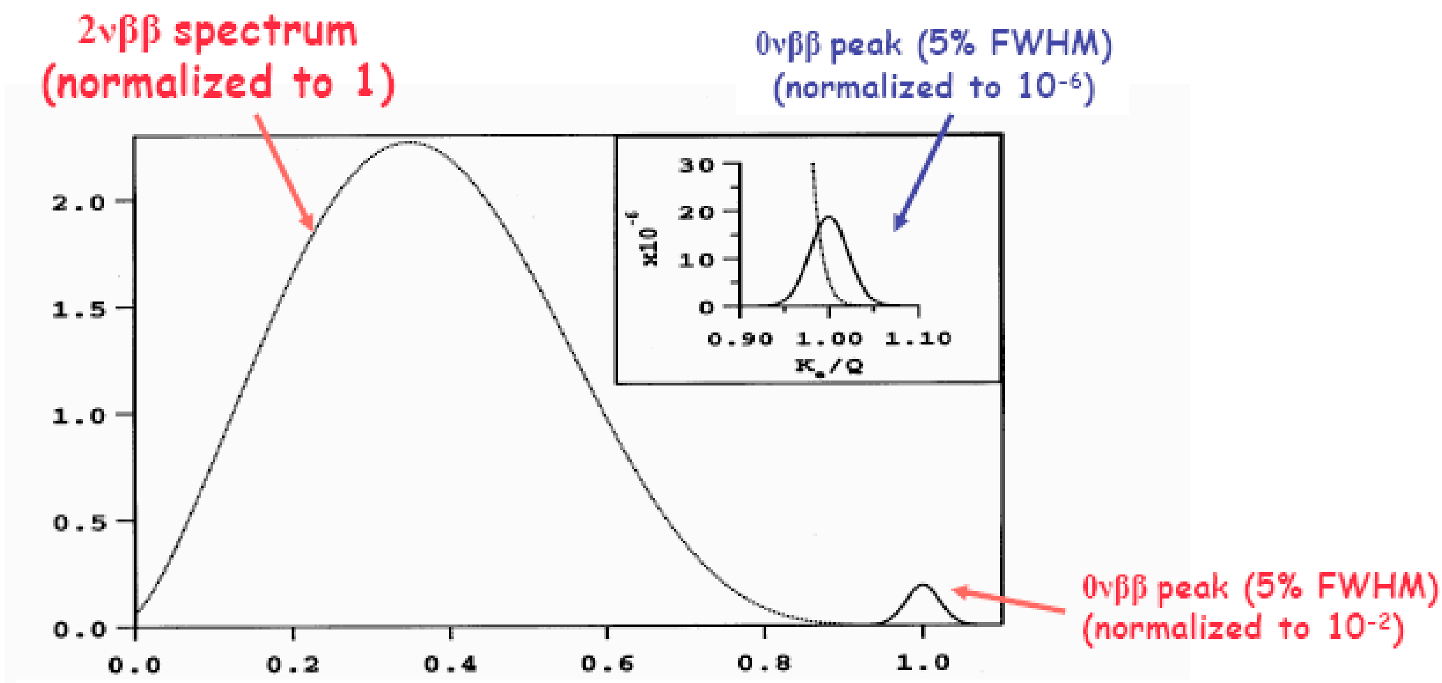
High-Pressure Xenon Gas TPC

for 0-ν $\beta\beta$ Search

David Nygren
LBNL

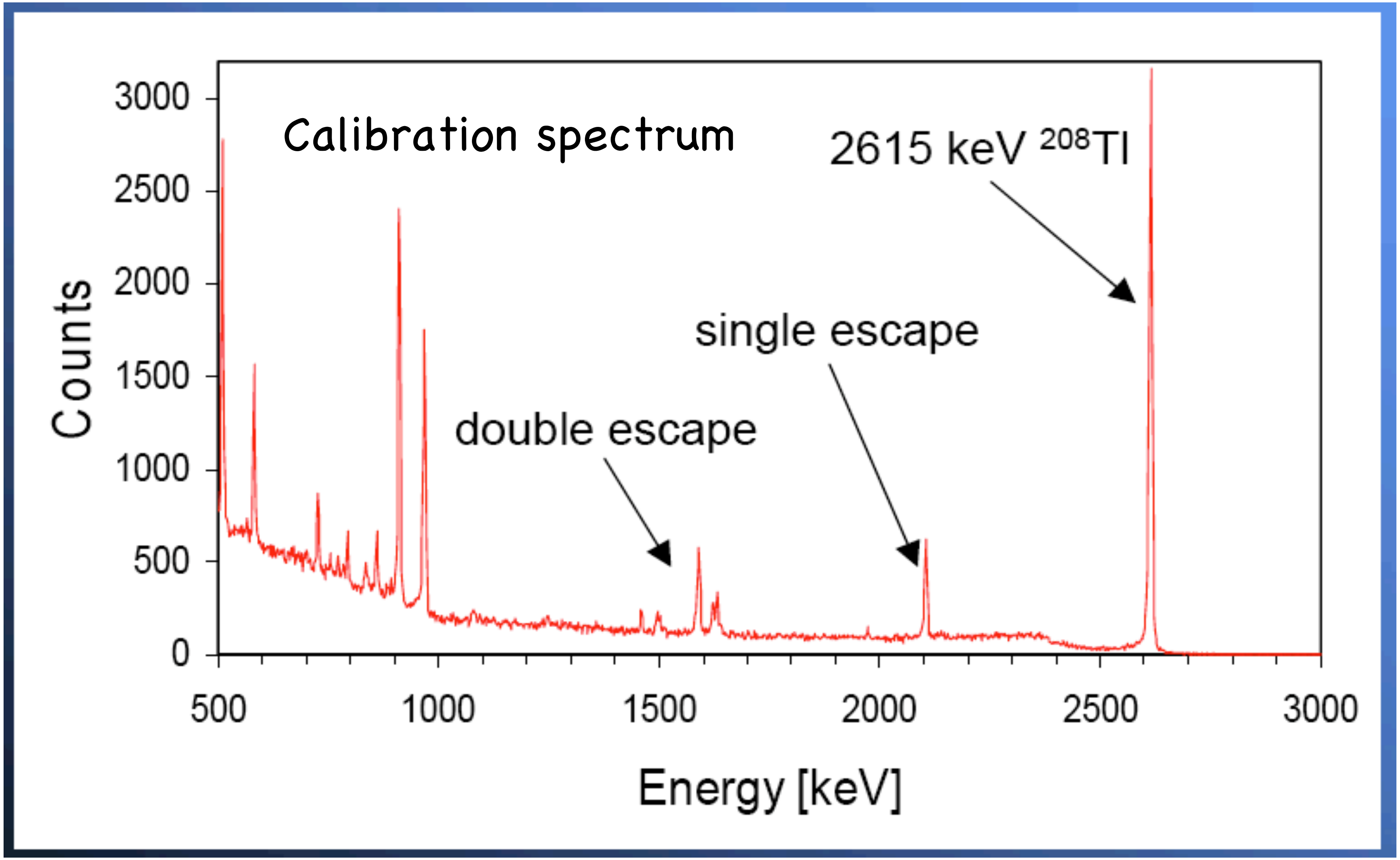
To search for 0-ν ββ decay:

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



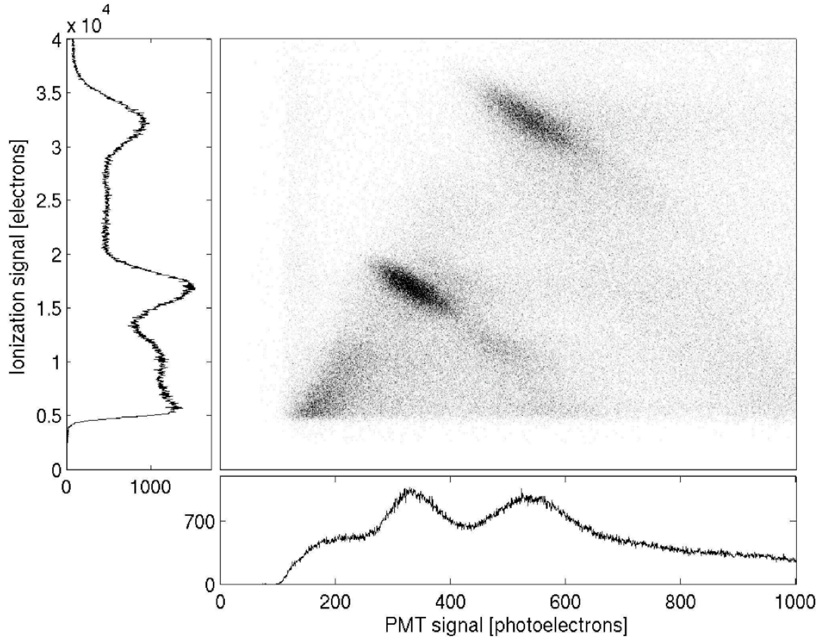
Summed electron energy in units of the kinematic endpoint (Q)

