Searching for Neutrinoless Double Beta Decay with EXO

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WNPPC, Mont Tremblant

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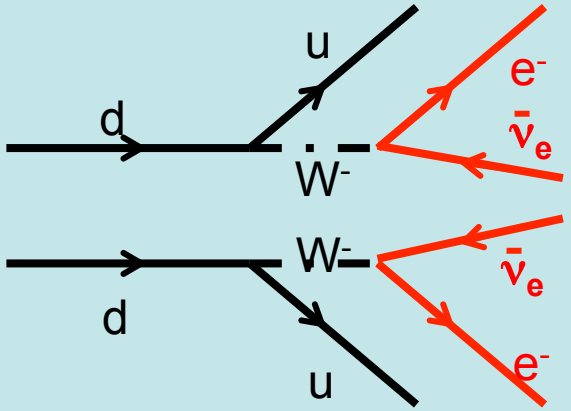
Neutrinoless Double Beta Decay

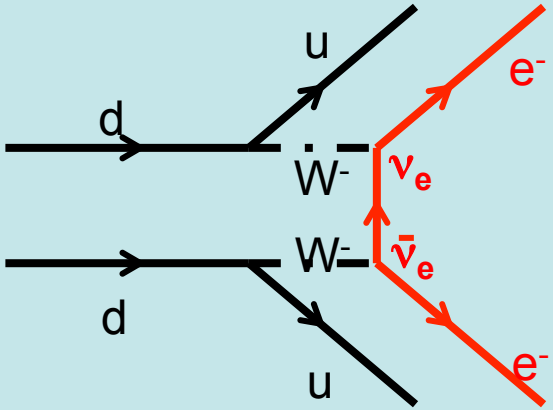


$$\left[T_{0\nu}^{1/2}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left\langle m_{\beta\beta}\right\rangle^2$$

G = phase space factors (easy)
$|M|$ = nuclear matrix elements (hard)

$m_{\beta\beta} = |\sum_i U_{ei}^2\, m_i|$

$T^{1/2}_{0\nu}$ = half-life (current limit >5.7x10^{24}yrs)



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

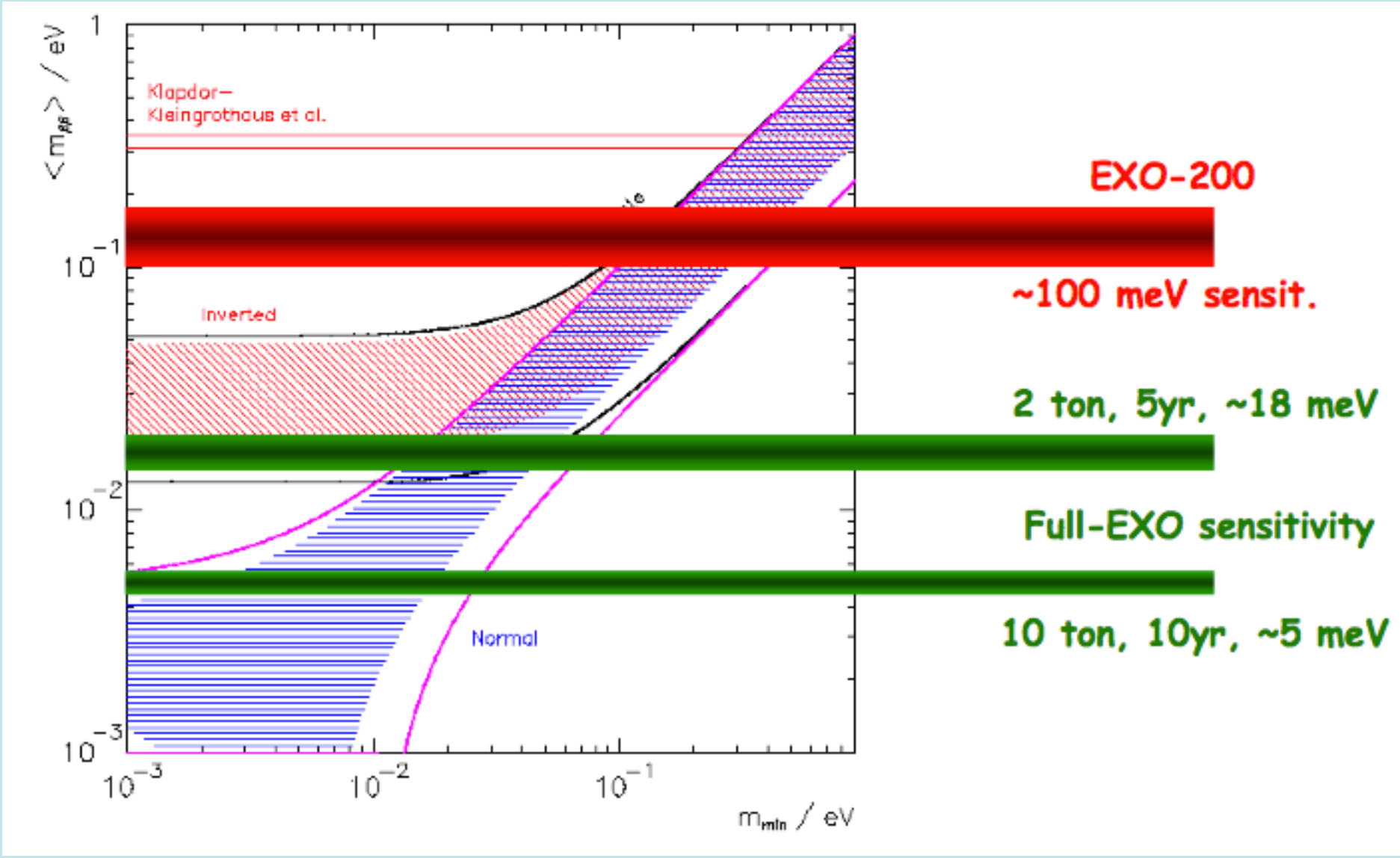
are neutrinos Majorana particles ?

$\Delta L=2$ lepton number violation?

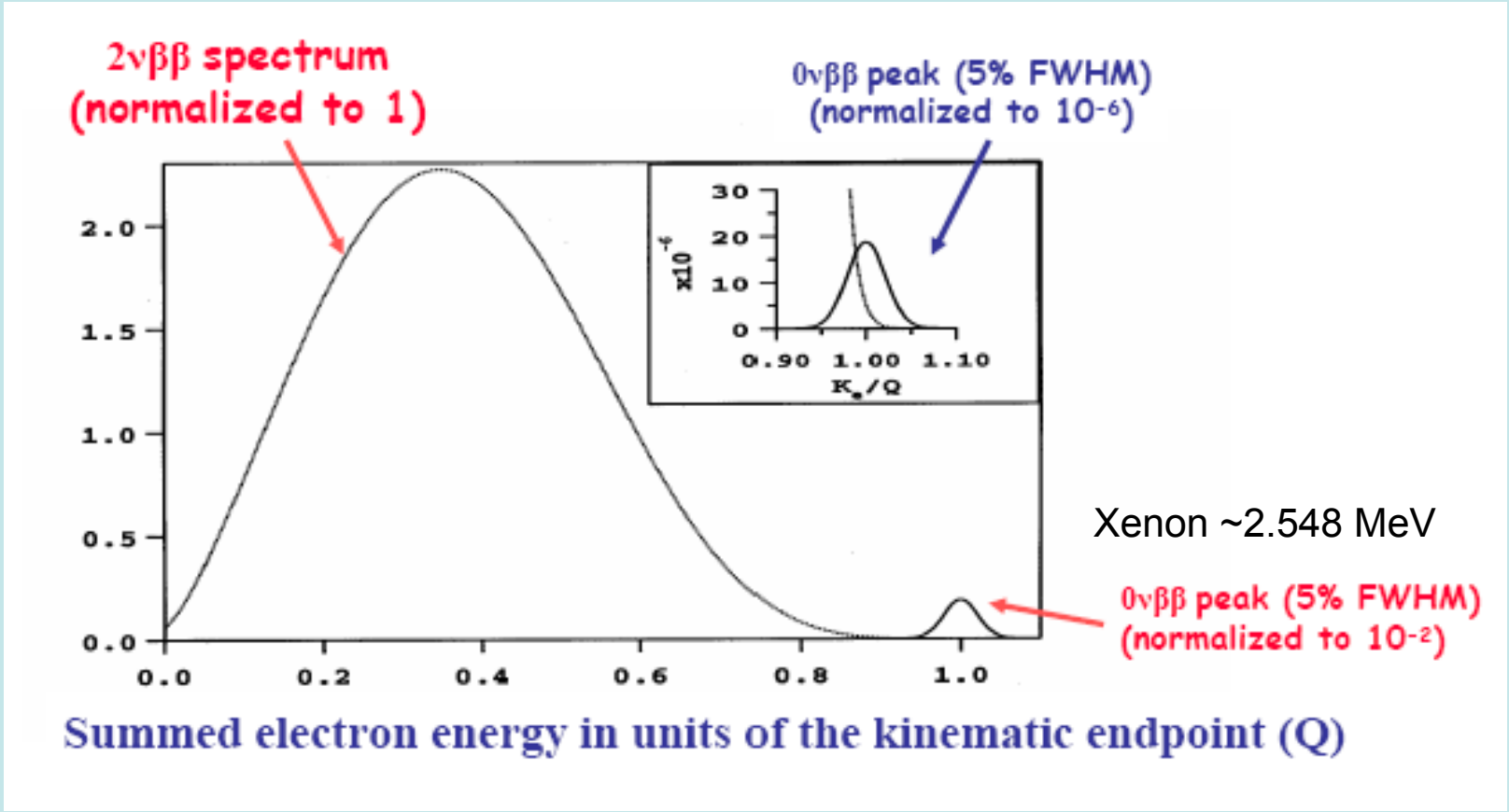
neutrino mass scale

neutrino mass hierarchy

EXO: Sensitivity



Double Beta Decay of ^{136}Xe



$$T_{1/2}^{0\nu}(y) \approx \sqrt{\frac{M \cdot t}{N_{Bkg} \cdot \Delta E}}$$

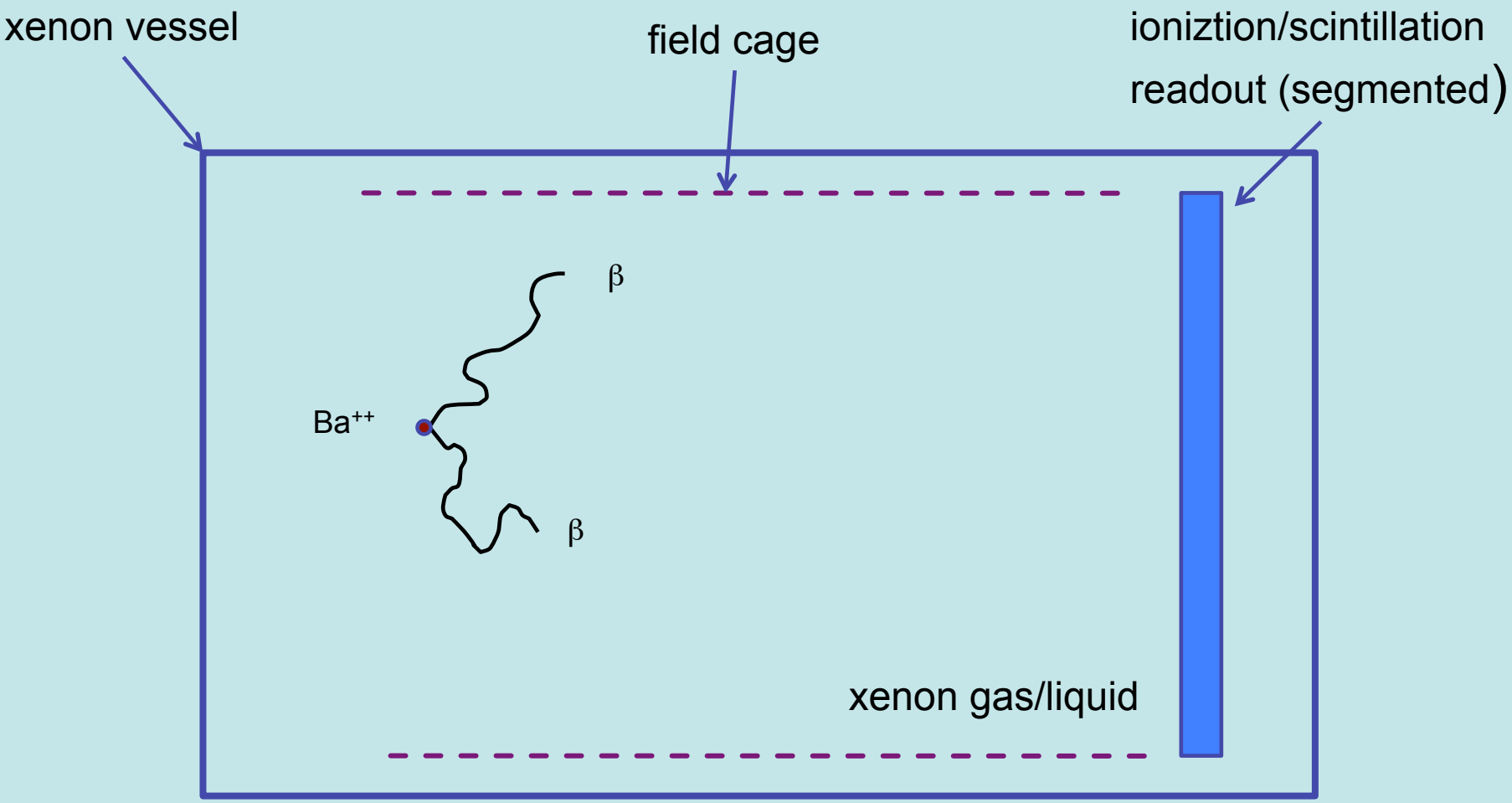
1) Mitigate non-ββ backgrounds
2) Minimize 2νββ contamination
3) Large mass x exposure time

