# New Mission Concept (MeGaT): a high precise MeV Gamma Telescope using TPC Technique read out with Micromegas

**Ruizhi Yang**

**On behalf of the MeGaT Group**

# MeGaT Group members

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# Outline

- Introduction on MeV γ-ray astronomy
- MeV γ-ray detection
  - Key technological challenges
  - Some experimental proposals
- MeGaT experiment & R&D process
  - Conceptual design
  - Simulation framework and results
  - Prototype of R&D
  - Electronics
- Summary

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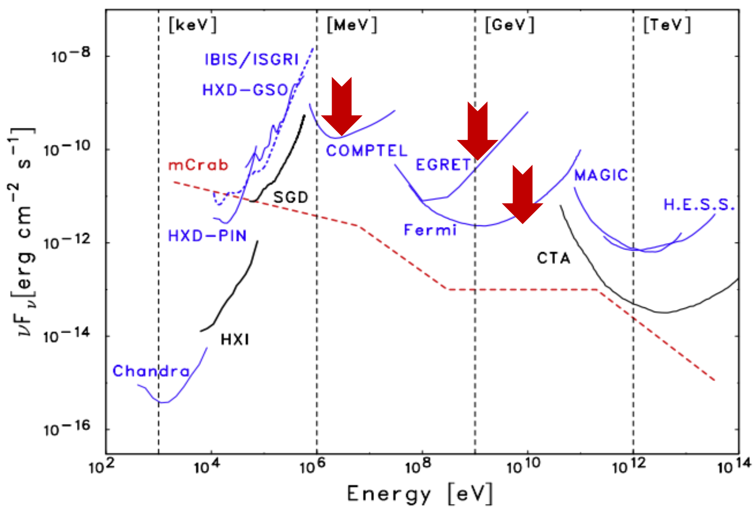
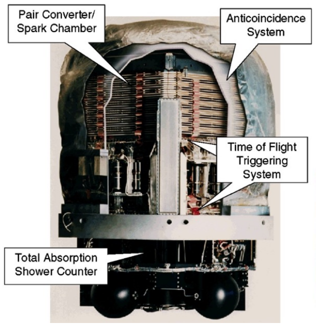
# MeV γ-ray astronomy observations

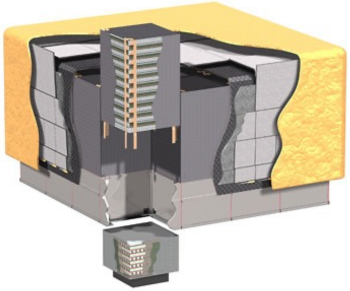
*T. Takahashi et al. / Astroparticle Physics 43 (2013) 142–154*

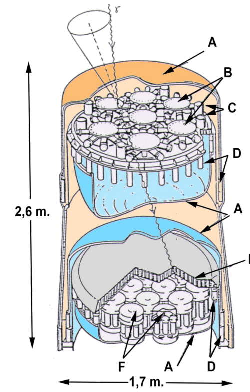



EGRET

Fermi-LAT



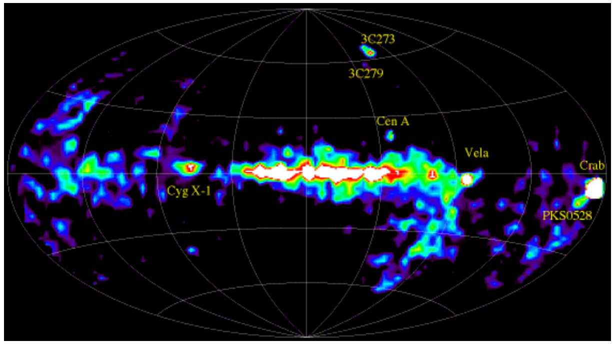


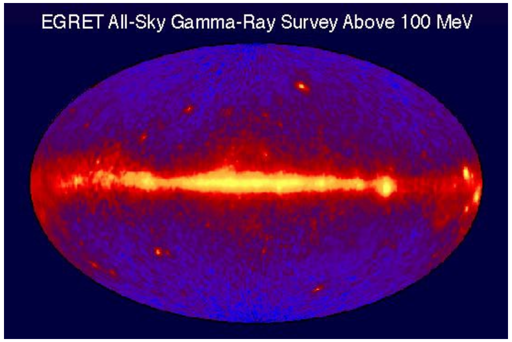

Comptel

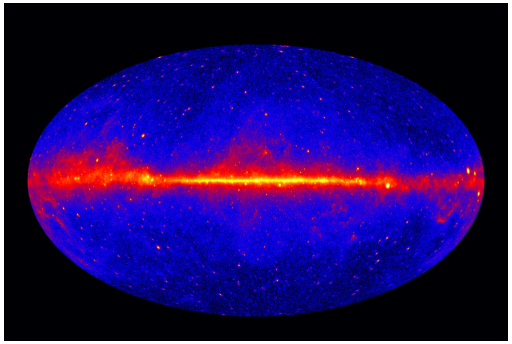
Comptel (1991-2000)
63 sources 1-30MeV

EGRET (1991-2000)
271 sources>100MeV

Fermi (2008-)
6000+ sources>100MeV



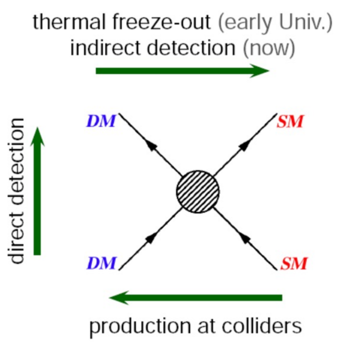



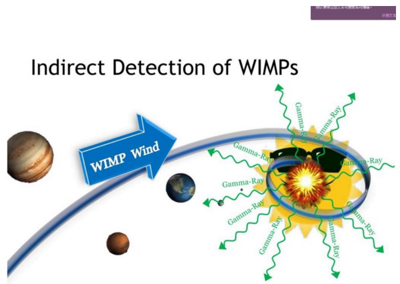
There is great discovery potential for the MeV gap

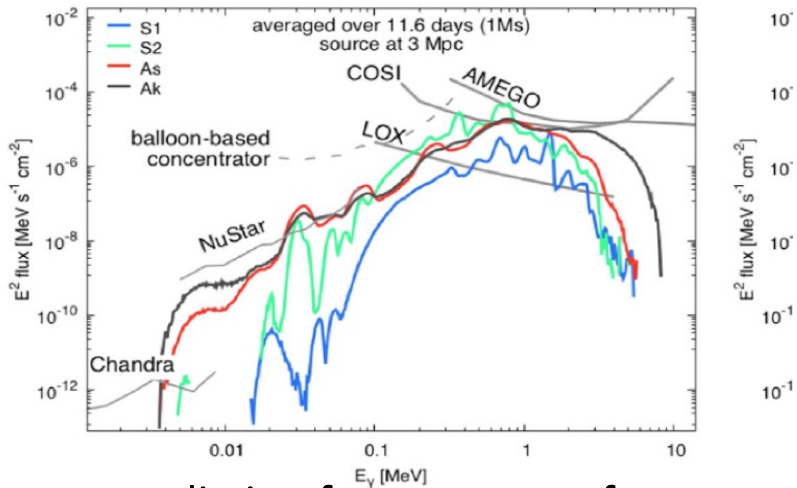
# MeV γ-ray astronomy

□Studying the origin, composition, and evolution of the universe, and other related phenomena.

- MeV spectral line astronomy
- Ultra-high-energy neutrinos and cosmic rays
- MeV bremsstrahlung
- Sub-GeV dark matter and primordial black holes
- MeV polarization




Gamma spectra prediction from merger of neutron stars

A brand-new astronomical observation window for MeV γ rays

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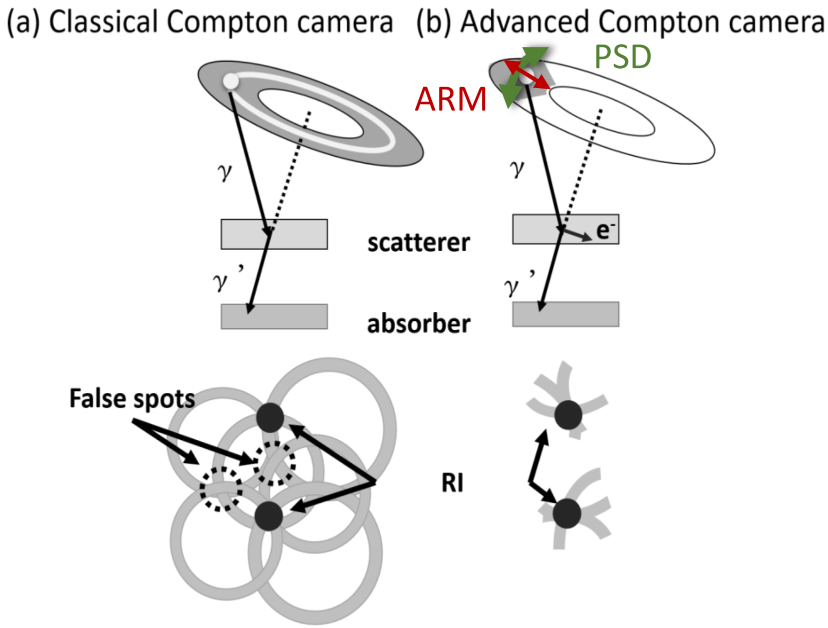
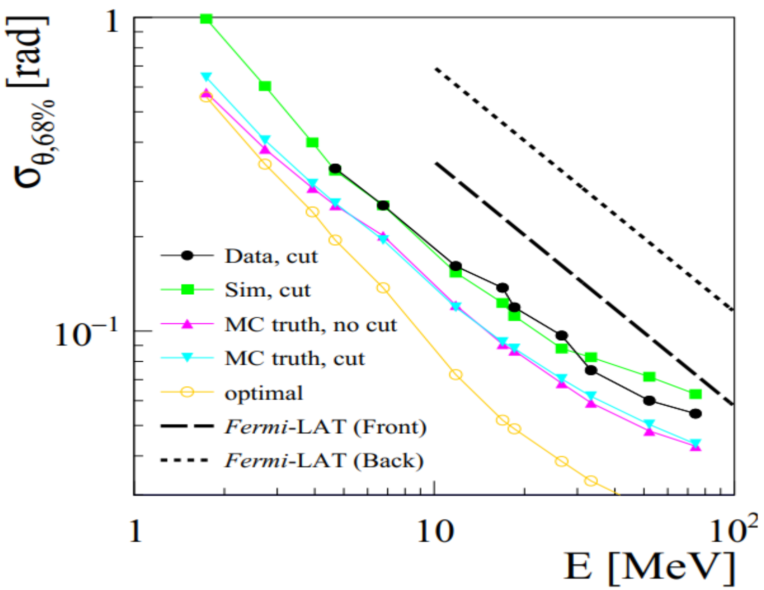
# Key technological challenges

- The energy is too high to be collimated
- It is difficult to measure 3D trajectories of electrons, that produced in Compton scattering and pair conversion according to Coulomb multi-scattering.




