SMILE-II : Observation of celestial and atmospheric MeV gamma rays using a balloon-borne wide field of view electron tracking Compton camera

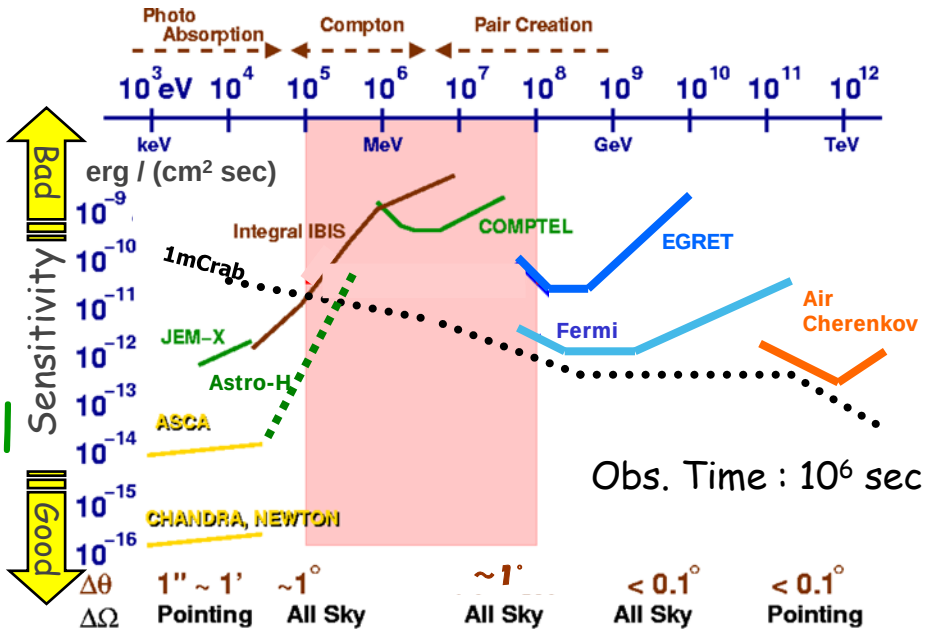
A. Takada, T. Tanimori, H. Kubo, K. Miuchi, S. Kabuki, J. D. Parker, Y. Kishimoto, T. Mizumoto, K. Ueno, S. Kurosawa, S. Iwaki, T. Sawano, K. Taniue, K. Nakamura, N. Higashi, Y. Matsuoka, S. Komura, Y. Sato (Kyoto Univ.), S. Arvelius (Lulea Univ.), E. Turunen (EISCAT Association)

1. MeV gamma ray Imaging & ETCC
2. Results of SMILE-I
3. Preparations of SMILE-II

Motivation

Observation of MeV gamma-ray will provide us…

- **Nucleosynthesis**
  - SNR : Radio-isotopes
  - Galactic plane : ^{26}Al • ^{60}Fe
  - Annihilation
- **Acceleration**
  - Jet (AGN) : Synchrotron
    + Inverse Compton
- **Strong Gravitational Potential**
  - Black Hole : accretion disk, π^0
- **Etc.**
  - Gamma-ray Pulsar, solar flare



- The observation of continuum component is also important.
- Where are MeV gamma-ray objects?
- There are many background events which obstruct the observations.

Requirements for
the next-generation detectors are …

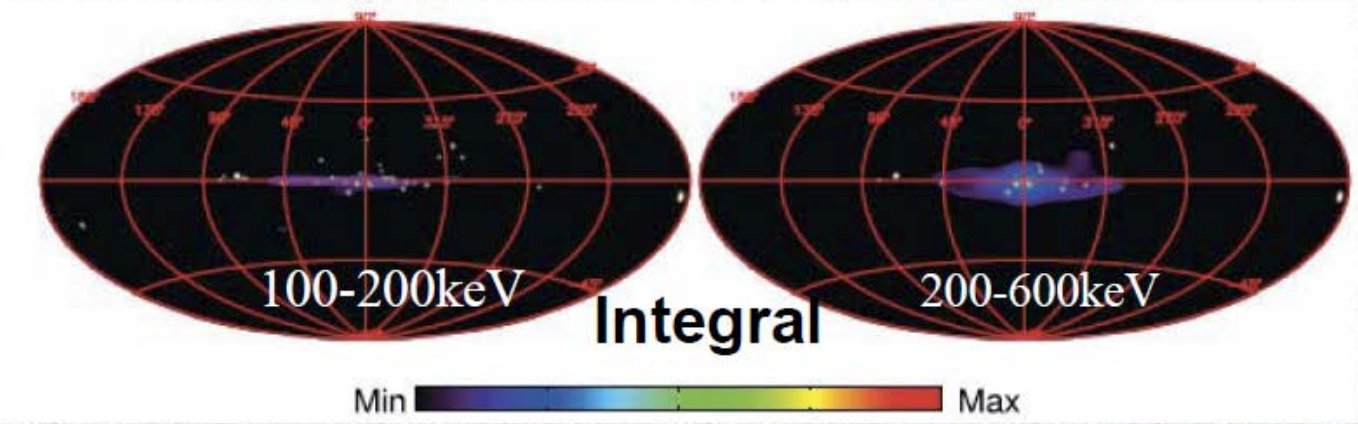
- Wide-band detection
- Large Field of View
- Background rejection

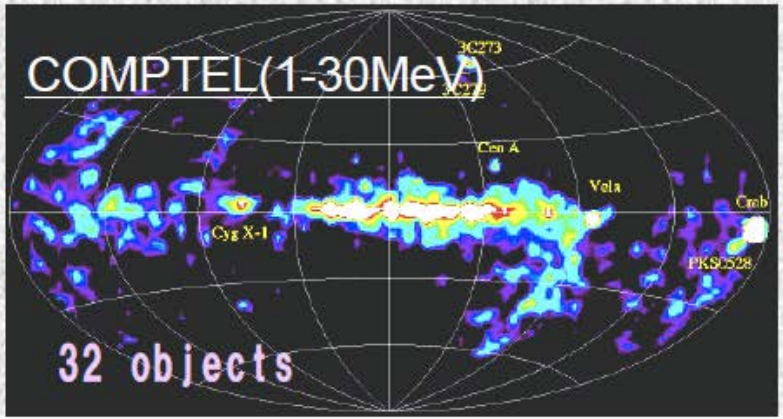
Sky Map of MeV Gamma rays

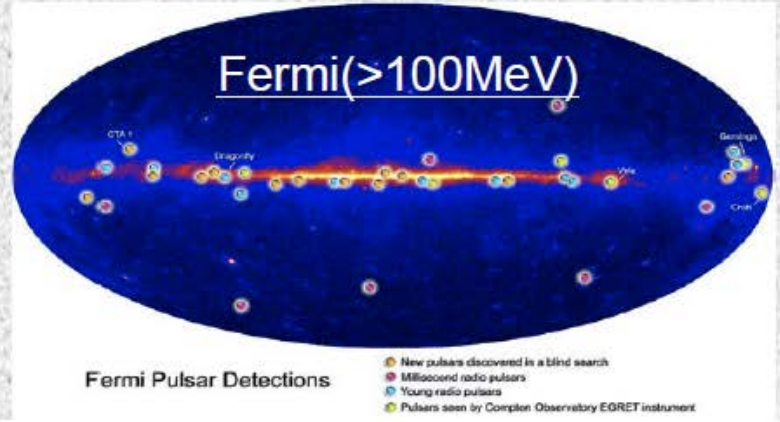
COMPTEL(1-30MeV) 32 objects

AGN 10
Line Emissions from SNR 7
Crab 1 γ-Pulsar 3
B.H.Candidates 2,
UnID 9

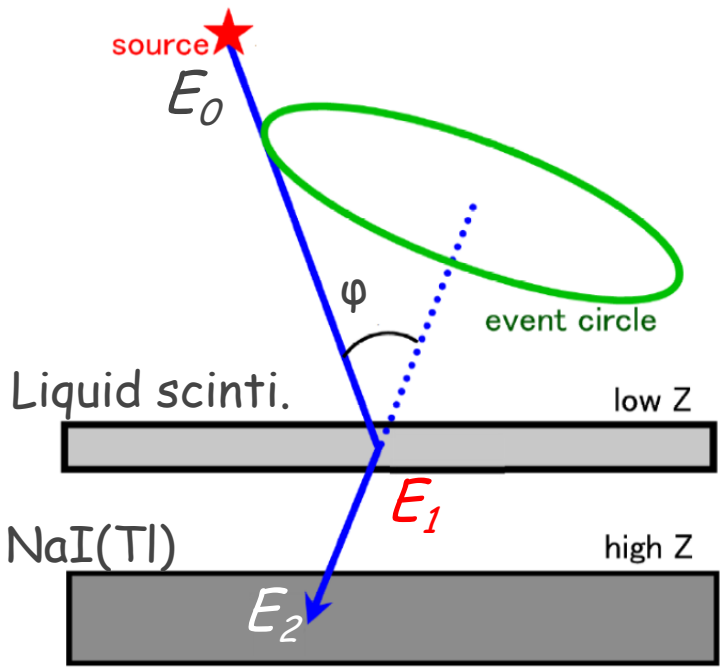
Integral Point Sources
25-50keV 173
50-100keV 79 (>3.5σ)
100-200keV 30(>2.5σ)
200-600keV 12
>600keV 4

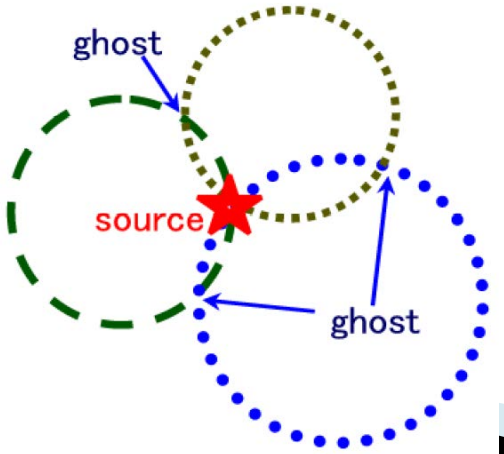






COMPTEL (CGRO:1991～2000)





Using Compton Scattering

- energies of scattered gamma and recoil electron
  → Energy of incident gamma
  Scattering angle

