SMILE : Sub-MeV/MeV Gamma-ray Survey using Electron-Tracking Compton Camera loaded on Balloon

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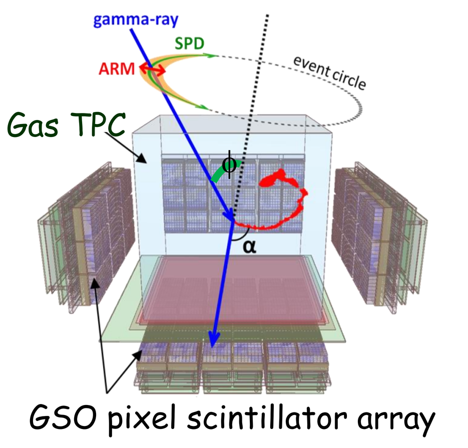
1. To Open MeV-gamma ray Window

MeV gamma rays from hundreds keV to tens MeV provide us the information of nucleosynthesis in supernovae, particle acceleration in jets of active galactic nuclei or gamma-ray bursts, and strong gravitational potential around black hole candidates. Especially, line gamma rays from fresh radioisotopes are unique probe for direct search of nucleus factories. ^{56}Ni produced in type Ia supernovae, which are famous standard candles in universe, determines the explosion mechanism. Long-lived isotopes such as ^{26}Al or ^{60}Fe have the information of old star production or material transmission in our galaxy. In addition, the universe in MeV region is quite transparent, we can thus see the first star as a long gamma-ray burst. However, the observation in this region is not explored due to the difficulty of clear images. To open the MeV gamma-ray window, we need a new telescope having a good point spread function (PSF), a large effective area, and a wide field of view.

➡ Aim to the detection sensitivity of 1 mCrab

2. To Realize 1 mCrab sensitivity

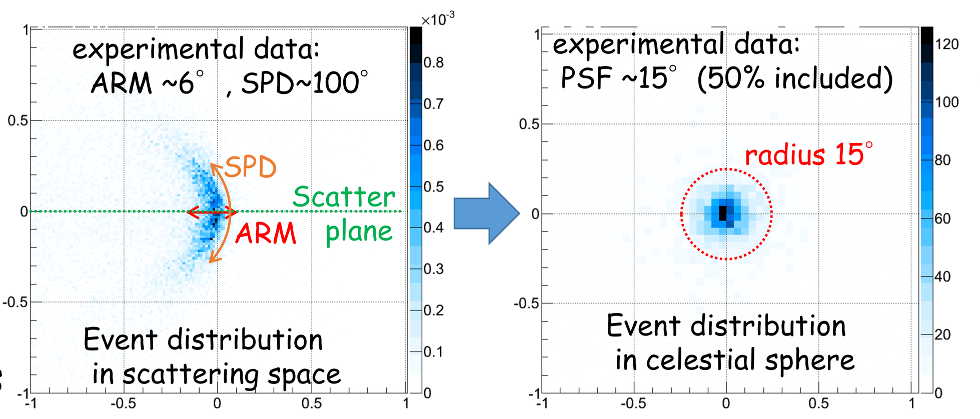


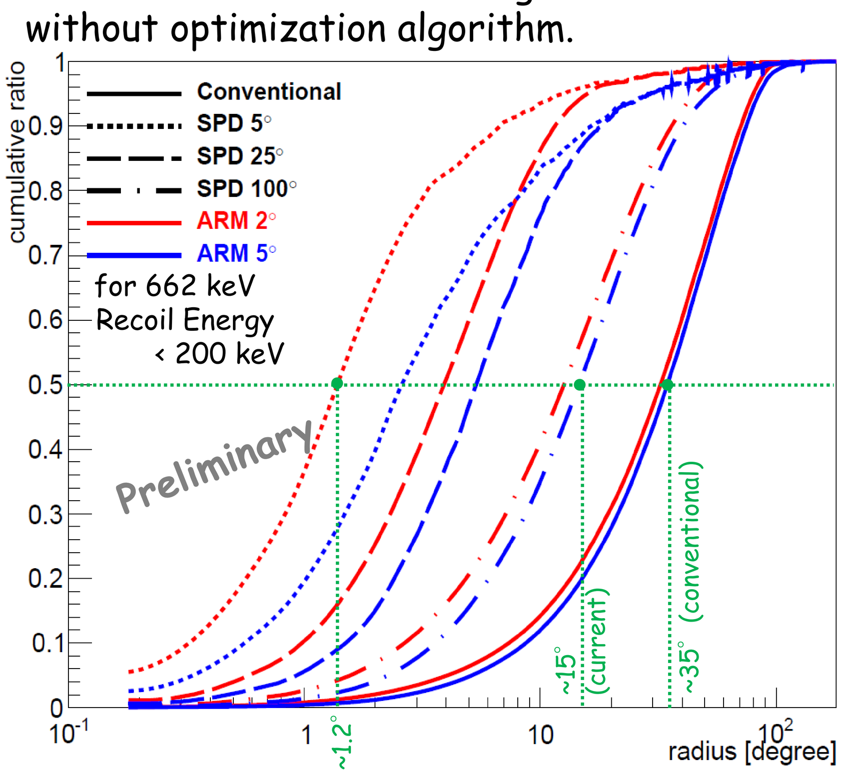
◆ ETCC using a gaseous time projection chamber

