"ISAI" Investigating Solar Axion by Iron-57

Takeshi TSURU (Kyoto Univ.)
D02 公募研究

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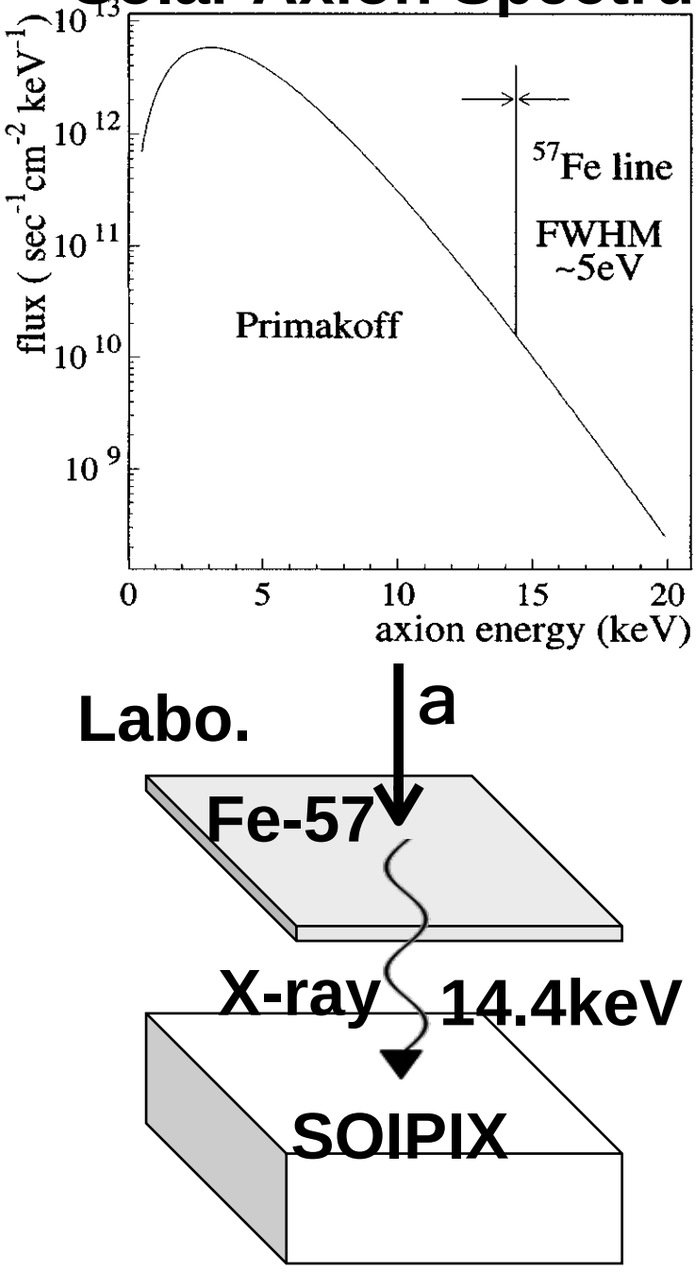
20230309_ISAI_DMconf_Tsuru_v6A

ISAI (Investigating Solar Axion by Iron-57)

Solar Axion Spectrum



- Monochromatic axions emitted from the sun by M1 transition of the excited Fe-57 through a-N coupling
- Detect 14.4 keV X-rays from the reverse reaction in Fe-57 targets placed in a laboratory.

$$a + {}^{57}Fe \rightarrow {}^{57}Fe^{*} \rightarrow {}^{57}Fe + \gamma\ (14.4keV)$$

- Dependent only on a-N coupling
- No ambiguity due to mixing of a-e or a-γ coupling

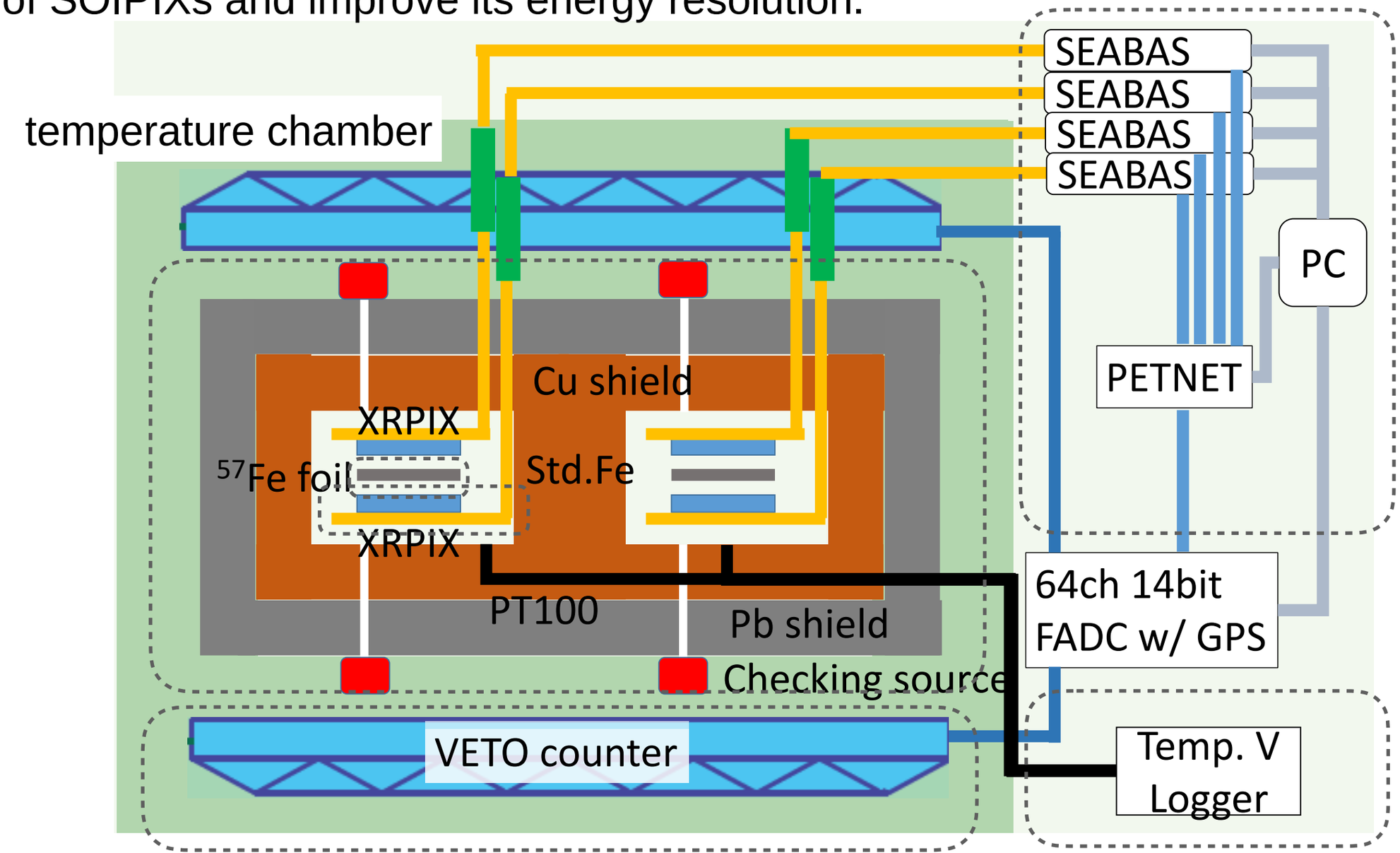
Previous and on-going works

- Moriyama (1995). PRL 75, 3222
- Namba (2007), Phys.Lett.B, 645, 398
- Derbin (2011), Phys.At.Nucl.74, 596
- B04 group of DM学術変革領域 etc.

From the point of view of experimentation,
Detection of X-ray emission lines
in a low BGD environment

Configuration of the ISAI experiment

- Table top level experiment running in a temperature chamber placed in our laboratory at Kyoto University.
- New and unique sensors, SOI pixel sensors (SOIPIXs), detect 14.4 keV X-rays from Fe-57.
- Surrounded by passive shield of O-free-Cu & low BGD Pb, and VETO counter of plastic scintillators.
- The camera is installed in a temperature chamber and cooled down to reduce the readout noise of SOIPIXs and improve its energy resolution.



the ISAI team

Multi-Disciplinary Team

HEP: Onuki
CR: Fujii, Taketa, Iwasaki, Namba, Nagasawa
DM: Miuchi, Inoue, Ikeda
Nuclear Medical: Uenomachi
Astro.: Tsuru, Matsuda, Kayama, Amano
Detector Sci.: Takeda, Tsuru
Undergraduate: Anazawa, Yoshimura

