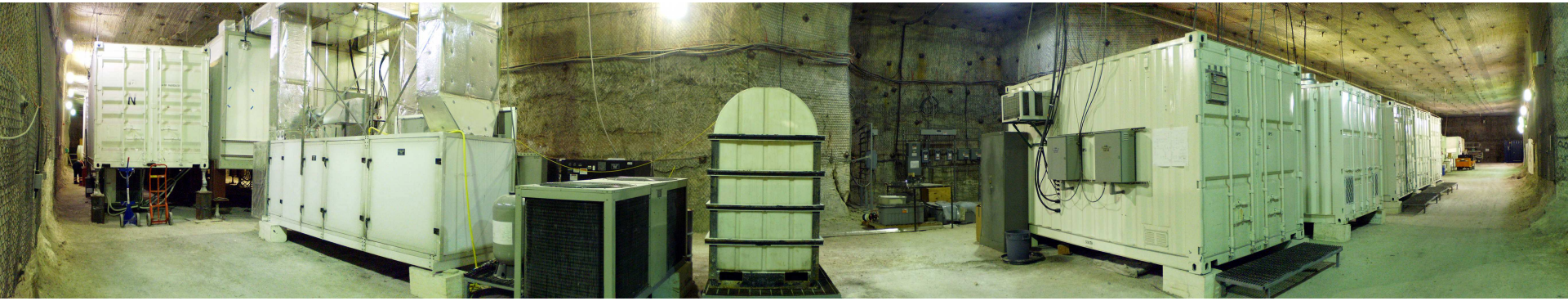
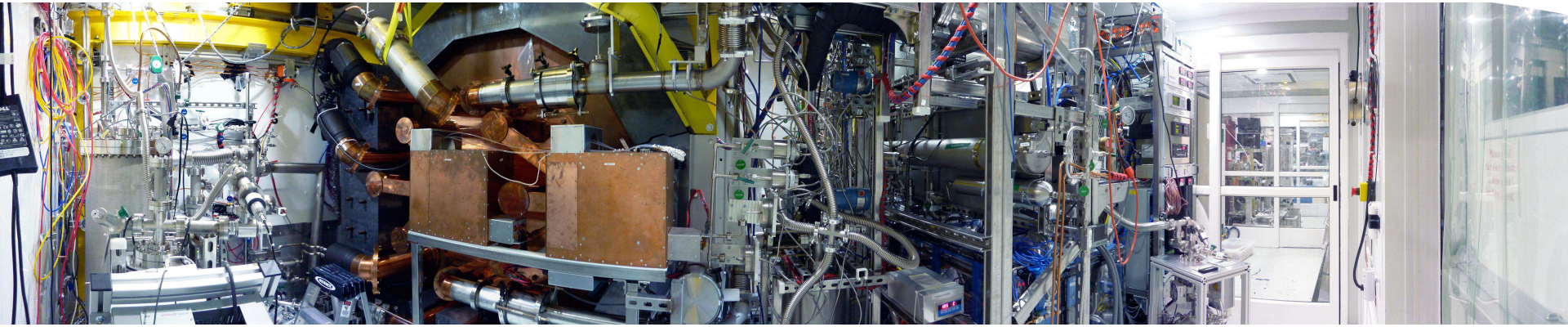


Low Background Challenges and Solutions in EXO



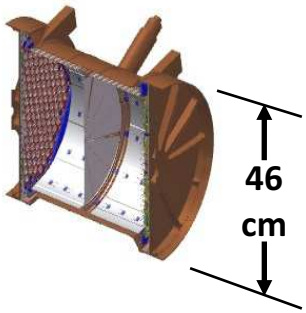
Brian Mong

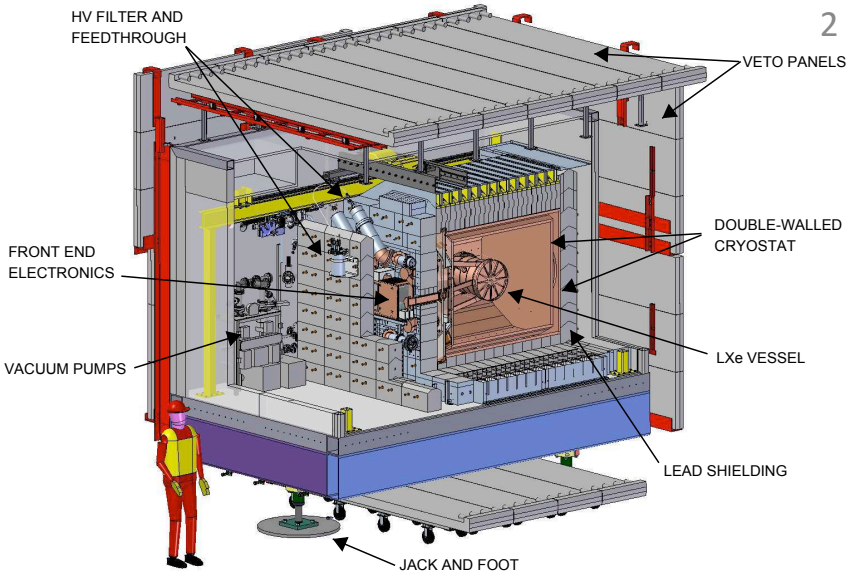
SLAC NATIONAL ACCELERATOR LABORATORY

EXO-200 and nEXO

EXO200:

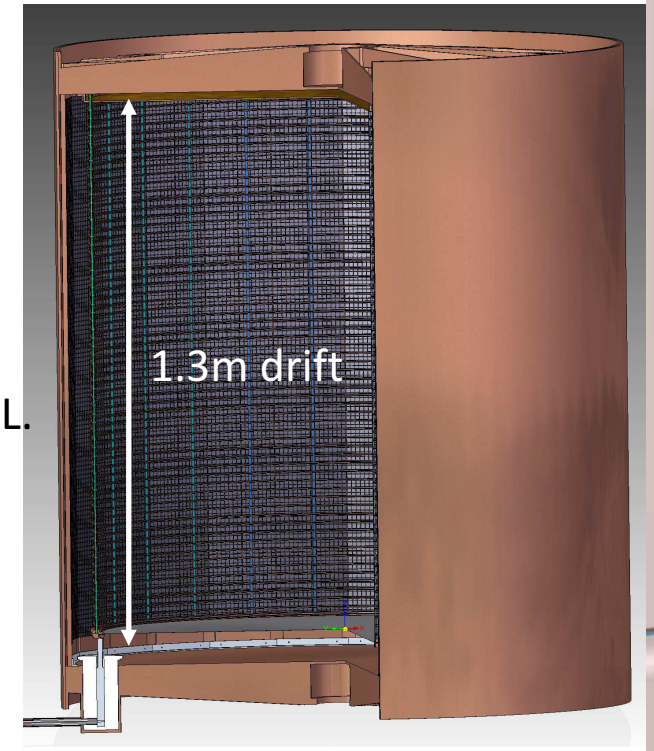
- ~175 kg LXe (single phase)
- Operational since 2011
- Sensitivity goal: $T_{1/2}$ 6E25yr

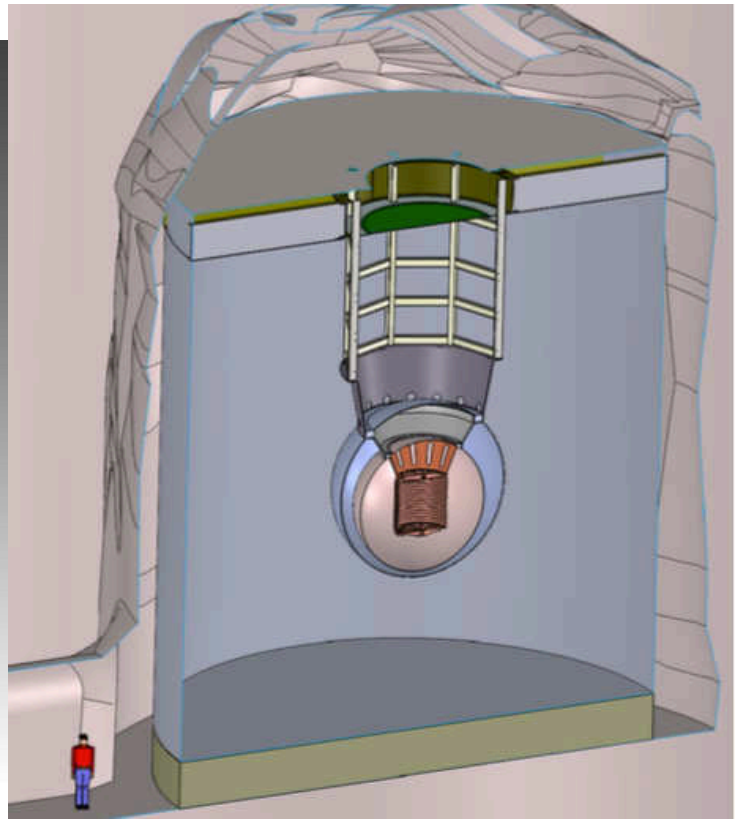




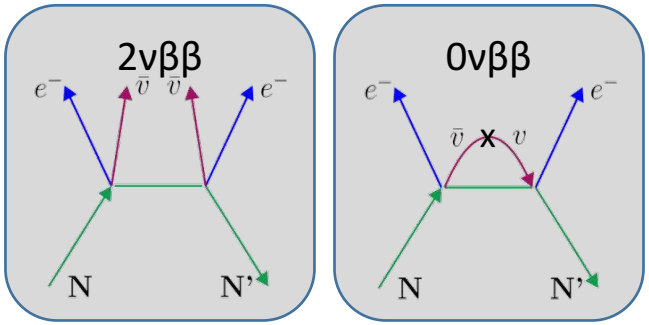
nEXO

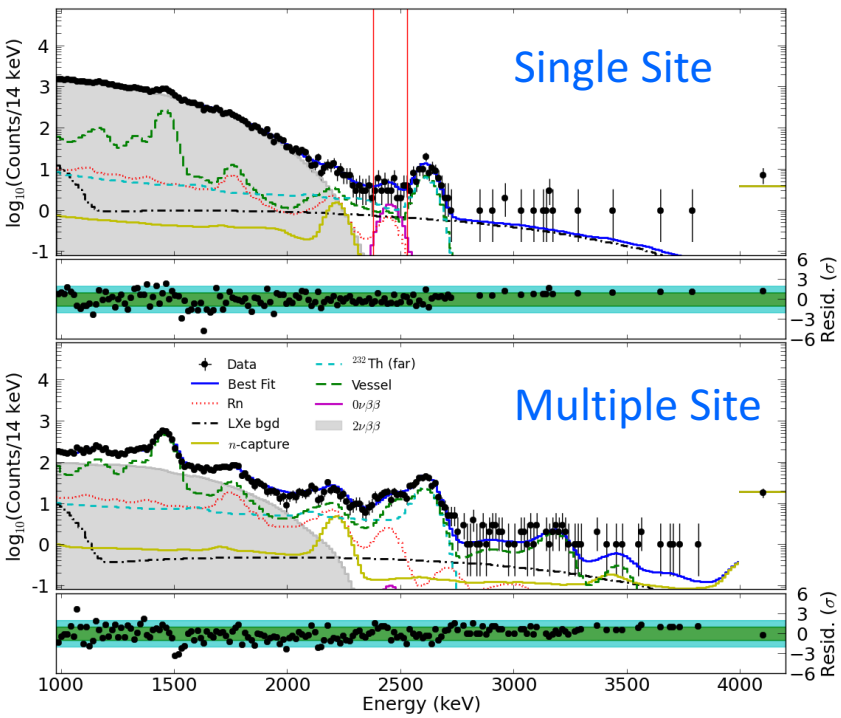
- ~5000 kg LXe
- R&D phase
- Sensitivity goal:
  $T_{1/2}$ 1E28yr @90% C.L.

