Imaging polarization measurement above 100 keV with a wide field of view by electron tracking Compton camera

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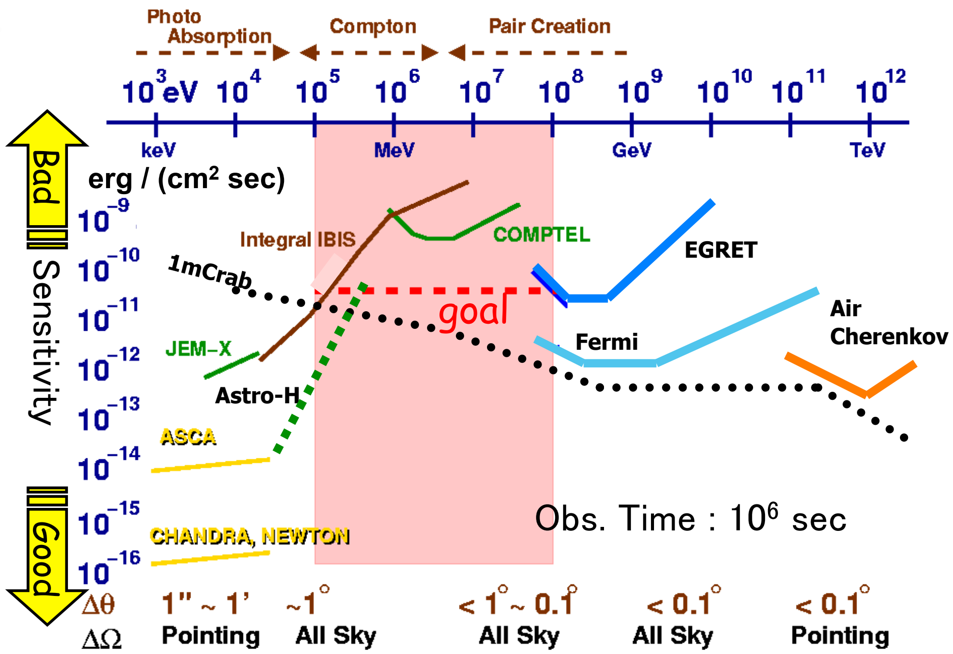
1. Motivation & Detector concept
2. Performance
3. Confirmation experiments
4. Summary

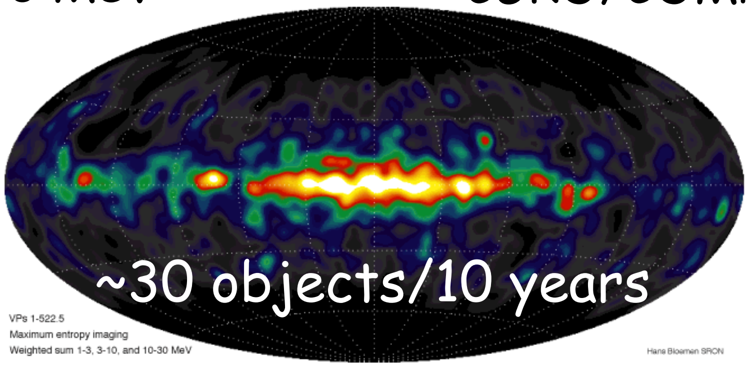
MeV Astronomy

- 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

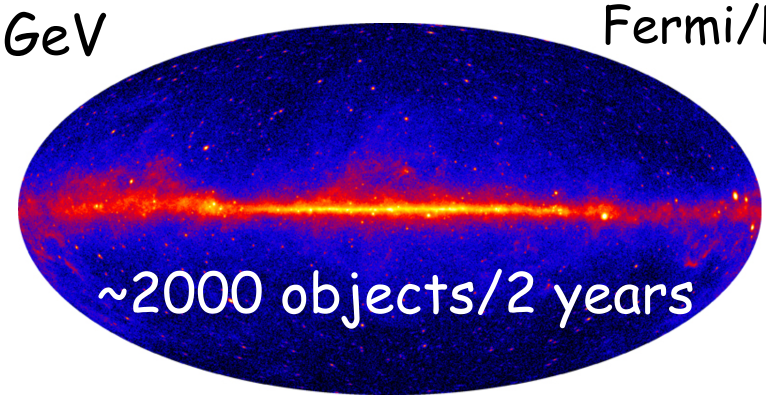


~30 objects/10 years

V. Schönfelder+ (A&AS, 2000)

GeV sky map

> 1 GeV Fermi/LAT



~2000 objects/2 years

P. L. Nolan+ (ApJS, 2012)

Requirements for the next-generation detectors are …

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

Polarimetry in sub-MeV region

- Hard X-ray polarization : a good probe of high energy astrophysics
- Observation : only few objects (Crab, Cyg X-1, GRBs) over 100 keV

Minimum Detectable Polarization

$$\underset{[\%]}{MDP} = \frac{429}{ASM}\sqrt{\frac{AS+B}{T}} \quad \begin{matrix} 99\% \\ \mathrm{CL} \end{matrix}$$

$B \gg AS$ -> $\mathrm{MDP} \propto \sqrt{B}/AS$

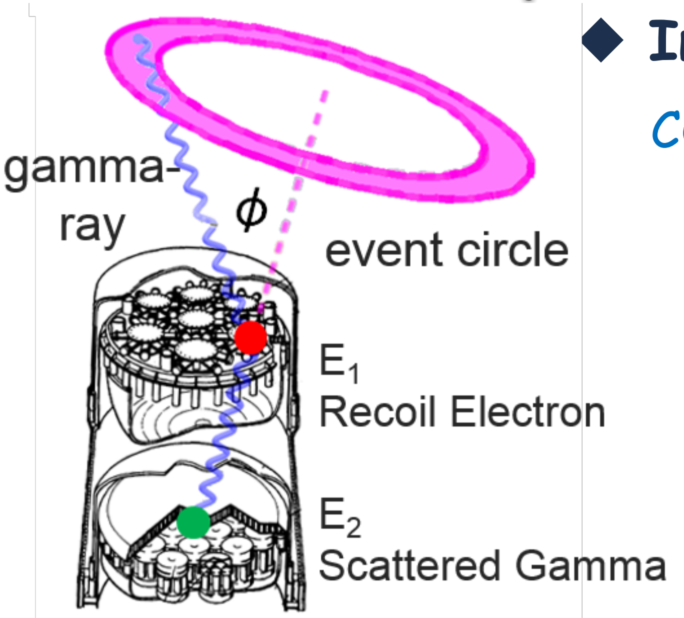
A	Effective area [cm^2]
N	Modulation Factor
S	Signal [cm^{-2} sec^{-1}]
B	Background [sec^{-1}]
T	Observation time [sec]

- Faint source -> sensitivity is limited by background rate
- Several sources in signal region
  -> obtain averaged modulation
  -> big systematic error

For high polarization-sensitivity…

- Large effective area
- Large modulation factor
- Suppress background
- Imaging (modulation of each object)

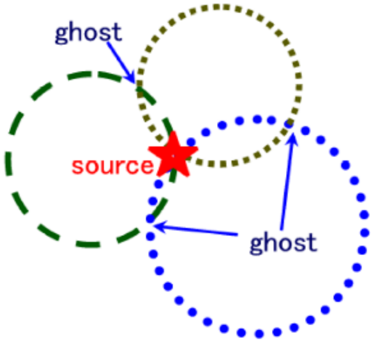
Causes of problems

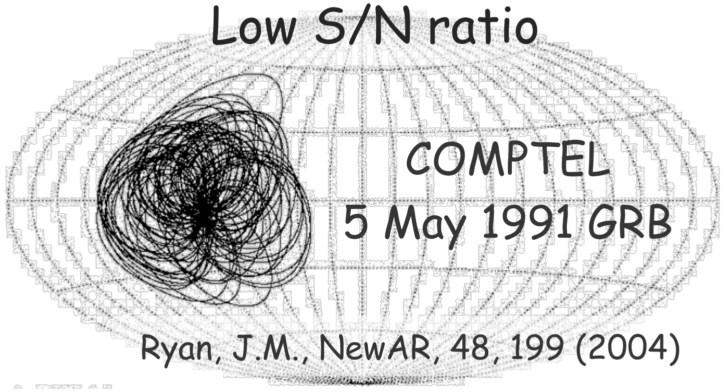


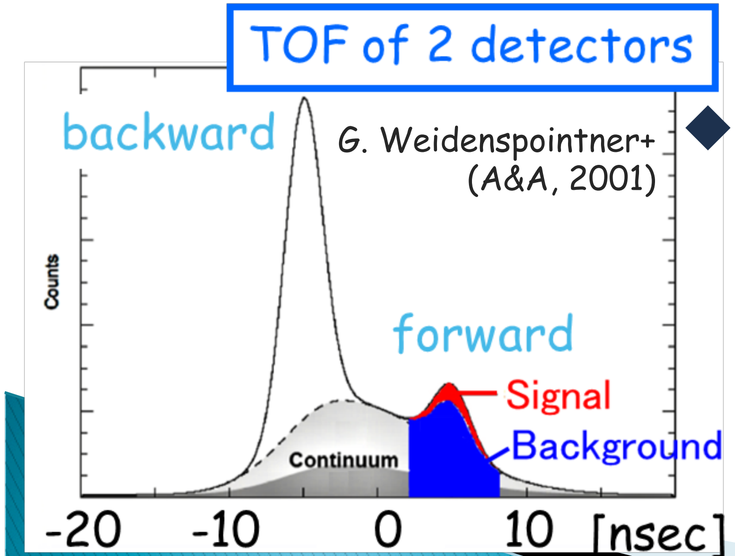
◆ **Incomplete Compton reconstruction**

COMPTEL did not use direction of recoil electron.

➡ Imaging by superposition of event circles







◆ **Huge Background in space**

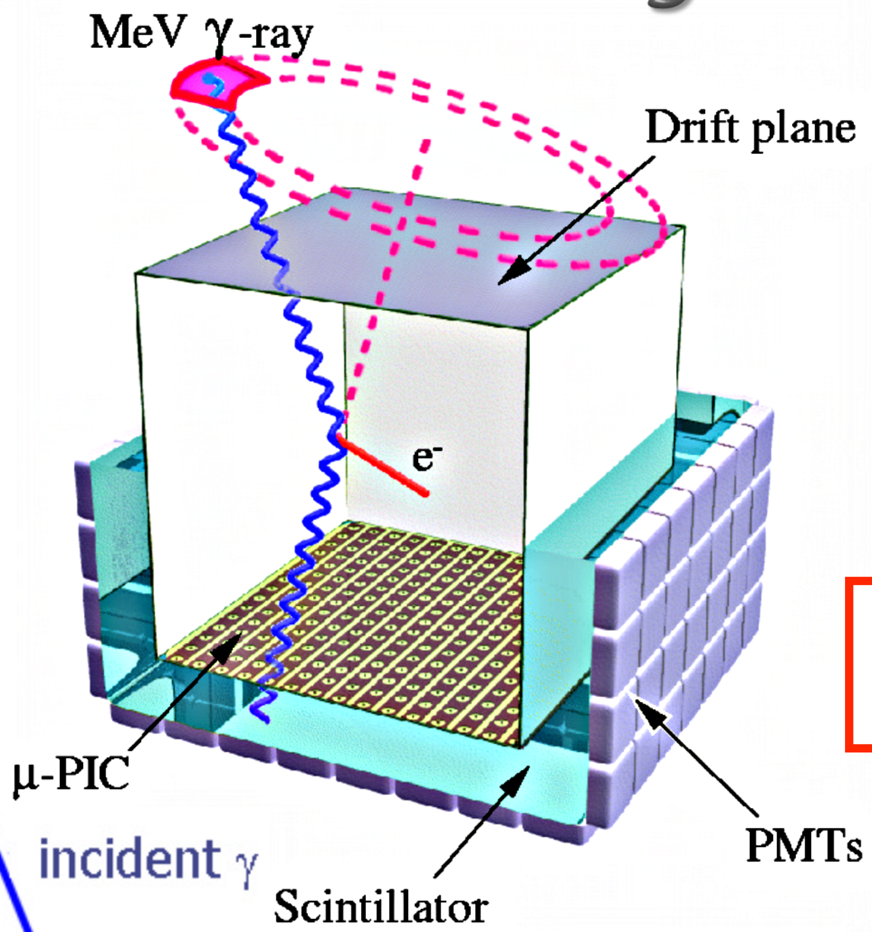
produced by cosmic-ray interactions with detector

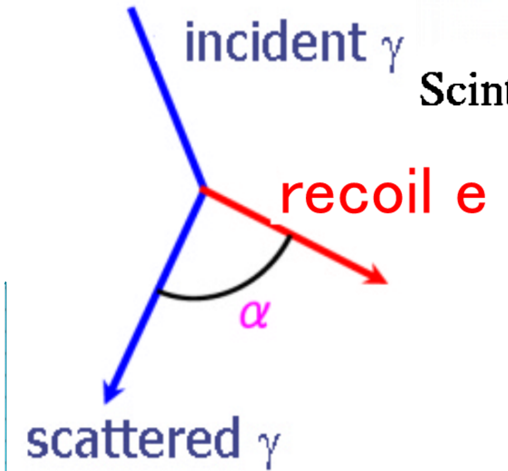
COMPTEL's BG rejection was not sufficient.

