Dec. 16-18, 2025.
MeV-PeV Frontiers: New Perspectives in Gamma-Ray Astronomy and Particle Acceleration

Exploring the MeV Gamma-Ray Sky: Results from SMILE-2+ and the SMILE-3 Project

SMILE-3
Exploring the MeV Sky

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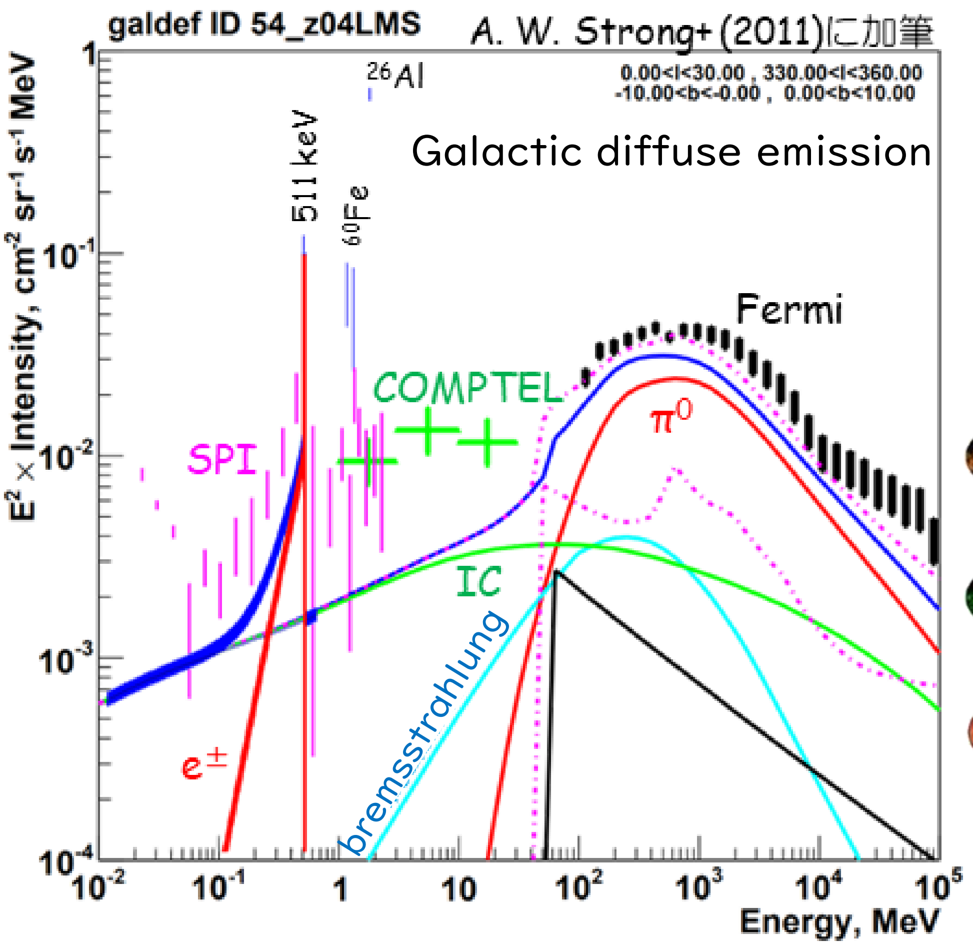
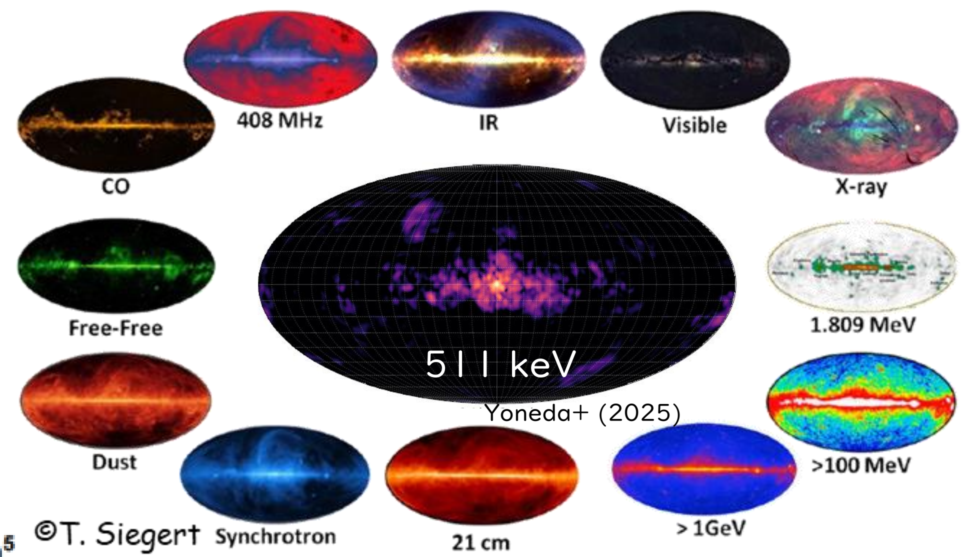
Galactic diffuse MeV gamma rays

Extended unidentified gamma-ray radiations around G.C.

- Continuum in MeV band (0.1-100 MeV)
  - 1 order of magnitude above the expected IC emission
  - No identified population of sources can explain the emission



- Electron-Positron annihilation
  - The origin of the positions is still unclear
  - The morphology differs from other wavelengths



Galactic diffuse MeV gamma rays

What are the possible origin candidates, and what spatial distribution is expected for each?

Possible origins	Expected spatial distribution	Key issues
Cosmic-ray interaction with interstellar matter	Distributed along the Galactic plane	✓ One order of magnitude above the expected IC emission. ✓ It requires the known Galactic parameters to be incorrect.
Many unresolved and unidentified sources	Distributed along the Galactic plane	✓ No source class bright only in the MeV band has been found. ✓ It requires the existence of an unknown class of sources.
Dark Matter	Proportional to $(\text{mass density})^2$	✓ Gamma rays may be generated through the annihilation or decay of low-mass WIMPs. ✓ It may lead to the discovery of DM.
Primordial Black Holes	Proportional to mass density	✓ A PBH with mass of $\sim 10^{16-17}$ g would emit gamma rays via Hawking radiation. ✓ It may lead to the discovery of PBH.

Galactic diffuse MeV gamma rays

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Da		✓ Gamma rays may be generated … f
Pri Black Holes	mass density	… g radiation. ✓ It may lead to the discovery of PBH.

MeV gamma-ray observations not only fill the MeV gap in multi-wavelength coverage but also may provide complementary information for advancing our understanding of Galactic PeVatrons.

Galactic diffuse MeV gamma rays

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Da		✓ Gamma rays may be generated … f
Pri… Blo…		… g ✓ It may lead to the discovery of PBH.

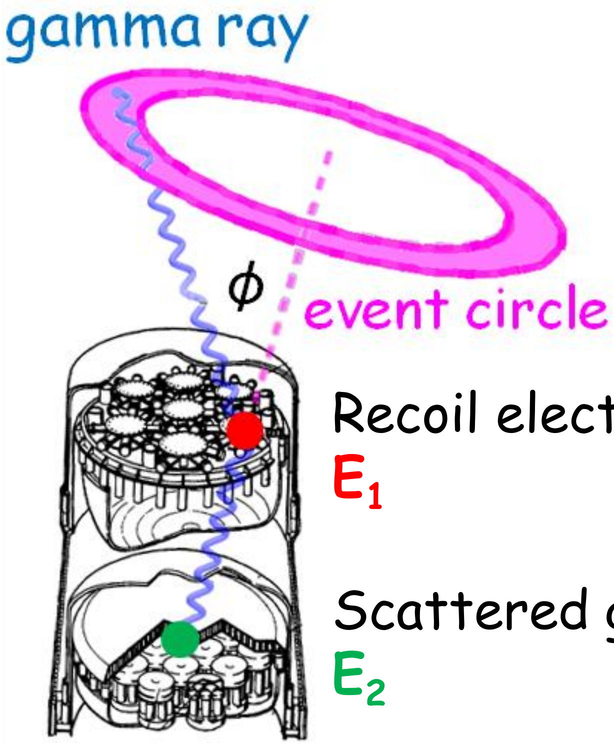
To uncover the origin of the diffuse MeV gamma rays in the Galaxy, both

- Detailed spectral information
- Wide-area (or all-sky) intensity map

are required.