Astroparticle Physics 97 (2018) 10-18



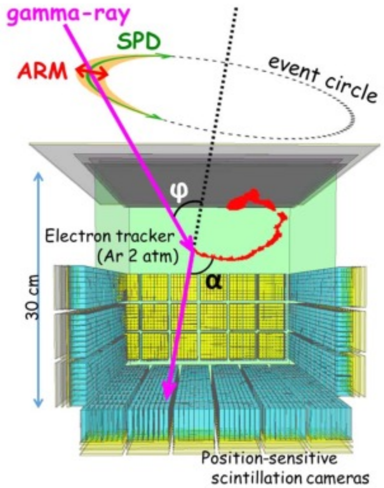

It is practical to improve the e-tracking measurement by reducing the material density with gas detectors

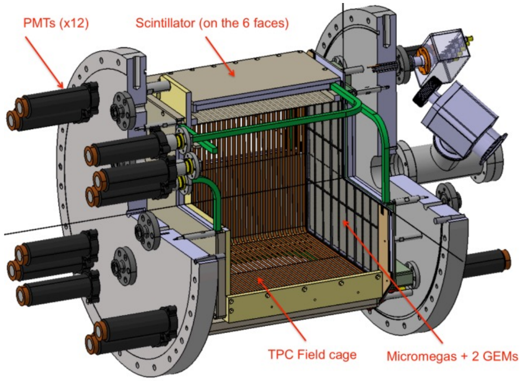
# Some experimental proposals

SMILES （0.3-3MeV）

TPC Compton camera

*The Astrophysical Journal, 930:6 (13pp), 2022 May 1*




*NIM A 718 (2013) 395*

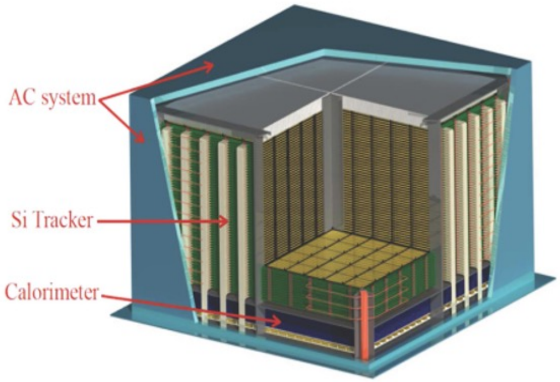
HARPO（MeV-GeV）

TPC Gamma polarization measurement

e-ASTROGAM（0.3MeV-3GeV）

Silicon gamma telescope

*Journal of High Energy Astrophysics 19 (2018) 1–106*




## Advantages of 3D e-tracking with TPC

- Providing Scattering plane limits to reduce background
- Achieving optimal angular resolution by lowering electron scattering
- Electron emission angles carrying polarization information

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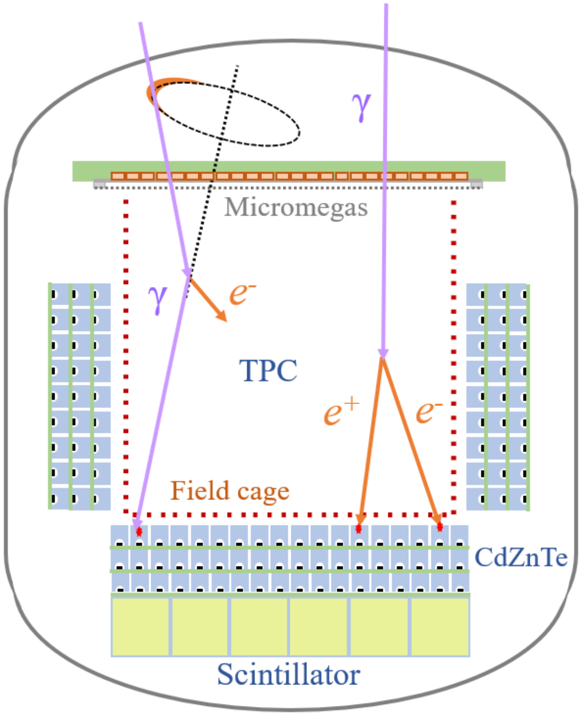
# Conceptual design

- **TPC based technique**
  - 30 cm cubic volume（prototype）
  - four 50 cm cubic or a single 100 cm ×100cm ×50(or larger)cm volume（satellite）
  - 3-10 bar high pressure
- **Expected performance**
  - High dynamic range:
    0.3 MeV -100 MeV
  - Angle resolution (PSF):
    2 ° @MeV, 0.5 ° @100 MeV

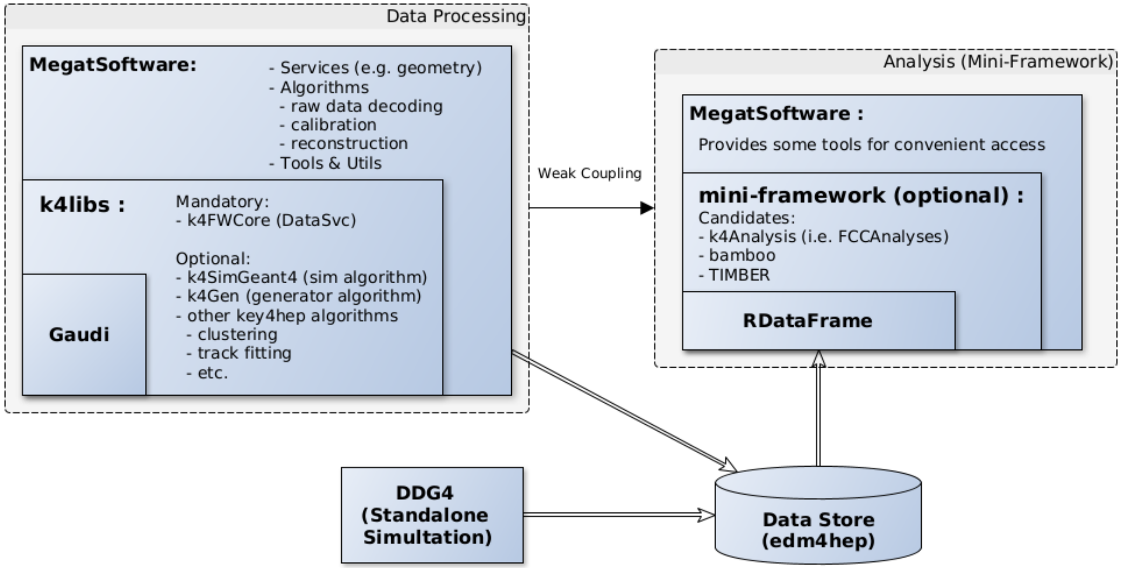


# Software framework

## Goal: single software for simulation, reconstruction & analysis

**Software stacks:**

- Simulation:
  - k4SimGeant4
- Event data model:
  - EDM4hep
- Event-processing:
  - Gaudi
  - k4FWCore




**Data processing (on server):**

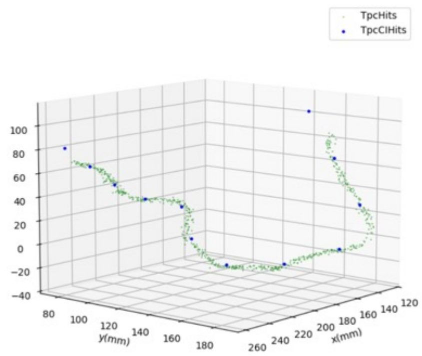
- official data production:
  - simulation & reconstruction
  - standardized & trackable
- flexible kernel:
  - Gaudi

**Exploratory analysis (on desktop):**

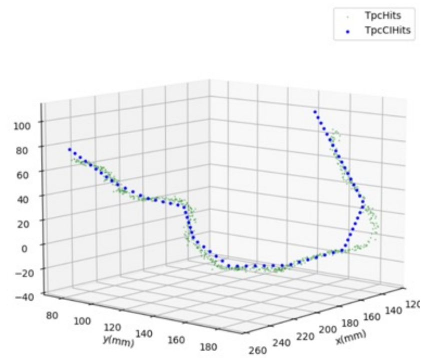
- personal data analysis:
  - quick turn-around workflow
- lightweight kernel:
  - RDataFrame (ROOT)

# Simulation performance

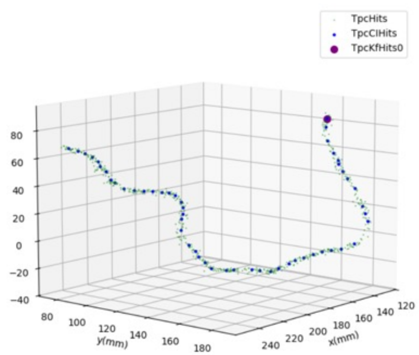
- **Track reconstruction of recoil electron by Kalman Filter Algorithm**



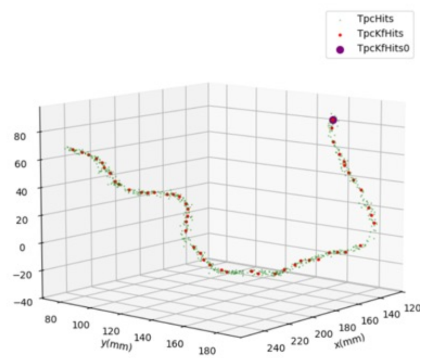

1.clustering



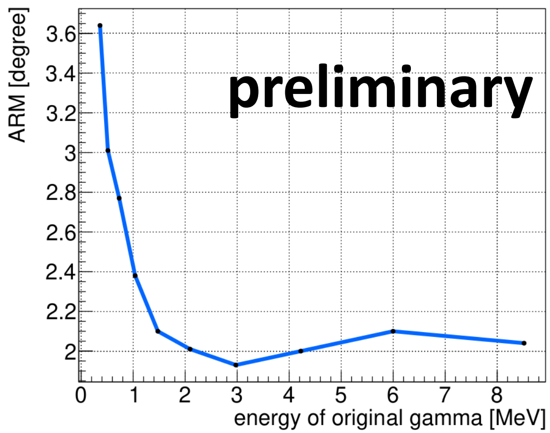

2.interpolation

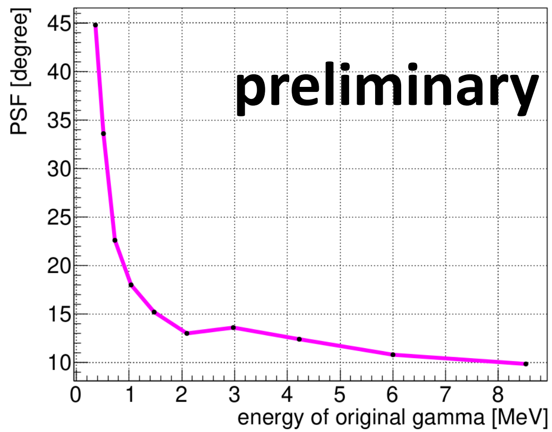



3.get charge center




4.Kalman filter



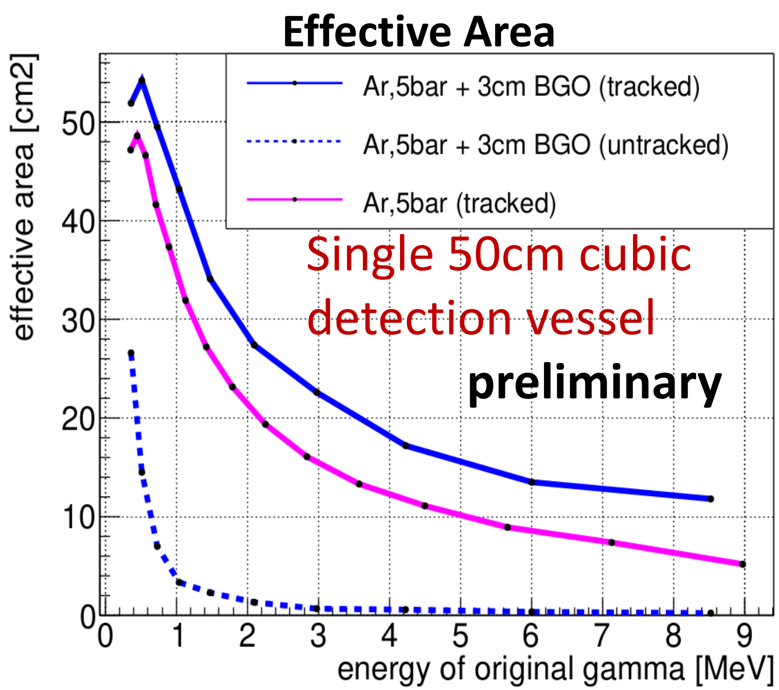



# Simulation performance

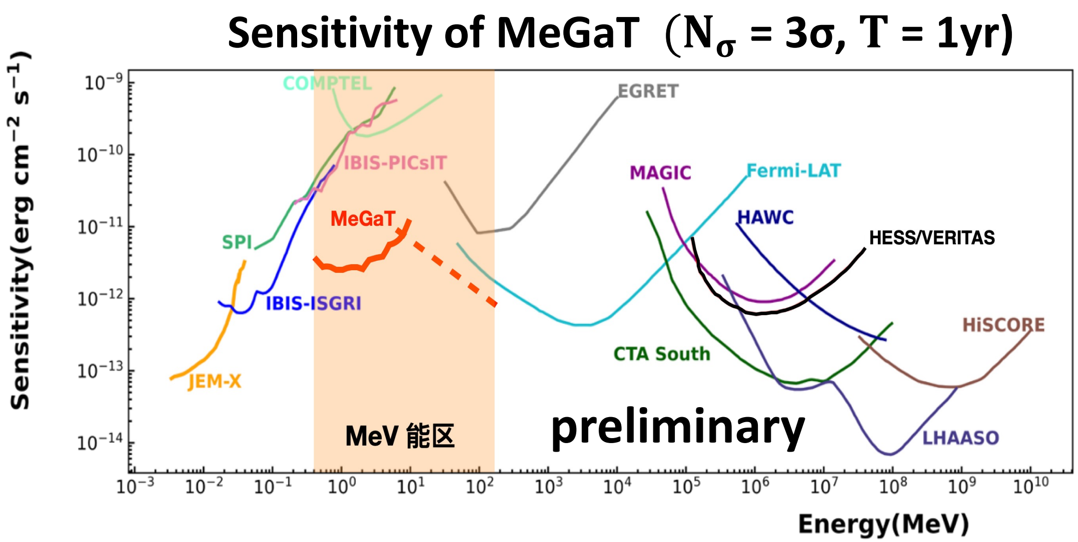
Four identical 50cm cubic detection vessels

