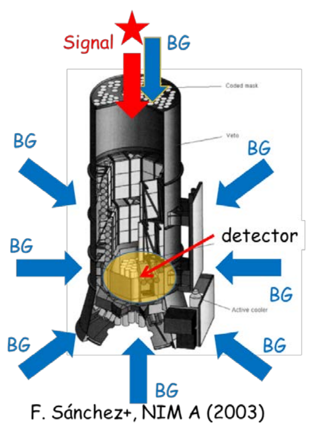
Proposal of balloon and satellite observations of MeV gamma-ray using ETCC for reaching a high sensitivity of 1 mCrab

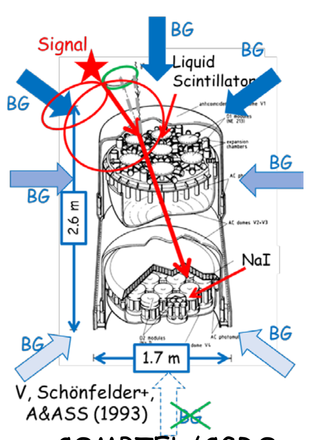
A. Takada, T. Tanimori, H. Kubo, T. Mizumoto, Y. Mizumura, T. Sawano[1], K. Nakamura, Y. Matsuoka, S. Komura, T. Kishimoto, M. Oda, T. Takemura, S. Miyamoto, Y. Nakamasu, K. Yoshikawa, J. D. Parker, K. Miuchi[2], S. Kurosawa[3]
(Kyoto University, [1]Kanazawa University, [2]Kobe University, [3]Tohoku University)

1. Open an MeV gamma-ray window

MeV gamma rays from hundreds keV to tens MeV provide us the information of nucleosynthesis in supernovae, particle acceleration in jets of active galactic nuclei or gamma-ray bursts, and strong gravitational potential around black hole candidates. Especially, line gamma rays from fresh radioisotopes are unique probe for direct search of nucleus factories. ^{56}Ni produced in type Ia supernovae, which are famous standard candles in universe, determines the explosion mechanism. Long-lived isotopes such as ^{26}Al or ^{60}Fe have the information of old star production or material transmission in our galaxy. In addition, the universe in MeV region is transparent, we can thus see the first star as a long gamma-ray burst. However, the current detection sensitivity is not enough to study such interesting phenomena.



SPI/INTEGRAL
Each event has no directional information.

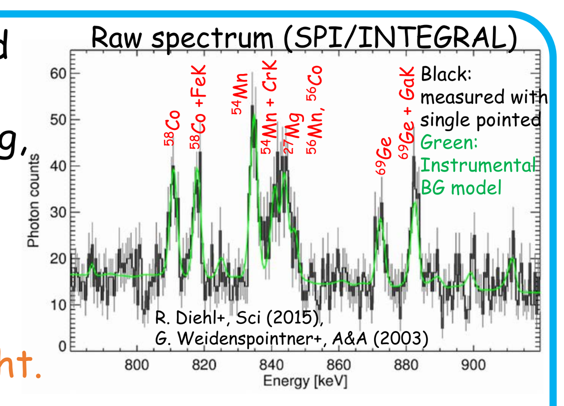


COMPTEL/CGRO
Each event has partial directional information.

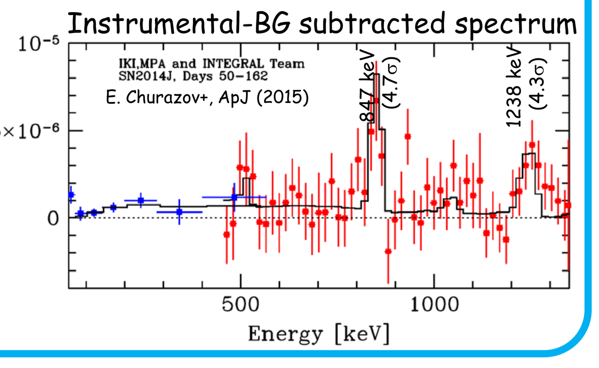
Cosmic rays create gamma rays, neutrons, and charged particles by the interaction with the satellite body. Using coded aperture imaging or usual Compton imaging, we can not obtain two angles of incident direction, event by event. Therefore, the detectors can not exclude the instrumental BG completely. If we use a telescope having a well-defined point spread function, the observations will include only BG on the line of sight.

cf.) observation of SN2014J:
flux: 5×10^{-6} ph/cm²/keV (847 keV), effective area: 65 cm²
100 days & ΔE ~50 keV -> detection: ~1.5×10^{5} events
significance 4.7σ -> included BG events: ~10^{9} events
If the detector can reduce BG to 1/1000, significance is ~150σ.

