TRIUMF

CANADA'S NATIONAL LABORATORY FOR PARTICLE AND NUCLEAR PHYSICS

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A liquid Xenon detector for micro-PET

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Micro Positron Emission Tomography

- Typical performances (LSO crystals)
  - Efficiency: 85%
  - 3D position resolution ~6 mm
    - Depth of interaction issue: crystal length ~ 30 mm
    - Resolution at center of field of view < 1.3 mm
  - Timing resolution: 3 ns (FWHM)
  - Energy resolution: <18% @ 511 keV
    - Critical to reject scattered photons

Why liquid Xenon for PET?
A good scintillator

Parameter	BGO	LSO	LXe	Comment
Attenuation length at 511 keV	11 mm	12 mm	36 mm	Required depth ≥ 10 cm
Photo-electric fraction	42%	33%	22%	Require handling Compton interactions
# Photons at 511 keV	3,300	16,400	12,000 (2kV/cm)	
Decay time	300 ns	40 ns	2 ns (97%) 27 ns (2%)	< 1ns timing resolution possible in principle
Peak wavelength	480 nm	420 nm	178 nm	Require special photo-sensors

Why liquid Xenon for PET? Adding charge measurement

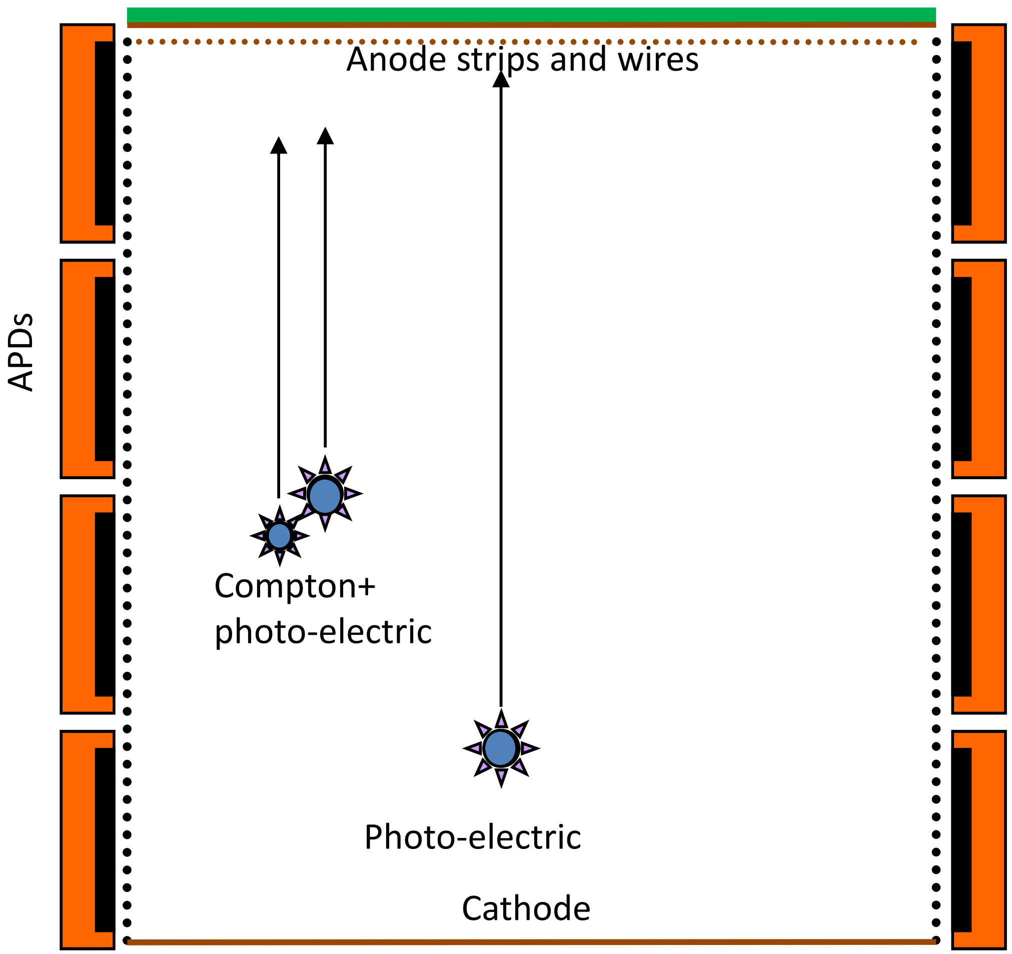
- # electrons ~ 20,000 @ 511 keV (2kV/cm)
  - To be compared with typical electronics noise ~ 1,000 e- (equivalent noise charge)
- Charge collection can be 100% efficient
  - With proper care. 100 μs e- lifetime require part per billion H20 and 02 level
- Position resolution defined by electrode granularity
  - Diffusion is very small 50 μm for 10 cm drift length
  - True 3D position. No depth of interaction issues
- Ability to identify individual interactions
  - Compton and photo-electric

Why Liquid Xenon for PET?

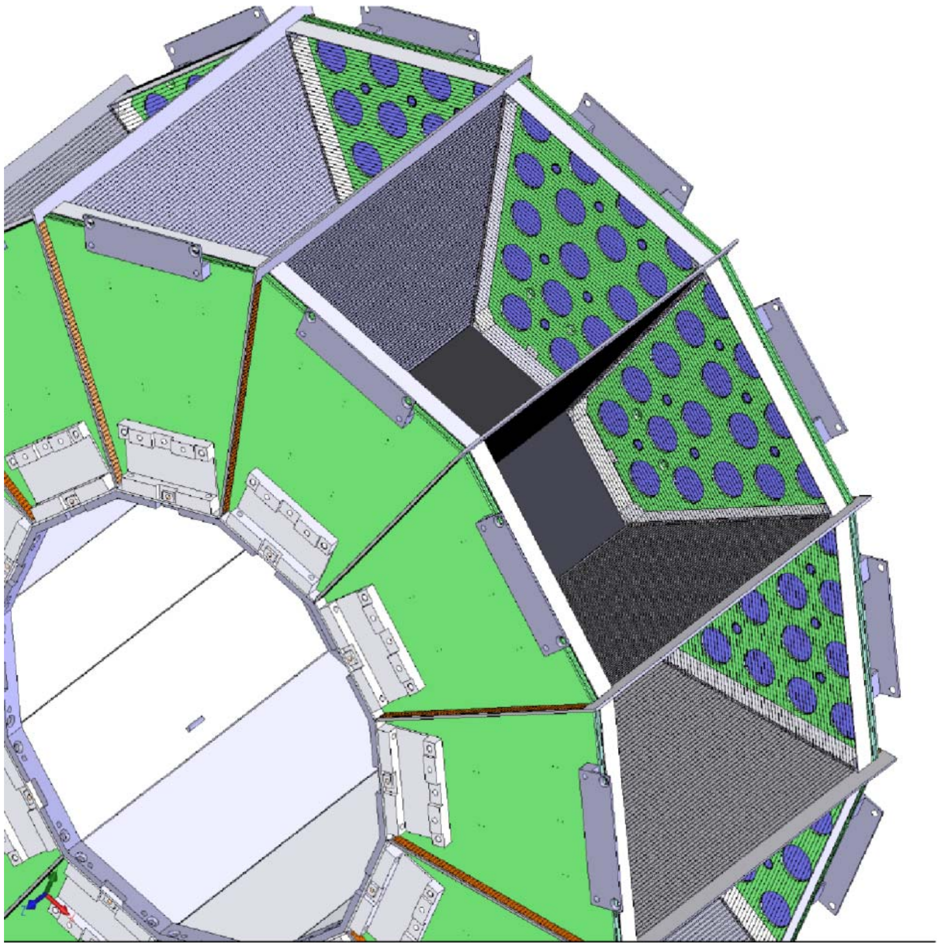
- Superior energy resolution by combining light and charge
- Superior position resolution from charge
  - No depth of interaction issue
- Superior two-hit separations
  - Ability to measure individual interactions
- Continuous detection medium
  - Improved efficiency
- Superior timing resolution from light
- Lets see how we can make this work

Concept
A liquid Xenon TPC for PET

- Time Projection Chamber
  - Electron drift to anode pads or strips
  - Reconstruct position along drift length as time between light flash and e- arrival time on anode
- Segmentation of light sensors
  - Provide some position information
  - Necessary for light-charge matching at high rate
    - Electron drift time 0.2 cm/μs