— Very preliminary simulation result without pair conversion

- - - Rough estimation by taking pair into account



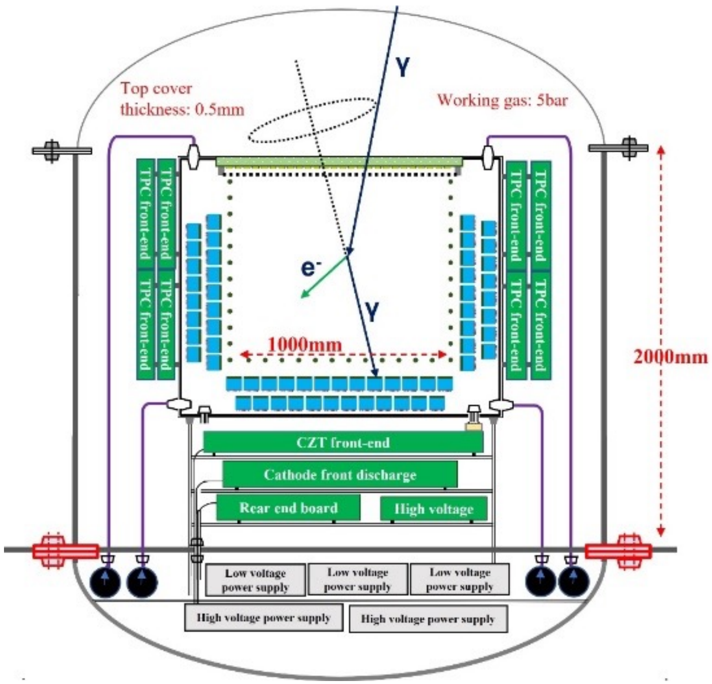

$$S = \frac{N_\sigma\, \sigma_\theta\, E^2}{\epsilon_{68}\, \Delta E}\sqrt{\frac{\pi \int B(E)dE}{A_{eff}\, T}}$$

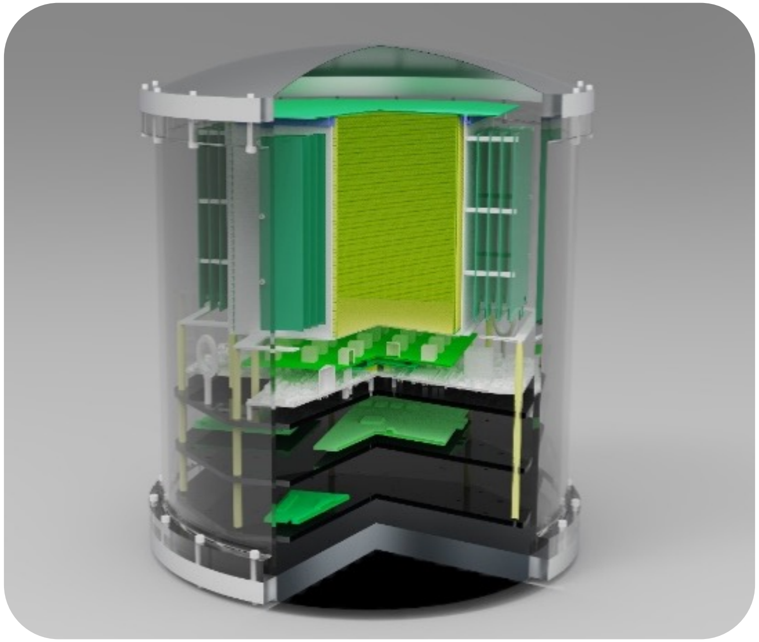



Perfect performance on spatial and energy resolution are required for the TPC and calorimeter

# Prototype of R&D

- **30 cm cubic volume**

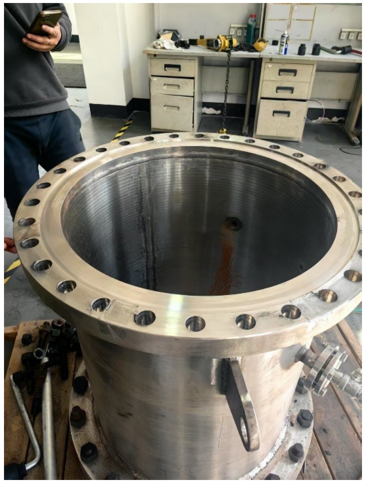


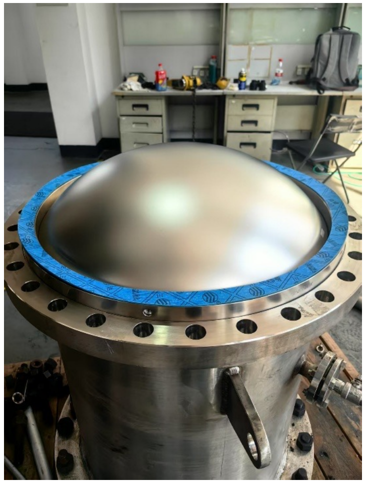
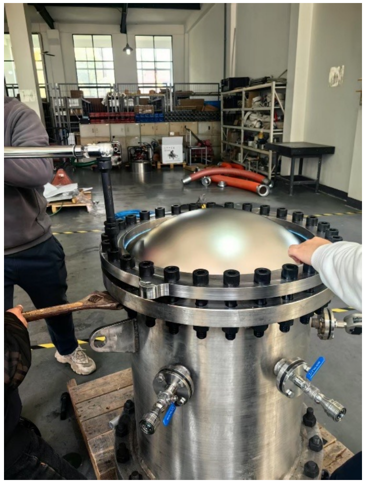



**Technical challenges**

- High voltage: Micromegas ~ 3000V， Field cage ~ 15000V
- High-pressure sealing: 0.5 Mpa
- Mechanical support and heat dissipation issues

# 罐体耐压测试



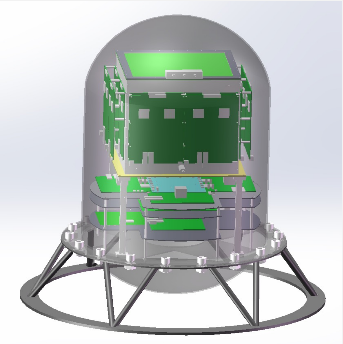



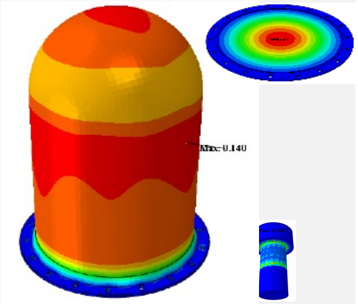
| 日期 | 3月21日 | 24日 | 25日 | 26日 | 28日 | 28日 |
|---|---|---|---|---|---|---|
| 气压 | 0.489MPa | 0.489 | 0.491 | 0.494 | 0.486 | 0.689 |
| | 1周保压测试 | | | | | 1小时过压测试 |

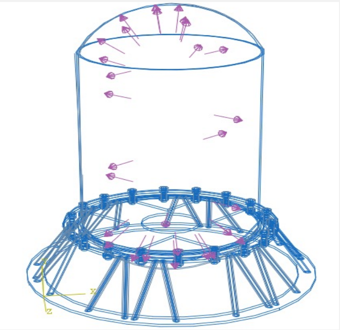
窗口厚度0.4mm不锈钢，气压可达到7bar，但是总重接近700公斤！

# 结构优化设计与试验

## 罐体结构轻量化

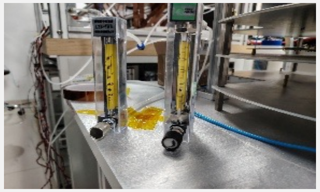






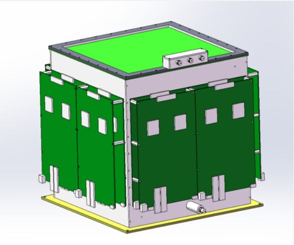
尝试3D打印新技术，窗口厚度~3mm铝合金，承压更强；
罐体重量降低10倍以上（不锈钢为670公斤）

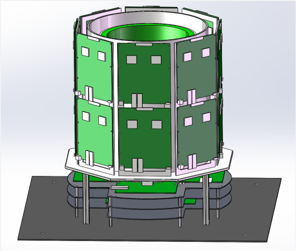
## TPC结构优化



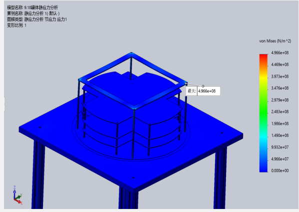
TPC通气测试进行2周，没有明显漏气

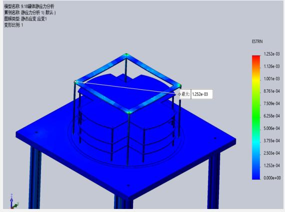
| 时间 (hour) | 0 | 12 | 24 | 36 | 48 |
|---|---|---|---|---|---|
| 进气量 (ml/min) | 35 | 35 | 35 | 35 | 35 |
| 出气量 (ml/min) | 35 | 32 | 30 | 30 | 30 |





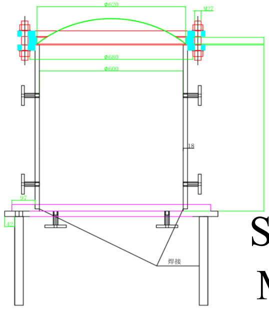
同样基于3D打印进行优化

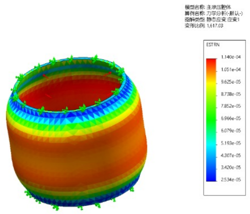




受力及应变仿真，对整体结构进行仿真，仿真载荷取实际载荷的约1.5倍

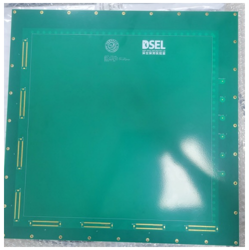
# Prototype of R&D

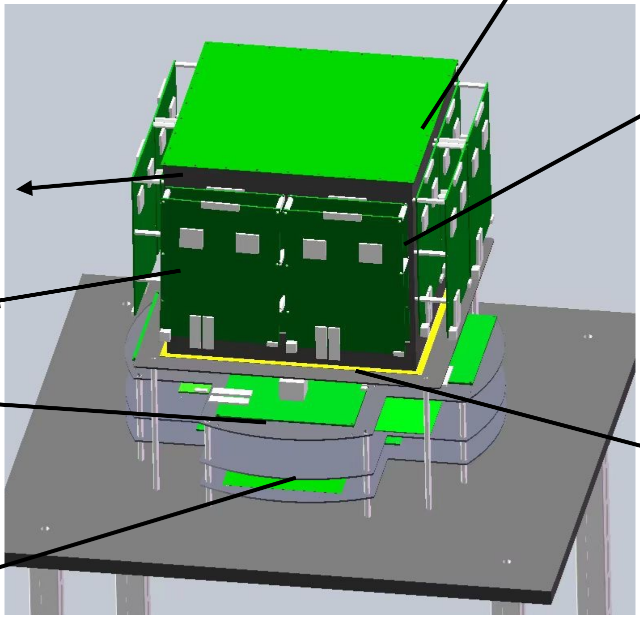




Sealed jar & Mechanical simulation

The thermal bonding Micromegas

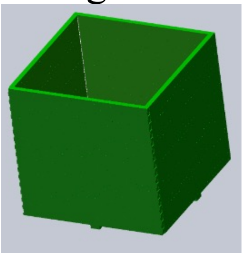




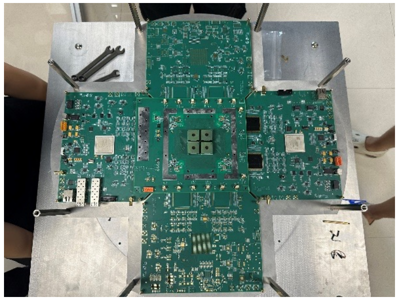
Small chamber

FEE of TPC

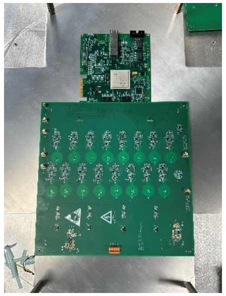
Field cage



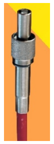
CZT front-end & carrier board



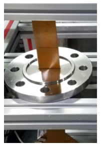
High Voltage & back-end board



CSA & ADC board



20000 V high voltage connector



Panda signal line

# Readout Electronics

**Challenges:**

- Large mount of readout channels
- High dynamic range, low noise
- Multiple detector system