Raw spectrum (SPI/INTEGRAL)



Instrumental-BG subtracted spectrum

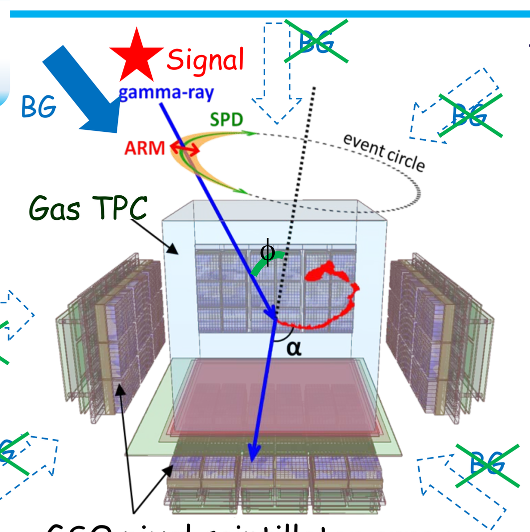


What is the problem?
-> Huge background obstructs the observations.

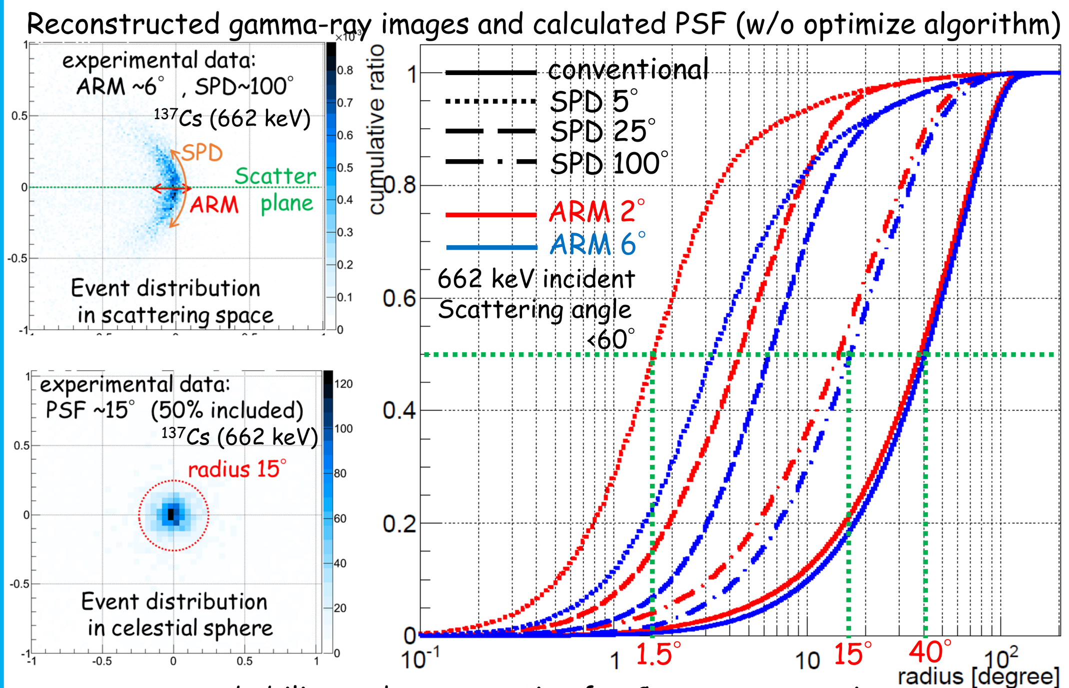
We need a new MeV gamma-ray telescope having a well-defined point spread function of ~1 degree.

2. Electron-Tracking Compton Camera

To open the MeV gamma-ray window, we need a new telescope having a good point spread function (PSF), a large effective area, and a wide field of view. For these purposes, we are developing an electron-tracking Compton camera (ETCC). Our ETCC consists of a gaseous time projection chamber (TPC), which detects the track and energy of the recoil electron, and a scintillator, which detects the absorption point and the energy of the scattered gamma ray. Although ETCC detects gamma rays using Compton scattering similar to COMPTEL, new information of electron tracking (two directional angles and energy loss rate: dE/dx) provides us clear images with a sharp and well-defined PSF and strong background rejection compared to the conventional MeV gamma-ray detectors.



