Observation of two-neutrino Double Beta Decay in ^{136}Xe with EXO-200

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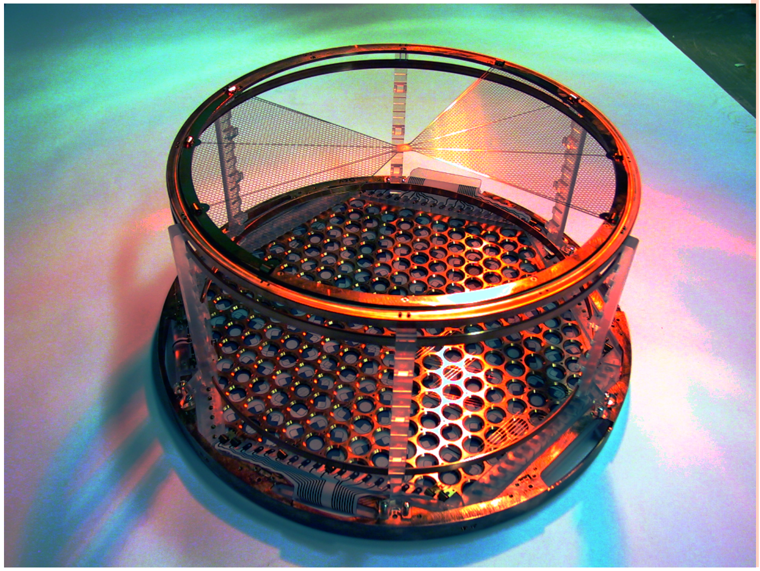
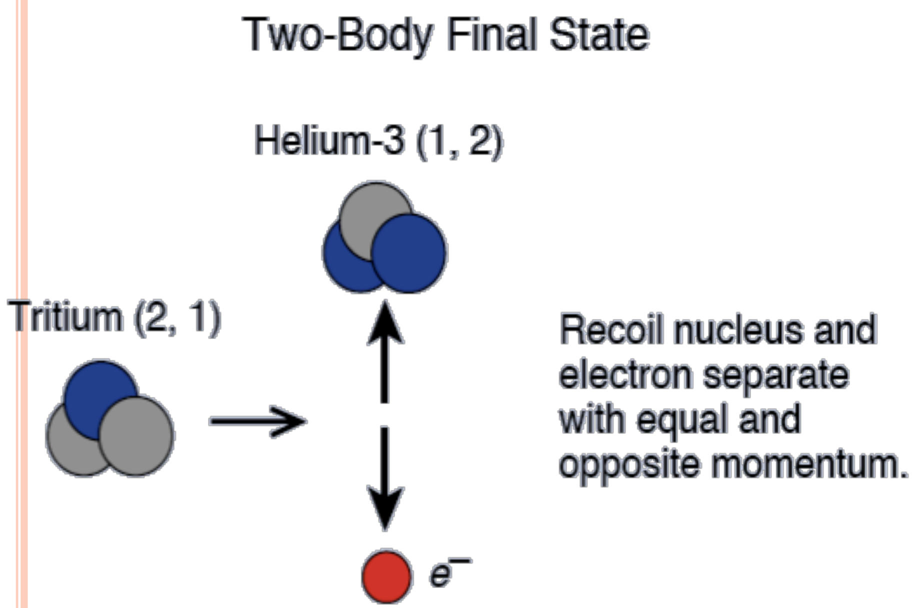
February 6, 2012

Outline

- Known knowns about neutrinos
- Known unknowns about neutrinos
- Double beta decay
- Overview of EXO purpose and design
- EXO-200 at WIPP
- First physics results from EXO-200
- Conclusions and future plans

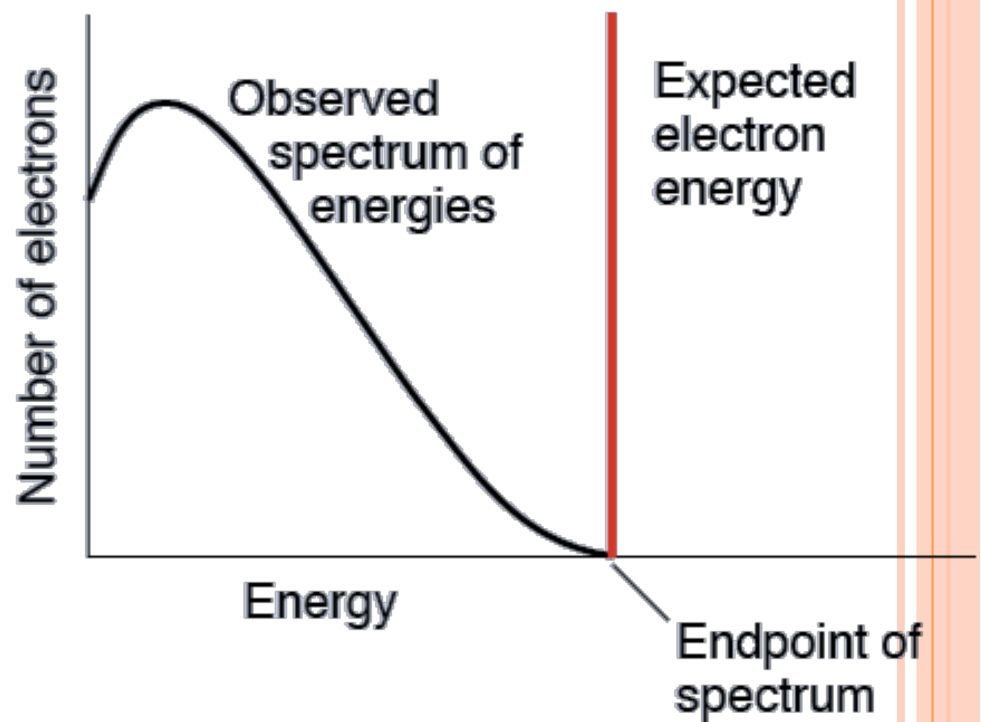


BETA (β) DECAY, AT THE BEGINNING



$$(N, Z) \rightarrow (N-1, Z+1) + e^- ,$$

where N = number of neutrons, and
Z = number of protons.



From Los Alamos Science No. 25, 1997.

Neutrinos are born!

Davis – 1970s (solar νs)

- 1911: Rutherford has trouble explaining continuum of electron spectrum in beta decay
- 1930: Pauli introduces the idea of the neutron(ino), lightweight and neutral, to explain beta decay
- 1930: Bohr is ready to dismiss energy conservation rather than believing in an "invisible" particle
- 1932: Neutrons are discovered
- 1934: Fermi puts it all together – "… to every transition from neutron to proton is correlated the creation of an electron and a neutrino."

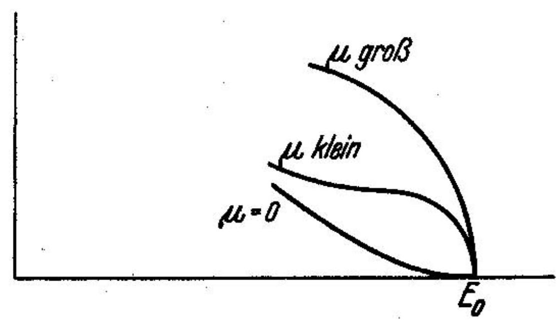
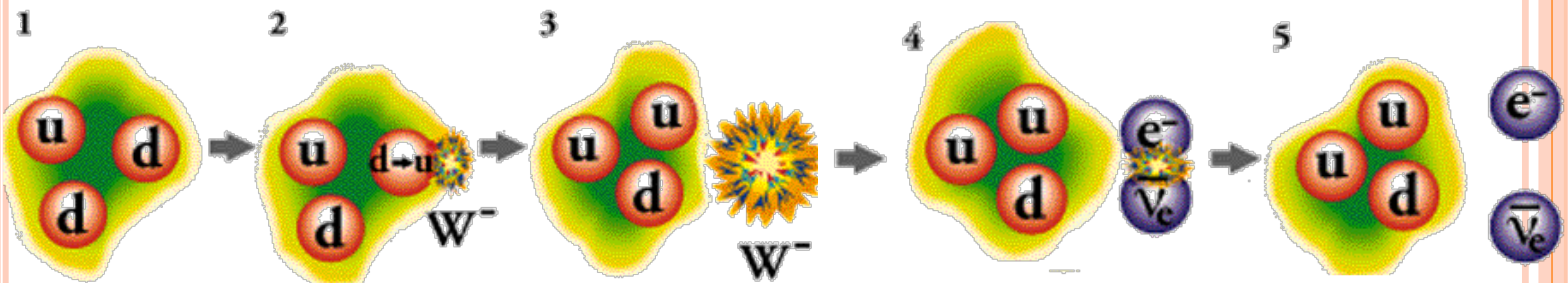
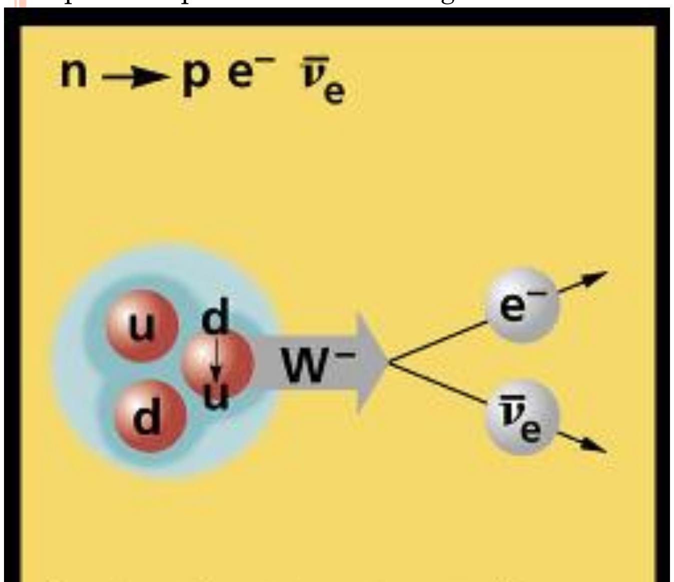


Fig. 1.

NUCLEAR BETA (β) DECAY: THE SOLUTION



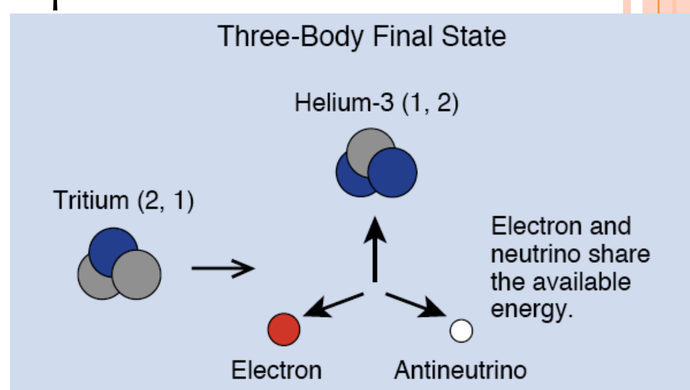
Graphics courtesy of The Particle Adventure
http://www.particleadenture.org



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

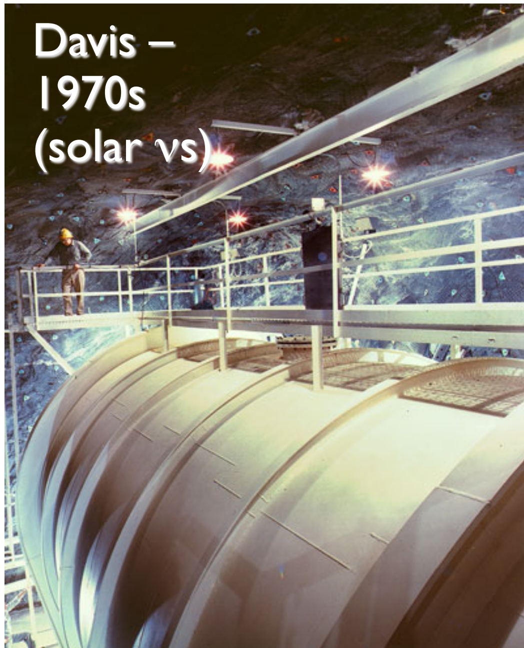
1. Free neutron or neutron in an unstable nucleus is converted to a proton via the weak force

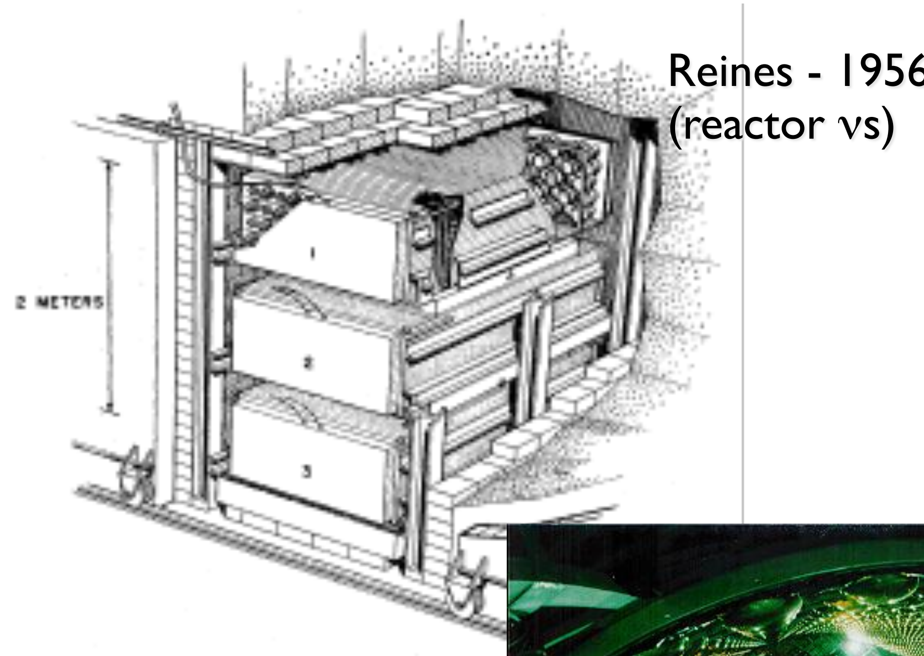
2. To conserve energy, an electron and antineutrino are produced in the process

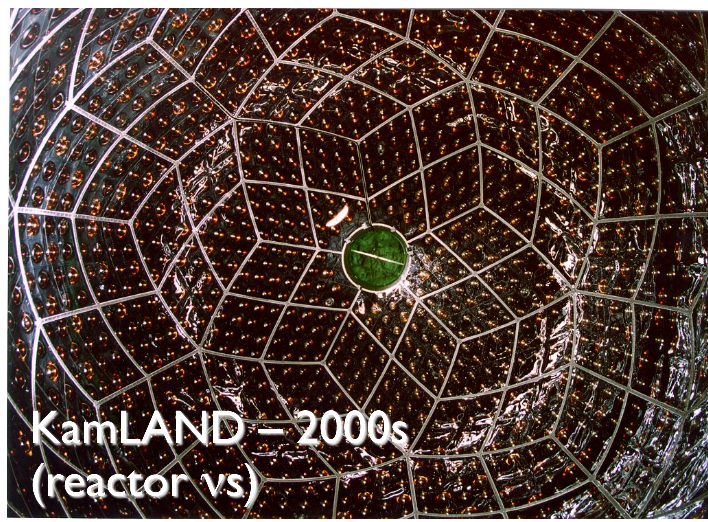


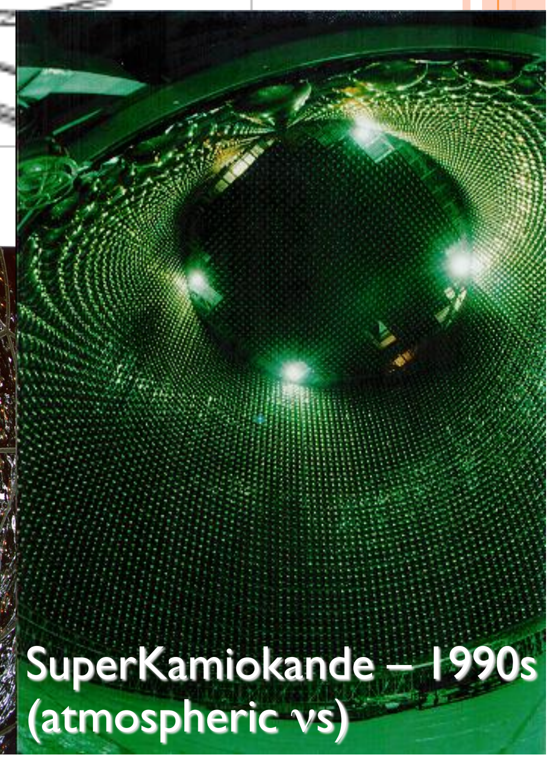
From Los Alamos Science No. 25, 1997.

