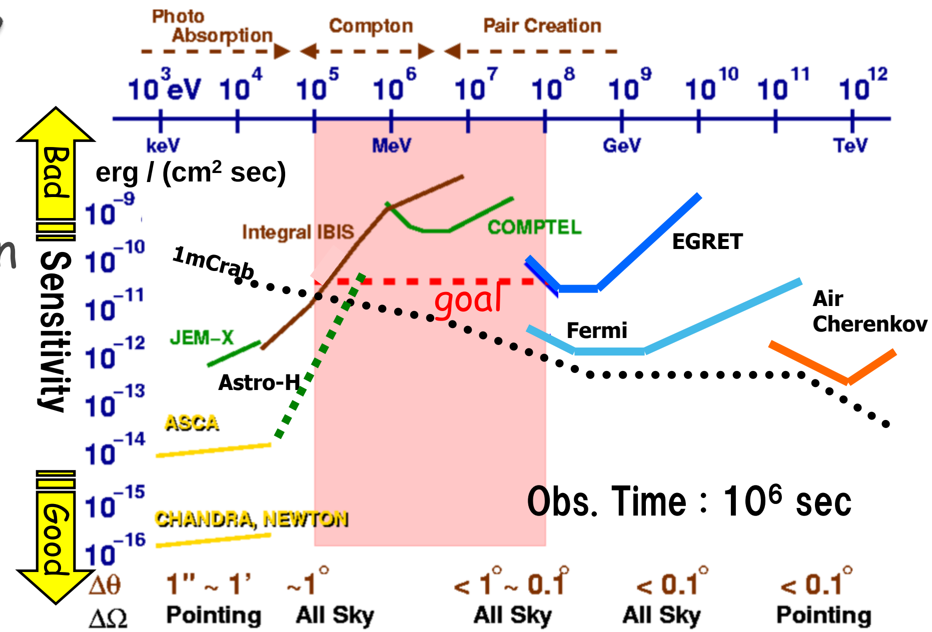
MeV gamma-ray observation with a well-defined point spread function based on electron tracking

A. Takada (Kyoto univ.), T. Tanimori, H. Kubo, T. Mizumoto, Y. Mizumura, S. Kokura, T. Kishimoto, T. Takemura, K. Yoshikawa, Y. Nakamasu, Y. Matsuoka, M. Oda, S. Miyamoto, S. Sonoda, D. Tomono, K. Miuchi, S. Kurosawa, T. Sawano

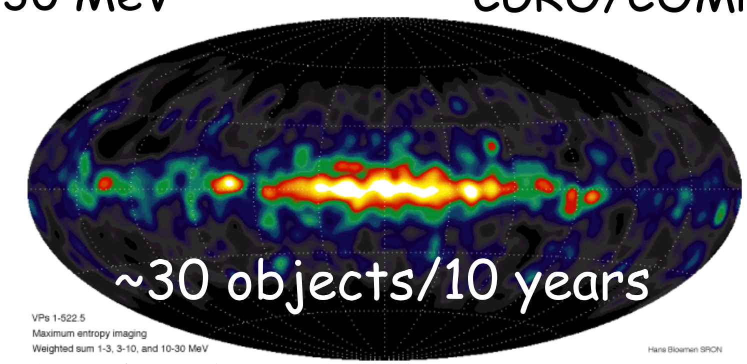
1. Motivation & Detector concept
2. Point spread function
3. Effective area and expected sensitivity
4. Expected observations
5. Summary