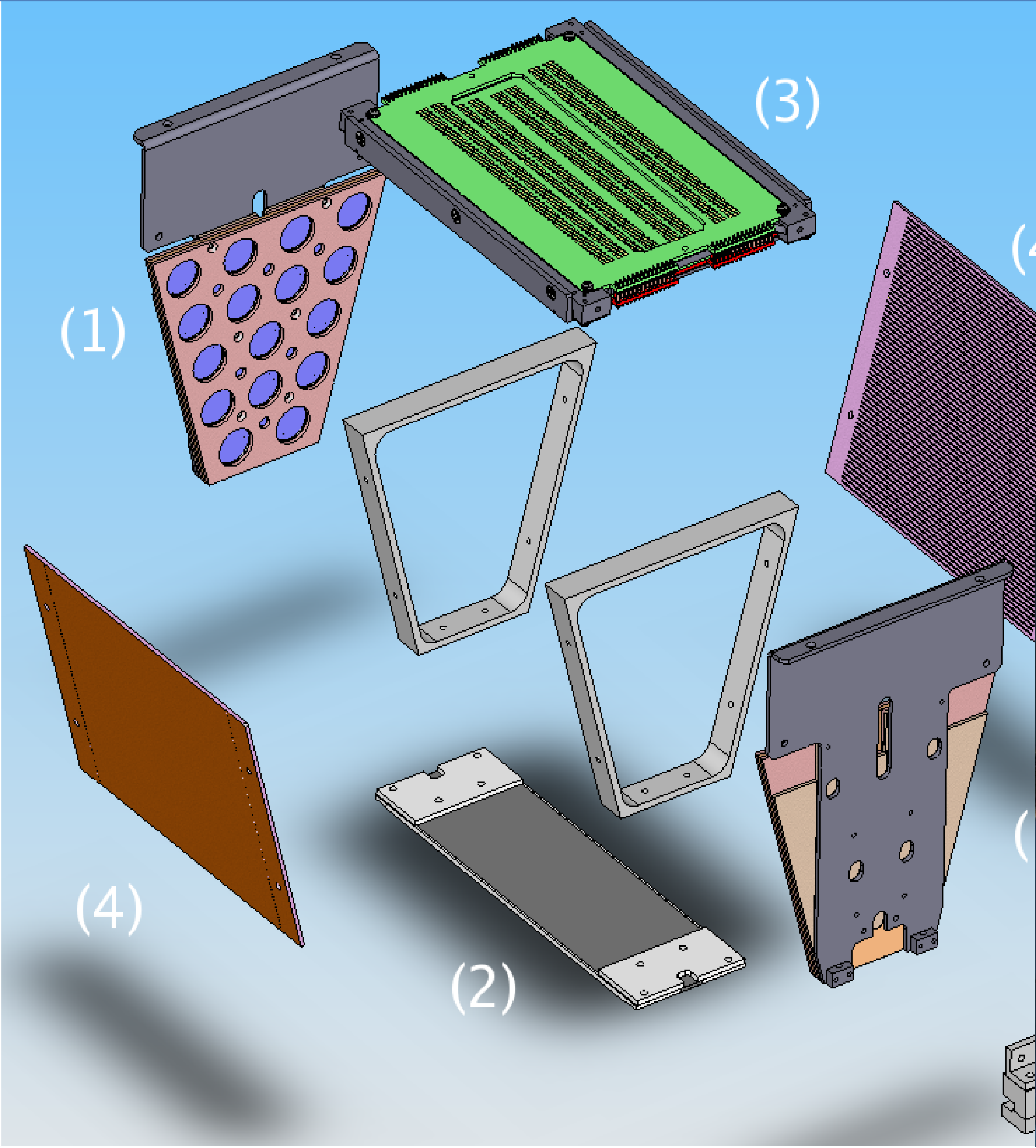


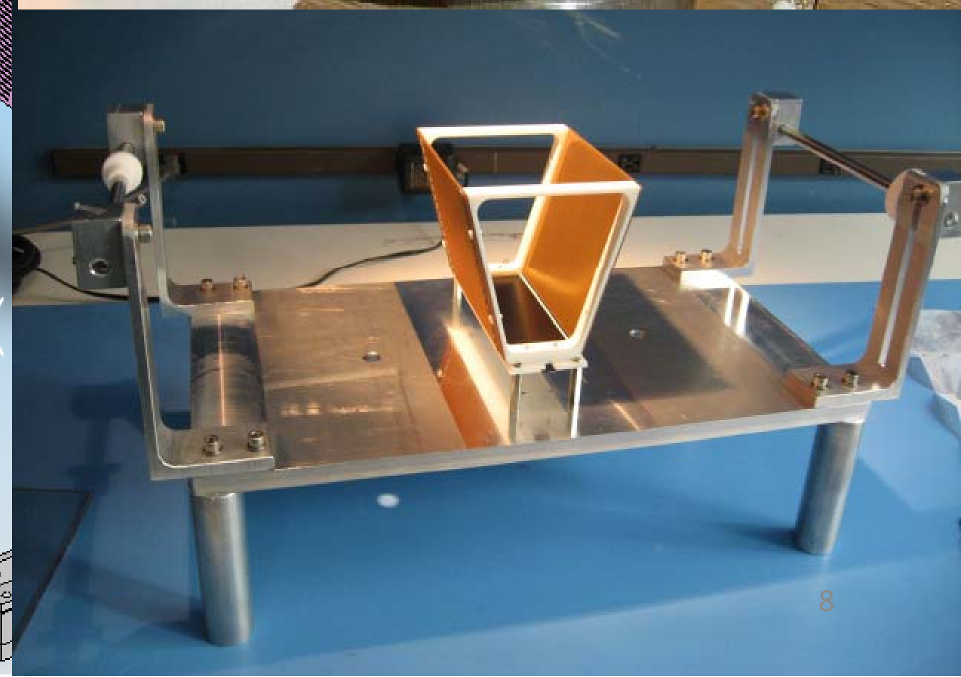
Micro-PET concept



- 12 trapezoidal sectors
  - Axial length = 8cm
- Electron drift from inner to outer radius
  - Maximum drift length 12 cm
  - Readout on sets of strips and wires
- APDs on both side of the trapeze

Micro-PET concept





Current work

- Building and operating a sector prototype
- Addressing some liquid Xenon issues
  - How to optimize energy resolution?
    - Combining light and charge is required
    - What is driving the energy resolution
  - How to handle Compton interactions?

Energy loss in Liquid Xenon

$$R^* + R \rightarrow R_2^* \rightarrow 2R + h\nu$$

or

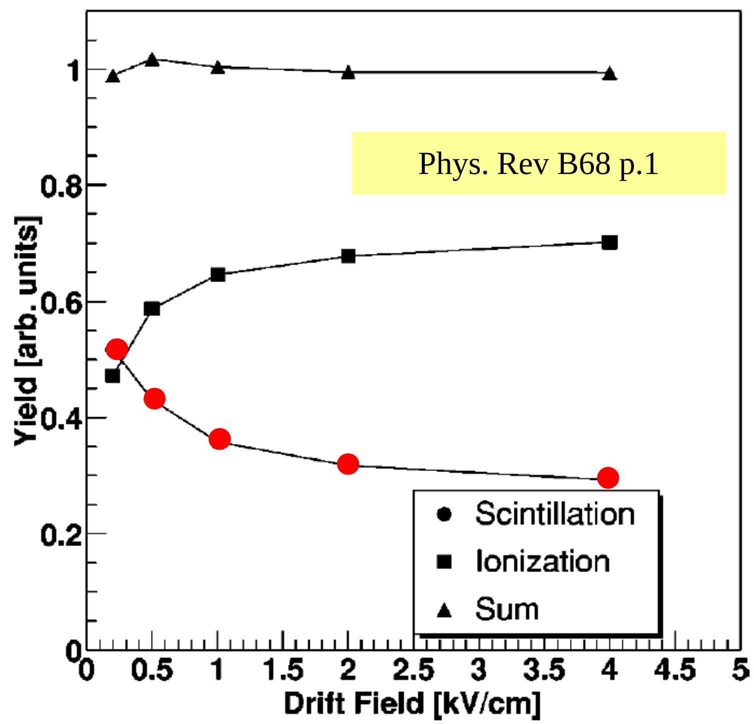
$$R^+ + R \rightarrow R_2^+,$$

$$R_2^+ + e^- \rightarrow R^{**} + R,$$

$$R^{**} \rightarrow R^* + \text{heat}$$

$$R^* + R \rightarrow R_2^* \rightarrow 2R + h\nu$$

Deep UV light
Ionization
Heat (IR, phonon)