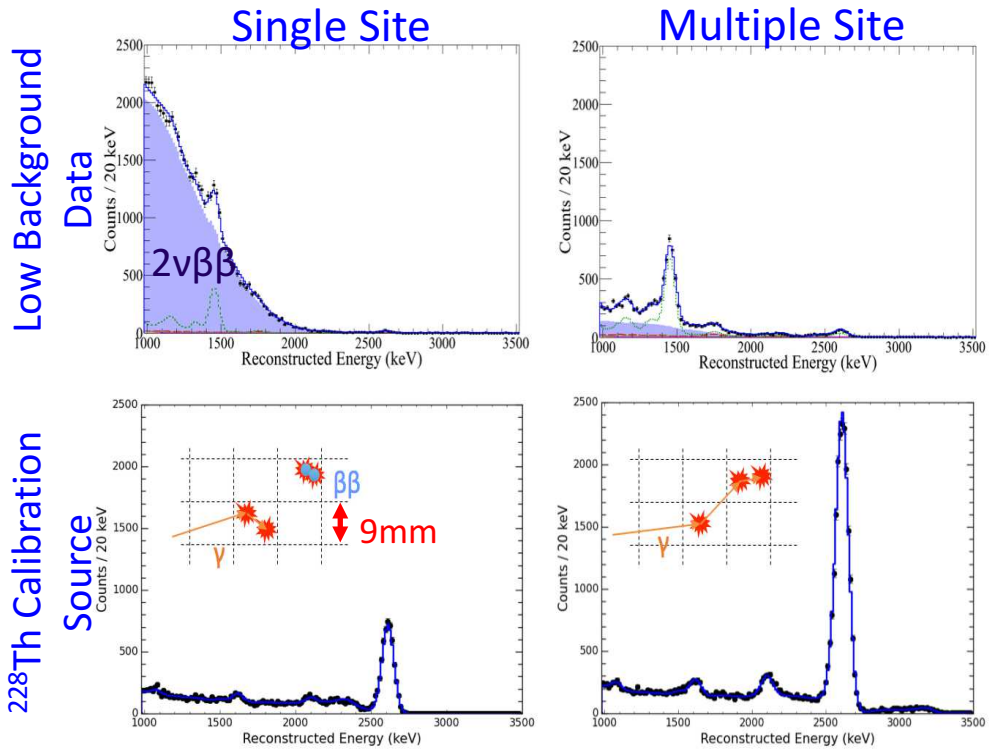




Backgrounds are relative



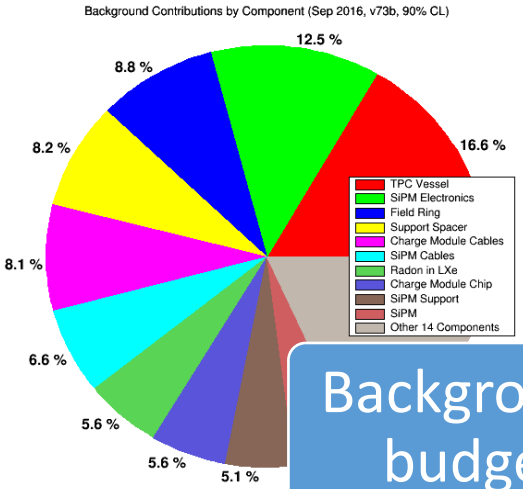




EXO signal:

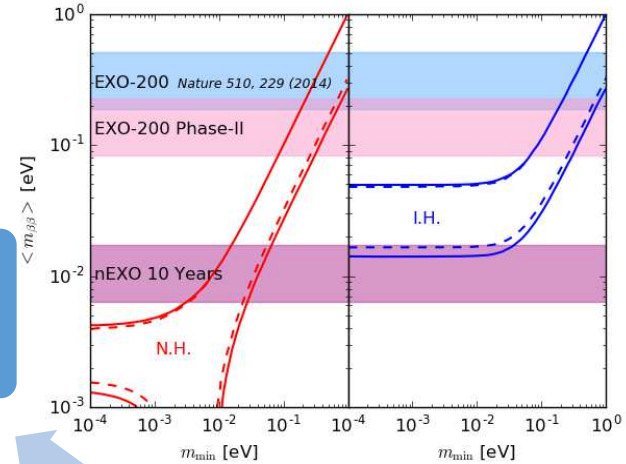
- $Q_{\beta\beta}$= 2458 keV
- Electron scattering
- Predominately single site

Design process

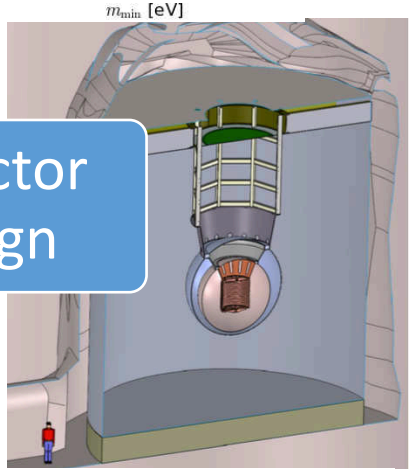


Background budget

Physics sensitivity



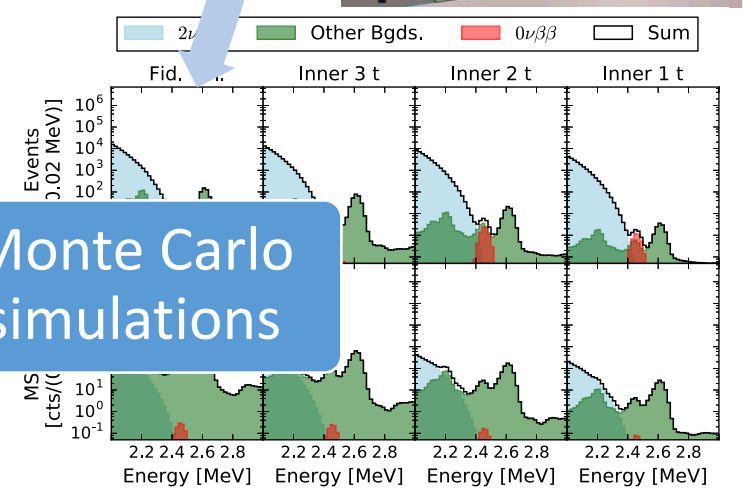
Detector design



Material assays

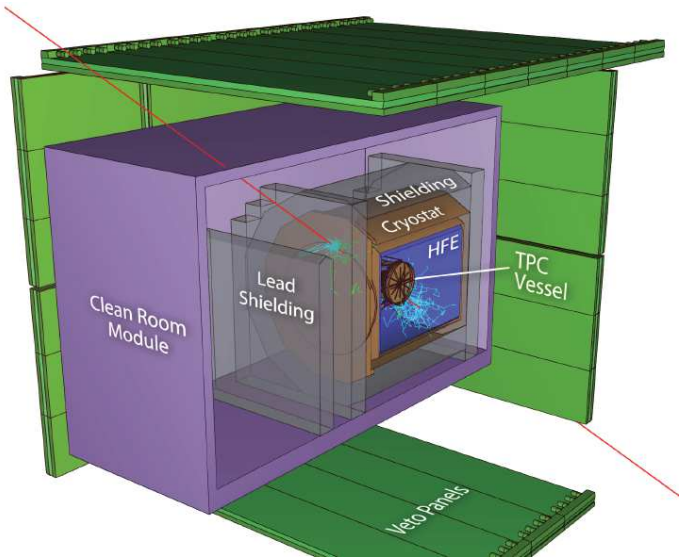
#	Material	Method	conc. $[10^{-9} g/g]$	Th conc. $[10^{-12} g/g]$	U conc. $[10^{-12} g/g]$
	Bulk Copper				
1	Norddeutsche Affinerie, NOSV copper made May 2002.	Shiva Inc. GD-MS	0.4	<5	<5
2	Norddeutsche Affinerie, NOSV copper made May 2002.	Ge	<120	<35	<63
3	Norddeutsche Affinerie OFRP copper made May 2006, batch E263/2E1.	ICP-MS	<55	<2.4	<2.9
4	Norddeutsche Affinerie OFRP copper made May 2006 batch E262/3E1.	ICP-MS	<50	<2.4	<2.9
5	Rolled Norddeutsche Affinerie OFRP copper, May 2006 production. Rolled by Carl-Schreiber GmbH.	ICP-MS	-	<3.1	<3.8
6	TIG welded Norddeutsche Affinerie OFRP copper made May 2002. No cleaning after welding. Result are normalized to length of weld.				10.2±3.4"pg/cm
7	Valcool VNT 700 metal working lubricant, concentrate.				<3700
8	Water alcohol mixture, lubricant for machining of Cu parts.				
9	JL Goslar cutting oil. Used for cutting 98% distilled water, 2% cutting oil. ^{60}Co: <1.8 mBq/kg, ^{137}Cs: <12 mBq/kg.				3650±510
10	Paint for lead bricks, JL Goslar, type: Glasurit MS-Klarlack. Proportions: 2 paint, 1 hardener, 0.1 solvent.	Ge	720±170	<170	790±90
11	EXO Pb, JL Goslar smelting lot 3-706.	ICP-MS	-	<1	<1
12	EXO Pb, JL Goslar smelting lot 3-706.	GD-MS	<15	<6	<6

Monte Carlo simulations



EXO-200 backgrounds

- All materials internal to lead assayed; 225 candidate materials+preparations published (NIMA 2008)
  - ICP-MS / GD-MS
  - Neutron Activation + Ge counting
  - Gamma counting (Ge)
- Xenon wetted materials assayed for Rn emanation
  - Electro static chamber
- Design Monte Carlo (Geant3)
  - Assay sensitivity requirements
  - Predict background + find radioactive offenders
- Final design and background estimate published (JINST 2012)
  - Geant4 Monte Carlo with detailed design, electronics sim, etc.
- EXO-200 data confirms predictions were accurate (PRC 2014, Nature 2014, PRC 2015, JCAP 2016)
- Follow up assay paper to be published soon with many more measurements

