CANADA'S NATIONAL LABORATORY FOR PARTICLE AND NUCLEAR PHYSICS

Owned and operated as a joint venture by a consortium of Canadian universities via a contribution through the National Research Council Canada

MPPC and Liquid Xenon technologies from particle physics to medical imaging

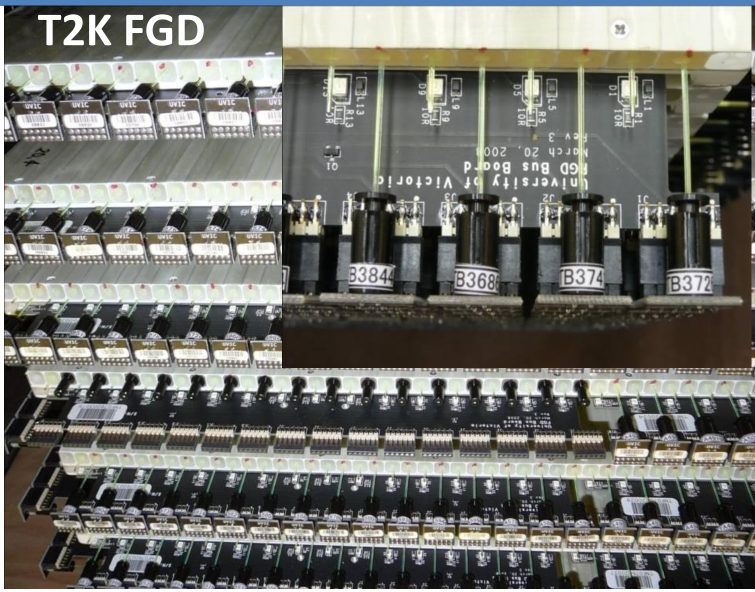
Fabrice Retière

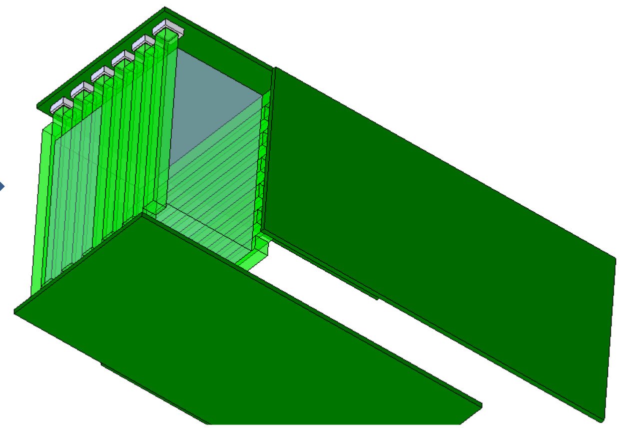
TRIUMF

LABORATOIRE NATIONAL CANADIEN POUR LA RECHERCHE EN PHYSIQUE NUCLÉAIRE ET EN PHYSIQUE DES PARTICULES

Propriété d'un consortium d'universités canadiennes, géré en co-entreprise à partir d'une contribution administrée par le Conseil national de recherches Canada

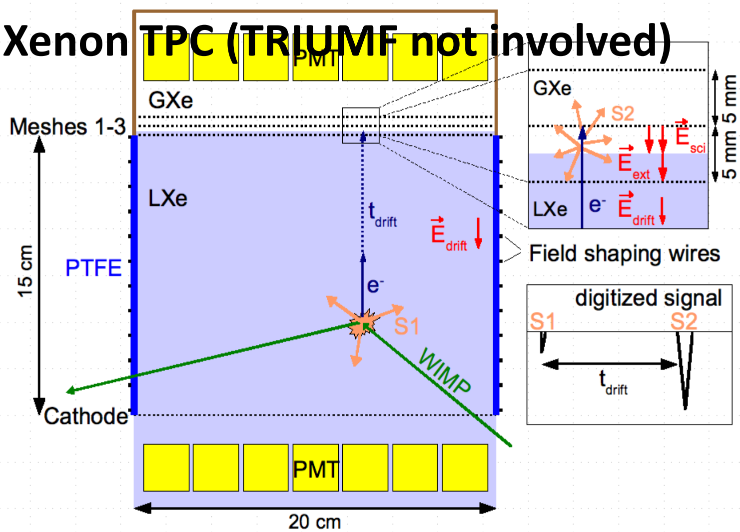
Outline

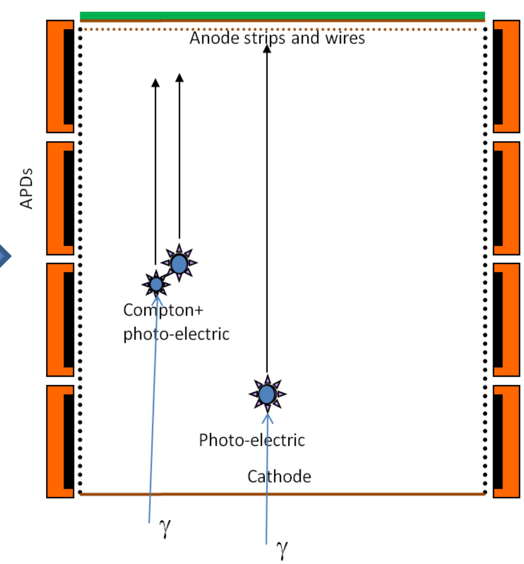




Monolithic LSO crystal readout for PET

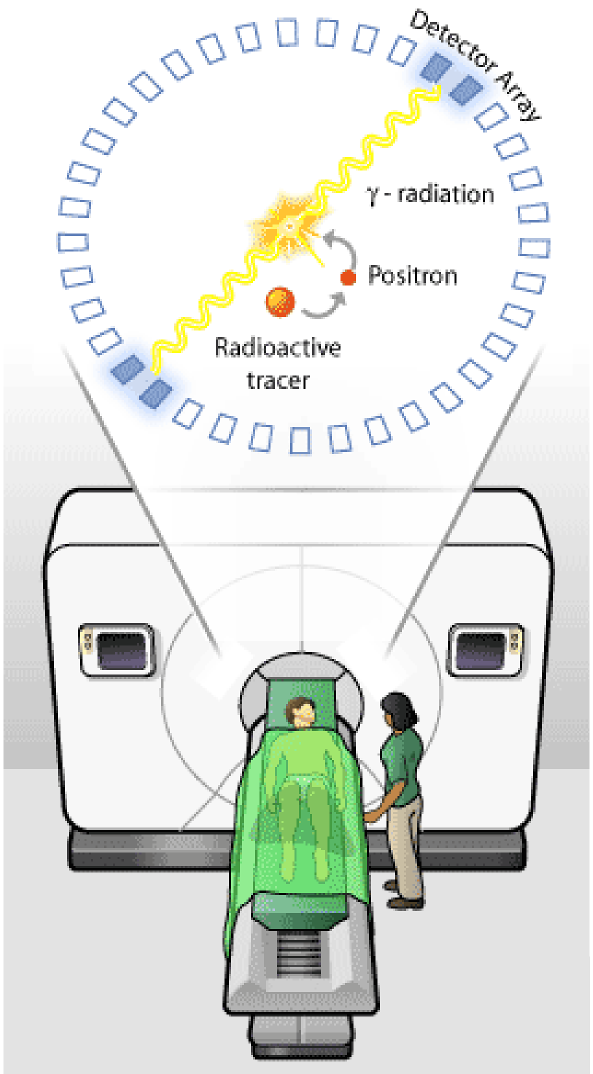
Xenon TPC (TRIUMF not involved)

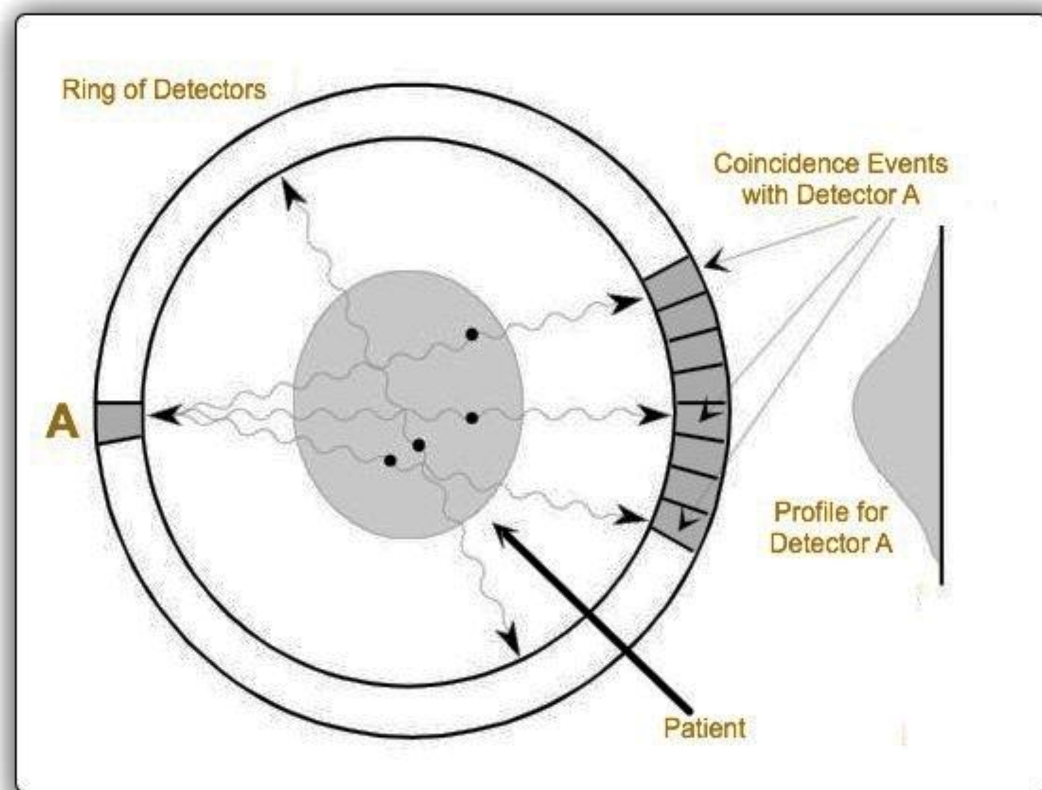




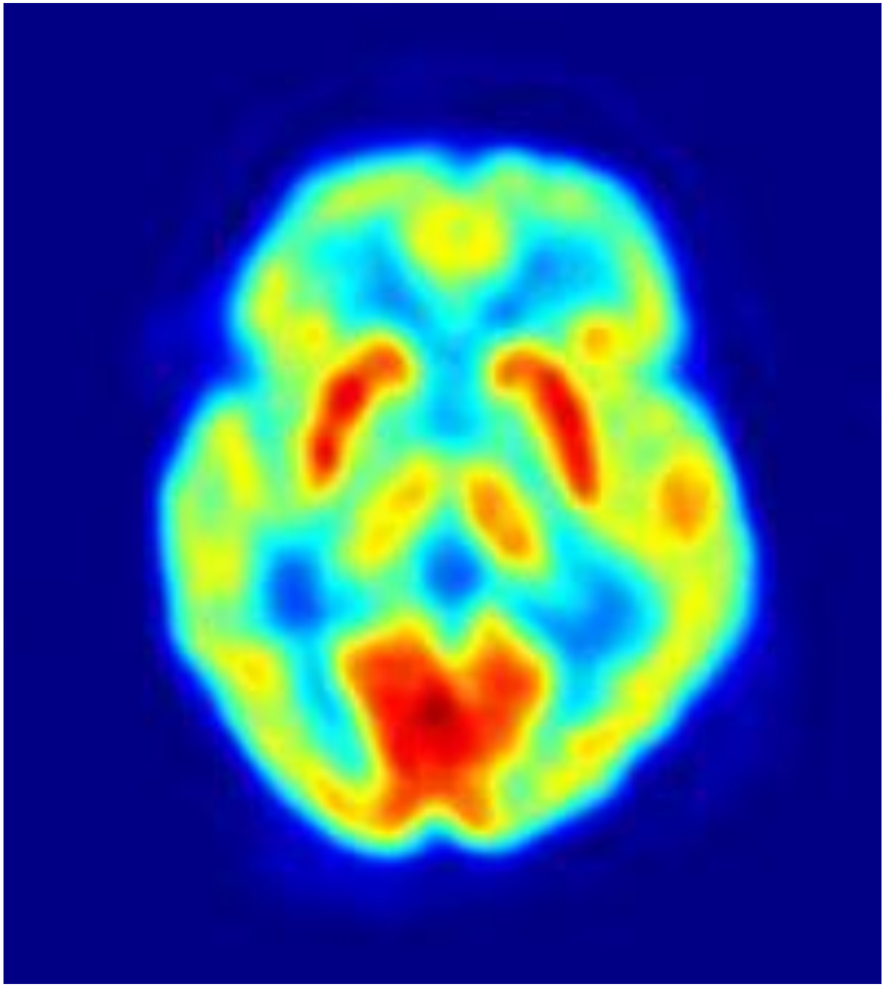
Liquid Xenon TPC for PET

Positron Emission Tomography



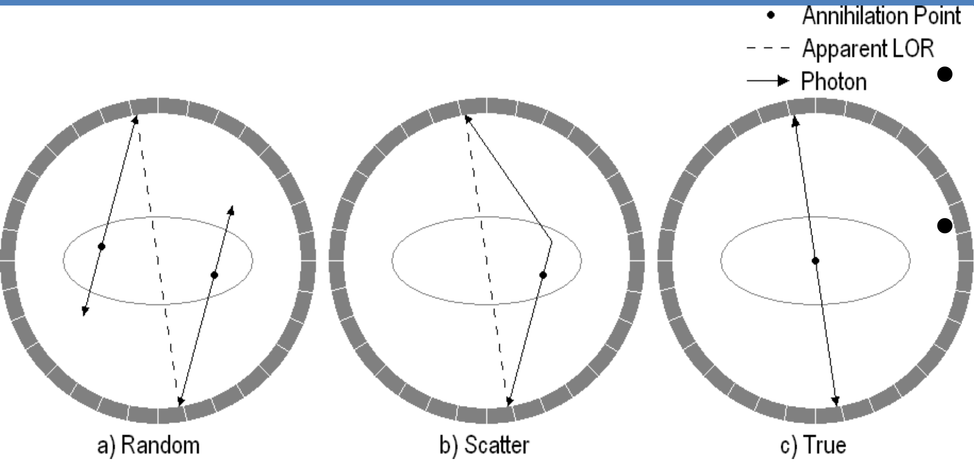


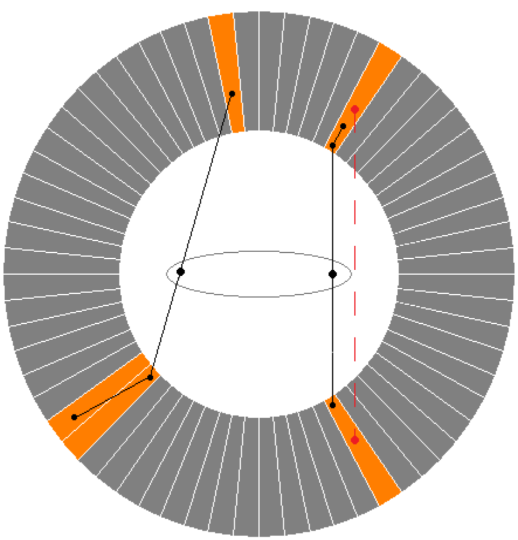
PET imaging



- PET is a functional imaging technique
  - Image biological processes
  - Tracer are design to target specific processes (e.g. tumors)
- PET does not necessarily show anatomical feature
  - The better the tracer the fewer additional features
  - Need an additional imaging technique (MRI, CT)

