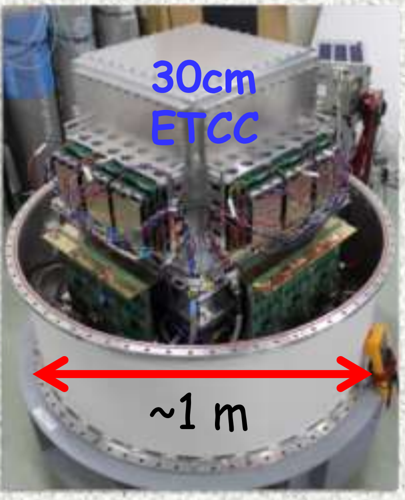
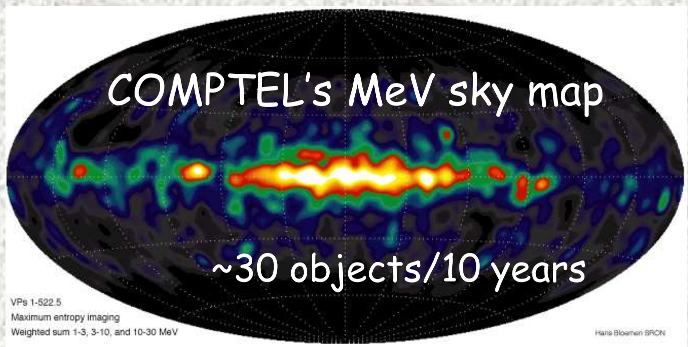
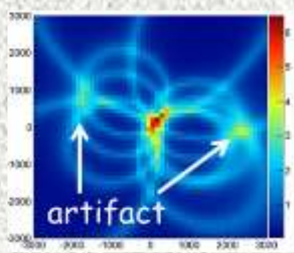
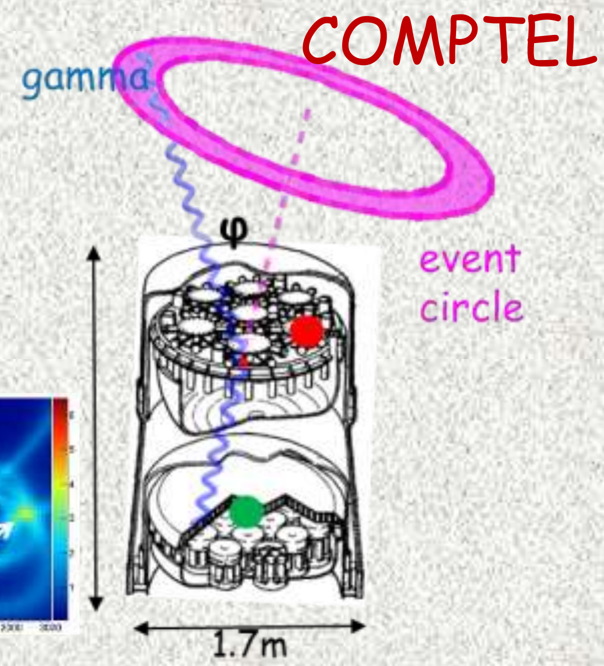
Survey of most distant GRBs in sub-MeV gammas by Electron Tracking Compton Camera with a well-defined PSF





V. Schönfelder+ (A&AS, 2000)





CONTENTS

1. Point Spread Function in MeV region
2. MeV gamma-ray imaging by ETCC
3. Imaging Observations for GRBs and SNe
1. Future plan & Summary

20-21/Sep./2015 @IPMU

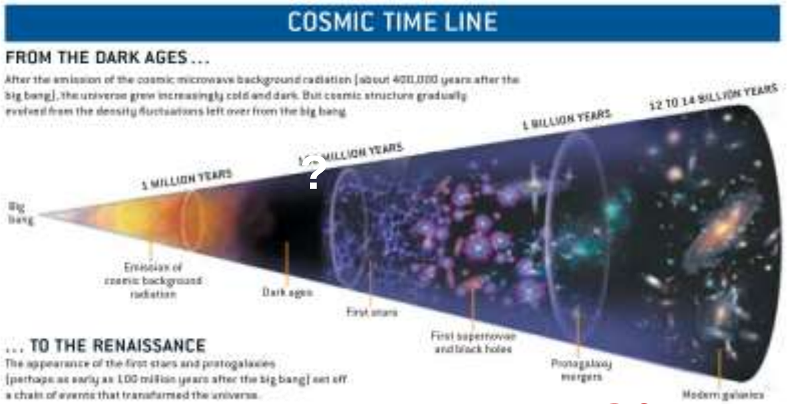
Two big problems in MeV Astro.

1. Imaging is very difficult
2. Huge background

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

Deep Universe explored by GRBs

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

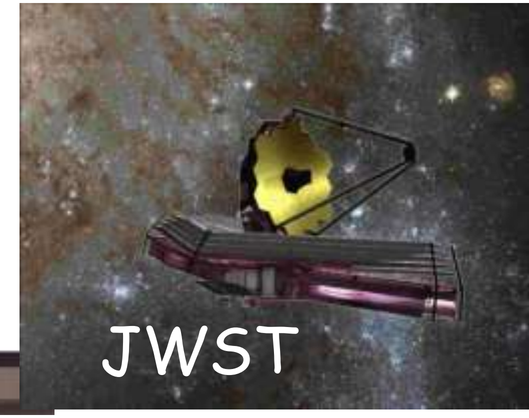


Larson&Bromm 02

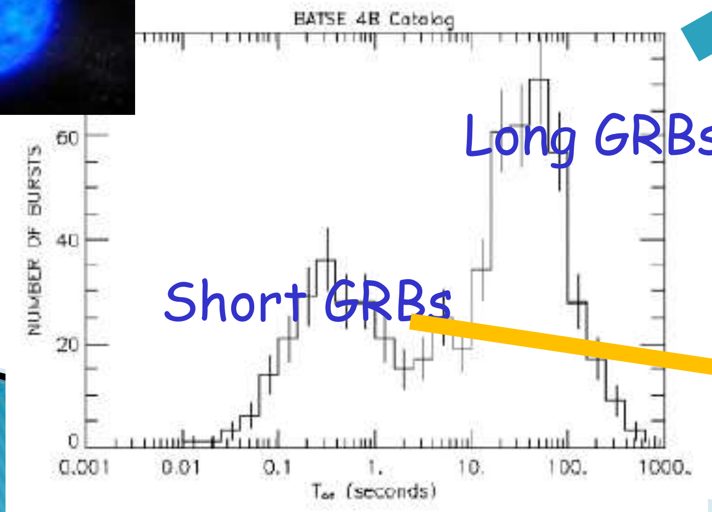
GRB z~>20

Galaxy & QSO z~10

TMT

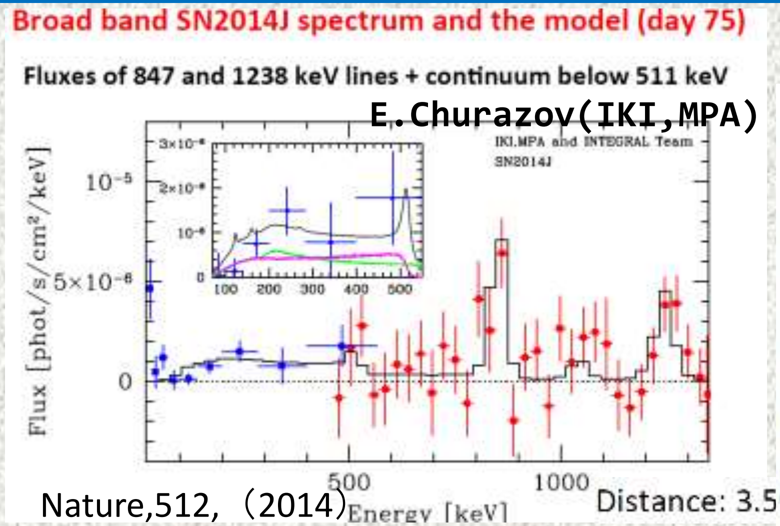


First Star & Galaxy

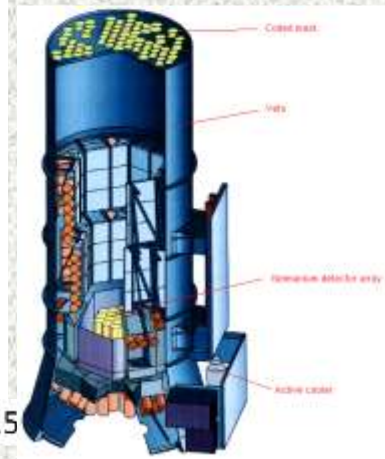


Neutron Star Merger

Line gammas from SN Ia SN2014J (INTEGRAL-SPI)