**Solutions：**

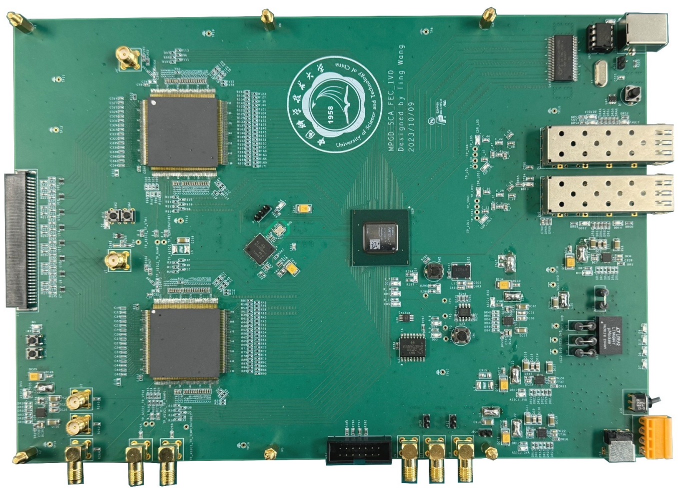
- Encoding Method to minimize the readout channels
- Develop low noise FEE with dedicated ASIC
- Modular design to ensure the extensibility of the system

# FEE for the TPC

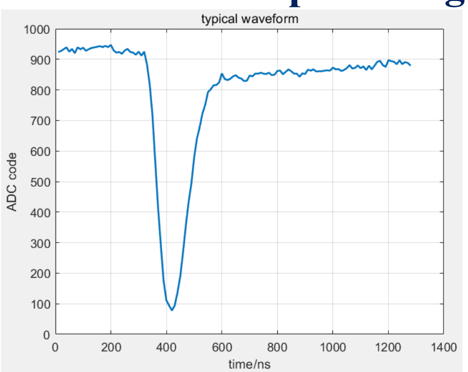
## All-digital output ASIC (design by Professer L. Zhao)

- High-Speed Switched Capacitor Array (SCA) & Wilkinson ADC
- The development of the front-end readout board has been completed, and performance testing is underway

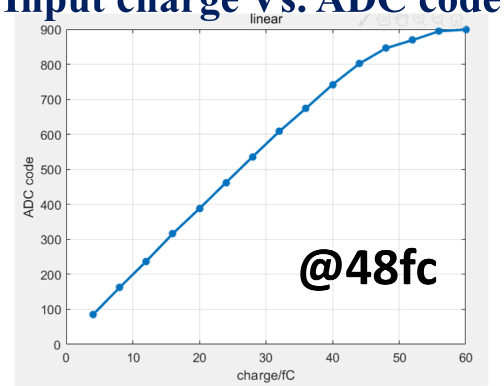
| Dynamic range | 48 fC-1pC |
| --- | --- |
| INF | < 1% |
| Shaping Time | 70ns-1us |
| Maximum sample rate | 160 MSPS |
| Sample units | 128 cells |
| Noise (RMS) | < 0.5 fC @ 48fC |
| Timing precision(RMS) | < 1 ns @ 48fC |
| Dead time | < 75 μs @ 120 MSPS |



Result of 48fC input charge



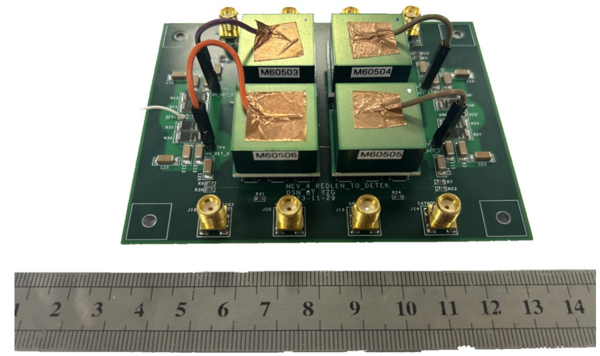

Input charge Vs. ADC code

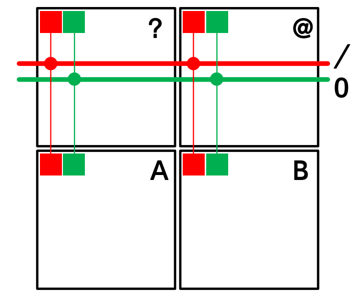


# FEE for the CZT

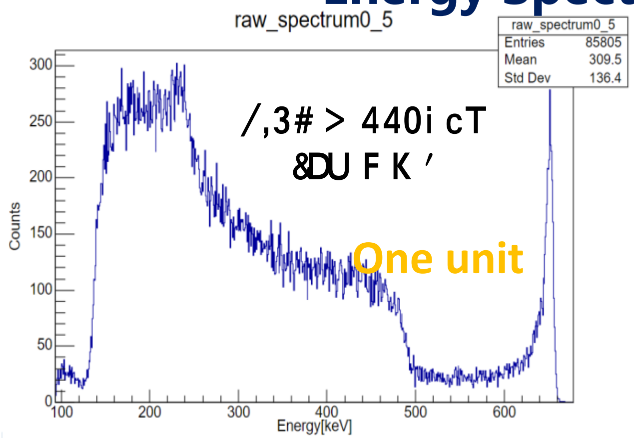
## Multiplexing method

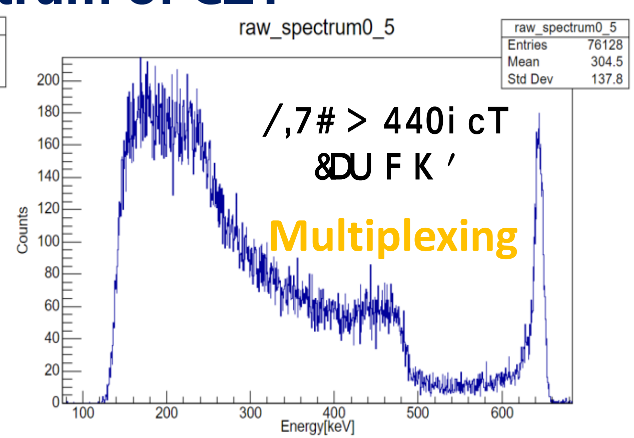
- Multiple pads of different detectors can be connected to one readout channel.
- The cathode signal of CdZnTe shows which detector has been hit.

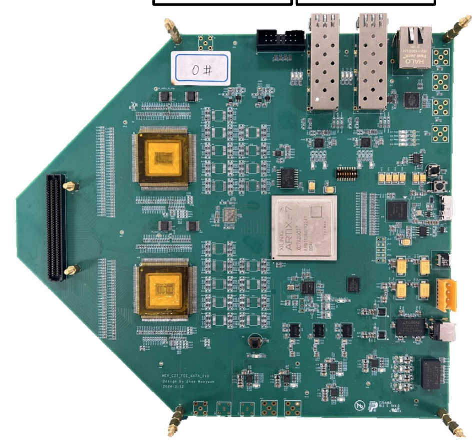



**Energy Spectrum of CZT**



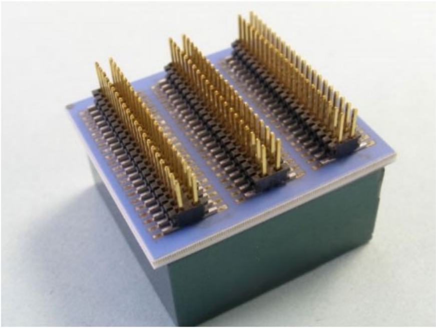
# Summary

- MeGaT is aiming to open up the MeV γ-ray observation window with very high sensitivity.
- Technologies are innovative and challenging, but are proven to be reliable.
- First 30 cm cubic prototype will be built and characterized with photon beam soon.

# Channel encoding method

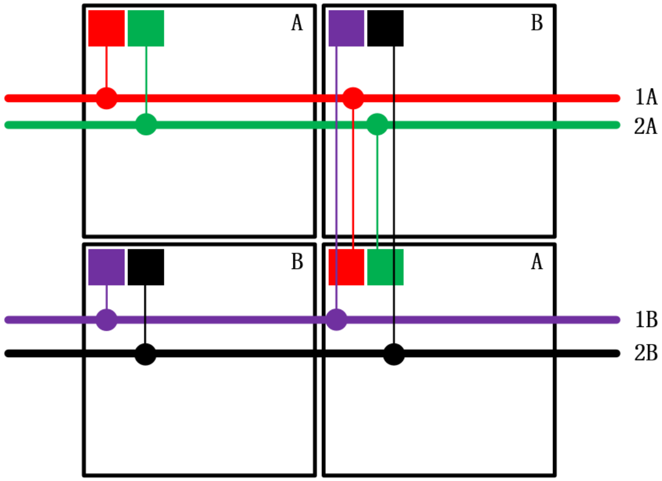
## □Pixelate CZT

- 20 × 20 × 15 $mm^3$ size for single piece
- 121-pixel array with 1.72 mm-pitch
- 128k channels in total for a 30 cm cubic prototype



## □Encoding method

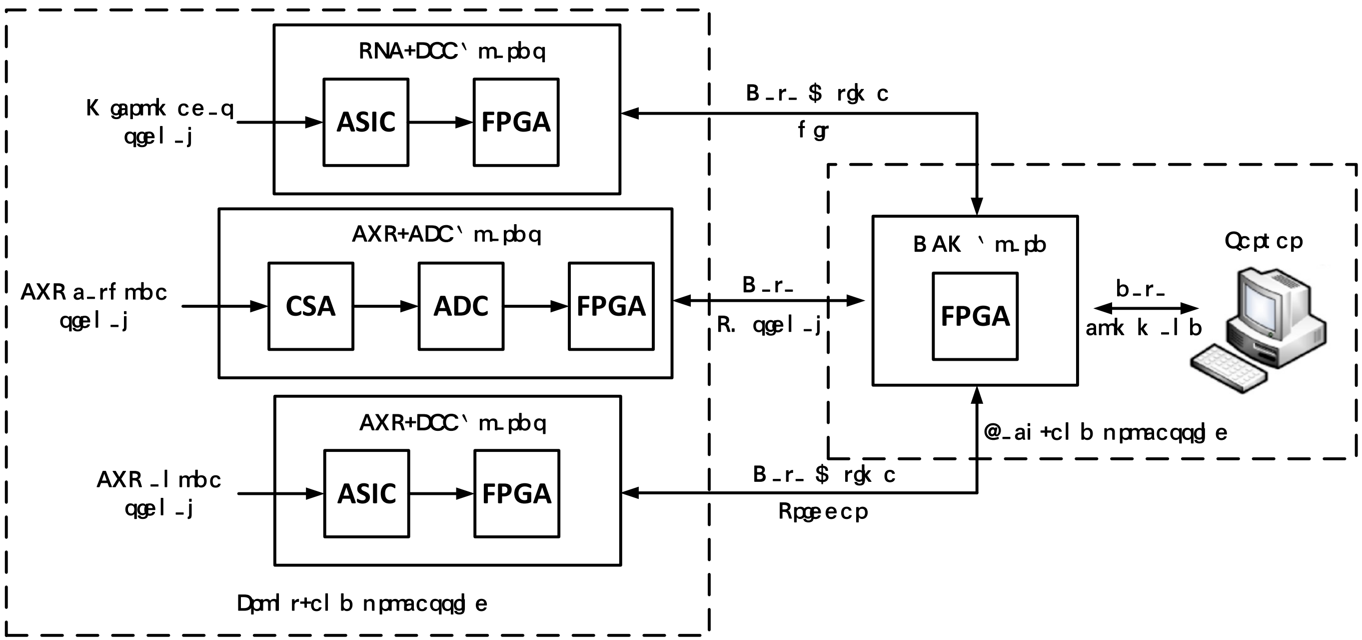
- Multiplexing readout channels for the pads from different CZTs.
- The cathode signal gives the judgement.
- The channel number is expected to be reduced with a factor of more than 10.



