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

Libo Wu

On behalf of the MeGaT Group

The 8th International Conference on Micro-Pattern Gaseous Detectors (MPGD 2024)

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 and R&D process
  - Conceptual design
  - Simulation framework and results
  - Prototype of R&D
  - Electronics
- Summary

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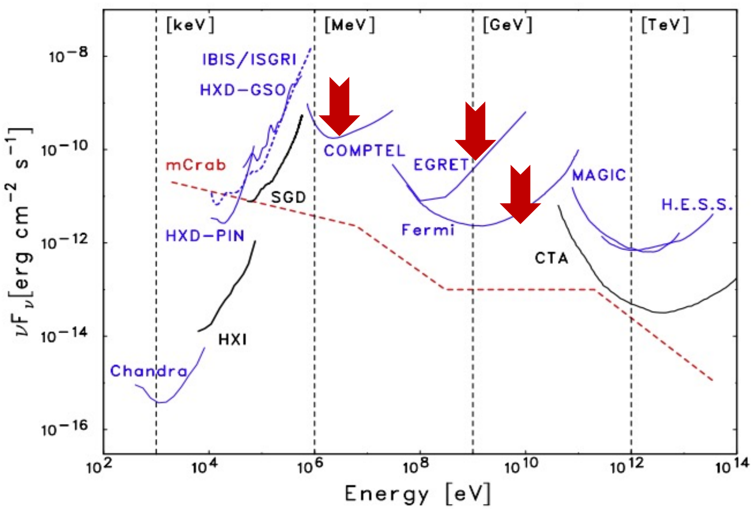
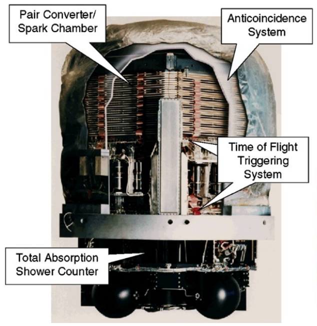
MeV γ-ray astronomy observations

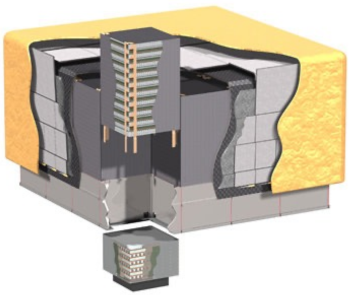
T. Takahashi et al. / Astroparticle Physics 43 (2013) 142–154

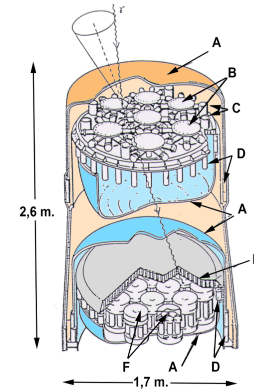




EGRET

Fermi-LAT



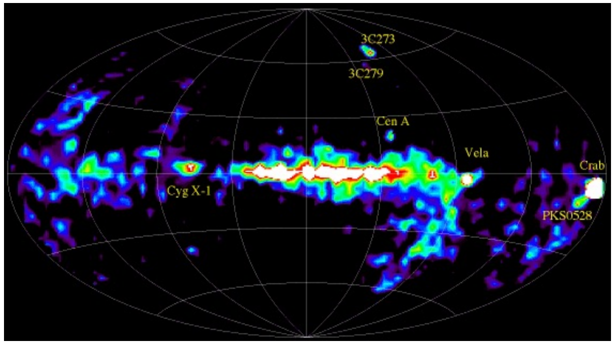


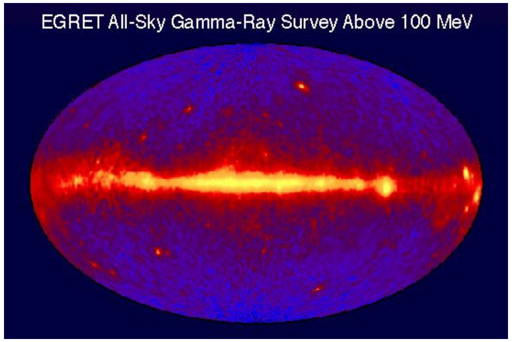
Comptel

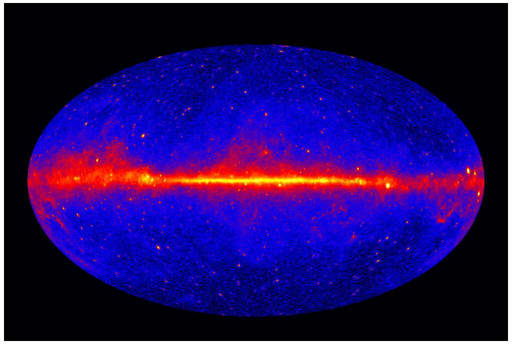
Comptel (1991-2000)
63 sources 1-30MeV

EGRET (1991-2000)
271 sources>100MeV

Fermi (2008-)
6000+ sources>100MeV



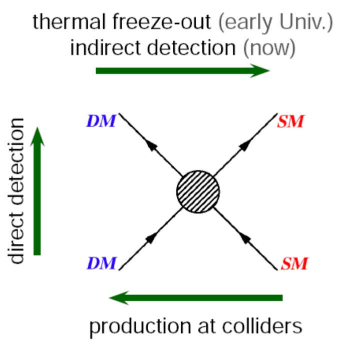


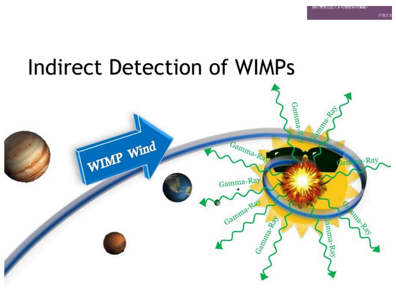


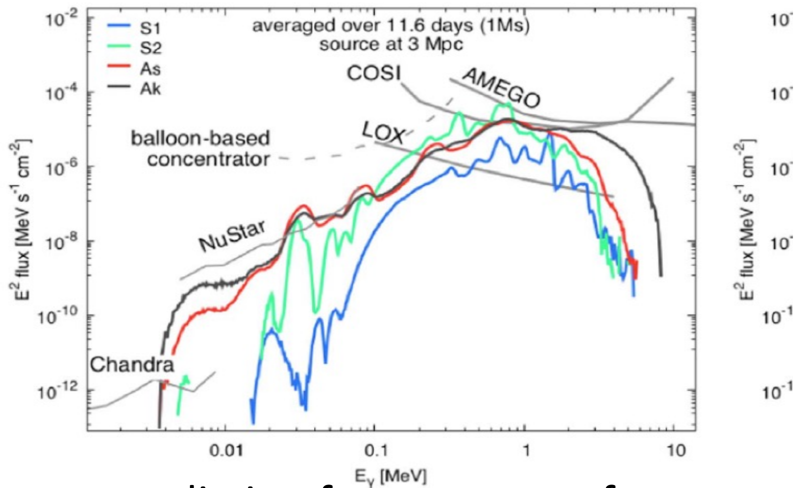
There is great discovery potential for the MeV gap

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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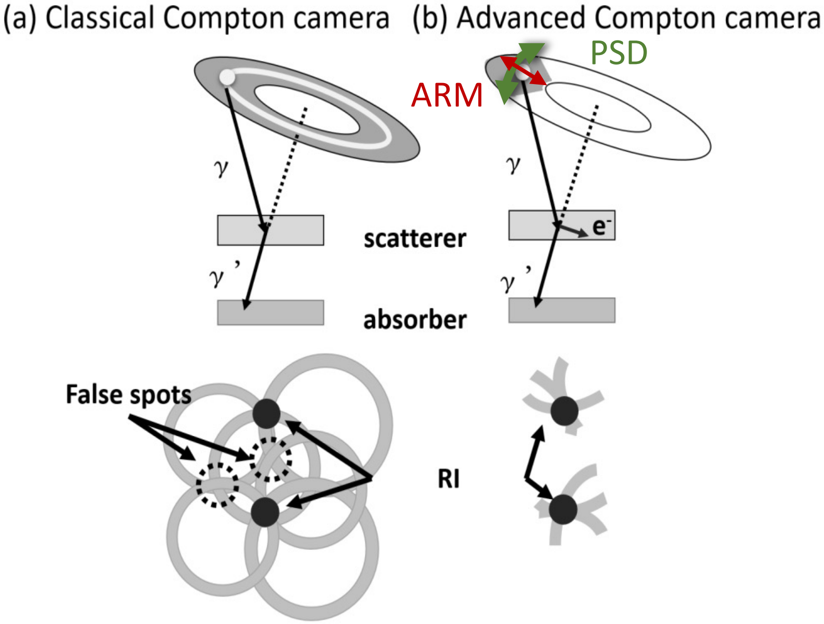
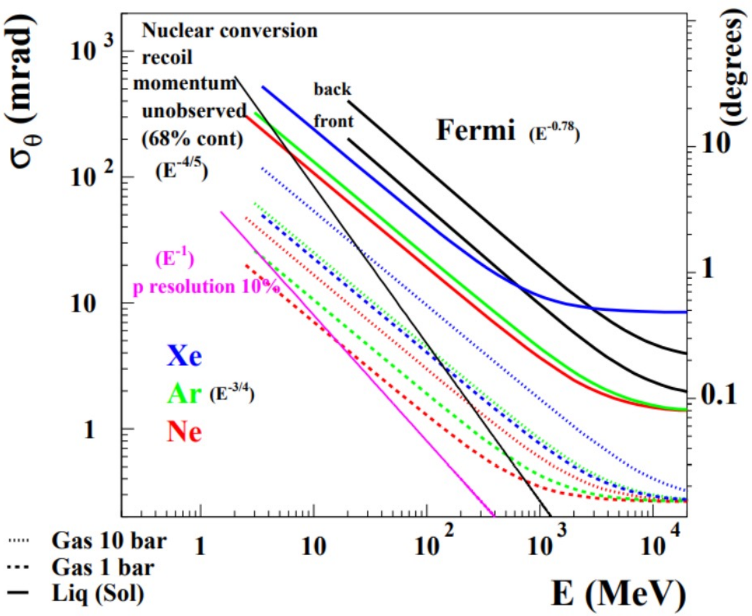
Key technological challenges

