Commissioning and the first observation of ISAI, Investigating Solar Axion by Iron-57, experiment

Yoshiyuki Onuki

Yoshizumi Inoue,[a]Kenji Shimazoe, [b]Akimichi Taketa, [c]Toshihiro Fujii, [d]Takeshi Tsuru, [d]Tomonori Ikeda, [d]Masamune Matsuda,[d]Kazuho Kayama, [d]Hiromu Iwasaki, [d]Hiroki Namba, [d]Mei Anazawa,[d]Mizuki Uenomachi, [e]Kentaro Miuchi and [f]Ayaki Takeda

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[b]University of Tokyo, ERI,
[c]Osaka Metropolitan University,
[d]Kyoto University,
[e]Kobe University,
[f]Miyazaki University

TAUP VIENNA 2023

東京大学 THE UNIVERSITY OF TOKYO

Early BG

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Axion

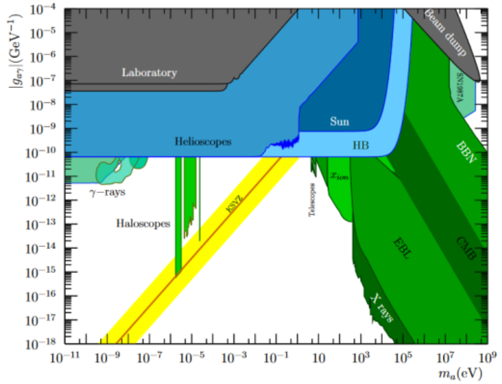
- Strong CP problem in QCD
  - CP non-conserving term in QCD Lagrangian
  - EDM in neutron can be induced however the EDM highly suppressed.
- Peccei-Quinn mechanism solves the strong CP problem
  - Axion appears
- Invisible axion models
  - DFSZ axion…interacts with lepton and quark at tree level
  - KSVZ(hadronic) axion…interacts with nucleus, and both lepton and quark at loop level

$$m_a \simeq \left(\frac{6 \times 10^6}{f_a(\mathrm{GeV})}\right)$$

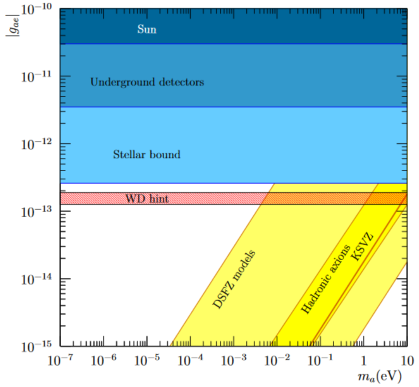
Low-reheating scenarios

Pierluca Carenza et al., JCAP07(2021)031

axion-gamma interaction $g_{a\gamma}$

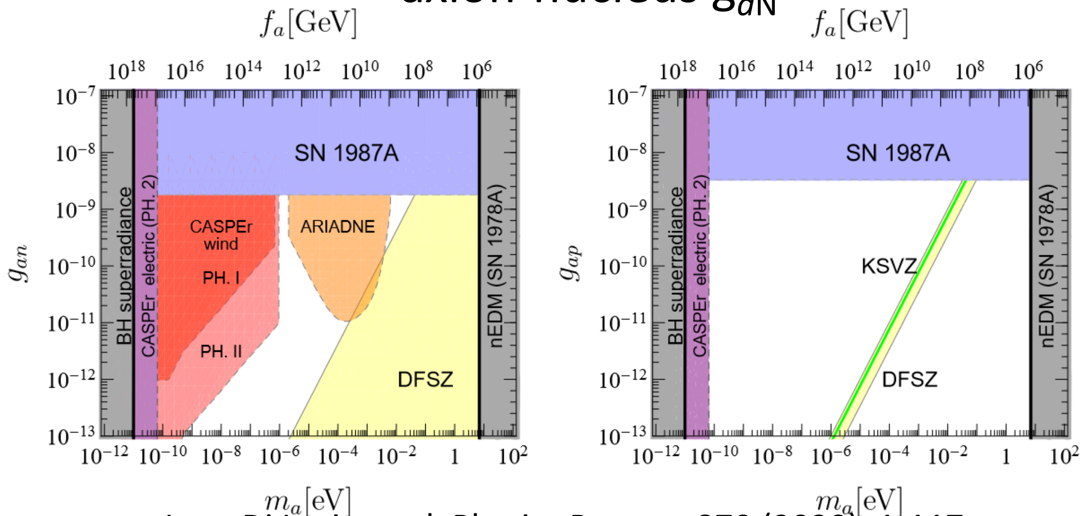


axion-electron g_{ae}



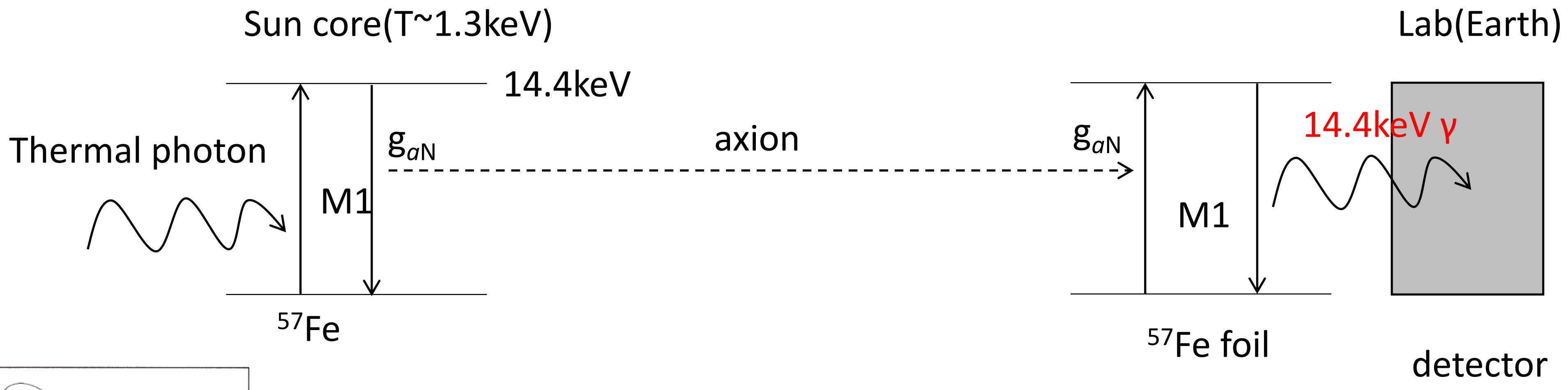
Igor G. Irastorza et al., Progress in Particle and Nuclear, 102(2018)89-159