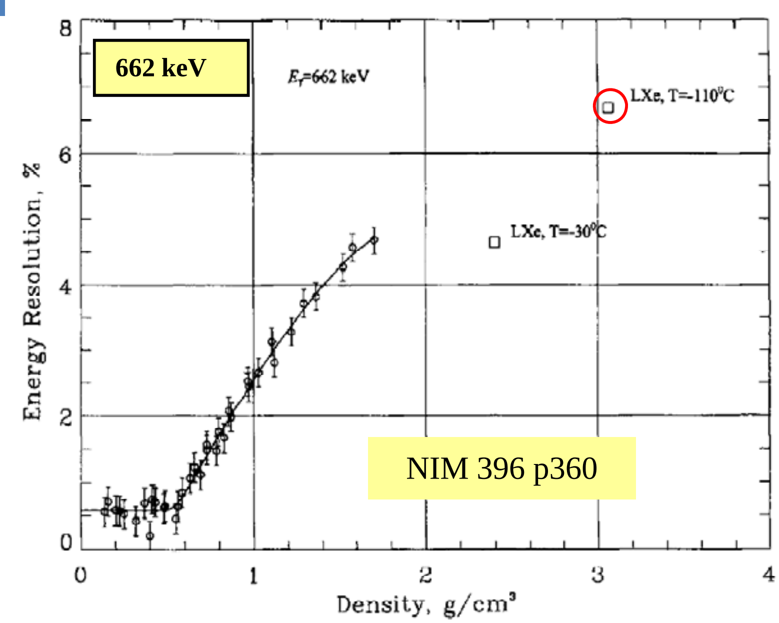
- Different type of quanta a produced
  - Scintillation
    - Enhanced by recombination
  - Ionization
    - Reduced by recombination
  - Heat/phonon
- Simple model:

$$Q = Q_0(1 - Fr) \text{ and } S = S_0 + Q_0 Fr P_{q\rightarrow\gamma}$$

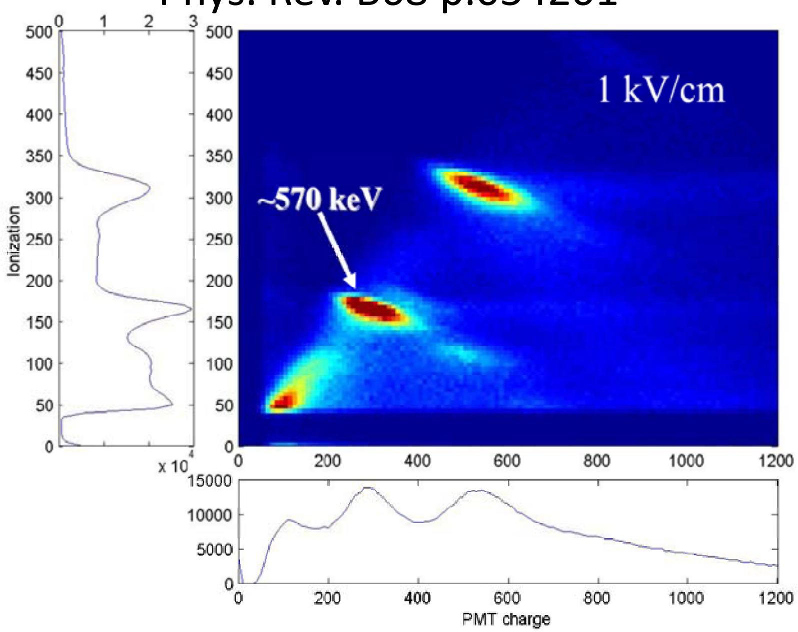
Q_0 Number of e^--ion initially produced = 511keV/15.6eV
S_0 Number of UV photons initially produced ~ 0.2 Q_0
Fr Fraction of e^--ion recombining
$P_{q\rightarrow\gamma}$ Probability that a recombination produce a photon
Has been measured to be 1 (Aprile et al.)

Event by event fluctuations worsen the energy resolution

- Energy resolution from ionization much worse than Fano limit
  - Density fluctuations?
    - Variation of recombination
  - Correlation with scintillation improves resolution



Phys. Rev. B68 p.054201

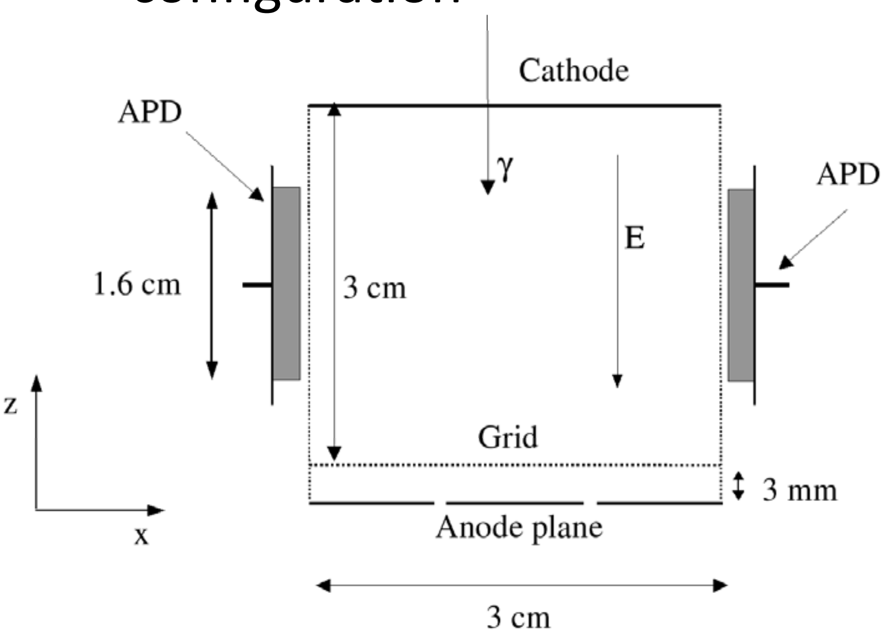


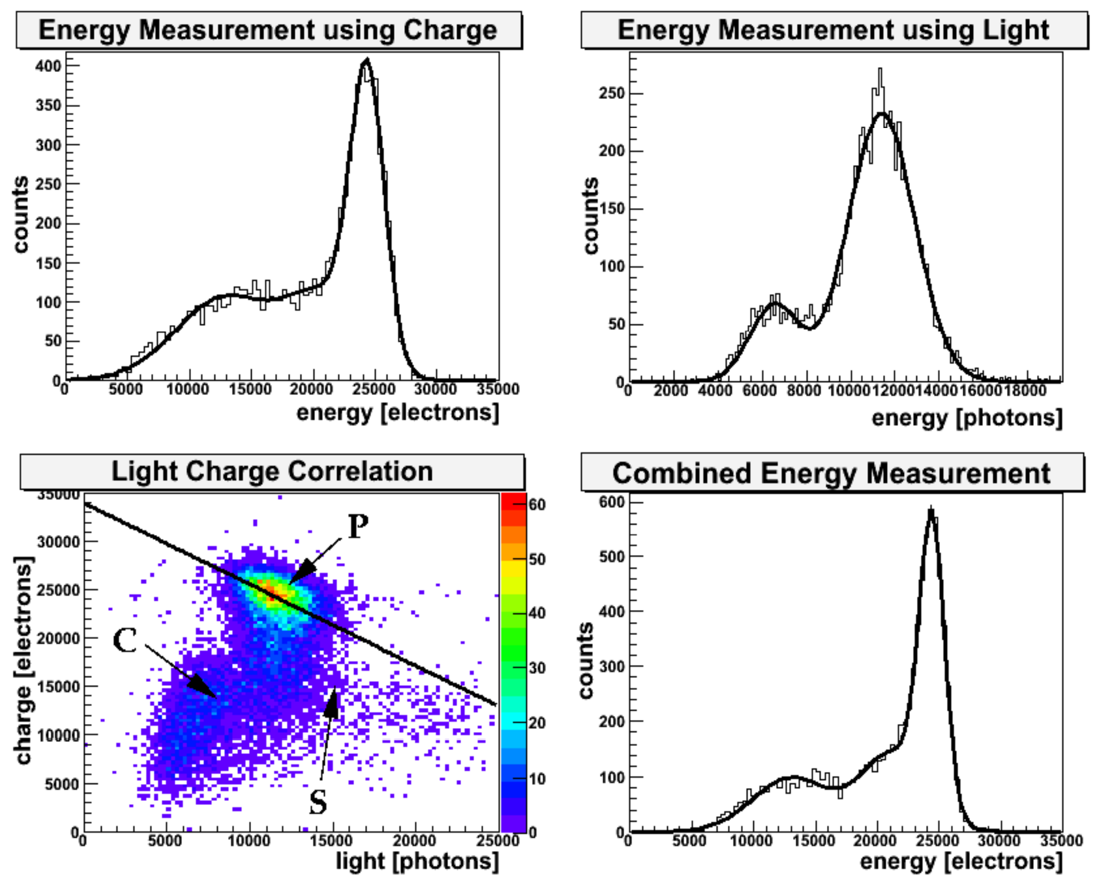
$$\frac{\Delta Q}{Q}=\frac{\Delta Fr}{(1-Fr)} \text{ and } \frac{\Delta S}{S}=\frac{\Delta Fr}{0.2+Fr}$$

