B02

Progress of development of pnCCD image sensor onboard the next generation GRBs observation satellite mission HiZ-GUNDAM

Multi-messenger Astrophysics 2nd annual conference

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S. Takahashi et al., NIM-A, 2024, Volume 1064, pages 169413

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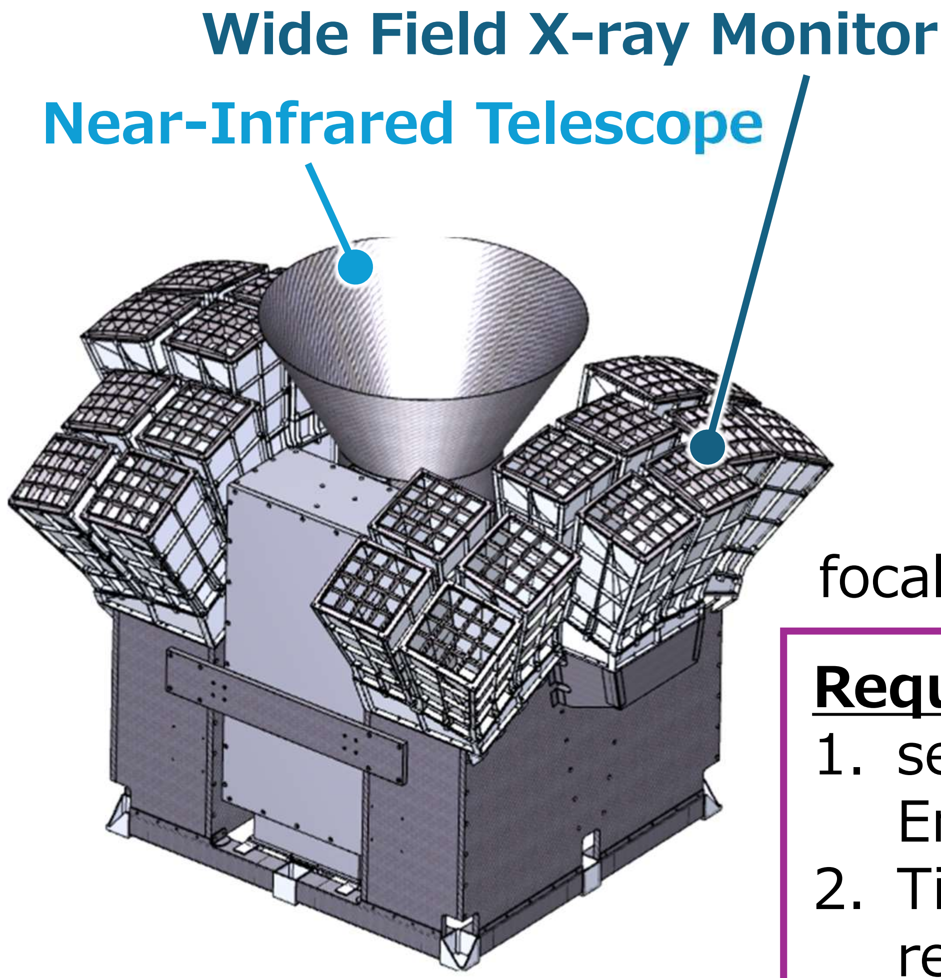
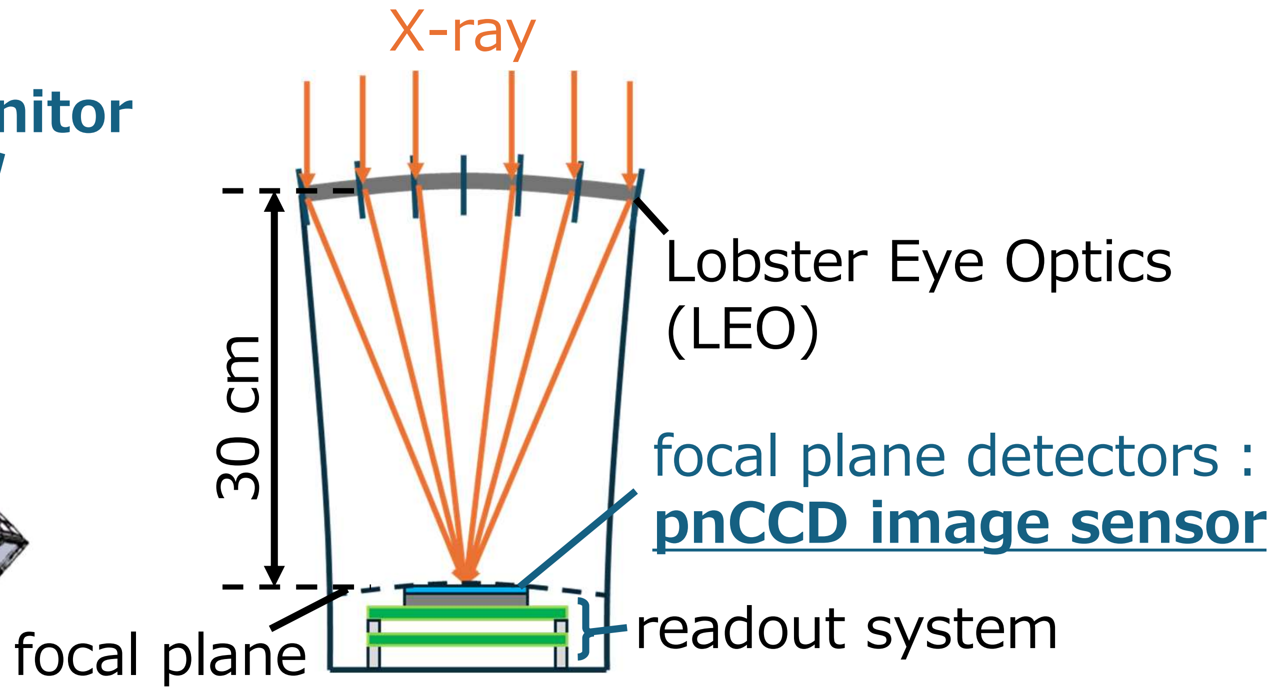
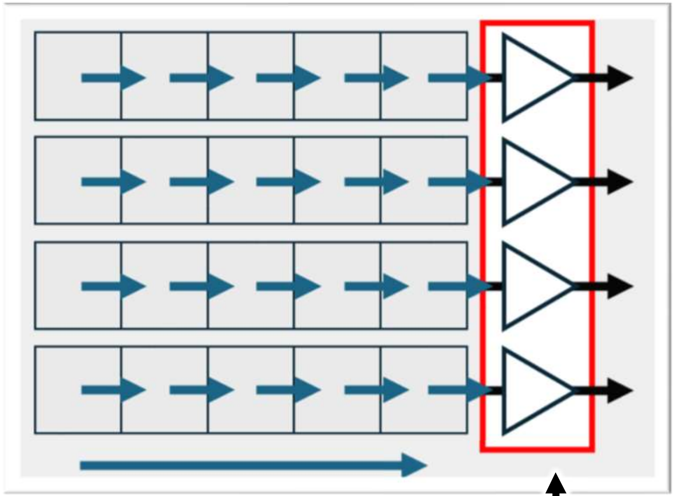
HiZ-GUNDAM and Wide Field X-ray Monitor





