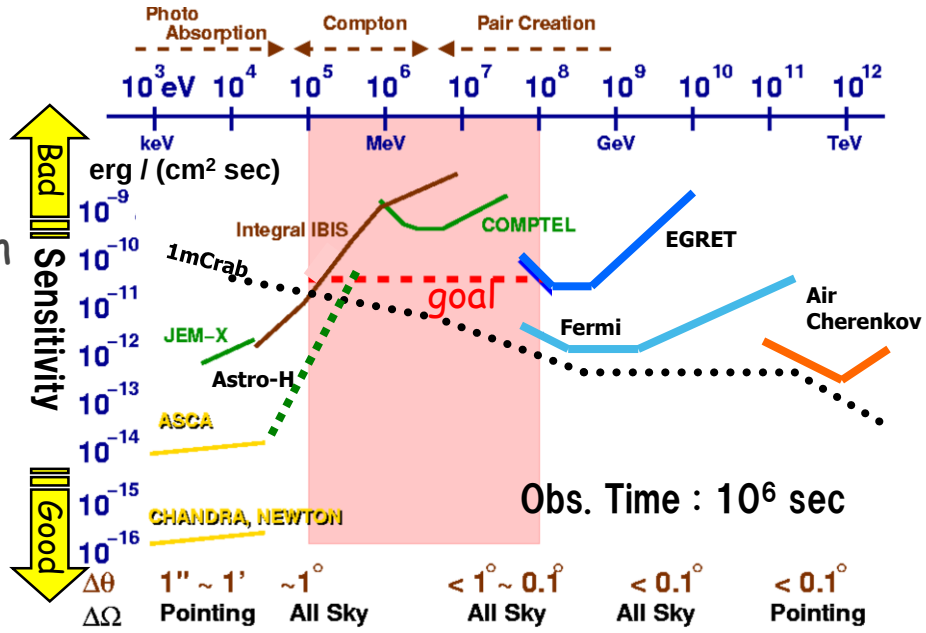
MeV Gamma-Ray Observation based on the Ray-Tracing Cameras loaded on Balloons

A. Takada (Kyoto Univ.)

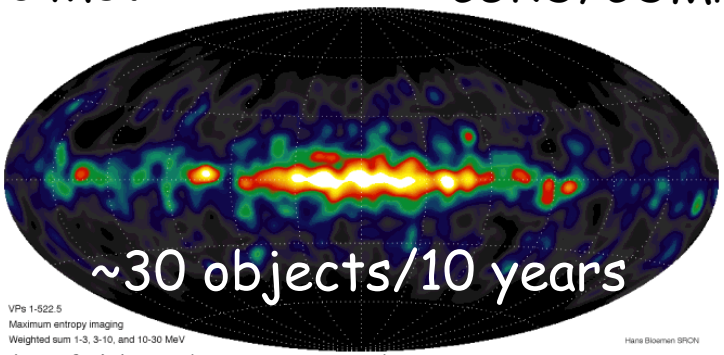
MeV Astronomy

- 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

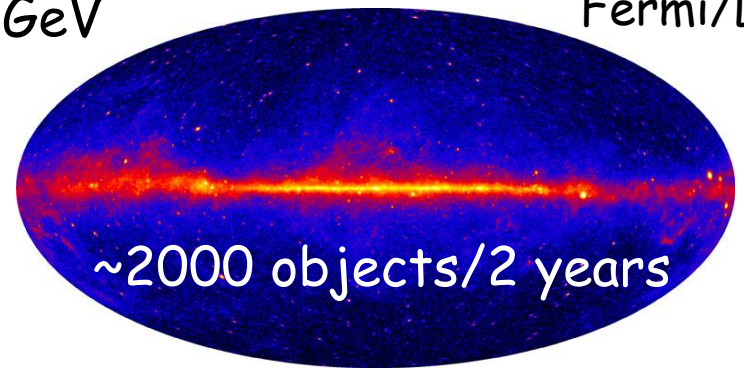
1-30 MeV CGRO/COMPTEL



V. Schönfelder+ (A&AS, 2000)

GeV sky map

> 1 GeV Fermi/LAT



P. L. Nolan+ (ApJS, 2012)

Requirements for the next-generation detectors are …

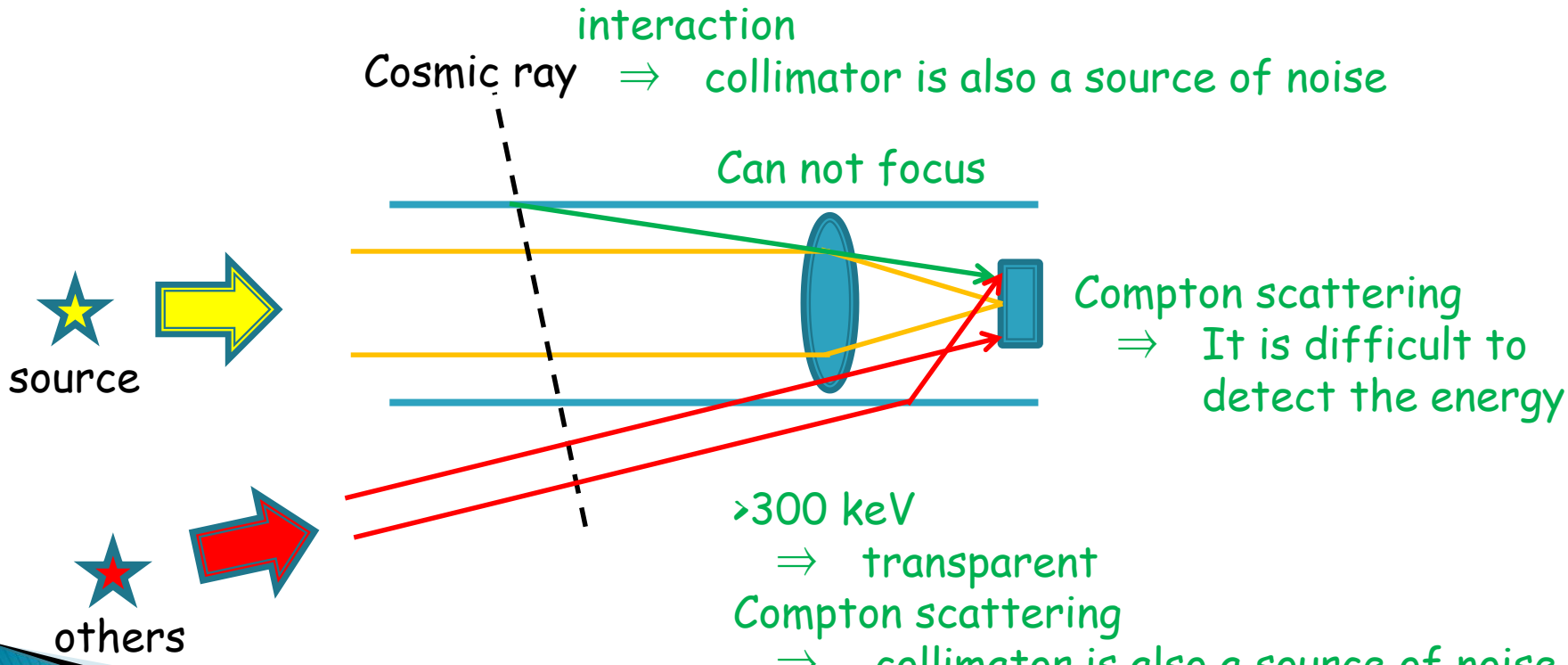
- Wide-band detection
- Large Field of View
- High quality image