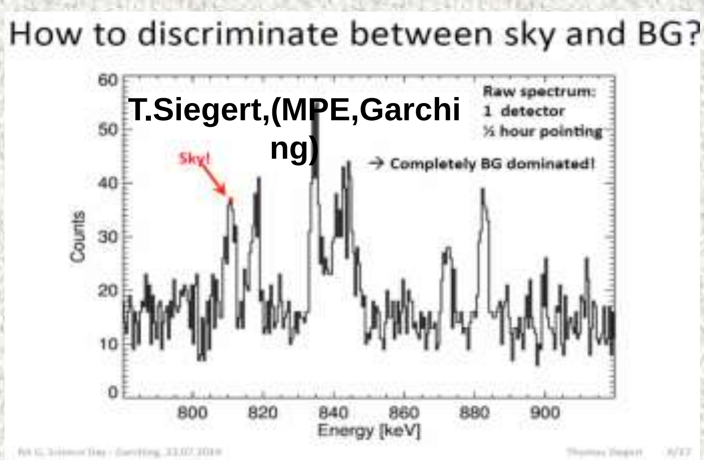


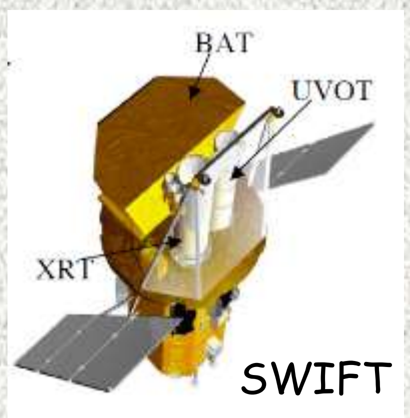
SPI: Codded Mask 19 xGe FoV ~1 str

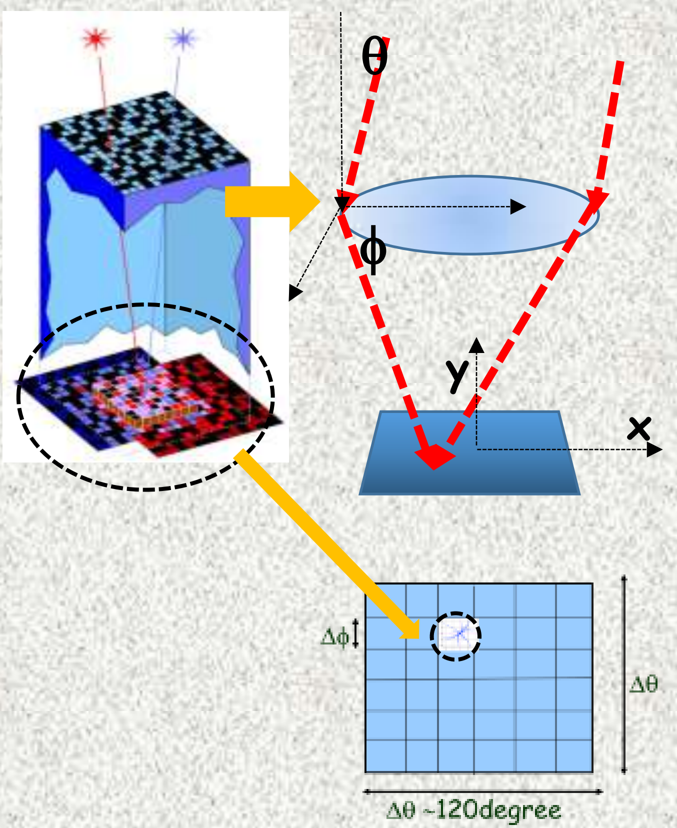


SN2014J

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







SPI Effective Area 65cm^2@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 and Point Spread Function (PSF)

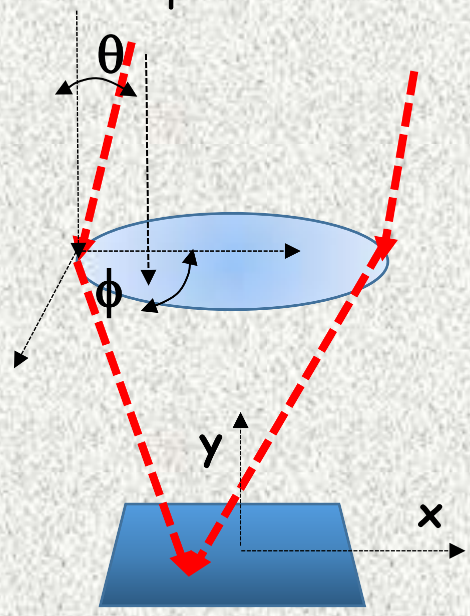
◆General Imaging

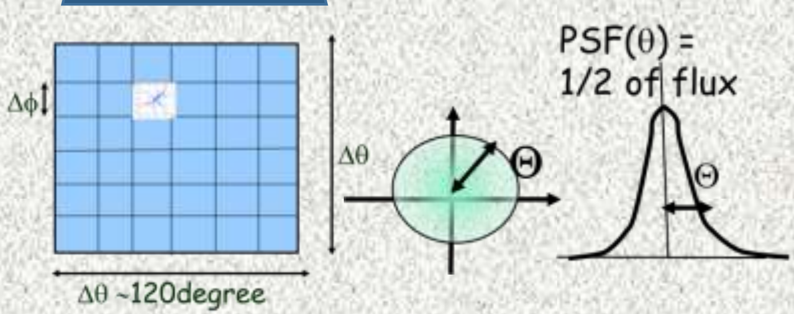
◆(measures θ and ϕ)

Two directional angles

↓ Transformation $\begin{cases} f(\theta, \phi) = x \\ g(\theta, \phi) = y \end{cases}$

2D position



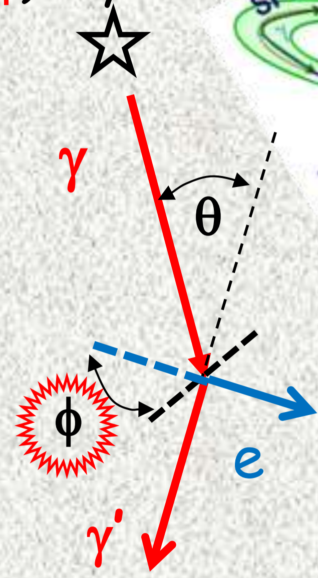


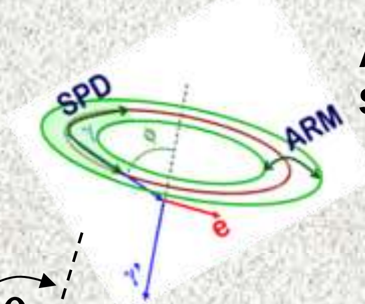
◆Compton Imaging

(measures only θ)

imaging with θ and ϕ

(3D-electron tracking gives ϕ)



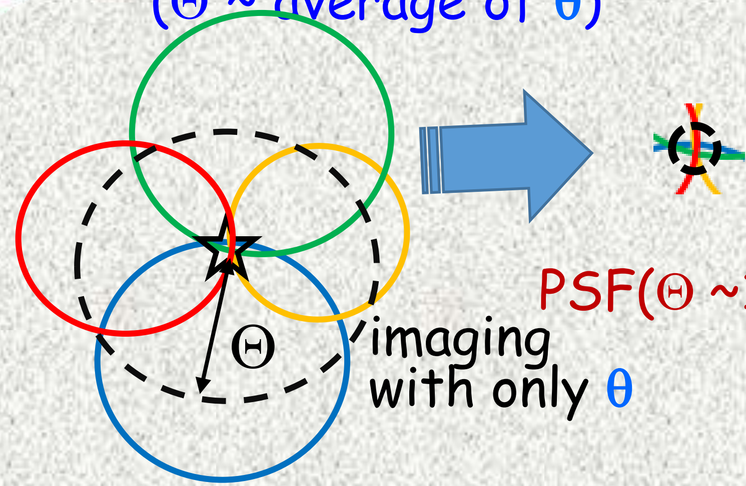


ARM (Angular Resolution Measure)

SPD (Scatter Plane Deviation)

PSF(Θ ~20-40°)

(Θ ~ average of θ)

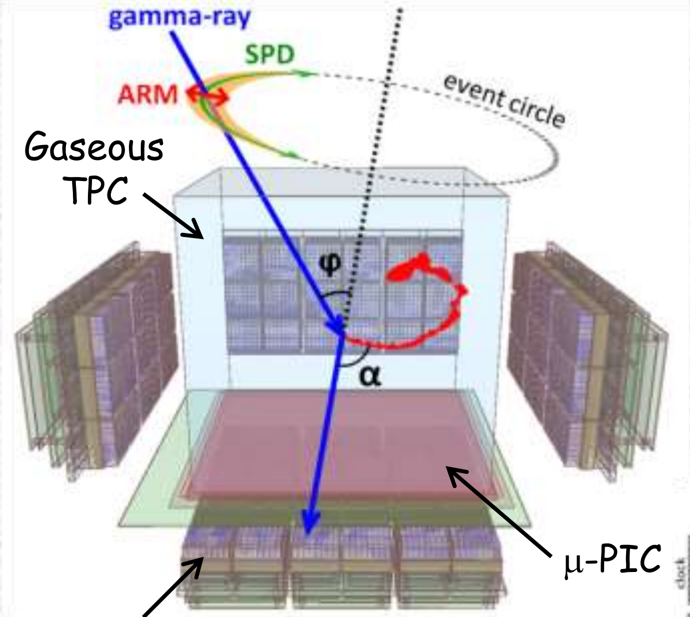


PSF(Θ ~1°)

If accuracies of θ and ϕ are similar to a few degree well-defined PSF with ~1°

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

Electron-Tracking Compton Camera (ETCC) in SMILE-II



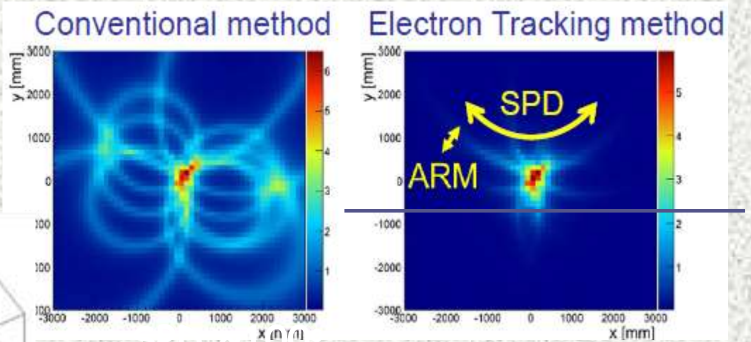
30cm-cubic Gaseous Time Projection Chamber

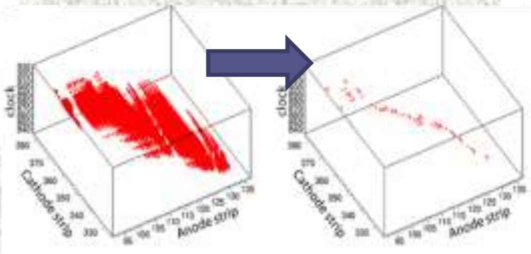
--- tracking of recoil electron ---

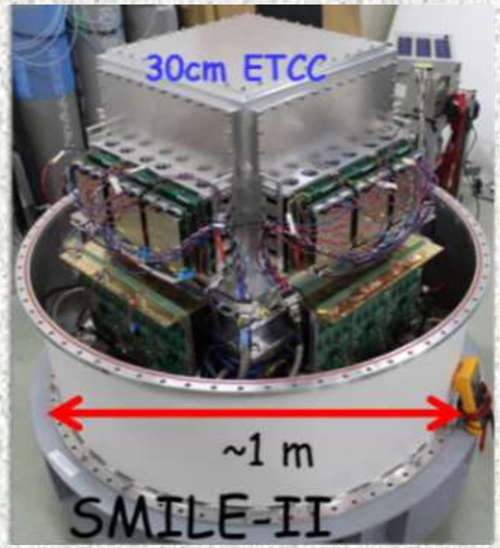
SPD (Scatter Plane Deviation) + dE/dx + α