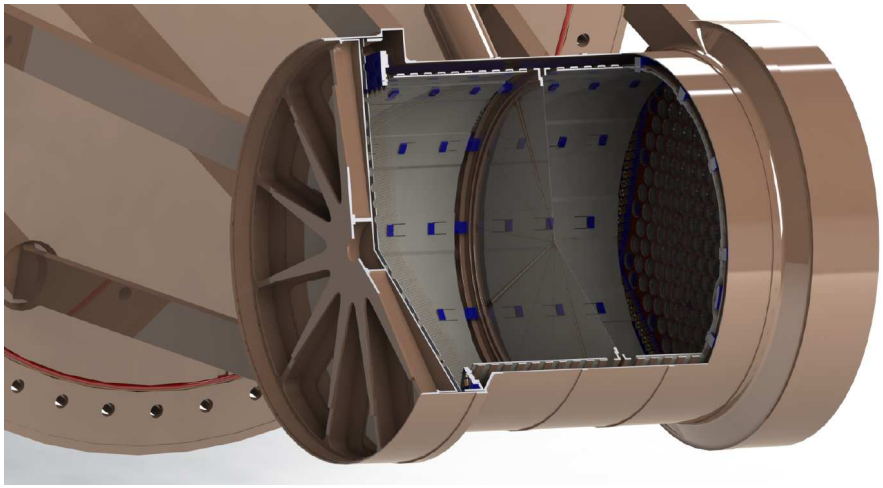


Events in ±2σ around Q	Radioactive bkgd prediction during design	Radioactive bkgd prediction using present Monte Carlo	^{137}Xe bkgd	Background from 0ν analysis fit (PRC 2014)
90%CL Upper	48	22	7	31.1 ± 1.8 ± 3.3 (39 events observed)
90%CL Lower	9.4	3.3		

Design trade-offs (EXO-200)

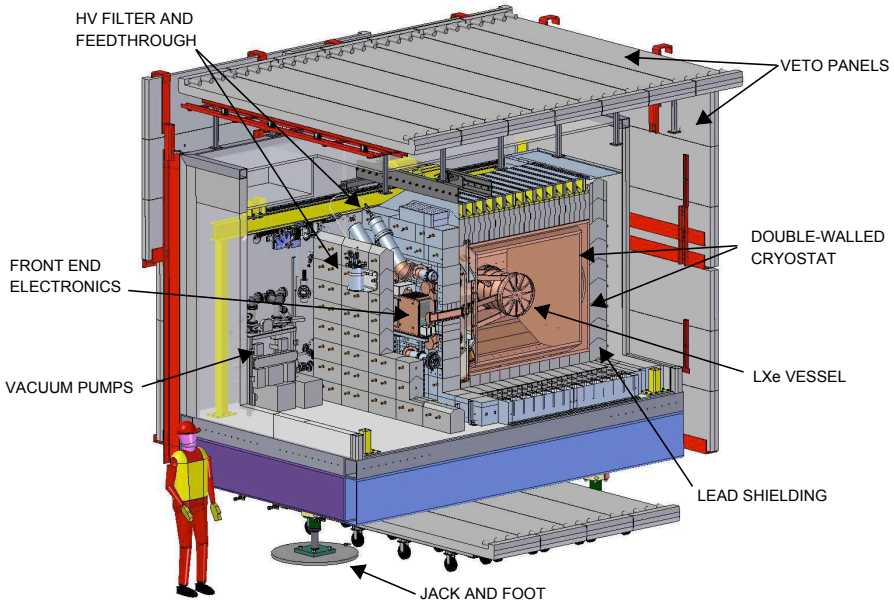
Large Xe volume

HV design limits



HFE radiation shield (4 tons)

Large cryostats



Thin copper vessel (1.3 mm)

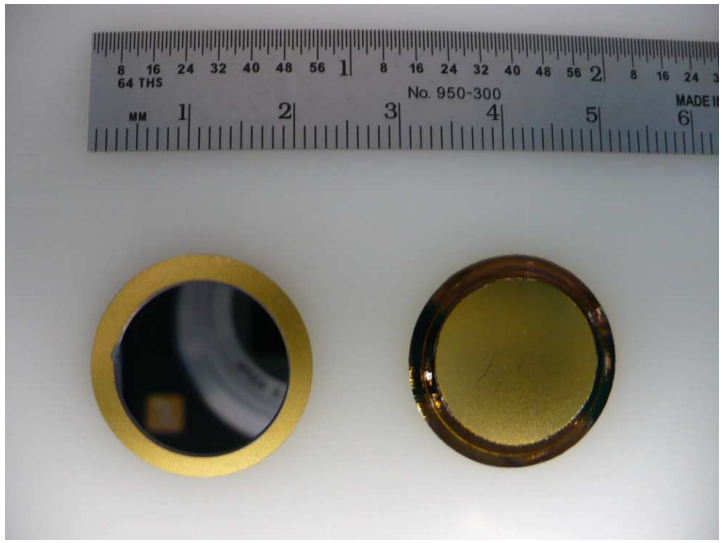
Precision gas handling system

External electronics

Increased readout noise

Working with manufacturers (example)

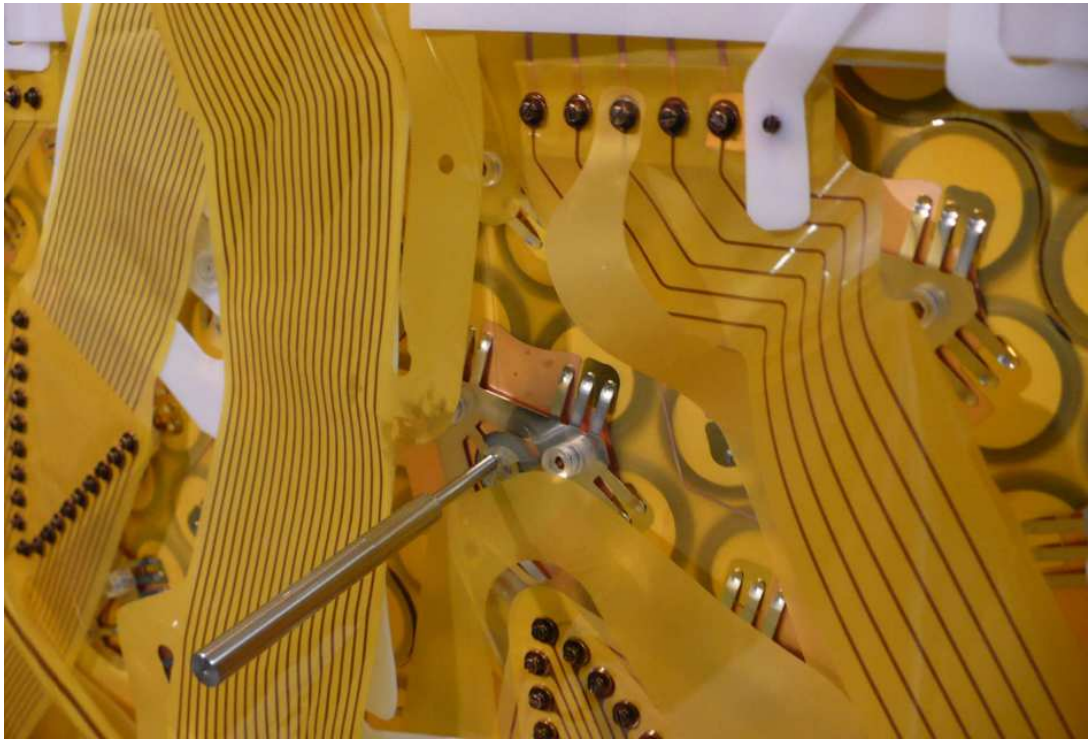
- Large area APDs from Advanced Photonics Inc. (NIMA 2009)
  - No ceramic encapsulation or window
  - Access to raw materials to check radioactivity
  - Default mfg. aluminum found to have high background
    - We supplied O(3) cleaner aluminum for the mfg of our APDs

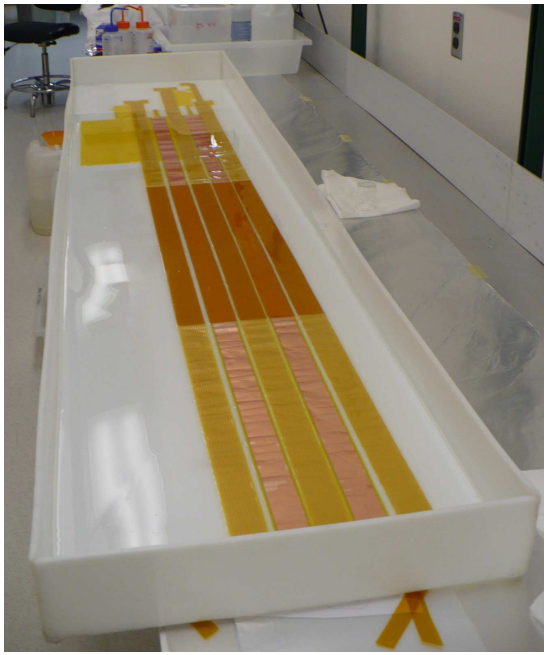


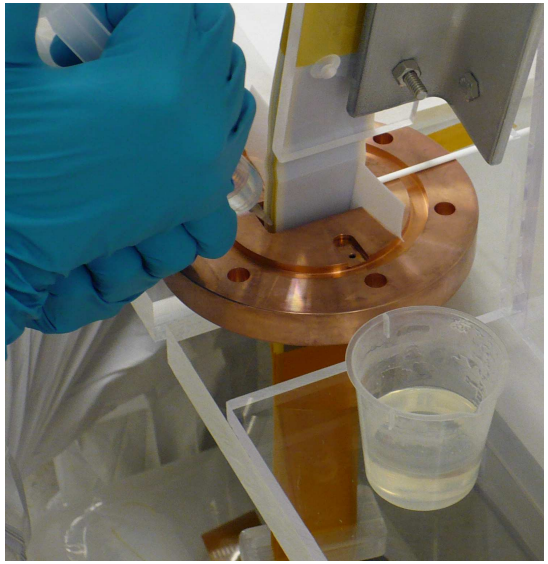
Solderless connections
Custom kapton cables

Kapton cables and feedthroughs

- Kapton (polyimide sheets) can be very clean
  - Th232 = 0.55 pg/cm^2, U238 = 1.6 pg/cm^2
- Low mass cables can be manufactured
  - 18 µm copper traces laminated between 25 µm polyimide sheets
- All mechanical connections (solderless)