Difficulty of MeV imaging

Compton scattering dominates in MeV cross section

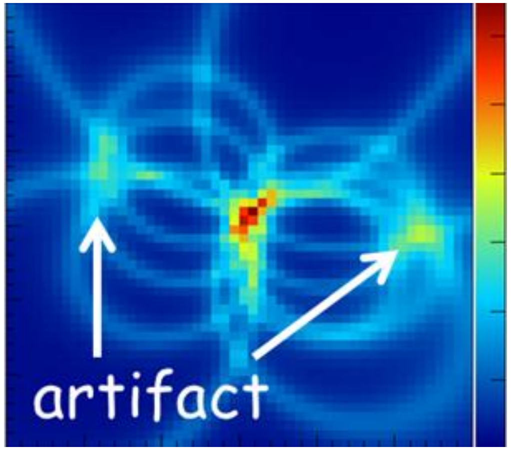


Recoil electron
E_1

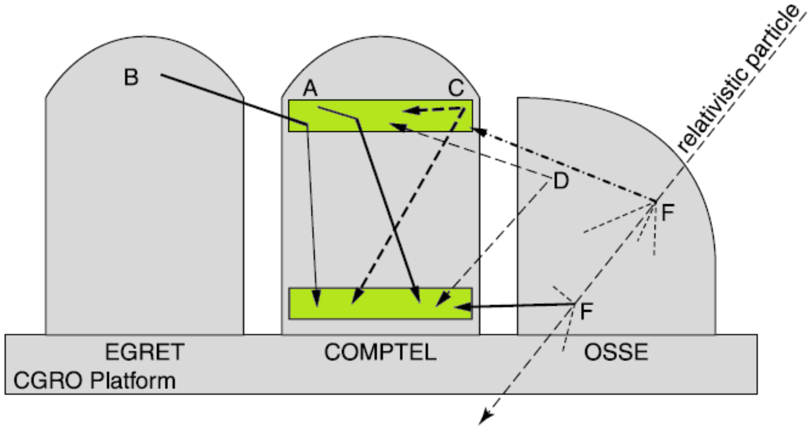
Scattered gamma
E_2

Principle of Compton Imager

$$\cos\phi = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)$$



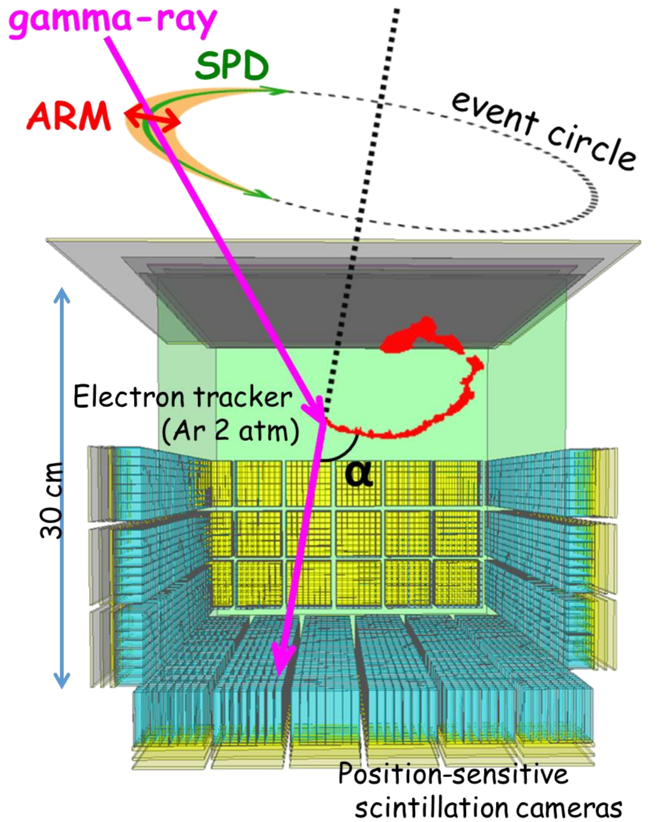
Unclearness
&
Artifacts

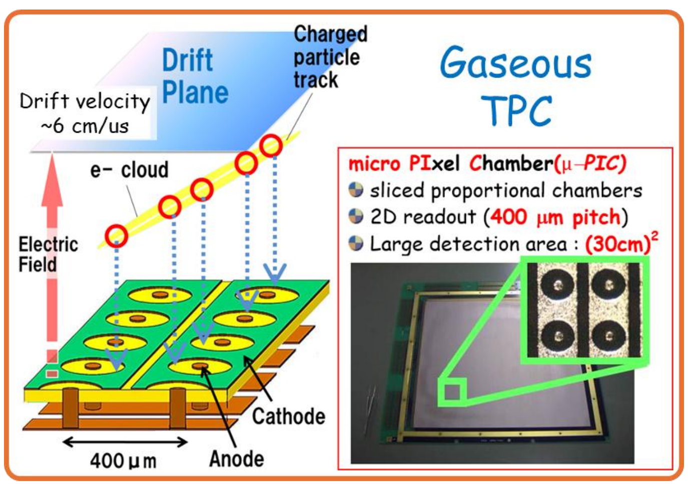


- Improvement of imaging
- Background suppression

are two big tasks in MeV

Electron-Tracking Compton Camera





Scatterer: Gaseous TPC

- ✓ Energy and detailed track information of the recoil electron

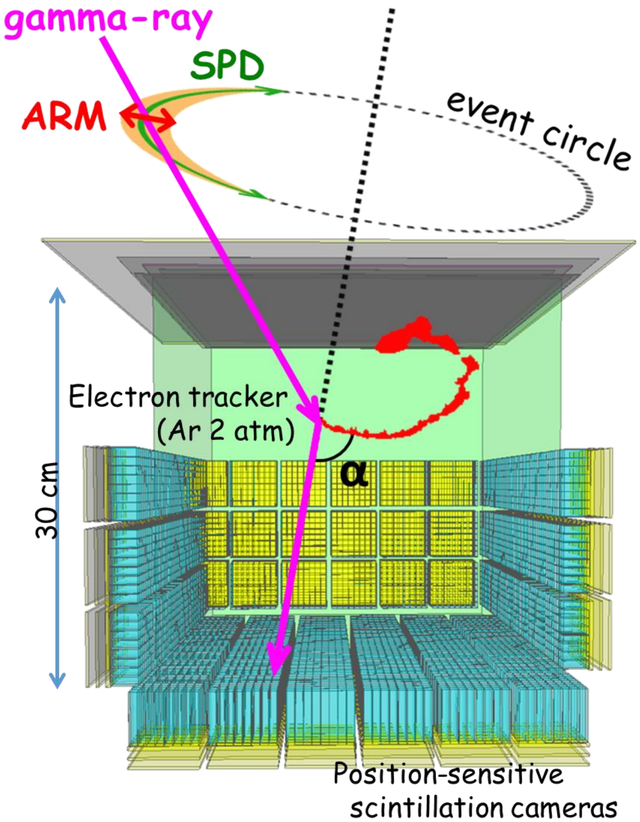
Absorber: Position-sensitive Scinti.

- ✓ Energy and position of the scattered gamma-ray

Three additional parameters compare to Compton camera

1. **SPD**, Direction of scattering plane
   -> Event by event arrival direction
2. **dE/dx**, Energy deposit rate of particle
   -> BG rejection by particle ID
3. ***α***, Angle between scattered gamma and recoil electron
   -> BG rejection by kinematics test

Electron-Tracking Compton Camera



Scatterer: Gaseous TPC

- ✓ Energy and detailed track information of the recoil electron

Absorber: Position-sensitive Scinti.

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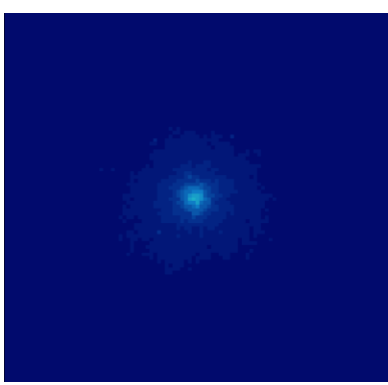
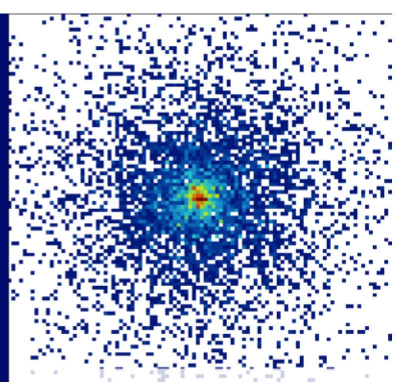
ETCC provides a well-defined point spread function (PSF) and powerful background-rejection capability with a wide field of view.

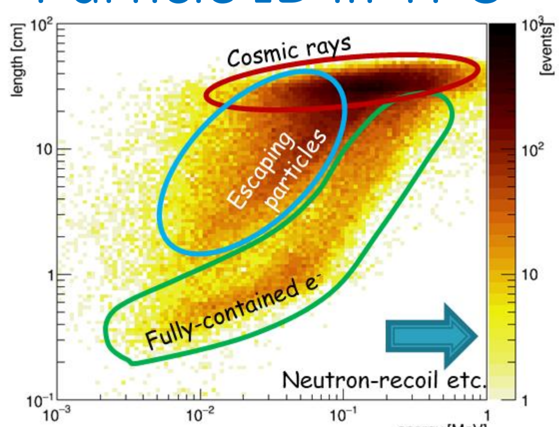


Conventional Compton camera

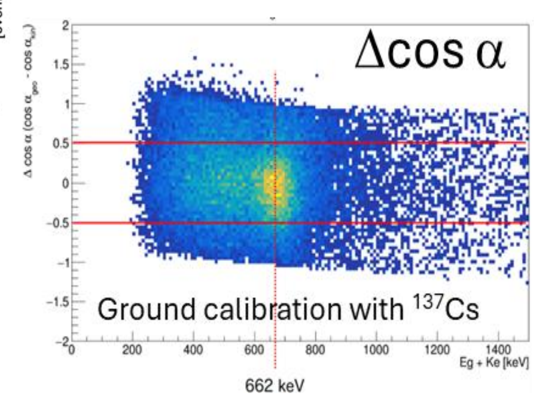


Gamma-ray image by ETCC

Particle ID in TPC

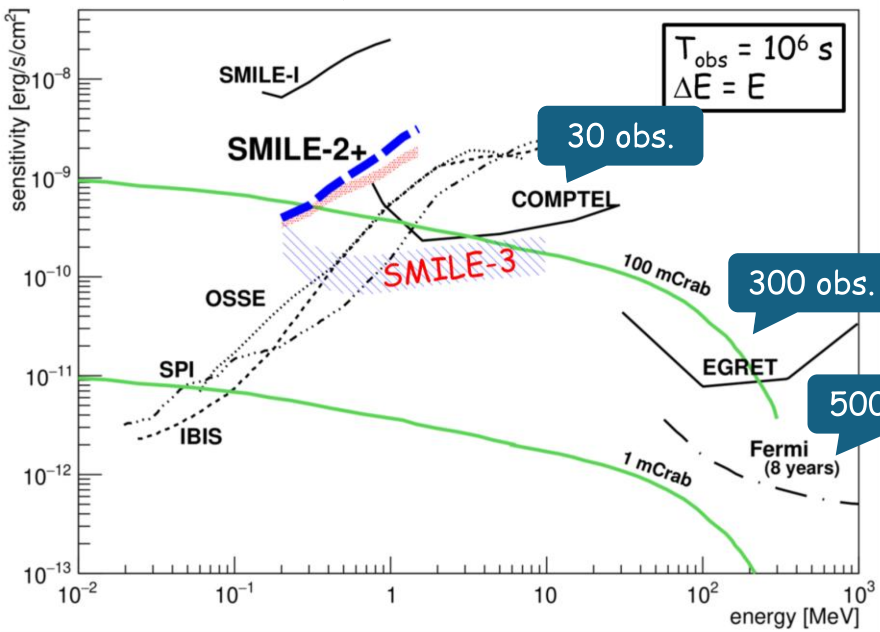


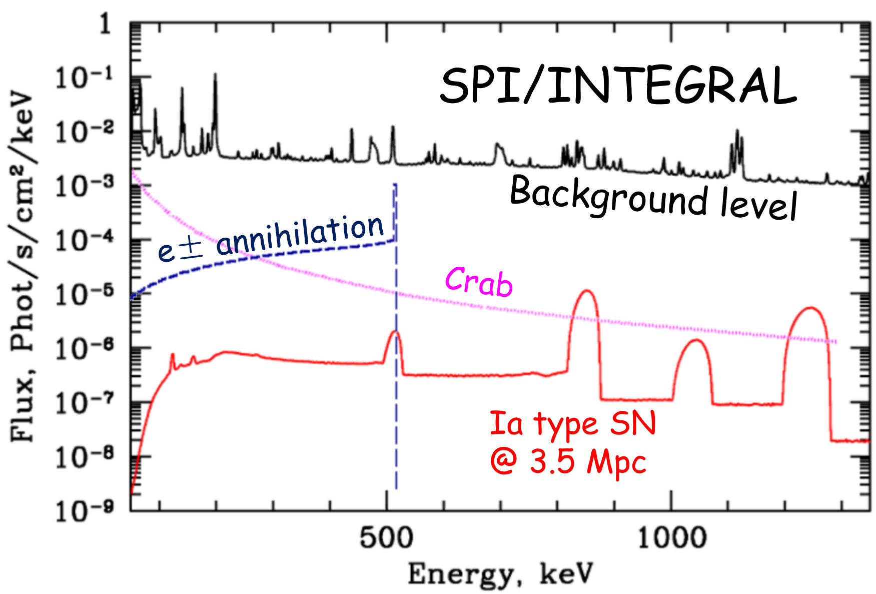
Kinematic test



Observational challenges in MeV sky

Sensitivity in keV to GeV band





Challenges:

Unclear imaging and artifacts

⇒ Severe contamination from out of region of interest

Huge amount of background

⇒ S/N ~ 1/1000 (in case of a brightest source)

ETCC is well suited to address both of these challenges.