- 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



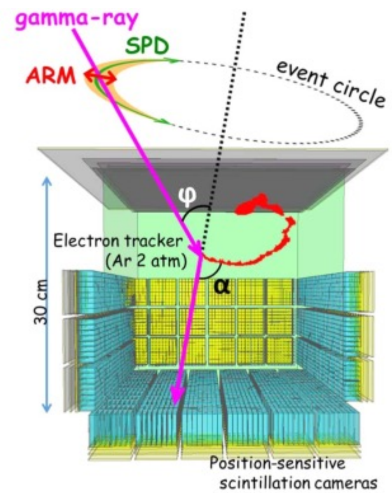
It is practical to improve the e-tracking measurement by reducing the material density with gas detectors

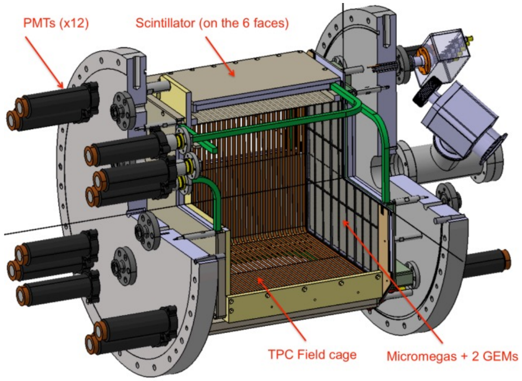
Some experimental proposals

SMILES （0.3-3MeV）

TPC Compton camera

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





NIM A 718 (2013) 395

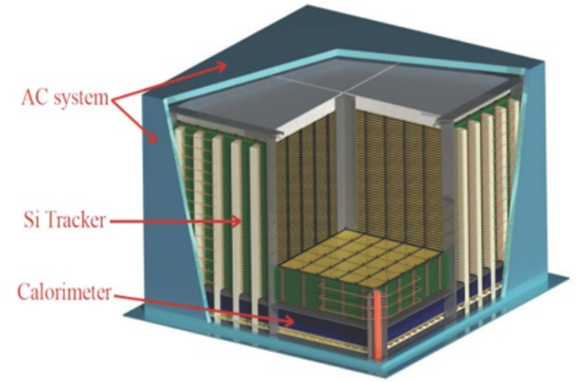
HARPO（MeV-GeV）

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 minimizing electron scattering
- Electron emission angles carrying polarization information

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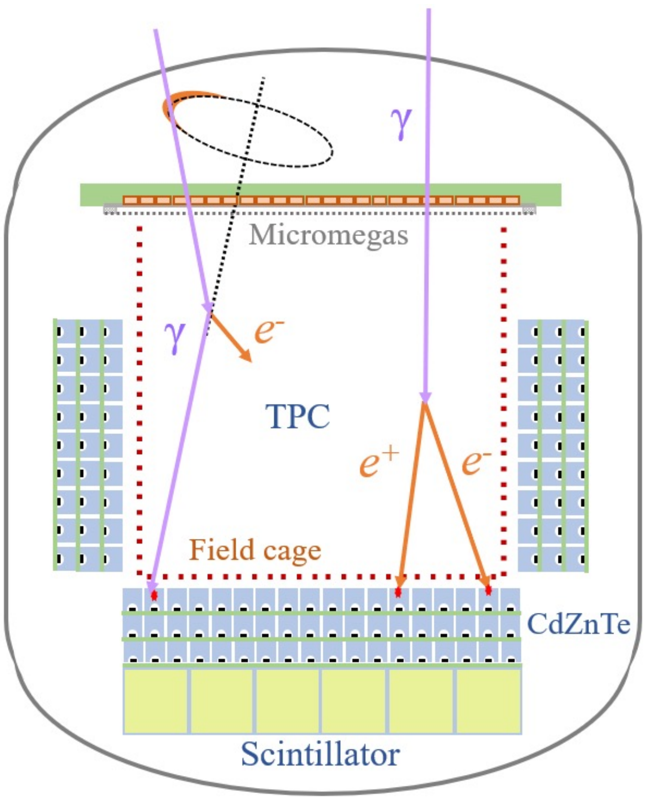
Conceptual design

- **TPC based technique**
  - 30 cm cubic volume（small prototype）
  - Four 50 cm^3 unit or a single 100 ×100 ×50 cm^3 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

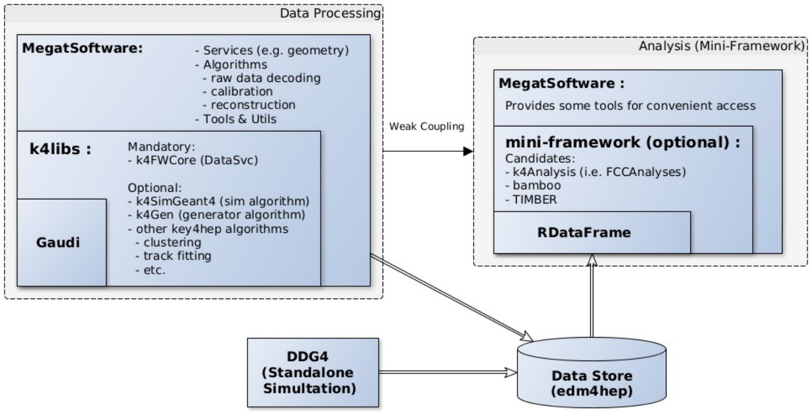
Software stacks:

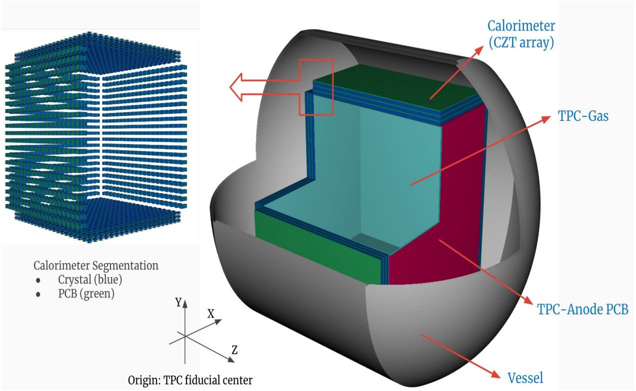
- Simulation:
  - k4SimGeant4
- Event data model:
  - EDM4hep
- Event-processing:
  - Gaudi
  - k4FWCore

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

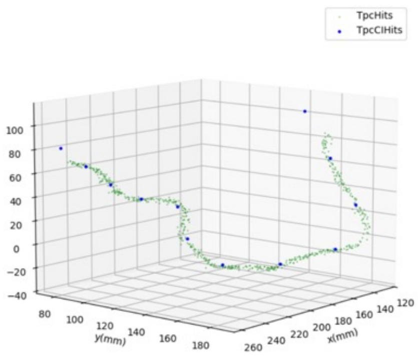
Readout segmentation

Calorimeter:
- Pixel

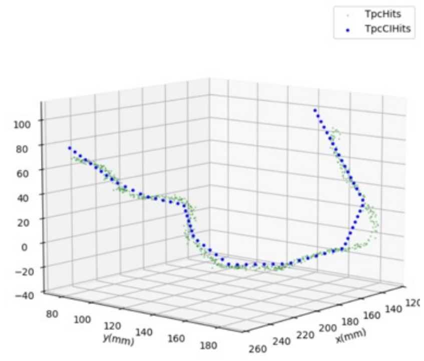
TPC:
- Strip/Pixel
- Extra stage needed in digitization
- Surface attached to PCB
  - Drift distance determination
  - Coordinate transformation

Simulation performance

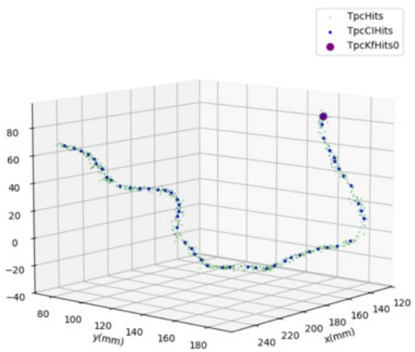
- **Track reconstruction of recoil electron by Kalman Filter Algorithm**