Observe gamma rays

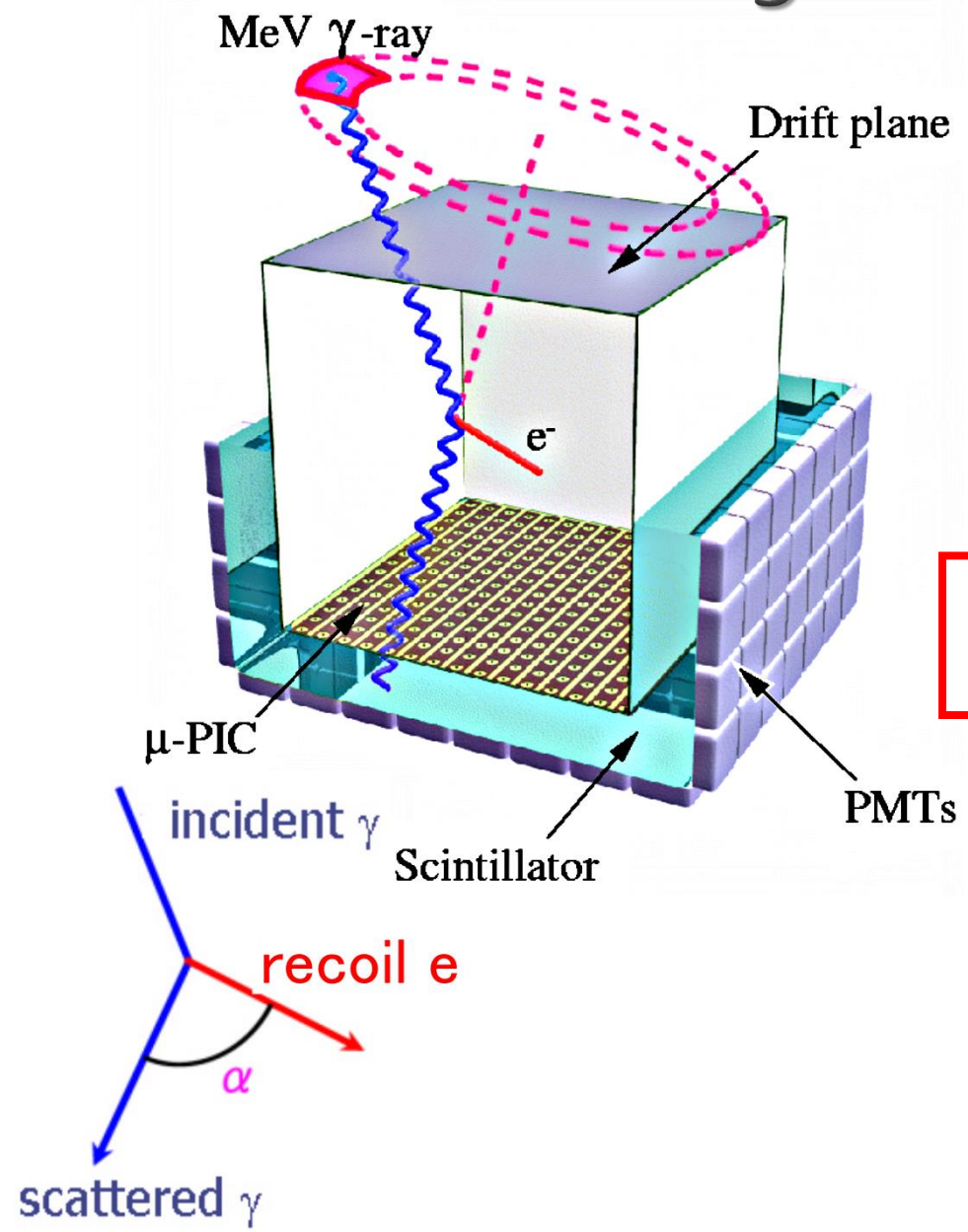
RIs • de-excitation • annihilation
bremsstrahlung • synchrotron radiation
Inverse Compton-scattering …etc

We want observe
radiation from source

New imaging technology is needed for MeV gamma ray



Electron-Tracking Compton Camera (ETCC)

