Observation of $2\nu\beta\beta$ in ^{136}Xe with EXO-200

Jesse Wodin for the EXO collaboration

International workshop on double beta decay and neutrinos
Osaka, November 2011

Overview of the EXO experiment

- EXO-200 (first phase)
  - 200 kg enriched ^{136}LXe (80%)TPC
  - Currently operating (as of early 2011) underground
  - Probe Majorana m_ν ~ 100 meV scale
  - Confirm or refute KKDC result
  - Demonstrate feasibility of ton-scale xenon experiment
- "Full-EXO" (second phase)
  - 1-10 ton-scale enriched ^{136}Xe $0\nu\beta\beta$ experiment
  - Probe Majorana m_ν ~ 5-20 meV scale
  - R&D effort for "Ba-tagging" of $0\nu\beta\beta$ daughter nucleus as a means of radioactive background rejection

Advantages of Xenon

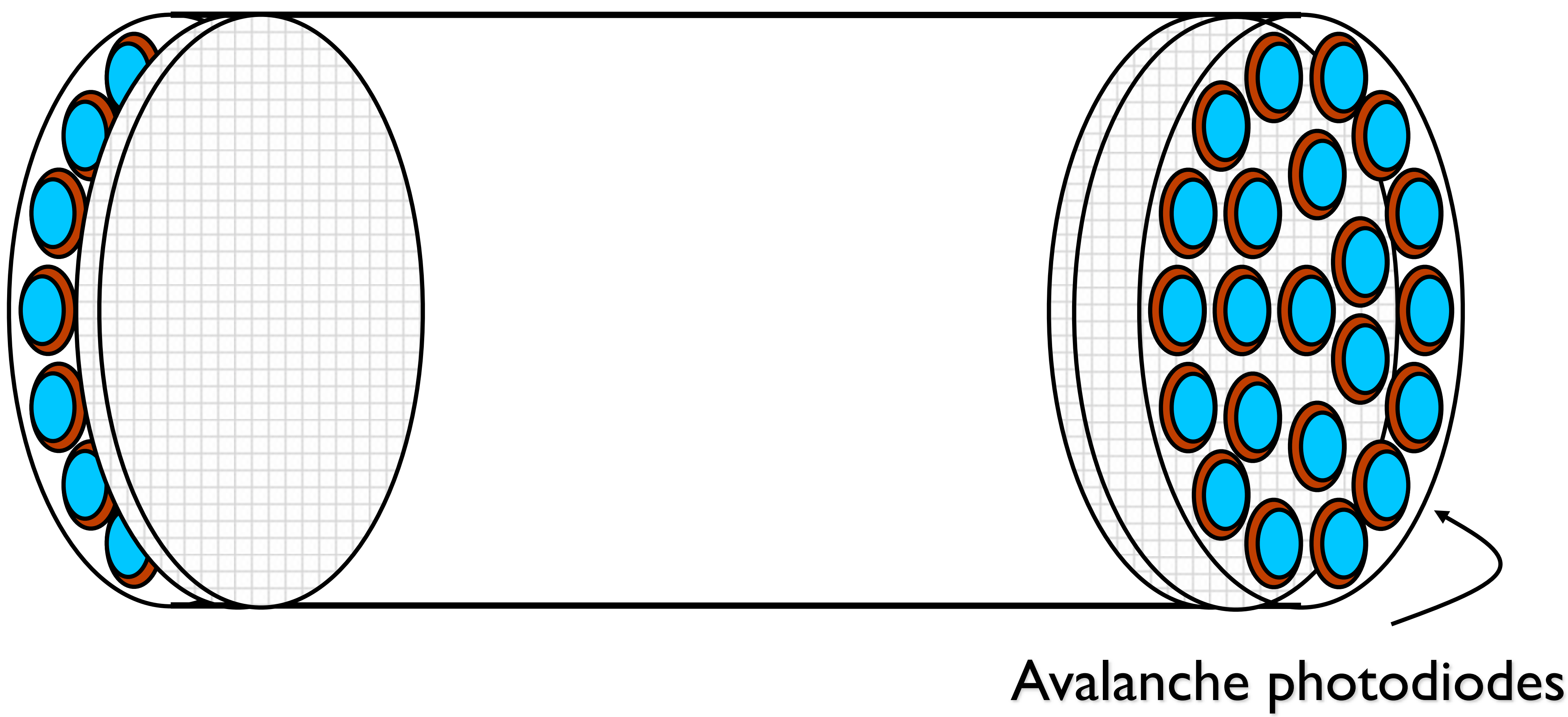
- No need to grow crystals
- Can be re-purified during the experiment (noble gas, easy with commercially available systems)
- No long-lived Xe isotopes to activate
- Can be easily transferred from one detector to another if new technologies become available
- Ba tagging (identification of ^{136}Ba daughter nucleus)
- ^{136}Xe enrichment
  - World production of Xe ~ 40 ton/yr
  - Noble gas: easy(er) to enrich
  - Centrifugal process very efficient (feed rate in g/sec, efficiency ~ $\Delta m = 4.7$ amu)

Measuring 0νββ with EXO-200

e^- Ionization electrons

Xe$^+$ and Xe*

^{136}Ba$^+$



Measuring $0\nu\beta\beta$ with EXO-200

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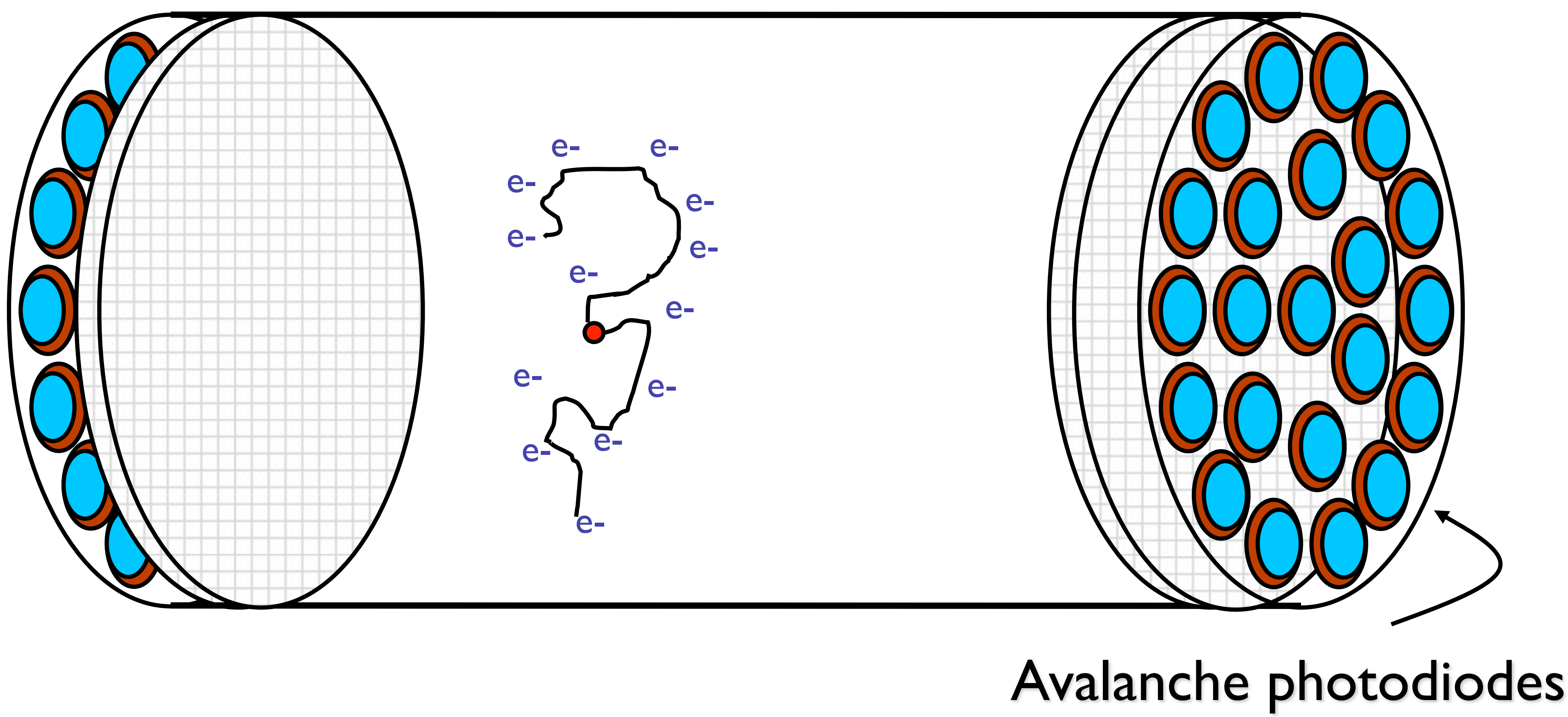

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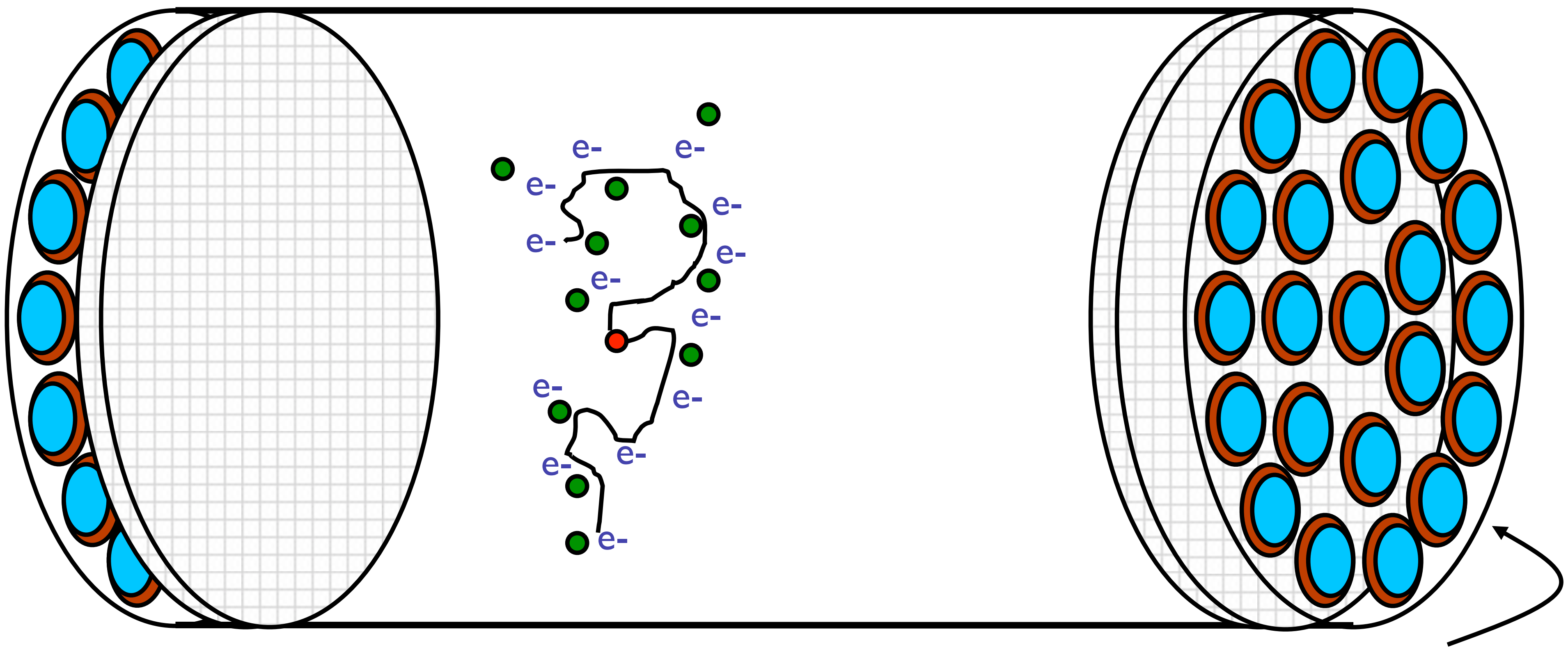
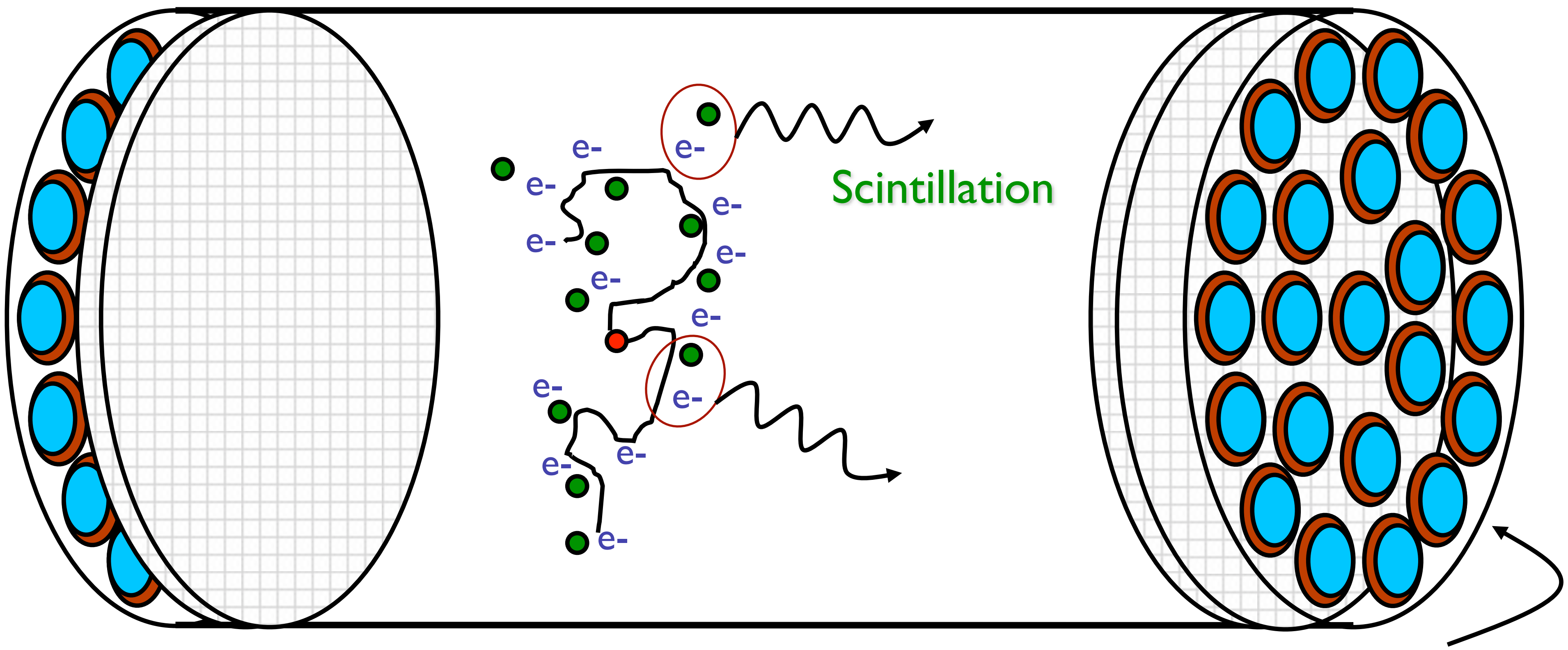


Avalanche photodiodes

Measuring $0\nu\beta\beta$ with EXO-200

e^-	Ionization electrons
●	Xe^+ and Xe^*
●	$^{136}Ba^+$



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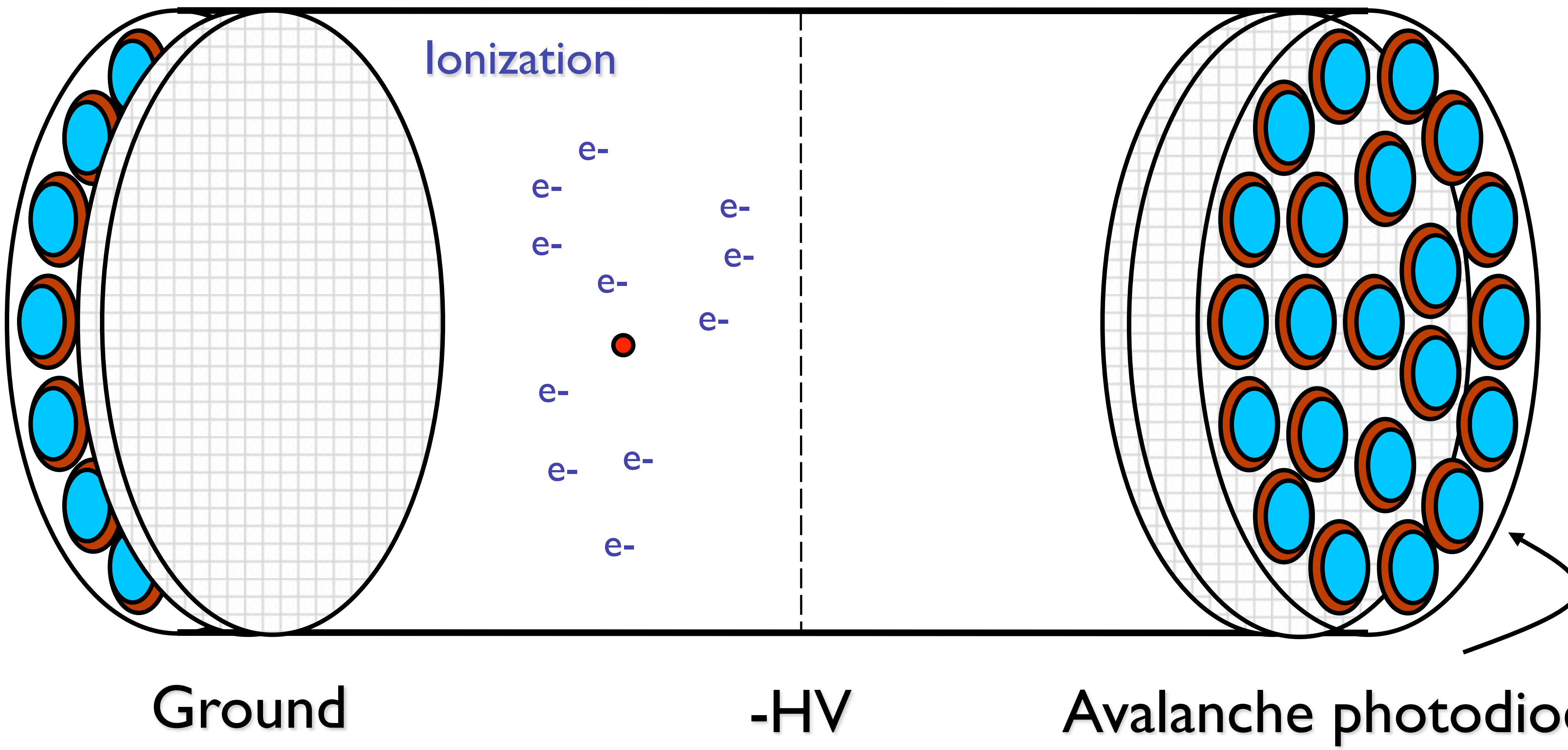
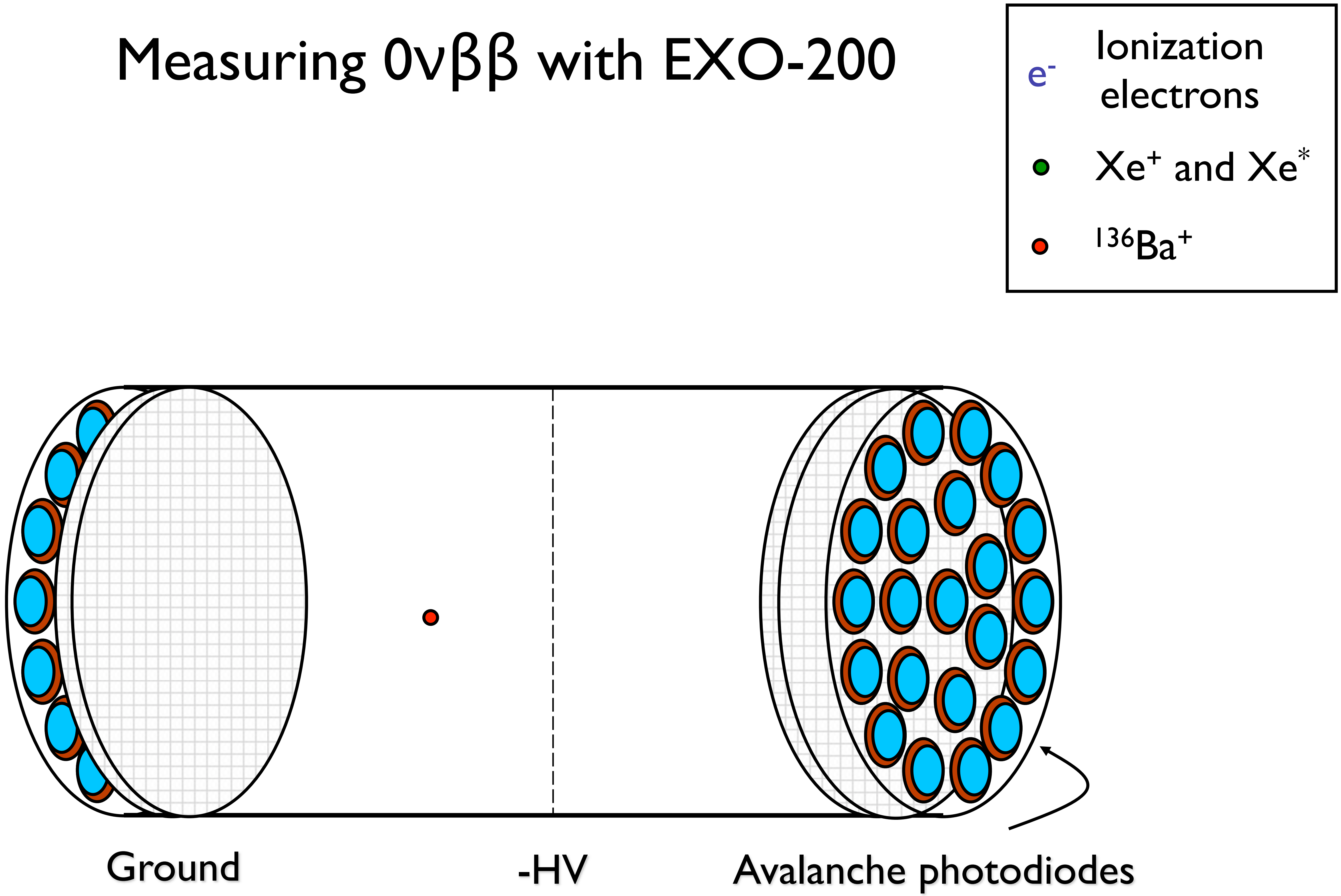