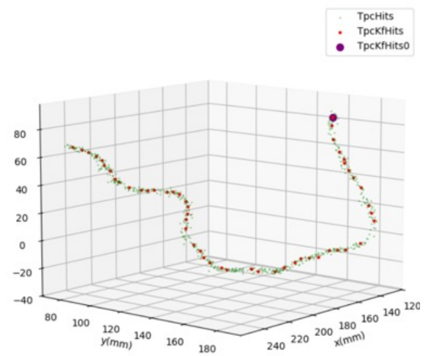
1.clustering



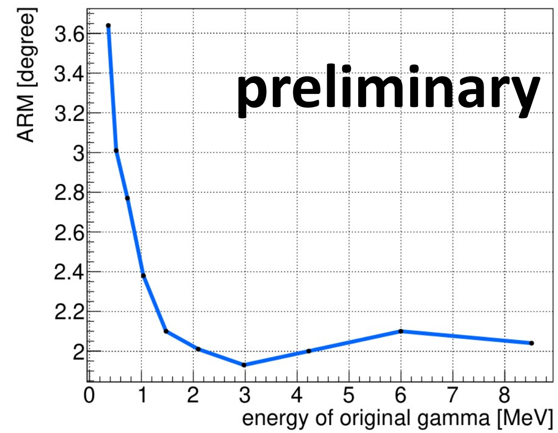
2.interpolation

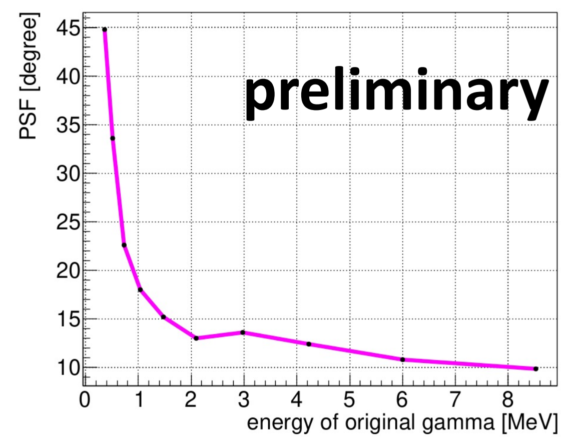


3.get charge center



4.Kalman filter





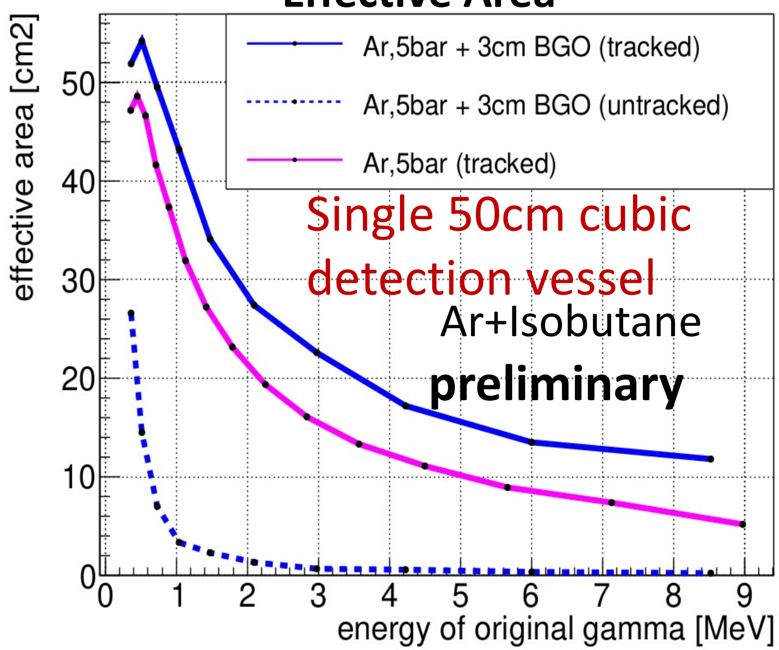
Poster by R.Zhou

Simulation performance

Four identical 50cm cubic detection vessels

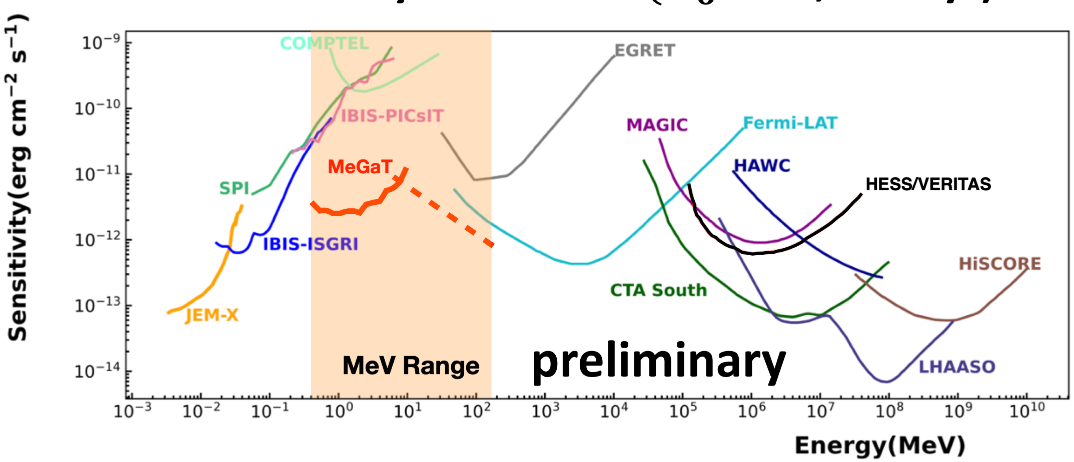
— Very preliminary simulation result without pair production

- - - Rough estimation by taking into account pair production



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

Sensitivity of MeGaT (N_σ = 3σ, T = 1yr)

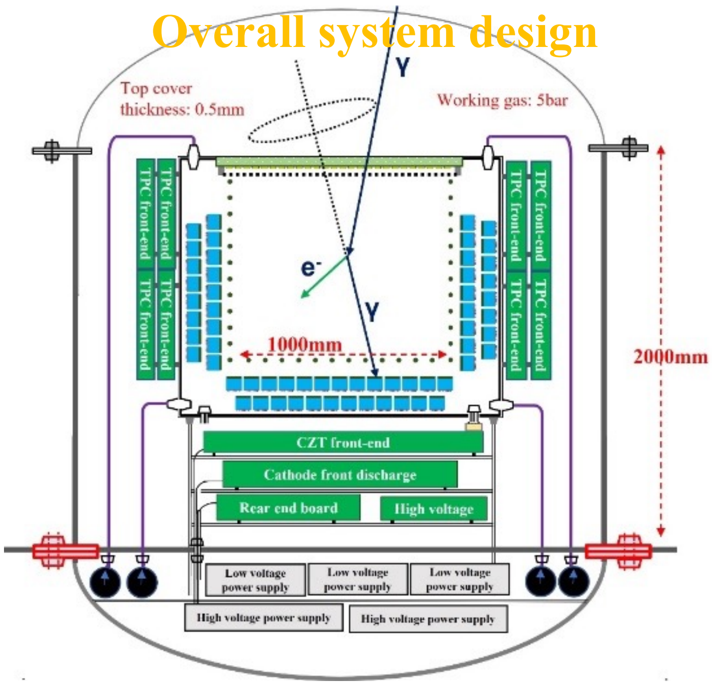


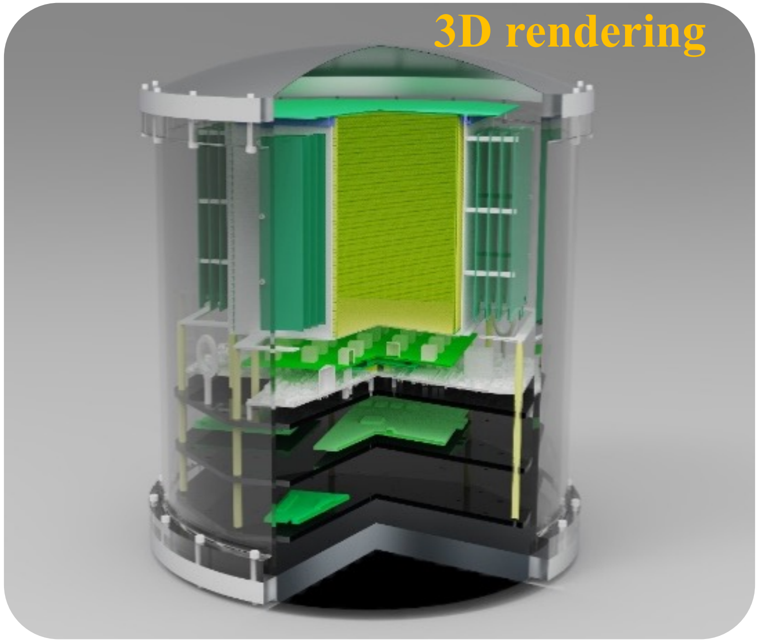
Perfect performance on spatial and energy resolution are required for the TPC and calorimeter

Poster by R.Zhou

Prototype of R&D

- **30 cm cubic volume**

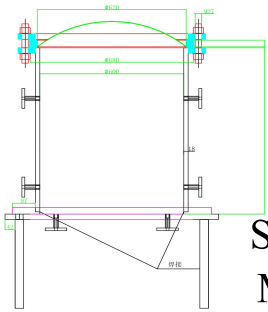


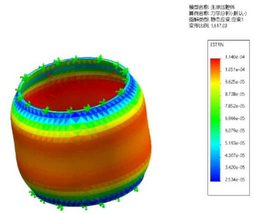


Technical challenges

- High voltage: Micromegas ~ 3000 V， Field cage ~ 15000 V
- High-pressure sealing: 5 bar
- Mechanical support and heat dissipation issues

