Simulation Study for the Higher Sensitivity of an Electron-Tracking Compton Camera at over 1 MeV

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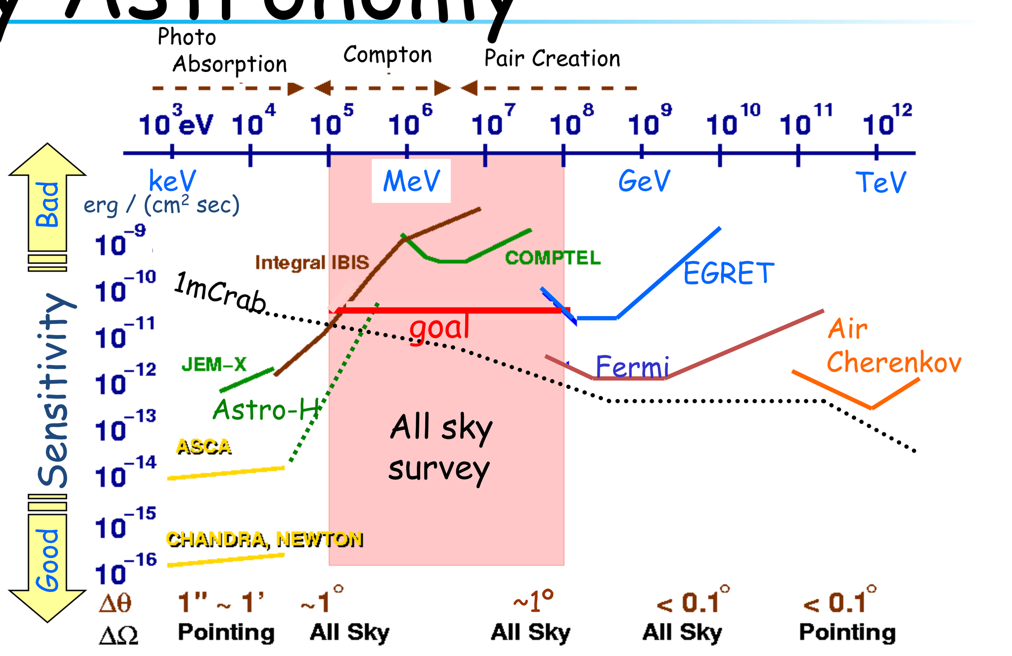
1. MeV gamma-ray Astronomy

Universe in MeV gamma ray

- Nucleosynthesis
  - SNR : Radio-isotopes
  - Galactic plane : ^{26}Al , ^{60}Fe
- Acceleration
  - Jet (AGN), GRB :
    - Synchrotron radiation
    - Inverse Compton scattering
  - SNR : π^0-decay or Inverse Compton
- Strong Gravitational Potential
  - Black Hole : accretion disk, π^0-decay
- Etc.
  - gamma-ray pulsar, solar flare
  - annihilation, neutron capture