➡ ~ 1/10 of the expected sensitivity

Low BG is most important for MeV observation.

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)
- Simple structure
- Compton Kinematical test with angle α
- Particle identify with dE/dx
- No VETO & shield around ETCC

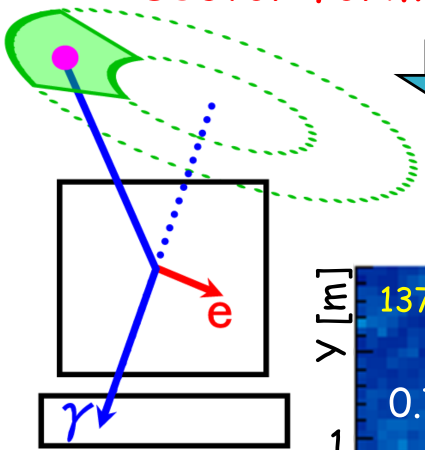
Comparison with the usual Compton method

Electron-Tracking Compton (ETCC)

Using the electron tracks

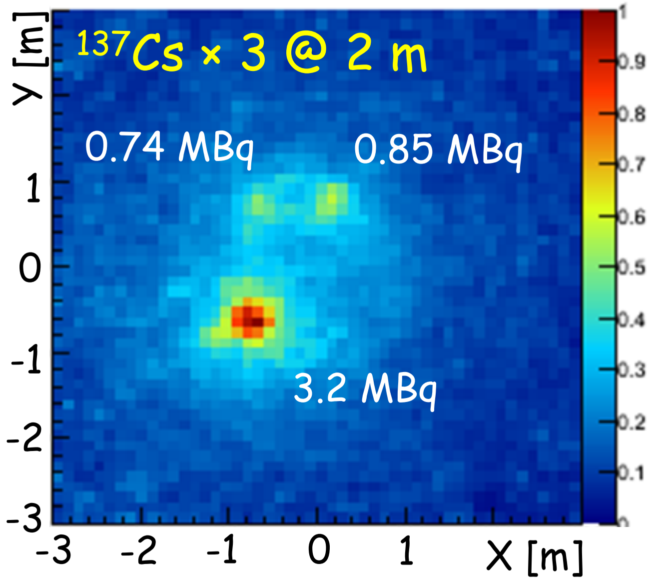
complete direction within

sector form error region



Simply overlay

- High S/N
- No fakes

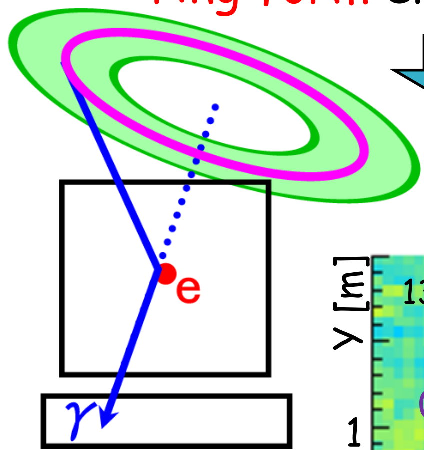


Usual Compton Imaging (COMPTEL)

Not using the electron tracks

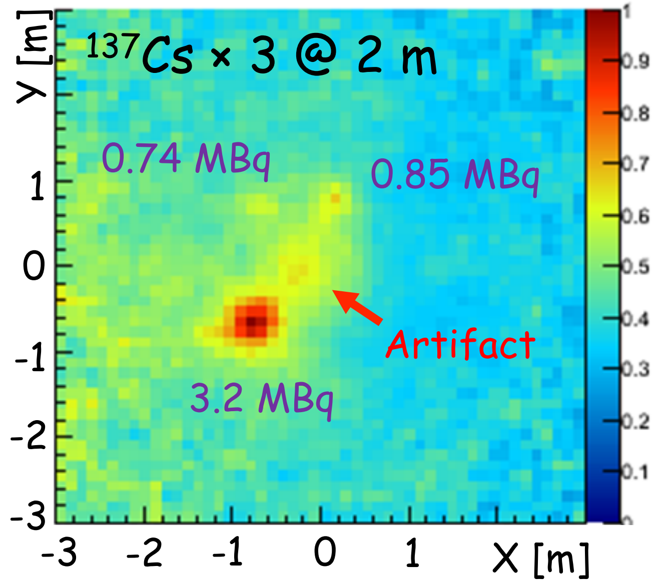
only event circle within

ring form error region



Simply overlay

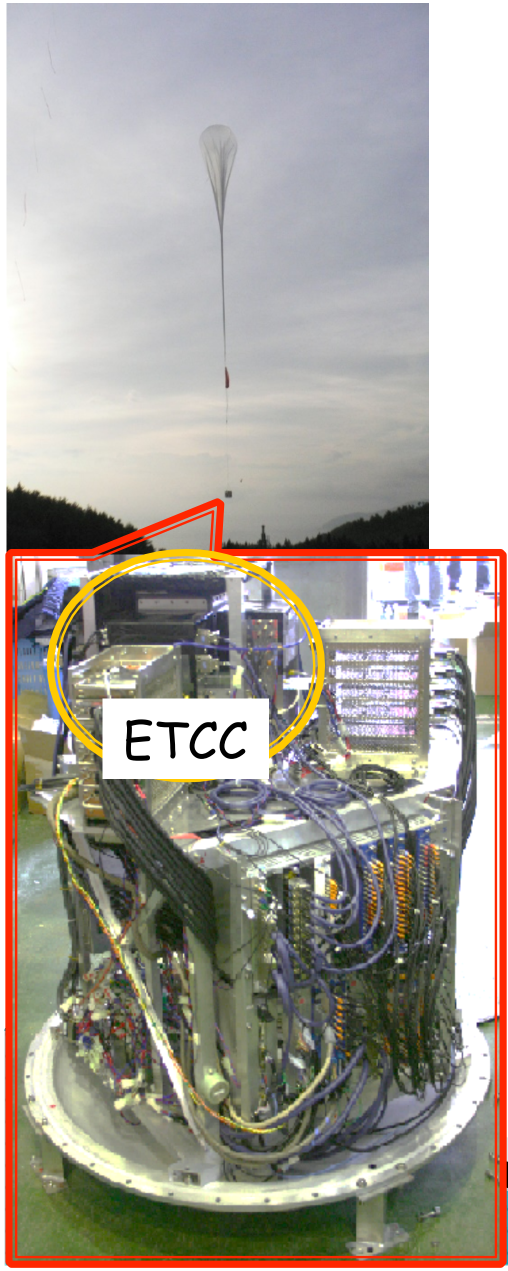
- Low S/N
- Artifacts appear



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

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

1st balloon experiment (SMILE-I)



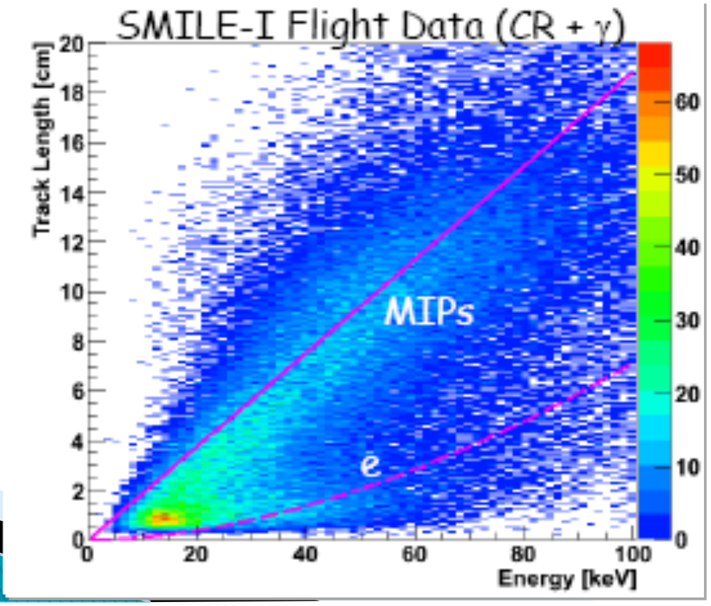
Sub-MeV gamma-ray imaging Loaded-on-balloon Experiment

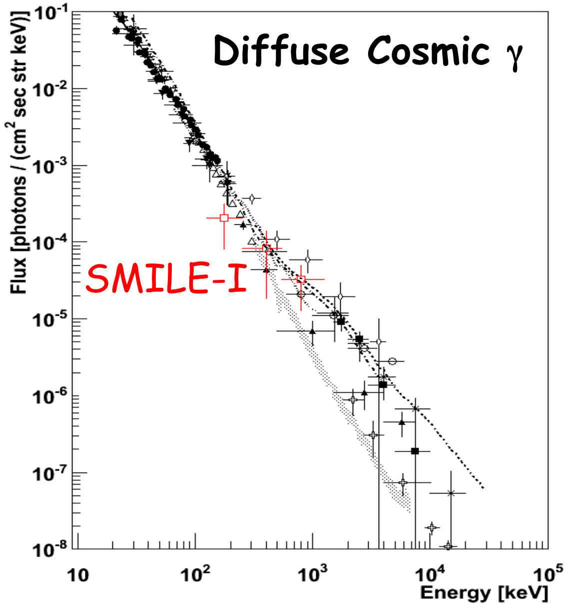
Launched on Sep. 1, 2006 @ Sanriku (ISAS/JAXA)

- Test flight using (10 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 balloon experiment

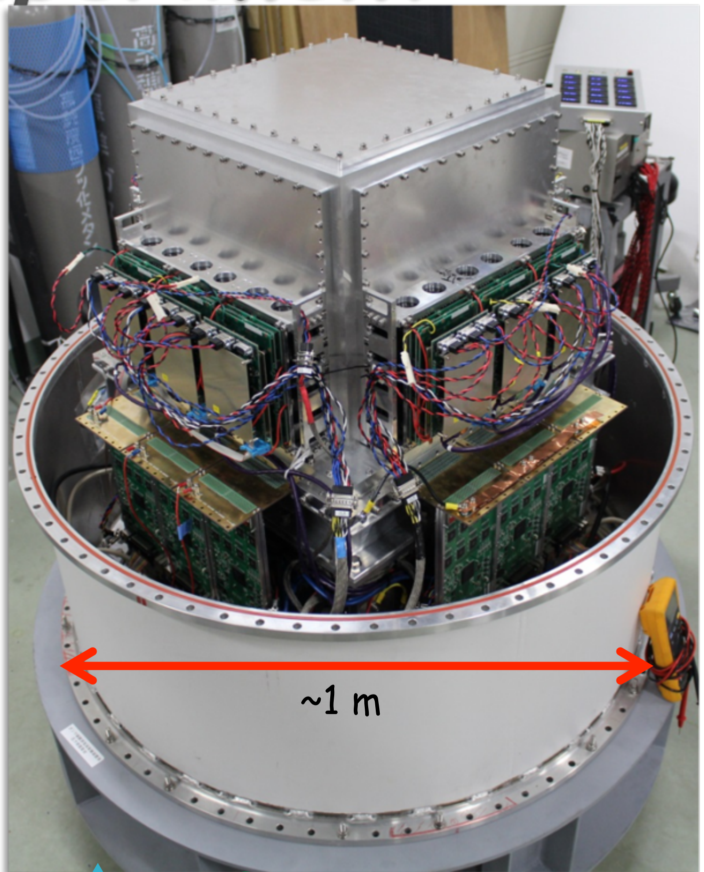
SMILE-II

Target: Crab nebula

>3σ detection (40 km, several hours)

