# High Energy Resolution in High-Pressure Xe Gas TPCs

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# Goal:

Develop a novel detector that combines high energy resolution with measurements of event topologies to separate the desired signals from backgrounds.

The design should be scalable to match a wide range of applications, including searches for ultra-rare events.

# Potential Applications

1. Search for neutrinoless double-beta decay

    a) Verify that the neutrino is its own anti-particle
    b) Helps determine absolute neutrino mass
    c) If observed, lepton number not conserved

2. Large-area gamma detectors that require background suppression

# Current Emphasis: Verify Energy Resolution

This device addresses only a subset of final requirements.

These applications require separation of the desired signals from a wide range of backgrounds.

This requires

- High energy resolution for electrons and gamma rays into the MeV regime
- Reconstruction of energy deposition sequence to separate full from partial energy deposition
- Discrimination between neutron and gamma signals

High-pressure Xe gas can provide energy resolution much superior to liquid Xe.

$E$= 2.5 MeV (= $Q$ $^{136}$Xe):

- High-Pressure Xe: $\Delta E / E \approx 3 \cdot 10^{-3}$ (Fano factor ≈ 0.15)
- Liquid Xe (EXO prediction): $\Delta E / E \approx 35 \cdot 10^{-3}$ (Fano factor ≈ 20)

Implementation as a TPC yields position resolution adequate to reconstruct beta decays and the tracks of Compton recoils.

The ratio of ionization to scintillation signals provides neutron-gamma discrimination.

Neutrinoless double-beta decay is a rare nuclear transition between same mass nuclei:

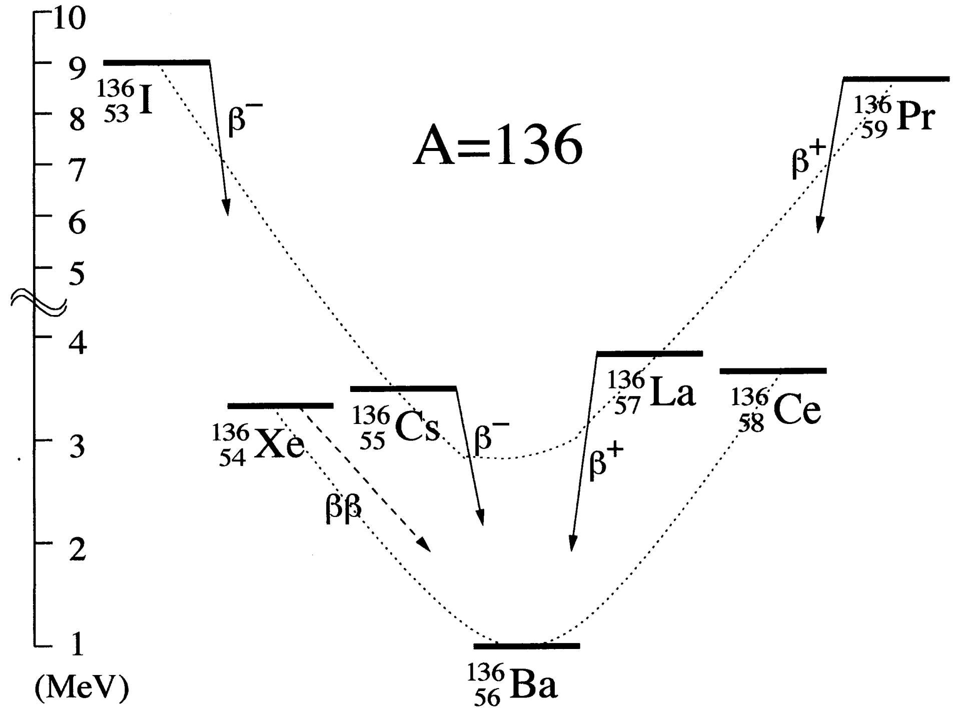


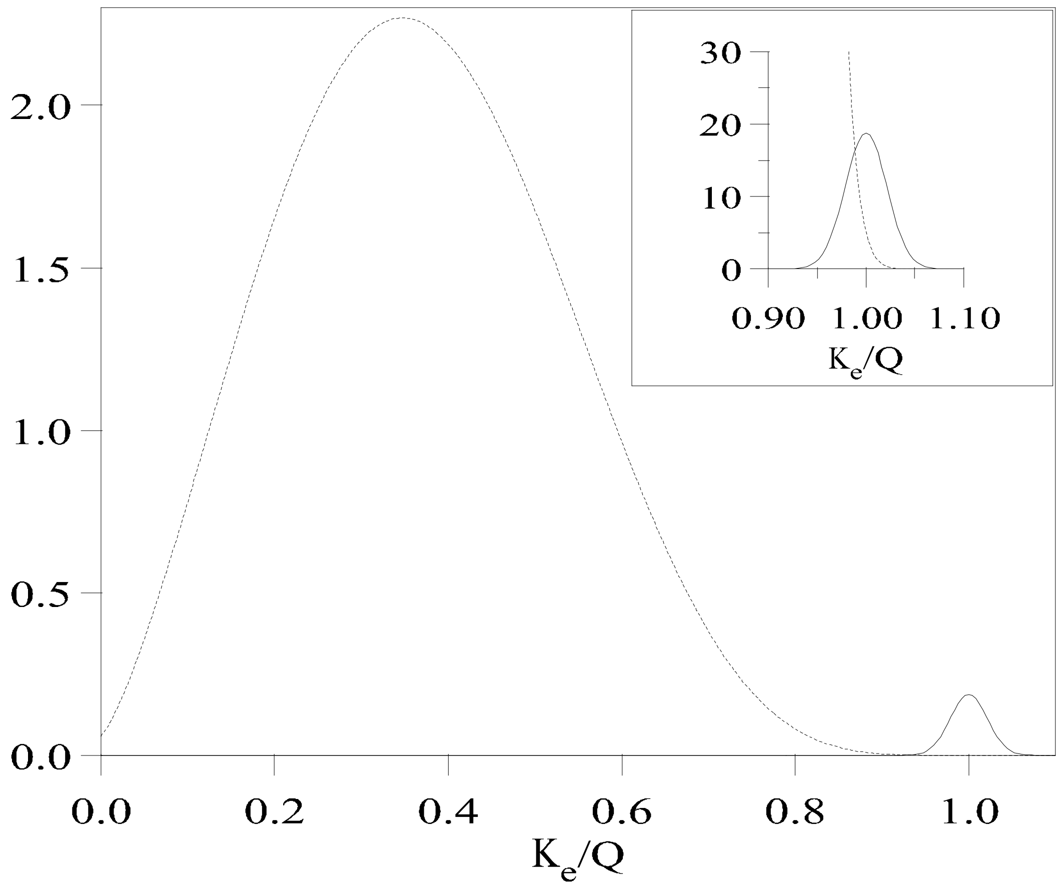

Figure 2.1: Simplified atomic mass scheme for nuclei with A=136. The parabolae connecting the odd-odd and even-even nuclei are shown. While $^{136}$Xe is stable to ordinary beta decay, it can decay into $^{136}$Ba by double-beta decay.

Energy level for daughter of $^{136}$Xe standard beta decay is too high – very rare events! $T^{0\upsilon}_{1/2} > 10^{21} – 10^{25}$ y

# Double-Beta Decay Energy Spectra

Neutrinoless Double-Beta Decay

↓

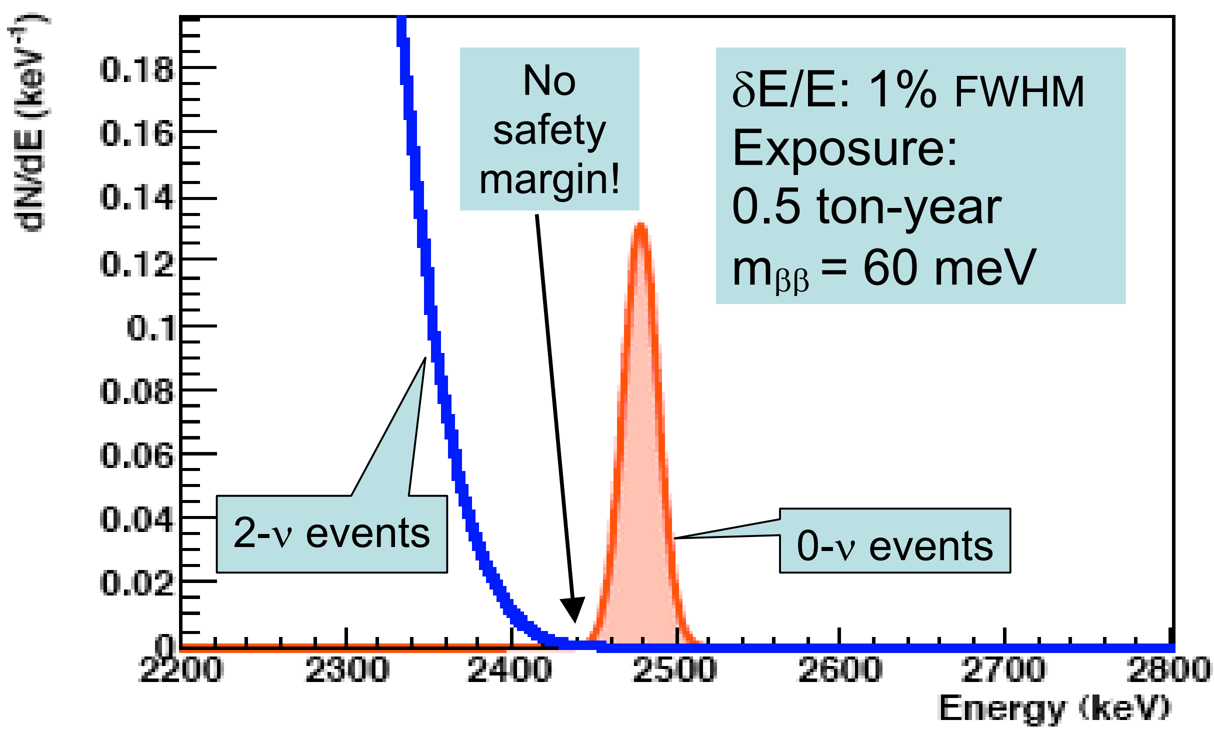



Elliot & Vogel, Ann. Rev. Nucl. Part. Sci. **52** (2002) 1

# Neutrinoless Double-Beta Decay

In the $^{136}Xe \rightarrow {}^{136}Ba$ decay the entire Q value is transferred to an electron pair with a total energy of 2480 keV.

An energy resolution <1% is required to separate contamination from the tail of the 2-ν ββ spectrum.



The ββ topology is unique: “spaghetti with two meatballs”

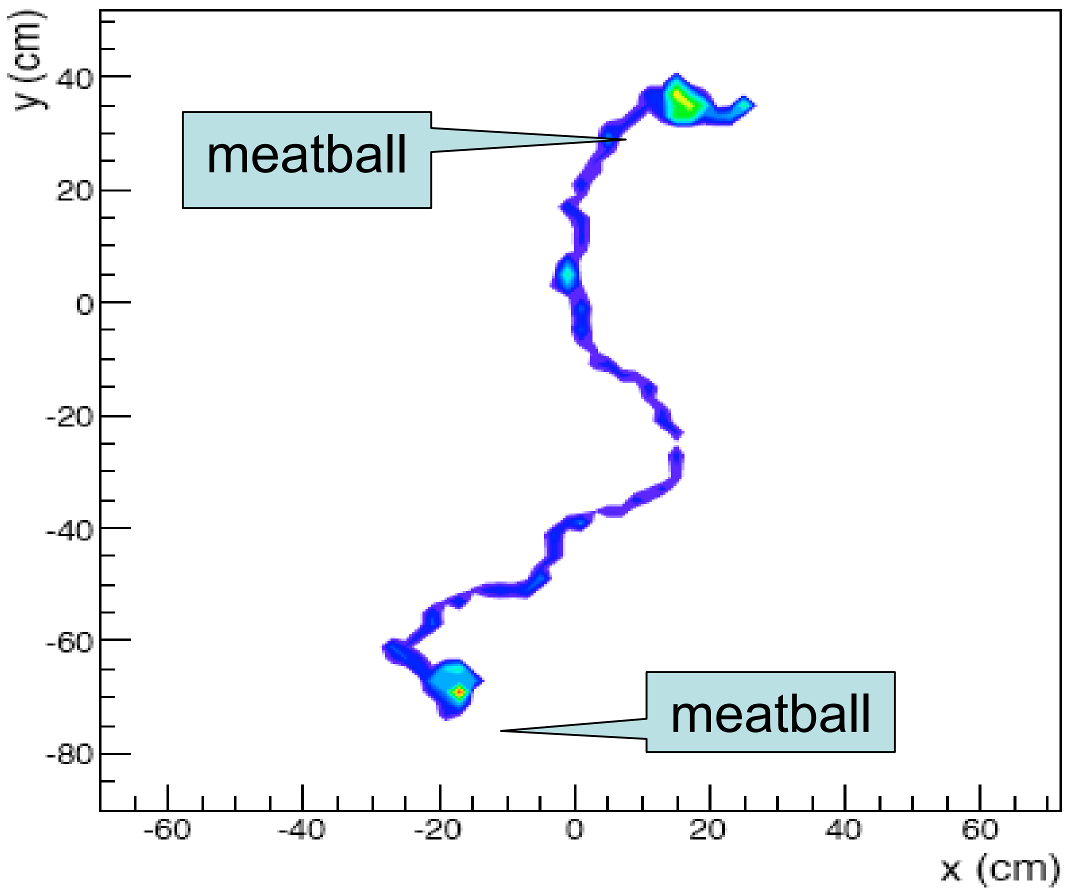



Figure: J.J. Gomez, NEXT

Energy “blobs” at end of track:

ββ events: 2

γ events: 1

Data from Gotthard TPC:

~ x30 rejection

Figure shows track length at 10 atm,

At 20 atm 2.5 MeV track length ~16 cm

# Gamma Backgrounds

a) Large Detector
(adapted from G. Knoll, *Radiation Detection and Measurement*)

Three types of interactions:

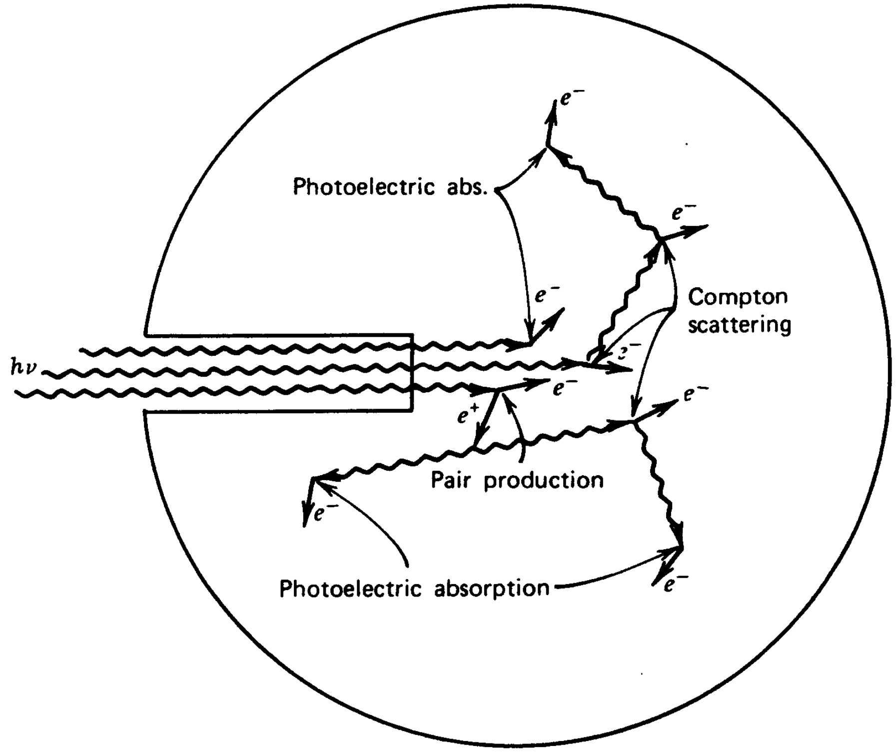
1. Photoelectric

   Emitted $e^-$ energy $\approx E_\gamma$

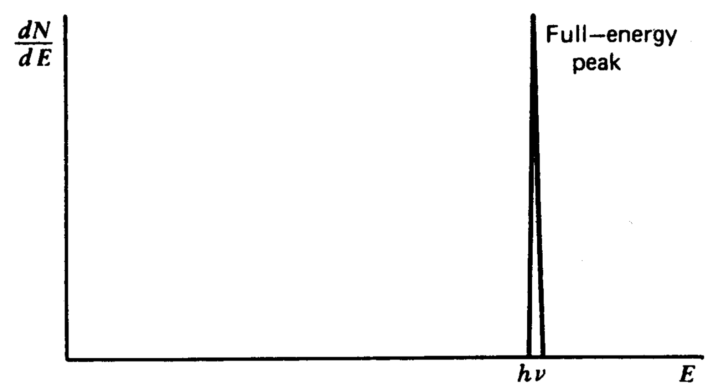
2. Compton scattering

   Energy distributed between scattered gamma and $e^-$

3. Pair production
   ( if $E_\gamma >$ 2x 511 keV)




A sufficiently large detector will capture all secondary emissions:



# b) Small Detector

In a small detector there
is a substantial probability that

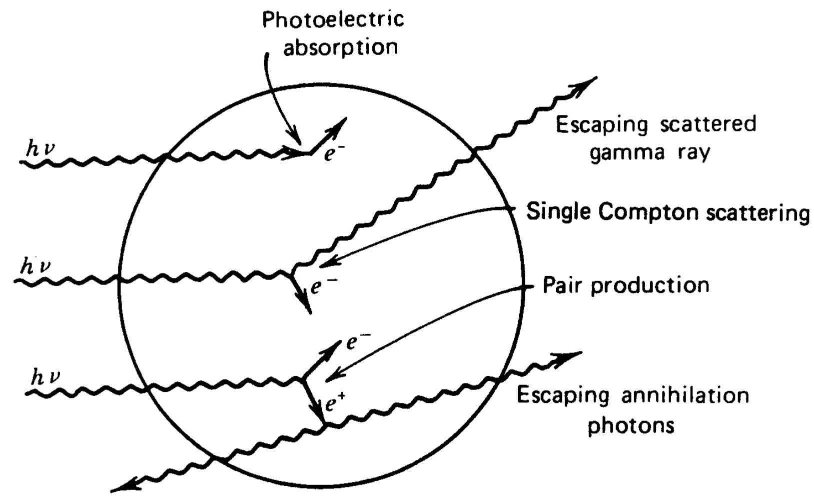
neither the

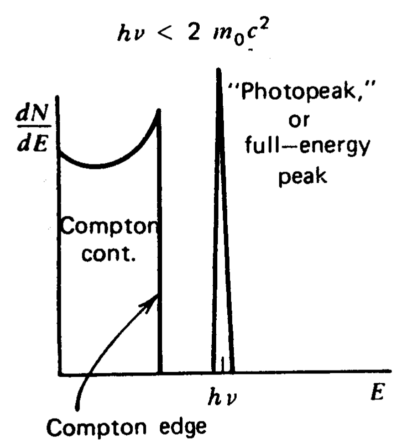
- Compton scattered gammas

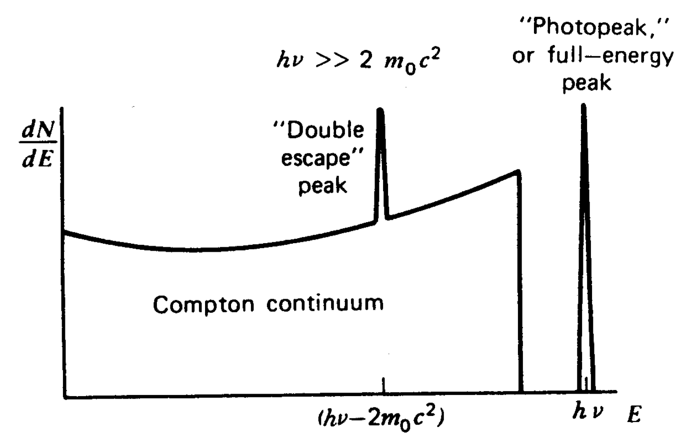
nor the

- two 511 keV annihilation photons
  from pair production

are registered in the detector.



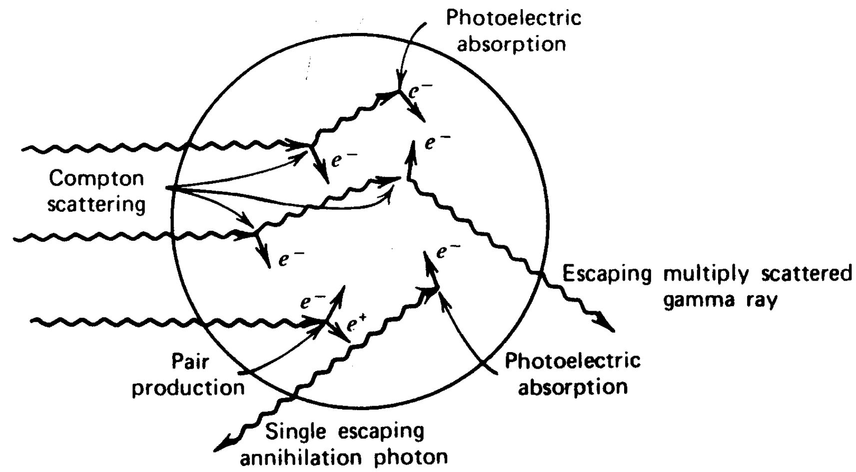
# c) Intermediate Size Detector

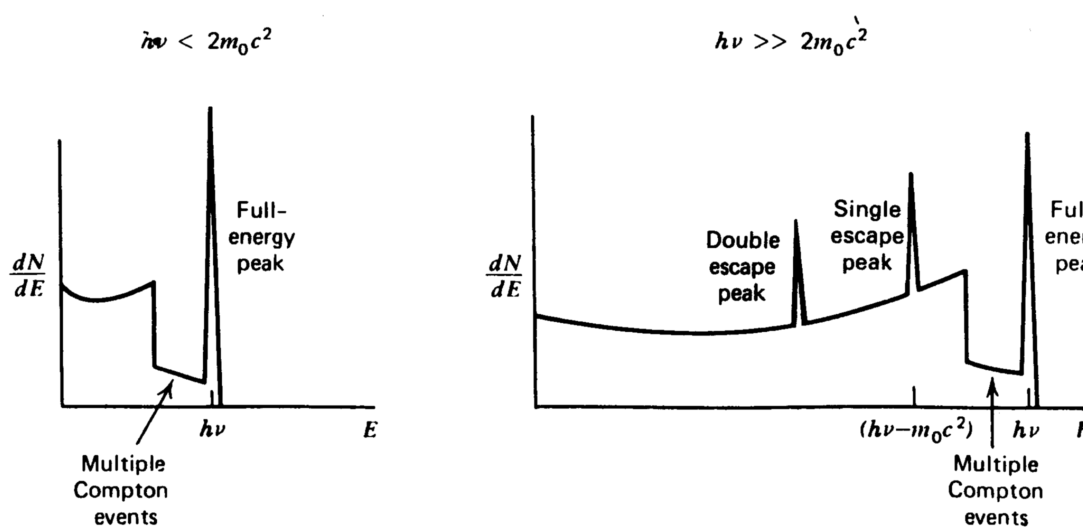
- The initial Compton-scattered photon can scatter again with escape of the final scattered photon.

⇒ energy deposition above Compton edge

- One annihilation photon from pair-production is absorbed and one escapes

⇒ "single escape peak"



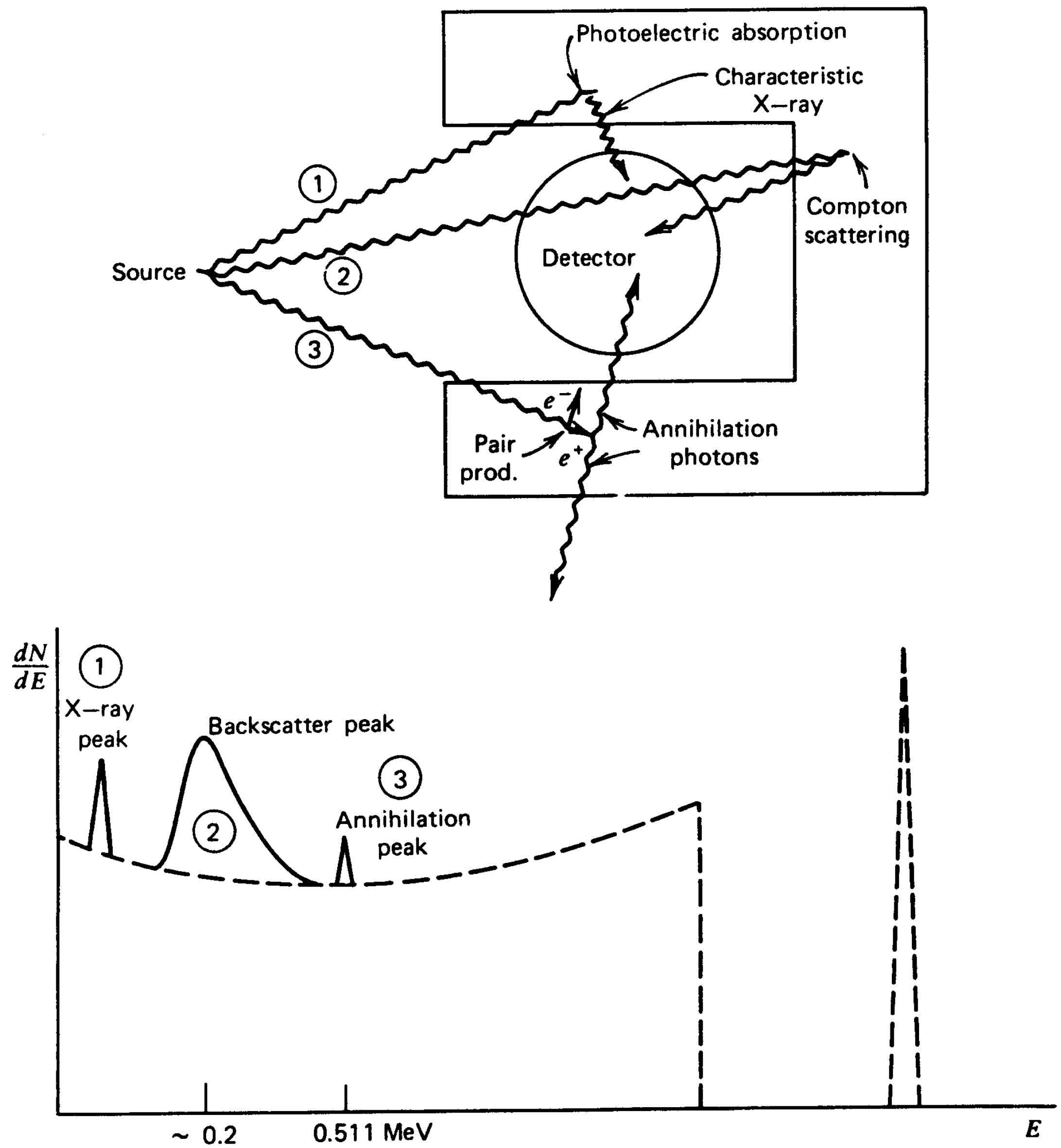
# d) Effect of Surrounding Material (neglecting radioactivity)

1. x-ray from photoelectric absorption in external material

2. Compton backscatter peak (see next page)

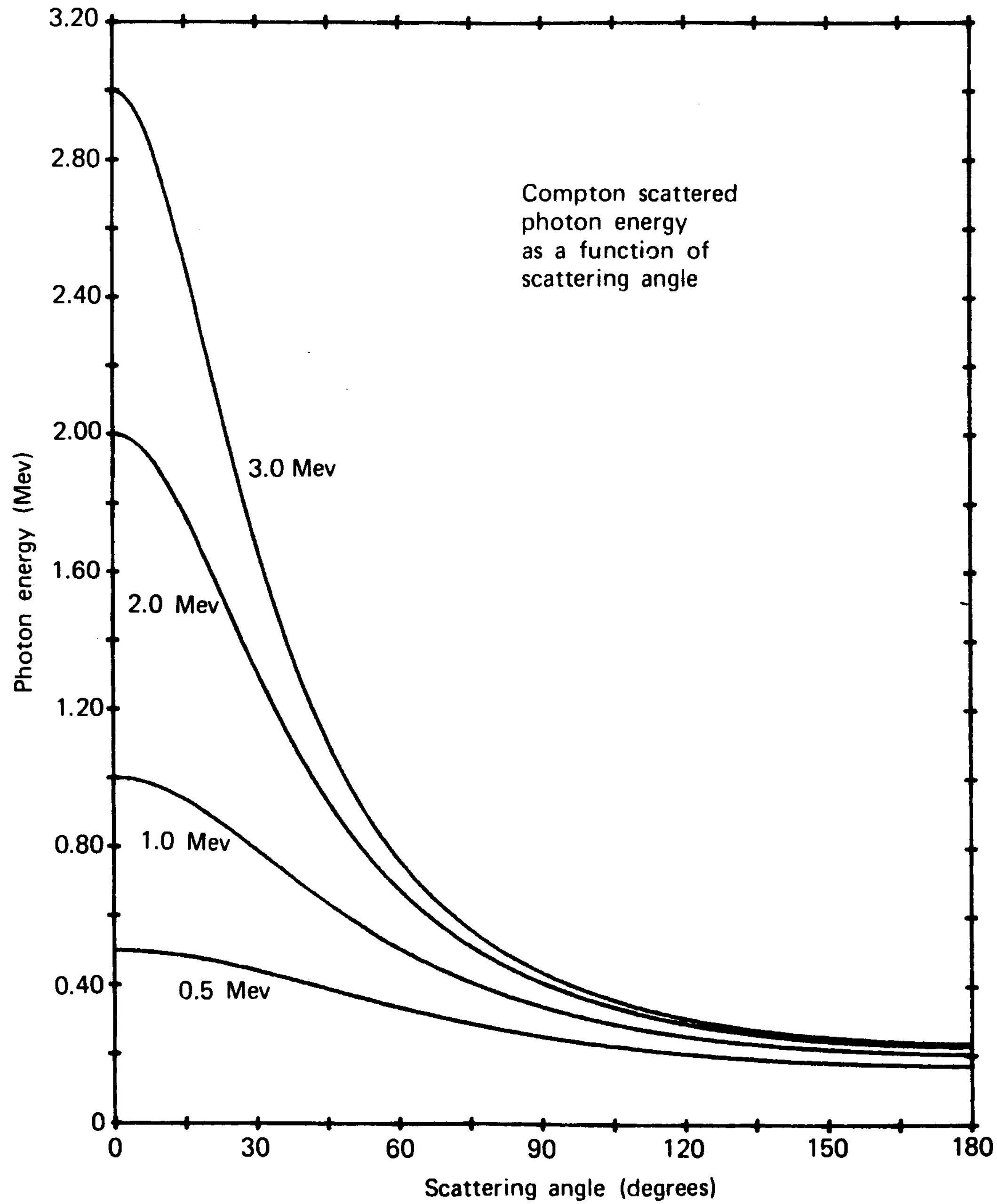
3. Absorption of one 511 keV annihilation photon from pair-production in external material.

⇒ Collimate test source to reduce interactions with surroundings.