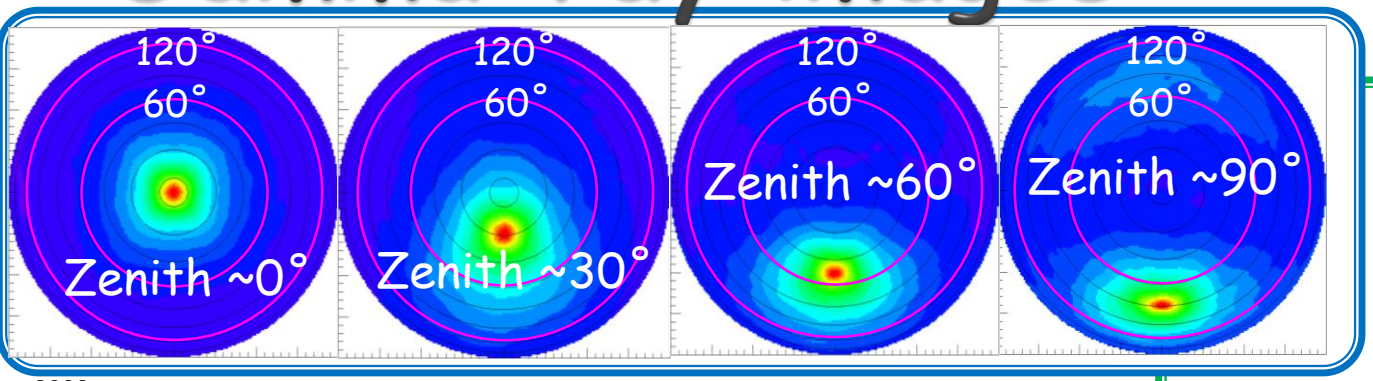


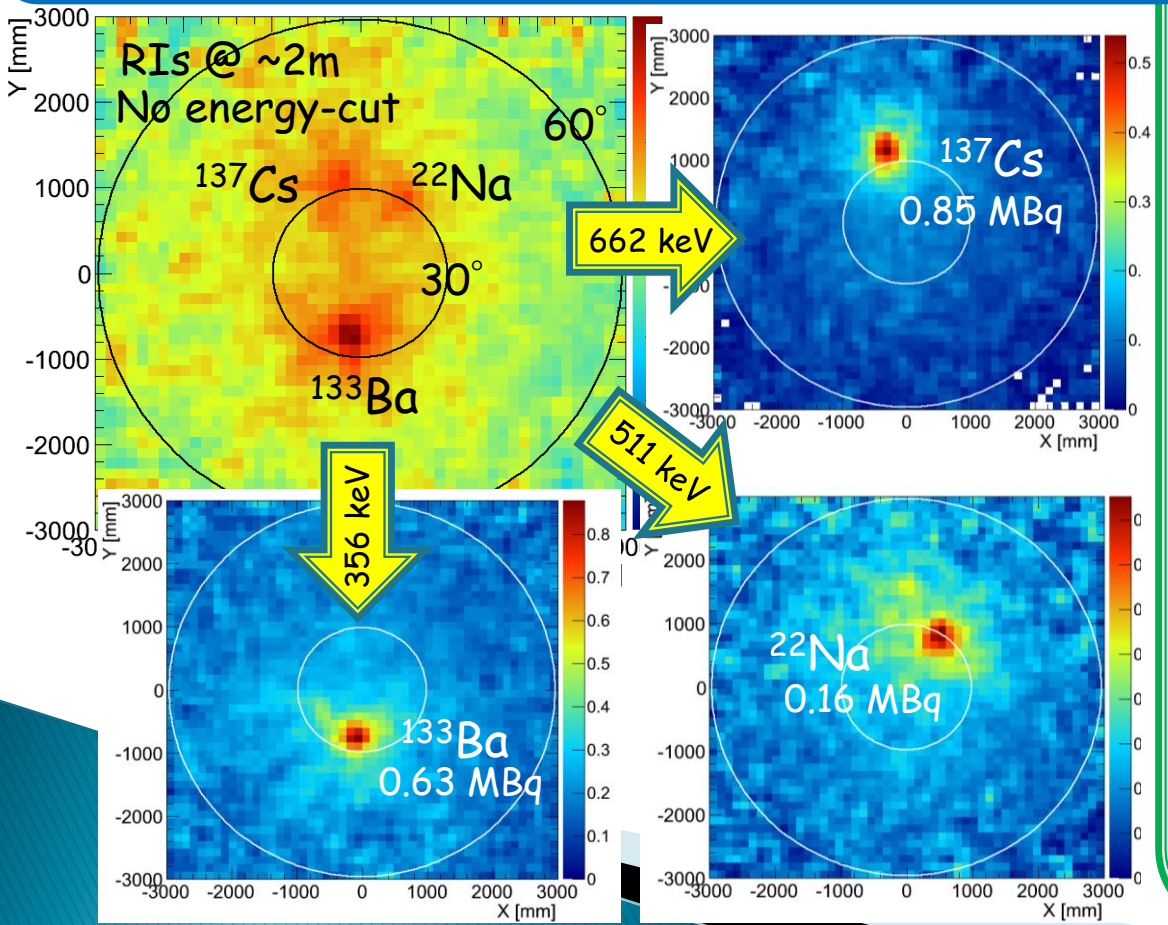
- Gaseous TPC : Tracker
  track and energy of recoil electron
- Scintillator : Absorber
  position and energy of scattered gamma ray

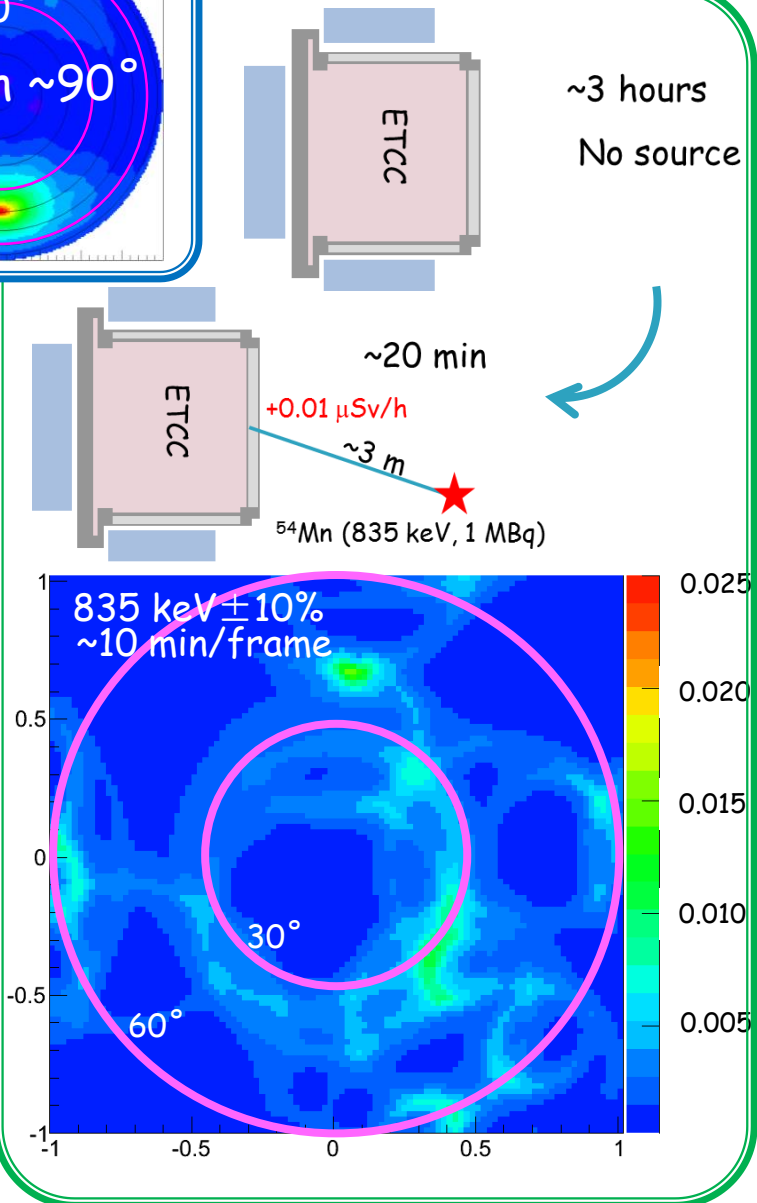
Reconstruct Compton scattering event by event

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

Gamma-ray images







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

SMILE-II

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

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

30 cm cubic, Ar >1 atm

- Observation of bright objects
- eff. area : a few cm^2 @ <300 keV
  PSF : ~5° @ 662 keV

511 keV from G.C. @ Alice Spring
Crab nebula/Cyg X-1 @ Fort Sumner

SMILE-3

30 cm cubic, CF_4 3 atm

- Scientific observation loaded on a long duration balloon
- eff. area : ~10 cm^2 @ <300 keV
  PSF : <5° @ 662 keV

All sky survey with a satellite

50 cm cubic, CF_4 3 atm

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

1st balloon experiment (SMILE-I)

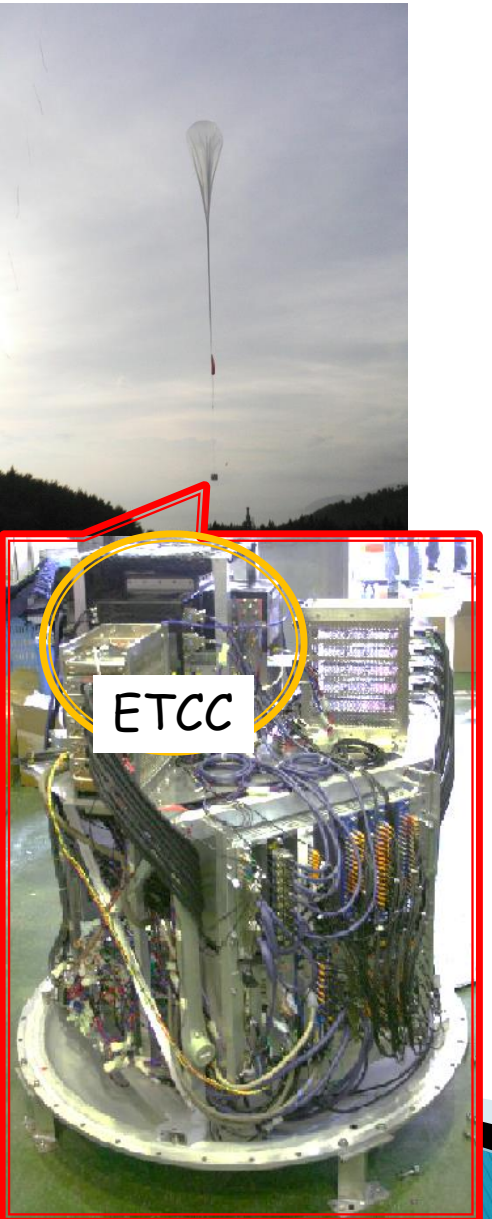
Sub-MeV gamma-ray imaging Loaded-on-balloon Experiment

