"ISAI" Investigating Solar Axion by Iron-57

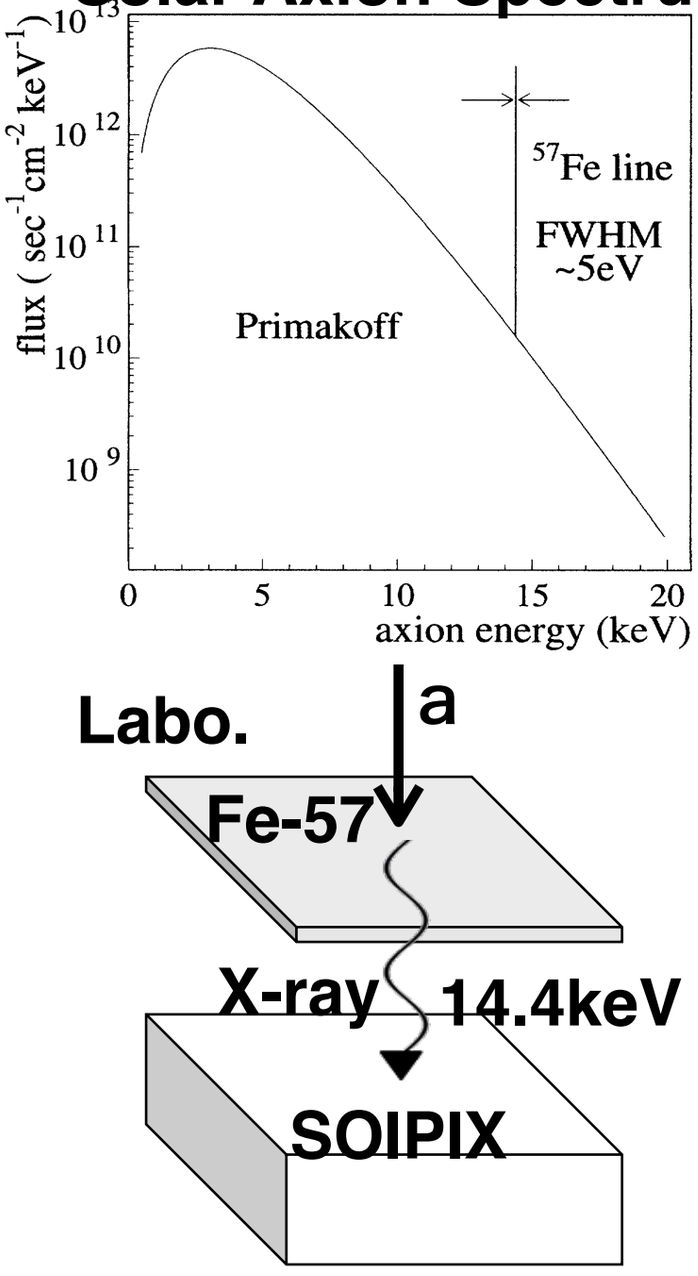
Takeshi TSURU (Kyoto Univ.)
D02 公募研究

Tomonori Ikeda, Masamune Matsuda, Hiroki Namba, Moe Anazawa,
Mizuki Uenomachi, Teruaki Enoto (Kyoto U.), Toshihiro Fujii (OMU),
Yoshiyuki Onuki, Yoshizumi Inoue (U. Tokyo, ICEPP), Kentaro Miuchi (Kobe U.),
Akimichi Taketa (U. Tokyo, ERI), Ayaki Takeda (U. Miyazaki),
Kenji Shimazoe (U. of Tokyo, Nuclear Engineering and Management),

20240425_ISAI_DMconf_Tsuru_v2

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

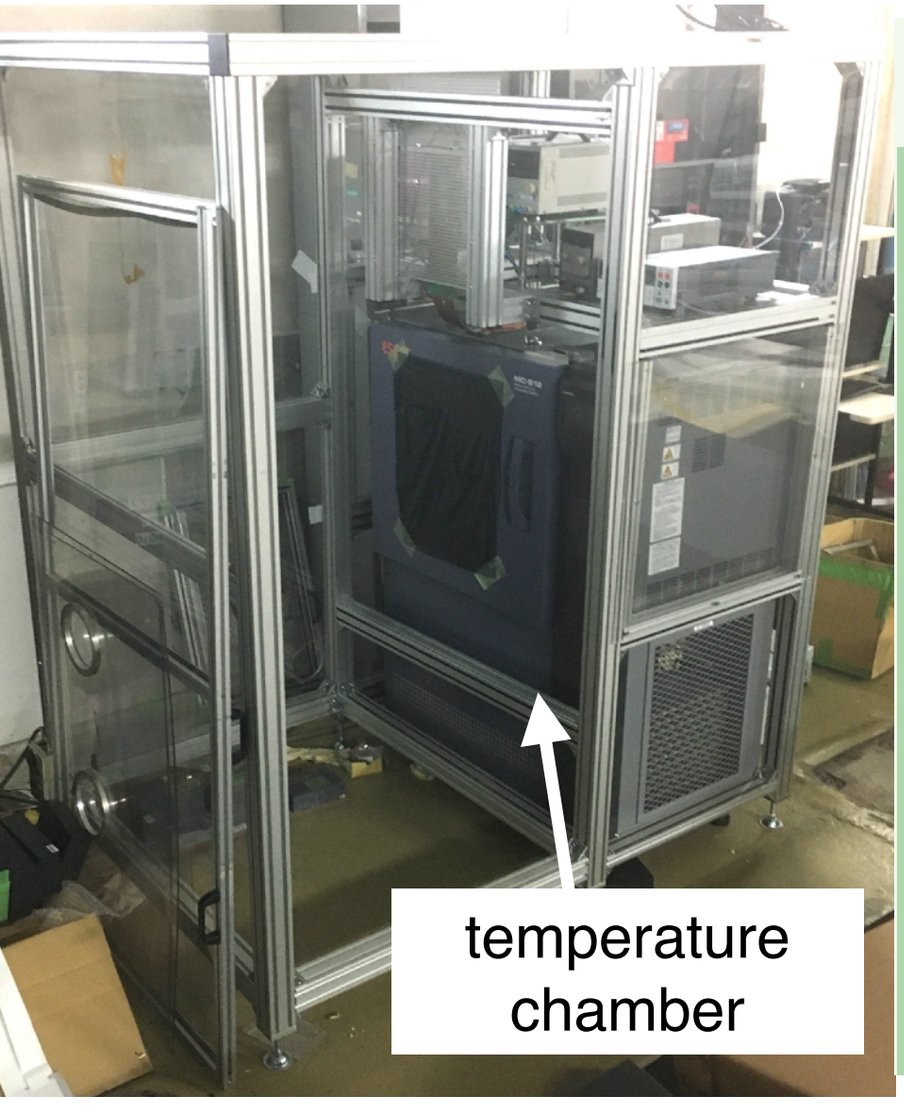
Previous and on-going works

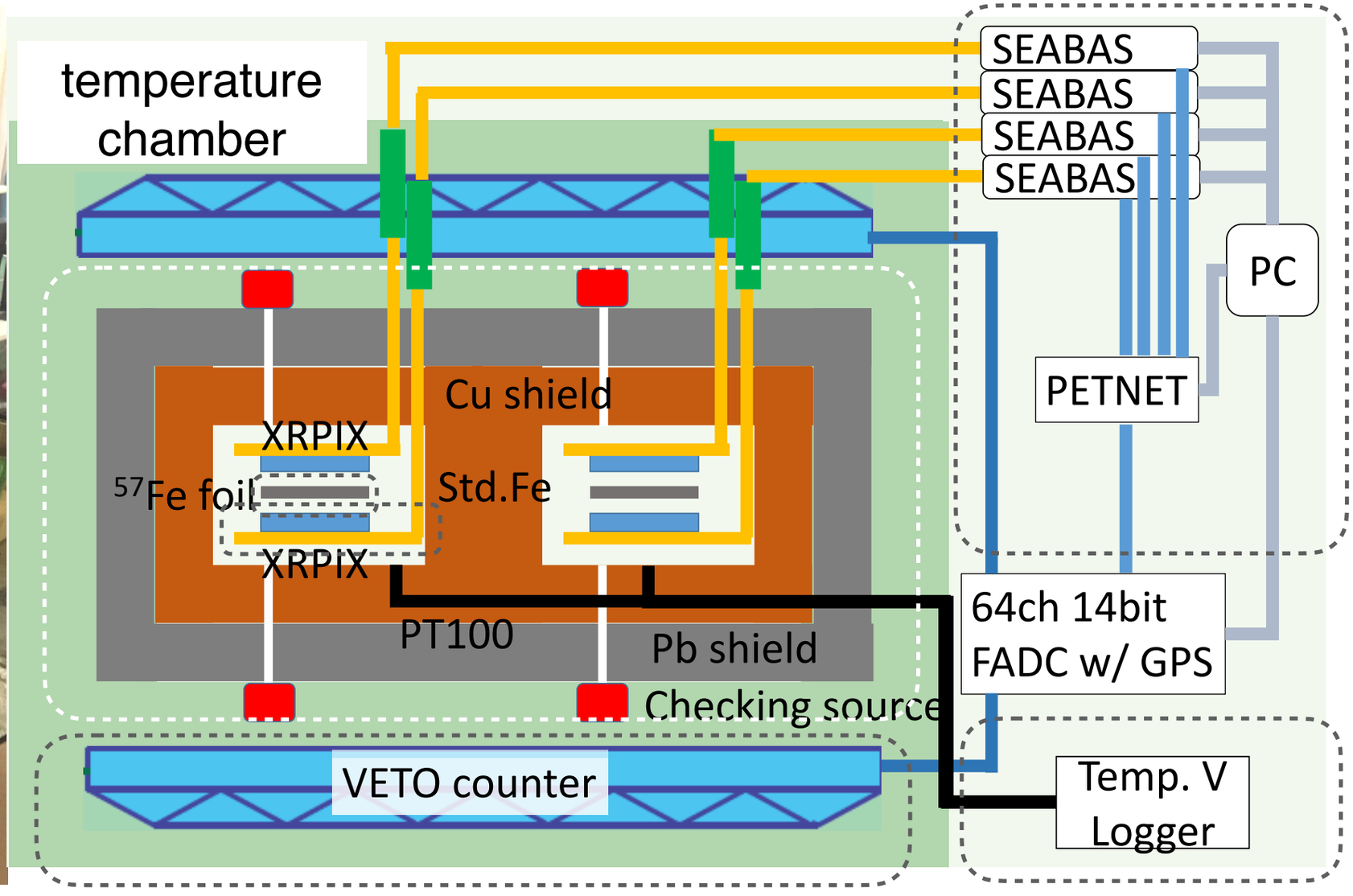
- Moriyama (1995). PRL 75, 3222
- Namba (2007), Phys.Lett.B, 645, 398
- Derbin (2011), Phys.At.Nucl.74, 596
- D04 group of DM学術変革領域 etc.

