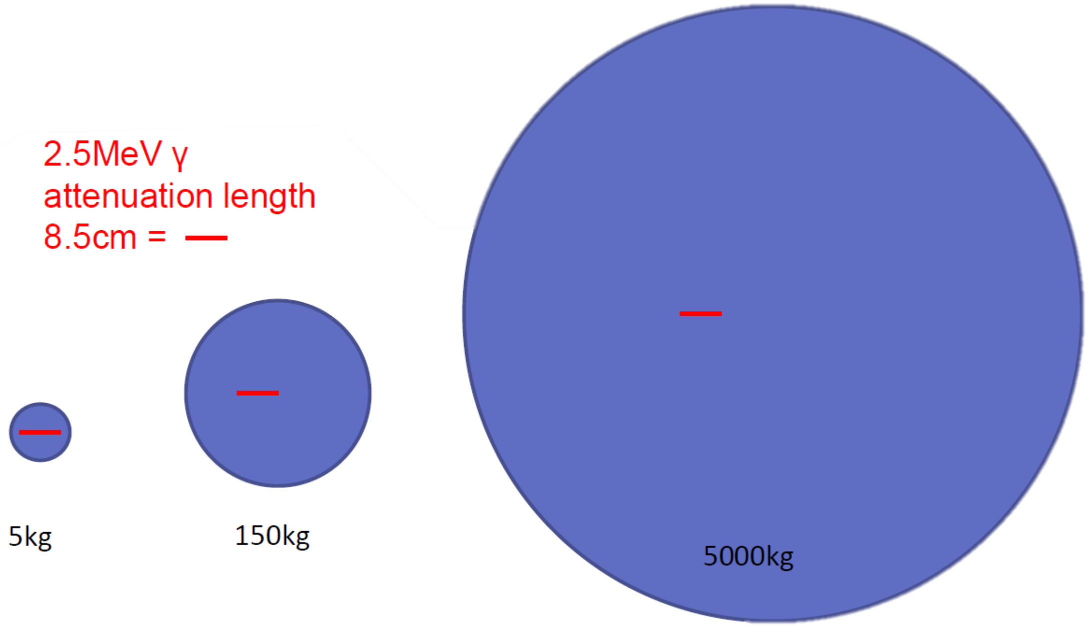
Thank you for your attention

Backup

nEXO - Homogeneity is Crucial

- Increased mass
- Taking full advantage of self shielding
  - more effective
  - Improve Compton tag efficiency by double-hit recognition

LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13



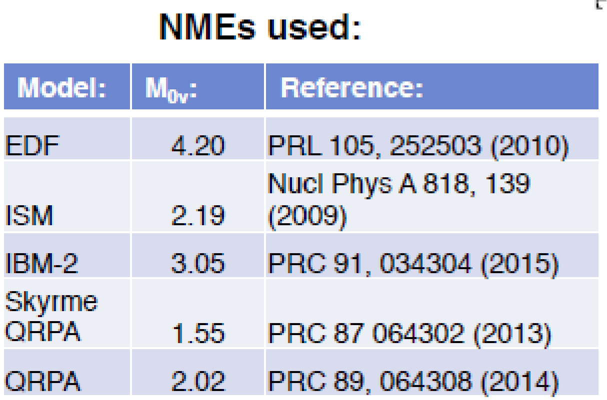
→ **Benefits of monolithic detector compared to segmented detectors**