Our ETCC 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 energy of the scattered gamma ray. Although ETCC detects gamma rays using Compton scattering similar to COMPTEL, new information of electron tracking (two directional angles and energy loss rate: dE/dx) provides us clear images with a sharp and well-defined PSF and strong background rejection compared to the conventional MeV gamma-ray detectors.

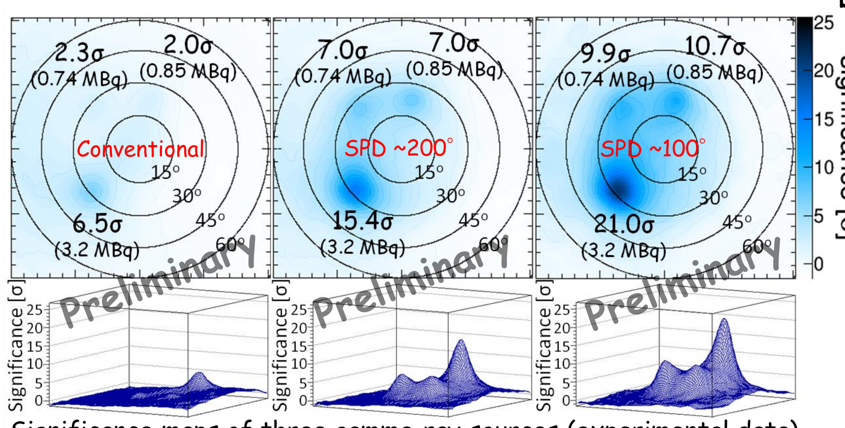
◆ Well-defined point spread function

The angular resolution of usual telescopes are described with a point spread function (PSF). Until now, the angular resolutions of Compton cameras including ETCCs are evaluated by angular resolution measure (ARM) and scatter plane deviation (SPD), each parameter however does not represent a PSF. In this time, we tried to evaluate a PSF of ETCC with assuming ARM/SPD resolutions without optimization algorithm.

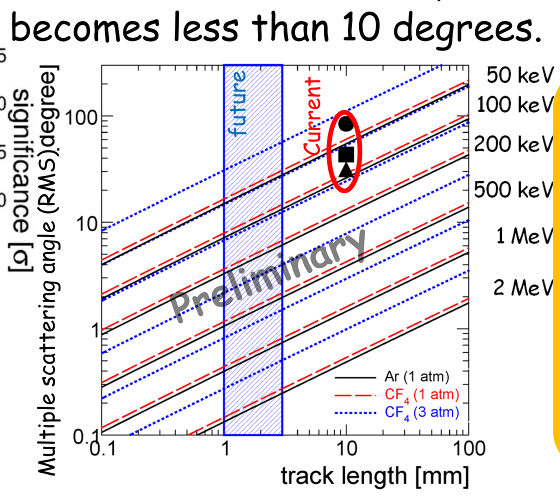




The left figure shows the cumulative ratio with different ARM/SPD resolutions as a function of radius angle. In the case of overlaying the event circles (conventional method), because the PSF is quite wide (35° for 50% included), a conventional Compton camera needs the use of an optimization algorithm as like maximum likelihood-expectation maximization (ML-EM) to survey sources. On the other hand, ETCC has a sharp PSF, even if not using ML-EM. Therefore the sensitivity of ETCC should be determined simply from the effective area and the PSF of the instrument. The PSF strongly depends on the SPD resolution. The better SPD resolution caused a sharper PSF and lower background, as shown in the left bottom images. SPD resolution is limited by multiple scattering of recoil electron in gas. If we can decide the recoil direction within few mm, SPD resolution of our ETCC becomes less than 10 degrees.