EVIDENCE OF NEUTRINOS

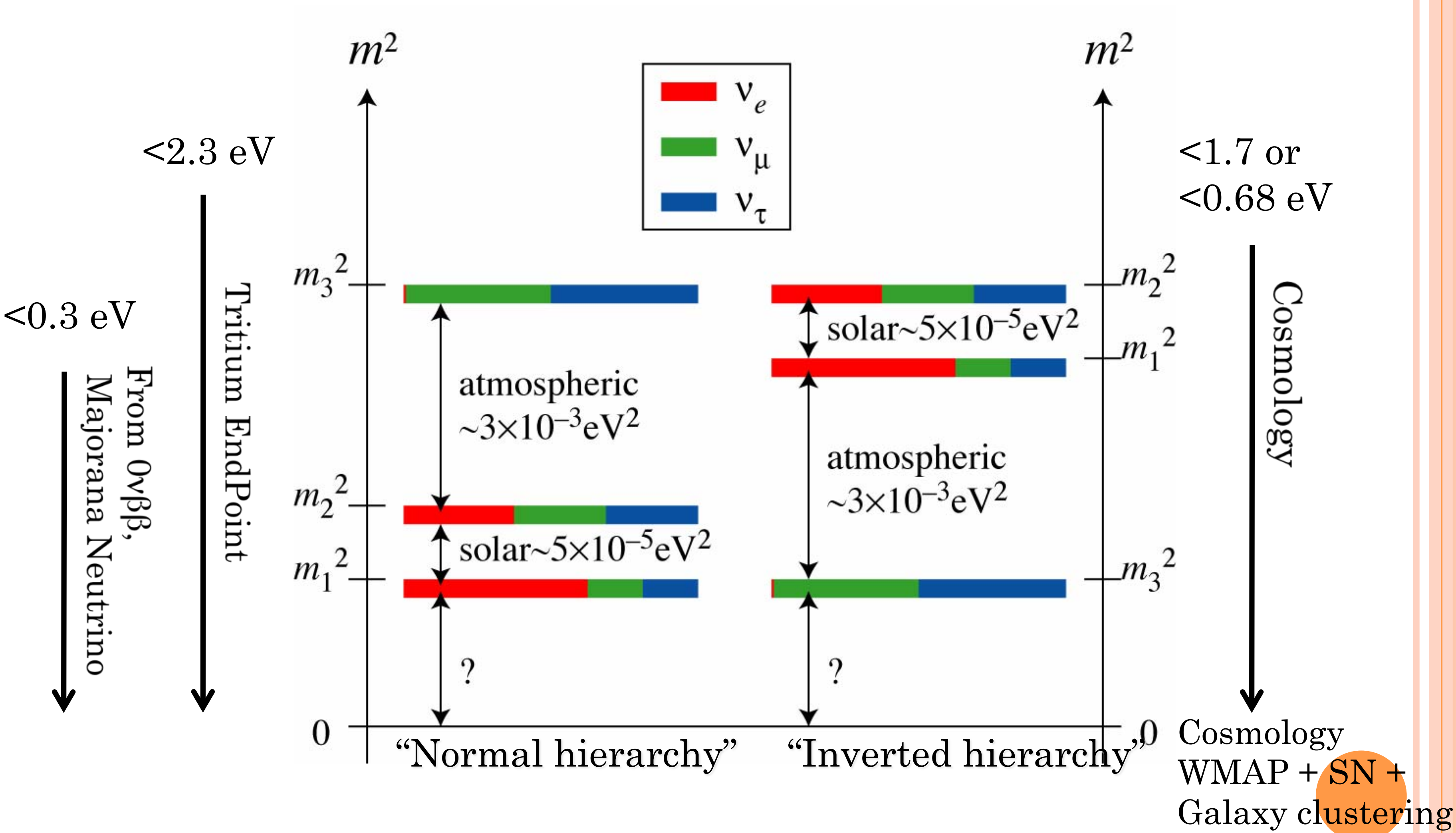








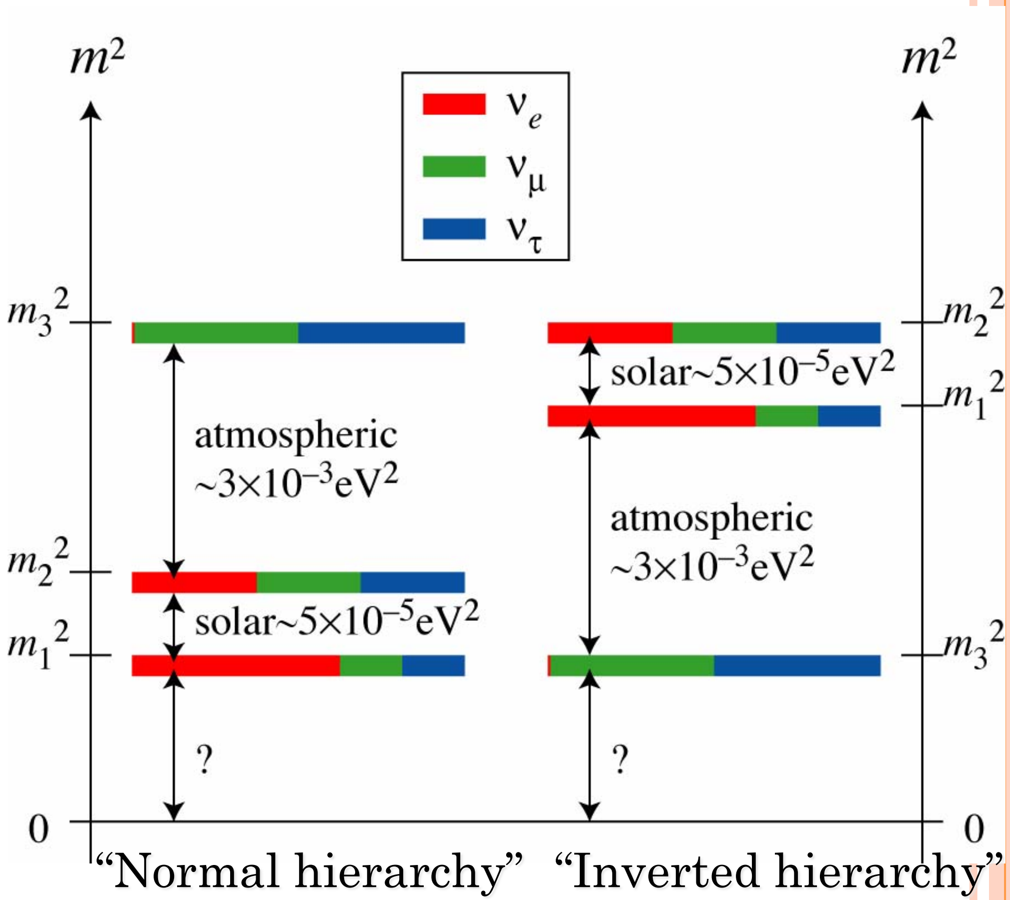
THE NEUTRINO MASS SCALE AND HIERARCHY



UNKNOWN PROPERTIES OF THE NEUTRINO

Major Questions in Neutrino Physics

- Majorana particle, (i.e. its own antiparticle)
- Absolute mass scale of neutrinos.
- Mass hierarchy
- Mixing angle, θ_{13}
- CP violation phase



The search for neutrinoless double beta decay can shed light on the first three questions.

Dirac and Majorana Neutrinos

Don't we already know that $\nu \neq \overline{\nu}$?

Typical neutrino scattering experiment:

$$\pi^- \to \mu^- \, \overline{\nu}_\mu^R \longrightarrow \overline{\nu}_\mu^R N \to \mu^+ X$$

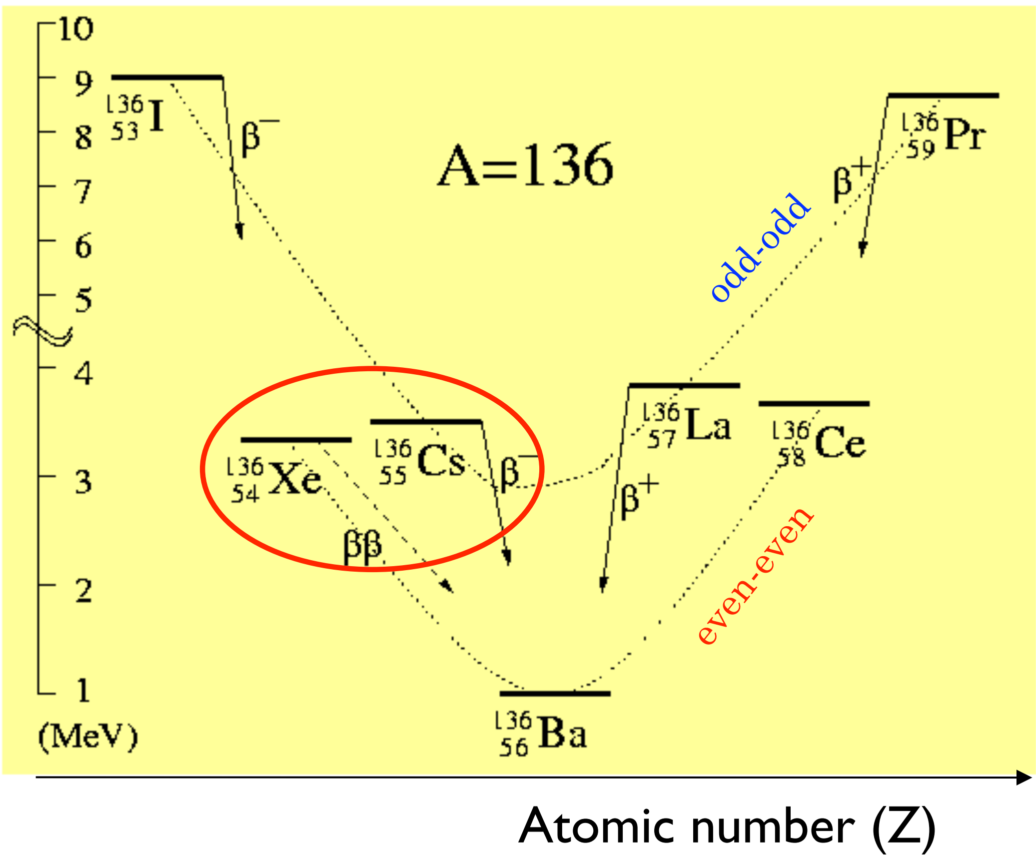
charges always opposite

For Dirac neutrinos, the charge of the μ^+ is determined by Lepton number conservation and the neutrino helicity (weak interaction is 100% left handed).

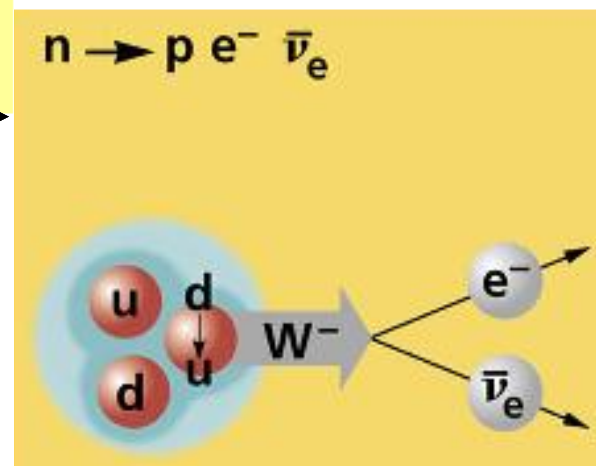
For Majorana neutrinos, the charge of the μ^+ is determined solely by neutrino helicity.

No experiment has been able to tell us which view is correct.

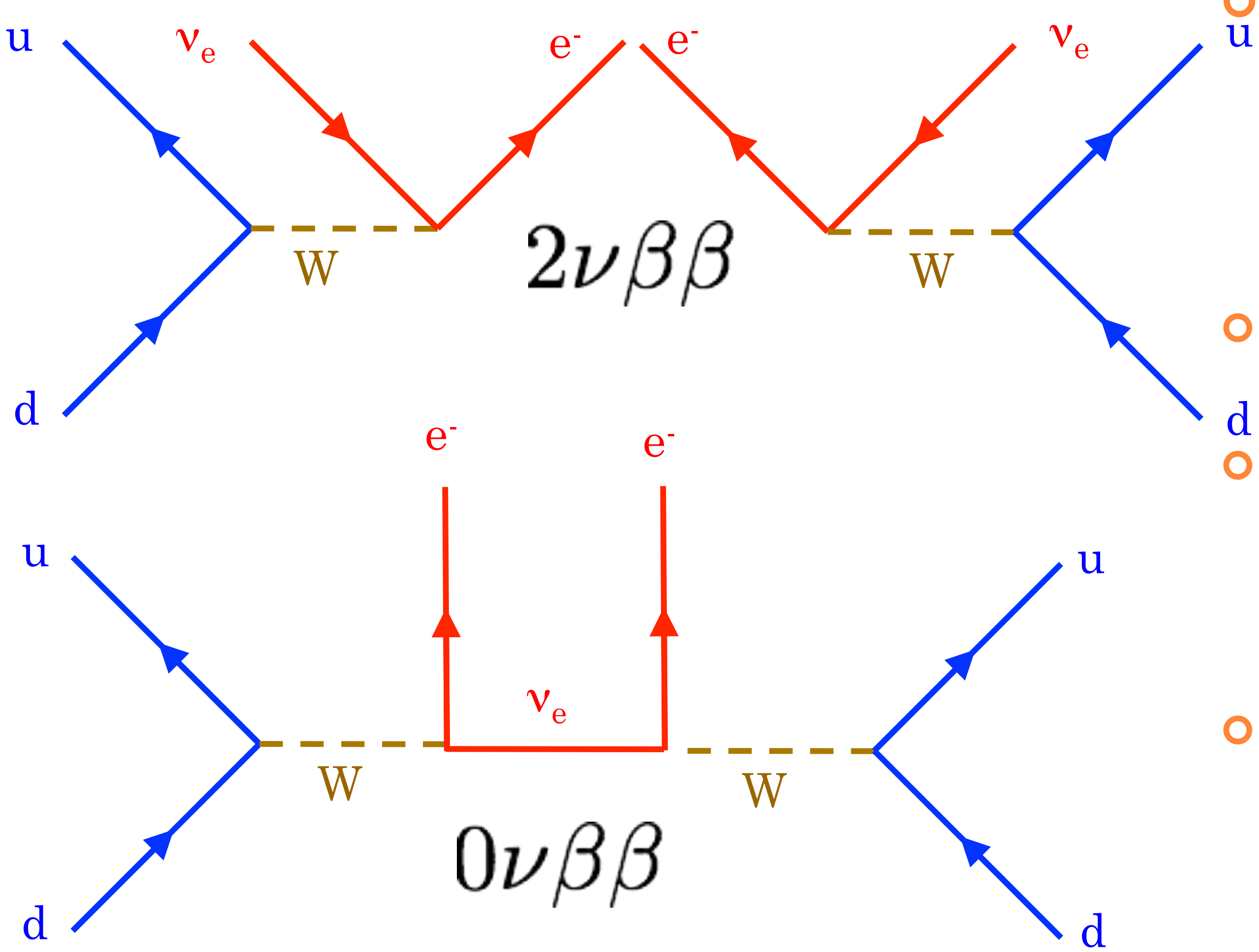
WHAT IS $\beta\beta$ DECAY?



- Second-order weak process by which two neutrons decay to two protons
- Only allowed for nuclei where beta decay is energetically forbidden or highly suppressed due to a large angular momentum difference

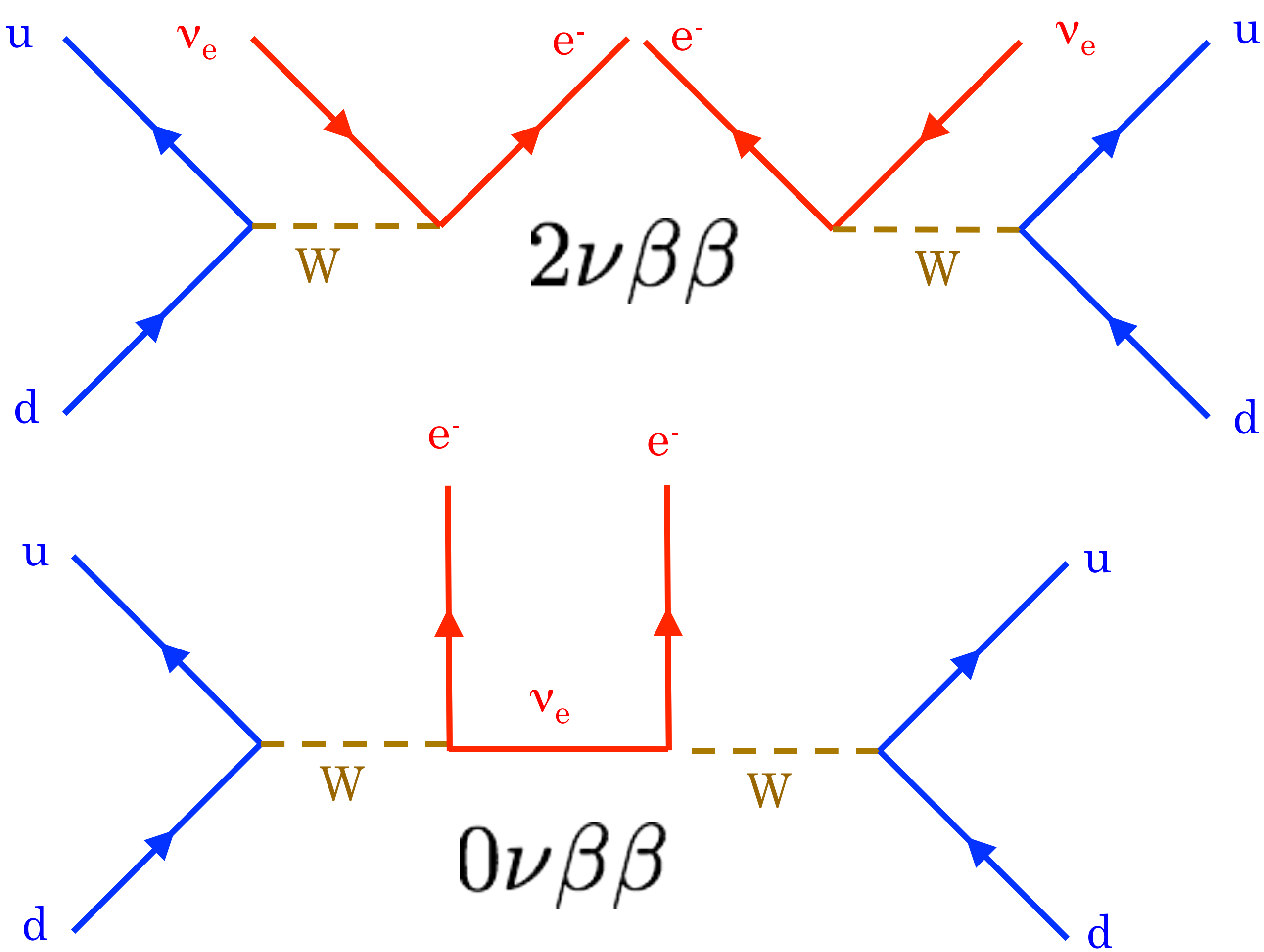


Two ways for Double Beta Decay to Occur



- $2\nu\beta\beta$ observed in several nuclides: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{150}Nd
- Half lives are 10^{18}-10^{21} years
- Standard Model process: decay rates are used to compare nuclear models
- First direct observation by Elliot, Hahn, and Moe in ^{82}Se (1987).

Two ways for Double Beta Decay to Occur



- $0\nu\beta\beta$ can only occur if neutrinos have mass and are their own antiparticle (Majorana)
- Process violates lepton number conservation (by 2!)
- New Physics!
- Several theories for the mechanism: right-handed currents, super-symmetry, light neutrino or heavy neutrino exchange

WHAT DO WE MEASURE?

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q,Z)\left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

$G^{0\nu}(Q,Z)$ Calculable phase space factor $\sim Q^5$

$\left|M^{0\nu}\right|^2$ Nuclear matrix elements are difficult to calculate

$\langle m_{\beta\beta}\rangle^2$ Effective Majorana mass $= \left|\sum_{i=1}^{3} \eta_i U_{ei}^2 m_i\right|^2$

Neutrino masses

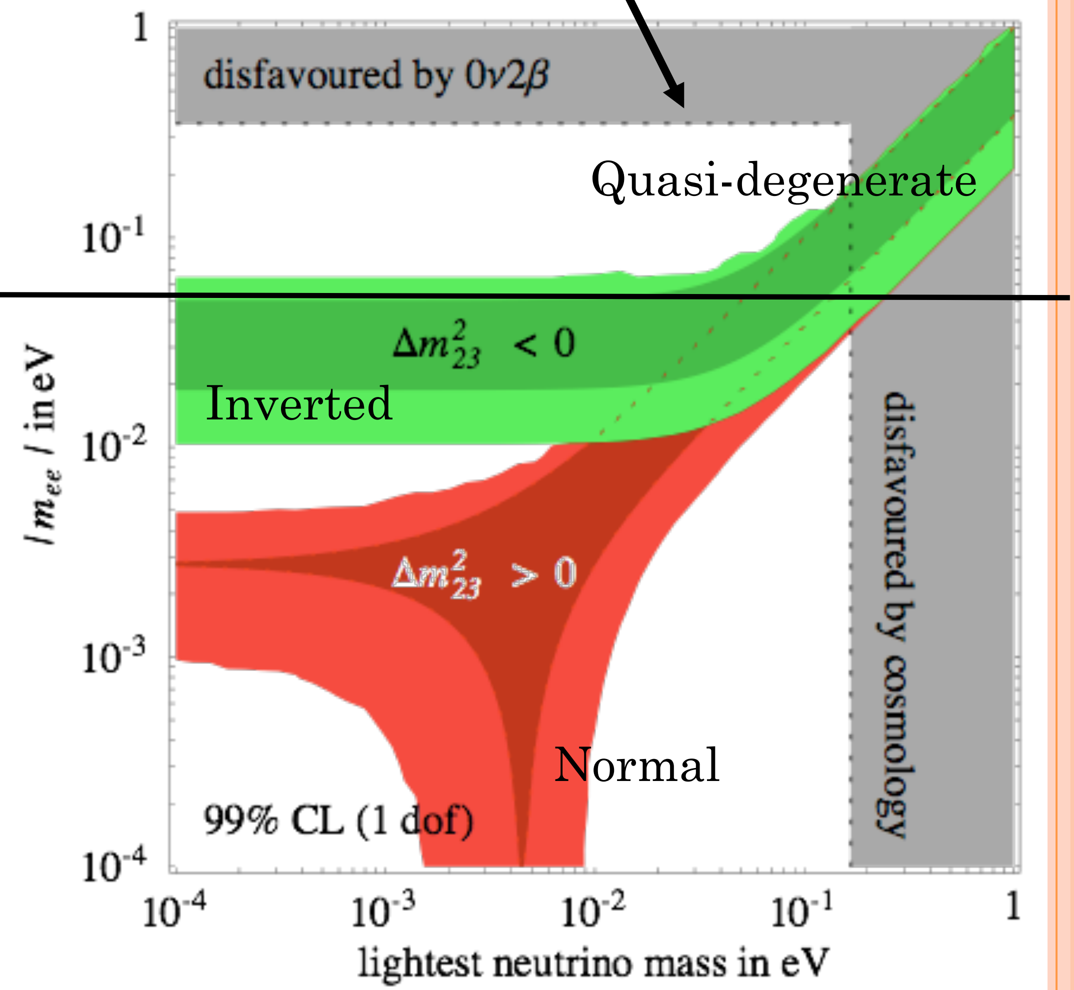
CP phases

Neutrino mixing matrix

Neutrino Mass Scale

current 0νββ sensitivity
Claim by Klapdor-Kleingrothaus et al.
MPLA 21, 2006.