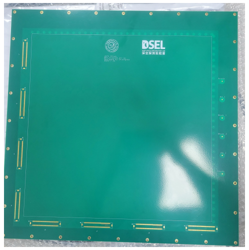
Prototype of R&D





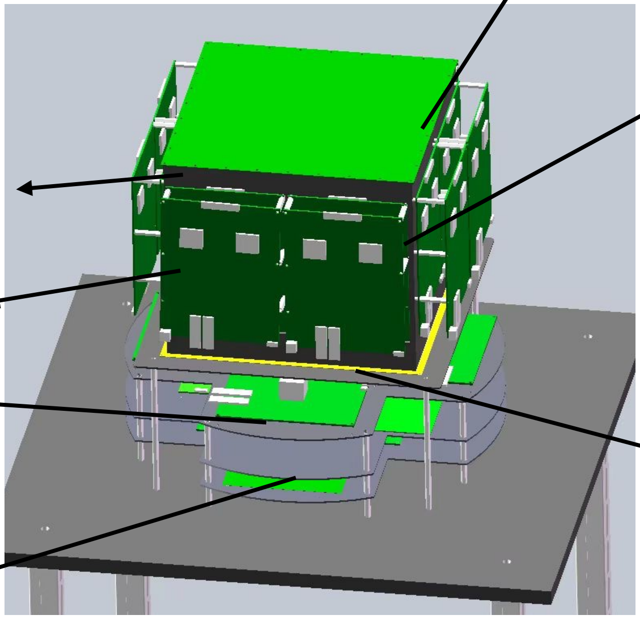
Sealed jar &
Mechanical
simulation

The thermal bonding
Micromegas

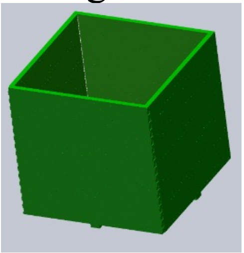


Small chamber

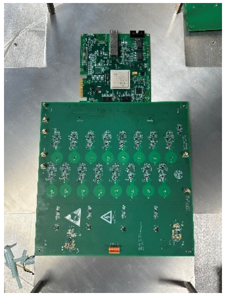
FEE of TPC



Field cage

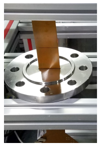


High Voltage &
Data Collection
Module(DCM)



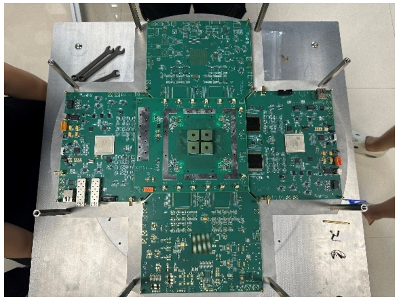
Cathode FEE：
CSA+ADC

20000 V
high voltage
connector



signal line

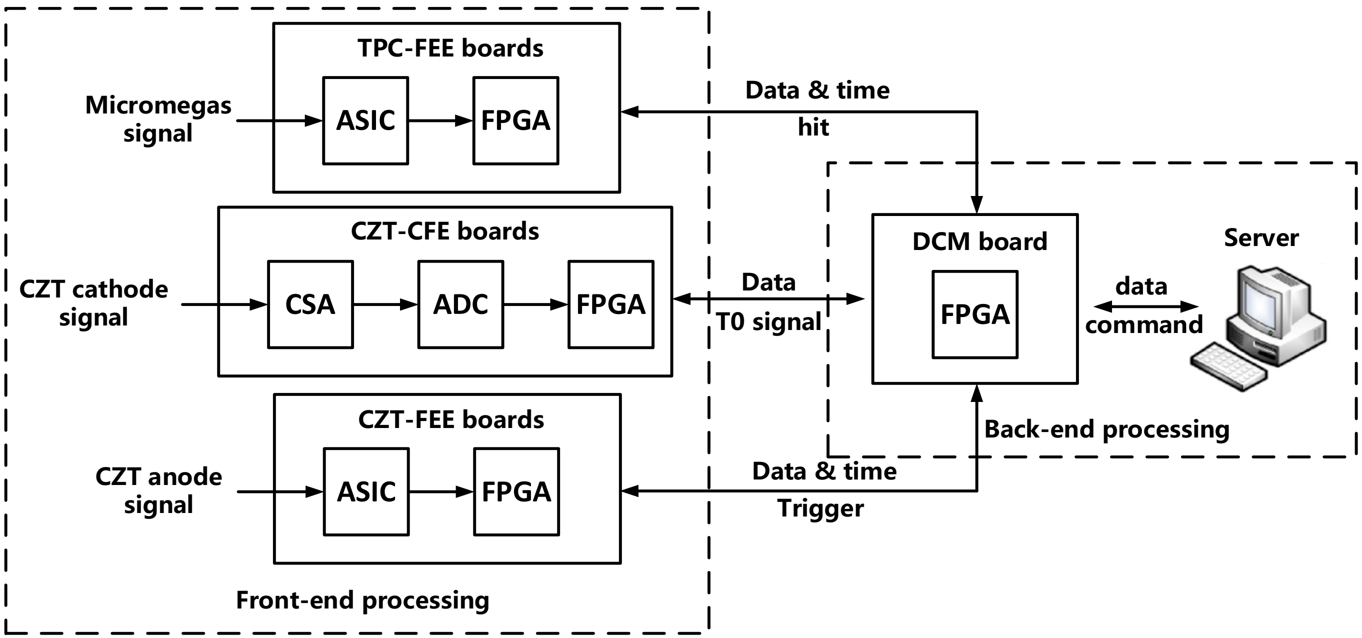
CZT front-end & carrier board



Schematic design for system

☐ Multiple detector system

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

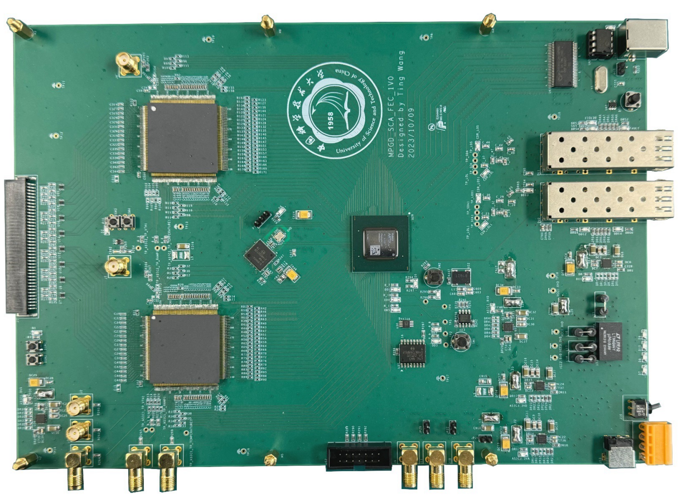


FEE of the TPC

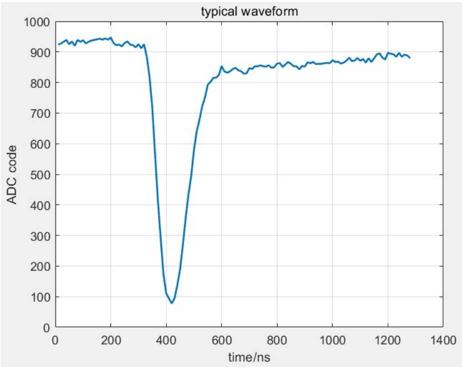
Dynamic range	48 fC-1 pC
INL	< 1%
Shaping Time	70ns-1us
Maximum sample rate	160 MSPS
Sample units	128 cells
Noise (RMS)	< 0.5 fC @ 48fC
Timing resolution(RMS)	< 1 ns @ 48fC
Dead time	< 75 μs @ 120 MSPS

Digital output ASIC (design by Professor L. Zhao)

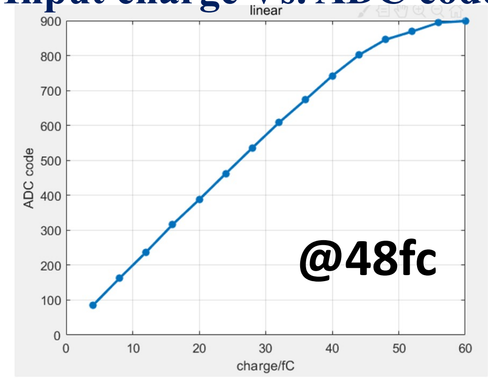
- Switched Capacitor Array (SCA) & Wilkinson ADC
- The development and performance of the front-end readout board has been completed



