Development of a new MeV gamma-ray camera

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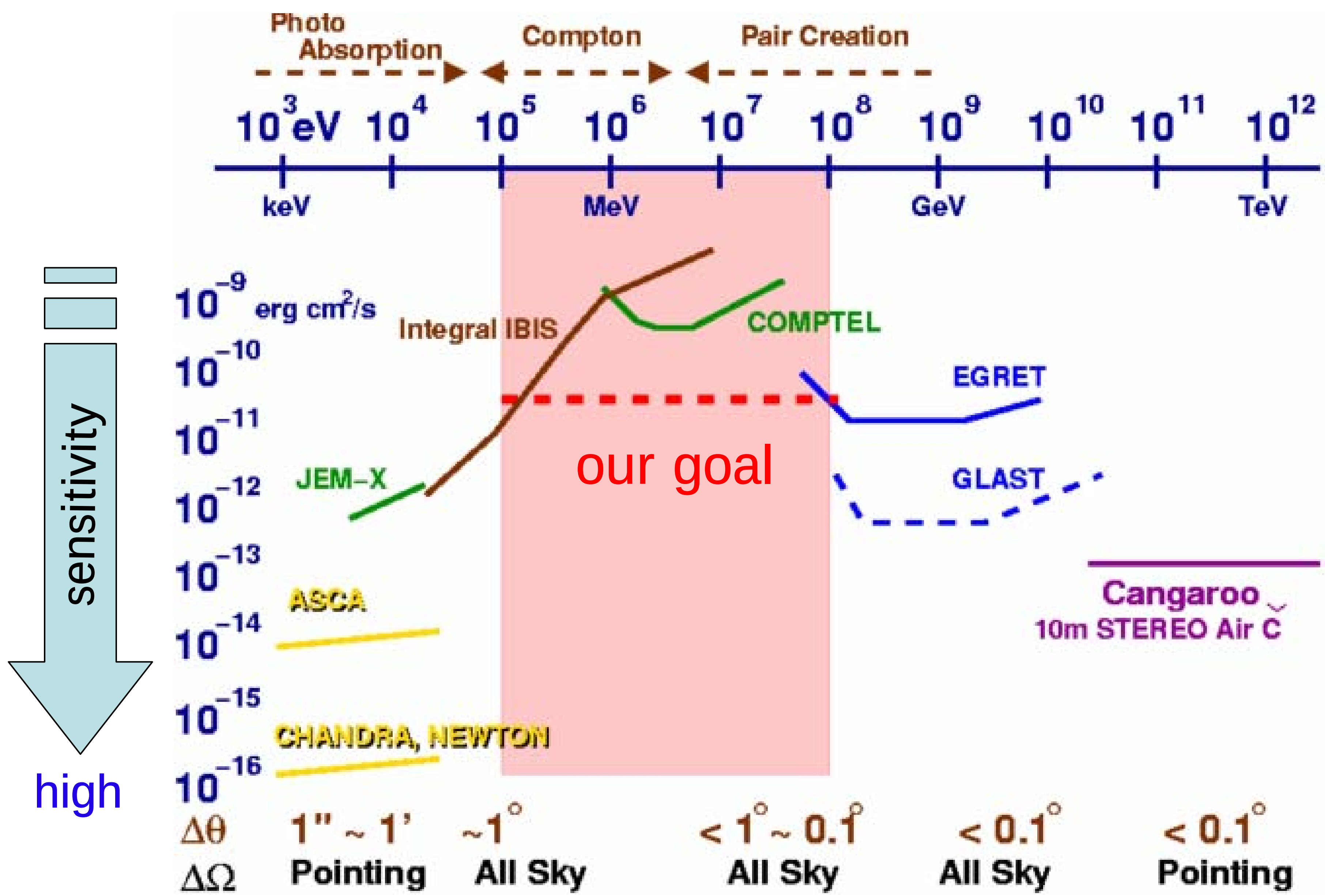
1. MeV Gamma-ray Astronomy
2. New MeV Gamma-ray Camera
3. Prototype Detector
4. Summary & Future Works

1. MeV Gamma-ray Astronomy



Expected sources in MeV region

- Supernova Remnants (SNRs)

  ^{26}Al(1.8MeV), ^{44}Ti(1.16MeV), Nuclear gamma

- Active Galactic Nuclei (AGN) jets

  Optical Violent Variable (OVV) galaxy, Blazar

- Black Hole

  Binaries, Galactic Center, Primordial BH, 511keV

- Gamma Ray Bursts

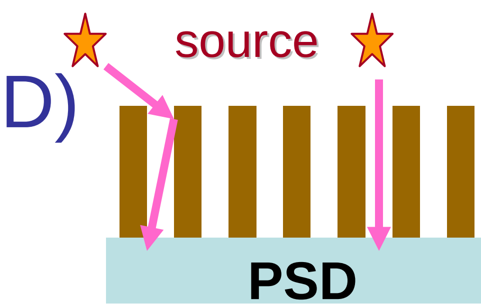
  Polarization

- Pulsars

Mev γ-ray imaging detectors

1. Collimator + Position Sensitive Detector (PSD)

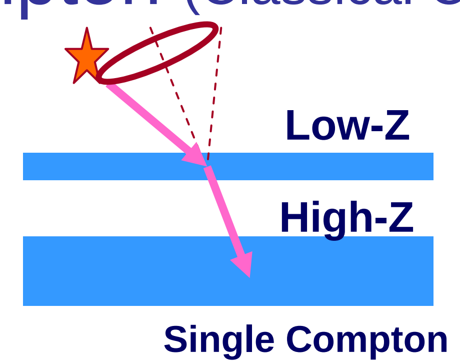
- Narrow field of view
- Background from collimator
- Energy < 1MeV

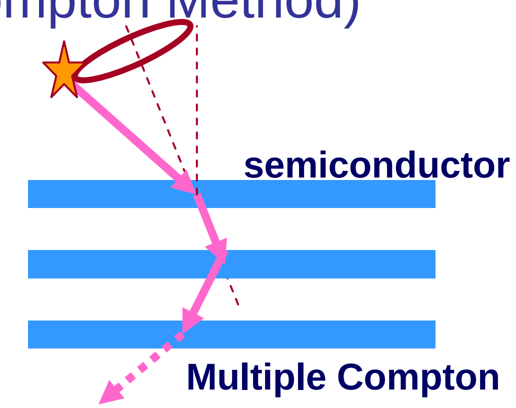


2. Single or Multiple Compton (Classical Compton Method)

- Only event circle
- No background rejection

⇨ **COMPTEL**

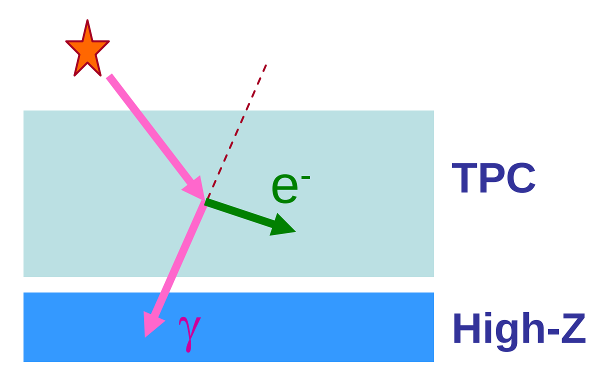




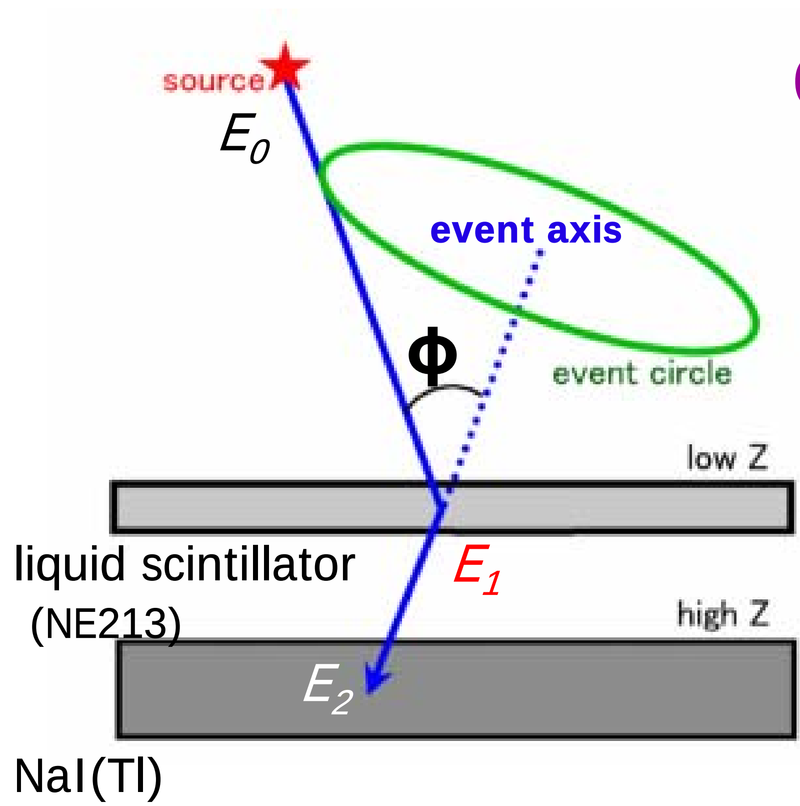
3. Advanced Compton Method

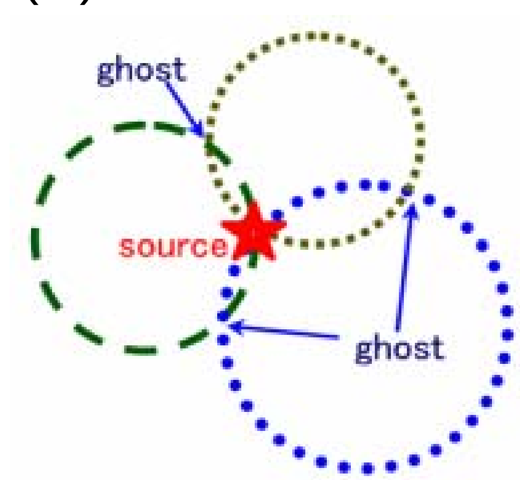
- Full event reconstruction
- Kinematical background rejection
- Large field of view

⇨ **MeV gamma-ray camera**



COMPTEL (aboard CGRO satellite: 1991~2000)





Classical Compton method

- energies of scattered γ and recoil e^- : E_1 , E_2

  ⇒ E_0 , ϕ

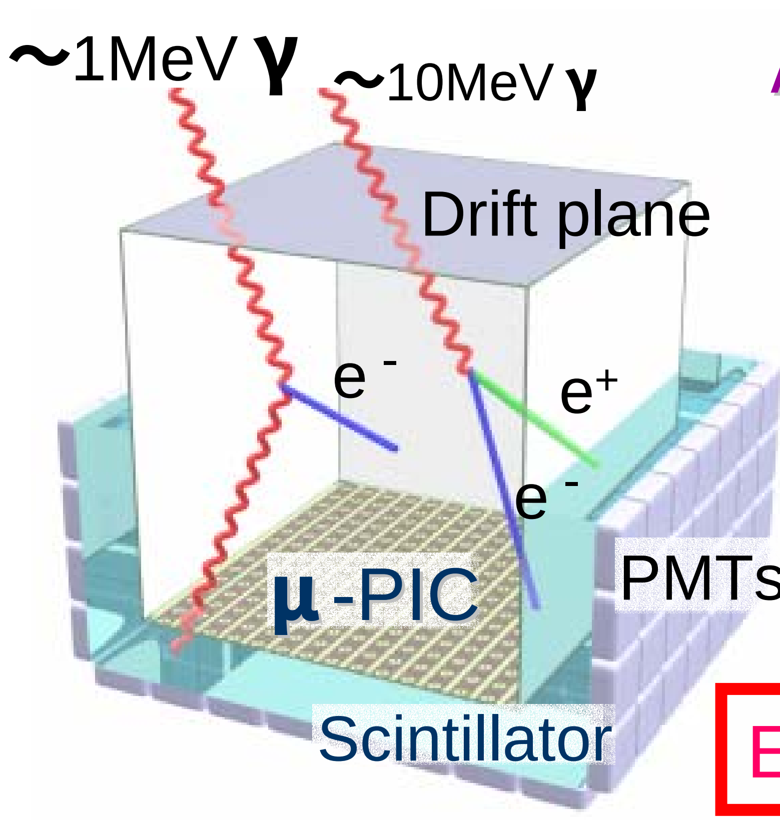
$$\cos\phi = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)$$

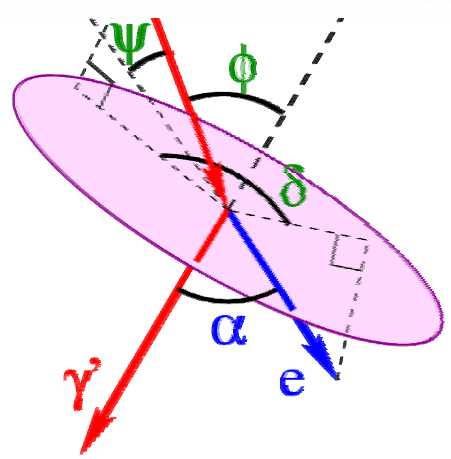
- positions where scattering and γ absorption occurred