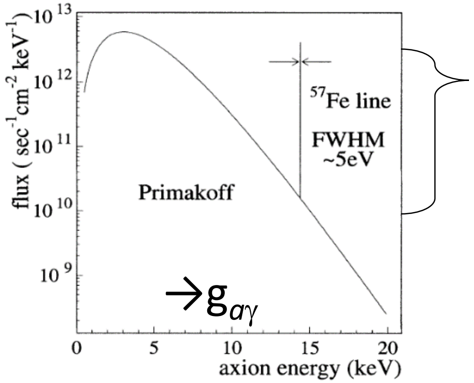
axion-nucleus g_{aN}



Luca Di Luzio et al, Physics Reports 870 (2020), 1-117

Solar axion via ^{57}Fe





KSVZ axion
→g_{aN}

^{57}Fe natural abundance 2.119% Mössbauer nuclei can absorb axion thanks to Doppler broadening.

$$m_a = 5.55 \times \left(\frac{R_d}{1\mathrm{day}^{-1}\mathrm{kg}^{-1}} \right)^{1/4} \mathrm{eV}$$

$$R_d = \frac{N}{M\eta\varepsilon}$$

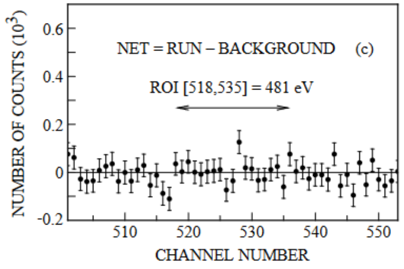
R_d: ^{57}Fe de-excitation rate
N: observed event
M: ^{57}Fe mass
η: γ fraction without internal conversion 0.105
ε: detection efficiency

Moriyama, Phys.Rev.Lett,75,3222

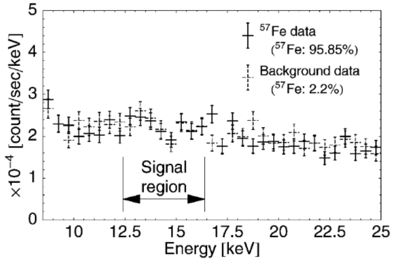
Independent g_{aN} measurement by 14.4 keV γ without introducing the other interactions.

Measurements and feasibility study

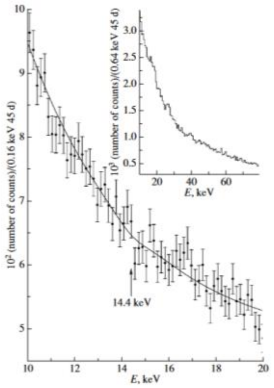
- $m_a < 745$ eV@95%C.L,
  Si(Li), 61days, M. Krčmar et al., Phys. Lett. B 442 (1998) 38.
- $m_a < 216$ eV@95%C.L,
  PIN photo diodes, 14days T. Namba, Phys.Lett.B 645, 398 (2007)
- $m_a < 145$ eV@95%C.L.,
  Si(Li), 45days, A.V. Derbin et al., Phys.At.Nucl. 74, 596 (2011)



M. Krčmar



T. Namba



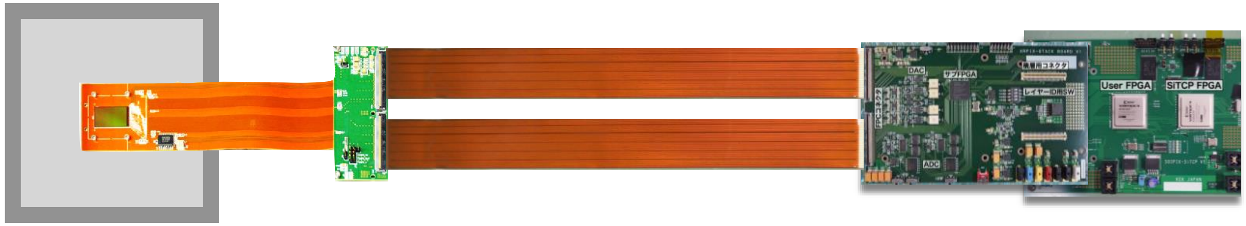
A.V. Derbin

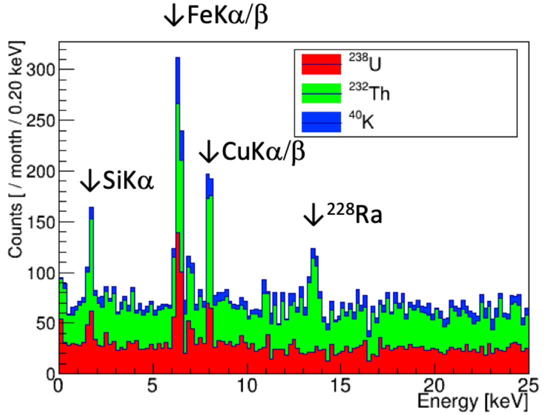
New experiment using X-ray SOI pixel sensor equipped with self-trigger and high energy resolution (XRPIX)