Significance maps of three gamma-ray sources (experimental data)



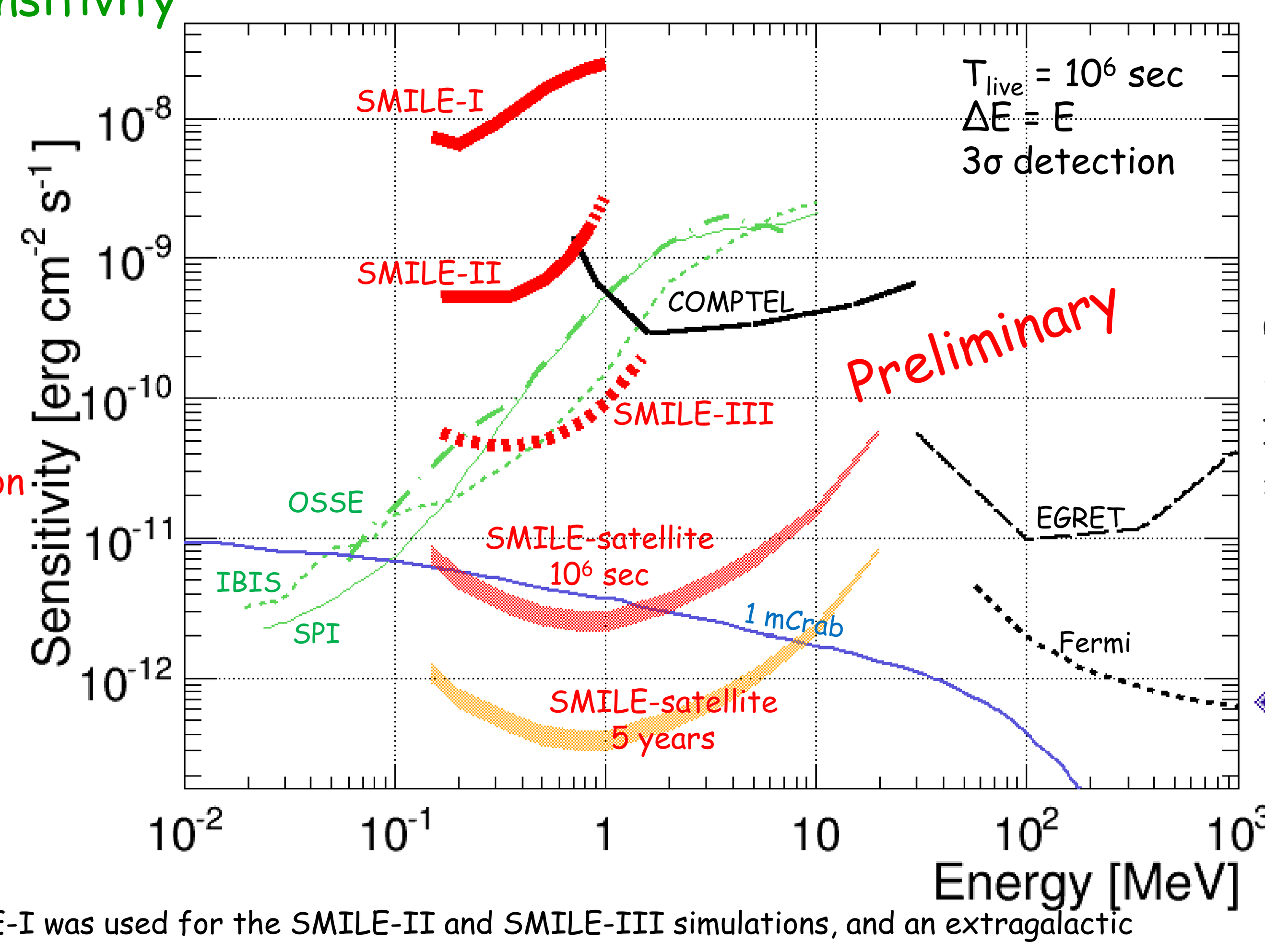
1 mCrab sensitivity
-> ~1 degree PSF is needed
ARM: < a few degrees
SPD: < 10 degrees
ETCC is an unique answer as a pioneer in MeV astronomy.

