早稲田大学
WASEDA University

東京工業大学
Tokyo Institute of Technology

ERATO

GRAPHIUM
MeV gamma-ray survey & formation flight

INSPIRE onboard GRAPHIUM: exploring MeV gamma-ray sky with a small satellite

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On behalf of

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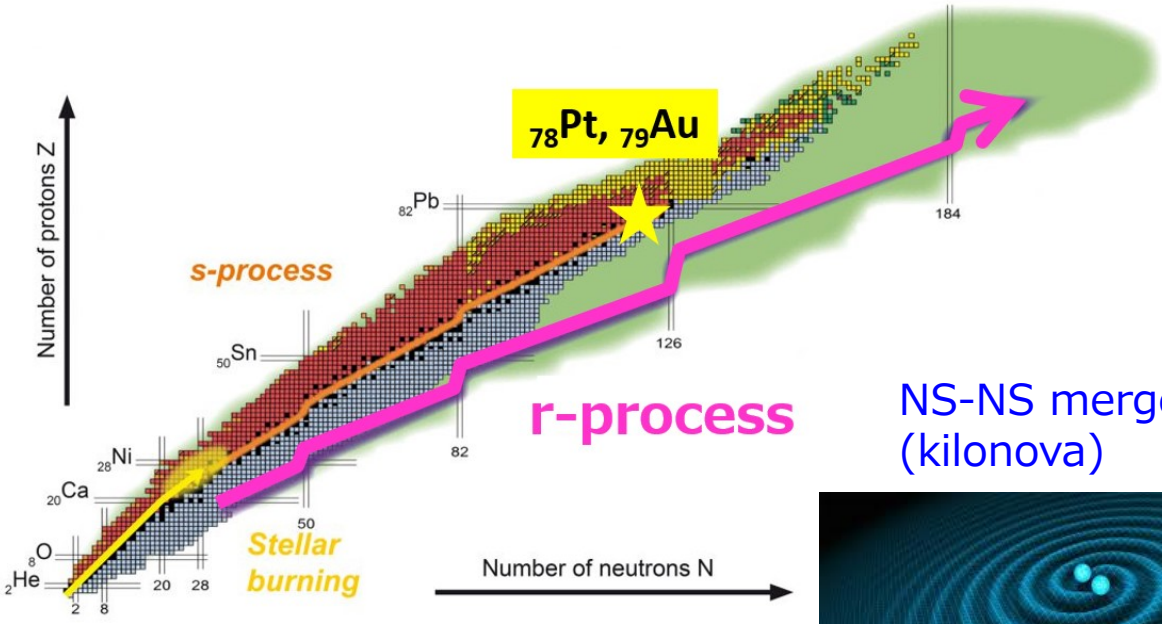
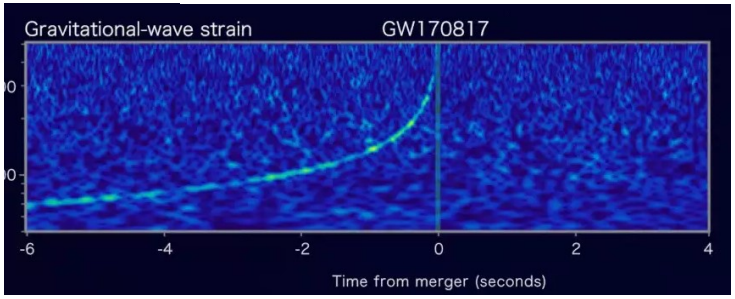
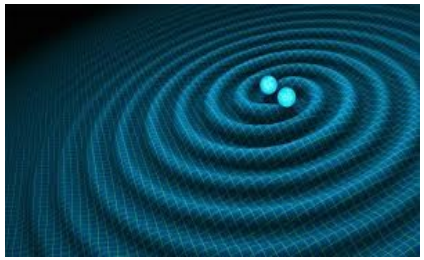
MeV γ rays as nucleosynthesis probe

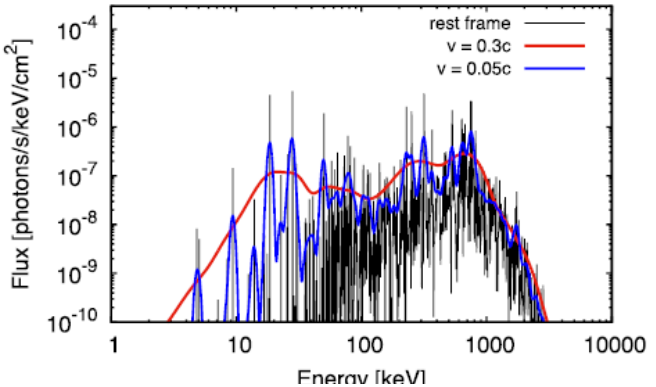


LIGO collaboration 2017



NS-NS merger (kilonova)



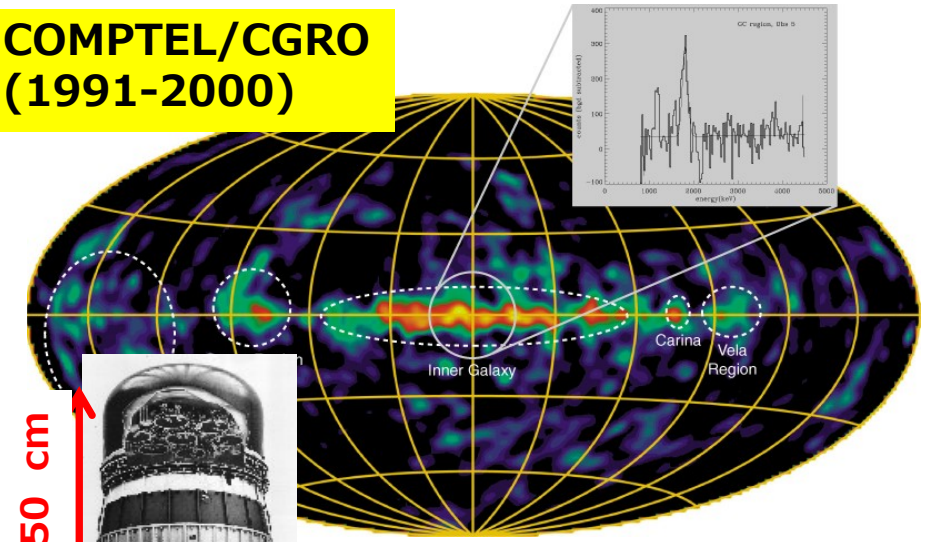


Hotokezaka et al. 2016

- Typical nuclear reactions: Q value ~ *o* (MeV)
- Heavy elements than $_{26}$Fe are thought to be produced via NC by ***s-process***, but origin of Pt , Au ++ (rare metals) remains mystery
- "Kilonova" is a candidate - also emit line γ rays at 30 keV – 3 MeV ?

MeV observations in the past

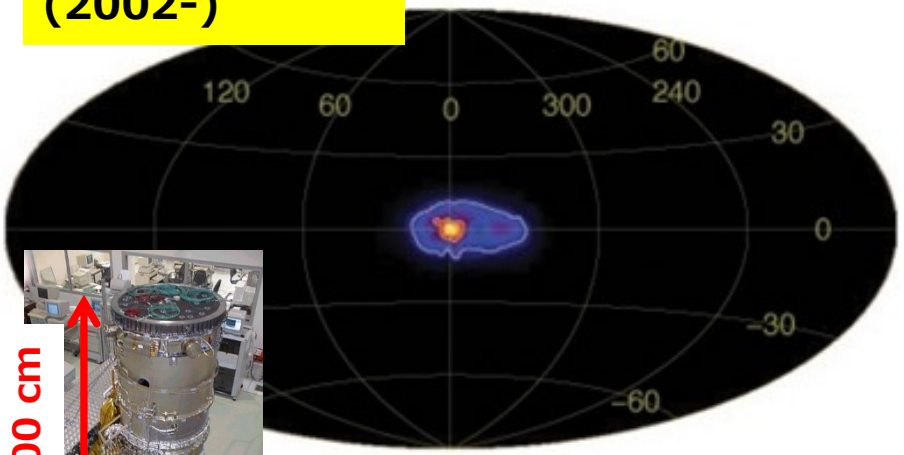
COMPTEL/CGRO (1991-2000)