Blurring in PET

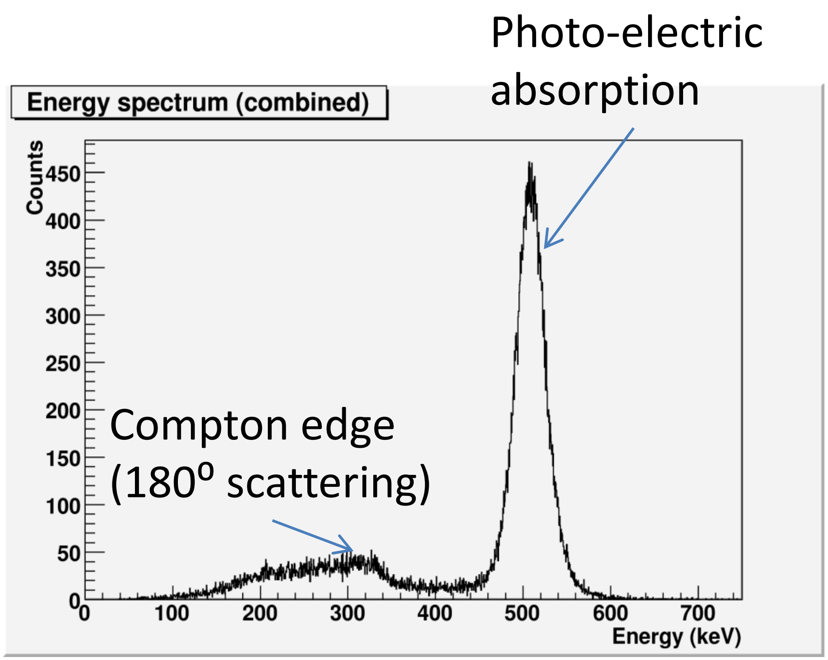




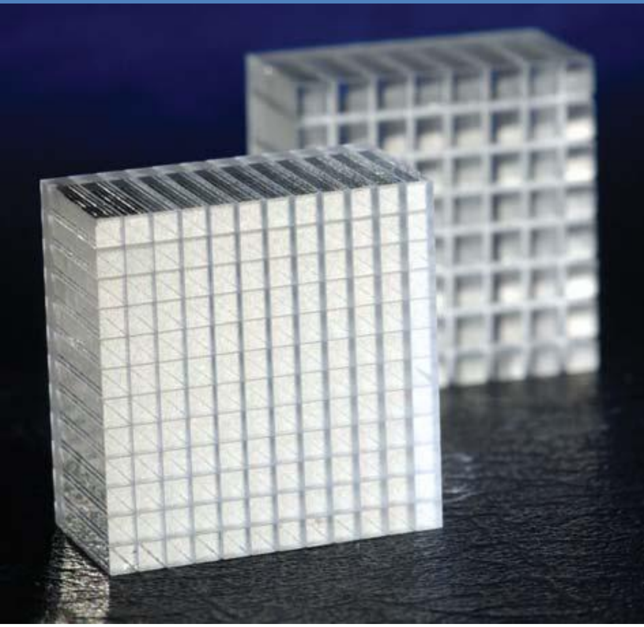
- Random combinations
  - Reduced by timing resolution
- Scatter (Compton interactions in patient)
  - Reduced by good energy resolution
- Position resolution
  - Depth of interaction
    - Need new techniques
- Compton interactions in detector
  - Reduced by higher atomic Z
- Statistics!!!
  - Image reconstructed by combining many lines of response
  - Time of flight would help

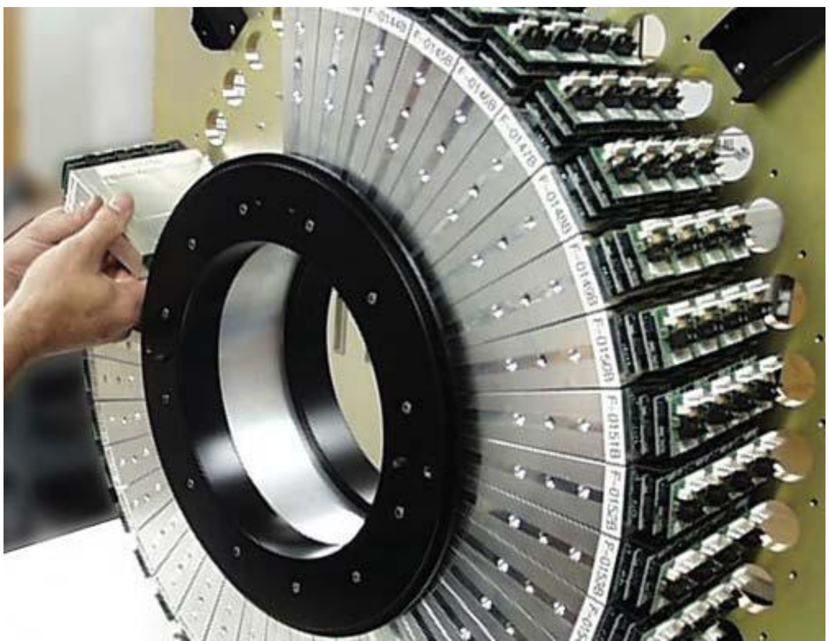
Requirement for PET
Energy resolution

- Important for removing scatters
  - Energy lost in scatters implies lower energy
  - 4% FWHM resolution is typically sufficient for removing all scatters
- Randoms are often scatter and are hence also reduced
- Energy resolution is critical for Compton reconstruction if multiple interactions are to be reconstructed



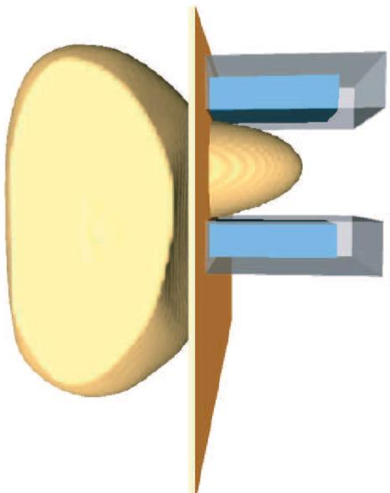
A typical micro-PET detector
Siemens Focus 120

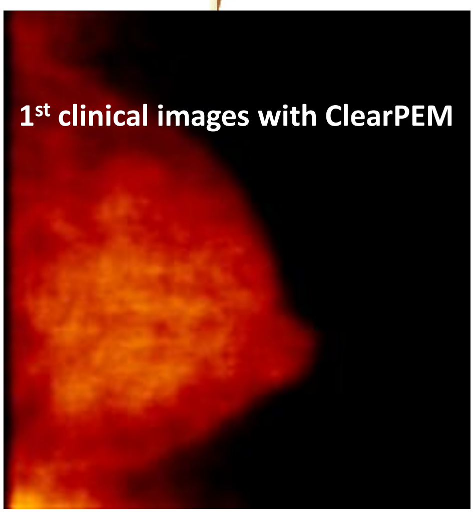


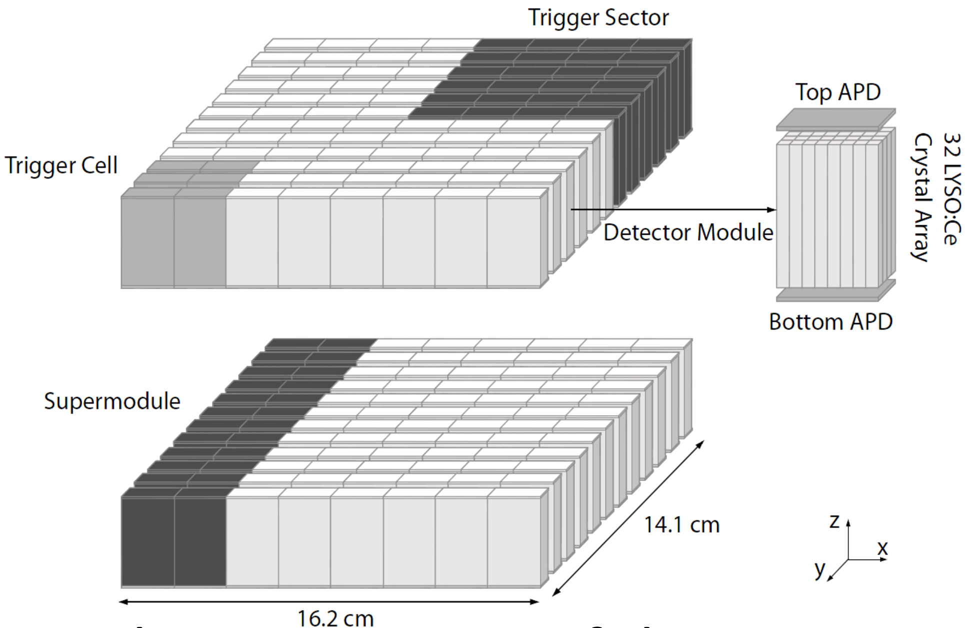


Features	Focus 120
Detector diameter	15 cm
Bore size	12 cm
Axial field of view	7.6 cm
Number of detector blocks	96
Number of LSO elements	13,824
LSO element size	1.6x1.6 mm^2
Performances	**Focus 120**
Peak sensitivity	>7%
Resolution at center of FOV	<1.4mm
Average energy resolution	18%

State of the art: clearPEM





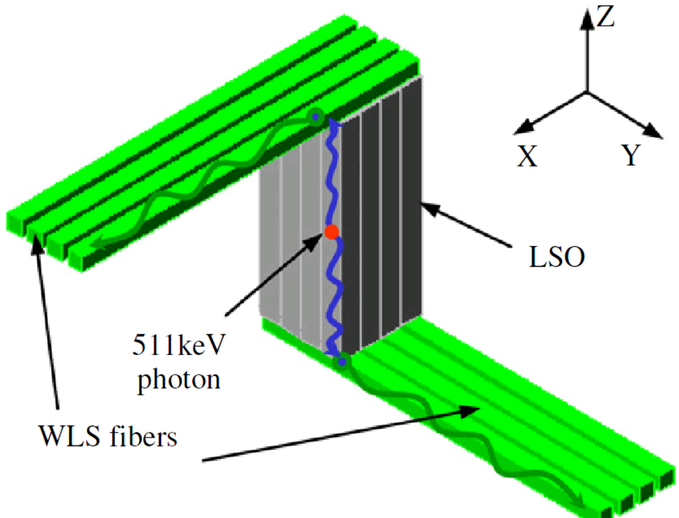


- ClearPEM: State of the art PEM
  - Very good 3D resolution
  - High sensitivity
  - Complex: 12,000 avalanche photodiodes and associated electronics
    - MPPCs could easily replace APDs

Nucl. Instrum. And meth. Volume 571, Issues 1-2, (2007), Pages 81-84

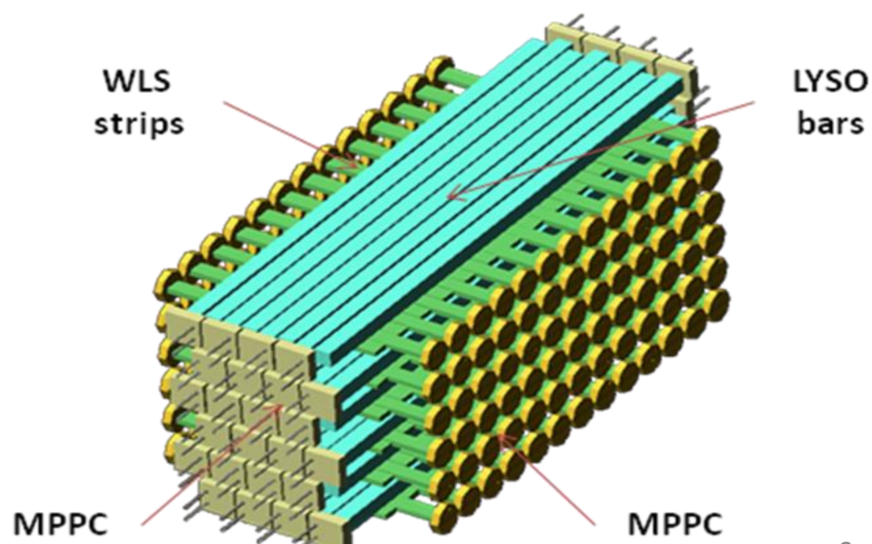
Reducing complexity by optical multiplexing

- R&D by UC Davis group using Wavelength shifting bars
  - $2\times2\times20$ mm^3 LYSO crystals
  - $2\times2\times20$ mm^3 WLS bars



H. Du, Y. Yang, and S. Cherry
Phys. Med. Biol. **53 (2008) 1829–1842**

- Large prototype by AXPET collaboration
  - $3\times3\times100$ mm^3 LYSO crystals
  - $0.9\times3\times40$ mm^3 WLS bars
  - Detector being tested



https://twiki.cern.ch/twiki/bin/view/AXIALPET/WebHome

An optical multiplexer:
The Fine Grained Detector

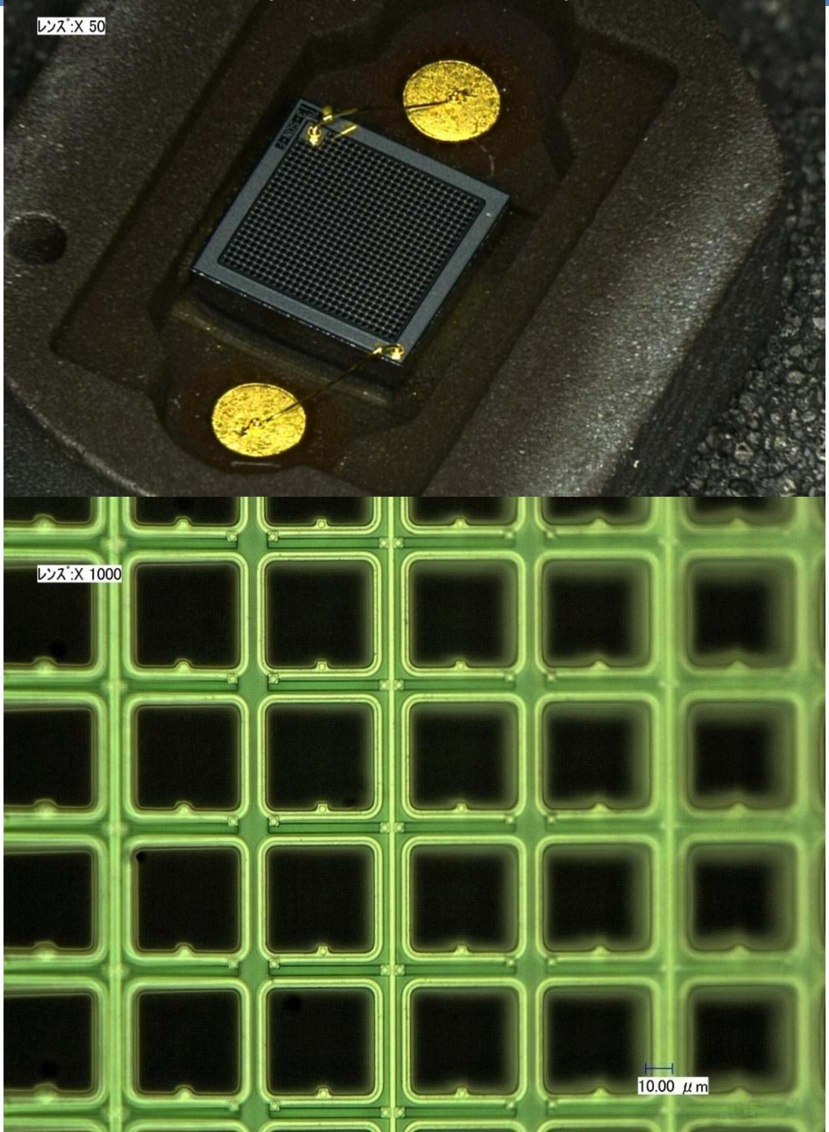
U. British Columbia, Kyoto U., U. Regina, TRIUMF, U. of Victoria

- Two detectors
  – 15 XY layers (192 bars)
  – 7 XY layers + 7 water panels
- 8448 channels

T2K Multi-Pixel Photon Counter

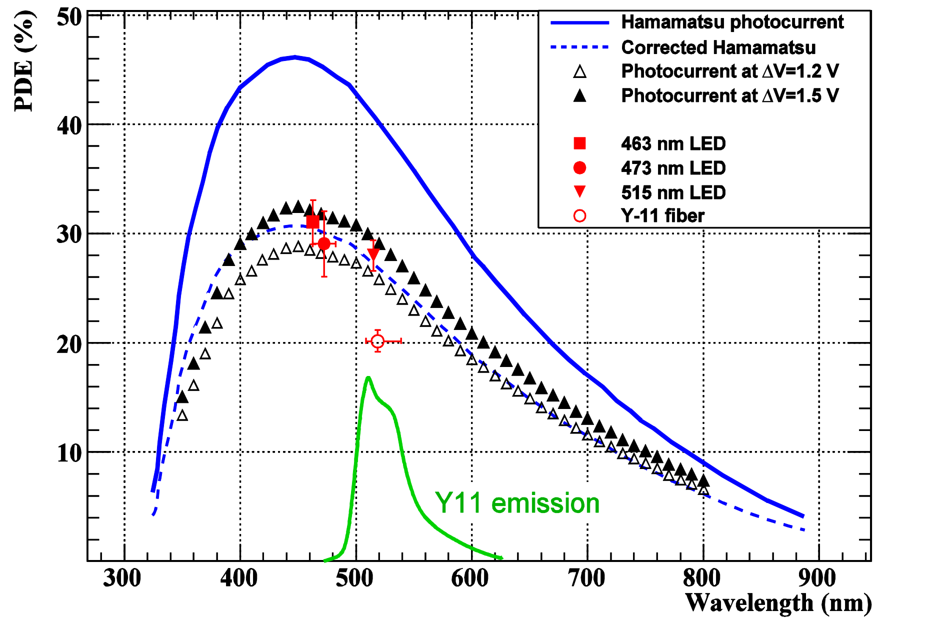
- A type of Pixelated Photon Detector (PPD) made by Hamamatsu Photonics
- Main features
  - High gain (10^6)
  - 1.3x1.3 mm^2 active area
    - 667 50 μm pixels
  - Photon detection efficiency ~ 30%
  - Insensitive to magnetic field
  - Pixelated: 1 pixel = 1 photon (or multiple photons)

