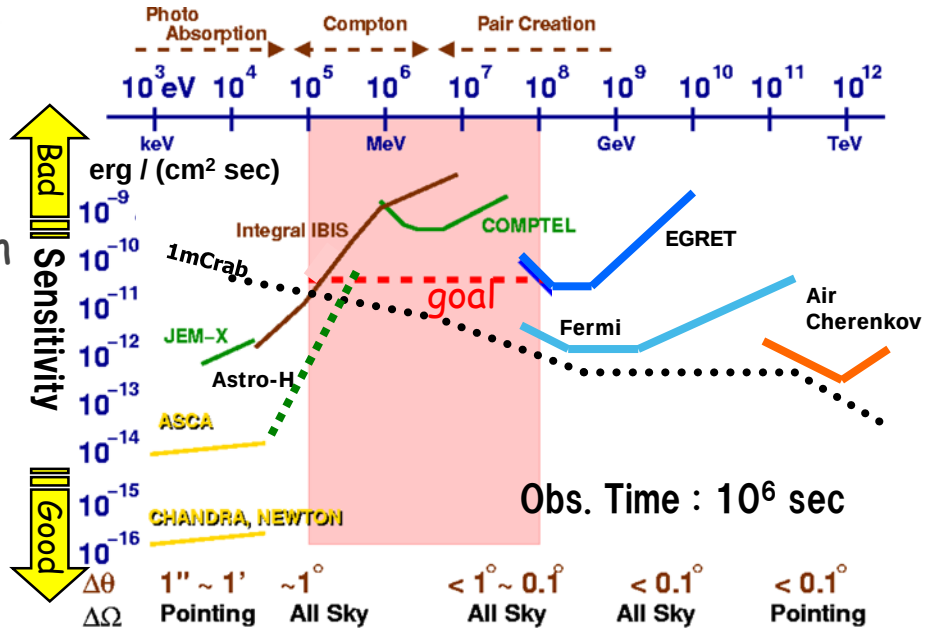
MeV Gamma Imaging by Fully Reconstructing Compton Scattering

A. Takada, T. Tanimori, H. Kubo, K. Miuchi, J. D. Parker, T. Mizumoto, Y. Mizumura, T. Sawano, Y. Matsuoka, S. Komura, S. Nakamura, M. Oda, S. Iwaki, K. Nakamura, S. Sonoda, D. Tomono (Kyoto Univ.)

1. Motivation & Detector concept
2. Performance
3. Applications
4. Summary

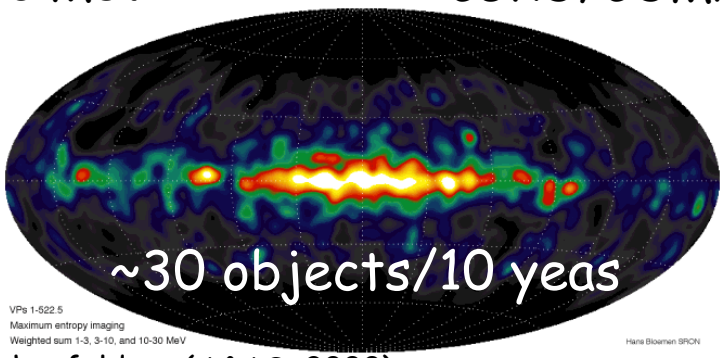
MeV Astronomy

- Nucleosynthesis
  - SNR : Radio-isotopes
  - Galactic plane : ^{26}Al • Annihilation
- Particle acceleration
  - Jet (AGN) : Synchrotron
    + Inverse Compton
- Strong gravitational potential
  - Black hole : accretion disk, π^0
- Etc.
  - Gamma-ray Pulsar, solar flare



MeV sky map

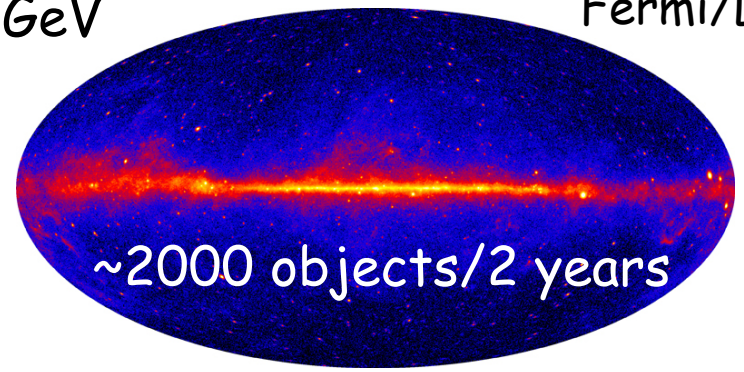
1-30 MeV CGRO/COMPTEL



V. Schönfelder+ (A&AS, 2000)

GeV sky map

> 1 GeV Fermi/LAT



P. L. Nolan+ (ApJS, 2012)

Requirements for
the next-generation detectors are …

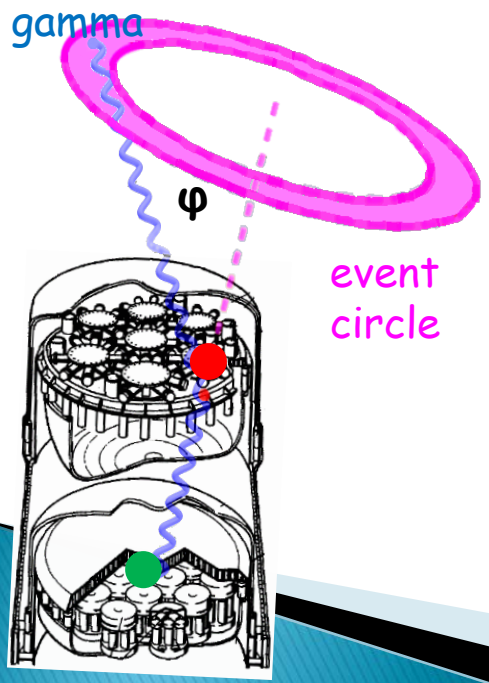
- Wide-band detection
- Large Field of View
- High quality image

Detection of MeV gamma ray

Dominant process in MeV region -> Compton scattering

- Elastic scattering between photon and electron.
- If detect momenta of scattered gamma ray and recoil electron
  -> We can obtain original direction and energy.

Compton Imaging



Consists of two detectors

1st : interaction point & energy of recoil electron

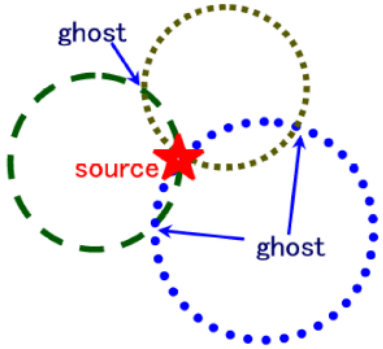
2nd : absorption point & energy of scattered gamma

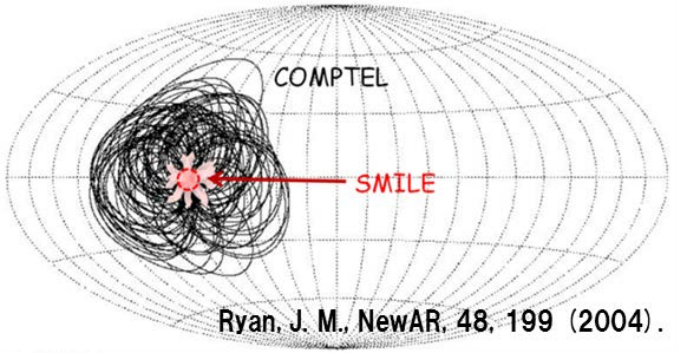
Not detect recoil direction

-> incomplete reconstruction

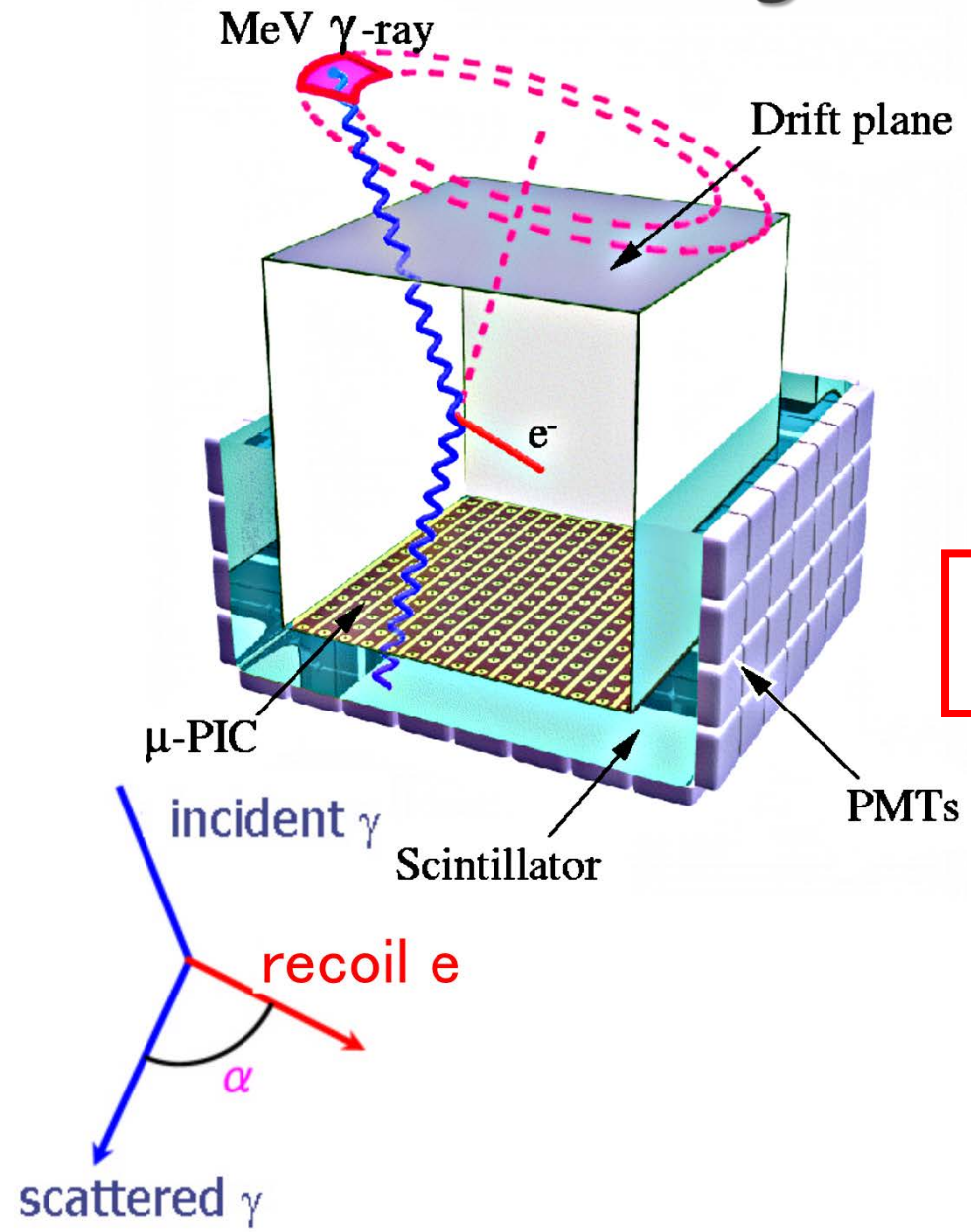
obtain source position by overlaying event circles

artifacts appear in image





Electron-Tracking Compton Camera (ETCC)