Requirements

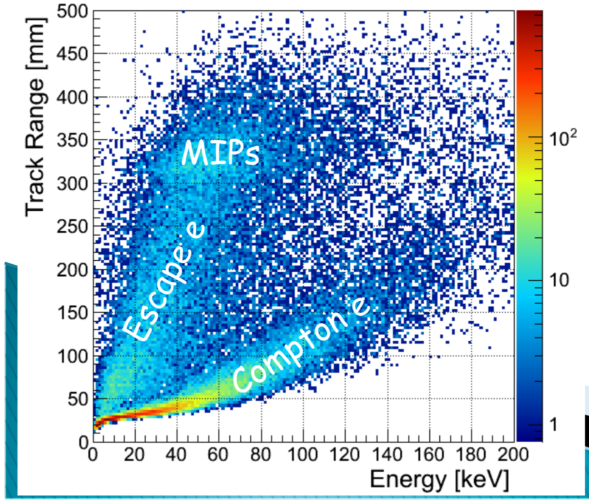
Effective area	:	> 0.5 cm^2 (300 keV)
Angular resolution	:	< 10° (600 keV)
Sensitivity	:	×100 SMILE-I

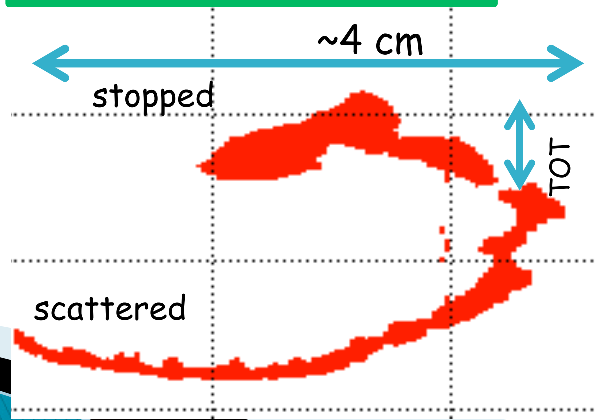


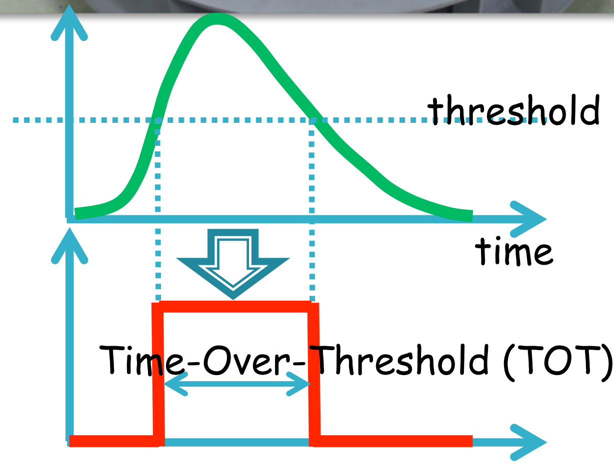
Improvements for SMILE-II

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

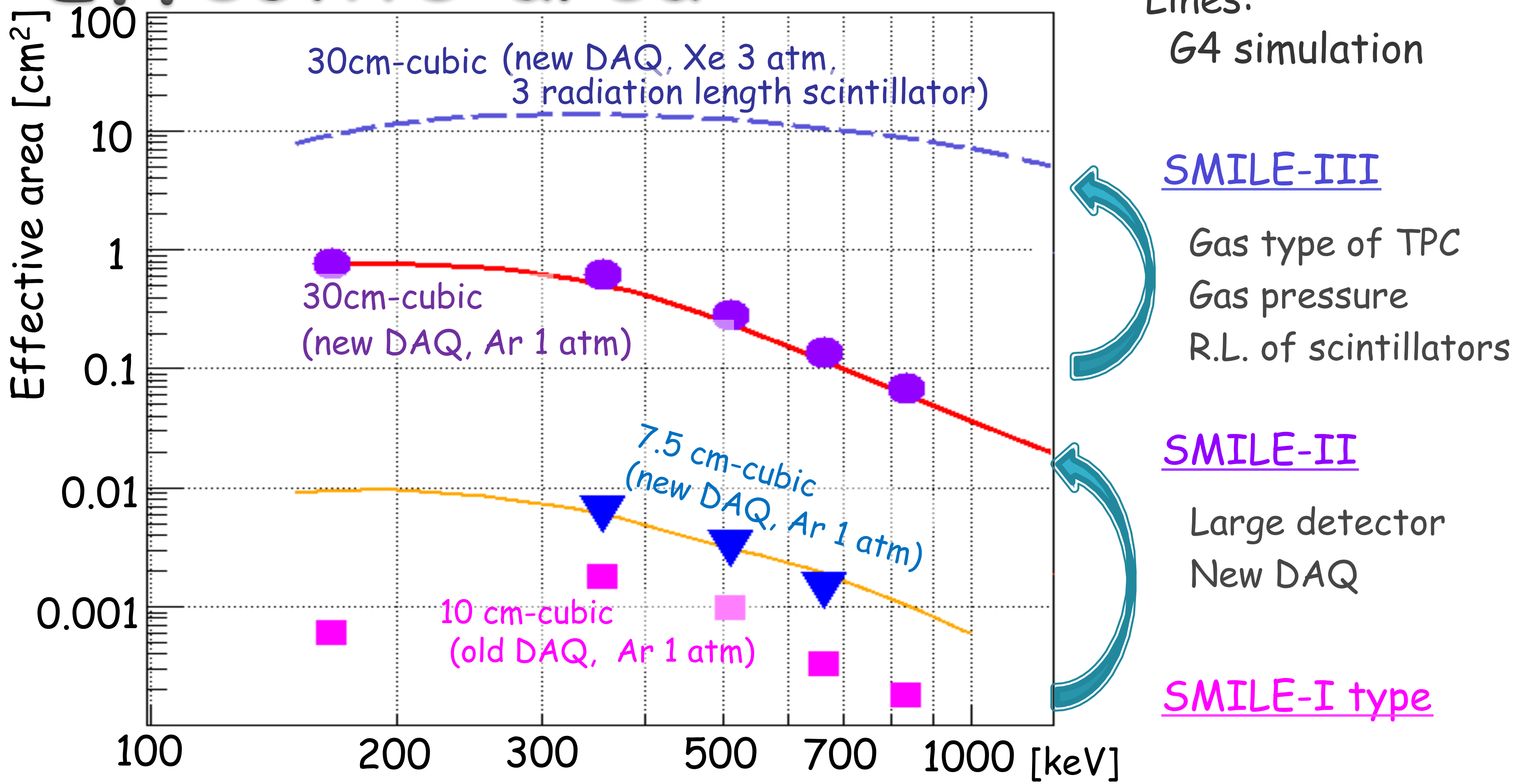
×10 Sensitivity will reach to (×100 SMILE-I) !







Effective area



Points:
measured
Lines:
G4 simulation

- ✓ SMILE-II ETCC ~1 cm^2 @ 300 keV (requirement > 0.5 cm^2)
- ✓ Experiment ≈ Simulation (not including detector response)

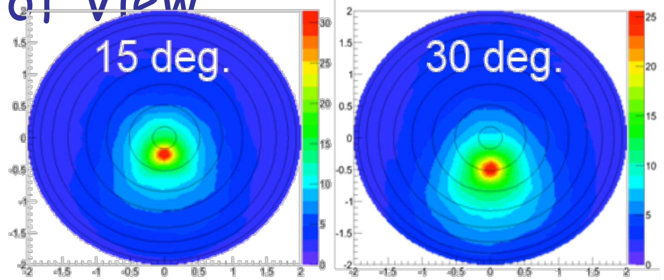
  ETCC obtains ~100 % of Compton events.
- ✓ We will upgrade to SMILE-III ETCC ~10 cm^2 (in 2016)

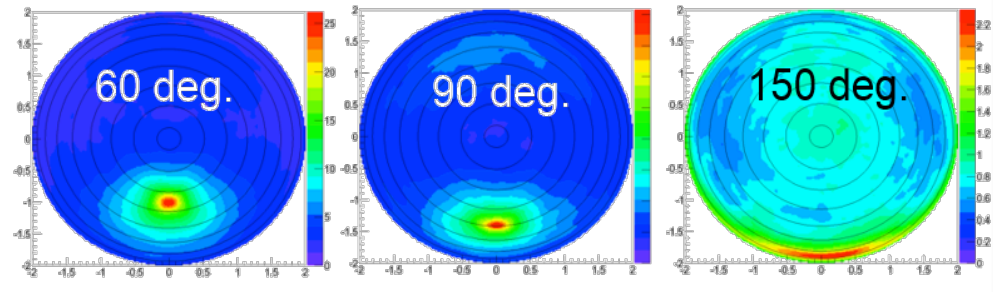
Performance of 30-cube ETCC

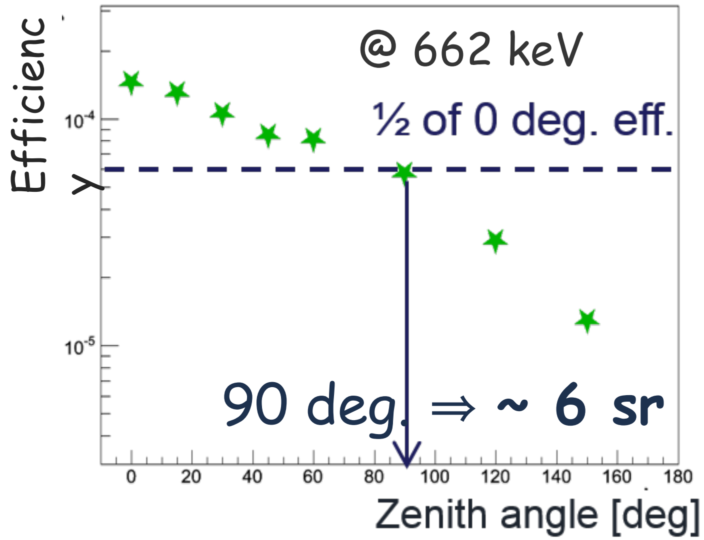
◆ Large Field of View

^{137}Cs (662 keV)