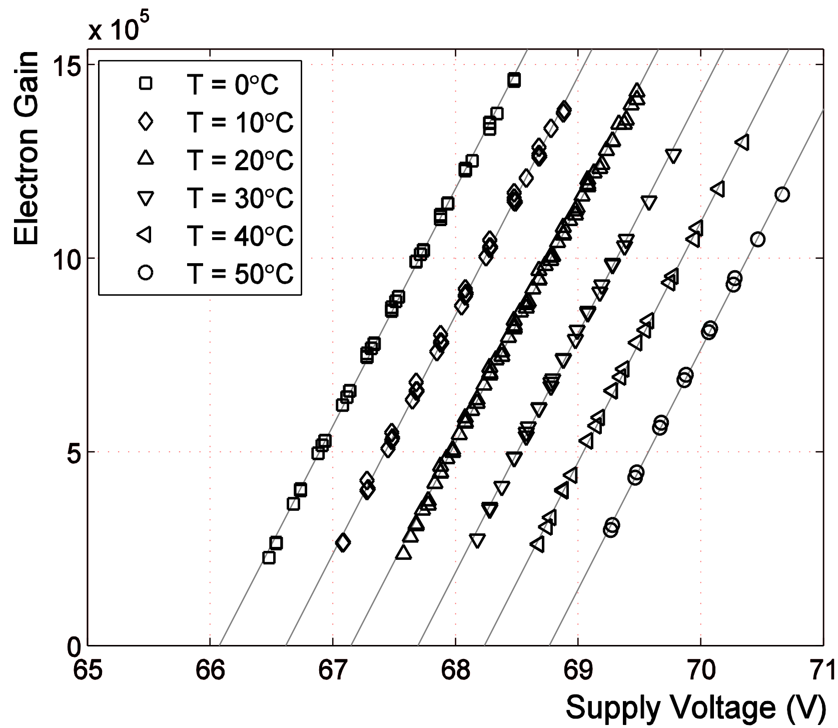
Pictures courtesy of Kyoto University



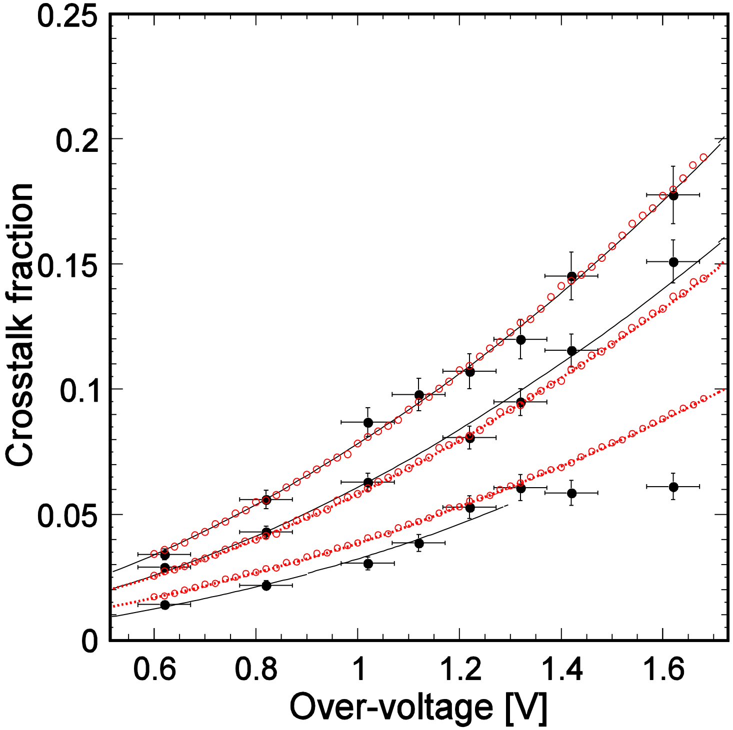
Characterization of T2K MPPCs

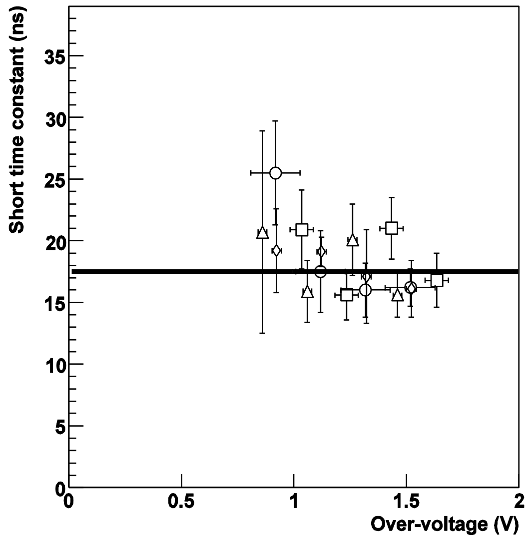
- Gain
  - Including fluctuations
- Dark noise
- After-pulsing
- Cross-talk
- Recovery
- Saturation

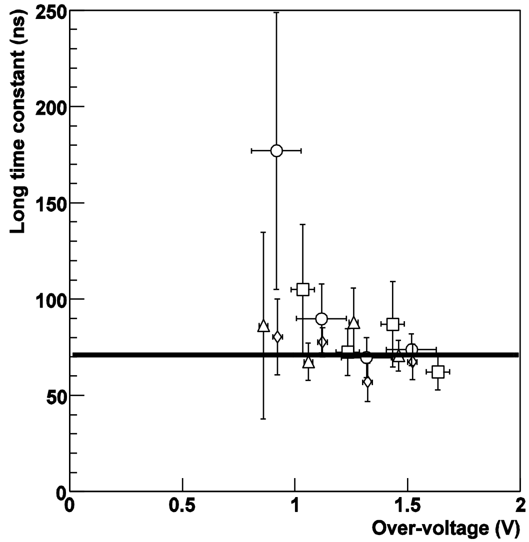


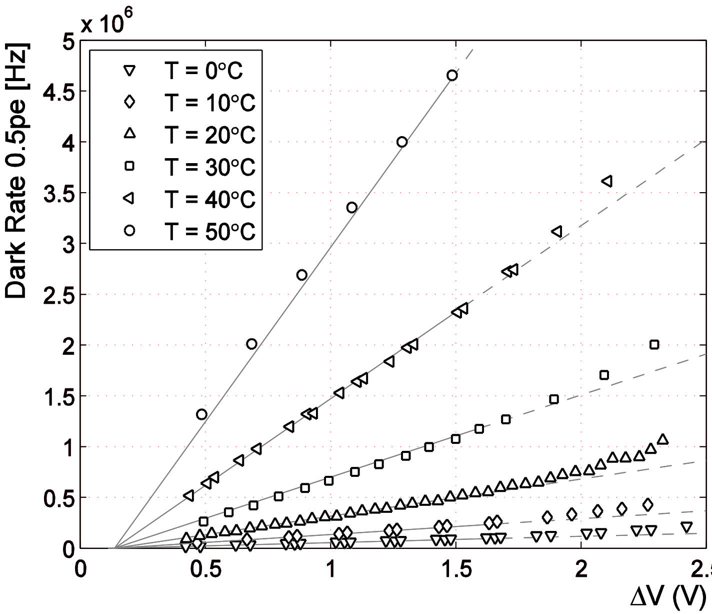


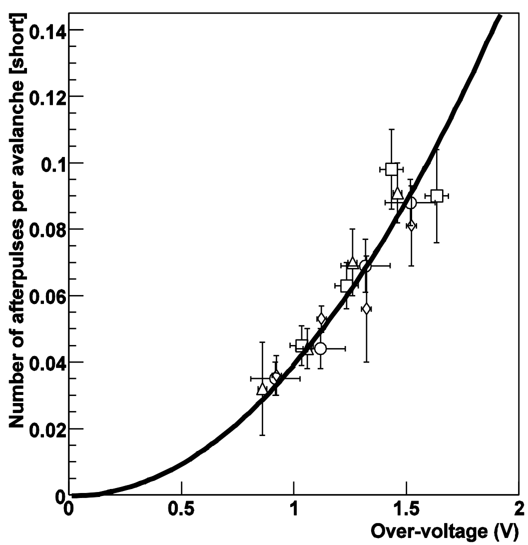
MPPC nuisances

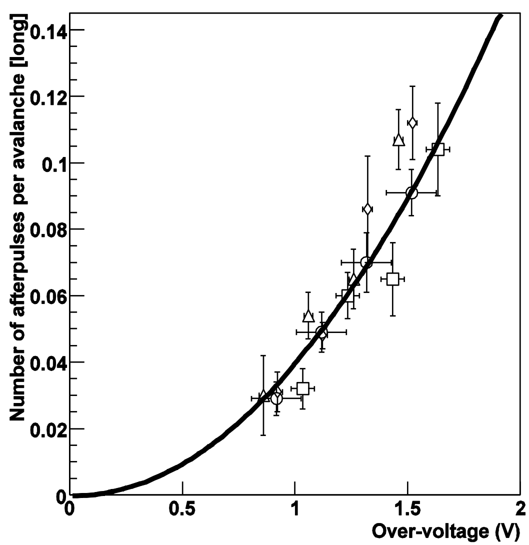




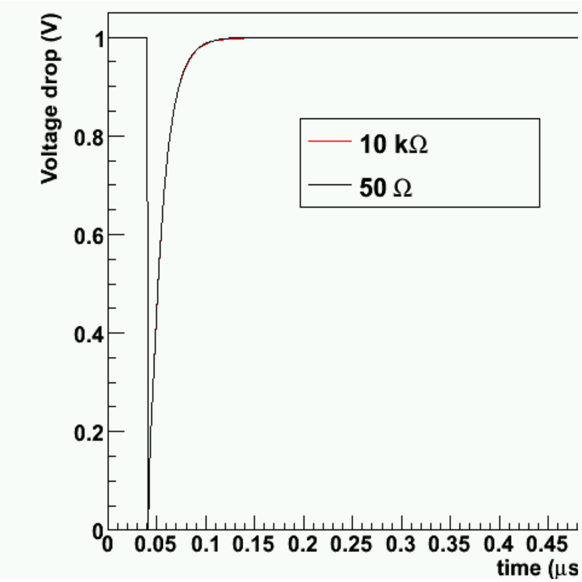


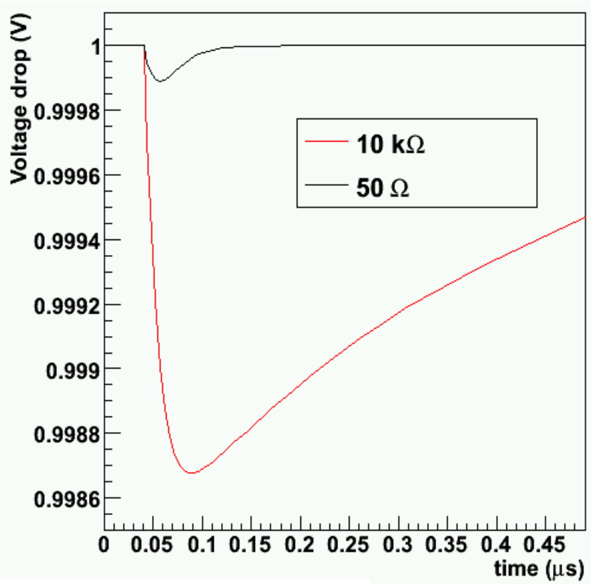


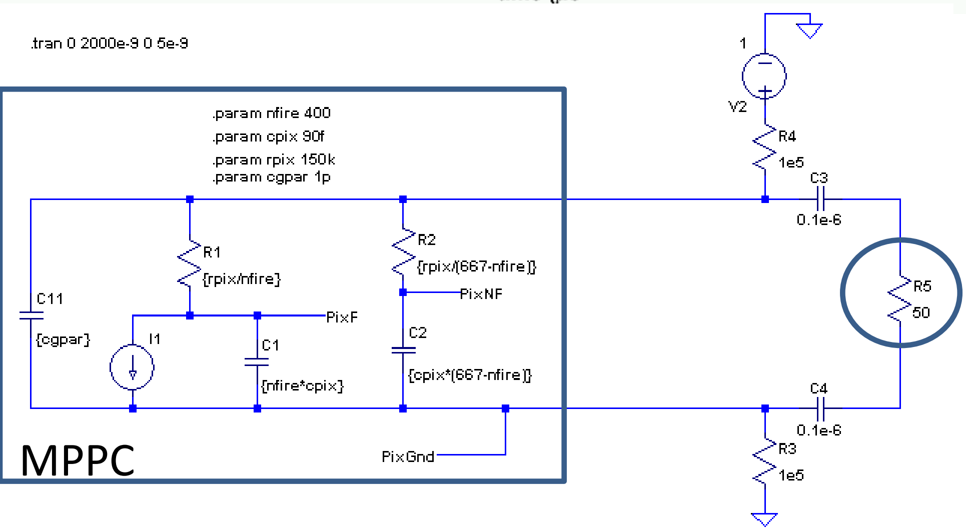


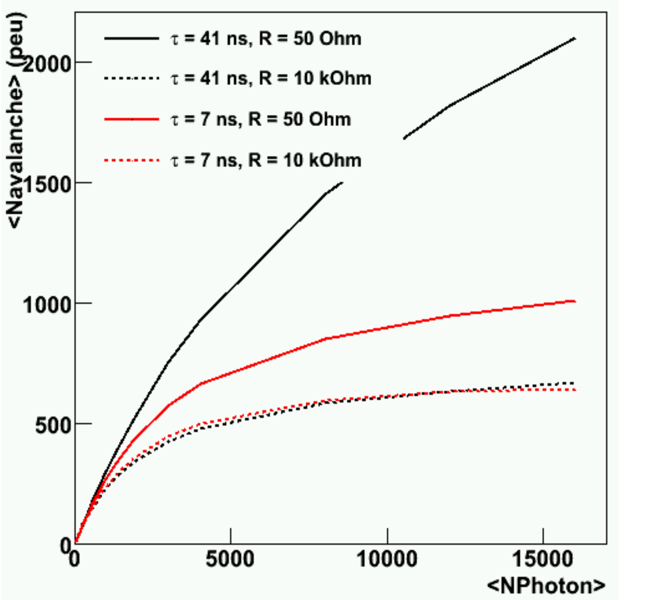


MPPC recovery and saturation







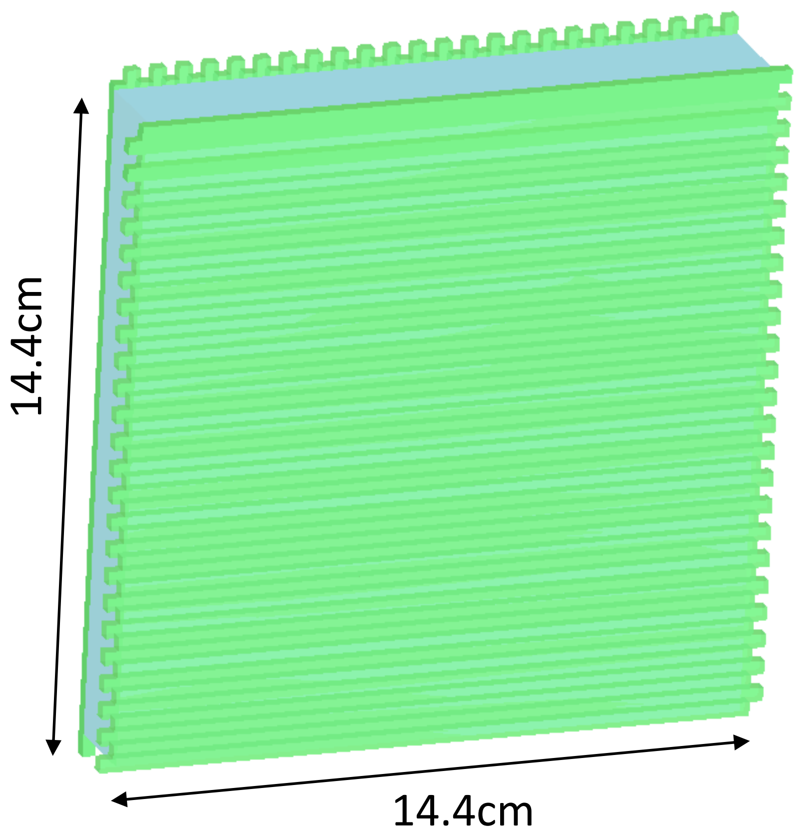


Using MPPCs from T2K to PET

Features and drawbacks	T2K	PET
Insensitivity to magnetic field	Yes	Yes, with MRI
High photon detection efficiency	Yes	Yes
High gain	Yes	Yes (simplify electronics)
Fast rise time	No	Yes
Saturation	Not a big issue	May affect resolution
Small active area	Not an issue	May be an issue
Dark noise	Small enough	Depend on area
After-pulsing	Small enough	?
Cross-talk	Small enough	?