EXO Program

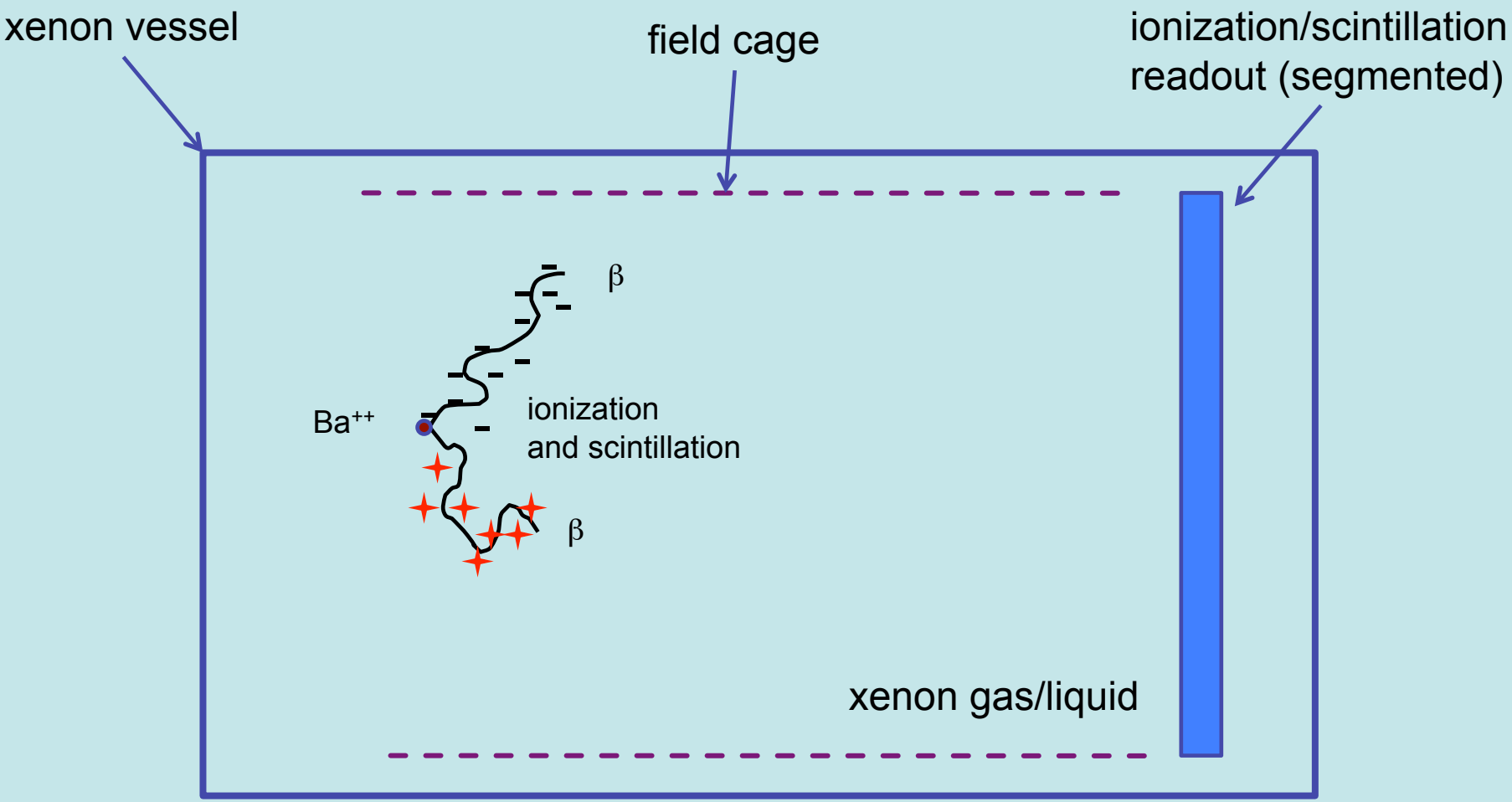
Measurement of ^{136}Xe $2\nu\beta\beta$ and search for $0\nu\beta\beta$

- **EXO 200**
  - liquid xenon time projection chamber (scintillation and ionization)
  - 200 kg of enriched xenon (~80%)
  - demonstrate energy resolution/low bkgs/**physics results**
- **EXO Gas-phase**
  - prototype gas-phase TPC (scintillation and ionization)
  - event reconstruction (σ_E~1%, tracking, dE/dx)
- **Barium Tag**
  - could eliminate all non-$\beta\beta$ backgrounds
- **"Full EXO"**
  - multi-tonne TPC…utilize 'best' technologies developed

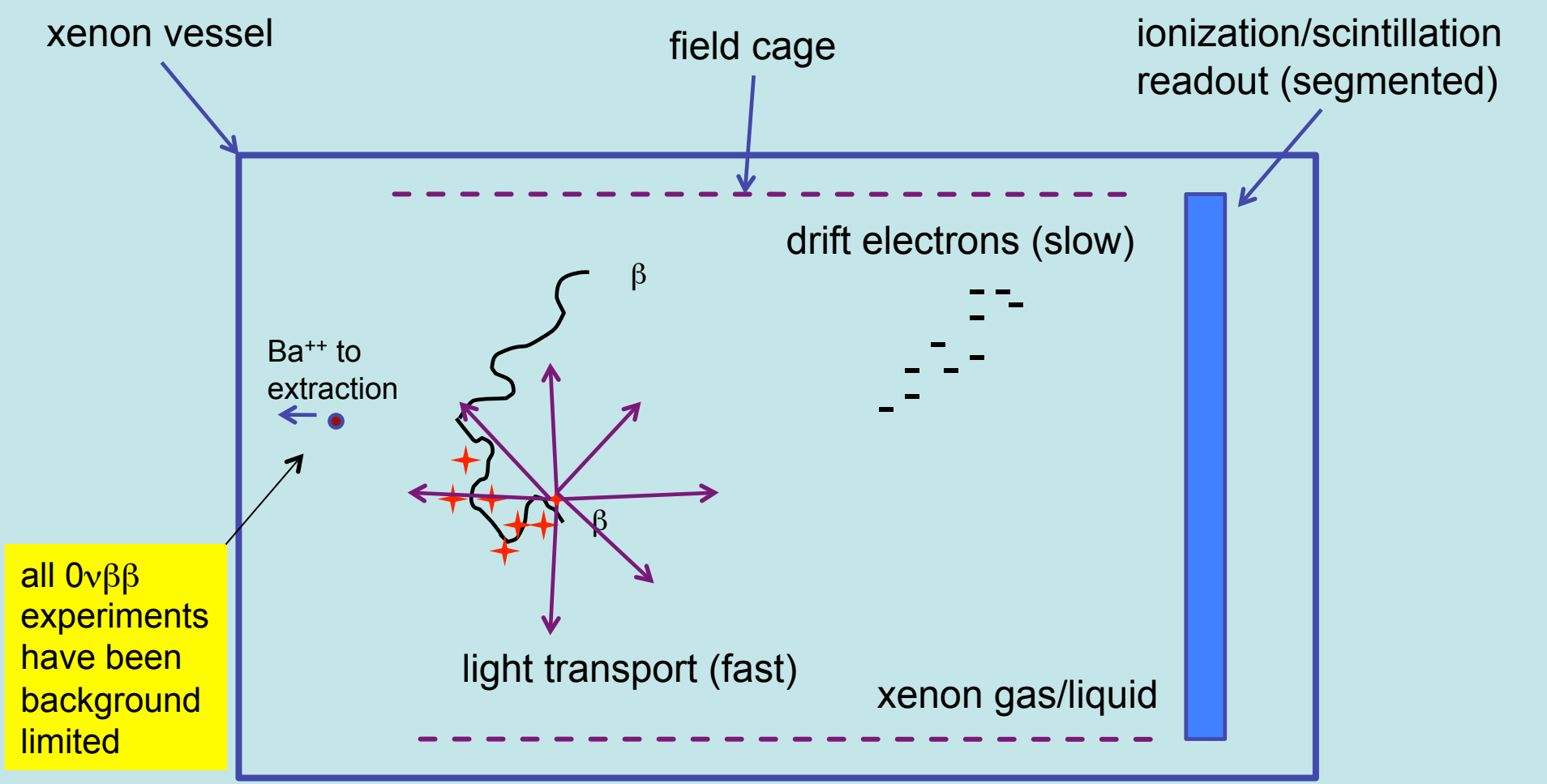
Detector Cartoon for EXO



Detector Concept for EXO



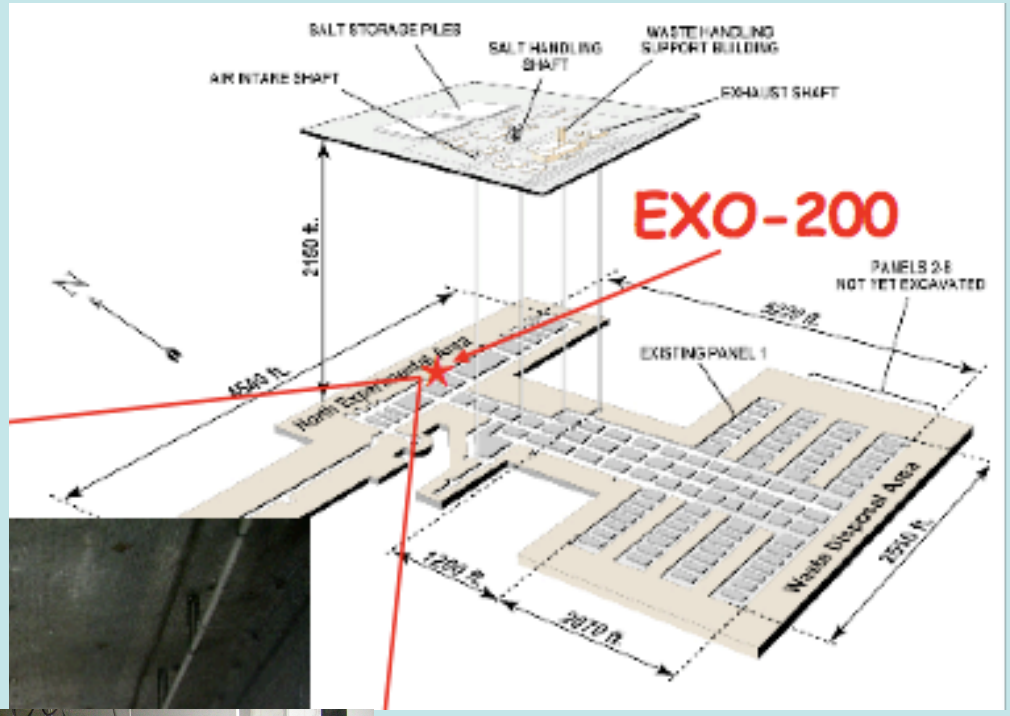
Detector Concept for EXO



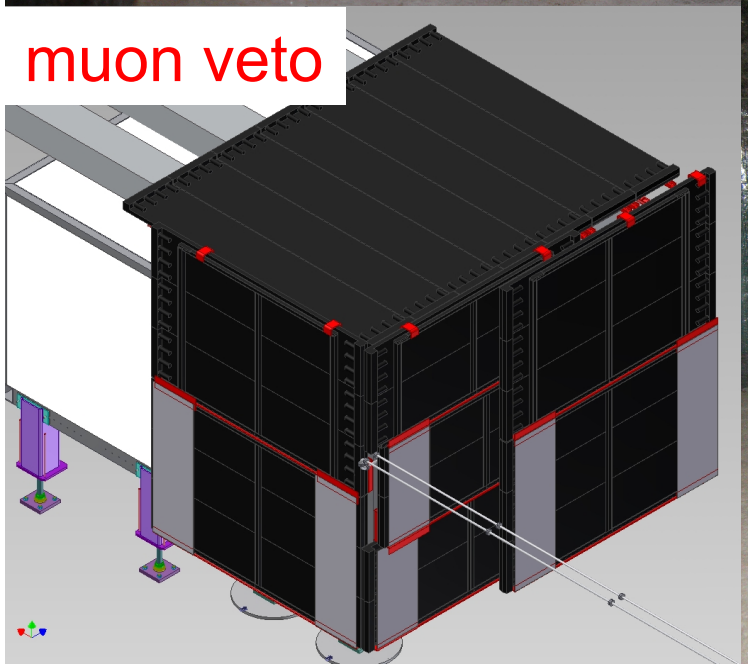
- signals read out
- processed by electronics
- event reconstruction

