Prospects for 0-ν ββ Search with a High-Pressure Xenon Gas TPC

What's NEXT ?

David Nygren
LBNL

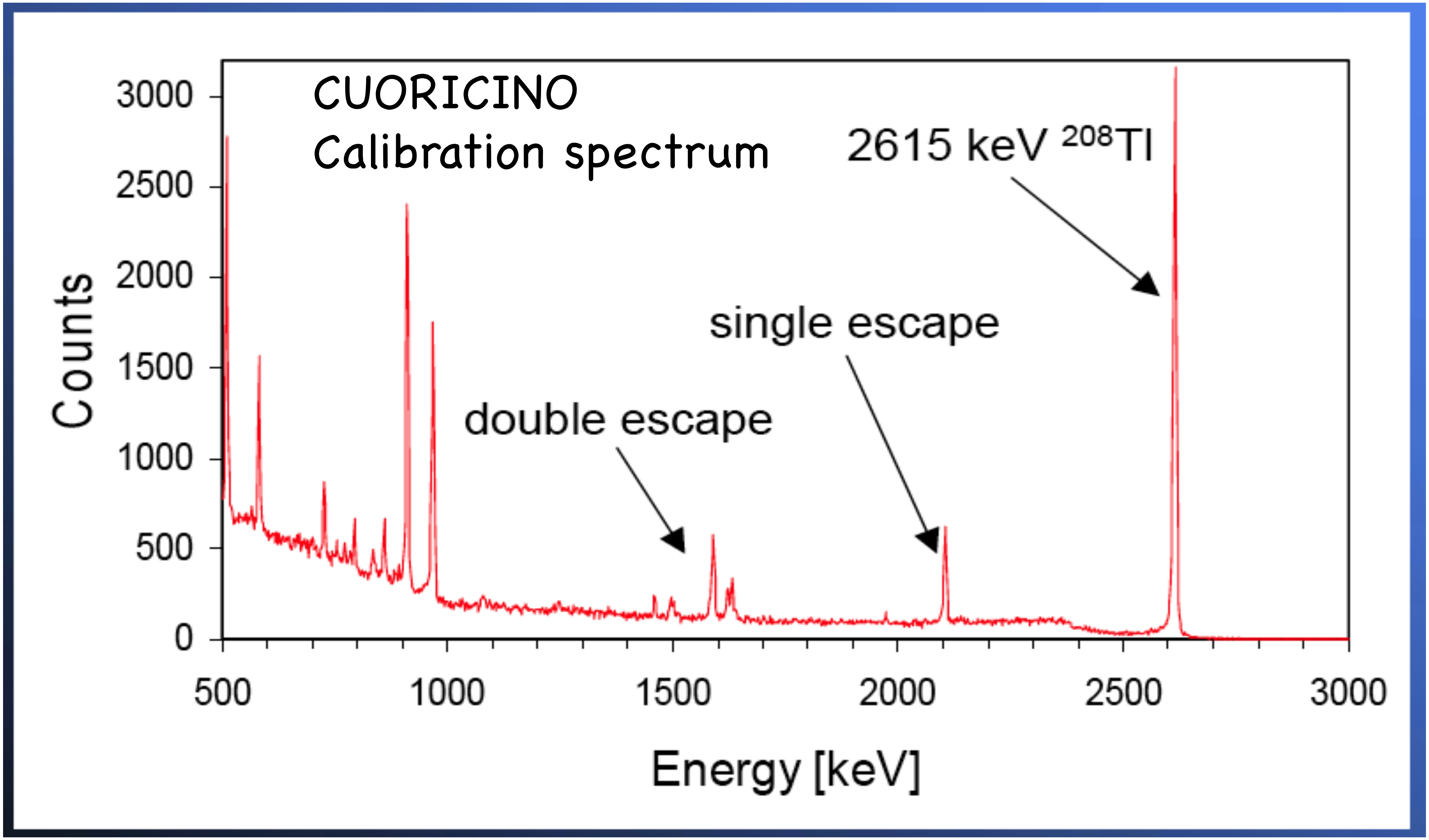
Why xenon?

Xenon for 0−ν ββ

- Only inert gas with a 0−ν ββ candidate
- Q-value of ^{136}Xe is reasonably high: ~2470 keV
- No long-lived Xe radio-isotopes
- No need to grow crystals - no modular surfaces!
- Monolithic, fully active fiducial surface is possible
- Can be easily re-purified in place (recirculation)
- ^{136}Xe enrichment easy (natural abundance 8.9%)
- Gas Phase advantages:
  - **Event topology is available (in principle!)**
  - **Excellent energy resolution (not demonstrated - yet!)**

Energy Resolution CUORE: $\delta E/E \approx 1 \times 10^{-3}$ FWHM

Germanium Majorana/GERDA: $\delta E/E \approx 1 \times 10^{-3}$ FWHM



Background Rejection

- Ultra-high energy resolution is first line of defense

  ⇒ **Extreme radio-purity of materials**

  - ***insufficient to remove all backgrounds (so far)***
  - Try other tactics:
    - Event topology - single-site requirement
    - Event topology - two opposed electrons in B-field
    - Event topology - two "Bragg" peaks on one track
    - Tag daughter atom - *somehow*…
    - Use ^{48}Ca - ultra-high Q-value
    - … ?

Energy resolution in LXe

Anomalously large fluctuations exist in LXe

in **partitioning** of energy between charge and light

Scintillation ⇔ Ionization "anti-correlation"

High atomic plus high ionization densities ⇒ recombination

⇒ Landau fluctuations govern partitioning in LXe

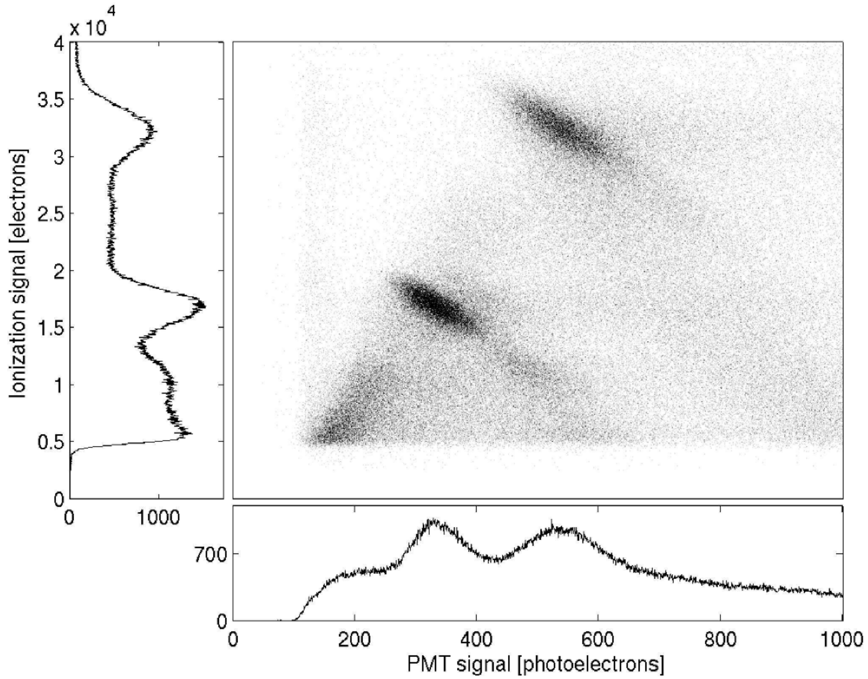
In LXe, it is necessary to detect/combine both signals, but:

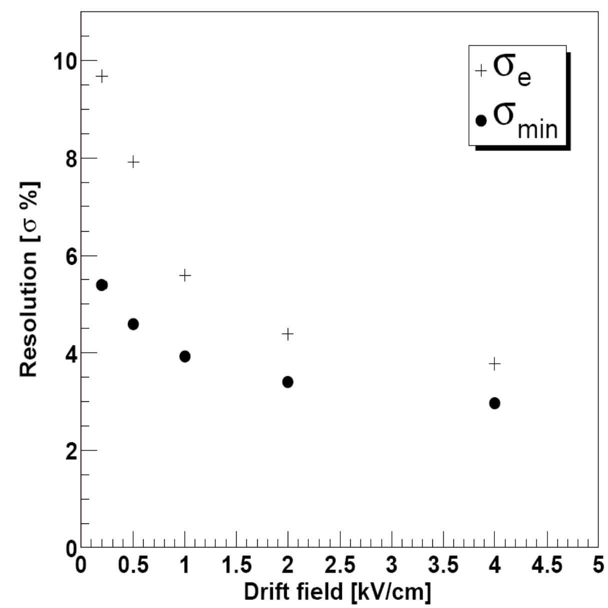
Only a limited fraction of scintillation signal is recoverable