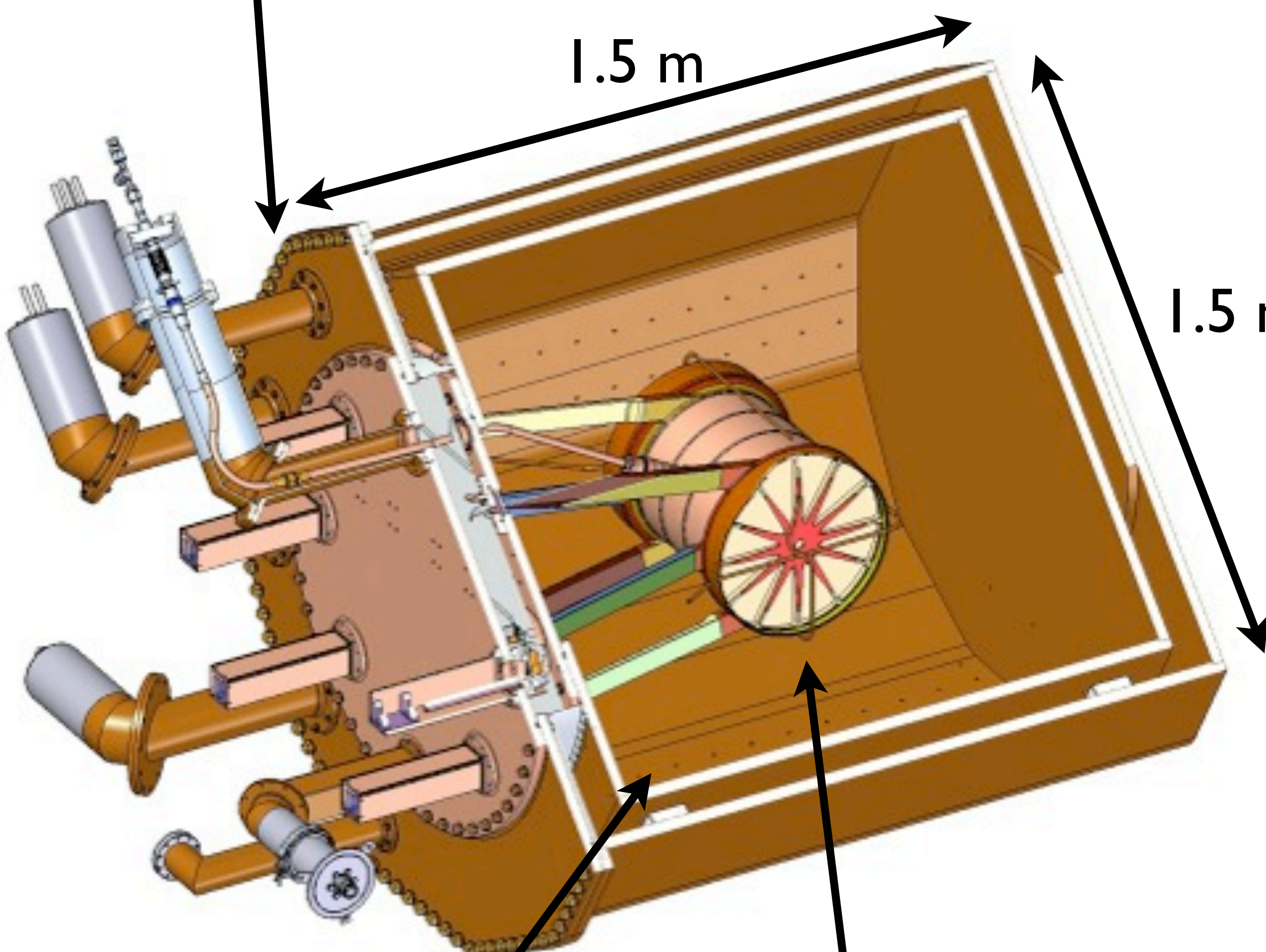
Measuring 0νββ with EXO-200

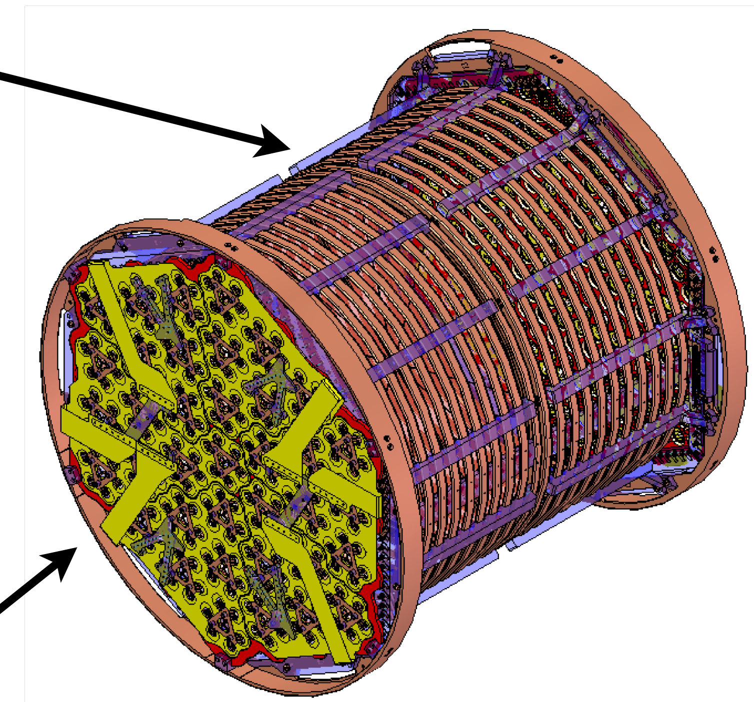


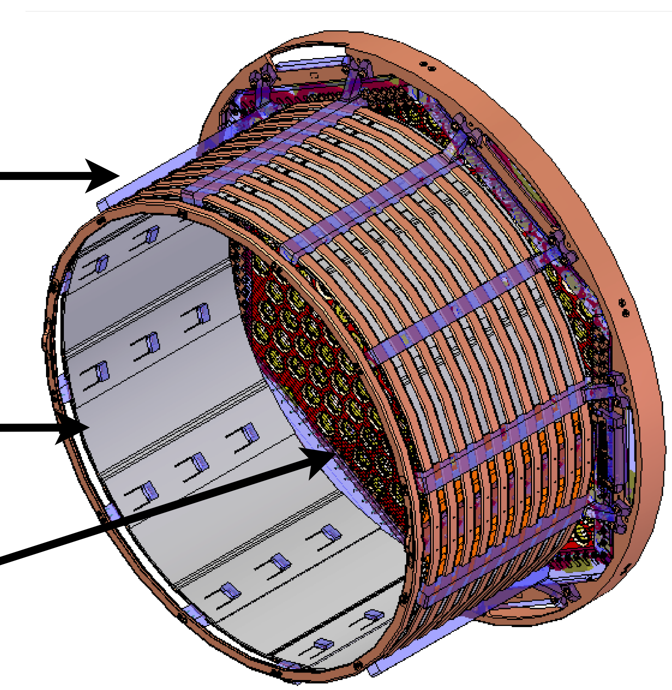
EXO-200 details

- 175 kg ^{136}Xe at 80.6% enrichment, liquid phase (167±0.1 K), both source and detector of $0\nu\beta\beta$
- Continuous Xe purification
- 468 Avalanche Photodiodes (LAAPDs) for scintillation light detection (ganged in groups of 7x, 67 total channels)
- 38/38 crossed U/V wire channels per side of TPC for ionization charge detection, 9 mm spacing (152 ch. total)
- Source calibration system allows for multiple miniaturized sources spanning wide energy range at different positions around TPC
- U/V charge signals and relative timing between charge and light give x,y,z event position, energy, PID, etc.
- Sited 2150' (1600 mwe) underground for shielding
- Muon veto system surrounding cleanrooms (~96% efficiency for μ traversing Pb)
- TPC surrounded by 50 cm (4 tonnes) HFE7000 cryo/shielding fluid (1.8 g/cm3), 2x 5cm low-activity Cu cryostats, 25 cm Pb
- Extensive program on radiopurity
    - All materials screened for low U/Th/K content
    - Thin walled (~ 1.4 mm) Cu TPC for radio-purity

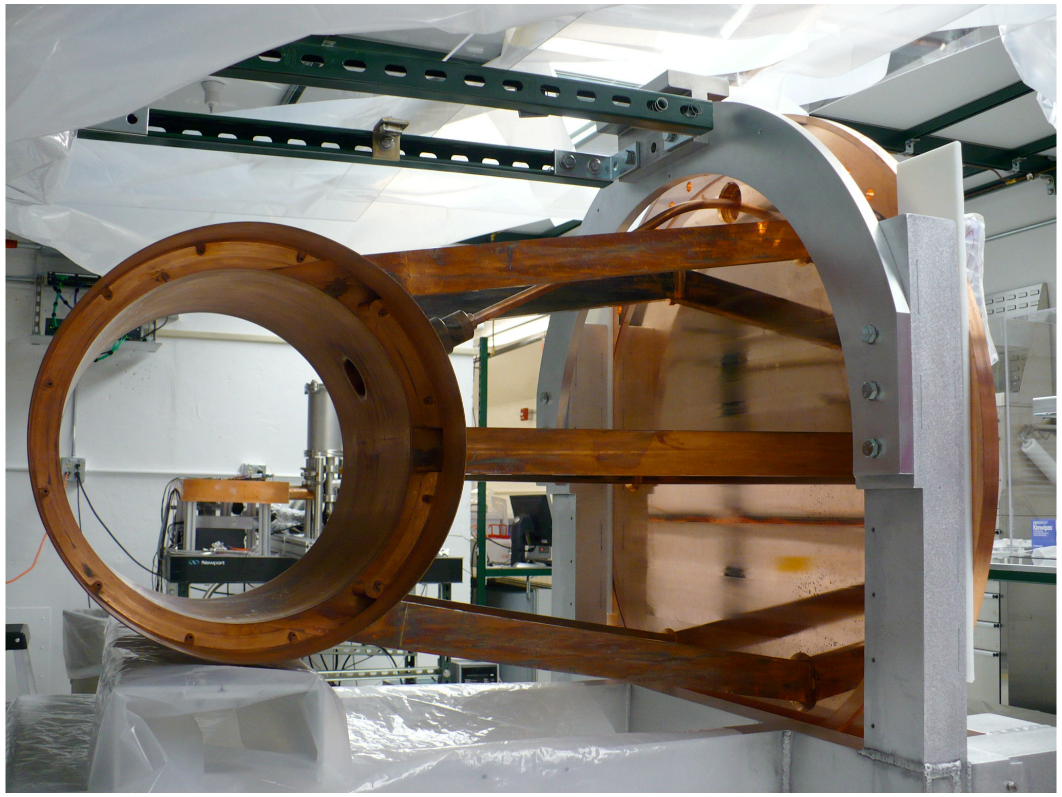
EXO-200 cryostat and TPC



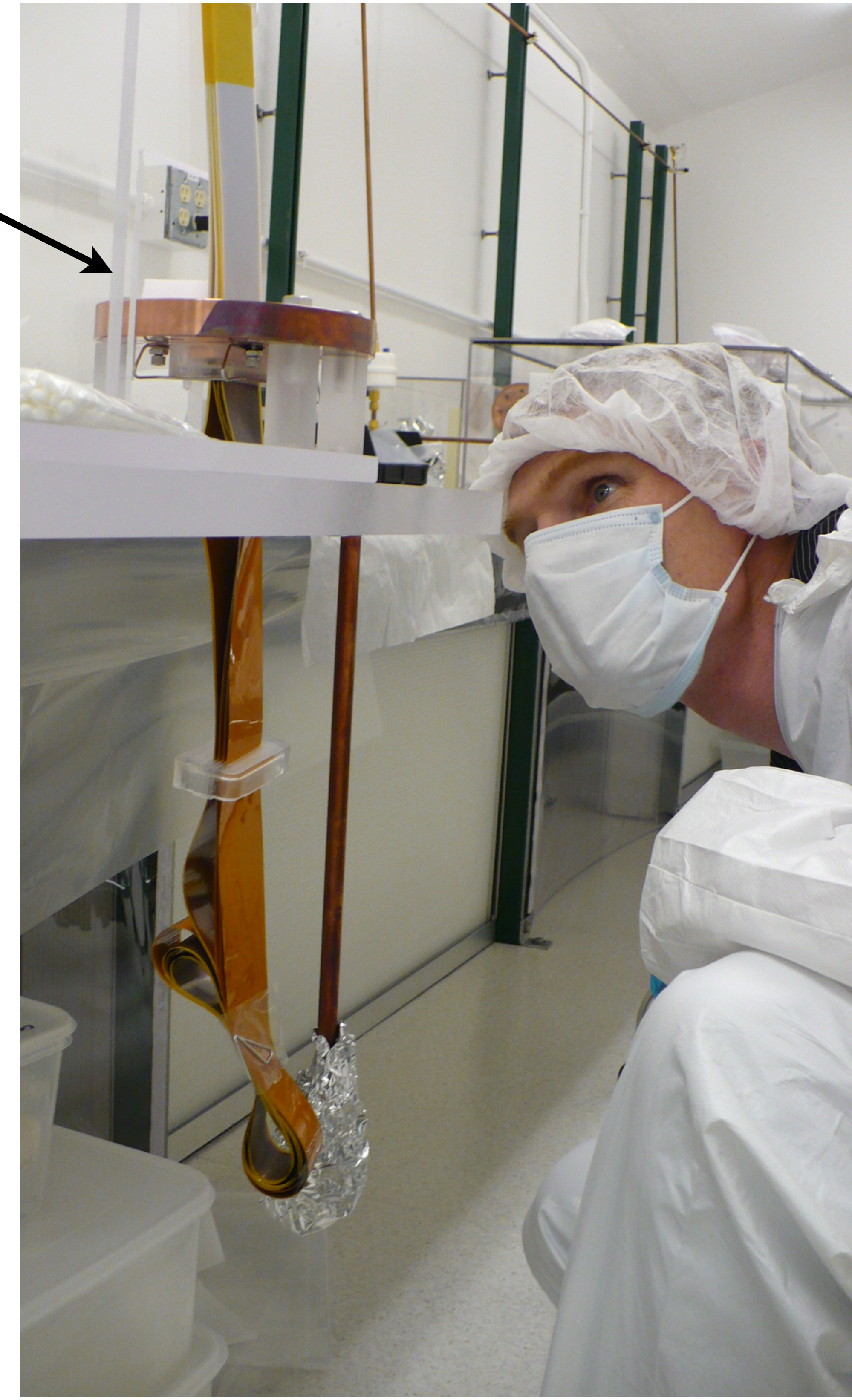




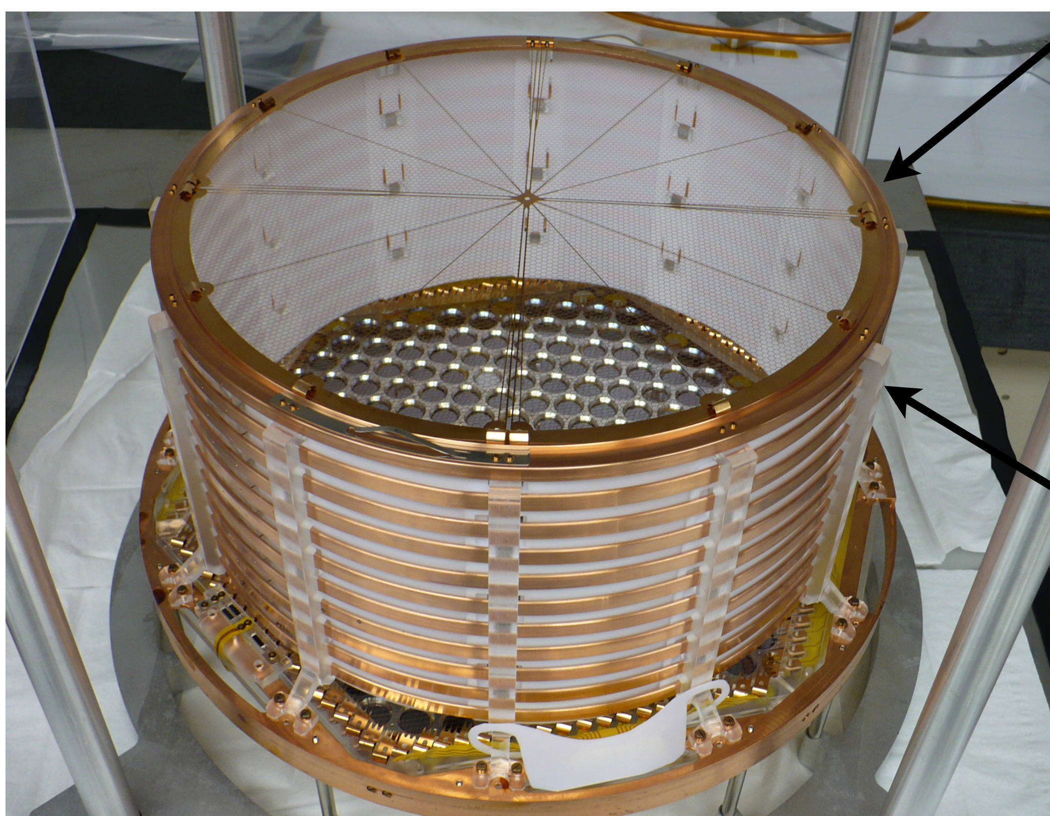
EXO-200 TPC construction



Signal cabling penetrates TPC and cryostat (no "feedthroughs")