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

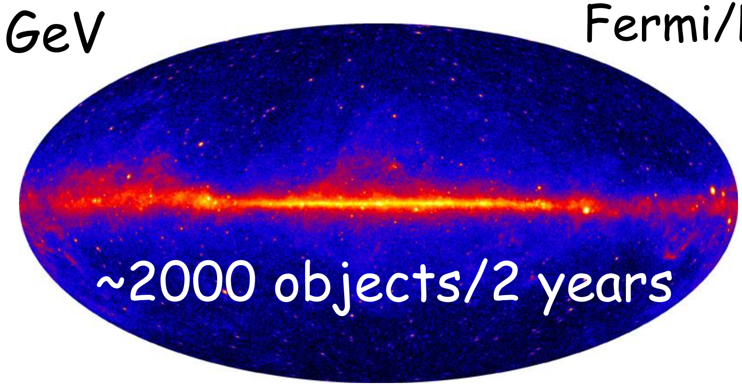


MeV sky map



V. Schönfelder+ (A&AS, 2000)

GeV sky map

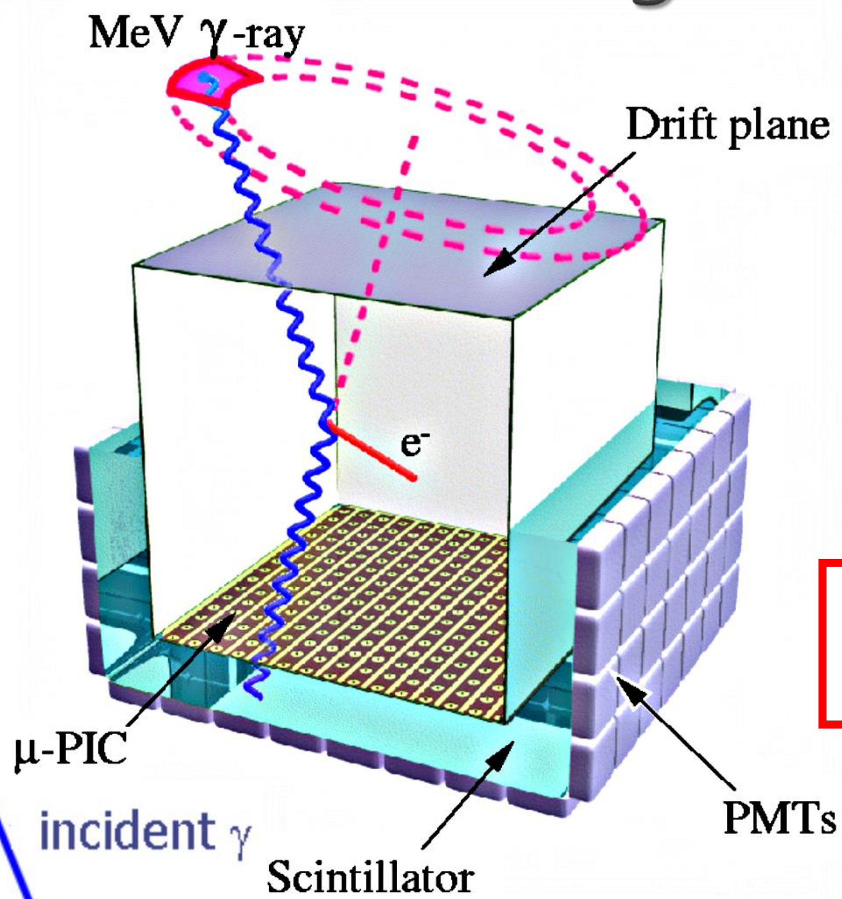


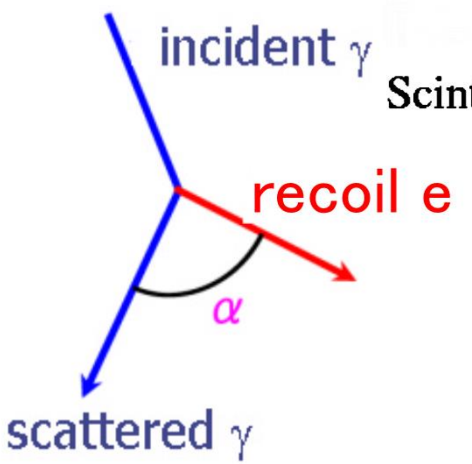
P. L. Nolan+ (ApJS, 2012)

Requirements for the next-generation detectors are …

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

ETCC for 2nd balloon experiment

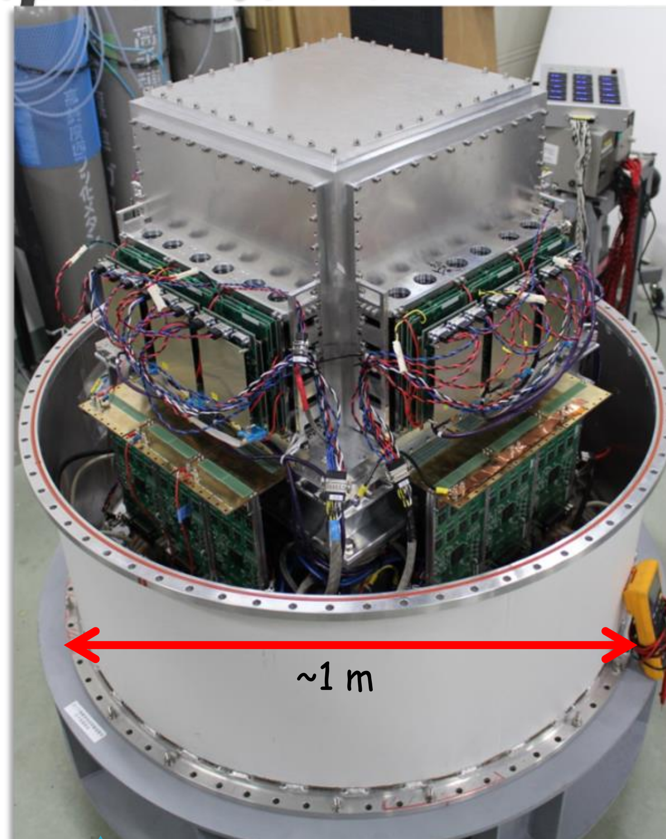
SMILE-II

Target: Crab nebula

5σ detection (40 km, several hours)

Requirements

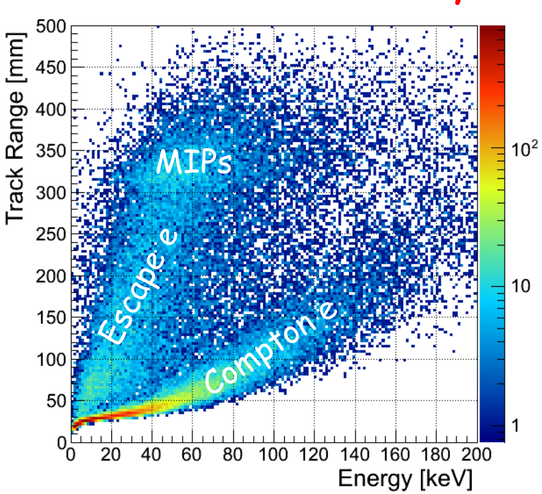
Effective area	:	> 0.5 cm² (300 keV)
Angular resolution	:	< 10° (600 keV)
Sensitivity	:	×100 SMILE-I