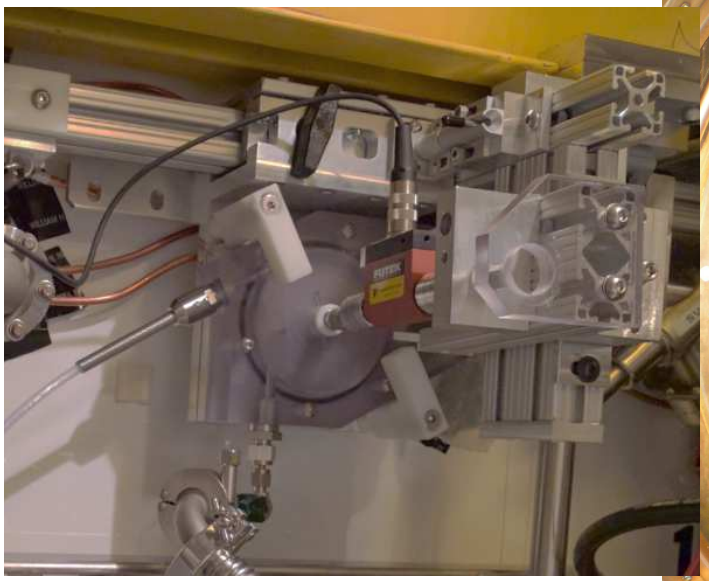


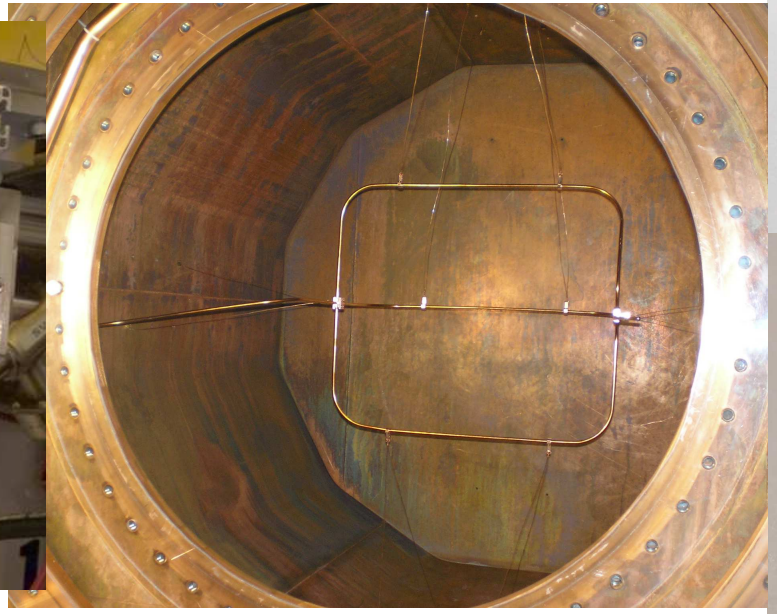


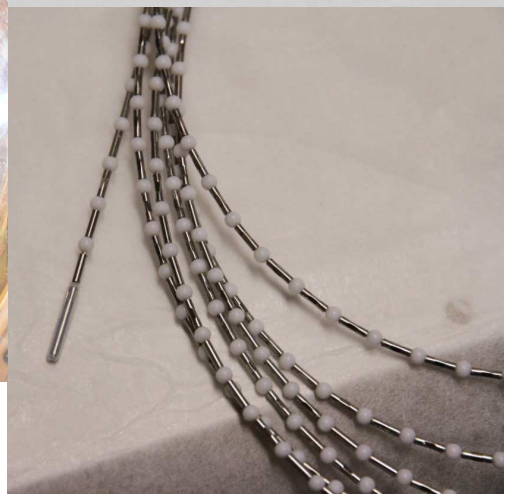
B.G. constraints leading to design

Source calibration system

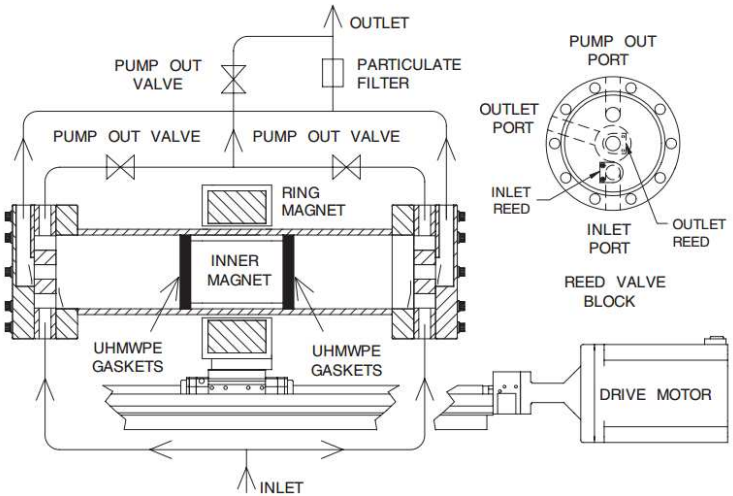
- Max tube size ¼” with cleanest (commercial) copper available to limit mass
  - Sourced in Switzerland, shipped by boat to Stanford
- Miniaturized source needed to be designed



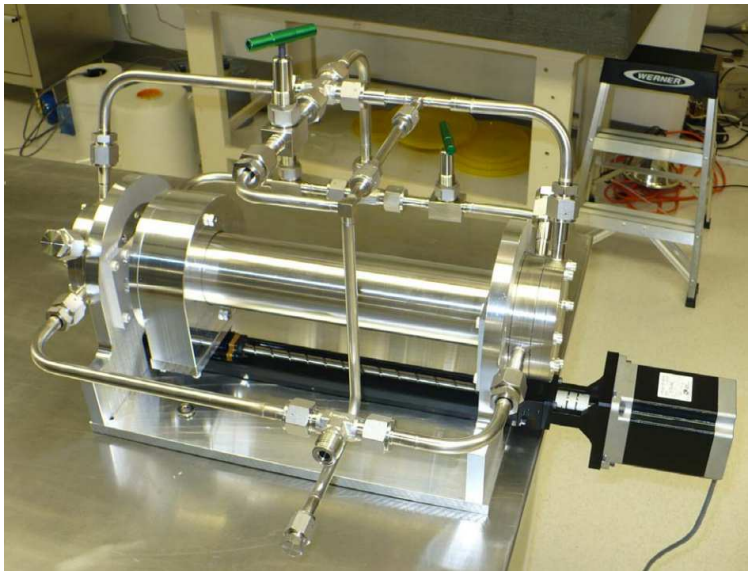




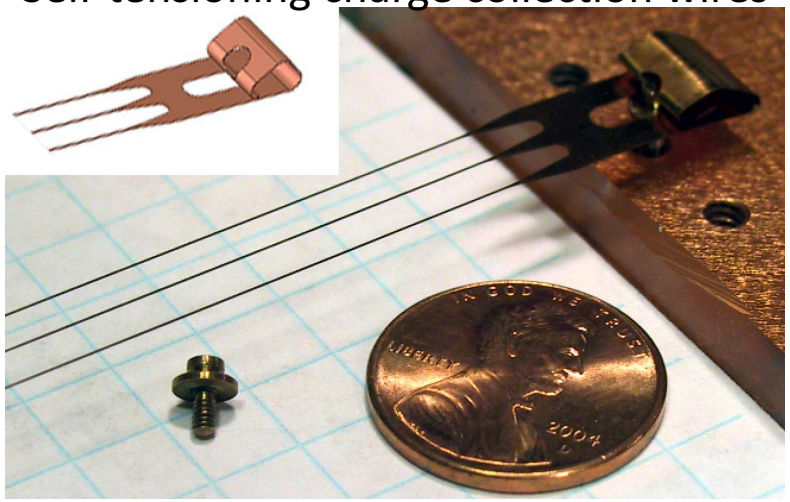
EXO-200 unique solutions

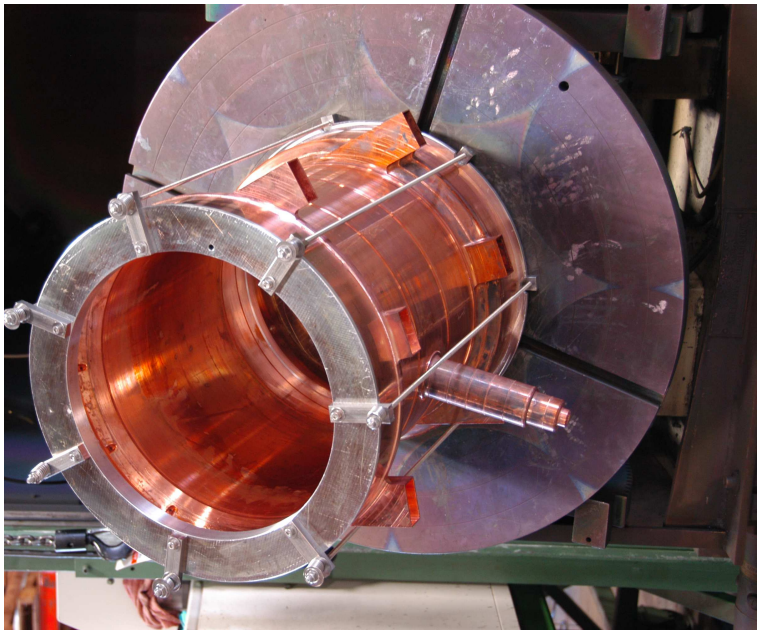


Gas Xe pump w/ all metal seals (RSI 2010)



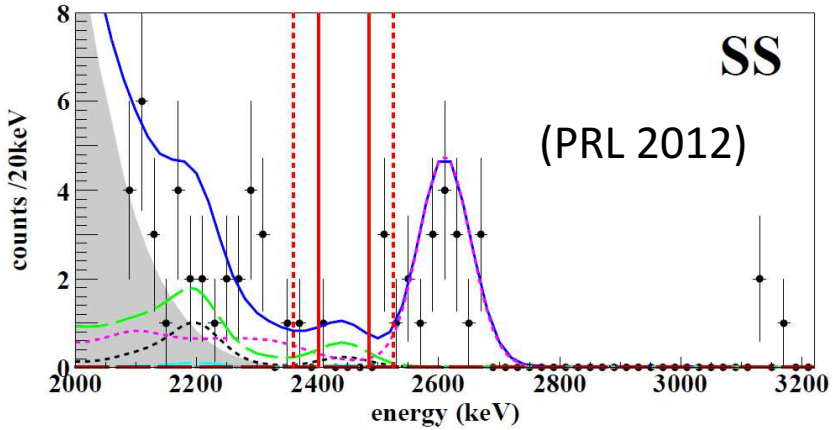
Self-tensioning charge collection wires



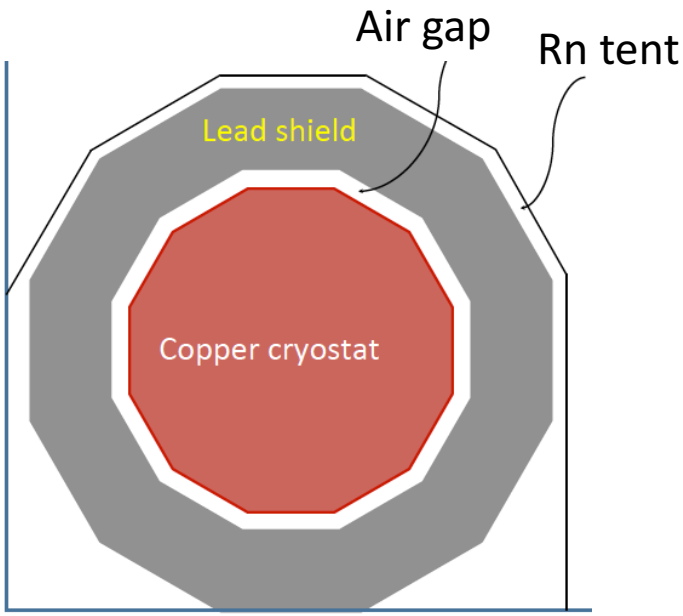


Chamber welded w/ E-beam

DeRadonator – Removing Rn222 from air



- Rn222 Air Gap
- Th232 Vessel
- U238 Vessel



DeRadonator (vacuum swing adsorption charcoal filter) can deliver 0.85 m^3/min of low Rn air

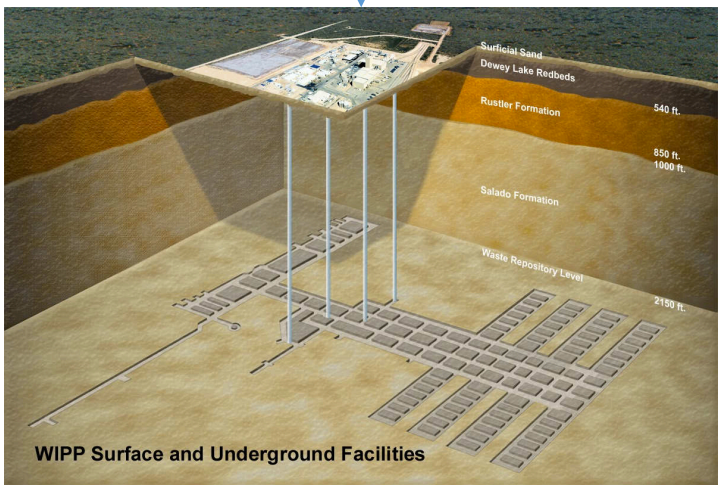
Measurements show that the Rn level in the air gap has been reduced by a factor >10, sufficient to suppress this background for $0\nu\beta\beta$ search.