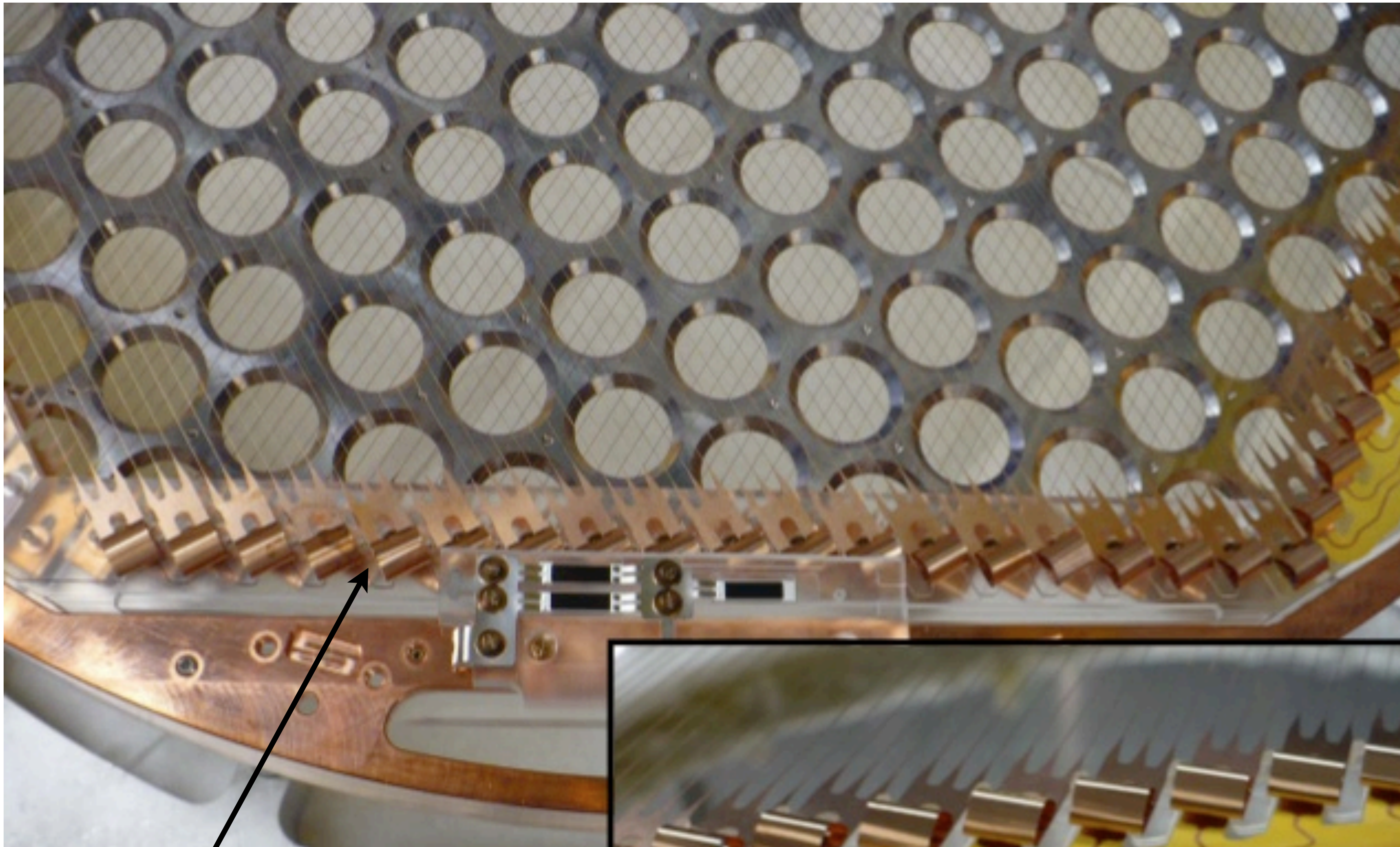


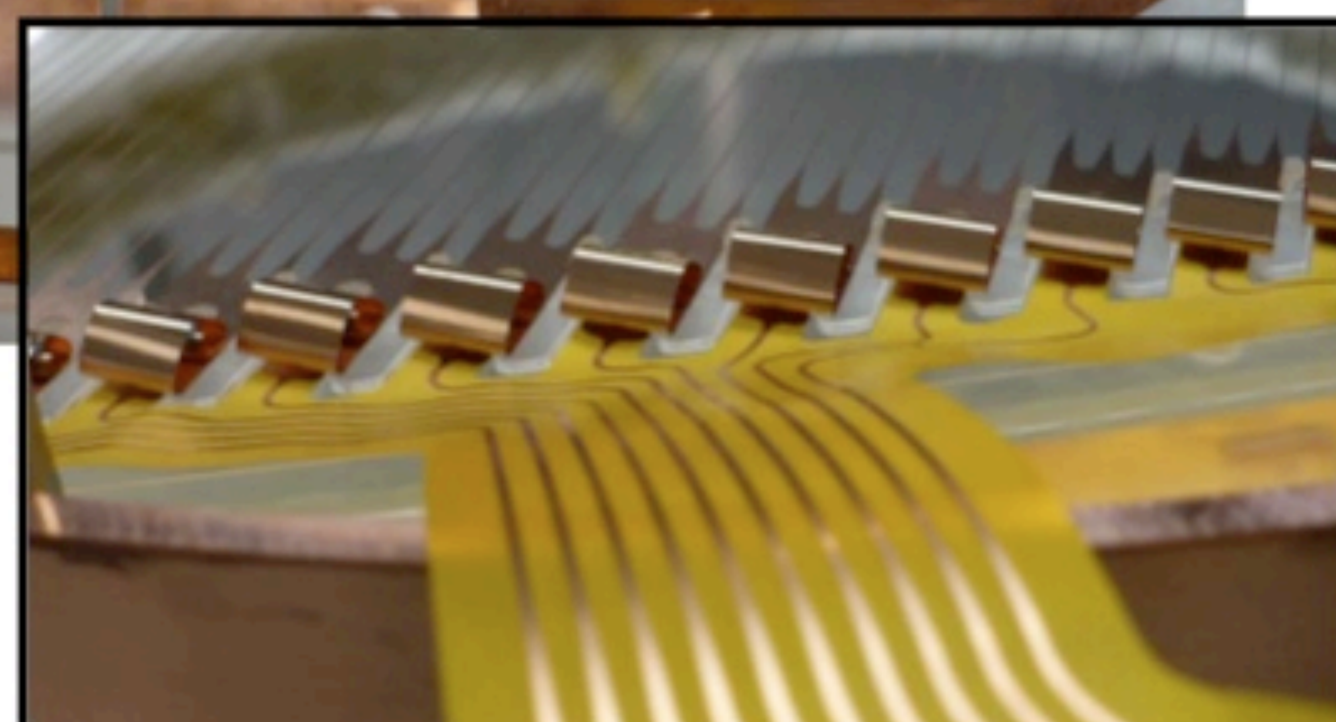
Cathode



Field shaping rings

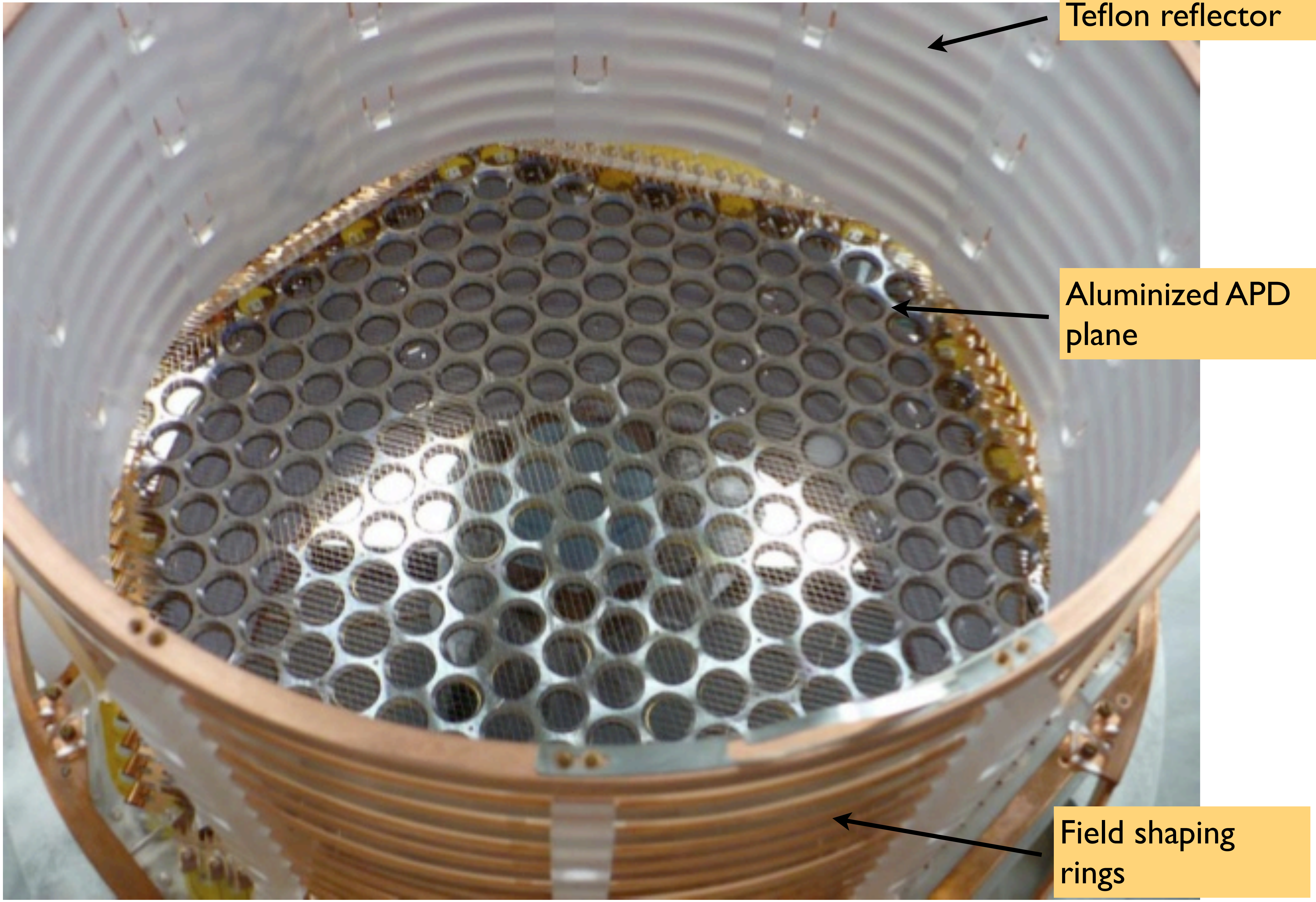
EXO-200 TPC construction





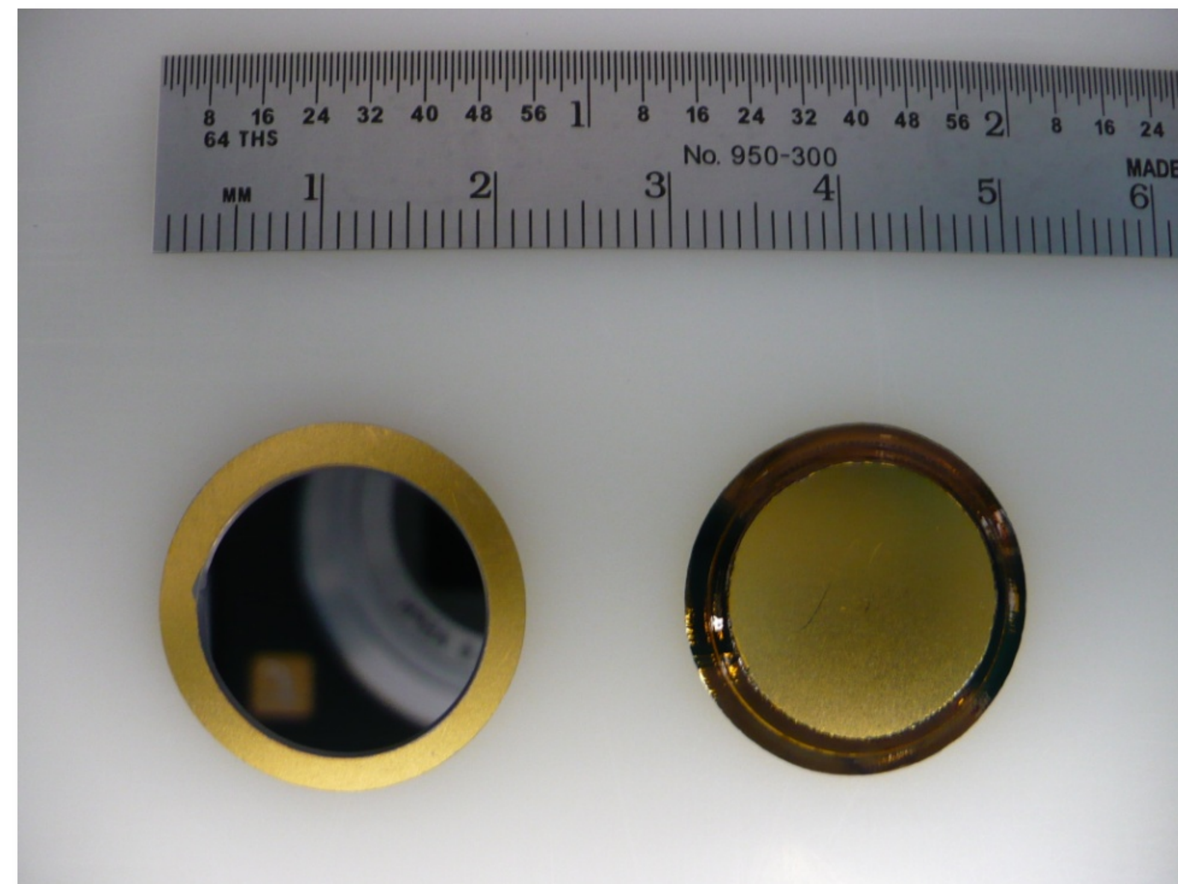
Photoetched phosphor bronze U/V wires (9 mm spacing)

EXO-200 TPC construction



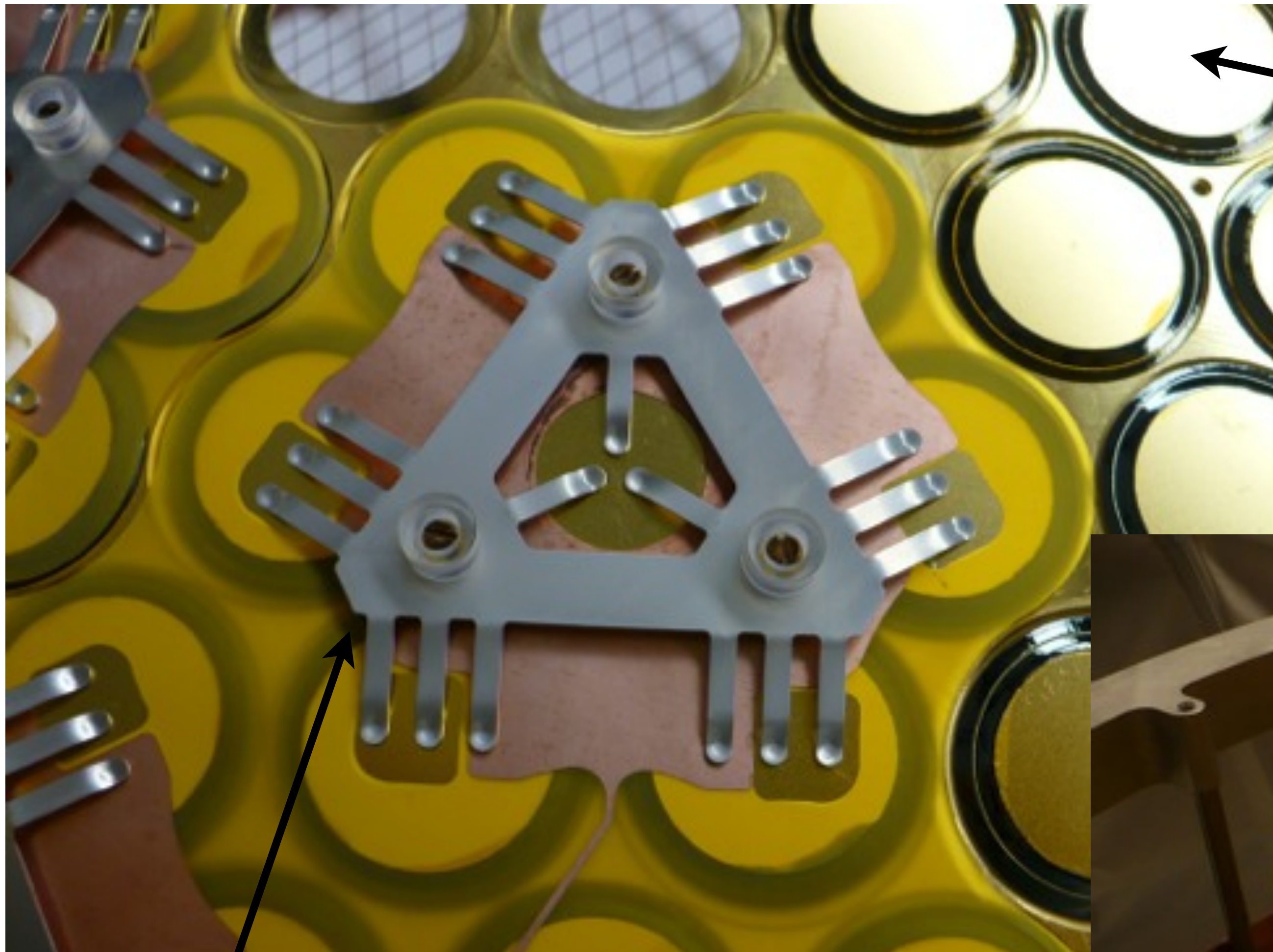
Large Area Avalanche photodiodes

- Company: Advanced Photonix
- Low radioactivity construction (used bare, no window, no ceramic, EXO-supplied chemicals and metals*)
- Mass ~ 0.5 g/LAAPD
- ϕ16mm active diameter per LAAPD
- PE yield per photon >1 at 175 nm (NIST)
- Capacitance ~ 200 pF at 1400 V
- V ~ 1500 V, Gain ~ 200
- ΔV < +/- 0.5 V
- ΔT < +/- 0.1K (driver for system temperature stability)
- Leakage current of array < 1μA