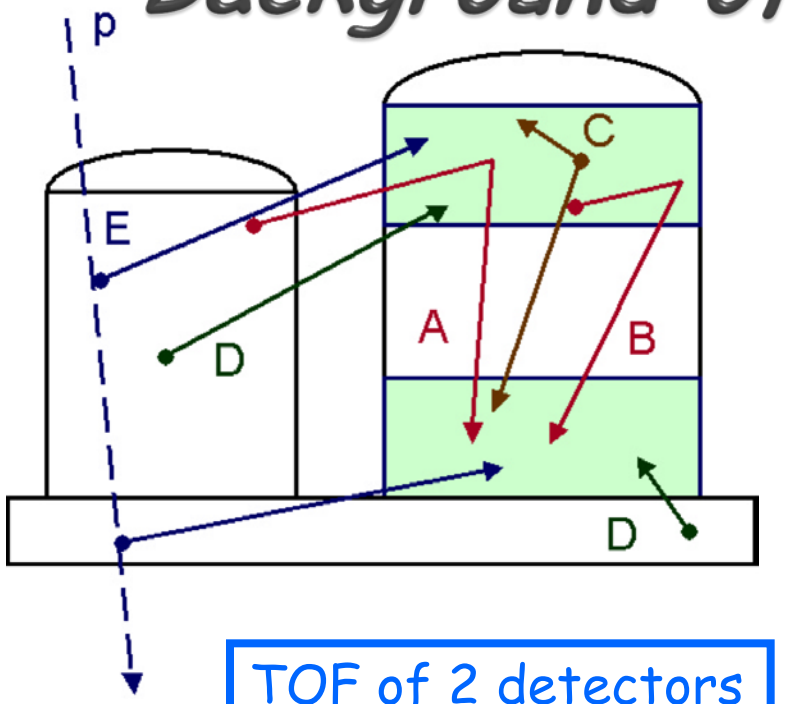
$$\cos\phi = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)$$

- Compton scattering point & Absorption point
  → Direction of scattered gamma
- ignore the direction of recoil electron

➢ Restrict the direction of incident gamma-ray to a circle

➢ The source position is determined fully by piling up circles
  → require 3 γ at least

Background of COMPTEL



G.Weidenspointner, et.al. (A&A, 2001)

A : external γ
B : internal γ
} Intrinsic background

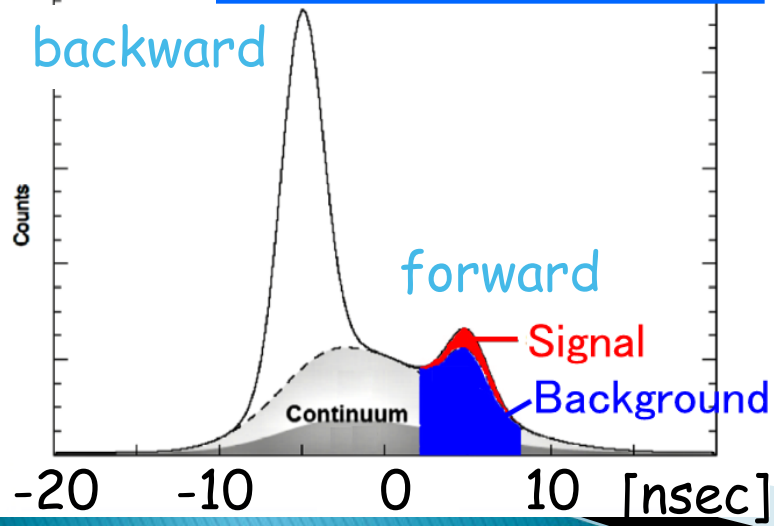
C : two γ

D : random coincidence

E: proton-induced γ

Other background
- neutron
- electron
- gamma from atmosphere

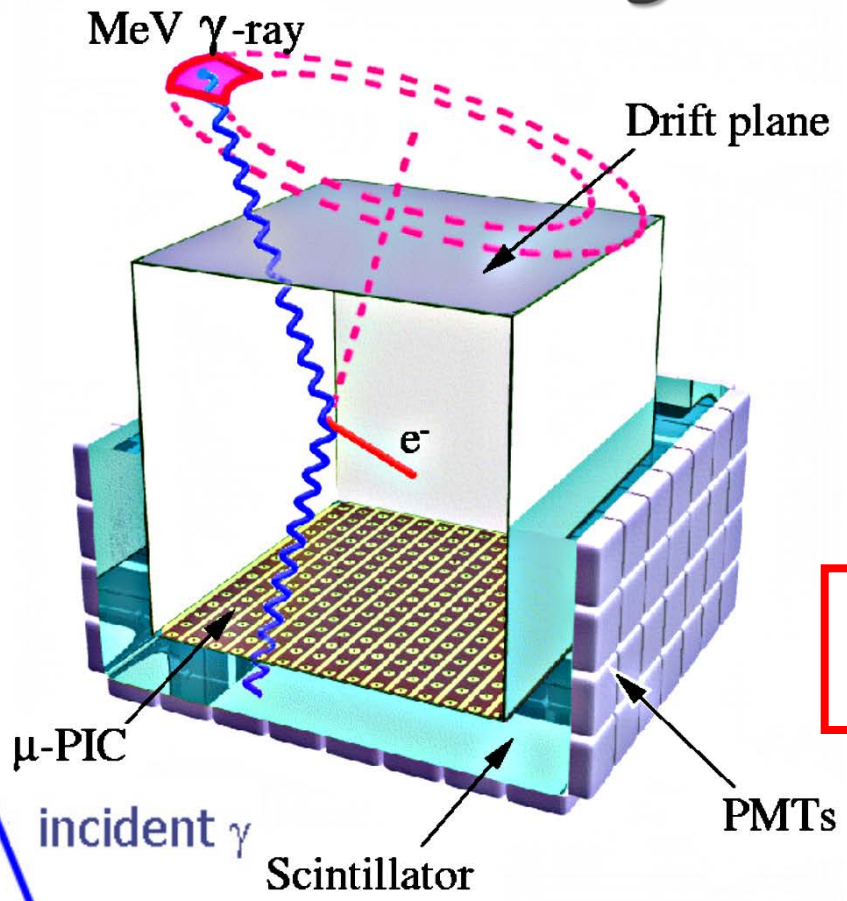
TOF of 2 detectors



COMPTEL has rejected such background by the measurement of the Time Of Flight between 2 detectors.

Background rejection was not complete
Bad S/N

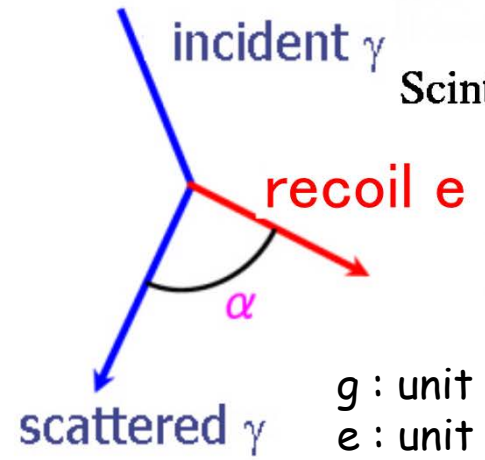
Electron-Tracking Compton Camera (ETCC)



- Gaseous TPC : Tracker
  track and energy of recoil electron
- Scintillator : Absorber
  position and energy of scattered gamma

Reconstruct Compton scattering event by event

- 1 photon ⇒ direction + energy
- Large FOV (~3str)
- Kinematical background rejection



$$\cos\alpha_{\mathrm{geo}} = \vec{g}\cdot\vec{e} \quad \Leftrightarrow \quad \cos\alpha_{\mathrm{kin}} = \left(1-\frac{m_e c^2}{E_\gamma}\right)\sqrt{\frac{K_e}{K_e+2m_e c^2}}$$

g : unit vector of scattering direction
e : unit vector of recoil direction

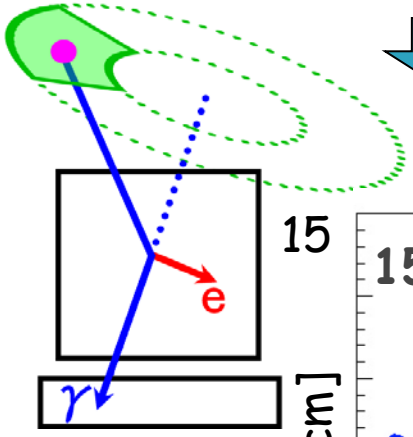
E_γ : Energy of scattered gamma-ray
K_e : Kinematic energy of recoil electron
$m_e c^2$: Rest mass of electron

Comparison with the usual Compton method

Electron-Tracking Compton (ETCC)

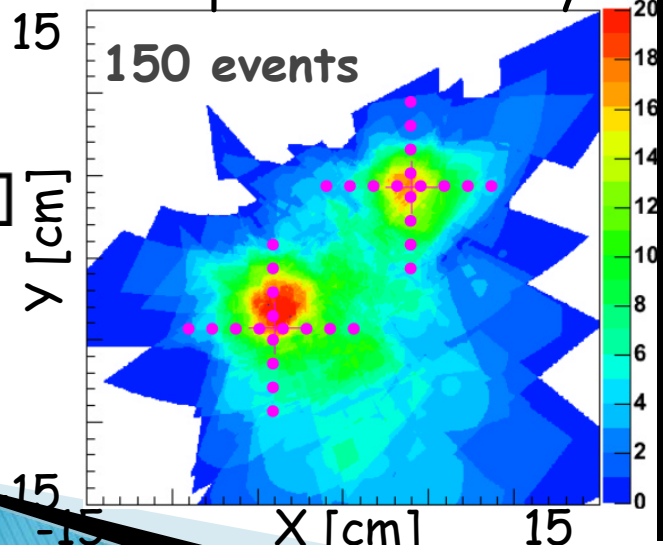
Using the electron tracks

- complete direction within sector form error region



Simply overlay

2 sources were separated clearly

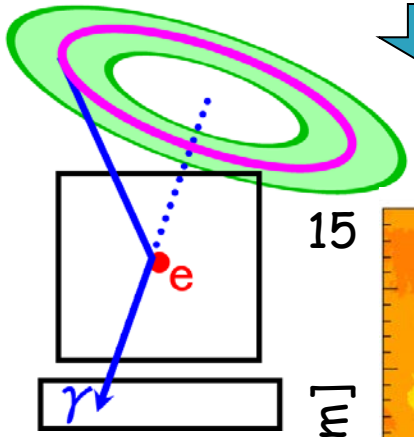


^{137}Cs(1MBq)×2, Advanced Compton

Usual Compton Imaging (COMPTEL)

