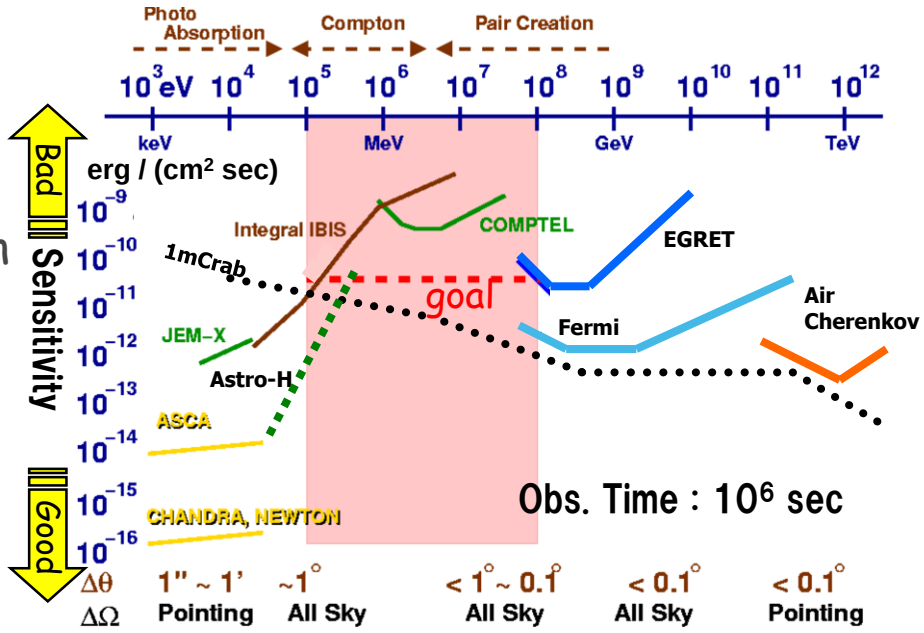
MeV gamma-ray observations utilizing electron-tracking Compton cameras loaded on balloons (SMILE project)

A. Takada (Kyoto University)

- MeV gamma-ray astronomy & SMILE project
- Preliminary results of SMILE-2+
- Next balloon: SMILE-3

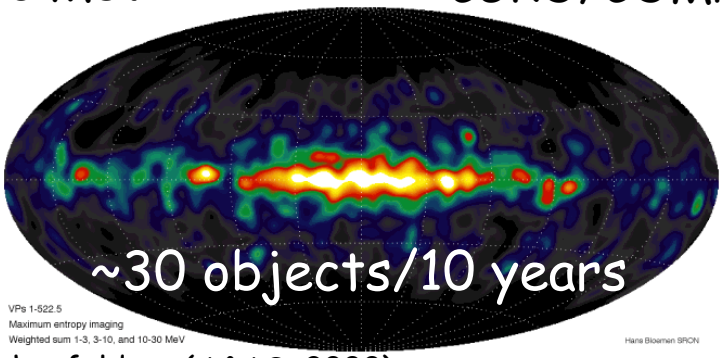
MeV Astronomy

- 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

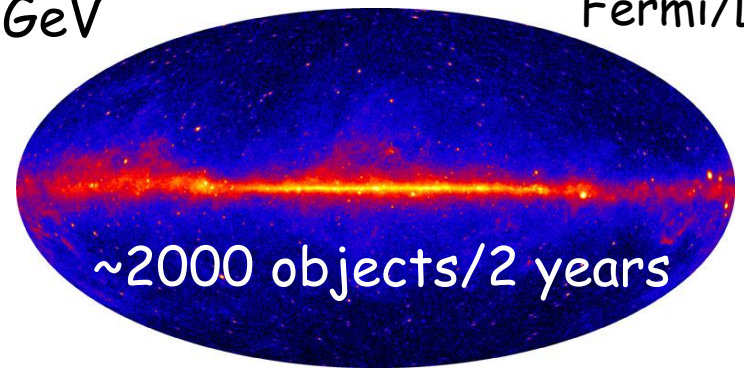
1-30 MeV CGRO/COMPTEL



V. Schönfelder+ (A&AS, 2000)

GeV sky map

> 1 GeV Fermi/LAT



P. L. Nolan+ (ApJS, 2012)

Requirements for the next-generation detectors are …

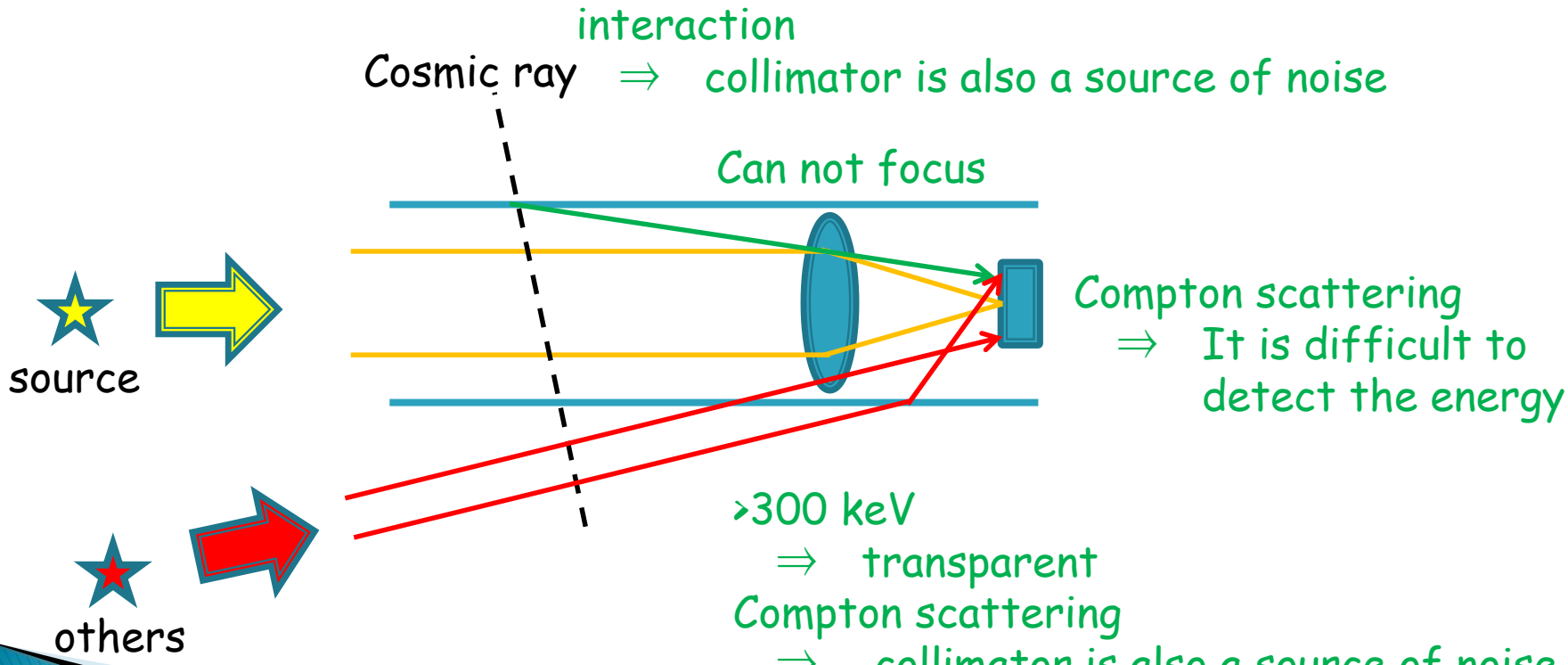
- Wide-band detection
- Large Field-of-View
- Sharp point-spread-function

Observe gamma rays

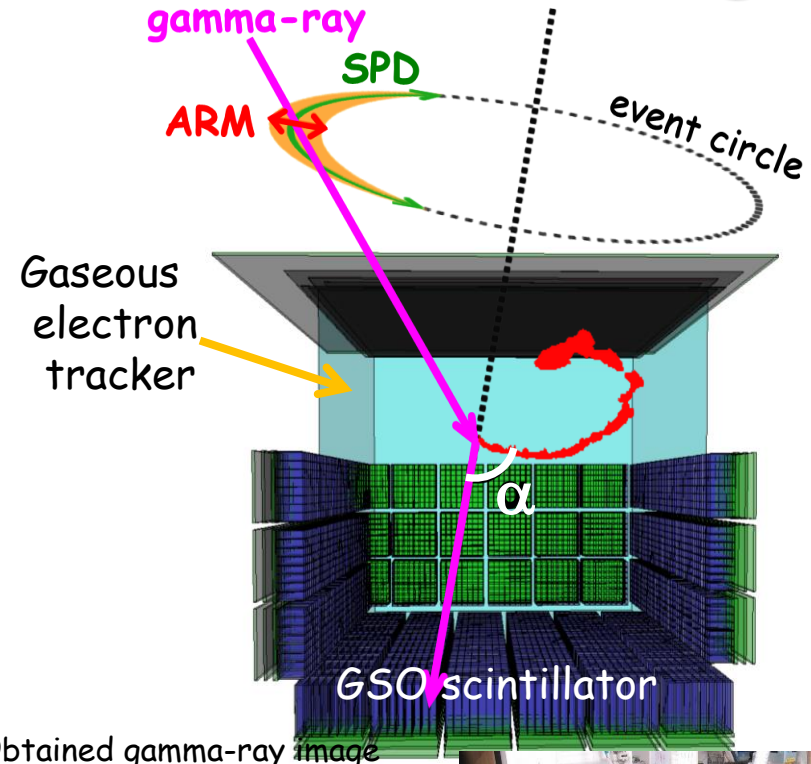
RIs • de-excitation • annihilation
bremsstrahlung • synchrotron radiation
Inverse Compton-scattering …etc

We want observe
radiation from source

New imaging technology is needed for MeV gamma ray



Electron-tracking Compton camera (ETCC)

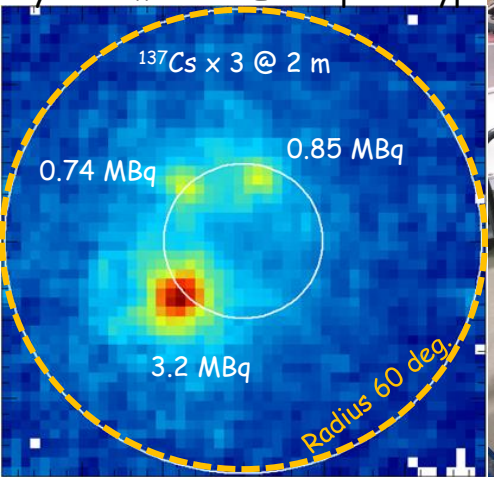


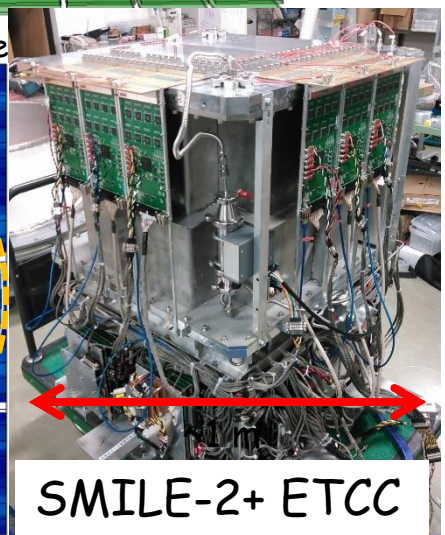
- Gaseous TPC : Tracker
  track and energy of recoil electron
- Scintillator : Absorber
  position and energy
  of scattered gamma ray

Reconstruct Compton scattering event by event

- 1 photon -> direction + energy
- Large FOV (~3 sr)
- Sharp PSF based on electron tracks
  -> We can select the photons comes from the target region
- Compton kinematical test with angle α
- Particle identify with dE/dx
- No heavy VETO & shield

