High Pressure Xenon Electroluminescent TPC for neutrino-less double beta decay

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LBNL, Brown Bag Instrumentation Talk

May 25 2011

Motivations

- Xenon gas at high pressure offers excellent energy resolution - *in principle*
  (only x 3 worse than best Ge diodes!)
- Electroluminescence provides linear gain with extremely low fluctuations
- HP Xe TPC can provide total energy and image of the particle tracks for topological discrimination of event type (Gotthard TPC: x30 g rejection)

- Applications range from g-ray imaging for Homeland security/non-proliferation, medical physics/imaging and 0-n bb decay search in ^{136}Xe
- R&D is focused on the ***NEXT Collaboration***, now preparing for a 100 kg ^{136}Xe TPC detector for Canfranc Underground Laboratory, Spain.

  NEXT is funded at ~5M € for construction

  Spain-Portugal-Colombia-France-Russia-US collaboration

- **Rare nuclear transition between same mass nuclei**
  - **Energetically allowed for even-even nuclei**

- **$(Z,A) \rightarrow (Z+2,A) + e^-_1 + \underline{n}_1 + e^-_2 + \underline{n}_2$**
- **$(Z,A) \rightarrow (Z+2,A) + e^-_1 + e^-_2$**
- **$(Z,A) \rightarrow (Z+2,A) + e^-_1 + e^-_2 + c$**

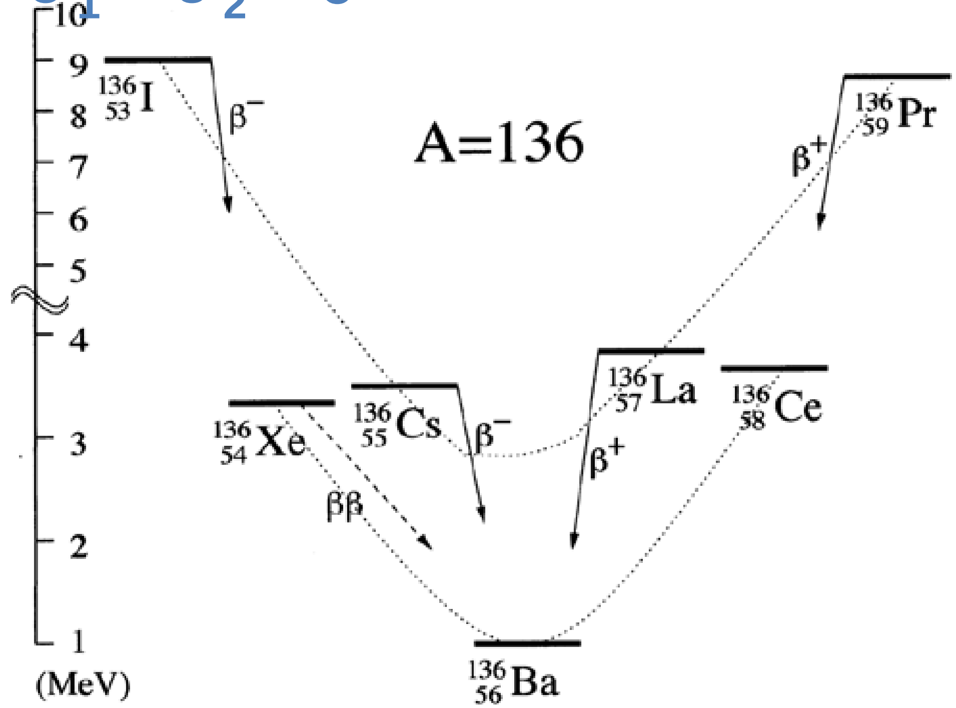
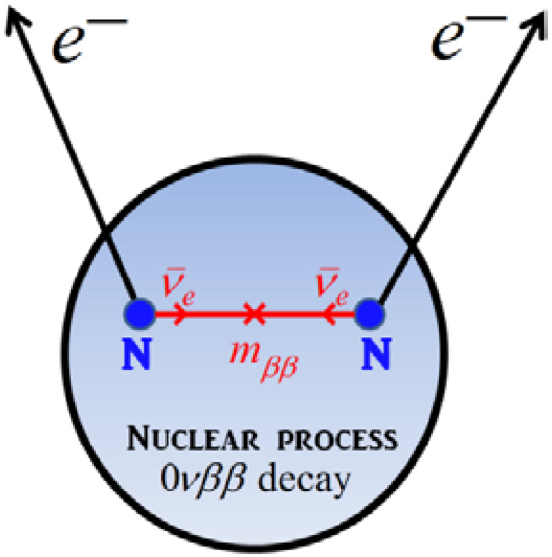


Figure 2.1: Simplified atomic mass scheme for nuclei with A=136. The parabolae connecting the odd-odd and even-even nuclei are shown. While ^{136}Xe is stable to ordinary beta decay, it can decay into ^{136}Ba by double-beta decay.

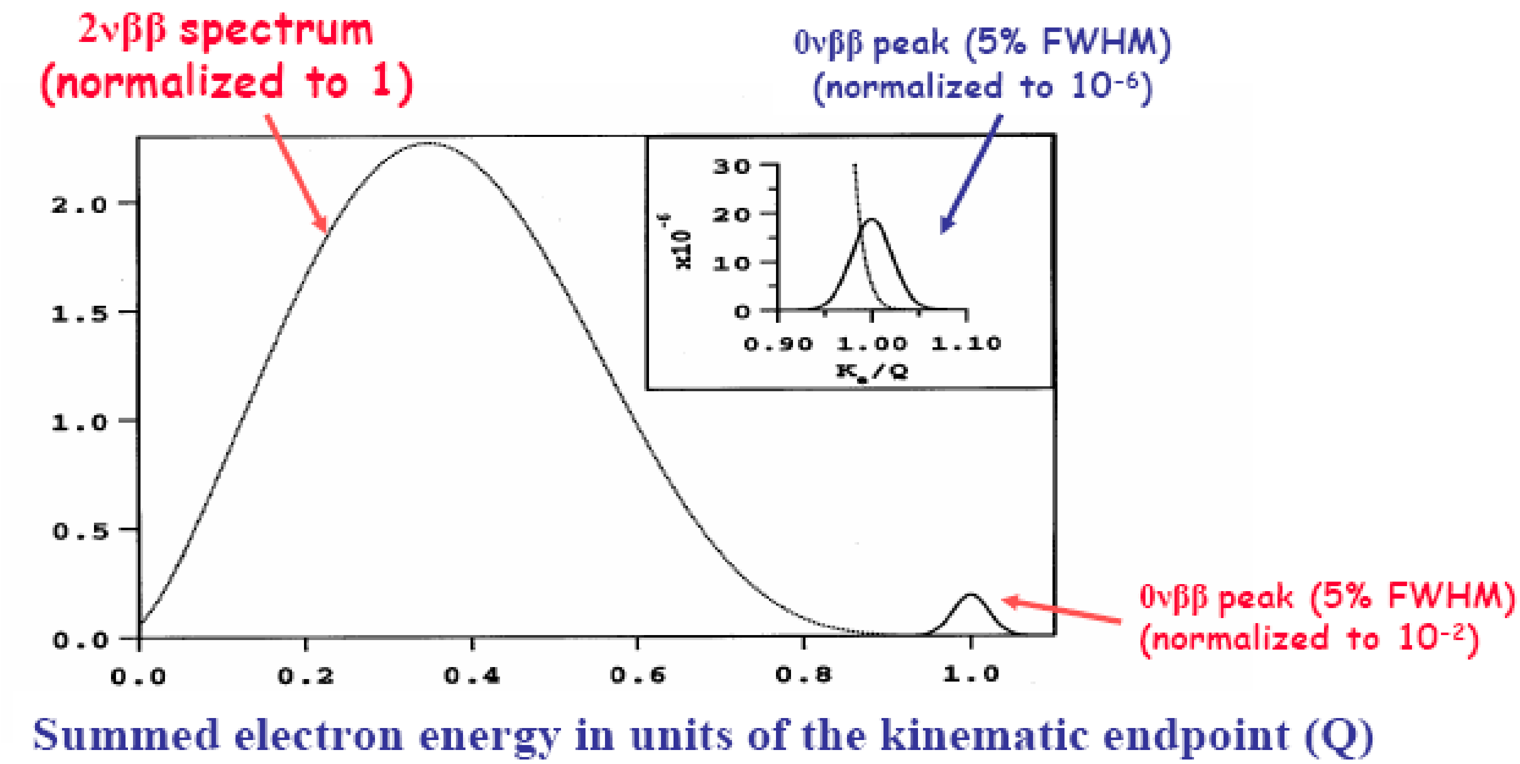
Physics

- Neutrinoless double beta decay (bb0n):
  - Tests Majorana nature of neutrino
  - Helps determine absolute neutrino mass
  - If observed, lepton number NOT conserved
  - Current situation: controversial (one claim), may require new and richer approach



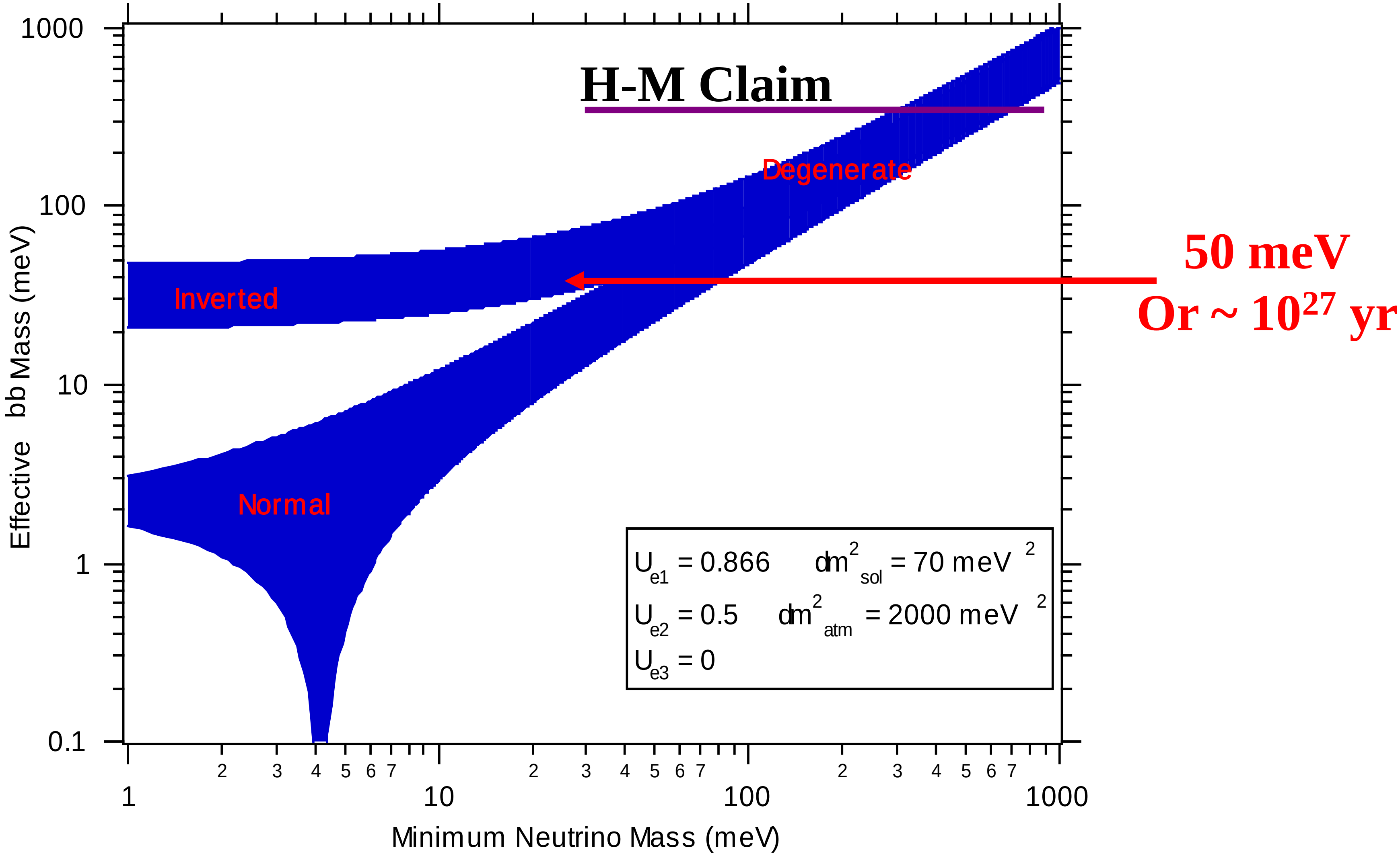
How to look for neutrino-less decay

- Measure the spectrum of the electrons



$$\left[T_{1/2}^{0\nu}(0^+ \rightarrow 0^+)\right]^{-1} = G^{0\nu}(E_0, Z)\left|M_{\rm GT}^{0\nu} - \frac{g_V^2}{g_A^2} M_{\rm F}^{0\nu}\right|^2 \langle m_\nu \rangle^2$$

$$\langle m_\nu \rangle^2 = \left|\sum_i^N U_{ei}^2 m_i\right|^2 = \left|\sum_i^N |U_{ei}|^2 e^{\alpha_i} m_i\right|^2$$



Xenon: Strong dependence of energy resolution on density!

