EXO-200 Status

David Auty for the EXO Collaboration
University of Alabama
18th July 2011

Overview

- Motivation
  - Knowledge of neutrinos
  - What is $\beta\beta$ decay
- EXO
  - Why Xe^{136}
  - WIPP
  - Commissioning

What do we know about neutrino mass assuming three flavors?

From experiments using solar ν and reactor $\bar{\nu}$:

$$\Delta m^2_{21} = \Delta m^2_{sol} = (7.59 \pm 0.21) \cdot 10^{-5}\ \mathrm{eV}^2$$

$$\sin^2(2\theta_{12}) = \sin^2(2\theta_{sol}) = 0.861^{+0.026}_{-0.022}$$

From experiments using atmospheric and accelerator ν:

$$\Delta m^2_{32} = \Delta m^2_{atm} = \pm(2.42 \pm 0.13) \cdot 10^{-3}\ \mathrm{eV}^2$$

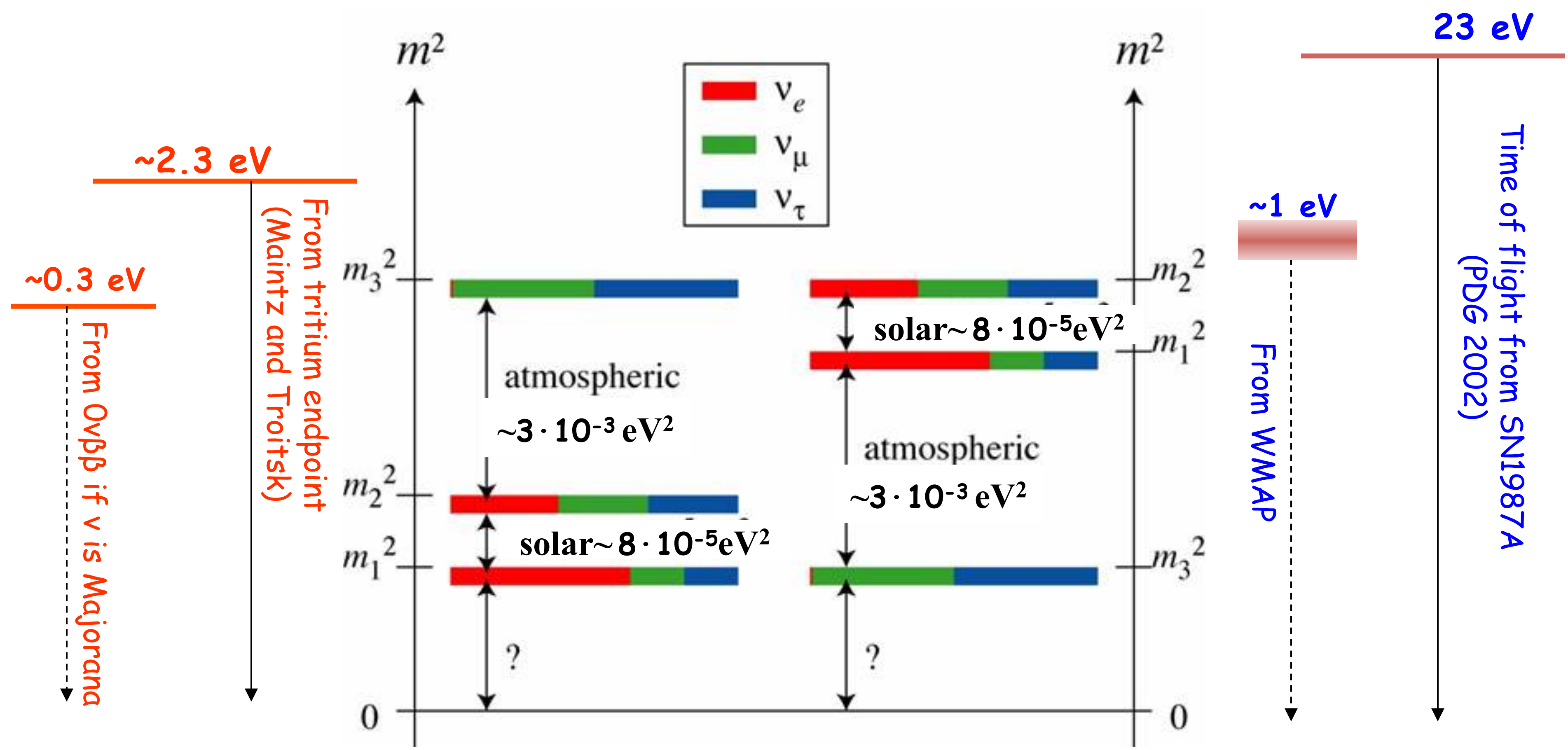
$$\sin^2(2\theta_{23}) = \sin^2(2\theta_{atm}) > 0.92^{[i]}$$

From experiments using reactor $\bar{\nu}$:

$$\sin^2(2\theta_{13}) = 0.09^{+0.13}_{-0.09}$$

K. Nakamura et al. (Particle Data Group), JP G 37, 075021 (2010)

Our knowledge of the ν mass pattern



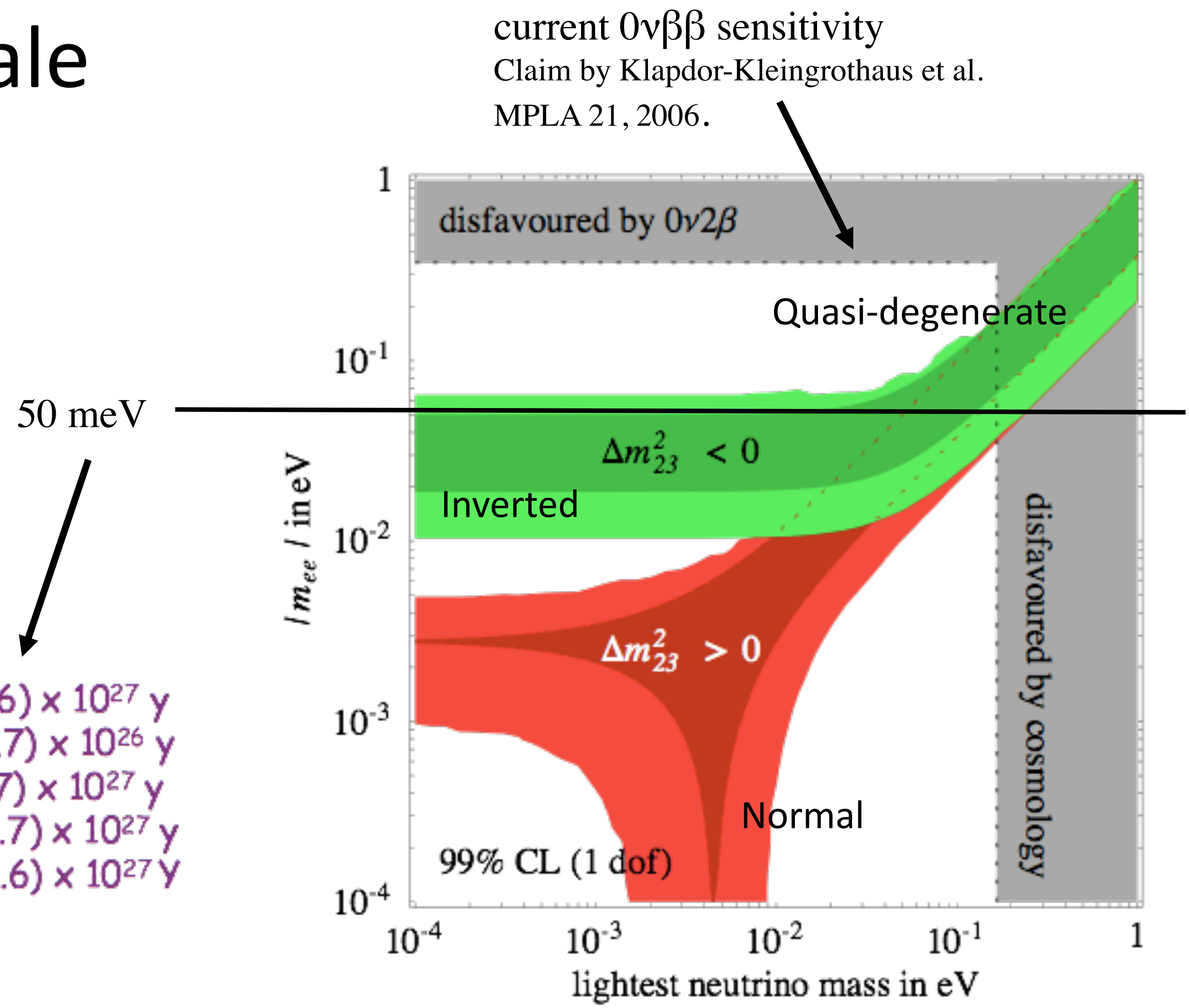
From neutrino oscillations we know

- Neutrinos have mass
- There masses are not the same
- Some mixing and parameters of the flavour states

We don't know

- The absolute masses of the eigen states
- Whether the neutrino is Dirac or Majorana
- Some mixing and parameters of the flavour states

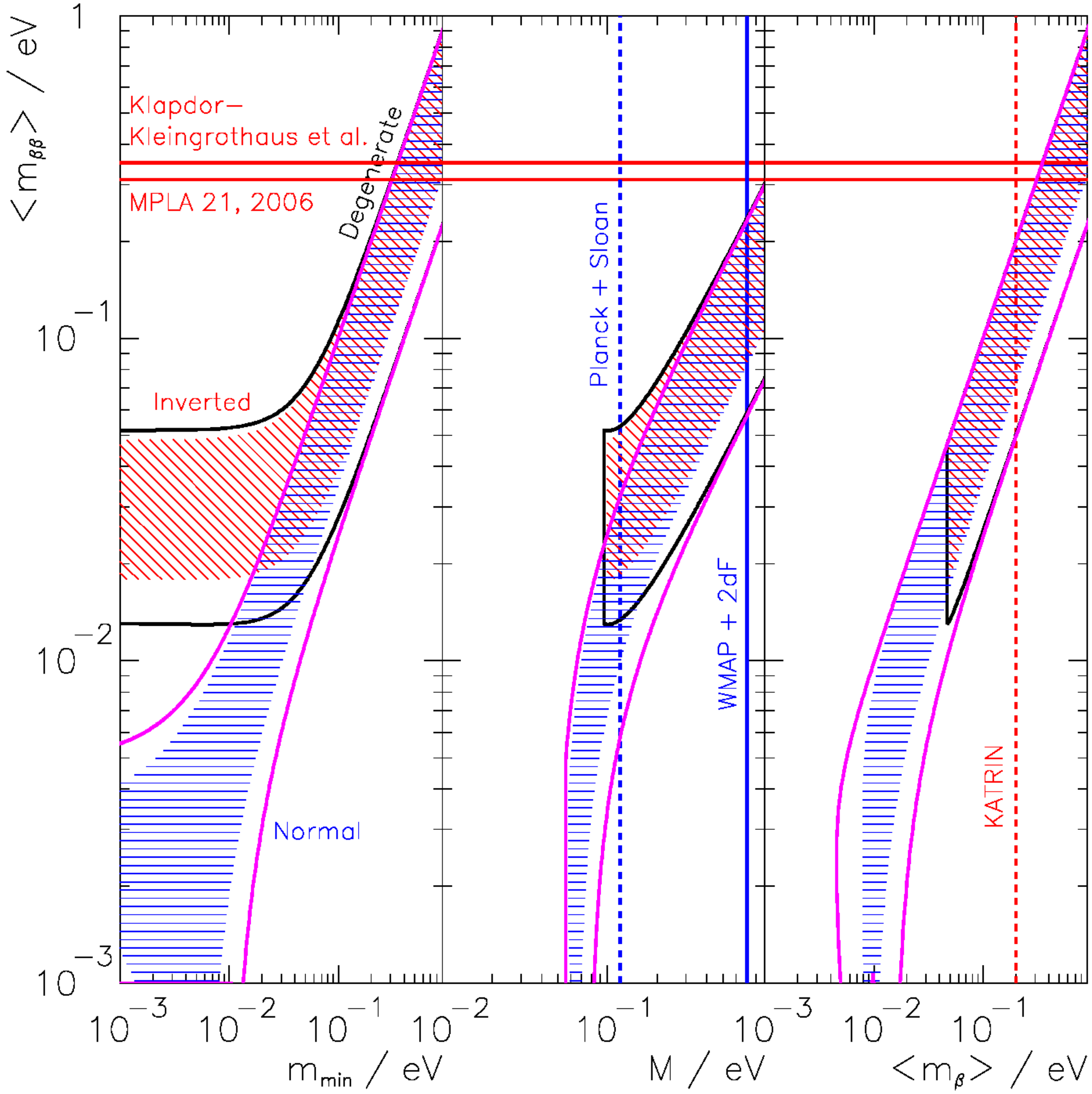
Neutrino Mass Scale



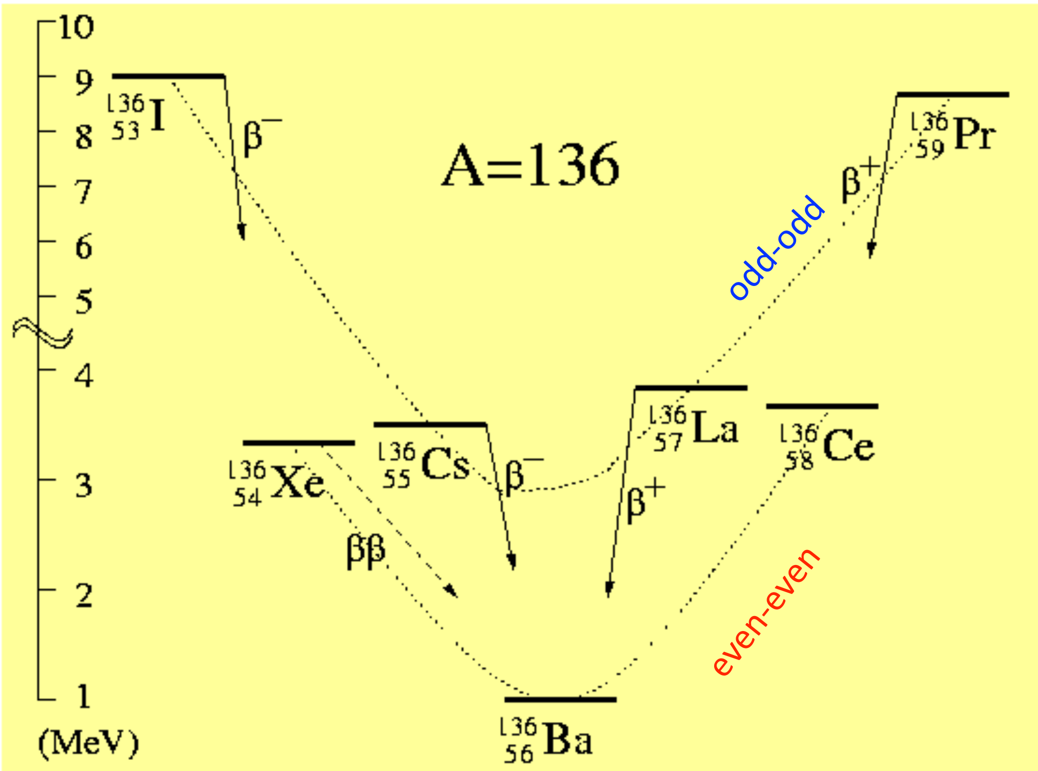
^{76}Ge	$(2.1 - 2.6) \times 10^{27}$ y
^{82}Se	$(6.0 - 8.7) \times 10^{26}$ y
^{100}Mo	$(1.1 - 1.7) \times 10^{27}$ y
^{130}Te	$(0.7 - 1.7) \times 10^{27}$ y
^{136}Xe	$(1.5 - 5.6) \times 10^{27}$ y

[Strumia and Vissani, hep-ph/0606054]

Neutrino Mass Scale



What is double β decay



- A second order weak interaction where two neutrons turn into two protons
- Only allowed for nuclei where beta decay is energetically forbidden or highly suppressed due to a large angular momentum difference

2 ways for ββ to occur

B L

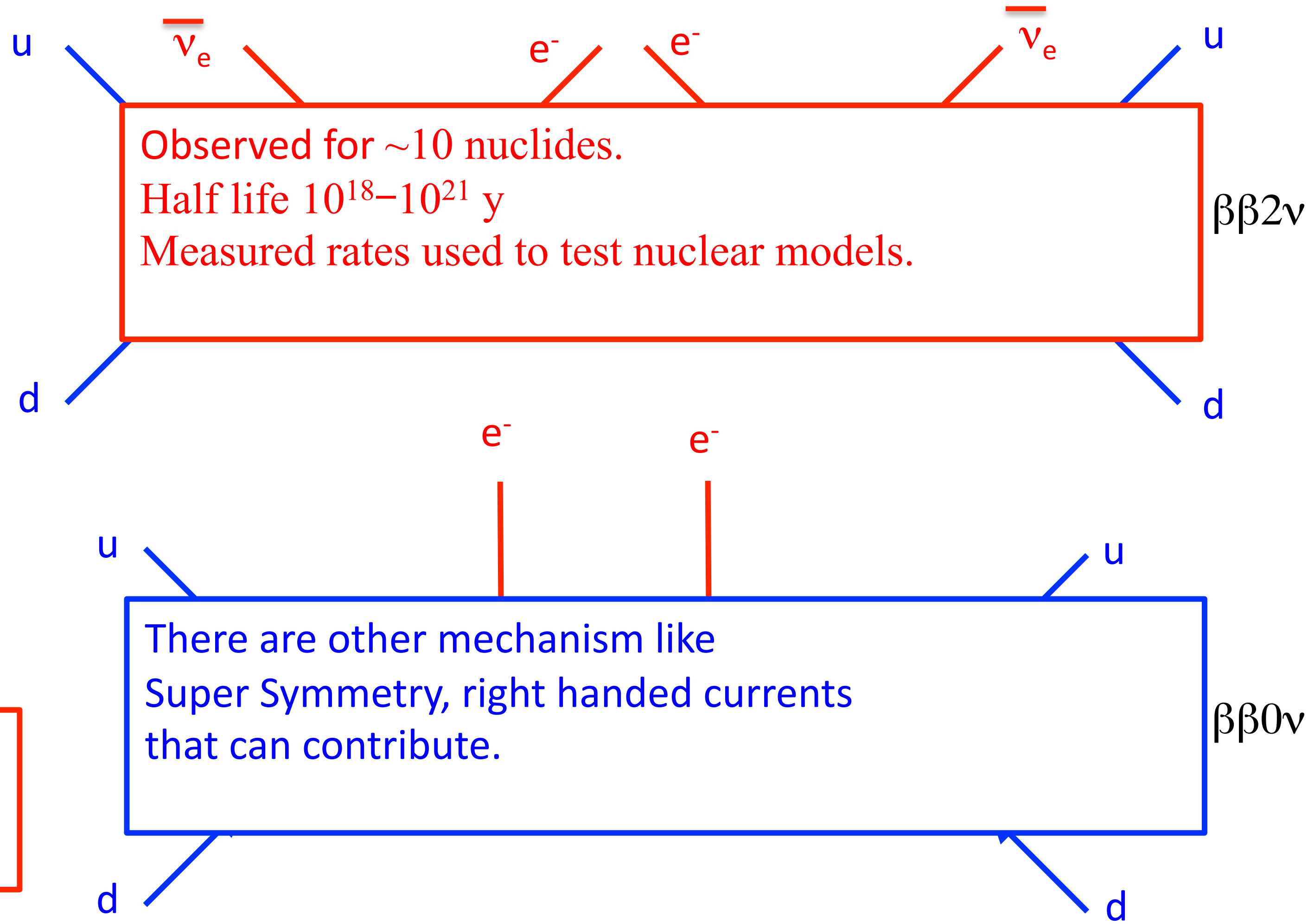
1/3 0

$\Delta B=0$

$\Delta L=0$

$\Delta(B-L)=0$

1/3 0



B L

1/3 2

$\Delta B=0$

$\boxed{\Delta L=2 \quad \Delta(B-L)=-2}$

1/3 0

B: Baryon Number
L: Lepton Number

How to way lepton mass

- Measurement of energy distribution of charged Leptons in weak decays. $$\langle m \rangle_{\beta}^{2} = \sum_{i} |U_{ei}|^{2} m_{i}^{2}$$

- Neutrino-less double decay (Dirac versus Majorana).

$$\langle m \rangle_{\beta\beta}^{2} = \left| \sum_{i} \eta_{i} U_{ei}^{2} m_{i} \right|^{2}$$

It turns out that nuclear double beta decay is the only practical way to distinguish Dirac from Majorana neutrinos.