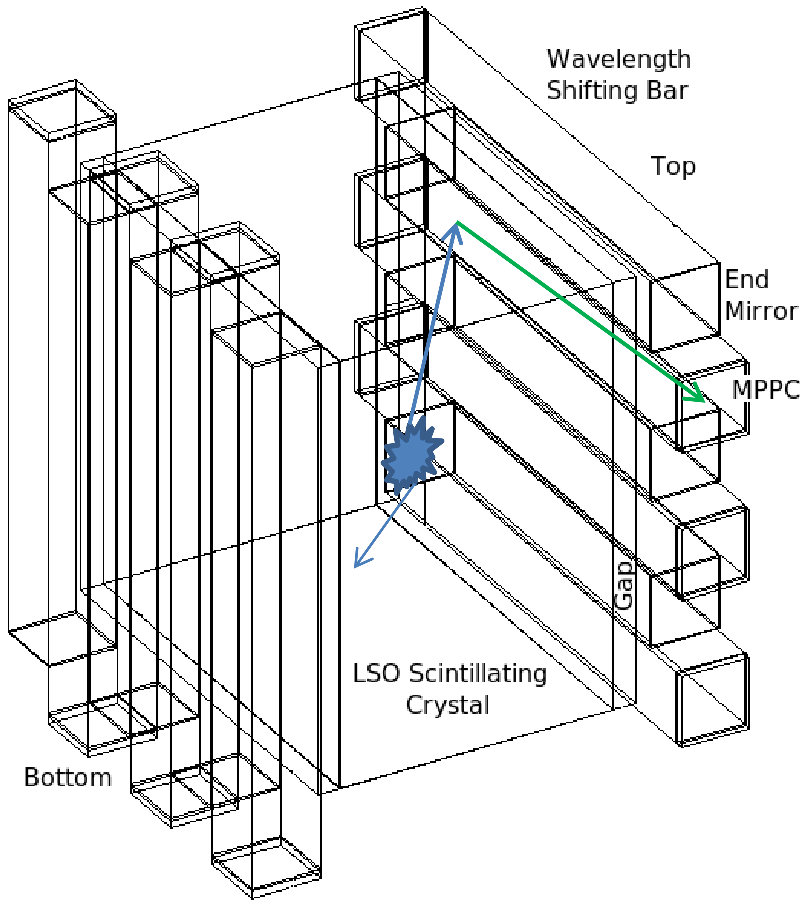
MPPC are a good match to small (1x1 to 3x3 mm2) LSO crystals.
New PET detector are being designed with MPPCs, lots of MPPCs…

Reading out a monolithic LSO crystal with WLS bars and MPPCs



- Goals
  - Position resolution < 2 mm (FHWM) in every dimension
  - Energy resolution < 20% (FHWM)
  - Timing resolution < 3 ns (FWHM)
- Concept
  - Large LSO crystal: 144×144×20 mm^3
  - Light transported to the side by Wavelength shifting bars or clear light guides
    - Dimension: 3×3×150 mm^3
    - 48 bars per side
    - 96 channels per module compare to 12,000 for clearPEM!
  - Readout by 3×3 mm^2 MPPCs

Using wavelength shifting bar to reduce the number of channel

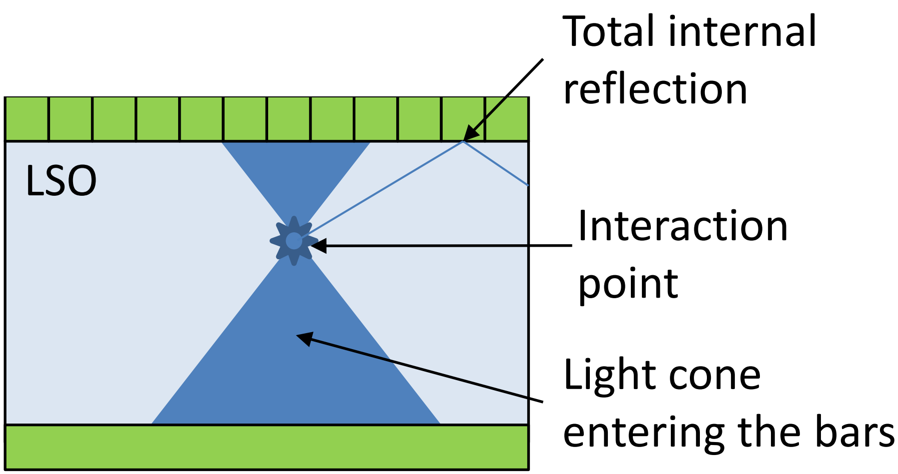


- 16,500 blue photons are emitted by a 511 keV photon in a LSO crystal
- Some blue photons are absorbed in wavelength shifting bars at the top and bottom
  - The WLS bar reemitted green photons
  - A small fraction of the photons is trapped in the bar and travel to the end to be detected

Position reconstruction

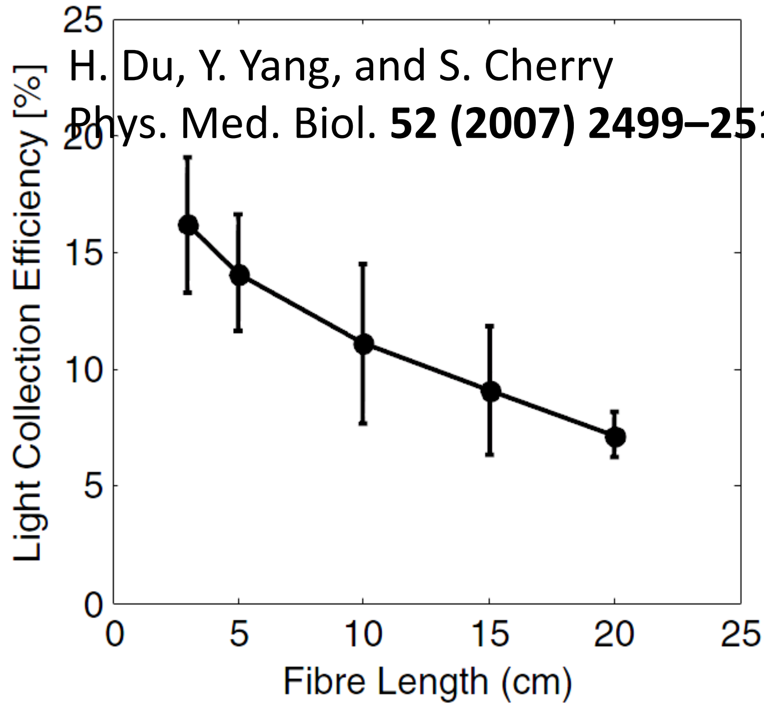
- Along crystal transverse directions: “weighted mean”
- Along crystal depth: light spread
  - Limited by angle of total reflection: ~50 degree with optical gel, ~30 degree with air gap

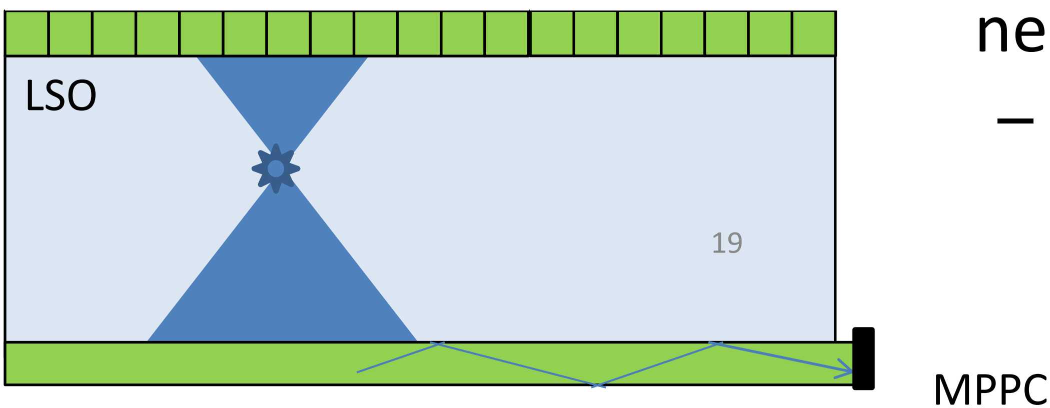
- Keys to good resolution
  - Light collection > 5%
  - Noise < 0.1 photo-electron
    - Possible with MPPCs



Photon collection: key to good performances

H. Du, Y. Yang, and S. Cherry
Phys. Med. Biol. **52 (2007) 2499–2514**

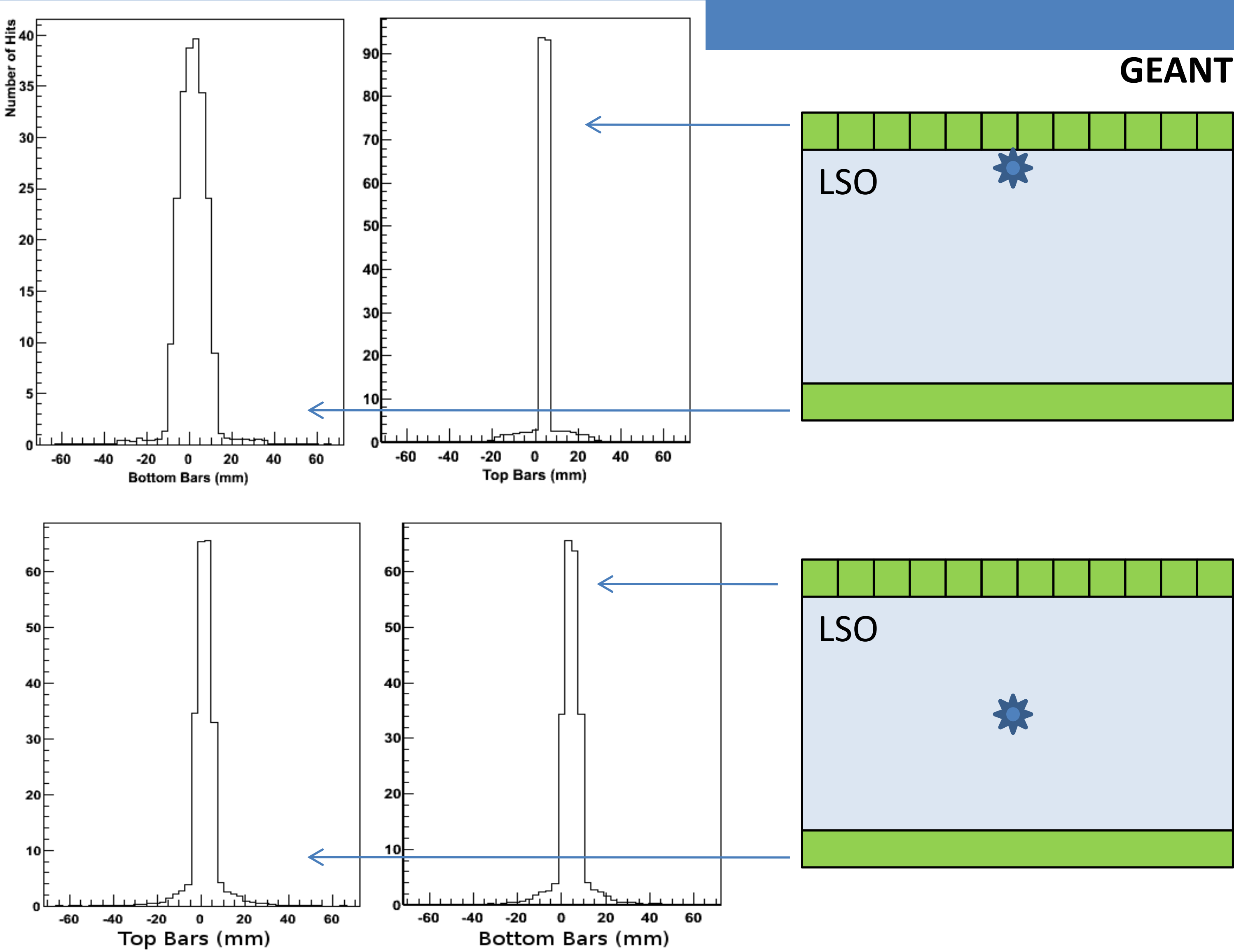




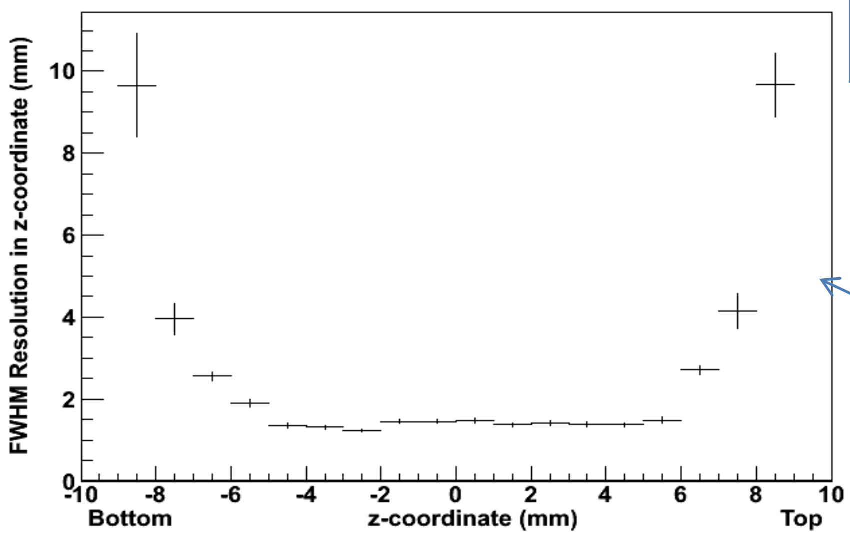
- Photon propagation in LSO and LSO-WLS reemission well understood
- Main issue is reflection efficiency along the edges of the fibers
- For this concept to work need > 100 photons
  - > 97% reflection effiency

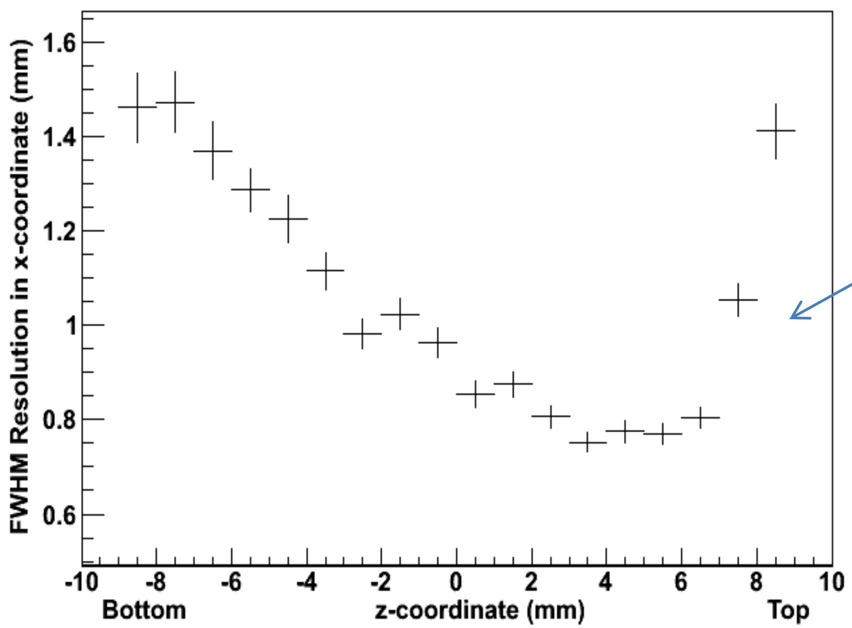
Light collection (simulations)