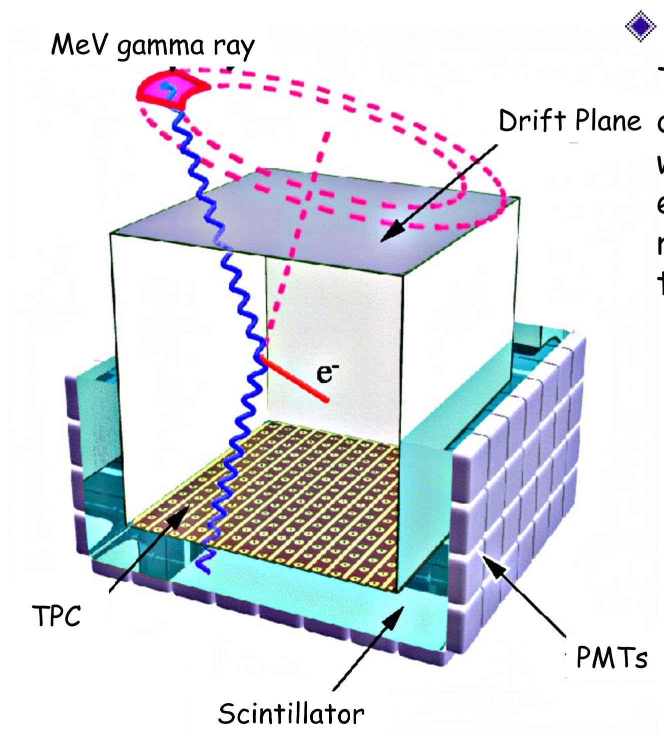


Past Observations

- COMPTEL (CGRO) : Compton Imaging
  COMPTEL discovered ~30 steady sources in all sky.
  The observation was obstructed by many backgrounds,
  so that the actual sensitivity was lower than the designed one.
- IBIS, SPI (INTEGRAL) : Coded Aperture Imaging
  The sensitivity is nearly equal to that of COMPTEL in MeV region.

Next generation detector must have …
- Wide-band detection
  for study of radiation processes
- Large Field of View
  for all sky survey
- Background rejection
  for higher detection sensitivity

2. Electron Tracking Compton Camera



Schematic view of ETCC

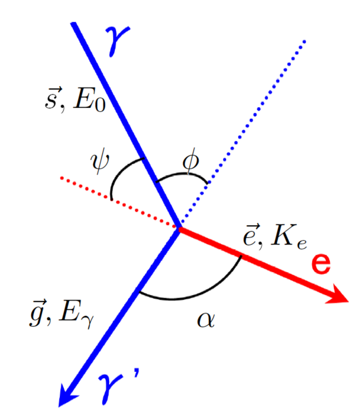
Electron Tracking Compton Camera (ETCC)

The camera consists of a gaseous time projection chamber (TPC), which detects the track and energy of the recoil electron, and a scintillator, which detects the absorption point and the scattered gamma-ray energy. By the detection of the direction of the recoil electron, we can reconstruct the Compton scattering completely and obtain the fully ray-traced gamma-ray image.

$$E_0 = E_\gamma + K_e$$

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

$$\vec{s} = \left(\cos\phi - \frac{\sin\phi}{\tan\alpha}\right)\vec{g} + \frac{\sin\phi}{\sin\alpha}\vec{e}$$



- E_0 : Energy of the incident gamma-ray
- E_γ : Energy of the scattered gamma-ray
- K_e : Kinetic energy of the recoil electron
- $\vec{s}$: Direction of the incident gamma-ray
- $\vec{g}$: Unit vector of the scattering direction
- $\vec{e}$: Unit vector of the recoil direction
- ϕ : Scattering angle
- α : Differential angle between $\vec{g}$ and $\vec{e}$

Background Rejection

The angle α between the scattering direction and the recoil direction is measured geometrically

$$\cos\alpha_{geo} = \vec{g}\cdot\vec{e}$$

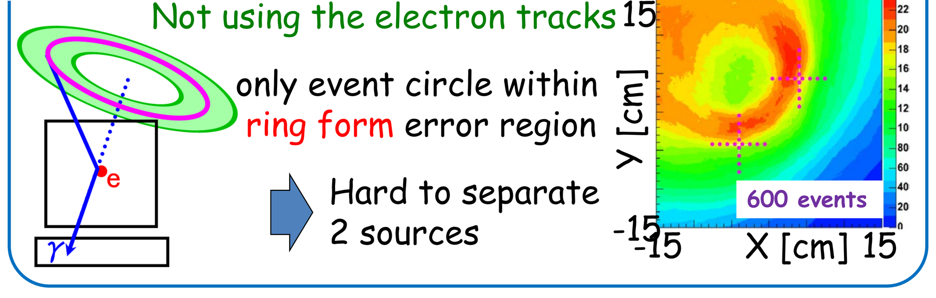
and also this angle is obtained by the calculation using the energies of the recoil electron and the scattered gamma-ray

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

Therefore we can select the good events of which the kinematical calculated angle is consistent with the measured one. Because of the background rejection by the angle α, the ETCC fits for the MeV gamma-ray astronomy, whose serious problem is the obstruction by background.