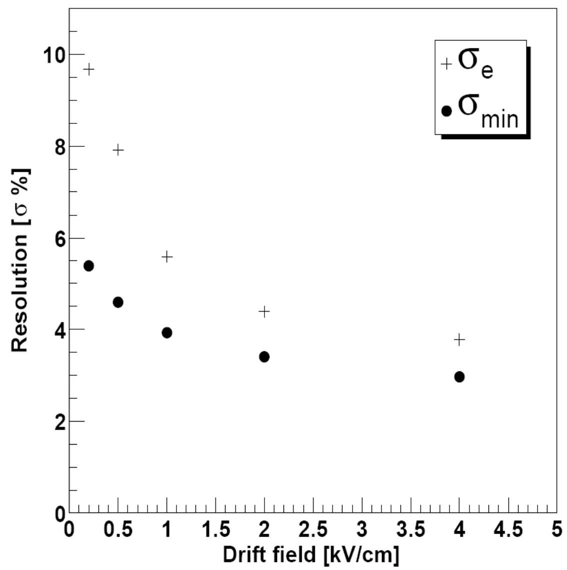
Energy Resolution: CUORE $\delta E/E = 3 \times 10^{-3}$ FWHM !



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

Energy partitioning
charge : light : heat

LXe: Anomalously large fluctuations
exist in **partitioning** of energy

Fluctuations cause "anti-correlation" in LXe

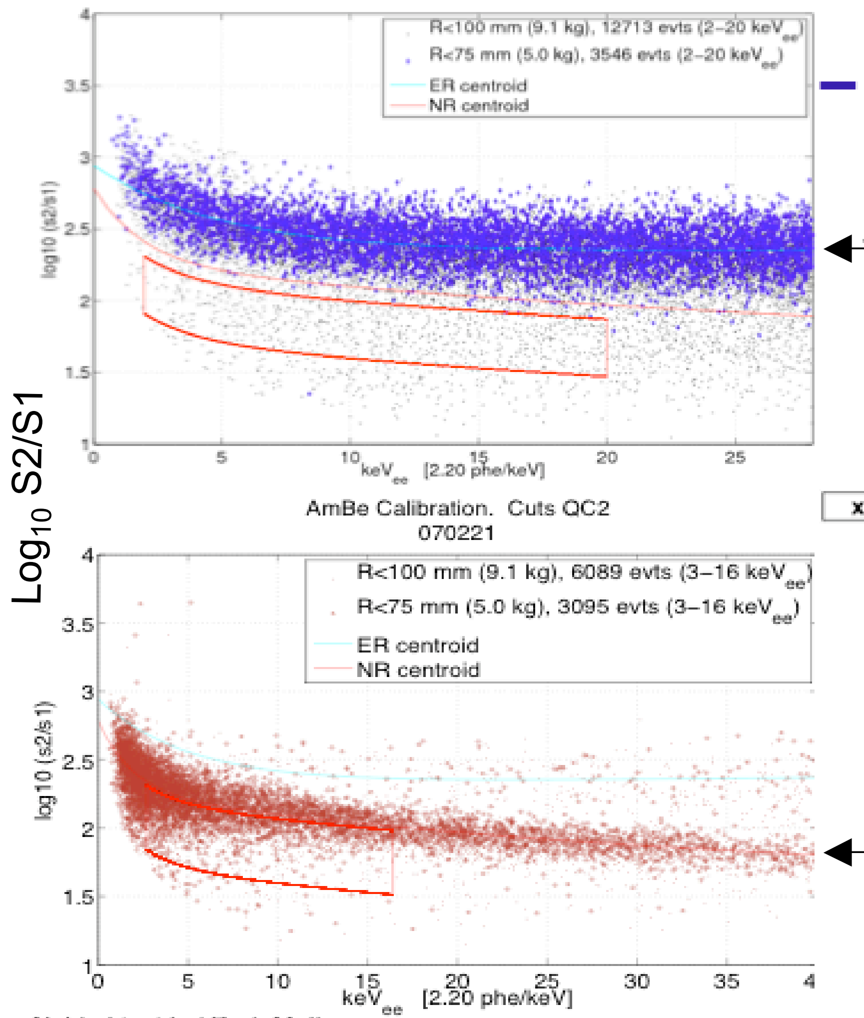
Energy loss process → ionization density fluctuations
Recombination introduces energy partitioning fluctuations
Ionization → Scintillation
high ionization density + high atomic density: **maximal** effect

Energy resolution

In principle: add scintillation + ionization and
recover total signal...

In practice:
Only a small fraction of scintillation signal is recoverable;
statistical precision is compromised.

Energy resolution cannot be fully restored in LXe
Double beta decay search: more vulnerable to backgrounds



Xenon10 Experiment

Gamma events (e-R)

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

Neutron events (N-R)

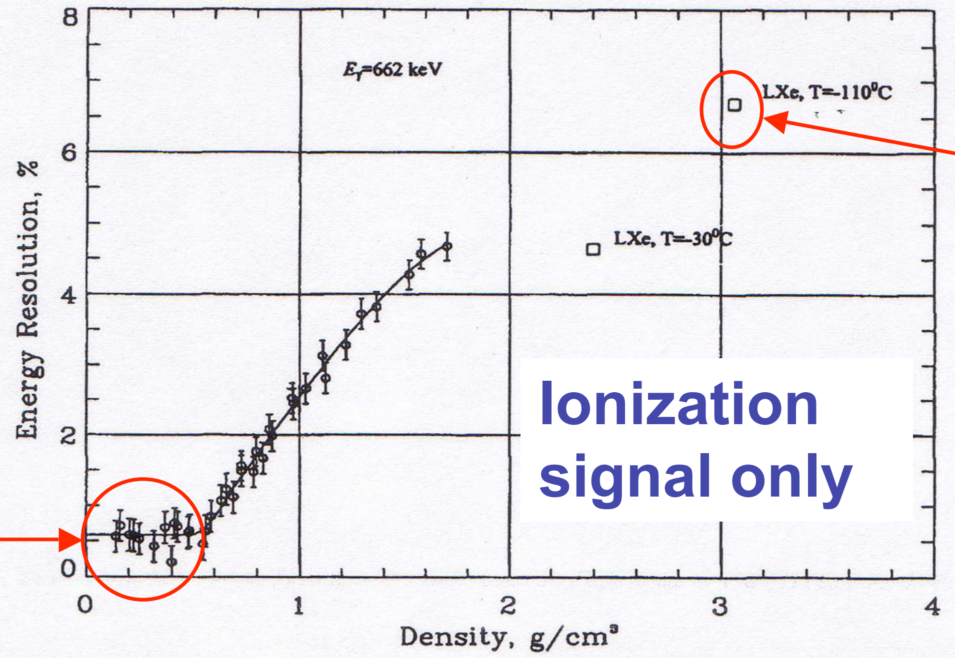
Noble Liquids / Dark Matter

Rick Gaitskell, Brown University, DOE

WIMP search: S2/S1 resolution inescapably compromised!

Xenon: Strong dependence of energy resolution on density!

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



Large fluctuations

Here, the fluctuations are normal

Ionization signal only

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: xenon gas

Anomalous fluctuations are negligible in HPXe

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

What is the “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

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

N = Q/W ~100,000 primary electrons

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

Gain and noise

Impose a requirement:

(noise + fluctuations) $< 120\ e^{-}$

Need gain G with <u>very</u> low noise/fluctuations!

Uncorrelated fluctuations, add in quadrature:

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

F ≡ constraint due to fixed energy deposit

$\mathcal{G}$ ≡ noise/fluctuations of detection process

Gain mechanisms

- Amplification by electronics alone:
  - FE noise ~ several hundred electrons rms
- Avalanche gain in gas around wires:
  - 𝔊 ~ 0.8 - early fluctuations are amplified
- Microstructures: GEM, Micromegas,...
  - 𝔊? G? stability? ageing? quenching? scale?