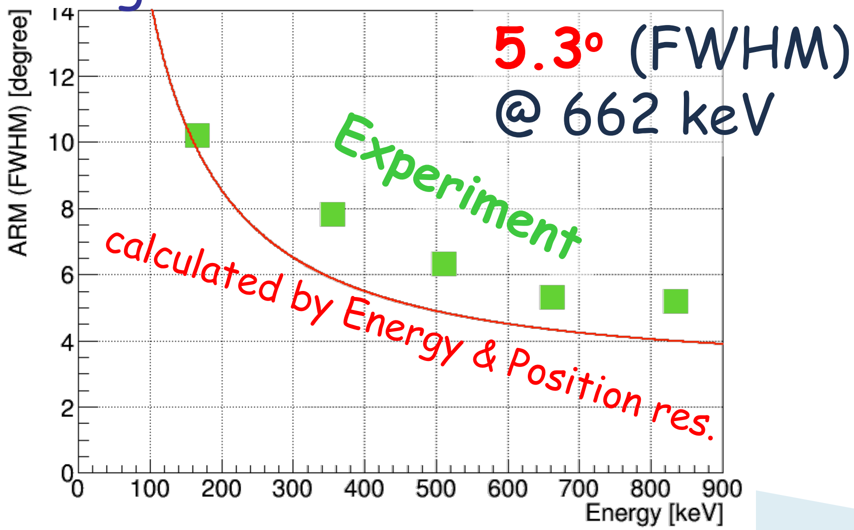
0.7 MBq @ 2 m



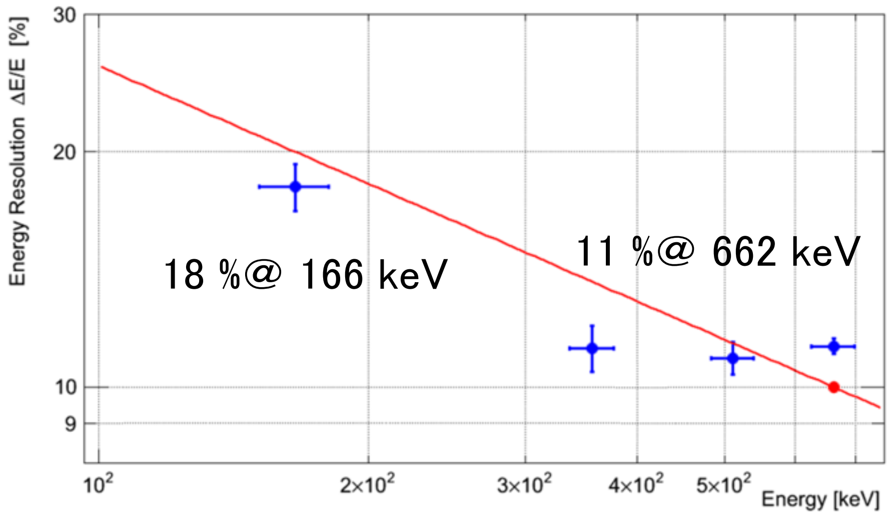




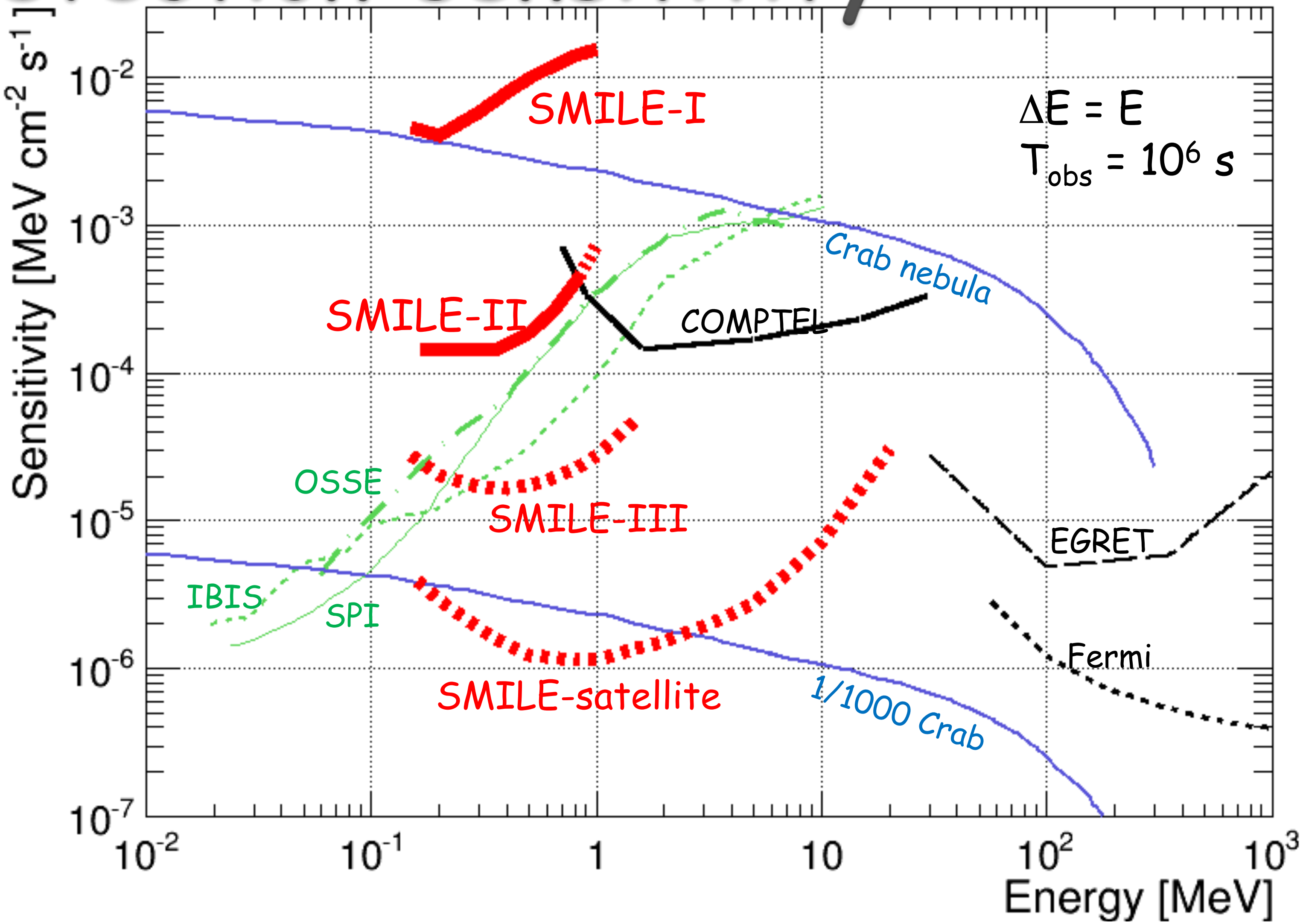
◆ Angular resolution



◆ Energy resolution



Detection sensitivity



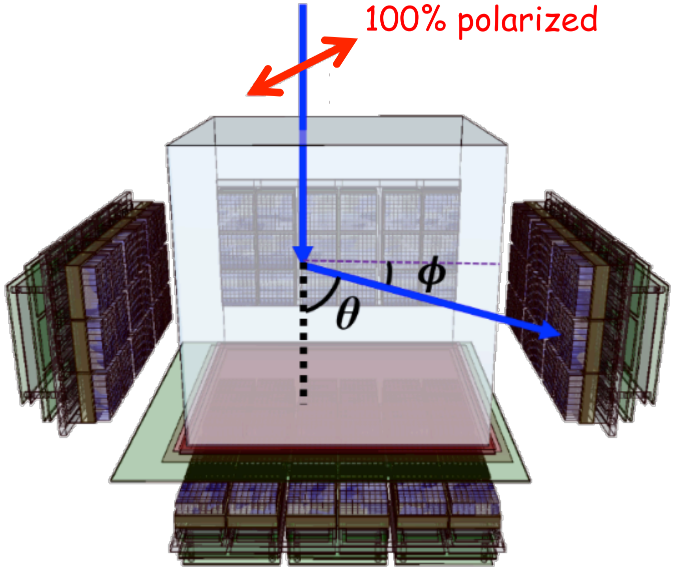
SMILE-II : detectable Crab nebula with 3 h at 40 km

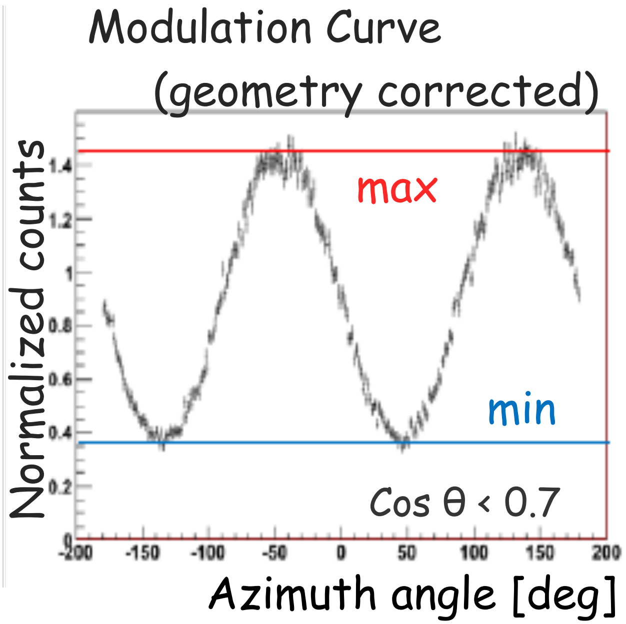
SMILE-III : CF_4, 3 atm and 2-3 Radiation length GSO -> 10 times better sensitivity

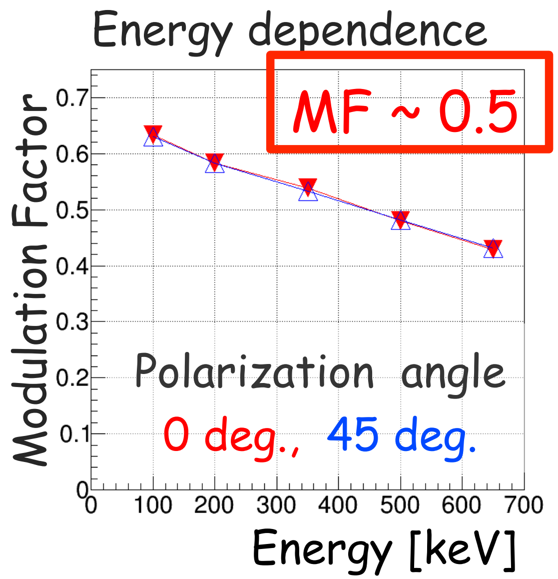
Satellite : (50 cm-cube, Xe 3 atm, 10 Rad. Len. $LaBr_3$)×4 -> reach to 1 mCrab

Geant4 Simulation

Ability of polarization measurement







SMILE-III (effective area ~10 cm^2)

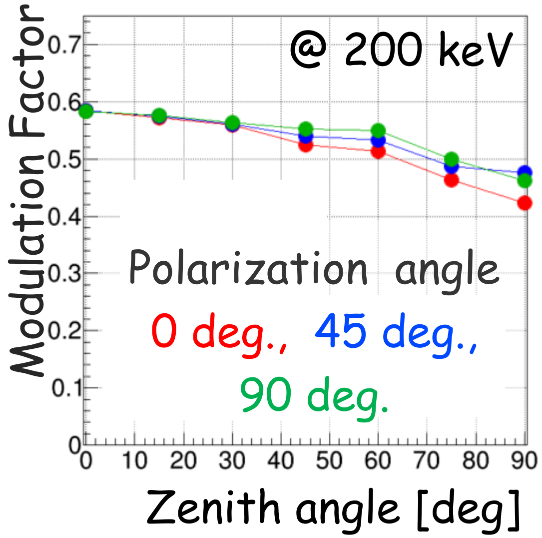
- Crab : 3σ Minimum Detectable Polarization ⇨ ~ 20%
- Cyg X-1 : ~ 30%

mid-latitude, 40 km, 10hours flights

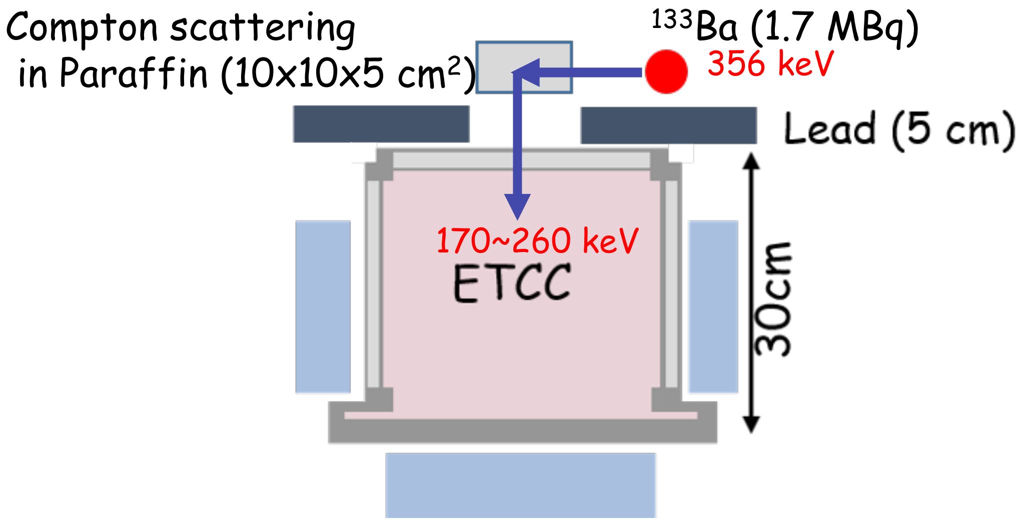
- GRBs : 10^{-6} erg/cm^2/s (2-3 GRBs/month) ⇨ ~ 8%