GEANT simulations

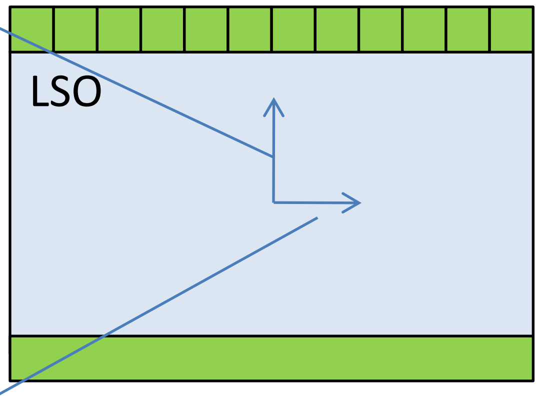


Position resolution (simulations)

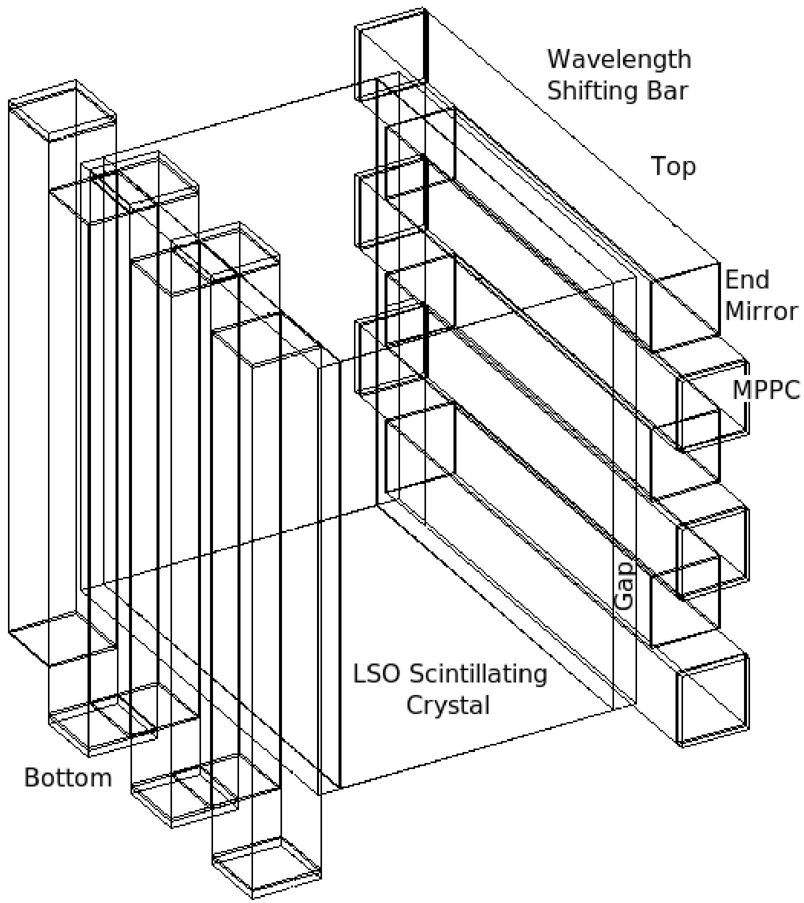




GEANT simulations



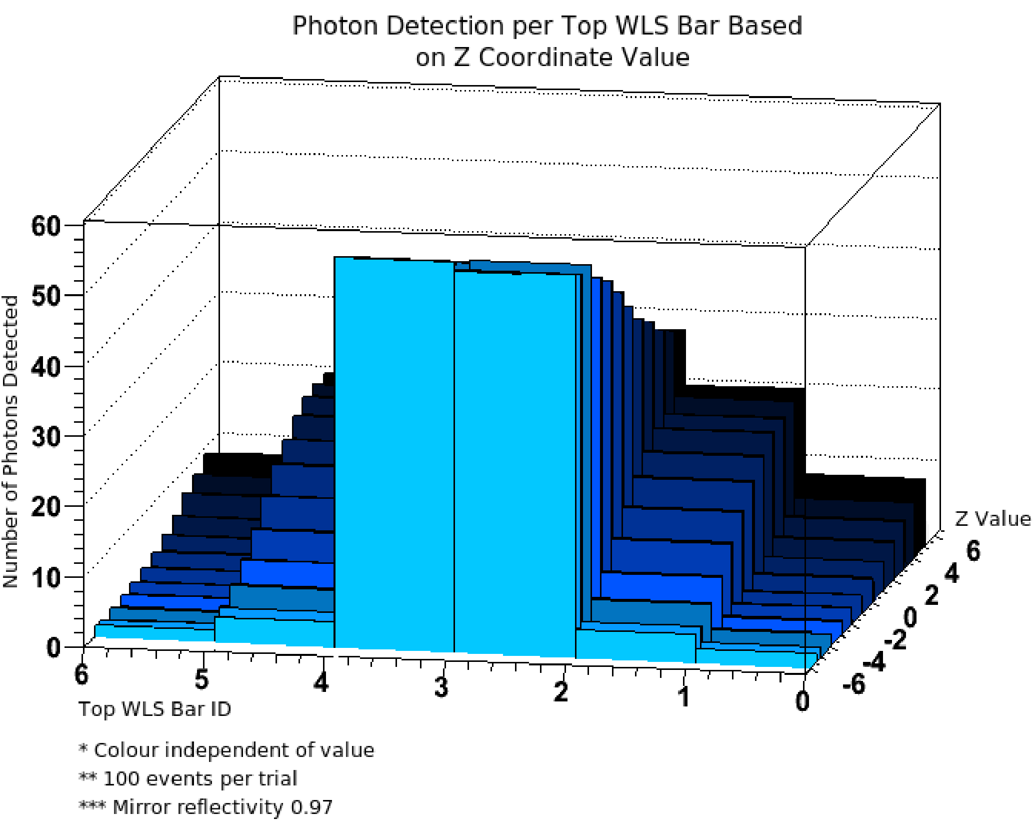
Prototype

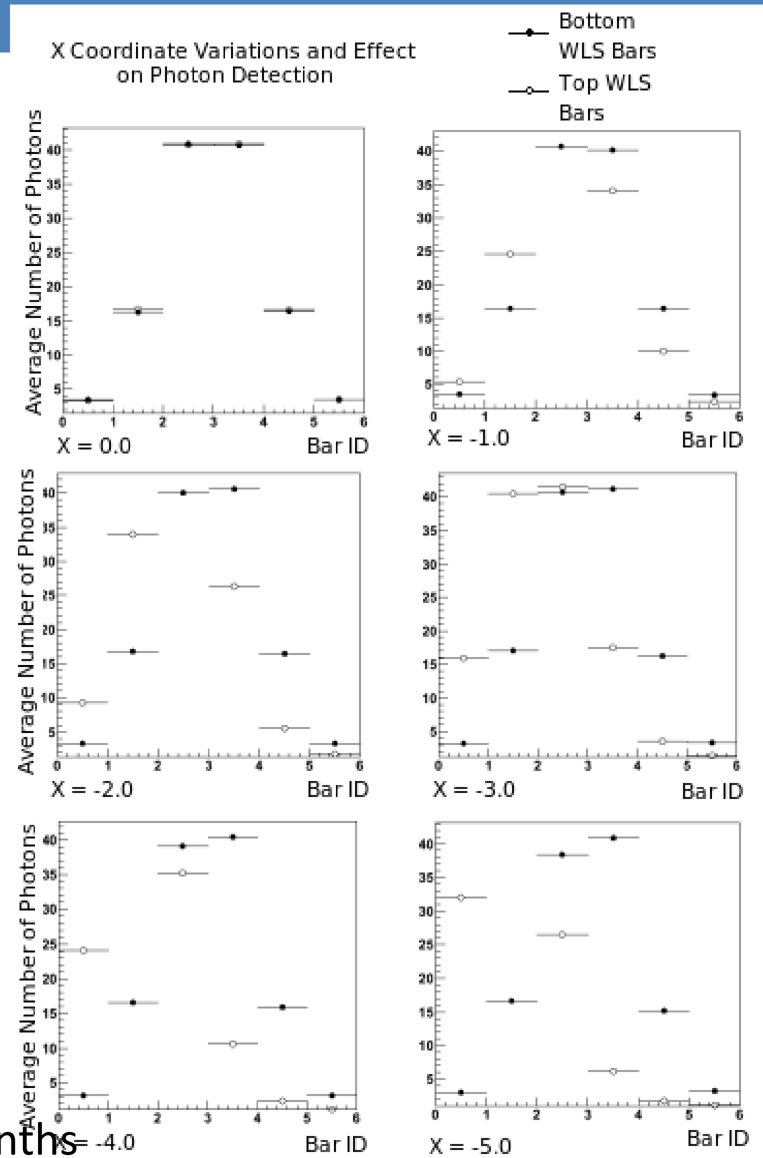


- Building a prototype in summer 2010
- Test in fall 2010
- 6 by 6 WLS bars
  - Readout alternatively on either side
  - Need 12 MPPCs
- 1.8x1.8x1.2 cm^2 LSO crystal
- We will know if this concept is sound

Light spread for different positions

GEANT simulations





If the measured photon collection is as good as simulated, this concept will work… <u>Answer in 3-4 months</u>

From LSO to liquid Xenon

Liquid Xenon is a good scintillator

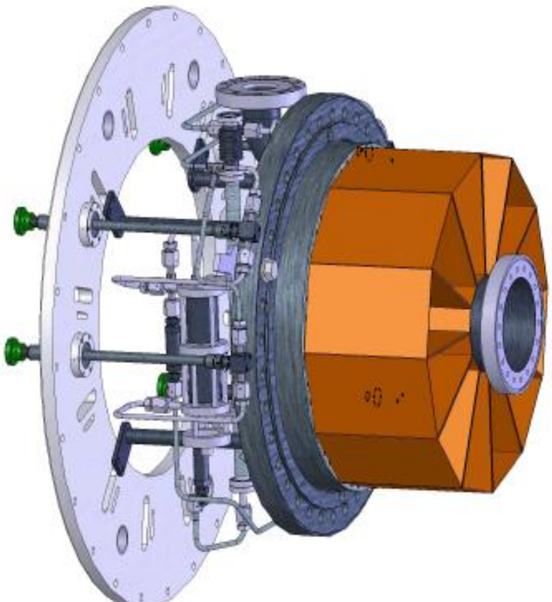
Parameter	BGO	LSO	LXe	Comment
Attenuation length at 511 keV	11 mm	12 mm	36 mm	Required depth ≥ 10 cm
Photo-electric fraction	42%	33%	22%	Require handling Compton interactions
# Photons at 511 keV	3,300	16,400	12,000 (2kV/cm)	
Decay time	300 ns	40 ns	2 ns (97%) 27 ns (2%)	< 1ns timing resolution possible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

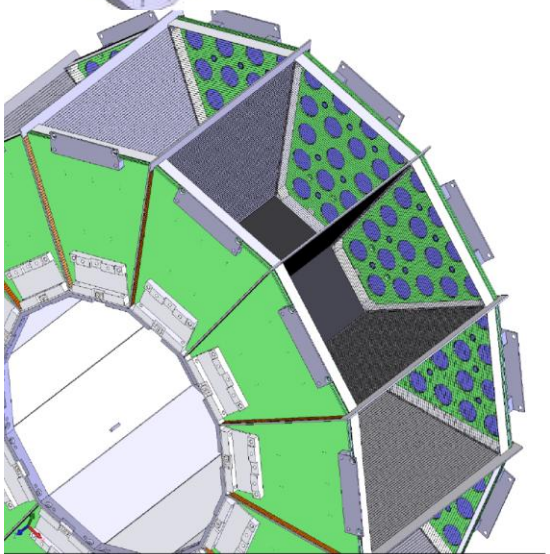
And, an excellent ionization detector

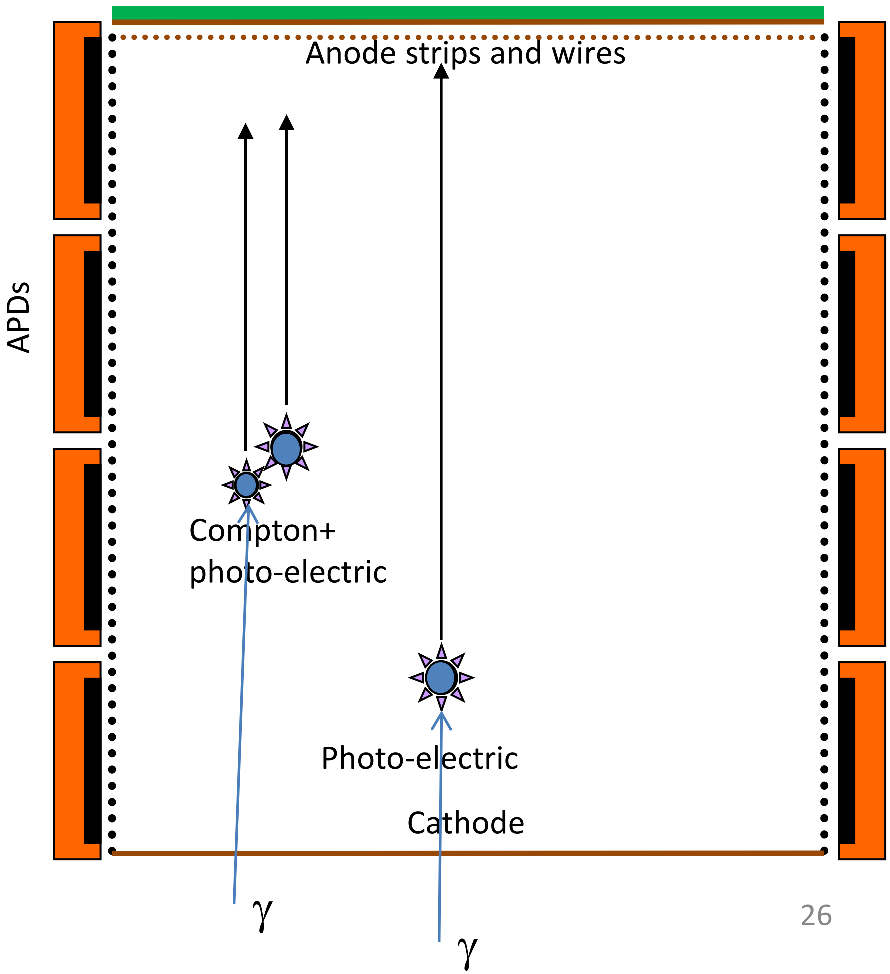
Liquid Xenon for microPET
A breakthrough technology?