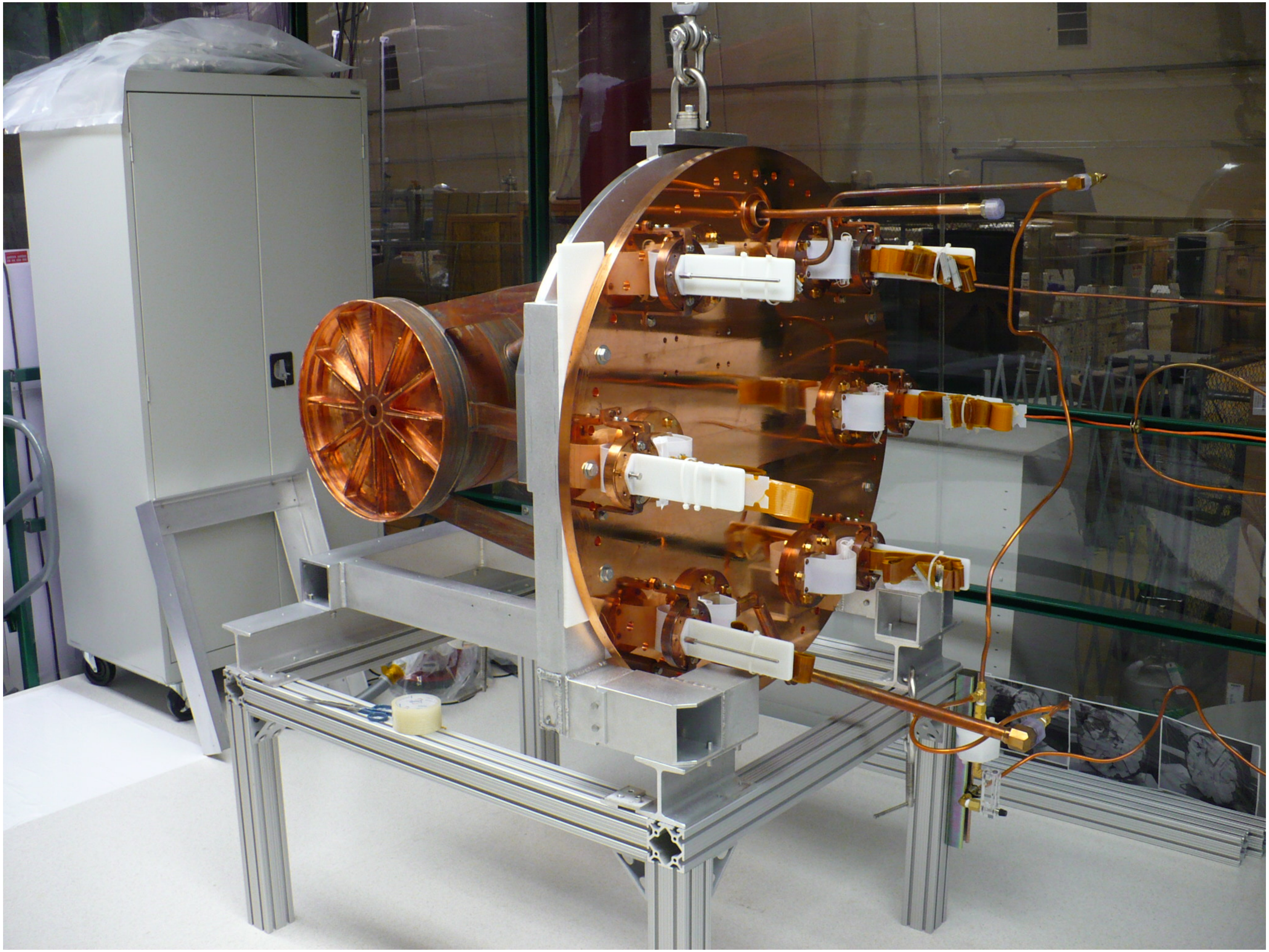


* Nielson, R. et al., NIM A 608, 1 (2009)

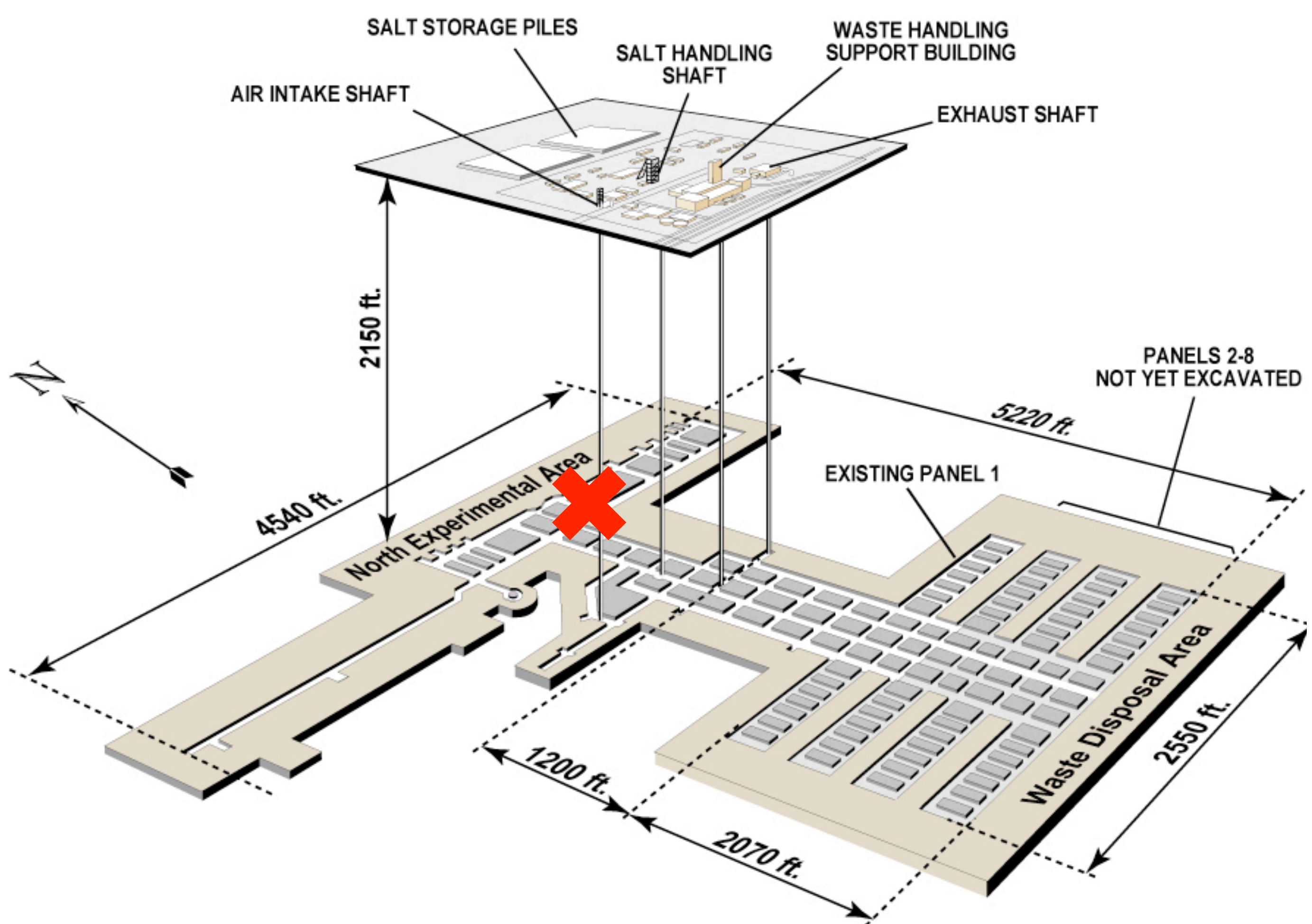
EXO-200 LAAPD installation



EXO-200 TPC ready for shipment



EXO-200 Installation Site



- EXO-200 installed at WIPP (Waste Isolation Pilot Plant) in Carlsbad, NM
- 1600 mwe (2150-ft, 650m)
- Salt mine for radioactive waste storage
- Salt "rock" low activity relative to hard-rock mine

$$\Phi_{\mu} \sim 1.5 \times 10^{5} yr^{-1} m^{-2} sr^{-1}$$

$$U \sim 0.048\, ppm$$

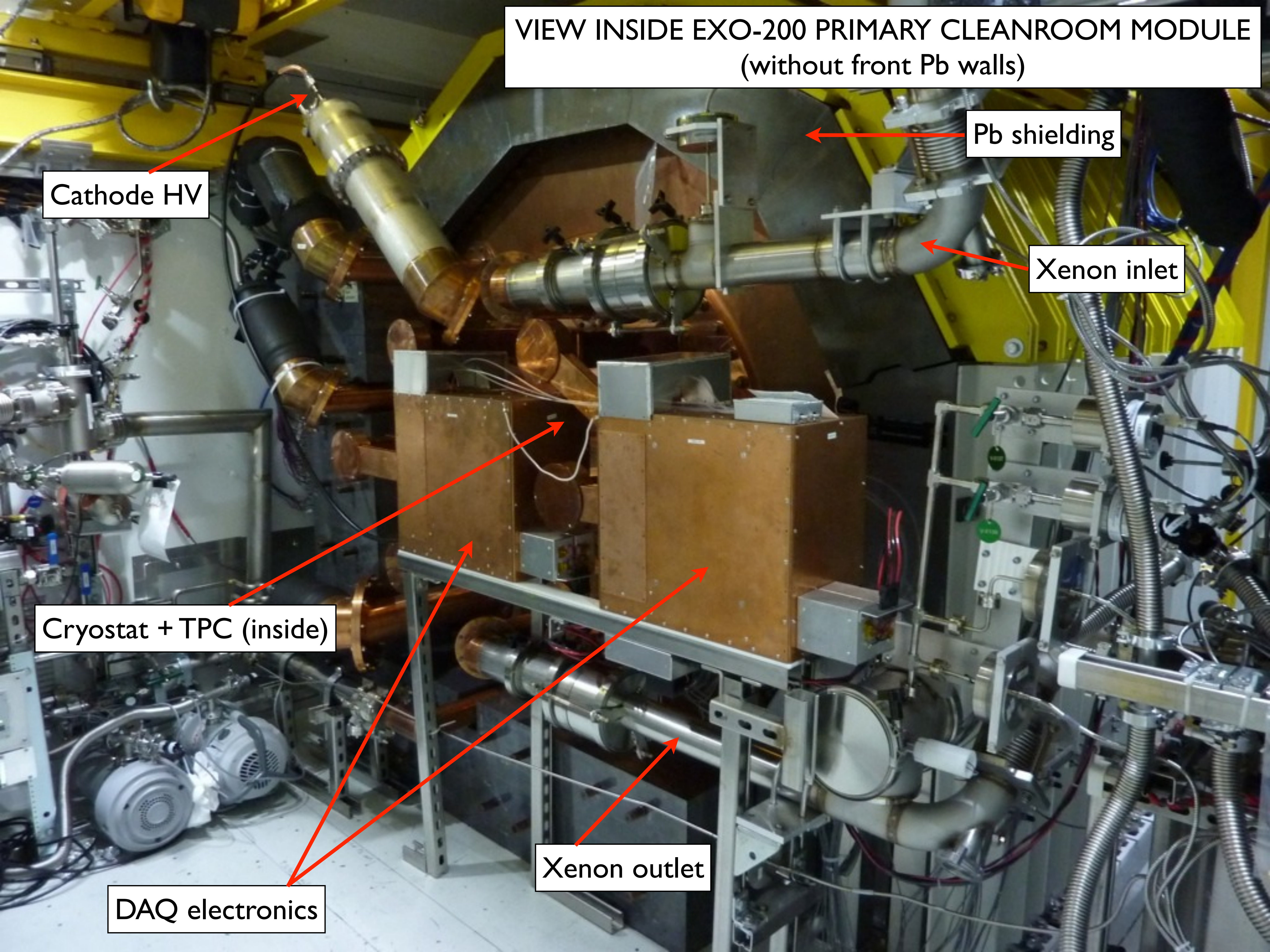
$$Th \sim 0.25\, ppm$$

$$K \sim 480\, ppm$$

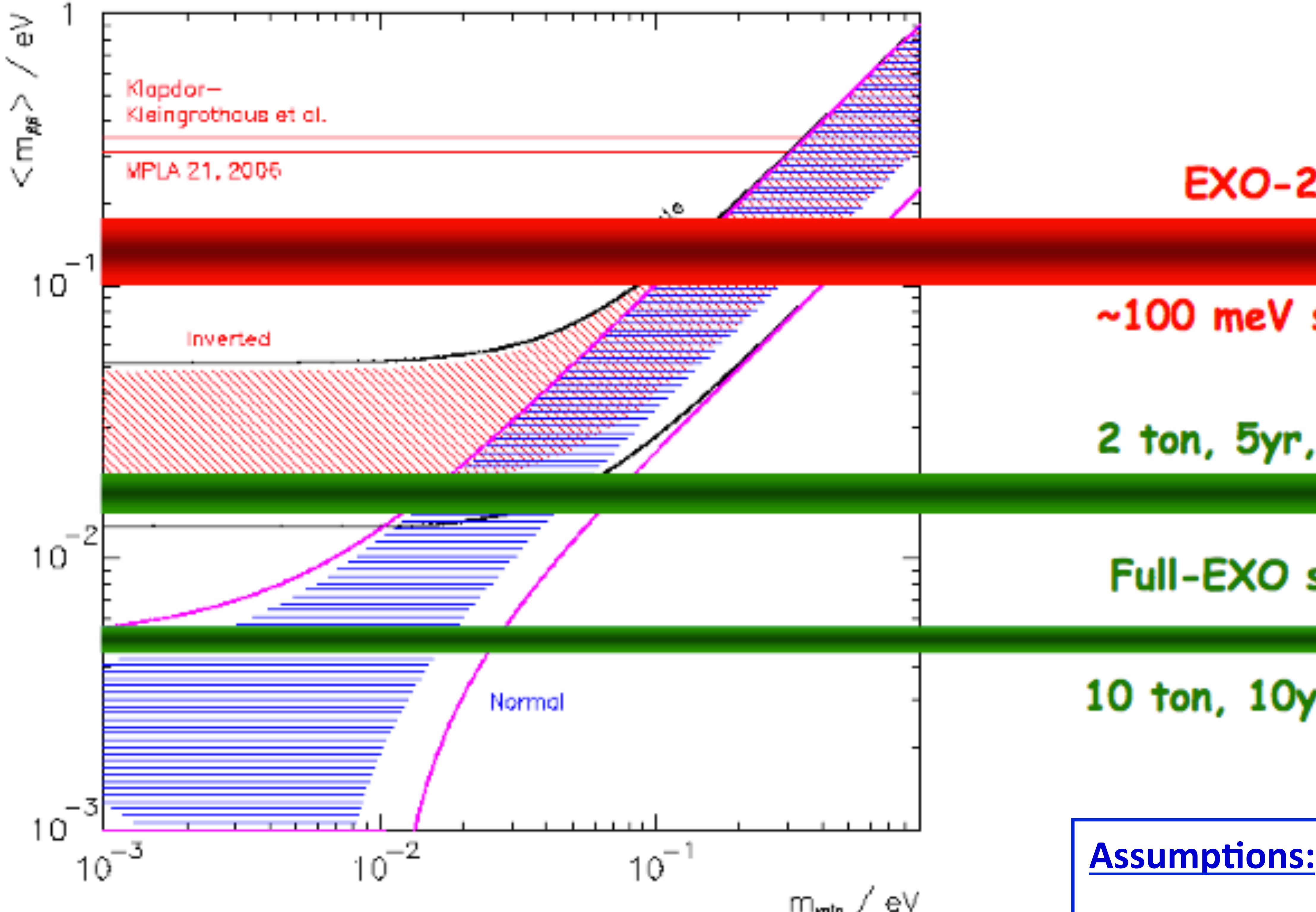
Esch et al, arXiv:astro-ph/0408486 (2004)


Completed EXO-200 facility
at WIPP (2150' underground)
6 modular
cleanrooms
N

VIEW INSIDE EXO-200 PRIMARY CLEANROOM MODULE
(without front Pb walls)



Reach of EXO-200 and the future Full EXO experiment



EXO-200

~100 meV sensit.