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





SMILE-2+ ETCC

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

SMILE-I @ Sanriku (Sep. 1st 2006)

10 cm cubic, Xe+Ar 1 atm

- Confirmation of operation at the high altitude
- Observation of diffuse cosmic/atmospheric gamma-ray
  - -> ETCC was operated stably @ 35 km
  - Results were consistent with past observations

A. Takada+, ApJ, 2011

(30 cm)^2 prototype

only ground tests

30 cm cubic, Ar 1 atm

- Ground cal. -> eff. area : ~1 cm^2 @ <300 keV
  - ARM : 5.3° SPD : ~100° @ 662 keV
  - -> PSF : ~15° @ 662 keV

T. Tanimori+, ApJ, 2015

SMILE-2+ @ Alice Springs (Apr. 2018)

30 cm cubic, Ar 2 atm

- Observation of bright objects G.C. region & Crab nebula
- eff. area : ~1 cm^2 @ 300 keV PSF : ~30° @ 662 keV
  - -> detected G.C region (~10σ) and Crab nebula (~3.5σ)

SMILE-3

30 cm hexagonal column, CF_4 3 atm

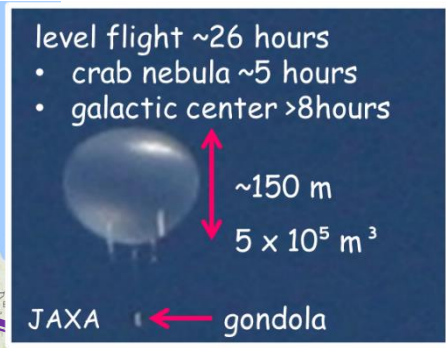
- Scientific observation loaded on a long duration balloon
- eff. area : ~10 cm^2 @ <300 keV
  - PSF : ~9° @ 511 keV

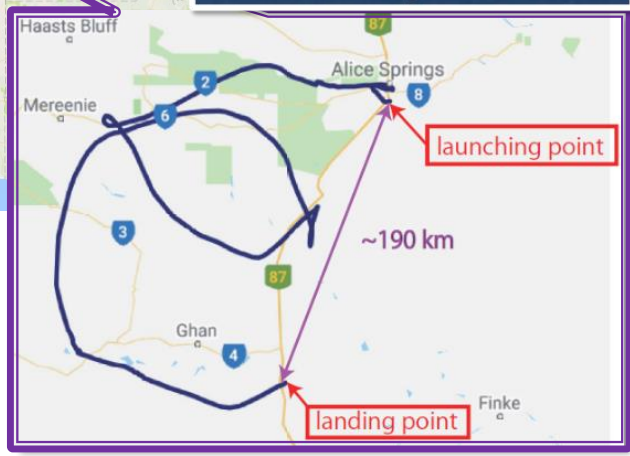
All sky survey with a satellite

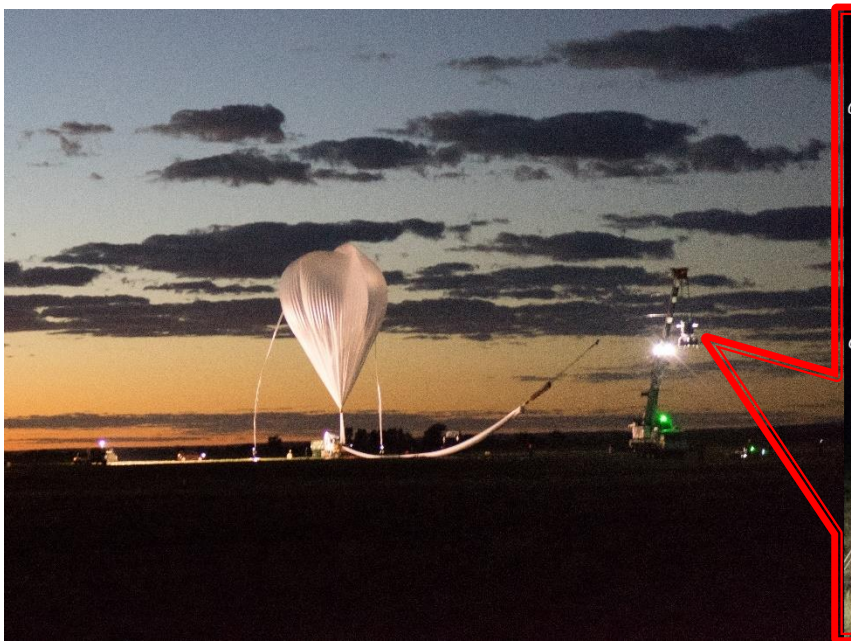
50 cm cubic, CF_4 3 atm

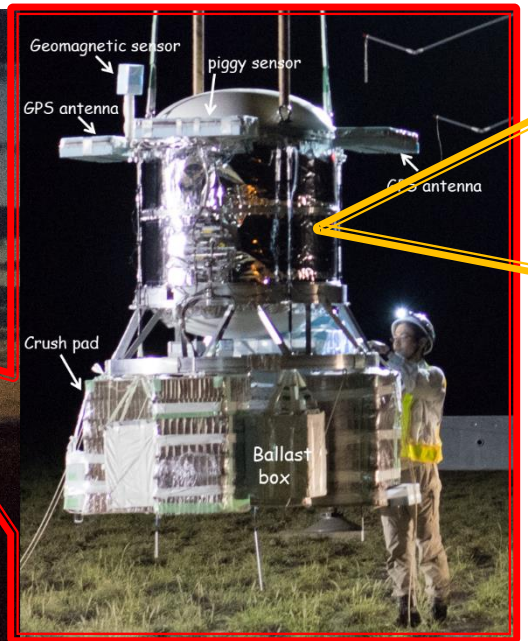
SMILE-2+

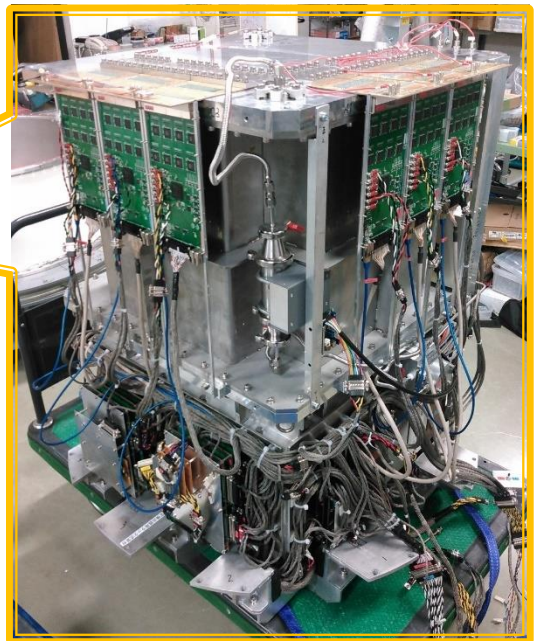
- ETCC
  - Range : 0.3~5 MeV
  - effective area : ~1 cm^2 (0.3 MeV)
  - PSF : ~20° (0.6 MeV)
  - weight : 511 kg power : ~250W
- Observation targets :
  - Galactic center region
  - Crab nebula
- Launched on April 7th, 2018, from Alice Springs
- Level flight lasted 26 hours at altitude > 38km
- System worked stably during level flight
- We successfully recovered SMILE-2+ gondola