Result of 48fC input charge



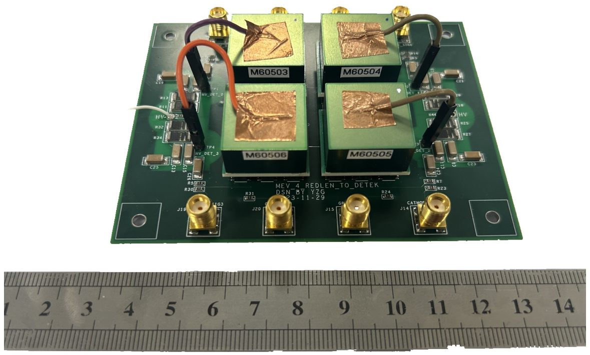
Input charge Vs. ADC code

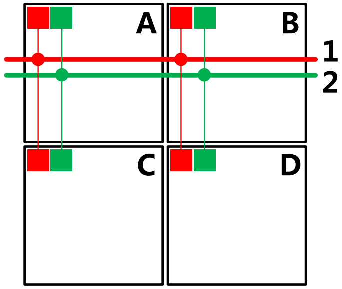


FEE of the CZT

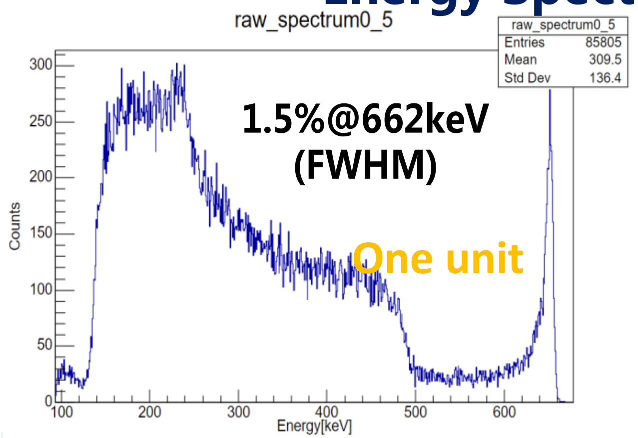
Multiplexing method

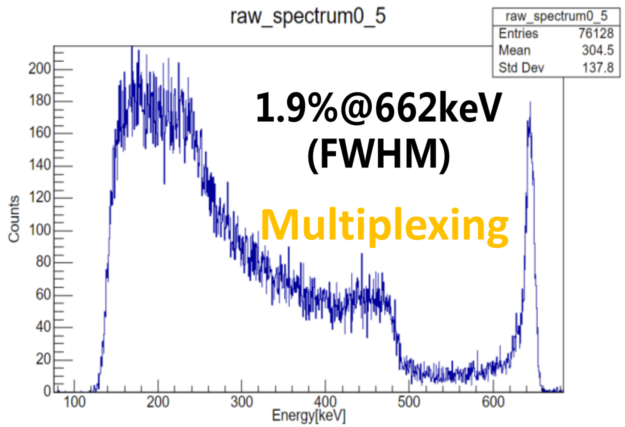
- Multiple pads of different detectors can be connected to one readout channel.
- The cathode signal of CdZnTe shows which detector has been hit.

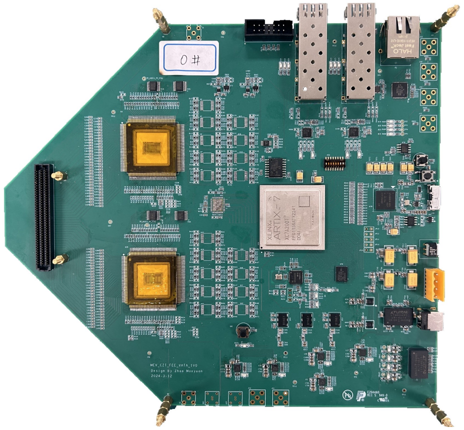




Energy Spectrum of CZT







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.
- The first 30 cm cubic prototype is under build and characterized with photon beam in the end of 2024.

Summary

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- Technologies are innovative and challenging, but are proven to be reliable.
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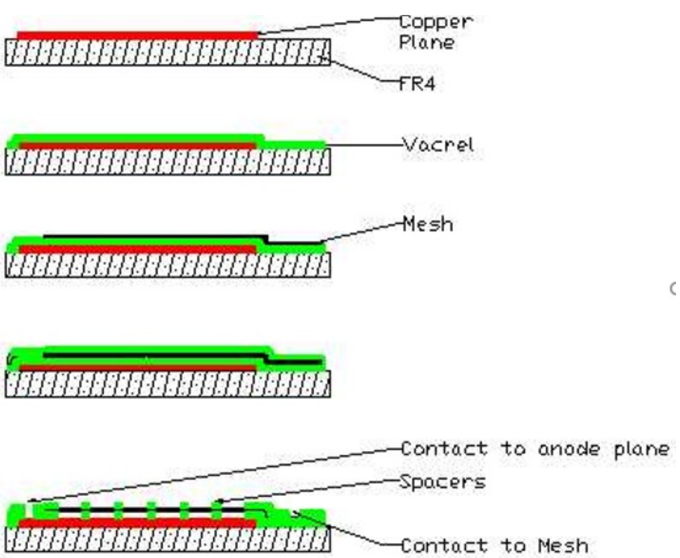
Thank you for your attention!

Backup slides

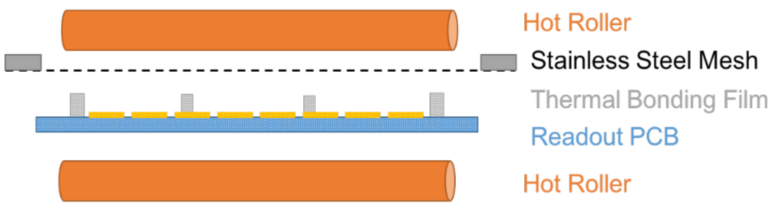
The thermal bonding method

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

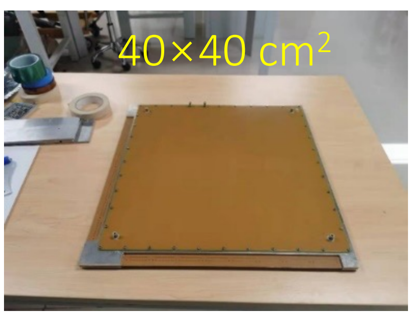
➔easy to clean, especially for large area

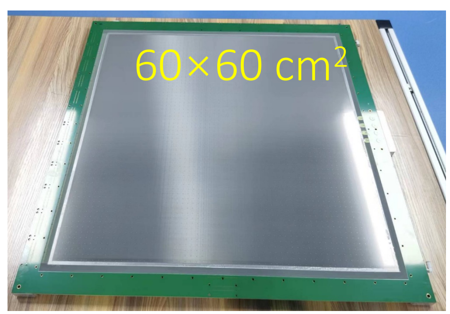
➔less than 1% spacer area

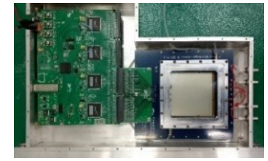
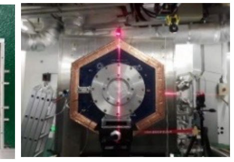
Fabrication and applications





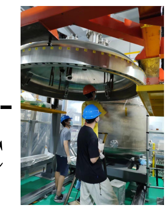
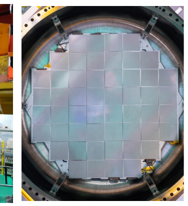




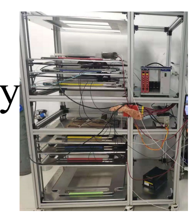
Neutron detectors for the Chinese Spallation Neutron Source

PandaX-III TPC MM

CEPC-RICH &STCF-RICH

Muography



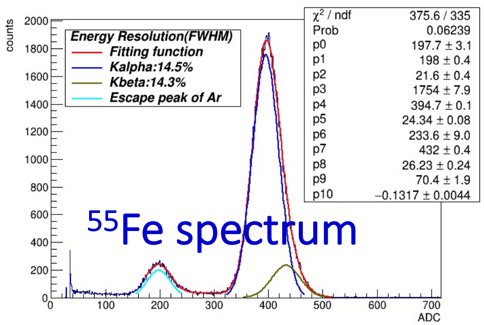

Performance of the Micromegas detector

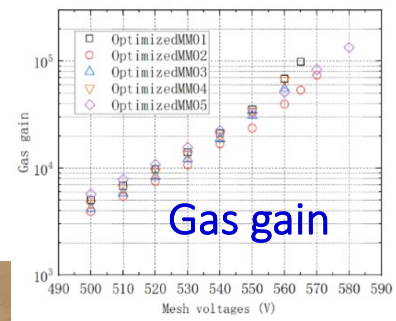
5.9 keV X-ray test

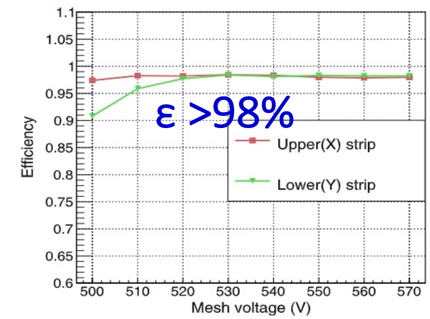
- Gas gain： ~10^5 (Ar+7%CO_2)
- Energy resolution： < 15% (FWHM)

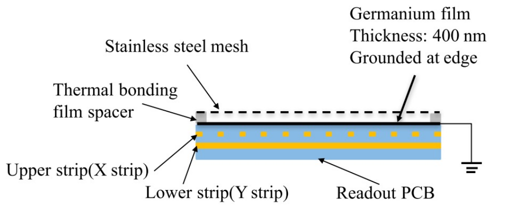
Electron beams（5GeV）at DESY

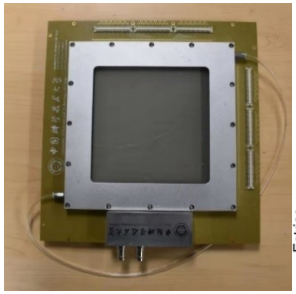
- X-Y 2D readout
- Efficiency： >98%
- Resolution： 65μm