◆ Expected detection sensitivity

SMILE-II (current ETCC) :
30 cm-cubic TPC (Ar 1 atm)
GSO (1 Radiation length)
➡ detectable Crab nebula with 3 h at 40 km (2016~)

SMILE-III :
40 cm-cubic TPC (CF_4 3 atm)
GSO (3 Rad. length)
➡ detectable polarization of Crab nebula with balloon (2018~)

SMILE-Satellite :
50 cm-cubic TPC (CF_4 3 atm)
$LaBr_3$ (10 Rad. length) × 4
➡ reach to 1 mCrab ×100 higher sensitivity than COMPTEL

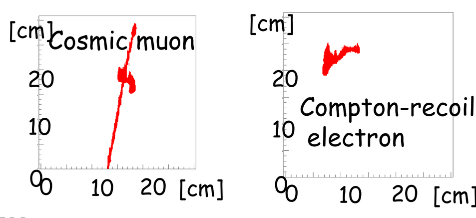


The background observed in SMILE-I was used for the SMILE-II and SMILE-III simulations, and an extragalactic diffuse gamma flux in 0.1-5 MeV reported by SMM and COMPTEL were included for the Satellite-ETCC. Also the point spread function was assumed with a half of ARM resolution (the expected SPD resolution is 5-10 degrees). A duty factor of 1/3 in the operation of the Satellite-ETCC was assumed.

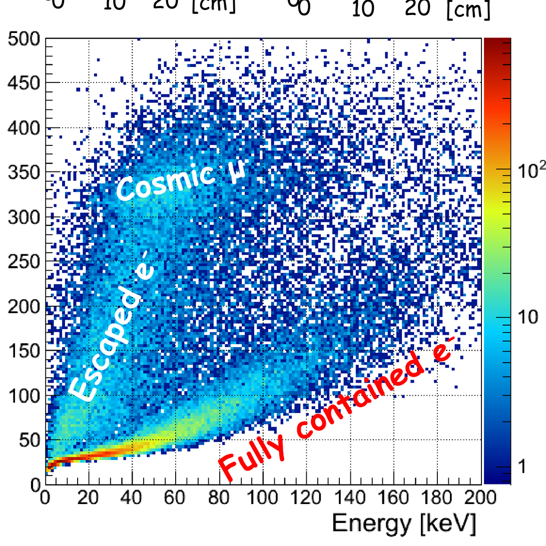
◆ Background suppression

The angle α between the scattering direction and the recoil direction can be obtained by two independent methods as follows;

$$\cos\alpha_{\rm geo} = \vec{g}\cdot\vec{e} \qquad \cos\alpha_{\rm kin} = \left(1-\frac{m_e c^2}{E_\gamma}\right)\sqrt{\frac{K_e}{K_e+2m_e c^2}}$$



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.
In addition, because the energy-loss rate (dE/dx) depends on the mass, charge, kinetic energy of charged particles, we can identify the particle kind using dE/dx. A Compton scattering create only one electron. Utilizing this dE/dx event selection, an ETCC can reject neutrons-recoil events and charged particles. The right figure shows the dE/dx distribution obtained by our ETCC. The events of fully-contained electron is clearly separated from other components.



3. Performance of Current ETCC

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

For the future observations with loading on a satellite, we have a plan of balloon experiments. As the first step, we launched a small ETCC using a 10 cm cube TPC in 2006 (SMILE-I). By the background rejection power of ETCC, it was successful to observe diffuse cosmic and atmospheric gamma rays. The next SMILE (SMILE-II) is an observation of the Crab nebula using a middle size ETCC.

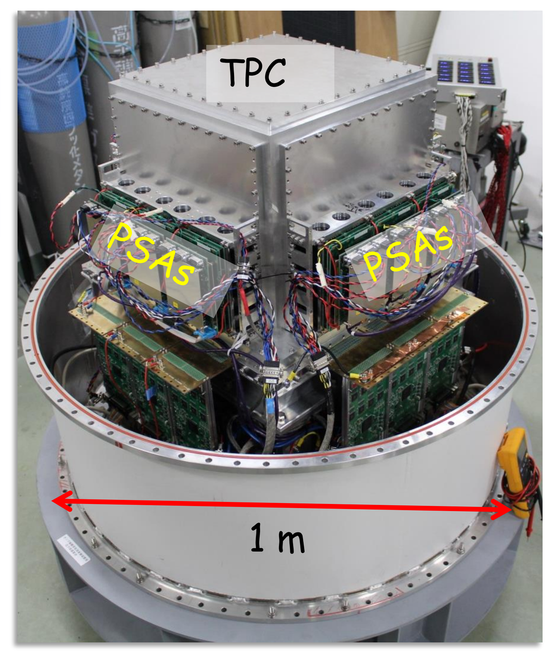
Requirements for SMILE-II
- Effective area : > 0.5 cm² (< 300 keV)
- Angular resolution : < 10° (662 keV)

