Xenon High-pressure Gas TPCs
for 0-ν $\beta\beta$ & WIMP Searches, ...

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Why bother with high-pressure?

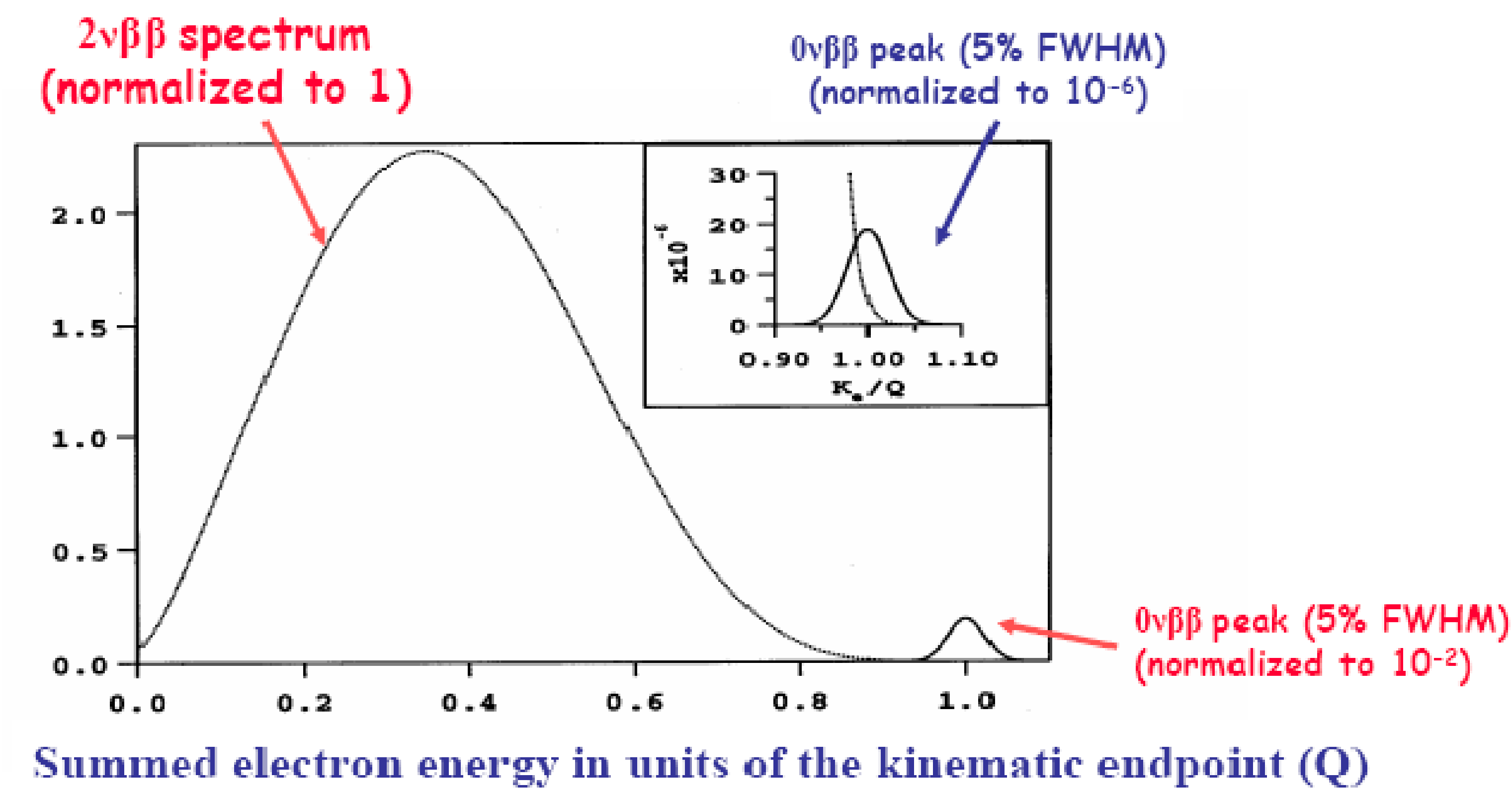
- Neutrino-less double beta decay:
  - Energy resolution may be an order of magnitude better than in liquid xenon ...
  - Tracking in gas phase reveals event topology...
- Direct detection WIMP search:
  - S2/S1 ratio shows better discrimination than LXe
  - Gas phase may permit extremely low threshold
- Flexibility: molecular additives, nuclear safeguards

Goals for 0-ν $\beta\beta$ search

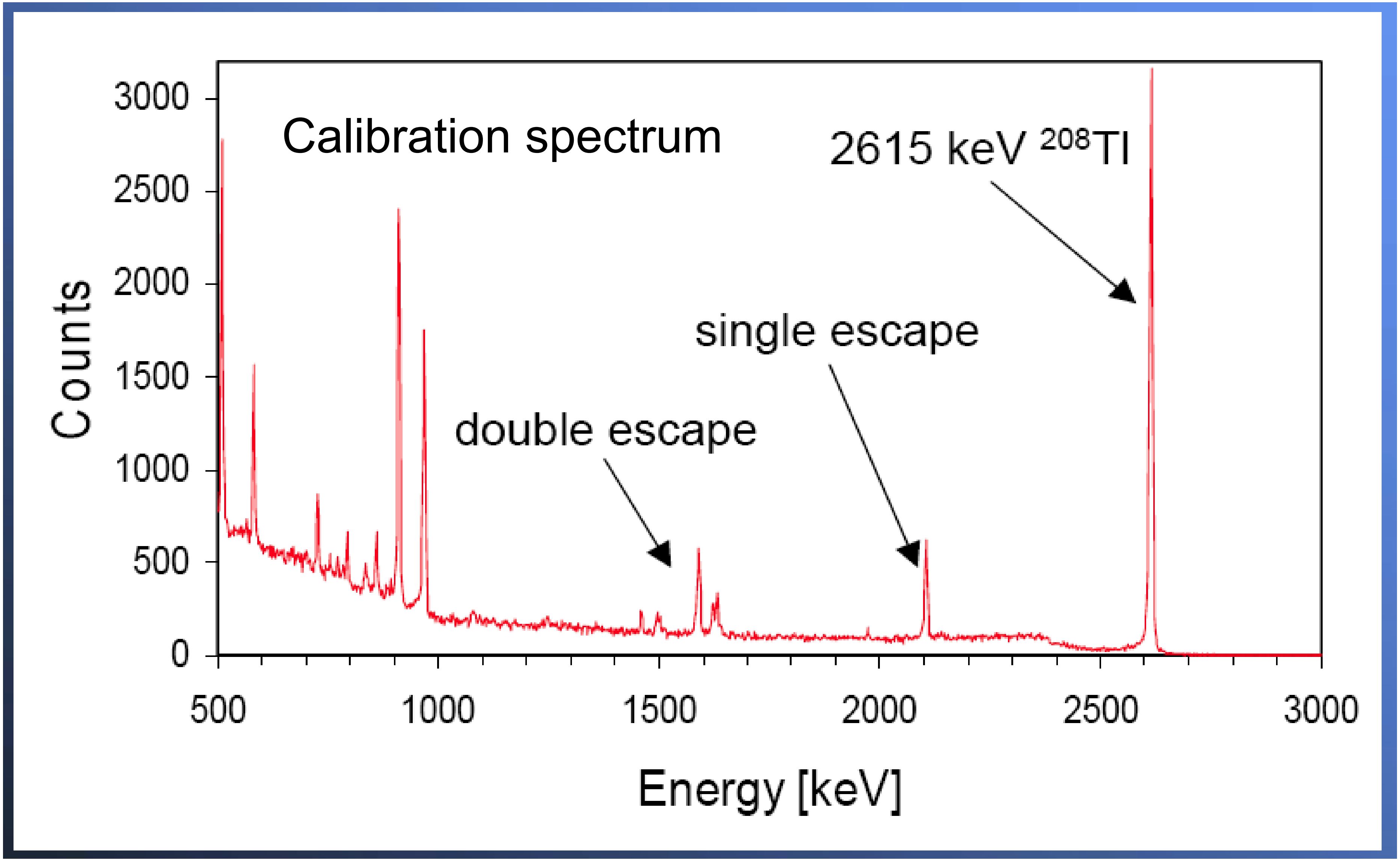
- Near-term: demonstrate energy resolution and tracking at 20 bars
  - Reconfigure, operate small LLNL TPC
  - Design & construct medium-scale TPC
- Longer-term:
  - If performance goals are met, a design for a serious ton-scale experiment can be prepared

To search for 0-ν ββ decay:

1. Acquire 100 - 1000 kg of candidate nuclei
2. Measure the two electron energies, <1% FWHM
3. Reject backgrounds!



Energy Resolution: CUORE $\delta E/E = 3 \times 10^{-3}$ FWHM !



Xenon: Strong dependence of energy resolution on density!