Scintillator Array for scattered γ

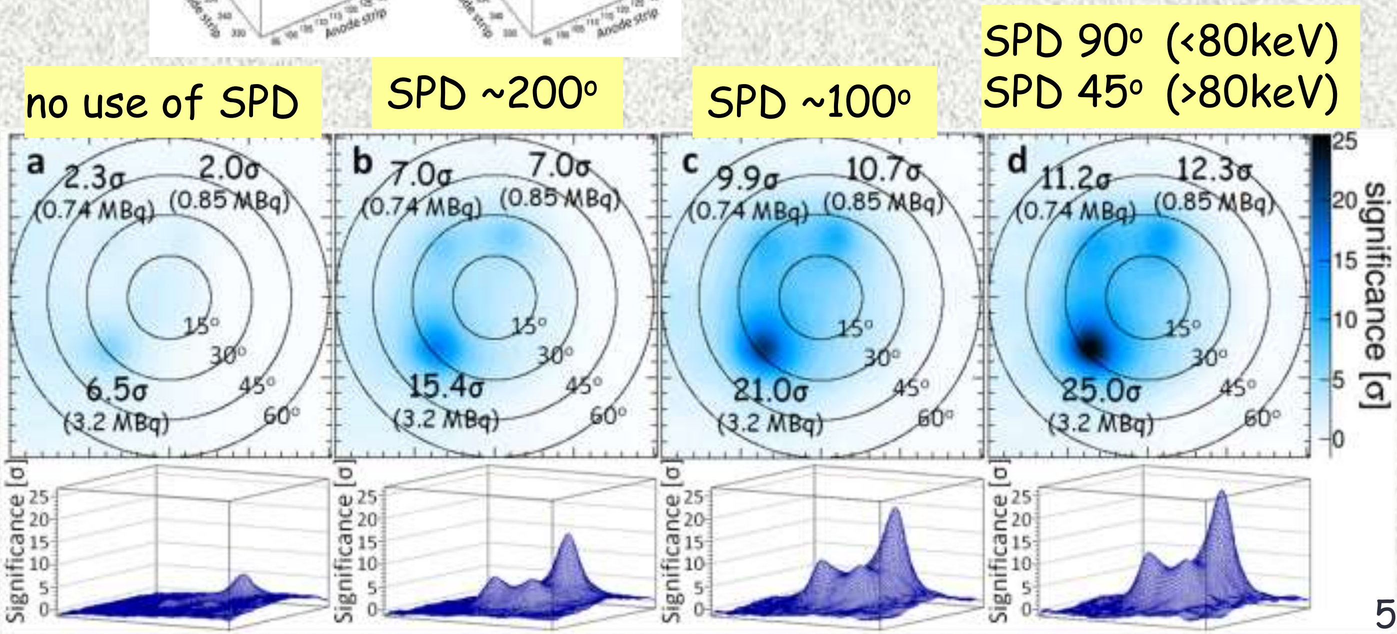
FoV ~6 str



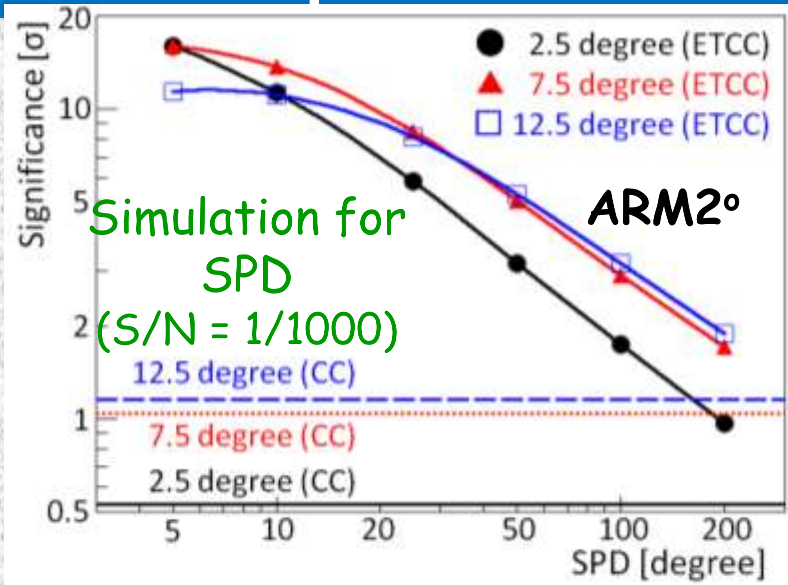


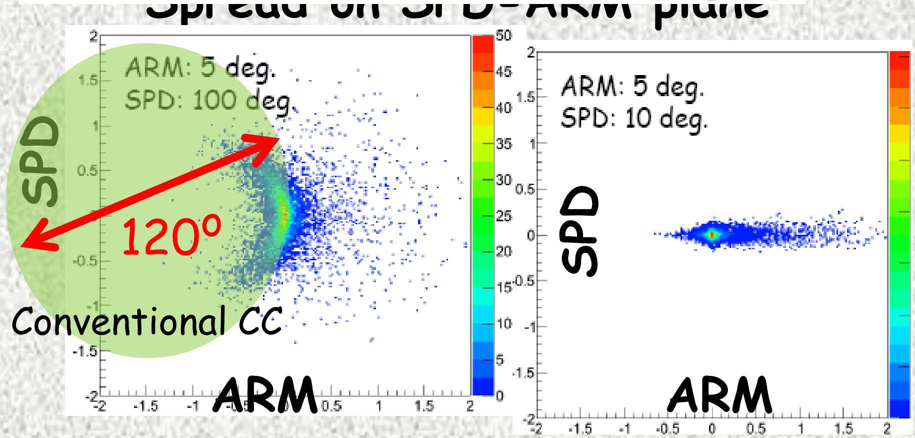


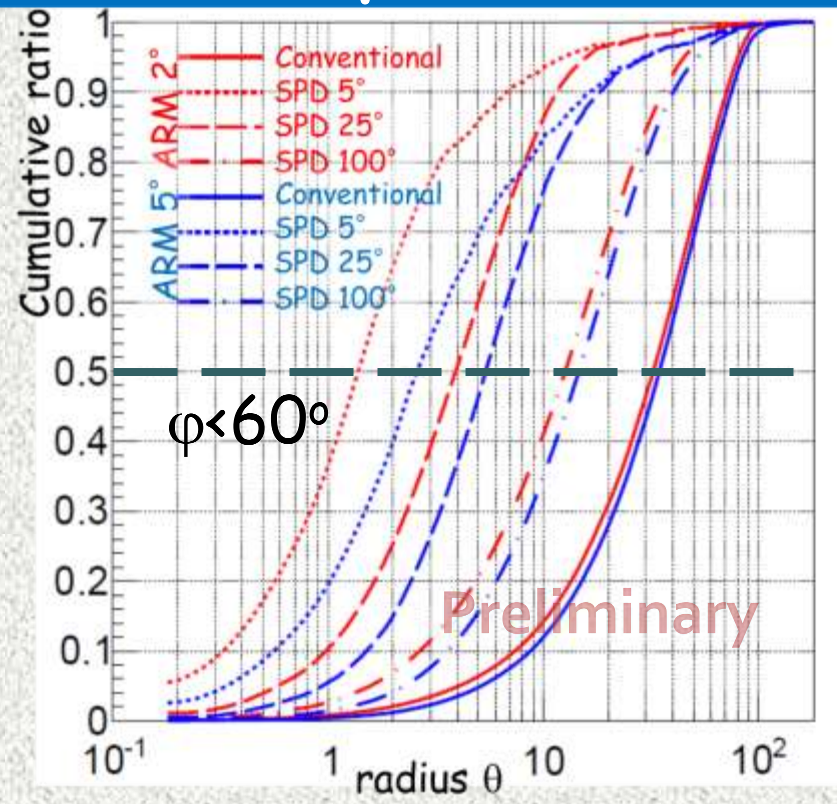
30cm cubic ETCC
Eff. Area of 1-20cm^2



Point Spread Function in Compton Camera







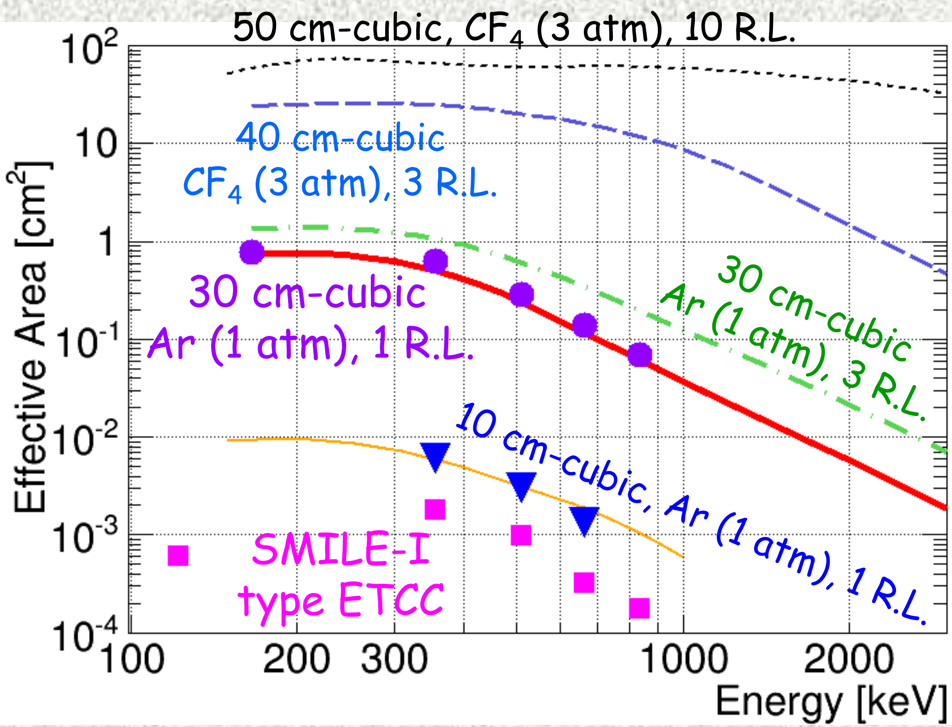
Conventional CC			PSF(35°)
SPD	50°	ARM 5°	PSF(7°)
SPD	25°	ARM 5°	PSF(5°)
SPD	5°	ARM 2°	PSF(1.2°)