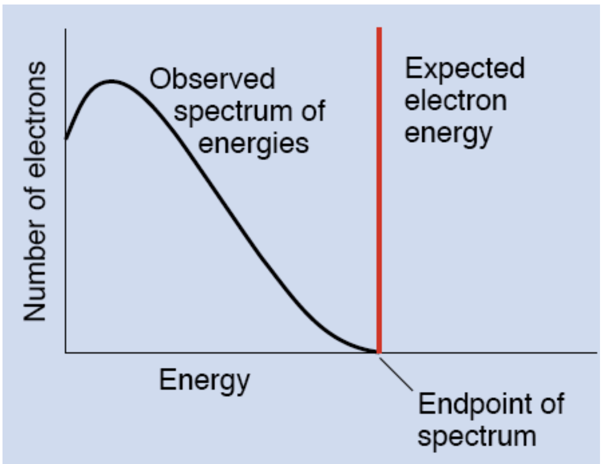
50 meV

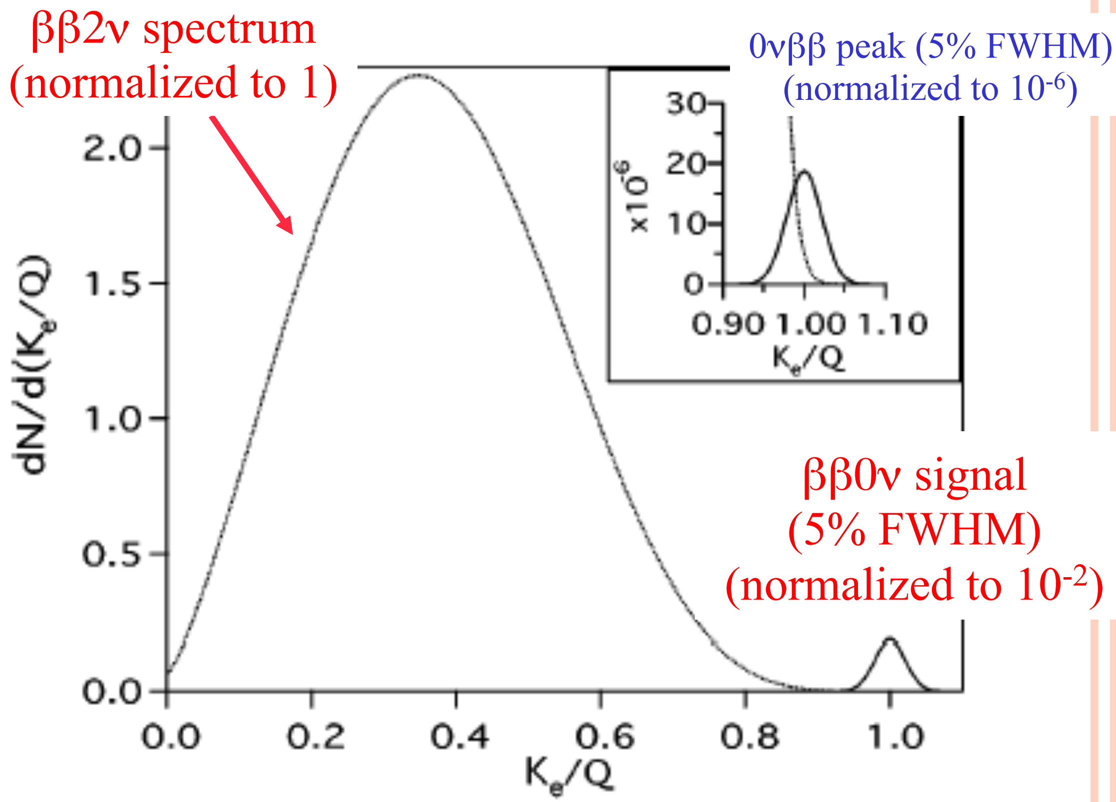


^{76}Ge	(2.1 - 2.6) x 10^{27} y
^{82}Se	(6.0 - 8.7) x 10^{26} y
^{100}Mo	(1.1 - 1.7) x 10^{27} y
^{130}Te	(0.7 - 1.7) x 10^{27} y
^{136}Xe	(1.5 - 5.6) x 10^{27} y

[Strumia and Vissani, hep-ph/0606054]

HOW DO WE MEASURE THE RATE?





Elliot, S. et al., Annu. Rev. Nucl. Part. Sci. 2002. 52:115–51

Summed electron energy in units of the kinematic endpoint (Q)

To maximize sensitivity:

- Large mass
- Low background
- High detection efficiency
- Good energy resolution

$$S^{0\nu}_{1/2} \propto \varepsilon \frac{a}{A} \left[\frac{MT}{B\Gamma} \right]^{1/2}$$

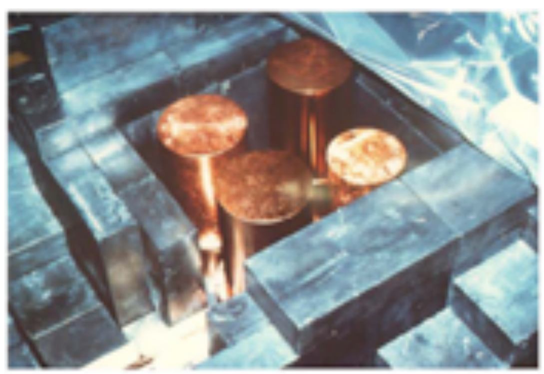
ε is efficiency
a is isotopic abundance
A is atomic mass
M is source mass
T is time
B is background
Γ is resolution

EXPERIMENTAL OBSERVATION OF DOUBLE BETA DECAY

Double beta decay is one of the rarest nuclear decay events.
The first direct detection of $2\nu\beta\beta$ was observed by Elliot *et al.* in 1987 (^{82}Se).
Since then $2\nu\beta\beta$ has been observed in several different isotopes.

$0\nu\beta\beta$ has not been conclusively observed despite a claim in 2004.
About a dozen experiments are actively searching for this decay, with different techniques and isotopes.

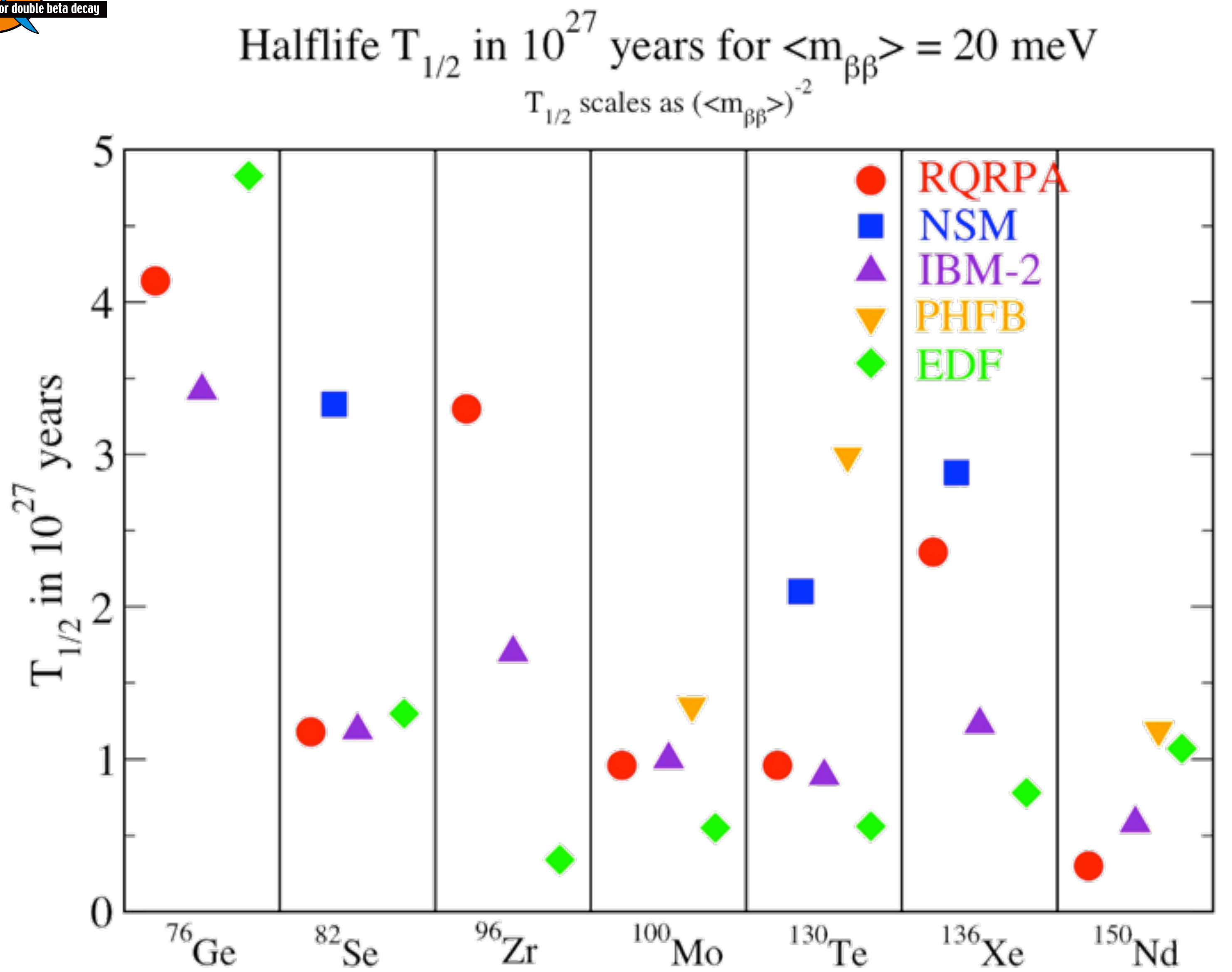
CUORE



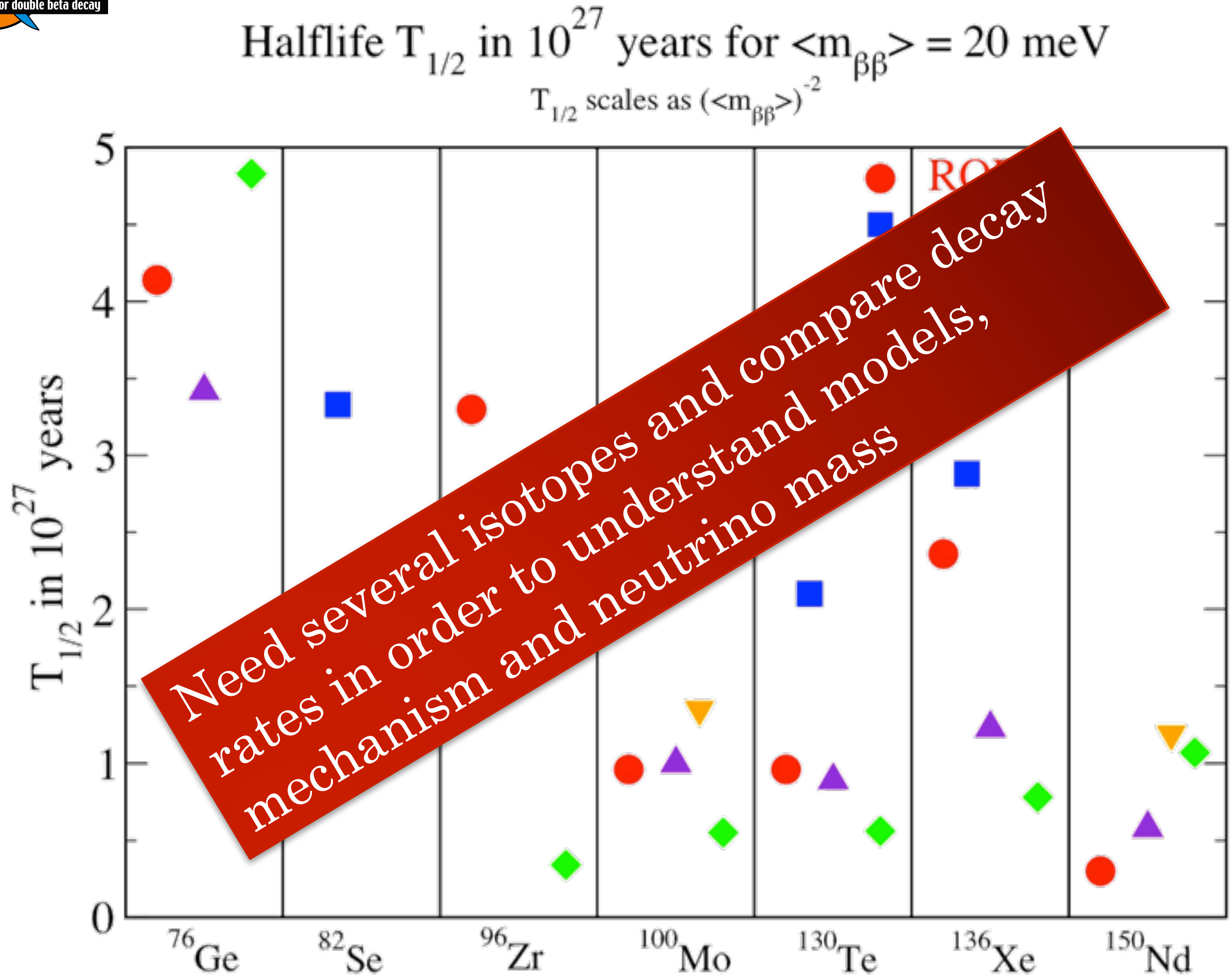
Majorana

NEMO

IS THERE A SMOKING-GUN ISOTOPE?



IS THERE A SMOKING-GUN ISOTOPE?



	Nuclide	Q [MeV]	Principle	Det mass [kg]	Decay mass [kg]	Site
CANDLES	^{48}Ca (0.19%)	4.271	CaF_2 scint.	305	0.3	Kamioka
Cobra	^{116}Cd (90%)	2.802	CdZnTe semicond.	420	142	Gran Sasso
CUORE	^{130}Te (34%)	2.527	Bolometer	740	200	Gran Sasso
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	DUSEL/SNOLab
GERDA	^{76}Ge (86%)	2.039	Ge semicond.	40	34	Gran Sasso
KamLAND	^{136}Xe (90%)	2.458	Liquid. scint.	400	360	Kamioka
MAJORANA	^{76}Ge (86%)	2.039	Ge semicond.	60-1000	52-860	DUSEL
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

In blue: passive source

Enriched Xenon Observatory (EXO)

EXO is a multi-phase program to search for the neutrinoless double beta decay of ^{136}Xe.

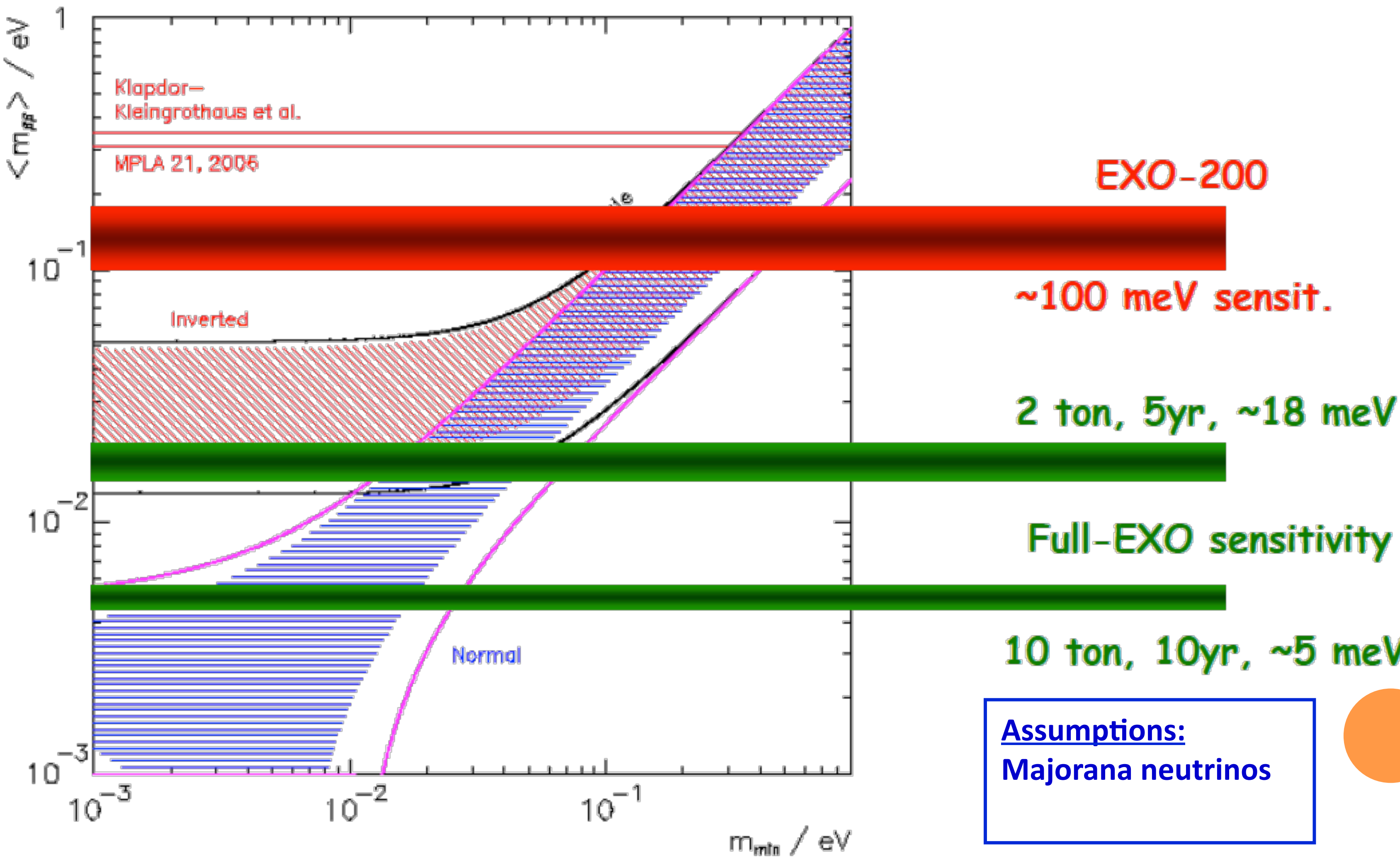
EXO-200 (first phase):