What do we measure

ββ2ν-mode:

$$\left(T_{1/2}^{2\nu}\right)^{-1} = G^{2\nu} \mid M^{2\nu} \mid^2$$

Cancellation of contributions of virtual intermediate states.
Measured for many nuclides.
Not directly relevant to ββ0ν, calibrates nuclear models

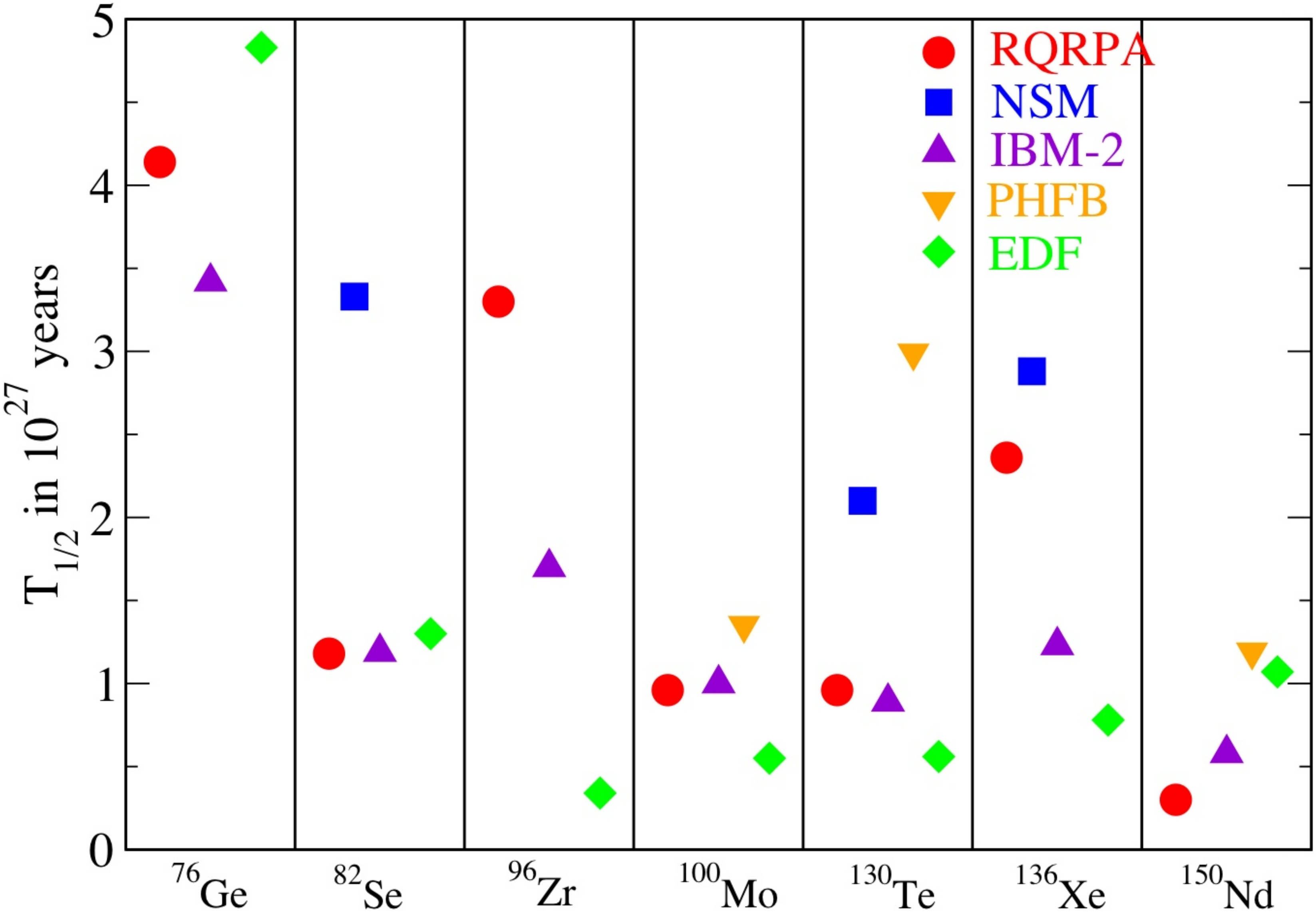
ββ0ν-mode:

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

Nuclear matrix element by calculations. Uncertainty?
spread of all values in literature: factor ~3.

Halflife $T_{1/2}$ in 10^{27} years for $<m_{\beta\beta}> = 20$ meV

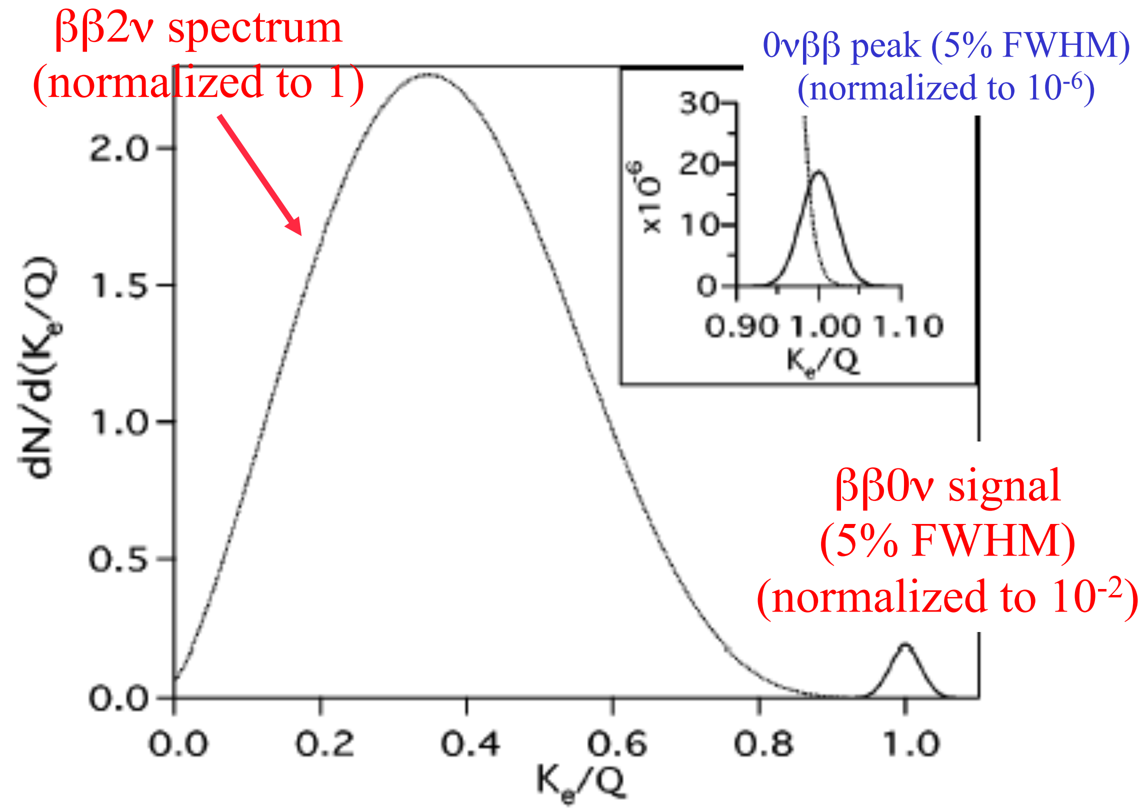
$T_{1/2}$ scales as $(<m_{\beta\beta}>)^{-2}$



Note: For ^{76}Ge the NSM entry 12.9×10^{27} years is not plotted

P. Vogel, 9/2010

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

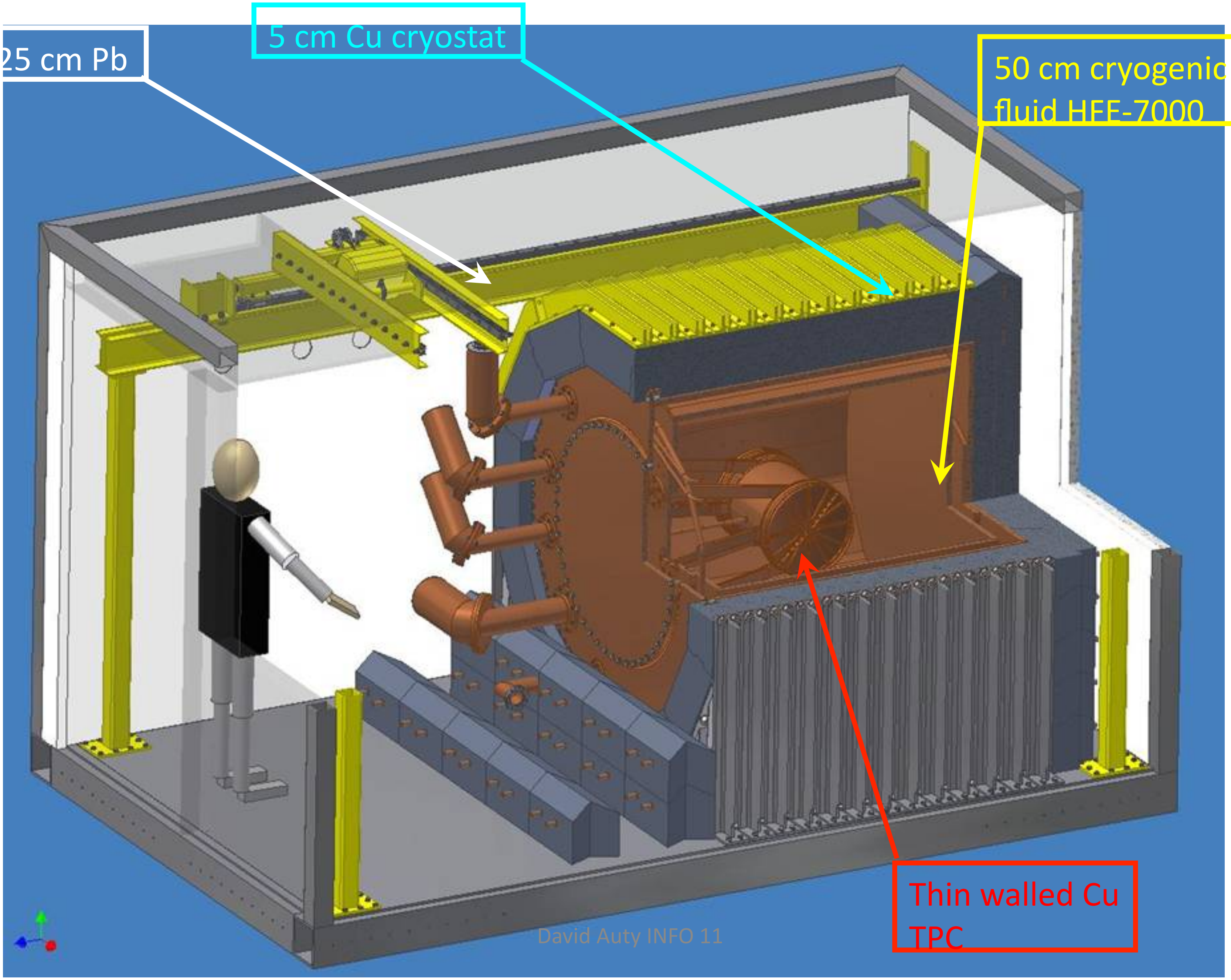
Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	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

Elements that decay via $\beta\beta$ emission with a Q value above 2MeV

Why 136Xe?

- Reasonable Q-value of **2457.8±0.4 keV**
- Active detection medium in both liquid and gaseous phase. Suited for charge collection plus high yield UV scintillator (@ 3 kV/cm ~25 ph/keV,~50 e/keV, anti-correlated[1]). No crystal growth needed.
- Isotope ^{136}Xe has reasonable natural abundance 8.9%.
- No chemistry needed.
- Noble gas, isotopic enrichment by ultra centrifugation cost effective.
- Xenon can be re-purified during operation and moved to different detector
- Ionization potentials Xe: 12.130 eV, Ba^{+}: 5.212 eV, Ba^{++}: 10.004 eV → bb-decay product atom remains charged → opens possibility of Ba removal and final state tagging through Ba single ion detection

EXO-200: the first 200 kg ββ0ν experiment



EXO-200

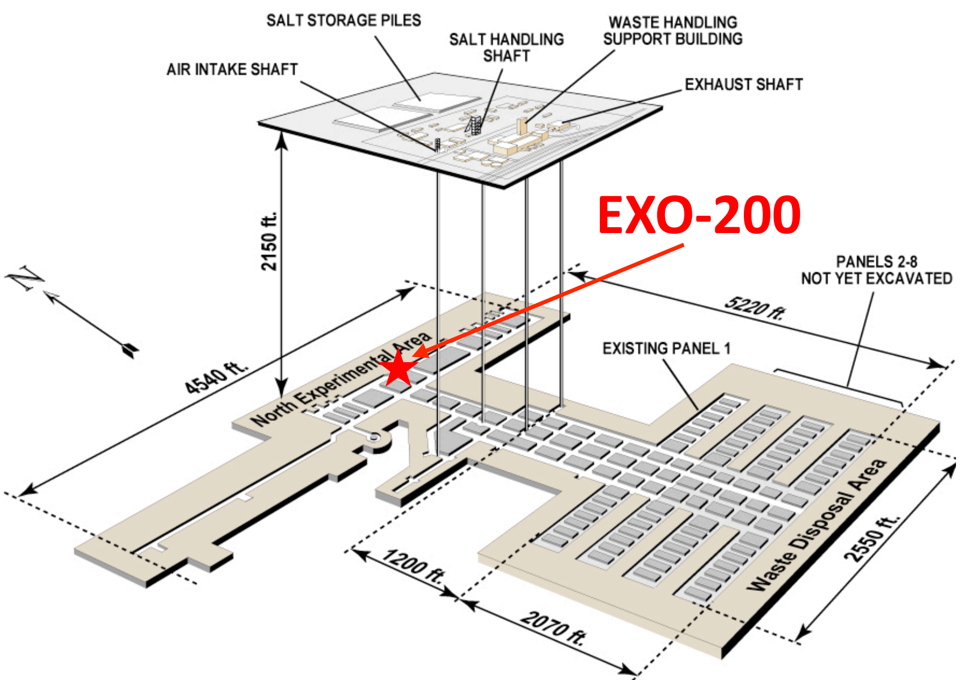
Make use of the fact that Xenon is relatively cheap to enrich, allows drifting of charges, scintillates and may admit identification of the Ba final state in a later phase.
Use a TPC for 3d reconstruction of charge tracks, discriminate single site e-events from multi site γ events.

To achieve a compact experiment use liquid Xenon (3 g/cm^3).
Read out both ionization and scintillation to optimize energy resolution and obtain particle ID. Resolution at $Q_{\beta\beta}$: 1.4% or 37 keV (σ).

Build the detector exclusively from radio-screened materials and components to achieve low background. More than 450 material analyses by ICPMS, NAA, counting, Rn emanation.

Develop Ba removal and tagging in parallel in the lab.

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 (Drift E-300)

EXO detection strategy

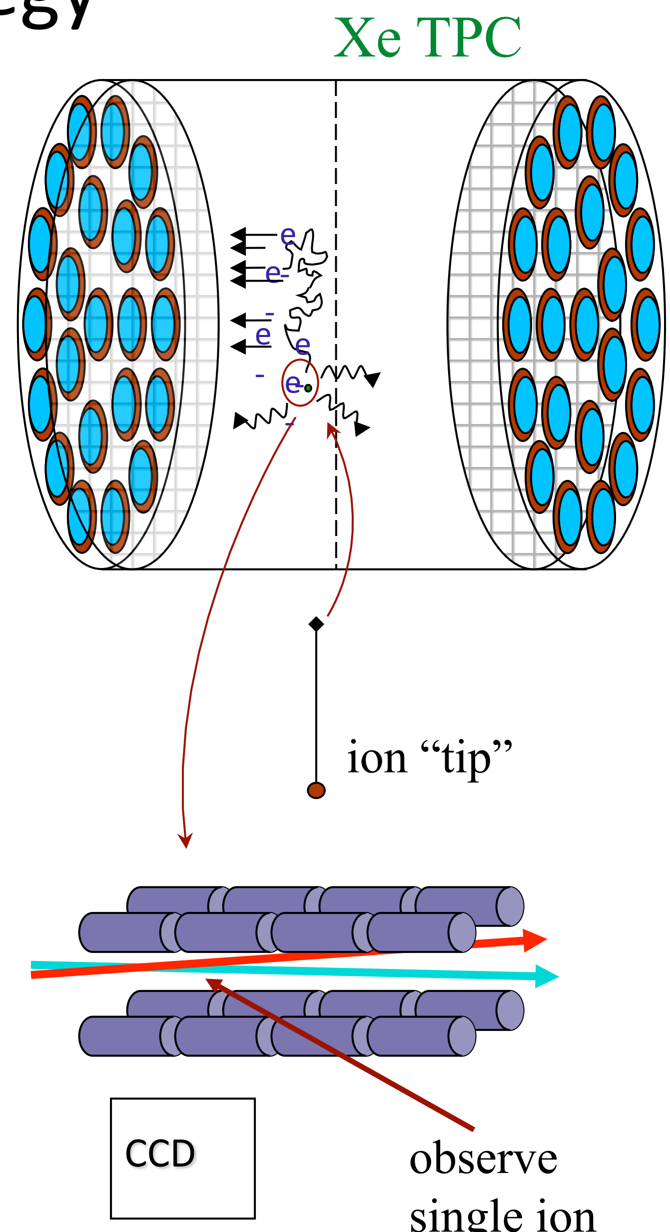
detect the 2 electrons
(ionization + scintillation in xenon detector)

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

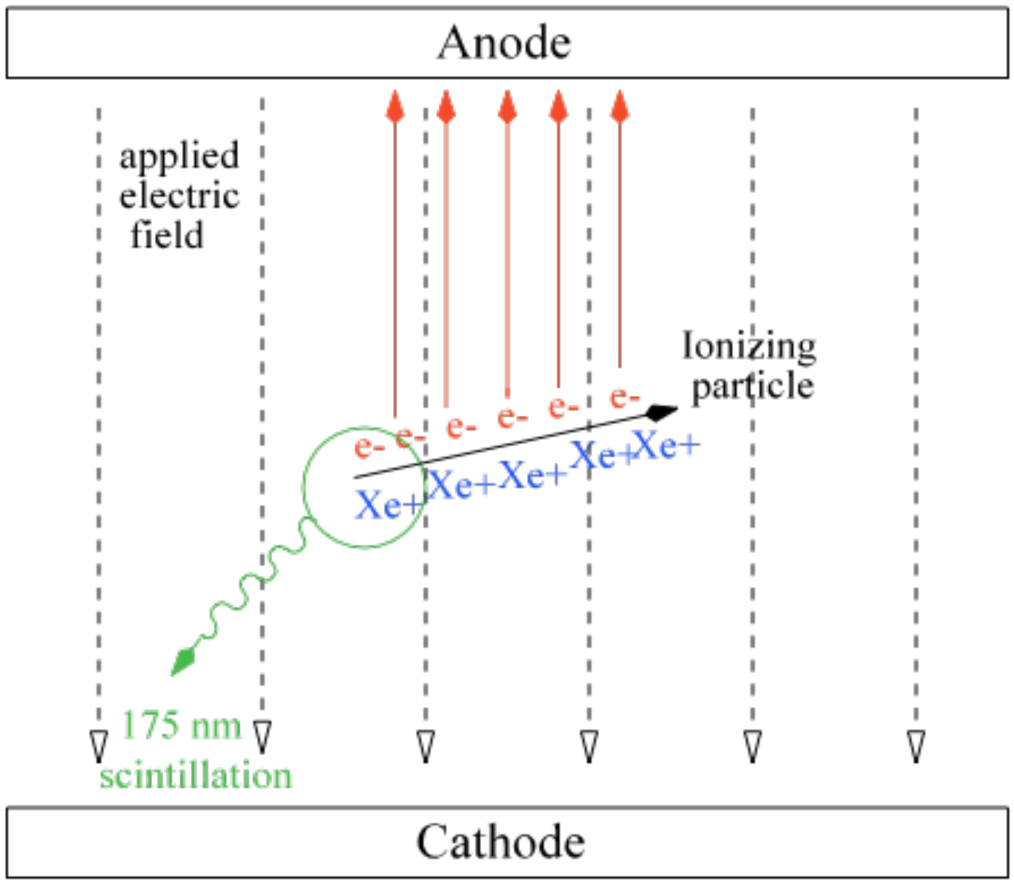
positively identify daughter via
optical spectroscopy of Ba^{+}

[M. Moe, Phys. Rev. C 44 (1991) R931]

other Ba^{+} identification strategies are also being
investigated within the EXO collaboration



EXO-200 Detection Scheme



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

Charge Detection

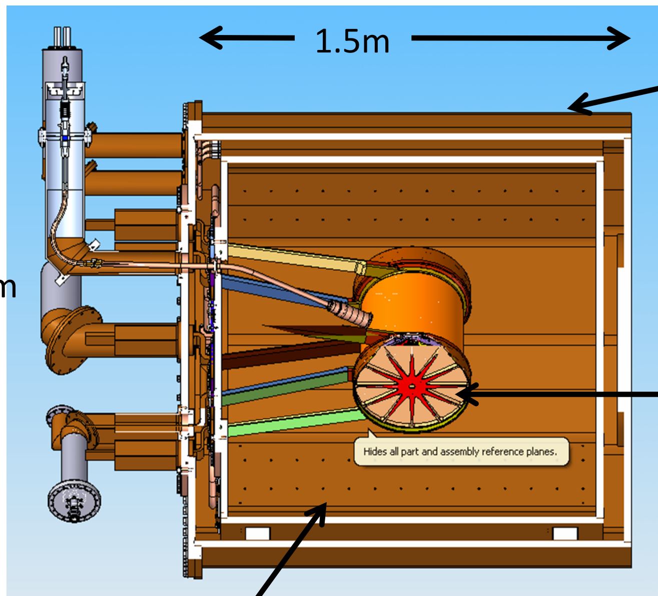
- Double-ended TPC chamber with ~20 cm drift regions. In Xe about 50 e/keV → at 2458 keV results in 124,000 e-, into 1 pF equivalent charge amplifier 20 mV signal → amplify by factor 10 using shaping amplifier. Noise is ~700 e.
- Mid-plane cathode can be biased up to -75 kV
- 38 Inductive "V" wires per side at -4 kV, 100% charge transparent.
- 38 "U" wires at virtual ground to collect the charge.
- LXE electron mobility ~2000 $cm^2/(Vs)$
- Saturation velocity ~ 0.28 cm/μs
- Long electron lifetime is required to minimise charge loss.