Electro-Luminescence (EL) is the key

(Gas Proportional Scintillation)

- Physics process generates ionization signal
- Electrons drift in low electric field region
- Electrons then 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
- Linear growth of signal with voltage
- Photon generation up to ~1000/e, but no ionization
- Early history irrelevant, ⇒ fluctuations are very small

Virtues of Electro-Luminescence in HPXe

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

Fluctuations in Electroluminescence (EL)

EL: a linear gain process: electrons excite, atoms radiate

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

EL can provide $\mathcal{G}$ less than F:

$\mathcal{G}$ 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:

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

For $\mathcal{G} \leq F = 0.15 \Rightarrow n_{pe} \geq 10$ (per primary electron)

Equivalent noise: much less than 1 electron rms!

Total signal at Q-value

$n_{pe} \geq 10$ (per primary electron)

$Q/W = N = 1 \times 10^5$

$\Rightarrow$

$N_{pe} \geq 1 \times 10^6$

One million photoelectrons!

However:

N_{pe} is spread out over >100 PMTs and 10 - 100 μs

No dynamic range problem

EL in 4.5 bar of Xenon (Russia - 1997)

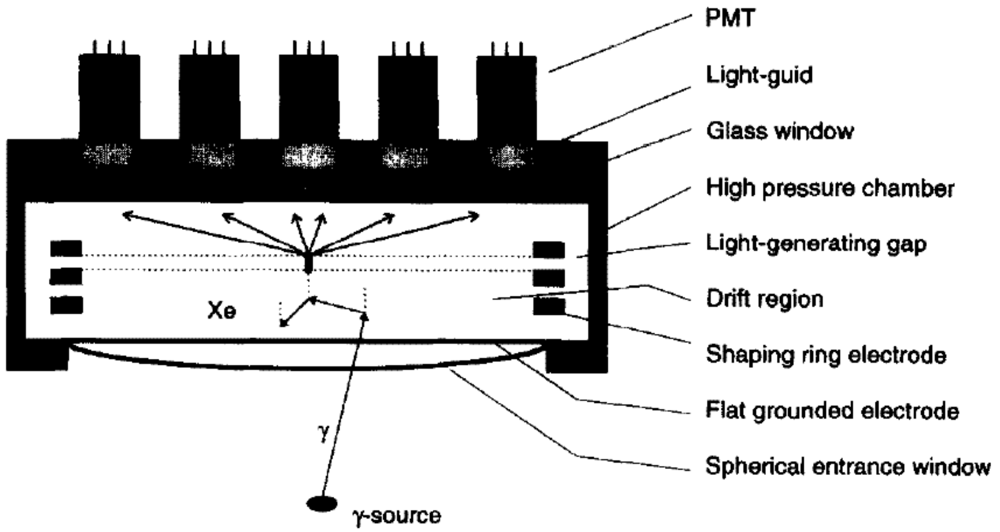
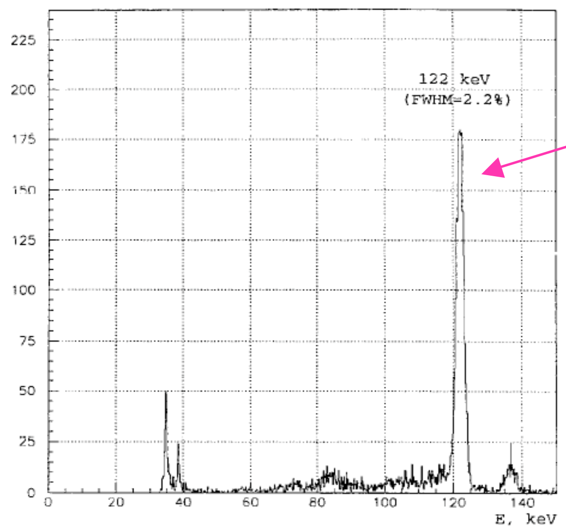


Fig. 1. Schematic diagram of the gas scintillation drift chamber with 19 PMT matrix readout.

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



This resolution corresponds to

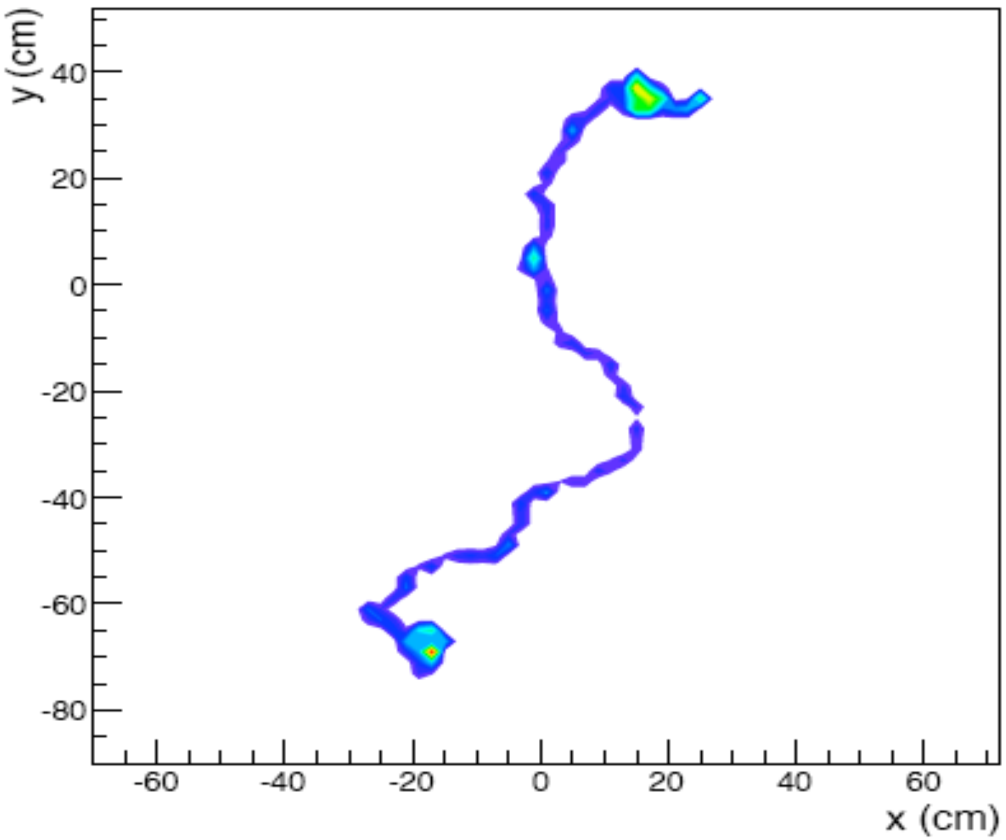
$\delta E/E = 5 \times 10^{-3}$ FWHM

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

Goal: HPXe EL TPC

- Primary Goal #1: Energy resolution
  - $\delta E/E \leq 5 \times 10^{-3}$ FWHM at Q-value (2.48 MeV)
  - Must be demonstrated at MeV energies!
- Primary Goal #2: 3 -D tracking
  - Multiple scattering ⇒ complex topologies
  - Verify meatball recognition efficiency!

Topology: “spaghetti, with meatballs”



