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ERATO

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INSPIRE: challenge of 50-kg class satellite to open up MeV gamma-ray astronomy

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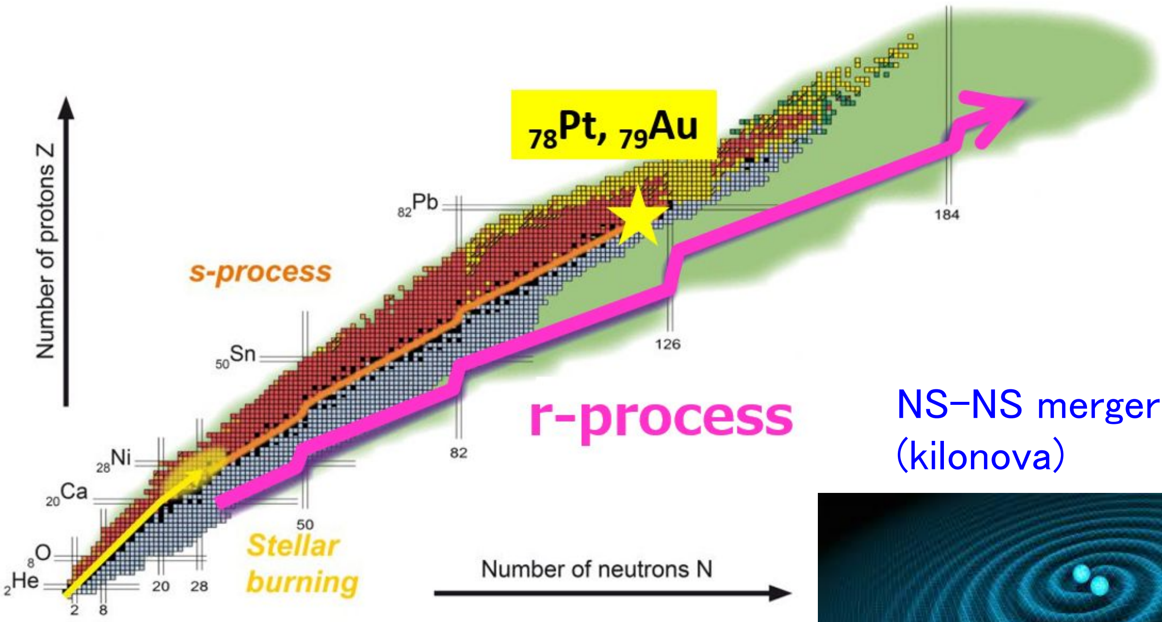
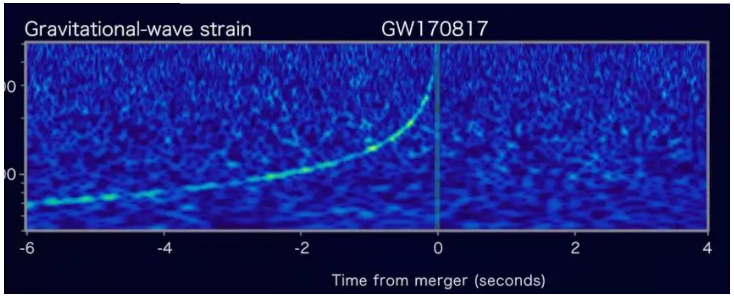
D.Yoshimura, H.Yoshida (Tokyo Tech), M.Onishi, S.Takeda (iMAGINE-X)
and *INSPIRE* collaboration

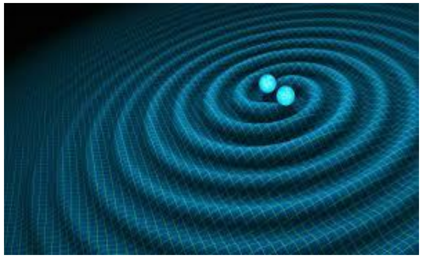
MeV γ rays as nucleosynthesis probe

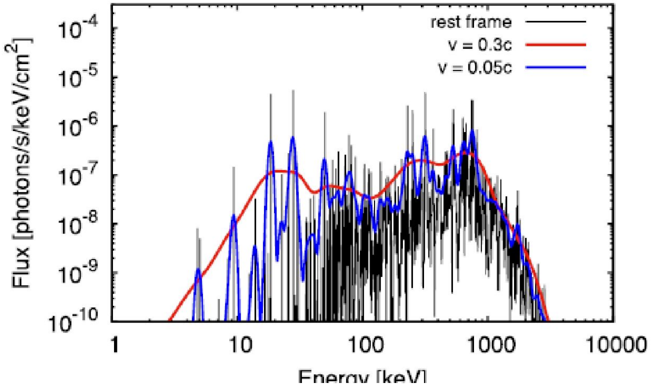


LIGO collaboration 2017



NS–NS merger
(kilonova)



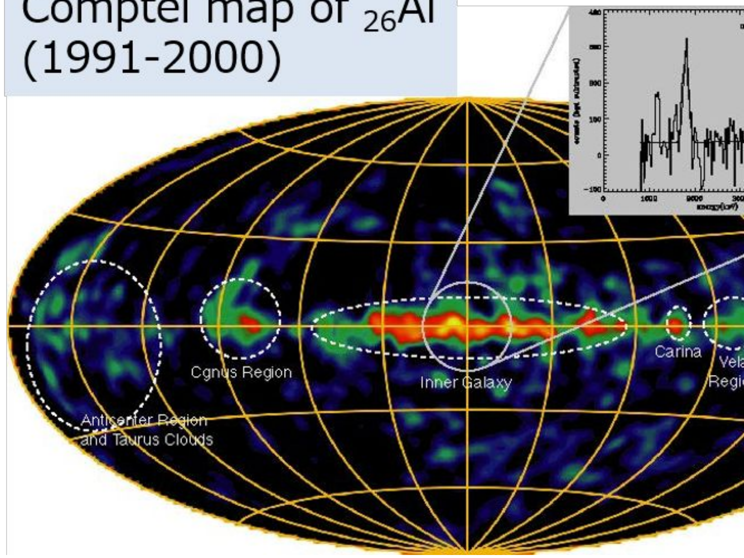


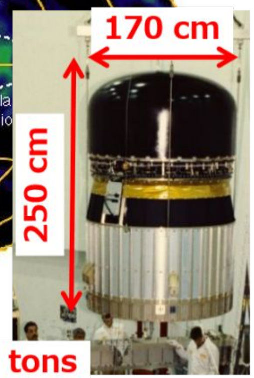
Hotokezaka et al. 2016

- 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 ?

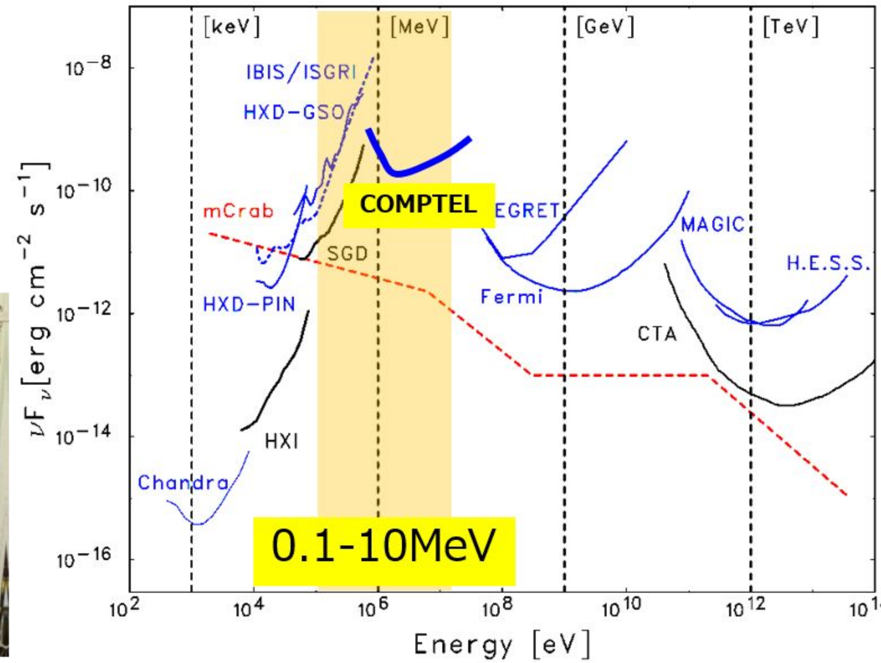
MeV challenge in the past

Comptel map of $_{26}$Al (1991-2000)





Takahashi et al. 2012



- 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 1990's – many difficulties in terms of cost, man power, rockets etc

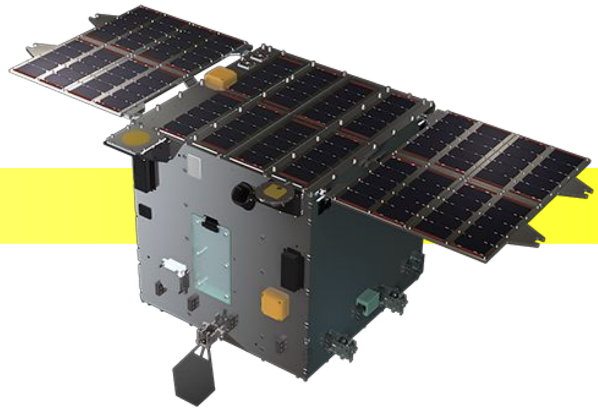
→ ***What if we can do MeV observation with a university-class, small satellite?***