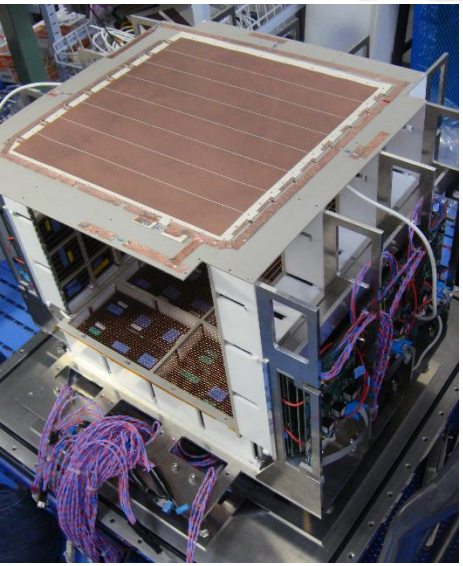


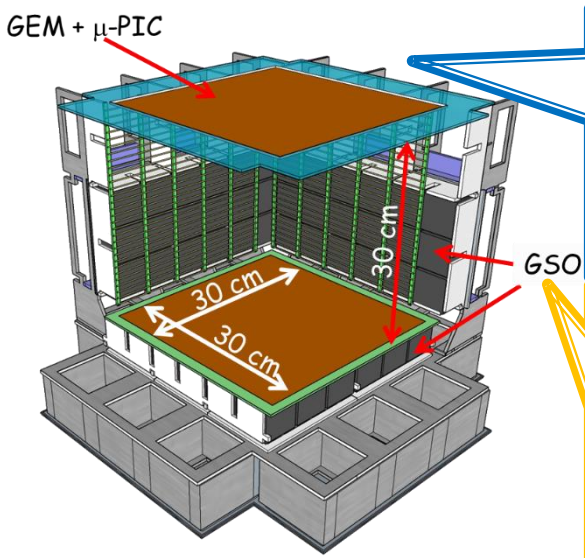


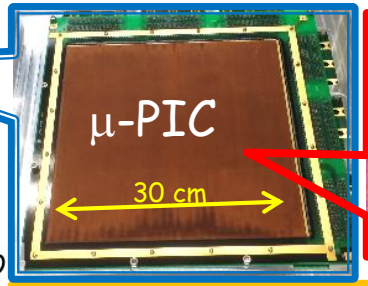


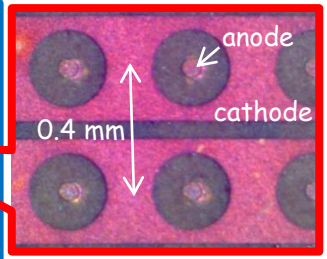


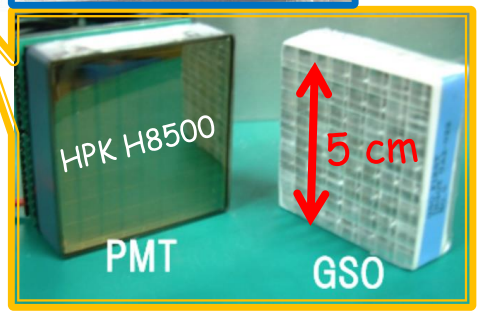
SMILE-2+ ETCC

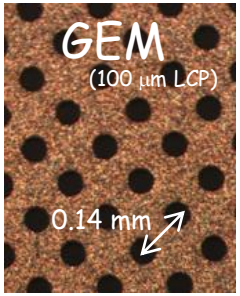


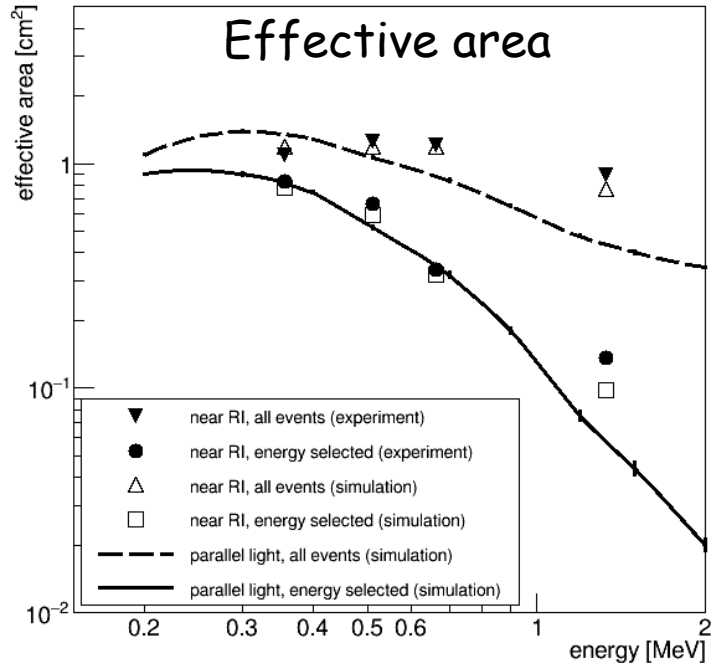


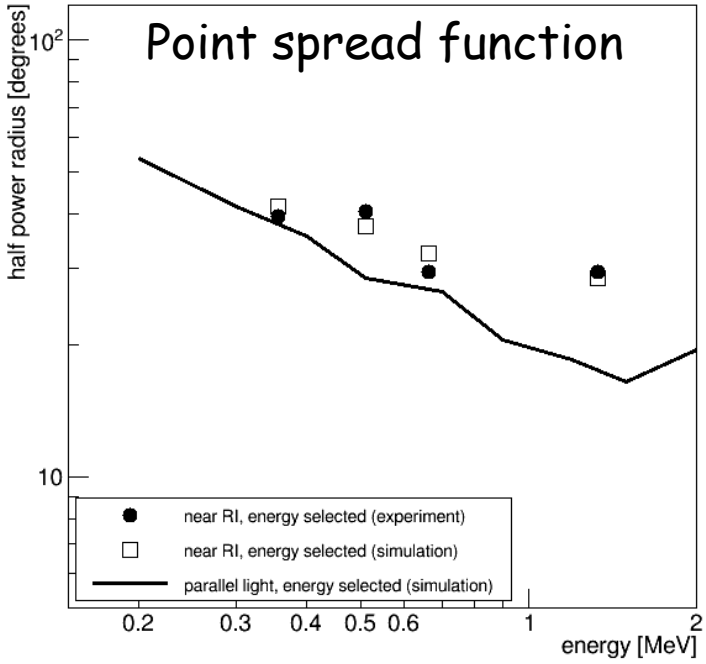










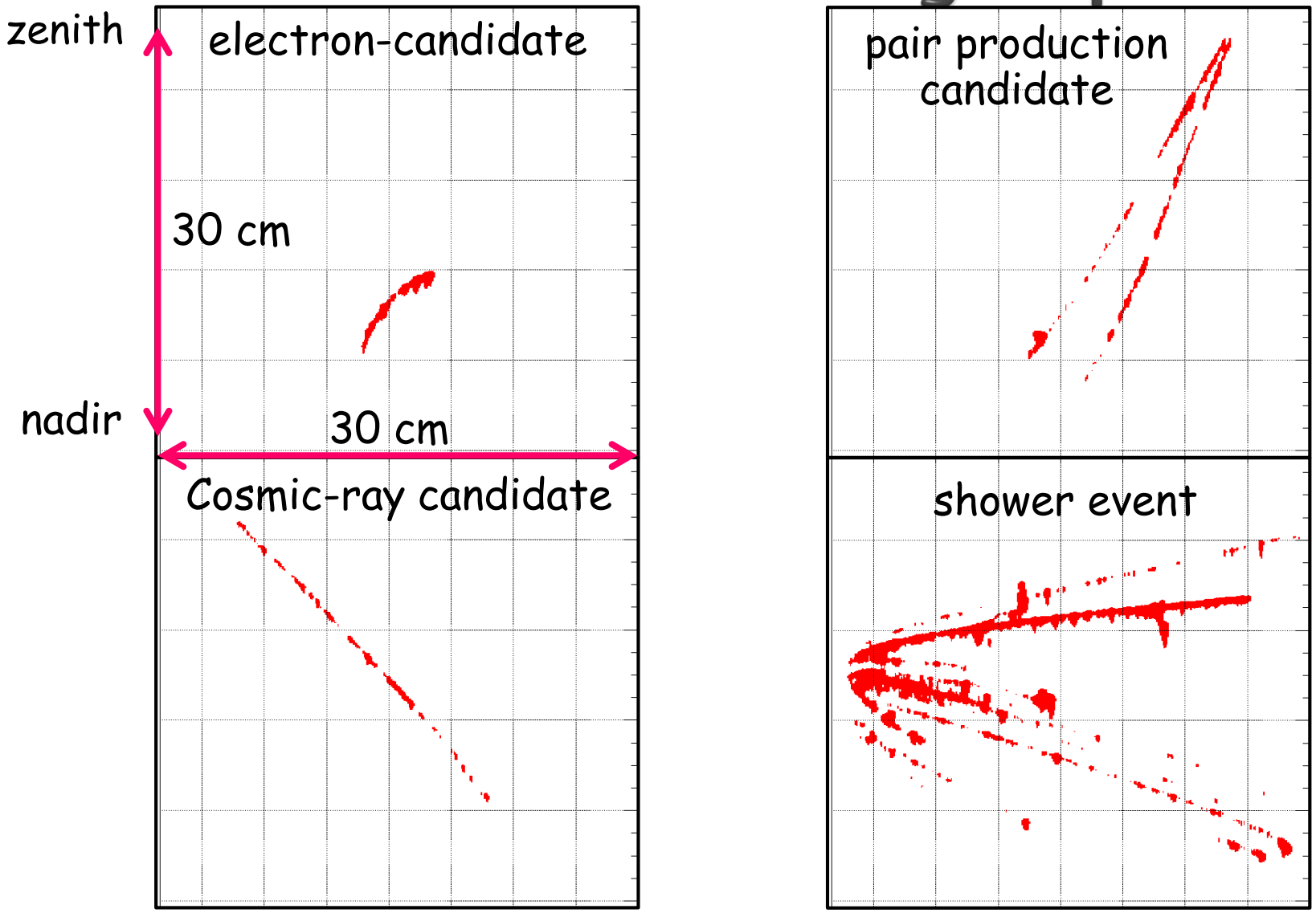


Effective area :
~1 cm^2 @ 0.3 MeV

PSF :
~30 deg. @ 0.6MeV

Crab nebula
will be detect ~3σ
@ 3.5 g/cm^2, Alice Springs

Obtained tracks of charged particles

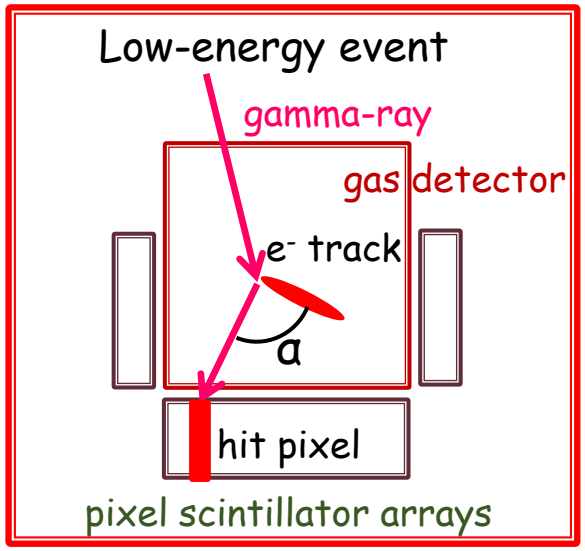


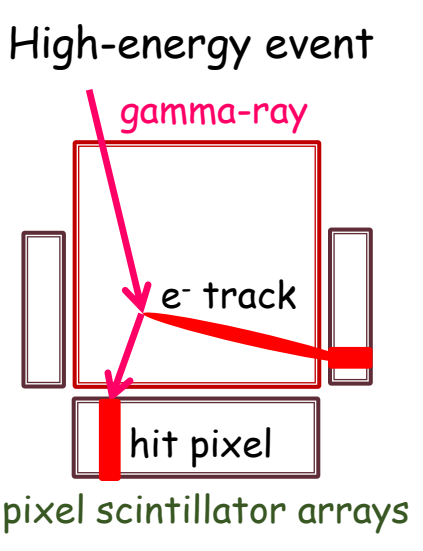
Our gas detector succeeded in getting charged particles.

Data analysis

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

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



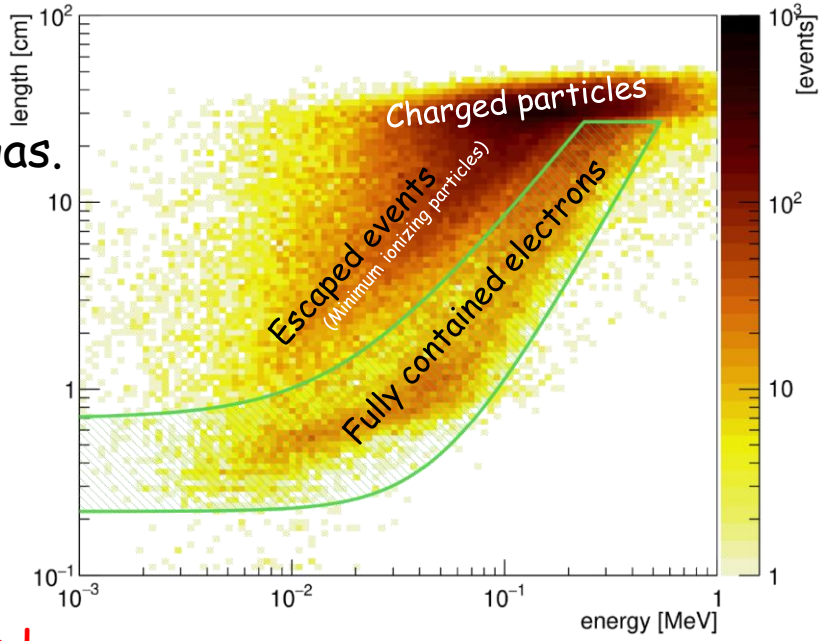


Criteria of event selection

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
   -> $|\cos\alpha_{geo}-\cos\alpha_{kin}| < 0.5$