Energy resolution cannot be fully restored in LXe

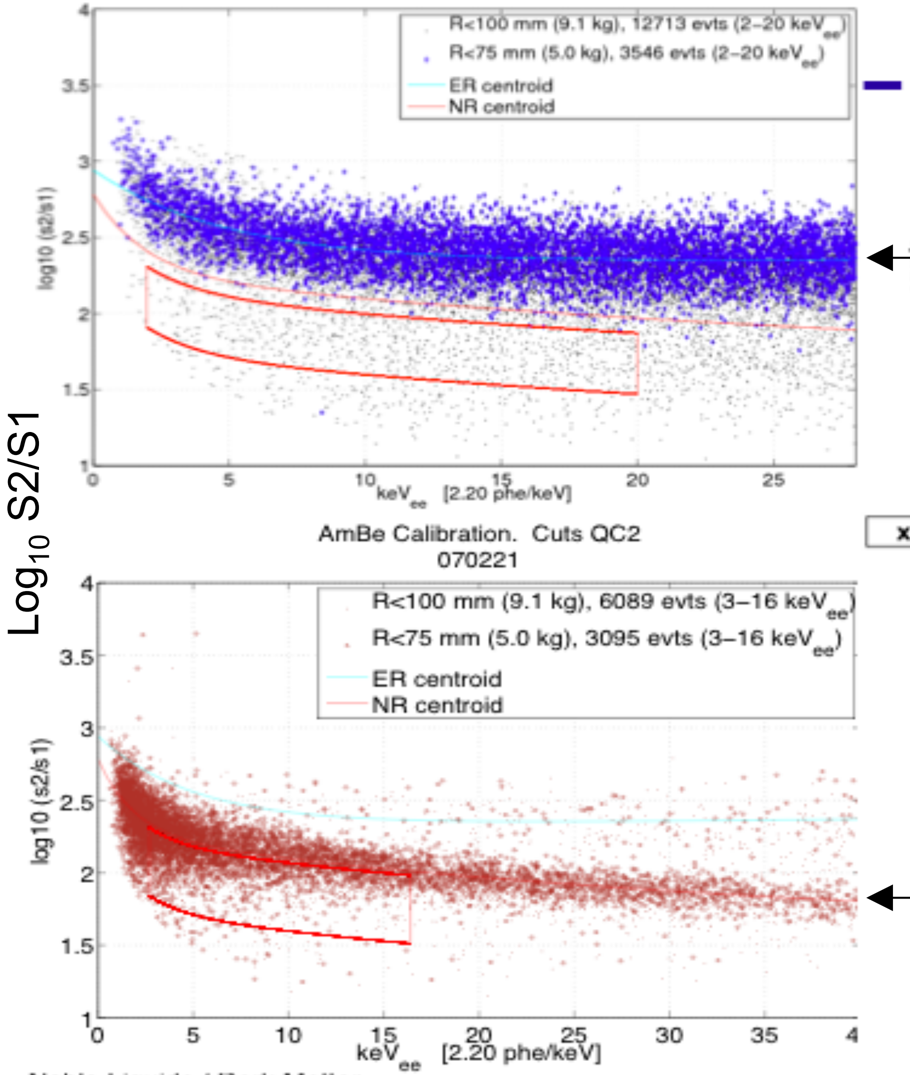
Energy resolution: EXO-200

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





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



Xenon10 Experiment

Gamma events (e-R)

Latest Xenon-10 results look better, but nuclear recoil acceptance still needs restriction

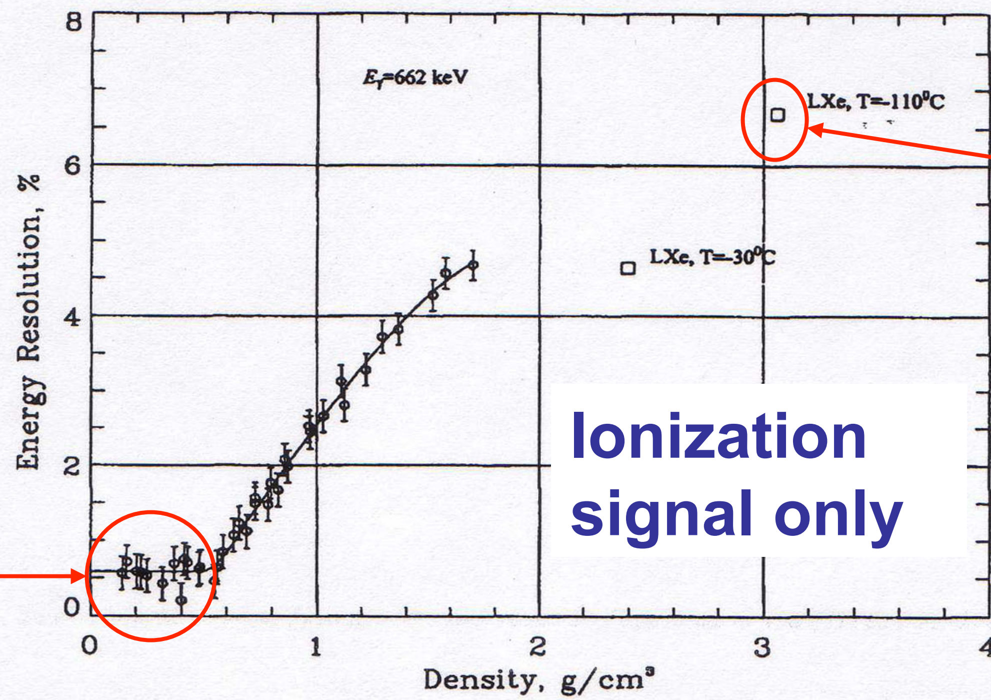
Neutron events (N-R)

Rick Gaitskell, Brown University, DOE

WIMP search: fluctuations - very bad news for S2/S1 resolution!

Xenon: Strong dependence on density observed for energy resolution

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



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

Bad news!

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”

Intrinsic energy resolution - xenon

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

- F ≡ Fano factor: F = 0.15 (HPXe); F ~20 (LXe)
- W ≡ Average energy per ion pair: W ~ 25 eV
- Q ≡ Energy release in decay of ^{136}Xe: ~2500 keV

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

Close to the champions!

N = Q/W ~100,000 primary electrons

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

Intrinsic energy resolution

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

To preserve this intrinsic resolution, we
Need gain with very low noise/fluctuations!

Avalanche gain cannot meet this objective, as
early fluctuations are exponentially amplified.
A linear gain mechanism is needed

Answer: Electroluminescence!

Electroluminescence (EL) in xenon

1. Drift primary electrons to a region of high, but not too high, electric field.
2. Primary electron gains energy from high electric field, reaches an energy greater than 8.3 eV
3. Electron excites atom, losing ~all energy to atom
4. Excimer forms and radiates UV at 7.3 eV
5. Electron repeats 2 - 4, until it reaches anode

Typical energy expenditure/photon: 10 eV

Example: 10kV ⇒ n_{uv} = 1000

Some Virtues of Electroluminescence

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

Detection process

Energy resolution depends on the precision for counting each single primary electron

Define an EL gain fluctuation factor: $G \equiv \sigma^2_{EL}$

G for EL contains three terms:

$$G = 1/(n_{uv}) + (1 + \sigma^2_{detector})/ n_{detected\ photons})$$

$\sigma^2_{detector} \approx 0.5$ for PMTs

Let's impose a requirement that $G = F = 0.15$

Then: $n_{pe} \geq 10$ photo-electrons/primary electron

Energy resolution

$n_{pe} \geq 10$ photo-electrons/primary electron implies:

Equivalent noise: much less than 1 electron rms!

N_{pe} = 1,000,000 photoelectrons at Q-value - not a problem!

Finally,...

Fluctuations between energy deposition process (F) and gain process (G) are uncorrelated:

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

$\delta E/E = 4 \times 10^{-3}$ FWHM

Xenon gas advantage:

Below 0.55 g/cm^3, the energy resolution is "intrinsic"

Anomalous fluctuations in energy partitioning
do not exist in HPXe

A measurement of ionization alone is sufficient to obtain **near-**intrinsic energy resolution…

EL in 4.5 bar of Xenon (Russia - 1997)

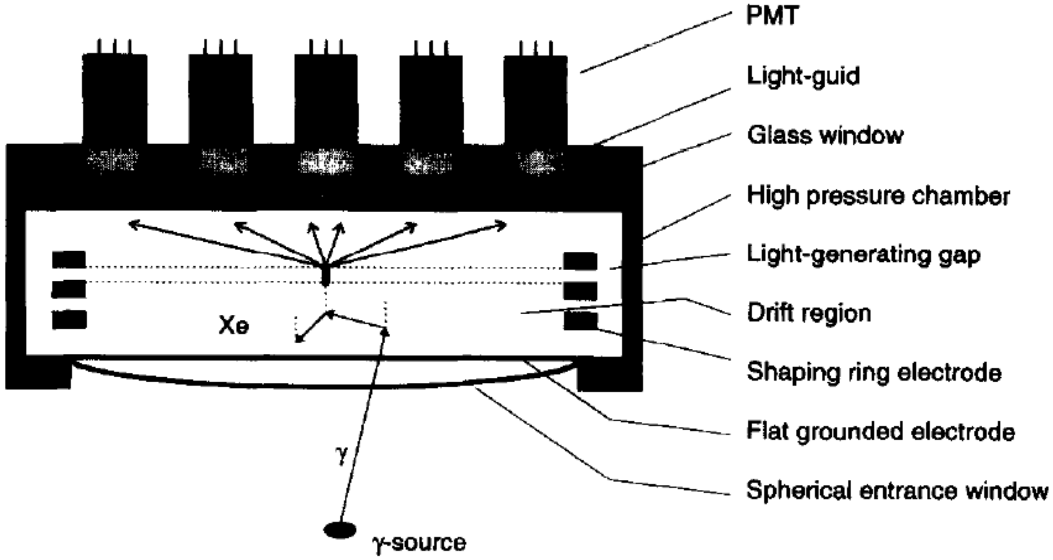
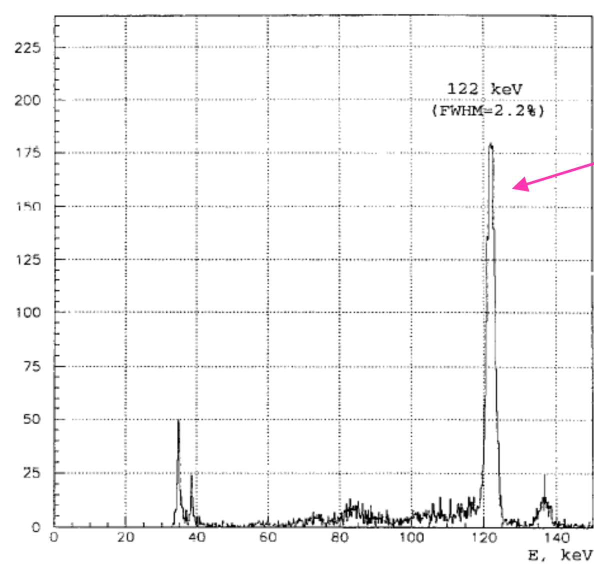


Fig. 1. Schematic diagram of the gas scintillation drift chamber with 19 PMT matrix readout.

