True Imaging trigger for GRBs by Electron-Tracking Compton Camera (ETCC) with an well-defined PSF

CONTENTS
1. How to access 1 mCrab sources
2. MeV gamma-ray imaging by ETCC
3. Fluence trigger for GRBs
4. Future plan & Summary

Y. Mizumura\textsuperscript{1}, T. Tanimori\textsuperscript{1}, A. Takada\textsuperscript{1}, S. Iwaki\textsuperscript{1}, T. Kishimoto\textsuperscript{1}, S. Komura\textsuperscript{1}, H. Kubo\textsuperscript{1}, Y. Matsuoka\textsuperscript{1}, T. Miyamoto, K. Miuchi\textsuperscript{2}, T. Mizumoto\textsuperscript{1}, K. Nakamura\textsuperscript{1}, M. Oda\textsuperscript{1}, J.D. Parker\textsuperscript{1}, T. Sawano\textsuperscript{3}, S. Sonoda\textsuperscript{1}, T. Takemura\textsuperscript{1}, D. Tomono\textsuperscript{1}

\textsuperscript{1) Dept. of Physics, Kyoto University, Japan, 2) Dept. of Physics, Kobe University, Japan, 3) Dept. of Physics, Kanazawa University, Japan}
How to reach 1 mCrab

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

\[
\text{Significance} \propto \frac{EA \cdot S}{\sqrt{EA \cdot (S + BG \cdot \theta^2)}}
\]

- Effective Area (EA) $> 2 \times 100$ cm$^2$
  - Possible!

- Good BG rejection $\rightarrow$ BG/(str) $\sim$ Cosmic diffuse gamma
  - Possible (only ETCC)!

- Point Spread Function (PSF) radius $\theta \sim 1^\circ$
  - PSF in Compton Camera is very ambiguous!

Solution is Fine Electron Tracking
**Imaging and Point Spread Function (PSF)**

**General Imaging** (measures $\theta$ and $\phi$)

Two directional angles

\[
\begin{align*}
  f(\theta, \phi) &= x \\
  g(\theta, \phi) &= y
\end{align*}
\]

**Compton Imaging** (measures only $\theta$ / both of $\theta$ and $\phi$)

Direction $(\theta, \phi)$

- **Imaging with only $\theta$**
  - PSF($\Theta \sim 20-40^\circ$)
  - $\Theta \sim \text{average of } \theta$

- **Imaging with $\theta$ and $\phi$**
  - (Fine 3D-electron tracking gives $\phi$)
  - PSF($\Theta \sim 1^\circ$)

If accuracies of $\theta$ and $\phi$ are similar to a few degrees, it enables a well-defined PSF with $\sim 1^\circ$.

True imaging (PSF($\sim 1^\circ$)) + wide FoV (>4str) enables a fluence trigger for GRB search.

Transformation

True imaging (PSF($\sim 1^\circ$)) + wide FoV (>4str) enables a fluence trigger for GRB search.
Electron-Tracking Compton Camera (ETCC) in SMILE-II

30cm-cubic Gaseous Time Projection Chamber --- tracking of recoil electron ---
SPD (Scatter Plane Deviation) + $dE/dx + \alpha$

Scintillator Array for scattered $\gamma$

Conventional method   Electron Tracking method

Improvement of Sensitivity
$dE/dx \times 3$
SPD $\times 3 \sim 4$
Total $\times 5 \sim 10$

SPD 90° (<80keV)
SPD 45° (>80keV)

no use of SPD   SPD ~200°   SPD ~100°

30cm cubic ETCC
Eff. Area of 1-20cm$^2$
- **PSF of Compton Camera** is determined by $\varphi$ (NOT by ARM).
- **PSF of ETCC** is determined by $\max\{\text{ARM, SPD}\}$.

### 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°)

**Spread on SPD-ARM plane**
- ARM: 5 deg.
- SPD: 100 deg.

**Simulation for better SPD (S/N = 1/100)**
- 2.5 degree (ETCC)
- 7.5 degree (ETCC)
- 12.5 degree (ETCC)

**Preliminary**

$\text{PSF}(\theta) = \frac{1}{2} \text{ gammas in the radius of } \theta$
Future Sensitivities by ETCC

Sensitivities are calculated simply from effective area and PSF with no use of MLEM.