  ⇒ event axis direction

➢ Only event circle can be determined
➢ No background rejection

2. New MeV Gamma-ray Camera





Advanced Compton method

- micro-TPC (μ -PIC + TPC)
  recoil electron energy & track

+

- Scintillation camera
  scattered γ energy & position

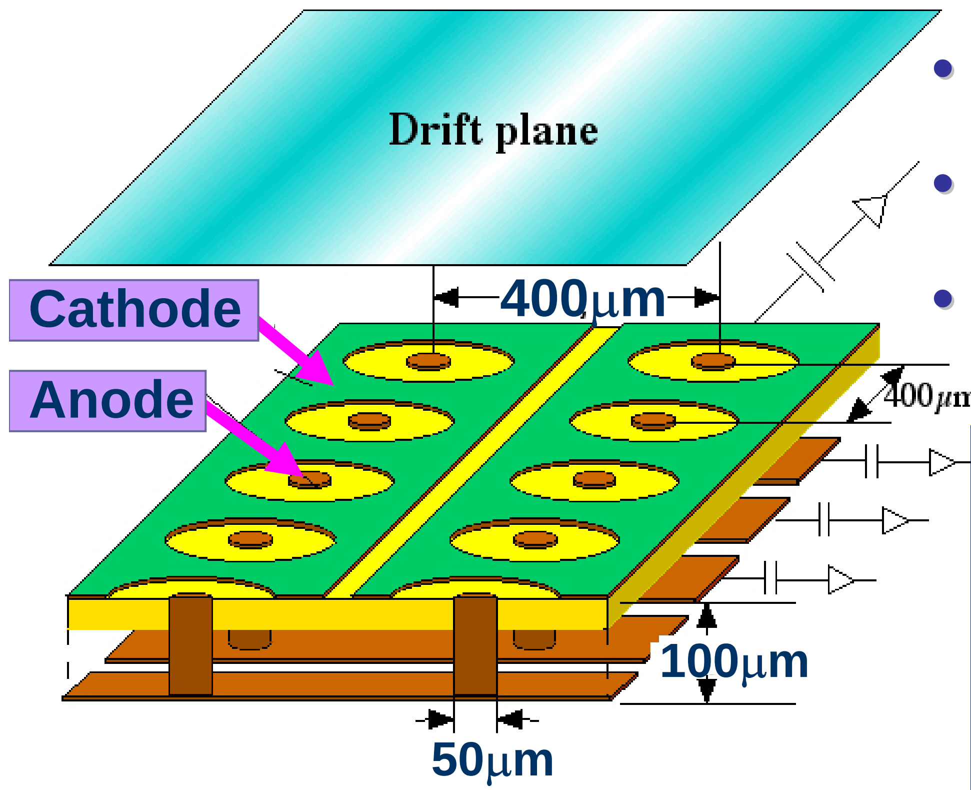
Event by event full reconstruction

- large field of view
- **α** ⇒ background rejection

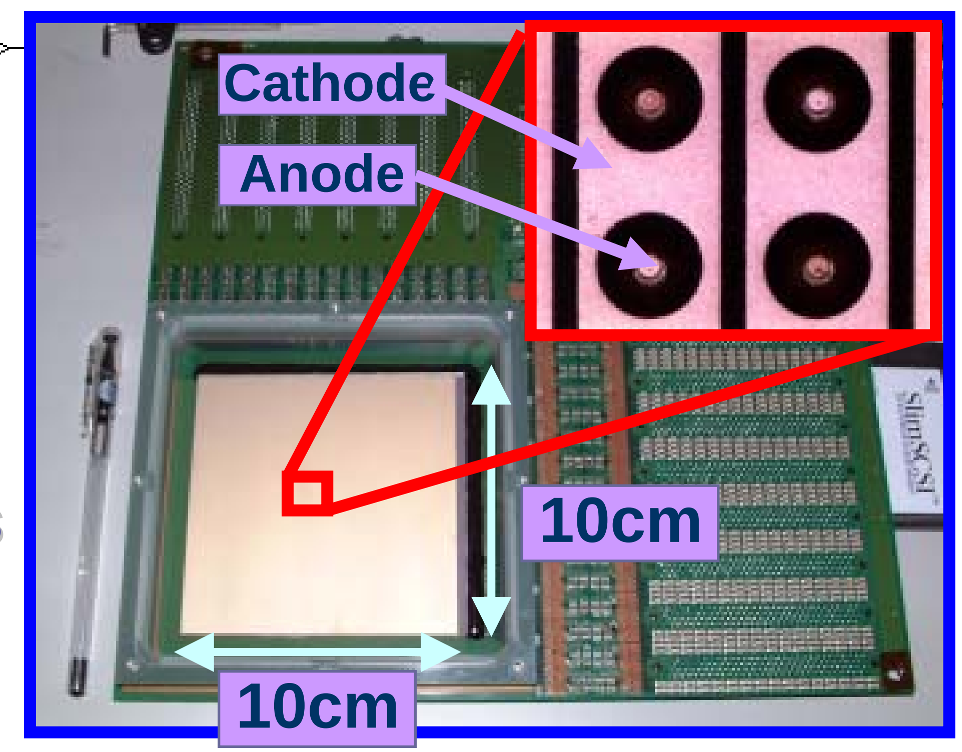
$$\cos\alpha = \left(1 - \frac{m_e c^2}{E_g}\right)\sqrt{\frac{K_e}{K_e + 2m_e c^2}}$$

Micro PIxel gas Chamber (μ-PIC)

Key device for the recoil electron tracking



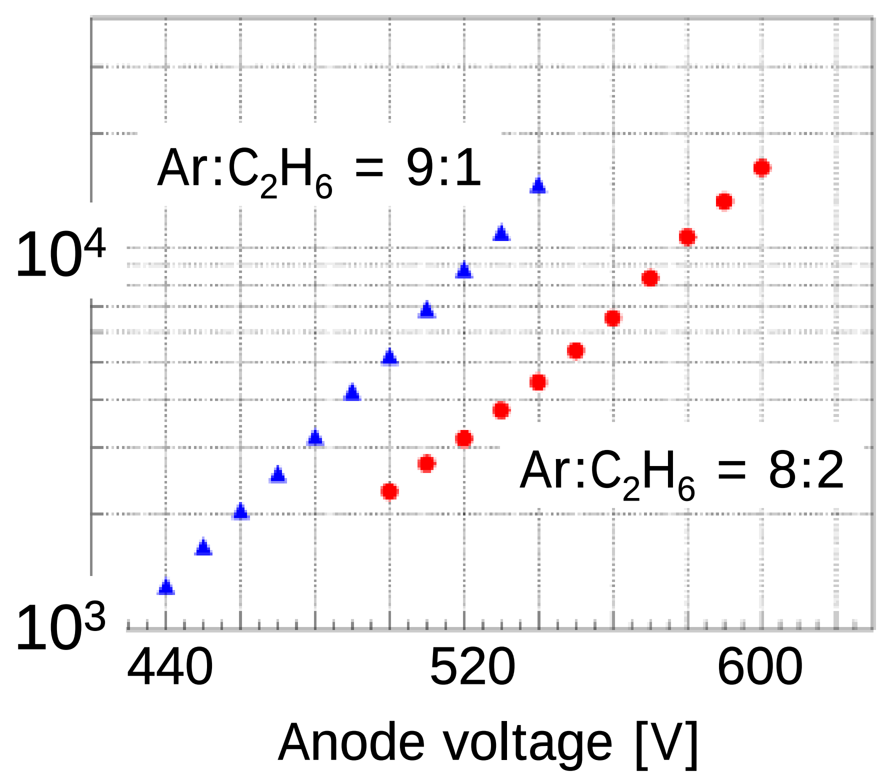
- High gain > 10^4
- Fine position resolution ~120μm
- Discharge damage is not serious



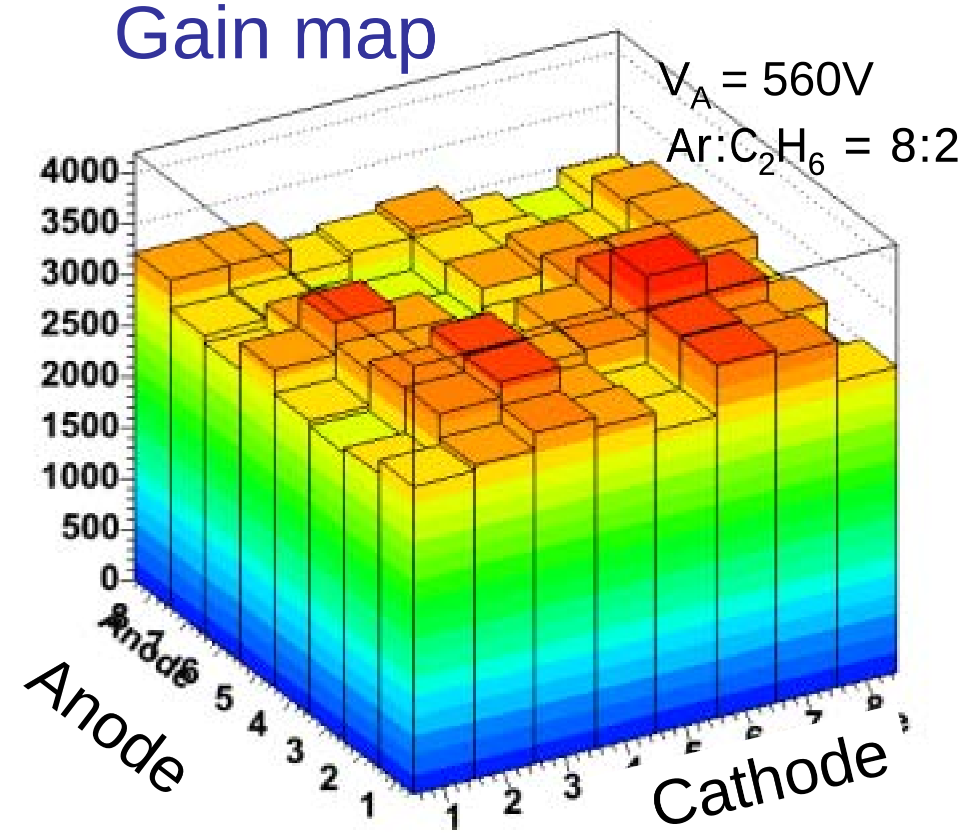
- 400μm pitch electrodes
- 256 anodes and 256 cathodes
- Printed Circuit Board (PCB) technology

Performance of the μ-PIC

Gas gain



Gain map



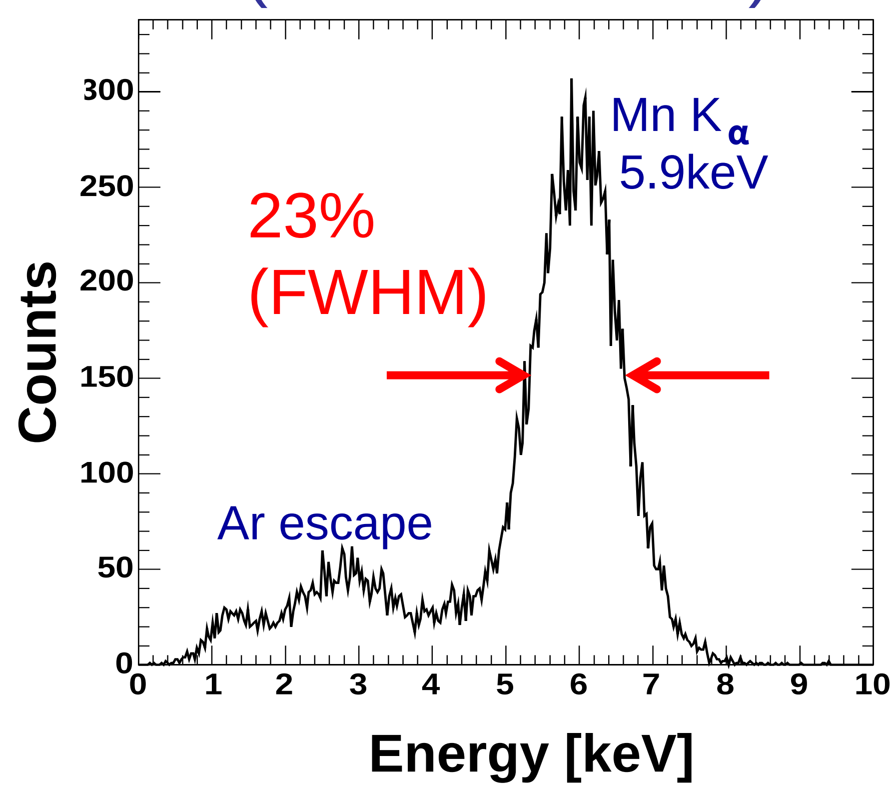
Max gain: 16000

Uniformity (s) ~ 7%

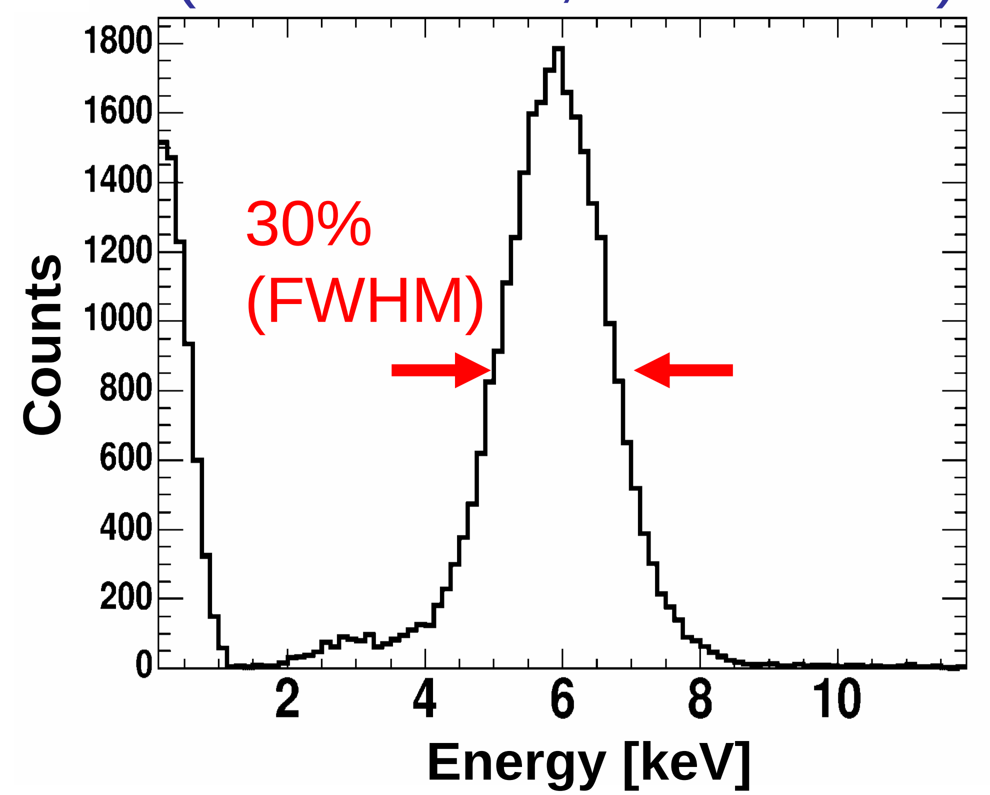
Stable operation: > 1000 hours with gain of 6000