  10^{-7} erg/cm^2/s (~10 GRBs/month) ~ 30%

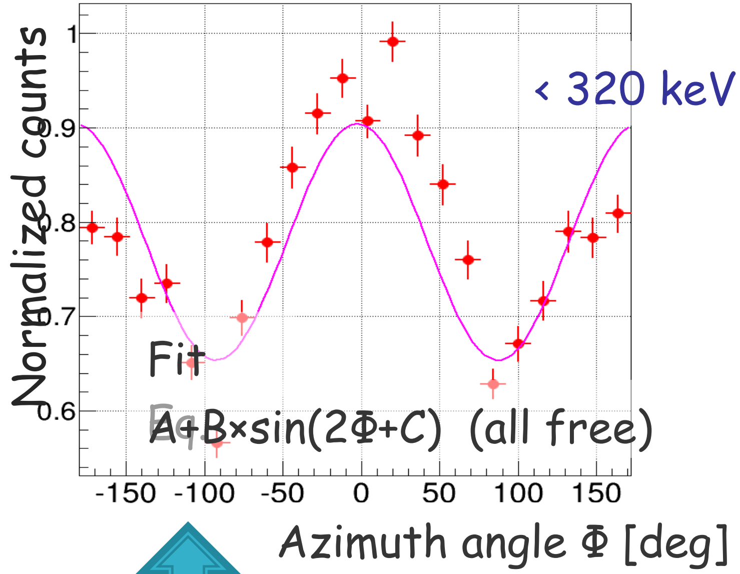
polar region, 40 km, 1 month flights



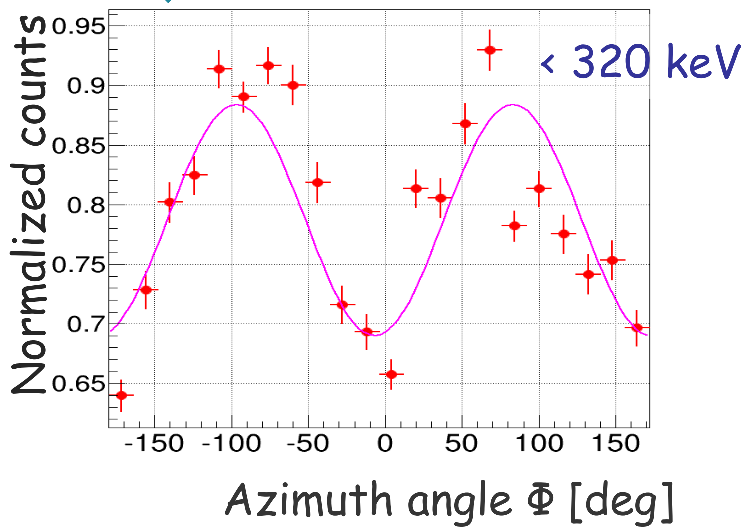
Ability of polarization measurement



~ 90 deg. scattered gamma on Paraffin is polarized ~ 40 % (calculated by simulation)



90°rotation

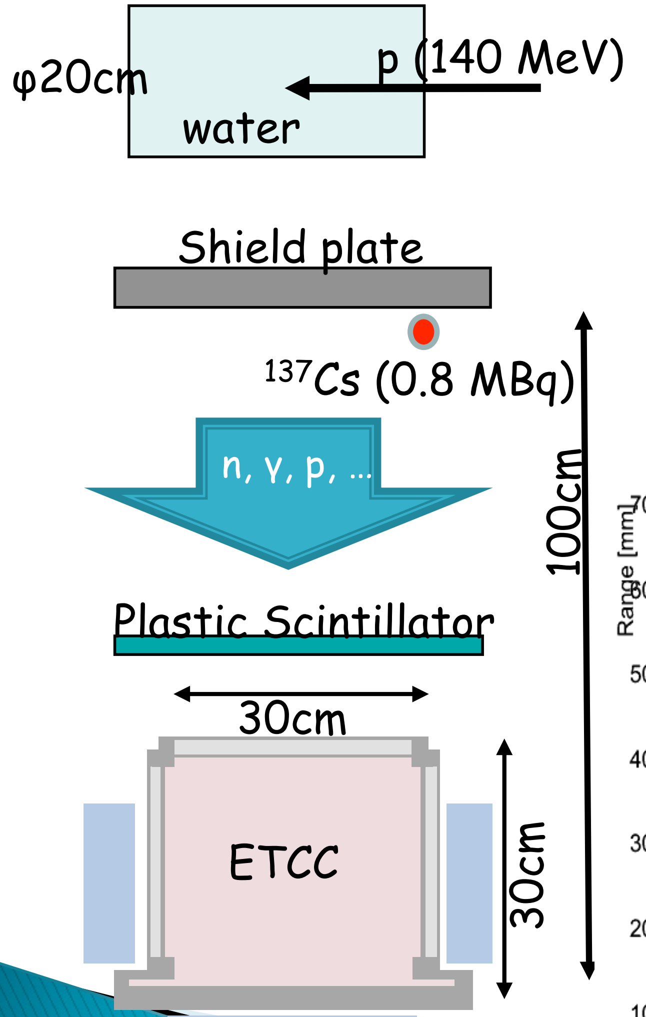


Signal : BG = 0.08 : 1

ETCC succeed to detect
the polarization modulation with low S/N.

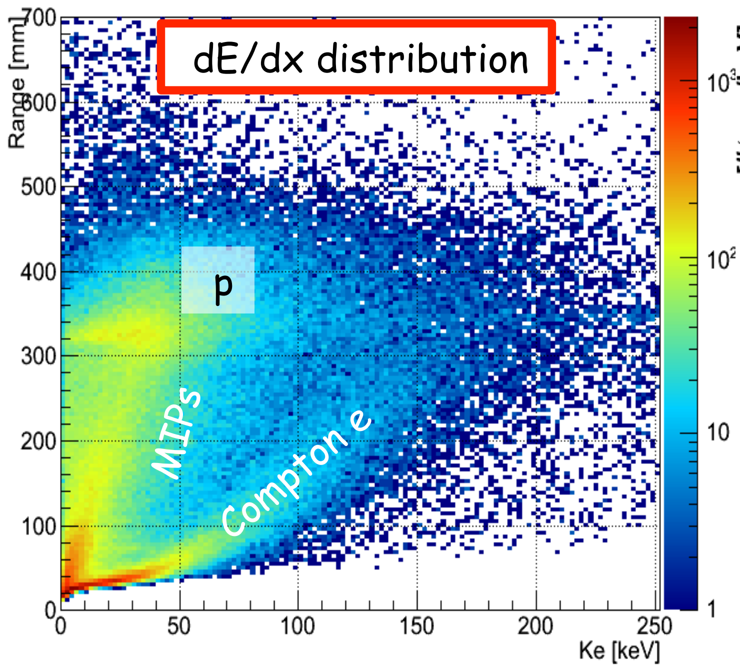
SMILE-II ETCC will be tested at Spring-8

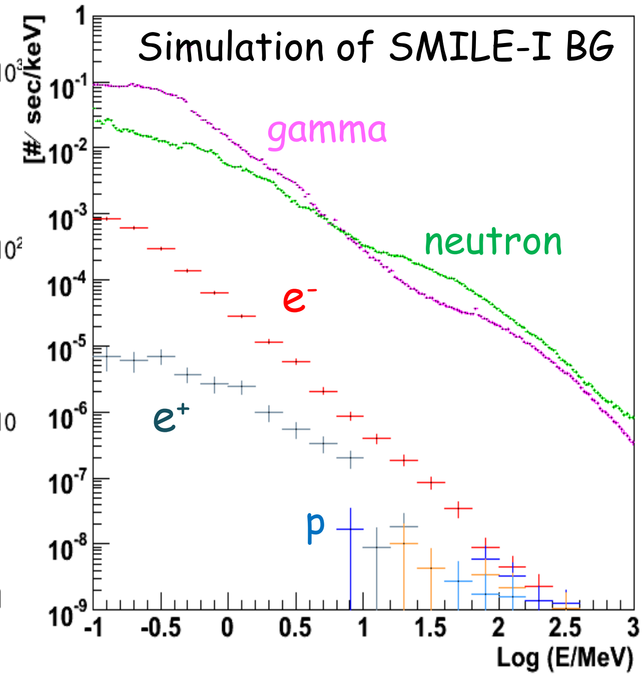
Confirmation of background rejection power



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

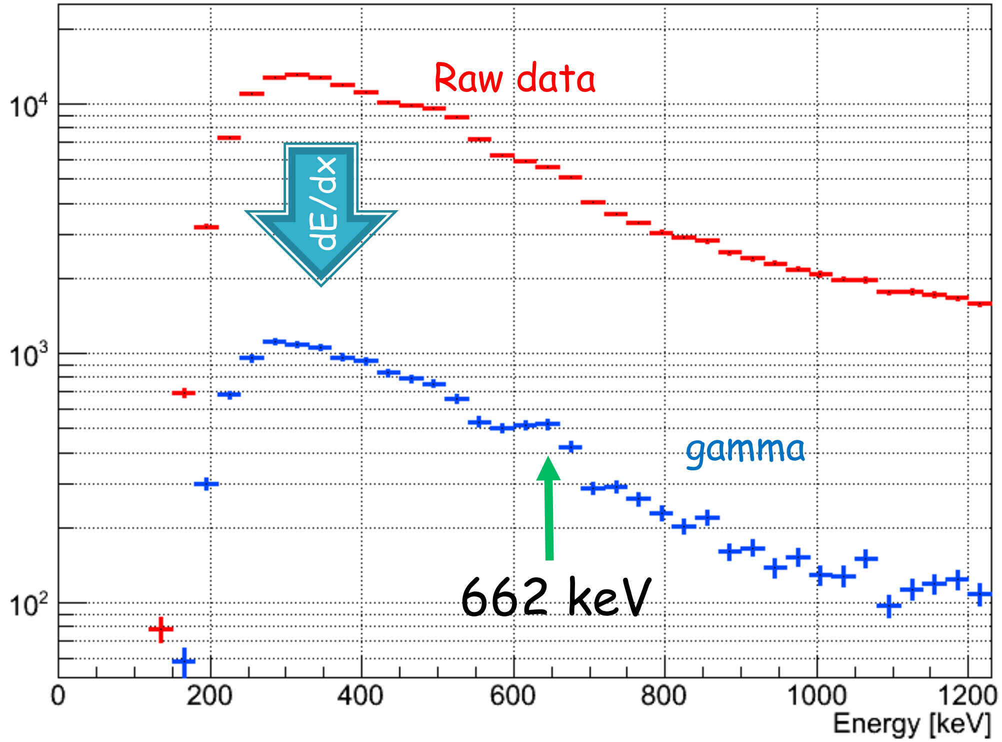




Confirmation of background rejection power

With dE/dx selection, background events are rejected.