- A 200 kg liquid xenon detector currently operating underground
- Probe Majorana neutrino mass at 100-200 meV range
- Demonstrate technical feasibility of ton scale experiment

Full EXO (second phase):

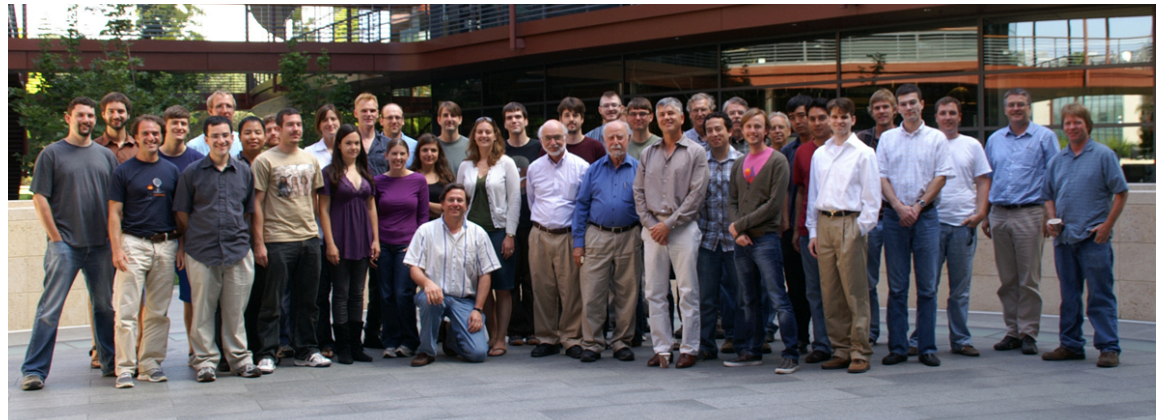
- A proposed 1- 10 ton liquid or gas xenon detector
- Probe Majorana neutrino mass at 5 – 30 meV range
- R&D work for novel techniques for background suppression and energy resolution in progress

EXO Sensitivity



Assumptions:
Majorana neutrinos

EXO Collaboration



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

Colorado State University, Fort Collins CO, USA - C. Benitez-Medina, S. Cook, W. Fairbank, Jr., K. Hall, N. Kaufold, B. Mong, T. Walton

Indiana University, Bloomington IN, USA - T. Johnson, L.J. Kaufman, C. Passolano, K. Scott

University of California, Irvine, Irvine CA, USA - M. Moe

ITEP Moscow, Russia - D. Akimov, I. Alexandrov, V. Belov, A. Burenkov, M. Danilov, A. Dolgolenko, A. Karelin, A. Kovalenko, A. Kuchenkov, V. Stekhanov, O. Zeldovich

Laurentian University, Sudbury ON, Canada - E. Beauchamp, D. Chauhan, B. Cleveland, J. Farine, J. Johnson, U. Wichoski, M. Wilson

University of Maryland, College Park MD, USA - C. Davis, A. Dobi, C. Hall, S. Slutsky, Y-R. Yen

University of Massachusetts, Amherst MA, USA - J. Cook, T. Daniels, K. Kumar, P. Morgan, A. Pocar, J.D. Wright

University of Seoul, South Korea - D. Leonard

Stanford Linear Accelerator Center (SLAC), Menlo Park CA, USA - M. Breidenbach, R. Conley, R. Herbst, S. Herrin, J. Hodgson, A. Johnson, D. Mackay, A. Odian, C.Y. Prescott, P.C. Rowson, J.J. Russell, K. Skarpaas, M. Swift, A. Waite, M. Wittgen, J. Wodin, L. Yang

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

Why Xenon?

Xenon isotopic enrichment is easier: Xe is a gas and ^{136}Xe is the heaviest isotope.

Xenon is "reusable": can be re-purified and recycled into new detector (no crystal growth).

Monolithic detector: LXe is self shielding, surface contamination minimized.

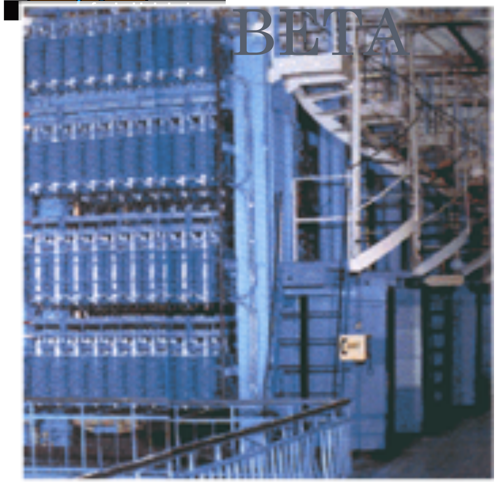
Minimal cosmogenic activation: no long lived radioactive isotopes of Xe.

Energy resolution in LXe can be improved: scintillation light + ionization anti-correlation.

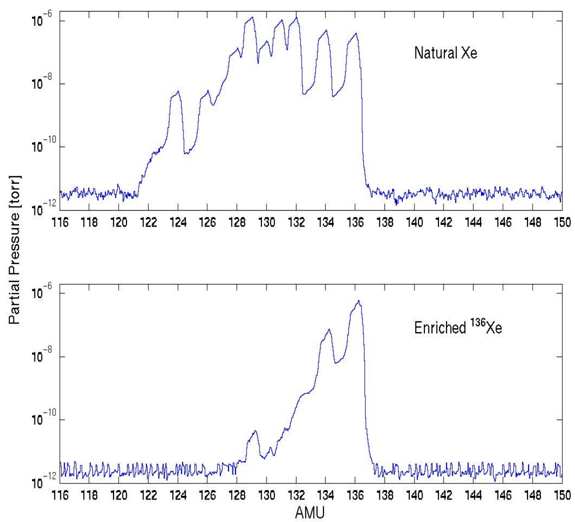
… admits a novel coincidence technique: background reduction by Ba daughter tagging.

EXO-200: THE FIRST 200 KG DOUBLE BETA DECAY EXPERIMENT

BETA



Centrifuge facility in Russia

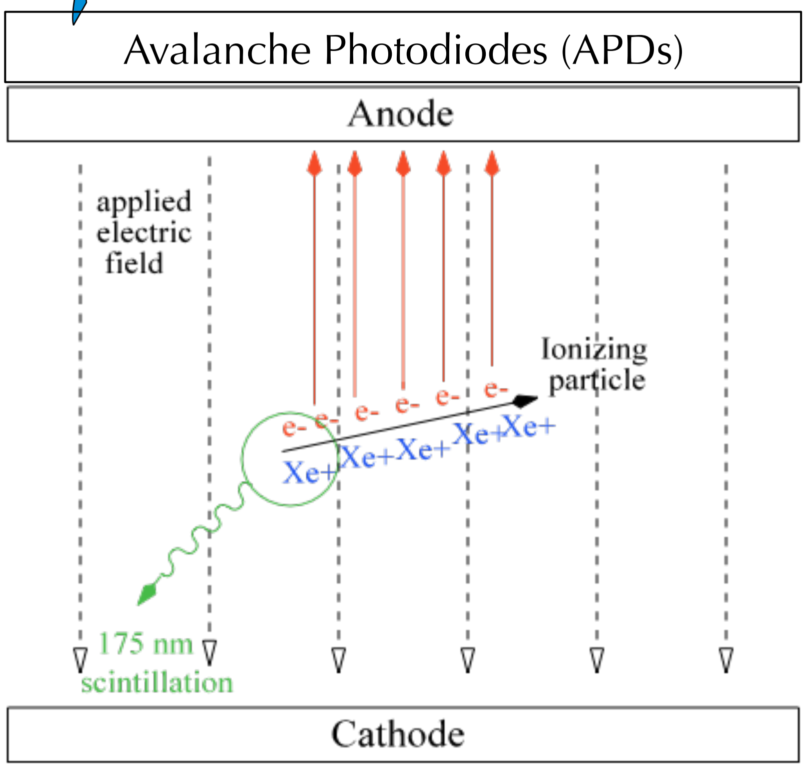


RGA mass scan of xenon samples

Enriched xenon storage bottles for EXO

EXO collaboration currently have 200 kg of xenon enriched to 80% = 160 kg of ^{136}Xe

LIQUID XENON AS SOURCE AND DETECTOR



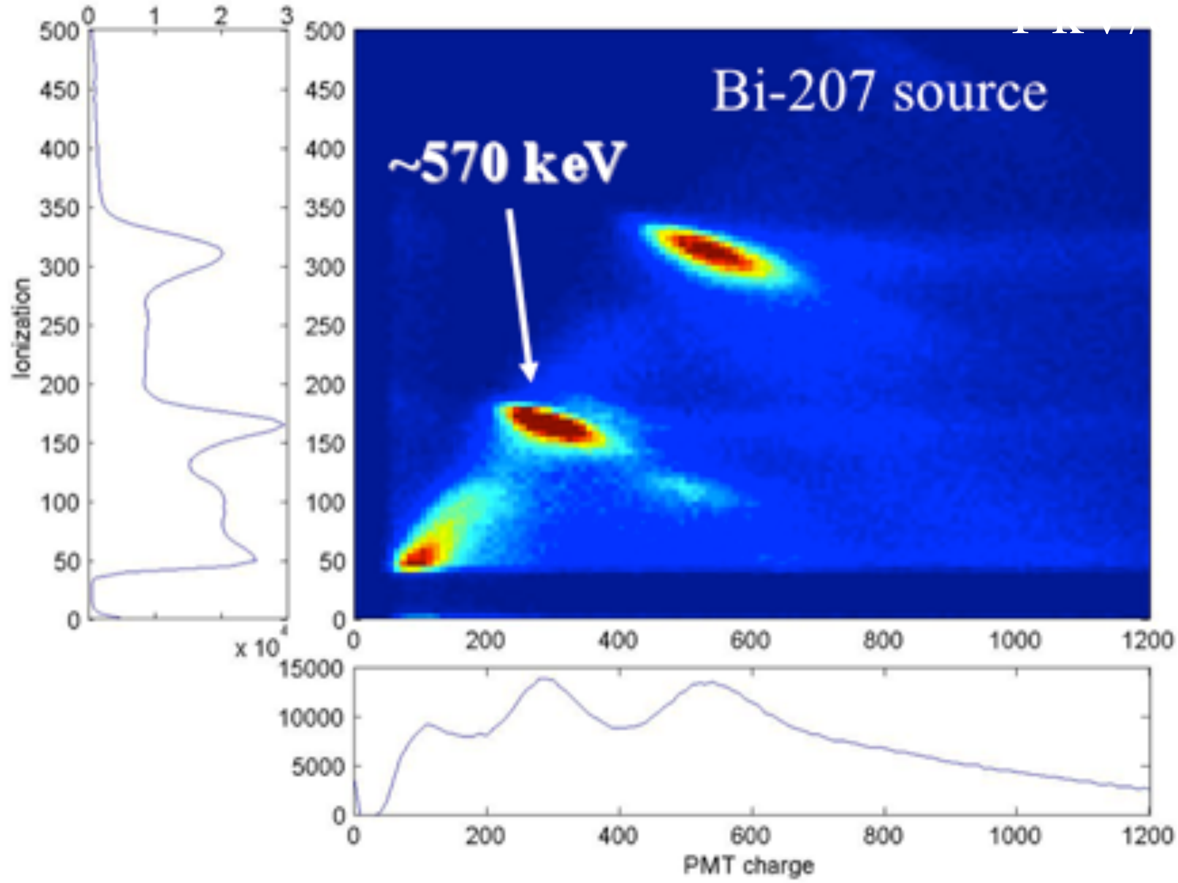
- Timing of the event:
  Scintillation light gives
  t = 0 for drift time (z)
- Position of the event:
  Crossed wires at the anode (x-y) collect charge at t=z
- Event energy:
  Ionization + scintillation light

When ionizing radiation enters liquid xenon, it creates many Xe^+ and e^- pairs and Xe*, some of the Xe+ and Xe* undergo recombination and give off 175nm VUV photons or heat.

Using xenon as both source and detector material allows more compact detector design and higher collection efficiency of light and charge.

LIQUID XENON ENERGY RESOLUTION

Liquid xenon data show an anti-correlation between ionization and scintillation

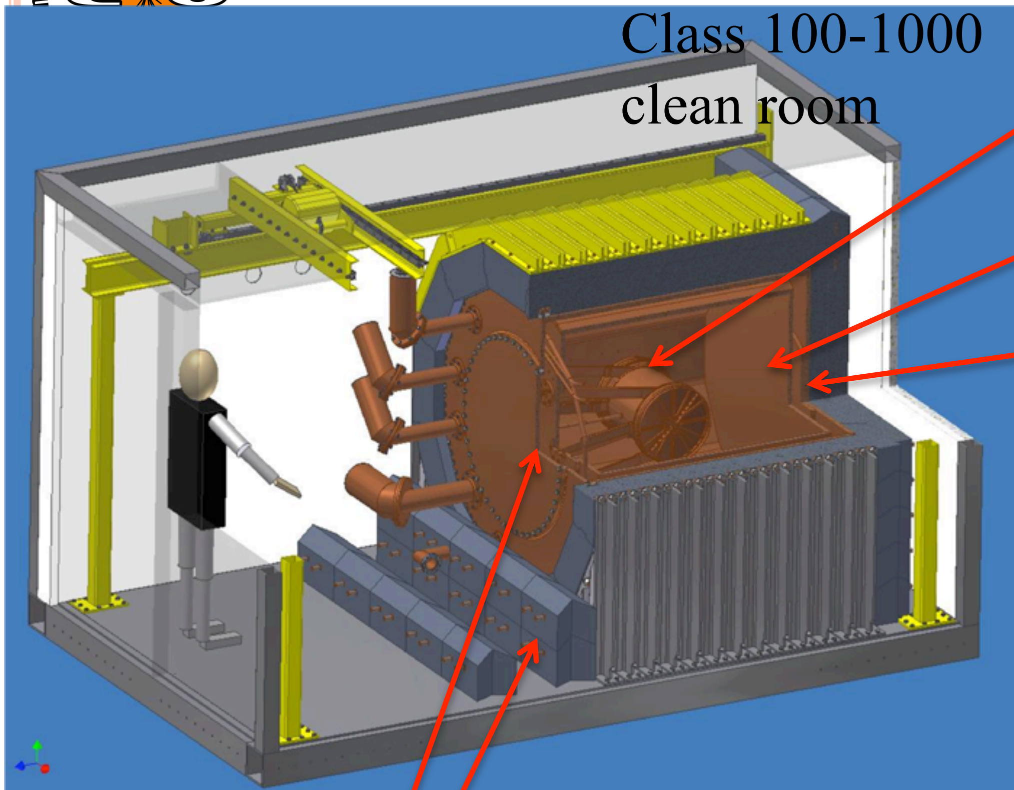


Ionization alone: 3.8% @ 570 keV or 1.8 % @ Q(ββ)

Ionization & Scintillation: 3.0% @ 570 keV or 1.4 % @ Q(ββ)

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

EXO-200 DETECTOR



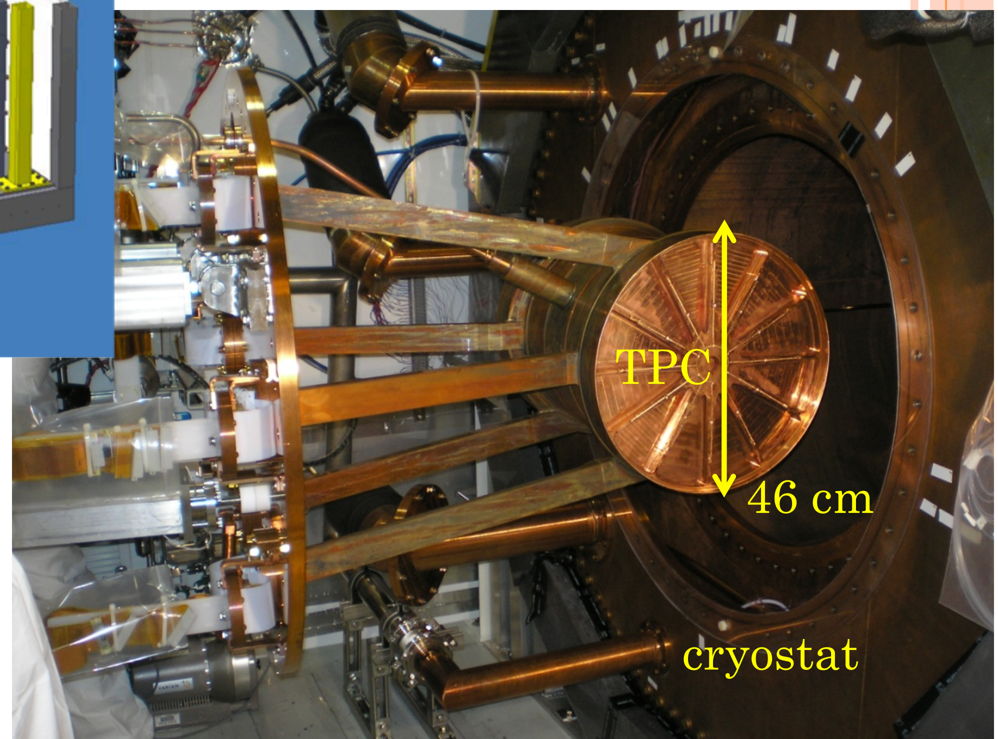
Xe Vessel

HFE (Heat transfer fluid)

