Xenon Gas TPCs for 0-ν $\beta\beta$ and WIMP Searches
Recent Developments and Prospects:
What's ***NEXT***?

David Nygren

Instrumentation Seminar

FNAL May 2009

Outline

- 0-ν $\beta\beta$ & WIMPs: quests or quagmires?
- Experiments: past, present, ...
- Xenon: - molecular physics in action
- *NEXT*: Spanish groups see the light
- WIMPs: has DAMA-LIBRA seen a signal?
- Ions, maligned and neglected partners...
- Perspective

Physics Motivations

- Neutrino-less double beta decay:
  – Tests Majorana nature of neutrino
  – Determine range of absolute neutrino mass
  – If observed, lepton number NOT conserved
- Dark matter:
  – 24% of mass of Universe - what is it?
  – Direct or indirect detection of WIMPs?
  – Is DAMA-LIBRA right or wrong?

- $\beta\beta$ **decay: Rare transition between same A nuclei**
  - **Energetically allowed for some even-even nuclei**

- **$(Z,A) \rightarrow (Z+2,A) + e^-_1 + \bar{\nu}_1 + e^-_2 + \bar{\nu}_2$**
- **$(Z,A) \rightarrow (Z+2,A) + e^-_1 + e^-_2$**
- **$(Z,A) \rightarrow (Z+2,A) + e^-_1 + e^-_2 + \chi$**

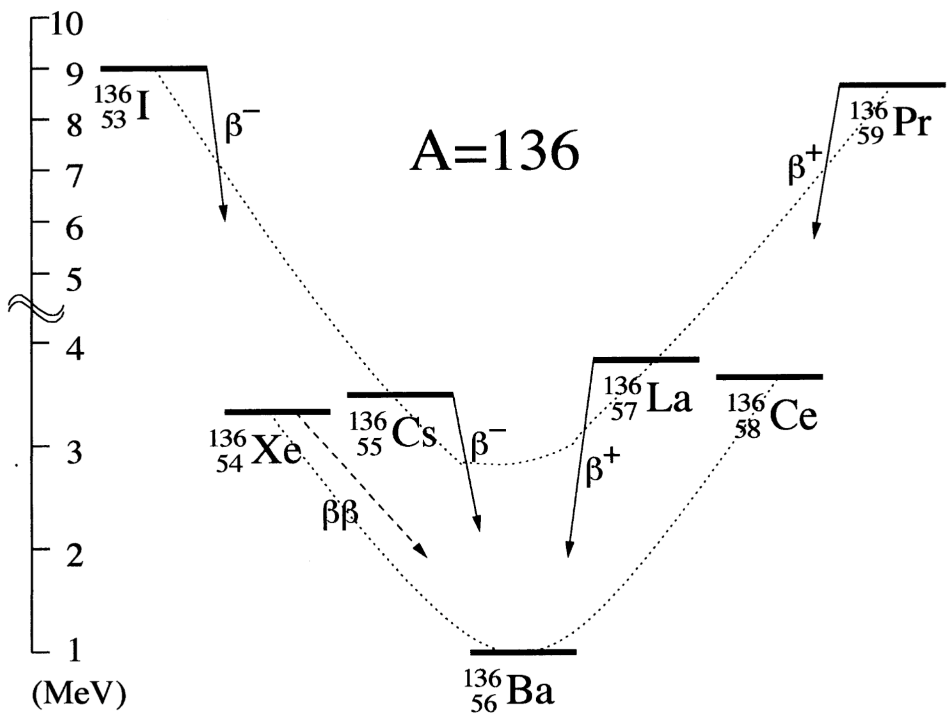
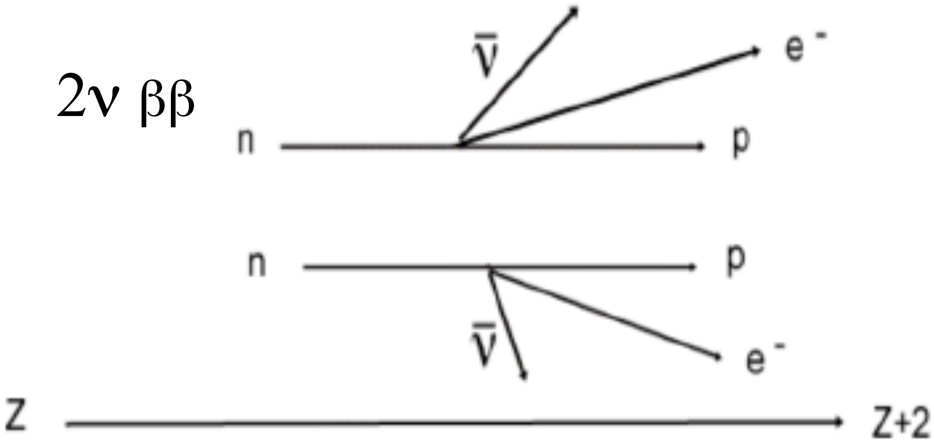
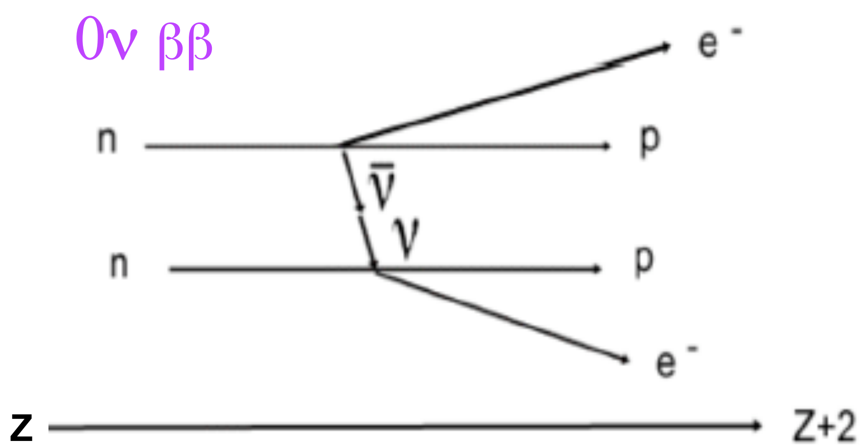


Figure 2.1: Simplified atomic mass scheme for nuclei with A=136. The parabolae connecting the odd-odd and even-even nuclei are shown. While ^{136}Xe is stable to ordinary beta decay, it can decay into ^{136}Ba by double-beta decay.

Two Types of Double Beta Decay





Neutrinoless double beta decay.

A known standard model process and an important calibration tool

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

If this process is observed:

Neutrino mass ≠ 0

Neutrino = Anti-neutrino!

Lepton number is not conserved!

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

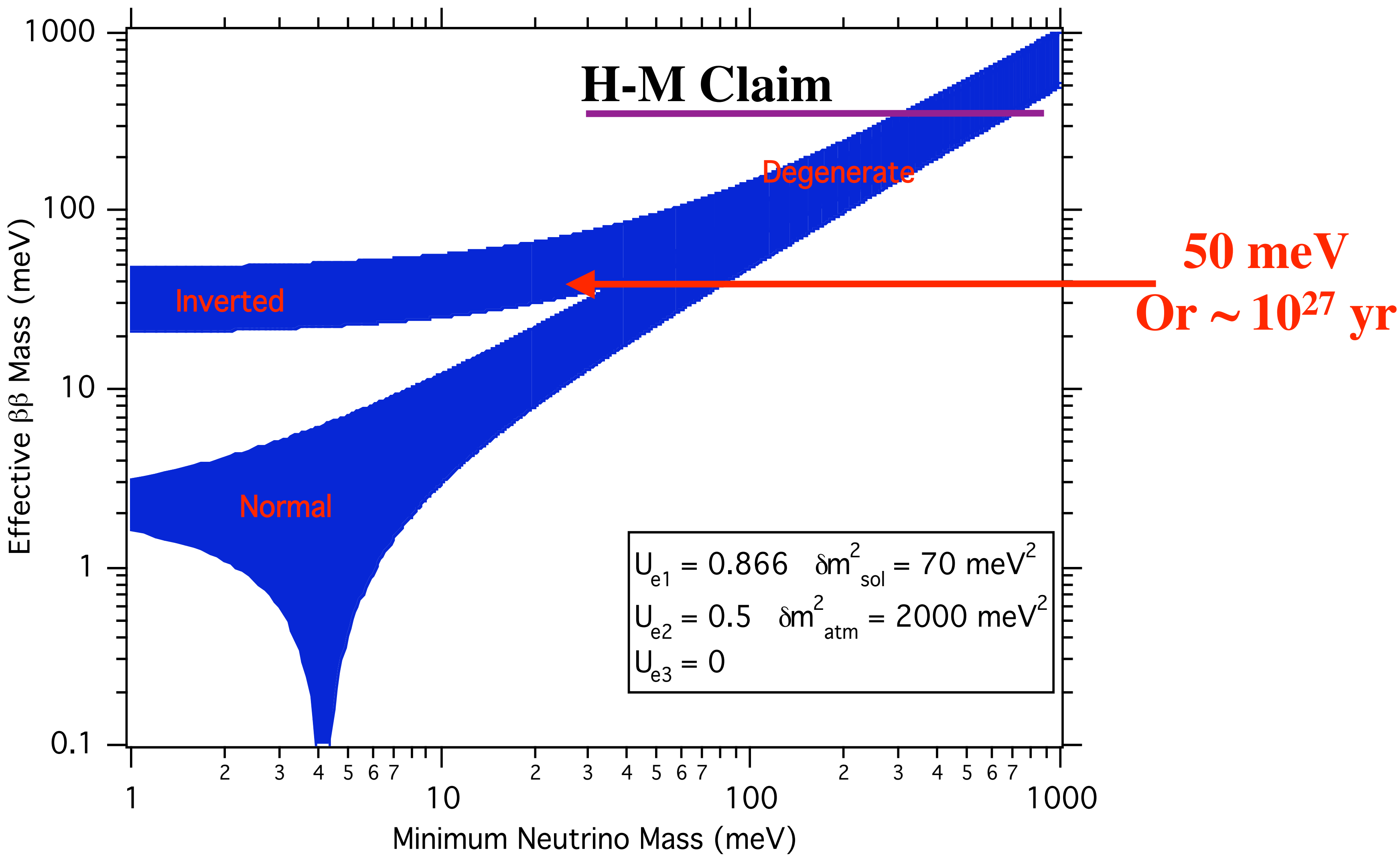
?

Neutrinoless double beta decay lifetime

Neutrino effective mass

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

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



Double Beta Decay Spectra

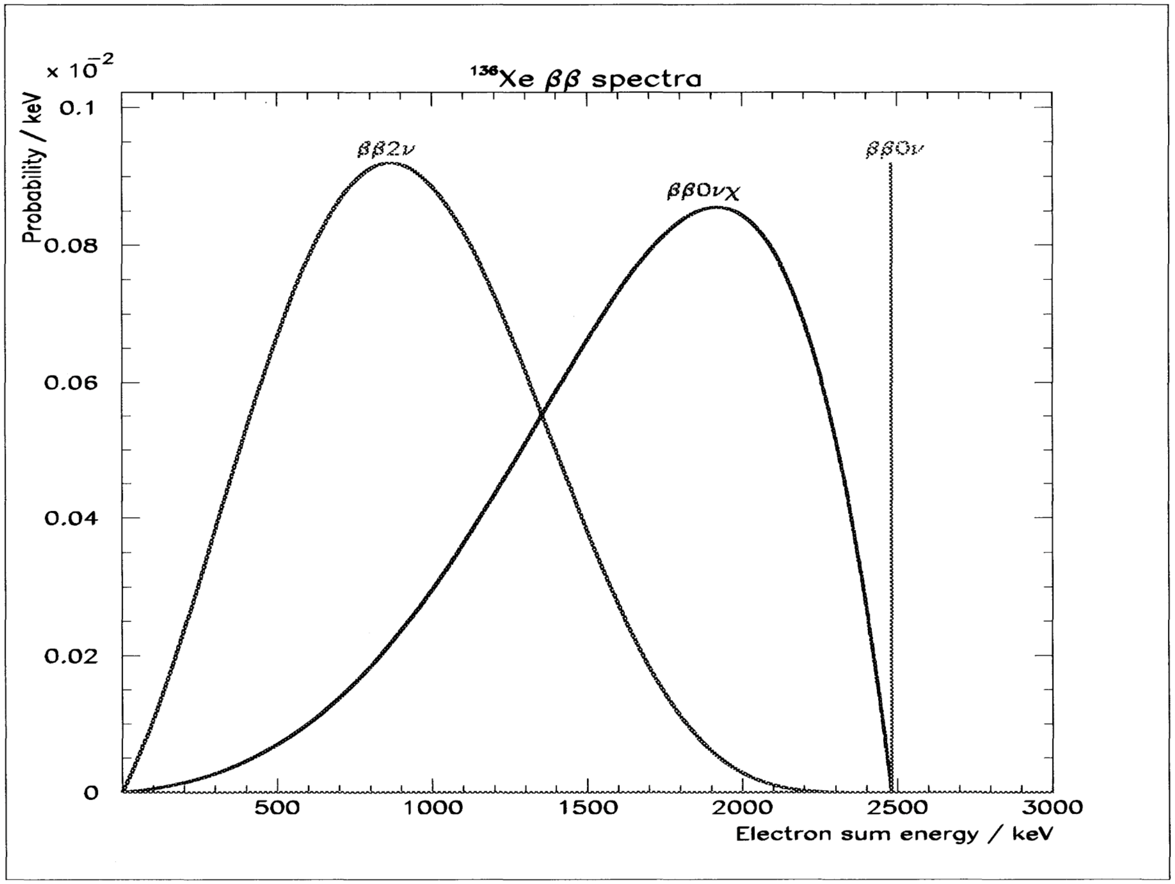
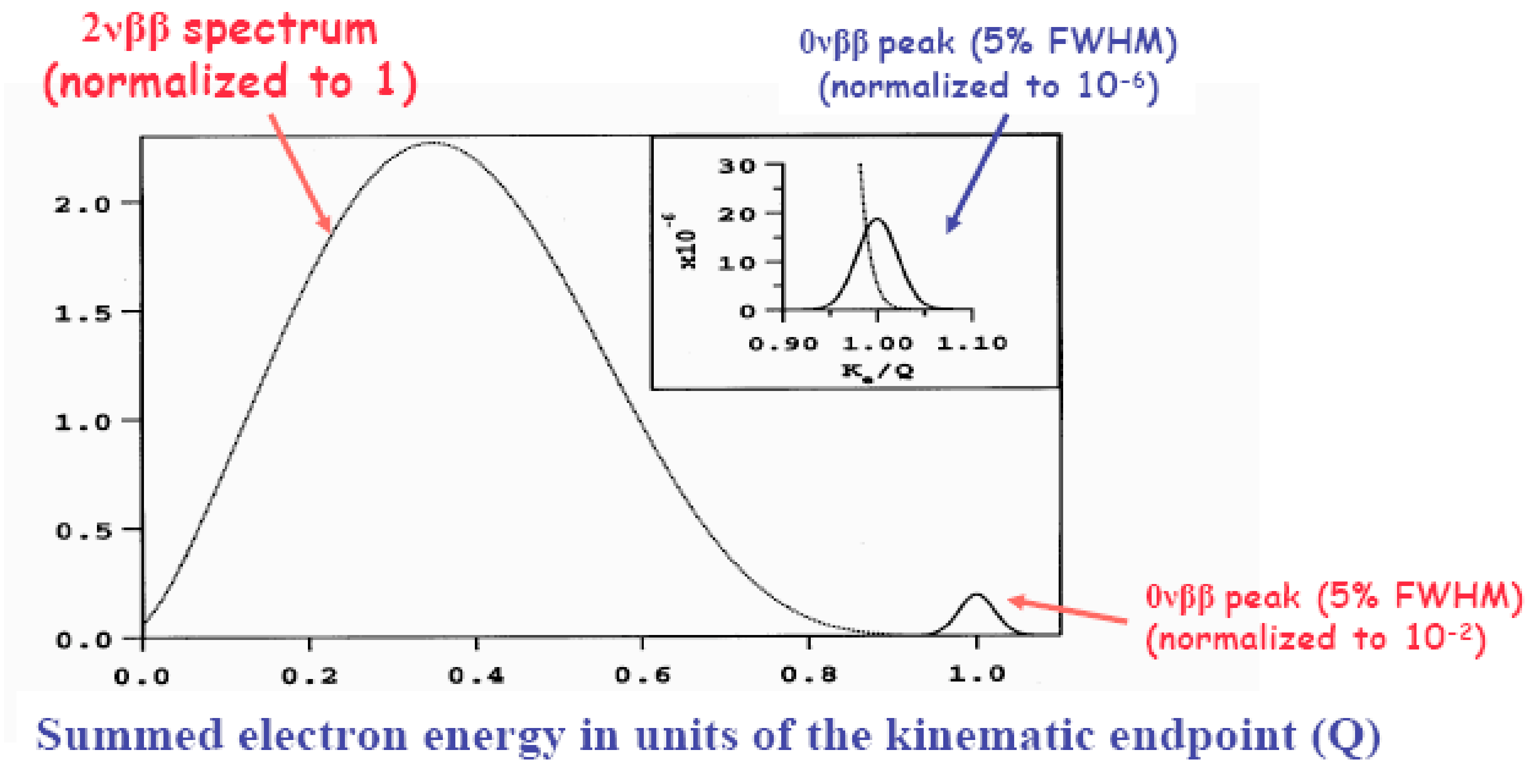


Figure 2.4: The two neutrino, zero neutrino, and Majoran double beta decay modes. The only method to distinguish the modes is via kinematic measurement.