Our approach: 50kg-class satellites

2021: HIBARI

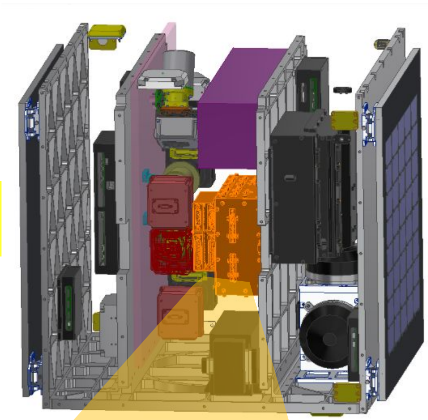
Demonstration of variable shape control

2024: Petrel



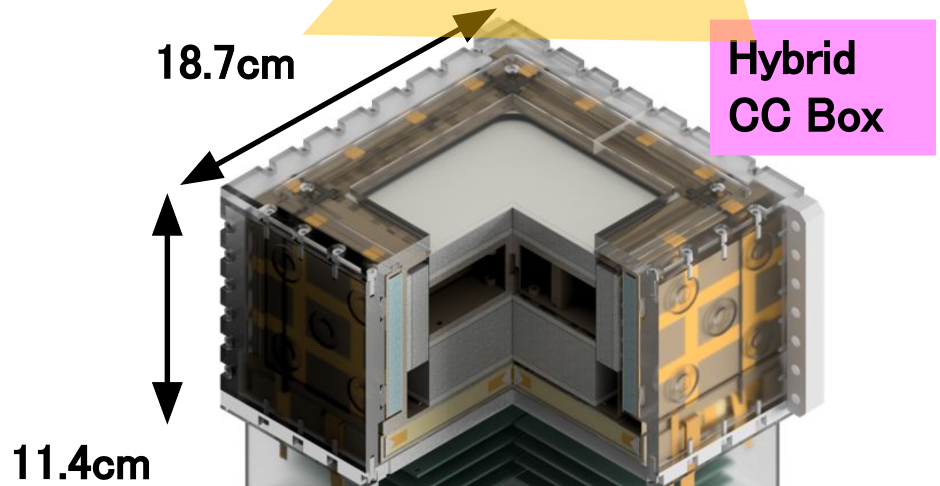
UV telescope and Earth monitor

2027: INSPIRE

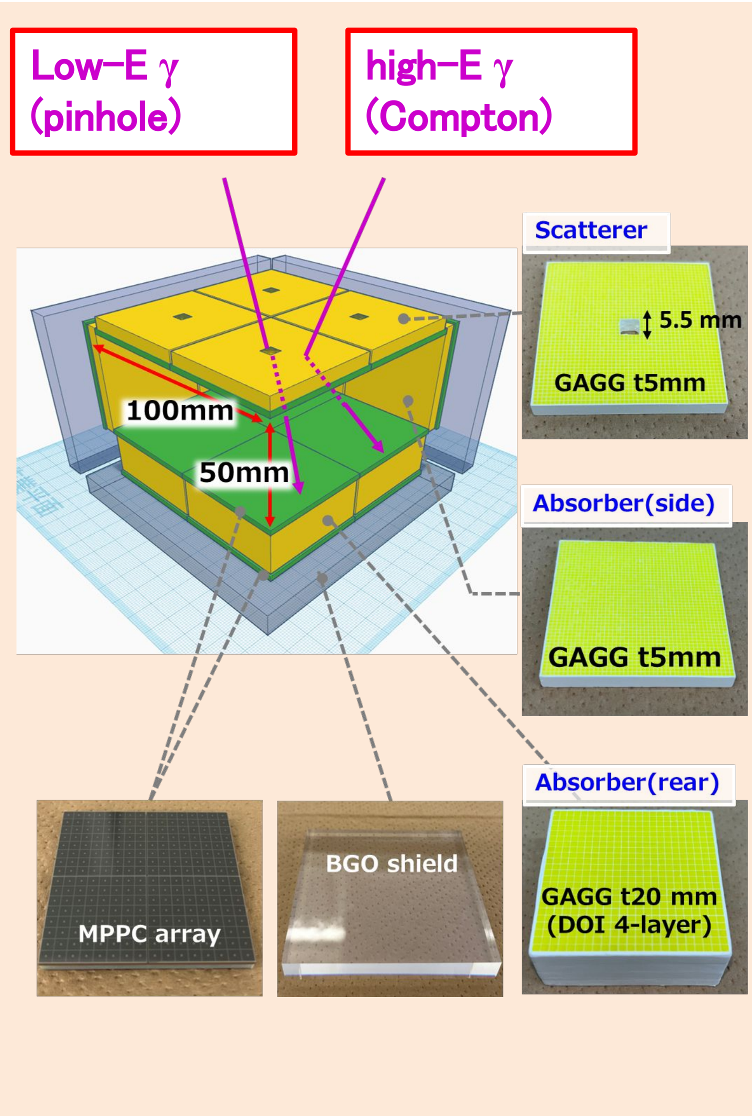


UV+MeV survey, transients search

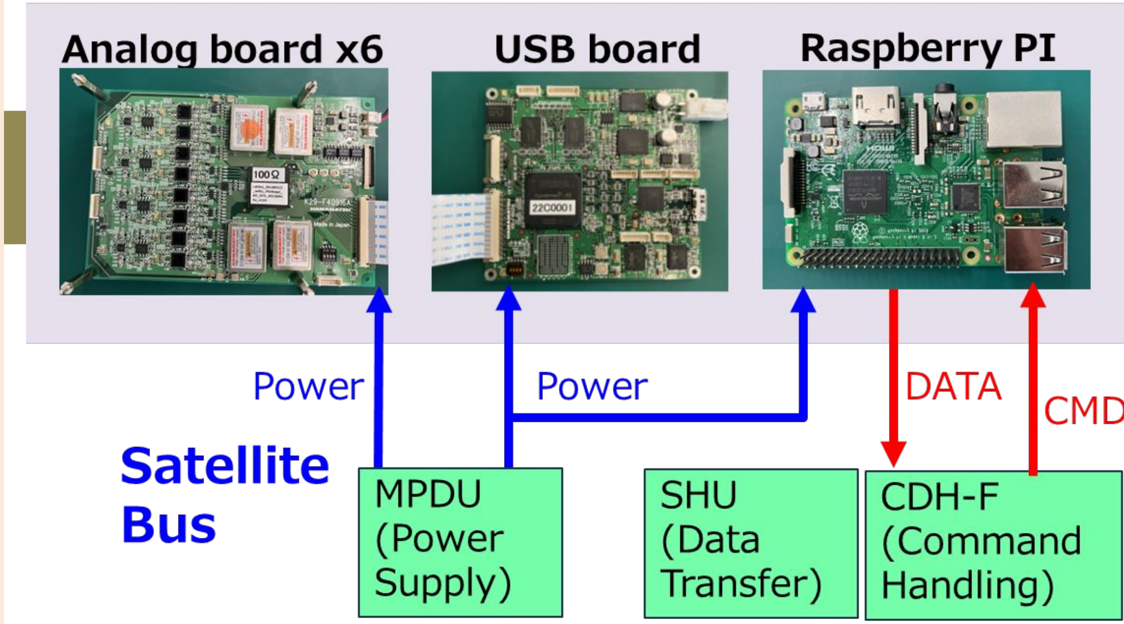
- 3rd Series of Tokyo Tech satellite w/ **50kg and 50x50x50 cm** in size
- Hybrid Compton Camera to monitor **30 keV – 3 MeV** γ rays in a single detector



HCC-BOX: system configuration

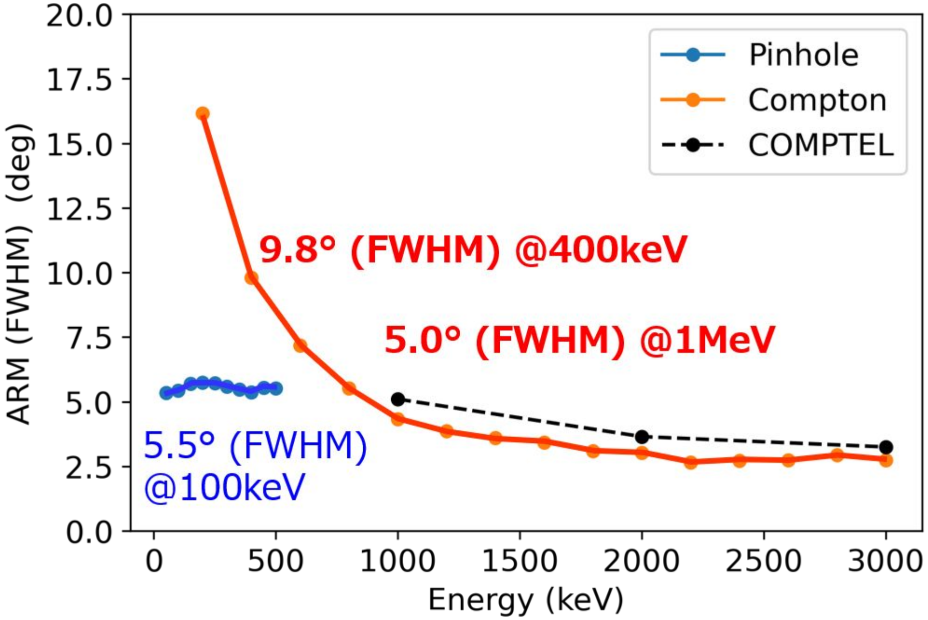


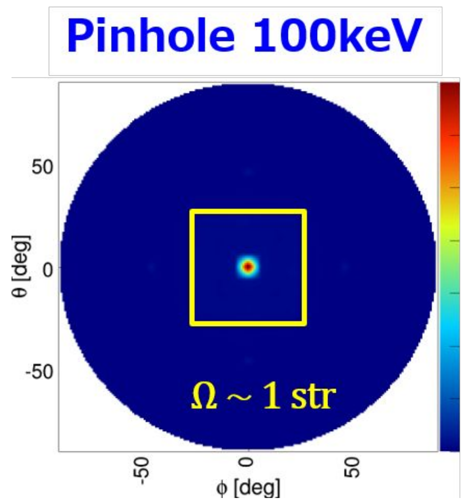
DAQ system

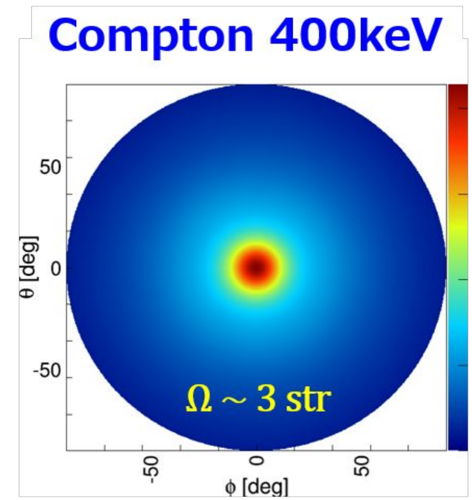


- Simultaneous X and γ-ray imaging:
  Pinhole (30-200 keV)
  + CC box (150-3,000 keV)
- 3D position sensitive Ce:GAGG array
  + 16x16ch MPPC array
- Compact DAQ system :
  total power ~ 18W