2 ton, 5yr, ~18 meV

Full-EXO sensitivity

10 ton, 10yr, ~5 meV

Assumptions:

Majorana neutrinos

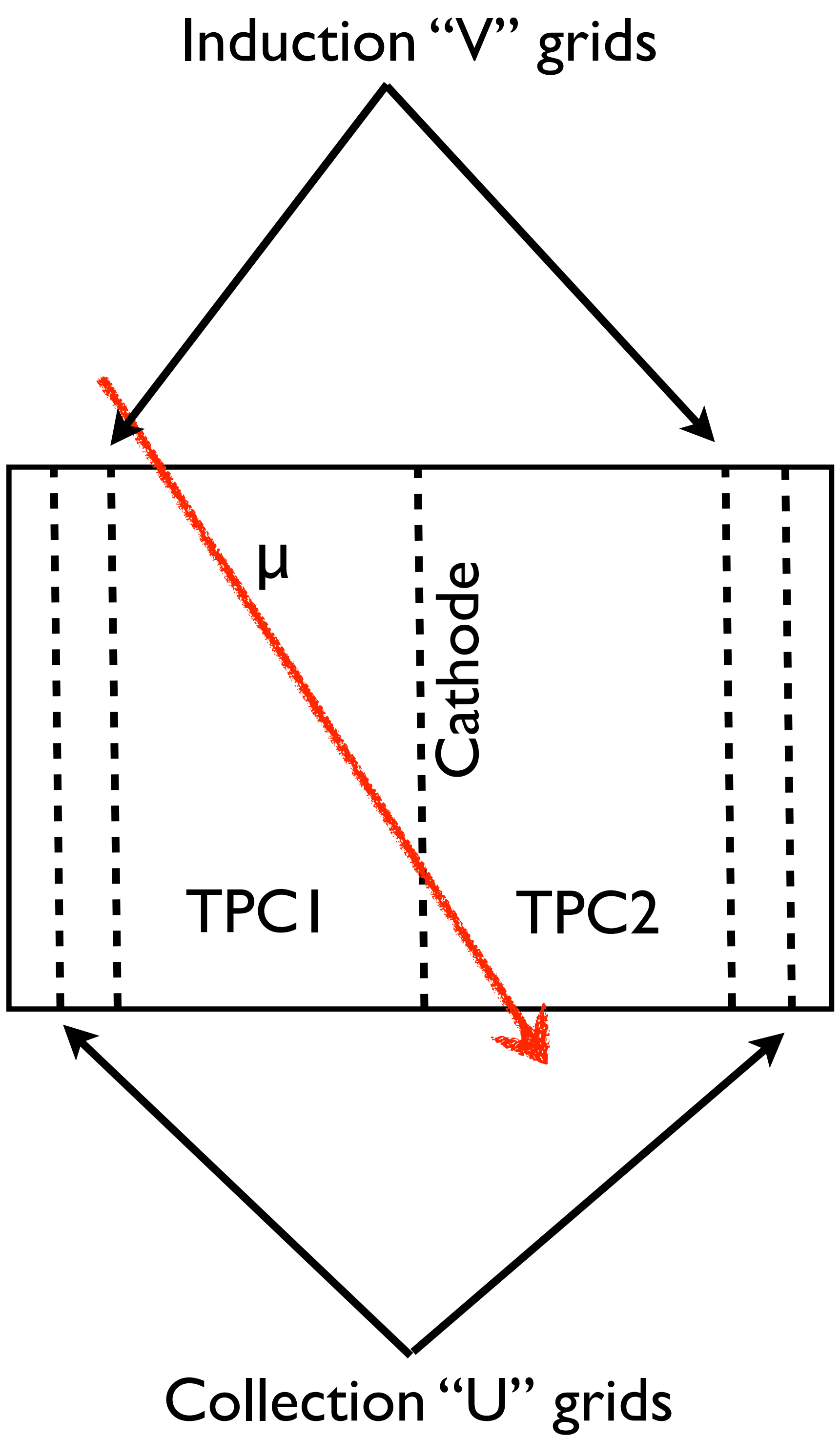
Running configuration for spring 2011 $2\nu\beta\beta$ analysis

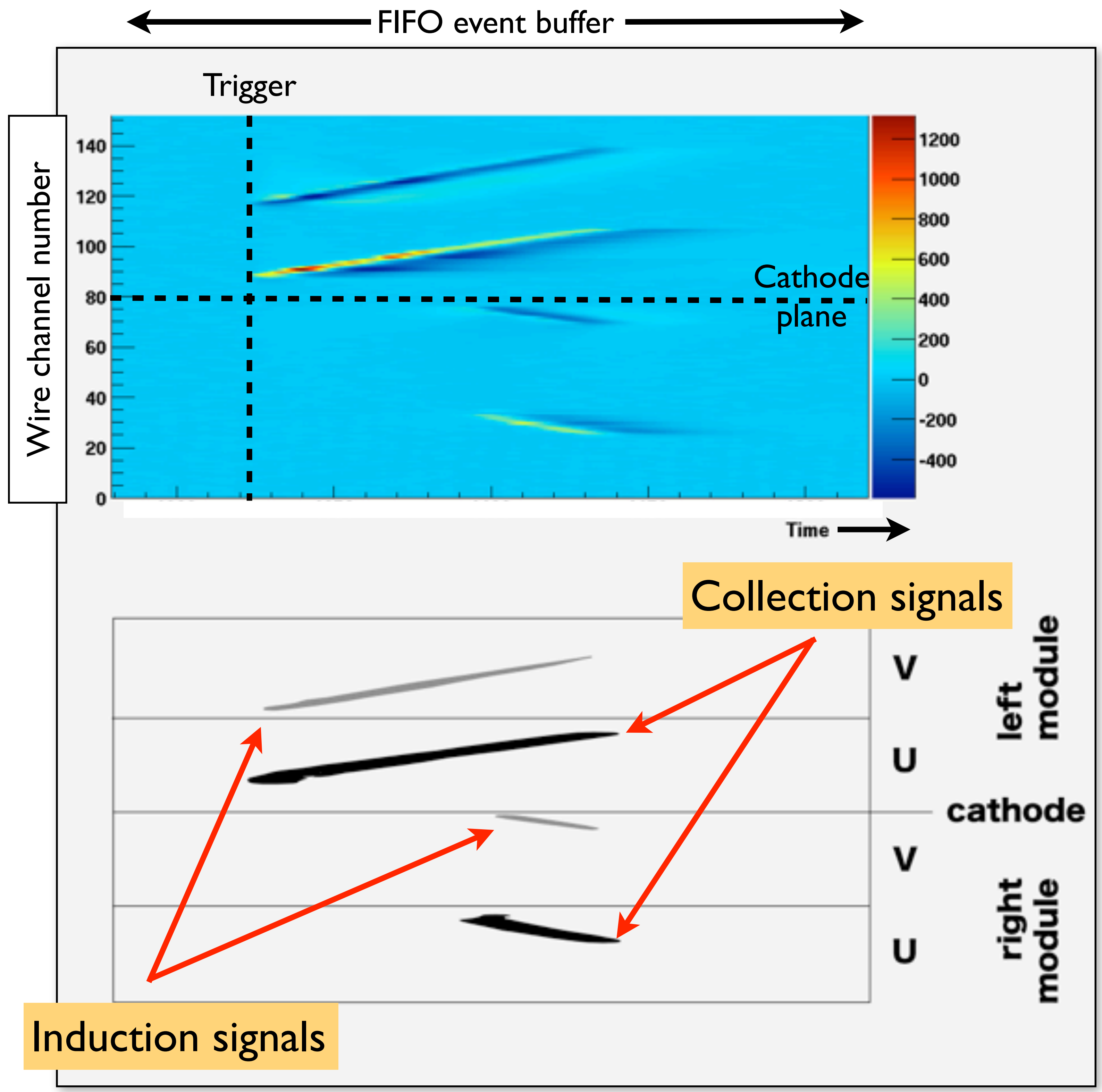
- Drift field E = -376 V/cm
- ~ 31 live days
- Source calibration ~ 2 hrs each day (^{60}Co, ^{228}Th, multiple locations) for to monitor purity, resolution, calibration, other detector effects
- Continuous Xe recirculation through SAES purifiers at ~ 5 SLPM, LXe purity ~ 210-280 μs (max drift time ~ 110 μs)
- Conservative fiducial volume ~ 63 kg chosen for first analysis

Spring 2011 $2\nu\beta\beta$ analysis details

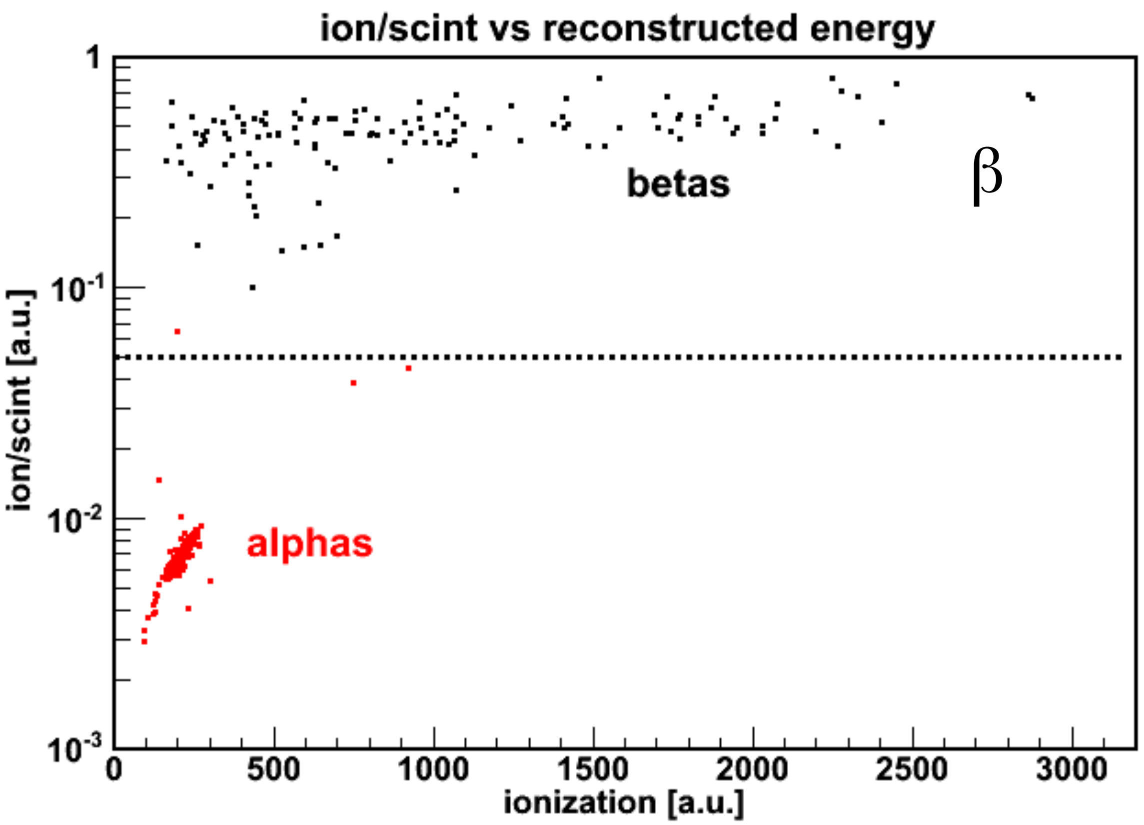
- Developed GEANT4 MC of EXO-200 (including geometry, signal generation, digitization, etc.); agrees well with source calibration
- Use charge + scintillation for event position reconstruction and PID
- Detector energy calibration with radioactive sources (511, 1173, 1333, 1593, 2615 keV)
- Charge signal corrected for Xe purity, monitored daily
- Muons (0.12% dead-time) and ^{220}Rn events (6.3% dead-time) removed with cuts
- α spectroscopy used to bound ^{238}U in LXe (daughter ^{234m}Pa β-decay with 2195 keV endpoint)
- 720 keV energy analysis threshold, (includes ~ 65% of $2\nu\beta\beta$ spectrum)
- Large library of PDFs (natural radioactivity, cosmogenics, exotics) generated for spectral fitting
- Use charge energy spectrum only for fitting (currently optimizing combined ionization + scintillation energy resolution)
- Final signal extraction: simultaneous fit of single and multiple cluster spectra to PDFs

Muon passing through TPC

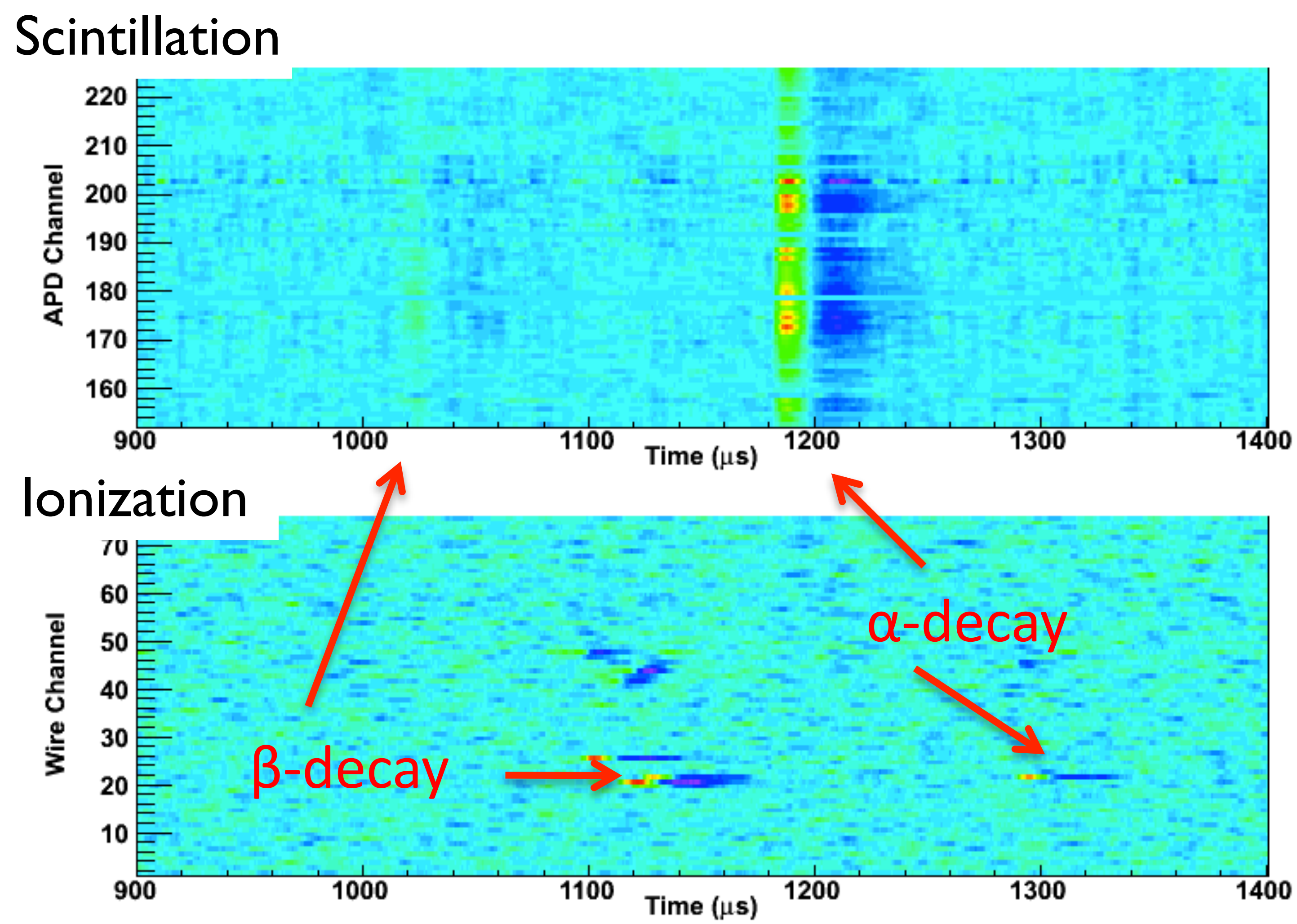




Rn identification in LXe



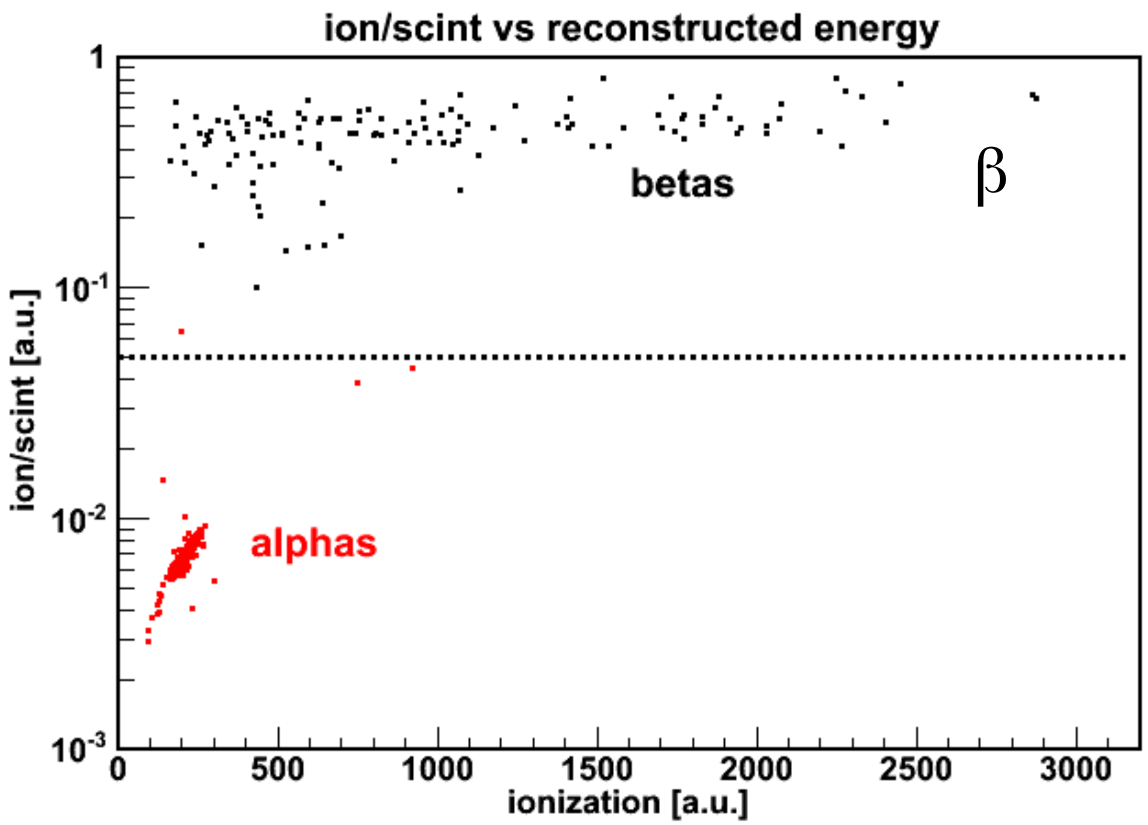
α: strong light signal, weak charge signal
β: weak light signal, strong charge signal



^{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. The ^{214}Bi decay rate is consistent with measurements from alpha-spectroscopy and the expectation before the Rn trap is commissioned.