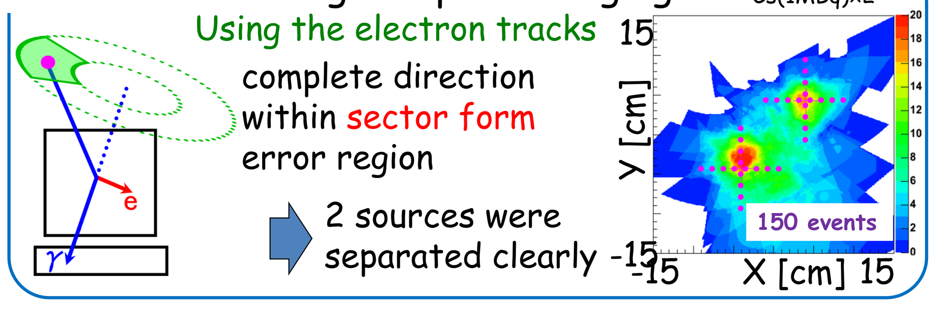
Conventional Compton Imaging

Not using the electron tracks



Electron-Tracking Compton Imaging

Using the electron tracks



Sub-MeV gamma-ray Imaging Loaded-on-balloon Experiment

For the future observations with loading on a satellite, we have a plan of balloon experiments. As the first step, we developed a small size ETCC using a 10cm cube TPC, and launched from Sanriku Balloon Center, ISAS/JAXA, on Sep. 1, 2006 (SMILE-I). SMILE-I ETCC observed diffuse cosmic and atmospheric gamma rays for the confirmation of gamma-ray detection at the balloon altitudes, and it was successful that we obtained approximately 420 photons at the altitude of 35 km, during the live time of 3 hours. The next step of SMILE is an observation of a bright source using a middle size ETCC for the test of imaging properties (SMILE-II). Now, we are preparing and testing a prototype of 30cm cube ETCC, and are designing a flight model of SMILE-II. After the second flight, we will develop the larger volume ETCC, and will observe the celestial objects and the terrestrial gamma ray burst caused by electron precipitation using balloons, and finally we try all sky survey in MeV band using a satellite.

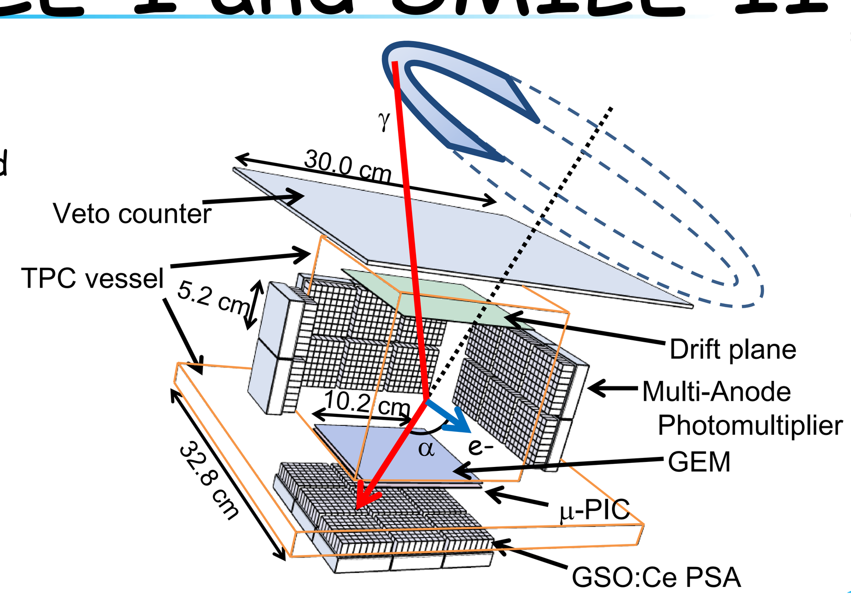
SMILE-I (2006/9/1)