Introduce ΔFr the fluctuation of the number of recombining e$^-$-ion

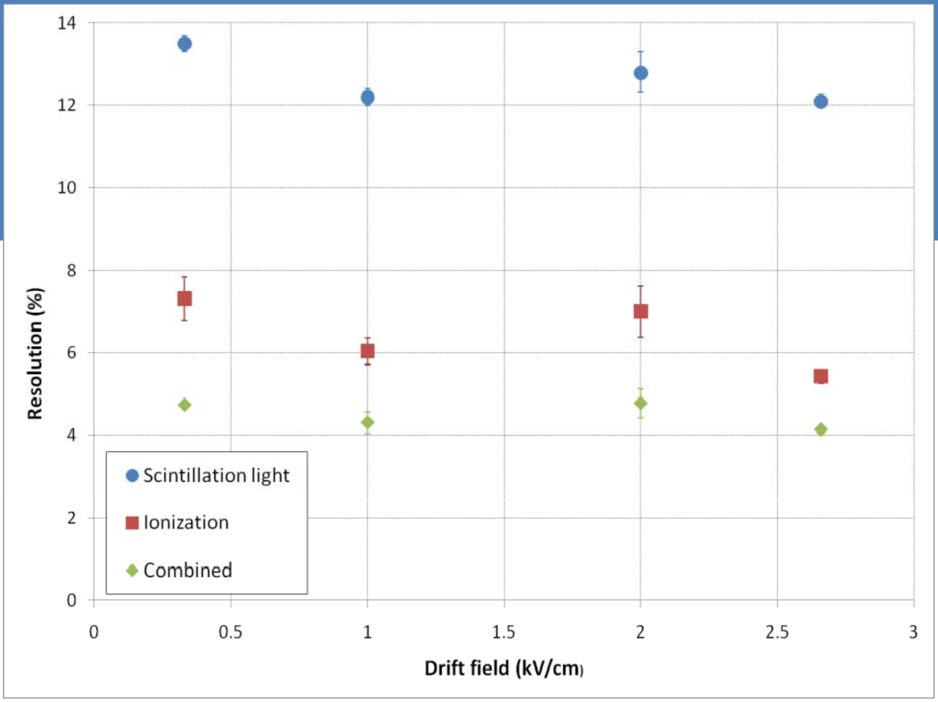
Solution: combining light and charge

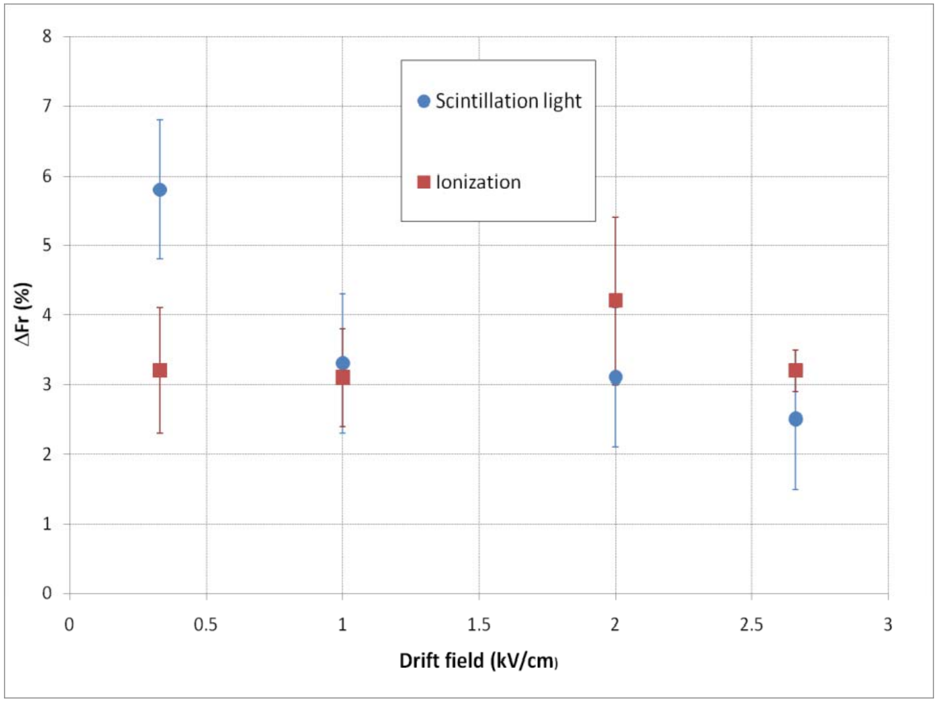
- 4% (sigma) has been measured
- Build a test chamber to investigate energy resolution
  - Use APD
  - Use Time Projection Chamber configuration





Energy resolution



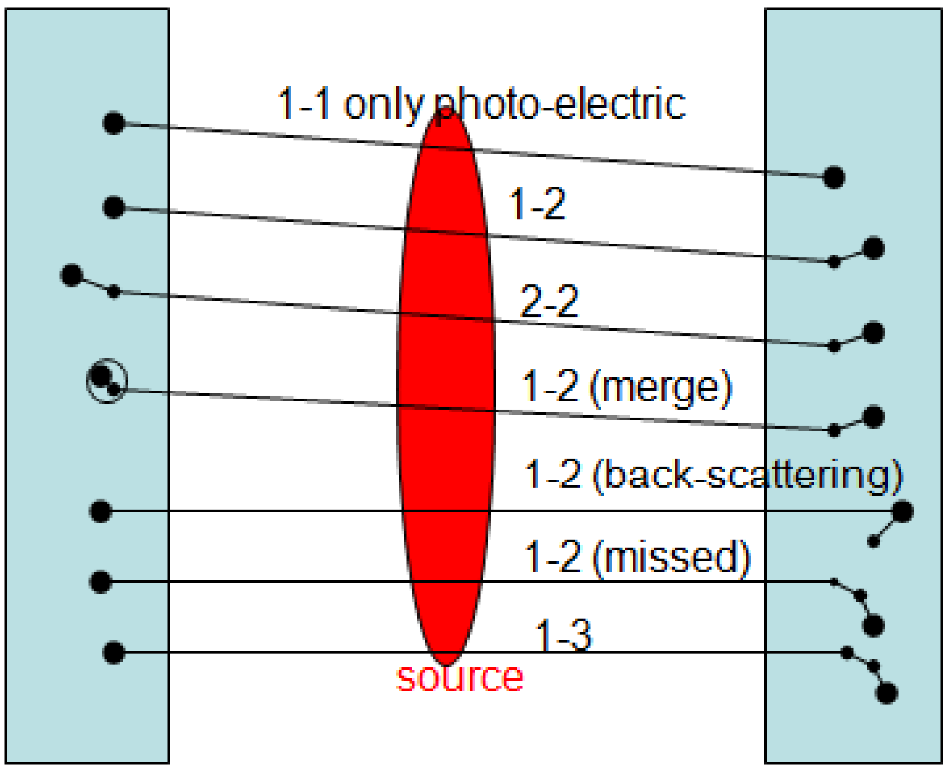


- Before combining resolution dominated by recombination fluctuations
- After combination main source of fluctuations:
  - Electronic noise on electrode (ionization)
    - 2.7%
  - APD gain fluctuation
    - 2.7%
- ΔFr parameterization is self-consistent

Dealing with Compton interactions

- The 1st interaction in Xenon is a Compton 78% of the time
  - Distance between the 1st and 2nd interactions exceed position resolution
- Finding the first interaction point is critical to achieve pointing resolution
- In addition Compton reconstruction may be used to reject background