Light Detection

- 516 16 mm (active area) APD's (Avalanche Photo Diodes).
- QE measured to be 120% at 175 nm by NIST.
- Geometrical photo-coverage ~17%.
- Read-out: gangs of seven APD's
- Yield enhanced by reflective Teflon reflectors in TPC.
- Charge amplifier 5 pF per gang of seven.
- Low gain (compared to PMT's), of ~100.
- Clean materials, mostly refined silicon.
- Connections made by contact springs for easy maintenance.

EXO-200 TPC and cryostat

1.5m

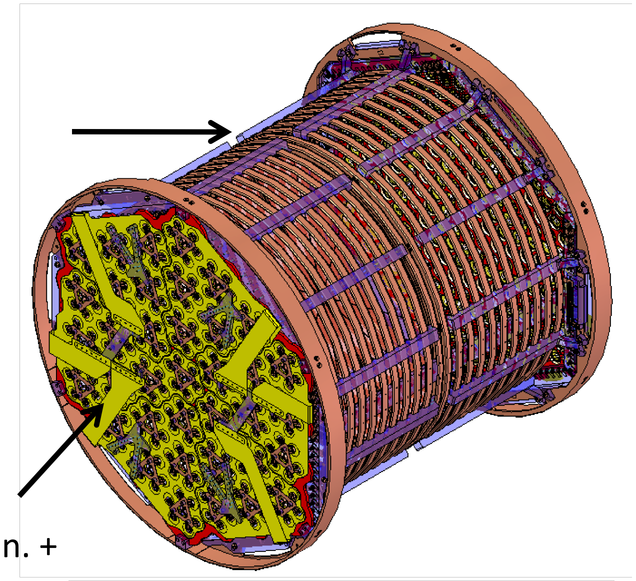


Outer cryostat

TPC

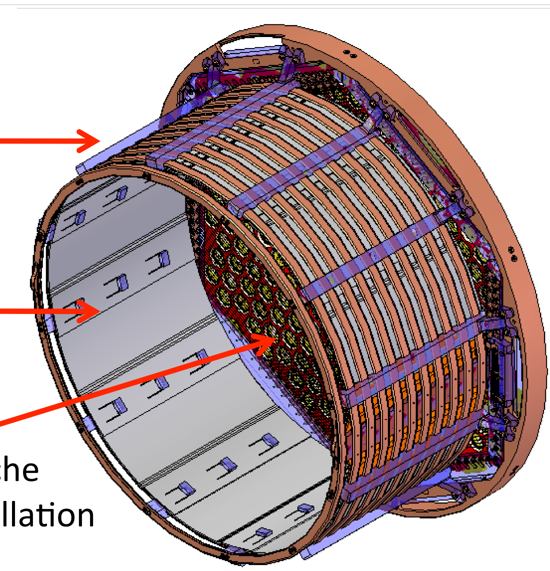
Inner cryostat filled with 50 cm HFE7000 cooling/shielding fluid (~ 1.8 g/cm^3 at 170 K)

Central HV plane (photoetched phosphor bronze)



Custom kapton signal cables (ion. + scint. readout)

Acrylic supports and field shaping rings

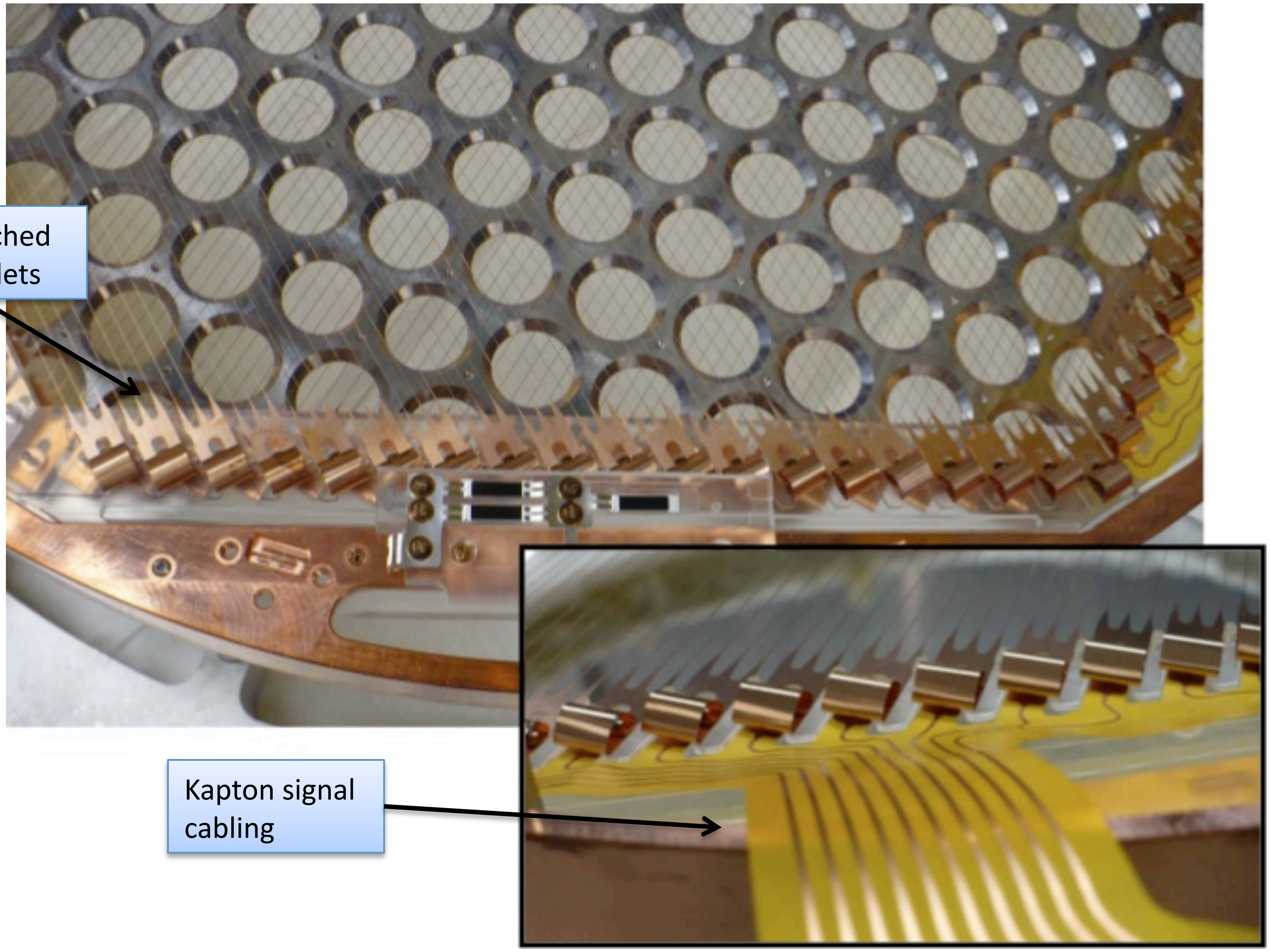


Teflon light reflector

APD plane (avalanche photodiodes, scintillation detection)


ACETONE
Nitrile
FIVE

EXO-200 crossed ionization collection wires



•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.

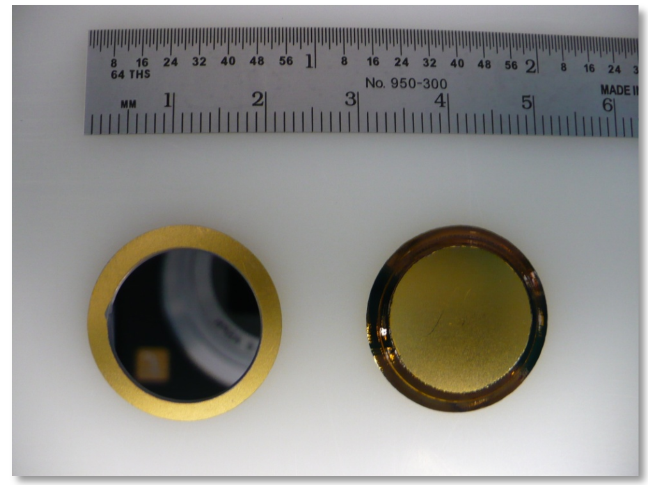
TPC is ebeam welded from thin copper plates custom manufactured.

Composed from many parts, required extensive fixturing.

Only few hard to reach seams were welded using TIG welding with Se doped electrodes.

EXO-200 LAAPD specs

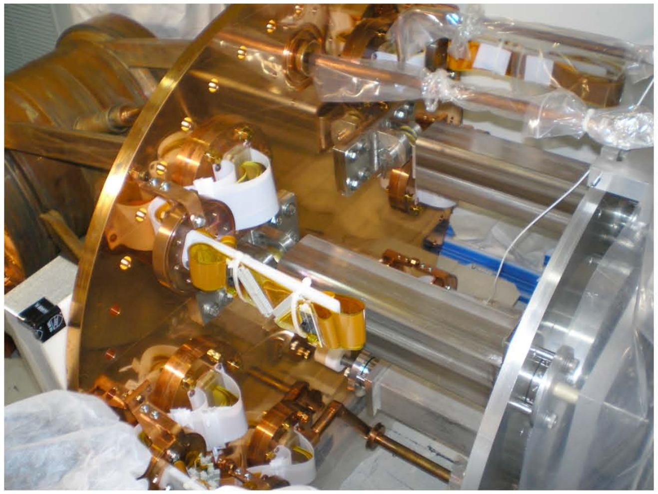
- Mass ~ 0.5 g/LAAPD
- Low radioactivity construction (used bare, no window, no ceramic, EXO-supplied chemicals & metals)[a]
- QE > 1 at 175 nm (NIST)
- Gain set at 100-150
- V ~ 1500V
- ΔV < ±0.5V
- ΔT < ±1K   APD is the driver for temperature stability
- Leakage current cold < 1μA
- Capacitance ~ 200 pF at 1400 V
- ϕ16 mm active area per LAAPD

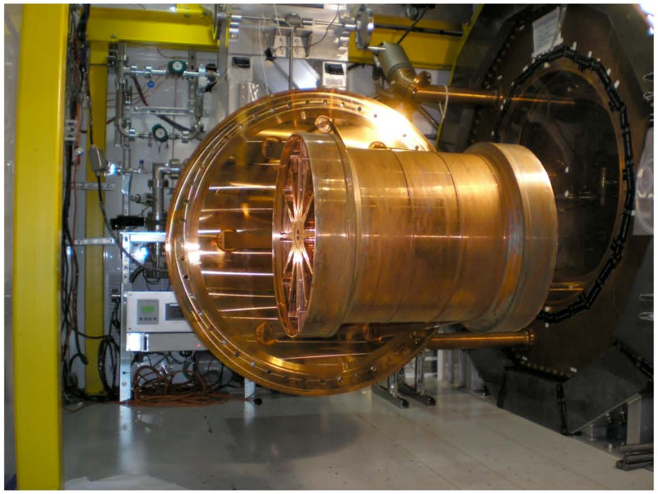


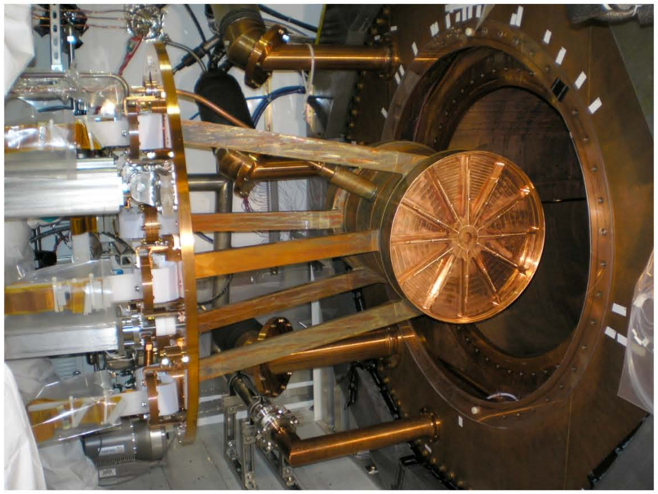
Neilson, R. et al., NIM A 608, 1 (2009)

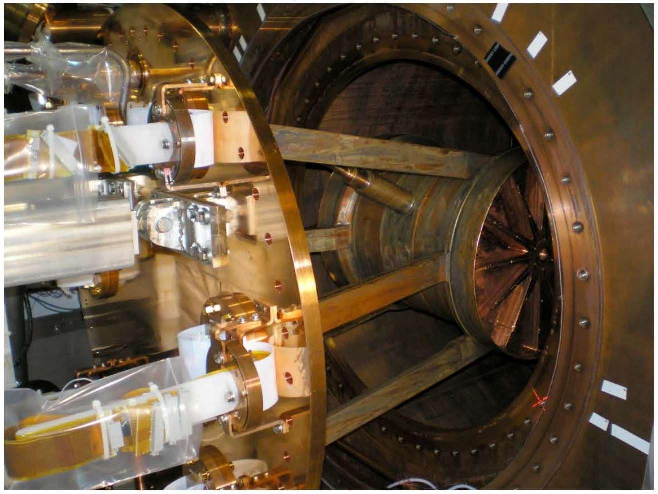
[a] D. S. Leonard, et al., Nucl. Instr. and Meth. A 591 (2008) 490-509