- G10 rigid circuit board
  XRPIX on G10

Radiation shield

- Rigid-flex circuit board
  XRPIX on flex





Feasibility study w/ Geant4

Y. Onuki et al., NIM A, 924, 448–451 (2019)

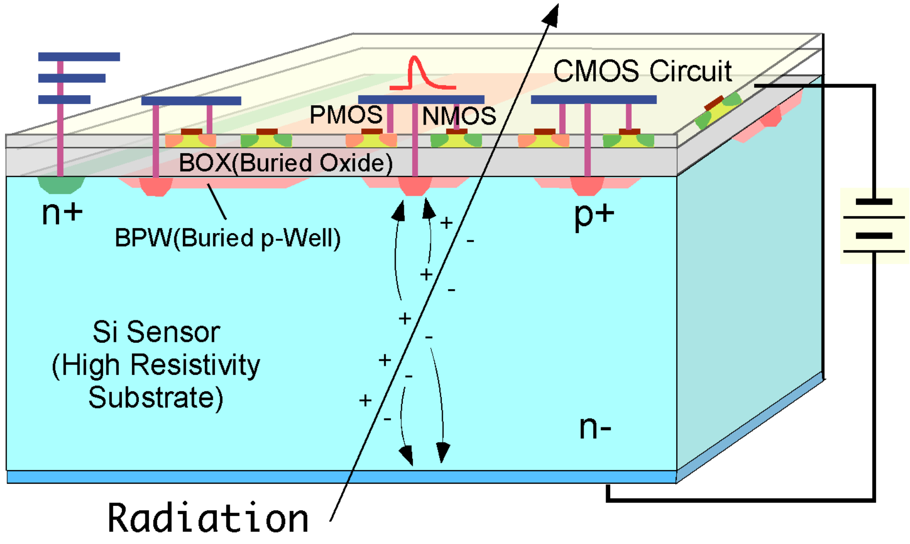
^{228}Ra from ^{232}Th series could be crucial BG.

Rebooted as "ISAI" experiment since 2021
"Investigating Solar Axion by Iron-57"

ISAI means conspicuous in Japanese

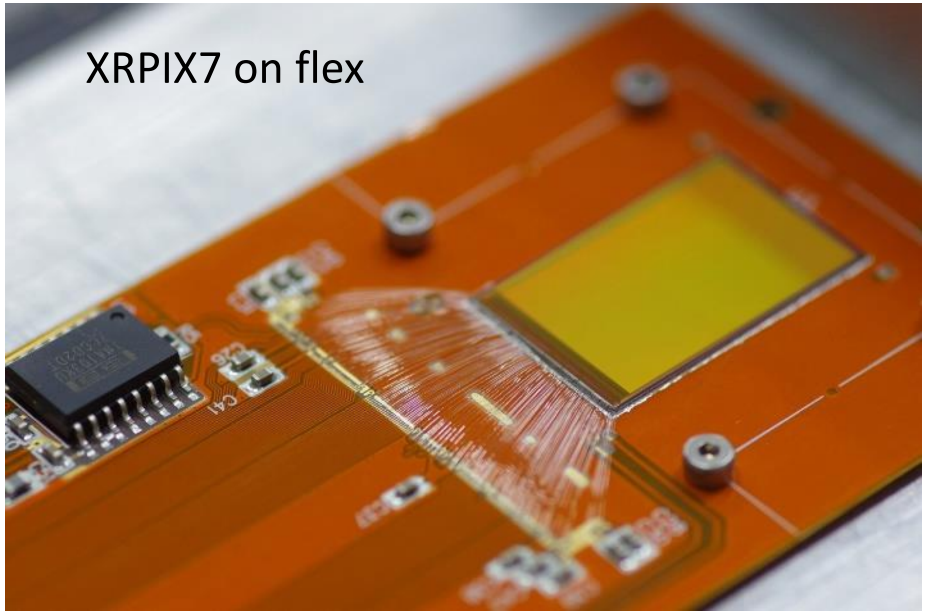
XRPIX: X-ray pixel sensor using SOI technology

- Originally developed(ing) for future X-ray astronomy mission
- Full depleted SOI process(0.2μm) by Lapis-semiconductor Co., Ltd.
- 24.6 mm × 15.3 mm × 300 μm (608 × 384 pixels, pix size 36 μm square)
- Each pixel has a trigger circuit with a 10 μs timing resolution
  - Anti-coincidence enables to reduce cosmic-ray backgrounds
- High energy resolution : 590 eV (FWHM) @14.4 keV(Goal : 250 eV)



T.G. Tsuru et al., Proc. SPIE 10709,(2018)