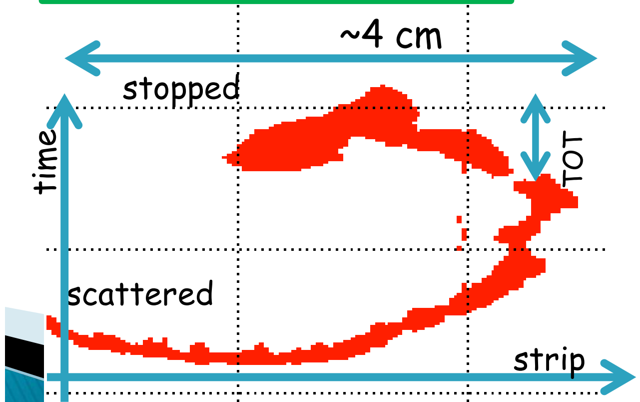


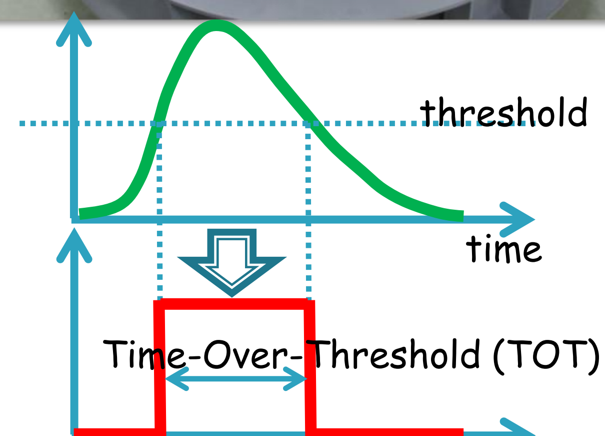
Improvements for SMILE-II

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

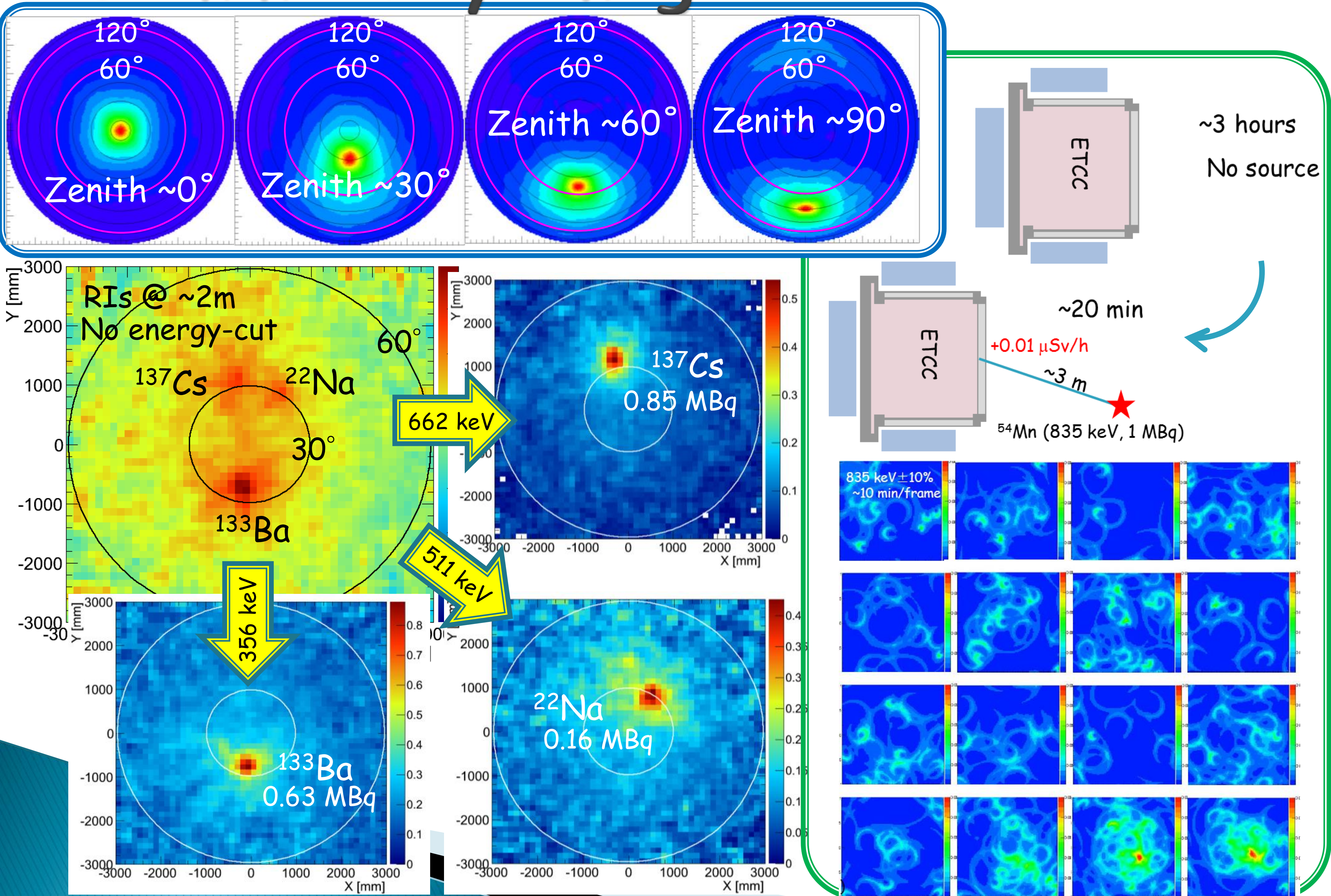
Sensitivity will reach to (×100 SMILE-I) !







Gamma-ray images

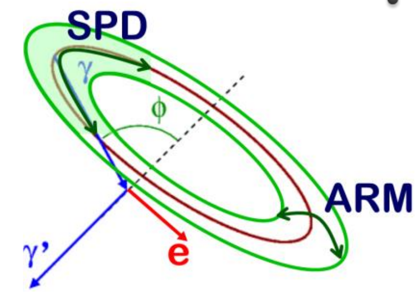


Angular resolution of Compton telescope

Conventional evaluation

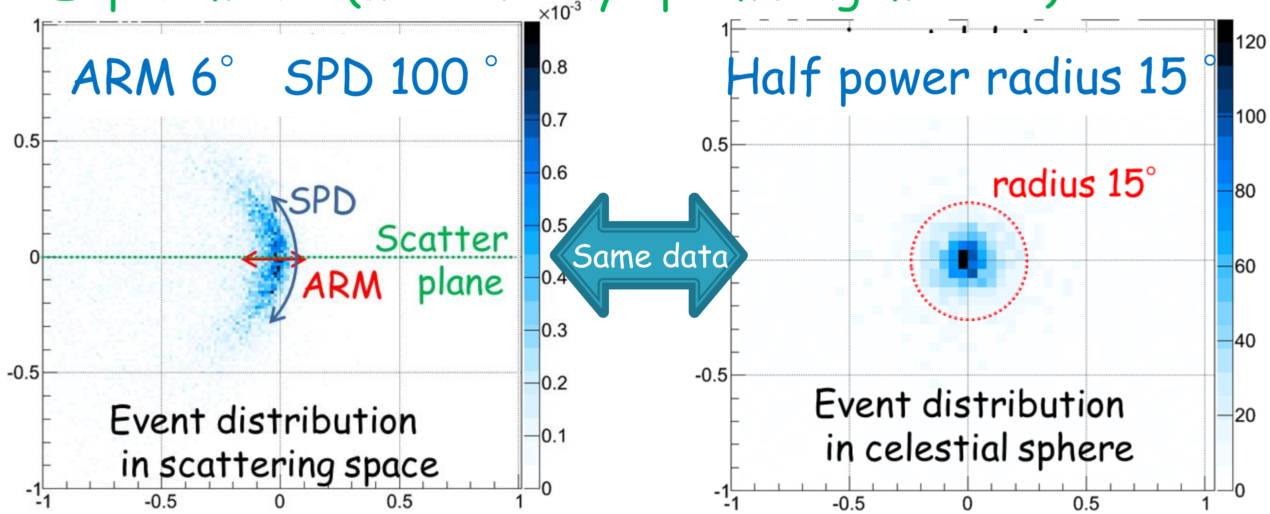
Angular Resolution Measure：
accuracy of Compton-scattering angle

Scatter Plane Deviation：
accuracy of Compton-scattering plane



➡ Angular resolution of Compton telescope will be nearly equal to ARM.

Experiments (without any optimizing method)



ARM is not equal to the distribution of reconstructed images.

For the estimation of detection sensitivity, we need Point Spread Function.

