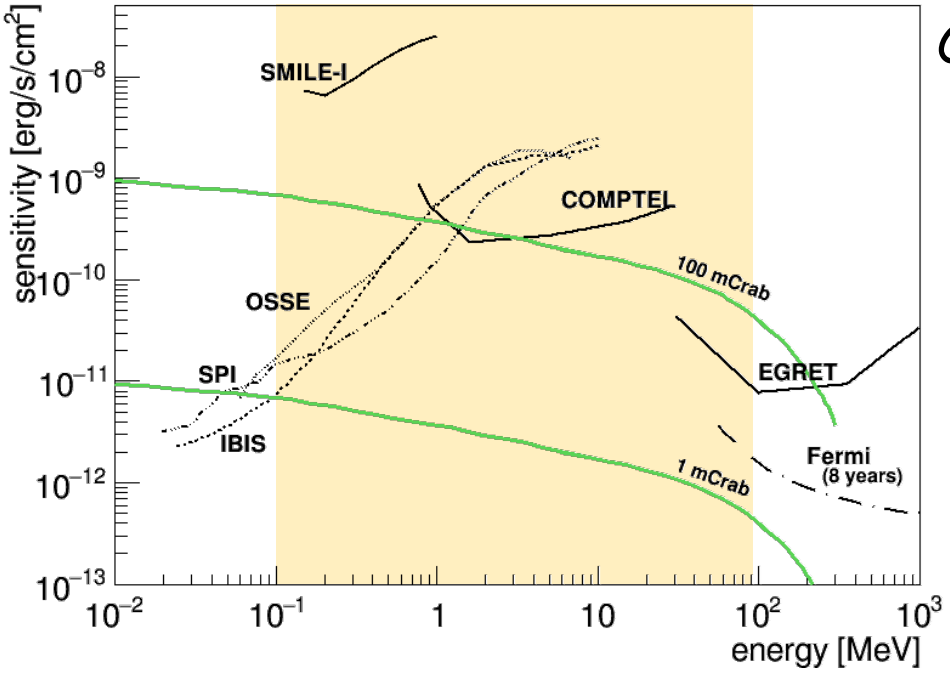
SMILE

Atsushi Takada (Kyono Univ.)

preparation for SMILE-2+ launching (Alice Springs, Australia)

For higher sensitivity



COMPTEL still has
the highest detection sensitivity.

$$\text{Sensitivity} \propto \sqrt{\frac{f_{BG}\,\Delta E\,\Delta\Omega}{A\,T}}$$

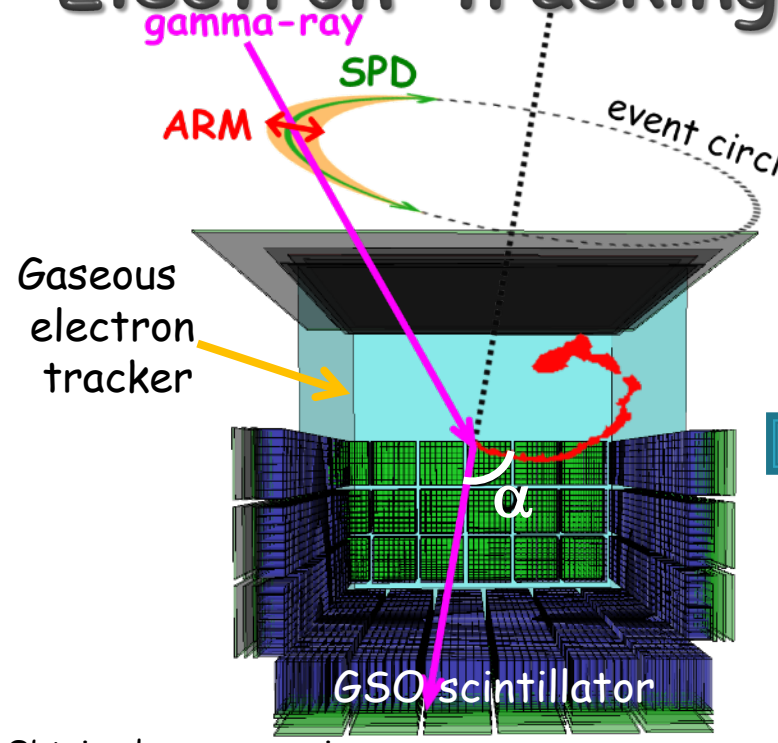
For higher sensitivity, we want…

- Low background
- Sharp point spread function
- Large effective area

- Low background
  light material, BG-rejection tools, …
- Sharp PSF
  recoil direction, good energy res., …
- Large area
  large volume, high density, …

We think
electron tracking
is most important.

Electron-tracking Compton camera (ETCC)

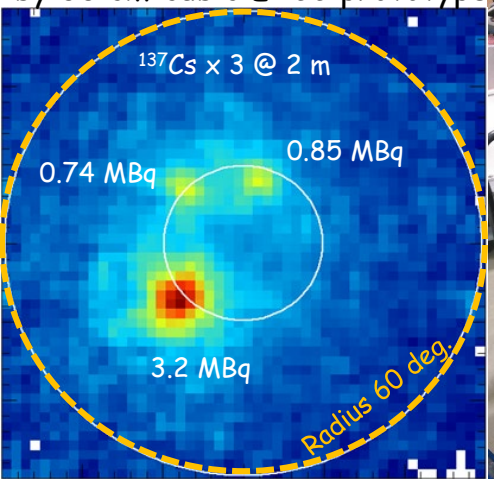


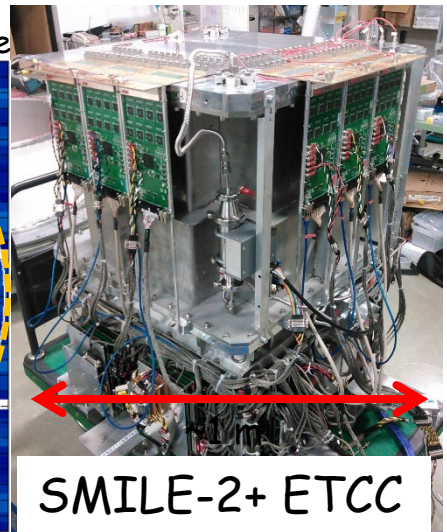
- Gaseous tracker
  Track & energy of recoil electron
- pixel scintillator array
  position & energy of scattered gamma

Reconstruct Compton scattering with momentum conservation

- Incident direction
  -> single point on celestial sphere
- Bijection telescope
  -> same as telescopes in the other band
  conventional camera is not bijection
- Sharp PSF based on electron tracks
  -> We can select the photons comes from the target region
- Compton kinematical test with angle α
  Particle identification with dE/dx
  -> No heavy VETO
  large FoV of 3 sr

Obtained gamma-ray image by 30 cm-cubic ETCC prototype





SMILE-2+ ETCC

Sub-MeV/MeV gamma-ray Imaging Loaded-on-balloon Experiments

✓ SMILE-I (Sanriku, 2006, 4h)
- Diffuse cosmic/atmospheric gamma-rays
- BG reduction by dE/dx

Eff. area 1 mm^2
Xe + Ar 1 atm
A. Takada+, ApJ (2011)

✓ SMILE-2+ (Alice Springs, 2018, 26h)
- first observation with a bijection telescope
- reached to the expected sensitivity
- Galactic center region (~8σ), Crab (~4σ)