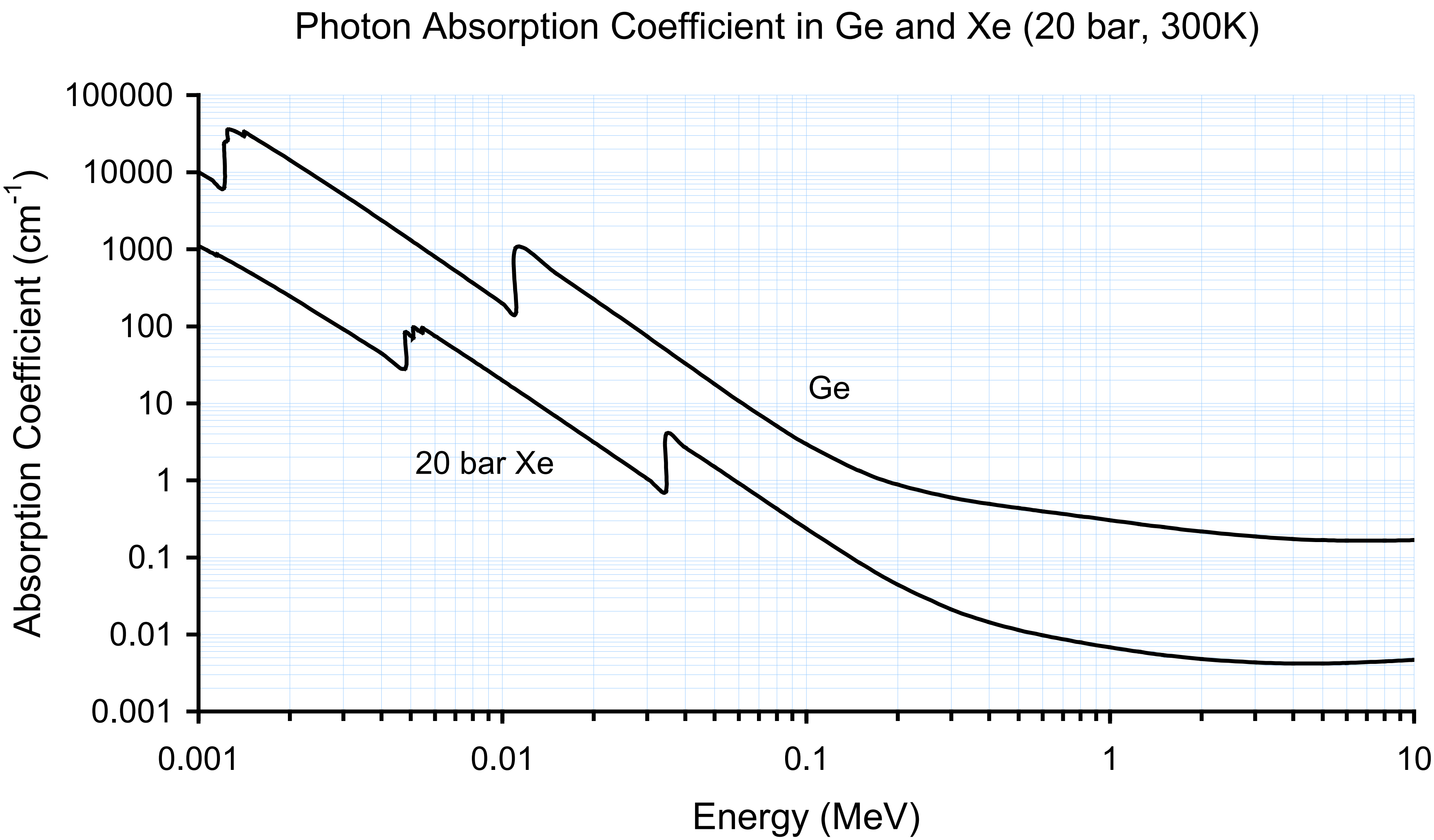


## Compton Backscattering

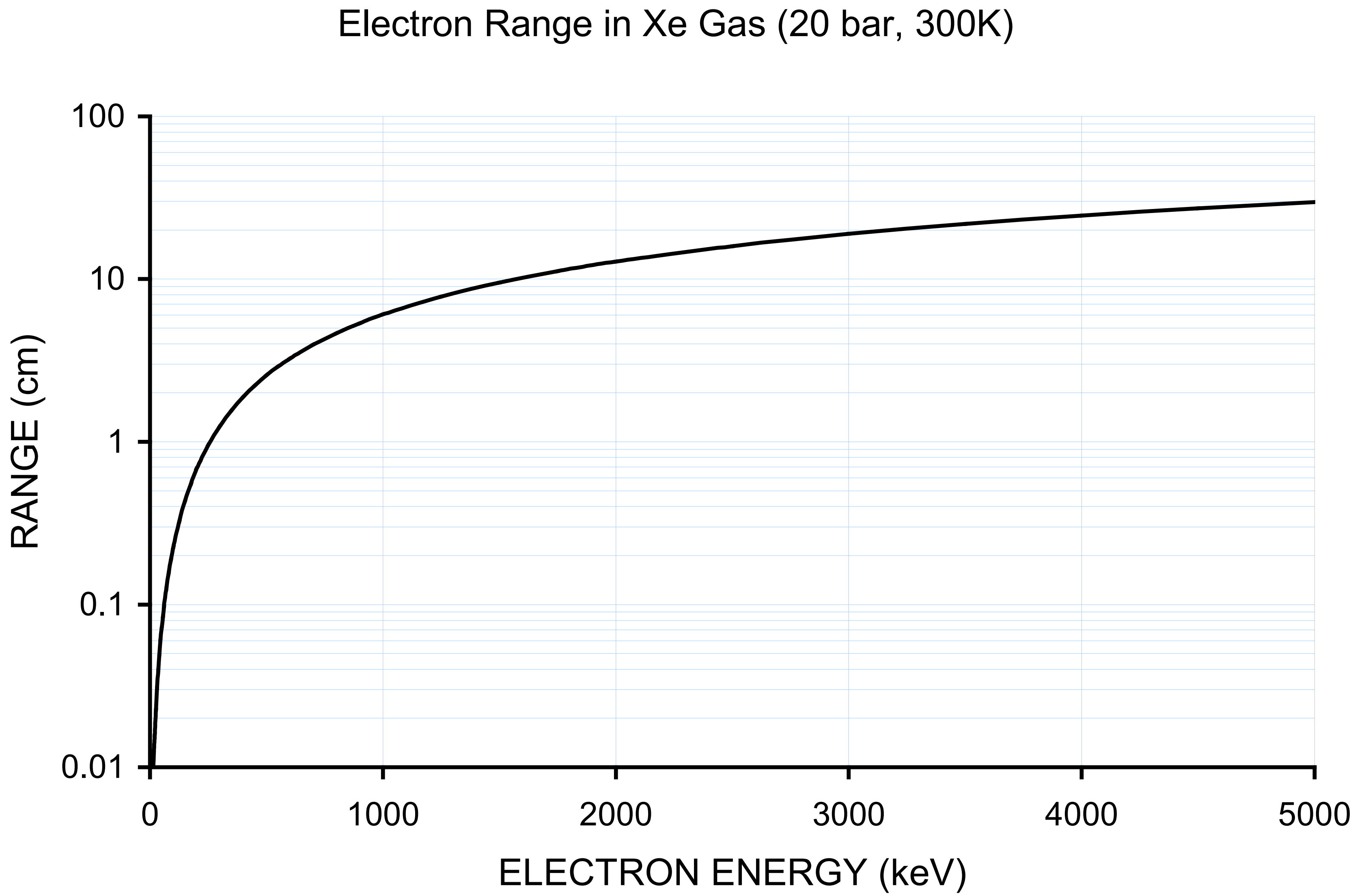
At 180° all incident photon energies yield a narrow energy distribution of the scattered photon ("backscatter peak").



# Photon Absorption Coefficients $\mu$ (fraction of interactions = $1-e^{-\mu x}$)

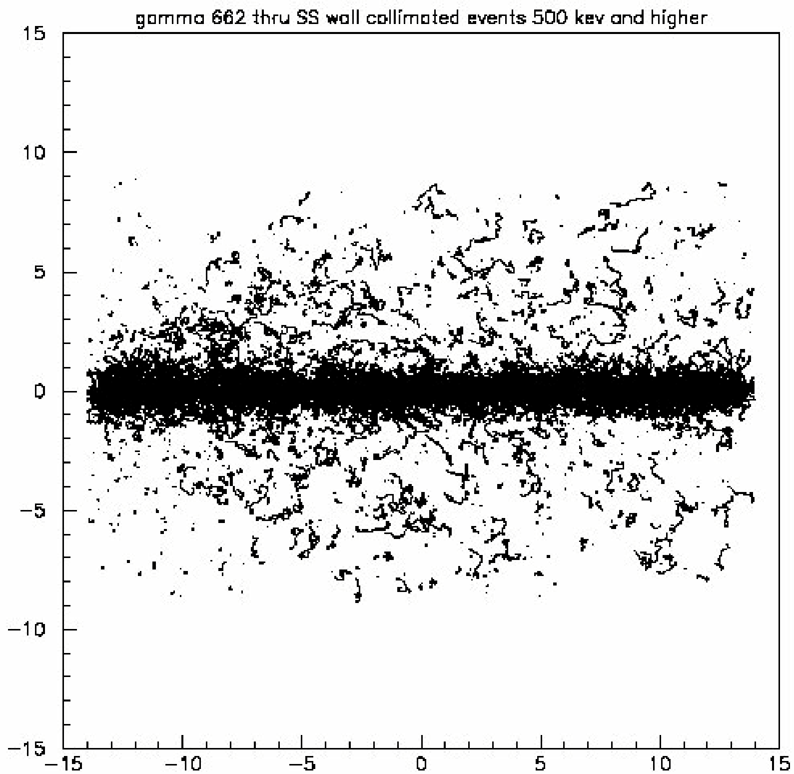


Range of electrons is much smaller than absorption length of gammas

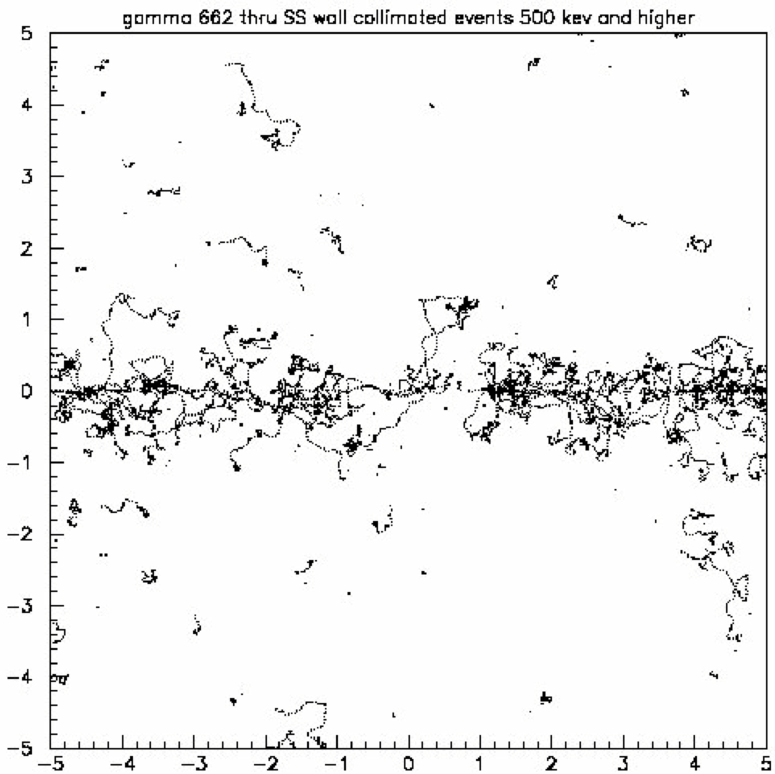


# Example

Collimated 662 keV gammas incident through 15 cm thick steel left wall

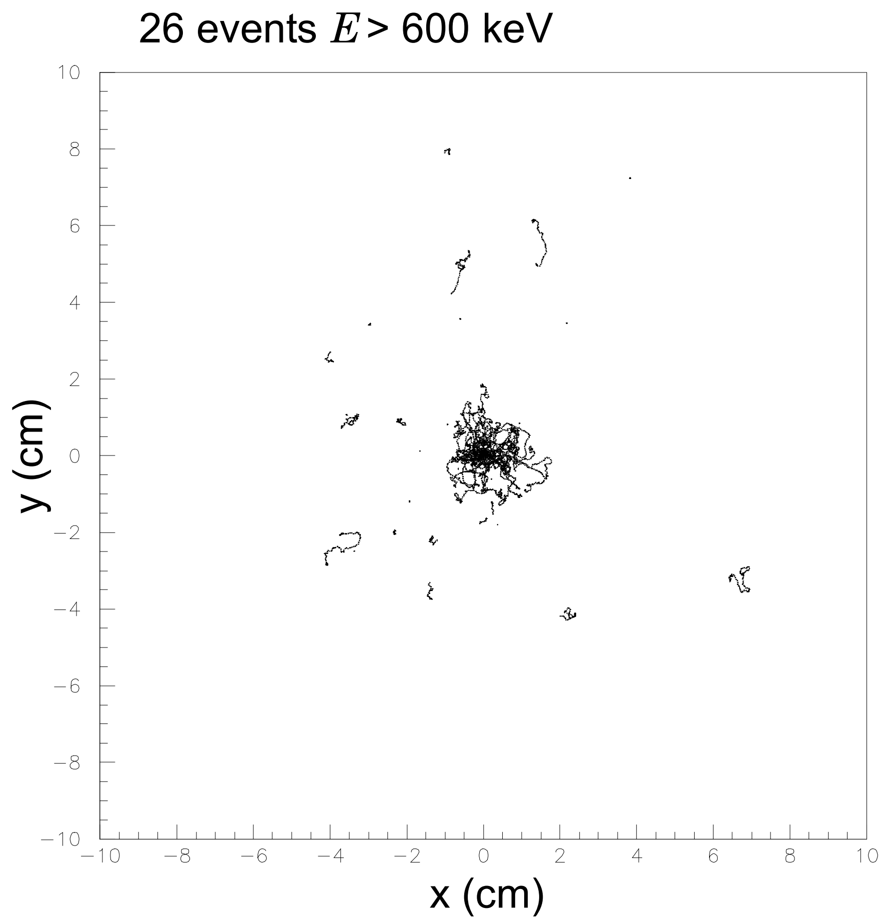


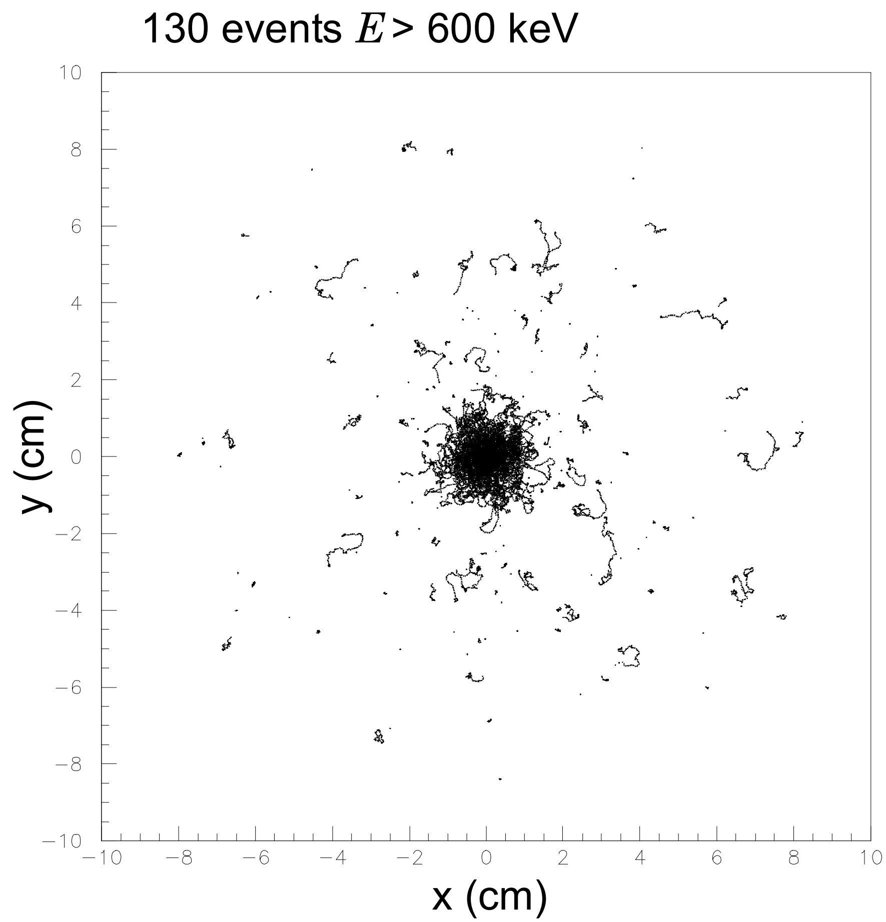

Events in central region >500 keV




(A. Goldschmidt)