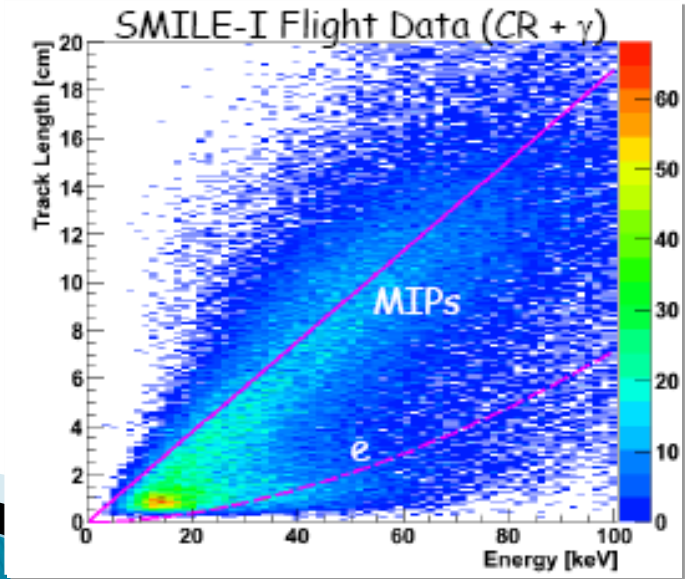
Launched on Sep. 1, 2006 @ Sanriku (ISAS/JAXA)

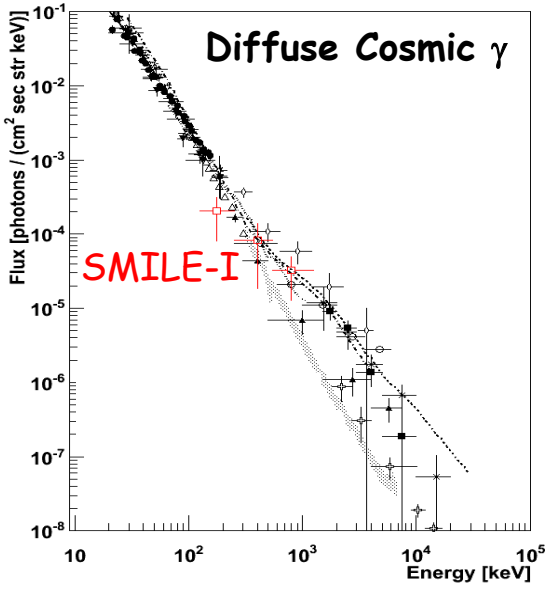
- Test flight using $(10\ \mathrm{cm})^3$ ETCC
- Measure diffuse cosmic and atmospheric gamma ray
  0.1 – 1 MeV, @ 35 km, 3 hours

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

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



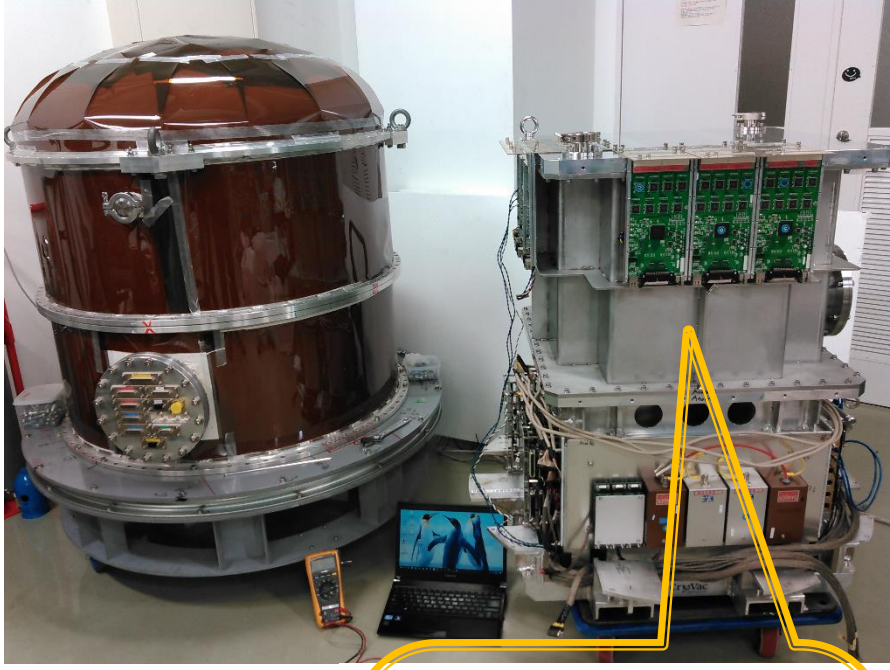




SMILE-2+

➢ Balloon

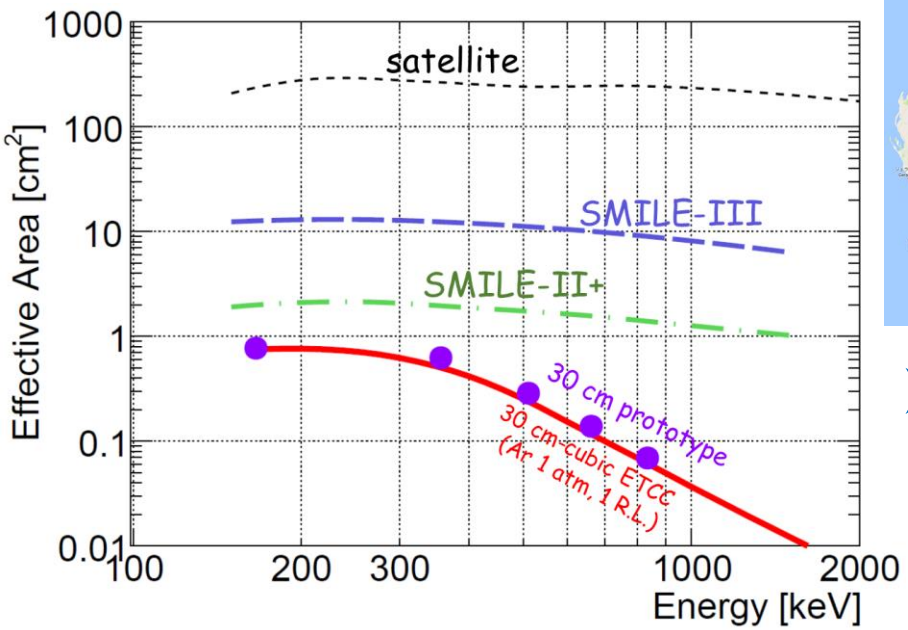
Launch from Alice Springs (Apr. 2018)
Expected altitude : 38.9 km
Gondola weight : ~500 kg