Reconstructed gamma-ray images and calculated PSF (w/o optimize algorithm)



probability and cross section for Compton scattering

	gaseous TPC		semiconductor
	Ar 1 atm	CF_4 3 atm	Si
# of e⁻/molecule	18	42	14
density	1.78 mg/cm³	10.9 mg/cm³	2.33 g/cm³
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 cm²		10×10 cm²
cross section @ 300 keV	4.56 cm²	29.3 cm²	16.8 cm²
cross section @ 600 keV	3.47 cm²	22.3 cm²	13.1 cm²

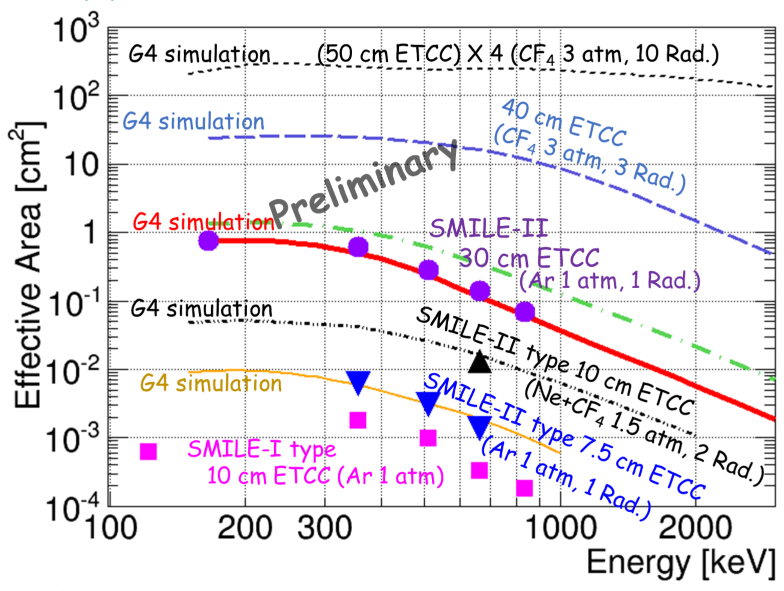
◆ How to realize a well-defined PSF?

The angular resolution of usual telescopes are described with a point spread function (PSF). Until now, the angular resolutions of Compton cameras including ETCCs are evaluated by angular resolution measure (ARM) and scatter plane deviation (SPD), each parameter however does not represent a PSF. The left figure shows the cumulative ratio with different ARM/SPD resolutions as a function of radius angle. This figure says that the PSF of Compton camera depends on ARM and SPD, and the PSF of conventional Compton imaging is limited by the range of scattering angle. For realizing a PSF of ~1 degree, an ETCC needs an ARM of ~2 degrees FWHM and SPD of ~5 degrees FWHM.

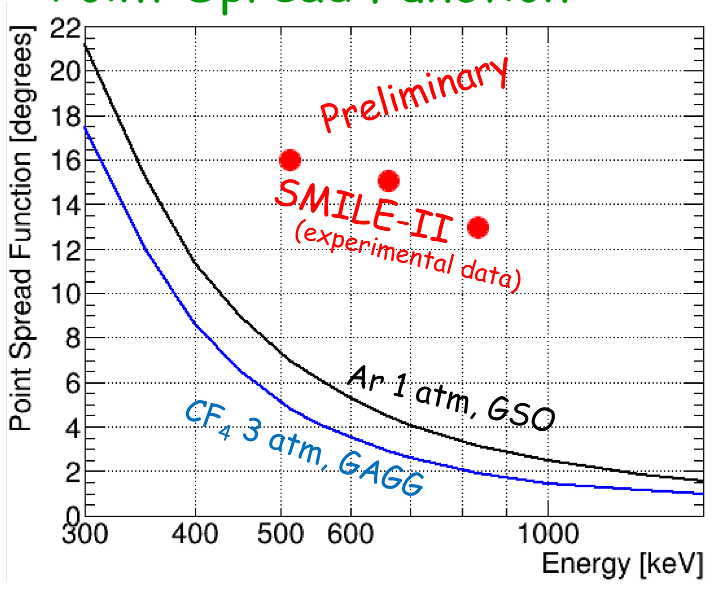
◆ Why gaseous Compton target?