# Axial view of fraction of events

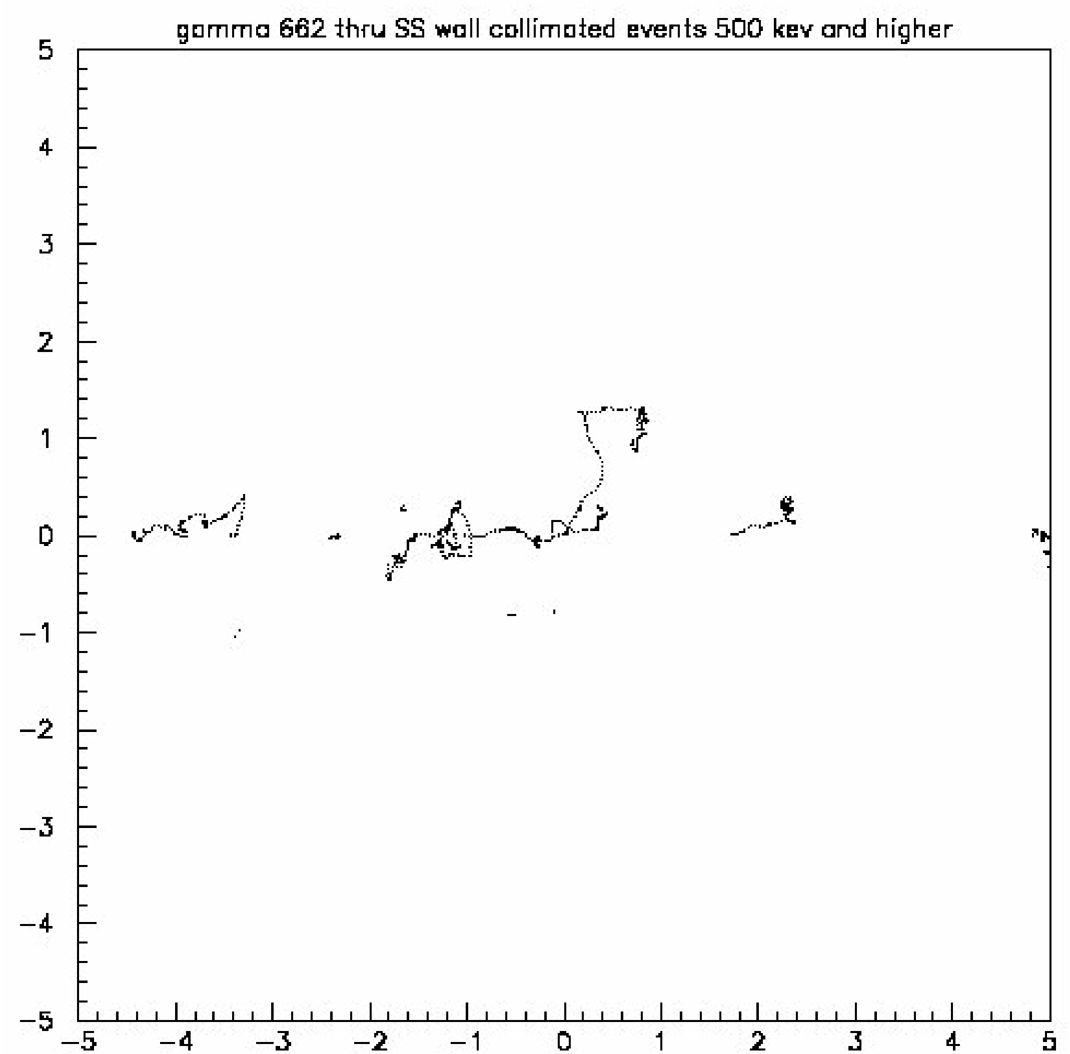



Significant fraction of interactions associated with one gamma distributed in space

Longitudinal structure of some individual events

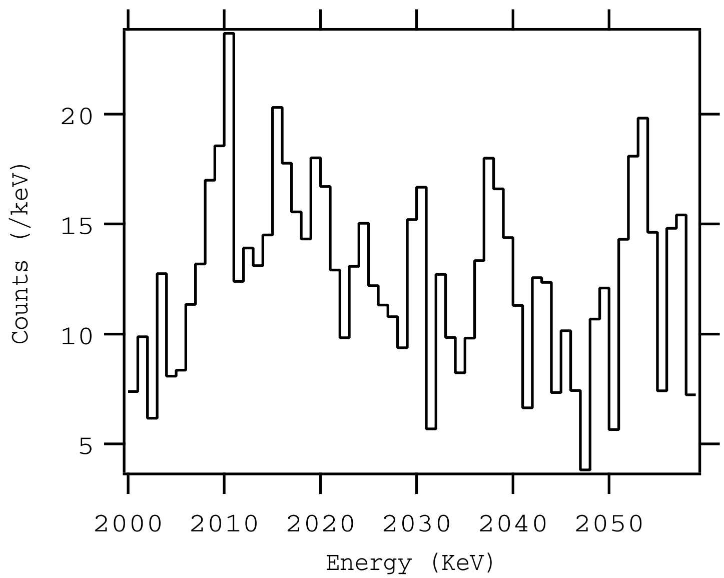
Energy threshold
$E$ > 500keV

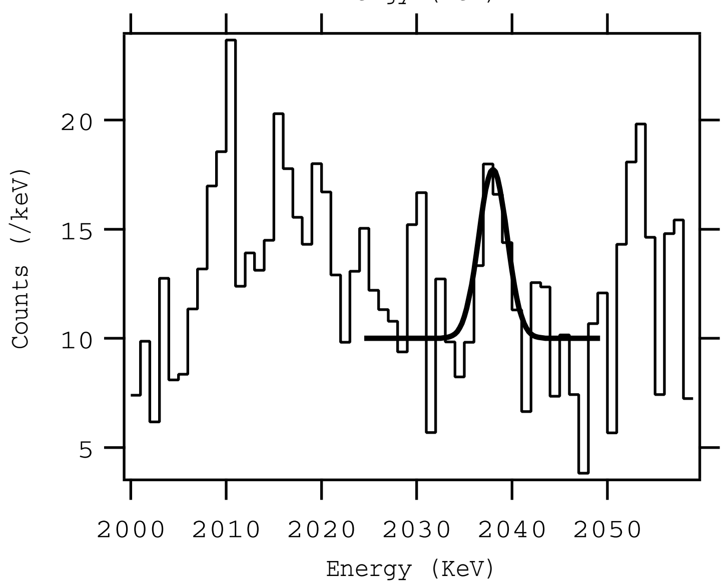



Track reconstruction must distinguish multiple squiggly tracks.

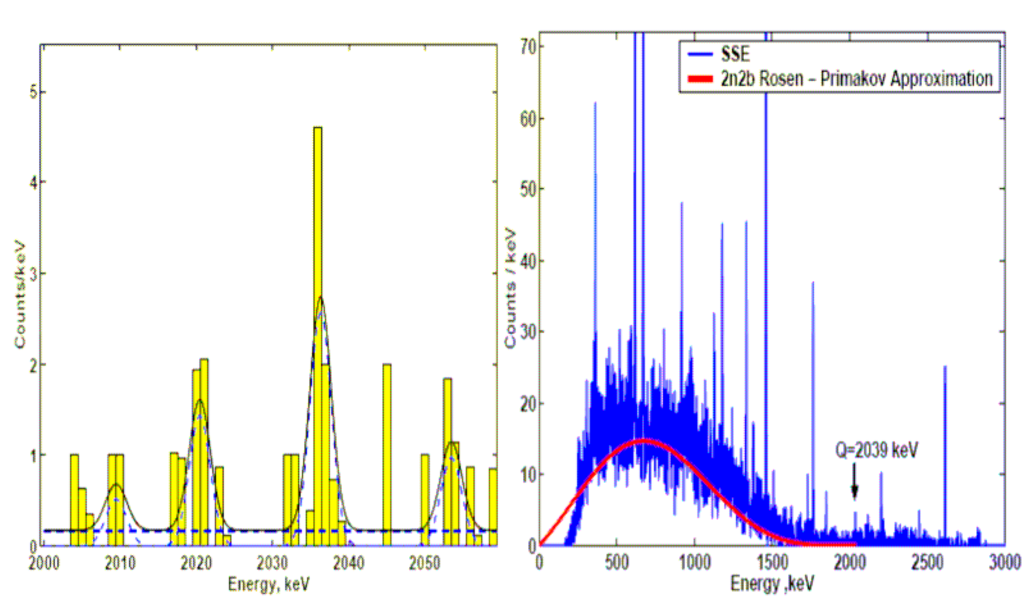
# Gamma Background Example: $^{76}$Ge Data

Klapdor et al. NIM **A522** (2004) 371




Utilizing pulse shape discrimination to recognize spatially distributed energy depositions:




$$T_{1/2} \approx 1.2 \cdot 10^{25}\ \text{y},\ \langle m \rangle \approx 0.44\ \text{eV}$$

Klapdor et al. Phys. Lett. **B586** (2004) 198

Two important measurement properties:

- Energy Resolution
- Event Topology

TPCs are well recognized as tracking devices, but

high-pressure Xe gas may add

- High Energy Resolution
- Acceptable Detection Efficiency

Energy deposition in Xe leads to

Prompt scintillation ($\lambda$ = 170 nm)
$\Rightarrow$ start signal for TPC drift time measurement

Ionization $\Rightarrow$ charge signal

# Xenon: Strong dependence of energy resolution on gas density

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

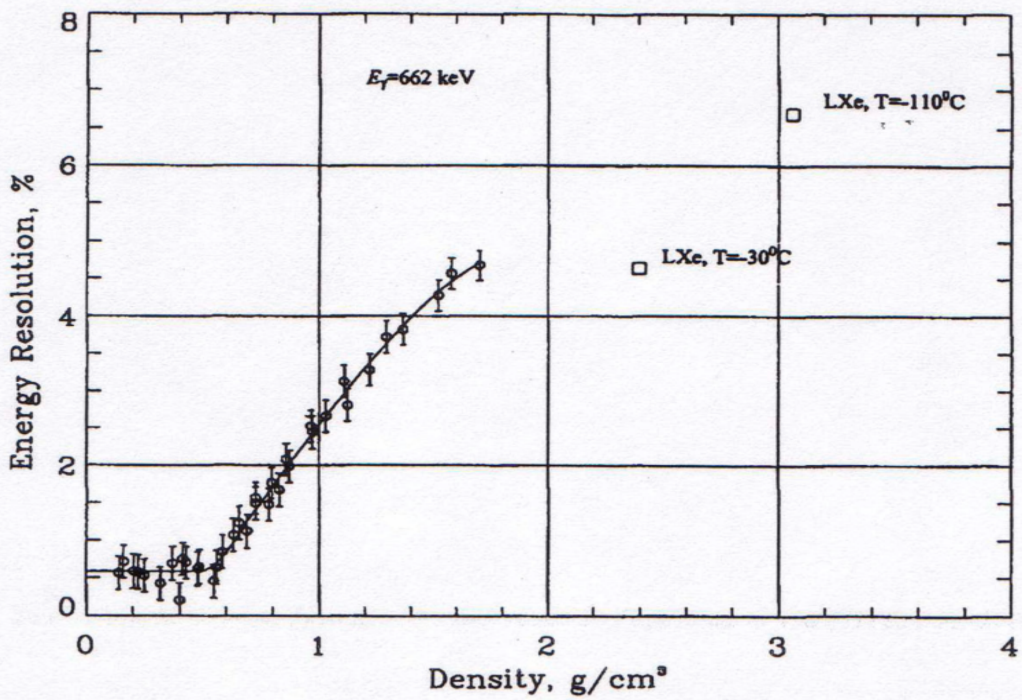



Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

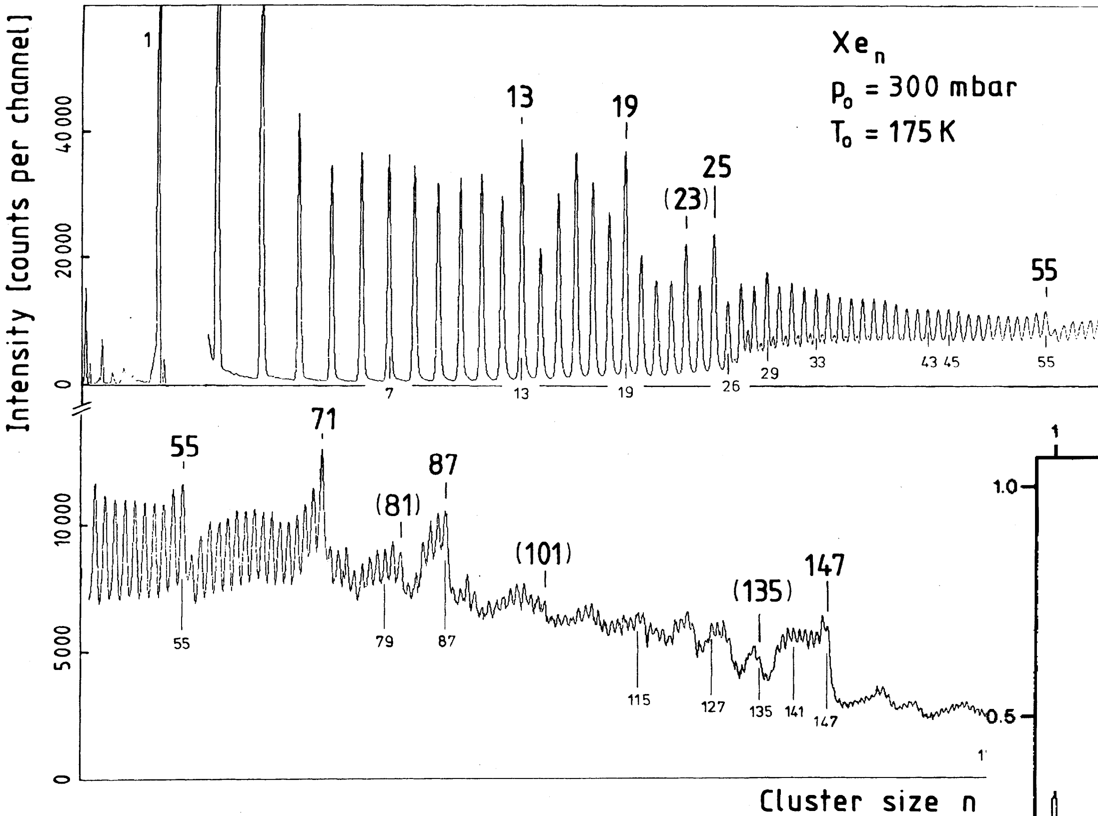
Measurement of ionization component only.

For $\rho$ < 0.55 g/cm$^3$ ionization resolution is "intrinsic".