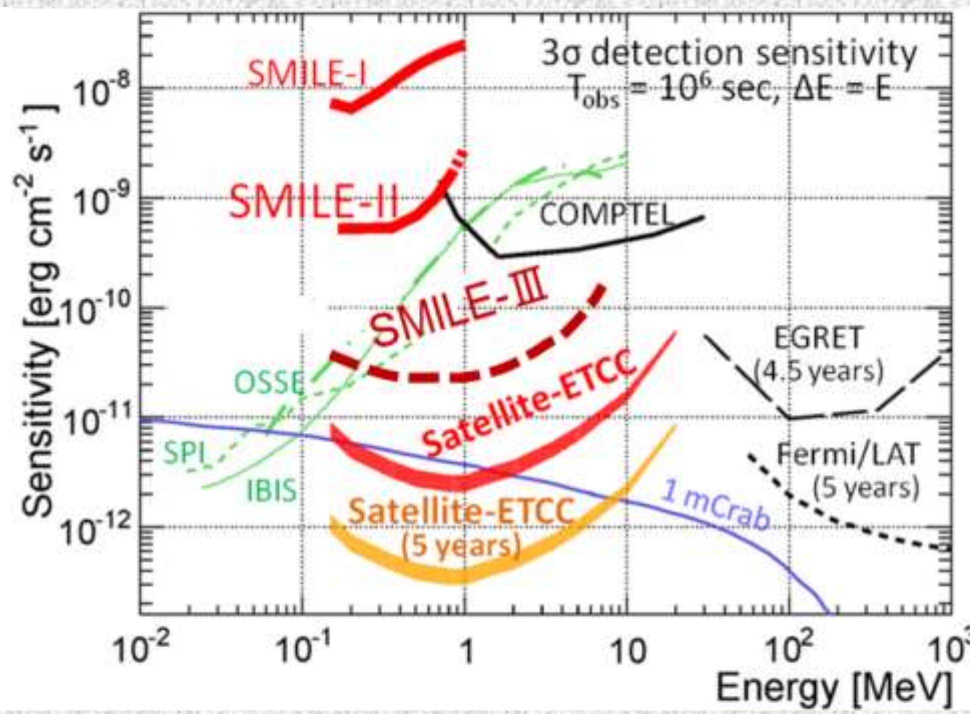
PSF(θ) = ½ gammas from point sources in the radius of θ

- PSF of Compton Camera is by φ (NOT by ARM).
- PSF of ETCC is Max{ARM, SPD}

Future Sensitivities by ETCC

Sensitivities are calculated simply from effective area and PSF for the first time!



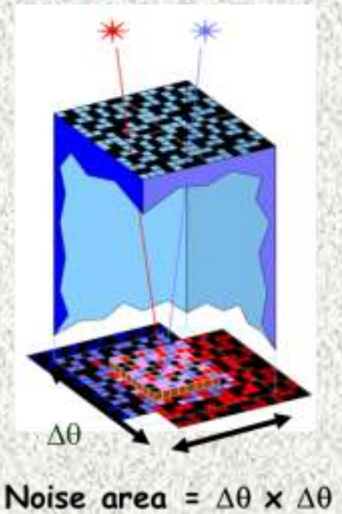


- SMILE-II (one-day Balloon)
  (30 cm)^3 ETCC= 1~4cm^2
  Crab or 511keV at >>5σ
- SMILE-III (Balloon, in polars)
  (40 cm)^3 ETCC x2 =80cm^2 GRBs
- SMILE-Satellite:
  (50 cm)^3 ETCC x 4 =250cm^2

SMILE-II, III PSF(7-10°)
SMILE-Satellite PSF(1.2°)

PSF(θ<5°) @ 1mm tracking in Gas
=> <1μm in Solid state

Luminosity and Fluence (Real Imaging) Triggers



Luminosity Trigger -> $\frac{dN_{ph}}{dt}$ with Counting Type detector

(Swift Beppo-SAX, Fermi-GBM, SVOM, GUNDSAM,etc)

N_{ph}: detected Photon number =Cs(signal)+BG(background)

N_{ph} mainly depends on the photon number of lowest energy

Accumulation time(dt), 1~several seconds

-> Narrow band trigger in vFv

Sensitive for dilation factor by General Relativity (1+z)

also Sensitive for E_{peak} (Swift for Short GRBs)

and time variability of BG

$$S \propto \frac{0.7 EA \bullet Cs}{\sqrt{EA \bullet (Cs + BG)}}$$ Cs<<BG

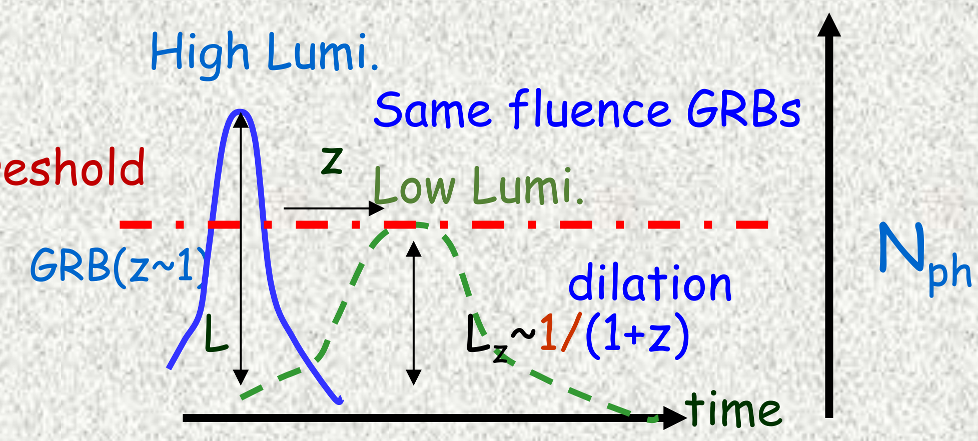
Imaging Trigger with Coded Mask

(Not real Imaging)

longer accumulation time 64s (Swift)

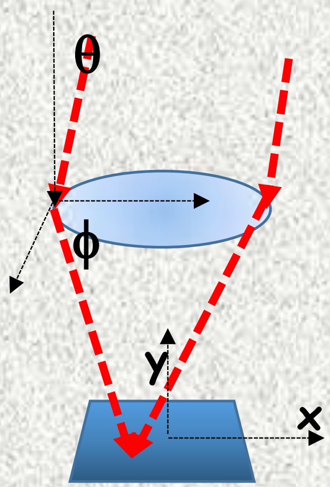
Needs more Nph > Luminosity Trig.

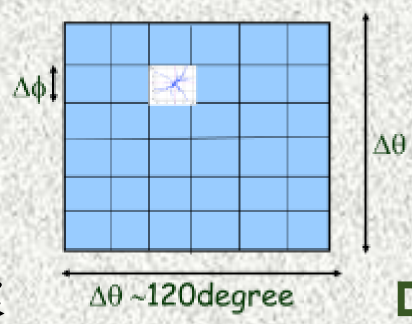
But sensitive for longer GRB



fluence = ∫ L_z dt, cancels a dilation effect

Fluence (Real Imaging) Triggers





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

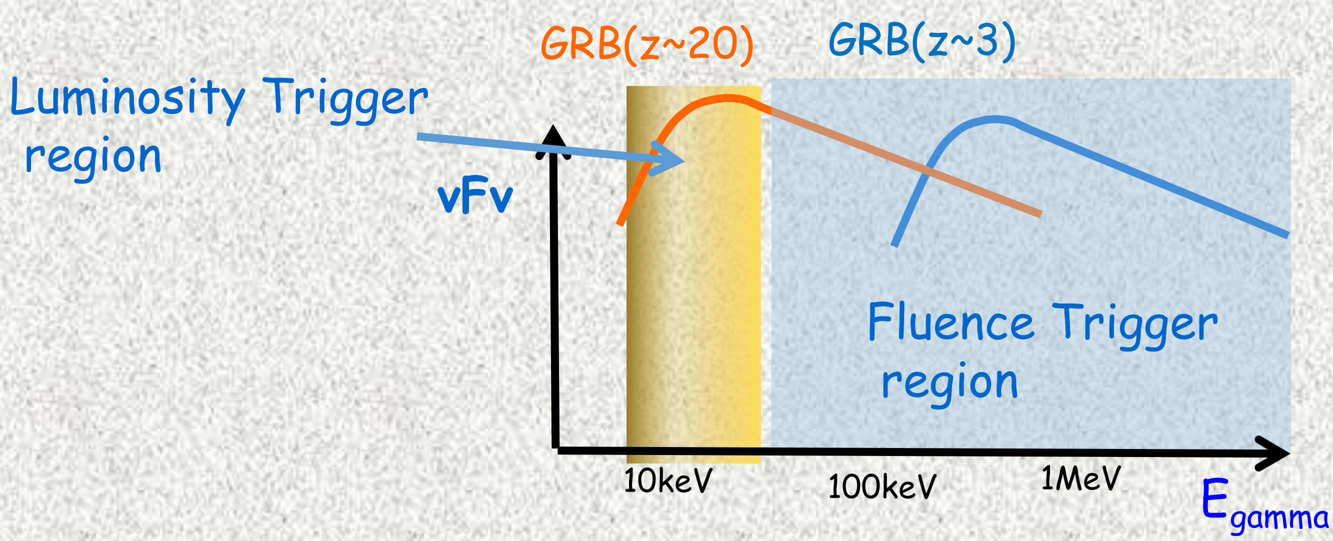
Noise area = (Δφ x Δφ)

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

- Very Low BG and Large Field of View (>4str)
- Wide band trigger in vFv (70keV ~>10MeV)
- Wide range of accumulation time $0.1\text{-}10^6$s

little bias for any type of GRBs
insensitive for dilation factor
little Sensitive for E_{peak} and Redshift

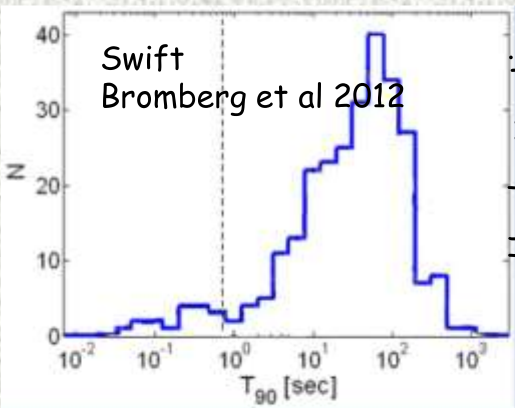
Position Accuracy
~20gammas <0.5°

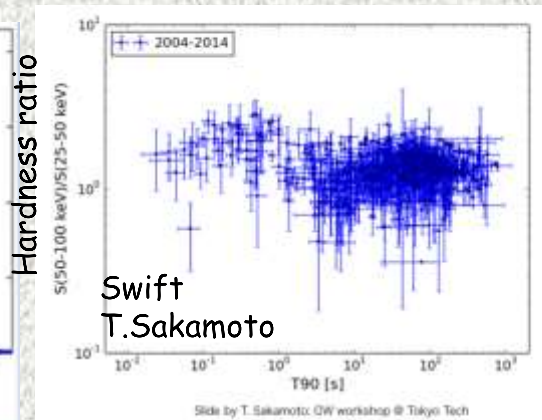


Detection of GRB by "True Imaging"

Short GRBs (E_{peak} > ~300 keV)

Swift less efficient for short GRB than BATSE due to its low sensitivity >100 keV