Because the density of gas detector is low, people think that a gaseous Compton target is not useful. But it is not correct. The left table is simple calculations of probabilities and cross sections of Compton scattering. This table says that a cross section of a gaseous detector is as large as that of a Si-stack detector. Thus, a gaseous Compton target does not become a disadvantage for gamma-ray detection. To obtain SPD of ~5 degrees, we must decide the recoil direction within the ~10^{-5} radiation length. For this purpose, a gaseous and solid detectors must have sub-mm and sub-μm sampling, respectively. Thus a gaseous detector needs 10^{3-4} ch readout circuits, and a Si-stack detector must have 10^{7-8} ch readout circuits. A gas is a unique material for Compton camera having a large effective area and a sharp PSF.

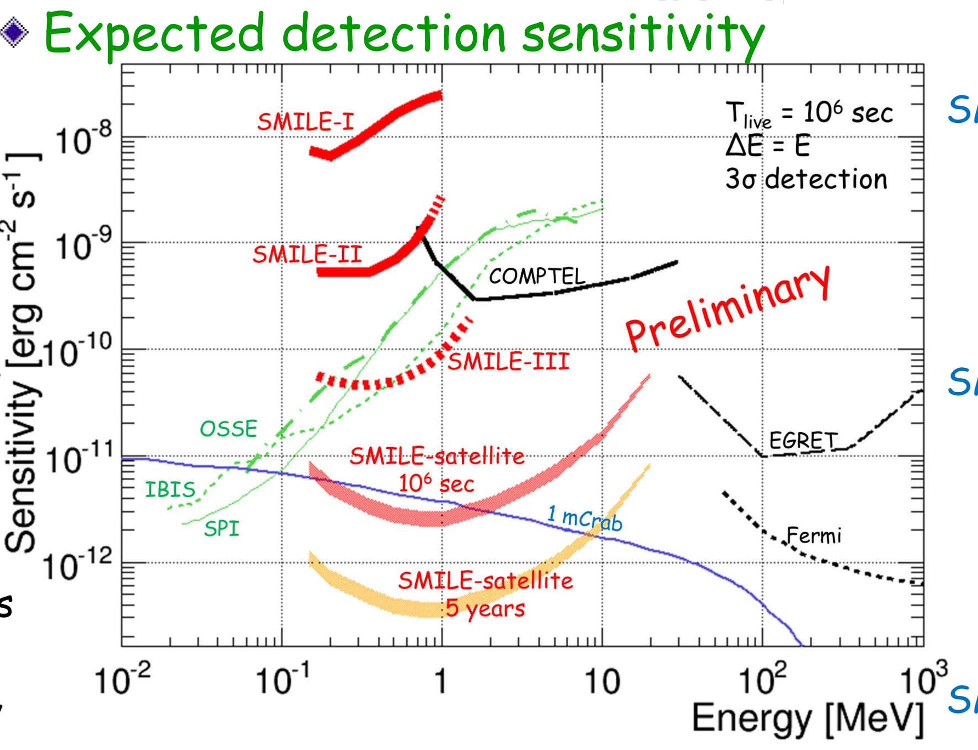
◆ Effective area



◆ Point Spread Function



◆ Expected detection sensitivity



The background observed in SMILE-I was used for the SMILE-II and SMILE-III simulations, and an extragalactic diffuse gamma flux in 0.1-5 MeV reported by SMM and COMPTEL were included for the Satellite-ETCC. Also the point spread function was assumed with a half of ARM resolution (the expected SPD resolution is 5-10 degrees). A duty factor of 1/3 in the operation of the Satellite-ETCC was assumed.

SMILE-II (current ETCC):
30 cm-cubic TPC (Ar 1 atm)
GSO (1 Radiation length)
➡ detectable Crab nebula with 3 h at 40 km

SMILE-III:
40 cm-cubic TPC (CF_4 3 atm)
GSO (3 Rad. length)
➡ detectable polarization of Crab nebula with balloon

SMILE-Satellite:
50 cm-cubic TPC (CF_4 3 atm)
$LaBr_3$ (10 Rad. length) × 4
➡ reach to 1 mCrab ×100 higher sensitivity than COMPTEL