Rn identification in LXe



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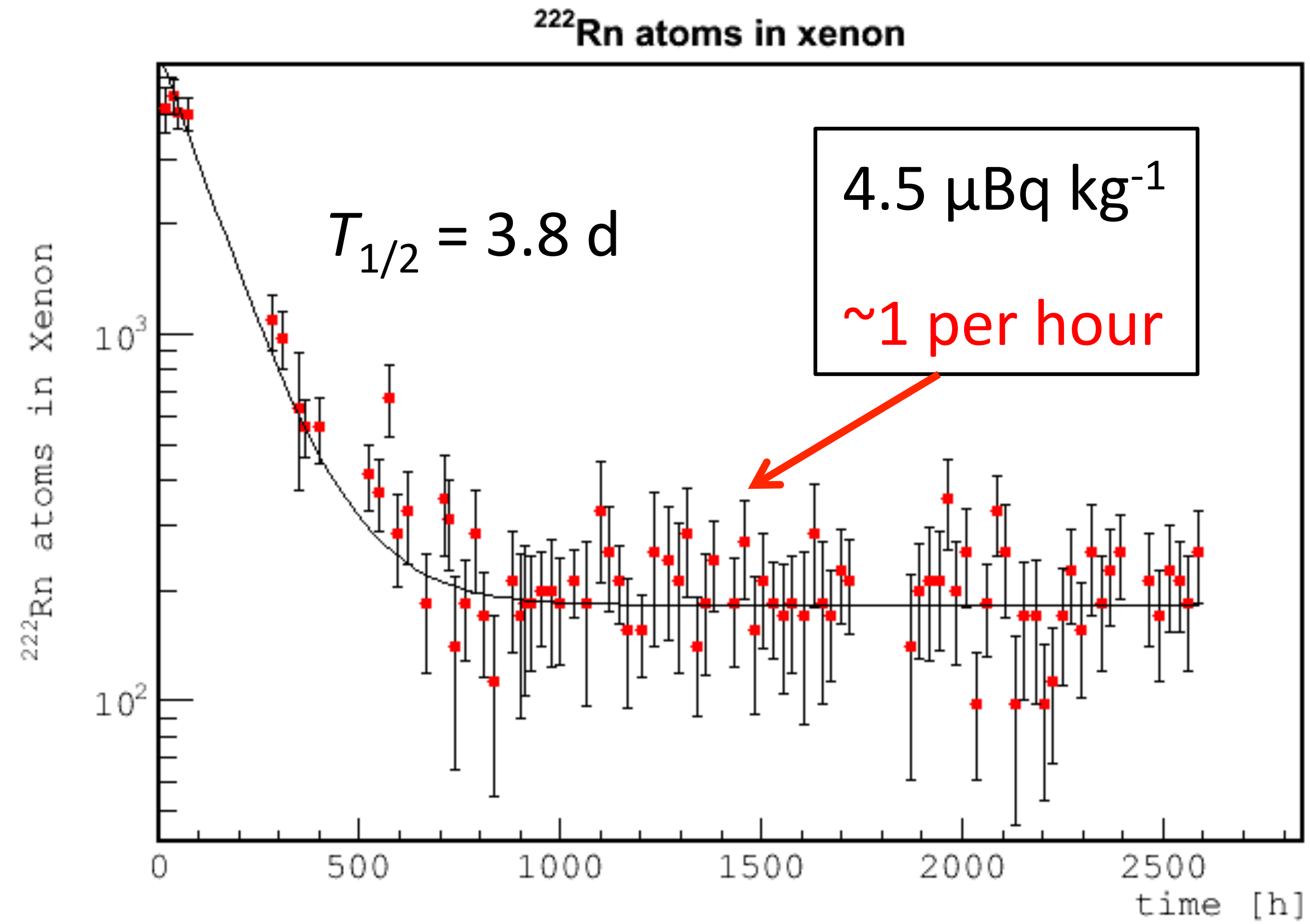

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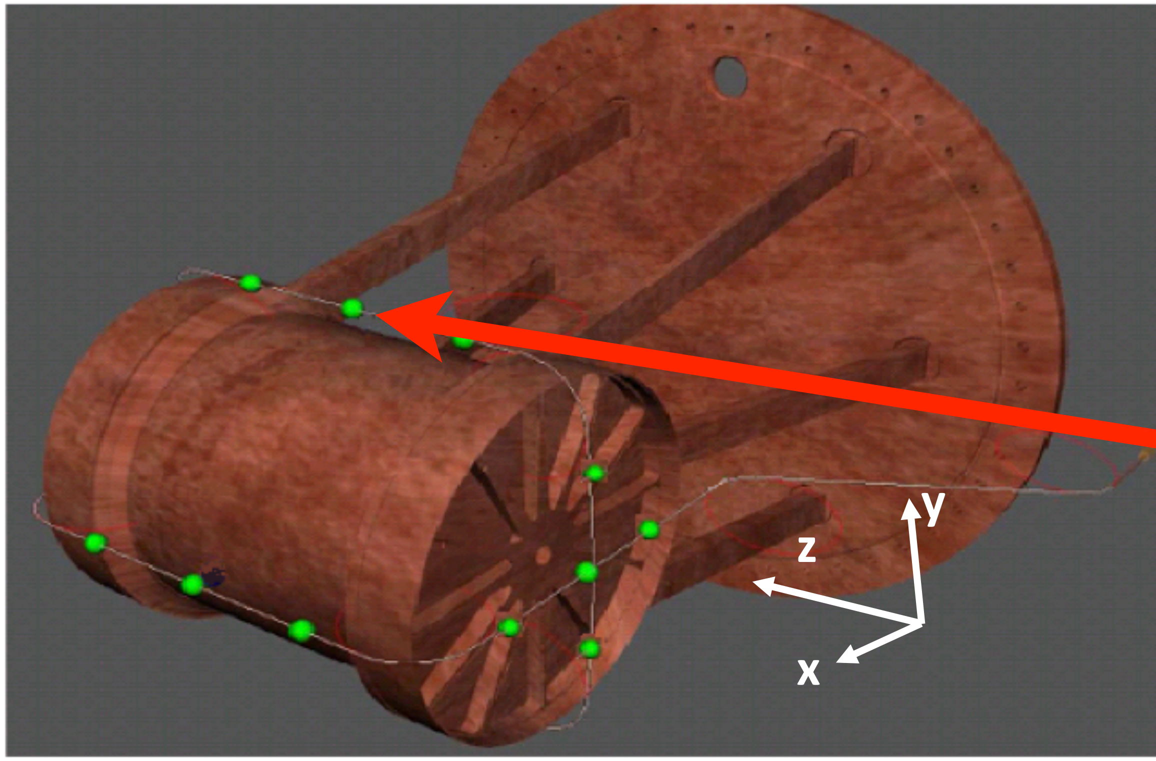
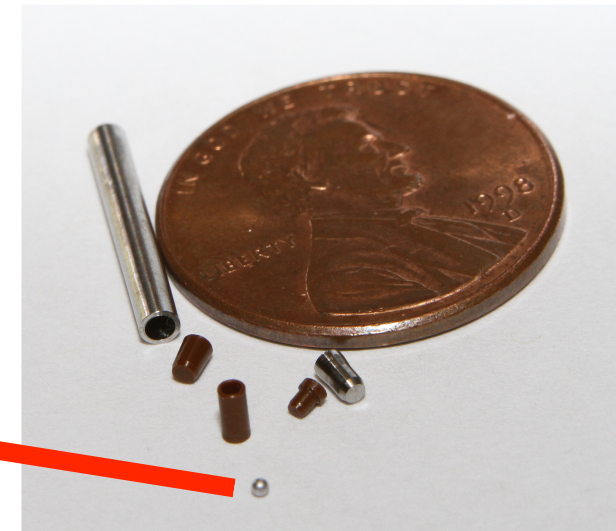
Source calibration in EXO-200



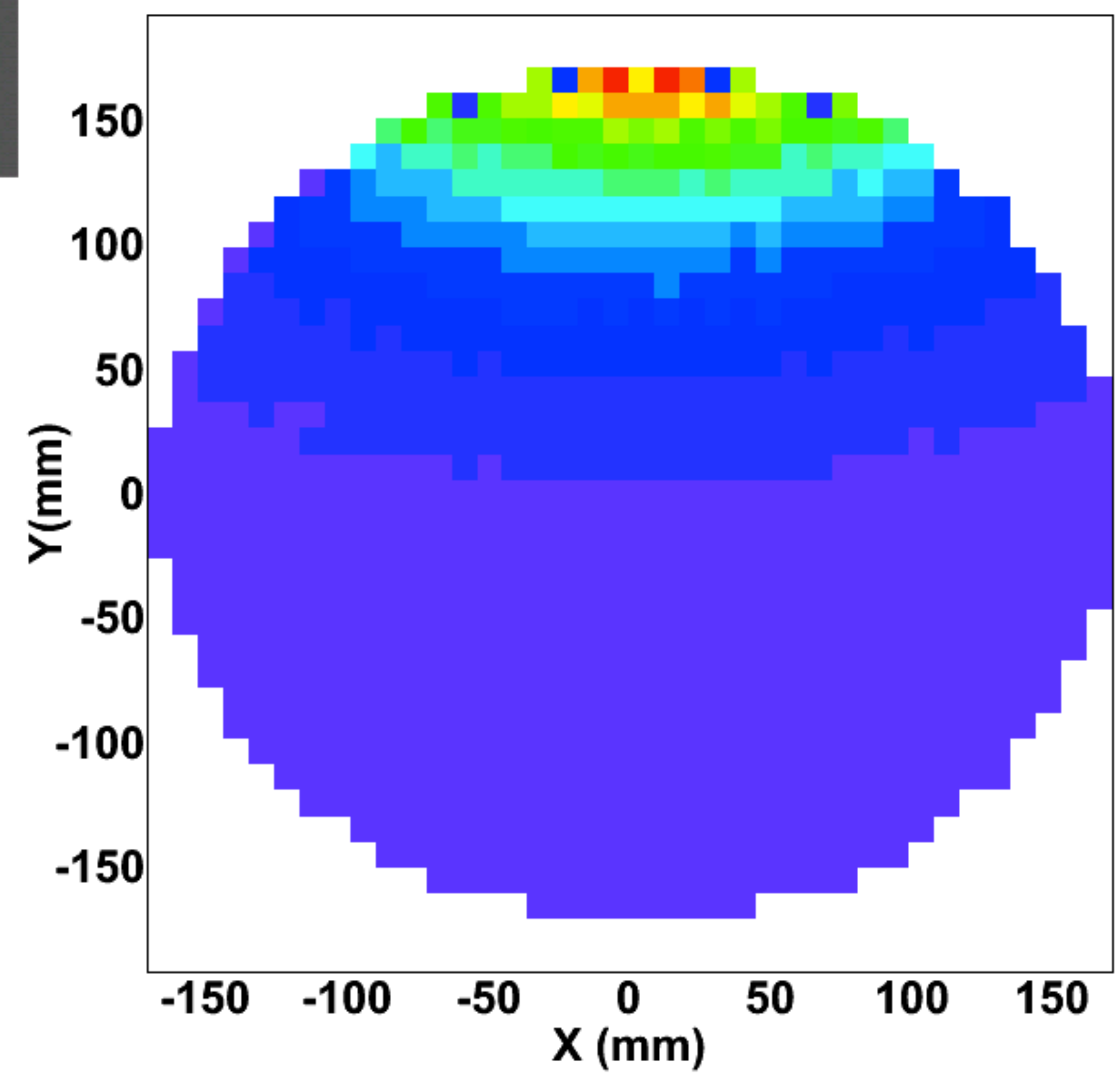


Sources:

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

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



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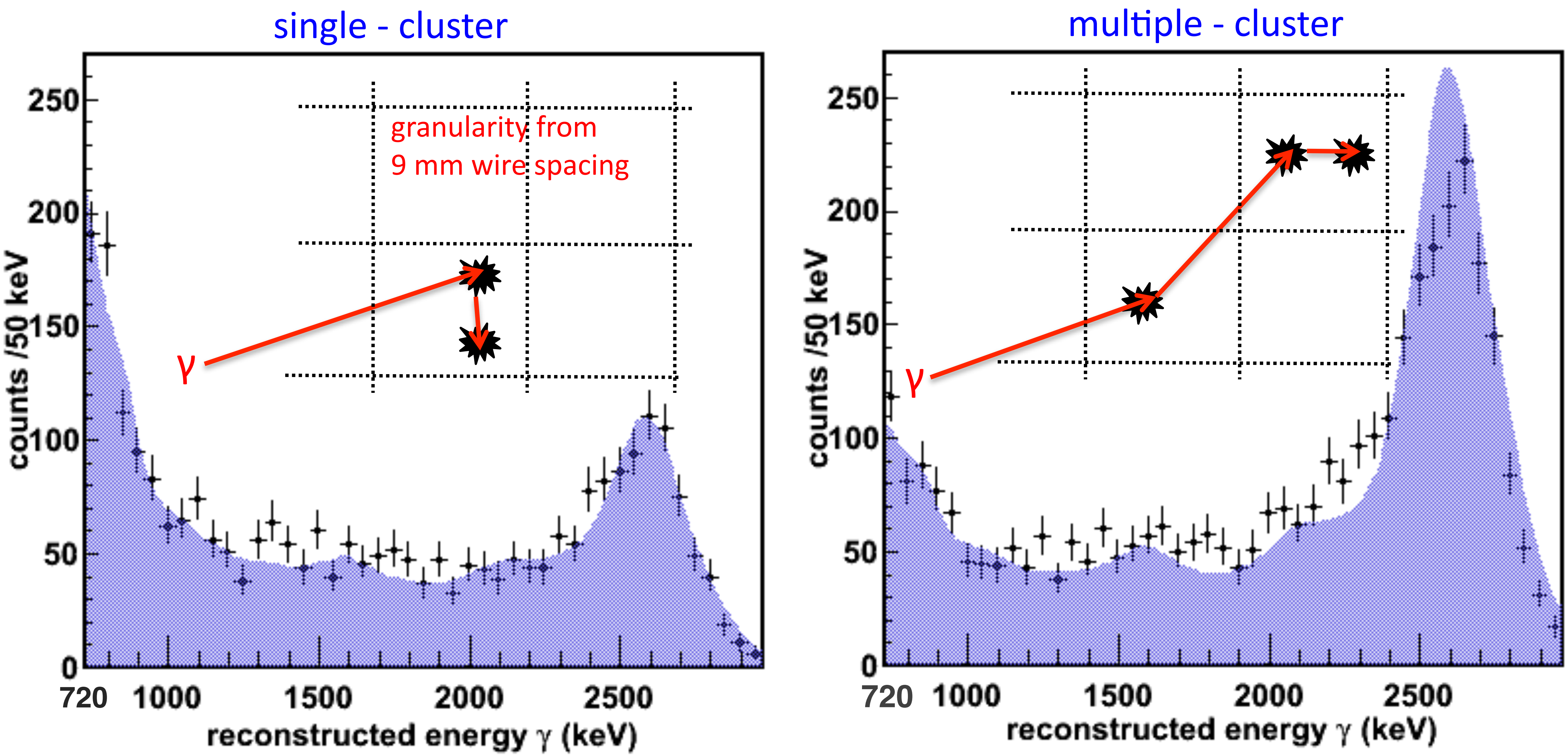
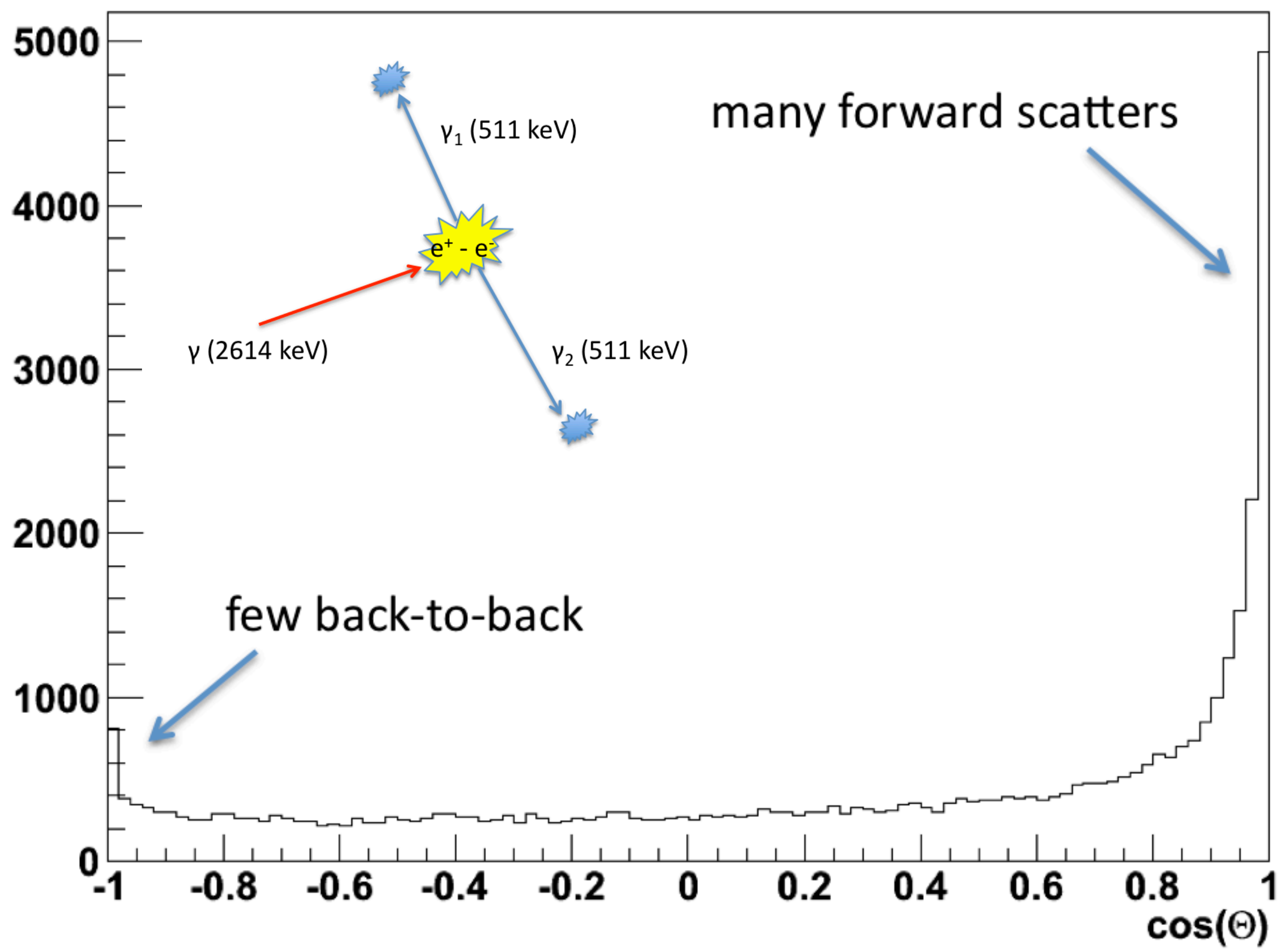
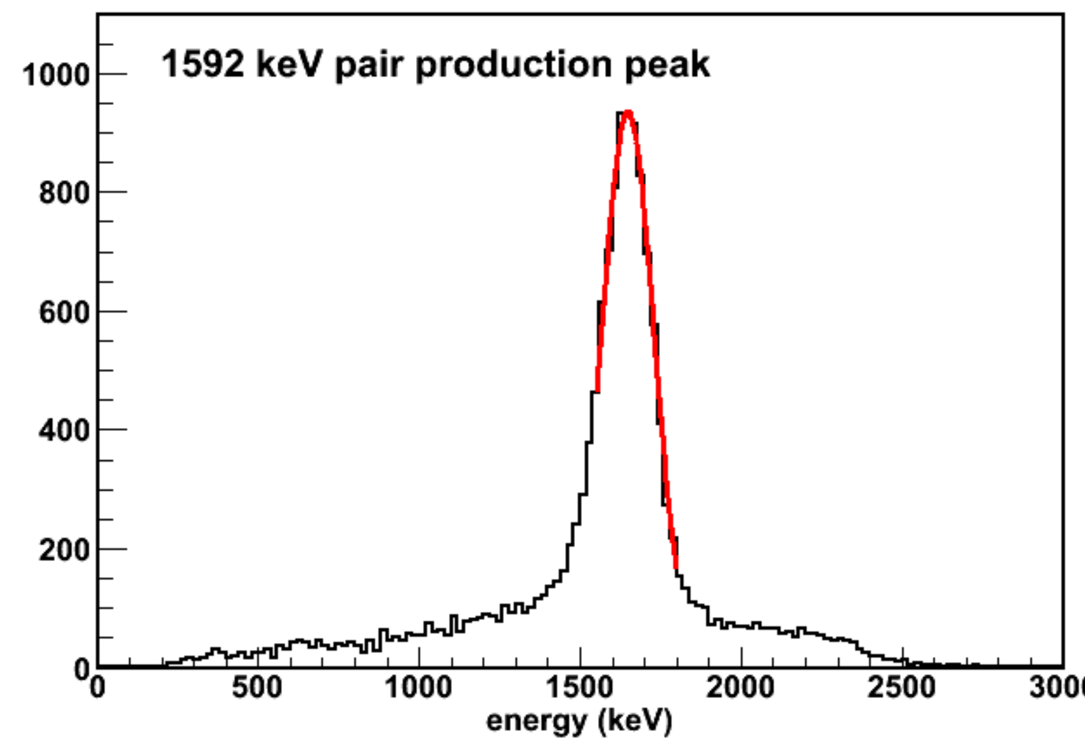
Example: 228Th energy calibration