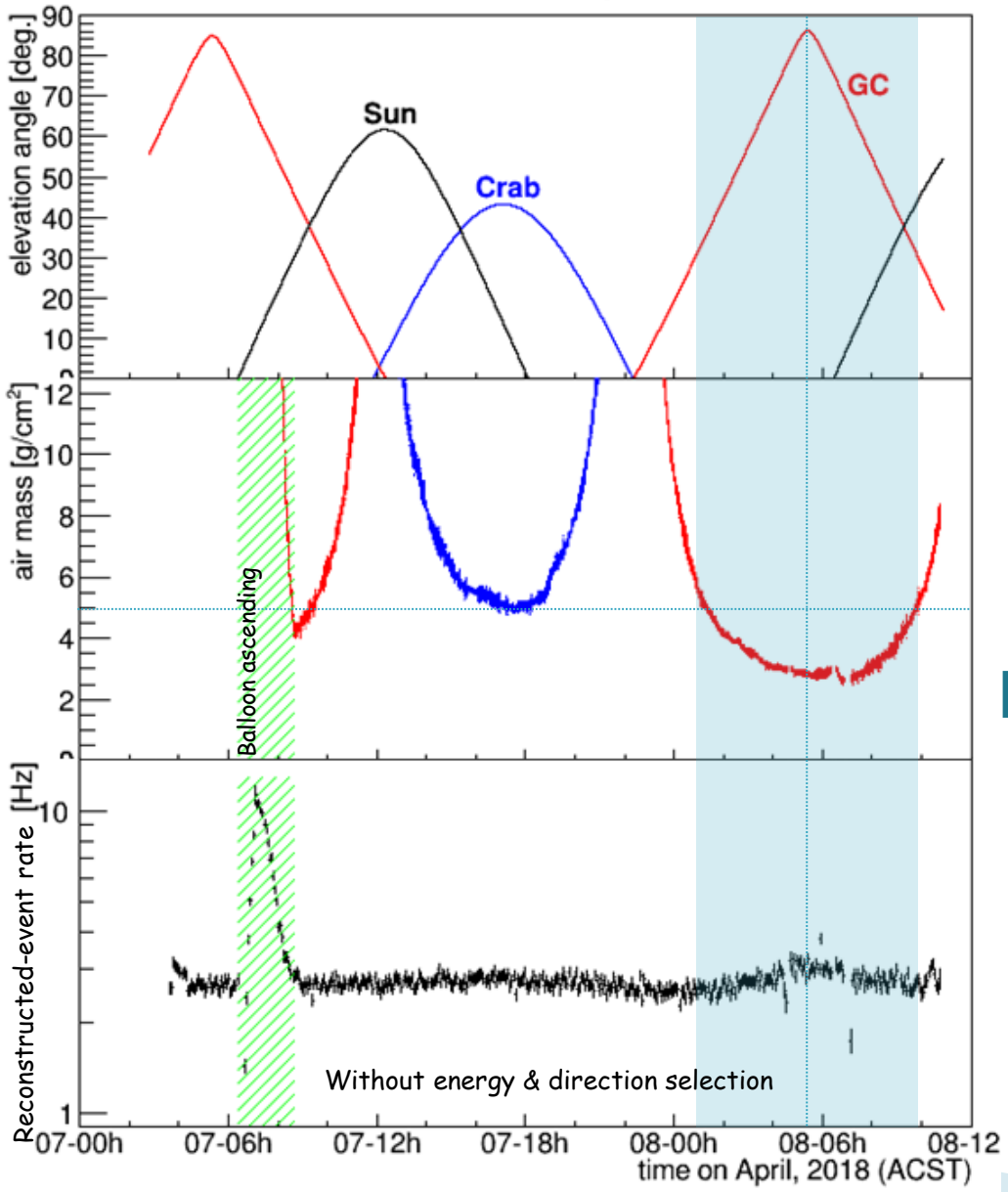
$$\cos\alpha_{\mathrm{geo}} = \vec{g}\cdot\vec{e}$$

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



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

Reconstructed-event rate

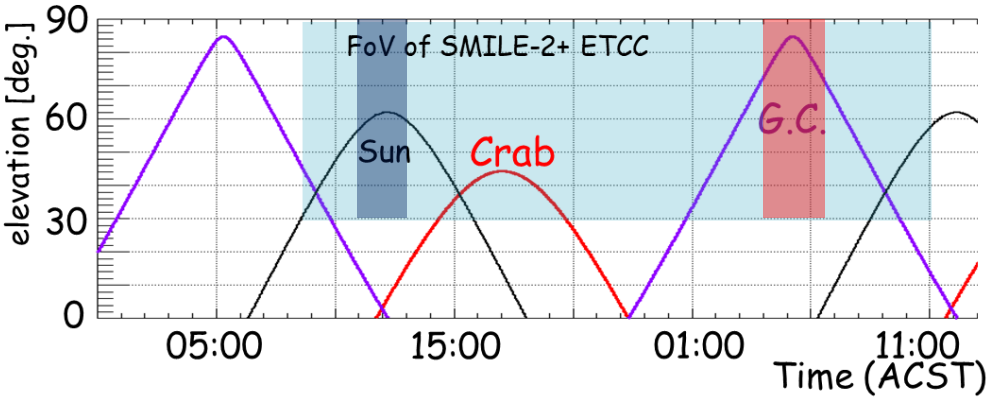


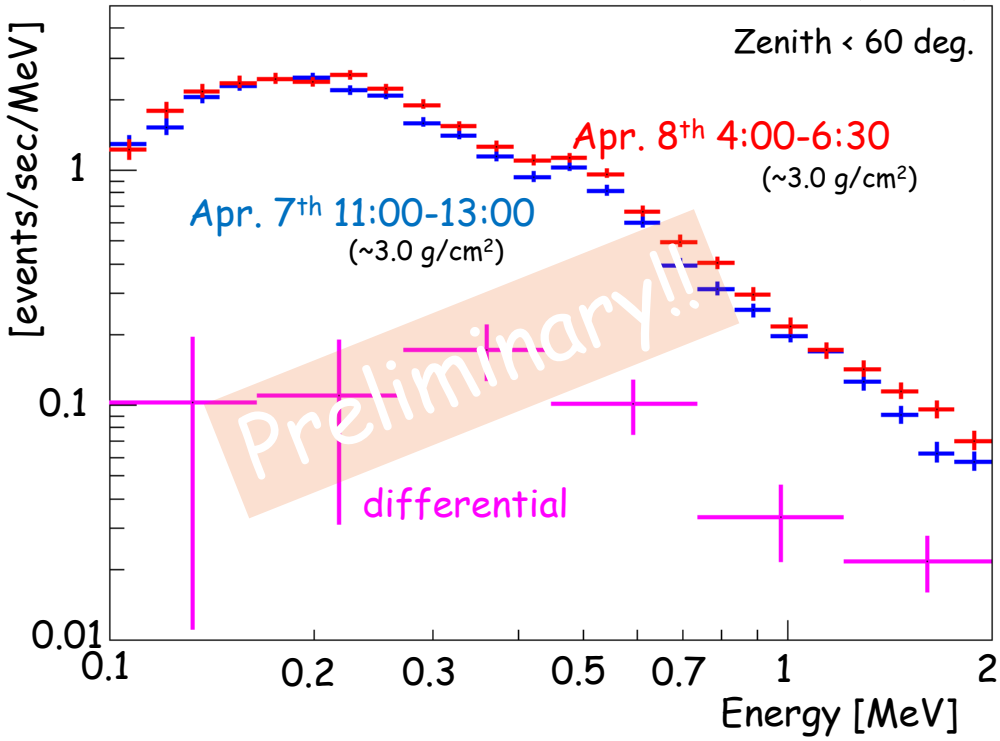
- Reconstructed event rate:
  ~2.5 Hz @ ground
  ~12 Hz @ ~ Pfotzer Max.
  ~2.5 Hz @ level flight
- Event rate was nearly constant during the level flight.
- An excess appeared (total: ~10σ)
  @ air mass < 5 g/cm^2 for *GC*

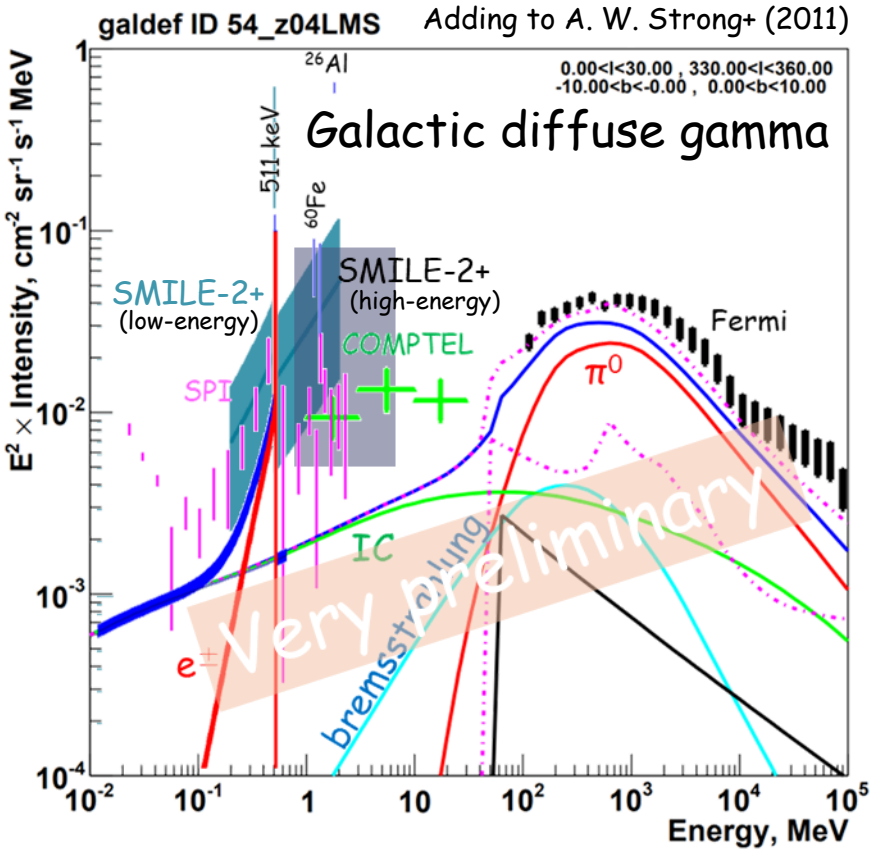
➢ Peak time
  ≈ culmination of *GC*
➢ ~0.5 Hz
  -> $10^{-2\sim-1}$ [ph/s/cm^2/sr/MeV]
  ≈ past observation of galactic diffuse gamma

We possibly detected galactic center region by simple light curve.

