Status of the EXO-200 double beta decay search at WIPP

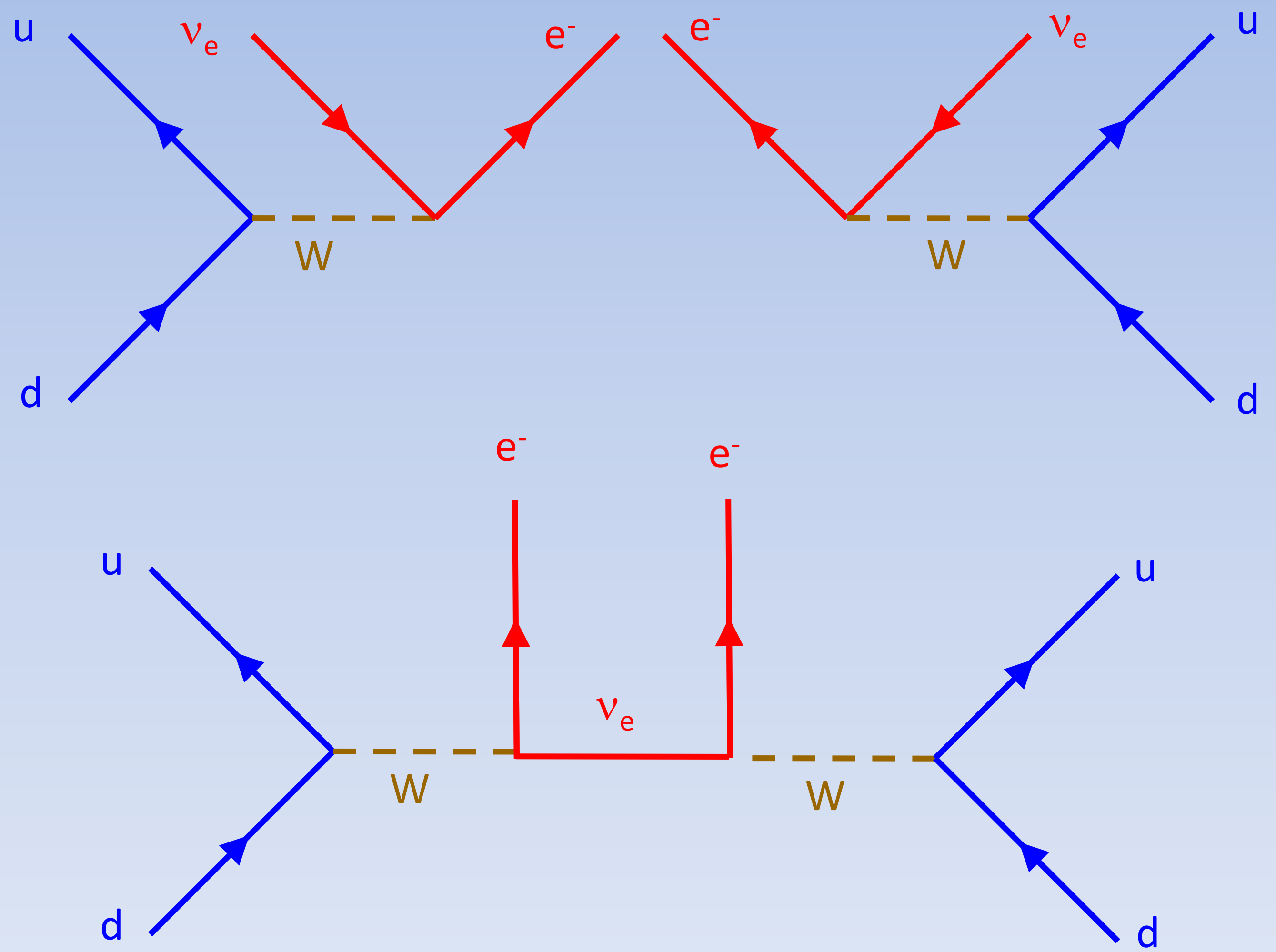
THE UNIVERSITY OF ALABAMA

Ryan MacLellan

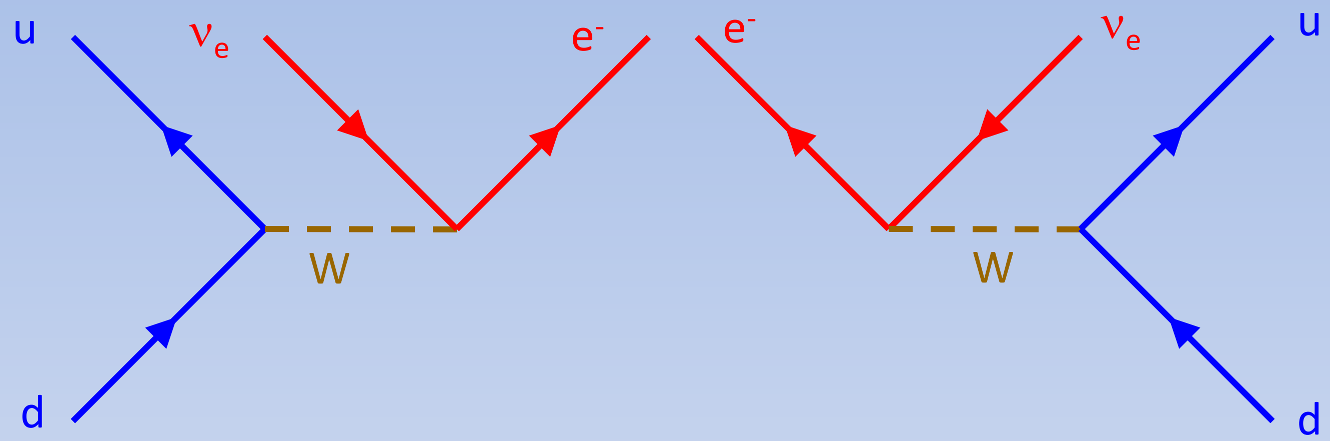
for the EXO Collaboration

Recontres de Moriond EW 2012

Favorite double beta decay channels



$2\nu\beta\beta$



$\Delta B=0$	Baryon number conserving
$\Delta L=0$	Lepton number conserving
$\Delta(B-L)=0$	Baryon – lepton number conserving

Standard model second order weak process

Dominant decay mode for some even-even nuclei

Directly observed for ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{130}Te, ^{136}Xe, and ^{150}Nd

with $t_{1/2} = 7 \times 10^{18}$–$2 \times 10^{21}$ yr

0νββ

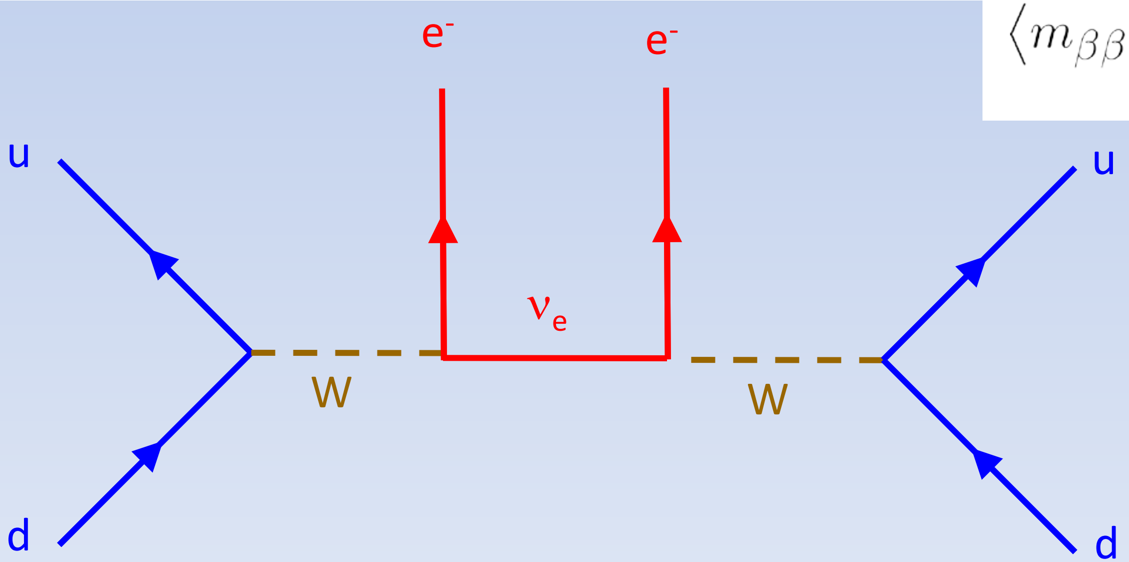
ΔB=0	Baryon number conserving
ΔL=2	Lepton number violating
Δ(B – L)= –2	Baryon – lepton number violation

Neutrinos are Majorana in nature

Majorana mass given by: $$\left(t^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

where

$$\langle m_{\beta\beta}\rangle^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$$

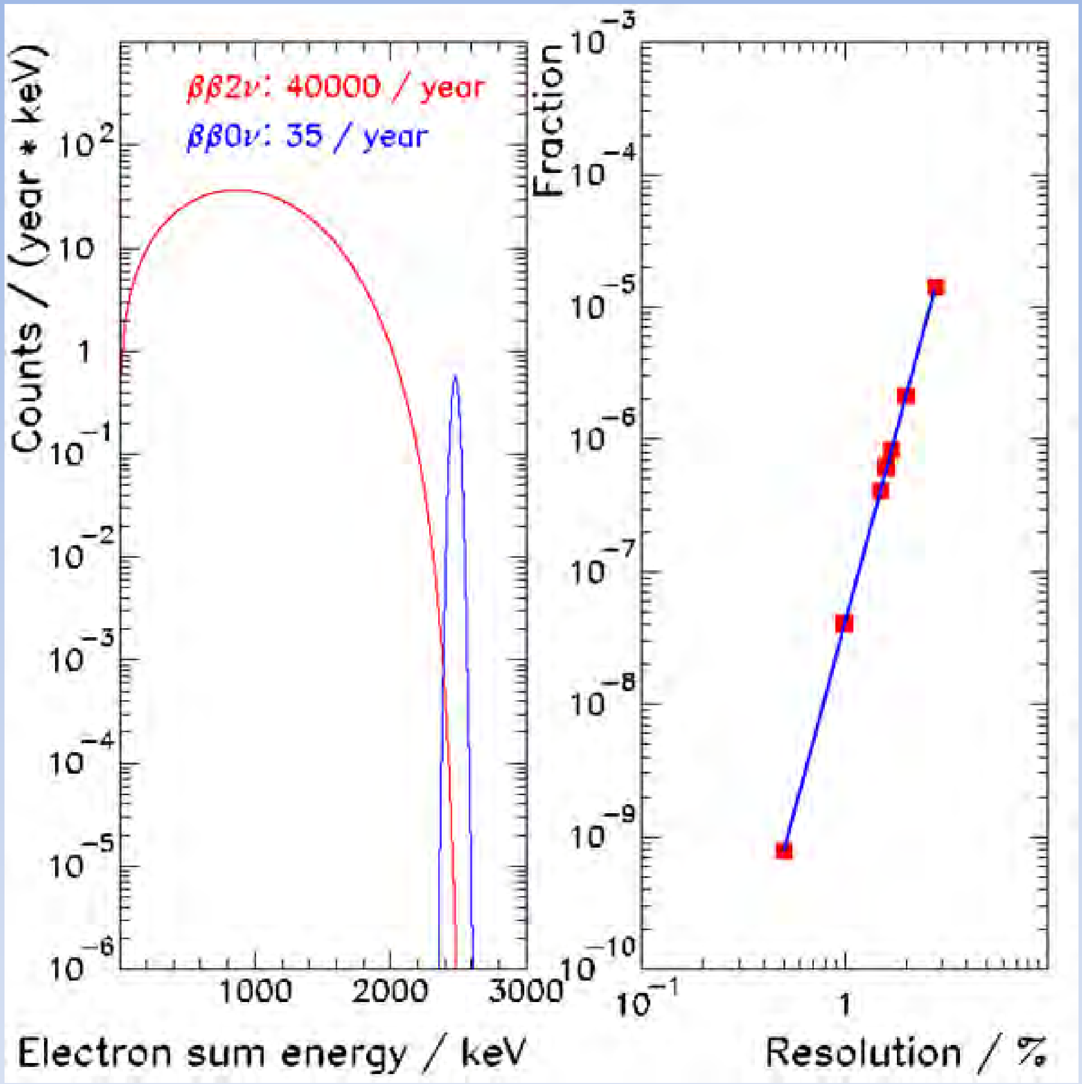


Distinguishing ^{136}Xe decay channels

Only by electron energy sum.

On the left: experimental limit on 2νββ rate + 0νββ claim with 1.5% energy resolution.

On the right: leakage of 2νββ events into the 0νββ peak increases with resolution to the 6th power!

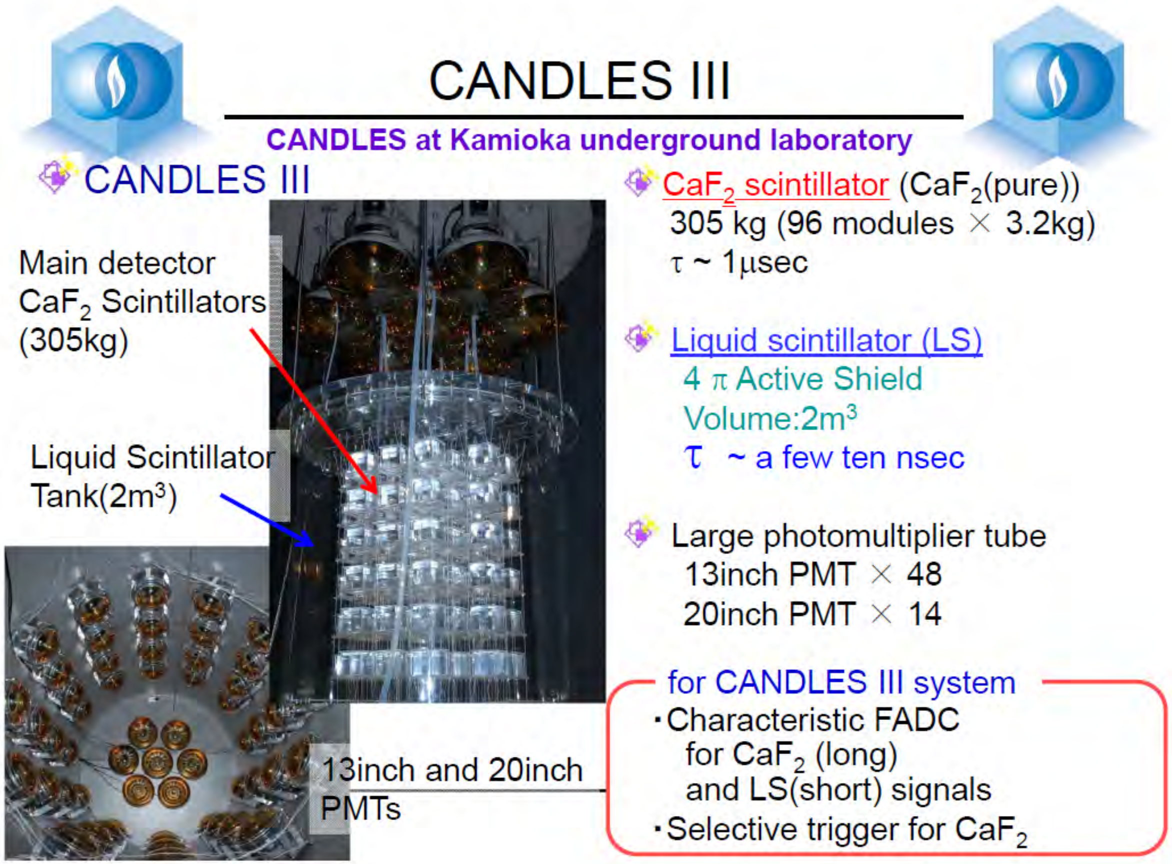


ββ-decay experiments

	Nuclide	Q [MeV]	Principle	Det mass [kg]	Decay mass [kg]	Site
CANDLES	^{48}Ca (0.19%)	4.271	CaF_2 scint.	305	3.2	Kamioka
Cobra	^{116}Cd (90%)	2.802	CdZnTe semicond.	420	142	LNGS
CUORE	^{130}Te (34%)	2.527	Bolometer	740	200	LNGS
EXO-200	^{136}Xe (80%)	2.458	Liquid TPC	120	96	WIPP
EXO	^{136}Xe (80%)	2.458	Liquid/gas TPC final state tag	10^3–10^4	800-8000	SNOLab
GERDA	^{76}Ge (86%)	2.039	Ge semicond.	40	34	LNGS
KamLAND	^{136}Xe (90%)	2.458	Liquid. scint.	400	360	Kamioka
MAJORANA	^{76}Ge (86%)	2.039	Ge semicond.	60-1000	52-860	SUSEL
MOON	^{100}Mo (90%)	3.034	Source foil plastic scint.	480	430	Oto
SNO+	^{150}Nd (5.6%)	3.367	Liquid. scint.	780	44	SNOLab
Super NEMO	^{82}Se	2.995	Source foil tracking & scint	100+		Frejus