Physics searches with EXO-200

An Optimal Energy Estimator to Reduce Correlated Noise for the EXO-200 Light Readout
C.G. Davis et al. Submitted to JINST (May 2016). arxiv:1605.06552 [physics.ins-det]
Cosmogenic Backgrounds to 0νββ in EXO-200
J.B. Albert et al., J. Cosmol. & Astropart. Phys. (JCAP) 2016 4 (2016) 029
First Search for Lorentz and CPT Violation in Double Beta Decay with EXO-200
J.B. Albert et al., Phys. Rev. D 93, 072001
Search for 2νββ decay of ^{136}Xe to the 0_1^+ excited state of ^{136}Ba with EXO-200
J.B. Albert et al., Phys. Rev. C 93, 035501
Measurements of the ion fraction and mobility of alpha and beta decay products in liquid xenon using EXO-200
J.B. Albert et al., Phys. Rev. C 92, 045504 (2015).
Investigation of radioactivity-induced backgrounds in EXO-200
J.B. Albert et al. Phys. Rev. C 92, 015503 (2015).
Search for Majoron-emitting modes of double-beta decay of ^{136}Xe with EXO-200
J.B. Albert, et al. Phys. Rev. D 90, 092004 (2014).
Search for Majorana neutrinos with the first two years of EXO-200 data
J.B. Albert, et al. Nature 510 (2014) 229-234
An improved measurement of the 2νββ half-life of Xe-136 with EXO-200
J.B. Albert, et al. Phys. Rev. C 89, 015502 (2014)
Search for Neutrinoless Double-Beta Decay in ^{136}Xe with EXO-200
M. Auger, et al. Phys. Rev. Lett. 109, 032505 (2012)
Observation of Two-Neutrino Double-Beta Decay in Xe-136 with EXO-200
N. Ackerman, et al. Phys. Rev. Lett. 107, 212501 (2011)

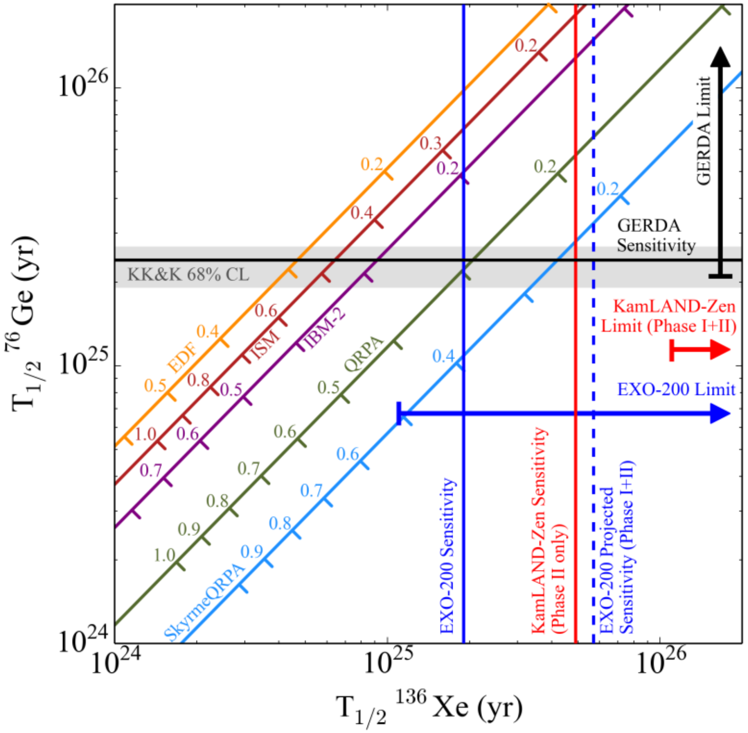
EXO-200 $0\nu\beta\beta$ search

2011	First measurement of $2\nu\beta\beta$ in ^{136}Xe [PRL 107, 212501 (2011)]
2012	First $0\nu\beta\beta$ result, best $m_{\beta\beta}$ limit [PRL 109, 032505 (2012)]
2013	Most precisely measured $2\nu\beta\beta$ rate — and the lowest →slowest process ever directly measured in nature! [PRC 89, 015502 (2014)]
2014	Improved sensitivity to $m_{\beta\beta}$ [Nature 510, 229 (2014)]