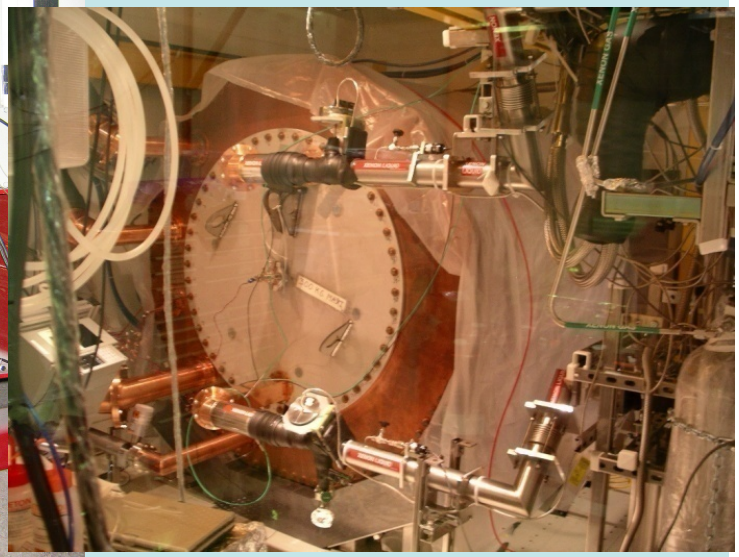
EXO-200 at WIPP

near Carlsbad New Mexico



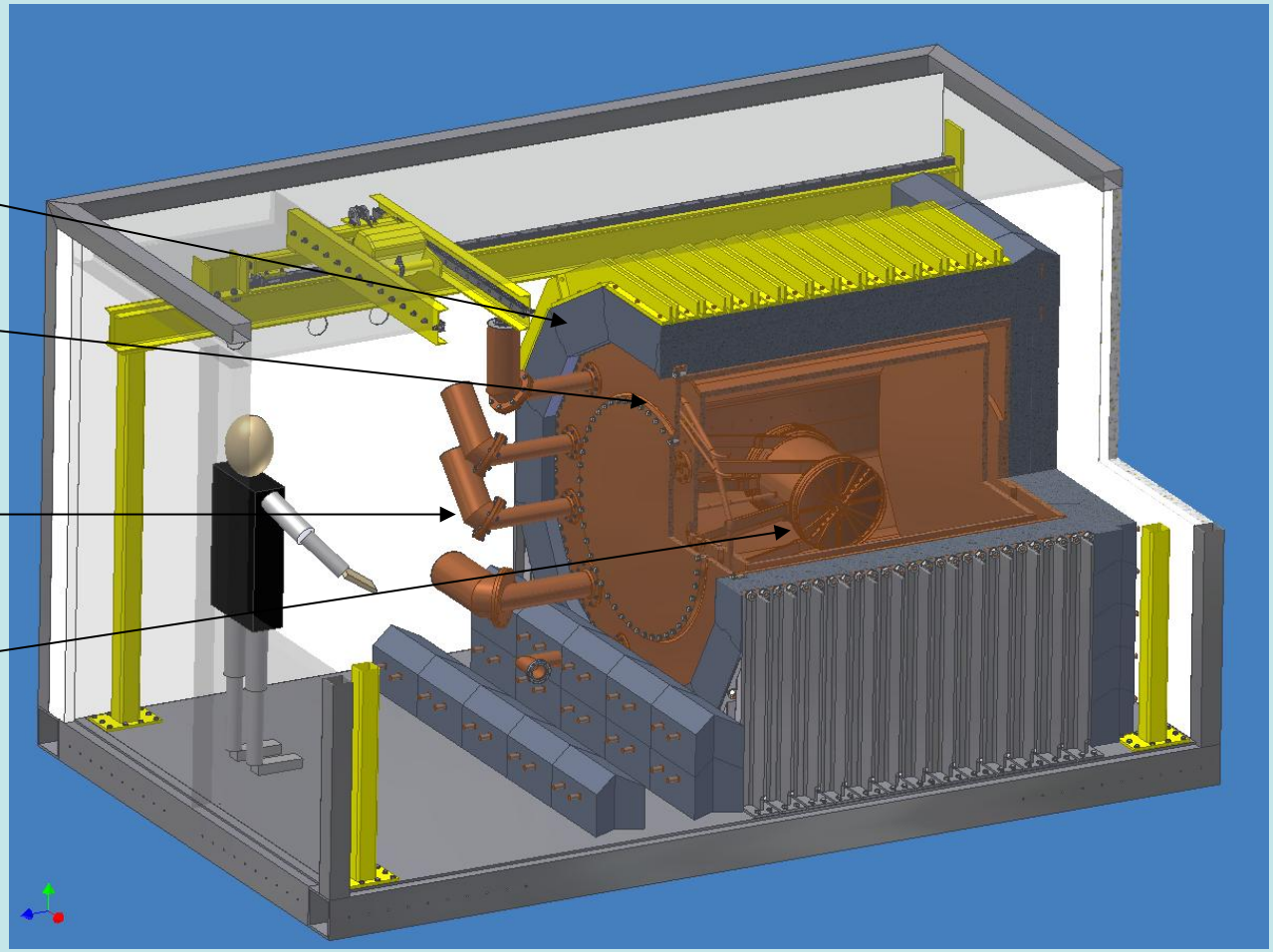
muon veto



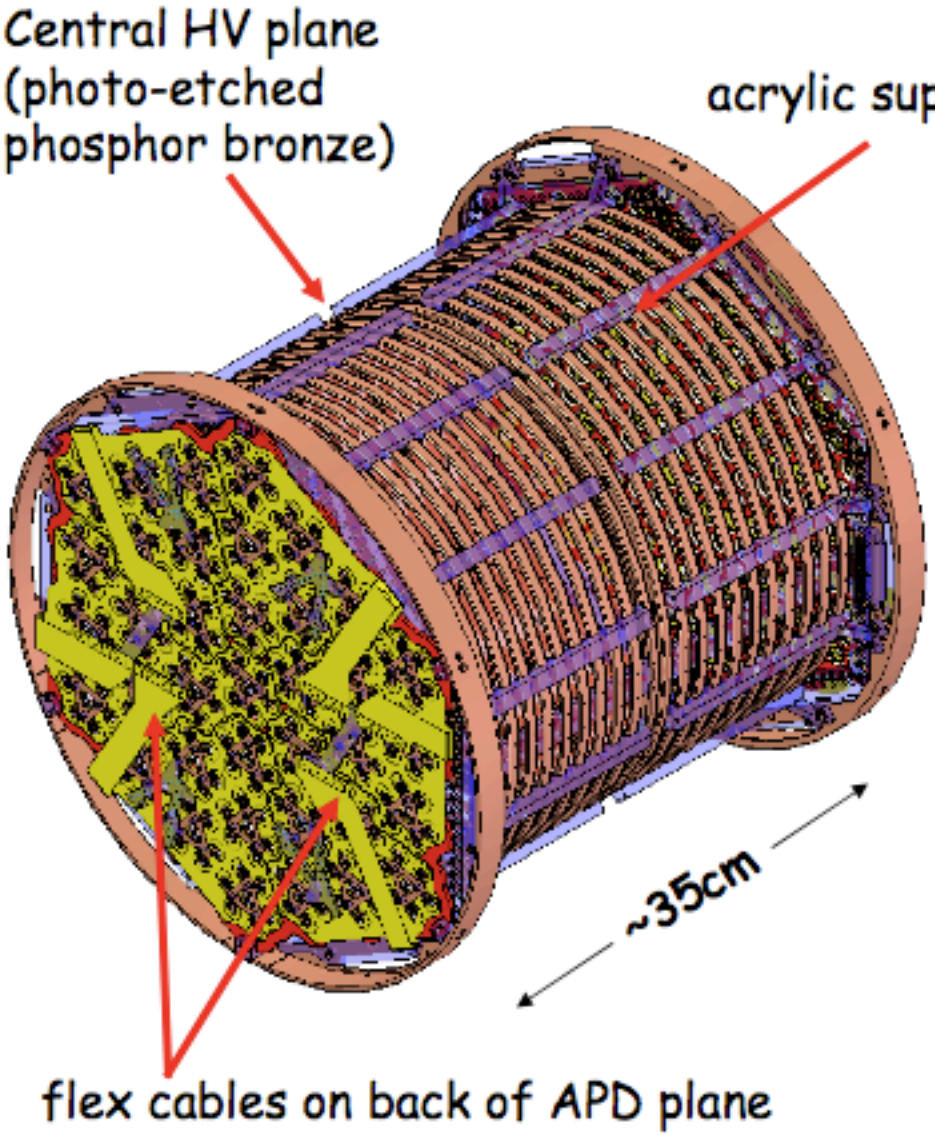


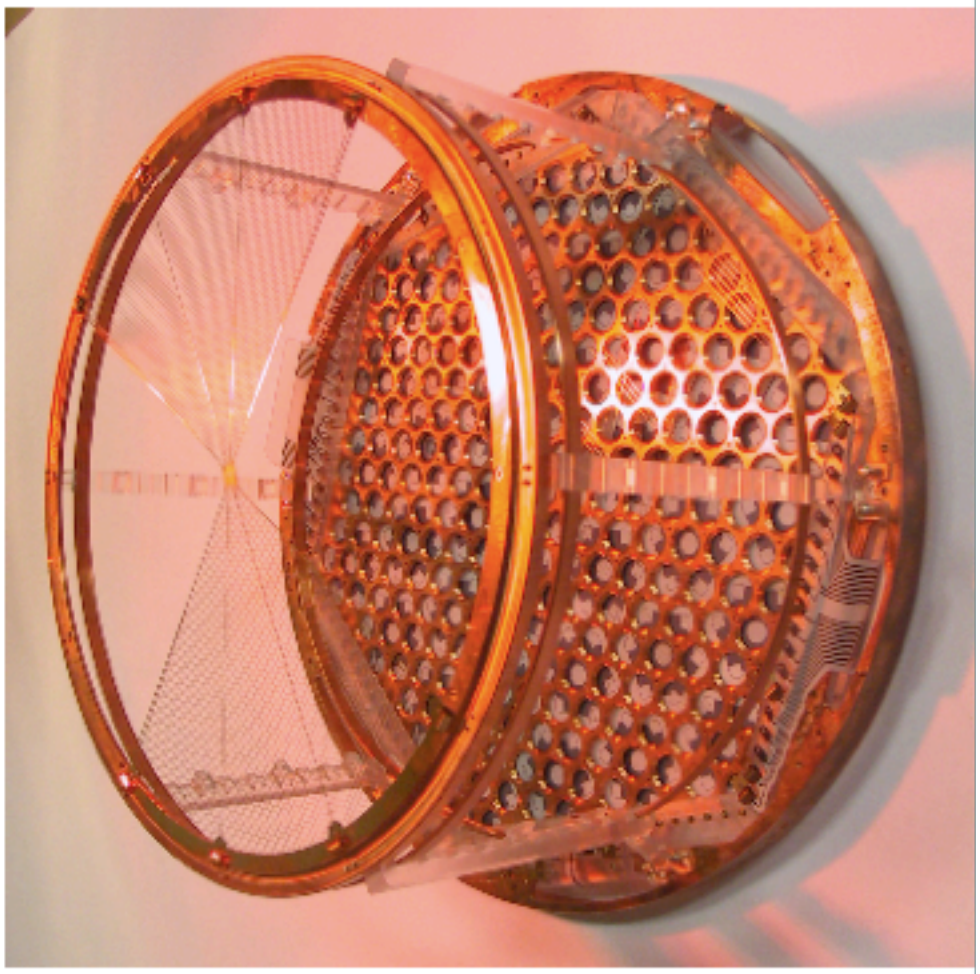
EXO-200

- liquid phase TPC holding 200 kg of enriched liquid xenon
- ionization collection (wires) + light collection (APDs)
- no barium tagging for this prototype but being developed

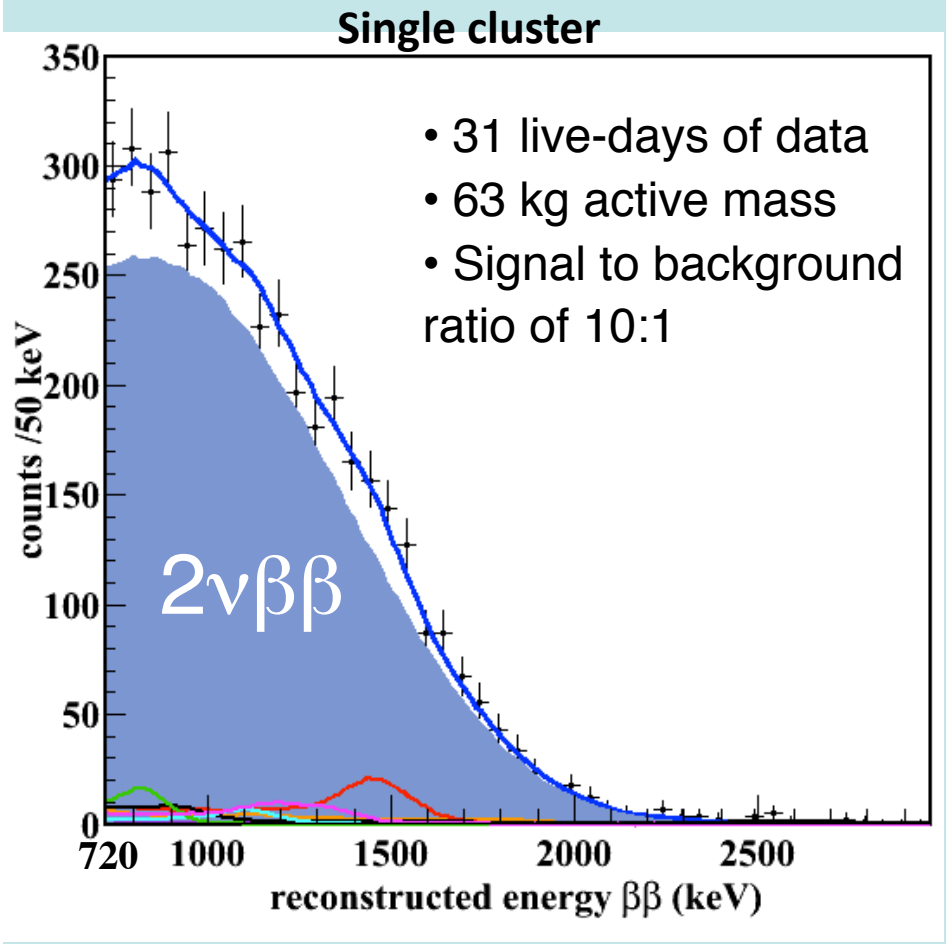


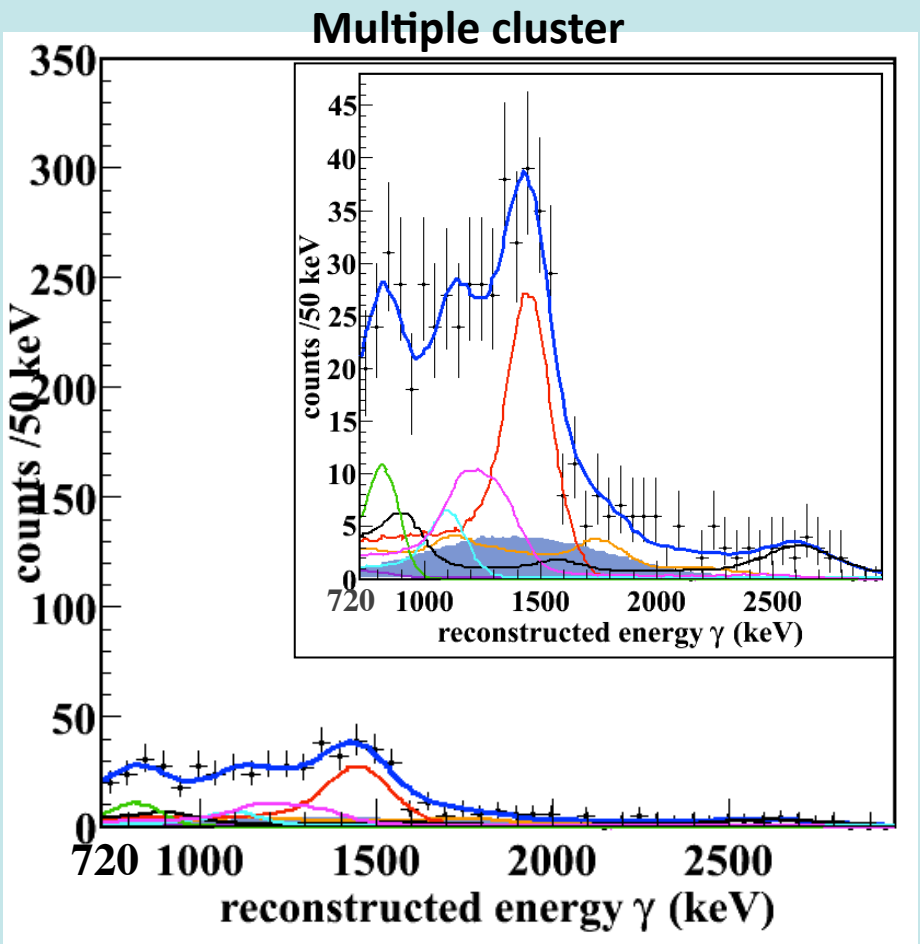
EXO-200 LXe TPC field cage & readout planes