Emission from galactic center region

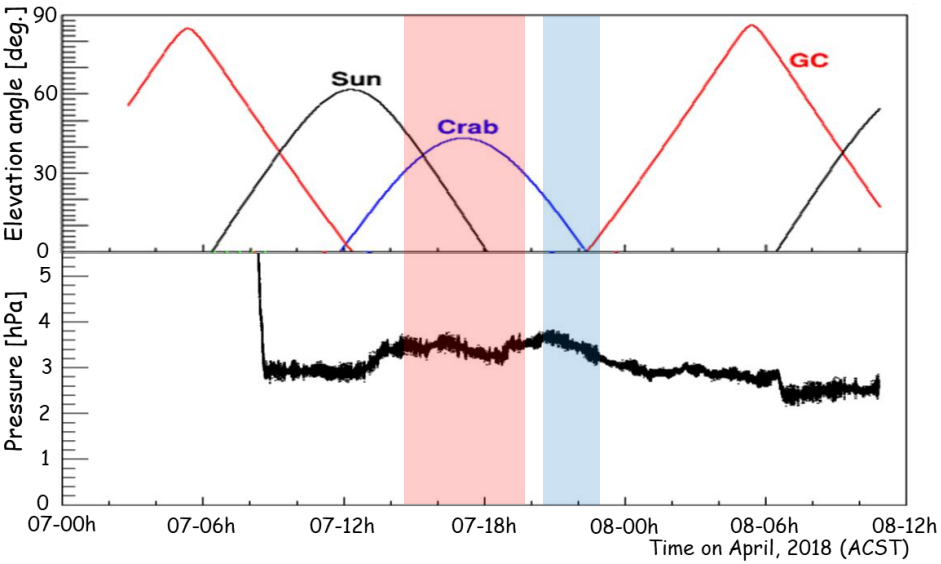


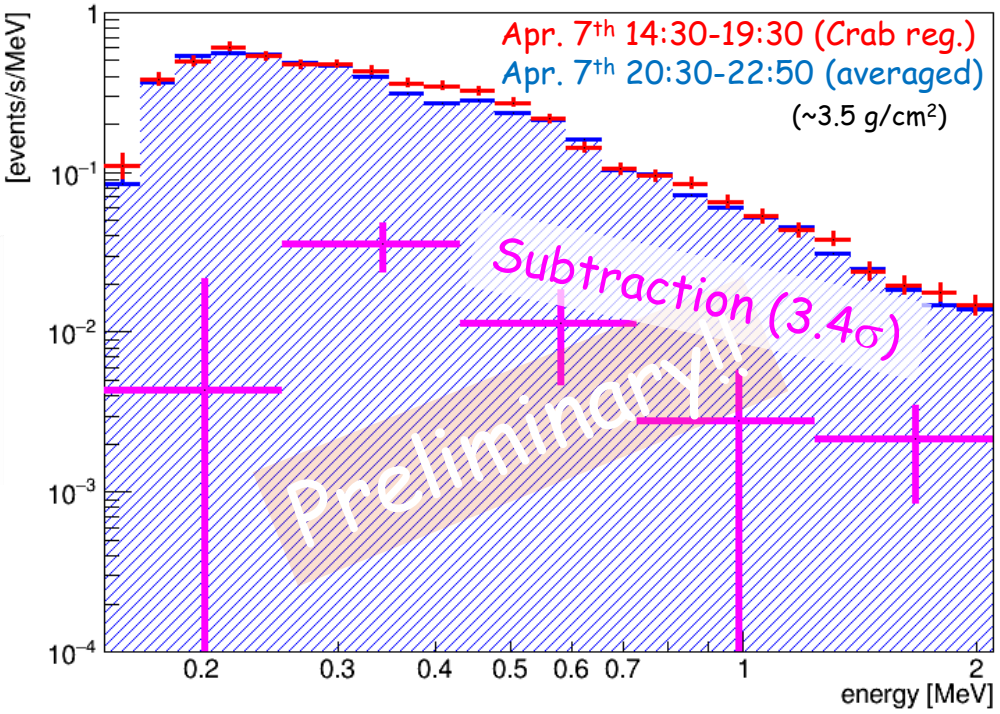




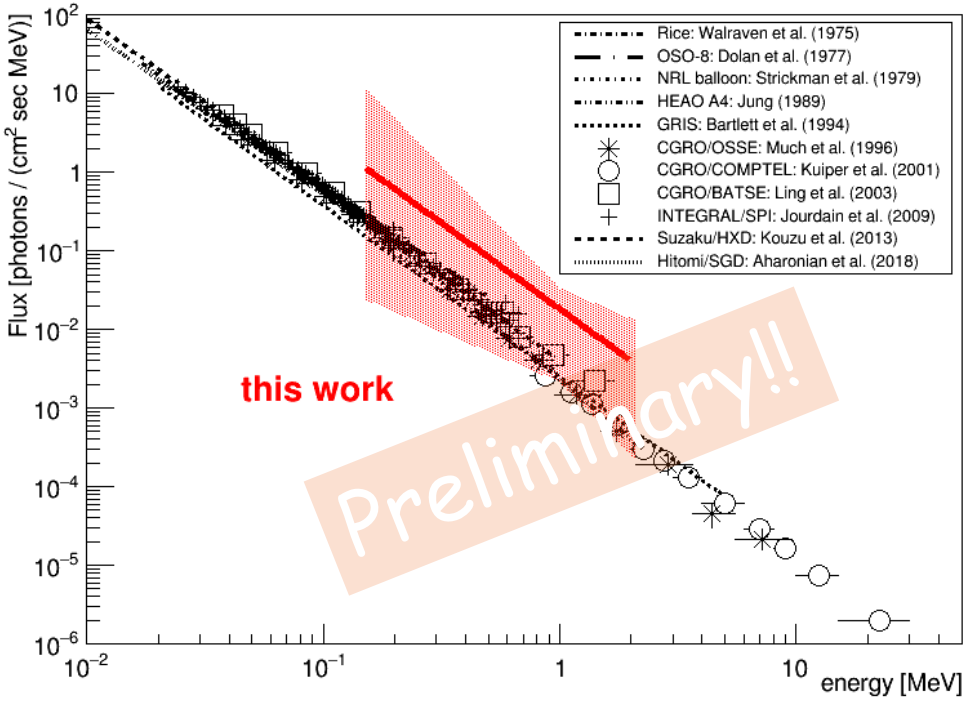
- Deconvoluted spectrum is consistent with SPI & COMPTEL.
- All of observations in MeV band have an excess compared with the expected emission.

Crab nebula



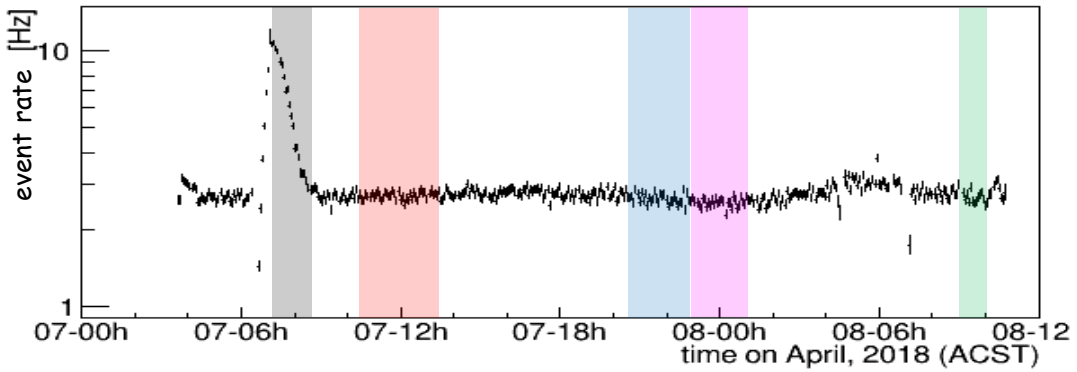


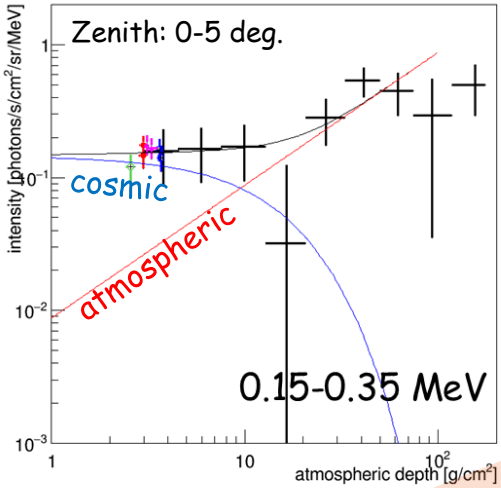
- Unfortunately, balloon altitude decreased during the observation of Crab nebula.
- There is excess with 3.4σ by simple ON-OFF method.
  -> matched the expectation !
- Obtained photon-flux was consistent with the past observations.

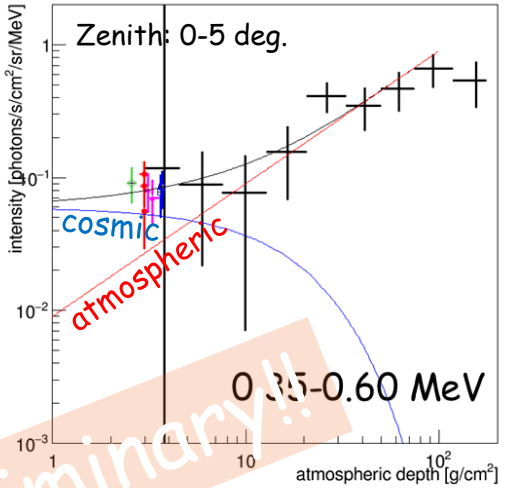


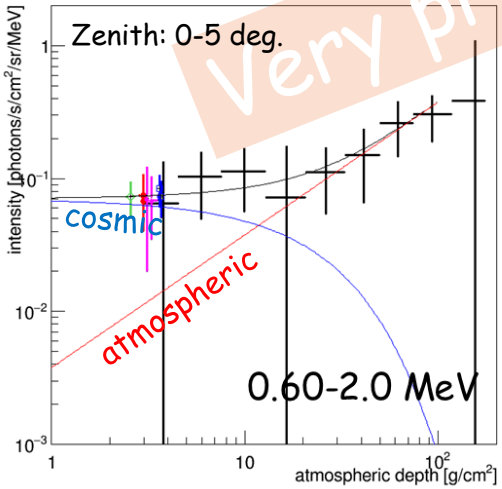
Growth curve

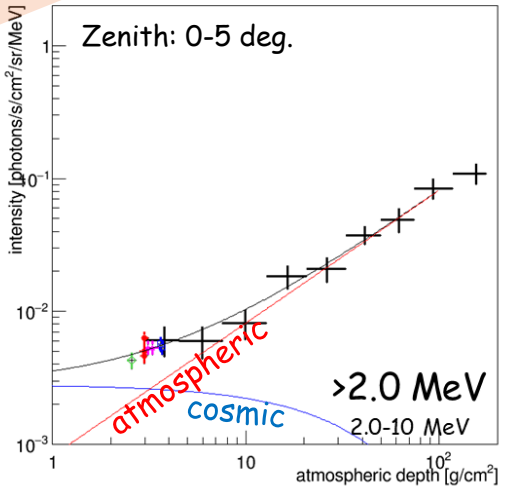
- Photon intensity as a function of atmospheric depth
- When there are no bright sources in FoV, the incident gamma-rays consist of
  - extragalactic diffuse
  - atmospheric gamma
  - instrumental background
- Extragalactic diffuse and atmospheric gamma-rays have different dependence on atmospheric depth.
  - -> Using growth curve, we can estimate the intensity of each component.
- Instrumental BG:
  estimate by simulation but not yet