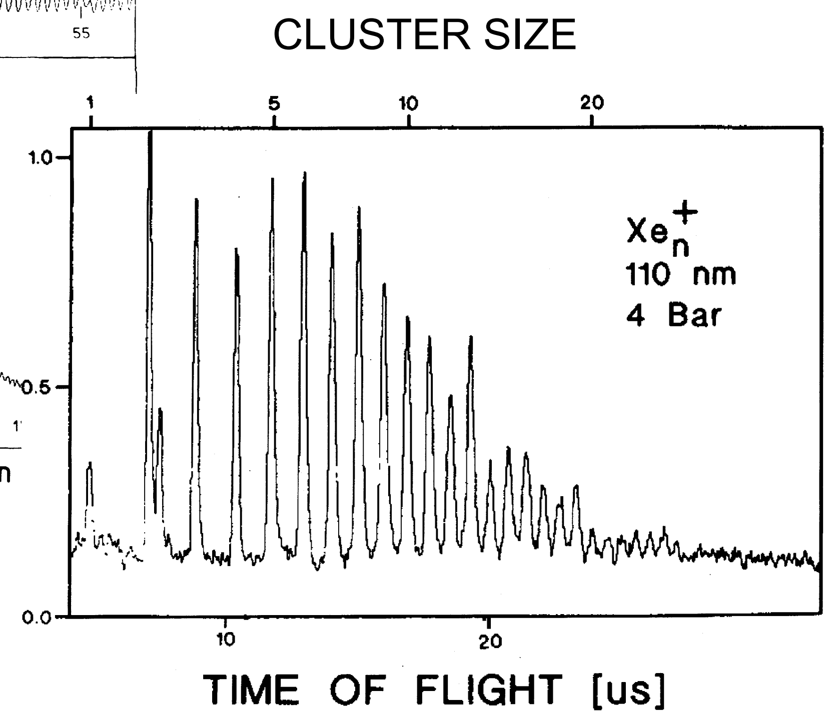
Degraded resolution in liquid Xe due to additional energy states at high density (quasi conduction band) + large fluctuations in ionization-scintillation partitioning.

# Noble gases aren’t as simple as many think: Atom Clusters in Noble Gases

An excited noble gas atom can attach to another, but even larger clusters have been predicted and detected (ionization potential decreases with cluster size):




Echt et al., Phys. Rev. Lett. **47** (1981) 1121




Ganteför et al., J. Chem. Phys. **91** (1989) 7972

# "Intrinsic" Energy Resolution for Ionization at $^{136}$Xe Q-Value

$Q$-value ($^{136}$Xe $\rightarrow$ $^{136}$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)

$$\frac{\Delta E}{Q} = 2.35 \cdot \frac{\sqrt{FN}}{Q} = 2.35 \cdot \sqrt{\frac{FW}{Q}} \approx 2.9 \cdot 10^{-3} \text{ FWHM}$$

Comparison:

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

Fano Factor of Liquid Xe ~20 $\Rightarrow$ $\Delta E / E \approx 3.5 \cdot 10^{-2}$ FWHM
(mixed ionization + scintillation)

# Absolute Signal Charge Fluctuations

$Q$ =2480 keV

$W$ =24.8 eV

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

$N$ = 2480 x $10^3$ 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 $F$.

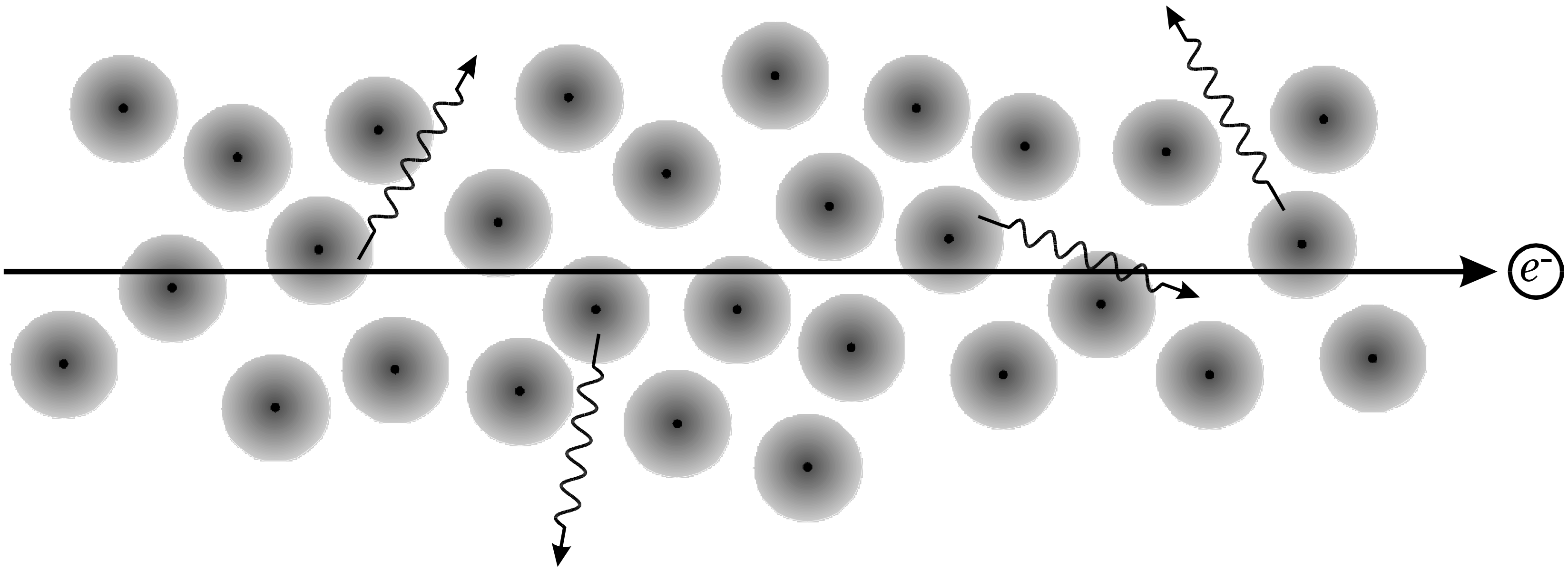
Avalanche charge gain introduces excessive noise because early fluctuations are amplified exponentially.

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

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

# Alternative: Electroluminescence

Accelerate electrons in an electric field so that over a certain distance they gain just enough energy to excite optical states – NOT emit secondary electrons.




Typically one photon (170 nm ≙ 7.3 eV) per 8 – 10 V traversed by the electron.

No additional electrons released.

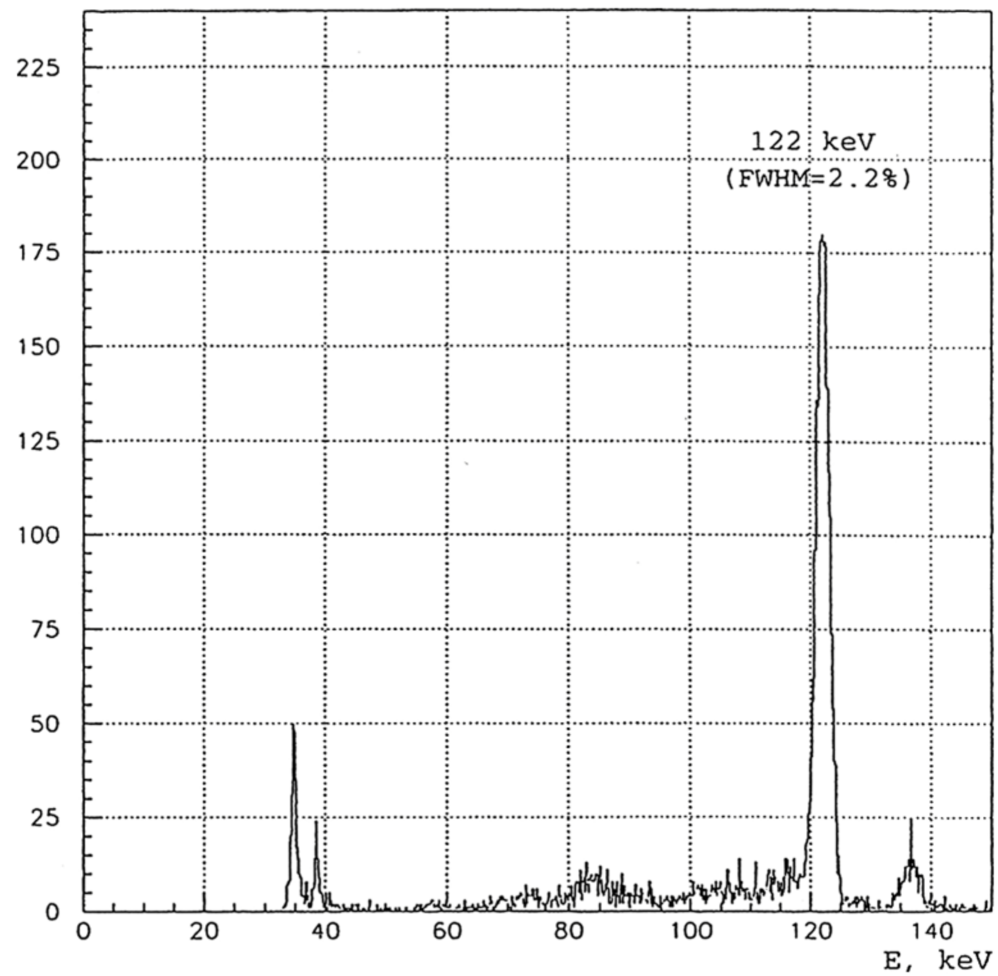
Linearly sequential gain process – photons don't excite additional emissions

⇒ Excitations are independent of one another.

⇒ Initial fluctuations are not magnified.

# Electroluminescence has been demonstrated

- Amplification is **linear** with voltage
- Sequential gain process (photons don't excite additional emissions)
- Gain set by $E\,/\,p$ and length of field region
- Gains of $10^2 - 10^3$ practical
- Fluctuations are very small: $G \approx 0.1$ achievable




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

# High-Pressure Xe Gas TPC

Energy deposition yields both ionization and scintillation.

Scintillation light yields prompt start signal to measure drift time of ionization electrons

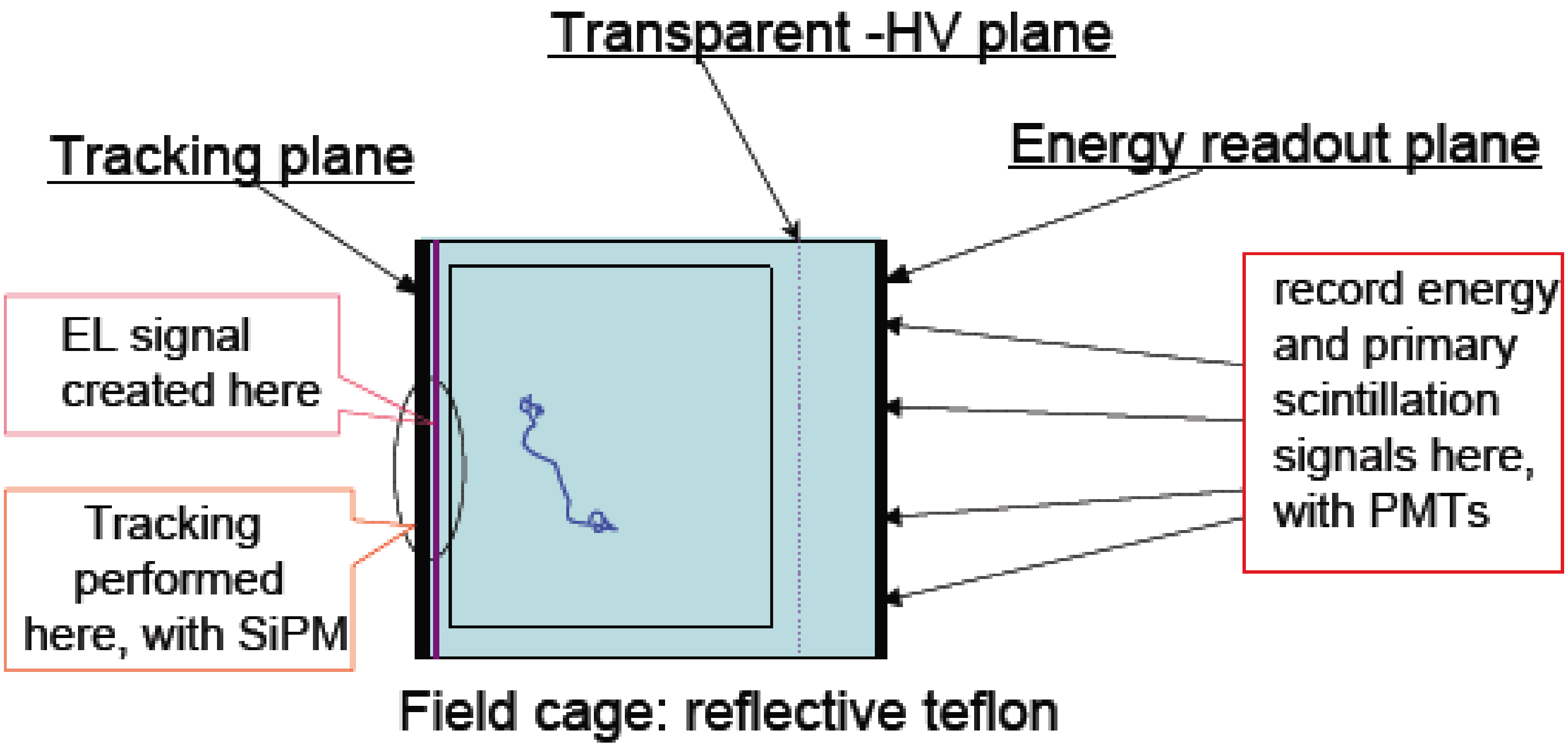
- Fiducial volume surface:
  - Single, continuous, fully active, variable,...
  - 100.000% rejection of charged particles (surfaces)

- Excellent tracking capability:
  - Available in gas phase only!
  - Topological discrimination against single electrons (meatballs)
  - X-ray fluorescence can tag $\gamma$ photo-conversion events

Combination of high-pressure gas and electroluminescent internal gain has not been demonstrated!

Should be scalable to 1000 kg with no degradation in resolution.

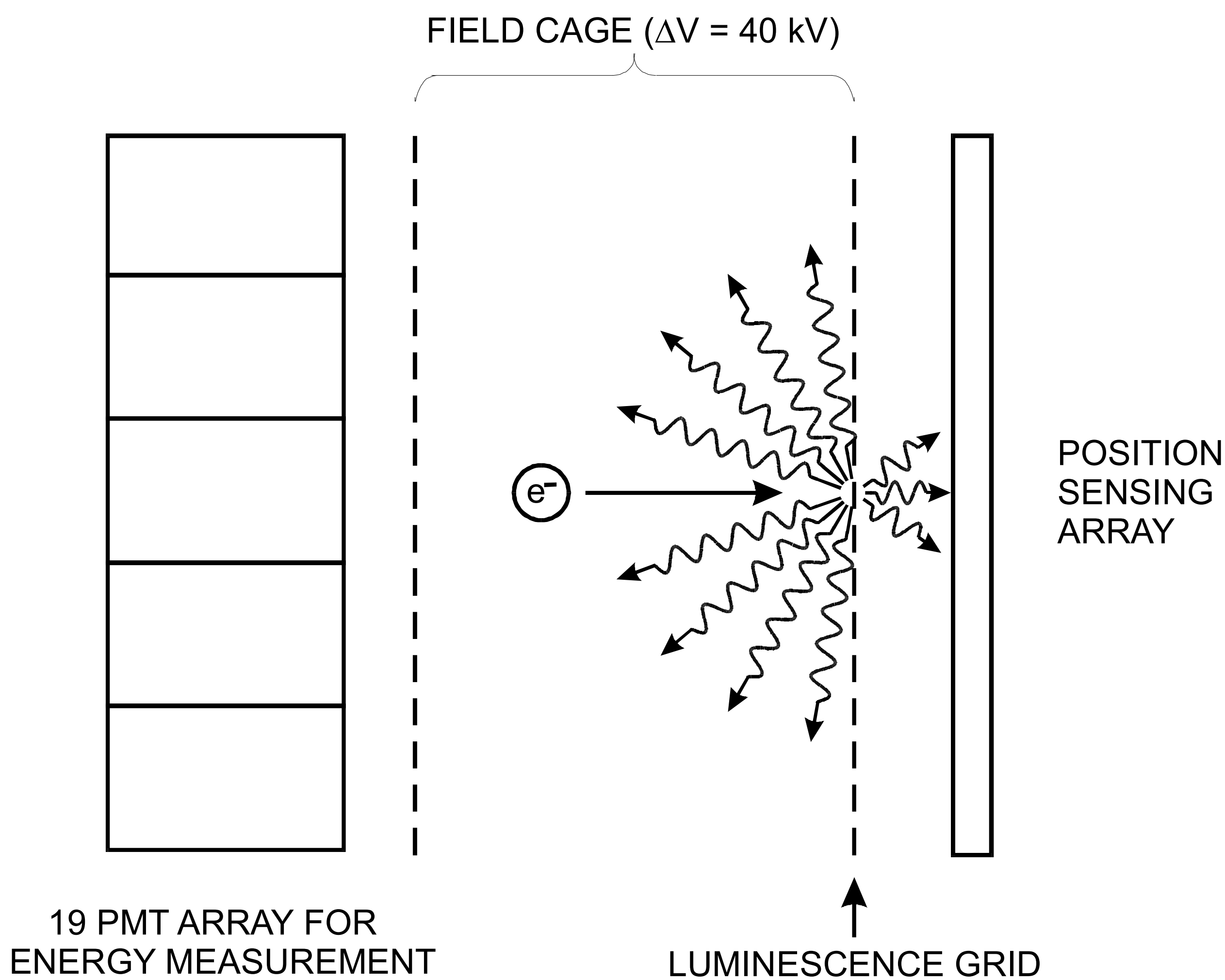
# TPC Readout




z-coordinate (horizontal) is determined by measuring the drift time of the signal charges. Prompt scintillation provides the start signal.