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



This resolution corresponds to

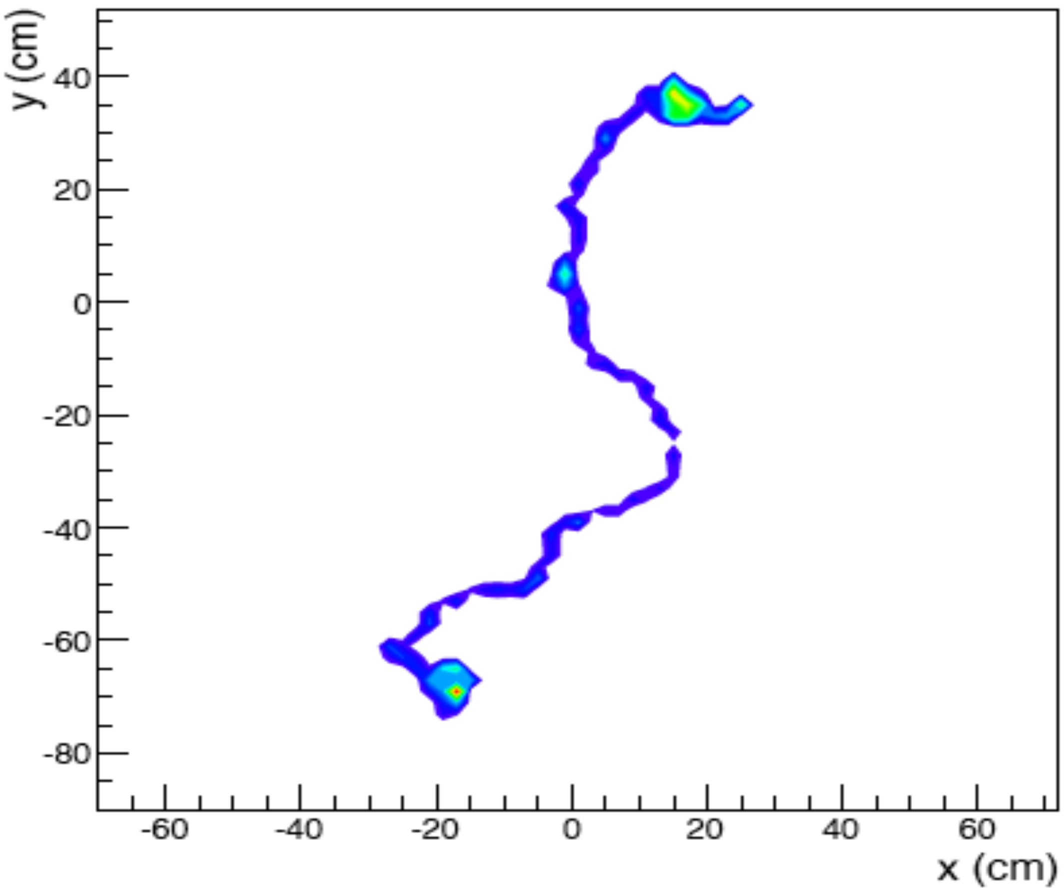
$\delta E/E = 5 \times 10^{-3}$ FWHM

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

HPXe EL ββ decay TPC: R&D

- Primary Goal #1: Energy resolution
  - Must be demonstrated at 2000+ keV energy
- Primary Goal #2: Background rejection
  - Eliminate threat of ^{208}Tl at 2615 keV, other γ's
- Primary Goal #3: 3 -D tracking in xenon
  - Topology: measure Bragg peak-finding efficiency

Topology: “spaghetti, with 2 meatballs”



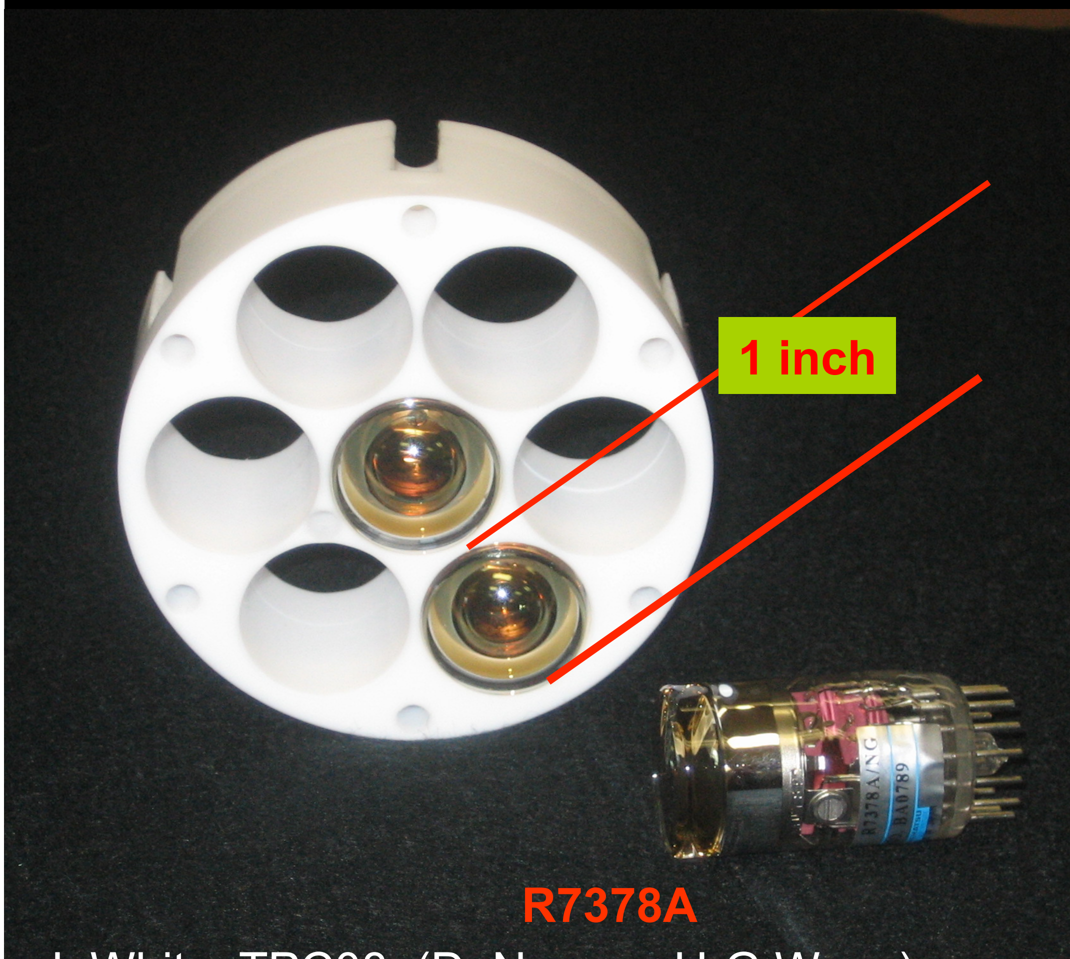
$\beta\beta$ events: **2**

γ events: **1**

Gotthard TPC:

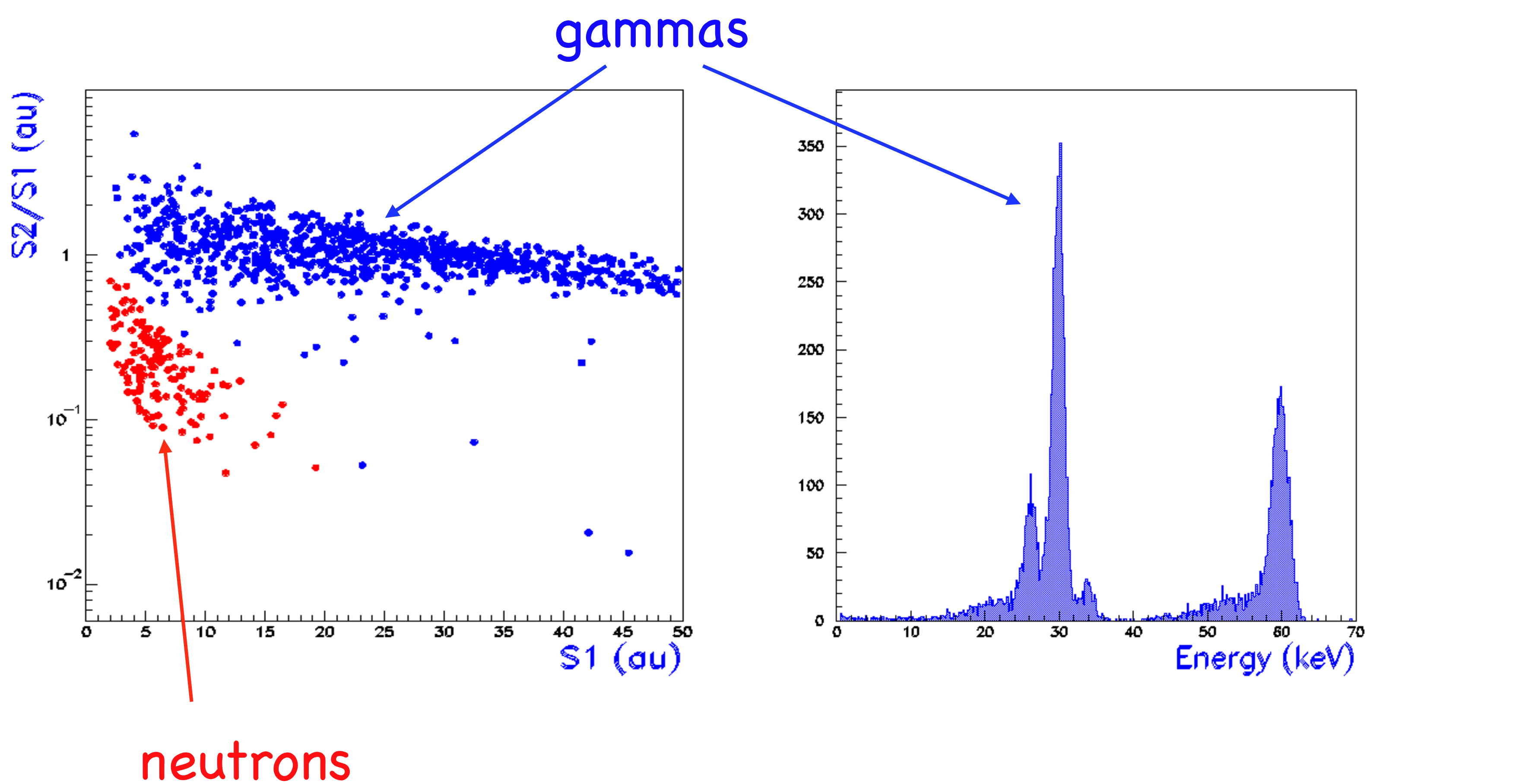
~ x30 rejection

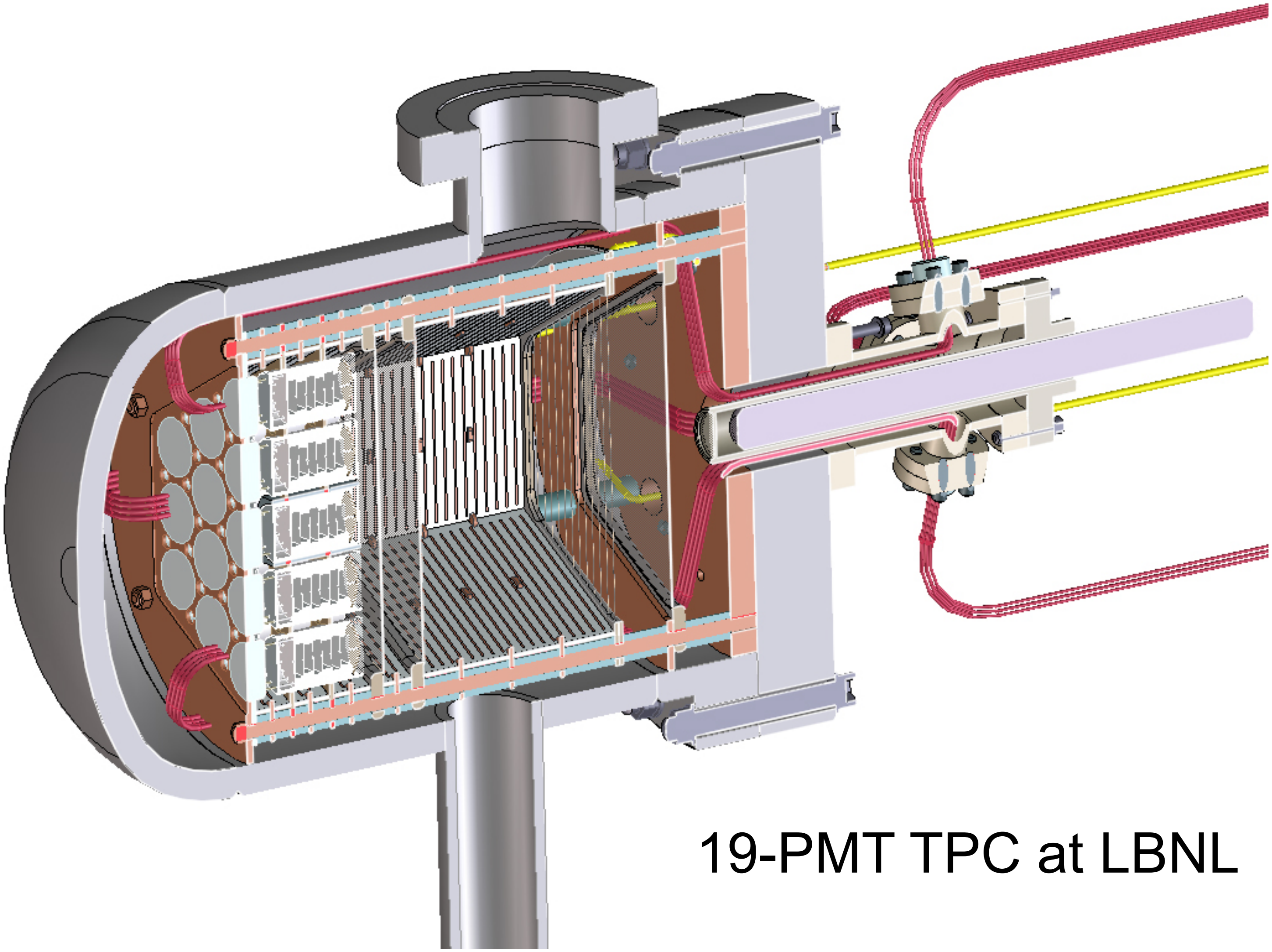
7-PMT, 20 bar
TAMU HPXe TPC



J. White, TPC08, (D. Nygren, H-G Wang)

Nr Discrimination in HPXe with TAMU 7-PMT TPC





19-PMT TPC at LBNL

Goals for 19-PMT HPXe TPC

- Determine conditions for optimum δE/E
  - Density up to 20 bars, optical systematics,…
- Explore energies up to/beyond 662 keV
  - Tracks must be contained within volume
- Explore wide range of drift field
  - Does "intrinsic" resolution depend on ***E*** ?
- Get experience, prepare for larger system!

Neutrino Experiment with a Xenon TPC

NEXT collaboration:

Spain/Portugal/France/

Russia/US…

funded: **5M €** !

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

The NEXT Collaboration

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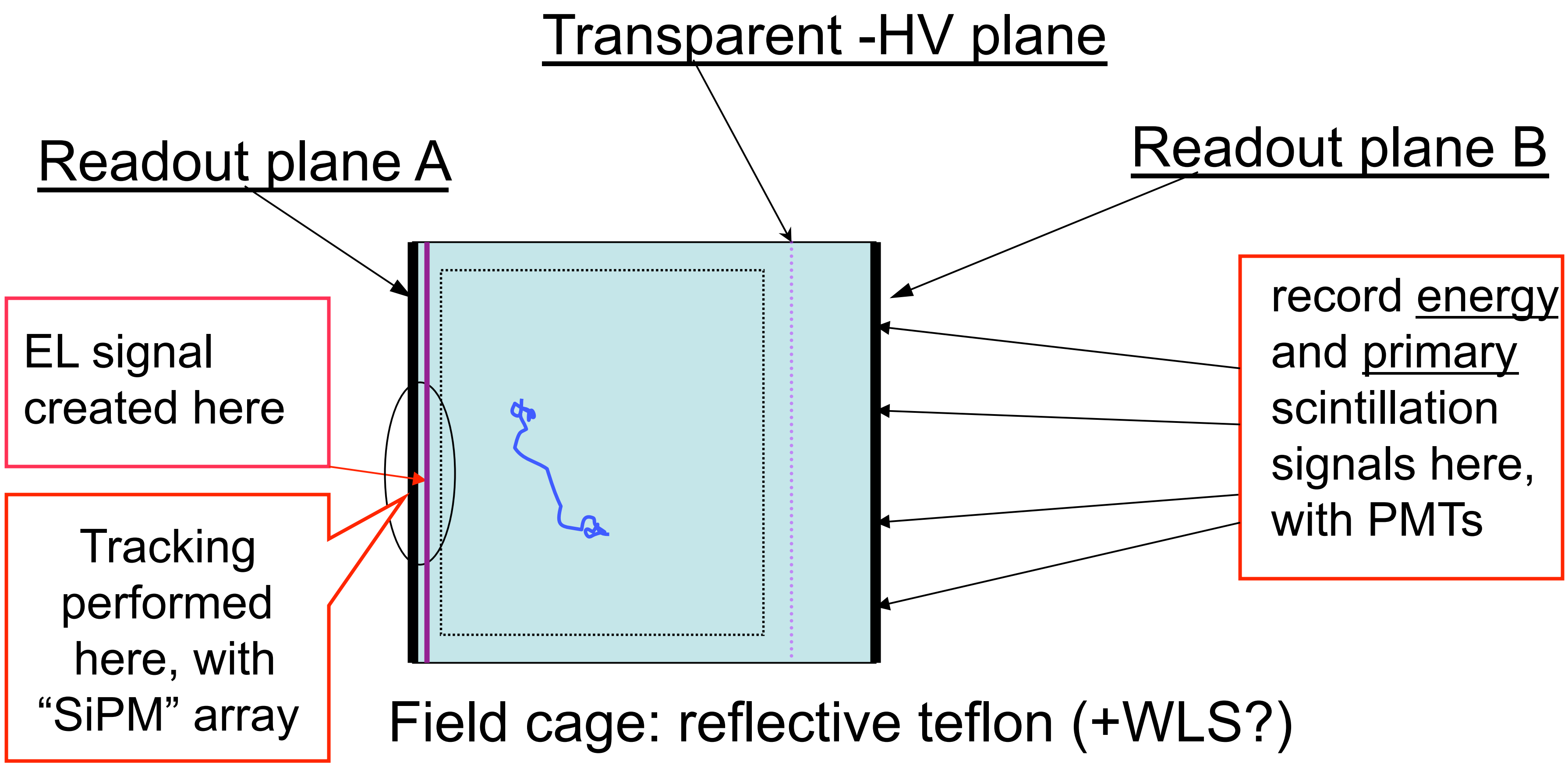
A chance for Canfranc