Event distribution with various ARM and SPD

for ETCC

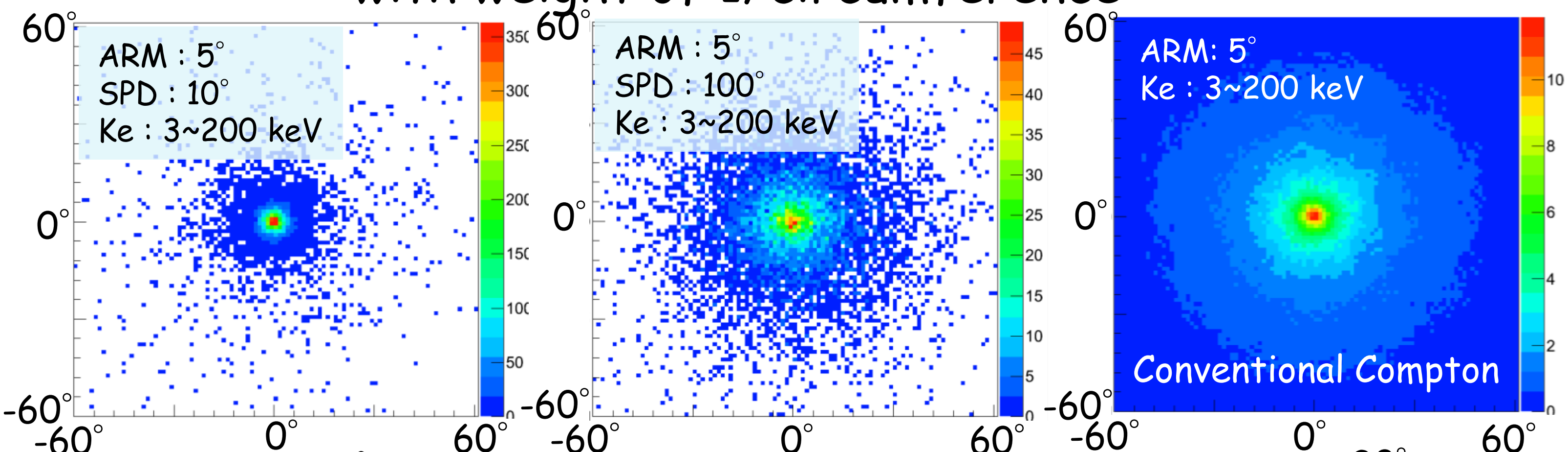
ARM -> Cauchy distribution with assumed FWHM

SPD -> Gauss distribution with assumed FWHM

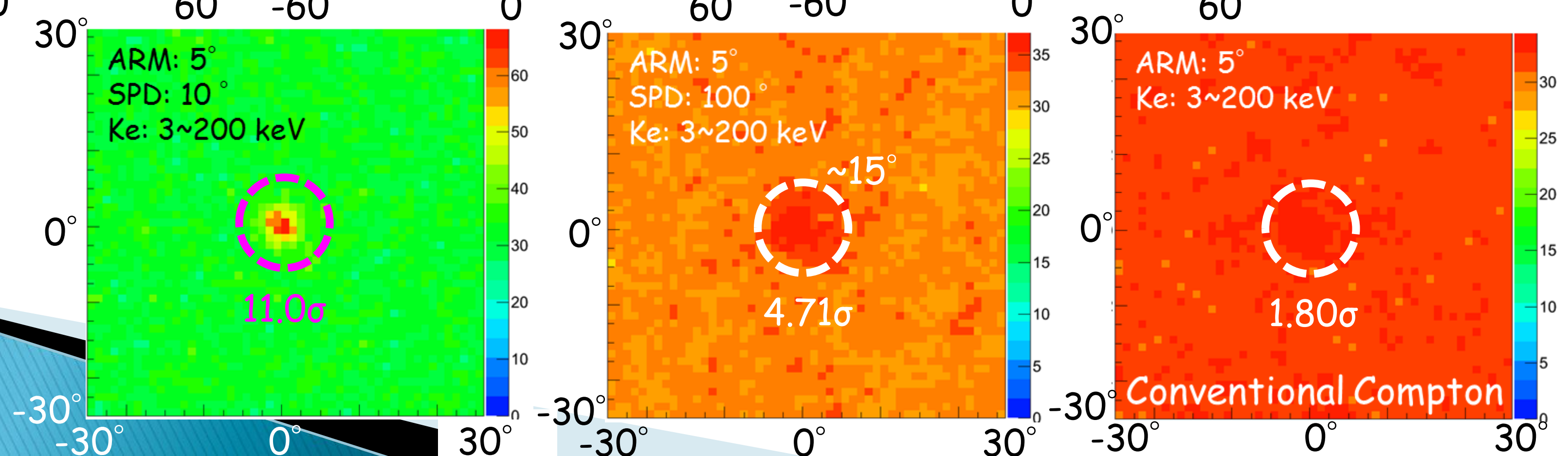
for Conventional Compton Camera

ARM -> Cauchy distribution with assumed FWHM with weight of 1/circumference

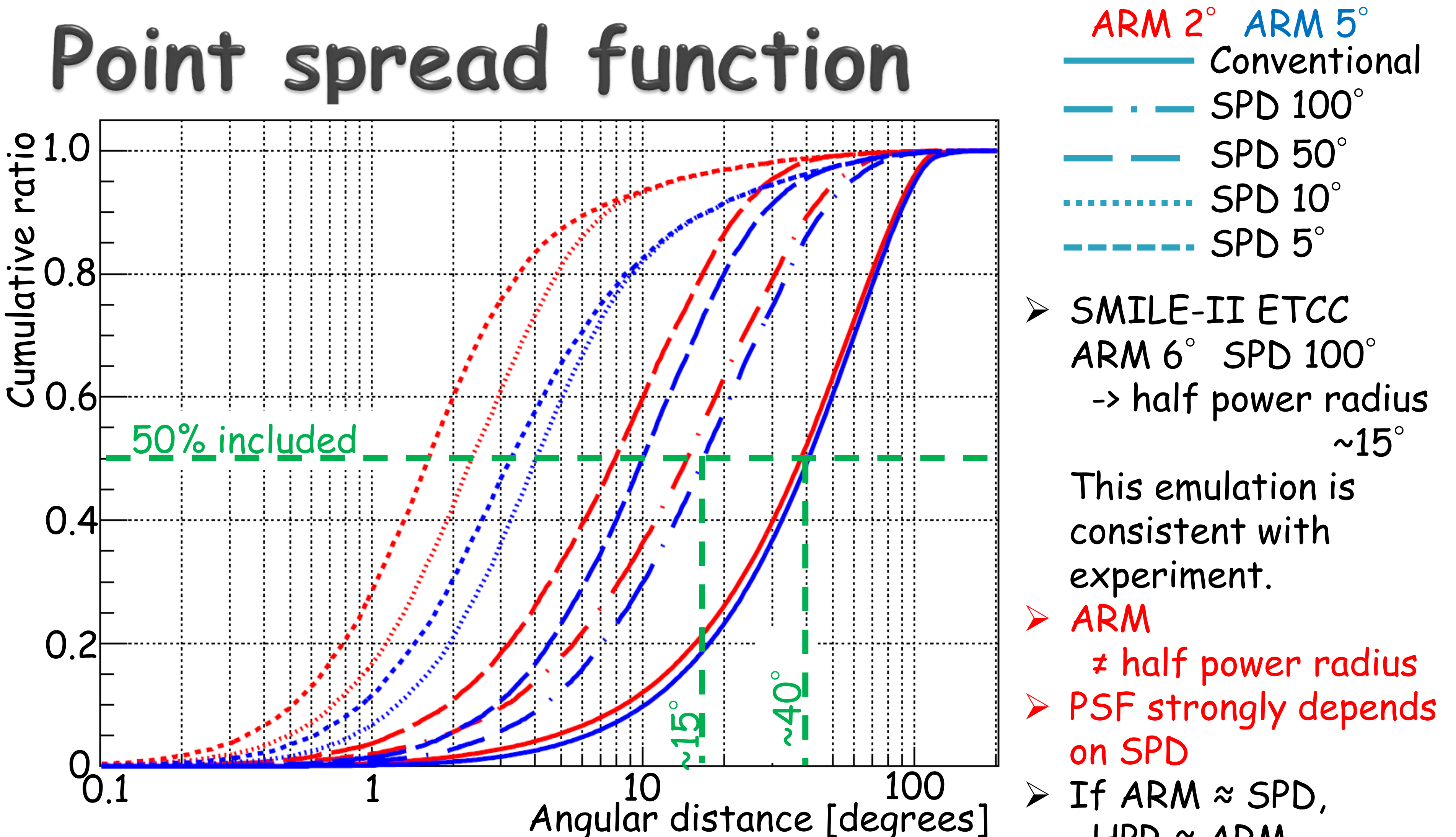
Estimate event distribution of reconstructed image