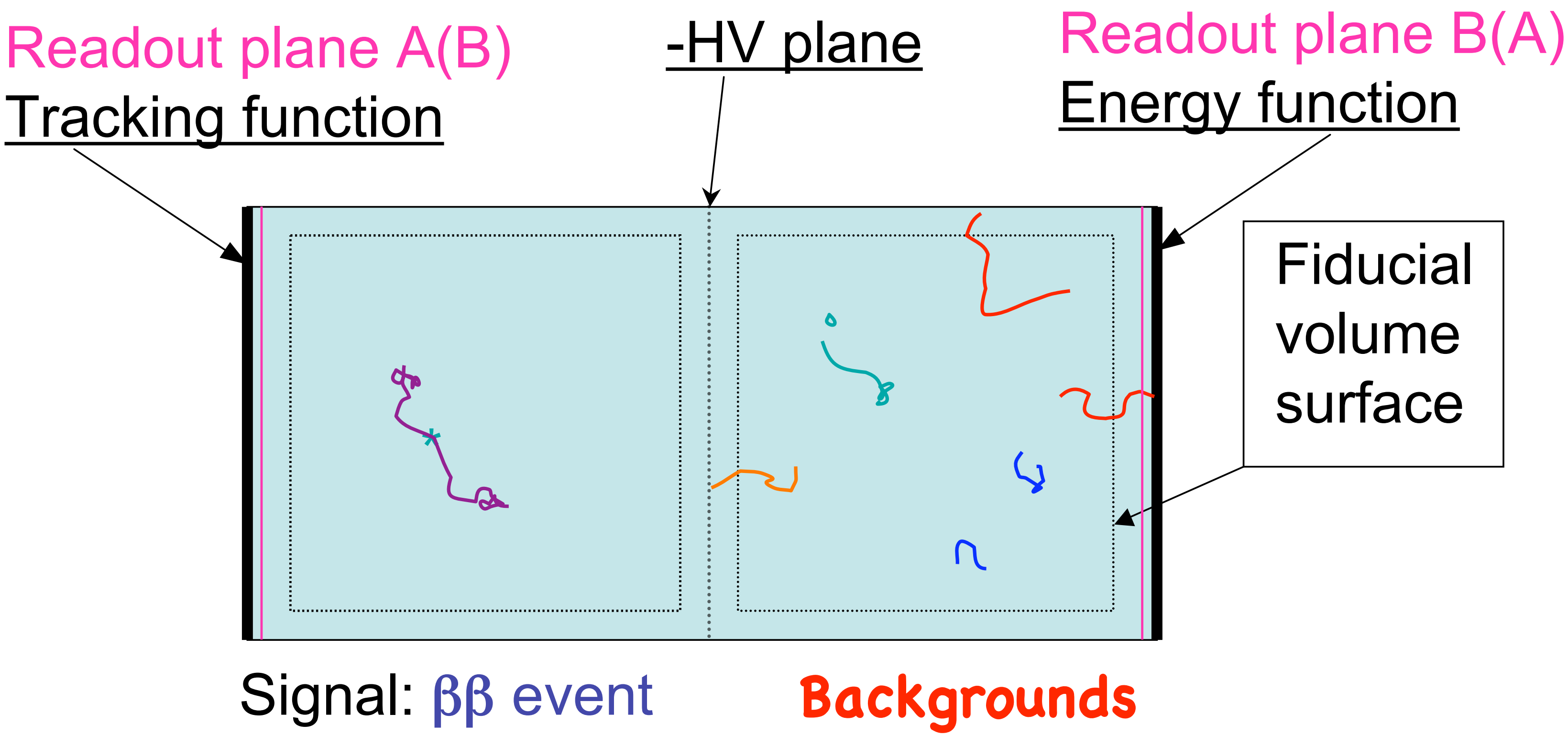
ββ events: **2**

γ events: **1**

Gotthard TPC:

~ x30 rejection

Separated-function symmetric TPC:



High-pressure xenon EL TPC

- Ideal fiducial volume
  - Closed, seamless, fully active, variable,…
    - No dead or partially active surfaces
  - 100.000% charged particle sensitivity
    - Reject all backgrounds from surfaces (not shown yet!)
  - Use t_o (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)

Other HPXe efforts

X-ray spectrometers - Coimbra

Gotthard TPC - pioneering 0-ν $\beta\beta$ experiment

Beppo-SAX satellite 7-PMT 5-bar TPC

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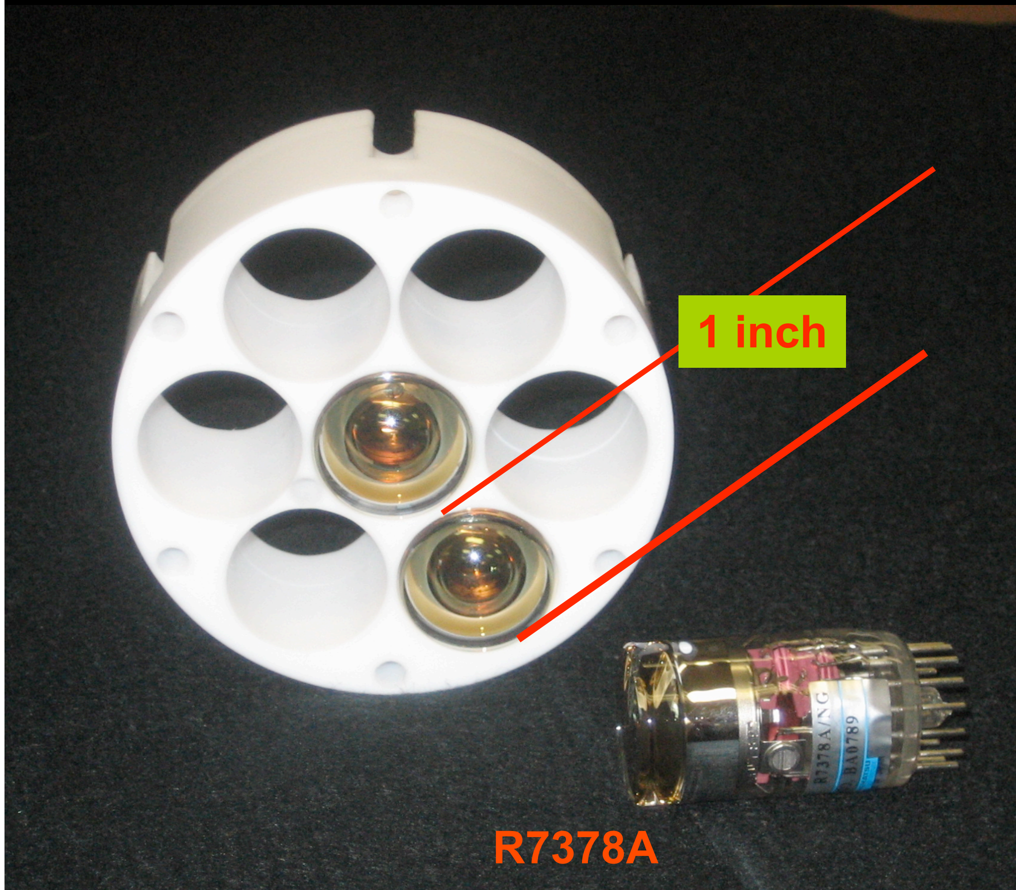
EXO - gas Ba^{++} ion tagging, tracking, …

Texas A&M 7-PMT 20 bar HPXe TPC

LBNL-LLNL-TAMU 19/PMT HPXE TPC

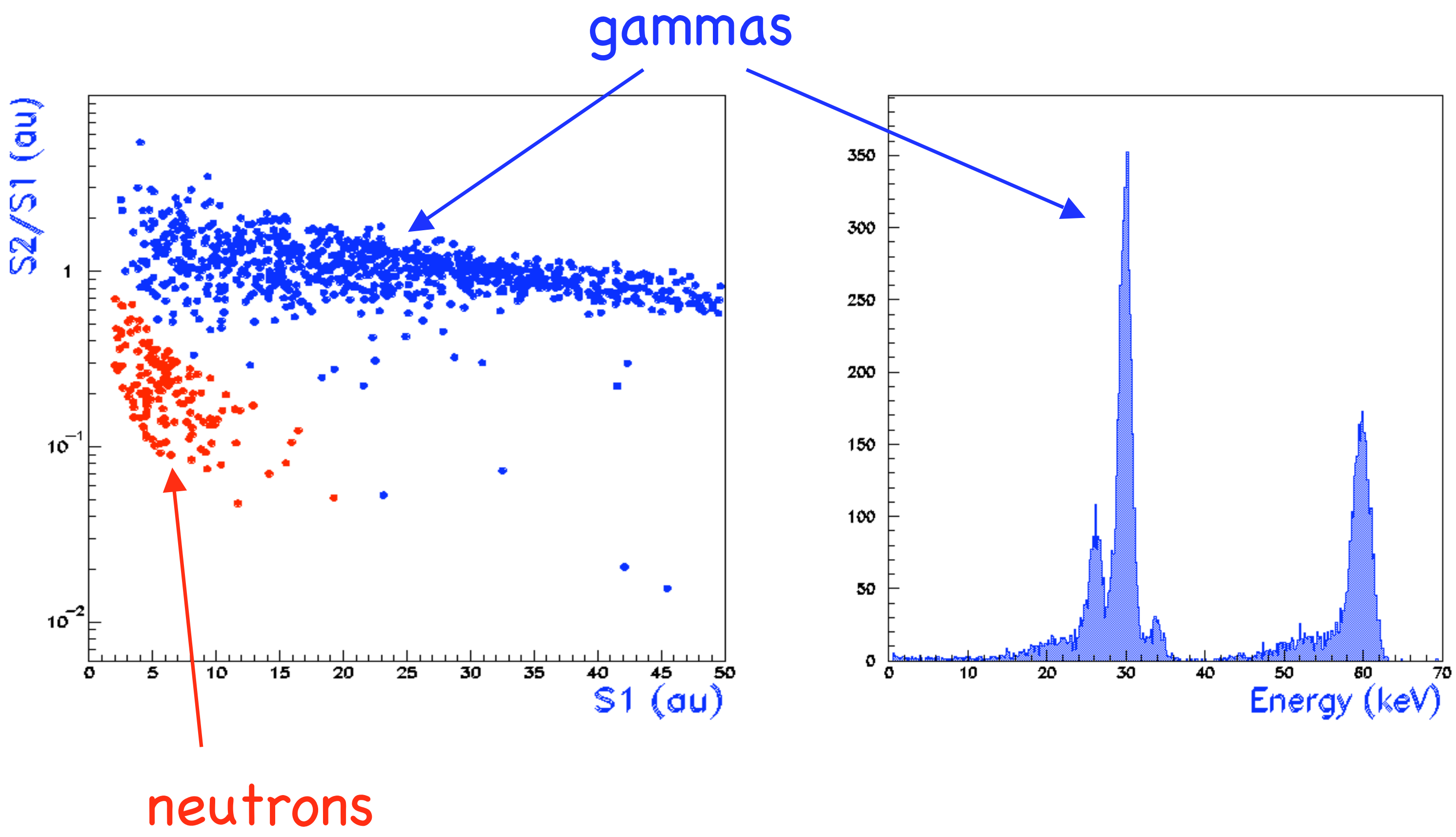
NEXT!