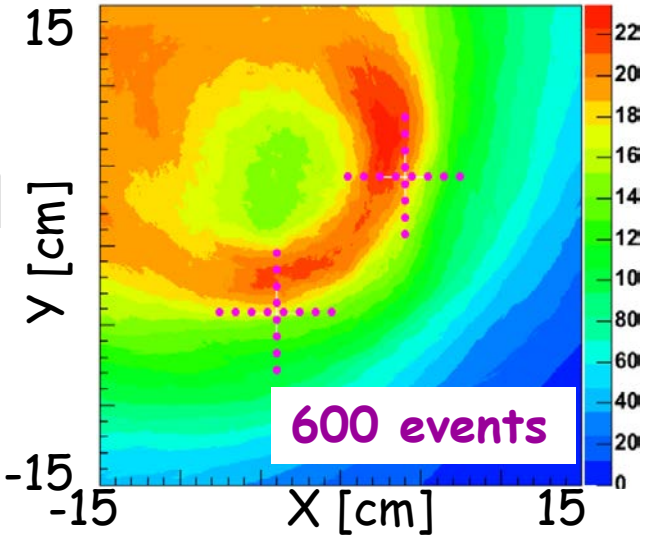
Not using the electron tracks

- only event circle within ring form error region



Simply overlay

Hard to separate 2 sources



^{137}Cs(1MBq)×2, usual Compton

Sub-MeV gamma-ray Imaging Loaded-on-balloon Experiment

10cm cube camera @ Sanriku (Sep. 1st 2006)

- Operation test @ balloon altitude
- Observation of
  diffuse cosmic/atmospheric gamma
  ~400 photons during 3 hours
  (100 keV~1MeV)

30cm cube camera Sub-MeV ~ MeV

- Observation of Crab/Cyg X-1

40cm cube camra

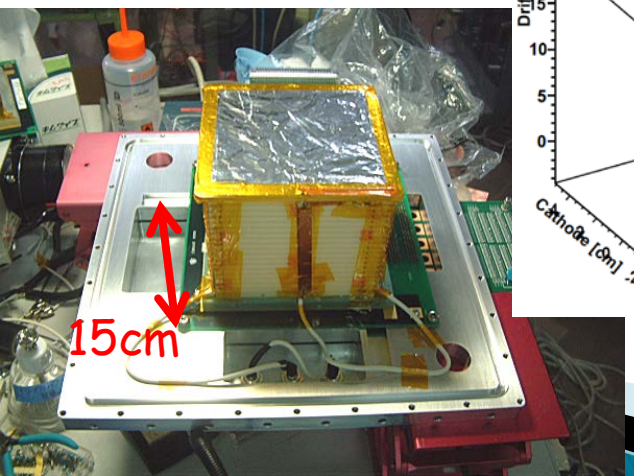
- Long duration observation with super pressure balloon
- Adding pair-creation mode

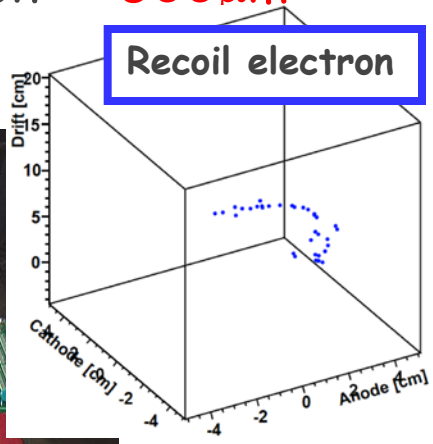
50cm cube camera

- All sky survey (load on a satellite)

Tracker

- Gas : Xe 80% + Ar 18% + C_2H_6 2%
  1atm, sealed
- Gain : ~35000
- Drift velocity (V_d=400V/cm) :
  measured 2.5cm/μsec
  simulation 2.48cm/μsec
- Volume : 10×10×14 cm^3
- Energy resolution :
  ~45% (22.2keV, FWHM)
- Position resolution : ~500μm

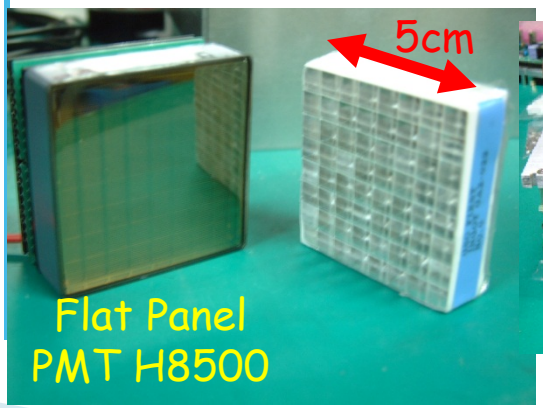


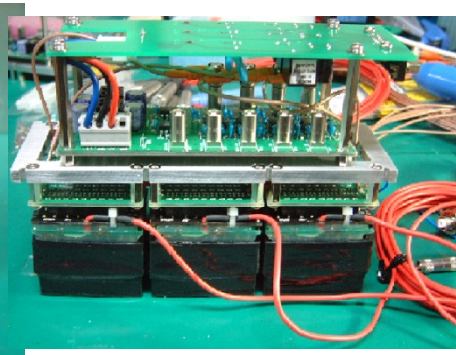


Absorber

- Scintillator : GSO(Ce)
- Pixel size : 6x6x13 mm^3
- Photo readout : H8500 (HPK)
- DC/HV : EMCO Q12N-5
- A unit consists of 192 pixels, 3 PMTs, 3 DC/HV and 4 preamplifier
- 4 channels readout with resistive chain (H. Sekiya et al., NIM, 2006)
- Bottom : 3×3 PMTs
- Side : 3×2 PMTs × 4
- Energy resolution :
  ~11% (662keV, FWHM)

} 2112 pixels





1st Flight SMILE

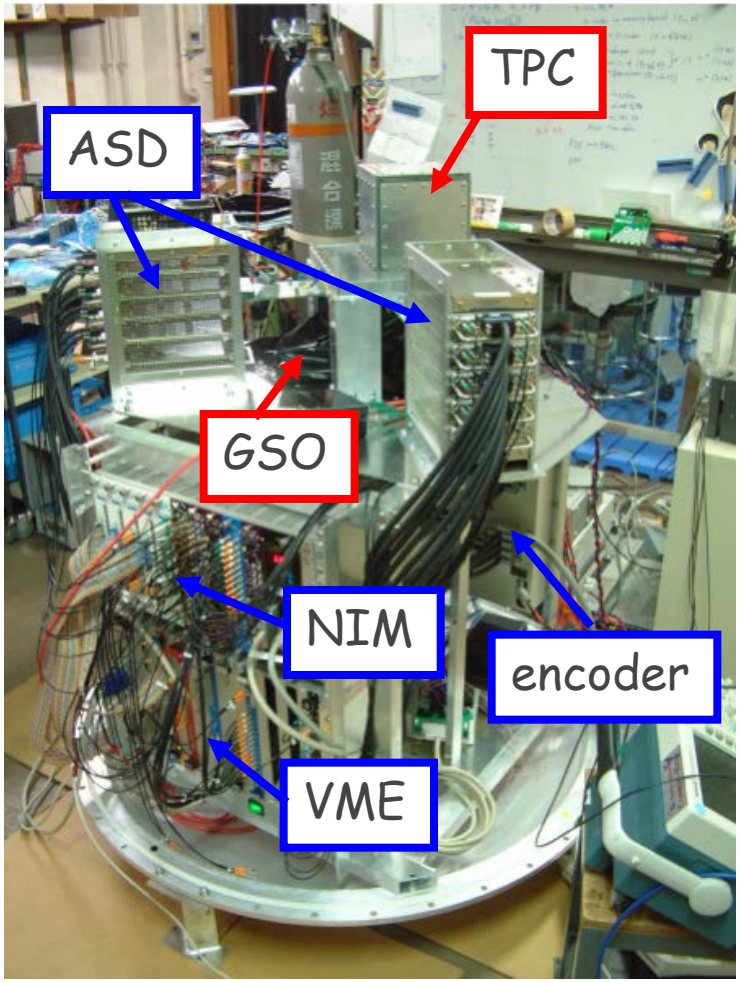
- Gondola size: 1.45×1.2×1.55m^3
- Gondola weight: 397kg
- Bessel: ϕ1×1.4m^3
- Power: ~350W
  in Bessel : 220W

In Bessel (1 atm)
Detector, DAQ system,
Storage, Thermometer,
Pressure gauge,
GPS, Clinometer

Out of Bessel
Battery & Regulator,
Thermometer,
Pressure gauge,
GPS antenna,
Geomagnetic aspectmeter

Flight Control
Telemetry,
Transponder,
Buoy, Radiosonde,
GPS, Thermometer,
Pressure gauge, etc.

Balloon
B100 (100,000m^3)
Weight 816kg
Buoyancy 888.2kg



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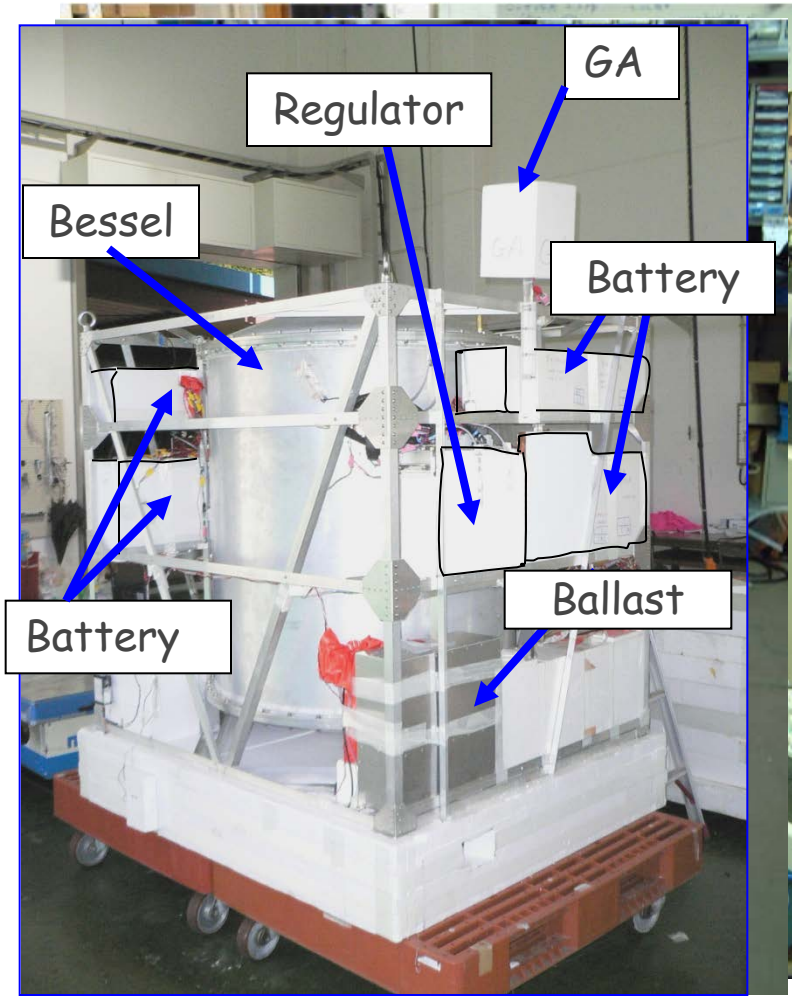