Spectrum:
excess @ 511, 662 keV



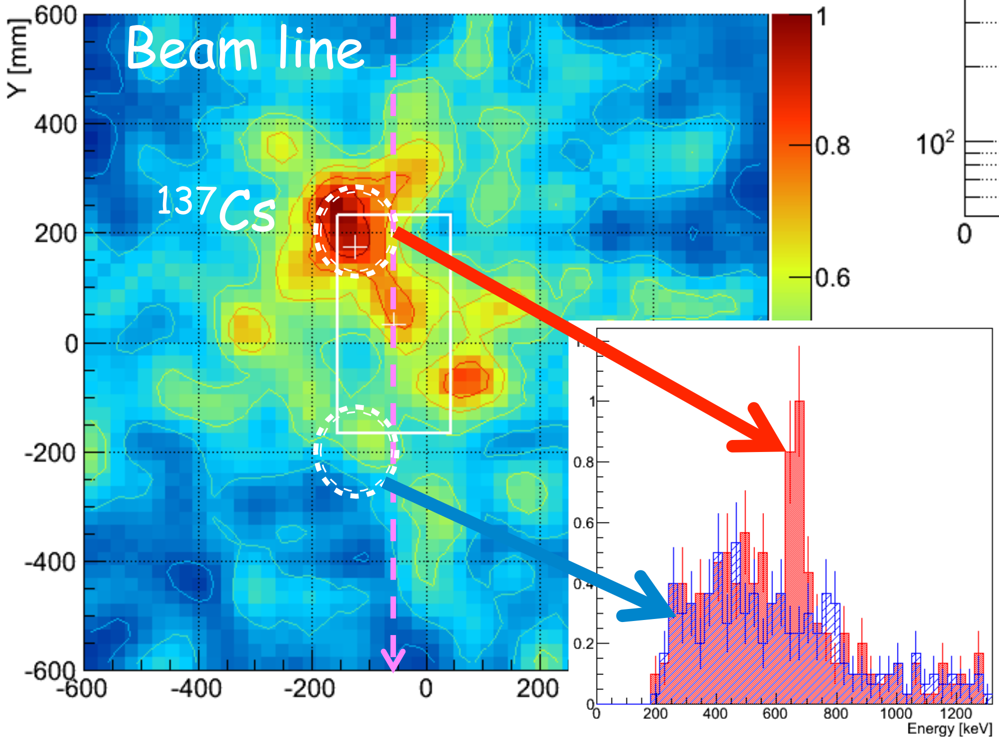


Image:
compact excess @ ^{137}Cs
excess @ 662 keV in ON-region
no excess in OFF-region

ETCC detected gamma ray correctly.

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)
    - -> Crab nebula with 5σ level with 3 h at 40 km
- Future improvement:
  - SMILE-III : effective area ~10 cm^2 (< 300 keV)
    - -> ~20% polarization of Crab nebula with 3σ level
  - Satellite : effective area ~240 cm^2 (500 keV)
    angular resolution ~2.5° (500 keV)
    - -> sensitivity will reach to 1 mCrab
- Ability of polarization measurement
  - Modulation factor >0.5 (< 300 keV)
  - Detected polarization of Compton-scattered gamma at Lab.
  - Beam test in Jan. 2015
- ETCC has redundancies of background rejection
  - complete reconstruction using electron track
  - particles identify using dE/dx
  - Compton kinematic test using angle α

Thank you for your attention!

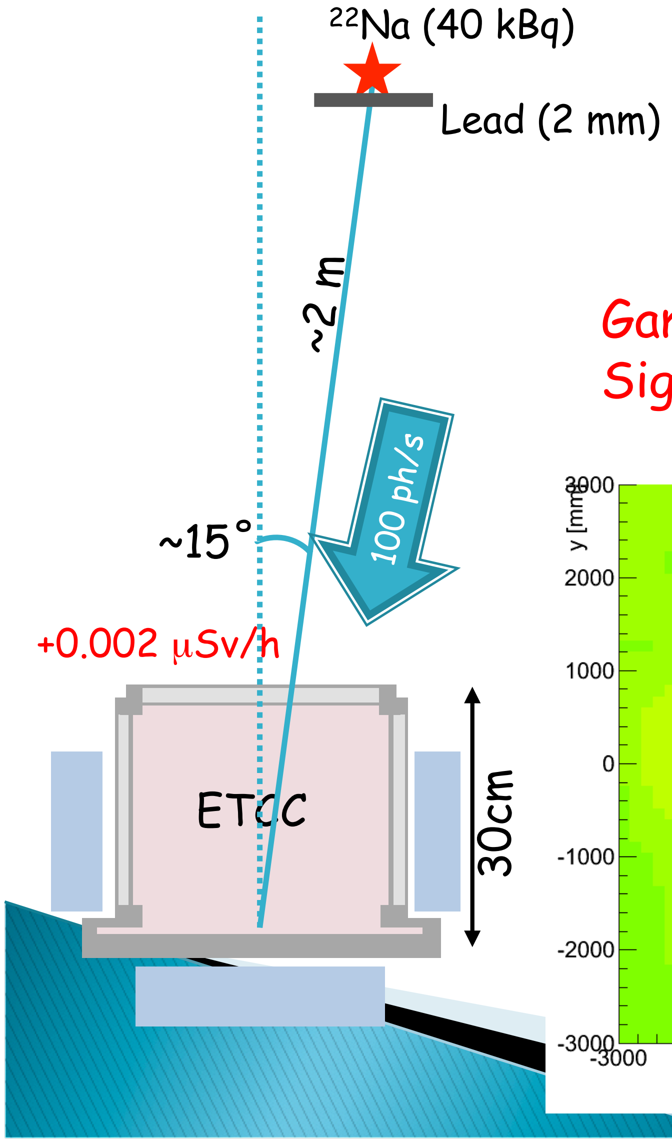
Observation of a week source

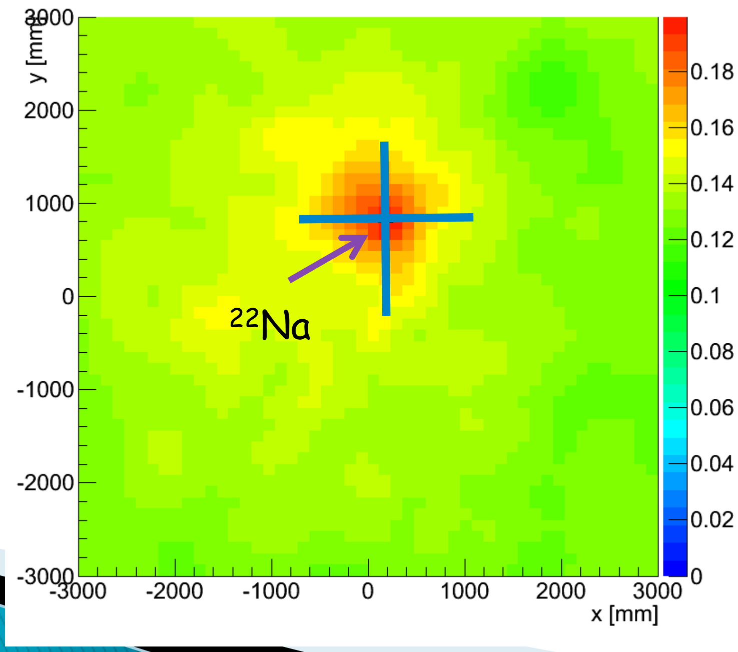
Can ETCC detect gamma-ray source with low S/N?

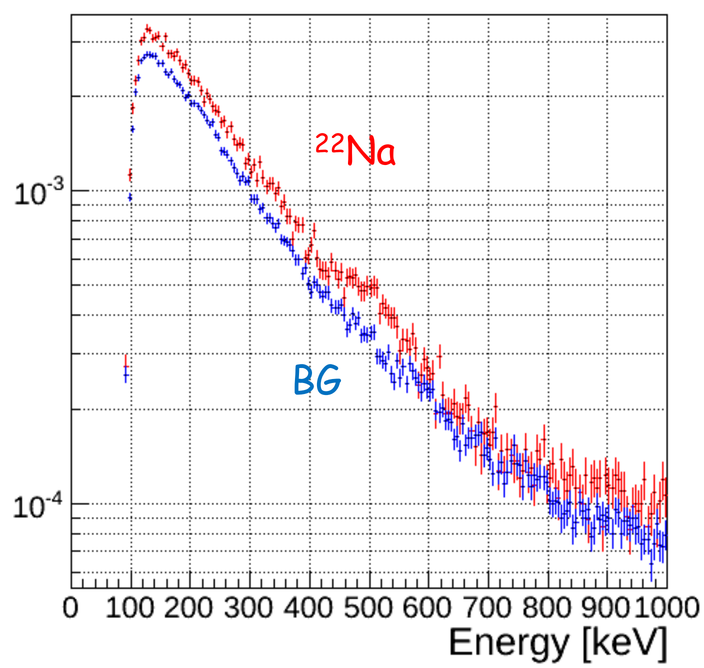
Crab nebula : BG-gamma ≈ 0.01 : 1

Weak ^{22}Na -> ~100 ph/s come into ETCC
511 keV : BG = 0.02 : 1

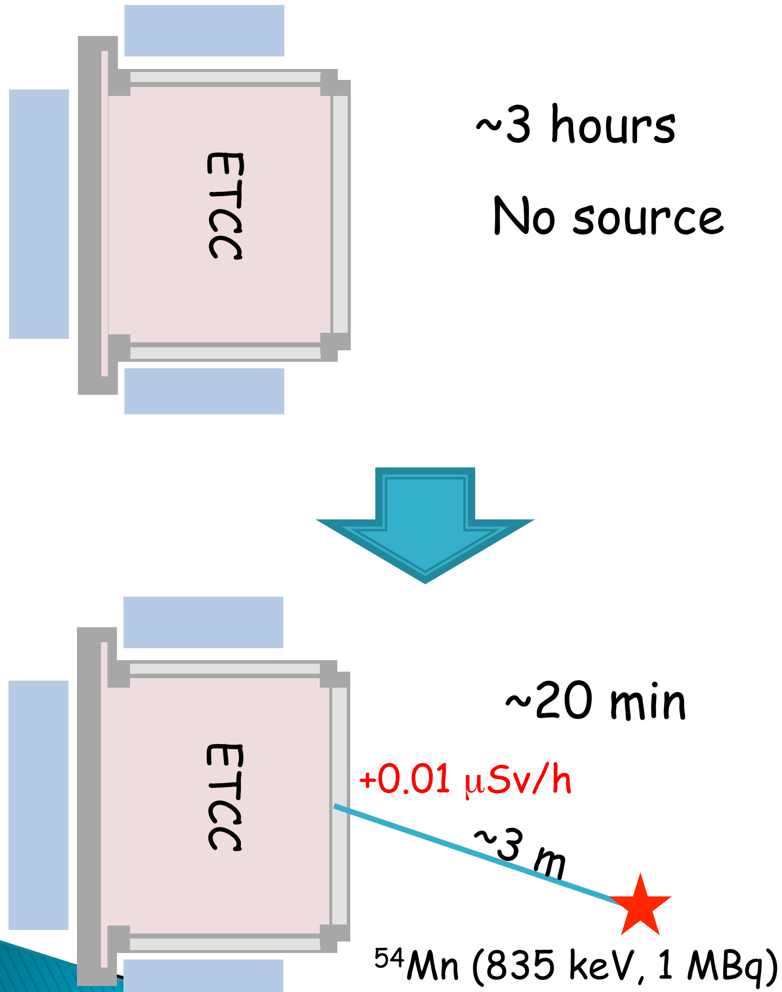
Gamma-ray image has a clear excess.
Significance of excess @ 511 keV is about 11σ during 5.5 h.

