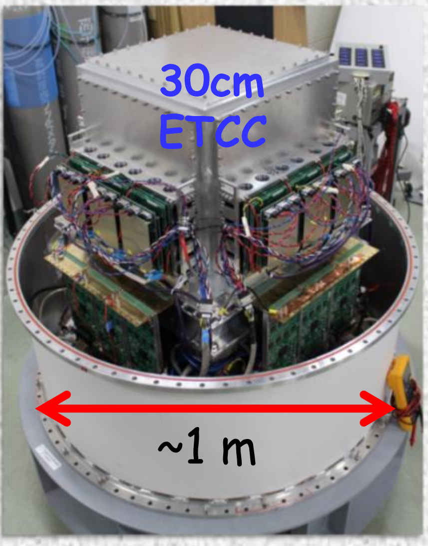
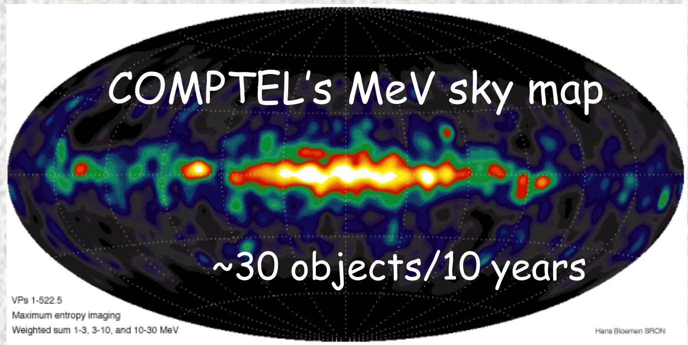
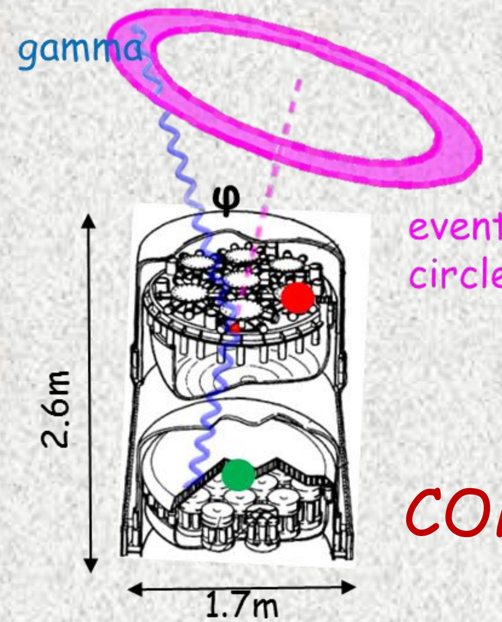
Establishment of complete imaging spectroscopy in MeV gamma-ray Astronomy by Electron Tracking Compton Camera





V. Schönfelder+ (A&AS, 2000)



COMPTEL

13/Apr./2017 @ MeV TPC.

- "Establishment of Imaging Spectroscopy of Nuclear Gamma-Rays based on Geometrical Optics" T.Tanimori et al. Scientific Reports 7, (2017).
- "First On-Site True Gamma-Ray Imaging-Spectroscopy of Contamination near Fukushima Plant", D.Tomono et al. Scientific Reports 7, (2017).
- An Electron-Tracking Compton Telescope for a Survey of the Deep Universe by MeV gamma-rays" T.Tanimori et al. ApJ 810 (2015)

T. Tanimori on behalf of SMILE-Project,
Cosmic-ray group, Physics Division, Kyoto Universty, Japan

MeV gamma-ray Astronomy with Line gammas

New Astrophysics due to Deep Sky Survey with <1mCrab

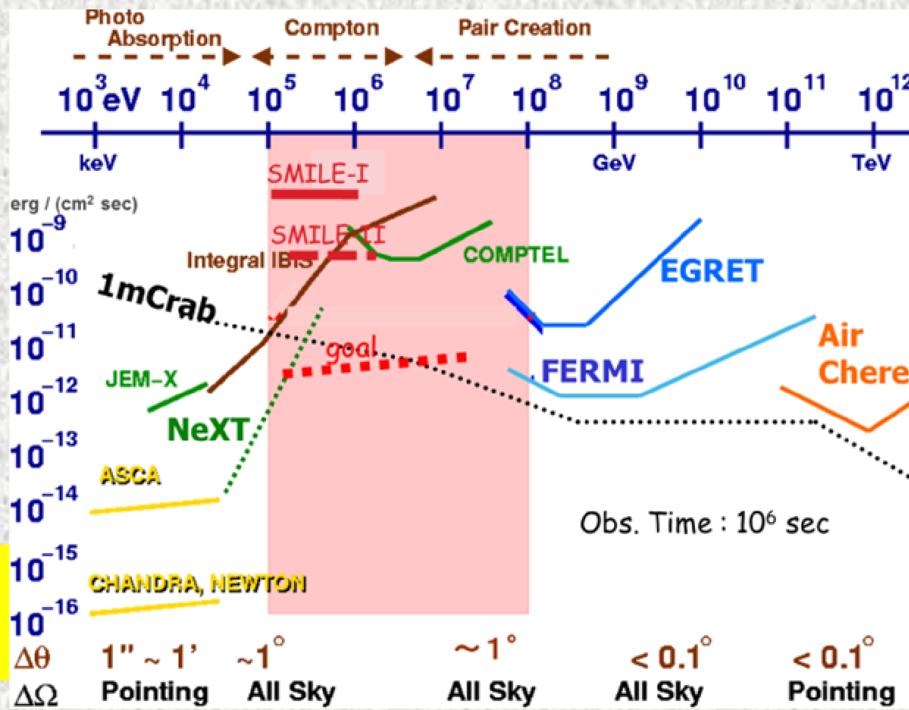
1. *Super Nova Explosion, and Nucleosynthsesis (>100 SNe Observation)
2. *Detection of early GRBs with >z~10, Population-III GRB
3. Proof of Proton Acceleration, Origin of Cosmic-Ray (line gammas of C,O)
4. Polarization =>Another presentation
5. *Chemical evolutions of Galaxies and AGNs (MeV extragalactic background)
6. Compact objects, Pulsars, Black Hole candidates,
7. Particle accelerations in Solar and Geomagnetic sphere

MeV gamma-ray window is unopened frontier !!

But, Two big problems in MeV

1. Imaging is not easy
2. Huge background

100 times better sensitivity than COMPTEL; ~1mCrab is inevitable!

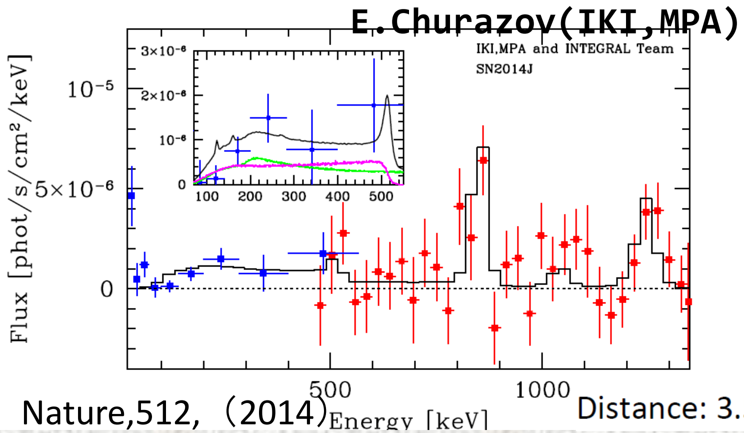


Line gammas from SN Ia SN2014J (INTEGRAL-SPI)

Broad band SN2014J spectrum and the model (day 75)

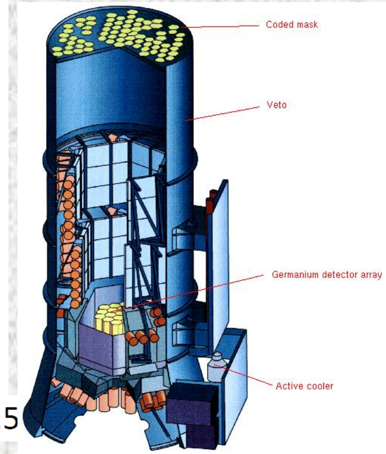
Fluxes of 847 and 1238 keV lines + continuum below 511 keV

E.Churazov(IKI,MPA)



Nature,512, (2014) Distance: 3.5

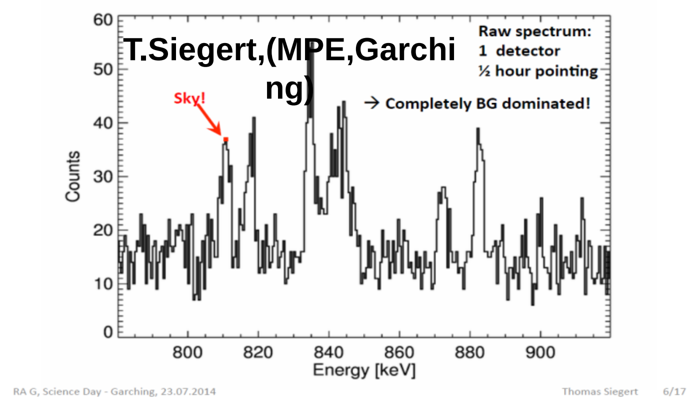
SPI: Codded Mask 19 xGe FoV ~1 str

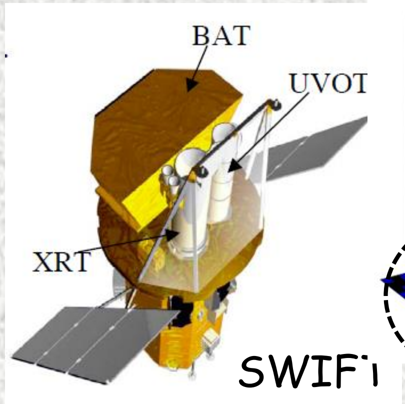


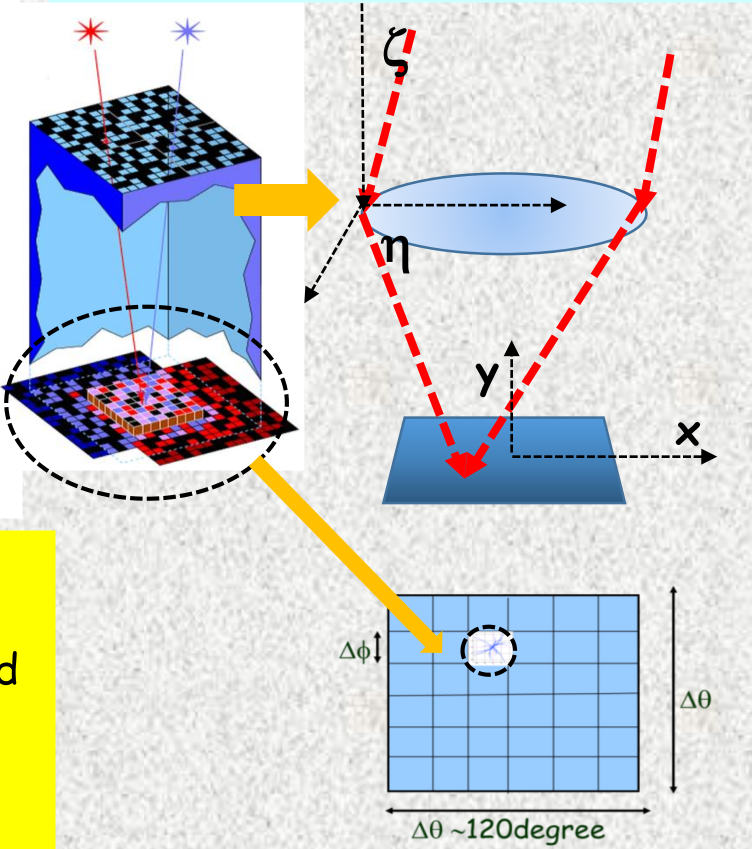
SN2014J

Tanimori et al., ApJ (2015), 810, 28

How to discriminate between sky and BG?







SPI Effective Area 65cm²@1MeV

#of Photons ; $5\times10^{-6}\times65\text{cm}^2\times30\text{keV}\times5\times10^6\text{s}$ ~$4\times10^4\gamma$

From ~4σ detection BG Estimation ->~$10^8\gamma$ at 60keV band

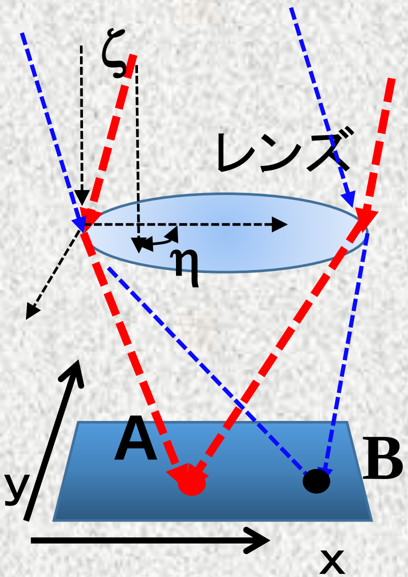
If BG were reduced by 3 orders

BG ~10^5 => $4\times10^4/\sqrt{(10^5)}$ > 100σ

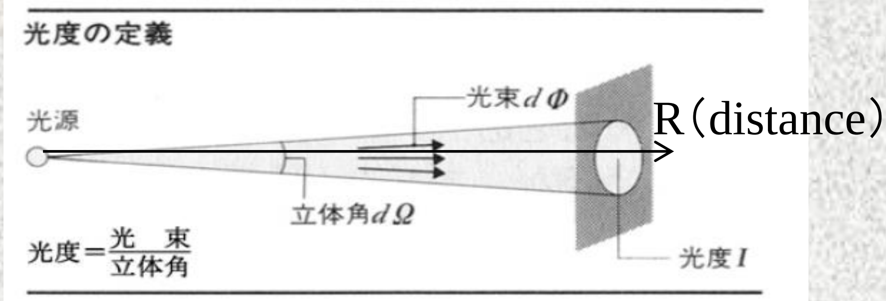
PSF (radius=2°) -> ~10^{-3} of π sr

Imaging Spectroscopy based on Optics

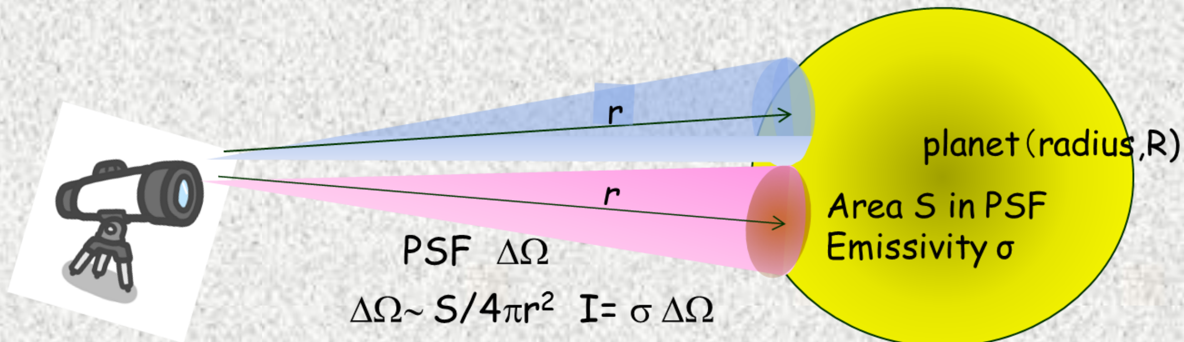
- Visible & X rays: can be focused by lens and refractor
- Focus in Optics, transformation of two incident angles to two positions



$$f(\zeta, \eta) = x$$
$$g(\zeta, \eta) = y$$



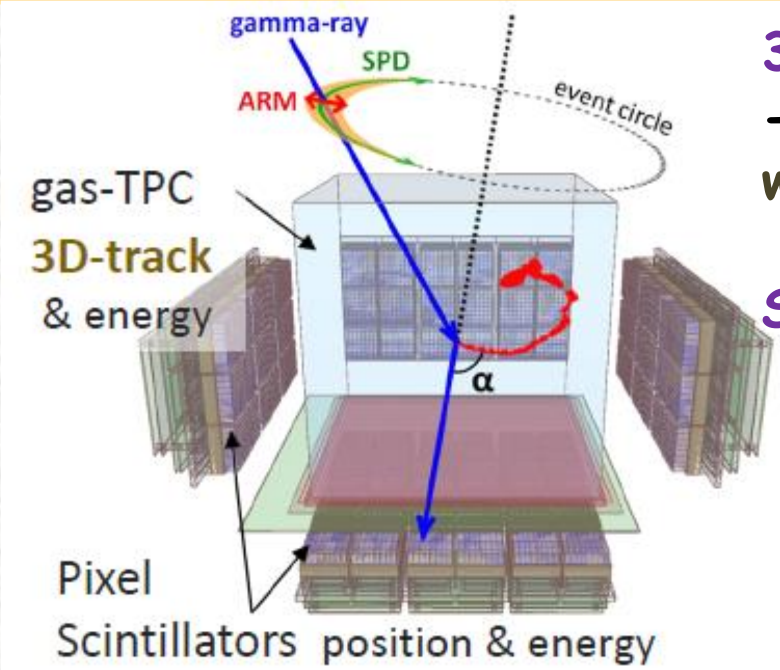
Intensity of rays in dΩ is converved



Points A and B are separated by focusing.
Ability of the separation is defined by Point Spread Function (PSF)