Angular resolution

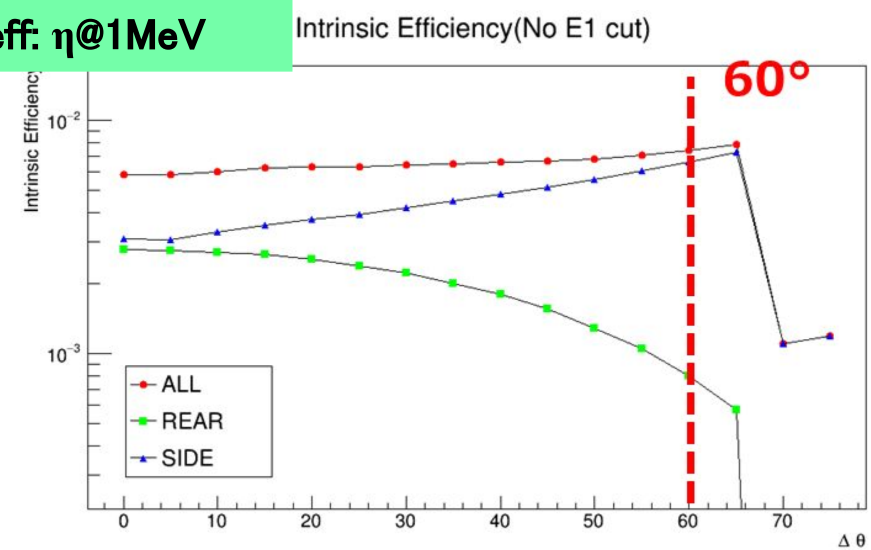




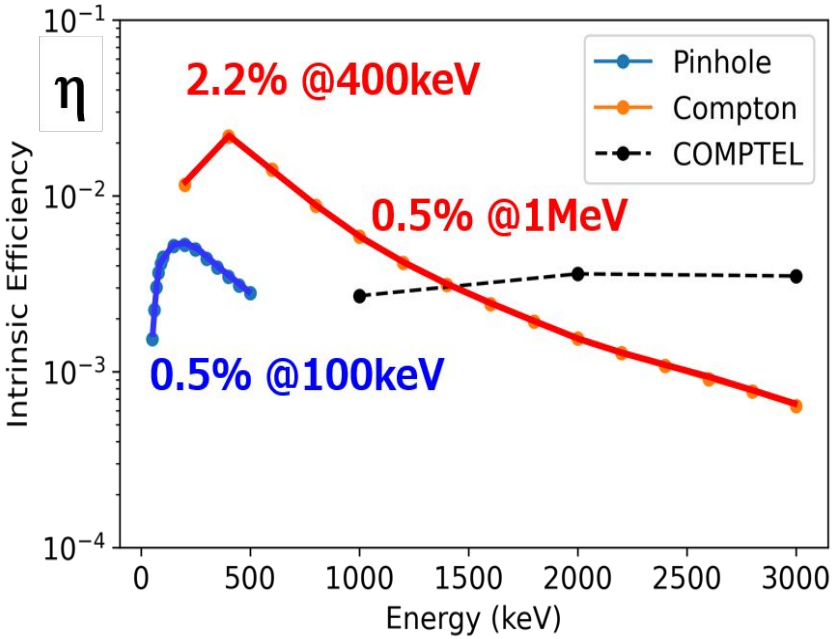


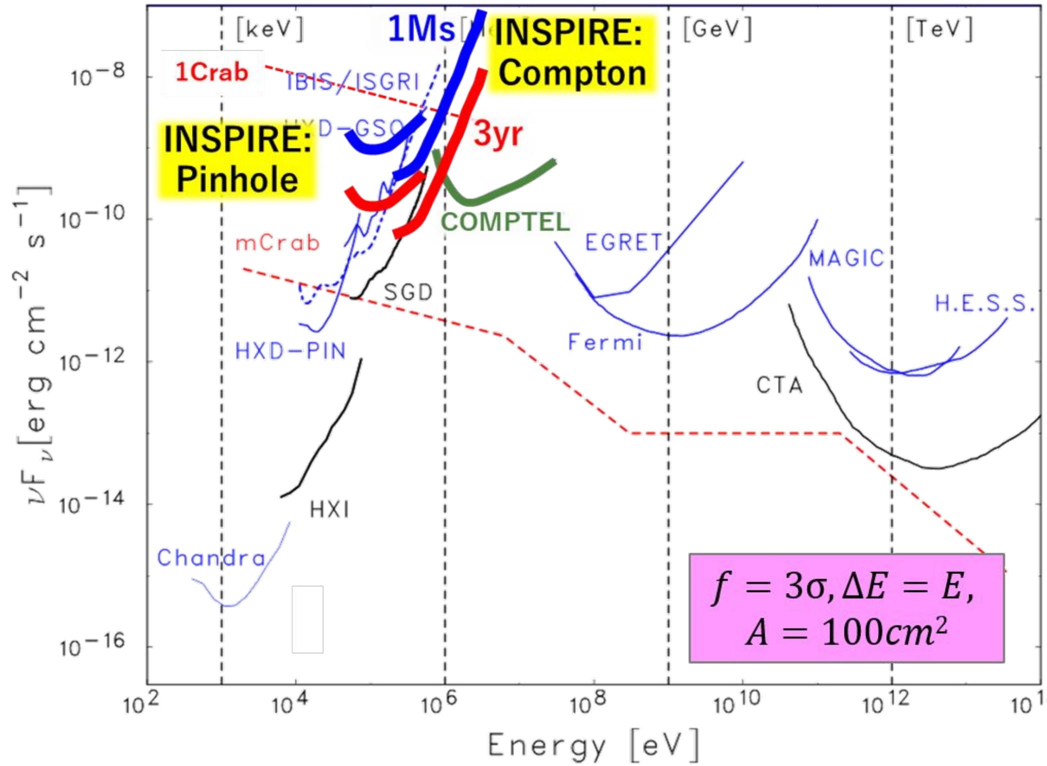
- Wide FOV: **~ 1str (pinhole),**
  ~ 3str (Compton)
- Typical angular resolution
  $\Delta\theta$ ~ 5deg (FWHM)
  between 30 keV to 3 MeV,
  that is better than COMPTEL

intrinsic
eff: η@1MeV



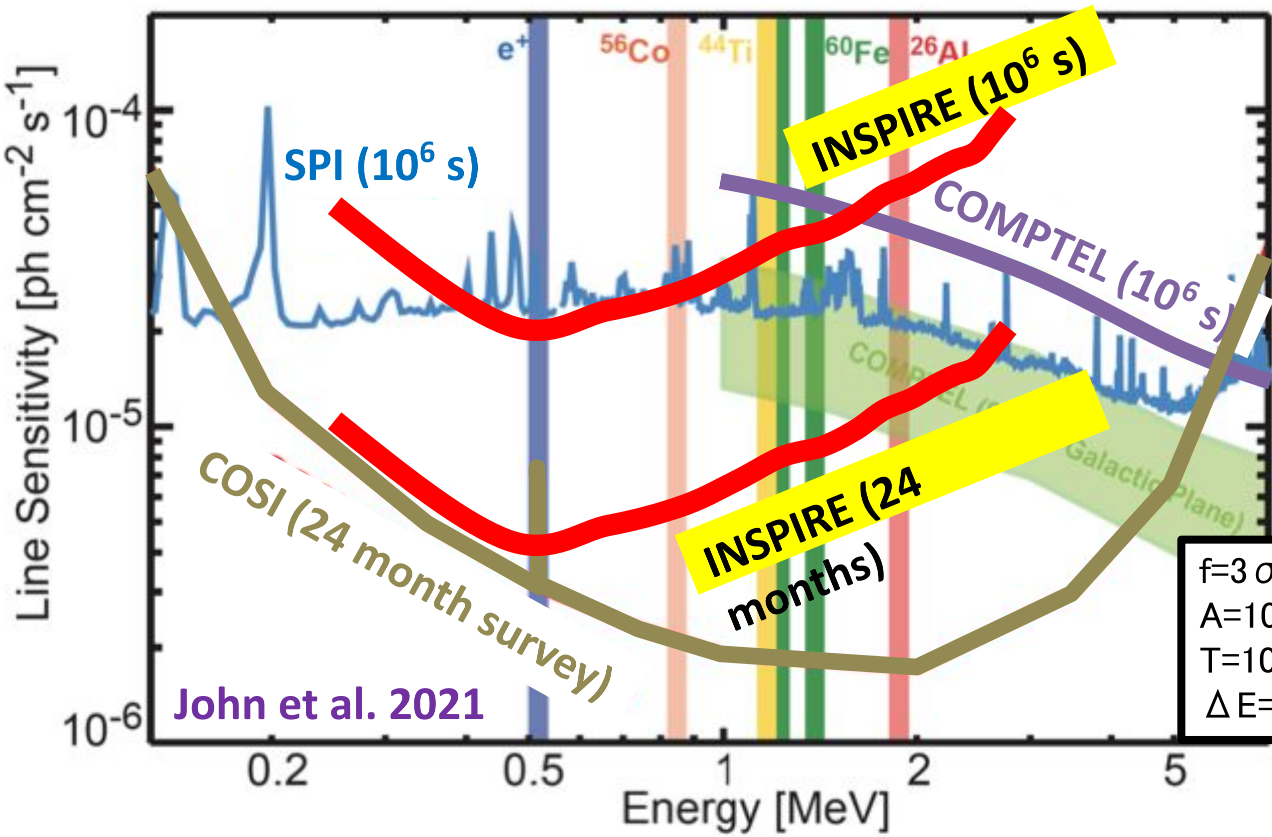
Efficiency & Continuum Sensitivity





- Wide energy coverage :
  30 keV – 3 MeV with **η > 0.1%**
- Intrinsic efficiency better than COMPTEL below ~1.5 MeV
  - ✔ Scatterer and absorber separation : 5cm
    (c.f., ~ 160cm for COMPTEL)
  - ✔ 3D position sensitive GAGG array
    (c.f., single bulk NaI(Tl) of 28cm φ for COMPTEL)

Line Sensitivity



Continuum Sensitivity

$$S(E) = \frac{f}{\eta(E)}\sqrt{\frac{b(E)}{A\,\Delta E\,T}}$$

Line Sensitivity

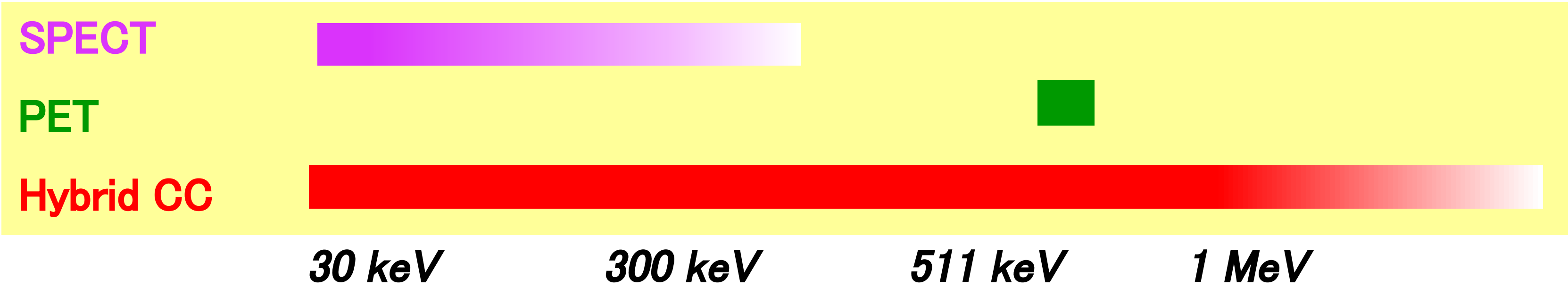
$$S(E) = \frac{f}{\eta(E)}\sqrt{\frac{2b(E)\delta E}{AT}}$$