- Gaseous TPC : Tracker
  track and energy
  of recoil electron
- Scintillator : Absorber
  position and energy
  of scattered gamma ray

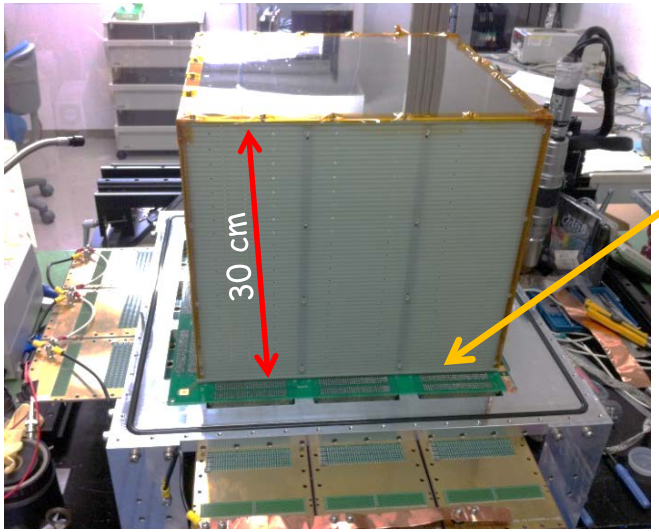
Reconstruct Compton scattering event by event

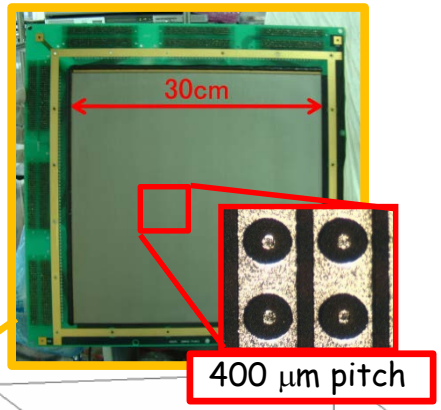
- 1 photon ⇒ direction + energy
- Large FOV (~3str)
- Compton Kinematical test with angle α
- Particle identify with dE/dx
- No VETO & shield around ETCC

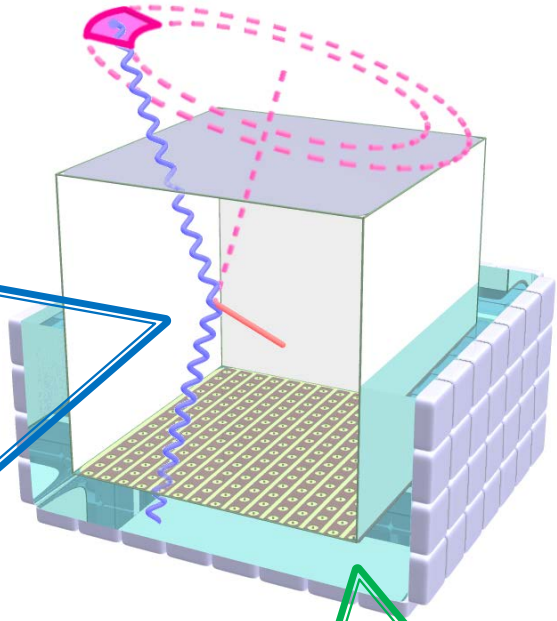
Detector contruction

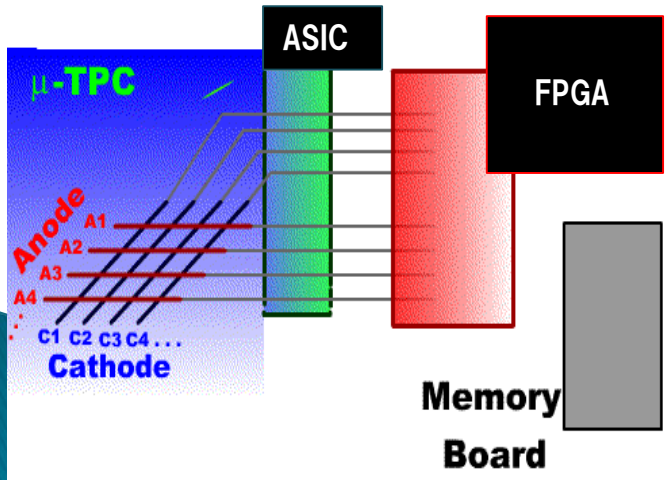
Electron Tracker

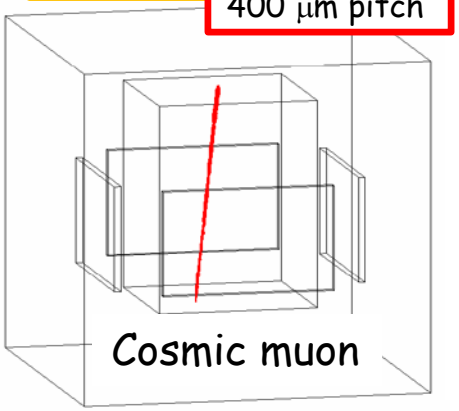
Gaseous Time Projection Chamber

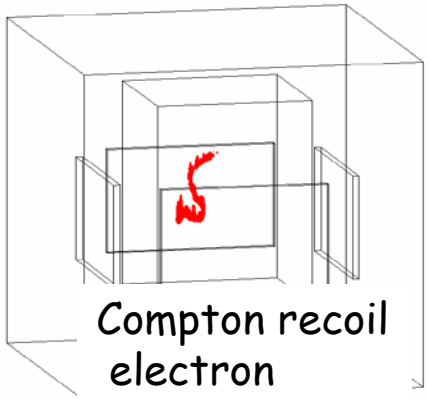




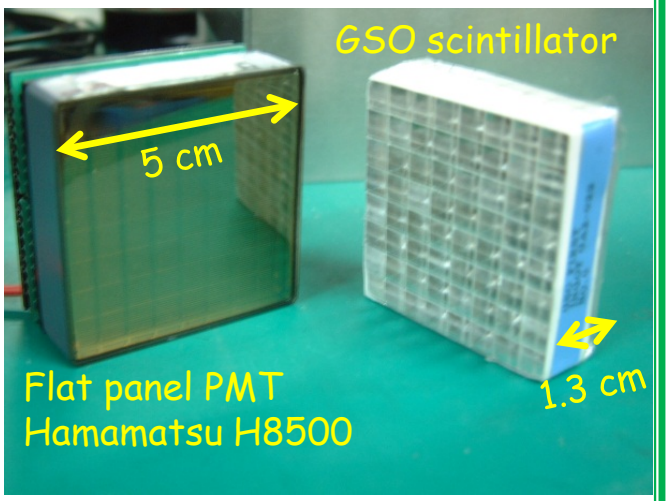








Absorber

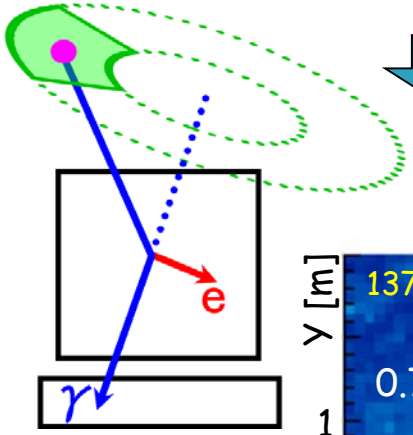


Comparison with the usual Compton method

Electron-Tracking Compton (ETCC)

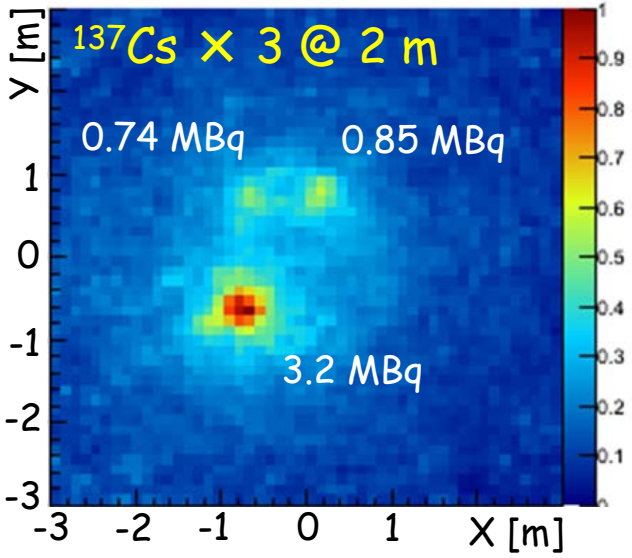
Using the electron tracks

complete direction within sector form error region



Simply overlay

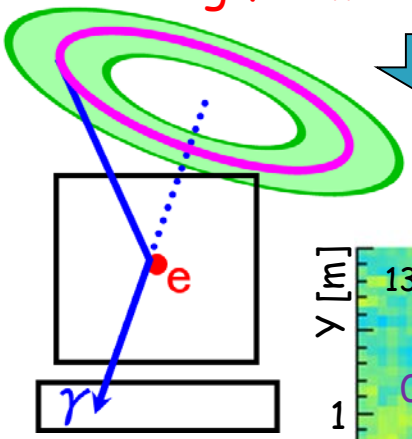
- High S/N
- No fakes



Usual Compton Imaging (COMPTEL)

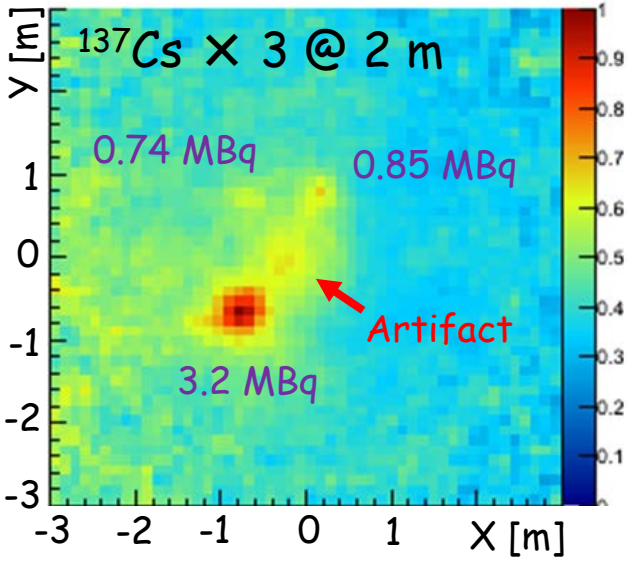
Not using the electron tracks

only event circle within ring form error region



Simply overlay

- Low S/N
- Artifacts appear



Electron tracks provide 4 times better S/N than usual Compton imaging !