1.3 tons

1.8MeV (^{26}Al)

SPI/INTEGRAL (2002-)



1.3 tons

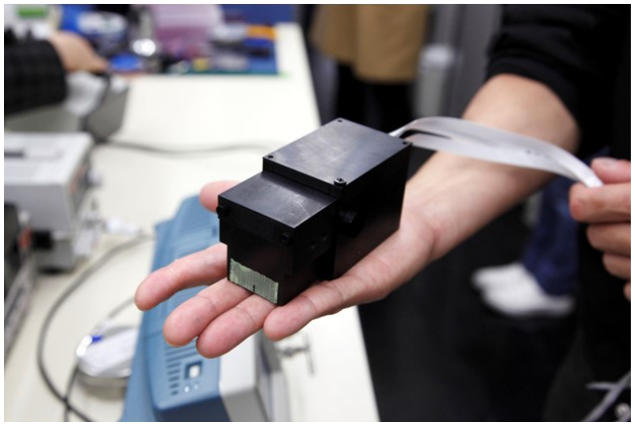
511keV (e^-e^+)

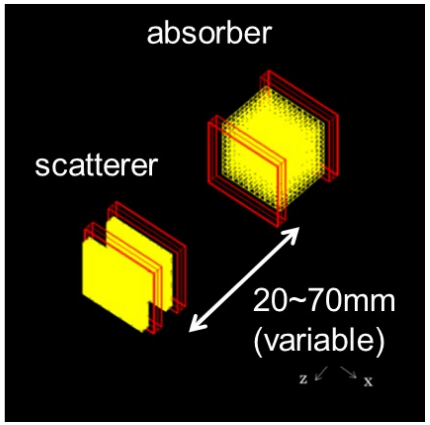
- First MeV survey by COMPTEL/CGRO resulted in many discoveries, like 511 keV emission from GC, 1.8 MeV (^{26}Al) from Gal. plane
- "Dark age" after 2000's – many difficulties in terms of cost, man power, rockets etc

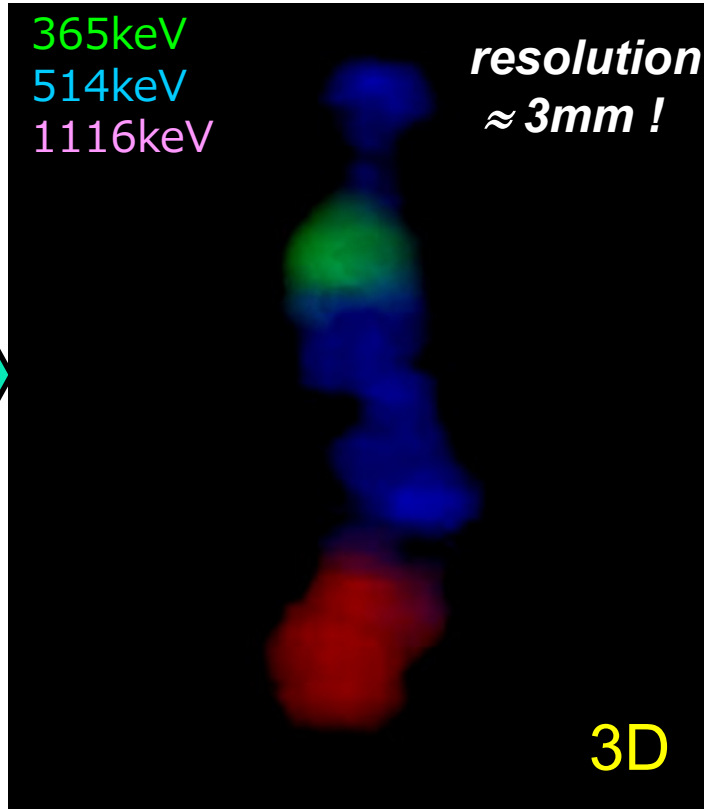
→ ***What if we can do MeV observation with a 50-kg class, very small satellite?***

Challenge 1 : palm-sized CC

Kishimoto et al. 2017, *Sci. Rep.*





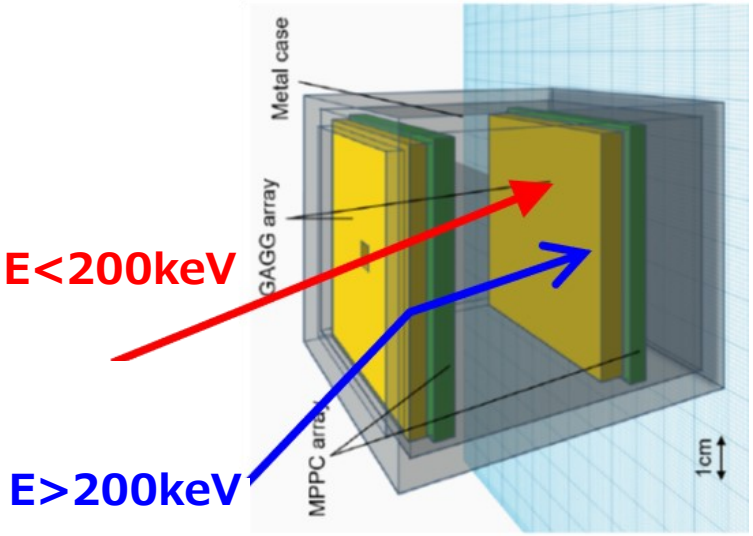


Parm-sized CC w/ 3D position-sensitive scintillator

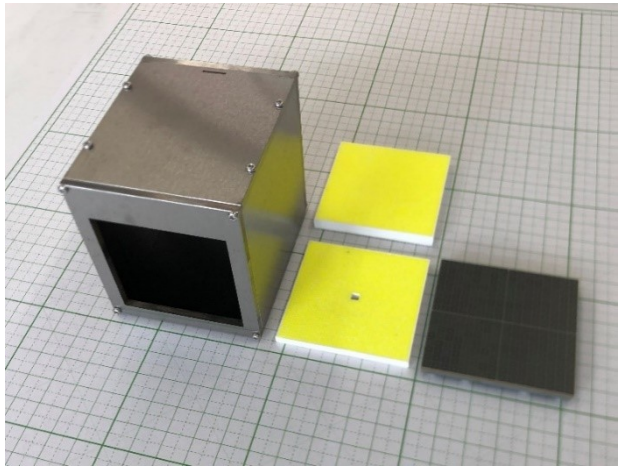
JP6145248/5991519

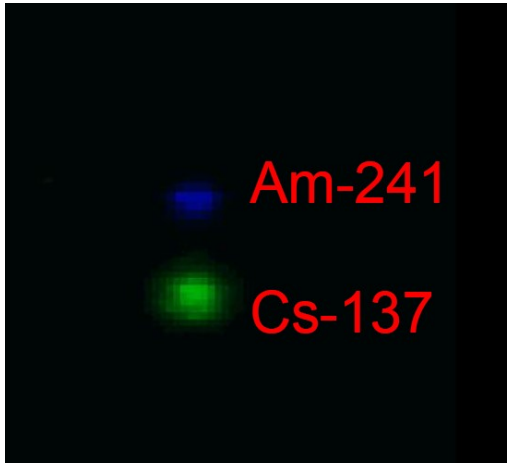
- **3D *in vivo* CC imaging of a mouse**
  - ✓ Accumulation of ^{131}I (throat), ^{85}Sr (bone), ^{65}Zn (stomach) w/ activity 1MBq ~ 1ng/ml
- **Reduced weight and size of gamma-ray imager**