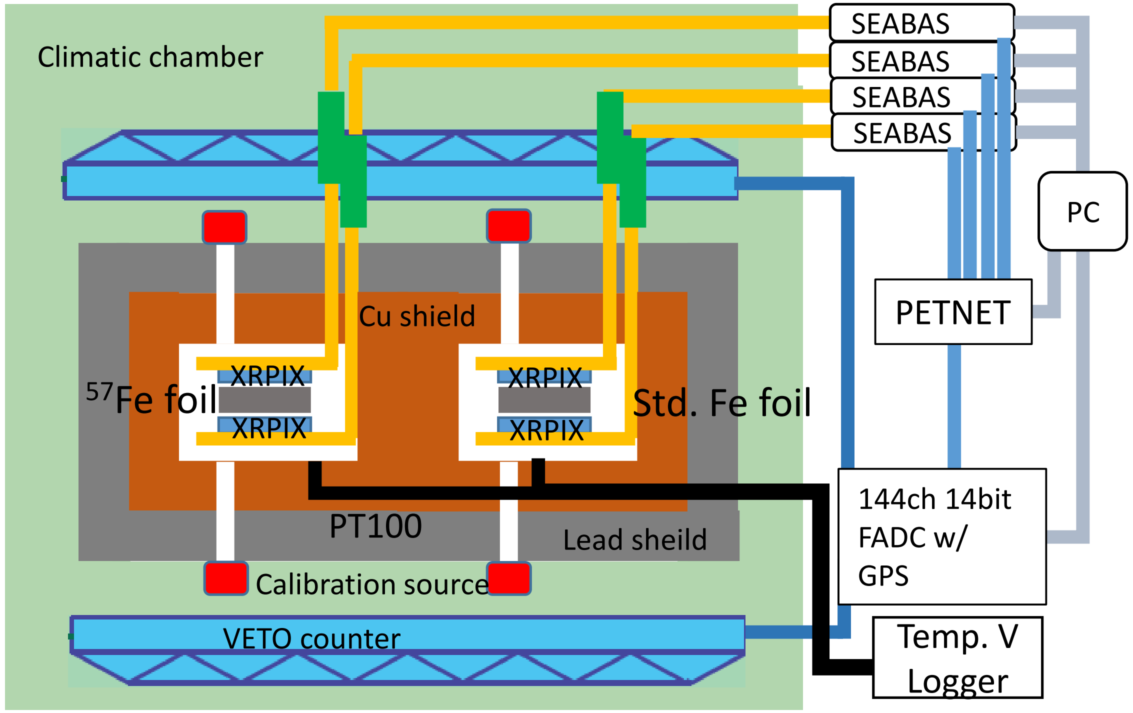
Rigid-flex circuit board

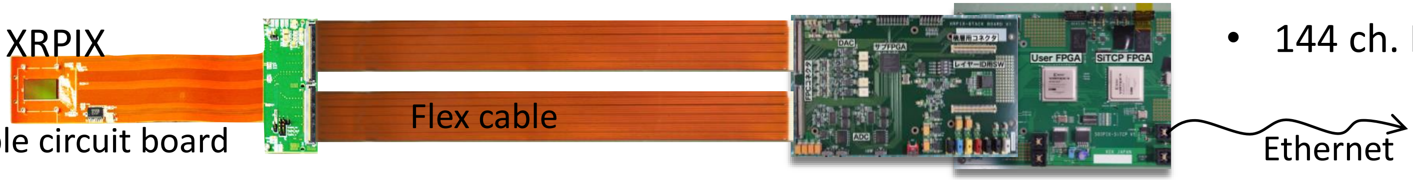


Current latest chip is XRPIX10.
XRPIX7 (double SOI) is adapted for ISAI experiment.

ISAI detector configuration and the status

- Enriched ^{57}Fe foil sandwiched by two XRPIX7 sensors -> Signal module
- Standard Fe foil sandwiched by two XRPIX7 sensors -> BG module
- In climatic chamber, the detectors shielded by t5mm OFC and t50mm lead.

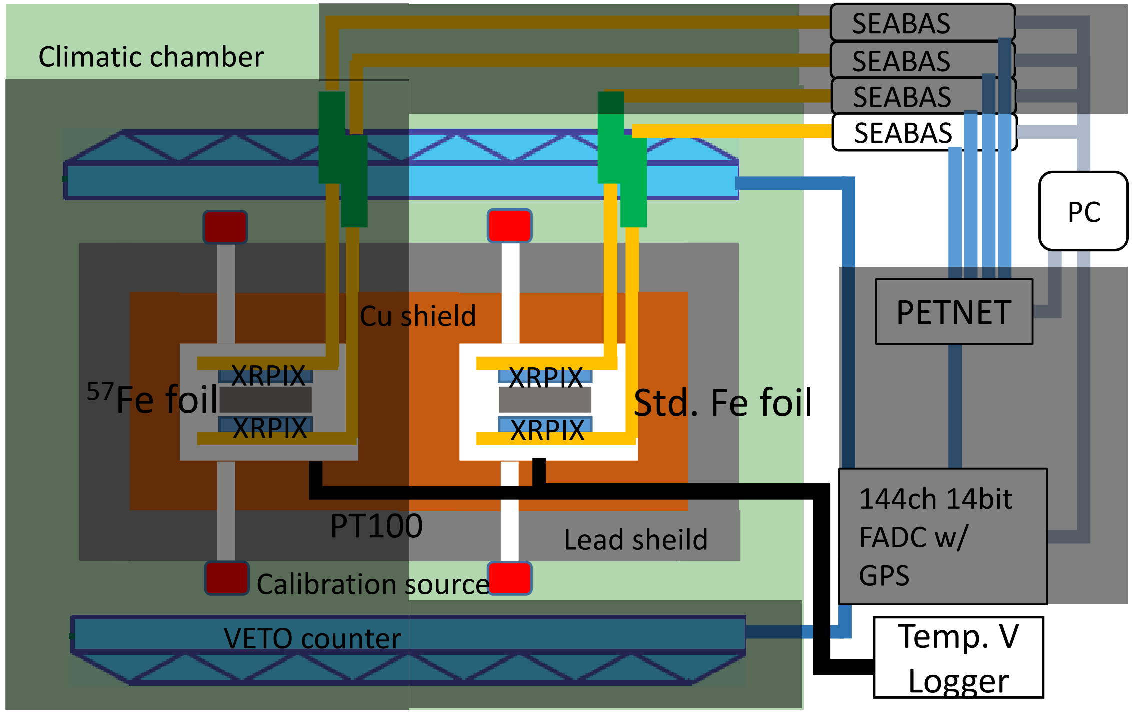


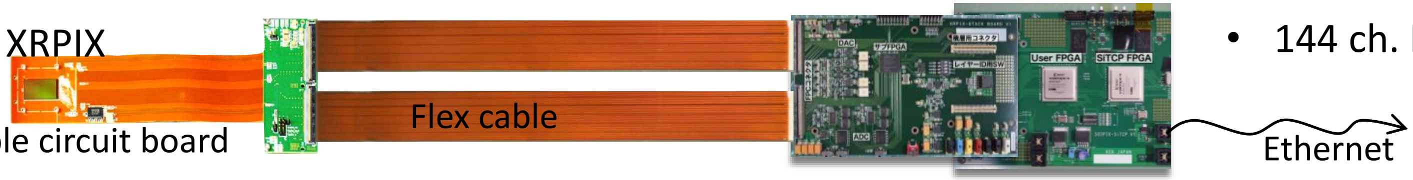


- Readout by SEABAS IEEE Trans. Nucl. Sci. 55(3) 1631 (2008).
- Temperature monitors
  - Climatic chamber
  - PT100 logger inside shield
- Calibration source through pin-hole
  - Collimated irradiation on the part of XRPIX
  - Gain monitoring while observing.
- Position sensitive plastic scintillator VETO counter
  - Staggered triangular scinti. bars with SiPM.
- Time stamp IEEE Trans. Nucl. Sci. , 68(8), 1801(2021)
  - PETNET originally developed for PET application
  - 144 ch. Input with 62.5psec resolution

ISAI detector configuration and the status

- Enriched ^{57}Fe foil sandwiched by two XRPIX7 sensors -> Signal module
- Standard Fe foil sandwiched by two XRPIX7 sensors -> BG module ☑ but single XRPIX readout
- In climatic chamber, the detectors shielded by t5mm OFC and t50mm lead. ☑