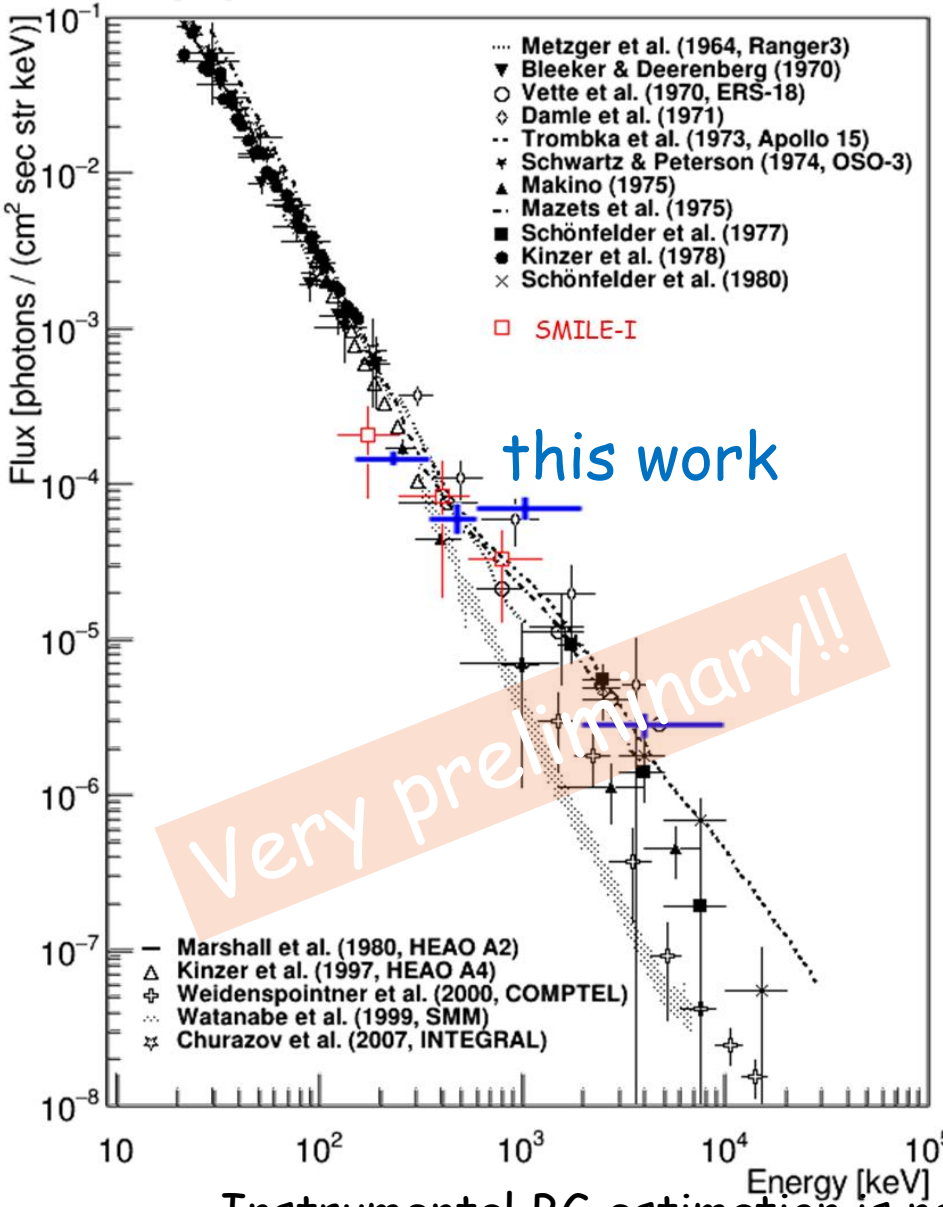


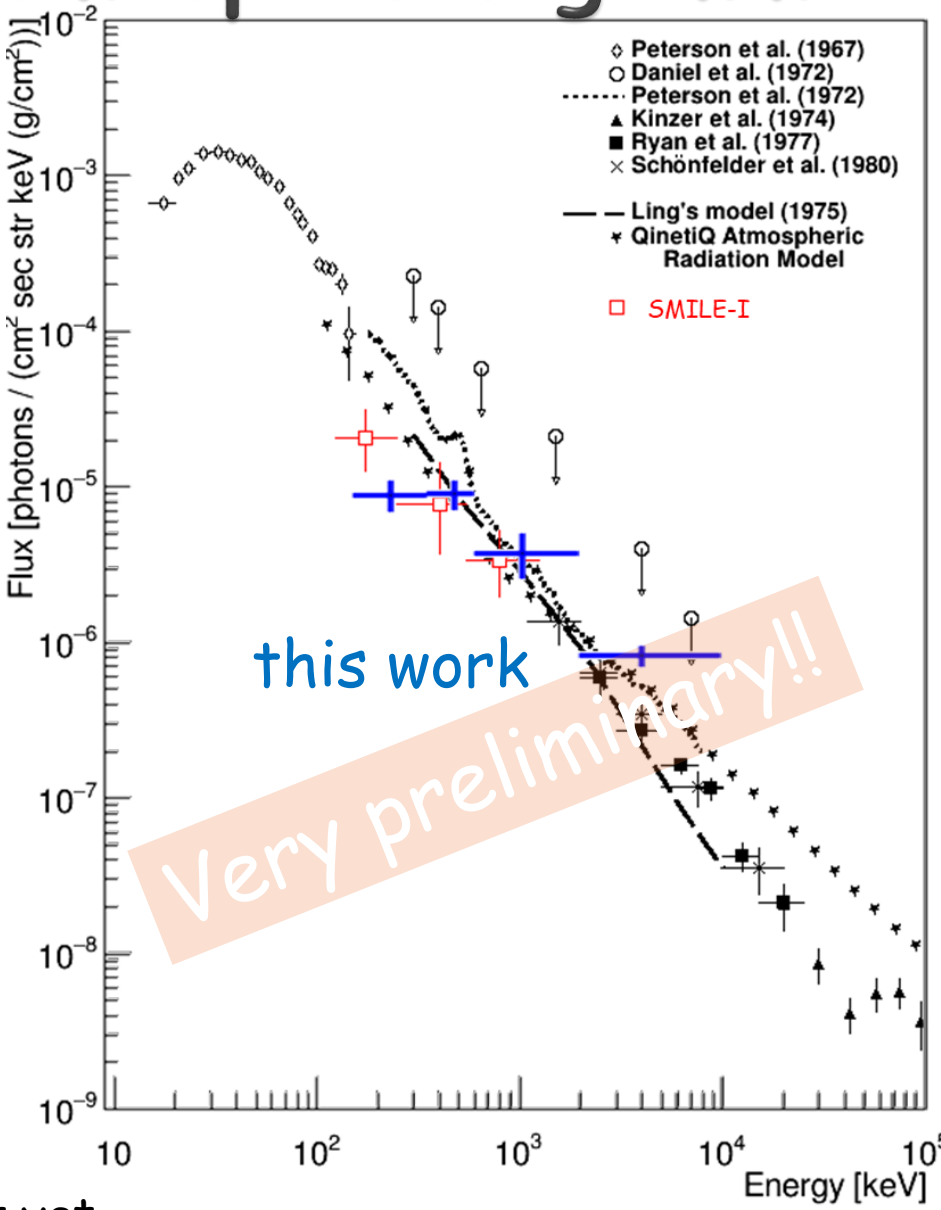






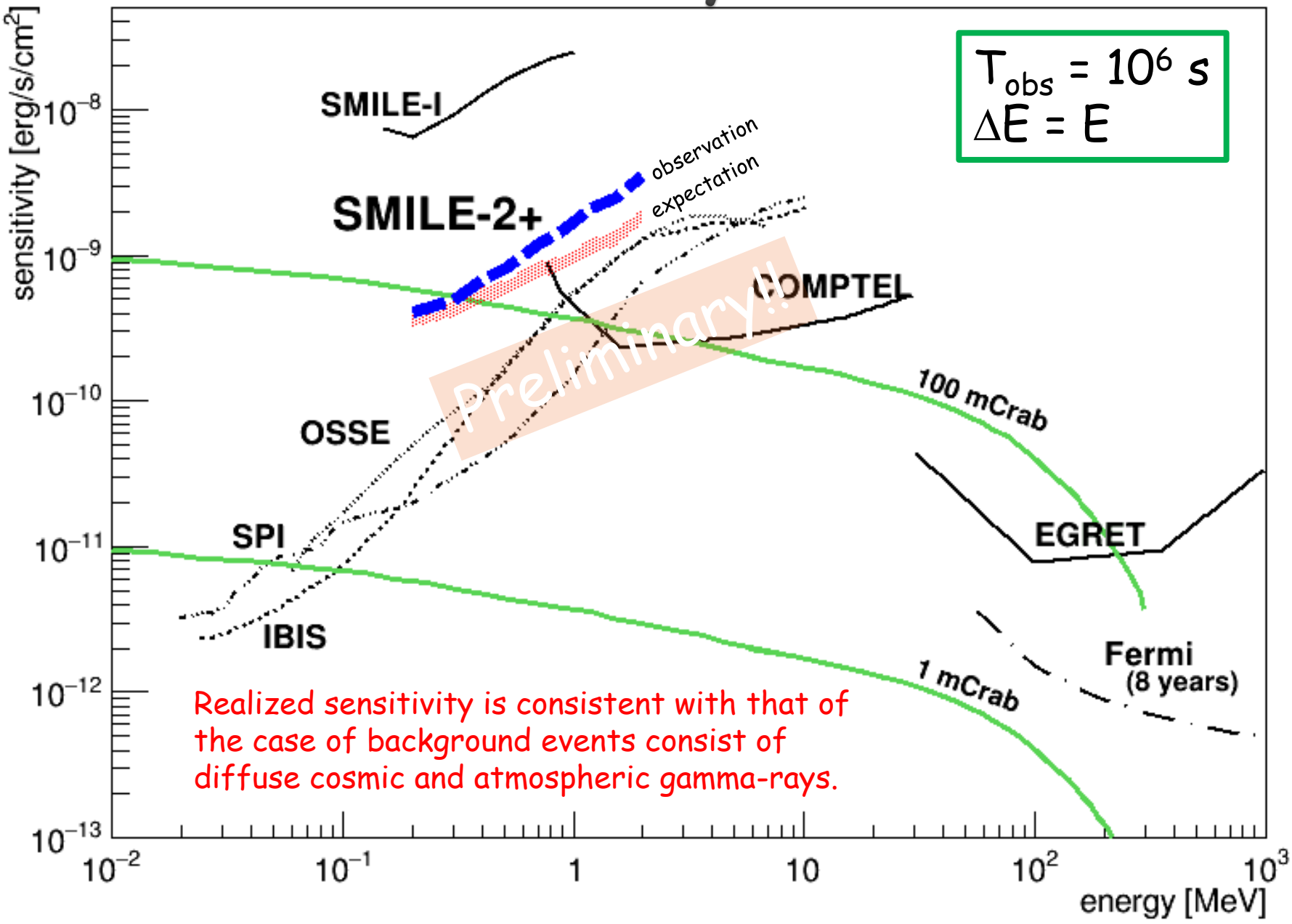
Diffuse cosmic & atmospheric gamma





Instrumental BG estimation is not yet.
But obtained intensities are well consistent with the past observations.

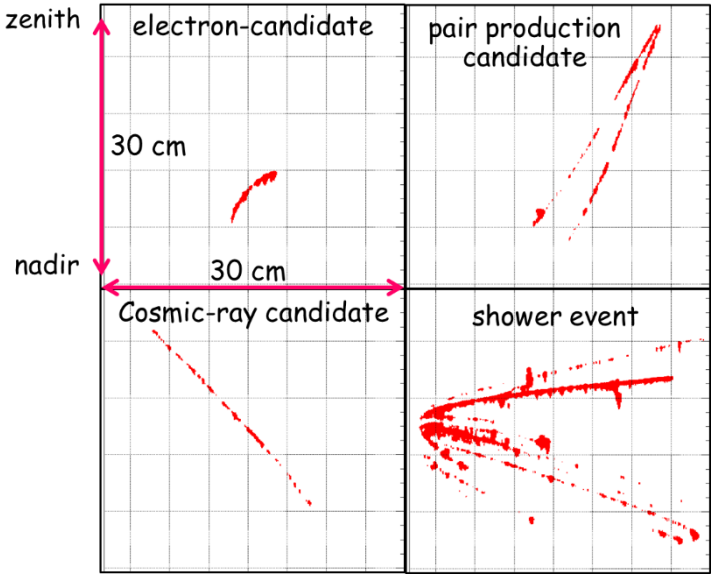
Detection sensitivity of SMILE-2+



Suggestion from SMILE-2+

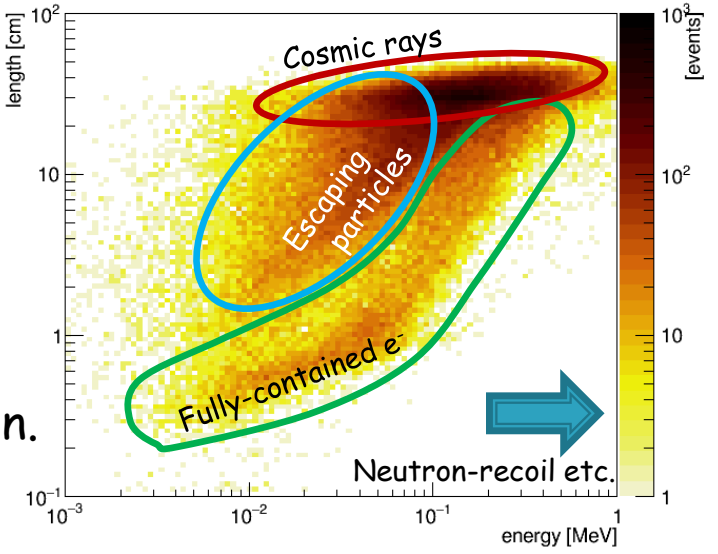
"Track images of charged particles"
have big information.

- 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 3.4σ.
- Realized sensitivity matched the expectation.



Track image is necessary
in MeV gamma-ray observations.