Eff. area 1 cm^2
Ar 2 atm
T. Tanimori+, J. Phys CS (2020)
A. Takada+, ApJ (2022)

Now

➢ SMILE-3

Eff. area 5~10 cm^2
CF_4-base 3 atm

- scientific observation using long duration balloons
  - GC region -> $e^{\pm}$ annihilation, galactic diffuse
  - galactic plane -> ^{26}Al, ^{60}Fe
  - high latitude -> extragalactic diffuse, GRB
  - Crab, Cyg X-1, Cen A, sky survey

South :
- SPB @ mid. latitude
- ZPB @ Antarctic (NASA)
- ZPB @ mid. latitude (JAXA)

North :
- ZPB @ mid. latitude (NASA)
- ZPB @ high latitude (SSC, NASA)

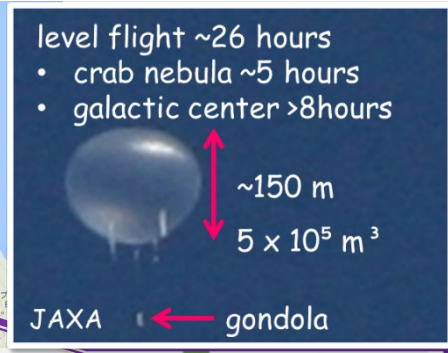
- one flight per a few years

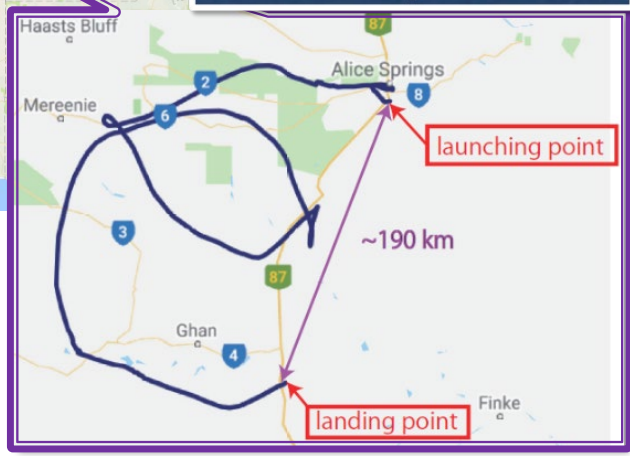
➢ SMILE satellite

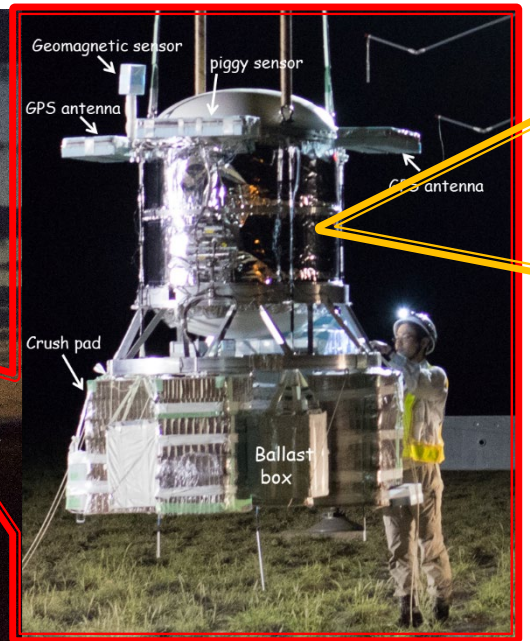
Eff. area ~100 cm^2
CF_4-base 3 atm

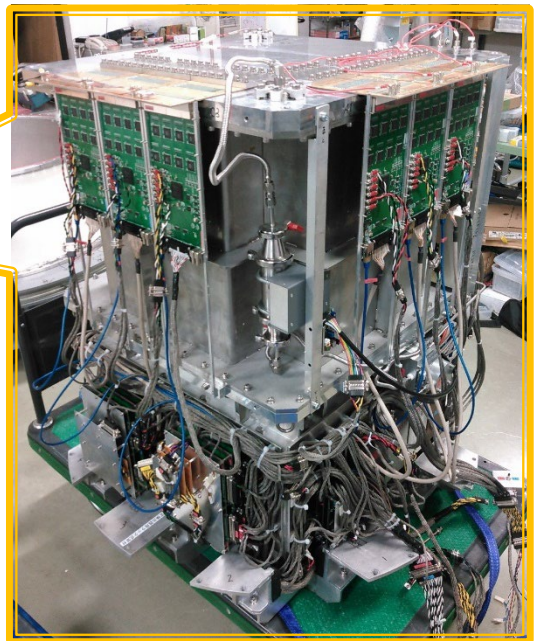
SMILE-2+

- ETCC
  - Range : 0.3~5 MeV
  - effective area : ~1 cm^2 (0.3 MeV)
  - PSF : ~30° (0.6 MeV)
  - weight : 511 kg power : ~250W
- Observation targets :
  - Galactic center region
  - Crab nebula
- Launched on April 7th, 2018, from Alice Springs
- Level flight lasted 26 hours at altitude > 38km
- System worked stably during level flight
- We successfully recovered SMILE-2+ gondola