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 experiment running in a temperature chamber placed in our laboratory at Kyoto U.
- 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 and its shields are 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

(only 3 DM experts)

HEP: Onuki
CR: Fujii, Taketa, Namba,
DM: Miuchi, Inoue, Ikeda

Nuclear Medical: Uenomachi, Shioazoe
Astro.: Tsuru, Matsuda, Anazawa, Enoto
Detector Sci.: Takeda, Tsuru

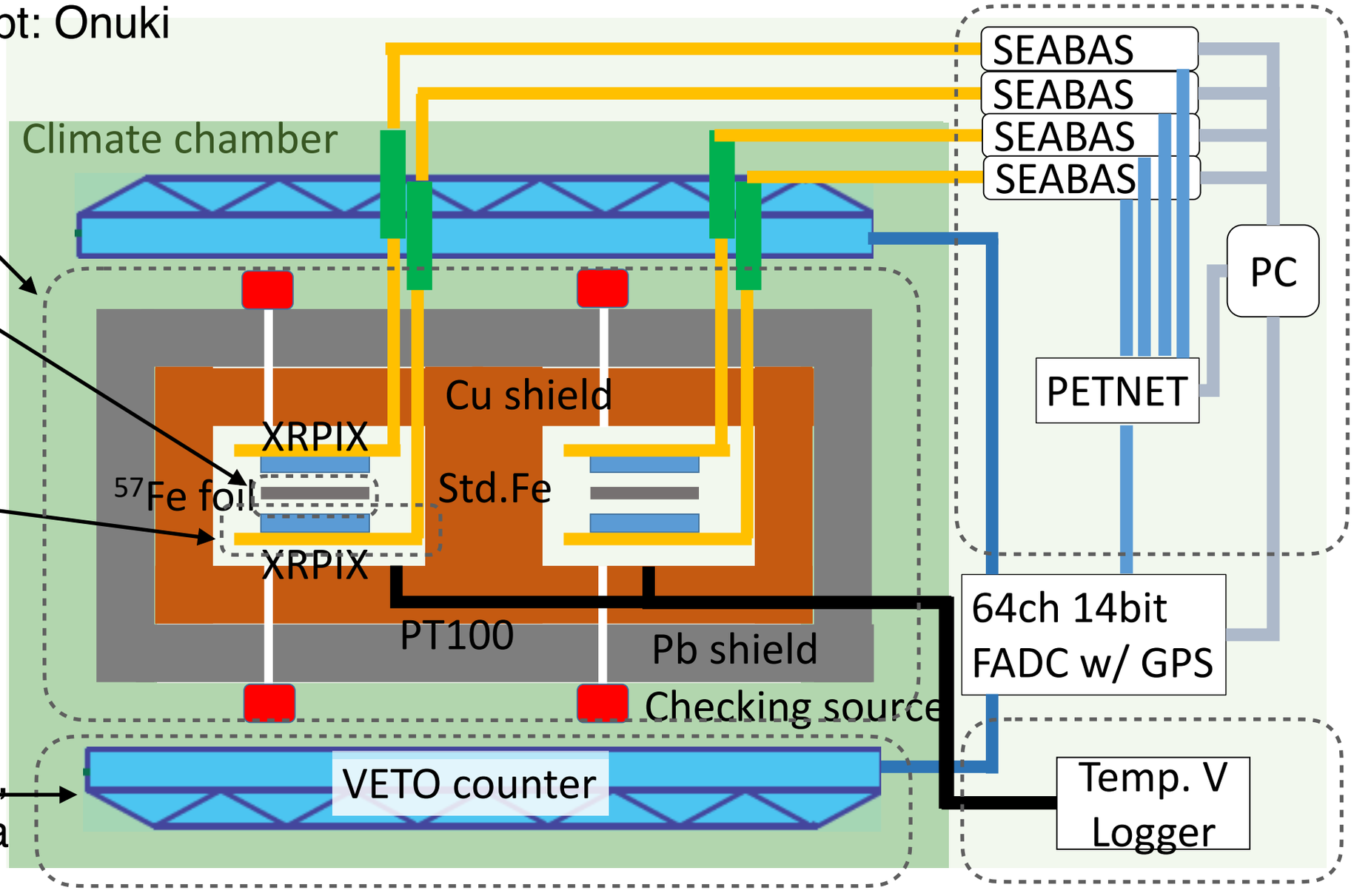
Overall Concept: Onuki

Mech. Design:
Onuki, Inoue

Fe-57:
Fujii, Miuchi

SOIPIX:
Tsuru, Takeda,
Ikeda, Onuki,
Uenomachi,
Shimazoe,
Matsuda

VETO:
Fujii, Anazawa,
Takata, Namba



Anti-Co.:
Uenomachi,
Takeda,
Matsuda
Ikeda

Parts BG:
Onuki,
Inoue,
Miuchi

Low BG Pb
Enoto,
Onuki,
Inoue

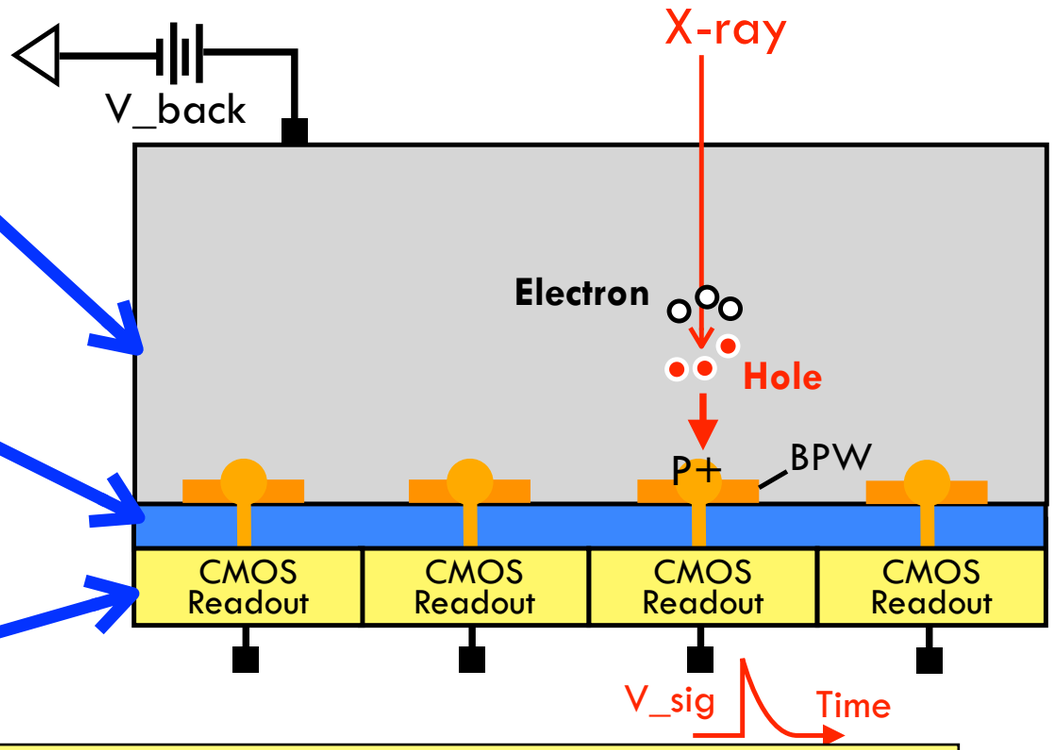
HK:
Miuchi

“XRPIX” Event-driven X-ray SOI pixel sensor

Sensor (high ρ, depleted Si)

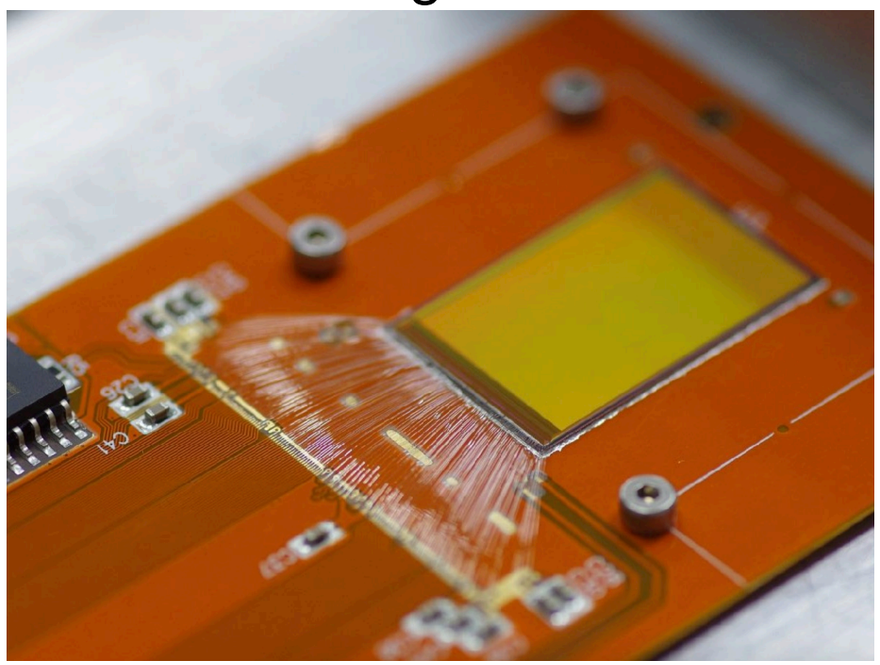
BOX (SiO_2)

Fast CMOS (low ρ Si)



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

XRPIX7 assembled on a low BG rigid-flex board



- format 608 × 384
- pixel size 36μm × 36μm
- sensor size 13.8mm x 21.9mm
- trigger time resolution better than 10μs

- We have been developing X-ray SOI pixel sensors, “XRPIXs”.
- SOI pixel sensor is monolithic using bonded wafer of high resistivity depleted Si layers for X-ray detection, SiO2 insulator, and low resistivity Si for CMOS circuits.
- In XRPIX, each pixel has its own trigger logic circuit and analog readout CMOS circuit.
- The trigger function realizes low detector BGD by anti-coincidence with surrounding scintillators.
- Thick depletion layer ~300μm is thick enough to detect 14.4 keV X-rays.

XRPIX is an ideal Si sensor for the ISAI experiment

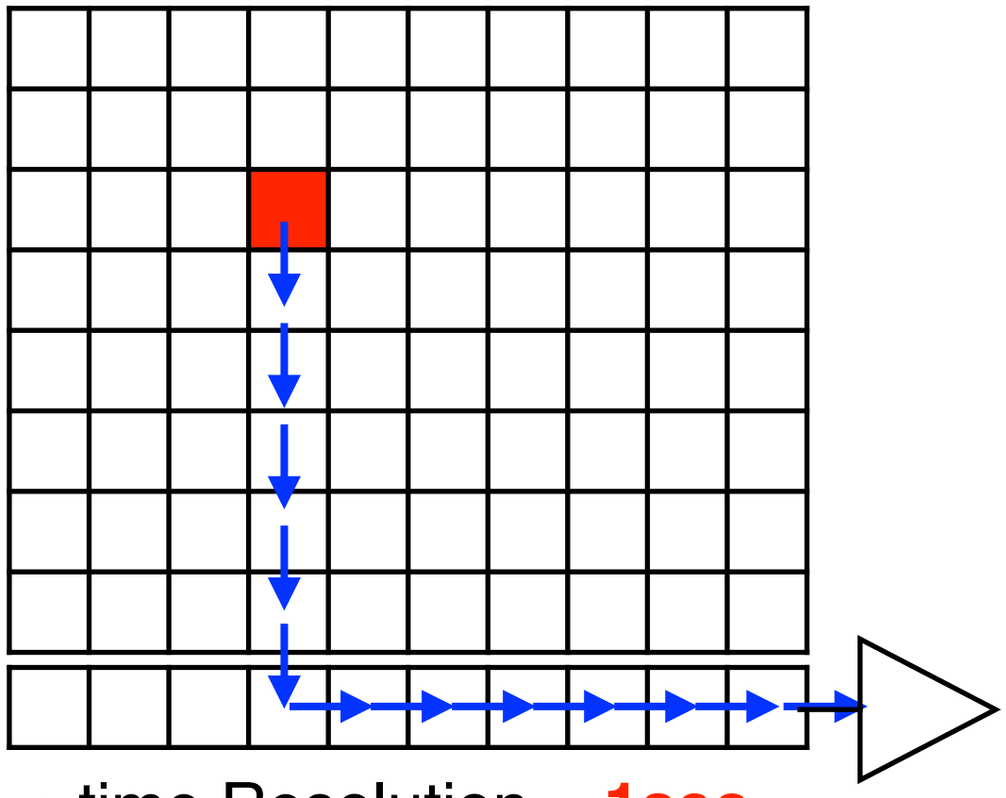
High Time Resolution 10μsec : Pixel Circuit

XRPIX = CCD/CMOS + Trigger Signal Output Function

- Originally, XRPIX has been developed for future X-ray Astronomy Satellites.
- in order to improve time resolution for anti pile up and for reduction of detector BGD by anti-coincidence.