A. Takada+, ApJ, 733(2011), 13

1st balloon experiment (SMILE-I)

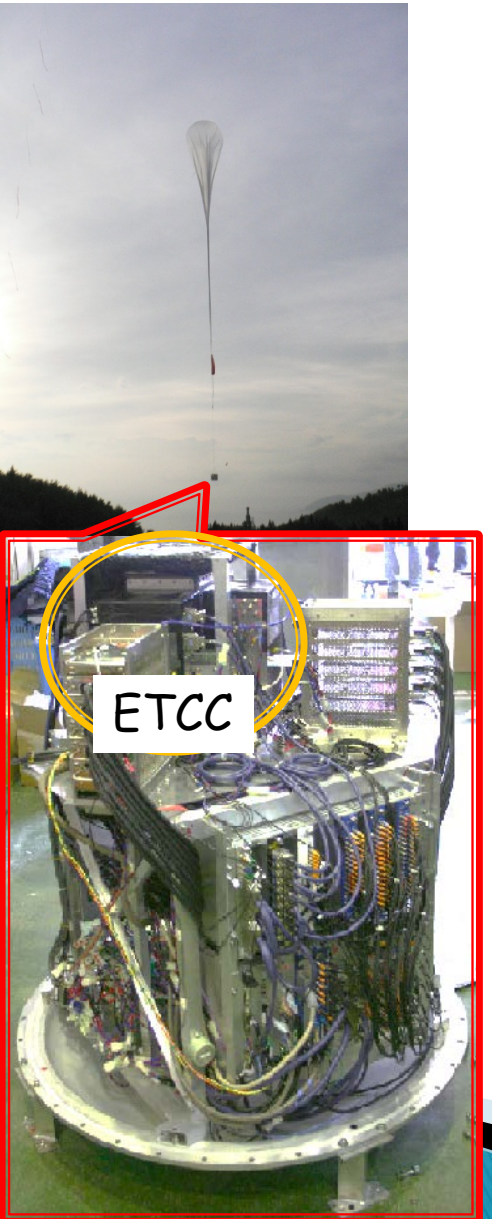
Sub-MeV gamma-ray imaging Loaded-on-balloon Experiment

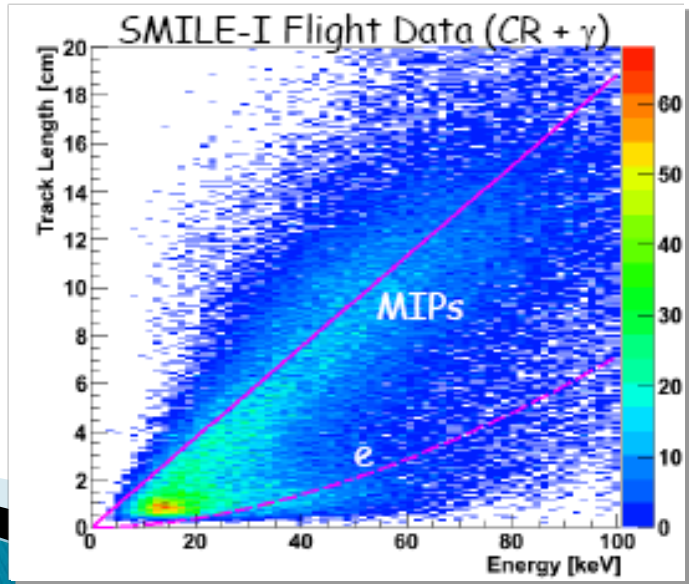
Launched on Sep. 1, 2006 @ Sanriku (ISAS/JAXA)

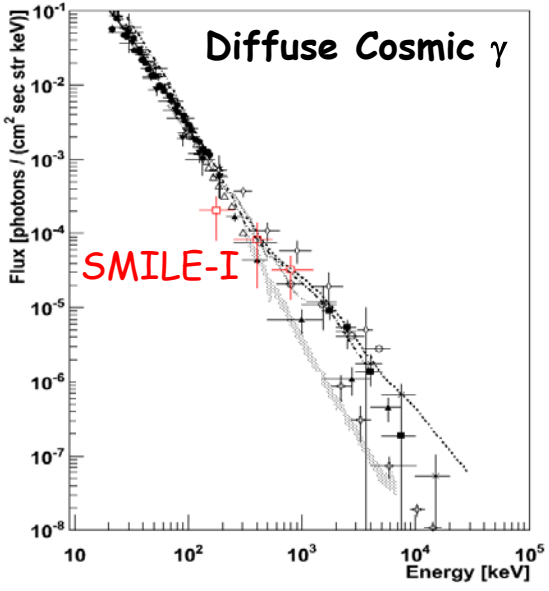
- Test flight using $(10\ \mathrm{cm})^3$ ETCC
- Measure diffuse cosmic and atmospheric gamma ray
  0.1 – 1 MeV, @ 35 km, 3 hours

Measured : 420 events
Simulation : ~400 events (cosmic + atmospheric)

Compton kinematic test and Particle identify provided low-background observation.







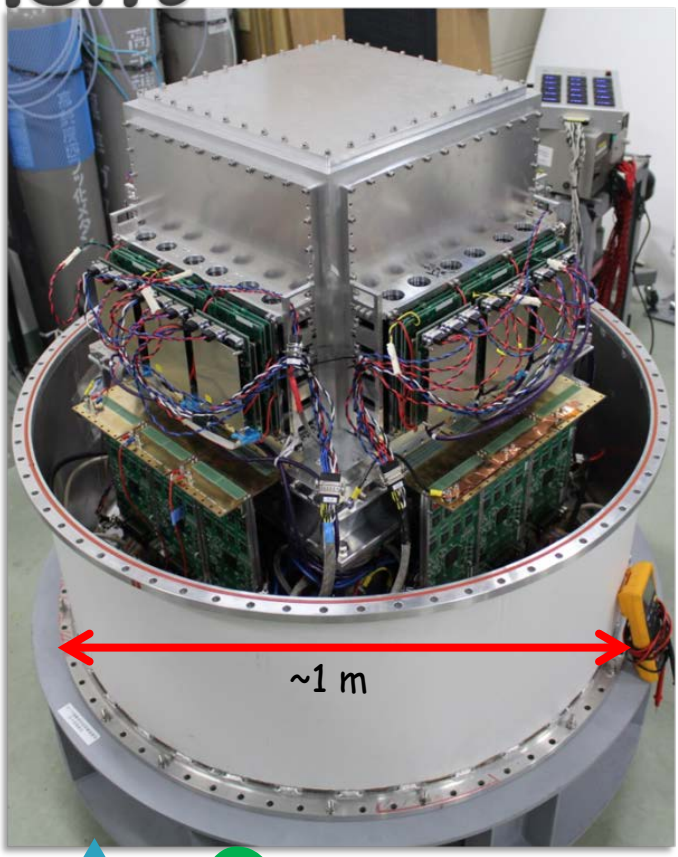
ETCC for 2nd experiment

Target: Crab nebula

5σ detection (40 km, several hours)

Requirements

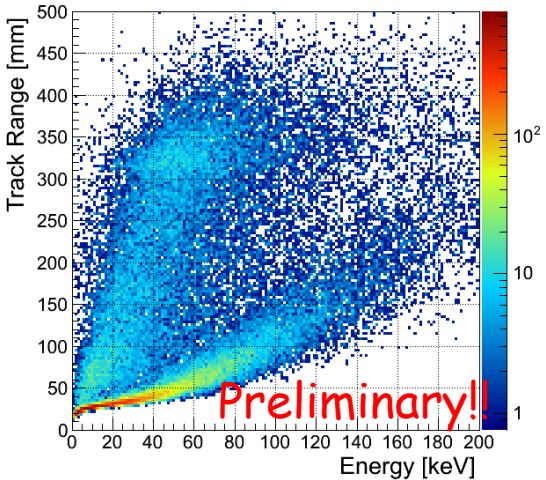
Effective area	:	> 0.5 cm² (300 keV)
Angular resolution	:	< 10° (600 keV)
Sensitivity	:	×100 SMILE-I