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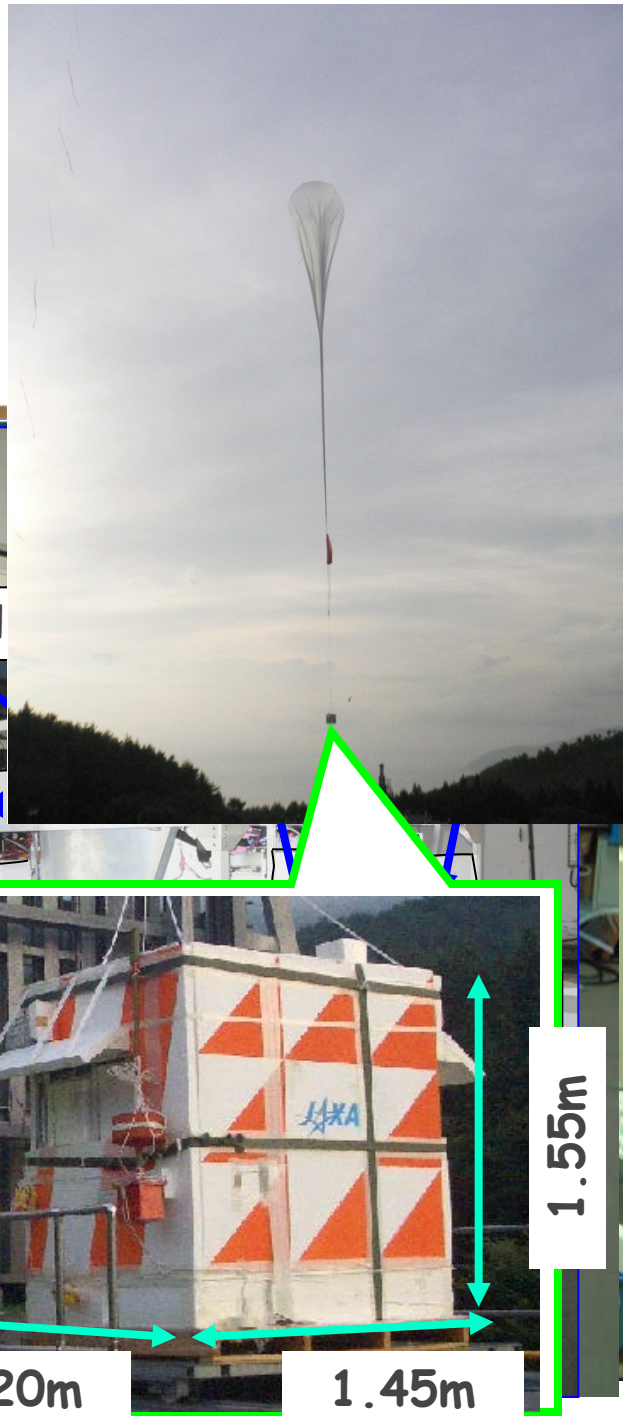
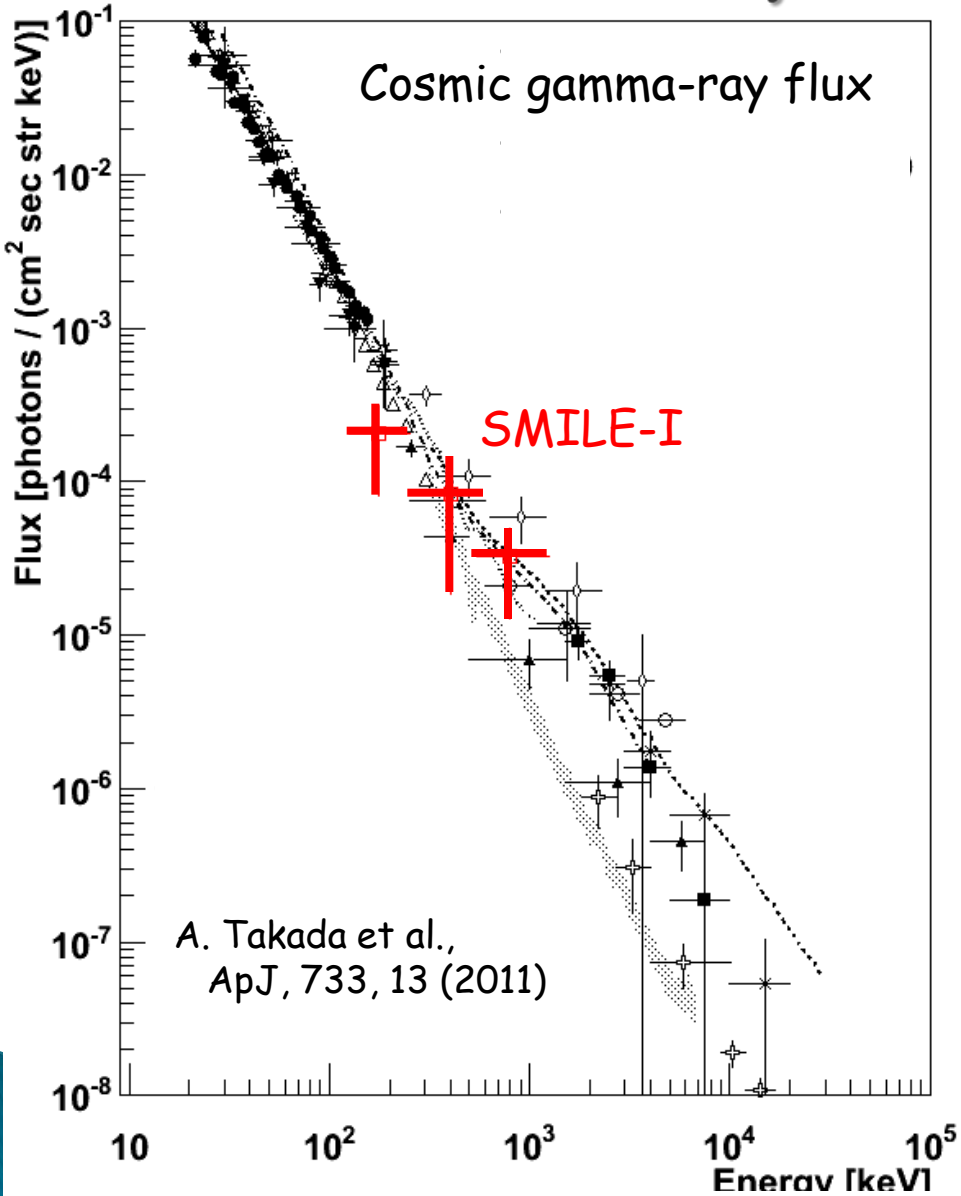
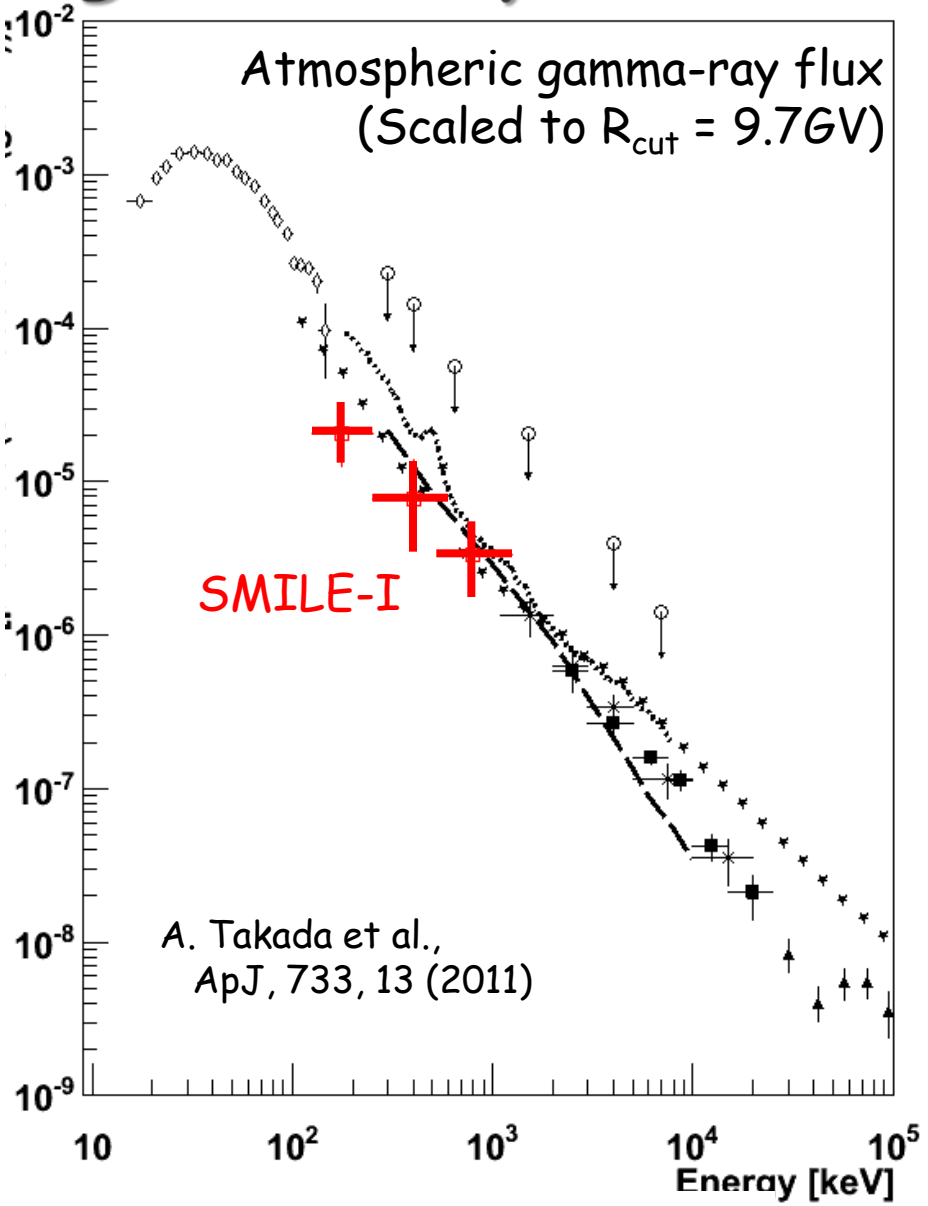