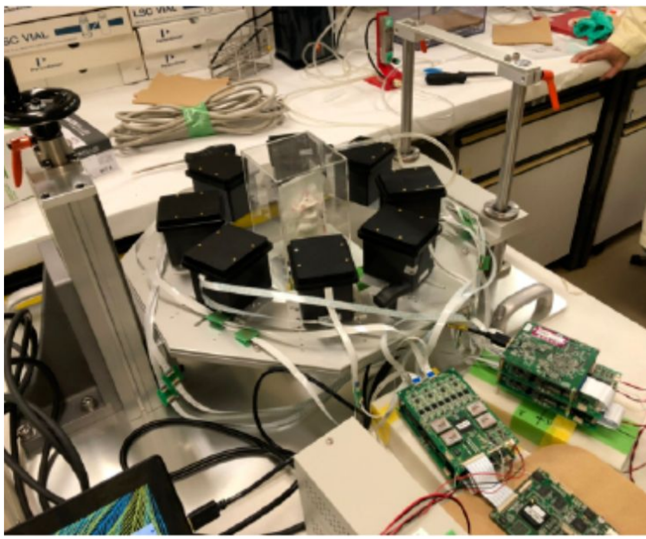
f=3σ
A=100 cm^2
T=10^6 s, 2.4×10^7 s
ΔE=9 % @662keV

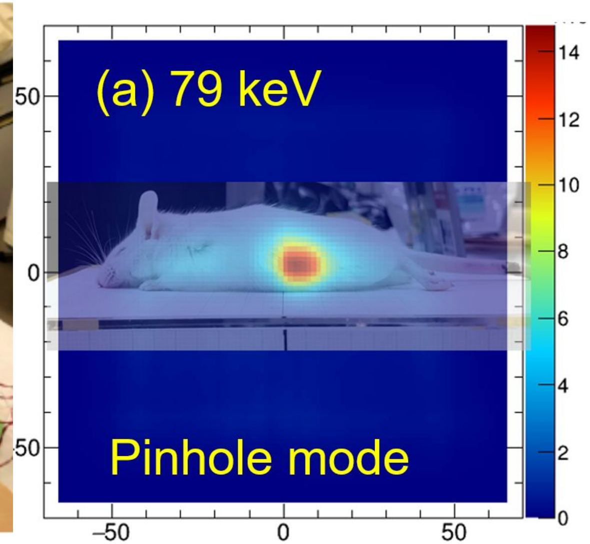
- Line sensitivity is almost equal to that of COMPTEL at 1.5 MeV, but extend the sensitivity well **below 1 MeV**
- E < 0.5 MeV sensitivity almost comparable w/ COSI

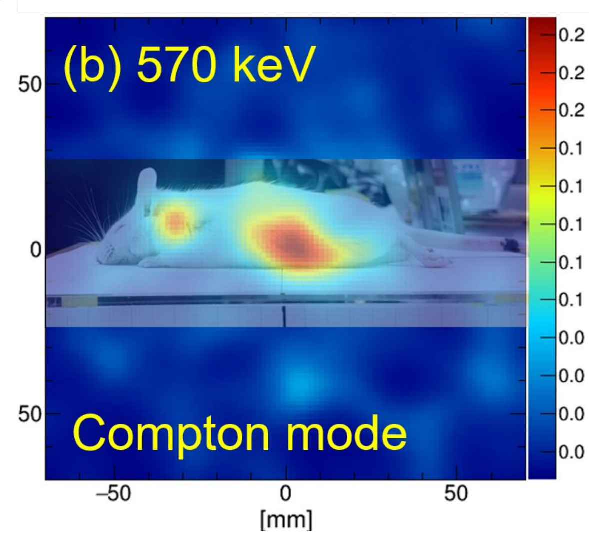
e.g.1 : nuclear medicine

Koshikawa, Masubuchi + 2023, NIM-A



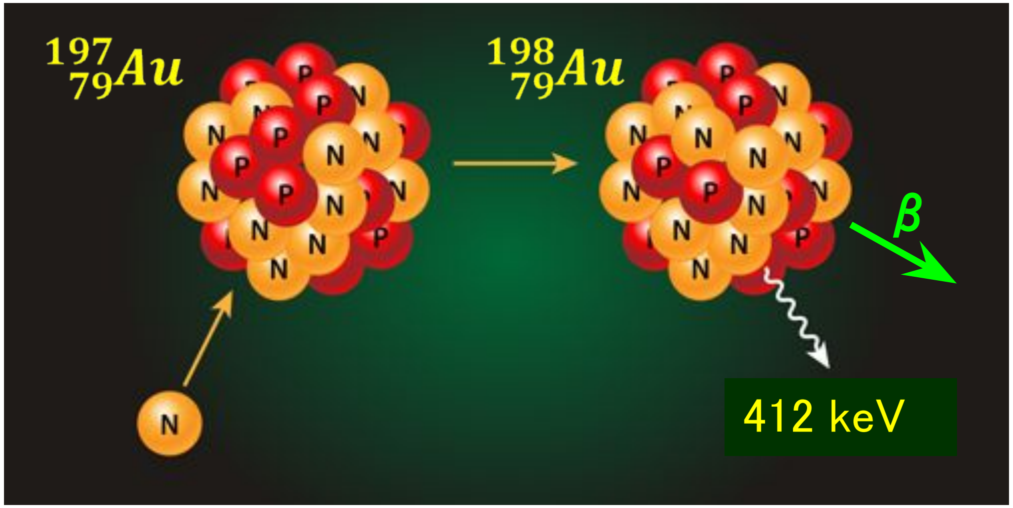


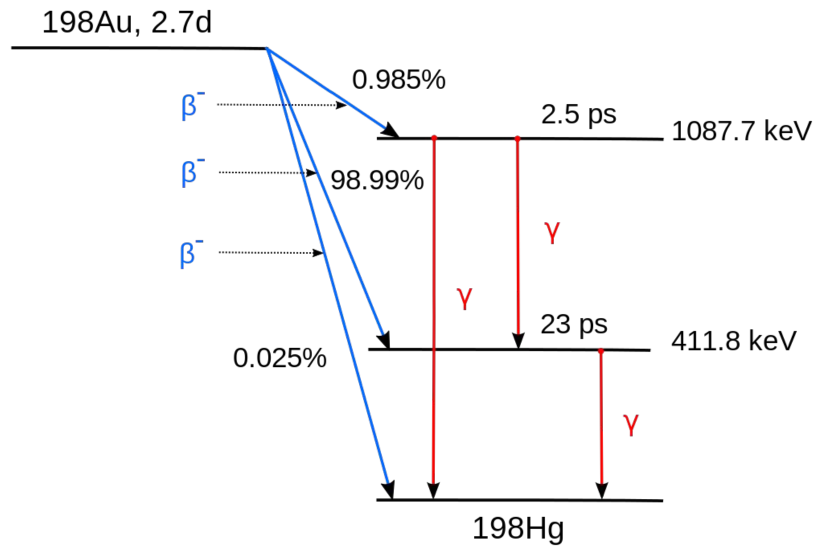


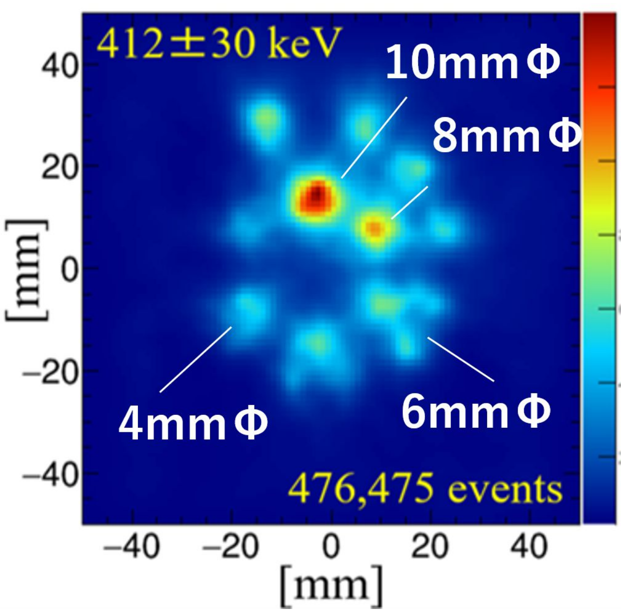


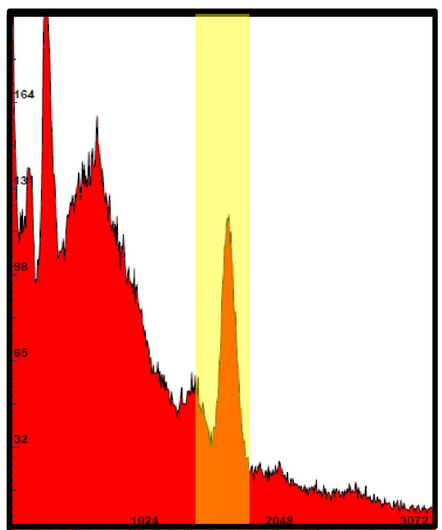
- Develop the energy frontier of nuclear medicine, that was conventionally limited by use of SPECT and/or PET
- Dynamical imaging of pharmacokinetics of ^{211}At in a mouse at 79 keV/ 570 keV