7-PMT, 20 bar
TAMU HPXe TPC



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

Nr Discrimination in HPXe with TAMU 7-PMT TPC



Europe:

NEXT collaboration

Spain/Portugal/France…

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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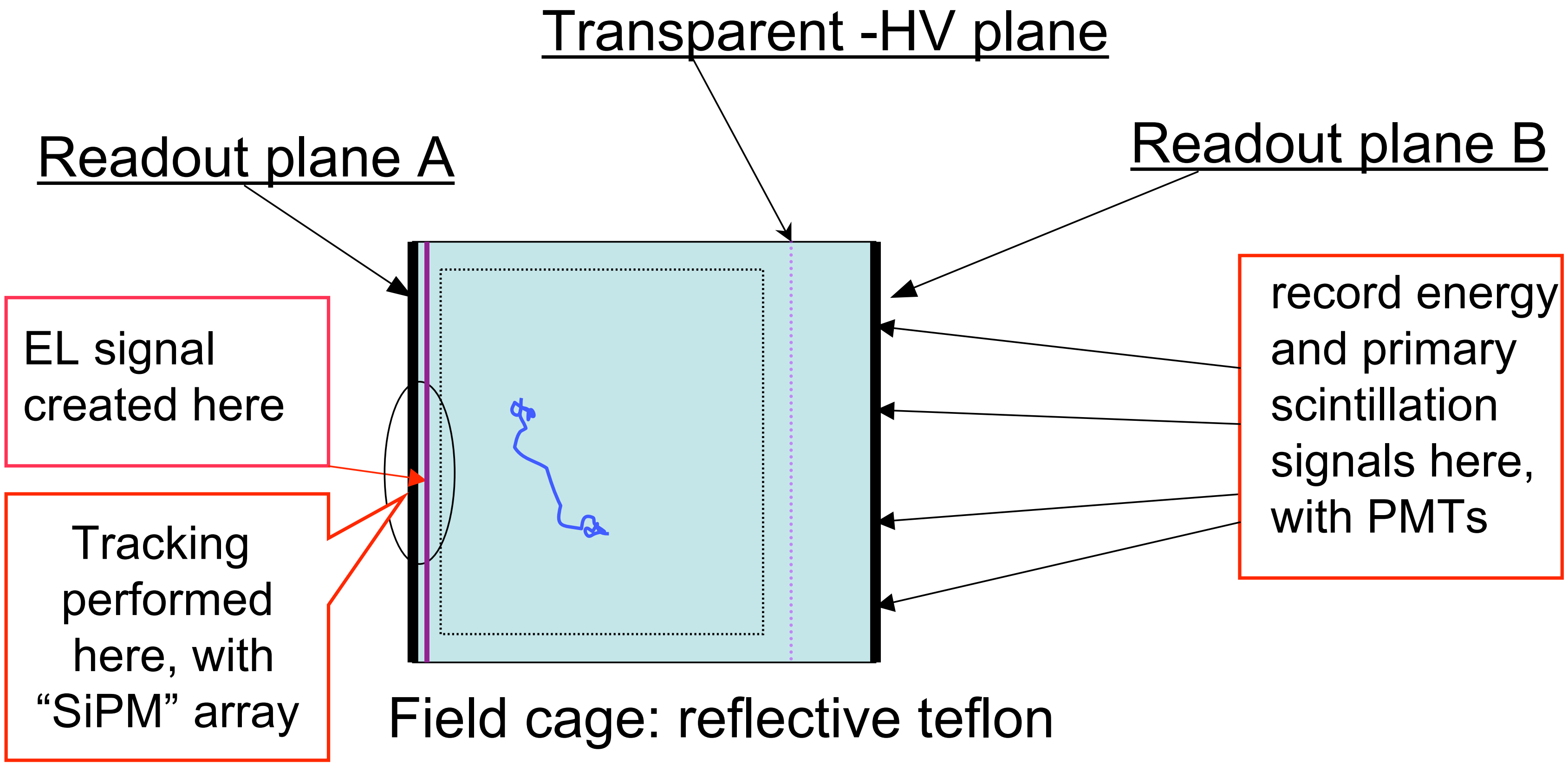
NEXT: Asymmetric EL TPC

"Separated function"

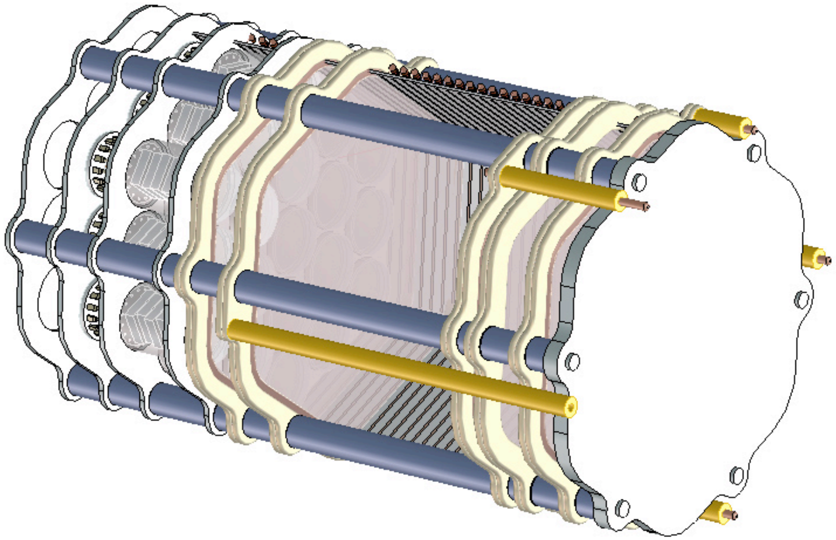


Goals in US

- Near-term:
  - Construct 10 - 20 bar HPXe 19 PMT TPC, demonstrate energy resolution goal at 662 keV, together with NEXT collaboration.