Sensitivity for GRBs

- Satellite-ETCC 240cm^2
- Trigger FoV = 4x4°
- $T_{obs.}$ ~ 10 sec

BG (4x4°) 2γ --> 12γ >8σ

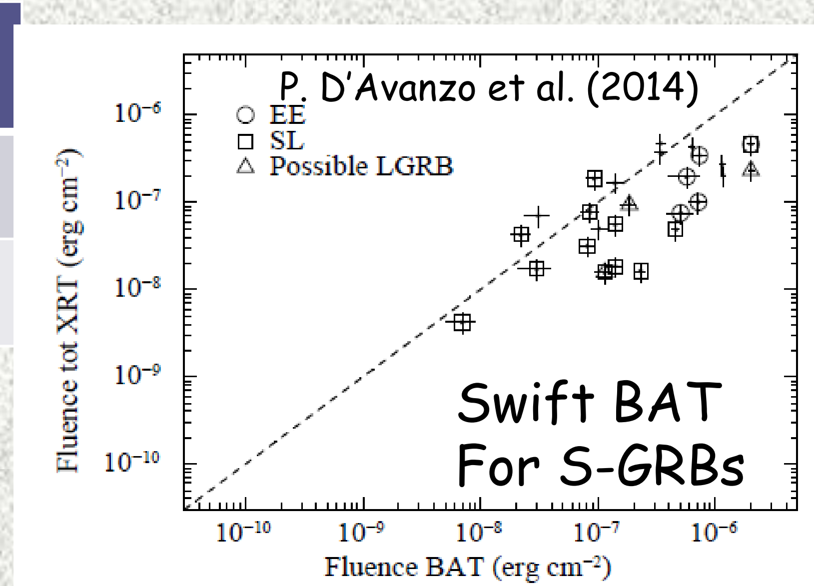
$\Delta\theta$ <0.5° (position accuracy)

--> S ~20γ ->10^{-9} erg cm^{-2} s^{-1}

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

	15-150 keV (Swift band)	0.05-5 MeV (ETCC band)
Swift threshold [erg cm^{-2}]	~5x10^{-7} ⇨	3-5x10^{-6}
ETCC threshold [erg cm^{-2}]	1-5x10^{-9} ⇦	~1x10^{-8}

ETCC improves fluence threshold about >10 times in Swift-band



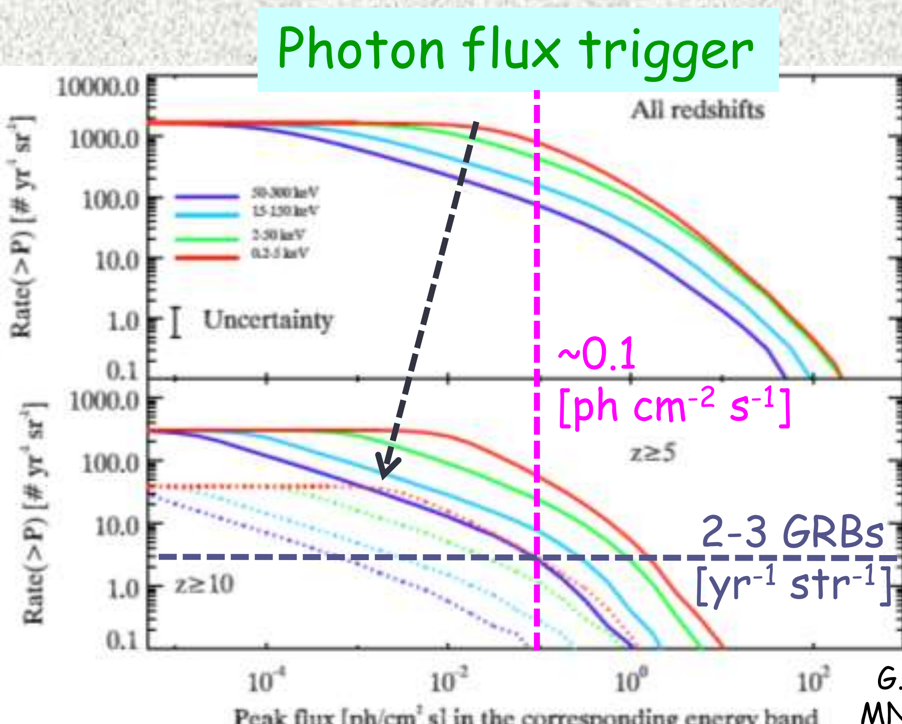
Fluence Trigger for standard long GRB

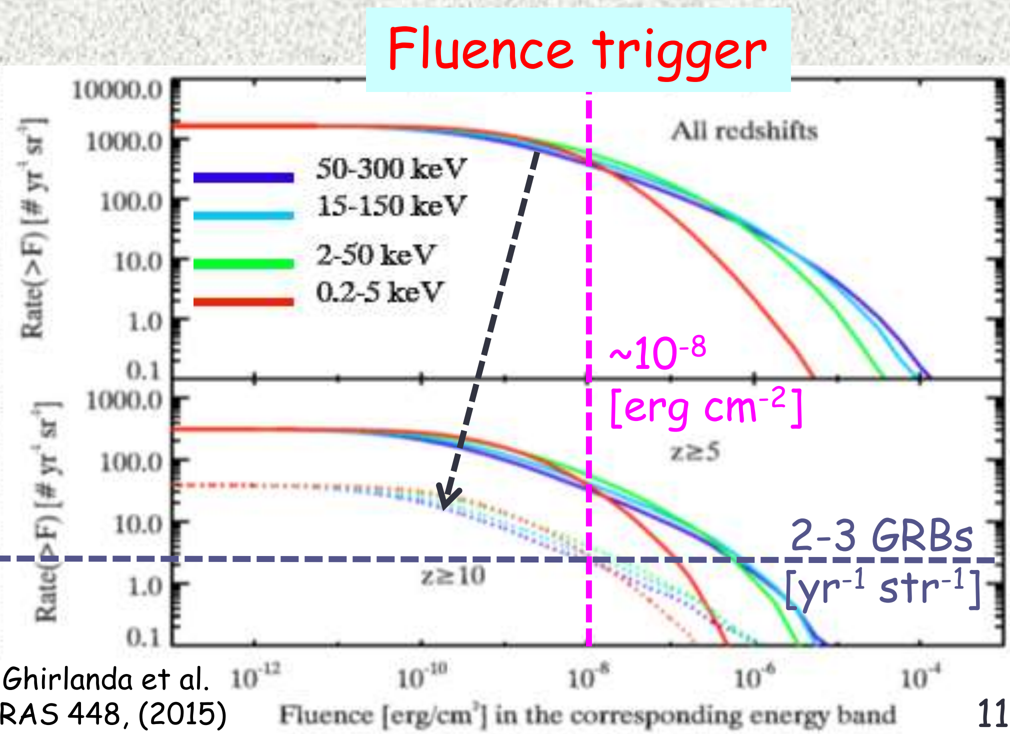
(G. Ghirlanda et al. MNRAS 448, (2015))

1. Time dilation
   Photon flux trigger is affected strongly by time dilation.
   Fluence trigger is NOT affected.
2. Redshift
   Broad band SED (keV to 10 MeV) very little effect on fluence.

Satellite-ETCC (T_{90}: 10-100 sec)
--> Fluence ~10^{-8} erg cm^{-2}
(2-3 GRBs/year/str (z>10))
+ wide FoV >4 str
--> ~10 GRBs/year (z >10)
200 GRBs/year (z > 5)

Energy band
50-300 keV --> 50 keV-10 MeV
more GRBs will be detected.





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

Ultra Long duration GRBs (POP-III)

D. Nakauchi et al. ApJ 759 (2012)

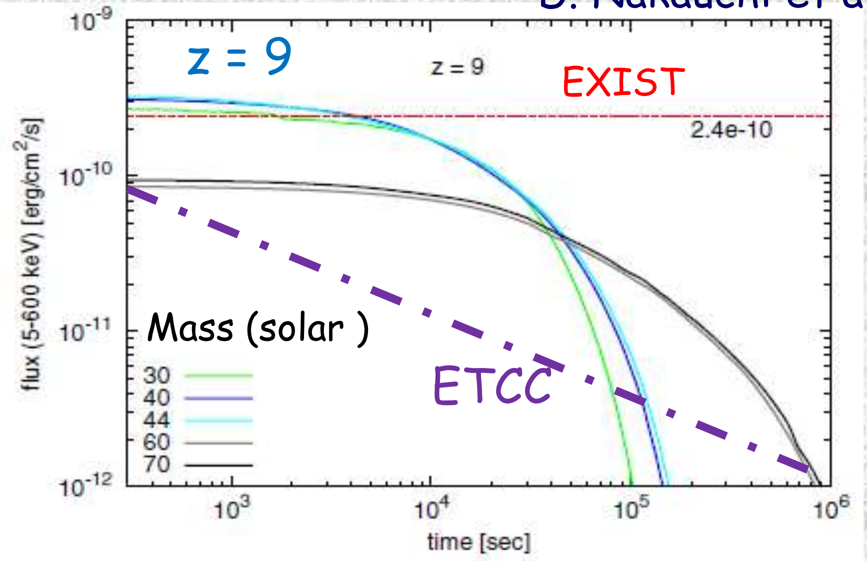


Figure 6. Same as Figure 5, but for the *EXIST* (5–600 keV) case. The red dashed line represents the *EXIST* sensitivity $f_{sen} \sim 2.4 \times 10^{-10}$ erg cm^{-2} s^{-1} (5–600 keV, 5σ) in the longest exposure timescale at the on-board process ($\Delta t \sim 512$ s; Hong et al. 2009). Note that we focus on Pop III GRBs at $z = 9$ in this figure.