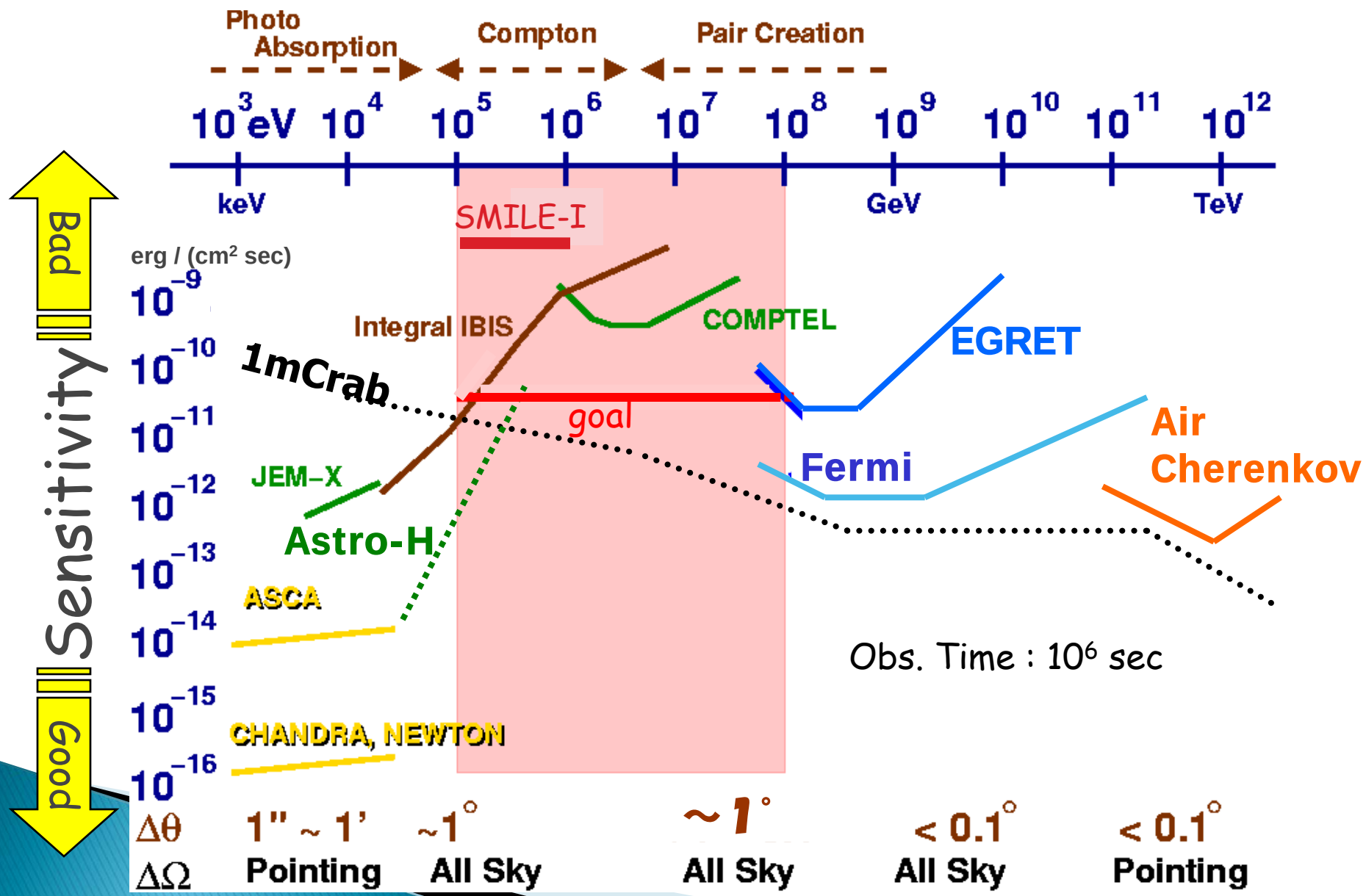
Cosmic & Atmospheric gamma-ray flux





Our results were consistent with those of past observations!!!

Sensitivity of X/Gamma-ray observations



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- Operation test @ balloon altitude
- Observation of
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  ~400 photons during 3 hours
  (100 keV~1MeV)

30cm cube camera Sub-MeV ~ MeV

- Observation of Crab nebula

2012- test flight @ Taiki
2013- Observation @ Kiruna
with circumpolar balloon

40cm cube camra

- Long duration observation with super pressure balloon
- Adding pair-creation mode

50cm cube camera

- All sky survey (load on a satellite)

Toward Next Step

- SMILE-I : 1st Sep. 2006 launched
  - Observation of diffuse cosmic/atmospheric gamma-rays
    -> detection by integration in a large FOV
  - Electron Tracker : 10x10x15 cm^3 , Xe+Ar 1atm
  - Absorber : 15x15x1.3 cm^3 @ Bottom
    15x10x1.3 cm^3 x4 @ Side

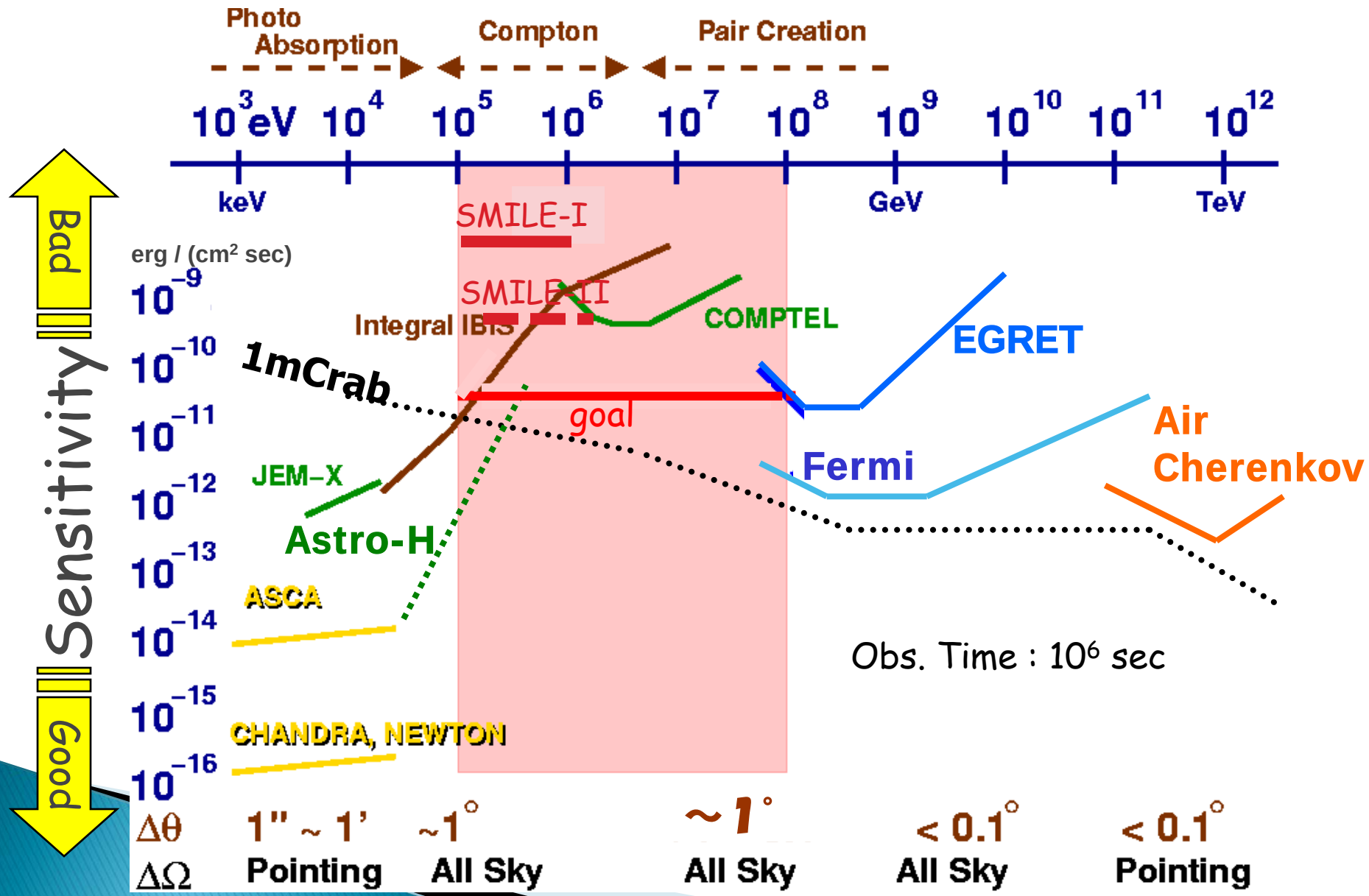
  ⇒ Effective area : ~2x10^{-2} cm^2

- SMILE-II
  - Observation of a Bright object (Crab nebula)

  ⇒ Requirement : ~0.5 cm^2

  - Electron Tracker : 30x30x30 cm^3 , Ar/CF_4 1.5atm
  - Absorber : 40x45x1.3 cm^3 @ Bottom
    40x20x1.3 cm^3 x4 @ Side
  - Improvement of Angular resolution

Sensitivity of X/Gamma-ray observations



γ-ray burst due to Relativistic Electron Precipitation in 1996 @Kiruna for SMILE-II

K.R.Lorentzen et al.,(2000)

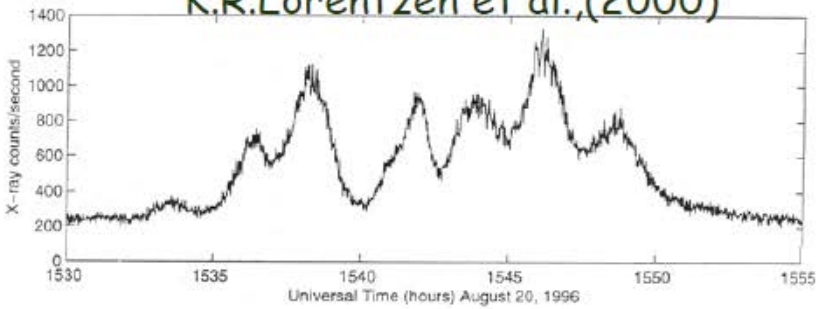
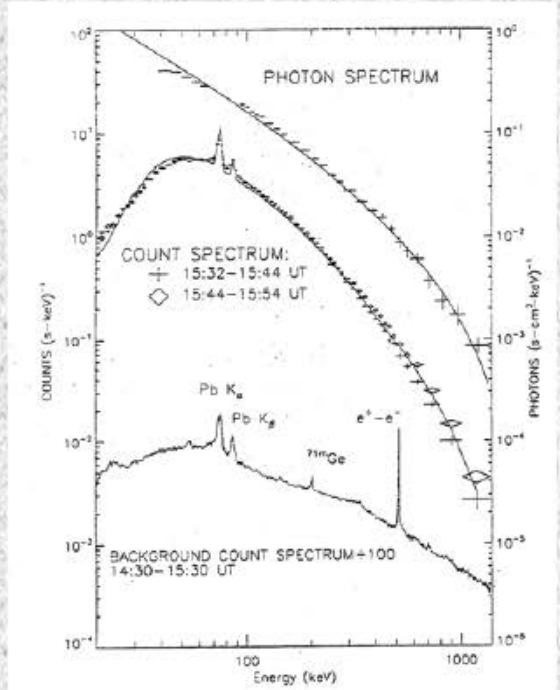


Figure 1. X-ray imager data taken during the relativistic electron precipitation event of August 20, 1996. The X-ray count rate between 20 and 120 keV is averaged over 1 s. The 10–20 s modulation is most clearly visible superposed on the peak starting near 1545 UT.