Ability of Imaging Spectroscopy is determined by PSF defined by geometrical optics

Electron Tracking Compton Camera



30cm-cubic Gas Time Projection Chamber

--- tracking of recoil electron ---

well-defined PSF based ARM & SPD

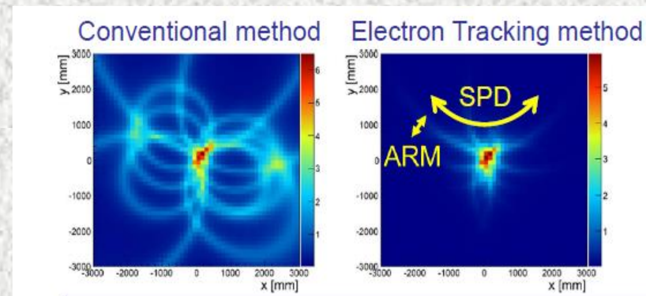
dE/dx + kinematical test using α

Scintillator Array for scattered γ

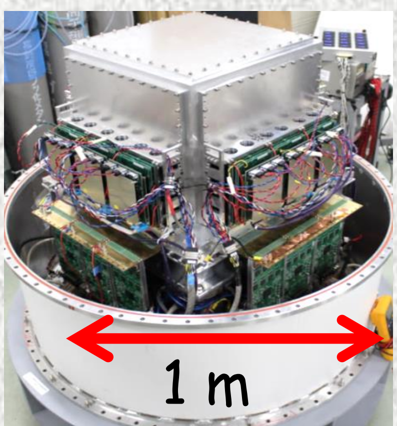
Focus image

Left CC

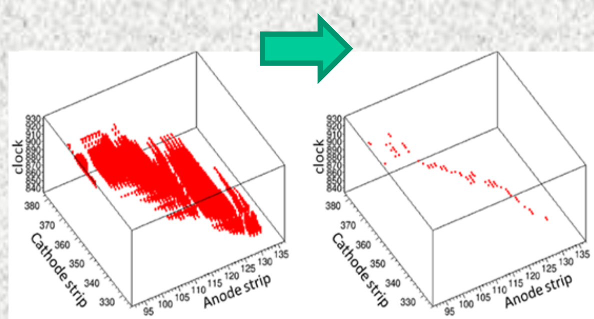
Right ETCC

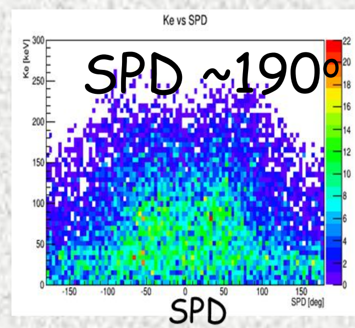


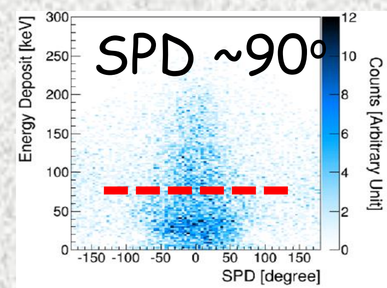
ETCC for balloon Exp. (SMILE-II)

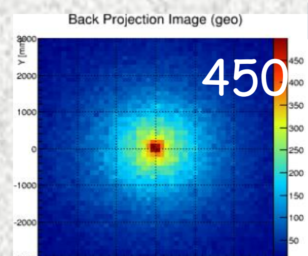


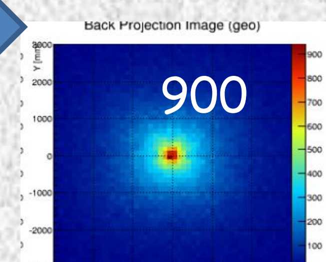
electron





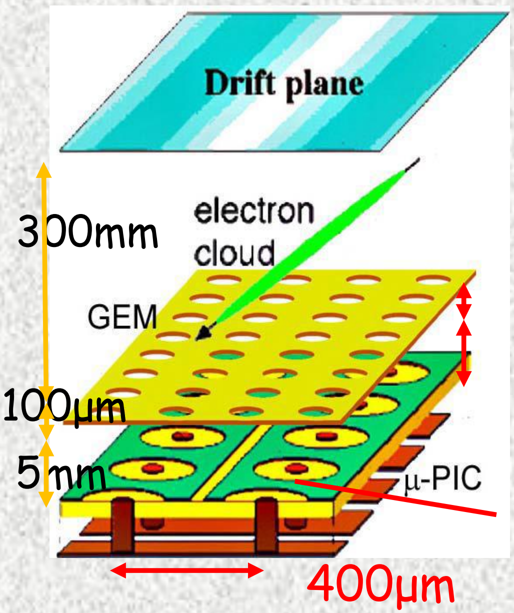






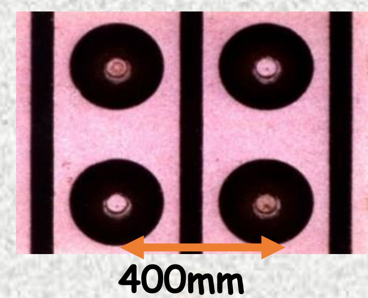
Structure of ETCC

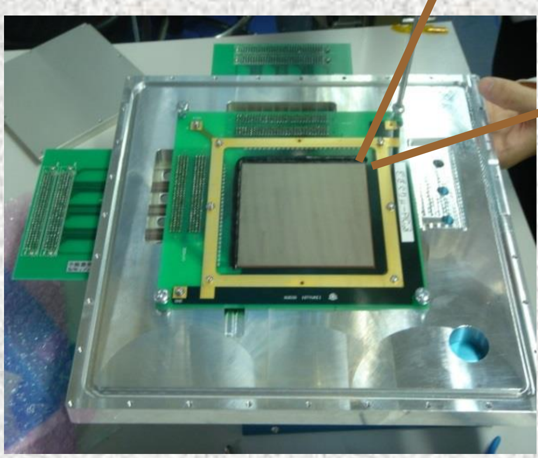
Timing Projection Chamber (TPC)



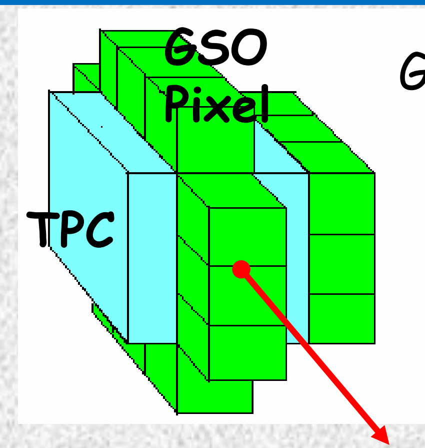
Gas Ar 95%+quencher
1 atm

μ-PIC
Micro Pixel Chamber



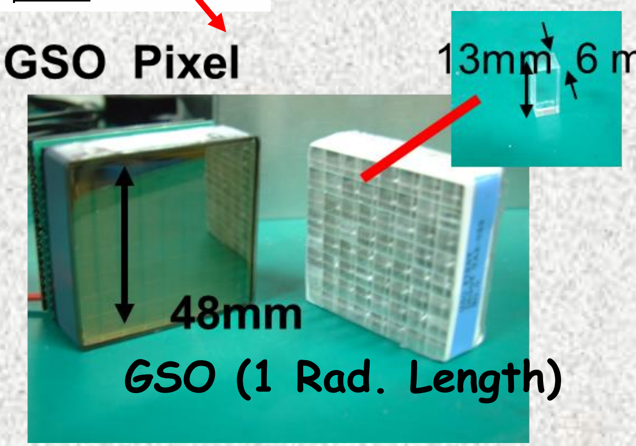


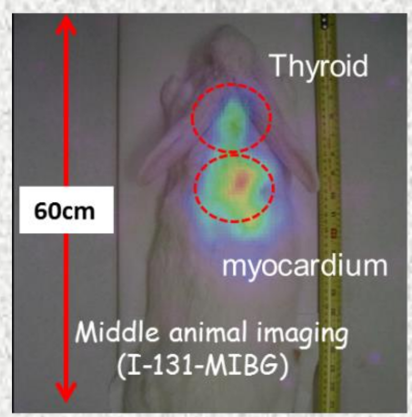
Gain μPIC ×6000
GEM ×3

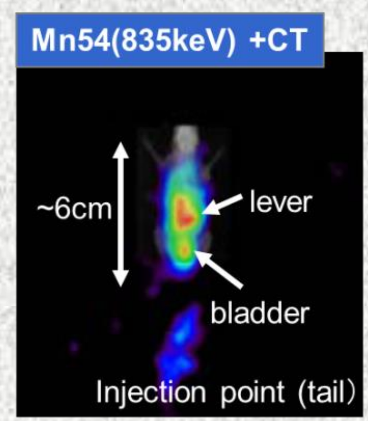


GSO:Gd_2SiO_5(Ce)

11%@ 662 keV
(FWHM)

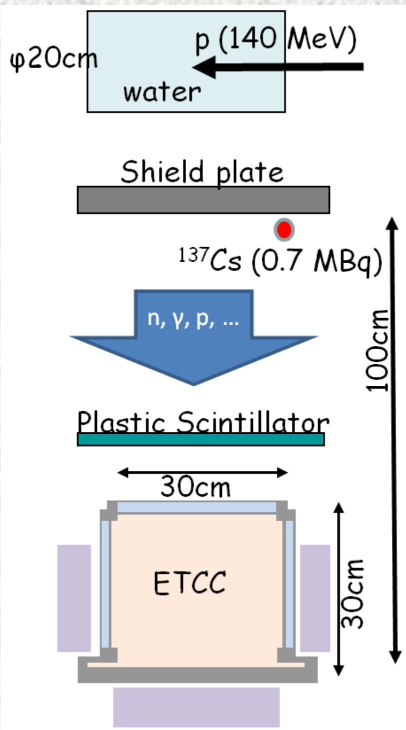


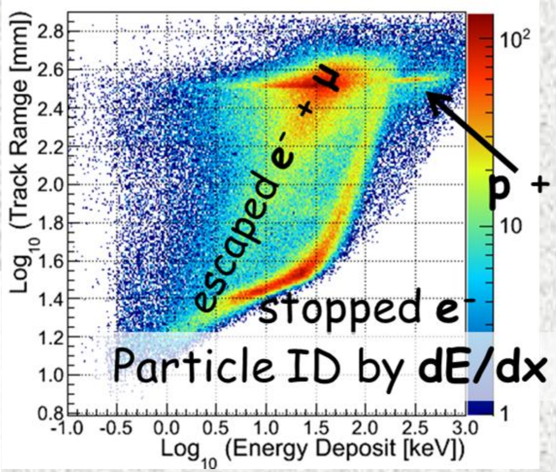


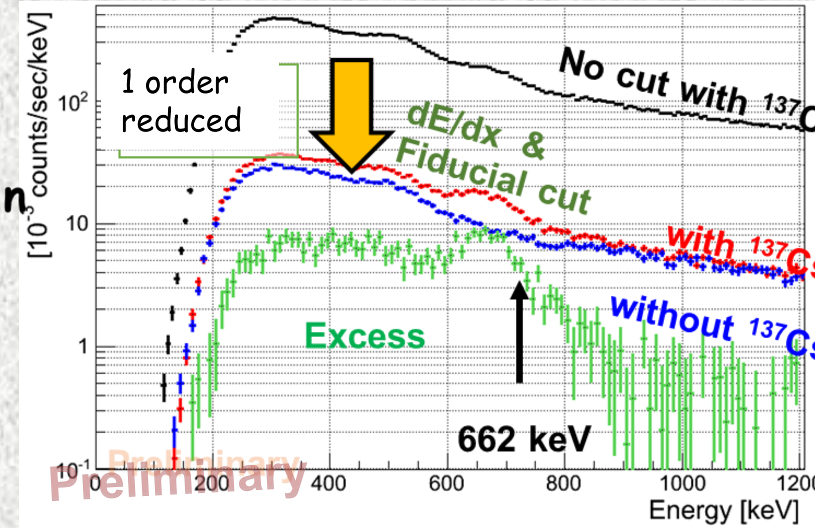


dE/dx Nose reduction in intense Background

140MeV P beam @ RCNP







Trigger rate: 300~1000 Hz

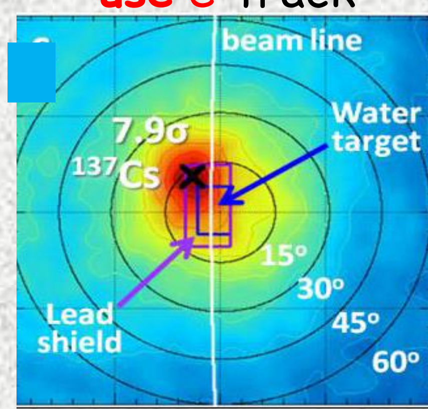
Fast Neutron / Gammas = ~1 similar to radiation condition of Space

Intense Radiation (>x4 in Space)