How to search for neutrino-less decay:

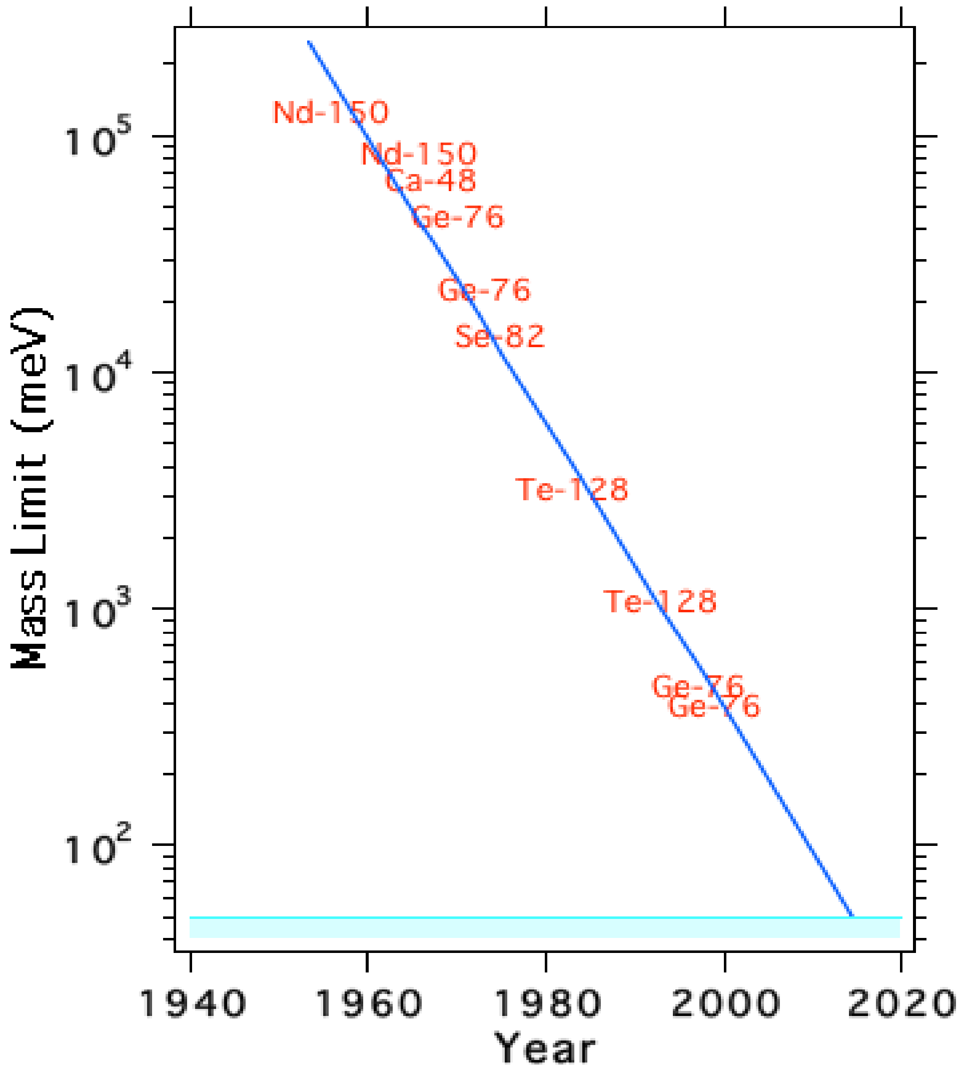
Measure the spectrum of the electrons



Elliott & Vogel
Annu. Rev. Part. Sci. 2002 52:115

Past Results

^{48}Ca	>1.4x10^{22} y	<(7.2-44.7) eV
^{76}Ge	>1.9x10^{25} y	<0.35 eV
^{76}Ge	>1.6x10^{25} y	<(0.33-1.35) eV
^{76}Ge	=1.2x10^{25} y	**= 0.44 eV**
^{82}Se	>2.1x10^{23} y	<(1.2-3.2) eV
^{100}Mo	>5.8x10^{23} y	<(0.6-2.7) eV
^{116}Cd	>1.7x10^{23} y	<1.7 eV
^{128}Te	>7.7x10^{24} y	<(1.1-1.5) eV
^{130}Te	>3.0x10^{24} y	<(0.41-0.98) eV
^{136}Xe	>4.5x10^{23} y	<(1.8-5.2) eV
^{150}Nd	>1.2x10^{21} y	<3.0 eV



What’s needed…

- Long lifetimes (>10^{25} years) require:
  - Large Mass of relevant isotope (100 - 1000 kg)
  - No background, if possible:
    - Clean materials
    - Underground, away from cosmic rays
    - Background rejection methods:
      - Energy resolution
      - Event topology
      - Particle identification (no alphas, protons, or positrons, please)
      - Identification of daughter nucleus?
  - Years of data-taking

Experimental Outlook (2006)

Experiment	Isotope	Mass	Technique	Present Status
CANDLES	^{48}Ca	few tons	CaF_2 scint. crystals	Prototype
CARVEL	^{48}Ca	1 ton	CaF_2 scint. crystals	Development
COBRA	^{116}Cd	418 kg	CZT semicond. det.	Prototype
CUORICINO	^{130}Te	40.7 kg	TeO_2 bolometers	Running
CUORE	^{130}Te	741 kg	TeO_2 bolometers	Proposal
DCBA	^{150}Ne	20 kg	^{enr}Nd foils and tracking	Development
EXO-200	^{136}Xe	200 kg	Liq. ^{enr}Xe TPC/scint.	Construction
EXO	^{136}Xe	1-10 t	Liq. ^{enr}Xe TPC/scint.	Proposal
GEM	^{76}Ge	1 ton	^{enr}Ge det. in liq. nitrogen	Inactive
GENIUS	^{76}Ge	1 ton	^{enr}Ge det. in liq. nitrogen	Inactive
GERDA	^{76}Ge	$\simeq$35 kg	^{enr}Ge semicond. det.	Construction
GSO	^{160}Gd	2 ton	Gd_2SiO_5:Ce crys. scint. in liq. scint.	Development
MAJORANA	^{76}Ge	120 kg	^{enr}Ge semicond. det.	Proposal
MOON	^{100}Mo	1 t	^{enr}Mofoils/scint.	Proposal
SNO++	^{150}Nd	10 t	Nd loaded liq. scint.	Proposal
SuperNEMO	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal
Xe	^{136}Xe	1.56 t	^{enr}Xe in liq. scint.	Development
XMASS	^{136}Xe	10 ton	liquid Xe	Prototype
HPXe	^{136}Xe	tons	High Pressure Xe gas	Development

"Gotthard TPC"

Pioneer TPC detector for 0-ν $\beta\beta$ 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 $\Rightarrow$ no TPC start signal!
  - No measurement of drift distance
- $\delta E/E \sim 80 \times 10^{-3}$ FWHM (1592 keV)

  $\Rightarrow$ 66 x 10^{-3} FWHM (2480 keV)

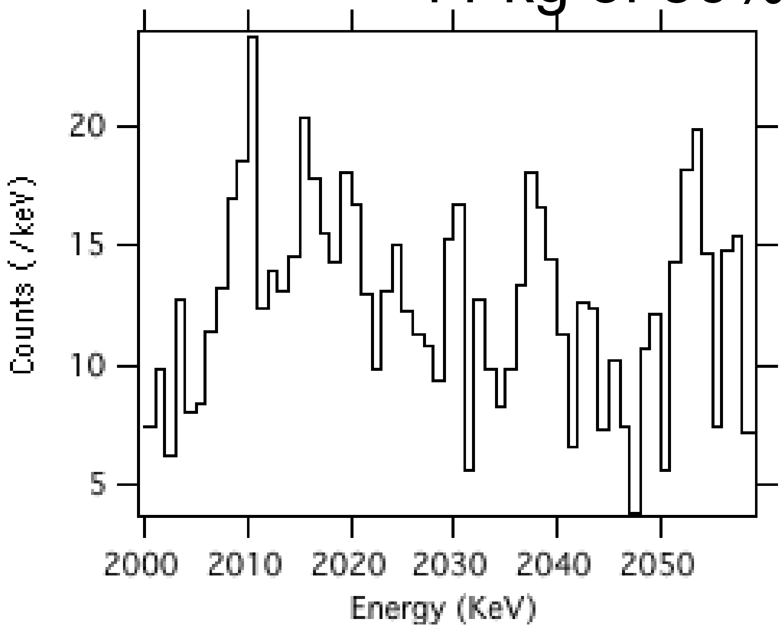
Reasons for this less-than-optimum resolution are not clear…

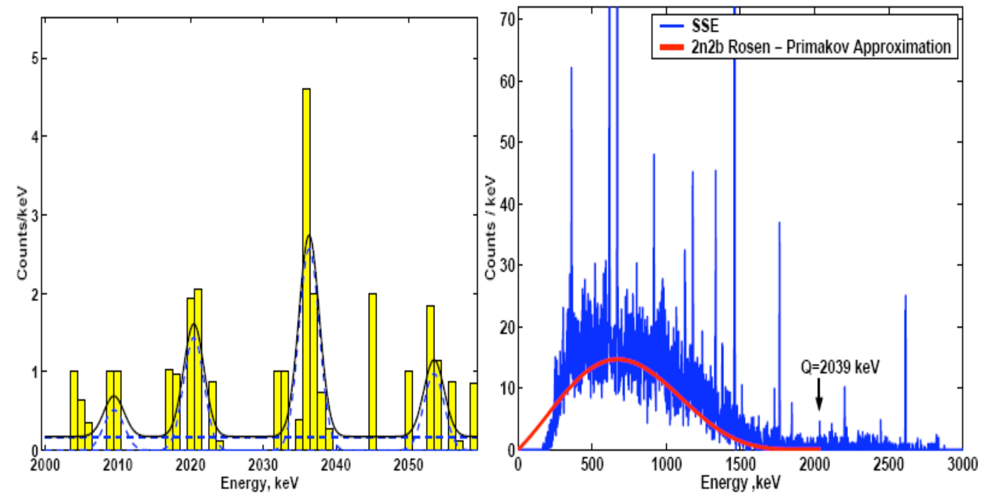
Possible: uncorrectable losses to electronegative impurities

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

But: ~30x topological rejection of γ interactions!

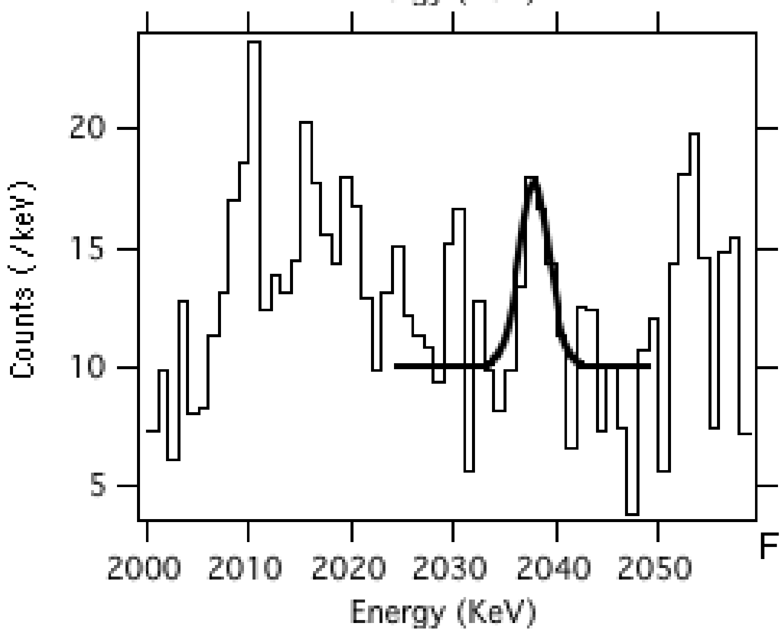
- H-M: Only positive claim for $0-\nu\ \beta\beta$ detection
- 11 kg of 86% enriched ^{76}Ge for 13 years





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

NIM A522, 371 (2004)