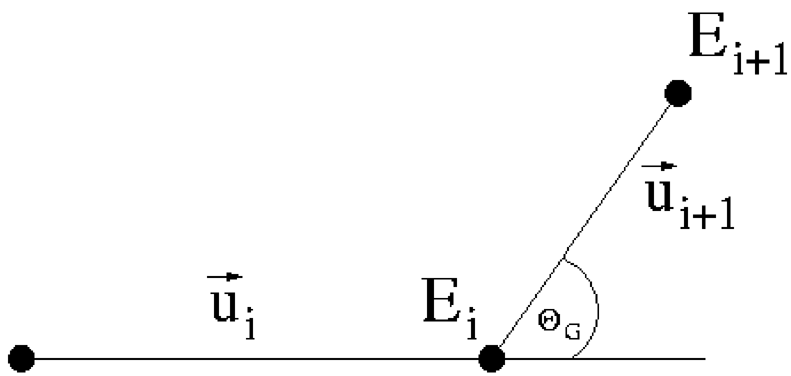
A large number of configurations

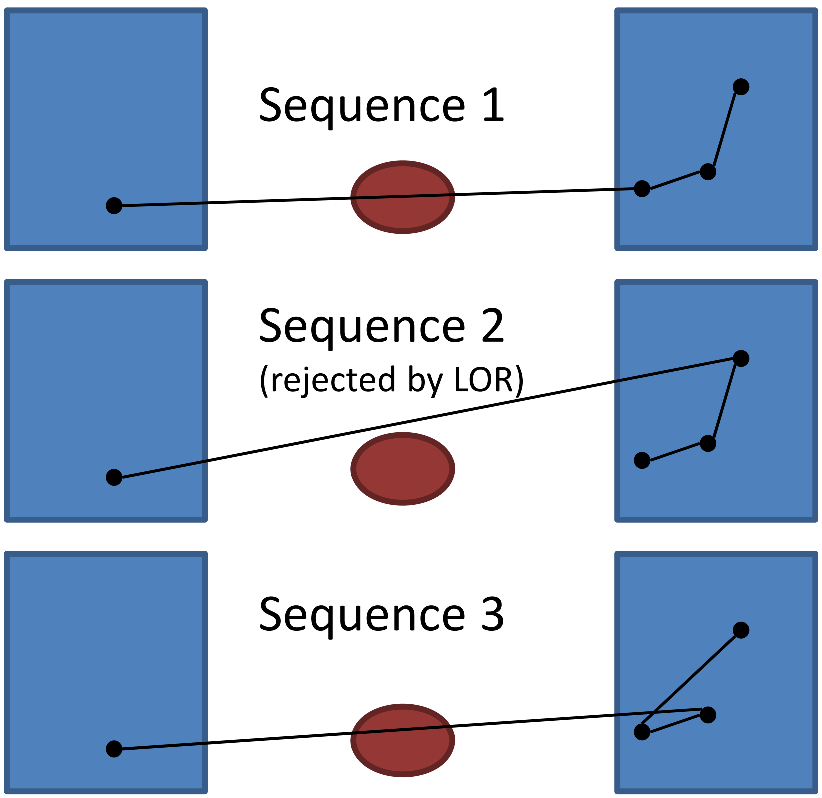


Topology	Intrinsic	2 hit distance > 1 mm	Hit E > 50 keV	both
1-1	7.6%	9.7%	9.7%	12.3%
1-2	20.8%	24.4%	28.0%	31.6%
1-3	12.6%	13.1%	12.5%	12.0%
1-4	4.9%	4.4%	2.2%	1.8%
2-2	14.1%	15.0%	20.2%	20.3%
2-3	17.3%	16.3%	18.1%	15.5%
2-4	6.7%	5.5%	3.2%	2.3%
3-3	5.3%	4.4%	4.0%	2.9%
3-4	4.0%	2.9%	1.4%	0.9%
4-4	0.8%	0.5%	0.1%	0.1%

No need to investigate higher order topological configurations

Compton reconstruction algorithm



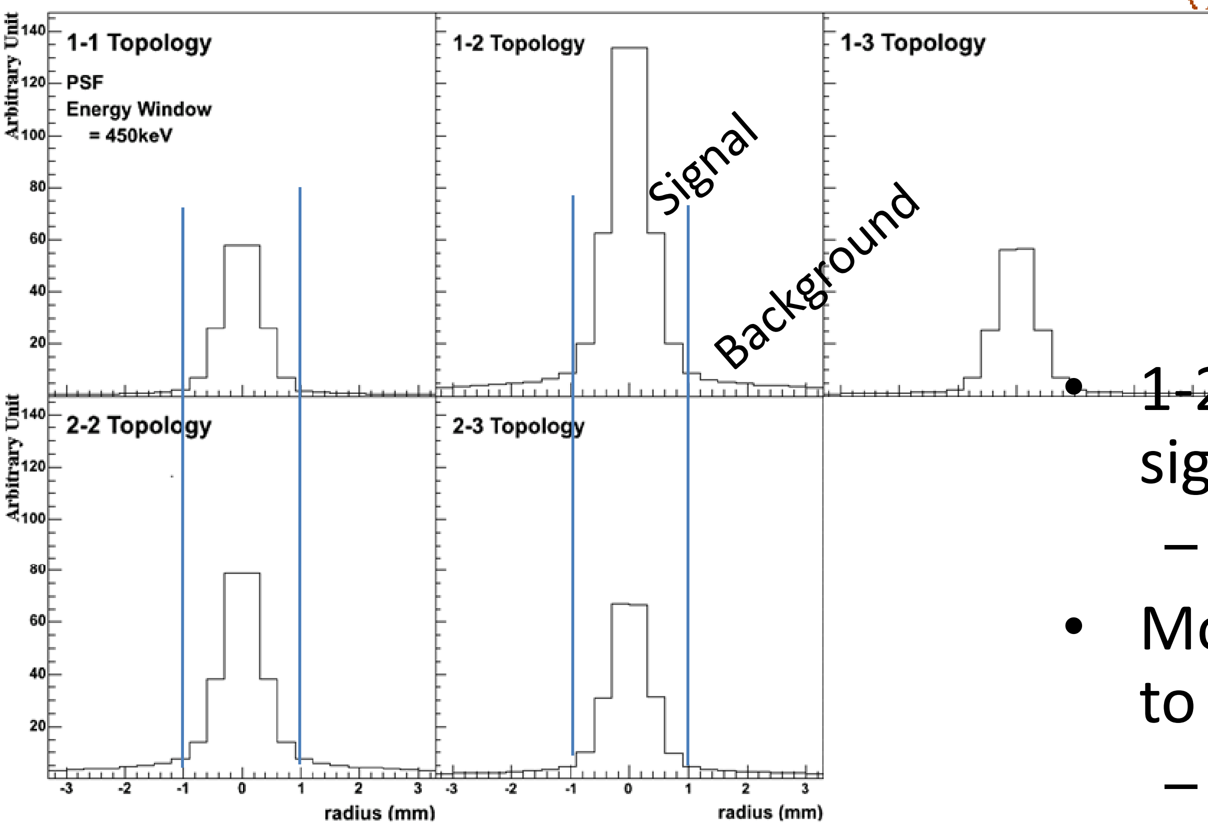


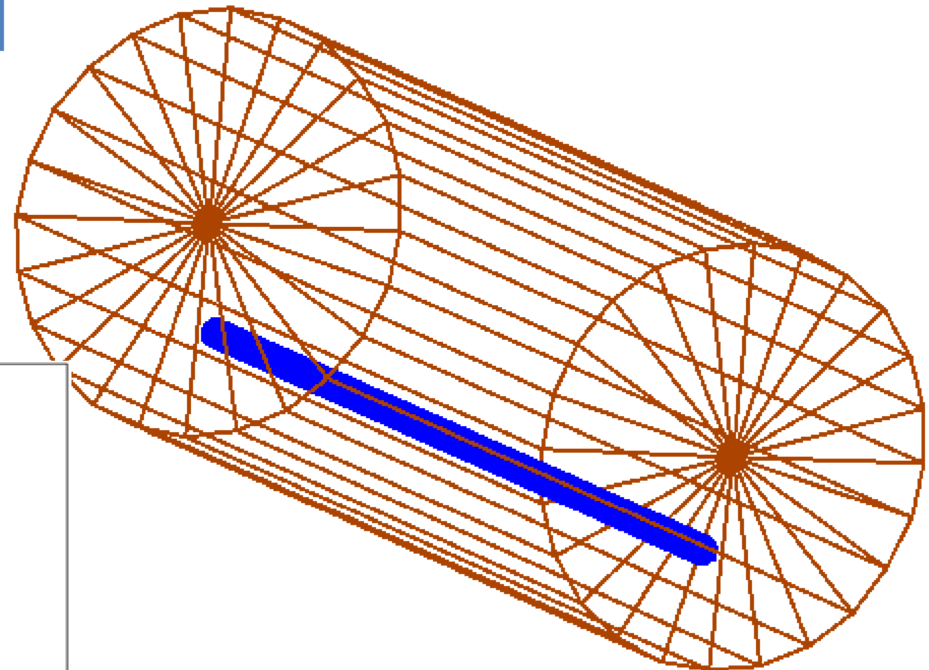
Sequence 4, 5, 6 not shown

- Build every possible interaction sequence using the information on both detector sides
  - Reject the sequence that lead to Line of Response outside the sample volume
- For each sequence
  - Calculate two angles at every possible scattering point
    - From energy deposited
    - From geometry
    - Assess the errors of both methods (energy always dominate errors)
  - Calculate a chi2 quantity comparing the energy and geometrical angle
  - Select the sequence with lowest chi2