S : N = 10^3 : 10^6



Point spread function



- 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.

Effective area

Density of gas is ~1/1000 lower than that of solid.
So, is an effective area of a gaseous Compton also small?

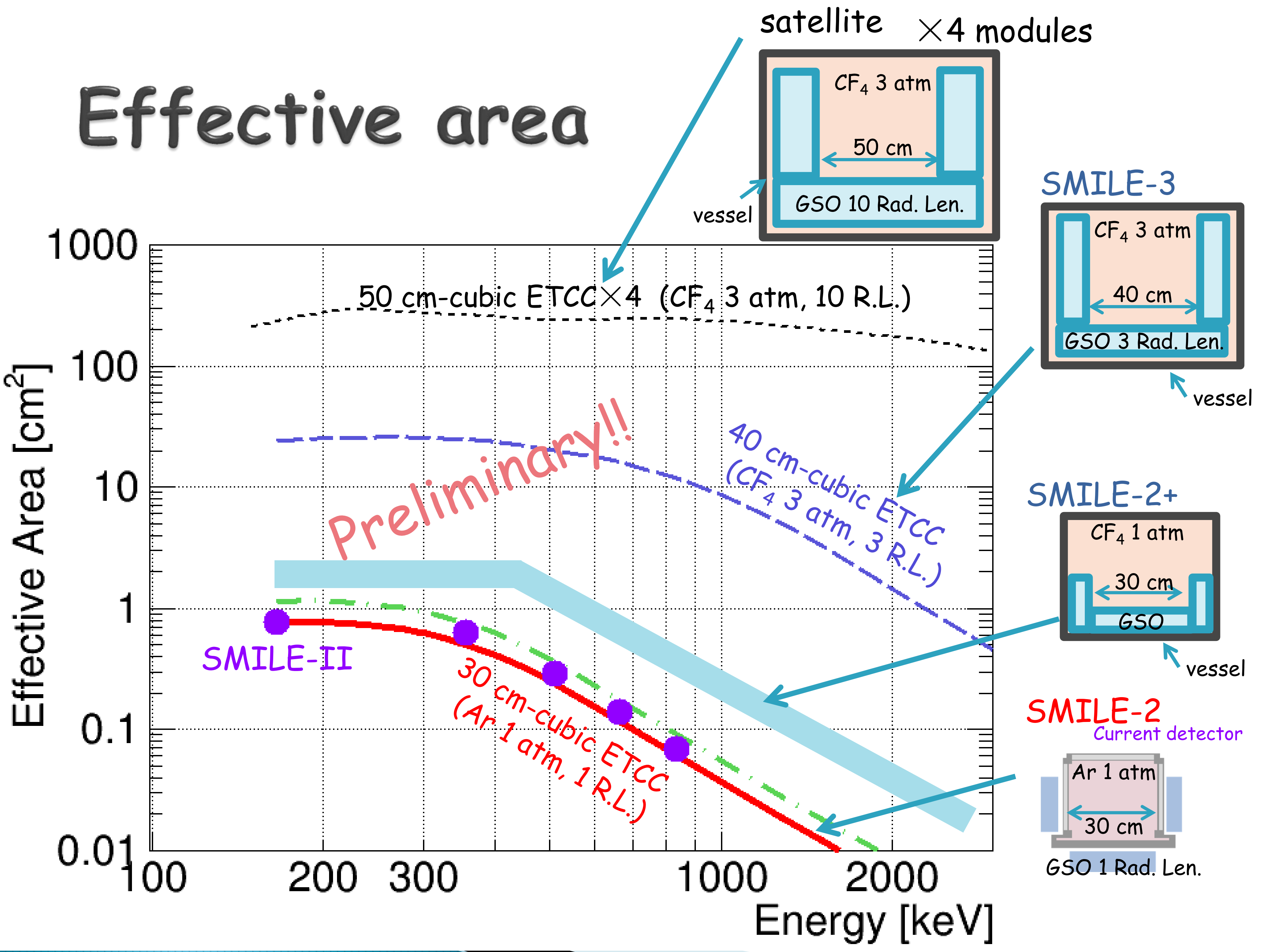
Answer :
No!

- Effective area depends on detection efficiency and geometrical area.
- Detection efficiency depends on opacity (not density).
- It is easy to make a large-volume gaseous detector.

