"ISAI" Investigating Solar Axion by Iron-57

Takeshi TSURU (Kyoto Univ.)
D02 公募研究

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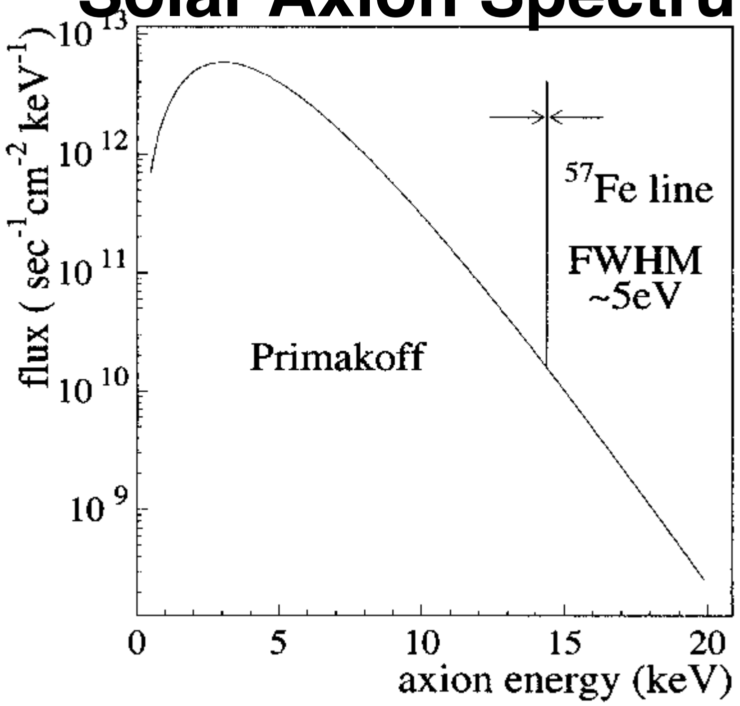
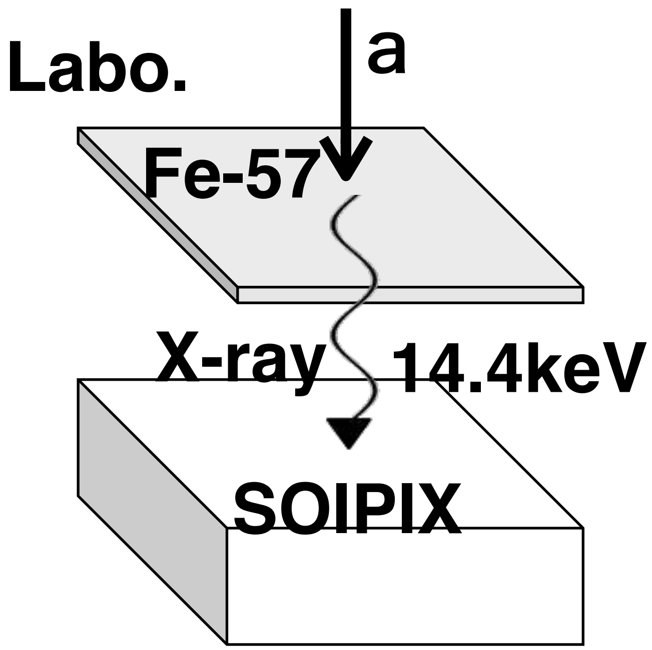
ISAI (Investigating Solar Axion by Iron-57)

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.

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

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

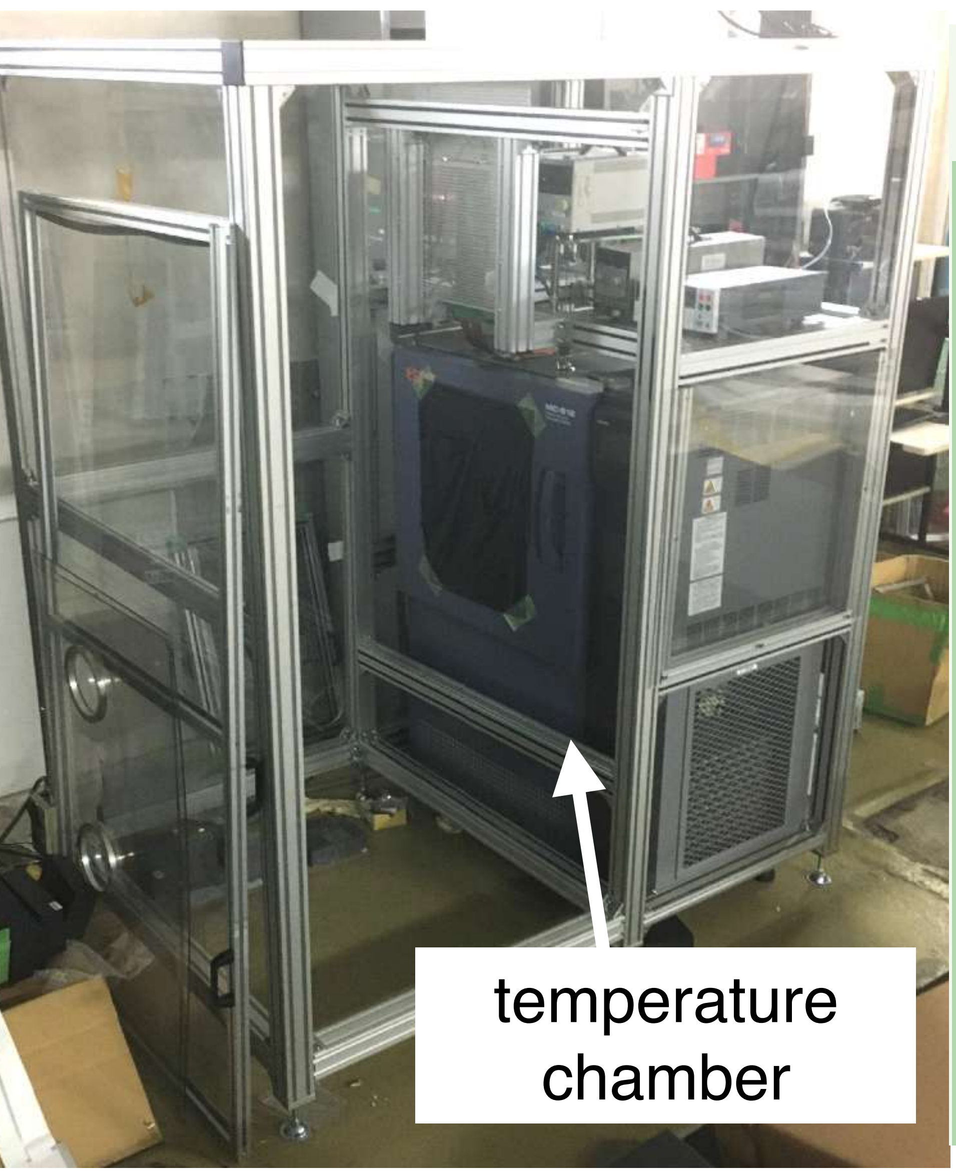
Previous and on-going works

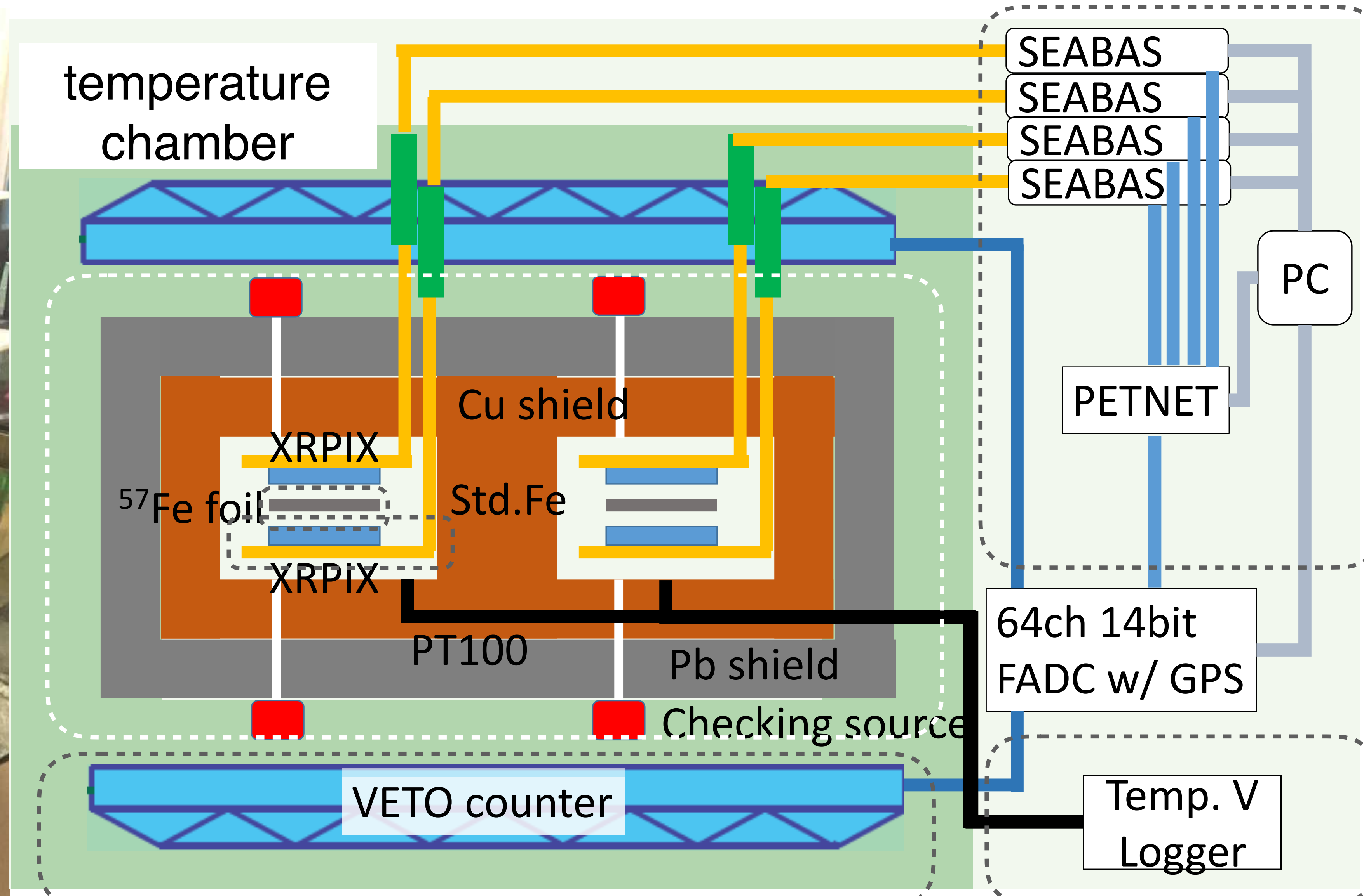
- Moriyama (1995). PRL 75, 3222
- Namba (2007), Phys.Lett.B, 645, 398
- Derbin (2011), Phys.At.Nucl.74, 596
- D04 group of DM学術変革領域 etc.