ββ-decay experiments: Candles III

currently performance testing detectors



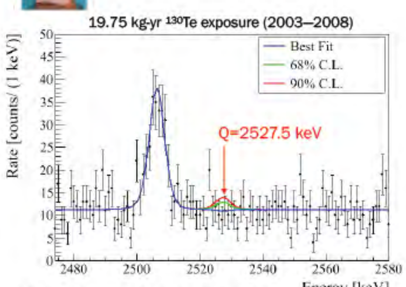
ββ-decay experiments: CUORE

fully operation in 2014

Cuoricino → CUORE-0 → CUORE

Cuoricino (2003-2008):
44 5x5x5 cm^3 and 18 3x3x6 cm^3 TeO_2 crystals
detector mass 40.7 kg
^{130}Te mass 11.3 kg
standard dilution refrigerator

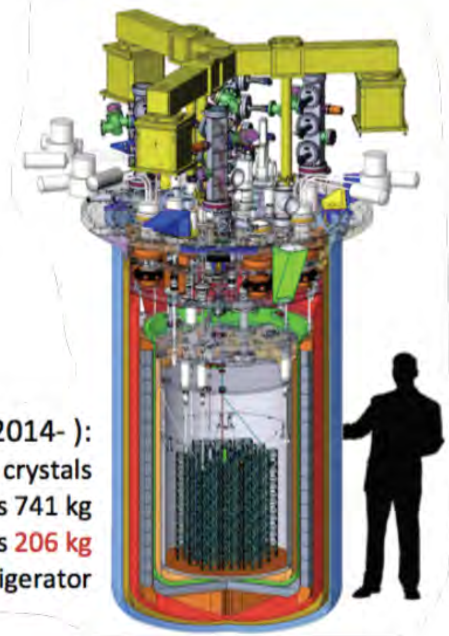
Cuoricino set a limit of
$T_{1/2}$ > 2.8 x 10^{24} y (90% C.L.)
on the 0νββ of ^{130}Te
$\langle m_{\beta\beta} \rangle$ < 300-710 meV *
19.75 kg-yr exposure



* E.Andreotti et al. (CUORICINO collaboration), Astropart. Phys. 34: 822-831 (2011)

CUORE-0 (2012-2014):
the first CUORE-like tower
52 5x5x5 cm^3 TeO_2 crystals
detector mass 39 kg
^{130}Te mass 11 kg
refurbished Cuoricino cryostat

CUORE (2014-):
988 5x5x5 cm^3 TeO_2 crystals
detector mass 741 kg
^{130}Te mass 206 kg
cryogen-free dilution refrigerator



<u>CUORE goals</u>
5 keV FWHM resolution
0.01 c/keV/kg/yr bkgnd
5 yr livetime

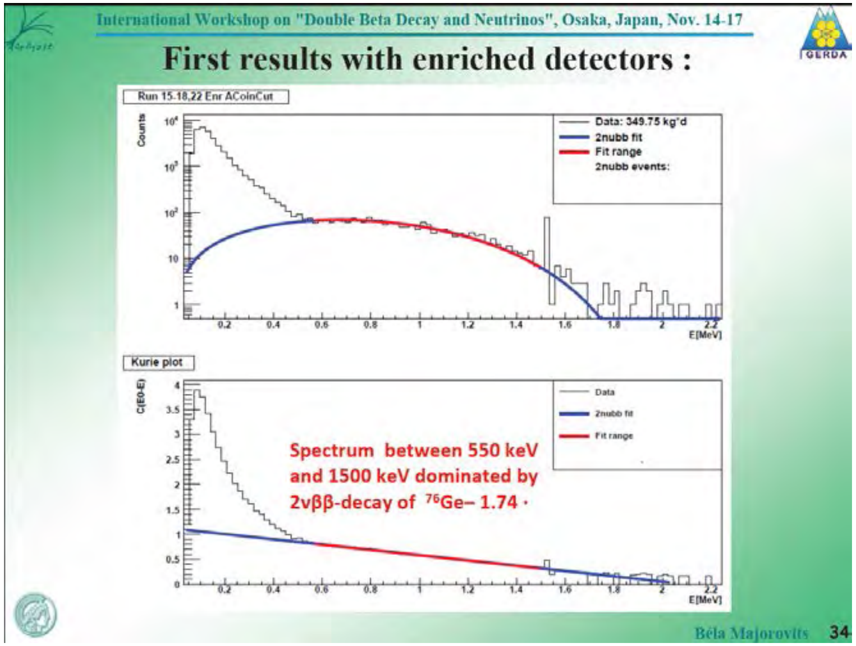
→

$T_{1/2}^{0\nu}(^{130}Te)$ > 1.6e26 y (68% CL)
$m_{\beta\beta}$ < 41-95 meV

$T_{1/2}^{0\nu}(^{130}Te)$ > 9.5e25 y (90% CL)
$m_{\beta\beta}$ < 52-120 meV

ββ-decay experiments: GERDA

- Bare H-M ^{76}Ge enriched crystals suspended in liquid argon shielding/cooling
- First results confirm $2\nu\beta\beta$ observations
- Next phase new BEGe detectors with better pulse shape discrimination and LAr veto
- Very careful to avoid surface activation of ^{68}Ge



Lifted from Béla Majorovits

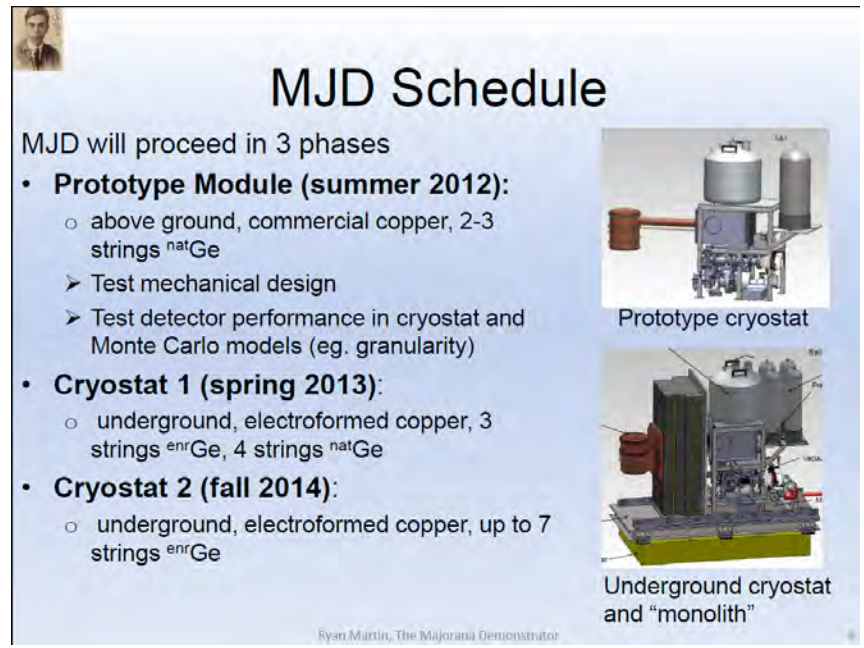
ββ-decay experiments: GERDA

- Bare H-M ^{76}Ge enriched crystals suspended in liquid argon shielding/cooling
- First results confirm 2νββ observations
- Next phase new BEGe detectors with better pulse shape discrimination and LAr veto
- Very careful to avoid surface activation of ^{68}Ge

Lifted from Béla Majorovits

ββ-decay experiments: Majorana

- Enriched germanium being processed into detector grade
- PPC Ge detectors that lead into next phase of GERDA
- Moving things into the underground lab this month (prototype module)
- Growing electroformed copper underground since last July "EXO-200 copper not good enough for Majorana"

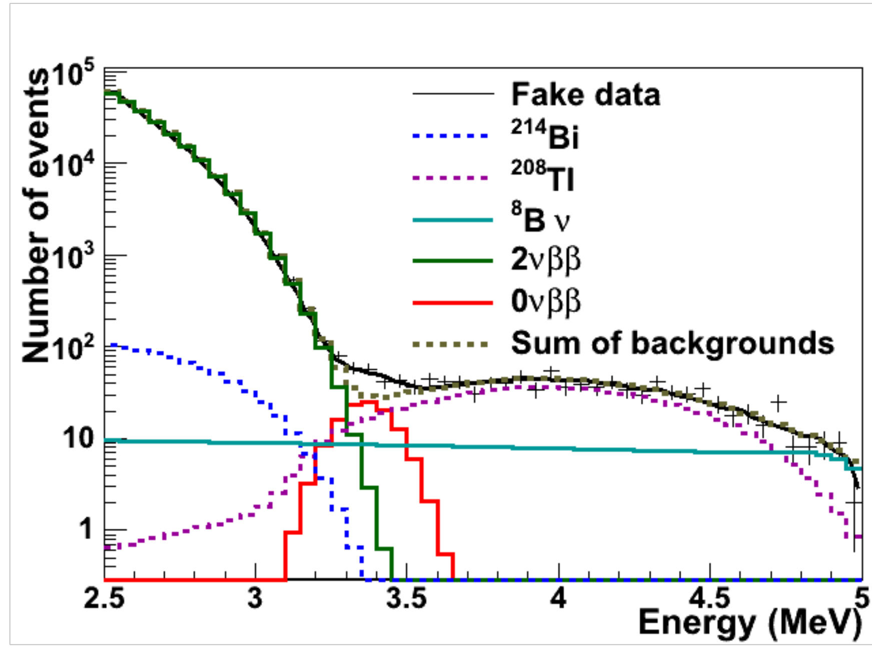


Courtesy Ryan Martin

Neutrinoless ββ-decay

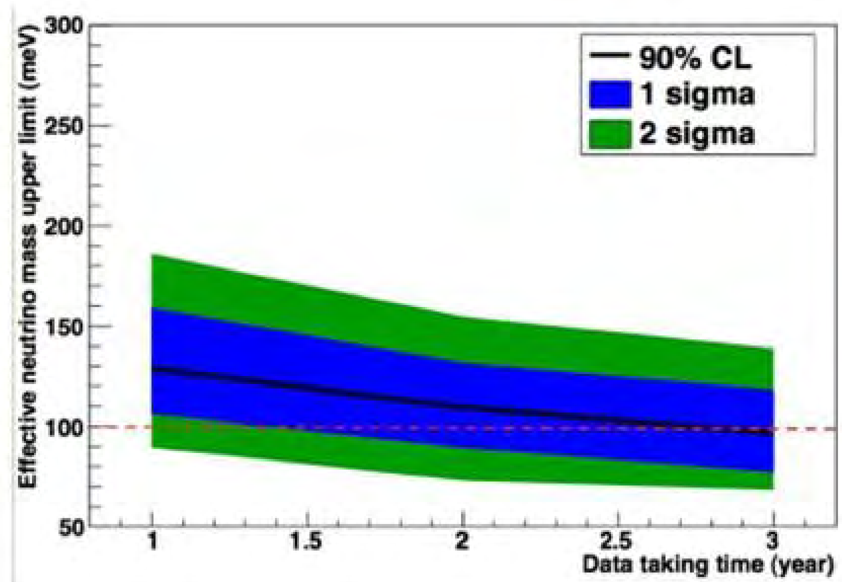
Courtesy Mark Chen

ββ-decay signal for 0.1% Nd loaded scintillator



- signal at the level of Klapdor [Phys. Lett. B 586 (2004) 198]
- ~2 years live time
- ^{214}Bi can be tagged and removed
- constrain ^{208}Tl with ^{212}Bi-Po delayed coincidence
- 3 min alpha tag of ^{208}Tl under study

Neutrino mass sensitivity for 0.3% Nd loading.