3. Energy band of SMILE-I and SMILE-II

SMILE-I ETCC specification

- TPC
  - gas : Xe 80% + Ar 18% + C_2H_6 2% (mass ratio), 1 atm, sealed
  - size : 10 x 10 x 14 cm^3
  - energy resolution : 45% @ 22.2keV, FWHM
  - position resolution : 500μm
  - gas gain : 35000
- Scintillator
  - material : Gd_2SiO_5:Ce
  - pixel size : 6 x 6 x 13 mm^3
  - \# of pixels : 576 pixels @ bottom of TPC; 384 pixels @ each side of TPC } 2112 pixels
  - energy resolution : 11% @ 662 keV, FWHM

→ Energy band of ETCC : 0.15 – 1.0 MeV

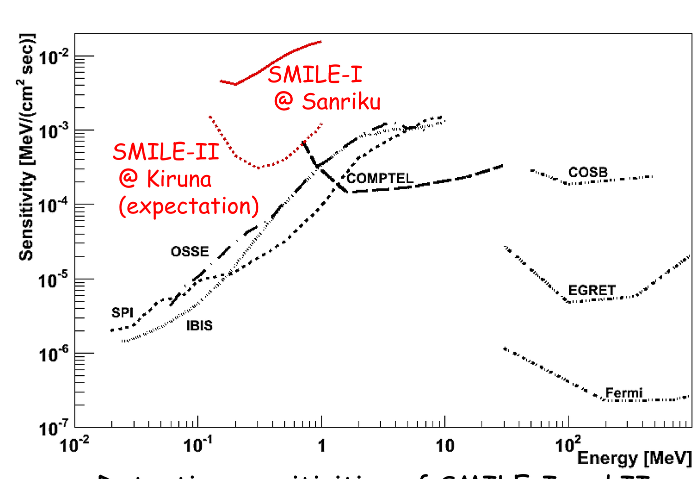


SMILE-I ETCC structure

Current Design of SMILE-II ETCC

- TPC
  - gas : CF_4 40% + Ar 54% + iso-C_4H_{10} 6% (pressure ratio), 1.5 atm
  - size : 30 x 30 x 30 cm^3
- Scintillator
  - material : Gd_2SiO_5:Ce
  - pixel size : 6 x 6 x 13 mm^3
  - \# of pixels : 4608 pixels @ bottom of TPC; 2304 pixels @ each side of TPC } 13824 pixels

→ Energy band of ETCC : 0.15 – 1.0 MeV



Detection sensitivities of SMILE-I and II

- The energy band of the current ETCC is limited below 1 MeV.
- For the MeV gamma-ray astronomy, we want to detect the energy band of 0.5-100 MeV.

→ It is necessary to develop the ETCC for the higher energy band.