Overall Concept: Onuki

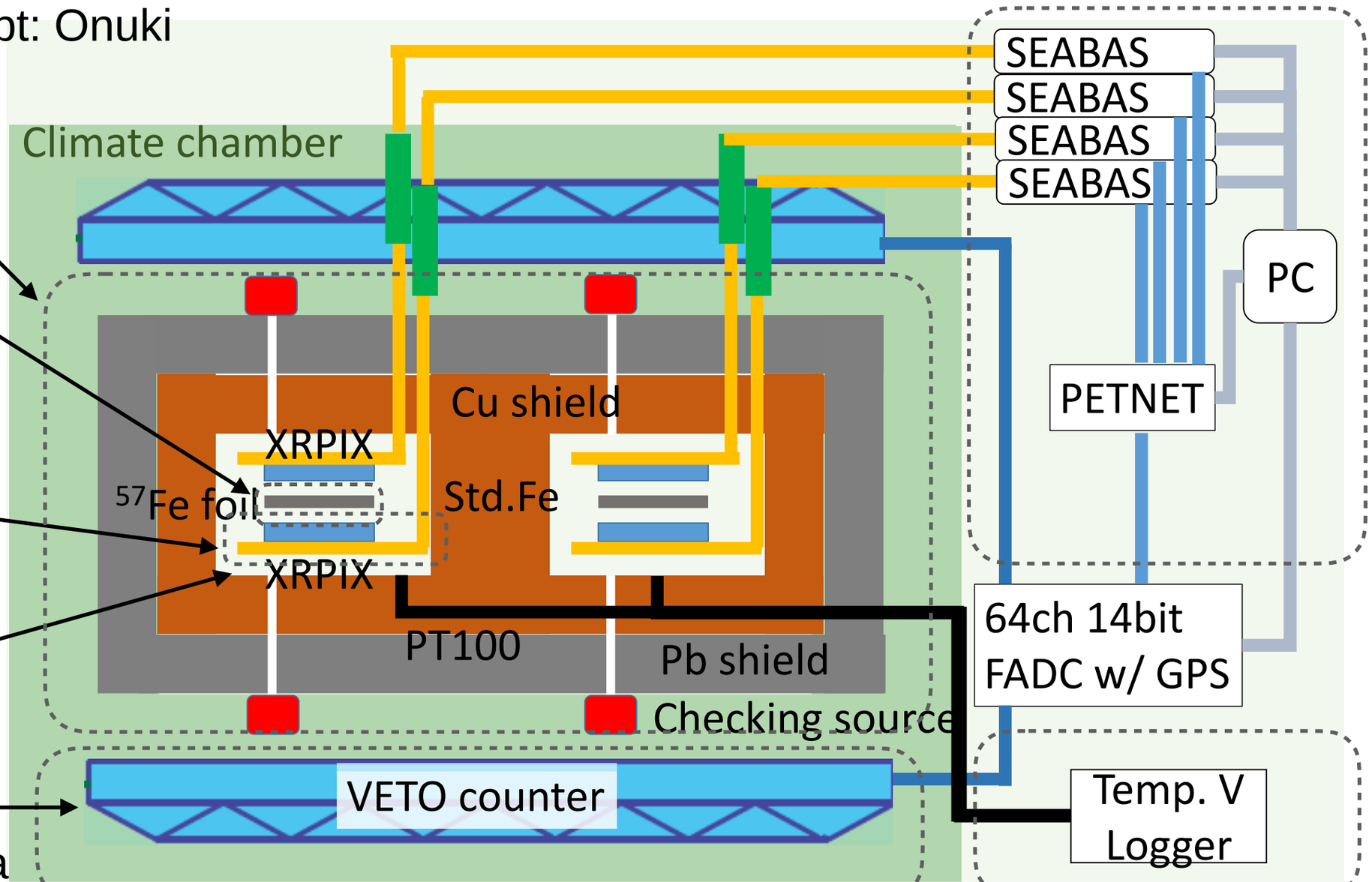
Mech. Design: Onuki, Inoue

Fe-57: Fujii, Miuchi

SOIPIX: Tsuru, Takeda, Ikeda, Onuki

Si PIN: Anazawa, Yoshimura

VETO: Fujii, Iwasaki, Takata, Namba



Anti-Co.: Uenomachi, Takeda, Matsuda

Parts BG: Onuki, Inoue, Miuchi

Emv. BG: Enoto

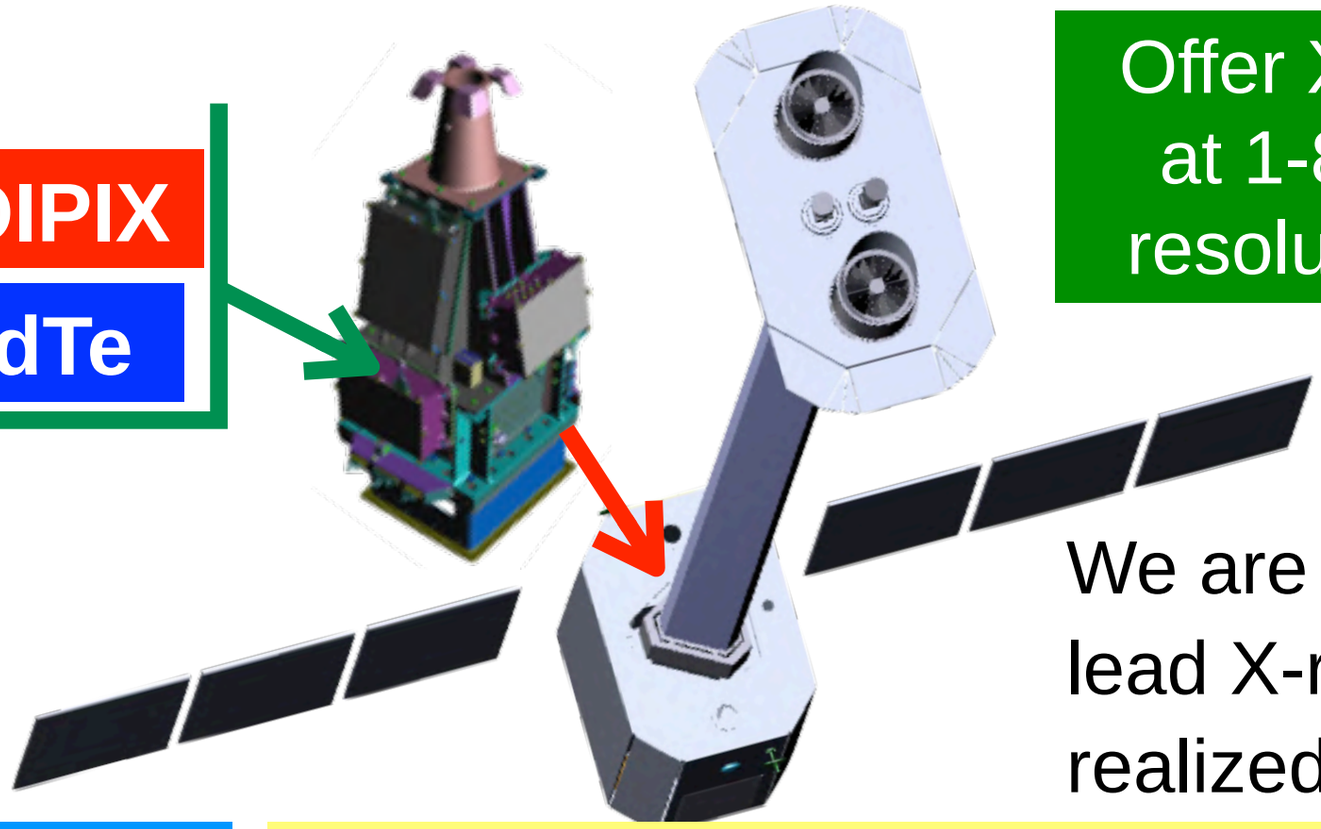
HK: Miuchi

Broadband X-ray observatory FORCE

ISAI uses SOIPIX, which we have been developing for FORCE.

SOIPIX

CdTe



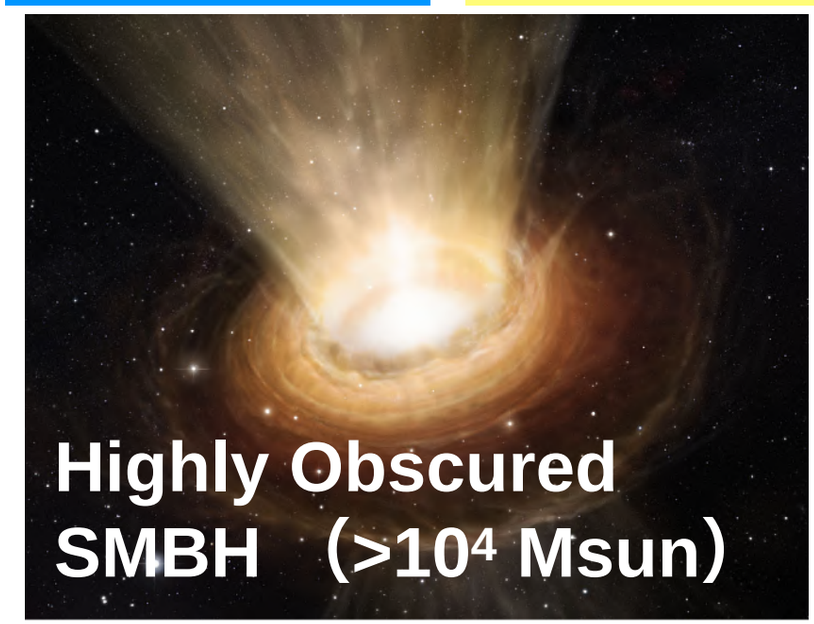
Offer X-ray imaging spectroscopy at 1-80 keV with a high angular resolution better than 15” in HPD

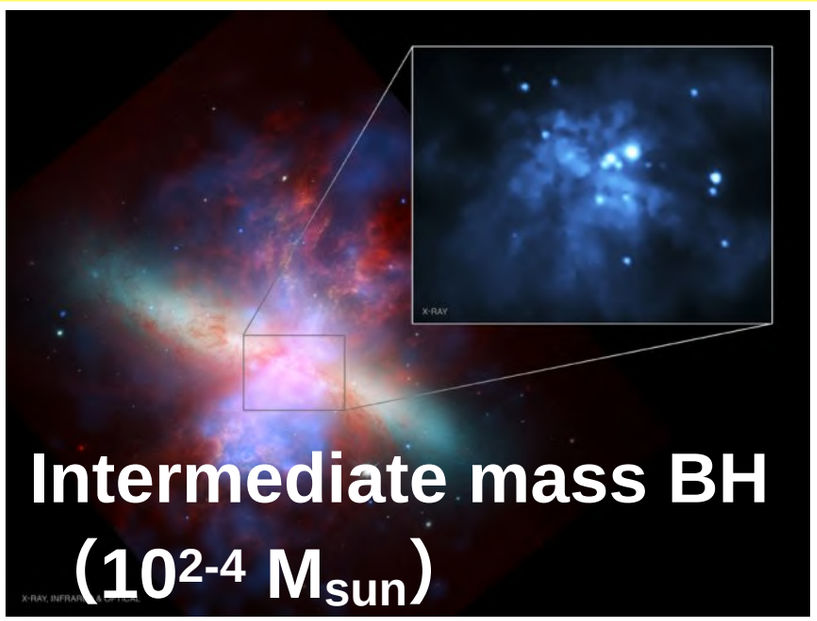
x10 higher sensitivity than NuSTAR

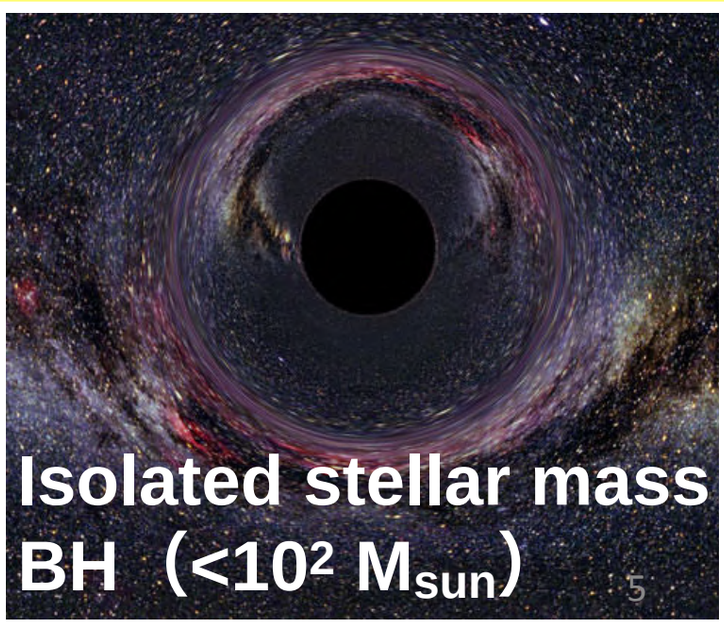
We are proposing a future Japan-lead X-ray mission, FORCE, to be realized at early 2030s.

Scientific Objective

Hunt for “missing black holes” in various mass-scales from stellar mass BH to SMBH to trace their cosmic evolution.







"XRPIX" = SOI pixel sensor for X-ray Astronomy

In order to detect faint X-ray source

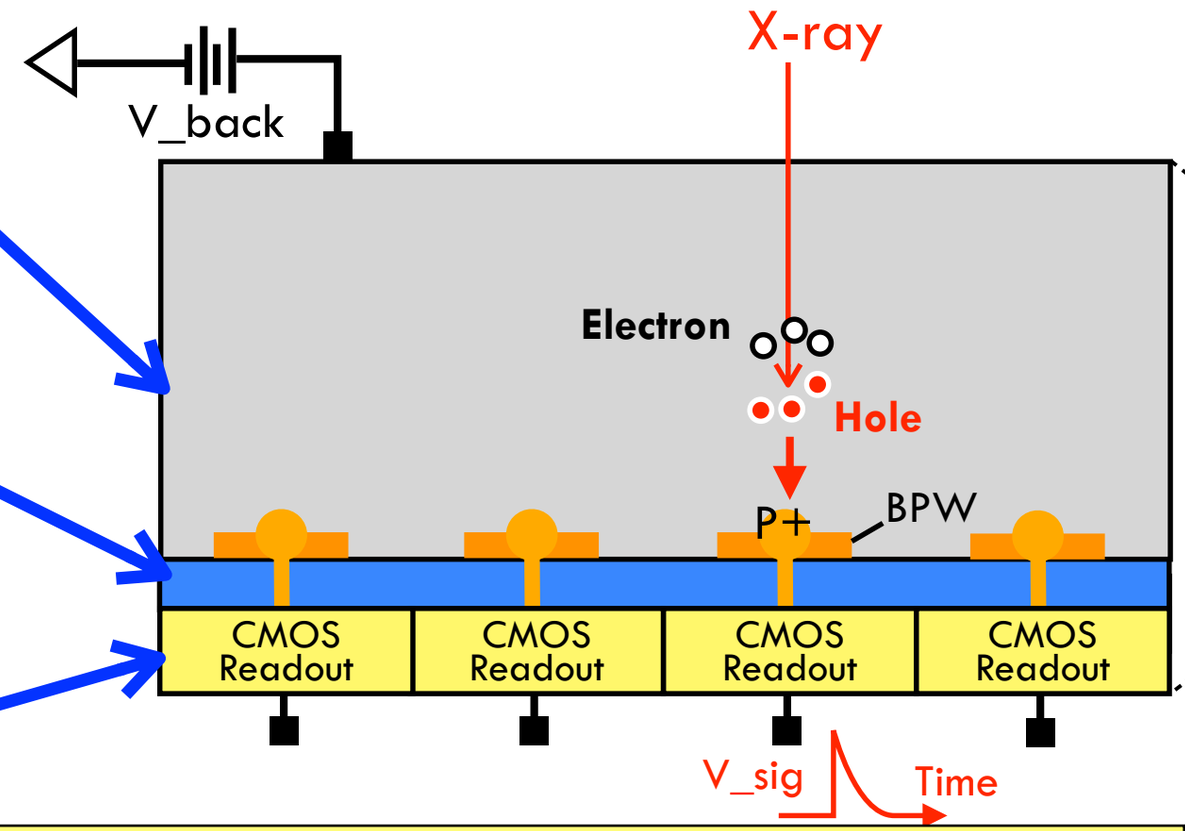
Reduce non-X-ray (particle) BGD.