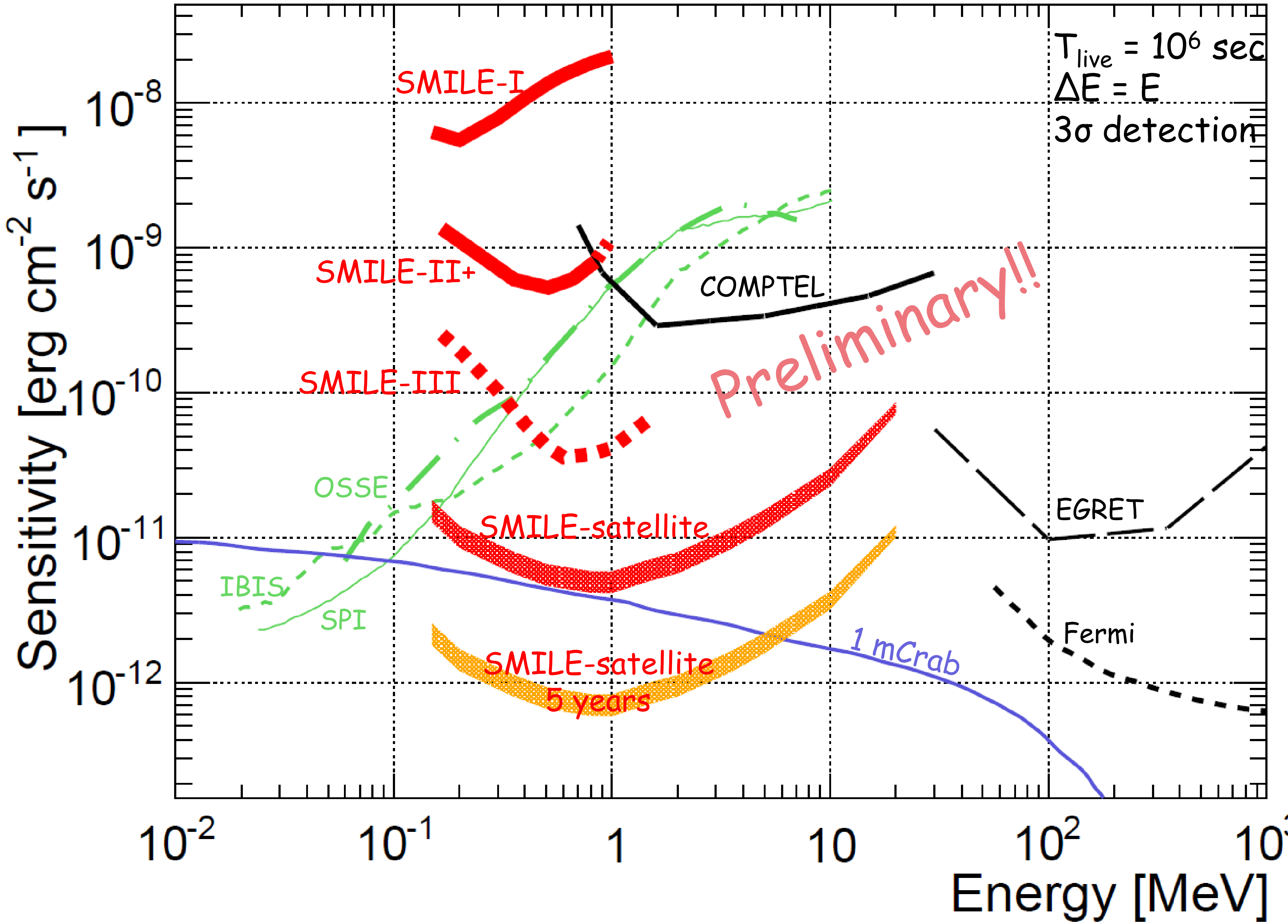
Detector's configuration, rather than material phase, determines the effective area.

	gaseous TPC		semiconductor
	Ar 1 atm	CF_4 3 atm	Si
# of e^-/molecule	18	42	14
density	1.78 mg/cm^3	10.9 mg/cm^3	2.33 g/cm^3
Thickness	300 mm		0.5 mm × 15 layers
probability @ 300 keV	0.507 %	3.26 %	16.8% (1 layer : 1.22 %)
probability @ 600 keV	0.386 %	2.48 %	13.1 % (1 layer : 0.930 %)
geometrical area	30×30 cm^2		10×10 cm^2
cross section @ 300 keV	4.56 cm^2	29.3 cm^2	16.8 cm^2
cross section @ 600 keV	3.47 cm^2	22.3 cm^2	13.1 cm^2

Effective area



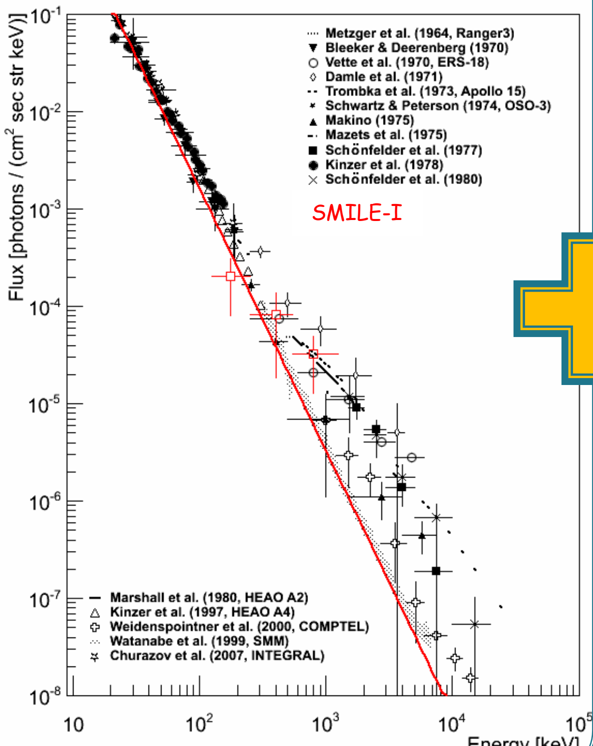
Expected detection sensitivity



Estimation of sky image at 1.8 MeV

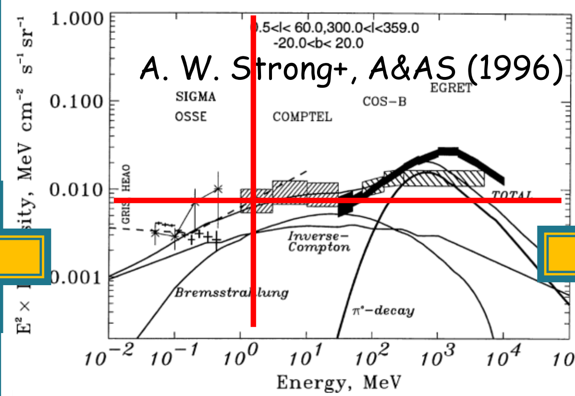
Extragalactic diffuse

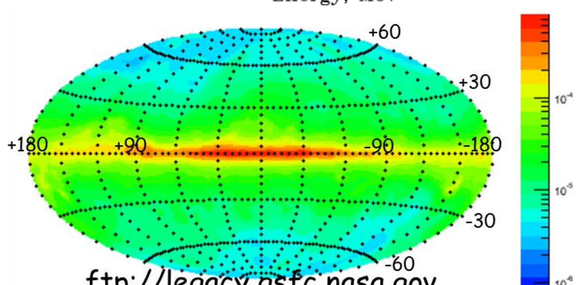
Intensity: power-law (SMM)
Distribution:
uniform, isotropic



Galactic diffuse

Intensity: COMPTEL
Distribution:
galactic diffuse model
(EGRET)