4. High Energy mode ETCC (HE-ETCC)

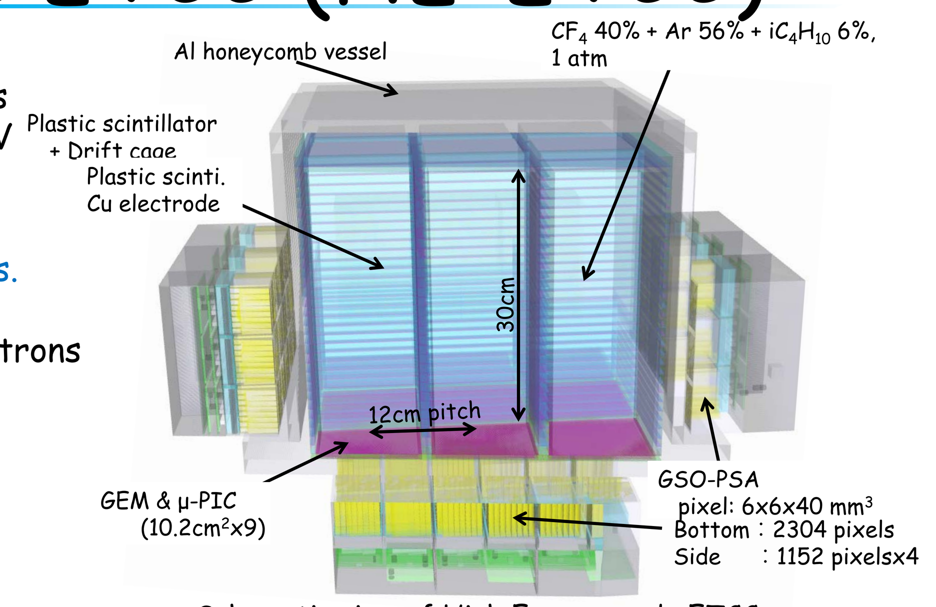
Concepts

The reason of the limitation in the detection energy is that the recoil electrons with the energy over 100 keV escape from the fiducial volume of the TPC.

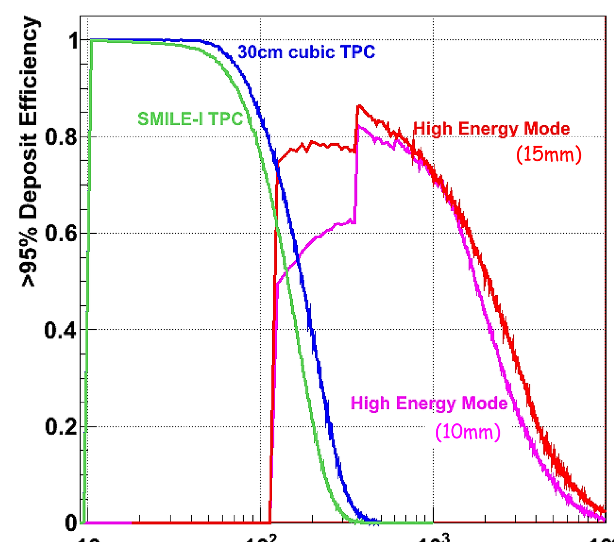
→ TPCs are placed side by side, and there are plastic scintillators between TPCs.

When the incident gamma rays make Compton scatterings in the gaseous TPCs, the recoil electrons run through the TPCs, and are absorbed in the plastic scintillators.

- Compton point, Recoil direction : detect by the gaseous TPCs
- Electron energy: detect by the scintillators and TPCs



Schematic view of High Energy mode ETCC



Full-energy deposit efficiency of electron

Dynamic range of Electron tracker

As the confirmation of the effect of plastic scintillator, we simulated the full deposit efficiency, which is the probability of electrons depositing over 95% of the initial energy.

- Current type Tracker
  SMILE-I TPC: < 0.14 MeV, 30cm cube TPC: < 0.18 MeV
  The extension of the energy range is only 0.04 MeV, whereas the fiducial volume of 30cm cube TPC is 18 times larger than that of SMILE-I TPC.
- High energy mode Tracker
  thickness of plastic scintillator = 10 mm : 0.12 - 1.8 MeV
  thickness of plastic scintillator = 15 mm : 0.12 – 2.2 MeV
  below 350 keV -> The efficiency depends on the gap size between plastic scintillator and TPC.
  over 350 keV -> The efficiency depends on the thickness of plastic scintillator, but the difference is slight (< 10% increase).

5. Simulation study of HE-ETCC

Design of HE-ETCC simulator

- TPC
  - gas : CF_4 + Ar + iso-C_4H_{10}, 1 atm
  - size : (10 x 10 x 30 cm^3) x 9
  - energy resolution : 45% @ 22.2keV, FWHM
  - position resolution : 500μm
- Plastic scintillator
  - thickness : 15 mm
  - energy resolution : 50% @ 100 keV, FWHM
- GSO Scintillator
  - material : Gd_2SiO_5:Ce
  - pixel size : 6 x 6 x 40 mm^3
  - \# of pixels : 2304 pixels @ bottom of TPC; 1152 pixels @ each side of TPC
  - energy resolution : 11% @ 662 keV, FWHM