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

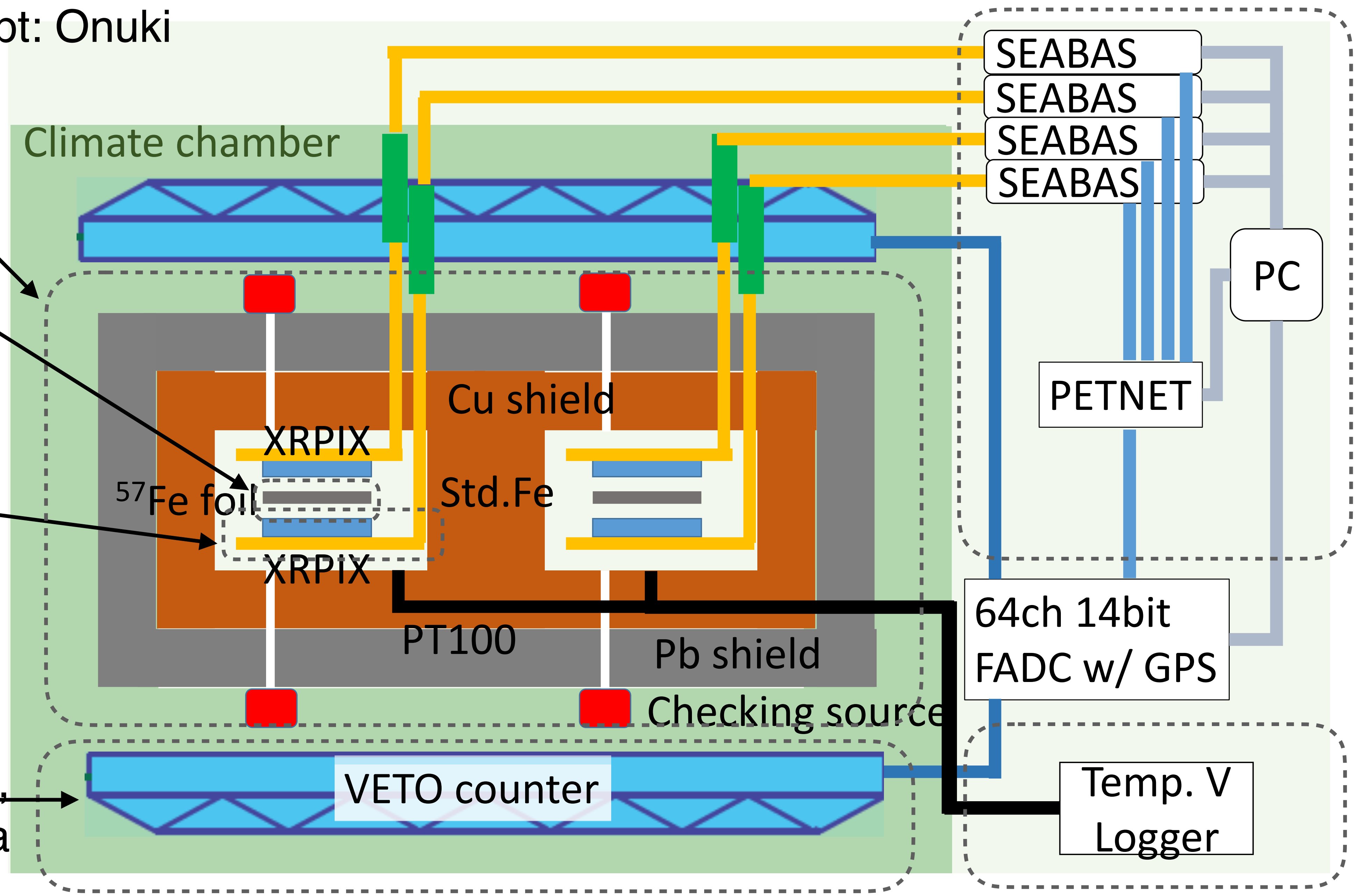
Overall Concept: Onuki

Mech. Design: Onuki, Inoue

Fe-57: Fujii, Miuchi

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

VETO: Fujii, Anazawa, Takata, Namba

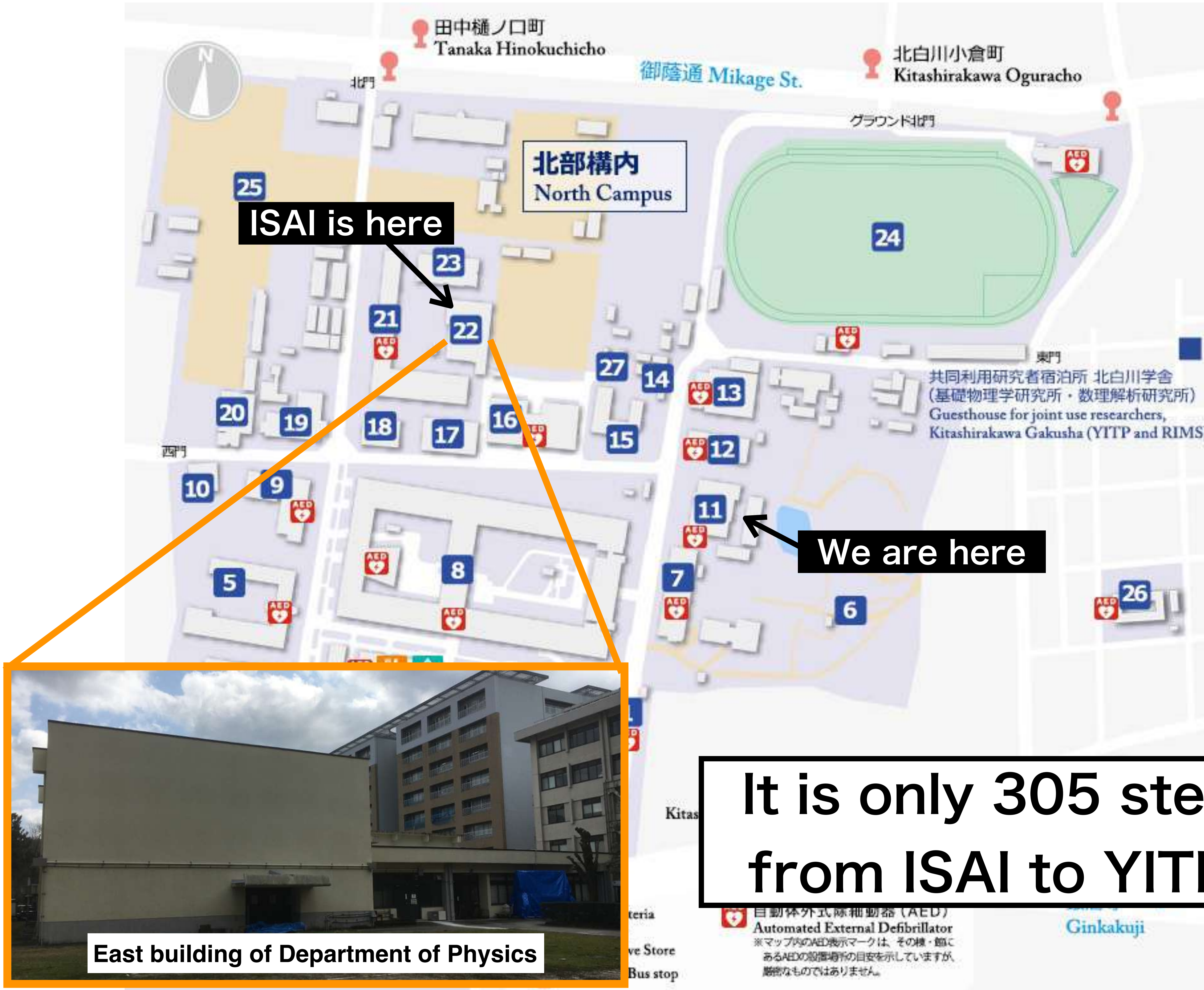


Anti-Co.: Uenomachi, Takeda, Matsuda Ikeda

Parts BG: Onuki, Inoue, Miuchi

Low BG Pb: Enoto, Onuki, Inoue

HK: Miuchi



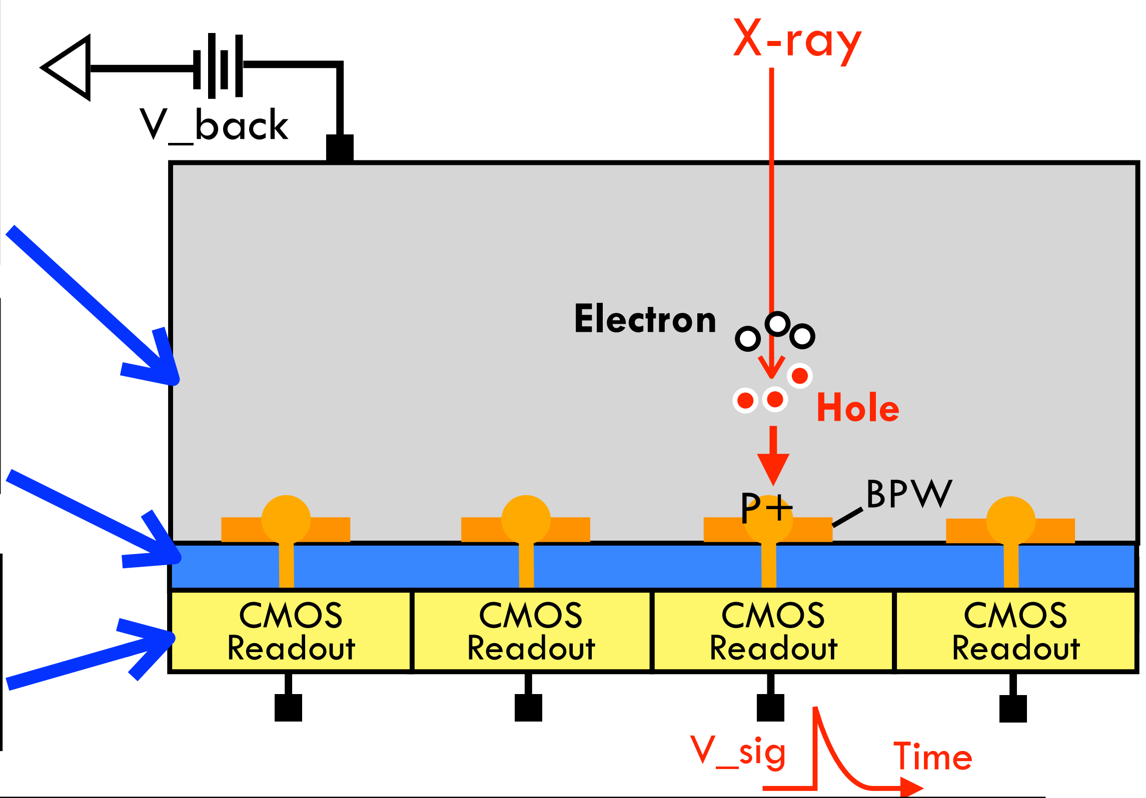
It is only 305 steps from ISAI to YITP !