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

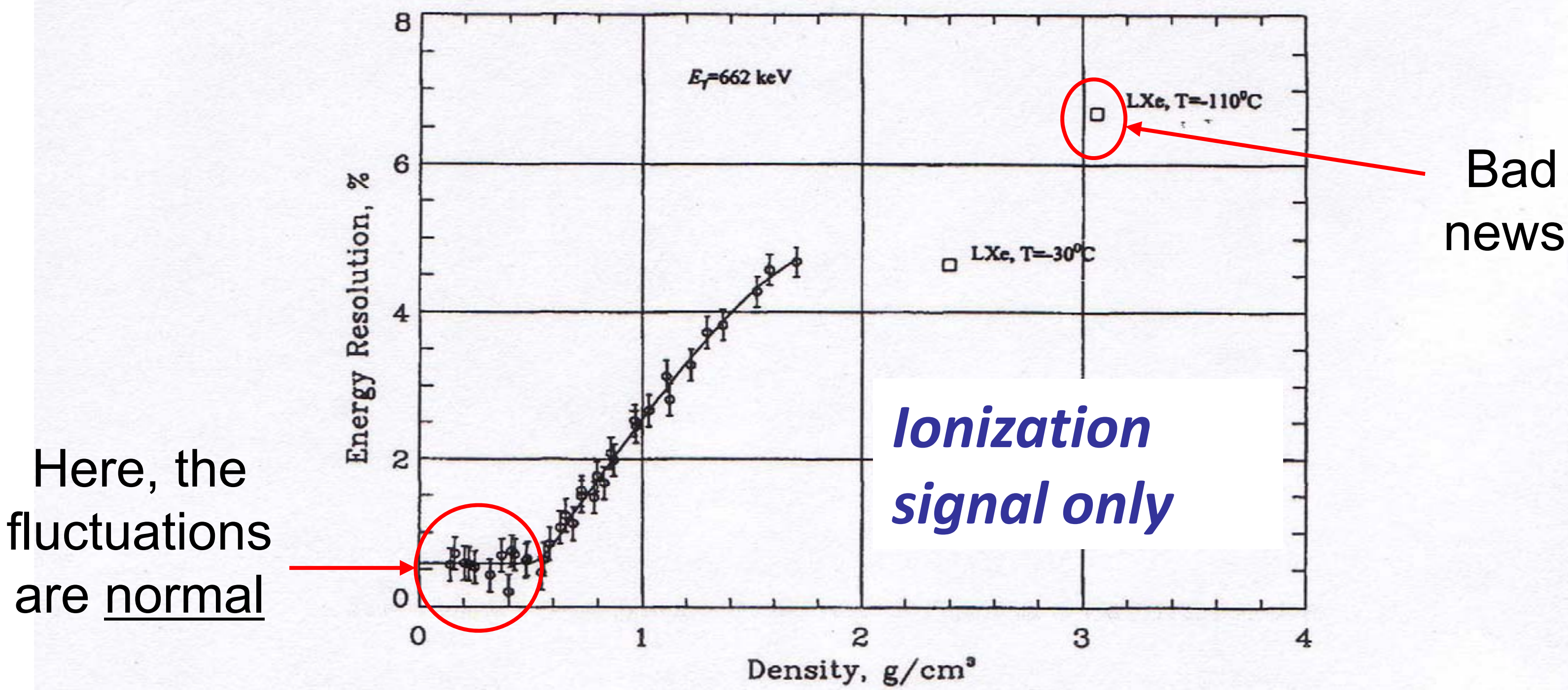


Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

For ρ <0.55 g/cm^3, ionization energy resolution is "intrinsic"

Energy Partitioning in Xenon

Anomalously large fluctuations
exist in **partitioning** of energy in LXe
Fluctuations cause “anti-correlation” in LXe
WIMP search: very bad news for S2/S1 resolution!

Only a small fraction of scintillation signal is recoverable
Energy resolution cannot be restored in LXe

Anomalous fluctuations do not exist in HPXe
A measurement of ionization **alone**
is sufficient to obtain **near-intrinsic energy** resolution…

Intrinsic energy resolution

- $\delta E/E = 2.35 \cdot (F \cdot W/Q)^{1/2}$
  - F ≡ Fano factor: F = 0.15 (HPXe) (LXe: F ~20)
  - W ≡ Average energy per ion pair: W ~ 25 eV
  - Q ≡ Energy release in decay of ^{136}Xe: ~2500 keV

$\delta E/E$ = 2.8×10^{-3} FWHM (HPXe)

N = Q/W ~100,000 primary electrons

$\sigma_N = (F \cdot N)^{1/2}$ ~120 electrons rms!

Need gain with very low noise/fluctuations!

Avalanche gain cannot meet this objective

Fluctuations in Electroluminescence (EL)

EL: linear gain process: electrons excite, atoms radiate

Uncorrelated fluctuations: $\sigma = ((F + G)\cdot N)^{1/2}$

EL can provide G less than F:

G for EL contains three terms:

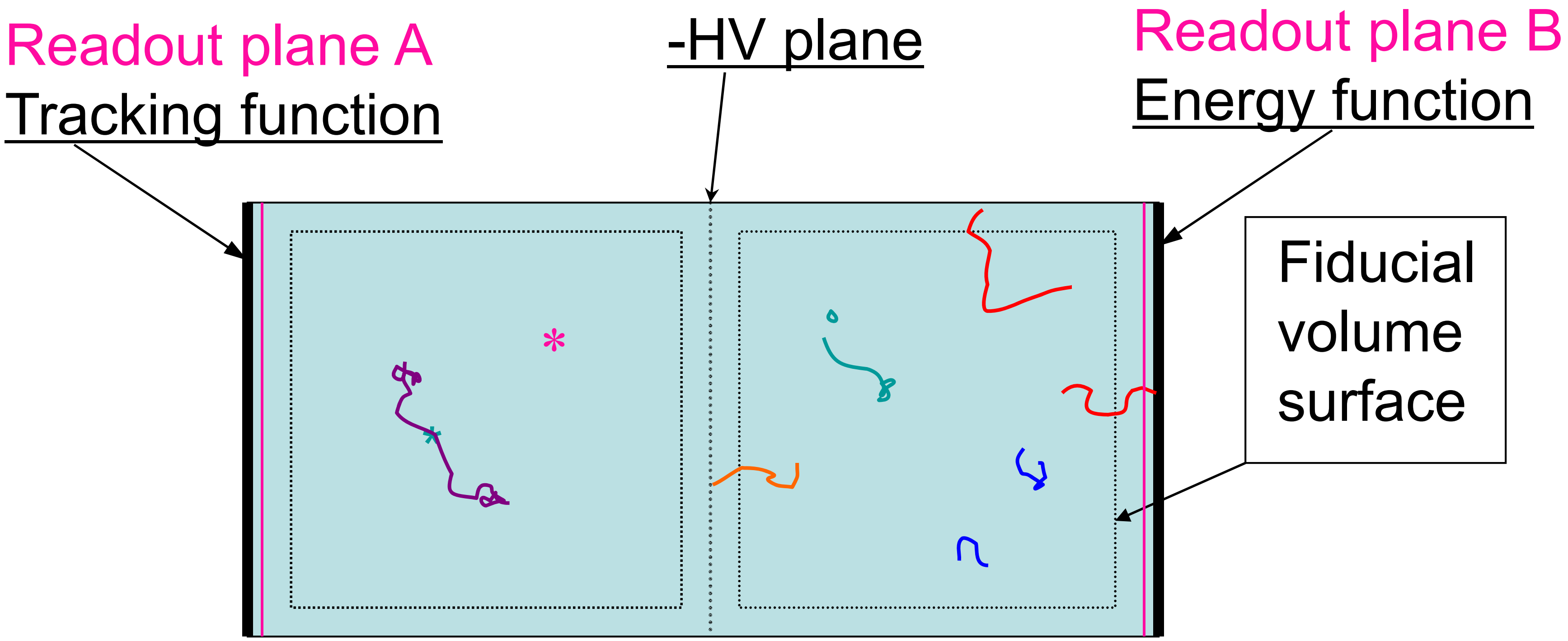
1. Fluctuations in n_{uv} (UV photons per e):
2. Fluctuations in n_{pe} (detected photons/e):
3. Fluctuations in photo-detector single PE response:

$$G = \sigma^2 = 1/(n_{uv}) + (1 + \sigma^2_{pmt})/\ n_{pe})$$

For $G \le F = 0.15 \Rightarrow n_{pe} \ge 10/e$ $\Rightarrow \Sigma\ n_{pe} \ge 10^6$ @Q-value