We are developing the ETCC and conducting the SMILE project to explore the MeV sky.

Sub-MeV/MeV gamma-ray Imaging Loaded-on-balloon Experiments

2000

SMILE-I (2006, Sanriku, JPN, 4 hours)

Xe+Ar 1 atm, 10 cm cubic

- Demonstration of an ETCC operated at high altitude
- Successfully detection of extragalactic diffuse and atmospheric gamma-rays

A. Takada+, ApJ (2011); A. Takada+, JPSJ (2009)

2010

SMILE-2+ (2018, Alice Springs, AUS, 26 hours)

Ar 2 atm, 30 cm cubic

- Demonstration of observations of celestial objects
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A. Takada+, ApJ (2022); T. Ikeda+, astro-ph:2509.15851

2020

- Precise BG measurement at high altitude

T. Ikeda+, PRD (2023)

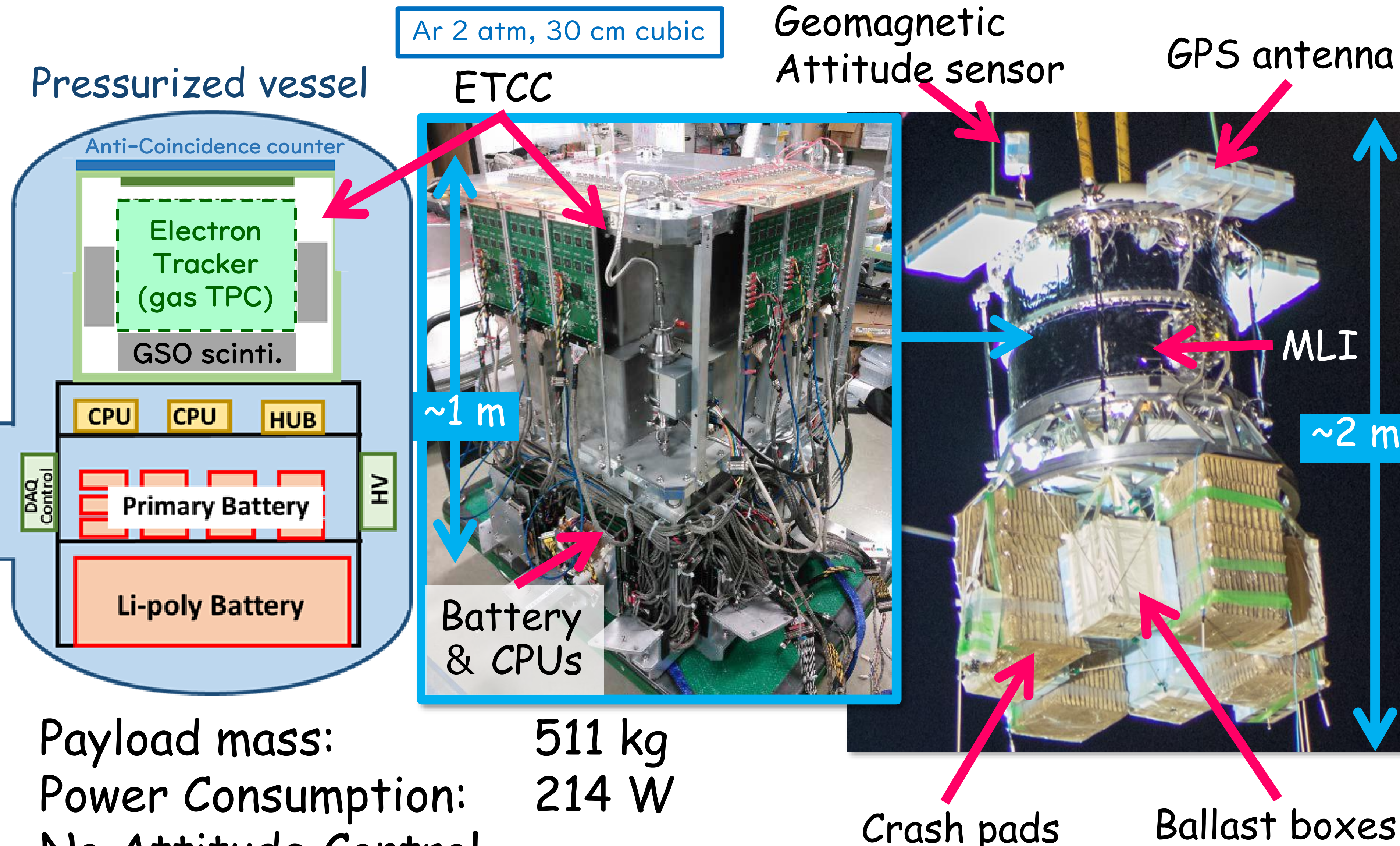
SMILE-3 (2028, Alice Springs, AUS)

CF_4 3 atm, 30 cm cubic

- First science observation
- with a few Long Duration Balloons

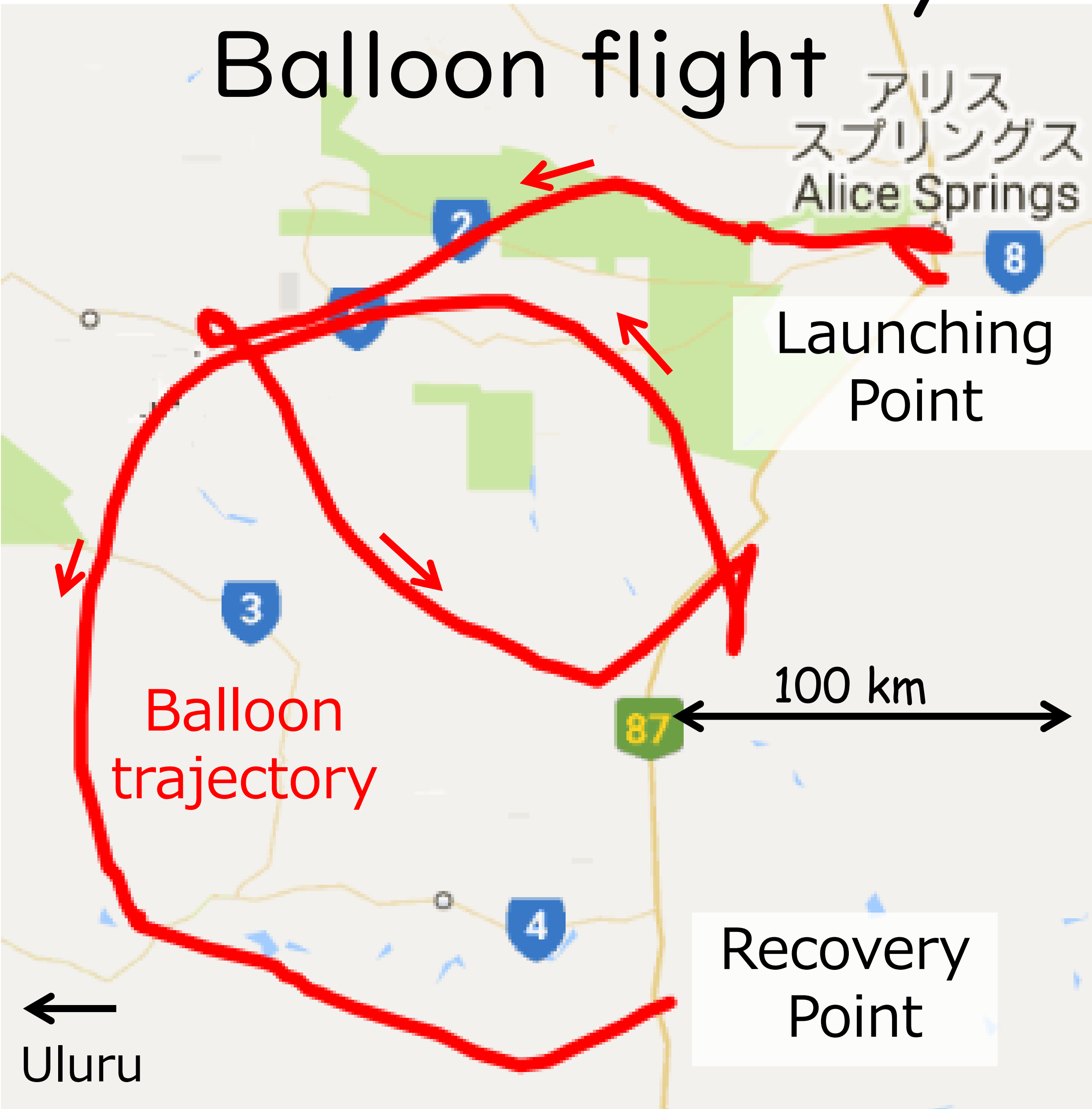
Satellite observatory for all-sky survey

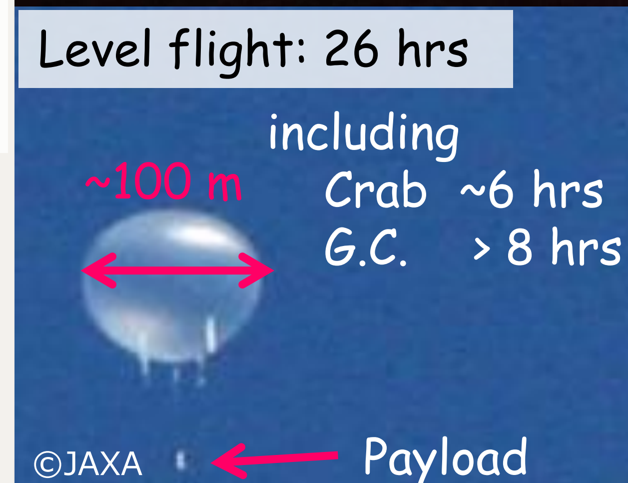
SMILE-2+ balloon payload



Payload mass: 511 kg
Power Consumption: 214 W
No Attitude Control
(Attitude sensor: ~5°)