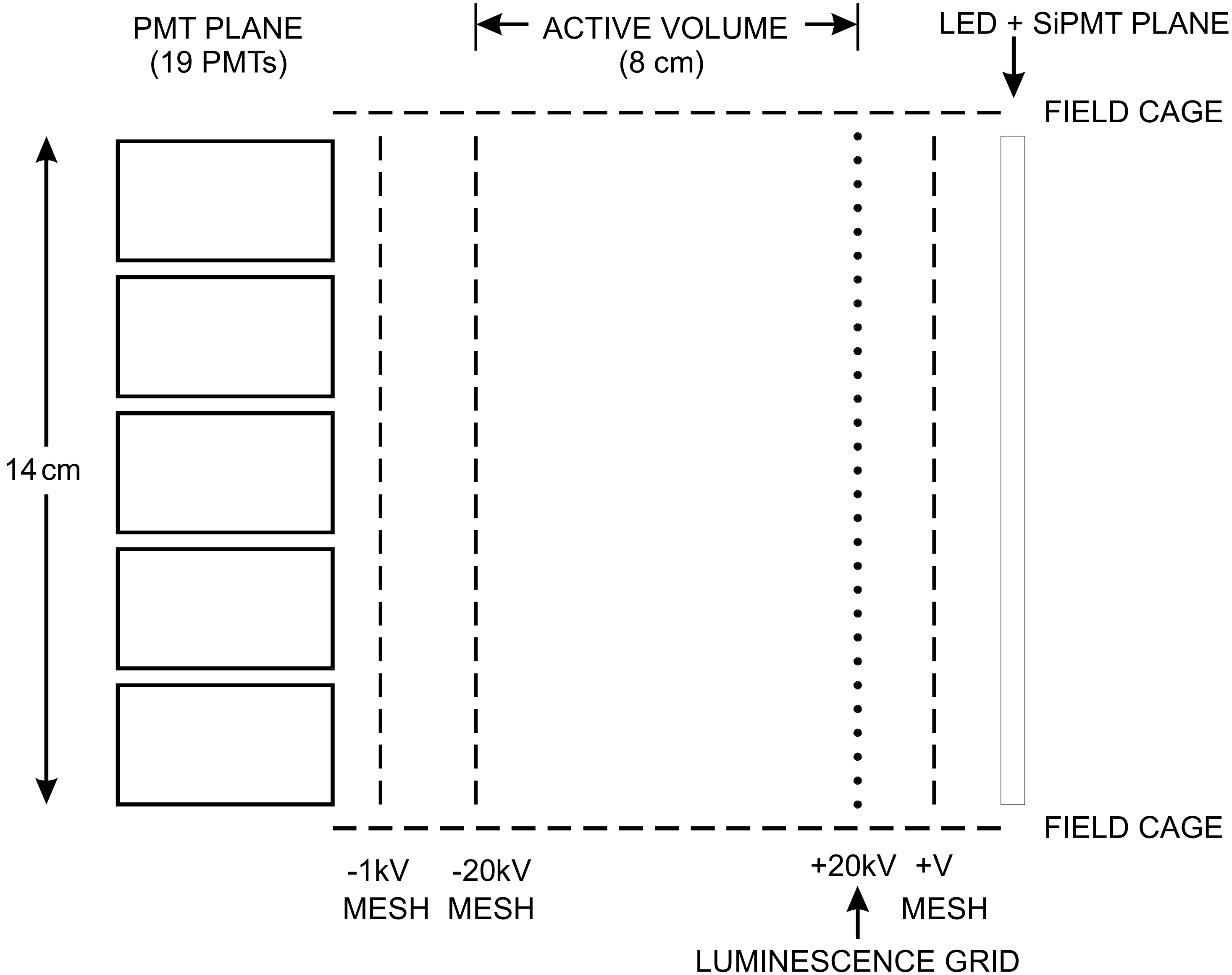
The tracking plane (left) provides x and y-coordinates,

# Principle of Current LBL Chamber




Field cage enclosed in reflective Teflon to increase light collection efficiency and distribute light uniformly over the PMT array.

# Layout of Current LBL Chamber



# Luminescent Gain

$$\eta = 140\left(\frac{E}{p} - 0.83\right)p \cdot \Delta x \quad \frac{\text{UV photons}}{e}$$

C.M.B. Monteiro et al. 2007 JINST 2 P05001

The luminescent field can be formed by

1. A pair of spaced grids
2. A single wire-grid

The spacing of a grid pair is critical $\Rightarrow$ Electric force deforms grids
$\Rightarrow$ Variation of luminescent gain vs. radius

Wire Grid: Combination of applied voltage and wire radius determine the radial range where luminescent gain occurs.

Parameters must also be chosen to avoid avalanching.

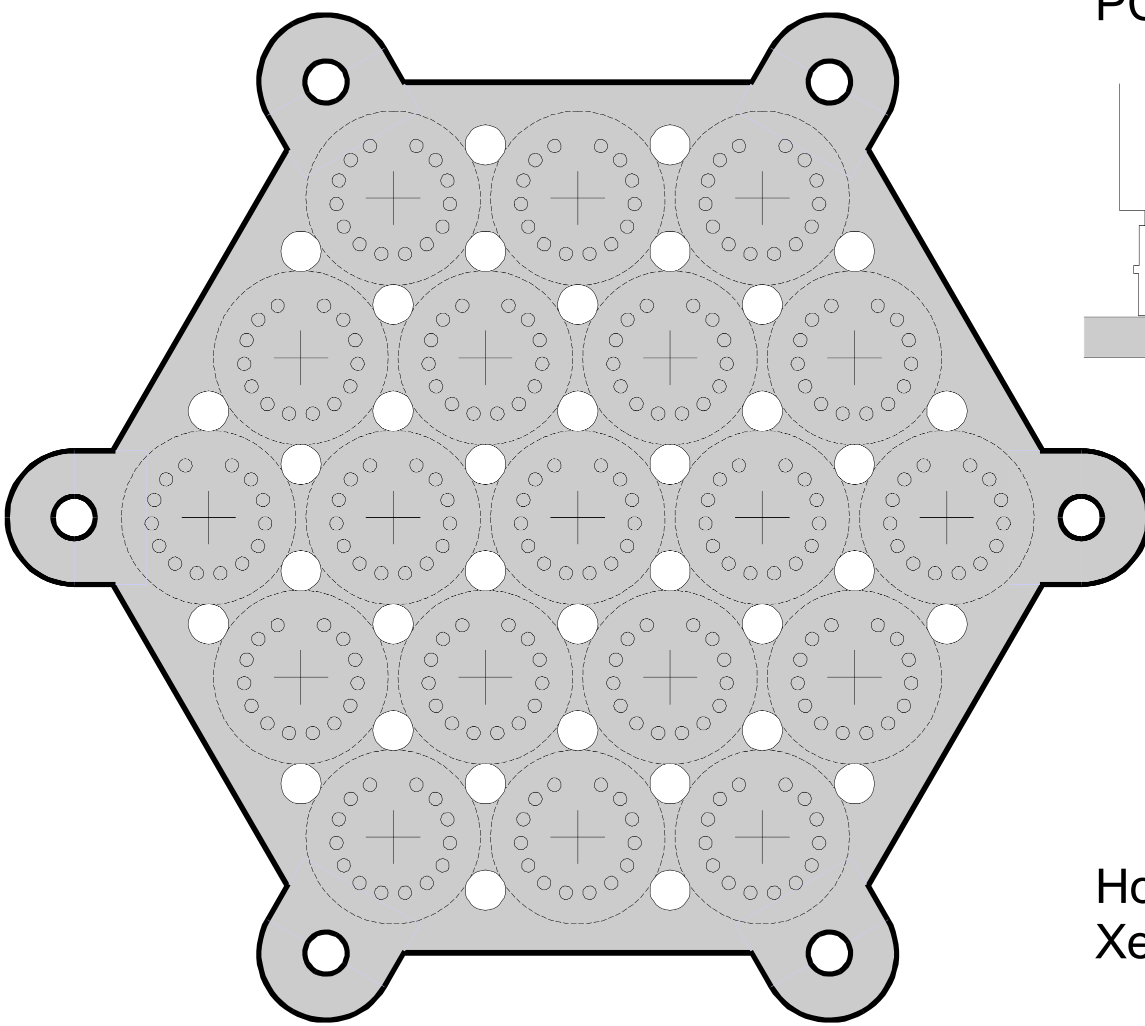
Wire diameter of 300 μm, 6mm spacing yields gain of 300.

Variations in wire diameter < 1 μm.

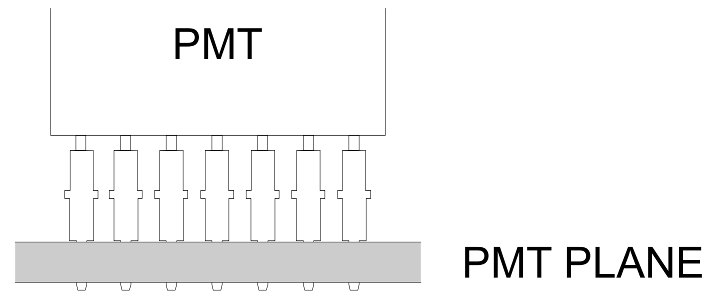
However, reduces range of TPC drift fields.

$\Rightarrow$ Will test both schemes

# PMT Plane



Individual pin-contacts in
PC board form PMT socket




Local voltage dividers
with surface-mount
components

Holes in PMT plane to direct
Xe flow through active volume

# Challenges

- Signal is distributed over many detectors

  Relative calibrations must be accurate to <0.1%

- Signal duration depends strongly on track location and shape:

  Drift velocity ~1 mm/$\mu$s

  Diffusion spreads out track signal: ~0.3 mm/cm$^{1/2}$ longitudinal
  ~0.8 mm/cm$^{1/2}$ transverse

  Signals spread over time: min for tracks parallel to luminescence plane
  max for tracks normal to luminescence plane
  (2.5 MeV electron track length ~16cm)

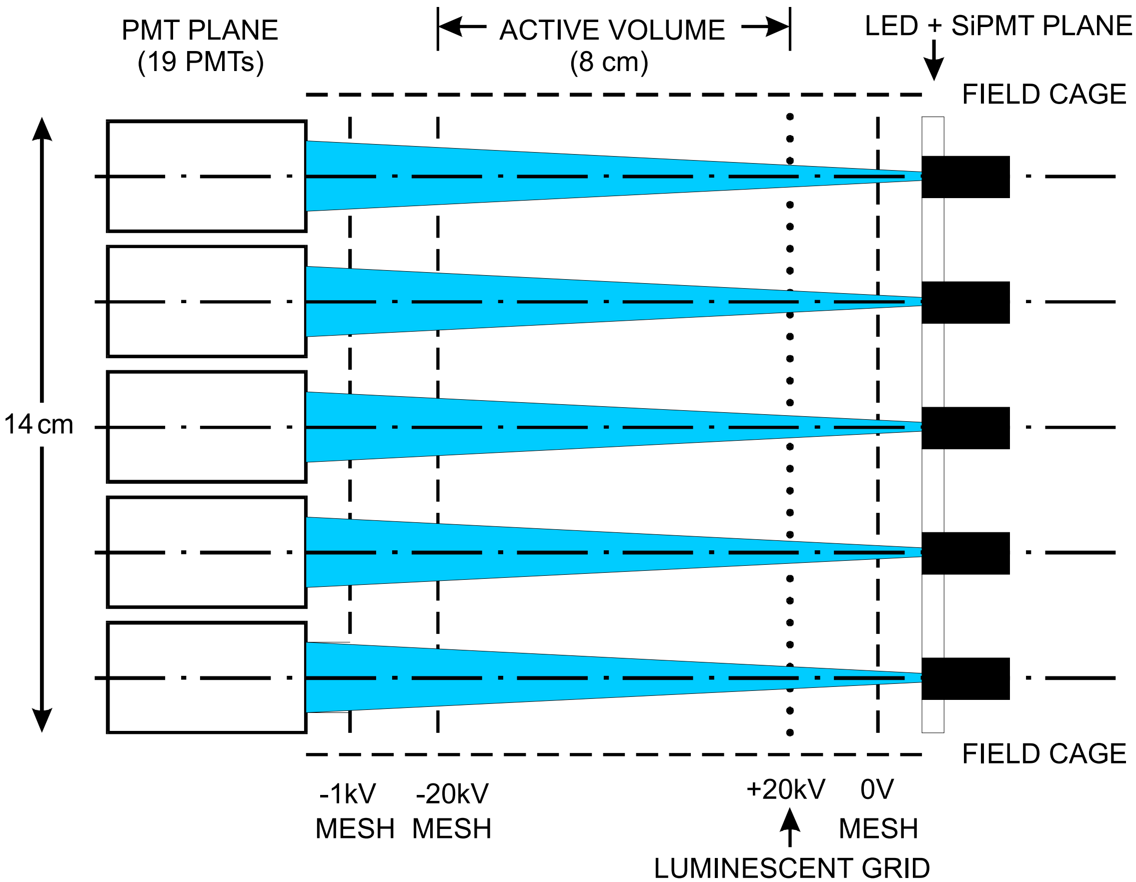
  $\Rightarrow$ requires digital integration over 1 – 200 $\mu$s

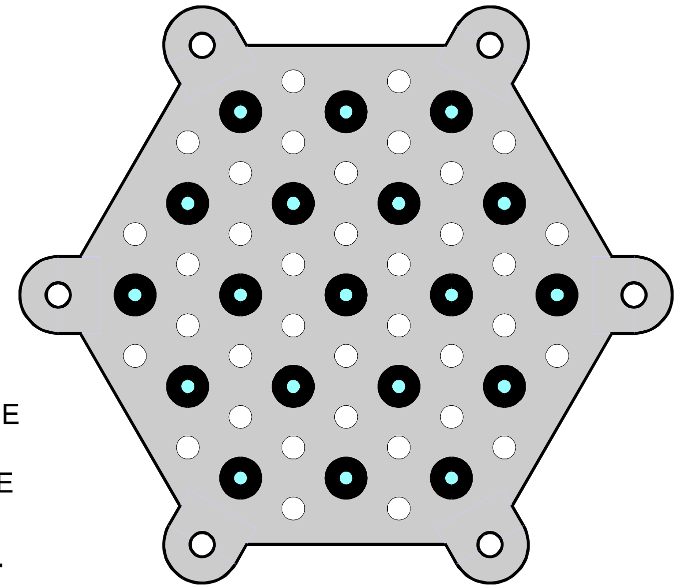
- Light collection efficiency depends on track position
- Luminescent gain must be well controlled
- Contaminants that quench signals
- Xe light emission at 170 nm, UV beyond standard photodetectors
- Energy resolution measured with gammas (distributed energy deposition)