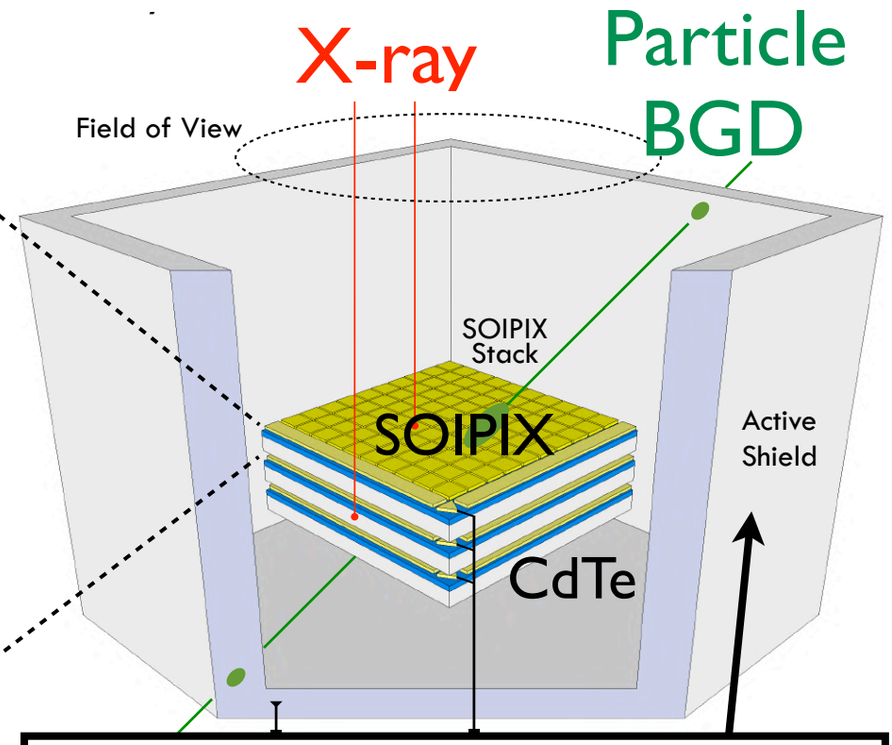
Anti-coincidence
But, CCD, CMOS are slow

Sensor (high ρ, depleted Si)

BOX (SiO_2)

Fast CMOS (low ρ Si)





Low Non-X-ray BGD
Anti-coincidence with surrounding scintillators.

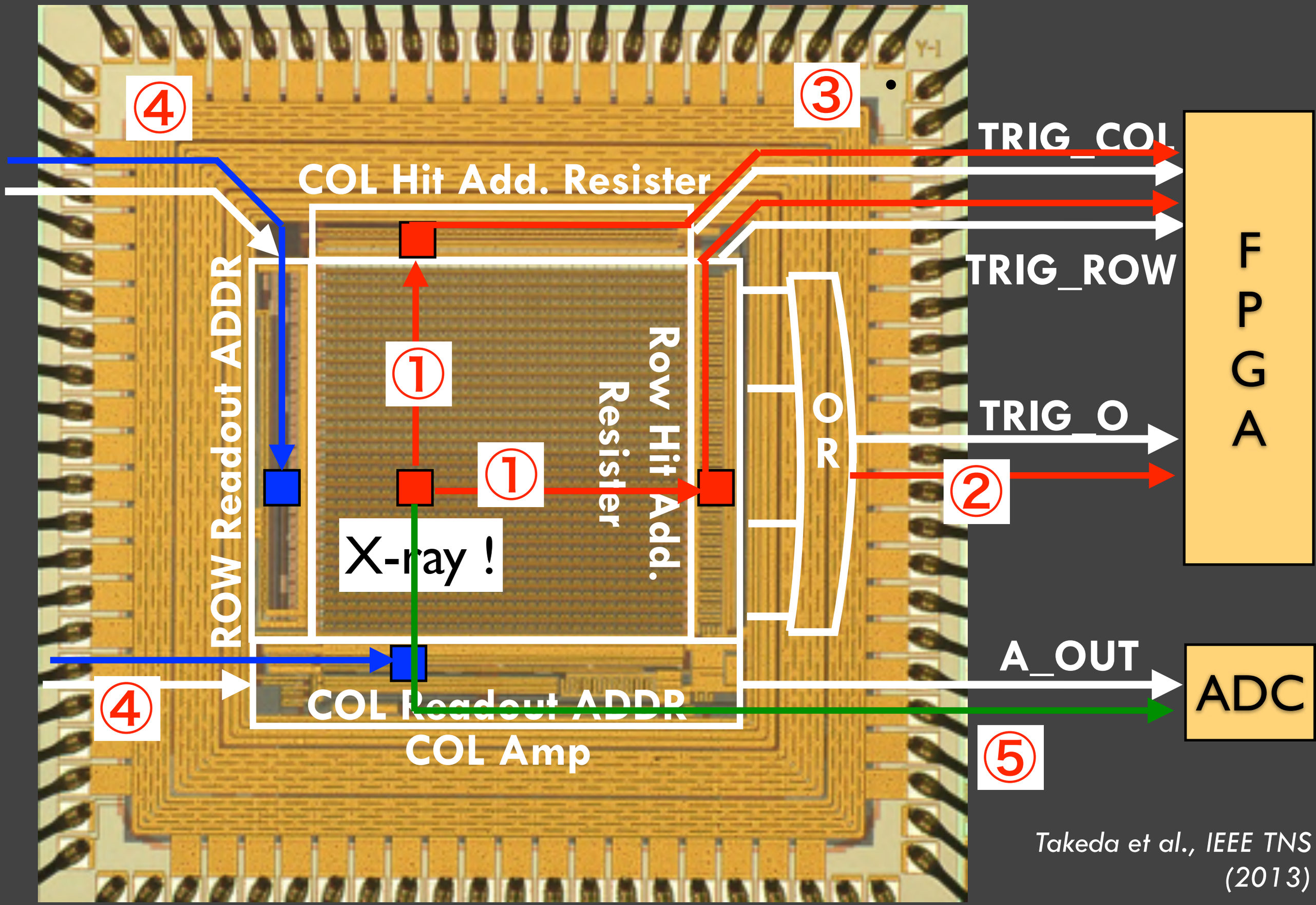
Each pixel has its own trigger logic and analogue readout CMOS circuit.

- Event rate from the scintillators is about 10kHz.
- SOI pixel sensor is required to have a time resolution much faster than 10kHz.

Time Resolution better than 10 μsec

This is the very performance required by the ISAI experiment.

Event Driven Readout using Trigger Function



Takeda et al., IEEE TNS (2013)

X-ray SOIPIX - “XRPIX” : becoming mature

2010 2011 2012 2013 2014 2015 2016-2017 2018~ 2020~

1st Generation | 2nd Generation | 3rd Gen. | 4th Gen. | 5th Gen.

XRPIX1
XRPIX1b
XRPIX2
XRPIX2b
XRPIX3
XRPIX3b
XRPIX4
XRPIX5b
36μm□
608×384
XRPIX6H
XRPIX6D
XRPIX6E
XRPIX7
We currently use for ISAI.
XRPIX8
XRPIX9
XRPIX10
We plan to use in future.

LAPIS Semi.
0.2μm FD-SOI CMOS

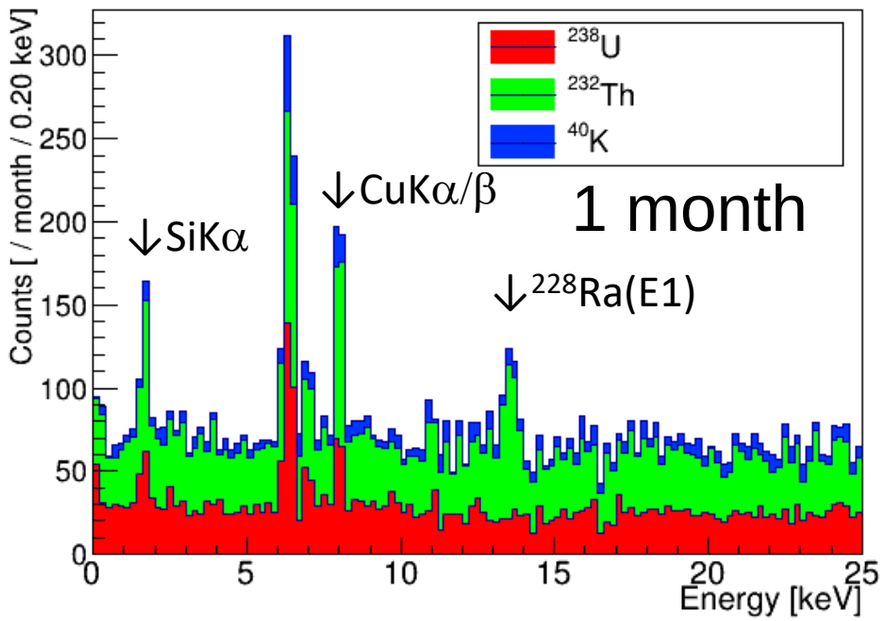
Pixel Amp.
Source Follower → Charge Sensitive Amp.

Device Structure
Single SOI → Double SOI → PDD SOI

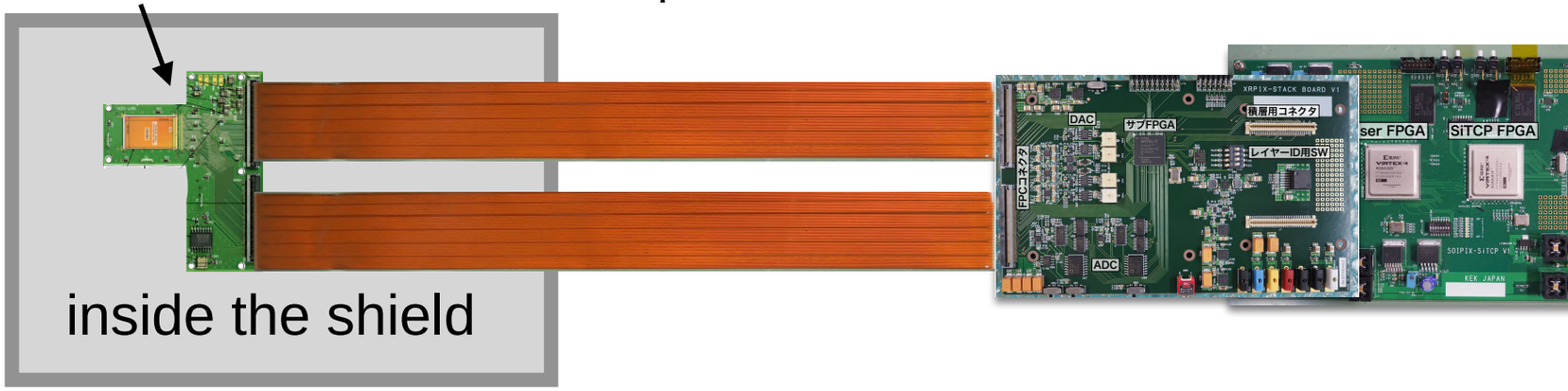
Function
Analog Output → Digital Output

Low BG Readout Board

The sensor itself must be very low BGD in ISAI.

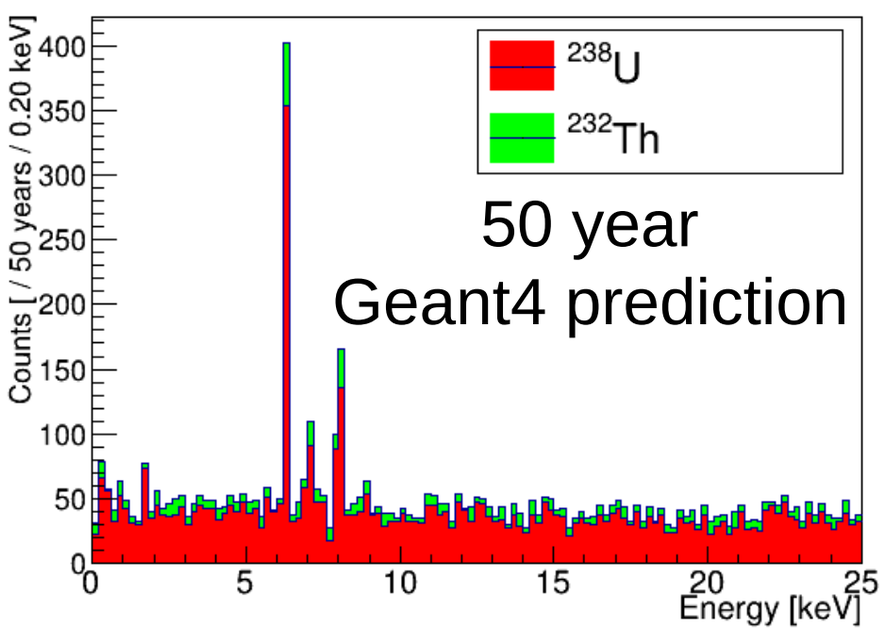


detector head developed for nuclear medical use



- Radioactivity of the detector head is dominated by G10 PCB (Onuki+19, NIMA, 924, 448)