Performance of the μ-PIC

^{55}Fe energy spectrum
(12.8×12.8mm^2)

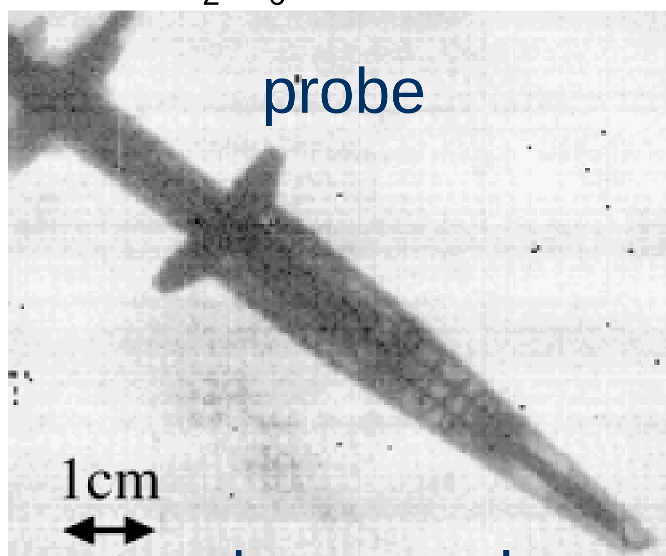


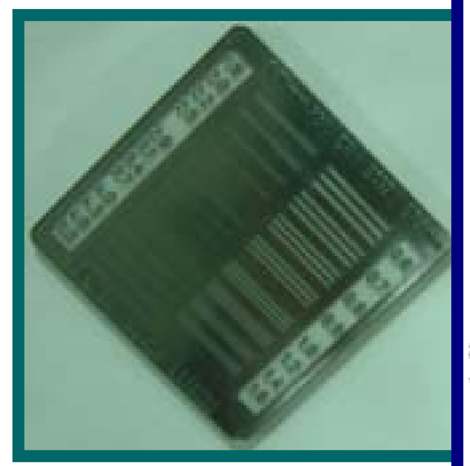
(10×10cm^2 , whole area)

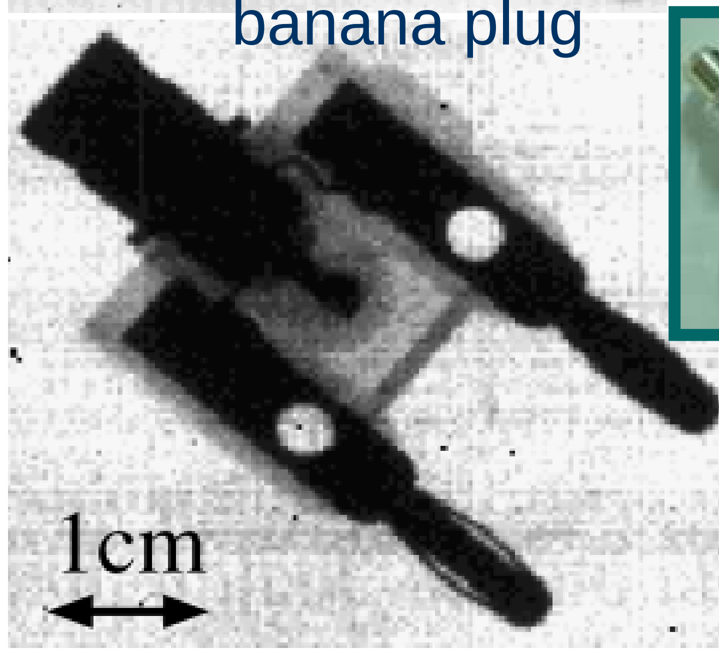


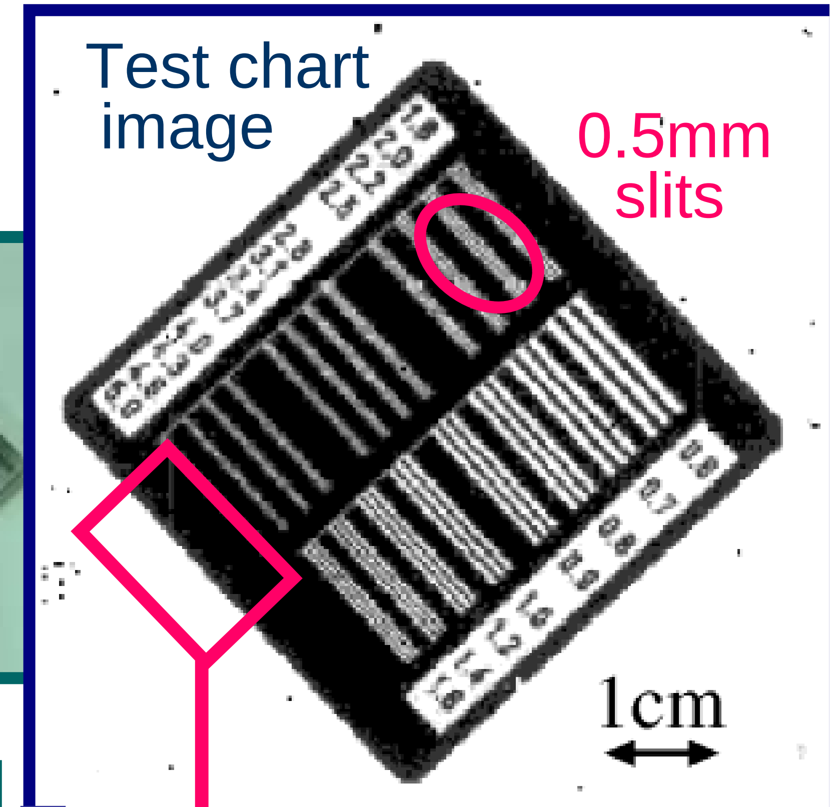
X-ray images obtained with μ-PIC

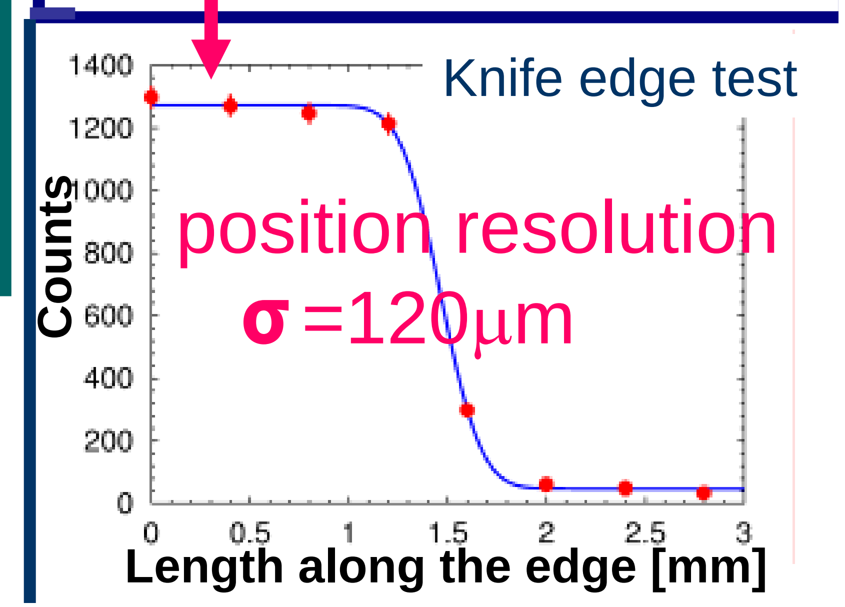
$Xe:C_2H_6 = 7:3$







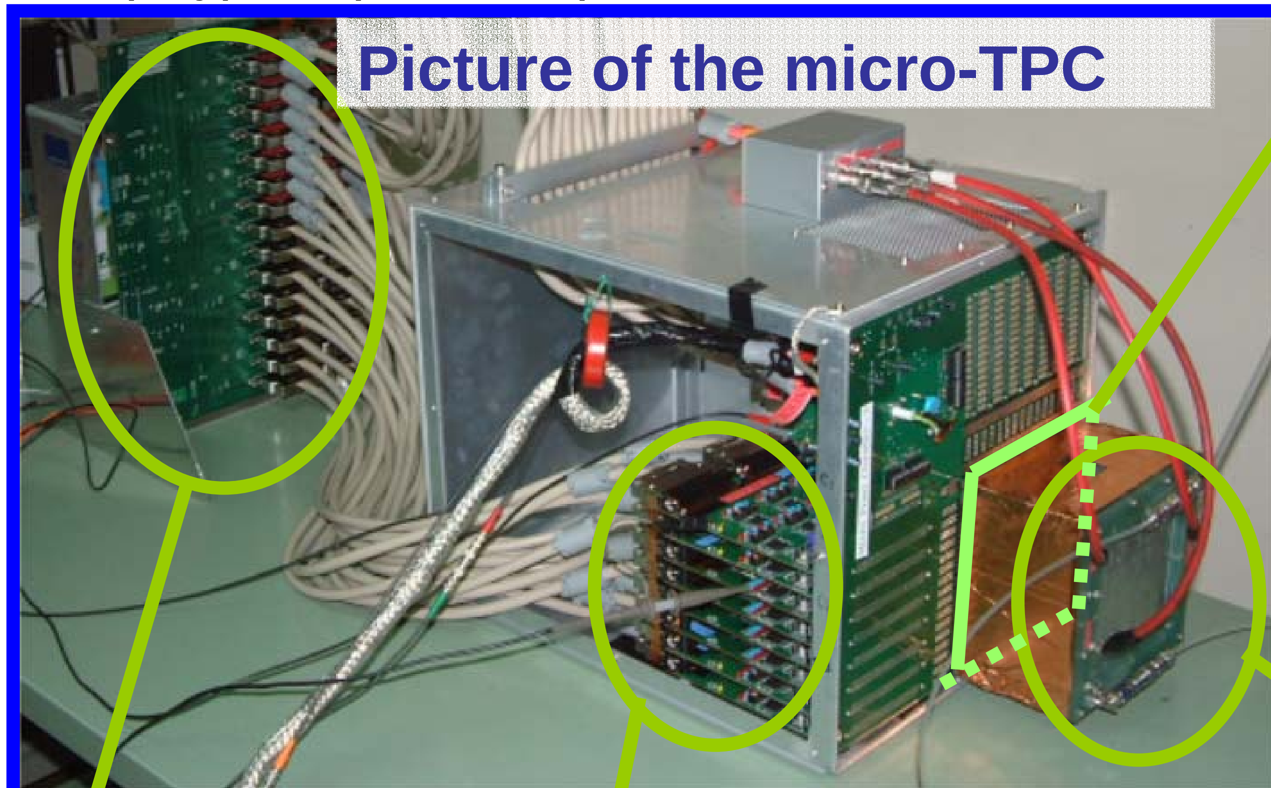


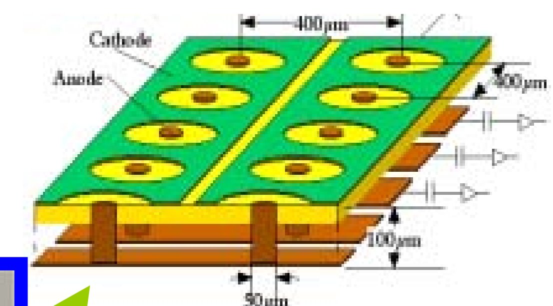


Micro-TPC

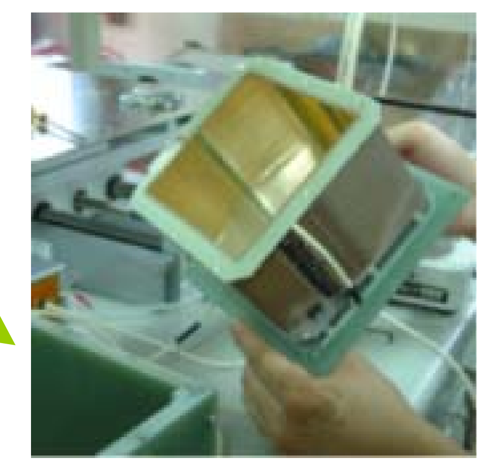
= **μ**-PIC + TPC ⇒ 3D tracking

(x, y) (drift time)