"XRPIX" Event-driven X-ray SOI pixel sensor

Sensor (high ρ, depleted Si)

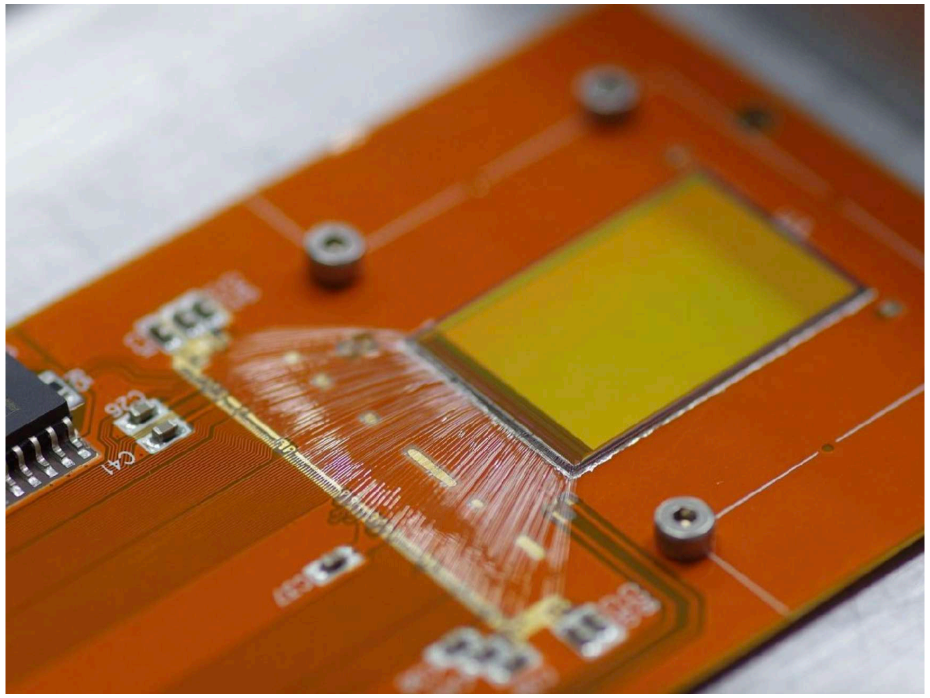
BOX (SiO_2)

Fast CMOS (low ρ Si)



<u>Each pixel</u> 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

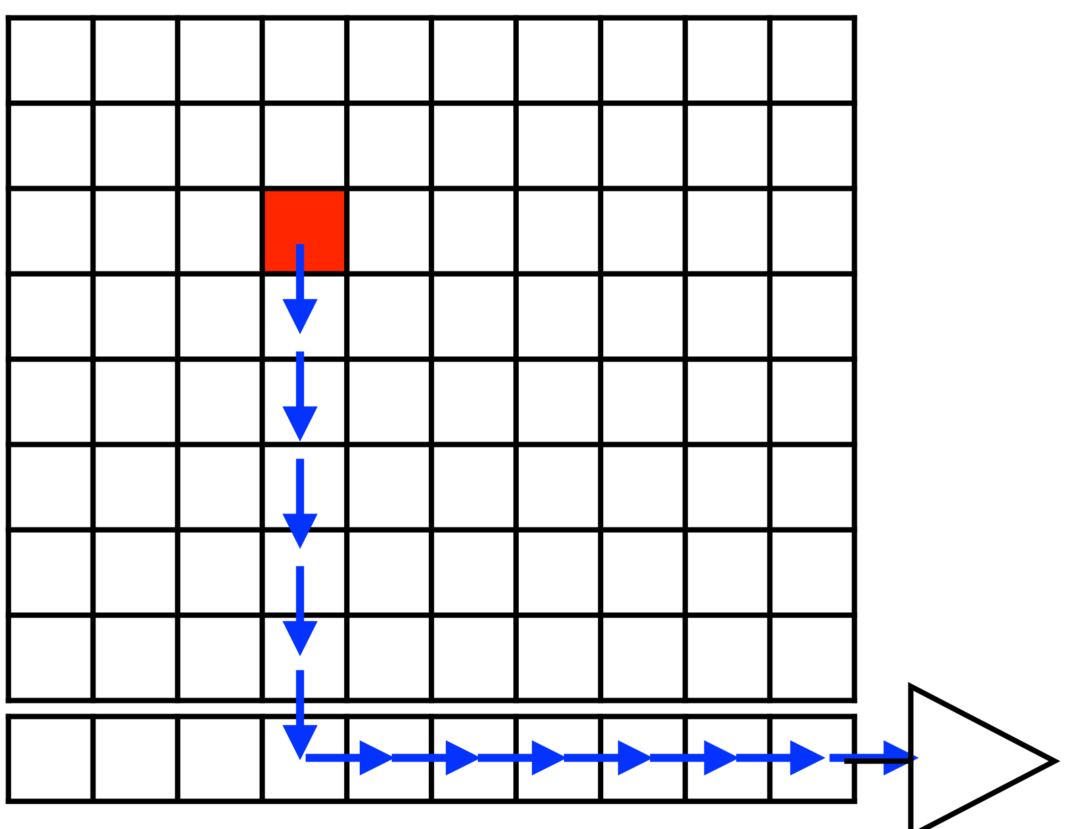
High Time Resolution 10μsec : Pixel Circuit

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)

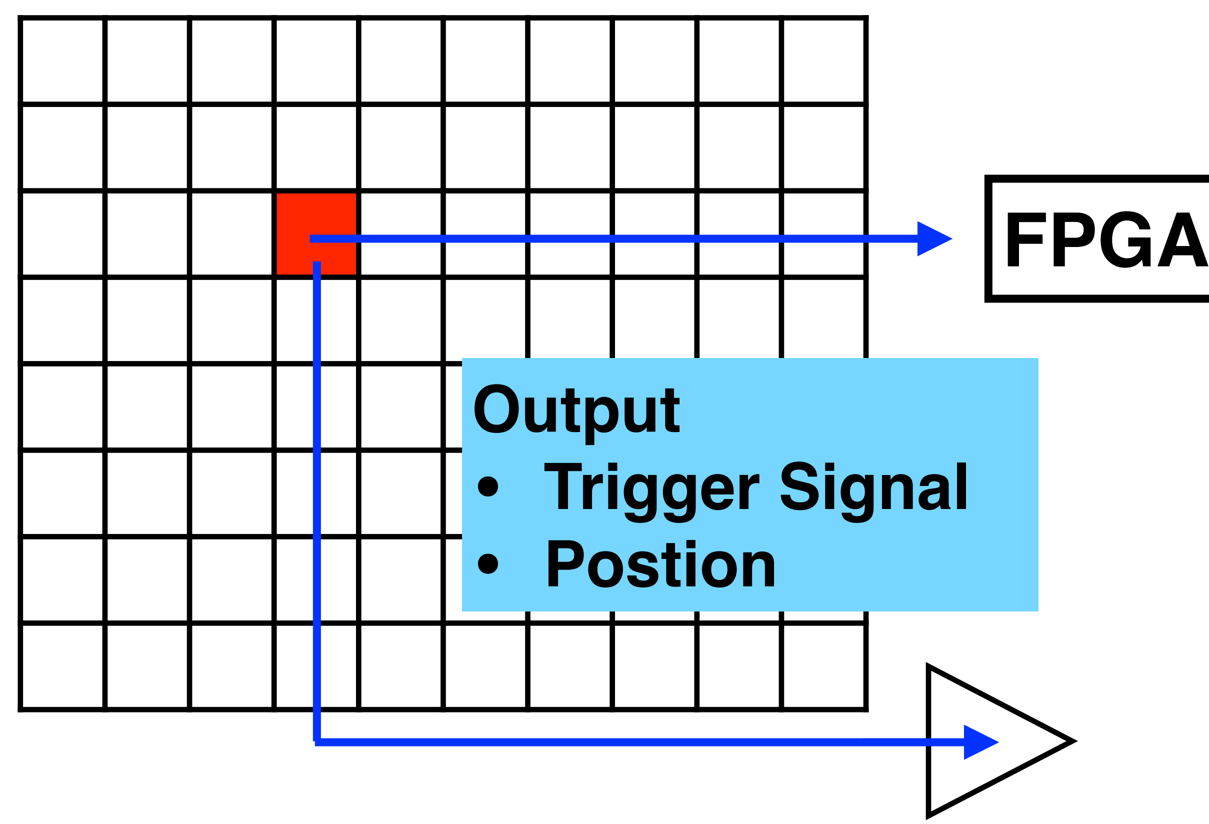
Read all pixels regardless X-ray incident



・time Resolution **~ 1sec**

Trigger output event driven readout
(X-ray SOIPIX)

Read only X-ray incident pixels



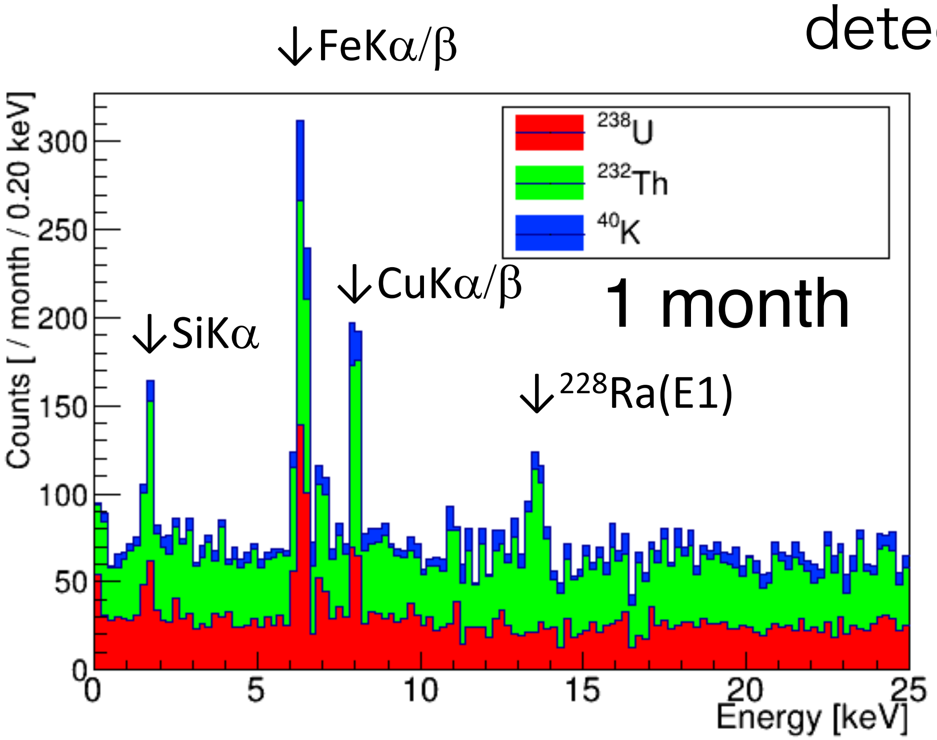
・time resolution better than **10μsec**

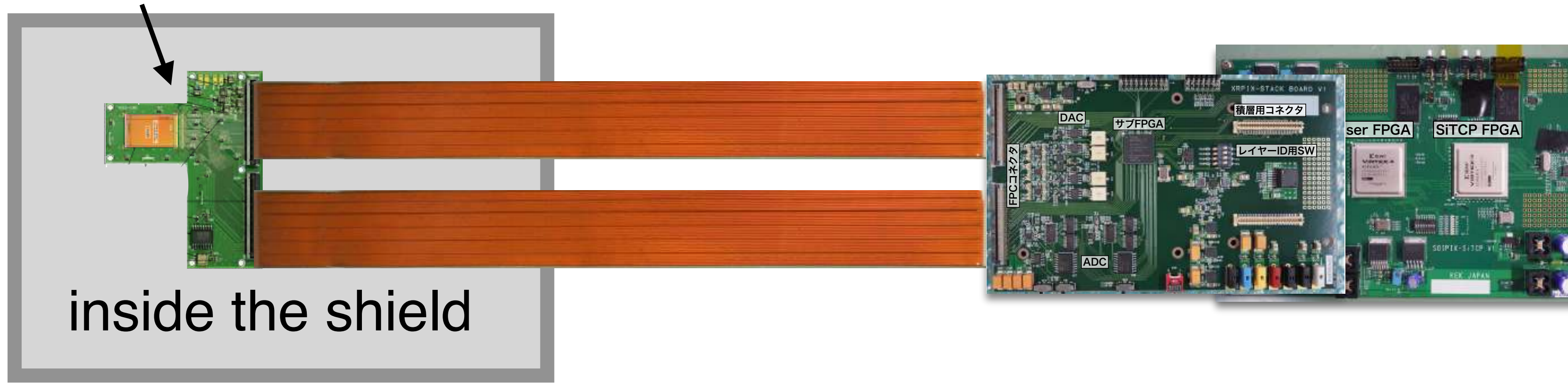
~10^5 higher Δt than Chandra and XRISM X-ray CCDs, and
~10^2 higher Δt than DEPFETs of Athena, etc.