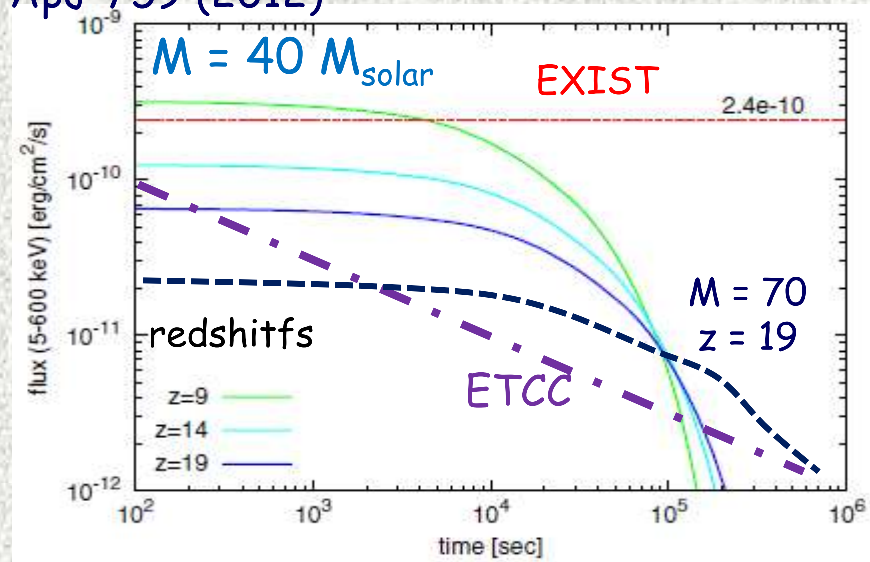


Figure 3. Same as Figure 2 but for the *EXIST* case. *EXIST* will have the limited energy range of 5–600 keV. The red dashed line represents the *EXIST* sensitivity $f_{sen} \sim 2.4 \times 10^{-10}$ erg cm^{-2} s^{-1} (5–600 keV, 5σ) in the longest exposure timescale at the on-board process ($\Delta t \sim 512$ s; Hong et al. 2009).

Assumed E_p-E_{iso} relation (Amati) --> E_p~120 keV @z = 9

EXIST limit: 2.4×10^{-10} erg cm^{-2} s^{-1} (500 s)

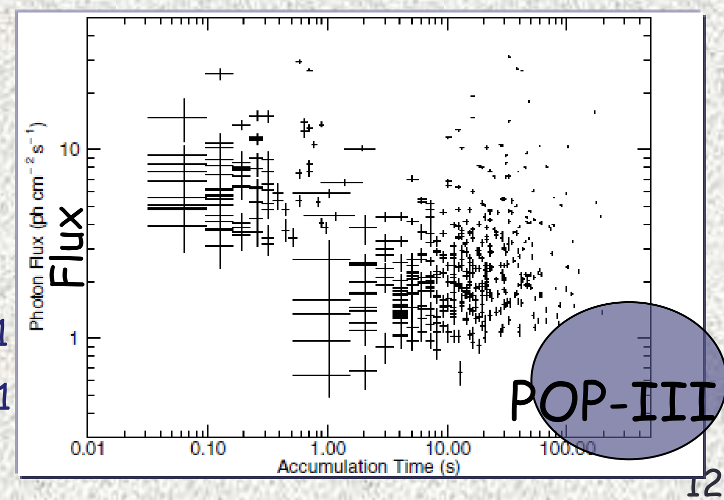
Pop-III Flux <10^{-10} erg cm^{-2} s^{-1} (very faint)

But, Fluence ~10^{-5} erg cm^{-2} (Intense)

Satellite-ETCC; S/√N >5σ

10^3s; S ~90γ BG 200γ -> 4×10^{-11} erg cm^{-2} s^{-1}

10^5s; S ~800γ BG 2×10^4 γ -> 4×10^{-12} erg cm^{-2} s^{-1}



Exploring GRB astronomy by Balloon-SMILE

1. SMILE-II one-day flight(s) for Crab or 511keV (Anytime, OK)
2. Next plan, SMILE-III Long-duration flight with larger ETCCs

Polar region 14-50 days (T_{obs} >10^6 sec)

40 cm-cubic ETCC x2 modules (Eff. Area ~80 cm^2)

GRB Search in Long duration flight

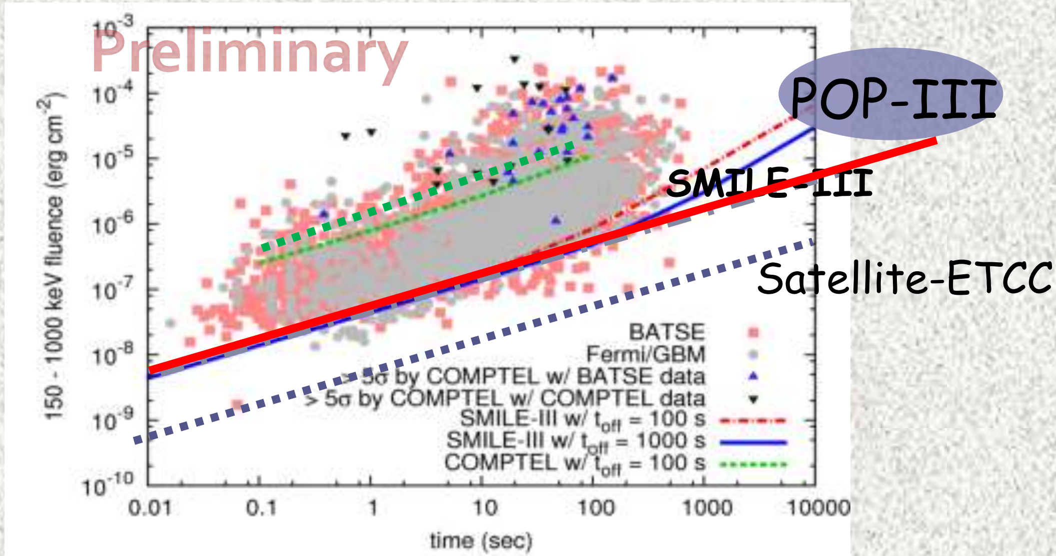
10^6 s --> ~3×10^{-11} erg cm^{-2} s^{-1} (+ FoV of 4 str) --> ~1 GRBs/day

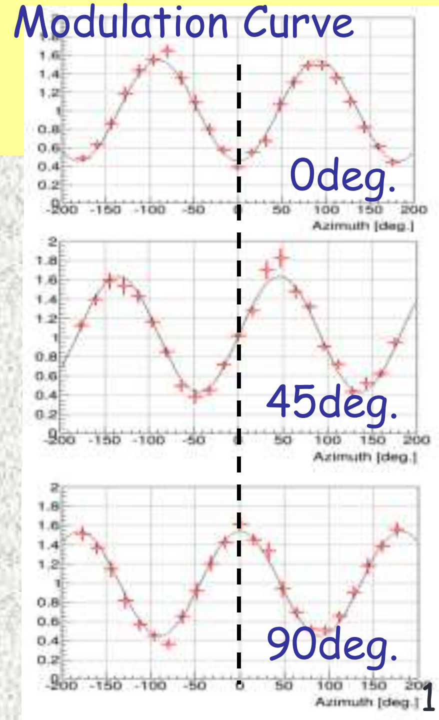
In addition, Polarization Measurements

MDP ~ 6% for 10^{-6} erg cm^{-2} s^{-1} (several GRBs/month)

~ 20% for 10^{-7} erg cm^{-2} s^{-1} (~20 GRBs/month)

GRB detection in SMILE-III Simulated by T. Sawano





Explosion Mechanism of SNIa

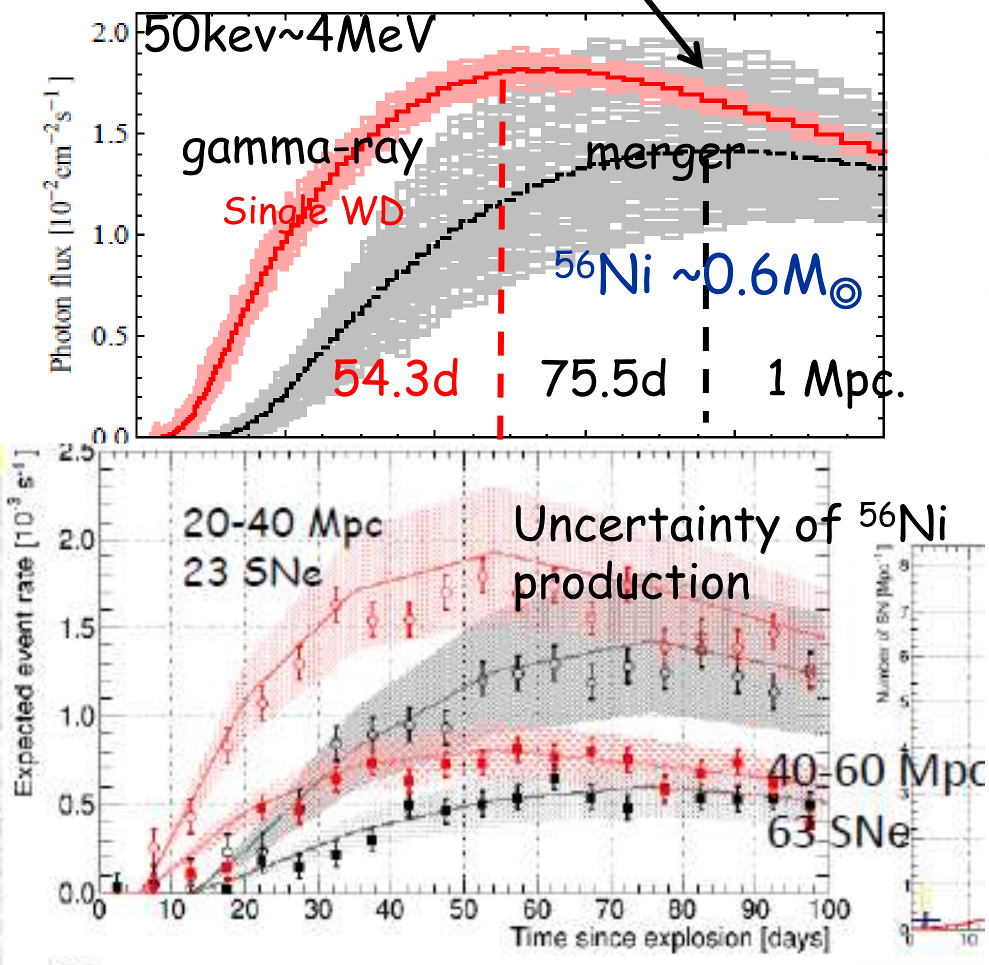
Summa, Maeda et al.
A&A 554 (2013) A67

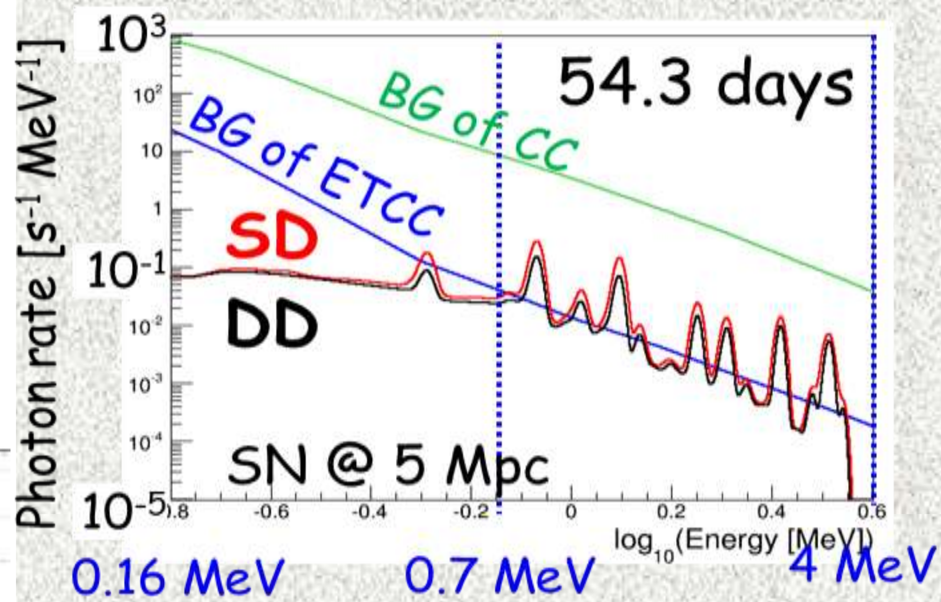
Origin of Ia: thermonucl. explosion S.W.D. or Double W.D. merger

Clear Difference of Light Curves in MeV γs beteen SD and DD models

Uncertainty of Jet axes

Rate SN-Ia ~18 SNe/year (<60Mpc)
(Private Comm. From Prof. Maeda)





3σ detection (10^2days) up to 110Mpc
SNe >~700/5year with Optical Tel.