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

SMILE-I @ Sanriku (Sep. 1st 2006)

10 cm cubic, Xe+Ar 1 atm

- Confirmation of operation at the high altitude
- Observation of diffuse cosmic/atmospheric gamma-ray
  - -> ETCC was operated stably @ 35 km
  - Results were consistent with past observations

A. Takada+, ApJ, 2011

$(30\ cm)^2$ prototype

only ground tests

30 cm cubic, Ar 1 atm

- Ground cal. -> eff. area : ~1 cm^2 @ <300 keV
  - ARM : 5.3° SPD : ~100° @ 662 keV
  - -> PSF : ~15° @ 662 keV

T. Tanimori+, ApJ, 2015

SMILE-2+ @ Alice Springs (Apr. 2018)

30 cm cubic, Ar 2 atm

- Observation of bright objects 511 keV from G.C. & Crab nebula
- eff. area : ~1 cm^2 @ <300 keV PSF : ~30° @ 662 keV
  - -> detected G.C region (~10σ) and Crab nebula (~3.5σ)

SMILE-3

30 cm hexagonal column, CF_4 3 atm

- Scientific observation loaded on a long duration balloon
- eff. area : ~10 cm^2 @ 300 keV
  - PSF : ~9° @ 511 keV

All sky survey with a satellite

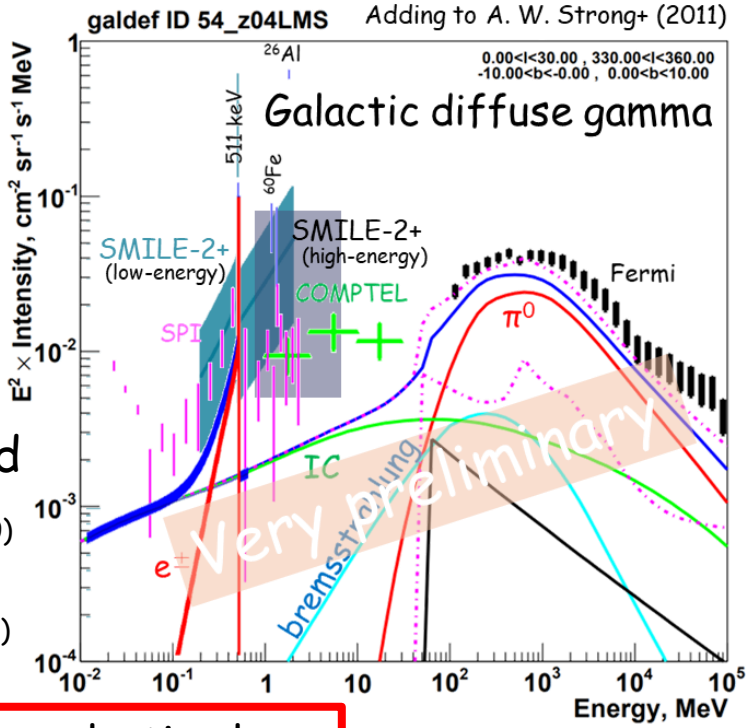
50 cm cubic, CF_4 3 atm

Scientific goals of SMILE-3

Observation result of SMILE-2+ :
Galactic center region is very luminous.

What is origin ?

- Unresolved celestial objects ?
  -> (Crab @ G.C.) x O(100)
- Convolution of some gamma-ray lines ?
  -> de-excitation lines are not discovered
- Others ?
  -> evaporation of primordial black holes Carr+ (2010)
  -> annihilation of dark matters Ahn+ (2005)



Celestial-objects origin -> concentrate to galactic plane
Dark matter origin -> like mass-distribution

SMILE-3 Long-duration balloon @ southern hemisphere

- Galactic diffuse (continuum + annihilation line) and extragalactic diffuse gamma-rays
  -> We search for a dark-matter signal in MeV band.
- Deep survey with the highest detection sensitivity.

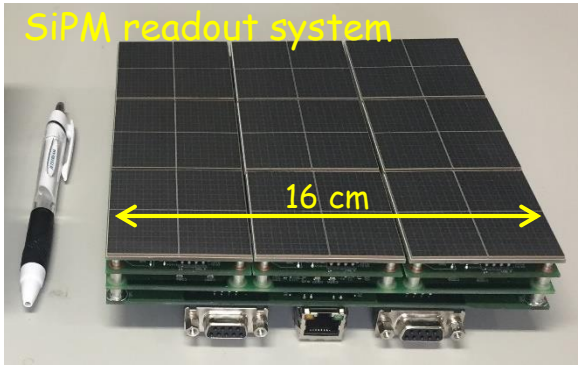
SMILE-3 ETCC

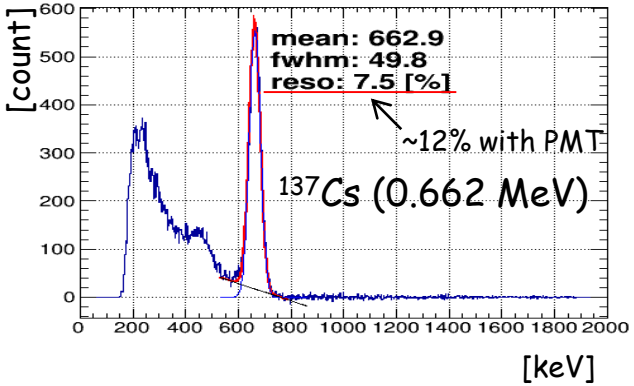
SMILE-3 ETCC must have…
- Eff. area : ~10 cm^2 @ 0.3 MeV
- Angular res. : ~10 deg. @ 0.5 MeV
- sensitivity : > 5 times SMILE-2+

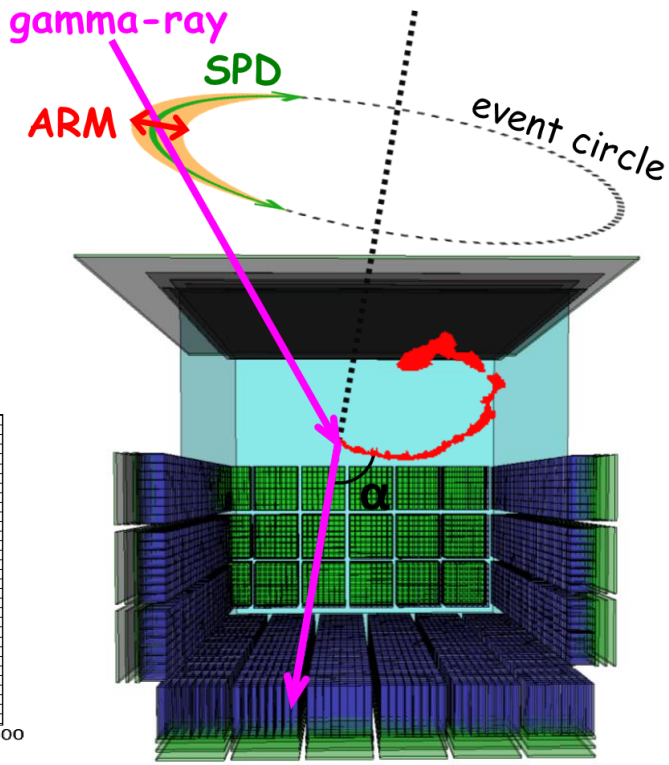
Tracker : CF_4 3 atm, 30x30x30 cm^3
accuracy of scattering point
< 5 mm

absorber : GSO scintillator with SiPM

Scintillation camera

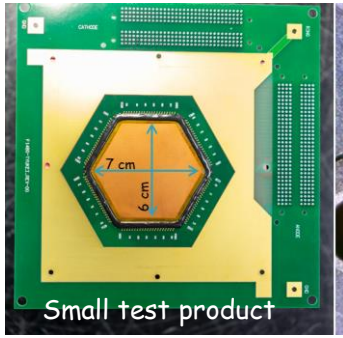


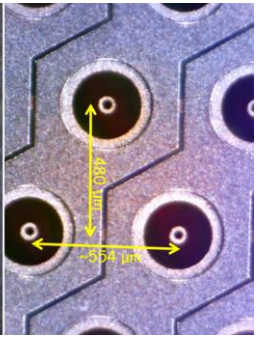


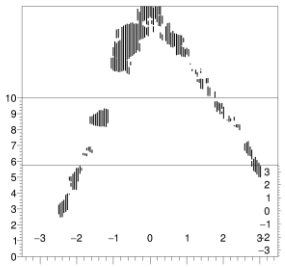


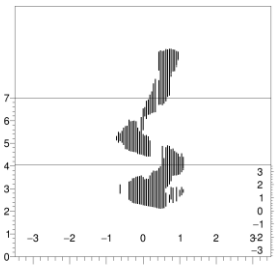
Gaseous tracker

- Tracker operated with CF_4 3 atm
- New electrode structure
  for detailed track-images