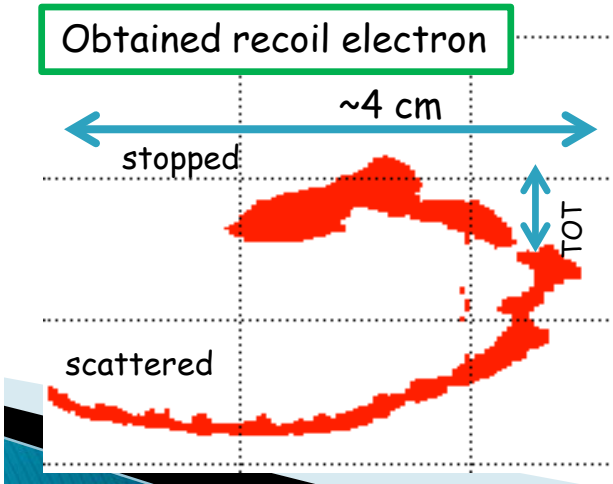


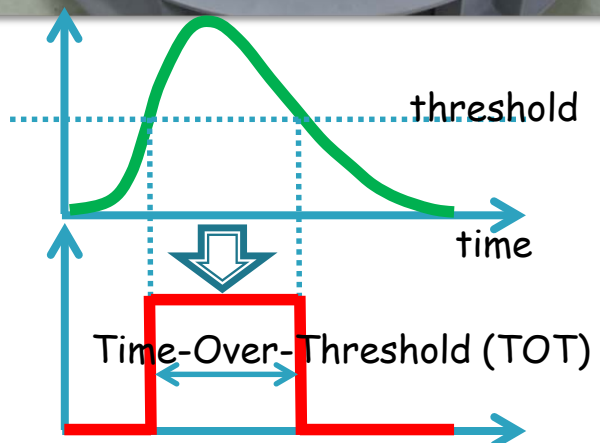
Improvements for SMILE-II

- 30 cm cube tracker ×√10
- Updating of data acquisition system ×√10
- Improvement of imaging ability ×10

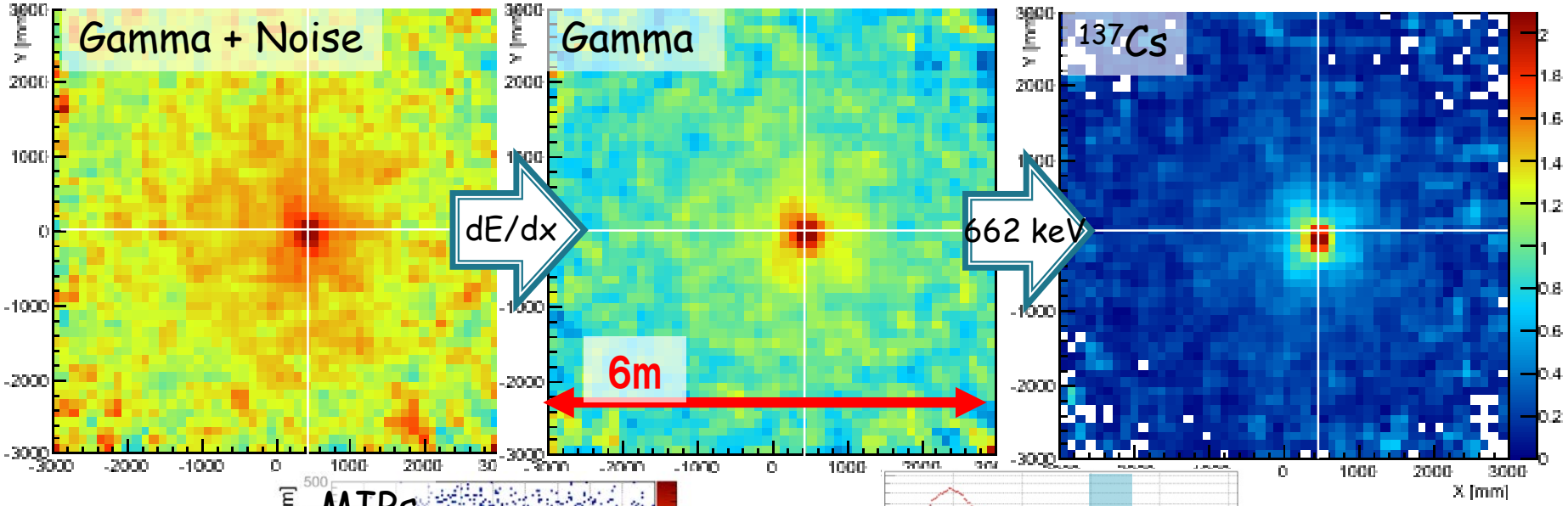
Sensitivity will reach to (×100 SMILE-I) !

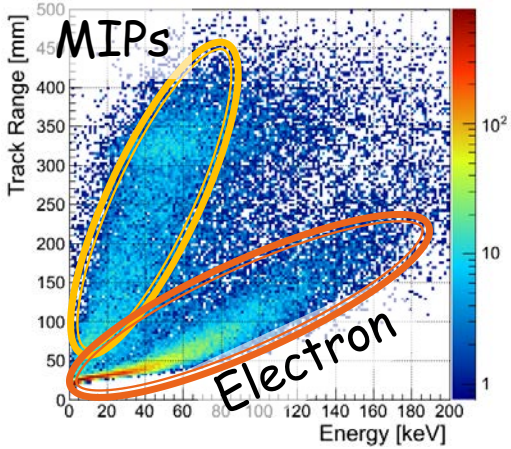


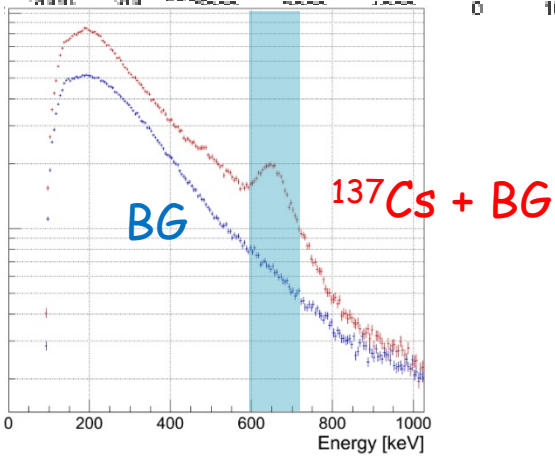




Event reconstruction

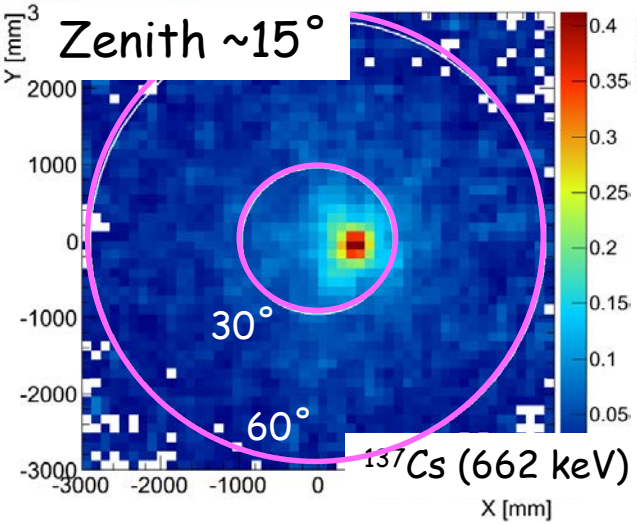


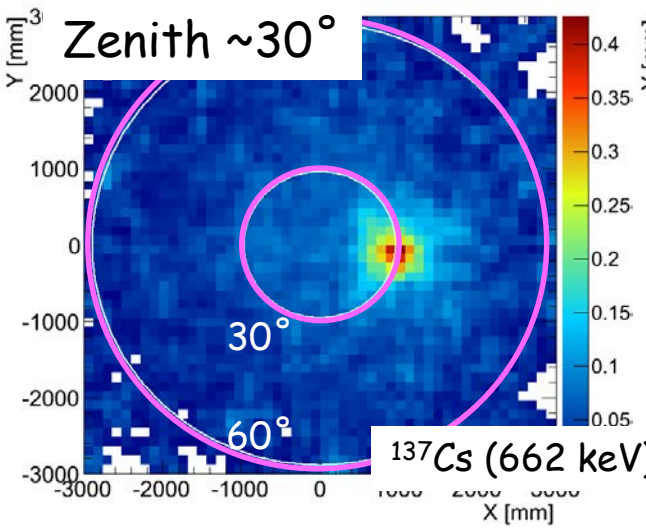


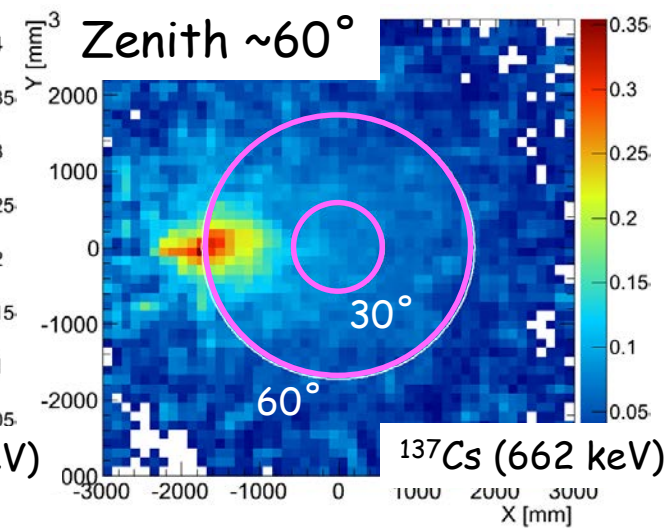


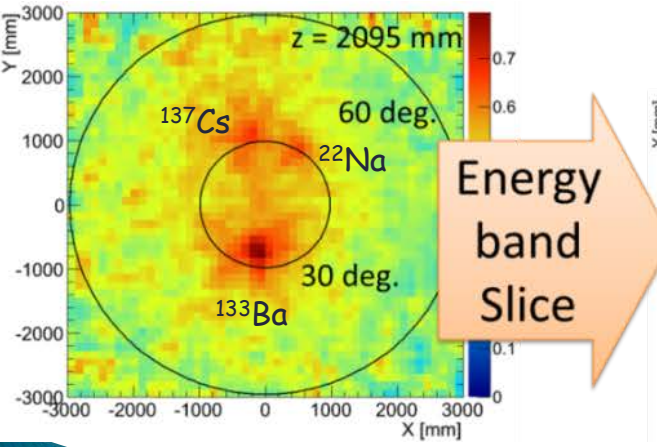
We can obtain a clear image with simple analysis.