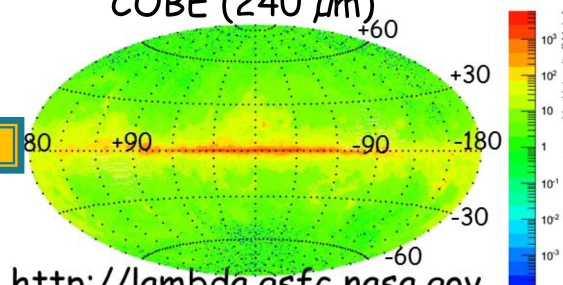


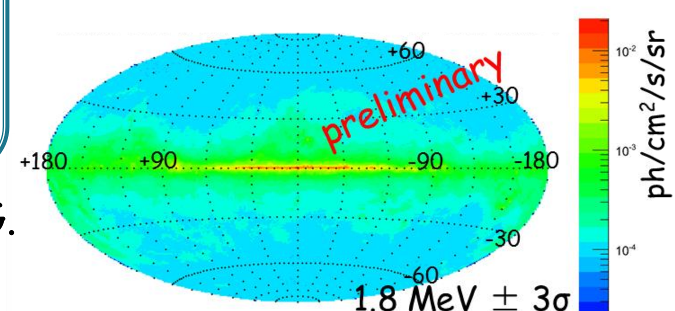
^{26}Al 1.8 MeV

Intensity: SPI/INTEGRAL
3.5×10^{-4} ph/cm²/s
$|l| \leq 30^\circ$ $|b| \leq 10^\circ$
L. Bouchet+, ApJ (2015)

Distribution:
sky map by other bands

COBE (240 μm)





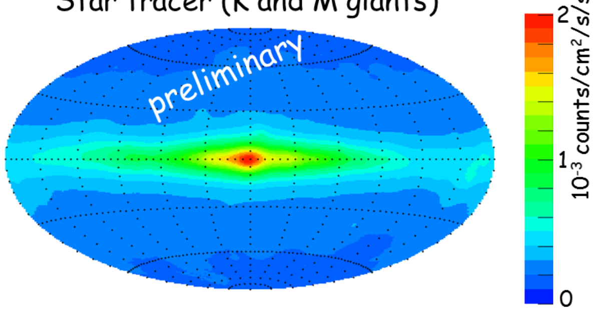
Confirm extragalactic and galactic diffuse gamma rays as BG.
Assumed the distribution of ^{26}Al using a template
-> roughly estimation with the expected PSF and effective area

Expected observation with SMILE-3

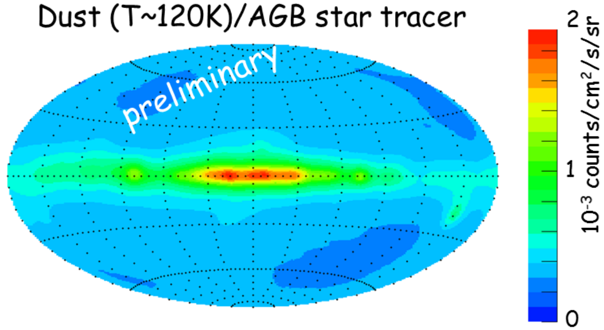
Sky image with the PSF of SMILE-3 @ 1.8 MeV

Energy resolution: 6%@1.8MeV (FWHM)
integrated within 1.8MeV±3σ

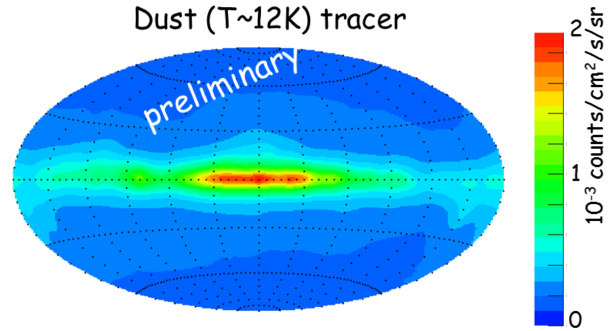
COBE DIRBE 1.25μm
Star tracer (K and M giants)



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

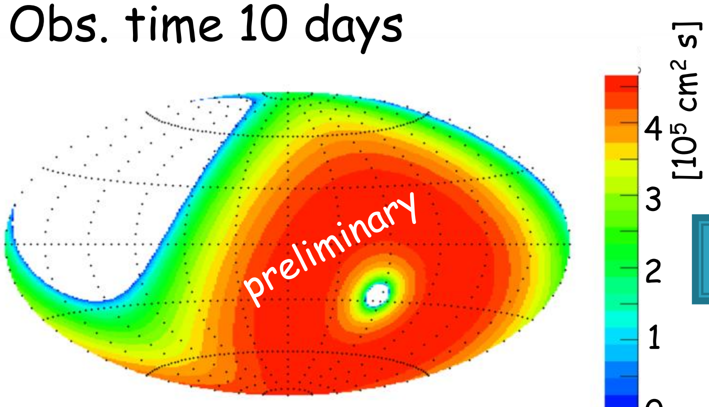


COBE DIRBE 240μm
Dust (T~12K) tracer



atmospheric attenuation:
×0.85 @ 40km

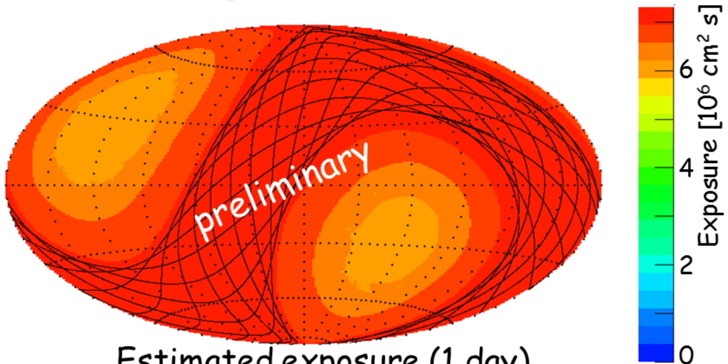
Exposure map @ Alice Springs (Australia)
Eff. area 1.5 cm², FoV ~π sr,
Obs. time 10 days



	1.25 μm	25 μm	240 μm
-30° ≤ *l* ≤ 30° -6° ≤ *b* ≤ 6°	120 counts	120 counts	120 counts
-30° ≤ *l* ≤ 30° -32° ≤ *b* ≤ 20°	24 counts	29 counts	20 counts
-120° ≤ *l* ≤ -60° -6° ≤ *b* ≤ 6°	50 counts	56 counts	49 counts

SMILE-3 can detect the excess at GC with the significance of 5σ.