EXO-200: 2νββ observation



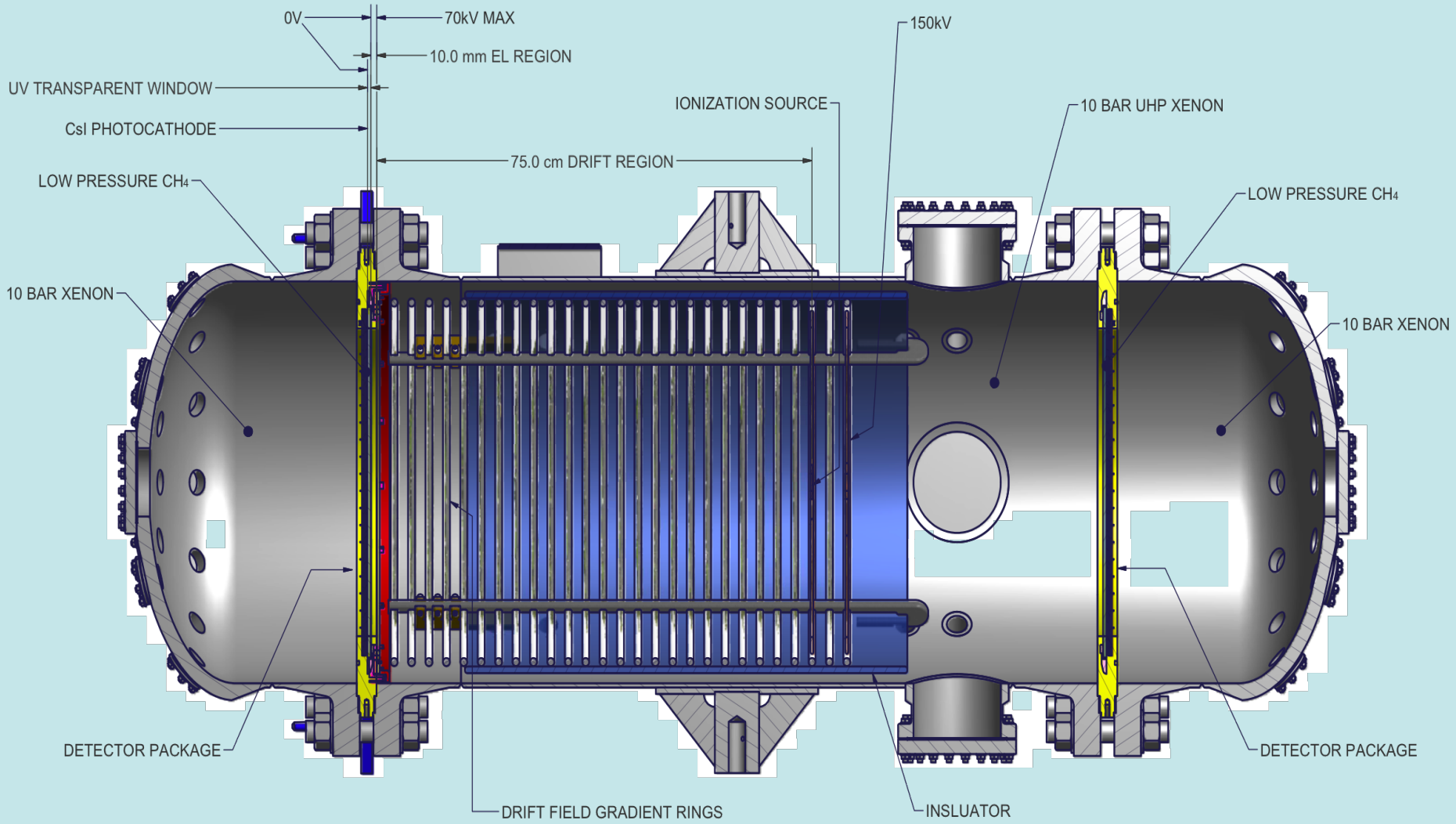


EXO: 2νββ $T_{1/2}$ = (2.11 ± 0.04 stat ± 0.21 sys) x 10^{21} yr

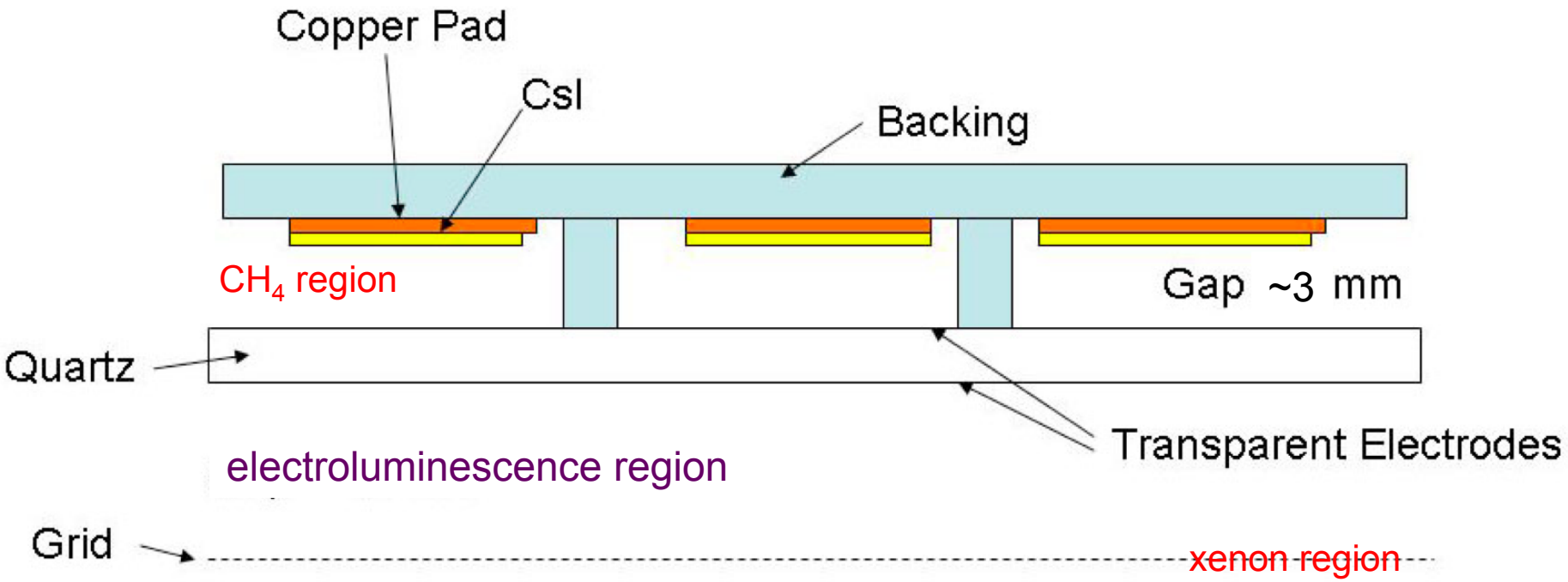
KamLAND-Zen: 2νββ $T_{1/2}$ = (2.38 ± 0.02 stat ± 0.14 sys) x 10^{21} yr

0νββ $T_{1/2} > 5.7 \times 10^{24}$ yr 90% CL (300 < $m_{\beta\beta}$ < 600) meV

XEP Gas-Phase Prototype TPC



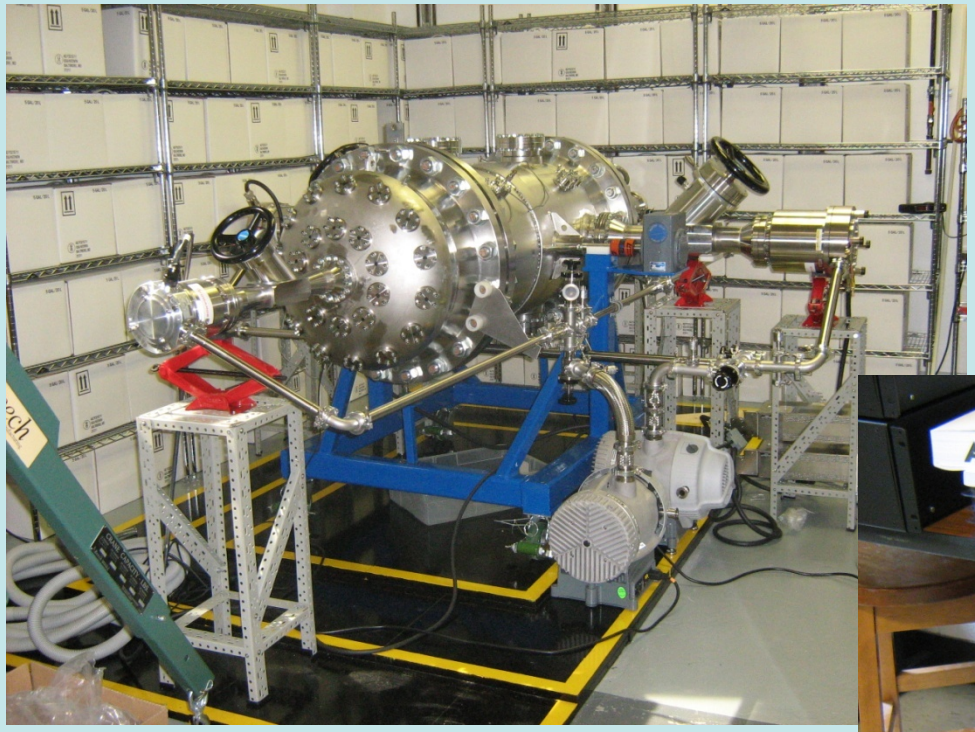
Readout Schematic



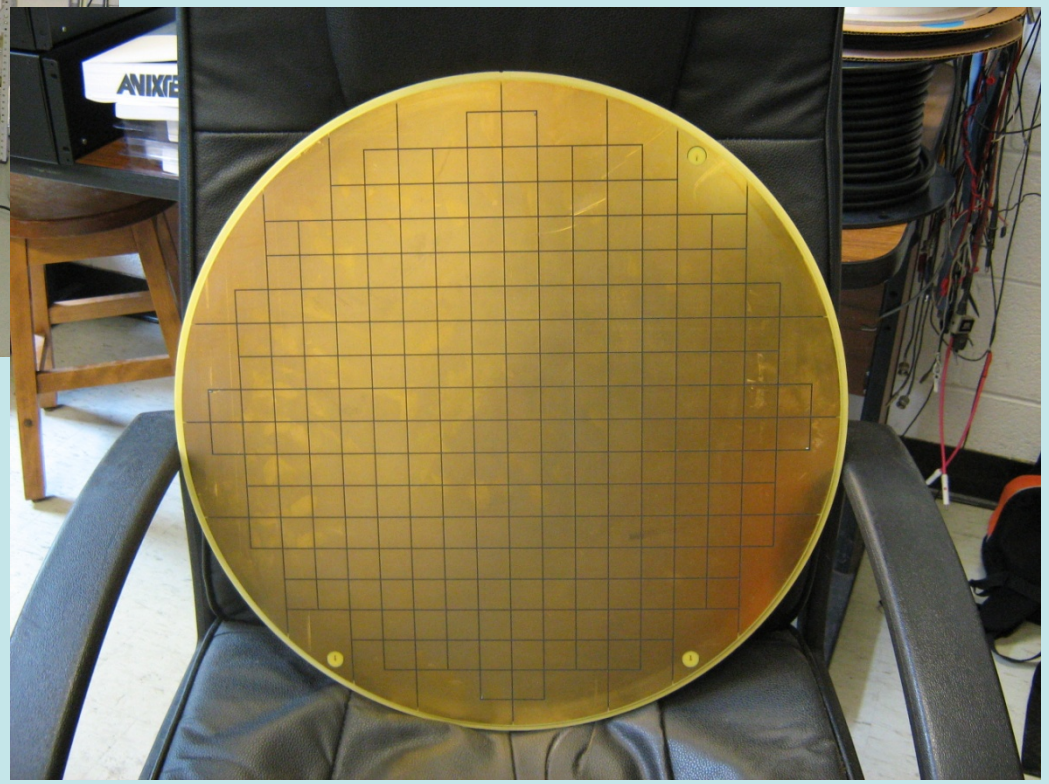
- use CsI coated readout pads to detect scintillation UV photons
- ionization signal converted to UV via electroluminescence

- segment in x-y plane…digitize in time for z 'segmentation'
- total charge (photons) provides energy measurement