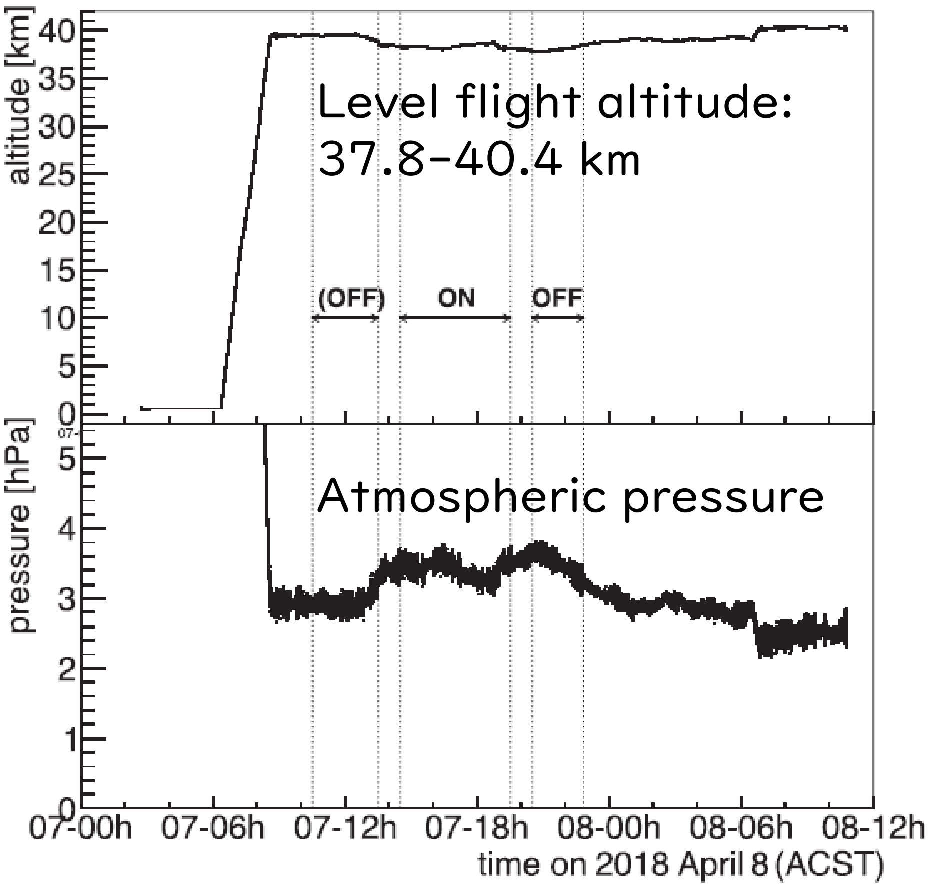
SMILE-2+ one-day Balloon flight



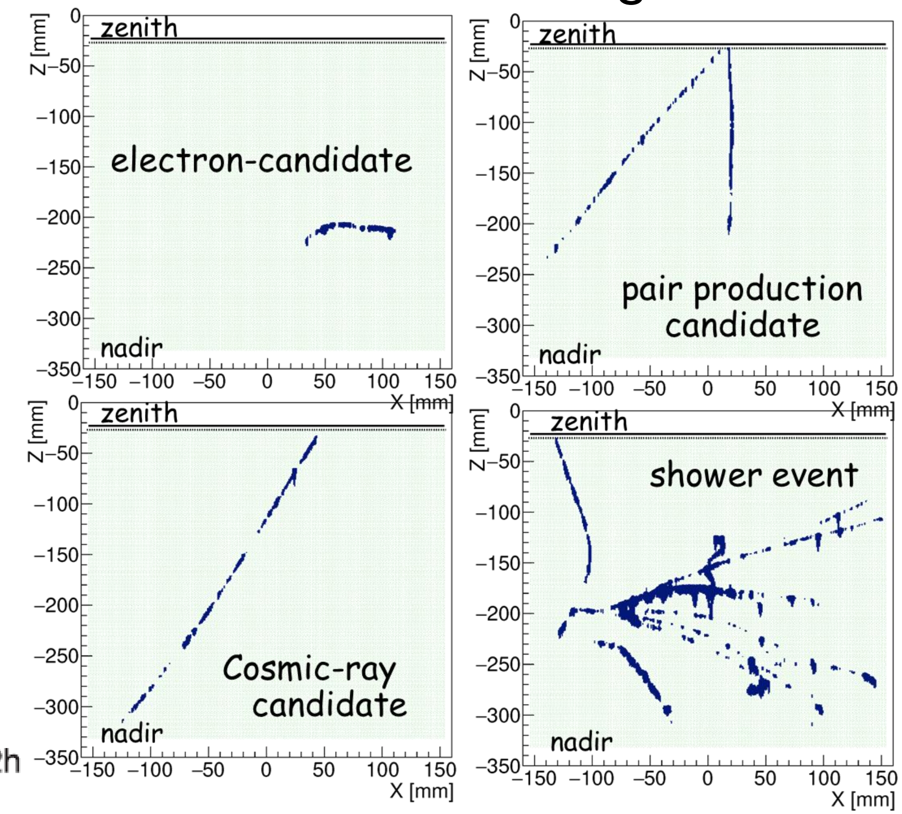


Time averaged cutoff rigidity: 8.2 ± 0.4 GV

SMILE-2+: Level flight condition

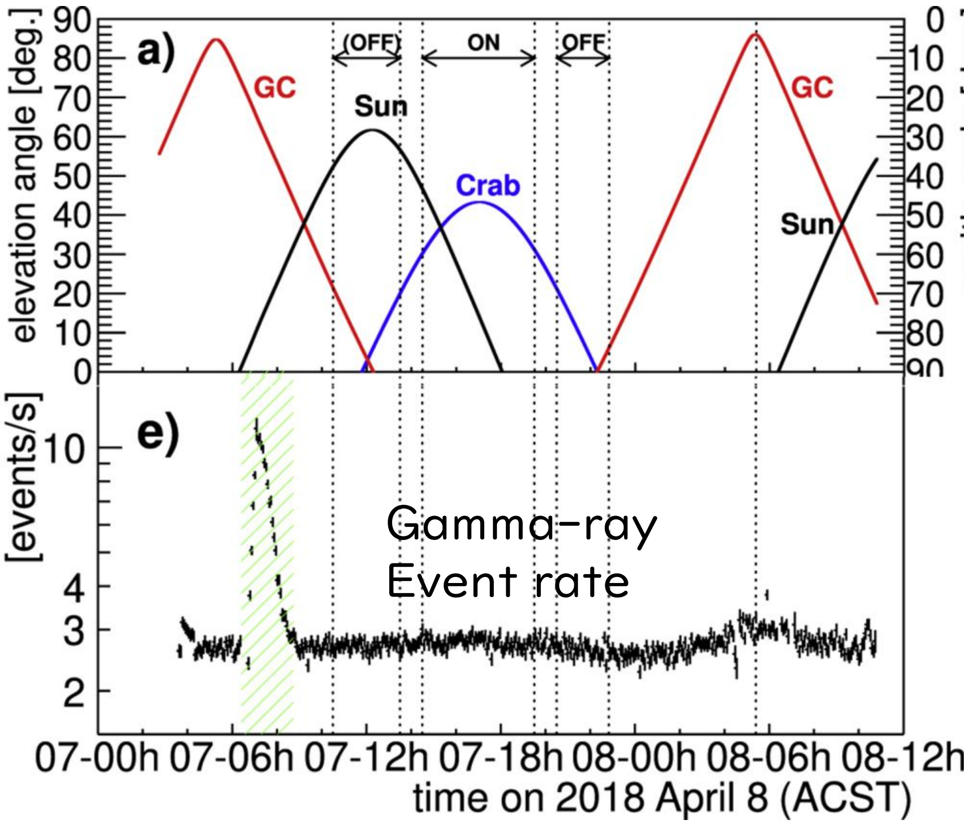


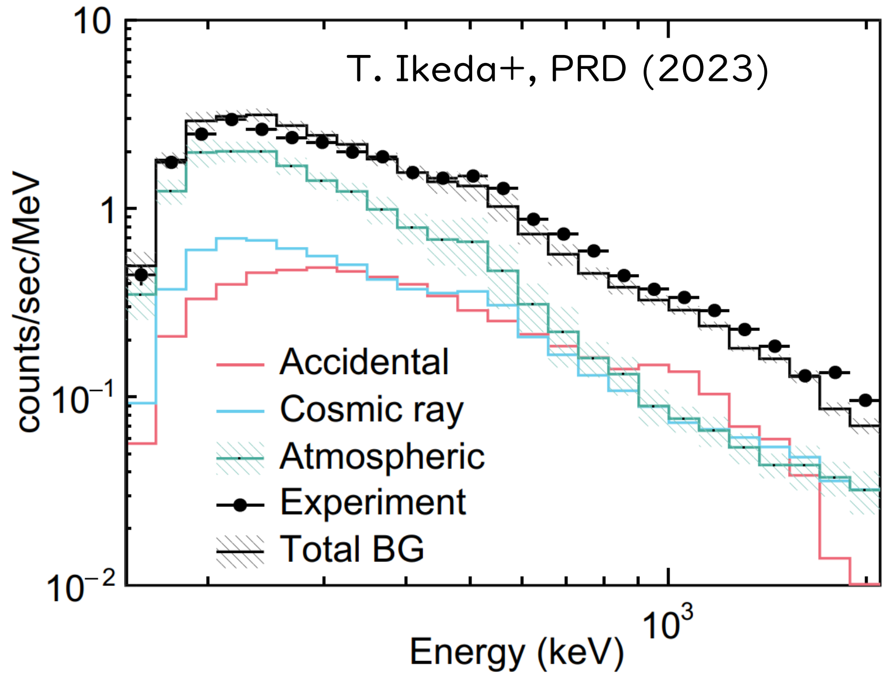
Obtained tracks at high altitude



- ✓ A 26-hour level flight was achieved, during which the flight altitude remained between 37.8–40.4 km.
- ✓ The track data obtained from the TPC during the level flight were of good quality, demonstrating that particles can be clearly identified.