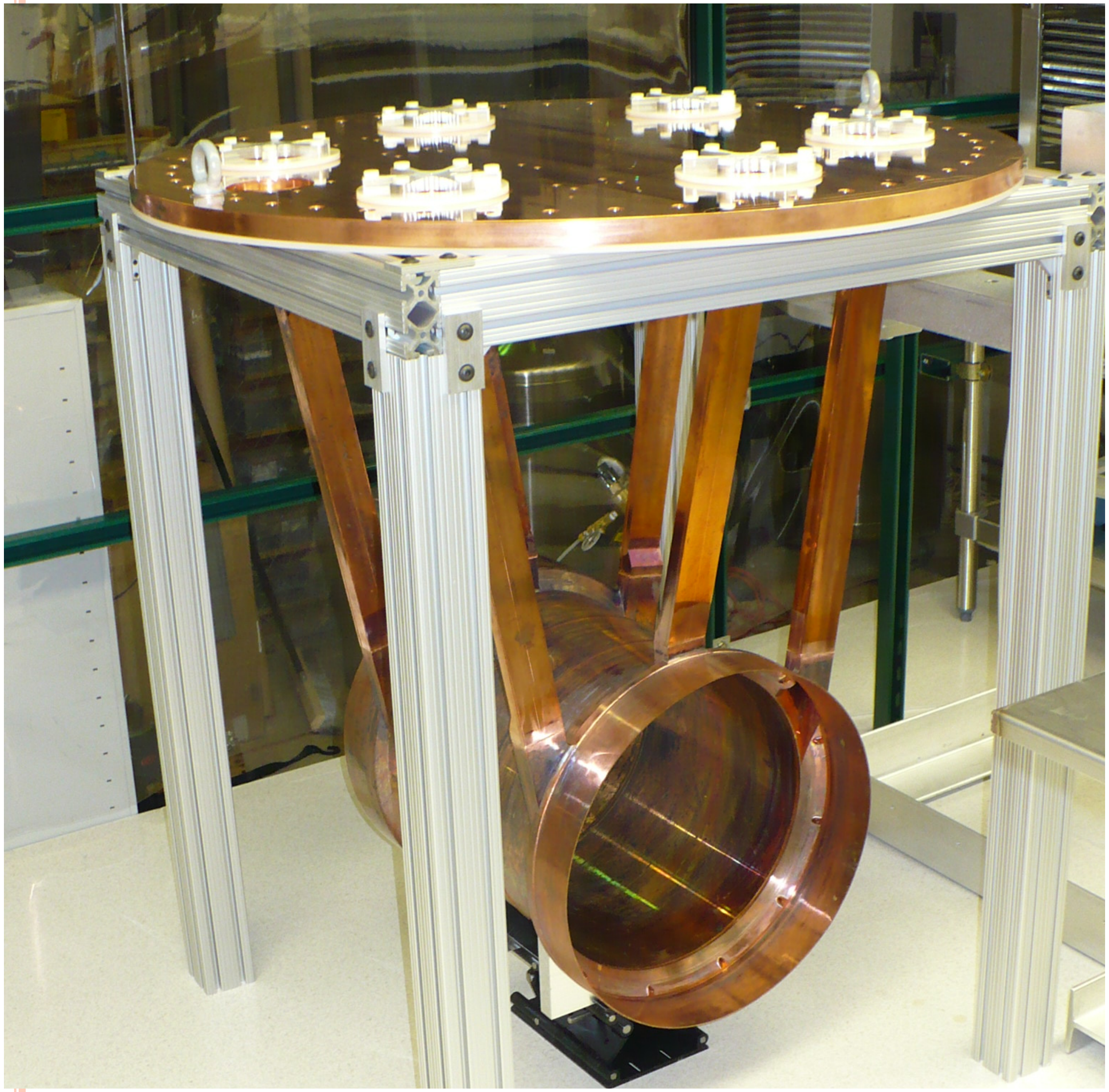
Vacuum insulation

Copper cryostat

25cm enclosure of
low-activity lead

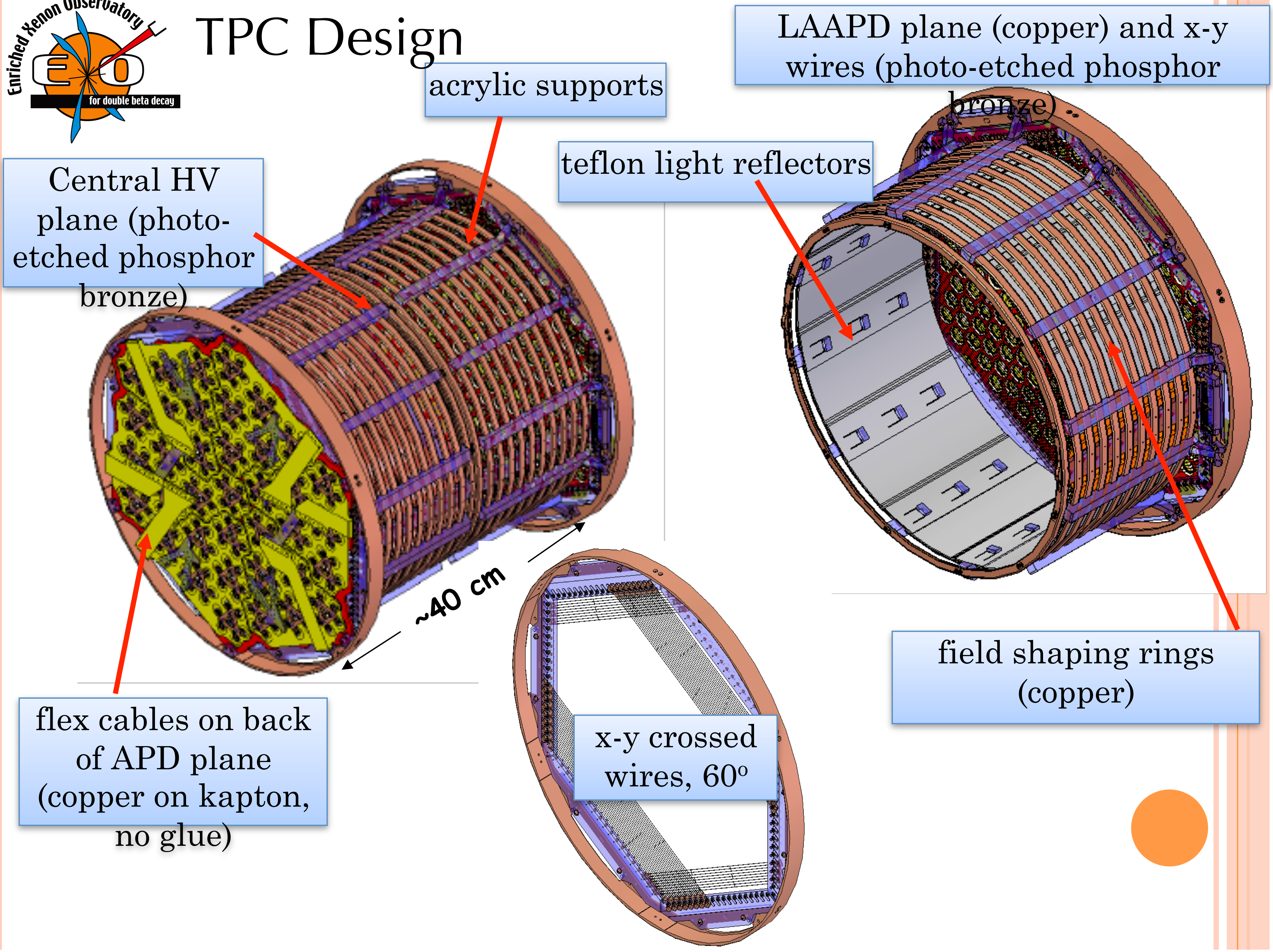


Copper Xe Vessel

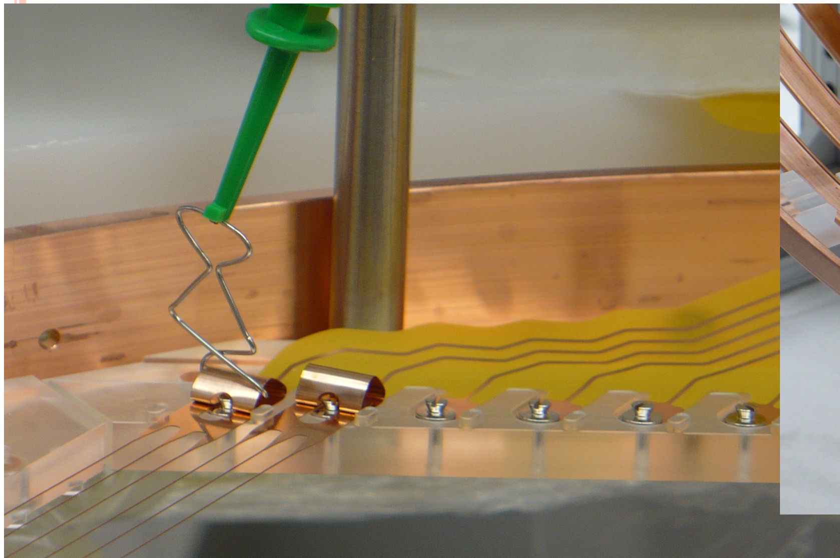


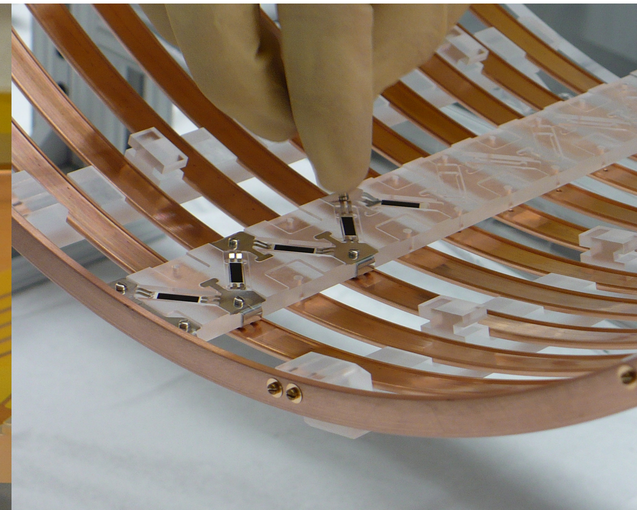
- Very light (wall thickness 1.5 mm, total weight 15 kg), to minimize material.
- All parts machined under 7 ft of concrete shielding to reduce activation by cosmic rays.
- Different parts are e-beam welded together at Applied Fusion. Construction of the vessel with 55 welds has been completed.
- End caps are TIG welded.

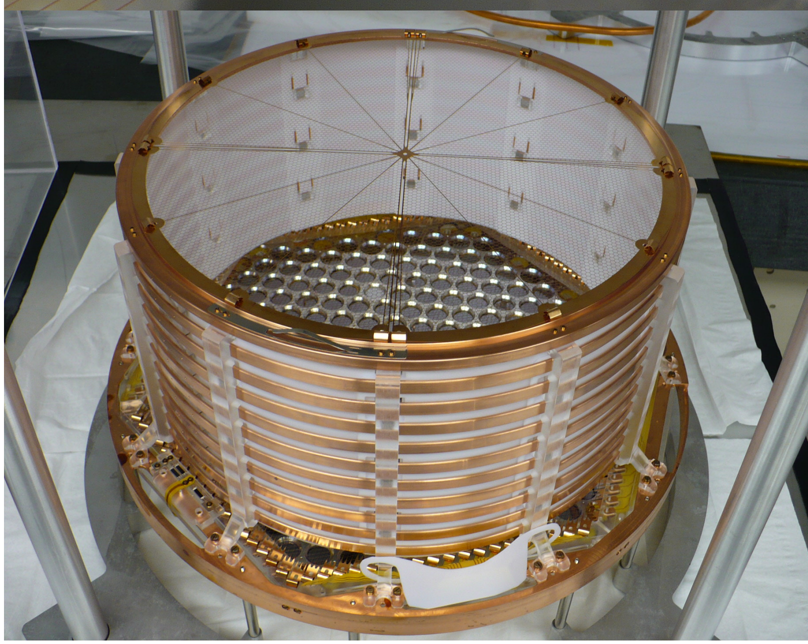
TPC Design


LAAPD plane (copper) and x-y wires (photo-etched phosphor bronze)
acrylic supports
teflon light reflectors
Central HV plane (photo-etched phosphor bronze)
~40 cm
flex cables on back of APD plane (copper on kapton, no glue)
x-y crossed wires, 60°
field shaping rings (copper)