1/1000

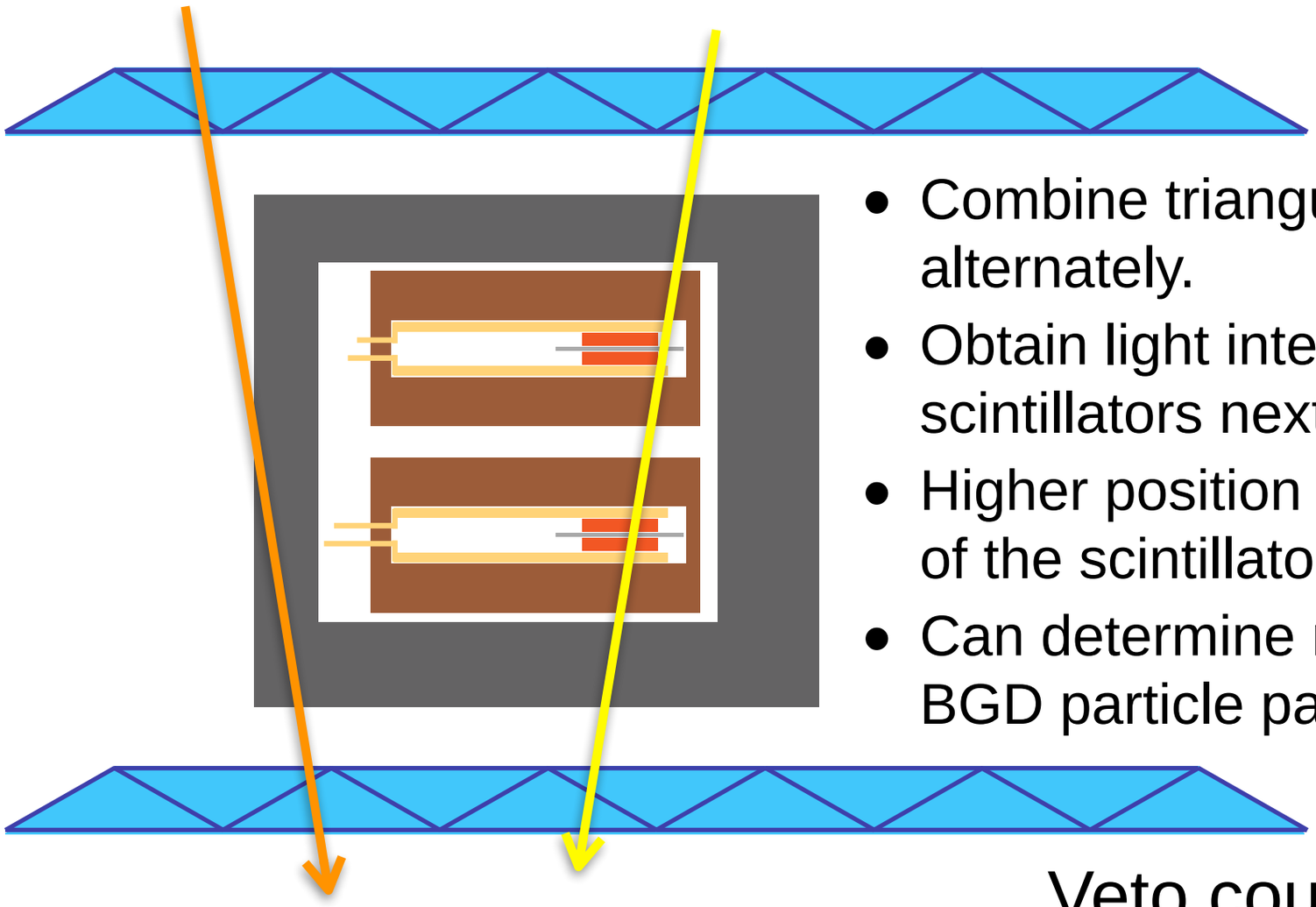


- Change G10 PCB to rigid FPC
  Only the rigid FPC is placed inside the shield

- Measure γ-rays from each circuit part with HPGe at UT to select and use quiet parts (Ose M-thesis,UT,2017).

Veto Counter : plastic scintillator with SiPM

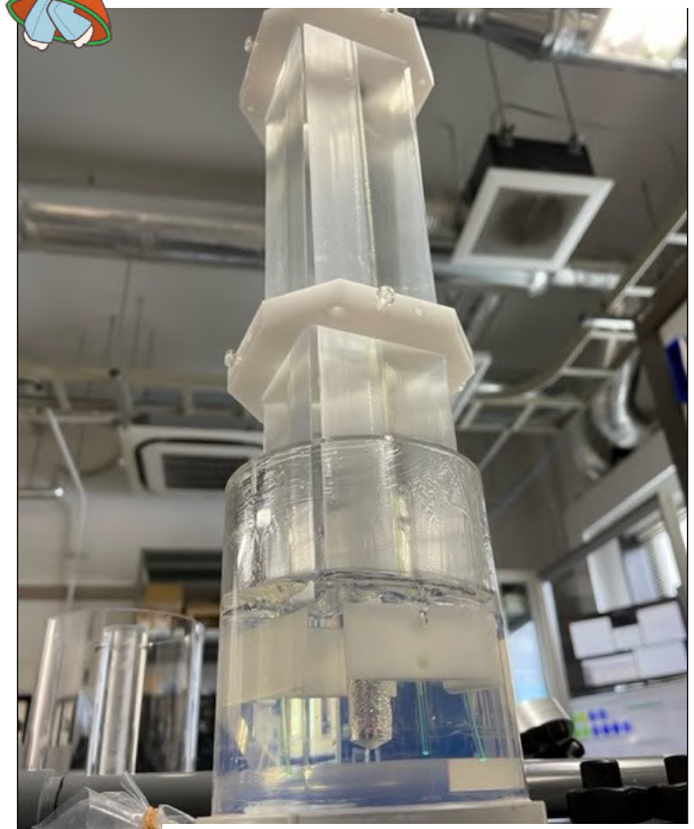
SiPM: HPK S13360-1375PE



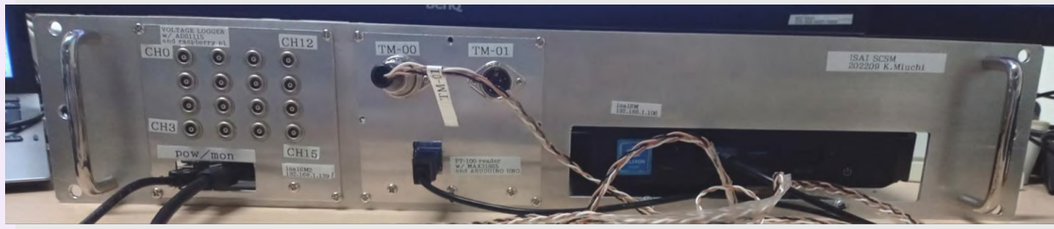
- Combine triangular shaped scintillators alternately.
- Obtain light intensity ratios between the two scintillators next to each other
- Higher position resolution than the physical size of the scintillator using the ratio
- Can determine more accurately whether each BGD particle pass through SOIPIX or not.

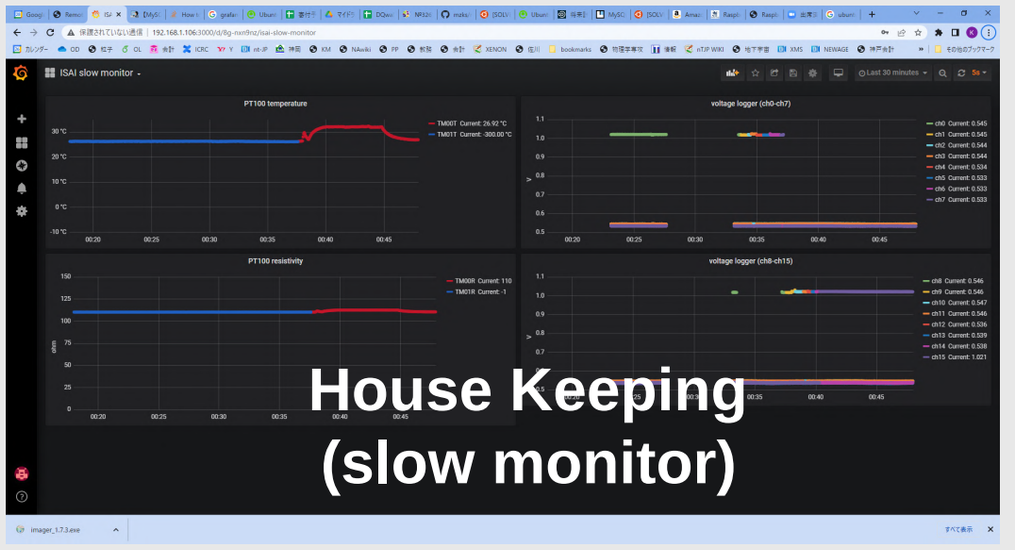
Veto counting rate ～10Hz

Assembly

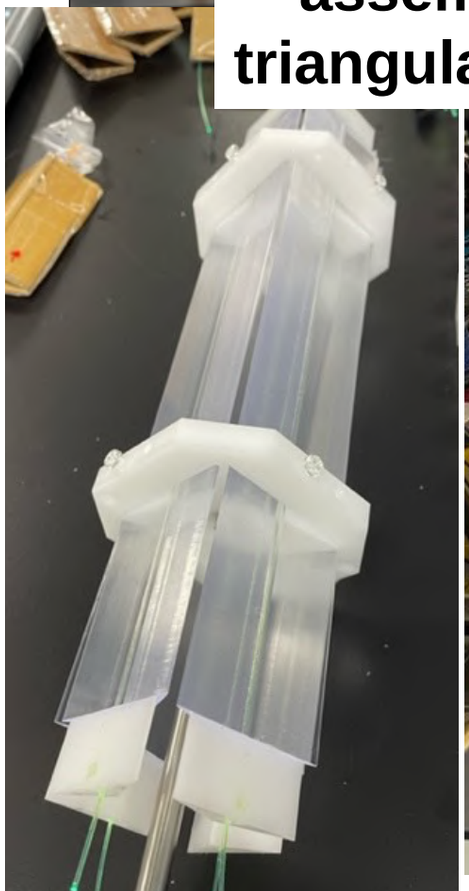


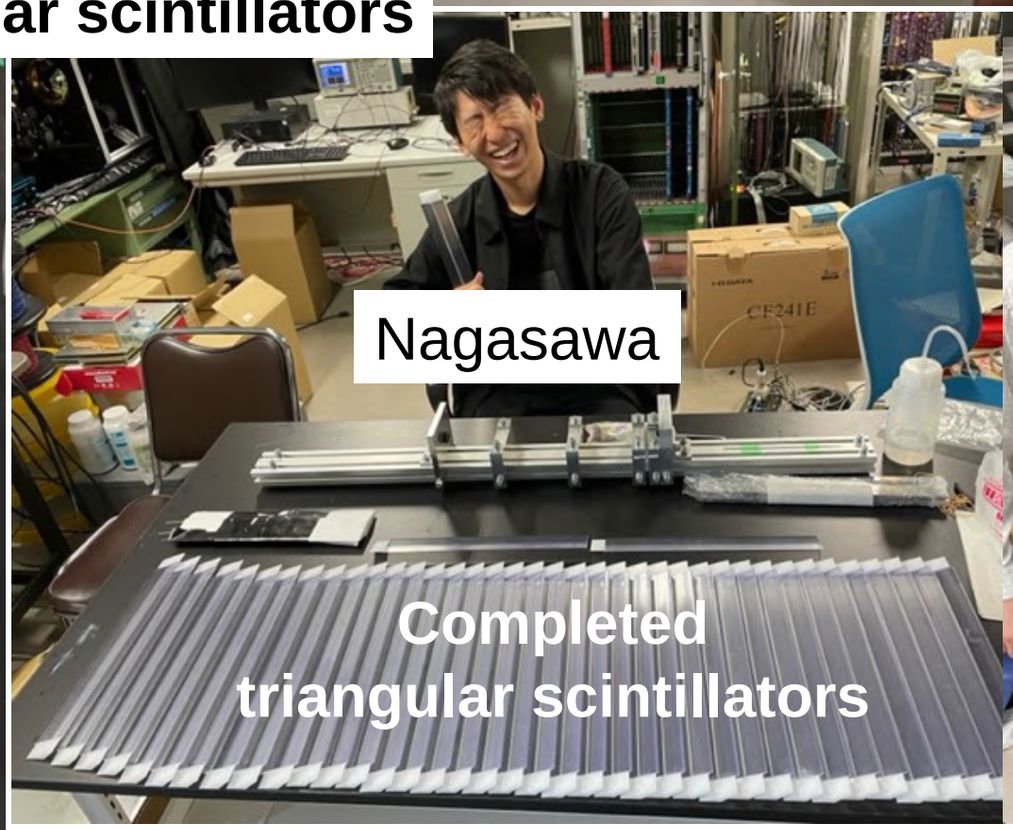
assembly lines of triangular scintillators





House Keeping (slow monitor)