e.g.2 : “activation” imaging





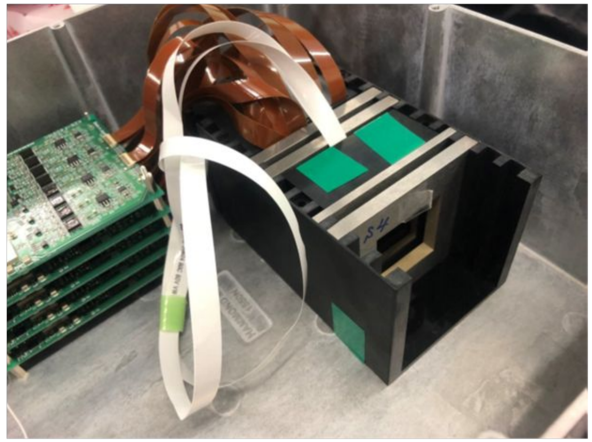


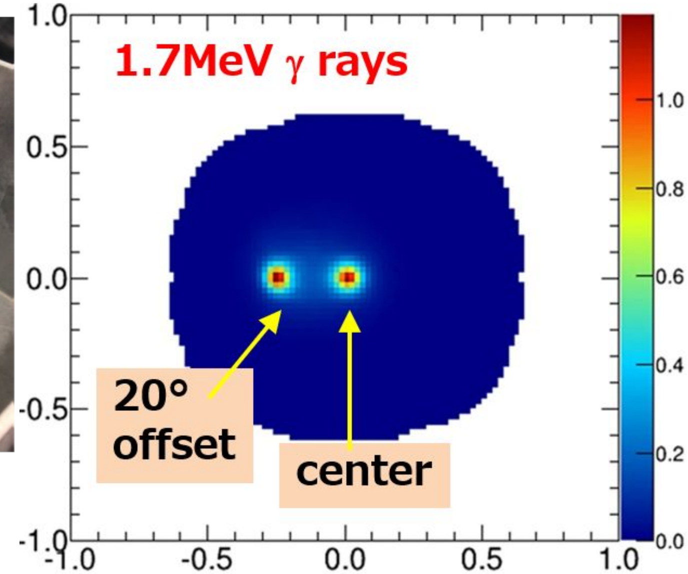


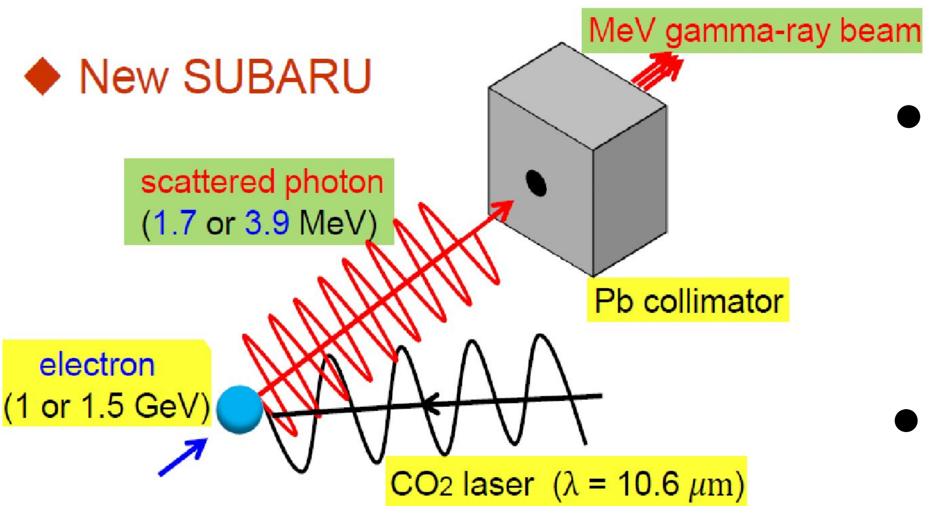
- Neutron capture activate stable ^{197}Au to ^{198}Au, that emits 412 keV γ rays
  → could be (might be?) also expected in n-rich environment like ***kilonova?***

e.g.3: MeV γ−ray imaging

Hosokoshi et al. 2019, Nature Sci. Rep.

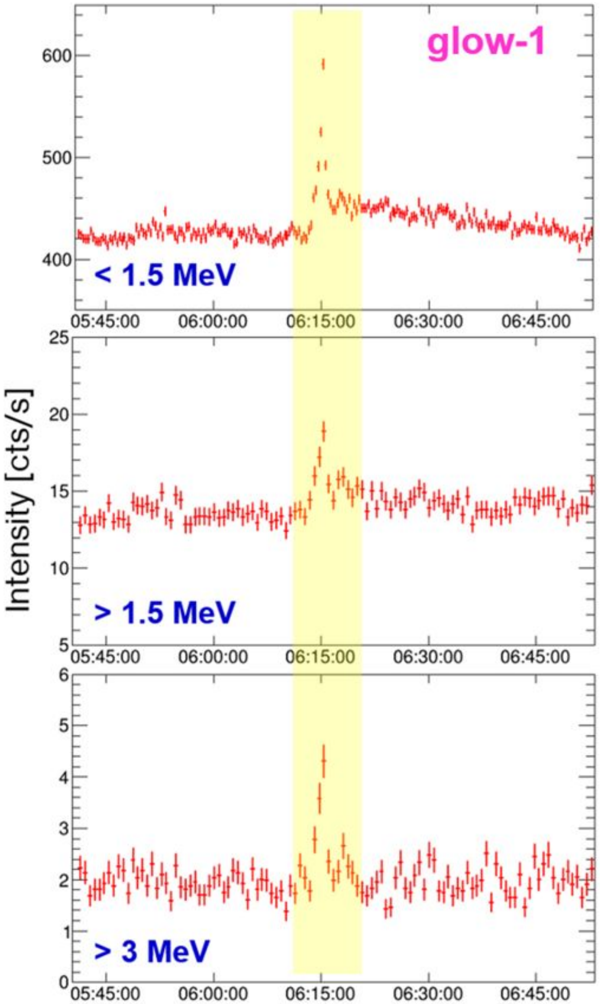






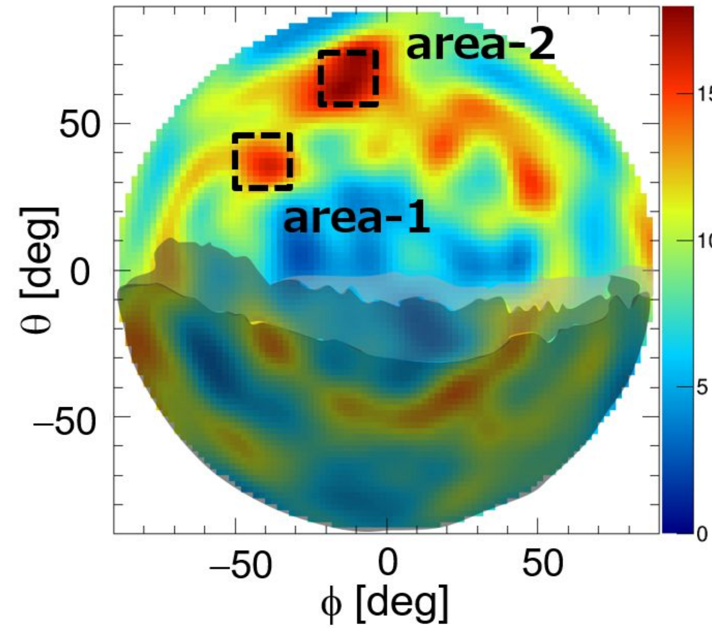
- Experiment was performed at New SUBARU, which provides **monochromatic γ−ray beam** by IC of GeV electrons from SP8
- Measured angular resolutions:
  3.4± 1.1° (FWHM) @ 1.7 MeV
  4.0± 0.5° (FWHM) @ 3.9 MeV

e.g.4: γ rays from thundercloud



Kuriyama et al. 2022, GRL

γ-ray image



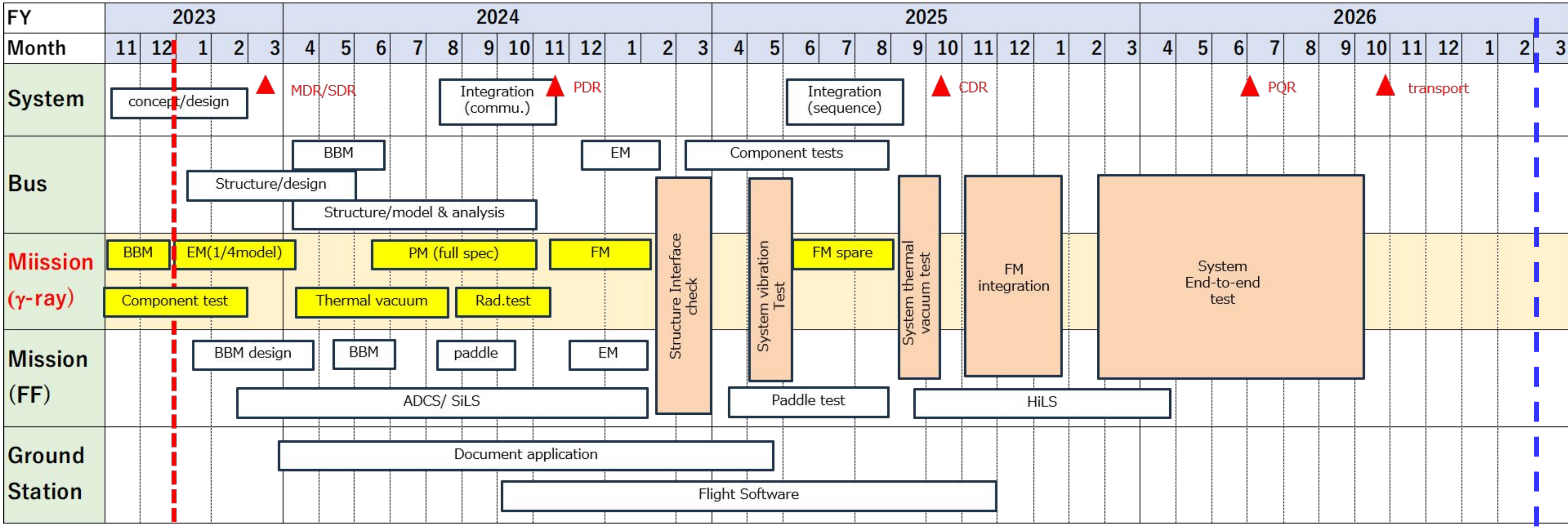
- Observation of thundercloud in winter using a Large-area CC of **$10 \times 10 cm^2$**
- World's firsr γ-ray imaging of thundercloud

✔ 150 – 1,000 keV

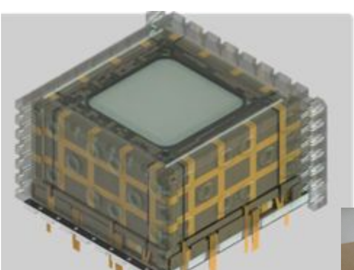
✔ significance : **4.0 σ (area-1), 5.9 σ (area-2)**

Schedule and status

launch

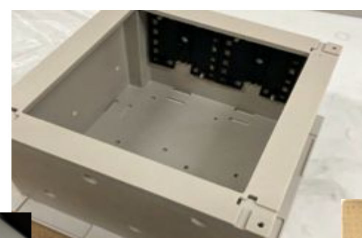


CAD design

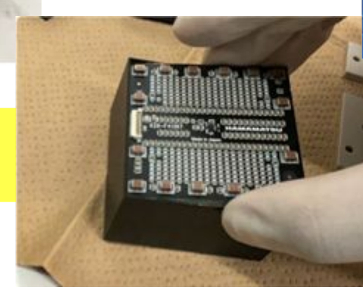


3D printing

EM package



EM (1/4 model)