# Relative PMT Gain Calibration

Collimated array of far-UV LEDs:  one per PMT

Individually pulsed and intensity controlled



LED Plane

Open holes for Xe flow

Simulated energy spectrum for collimated gamma beam entering on central axis
(A. Goldschmidt)

Wall reflectivity: 75%

No reflection from endcaps

Fixed charge for 662 keV

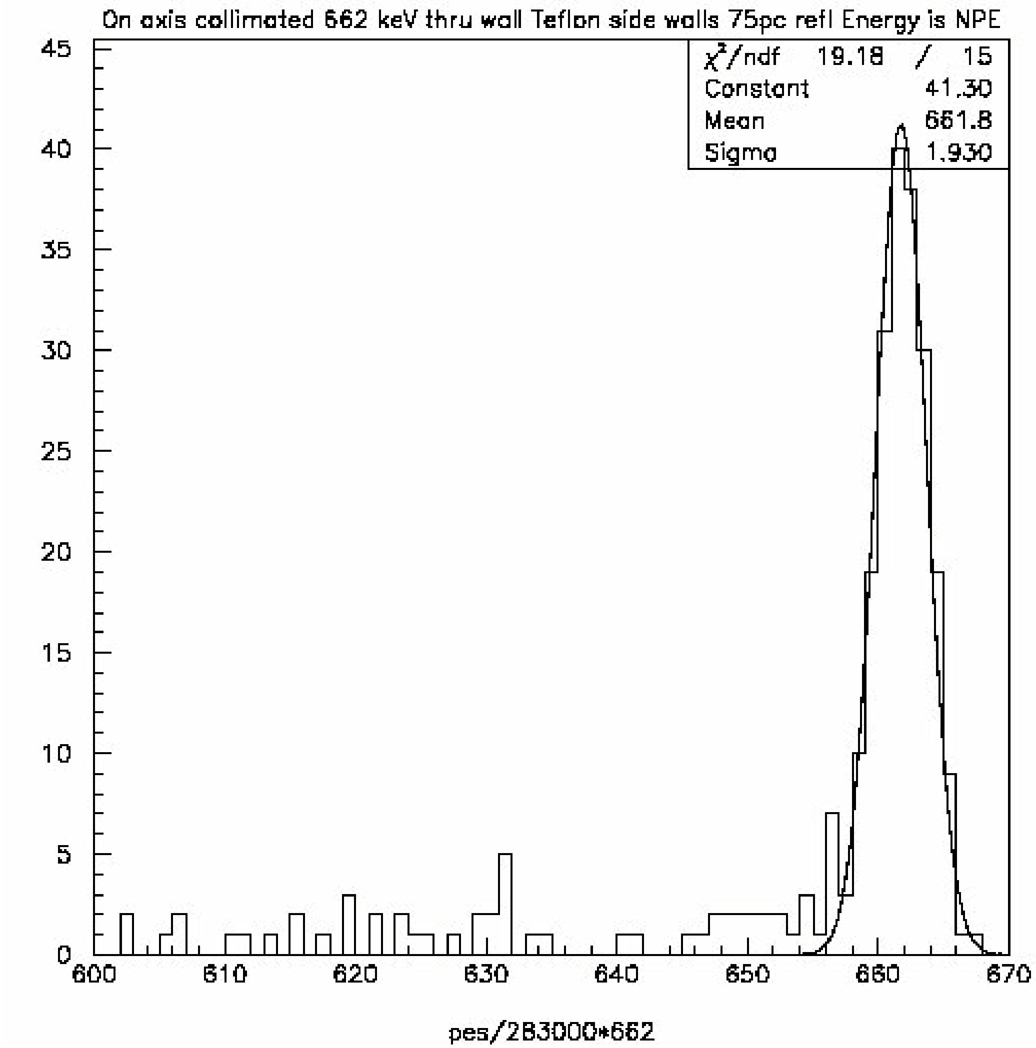
⇒ peak width due to variations in light collection efficiency vs. position

Peak width: 0.7% FWHM

Expected statistical width:
($F$ =0.15, $W$ =25 eV)

$$\frac{\Delta E}{E_\gamma} = 2.35 \cdot \sqrt{\frac{FW}{E_\gamma}}$$

$$= 5.6 \cdot 10^{-3} \text{ FWHM}$$

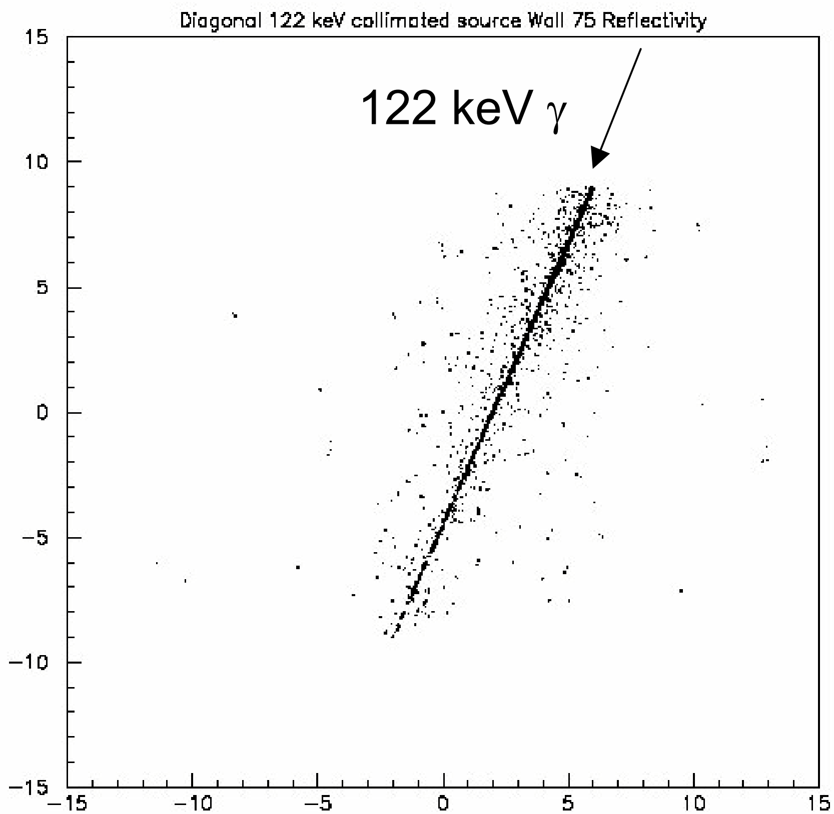


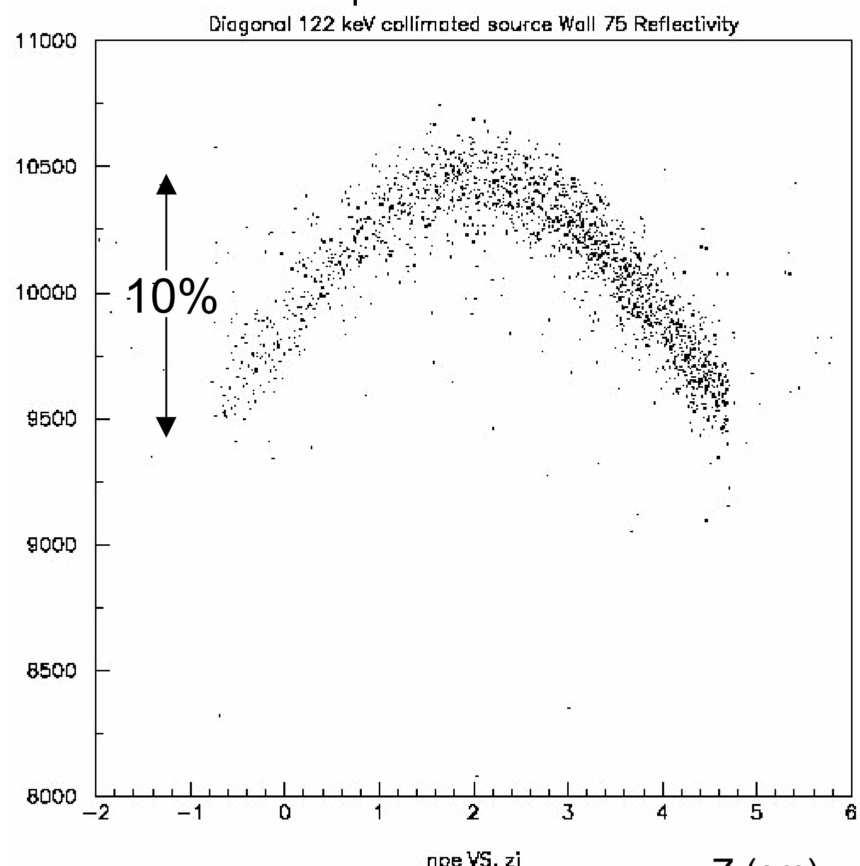

Position correction necessary to verify statistical variance.

# Simulated Light Collection Efficiency vs. Position

- Simulation with 75% reflectivity on walls
- Collimated source inside the pressure vessel
- Use drift time to determine z and thus radius

Number of photoelectrons vs radius



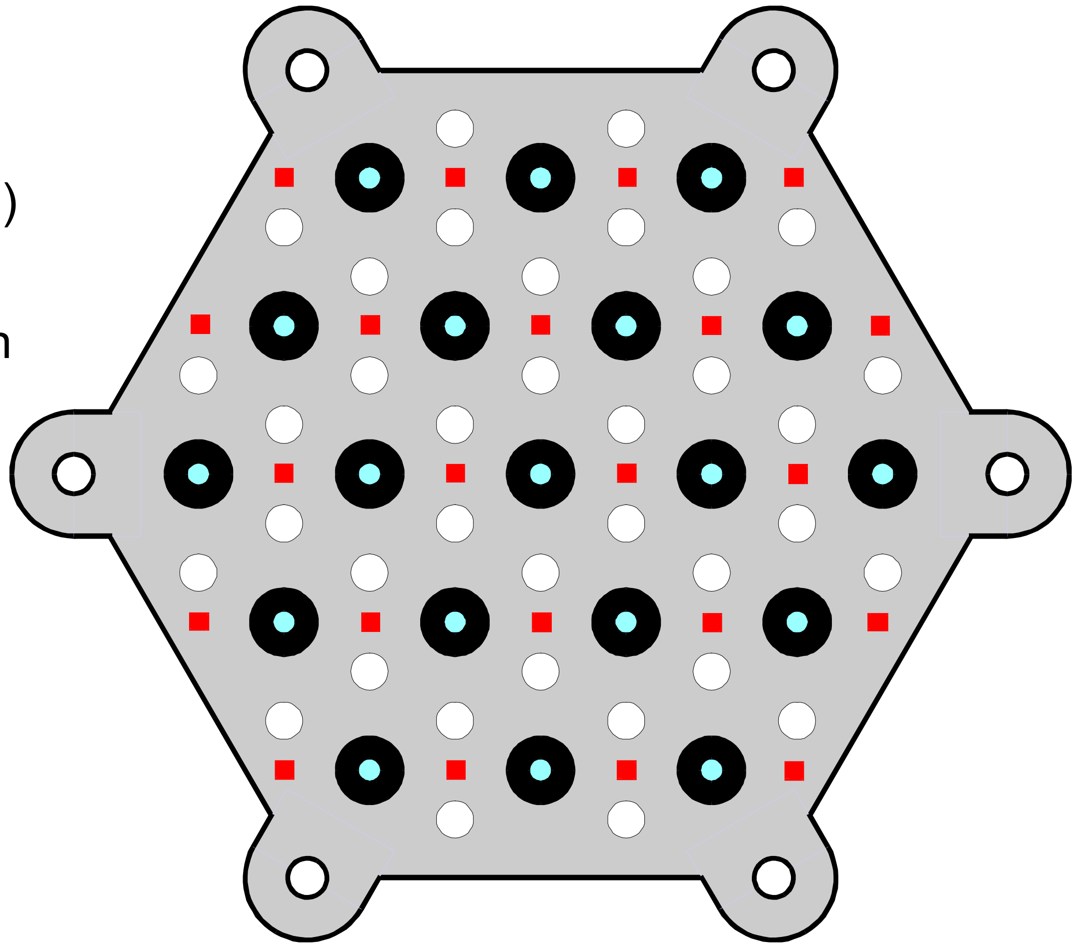

Measured signal also includes variation of luminescent gain vs. radius.

# Light collection efficiency vs. position requires coarse position sensing

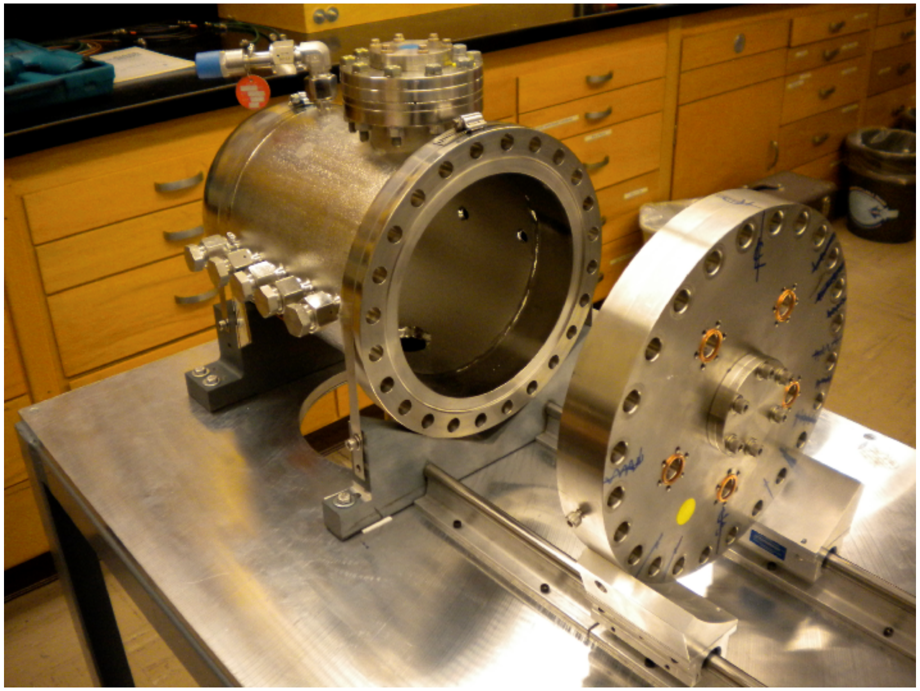
⇒ Array of SiPMTs ( ■ ) mounted on LED-SiPMT plane

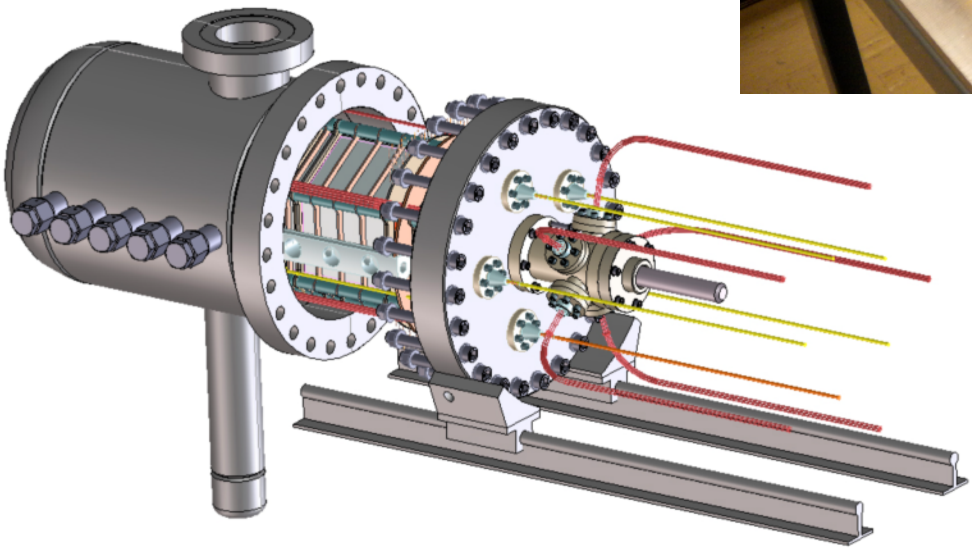
SiPMT surface-mount chips will be coated with TPB (Tetra-Phenyl-Butadiene) wavelength shifter.