Nagasawa

Completed triangular scintillators

Inoue

Tsuru

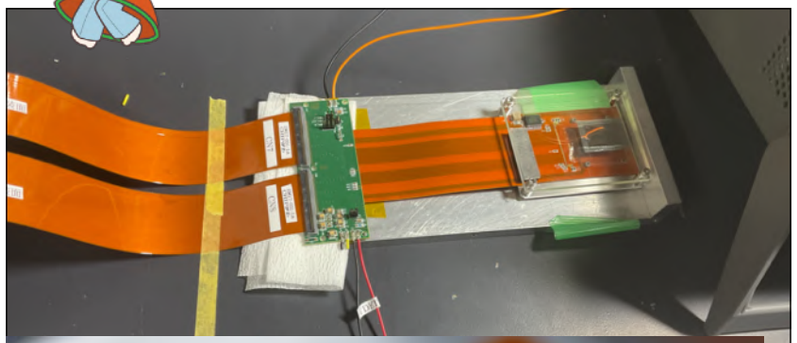
Miuchi

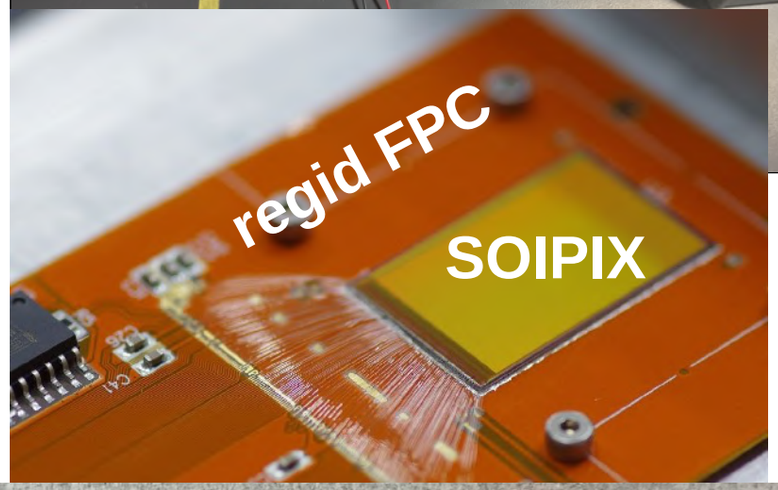
Ikeda

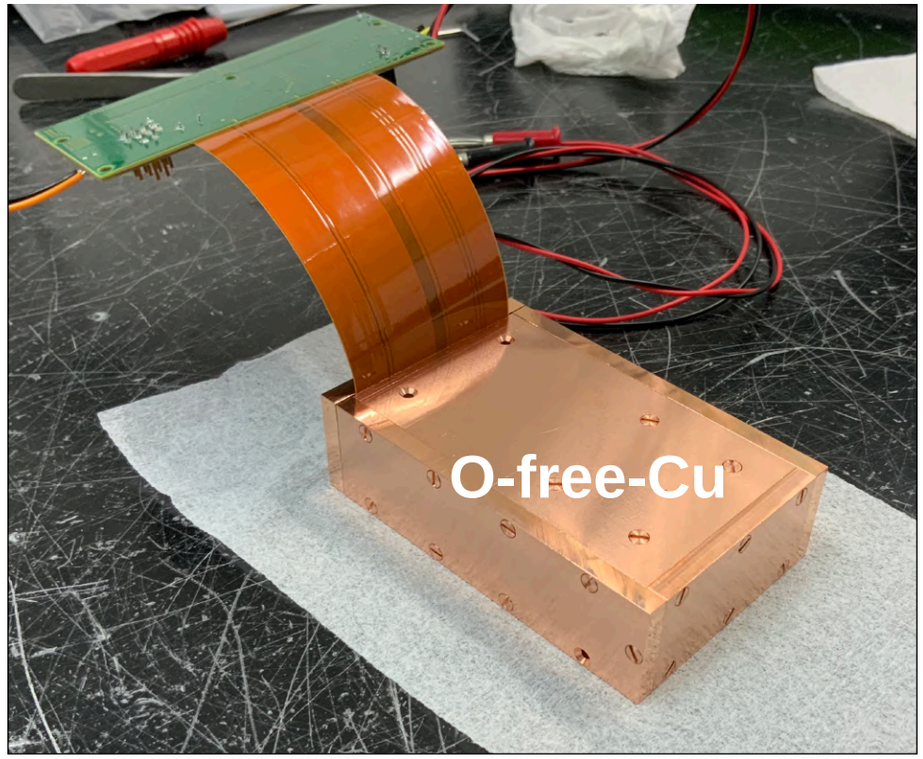
Onuki

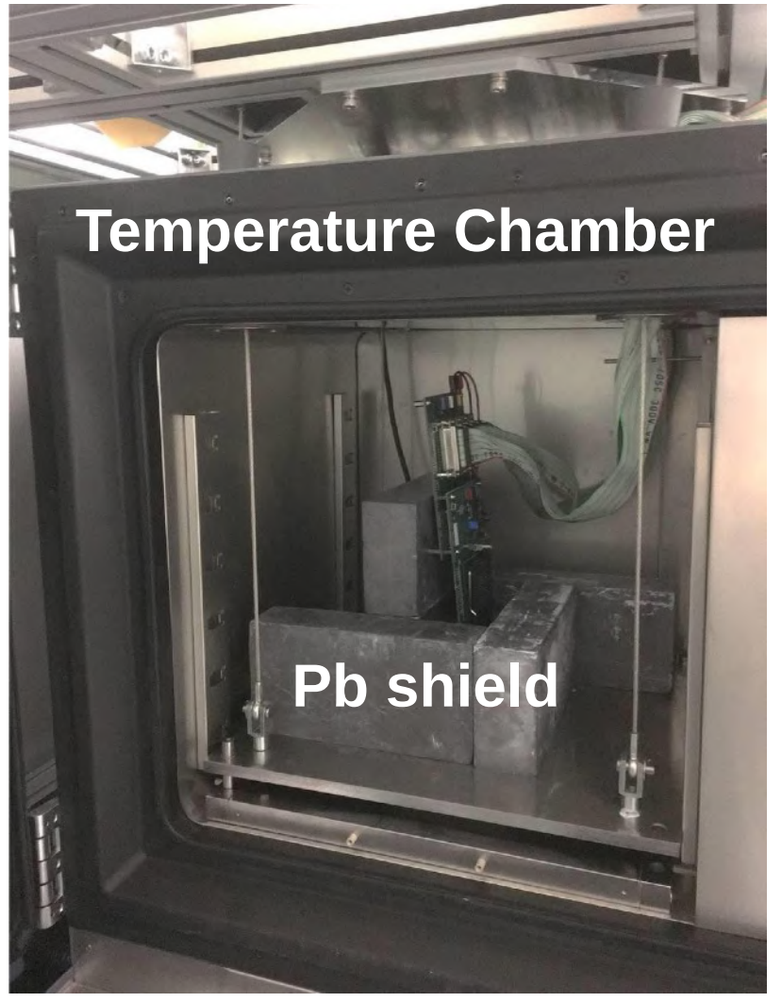
Matsuda

Assembly

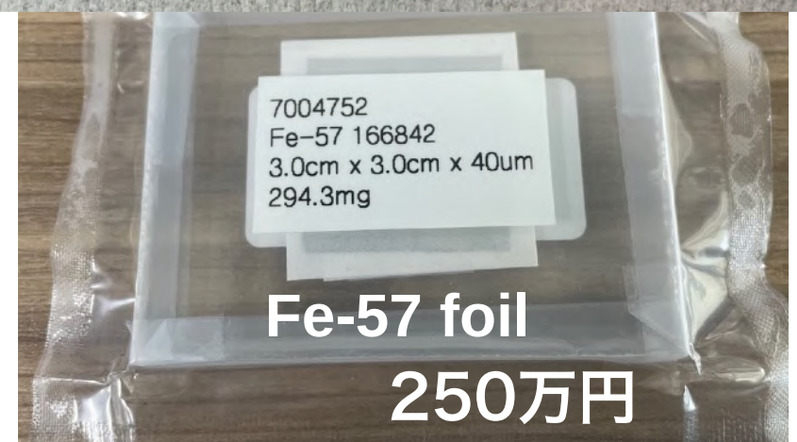


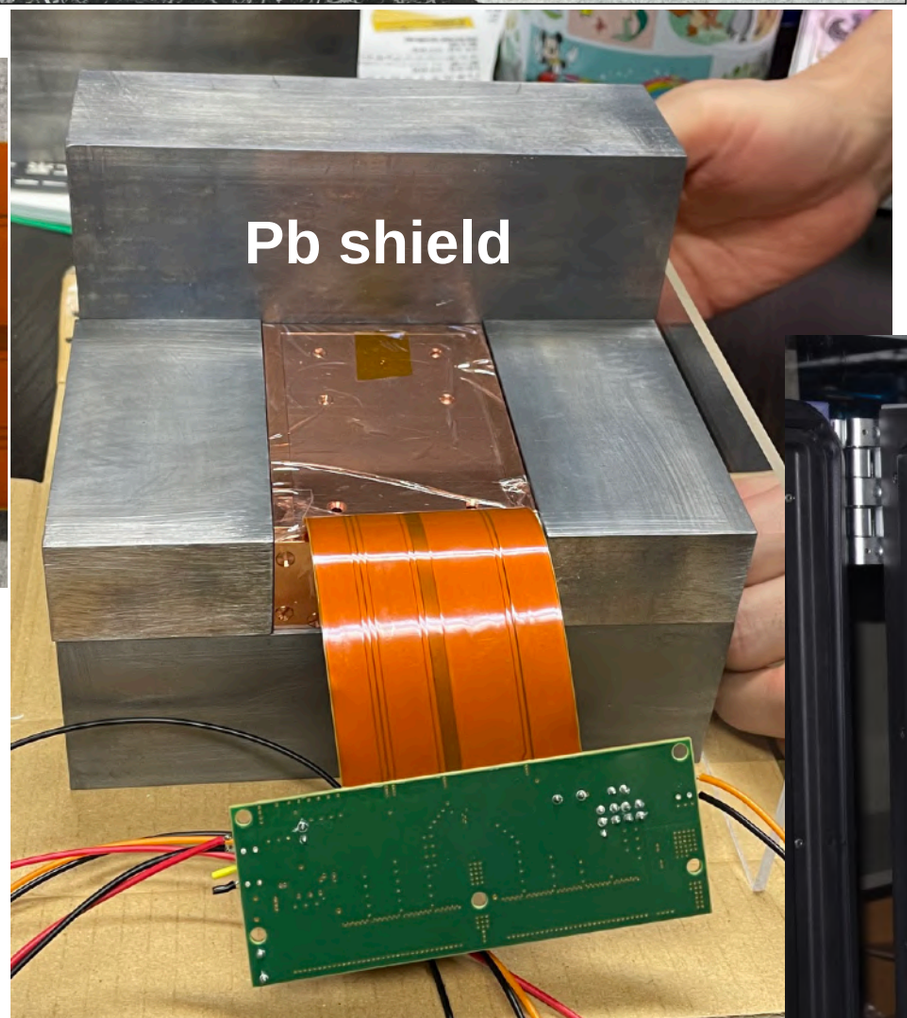

regid FPC
SOIPIX

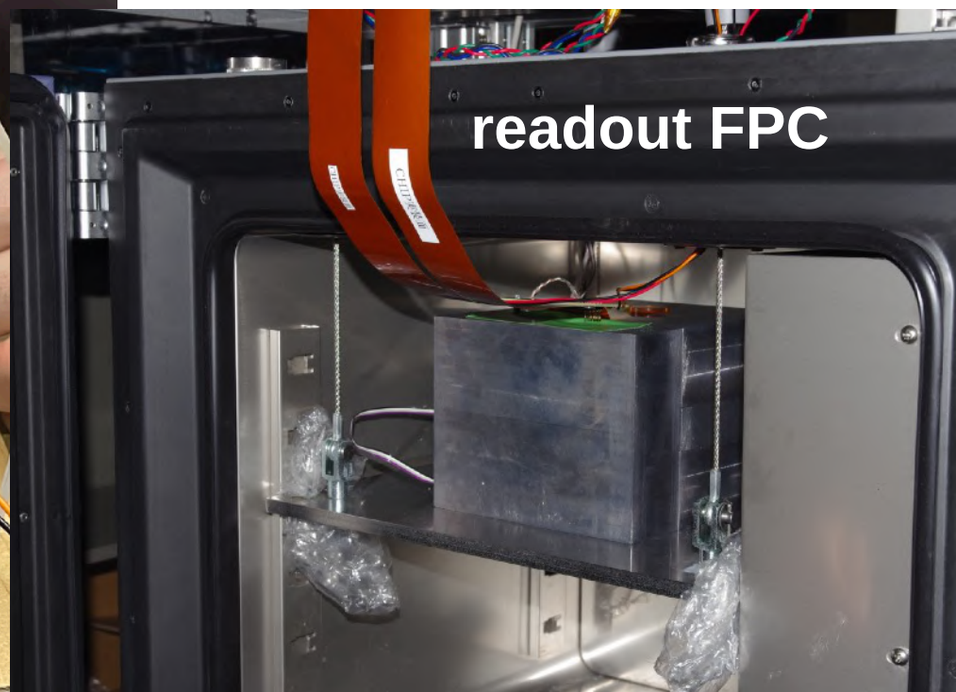

O-free-Cu


Temperature Chamber
Pb shield

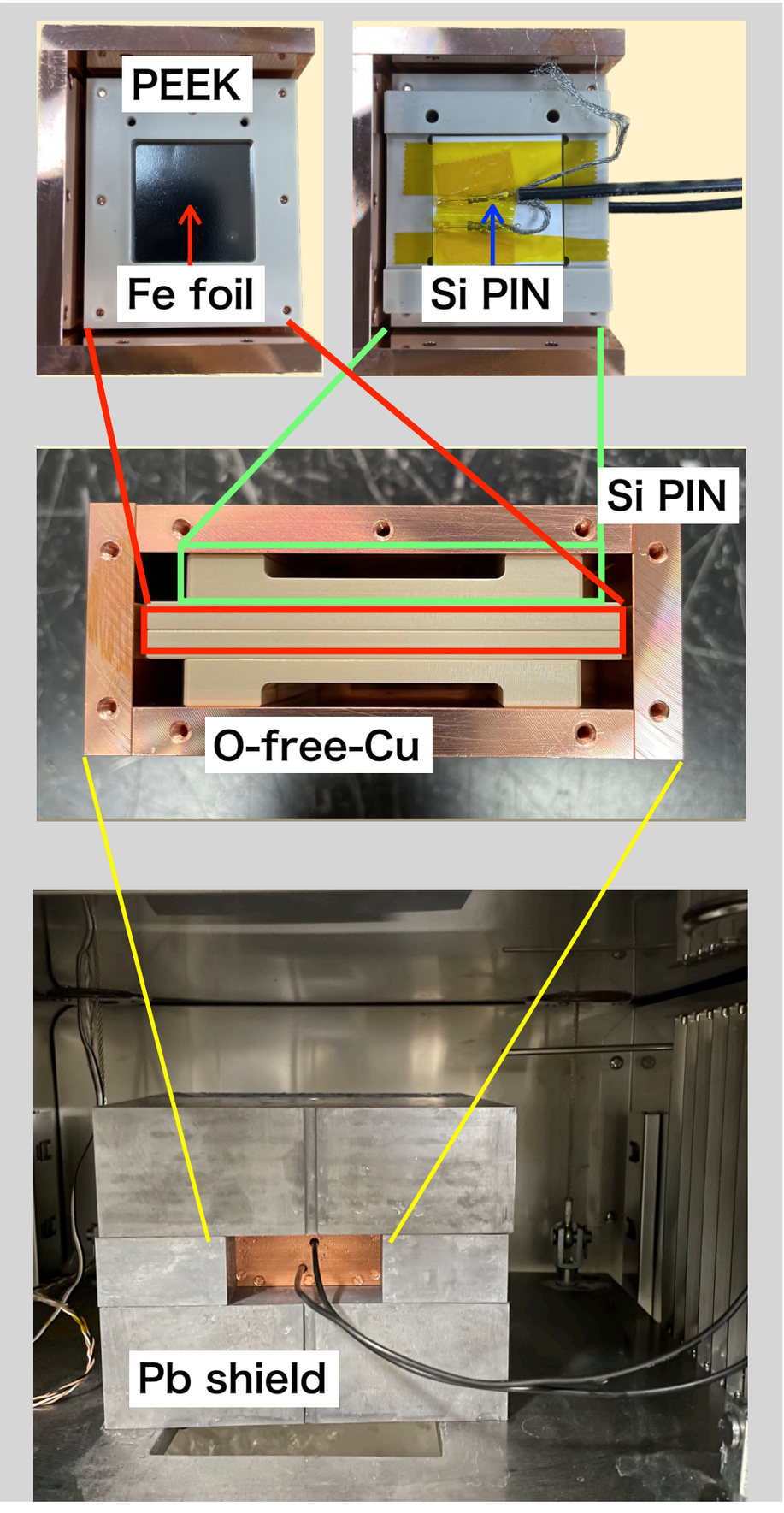

PEEK


7004752
Fe-57 166842
3.0cm x 3.0cm x 40um