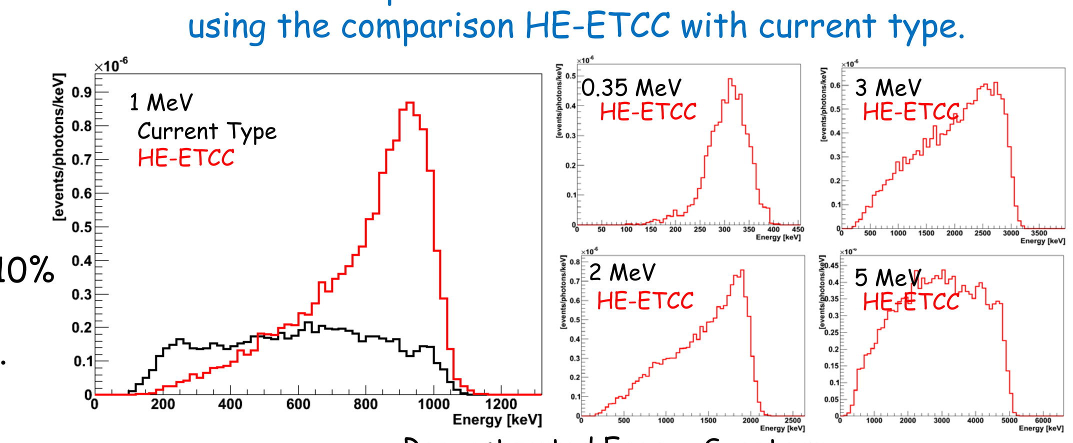
Design of current type ETCC simulator

- TPC
  - gas : CF_4 + Ar + iso-C_4H_{10}, 1 atm
  - size : 30 x 30 x 30 cm^3
  - energy resolution : 45% @ 22.2keV, FWHM
  - position resolution : 500μm
- GSO Scintillator
  - material : Gd_2SiO_5:Ce
  - pixel size : 6 x 6 x 13 mm^3
  - \# of pixels : 2304 pixels @ bottom of TPC; 1152 pixels @ each side of TPC
  - energy resolution : 11% @ 662 keV, FWHM

Studied the performance of HE-ETCC using the comparison HE-ETCC with current type.

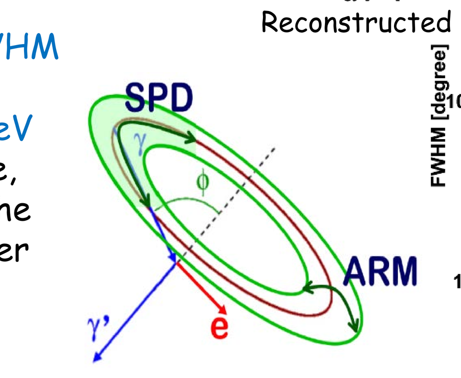
Performances of HE-ETCC

- Spectrum
  - Photo-peaks in HE-ETCC spectra are clearly seen between 0.35-2 MeV.
  - The Center of photo-peak is approximately 10% lower than the initial energy.
    -> Energy loss at the gap.
  - The energy resolution of HE-ETCC is worse than that of current type ETCC.
    HE-ETCC 20% <-> current type 15% @ 0.5 MeV, FWHM

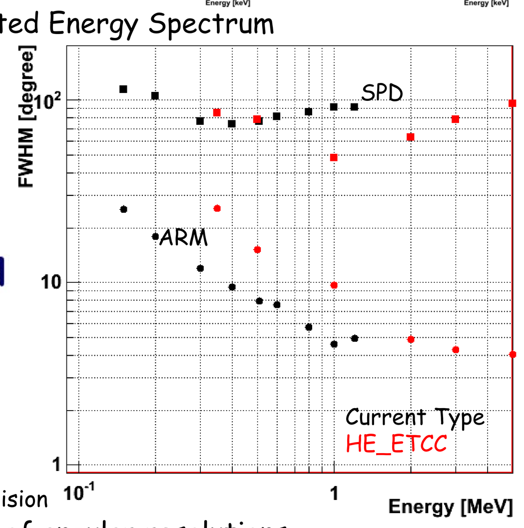


Reconstructed Energy Spectrum

- Angular resolution
  - ARM : HE-ETCC 15.1° <-> current type 8.0° @ 0.5 MeV
    ARM of HE-ETCC is worse than that of current type, because ARM depends on the energy resolution of the scattered gamma rays and HE-ETCC selects the lower energy scattered gamma ray events.
  - SPD : HE-ETCC 78° <-> current type 75° @ 0.5 MeV
    HE-ETCC 48° <-> current type 92° @ 1.0 MeV