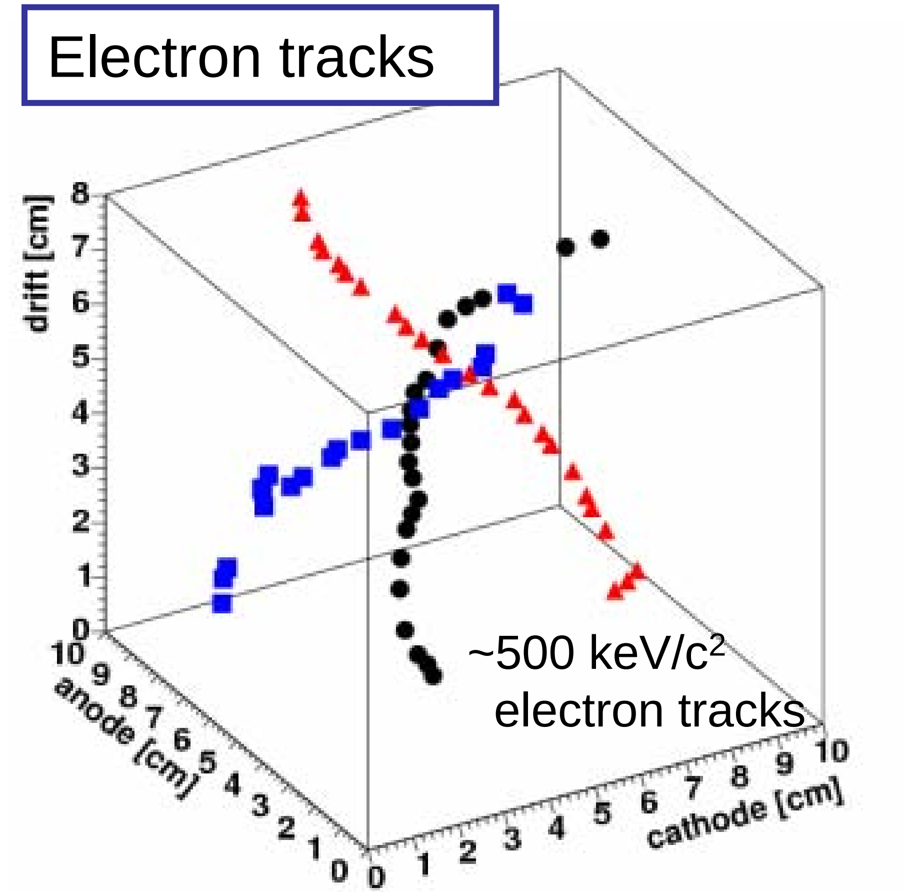


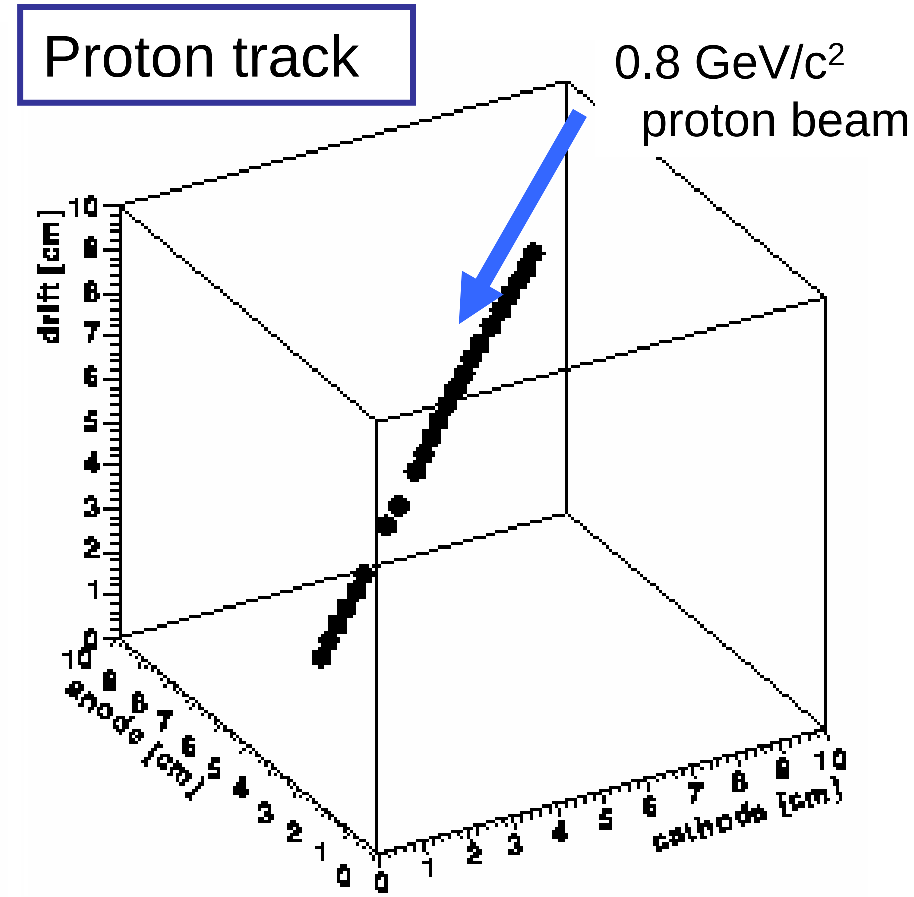
- **μ**-PIC
  - 10cm X 10cm



- Encoder
  - FPGA X 5
  - 20MHz clock
- Amp boards
  - Amplifier-shaper-discriminator (ASD) chip
  - discrimination → digital out
- TPC
  - 8cm drift length

Tracking performance of the micro-TPC

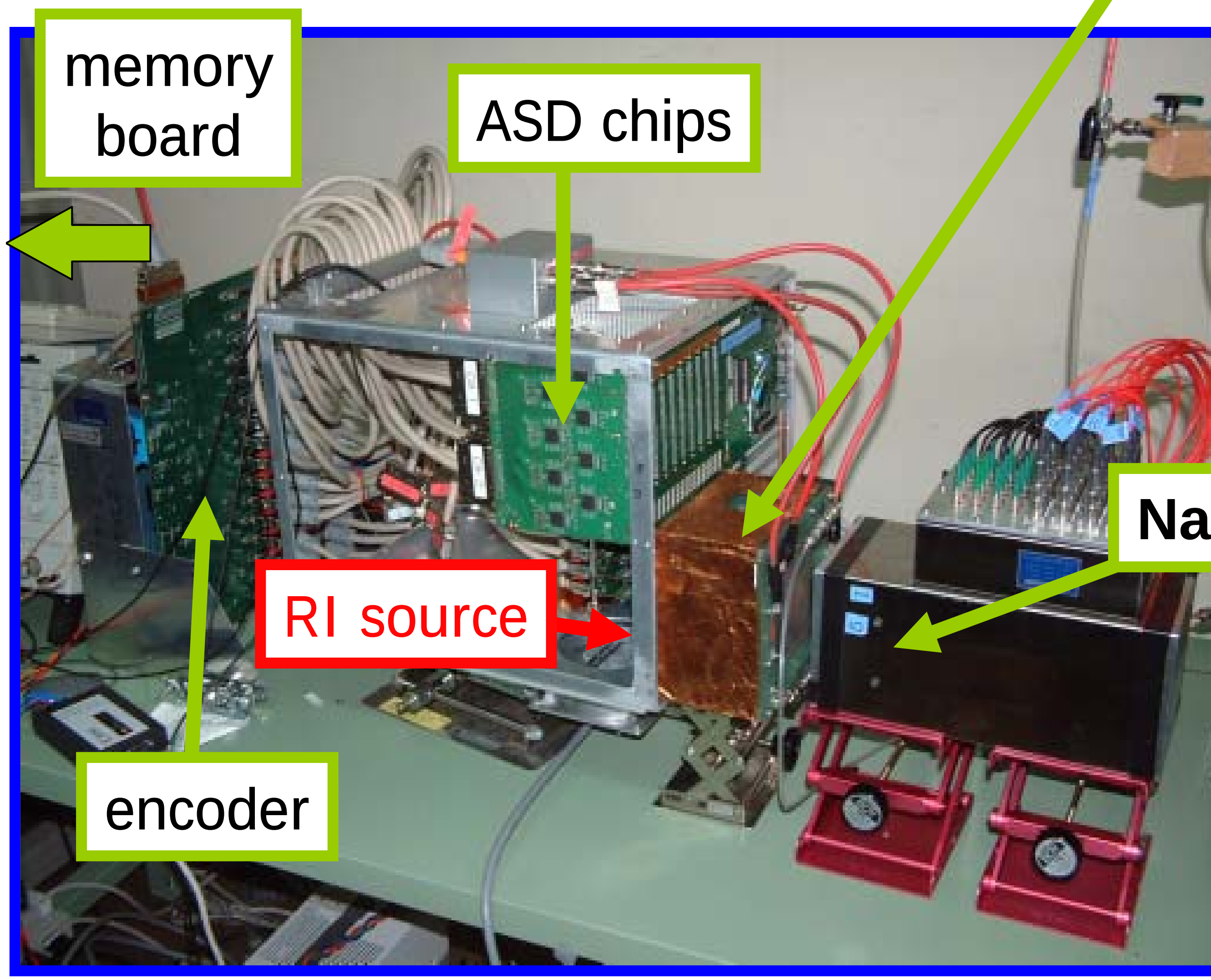




3-D spatial resolution : 260μm (limited by DAQ clock of 20MHz)
(Ar, 20MHz clock)

~210μm using 50MHz DAQ in the near future

3. Prototype Detector



Micro-TPC (μ-PIC)

- 10 X 10 X 8 cm^3
- Ar + C_2 H_6 (9:1)

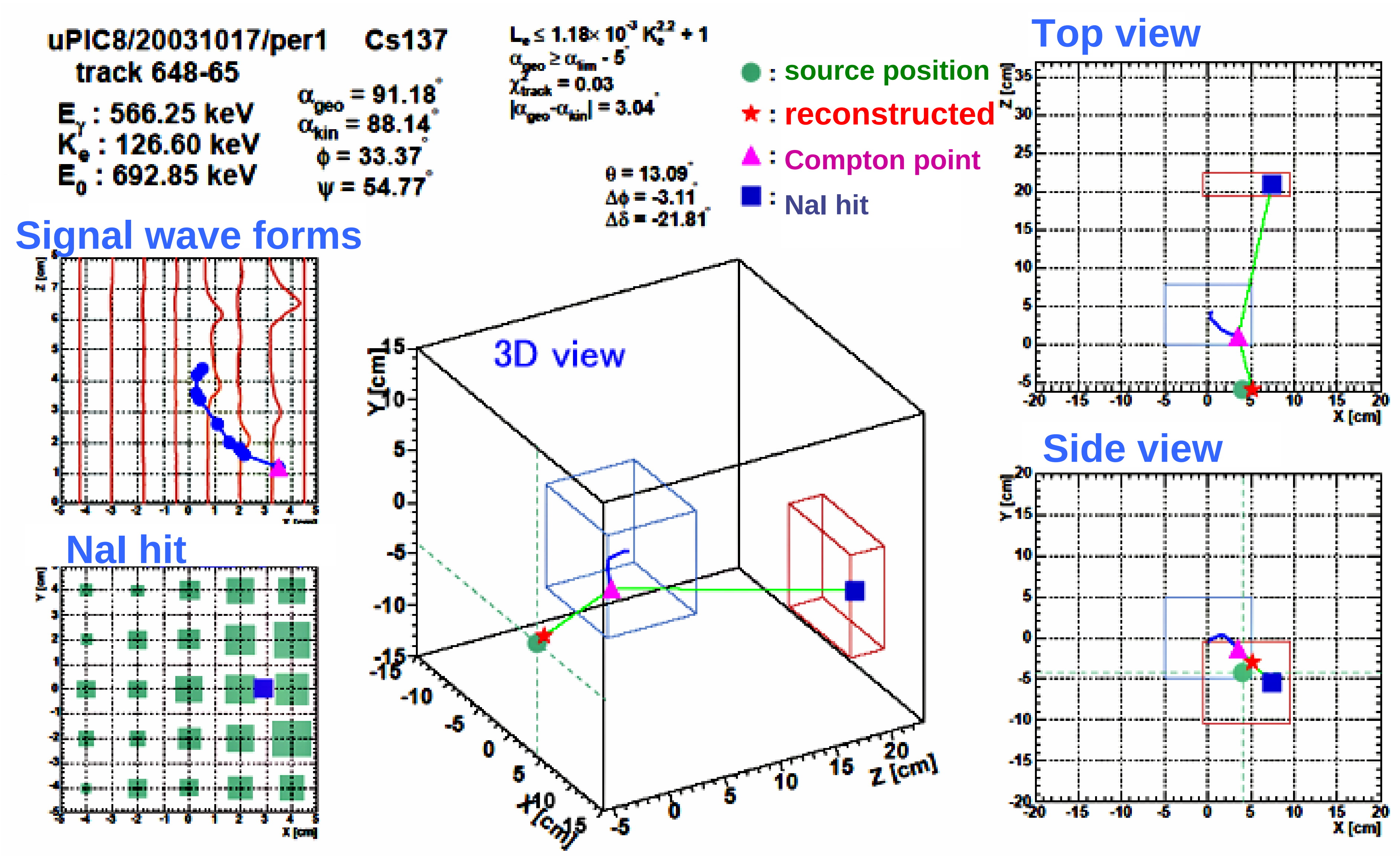
NaI(Tl) Anger camera

- 10 X 10 X 2.5 cm^3
- 25 PMTs

position resolution
~6.7mm (FWHM)
energy resolution
~11.2%
(662keV, FWHM)

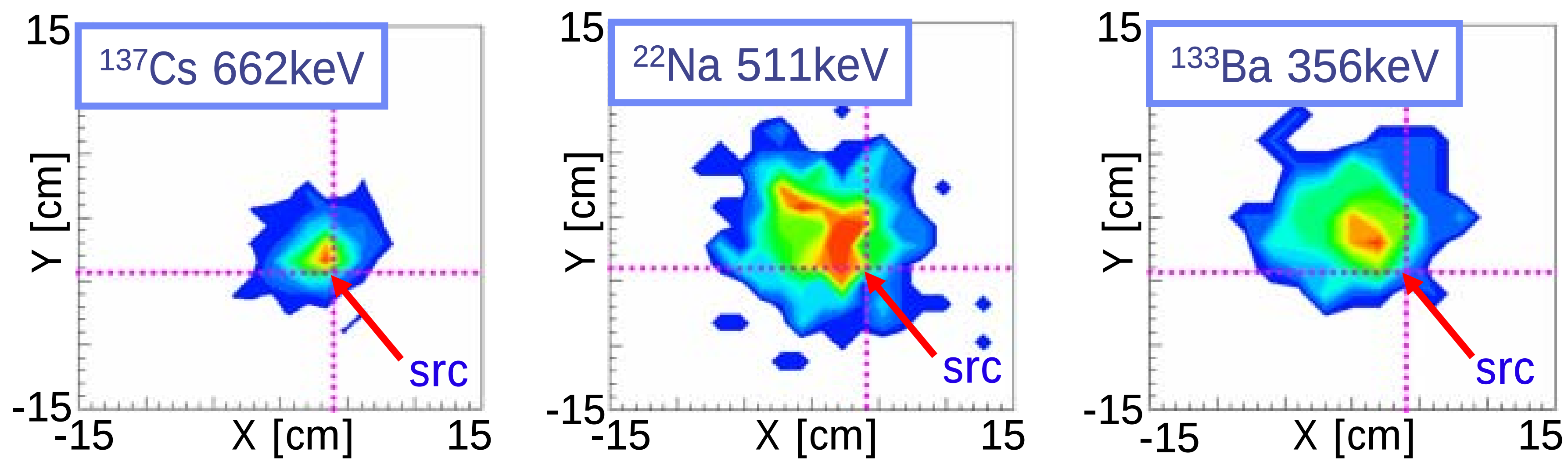
No Veto or Shield !