Converts 170 nm Xe emission to 440 nm.

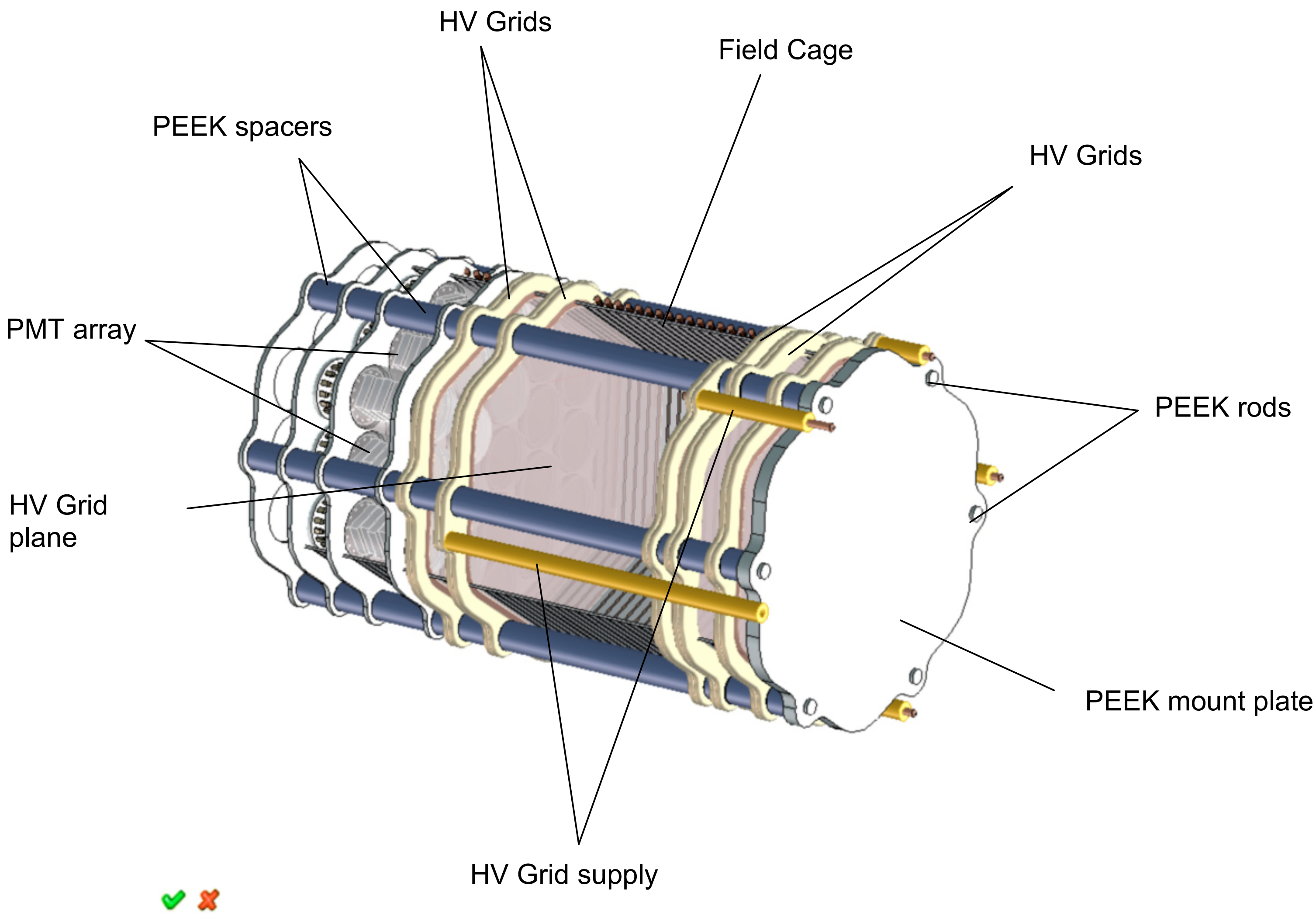


High-pressure chamber exists and inner components now under construction.

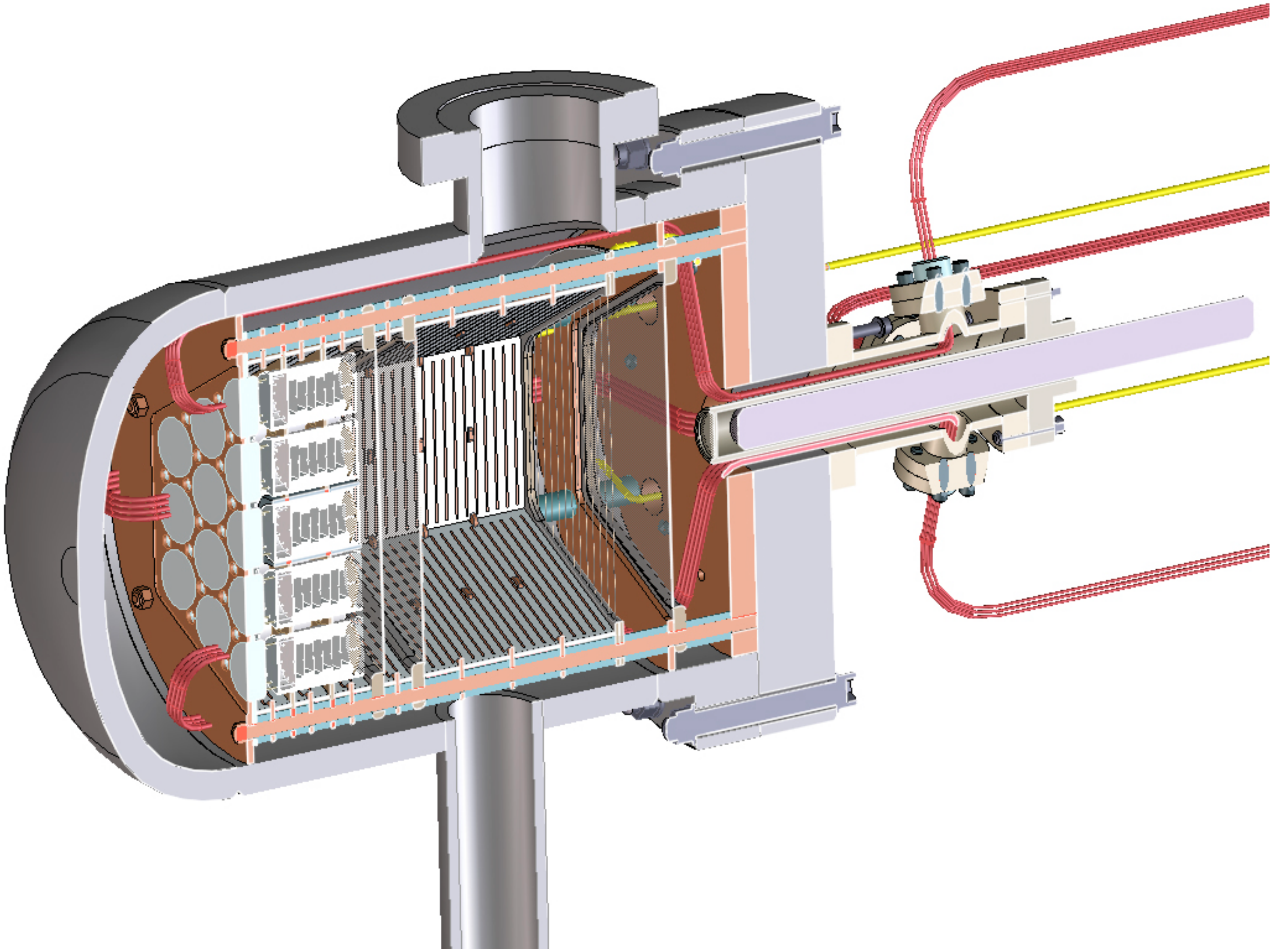




Chamber formed of individual layers supported by six rods to facilitate modifications in testing various configurations.

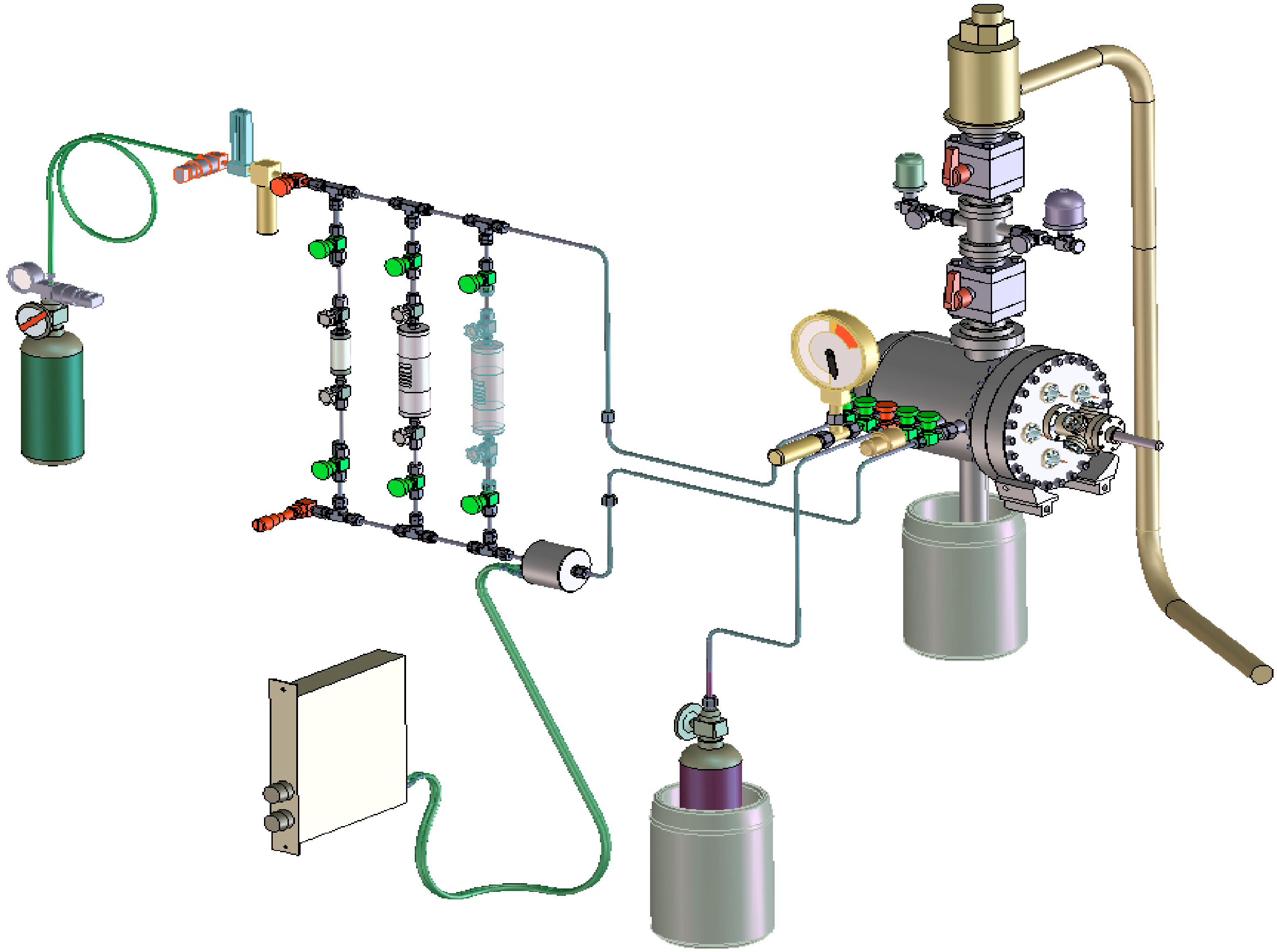



The Teflon field cage will enclose the active volume to direct the purified Xe flow.



# Gas System

Utilize getters and continuous recirculation to purify Xe.



# Gas Cycle

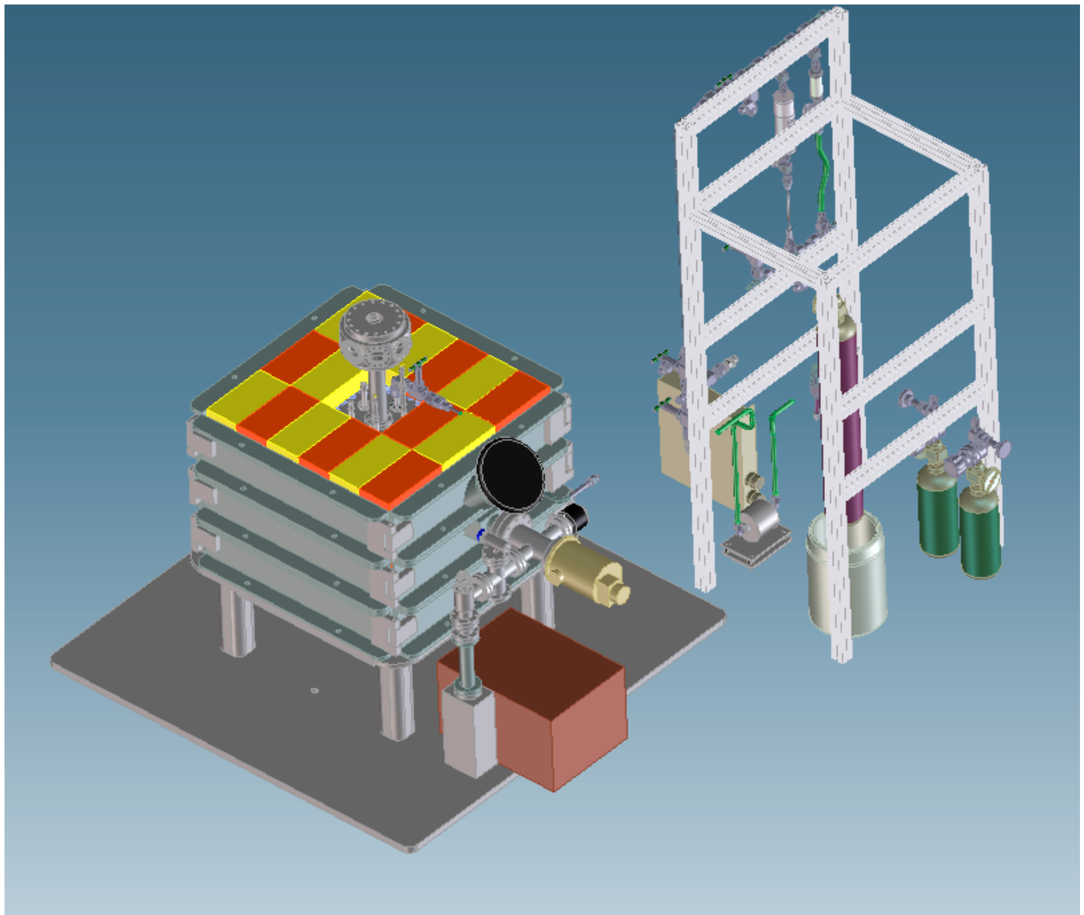
- Vacuum pump the chamber (< $10^{-4}$ Torr)
- Flush with Argon
- Vacuum pump again
- Transfer Xe by freezing in chamber reservoir
- Let Xe warm up and reach high pressure
- Recirculate Xe continuously
- Run experiments
- Recapture Xe by freezing in reservoir

Efficiency of full energy deposition in small chamber ~1%

⇒ Significant background rate from surrounding concrete walls

⇒ Lead shielding required (total weight ~1.5 tons, incl. seismic supports)

⇒ Vertical mounting of chamber to reduce amount of lead



# Summary

High-pressure Xe Time Projection Chambers can provide a unique combination of

- high energy resolution
- particle tracking
- mapping of event topology

to improve signal to background ratios.

Potential applications include

- Searches for rare events,
  e.g. neutrinoless double-beta decay and WIMP searches
- Large-area gamma-ray detectors with background suppression

Energy resolution still to be verified – lots of work ahead!

… + the unexpected: just been told to move our lab