EXO-200: Installation



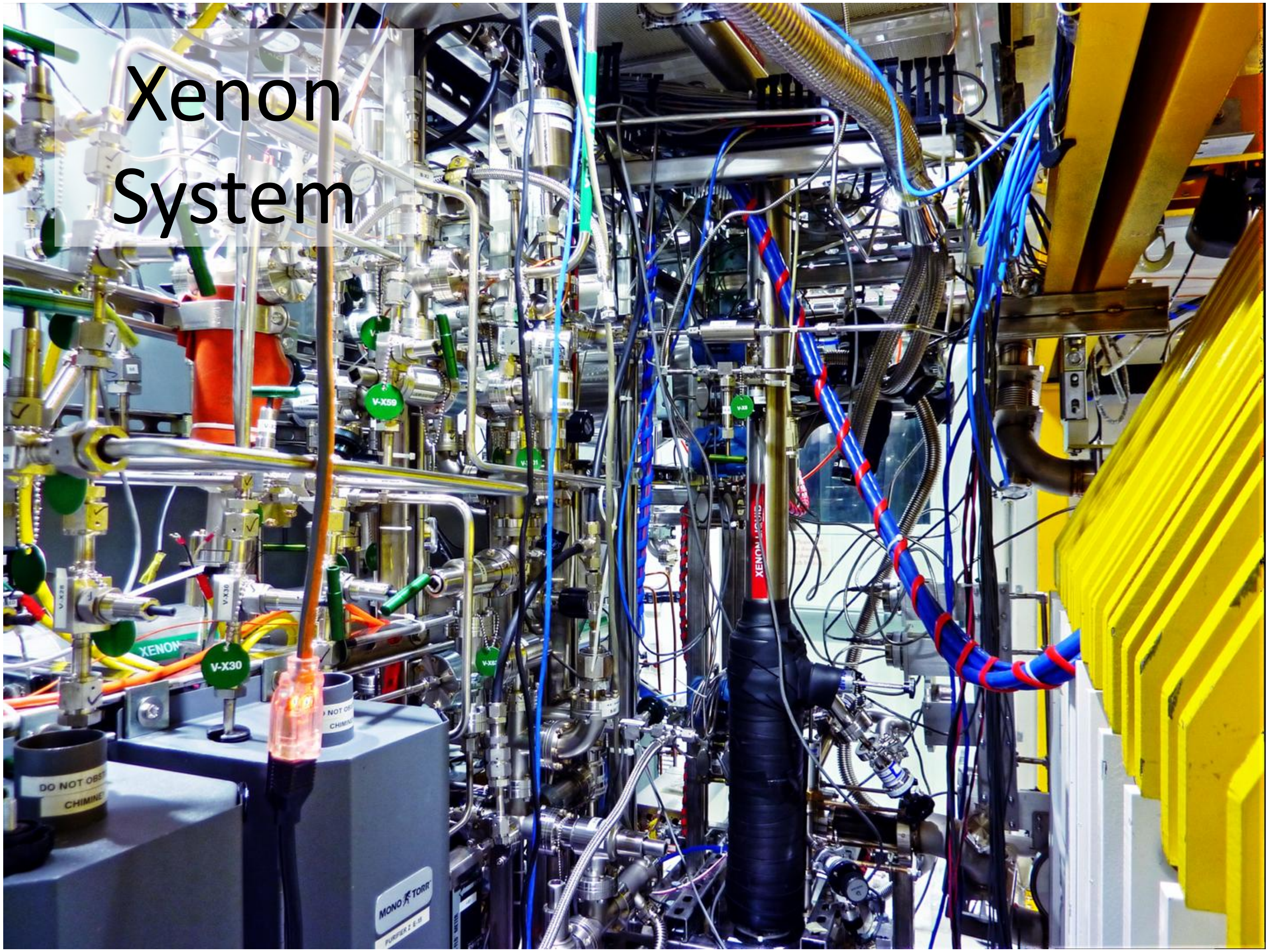




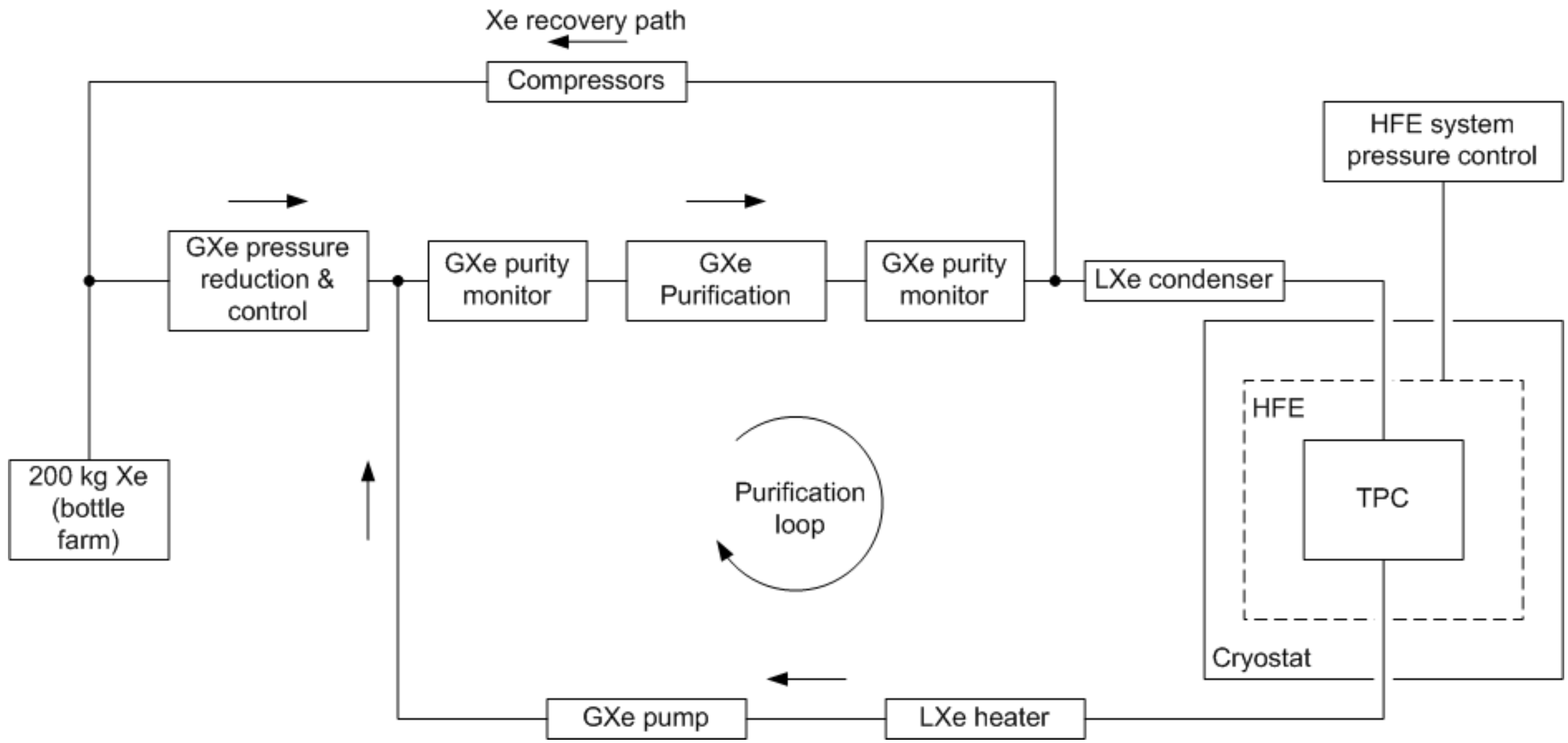


Dolinski

Xenon System



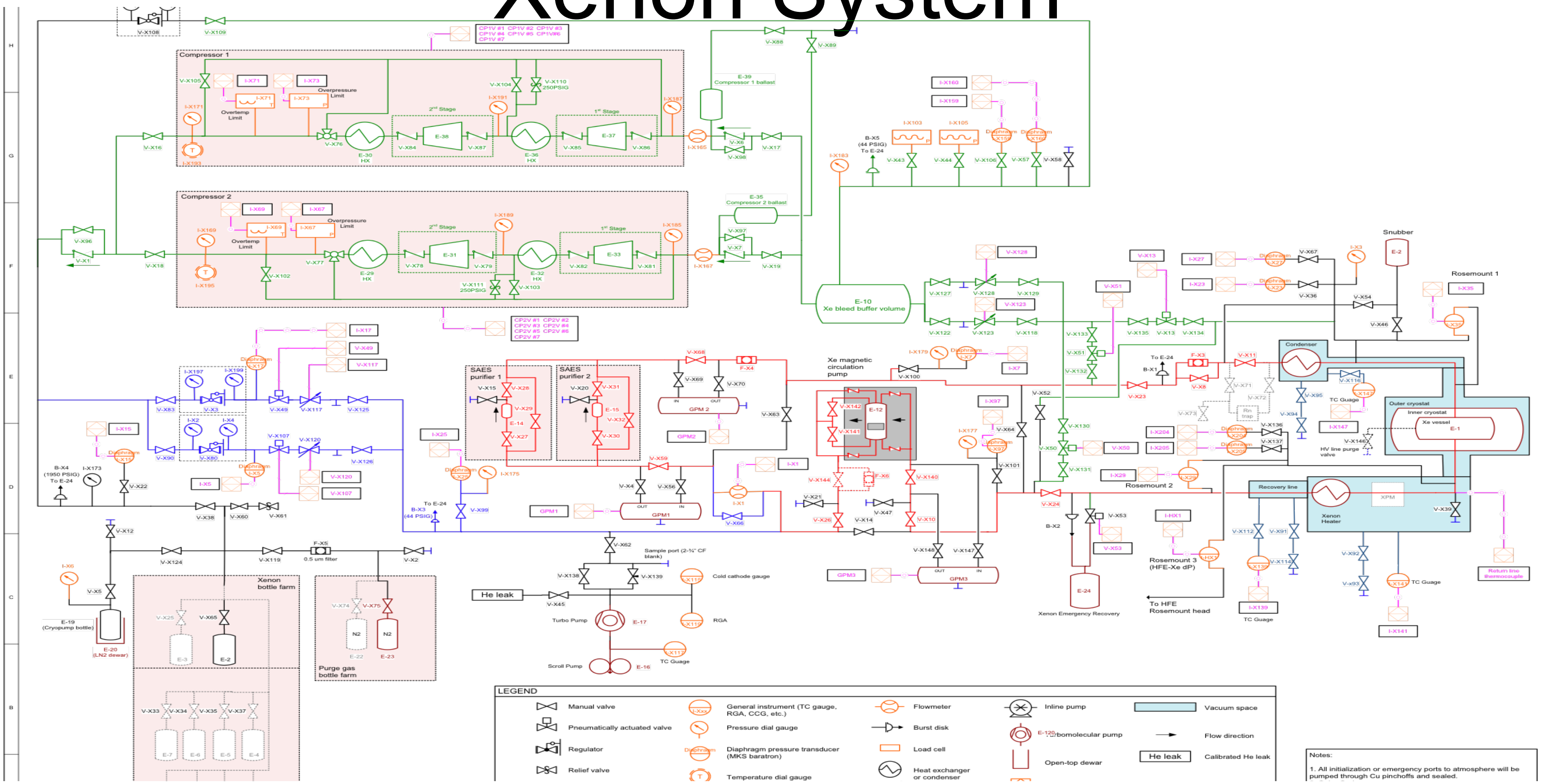
Xenon System



Design goals:

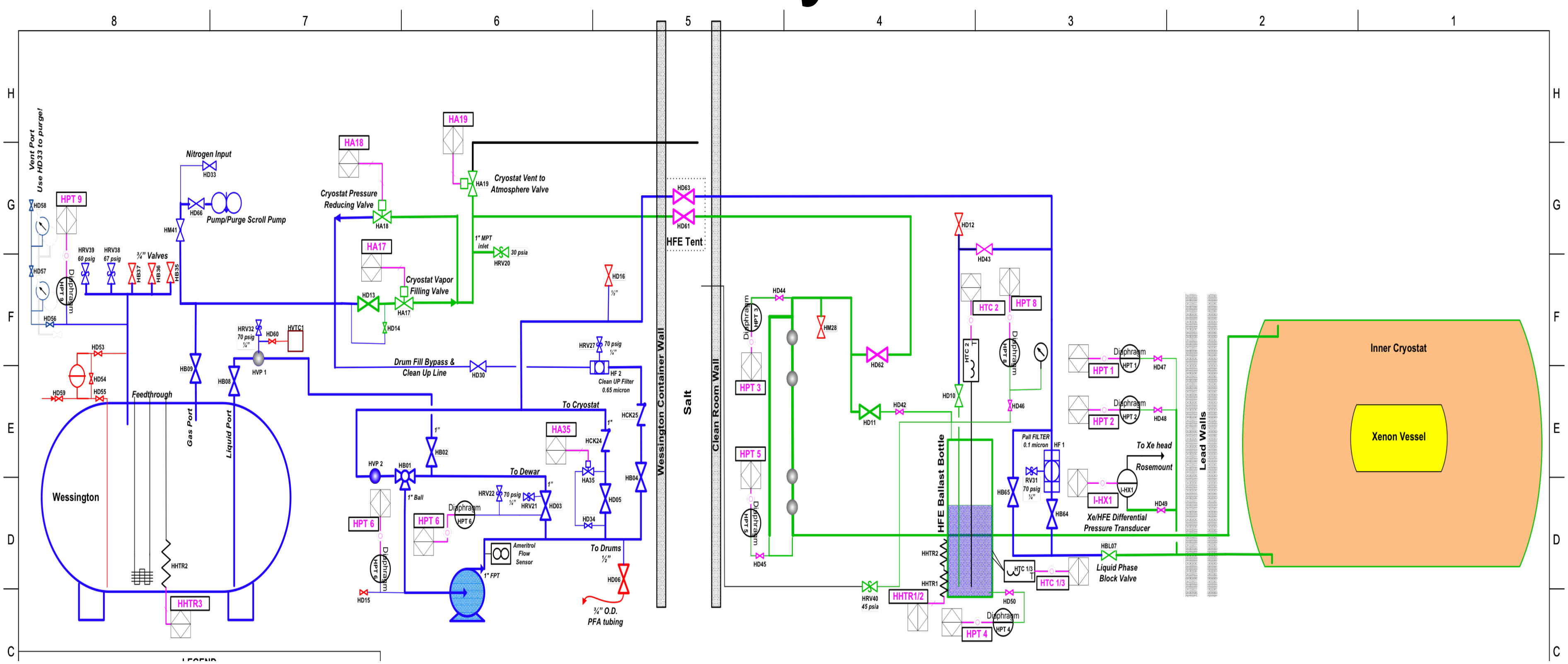
1. 20 SLPM circulation rate for continuous purification (uses heater, pump, condenser) while TPC full
2. Continuous purification with commercial (SAES) getters
3. Continuous purity monitoring of circulating gas
4. Differential pressure across TPC walls $|dP| = |P_{Xe}-P_{HFE}| < 15$ torr at all times, due to thin-walled (~ 1.5mm) TPC construction (driven by radiopurity requirements)
5. Xe recovery to bottle farm with compressors
6. Triply redundant cryocooling system (3x Polycold refrigerators)

Xenon System



- dP between Xe vessel and cryostat is maintained by the auto-feed-bleed system
- Purification through two SAES hot Zr getters
- Gas purity measured by home-built gas purity monitors
- Compressors used to recover Xe and push it back into the bottles.

HFE System



- Transfer HFE from Wessington Dewar to Inner cryostat (aka inner vessel or IV)
- The cryostat is full when HFE spills out the top into the standpipe
- The polycolds cool down the cryostat and the HFE shrinks – so we keep filling until the cryostat is at 170 K (or slightly colder)
- We maintain the height in the standpipe to keep the cryostat full
- We heat the HFE ballast bottle to set the pressure in the cryostat, and therefore, the pressure of the Xe system

Purity

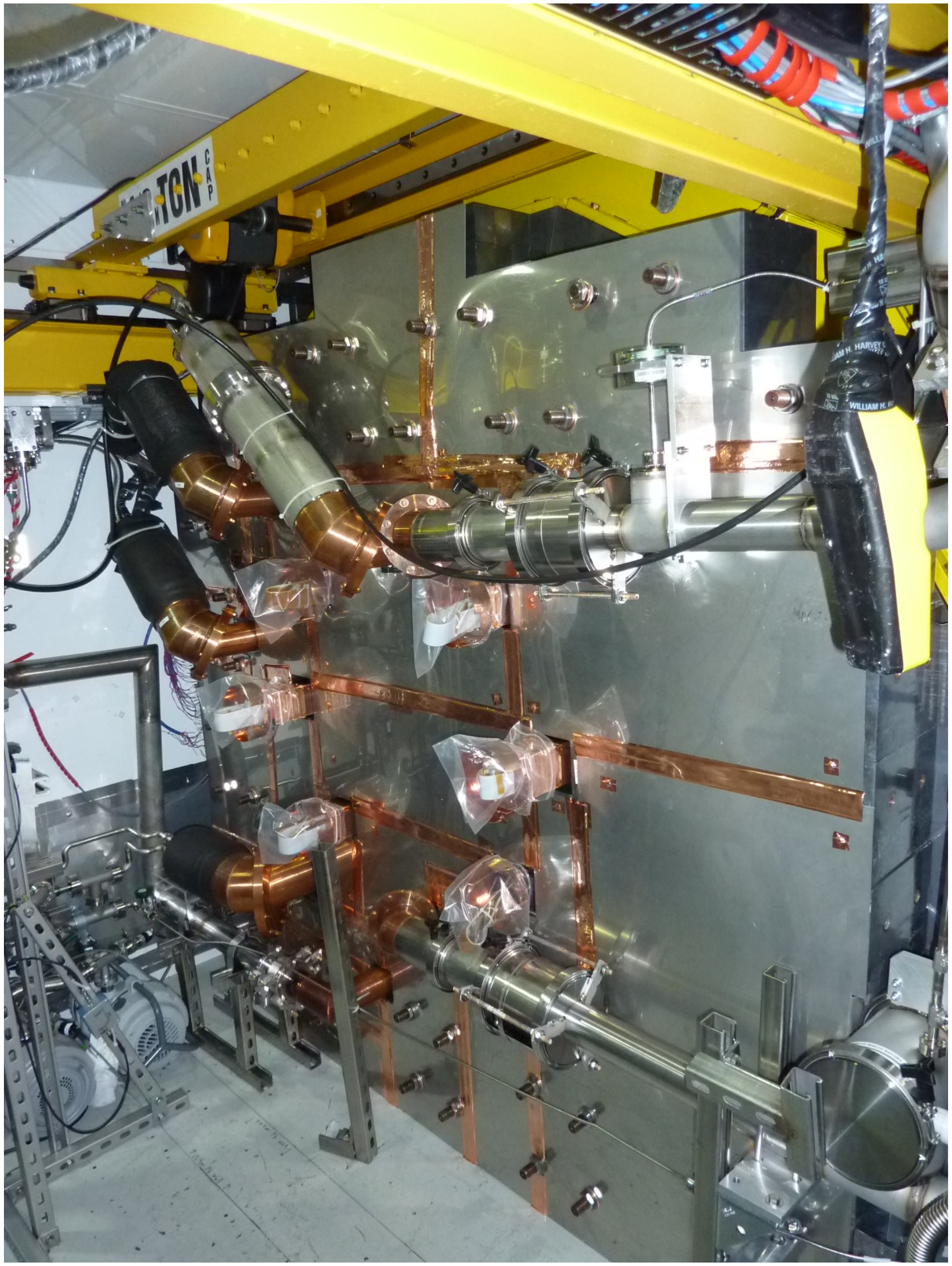
- All detector materials counted for radioactivity
  - *Leonard, et. al, Nucl. Inst. Meth. A 591 (2008)*
- Noble gas purifier - Zr getter
  - Leaves < 5 part-per-billion Oxygen and Nitrogen in Xe gas
- RGA Spectroscopy w/ Cold Trap
  - Freeze a sample of Xenon and analyze vapor
  - Detect sub-part-per-billion levels of many impurities, including Krypton to 5 part-per-trillion
  - *Leonard, et. al, Nucl. Inst. Meth. A 621 (2010)*
  - *Y.-R. Yen, Y8.00008: Mass spectroscopy for EXO-200*

Radon Tent

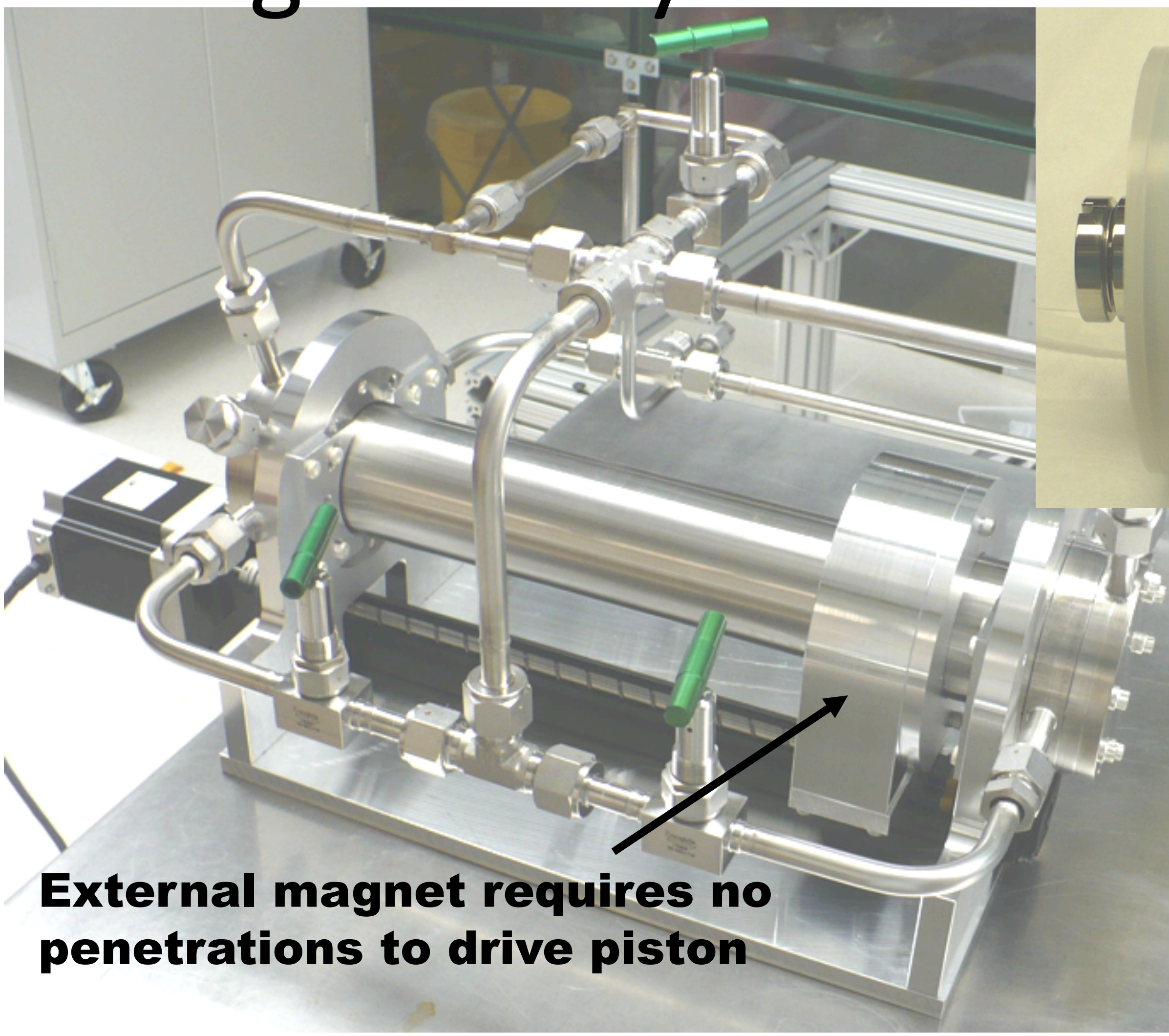
Stainless steel sheet surrounding lead shielding