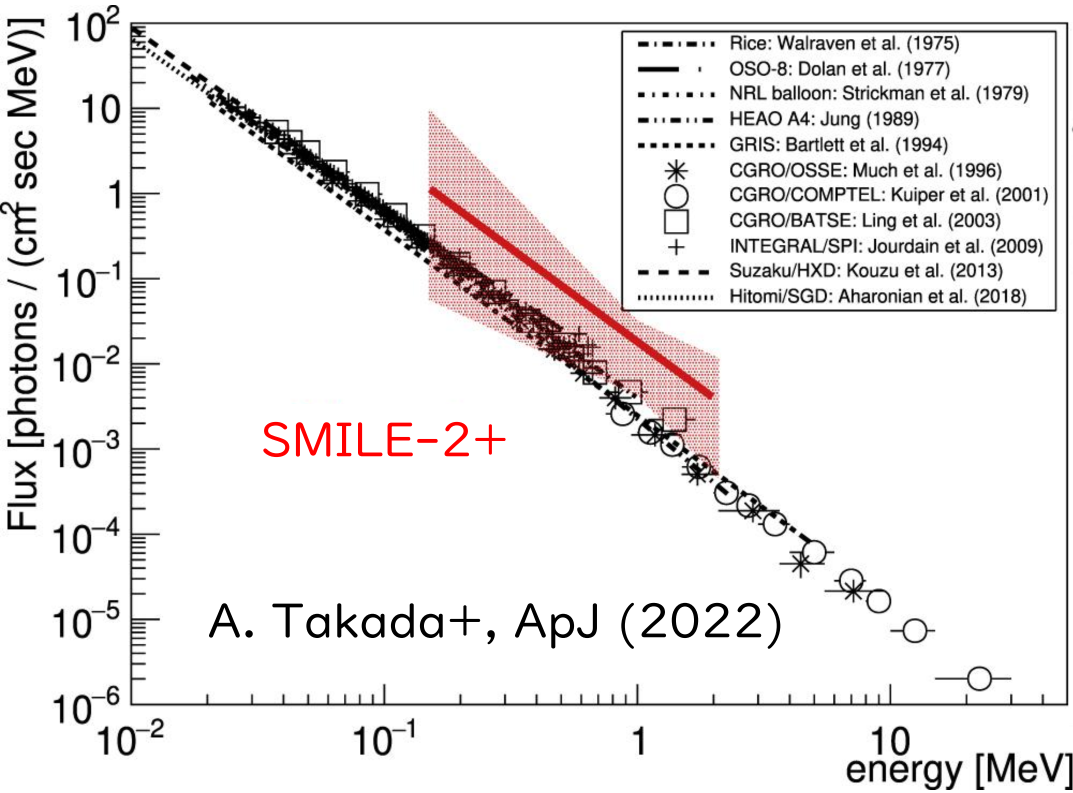
SMILE-2+: Light curve and BG spectrum

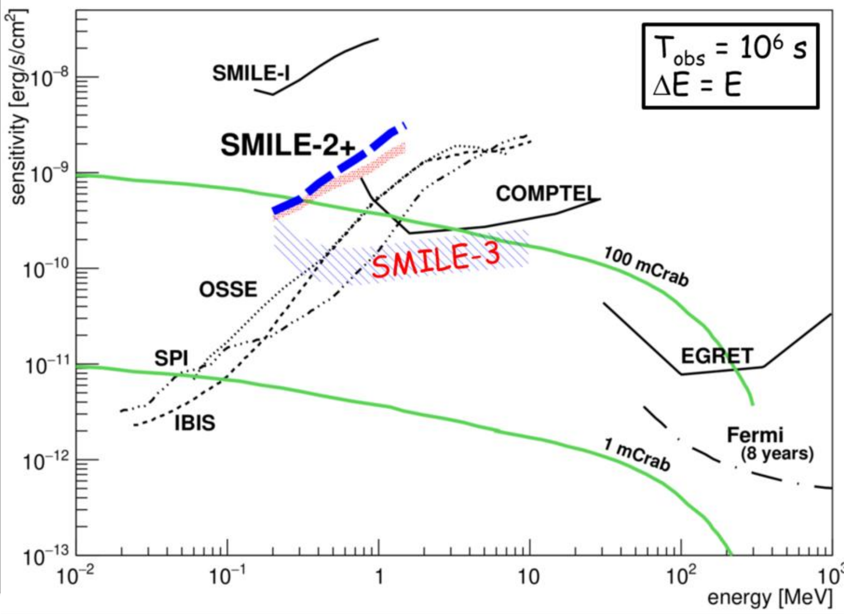




- ✓ The level flight included the periods when the Crab and the G.C. were at culmination.
- ✓ Detected events were explained by the summation of atmospheric/cosmic diffuse gamma-rays, BG events produced by cosmic-rays, and chance coincidence.
- ✓ LC shows a slight excess at the culmination of the G.C.

SMILE-2+: Results of the Crab



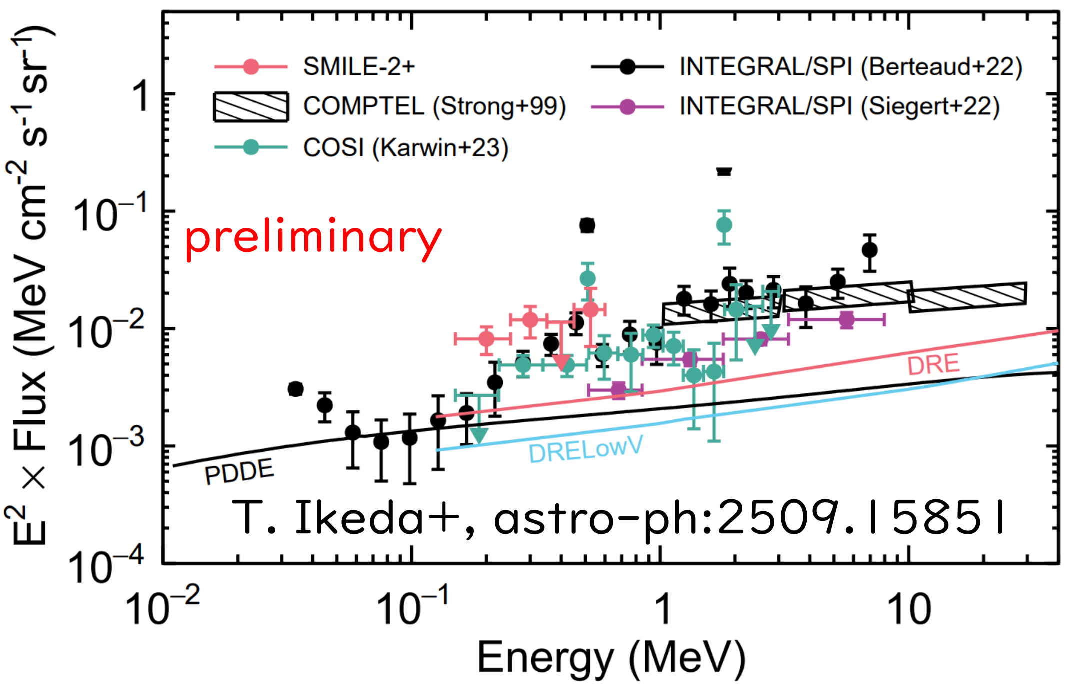


- ✓ 4.0 sigma detection in 0.15-2.1 MeV
- ✓ Crab flux obtained by SMILE-2+ was consistent with the results of previous experiments.
- ✓ The achieved detection sensitivity of SMILE-2+ was nearly equal to the designed sensitivity.

A demonstration of observations of celestial objects has been achieved.

SMILE-2+: Results of the G.C.

preliminary



Region of Interest

	Galactic Longitude | l |	Galactic Latitude | b |
SMILE-2+	< 33°	< 33°
COSI	< 65°	< 45°
INTEGRAL/SPI	< 47.5°	< 47.5°

- ✓ Significant detection of the excess from the G.C. region.
- ✓ The flux remains higher even when compared with several IC emission models.
- ✓ The flux tends to exceed that of INTEGRAL, but the statistical difference is limited to about 2σ.

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SMILE-3 (2028, Alice Springs, AUS)

CF_4 3 atm, 30 cm cubic

- First science observation
- with a few Long Duration Balloons

Satellite observatory for all-sky survey

SMILE-3: Scientific targets

Galactic Center region

MeV emission mechanism is still unclear.
Spatial distribution in MeV is important to resolve.

Continuum Components

- ✓ Integration of unresolved celestial objects?
- ✓ Primordial black holes?
- ✓ Annihilation of dark matters?

$e^{\pm}$ annihilation line

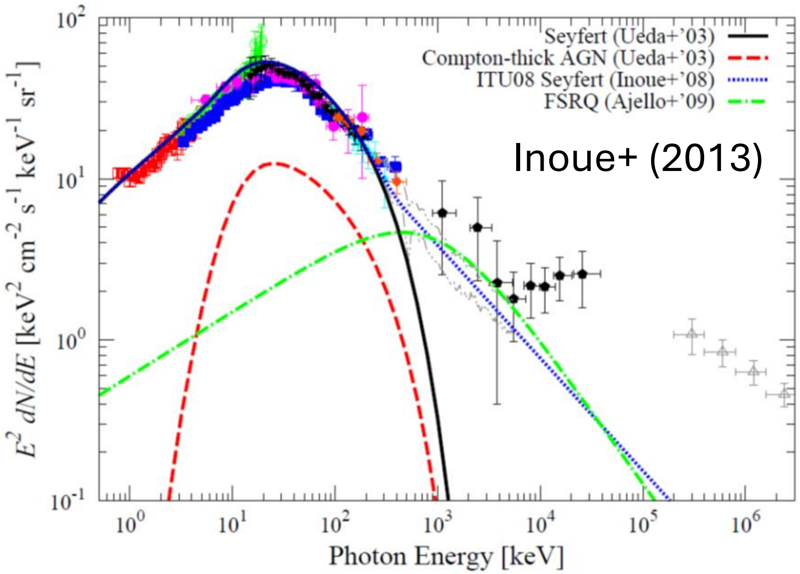
- ✓ The origin and propagation of positrons
- ✓ Annihilation of dark matters?

Crab nebula

The Crab nebula is explained by the synchrotron radiation in MeV. The shape of the spectrum suggests that electrons are being accelerated in two distinct regions.

SMILE-3: Scientific targets

Extragalactic diffuse gamma-ray



Approximately uniform and isotropic emission has also been detected in MeV band, but its origin remains unknown.

- Seyfert galaxies
- Flat Spectrum Radio Quasars
- Ia supernovae in the far galaxies
- annihilation of dark matter or evaporation of PBH in near galaxies

The spectrum and the anisotropy are the key to identifying the origins.

Centaurus A

The observed spectrum in MeV band has a large uncertainty, and its spectral structure is not smoothly connected between X-ray and GeV bands. If SMILE-3 achieves a long-duration observation exceeding 10^5 s, it will allow us to obtain the energy spectrum of Cen A in the energy range of 0.2-5 MeV.