Typical reconstructed event



Gamma-ray imaging for known energy sources

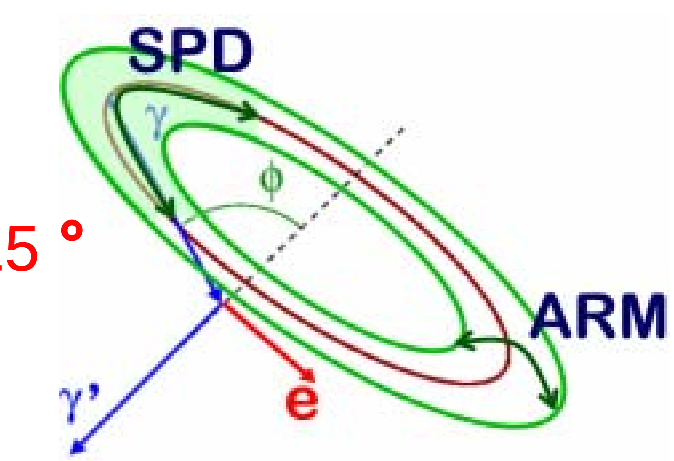
from track of recoiled e⁻ + energy and direction of scattered γ



- Angular resolution (RMS:662keV)

  Angular Resolution Measure (ARM): ~15 °

  Scatter Plane Deviation (SPD): ~25 °



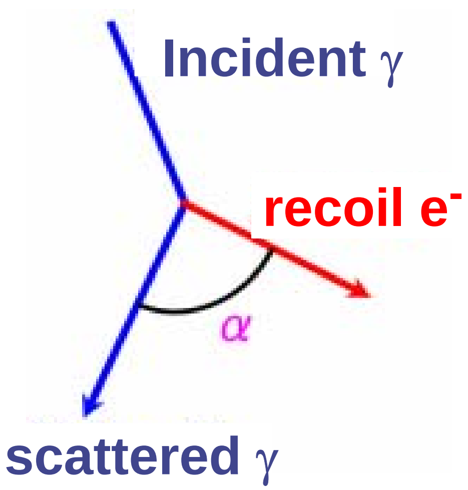
Background rejection

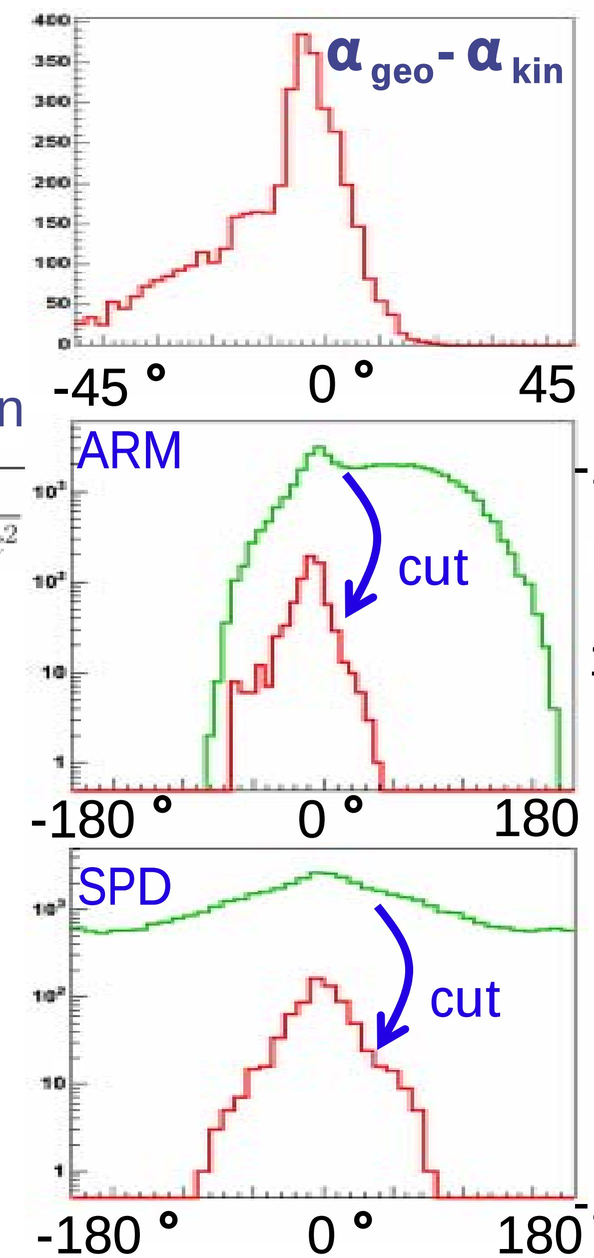
using redundant angle "α"

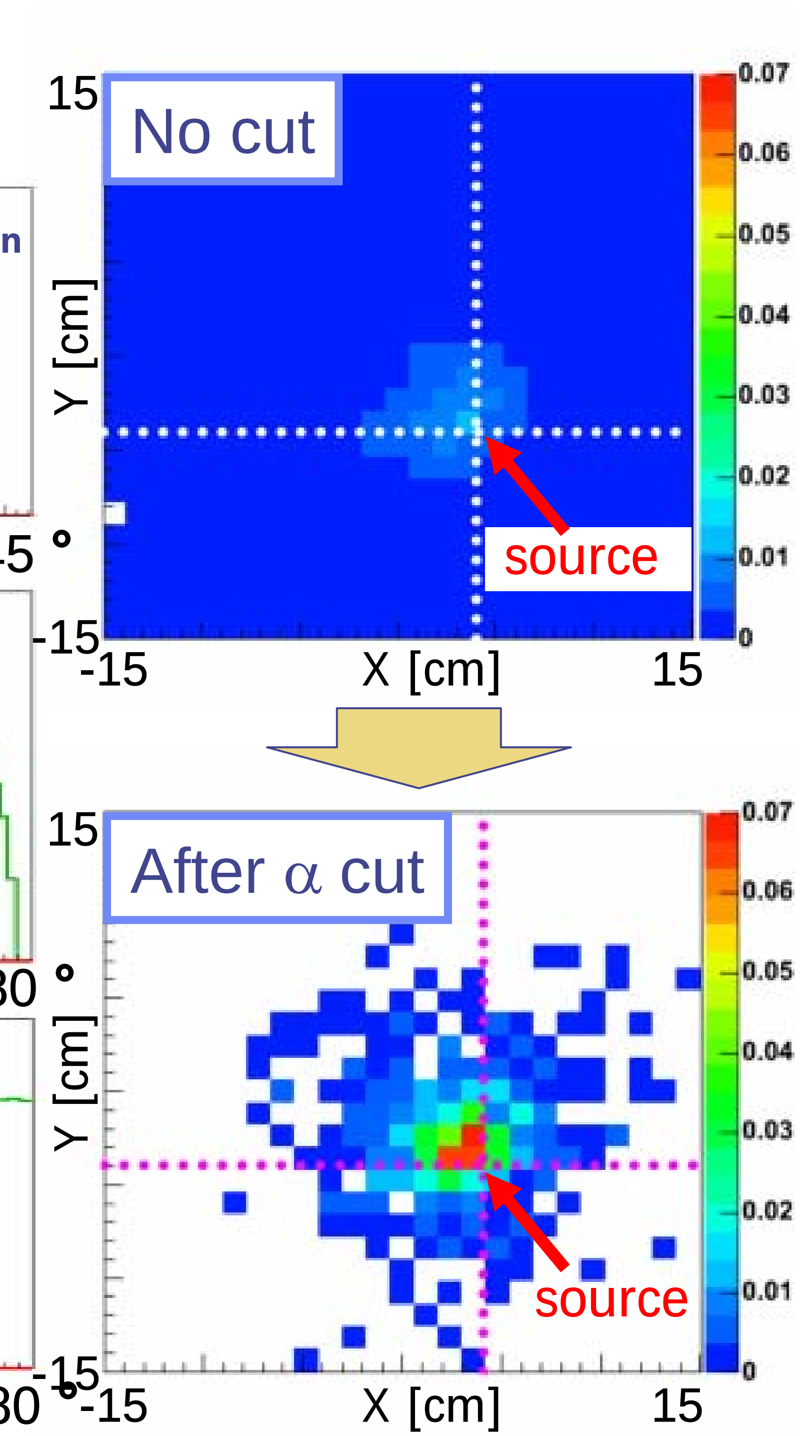
α_{geo} : measured α
α_{kin} : calculated α from energy information

$$\cos\alpha = \left(1 - \frac{m_e c^2}{E_g}\right)\sqrt{\frac{K_e}{K_e + 2m_e c^2}}$$

α cut
$\alpha_{geo} \sim \alpha_{kin}$







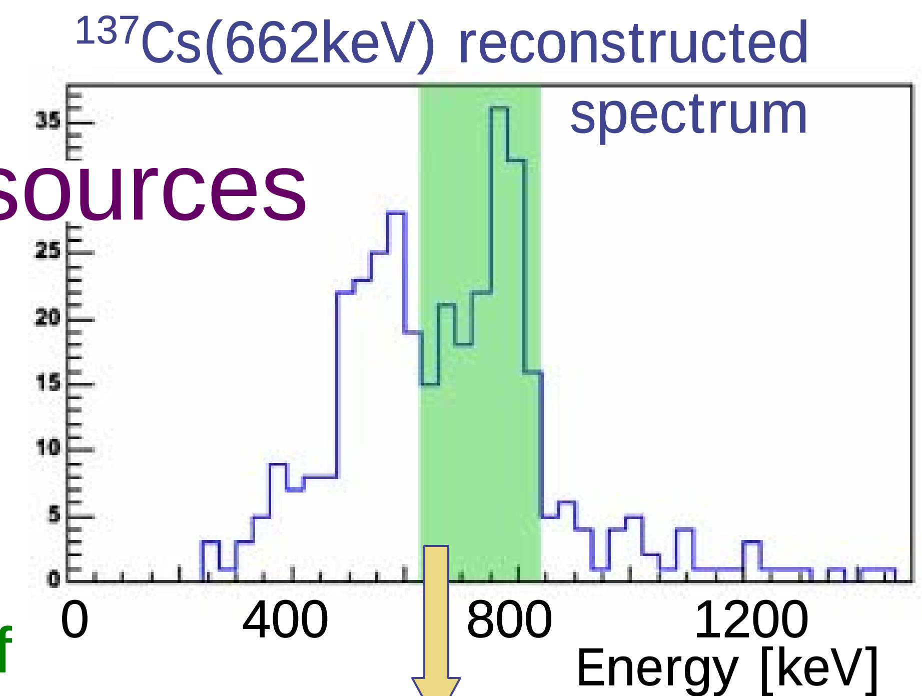
Gamma-ray imaging for unknown energy sources

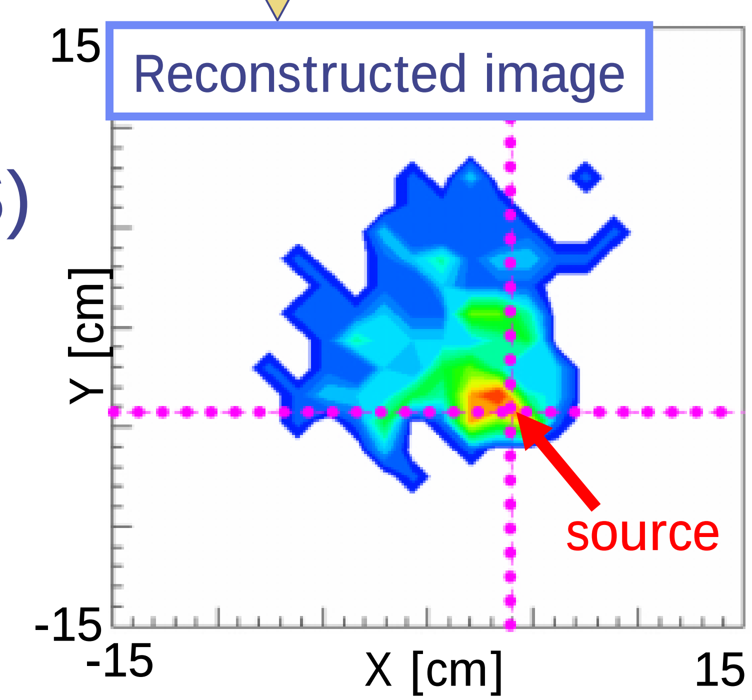
from

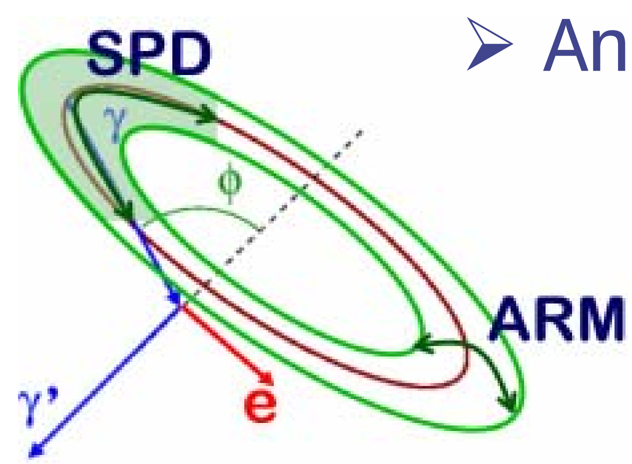
scattered γ 's energy & direction

recoiled e^- 's energy & direction

→ **Full reconstruction** of incident γ







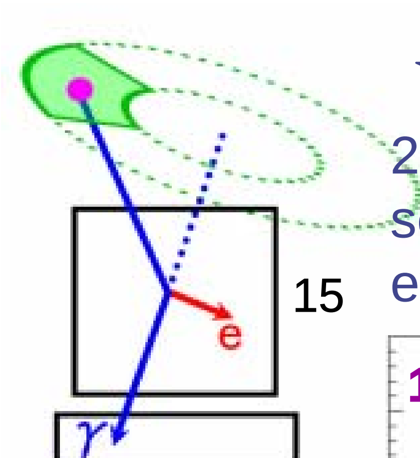
- Angular res. (RMS)
  - ARM ~15 °
  - SPD ~35 °

Comparison with the classical Compton method

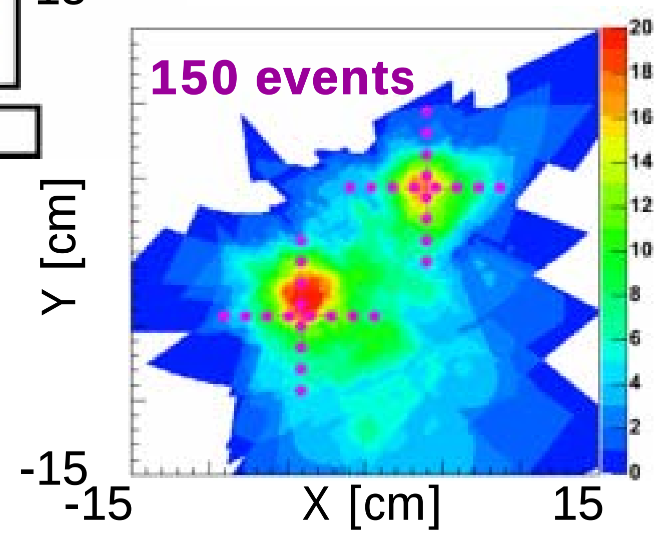
Advanced Compton Meth.