- Same analysis is used, and keep same efficiency as that with no beam

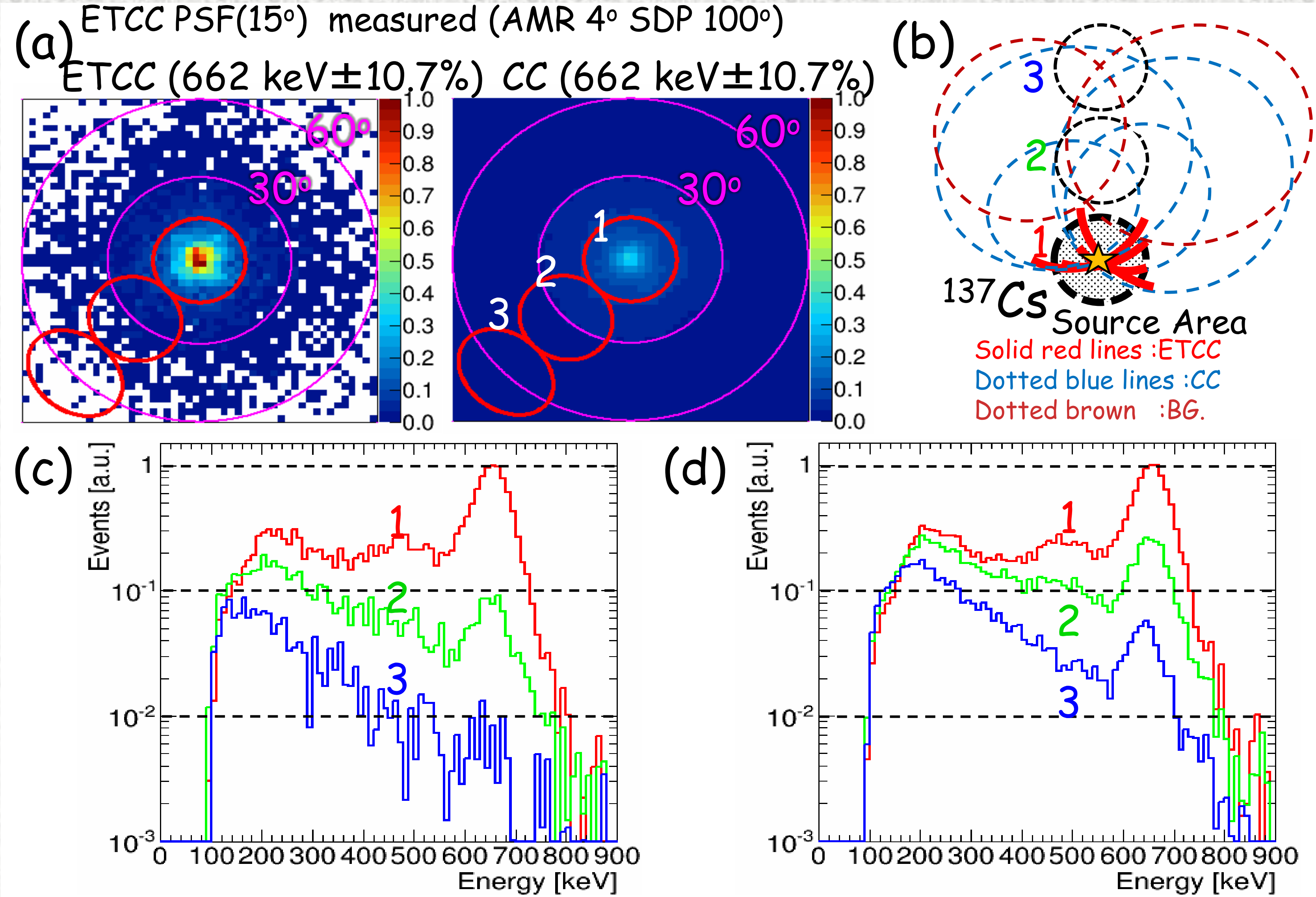
Old Data SPD =190°

use e-track



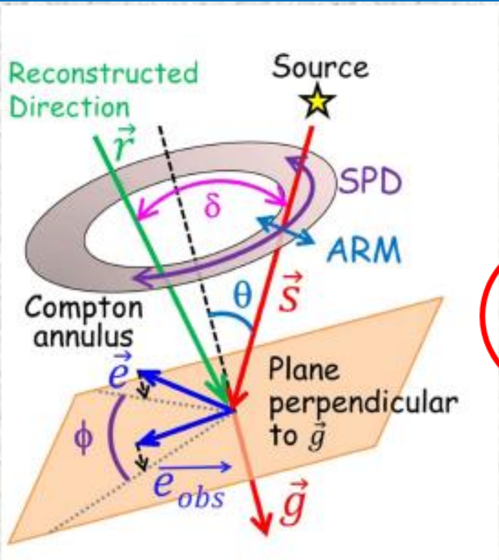
no use e-track

Well-defined PSF in ETCC and leakage in CC

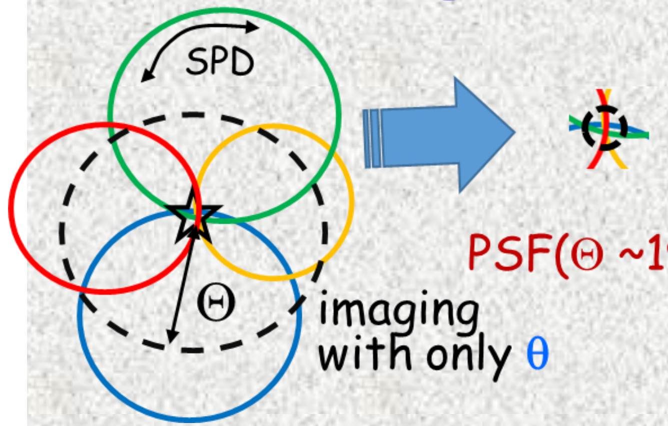


Case S/N ~1 : a peak density of CC increases by ~3 times due to the leakage of background to the source position

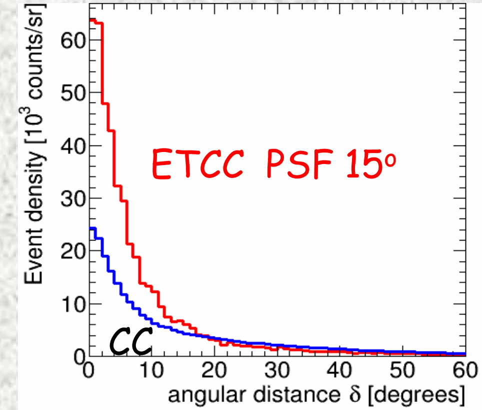
PSF of ETCC and CC

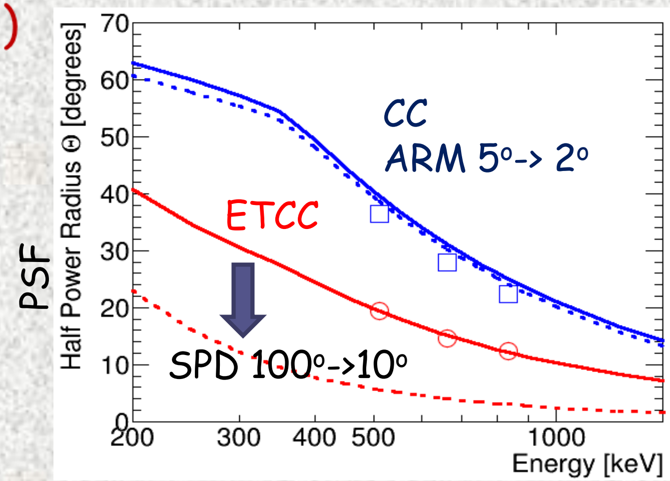


PSF(Θ ~20-40°)
(Θ ~ average of θ)



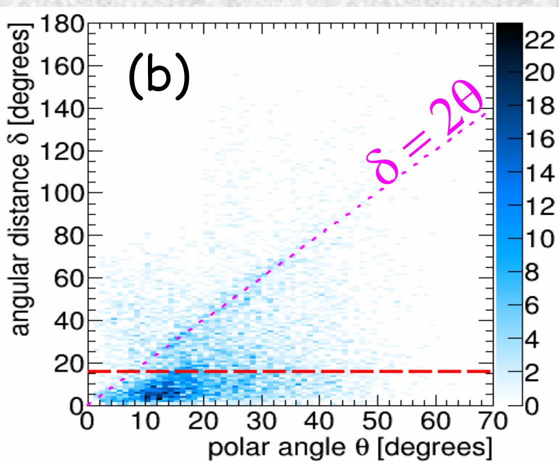
PSF(Θ ~1°)

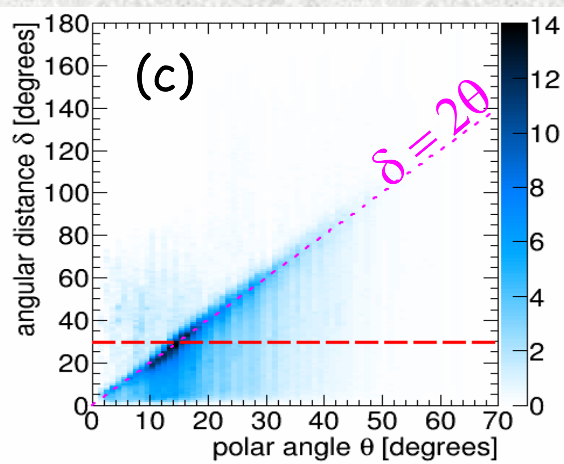


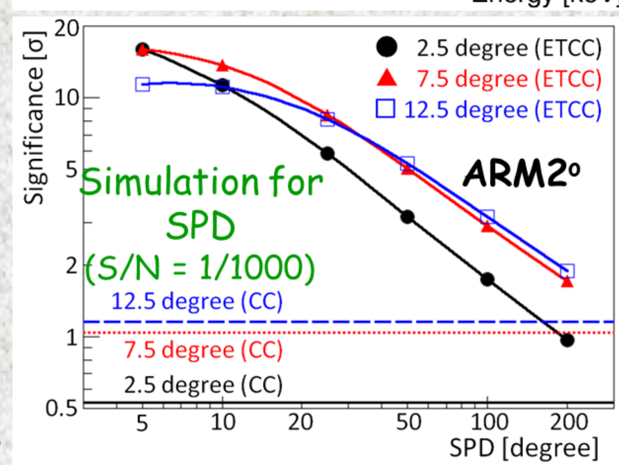


ETCC PSF(15°) measured

CC PSF(35°) measured

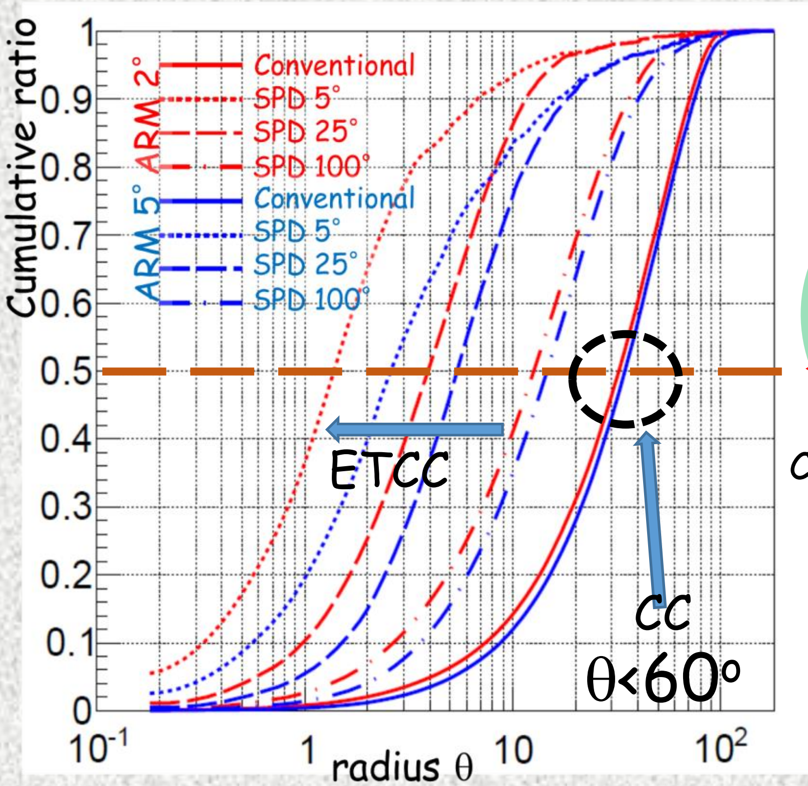




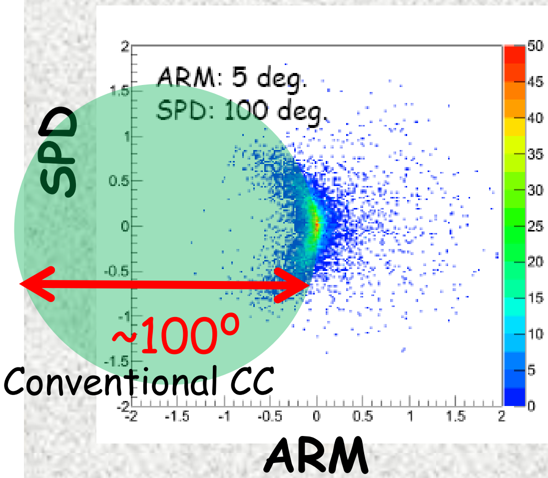


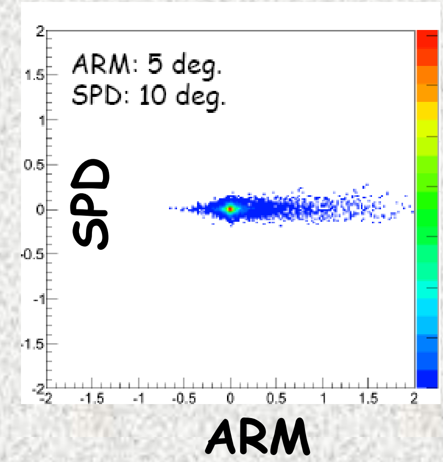
Tanimori et al., ApJ (2015), 810, 28

Point Spread Function in CC

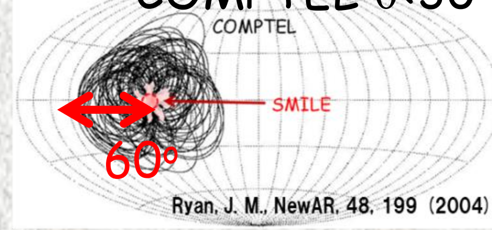


Spread on SPD-ARM plane





COMPTEL θ<30°



PSF(θ) =½ gammas in radius of θ

Conventional CC PSF(35°) i

SPD 100° ARM 5° PSF(15°) present

SPD 25° ARM 5° PSF(5°)

SPD 5° ARM 2° PSF(1.2°)

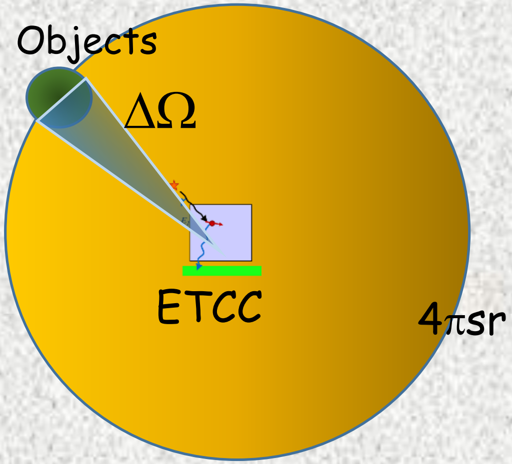
- PSF ofC.C. is determined by θ not by ARM.
- PSF of ETCC is determined by Max{ARM, SPD}

PSF of CC/ PSF (1.2°) of ETCFC ~x30 significance

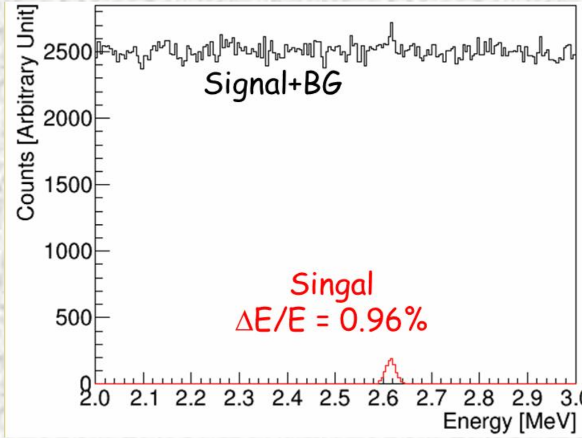
PSF (<2°) is inevitable to reach 1mCrab sensitivity @10^6s & a few 100cm^2

Noise Reduction by Imaging Spec.

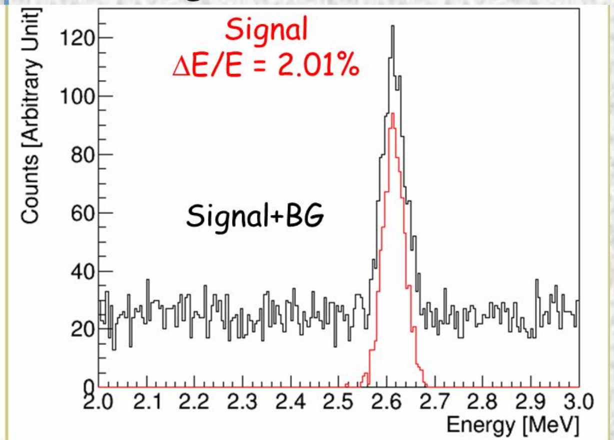
FoV 4 sr (~60° Radius)
PSF 5° FoV 0.02sr
BG~1/150

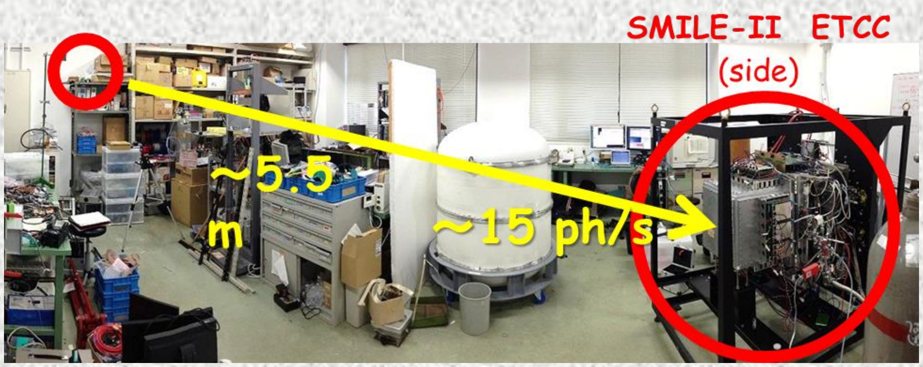


Kaguya-Ge: dE/E0.96% (@ 2.615 MeV, FWHM)
Kobayashi+, EPS Lett. 337-338 (2012) 10-16
Signal/BG= 1:500

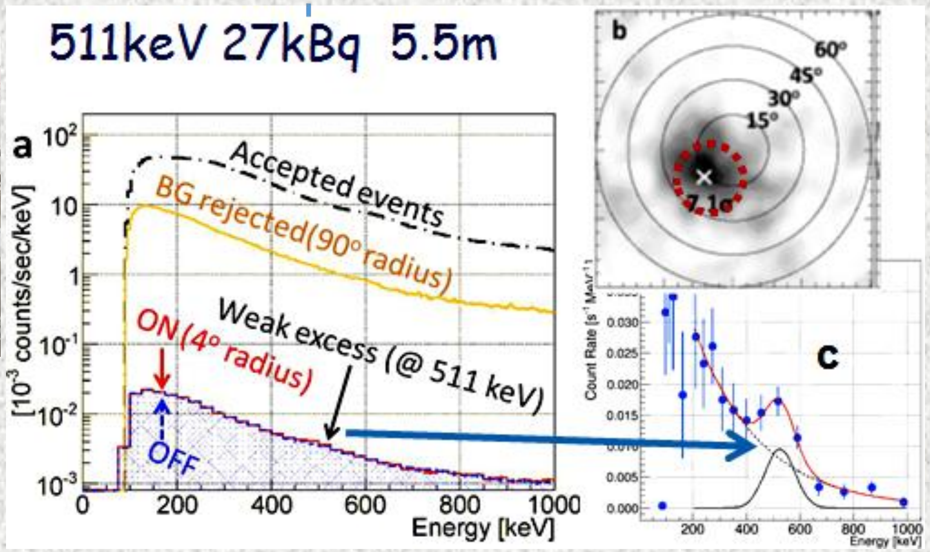


ETCC: possible dE/E 2.01% (@ 2.615 MeV, FWHM)
$LaBr_3$: 4.0%@662 keV→ $\propto E^{-0.5}$
Signal/BG: = 1:5





^{22}Na (27 kBq, 511 keV) 5.5m
8x10^{-5}μSv/h
(1/1000 of Environmental radiation)



Tanimori et al., ApJ (2015)

COMPTEL Analysis.