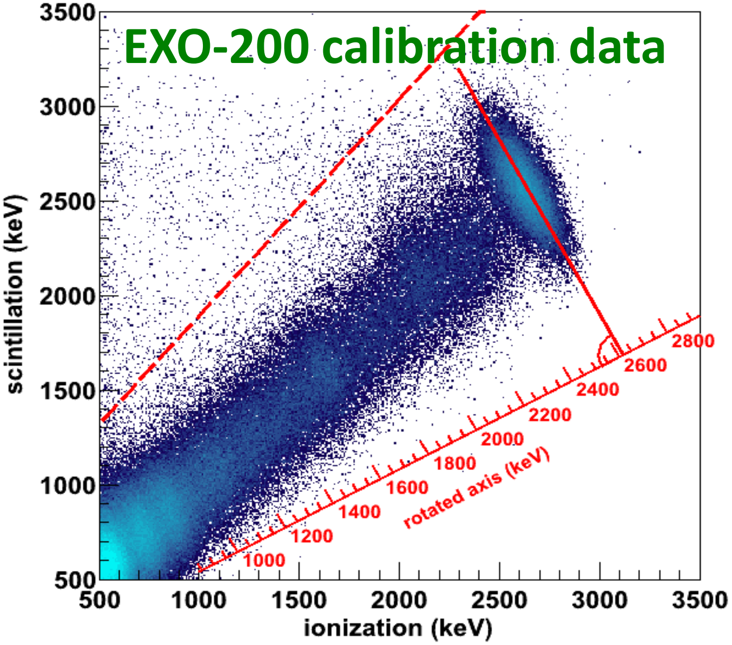
NMEs used:

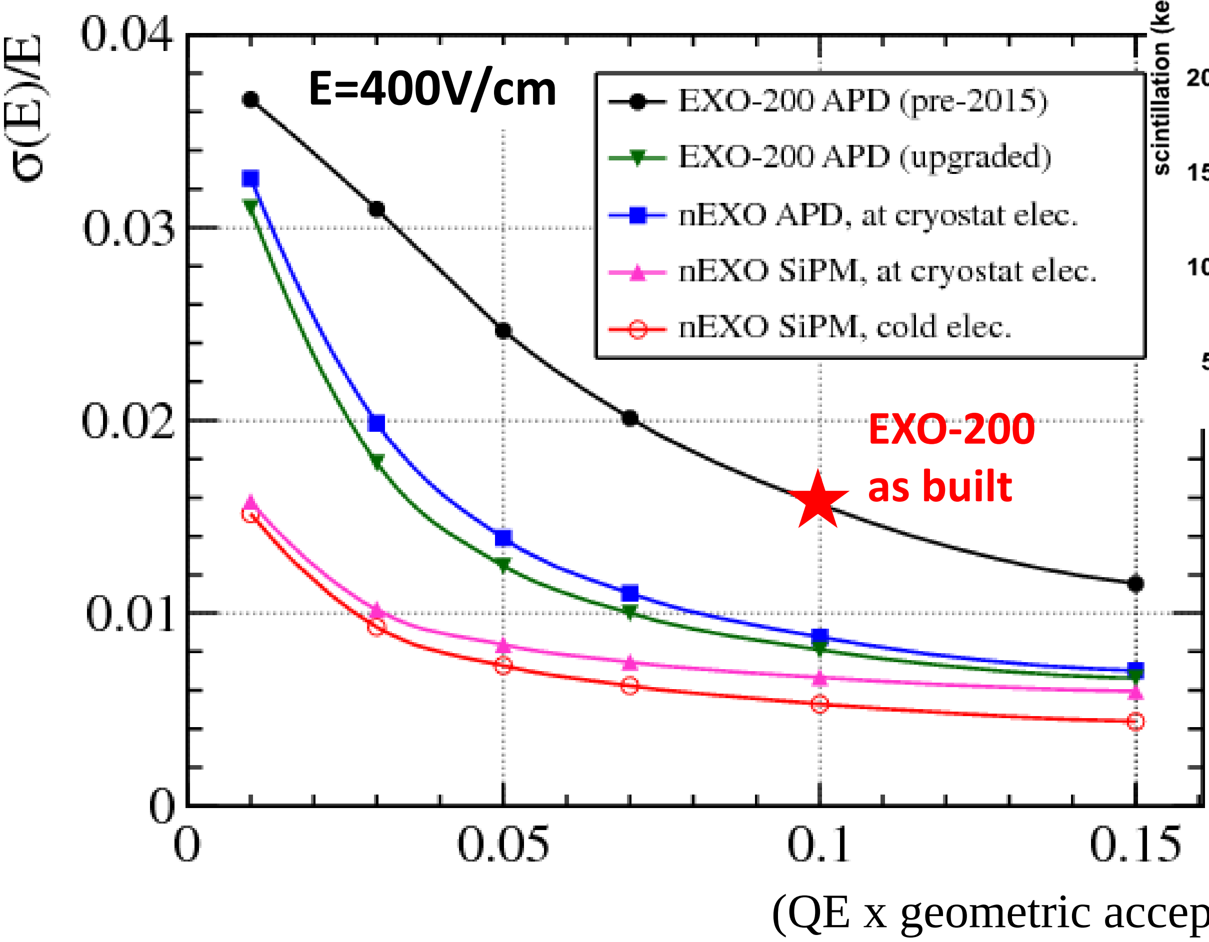
Model:	$M_{0\nu}$:	Reference:
EDF	4.20	PRL 105, 252503 (2010)
ISM	2.19	Nucl Phys A 818, 139 (2009)
IBM-2	3.05	PRC 91, 034304 (2015)
Skyrme QRPA	1.55	PRC 87 064302 (2013)
QRPA	2.02	PRC 89, 064308 (2014)