Using the electron tracks

- complete direction within sector form error region



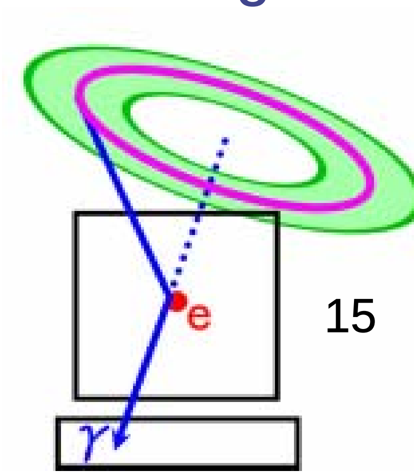
2 sources were separated clearly even from ~100 events



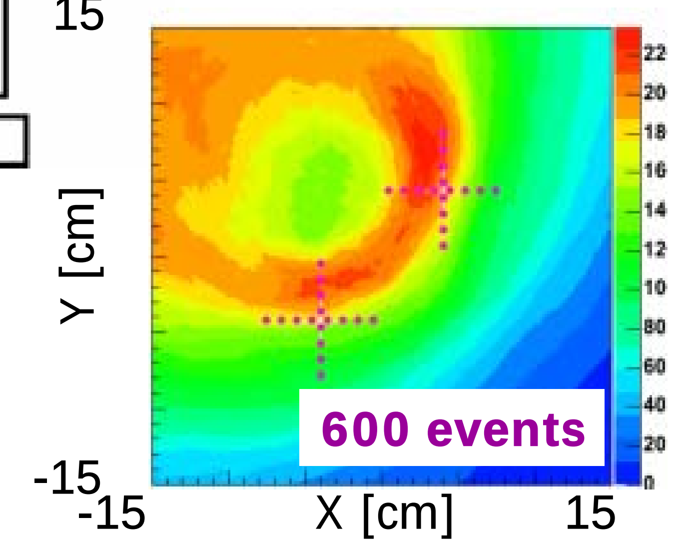
Classical Compton Meth.

Not using the electron tracks

- only event circle within ring form error region



Hard to separate 2 sources



4. Summary & Future works

- ✓ Event by event full reconstruction well established
  - ⇒ even for the continuous γ-ray
- ✓ Good background rejection capability
  - ⇒ higher S/N than that of classical Compton
- ✓ Prototype performance (full reconstruction)
  - ARM(RMS) ~15°
  - SPD(RMS) ~35°

➢ ARM (goal: **σ** ~3°)

- uniformity of micro-TPC

→ higher energy resolution

- pixelization of scintillator

→ higher position resolution

➢ SPD (goal: **σ** ~5°)

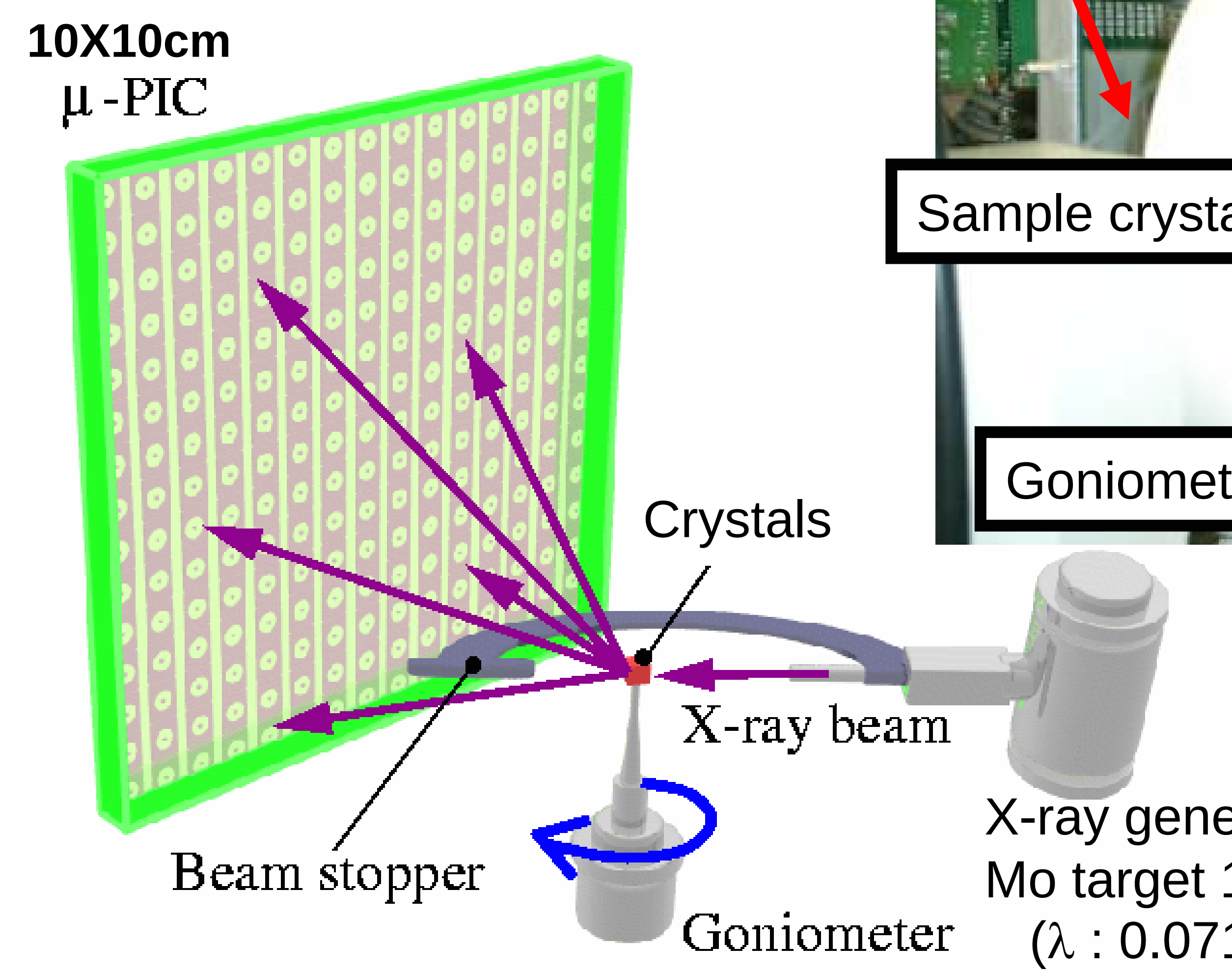
- clock up of micro-TPC (20MHz→50MHz)
- gas study (Ar→CF_4)
- large volume micro-TPC

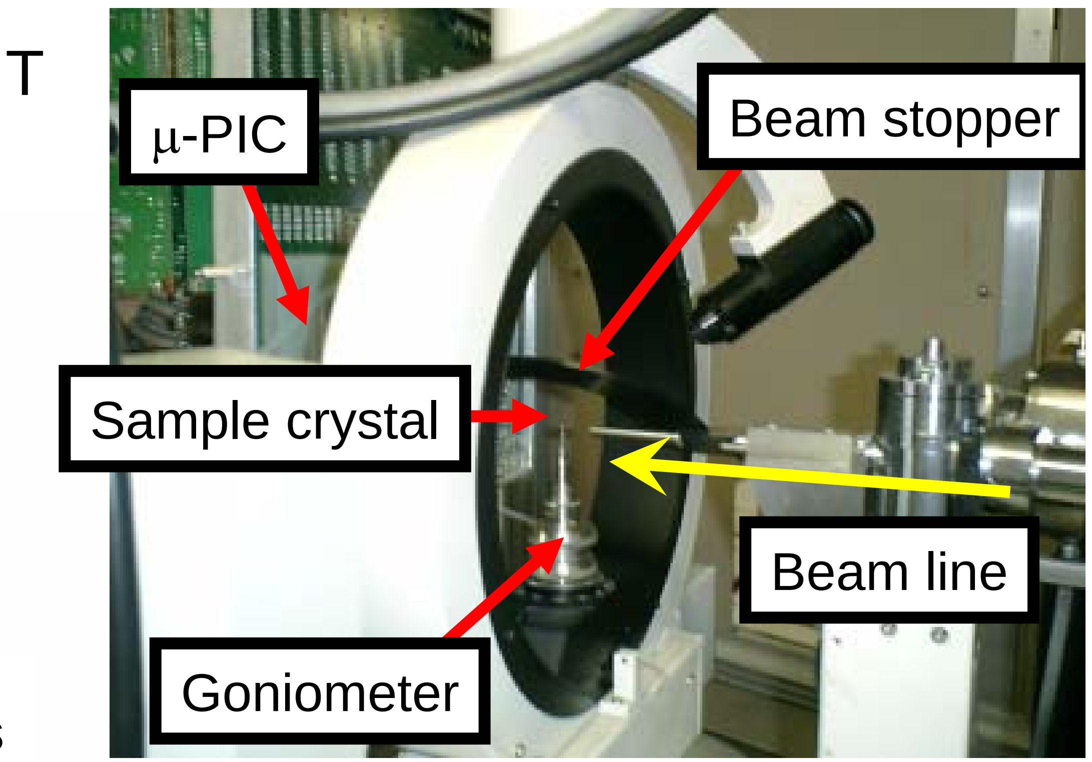
→ more precise tracking

Crystal structure analysis with RCP* method

*RCP: Rotation Continuous Photograph

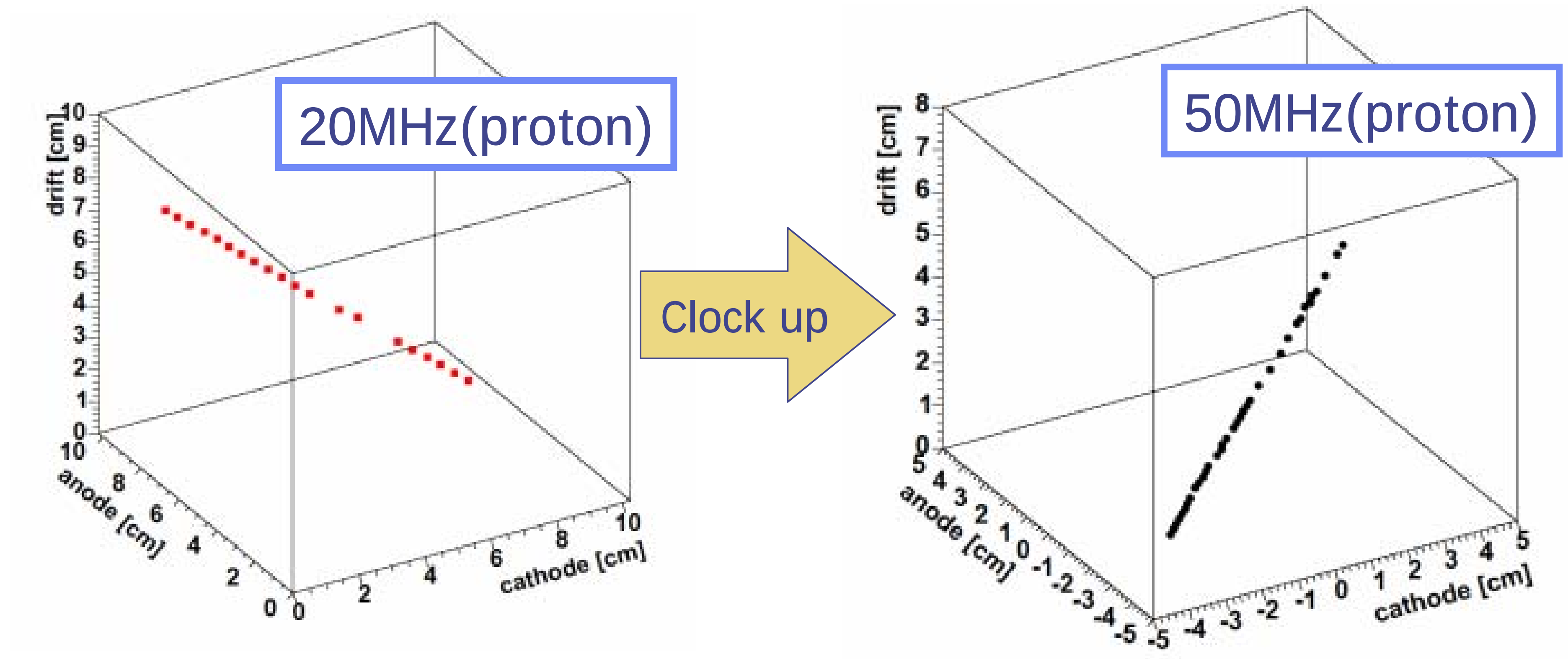
- Experimental setup @TIT





X-ray generator 50kV, 250mA
Mo target 17keV
(λ : 0.071 nm)

Clock up of the micro-TPC



Gaps in the drift direction：2mm　　　　　　　　：0.8mm

Higher spatial resolution of micro-TPC ➡ More precise tracking of recoiled electron