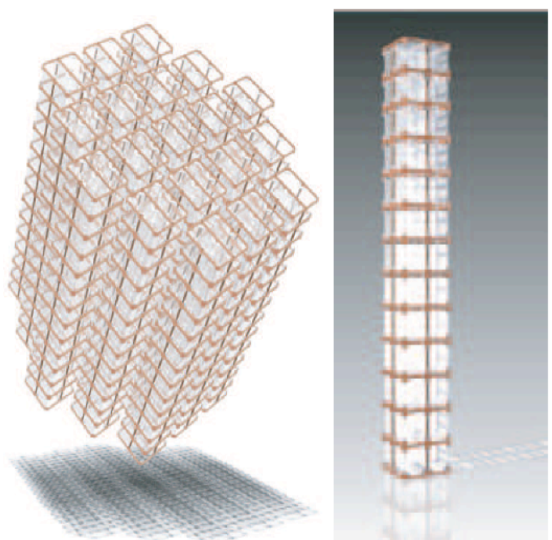


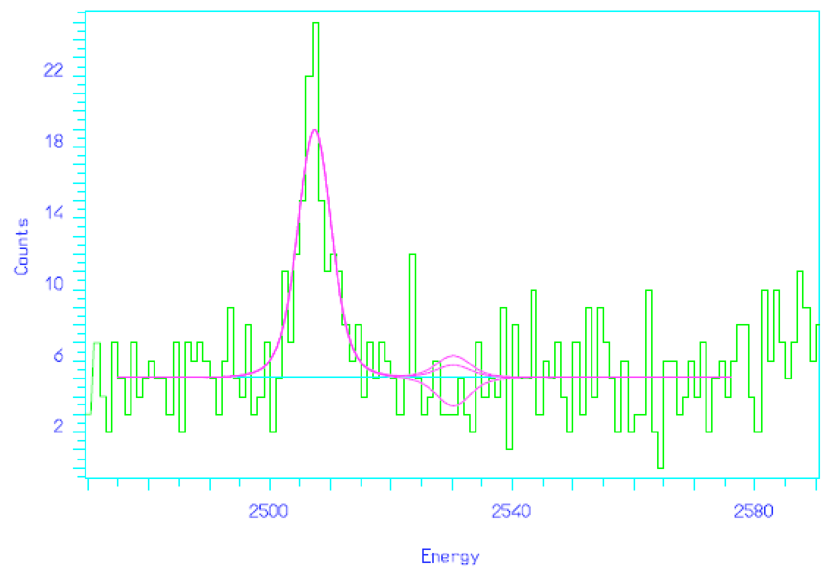
$T_{1/2}$~1.19×10^{25}y

$\langle m \rangle \sim 0.44$ eV

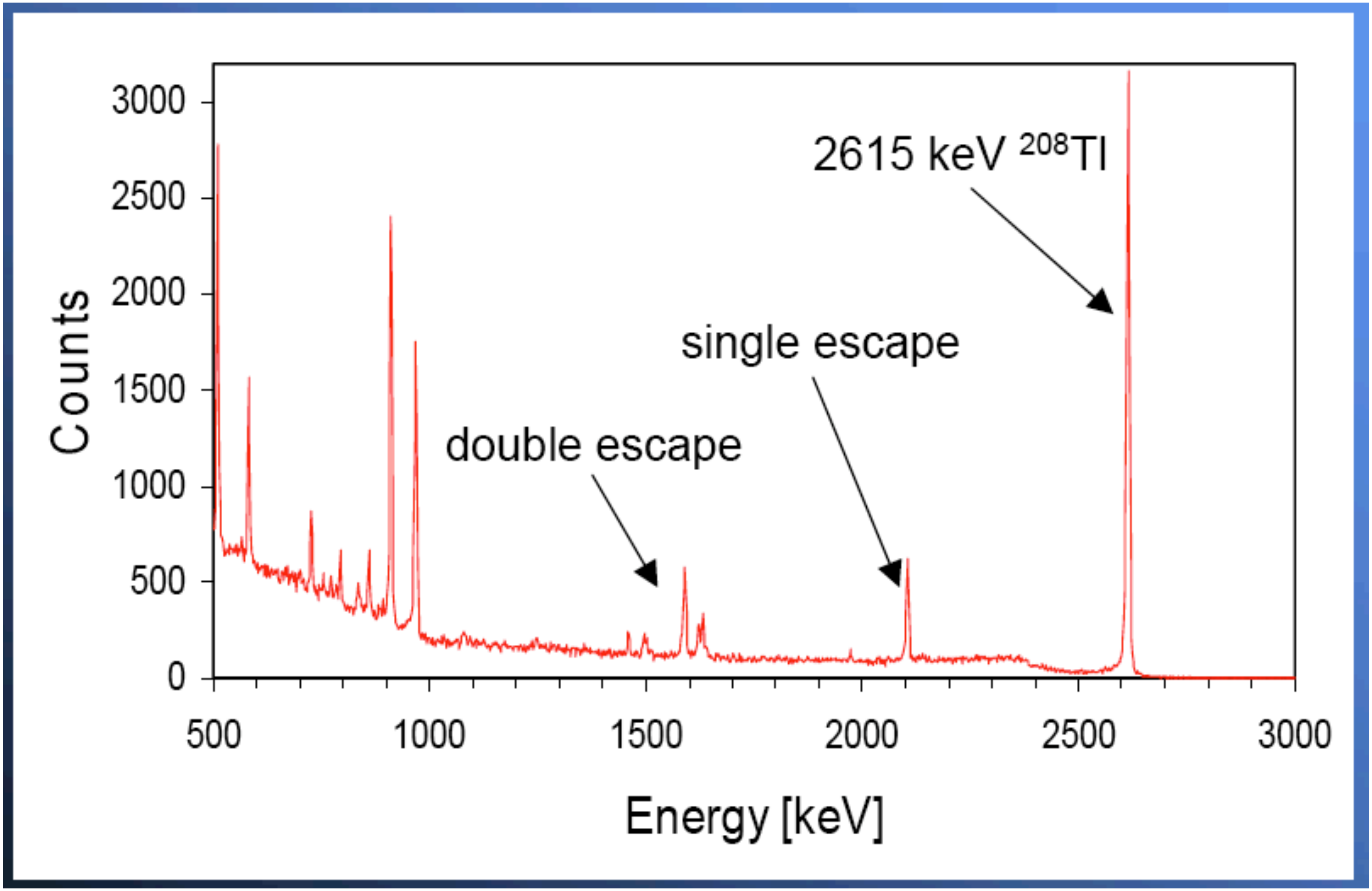
CUORE: Cryogenic "calorimeters"

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

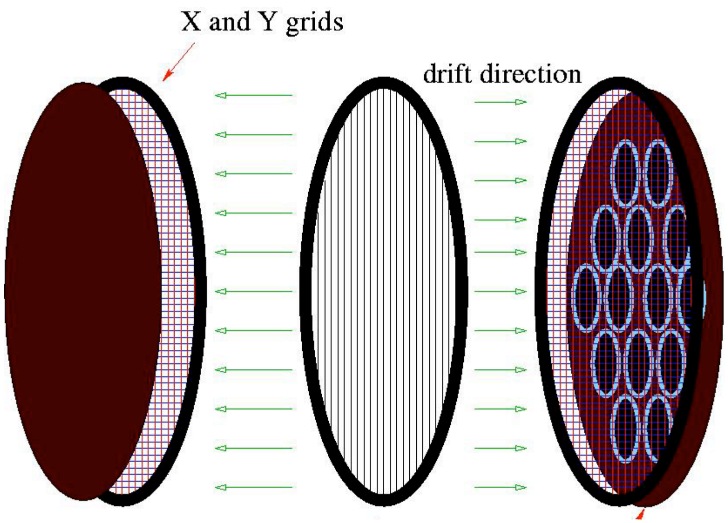




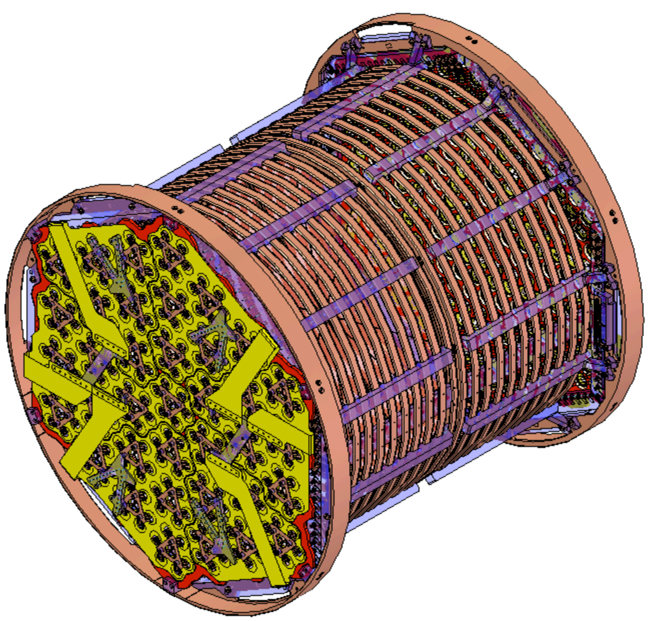
CUORE energy resolution: calibration spectrum

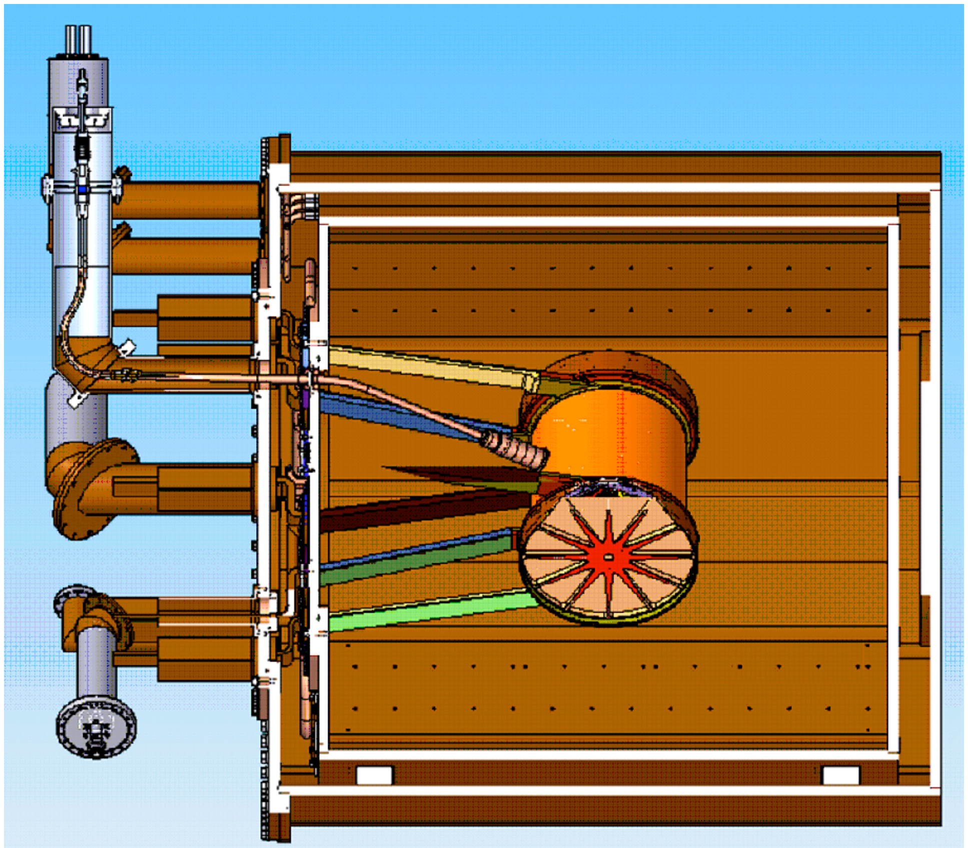


EXO-200: 200 kg enriched ^{136}Xe



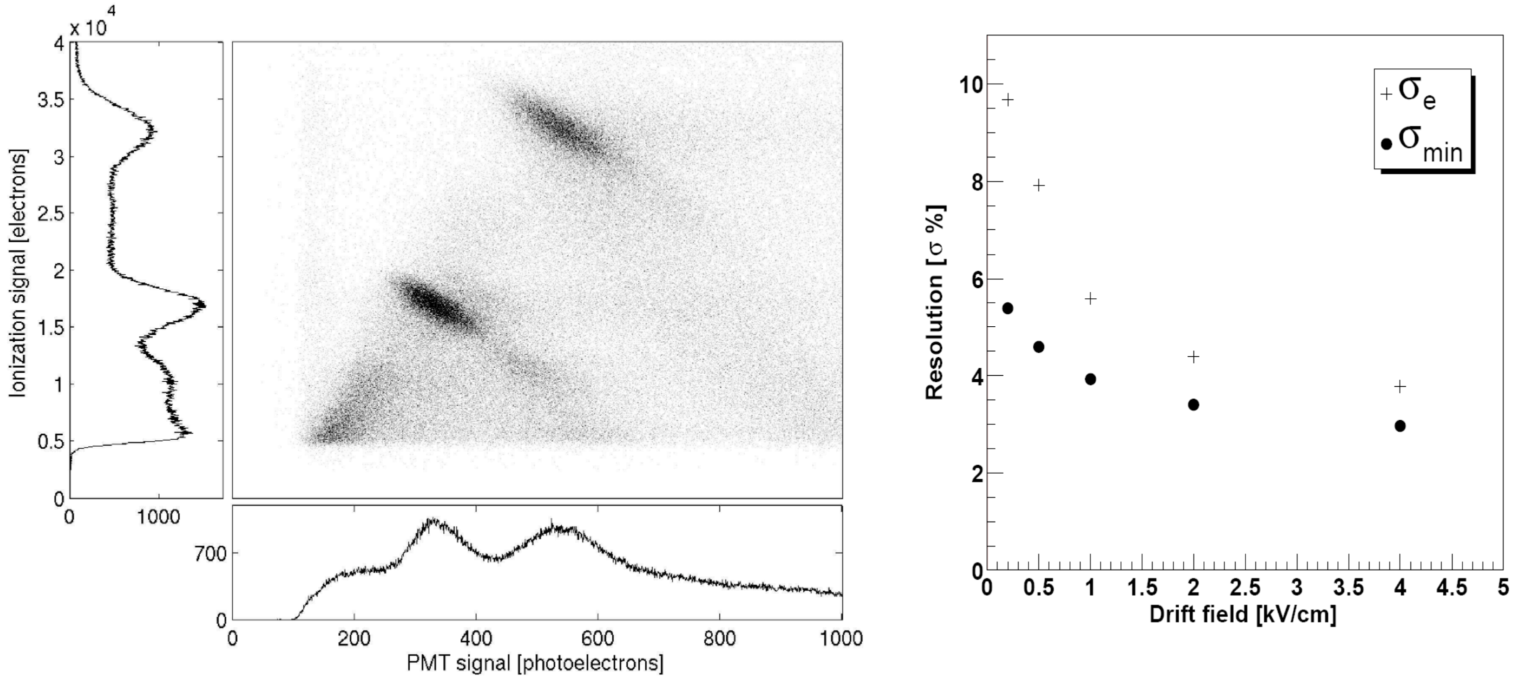
Charge & scintillation light readout





EXO-200 expected E resolution

Anti-correlation between ionization and scintillation signals in liquid xenon can be used to improve the energy resolution



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

FNAL May 2009

Why Xenon for $0-\nu\ \beta\beta$ search?

- Only inert gas with a $0-\nu\ \beta\beta$ candidate
- No long-lived Xe radio-isotopes
- Long $\beta\beta-2\nu$ lifetime ~10^{22}-10^{23} y (not seen yet!)
- No need to grow crystals - no surfaces
- Can be easily re-purified in place (recirculation)
- ^{136}Xe enrichment easy (natural abundance 8.9%)
- Event topology available in gas phase
- Excellent energy resolution (not demonstrated!)

Energy partition in xenon

- When a particle deposits energy in xenon, where does the energy go?
  - Ionization
  - Scintillation: VUV ~170 nm (τ_1, τ_2 …)
  - Heat
- How is the energy partitioned?
  - Dependence on xenon density ρ, E-field, dE/dx
  - Processes still not perfectly understood
  - Complex responses, different for α, β, ,p, nuclei

Xenon: Strong dependence of energy resolution on density!