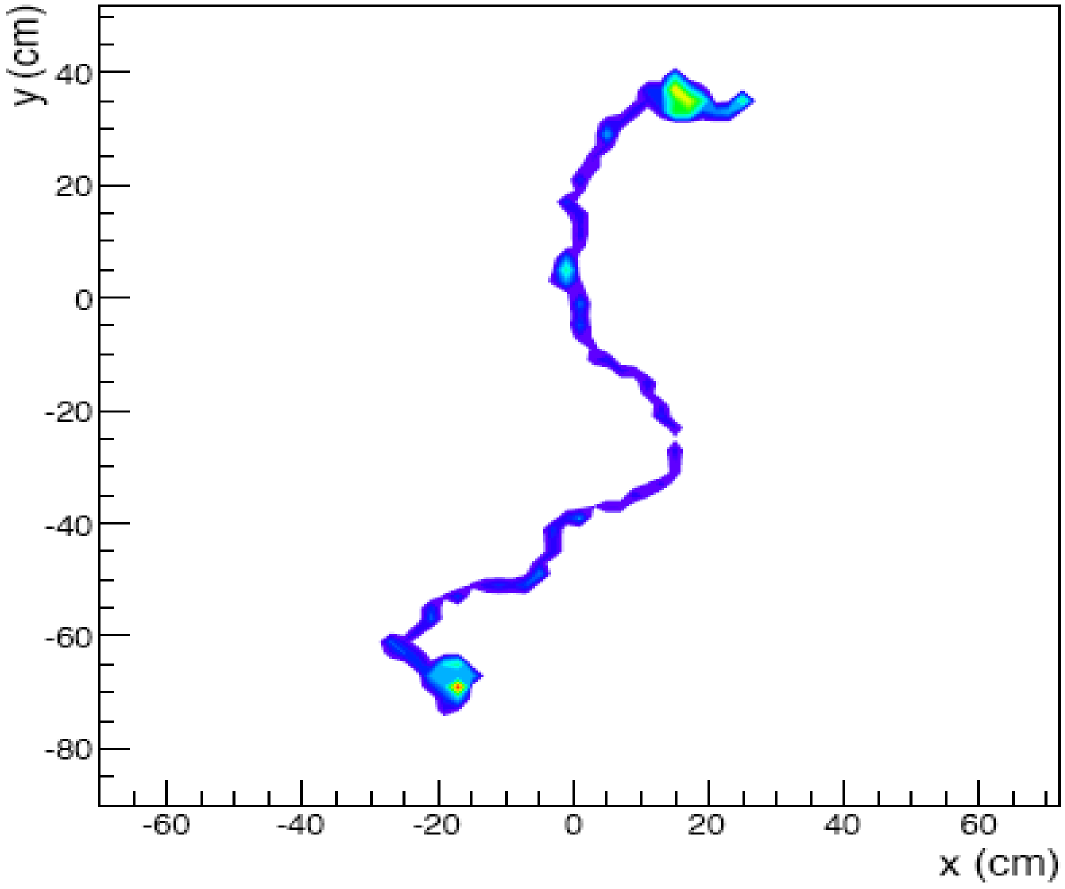
Equivalent noise: <u>much</u> <u>less</u> than 1 electron rms!

Separated-function TPC:



Signal: ββ or WIMP   Backgrounds

Topology: “spaghetti, with meatballs”



ββ events: **2**

γ events: **1**

Gotthard TPC:

~ x30 rejection

Slide: NEXT collaboration

Various HPXe efforts

“Gotthard” TPC: first xenon 0-ν ββ experiment

Coimbra: (Portugal) electroluminescence

Russia: several pioneering achievements

Beppo-SAX satellite: 7-PMT 5-bar TPC

Texas A&M: 7-PMT 20 bar HPXe TPC

BNL-Temple: HPXe scintillation decay time

EXO - gas: Ba^{++} ion tagging, tracking, …

LBNL/LLNL/TAMU/NEXT...

EL in 4.5 bar of Xenon (Russia - 1997)

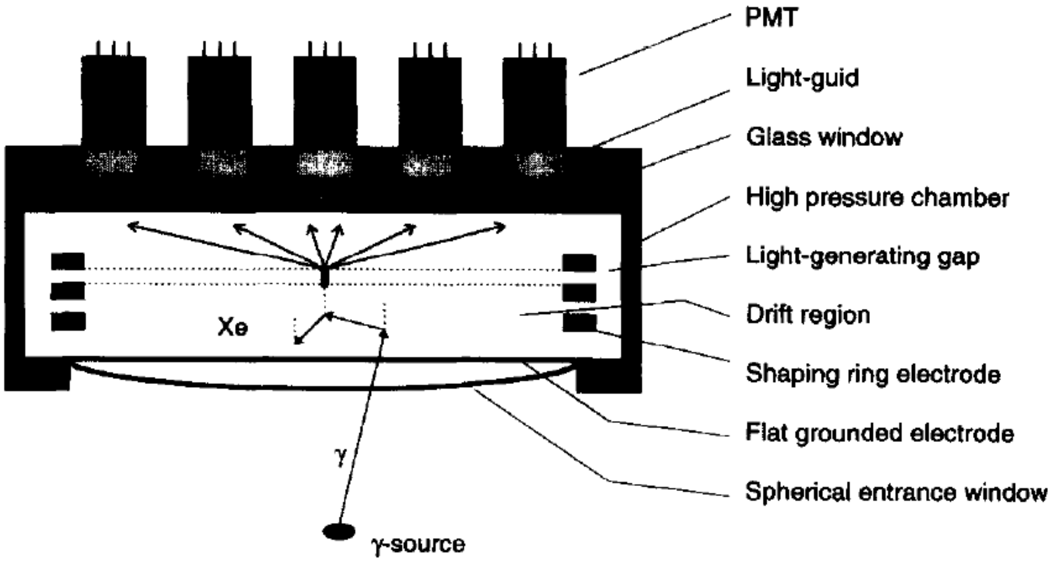
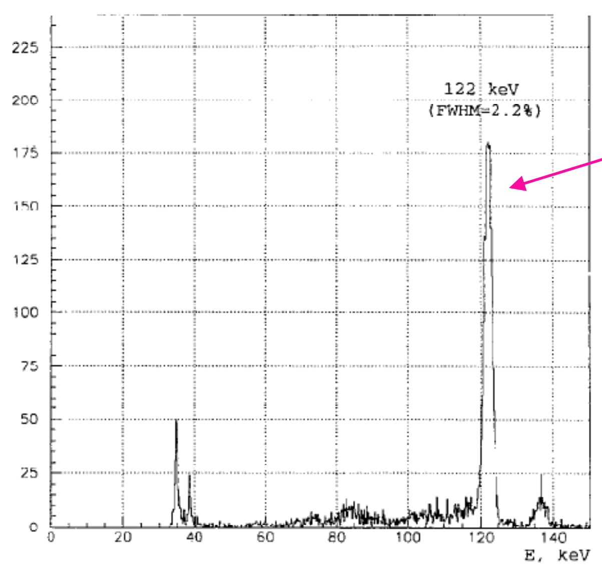


Fig. 1. Schematic diagram of the gas scintillation drift chamber with 19 PMT matrix readout.