XEP Pressure Vessel (10 bar) at Carleton

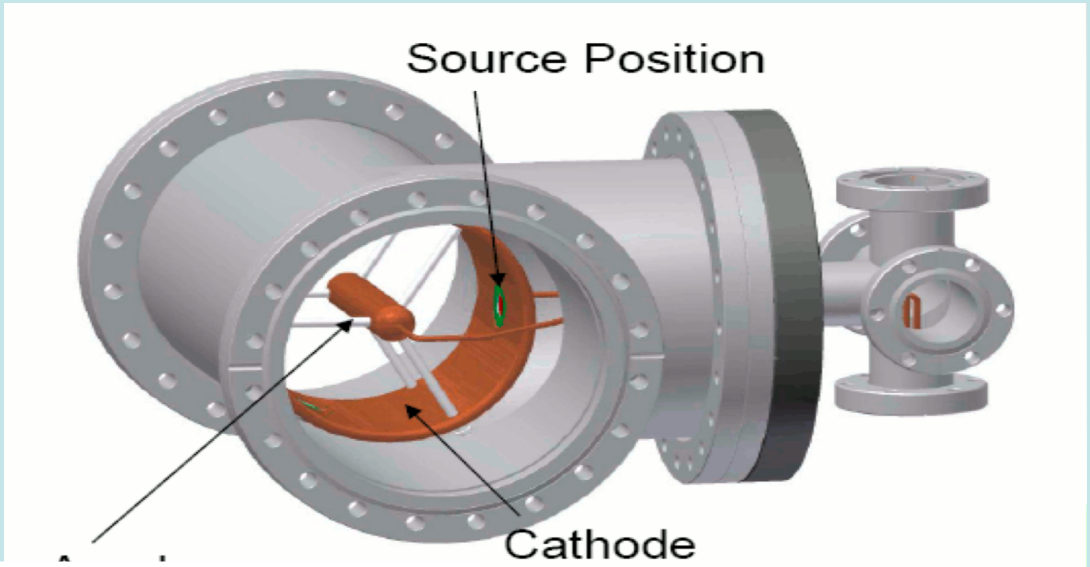


- vacuum/gas systems being installed
- final TPC components being fabricated
- electronics and HV supplies ready



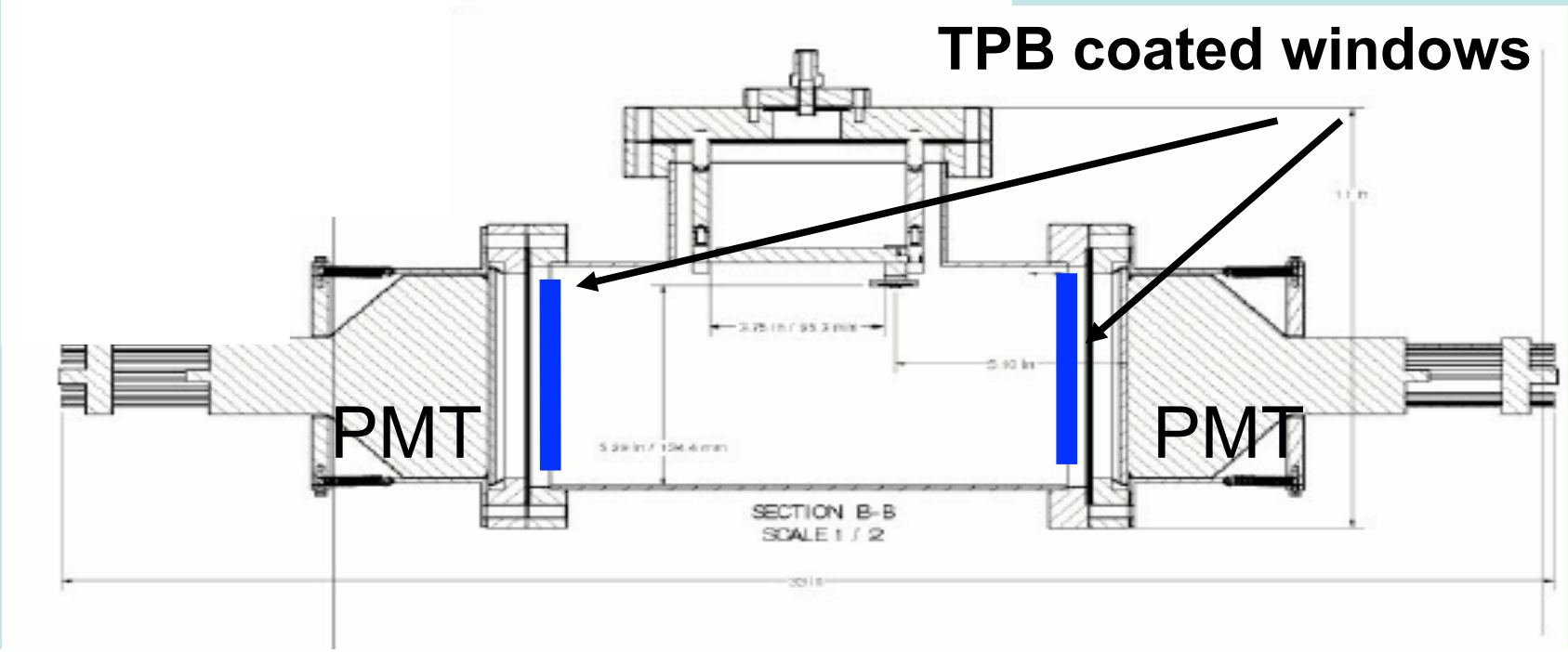
- commission systems in 2 months
- initial detector testing with UV source
- commence TPC operations

Electroluminescence Tests



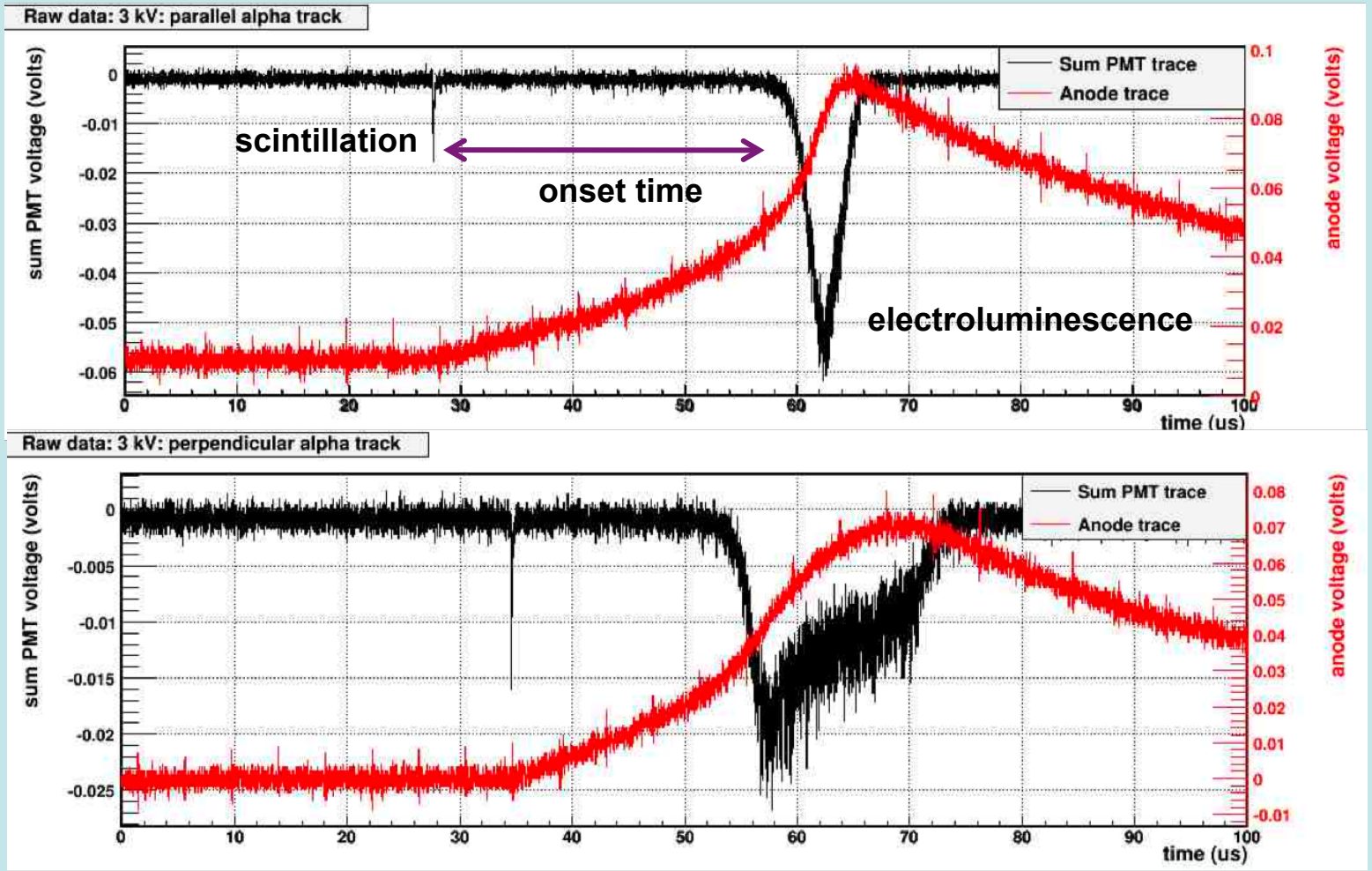
$$dN_\gamma = 140\left(E/p - 1\right)pdx$$

- two-channel detector
- ^{241}Am alpha source
- wavelength shift UV photons to optical

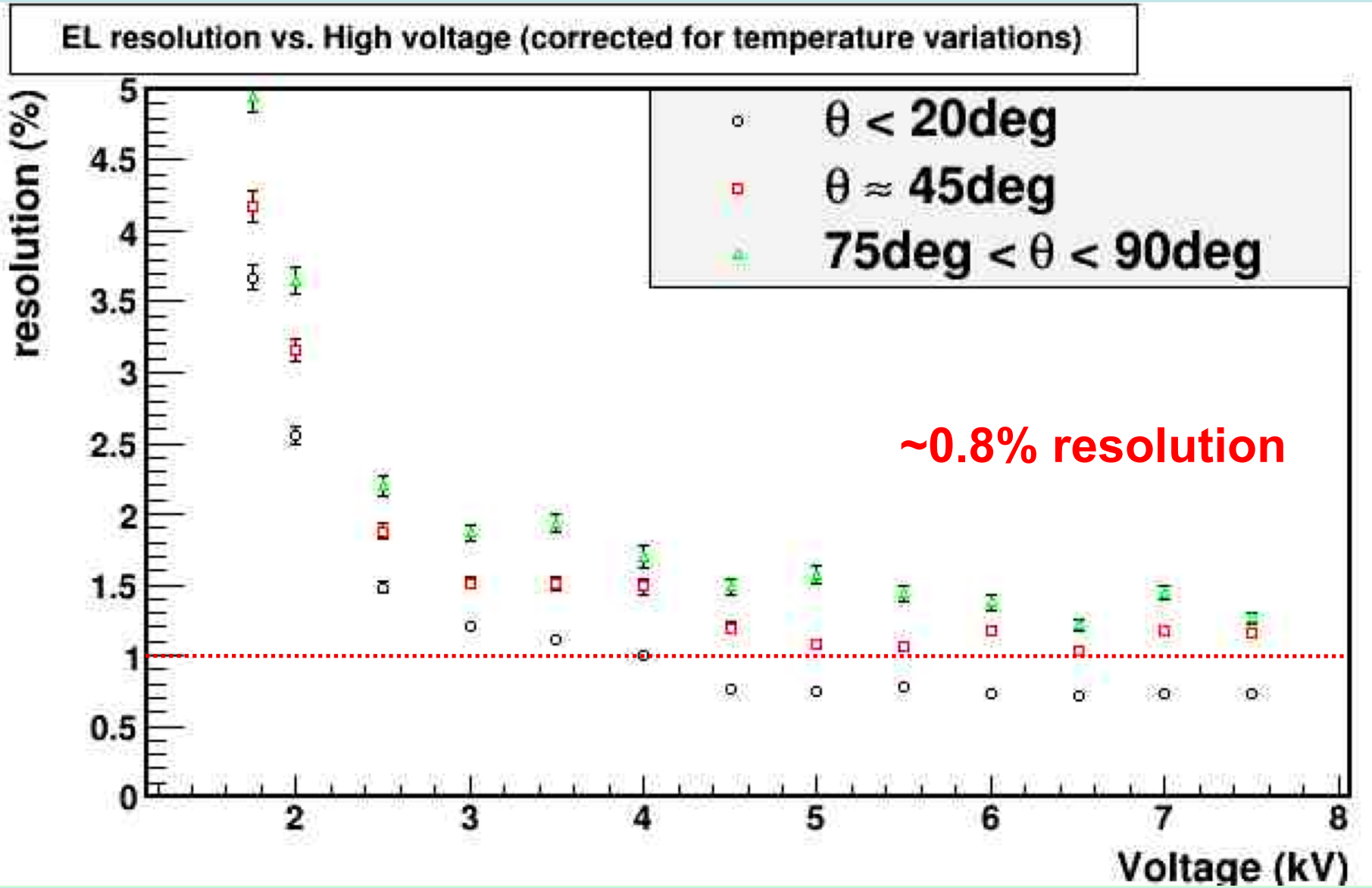


Sample Data Traces

- **Data was aquired over the voltage range (0 – 8000)** volts
- **25000 – 35000 events were taken at each voltage increment.**