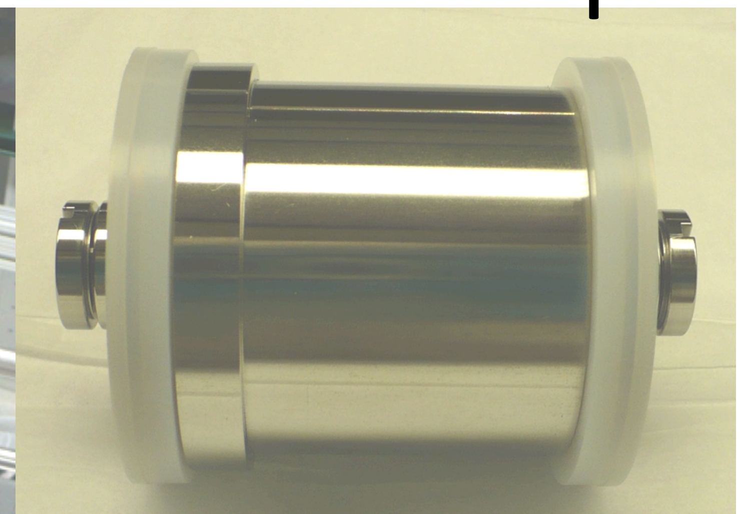
Sealed with copper tape over butyl tape

Flush with aged air



Magnetically-Driven Xenon Pump

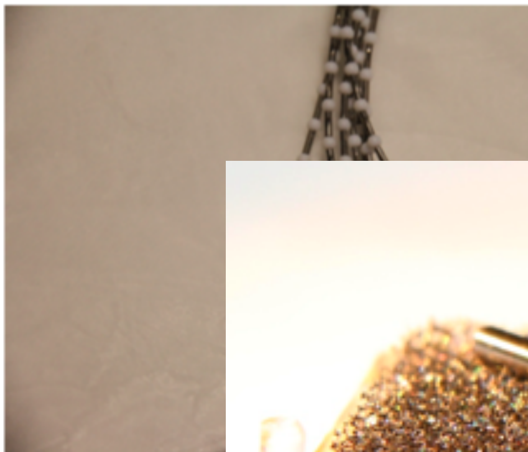




16 SLPM through a purifier at 750 torr differential

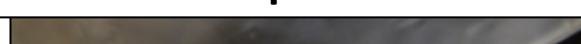
F. LePort, et al., arXiv: 1104.5041v1

Calibration Source



Segmented cable
with PTFE beads

ackage
ibrated
ion



Source attached to end
in welded capsule

Designed to
navigate bends

The Cosmic Ray Muon Veto

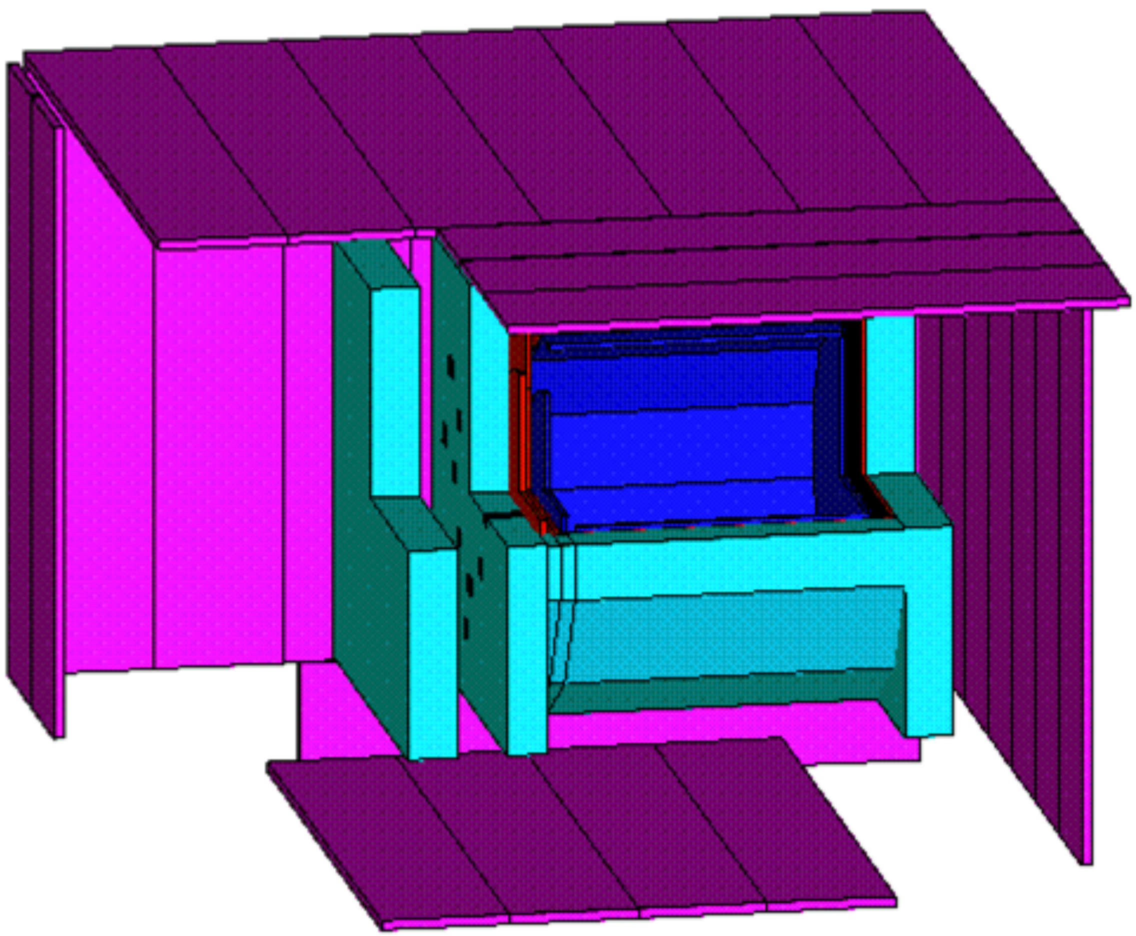
The vertical muon intensity has been measured to be: $268 \pm 6\ m^{-2}\ d^{-1}\ sr^{-1}$ by Esch et al., astro-ph/0408486.

The flux through a horizontal surface is $332\ m^{-2}\ d^{-1}$

Monte Carlo estimated muon related background:
$\beta\beta0\nu$: 15 cnts/year
$\beta\beta2\nu$: 1100 cnts/year
These are due to secondaries with the muon missing the TPC.

Muon veto with at least 90% efficiency needed to meet background goal.

EXO-200 active scintillation muon veto

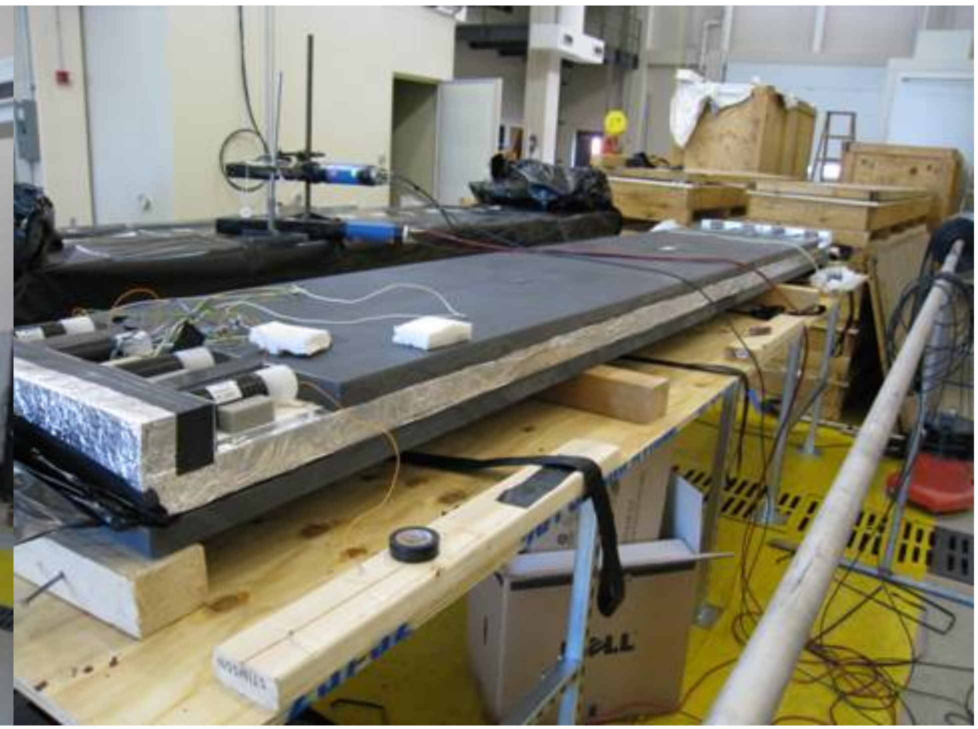


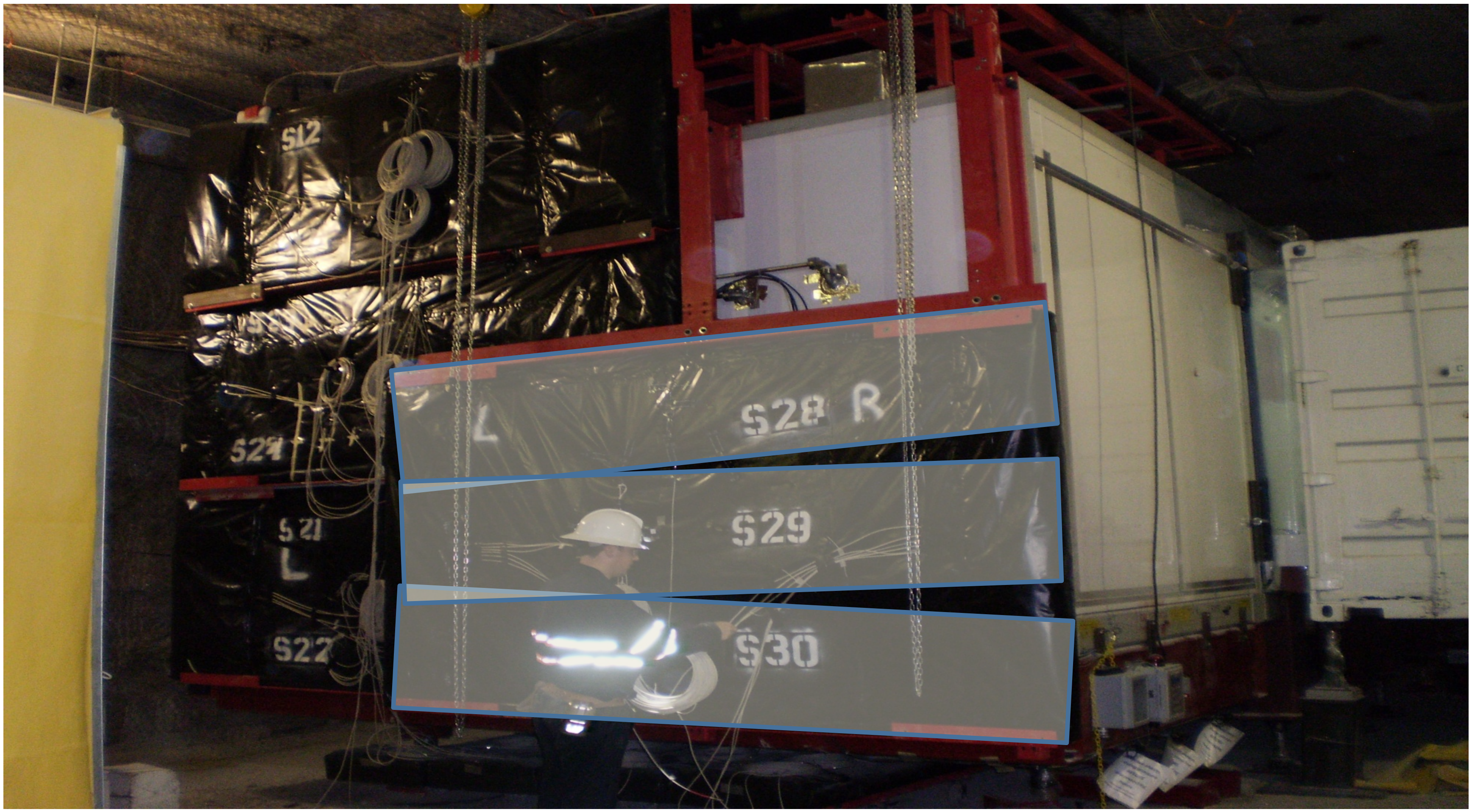
Geometrical placement is optimized by Monte Carlo.

To stay within background budget we need 90% efficiency. Depending on layout existing scintillator gives 95% to 99.8% efficiency.

31 large plastic scintillator panels, left over from the concluded KAREMEN neutrino oscillation experiment were acquired.

And were refurbished, tested, and calibrated at UA. Including gain matching of about 300 PMTs.



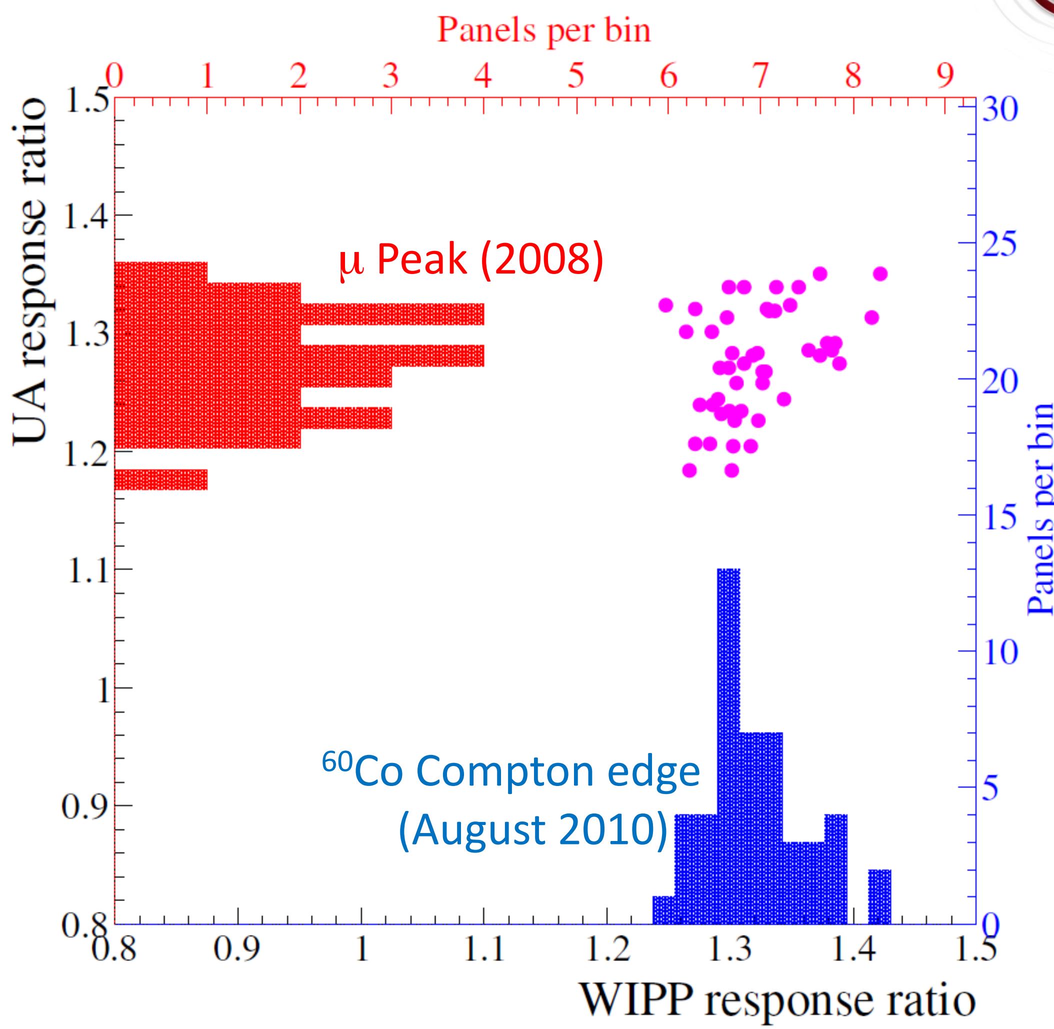

S12
S28 R
L
S29
S21
L
S22
S30

Comparison of surface muon response to ^{60}Co Compton edge at WIPP

response ratio ≡ response to a source at 20”/response to the same source at 40”

Similar mean implies no degradation of the optical properties of the panels on average.

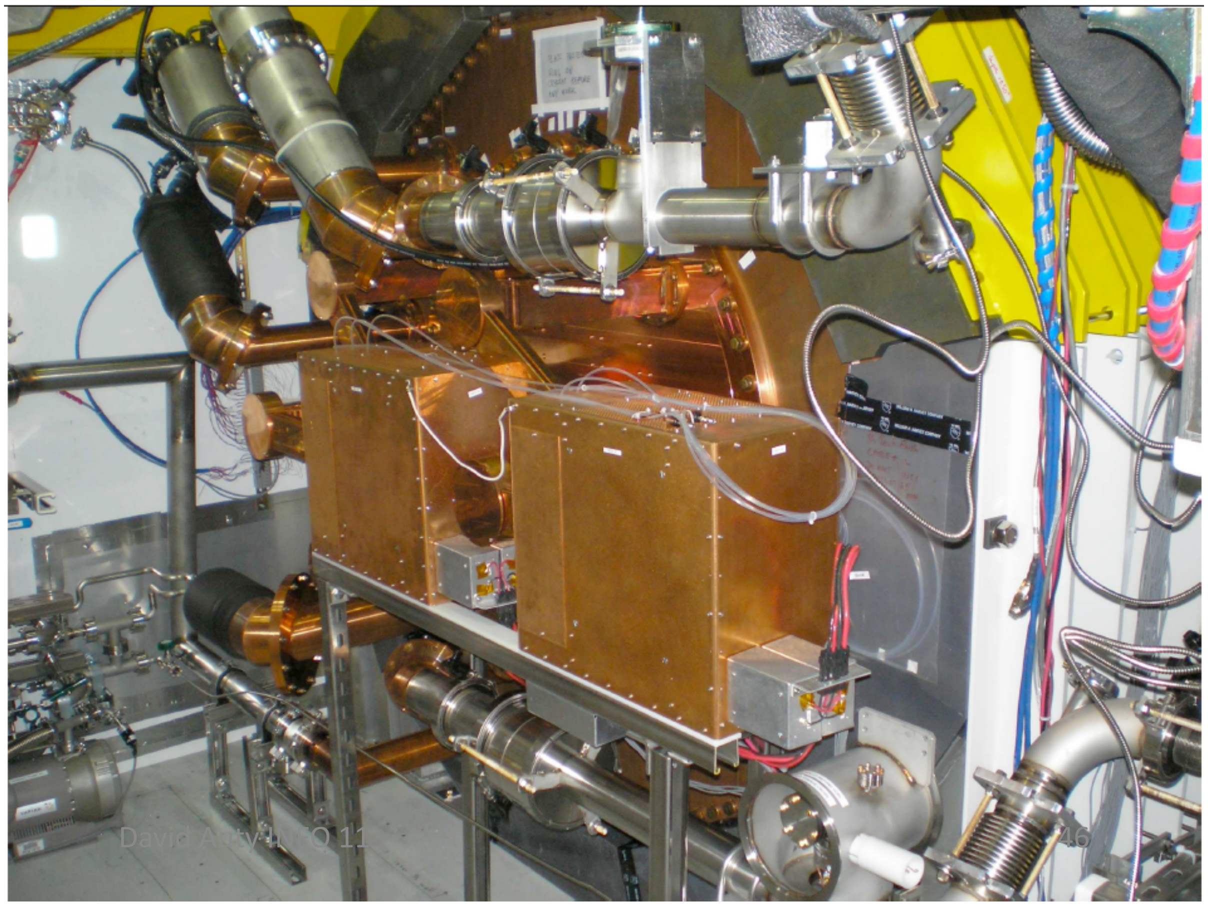
Correlation is hard to see because the resolution of the measurements is large and are highly uncorrelated.