A. Bolotnikov, B. Ramsey / Nucl. Instr. and Meth. in Phys. Res. A 396 (1997) 360–370

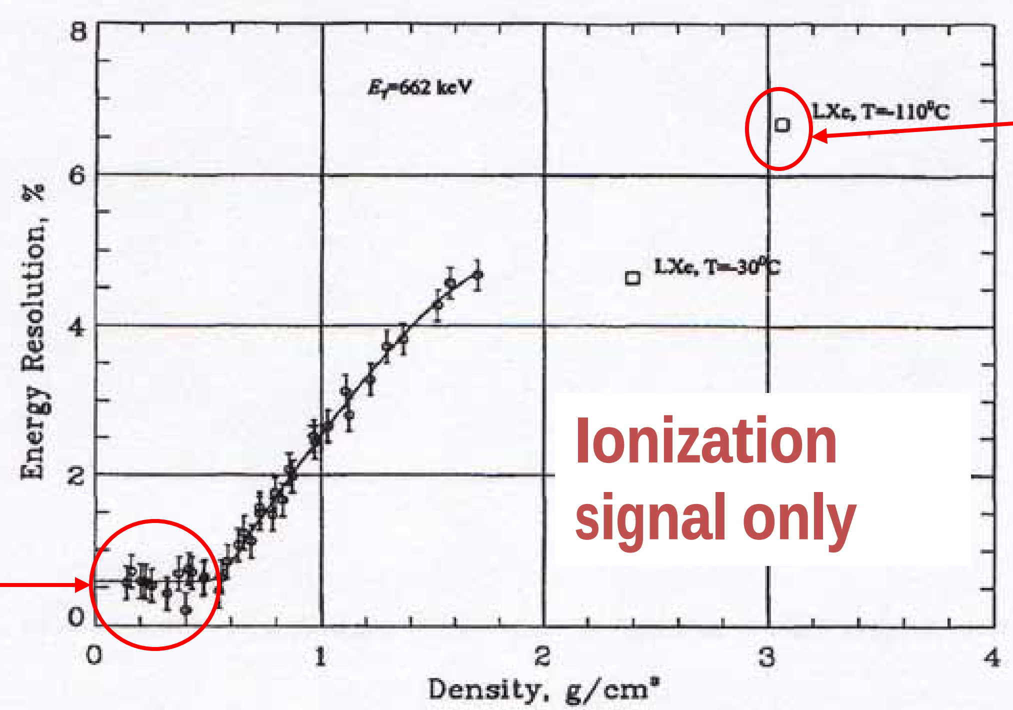


Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

Large fluctuations between light/charge

DM: S2/S1 suffers!

Here, the fluctuations are <u>normal</u>

For r <0.55 g/cm^3, ionization energy resolution is “intrinsic”

Intrinsic energy resolution

$$dE/E = 2.35 \times (F \times W/Q)^{1/2}$$

– F º Fano factor: F = 0.15 (HPXe) (LXe: F ~20)
– W º Average energy per ion pair: W ~ 25 eV
– Q º Energy deposited, e.g. 662 keV from Cs137 g-rays:

$$dE/E = \underline{0.56\%}\ \text{FWHM (HPXe)}$$

N = Q/W ~26,500 primary electrons

$s_N = (F \times N)^{1/2}$ ~63 electrons rms!

Intrinsic energy resolution

$$dE/E = 2.35 \times (F \times W/Q)^{1/2}$$

- F º Fano factor: F = 0.15 (HPXe) (LXe: F ~20)
- W º Average energy per ion pair: W ~ 25 eV
- Q º Energy deposited, e.g. 2457 keV from ^{136}Xe --> ^{136}Ba:

$$dE/E = \underline{0.28\%}\ \text{FWHM}\ \ (\text{HPXe})$$

N = Q/W ~100,000 primary electrons

$s_N = (F \times N)^{1/2}$ ~124 electrons rms!

Gain and noise

Impose a requirement:

(noise + fluctuations) < 124 e^{-}

Need gain G with **very** low noise/fluctuations!

Uncorrelated fluctuations can add in quadrature:

$$s = ((F + G) \times N)^{1/2}$$

F º constraint due to fixed energy deposit

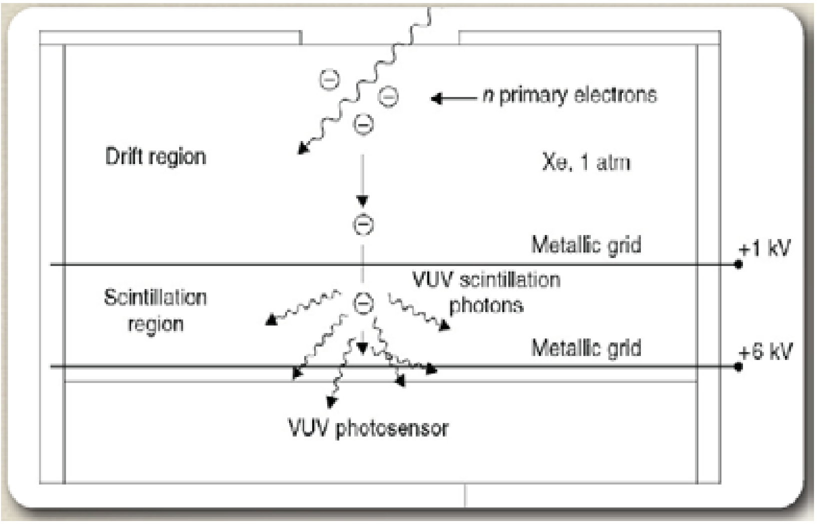
G º noise + fluctuations of detection process

G » 1.5 /(number of photo-electrons) **per** electron

Þ $n_{pe} > 10$ **per** electron for $G \leq F$

Electro-Luminescence (EL) is the key

(Gas Proportional Scintillation)

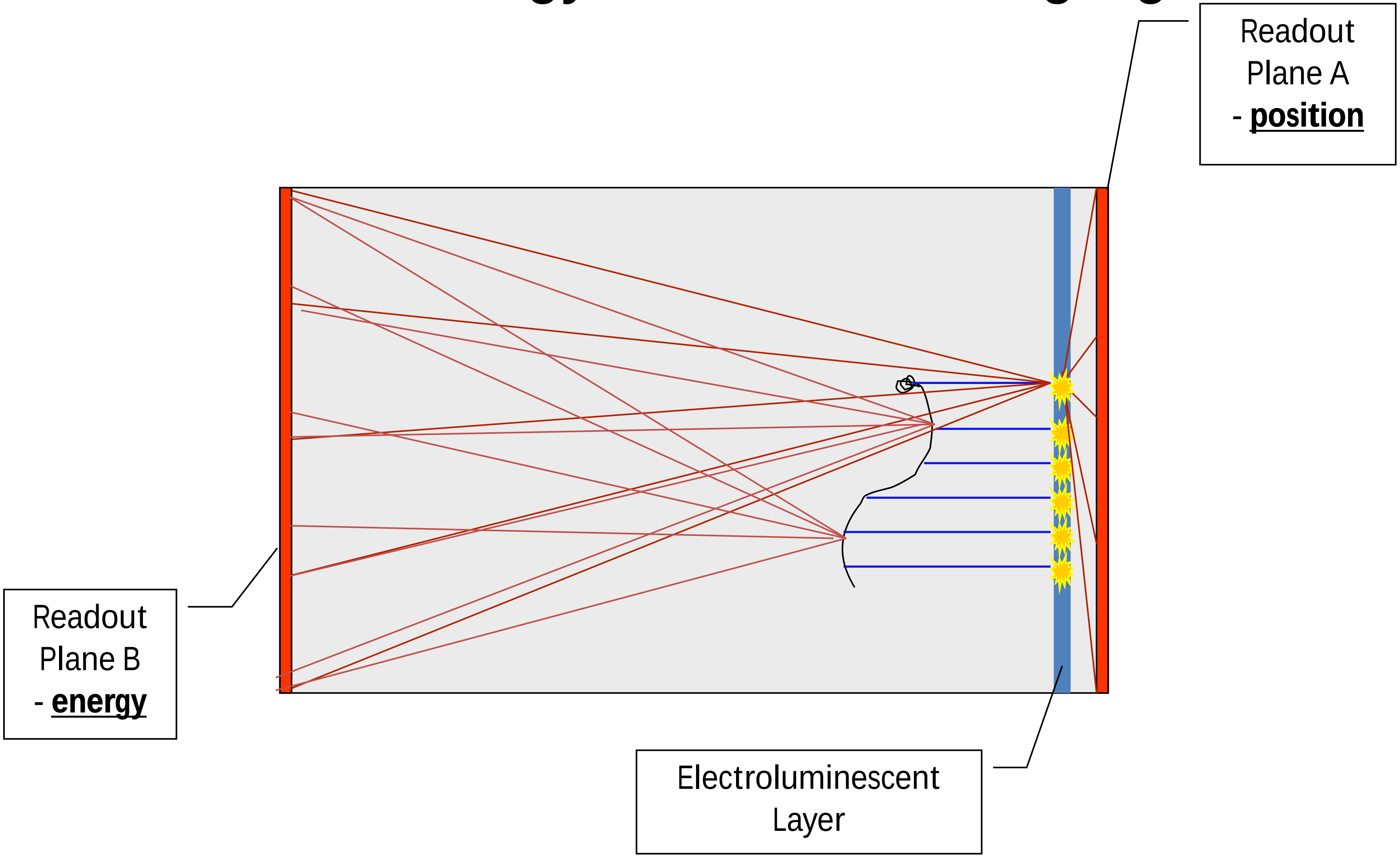


- Physics process generates ionization signal
- Electrons drift in low electric field region
- Electrons enter a high electric field region
- Electrons gain energy, excite xenon: 8.32 eV
- Xenon radiates VUV (»175 nm, 7.5 eV)
- Electron starts over, gaining energy again
- <u>Linear</u> growth of signal with voltage
- Photon generation up to ~1000/e, but <u>no</u> ionization
- No exponential growth Þ **<u>fluctuations are very small</u>**
- $dN_{UV} = J_{CP} \cdot N^{1/2}$
- Optimal EL conditions: $J_{CP} = 0.01$ (Poisson: $J_{CP} = 1$)