Gaseous TPC

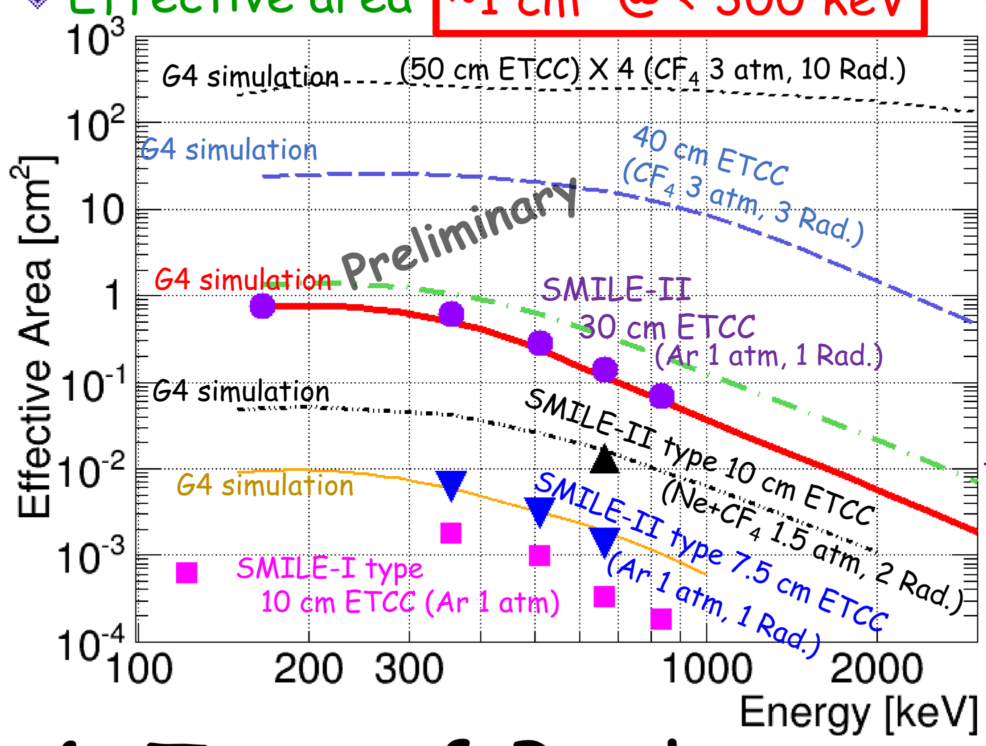
Effective volume	30 x 30 x 30 cm³
Gas	Ar:iso-C_4H_{10}:CF_4 (95:2:3), 1 atm.
Spatial resolution	~0.5 mm
Energy resolution (FWHM)	22 % (@ 22 keV)

Pixel scintillator arrays

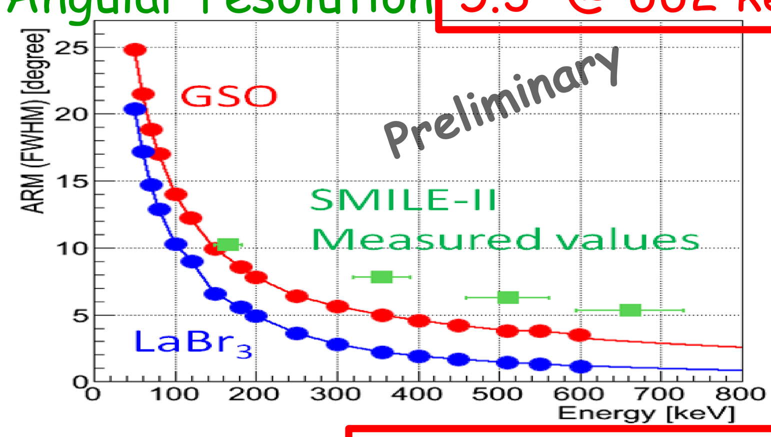
Scintillator	GSO:Ce (6.71 g/cm³)
Pixel size	6 x 6 x 13 mm³
# of pixels	6912
Dynamic range	80 keV—1.3 MeV
Energy resolution (FWHM)	10 % (@ 662 keV)