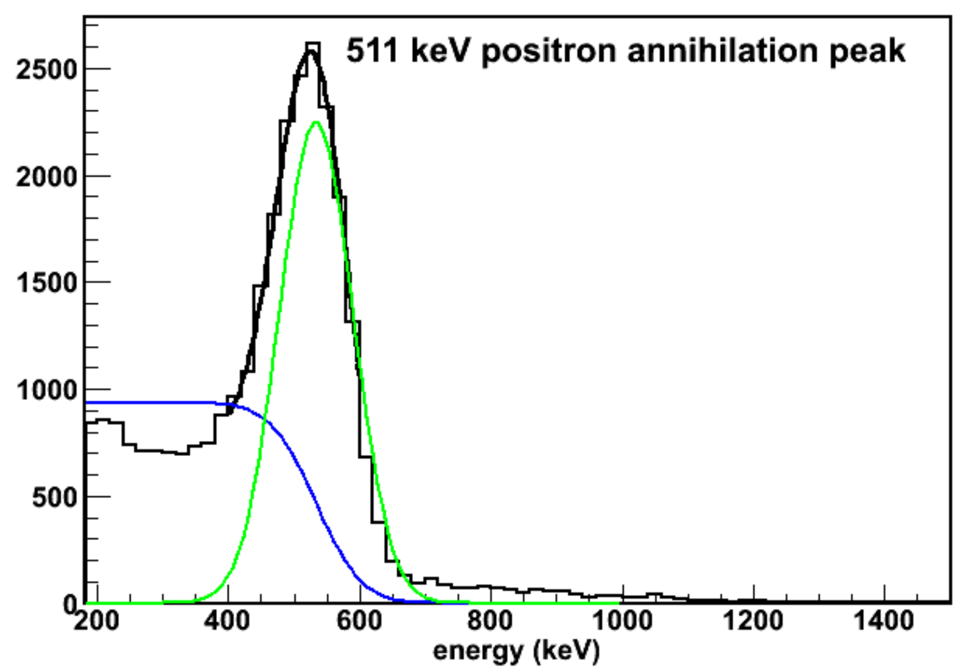


- Calibration runs compared to simulation
  - GEANT4 based simulation
  - charge propagation
  - scintillation propagation
  - signal generation
  - energy resolution parameterization is added in after the fact
- There are no free parameters for these comparisons (worst agreement is +8%)

Energy calibration from pair production events from ^{228}Th source

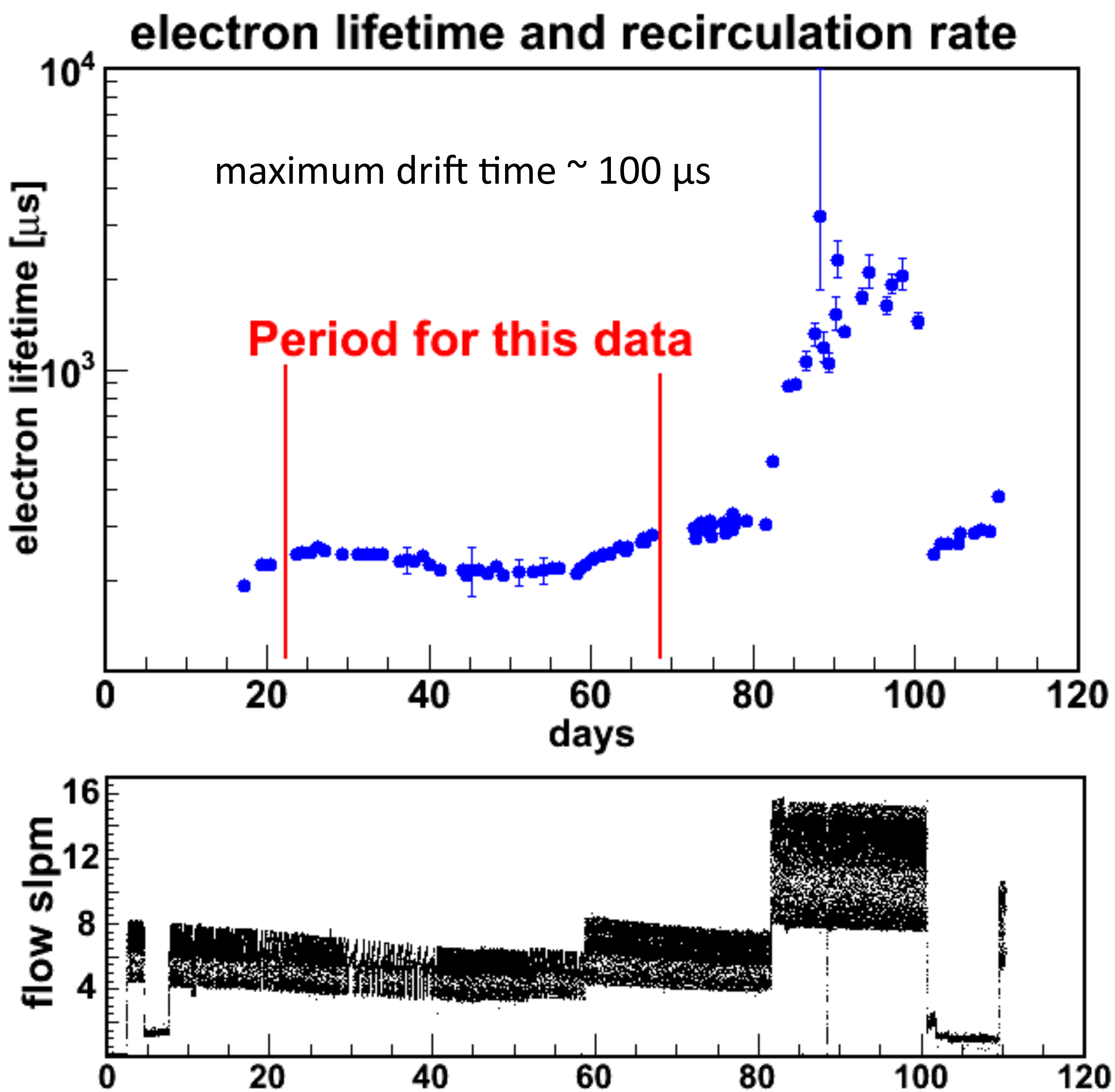






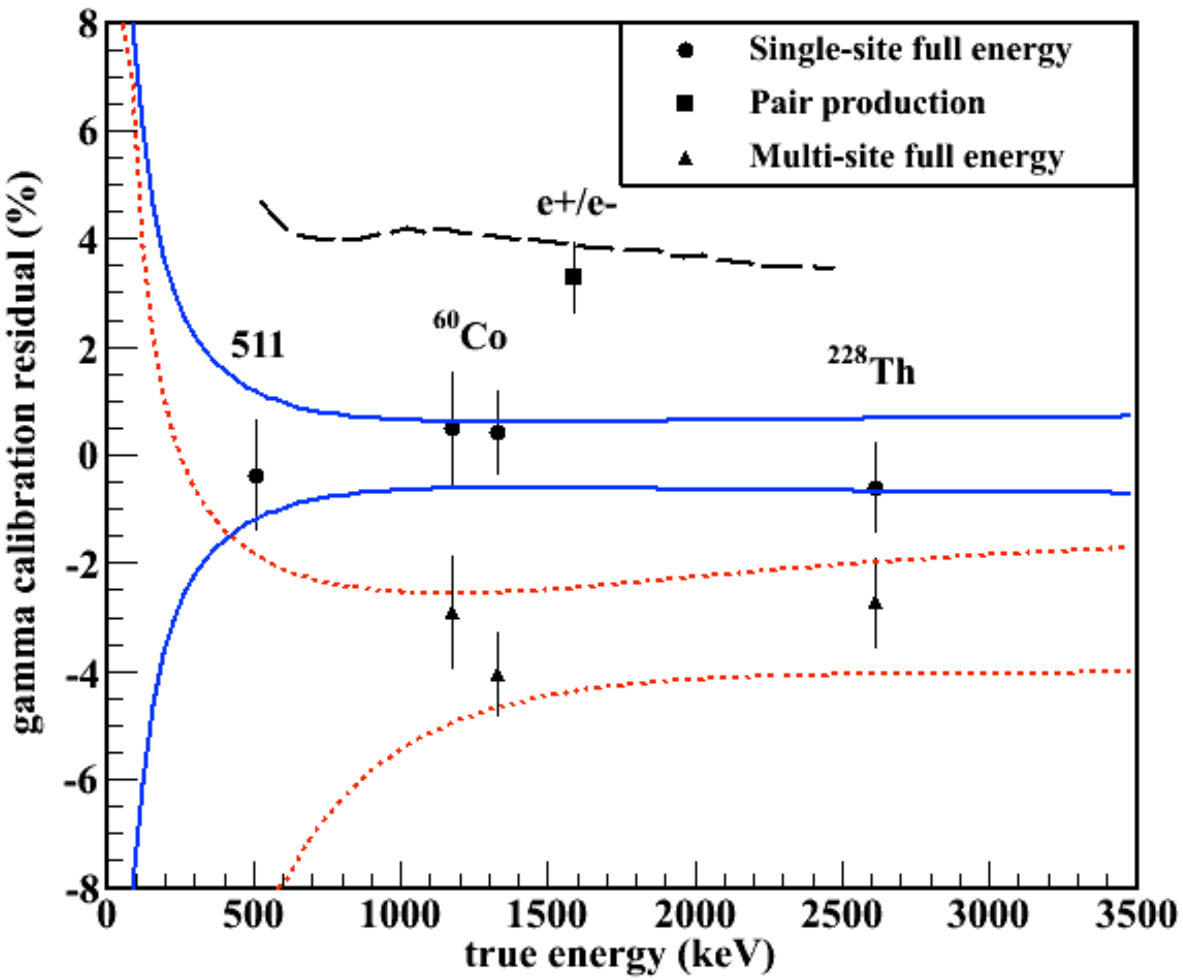
- Identifying 3-site events from pair-production and annihilation provides 2 extra charge calibration peaks
  - -511 keV gammas are our lowest energy calibration sources
  - -1592 keV pair production very similar topology to ββ decays

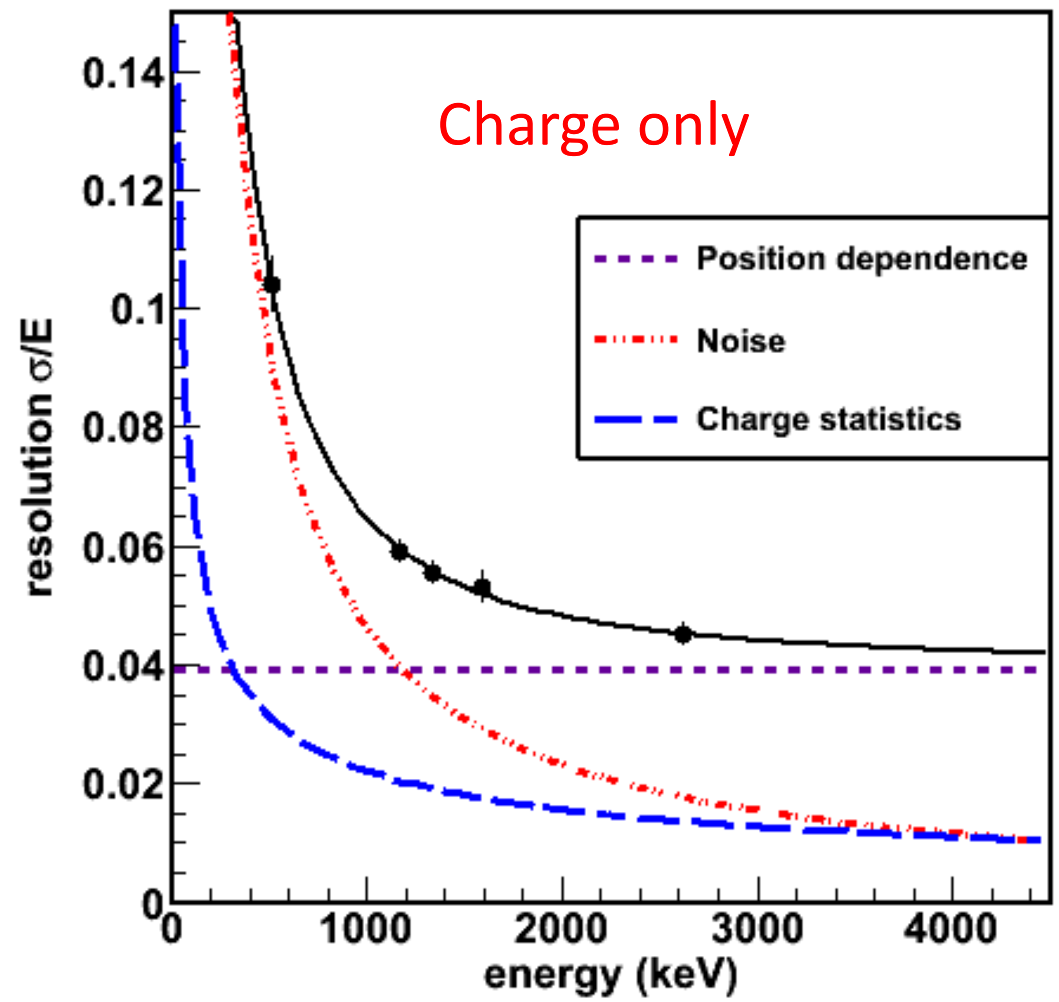
Xenon purity monitoring with calibration sources



- Use sources to measure purity of LXe in TPC
- Rapid achievement of ms lifetimes results is a clear benefit of recirculation.

Energy calibration for charge-only 2νββ analysis

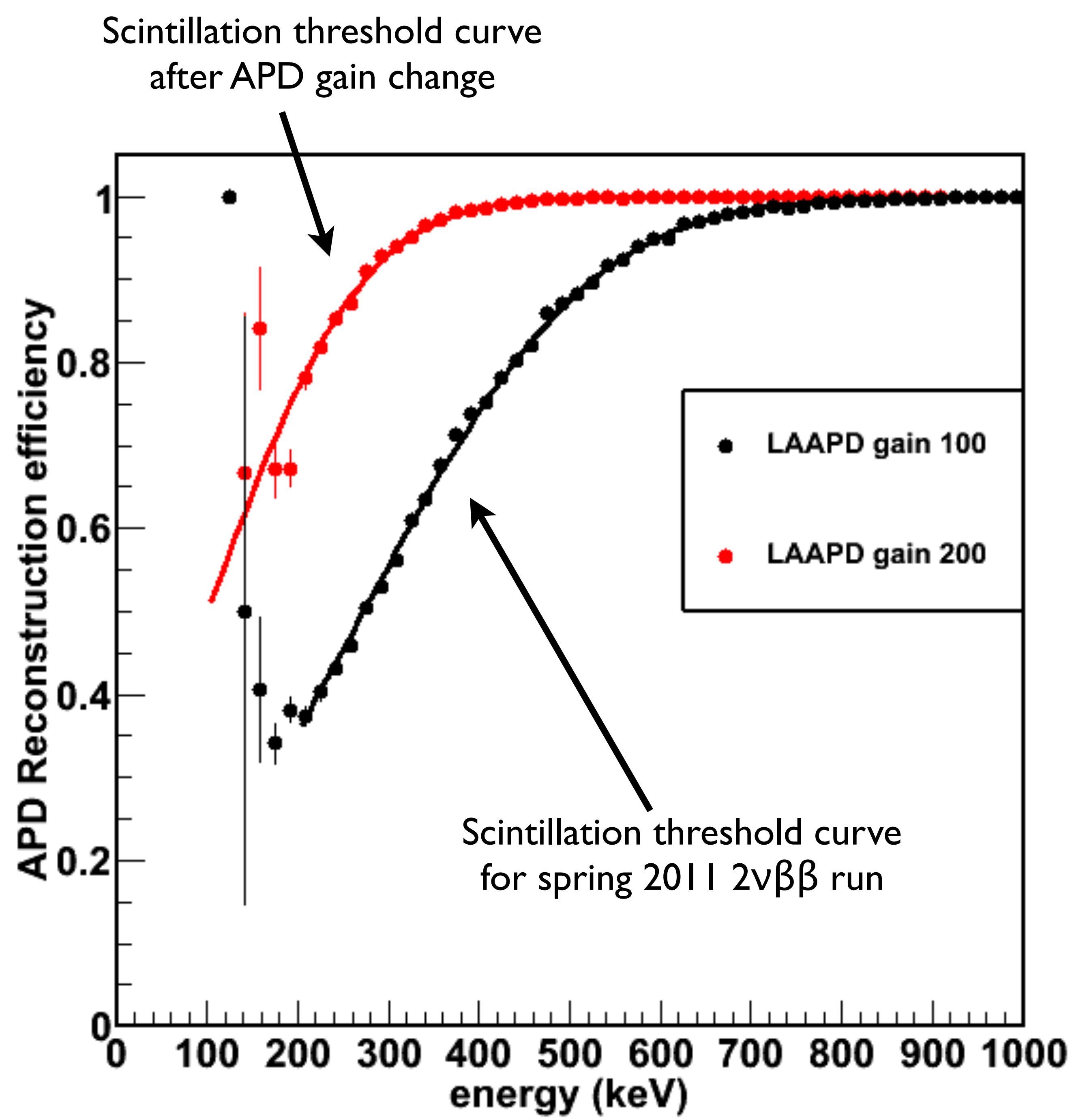




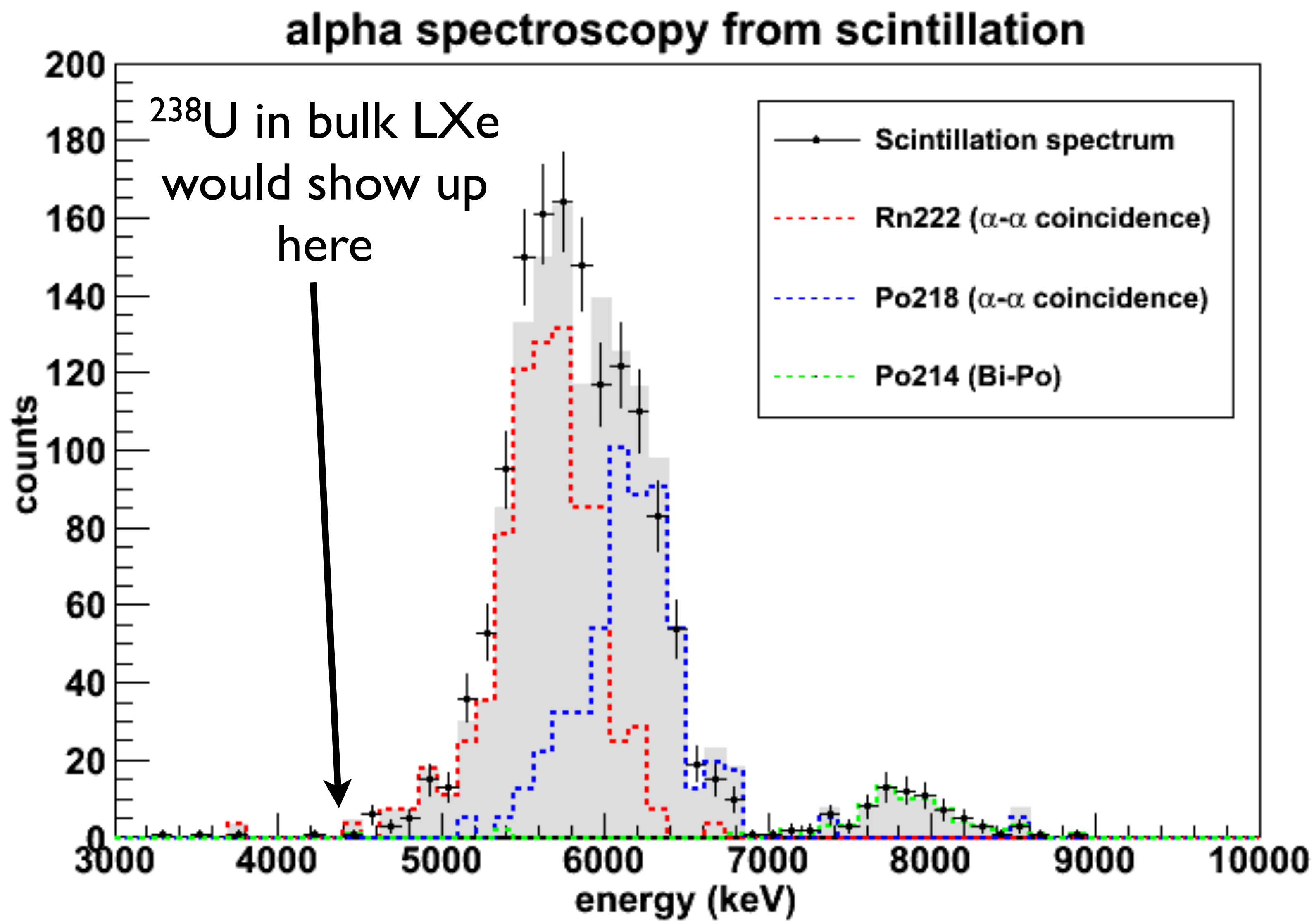
- After purity correction, calibrated single and multiple cluster peaks across energy region of interest (511 to 2615 keV)
  - -uncertainty bands are systematic
- Point-like depositions have large reconstructed energies due to induction effects
  - - observed for pair-production site (similar to β and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