Algorithm evaluation by simulations

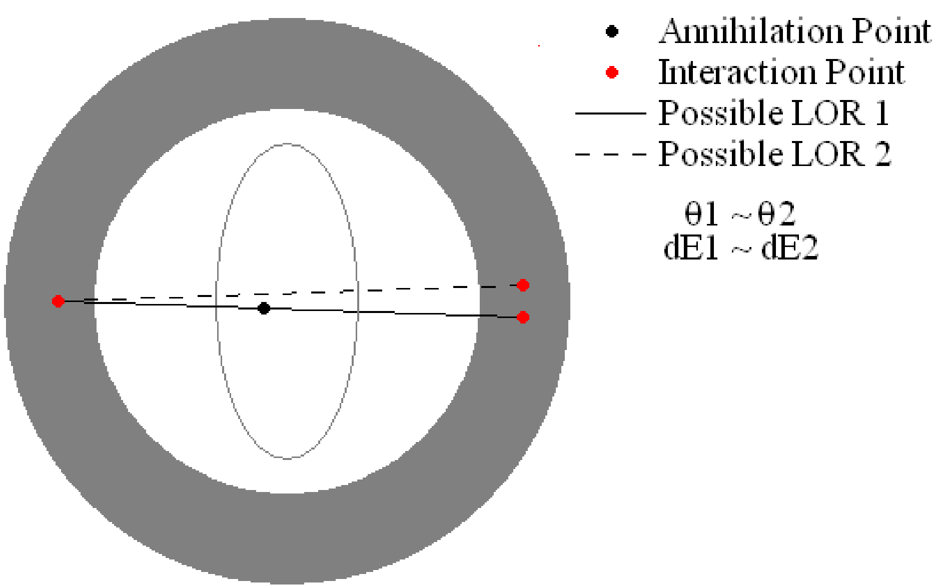
- Simulate using GEANT
- Use NEMA phantom scaled for micro-PET

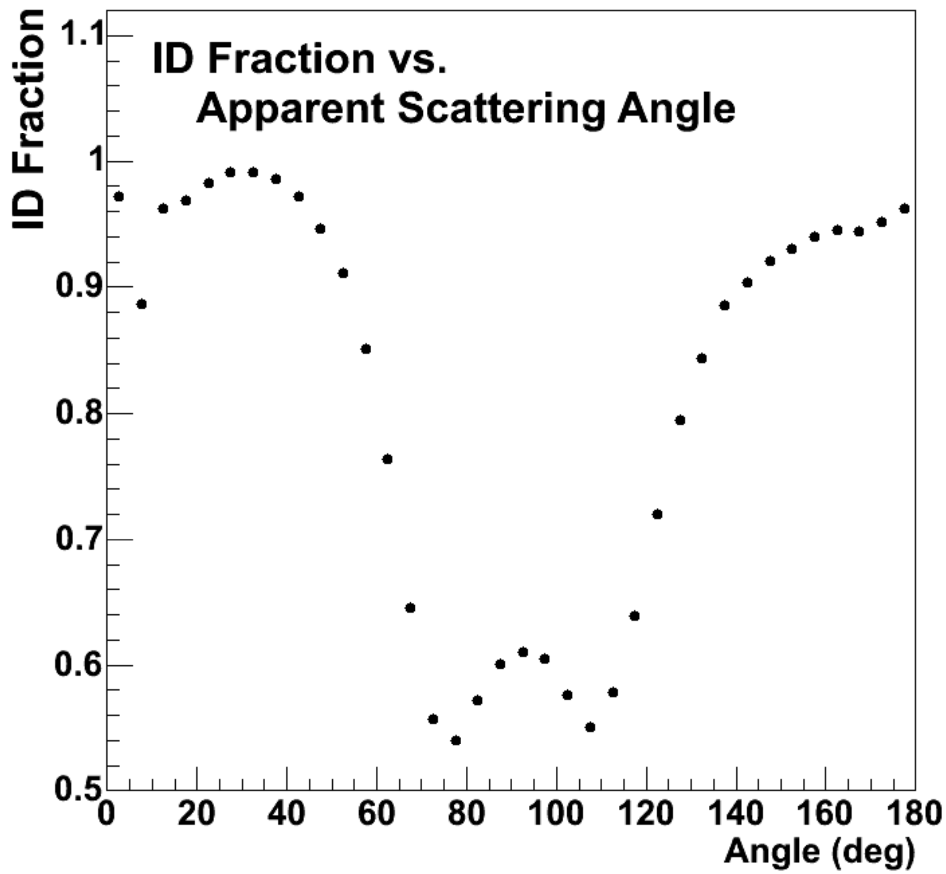




- 1-2 and 2-2 have the worst signal to background
  - Some irresolvable ambiguities
- Most of the background is due to selecting wrong first point
  - Random and scatter very much suppressed due to very good energy and time resolution