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

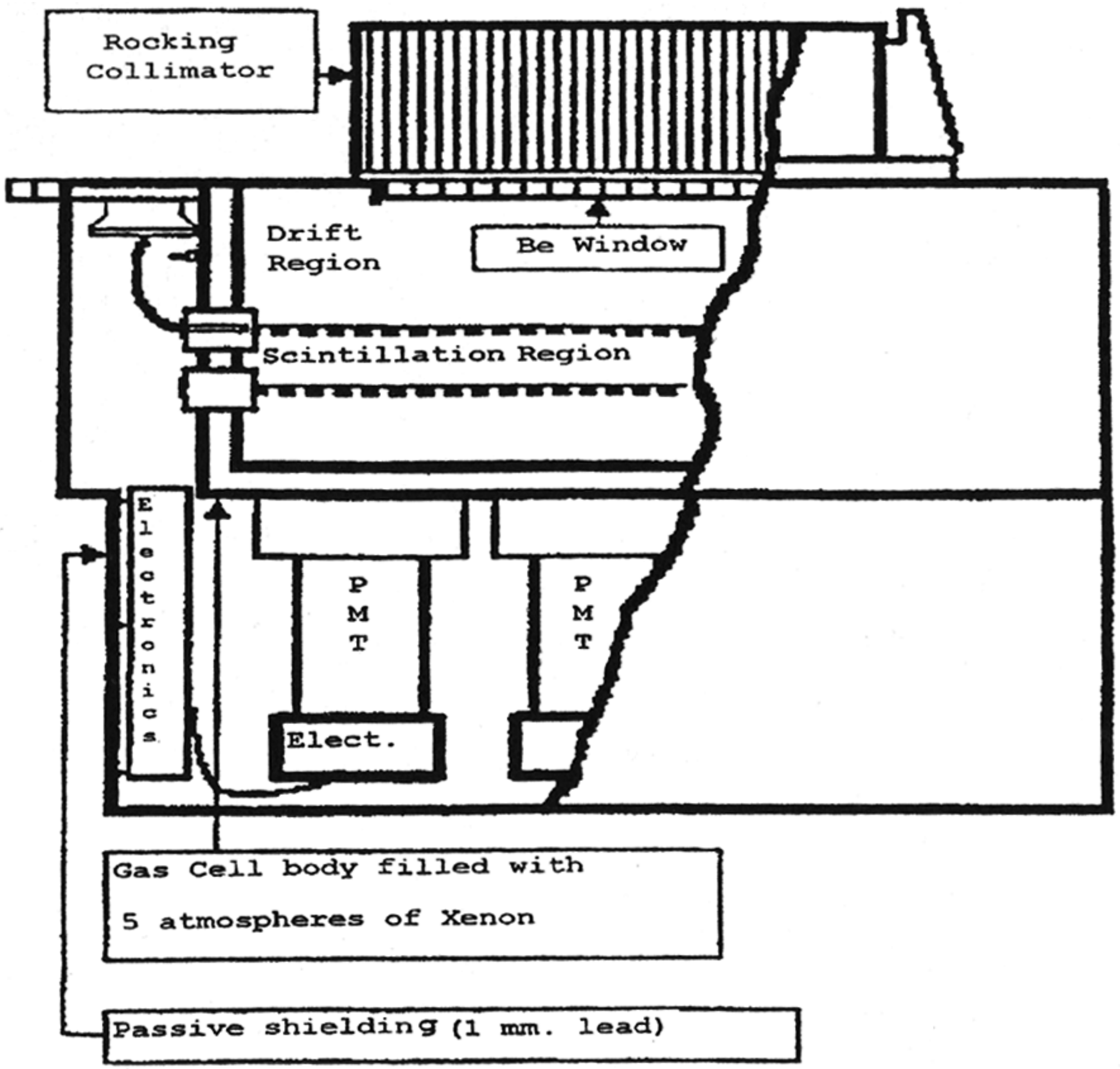


This resolution corresponds to

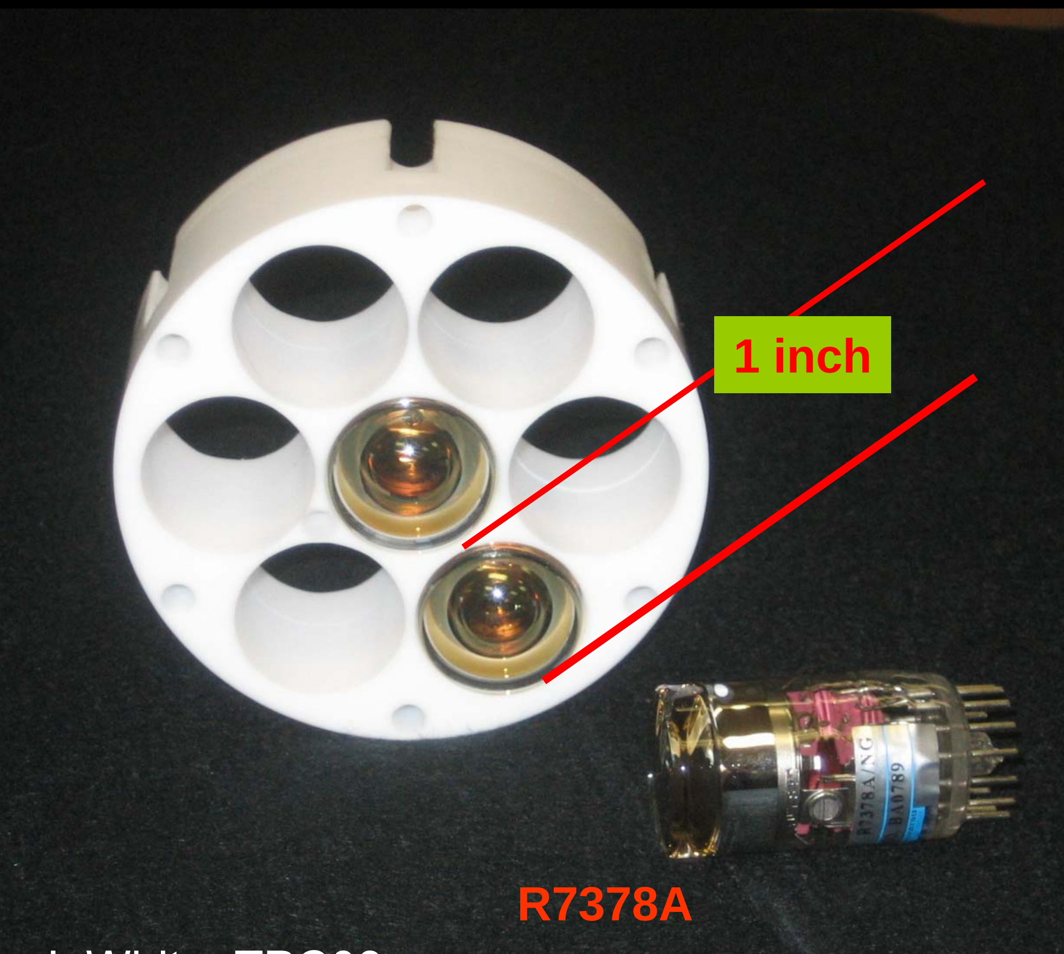
$\delta E/E = 5 \times 10^{-3}$ FWHM

-- if extrapolated ($E^{-1/2}$) to $Q_{\beta\beta}$ of 2.5 MeV

Europe: Beppo-SAX satellite: a HPXe TPC in space!



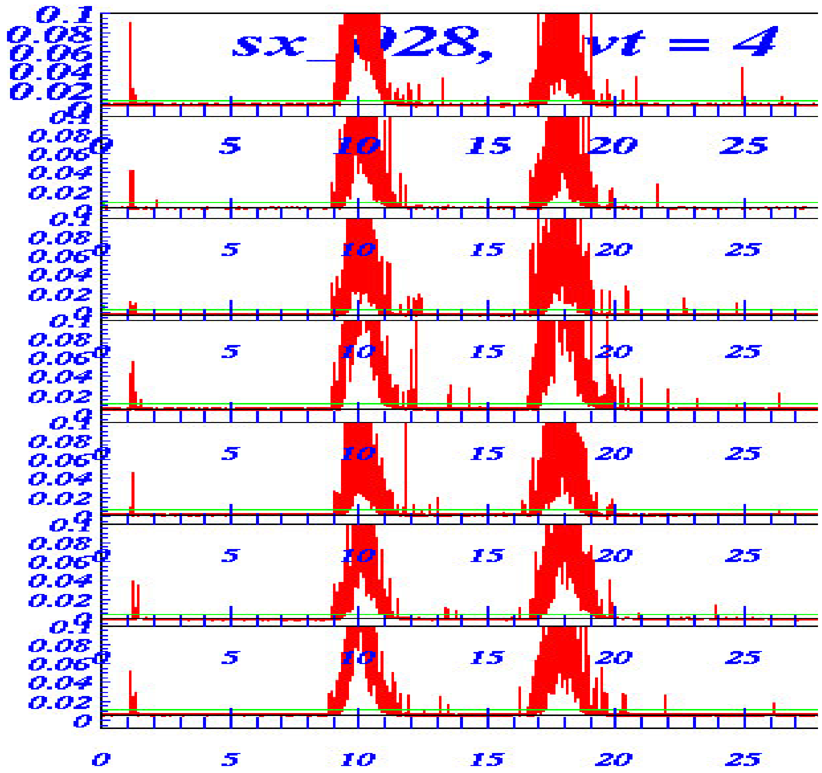
7-PMT, 20 bar
TAMU HPXe TPC

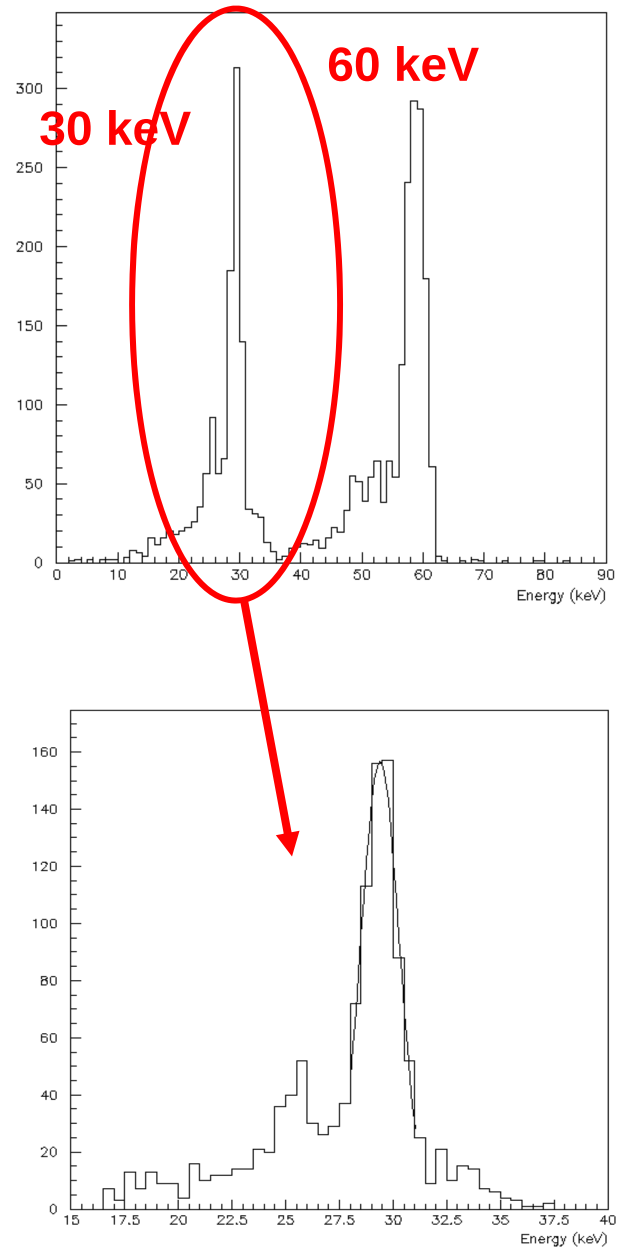


J. White, TPC08

^{241}Am γ-rays ~60 keV

(1st Look – PMT gains not yet calibrated)