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

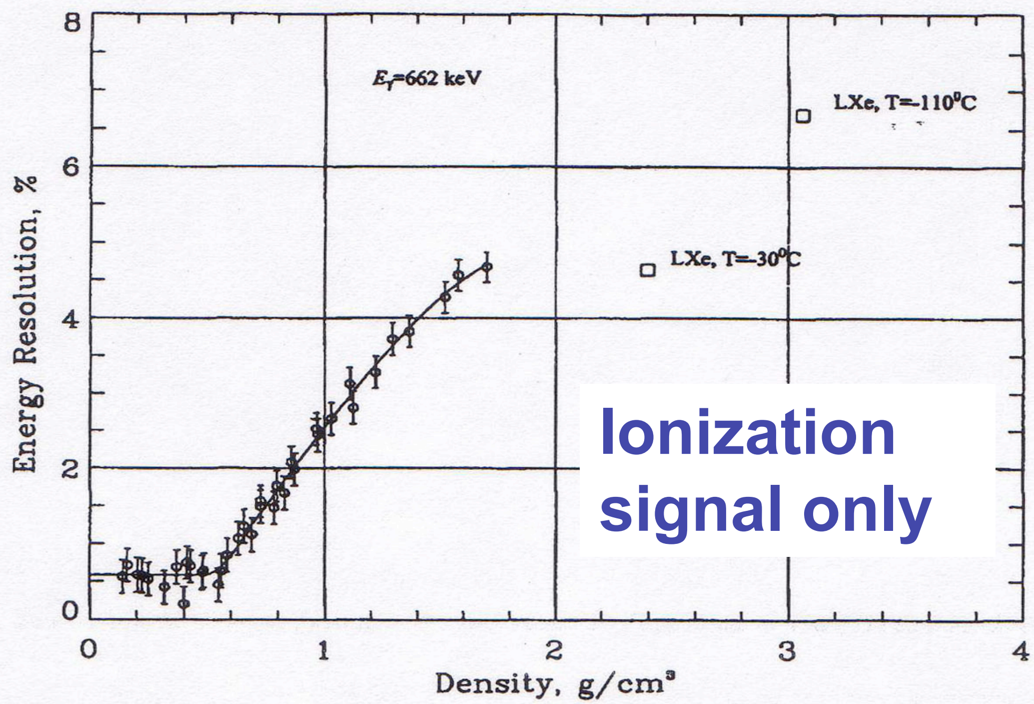


Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

For ρ >0.55 g/cm^3, energy resolution deteriorates rapidly

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

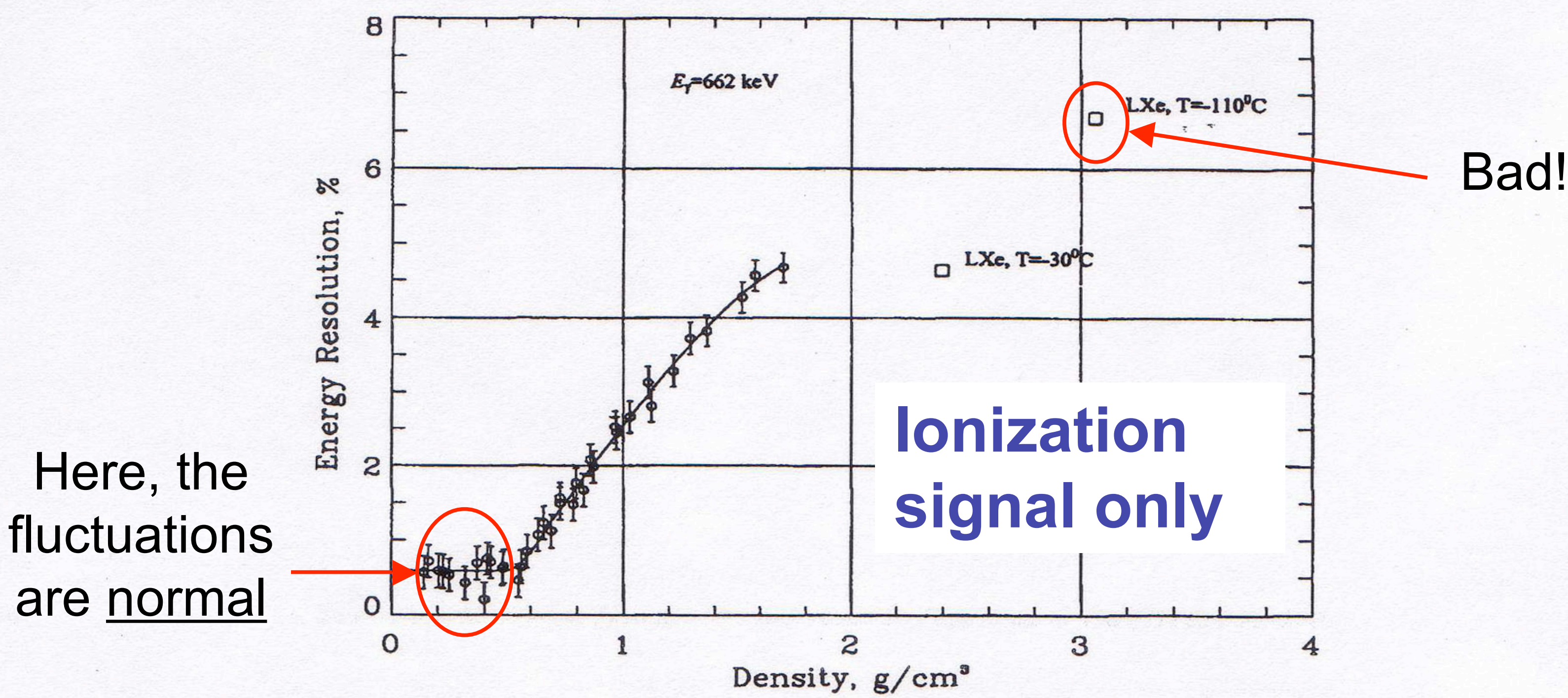


Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

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

LXe or HPXe?

With high-pressure xenon (HPXe)
A measurement of ionization alone
is sufficient to obtain
near-intrinsic energy resolution…

Anti-correlations seen in LXe are due to
anomalously large fluctuations
in partitioning of energy

“Intrinsic” Energy Resolution for Ionization at ^{136}Xe Q-Value

Q-value ($^{136}\text{Xe} \rightarrow {}^{136}\text{Ba}$) = 2480 keV

W = energy per ion/electron pair in xenon gas = 21.9 eV,
but W depends on electric field strength, might be ~24.8 eV

N = number of ion pairs = Q/W

F = Fano factor. Measured in Xe gas: F = 0.13 – 0.17 (assume 0.15)

$$\frac{\Delta E}{Q} = 2.35 \cdot \frac{\sqrt{FN}}{Q} = \sqrt{\frac{FW}{Q}} \approx 2.8 \cdot 10^{-3} \ \text{FWHM}$$

Comparison:

Germanium diodes @ 2.5 MeV $\quad \Delta E / E \approx 1 - 2 \cdot 10^{-3}$ FWHM

Fano Factor of Liquid Xe ~20 $\quad \Rightarrow \quad \Delta E / E \approx 3.5 \cdot 10^{-2}$ FWHM

Absolute Signal Charge Fluctuations

$Q = 2480$ keV

$W = 24.8$ eV

$N =$ number of ion pairs $= Q/W$

$N = 2480 \times 10^3$ eV / 24.8 eV = ~**100,000 electron/ion pairs**

$$\sigma_N = \sqrt{FN}$$

$F = 0.15$

$\Rightarrow \quad \sigma_N = \sqrt{FN} \approx$ **120** electrons rms @ 2480 keV

120 electrons: Electronic Noise Will Dominate in Practical Configurations

Need internal gain without introducing significant fluctuations.

Energy Resolution Including Gain Fluctuations

If fluctuations are uncorrelated, then

$$\sigma_N = \sqrt{(F+L+G)N}$$

where $F =$ Fano factor = 0.15
$L =$ Loss of primary ionization (set to 0)
$G =$ Fluctuations in gain process

To maintain resolution G must be smaller than F.

Avalanche charge gain introduces excessive noise because early fluctuations are amplified exponentially.

Example: for wire $G =$ 0.6 – 0.9 $\Rightarrow$ benefit of small F is lost!

In general, avalanche devices can't deliver $G < F$.

What is this factor “G”?

In a very real sense:

G is a measure of the precision with which a **single** electron can be counted.

How precisely can an electrons be counted in a 100 - 1000 kg system?

The answer is...

Electro-Luminescence (EL)

(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 UV
- Electron starts over, gaining energy again
- Linear growth of signal with voltage
- Photon generation up to ~1000/e, but <u>no</u> ionization
- Early history irrelevant, $\Rightarrow$ **fluctuations are small**
- Maybe… G ~ F, or even G<<F?

Electroluminescence in 4.5 bar of Xenon

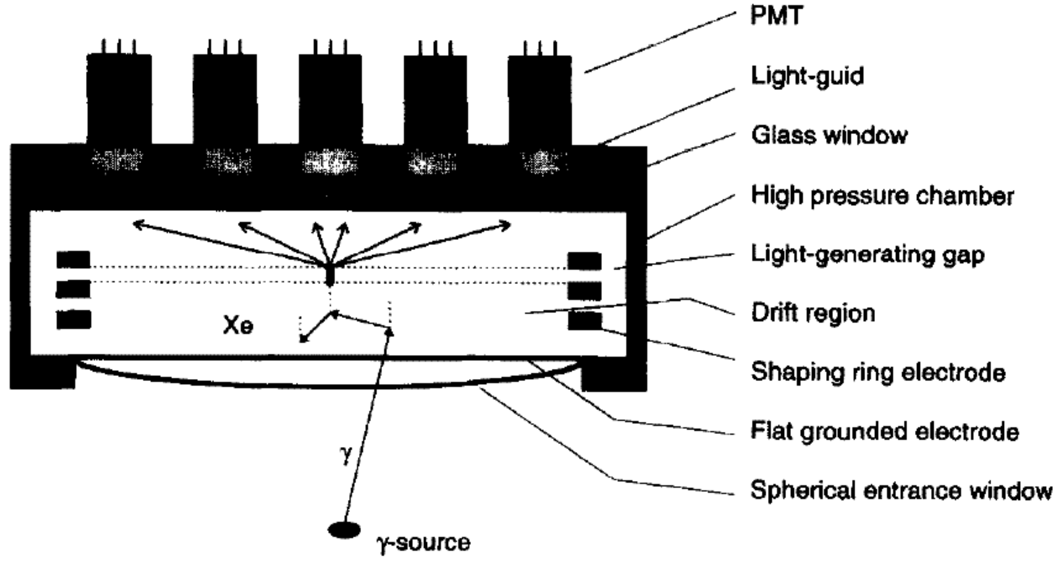
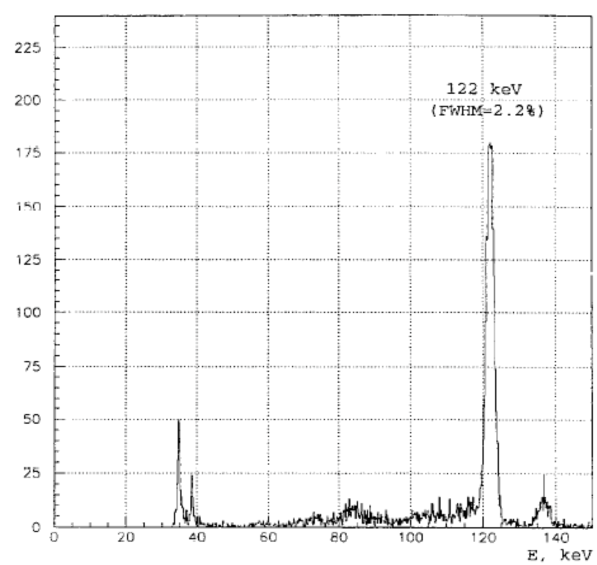


Fig. 1. Schematic diagram of the gas scintillation drift chamber with 19 PMT matrix readout.

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 naively extrapolated to
$Q_{\beta\beta}$ of 2.5 MeV

Fluctuations in Electroluminescence (EL)

EL is a linear gain process

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 $G = F = 0.15 \Rightarrow n_{pe} \geq 10$

The more photo-electrons, the better!

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

Other 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

Detector Concept: TPC

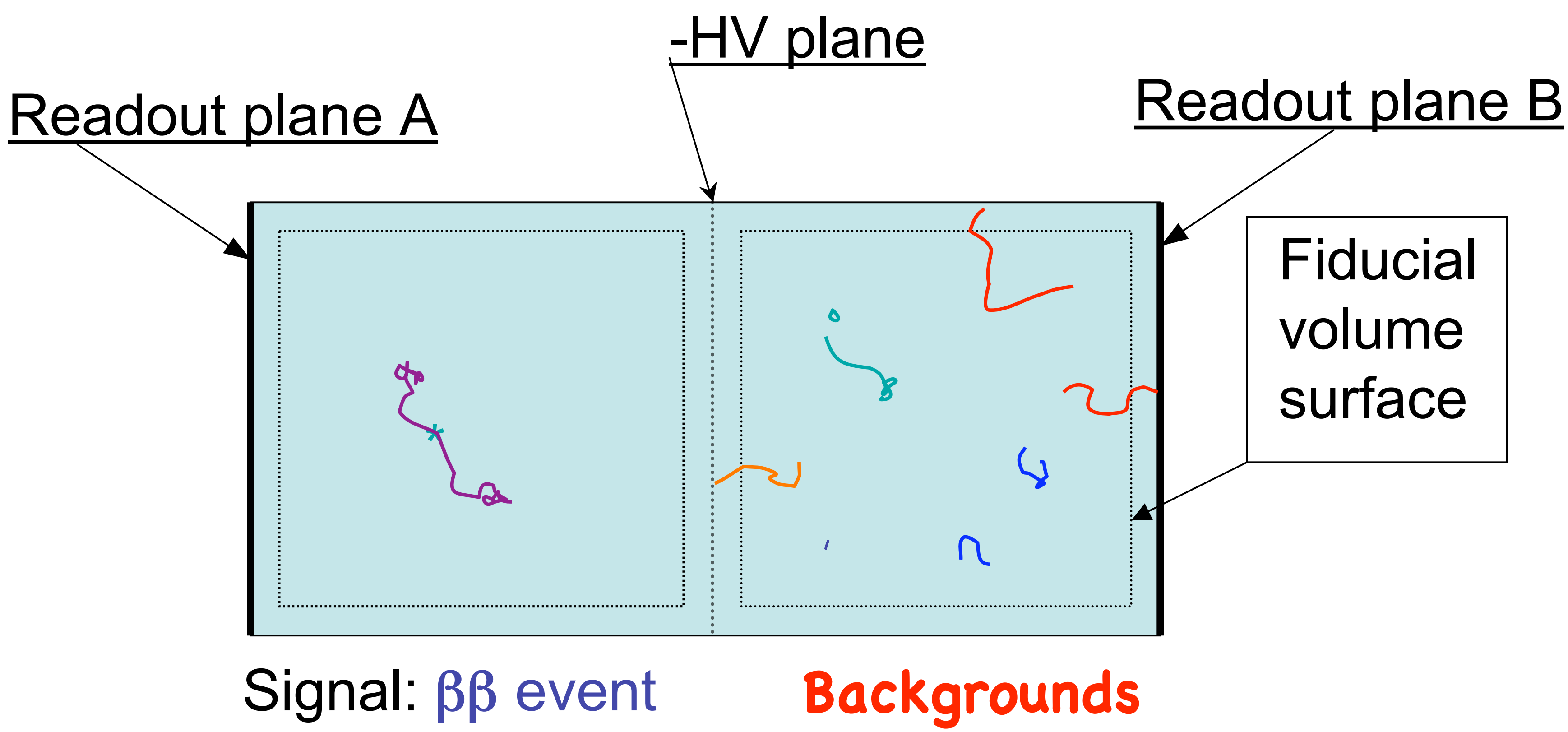
- Use enriched High Pressure Xenon gas
- TPC to provide image of the decay particles
- Design to also get an energy measurement as close to the intrinsic resolution as possible

High-pressure xenon gas TPC

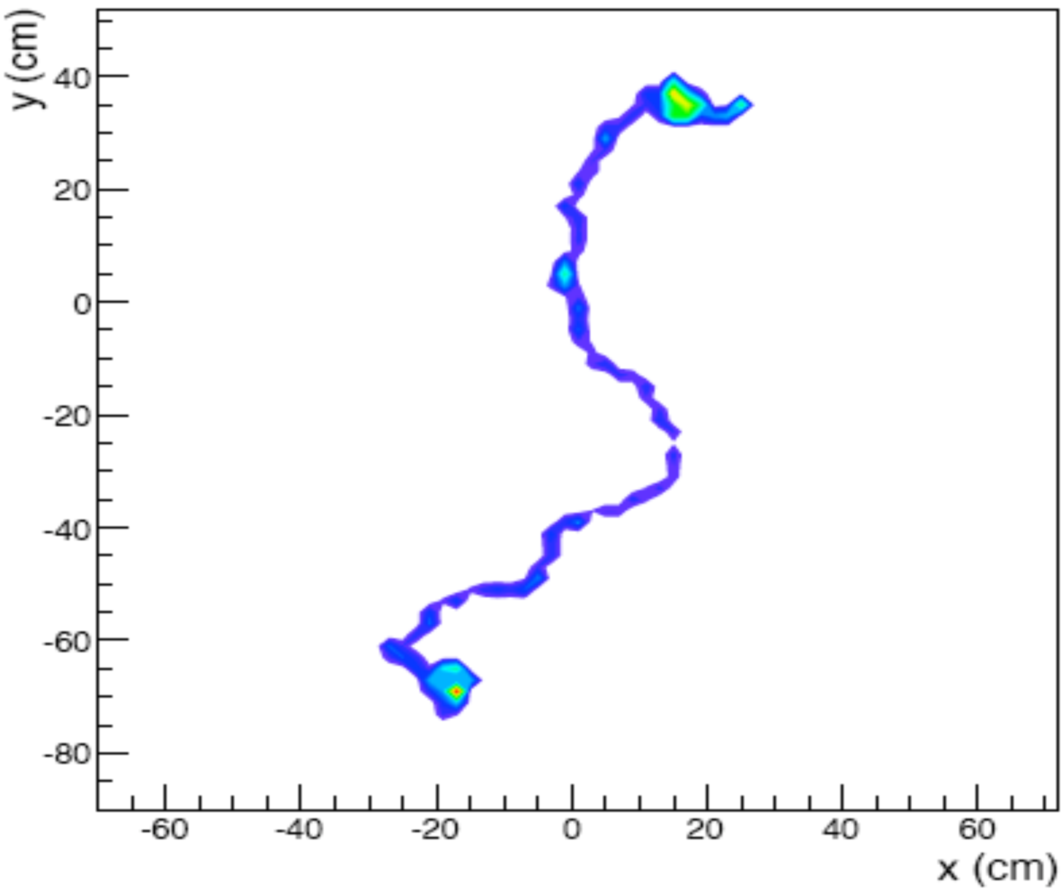
- Fiducial volume :
  - No dead or partially active surfaces
  - Closed, fully active, variable,...
  - 100.000% rejection of charged particles
  - Use t_0 to place event in z coordinate

- Tracking:
  - Available in gas phase only
  - Topological rejection of single-electron events