Frame Readout / Rolling Shutter
(Usual CCD / CMOS)

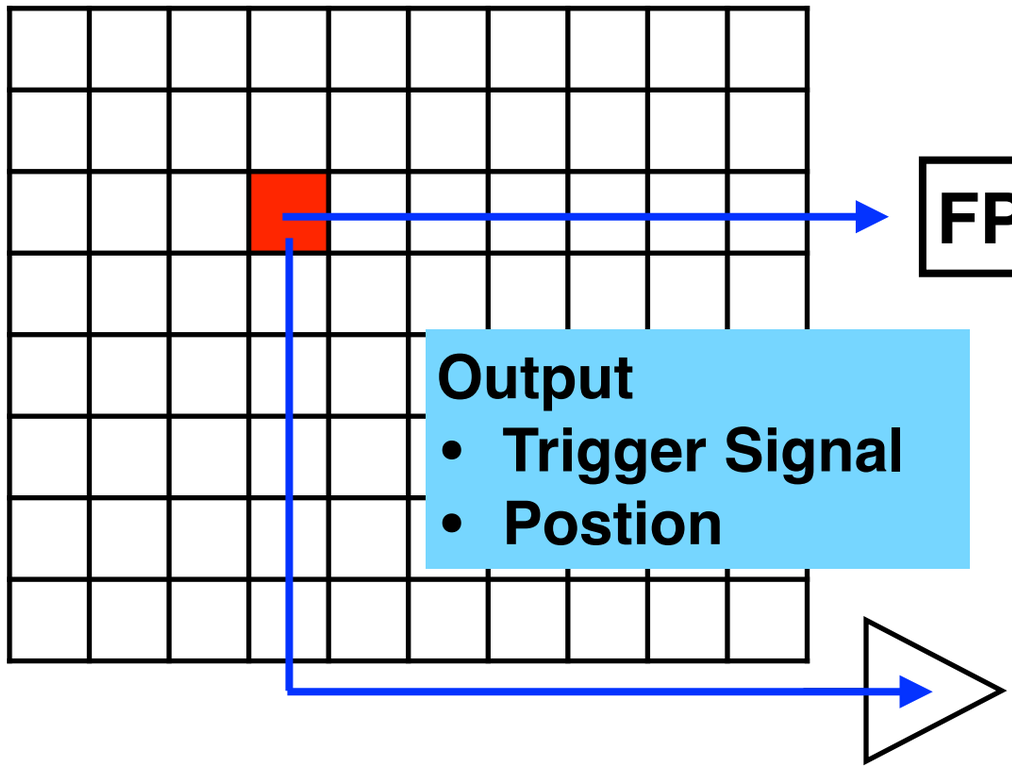
Read all pixels regardless X-ray incident



・time Resolution **~ 1sec**

Trigger output event driven readout
(X-ray SOIPIX)

Read only X-ray incident pixels

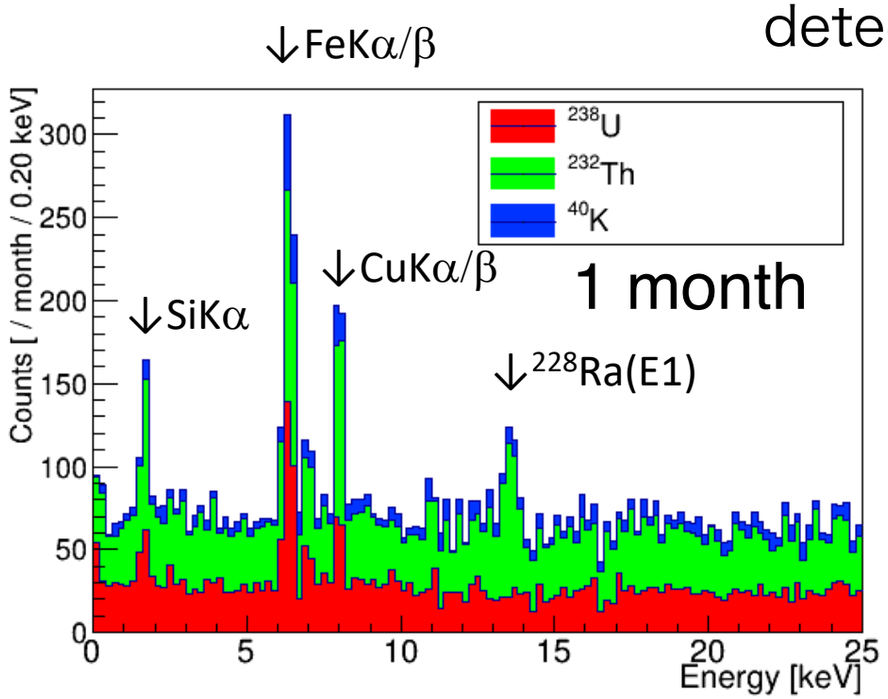


・time resolution better than **10μsec**

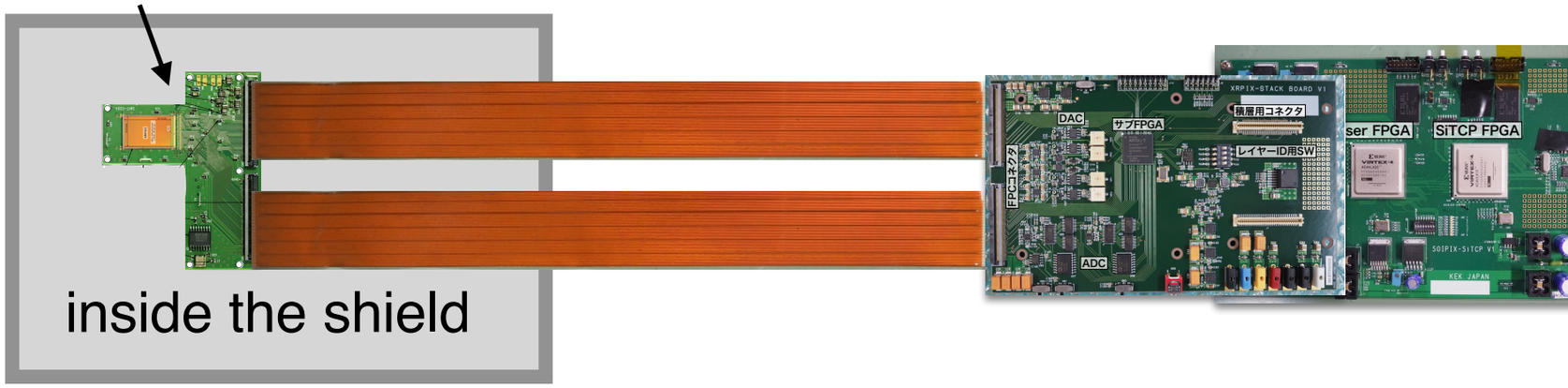
~10^5 higher Δt than Chandra and XRISM X-ray CCDs, and
~10^2 higher Δt than DEPFETs of Athena, etc.

Low BGD Readout Board

The sensor itself must be very low BGD in ISAI.