Europe:

NEXT collaboration

Spain/Portugal/France…

funded: **5M €** !

to develop & construct a 100 kg enriched HPXe TPC for 0-ν ββ decay search at Canfranc Laboratory within 5 years

The NEXT Collaboration

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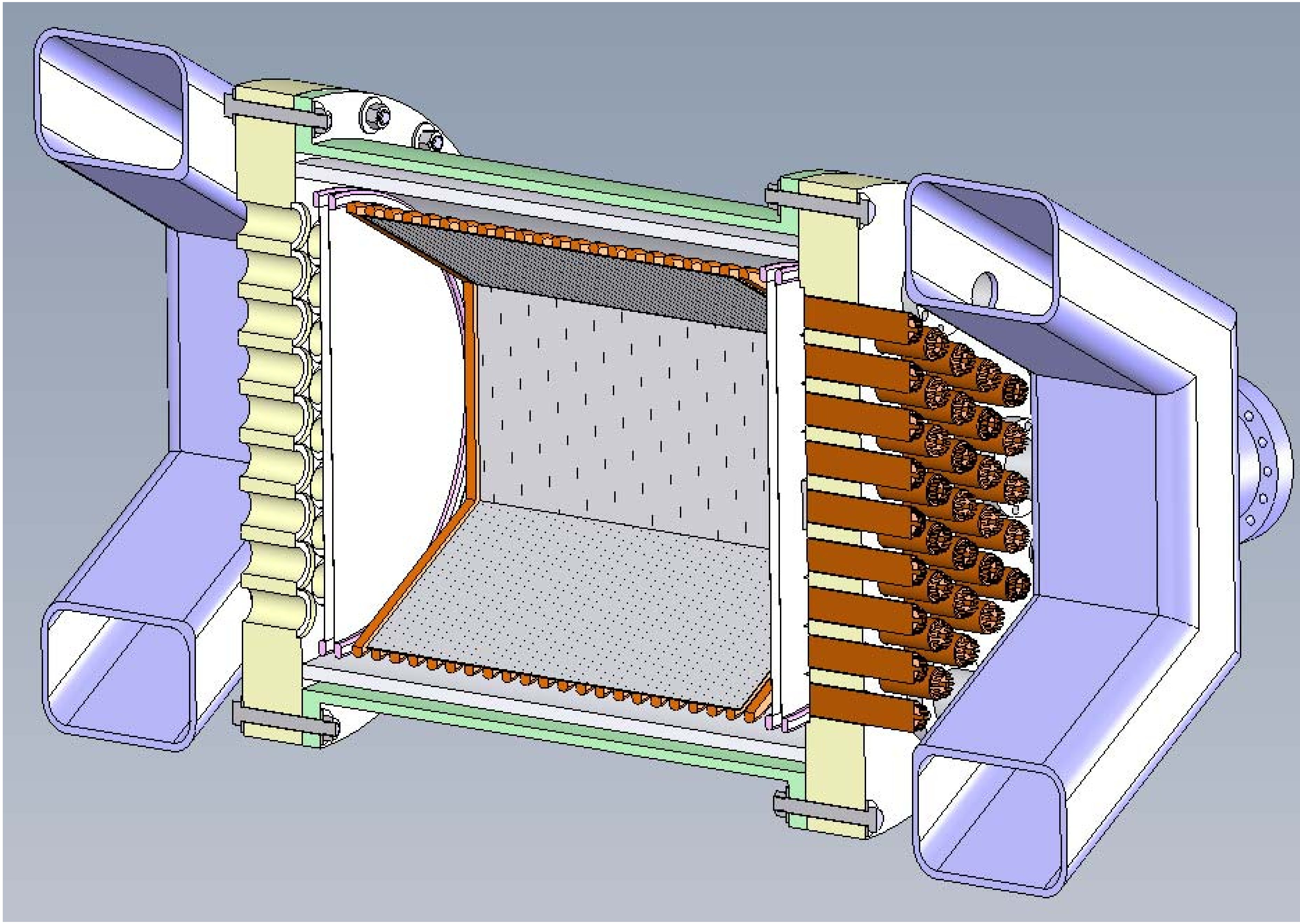
Medium-scale TPC @ LBNL

- Separated function TPC
  - Diameter of active volume: 30 cm
  - Length: 60 cm (drift length: ~30 cm)
  - 20 bars pure xenon ($M_{Xenon} \leq 2.5$ kg)
  - 28 mm PMTs detect t_0, measure energy, and track
  - $N_{PMT} = 61$ per end (BaBar PMTs requested)
  - Scale matched to 2500 keV Q-value of ^{136}Xe
  - AMANDA ADCs requested for signal capture



Medium-scale EL TPC

- Primary Goal #1: Energy resolution
  - $\delta E/E \leq 5 \times 10^{-3}$ FWHM at Q-value (2480 keV)
  - Must be demonstrated at MeV energies!
- Primary Goal #2: 3 -D tracking
  - Multiple scattering $\Rightarrow$ complex topologies

  Verify meatball recognition efficiency
- Other Goals: nuclear/electron recoil discrimination, Compton imaging, ...

FY10 Scenario

- LBNL, TAMU, LLNL, NEXT + ... collaborate
- "Xenophilia" workshop, November 2009:
  - how does the community want to proceed?
- small-scale TPC operation + simulations:
  - experience + optimized design of m-s TPC
- medium-scale TPC built and commissioned
  - initial operation at/near ground level
- study of performance & design issues at ton scale
  - radiopurity, background rejection, gas handling, ...

FY11 - FY12 Scenario

- Transition to operation at modest depth
- Data analysis, technical refinements +1-2 years
- Performance justifies serious 1000+ kg system
- Substantial new collaboration formed...

HPXe TPC Summary

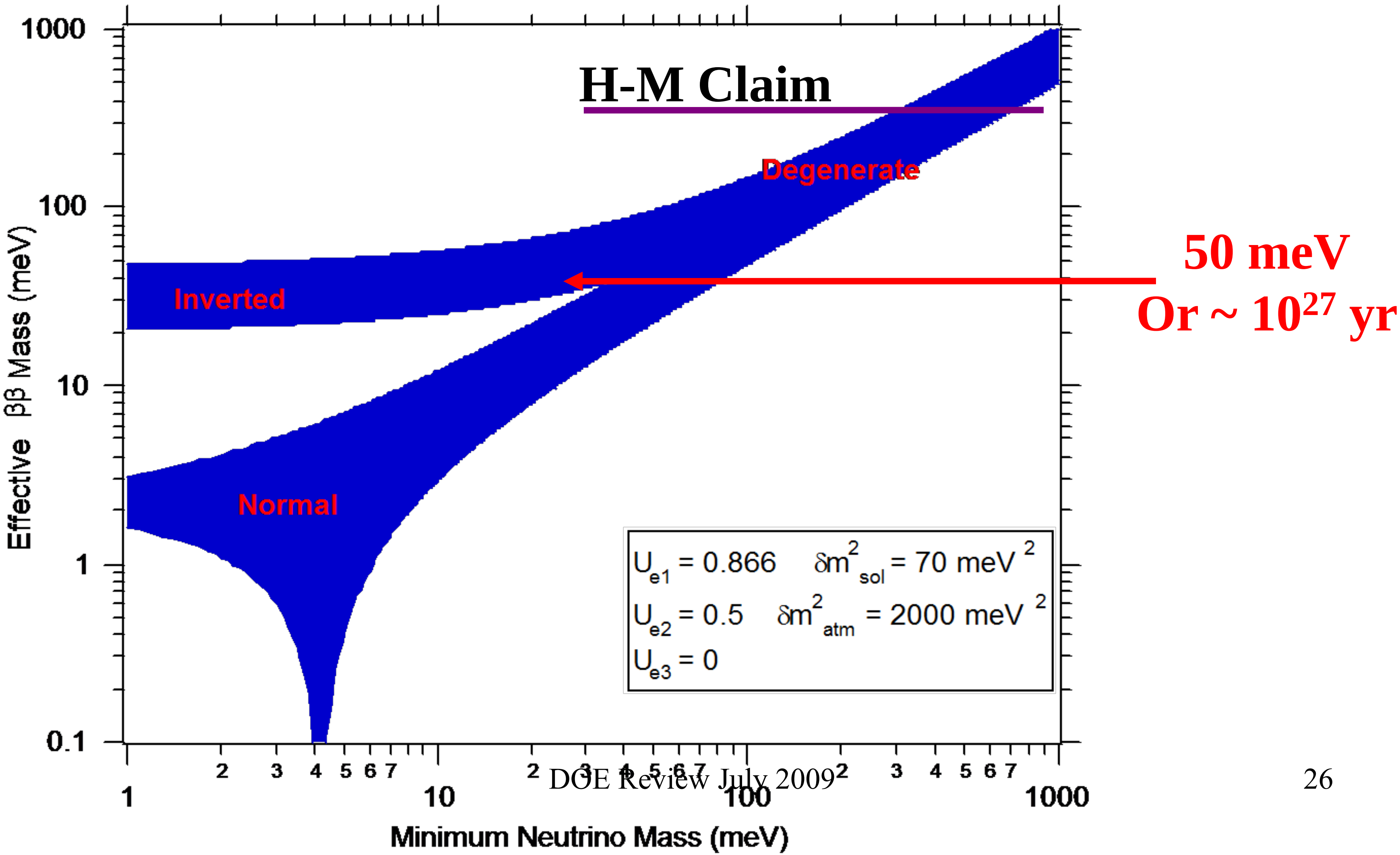
- Potential for superior performance is high
  - x11 better intrinsic energy resolution than LXe
- Performance of HPXe needs demonstration
  - EL scheme works better in larger systems
- Simultaneous WIMP/0ν $\beta\beta$ search possible
  - No compromise necessary for either purpose