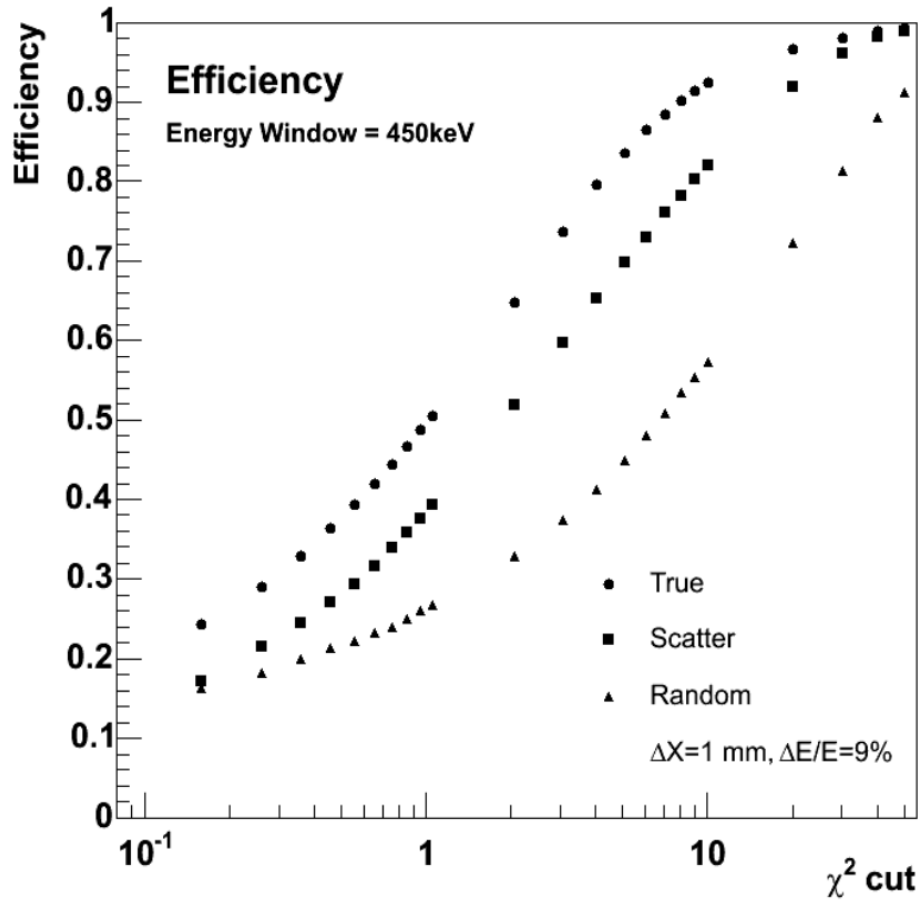
Some sequences are almost un-resolvable

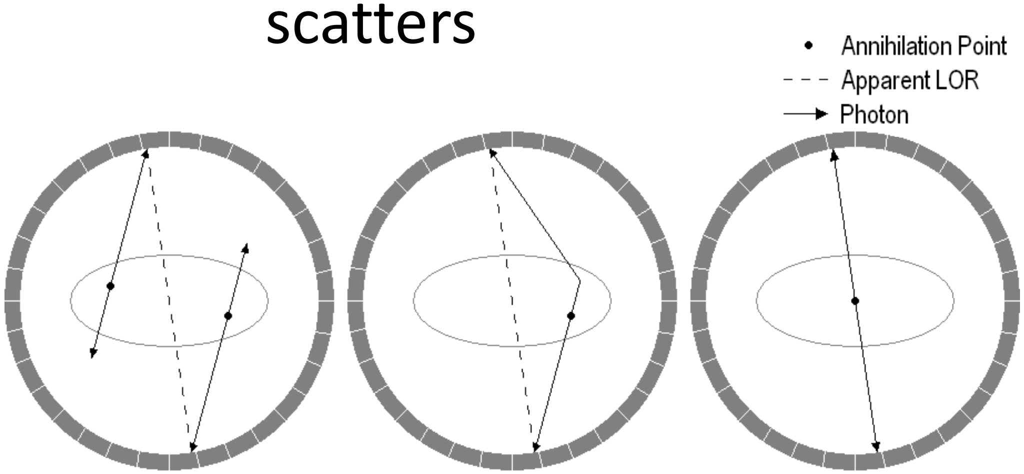




Using chi2 to reduce background

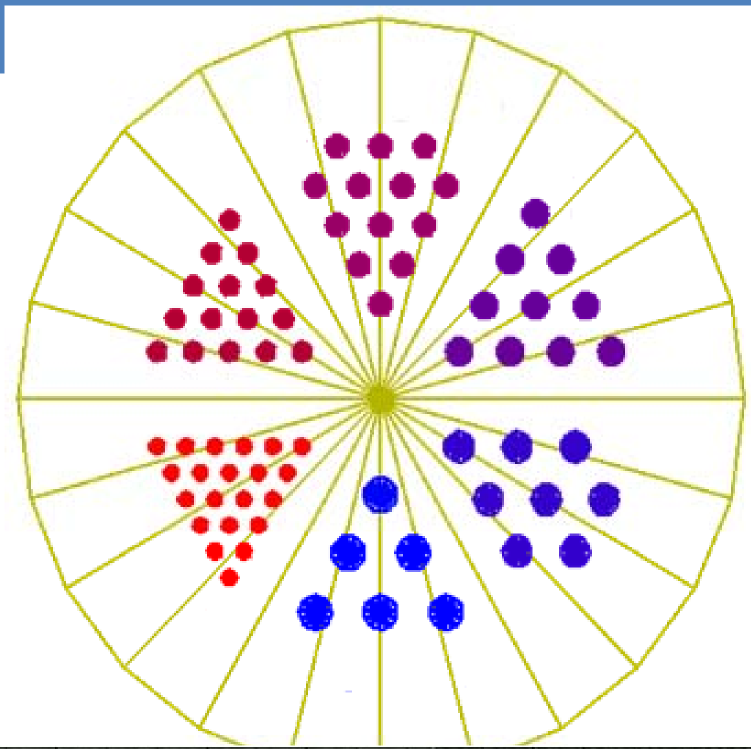
- Events with high chi2 could be removed
  - Price : loss of statistics
- Can remove scatter and randoms
  - However, 450keV energy window gets rid of most scatters