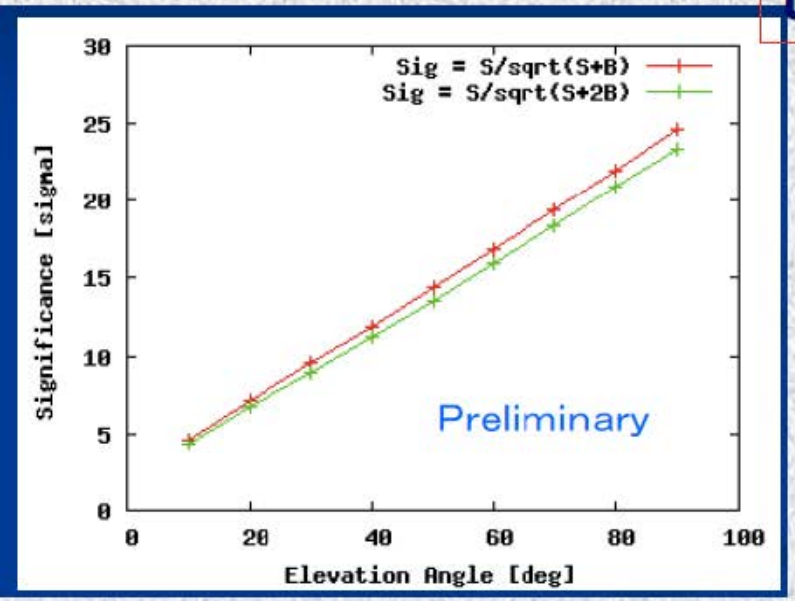


- Similar scale burst
  SIMILE-II(30x30x30cm ETCC)
  100kev-2MeV
  ~20σ detection for imaging Δθ 10°
- Good Spectroscopy from large crystal arrays.
- Wide field of View with ~3str
- Fixed point observation
  - -> spatial or temporal
- Direct Measurements of high energy electrons, proton, neutron and nucleus

Rep-burst observation

Wide FoV imaging-> Direction, Position
Spectroscopy, Light Curve,

γ-ray spectrum—>Depth of burst
D & θ -> L (Distance)

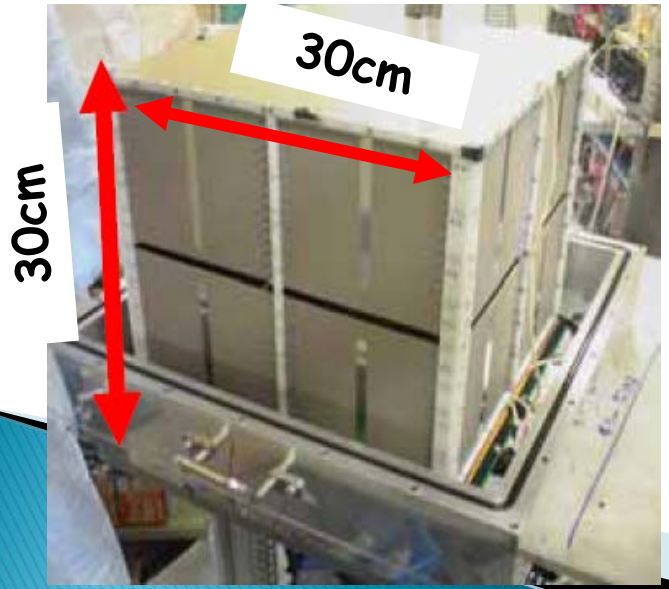


30×30×30cm³ ETCC current status

We are developing a larger ETCC based on the 30cm ×30cm×30cm TPC and 6 x 6 scintillation cameras.

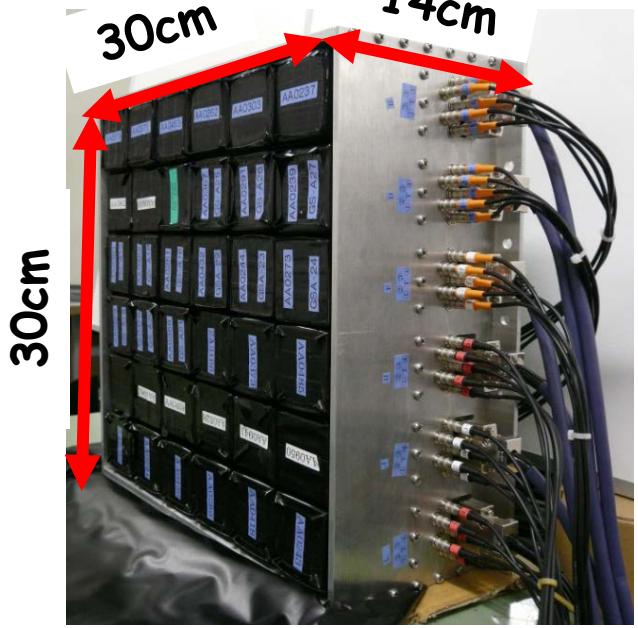
➢ Gaseous TPC

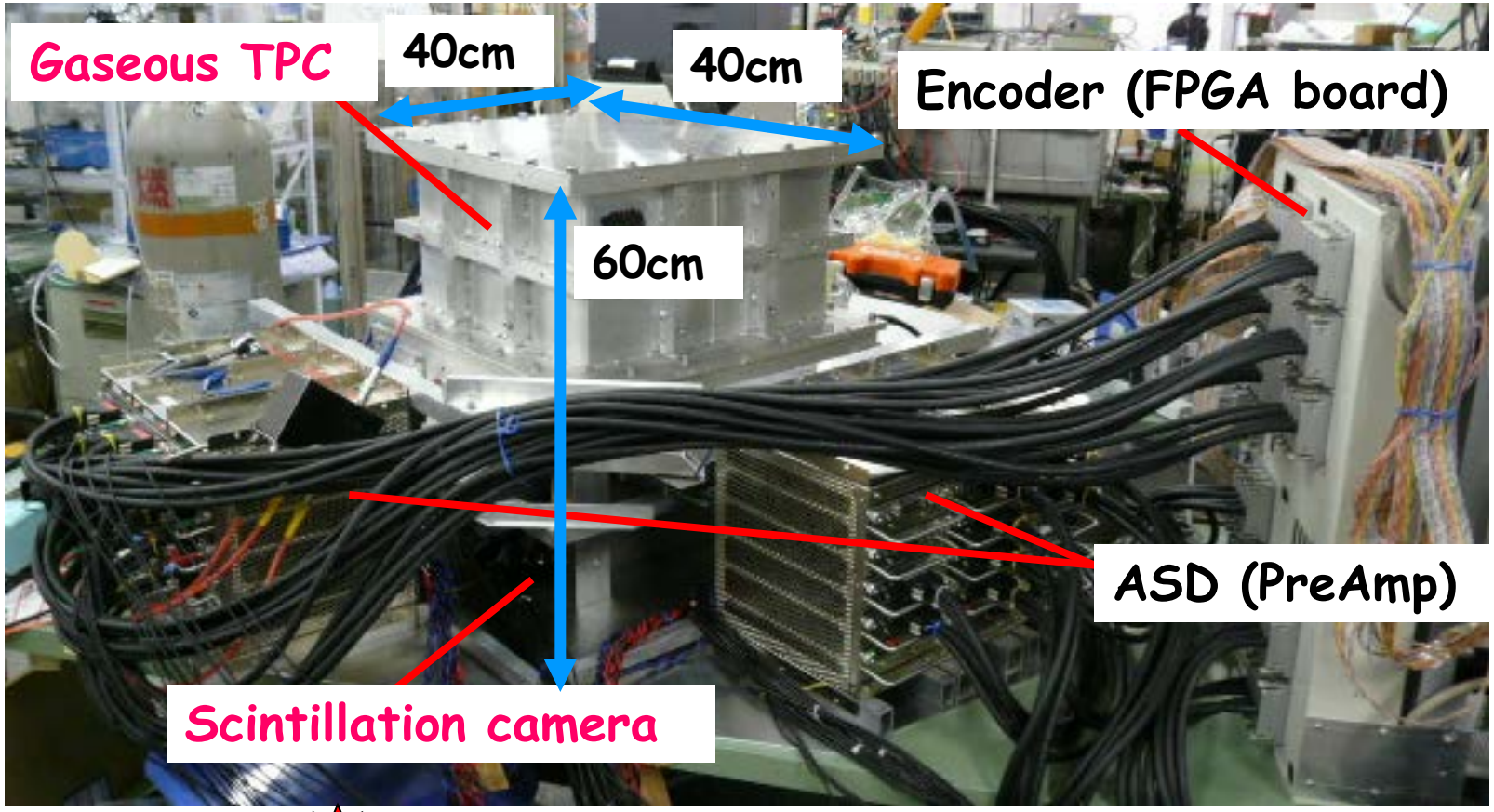
- volume : 30×30×30 cm^3
- gas : Ar 90% + $C_2H_6$10% (1atm)
- drift velocity : 4 cm/μsec
- gain : ～100000
- energy resolution : 46%@32keV
- position resolution: 400μm



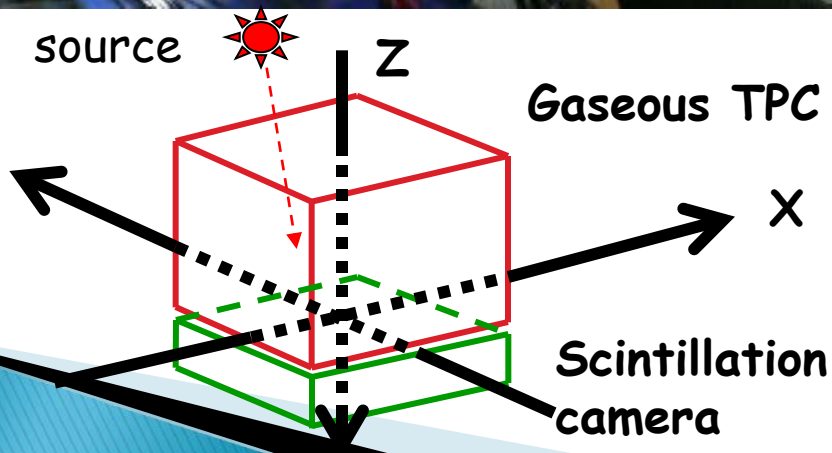
➢ Scintillation Camera

- number of pixels : 2304 pixels
- Crystal : GSO(Ce)
- pixel size : 6×6×13mm^3
- energy resolution : 10.9% (@662keV, FWHM)
- position resolution : 6mm