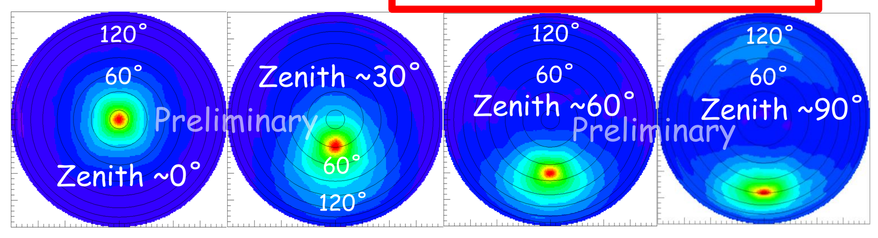
◆ Effective area ~1 cm² @ < 300 keV



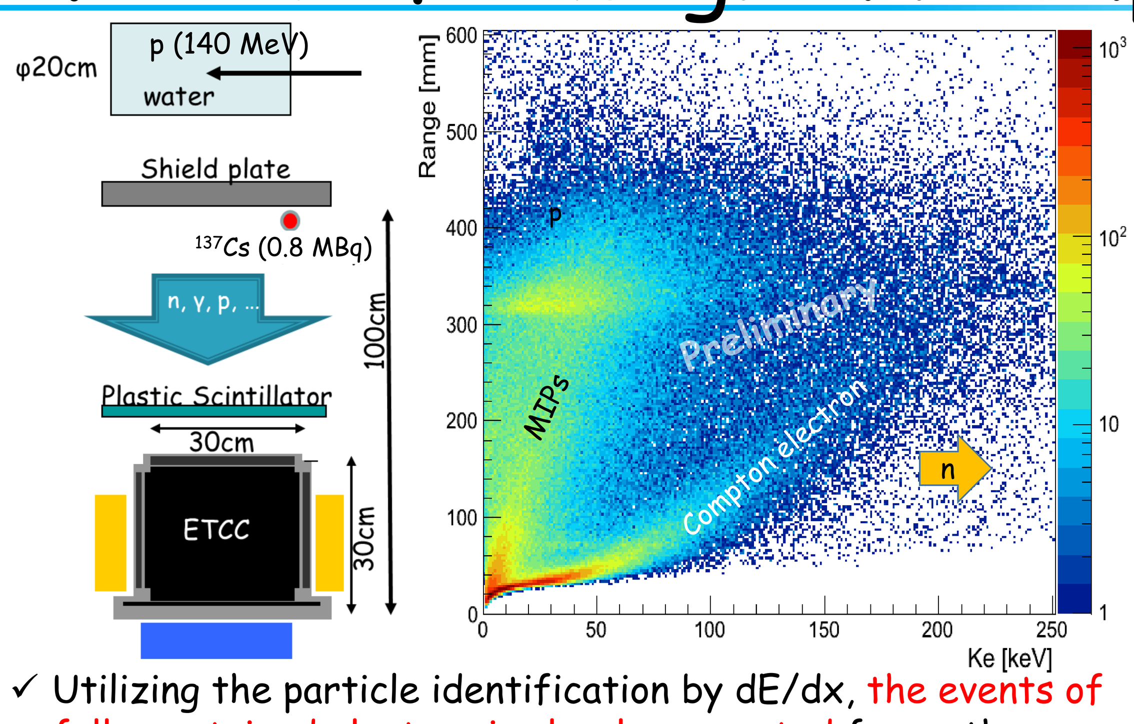
◆ Angular resolution 5.3° @ 662 keV

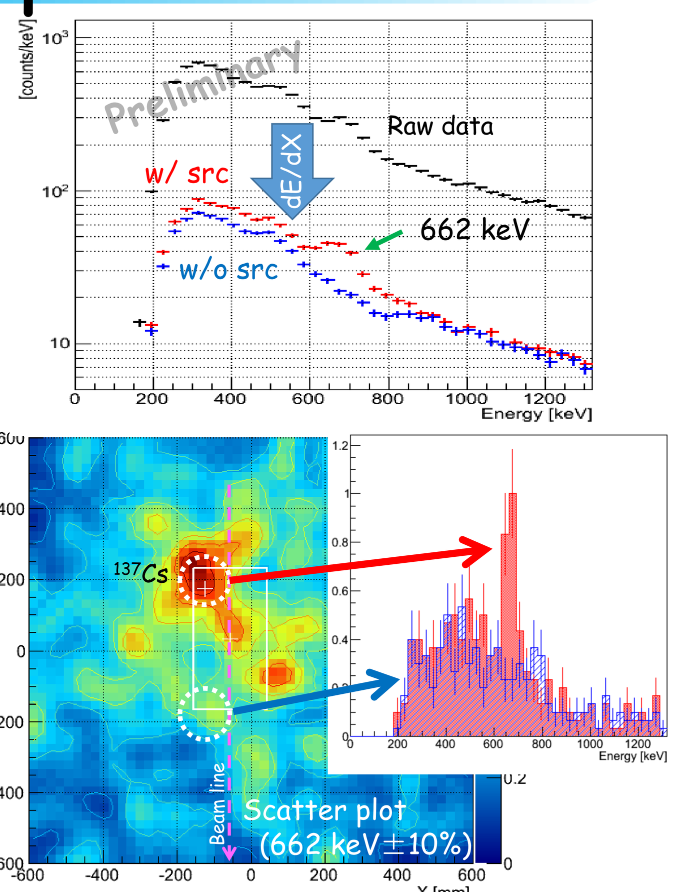


◆ Field of View ~6 sr @ 662 keV



4. Test of Background Suppression



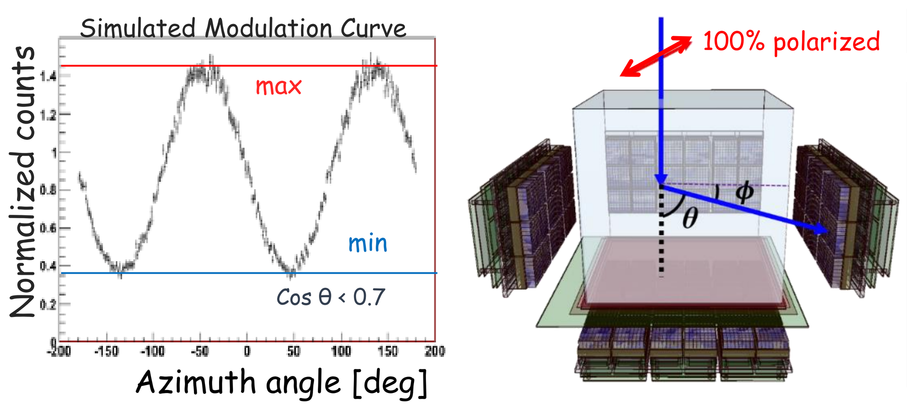


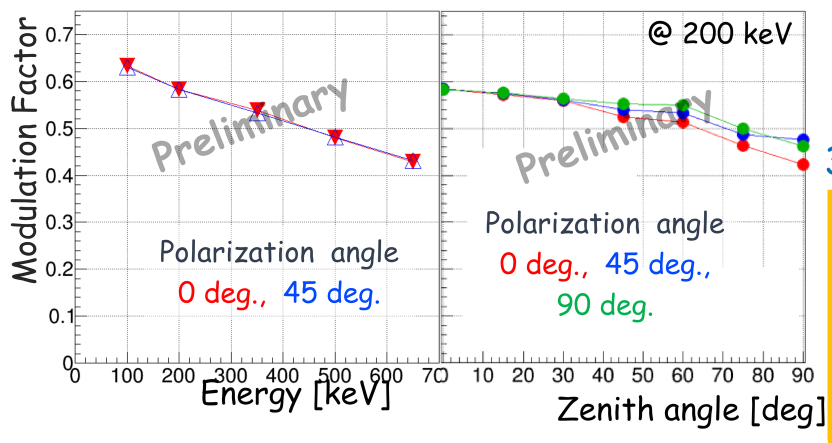
- ✓ Utilizing the particle identification by dE/dx, the events of fully-contained electron is clearly separated from other components.
- ✓ By the efficient background rejection of our ETCC, we can obtain the background-suppressed energy-spectra and images.

5. Ability of Polarization Measurement

◆ Simulation study by Geant4

For astronomical polarimetry, the requirements for detectors are a large modulation factor, a large effective area, an efficient background rejection, and a clear imaging. Because the azimuthal angle distribution of Compton scattering has asymmetry for polarization of incident gamma ray, our ETCC has a sensitivity for gamma-ray polarization. Therefore, we studied the current ETCC (SMILE-II) using Geant4 simulation.