294.3mg
Fe-57 foil
250万円

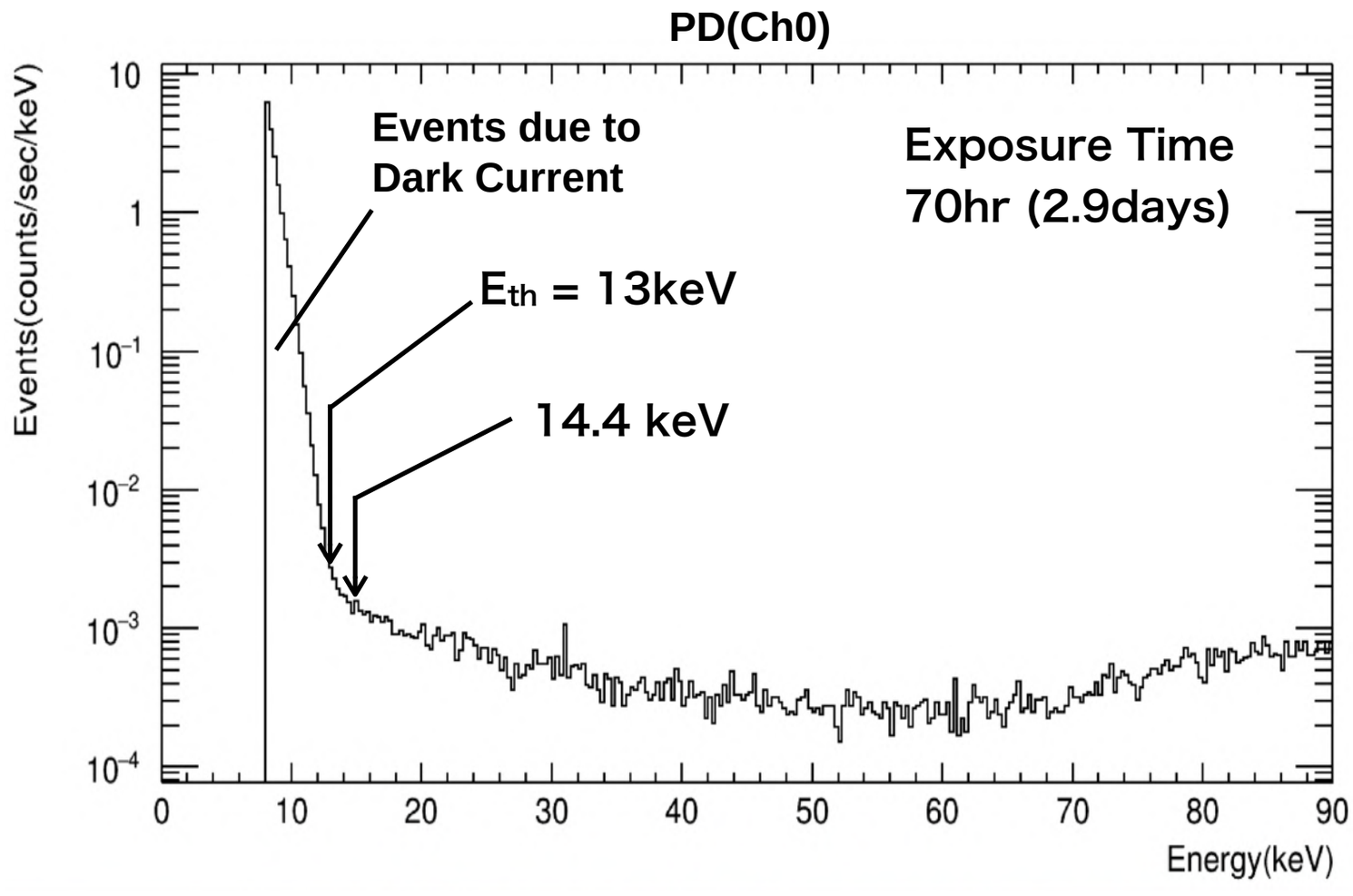

Pb shield


readout FPC

Si PIN diode by undergraduate students

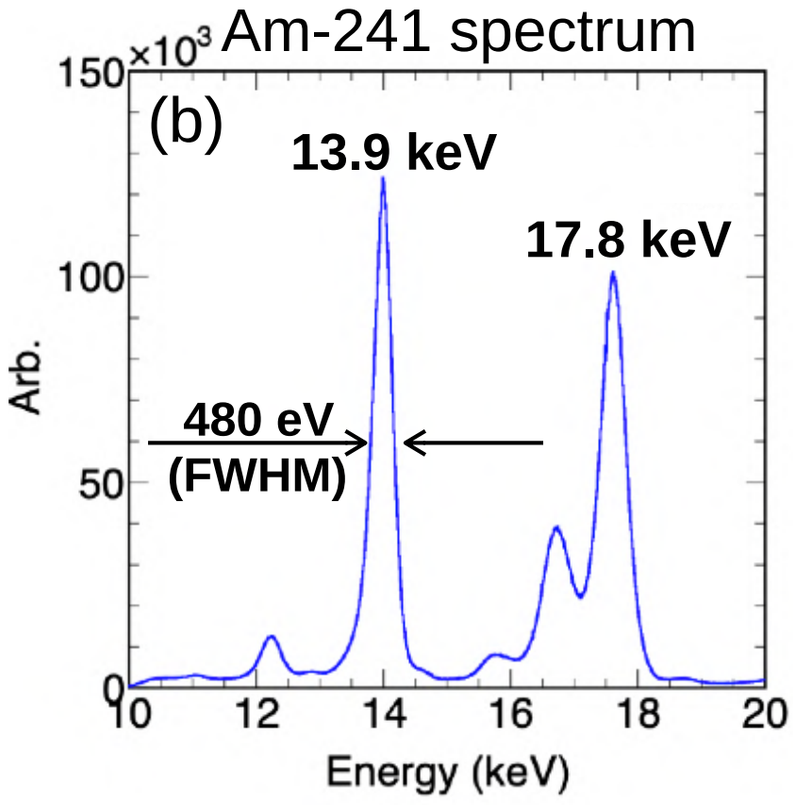


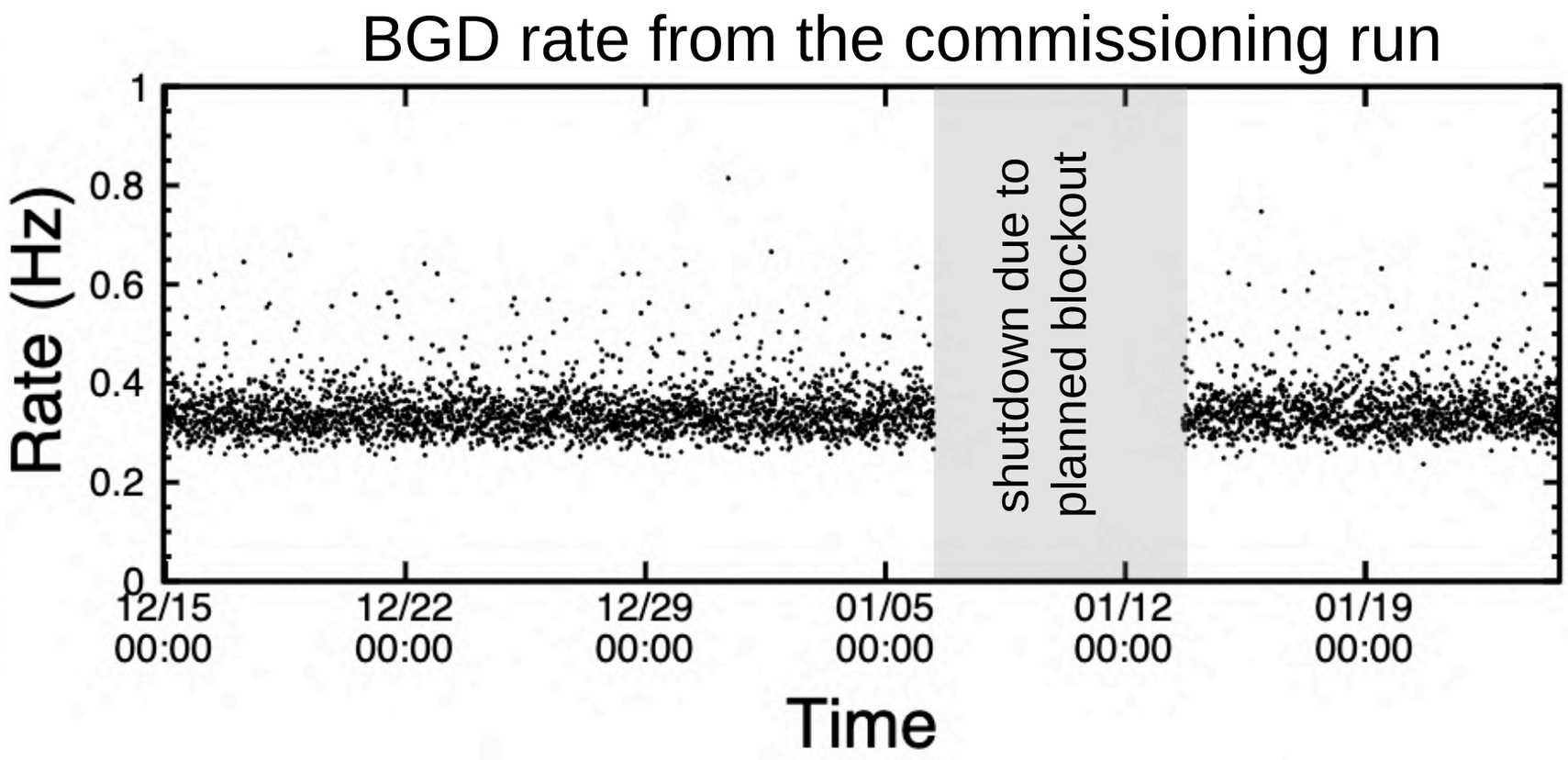
- A path finder observation mainly by undergraduate students with Si PIN diode placed at the same position for SOIPIX.
- Made BGD observation with a normal Fe foil in February, 2023, (but without anti-coincidence)
- Analyzing the data now in order to identify the source of BGD and find the way to reduce it.



