SMILE (Sub-meV & MeV gamma-ray Imaging  Loaded-on-ballooon Experiment) & ETCC-Satellite

SMILE Project
Electron Tracking Compton Camera (ETCC)

2006 SMILE-I
10cm cubic ETCC

SM2+ 2018
30cm ETCC

Contents
- What is ETCC?
- SIMLE2+ balloon Exp.
- Results
- Next and future perspectives
- Summary

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8th/Jan./2020@AAS 2020 Honolulu
Electron Tracking Compton Camera

--- tracking of recoil electron ---
Measuring all parameters of Compton process
1. true2D-PSF (8~15° @Half Power Radius) => Realization of proper imaging spectroscopy
2. dE/dx + kinematics using $\alpha$ (particle-ID)
3. FoV of .4sr, Energy 0.1~10MeV, No Veto!

30cm-cubic Gas Time Projection Chamber (TPC) + Scintillator Array for scattered $\gamma$

- Ar 2atm in TPC
  dE/E ~20%@30keV

GSO
dE/E ~12%@662keV

future
GSO; MPPC 8%
HR-GAGG 5%
CzT+HR-GAGG 3%

Low Energy Event
0.1-2MeV (1hit-event) 1-8MeV (2hits-event)

High Energy Event
H 2D-PSF (12°, 1.27MeV)
SMILE-2+ Balloon flight at Alice Springs (JAXA)

Proposed Targets: 511keV line, Crab (~5 sigma) Cosmic Diffuse gamma (CDG)

Observed Tracks in space
2arm Ar 30cm ~ 200µm thick SSD x3
Light Curve & Cosmic Diffuse gamma (CDG)

2/3 of events (<zenith 30°) are Cosmic Diffuse γ
1/3 are Atmospheric γ
Growth Curve gives same result.

We have ~10^5 events of CDG

Events (600-1000keV)

Direct CDG

Events 200-300keV (mostly atmosphere and scattered CDG)
Detection of Galactic Diffuse Gamma (GDG) around Galactic Center

Source region 9.000000-11.500000

Gamma ray spectrum

Galactic coordinates

- ON
- OFF
- Residual (ON-OFF)
Comparison of significance with other observations

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Efficiency Area</th>
<th>ΔE/E</th>
<th>Normalized Sensitivity to SPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPI</td>
<td>75 cm²</td>
<td>&lt;1%</td>
<td>1 Coded Mask with Veto</td>
</tr>
<tr>
<td>SM2+</td>
<td>1 cm²</td>
<td>13%</td>
<td>100—200 × ETCC with no-veto</td>
</tr>
</tbody>
</table>
First real MeV $\gamma$ sky map $<1$MeV

ON data: simple count map $<1$MeV

OFF sky model ($=CGB +$ atmospheric+instrumental)

- Simple Detection of Crab by ON-OFF with $>5\sigma$ (4hrs, zenith 45-60$^\circ$) as expected in proposal
- Halo-like emission around GC over 30$^\circ$ radius

Raw Photon Flux of Crab $<\text{Radius} 20^\circ$

4hrs, zenith 45-60$^\circ$

~210 events in low energy region $<3$MeV

100keV 1000keV

10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} photons/keV
Spectrum of Galactic diffuse $\gamma$ in 0.2-10 MeV

High energy event count spectrum (Raw)

- Obtained spectra may still include the effects of scattering (of several 10%) => uncertainty of ~50% for Photon fluxes
- Anyway GC is very bright from the enhancement in Light-curve, and simultaneously observed with 511keV and Crab
How to reach to sub-m Crab

S: signal   EA: Effective Area   BG: Backgrounds
θ_c: Half Power Radius (HPR) as PSF

Significance $\propto \frac{EA \cdot S}{\sqrt{EA \cdot BG}}$

- Effective Area $\sim 200 \text{ cm}^2$ @1MeV: gas (3atm CF$_4$) and Si in <1m$^3$ cub.

- Minimum Back Ground $\Rightarrow$
  Same as Cosmic MeV background
  $\Rightarrow$ We achieved!