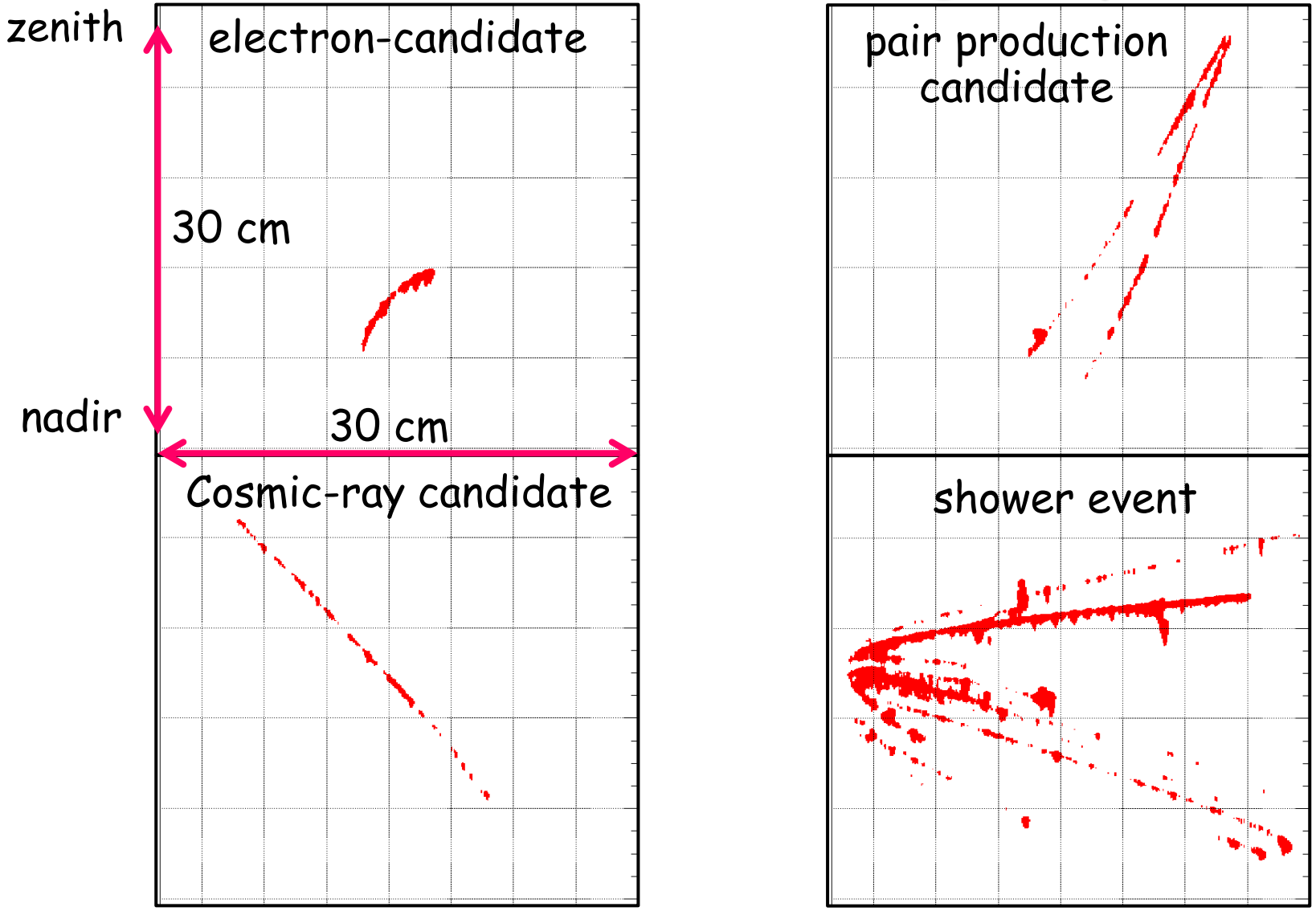








Obtained tracks of charged particles

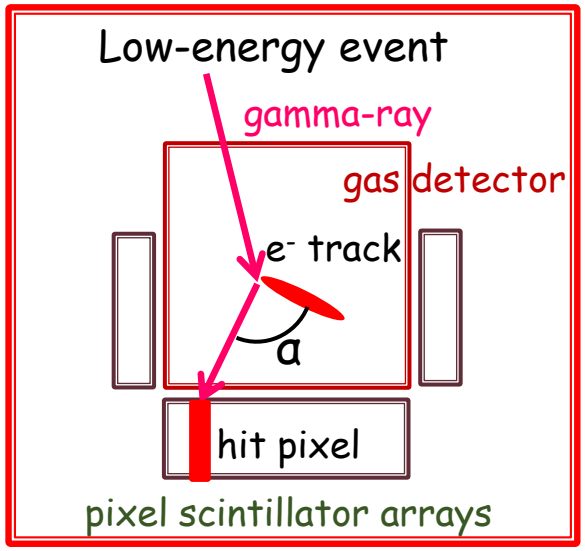


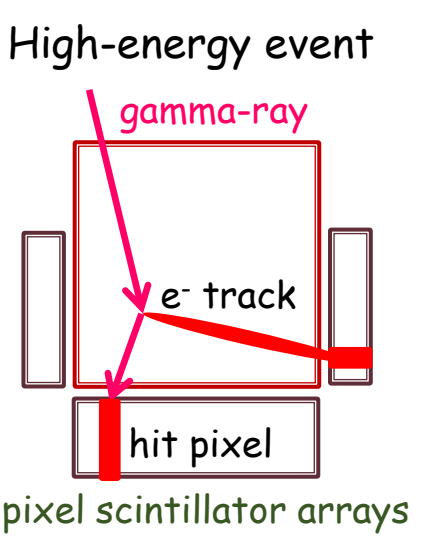
Our gas detector succeeded in getting charged particles.

Data analysis

We try to detect two type events with SMILE-2+ ETCC.

-> In this time, we present mainly 'low-energy events.'



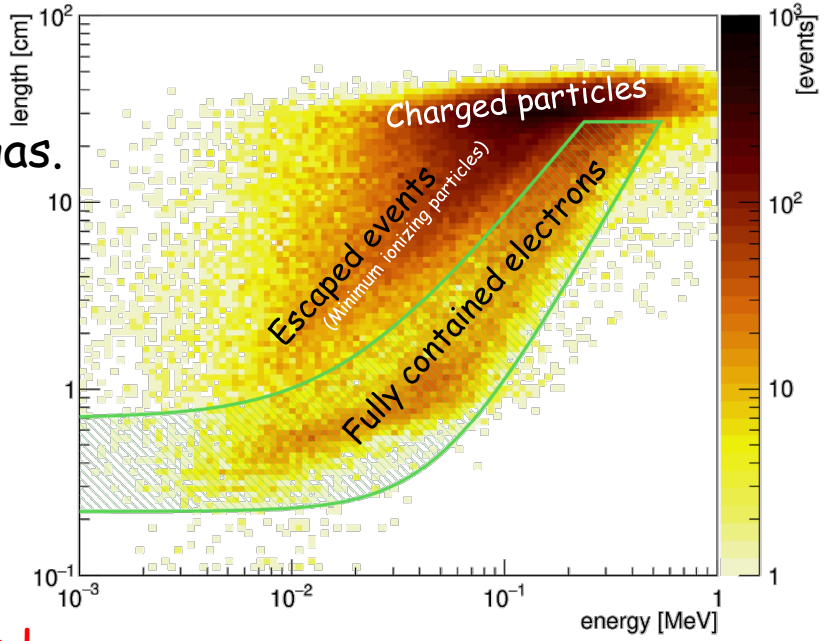


Criteria of event selection

1. Single pixel-scintillator hit
2. Fully contained electron selection
   -> select the events fitted to the range of electrons in argon gas.
3. Certification of Compton kinematics
   -> $|\cos\alpha_{geo} - \cos\alpha_{kin}| < 0.5$