COMPTEL Analysis

V. Schönfelder+ 1993 —> Maximum Entrotpy Maximizat （MEM)

However, MEM was used only for image in early phase

All quantitative results were derived using Maximum LikeliHood Method with 3D-PDF including θ

There seems little descriptions describing the detail of MLHM

Scattering angle $\theta = \varphi$

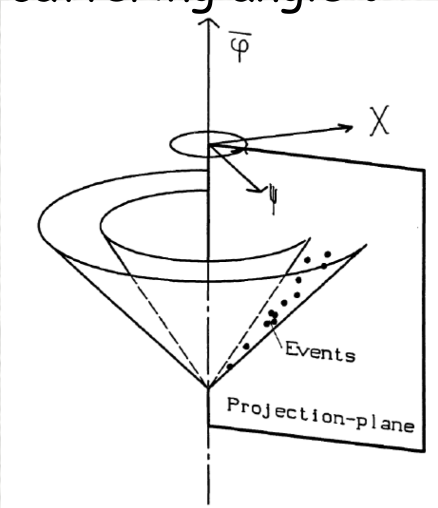
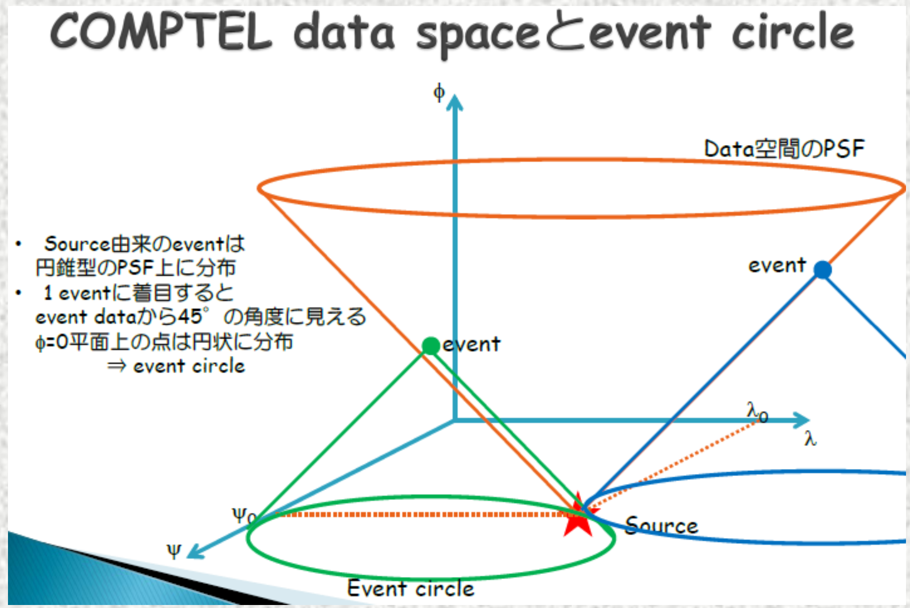


FIG. 4.—Illustration of the COMPTEL response of a celestial point source in the three-dimensional data space (χ, ψ, $\bar{\varphi}$). The data lie on a cone, the apex of which is at the position of the celestial source (χ_0, ψ_0). The cone semiangle is 45°. In practice, the cone mantle is blurred because of measurement inaccuracies.



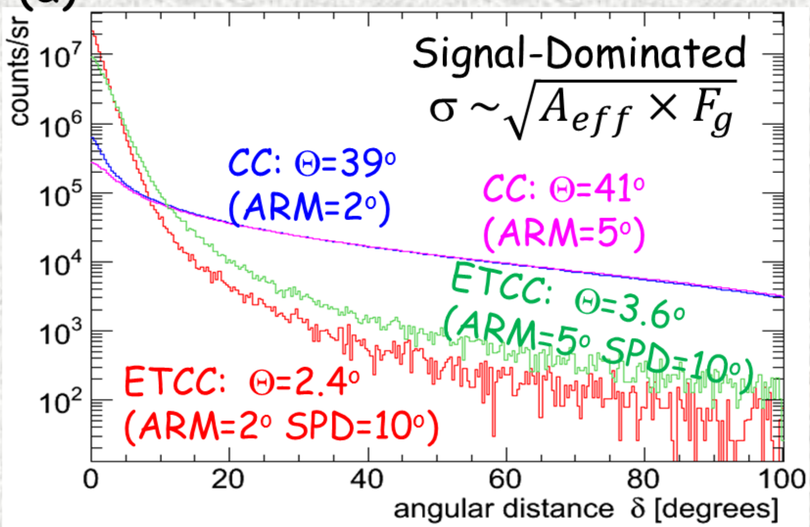
After COMPTEL　there may be no discussion about 3D-PSF,

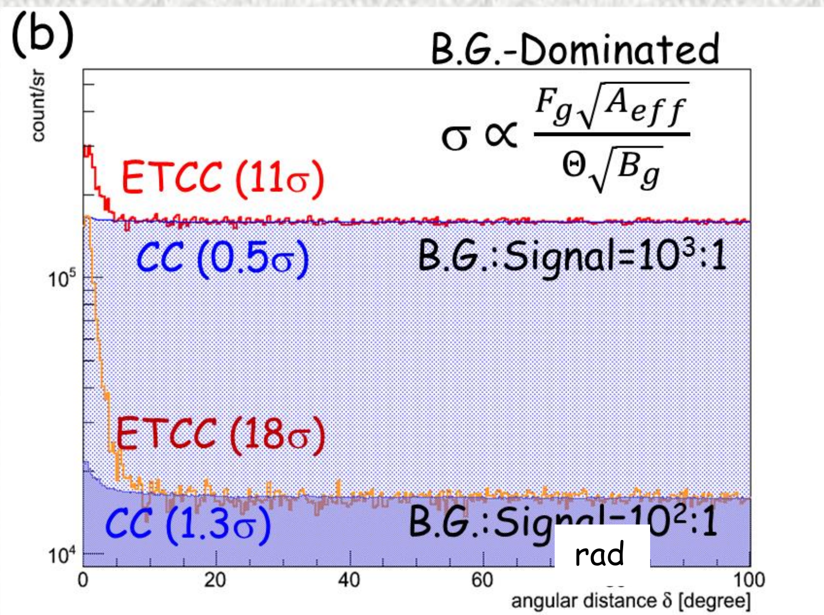
But Maximum Likelihood Expectation Maximization (MLEM)？？

Optimization Algorithm for Compton Imaging

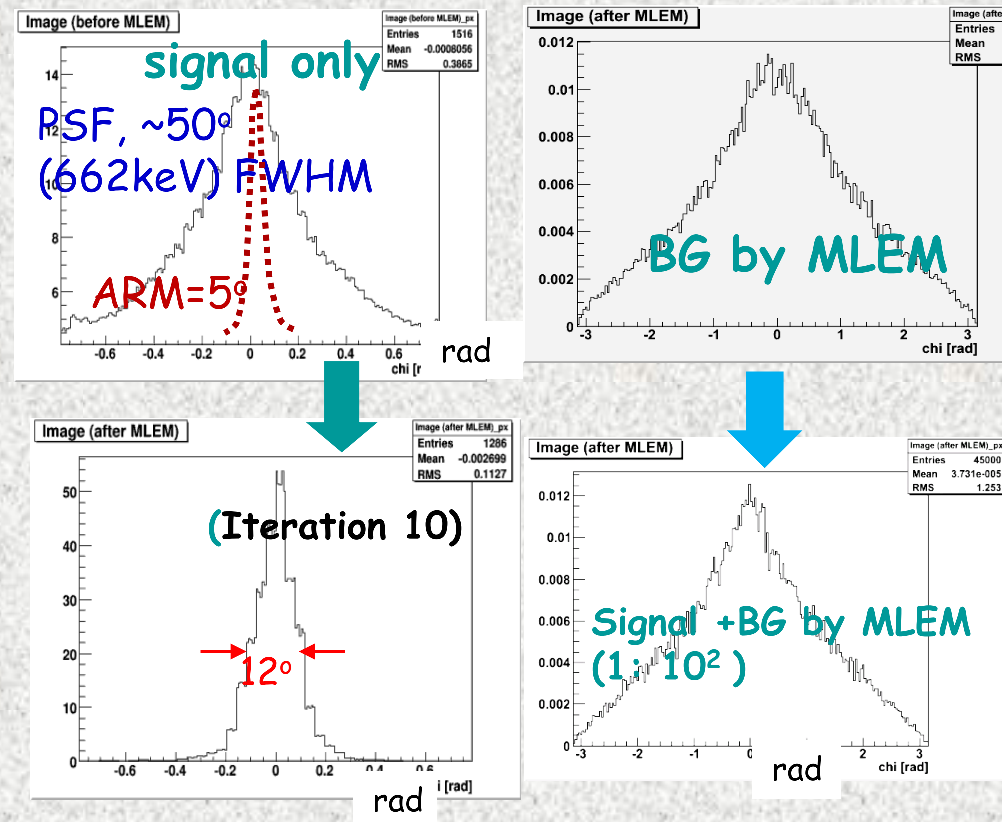
Maximum likelihood Expectation Maximization (MLEM)

(a)Tanimori et al., 2017), Scientific. Rep.

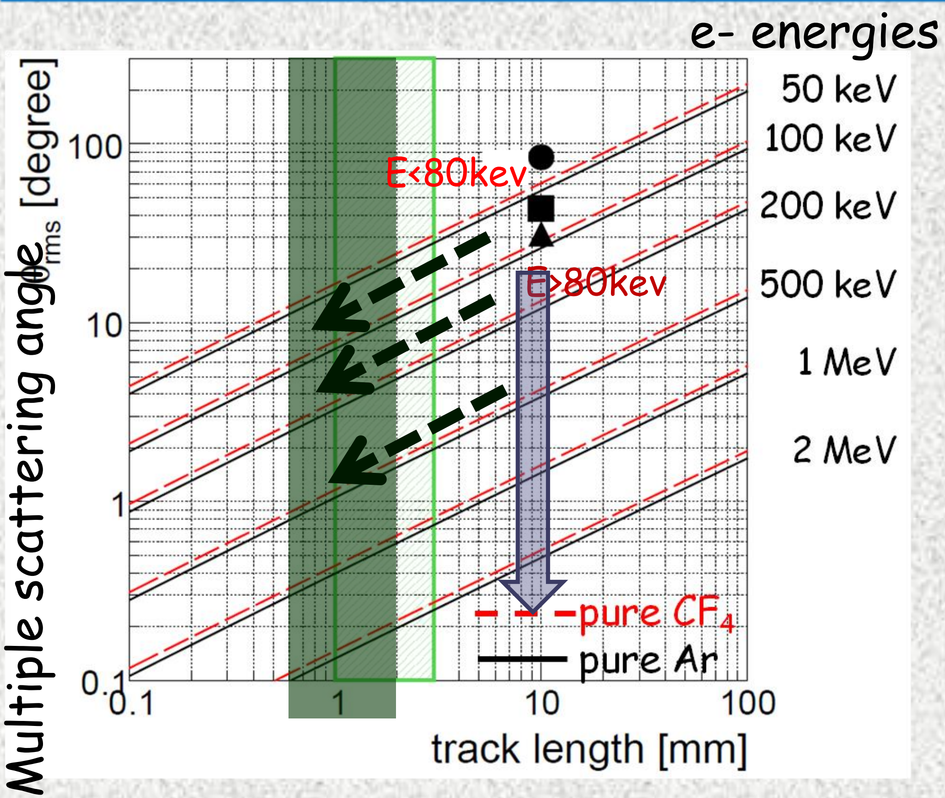




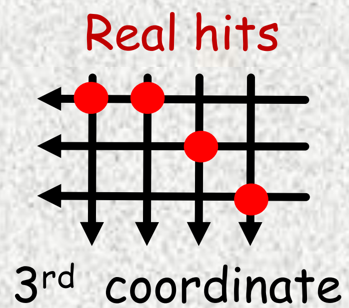
CC+MLEM

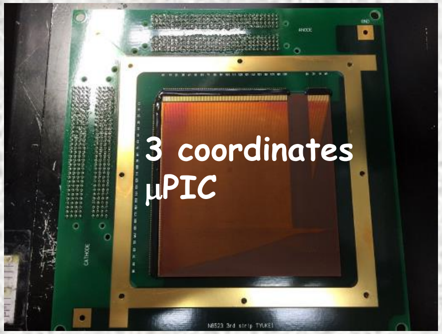


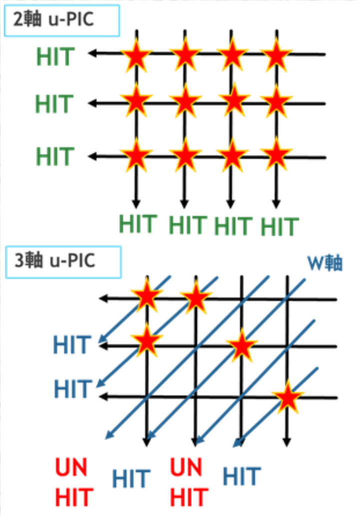
How to reach PSF of ~1°

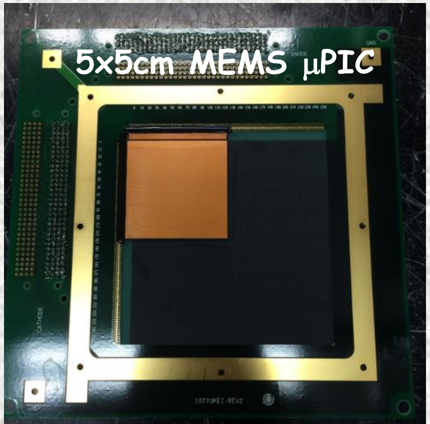


1. SMILE 2+ => SPD ~25°
   wide energy range of tracks
   0.2keV -> several MeV
   + HARPO method now trying
2. SMILE 3 or Satellite => ~5°
   3rd coordinate in μPIC
   or pixel chip in μPIC









PSF(12°)	SPD 100°	ARM 5°
PSF(5°)	SPD 25°	ARM 5°
PSF(1.2°)	SPD 5°	ARM 2°

- For good PSF of ~1°

3D-tracking with 1mm in Gas or
3D 1μm sampling in Solid State
Already GAS is possible !!!