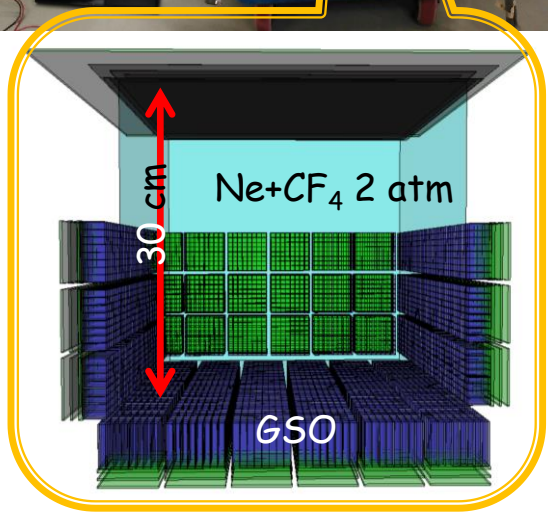


➢ Detector

Geant4 simulation ->

- Effective area : ~a few cm^2
- Point Spread Function : ~10°
- Energy range : 300~1.5 MeV



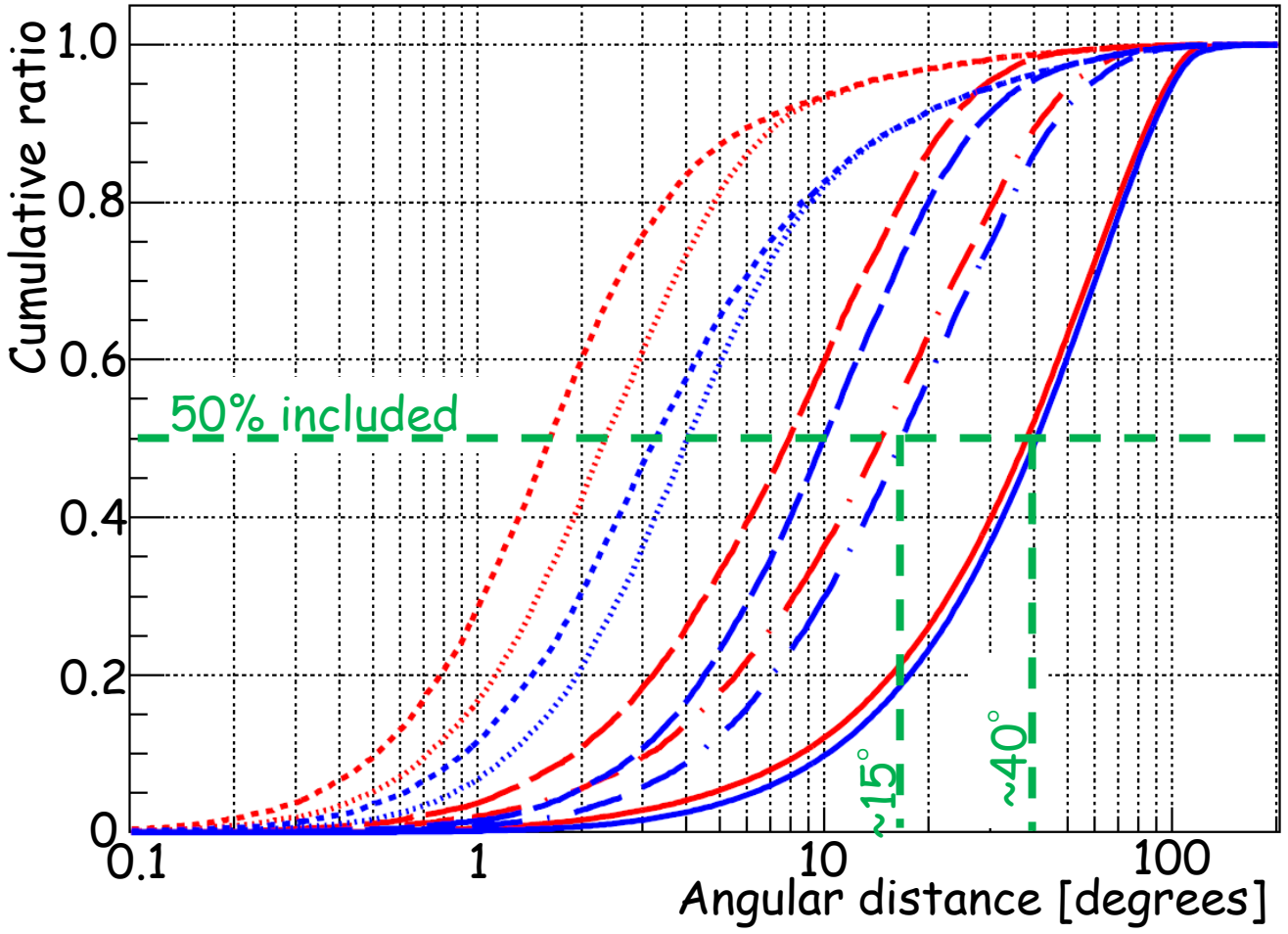


➢ Observation target

- $e^{\pm}$ annihilation line @ Galactic center
- Crab nebula

SMILE-2+ will detect
with the significance of ~5σ.