SMILE-3: Performance requirements

Balloon-flight opportunities provided by JAXA

- ✓ The next one-day balloon-flight opportunity is expected to be offered in Australia as early as 2028.
- ✓ If the mass of SMILE-3 gondola can be kept to ~500 kg, it will be able to reach an altitude > 38 km using a 500,000 m^3 size balloon.

Performance requirements for the SMILE-3 ETCC

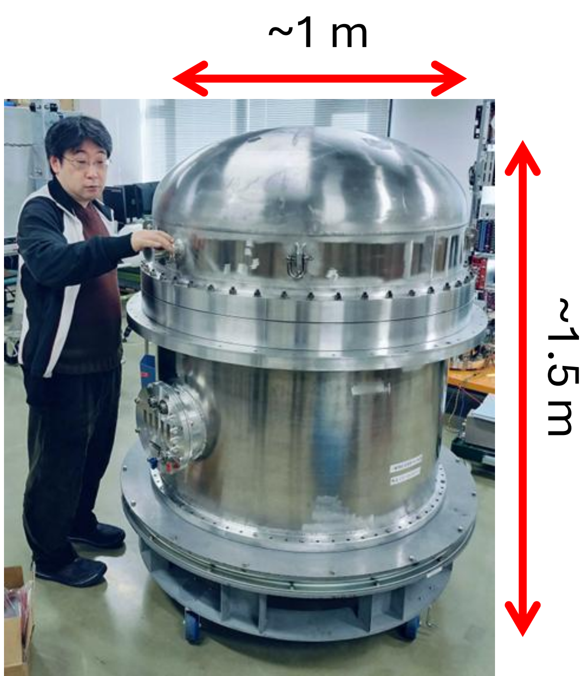
Assuming 38 km altitude and one-day flight in the next JAXA opportunities,

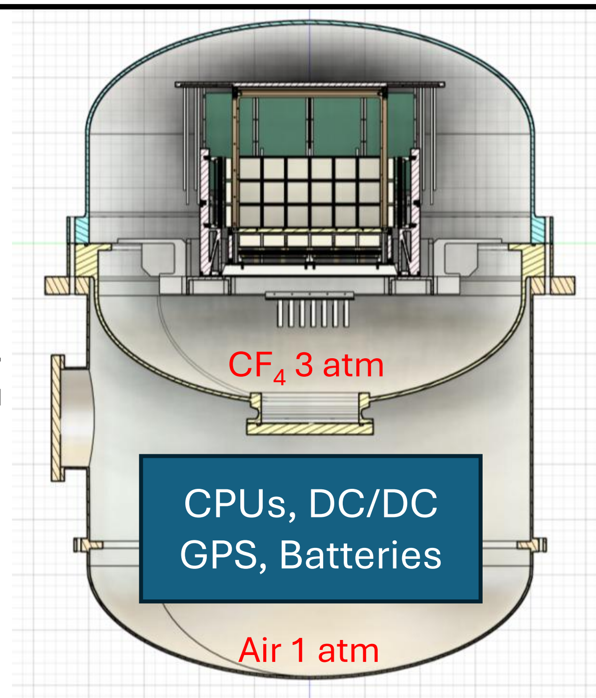
- ✓ An effective area of ~5 cm^2 @ 0.3 MeV
- ✓ A half power radius of <10 deg. @ 0.5 MeV

are required.

Enhancement from SMILE-2+ to SMILE-3

Enhancement goals		Method
Effective Area	×5	Gas in TPC (Ar 2atm → CF_4 3atm), & Remove one layer of the pressurized vessel to expose the TPC vessel
Energy Resolution	×1.5	Changes in the scintillator optics PMT ($\Delta E/E$ ~12%) → SiPM (~8%), & Readout pitch of TPC, & Track analysis using machine learning T. Ikeda+, 2021, PTEP
Angular Resolution	×3	
Energy Range	0.2 to 10 MeV (SMILE-2+: 0.2 to 2 MeV)	Expansion of the dynamic range of the optical readout circuit for scintillators





Mass estimation:

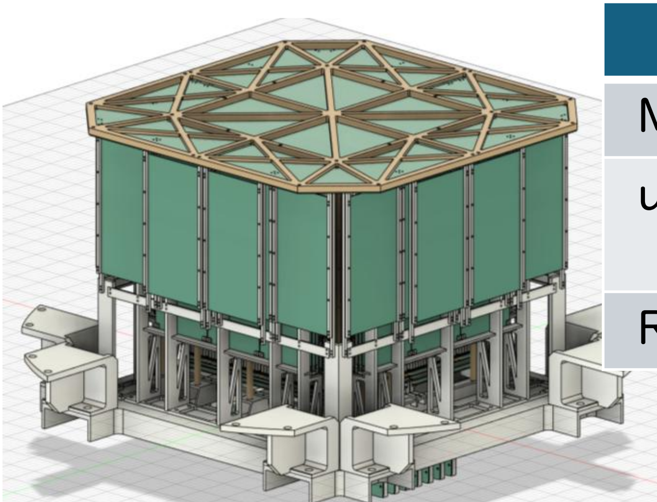
- ETCC 80 kg
- system part 100 kg
  (batteries are ~80 kg)
- Vessel 250 kg
- Gondola 70 kg

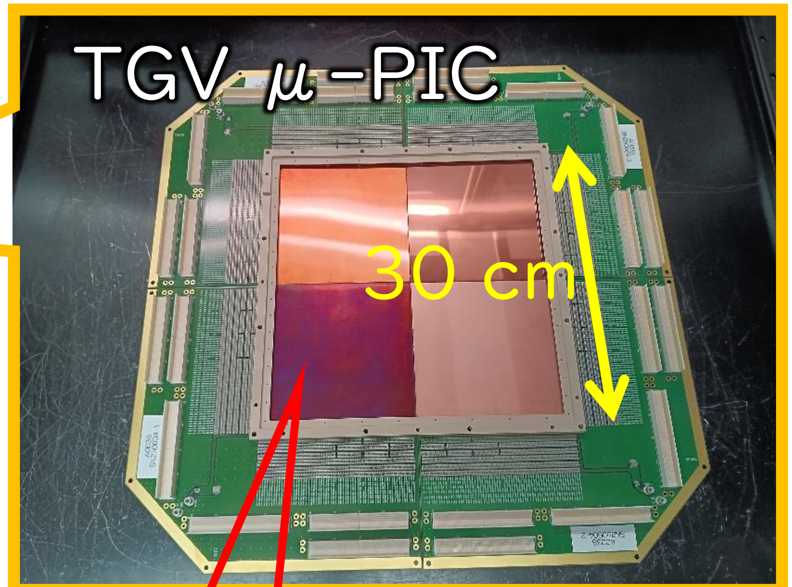
Total 500 kg

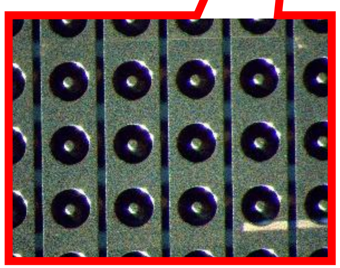
cf. SMILE-2+ 511 kg
(incl. telecom system)

SMILE-3: TPC

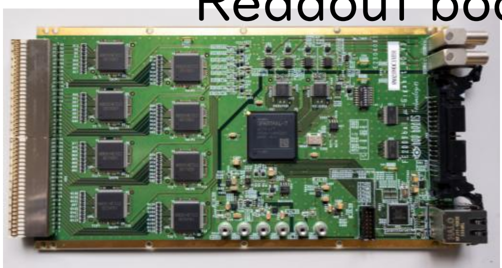
	SMILE-2+	SMILE-3
Main Gas	Ar 2 atm	CF_4 3 atm
u-PIC	Printed Circuit Board type	Through Glass Via type
Readout pitch	800 um	400 um







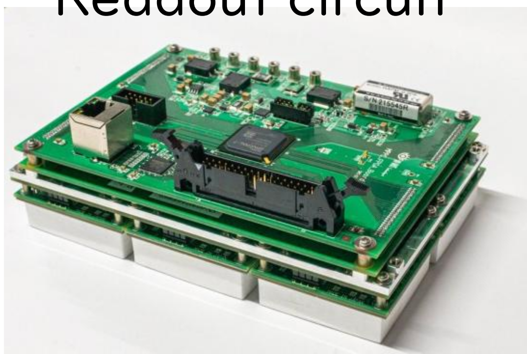
Readout board

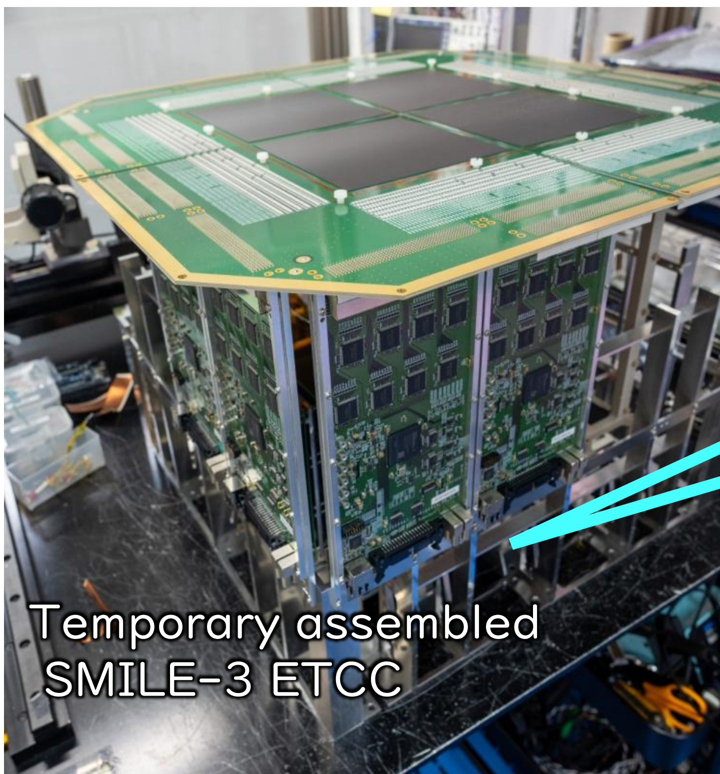


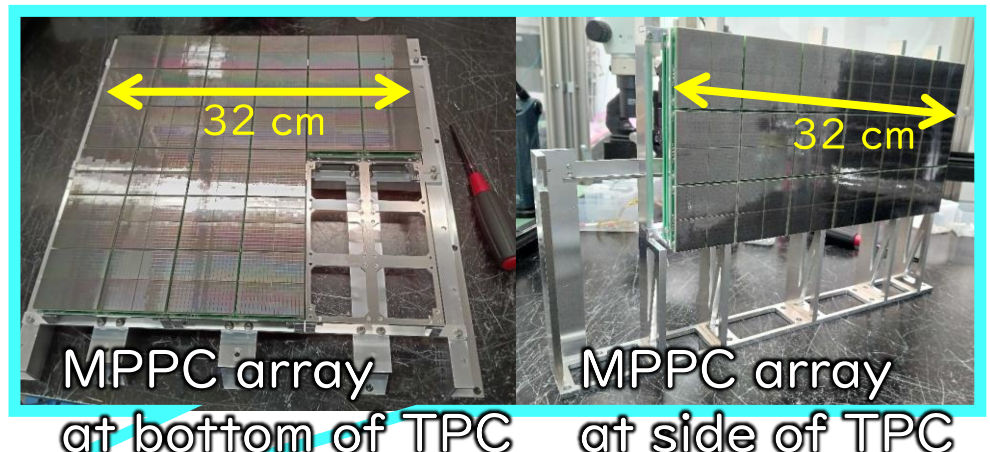
SMILE-3: Scintillators

	SMILE-2+	SMILE-3
Optical readout	Multi-anode PMTs	MPPC arrays
DAQ	Common start	Common stop
Amplifier	Single gain	Low/High gain (for dynamic range)