Gas optimization for Compton Scattering

Used gas : Ar(95%)+isoC_4H_{10}(2%)+CF_4(3%)

function: Penning (Ar + isoC_4H_{10}), Fast Drift Velocity (CF_4)

New gas : Ne(59.7%)+Ar(0.3%)+CF_4(40%)

Penning (Ne + Ar), Large Compton Prob. (CF_4)

※Ne+Ar(0.5%)・・・better dE/E (11.6 % @5.9 keV)
(Heikki Sipila (1976)) cf Ne: 14.5 %, Ar: 12.9 %

	Ratio of # of e	Ratio of Z^5
Used /New	1.2	0.09

Increase of Compton Probalility

Reduction of Photon Absorption (BG)

Penning Effect

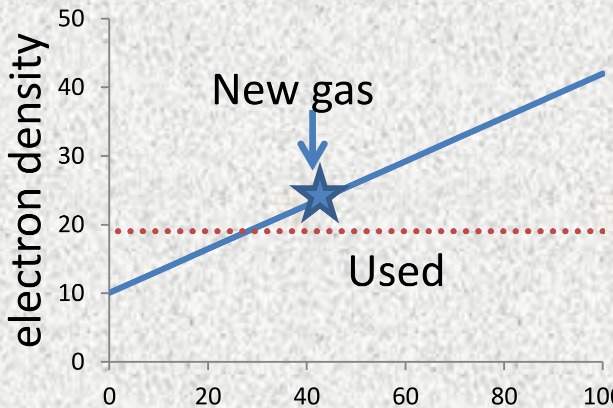
$$A^* + B \rightarrow A + B^+ + e^-$$

A Excitation -> B Ionization

☆Gain increasing

☆ decease of W-value

☆better dE/E

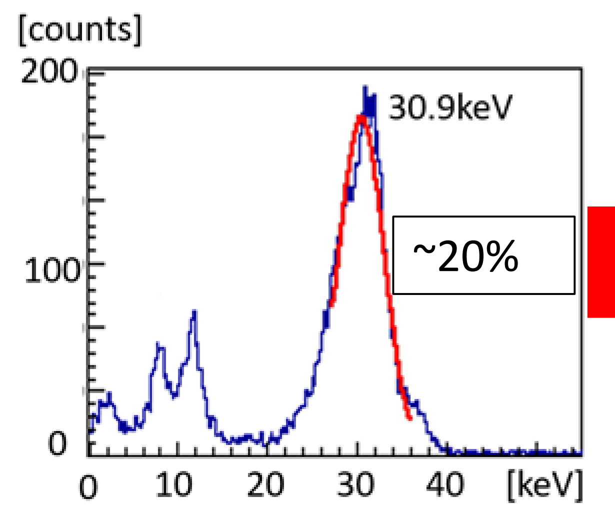


pureCF_4→x2.2

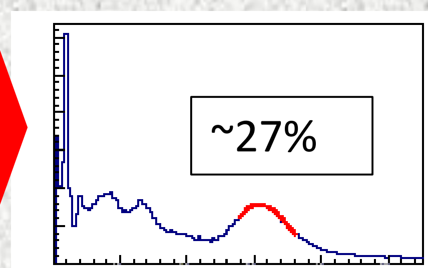
CF_4 60%→x1.5

Energy Resolution

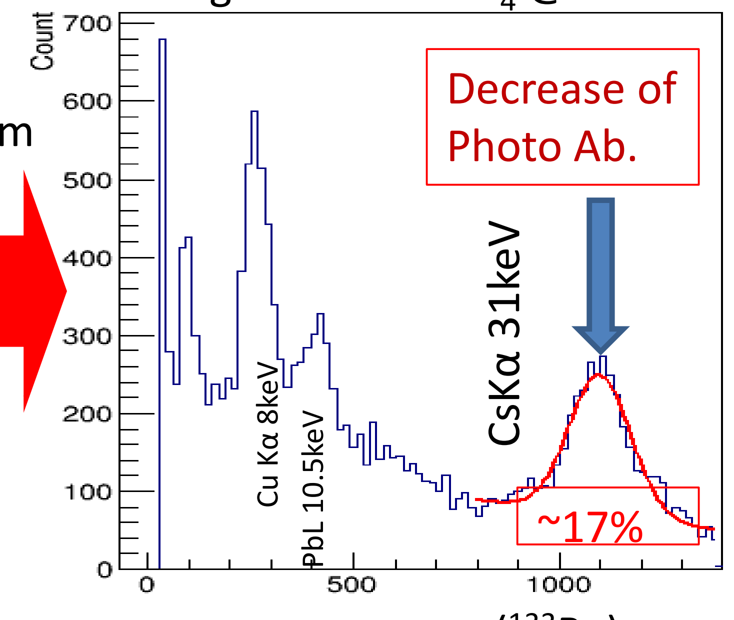
Used gas $Ar+CF_4+isoC_4H_{10}$ @1atm



Another trial
Ne(50%)+CF_4(50%)@1atm

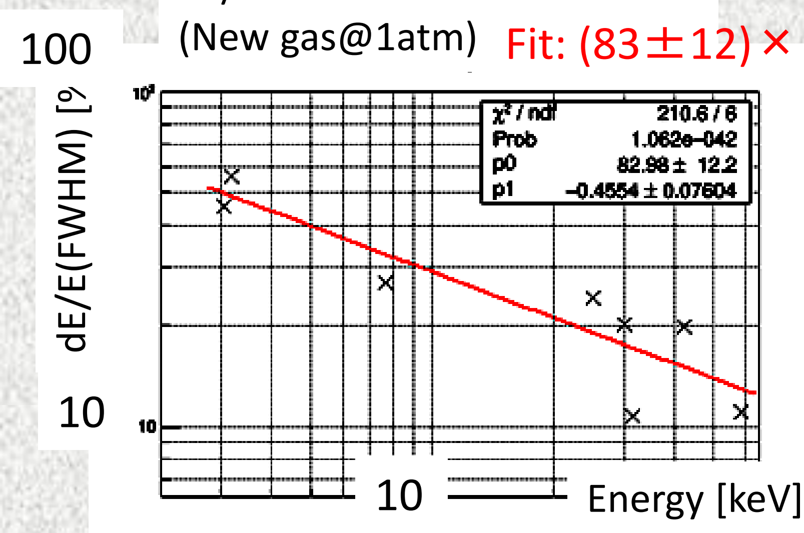


New gas $Ne+Ar+CF_4$ @1atm



dE/E
(New gas@1atm)

Fit: $(83 \pm 12) \times E^{-0.45 \pm 0.07}$



- By adding a small of amount of Ar,
 ->Better dE/dx and small photo Absorption (Hit rate reduces to 40%)

Possibility of <1m Crab

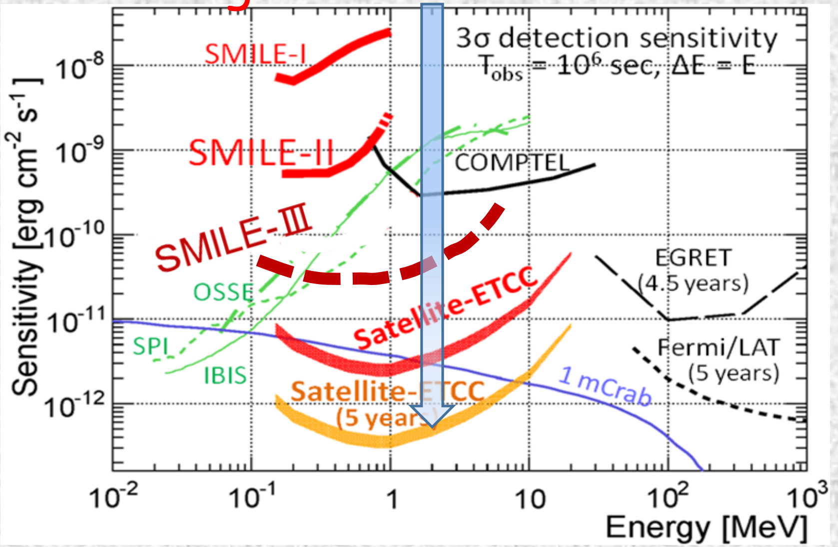
- For Next MeV Astronomy, significance ~10^{-13} erg cm^{-2} s^{-1}

  S: signal
  θ: PSF

$$\text{Significance} \propto \frac{EA \bullet S}{\sqrt{EA \bullet (S + BG \bullet \theta^2)}}$$

BG dominated

2. Significance $\propto \dfrac{EA \bullet S}{\theta\sqrt{(EA \bullet BG)}}$



- Effective Area several 100 cm^2 :
  gas (3atm CF_4) and Si in 1m^3 cube is possible.
  For above eff. Area, Sharp PSF $\theta = 1\sim2^\circ$ is needed !!

  \+ Minimum Back Ground => Cosmic MeV background

  \+ dE/dx and Kinematical test for complete rejection of cosmic-rays, neutron and accidental events.

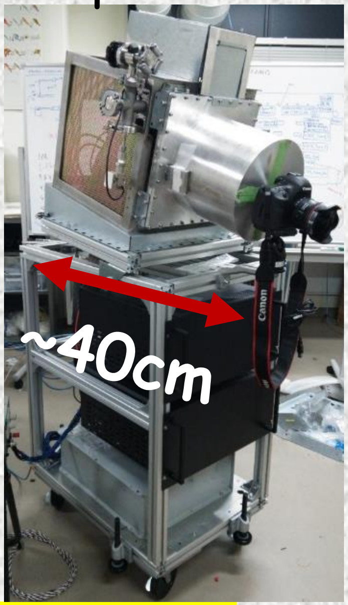
  Sharp PDF : Gas (3D-tracking with 1mm sampling) is possible,
  Si very difficult for 3D tracking with 1μm sampling)

- Energy resolution : inorganic scintillator is inevitable for both gas or to cover the wide range to 10MeV => determined by scintillator a few %@1MeV

=>Gas electron tracking is a most promising solution for 1mCrab.