Challenge 2 : wide-band imaging

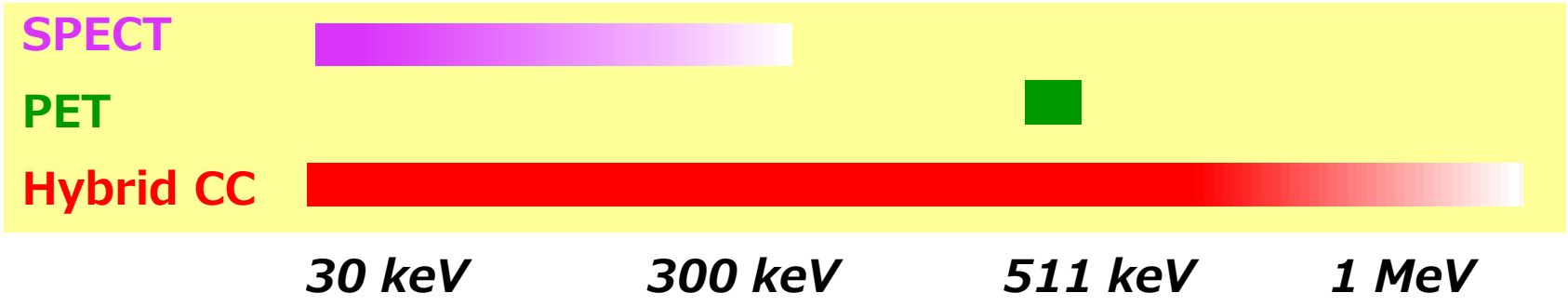


Omata et al. 2020; 2022, Sci. Rep.





- A scatterer with an "active pinhole" (5×5mm^2) in the center:
  - ✓ E < 200 keV as a pinhole camera
  - ✓ E > 200 keV as a conventional Compton camera
- Extend the imageable energy range down to **30 keV!**