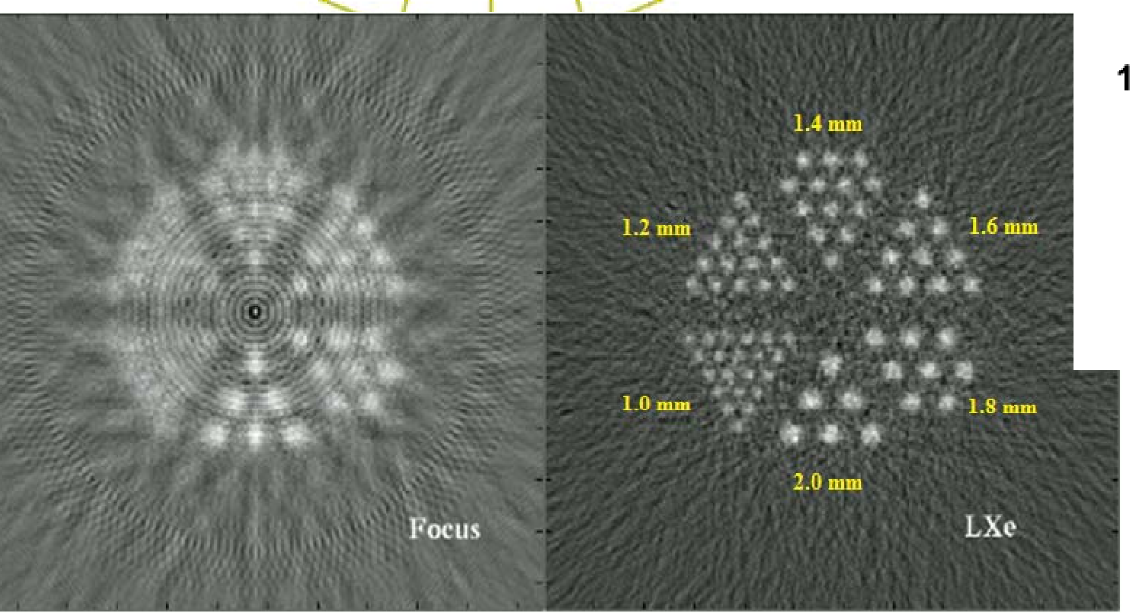


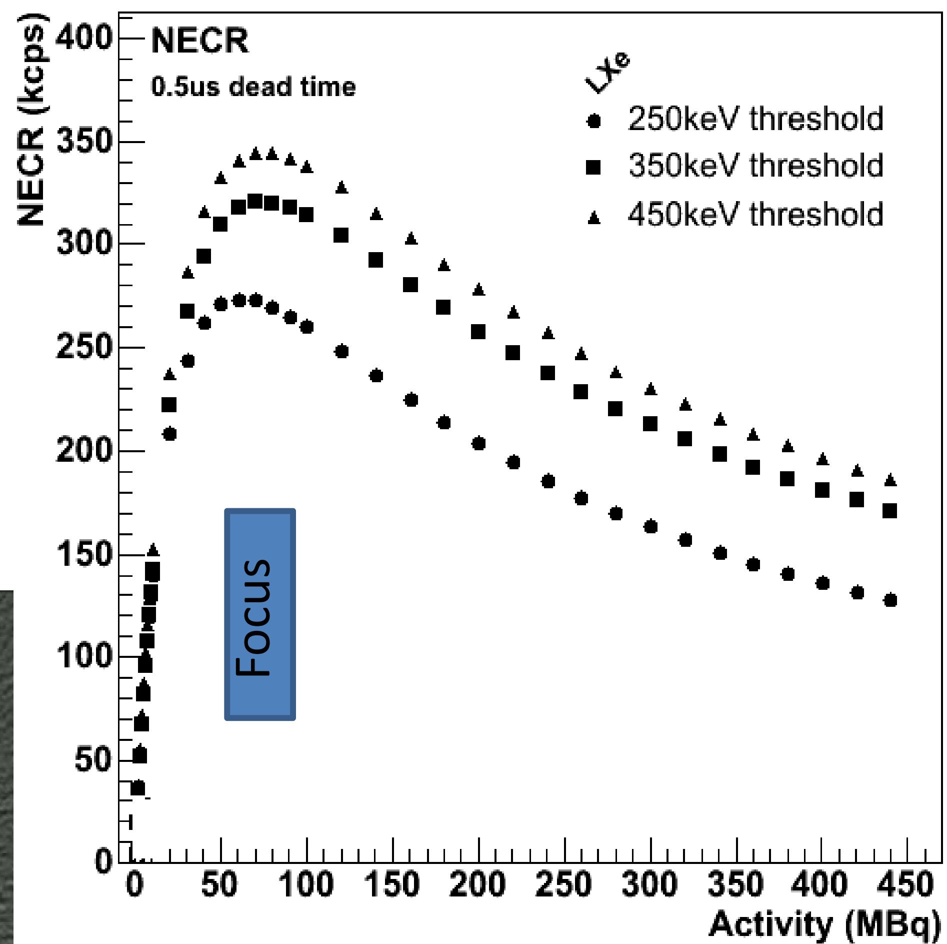


a) Random b) Scatter c) True

Image quality





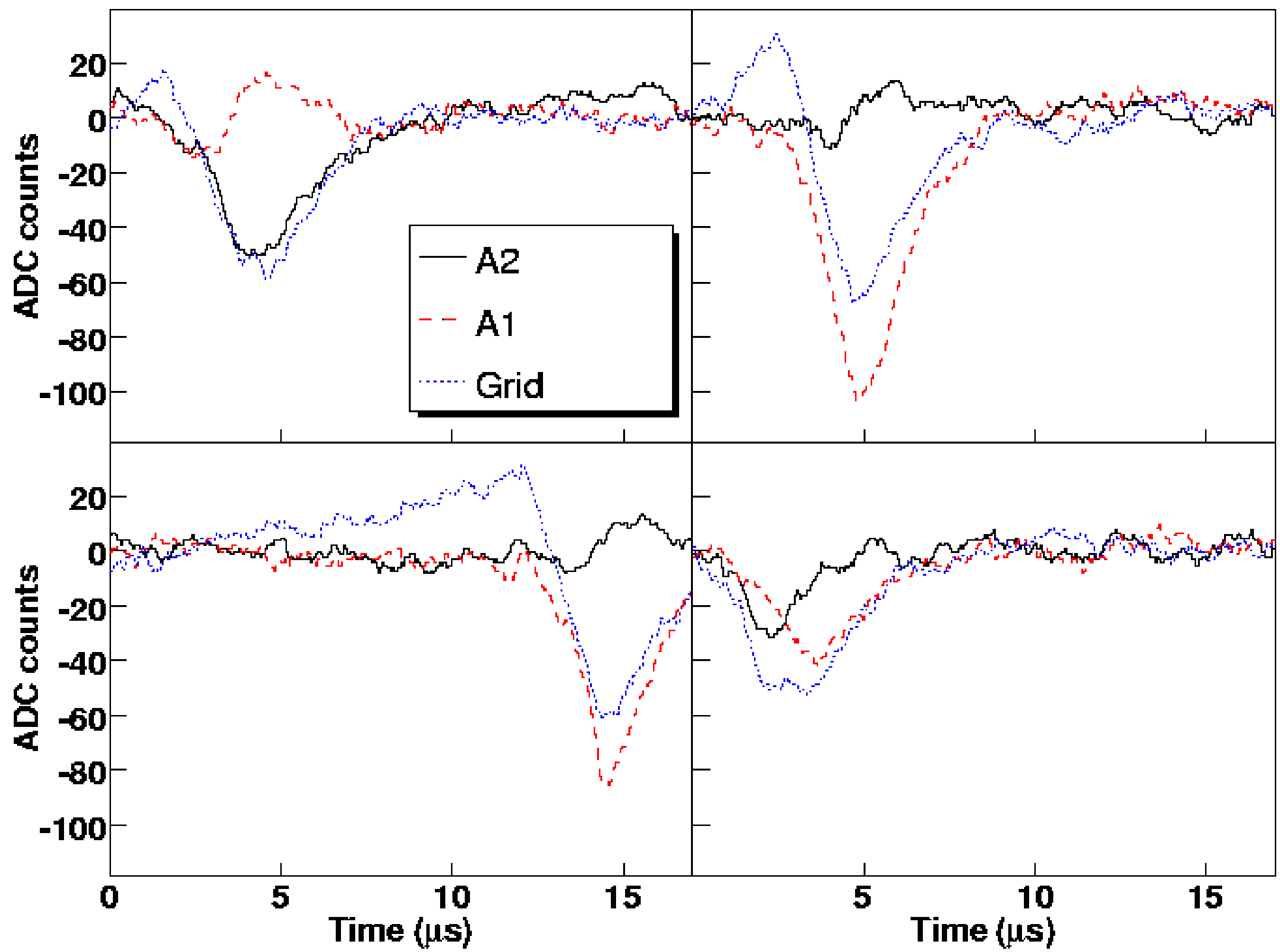


Summary

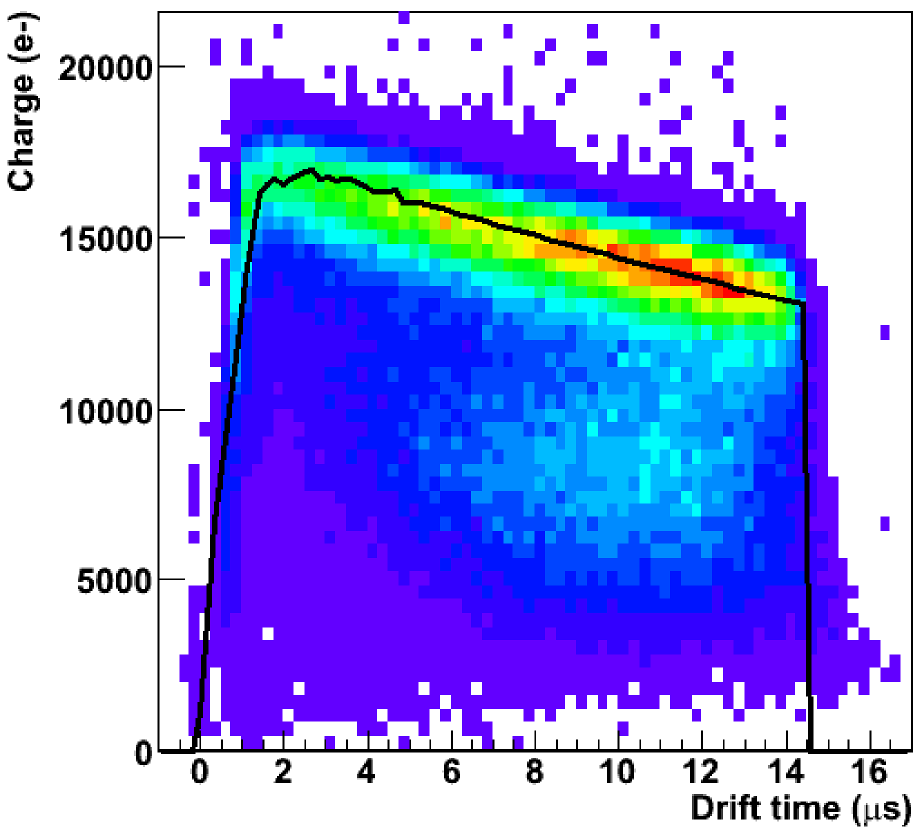
- A liquid Xenon micro-PET detector is being developed
  - Concept is established
  - Prototyping is on-going
    - Energy resolution issues are understood
  - First sector operational very soon
  - Ring (2 sectors) operational in 2010
- Simulations show very significant improvement in image quality
  - Compton interactions must be handled with great care
  - Mis-identified Compton sequences dominate the background

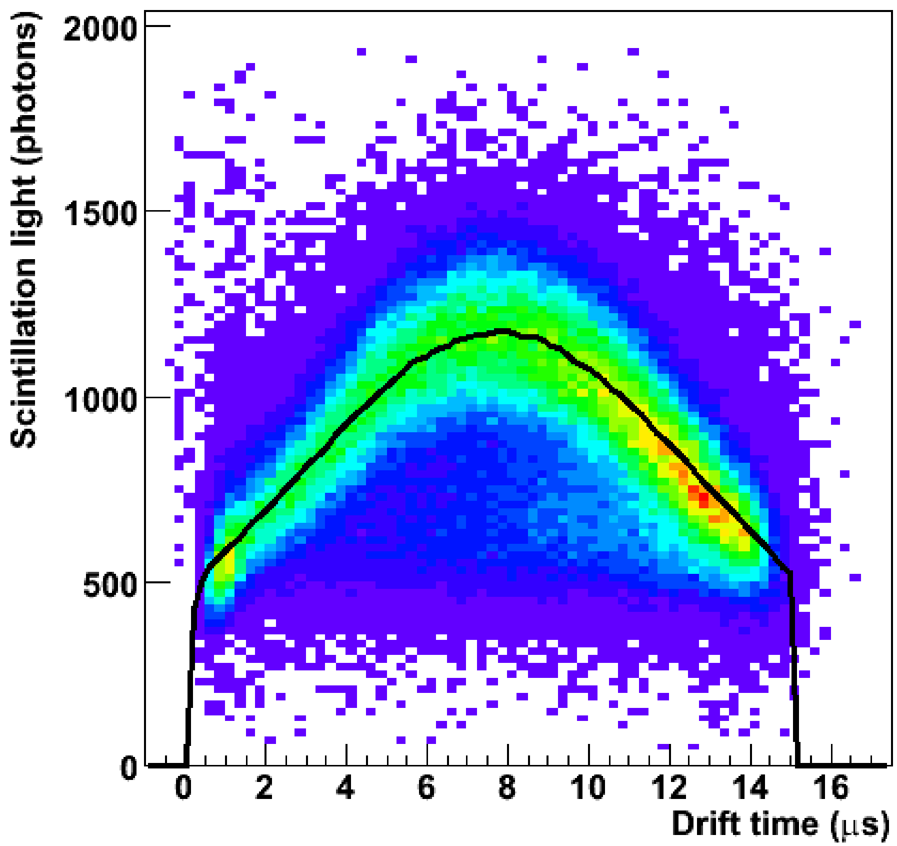
BACKUP

Waveforms in small chamber



Charge and light collection in small chamber





Chi2 vs topology