- Achieving ultimate performances at low cost?
- Used for physics experiments for example dark matter search
- Key advantage is to combine high Z material with the ability to detect scintillation light and ionization charge at the same time
  - Allow the best of both world

microPET detector concept



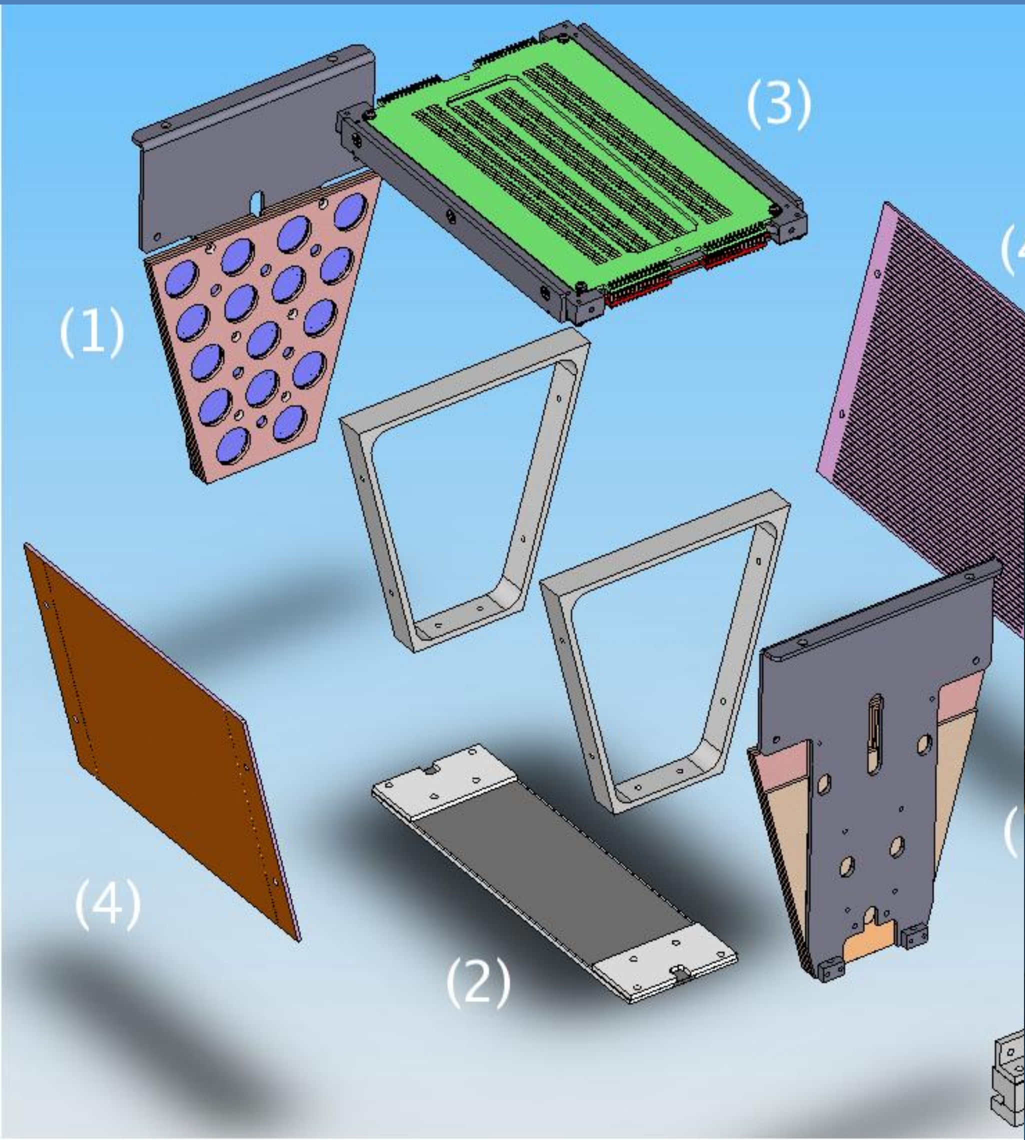


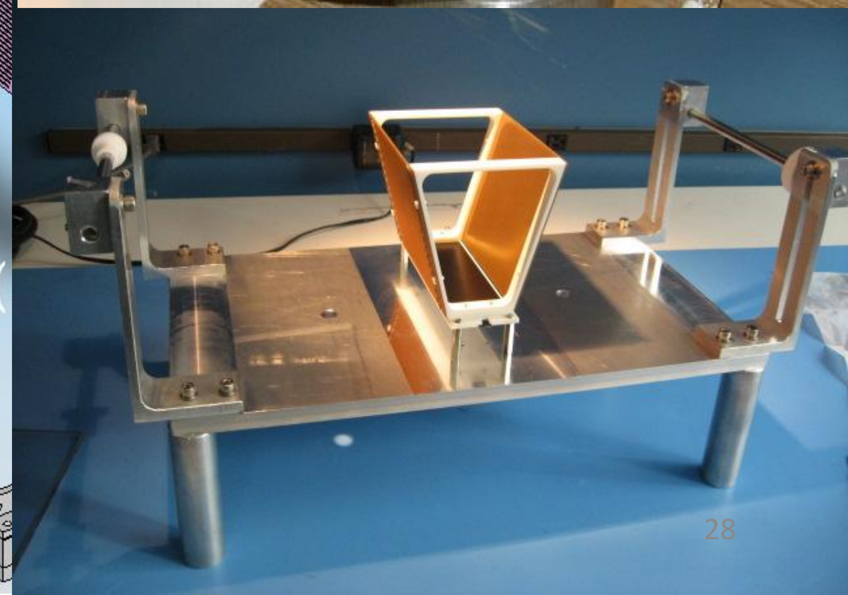


Liquid Xenon detector specifications

Features	Focus 120	Liquid Xenon
Detector diameter	15 cm	12 cm
Bore size	12 cm	10 cm
Axial field of view	7.6 cm	8 cm
Number of detector blocks	96	12
Number of readout elements	13,824	~3,000
Element size	1.6x1.6x20 mm^2	1x1x1 mm^3
Performances	**Focus 120**	**Liquid Xenon**
Peak sensitivity	>7%	>10%
Resolution at center of FOV	<1.4mm	< 1mm
Average energy resolution	18%	10%

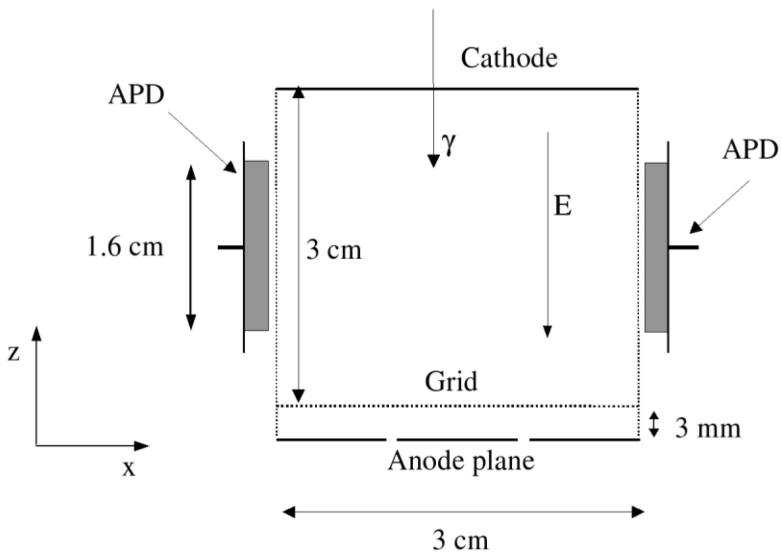
Micro-PET concept

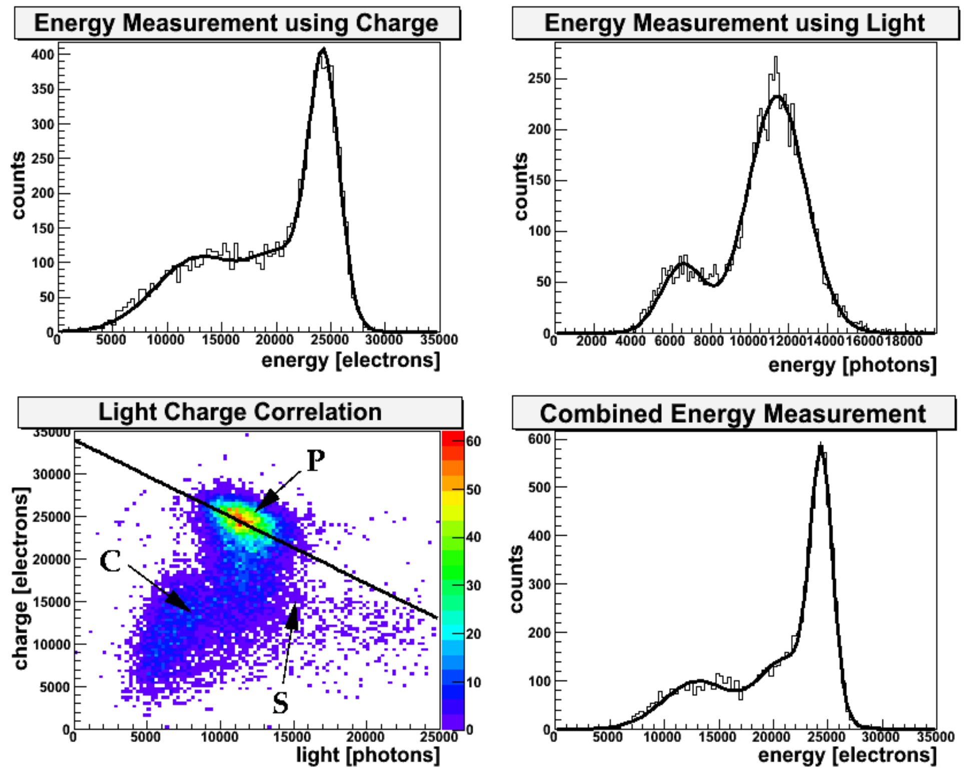




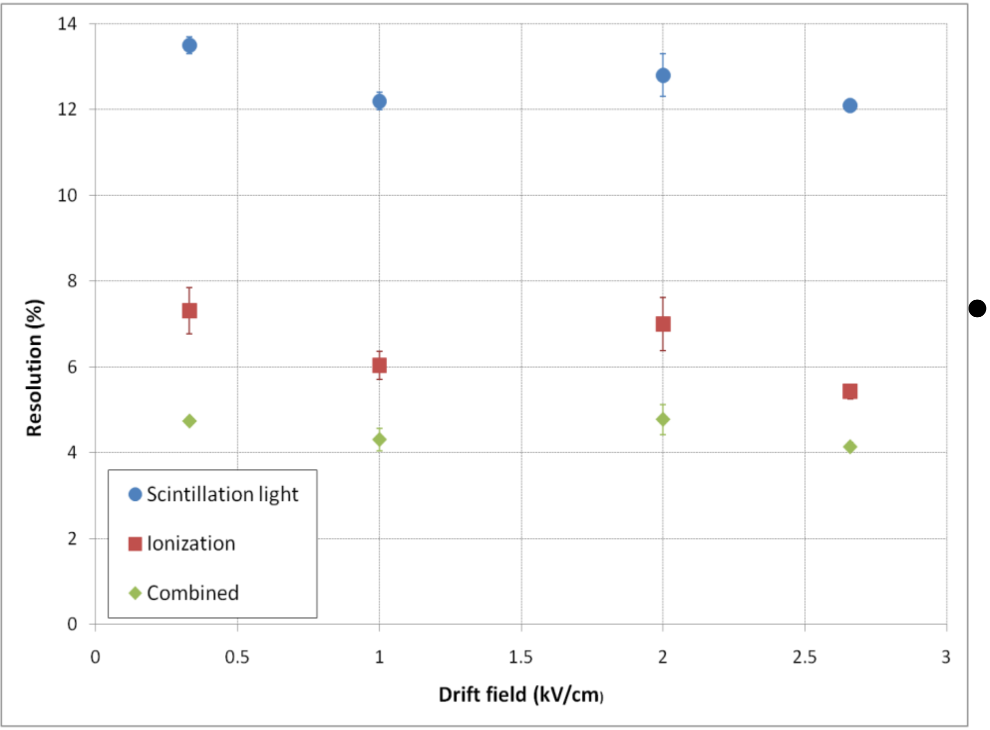
First prototype to investigate energy resolution

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



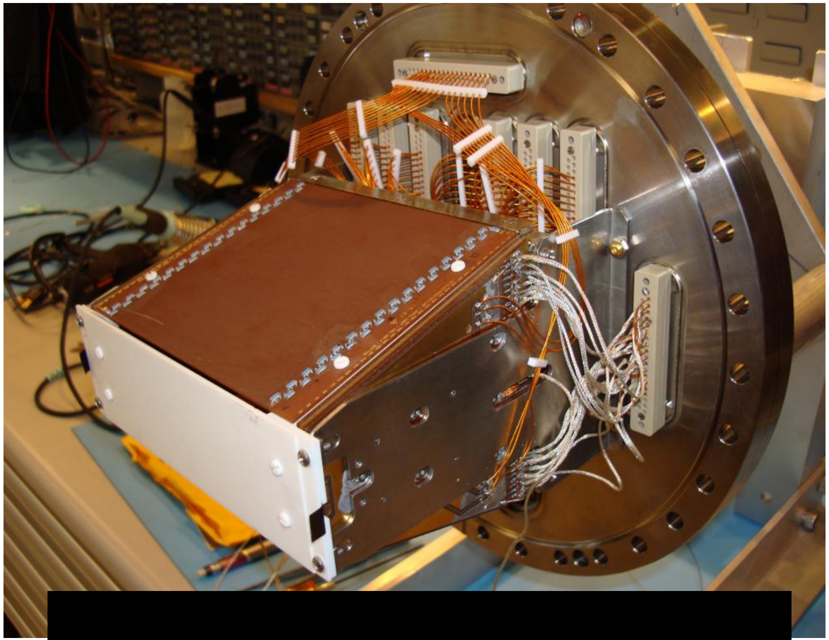


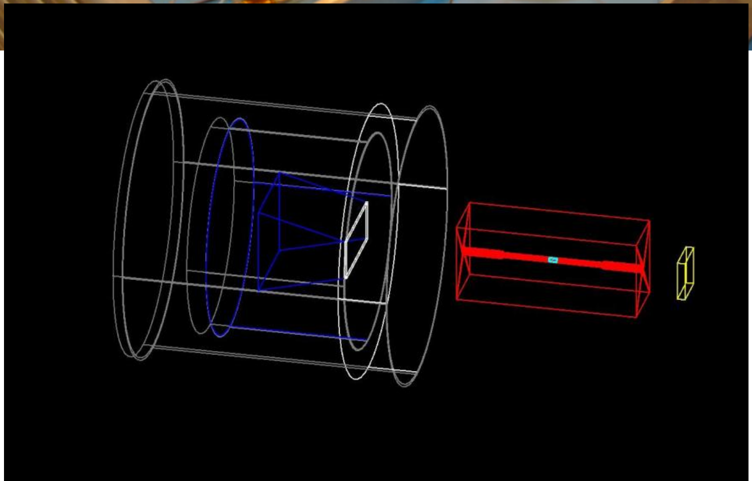
Energy resolution



- 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%

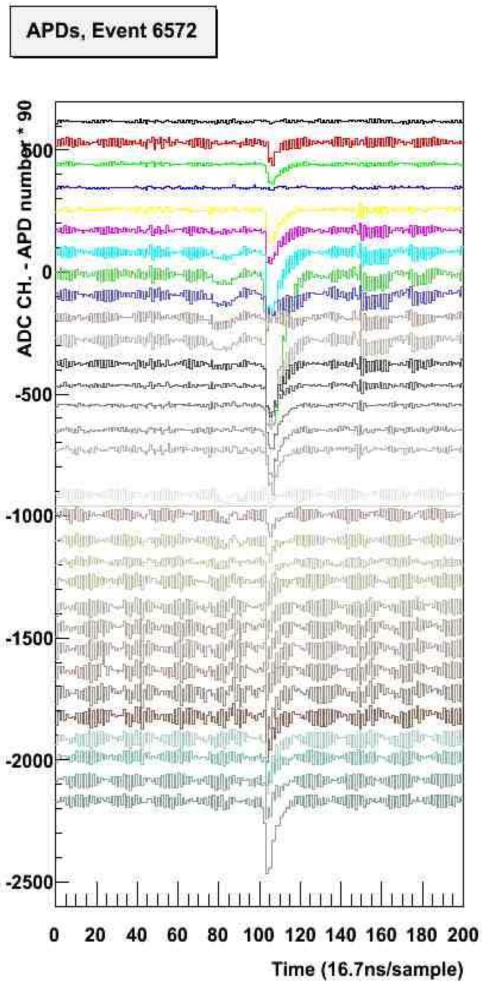
Second prototype. Full scale detector

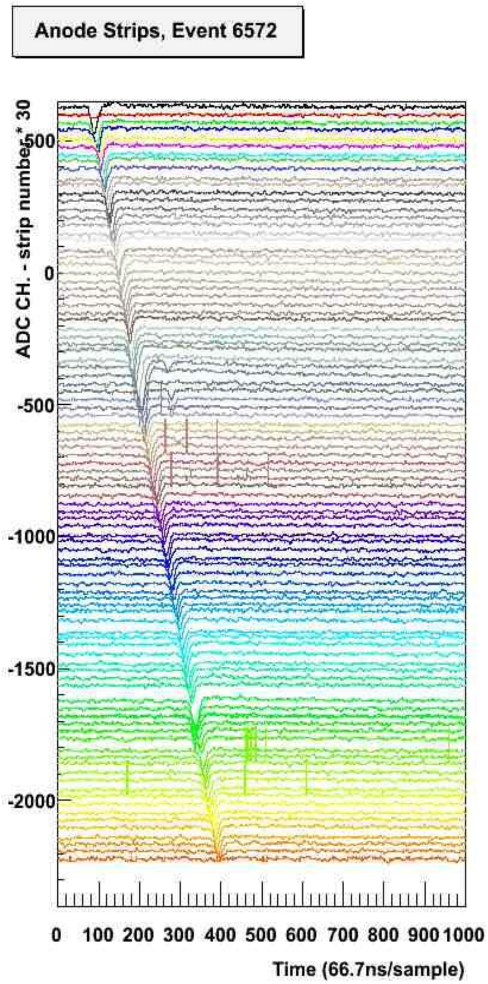


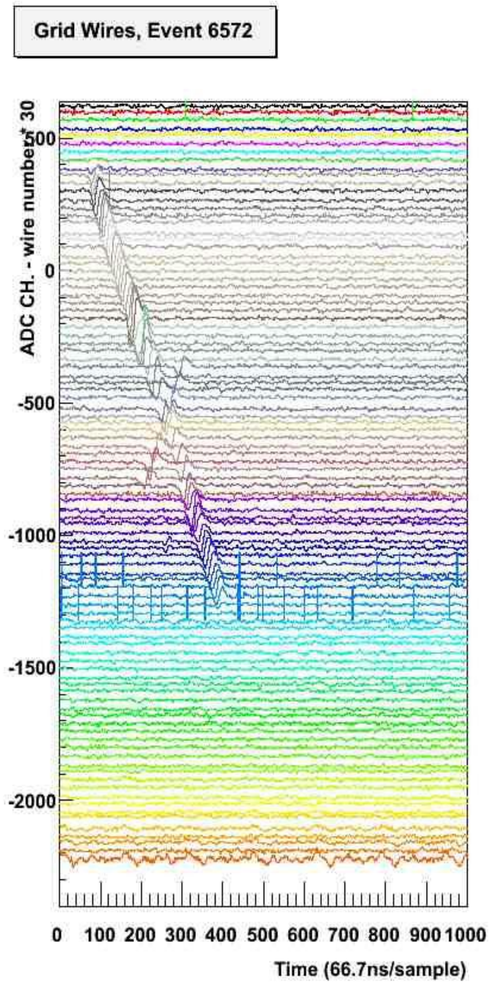


- Operated from fall 2009
- Few issues
  - Achieving required purity has been a challenge
  - Signal to noise on APD is border line