Back projection images

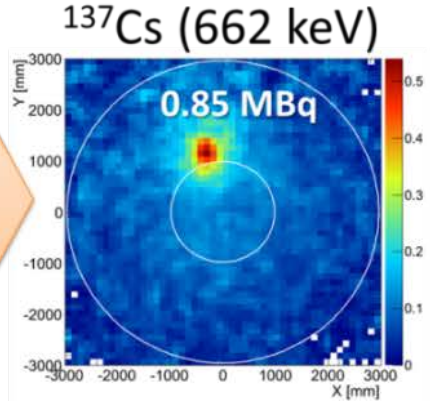


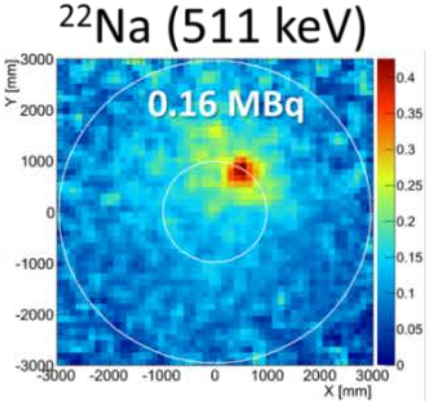


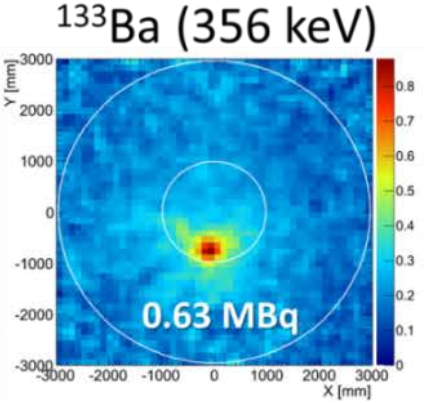




Energy band Slice

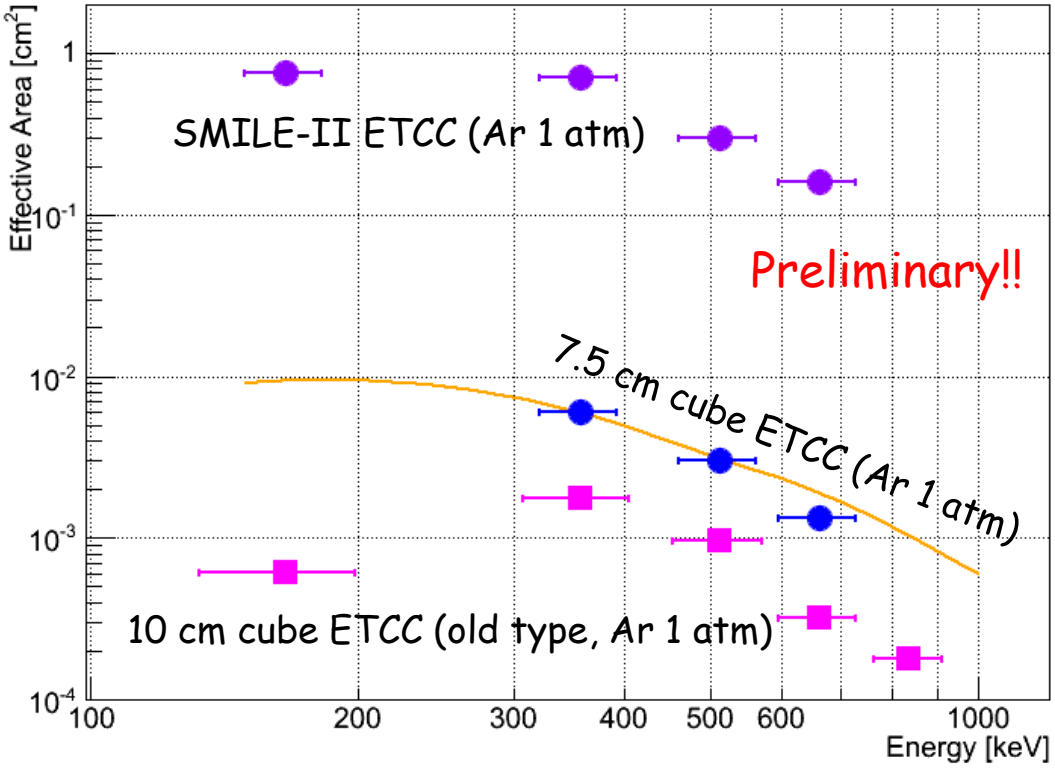






SMILE-II ETCC has a large field of view (~6 sr).
Energy range is 0.15 – 1 MeV.

Effective area



If we use CF_4 gas (3 atm) …

Effective area :

~10 cm² (< 300 keV

New Tracker

-> efficiency ×10

Large size tracker

-> effective area ×10

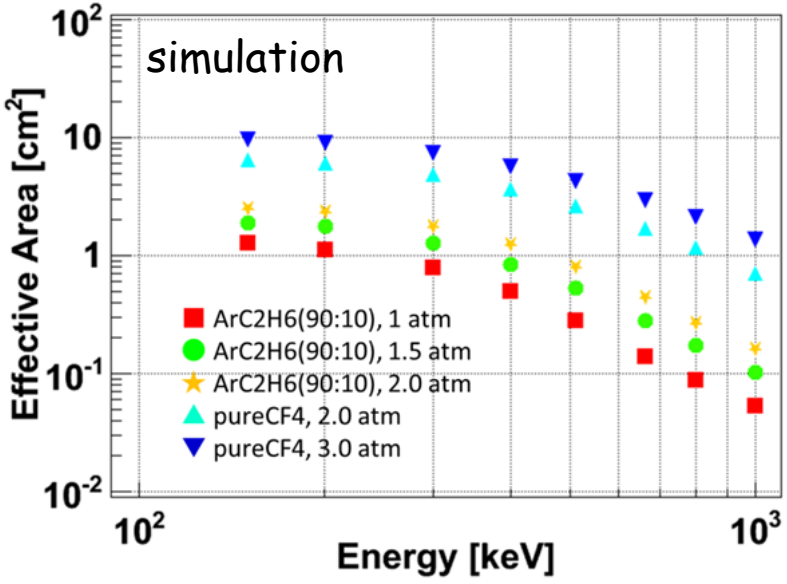
SMILE-II ETCC

~1 cm² (< 300 keV)

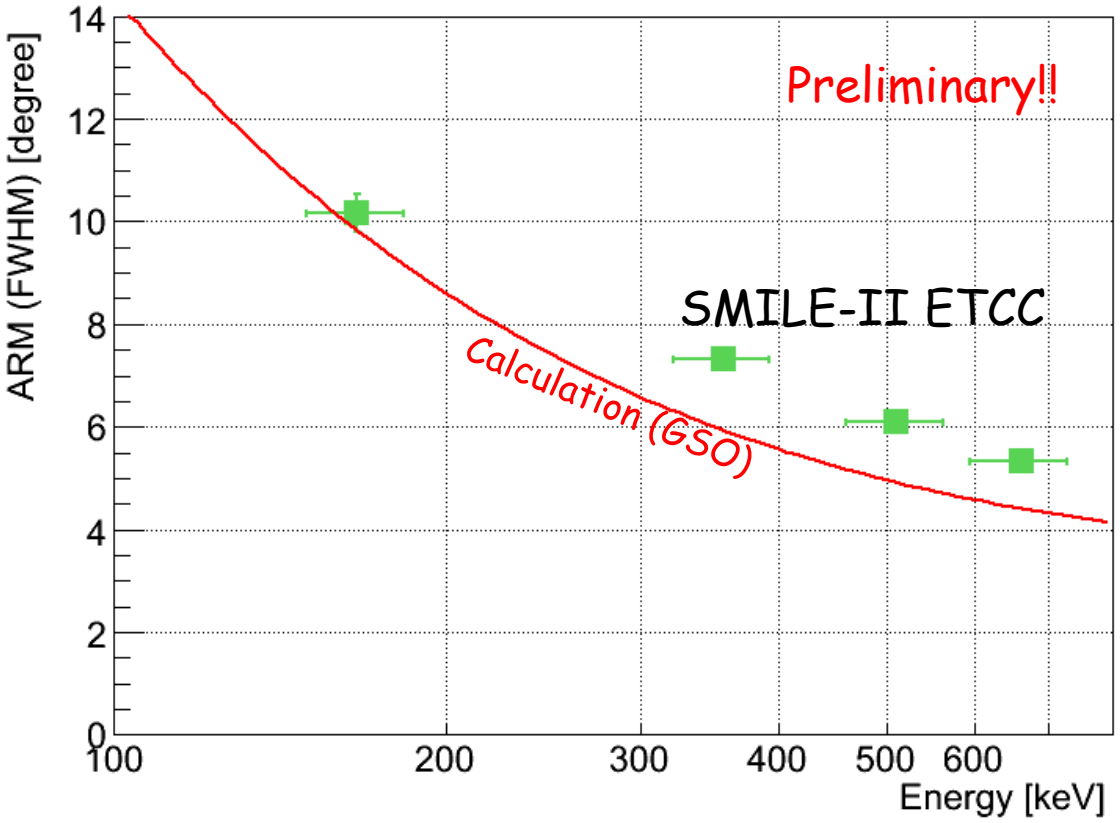
Requirement : > 0.5 cm² @ 300 keV

Experiment ≈ Simulation

ETCC obtains ~100% of Compton events



Angular resolution



New Tracker
-> higher special resolution
of Compton scattering point

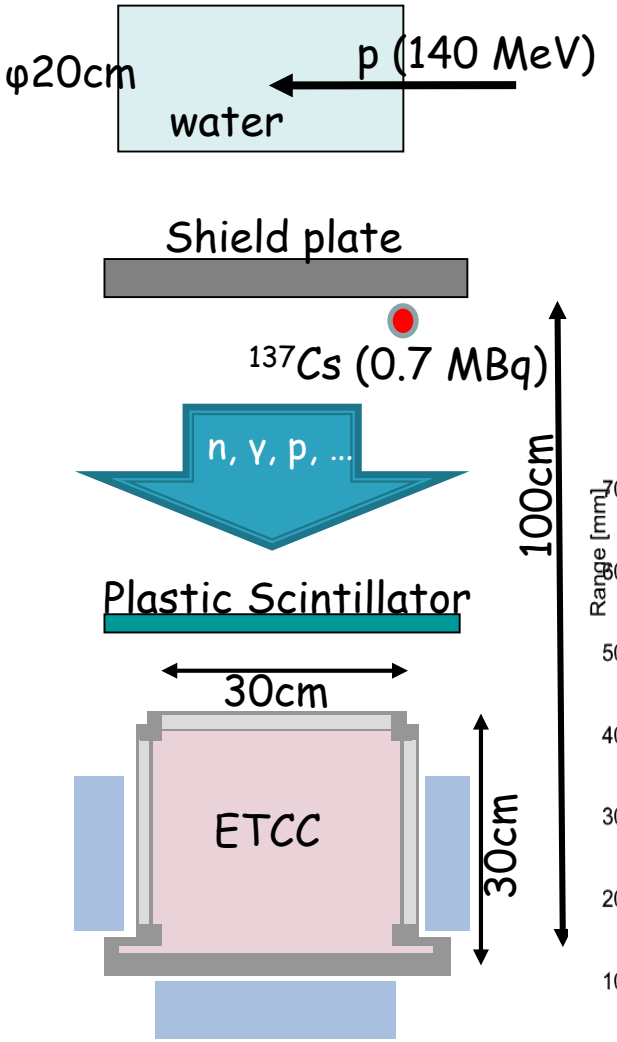
SMILE-II ETCC
5.3° (FWHM, 662 keV)