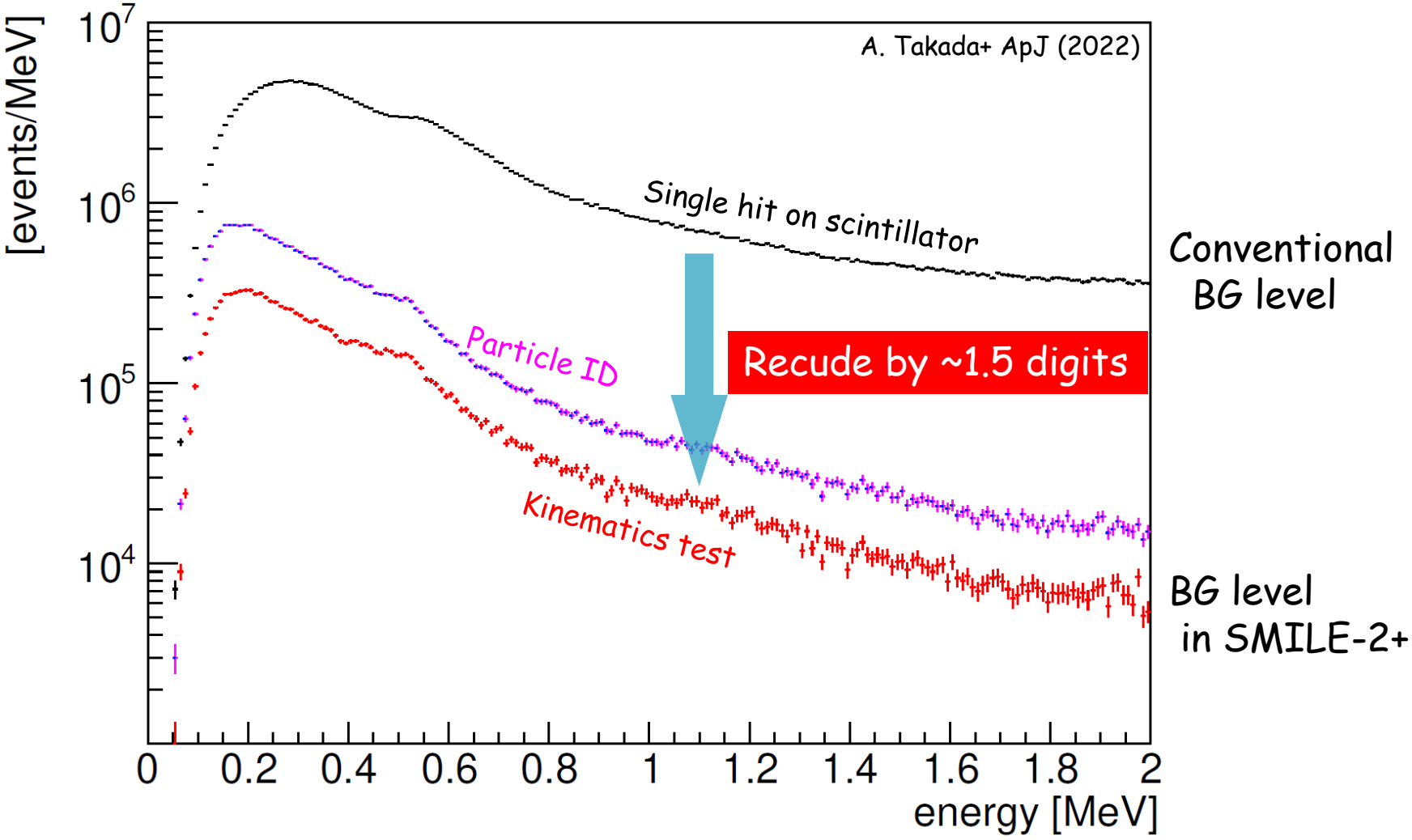
$$\cos\alpha_{\mathrm{geo}} = \vec{g}\cdot\vec{e}$$

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

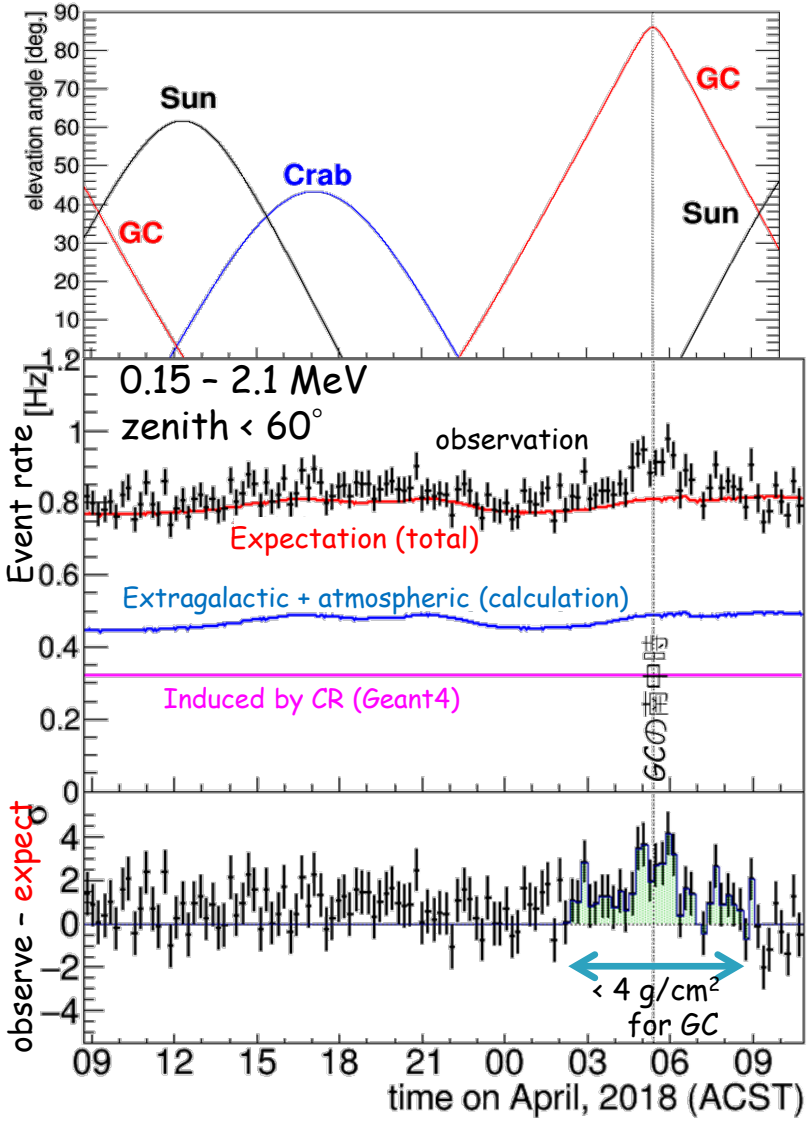


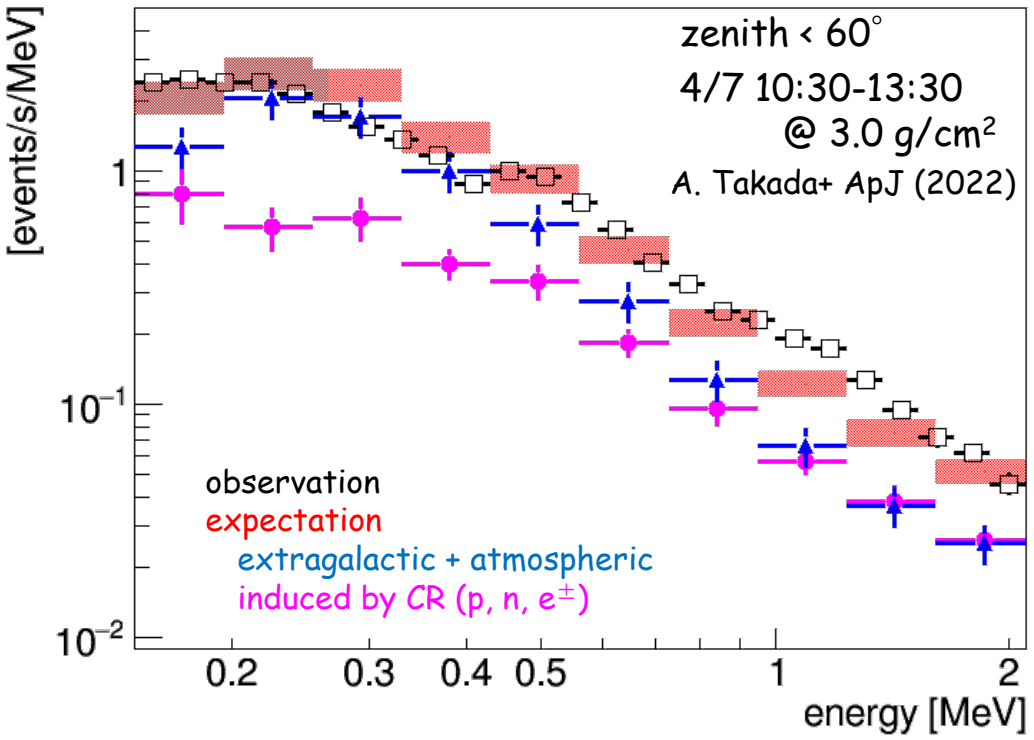
SMILE-2+ ETCC has no heavy veto counters, but criteria for noise-reduction are very simple.