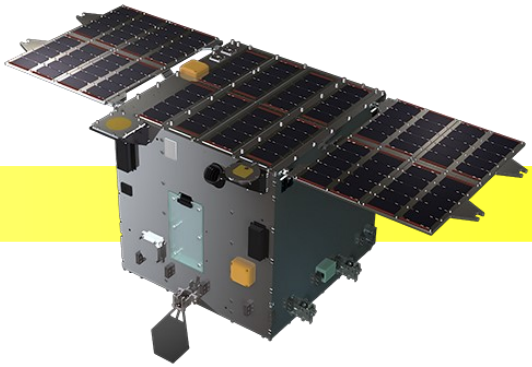


Challenge 3: small satellites

2021: HIBARI

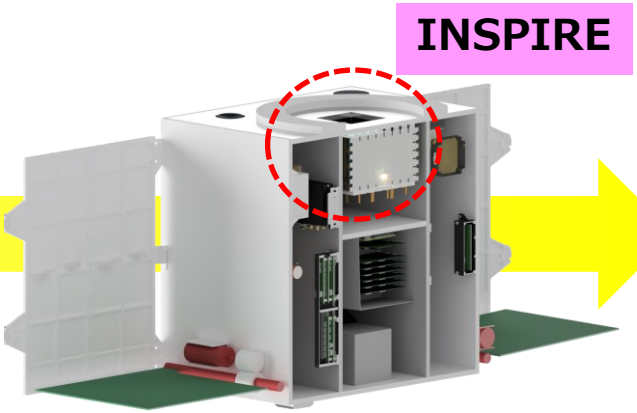
Demonstration of variable shape control

2025: Petrel



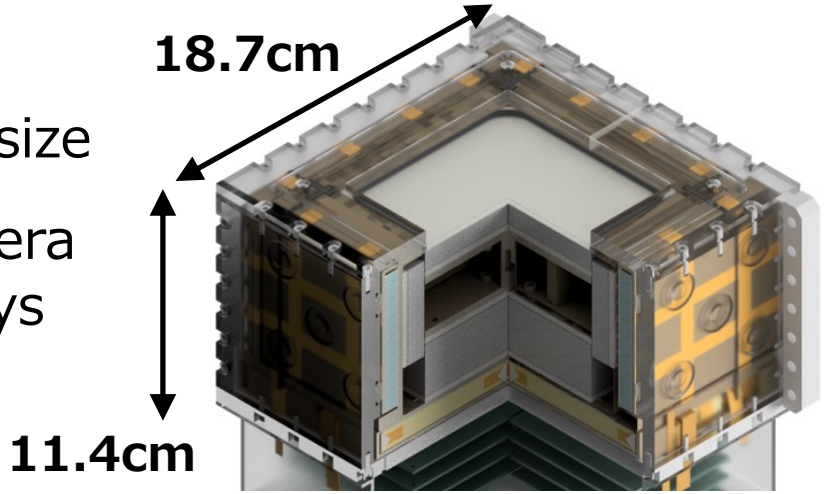
UV telescope and Earth monitor

2027: GRAPHIUM

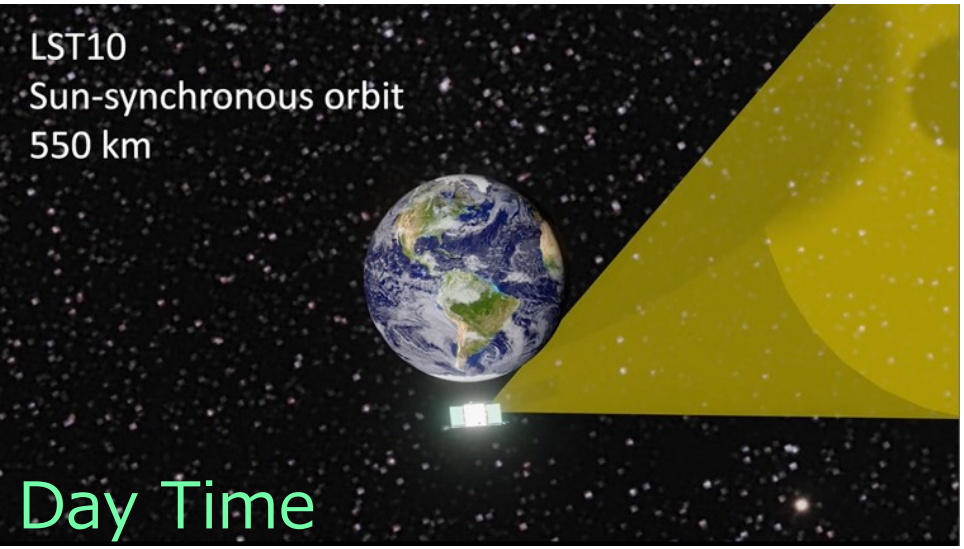


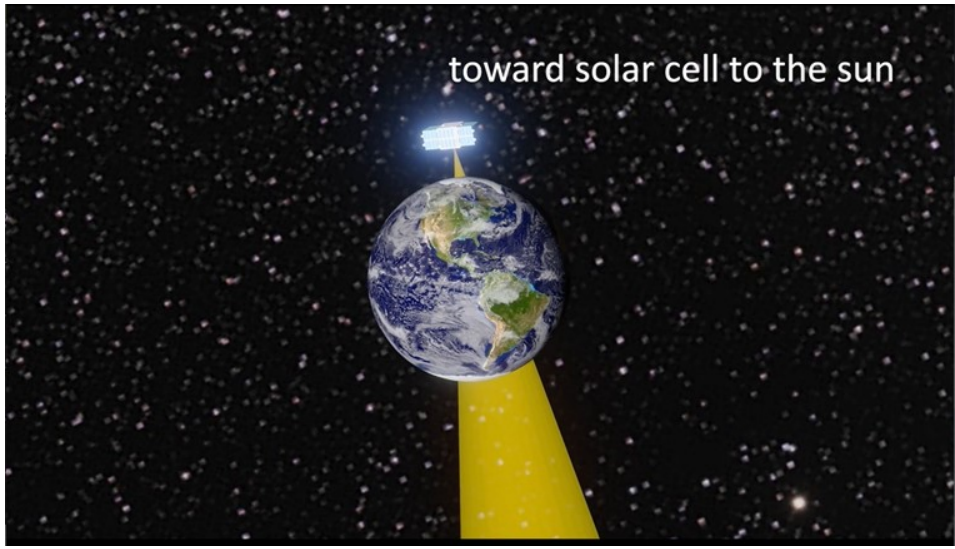
MeV all-sky survey + FF demonstration

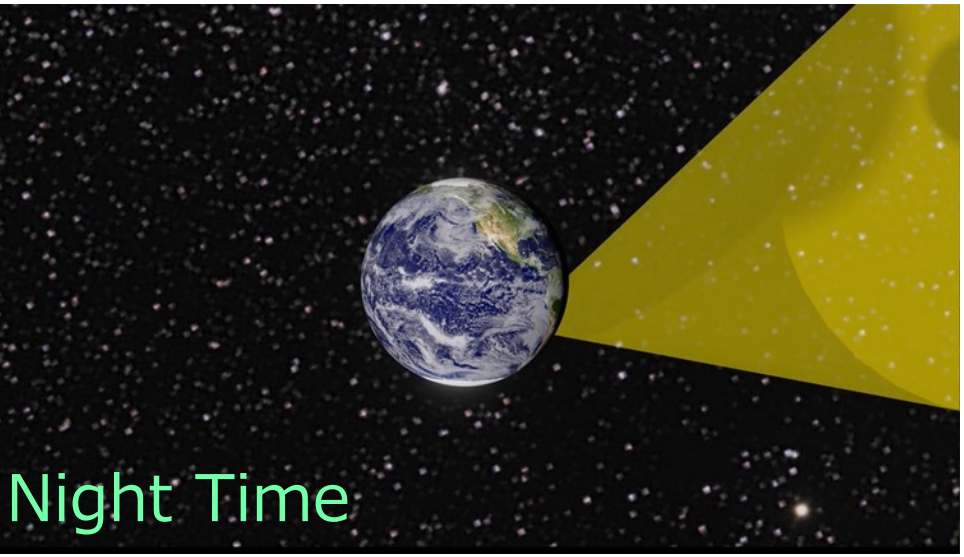
- 3rd Series of Tokyo Tech satellite w/ **75kg and 50x50x50 cm** in size
- **INSPIRE**: Hybrid Compton camera to monitor **30 keV – 3 MeV** γ rays w/ a single detector