Cosmic activation, building & shipping

- Copper shipped in concrete casket (2 m.w.e) by boat from Europe to Stanford
- TPC machined & assembled in ~7 m.w.e shielded CR (Stanford ESIII)
- TPC transported to WIPP in concrete casket (2 m.w.e) under N2 purge
  - A team of drivers made drive through elevation planned route
  - 36 hours from ESIII to U/G @ WIPP

Stanford, CA
ESIII ~ 7 m.w.e.

Carlsbad, NM
WIPP 1600 m.w.e.



Assay tools then and now

EXO-200

- ICPMS
  - NRC - Canada [1/1 ppt Th/U]
- GD-MS
  - NRC - Canada [10/10 ppt Th/U]
- Ge gamma spectroscopy
  - Alabama
  - Bern
  - SNOLab
- Neutron activation
  - Alabama [1/0.4 ppt Th/U]
- Rn emanation
  - Laurentian [~3 atoms/(m^2 d) ^{222}Rn]

nEXO (& still growing)

- ICPMS
  - IHEP – China [Commissioning]
  - PNNL [8/10 ppq Th/U]
  - CUP - S. Korea [Commissioning]
- GD-MS
  - NRC-Canada [10/10 ppt Th/U]
- Ge gamma spectroscopy
  - SNOLab [200/35 ppt Th/U]
  - SURF [Commissioning]
  - Alabama [300/100 ppt Th/U]
- Neutron activation
  - Alabama [1/0.4 ppt Th/U]
- Rn emanation
  - Laurentian [~3 atoms/m^2 d ^{222}Rn]
- Alpha counting
  - Alabama [~3 mBq/m^2 ^{210}Po]

Bern Ge moved to SNOLab for nEXO

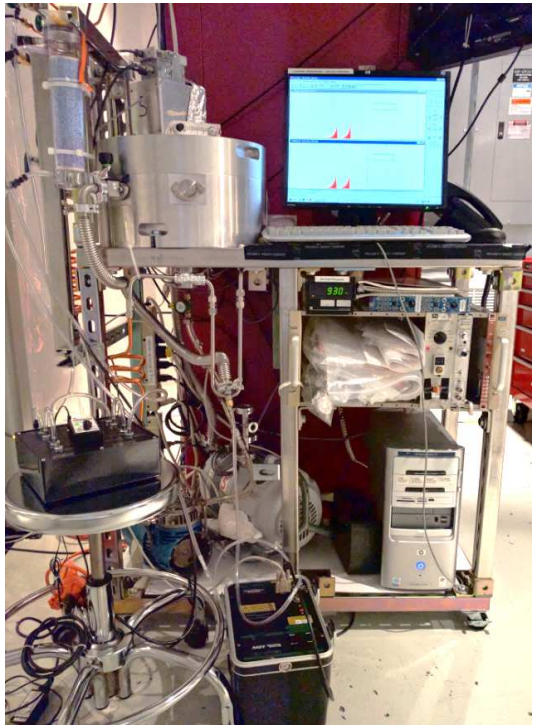
To keep the Bern detector as a nEXO resource, it was relocated to SNOLab in 2016.

Detector sensitivity is better thanks to larger overburden.

Rn emanation - Electro Static Chambers

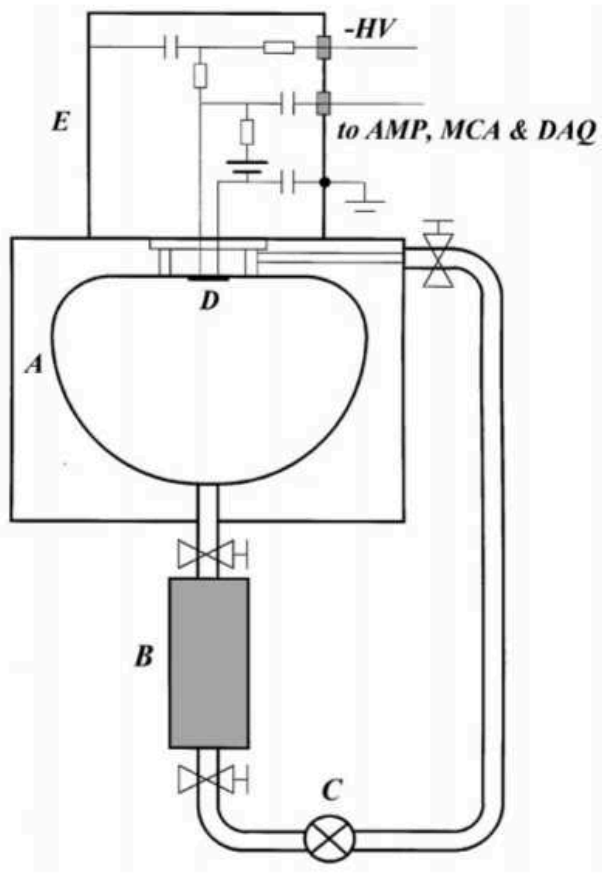
Operated by Laurentian University @ SNOLab surface lab

ESC's - purpose
6 – emanation
1 – RnTrap R&D
1 – RnTent monitoring and emanation @ WIPP



Basic layout of an Electro Static Counter

A. Drift Volume (~10 Liters)
B. Sample
C. Recirculation Pump
D. Si photo-diode (alpha detector)
E. Diode bias and readout circuit



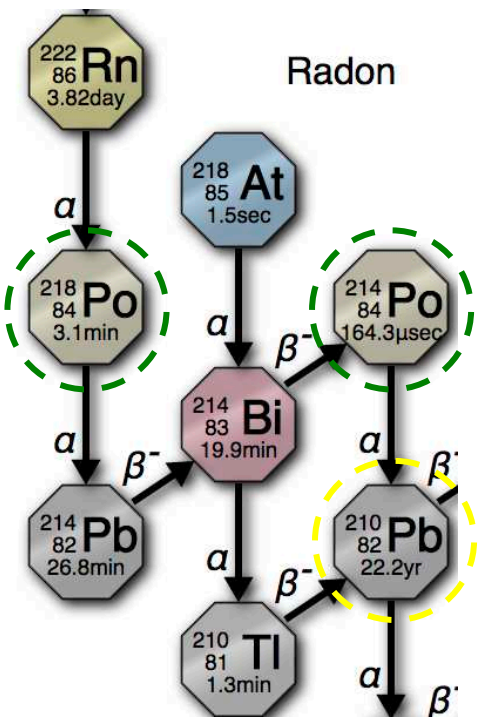
J.-X. Wang et al. / NIMA 421 (1999) 601-609

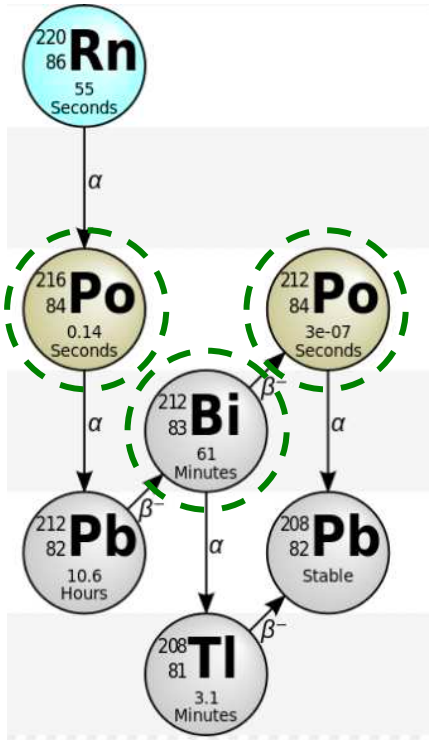
Chains with Rn measured by ESCs

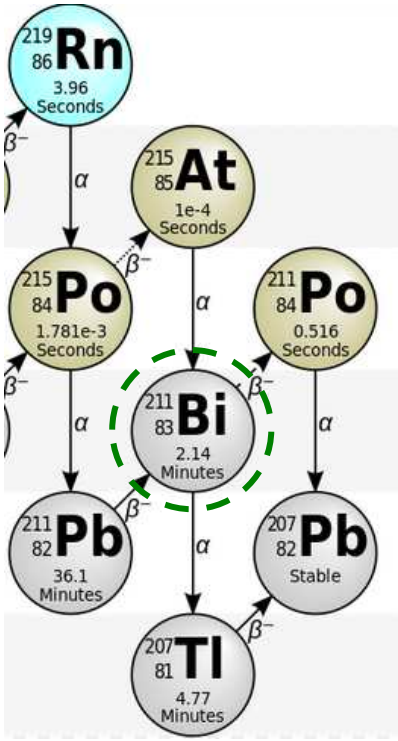
^{222}Rn – Uranium Chain
T12 = 3.8 days
Po218 @ 6.1 MeV
Po214 @ 7.8 MeV

^{220}Rn – Thorium Chain
T12 = 55 sec
Po216 @ 6.9 MeV
Po212 @ 9.0 MeV

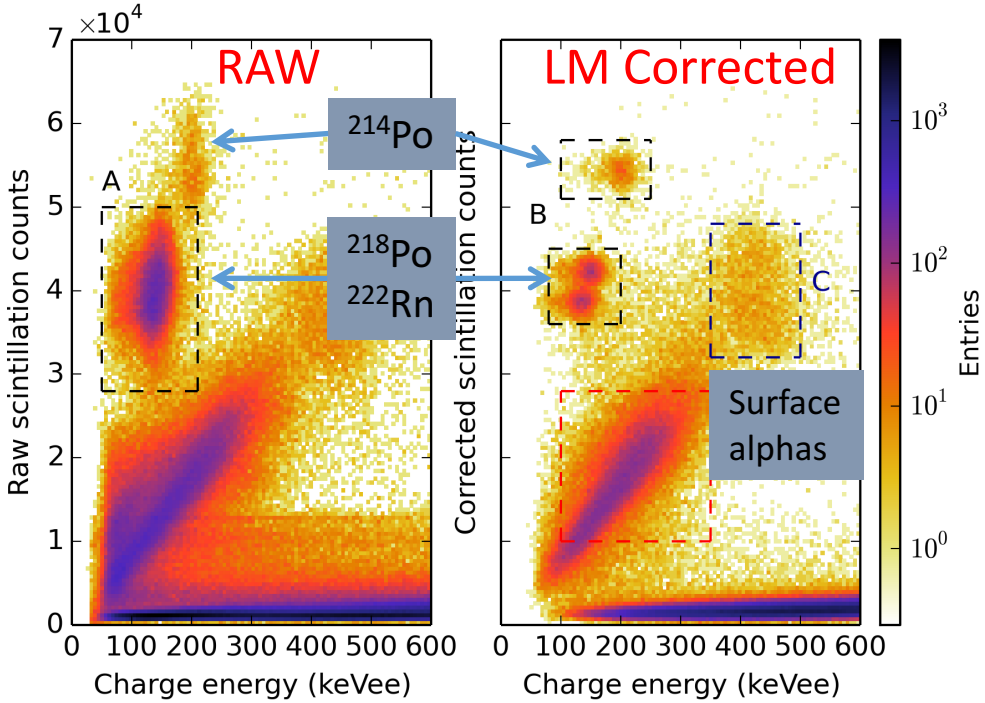
^{219}Rn – Actinium Chain
T12 = 4 sec
Bi211 @ 6.6,6.3 MeV