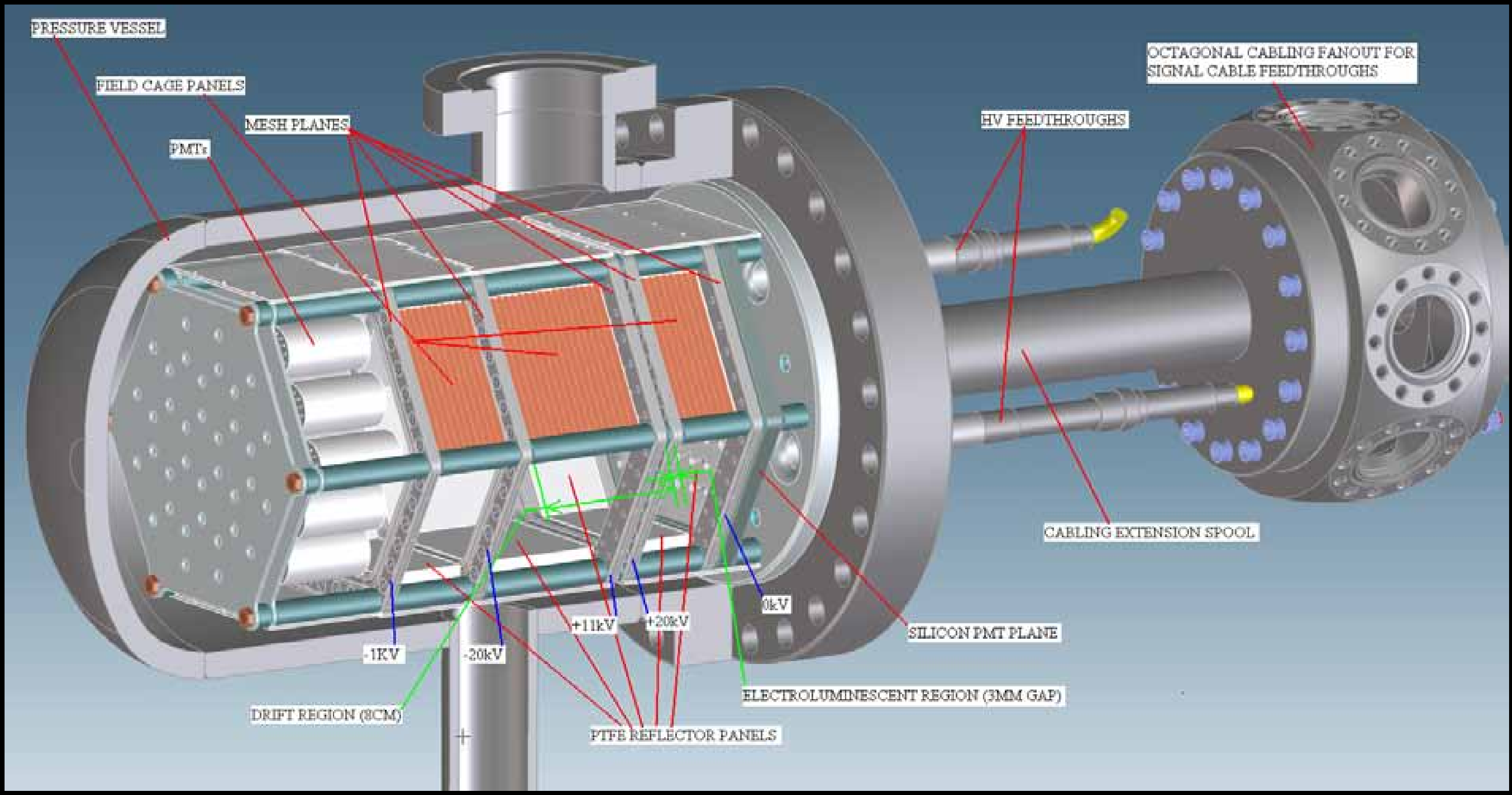
Virtues of Electro-Luminescence in HPXe

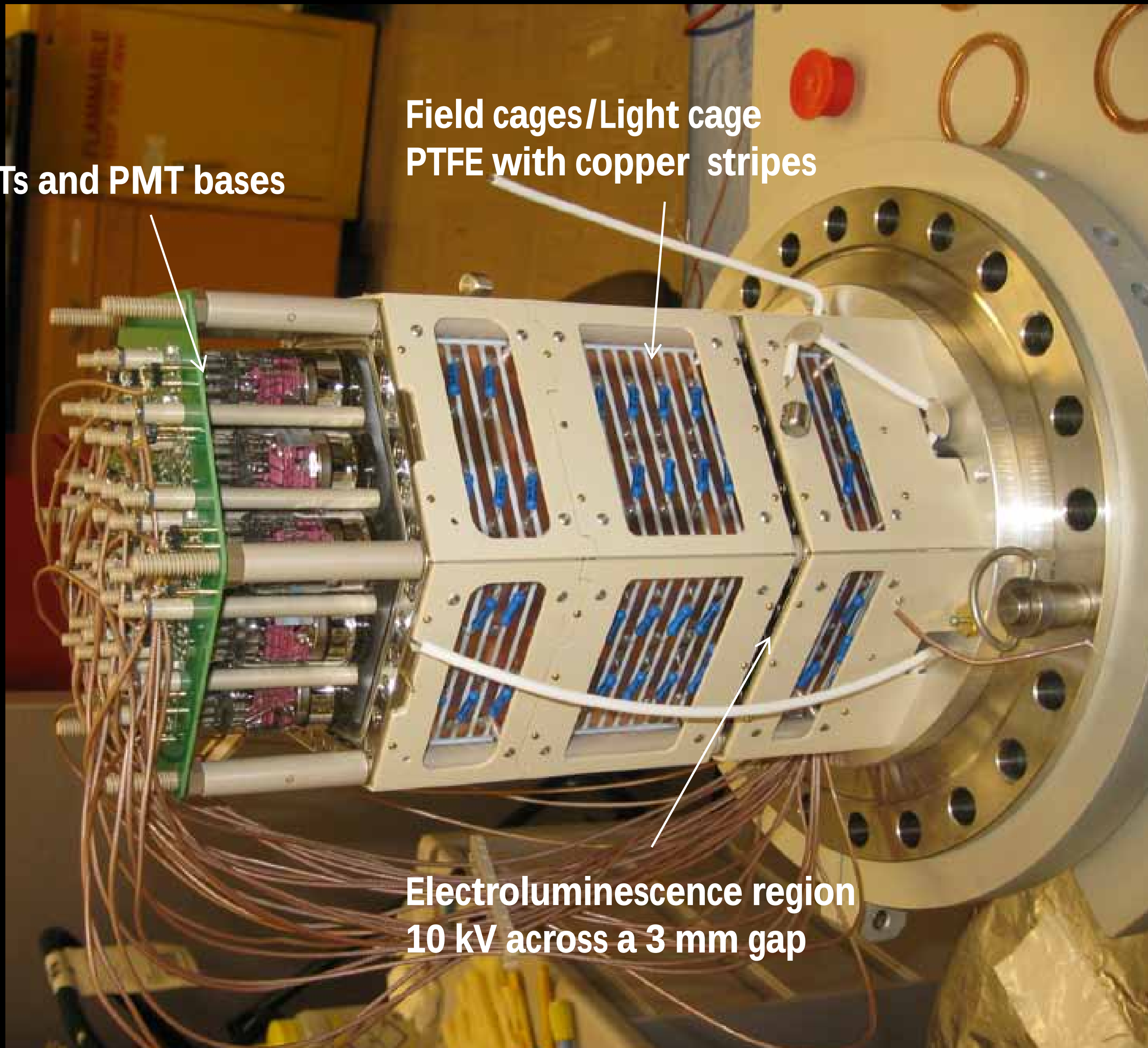
- Linearity of gain versus pressure, HV
- Immunity to microphonics
- Tolerant of losses due to impurities
- Absence of positive ion space charge
- Absence of ageing, quenching of signal
- Isotropic signal dispersion in space
- Trigger, energy, and tracking functions are accomplished with optical detectors