Requirement :
< 10° @ 662 keV

Obtained data ≈ expected data

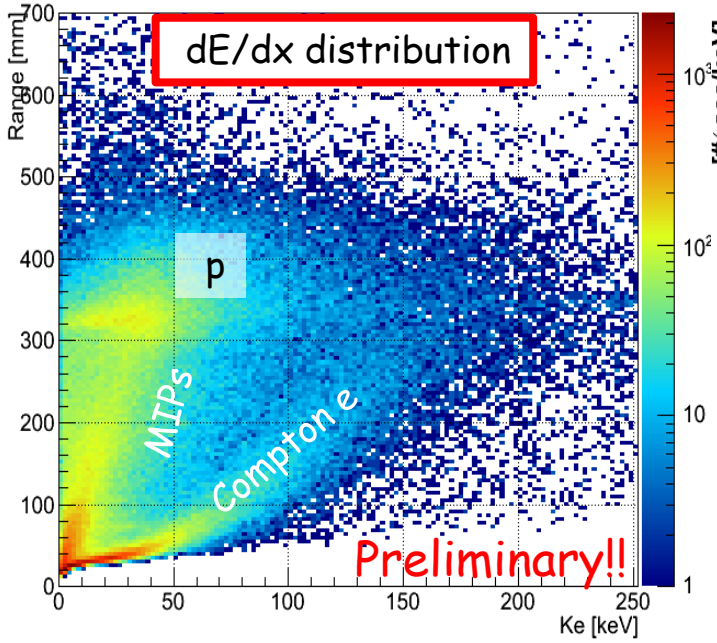
If we use $LaBr_3$ scintillator …
~3.5° (FWHM, 662 keV)

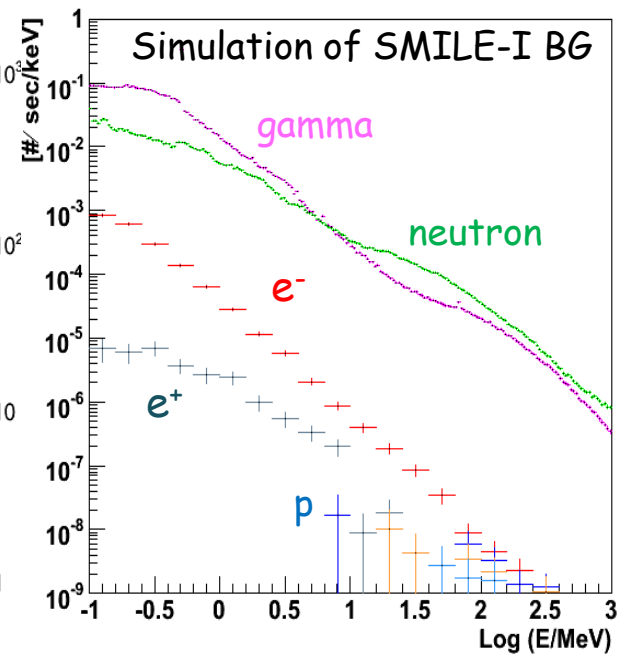
Experiment 1: Confirmation of background rejection power



Can our ETCC detect gamma-ray source in strong radiation field?

- Irradiation proton beam to water target
  -> produced gamma, neutrons, protons, …
- gamma : neutron = 3 : 1
  -> similar to background at balloon altitudes
- Observation ^{137}Cs under this situation

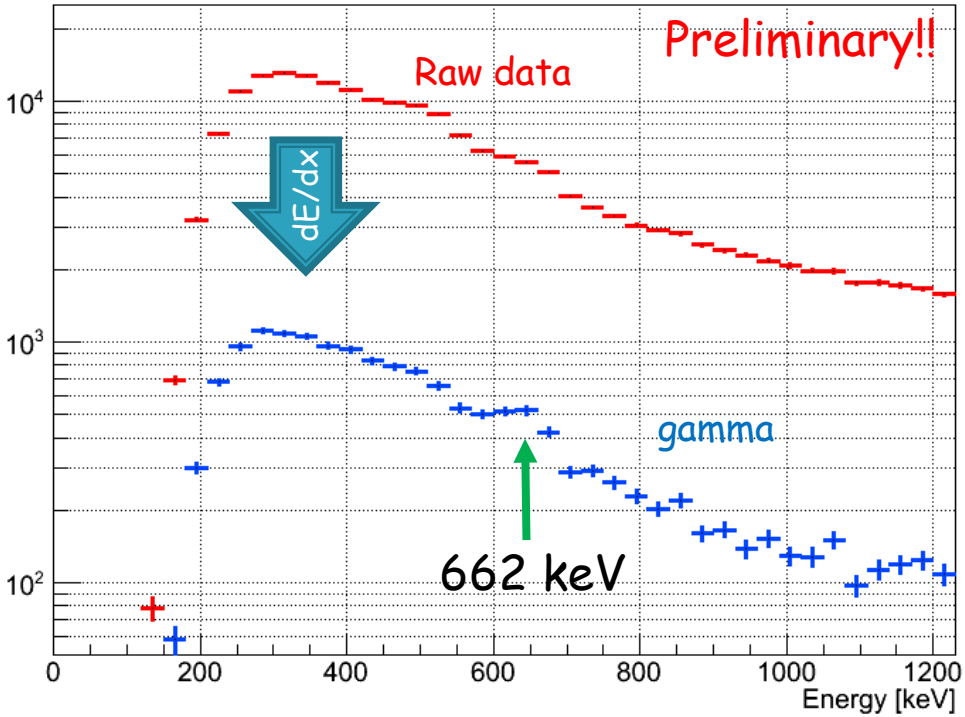




Experiment 1:
Confirmation of background rejection power

With dE/dx selection, background events are rejected.

Spectrum:
excess @ 511, 662 keV



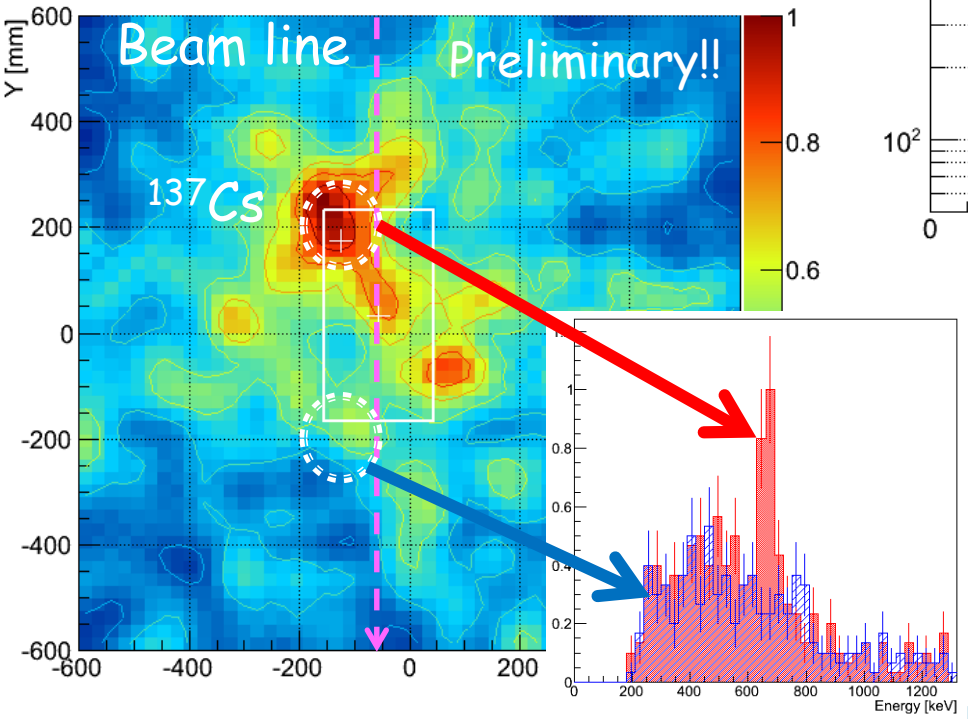


Image:
compact excess @ ^{137}Cs
excess @ 662 keV in ON-region
no excess in OFF-region

ETCC detected gamma ray correctly.

Experiment 2: Observation of a week source

Can ETCC detect gamma-ray source with low S/N?