Readout circuit







GSO arrays

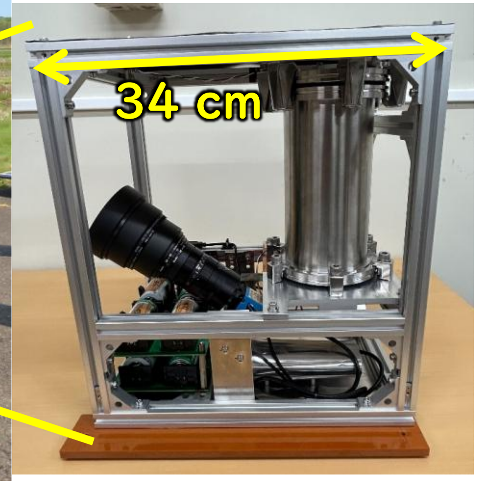
Bottom: $6\times6\times26$ mm^3/pix

Side: $6\times6\times13$ mm^3/pix

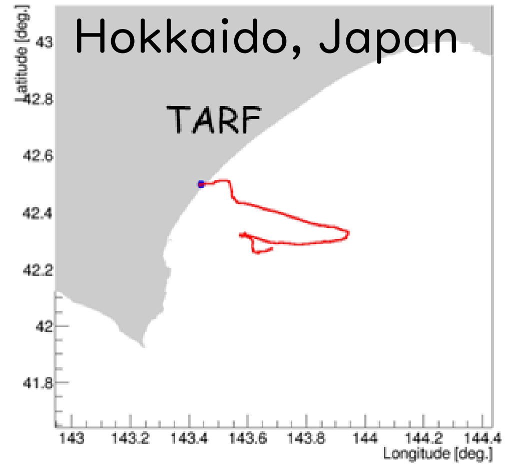
Preparation of sub-system

Testing of a Star Tracker (STT) system using a balloon piggyback

B25-03 gondola



SONY IMX264LLR-C
(19.2°x16.1°, 2448x2048 px)



Balloon trajectory of B25-03

- ✓ SMILE-3 ETCC attitude will be determined using STTs, an inertial sensor, and a GNSS compass.
- ✓ A prototype STT was flown in Hokkaido on June 20, 2025, to obtain star images for a demonstration.
- ✓ The test confirmed that the STT can detect 6.3-mag stars at ~40 km with 5-sigma significance.

SMILE-3: flight opportunity status

1-day flight at Australia in 2028 provided by JAXA

- ✓ The SMILE-3 application has been ranked as one of the leading candidates and has been ***tentatively selected*** by the JAXA balloon committee.

The feasibility of SMILE-3 has taken another step forward.

- ✓ The official selection has been postponed to around the autumn of 2026.

If any concerns are to be raised,…

- ✓ It remains possible that the balloon campaign could be further postponed due to various factors such as budget conditions at NASA.
  (because NASA contributes to the maintenance and management of the balloon launching station in Alice Springs, Australia.)

Summary

Key technologies for exploring the MeV sky: ETCC

- ✓ A well-defined point spread function (PSF)
- ✓ Powerful background-rejection capability
- ✓ A wide field of view.

Results from SMILE-2+ (2018, Australia)

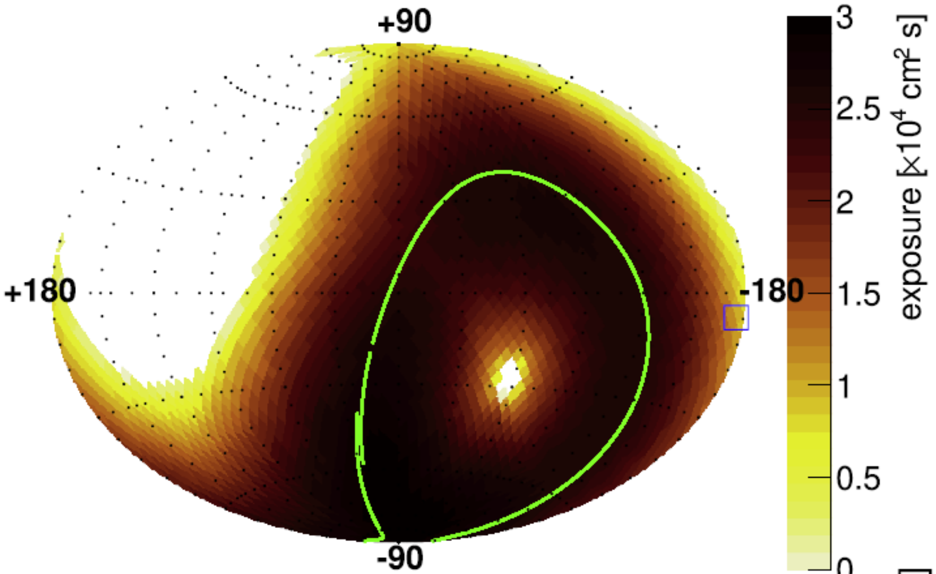
- ✓ Demonstration of observations of celestial objects
- ✓ Successfully detection of Crab Nebula and G.C. region
- ✓ Precise BG measurement at high altitude

The SMILE-3 project (2028, Australia)

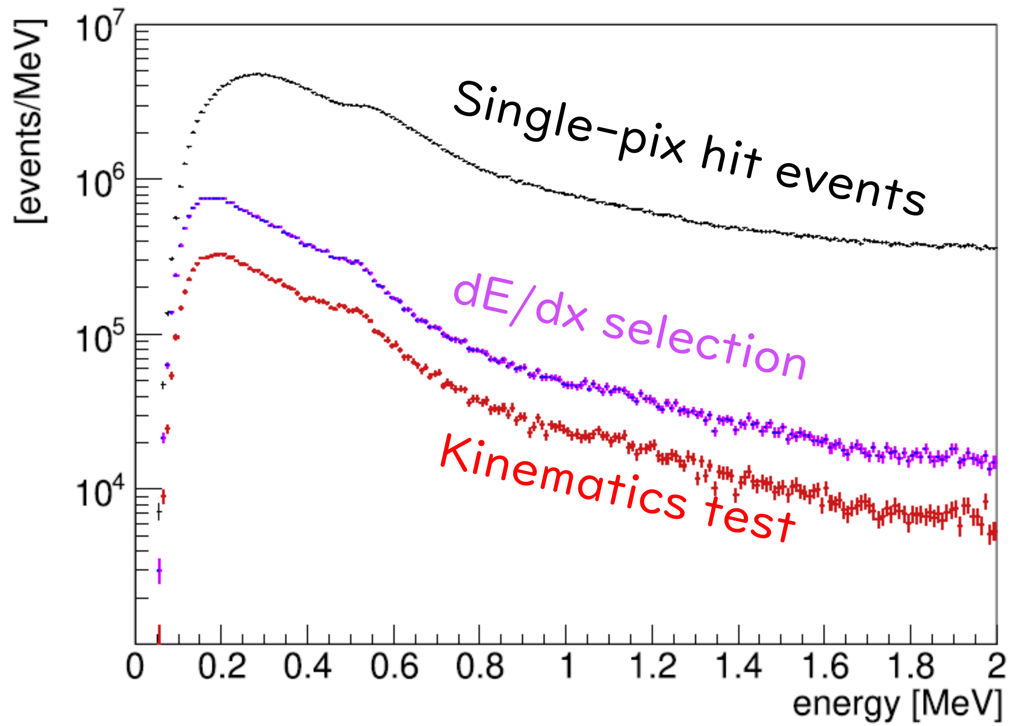
- ✓ First science observation with an ETCC at balloon altitude
- ✓ We are advancing the development of the instrument
- ✓ The SMILE-3 application has been ***tentatively selected***

We hope you look forward to what lies ahead
in our exploration of the MeV sky.

SMILE-2+: Exposure and Spectra



Exposure map in 0.3 MeV
Zenith < 60 deg.



Propagation and Proton injection models

MNRAS **475**, 2724–2742 (2018)

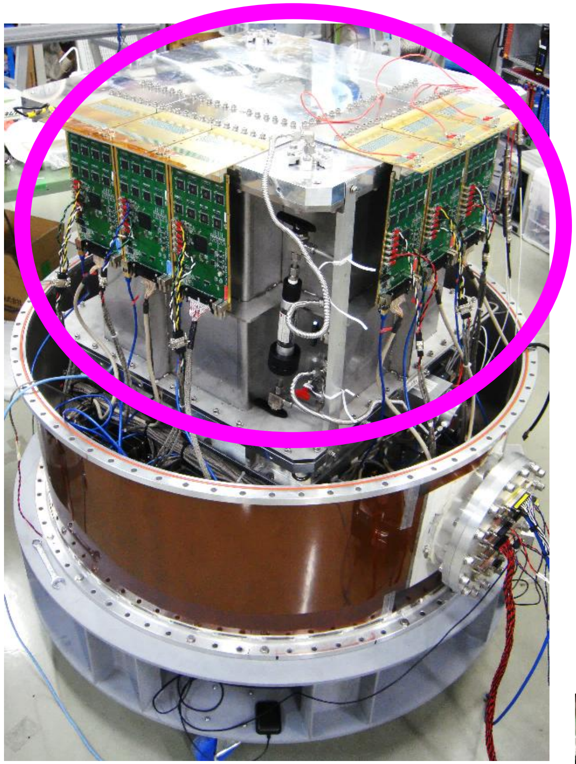
E. Orlando★
Hansen Experimental Phys

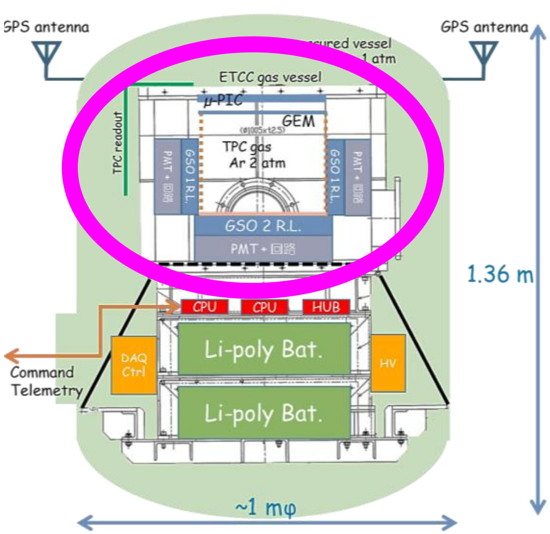
Table 1. The table shows the propagation and the proton injection parameters of the models. Injection parameters for other nuclei are as in the original works (Cummings et al. 2016; Boschini et al. 2017b) and are not repeated here. The description of each parameter can be found in the text.