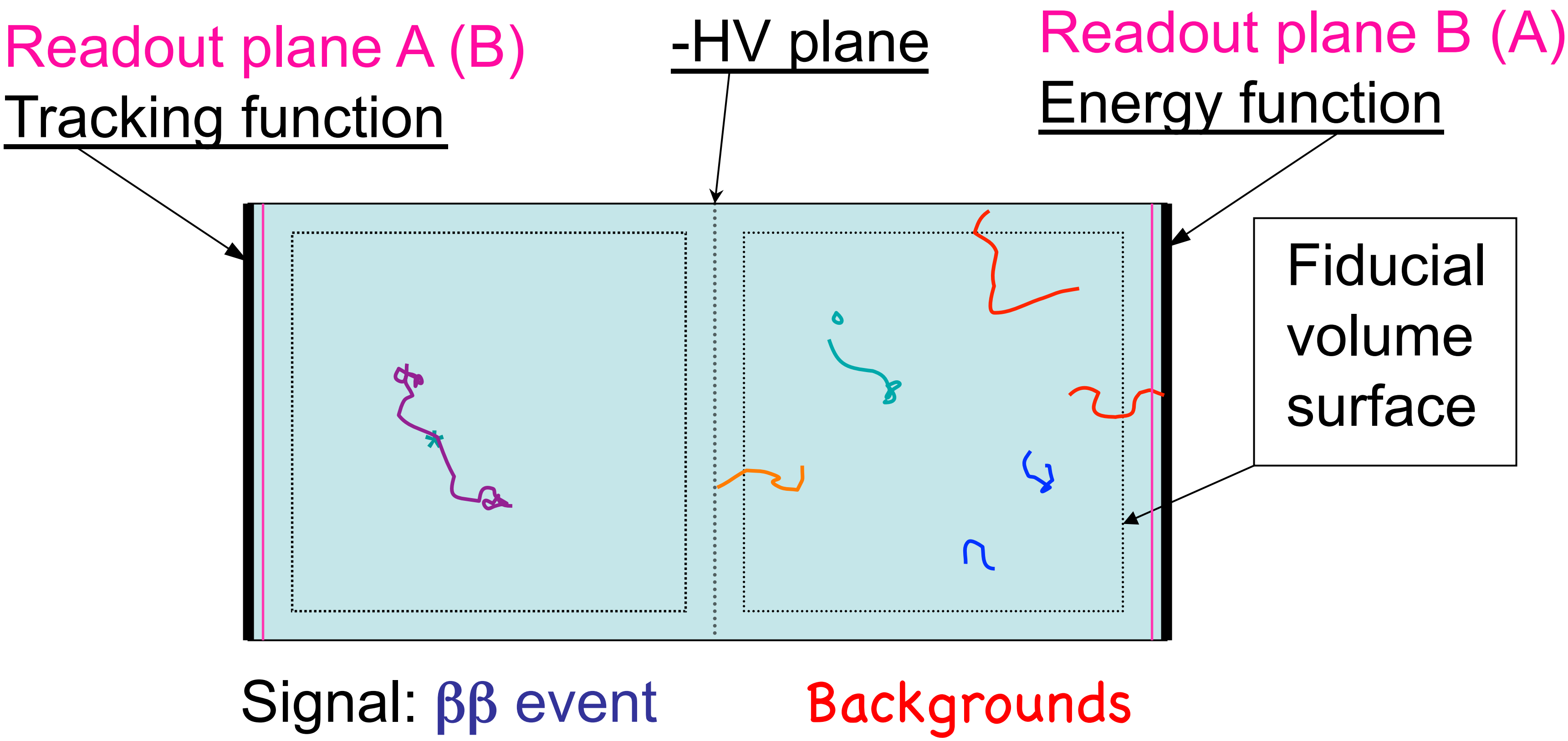
NEXT: To be built and installed at LSC in 5 years
Approval from LSC + Funding (5 million euro) from
Spanish Ministry of Science

NEXT: *"Separated function"* EL TPC

Asymmetric basic concept



Separated-function symmetric TPC:



Background threats for ^{136}Xe

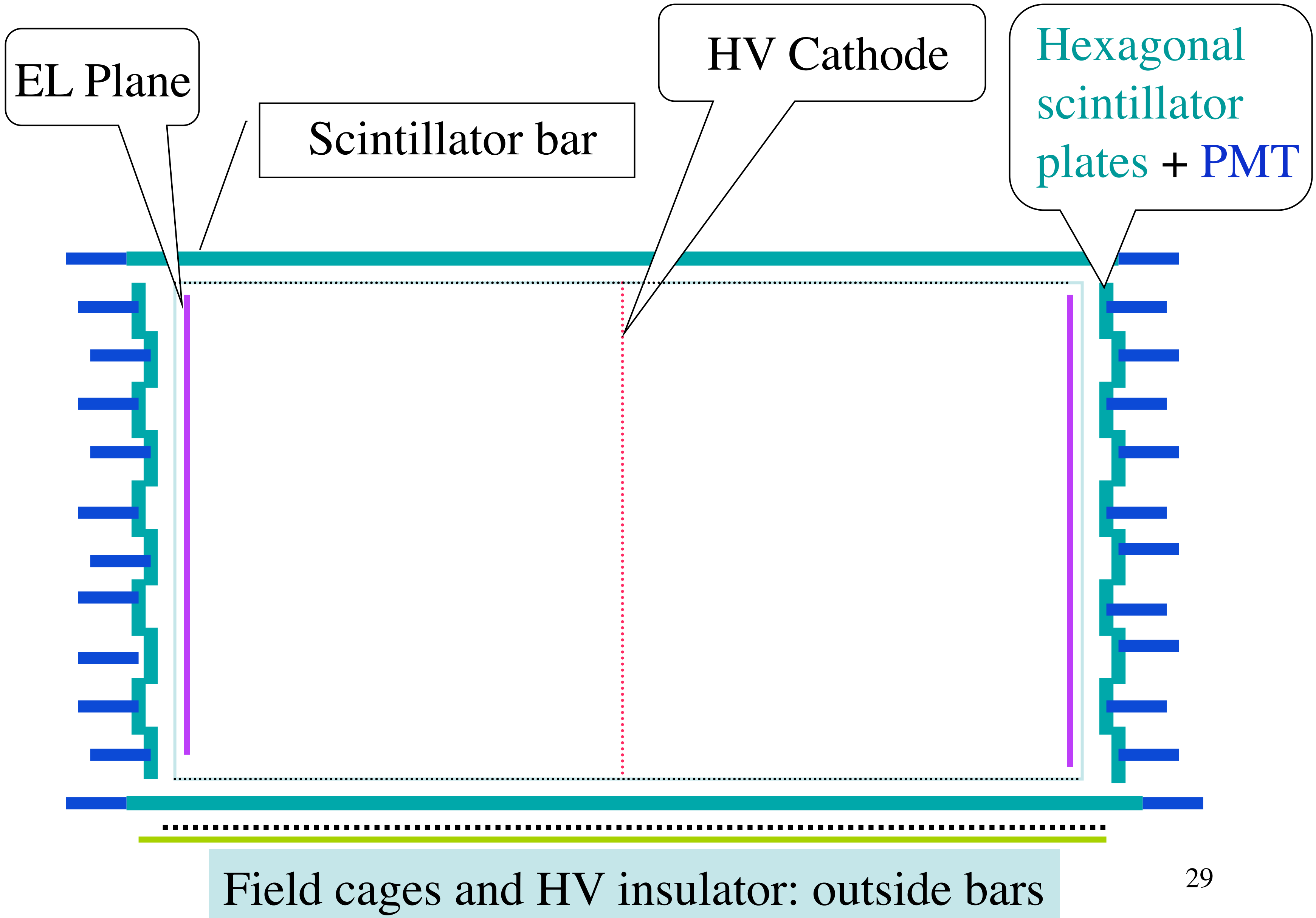
"It will not be possible to eliminate all U-Th series contamination in the structures"

A major threat: ^{208}Tl γ-rays (2615 keV)

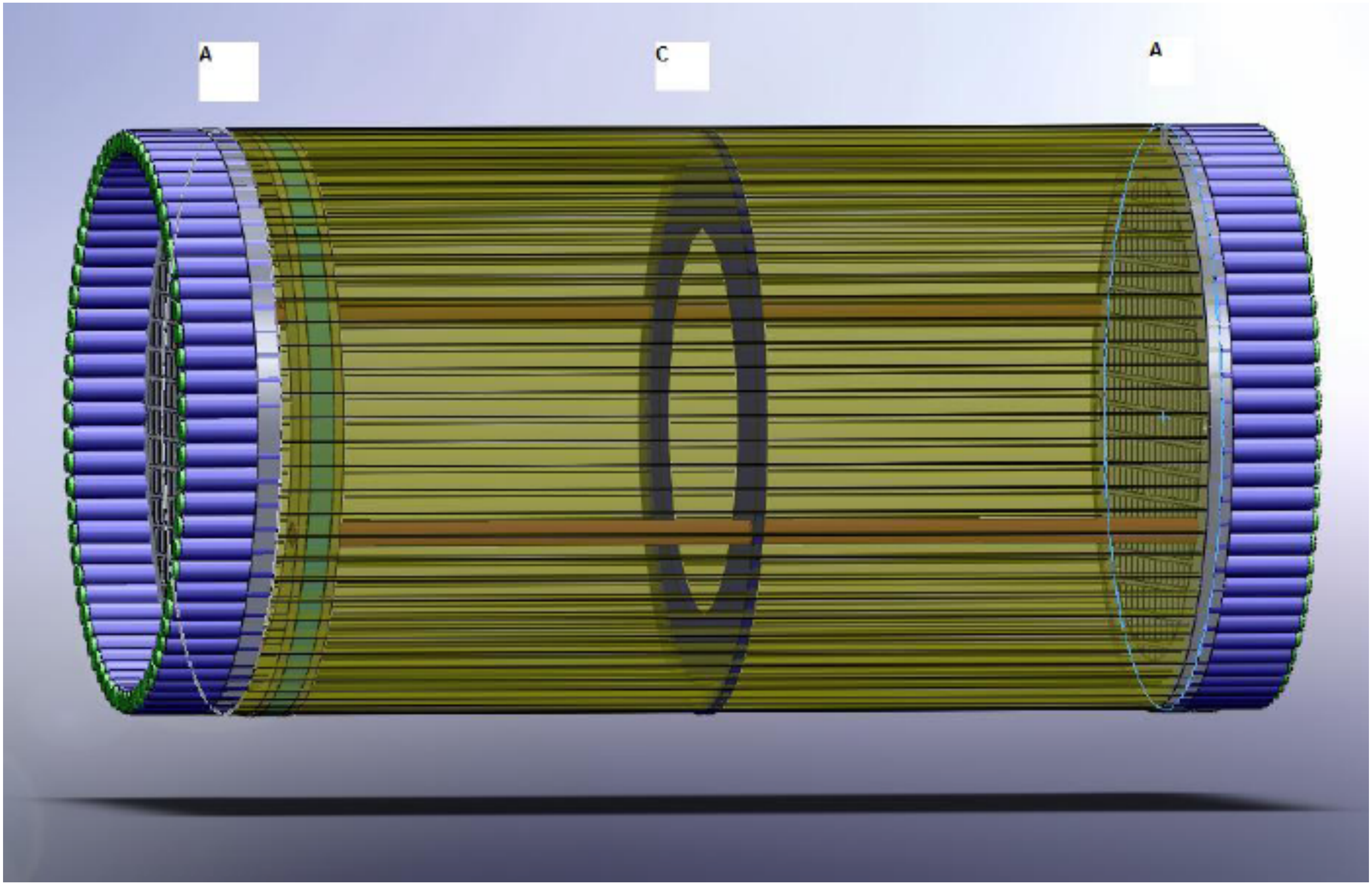
Process: gamma ray enters detector, radiates ~145 keV gamma that escapes, and deposits energy ≈ Q-value; looks like real ββ event.