SOIPIX “XRPIX7 (2017)” : Commissioning Run

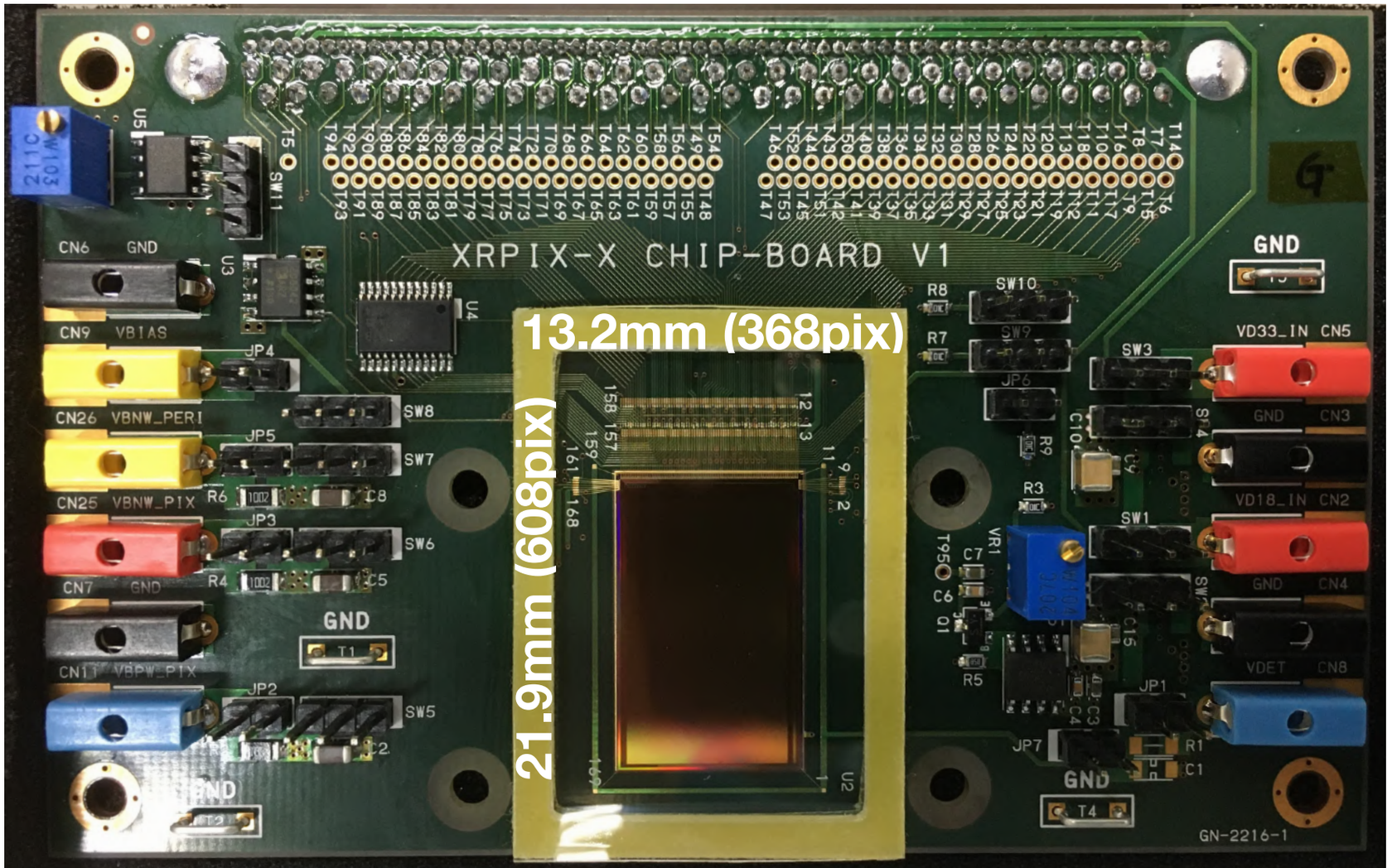
- Searched for optimal operating parameters of back bias voltages and the working temperature. Developed event analysis method
- Made calibration of overall gain and pixel-to-pixel gain variation
- Made a commissioning run from 14 December, 2022 to 25 January, 2023 with exposure time = 15.17 days (but without anti-coincidence)
- Confirmed stable operation of SOIPIX, Daq., temperature control
- Plan to start observation using Fe-57 at Q1, FY2023.





New SOIPIX ! : “XRPIX10 (2022)”

- “XRPIX7” was a 3rd generation sensor.
- In 2022, we developed XRPIX10, a 4th-generation sensor with a new device structure “pinned depleted diode” that improves energy resolution, modified circuit design that improves readout speed.
- Performance evaluation is currently underway.
- After 8 months of observation with XRPIX7, we will put XRPIX10 into the ISAI experiment (Q1 FY2024)

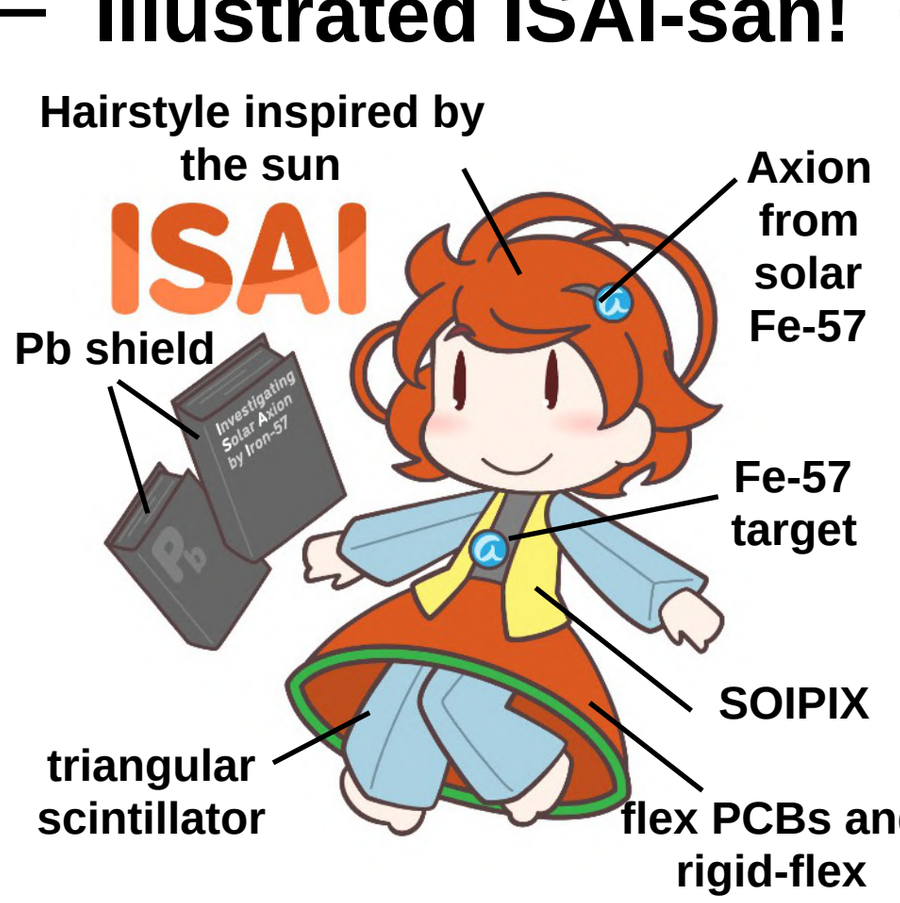


ISAI experiment : Summry

- Investigating Solar Axion by Iron-57
  - Dependent only on a-N coupling
  - No ambiguity due to mixing of a-e or a-γ coupling
- Table top experiment
  - Passive and active shield, X-ray SOIPIXs with high ΔE, high QE, high Δt
- Commissioning run with XRPIX7 using normal Fe foil
  - Observations to begin in Q1 of FY2023 using actual Fe-57 foil
- Preparing the new sensor XRPIX10 having higher energy resolution (210 eV) than XRPIX7 (480 eV)
  - Will start observation in Q1 of FY2024

We are ready to start observation with Fe-57.

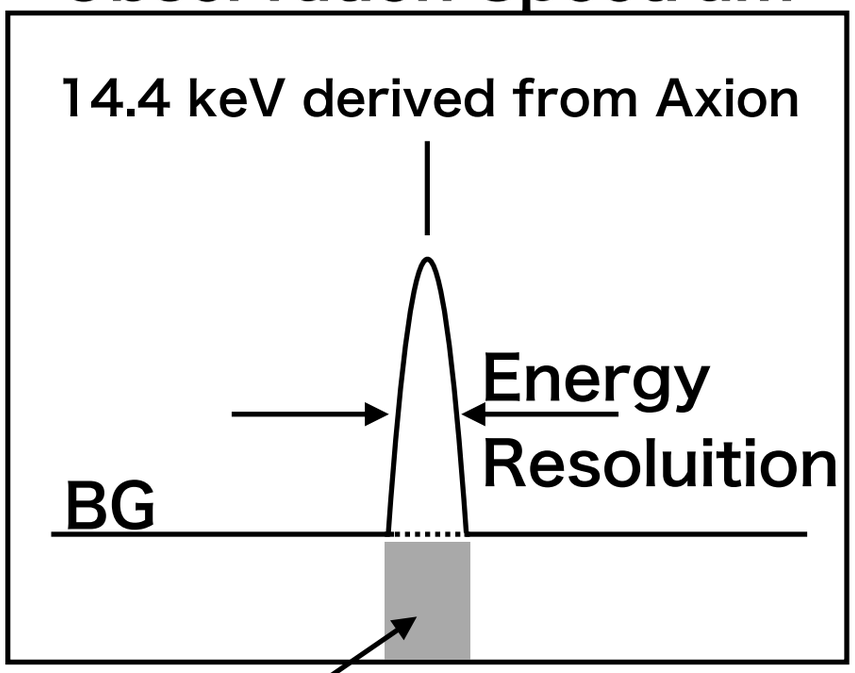
Illustrated ISAI-san!