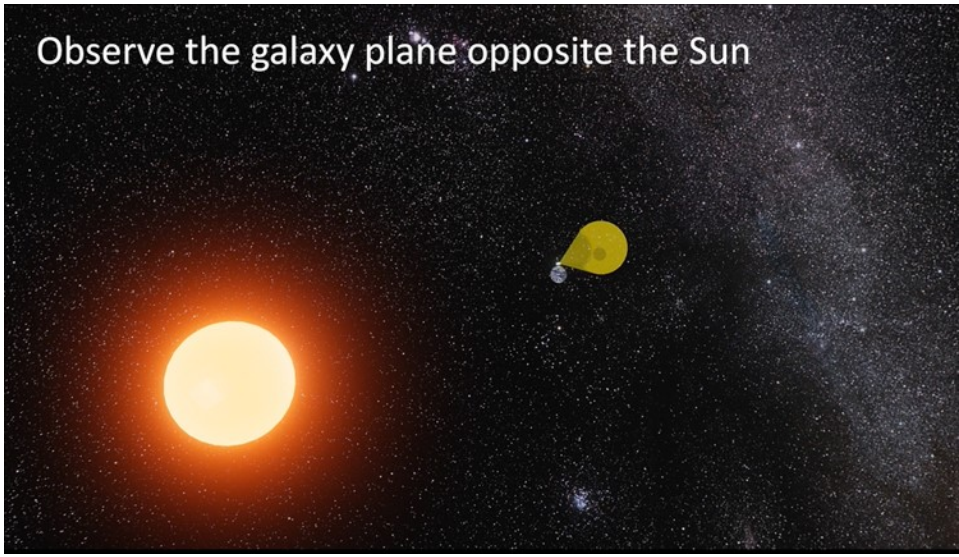


Observation Simulation

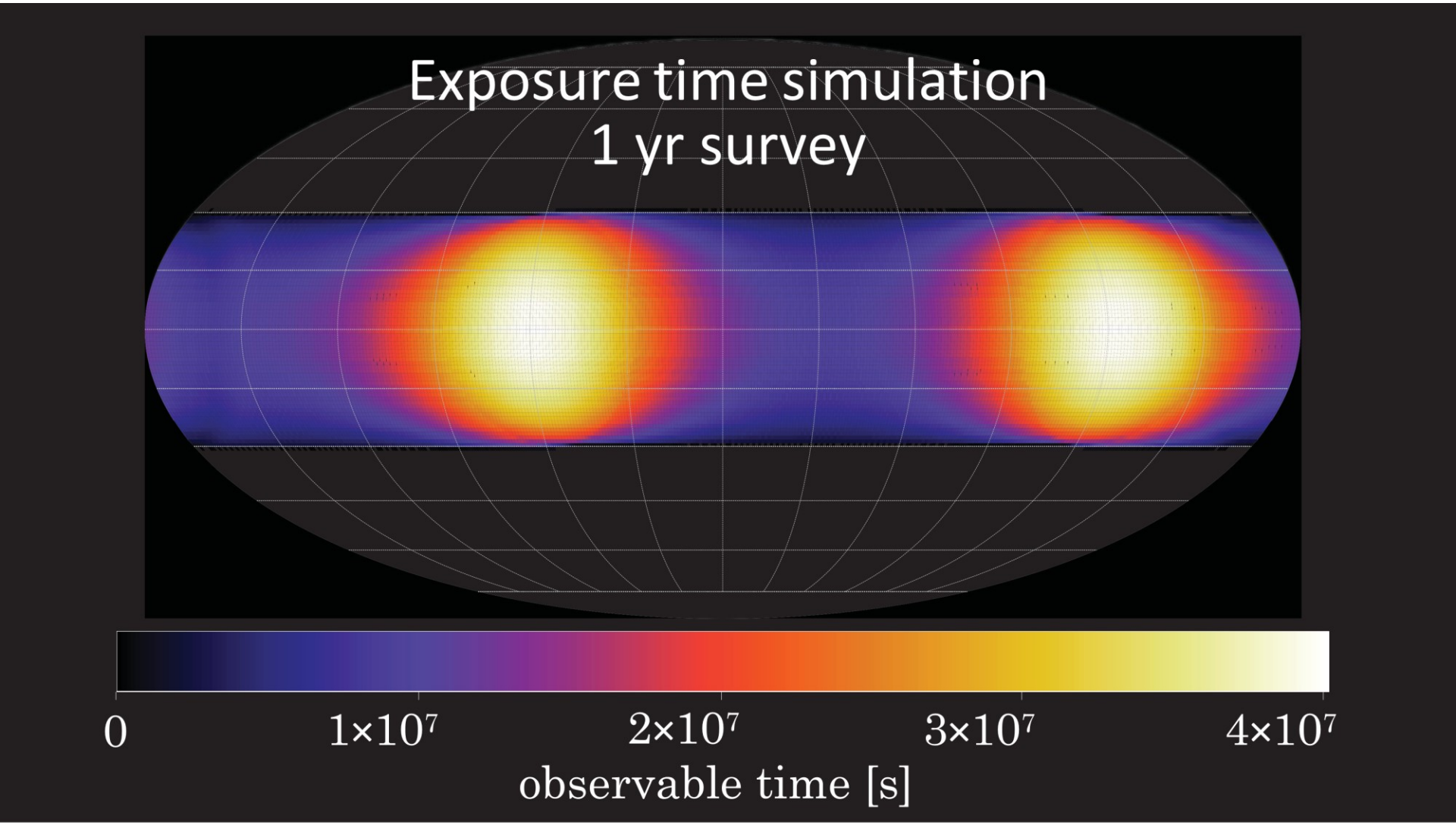




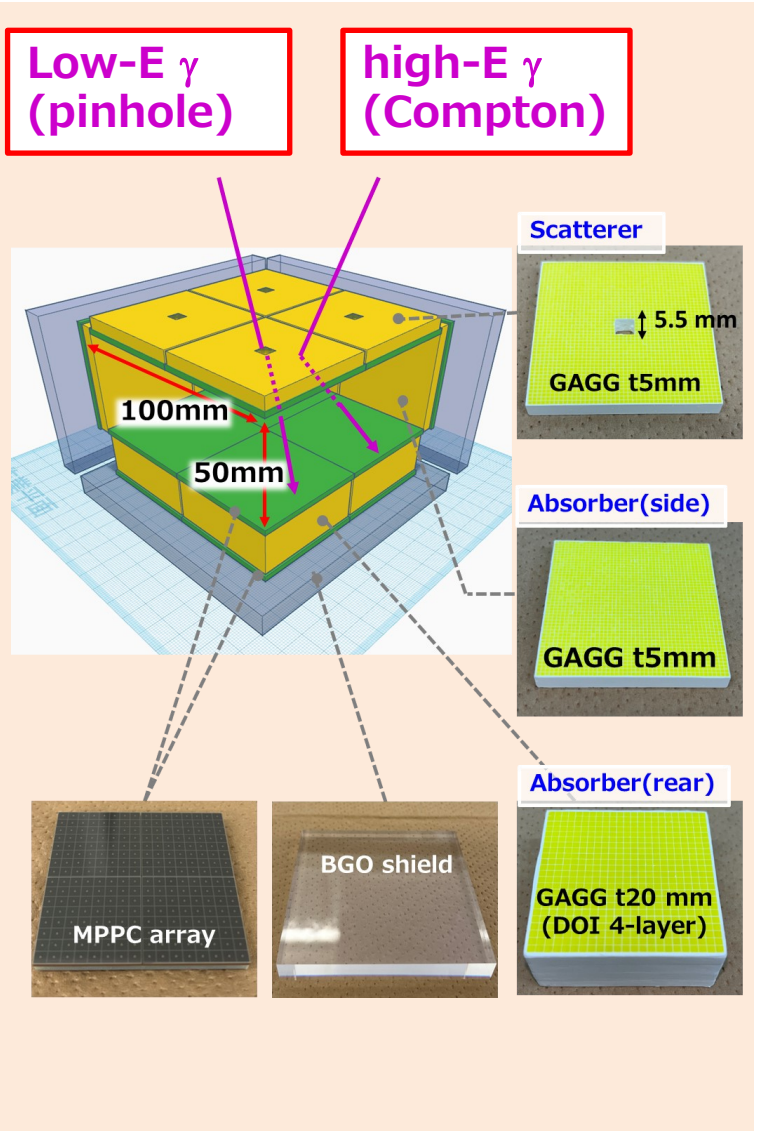


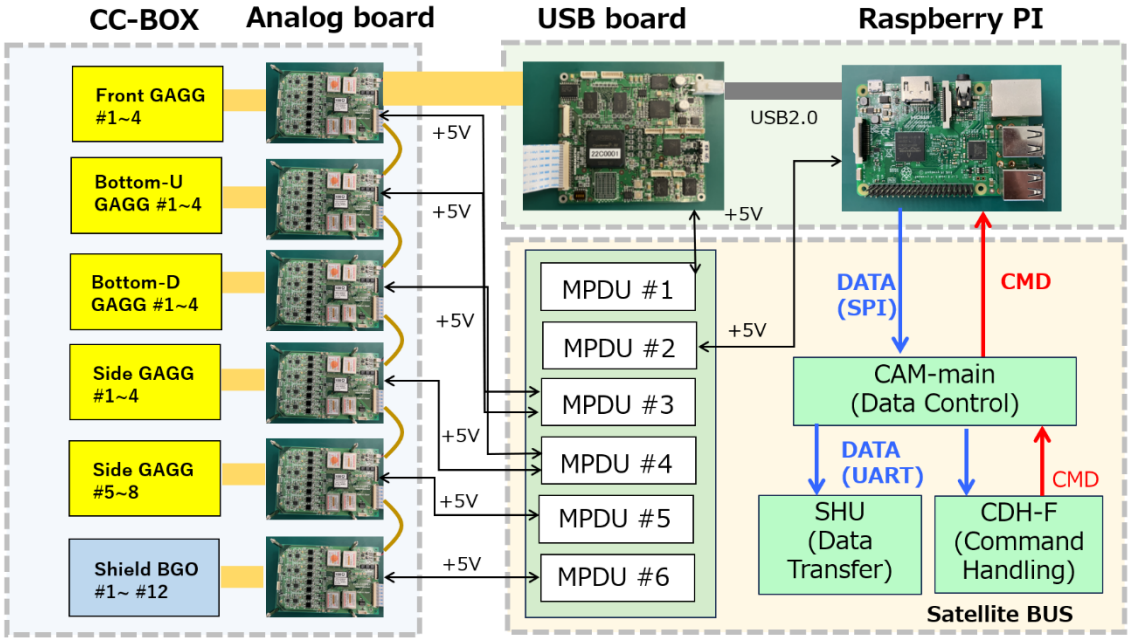


Exposure Map



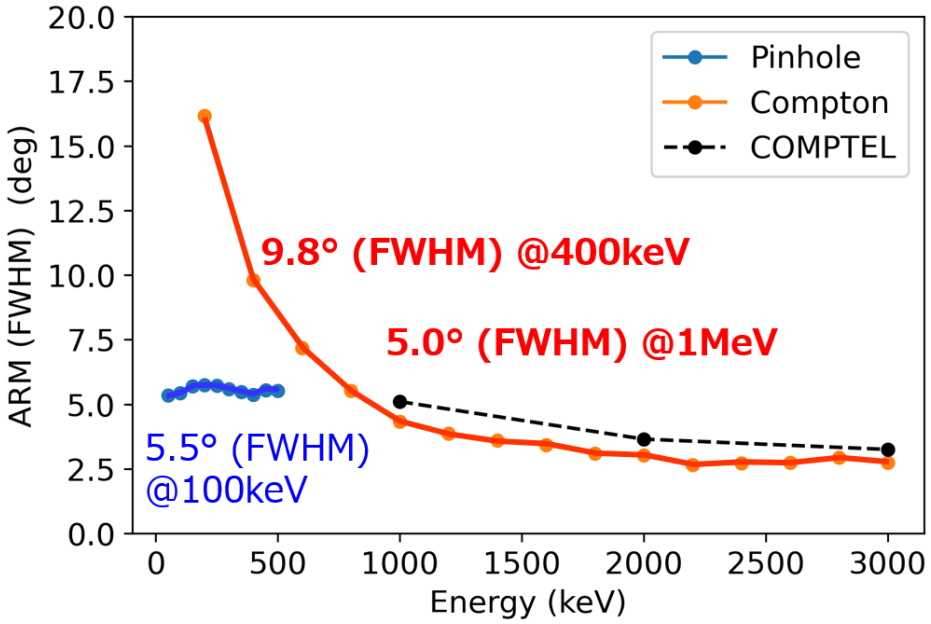
INSPIRE: system configuration

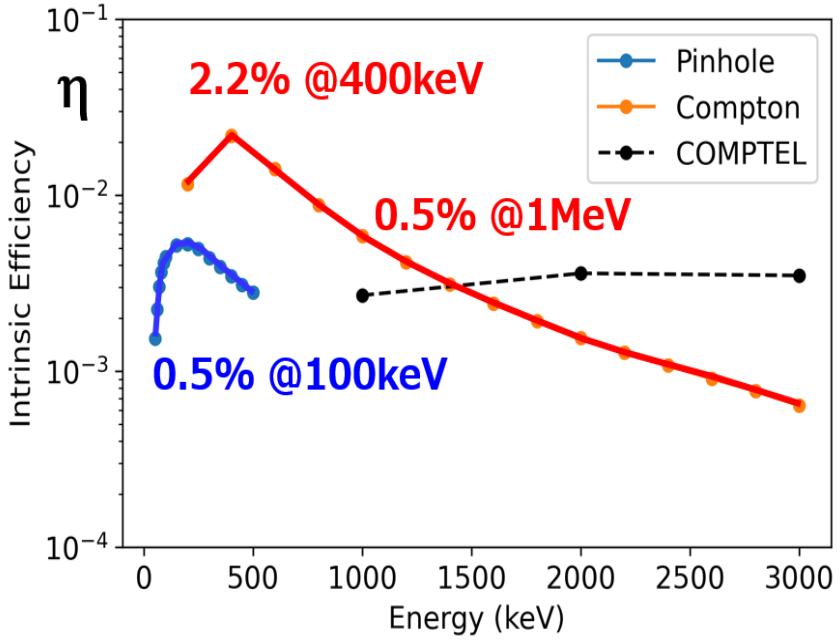




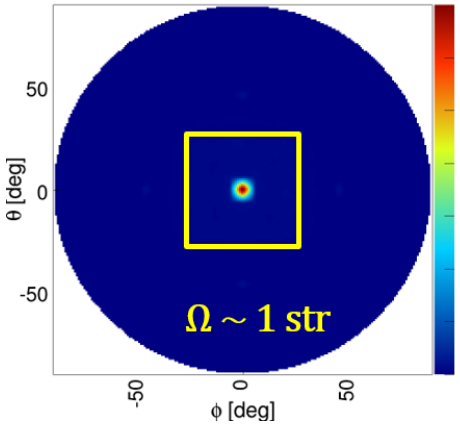
- 3D position sensitive Ce:GAGG array
  + 16x16ch MPPC array
- Simultaneous X and γ-ray imaging:
  Pinhole (30-200 keV)
  + CC box (150-3,000 keV)
- Compact DAQ system :
  total power ~ 18W, weight ~ 10kg

Δθ (ang. res.) and η (int. eff.)

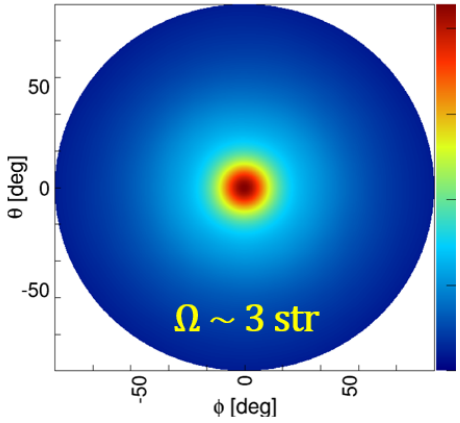




Pinhole 100keV



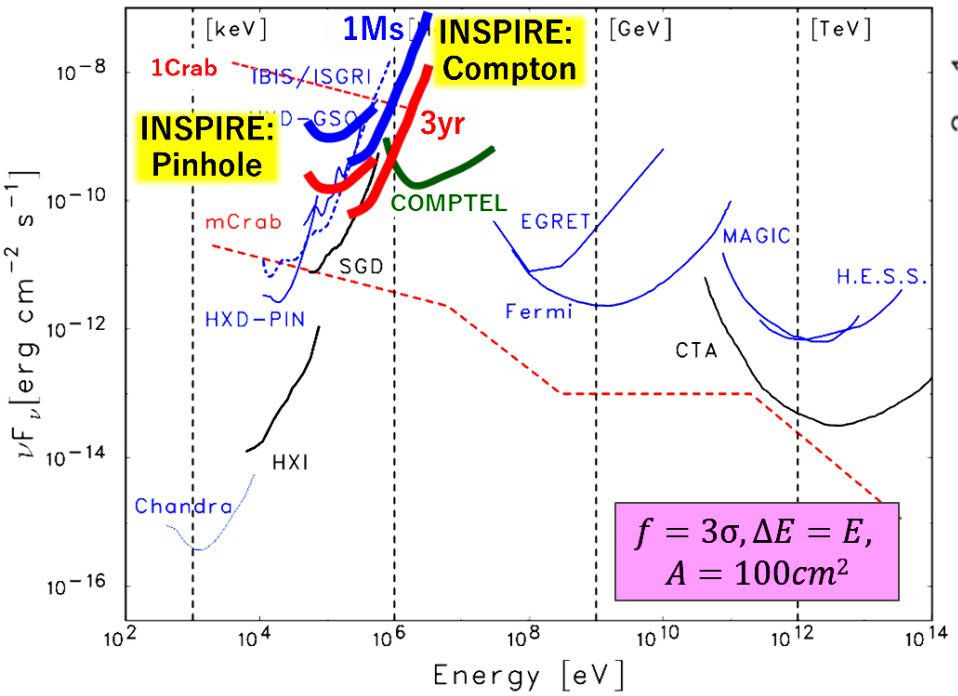
Compton 400keV



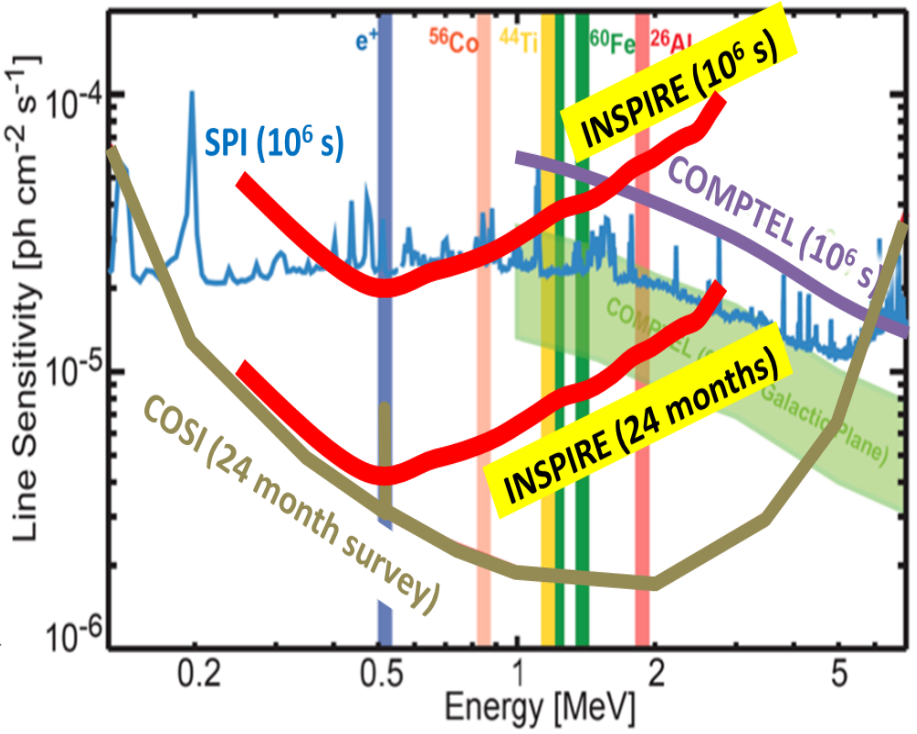
- 3D position sensitive GAGG
  - ✓ Typical angular resolution
    Δθ ~ 5deg (FWHM)
  - ✓ Wide FOV w/ **η > 0.5 %**
    dΩ ~ 1str (pinhole)
    ~ 3str (Compton)