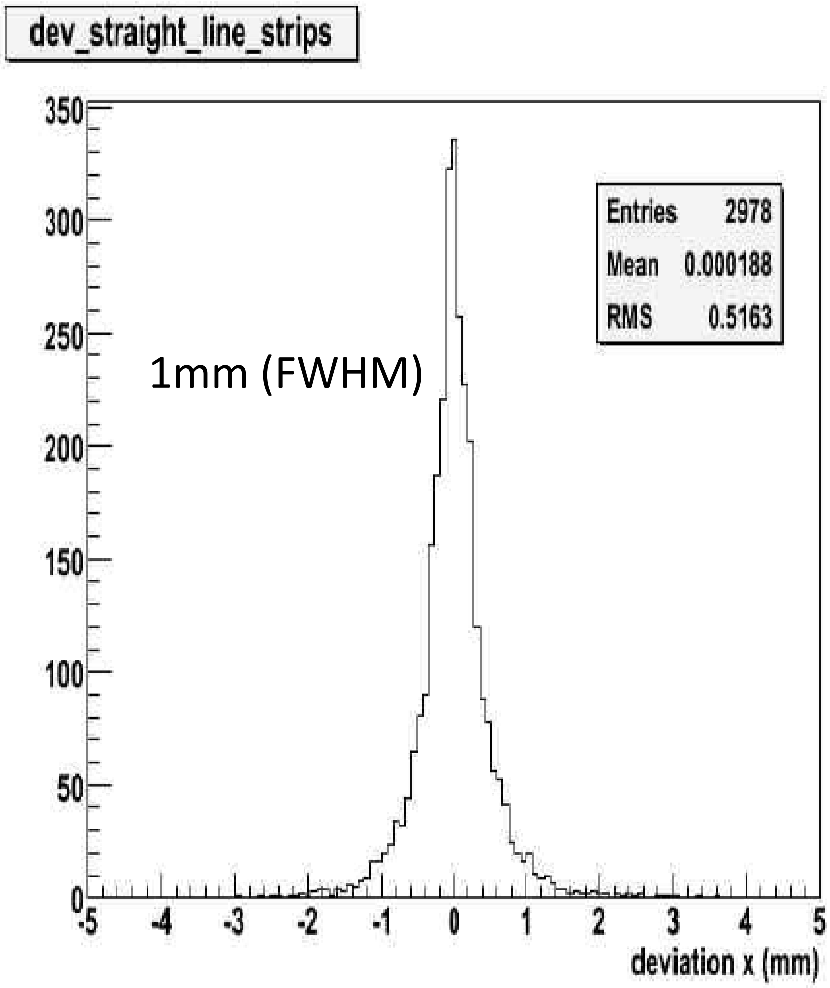
Such chamber can be used to measure cosmic rays



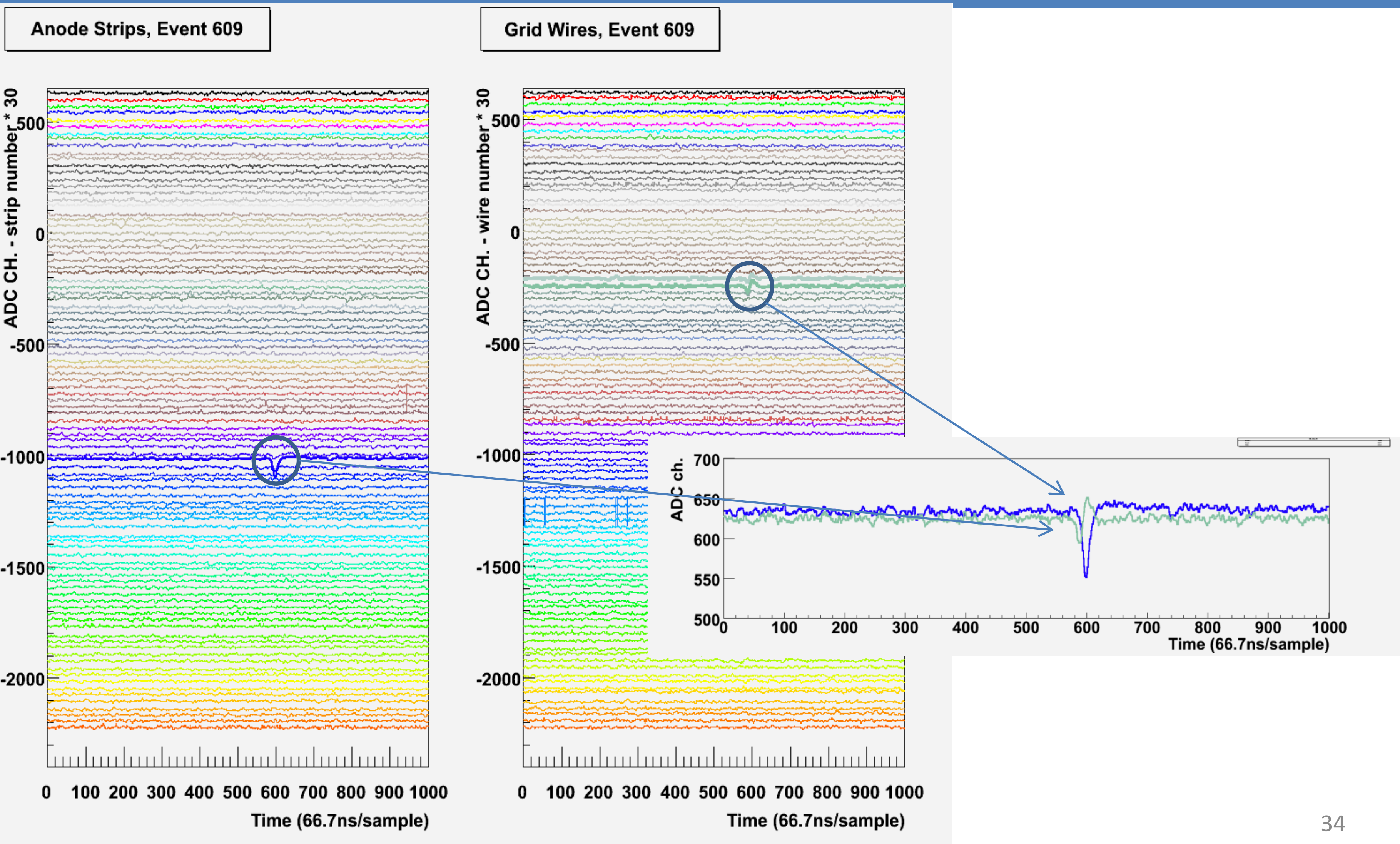




Position resolution from cosmics

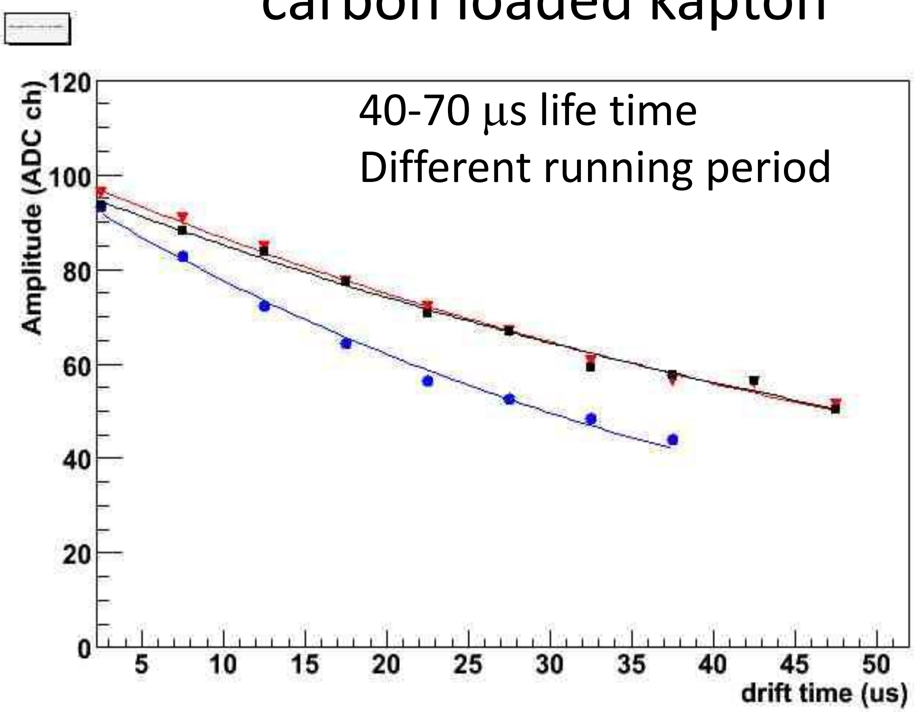


Detecting 511 keV photons



Two issues with prototype

- Purity
  - So far purity not goo enough
  - Carbon particle from carbon loaded kapton

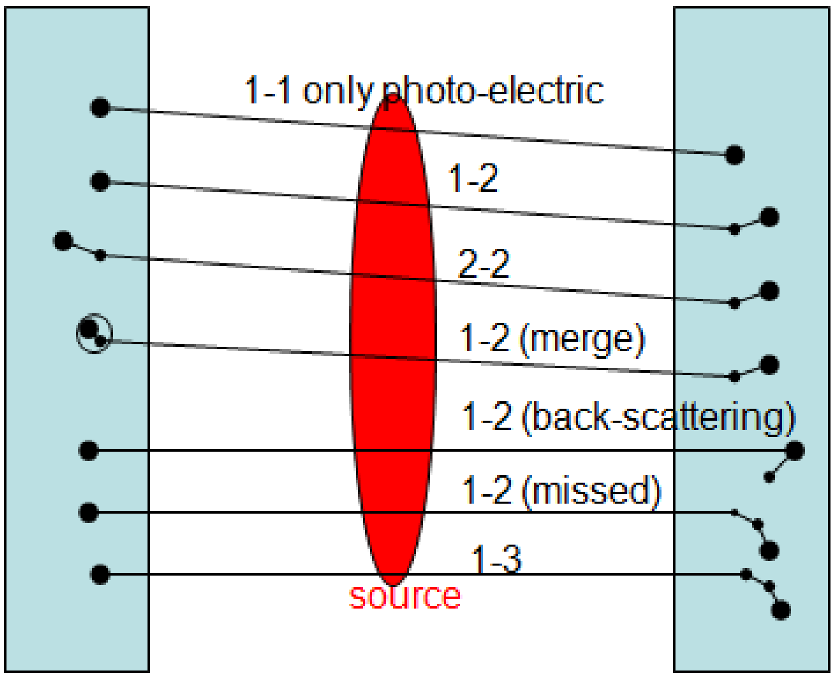


- Electronics noise
  - Collect 15,000 – 20,000 e- at 511 keV
  - Requirement, noise ~ 15 keV
    - Equivalent noise charge = 600 e-
    - Not so well defined over what frequency
    - Pick up noise can be a serious issue