TPC: ββ Signal & Backgrounds



Topology: spaghetti, with meatballs



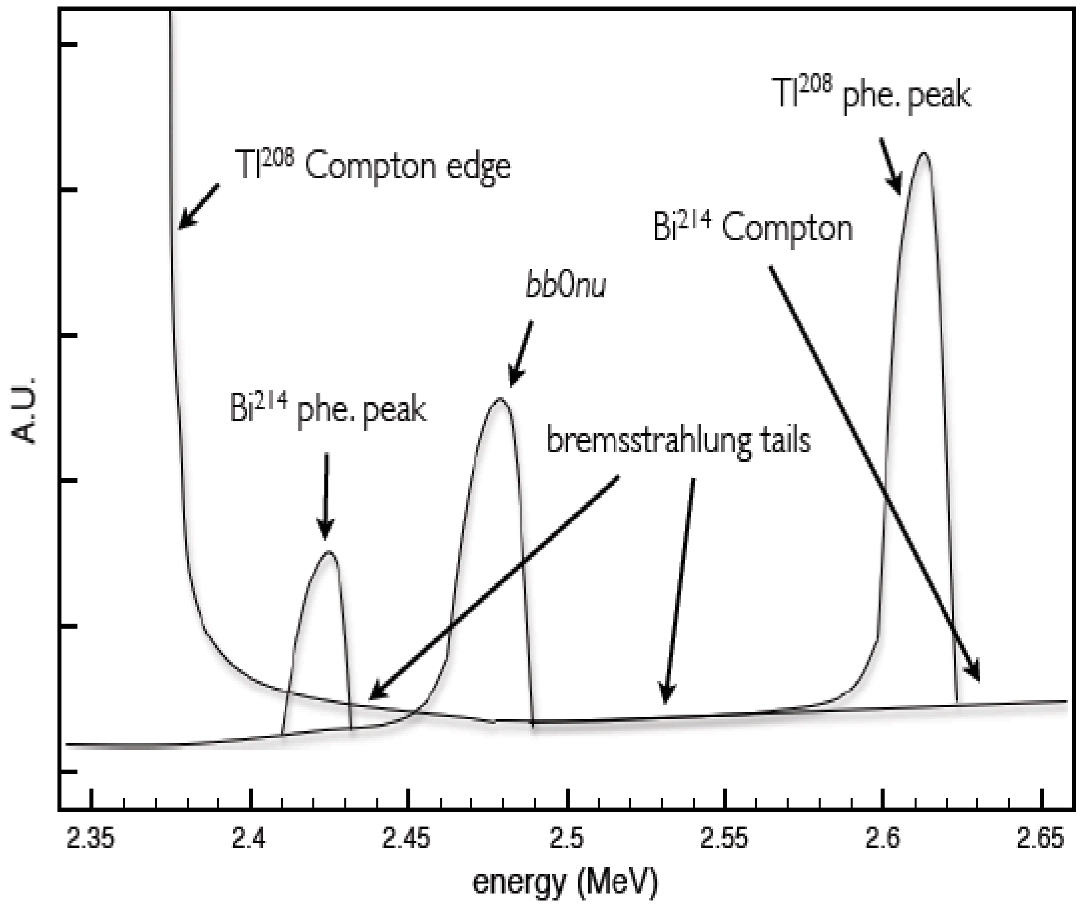
ββ events: **2**

γ events: **1**

Gotthard TPC:

~ x30 rejection

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



NEXT Collaboration

NEXT collaboration

Spain/Portugal/US...

funding: **5M €** !

to develop & construct a 100 kg HPXe TPC for 0-νββ decay search at Canfranc Laboratory

The NEXT Collaboration

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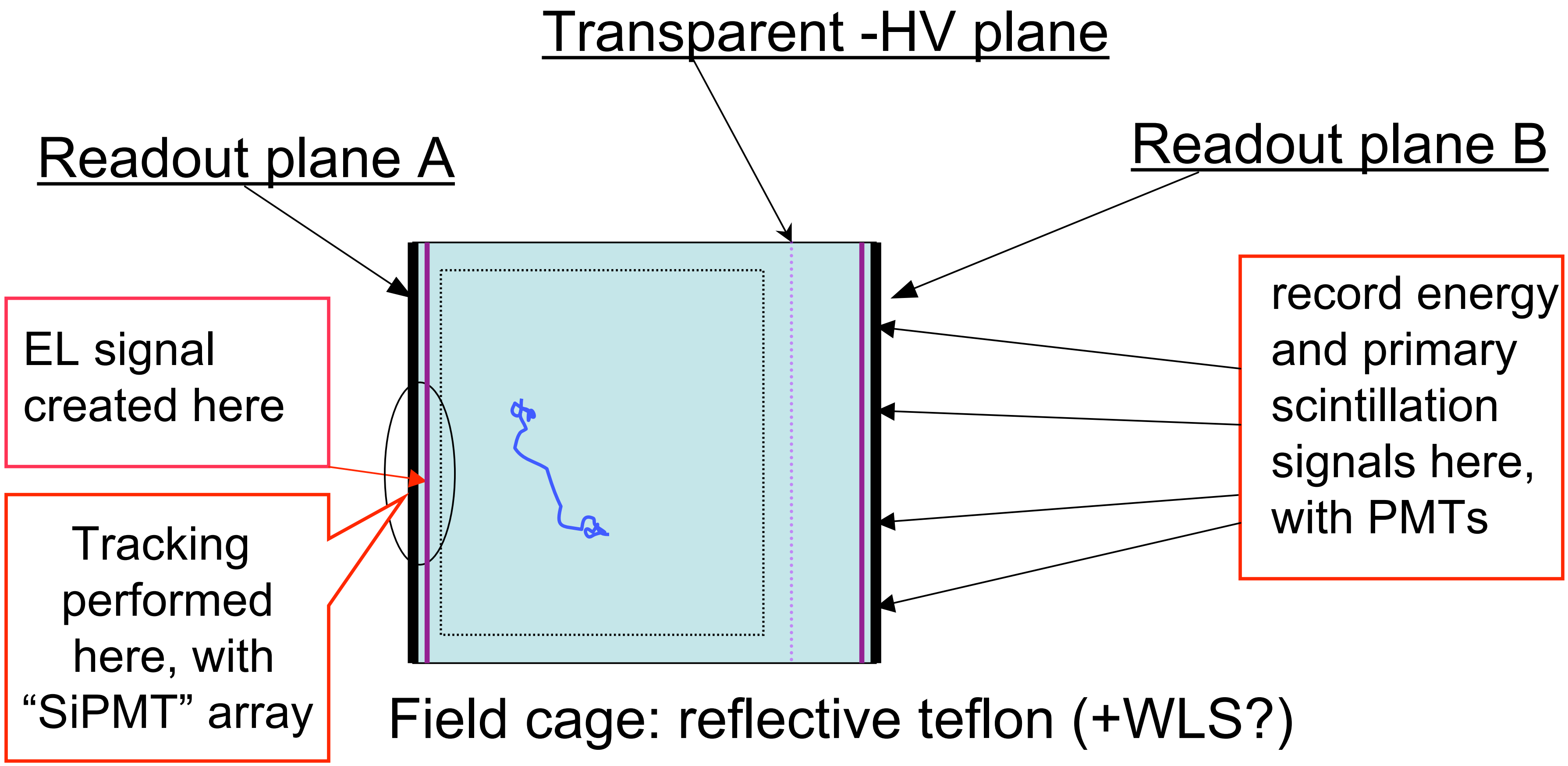
Asymmetric EL TPC: *NEXT*
"Separated function"



Field cage: reflective teflon (+WLS?)

Silicon Photomultiplier “SiPM”

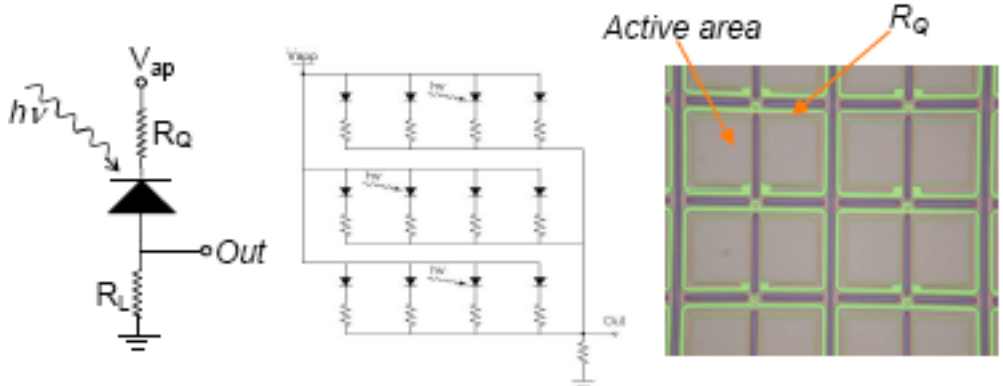
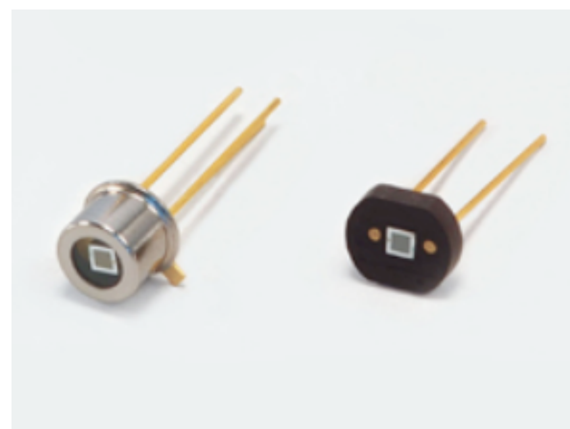
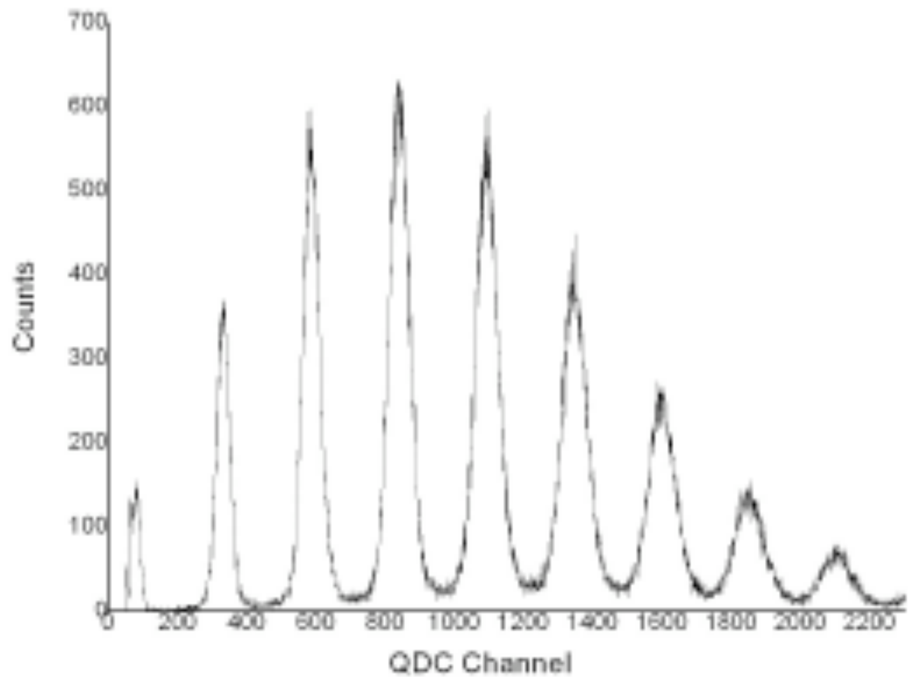


Figure 1 Schematic of a single microcell (left), schematic of part of an SPM array of microcells (center) and photo of a portion of the SPM microcells (right).

SiPM from Hamamatsu, “MPPC”