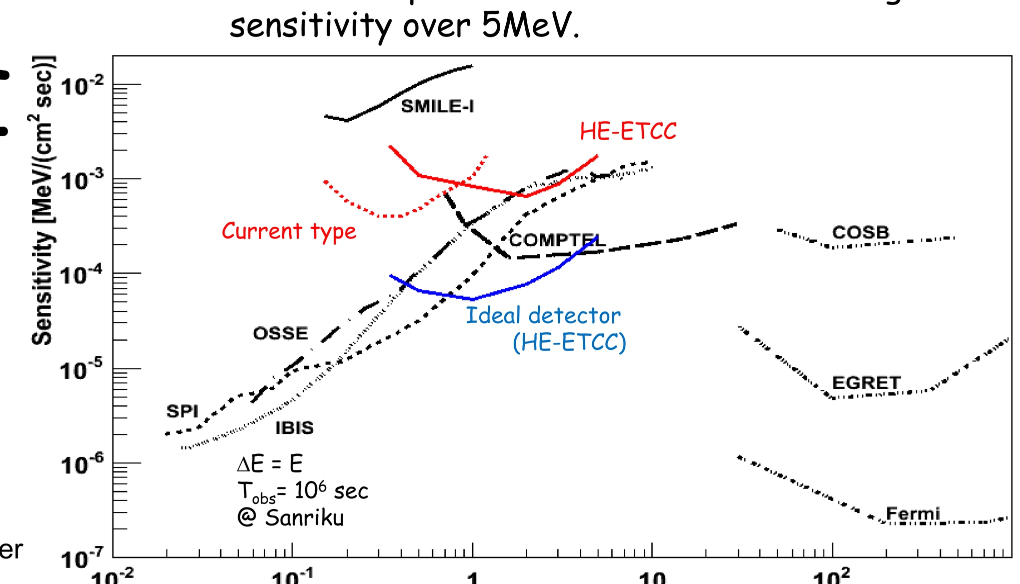


ARM : Angular Resolution Measure, accuracy of scattering angle
SPD : Scatter Plane Deviation, accuracy of scatter plane decision