Component tests

Summary

- We are developing "INSPIRE" as a new challenge of using 50-kg class satellite to open up new frontiers of space science

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

- Various prototype detectors have tested in variety of fields, which also leads important progress to visualize drug delivery in nuclear medicine, atmospheric research as well as homeland security

See also P.45
"Design and evaluation of a MeV γ-ray camera aboard a 50-kg class small satellite" by R.Iwashita for more details

Appendix

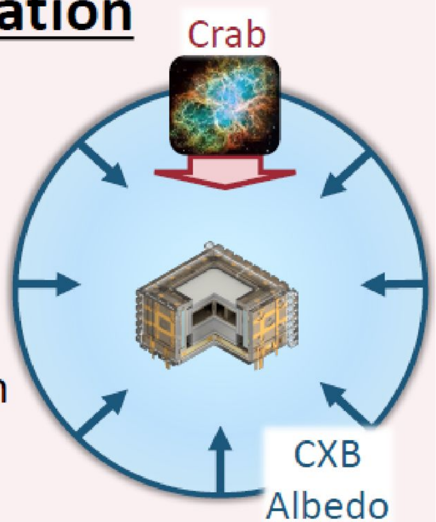
Crab image (simulation)

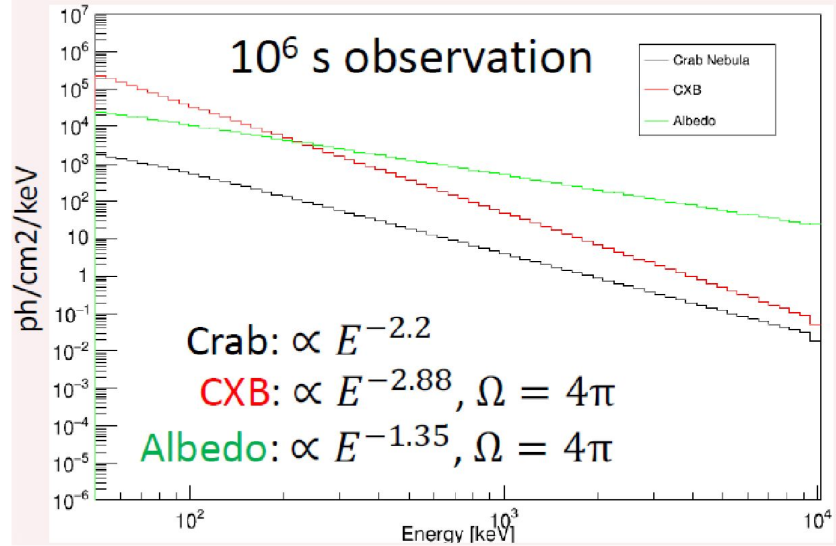
☐ Crab Observation

Assumption

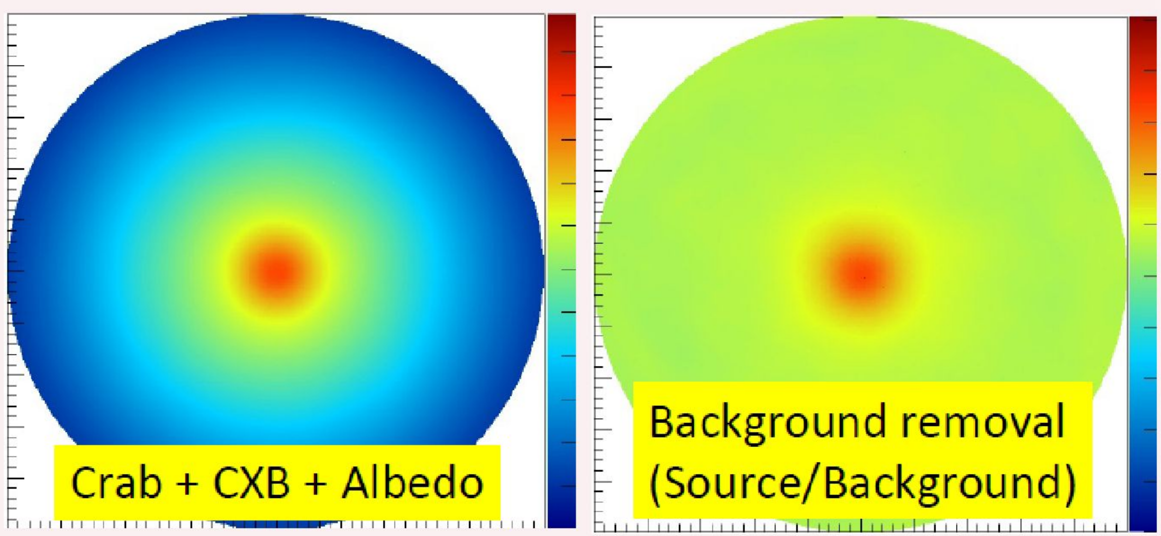
Crab: Center

CXB/Albedo:
Isotropic radiation

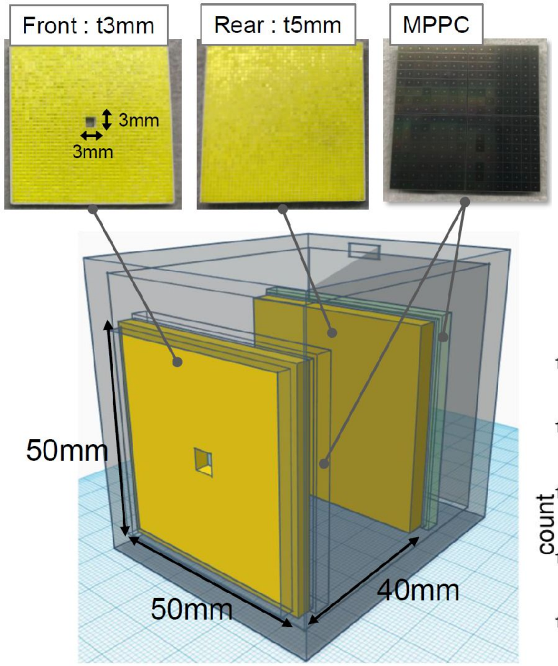


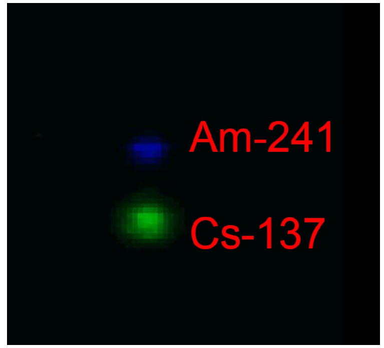


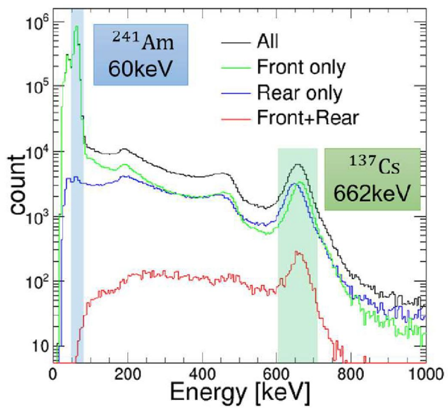
300keV – 1.5MeV Imaging (10^6 s)



Ex−1 : medical imaging (1)





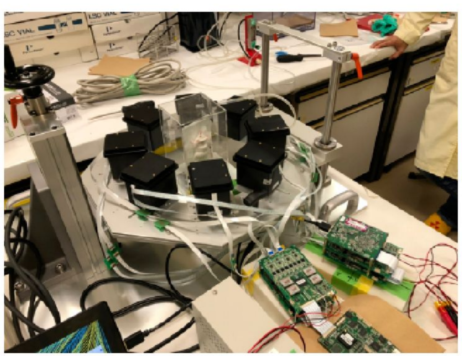


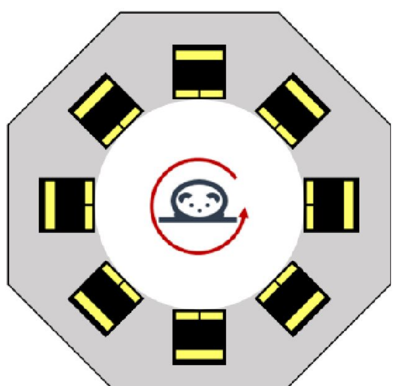
Hybrid CC

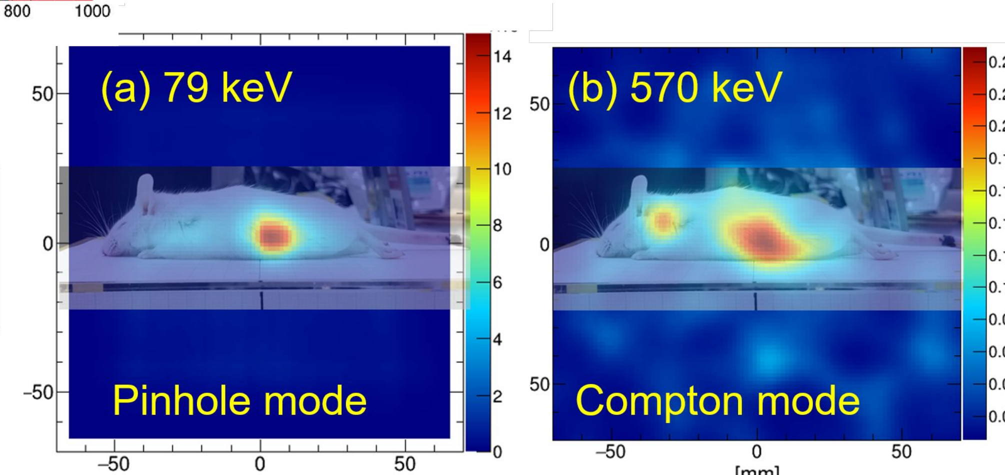
Omata et al. 2020;2022, Nature Sci. Rep.