- **SMILE-II (Balloon, in USA)**
  
  (30 cm)$^3$ ETCC with $\sim$1-4 cm$^2$
  
  Crab, Cyg X-1 at $>5\sigma$, +Polarization

- **SMILE-III (Balloon, in polars)**
  
  (40 cm)$^3$ ETCC $\times$2 = $\sim$80cm$^2$
  
  Deep Survey, GRB

- **SMILE-Satellite**: (50 cm)$^3$ ETCC $\times$ 4
  
  SMILE-II, III PSF(7$^\circ$)
  
  SMILE-Satellite PSF(1.2$^\circ$)

Assumed BG flux:

- SMILE-II, III: observed flux by SMILE-I
- SMILE-Satellite: 2x (Cosmic diffuse gamma)
Detection of GRB by “True Imaging”

ETCC improves fluence threshold about 10-100 times in Swift-band

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Swift Band</th>
<th>ETCC Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-150 keV</td>
<td>~5x10^-7</td>
<td>3-5x10^-6</td>
</tr>
<tr>
<td>0.5-5 MeV</td>
<td>1-5x10^-9</td>
<td>~1x10^-8</td>
</tr>
</tbody>
</table>

**Swift BAT**

For S-GRBs

Sensitivity for GRBs
- Satellite-ETCC: 250cm^2
- Trigger FoV = 4x4°
- $T_{\text{obs.}} \approx 10$ sec

BG (4x4°) $2\gamma \rightarrow 12\gamma > 8\sigma$
- $\Delta\theta < 0.5°$ (position accuracy)
- $S \approx 20\gamma \rightarrow 10^{-9}$ erg cm^{-2} s^{-1}

Fluence $\sim 10^{-8}$ erg cm^{-2}

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

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

D'Avanzo et al. (2014)
Fluence Trigger for standard long GRB


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\textsubscript{90}: 10-100 sec)

--> Fluence $\sim 10^{-8}$ erg cm\textsuperscript{-2}
(2-3 GRBs/year/str (z>10))
+ wide FoV >4 str

--> $\sim$10 GRBs/year (z >10)
200 GRBs/year (z > 5)

Energy band

50-300 keV --> 50 keV-10 MeV
more GRBs will be detected.
Ultra Long duration GRBs (POP-III)


Figure 6. Same as Figure 5, but for the EXIST (5–600 keV) case. The red dashed line represents the EXIST sensitivity $f_{\text{sen}} \sim 2.4 \times 10^{-10}$ 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.

Assumed $E_p - E_{\text{iso}}$ relation (Amati) --- $E_p \sim 120$ keV @ $z = 9$

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

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

But, Fluence $\sim 10^{-5}$ erg cm$^{-2}$ (Intense)

Satellite-ETCC: $S/\sqrt{N} > 5\sigma$

$10^3$ s; $S \sim 90 \gamma$ BG $200\gamma$ --- $4 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$

$10^5$ s; $S \sim 800 \gamma$ BG $2 \times 10^4 \gamma$ --- $4 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$
Exploring GRB astronomy by Balloon-SMILE

1. SMILE-II one-day flight(s) for Crab and Cyg X-1 (Anytime, OK)
2. Next plan, SMILE-III Long-duration flight with larger ETCCs
   - Polar region 14-50 days ($T_{\text{obs}} > 10^6$ sec)
   - 40 cm-cubic ETCC x2 modules (Eff. Area ~80 cm$^2$)

GRB Search in Long duration flight

- $10^6$ s --> $\sim 3 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ (+ FoV of 4 str) --> $\sim 1$ GRBs/day
- In addition, Polarization Modulation factor 0.6 at 130 keV in SPring-8
  - MDP $\sim 6\%$ for $10^{-6}$ erg cm$^{-2}$ s$^{-1}$ (2-3 GRBs/month)
  - $\sim 20\%$ for $10^{-7}$ erg cm$^{-2}$ s$^{-1}$ (~10 GRBs/month)

GRB detection in SMILE-III
Simulated by T. Sawano

Modulation Curve

Preliminary
Summary

◆ ETCC provides an **well-defined PSF** which reveals the way to reach 1 mCrab sensitivity without assuming the use of Optimization Algorithm.

◆ A good PSF gives a >10 times better significance than conventional Compton cameras with **efficient BG rejection ability** of dE/dx.

◆ Clear imaging with an **well-defined PSF** in sub-MeV band would enable a true Imaging Trigger (Fluence Trigger) for GRBs and provide changes to reach most distant GRBs of any type (Short, Long, and Ultra-long).

◆ **SMILE-III** (long-duration balloon) will surely certificate above ability of ETCC with measuring polarization of GRBs.