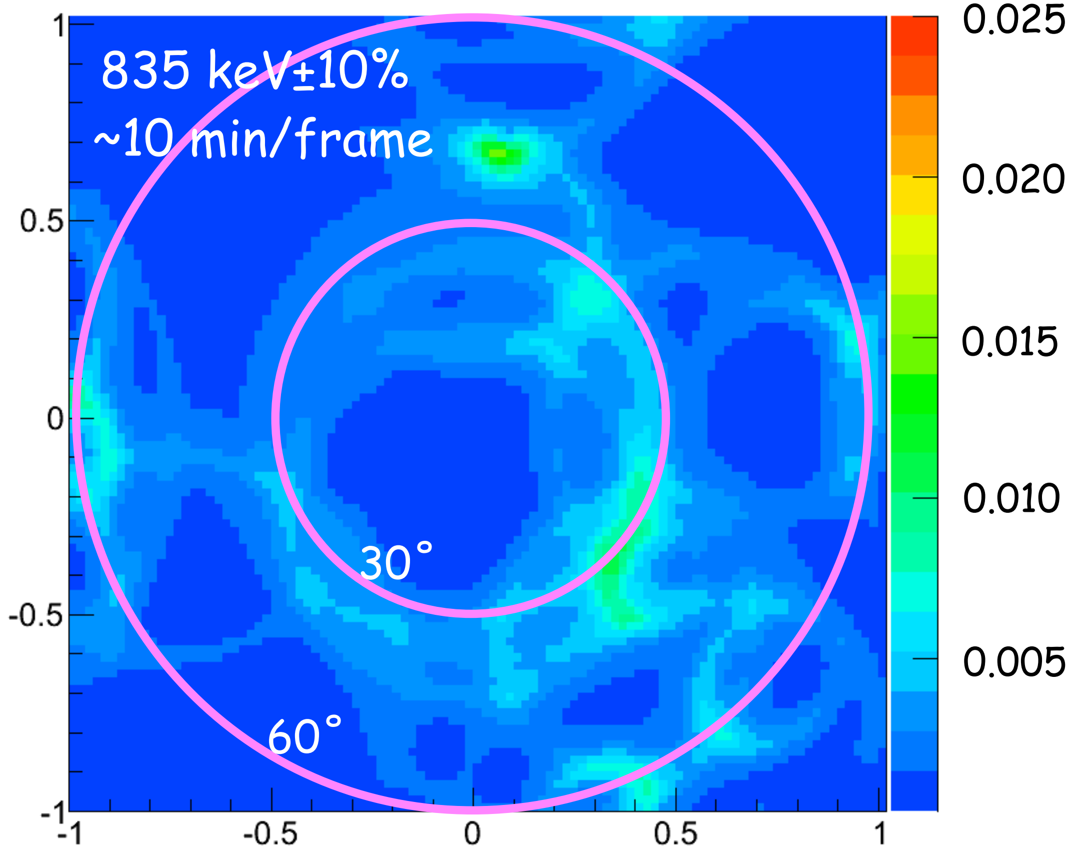




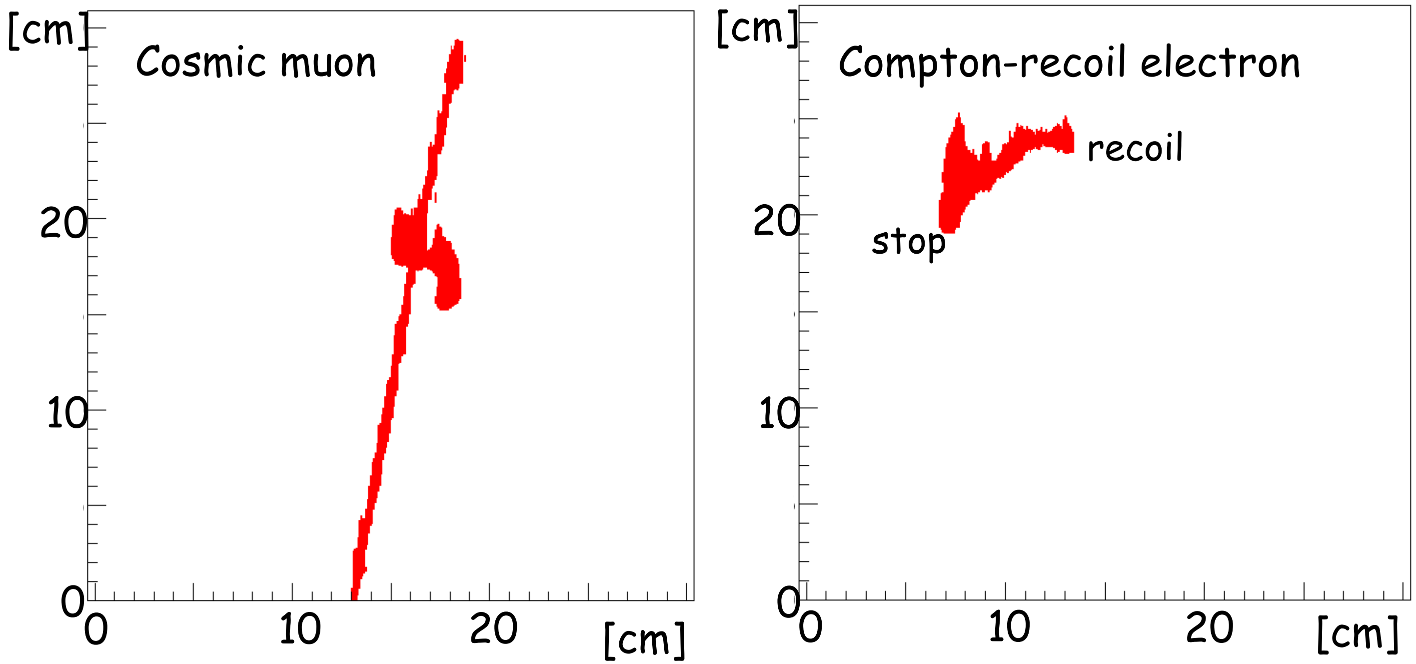


Experiment 3:
Observation of time variation



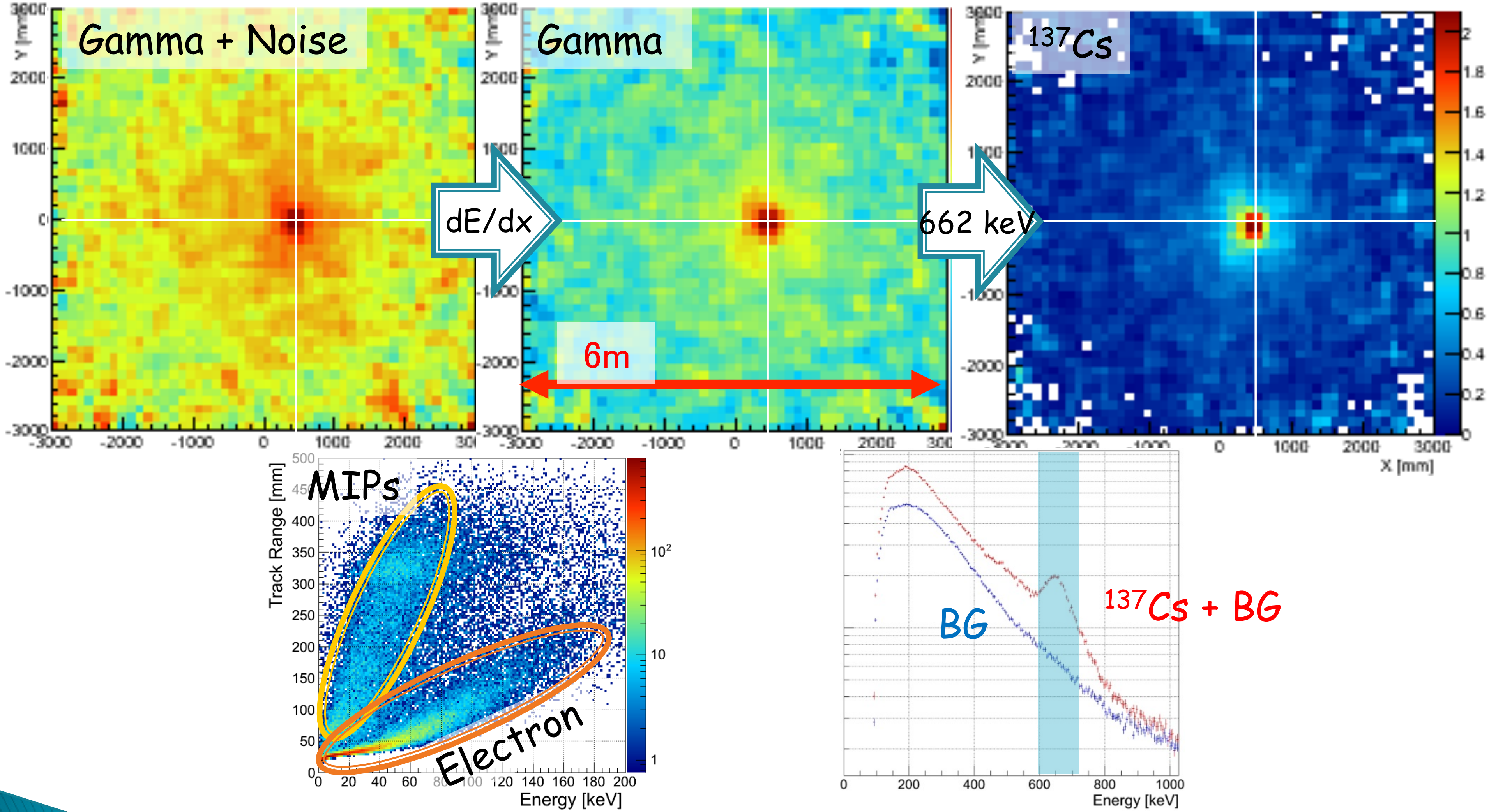


SMILE-II clearly detected
gamma-ray source with only 10 minutes.



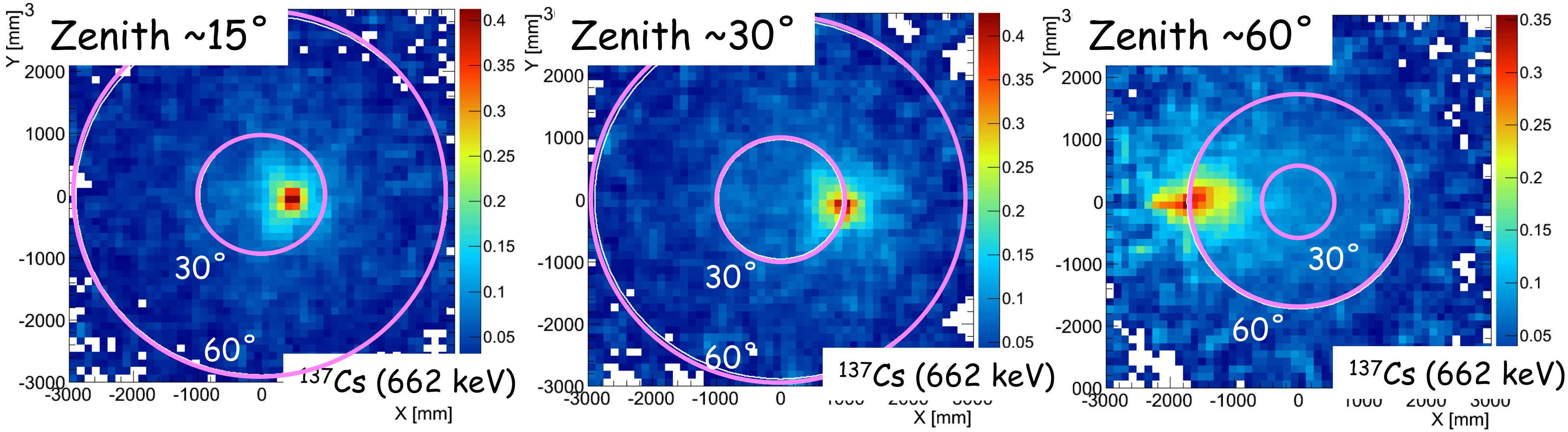
Cosmic muon
[cm]
0
10
20
[cm]
Compton-recoil electron
recoil
stop
[cm]
0
10
20
[cm]