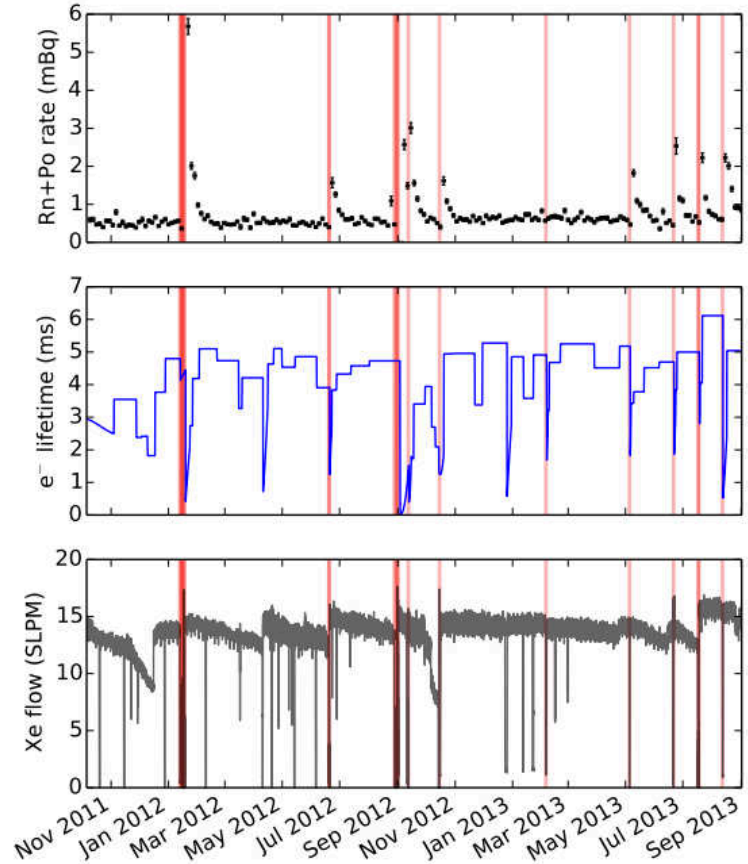


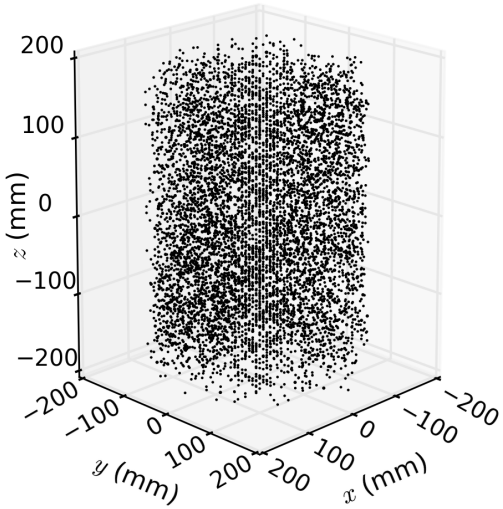


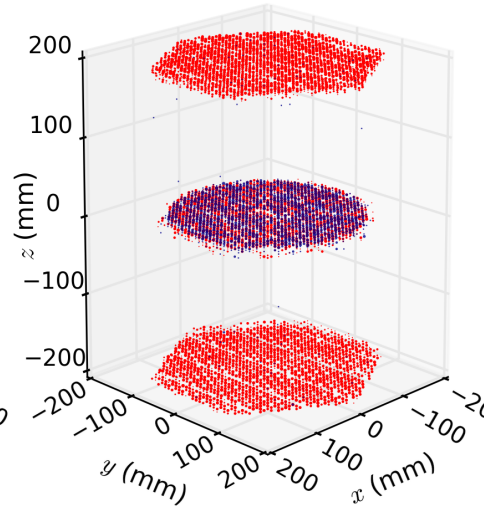


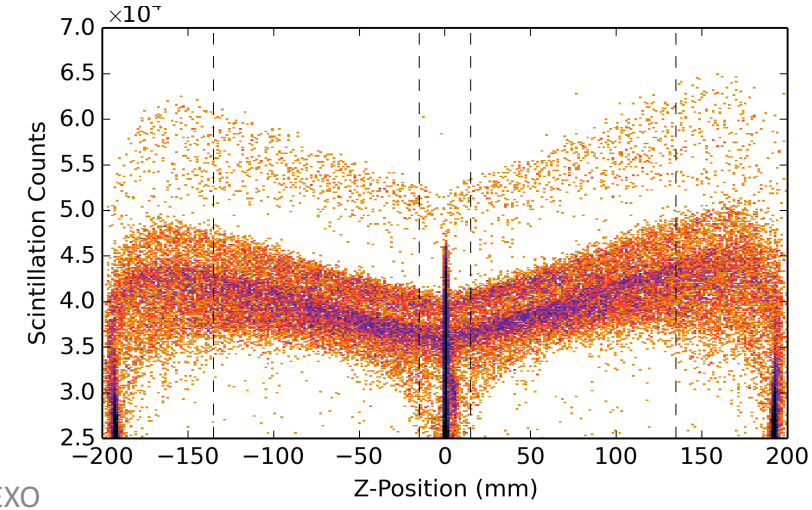
Rn in EXO-200


RAW
LM Corrected
^{214}Po
^{218}Po
^{222}Rn
Surface alphas
A
B
C
Raw scintillation counts
Corrected scintillation counts
Charge energy (keVee)
Entries

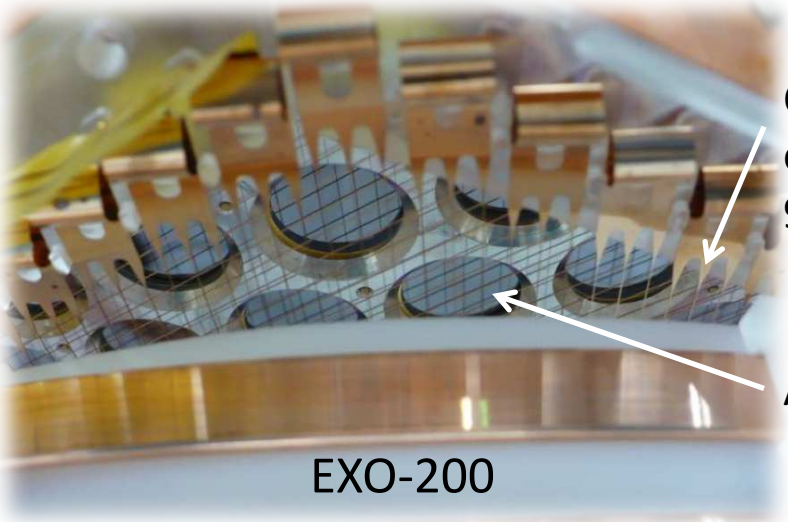

Rn+Po rate (mBq)
e⁻ lifetime (ms)
Xe flow (SLPM)
Nov 2011
Jan 2012
Mar 2012
May 2012
Jul 2012
Sep 2012
Nov 2012
Jan 2013
Mar 2013
May 2013
Jul 2013
Sep 2013

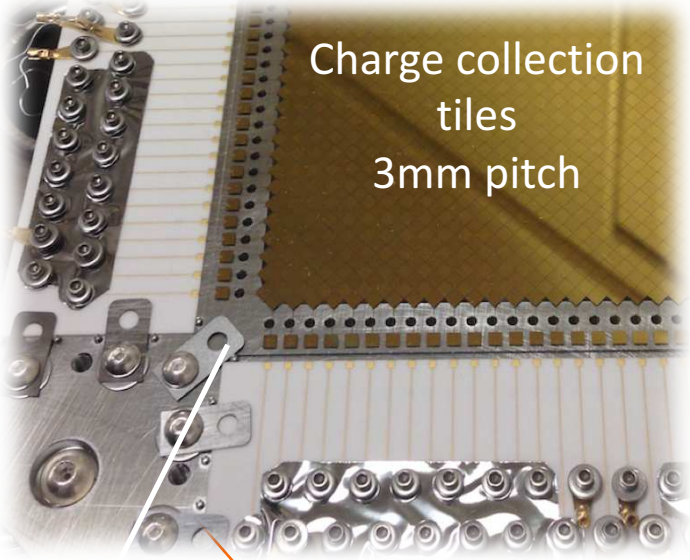

z (mm)
y (mm)
x (mm)

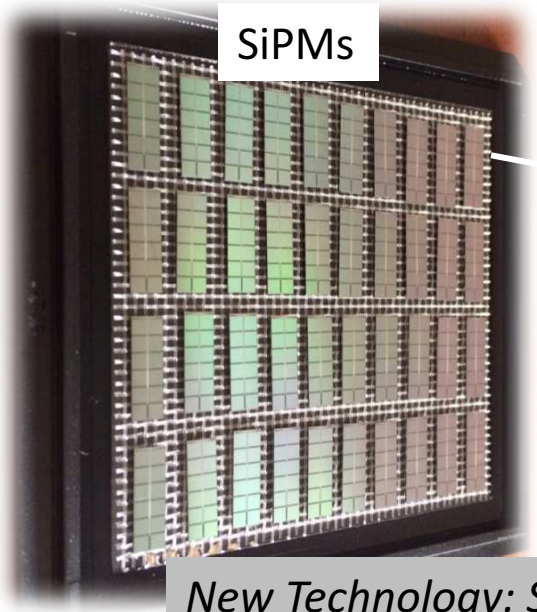

z (mm)
y (mm)
x (mm)