Continuum & line Sensitivity

Takahashi et al. 2012



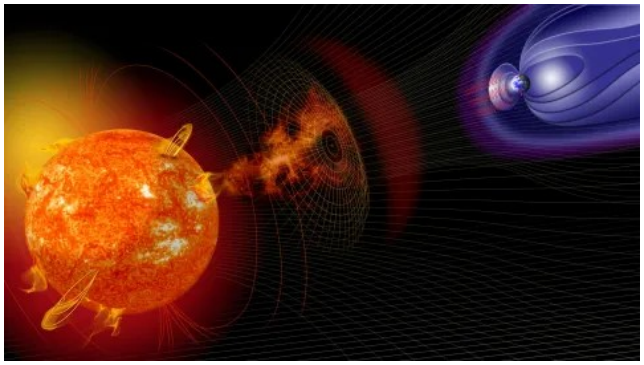
Tomsick et al. 2021

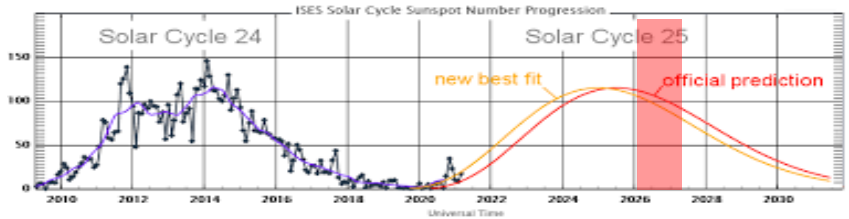


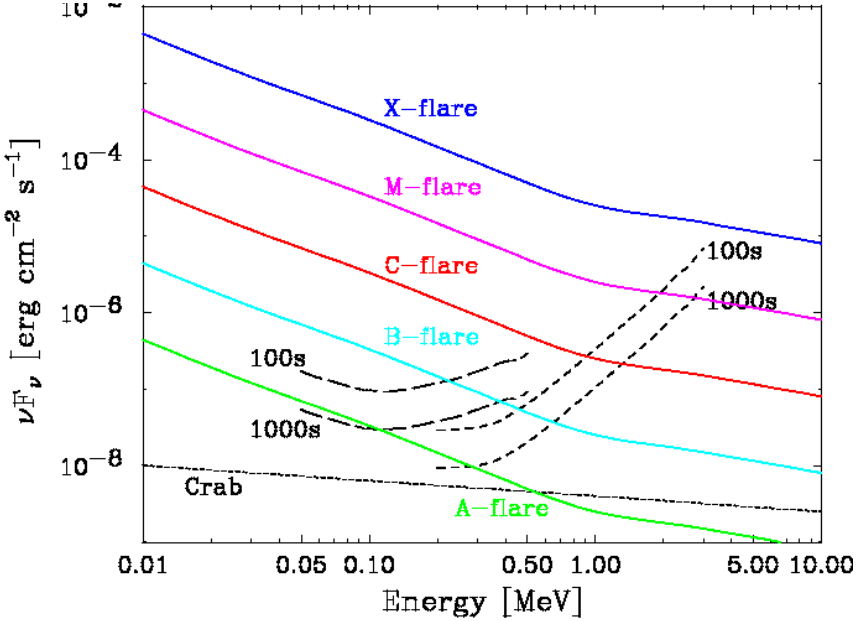
- **For continuum obs.**
  - ✓ Possible targets: Crab, Cyg X-1, Cen-A, NGC4151, AGN flare
- **For narrow line obs.**
  - ✓ Line sensitivity is almost equal to that of COMPTEL at 1.5 MeV, but can extend sensitivity well **below 1 MeV**
  - ✓ E < 0.5 MeV sensitivity almost comparable w/ COSI

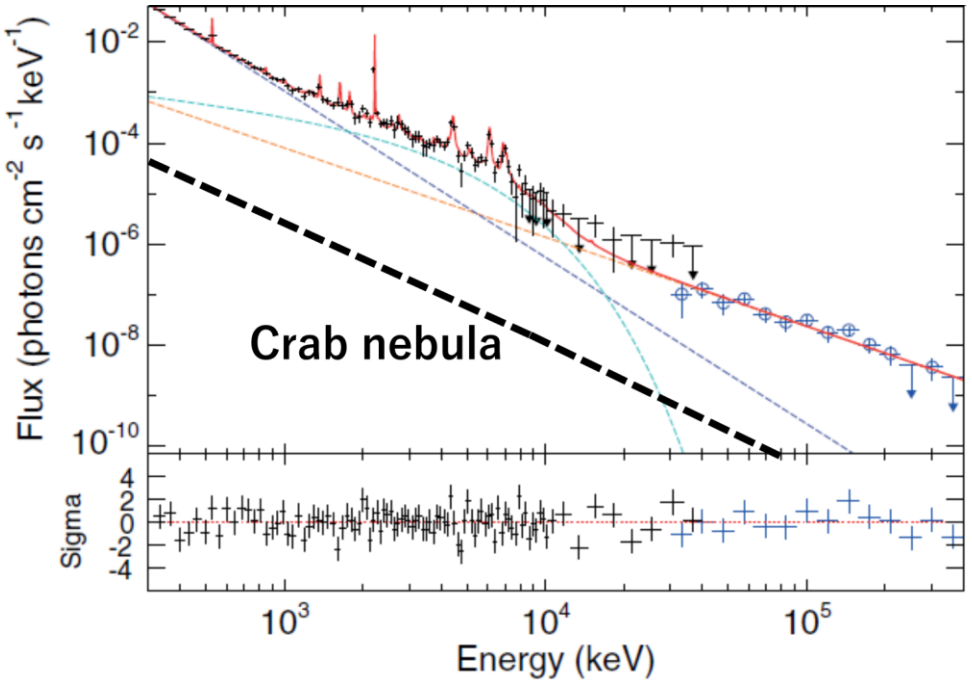
Observation of Solar flare

Ackermann et al. 2012



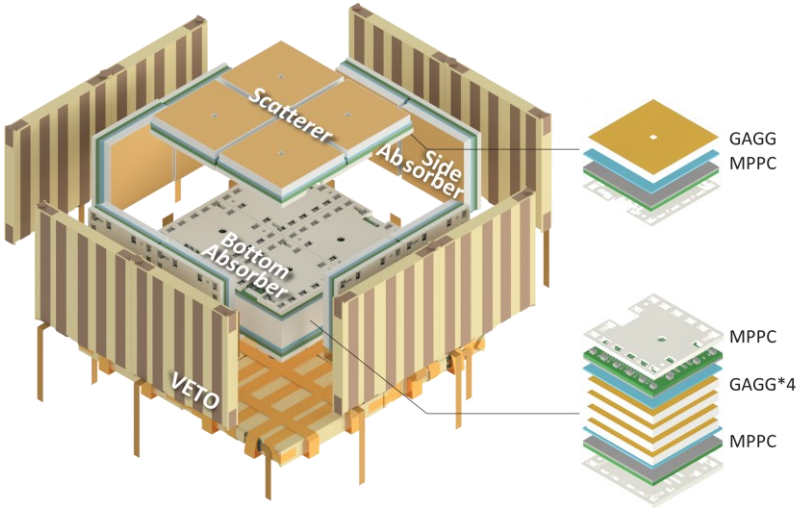




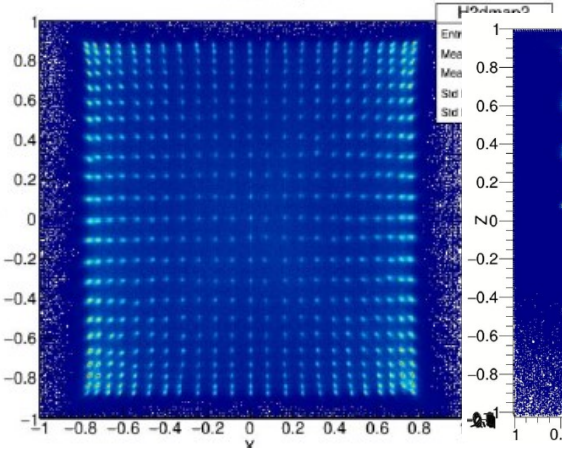


- Very bright and frequent :
  - ✓ ~5/day for C-class flare
  - ✓ ~0.7/day for M-class flare
- Various de-excitation lines w/ along with non-thermal bremss:
  e^-e^+(511keV), ^{56}Fe, ^{24}Mg (0.5-2MeV)
  NC (2.2MeV), ^{12}C (4.4MeV)++