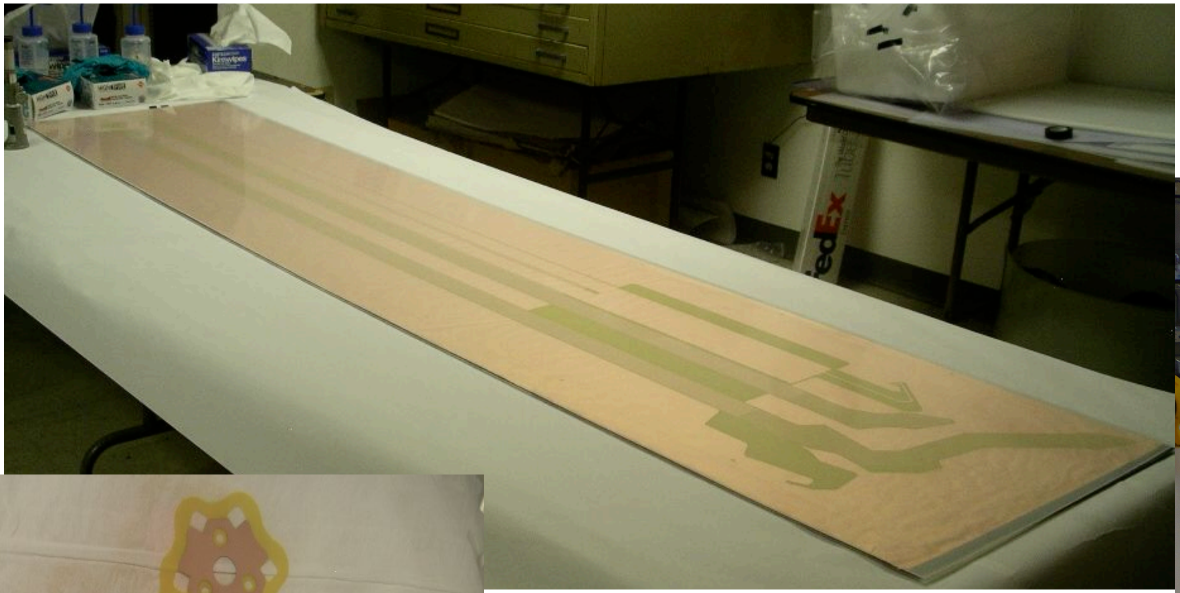
EXO-200 TPC Construction

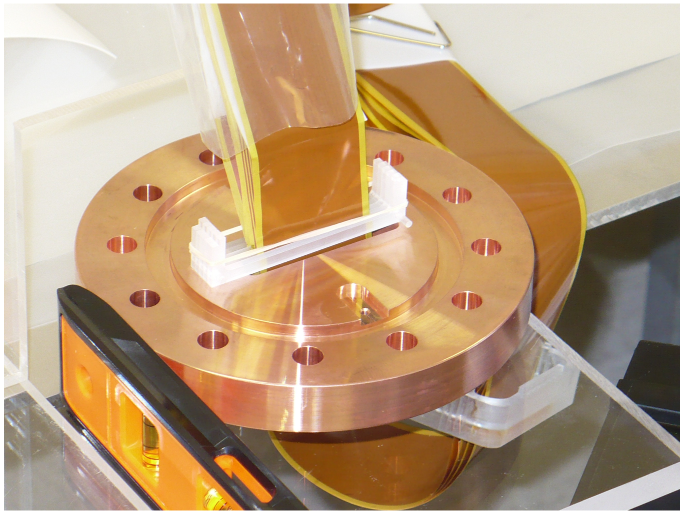


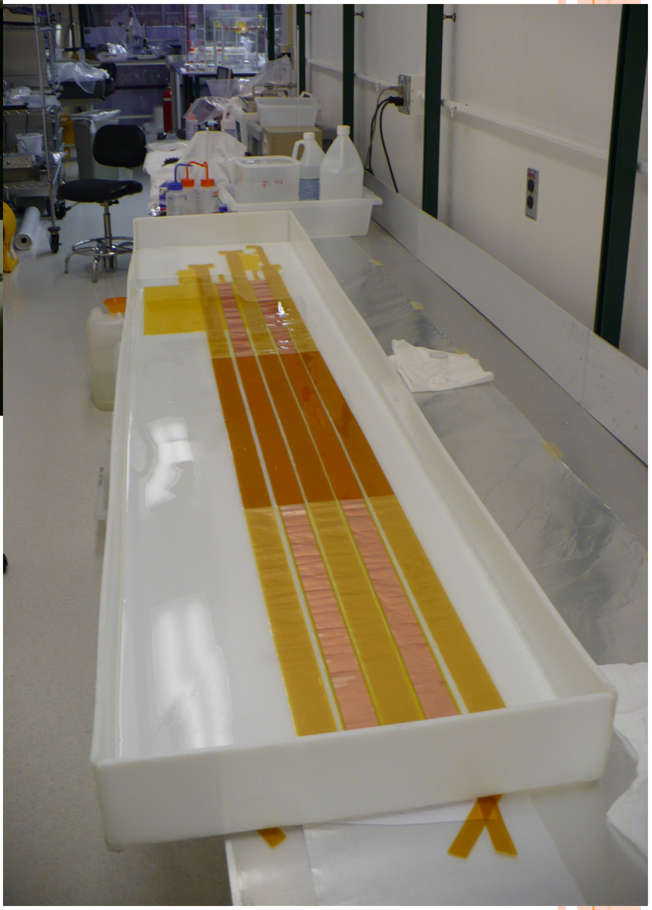




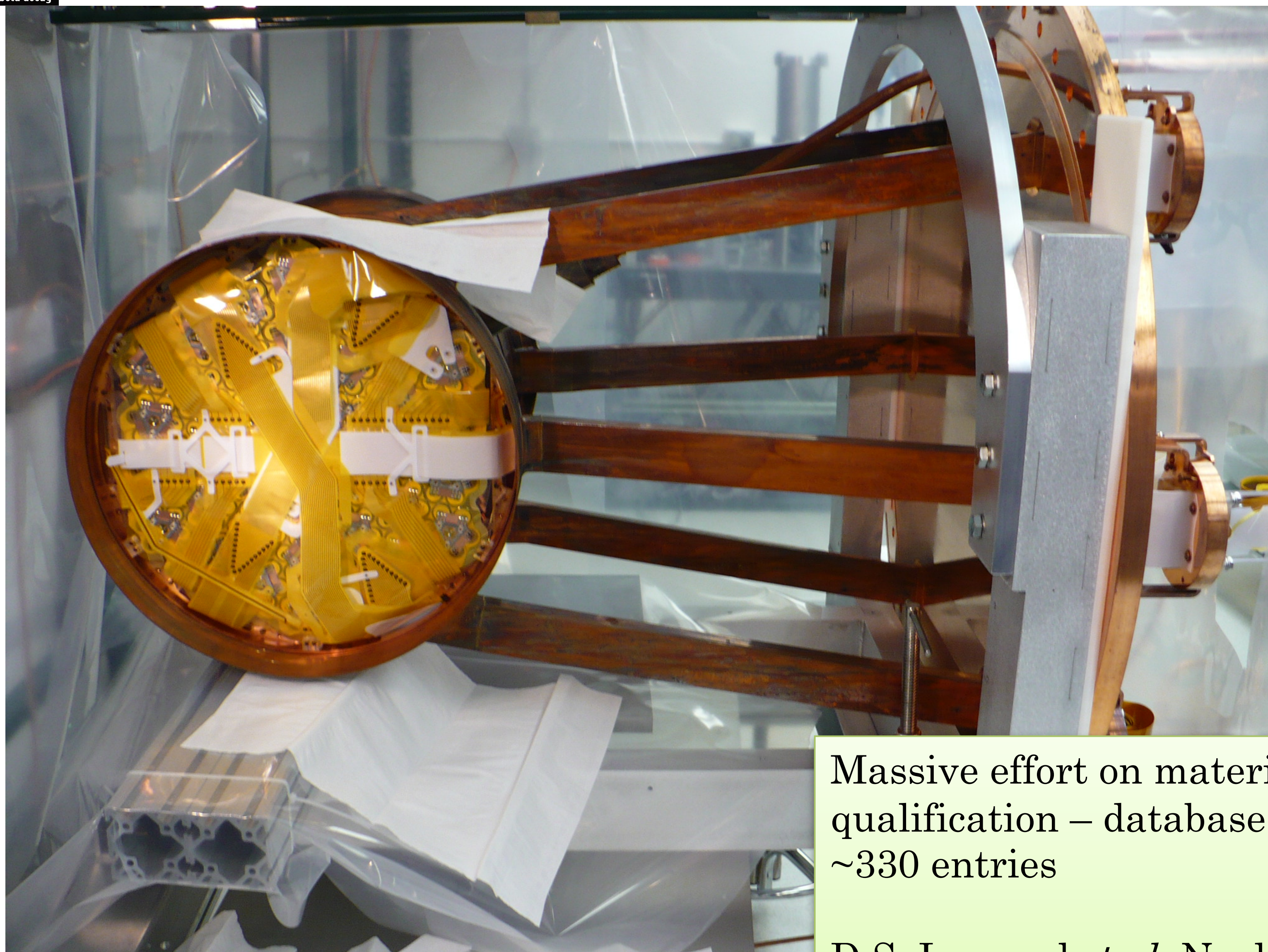
Flex cables







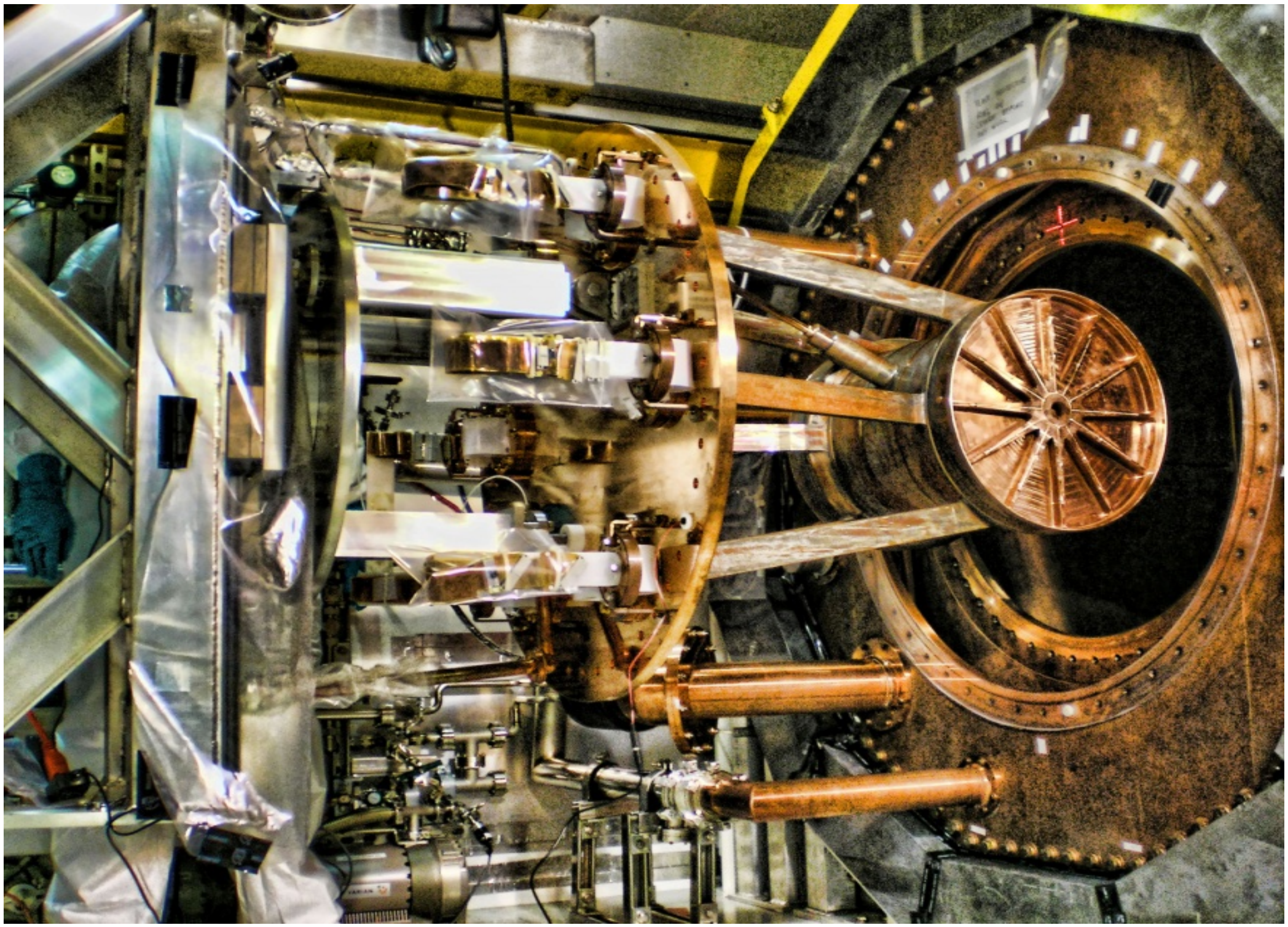
EXO-200 TPC Assembled



Massive effort on materials qualification – database of ~330 entries

D.S. Leonard *et al.* Nucl Inst. Meth. A 591 (2008) 490-509.

TPC Installation



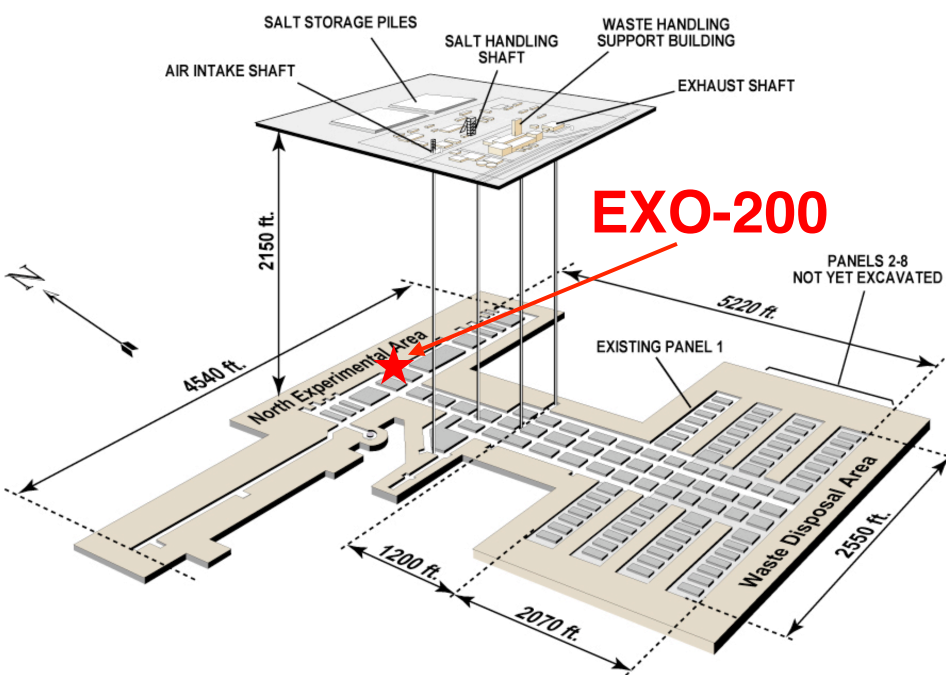
Underground Facility for EXO in Carlsbad, NM

Underground facility at WIPP

EXO-200 is sited at the Waste Isolation Pilot Plant in Carlsbad, NM, a radioactive waste disposal facility located 2150 ft underground in a salt deposit.

• ~1600 m water equivalent flat overburden [Esch et. al., *NIM* A**538**, 516(2005)]

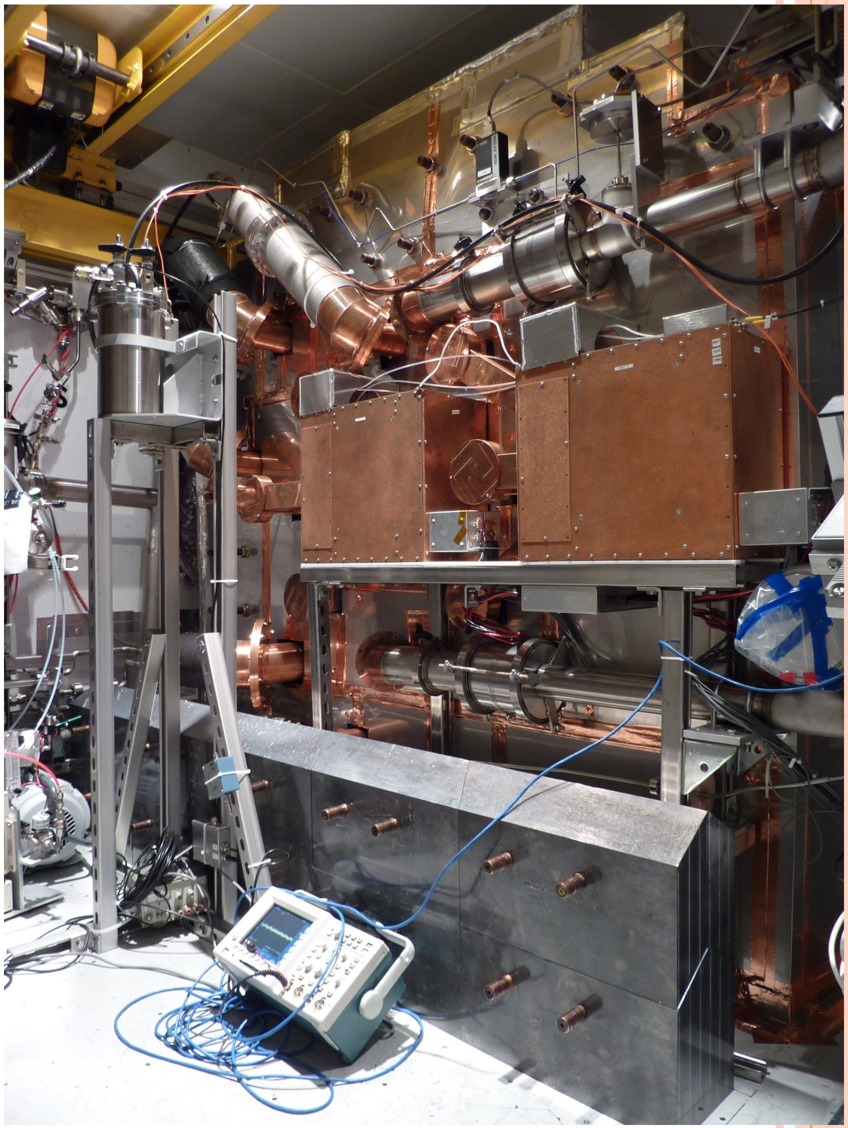
• Relatively low levels of U and Th (measurements < 100 ppb in EXO-200 drift), Rn (~20 Bq/m^3)



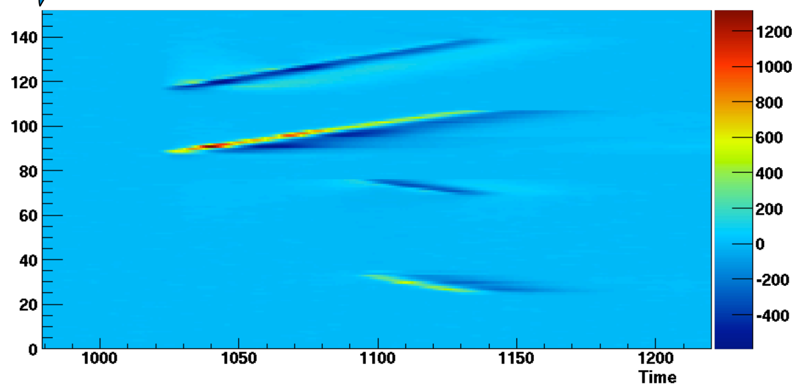
EXO-200 LOW-BACKGROUND ENRICHED XE RUN 2011

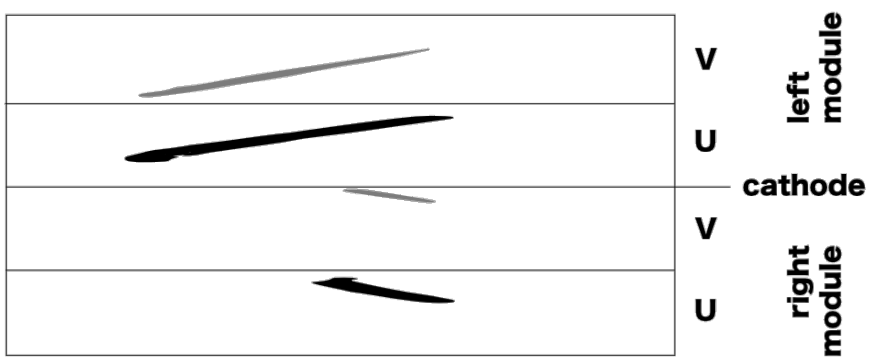
- Filled with enriched Xe in spring 2011.
- **First measurement of 2νββ half-life in ^{136}Xe!**
- Using source calibration runs and low background runs, we are understanding and optimizing the detector.

  - Rn enclosure not yet in operation
  - No Rn trap in Xe system
  - Still missing part of front lead enclosure

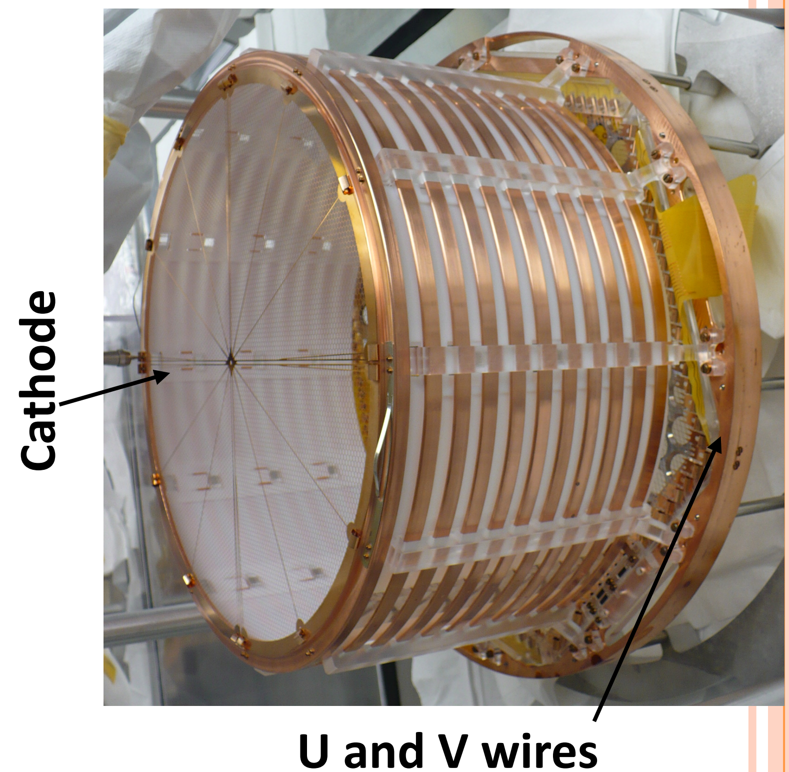


MUON TRACK IN EXO-200





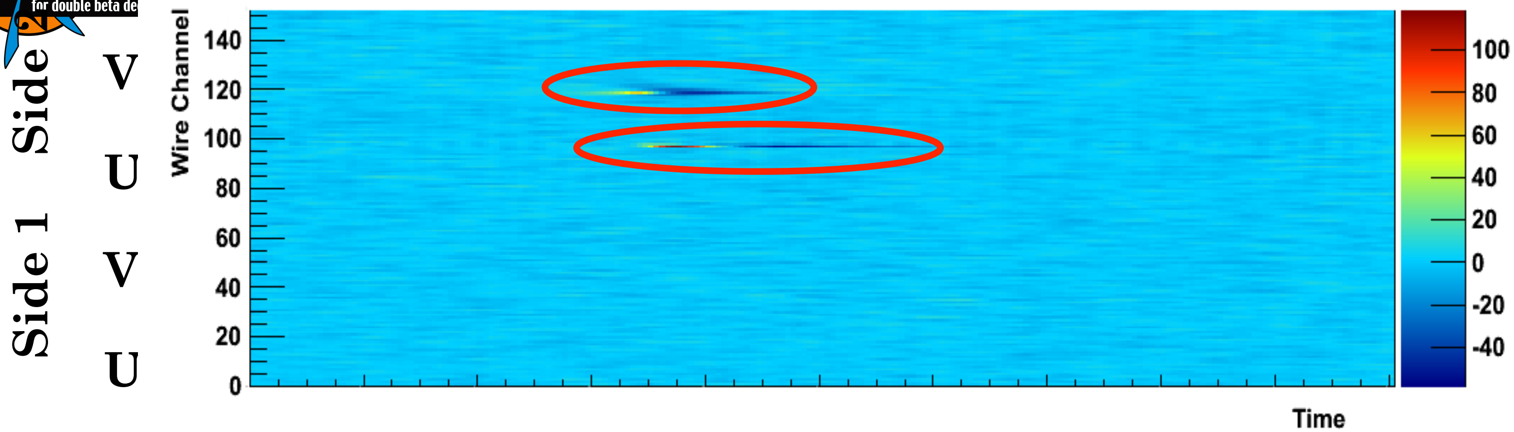
One of the two TPC modules

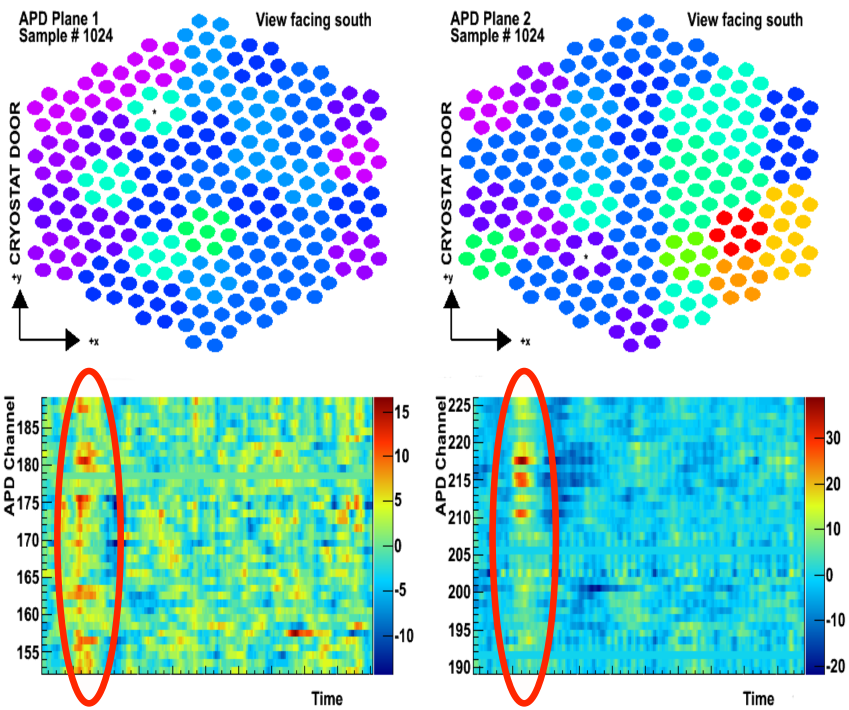


A track from a cosmic-ray muon in EXO-200. The horizontal axis represents time (uncalibrated for now) while the vertical is the wire position (see sketch). V wires see inductive signals while U wires collects the charge.

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.

SINGLE-CLUSTER EVENT IN EXO-200





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

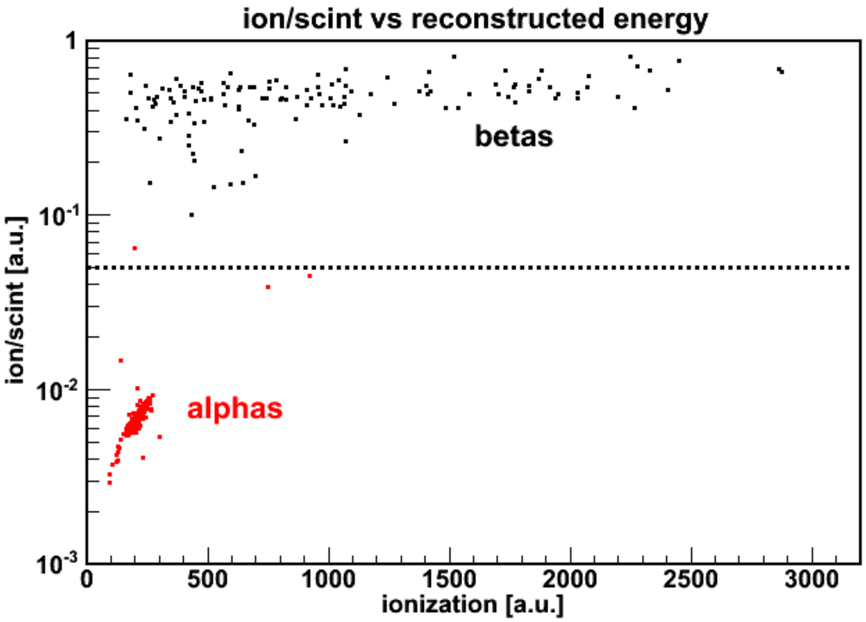
Left display is light readout. APD map refers to the sample with max signal.