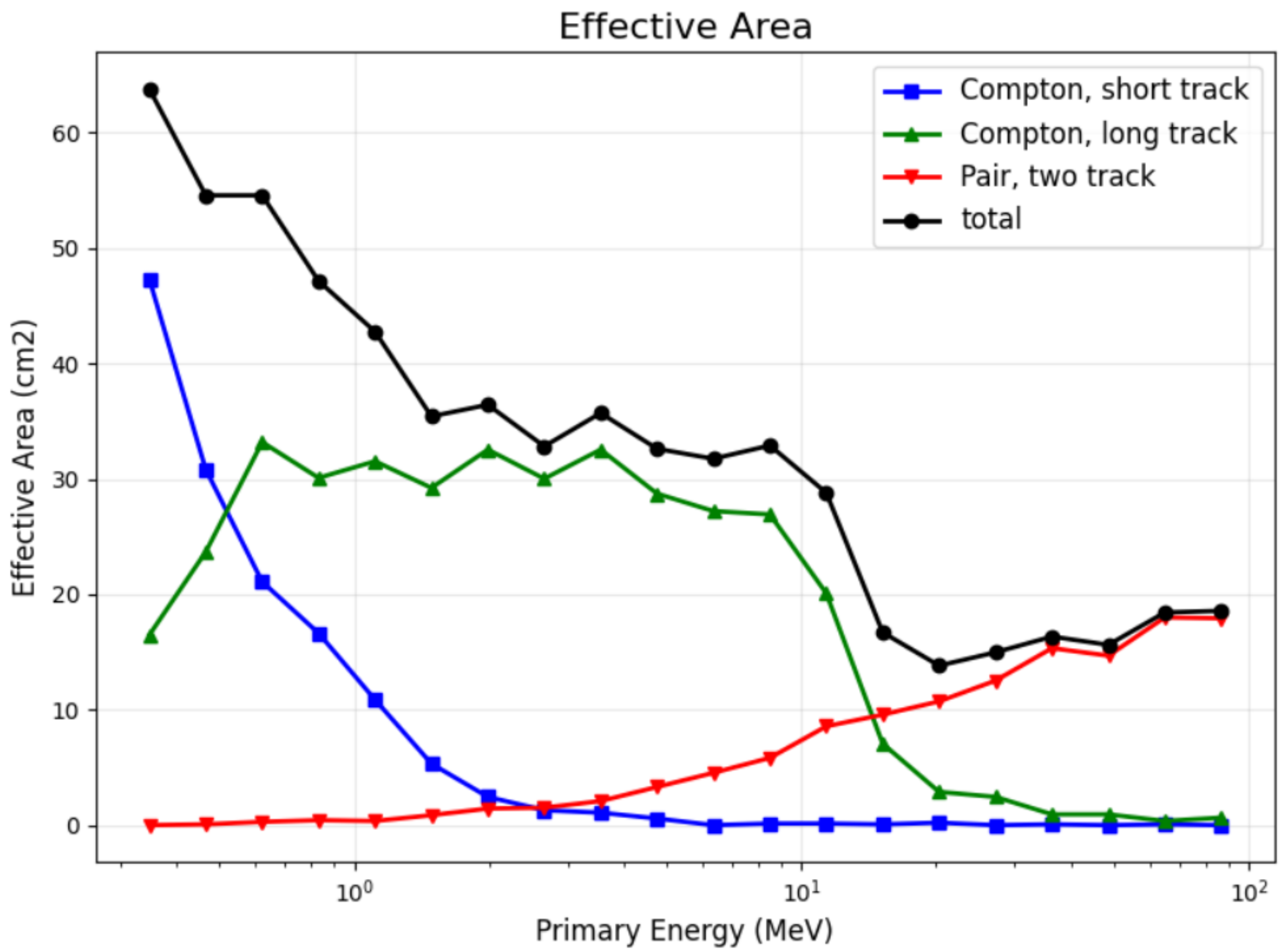
# Schematic design for system

## ◻ Multiple detector system

- High dynamic range, low noise FEEs
- T0 from cathode signal of CZT
- Encoding readout to minimize the channel number
- Modular design for extensibility

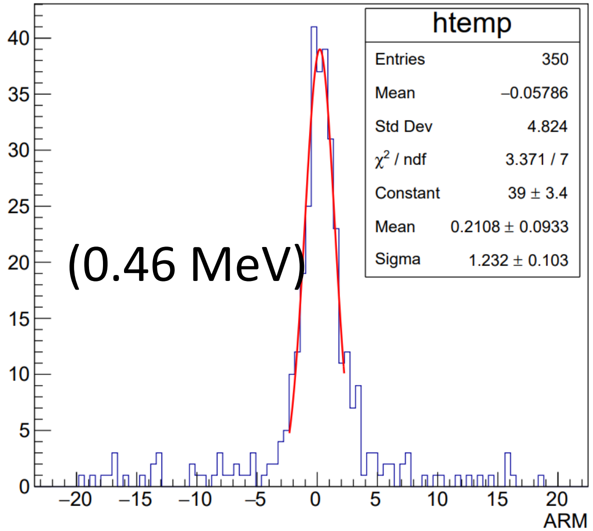


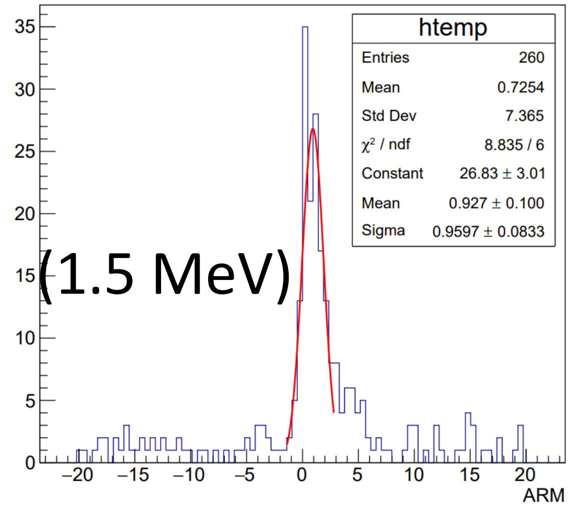
# 有效面积估计（考虑事例重建效率）



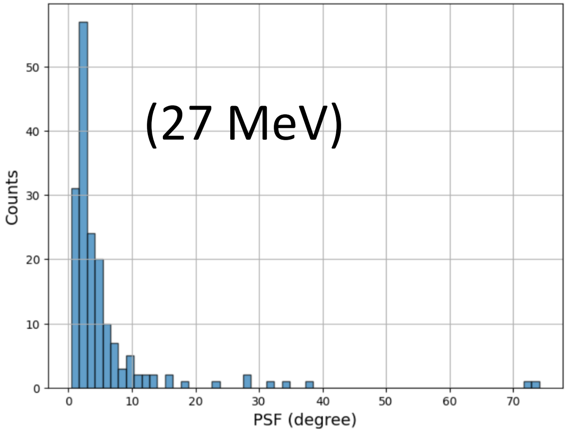

各种类型事例对应的有效面积随原初γ能量的变化

# 入射角度重建



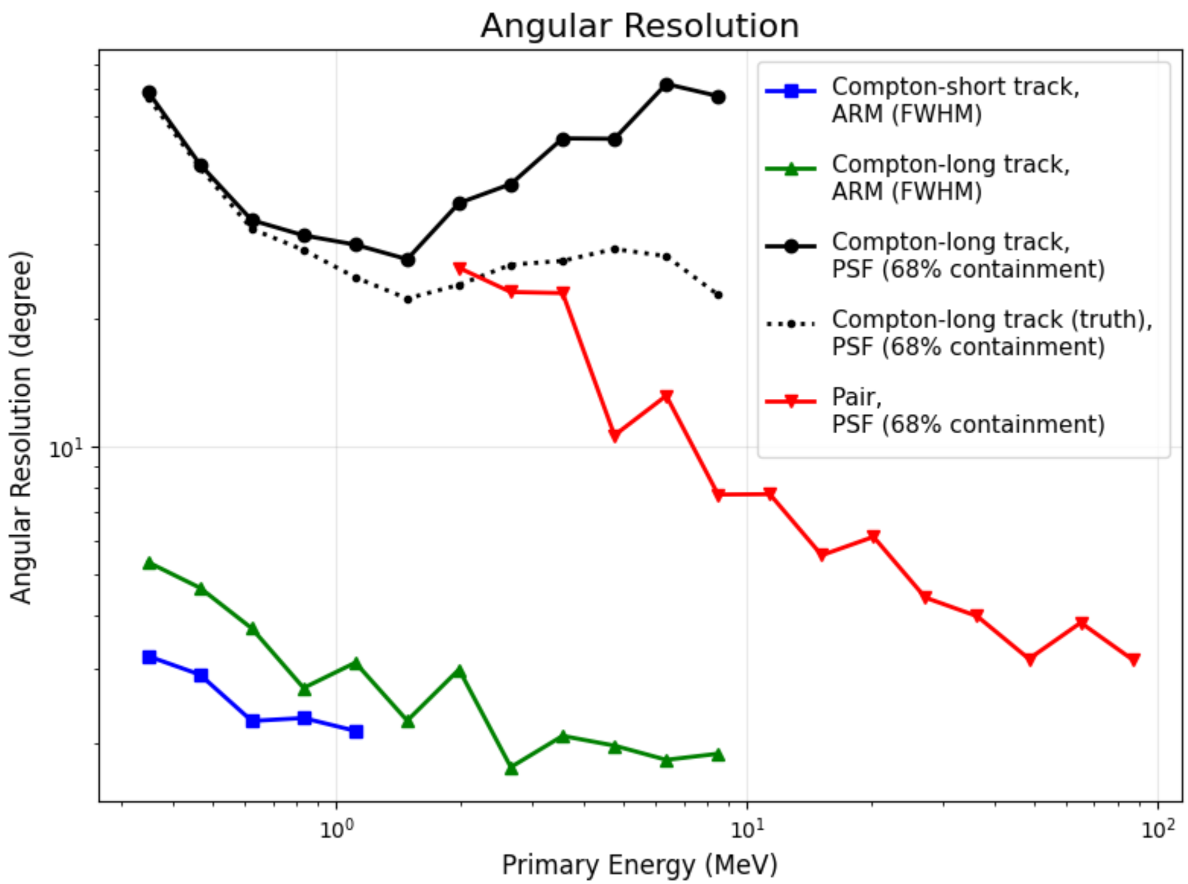




短径迹、长径迹康普顿散射事例ARM拟合




电子对产生事例PSF

# 角分辨计算



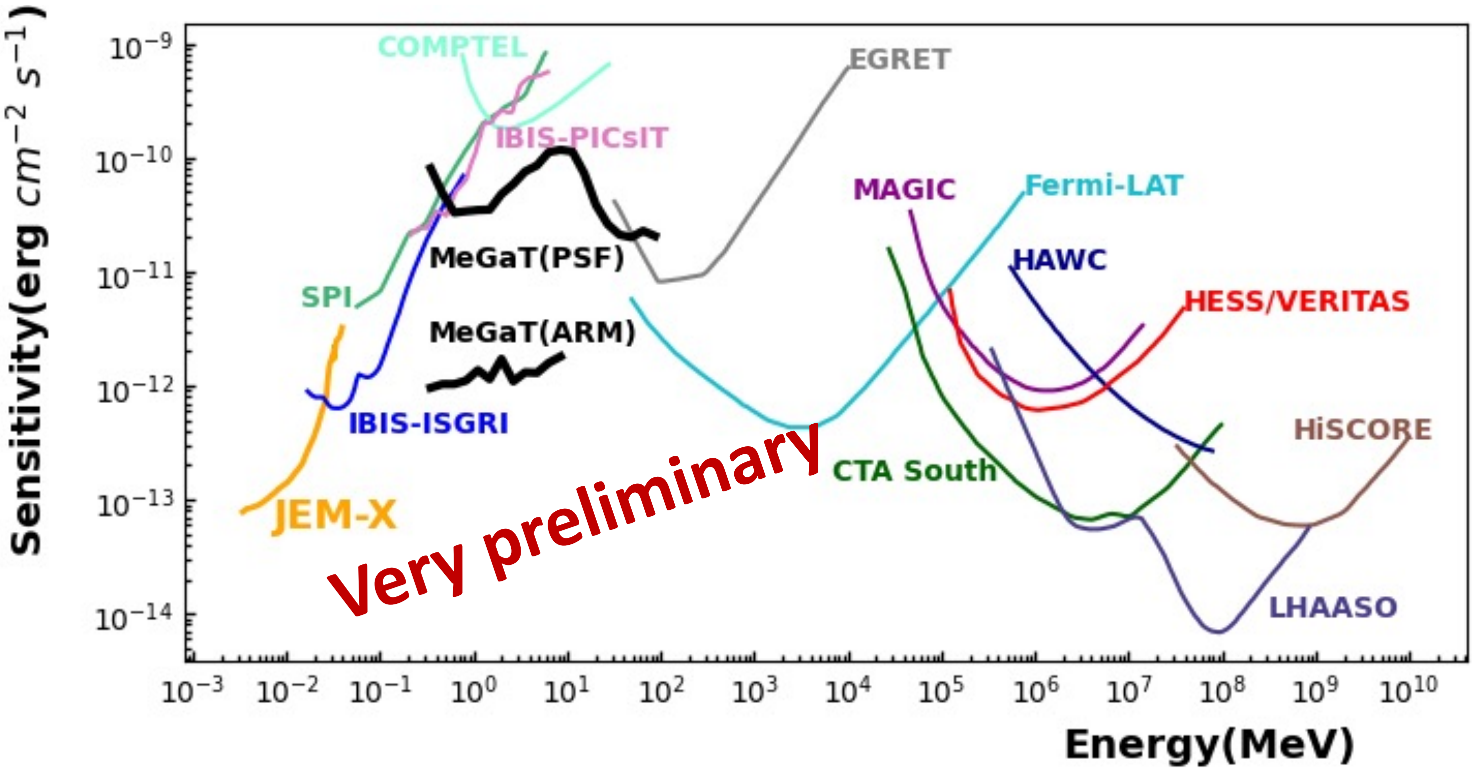

各种类型事例对应的角分辨随原初γ能量的变化

# MeGaT灵敏度估计

50×50× 50 cm³ TPC

$$S = \frac{N_\sigma\, \sigma_\theta\, E^2}{\epsilon_{68}\, \Delta E} \sqrt{\frac{\pi \int B(E)dE}{A_{eff}\, T}}$$