Noise reduction in SMILE-2+



Observation by SMILE-2+

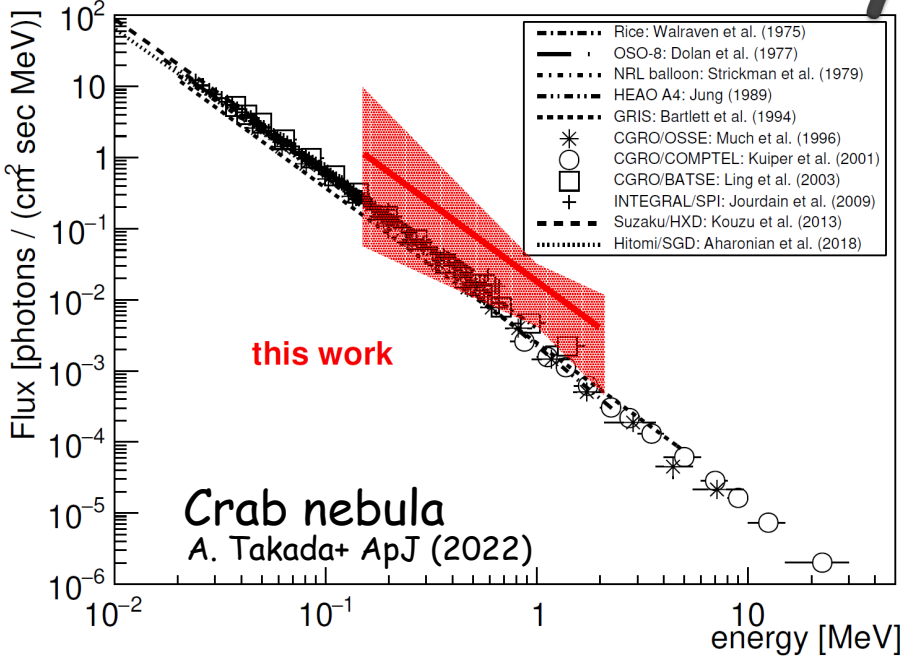


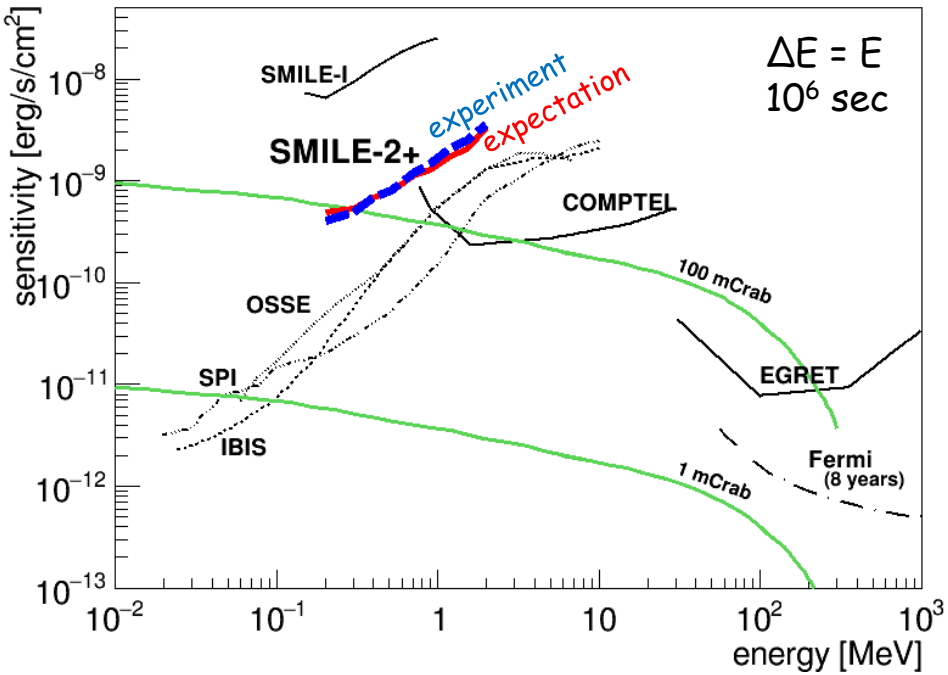


- Obtained event rate and spectrum be well consistent with expectation.
  -> It is completely known whose events become background in the observation of celestial objects.

Extragalactic + atmospheric : instrument = 1 : 1

Observation by SMILE-2+



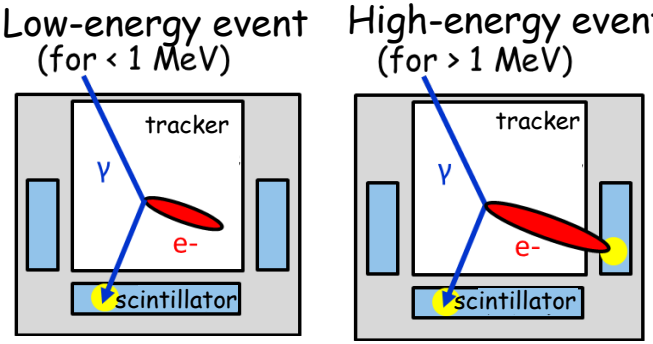


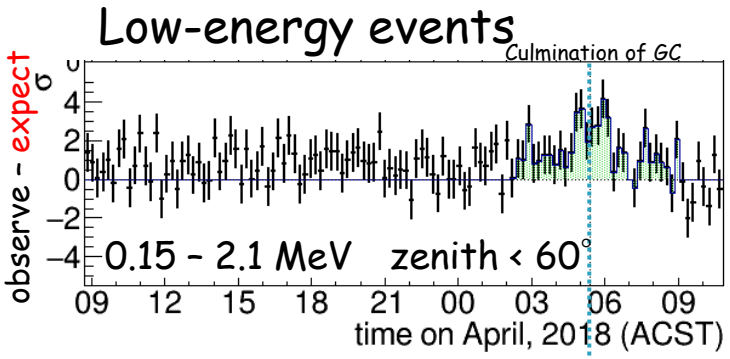
- Observation of Crab nebula
  expectation 3~5σ -> observation 4.0σ (0.15-2.1 MeV)
  Obtained energy spectrum is consistent with other observation.