Thank you

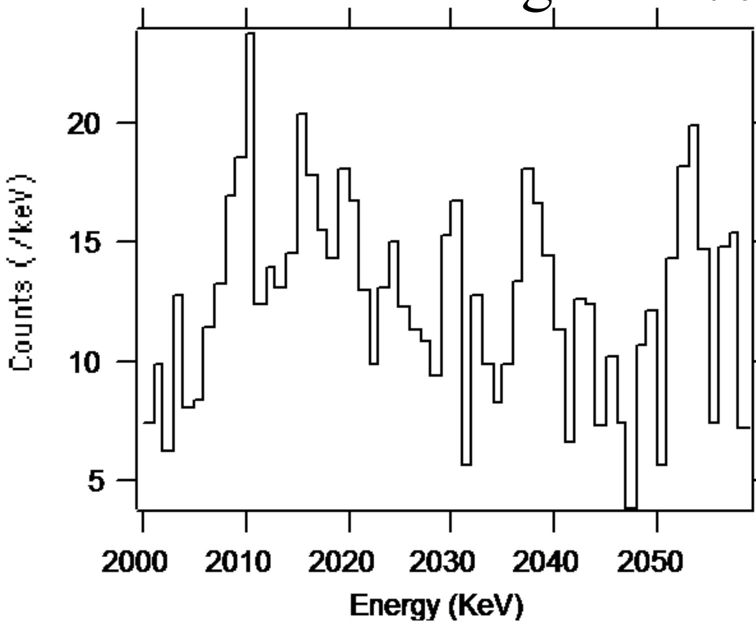
Backup slides…

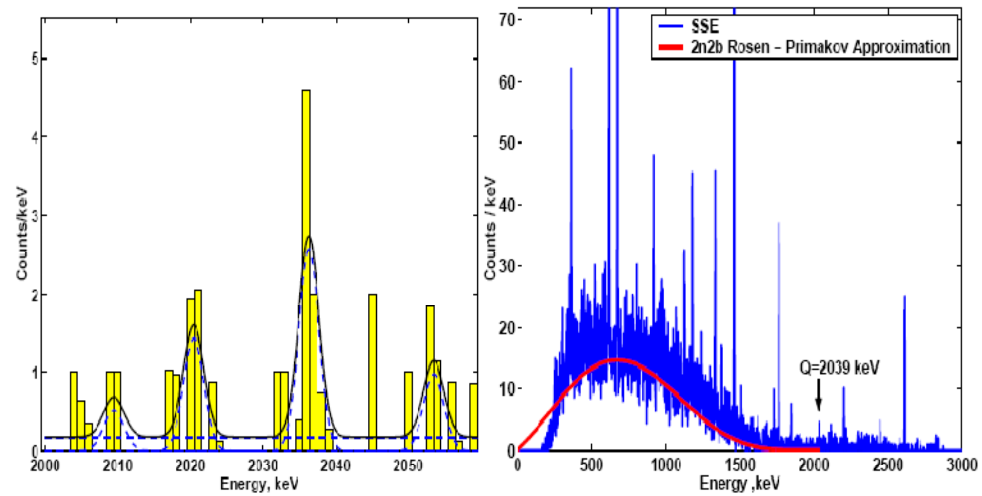
$$\left[T_{1/2}^{0\nu}(0^+ \rightarrow 0^+)\right]^{-1} = G^{0\nu}(E_0, Z)\left|M_{\rm GT}^{0\nu} - \frac{g_V^2}{g_A^2}M_{\rm F}^{0\nu}\right|^2 \langle m_\nu\rangle^2$$

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

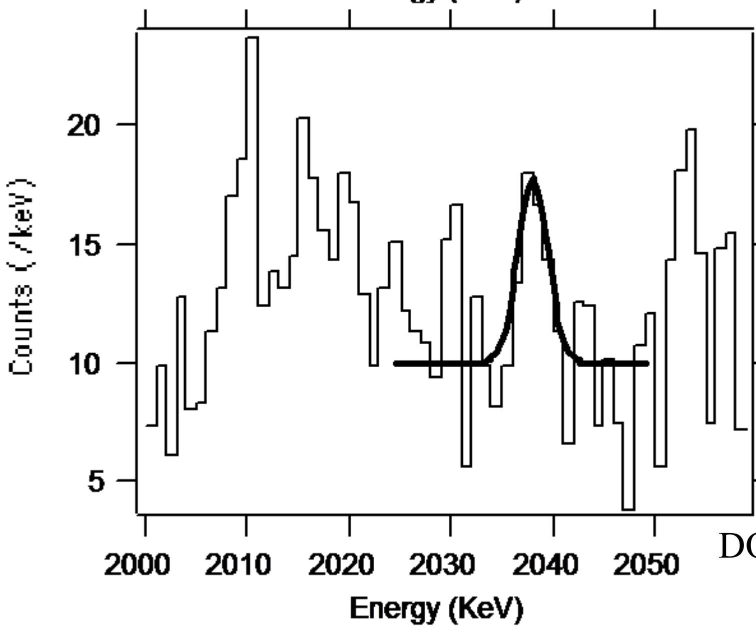


- H-M: Only positive claim for 0–ν ββ detection
- 11 kg of 86% enriched ^{76}Ge for 13 years





•Klapdor-Kleingrothaus et al **Phys.Lett.B586:198-212,2004**.



NIM A522, 371 (2004)

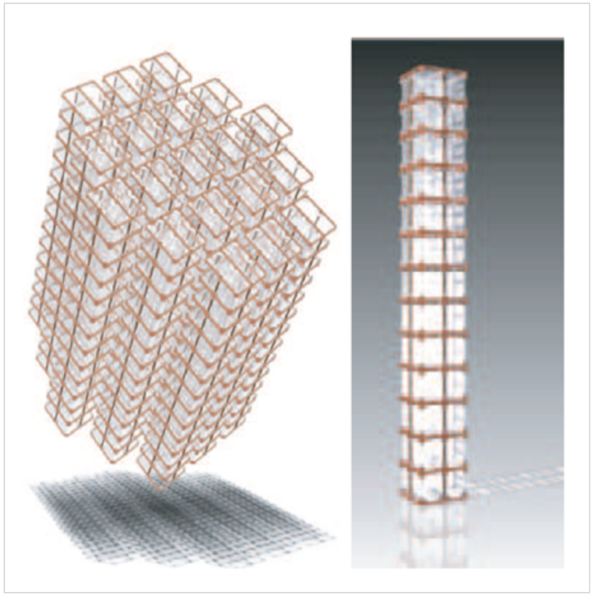
$T_{1/2}$~1.19x10^{25}y

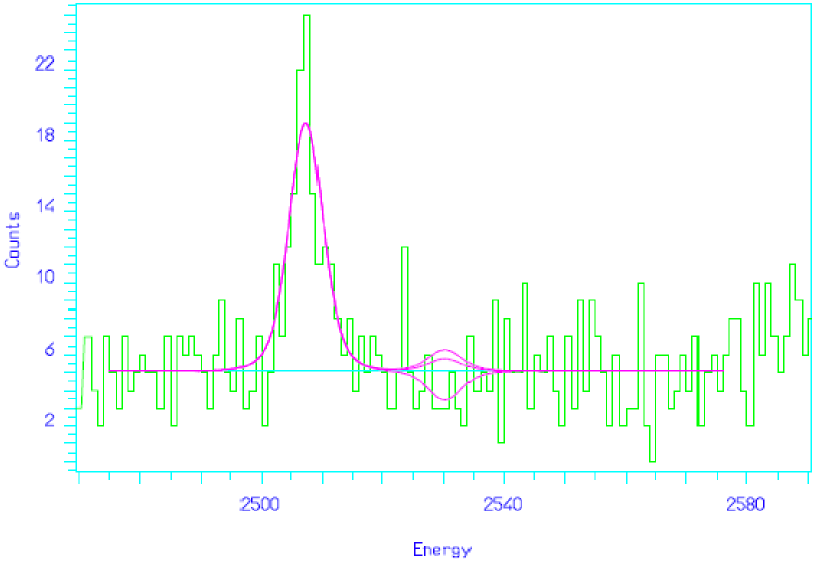
<m> ~ 0.44 eV

Excellent energy resolution not sufficient to reject BG!