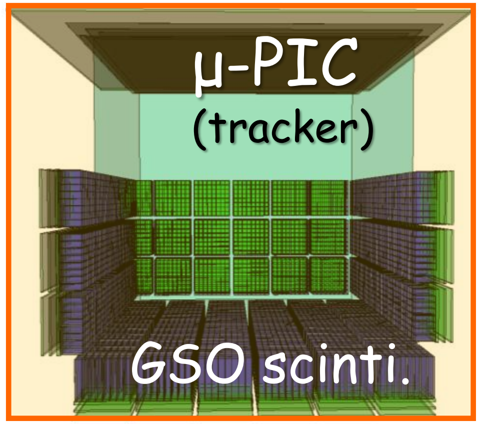
Model code	DRE	DRC	PDDE	DRELowV[b]
Propagation parameters				
D_0[a] ($cm^2\,s^{-1}$)	14.6	4.3	12.3	14.6
D_{br} (*GV*)	–	–	4.8	–
δ_1	0.327	0.395	−0.641	0.327
δ_2	0.323	0.395	0.578	0.323
$V_{\rm Alf}$ ($km\,s^{-1}$)	42.2	28.6	–	8.9
V_c ($km\,s^{-1}$)	–	12.4	–	–
dV/dz ($km\,s^{-1}\,kpc^{-1}$)	–	10.2	–	–
Proton injection parameters				
γ_1	0.65	1.69	1.18	–
γ_2	1.94	2.44	2.95	1.4
γ_3	2.47	2.28	2.22	2.47
$E_{\rm br_1}$ (*MV*)	117	700	124	–
$E_{\rm br_2}$ (*GV*)	17.9	360.0	6.5	2.7

Notes. [a]$D_{xx} = 10^{28}\beta D_0(R/D_R)^\delta$ $cm^2\,s^{-1}$, with D_R = 4GV for DRC model, and D_R = 40GV for the other models.
The propagation halo size is 4 kpc for all the models.
[b]This propagation model is described in Section 3.2.1.

SMILE-2+

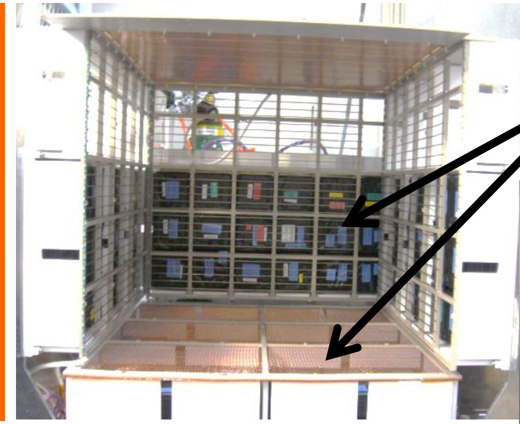


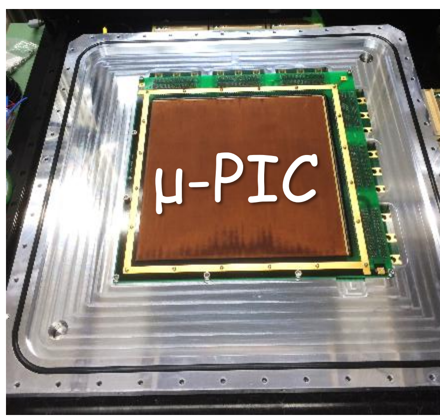


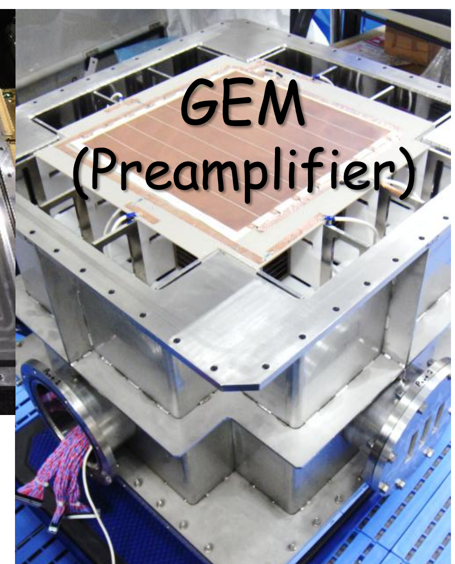


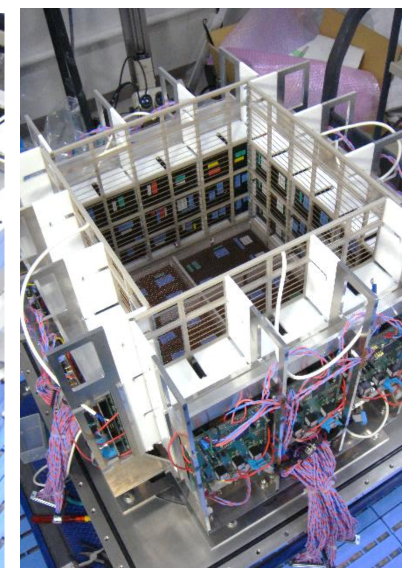
(30 cm)^3 TPC
Ar 2 atms

GSO scinti.



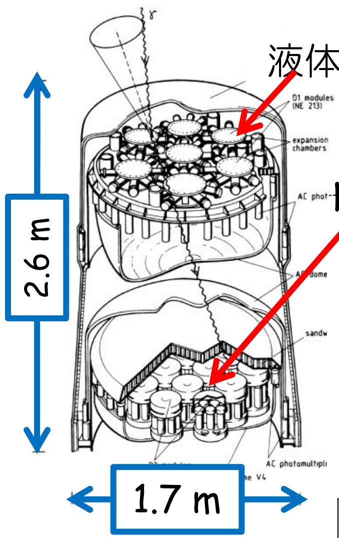


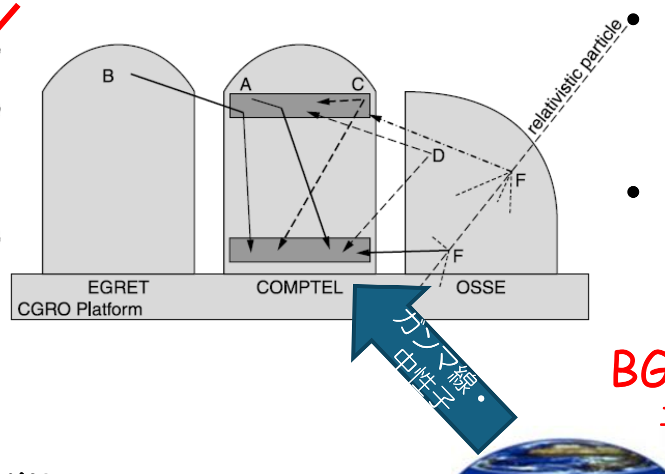




Mass of ETCC: 171 kg

COMPTELの雑音事象





COMPTEL 有効面積：13~20 cm^2

- 背景のガンマ線
  - 系外・系内拡散ガンマ線
  - 地球からのガンマ線
- 検出器そばで作られたガンマ線
  - 放射化から生じるガンマ線は
  - 大概MeVガンマ線
- 中性子
  - 宇宙線と衛星・大気との相互作用

G. Weidenspointner+, A&A (2001)

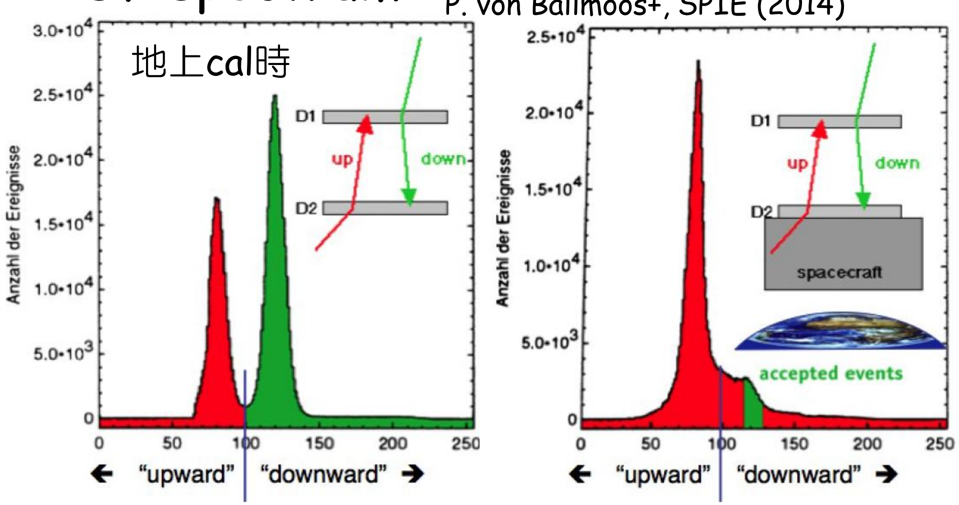
BGの除去努力をするも
予想より~3倍悪い感度に留まる

- 軽元素の散乱体 ⇐ 散乱優位
- 検出器間のTOF ⇐ 前後判定
- 検出器間距離 ⇐ 軸の精度向上
- 散乱角の制限 ⇐ 領域外の除去
- 液体シンチPSD ⇐ 中性子除去
- Anti用プラシン ⇐ 荷電粒子除去

V. Schönfelder, ApJSS (1993)

TOF spectrum

P. von Ballmoos+, SPIE (2014)



『観測領域のノイズを下げる』が重要

V. Schönfelder, New Astron. Rev. (2004)

Beam test for > 1 MeV

For the scientific motivation of SMILE-3, observations at energies above 1 MeV are also important. We checked the response of each component for the MeV gamma-rays using the inverse Compton scattering beam at UVSOR, Institute of Molecular Science, National Institutes of Natural Sciences.