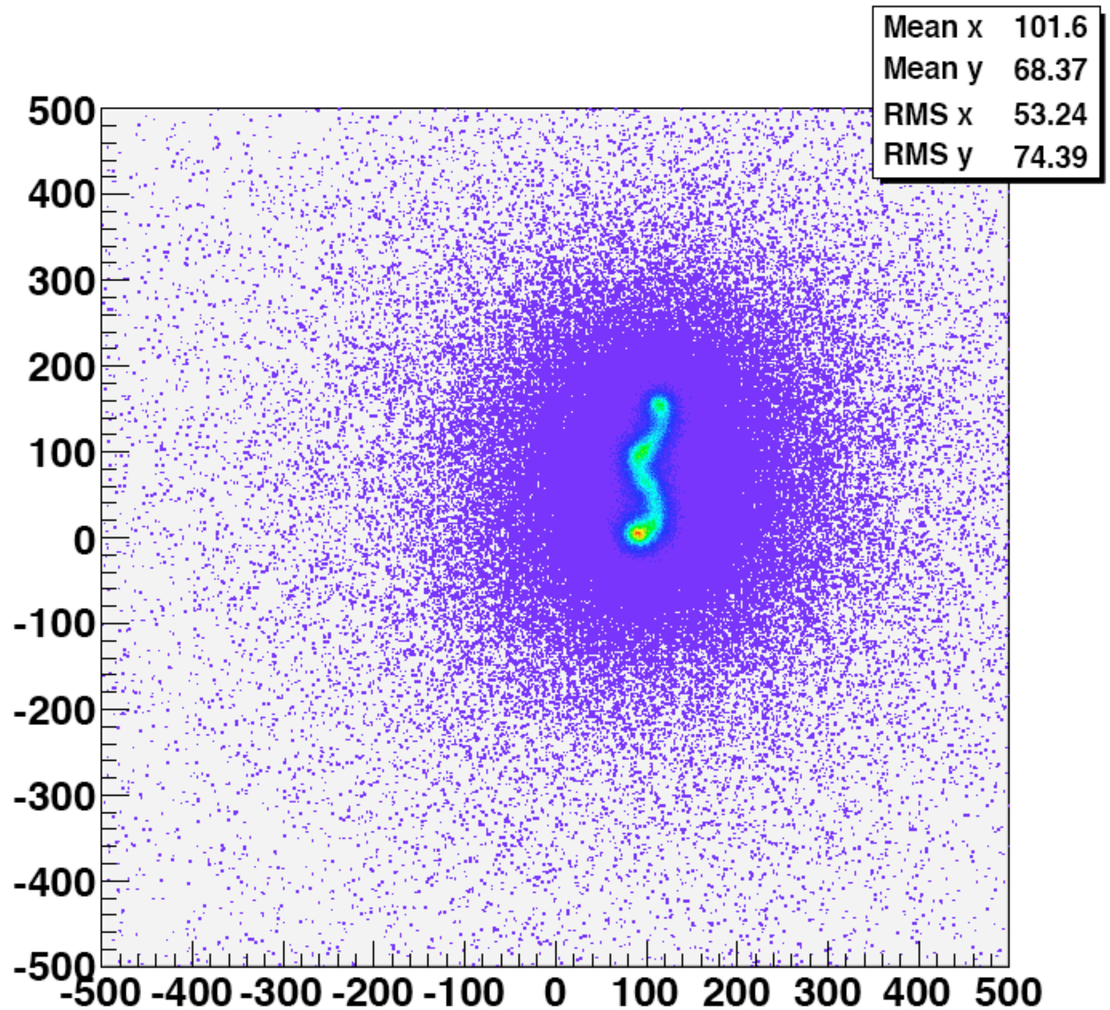
SiPM photoelectron spectrum



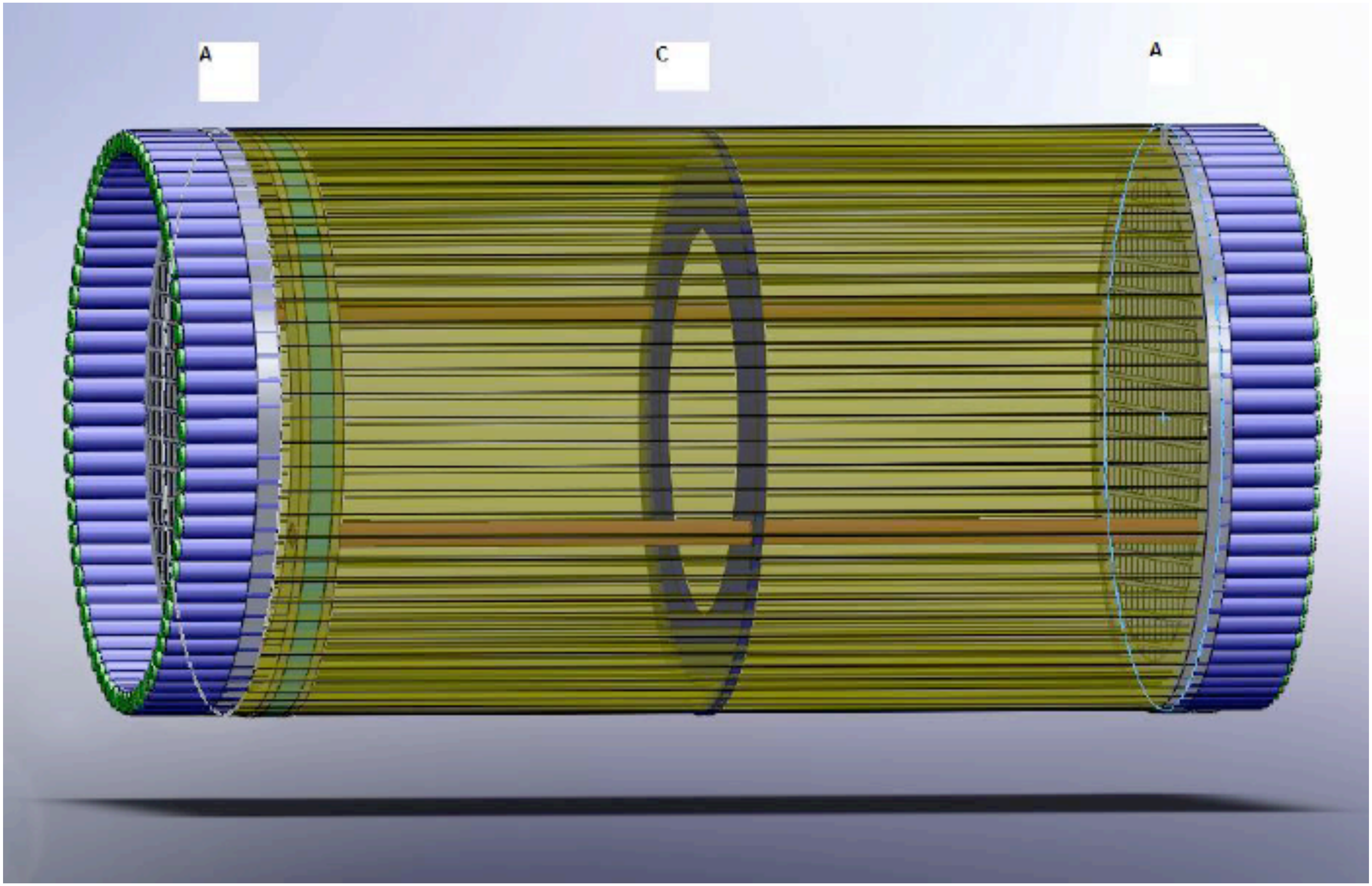
A simulated event, with MPPC

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

Slide: ***NEXT*** collaboration



2. Symmetric TPC with wavelength shifter bars



Electro-Luminescent Readout

For optimal energy resolution, 10^5 e^- * 10 pe/e^- = 10^6 photoelectrons need to be detected!

Energy readout plane is a PMT array

- electron (secondary) drift is very slow: ~1 mm/μs
- This spreads out the arriving signal in time - up to 100 μs for typical ββ event
- The signal is spread out over the entire cathode-side readout which has 100's of PMTs
- These two factors greatly reduce the dynamic range needed for readout of the signals

⇒ No problem to read out 1 electron to >100,000 electrons

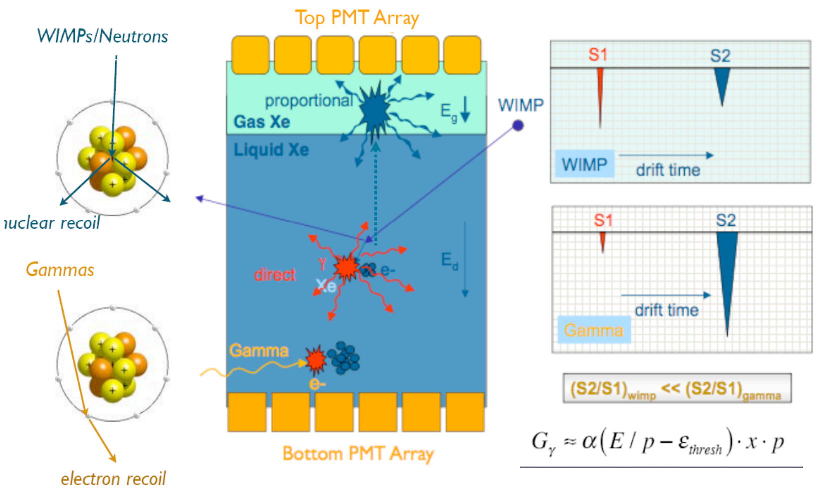
Xenon and the Dark Matter search

- Liquid Xenon has the lead on this topic
- LXe has advantage of density ~ 3 g/cm^3

but:

- HPXe offers better discrimination between nuclear recoils and electrons
- HPXe offers better discrimination for multi-site events within the active volume

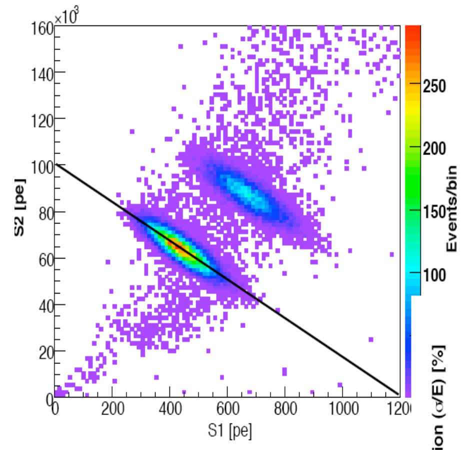
Energy resolution in Dual-phase TPC (XENON)

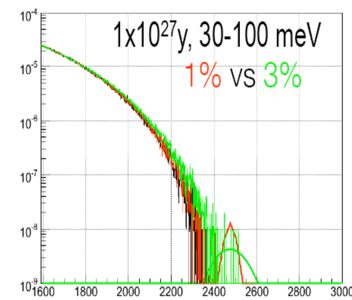


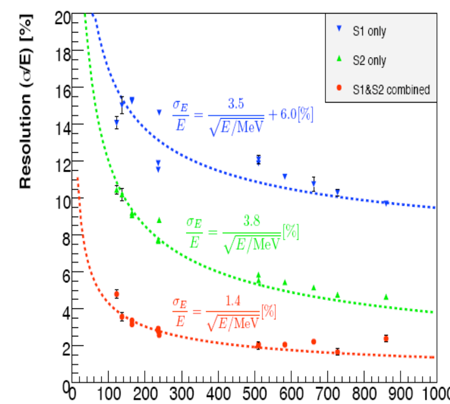
$$G_\gamma \approx \alpha(E/p - \varepsilon_{thresh}) \cdot x \cdot p$$

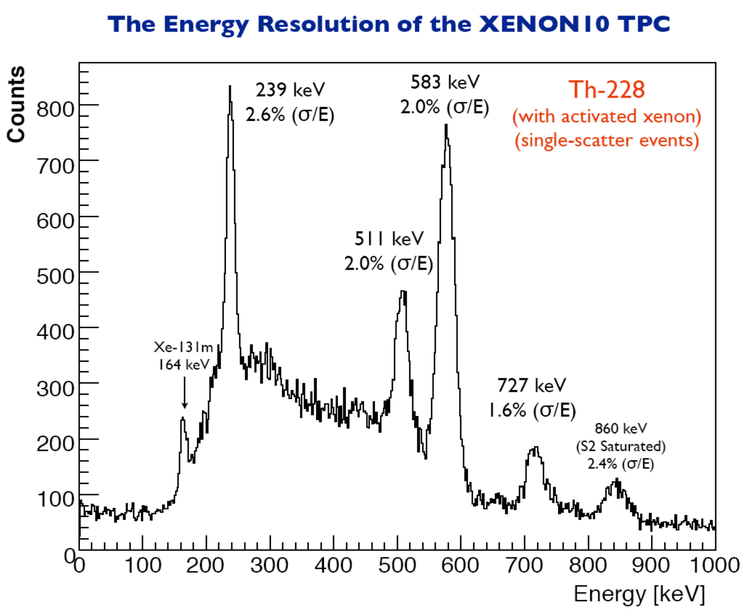
$$\alpha_{LXe} = 70\ \gamma/kV \qquad \varepsilon^{LXe}_{thresh} = 1.3kV/cm/atm$$

4

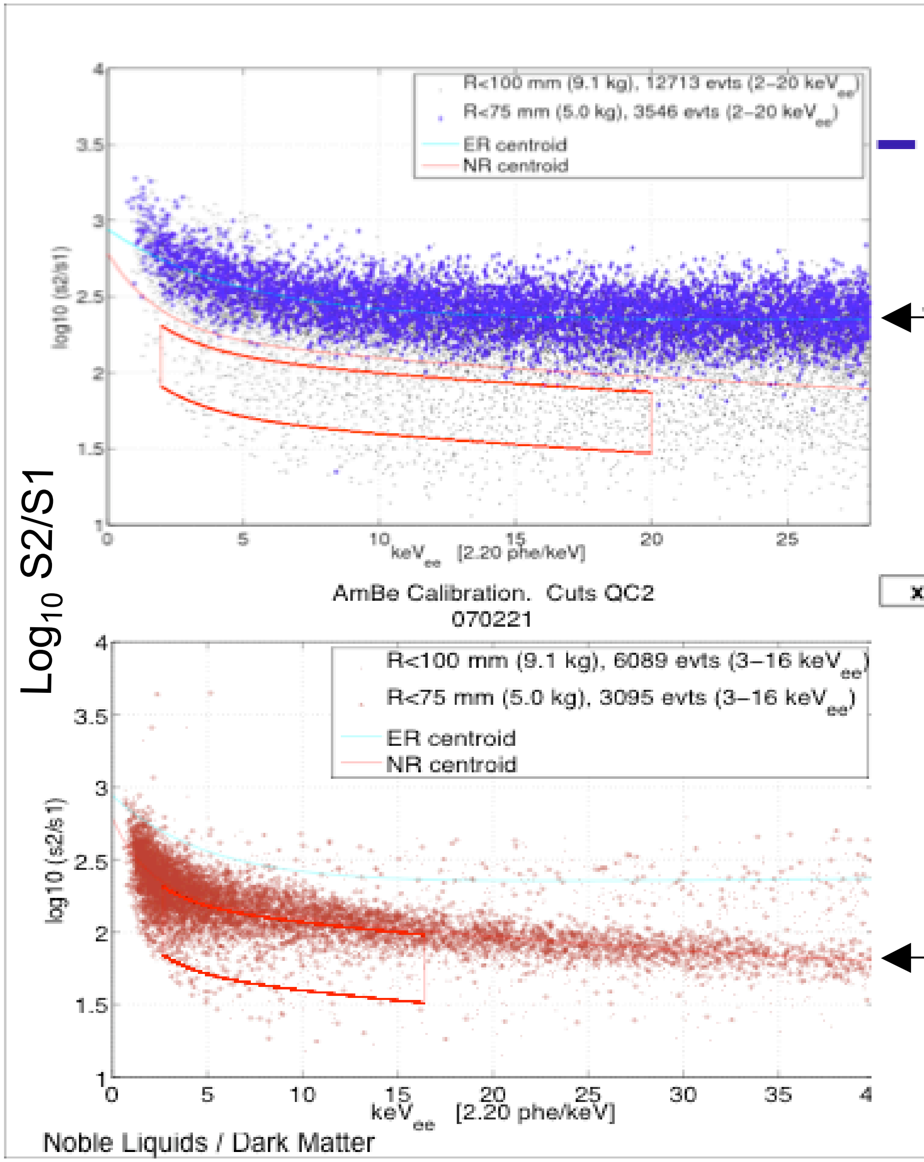








Aprile, Paris TPC 2008



Gamma events (e-R)

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

Neutron events (N-R)

WIMP Search: LXe or HPXe?

Scintillation (S_1) & Ionization (S_2) are the signals used to reject electron recoils: S_2/S_1

But, in LXe:

S_2/S_1 fluctuations are **anomalously** large

Bad news for discrimination power in LXe!

However, HPXe yields less scintillation; S_1 threshold is higher - bad news for HPXe!

But HPXe still better by ~5 (statistical power)

Is energy threshold important?

D-L annual modulation amplitude vs. E

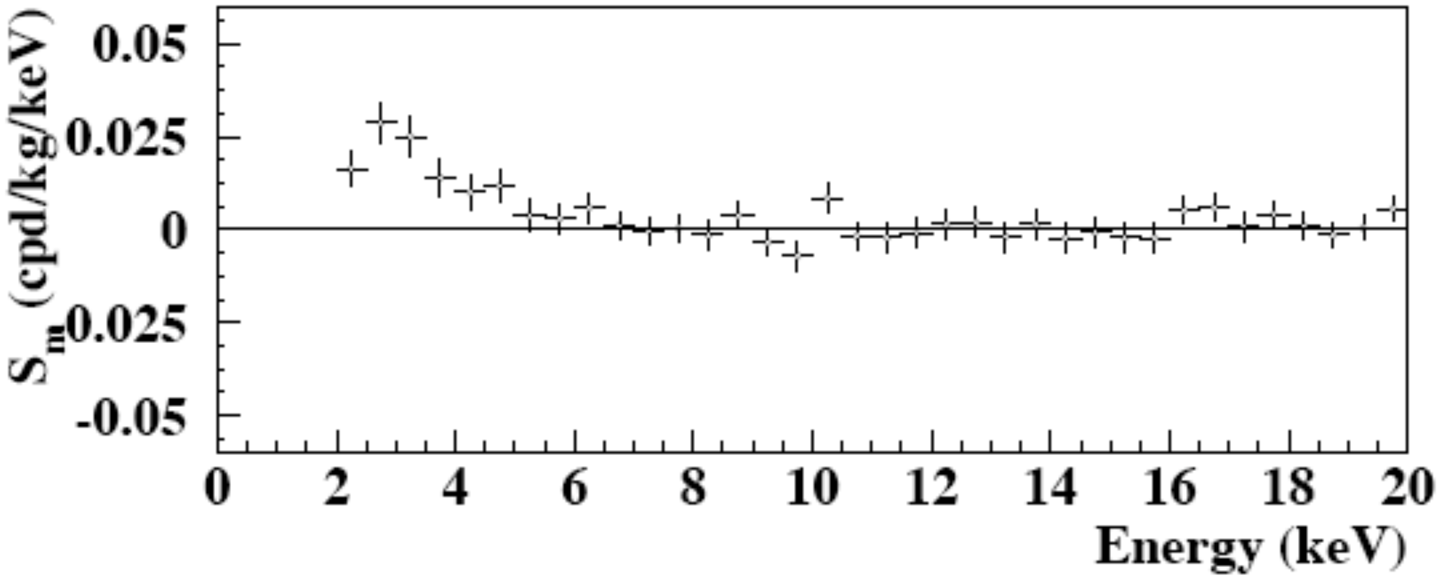


Figure 9: Energy distribution of the $S_{m,k}$ variable for the total exposure (0.82 ton$\times$yr, DAMA/NaI & DAMA/LIBRA). See text. A clear modulation is present in the lowest energy region, while $S_{m,k}$ values compatible with zero are present just above. In fact, the $S_{m,k}$ values in the (6–20) keV energy interval have random fluctuations around zero with χ^2 equal to 24.4 for 28 degrees of freedom. See also Appendix A.

WIMP Perspective

- The D-L spectrum is **soft** - most signal <5 keV?
- ⇒ E <5 keV_{ee} region ***must*** be explored
- The S_2/S_1 tactic may be marginal here

What to do?

- Instead, a monolithic volume with an *active virtual* fiducial surface could be the key to confronting D-L
- Look for an annual modulation appearing only in the 1 - 5 keV_{ee} region, uniformly distributed in space
- Backgrounds are non-uniform, have no modulation

⇒ must have robust placement in space

The neglected partners: ions

For each primary electron, an ion drifts off...