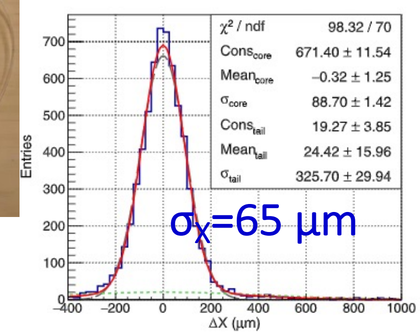


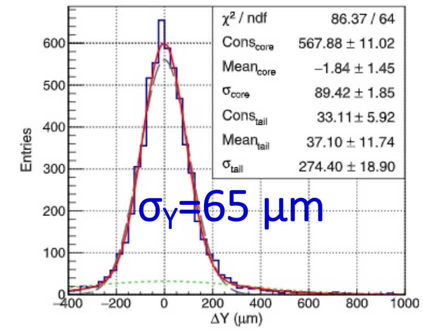








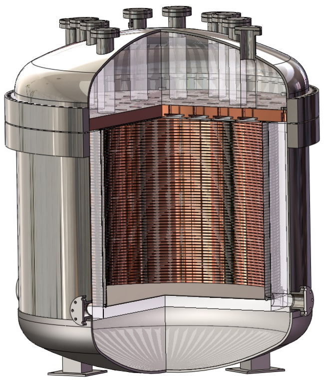


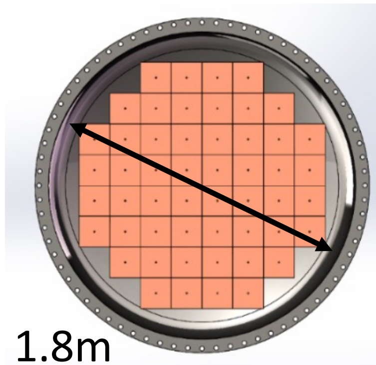


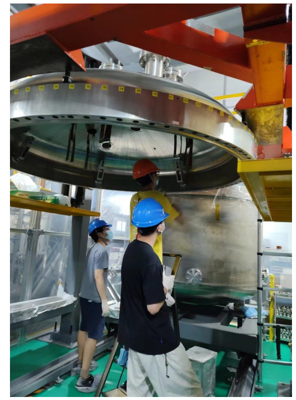
NIM-A 989 (2021) 164958； NIM-A 1031 (2022) 166595.

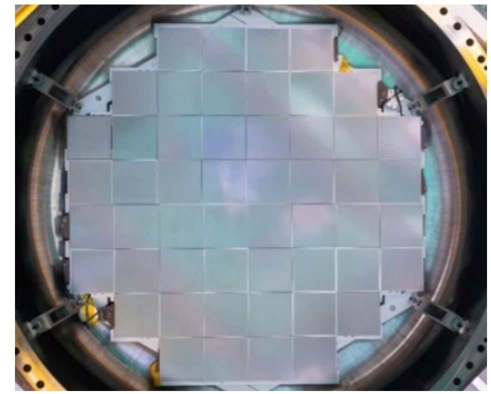
Performance of the Micromegas detector

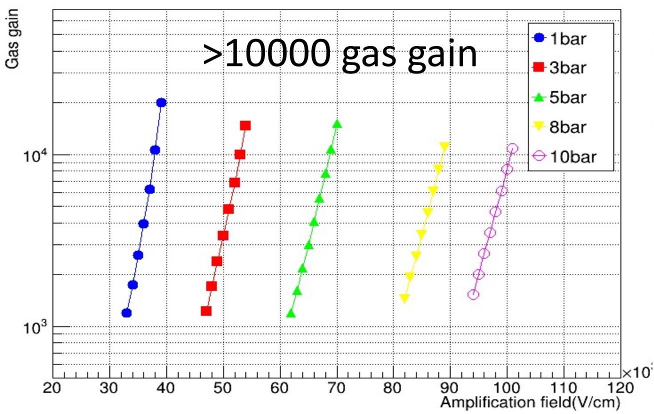
Performance in high gas pressure was studied in the PandaX-III experiment

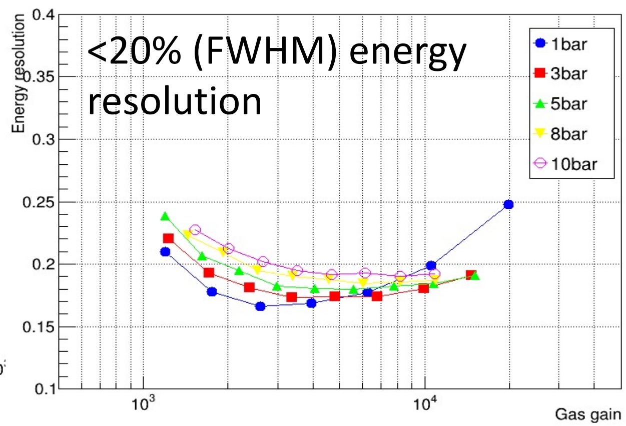










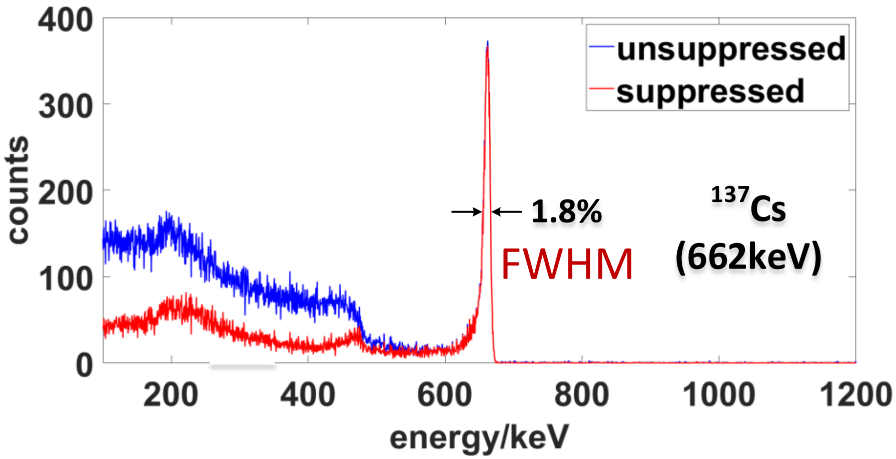


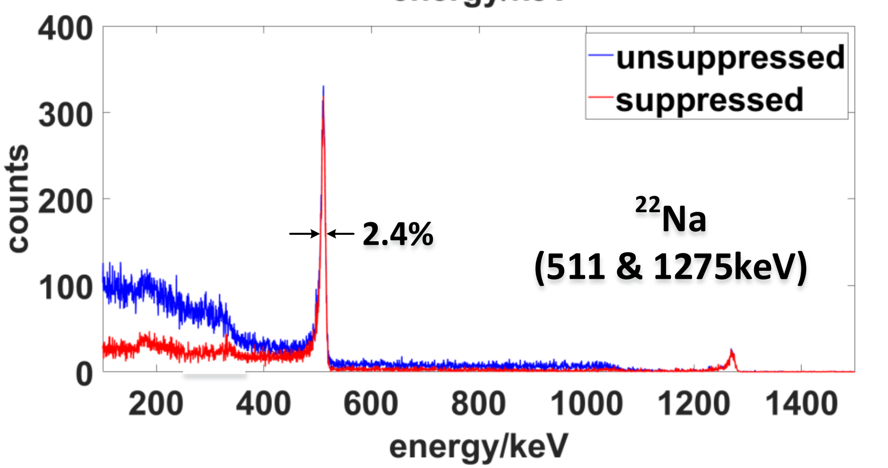
High gain and good energy resolution were verified in high gas pressure

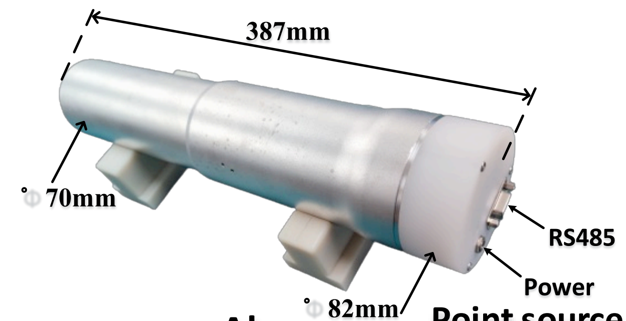
Test at 10bar Ar(2.5% Iso) with a 5.9 keV X-ray source