TPC with Electroluminescence: Total Energy and Track Imaging

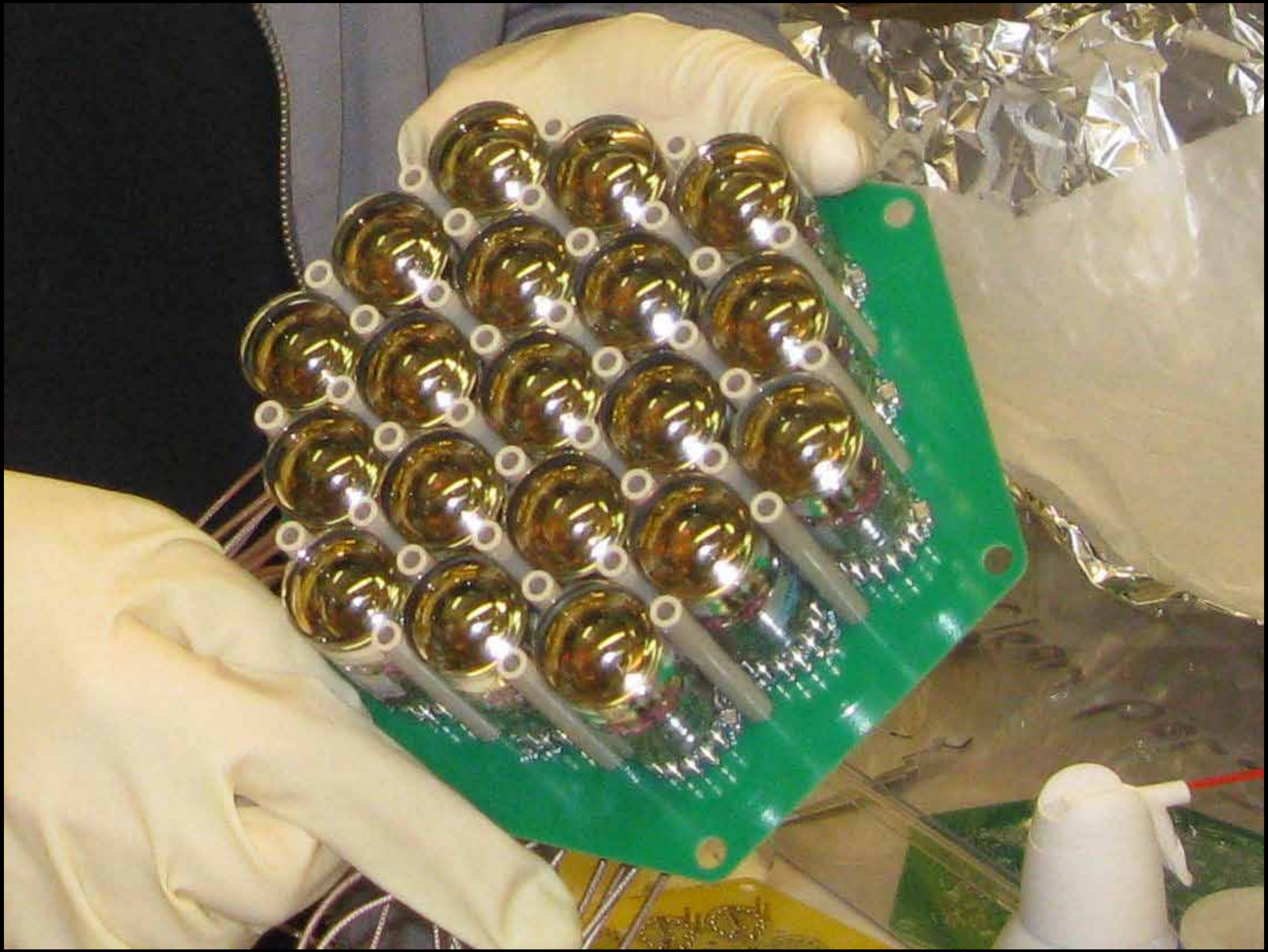


LBNL-TAMU TPC Prototype

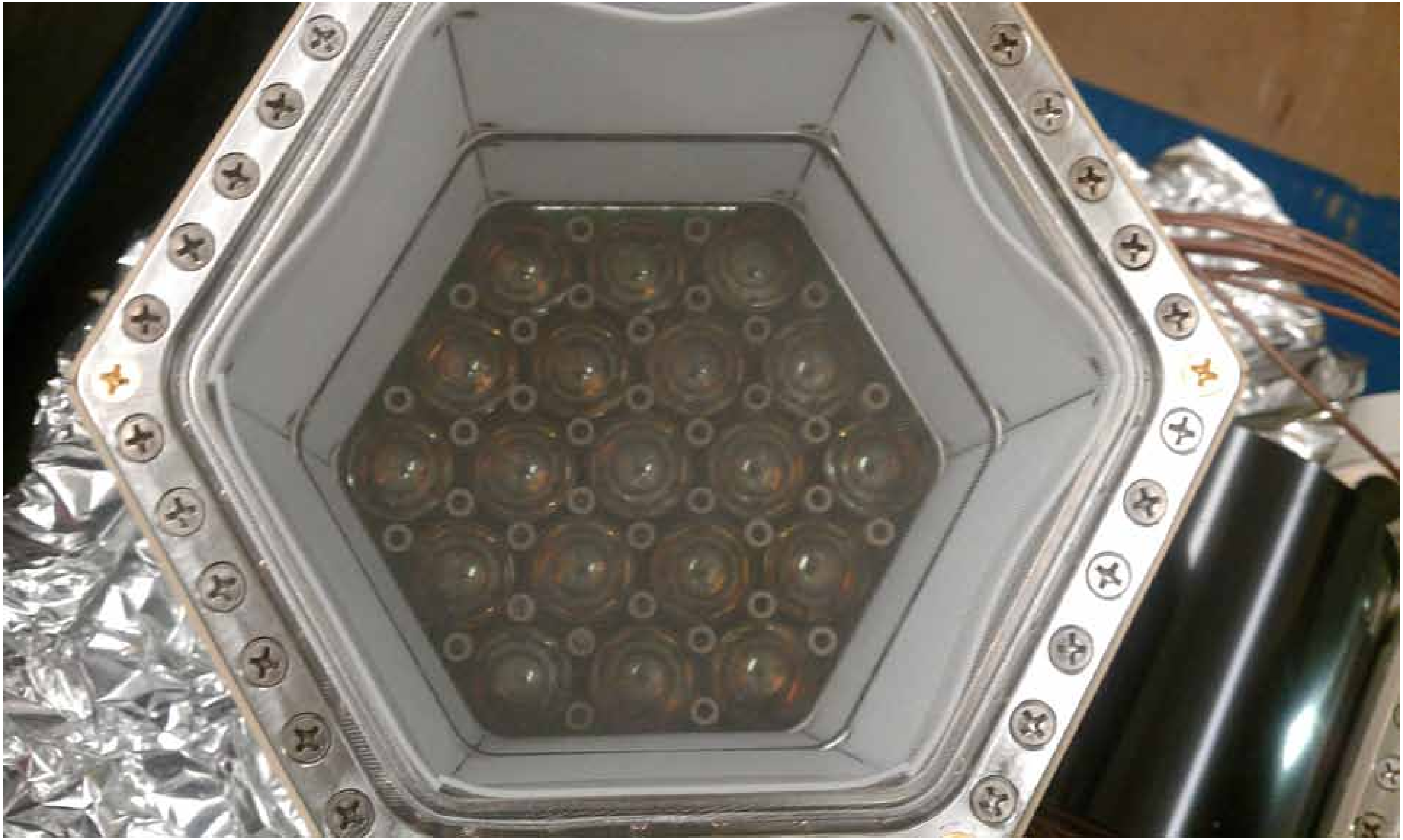



19 PMTs and PMT bases
Field cages/Light cage
PTFE with copper stripes
Electroluminescence region
10 kV across a 3 mm gap

PMT Array: inside the pressure vessel
Quartz window 2.54 cm diameter PMTs



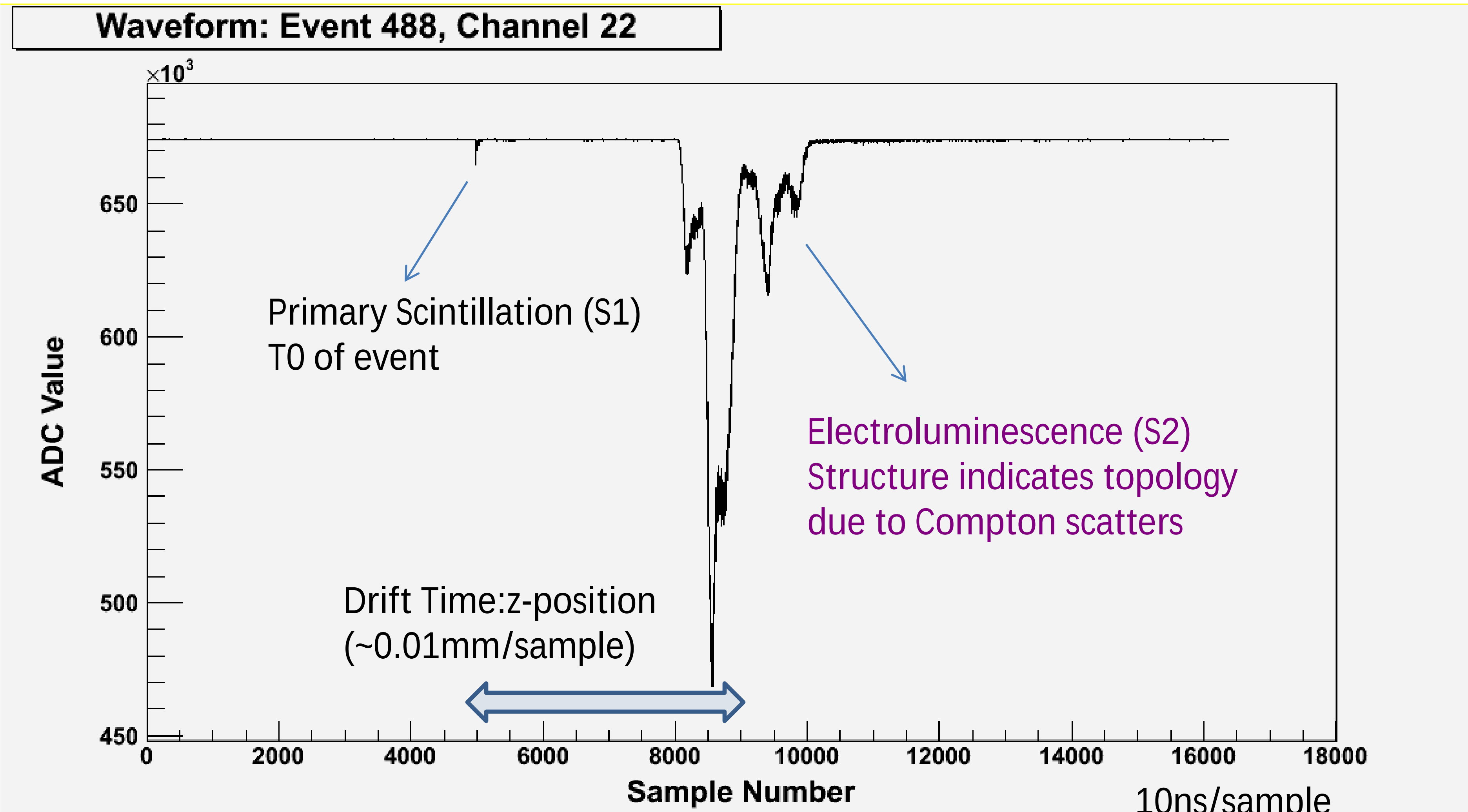
EL photons see this



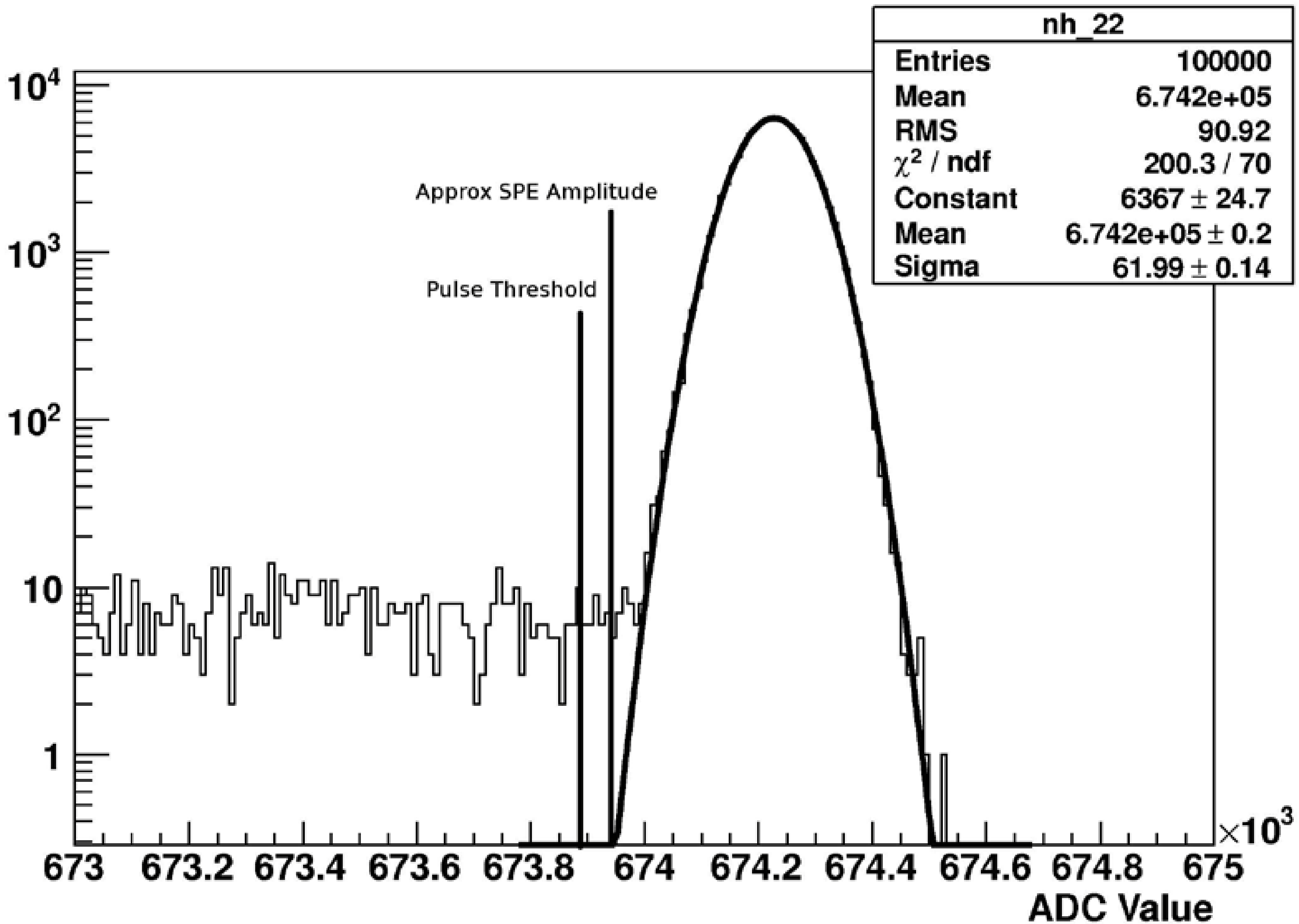
Inserting the TPC...

carefully!

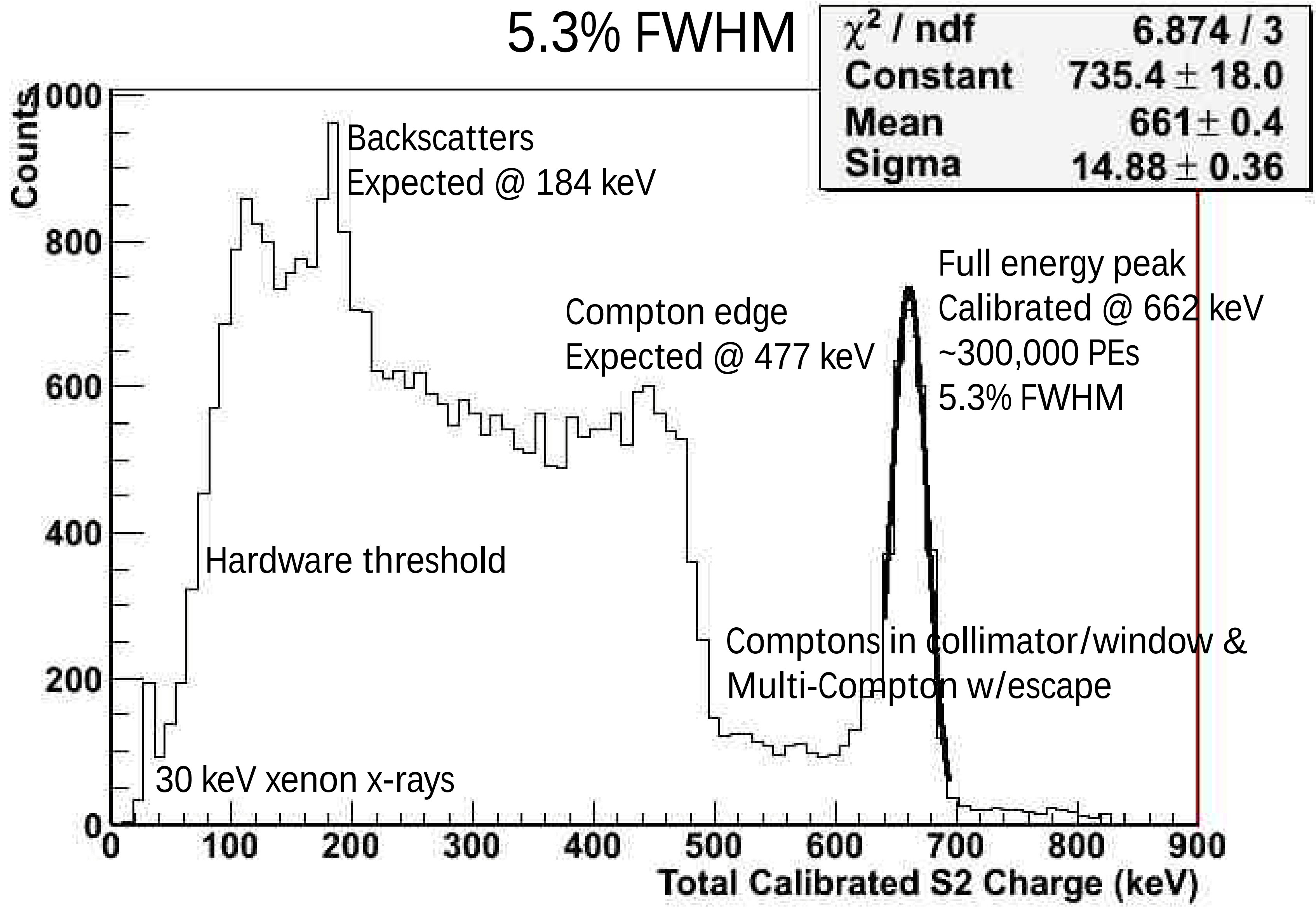
A typical ^{137}Cs gwaveform (sum of 19 PMTs) ~300,000 detected photoelectrons