- **60keV (4MBq) /662keV (1MBq)** simultaneous 3D imaging

- RIs for cancer therapy : At−211 **@79 keV/570 keV** simultaneous imaging of ~ a few tens kBq

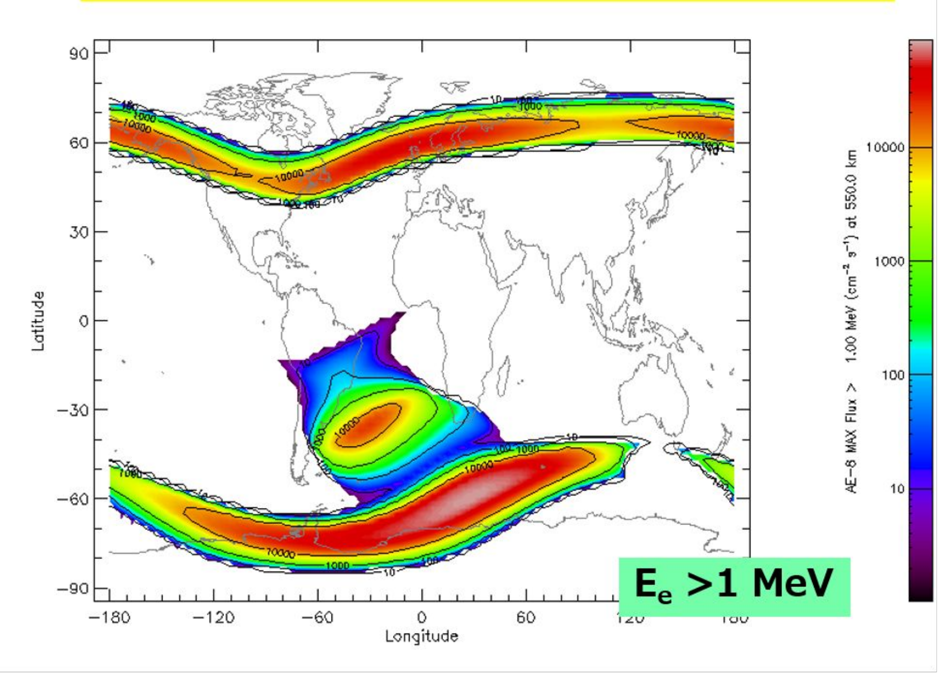


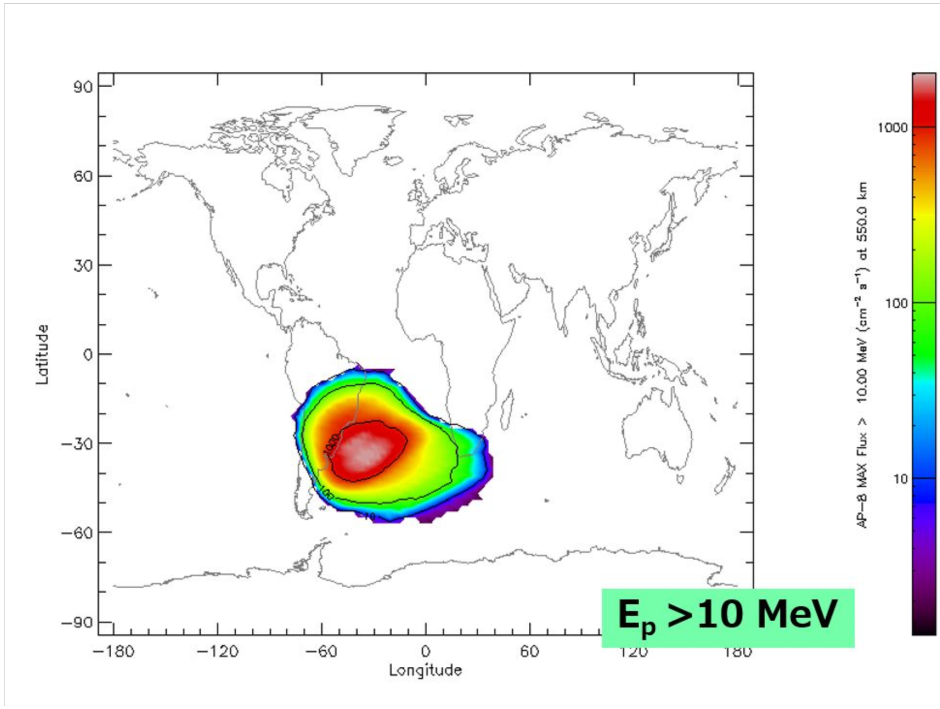




軌道高度 550 km での放射線環境 (Solar max)