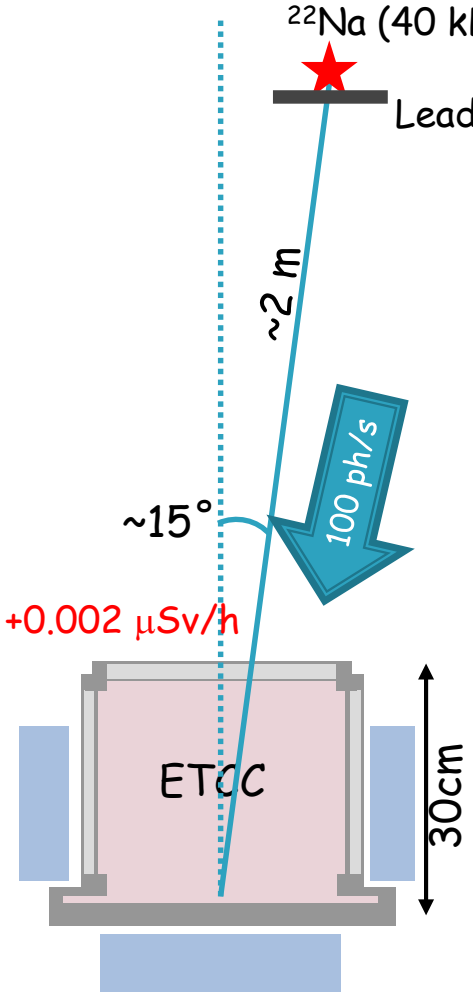
Crab nebula : BG-gamma ≈ 0.01 : 1

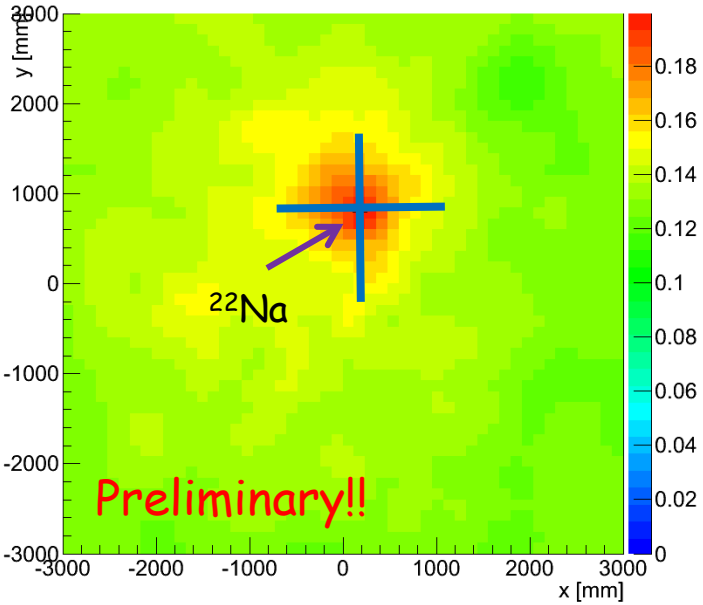
Weak ^{22}Na -> ~100 ph/s come into ETCC

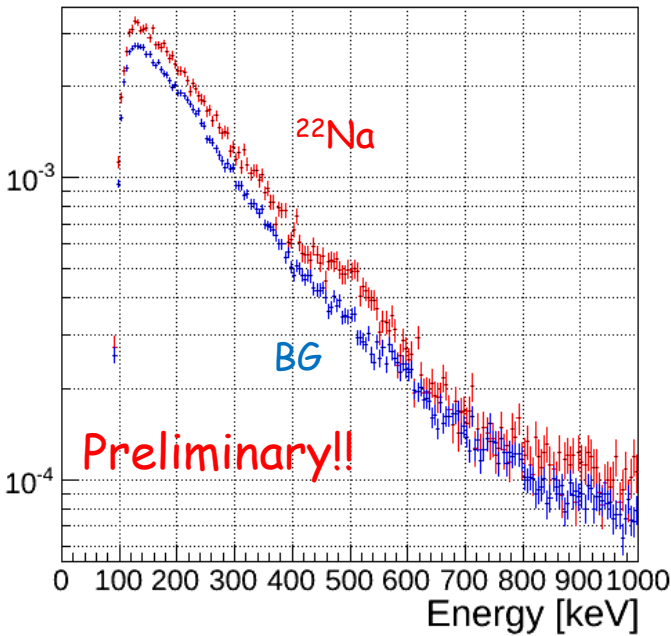
511 keV : BG = 0.02 : 1

Gamma-ray image has a clear excess.

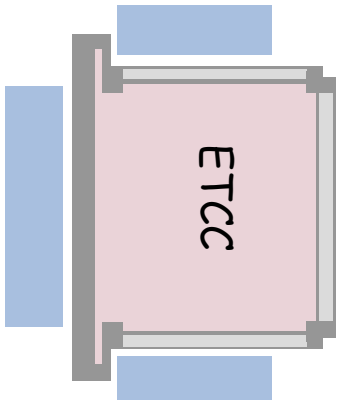
Significance of excess @ 511 keV is about 11σ during 5.5 h.





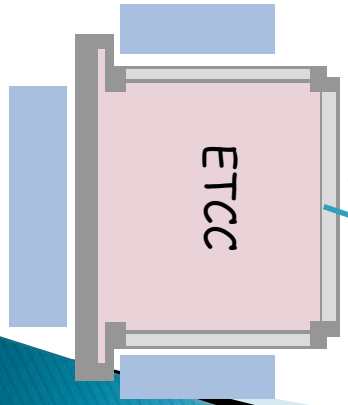


Experiment 3: Observation of time variation



~2.5 hours

No source

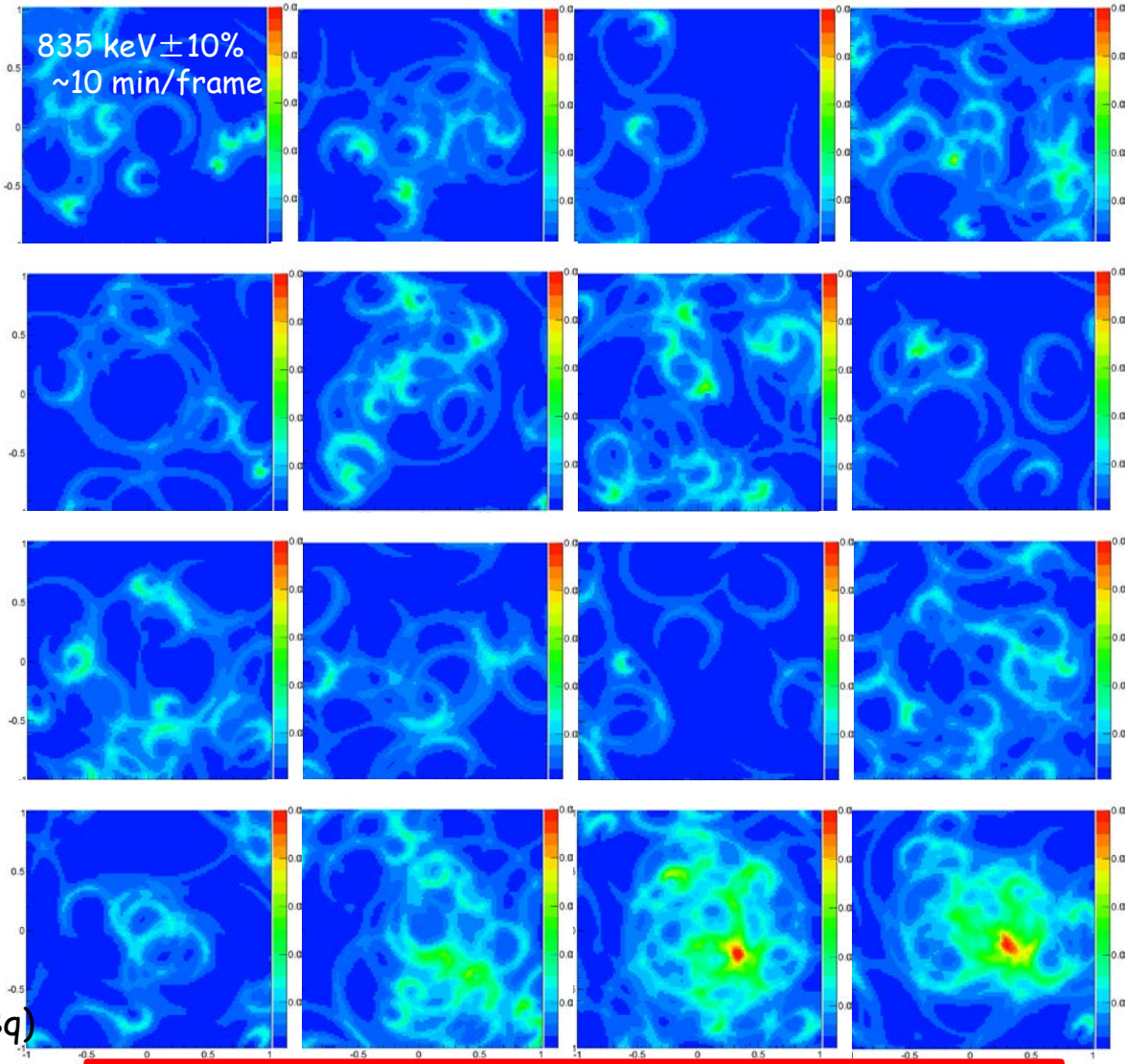


~20 min

+0.01 μSv/h

~3 m

^{54}Mn (835 keV, 1 MBq)



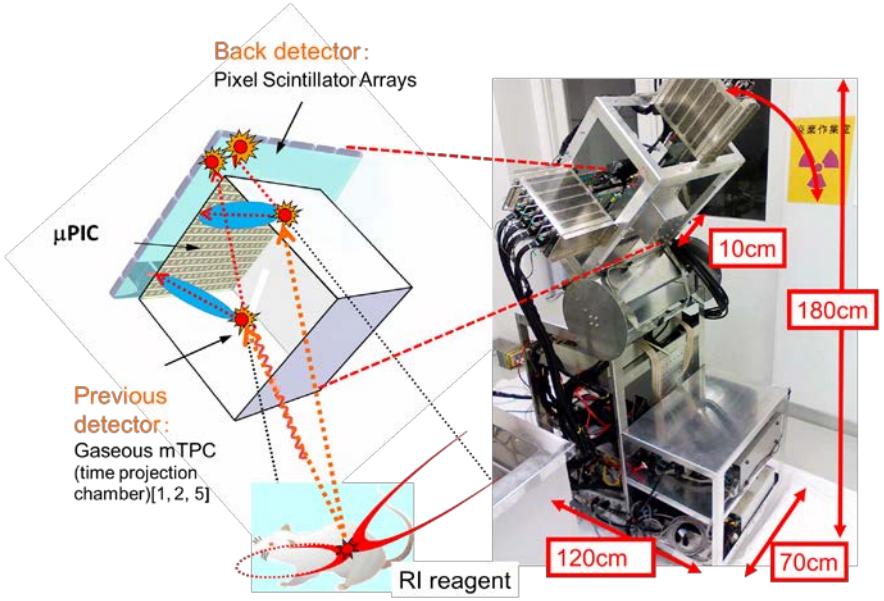
SMILE-II clearly detected
gamma-ray source with only 10 minutes.