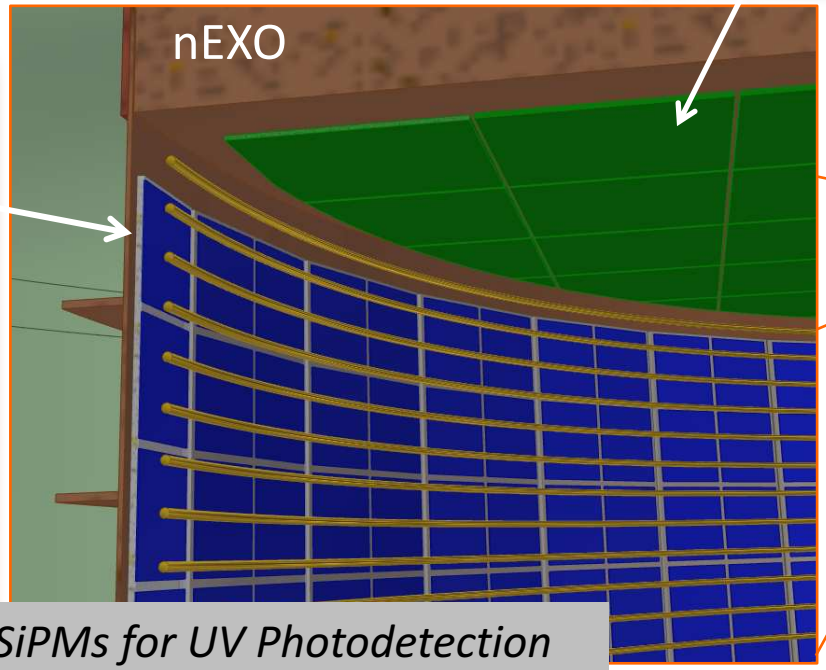

Scintillation Counts
Z-Position (mm)

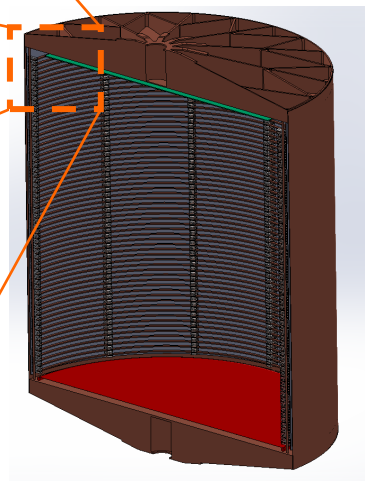
Background rejection and energy resolution (nEXO R&D)





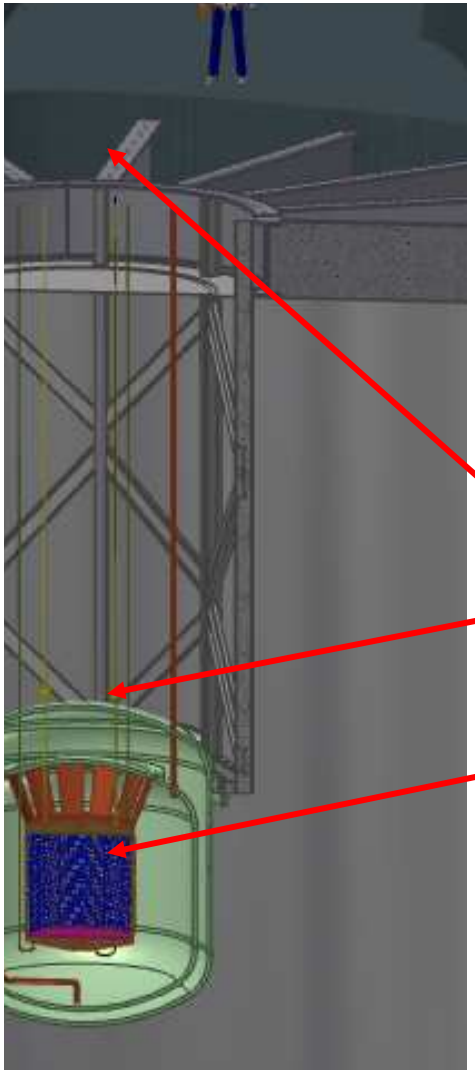






New Technology: SiPMs for UV Photodetection
Igor Ostrovskiy (Tomorrow)

nEXO energy resolution: cold electronics



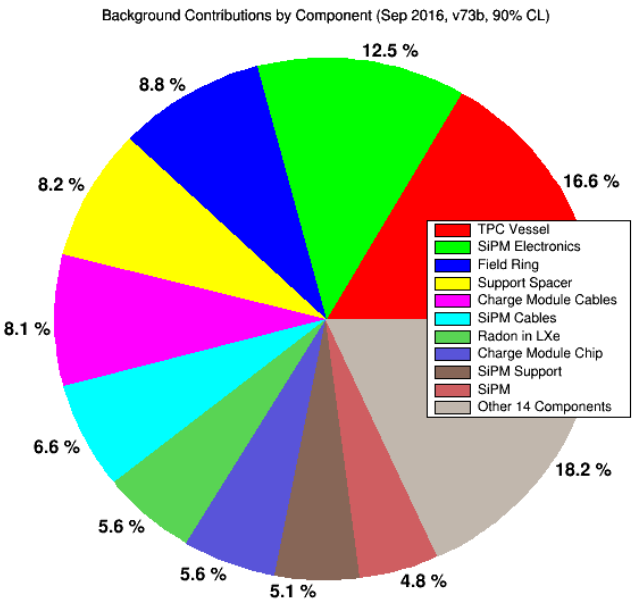
Comparison for noise and threshold between front-end locations for the charge channel

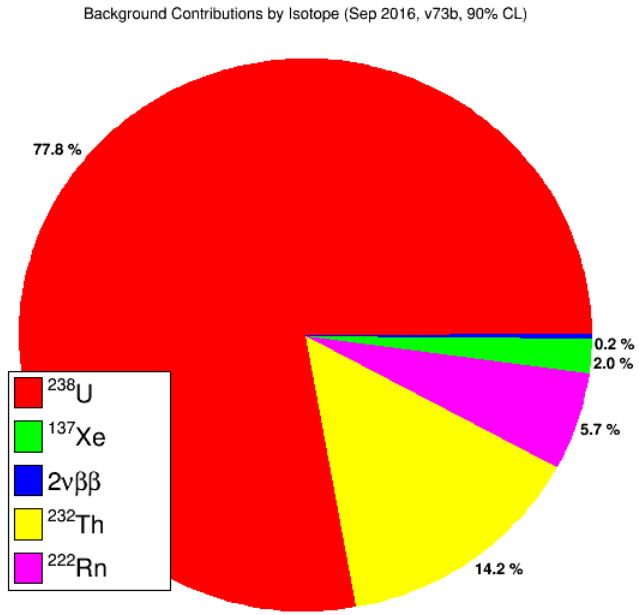
Location	Cable length (m)	Total cap (pF)	Intrinsic RMS Noise (e)	RMS contribution to charge energy resolution	Charge cluster threshold (keV)
In lab (warm)	8	800	3200	2.5%	600 keV
At cryostat (warm/cold)	2	200	800	0.6%	150 keV
Inside TPC (cold)	~0	<40	<200	0.2%	40 keV

Assumes simple tile charge collection system with interleaved strips and EXO-200 style cables for the remote location cases

Cold electronics new challenge for low BG experiments

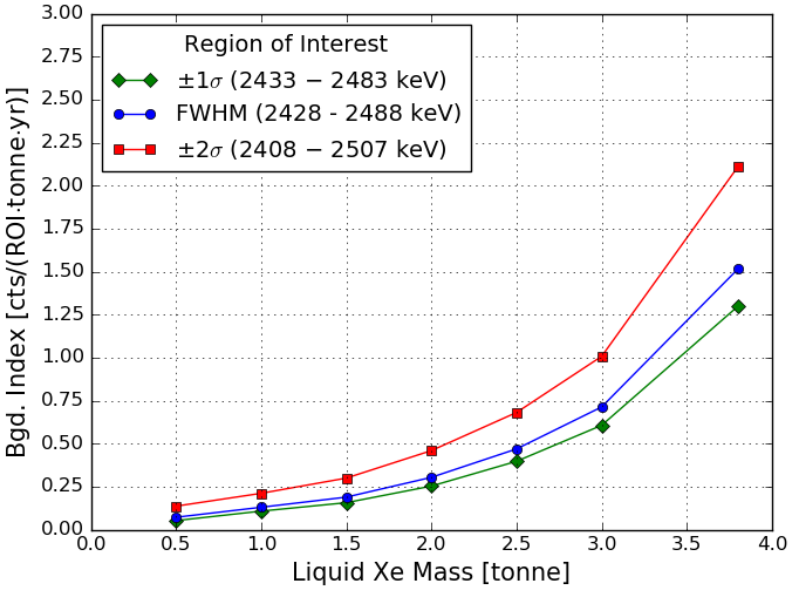
nEXO background budgets (90% U.L.)





3860 kg fiducial Xe
90% enrichment
90% background rejection
82% signal efficiency
1% σE/E resolution

- Background contributions in FWHM of inner 3 tons
  - Bgd index = 0.7 cts/ROI/t/yr
- Based on assays of currently available materials
  - R&D to focus on finding lower BG materials
- The innermost region of the detector is almost background free
  - Bgd index = 0.12 cts/ROI/t/yr
- Measure backgrounds with outer volumes, fit uses 3D information optimally



EXO copper

R&D on (and later qualification of) low background materials is in full swing for nEXO…

A note on the copper that is the dominant background from the TPC vessel:

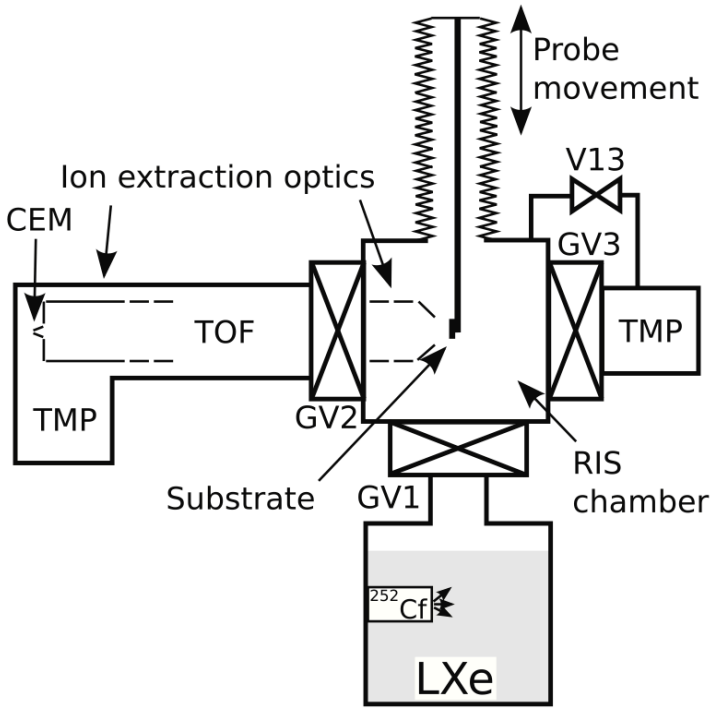
	~U, Th (ppt)
EXO-200 ICPMS measurement (Aurubis copper)	< 6, <14
EXO-200 measurement (Aurubis process)	< 4
nEXO measurement of Aurubis copper	< 1
PNNL measurement of electroformed Cu	~ 0.01

Study in progress of the Aurubis process seems to indicate that 0.1 ppt may very well be already achieved.

nEXO Ba tagging R&D (--> B.G. free?)