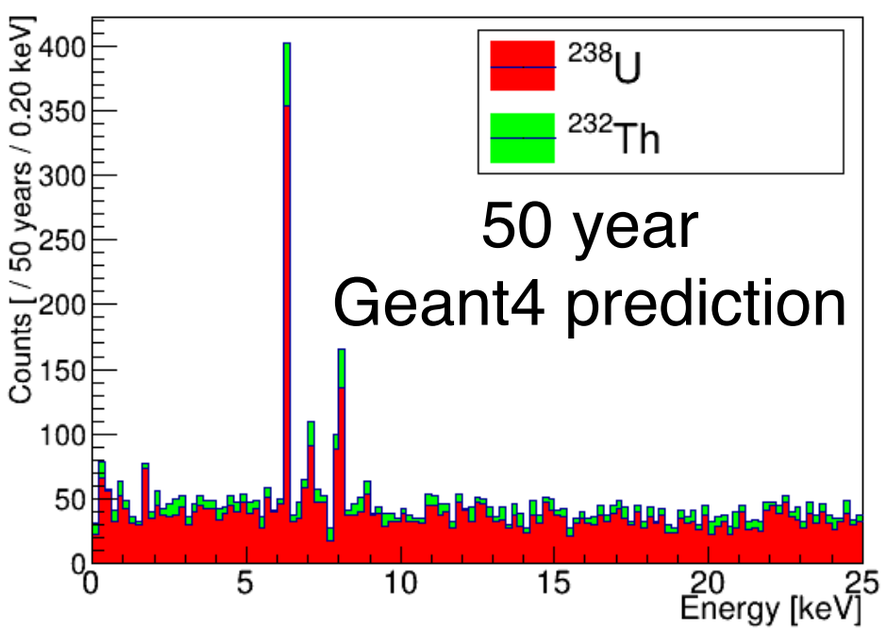


detector head developed for application of nuclear medical use



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

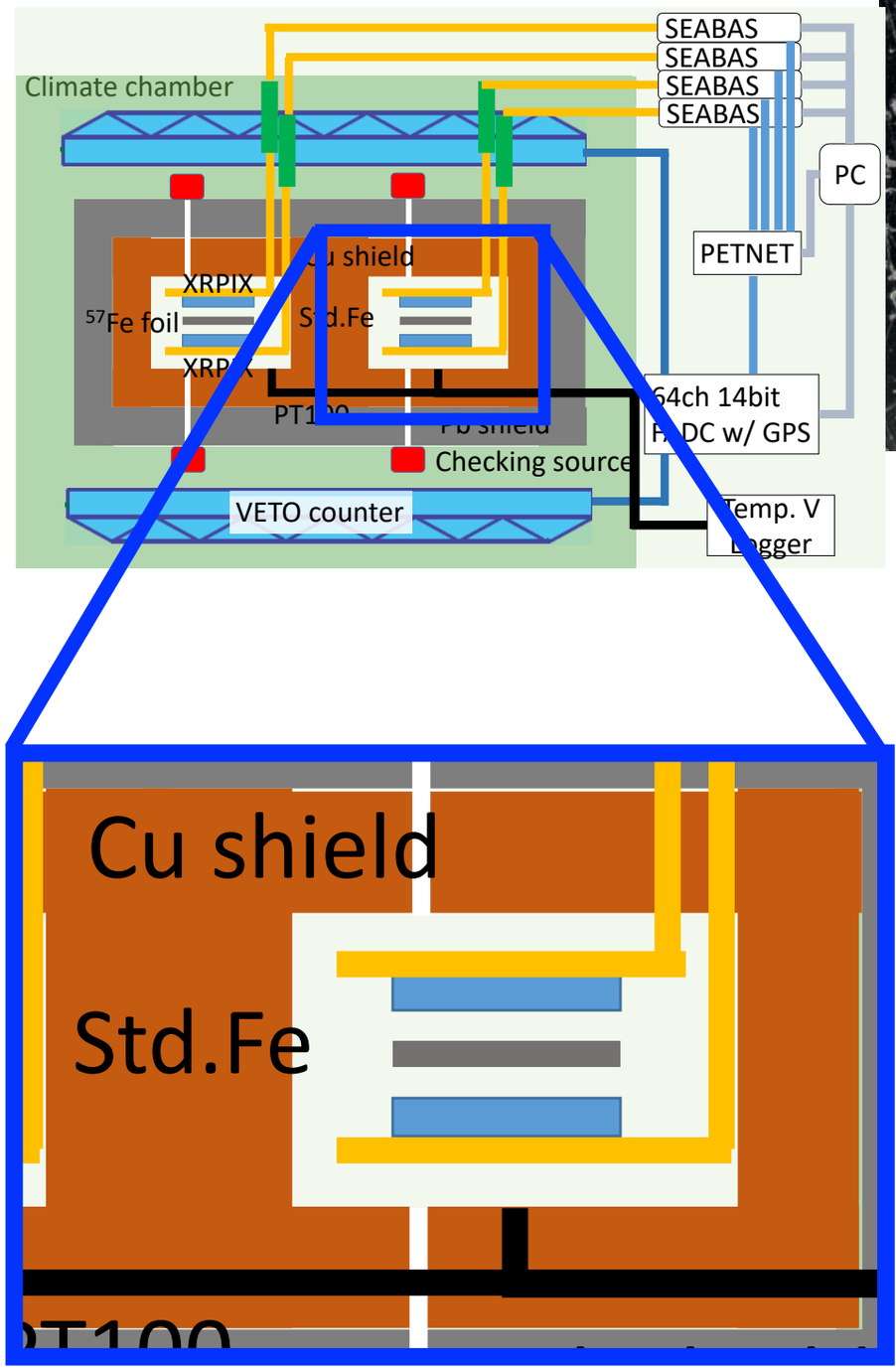
1/1000

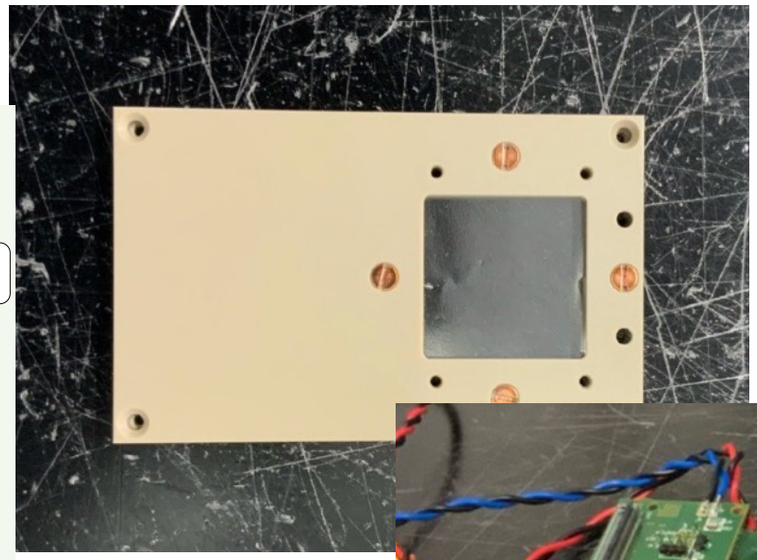


- Change G10 PCB to rigid FPC
  Only the rigid FPC is placed inside the shield

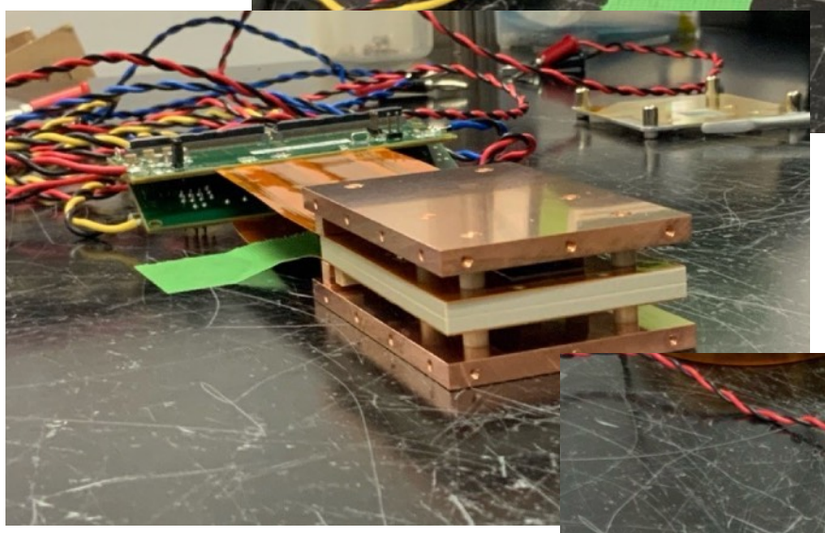
- Measure γ-rays from each circuit part with HPGe at UT to select and use quiet parts (Ose M-thesis,UT,2017).

Assembly of the Camera (1)

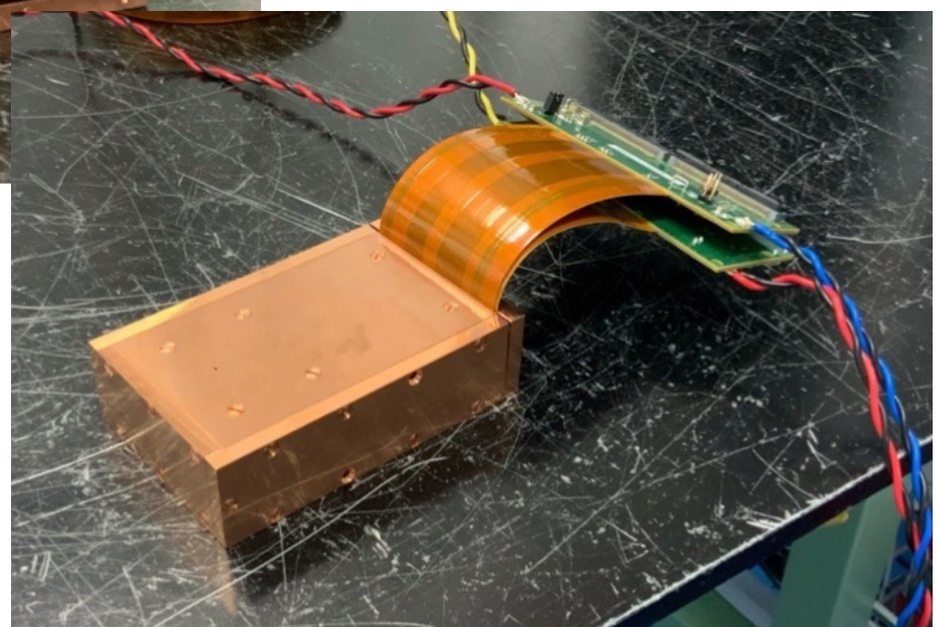




The iron film is fixed by sandwiching it with folders made with PEEK.

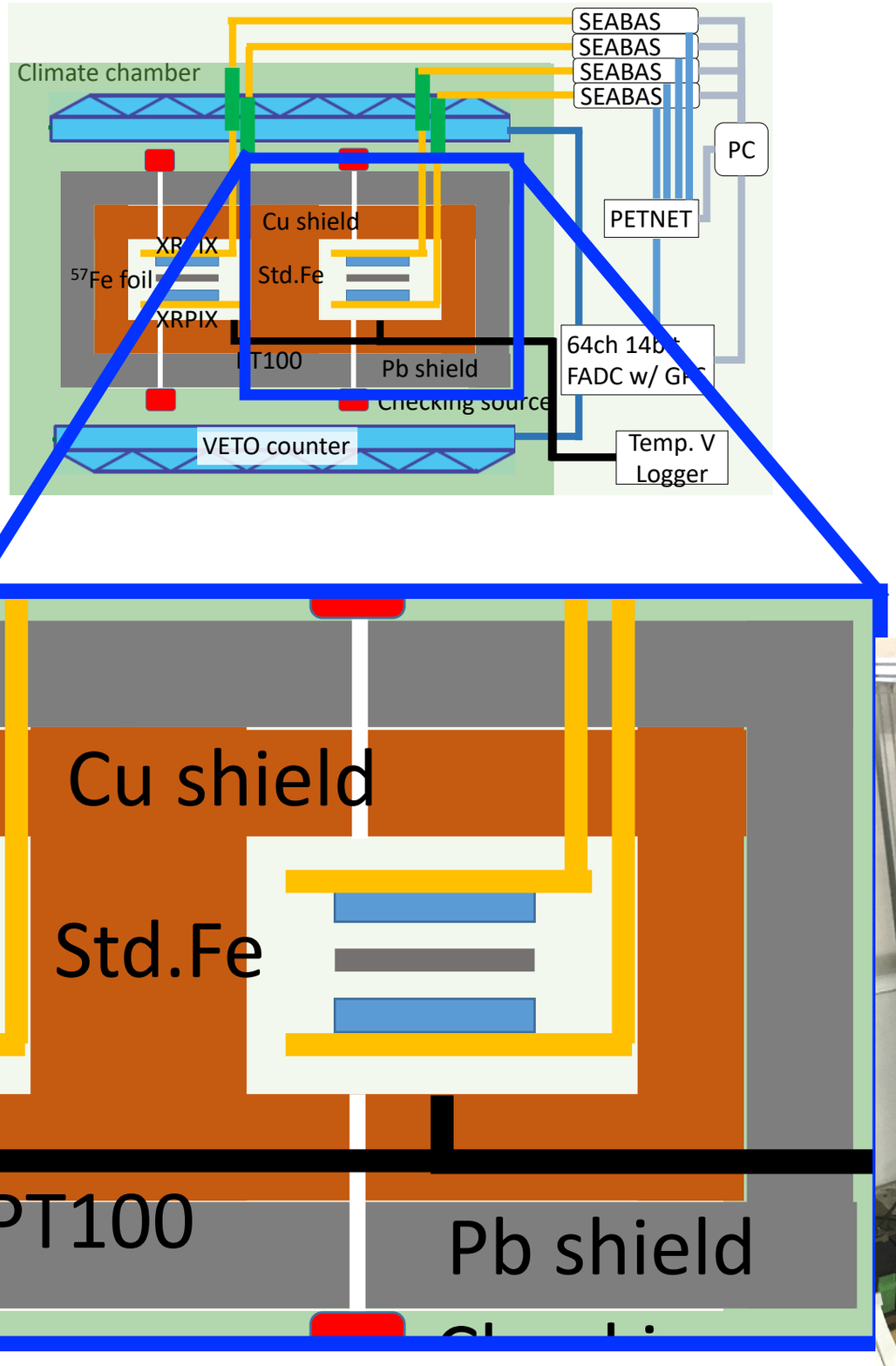


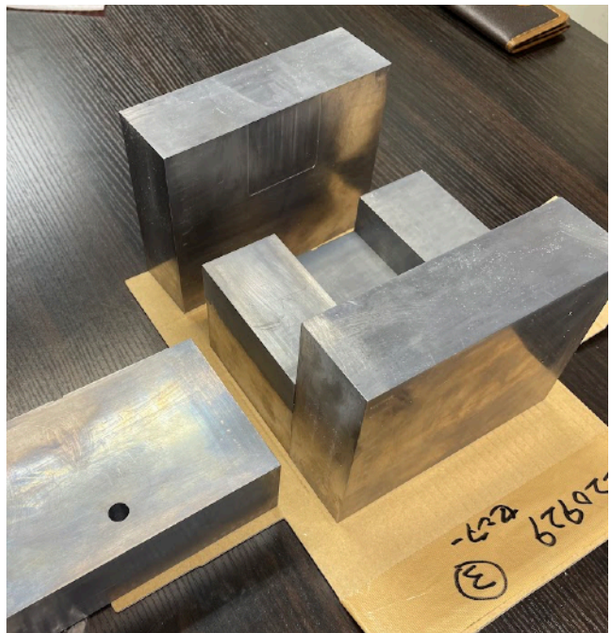
We enclose it with O-free Cu blocks.

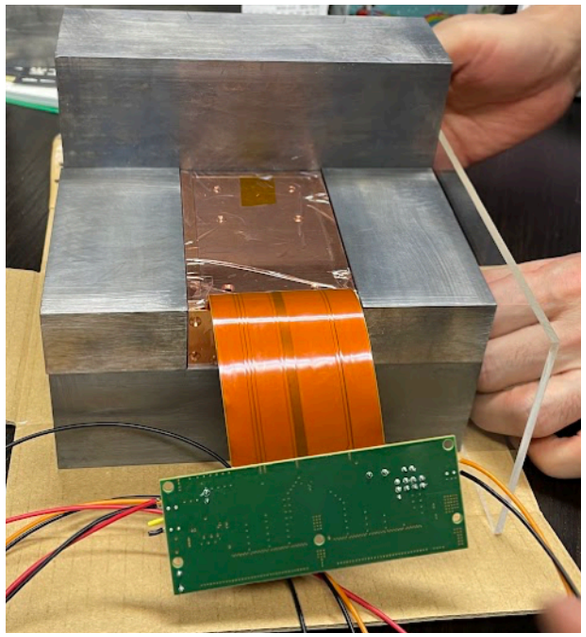


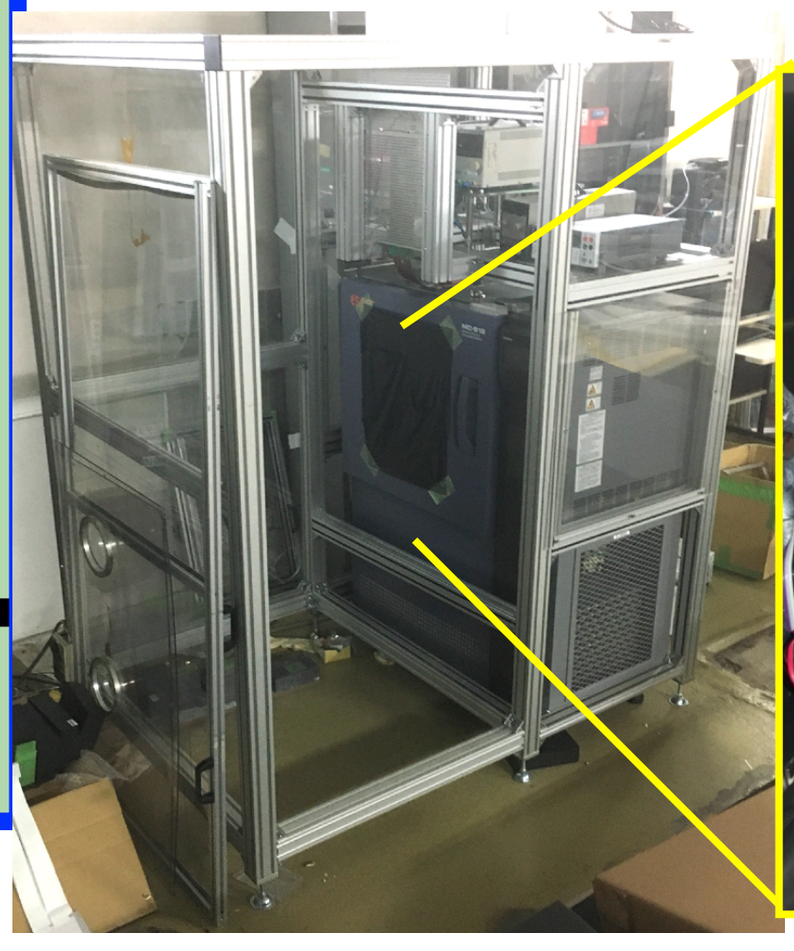
Assembly of the Camera (2)