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

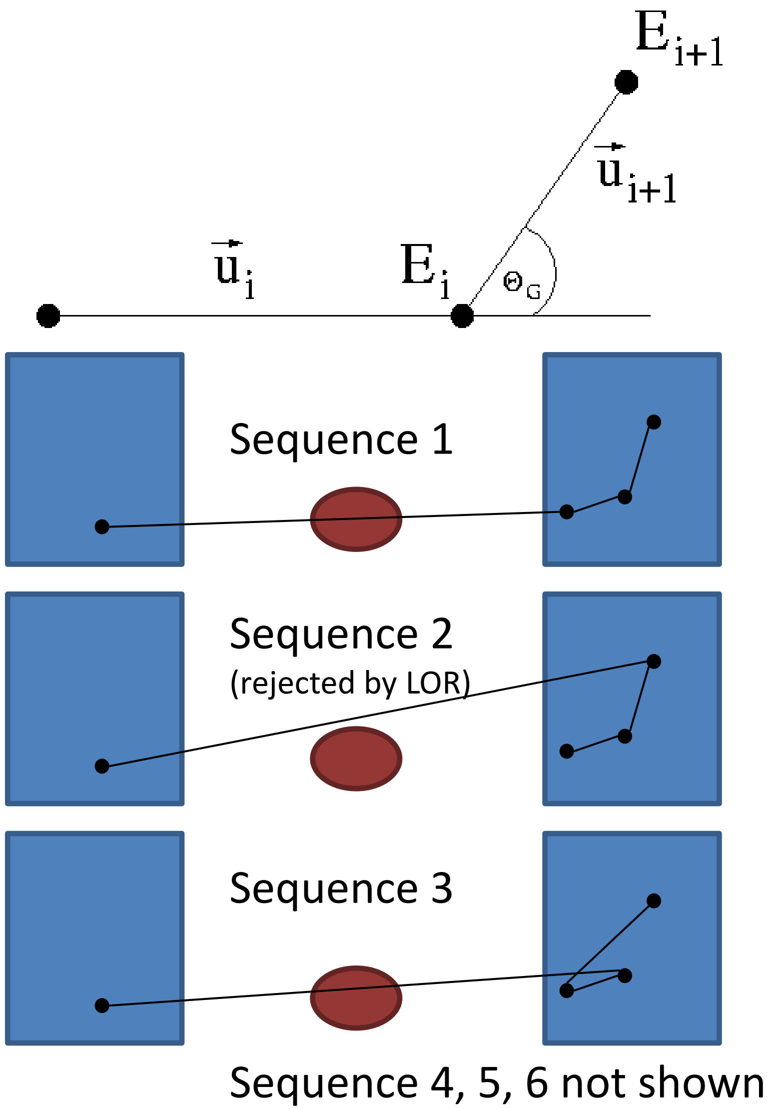
A large number of configurations



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

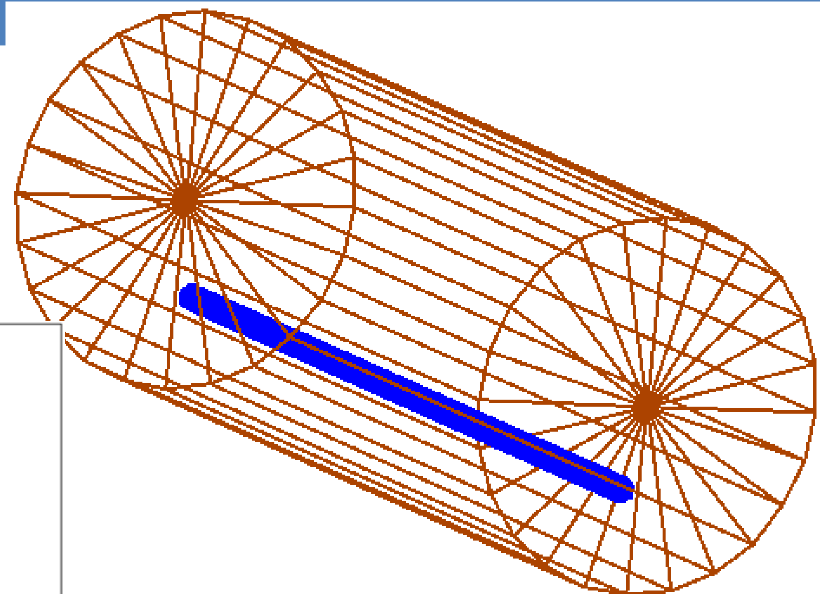
Compton reconstruction algorithm

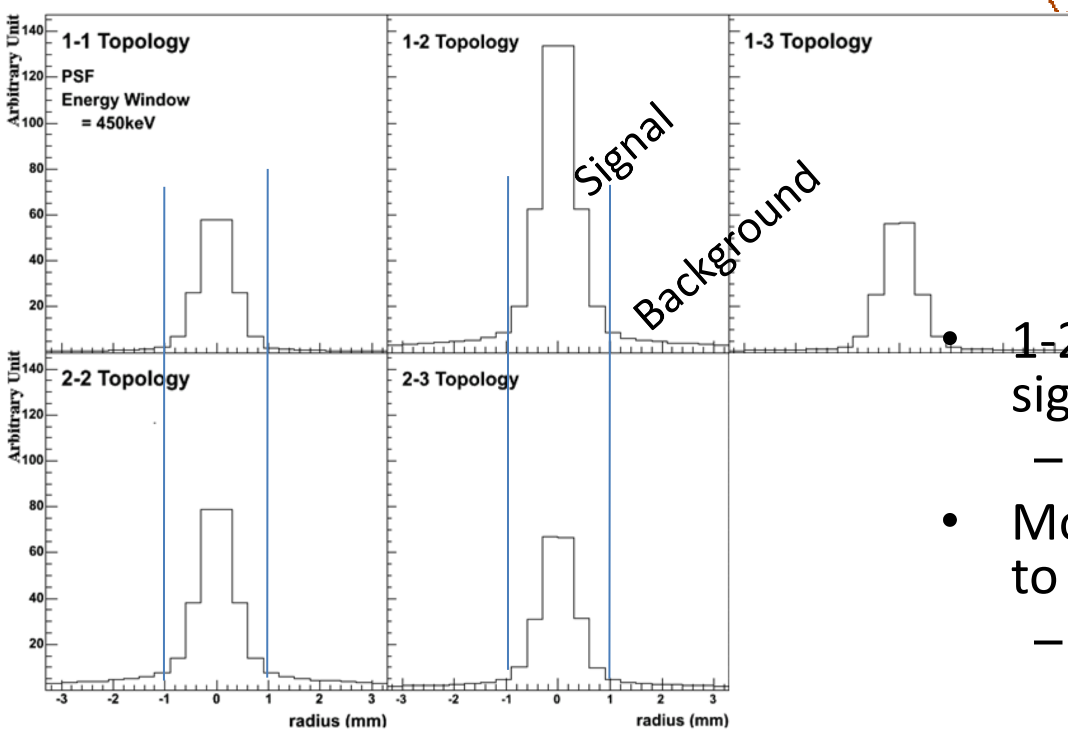


- Build every possible interaction sequence using the information on both detector sides
  - Reject the sequence that lead to Line of Response outside the sample volume
- For each sequence
  - Calculate two angles at every possible scattering point
    - From energy deposited
    - From geometry
    - 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

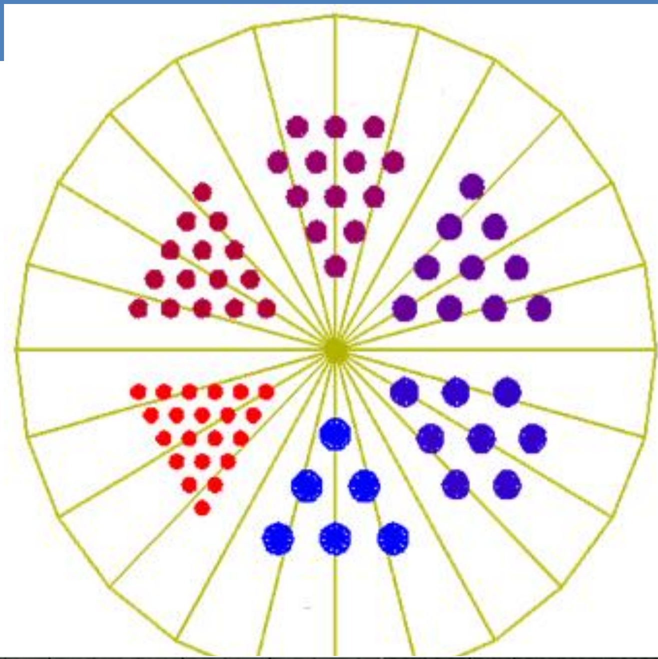
- Simulate using GEANT
- Use NEMA phantom scaled for micro-PET

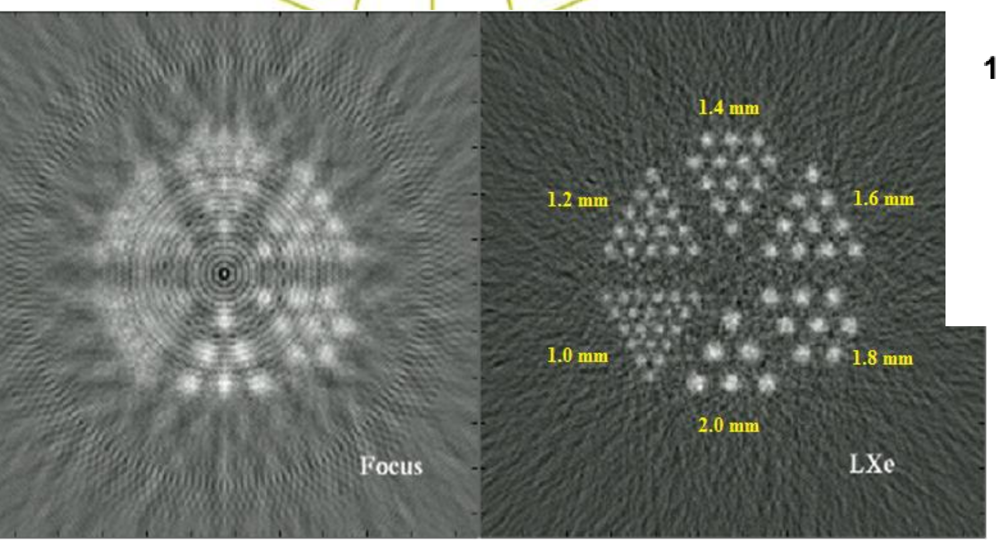


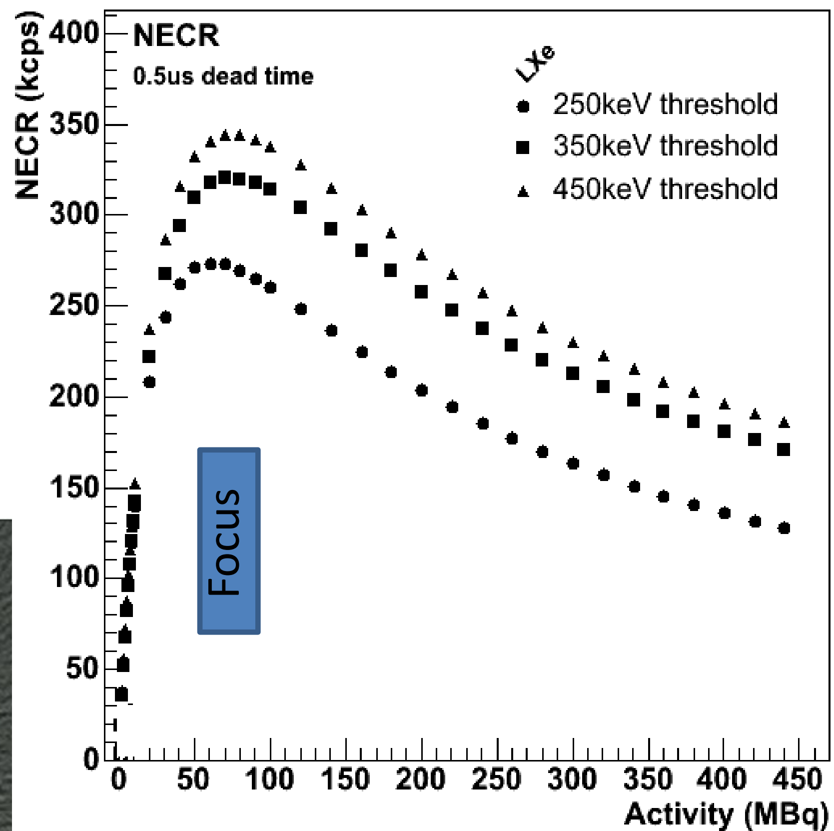


- 1-2 and 2-2 have the worst signal to background
  - Some irresolvable ambiguities
- Most of the background is due to selecting wrong first point
  - Random and scatter very much suppressed due to very good energy and time resolution

Liquid Xenon promise excellent image quality







Simulations

Summary

- PET is continuously evolving
  - Current trend is towards ever smaller crystals and an ever larger number of channels
- TRIUMF is developing alternate solution
  - Liquid Xenon
    - Extremely promising technology yet complex
  - Reading out monolithic LSO crystal with wavelength shifting bars
    - Hopefully validate the concept before end of 2010
    - Development of GEANT simulations

Collaboration

- Liquid Xenon collaboration

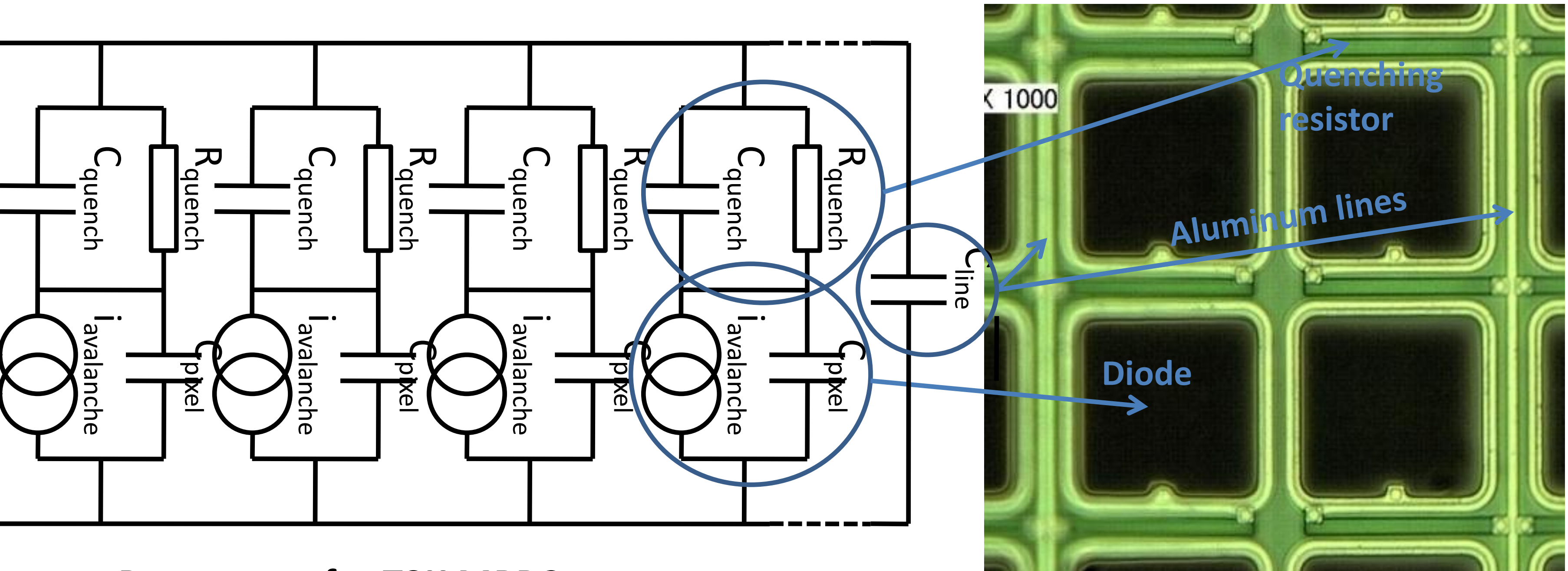
  A. Miceli, P-A. Amaudruz , J.Glister, L. Kurchaninov, F. Retière, T.J. Ruth (TRIUMF)
  F. Benard (BCCA)
  D.A. Bryman, C. Clements, A.J. Stoessl, V. Sossi, H. Zhu (UBC)
  J-P. Martin (U. Montreal)

- Scintillator detectors

  C. Lim, F. Retière, P. Gumplinger, C. Ohlman (TRIUMF)

Backup

Corresponding electrical circuit



Parameters for T2K MPPC

C_{pixel} = 90 fF

R_{quench} = 150 kΩ

C_{quench} ~ 4 fF (parasitic)

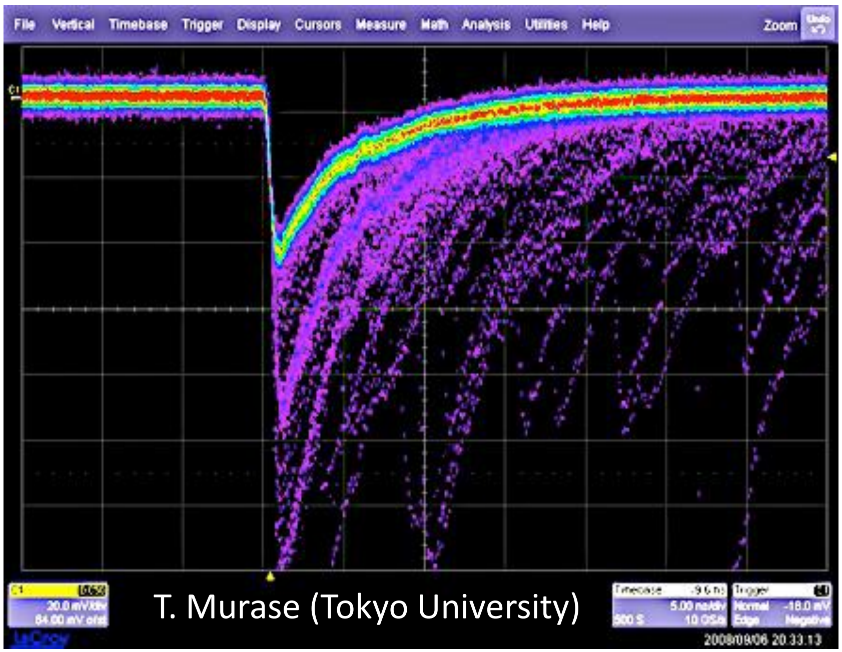
C_{line} ~ 10 pF (parasitic)

$I_{avalanche} = (V_{operation} - V_{breakdown}) / R_{quench}$ ~ 5-10 μA

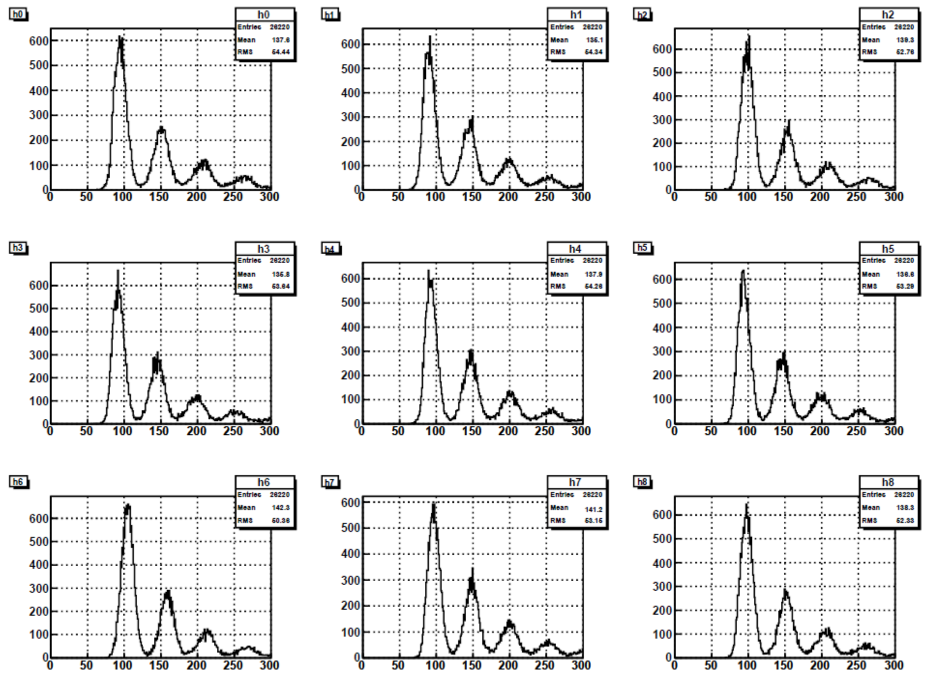
$Q_{avalanche} = (V_{operation} - V_{breakdown})\ C_{pixel}$ ~

MPPC signal

Charge distribution of 9 INGRID channels



T. Murase (Tokyo University)



M. Otani (Kyoto). PD09 talk