Low BGD Readout Board

The sensor itself must be very low BGD in ISAI.

detector head developed for application of nuclear medical use

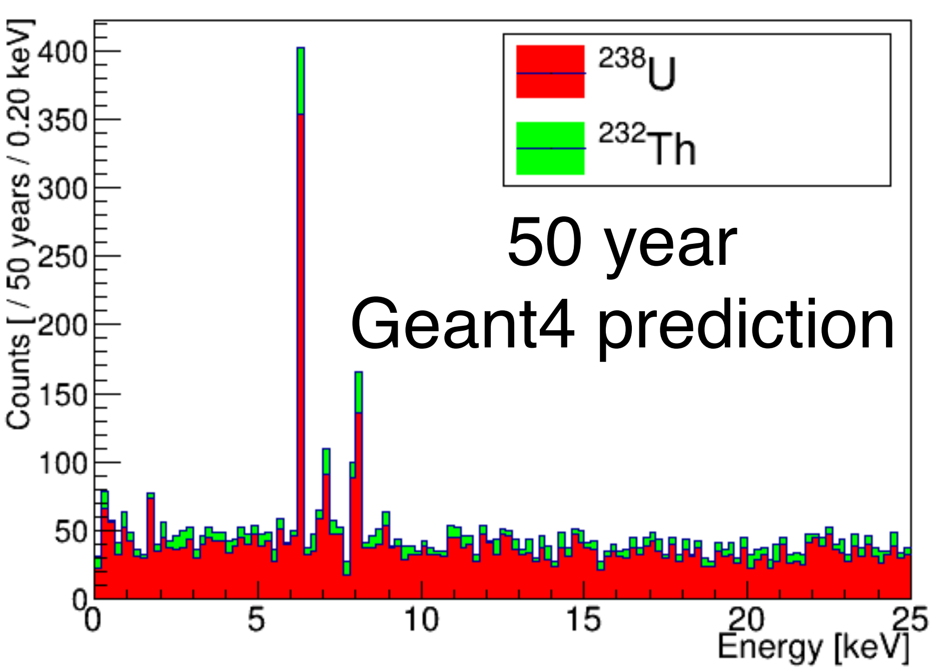




- Radioactivity of the detector head is dominated by G10 PCB (Onuki+19, NIMA, 924, 448)

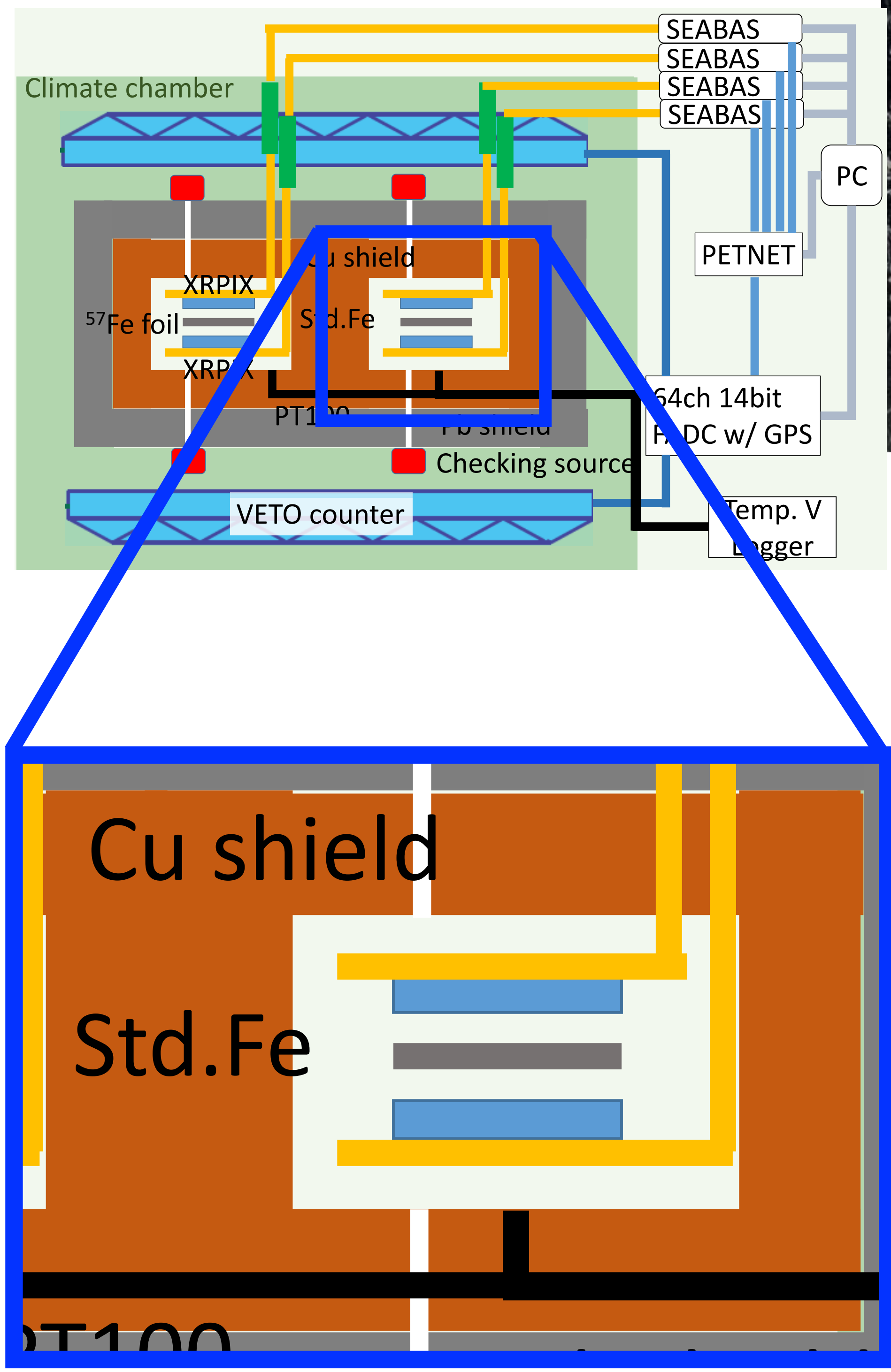
1/1000

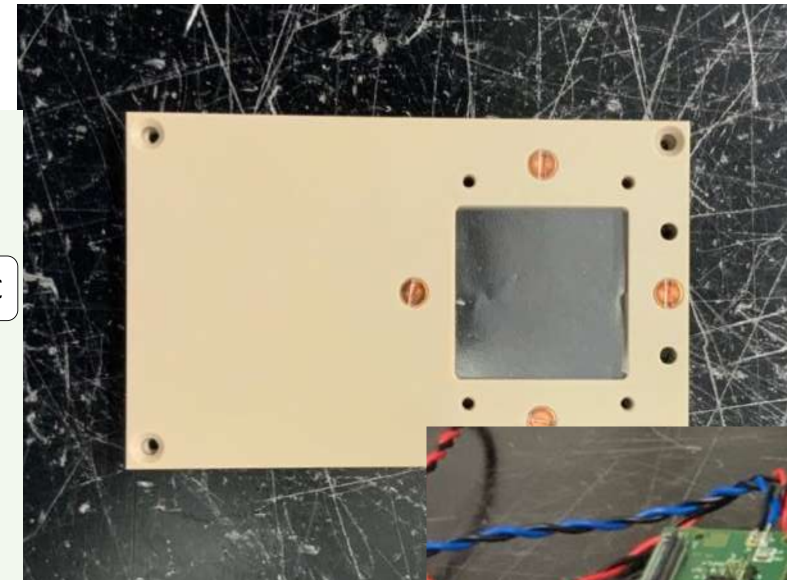
- Change G10 PCB to rigid FPC
  Only the rigid FPC is placed inside the shield



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

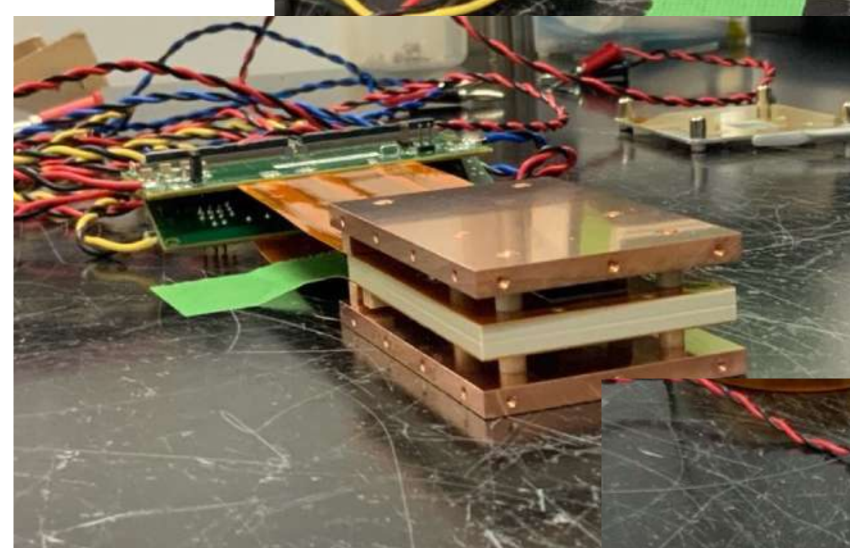
Assembly of the Camera (1)

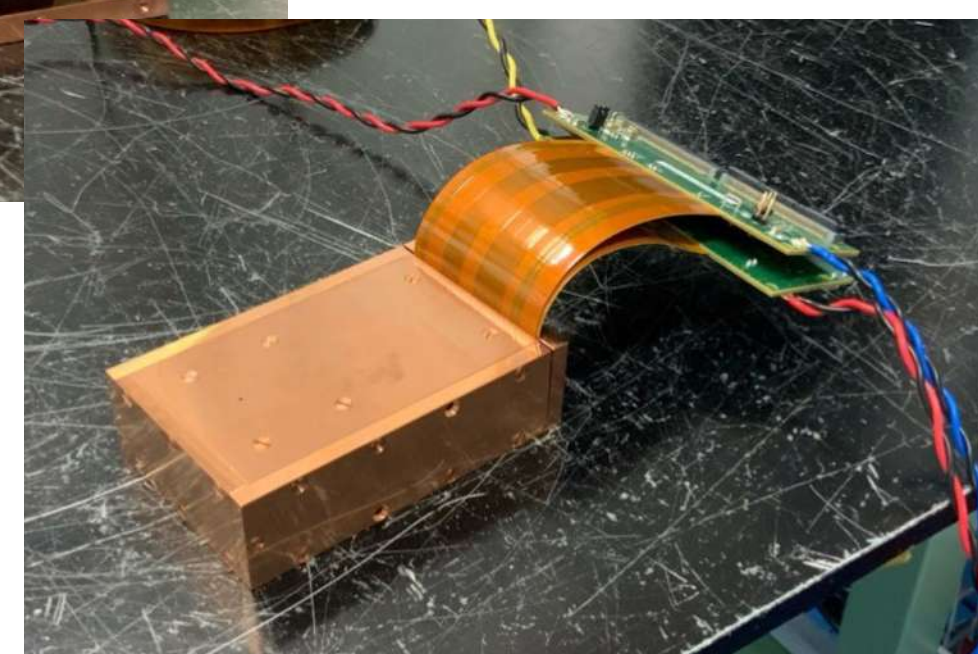




The iron film is fixed by sandwiching it with folders made with PEEK.

XRPIX rigid flex PCB is attached to it.