2回の公募研究の採択, ありがとうございます！
1回目の公募研究の予算でXRPIX10を作りました！

Previous Researches

Observation Spectrum



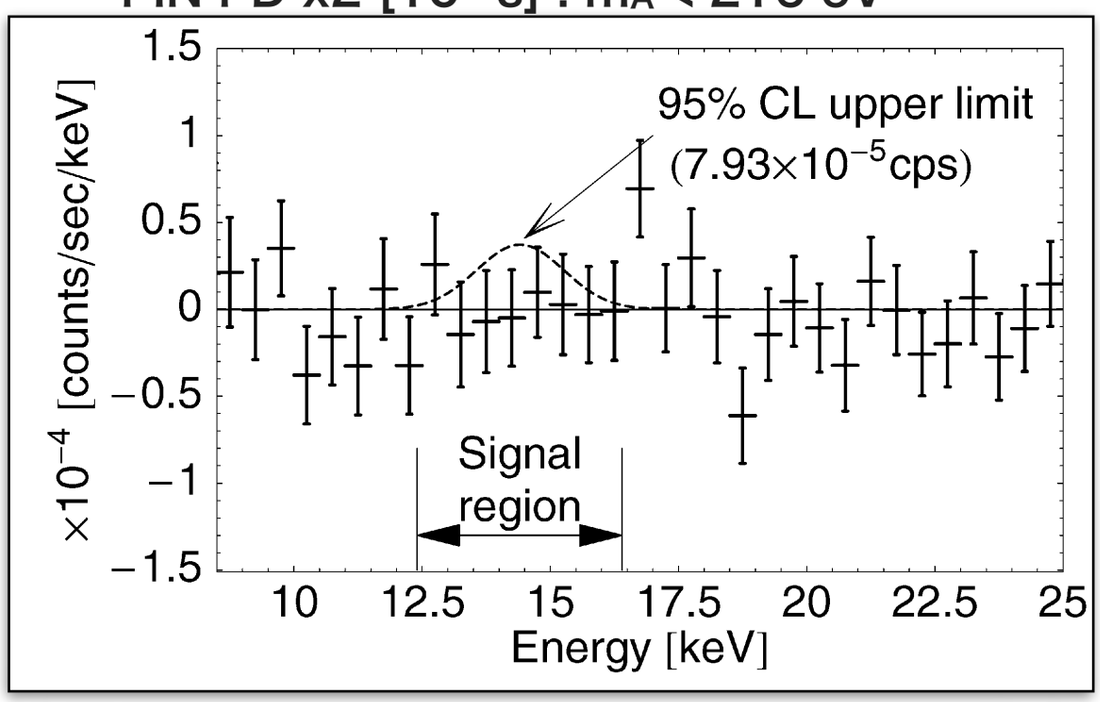
- QE suitable for 14.4 keV
- Good ΔE to reduce effective BG

→ Si

- Low BG → passive and/or anti-coincidence

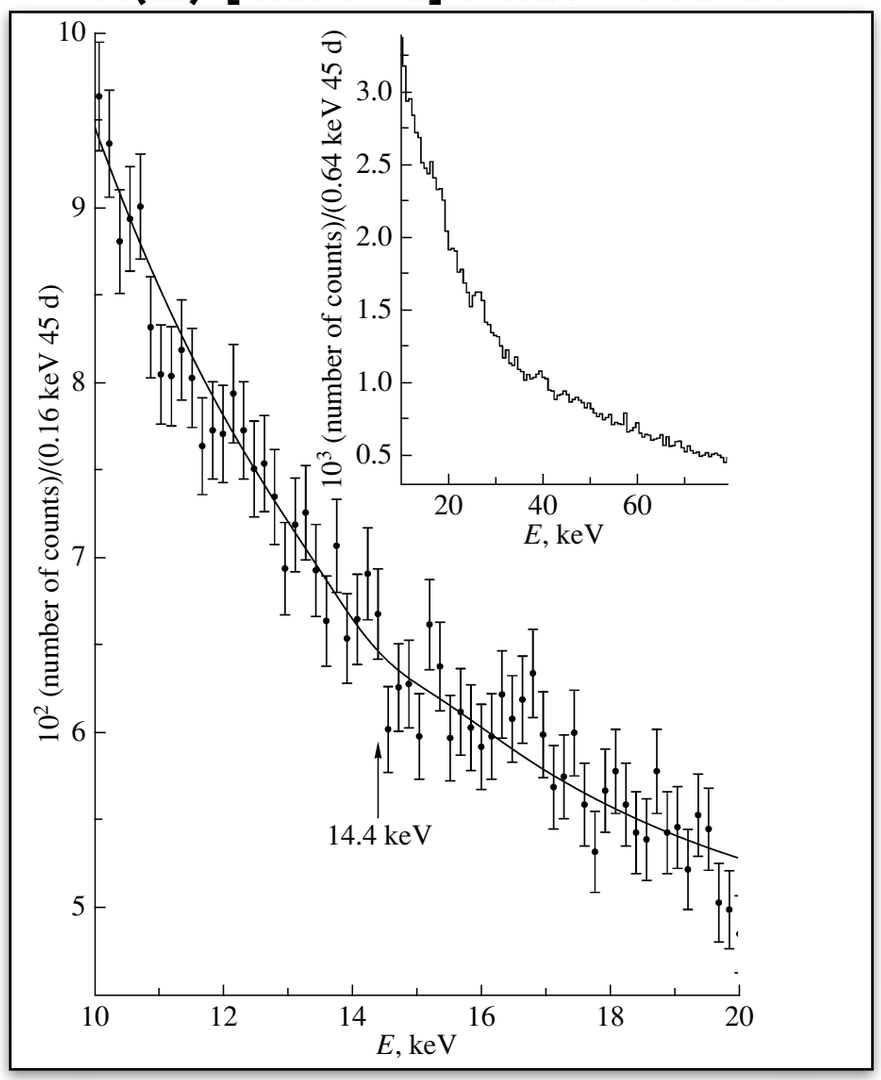
Namba07, Phys.Lett.B, 645, 398

PIN PD x2 [10^6 s] : m_A < 216 eV

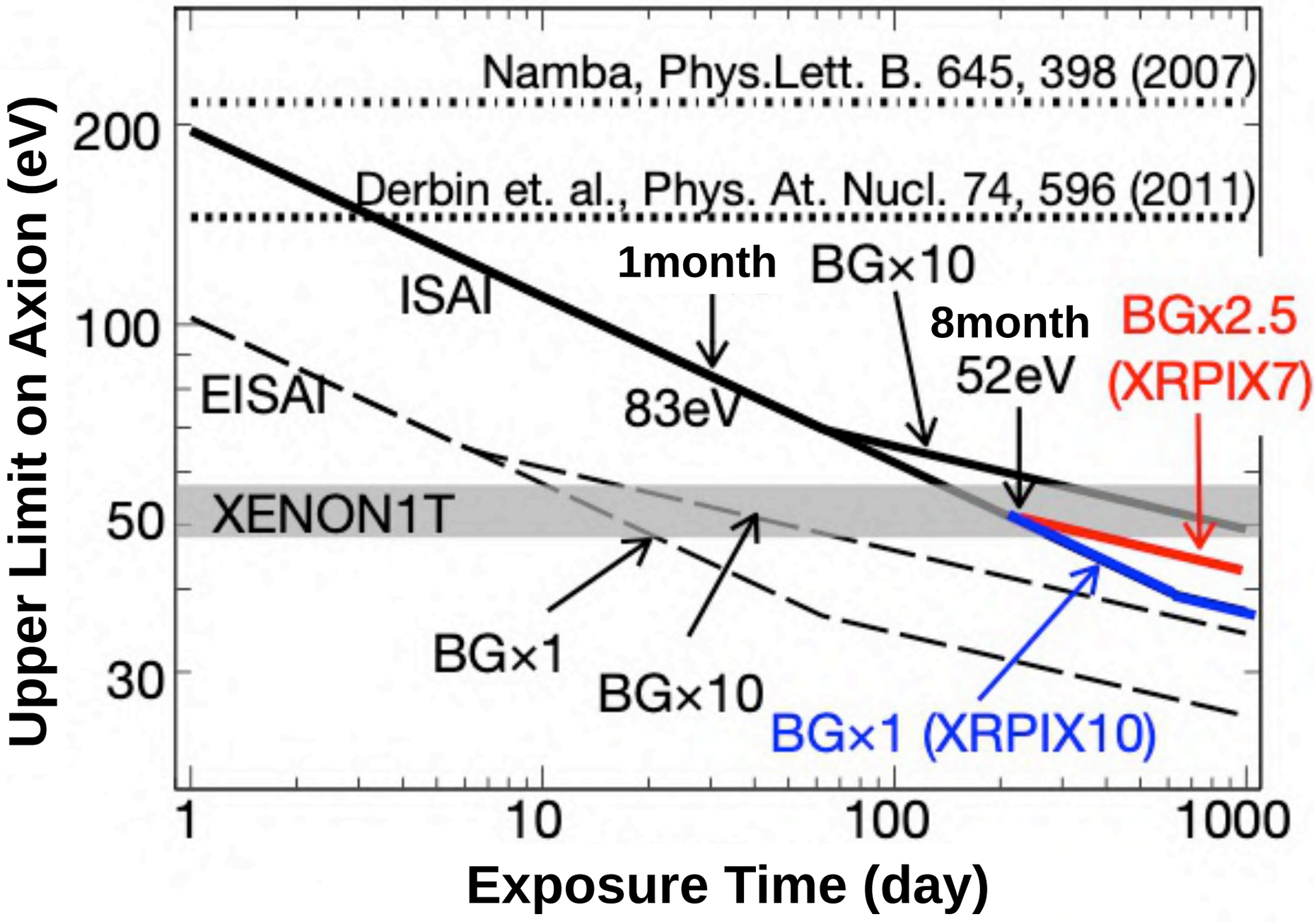


Derbin+11, Phys.At.Nucl.74, 596

Si(Li) [4x10^6 s] : m_A < 145 eV



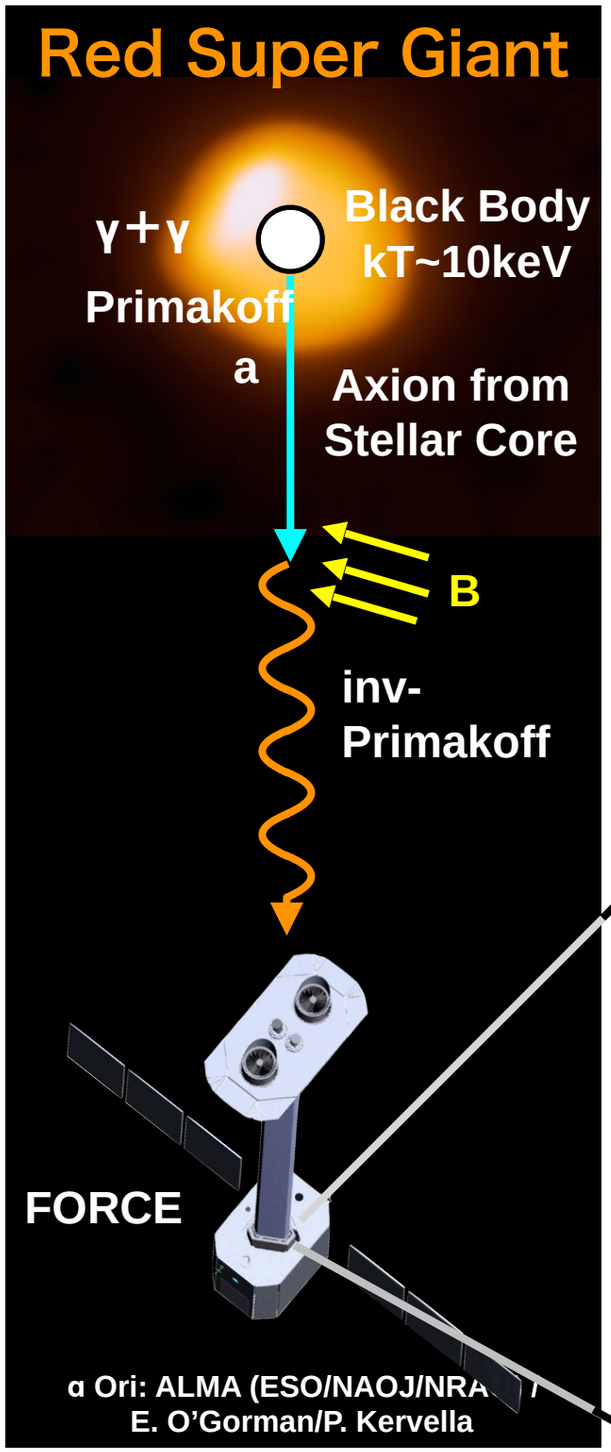
Predicted sensitivity to axion mass



- Fe-57 mass : 127 mg
- Efficiency (solid angle & Sensor QE) : 14.9% @ 14.4keV
- Energy Resolution: 250 eV (FWHM) @ 14.4 keV
- BGD : Assuming BGD only from circuit parts mounted on rigid FPC

FORCE-ALPINE (Axion Like Particle Investigation at Novel Extraterrestrial objects)

- Axions from core of a red-giant star are converted into X-rays by the interstellar magnetic field through the inv-Primakoff conversion [arXiv:1711.00345, PRL 126,031101].
- We observe the X-rays with the FORCE satellite equipped with SOIPIXs, whose sensitivity is one order of magnitude higher than that of the NuSTAR satellite.
- We will apply the background rejection function developed for the ISAI experiment to those for the FORCE satellite.



Parameter	FORCE (requirement)	NuSTAR	ASTRO-H (HXT & HXI)
angular resolution (HPD)	<15″	58″	1.7′
bandpass (keV)	1–79	3–79	5–80
effective area (cm^2@30 keV)	>200	184*	198*
fov (50% resp. @30 keV)	>49 $arcmin^2$	~85 $arcmin^2$	~36 $arcmin^2$
timing resolution	several × 10 μs	2 μs	several × 10 μs
energy resolution (FWHM)	<300 eV at 6 keV comparable with HXI	400 eV at 10 keV 900 eV at 68 keV	900 eV at 14 keV 1500 eV at 60 keV

* 4 arcmin radius extraction region