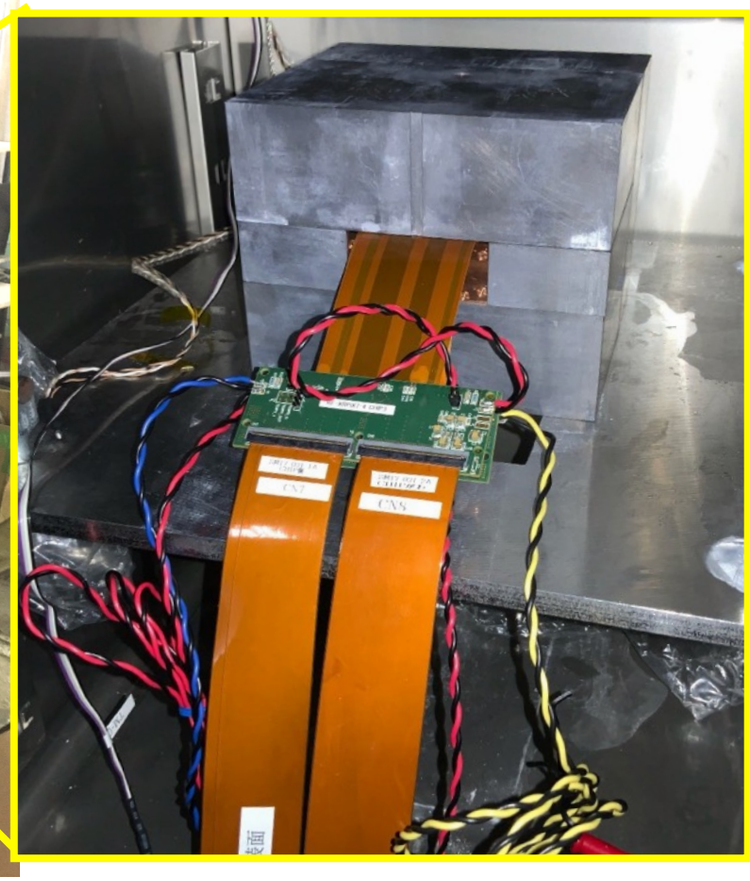
Assembly of the lead block and the instllation of the camera.



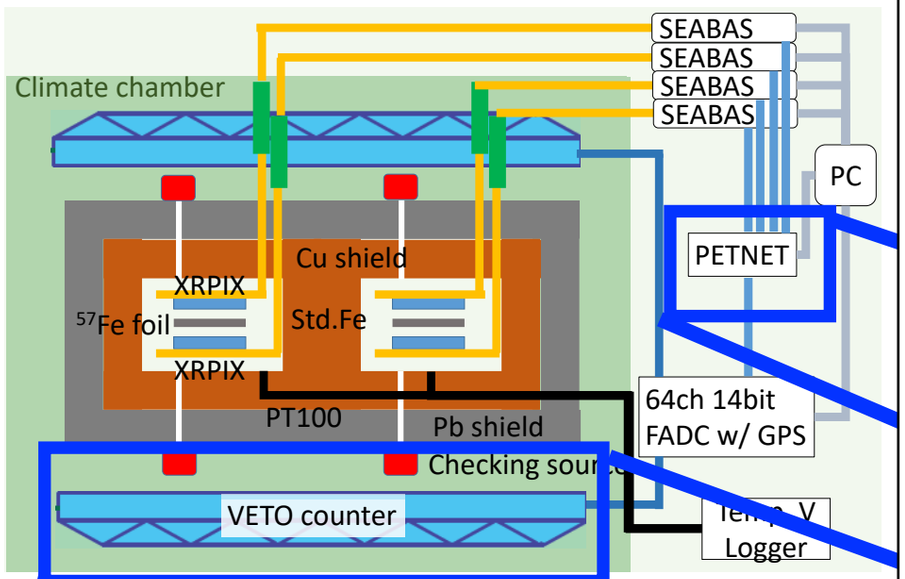




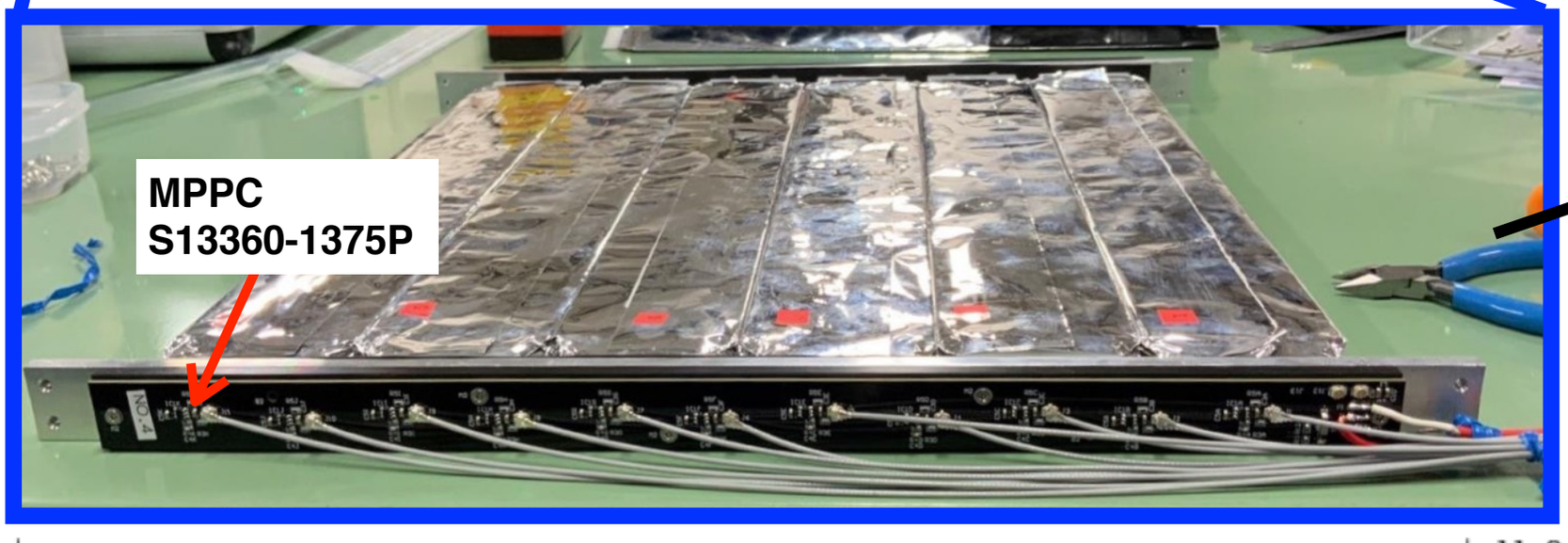


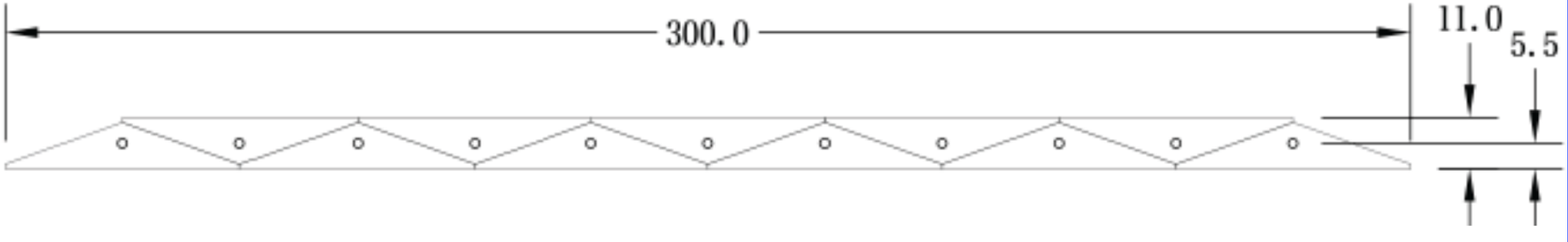


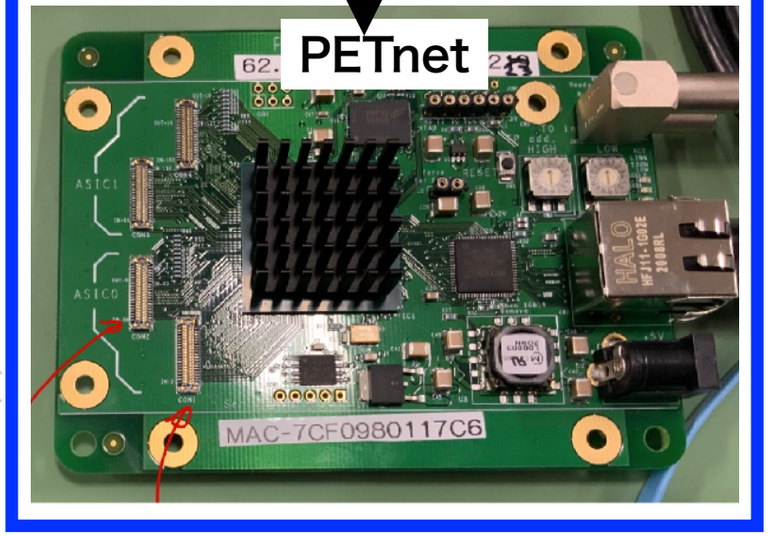
Veto Counter / Plastic Scintillator



- Combination of “Triangular scintillator” VETO system developed by OMU (Fujii)and U.Tokyo ERI (Taketa) and “PETnet” readout system developed by Nuclear Medical group of U.Tokyo (Shimazoe, Uenomachi).
- Timing and analog signals from 22 scintillators are read out.
- Triangular scintillators combined with each other. The ratio of adjacent scintillator signals yields a position resolution higher than the scintillator size.