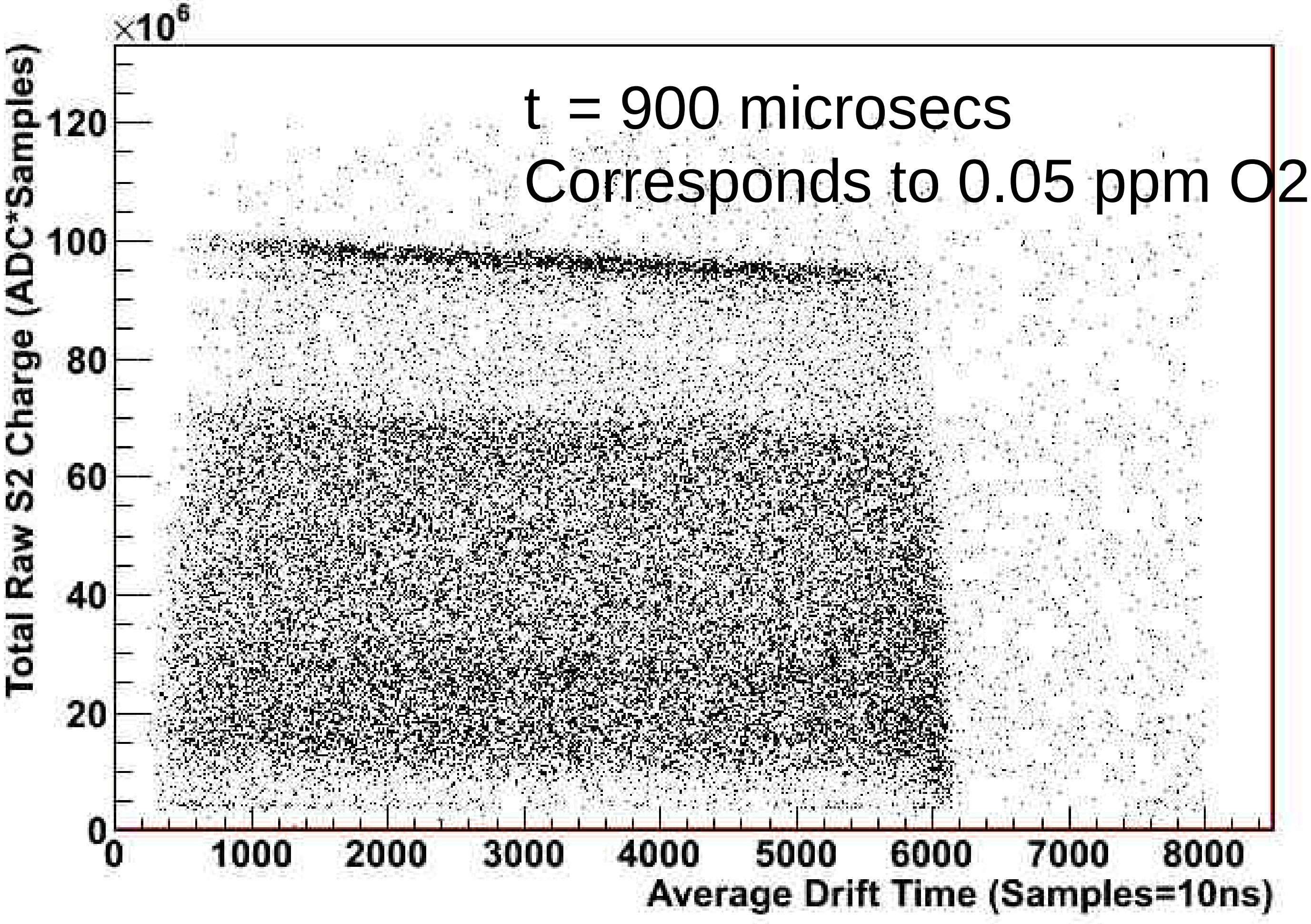
Summed waveform noise and PE level



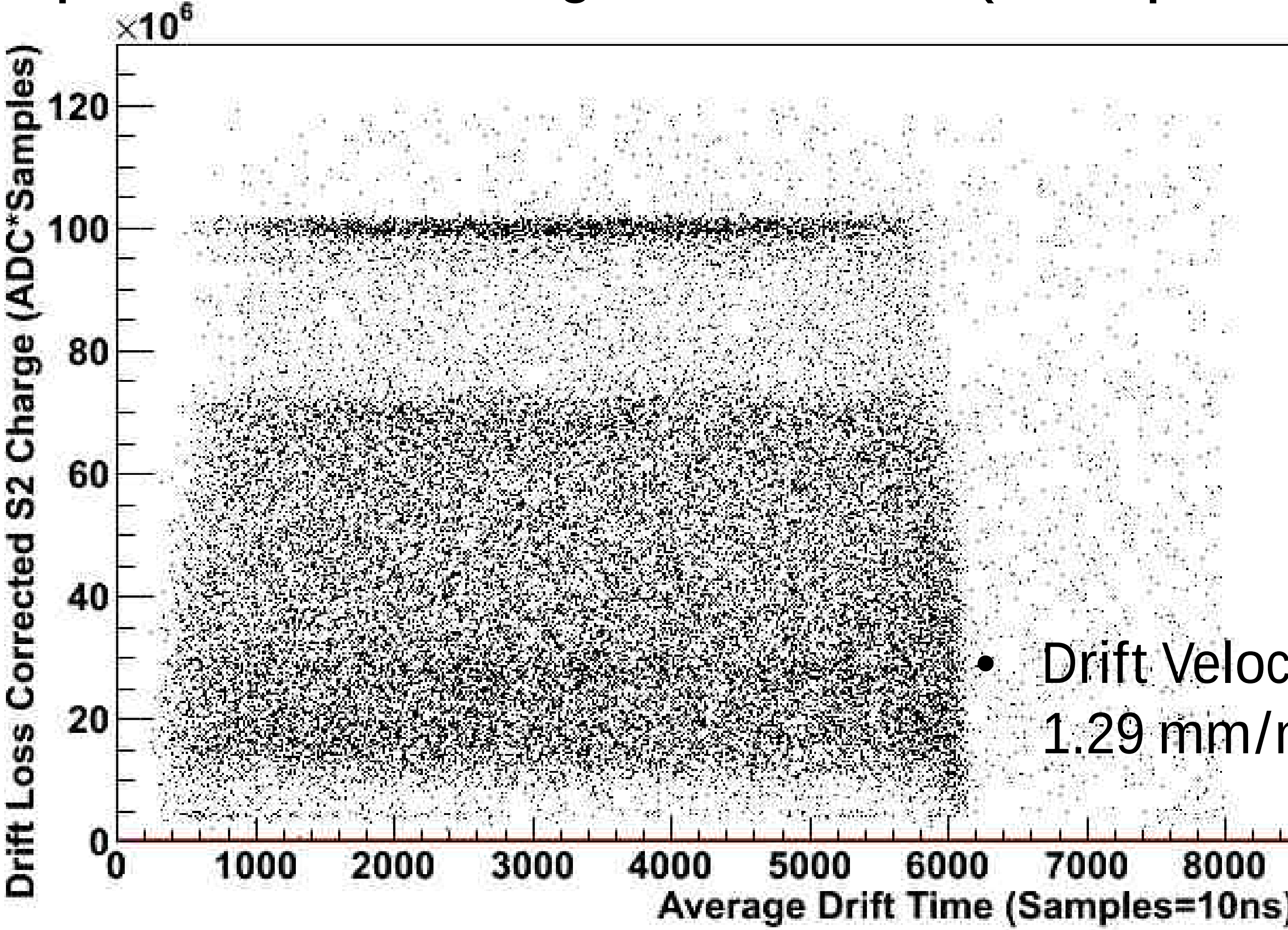
Calibrated (not corrected) S2 Spectrum



Raw S2 vs Drift Time

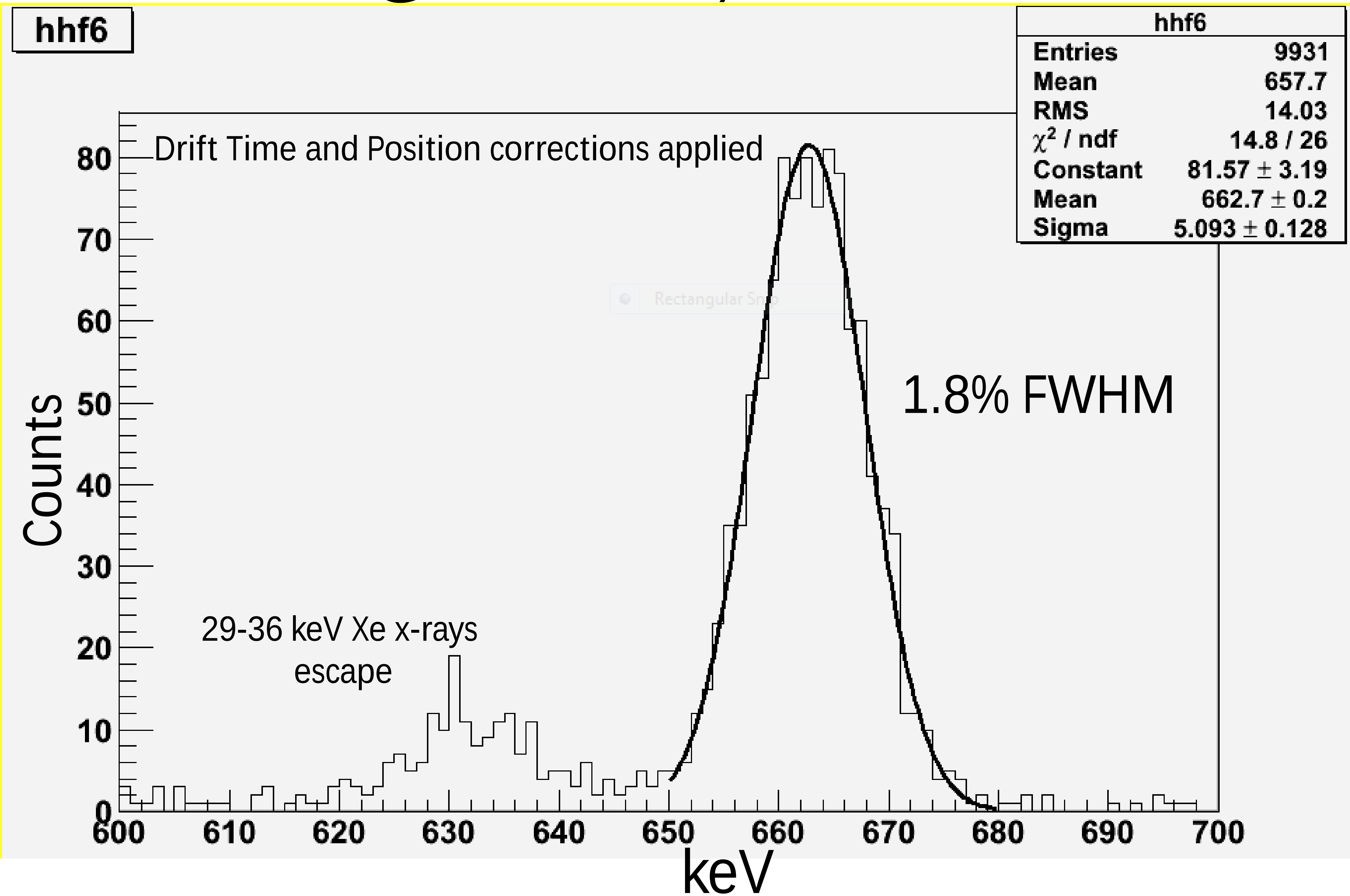


Drift Time Correction:
Computed with charge moments (e^x expansion)



- Drift Velocity 1.29 mm/microsec

HPXe @ 10 Atm, ^{137}Cs 662 keV



EL in 4.5 bar of Xenon (Russia - 1997)

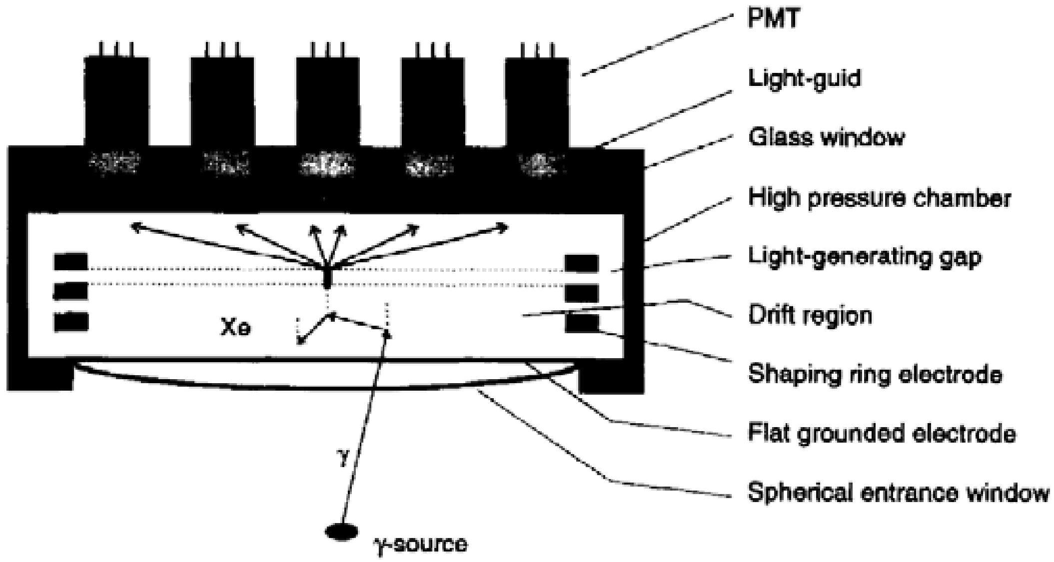
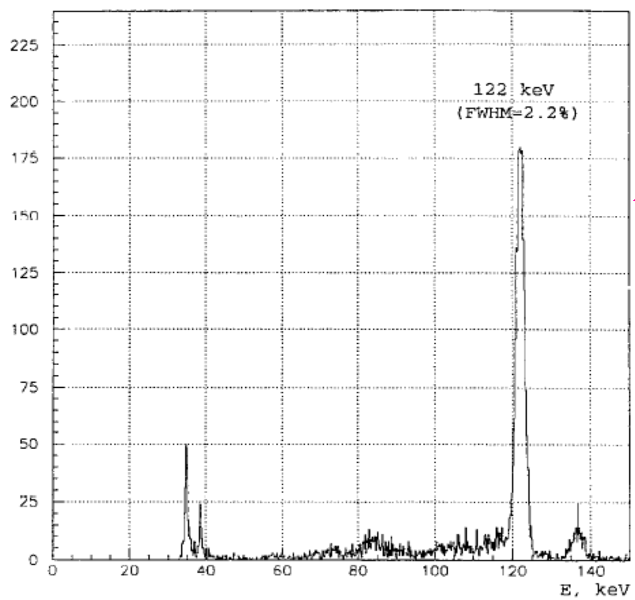


Fig. 1. Schematic diagram of the gas scintillation drift chamber with 19 PMT matrix readout.