Theoretical limits of angular resolution in the ARM direction

Owing to the Doppler broadening of the scattered g-ray energy

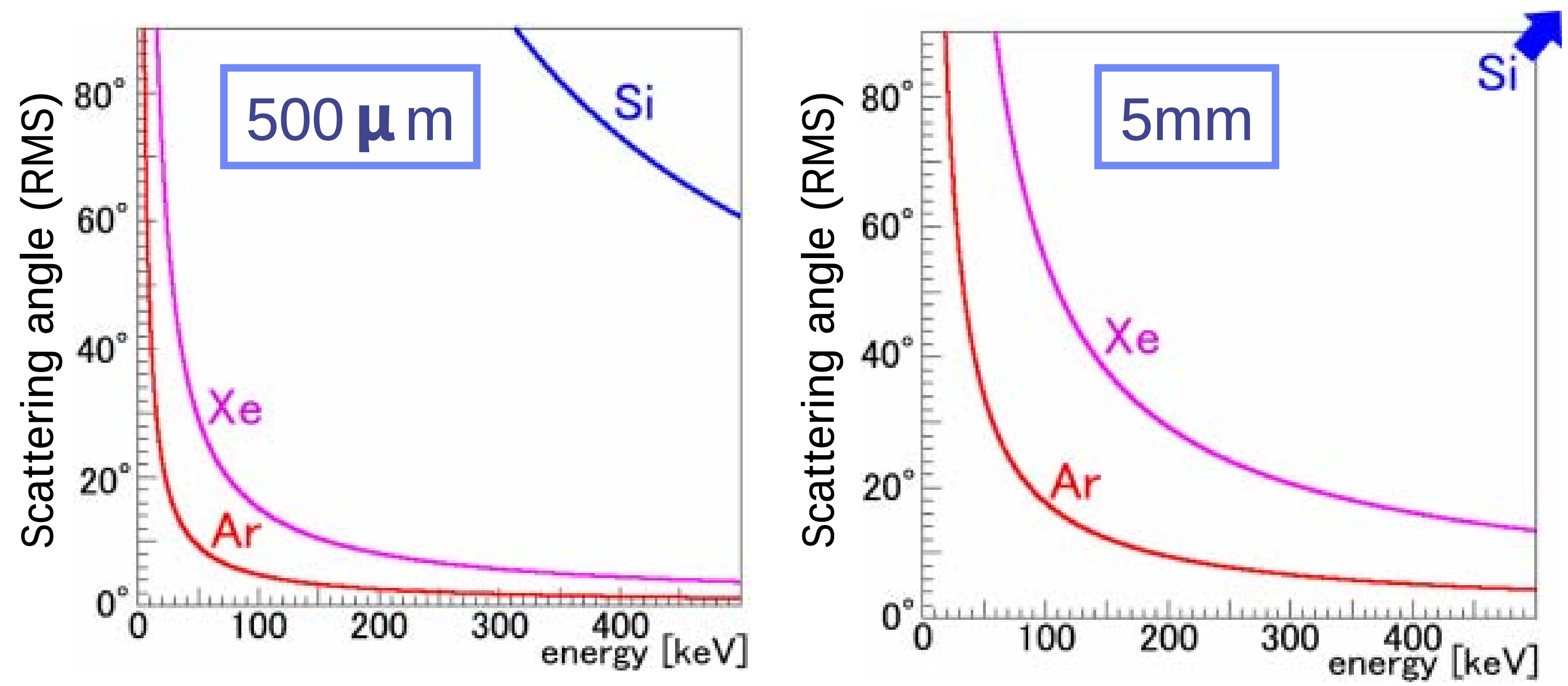
Angular resolutions (ARM) for various nuclei

A.Zoglauer, et.al.(SPIE,2003)

	Ar	Xe	Si	CdTe
200keV	2.6°	3.3°	1.8°	3.5°
500keV	1.1°	1.5°	0.8°	1.6°
1MeV	0.5°	0.8°	0.4°	0.9°

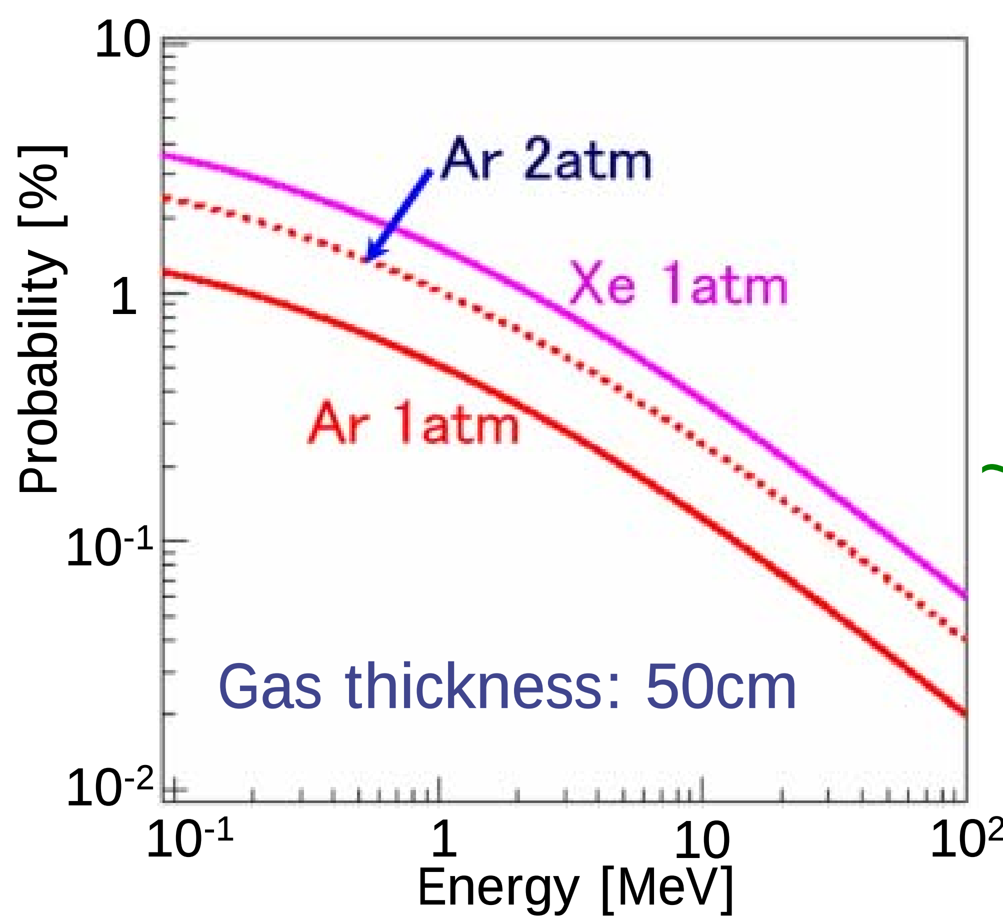
Theoretical limits of angular resolution in the SPD direction

Owing to the multiple scattering in the tracking detector



Very hard to obtain the precise direction of the recoiled e^- in the solid detector

Effective area

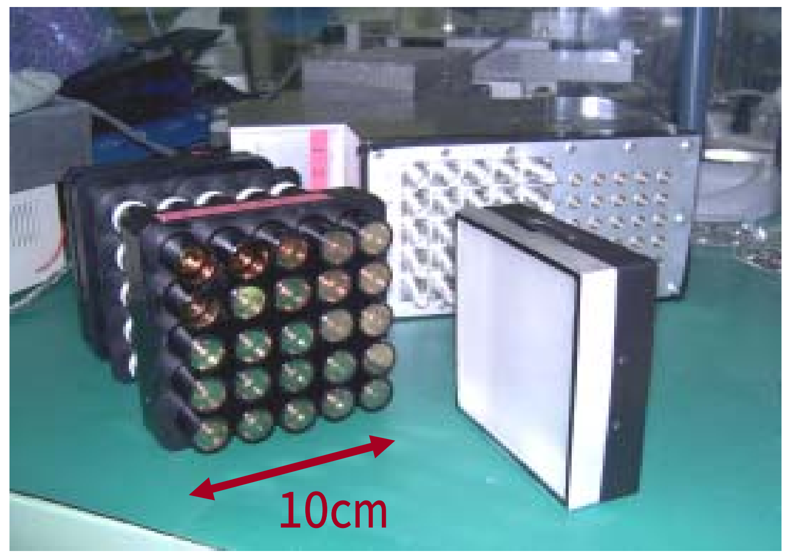


Effective area of COMPTEL
~40cm^2 @ 1MeV

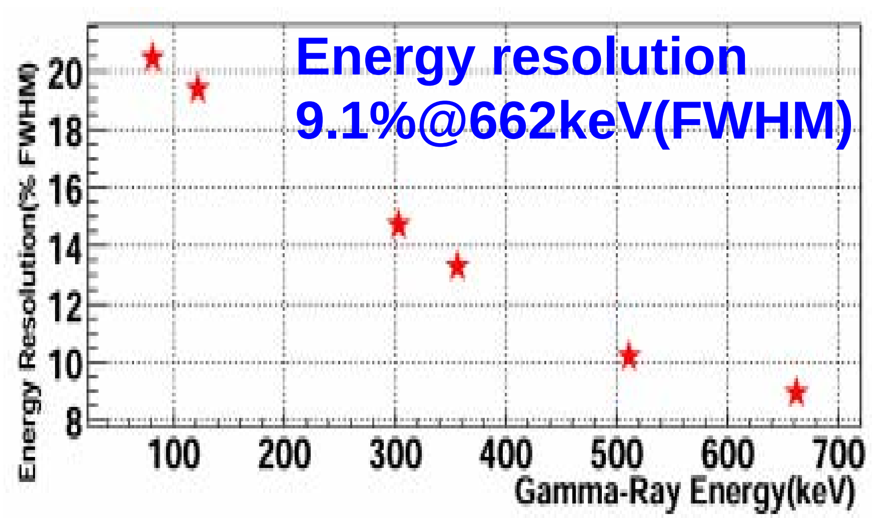
50cm cube gas detector
Compton effective area
~30cm^2 @ 1MeV (Xe 1atm)

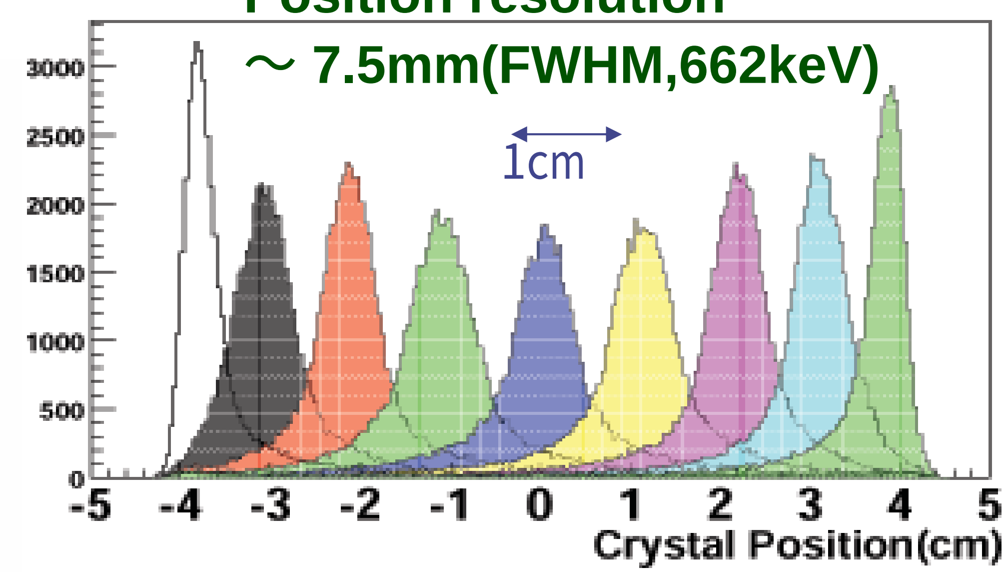
Gas detector has enough Compton scattering capability

Position Sensitive Scintillation camera

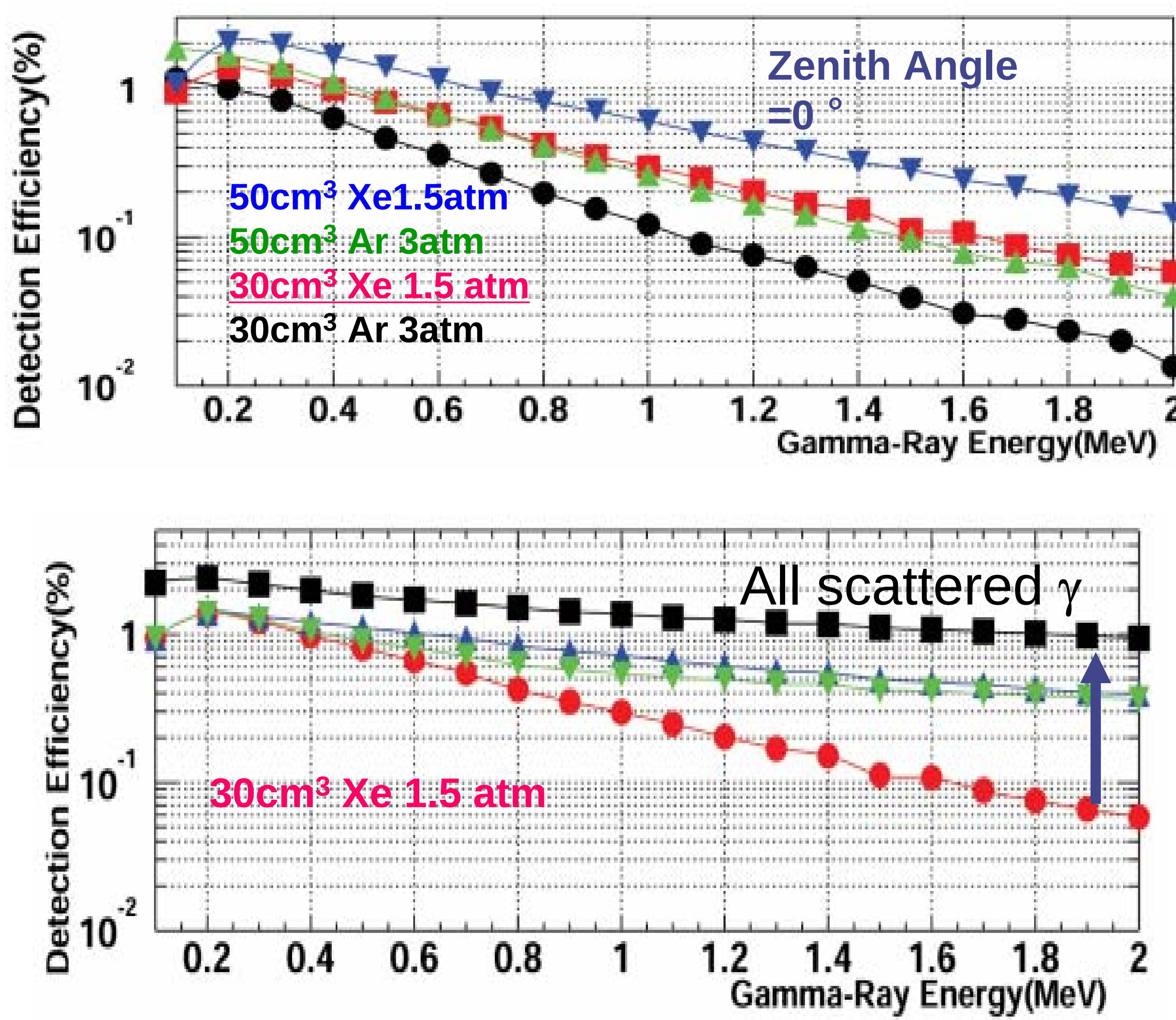


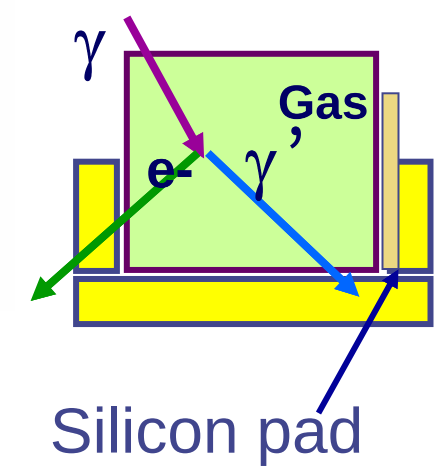
- ✓ 4”×4”×1” NaI(Tl) Scintillator
- ✓ 5×5 Hamamatsu ¾” R1166 PMT
- ✓ PhotoCathode Cover rate 40%
- ✓ Dynamic Range 0.1〜1MeV