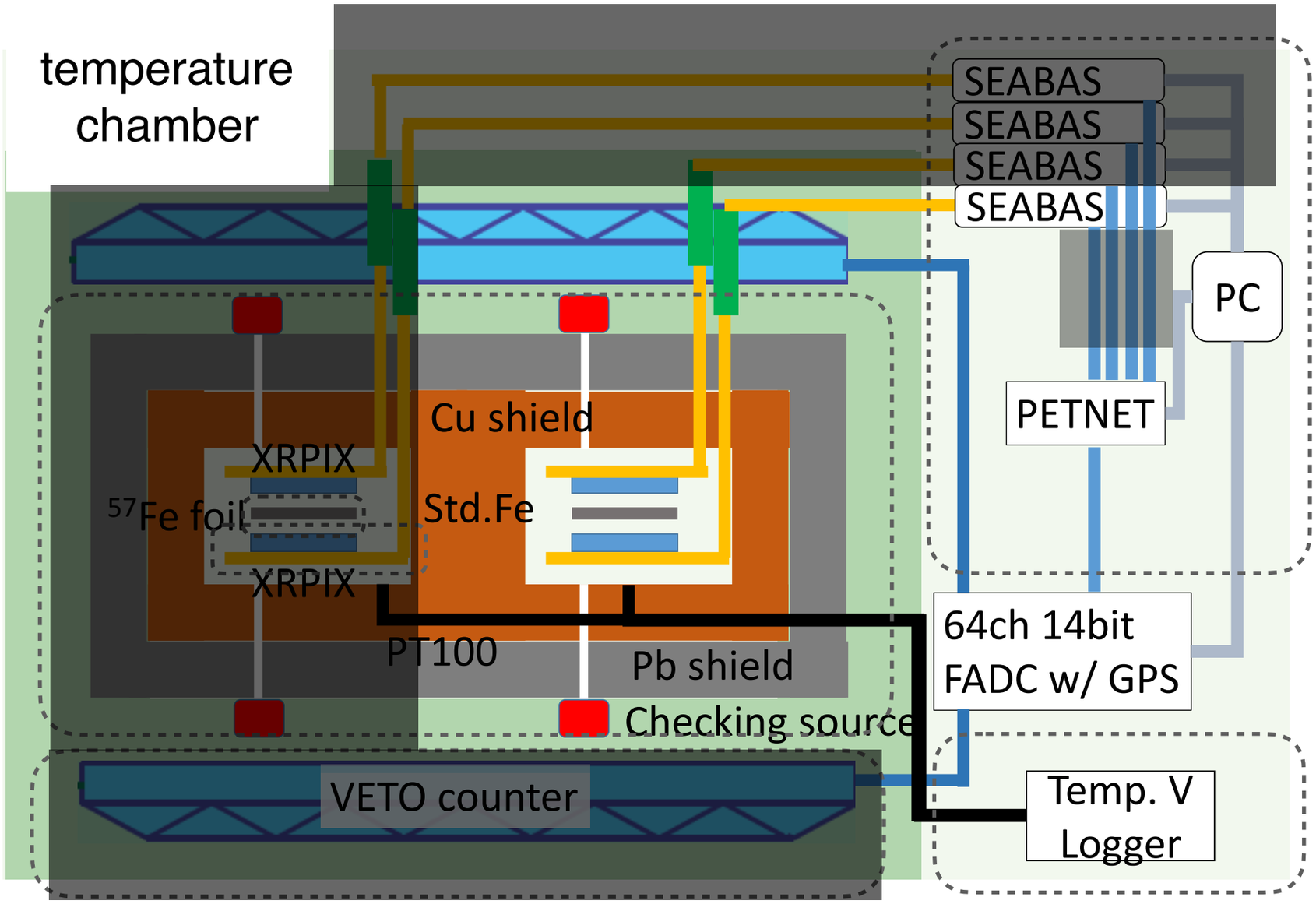




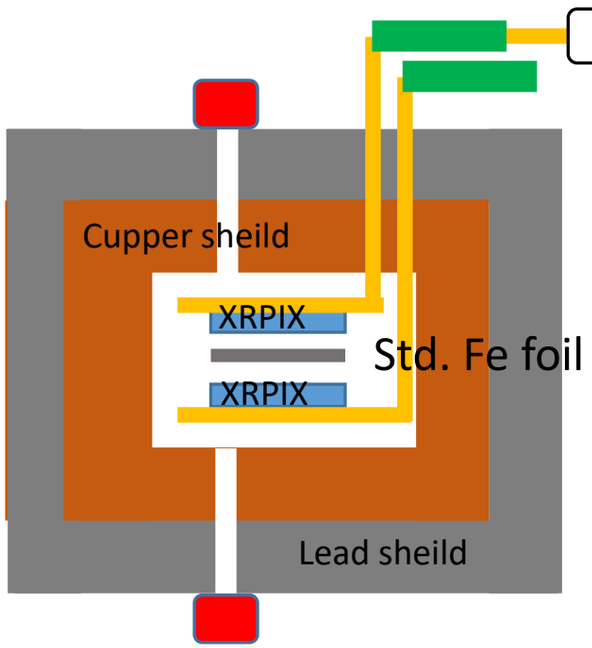
Current Preparation Status

1/2 ISAI system without VETO is installed

- One XRPIX sensor read out by SEABAS.
- Slow monitor
- Calibration source though a pin-hole.
- Position sensitive plastic scintillator VETO counter read out by PETnet.
- The anti-coincidence system will soon be available.