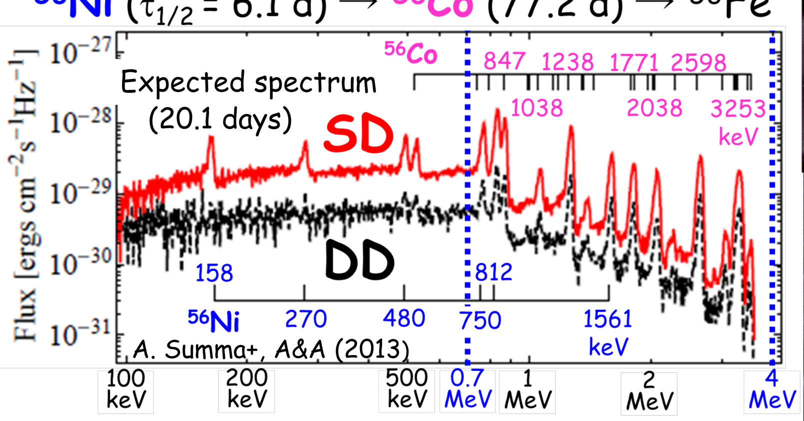
3. Expected observations with SMILE-satellite

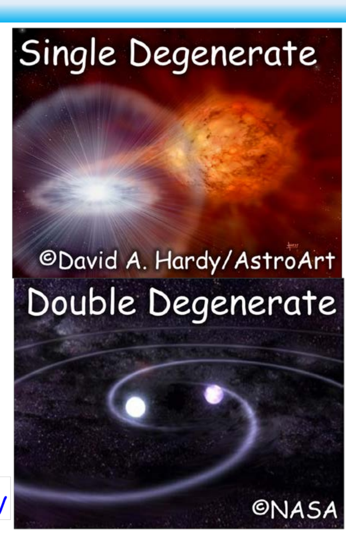
◆ Nucleosynthesis in supernovae and its explosion mechanism

Nucleosynthesis in SNe is one of main topics in MeV gamma-ray astronomy. However there are few detections of line gamma-rays from the fresh RIs. A SN Ia produces ^{56}Ni with the mass of ~0.6$M_\odot$, and various line gamma-ray emission is expected from ^{56}Ni decay chain, as shown in the right figure. But the detections of 0.85 MeV gamma ray from ^{56}Ni/^{56}Co are only two samples: SN1987A and SN2014J.

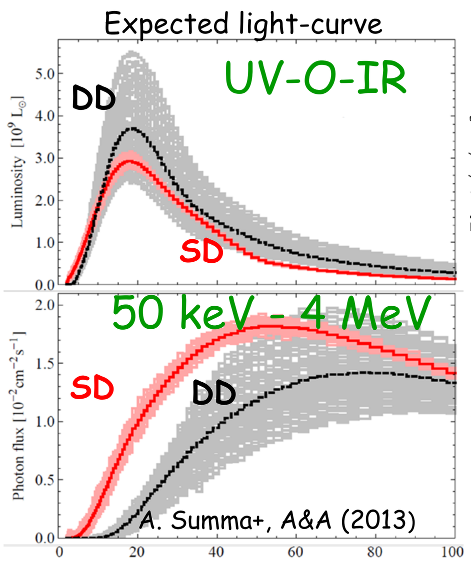
On the other hand, the progenitors of SN Ia is still unresolved puzzle. There are two main branches of SN Ia detonation models: single degenerate (SD) model and double degenerate (DD) model. A light curve in MeV gamma ray has a significant difference between two models, whereas optical light-curve has little difference. SPI/INTEGRAL tried to explain SN Ia progenitors using the observation of SN2014J, but the data can not discriminate any models.