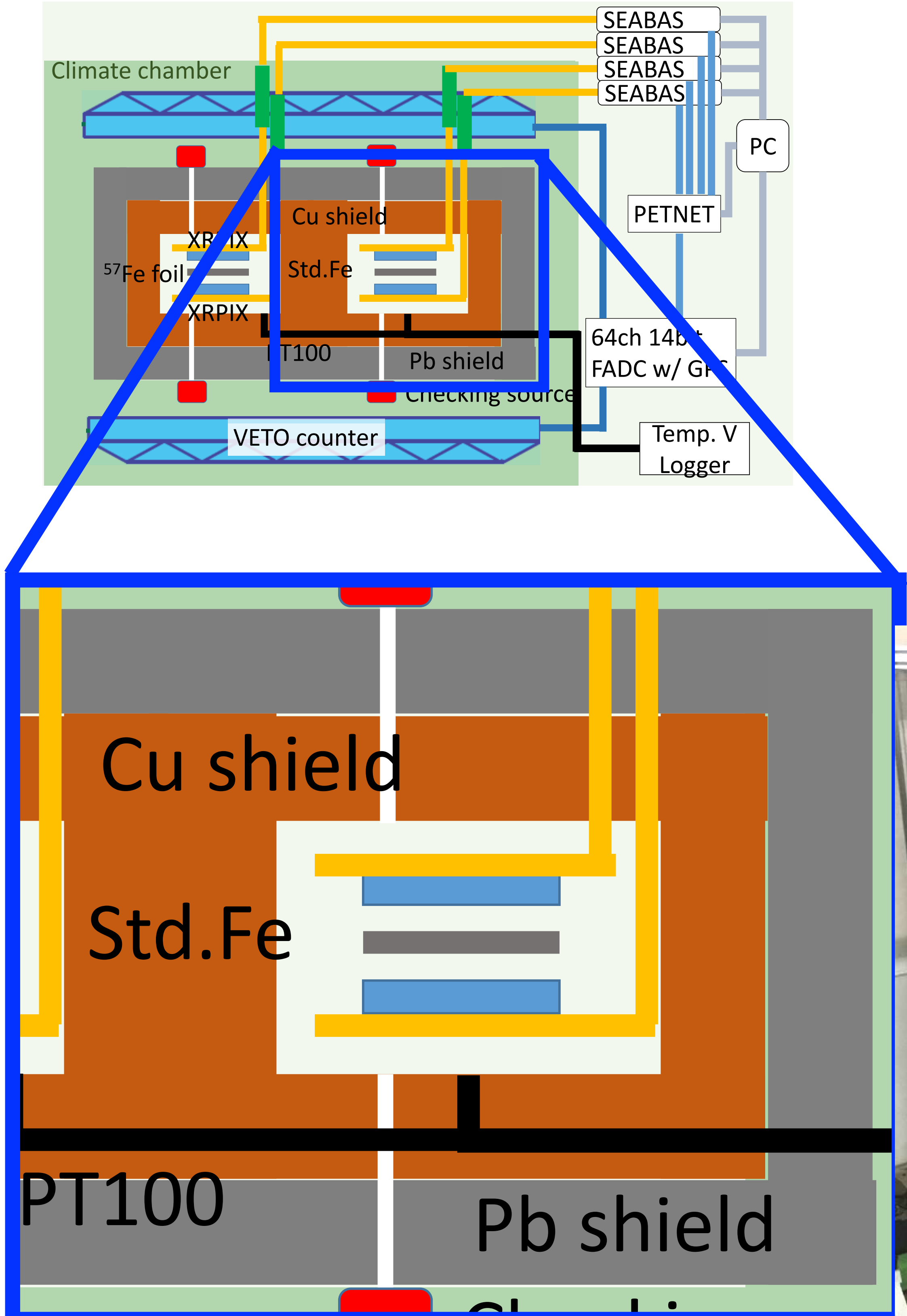


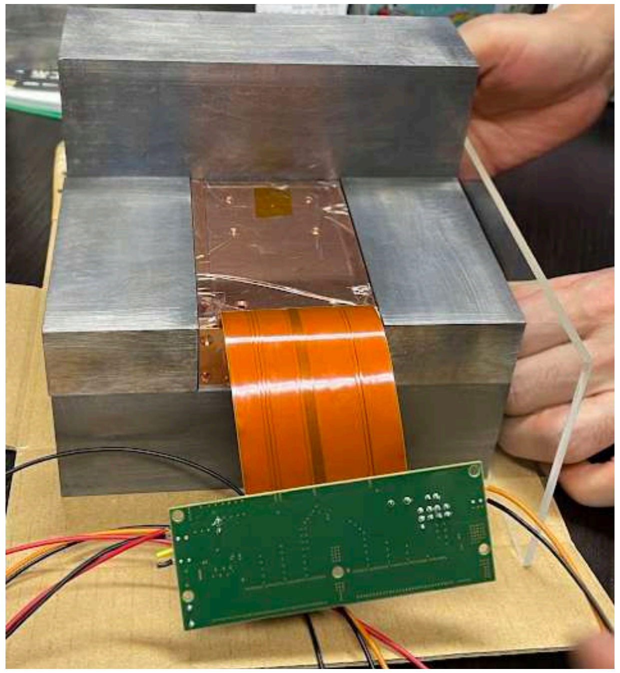


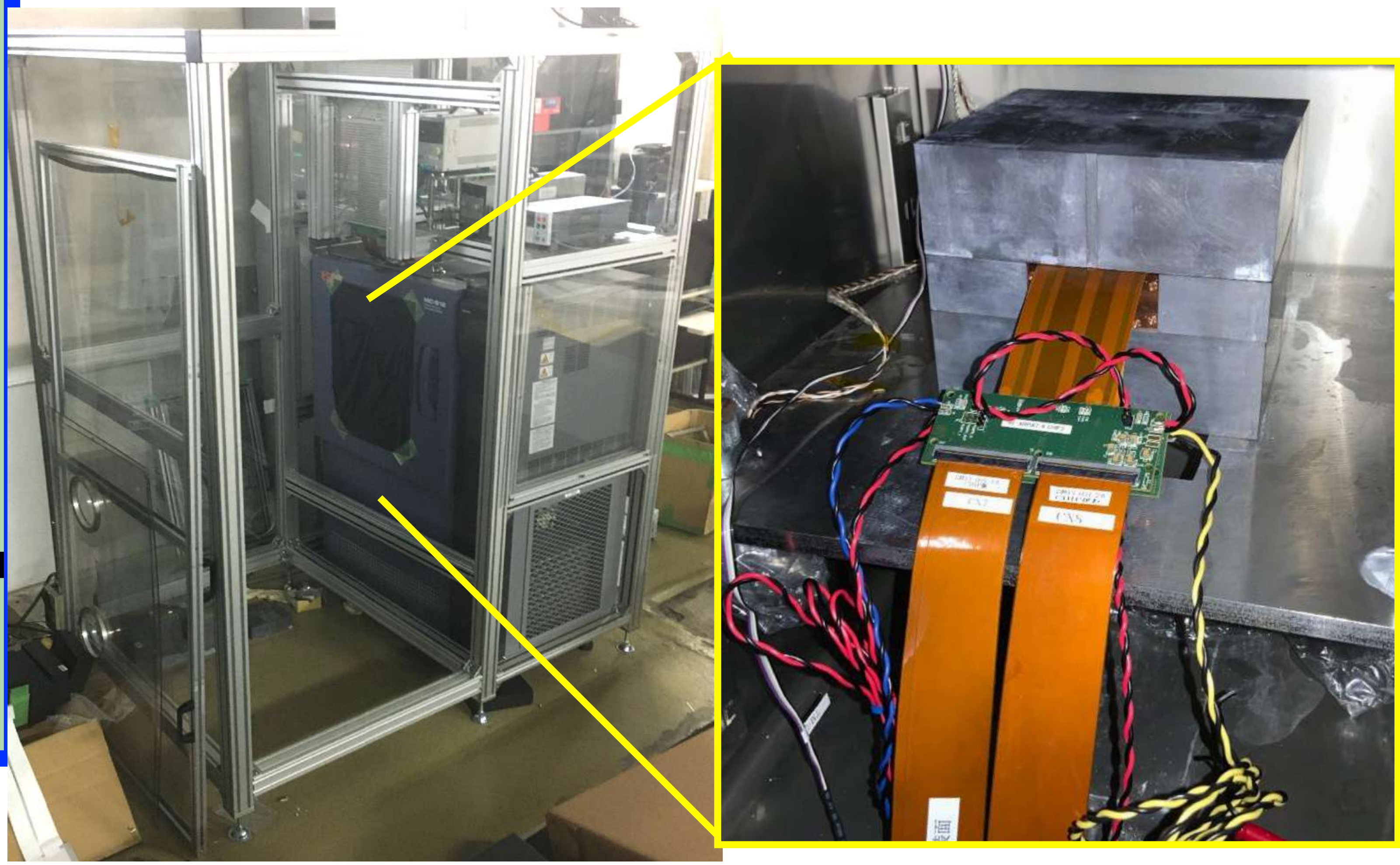
We enclose it with O-free Cu blocks.

Assembly of the Camera (2)

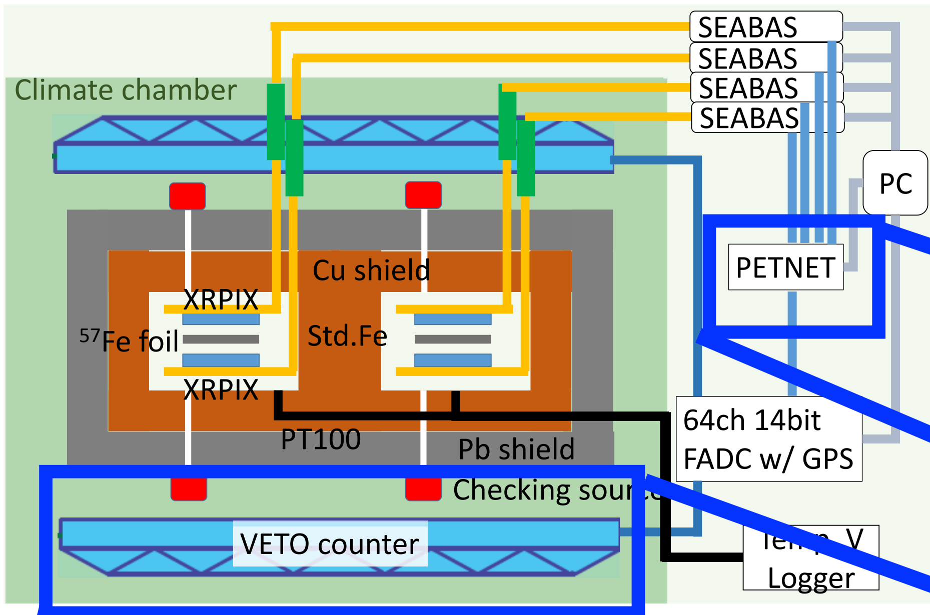
Assembly of the lead block and the instllation of the camera.