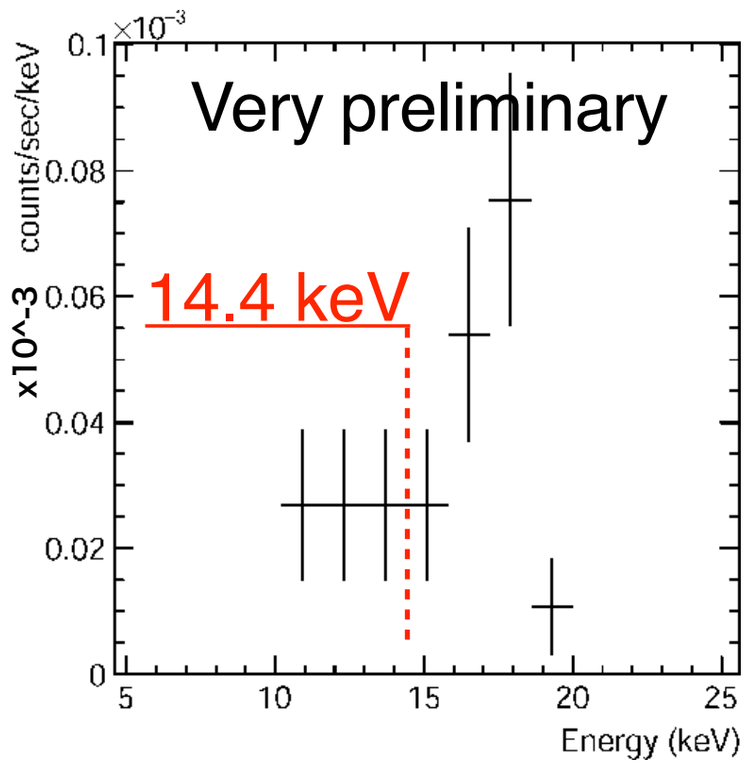


Background Run

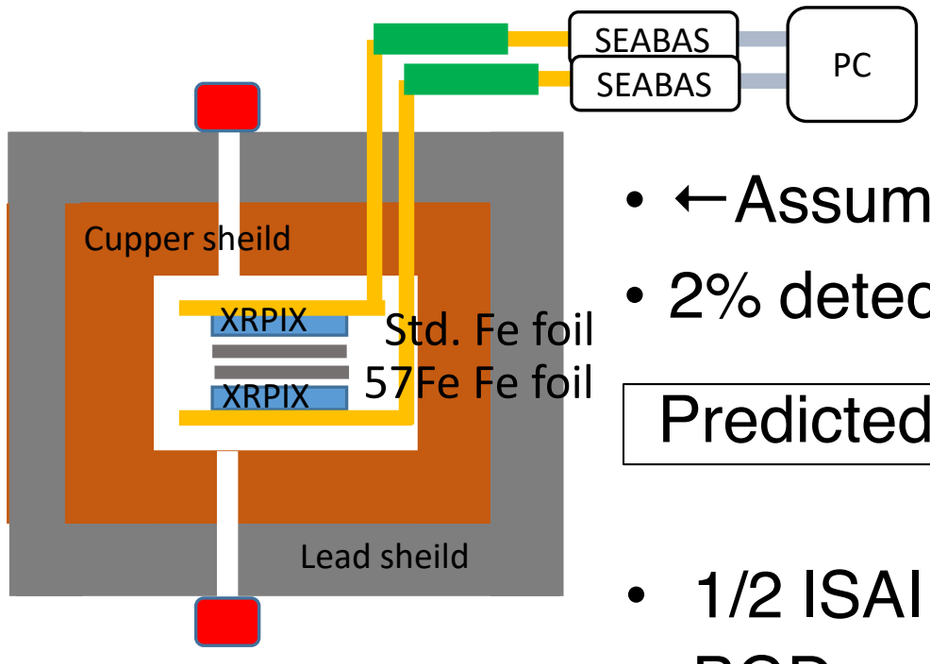


- 1/2 ISAI module without veto.
- 2023/07/13-2023/08/10
- Livetime 10.07days

~4.3 counts/day/2.8keV@14.4keV

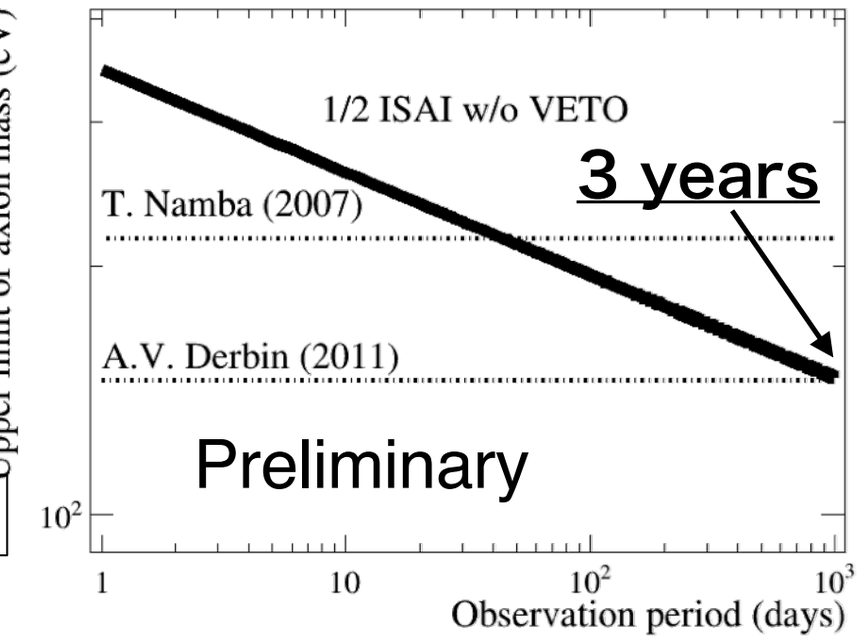


Predicted Sensitivity



- ←Assume 1/2 ISAI without veto.
- 2% detection eff. for 14.4 keV X-ray

Predicted upper limit @95% C.L. →

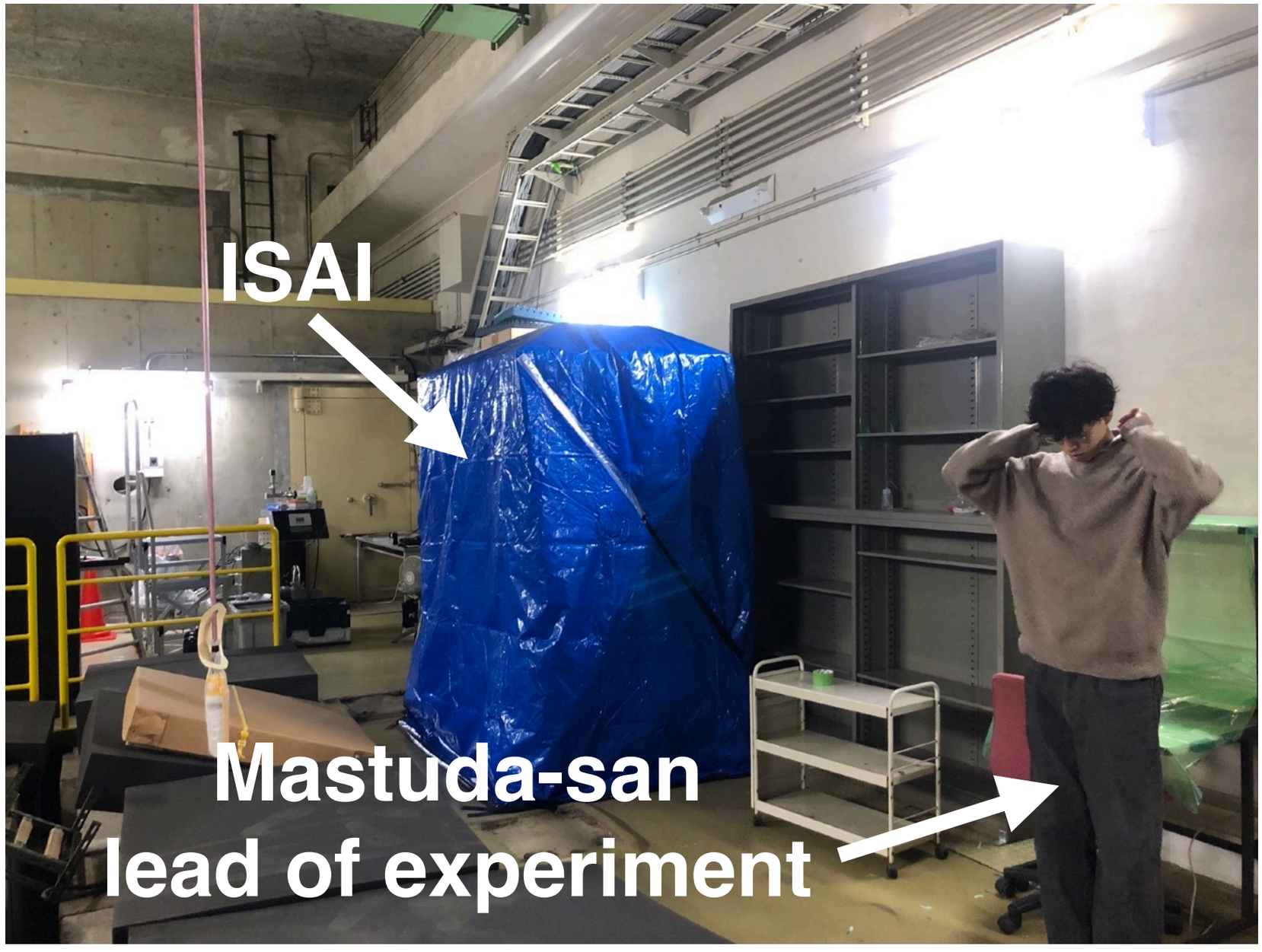


- 1/2 ISAI detector to full detector
- BGD reduction by timing-veto
- Pixel-to-pixel gain correction
- Recovery of the detection efficiency

are essential to precede the current limit.

Unfortunately...

- The experiment site underwent renovation work, so we were unable to conduct experiments in this 3 months.



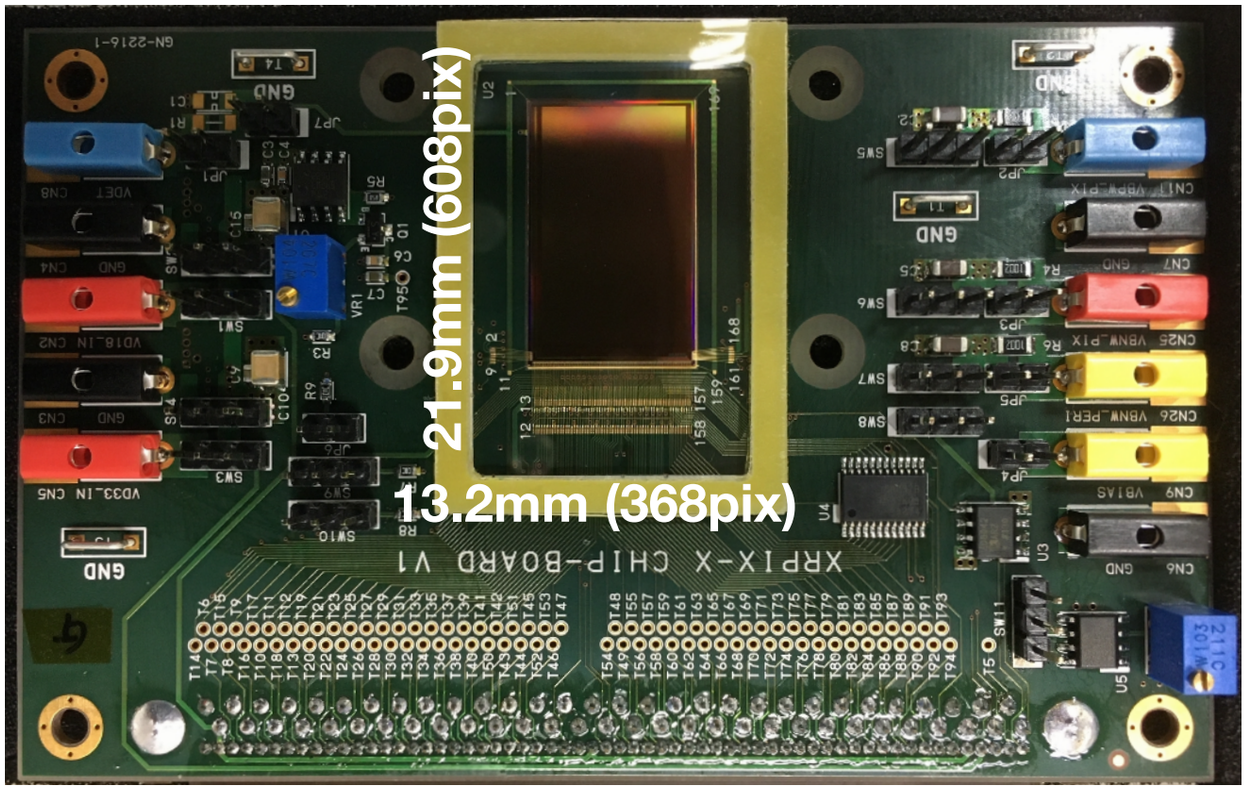
even worse

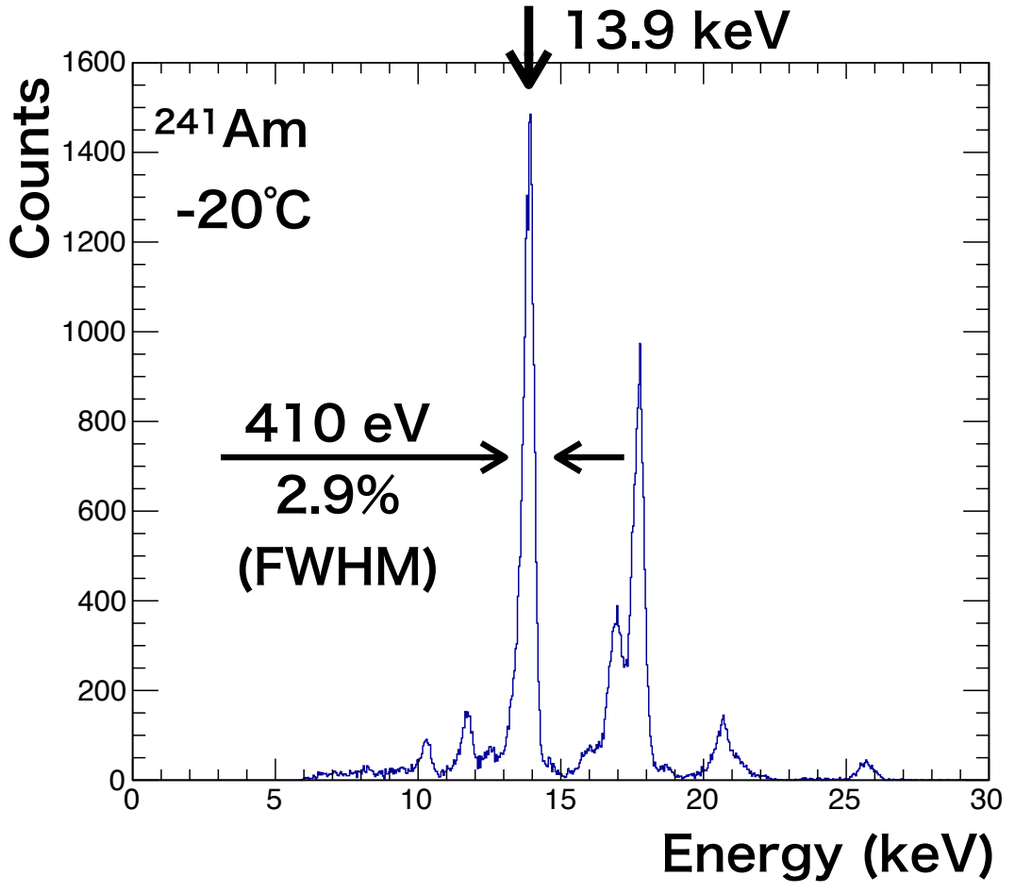
- One of the last two XRPIX7 sensors has failed while testing it.
- ONLY ONE XRPIX7 sensor is available now…

New SOIPIX ! : “XRPIX10 (2022)”

- The detection efficiency of XRPIX7 is unexpectedly low (~2%).
  - XRPIX7 did not work properly when trying to apply a high back bias to the sensor, which results in a thin depletion layer (~20μm).
  - This would be due to the use of a special SOI wafer called Double SOI.

- New large sensor, “XRPIX10”, a 4th-generation sensor developed in 2022.
  - XRPIX10 uses the well-proven Single SOI wafer.
  - The back bias can be applied up to 300V without any problem.
  - Can achieve full depletion (300μm) and a detection efficiency of ~50% as planned.

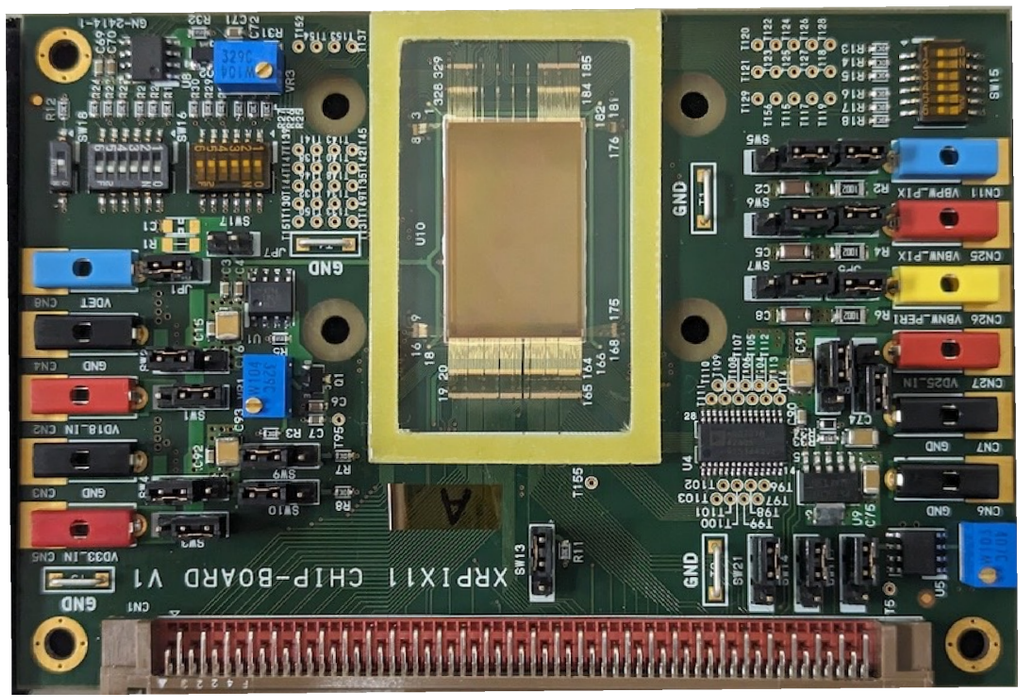


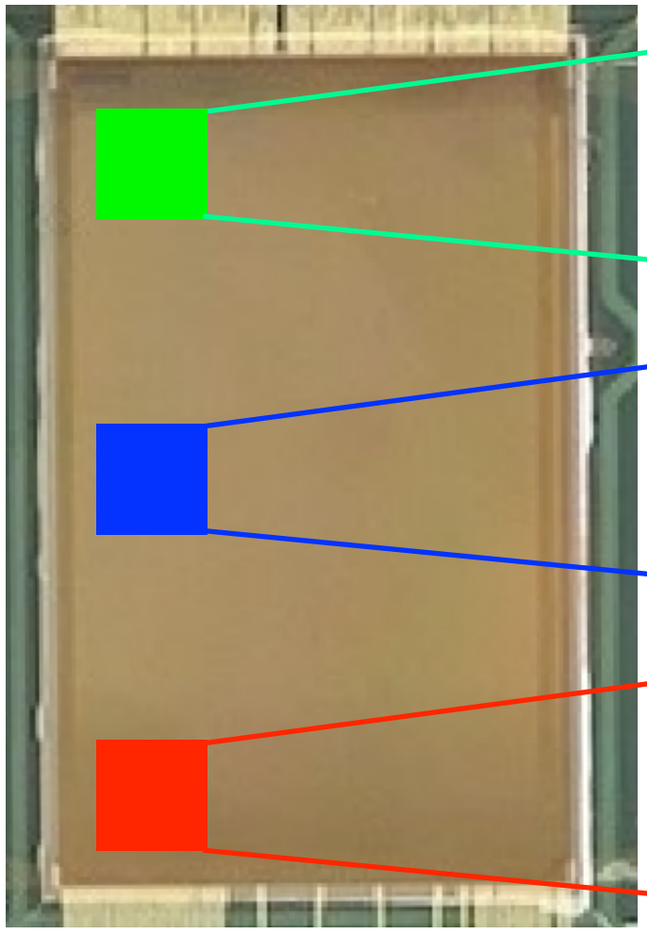


Even Newer SOIPIX ! : “XRPIX11 (2023)”