Setup



Center of μPIC :(0,0,0)

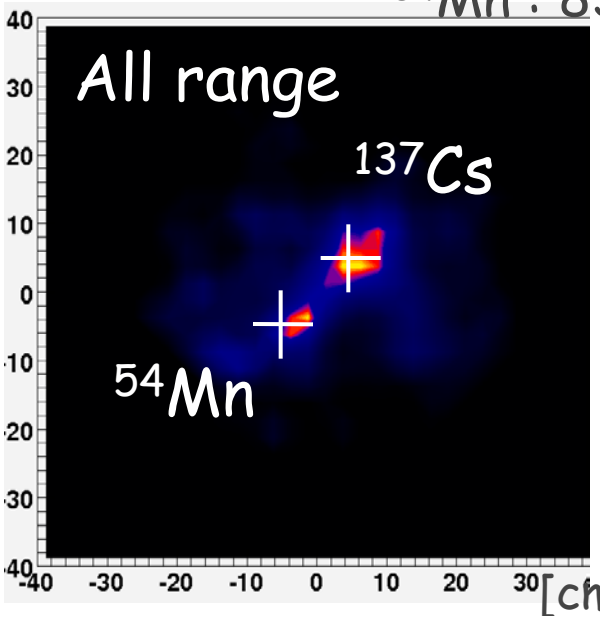
Center of Scinti.

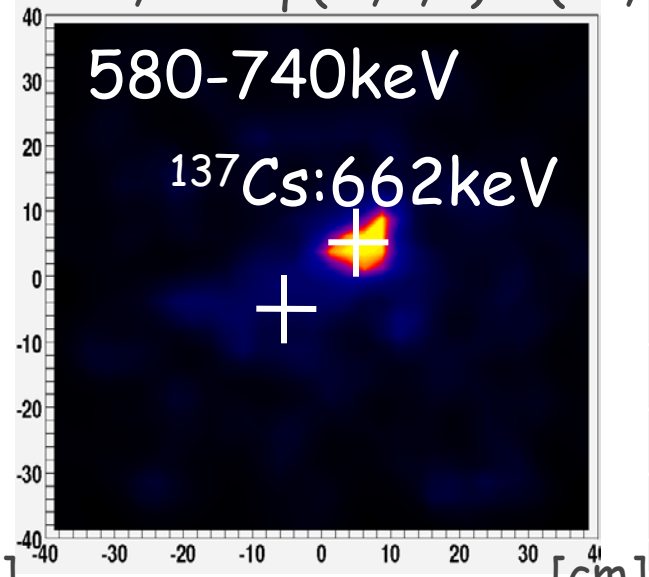
:(-3.3, 0.2, 5.7)

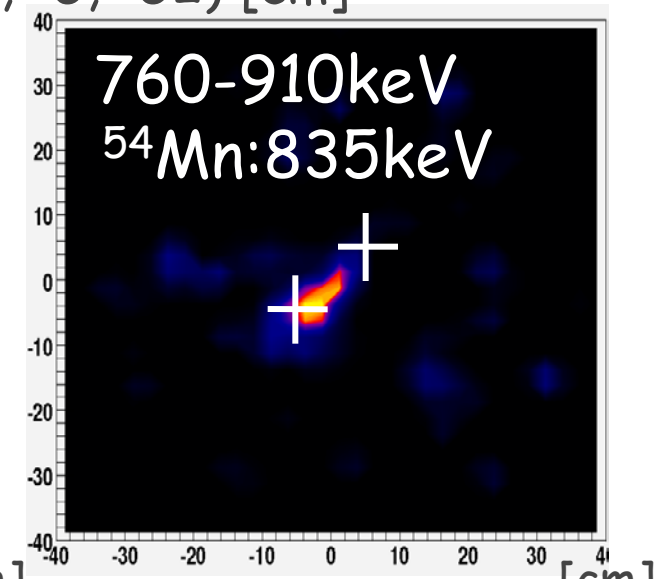
simultaneous imaging (preliminary)

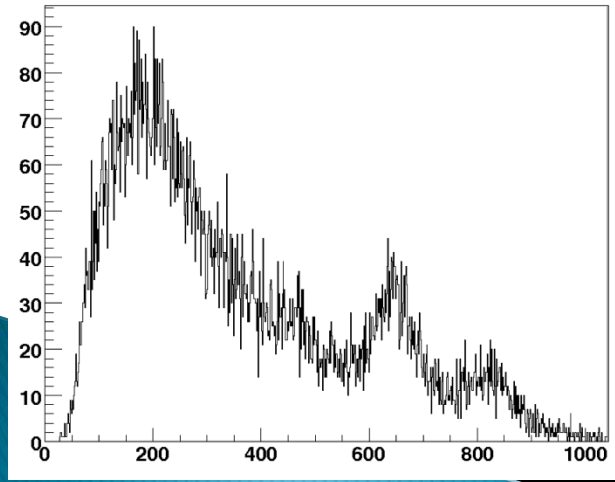
^{137}Cs : 662keV, 1MBq (X,Y,Z) = (5, 5, -52) [cm]

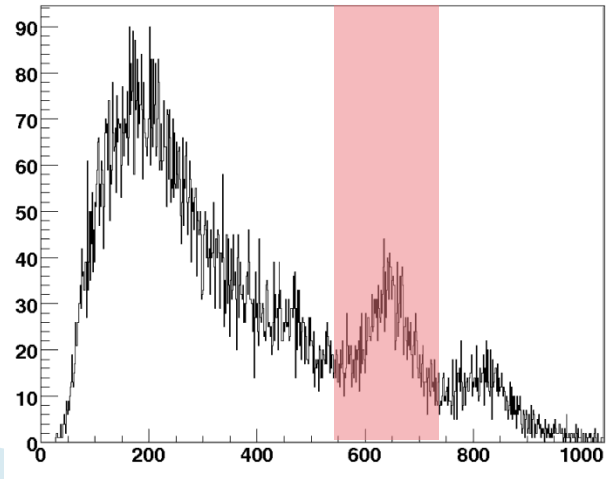
^{54}Mn : 835keV, 1MBq (X,Y,Z) = (-5, -5, -52) [cm]