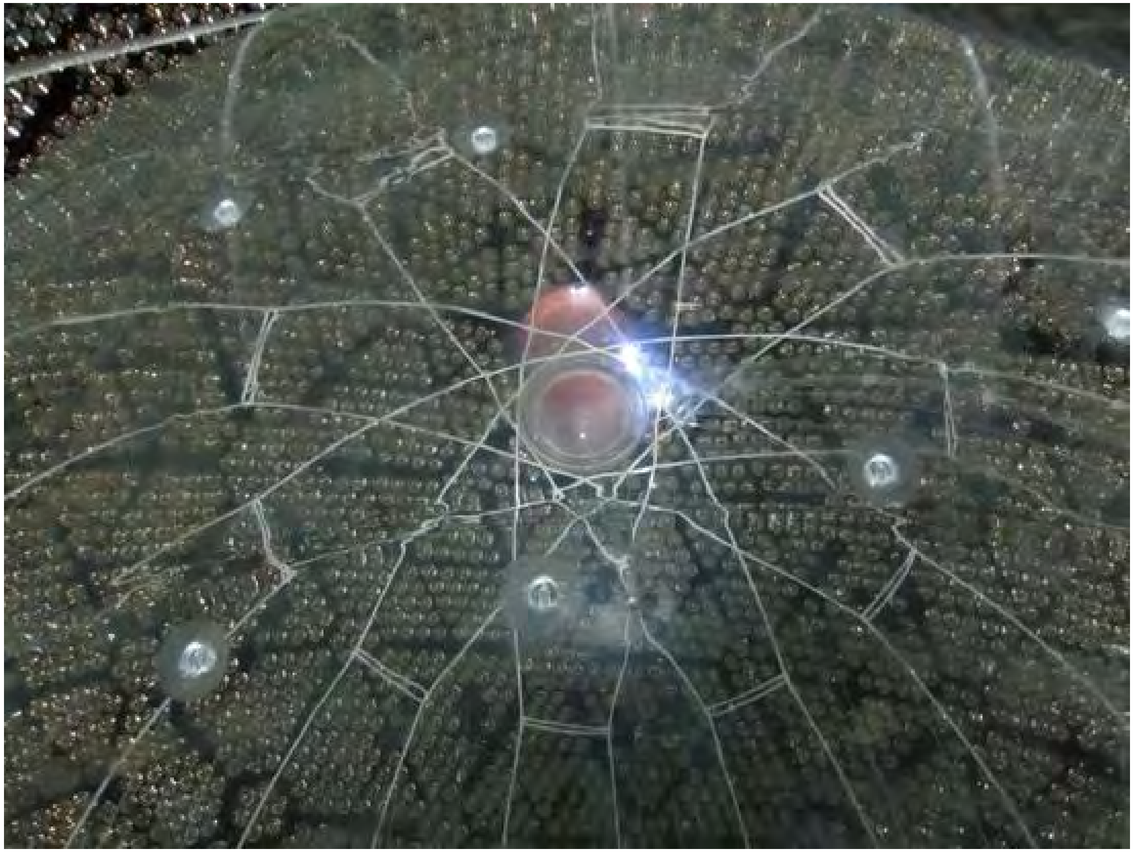


- IBM-2 [Phys. Rev. C 79 (2009) 044301] NME values were used (includes deformation)
- radioactivity backgrounds at the levels achieved by Borexino

Courtesy Mark Chen

SNO+ Status and Schedule

- Acrylic Vessel Hold Down Net installed
- New SNO+ Electronics and DAQ being tested
- Water fill and detector commissioning starting mid-2012
- Scintillator purification and process systems installed: end of 2012
- Scintillator fill and data taking in early 2013
- addition of Nd to the scintillator soon thereafter



EXO suite of experiments

^{136}Xe as both target and detector

$$^{136}\mathrm{Xe} \rightarrow ^{136}\mathrm{Ba}^{++} + 2e^{-}\ (+2\nu_e)$$

First phase: currently operating EX0–200 on the 200 kg scale

- Liquid xenon enriched to 80% in ^{136}Xe
- Demonstrate feasibility of ton-scale xenon ββ-decay experiment
- Test KKDC claim
- Probe Majorana mass down to 100 meV scale

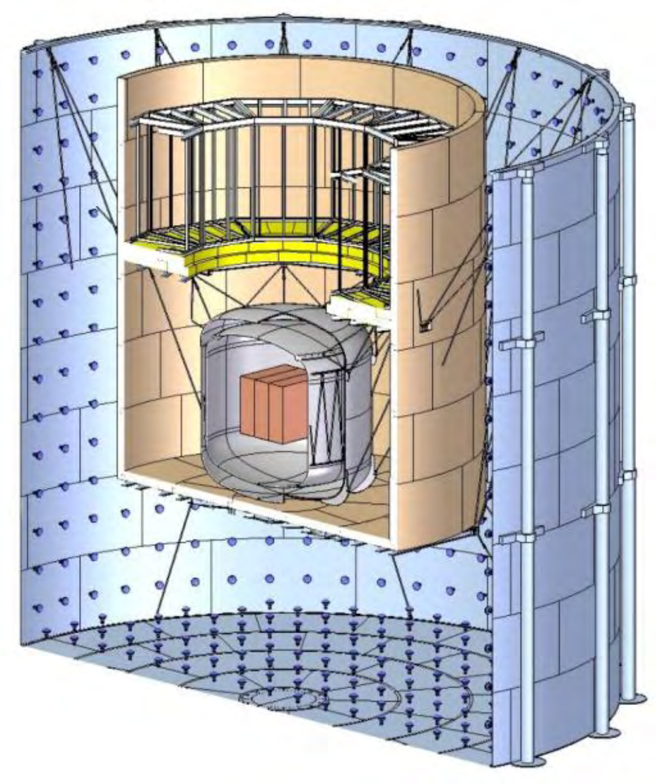
EXO suite of experiments

^{136}Xe as both target and detector

Second phase: EXO–full (or full–EXO) at the 1–10 ton scale

- Liquid or gaseous xenon (NEXT) enriched in ^{136}Xe 0νββ
- Probe Majorana mass down to the 5–20 meV scale
- Tag barium, daughter nucleus to eliminate all backgrounds other than that from 2νββ decay of ^{136}Xe
- Observe 0νββ

$$^{136}\mathrm{Xe} \rightarrow ^{136}\mathrm{Ba}^{++} + 2e^- \; (+2\nu_e)$$



Making the case for xenon

Generically, the case for studying another $\beta\beta$-decay candidate:

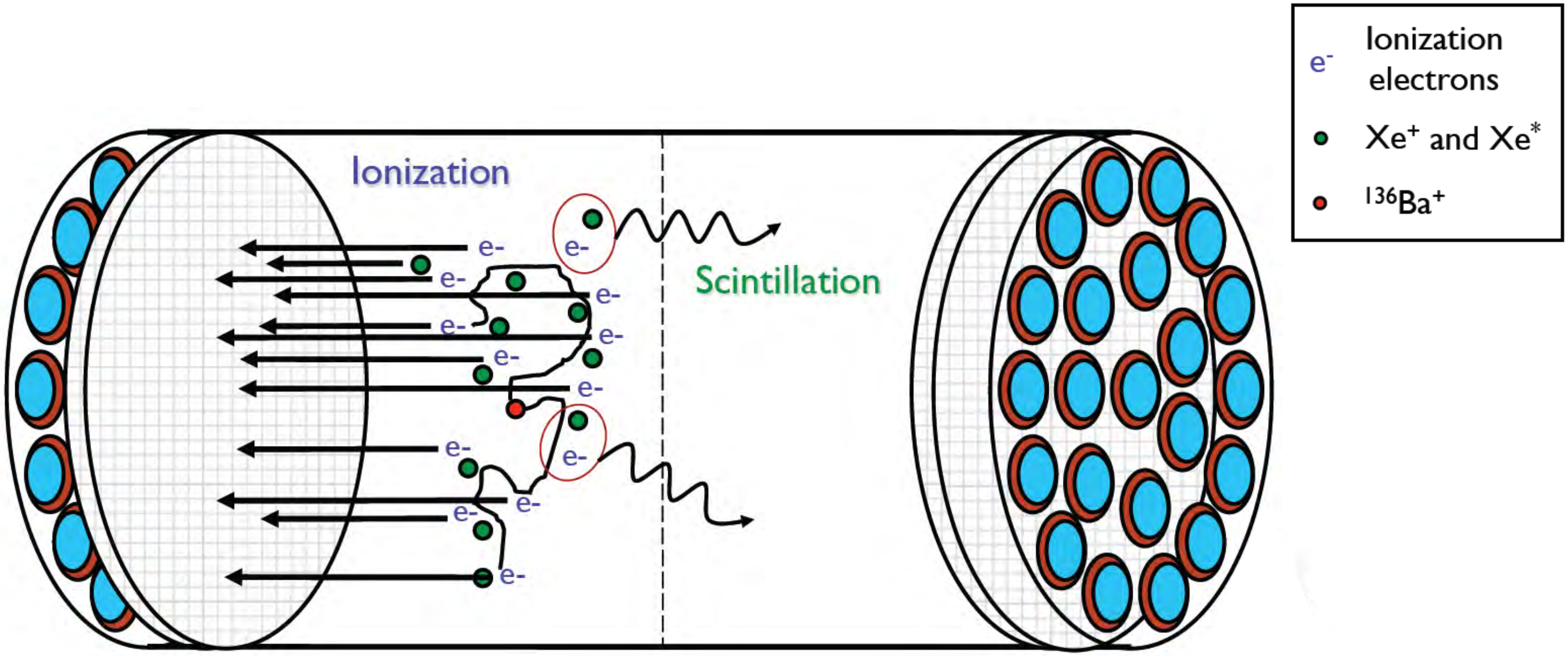
- Nuclear matrix elements are not well known
- Mechanism that facilitates $\beta\beta0\nu$ may require analysis of more than one isotope
- Many unknown γ–ray transitions that could be confused with a $\beta\beta0\nu$ signal

Specifically for xenon:

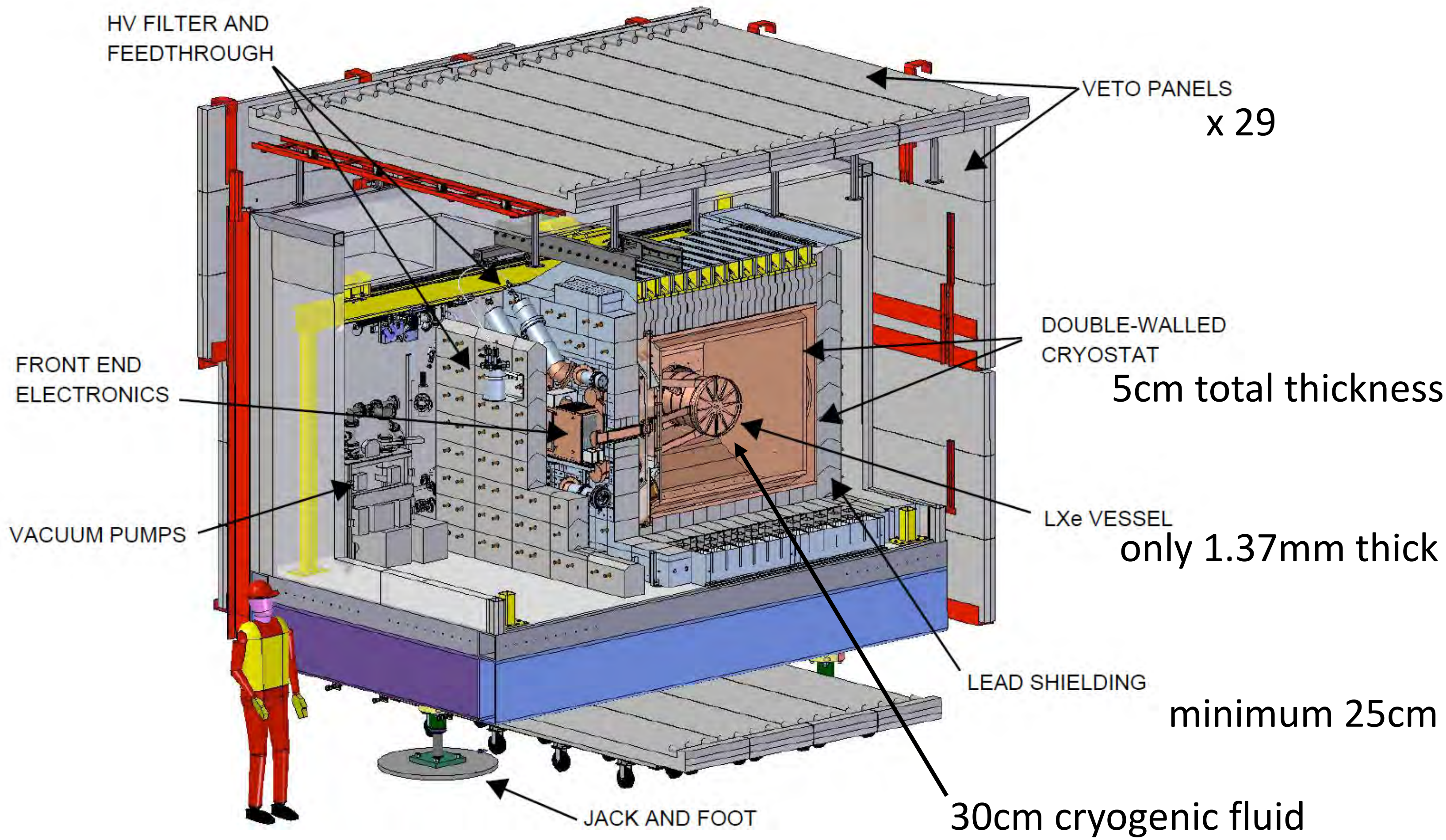
- Relatively easy to enrich
- Nobel gas can be continuously purified during the experiment
- No long-lived xenon isotopes
- $\beta\beta2\nu$ background is relatively low
- Potential to tag ^{136}Ba daughter nucleus

The EXO–200 signal collection

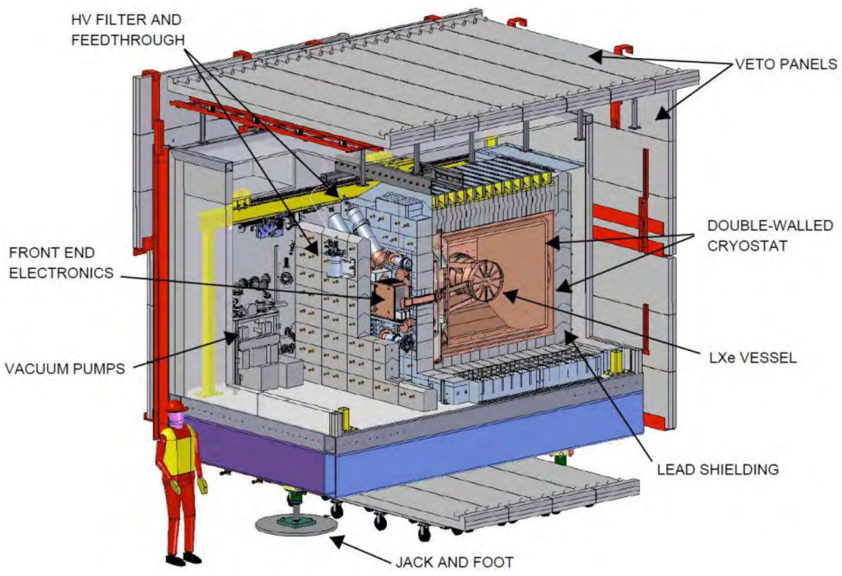
Dual channel: ionization (charge) and scintillation (light)



The EXO–200 detector

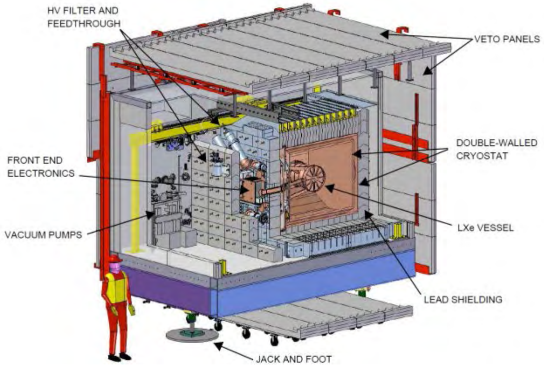


The EXO–200 detector

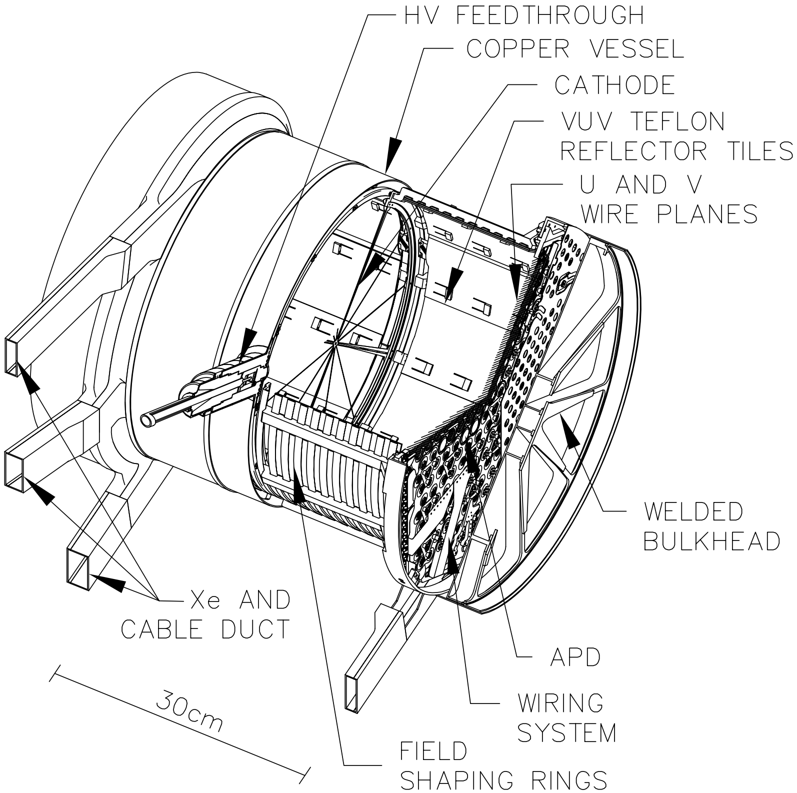


- situated 2150ft (1600 mwe) underground for cosmic ray shielding
- muon veto system outside clean rooms: ~4π x 4/6 coverage equates to ~96% efficiency for μ traversing TPC
- TPC surrounded by 50 cm (4 tonnes) HFE7000 cryogenic shielding fluid
- 5cm low-radioactivity Cu cryostat and 25 cm Doe Run Pb