A. Bolozdynya et al. / Nucl. Instr. and Meth. in Phys. Res. A 385 (1997) 225–238

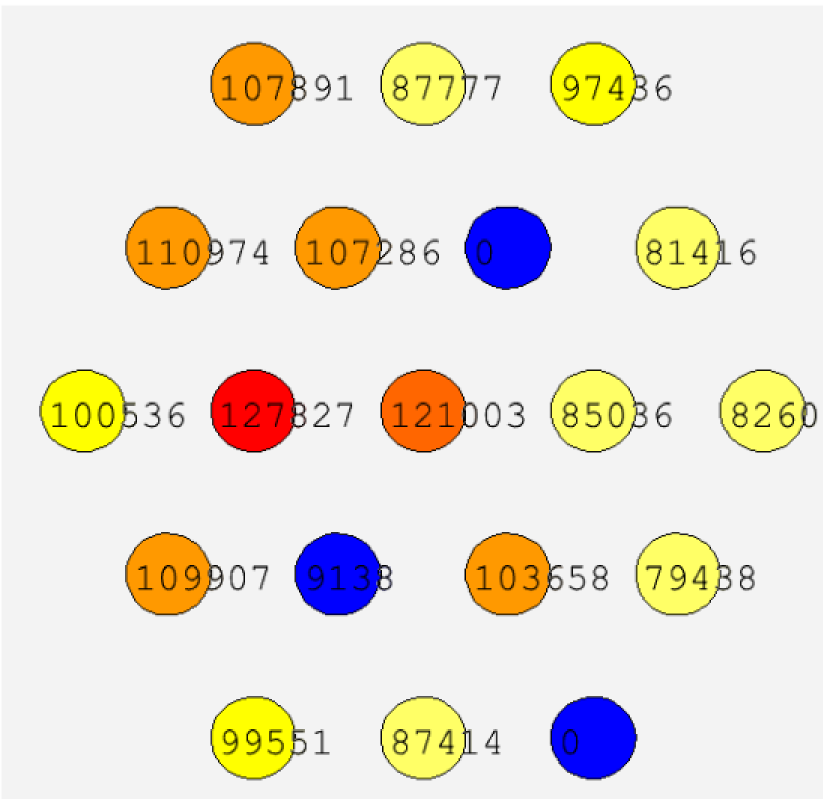


This resolution corresponds to

dE/E = 1% FWHM

-- if extrapolated ($E^{-1/2}$) to 662 keV

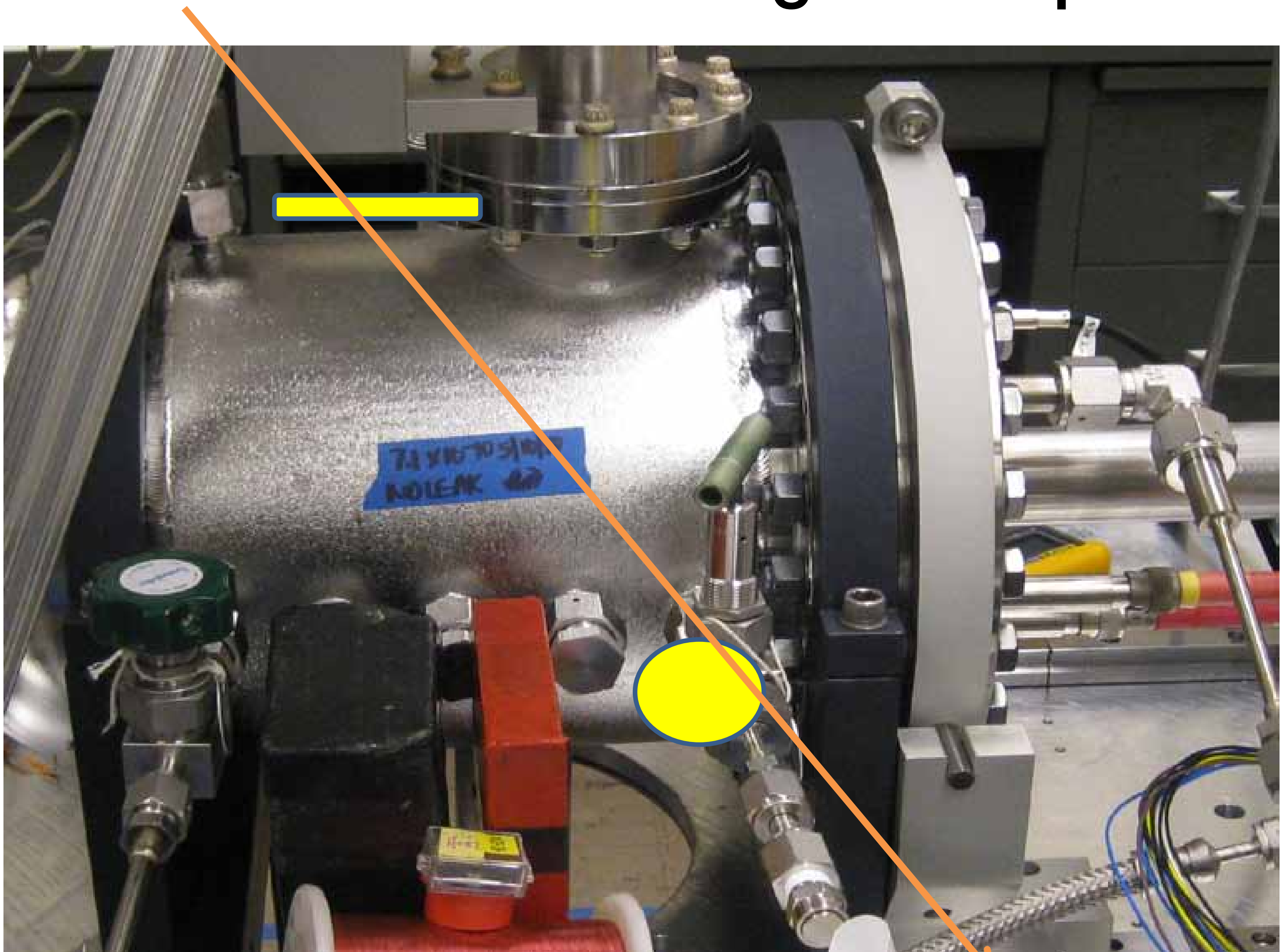
Position measurement



- EL light viewed by PMT array 13 cm away
- Solid angle and limited (~50%) reflectivity give position sensitivity
- 20-30% relative variations from position
- Large PE statistics is key

Dennis Chan

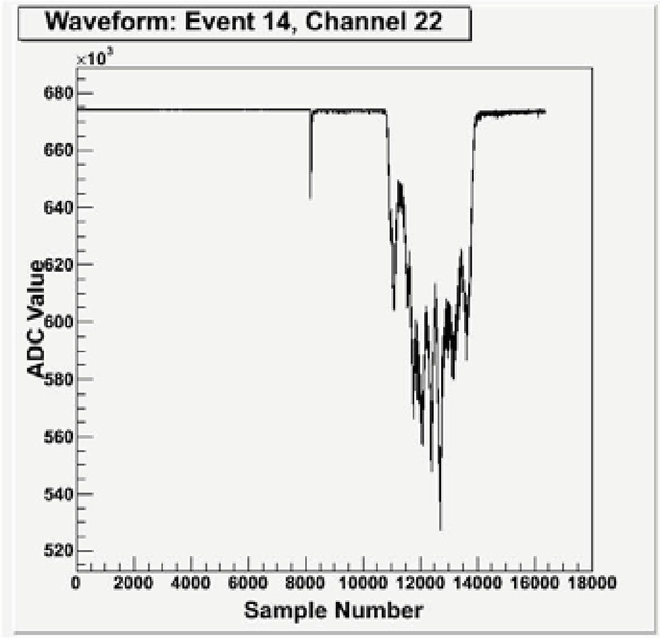
Muon Tracking: Setup

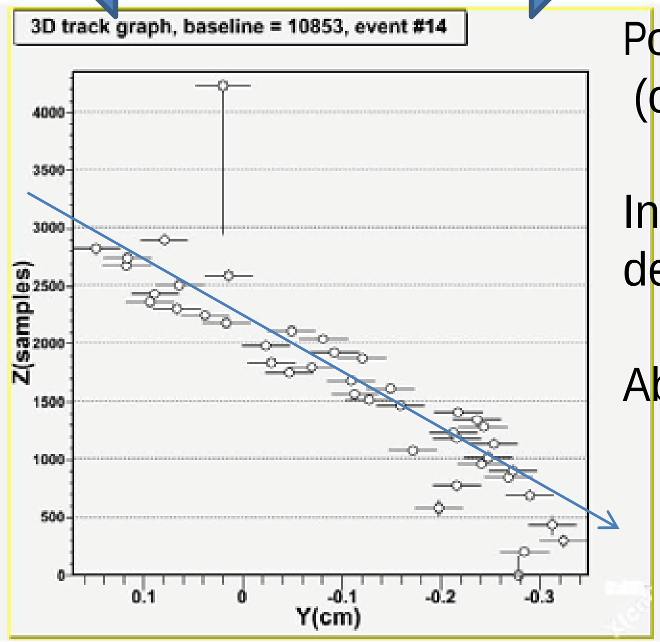


External 2-scintillators trigger

2 Sample Muons

14 cm vertical span

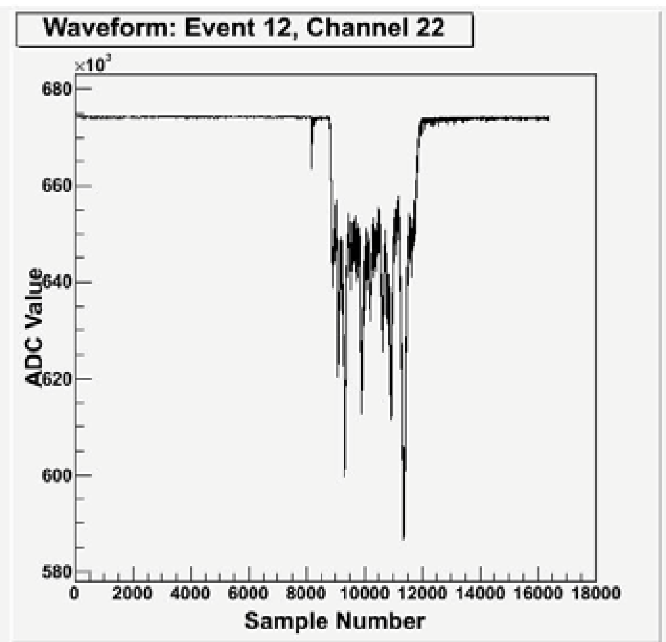


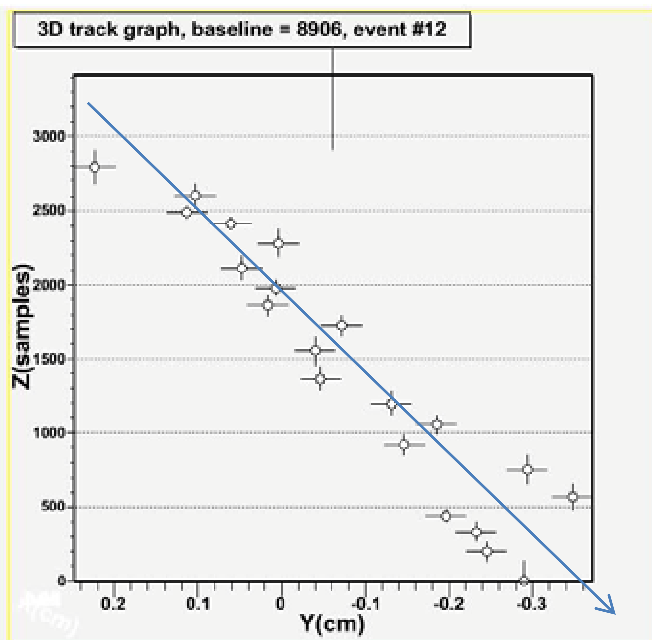


Points x & y averages
(only y shown) for a time slice

Individual points ~40 keV deposited

About 1 MeV total per muon





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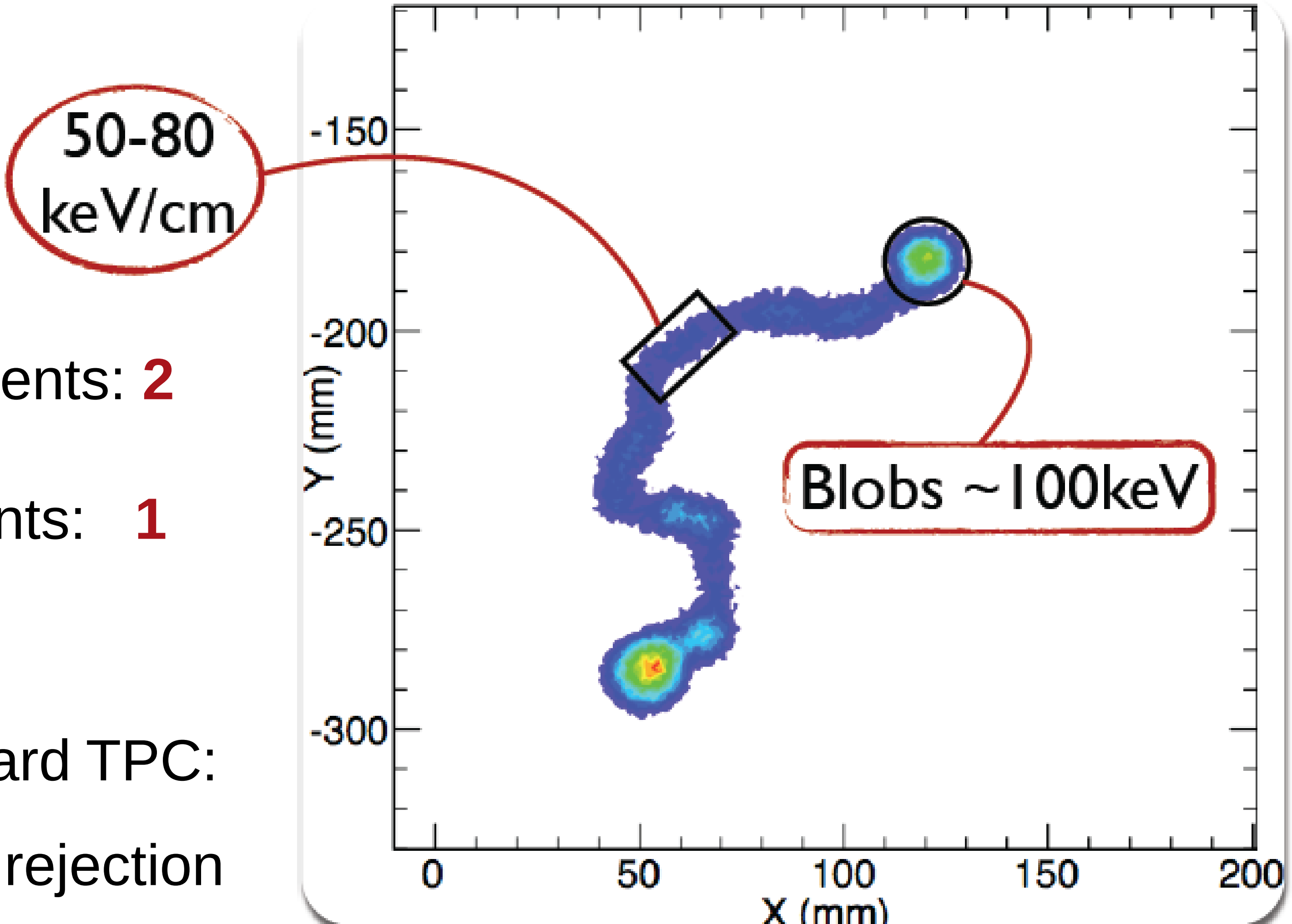
Topology: “spaghetti, with meatballs”