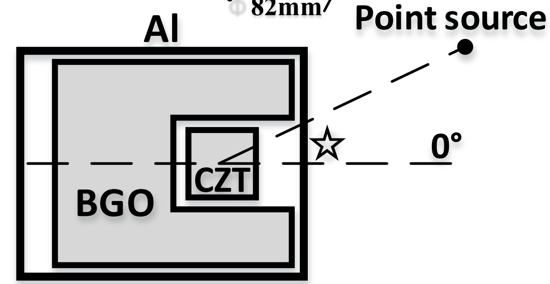
Performance of the CZT

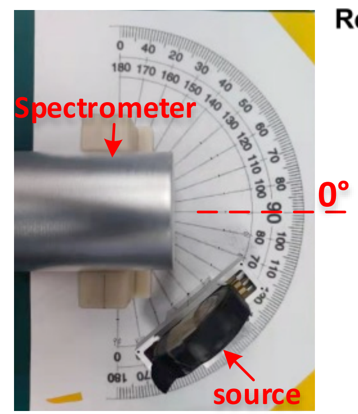
Cadmium zinc telluride （CZT）

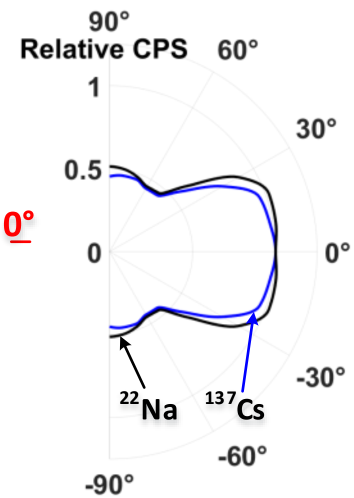








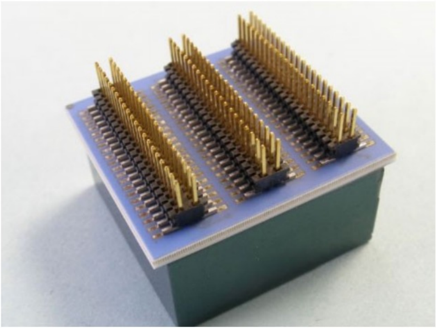




Channel encoding method

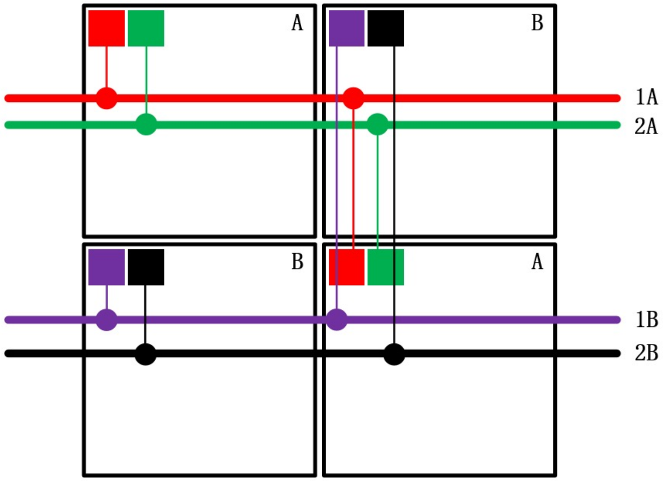
◻Pixelate CZT

- § 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.

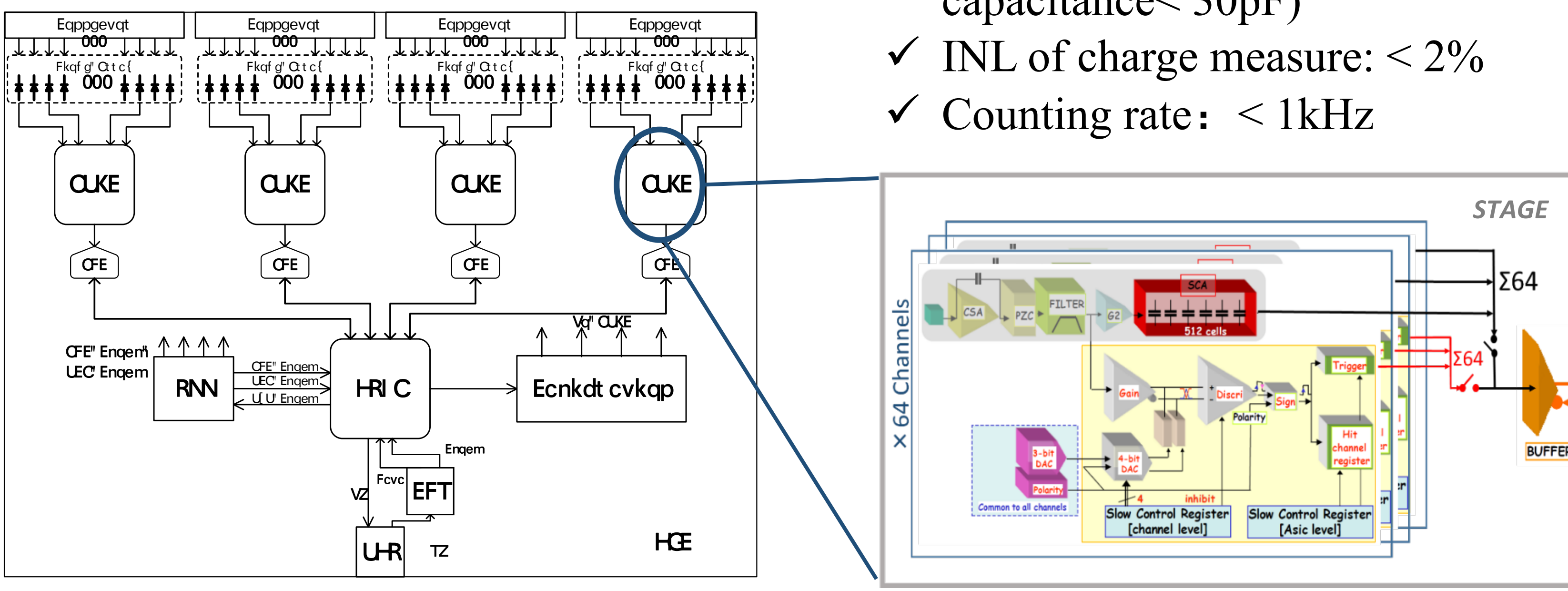


FEE for the TPC

- 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

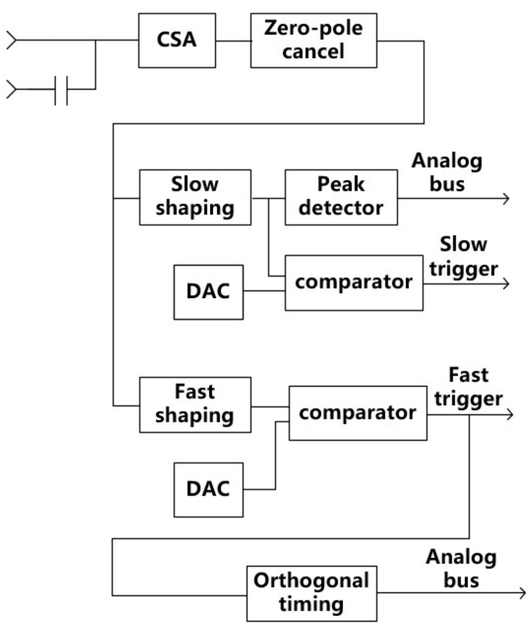
✓ Feedback capacitance: 15fF, 60fF, 0.5pF