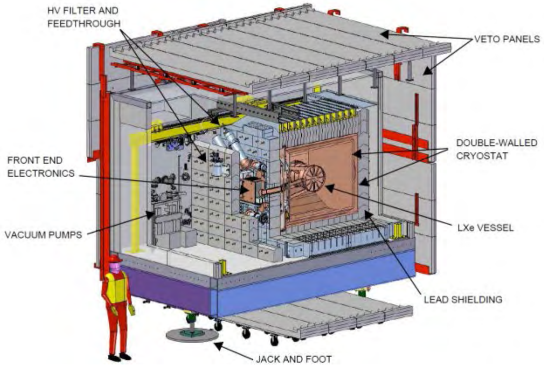
arXiv:1202.2192v1 [physics.ins-det] 10 Feb 2012



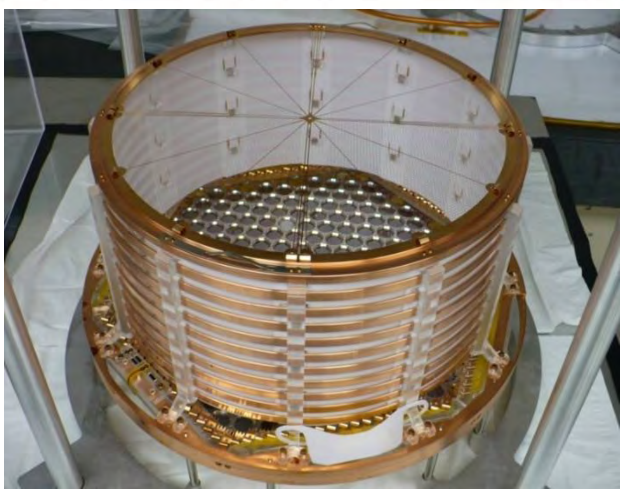
The EXO–200 detector



- 175 kg xenon enriched to 80.6% in ^{136}Xe
- liquid phase xenon at a temperature of 167.0±0.1 K
- xenon is both source of 0νββ and detector
- continuous Xe recirculation through commertial purifier

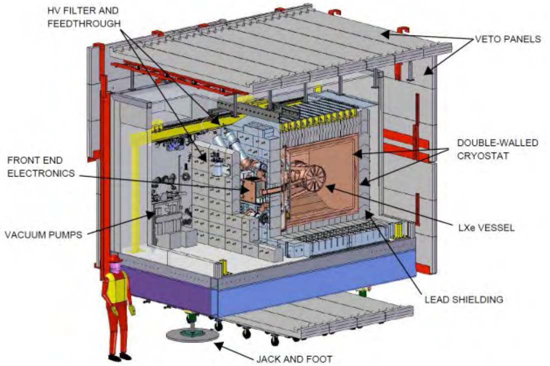


The EXO–200 detector



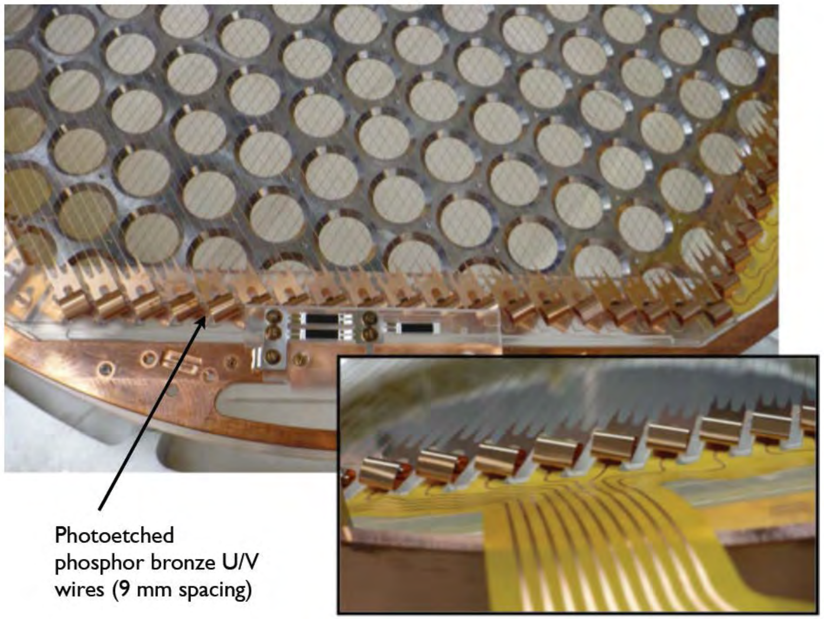
- 1.37mm thin walled TPC
- cathode spider plane centered between two sides of TPC
- 468 avalanche photodiodes (LAAPDs) detect scintillation light
- APDs ganged in groups of 7 for a total of 67 channels

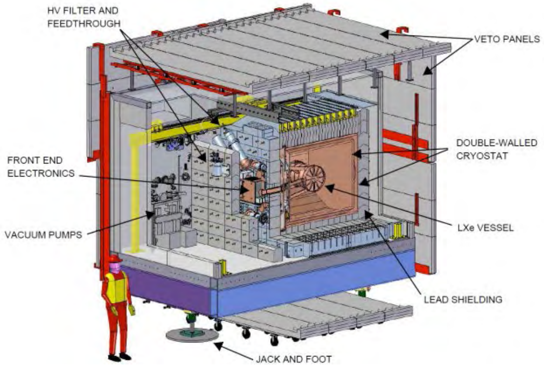
arXiv:1202.2192v1 [physics.ins-det] 10 Feb 2012



The EXO–200 detector

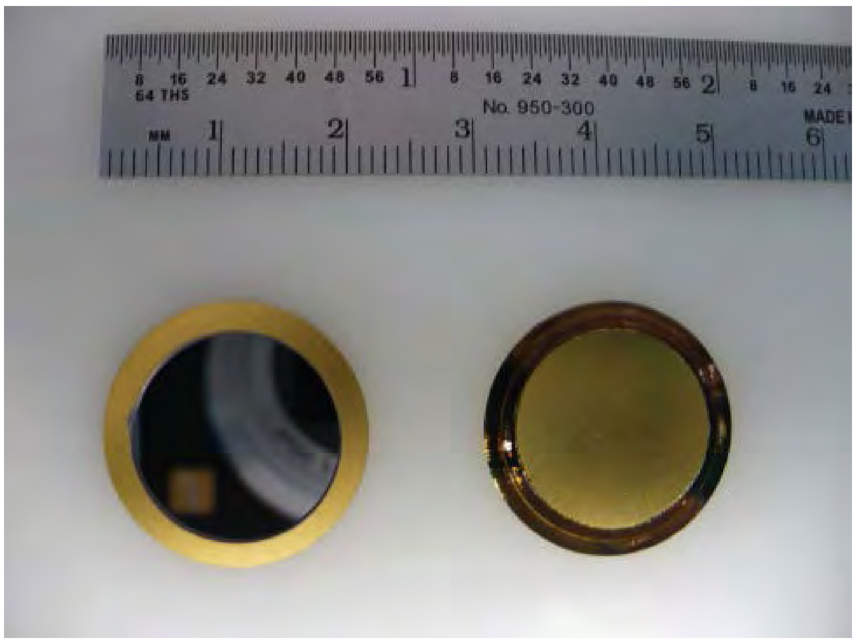
- 38x38 crossed U/V wire channels per side of TPC detect ionization charge for a total of 152 channels
- each wire channel consists of three wires with 3mm spacing
- to improve charge collection
- wires channels are spaced at 9 mm intervals
- low background custom readout cables





Nielson, R. et al., NIM A 608, 1 (2009)

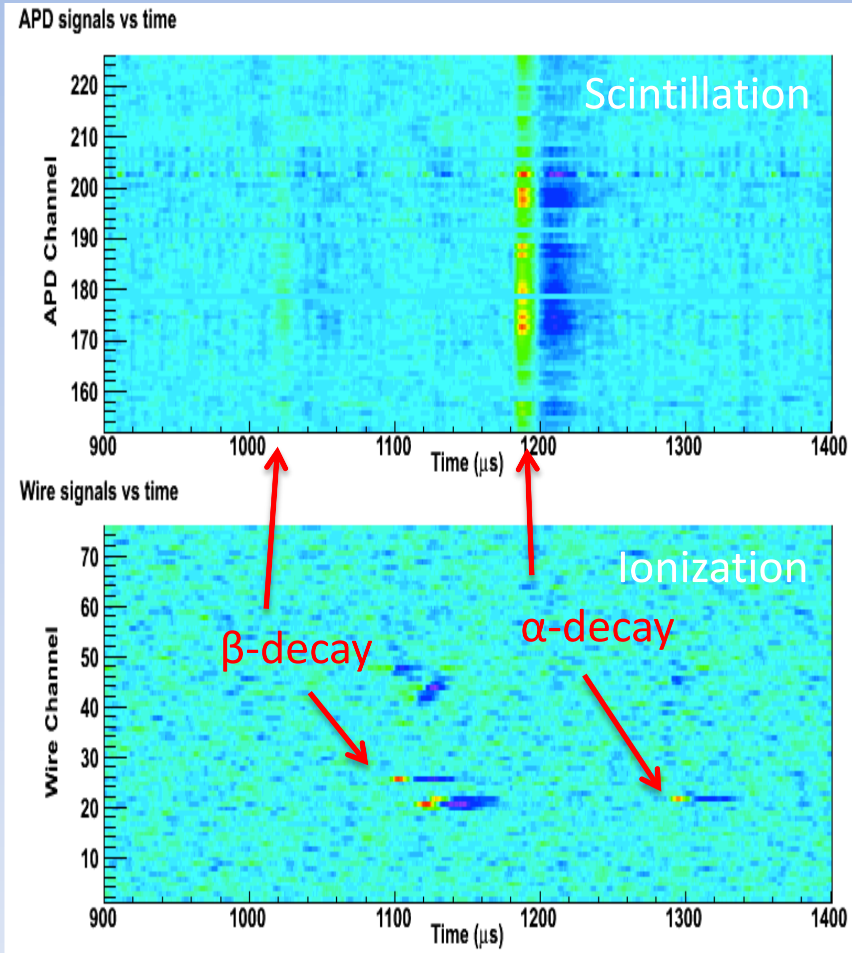
The EXO–200 APDs

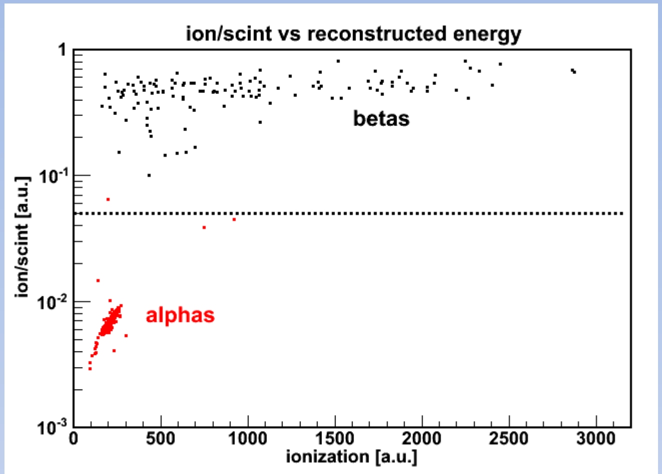


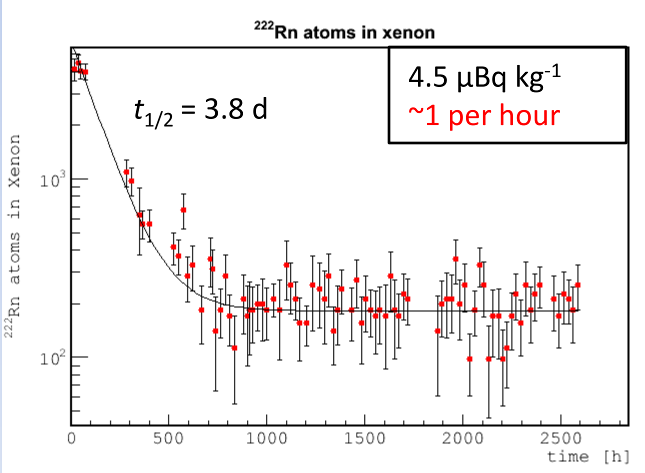
- Made by Advanced Photonix
- Low radioactivity construction using EXO supplied chemicals and metals
- mass ~ 0.5 g/LAAPD
- 16mm active diameter per LAAPD
- PE yield per photon >1 at 175 nm
- Capacitance ~ 200 pF at 1400 V
- V ~ 1500 V, Gain ~ 200
- ΔV < +/- 0.5 V
- ΔT < +/- 0.1K (requirement for temperature stability)
- leakage current of array < 1μA

Radon: ^{214}Bi – ^{214}Po correlations

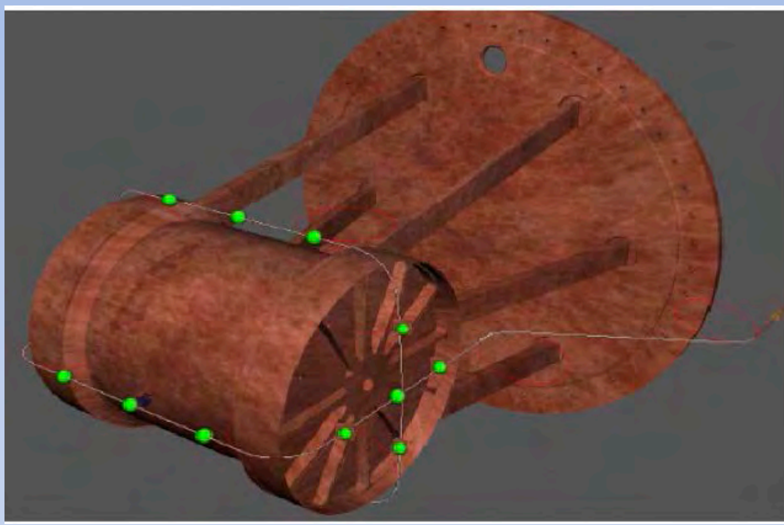
U/V charge signal and relative timing between charge and light give 3 coordinates of event