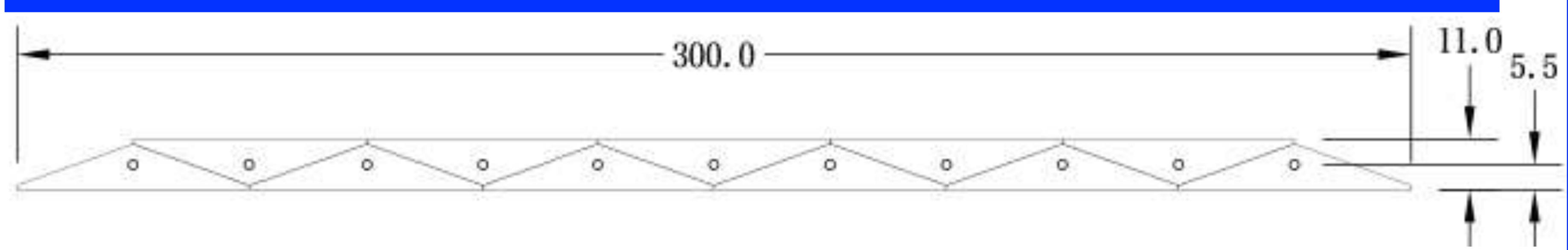


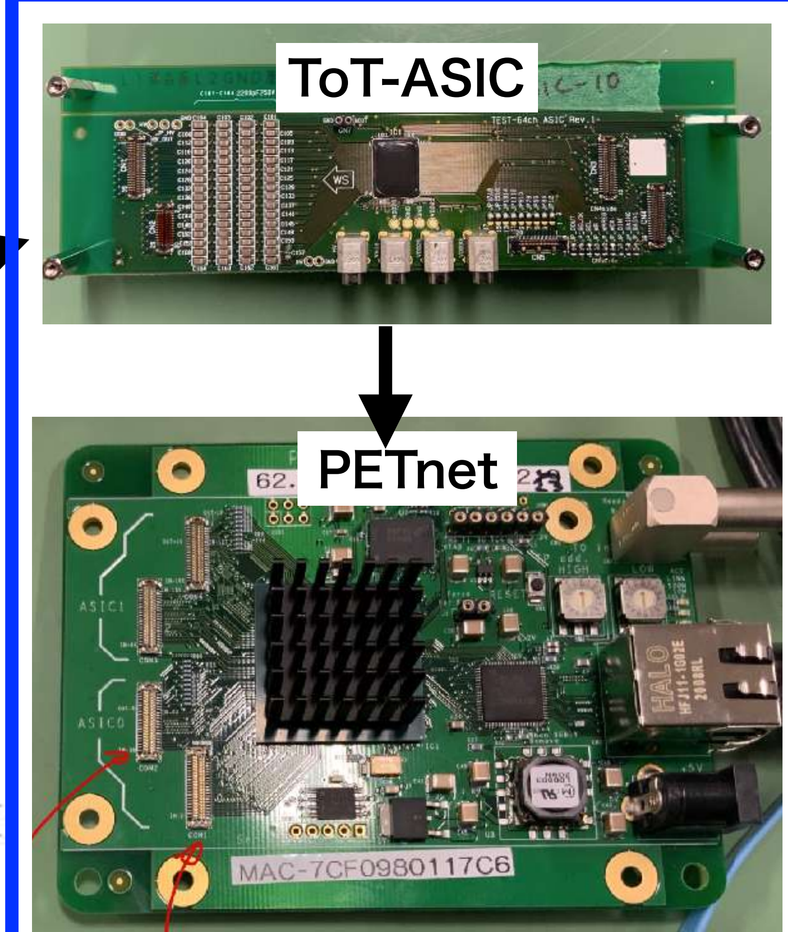


Veto Counter / Plastic Scintillator



- 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.

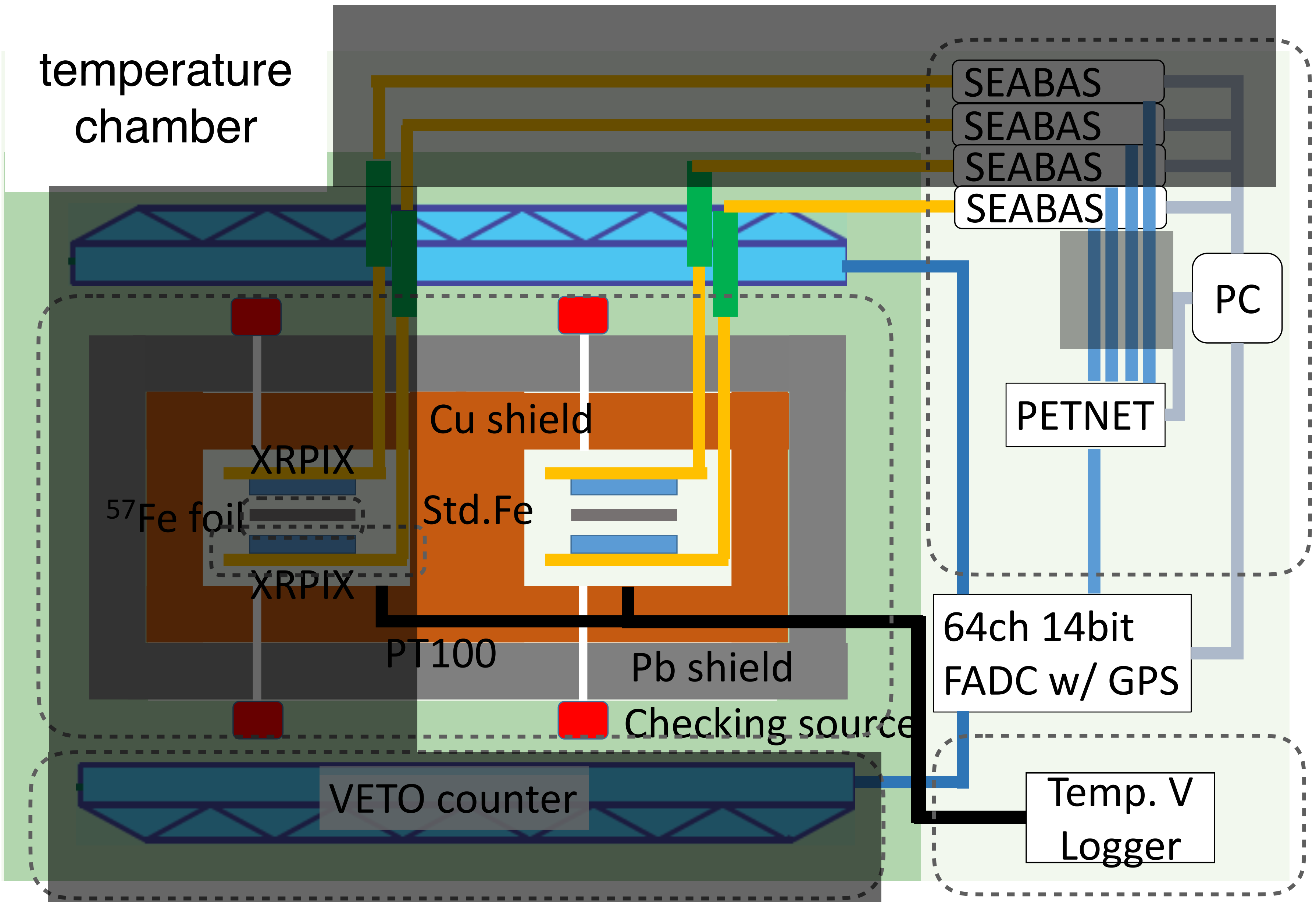




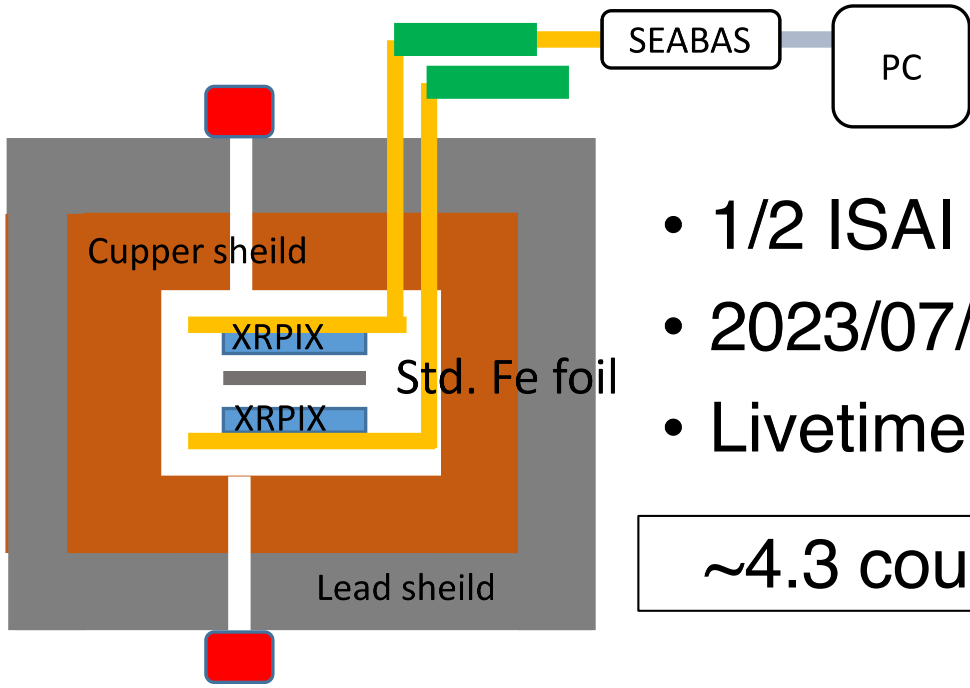
Current Preparation Status

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.
- Anti-coincident between XRPIX and VETO is still in preparation