- Readout by SEABAS ☑ IEEE Trans. Nucl. Sci. 55(3) 1631 (2008).
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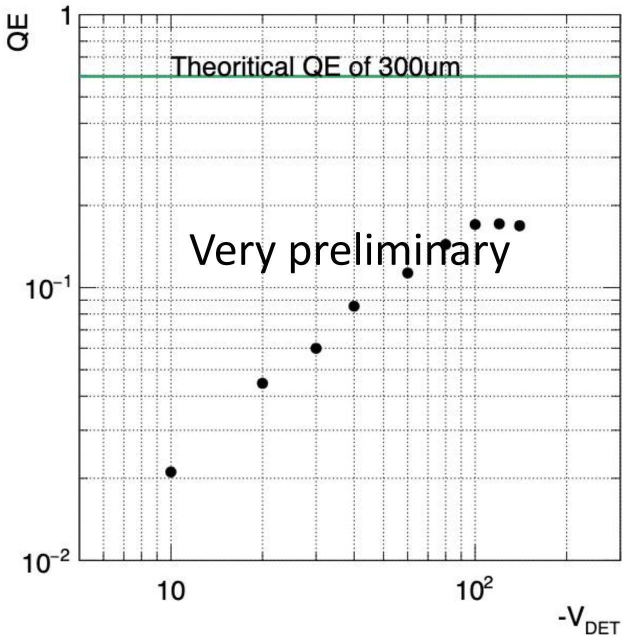
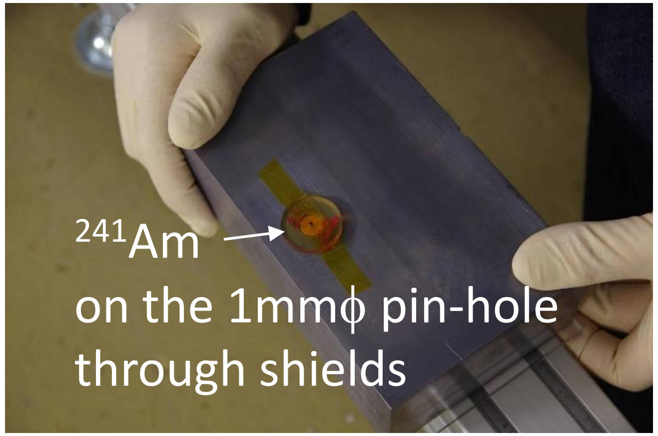
Detection efficiency

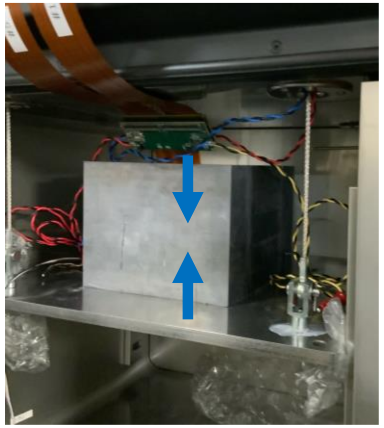
- XRPIX7 has an issue in higher sensor bias under a low temperature.
  - Several chips were broken. Still the reason is not understood.
  - Should operate moderate Vbias ~-10V and temperature 0℃.
- Collimated ^{241}Am 13.9keV source flux measured by SDD using the efficiency in spec sheet.
  - XRPIX7 detection efficiency rough estimation ~2% at Vbias= -10V.

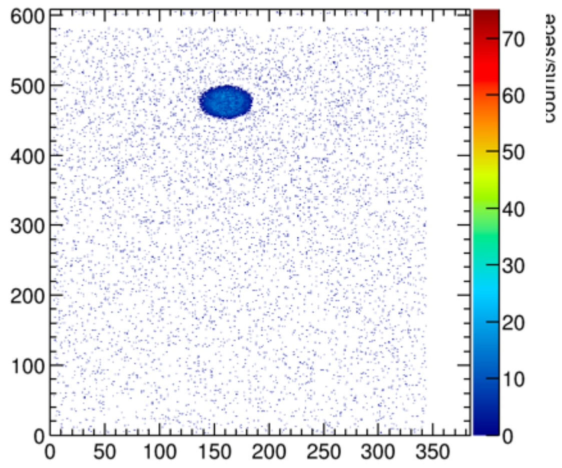


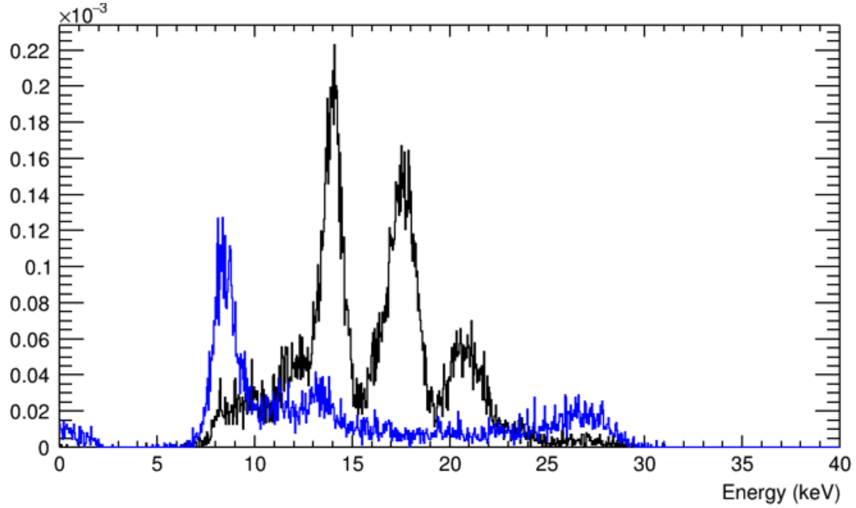
Need more study !