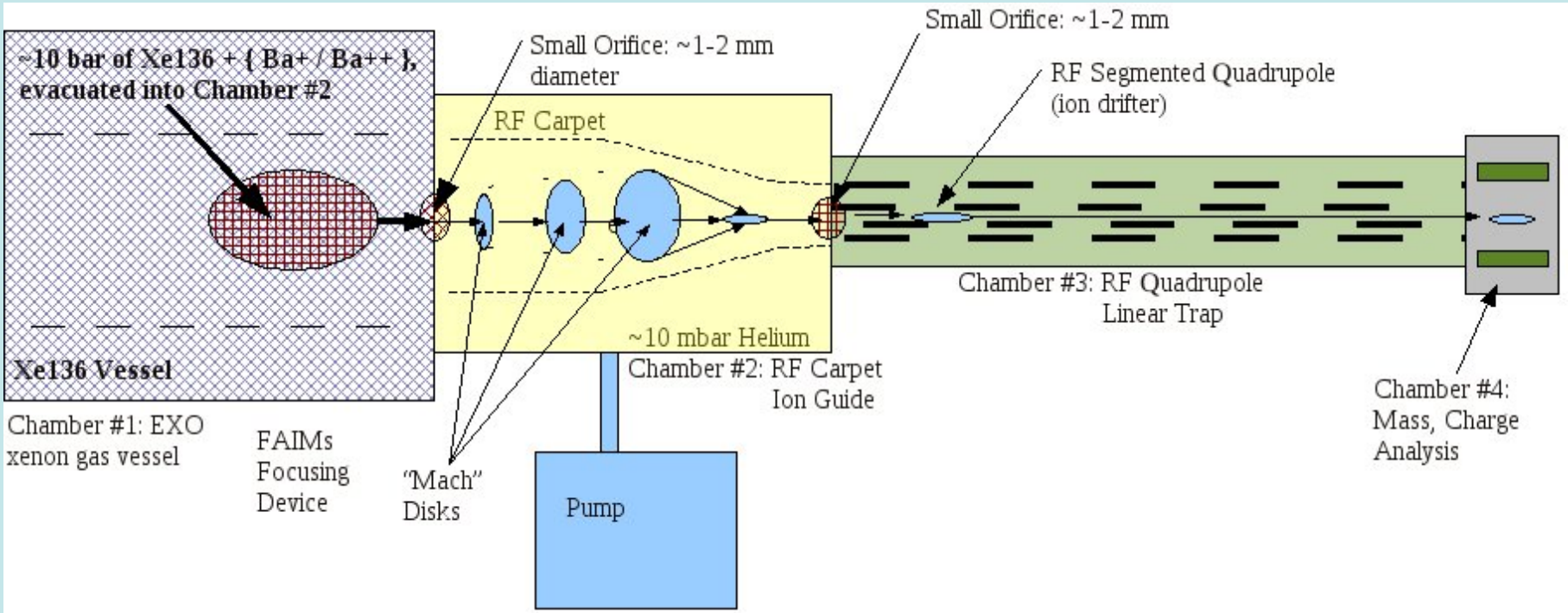
Energy Resolution vs ΔV



Ba Tag - Ion Transport

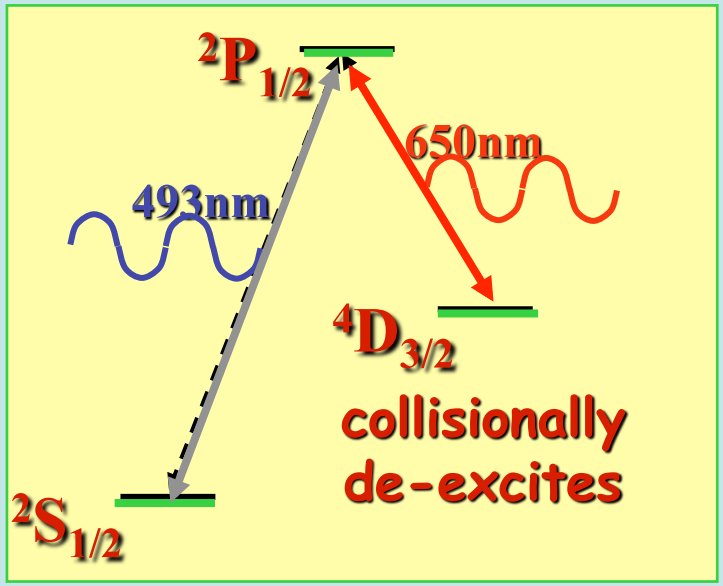
- efficient Ba tag would eliminate all non ββ background
- in-situ tag looks challenging
- instead, transport ion to low-pressure region for ID
- ‘commonly’ carried out for radioactive ion transport

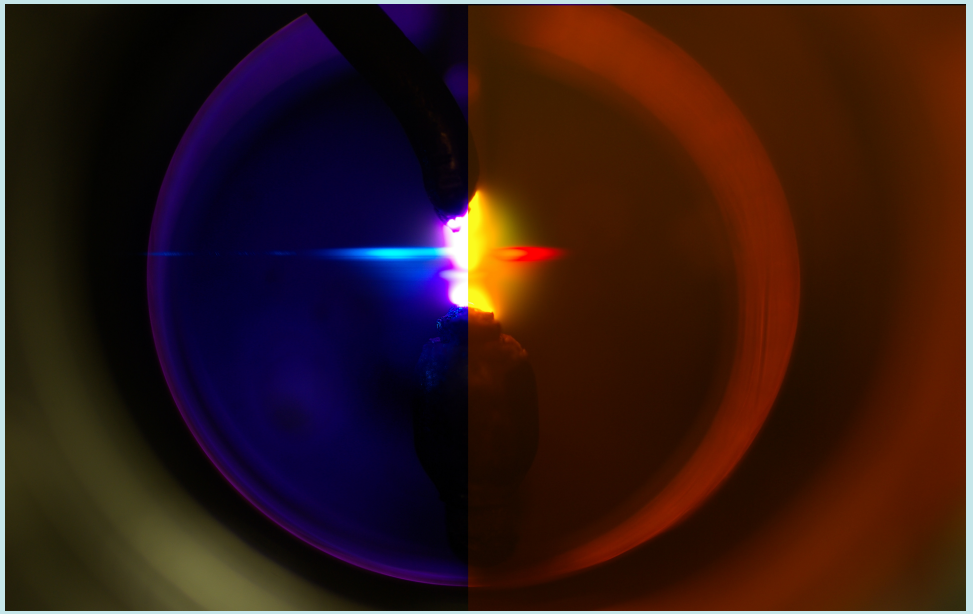
TPC at 10 bar low pressure vacuum Ba ID



Ba ID Techniques

- Ba^+ simple electronic structure
- excite with blue light and look for red





convert Ba^{++} to Ba^+ and then trap and identify spectroscopically

Summary

- EXO-200
  - first measurement of $2\nu\beta\beta$ for ^{136}Xe
  - $0\nu\beta\beta$ results coming soon
- Gas-phase XEP work
  - 0.8 % energy resolution @ 5.5 MeV achieved with EL
  - experience with single-channel CsI photocathode detecting EL photons
  - commission 10-bar TPC this spring
  - ~1 year to optimize and evaluate detector potential
    E resolution and tracking (background suppression)
- Build Complete Gas-phase barium tag
- Develop Large-Scale (multi-tonne) Detector

The 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 - L.J. Kaufman

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

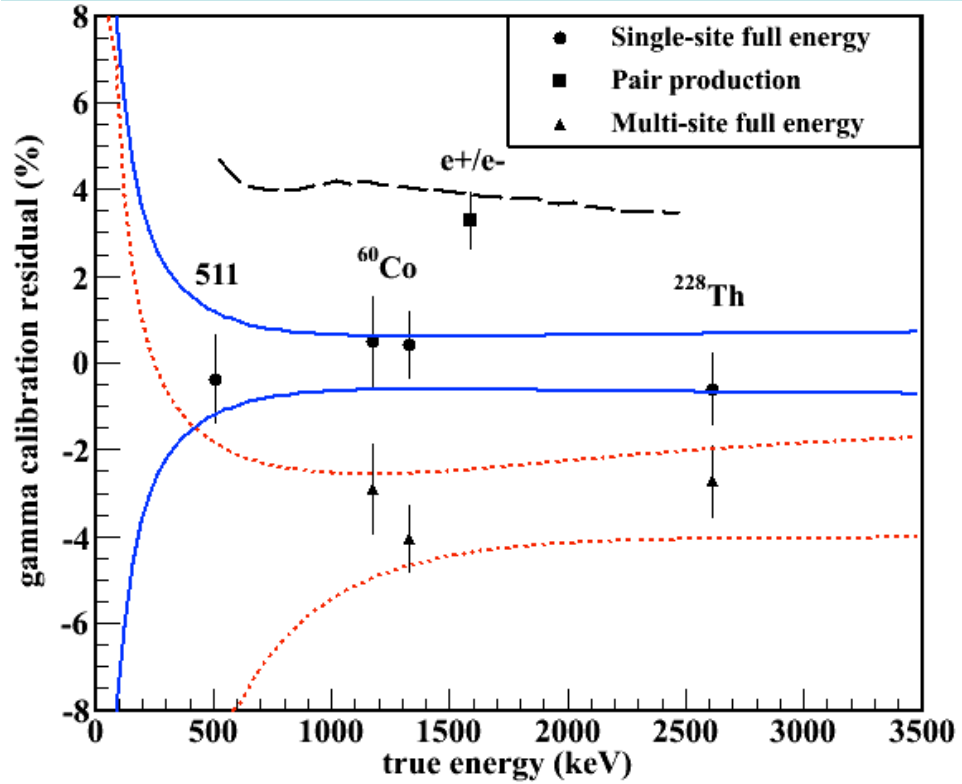
Stanford Linear Accelerator Center (SLAC), Menlo Park CA, USA - M. Breidenbach, R. Conley, R. Herbst, S. Herrin, J. Hodgson, A. Johnson, D. Mackay, A. Odian, C.Y. Prescott, P.C. Rowson, J.J. Russell, K. Skarpaas, M. Swift, A. Waite, M. Wittgen, J. Wodin, L. Yang

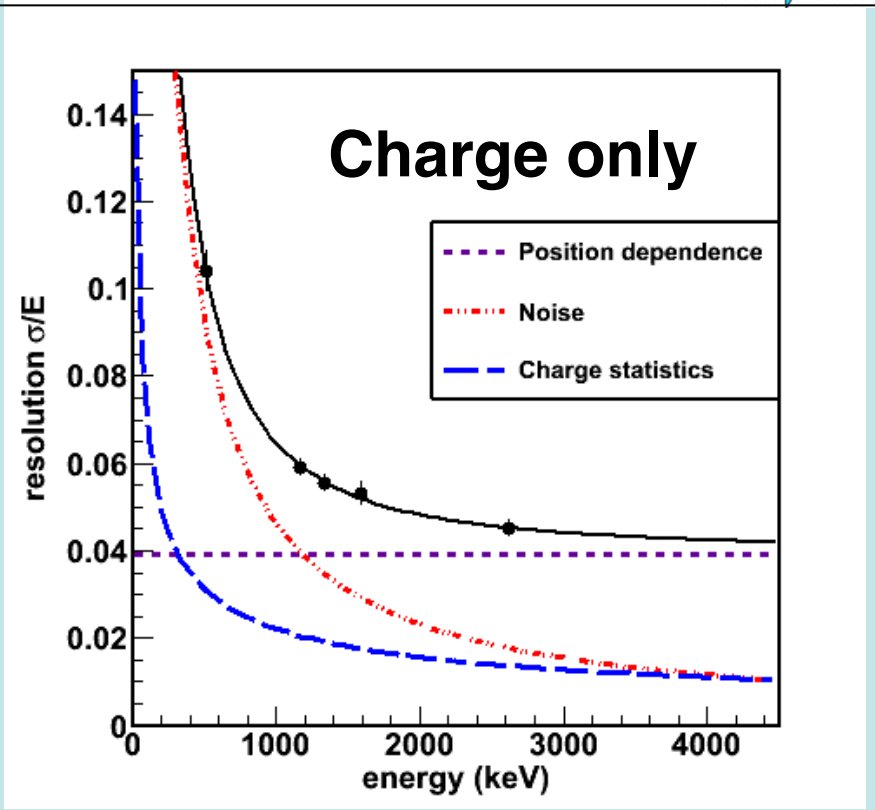
Stanford University, Stanford CA, USA - P.S. Barbeau, J. Davis, R. DeVoe, M.J. Dolinski, G. Gratta, M. Montero-Díez, A.R. Müller, R. Neilson, K. O'Sullivan, A. Rivas, A. Sabourov, D. Tosi, K. Twelker