Photon Detection

Good energy resolution requires efficient readout of the scintillation light to be combined with the ionization signal





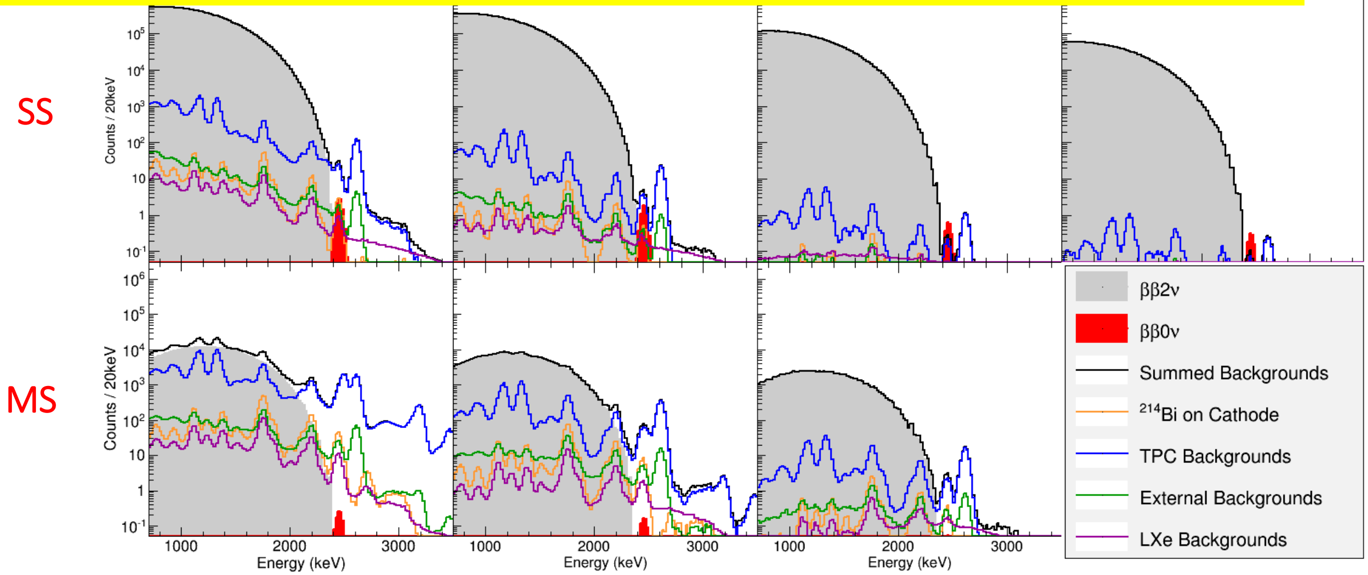
EXO-200 reaches 1.4% at $Q_{\beta\beta}$

Better than 1% resolution required for nEXO

The role of the standoff distance in background identification and suppression

Example: nEXO, 5 yr data, 0νββ @ $T_{1/2}$=6.6x10^{27} yr,
projected backgrounds from subsets of the total volume

Fid. LXe Mass = 4780kg 3000kg 1000kg 500 kg



The fit gets to see all this information and use it in the optimal way