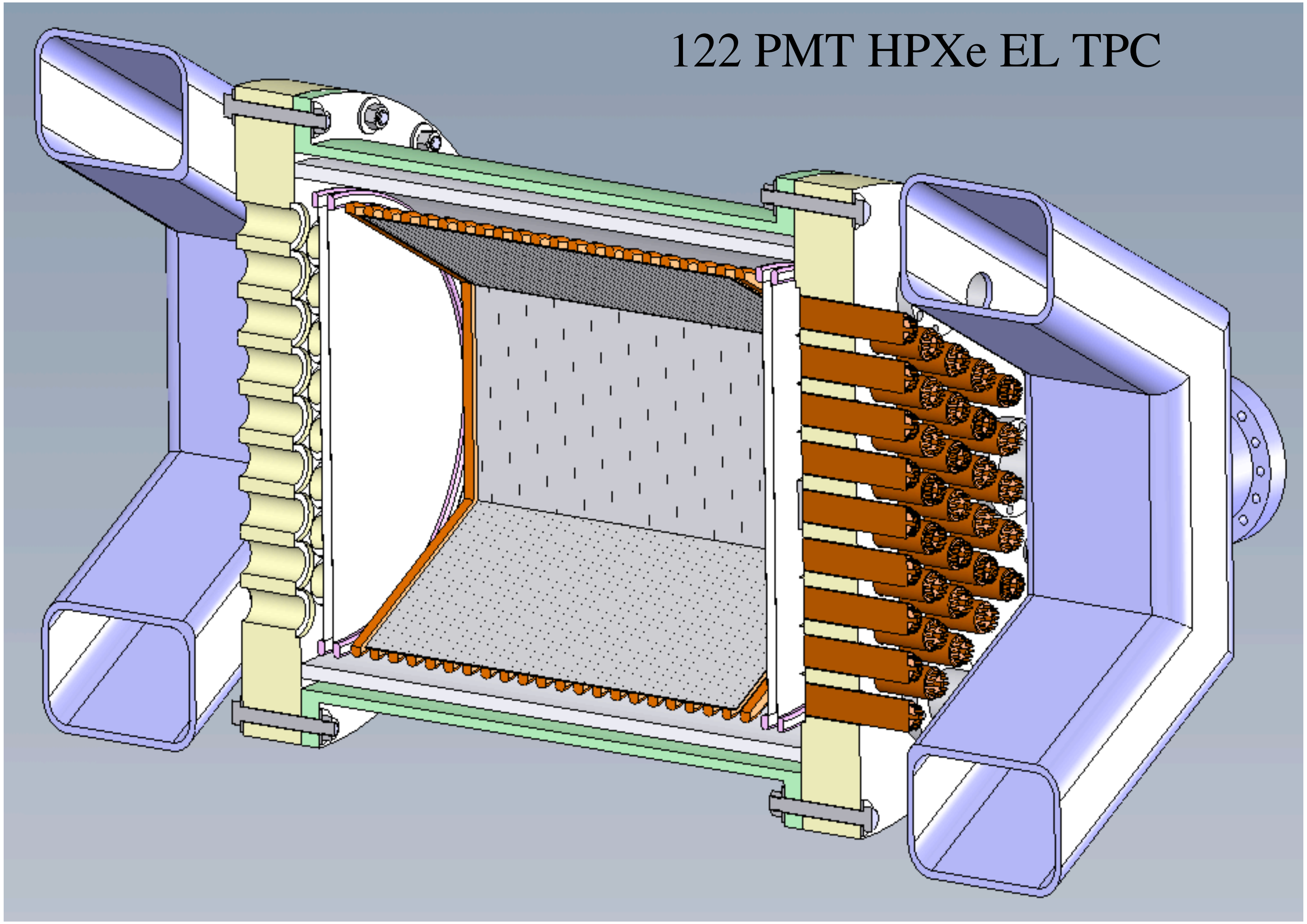
- Longer-term:
  - Construct 10 - 20 bar HPXe 122 PMT TPC, demonstrate energy resolution and tracking goals at ~2500 keV, together with NEXT collaboration.

19 PMT HPXe TPC



Goal: $\delta E/E$ resolution (662 keV), and to explore sensitivity of energy resolution to drift E-field

122 PMT HPXe EL TPC



Perspective

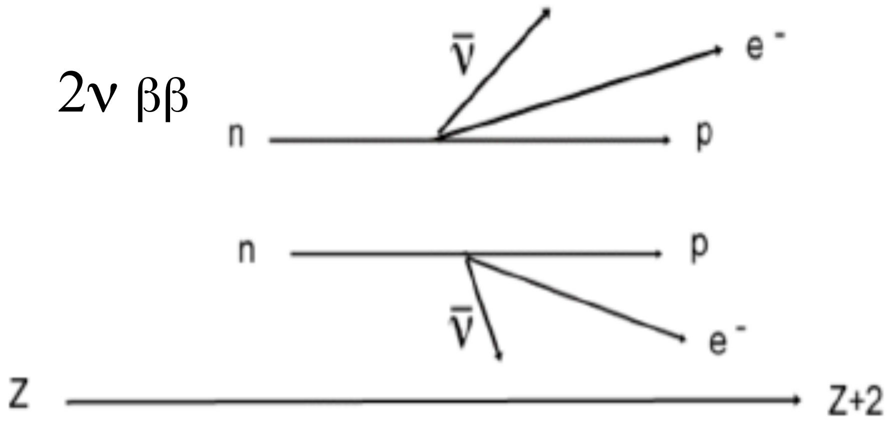
- Why bother with gas? - LXe has momentum

But, with HPXe:

  - Energy resolution: x10 better than LXe
  - Topology: rejection of backgrounds
  - Flexibility: HPXe + neon, Ar + 1% Xe, …
  - Noise: less than one electron rms!
  - HPXe EL TPC may do ββ & WIMP searches
  - New approach may be essential!

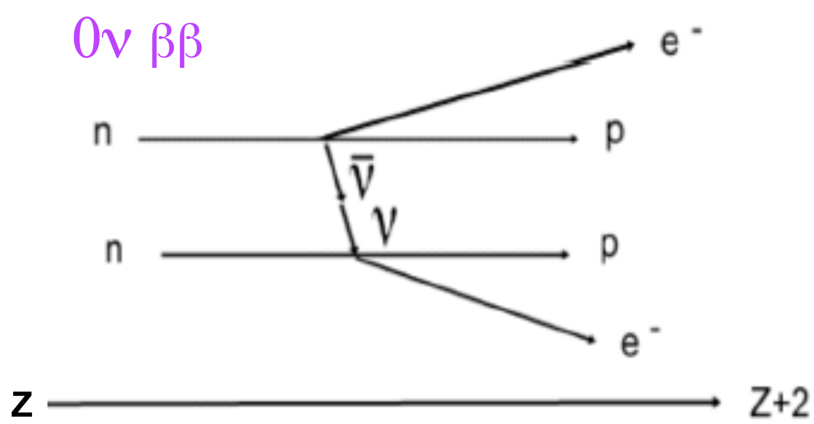
Thank you

Two Types of Double Beta Decay



A known standard model process and an important calibration tool

$$T_{\frac{1}{2}} \approx 10^{19}\ yrs.$$



Neutrinoless double beta decay.

If this process is observed:
Neutrino mass ≠ 0
Neutrino = Anti-neutrino!
Lepton number is not conserved!

$$\frac{1}{T_{\frac{1}{2}}} = G \times \|\mathbf{M}\|^2 \times m_{\bar{\nu}}^{\ 2}$$

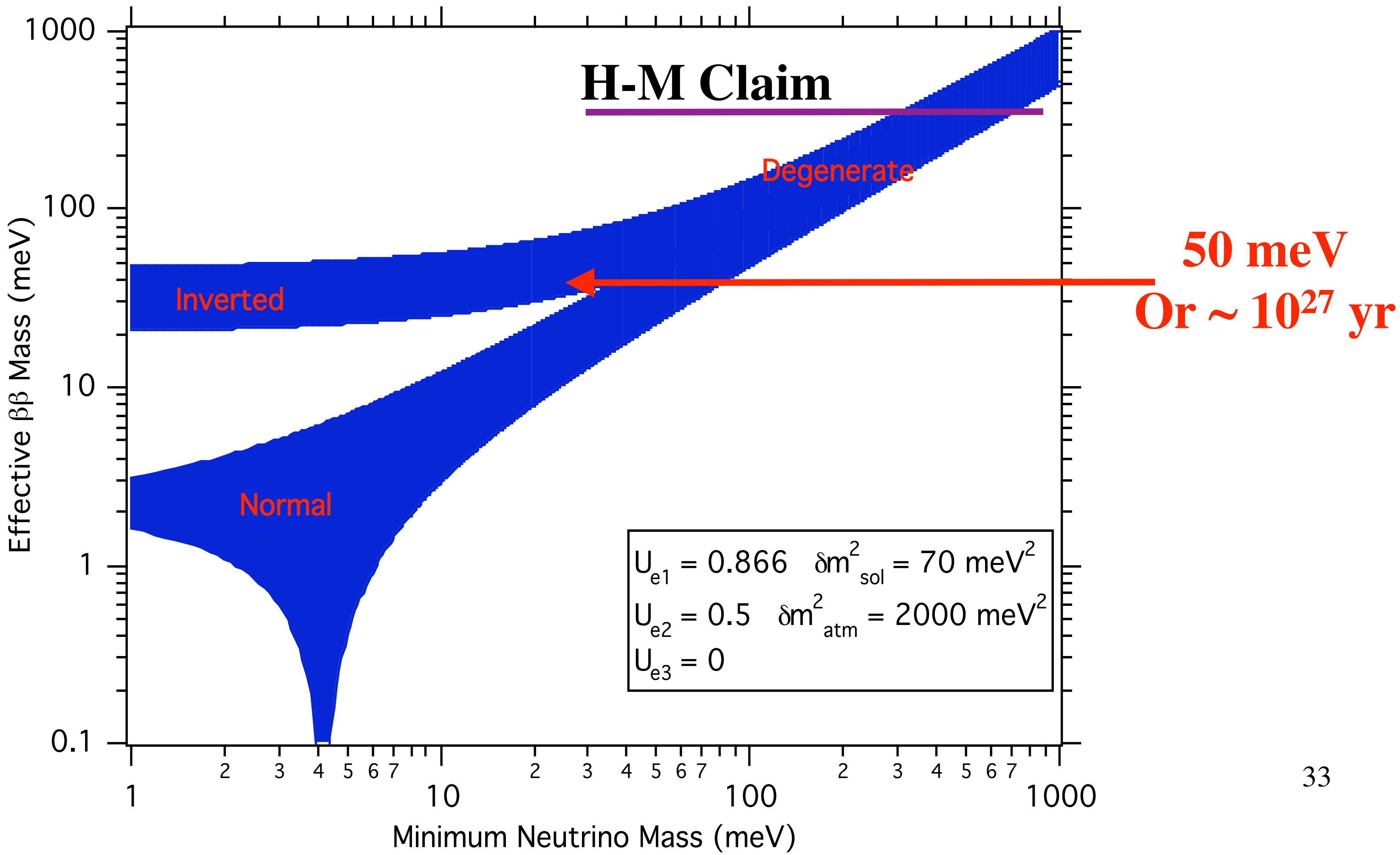
?