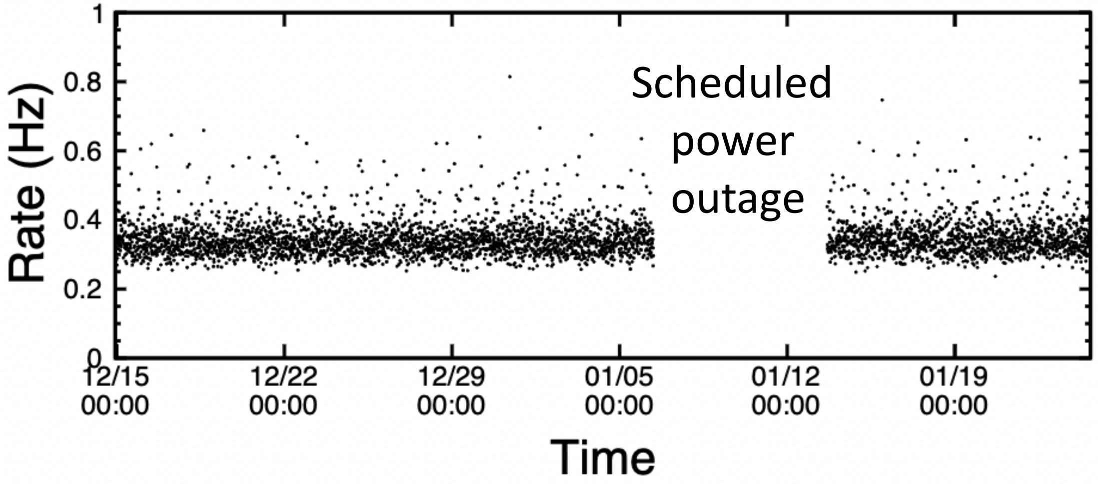
Calibration source through pin-hole.







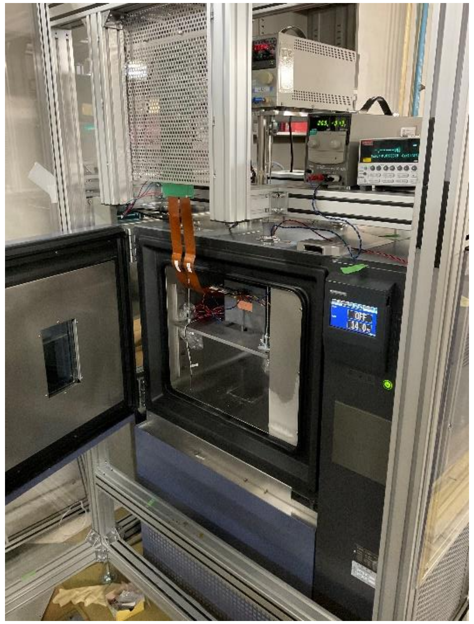




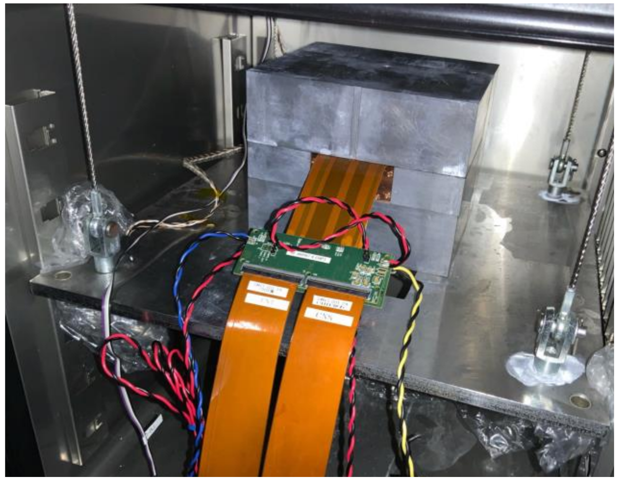
BG enhanced run for demonstration of pin-hole calibration.
- Stable operation for 42 days(15 days livetime).
- Gain monitoring area under the pin-hole.
- Observing area except for the are under pin-hole.
- No veto.
- 2.8keV(FWHM)@13.9keV

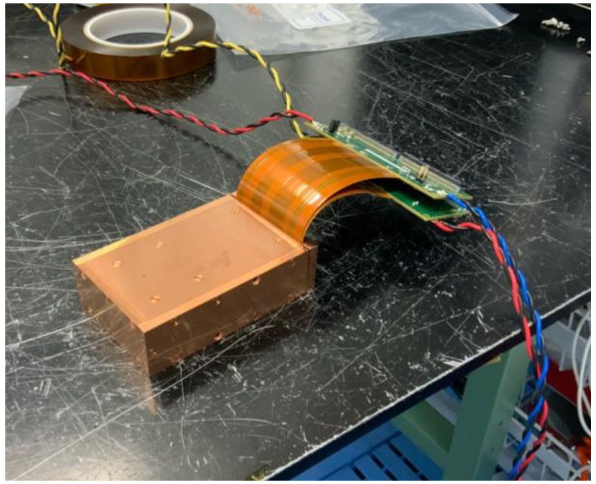
Pin-hole calibration seems working !