Solution: active γ-catcher surrounding active volume, in contact with the gas, and… **naked !**

Symmetric TPC with "99.99%" γ-catcher



2. Symmetric TPC with scintillator bars



Which scintillator?

- High-Z for stopping power ⇒ inorganic
- "Radio-pure"
- Reasonably fast (<30 ns)
- Good mechanical properties, non-hygroscopic
- Good transparency
- Effective wavelength shifter (why this?)

BaF_2 may satisfy these *desiderata*

Barium Fluoride Properties

- Emission:
  - 195, 220 nm <1 ns (2 photons/keV)
  - 300 nm ~630 ns (10 photons/keV)
  - Strong excitation of fast component by 175 nm UV
- Density: 4.88 g/cm^3
- X_0 = 2 cm; attenuation length for 150 keV: 2 mm
- BaF_2 absorption: ~140 nm - good transparency
- Not hygroscopic; pitted by standing liquid water
- Allegedly "radio-pure" - what does this mean?

Scenario: gamma tag

Full coverage of scintillator absorbs some of the 2.615 (or higher) Mev gammas, but of 150 keV (or lower/higher) gammas trying to escape, essentially 100% are detected.

Signature:

One scintillator element detects a much larger prompt signal than its neighbors

Scenario: event energy

- The scintillators are naked, exposed to the 175 nm UV of xenon (both primary and secondary scintillation)
  - BaF_2 shows strong excitation at ~175 nm
  - Re-radiates mainly at 220 nm, (fast?)
  - WLS photons easily detected by quartz PMT
- Full scintillator coverage: integrating sphere
- Measure event energy with "gamma tagger"

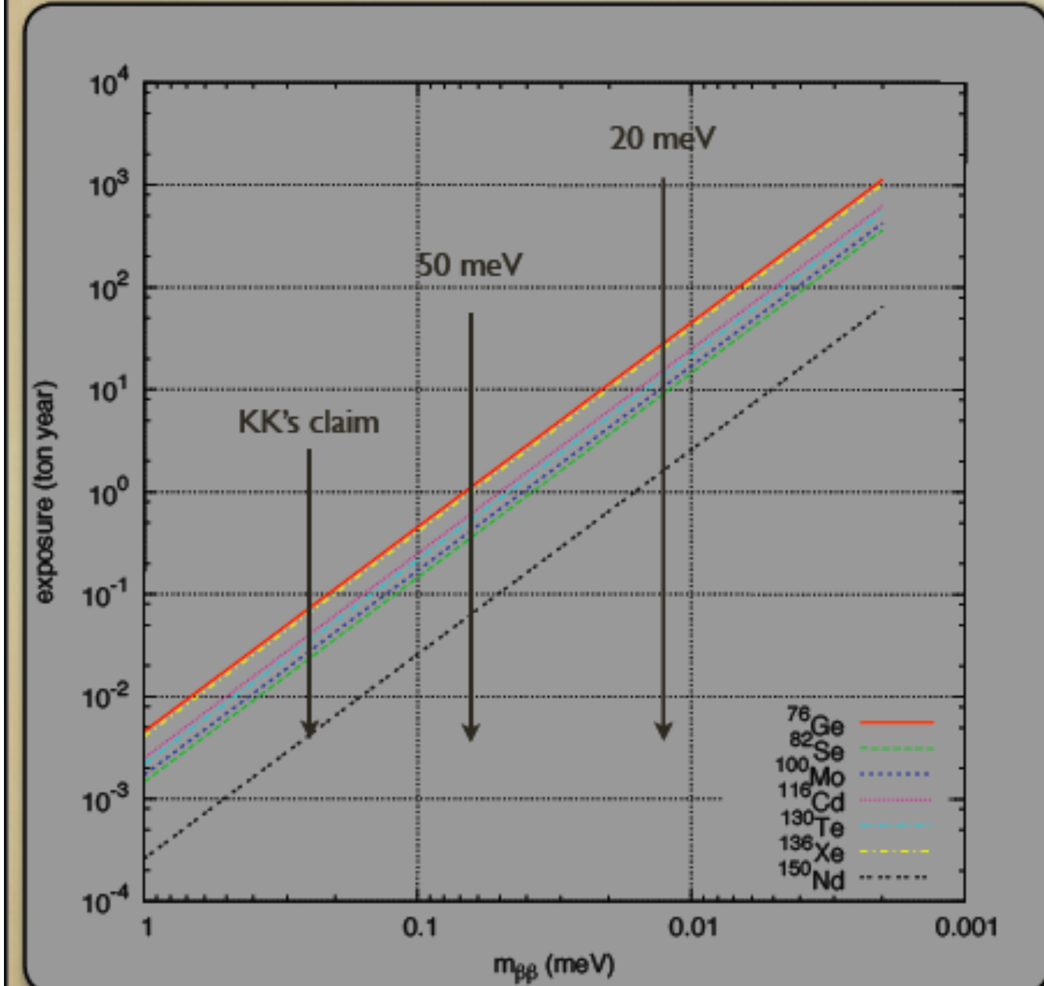
Gamma-catcher summary

- Most multi-MeV gammas are tagged on the way into active volume; all low-energy daughters are absorbed on their way out.
- Scintillators serve dual roles: γ-background rejection, and measurement of event energy
- Can such a scheme achieve background-free performance in energy ROI?

Detector mass critical for small mbb

Can Ge detectors reach 1 ton?

Resolution enough for background-free?



$$T_{1/2} = \ln 2 \, \frac{N_A \times 10^3}{A \, N_{\beta\beta}} \, Mt$$

zero-background

$$\langle m_{\beta\beta} \rangle \propto (Mt)^{-1/2}$$

background-limited

$$\langle m_{\beta\beta} \rangle \propto (Mt)^{-1/4}$$

To explore inverse hierarchy (20 meV) one needs O(10) ton x year if background free experiment! (impossible otherwise)

Conclusions

- **NEXT** enters the crowded arena of 0-*ν* ββ experiments, with ~100 kg enriched ^{136}Xe high-pressure gas electroluminescent TPC
- **R&D** goals include:
  - δE/E < 1% FWHM @ 2500 keV
  - Topological discrimination signal/background
  - Innovative combination of EL, WLS, γ-catcher
- **Reach**: touching the inverted hierarchy…
- **Future:** 1-ton ? *NEXO*?

Thank you

Backup slides...

Other HPXe efforts

Gotthard TPC Pioneering 0-ν ββ experiment

Beppo-SAX satellite 7-PMT 5-bar TPC

****

BNL-Temple HPXe scintillation decay time

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

Texas A&M 7-PMT 20 bar HPXe TPC

NEXT!

“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

– δE/E ~ 80 x 10^{-3} FWHM (1592 keV)

⇒ 66 x 10^{-3} FWHM (2480 keV)

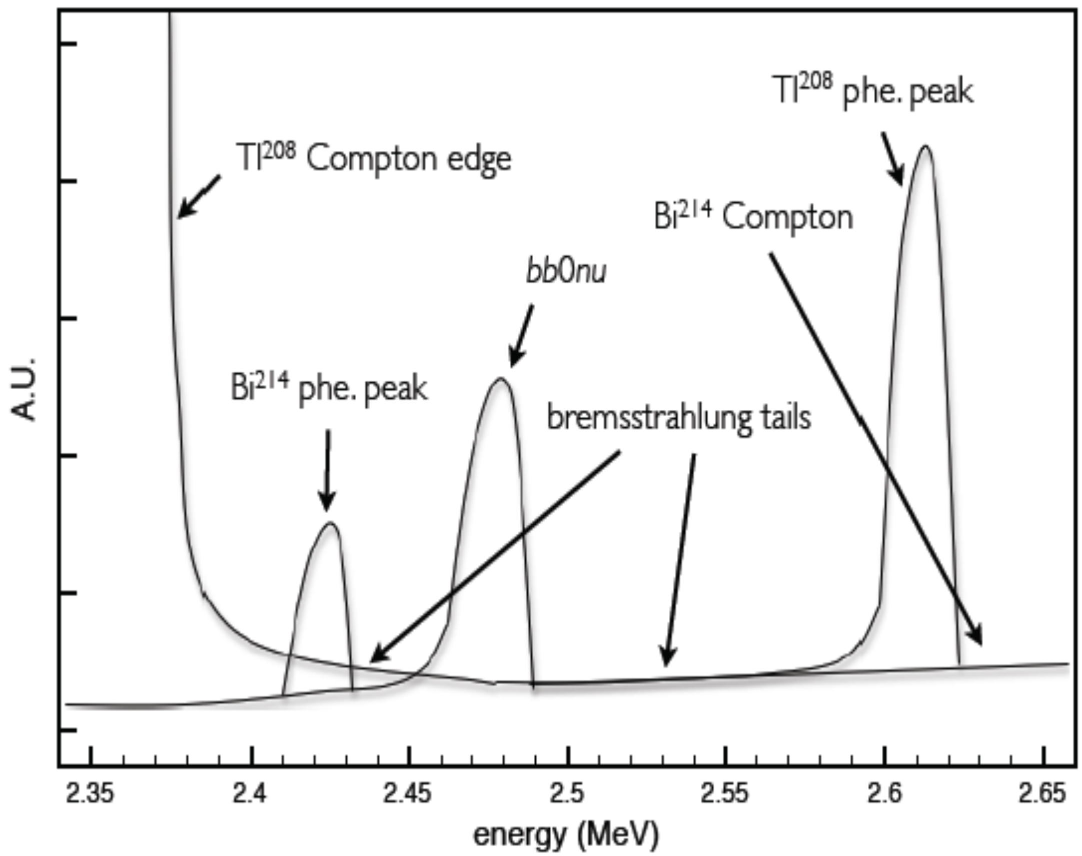
Reasons for this less-than-optimum resolution are not clear…

Possible: uncorrectable losses to electronegative impurities

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

But: ~30x topological rejection of γ interactions!