CUORE: Cryogenic "calorimeters"

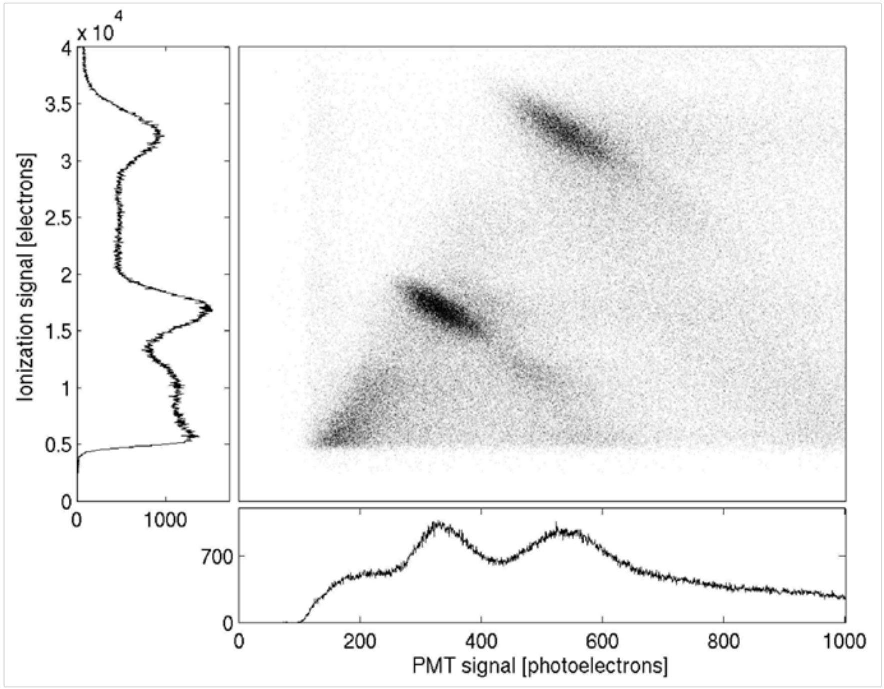
- CUORICINO: 40.7kg TeO_2 (34% abundant ^{130}Te)
  - $T^{0\nu}_{1/2} \geq 2.4 \times 10^{24}$ yr (90% C.L.)
  - $<m_\nu> \leq 0.2 - 0.9$ eV
  - Resolution: 7.5 keV FWHM at Q = 2529 keV!
- CUORE ~1000 crystals, 720 kg

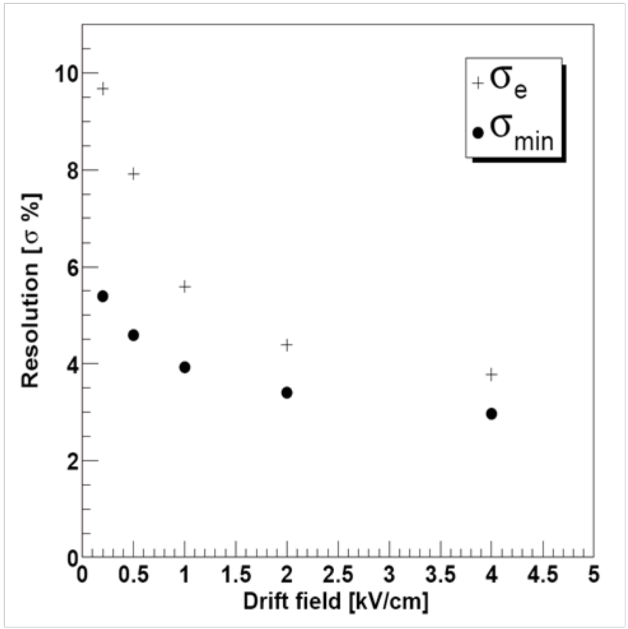




EXO-200: expected E resolution

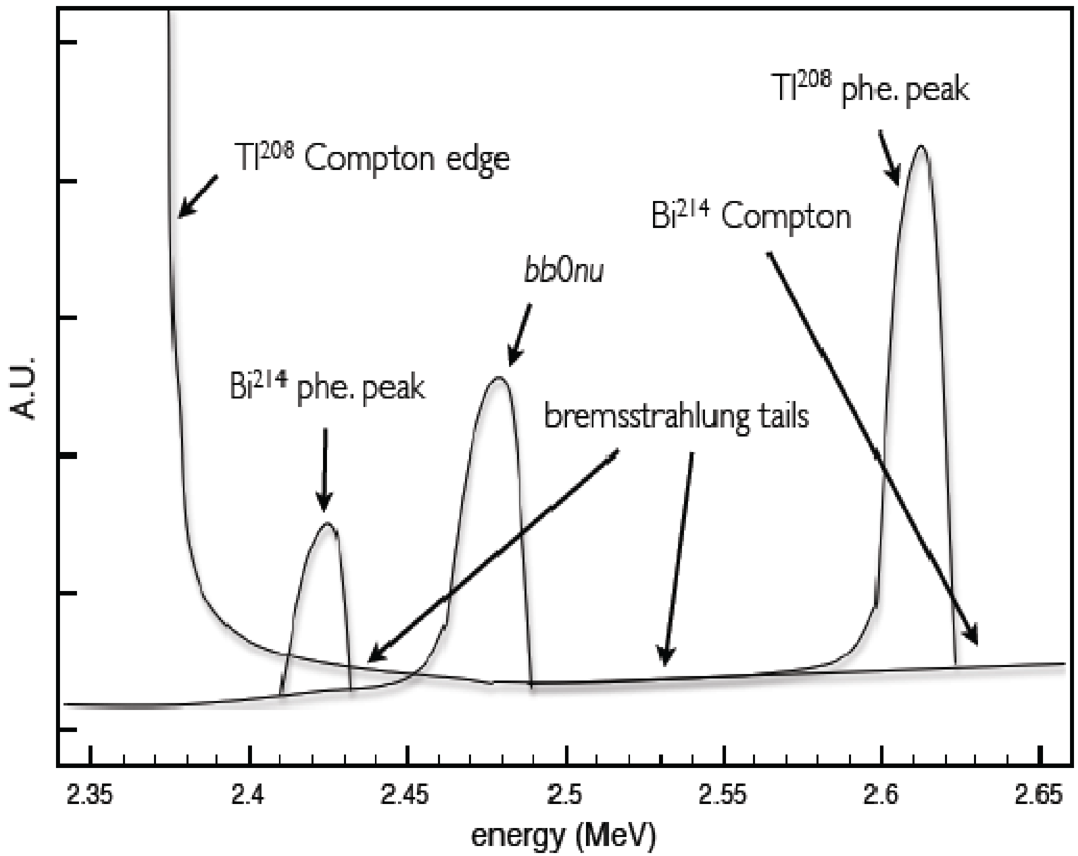
ionization and scintillation are strongly "anti-correlated" in LXe





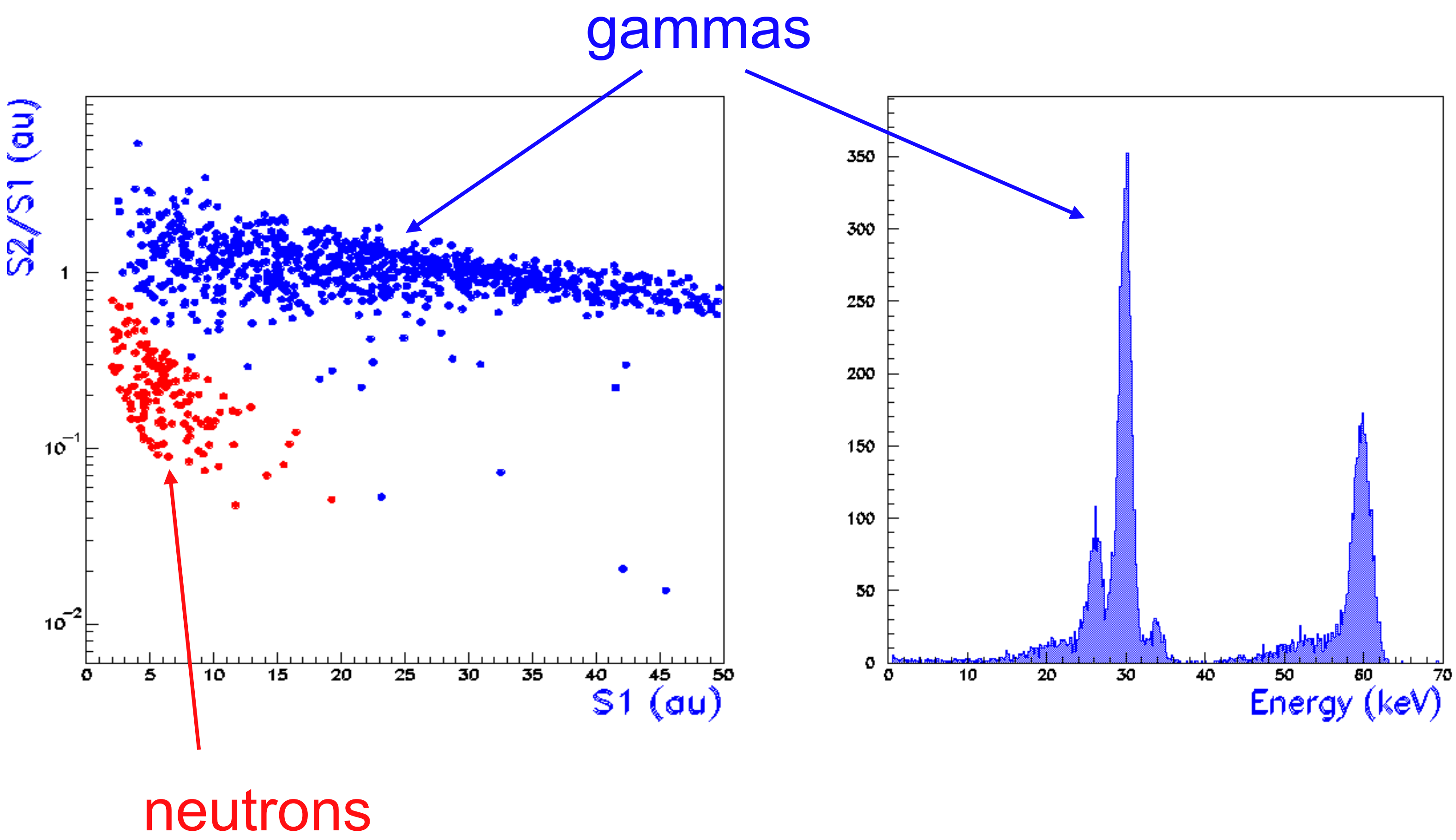
$\delta E/E = 33 \times 10^{-3}$ @ $Q_{0\nu\beta\beta}$ FWHM - predicted