Don't depend only on the primary scintillation: <u>use ions!</u>

1. detect electrons <u>and</u> ions in space <u>and</u> time
2. this fixes the origin of the event in 3-D
3. detect the ions with high efficiency, but not at the -100 kV cathode!
4. induce ions to emit electrons when they arrive at cathode surface
5. cathode: a sparse wire plane, this gives a high surface electric field
6. cathode surface: high emissivity (negative affinity...)
7. the electron "echo" is detected at the anode plane
8. 1 keV threshold "might" be achieved in this wild scheme...

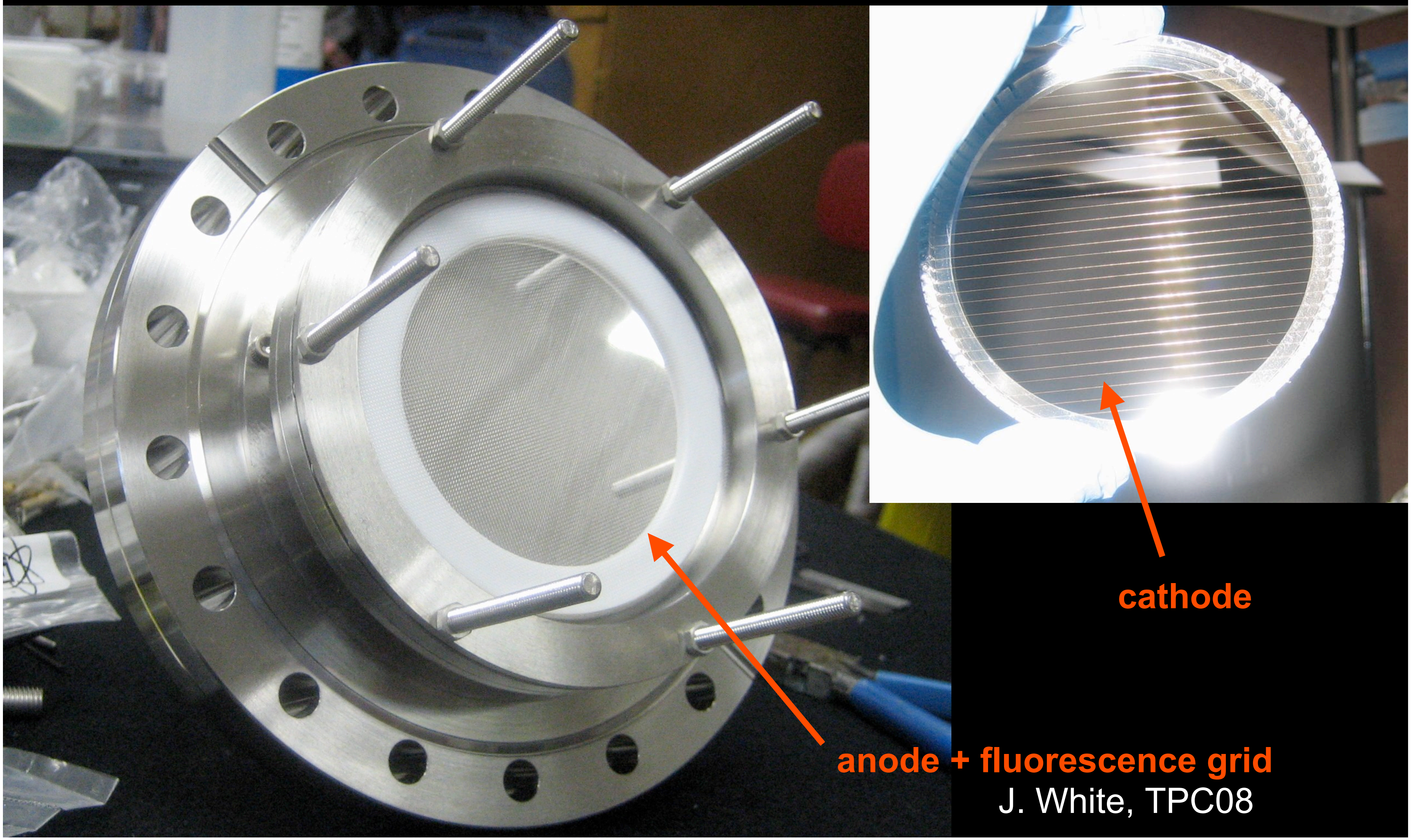
How many electrons/ions?

- Unfortunately, not so many per keV
- Quenching factor at low energies: ~0.15
  - – Nuclear recoils collide with atoms and deposit much more energy as heat than do electrons
  - – Fraction of energy given to ionization about a factor of ~7 smaller than for electrons
  - – LXe and HPXe: similar quenching factors
    - 4-6 electron ion pairs/keV in the few keV range
    - **2 keV: ~ 10 electron/ion pairs**

In the US...

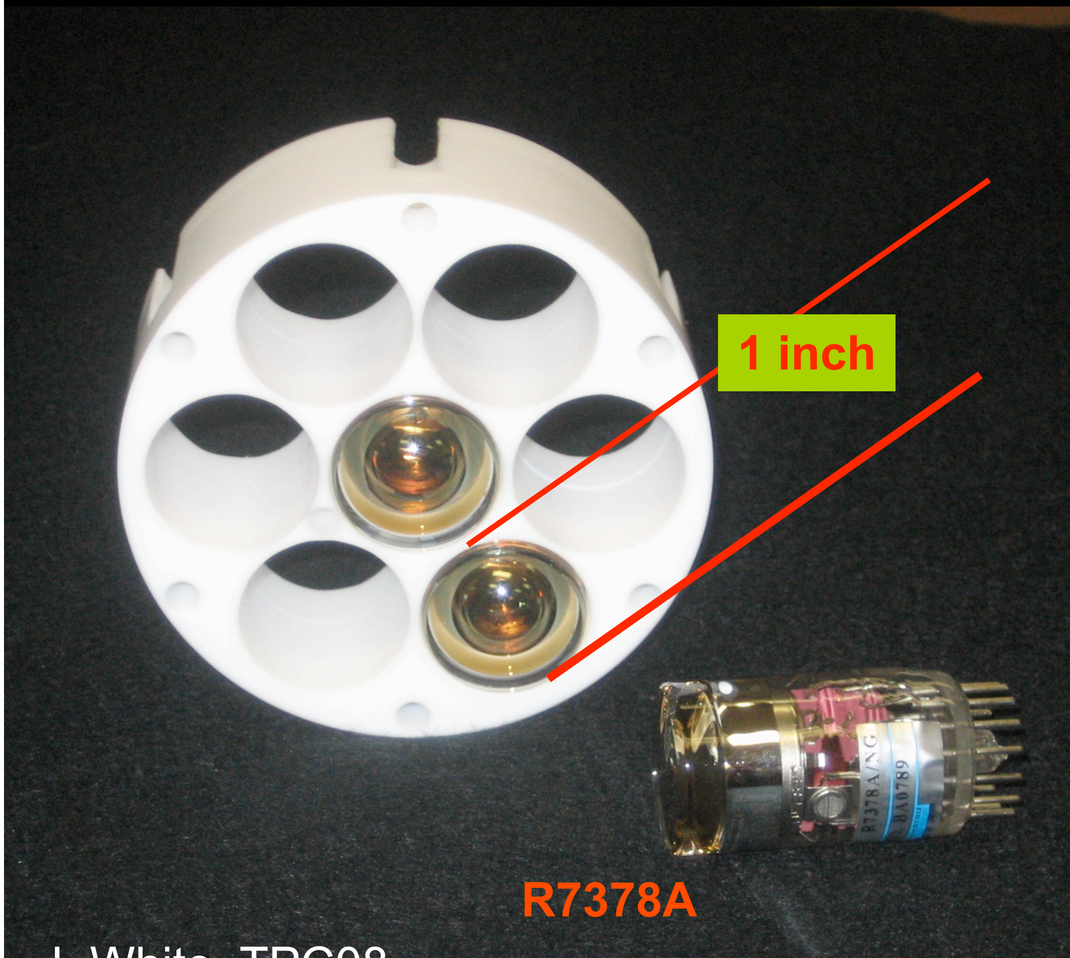
- At TAMU, James White, (with Hanguo Wang and me) has built and operated a small HPXe system
- Goals:
  - – quenching factor in HPXe for nuclear recoils
  - – demonstrate better S1/S2 resolution
- It worked well right out of the box
- Results presented at TPC2008 Paris

7-PMT 20 Bar Test Cell



J. White, TPC08

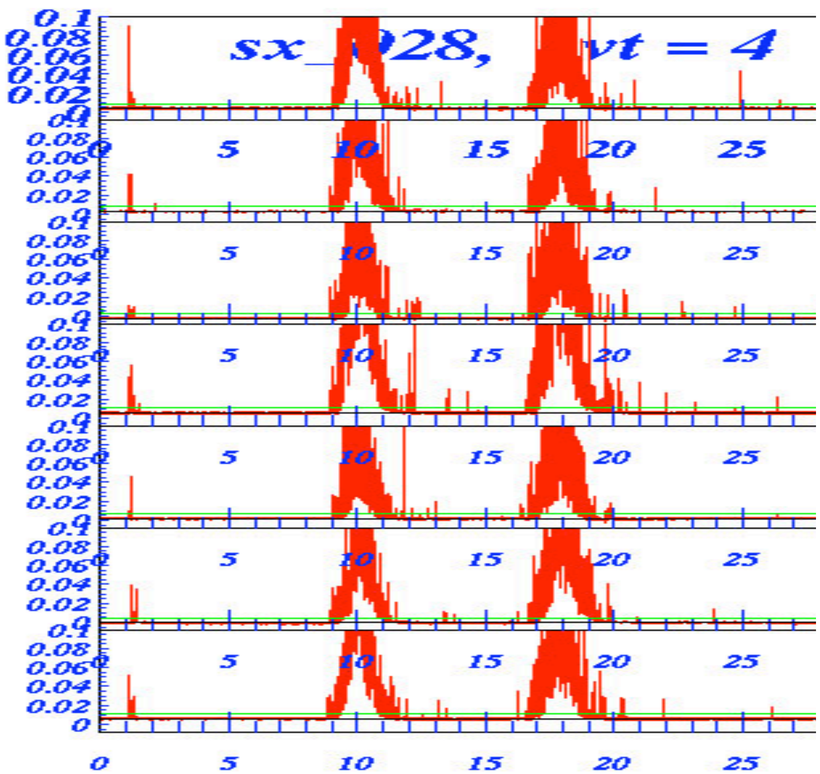
7-PMT,20 bar Test Cell

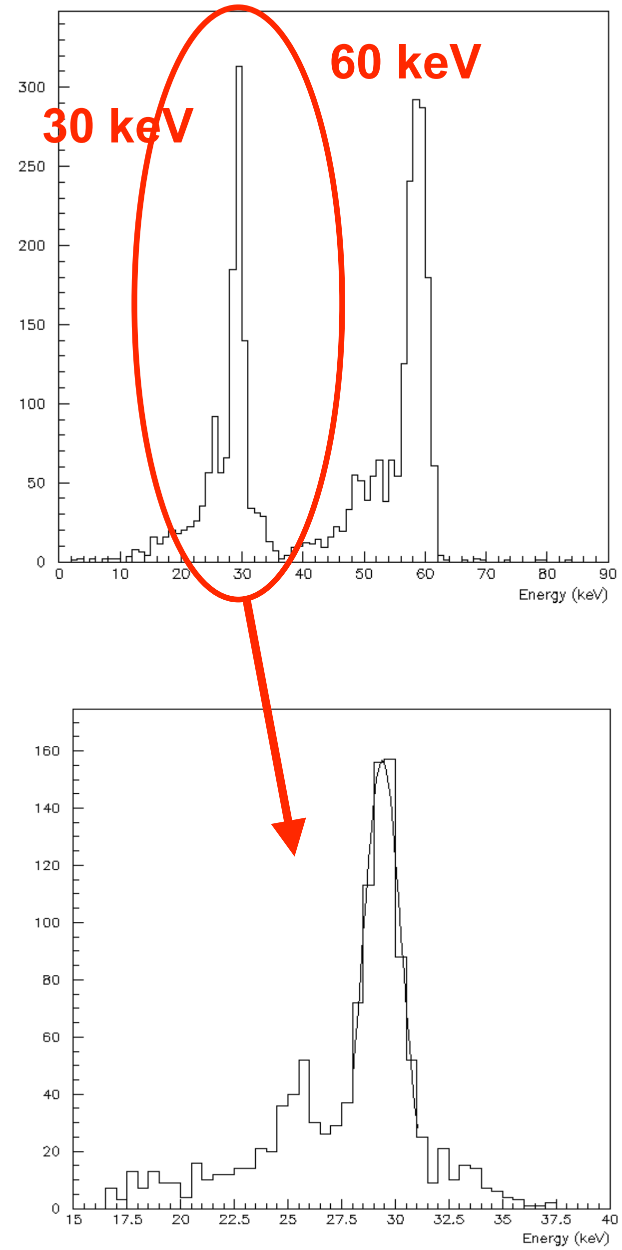


J. White, TPC08

^{241}Am γ-rays ~60 keV

(1st Look – PMT gains not yet calibrated)





Perspective

- 0-ν $\beta\beta$ decay and WIMP searches command our attention, but are high-risk.
- Experimental situations are controversial with disputed claims for positive signals.
- New approaches are probably needed to lead to robust results.

- Fantasy: HPXe TPC with “super-cathode” addresses both goals simultaneously...

Thank you

Backup slides...

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^{*+}…)

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

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

α particles

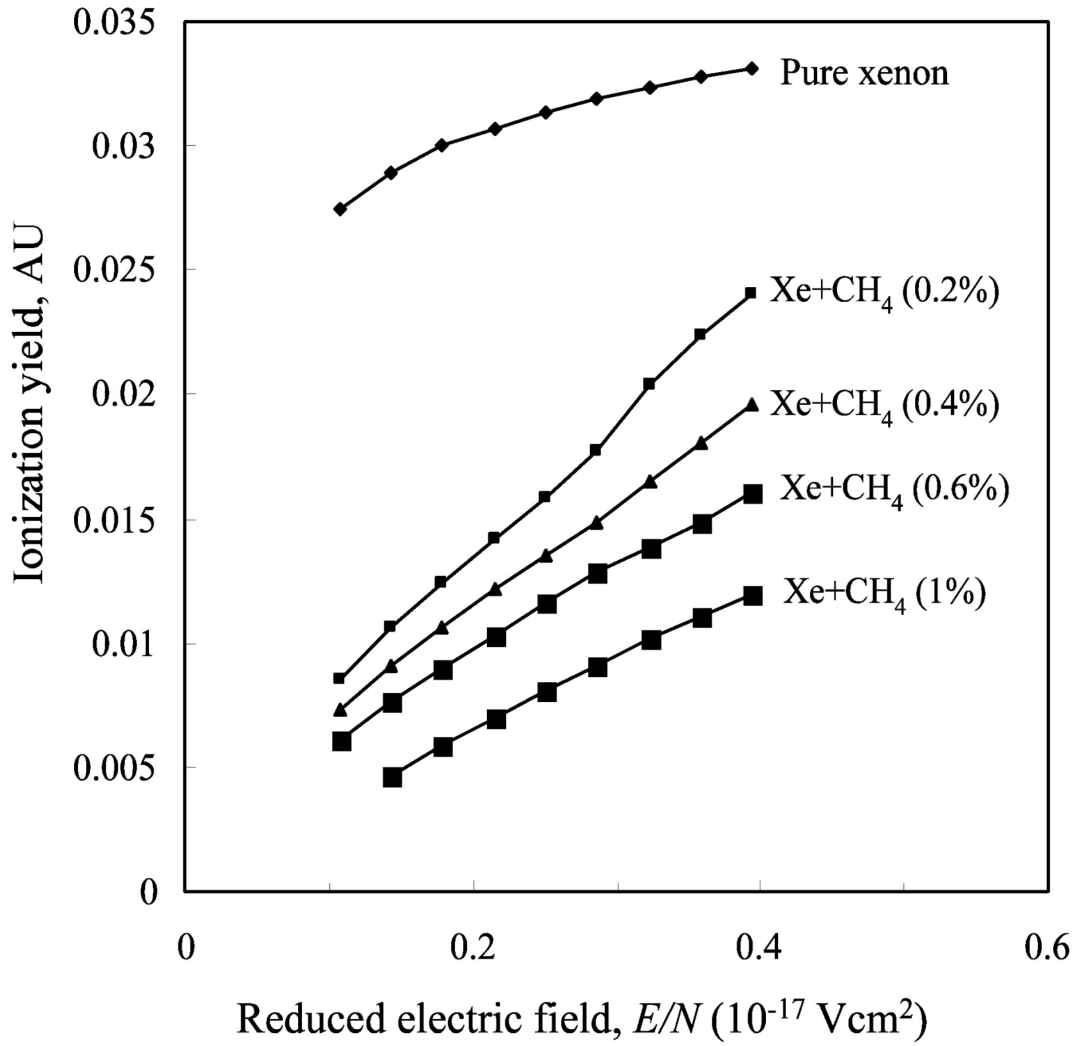


Fig.7. Dependence of ionization yield on reduced electric field (E/N) at a pressure of 2.6 MPa. **(~25 bars)**