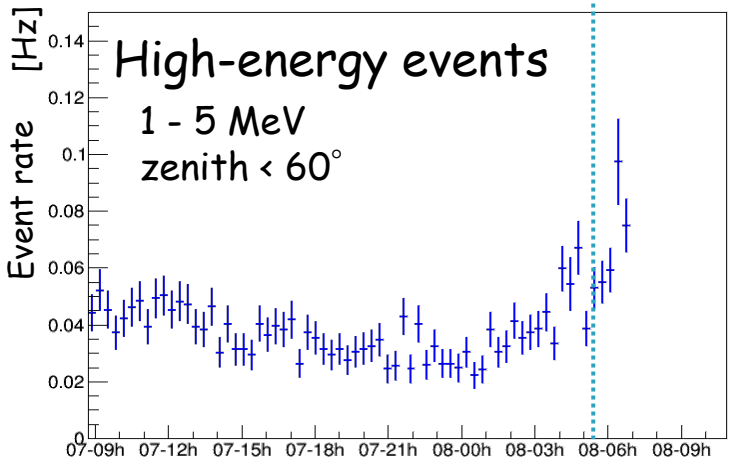
- understanding of observation background
  -> actual sensitivity = expectation based on ground calibration
  ETCC is the first designable telescope having a wide FoV in MeV
  sensitivity of COMPTEL was three time worse than expectation

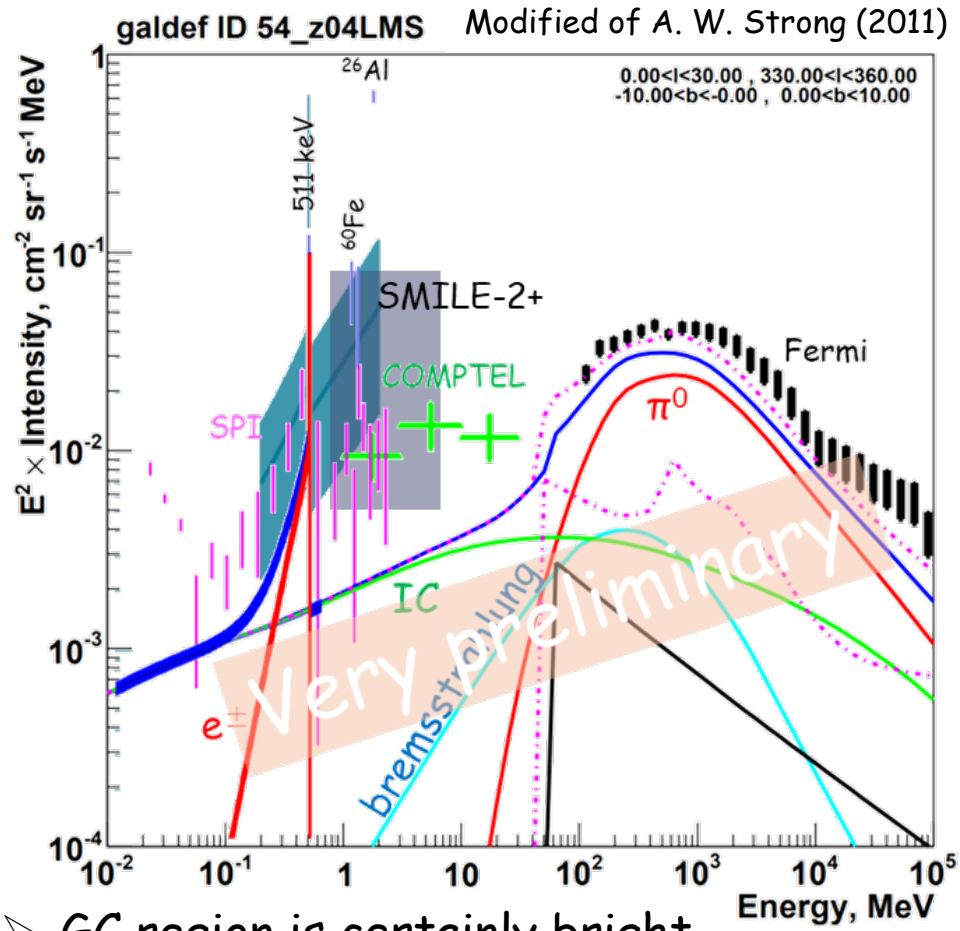
V. Schönfelder (2004)

Observation of GC region







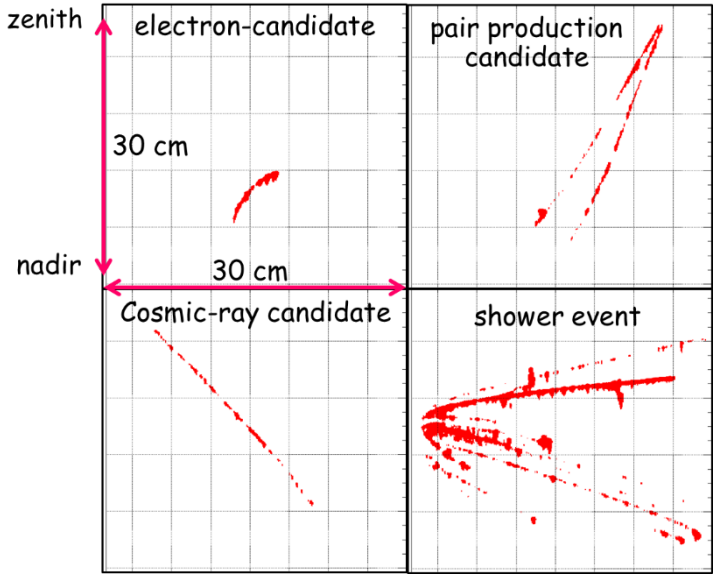


- GC region is certainly bright
- Consistent with SPI & COMPTEL
- 1 day balloon flight <-> ~10 years satellite

Suggestion from SMILE-2+

"Track images of charged particles"
have big information.

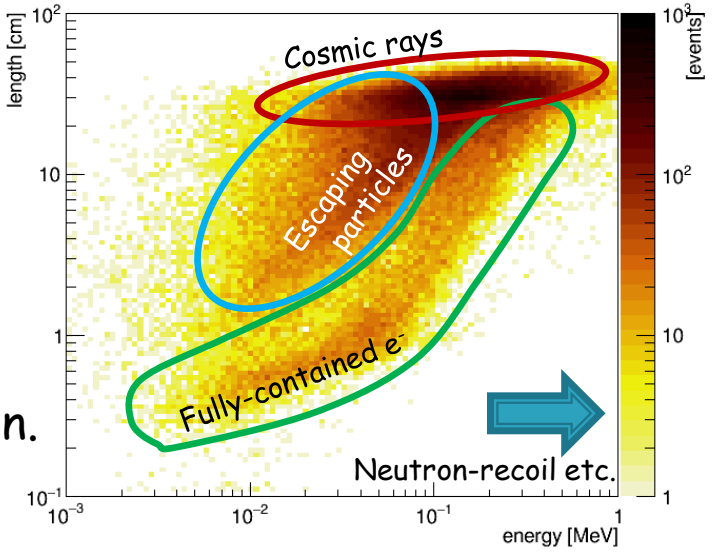
- Track image -> determine what happened
  - # of particles — Compton scattering, pair production
  - position — Cosmic rays
  - direction … — Shower event …
- Energy deposition rate
  -> particle identification
- Compton-recoil direction
  -> incident direction
  Compton-kinematical test