Point spread function



ARM 2° ARM 5°

Conventional

SPD 100°

SPD 50°

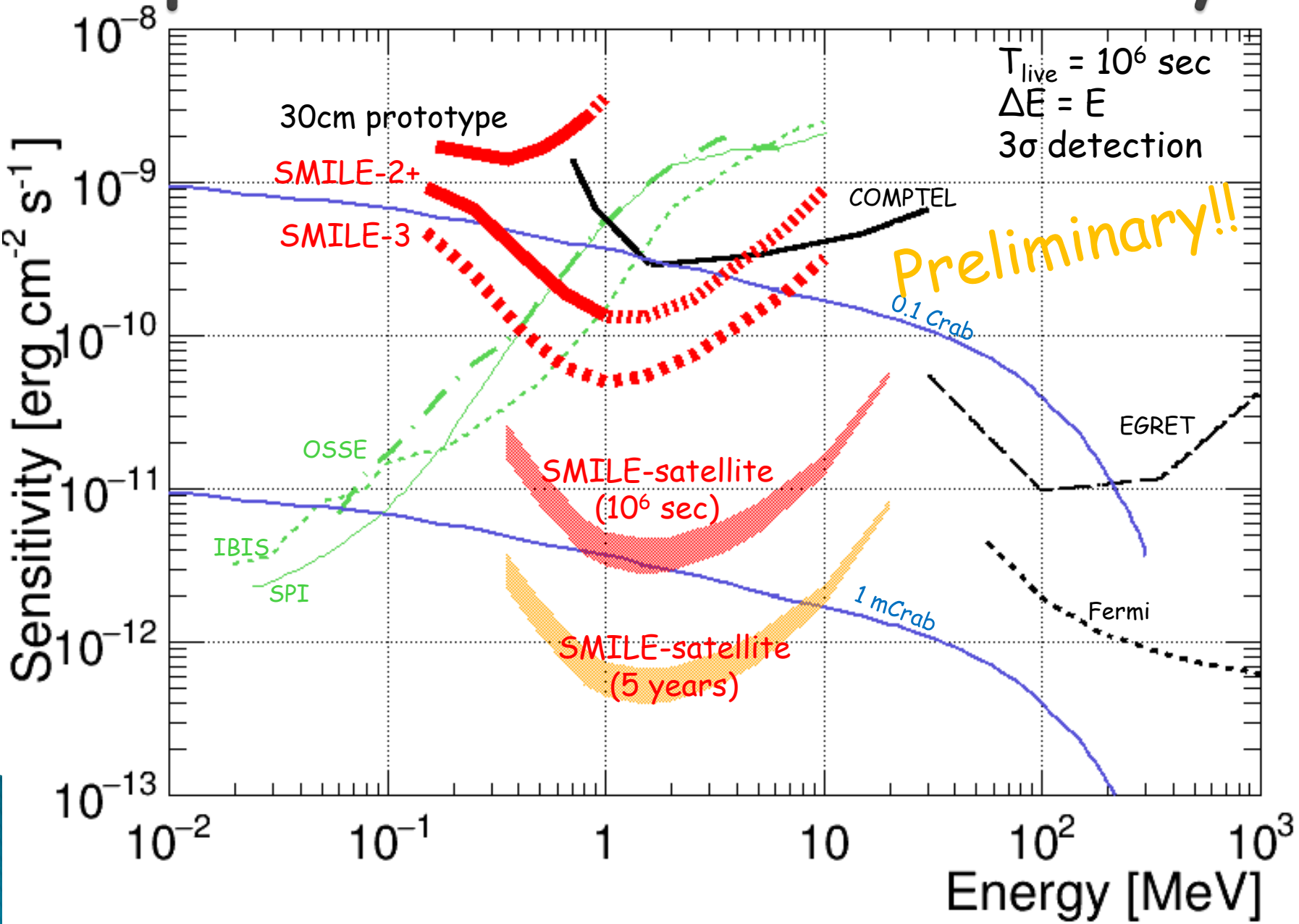
SPD 10°

SPD 5°

- SMILE-II ETCC
  ARM 6° SPD 100°
  -> half power radius ~15°
  This emulation is consistent with experiment.
- ARM ≠ half power radius
- PSF strongly depends on SPD
- If ARM ≈ SPD, HPR ≈ ARM

If we want to get a sharp PSF,
we need to improve both ARM and SPD.

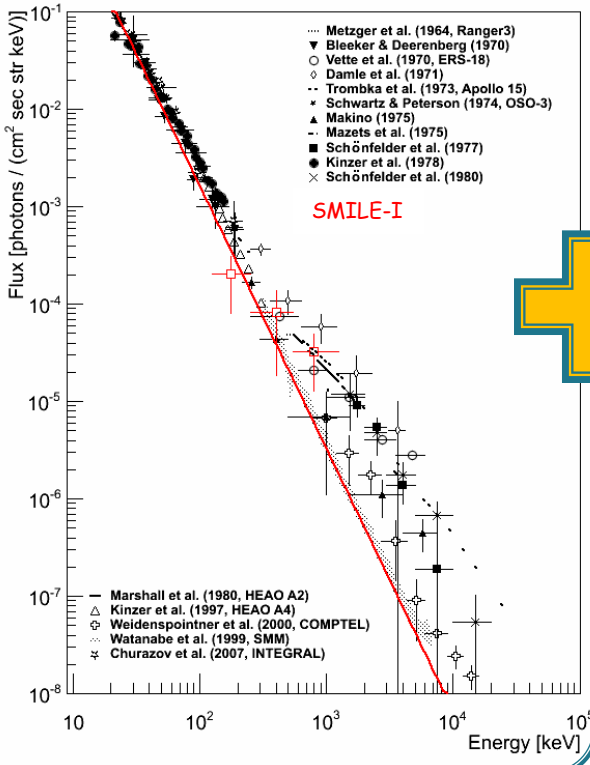
Expected detection sensitivity



Estimation of sky image at 1.8 MeV

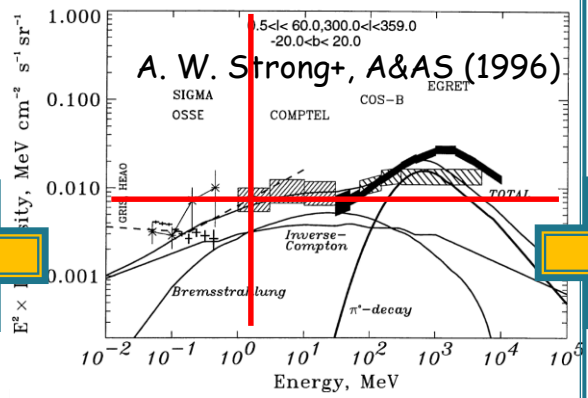
Extragalactic diffuse

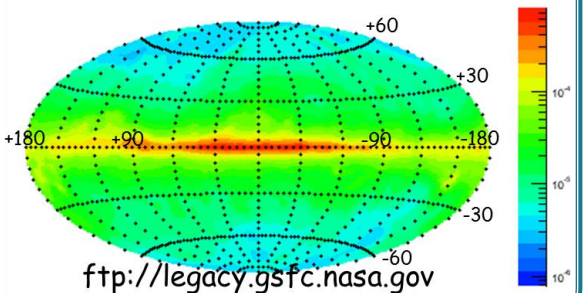
Intensity: power-law (SMM)
Distribution:
uniform, isotropic



Galactic diffuse

Intensity: COMPTEL
Distribution:
galactic diffuse model
(EGRET)

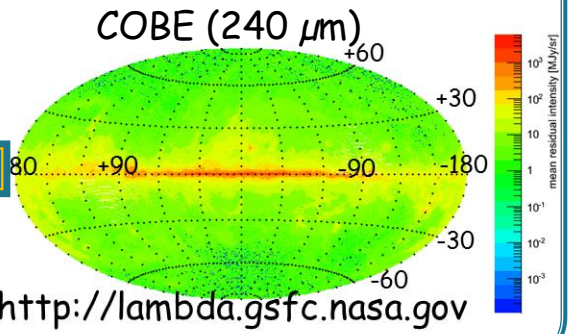


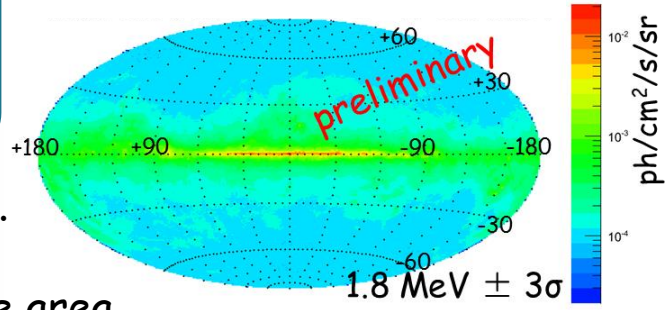


^{26}Al 1.8 MeV

Intensity: SPI/INTEGRAL
3.5×10^{-4} ph/cm^2/s
$|l| \leq 30^\circ$ $|b| \leq 10^\circ$
L. Bouchet+, ApJ (2015)