**($N_\sigma$ = 3σ, T = 1yr)**

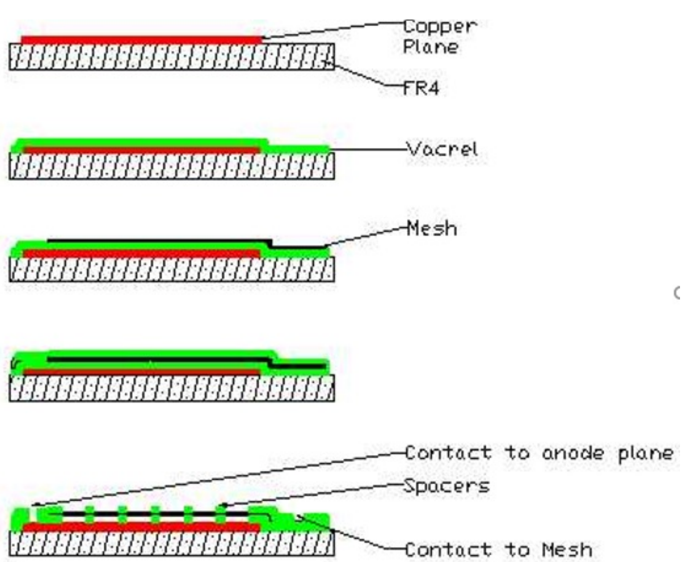


# Backup slides

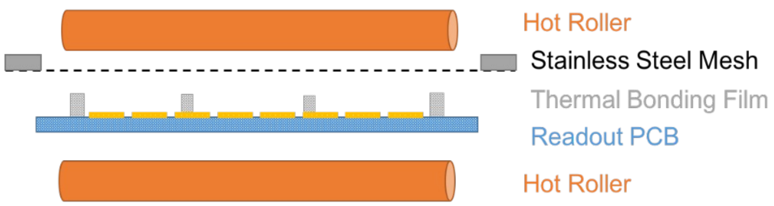
# The thermal bonding method

Over the past decade, We developed a novel thermal bonding method for the efficient fabrication of Micromegas detectors.

**Micromegas in a Bulk**




**Thermal bonding processing**

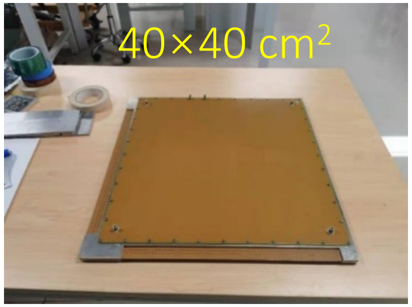


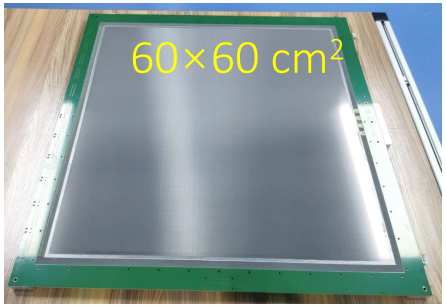

- No etching, no pollution
- Easy to handle at lab
- Easy to make new structures
- Φ0.5mm- Φ1mm spacers, ~1cm pitch

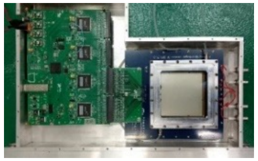
  ➔easy to clean, especially for large area

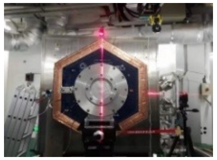
  ➔less than 1% spacer area

# Fabrication and applications



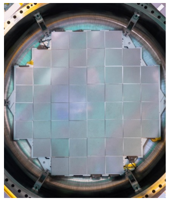





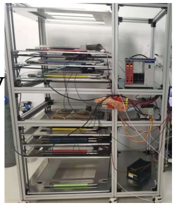
Neutron detectors for the Chinese Spallation Neutron Source

PandaX-III TPC MM



CEPC-RICH &STCF-RICH

Muography



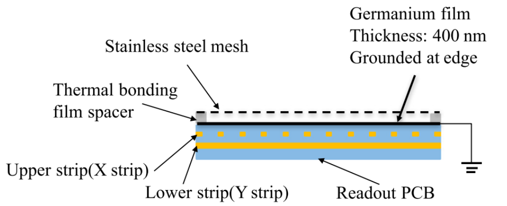
# Performance of the Micromegas detector

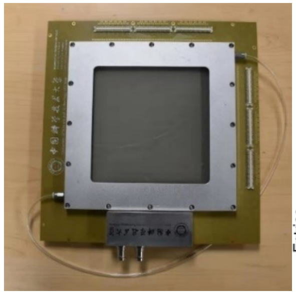
**5.9 keV X-ray test**

- Gas gain： ~$10^5$ (Ar+7%$CO_2$)
- Energy resolution： < 15% (FWHM)

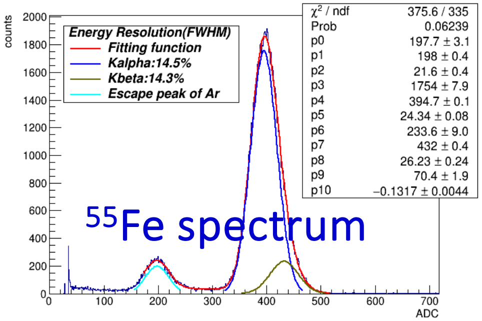
**Electron beams（5GeV）at DESY**

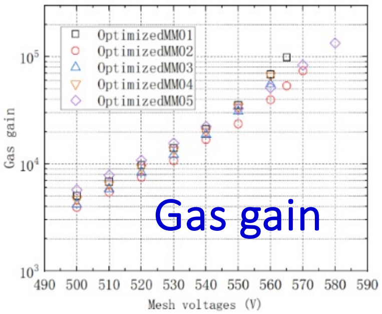
- X-Y 2D readout
- Efficiency： >98%
- Resolution： 65μm

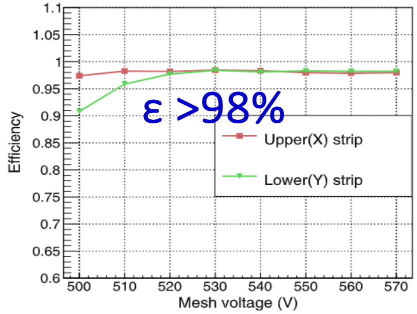


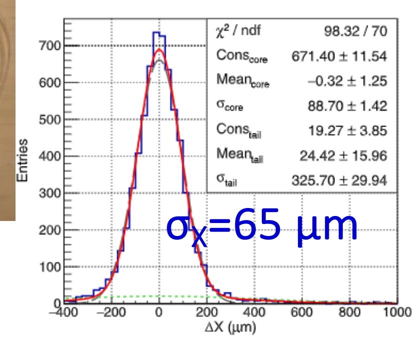



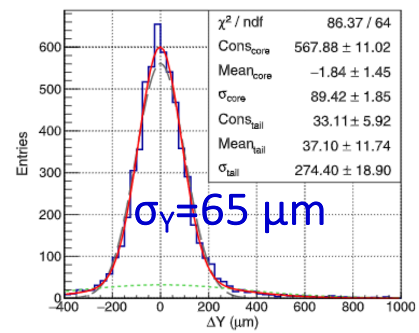
NIM-A 989 (2021) 164958； NIM-A 1031 (2022) 166595.



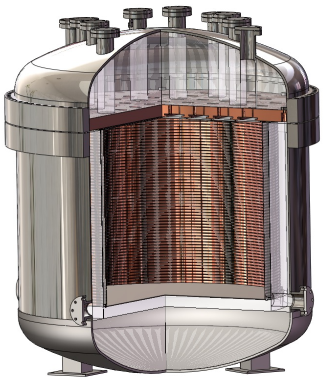



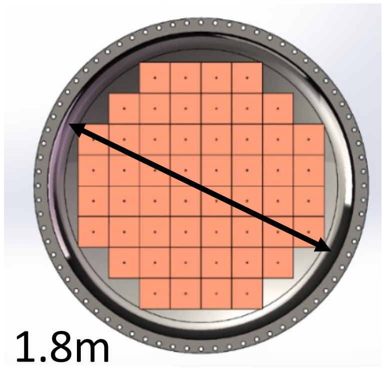



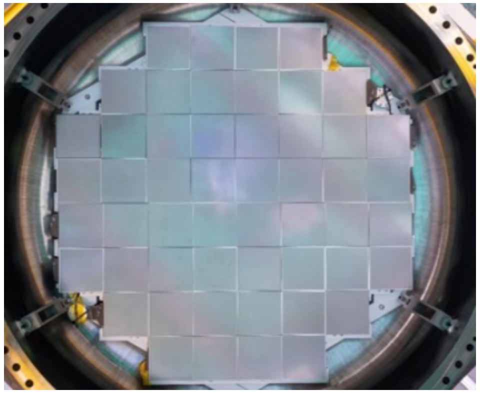



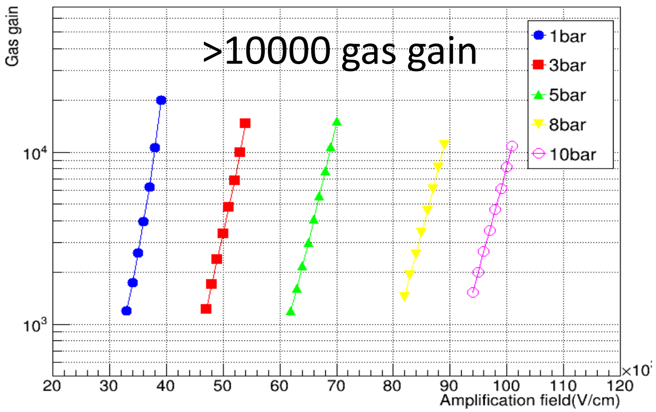
# Performance of the Micromegas detector

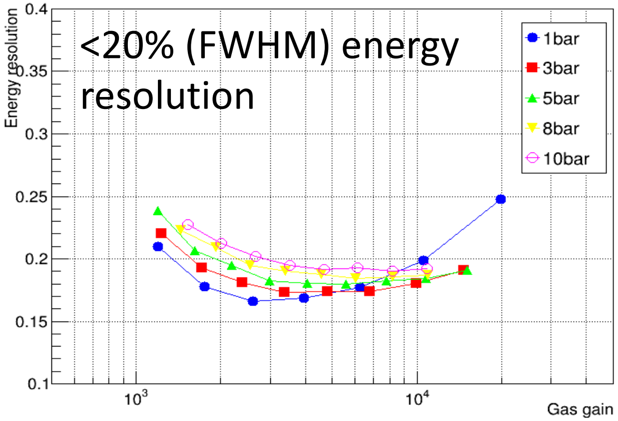
Performance in high gas pressure was studied in the PandaX-III experiment