Event reconstruction threshold

- Events > 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 ~700 keV
- Recent dramatic decrease with change in APD bias voltages ~300 keV



Constraints from alpha spectroscopy

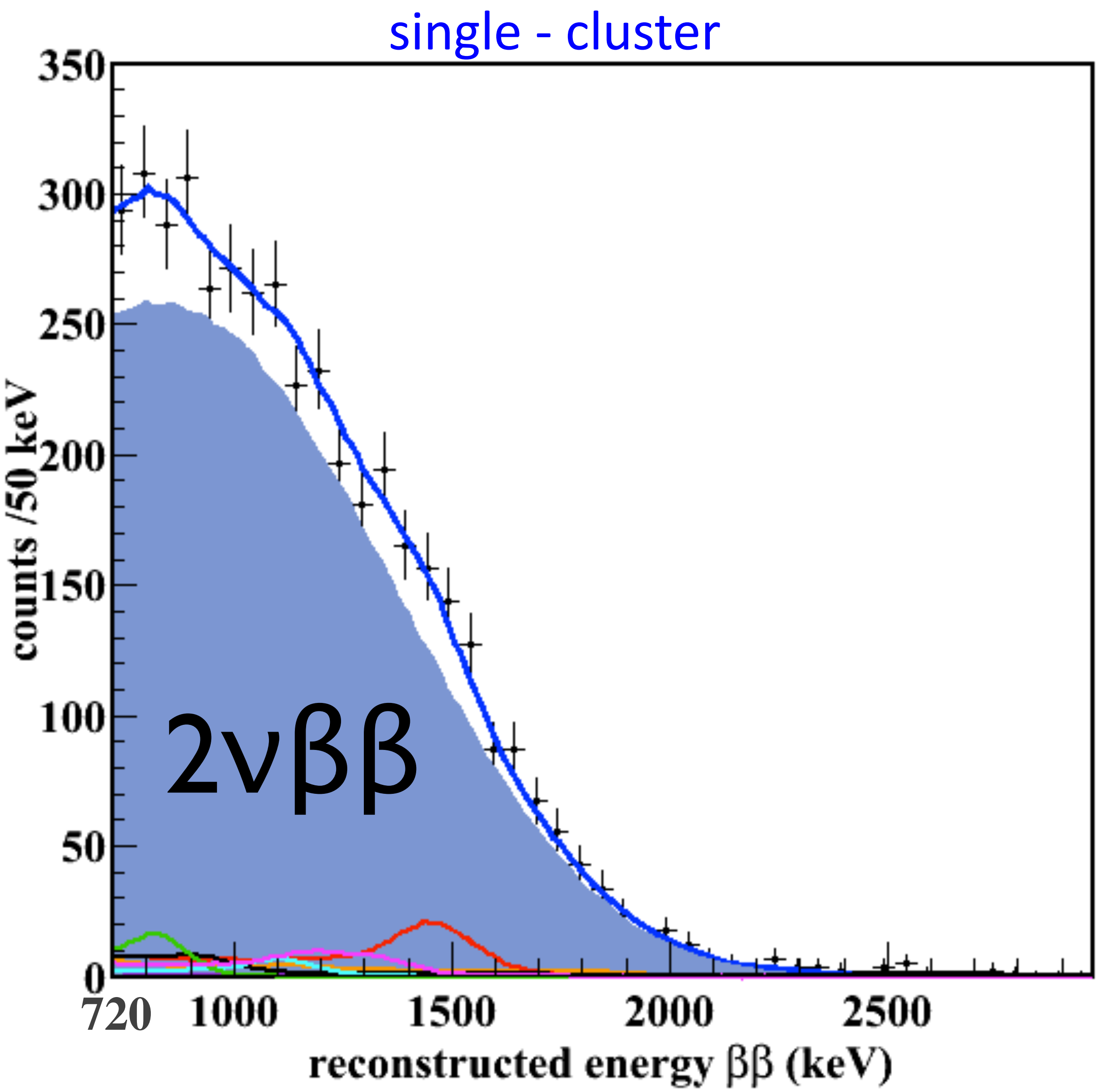


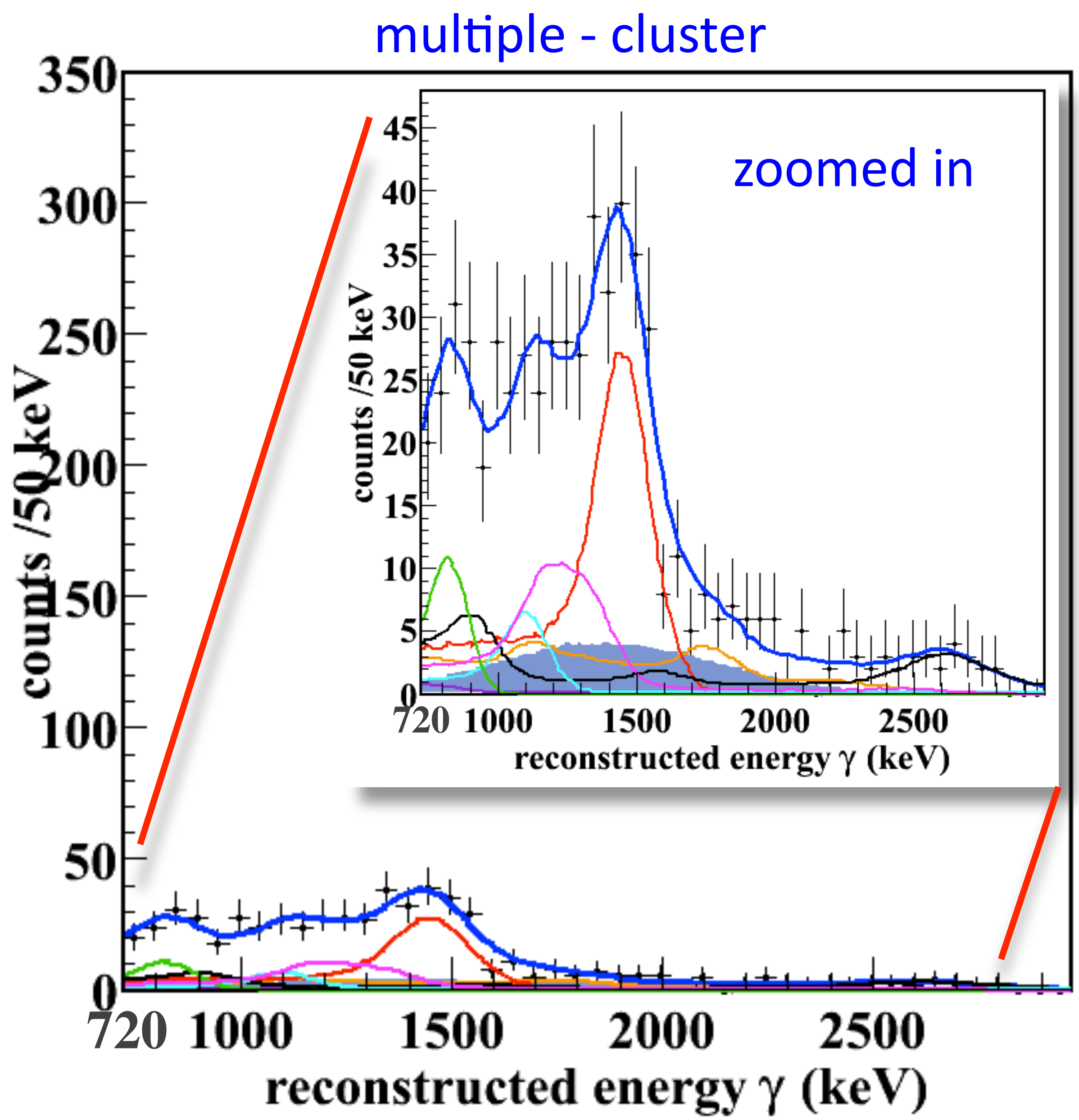
- Investigate alpha spectrum for scintillation signals from ^{238}U
- Calibrate spectrum with alphas in Rn chain
- Can constrain contamination of ^{238}U in bulk LXe by searching for 4.5 MeV alphas

  < 0.3 counts per day in our fiducial volume

  -The same limit applies to its daughter ^{234m}Pa which β decays with a Q-value of 2195 keV, which cannot then explain our LXe bulk signal

Measurement of 2νββ with EXO-200

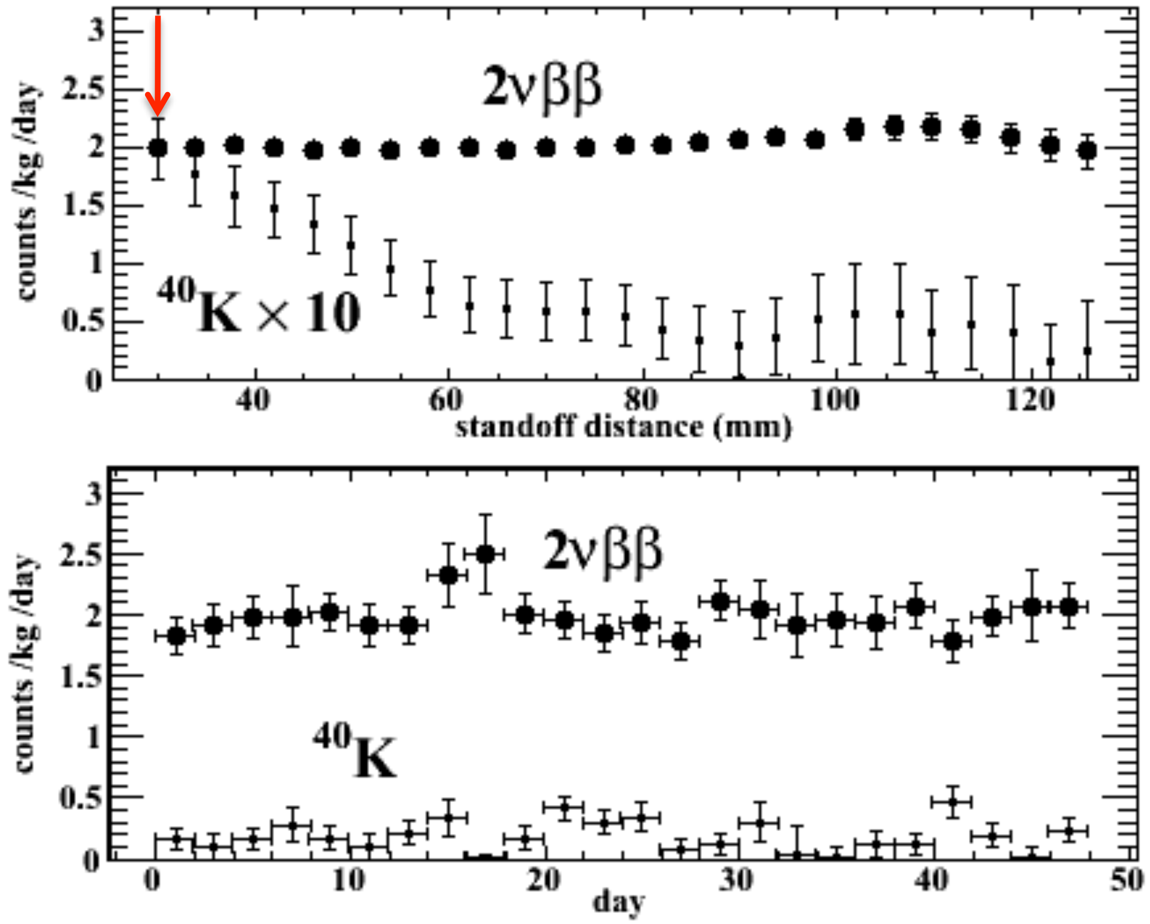




- 31 live-days of data
- 63 kg active mass
- Signal / Background ratio 10:1
  - -as good as 40:1 for some extreme fiducial volume cuts

$T_{1/2}$ = 2.11·10^{21} yr (± 0.04 stat) yr (± 0.21 sys) **[arXiv:1108.4193]**

Low background spectra



• constant in time
• 2νββ signal is clearly in the LXe bulk, while other gamma background contributions decrease with increasing distance from the walls.

Total background rate in 0νββ window < 4×10^{-3} cts/kg/yr/keV

- Backgrounds will further improve from
  - Rn tent installation
  - Closing of front outer Pb shield
  - Improvements in multicluster rejection

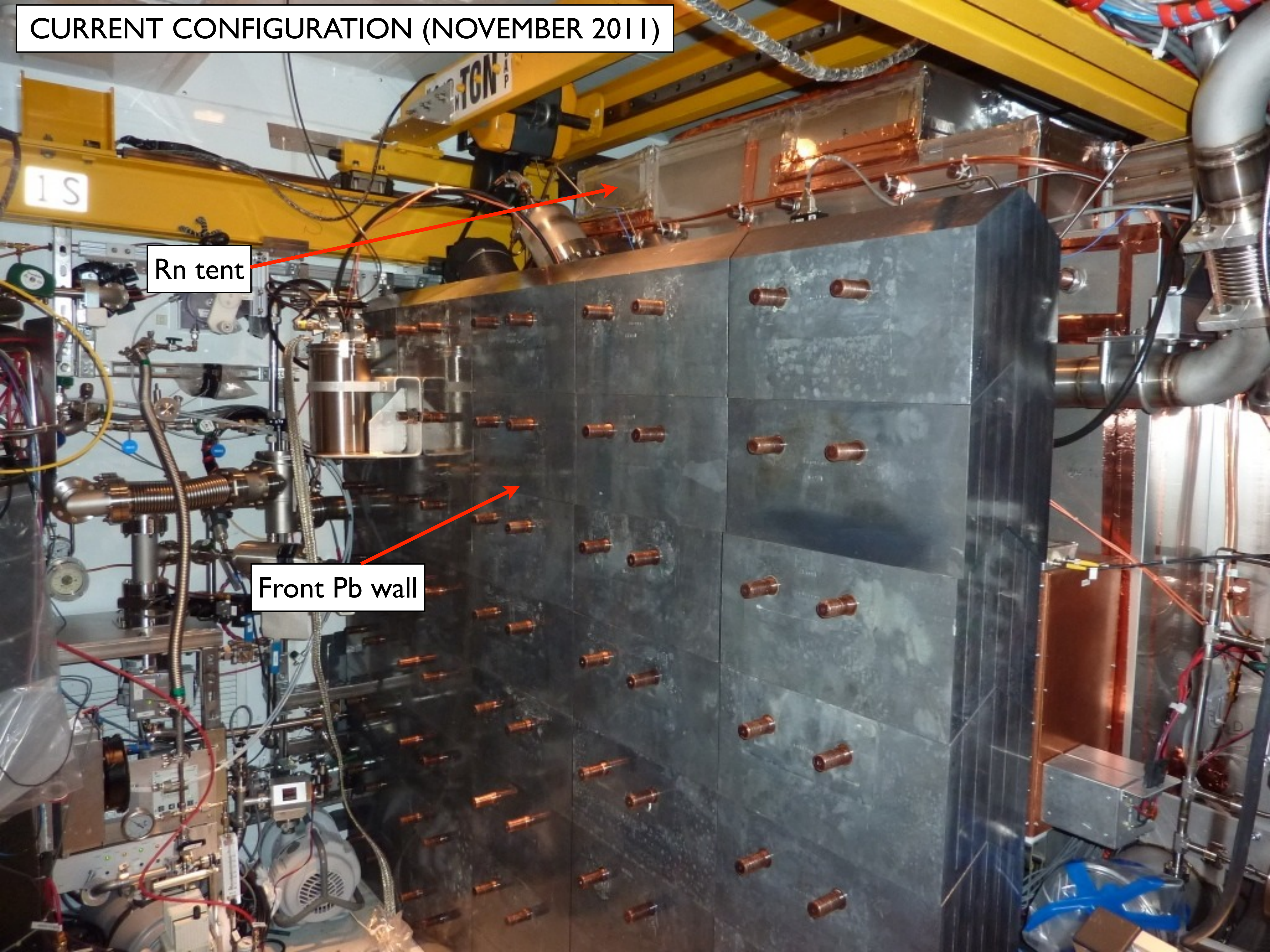
Systematic error budget for spring 2011 $2\nu\beta\beta$ analysis

$$T_{1/2}^{2\nu\beta\beta} = 2.11\times10^{21} \text{ yr } (\pm 0.04 \text{ stat}) (\pm 0.21 \text{ sys})$$

- Fiducial volume 9.3%
- Multiplicity assignment 3.0 %
- Energy calibration 1.8%
- Background models 0.6%

- Working hard to reduce these for upcoming analyses

CURRENT CONFIGURATION (NOVEMBER 2011)



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