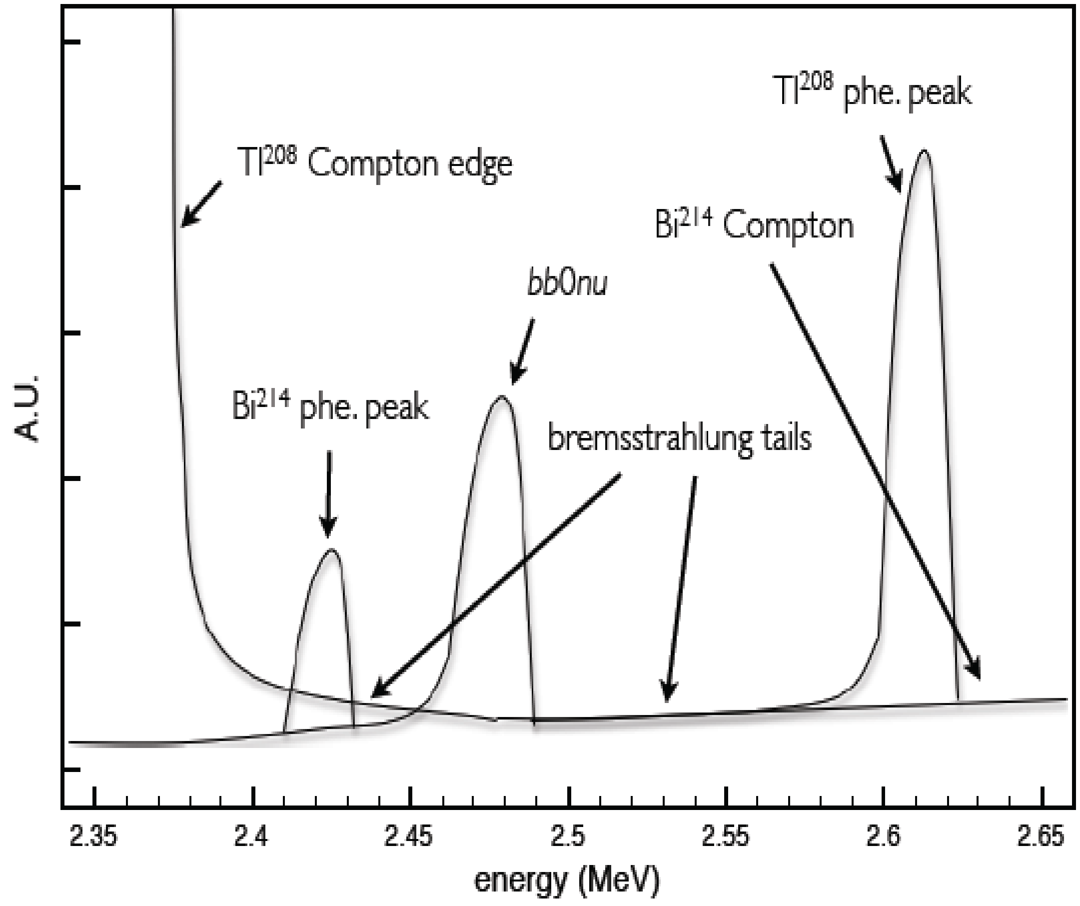
bb events: **2**

g events: **1**

Gotthard TPC:

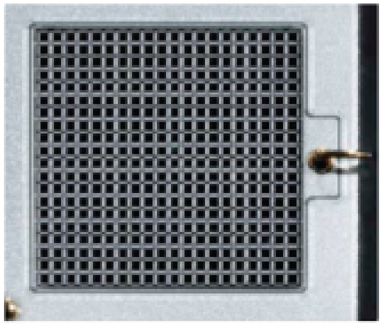
~ x30 rejection

Backgrounds for the bb0n search



NEXT Collaborat

SiPM Tracking Plane

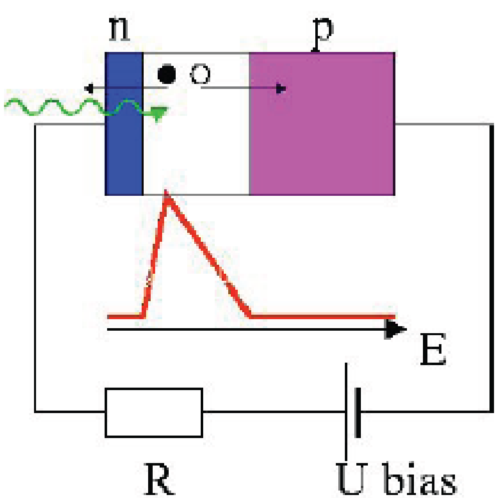


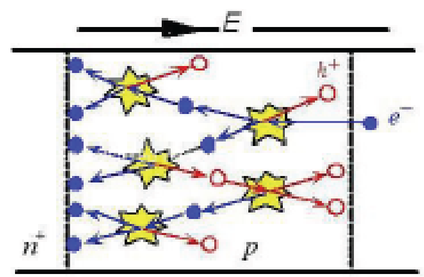
Hamamatsu S10362-025C

Multi Pixel Photon Counter (MPPC)

Active area: 1 mm^2

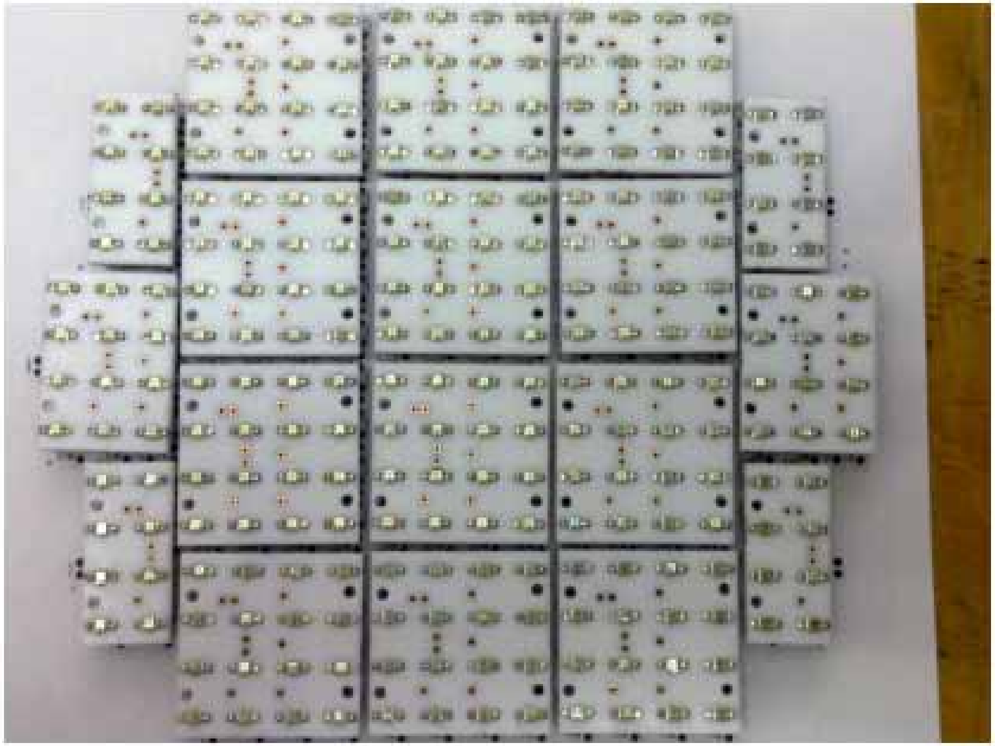
Pixel size: 25 µm





Array of APDs working in Geiger mode.

Si-PMs Plane



Selection of Si-PMs to have the minimun spread in gain.