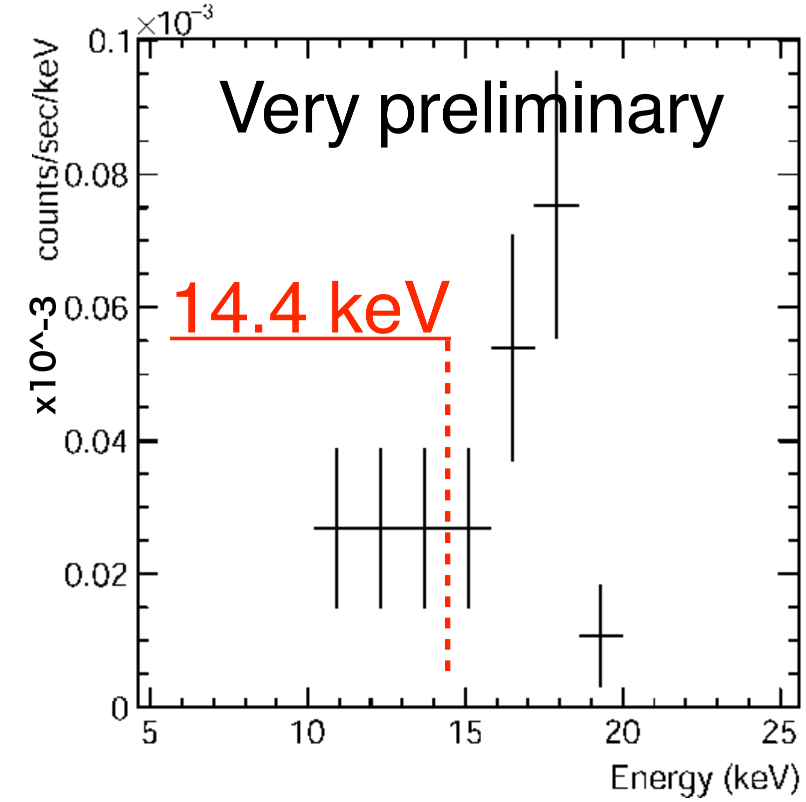


Background Run

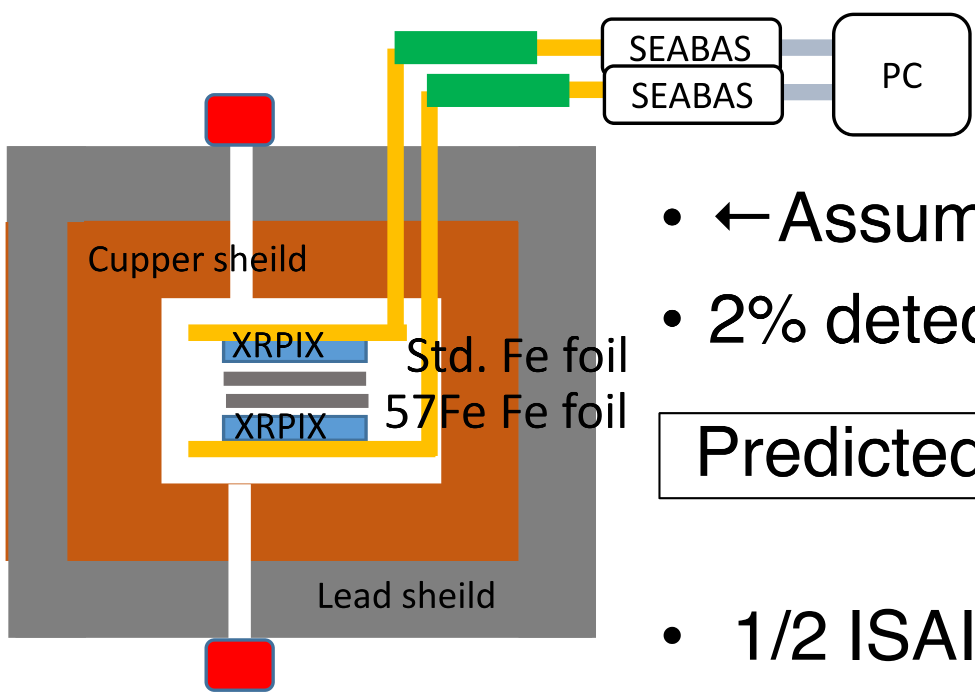


- 1/2 ISAI module without veto.
- 2023/07/13-2023/08/10
- Livetime 10.07days

~4.3 counts/day/2.8keV@14.4keV

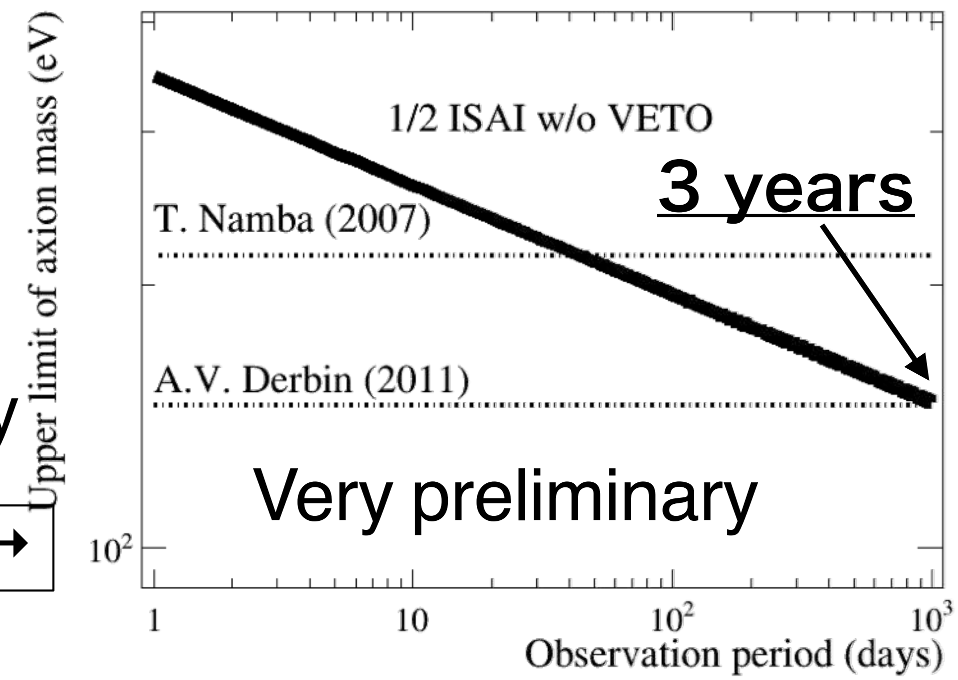


Predicted Sensitivity



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

Predicted upper limit @95% C.L. →



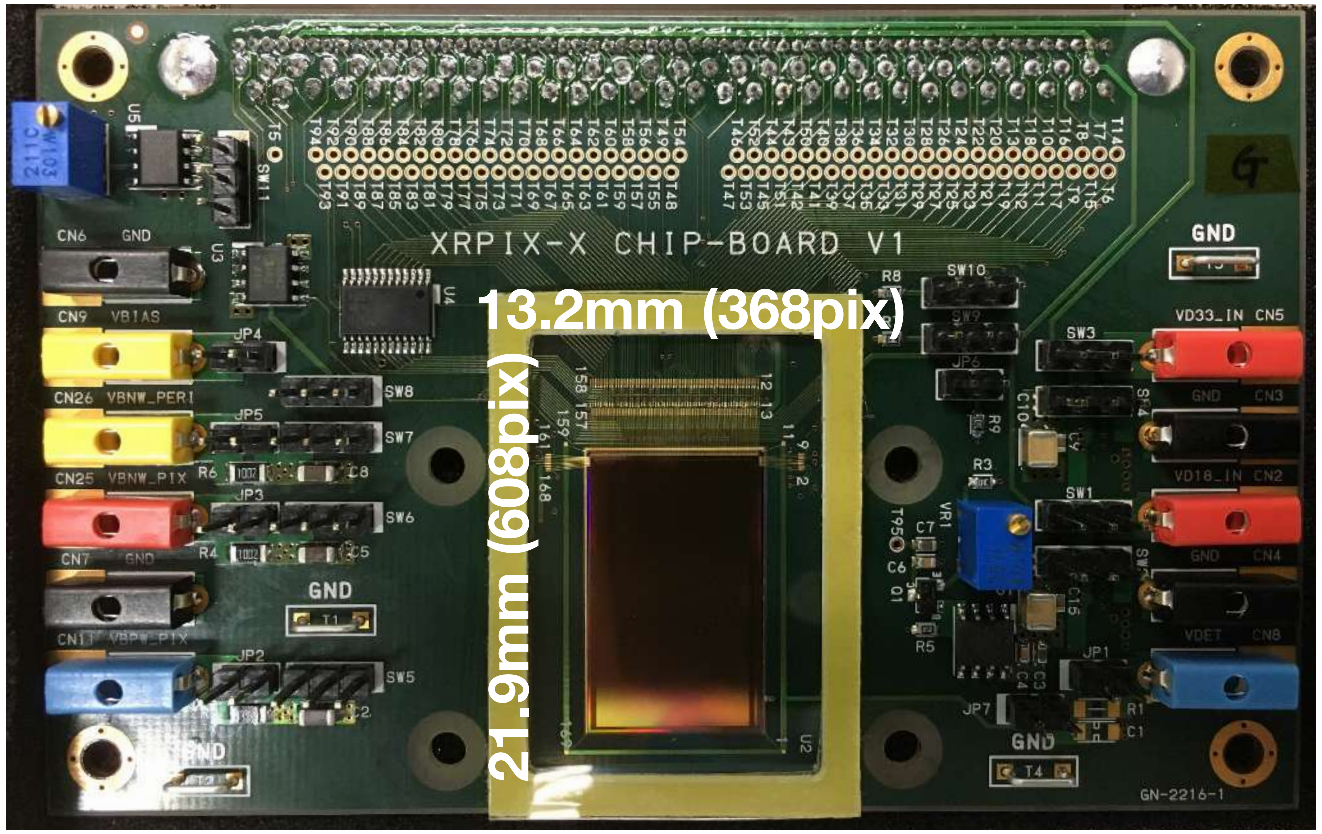
- 1/2 ISAI detector to full detector
- BGD reduction by timing-veto
- Pixel-to-pixel gain correction
- <u>Recovery of the detection efficiency</u>

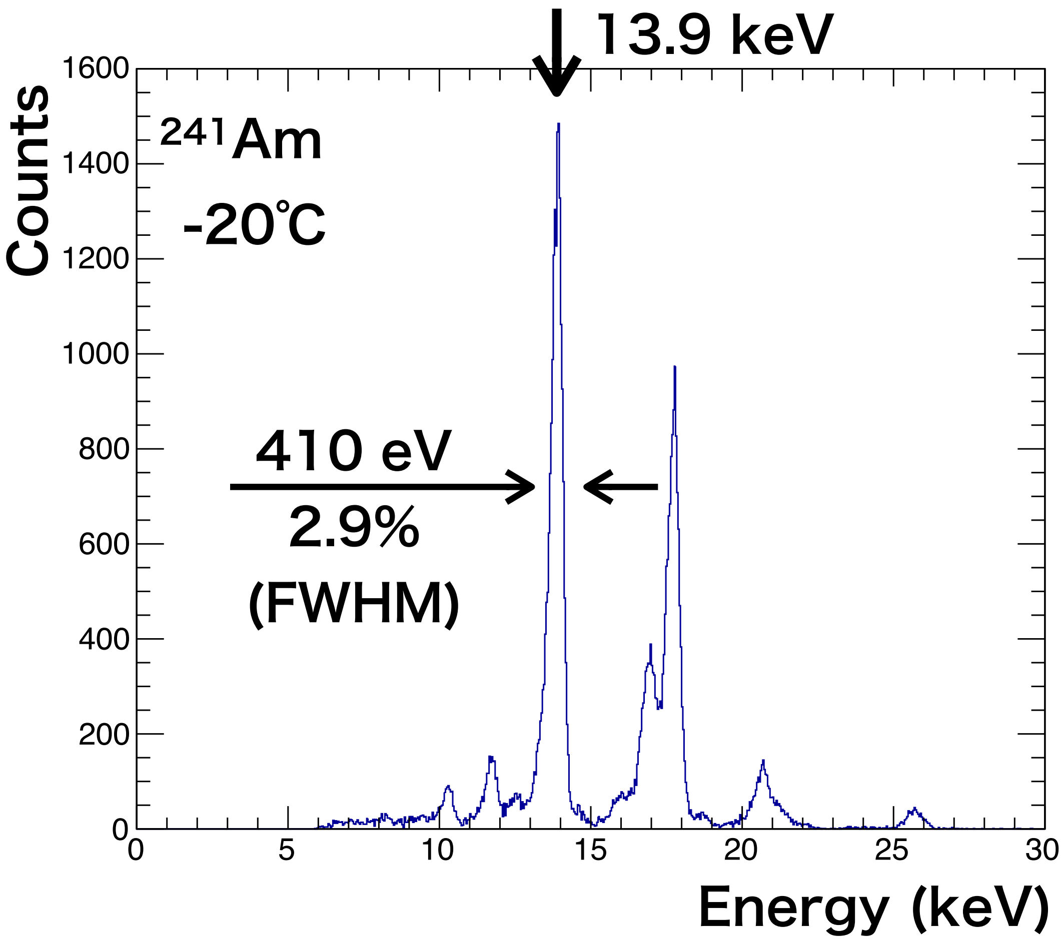
} are essential to precede the current limit.

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.