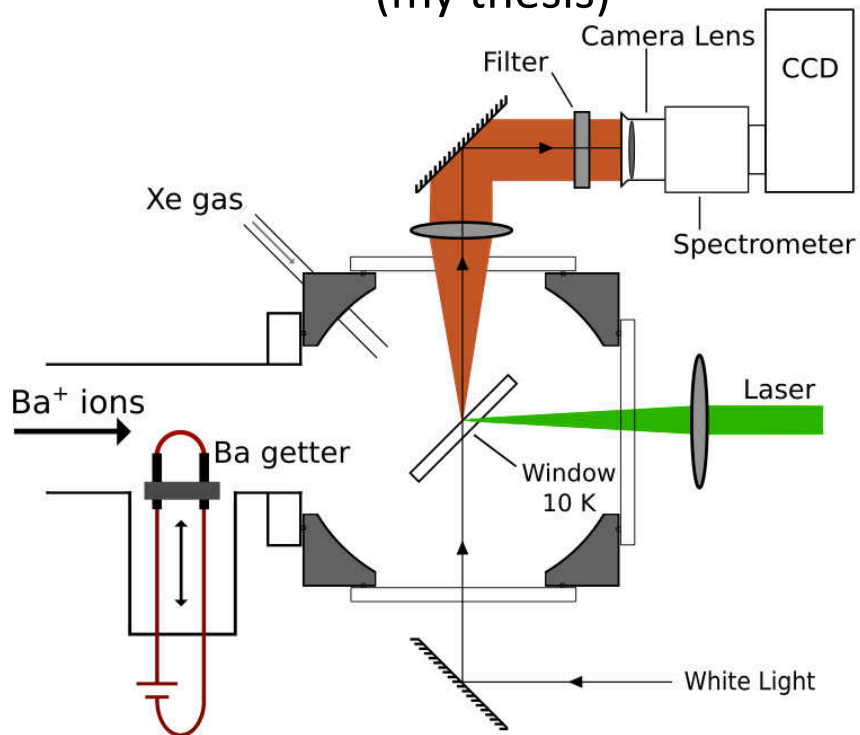
- Trigger on ionization/scintillation
- In real time estimate if 0v candidate
- Insert probe and electrostatically attract Ba-ion (or freeze it)
- Several detection methods being explored:

Remove → desorb → RIS → CEM



Rev Sci Inst 85 (2014) 095114

Spectroscopy in SXe matrix
(my thesis)



Phys Rev A 91 (2015) 022505

Enriched Xenon Observatory
for double beta decay

The EXO-200 Collaboration

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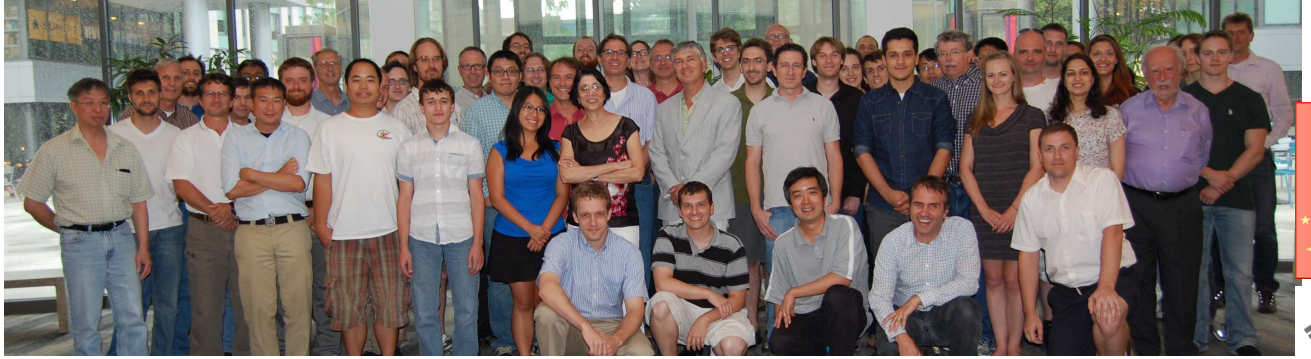
The nEXO Collaboration



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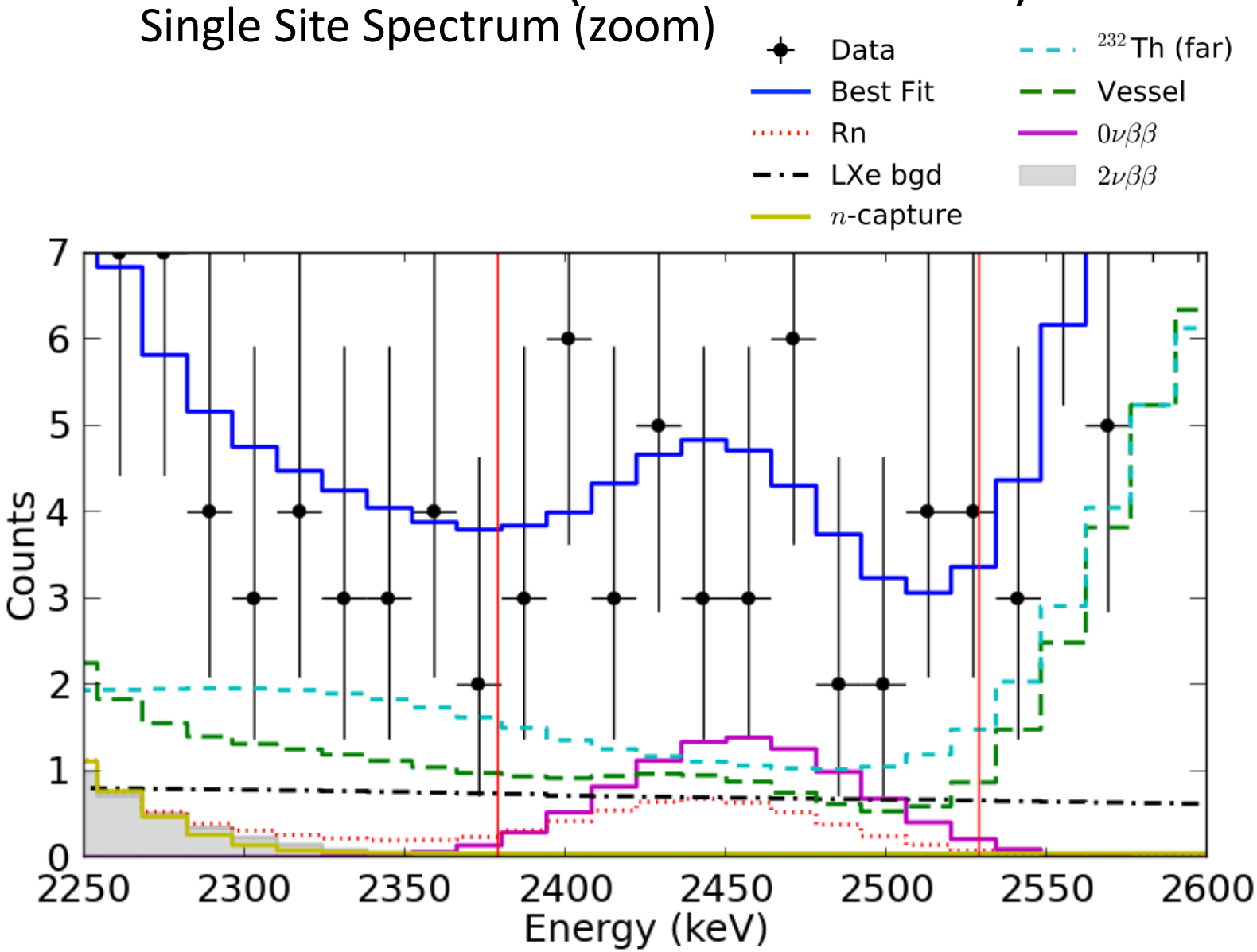
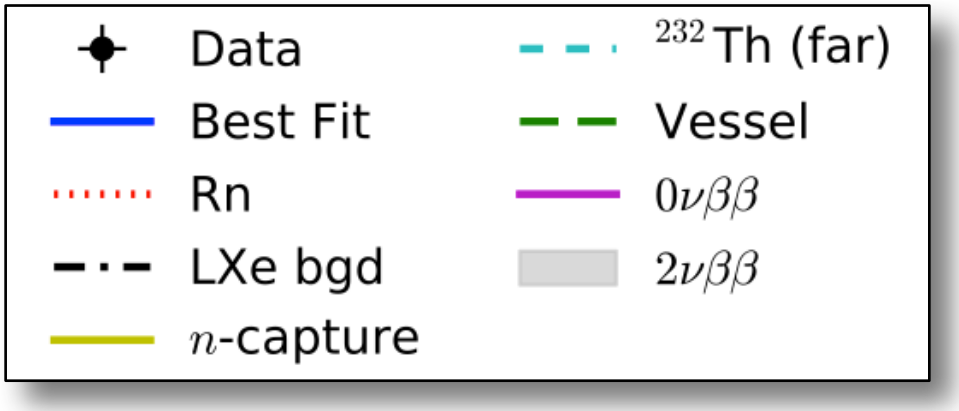
NLDBD Fit Results (Nature 2014)

Single Site Spectrum (zoom)



Fitting PDFs

- Vessel (All Cu components inside cryostat)
  - ^{60}Co, ^{40}K, ^{232}Th, ^{238}U, ^{65}Zn
- Rn
  - ^{214}Bi – cathode
  - ^{222}Rn – Active LXe
  - ^{214}Bi – Air Gap
  - ^{222}Rn – Inactive LXe
- LXe bgd
  - ^{135}Xe, ^{137}Xe
- n-capture
  - ^{1}H – HFE
  - ^{63,65}Cu – Vessel, InnerCryo, OuterCryo
  - ^{136}Xe – LXe



Optimization from EXO-200 to the nEXO scale

What	Why
~30x volume/mass	To give sensitivity to the inverted hierarchy
No cathode in the middle	Larger low background volume/no ^{214}Bi in the middle
6x HV for the same field	Larger detector and one drift cell
>3x electron lifetime	Larger detector and one drift cell
Better photodetector coverage	Energy resolution
SiPM instead of APDs	Higher gain, lower bias, lighter, E resolution
In LXe electronics	Lower noise, more stable, fewer cables/feedthroughs, E resolution, lower threshold for Compton ID
Lower outgassing components	Longer electron lifetime
Different calibration methods	Very “deep” detector (by design)
Deeper site	Less cosmogenic activation
Larger vessels	5 ton detector and more shielding

The mine is sometimes the challenge…

Feb 5, 2014 – Haul truck fire

Feb 14, 2014 – Rad event

Recovery

- Feb 18, 2014: begin remote recovery of LXe
- Sept 2014–June 2015: Clean up drift, TPC health checks
- June – Oct 2015: Equipment repair and maintenance

Phase-II Restart

- Oct 2015 – Jan 2016: system cooldown, gas purification, LXe filling
- Feb – April 2016: Detector electronics upgrades
- April 2016: Phase-II data taking begins

Background mitigation methods

- Experimental design
  - Large volumes of HFE/xenon
  - Low mass vessel
  - Only screened materials inside lead with budget
  - Underground with muon veto
  - Material choices for insitu activation
- Material screening
  - ICP-MS
  - GD-MS
  - Germanium gamma counting
  - Neutron activation
  - Rn emanation
- Clean material manufacturing & handling
  - Through surface cleaning procedure w/ acid etch
  - Materials storage w/ N2 purge (low Rn)
  - e-beam welding –or - ceriated welding rods for conventional welds
  - Working with manufacturers
- Operations
  - Radon exclusion with DeRadonator
  - RnTrap R&D