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

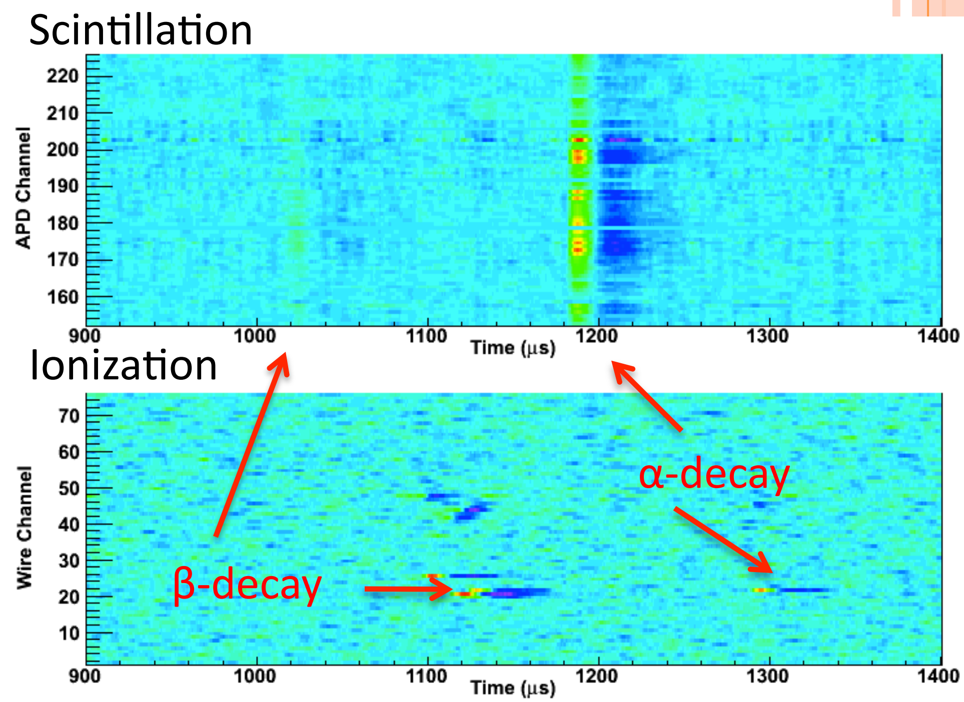
Small depositions produce induction signals on more than one V wires but are collected by a single U wire. V signal always comes before U.

Light signals precede in time the charge ones

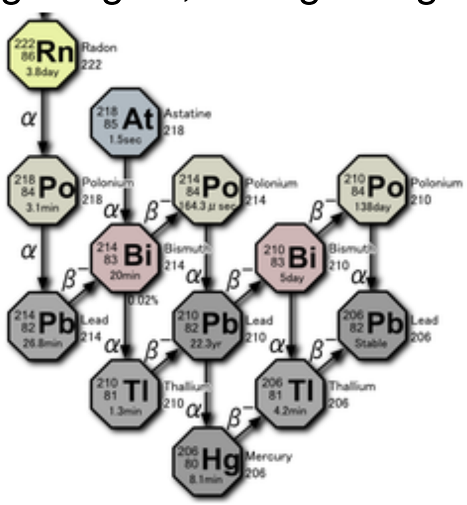
RN CONTENT IN XENON



α: strong light signal, weak charge signal
β: weak light signal, strong charge signal

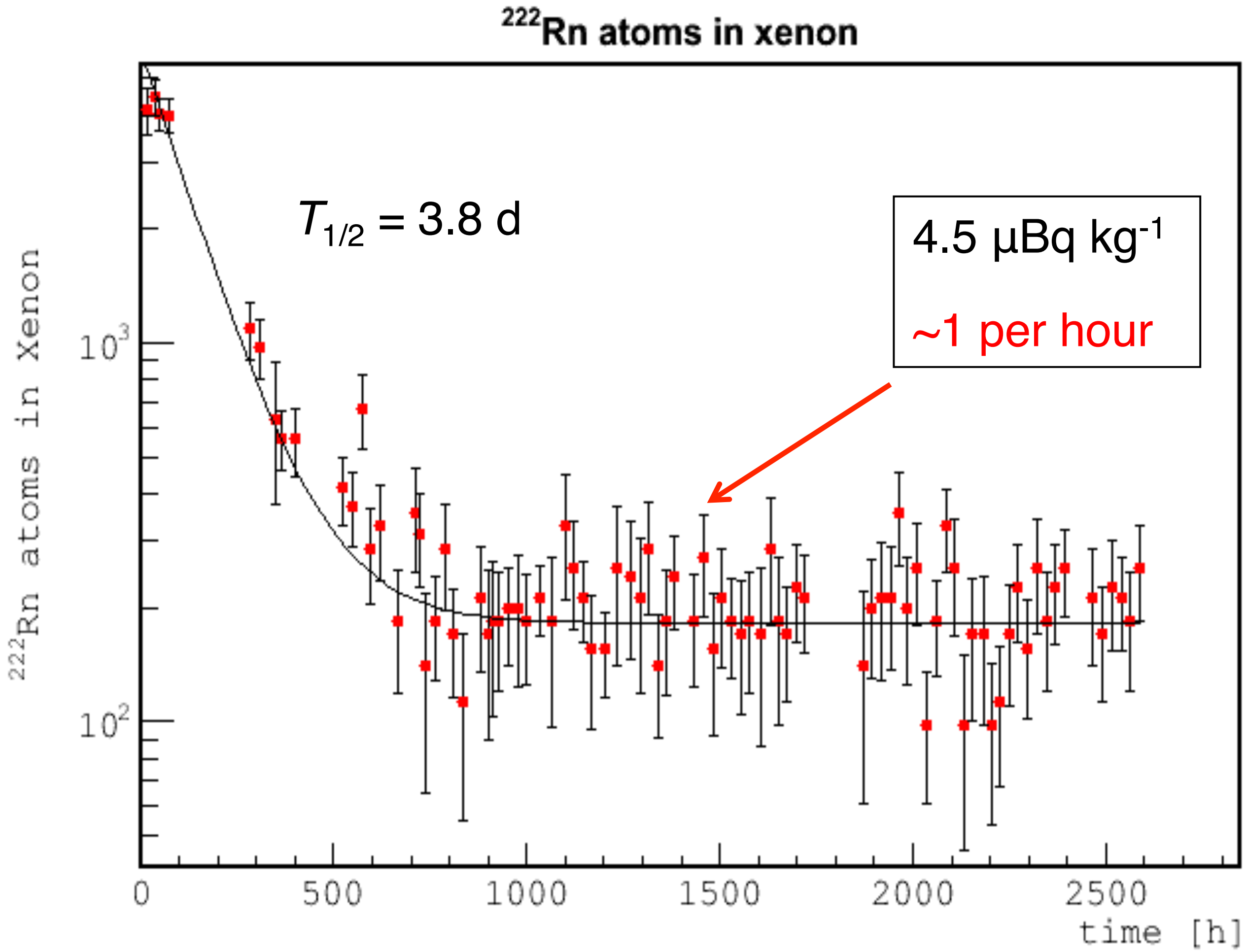


^{214}Bi – ^{214}Po correlations in the EXO-200 detector.



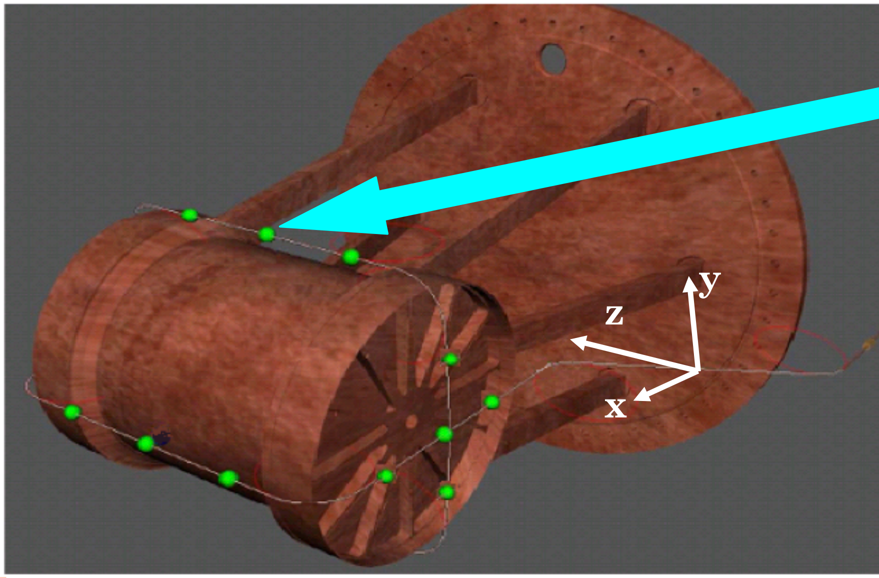
Using the Bi-Po (Rn daughter) coincidence technique, we can estimate the Rn content in our detector.

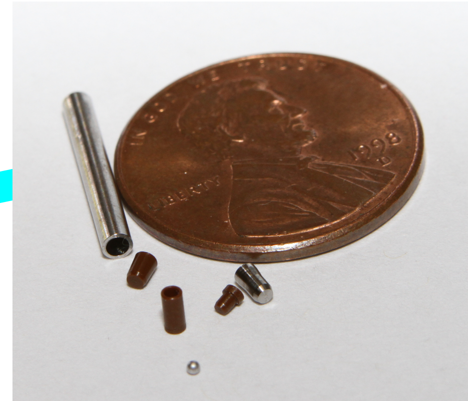
Rn content in xenon



The ^{214}Bi decay rate is consistent with measurements from alpha-spectroscopy and the expected Rn background with no Rn trap.

Calibration Source run



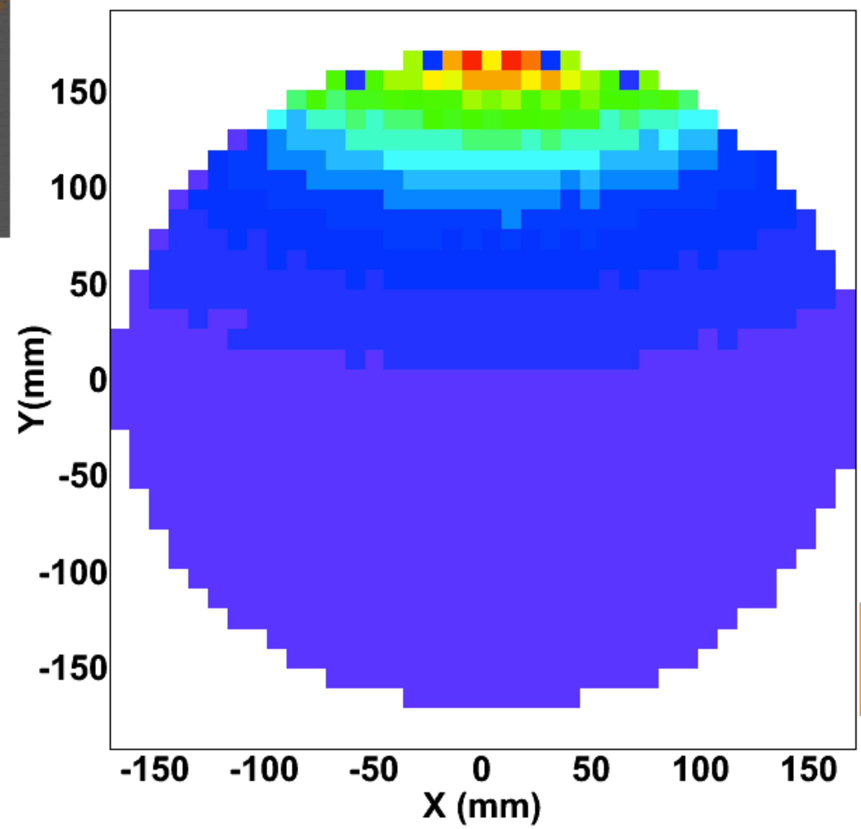


Sources:

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

Calibration sources are deployed through a guide tube that wraps around the copper vessel

Spatial distribution of events clearly shows excess near the source location

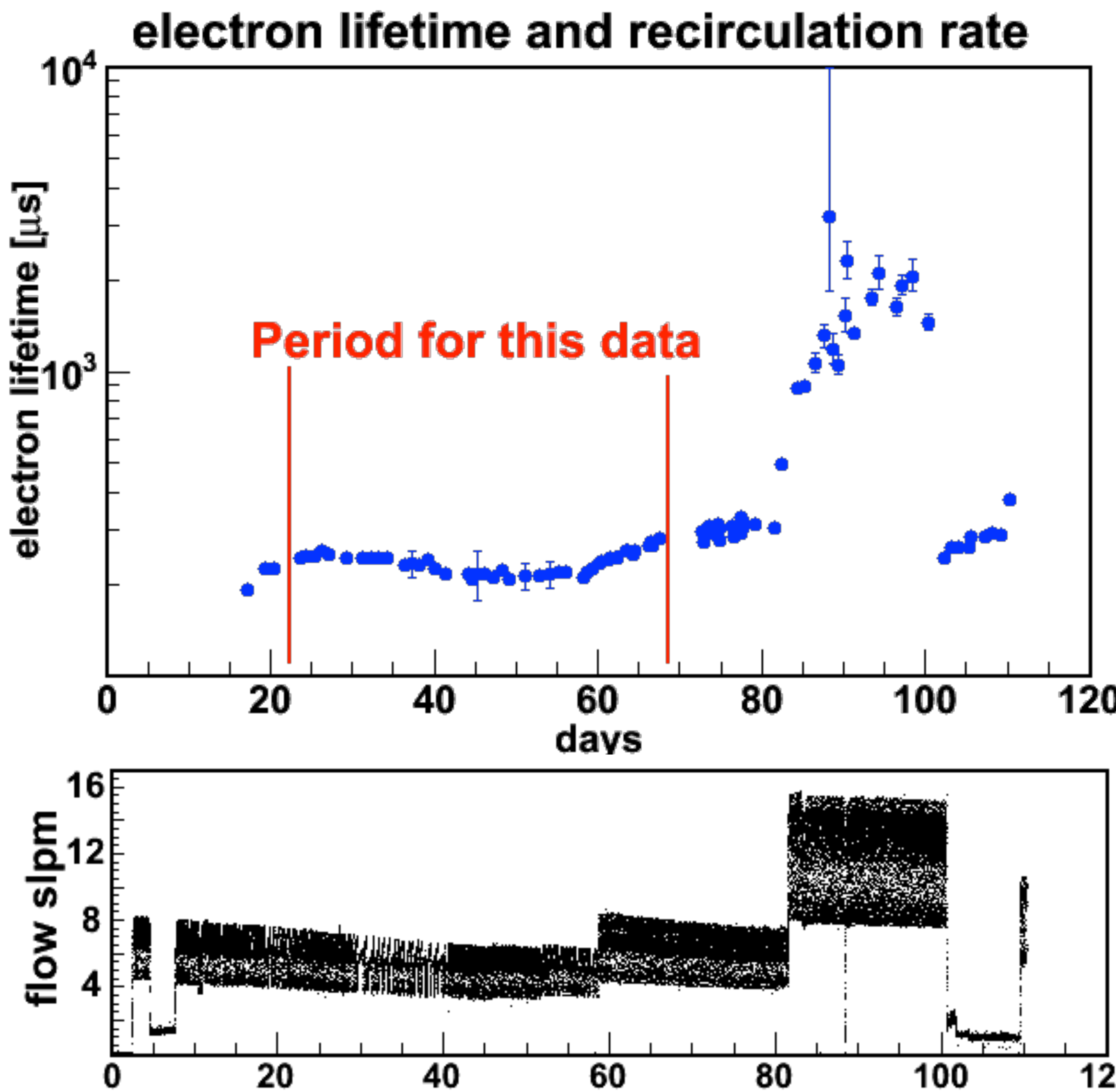


Xenon purity

•Continuously recirculate Xe through SAES high temperature purifiers using a custom designed magnetic piston pump [Neilson et al. (2011) arXiv:1104.5041v1].

•Demonstrated electron lifetimes of better than 1 ms at high recirculation rate.

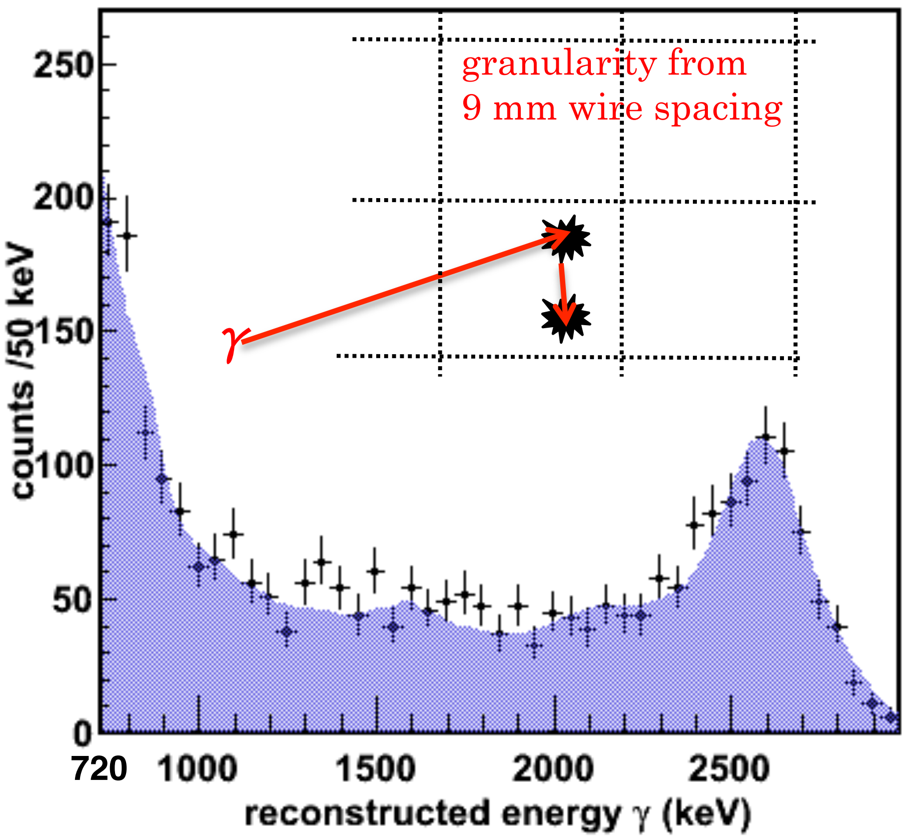
•Average electron lifetime for 2νββ data set was ~250 μs.