Backgrounds for the ββ0ν search



NEXT Collaboration

Silicon Photomultiplier "SiPM"

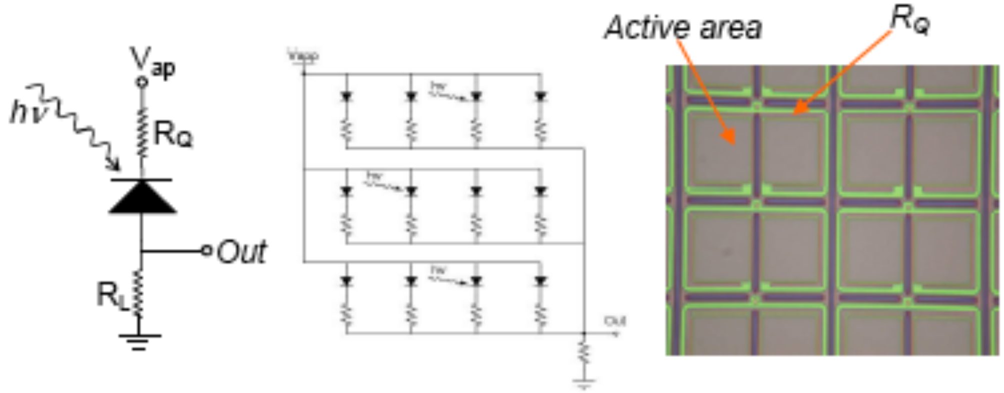
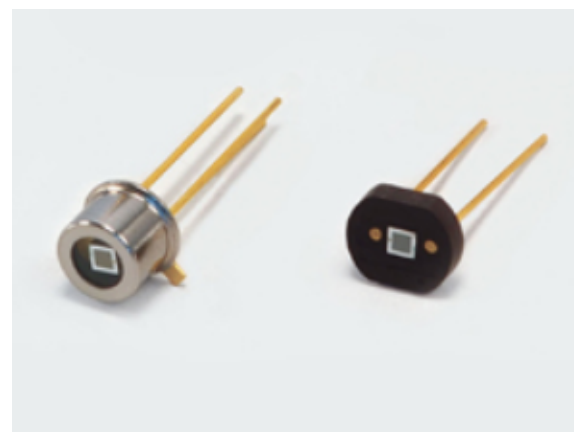
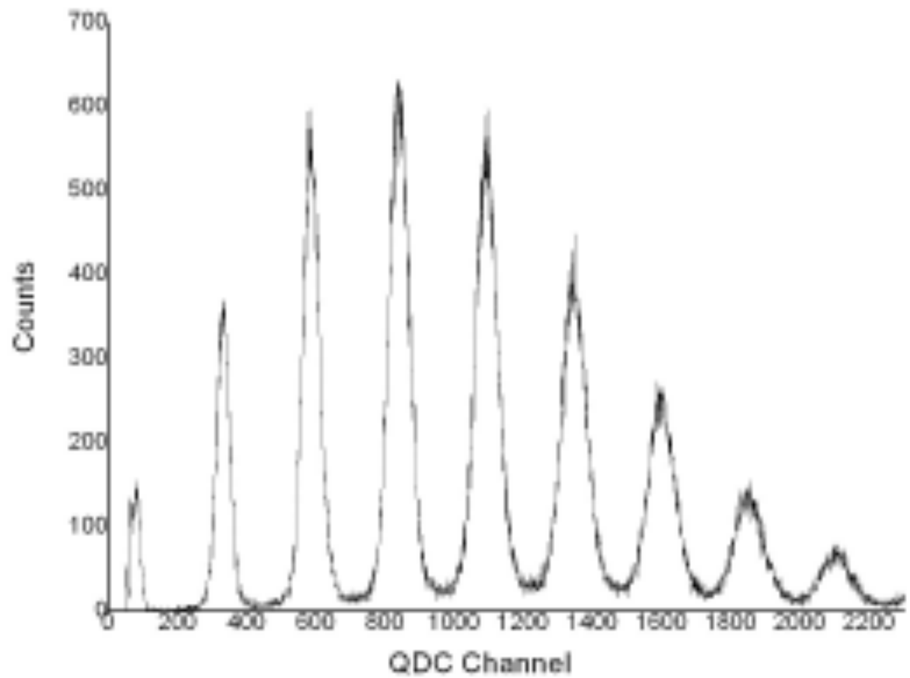


Figure 1 Schematic of a single microcell (left), schematic of part of an SPM array of microcells (center) and photo of a portion of the SPM microcells (right).

SiPM from Hamamatsu, "MPPC"



SiPM photoelectron spectrum



High-pressure xenon EL TPC

- Ideal fiducial volume
  - Closed, seamless, fully active, variable,...
    - No dead or partially active surfaces
  - 100.000% charged particle rejection (from surfaces)
    - Needs demonstration…
  - Use t_0 (primary scintillation) to place event in z
    - Ample signal over most of 2ν spectrum
  - Topological rejection of single-electron events
    - Factor of at least 30 expected (Gotthard TPC)

α particles

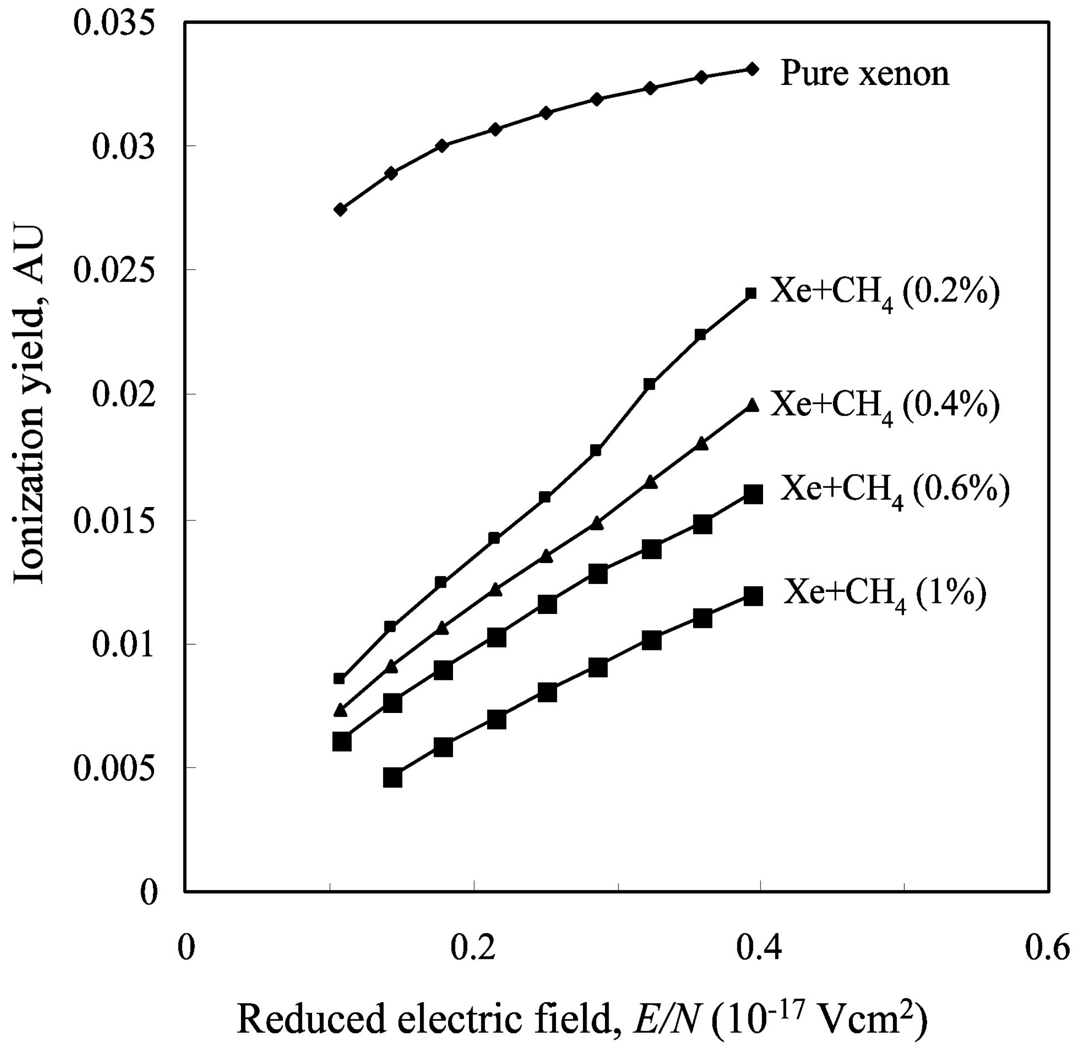


Fig.7. Dependence of ionization yield on reduced electric field (E/N) at a pressure of 2.6 MPa. **(~25 bars)**

K. N. Pushkin *et al,* 2004

IEEE Nuclear Science Symposium proceedings

A scary result: adding a tiny amount of simple molecules (CH_4, N_2, H_2) to HPXe quenches both ionization **and** scintillation for α's

α particle: dE/dx is very high

Gotthard TPC: 4% CH_4
Loss(α): factor of 6

For β particles, what was effect on energy resolution?