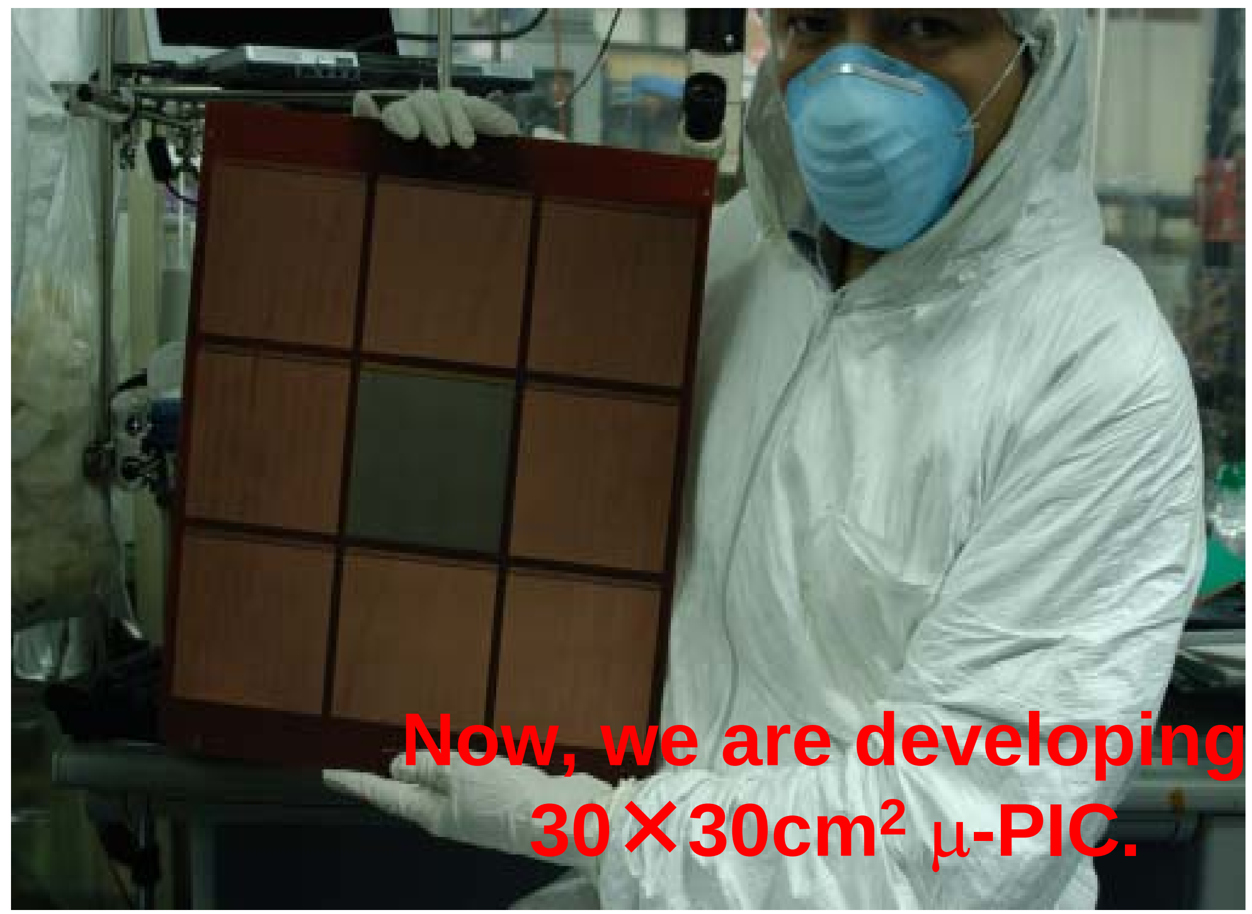
Detection Efficiency





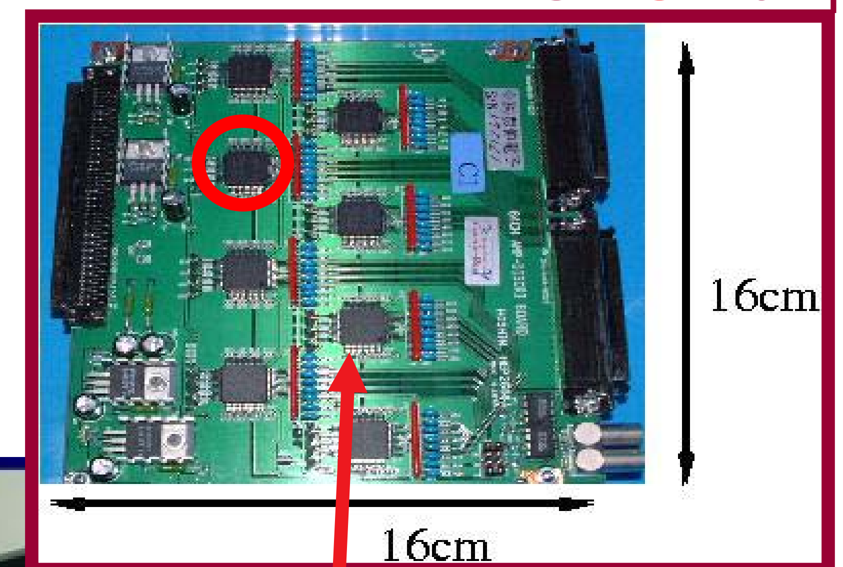
Through going electron
(δ also improved)

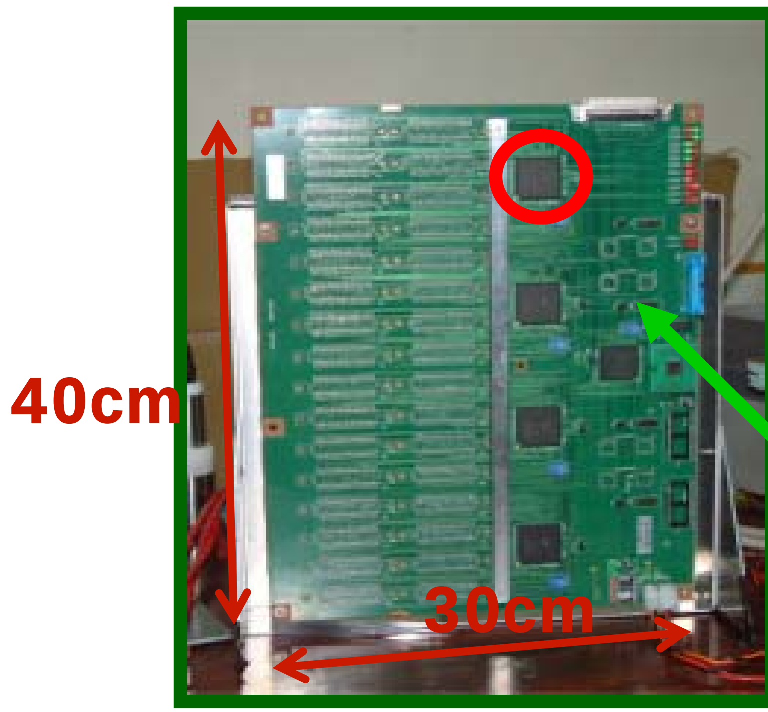
30cm×30cm μ-PIC

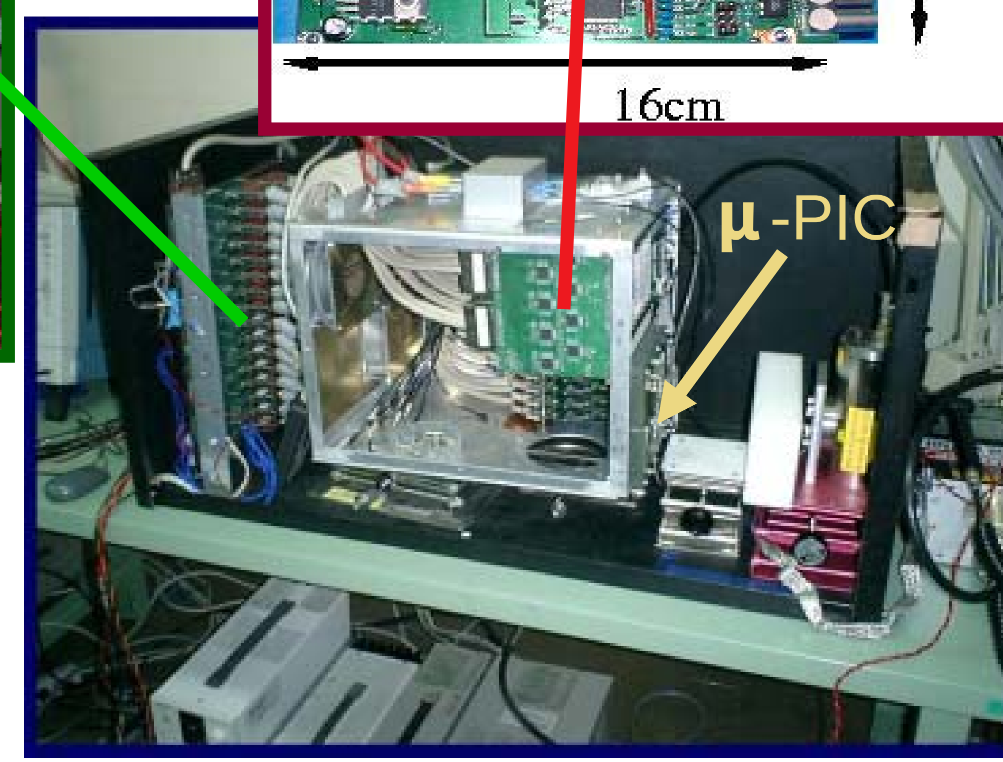


Electronics

◆ Preamplifier
- ATLAS ASD chip



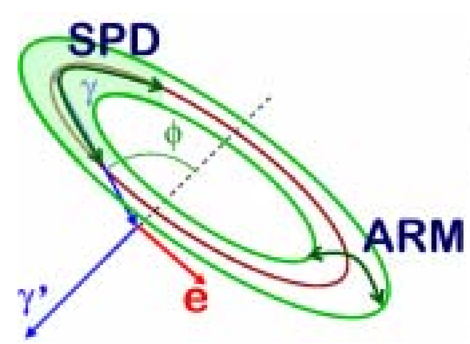


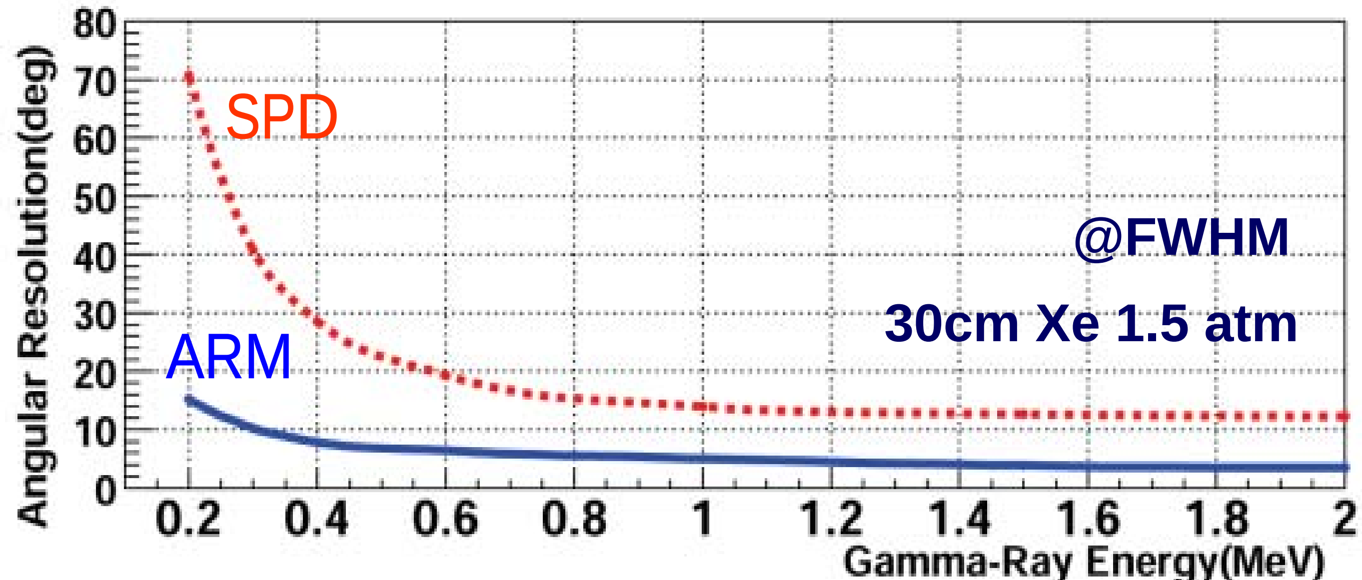


◆ Encoding board
- 5 FPGAs
- take anode–cathode coincidence @ 20MHz

Angular Resolution

ARM : Angular Resolution Measure
SPD : Scatter Plane Deviation





Effective Area