EXO-200 engineering run Dec 2010

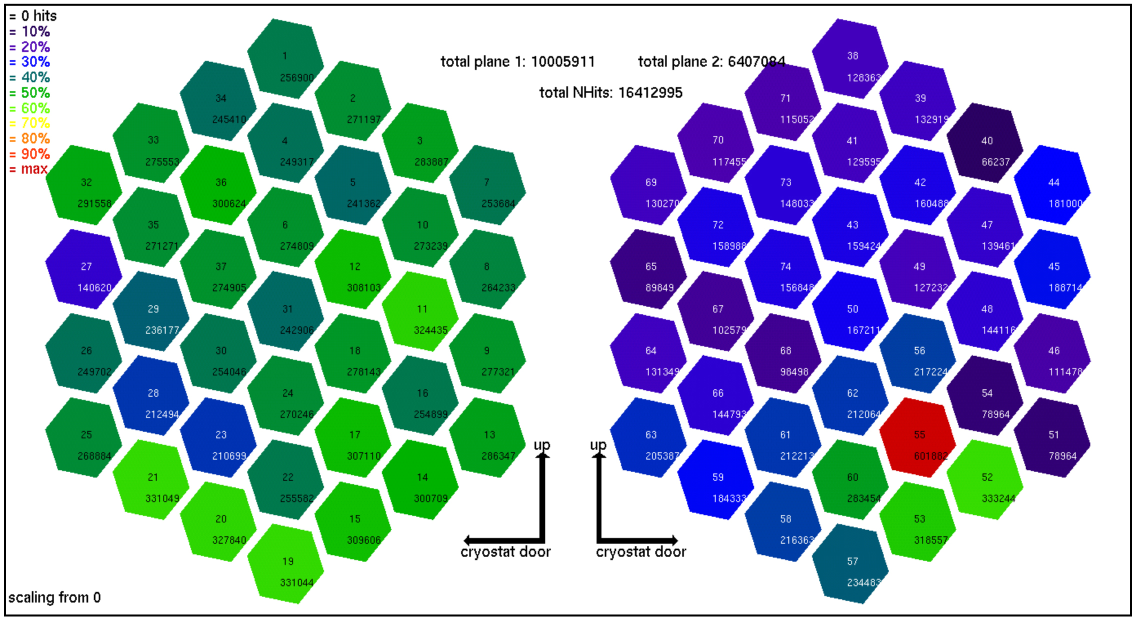
- Check stability of all LXe/GXe systems
- Check Xe purity
- Check electronics
- Generally test detector performance
- Test Xe emergency recovery

- No front shielding
- No Rn enclosure
- No Rn trap in Xe system
- No veto counter

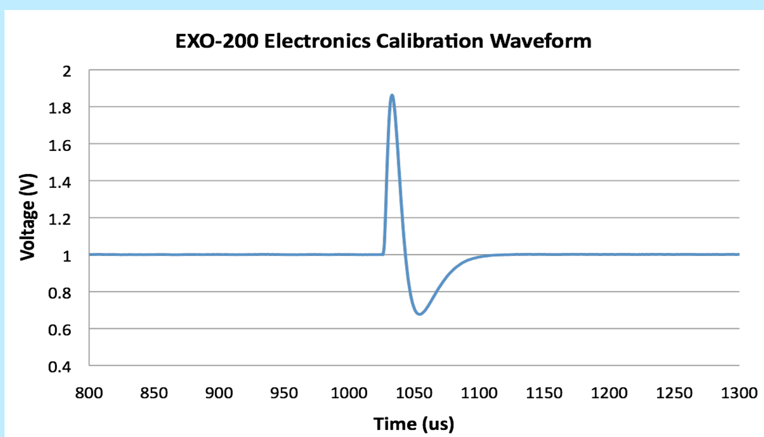


EXO-200: Electronics

Pulse amplitude on APD plane - 50V bias

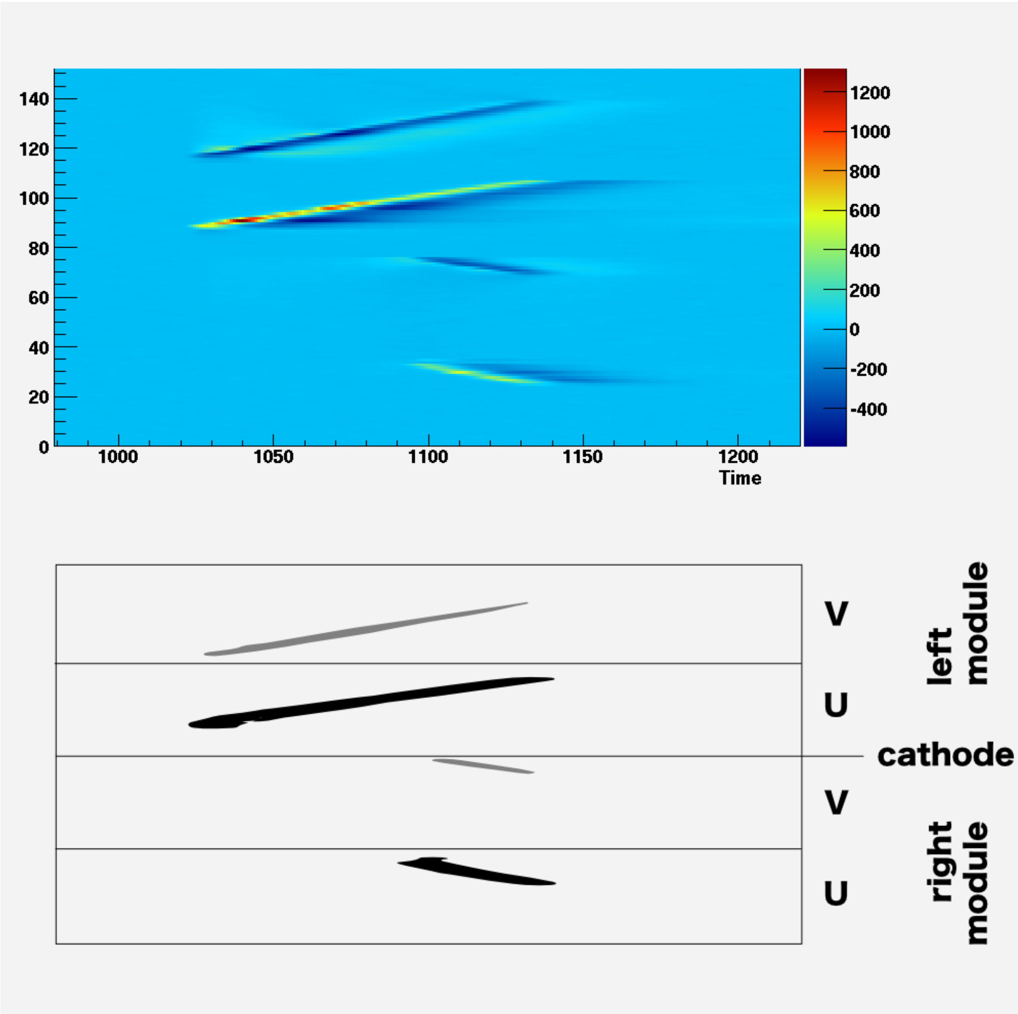


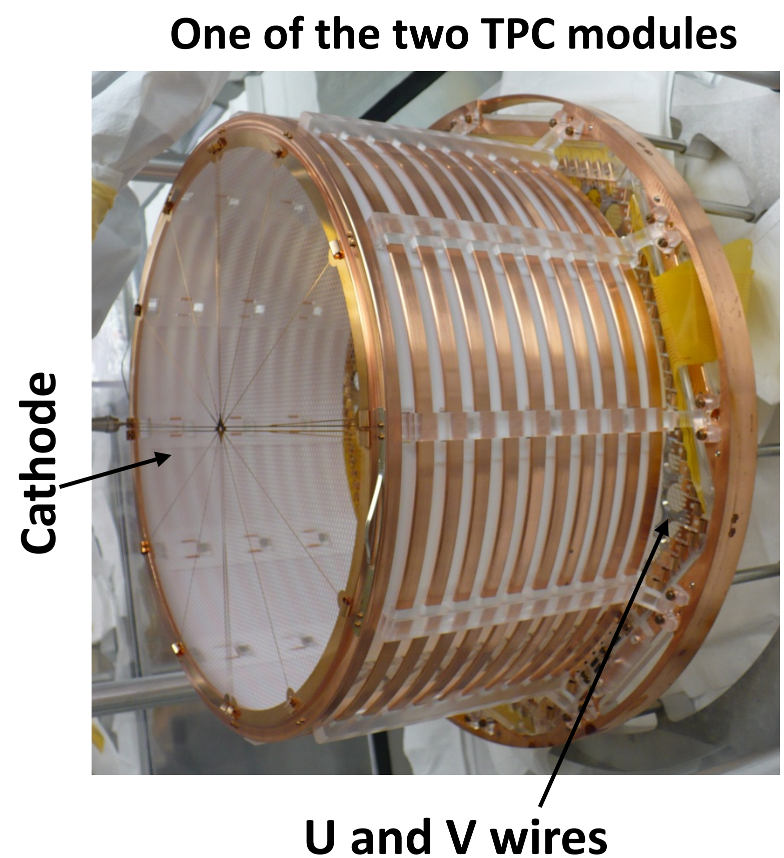
- We inject a laser pulse (405nm laser diode) into the detector to test APD functionality through one of six fibers.
- The fibers terminate one of two Teflon diffuser disks, in place of one APD on each APD plane.
- All channels can see the light pulser.
- Light pulser is on plane 2, the ratio of photons detected on plane 2 vs on plane 1 is about 64 : 100.



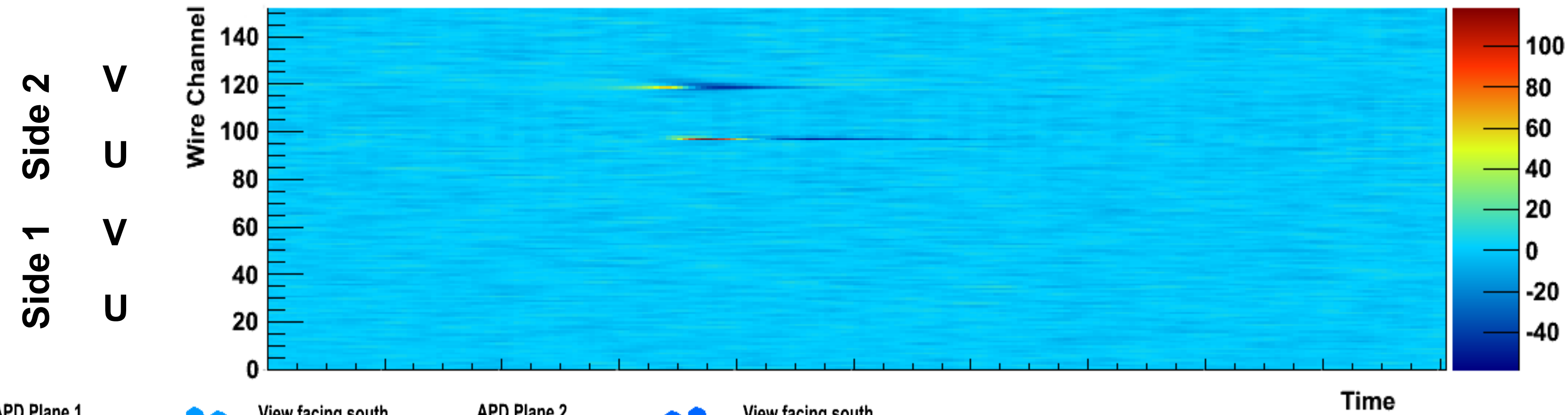
We are also taking noise data during the commissioning run. The electronics have internal calibration pulses to help characterize noise.

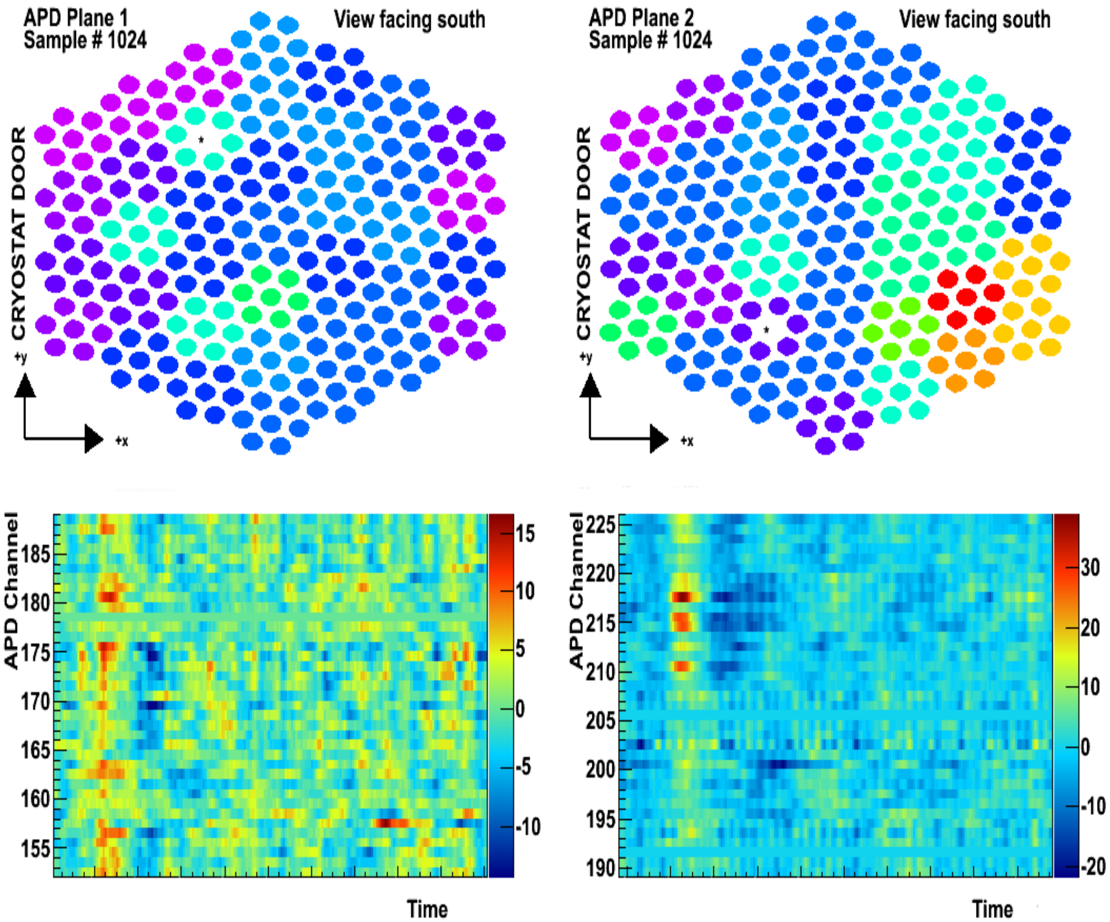
Muon track in EXO-200 (Dec 2010)





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, in front of the charge-collecting U-wires report a smaller inductive signal. The two sets of wires cross at 60º angle. 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.





A single-site energy deposition in EXO-200.

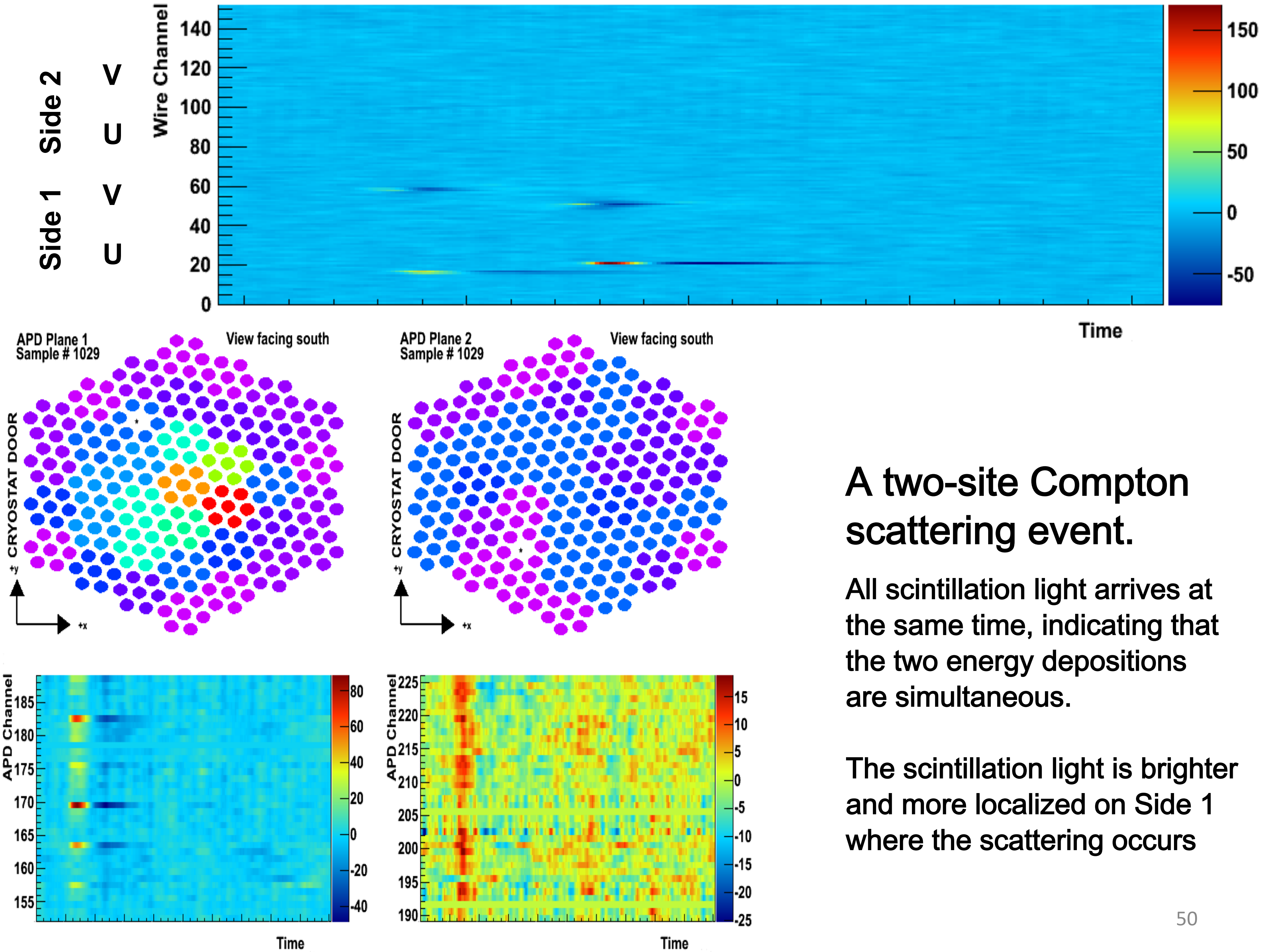
Top display is charge readout (V are induction wires and U are collection wires).

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.

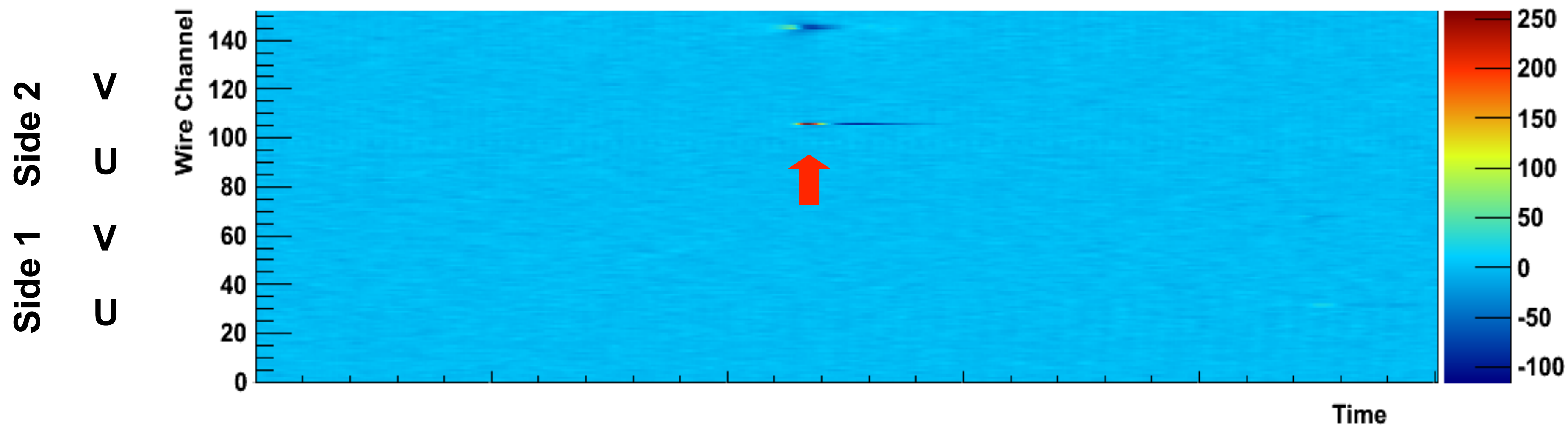
Light signals precede in time the charge ones

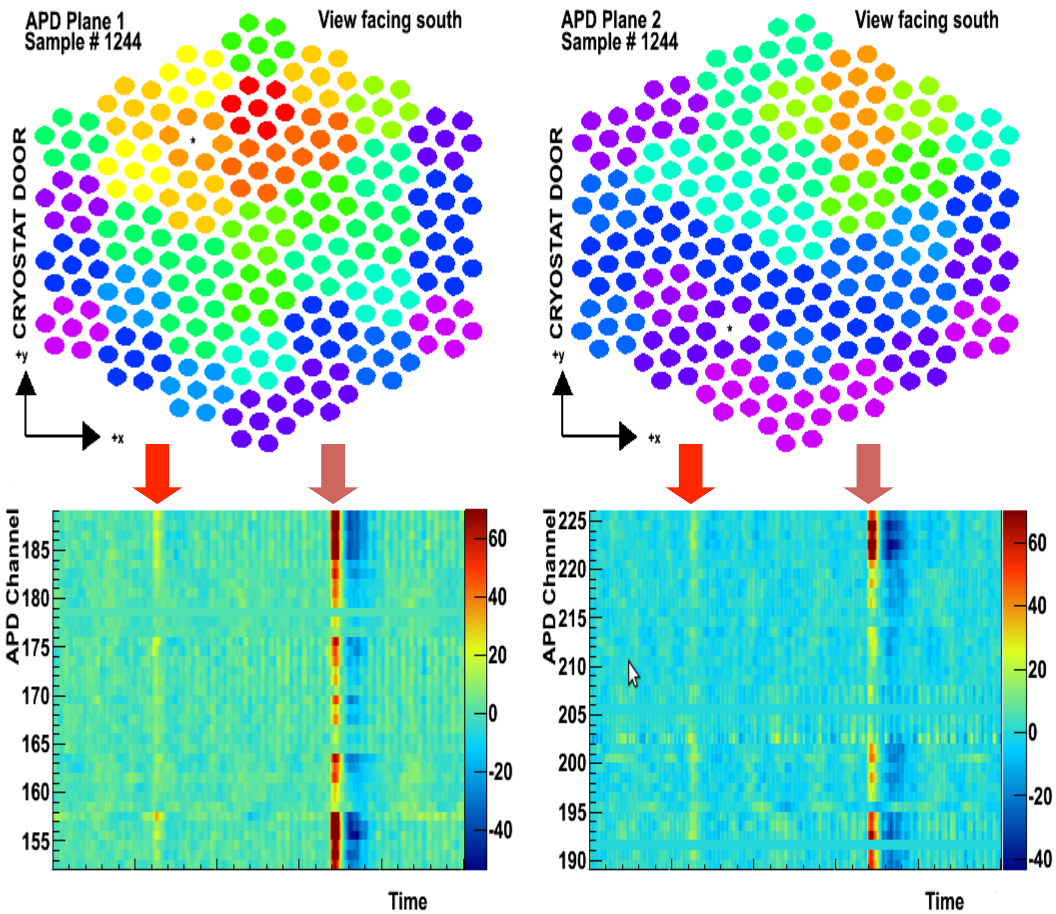


A two-site Compton scattering event.