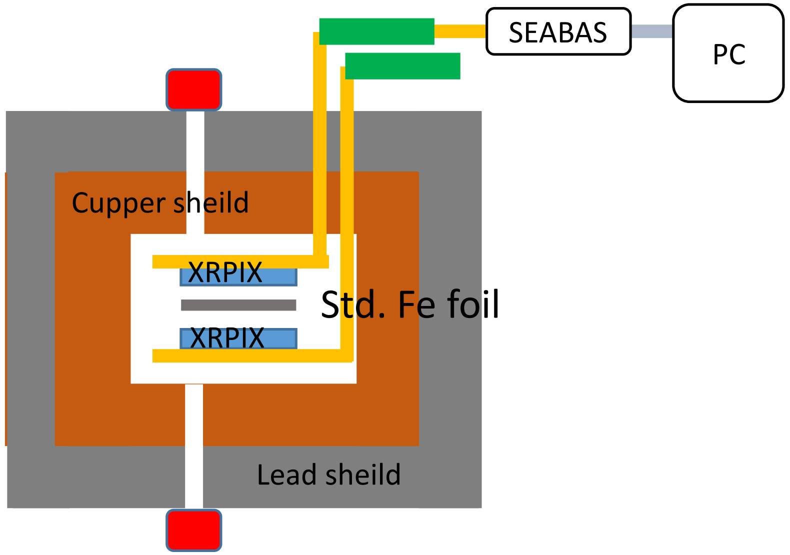
ISAI BG module assembly and the BG run



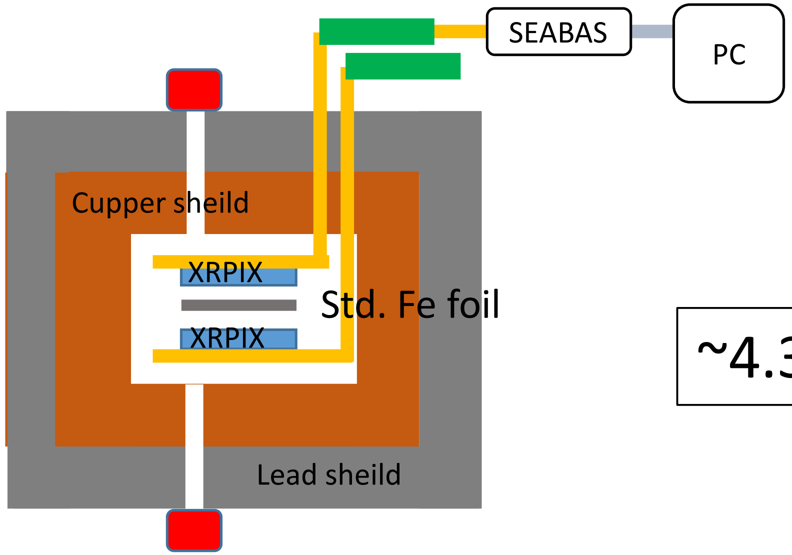
BG module was assembled and shielded.
First BG run conducted 2023/07/13-2023/08/10.
But only one of two XRPIX7 chips was readout.





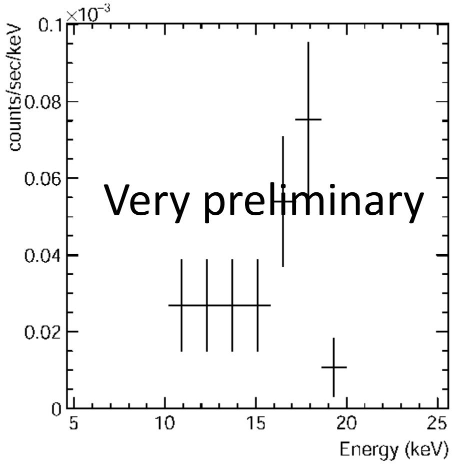


First BG run using ISAI BG detector and the sensitivity.



- BG module without veto.
- 2023/07/13-2023/08/10
- Livetime 10.07days

~4.3 counts/day/2.8keV@14.4keV obtained



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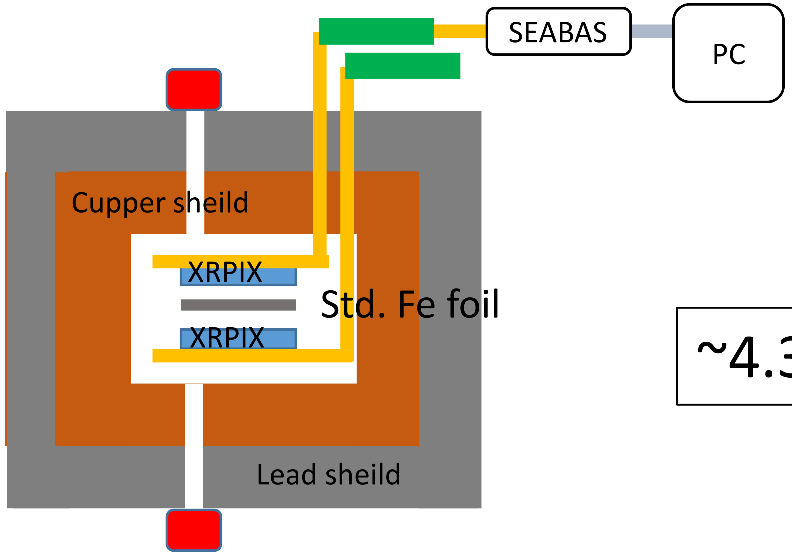

- BG module without veto.
- 2023/07/13-2023/08/10
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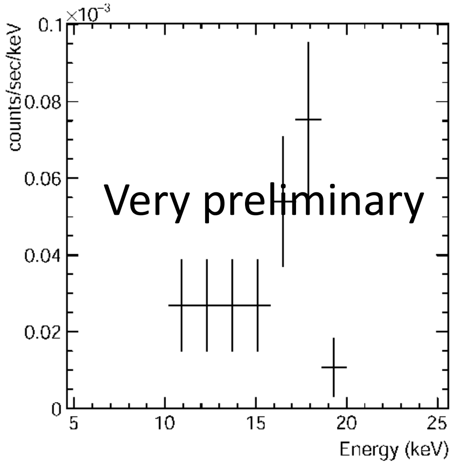
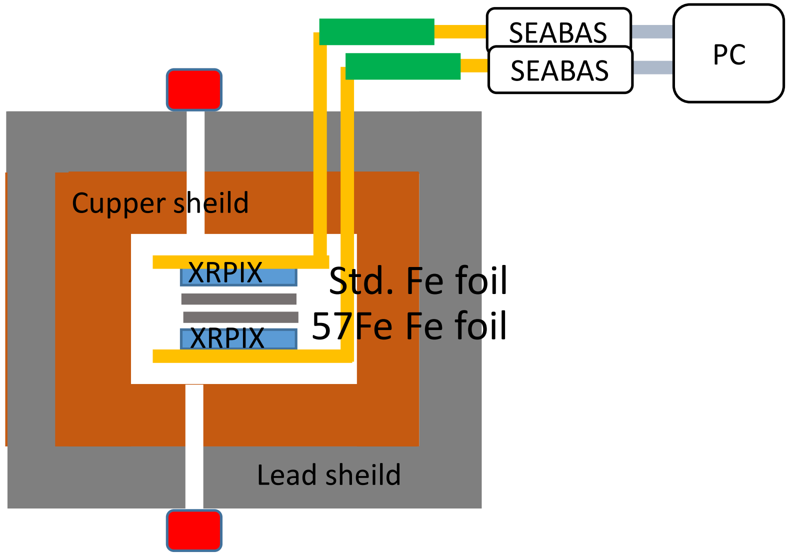
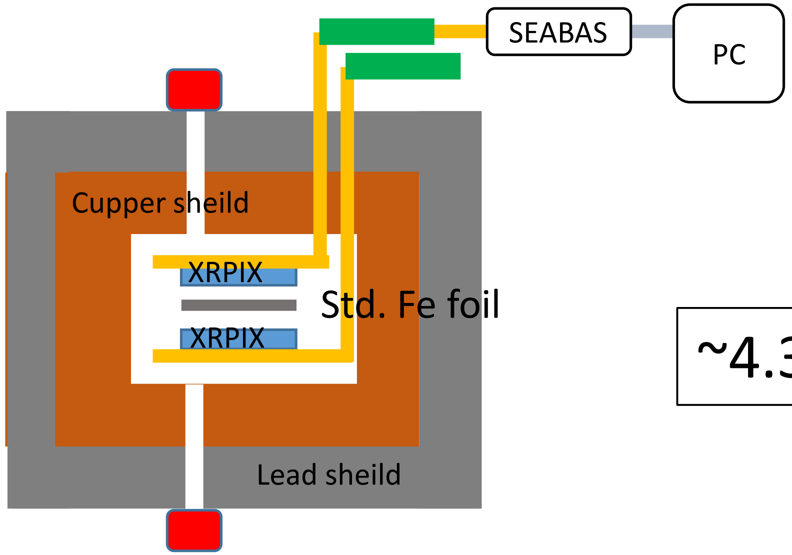
~4.3 counts/day/2.8keV@14.4keV obtained