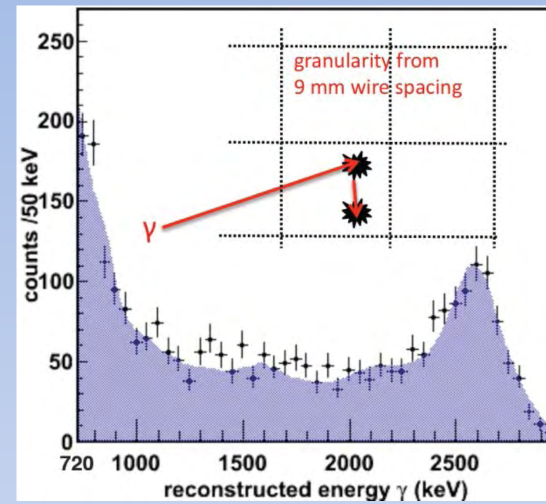


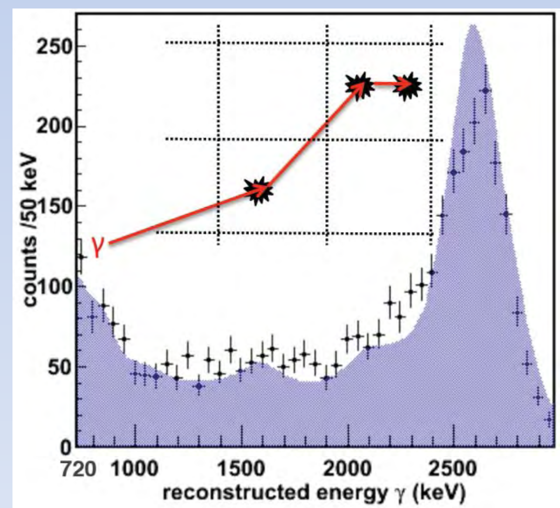


EXO–200 calibration



Calibration source locations



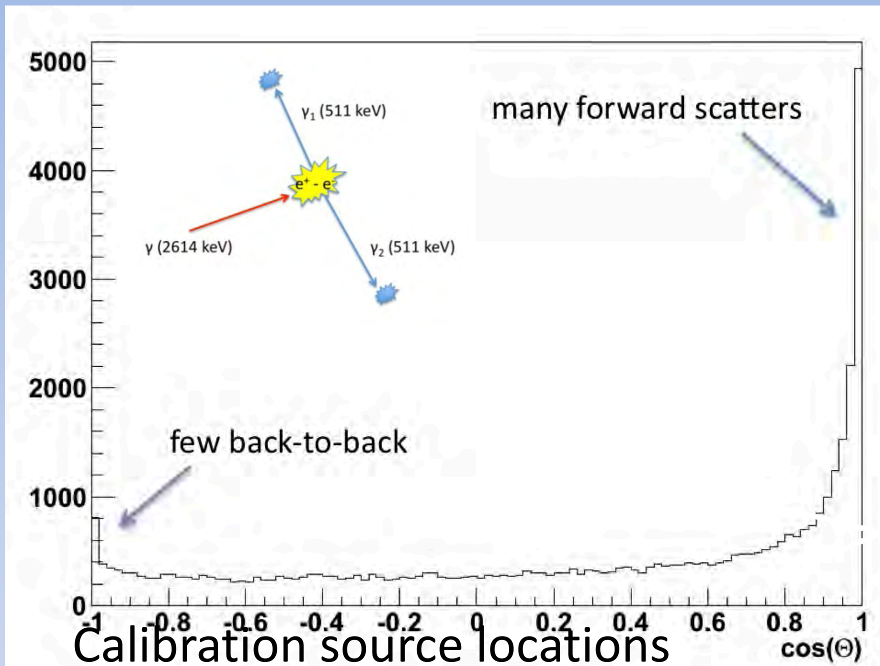


Sources:

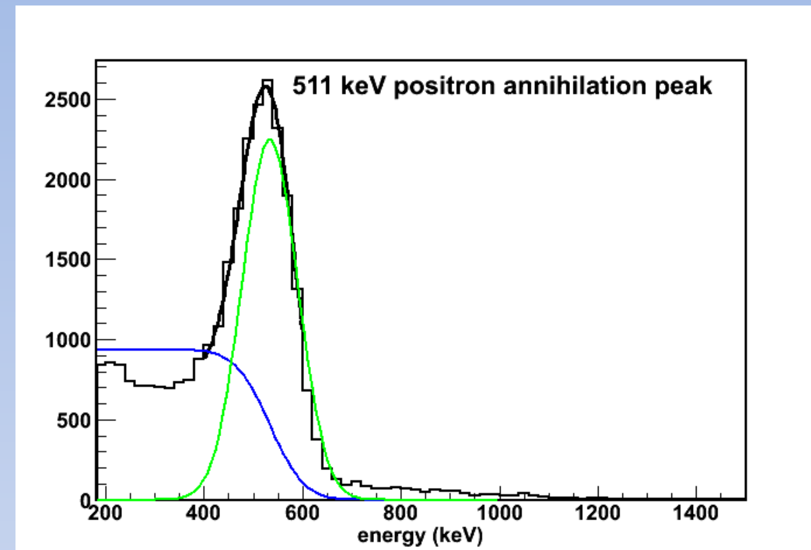
^{137}Cs, ^{60}Co, ^{228}Th

Custom designed, miniature source

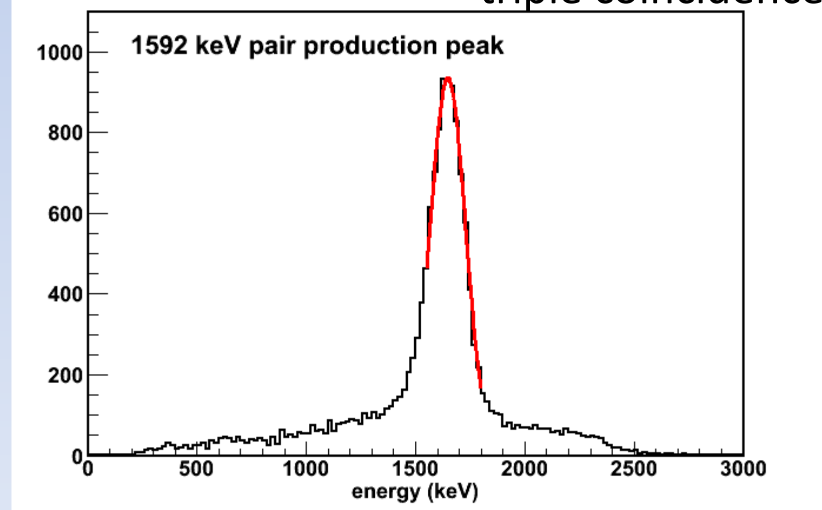
EXO–200 calibration



Calibration source locations



triple coincidence



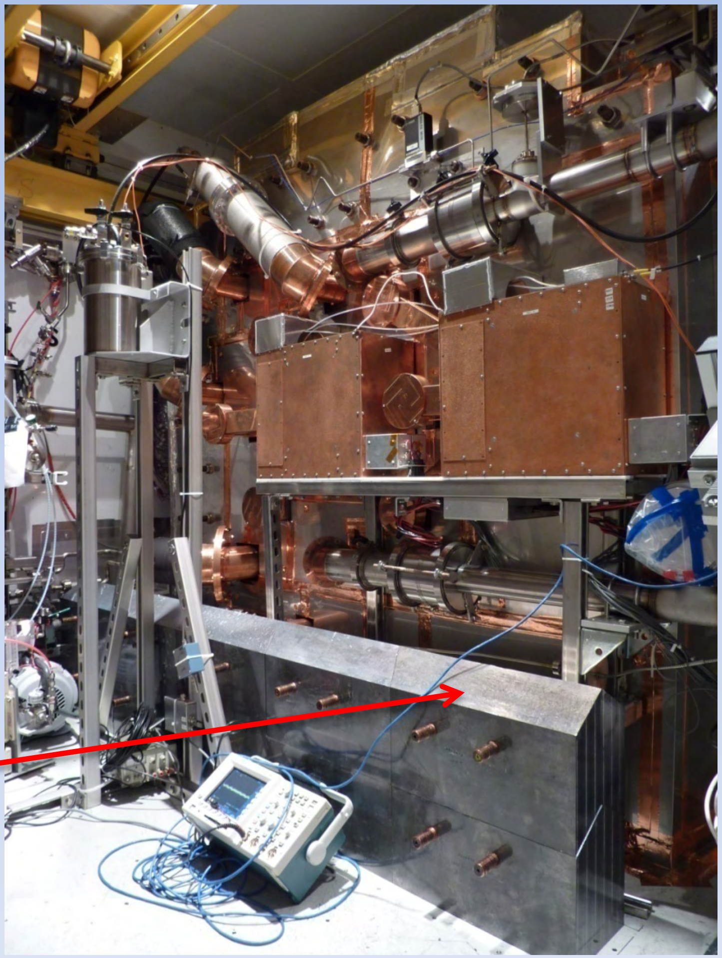
Sources:

^{137}Cs, ^{60}Co, ^{228}Th

Custom designed, miniature source

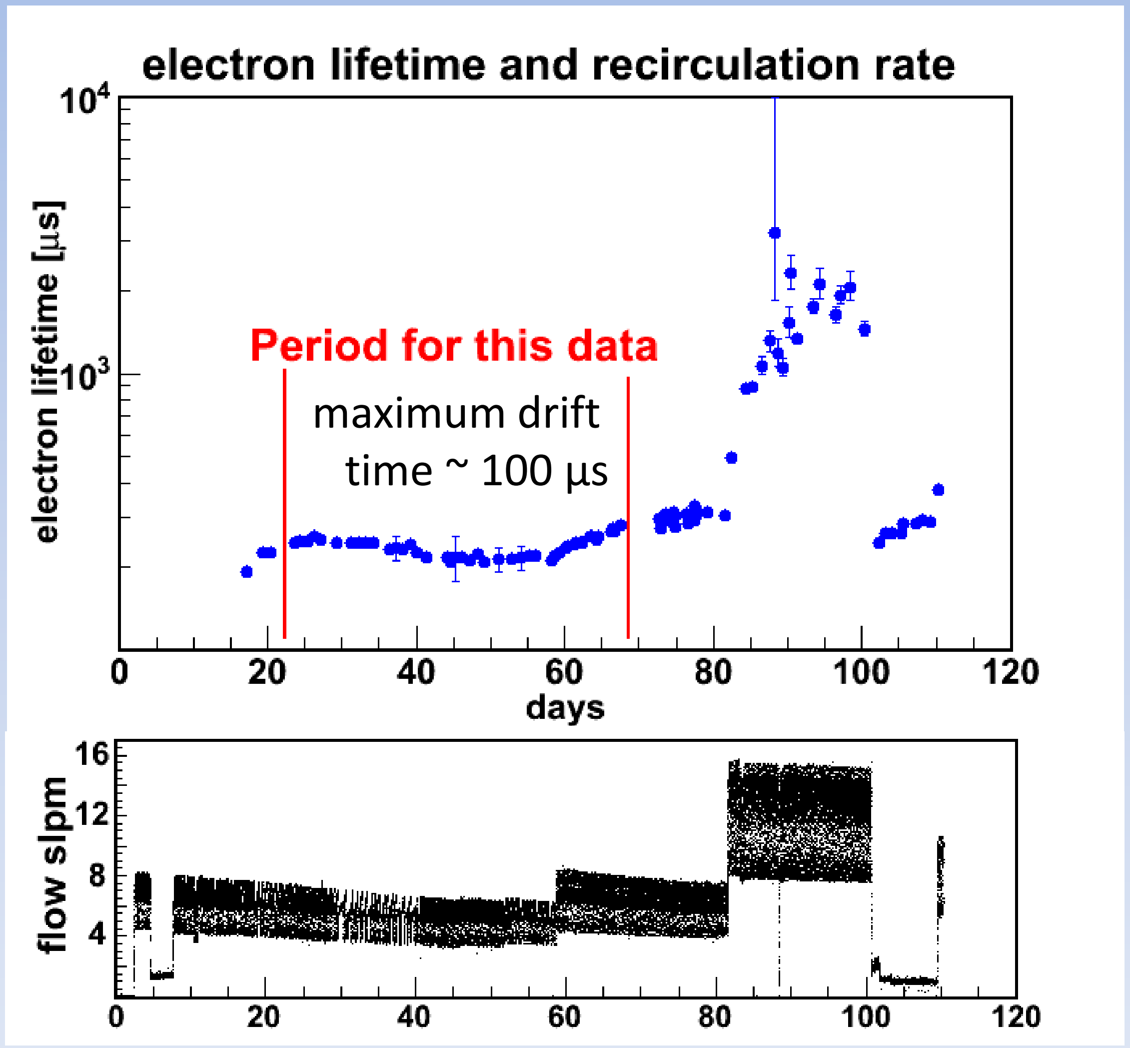
EXO–200 enriched low-background run in 2011

- EXO–200 filled with Enriched Xe; data taking began in spring 2011
- Drift field: E = -376 V/cm
- 31 live days
- Source calibration ~ 2 hrs each day to monitor purity, resolution, calibration, other detector effects
- Continuous xenon recirculation through commercial SAES purifiers at ~ 5 SLPM producing liquid xenon purity 210–280 μs
- Conservative fiducial volume ~ 63 kg chosen to reduce external low energy backgrounds
- Data collected were used for immediate measurement of the $2\nu\beta\beta$ $t_{1/2}$ of ^{136}Xe and to begin energy resolution studies
- Scintillation light for position reconstruction and PID only



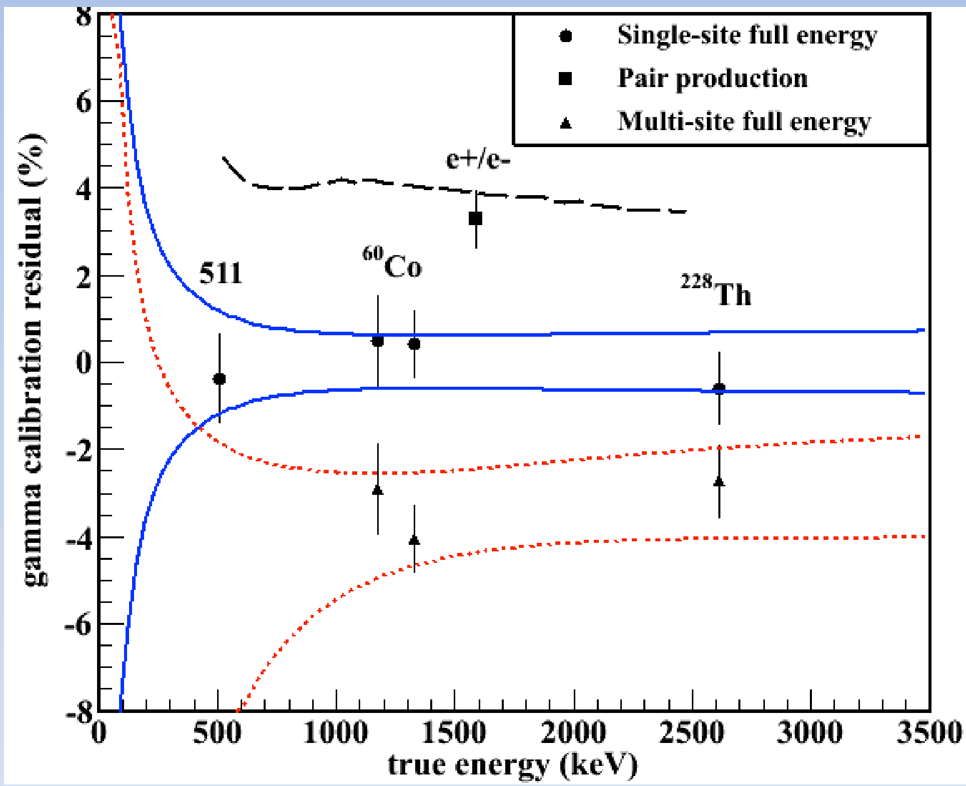
Also still missing part of front lead enclosure