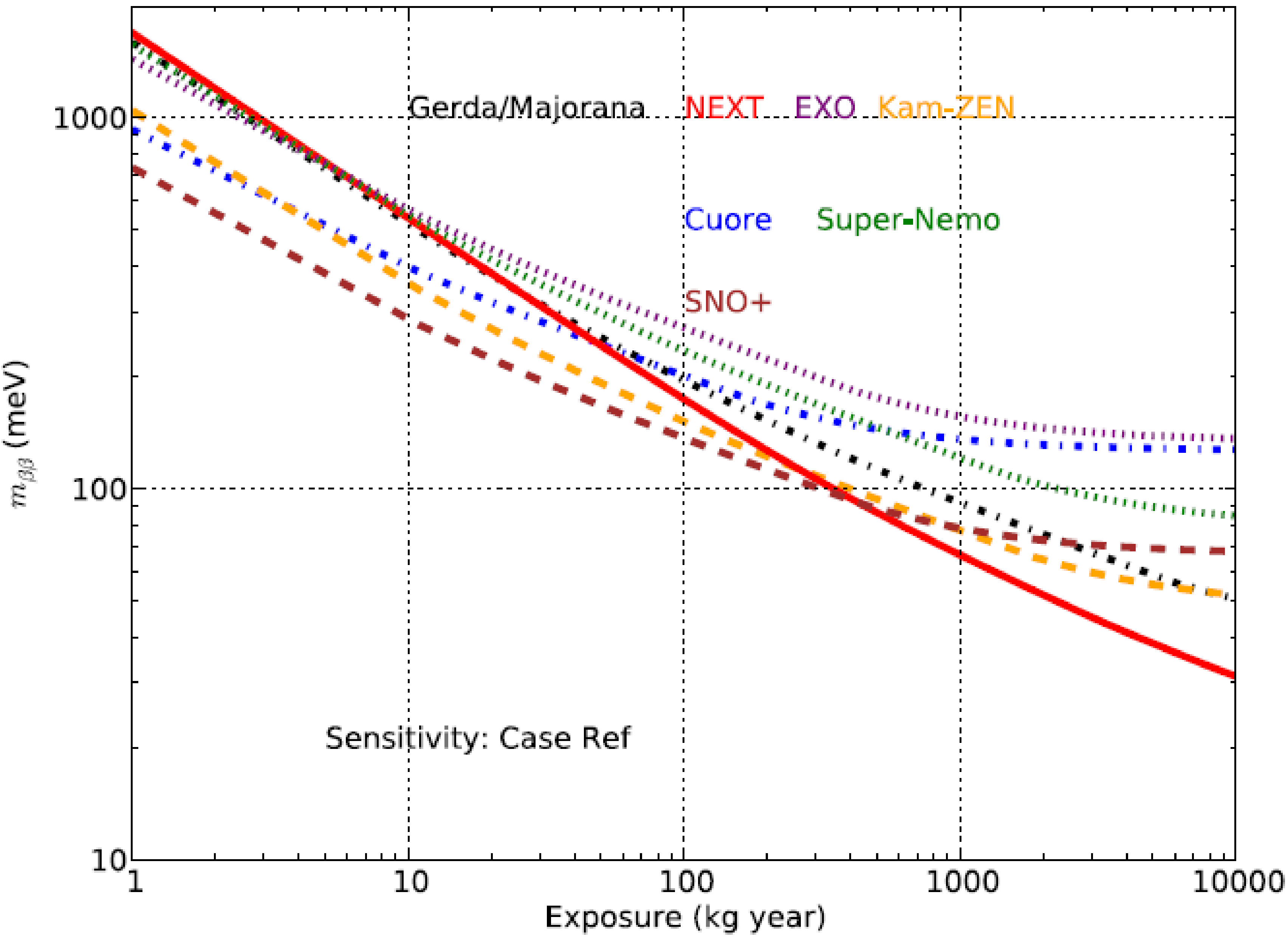
18 Daughter Boards

12 Boards with 16 Si-PMs

2 Boards with 12 Si-PMs

4 Boards with 8 Si-PMs

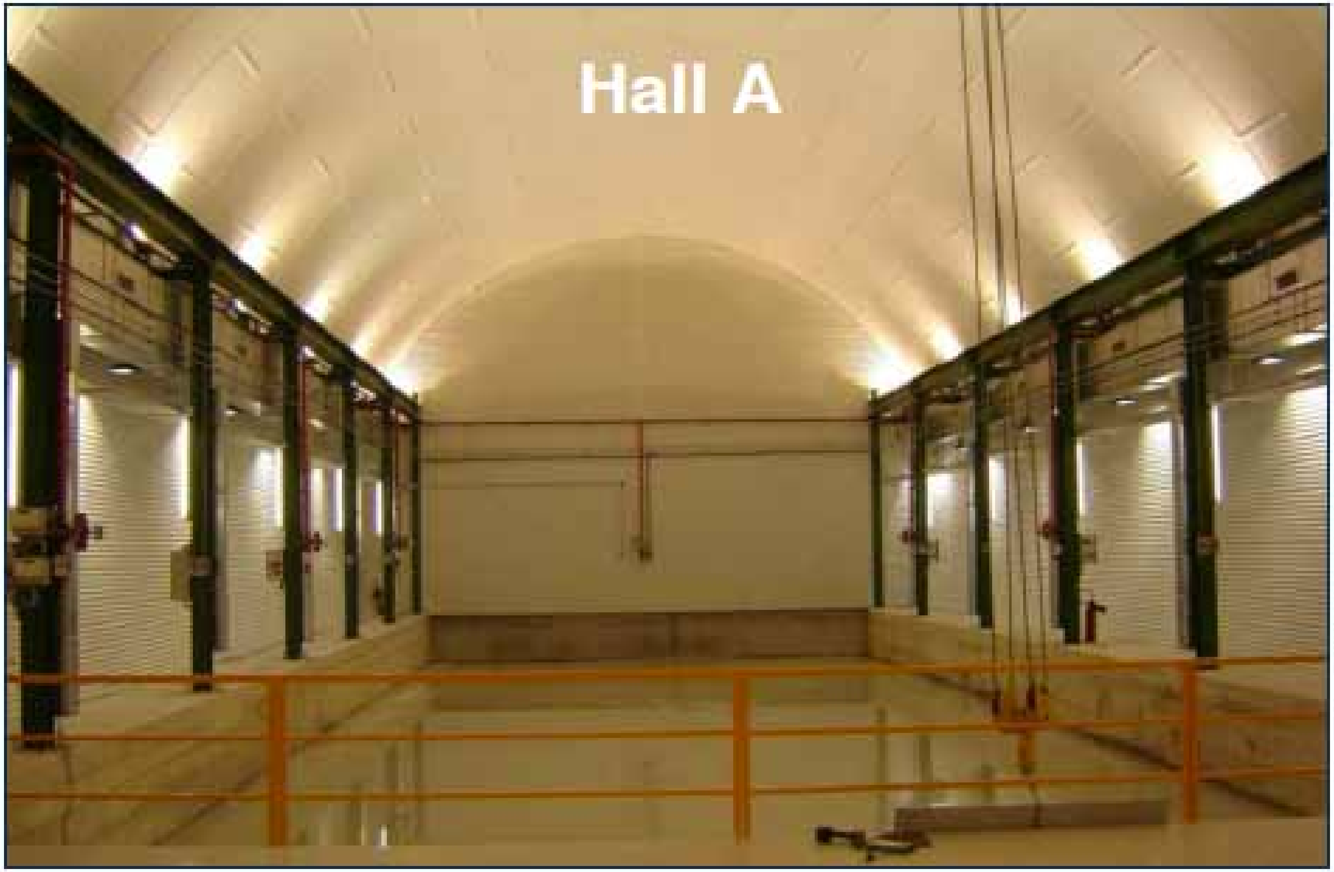
David Lorca, IFIC



Gerda/Majorana
NEXT
EXO
Kam-ZEN
Cuore
Super-Nemo
SNO+
Sensitivity: Case Ref
1000
100
10
1
10
100
1000
10000
Exposure (kg year)
$m_{\beta\beta}$ (meV)

Pressure vessel design study at 15 bars for 100 kg *NEXT*

Laboratorio Subterraneo de Canfranc



Waiting for NEXT...

Conclusions and Outlook

- Successful operation of xenon EL TPC in 10-15 Bar range
- We have achieved 1.8% FWHM @ 662 keV (10 Atm), intrinsic resolution is ~0.6% FWHM
- Improve: gas purity, localization, mesh flatness, and calibration
- R&D program includes:
  - Develop imaging with light sensor near the EL production region
  - Studying TMA as a gas additive (Penning and diffusion)
  - Variants for the readout with wavelength shifting bars
  - Scaling from current total mass of 1kg to 100 kg - and beyond
  - Develop prototype for applications in gamma ray imaging, gamma spectroscopy and medical imaging

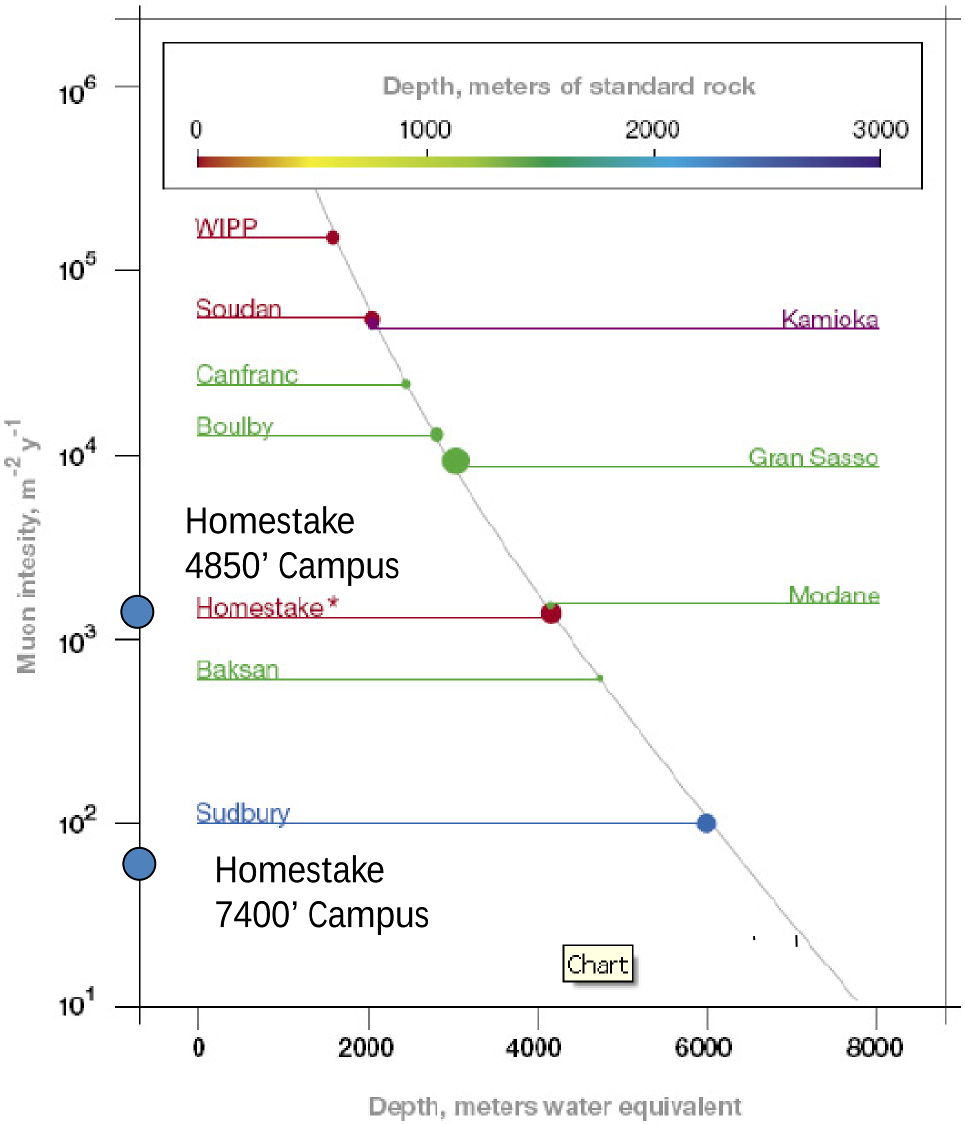
- *NEXT is starting to happen - now!*

Backup slides

Sample ^{137}Cs run

- Run #234, April-6-2011
- 40,000 events, 3h long, inst. rate ~20 Hz, 24GByte raw
- Source: 1 miliCurie 662 keV gamma highly collimated and on the TPC axis entering the pressure vessel through a 2 mm thick stainless steel window on a reentrance port.
- Pressure: 10.2 bar
- -10.6 kV @ cathode
- +2.7 kV first EL mesh
- +10.6kV second EL mesh.
- 8 cm drift region: 1.66 kV/cm
- 0.3 cm EL gap: 2.6 kV/(cm atm)

Cosmic-ray Muons

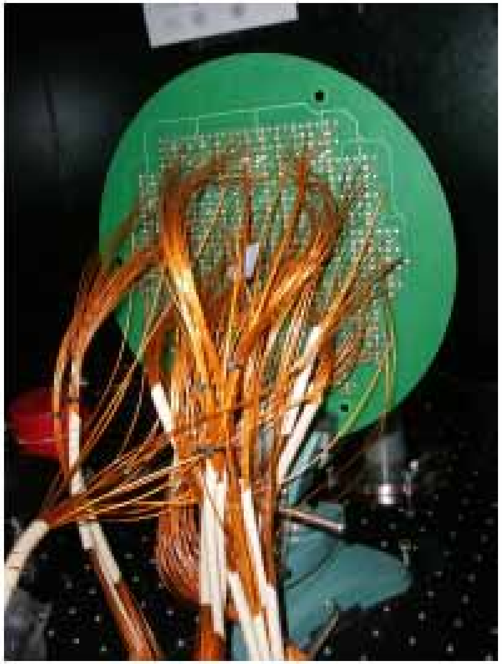


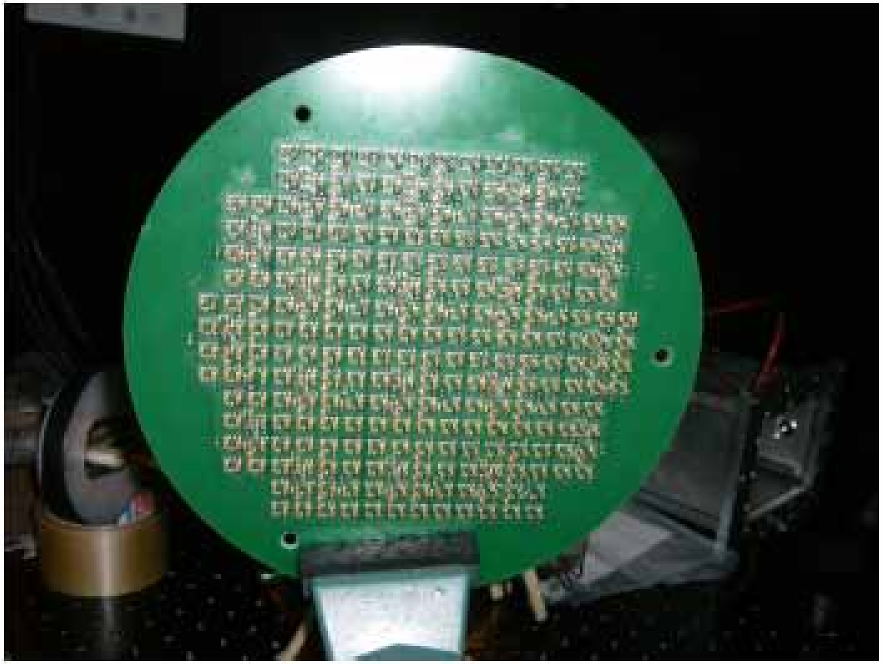
bb0n Experiments

- CANDLES ^{48}Ca CaF_2 scintillator crystals
- COBRA ^{116}Cd CdZnTe crystals
- CUORE ^{128}Te TeO2 Bolometers
- EXO ^{136}Xe Liquid Xenon TPC
- GERDA ^{76}Ge Enriched Ge diode
- MAJORANA ^{76}Ge Enriched Ge diode
- SNO+ ^{150}Nd Nd loaded liquid scintillator
- SuperNEMO ^{82}Se Foils in track/calorimeter

Parent isotope	$\langle F_N \rangle \equiv \langle G^{0\nu} \lvert M^{0\nu} \rvert^2 \rangle \text{year}^{-1}$	$\overline{\eta}$	$\lvert Q_{\beta\beta} \rvert$ (keV)
^{48}Ca	$(5.4^{+3.0}_{-1.4}) \times 10^{-14}$	0.54	4271
^{76}Ge	$(7.3 \pm 0.6) \times 10^{-14}$	0.73	2039
^{82}Se	$(1.7^{+0.4}_{-0.3}) \times 10^{-13}$	1.70	2995
^{100}Mo	$(5.0 \pm 0.3) \times 10^{-13}$	5.0	3034
^{116}Cd	$(1.3^{+0.7}_{-0.3}) \times 10^{-13}$	1.30	2802
^{130}Te	$(4.2 \pm 0.5) \times 10^{-13}$	4.26	2533
^{136}Xe	$(2.8 \pm 0.4) \times 10^{-14}$	0.28	2479
^{150}Nd	$(5.7^{+1.0}_{-0.7}) \times 10^{-12}$	57.0	3367

Mother Board





Mother Board which contains electronic components .

Feedtroughs and connectors.

David Lorca, IFIC