Surely small but not known, and needs investigation

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:

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

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

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

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

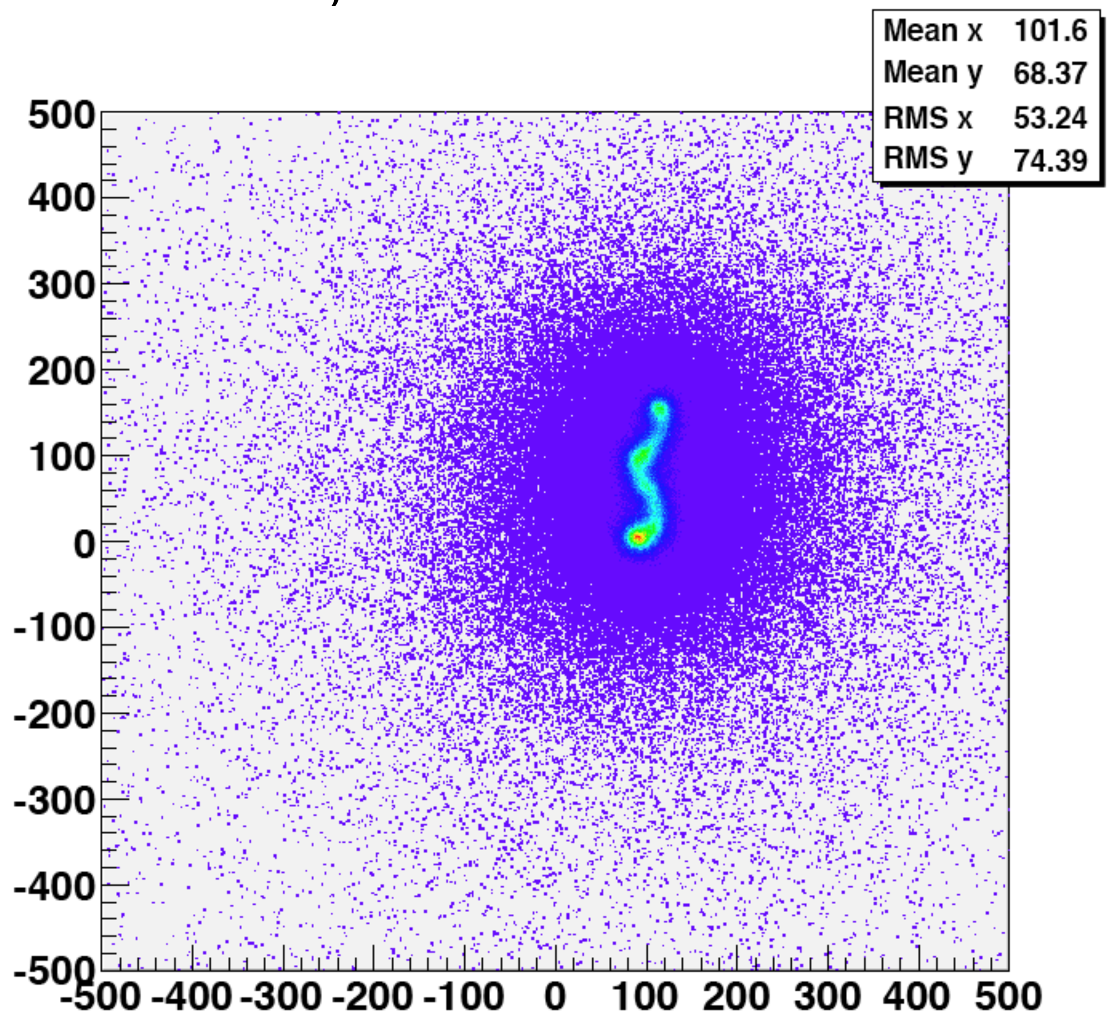
$Xe^+ + e^-(\text{cold}) + M + \text{heat} \rightarrow e^-(\text{cold}) + Xe^+ \rightarrow Xe^*$

A simulated event, with SiPM

Reconstruction of event topology, using SiPM to sense EL, at 1 cm pitch

Blob recognition is good

Slide: *NEXT* collaboration



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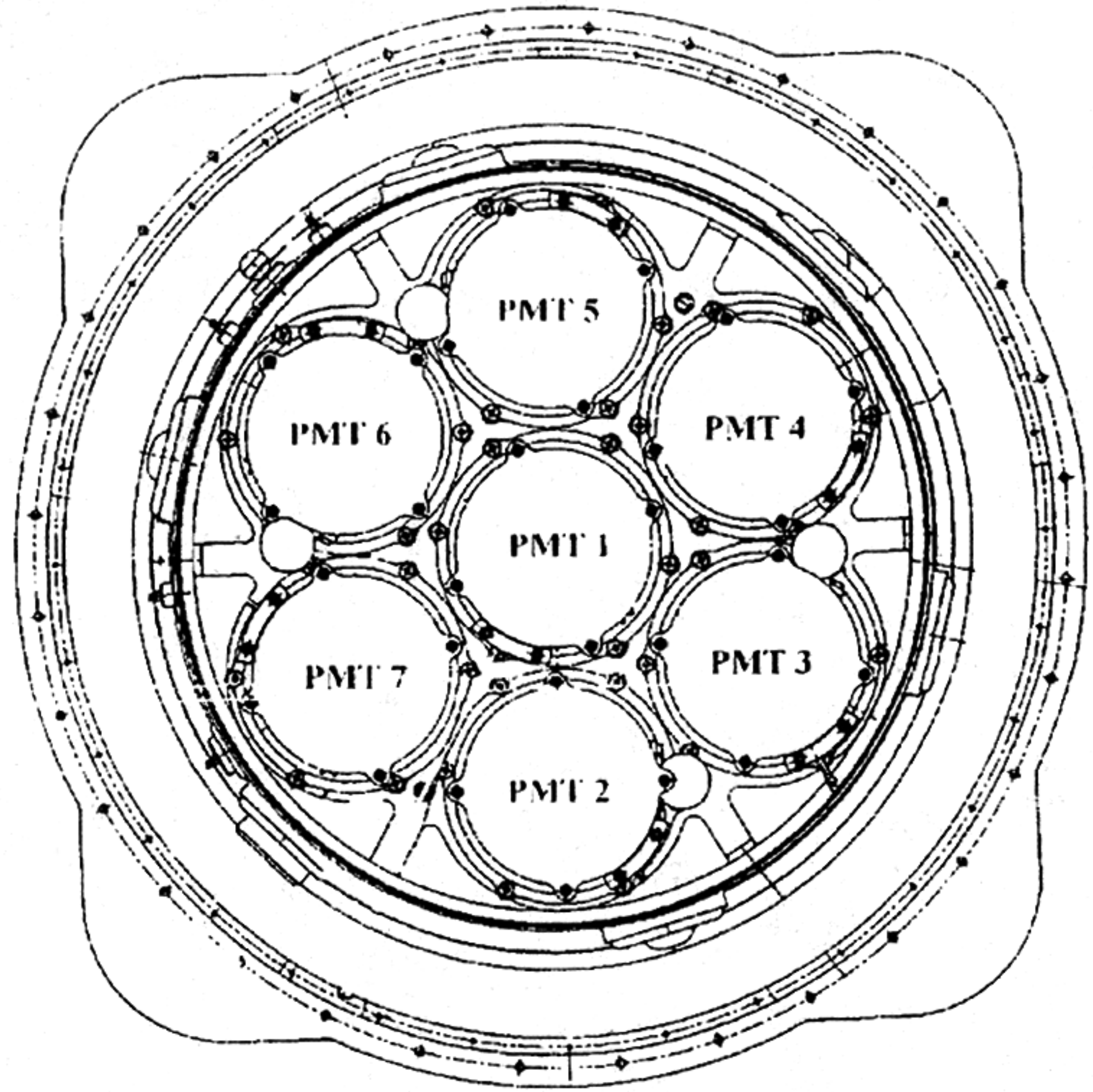
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PMT 6
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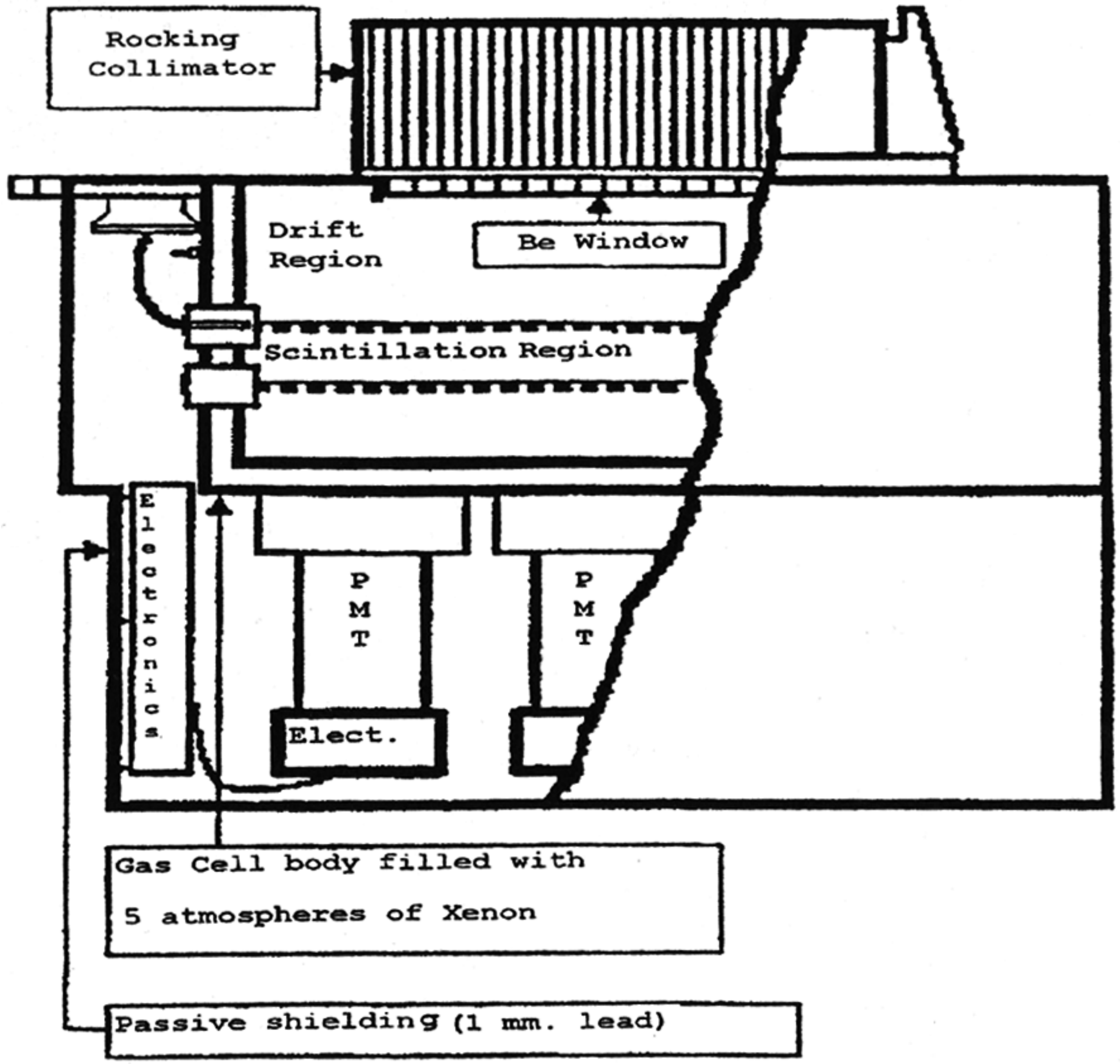
PMT 2

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



^{241}Am γ-rays ~60 keV

(1st Look – PMT gains not yet calibrated)