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





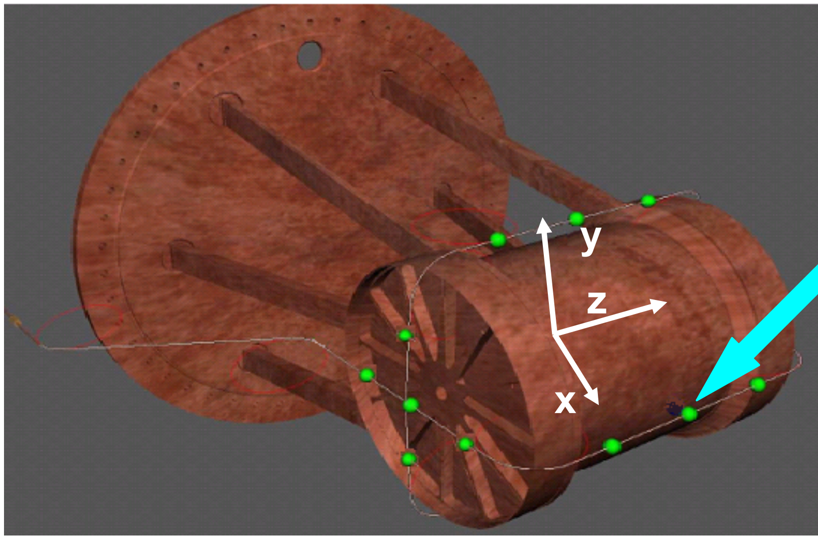
A possible ^{214}Bi - ^{214}Po correlated event

There are two scintillation flashes but only one event of charge collection.

Since light always comes first, the charge site is related to the first scintillation flash. This is consistent with the β from the ^{214}Bi→^{214}Po+β+ν decay in the ^{238}U chain. The second scintillation flash without a charge counterpart is consistent with the detection of the α from ^{214}Po→^{210}Pb+α

The time between the two scintillation flashes
is consistent with the $T_{1/2}$ of ^{214}Po (164μs). The timing is also consistent with the ^{214}Bi being very close to the cathode grid.

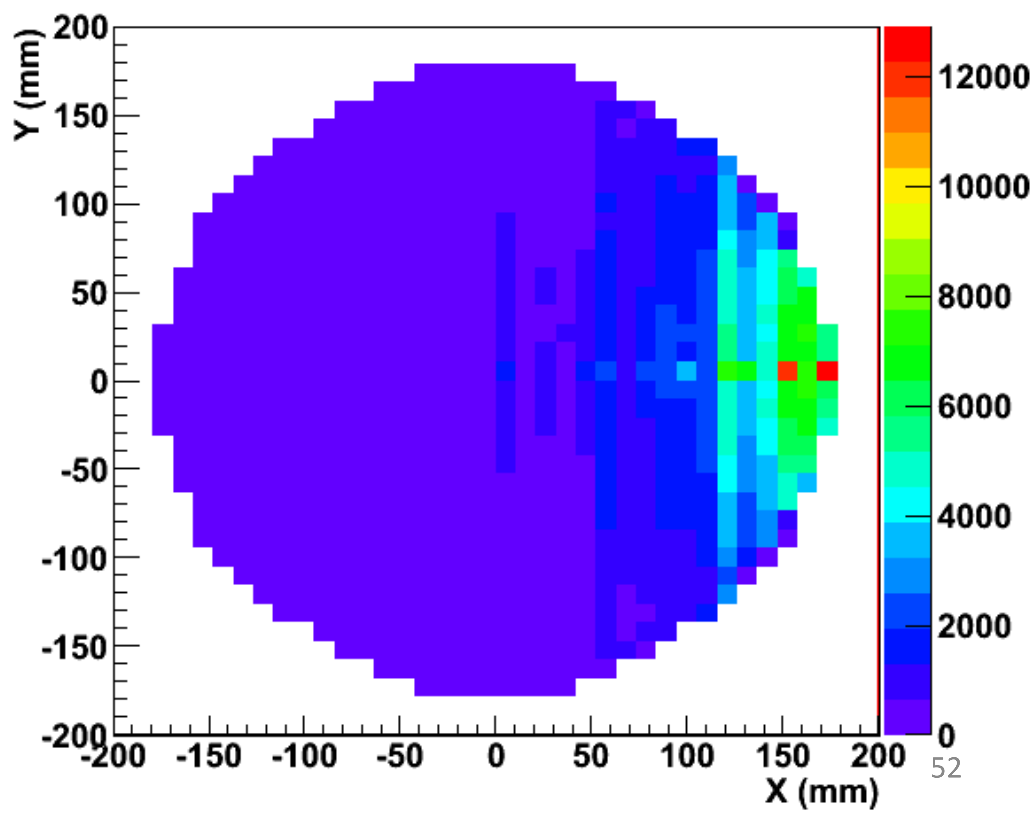
Early calibration source run

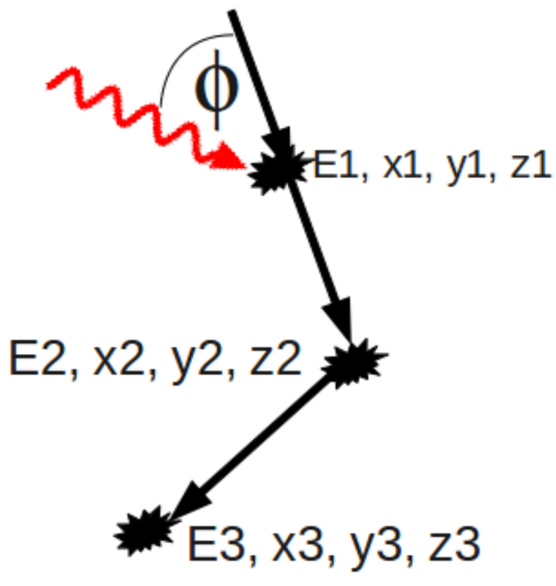


^{60}Co source

Various calibration sources can be brought to several positions just outside the detector

x-y distribution of events clearly shows excess near the source location



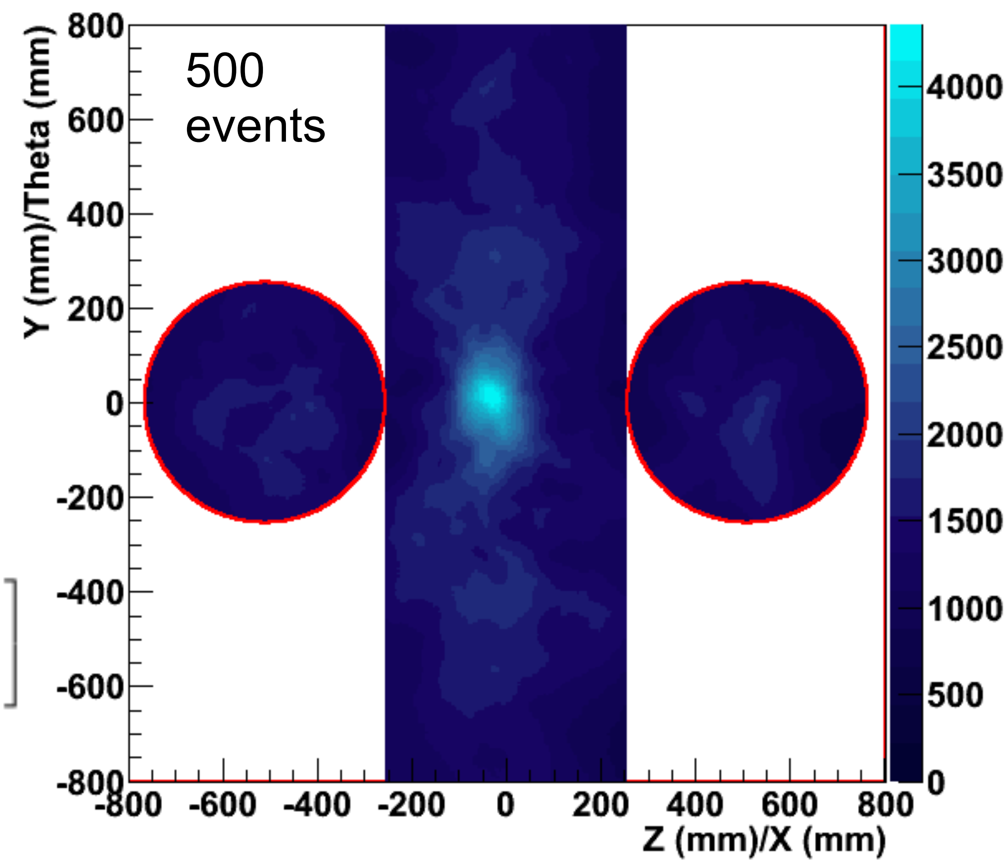


Can point to source using a Compton telescope technique

- Detector measures E, x, y, z for each site
- Use scattering formula

$$\phi = arccos\left[1 - m_e c^2 \cdot \left(\frac{1}{E_\gamma - E_1} - \frac{1}{E_1}\right)\right]$$

- From each site a cone is drawn and adding up these cones produces the image to the right



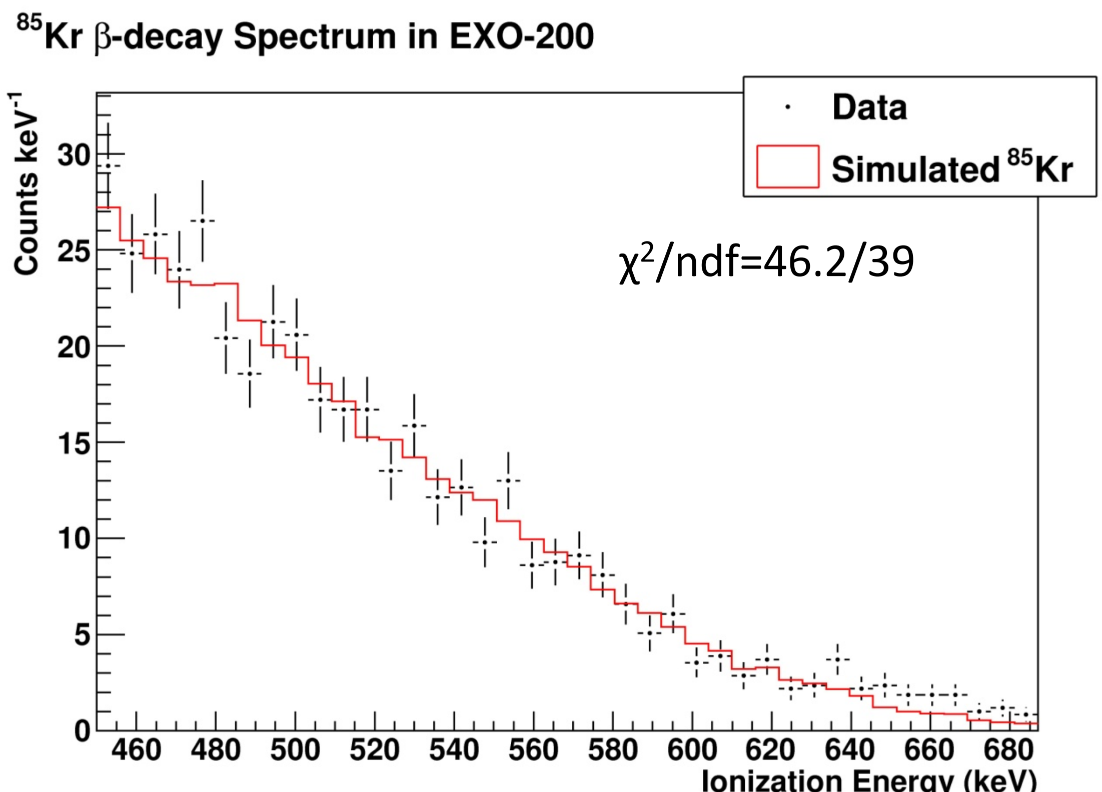
The NatlXe used for the EXO-200 engineering run contains Kr

The total Kr concentration in the ^{nat}Xe was measured to be, using a special technique involving mass-spec*, $(42.6 \pm 5.7) \cdot 10^{-9}$ g/g

*A.Dobi et al., arXiv:1103.2714v1

The ^{85}Kr fraction of the Kr in the detector can be seen in the low energy spectrum (for the time being only use charge readout, light-charge correlation analysis still in progress)

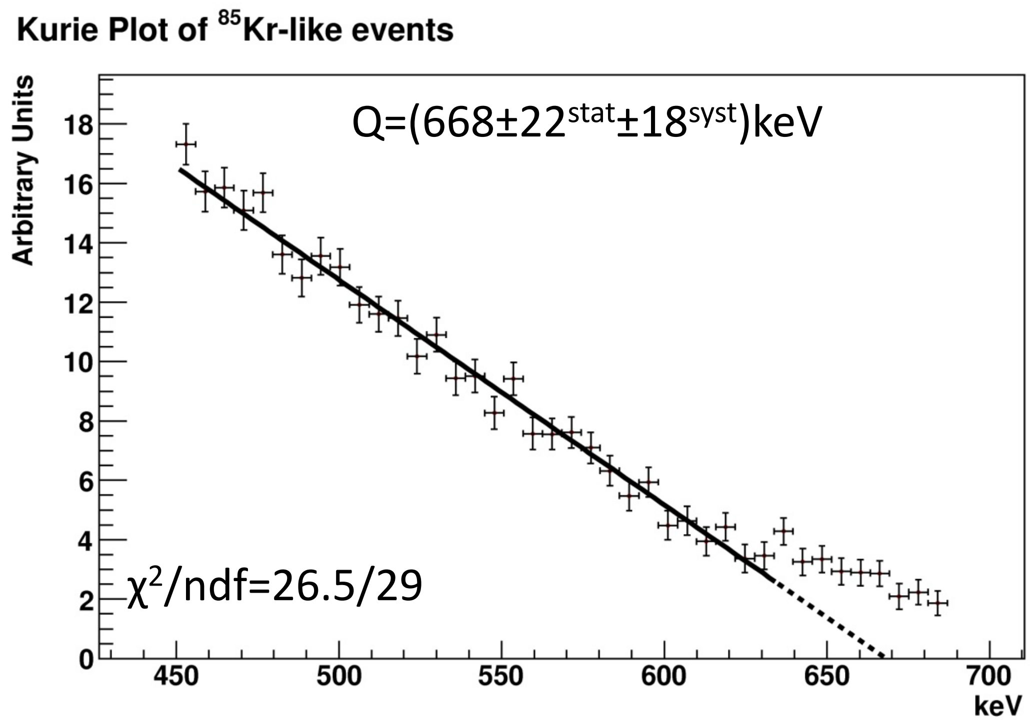
Energy scale set by ^{60}Co calibration



Adjust ^{85}Kr simulation to match the data in the integral from 450keV to the Q value (687keV)

→ Consistent with Mass Spec result assuming standard ^{85}Kr/Kr concentration of ~10^{-11}

A first look at the ^{85}Kr endpoint



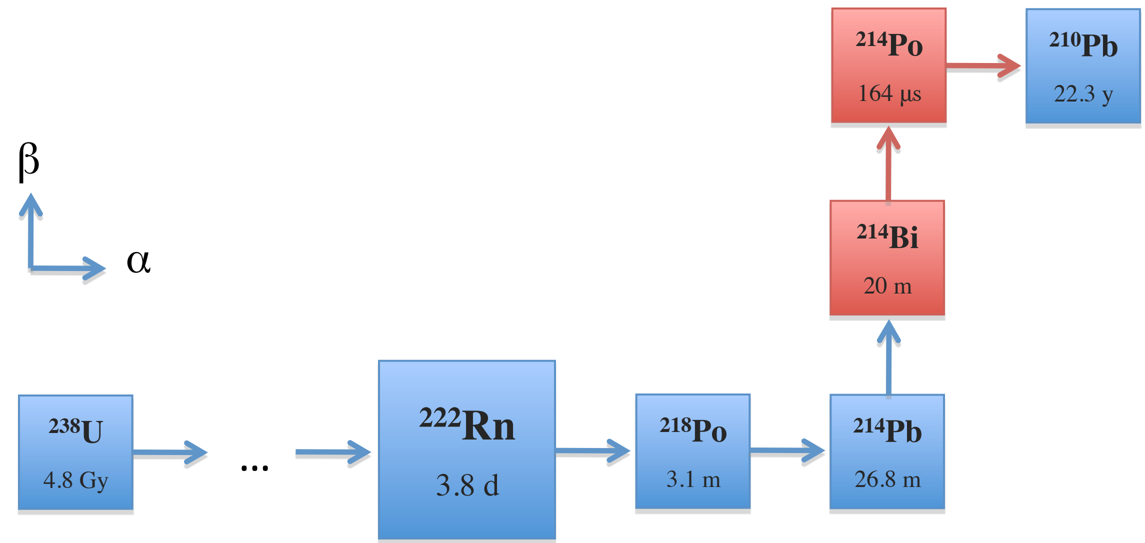
Near end point other backgrounds start to emerge:

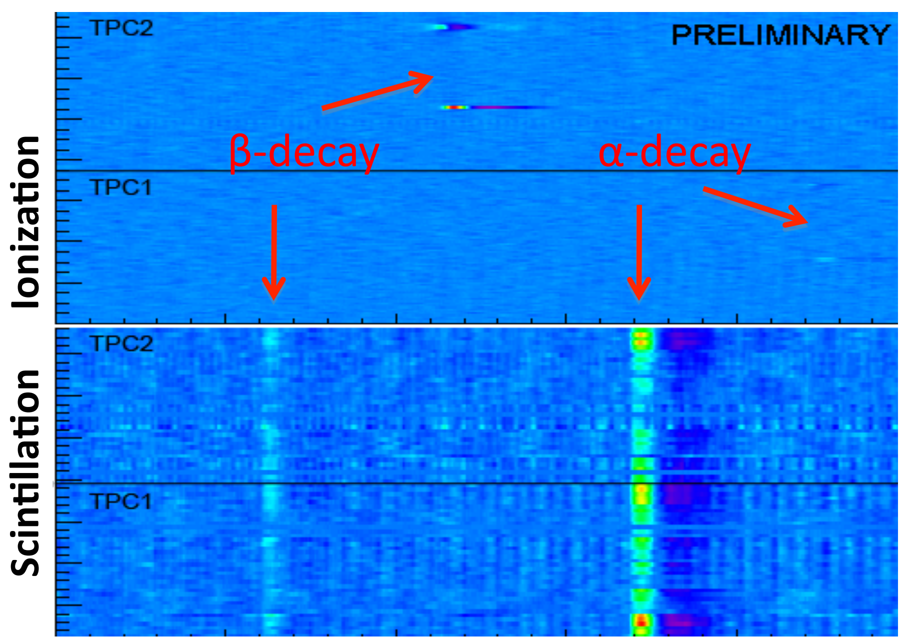
- Fit Kurie plot excluding data above 635keV
- Vary fit range to

Measured Q value in good agreement with expectation (687keV)

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

^{214}Bi undergoes β-decay into ^{214}Po which then undergoes α-decay with a half life of 164 μs.