Distribution:
sky map by other bands

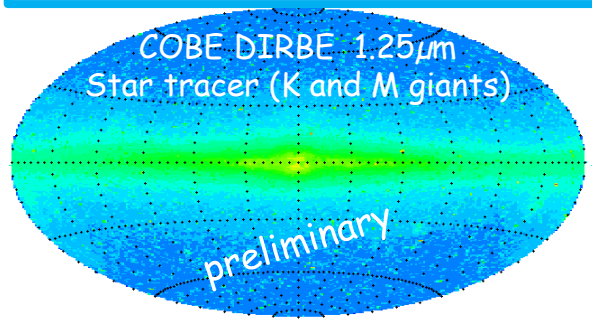


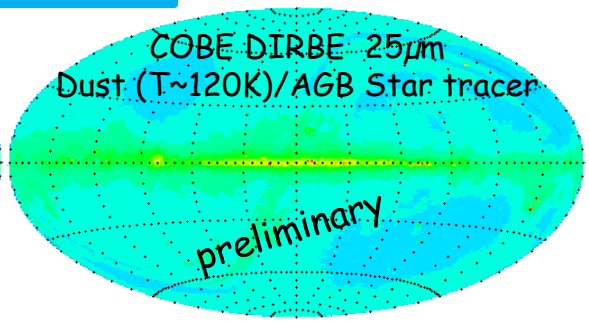


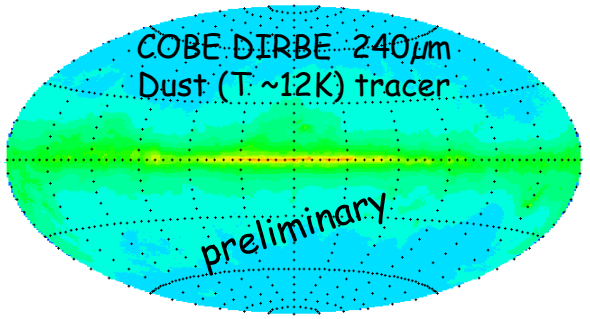
Confirm extragalactic and galactic diffuse gamma rays as BG.
Assumed the distribution of ^{26}Al using a template
-> roughly estimation with the expected PSF and effective area

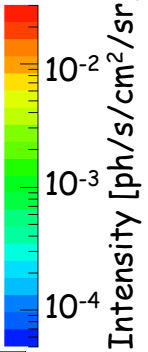
1.8 MeV observation by SMILE-3

Assumed all sky map @ 1.8 MeV



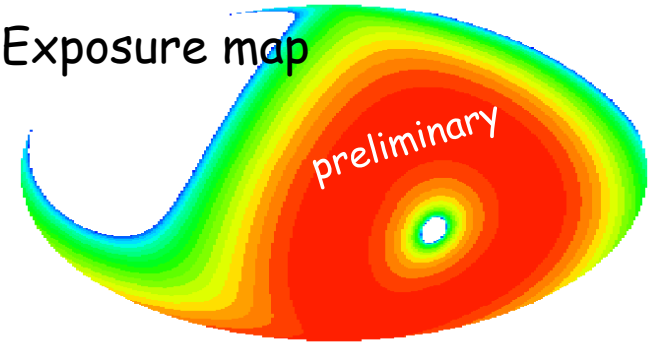


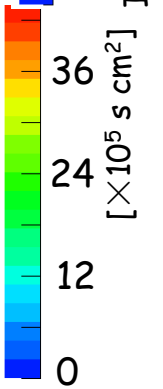




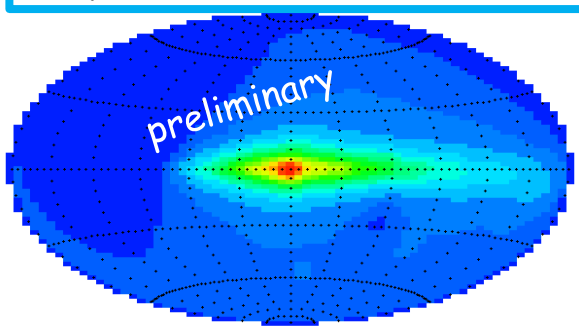
@ Alice Springs (Australia)
eff. area 5.8 cm², FoV ~π sr,
obs. time 30 days
energy resolution 6% @ 1.8 MeV (FWHM)
atmospheric attenuation ~85% (@ ~40 km)
ARM res. 5° , SPD res. 25°

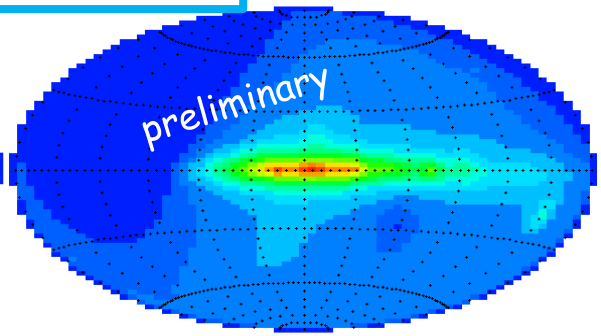
Exposure map

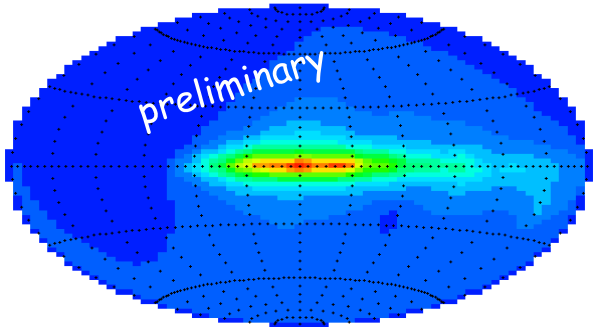


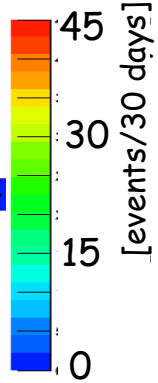


Expected detection event number





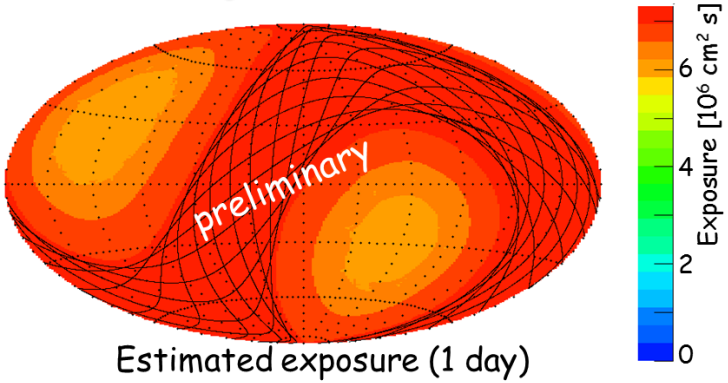




1 pixel ~ l 5° ×b 2.5°

We can discuss the distribution of 1.8 MeV with SMILE-3 observation.