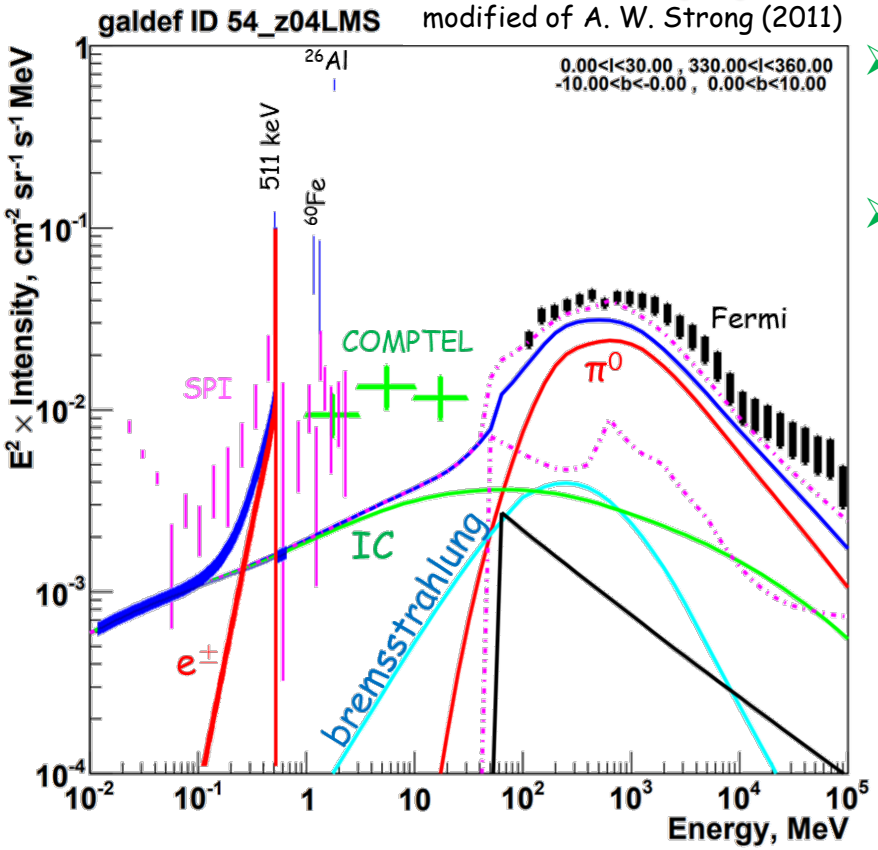
ETCC can restrict background powerfully.

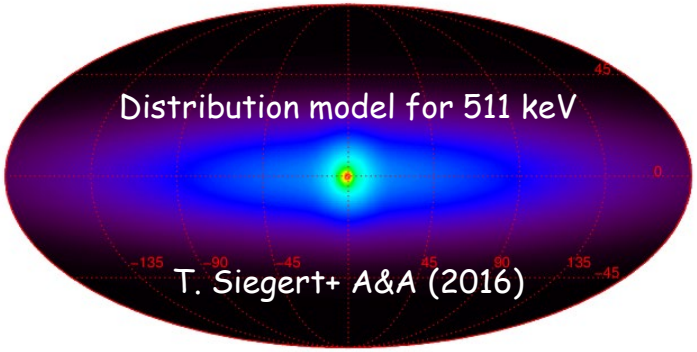
- Light curve has an excess at culmination of galactic center.
- Detected Crab nebula with 4σ.
- Realized sensitivity matched the expectation.

Track image is very important in MeV gamma-ray observations.



Galactic diffuse gamma-ray





- Continuum in MeV band
  - Stronger intensity than expectation of IC
  - Characteristic emission in MeV band
- Annihilation line of $e^{\pm}$
  - Origin of positron is unknown
  - Spatial distribution different from other band

- **Dark matter**
  annihilation or decay of light WIMPs
  -> electron, positron, gamma-ray
- **Primordial black hole**
  ~10^{17}g -> Hawing radiation at ~MeV
- **convolved point sources**
  Bright objects in MeV are unknown
  ~100 Crabs at GC.
- **Interaction between CR and ISM**
  expectation is 1/10 of intensity by IC

Celestial-objects -> concentrate to galactic plane
PBH or decay of DM -> proportional to density
Annihilation of DM -> proportional to (density)^2

Next step…

scientific observation using long duration balloons

GC region -> $e^{\pm}$ annihilation, galactic diffuse

galactic plane -> ^{26}Al, ^{60}Fe

high latitude -> extragalactic diffuse, GRB

Crab, Cyg X-1, Cen A, sky survey

North :
- ZPB @ mid. latitude (NASA)
- ZPB @ high latitude (SSC, NASA)

South :
- SPB @ mid. latitude
- ZPB @ Antarctic (NASA)
- ZPB @ mid. latitude (JAXA)

Eff. area	x5~10
PSF	x3
Obs. time	x30

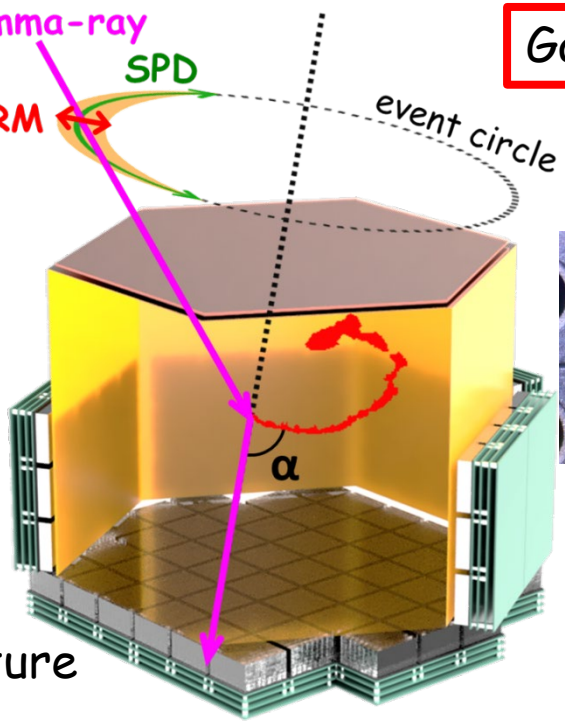
several time better sensitivity than that of COMPTEL