^{56}Ni ($\tau_{1/2}$ = 6.1 d) → ^{56}Co (77.2 d) → ^{56}Fe

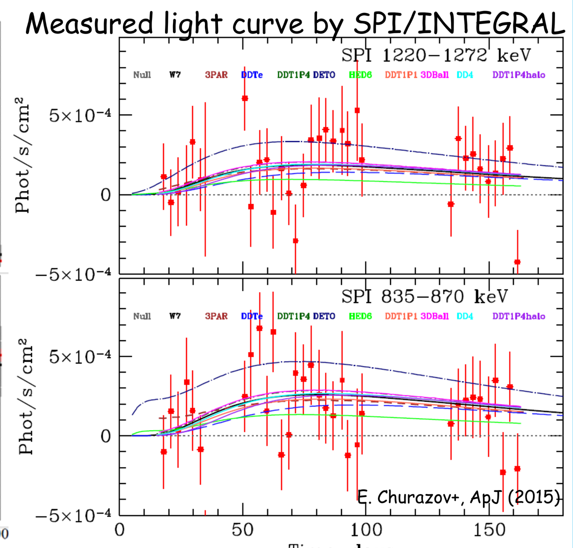




Expected light-curve

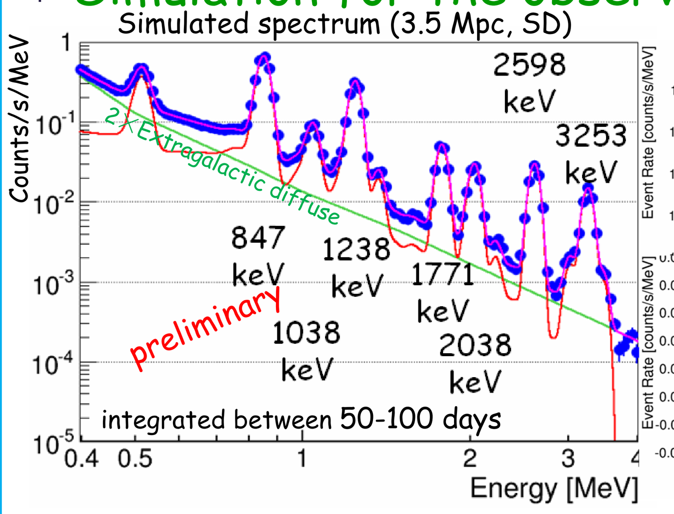


Measured light curve by SPI/INTEGRAL

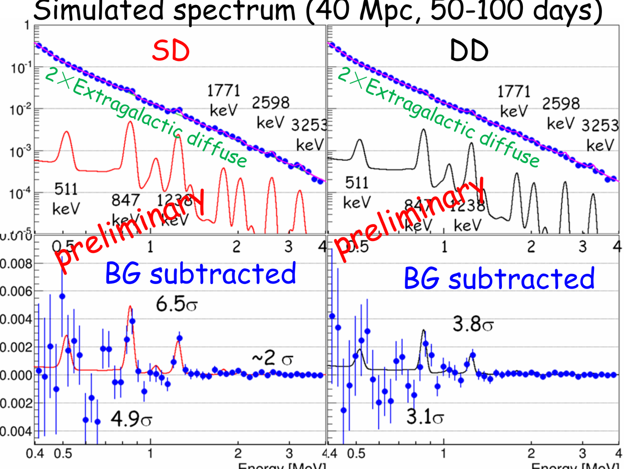


◆ Simulation for the observations of type Ia SNe

Simulated spectrum (3.5 Mpc, SD)

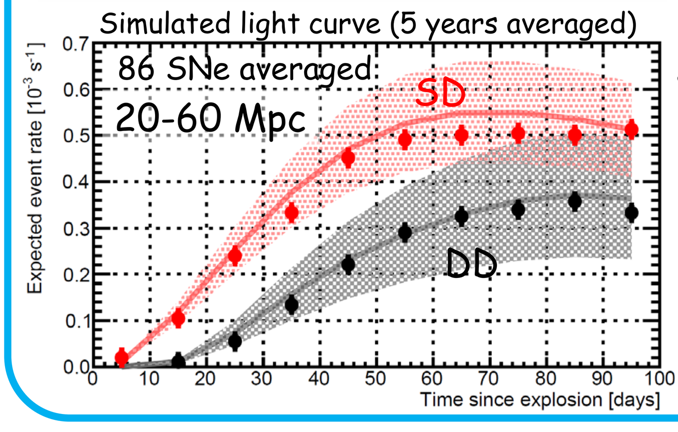


Simulated spectrum (40 Mpc, 50-100 days)

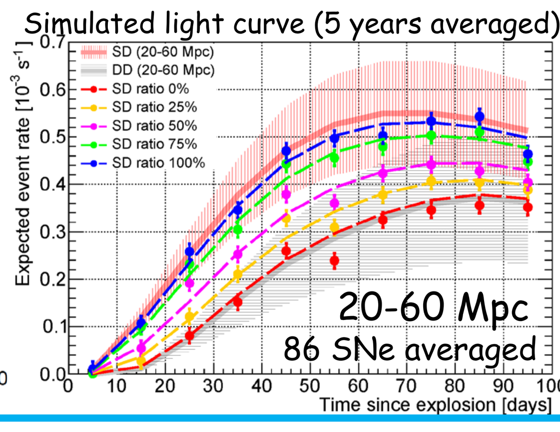


- ➤ ^{56}Co lines are observable for realistic distance SNe Ia
- ➤ Resolving of SD/DD scenarios is expected. MeV all-sky survey (Large # of SNe) is important to cancel-out individual characteristics of SNe.
- ➤ Co-existence ratio of SD & DD scenarios might be obtained with ~20% accuracy.