Detection SN Ia up to 60Mc for making Light Curve (5σ at every 10days)

Summary

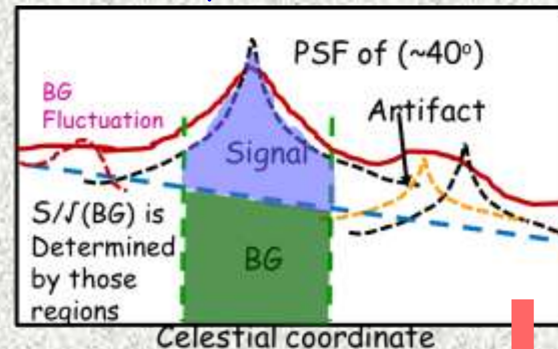
- ETCC provides well-defined PSF and strong Background rejection abiity both which reveal
  the reliable way to reach 1 mCrab sensitivity.

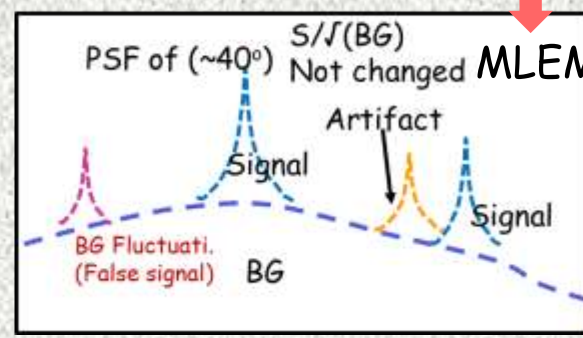
- Clear imaging with well-defined PSF in sub-MeV gives a true Imaging Trigger (Fluence Trigger) and provides a chance to reach most distant GRBs of any type (Short, Long, and Ultra-long).
- SMILE-III (long-duration balloon) will surely certificate above abilities of ETCC with measuring polarization of GRBs within several years
  (SMILE-II is already stand-by for one-day balloon)

Details of ETCC: Tanimori et al., ApJ (2015), 810, 28

Optimization Algorithm for Compton Imaging
Maximum likelihood Expectation Maximization (MLEM)

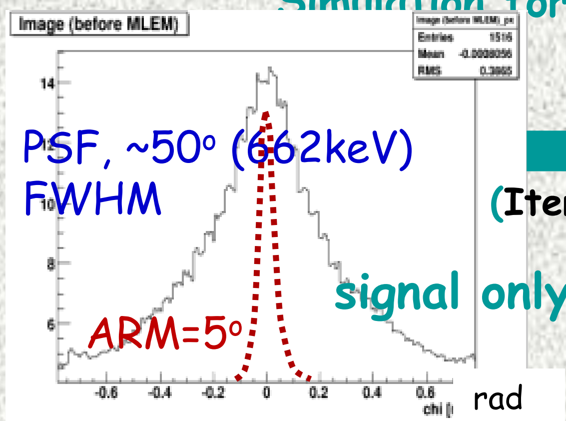
MLEM; optimizes the likelihood of ratios of known functions of signal and background such as detector acceptance or random noise, but can not improve the significance !! Know functions: Signal -> ARM resolution, and PSF



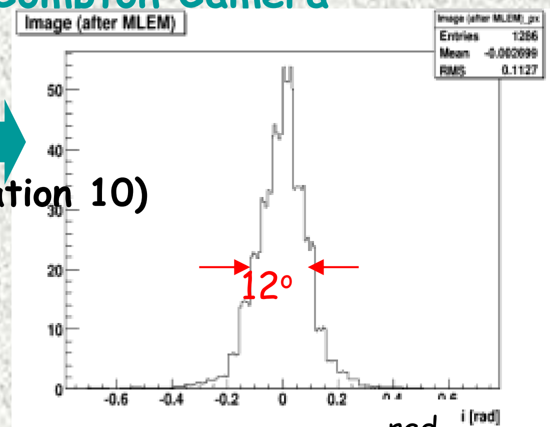


1.Significance~√(EA•S) Signal Dominated

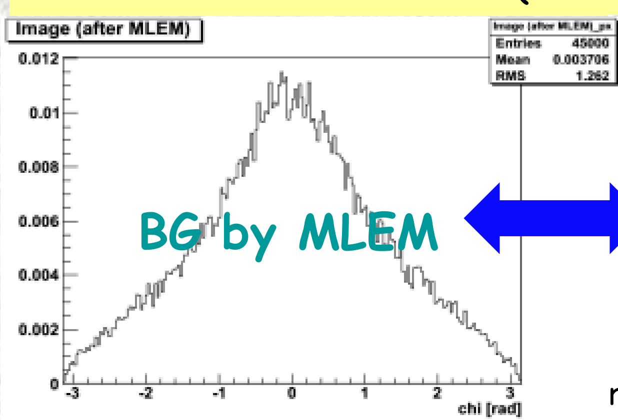
Simulation for Compton Camera

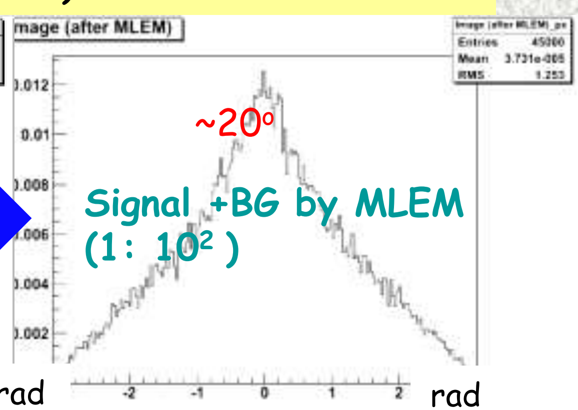


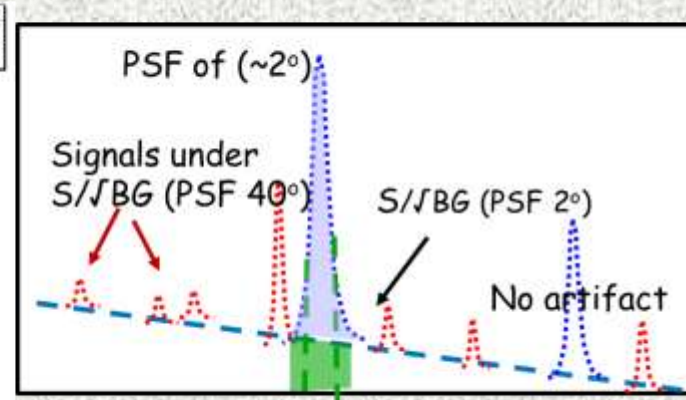
(Iteration 10)



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







How to reach 1 mCrab

- Target in the next generation MeV γ observatory
  Requested Sensitivity ~10^{-12} erg cm^{-2} s^{-1} (1 mCrab)@10^6 s

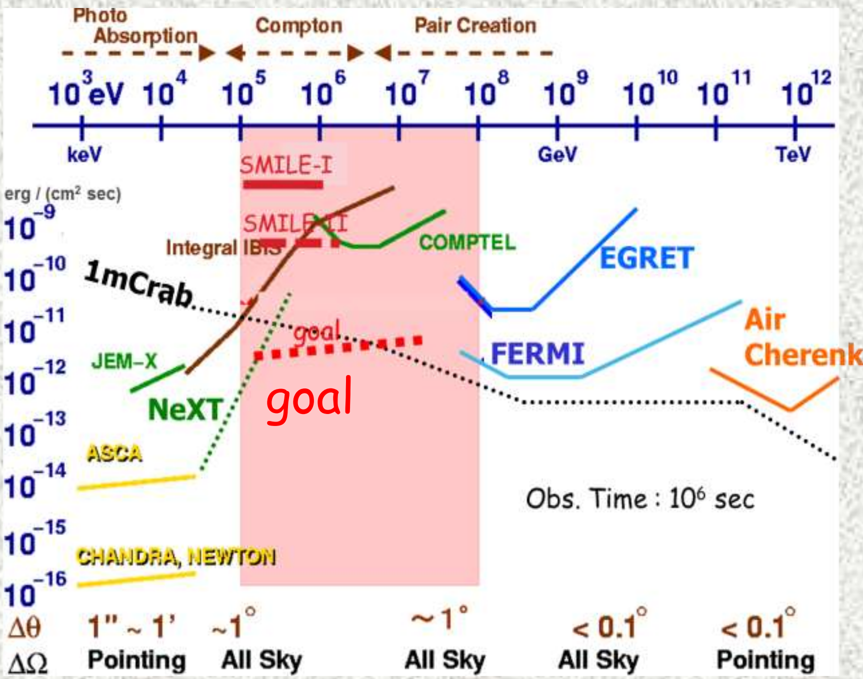
$$\text{Significance} \propto \frac{EA \bullet S}{\sqrt{EA \bullet \left(S + BG \bullet \theta^2\right)}}$$

S: γ-ray flux from object

- Effective Area (EA) >a few100 cm^2
  Possible !
- Good BG rejection --> BG(/str)
  ~ Cosmic diffuse gammas Possible!
- Point Spread Function (PSF)
  radius θ ~1°

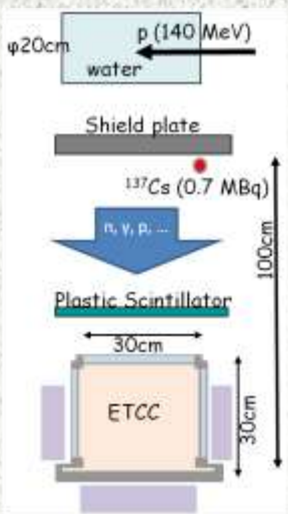
PSF in Compton Camera is ambiguous !