Scintillation camera

Photo readout with SiPM
-> improve PSF & energy resolution

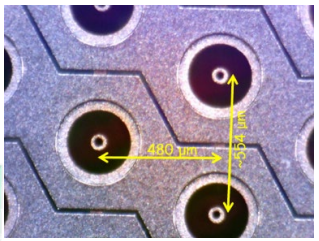
System & Gondola

expose ETCC to vacuum
weight reduction of structure



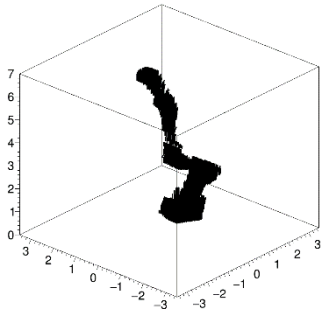
Gaseous tracker

CF_4 base, 3 atm
Triaxial μ-PIC

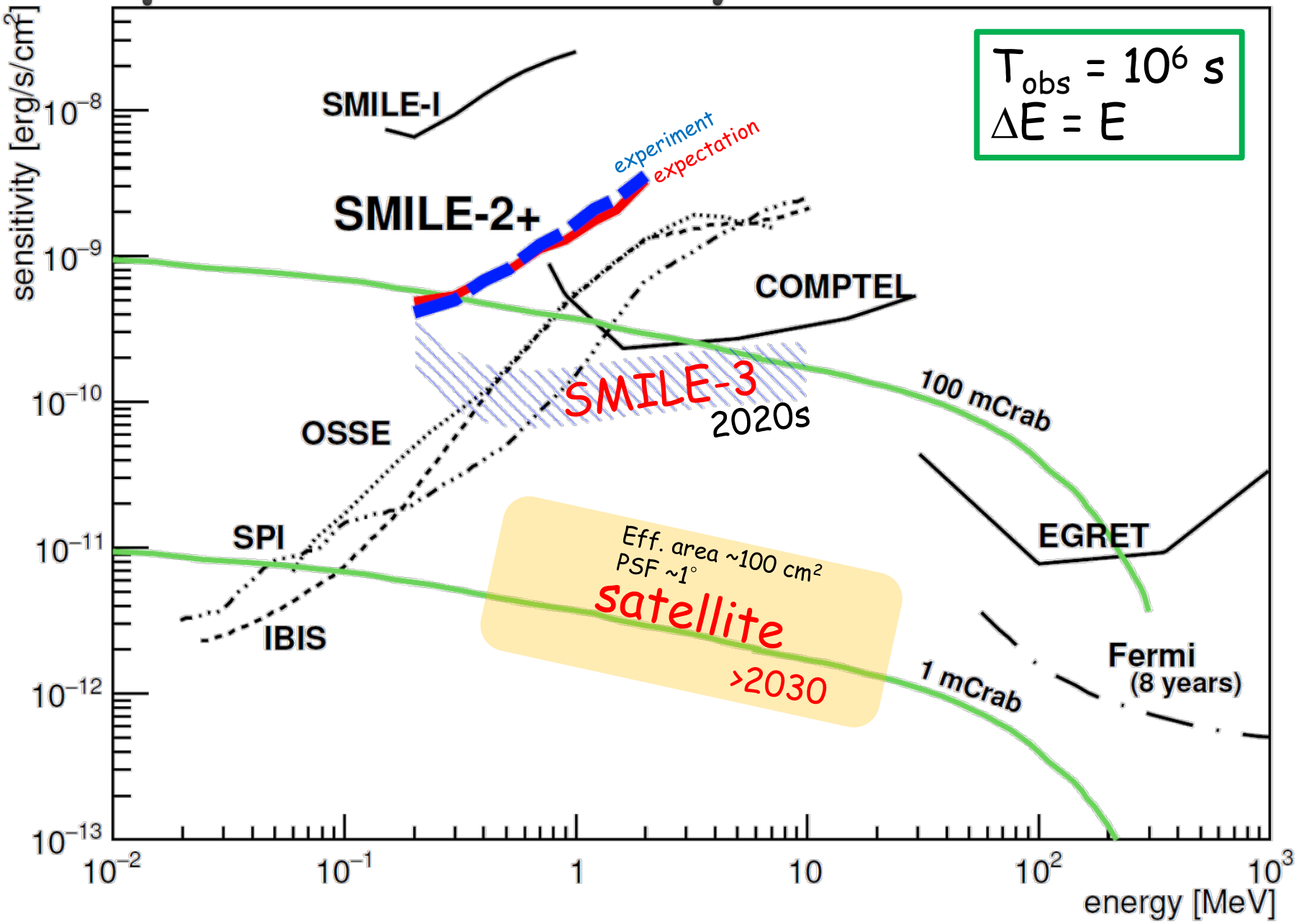


analysis

deep learning for tracks
high-energy events



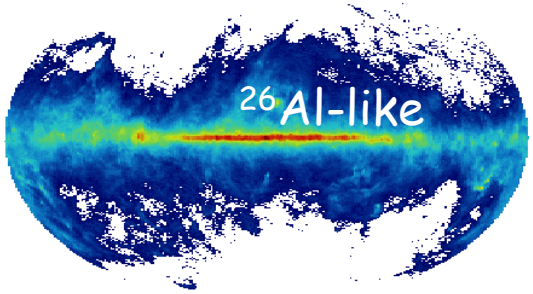
Expected sensitivity of SMILE-3



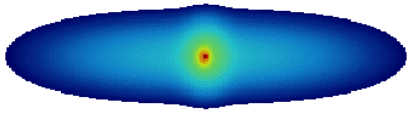
Expectation of SMILE-3 observation

Electron-positron annihilation

Along galactic plane ?

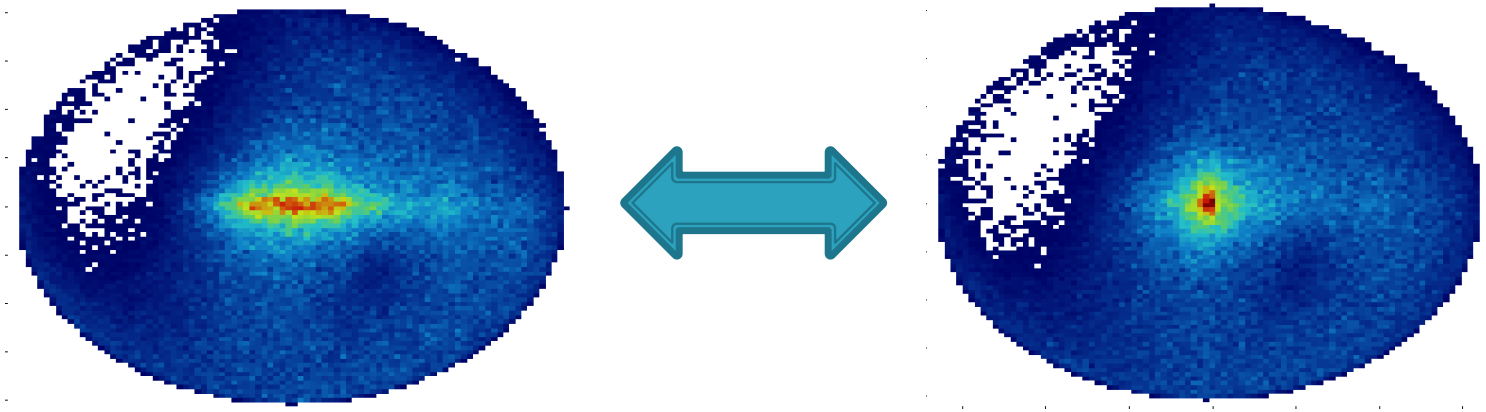


Bulge + Halo ?



SPI/INTEGRAL
T. Siegert+, 2016

Eff. area ~5 cm^2 @ 0.5 MeV
PSF ~10deg. @ 0.5 MeV
Southern hemisphere, 40 km, 30 days



Summary

- Electron-tracking Compton camera (ETCC)
  - ETCC is a bijection telescope
    mapping direction to single point on celestial sphere.
  - For the purpose of the observations in MeV,
    SMILE project is in progress.

- Observation of SMILE-2+
  - Event rate had a dependence on the elevation angle of galactic center.
  - Crab nebula was detected with 4.0σ. A. Takada+, ApJ (2022)
  - Realized detection sensitivity was consistent with expected sensitivity.
  - SMILE-2+ suggested that electron-tracking is most important.

- Next step, SMILE-3
  - detail observation of galactic center region
    with effective area of ~10 cm^2 and PSF of 5~10 degrees

- Long term future mission
  -> all sky survey with sensitivity of 1 mCrab

Thank you for your attention!

http://www-cr.scphys.kyoto-u.ac.jp