Simulated light curve (5 years averaged)



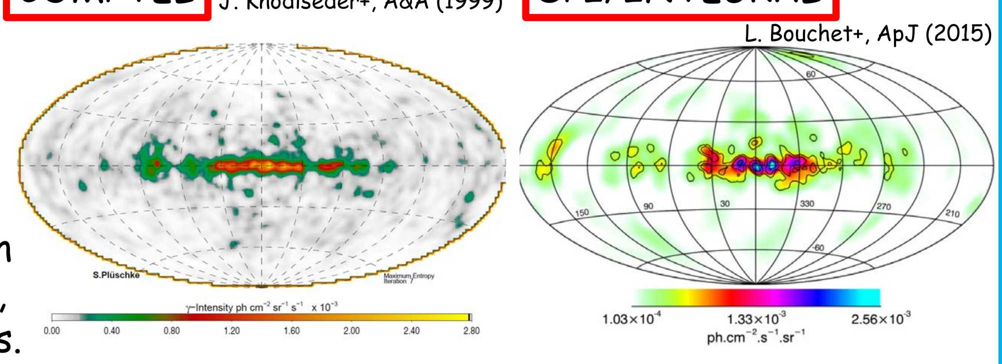
Simulated light curve (5 years averaged)



#SNe (SD, DD)	Generated ratio of SD [%]	Best-fit ratio [%]
0, 86	0.0	4 ± 11
20, 66	23.3	23 ± 3
42, 44	48.8	44 ± 3
64, 22	74.4	76 ± 3
86, 0	100	90 ± 3

◆ Distribution of ^{26}Al

^{26}Al, which is produced in AGB stars, Wolf-Rayet stars, type-II SNe, or outflows of novae, is expected to become a probe of material diffusion in galaxy, because ^{26}Al has a decay time of 7×10^{5} years as long as time scale of diffusion in galaxy. Its distribution was observed by COMPTEL and SPI/INTEGRAL, but the images is not clear for the detail studies.

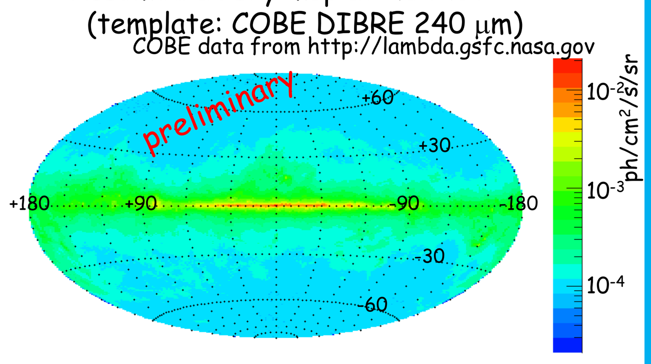


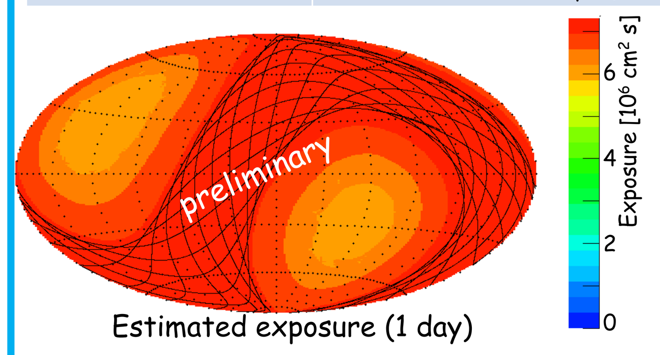
◆ Estimation of ^{26}Al observation by SMILE-satellite

As the distribution of gamma-ray radiation at 1.8 MeV, we assumed with the sum of ^{26}Al, galactic diffuse and extragalactic diffuse gamma ray. The intensity and distribution of each sources are listed in the below table.