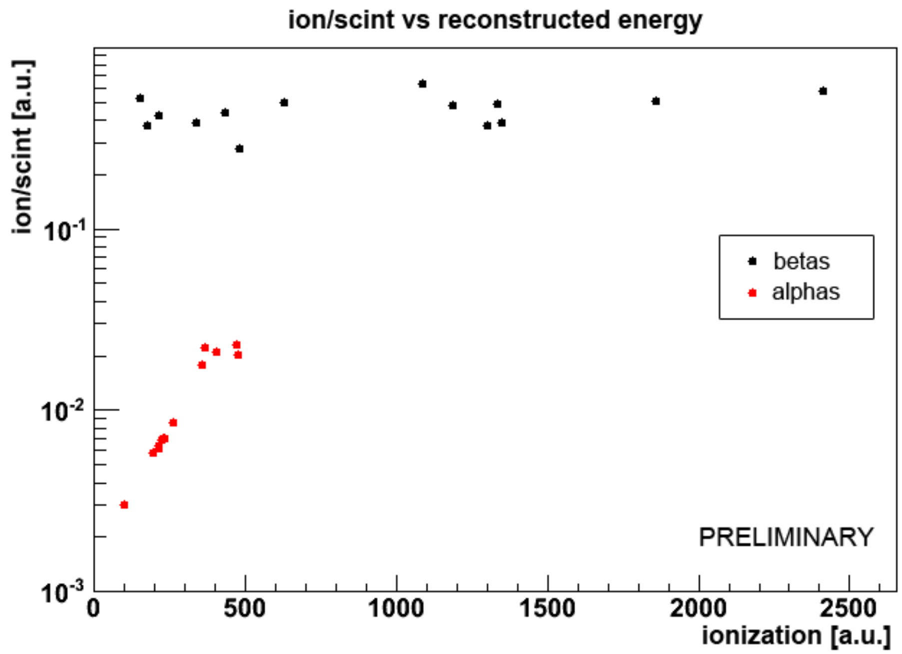
Bi-Po events are identified by their characteristic event topology which has a high probability to be detected in a single trigger window.

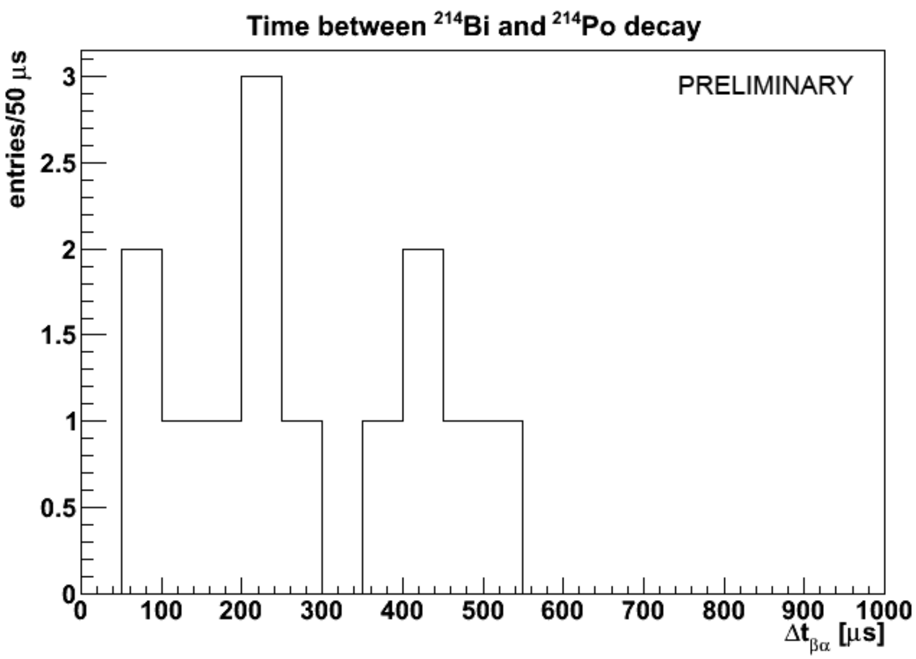
α: strong light signal, weak charge signal
β: weak light signal, strong charge signal

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

α and β particles can be identified by their ionization/scintillation ratio (right plot).

- 15 Bi-Po events were found in a commissioning run.
- 6 of them occurred on or near the cathode whereas the others are located in the bulk of detector.





The average time between the β and α decay (left plot) is 242 µs which corresponds to τ = 271 µs.
Considering the low statistics, this is in good agreement with the true value of τ=237 µs.

Accurate detection efficiency still under study but the 214Bi decay rate is consistent with expectation before the Rn trap is commissioned.

Sensitivity

- EXO 200

case	Mass	efficiency	Run Time	σ_E/@2.5MeV	Radioactive	$T^{0\nu}_{1/2}$	Majorana mass meV	
	(tonne)	(%)	(yr)	(%)	(events)	(yr, 90% CL)	QRPA*	NSM$^+$
EXO-200	0.2	70	2	1.6	40	6.4×10^{25}	109	135

TABLE 1. $\star$ Simkovic et al. Phys. Rev. C79, 055501(2009) (use RQRPA and gA= 1.25). + Menendez et al., Nucl. Phys. A818, 139(2009), (use UCOM results)

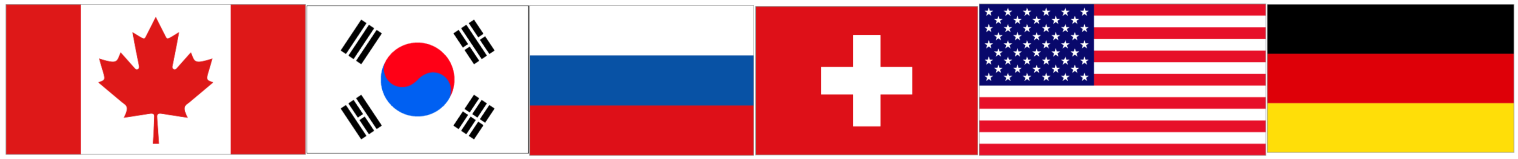
- EXO Full

case	Mass	efficiency	Run Time	σ_E/@2.5MeV	$2\nu\beta\beta$ Background	$T^{0\nu}_{1/2}$	Majorana mass meV	
	(tonne)	(%)	(yr)	(%)	(events)	(yr, 90% CL)	QRPA*	NSM$^+$
Conservative	1	70	5	1.6	0.5 (use 1	2×10^{27}	19	24
Aggressive	10	70	10	1	0.7 (use 1)	4.1×10^{28}	4.3	5.3

TABLE 1. $\star$ Simkovic et al. Phys. Rev. C79, 055501(2009) . + Menendez et al., Nucl. Phys. A818, 139(2009)

Summary

- Provided motivation for looking $0\nu\beta\beta$ decay
- Motivation for EXO 200
- Detector is build (still have to finish Radon tent and second front lead wall)
- The muon veto system is running
- Took an engineering run with natural Xe in December
- We are now taking data with enriched ^{136}Xe



D.Auty, M.Hughes, R.MacLellan, A.Piepke, K.Pushkin, M.Volk,
Dept of Physics & Astronomy, U. of Alabama, Tuscaloosa AL
M.Auger, D.Franco, G.Giroux, R.Gornea, M.Weber, J-L.Vuilleumier,
High Energy Physics Lab,Bern,Switzerland
P.Vogel *Physics Dept Caltech, Pasadena CA*
A.Coppens, M.Dunford, K.Graham, P.Gravelle, C.Hägemann, C.Hargrove,
F.Leonard, K.McFarlane, C.Oullet, E.Rollin, D.Sinclair, V.Strickland,
Carleton University, Ottawa, Canada
C.Benitez-Medina, S.Cook, W.Fairbank Jr., K.Hall, N.Kaufhold, B.Mong,
T.Walton, *Colorado State U., Fort Collins CO*
L.Kaufman, *Indiana University*
M.Moe, *Physics Dept UC Irvine, Irvine CA*
D.Akimov, I.Alexandrov, V.Belov, A.Burenkov, M.Danilov, A.Dolgolenko, A.Karelin, A.Kovalenko, A.Kuchenkov,
V.Stekhanov, O.Zeldovich, *ITEP Moscow, Russia*
E.Beauchamp, D.Chauhan, B.Cleveland, J.Farine, D.Hallman, J.Johnson, U.Wichoski, M.Wilson, *Laurentian U., Canada*
C.Davis, A.Dobi, C.Hall, S. Slutsky, Y-R. Yen, *U. of Maryland, College Park MD*
J. Cook, T.Daniels, K.Kumar, A.Pocar, K.Schmoll, C.Sterpka, D.Wright, *UMass, Amherst*
D.Leonard, *University of Seoul, Republic of Korea*
M.Breidenbach, R.Conley, W.Craddock, S.Herrin, J.Hodgson, J.Ku, D.Mackay, A.Odian, C.Prescott,
P.Rowson, K.Skarpaas, M.Swift, J.Wodin, L.Yang, S.Zalog, *SLAC, Menlo Park CA*
P.Barbeau, L.Bartoszek, J.Davis, R.DeVoe, M.Dolinski, G.Gratta, F.LePort, M.Montero Diez,
A.Müller, R.Neilson, A.Rivas, A. Saburov, K.O'Sullivan, D.Tosi, K.Twelker, *Physics Dept Stanford U., Stanford CA*
W.Feldmeier, P.Fierlinger, M.Marino, *TUM, Garching, Germany*

EXO-200 material screening

- Stringent requirements on K/Th/U concentrations on materials inside cryostat
- Large-scale materials testing, published in *Nucl. Instr. and Meth. A 591 (2008) 490–509*
- In particular:

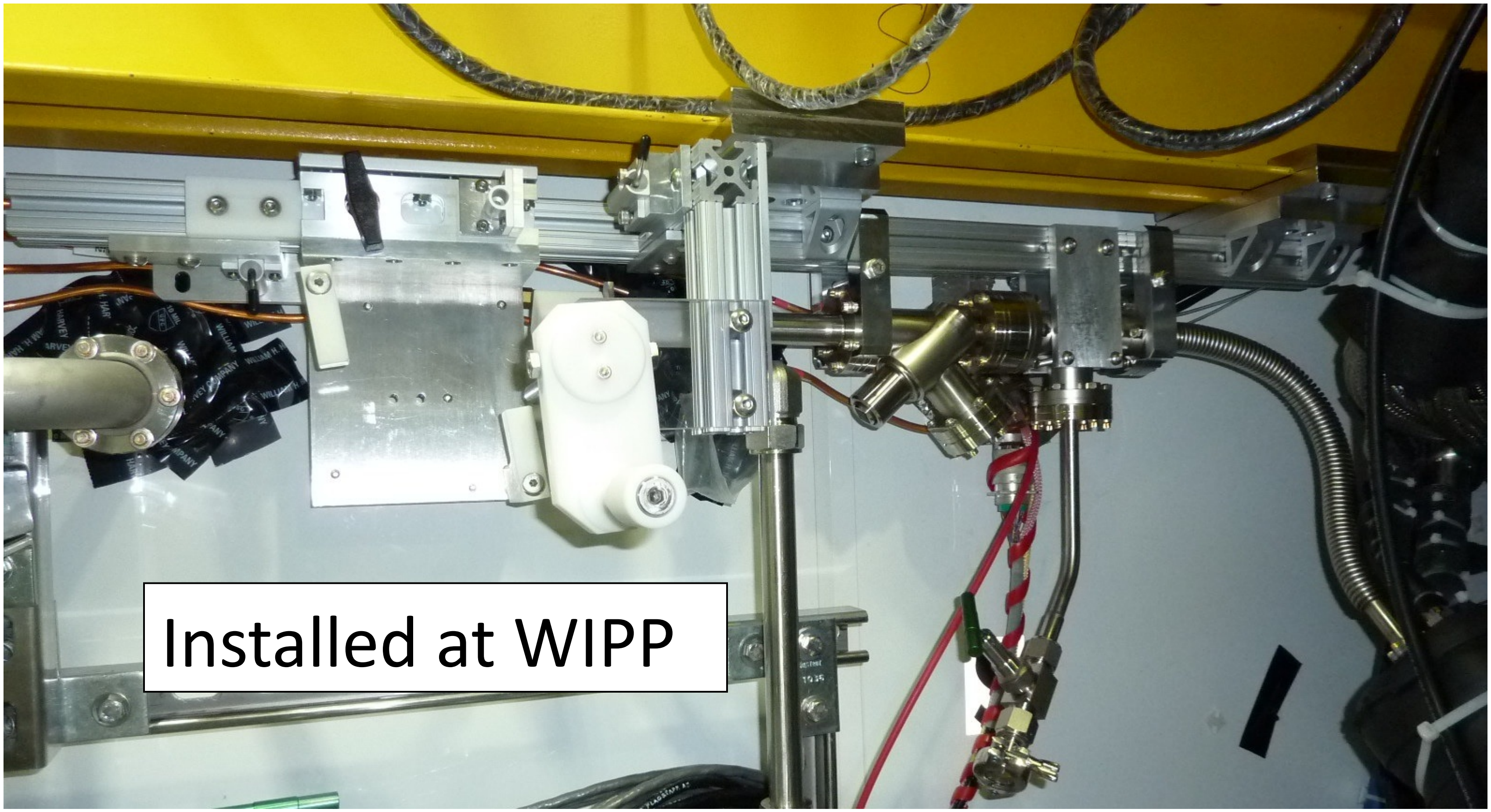
Component	K 10^{-9} g/g	Th 10^{-12} g/g	U 10^{-12} g/g	^{210}Po Bq/kg
3M Novec HFE-7000, 1-methoxyheptafluoropropane	<1.08	<7.3	<6.2	
Lead shielding	<7	<1	<1	17-20
Copper	<55	<2.4	<2.9	
Acrylic	<2.3	<14	<24	
TPC grid wires	<90	47 +/- 2	320 +/- 2	

Shielding

- Shielding MUCH HARDER for $0\nu\beta\beta$ 2.5 MeV electromagnetic signal than for low energy nuclear recoil DM search
- *Thin walled ~ 1.4 mm thick Cu TPC* surrounded by
  - 4000kg HFE7000 (~50 cm), density ~ 1.4 g/cm^3
  - 25 cm Pb shielding on all sides
- For comparison with DM experiments, assume N-ton spherical LXe $0\nu\beta\beta$ detector, using 50% LXe for shielding

Incident γ energy	γ attenuation factor (1-ton spherical LXe)	γ attenuation factor (10-ton spherical LXe)
100 keV	36	2200
2.5 MeV	1.08	1.2

Calibration Source Insertion



Choice of isotope

EXO will search for the decay $^{136}Xe \rightarrow {}^{136}Ba + 2e^-$.

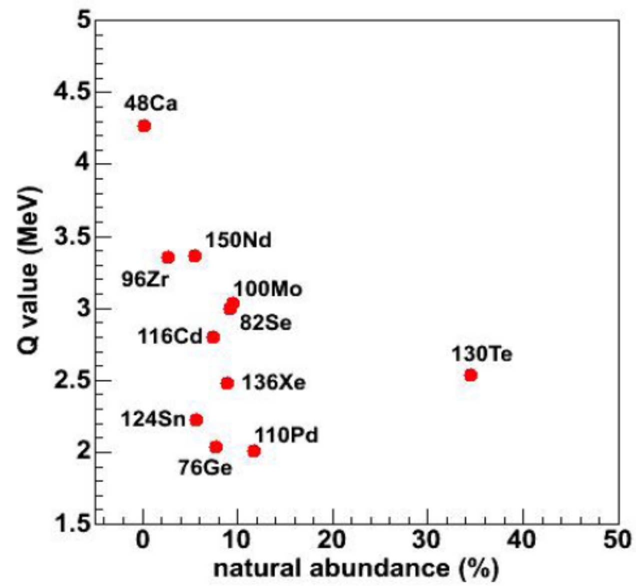
Current best limit from R.Bernabei et. al., Phys.Lett. 546B, 23 (2002): $T_{1/2}^{0\nu} > 1.2 \times 10^{24}$ y at 90% C.L.

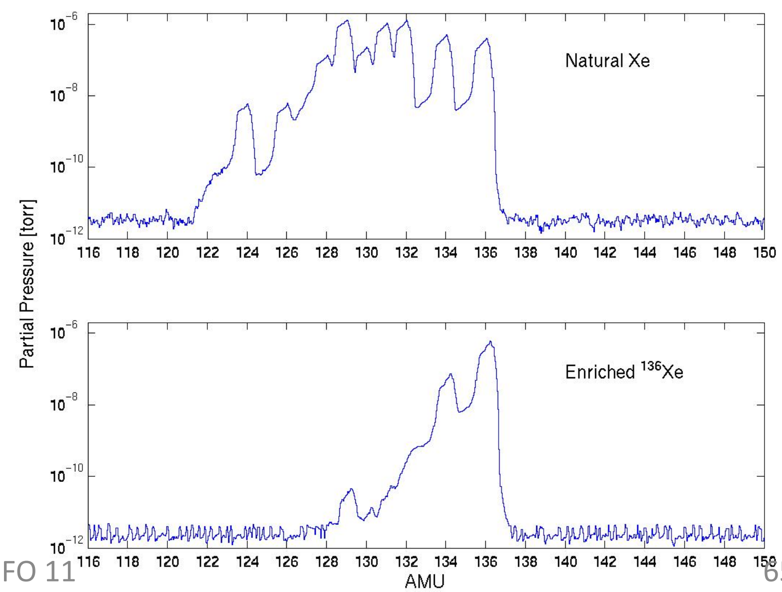
Natural isotopic abundance of 8.9% with inexpensive enrichment.

Q-value of 2458 keV gives favorable phase space and a $0\nu\beta\beta$ region of interest above most naturally occurring γ-rays.

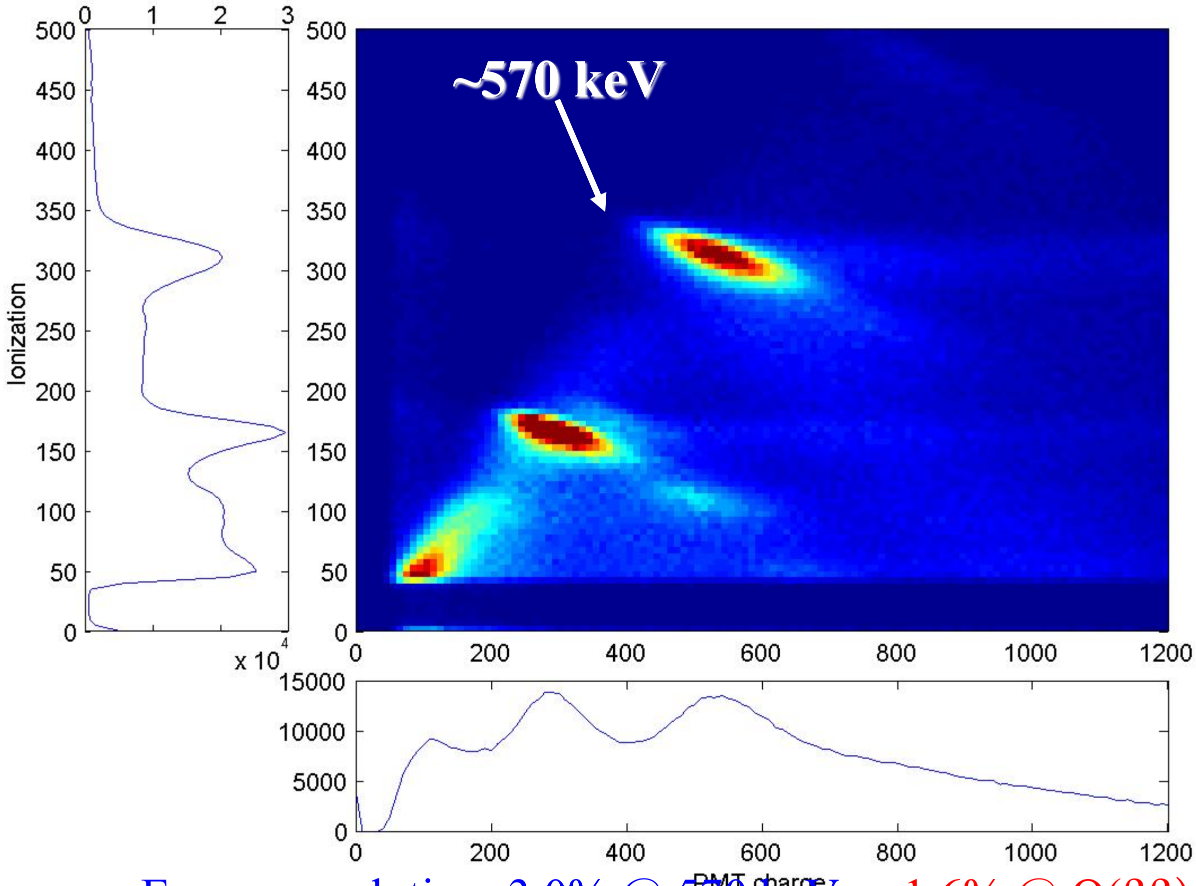
Noble gas/liquid detector allows continuous purification.

The EXO Collaboration has 200 kg of xenon enriched to 80% in ^{136}Xe.





LXe Data Show Anticorrelation between Scintillation and Ionization



Energy resolution: 3.0% @ 570 keV or 1.6% @ Q(ββ)