✓ Shaping time：0.3 us – 40 us

✓ Noise RMS: 80e- + 12e-/pF

✓ INL of charge measure: < 10%

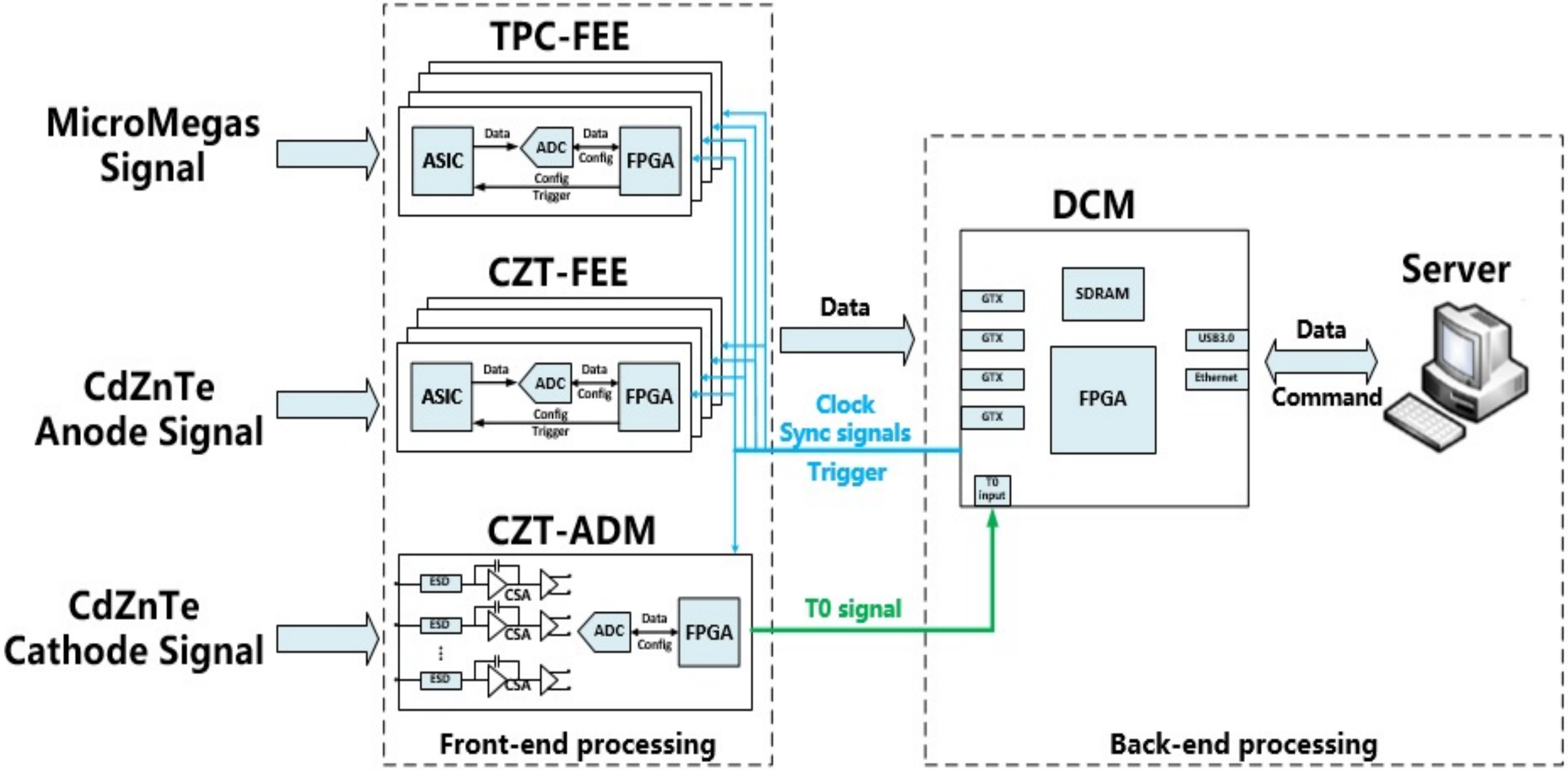
✓ Counting rate：< 200 kHz



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

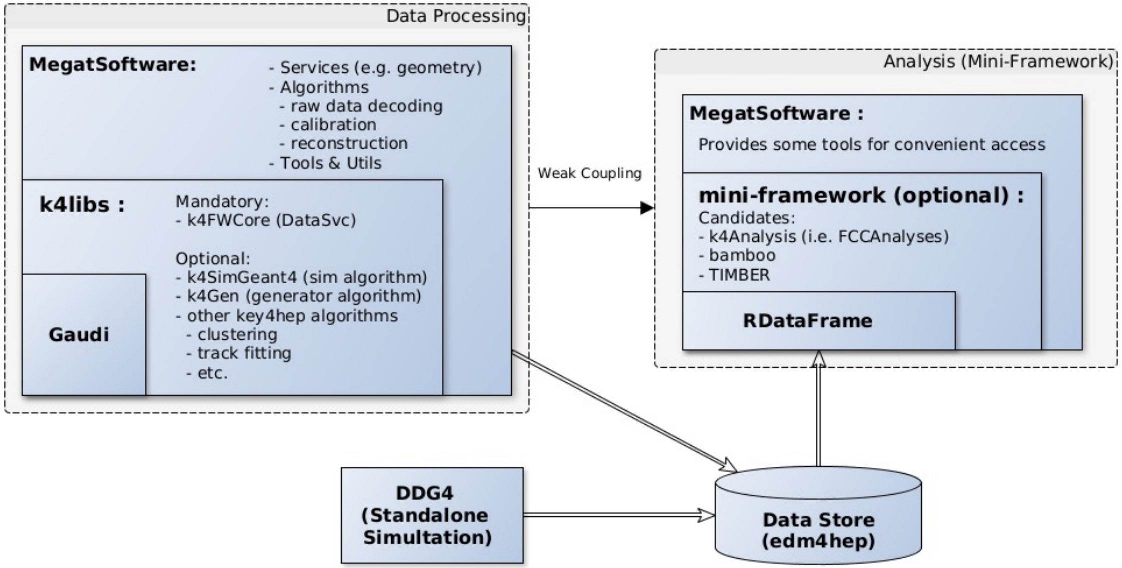


R&D status: software framework

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

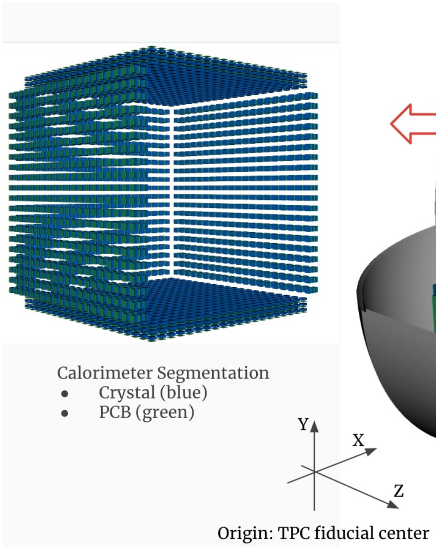
Exploratory analysis (on desktop):

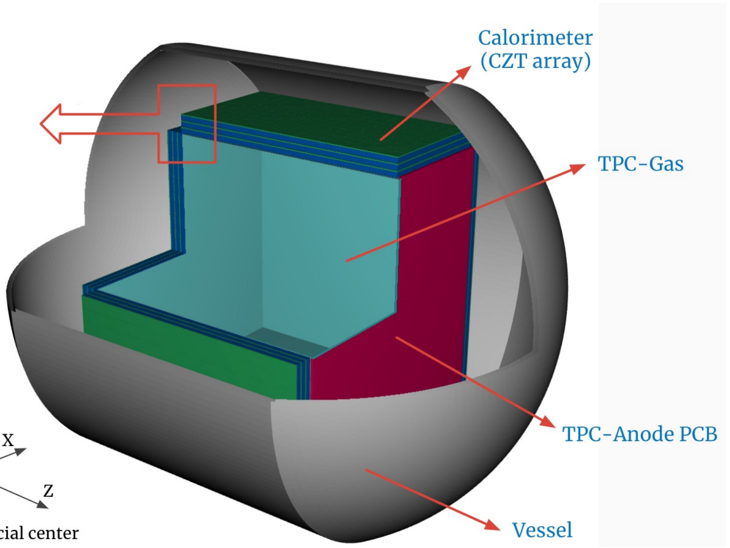
- personal data analysis:
  - quick turn-around workflow
- lightweight kernel:
  - RDataFrame (ROOT)

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

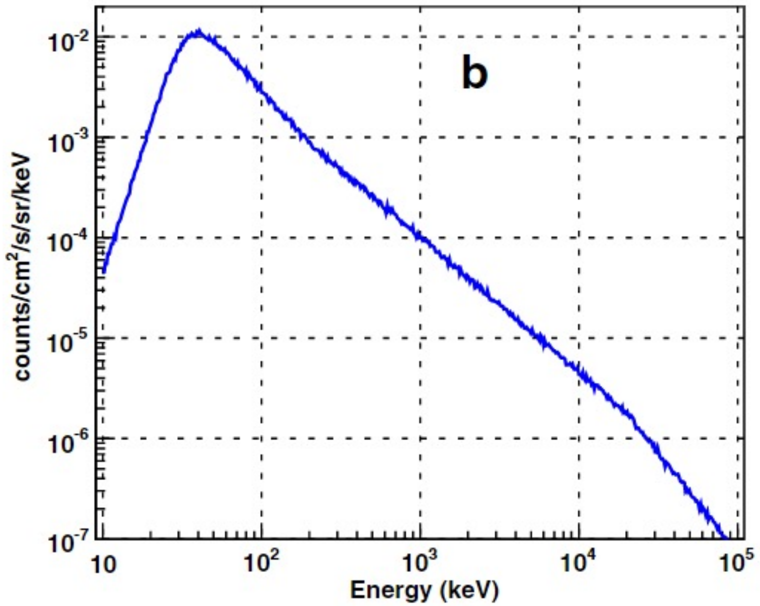
TPC:

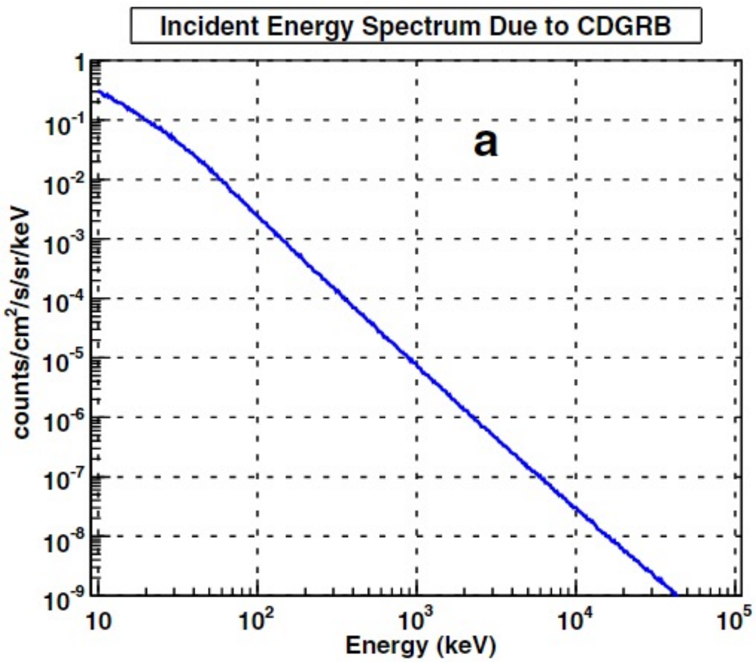
- Strip/Pixel
- Extra stage needed in digitization
- Surface attached to PCB
  - Drift distance determination
  - Coordinate transformation

Background estimate[1]

1. albedo gamma-ray

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





2.Cosmic Diffused Gamma-Ray Background (CDGRB)

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

[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

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

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

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

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

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