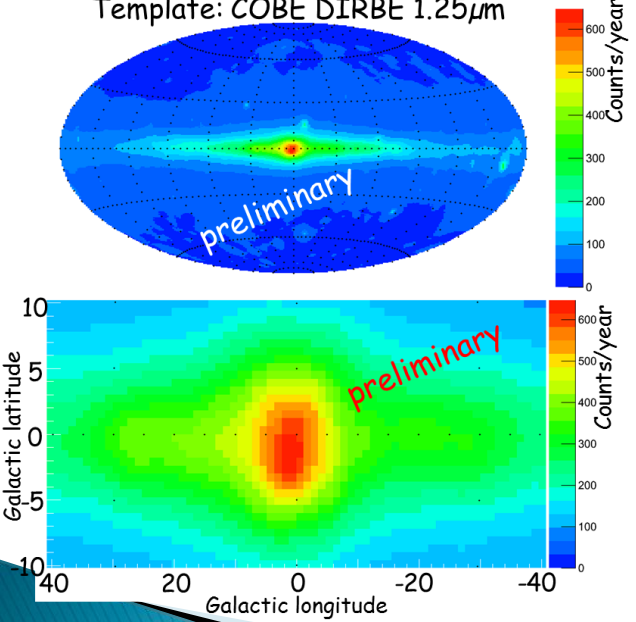
Expected observation with satellite



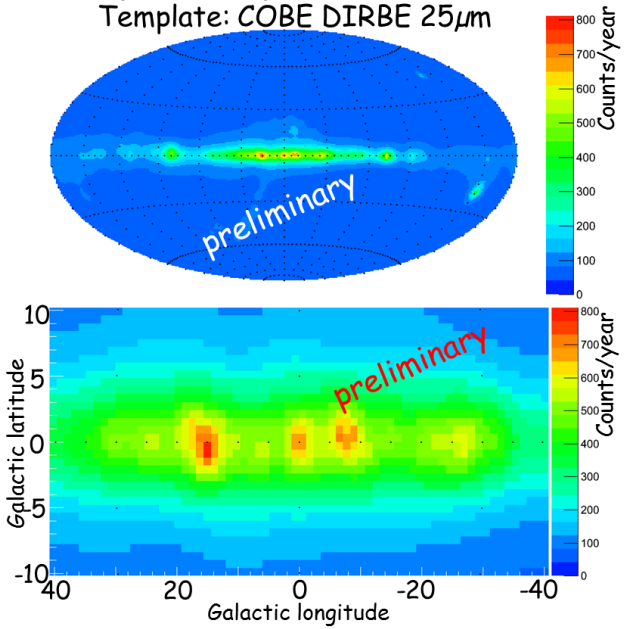
Estimated exposure (1 day)

Eff. area :	200 cm² (zenith direction)
FoV :	2π sr
PSF :	~2.3° (ARM: 2° & SPD: 10°)
Energy res.:	2.4% @ 1.8 MeV (FWHM)
energy cut:	±3σ @ 1.8 MeV
orbit:	same orbit as Fermi

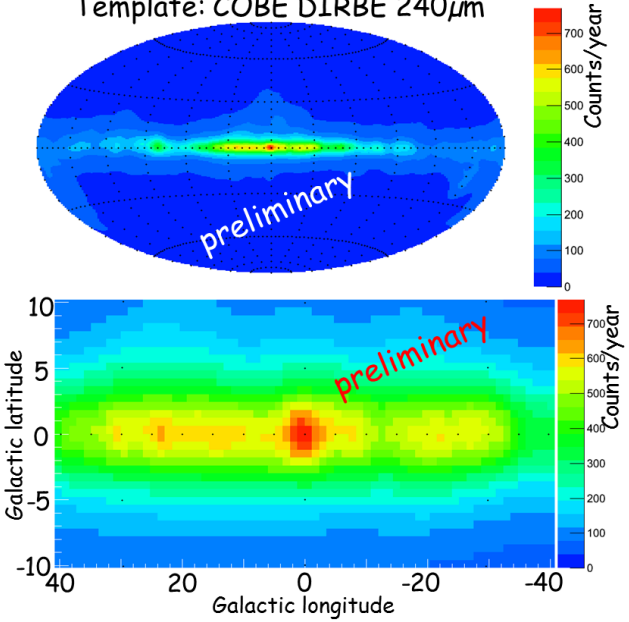
Star tracer (K and M giants)
Template: COBE DIRBE 1.25μm



Dust (T~120K)/AGB star tracer
Template: COBE DIRBE 25μm



Dust (T~12K) tracer
Template: COBE DIRBE 240μm

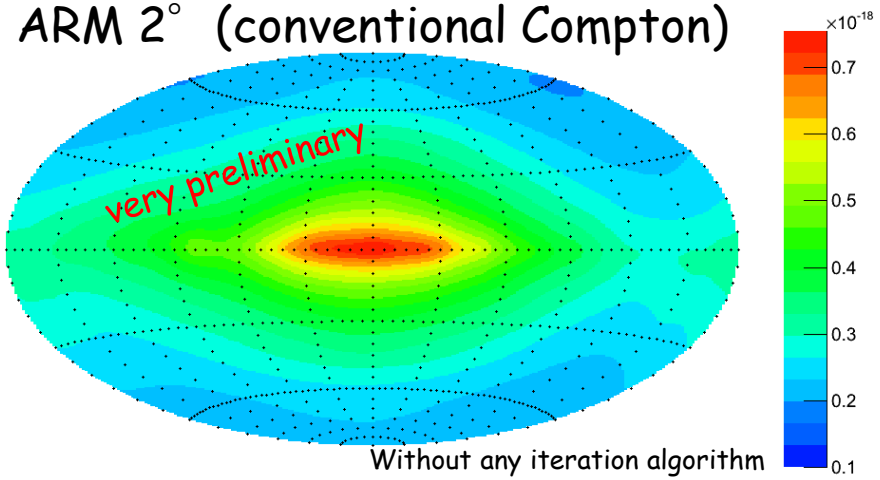


We can discuss the detail of 1.8 MeV distribution with the PSF of 2 degrees.

How about conventional Compton?

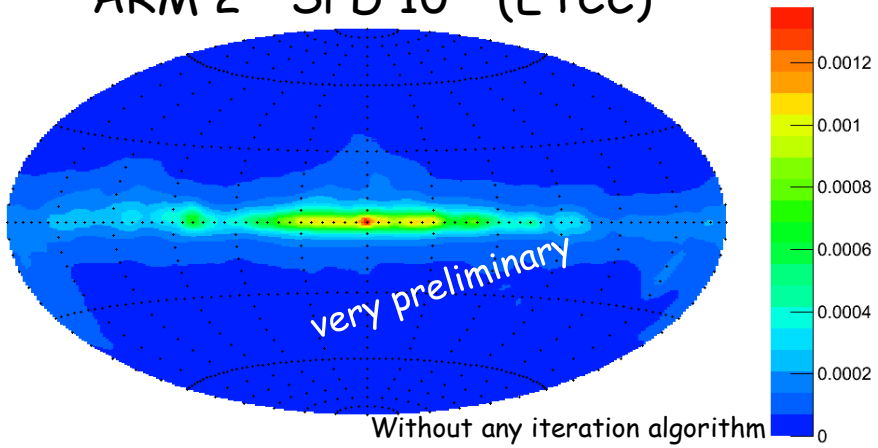
^{26}Al template: DIRBE/COBE (240 μm: dust tracer)

ARM 2° (conventional Compton)



Without any iteration algorithm

ARM 2° SPD 10° (ETCC)



Without any iteration algorithm

- PSF of Conventional Compton camera is limited by the averaged Compton-scattering angle.
  - -> Limitation of scattering angle increases angular resolution, but it decreases effective area.
- If the next MeV telescope has no SPD resolution, MeV gamma-ray astronomy will not have any progress.

Summary

- We defined an angular resolution using half power radius.
  - For calculation of detection sensitivity,
    we need a point spread function (not ARM).
  - PSF depends on both ARM and SPD.
    -> Compton camera must measure
    the direction of recoil-electron.
- SMILE-2 ETCC:
  - Effective area : ~1 cm^2 (< 300 keV)
  - Angular resolution : ~15° (ARM 5.3°, SPD 100° @ 662 keV)
    -> We will update the angular resolution of ~5° (SMILE-2+)
    Ar -> CF_4, Scintillator at the inside of gas vessel
- Expected observations of ^{26}Al:
  - SMILE-3 detect excess at GC with the significance of 5σ
  - satellite obtain detail sky map

Thank you for your attention!

http://www-cr.scphys.kyoto-u.ac.jp/research/MeV-gamma/wiki