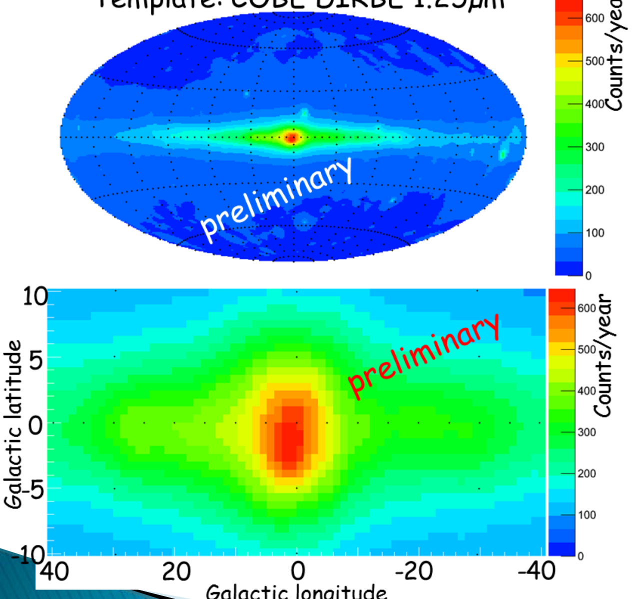
Expected observation with satellite



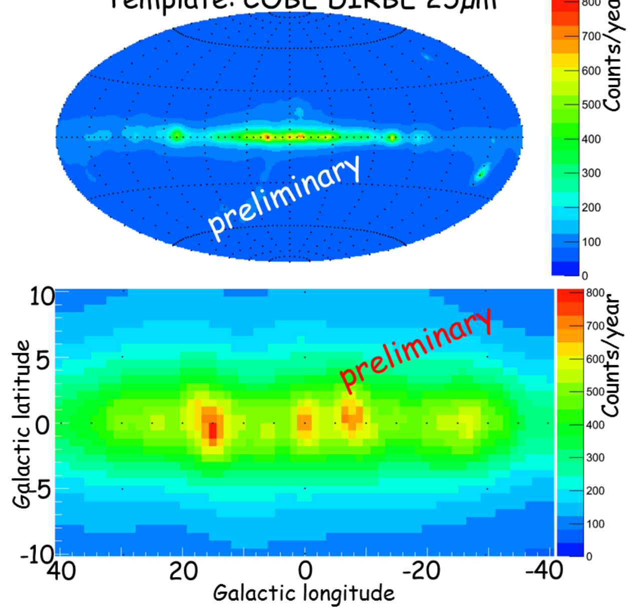
Estimated exposure (1 day)

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

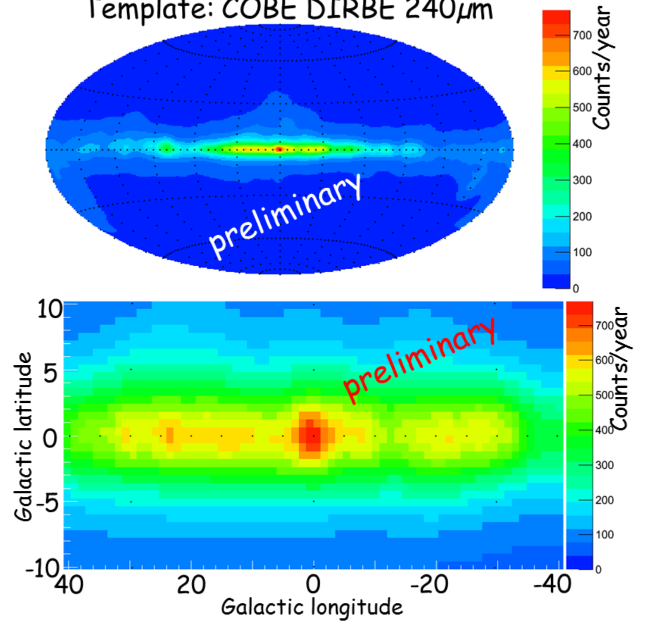
Star tracer (K and M giants)
Template: COBE DIRBE 1.25μm



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



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

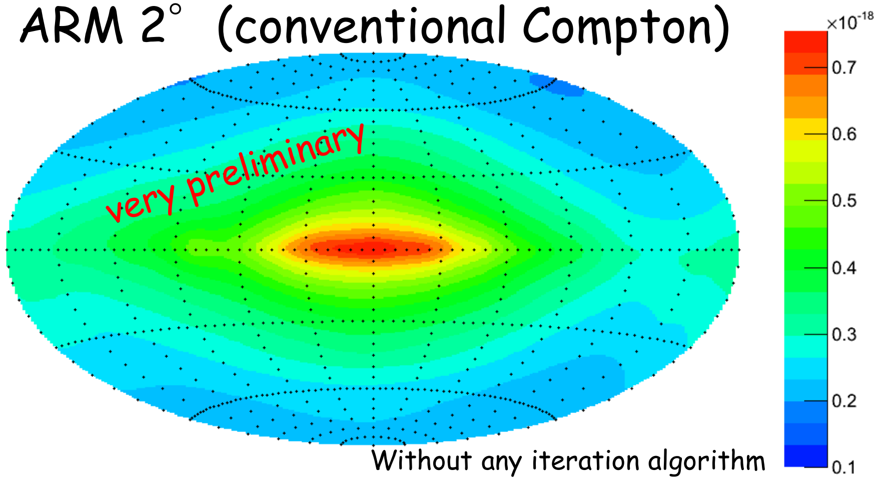


We can discuss the detail of 1.8 MeV distribution with the PSF of 2 degrees.

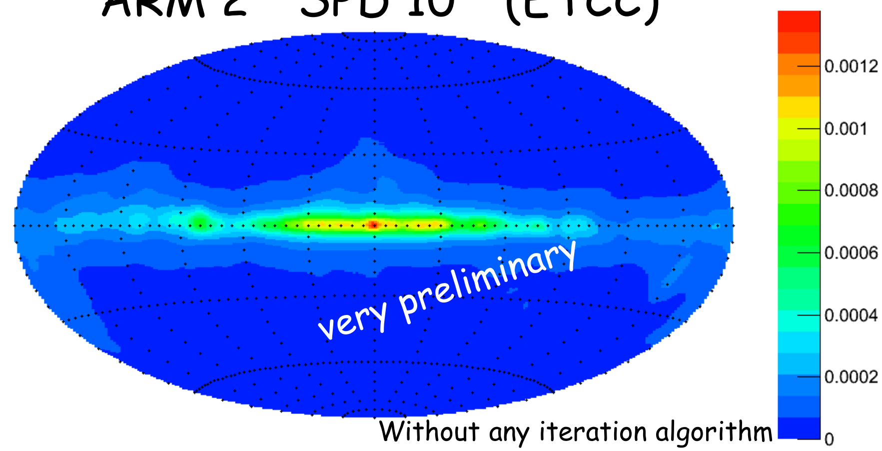
How about conventional Compton?

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

ARM 2° (conventional Compton)



ARM 2° SPD 10° (ETCC)



- 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