- PSF $\theta$(HPR) = 1~2$^\circ$ is needed!!
  $\Rightarrow$ fine 3D-tracking of a recoile electron is inevitable
  (mm sampling in gas, sub-$\mu$m sampling in Si) Key technology

Celestial MeV gamma is essentially rich; $\sim$1000 times of GeV gammas,
Then, if proper 2D-PSF of $\sim$2$^\circ$ and complete BG rejection were realized, we need a relatively small detector to go beyond 1m Crab
Expected Sensitivity based on well-defined PSF

SMILE3: long duration balloon (more one month) within 4~5 years
30cm cubic ETCC, CF4 3atm,
Effective Area 10~20cm² PSF <5°
Expected data 1000 times of SM2+

ETCC-Satellite 50cm-cubic ETCC (CF₄ 3atm) with >5RL Scinti. x 4 modules
Effective Area ~200cm²@1MeV and PSF:HPR<2°

Next & Future Plans

For Continuum $\gamma$ ($10^6$ sec)

SMILE-3
SMILE-2+
SMILE-2
satellite

$T_{\text{obs}} = 10^6 \text{ s}$
$\Delta E = E$

20Mpc SN in SM3+
~1 SNe/year
60Mpc SN in ETCC-ST
~20 Se/year

New MeV gamma Astronomy beyond 1mCrab
Summary

- ETCC provides true Imaging Spectroscopic Observation same as general astronomical telescopes, and reveals the reliable way to reach to sub mCrab
- Background is reduced less than CDG as proposed.
- Crab and 511keV line were detected with $\sim5\sigma$ as proposed with no use of optimization methods like MLEM
- Galactic Center region ($>10\sigma$) is unexpectedly bright!!
- CDG spectrum with high statistics will be soon opened.
- Next Balloon SMILE-3 $=>10$ times better sensitivity than COMPTEL: $\sim\times1000$ data ($10^8\gamma$) of SM2 within $\sim5$ years
- ETCC-Satellite will surely reach to the sub-mCrab sky.
  MeV $\gamma$ sky will be most clean and rich (1000 times of GeV gamma sky.) in near future!!

Collaborators are very welcome!
Members of SMILE Projects

- SMILE2+ Project
  Toru Tanimori, Atushi Takada, Yoshitaka Mizumura, Taito Takemura, Kei Yoshikawa, Yuta Nakamura, Mitsuru Abe, Tetsuya Mizumoto, Shinya Sonoda, Hidetoshi Kubo, Shotaro Komura, Tetsuro Kishimoto, Tomoyuki Taniguchi, Ken Onozaka, Kaname Saito, Shunsuke Kurosawa\(^A\), Kentaro Miuchi\(^B\), Kenji Hamaguchi\(^C\), Tatsuya Sawano\(^D\), Masayoshi Kozai\(^E\), Yasuhiro Syoji\(^F\)
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- ETCC-Satellite (Astro 2020 APC White Paper)
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  Co-authors:
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Thank you for your attention!
MeV γ astronomy suffers from two major problems:

1. Incomplete imaging method (Conventional Compton; CC)
   **Imaging spectroscopy is impossible**
2. Huge background by collision of cosmic-ray and instruments

→ No instruments of CC measured celestial source flux quantitatively after COMPTEL

COMPTEL 1d-auglar resolution (RMS) ~1.5° 32 sources (9 yrs)
Deconvolution image!!

>1 GeV

Fermi F. Acero + (2015)
~3000 objects/4 years

Fermi low energy (30-100 MeV) 198 sources 2D-PSF (3°-12°) 9 yrs.

Fine Tracking is inevitable

γs from different directions A and B are mixed

Intensity is not conserved!!
Estimation of BG & Cosmic Diffuse Gamma (CDG)

Atmospheric gamma
~1/3 <zenith 30°
2/3 of events are Cosmic Diffuse γ

- Minimum Back Ground was achieved!!
- We have clean several $10^4$ DDG =>

CDG +BG Zenith distribution
Events (>560keV)
normalized to Eve >560keV
(mostly scattered CDG)

Growth curve

Intensity of gamma
(count/sec/cm²/str/keV)

Atmospheric depth (g/cm²)

- Atmospheric
- Ballodon rising
- Cosmic

CDG spectra
COMPTEL 2000 unpublished

Direct CDG

Events <560keV