Xenon purity

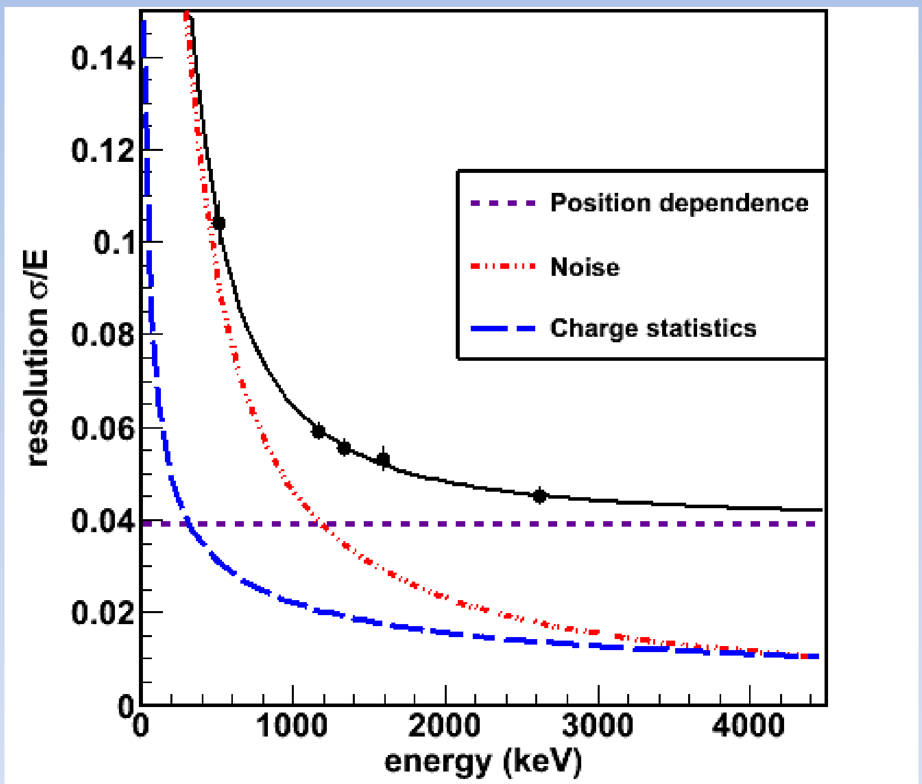


Energy Calibration

Calibration source agreement



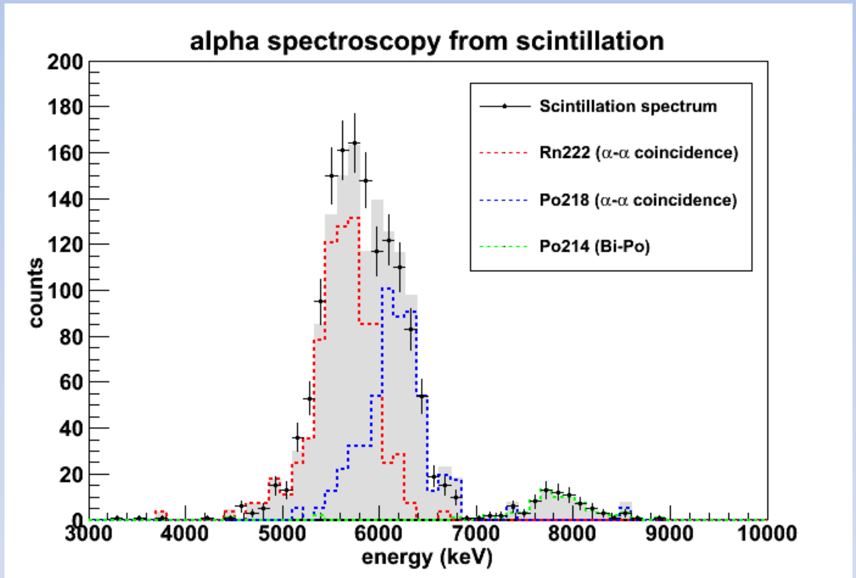
Energy resolution



Systematic uncertainty shown in bands

Constraints from alpha spectroscopy

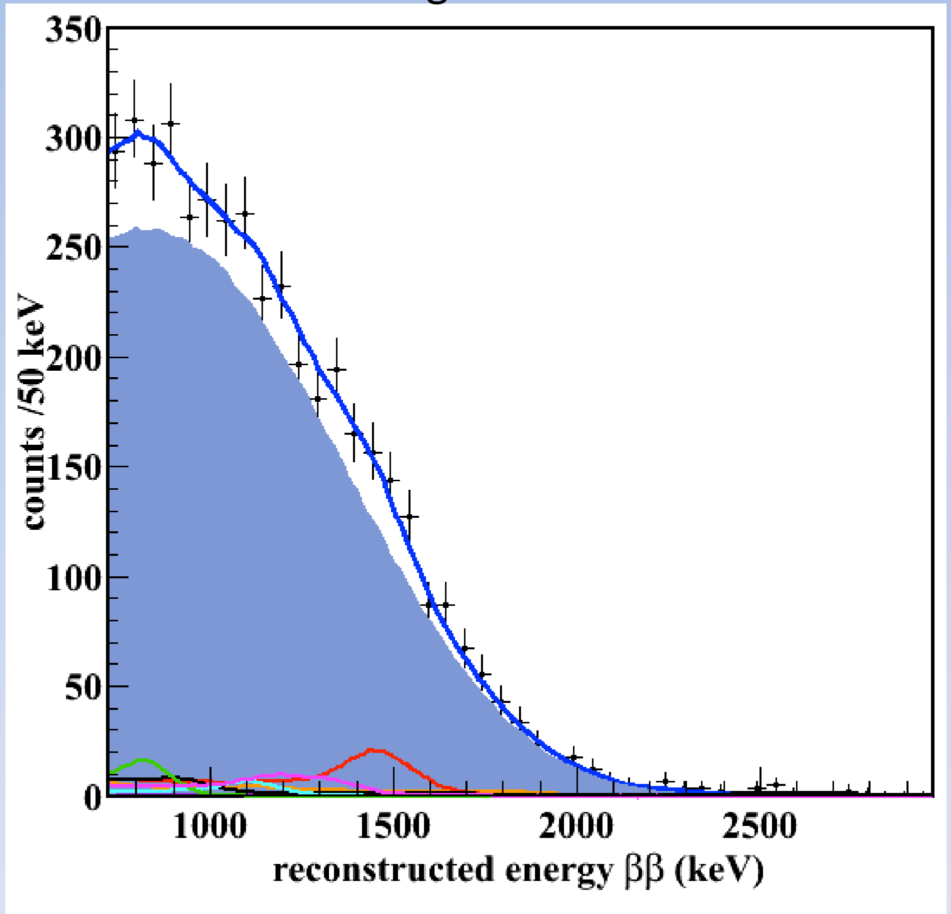
1. look for alpha spectrum of ^{238}U in scintillation
2. calibrate spectrum with alphas from radon chain
3. constrain ^{238}U in bulk liquid by searching for 4.5 MeV alphas
   - < 0.3 counts per day in fiducial volume
   - the same limit applies to its daughter ^{234m}Pa



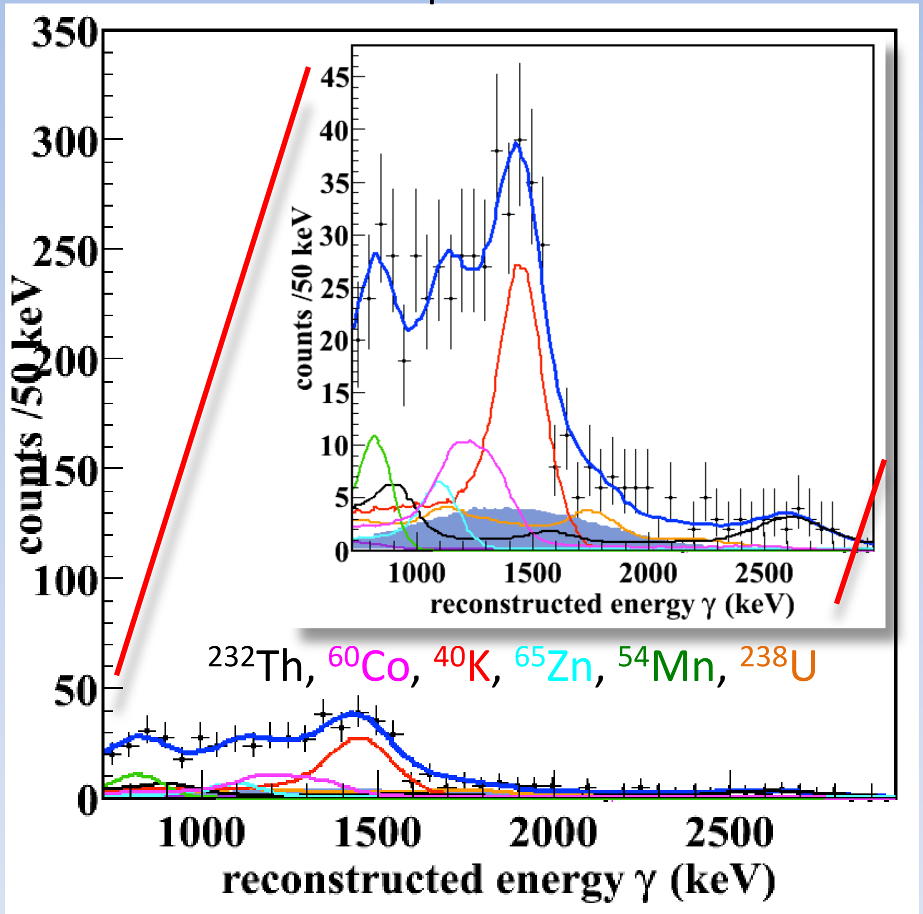
31 live-days of data | 63 kg active mass | Signal/Background 10:1

2νββ observation

single - cluster



multiple - cluster



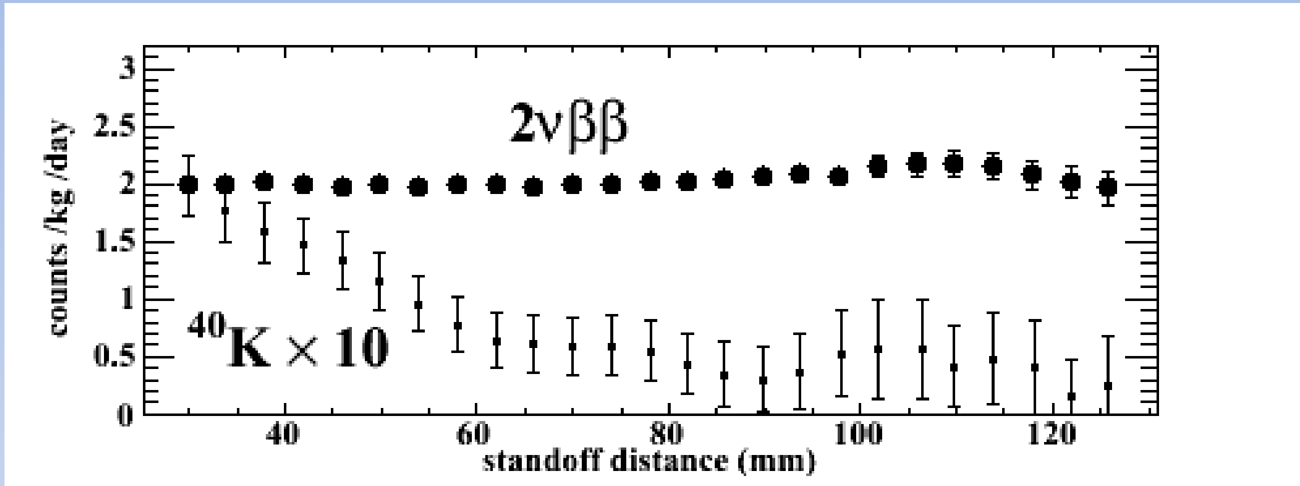
$t_{1/2} = 2.11 \cdot 10^{21}$ yr (± 0.04 stat) yr (± 0.21 sys) Phys. Rev. Lett. 107, 212501 (2011)

Comments about $0\nu\beta\beta$

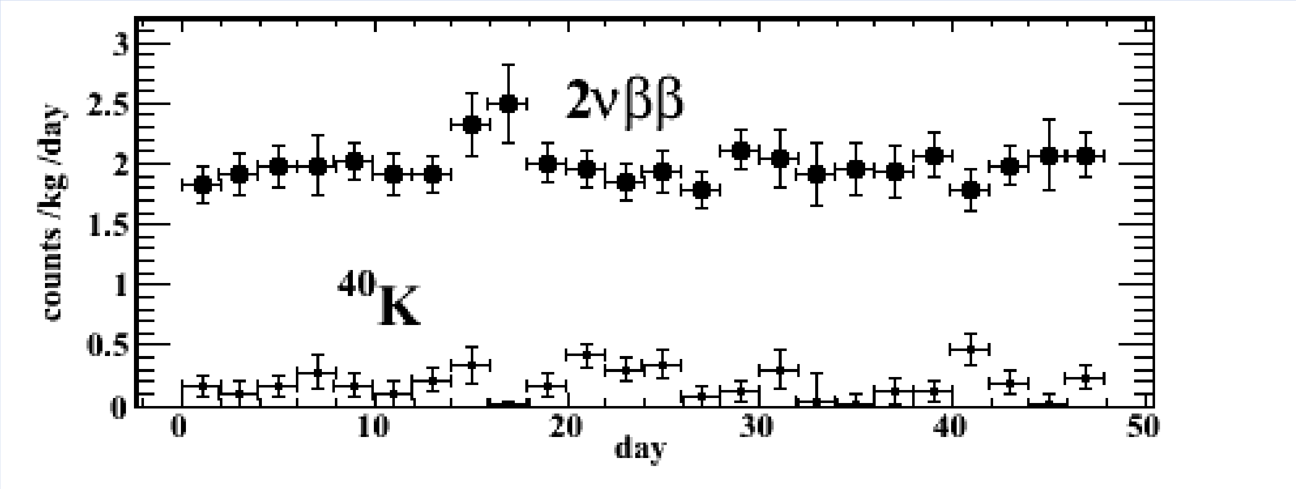
- Preliminarily see about $4x10^{-3}$ counts/(kg yr keV)
- This is already very competitive in the field
- This is not the lowest background configuration of EXO–200
- Projections based on assays and background impact studies of all components a factor of 4 lower
- See our most recent paper on the archive
  arXiv:1202.2192v1 [physics.ins-det] 10 Feb 2012