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

Extra Slides

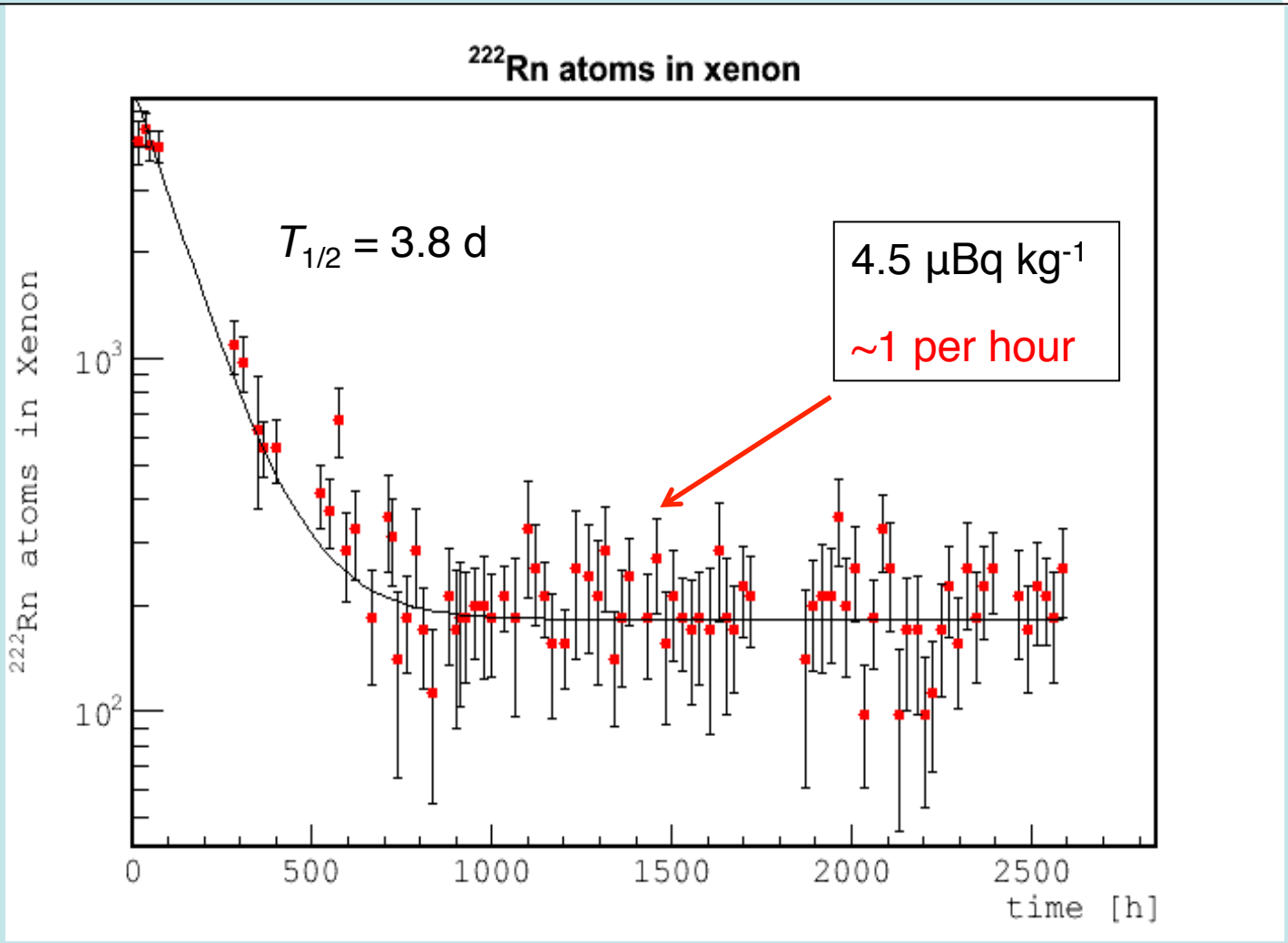
EXO-200: Energy scale





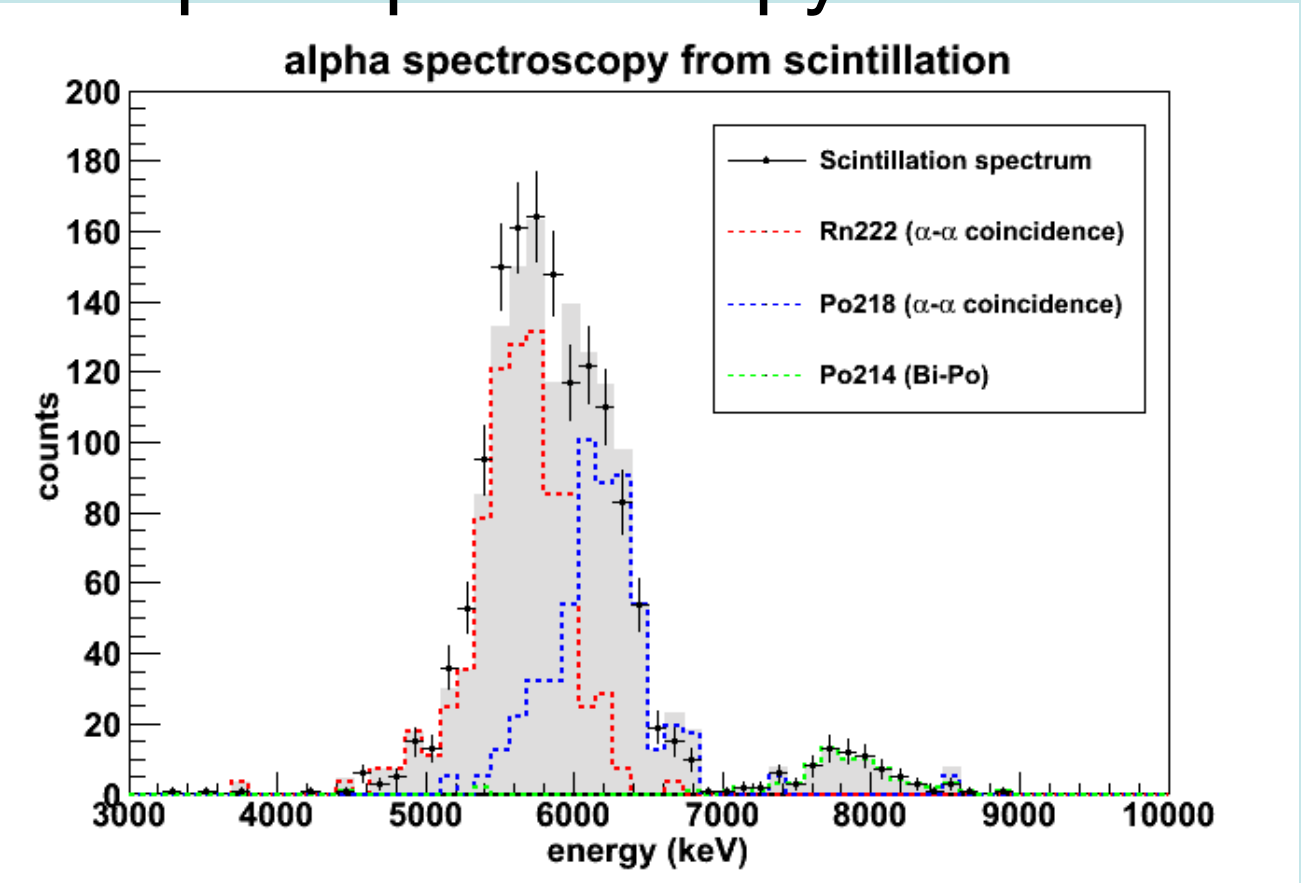
- Calibrated single and multiple cluster peaks across energy region of interest, 511 to 2615 keV (uncertainty bands are systematic)
- Point-like depositions have large reconstructed energies due to induction effects
  - observed for pair-production events (similar to β and ββ decays)
  - reproduced in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

EXO-200: Radon



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

EXO-200: Alpha spectroscopy

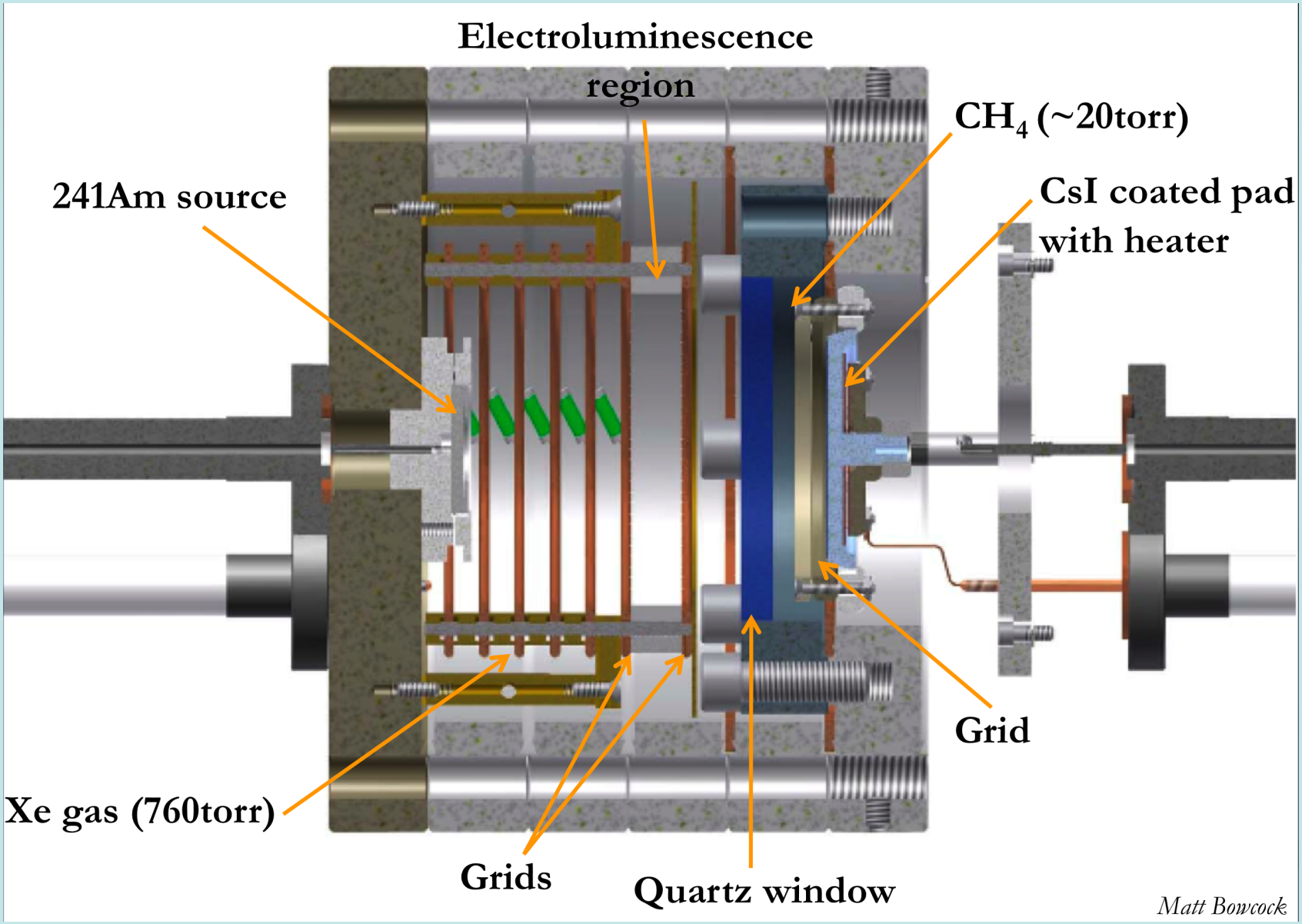


- Investigate alpha spectrum for scintillation signals from ^{238}U
- Calibrate spectrum with alphas in Rn chain
- Can constrain contamination of ^{238}U in bulk LXe by searching for 4.5 MeV alphas

  < 0.3 counts per day in our fiducial volume

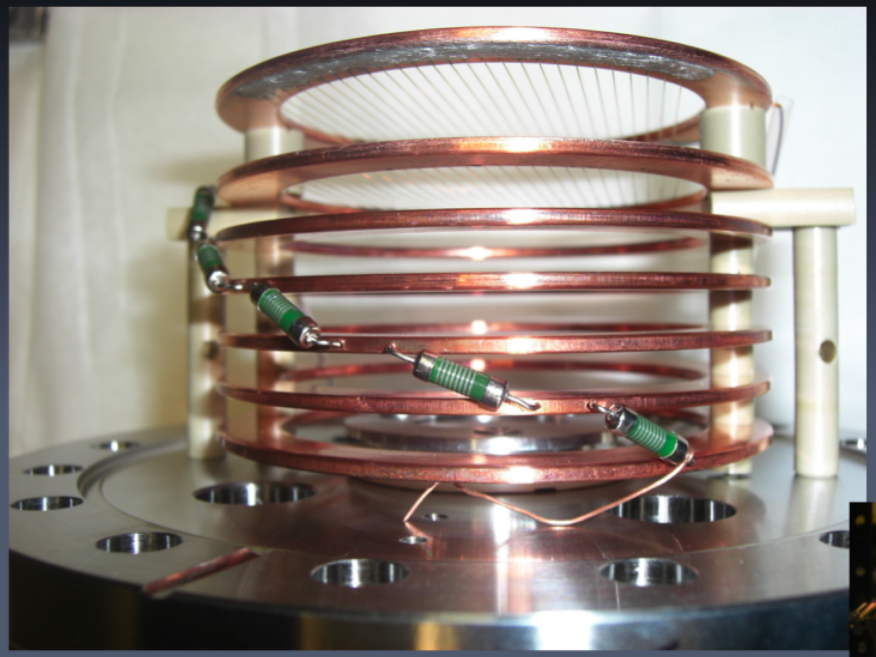
  -The same limit applies to its daughter ^{234m}Pa which β decays with a Q-value of 2195 keV, which cannot then explain our LXe bulk signal