「INSPIRE」（2027.Mar~）が対応

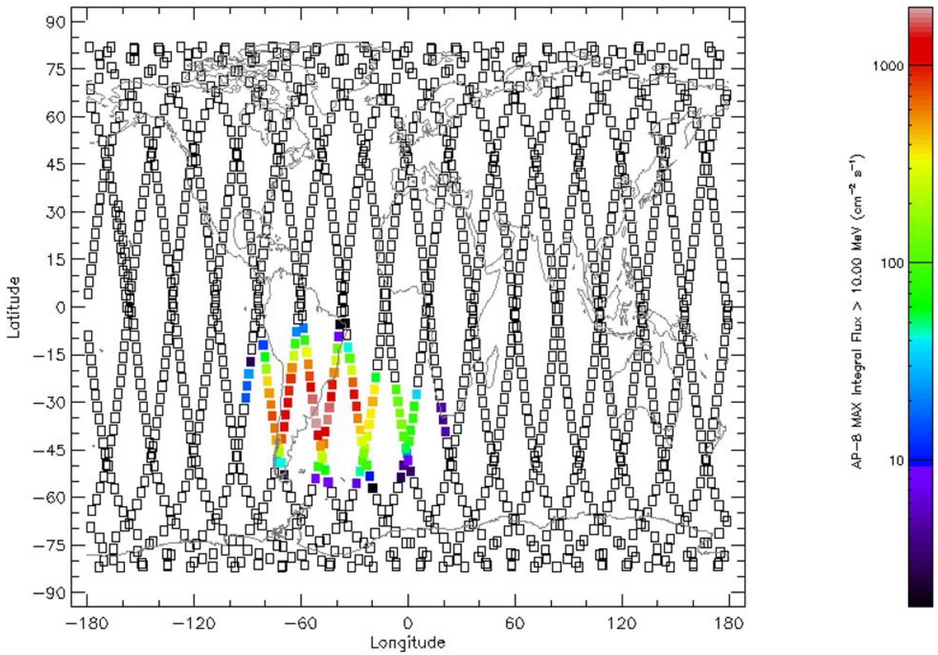


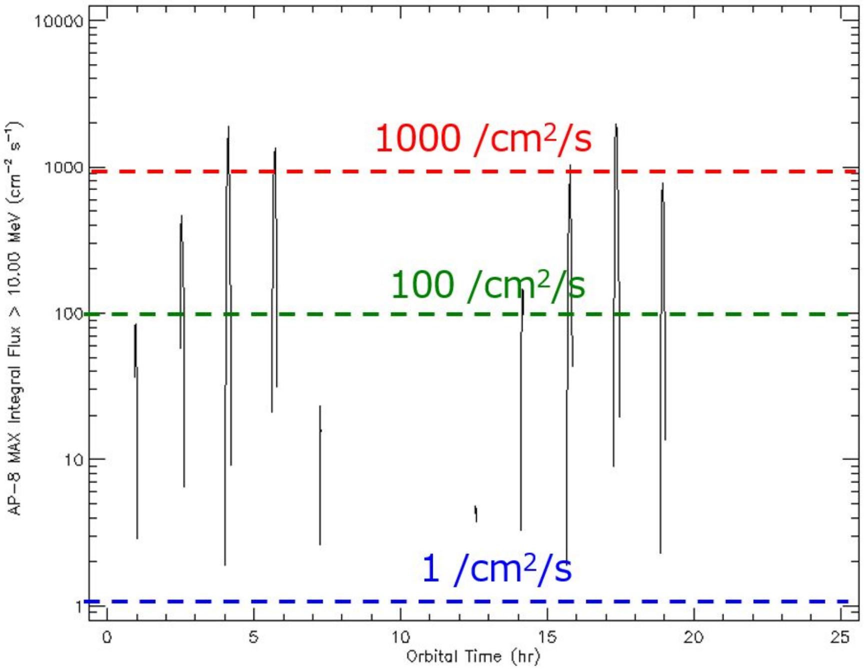


太陽活動極大期は、陽子のフラックスが減り、電子のフラックスが増える

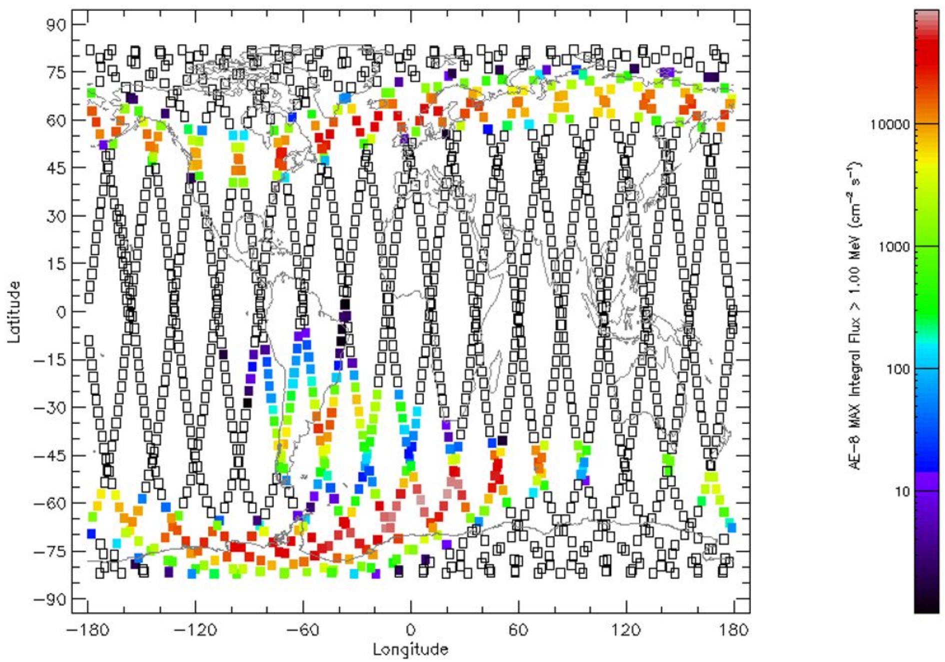
「INSPIRE」軌道での時間変化（陽子>10MeV）

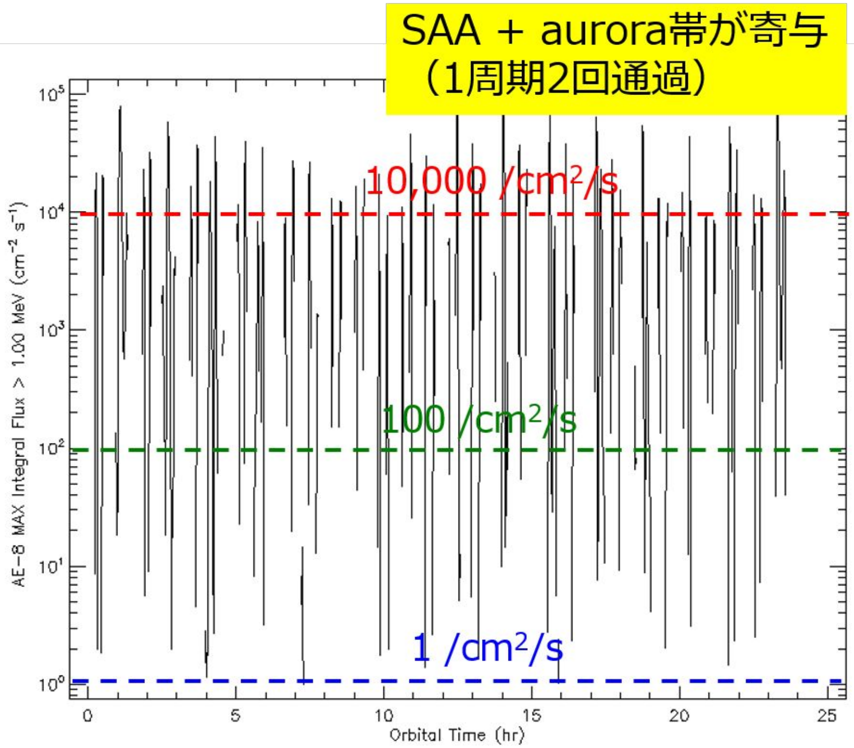
SAA のみが寄与





「INSPIRE」軌道での時間変化（電子>1MeV）



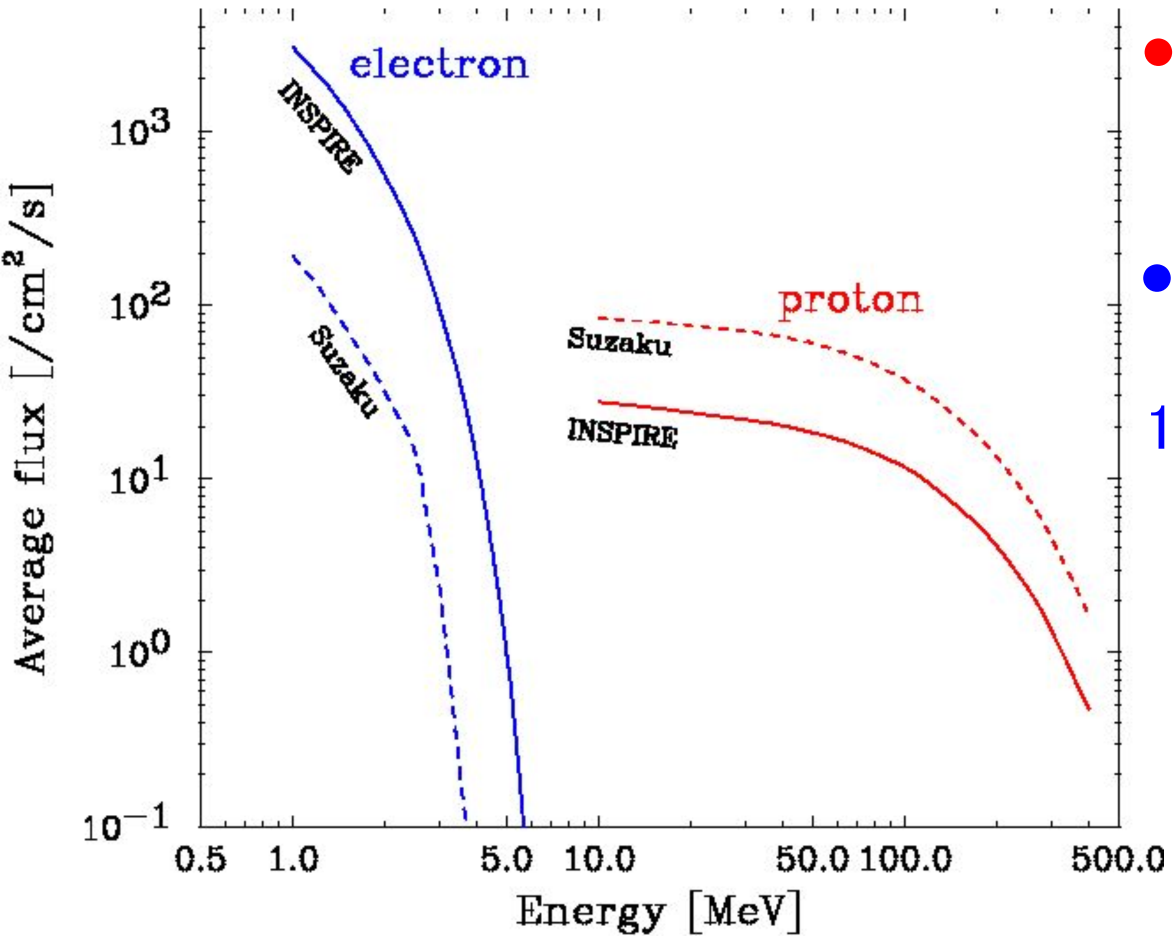


実際に観測に使える時間は？

	Suzaku	INSPIRE
high proton fraction in orbit		
(F [E_p>10MeV] > 1/cm^2/s)	11.18%	6.88%
(F [E_p>10MeV] > 100/cm^2/s)	8.06%	3.96%
high electron fraction in orbit		
(F [E_e>1MeV] > 1/cm^2/s)	11.25%	30.10%
(F [E_e>1MeV] > 100/cm^2/s)	5.97%	23.40%

- 「陽子」については、通常のLEO よりも SSO の方が少なく放射化の観点で有利 (オーロラ帯の陽子は、ほとんど低 E)
- 「電子」については、やはり SSO が不利。上記の閾値では **有効な観測時間は LEOで 90−95% , SSO で 70−80%** か？

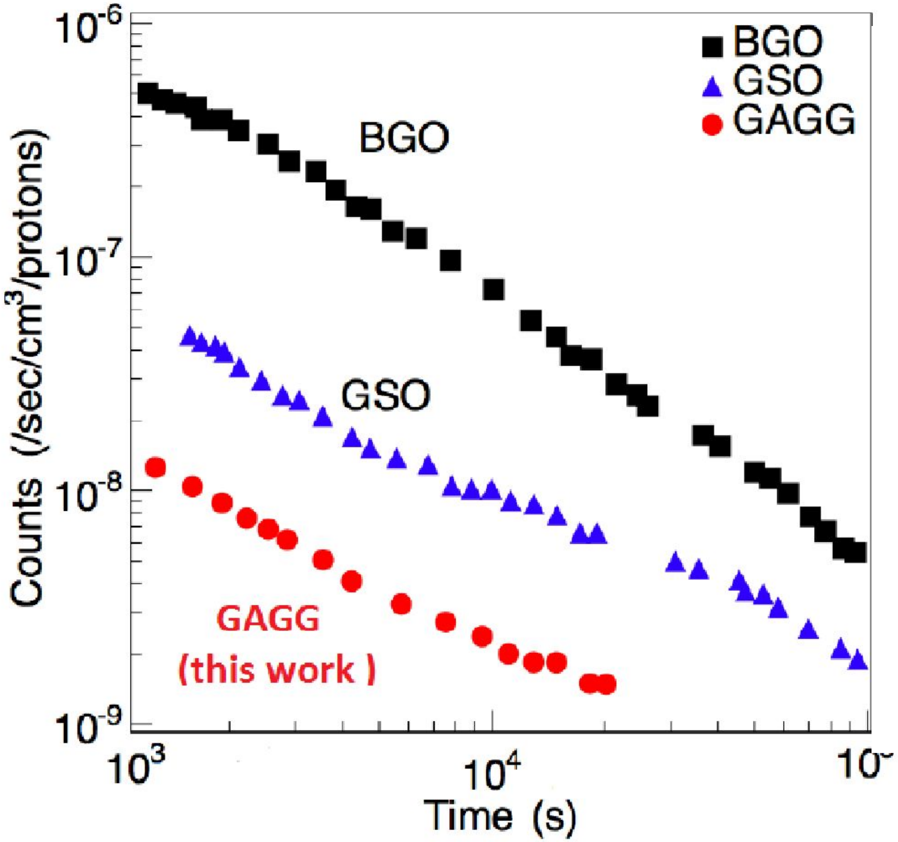
平均の積分フラックス（ E以上の陽子・電子）



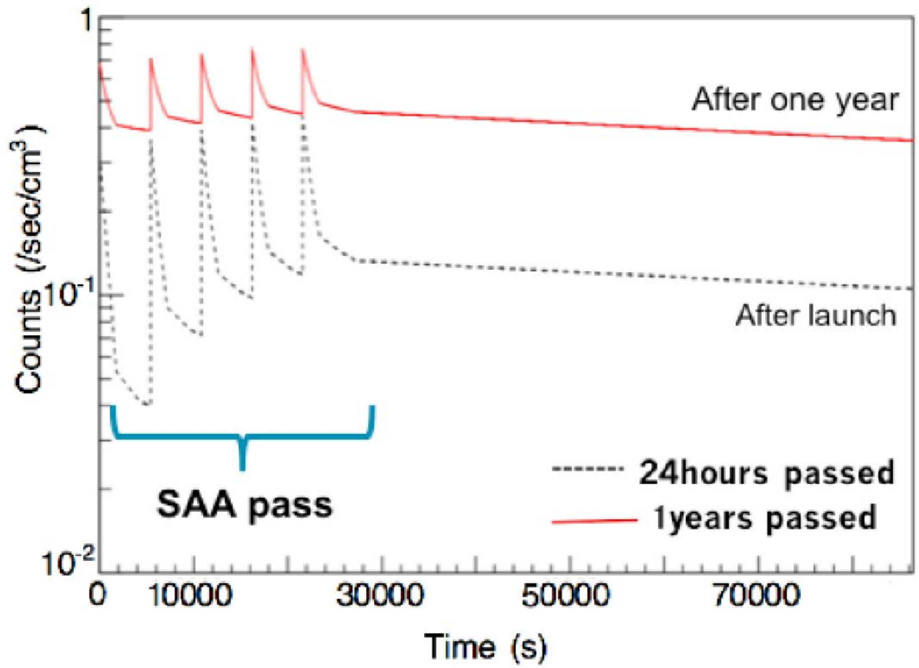
- **「陽子」**は 10MeV 以上でINSPIRE が 1/3 ほどで少ない
- **「電子」**は 1MeV 以上でINSPIREが 16 倍多い

（SSOでオーロラを通る、また solar max で フラックスが増えることの相乗効果）

GAGG activation properties



Yoneyama et al. 2018 Jinst



Scanning mode

基本のLVLH姿勢での周回