Neutrinoless double beta decay lifetime

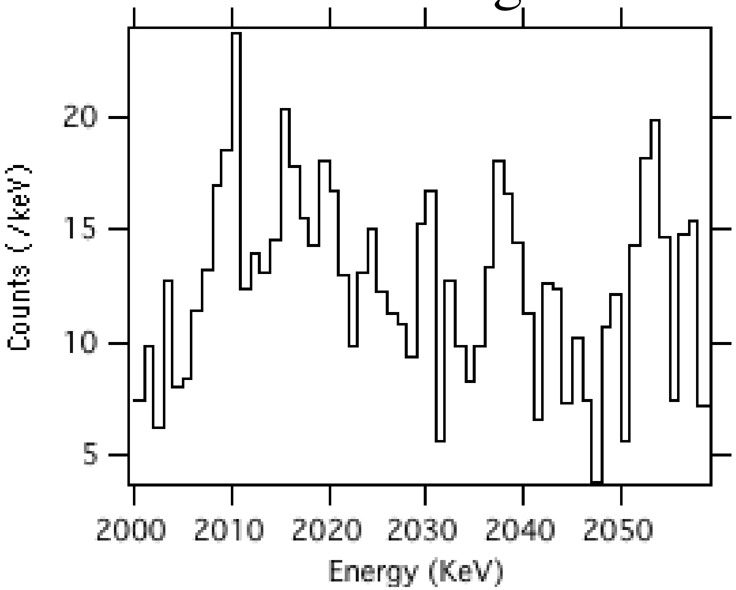
Neutrino effective mass

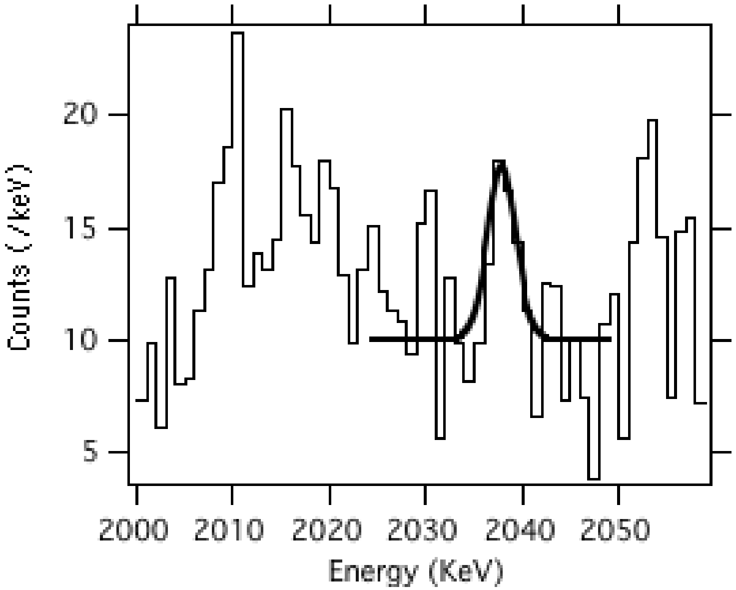
$$\left[T_{1/2}^{0\nu}(0^+ \to 0^+)\right]^{-1} = G^{0\nu}(E_0, Z)\left|M_{GT}^{0\nu} - \frac{g_V^2}{g_A^2} M_F^{0\nu}\right|^2 \langle m_\nu \rangle^2$$

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

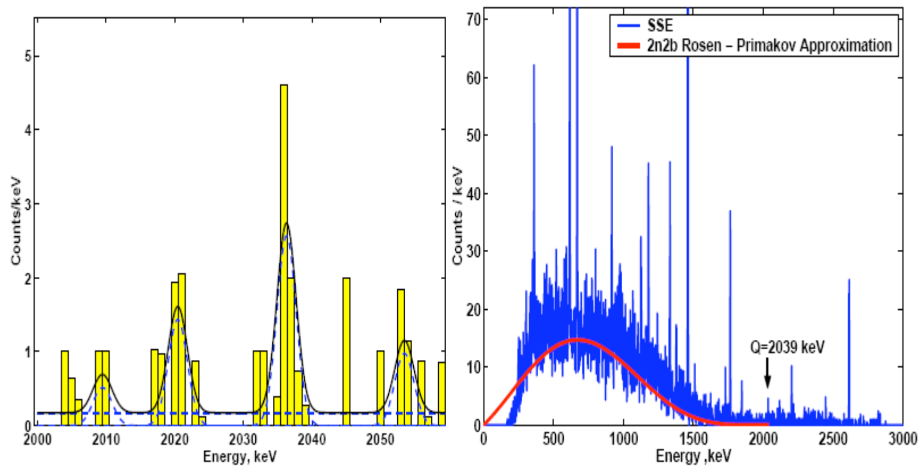


- H-M: Only positive claim for 0–ν ββ detection
- 11 kg of 86% enriched ^{76}Ge for 13 years





NIM A522, 371 (2004)



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

$T_{1/2}$~1.19×10^{25}y

<m> ~ 0.44 eV

Excellent energy resolution
not sufficient to reject BG!

“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)

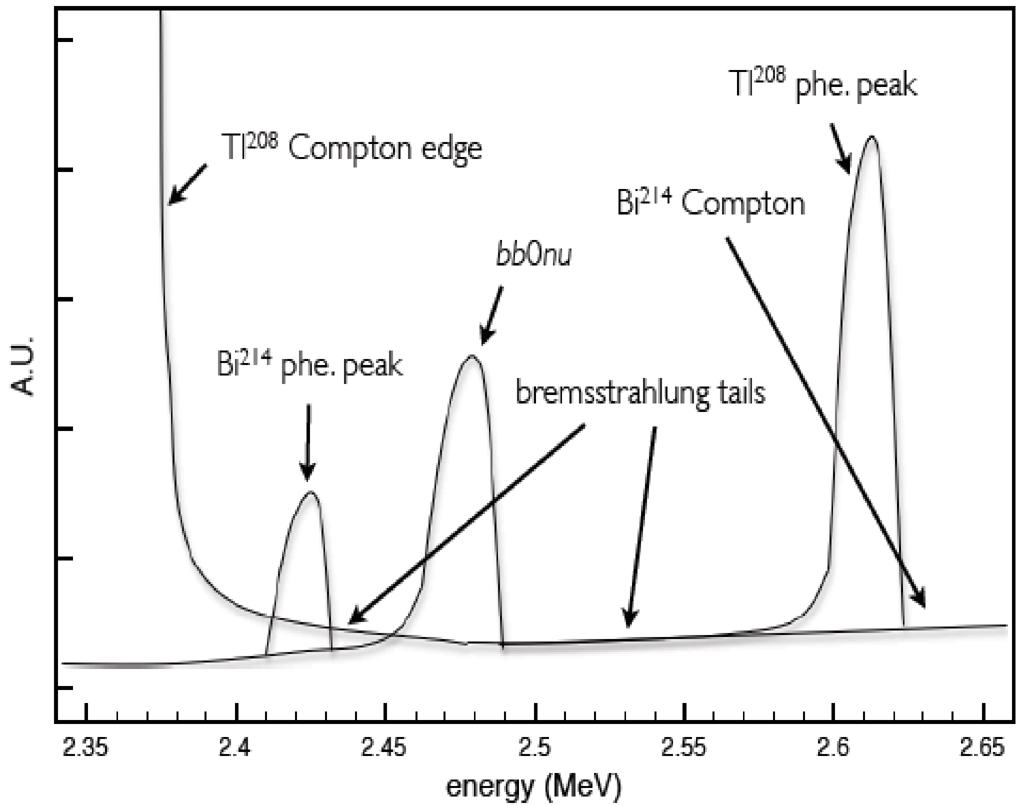
Reasons for this less-than-optimum resolution are not clear…

Possible: uncorrectable losses to electronegative impurities

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

But: ~30x topological rejection of γ interactions!