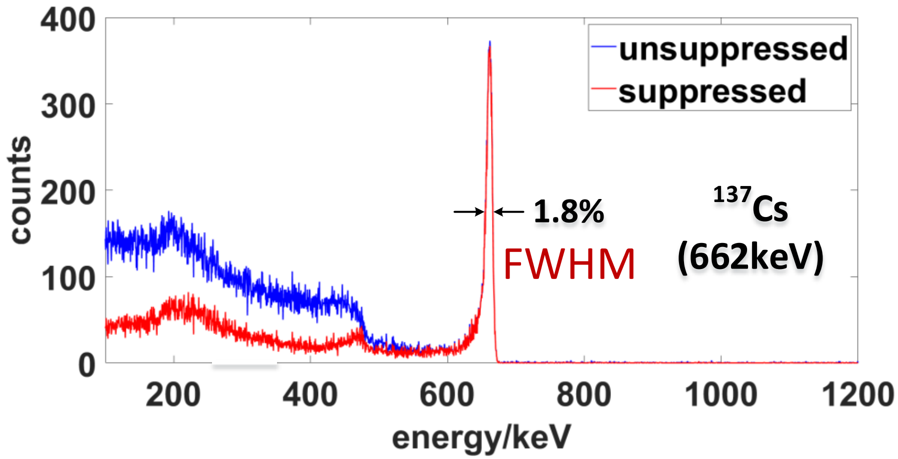



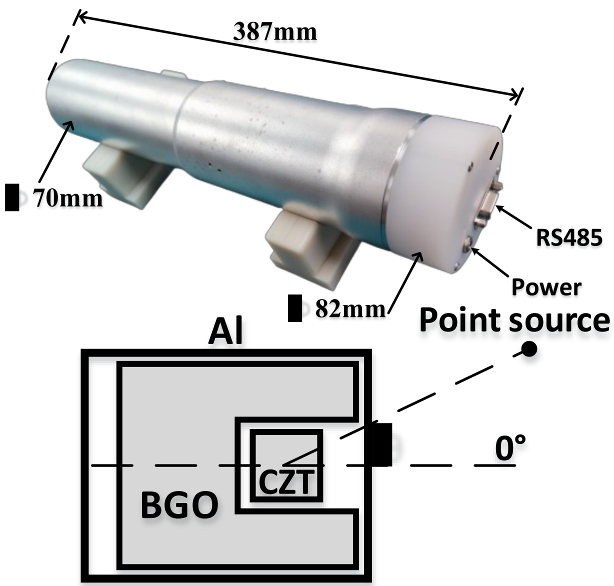

High gain and good energy resolution were verified in high gas pressure

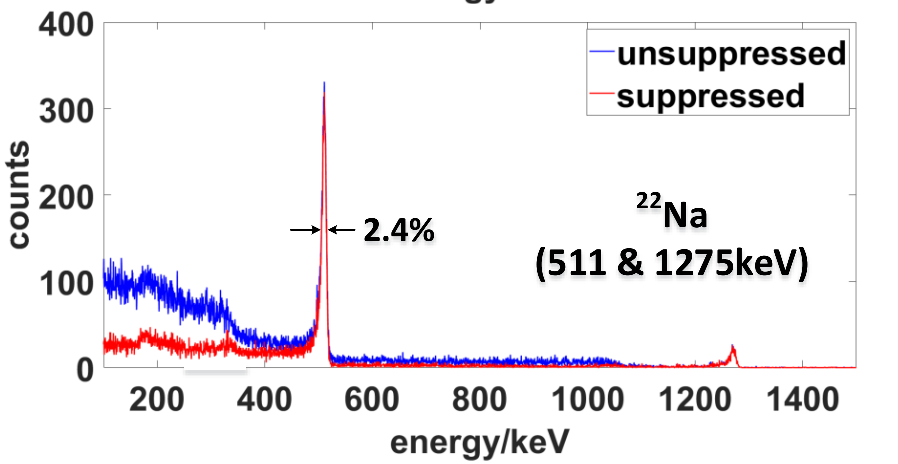
Test at 10bar Ar(2.5% Iso) with a 5.9 keV X-ray source

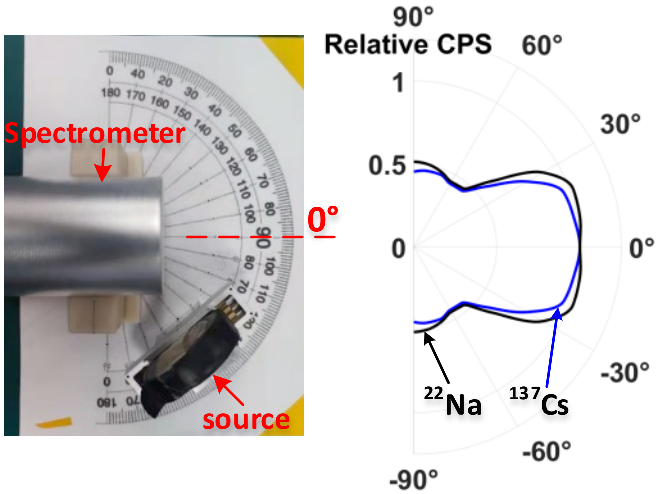
# Performance of the CZT

Cadmium zinc telluride （CZT）



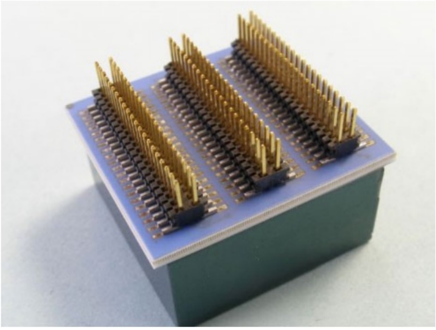



# Channel encoding method

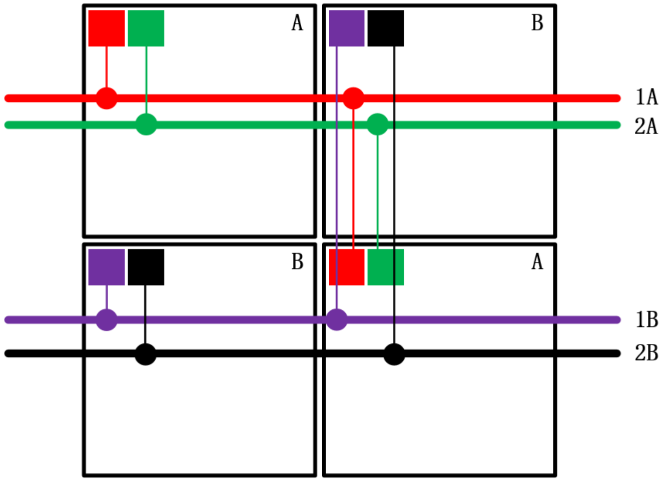
## ❑Pixelate CZT

- § 20 × 20 × 15 $mm^3$ size for single piece
- § 121-pixel array with 1.72 mm-pitch
- § 128k channels in total for a 30 cm cubic prototype



## ❑Encoding method

- § Multiplexing readout channels for the pads from different CZTs.
- § The cathode signal gives the judgement.
- § The channel number is expected to be reduced with a factor of more than 10.

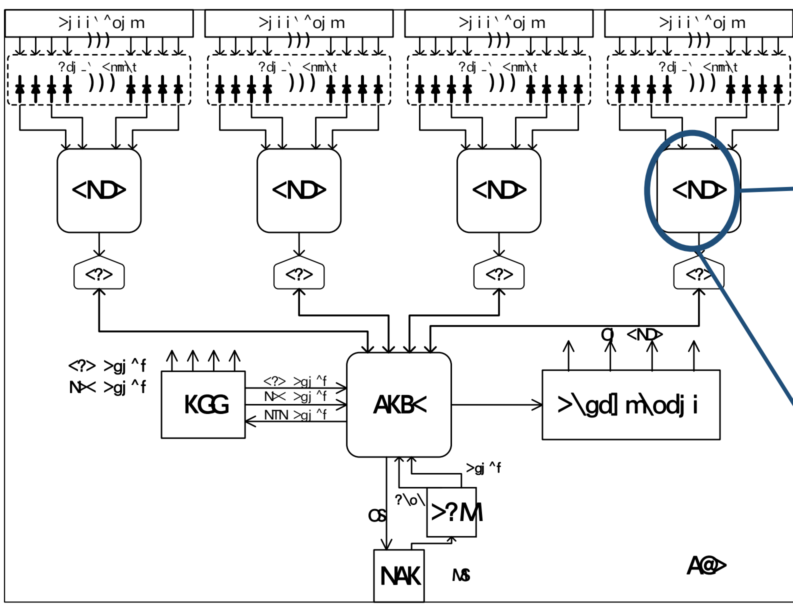


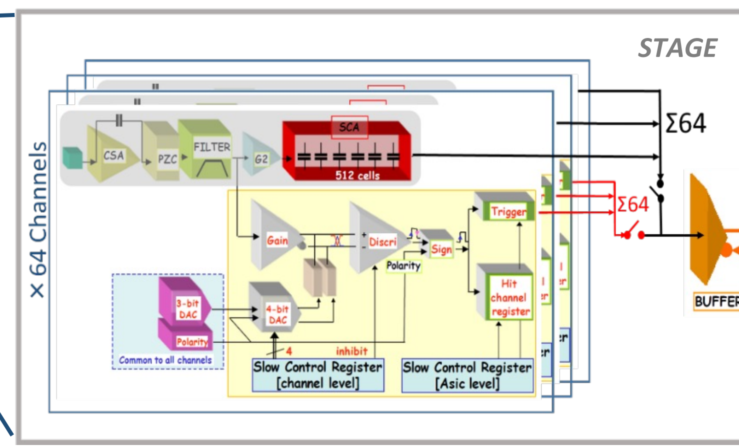
# FEE for the TPC

- ☐ There are 1200 signal strips to be readout for the 2D Micromegas (0.5mm pitch)
- ☐ FEE design for the TPC readout
  - § Dedicated STAGE chip for TPC (by Saclay France)
  - § Each board integrate 4 chips for readout 256 channels

## STAGE chip specifics

- ✓ 64 inputs with dynamic range of 120fC、1pC、10pC
- ✓ Shaping time： 50 ns – 1 us (16 values)
- ✓ Noise： < 850 e- (120fC, 200ns, input capacitance< 30pF)
- ✓ INL of charge measure: < 2%
- ✓ Counting rate： < 1kHz





# FEE for the CZT

- Pixelate CZT detectors
  - Wide energy range: 60 keV to 3 MeV
  - Energy Resolution (corrected): < 2% @662 keV FWHM

- Start with the JCF032EB ASIC, optimizing selection for the chip is still in progress

✓ 32 inputs

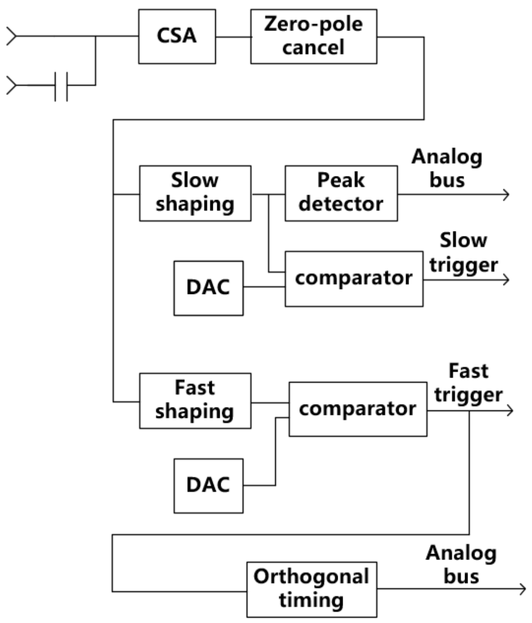
✓ Feedback capacitance: 15fF, 60fF, 0.5pF

✓ Shaping time： 0.3 us – 40 us

✓ Noise RMS: 80e- + 12e-/pF

✓ INL of charge measure: < 10%

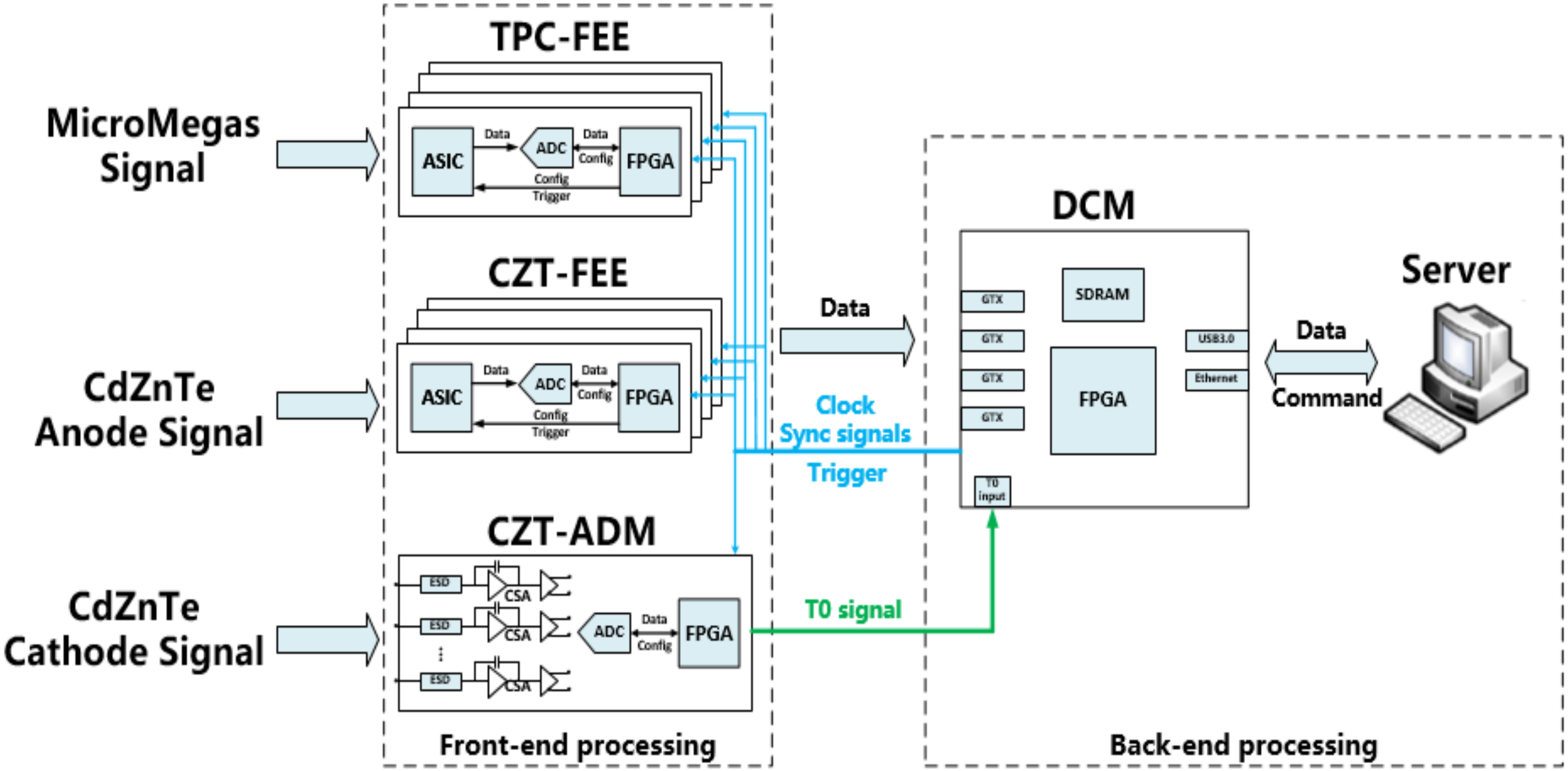
✓ Counting rate： < 200 kHz



# Schematic design for system

## ☐ Multiple detector system

- High dynamic range, low noise FEEs
- T0 from cathode signal of CZT
- Encoding readout to minimize the channel number
- Modular design for extensibility