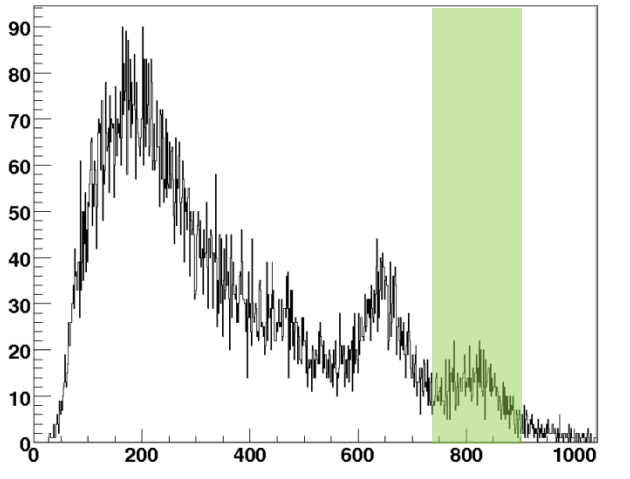




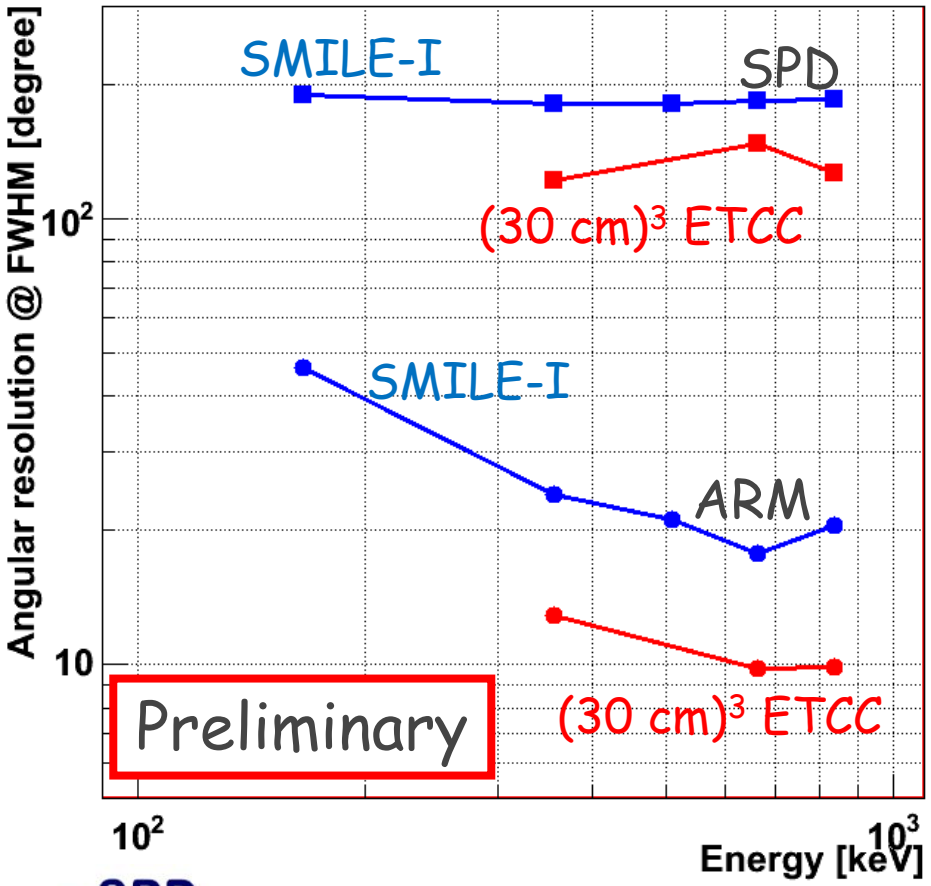


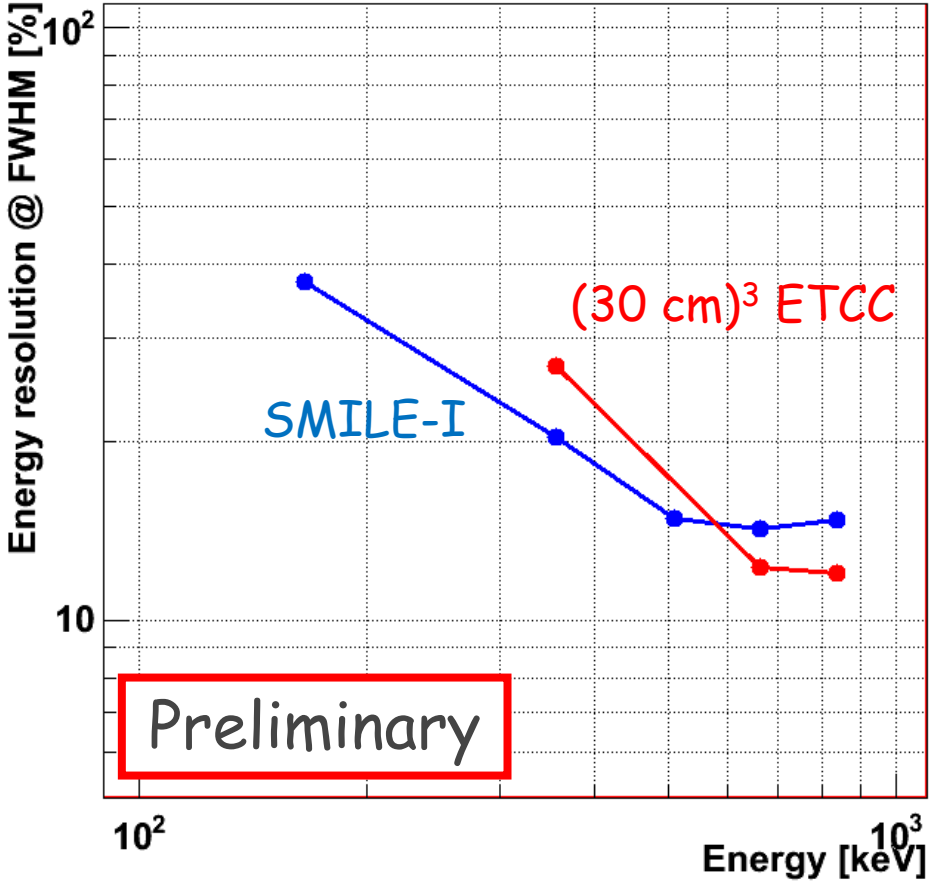


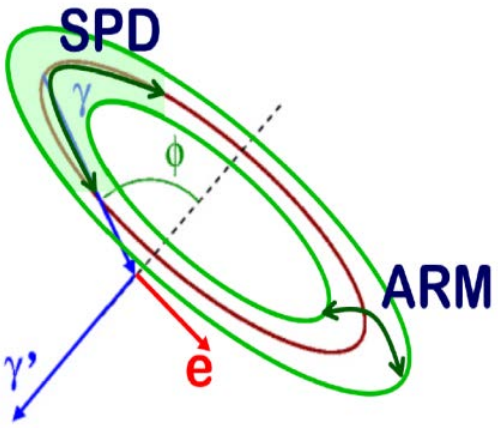




Angular resolution, Energy resolution







SPD: 147[deg]
ARM: 9.8[deg]
DE/E: 12.3%
(FWHM) @662keV

⟺

183[deg]
17.7[deg]
14.3%
SMILE-I

ARM : Angular Resolution Measure
SPD : Scatter Plane Deviation

Saving power consumption of the readout

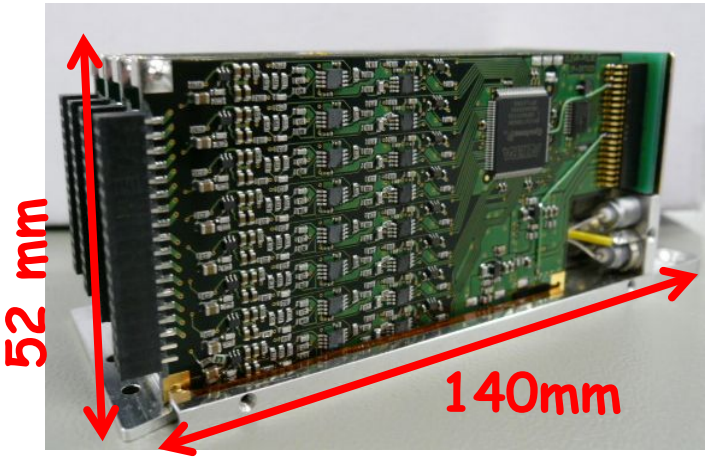
SMILE-I The power of readout system

33 PMTs : ~80 W
(10 cm)^3 μ-PIC (1024ch) : ~70 W

SMILE-II

~200 PMTs
(30 cm)^3 μ-PIC (1536ch)

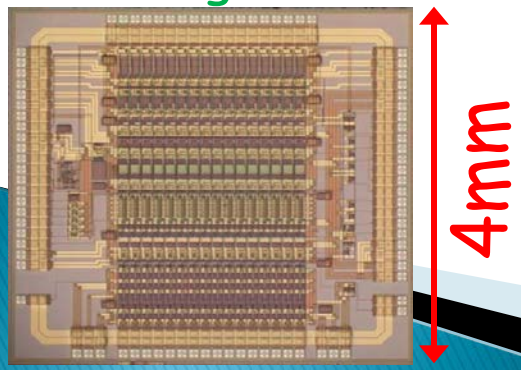
➢For scintillation camera (CP80190 Clear Pulse)



	GSO array ΔE / E (FWHM @ 662 keV)	Power (/PMT)
SMILE-I system	11 %	2700 mW
New system (SMILE-II)	10.5 %	100 mW

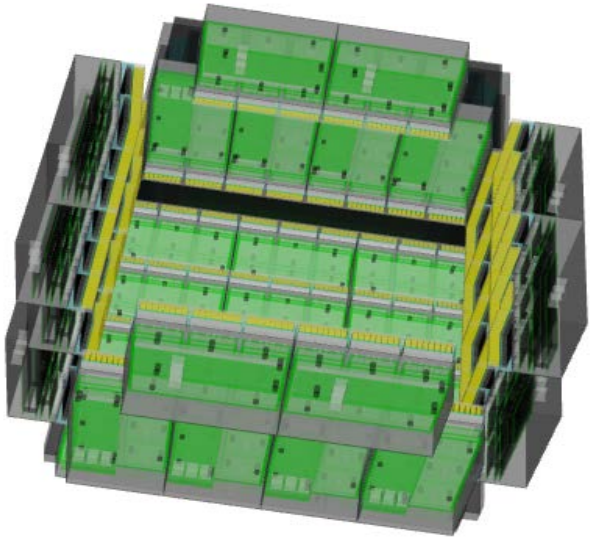
➢ASIC for gaseous TPC with a 0.5 μm-CMOS

Collaborator: M. Tanaka, and Y. Fujita (KEK)



	TPC ΔE / E (FWHM @ 22 keV)	Power (/ch)	ch # (/chip)
SMILE-I	~ 20 %	59 mW	4
New	~ 20 %	18 mW	16

Simulation of SMILE-II flight model

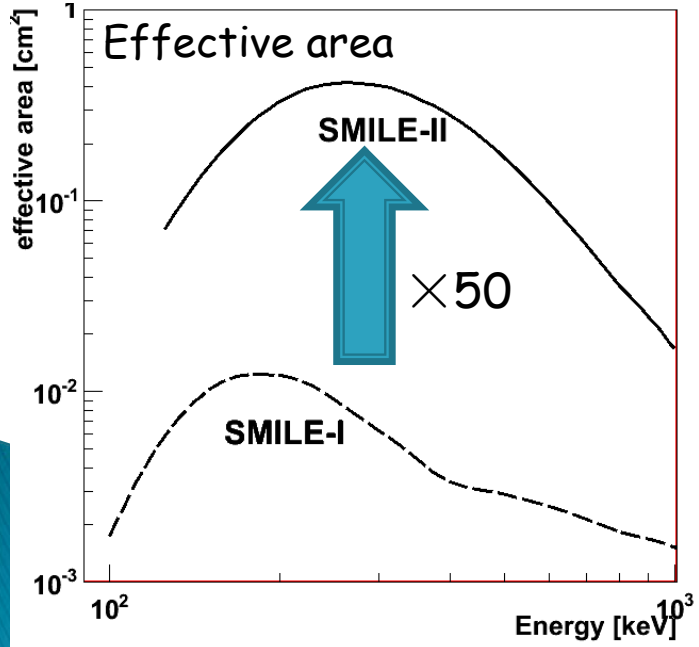


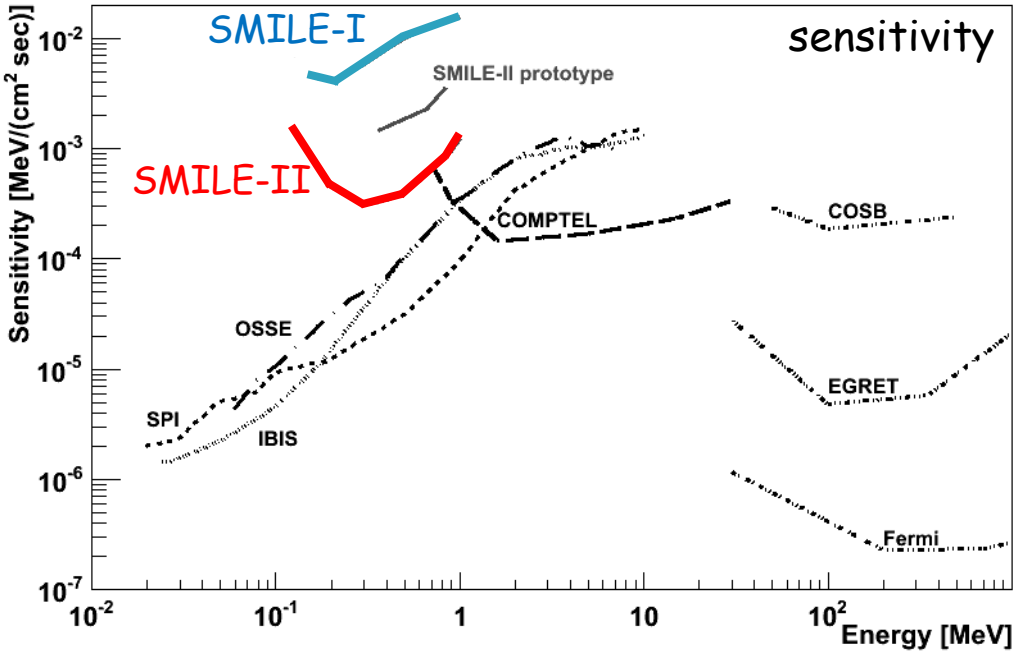
prototype

- Absorber: 36 GSO-PSAs
- Tracker gas: Ar 1atm

Flight Model

- Absorber: 216 GSO-PSAs
- Tracker gas: CF_4+Ar 1.5atm





Thank you!

http://www-cr.scphys.kyoto-u.ac.jp/research/MeV-gamma/en/index.html