Backgrounds for the ββ0ν search



NEXT Collaboration

Nr Discrimination in HPXe with TAMU 7-PMT TPC



Why Xenon for 0–ν ββ search?

- Only inert gas with a 0–ν ββ candidate
- No long-lived Xe radio-isotopes
- No need to grow crystals - no surfaces
- Can be easily re-purified in place (recirculation)
- ^{136}Xe enrichment easy (natural abundance 8.9%)
- Gas Phase advantages:
  - Purification easier
  - No liquid level or temperature challenges
  - **Event topology available**
  - **Excellent energy resolution (not demonstrated!)**

"Gotthard TPC"

Pioneer TPC detector for 0-ν ββ decay search

- Pressurized TPC, to 5 bars
- Enriched ^{136}Xe (3.3 kg) + 4% CH_4
- MWPC readout plane, wires ganged for energy
- No scintillation detection ⇒ no TPC start signal!
  - No measurement of drift distance
- $\delta E/E \sim 80 \times 10^{-3}$ FWHM (1592 keV)

  ⇒ 66×10^{-3} FWHM (2480 keV)

Reasons for this less-than-optimum resolution are not clear…

Possible: uncorrectable losses to electronegative impurities

Possible: undetectable losses to **quenching** (4% CH_4)

But: ~30x topological rejection of γ interactions!

Silicon Photomultiplier “SiPM”

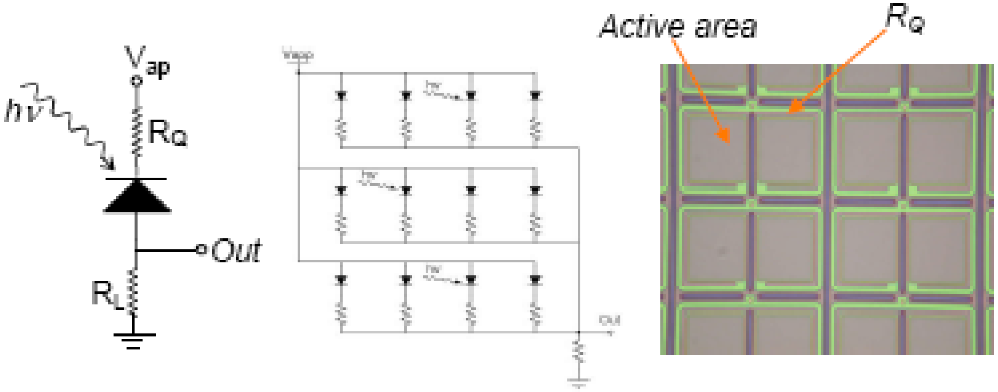
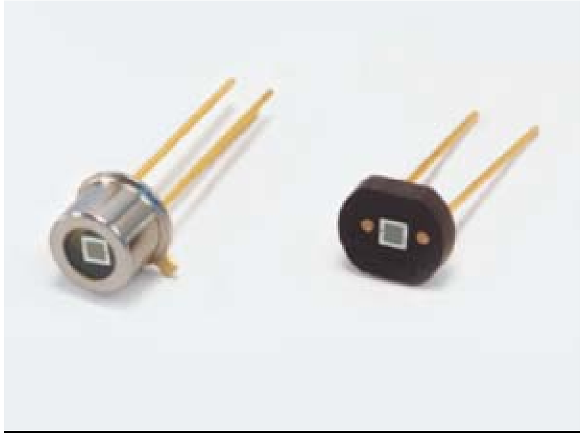
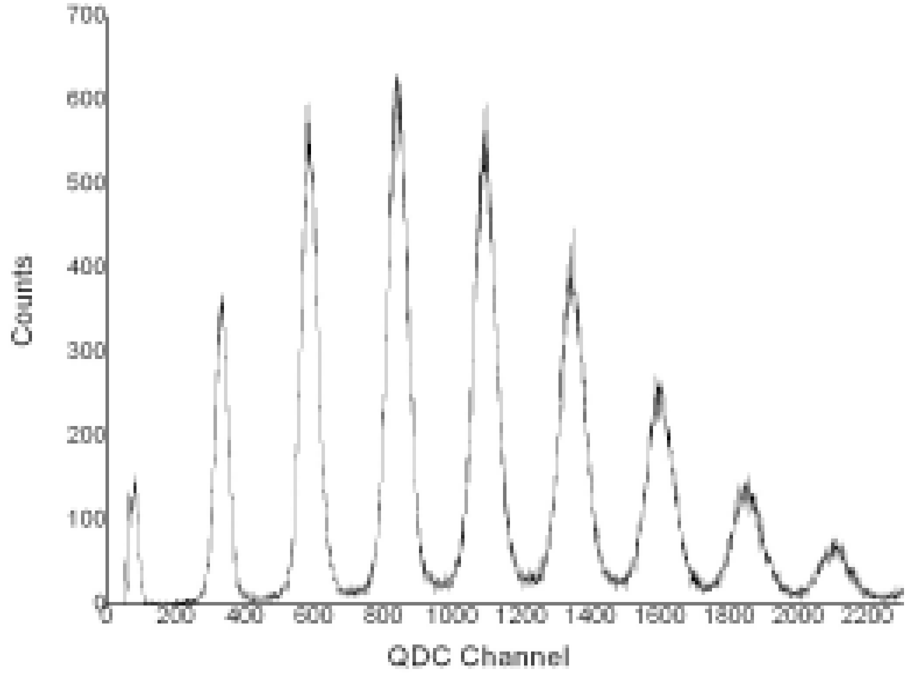


Figure 1 Schematic of a single microcell (left), schematic of part of an SPM array of microcells (center) and photo of a portion of the SPM microcells (right).

SiPM from Hamamatsu, “MPPC”



SiPM photoelectron spectrum



Electro-Luminescence (EL) is the key

(Gas Proportional Scintillation)

- Electrons drift in low electric field region
- Electrons then enter a high electric field region
- Electrons gain energy, excite xenon, lose energy
- Xenon generates VUV (175 nm)
- Electron starts over, gaining energy again
- Linear growth of signal with voltage
- Photon generation up to ~1000/e, but no ionization
- Early history irrelevant, $\Rightarrow$ **fluctuations are small**

More Virtues of Electroluminescence

- Immune to microphonics
- Absence of positive ion space charge
- Linearity of gain versus pressure, HV
- Isotropic signal dispersion in space
- Trigger, energy, and tracking functions accomplished with optical detectors

Molecular Chemistry of Xenon

- Scintillation:
  - Excimer formation: $Xe^* + Xe \rightarrow Xe_2^* \rightarrow h\nu + Xe$
  - Recombination: $Xe^+ + e^- \rightarrow Xe^* \rightarrow$
- Density-dependent processes also exist:

$$Xe^* + Xe^* \rightarrow Xe^{**} \rightarrow Xe^+ + e^- + heat$$

  - Two excimers are consumed!
  - More likely for both high ρ + high ionization density
  - Quenching of both ionization and scintillation can occur!

$Xe^* + M \rightarrow Xe + M^* \rightarrow Xe + M + heat$ (similarly for Xe_2^*, Xe^{**}, Xe_2^{*+}…)

$Xe^+ + e^-(hot) + M \rightarrow Xe^+ + e^-(cold) + M^* \rightarrow$

$Xe^+ + e^-(cold) + M + heat \rightarrow e^-(cold) + Xe^+ \rightarrow Xe^*$