- ←Assume 1/2 ISAI without veto.
- Assume 2% detection eff.

First BG run using ISAI BG detector and the sensitivity.



- BG module without veto.
- 2023/07/13-2023/08/10
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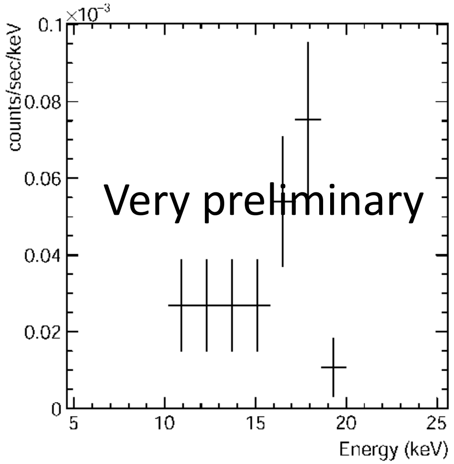
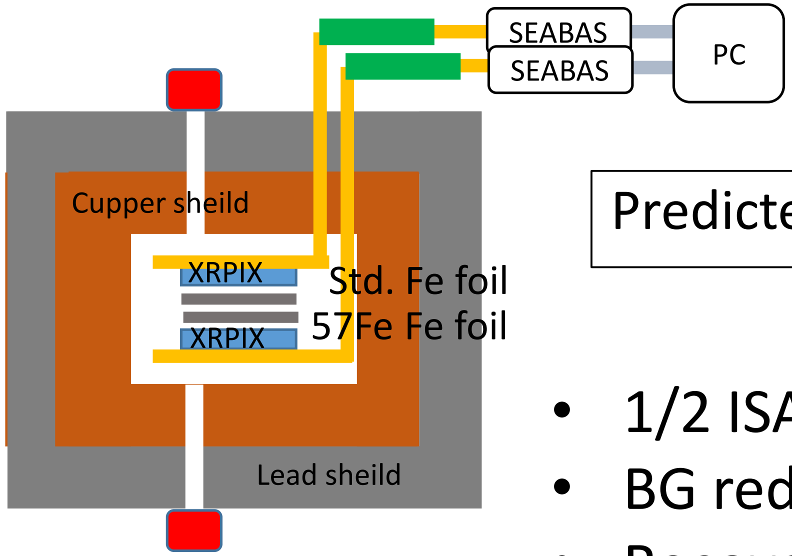
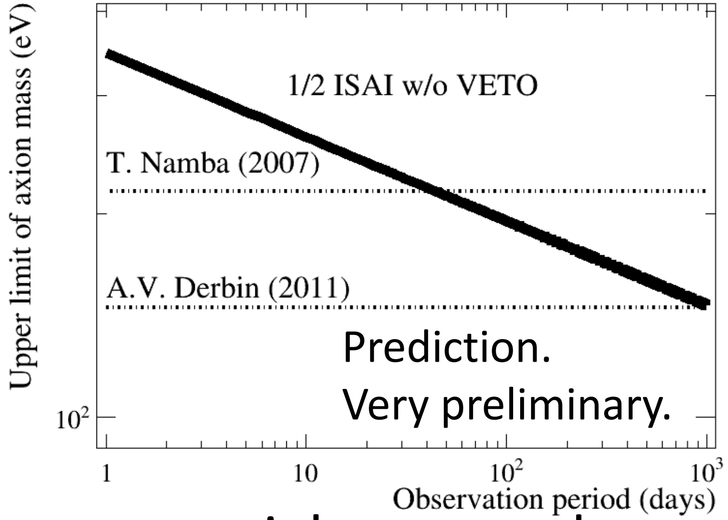




- ←Assume 1/2 ISAI without veto.
- Assume 2% detection eff.

Predicted upper limit @95% C.L. obtained →



- 1/2 ISAI detector to full detector
- BG reduction by timing-veto
- Recovery of the detection efficiency

are essential to precede the current limit.

Prospect

- Learning ISAI detector
  - BG reduction achieved by rigid-flex
  - Veto and recovery of detection efficiency is crucial for the sensitivity
  - Veto commissioning starts soon.
  - 1/2 ISAI to full ISAI => improve twice efficiency.
  - First physics run soon after the veto commissioning.
- The latest XRPIX10 solves the back bias issue
  - It can apply bias -70V(i.e. -10V for XRPIX7)
    though the detection eff. not measured yet
  - Switching XRPIX7 to XRPIX10 somewhere after the intensive study using XRPIX7.

Summary

- ISAI is dedicated measurement of g_{aN} using the solar axion.
- The module, stacking std. Fe foil sandwiched by two XRPIXs, was assembled and conducted BG run without veto.
- XRPIX7 issue compels operation in moderate Vbias and temperature.
  - the latest XRPIX10 seems the issue solved.
- BG run w/ corresponding 1/2 ISAI detector without veto conducted.

  found necessity
  - Full scale experiment
  - Significant BG reduction by veto
  - Recovery of detection efficiency
- Veto commissioning will start soon.

Thank you !

Backup

マスコットキャラ（ISAIさん）

ISAI