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

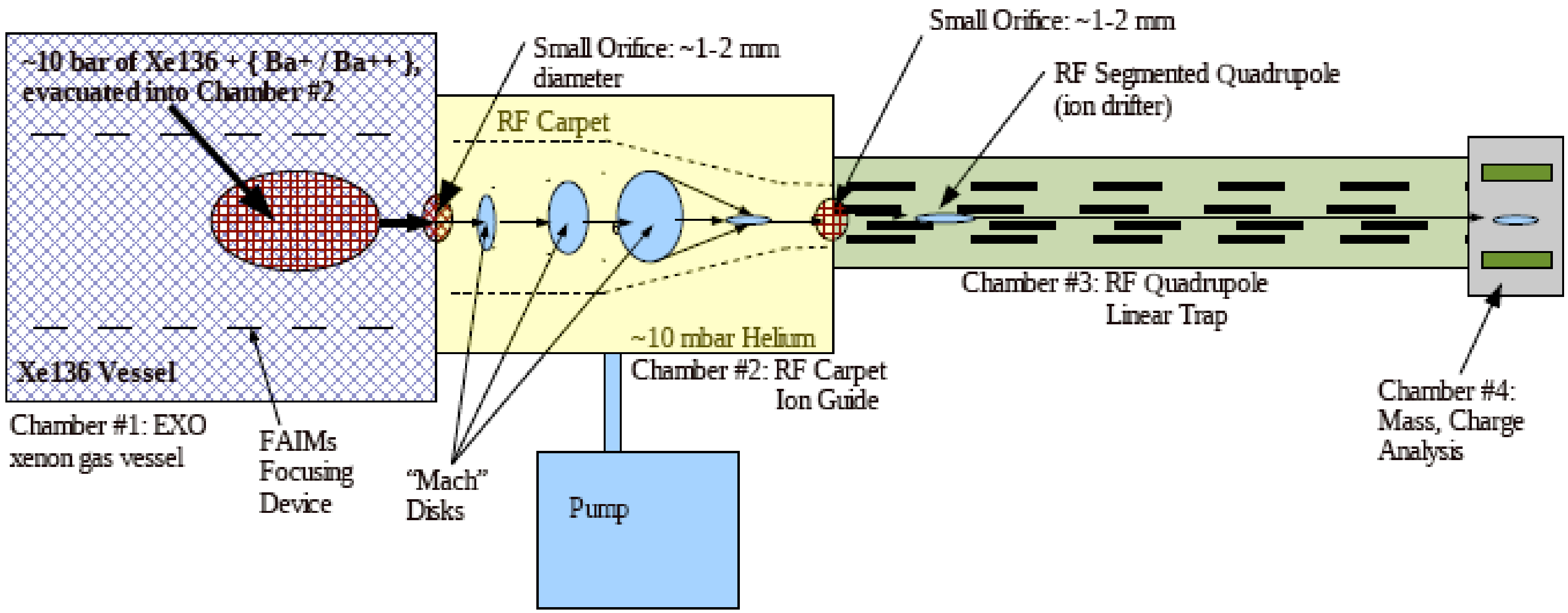
Gotthard TPC: 4% CH_4
Loss(α): factor of 6

For β particles, what was effect on energy resolution?

Surely small but not known, and needs investigation

Can one measure Ba++ Directly?

- Extract the ion from the high pressure into a vacuum
- Measure mass and charge directly
- A mass 136, ++ ion is a unique signature of Ba++. (Assumption is Xe++ cannot survive long enough to be a problem)
- This has been done for Ba++ in Ar gas



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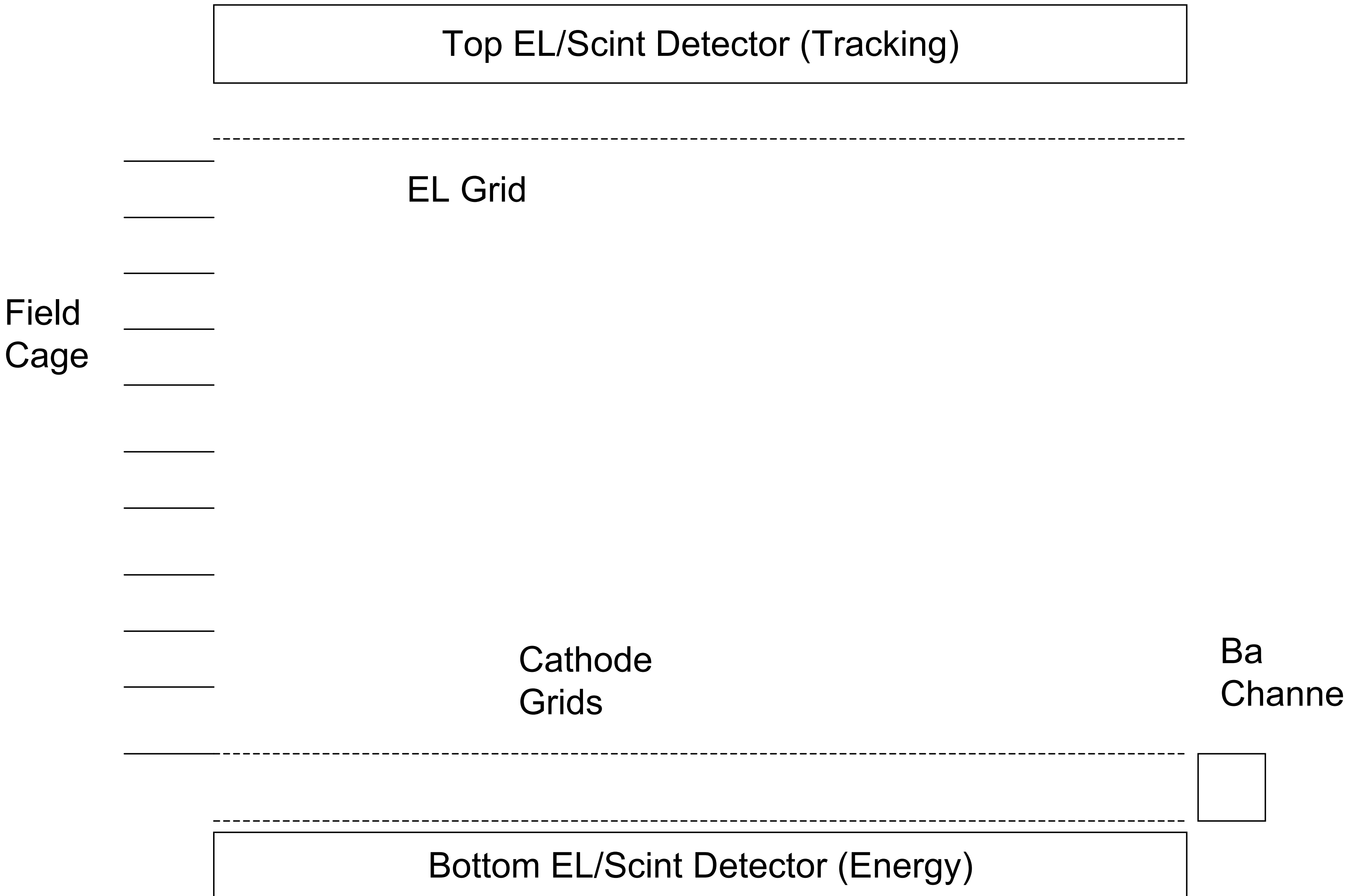
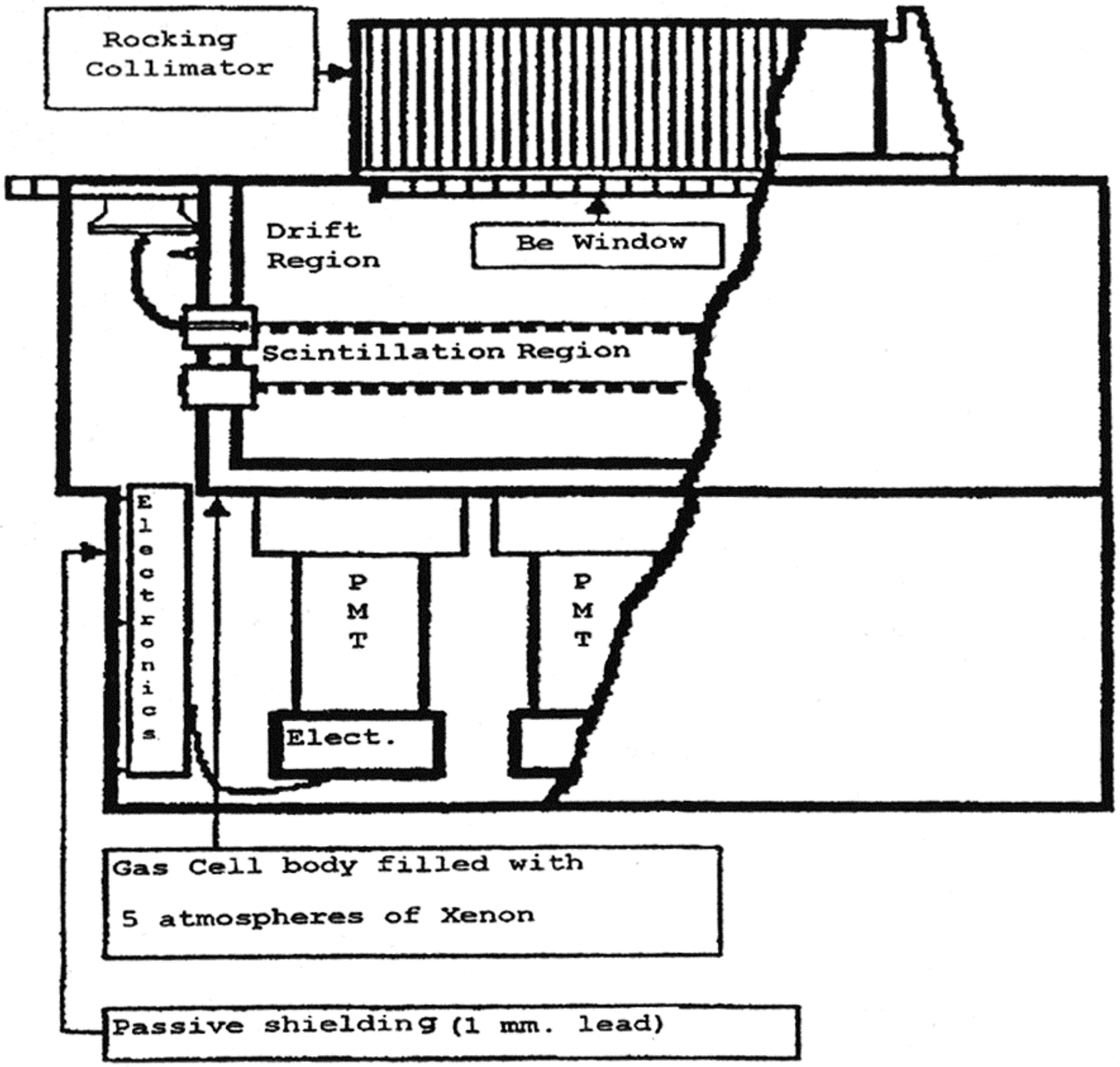
Barium ions are guided towards the exit orifice and focused using an asymmetric field technique. The second chamber is maintained at a pressure of ~10-30 mb Using a cryopump and is lined with an RF carpet. An RF funnel guides the ions Towards the RF quadrupole which is at high vacuum. The ion is identified using TOF and magnetic rigidity

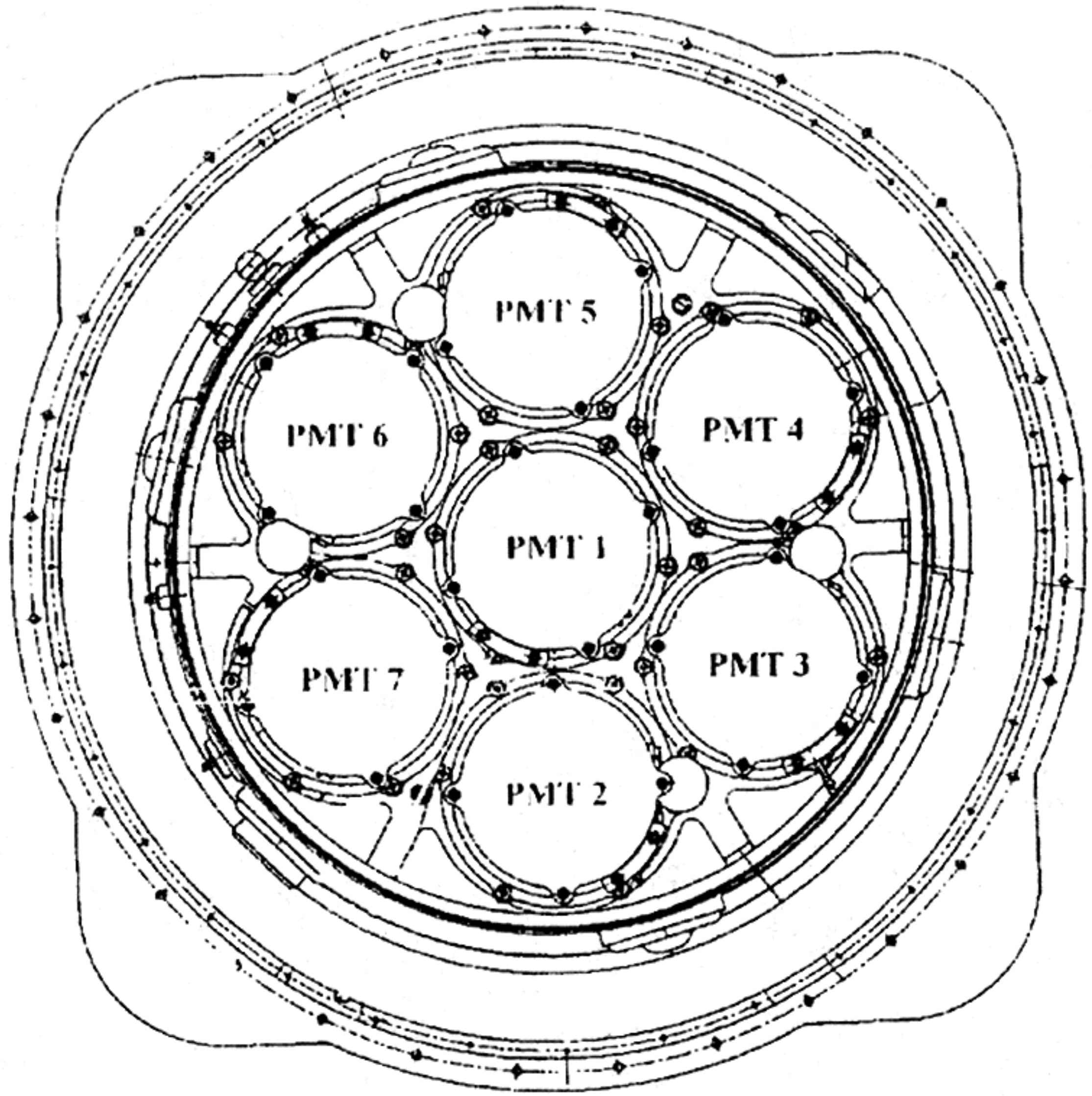
 Sinclair, TPC Workshop Paris 2008



Sinclair, TPC Workshop Paris 2008

Beppo-SAX satellite: a HPXe TPC in space!





FNAL May 2009

Separated Function TPC, with Electroluminescence