sources	intensity	distribution
Gamma ray from ^{26}Al (1.809 MeV)	$3.53.5\times10^{-4}$ ph/cm²/s, |l| ≤ 30° |b| ≤ 10° (SPI/INTEGRAL), L. Bouchet+, ApJ (2015)	Using all sky survey data with other region as a template
Galactic diffuse	7×10^{-3} MeV/cm²/s/sr @ 1-3 MeV, |b| < 20° |l| < 60° (COMPTEL), A. W. Strong+, A&AS (1996)	EGRET galactic diffuse model ftp://legacy.gsfc.nasa.gov
Extragalactic diffuse	$420\times(E/keV)^{-2.7}$ ph/cm²/s/sr/keV (Approximation of SMM observation with a single power-law), K. Watanabe+, ApJ (1999)	uniform and isotropic

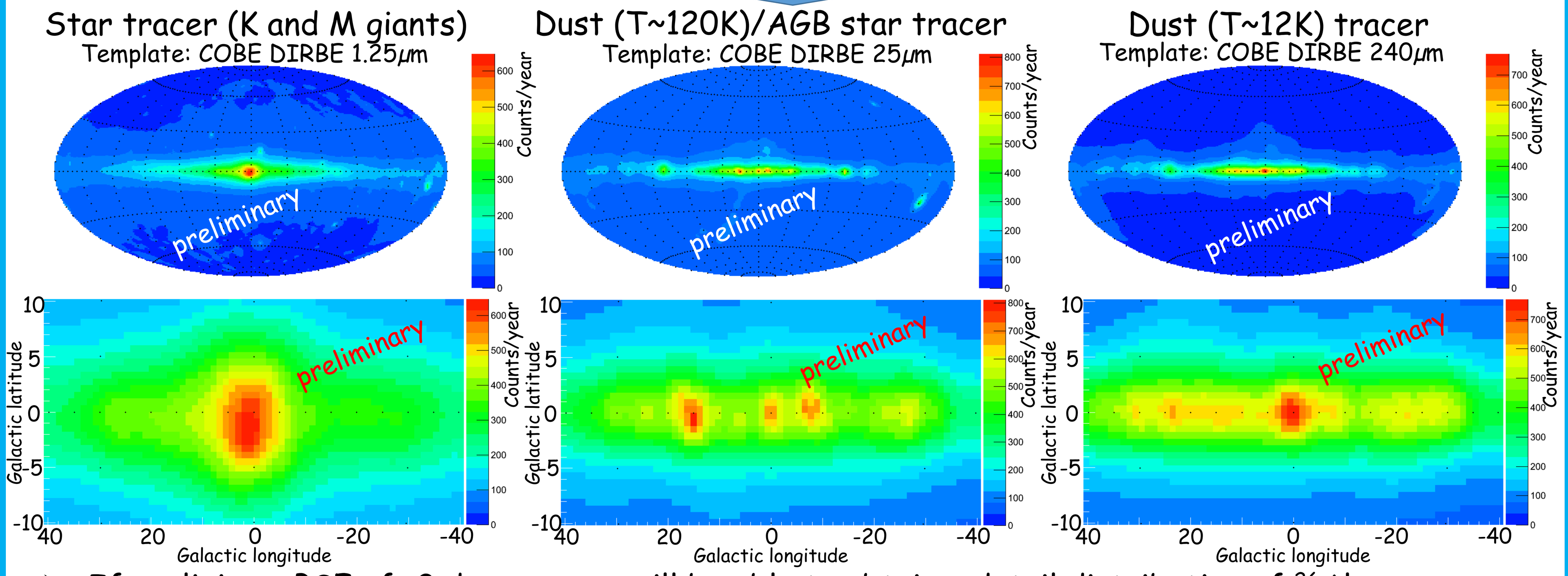
Assumed all sky map at 1.8 MeV (template: COBE DIBRE 240 μm)





Estimated exposure (1 day)

effective area: 200 cm² (zenith, simulated by Geant4) zenith angle dependence was assumed by the measurement of SMILE-II @ 662 keV
PSF: ~2.3 degrees (ARM: 2°, SPD: 10°)
energy resolution: 4% @ 662keV, 2.4% @ 1.8 MeV (FWHM)
energy cut: ±3σ @ 1.8 MeV
orbit: same as the orbit of Fermi satellite



- ➤ If realizing a PSF of ≲2 degrees, we will be able to obtain a detail distribution of ^{26}Al.
- ➤ As same as 1.8 MeV, SMILE-satellite will supply the clear images for ^{60}Fe and e⁺e⁻ annihilation.