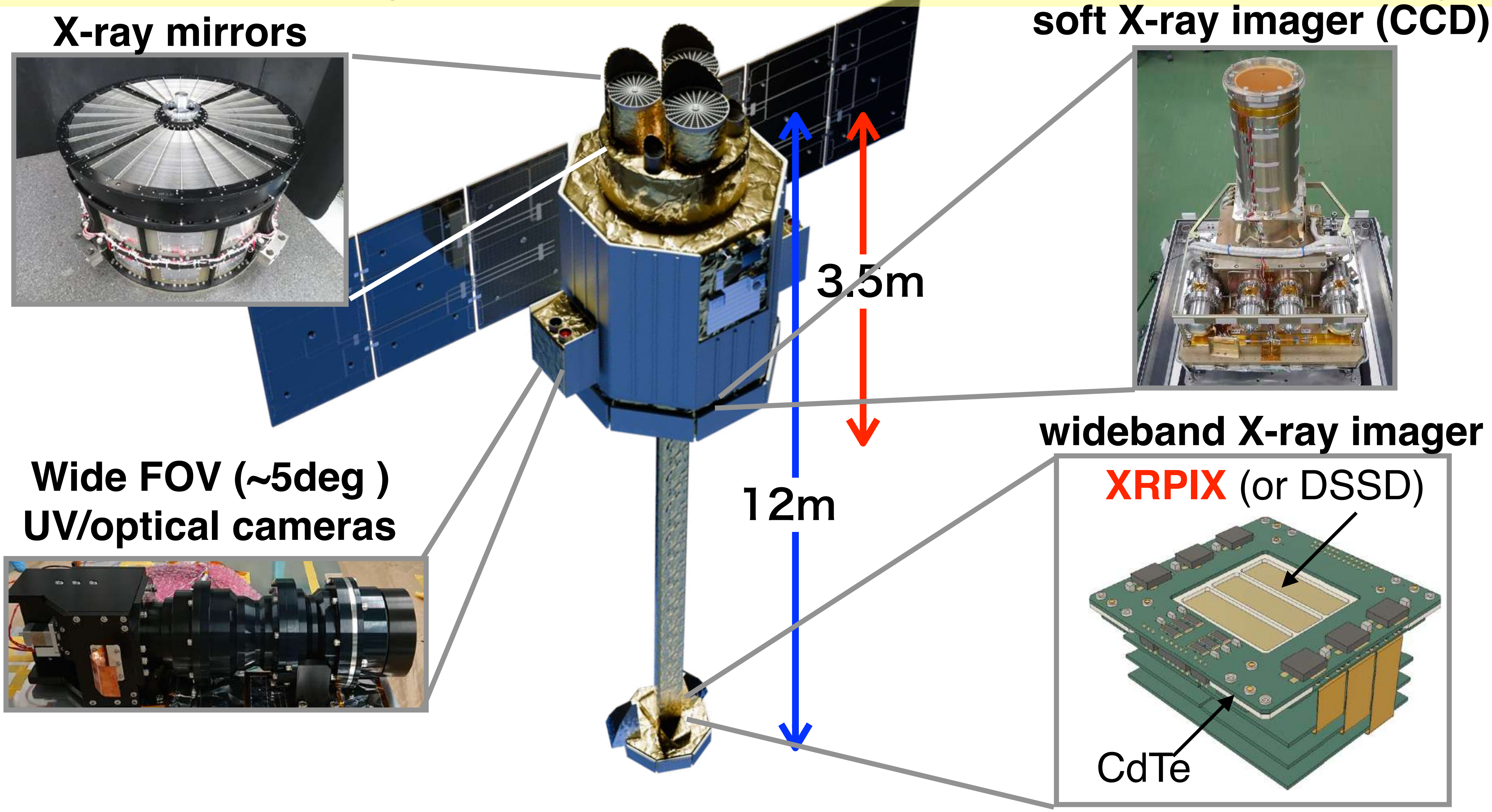
- New large sensor, “XRPIX10”, a 4th-generation sensor developed in 2022.
  - XRPIX10 uses the well-proven Single SOI wafer.
  - The back bias can be applied up to 300V without any problem.
  - Can achieve full depletion (300μm) and a detection efficiency of ~50% as planned.
- We plan to assemble XRPIX10 into a low BGD rigid FPC in FY2024, and deploy XRPIX10 in the ISAI experiment from FY2025.





JEDI (this name will be changed)

- We are considering a M-size X-ray satellite following XRISM
- Aiming realization in early 2030s
- Broad band from UV, soft X-rays to hard X-rays (0.3~80 keV)
- XRPIX is a strong candidate for the Si sensor of wideband X-ray imager



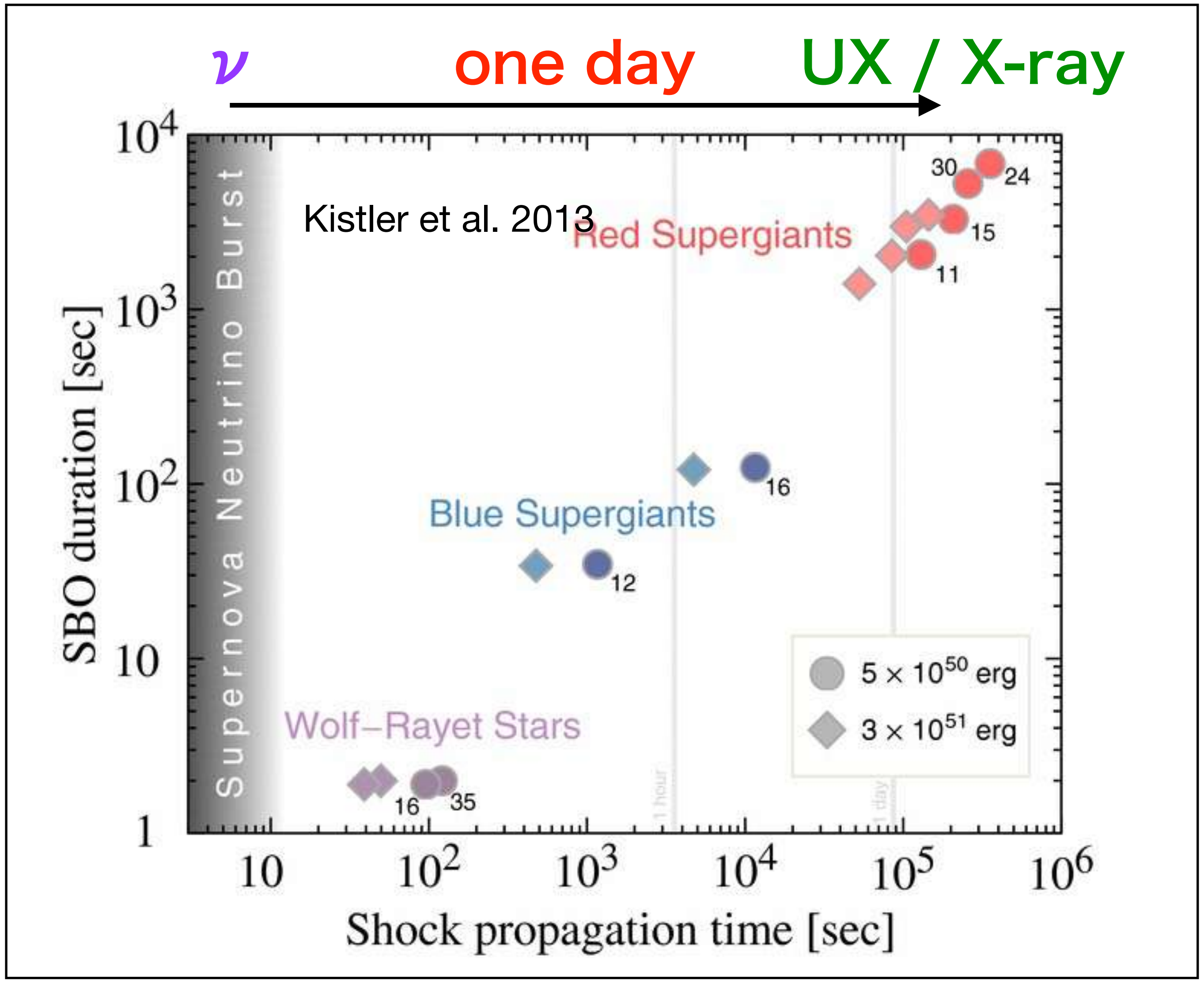
The Science is “TIME DOMAIN”

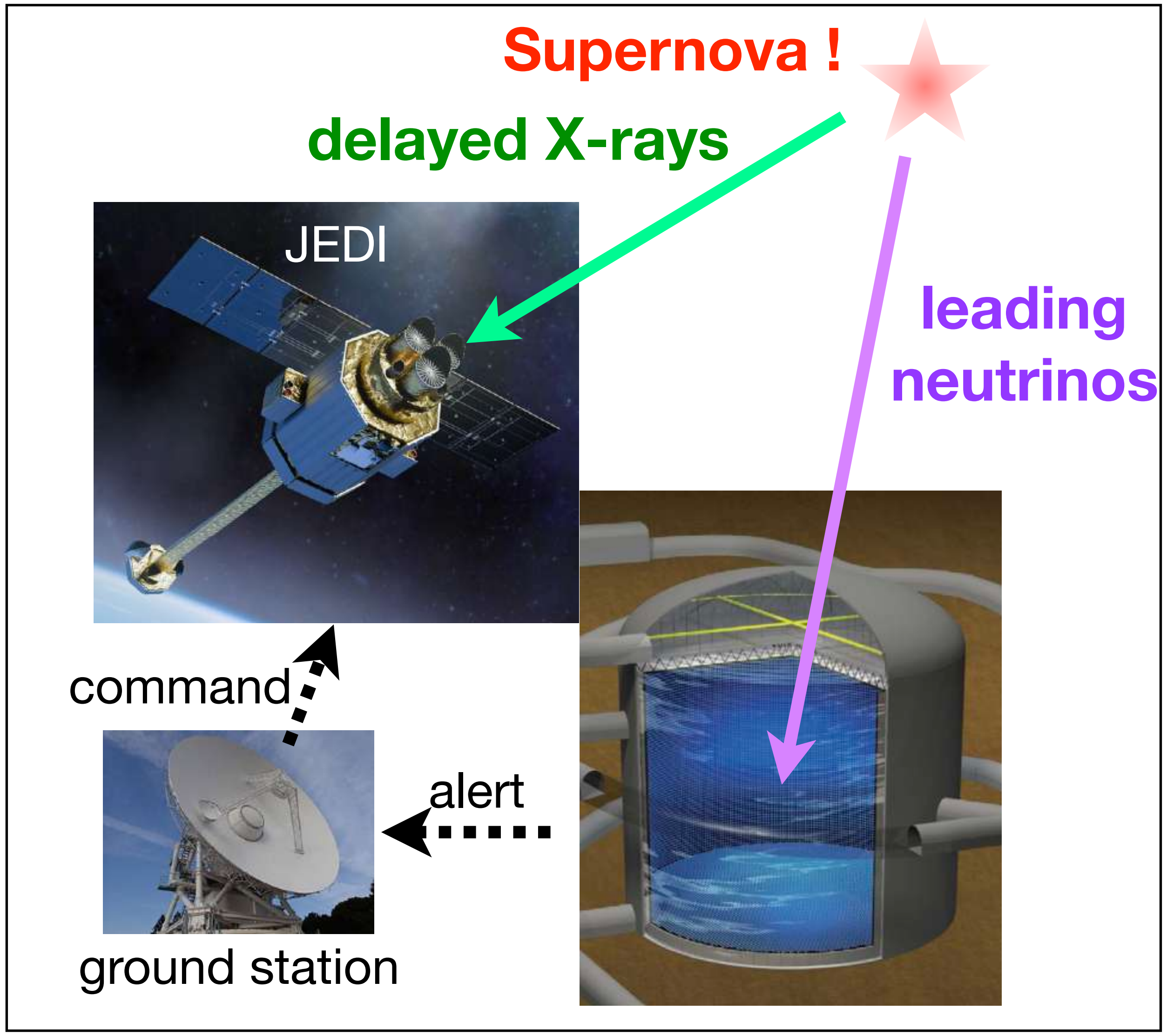
Triggered by EM (e.g., HiZ-G), GW, neutrino…, JEDI follows up the explosion as soon as possible.

JEDI (this name will be changed)

Aiming at the first "waiting observation" for supernova in history

- There is a delay of up to ~day in SN from the neutrino emission to the actual explosion (shock breakout).
- JEDI observes the progenitor of the SN by receiving the alert from Hyper-K (to be operational in 2027).





Is there any idea to search for DM using JEDI?

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 XRPIX10 that can achieve full depletion (300μm) and a detection sensitivity of ~50% as planned.
- We are considering a next M-size X-ray satellite, “JEDI”, for time domain astronomy.

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！