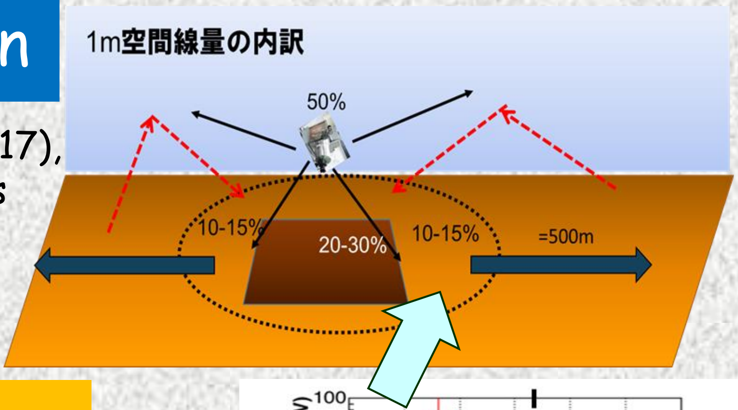
Decontamination

Compact ETCC

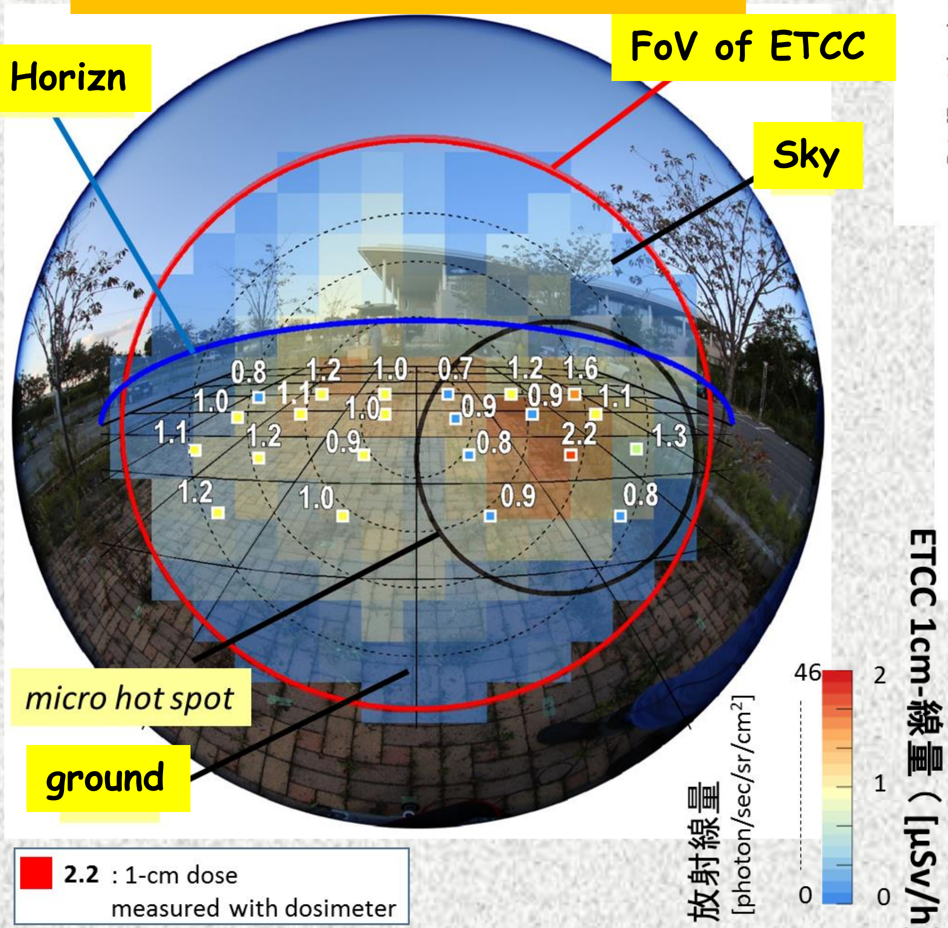


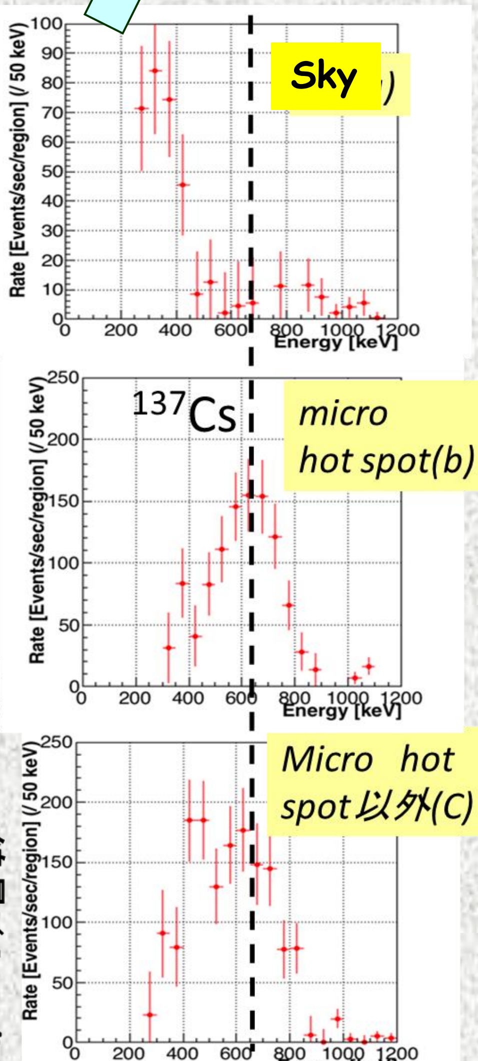
Eff. Area
a few mm^2
PSF ~15^o

Tomono et al., (2017), Scientific Reports



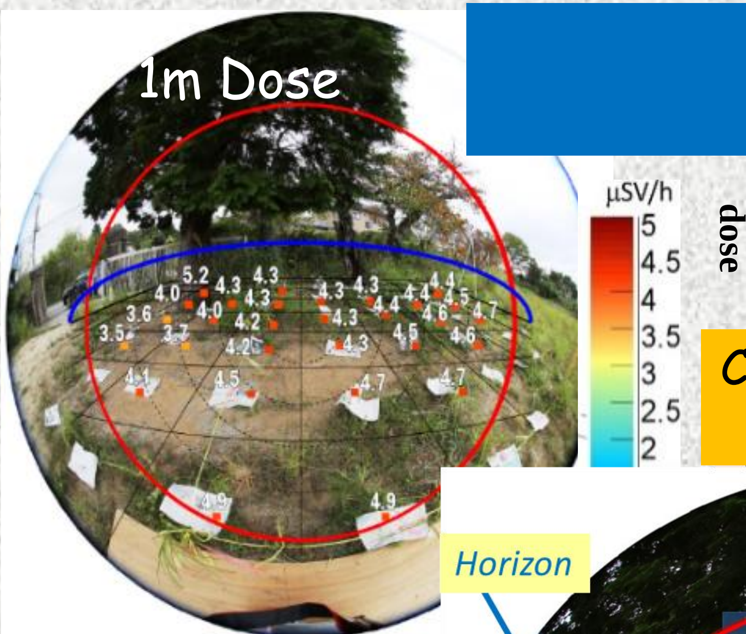
Decontamination Area <2μSv/h



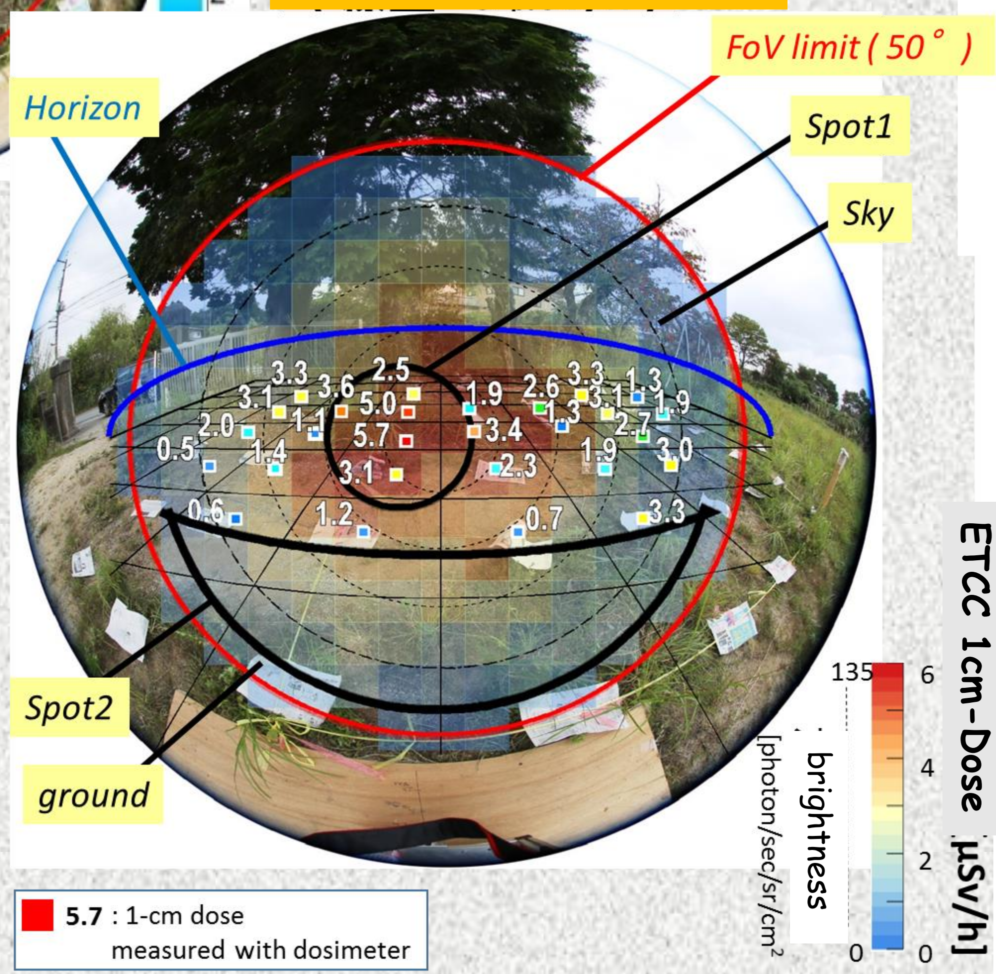


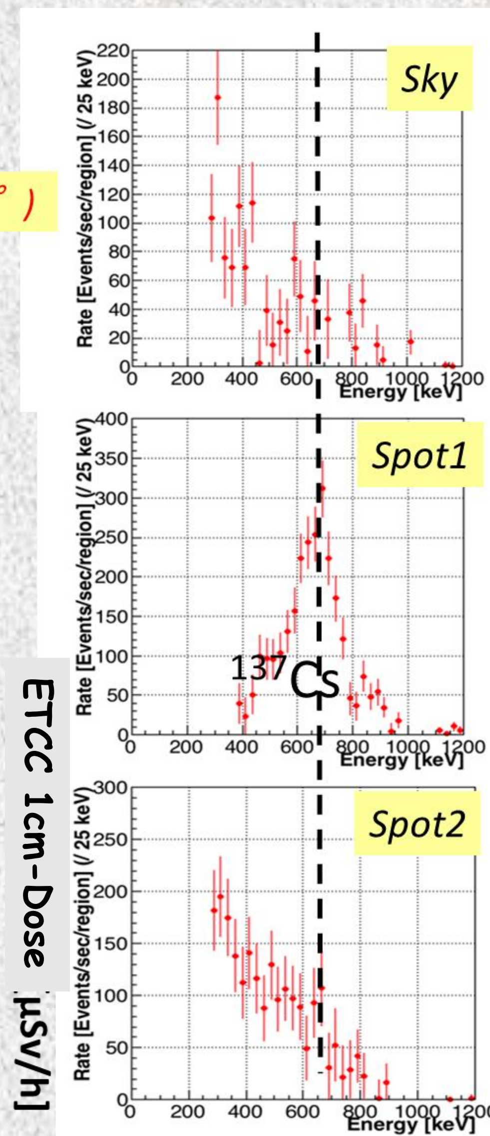
Contamination Area

Tomono et al., (2017), Scientific Reports



Contamination Area
~5μSv/h





Upgrade to SMILE-II+

- ➢ Wide band & sharp PSF 15°-> ~7

◆ GSO (2x longer) inside the vessel

higher energy electron OK

from 150keV to a few MeV SPD~20°

- ➢ Larger Effective Area

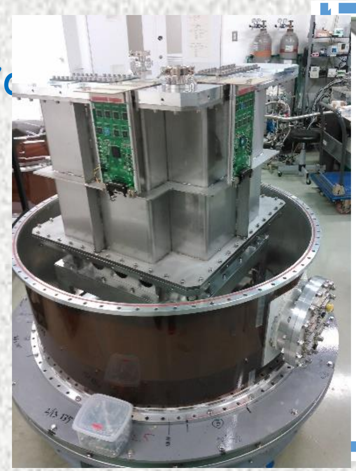
High density packing of GSO in vessel

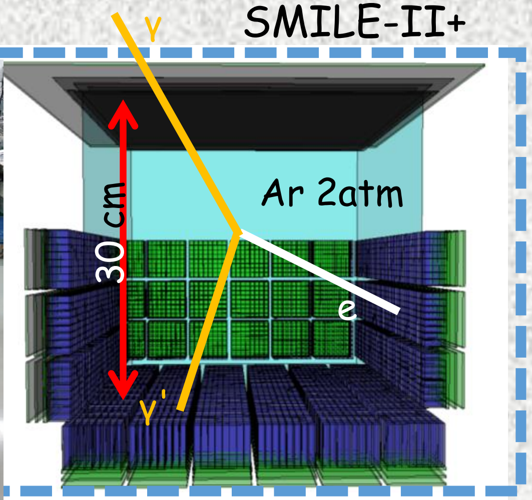
2 atm Ne+Ar+CF_4 Gas

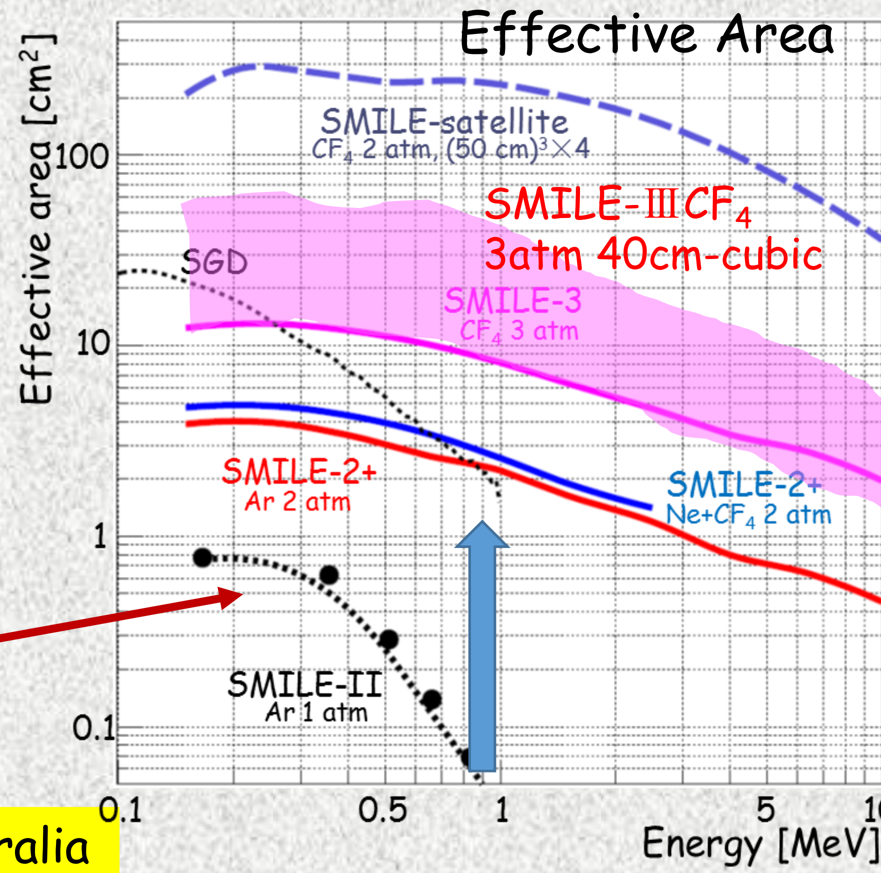
- ➢ Stability

◆ Gas purification sysem

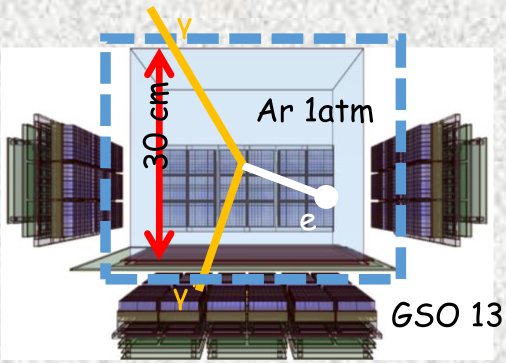
◆ All Ethernet DAQ system







SMILE-II

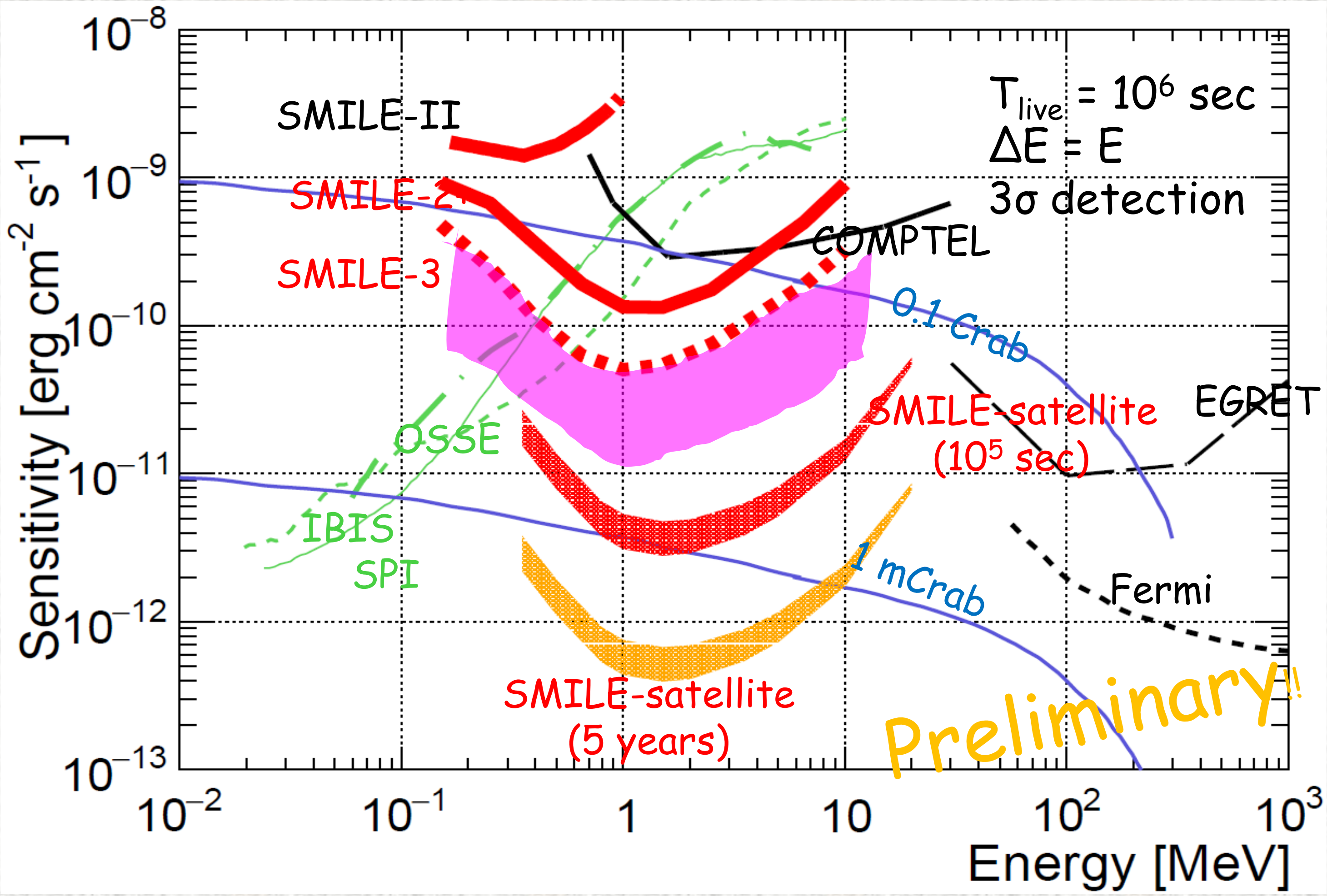


GSO 13 mm

SMILE-2+ 2018 JAXA Balloon Flight @ Australia

Expected Sensitivity based on well-defined PSF

Sensitivities area are calculated from effective area and PSF determined by ARM and SPD



SMILE-Satellite 50cm-cubic ETCC x 4 modules
Effective Area ~200cm^2@1MeV and PSF 1-2°