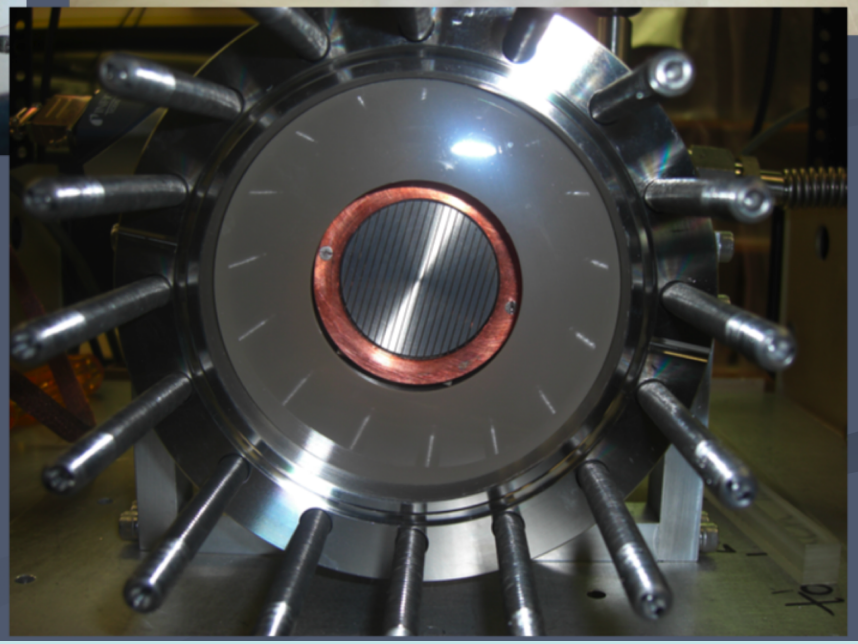
Single Channel CsI Detector



Xenon Side

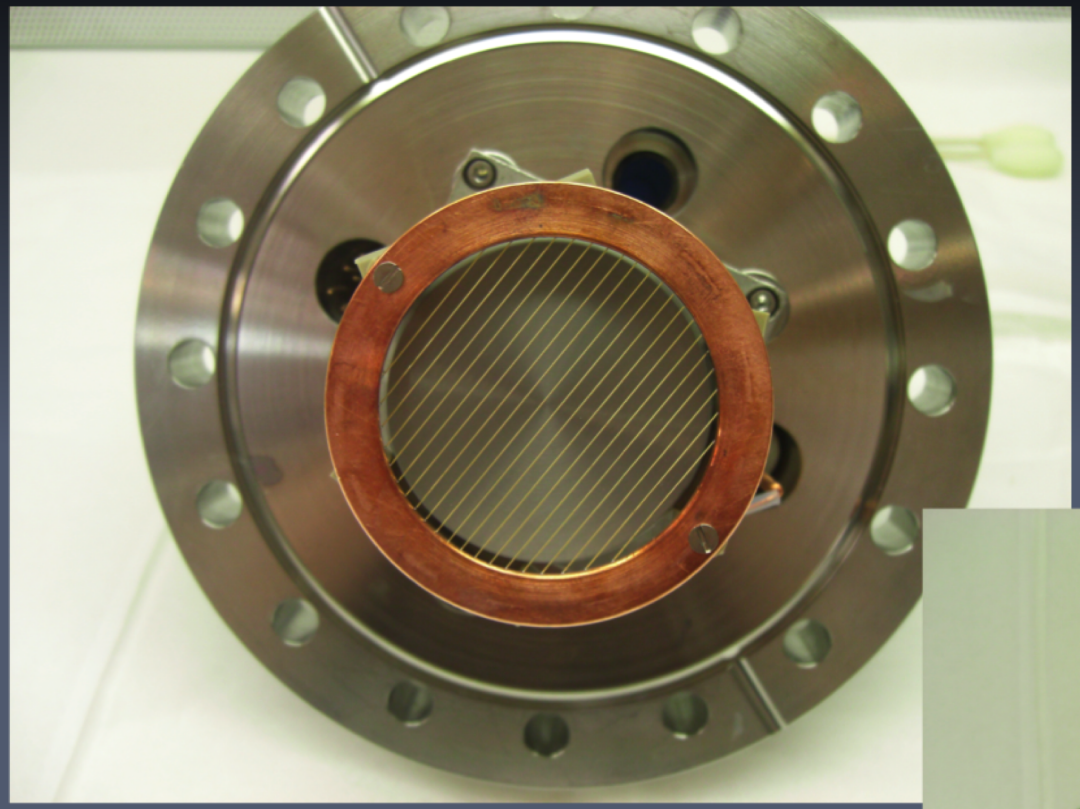
CsI test chamber concept: Xe side





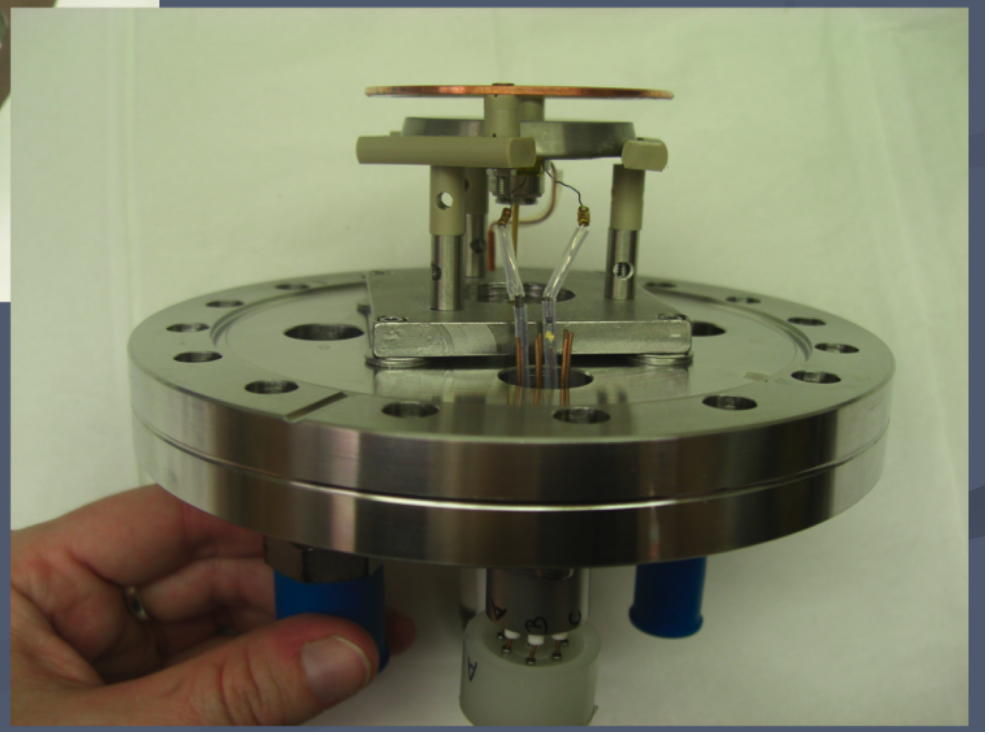
- Grids have pitch = 2.5mm, wire diameter = 0.25mm
- Highest E_{EL} achieved without breakdown is 2700V/cm
- Drift field set at ~70V/cm
- Xe purified through SAES getter when filling

CsI Side

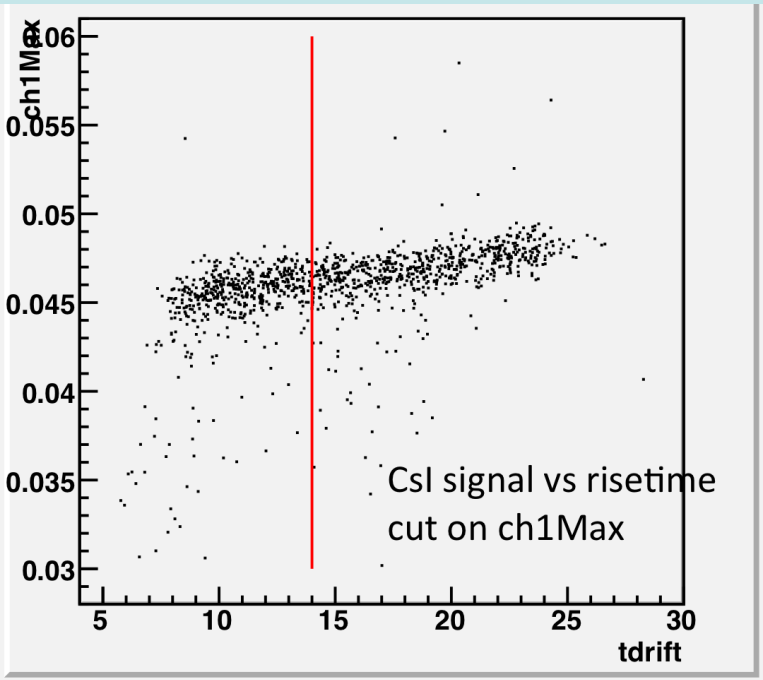


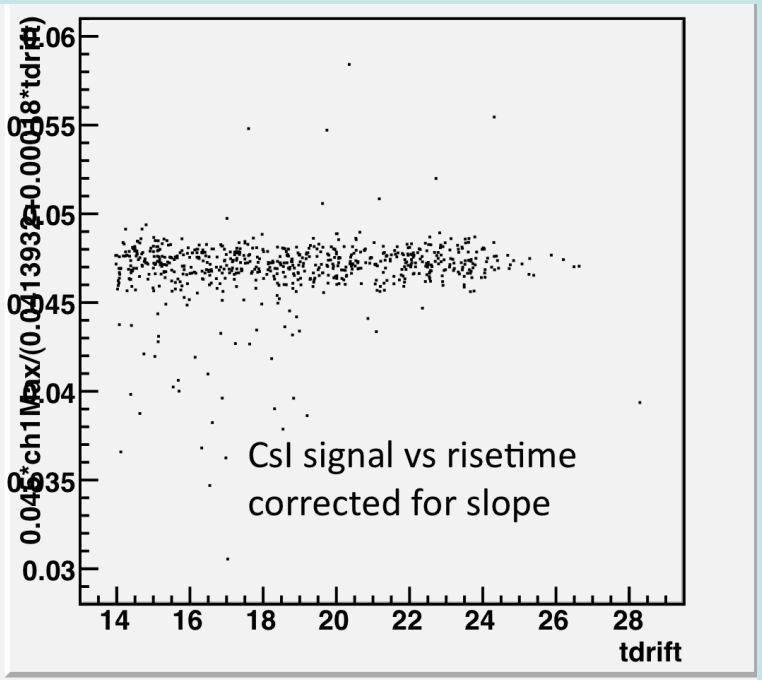
Main materials in the CH_4:
- Stainless
- Copper
- UHV solder
- PEEK
- Teflon (insulate wires)

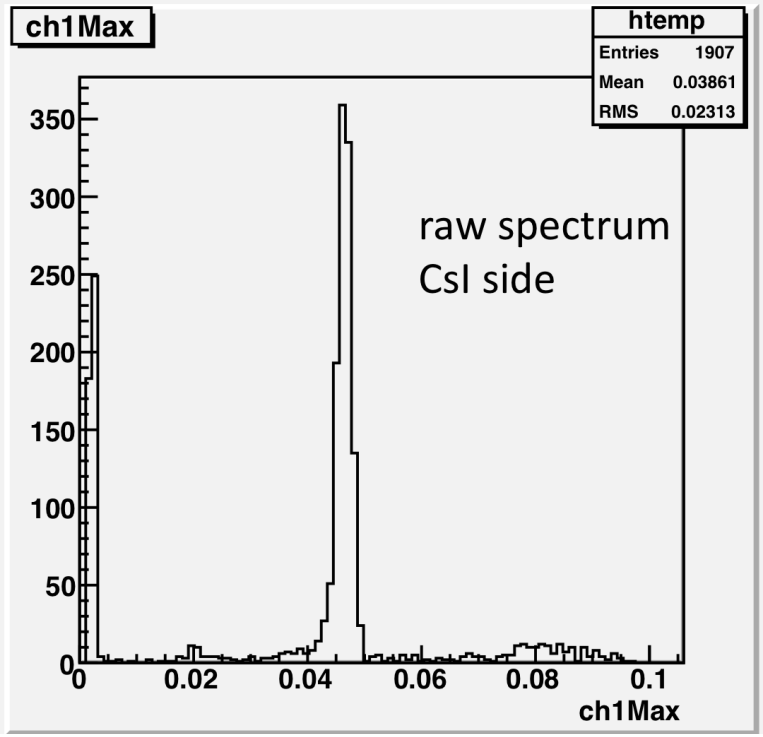
Grid has pitch = 2.5mm, wire diameter = 0.25mm

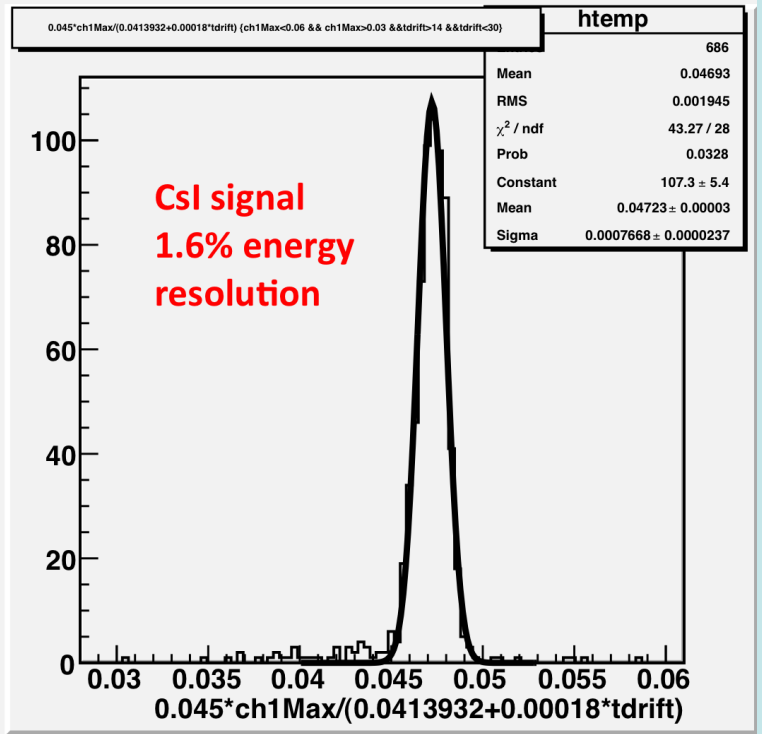


CsI evaporation:
- about 20 – 25min exposure to air before assembly
- thickness of coating ~ 300 – 500nm
- CsI/readout is always heated at 60C for at least 12h after assembly or before new CH4 is added to the chamber


ch1Max
0.06
0.055
0.05
0.045
0.04
0.035
0.03
5
10
15
20
25
30
tdrift
CsI signal vs risetime
cut on ch1Max


0.045*ch1Max/(0.0413932+0.00018*tdrift)
0.06
0.055
0.05
0.045
0.04
0.035
0.03
14
16
18
20
22
24
26
28
tdrift
CsI signal vs risetime
corrected for slope


ch1Max
htemp
Entries 1907
Mean 0.03861
RMS 0.02313
350
300
250
200
150
100
50
0
0
0.02
0.04
0.06
0.08
0.1
ch1Max
raw spectrum
CsI side


0.045*ch1Max/(0.0413932+0.00018*tdrift) {ch1Max<0.06 && ch1Max>0.03 &&tdrift>14 &&tdrift<30}
htemp
686
Mean 0.04693
RMS 0.001945
χ² / ndf 43.27 / 28
Prob 0.0328
Constant 107.3 ± 5.4
Mean 0.04723 ± 0.00003
Sigma 0.0007668 ± 0.0000237
100
80
60
40
20
0
0.03
0.035
0.04
0.045
0.05
0.055
0.06
0.045*ch1Max/(0.0413932+0.00018*tdrift)
CsI signal
1.6% energy
resolution