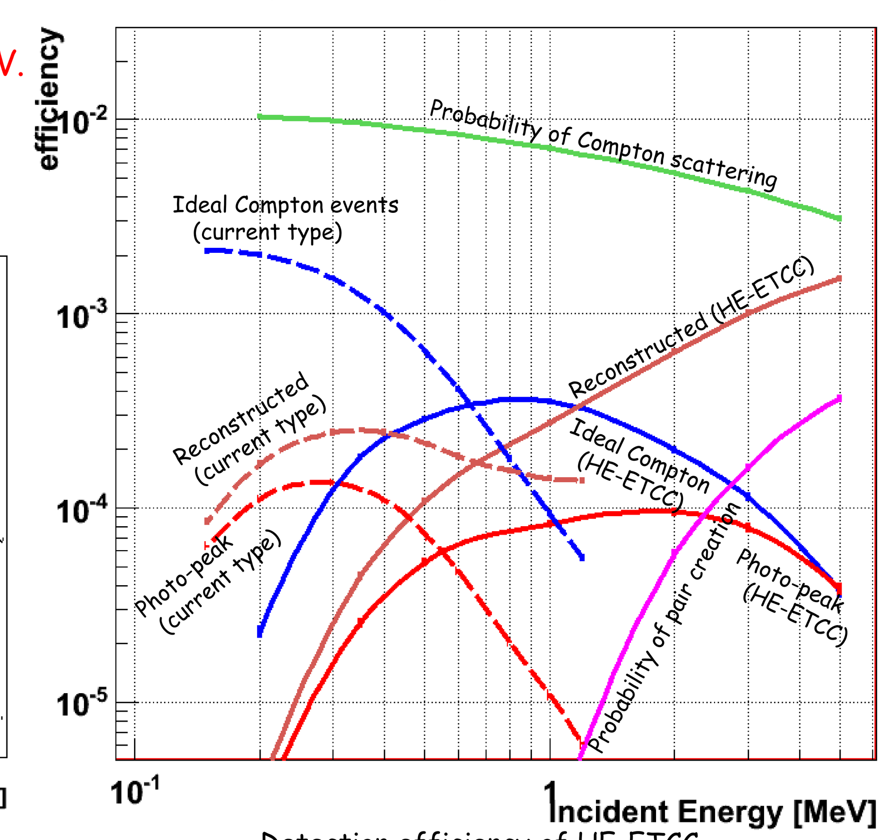


Comparison of angular resolutions

- Detection efficiency & Sensitivity
  - HE-ETCC : 5.2 x 10^{-5} @ 0.5 MeV, Photo-peak
    8.3 x 10^{-5} @ 1.0 MeV, Photo-peak
  - current type : 7.0 x 10^{-5} @ 0.5 MeV, Photo-peak
    1.1 x 10^{-5} @ 1.0 MeV, Photo-peak
  - The energy range of HE-ETCC is shifted to 0.35 – 5 MeV.
  - Over 2.5MeV, the pair creation events increase.
    -> We must improve HE-ETCC so that HE-ETCC can detect pair creation events for the higher sensitivity over 5MeV.



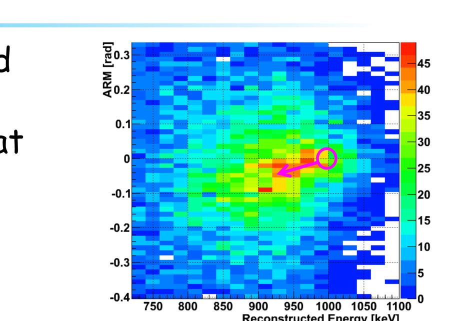
Detection sensitivity of HE-ETCC (only photo-peak)



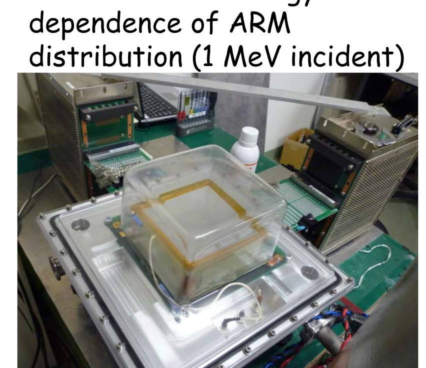
Detection efficiency of HE-ETCC

6. Summary

- By using the plastic scintillator as an electron absorber, the energy range is shifted to higher energy of 0.35 - 5 MeV.
- SPD, which depends on the multiple scattering of recoil electron, is better than that of the current type, because HE-ETCC detects the events of the higher energy recoil electron.
  -> It is expected that the tail of point spread function is shorter than that of current type or conventional Compton telescope.
- ARM and energy resolution are worse than those of the current type at the same energy, because HE-ETCC can not trigger low energy electron below 100 keV and selects the scattered gamma rays having lower energy.
  -> There is a relation between the reconstructed energy and ARM distribution, thus the improvements in the analysis, as like an estimation of energy loss at the gap, are needed for the higher energy resolution and better ARM.
- For the detection over 5MeV, it is necessary to reconstruct the pair creation events.
  -> For the detection of the electrons over 5MeV, we consider using GSO scintillators as both high energy electron stoppers and scattered gamma ray absorbers. Therefore, a low mass TPC vessel is needed. We already made a polyethylene terephthalate (PET) vessel with the thickness of 2mm, and test is on-going.



Reconstructed energy dependence of ARM distribution (1 MeV incident)


TPC vessel made with PET