Event distributions

self shielding of xenon
and
uniform distribution of 2νββ



uniform in time 2νββ
or
weak constraint on ^{40}K lifetime



EXO–200 summary

- Low background physics data taking with enriched xenon has begun and already producing results!
- $T_{1/2} = 2.11 \cdot 10^{21}$ yr (± 0.04 stat) yr (± 0.21 sys)
- Backgrounds already very low ($4 \cdot 10^{-3}$ counts kg^{-1} keV^{-1} yr^{-1} in $0\nu\beta\beta$ region) without full lead wall or full 3D reconstruction
- Stay tuned: improved energy resolution using charge AND scintillation signals and upgraded pattern recognition, event selection, ...
- Multi-tonne concept under development-next prototype just around the corner

The EXO Collaboration

Enriched Xenon Observatory
EXO
for double beta decay

University of Alabama, Tuscaloosa AL, USA - D. Auty, M. Hughes, R. MacLellan, A. Piepke, K. Pushkin, M. Volk

University of Bern, Switzerland - M. Auger, D. Franco, G. Giroux, R. Gornea, M. Weber, J-L. Vuilleumier

California Institute of Technology, Pasadena CA, USA - P. Vogel

Carleton University, Ottawa ON, Canada - A. Coppens, M. Dunford, K. Graham, C. Hägemann, C. Hargrove, F. Leonard, C. Oullet, E. Rollin, D. Sinclair, V. Strickland

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University of Seoul, South Korea - D. Leonard

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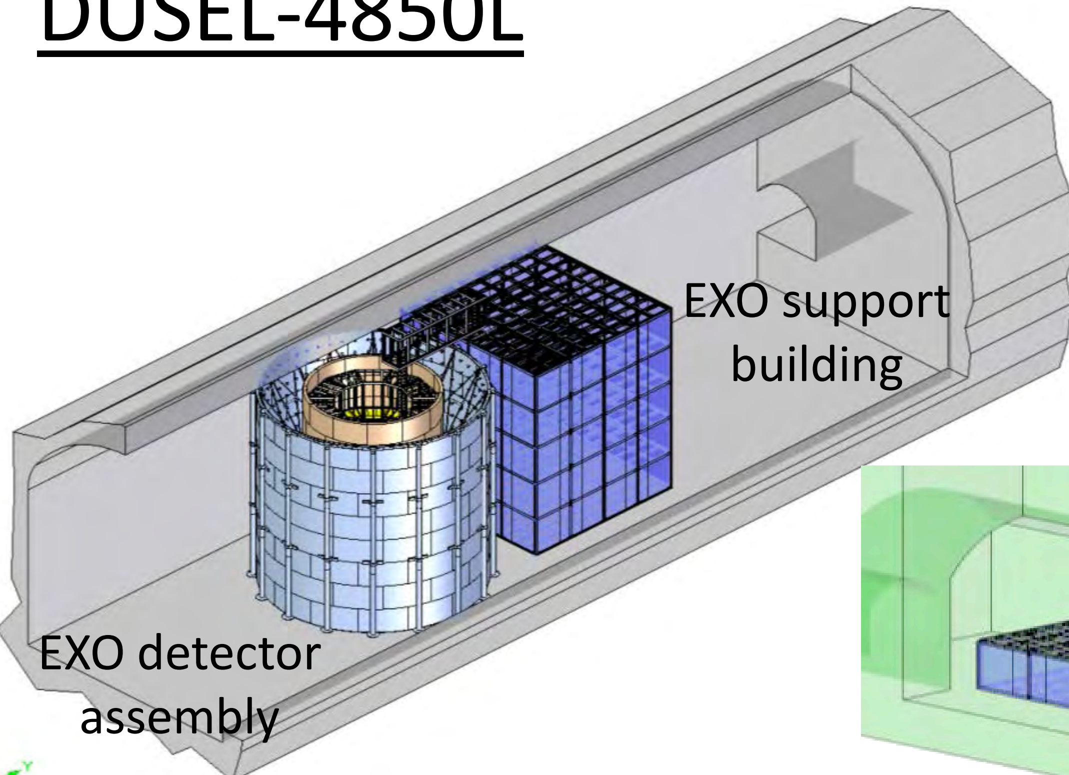
Stanford University, Stanford CA, USA - P.S. Barbeau, J. Davis, R. DeVoe, M.J. Dolinski, G. Gratta, M. Montero-Díez, A.R. Müller, R. Neilson, K. O'Sullivan, A. Rivas, A. Sabourov, D. Tosi, K. Twelker

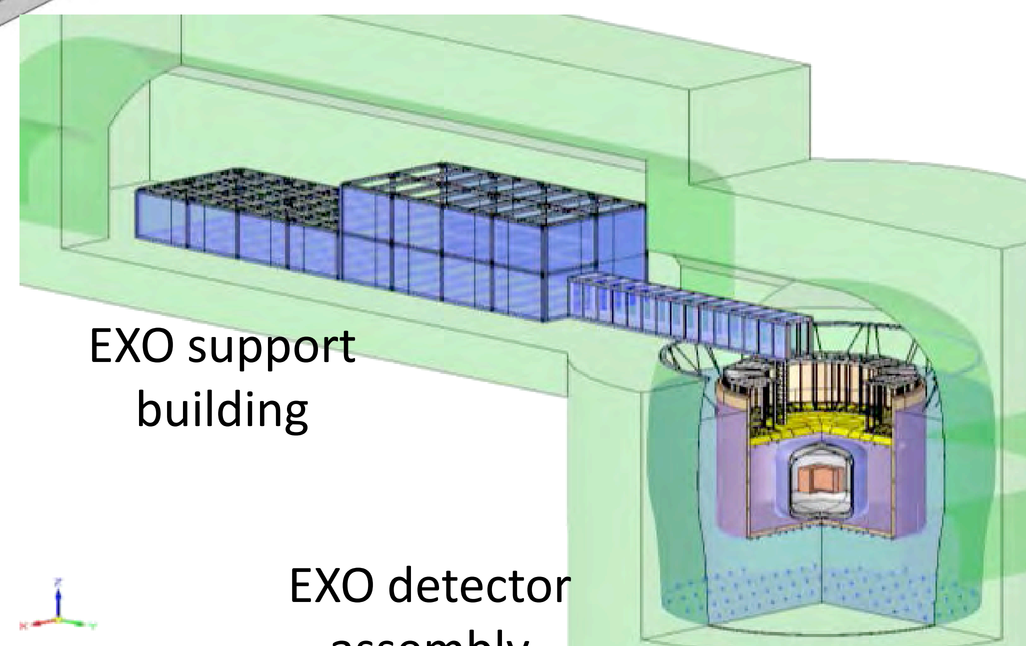
Technical University of Munich, Garching, Germany - W. Feldmeier, P. Fierlinger, M. Marino

Facilities

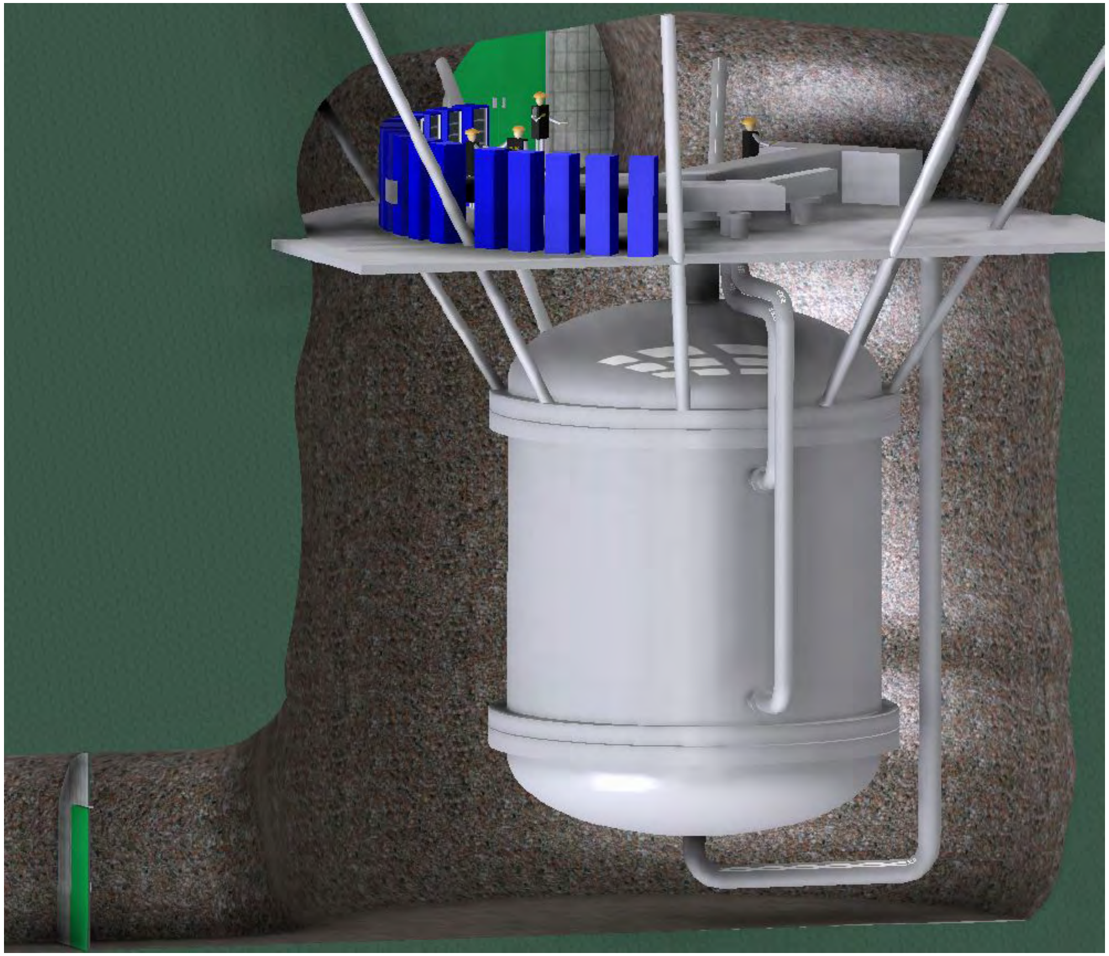
DUSEL-4850L



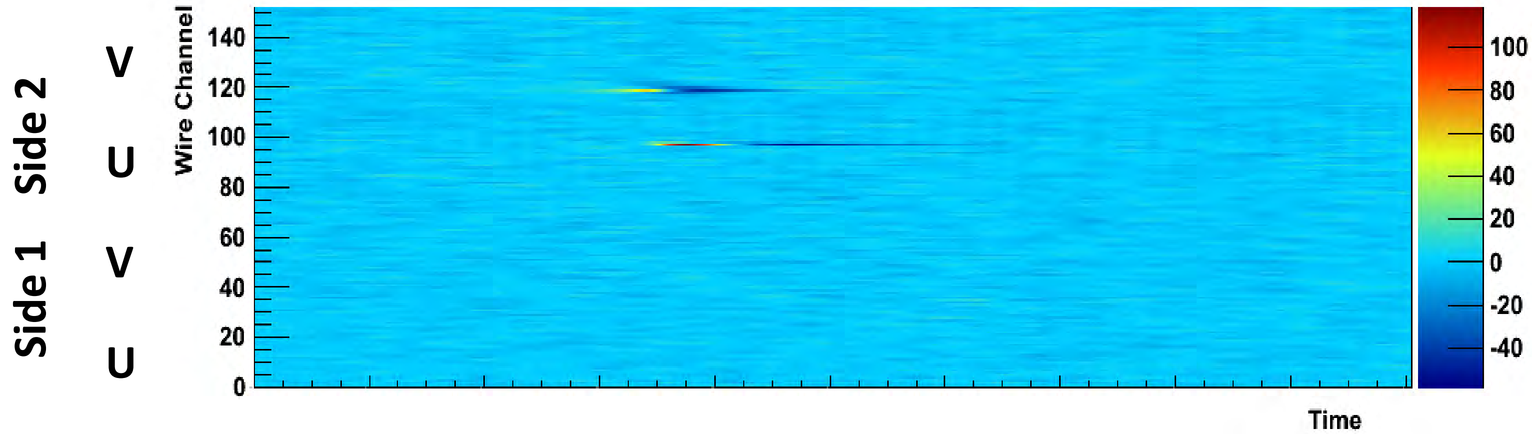
SNOLAB-6800L

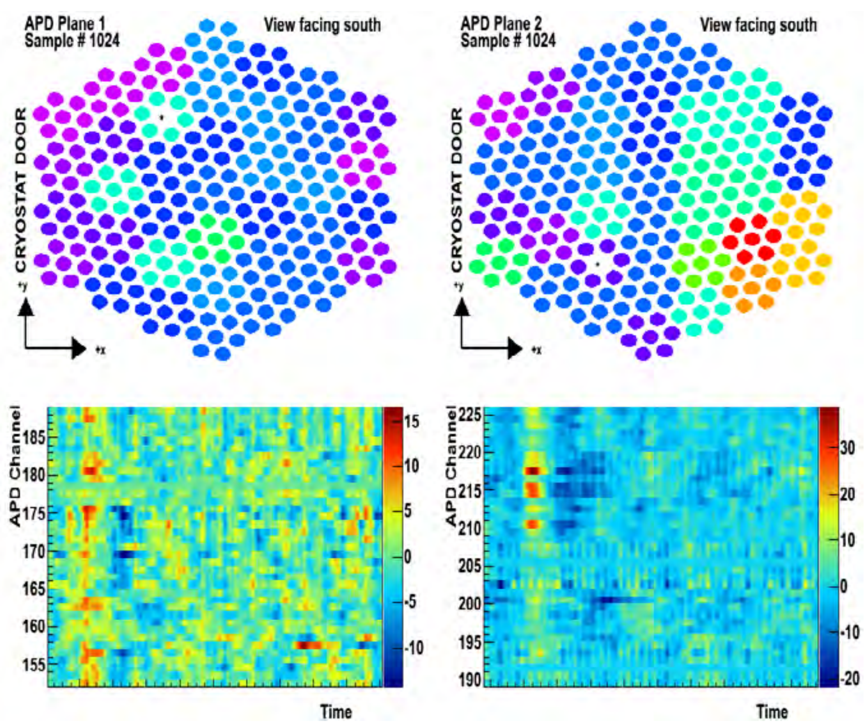


Gaseous xenon detector in SNOLAB cryopit



Single Site Event in EXO-200





Top display is charge readout (V are induction wires and U are collection wires).