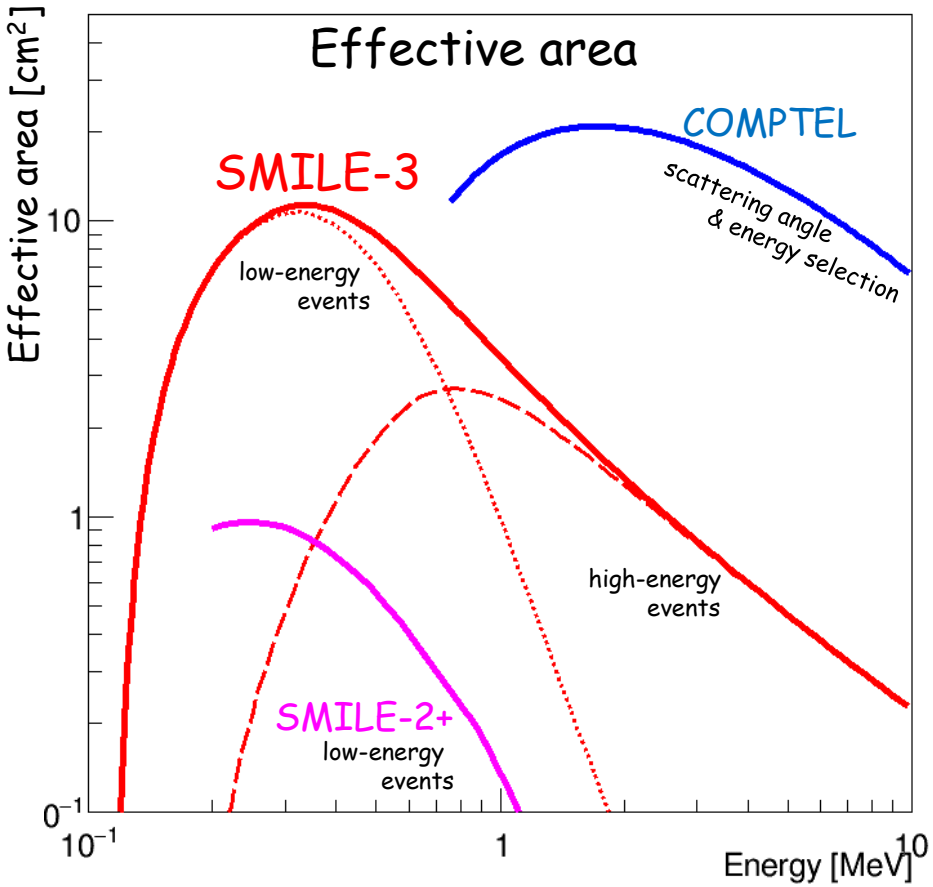


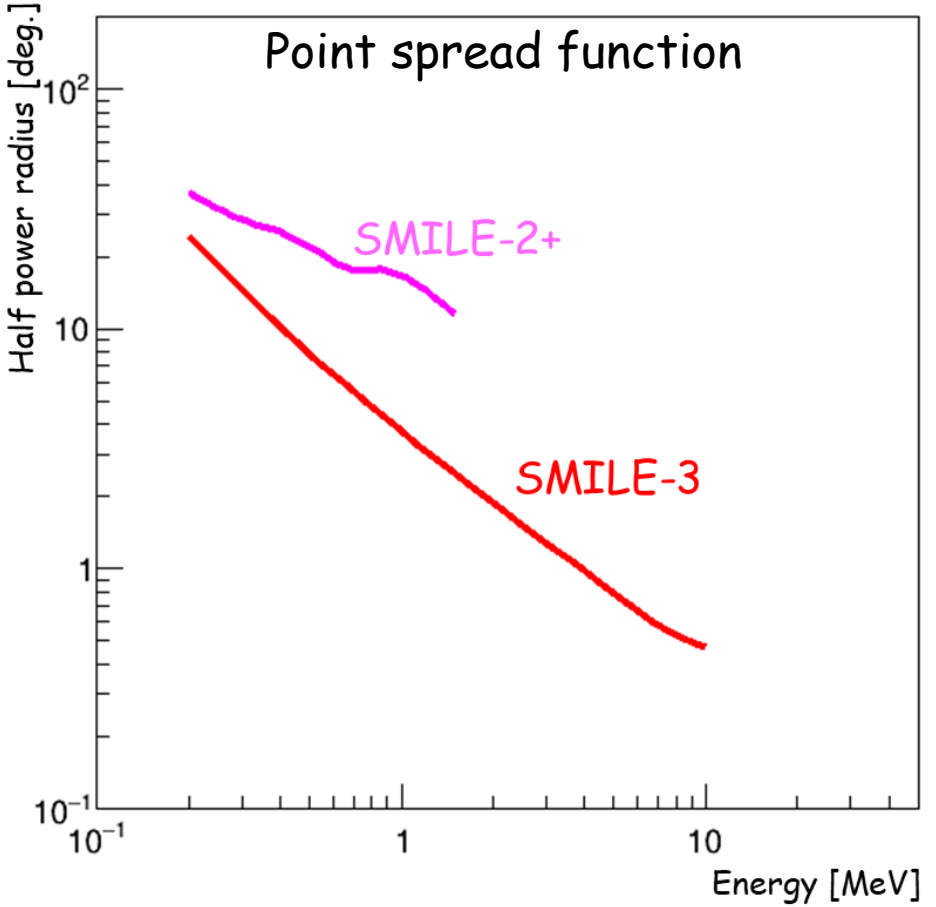


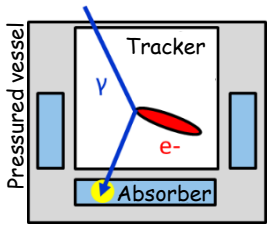




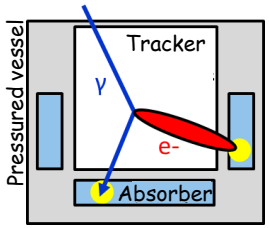
Effective area & PSF







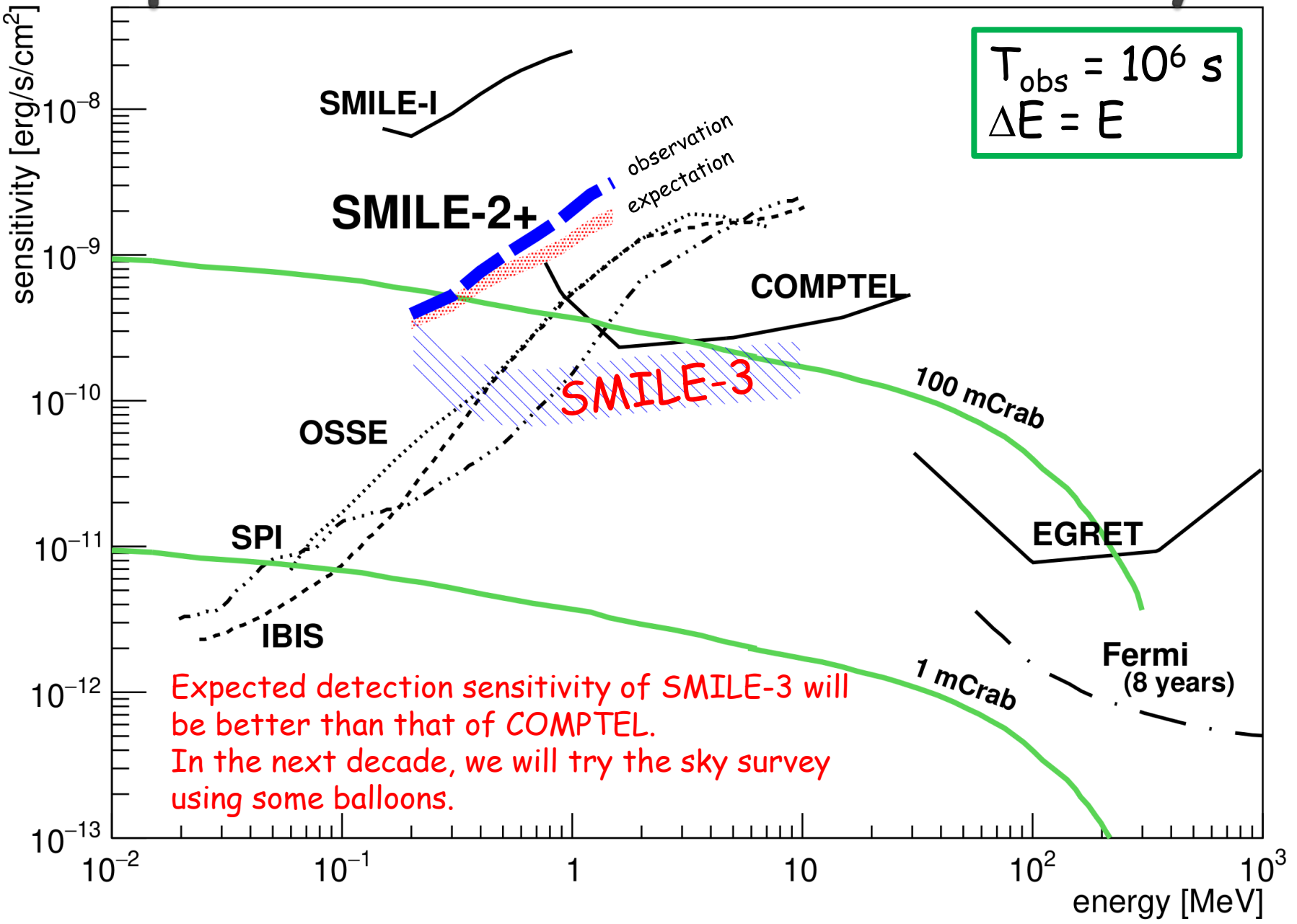
Low-energy event



High-energy event

Energy [MeV]	Eff. area [cm²]	PSF [deg.]
0.3	10	13
0.5	9	8
2.0	1.3	2

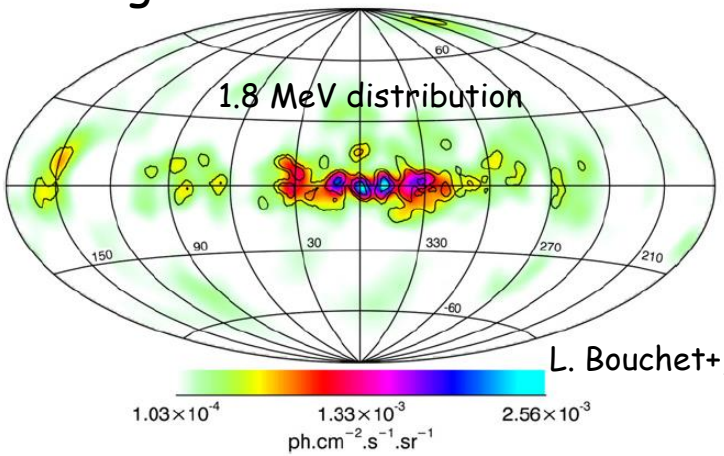
Expected detection sensitivity



Expected detection sensitivity of SMILE-3 will be better than that of COMPTEL.
In the next decade, we will try the sky survey using some balloons.

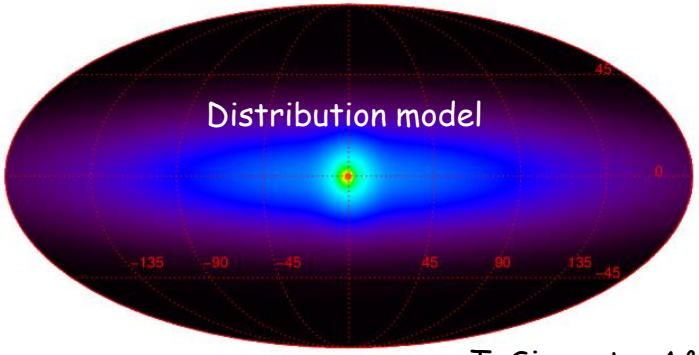
Expectation of SMILE-3 observation

Assuming the distribution of annihilation line with…



L. Bouchet+, ApJ (2015)

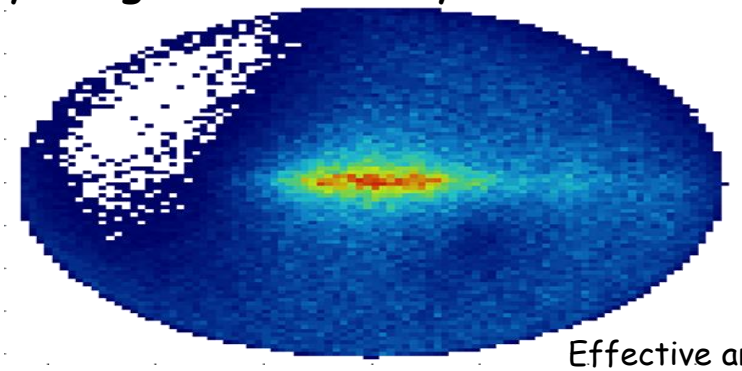
?

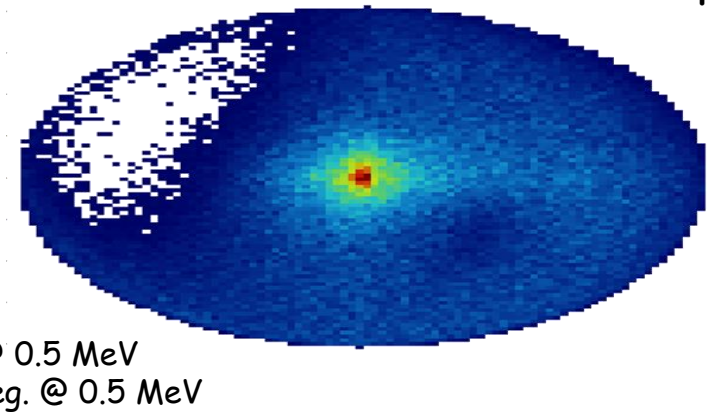


T. Siegert+, A&A (2016)

Sky image observed by SMILE-3 will be …

3.6° ×1.8° /pixel





Effective area: ~5 cm^2 @ 0.5 MeV
Spatial resolution: ~10 deg. @ 0.5 MeV
Altitude 40 km, 30 days, Southern hemisphere
BG: extragalactic & galactic diffuse gammas (continuum)
without atmospheric gamma, scattering in atmosphere

SMILE-3 will reveal how the annihilation line distributes.

Summary

- For opening a window in MeV gamma-ray,
  we are developing an electron-tracking Compton camera (ETCC).
- SMILE-2+ was launched from Alice Springs on April 7th, 2018.
  purpose : confirm to observe celestial objects
  observation of Crab nebula and G.C. region
- Preliminary results of SMILE-2+:
  - An excess appeared at around culmination time of G.C.
  - Energy flux observed in G.C. region was consistent with SPI & COMPTEL.
    -> G.C. region is very luminous.
  - Crab nebula was detected with 3.4σ.
  - Obtained fluxes of extragalactic diffuse and atmospheric gamma-rays were roughly consistent with past observations.
- Next flight SMILE-3:
  - Long-duration balloon in southern hemisphere
    -> the emission mechanism of galactic diffuse emission
  - Deep survey with the high detection sensitivity
  - We already started to discuss with NASA
    for a long-duration balloon experiment.

Thank you for your attention!

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