Solution is **Fine Electron Tracking**

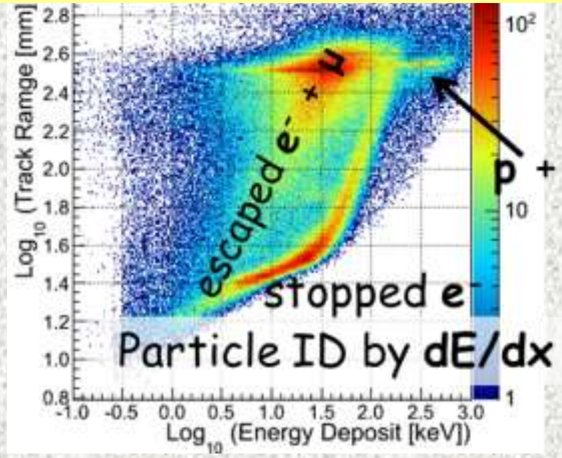


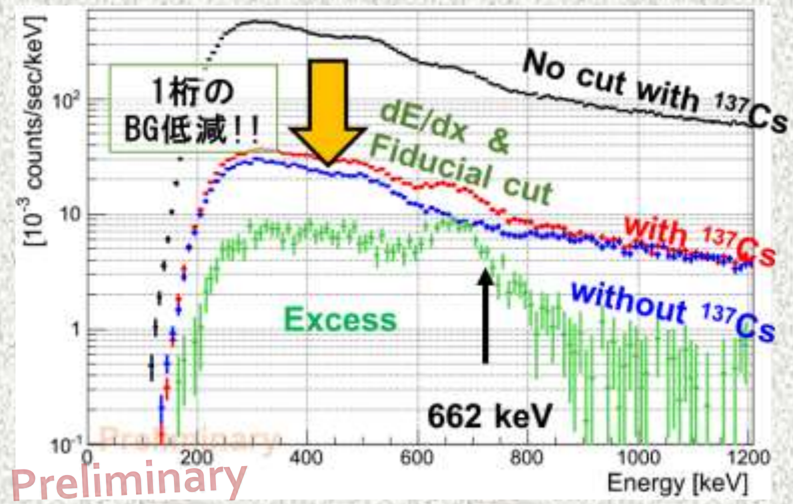
100 times better sensitivity than COMPTEL <(1mCrab) by PSF of ~1°

Test in intense BG environment by Proton Beam

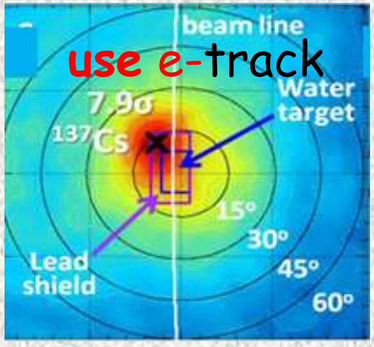


1. Power of dE/dx of a track

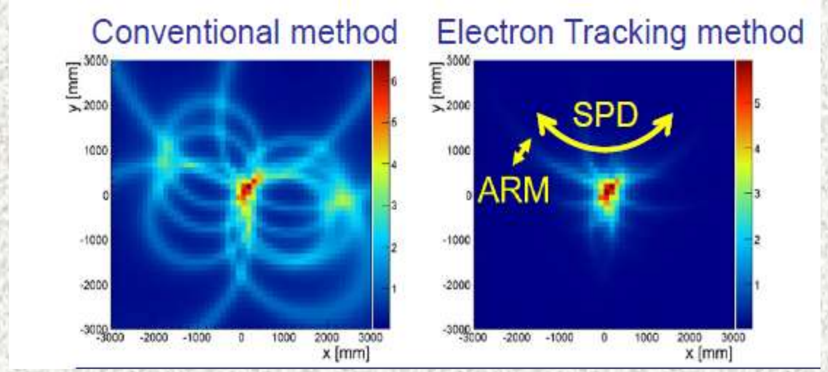




Intense Radiation (x4 of balloon altitude) with keeping an efficiency



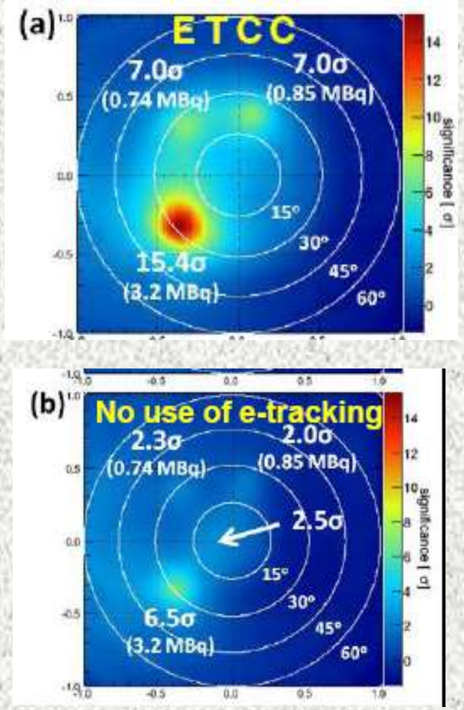
2. Power of Electron Tracking



Improvement of Sensitivity in 2014

dE/dx ~ x 3

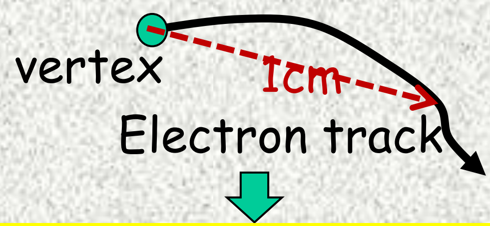
SPD x3~4 Total **x 5~10**



SPD resolution in TPC with μPIC

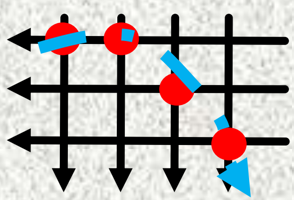
Present 800μm pitch

Linear Fitting
Between vertex to 1cm

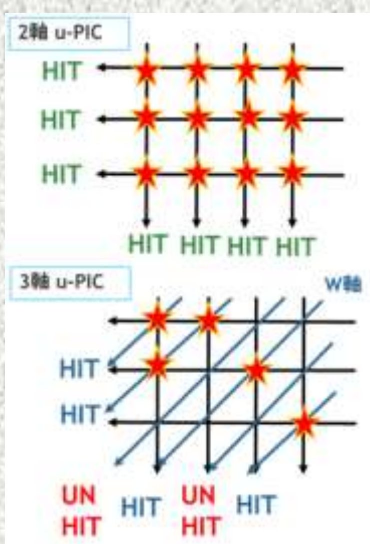


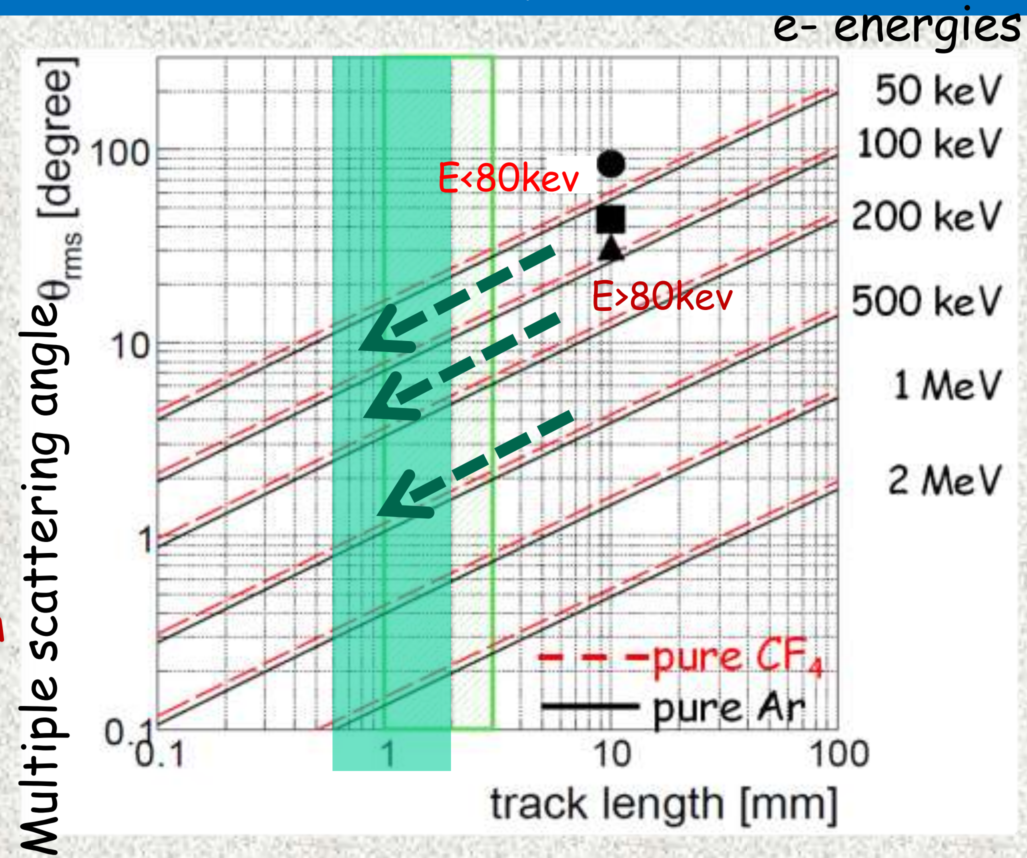
U,V,X electrodes in TPC

Spline Fitting Between vertex to 0.5cm



Real hits





Scattering Angle @ 1mm in gas
=> <1μm in Solid state

500keV Gamma Ee ~150keV SPD: 15° - 5°
>1MeV Gamma Ee ~300keV SPD: 10° - 2°

PSF(θ =1.2°) SPD 5° ARM 2° PSF(θ) θ -> 1°~2° **possible**

Case study: Detection of SNe up to 60Mpc

Publications of the Astronomical Society of Australia, 2012, 29, 447–465

SMILE-Satellite (~2mCrab @1MeV in 10^6sec、

PSF 1.5°@1MeV 90 Ia /5year (<60Mpc)

5σ @10^6s (10days observation:

Energy Resolution 3%@1MeV(FWHM)

3σ detection (10^2days) up to 110Mpc

SNe >~700/5year with Optical Tel.