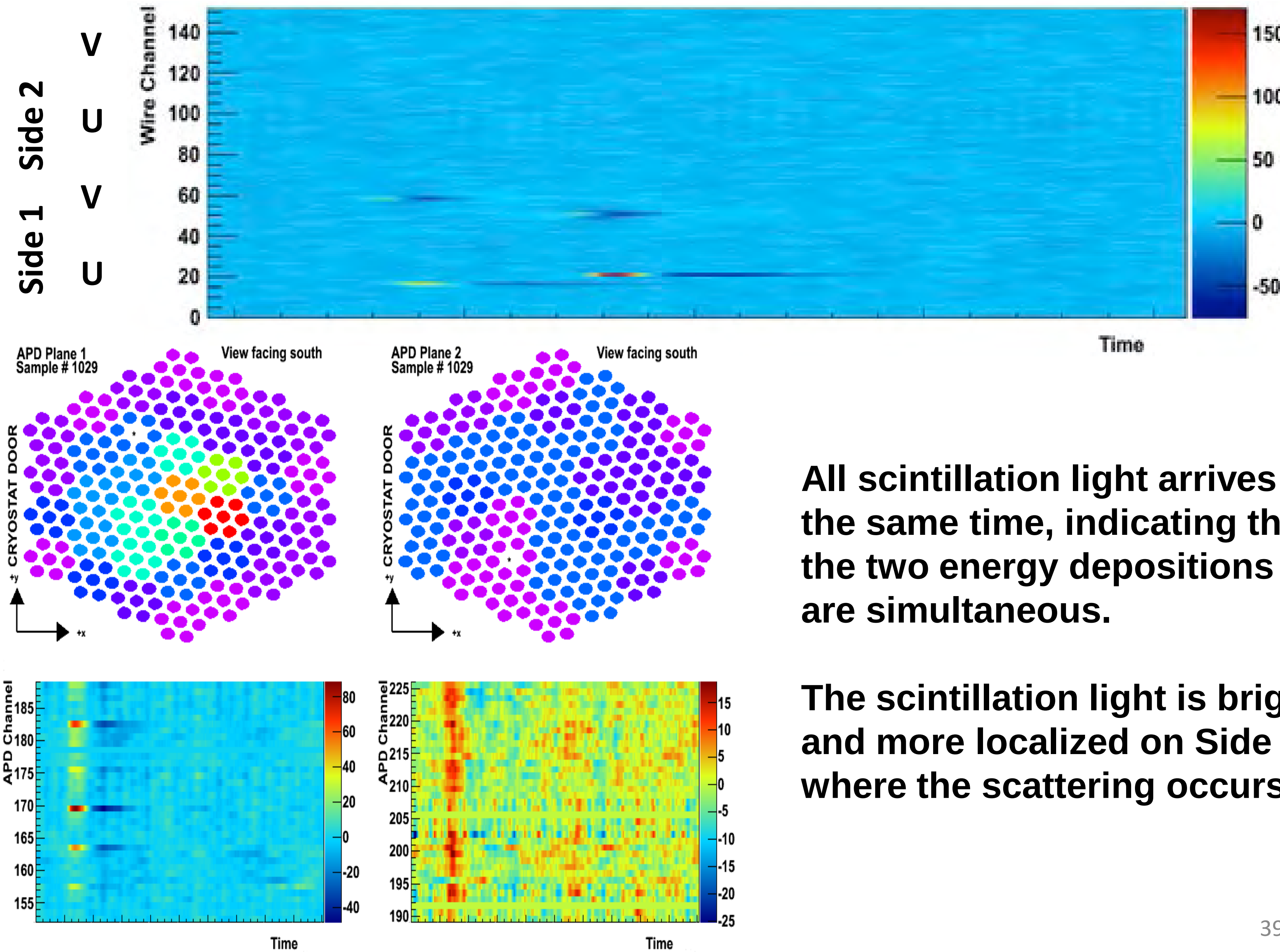
Left display is light readout. APD map refers to the sample with max signal.

Scintillation light is seen from both sides, although more intense and localized on side 2, where the event occurred.

Small depositions produce induction signals on more than one V wires but are collected by a single U wire. V signal always comes before U.

Light signals precede in time the charge ones

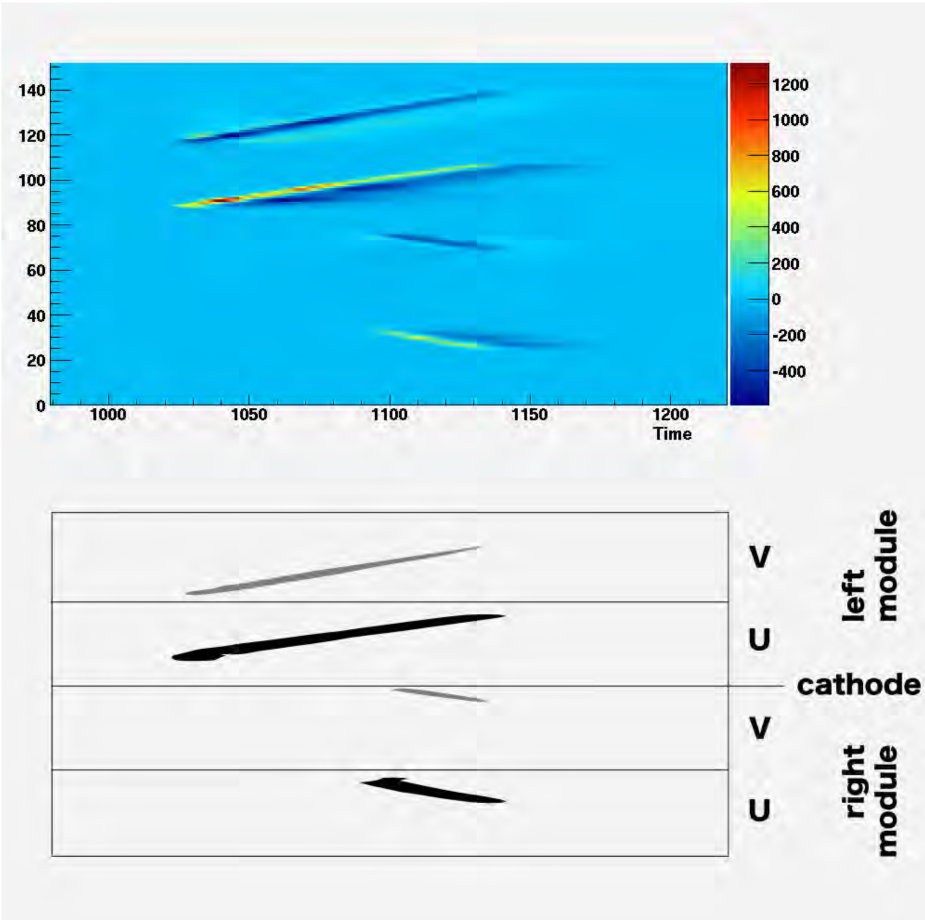
A Two-Site Compton Event in EXO-200



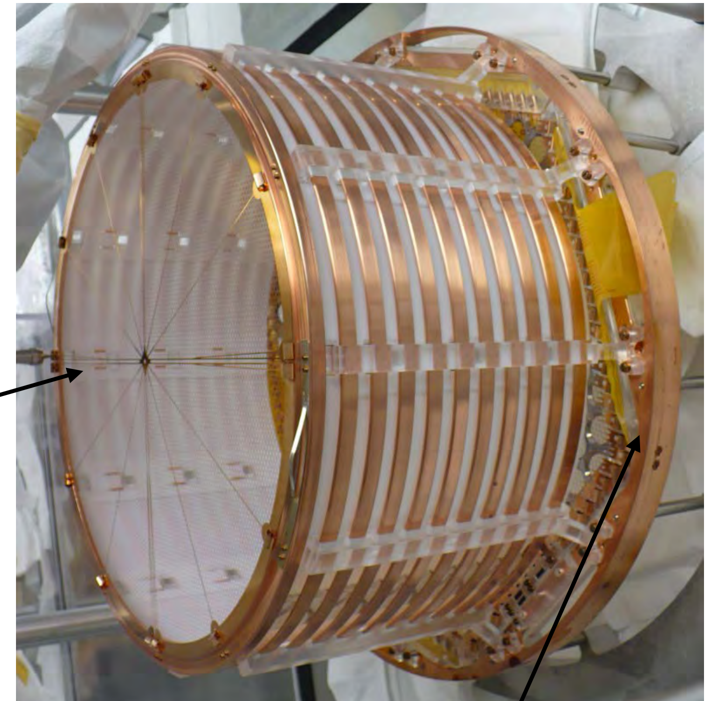
All scintillation light arrives at the same time, indicating that the two energy depositions are simultaneous.

The scintillation light is brighter and more localized on Side 1 where the scattering occurs

Muon track in EXO-200



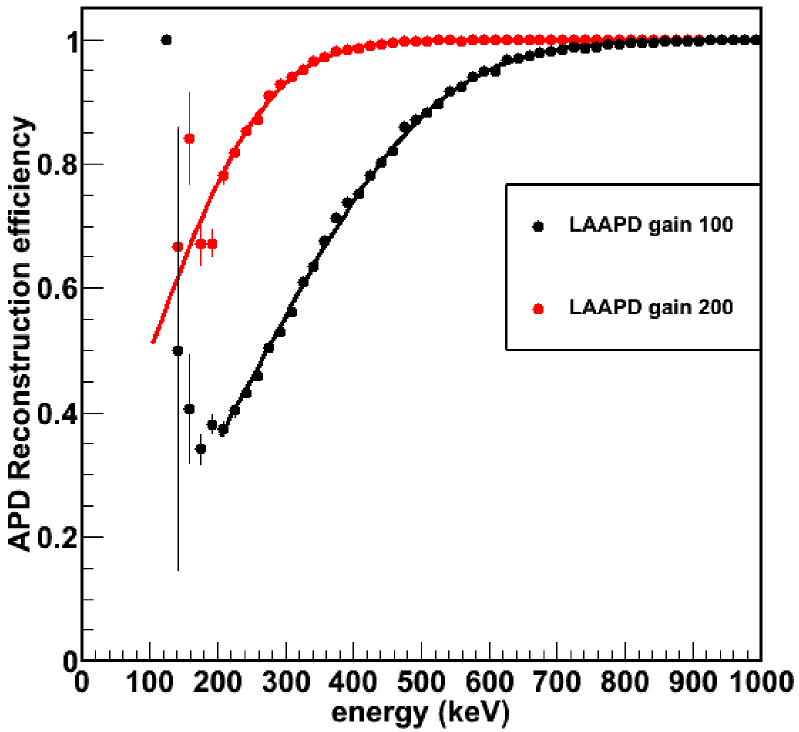
One of the two TPC modules



A track from a cosmic-ray muon in EXO-200. The horizontal axis represents time (uncalibrated for now) while the vertical is the wire position (see sketch). V wires see inductive signals while U wires collects the charge.
The muon in the present event traverses the cathode grid, leaving a long track in one TPC module and a shorter one in the other.

3D reconstruction threshold

- 100 keV well above charge trigger and reconstruction thresholds
- 3D reconstruction still requires determination of t_0 from scintillation signal
- compare ratio of fully reconstructed events to triggered events to determine reconstruction efficiency
- early software threshold of about 700 keV
- recent dramatic decrease with increase in APD bias voltages, to about 300 keV



Updated EXO neutrino effective mass sensitivity

Assumptions:

1) 80% enrichment in 136
2) 68% overall efficiency:
   95% energy cut * 80% tracking effic * 90% lifetime fraction from EXO-200 analysis
3) Intrinsic low background + Ba tagging eliminate all radioactive background
4) Energy res only used to separate the 0ν from 2ν modes:
   Select 0ν events in a ±2σ interval centered around the 2457.8 keV endpoint
5) Use for 2νββ $T_{1/2}=2.11 \cdot 10^{21}$yr (Ackerman et al. arXiv:1108.4193, 21 Aug 11)

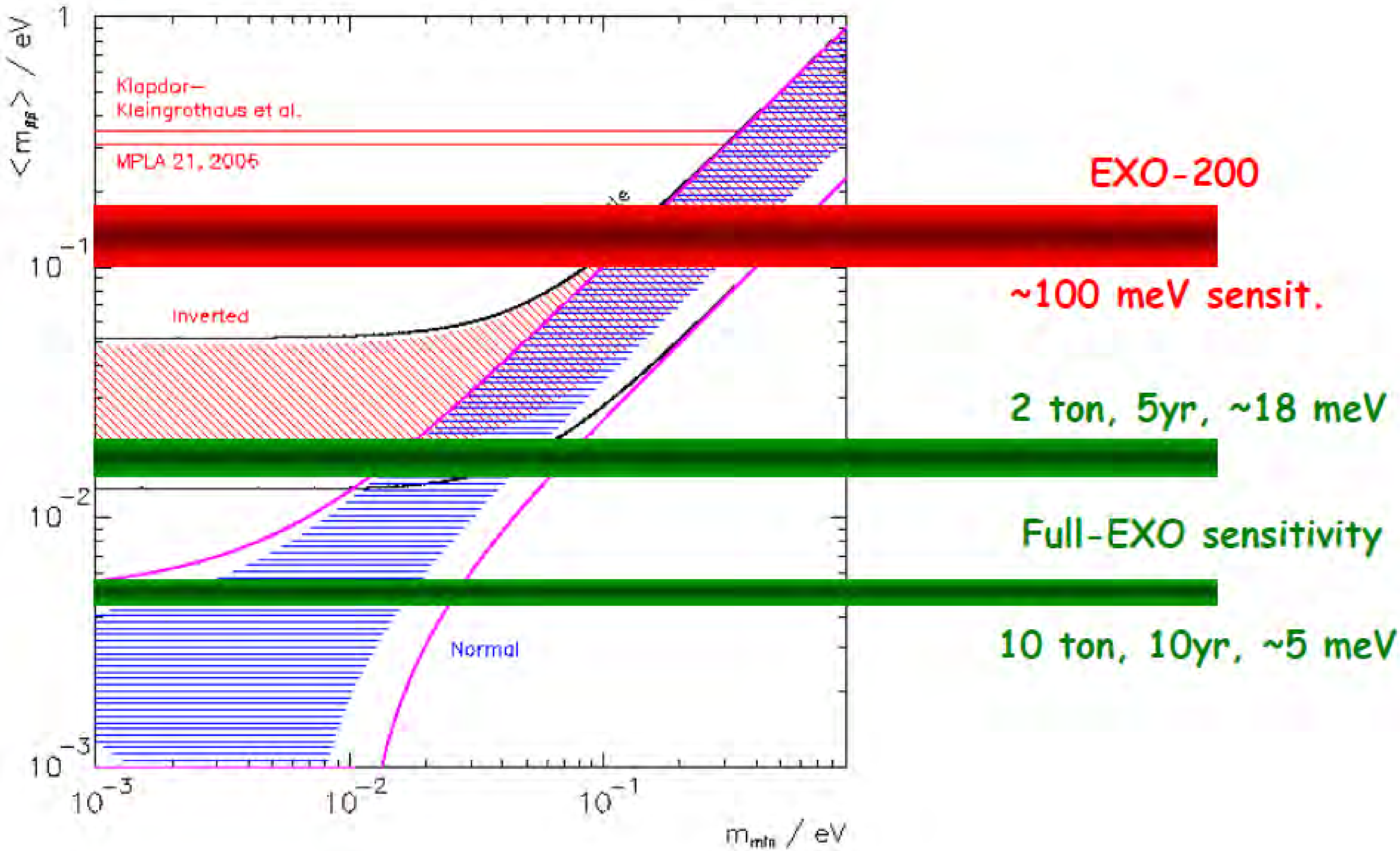
Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	2νββ Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (meV)	
							QRPA‡	NSM#
Conservative	2	68	5	1.6*	5.0	$2.8*10^{27}$	16	20
Aggressive	10	68	10	1†	3.4	$3.4*10^{28}$	4.7	5.8

* σ(E)/E = 1.4% obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201

† σ(E)/E = 1.0% considered as an aggressive but realistic guess with large light collection area

‡ F.Simkovic et al., *Phys. Rev.* C79, 055501 (2009)

\# Menendez et al., *Nucl. Phys.* A818, 139 (2009)


<m_ββ> / eV
1
Klapdor–
Kleingrothaus et al.
MPLA 21, 2006
Inverted
Normal
EXO-200
~100 meV sensit.
2 ton, 5yr, ~18 meV
Full-EXO sensitivity
10 ton, 10yr, ~5 meV
m_min / eV