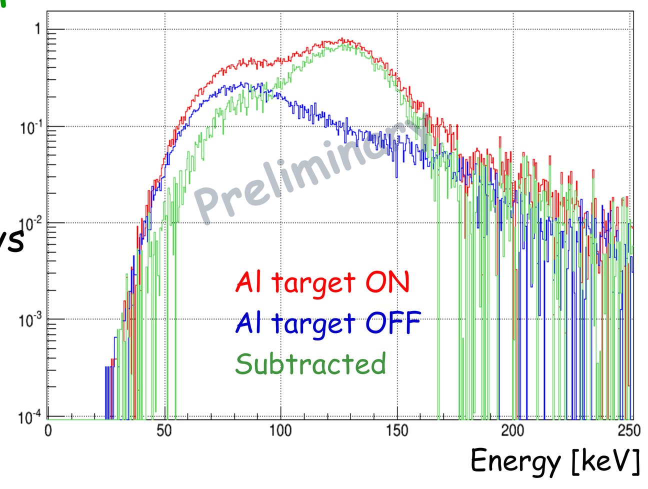


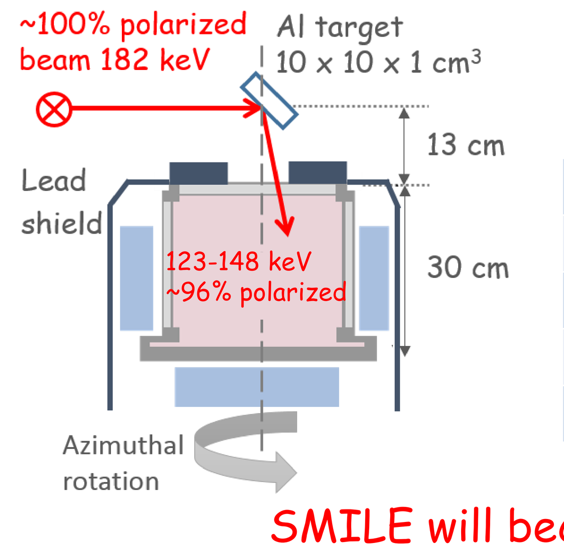
The low-energy gamma-ray polarimetry will be realized with balloon experiments, if our ETCC has a effective area of >10 cm².

3σ Minimum Detectable Polarization of SMILE-III
- ➢ mid-latitude, 40 km, 10 hours flights
  Crab : ~ 15%   Cyg X-1 : ~ 20%
- ➢ polar region, 40 km, 1 month flights
  GRBs : 10^{-6} erg/cm²/s (2-3 GRBs/month) ~ 6%
  10^{-7} erg/cm²/s (~10 GRBs/month) ~ 20%

◆ Experiment of polarization

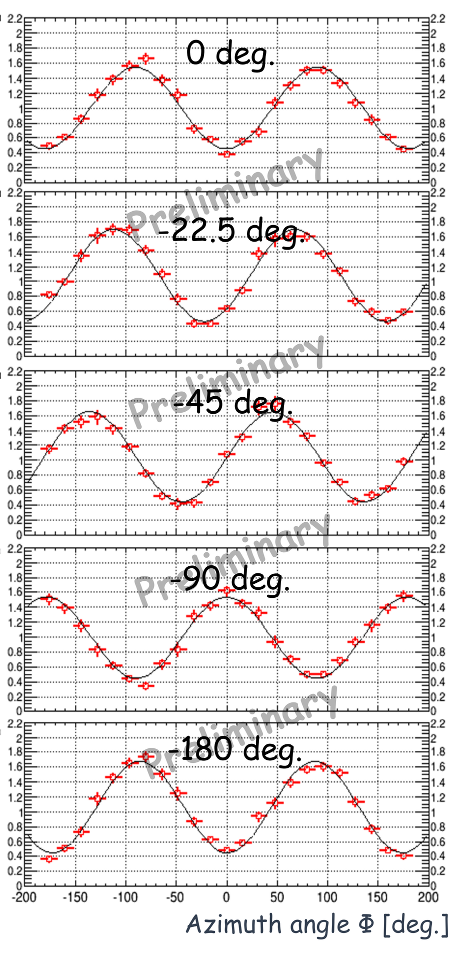
For confirmation of polarization measurement ability, we have a beam test using BL08W in SPring-8.
- ✓ ETCC clearly detected gamma-rays scattered in Al target.
- ✓ Obtained modulation factor was ~0.6 @ 130 keV, which was consistent to simulation results.





Fitting parameter

Azimuth angle [degree]	Modulation Factor	Polarized angle [degree]
0	0.57	0.3±1.3
-22.5	0.59	-22±1.0
-45	0.60	-44±0.7
-90	0.57	-90±1.1
-180	0.60	-2.3±1.1



SMILE will become a new pioneer of MeV astronomy.
Let's join the SMILE project !!
http://www-cr.scphys.kyoto-u.ac.jp/research/MeV-gamma/index_e.html