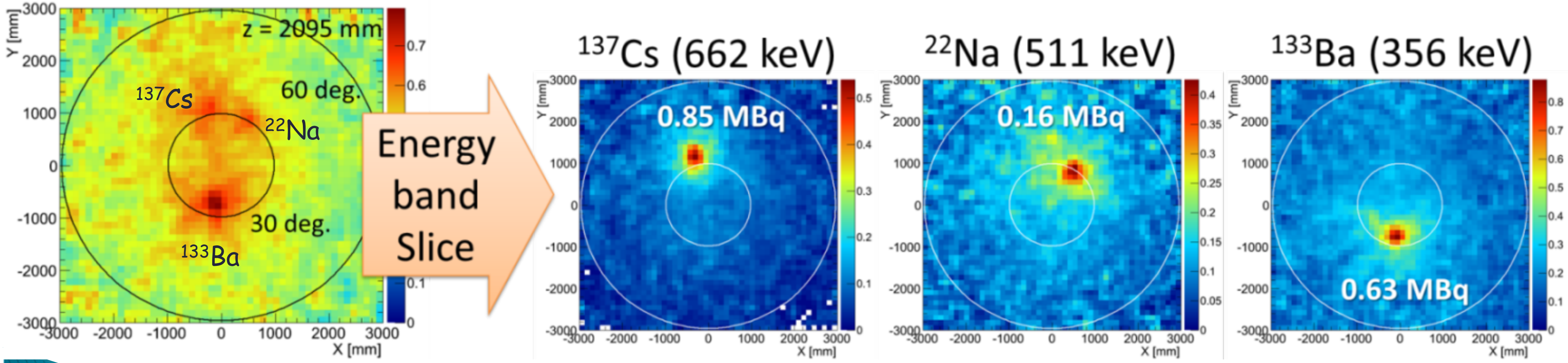
Event reconstruction



We can obtain a clear image with simple analysis.

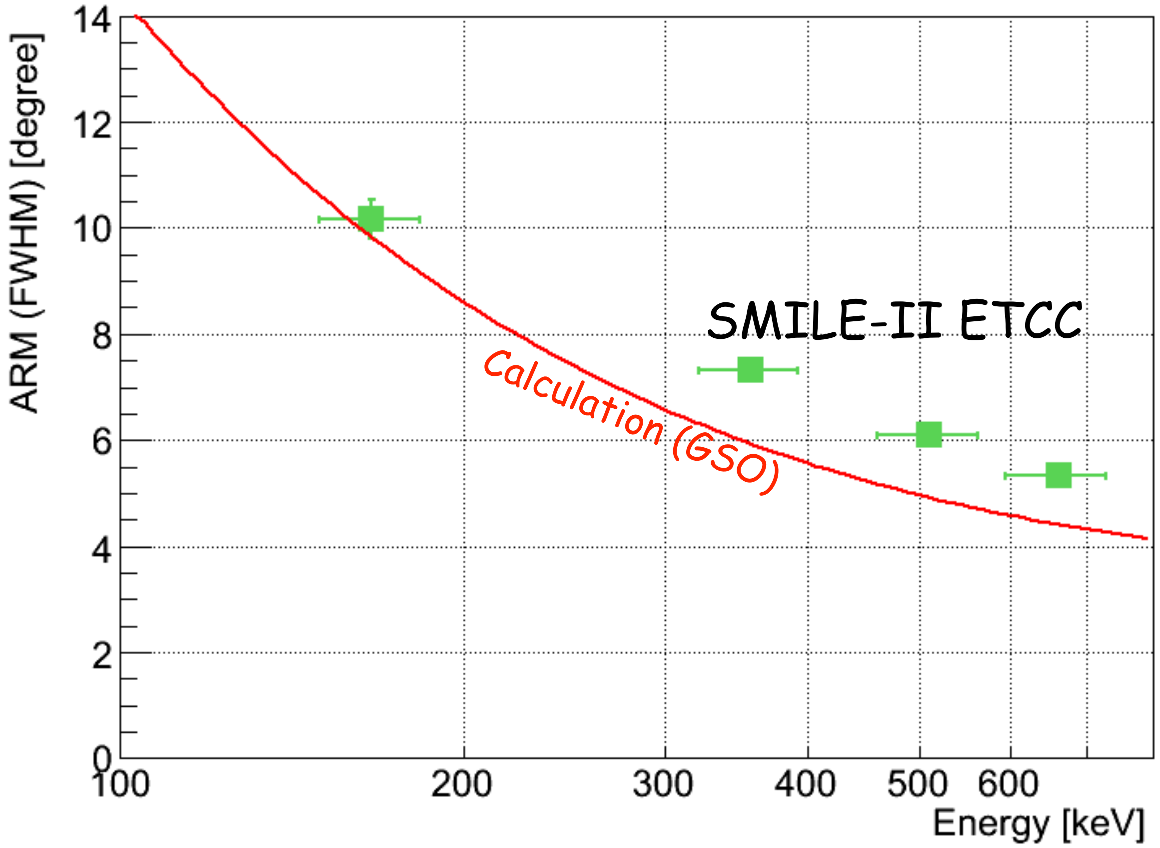
Back projection images





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

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

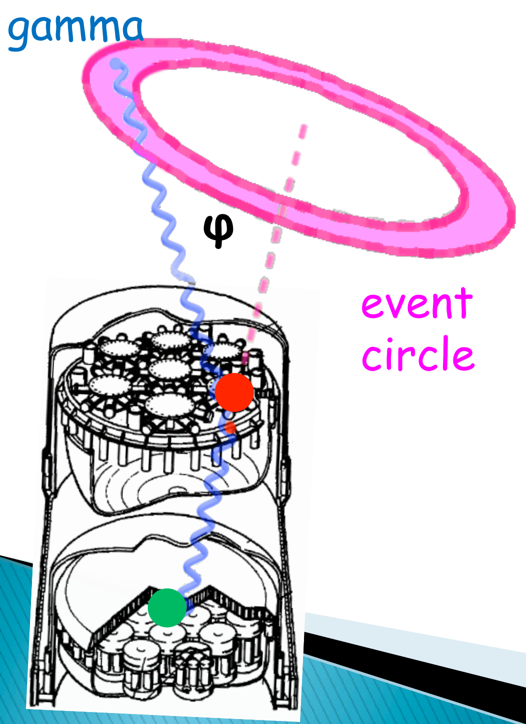
If we use $LaBr_3$ scintillator …
~3.5° (FWHM, 662 keV)

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

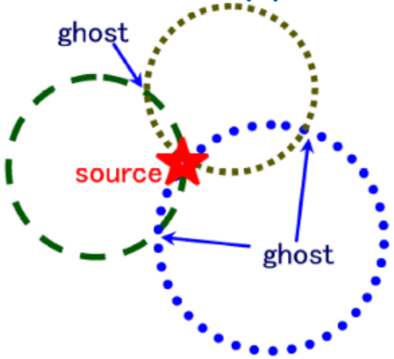
2nd : absorption point & energy of scattered gamma

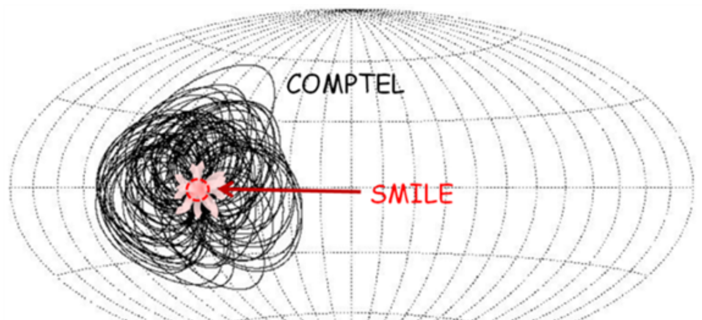
Not detect recoil direction

-> incomplete reconstruction

obtain source position by overlaying event circles

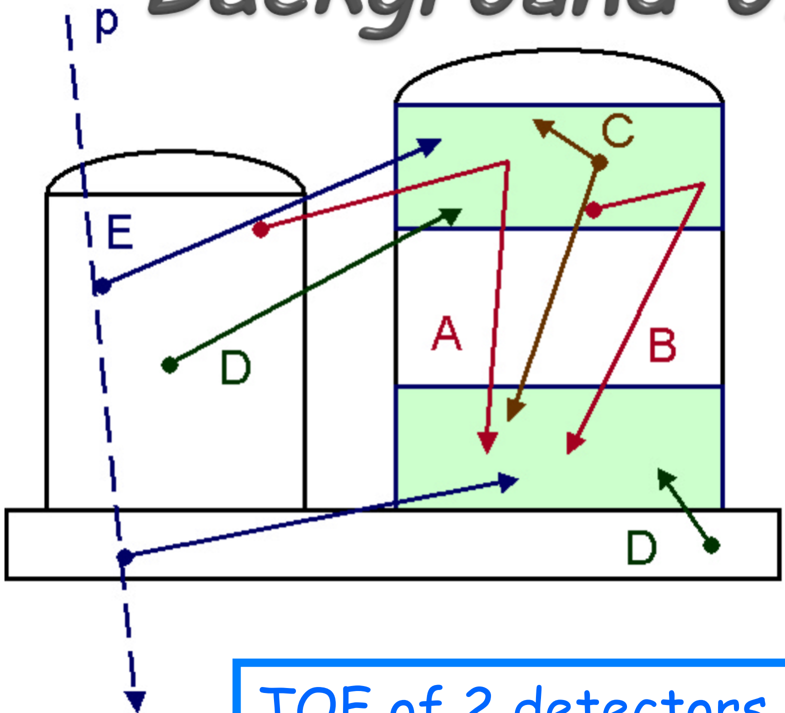
artifacts appear in image





Ryan, J. M., NewAR, 48, 199 (2004).

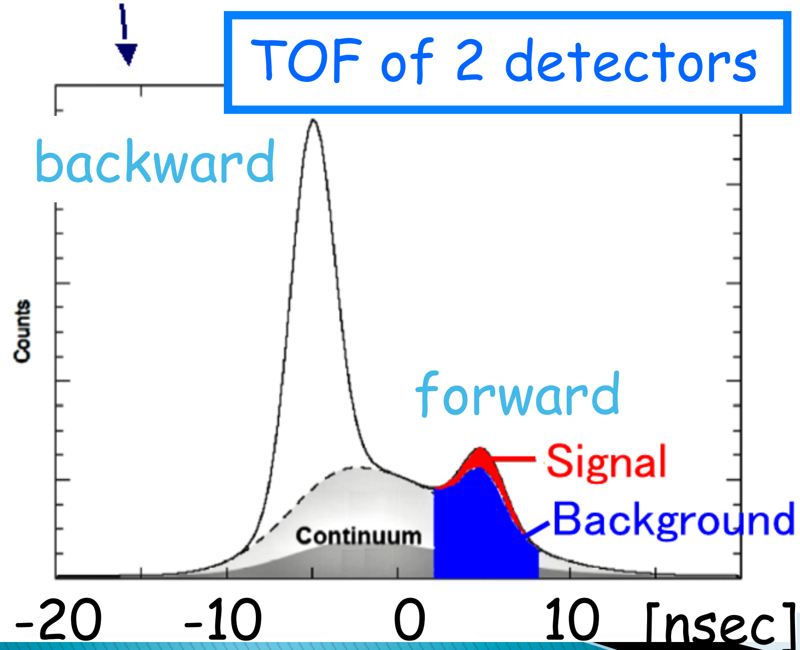
Background of COMPTEL



G.Weidenspointner, et.al. (A&A, 2001)

A : external γ
B : internal γ
} Intrinsic background
C : two γ
D : random coincidence
E: proton-induced γ

Other background
- neutron
- electron
- gamma from atmosphere



COMPTEL has rejected such background by the measurement of the Time Of Flight between 2 detectors.

Background rejection was not complete
Bad S/N