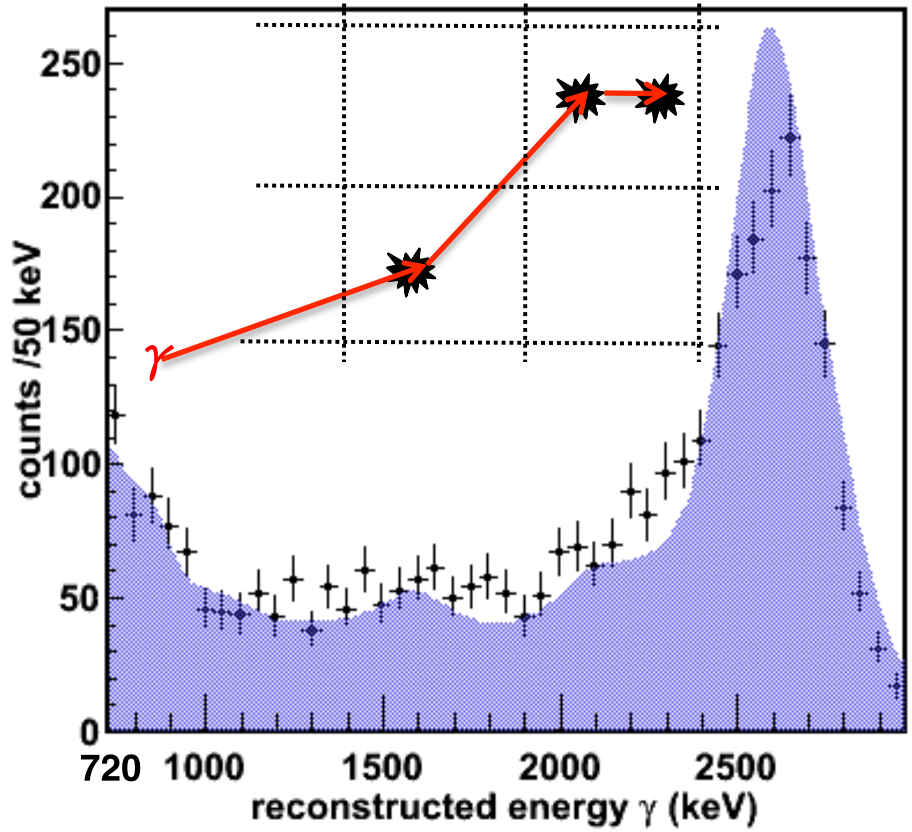
• Use sources to measure purity of LXe in TPC

^{228}TH CALIBRATION

single - cluster

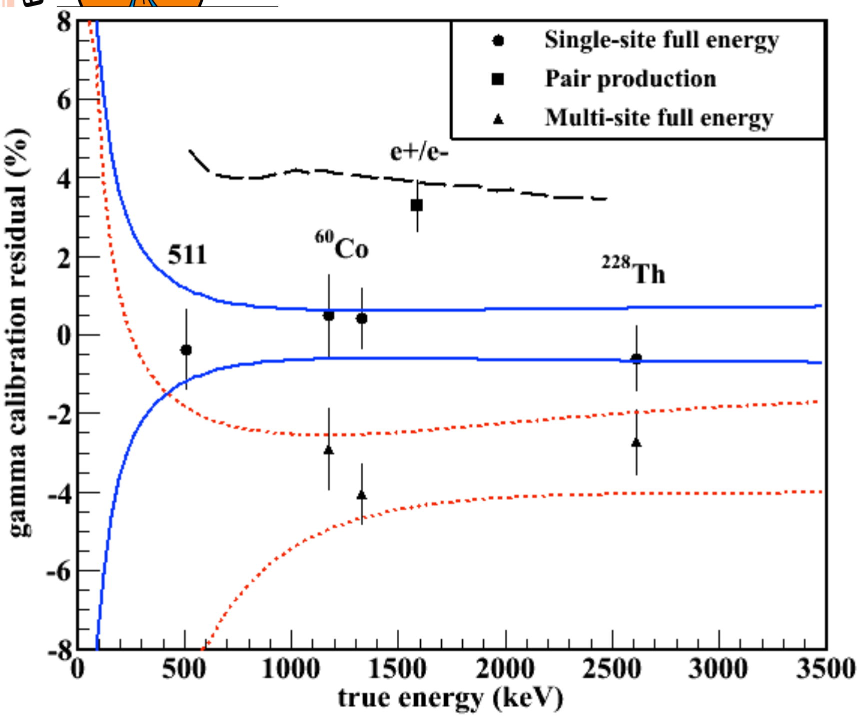


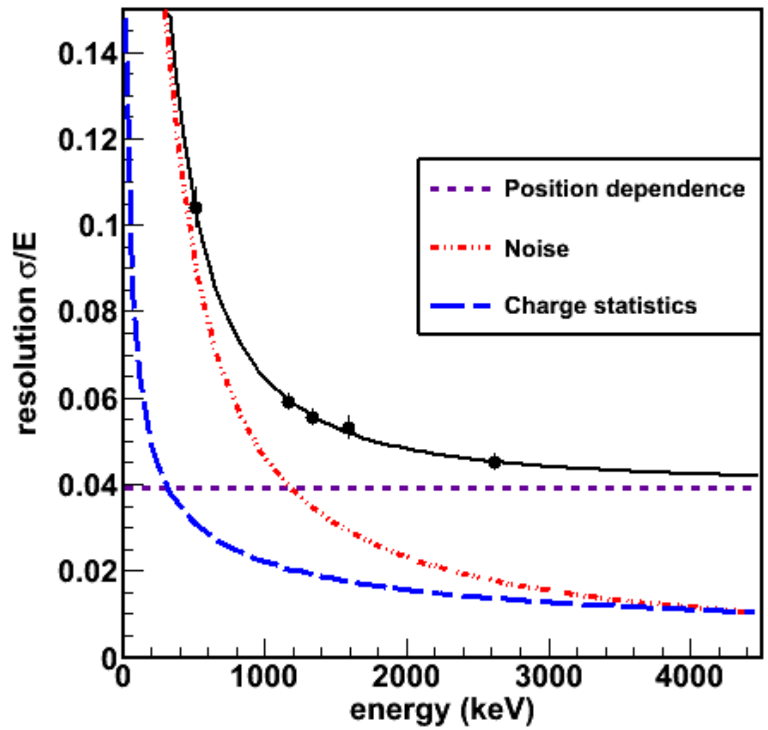
multiple - cluster



- Calibration runs compared to simulation
  - GEANT4 based simulation
  - charge propagation
  - scintillation propagation
  - signal generation
  - energy resolution parameterization is added in after the fact
- There are no free parameters for these comparisons (worst agreement is +8%)

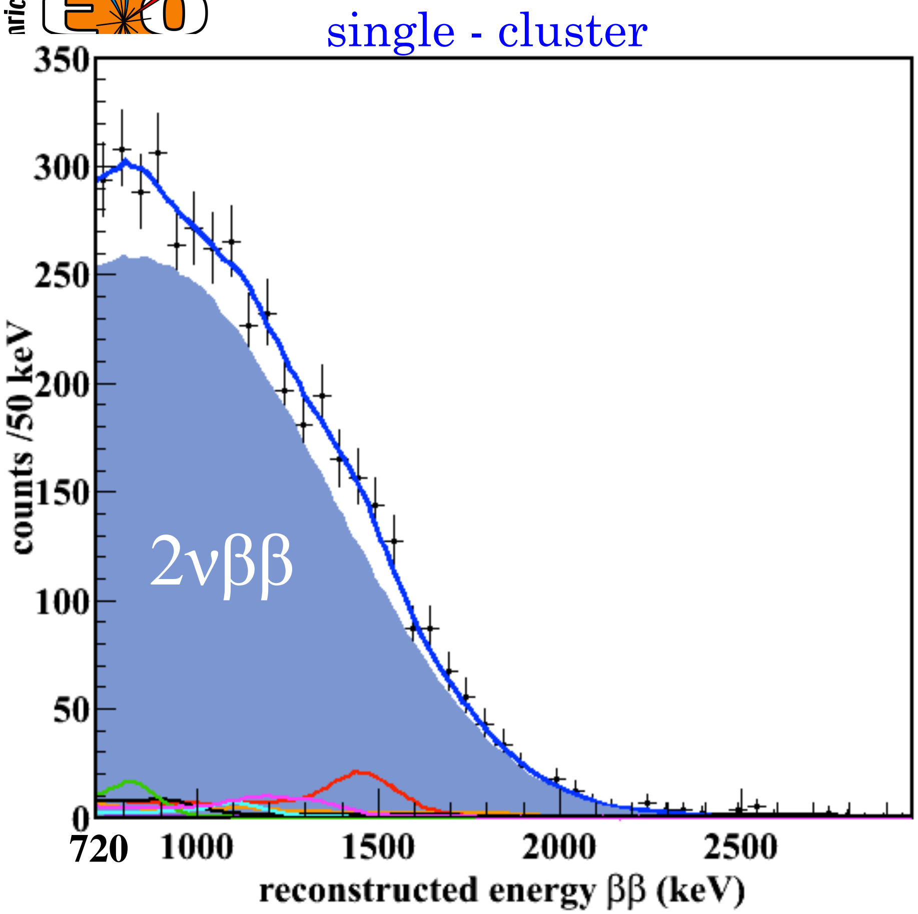
ENERGY CALIBRATIONS

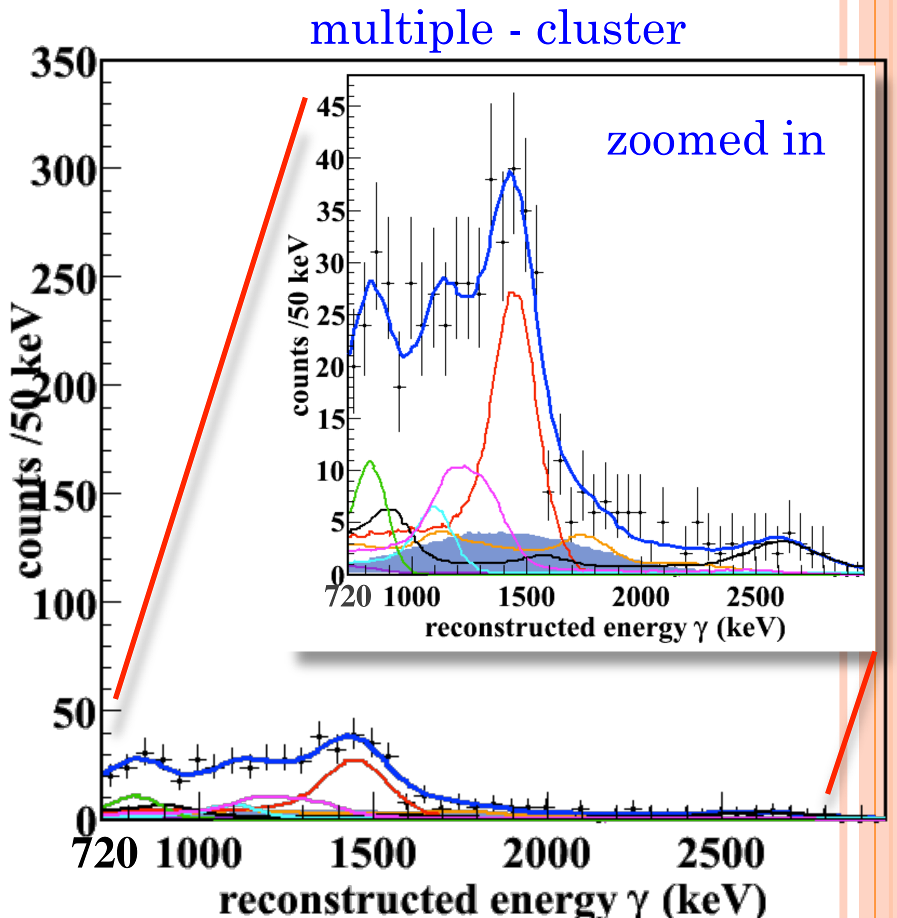




- After purity correction, calibrated single and multiple cluster peaks across energy region of interest (511 to 2615 keV)
  - -uncertainty bands are systematic
- Point-like depositions have large reconstructed energies due to induction effects
  - - observed for pair-production site (similar to β and $\beta\beta$ decays)
  - - reproduced in simulation
- Peak widths also recorded and their dependence on energy is parameterized.

LOW-BACKGROUND SPECTRA





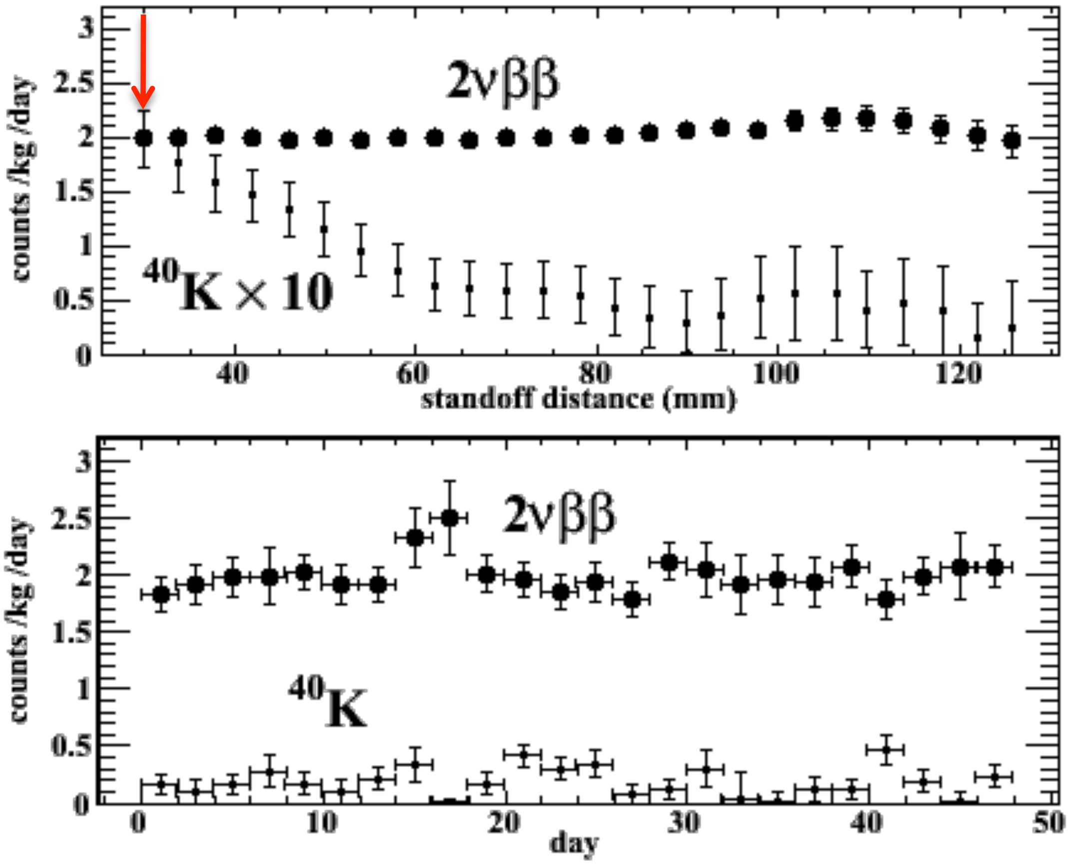
- 31 live-days of data
- 63 kg active mass
- Signal / Background ratio 10:1

-as good as 40:1 for some extreme fiducial volume cuts

$T_{1/2}$ = 2.11·10^{21} yr (± 0.04 stat) yr (± 0.21 syst)

N. Ackerman *et al.*, PRL **107**, 212501 (2011).

LOW-BACKGROUND SPECTRA



- constant in time
- $2\nu\beta\beta$ signal is clearly in the LXe bulk, while other gamma background contributions decrease with increasing distance from the walls.

$T_{1/2}$ = 2.11·10^{21} yr (± 0.04 stat) yr (± 0.21 syst)
N. Ackerman *et al.*, PRL **107**, 212501 (2011).

EXO-200: $2\nu\beta\beta$ Observation

	$T_{1/2}$ (y)	$M^{2\nu}$ (MeV^{-1})	
^{48}Ca	$(4.3\ ^{+2.4}_{-1.1} \pm 1.4)$E19	0.05 ± 0.02	Balysh,PRL**77**,5186 (1996)
^{76}Ge	$(1.74 \pm 0.01\ ^{+0.18}_{-0.16})$E21	0.13 ± 0.01	Doerr,NIMA**513**,596 (2003)
^{82}Se	(9.6 ± 0.3 ± 1.0)E19	0.10 ± 0.01	Arnold,PRL**95**,182302 (2005)
^{96}Zr	(2.35 ± 0.14 ± 0.16)E19	0.12 ± 0.01	Argyriades,NPA**847**,168 (2010)
^{100}Mo	(7.11 ± 0.02 ± 0.54)E18	0.23 ± 0.01	Arnold,PRL**95**,182302 (2005)
^{116}Cd	$(2.9^{+0.4}_{-0.3})$E19	0.13 ± 0.01	Danevich,PRC**68**,035501 (2003)
^{128}Te*	(1.9 ± 0.1 ± 0.3)E24	0.05 ± 0.005	Lin,NPA**481**,477 (1988)
^{130}Te	(7.0 ± 0.9 ± 1.1)E20	0.033 ± 0.003	Arnold,PRL**107**,062504 (2011)
^{136}Xe	**(2.1 ± 0.04 ± 0.21)E21**	**0.019 ± 0.001**	**Ackerman,PRL107,212501 (2011)**
^{150}Nd	$(9.11^{+0.25}_{-0.22} \pm 0.63)$E18	0.06 ± 0.003	Argyriades,PRC**80**,032501R (2009)
^{238}U**	(2.2 ± 0.6)E21	0.05 ± 0.01	Turkevich,PRL**67**,3211(1991)

*From geochemical ratio $^{128}Te/^{130}Te$.
**Radiochemical result.

Significantly shorter than previous limits reported:
$T_{1/2} > 1.0 \cdot 10^{22}$ yr (90% C.L.) (R. Bernabei *et al*. Phys. Lett. B 546 (2002) 23)

and $T_{1/2} > 8.5 \cdot 10^{21}$ yr (90% C.L.) (Yu. M. Gavriljuk *et al*., Phys. Atom. Nucl. 69 (2006) 2129)

EXO-200: BACKGROUND

Background at Q-value of 2458 keV is only
0.004 counts/keV/kg/year !

Coming up next:

- Close front lead wall completely.
- Radon tent to flush old air inside shielding.
- Radon trap to remove Rn in the detector volume.
- Electronics upgrade - done.
- 3D multiple site cut and anticorrelation.

EXO-200 Sensitivity projections

We expect a low but finite radioactive background: 20 events/year in the ±2 σ interval centered around the 2.458 MeV endpoint

The background from 2νββ will be negligible ($T_{1/2}$>1 ·10^{22} yr R.Bernabei et al. measurement)

The expected energy resolution is σ (E)/E = 1.6%

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	Radioactive Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (meV) QRPA	(NSM)
EXO200	0.2	70	2	1.6*	40	6.4×10^{25}	109[1]	(135)[2]

1. Simkovic et al., *Phys. Rev.* C**79**, 055501(2009); 2. Menendez et al., *Nucl. Phys.* A**818**, 139 (2009)

CONCLUSIONS

- Double beta decay is indispensible for our understanding of neutrinos.
- All subsystems of EXO-200 are working.
- We have begun to understand the detector performance and background with enriched xenon data.
- Using the first charge-only analysis of the data, we were able to measure the two-neutrino decay of ^{136}Xe.
- We just completed some hardware upgrades and are now using combined charge and light analysis to improve our energy resolution.
- Stay tuned for 0ν analysis ...

FULL EXO 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‡	Majorana mass (meV) NSM#
Conservative	2	68	5	1.6*	5.0	$2.8 \cdot 10^{27}$	16	20
Aggressive	10	68	10	1†	3.4	$3.4 \cdot 10^{28}$	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)