Applications of ETCC

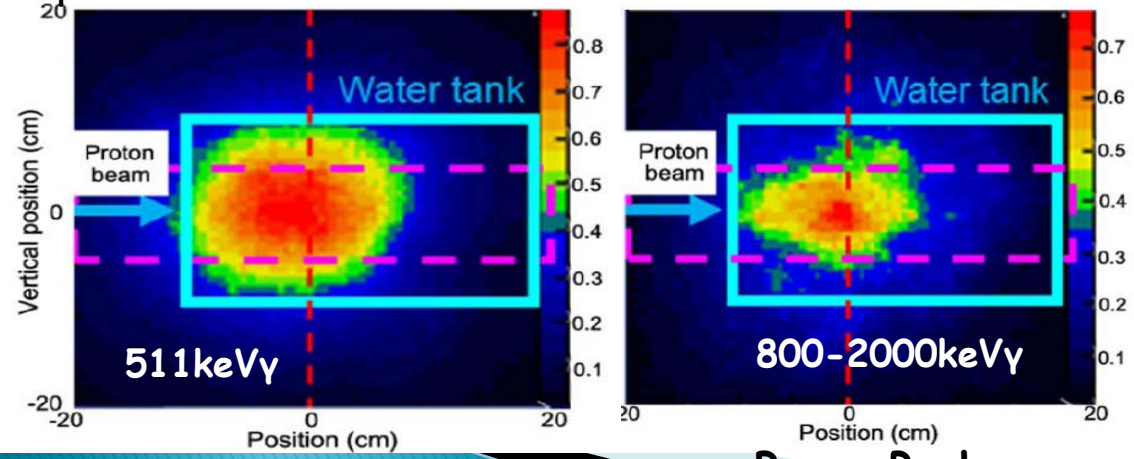
Medical imaging

- Tomography
  use as like PET/SPECT
  wide energy range
  -> possibility of new tracers

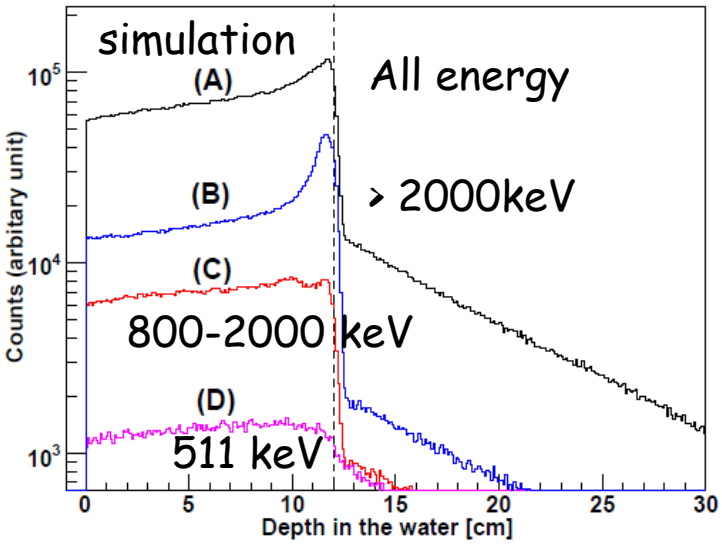
- Proton therapy
  monitoring of proton end point
  clear peak at high energy



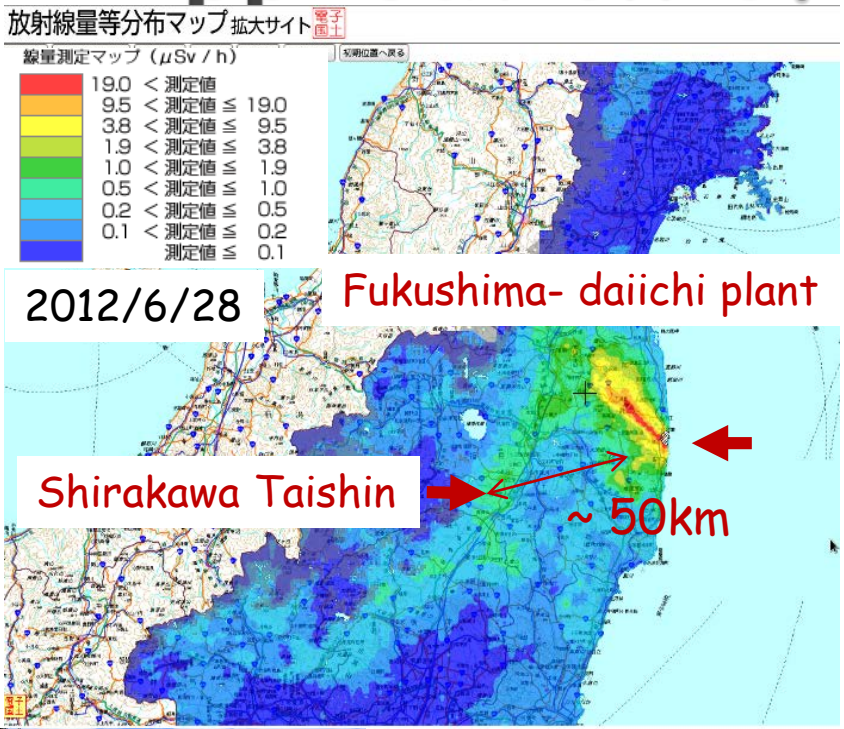
experiment



Bragg Peak



Application of ETCC



Provide new efficient gamma-ray imaging detector for ^{137}Cs, ^{134}Cs in contaminated soils in Fukushima.

Project : Horiba & Kyoto-U & Canon
supported by JST (Japan Science and Technology Agency)

- higher sensitivity
- compact and portable system
- smart data processing system and visualization software

10x10x15 cm^3 ETCC with pressurized gas

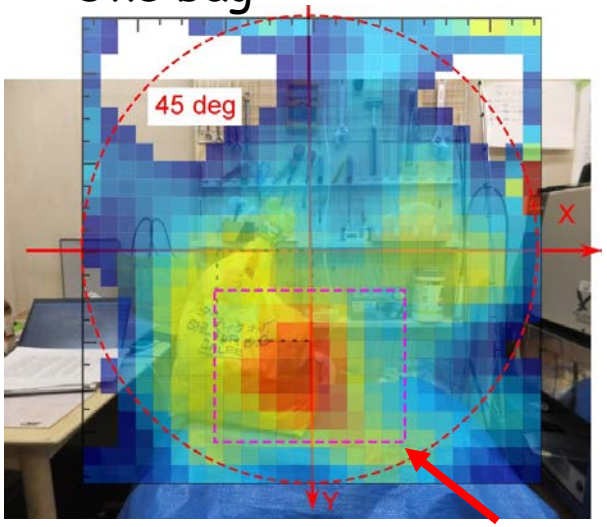
At the first step
soil bags were measured in Shirakawa city in Sep 2013.

- Imaging contrasts
- Separate spectrum components using images
- Naïve estimation of radiation from energy spectra

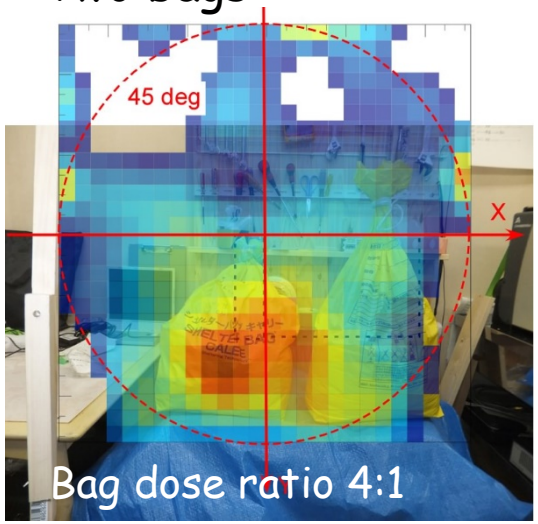
very low dose < 0.05 μSv/h @ 1m (standard)
(0.6 ~ 2.0 μSv/h @ surface)

Application of ETCC

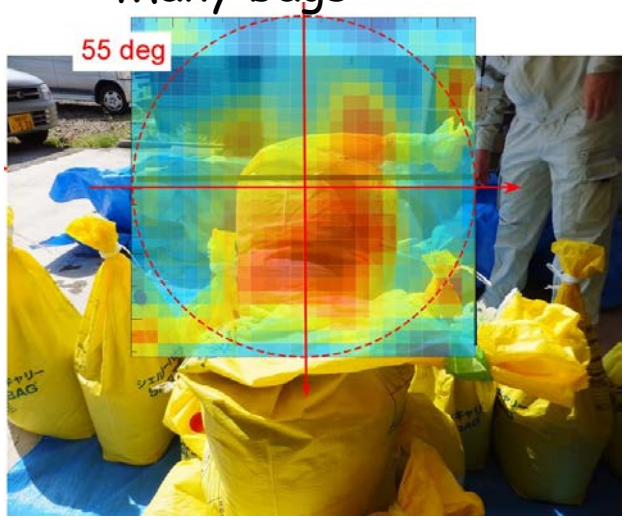
One bag



Two bags



Many bags



^{137}Cs cal-source @ 50 cm (0.36 μSy/h) -> 0.71 events/sec

One bag	+0.044 events/sec	estimate	+0.023 μSy/h
Two bag	+0.049 events/sec		+0.025 μSy/h
Many bag	+0.23 events/sec		+0.12 μSy/h

@ detector position

Compact-ETCC Sensitivity : 2.0 cps/(μSv/h)
ETCC can measure absolute radiation dose.
Concept of environment monitoring was confirmed.

Now, we are developing a new camera, and planning some tests.

Summary

- We are developing an Electron-Tracking Compton Camera using a gaseous tracker.
- SMILE-II ETCC:
  - Effective area : ~1 cm^2 (< 300 keV)
  - Angular resolution : 5.3° (662 keV)
- ETCC has redundancies of background rejection
  - complete reconstruction using electron track
  - particles identify using dE/dx
  - Compton kinematic test using angle α
- Confirmation experiments:
  - detected gamma-ray source in high radiation field
  - detected a low S/N source
    511 keV, S/N = 0.02, live time = 2.0×10^4 s -> 10.5σ
  - confirmed the time variation sensitivity
    835 keV, 1 MBq, 3 m -> detected with 10 min at least
- Applications
  - Medical : proton therapy, SPECT, PET
  - Environment monitoring : in Fukushima, around reactor

Thank you for your attention!