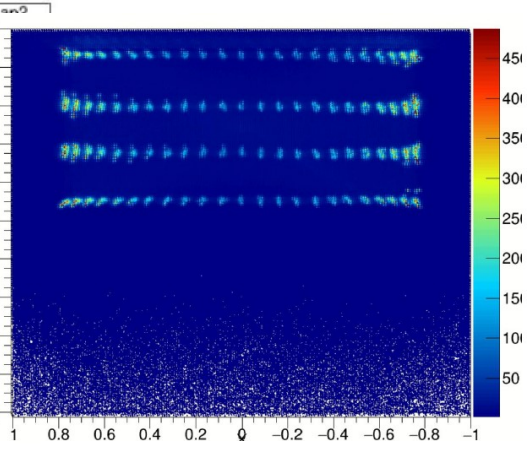
EM fabrication and testing

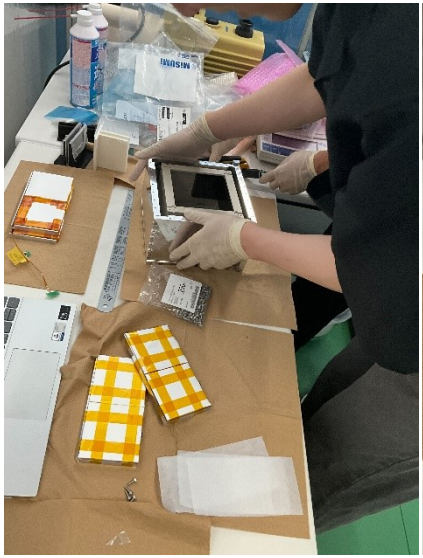


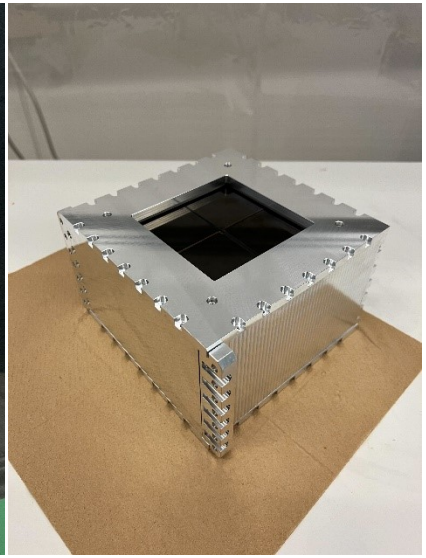
Position MAP (XY)



Position MAP (Z)



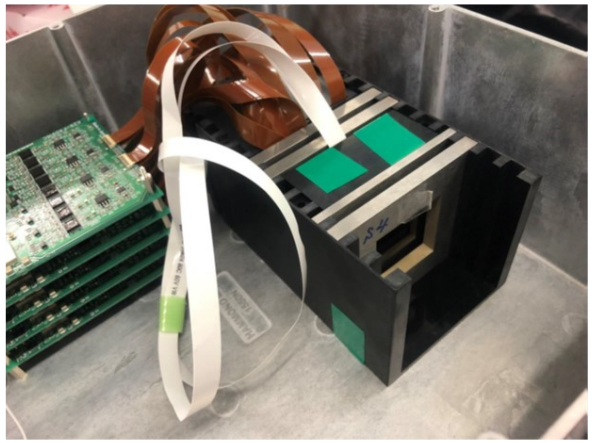


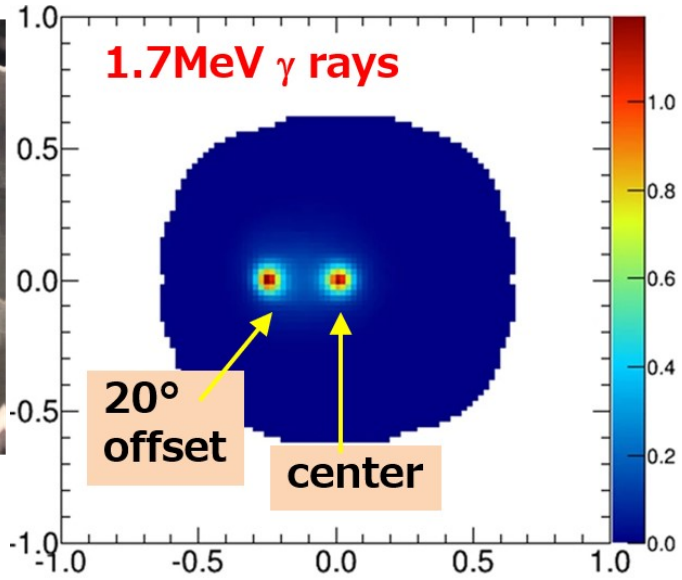


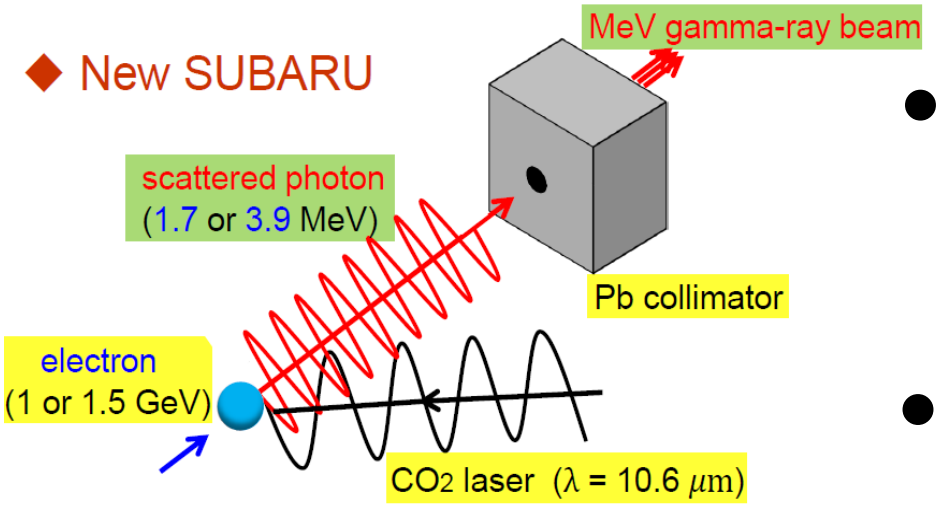
- ¼ scale of full-FM sensor
  (1 unit of hybrid CC implemented)
- **ΔE/E ~ 5.5%, Δθ ~ 5°** (FWHM)
  @1MeV as expected
- Confirmed detector performance between -40℃ and +85℃ w/ thermal vacuum testing

MeV gamma imaging

Hosokoshi et al. 2019, Nature Sci. Rep.







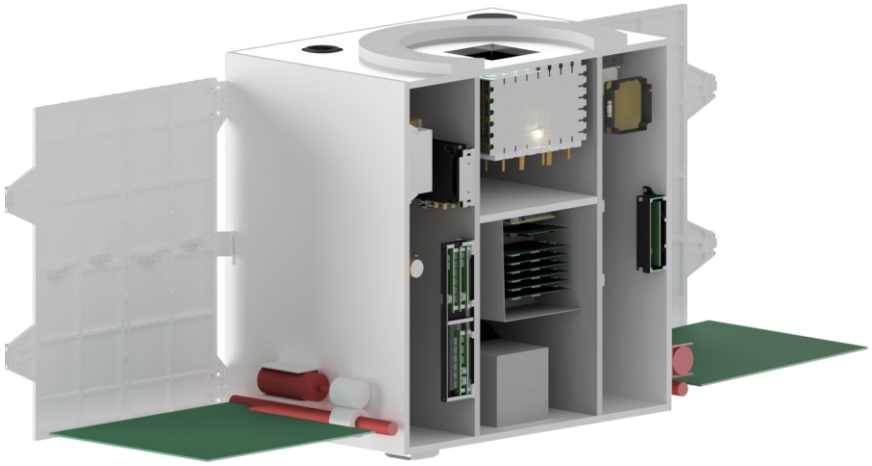
- Experiment was performed at New SUBARU, which provides **monochromatic γ-ray beam** by IC of GeV electrons from SP8
- Measured angular resolutions:
  3.4± 1.1° (FWHM) @ 1.7 MeV
  4.0± 0.5° (FWHM) @ 3.9 MeV

Summary

- We are developing **"GRAPHIUM"** as a new challenge of small satellites for frontiers in space science

- Despite limited resources (i.e., weight, size, budget :-) , GRAPHIUM provides important contribution to MeV astronomy, that is stagnated over 30 years

- Also a compact MeV camera is highly useful in various other fields, such as nuclear medicine and atmospheric science



Kataoka et al. 2024, NIM-A