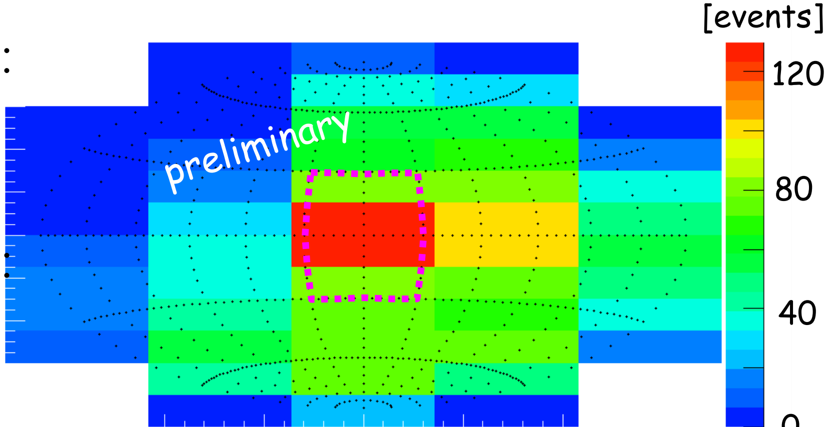
Expected image ofGlactic 511keV

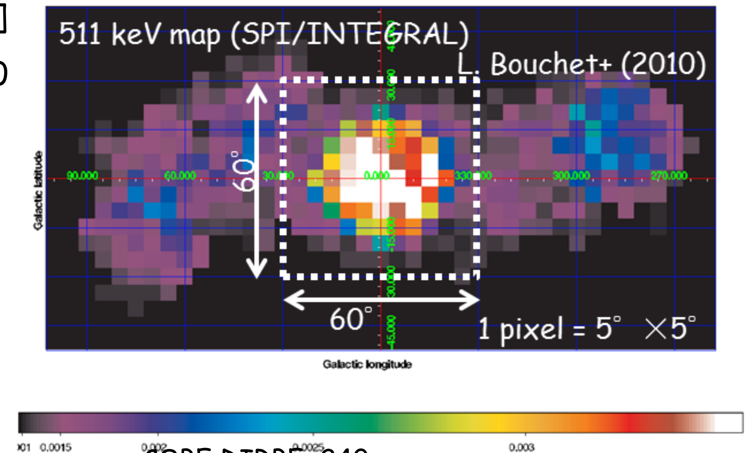
SMILE-2+

有効面積：
~3 cm²

PSF：
~10°

観測時間：
1 day





SMILE-3

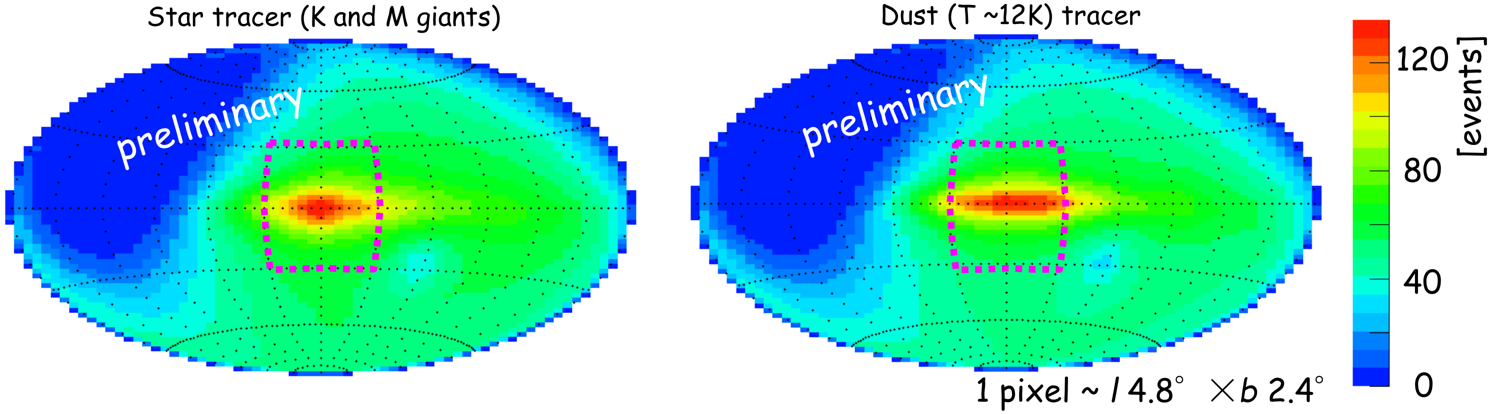
Eff.Area：
~10 cm²

PSF：
~7°

Obs. times：
30 days

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

COBE DIRBE 240μm
Dust (T ~12K) tracer

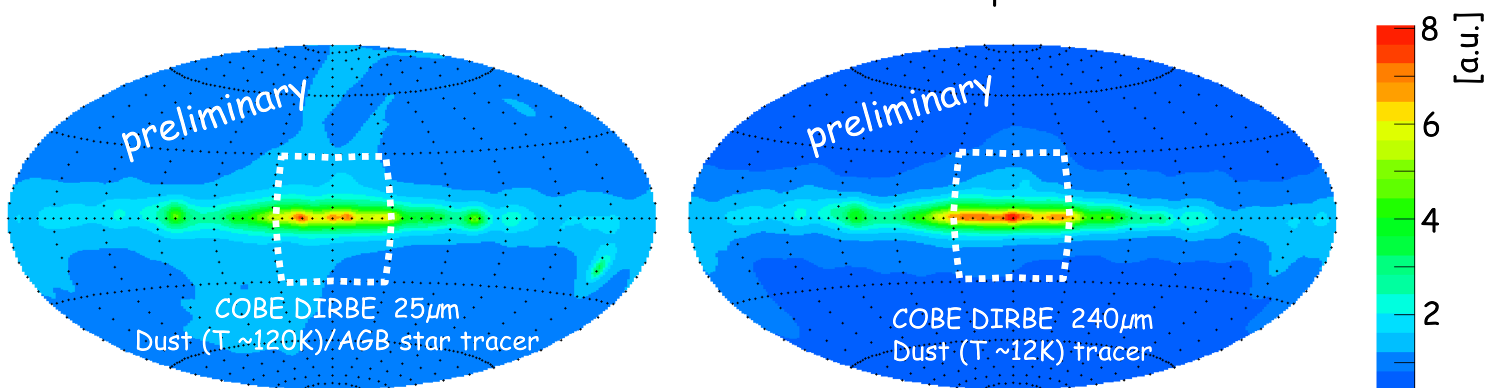


Satellite

Eff. Area：
~200 cm²

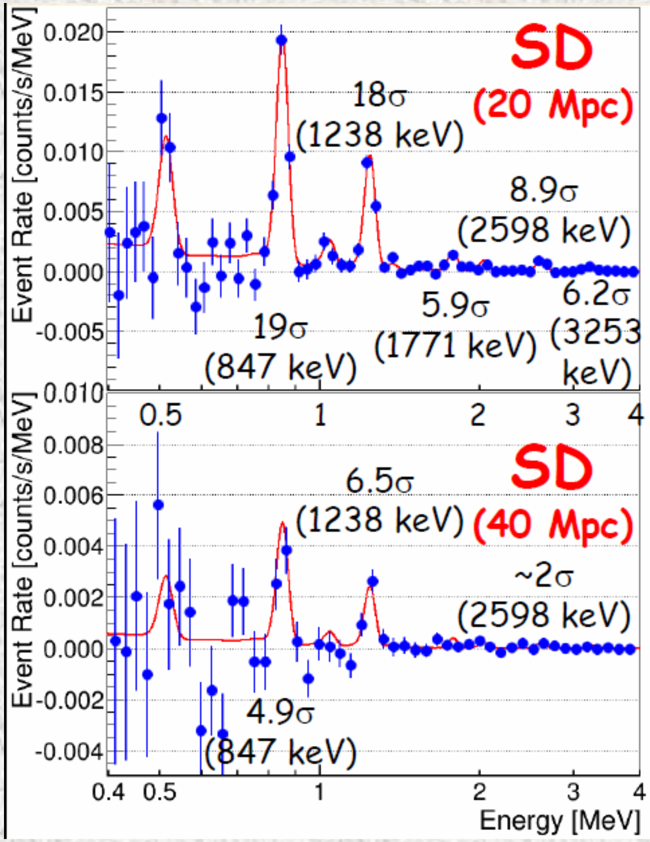
PSF：
4.5°

Obs. Time：
1 year



Line gammas from SN Ia

SMILE-Satellite 50days
20Mpc ~1 SN/year
40Mpc ~10 SNe/year

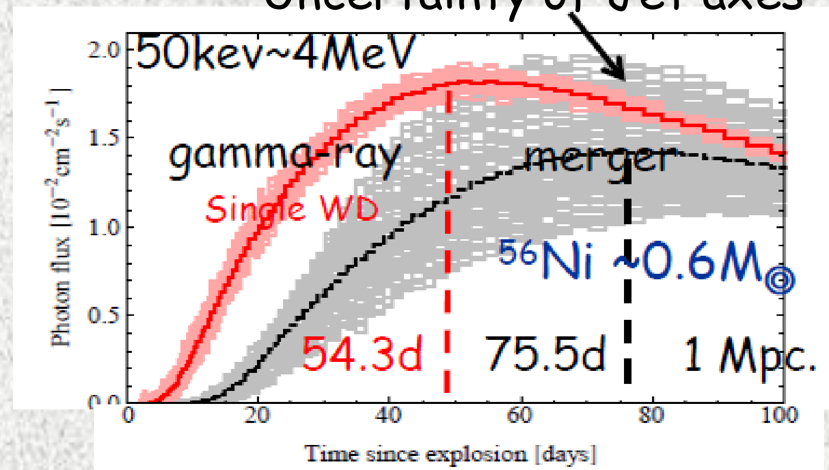


Detection up to 80-100Mpc

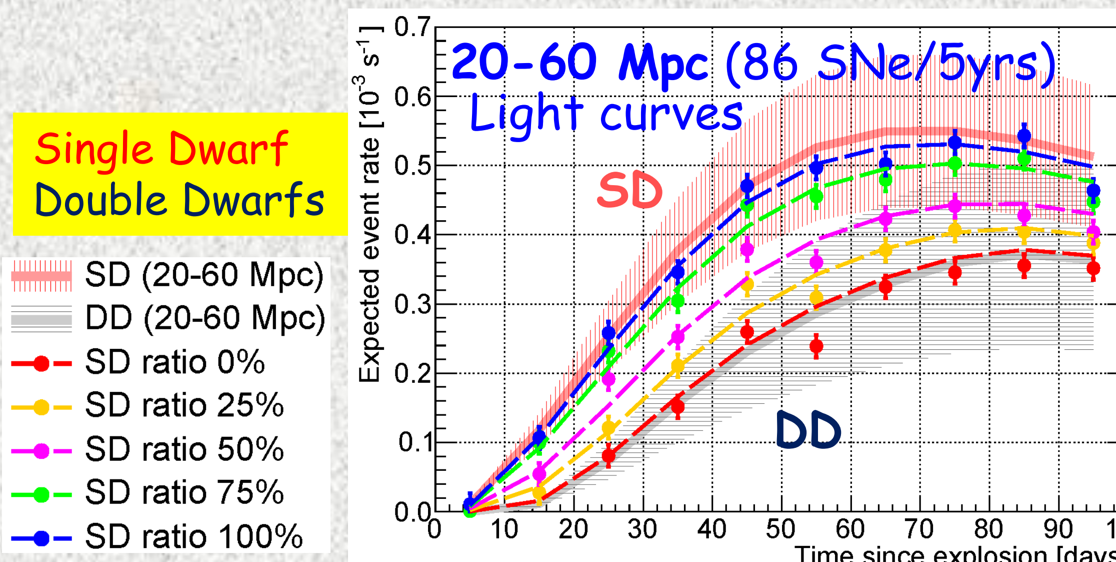
Origin of Ia: Single W.D. or Double W.D. merger ??

Summa, Maeda et al.
A&A 554 (2013) A67

Uncertainty of Jet axes

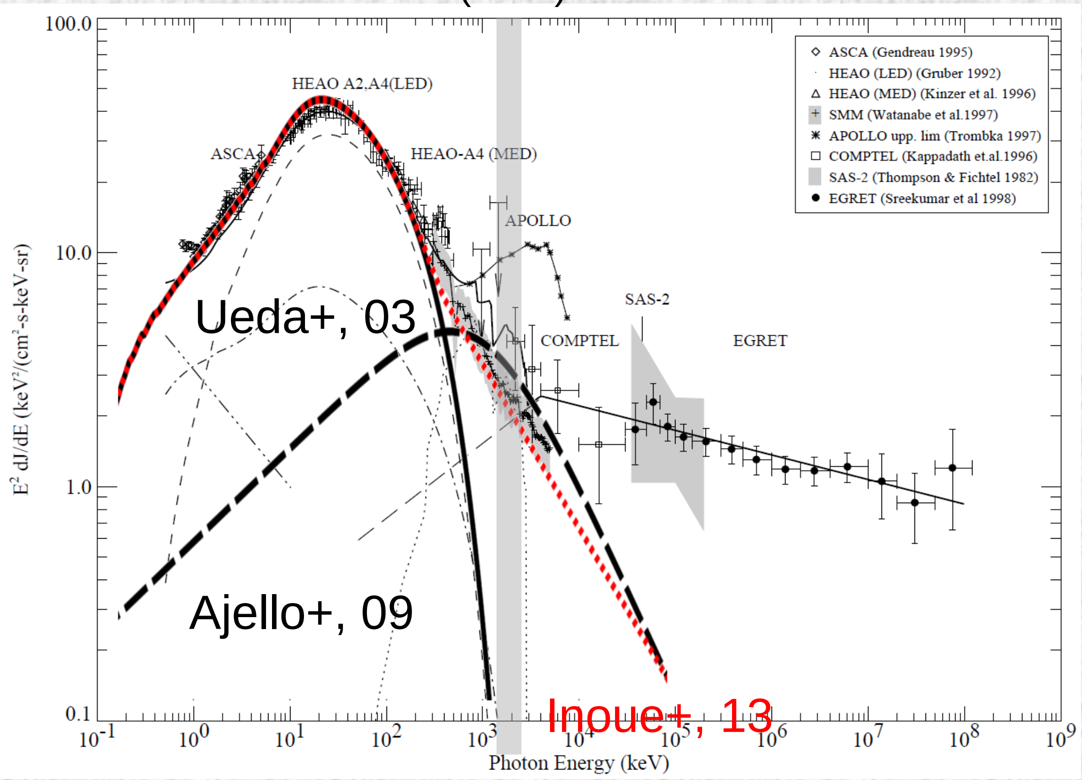


Single Dwarf
Double Dwarfs

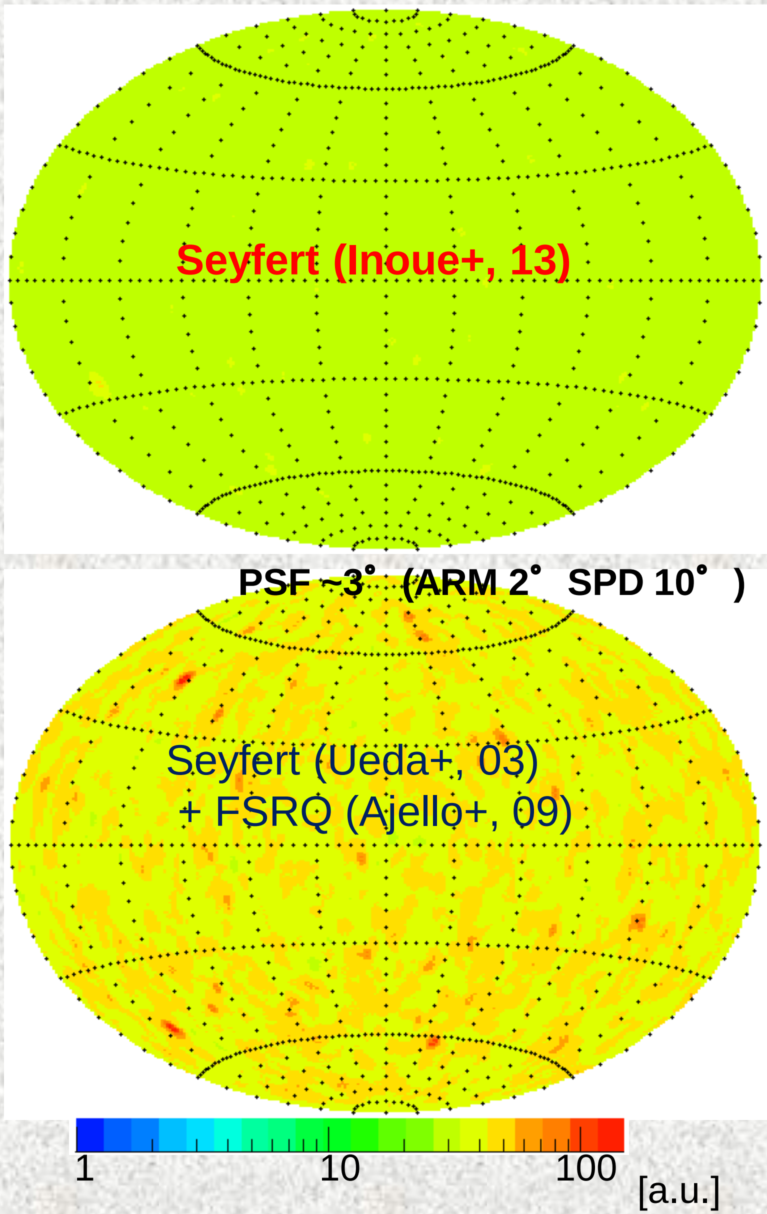


Extragalactic Diffuse Gamma(EDG)

Modified for M. Pohl (1998)

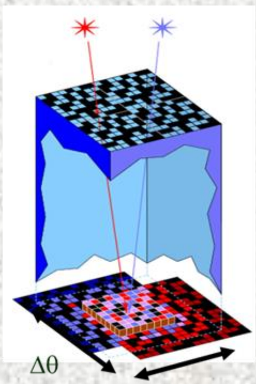


0.8~1.2 MeV Simulation

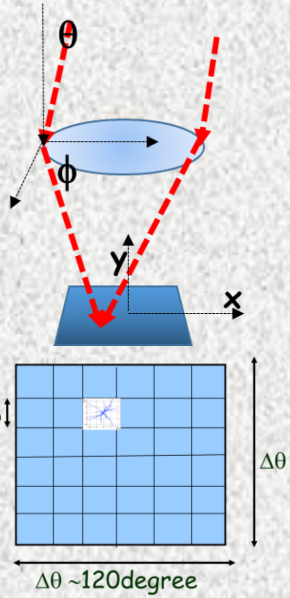


Accurate spectrum of EDG + non-uniformity
⇒ identification of the origin of EDG in MeV region
PSF<5º and verylow background are necessary
to observe the non-uniformity and

New Method for GRB
Luminosity Trigger to Fluence (Real Imaging) Trigger



Noise area = Δθ x Δθ



$$S \propto \frac{EA \bullet Cs}{\sqrt{EA \bullet \left(Cs + BG\Delta\phi^2\right)}} \sim \frac{EA \bullet Cs}{\sqrt{EA \bullet Cs}}$$

Cs<<BG

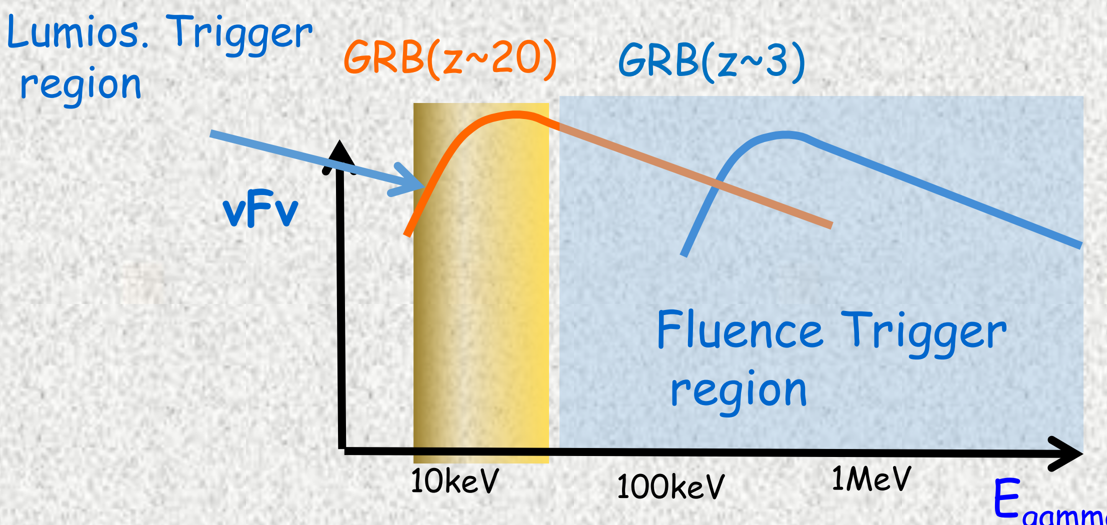
Noise area = (Δφ x Δφ)