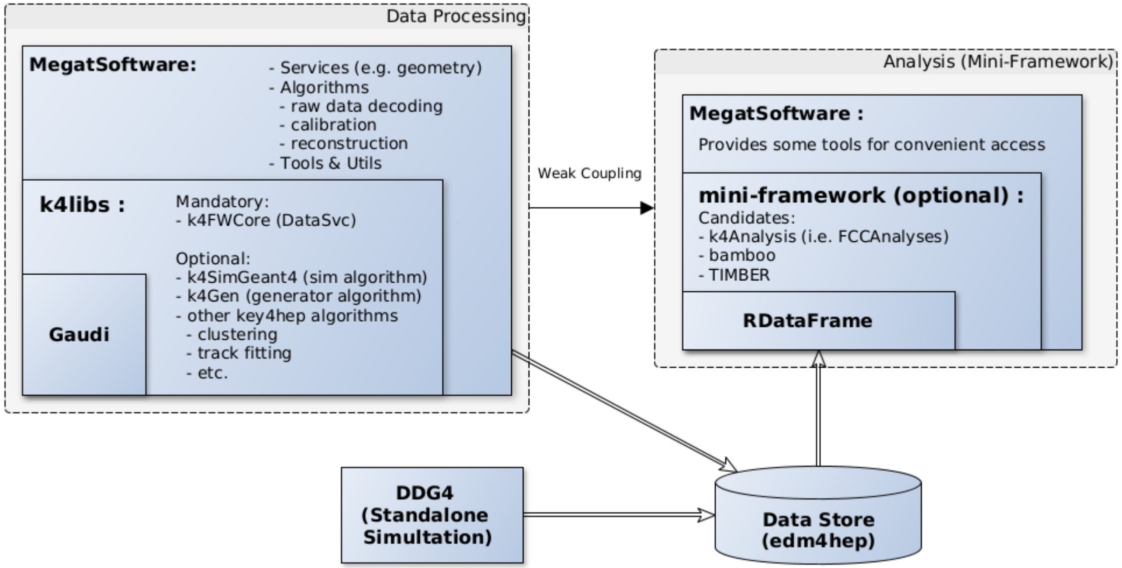


# R&D status: software framework

## Goal: single software for simulation, reconstruction & analysis

**Software stacks:**

- Simulation:
  - k4SimGeant4
- Event data model:
  - EDM4hep
- Event-processing:
  - Gaudi
  - k4FWCore




**Data processing (on server):**

- official data production:
  - simulation & reconstruction
  - standardized & trackable
- flexible kernel:
  - Gaudi

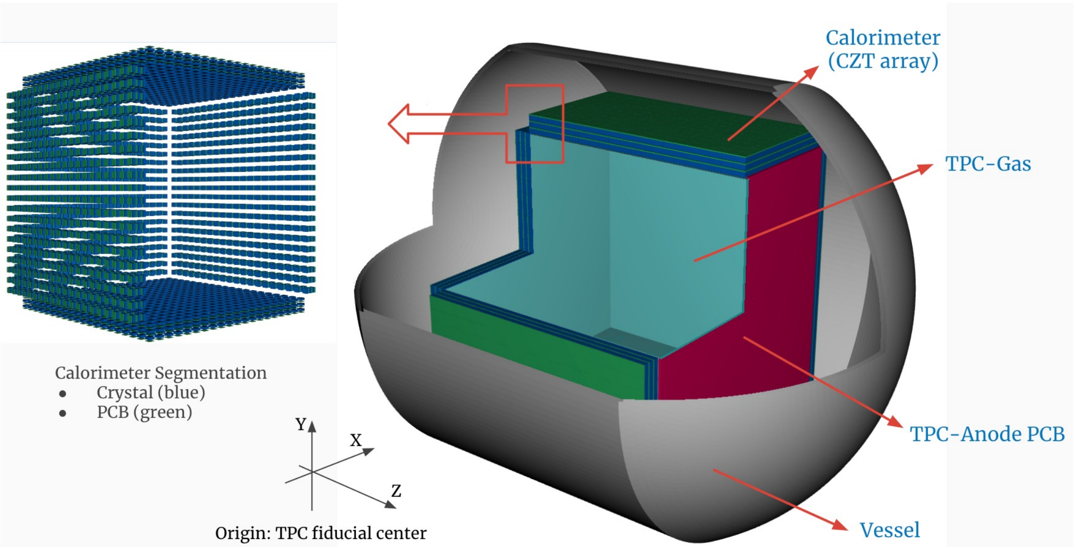
**Exploratory analysis (on desktop):**

- personal data analysis:
  - quick turn-around workflow
- lightweight kernel:
  - RDataFrame (ROOT)

# Current status of simulation package

**Geometry features**

1. Persistence format:
   - *XML* (dd4hep-native)
   - Covertible: *TGeo, GDML*
2. Fully-parameterized model:
   - Calorimeter
     - CZT-arrary + PCB-array
   - TPC
     - Gas + Anode-PCB + FieldCage
3. Tessellated CAD model:
   - Vacuum-vessel




**Geant4 Running Engine**

option 1: Gaudi-integrated
- Single-threaded
- No MC truth

option 2: Standalone process
- *ddg4* (dd4hep-native)
- Multi-threaded support
- MC truth support

**Sensitive Detector**

Calorimeter crystal:
- multi-steps per Hit

TPC gas:
- one-step per Hit

**Readout segmentation**

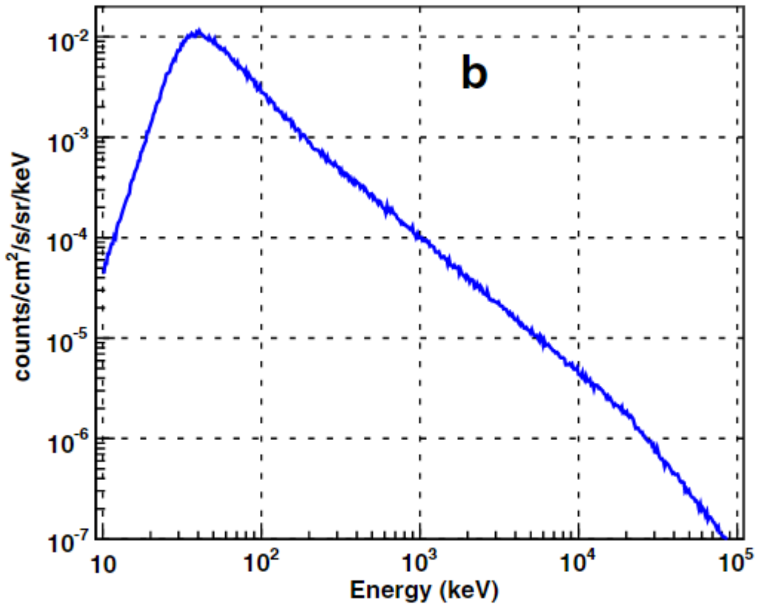
Calorimeter:
- Pixel

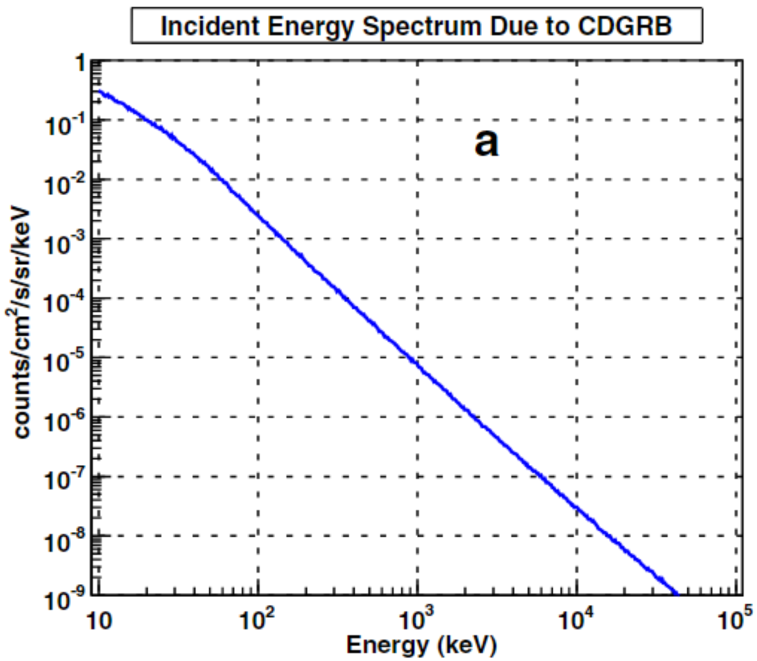
TPC:
- Strip/Pixel
- Extra stage needed in digitization
- Surface attached to PCB
  - Drift distance determination
  - Coordinate transformation

# Background estimate[1]

1. albedo gamma-ray

$$\frac{dN}{dE} = \begin{cases} \frac{1.87\times10^{-2}}{(\frac{E}{33.7})^{-5.0}+(\frac{E}{33.7})^{1.72}} & \text{if } E \le 200.0\ \text{keV} \\ 1.01\times10^{-4}\left(\frac{E}{MeV}\right)^{-1.34} & \text{if } 200.0\ \text{keV} \le E \le 20.0\ \text{MeV} \\ 7.29\times10^{-4}\left(\frac{E}{MeV}\right)^{-2.0} & \text{if } E \ge 20.0\ \text{MeV} \end{cases}$$




2.Cosmic Diffused Gamma-Ray Background (CDGRB)

$$\frac{dN}{dE} = \begin{cases} 7.877\,E^{-1.29}\exp^{-E/41.13} & \text{if } E \le 60.0\ \text{keV} \\ 4.32\times10^{-4}\left(\frac{E}{60}\right)^{-6.5} + 8.4\times10^{-3}\left(\frac{E}{60}\right)^{-2.58} & \\ +4.8\times10^{-4}\left(\frac{E}{60}\right)^{-2.05} & \text{if } E \ge 60.0\ \text{keV} \end{cases}$$

[1] Ritabrata Sarkar et al. "Instruments of RT-2 experiment onboard CORONAS-PHOTON and their test and evaluation IV: background simulations using GEANT-4 toolkit" Exp Astron (2011) 29:85–107 DOI: 10.1007/s10686-010-9208-z

# MeGaT design

$$\cos\varphi = 1 - m_e c^2\left(\frac{1}{E_\gamma} - \frac{1}{E_\gamma + K_e}\right)$$

$$\sigma_\varphi^2 = \left(\frac{\partial\varphi}{\partial K_e}\right)^2 \sigma_e^2 + \left(\frac{\partial\varphi}{\partial E_\gamma}\right)^2 \sigma_\gamma^2$$

$$\frac{\partial\varphi}{\partial K_e} = \frac{m_e c^2}{\sin\varphi}\cdot\frac{1}{\left(E_\gamma + K_e\right)^2}$$

$$\frac{\partial\varphi}{\partial E_\gamma} = -\frac{m_e c^2}{\sin\varphi}\cdot\left[\frac{1}{E_\gamma^2} - \frac{1}{\left(E_\gamma + K_e\right)^2}\right]$$

$$ARM = \sqrt{\sigma_{\varphi_{geo}}^2 + \sigma_{\varphi_{recon}}^2}$$