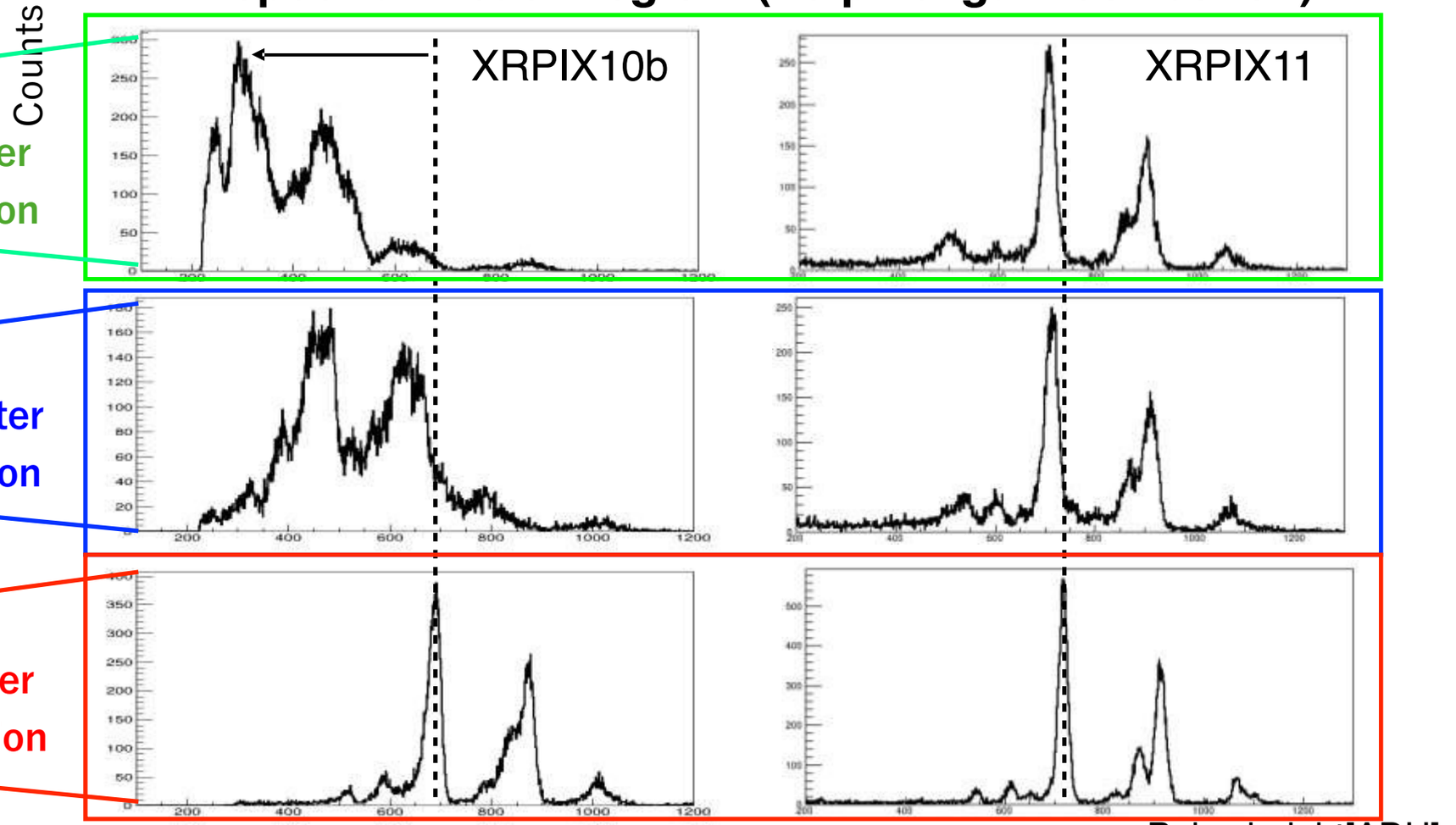
- We realized the XRPIX10 is still not perfect: gain and spectral quality exhibited significant positional dependency.

- The new XRPIX11 solves this problem.
- (We believe that) this completes the development of the (analog type) XRPIX.
- Note: full digital XRPIX13 equipped with ADC, DAC and pattern generator is coming up next year, which greatly simplifies the readout system.

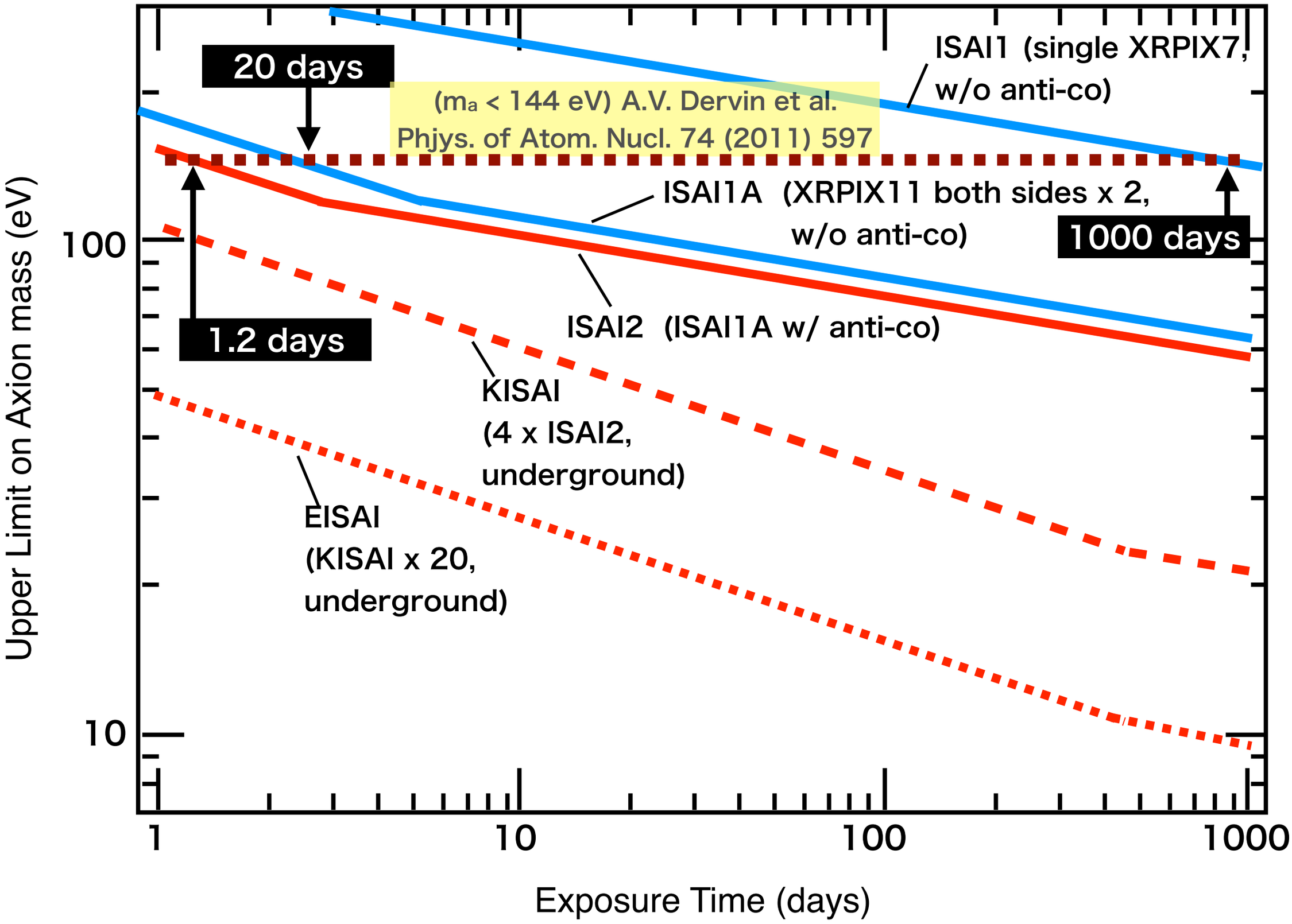




Am-241 spectra in each region. (no pixel gain correction)

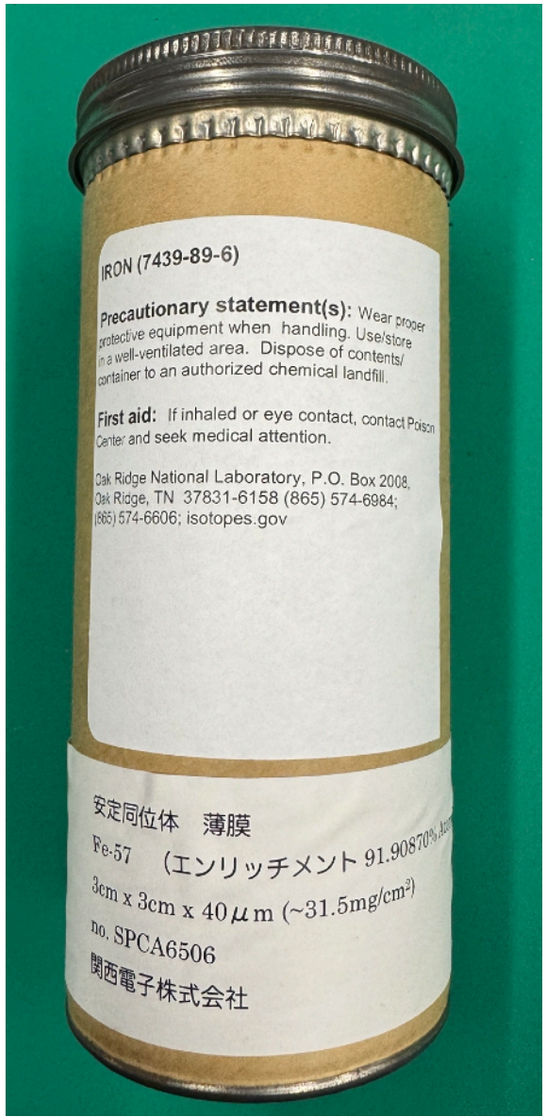


Predicted Sensitivity with new XRPIXs



DM学術変革領域での協力関係など

- We have promised to provide a part of our Fe-57 foils to B04.
- We can provide it to B04 at any time, so please contact us, (If still interested).



2回の採択および予算配分を頂きました
本当にありがとうございます！

項目	万円
第一期公募研究	380
第二期公募研究	460
高比抵抗SOIウェハ	194
XRPIX素子+低BGDフレキ	277.6
XRPIX10b	154
XRPIX8.5	77
XRPIX8.6GW	11
低BGリジッドフレキシブル基板	35.6
読み出し回路基板・電源・計算機	104.8
XR8サブボード x2 京大用	22.6
SEABAS1 x 1台	20
Mac mini	13
TEXIO電源	49.2
校正線源	51.7
国際会議参加・発表	124
SPIE2022	64
TAUP2023	60
その他	87.9

ISAI experiment : Summary

- 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.

- 1/2 ISAI system without VETO is completed.
- Background run with XRPIX7 using normal Fe foil.
- Need to improve detection sensitivity.
- Preparing the new sensor XRPIX11 that can achieve full depletion (300μm) and a detection sensitivity of ~50% as planned.
- We would like to somehow get to the world recode with XRPIX11.

Illustrated ISAI-san!