Backgrounds for the $\beta\beta0\nu$ search



NEXT Collaboration

α particles

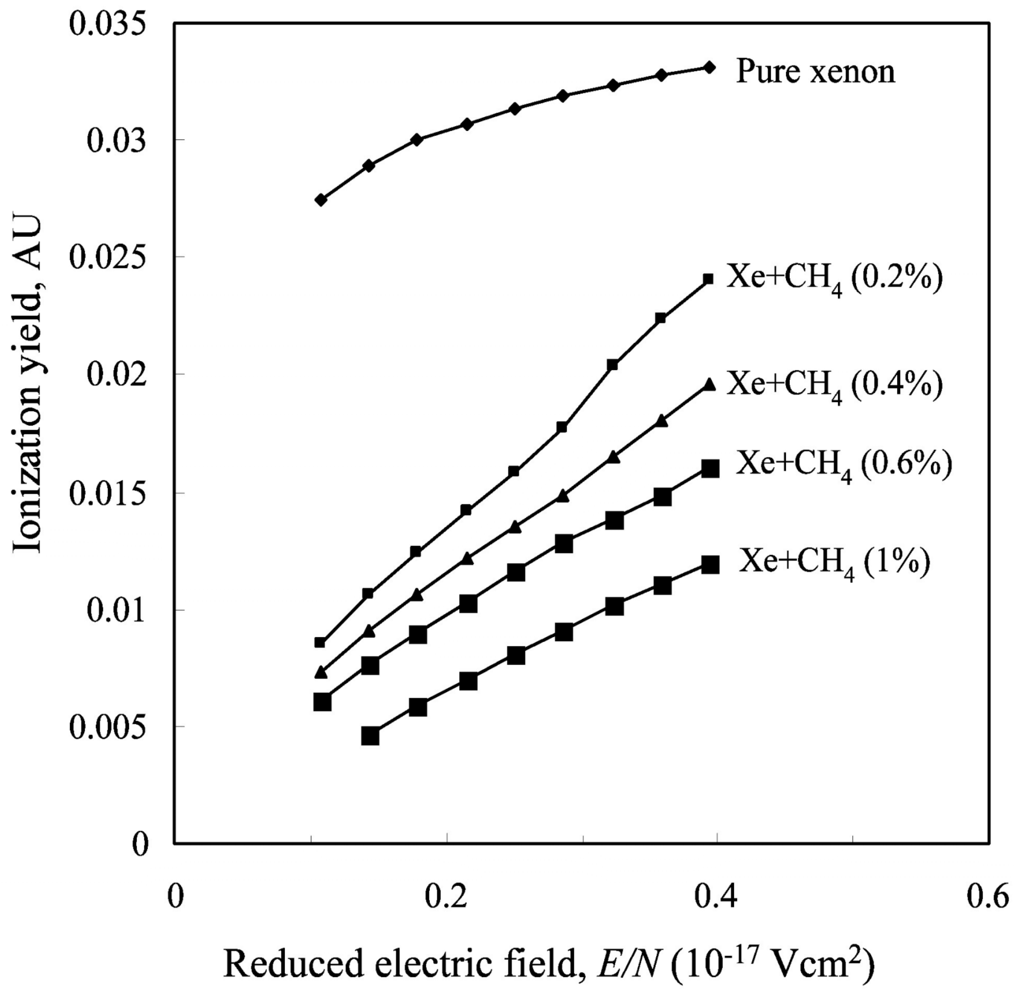


Fig.7. Dependence of ionization yield on reduced electric field (*E/N*) at a pressure of 2.6 MPa. **(~25 bars)**

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:

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

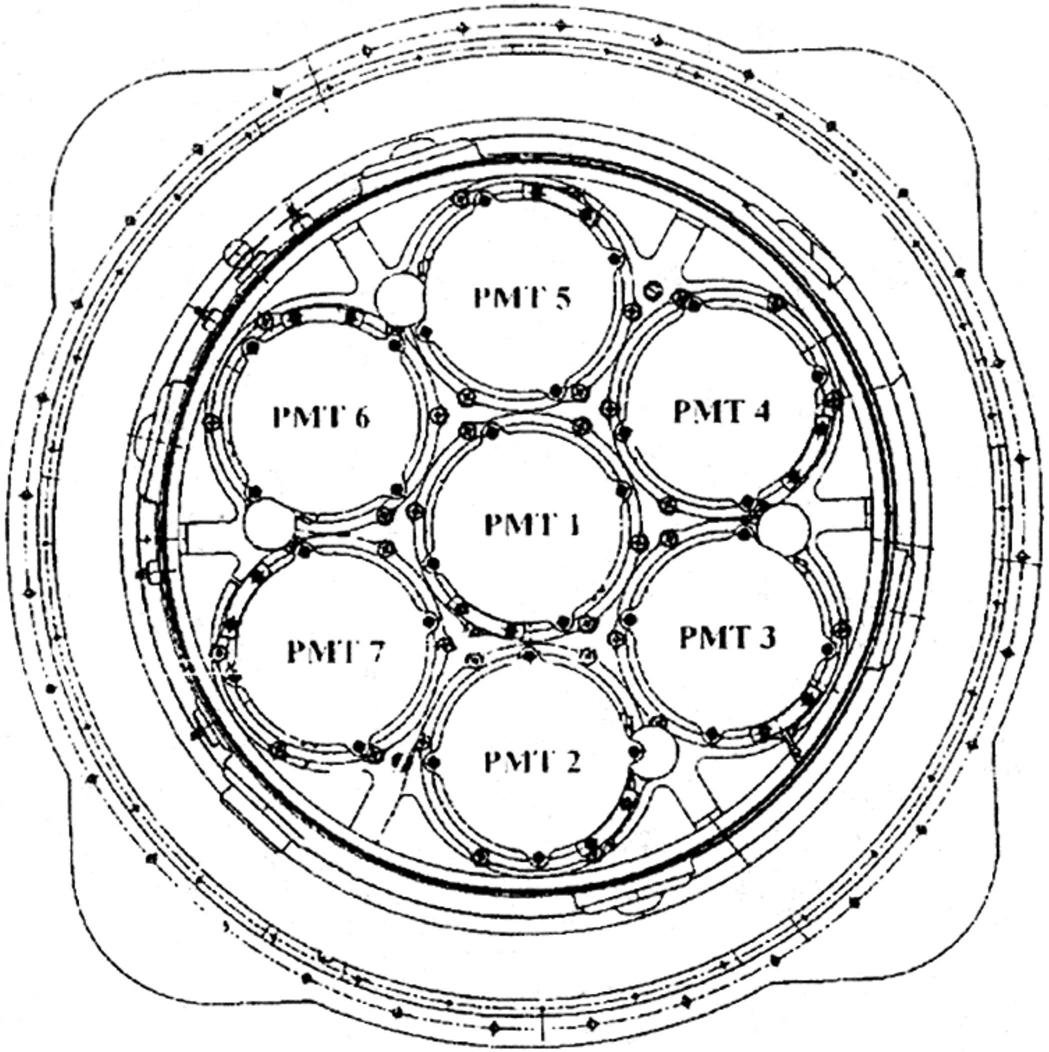
  - Two excimers are consumed!
  - More likely for both high ρ **+** high ionization density

– Quenching of both ionization and scintillation can occur!

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

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

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


PMT 5
PMT 6
PMT 4
PMT 1
PMT 3
PMT 7
PMT 2

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