$\Delta\phi/\Delta\theta = 10$ Noise reduction -> $1/10^2 \sim 1/10^3$

Wide band trigger in νFν (70keV ~>10MeV)

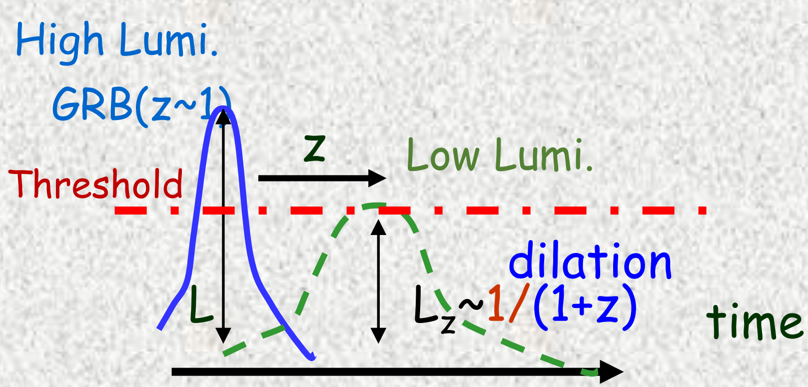
Wide range of accumulation time $0.1\text{-}10^6$s

Position Accuracy ~20gammas <0.5°



Luminosity Trigger

Same fluence GRBs



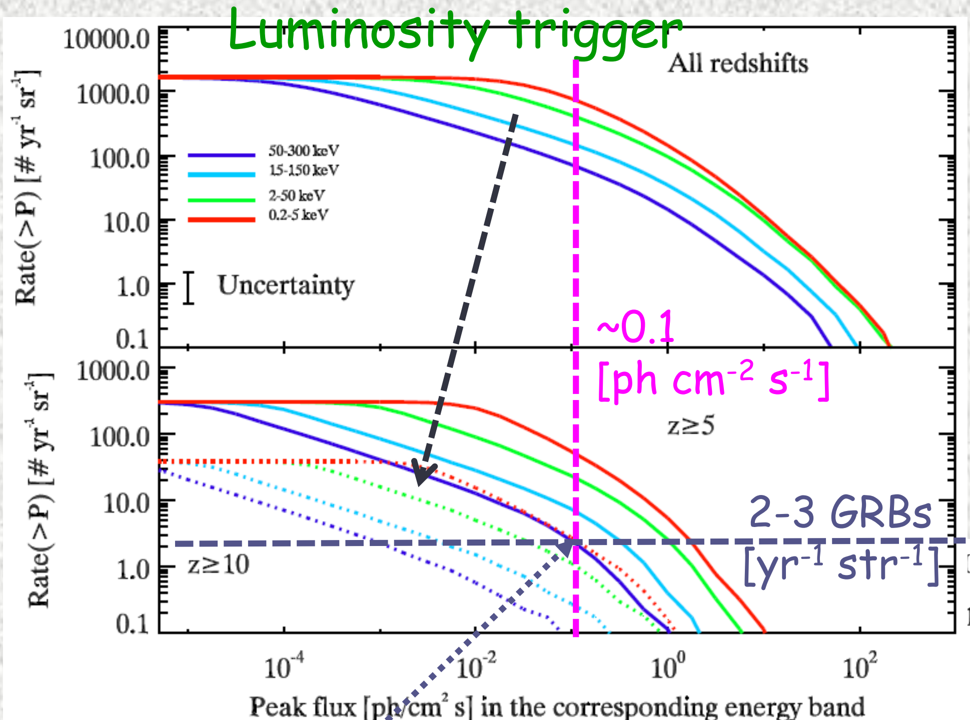
insensitive for dilation

little sensitive for E_{peak} and Redshift

fluence = $\int L_z\, dt$, cancels a dilation effect

Fluence Trigger for long GRB

(G. Ghirlanda et al. MNRAS 448, (2015))



Satellite-ETCC (T_{90}: 10-100 sec)

--> Fluence ~10^{-8} erg cm^{-2}

(2-3 GRBs/year/str (z>10))

+ wide FoV >4 str

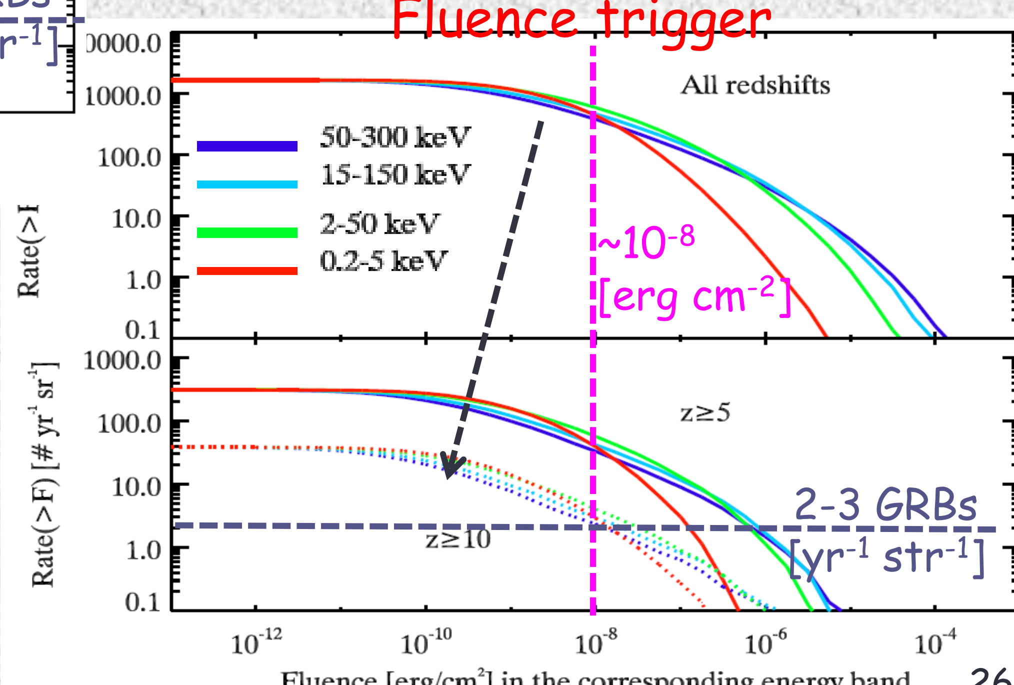
--> Several GRBs/year (z >10)

200 GRBs/year (z > 5)

Energy band

50-300 keV --> 50 keV-10 MeV

more GRBs will be detected.



0.2-5keV band

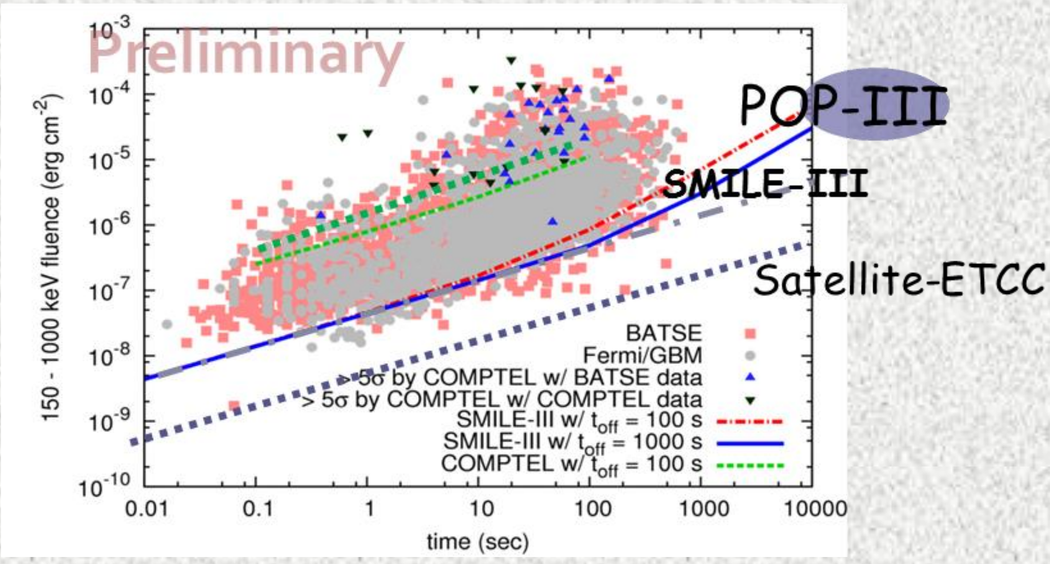
Threshold 0.1 phcm^{-2}s^{-1}

Very difficult !

G. Ghirlanda et al.
MNRAS 448, (2015)

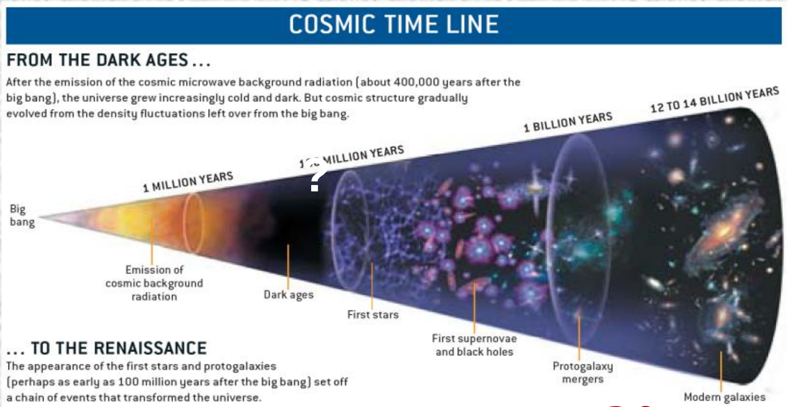
Summary

- ETCC provides Imaging Spectroscopic Observation for the first time, and hence reveals the reliable way to reach to sub mCrab sensitivity.
- Also ETCC provides a ability of imaging polarimetory.
  another my presentation in the evening.
- SMILE-II+ will be launched at Alice Spring Australia in Apr. 2018 to observe 511keV from Galactic center



Deep Universe explored by GRBs

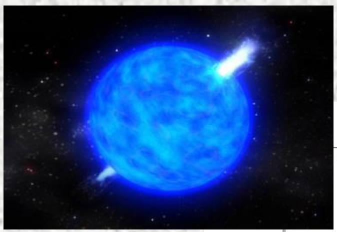
Biggest Explosion in Universe $10^{52\text{-}54}$erg



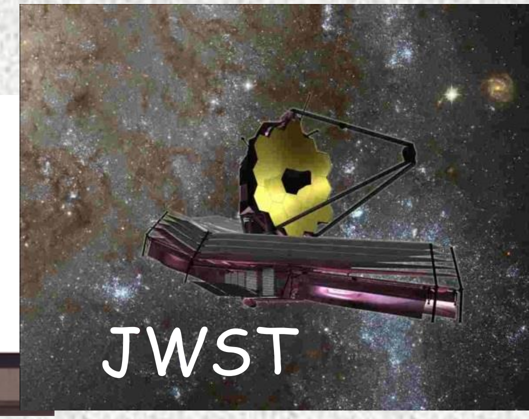
Larson&Bromm 02

GRB z~>20

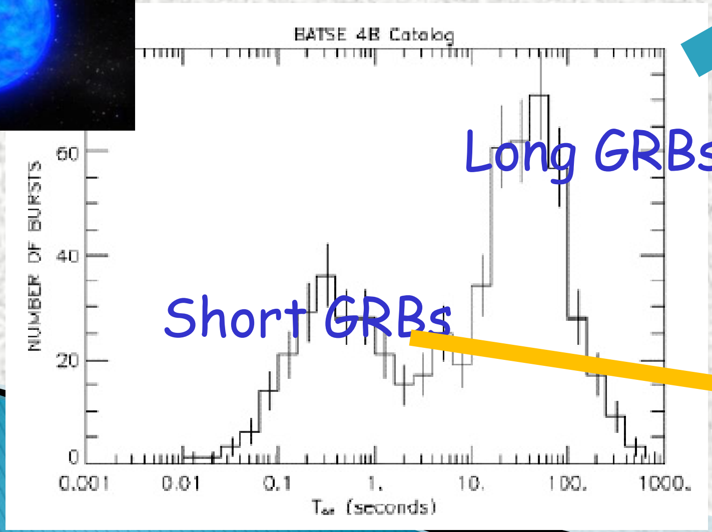
Galaxy & QSO z~10



TMT

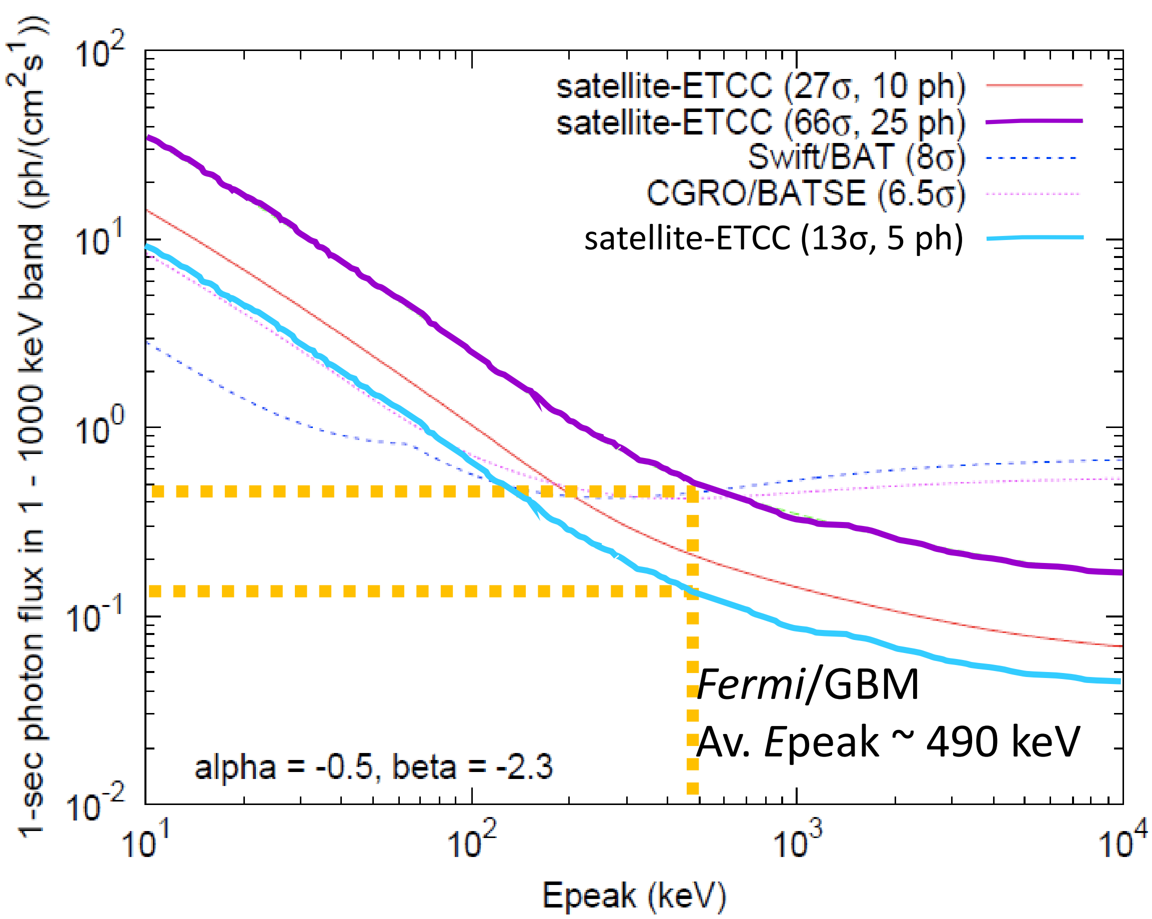


First Star & Galaxy



Neutron Star Merger

ETCC sensitivity for short GRBs



Sensitivity of ETCC for SGRBs

Case 1; 25ph/s in PSF, 66σ

0.5 ph/cm²/s (1-1000 keV)

⇒1.3 × 10^{-7} erg/cm²/s, ~ 0.4°

Case II 5 ph/s in PSF, 13σ

⇒2.6 × 10^{-8} erg/cm²/s, ~ 0.9°

+ X-ray Telescope -> <0.1°

BATSE flux limit

~ 1 × 10^{-6} erg/cm²/s

(Yonetoku et al. 2014)

ETCC 10 times better

Brightness fuction ∝ L^{-1}

Sensitivity x10 ⇒ # Det. x10

0.02 x10 ~ 0.2 events/year within 200Mpc

In 5years Observation. ~1 coincidence event with GW is expected !

From Doctor thesis of T.Sawano