Requirement for focal plane detectors
1. sensitivity range of LEO : 0.4 – 4 keV
   Energy range covering **0.4 - 4 keV** sufficiently
2. Time resolution **shorter than 0.1 second** is
   required to observe time variability of GRBs

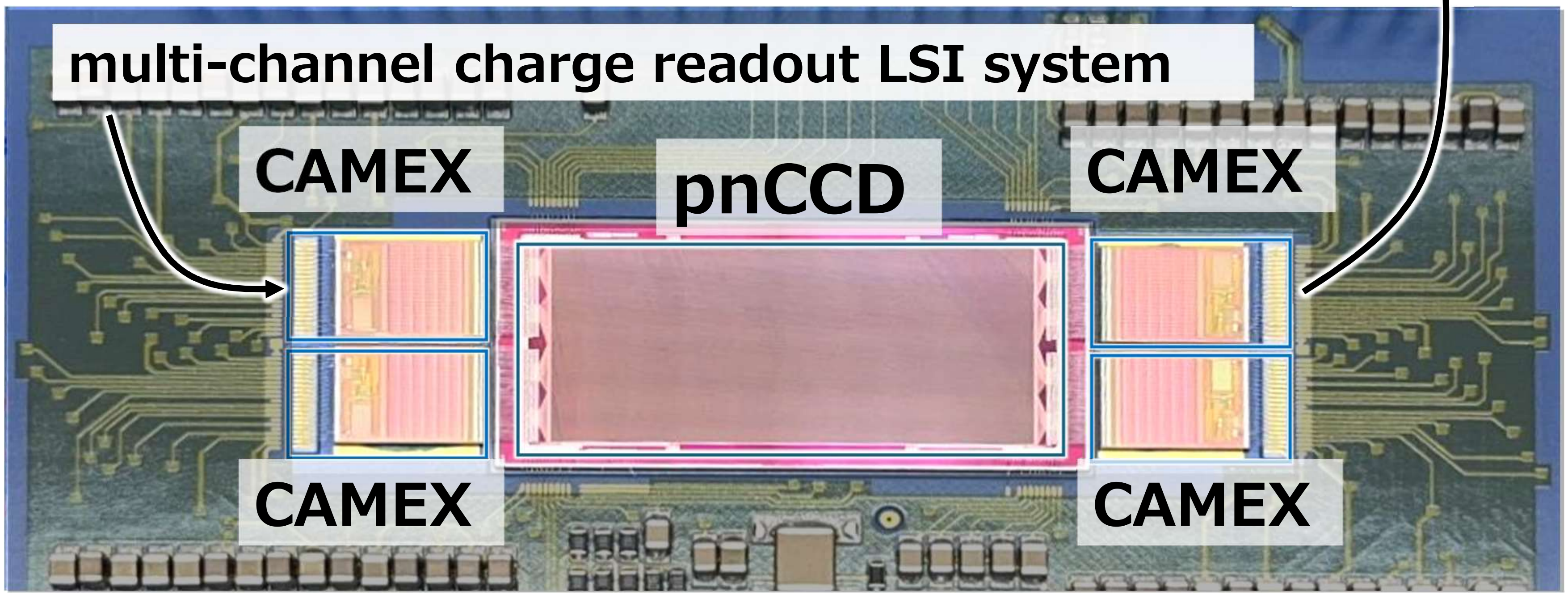
pnCCD Image Sensor



<u>pnCCD image sensor</u>

pnCCD system manufactured by PNsensor GmbH

- **Multi-Channel Readout**
- **High frame rate (up to 1000 frames/second !)**



Achievements of pnCCD in Spacecrafts

SRC/eROSITA(Germany)

SVOM/MXT(France)

- *HiZ-GUNDAM* is M-class mission(~500 kg)
- Costly mechanical chillers cannot be installed.
- The system will be operated at about -30 °C with passive cooling only due to the strict power requirements.

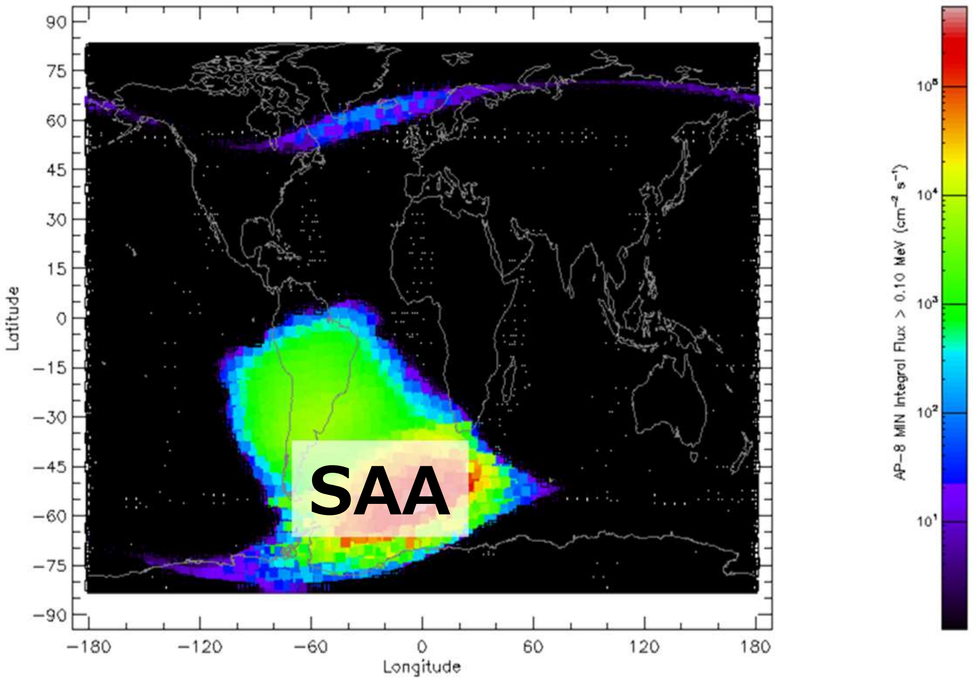
Temperatures are higher than the thermal environment of pnCCDs in previous spacecraft.
→ We need to investigate the effects of radiation on pnCCDs.

http://sci.esa.int/xmm-newton/18015-xmm-newton-spacecraft/

https://ep.bao.ac.cn/ep/cms/files/W020210609570525377403.png

Radiation and its effects on *HiZ-GUNDAM* in orbit

sun synchronous dawn-dusk orbit(altitude: 500 – 600 km, 98.1°)
mission term: 3 – 5 years



Mean Captured Proton Flux
(by SPENVIS)

Radiation Damage Effects on pnCCD

Increase in dark current
→ Worsen lower detectable energy

Requirement for
focal plane detector: 0.4 – 4 keV
may no longer be satisfied.

We must test radiation tolerance to various irradiation doses.

Purpose

To quantify the **change in soft X-ray detection performance** of pnCCDs in response to changes in irradiation dose.

During the *HiZ-GUNDAM* mission, can the pnCCD operate with the **lower detectable energy=0.4 keV** requirement?

→ Investigate in the parameter space of **frame rate** and **temperature**.

pnCCD operating range
before irradiation

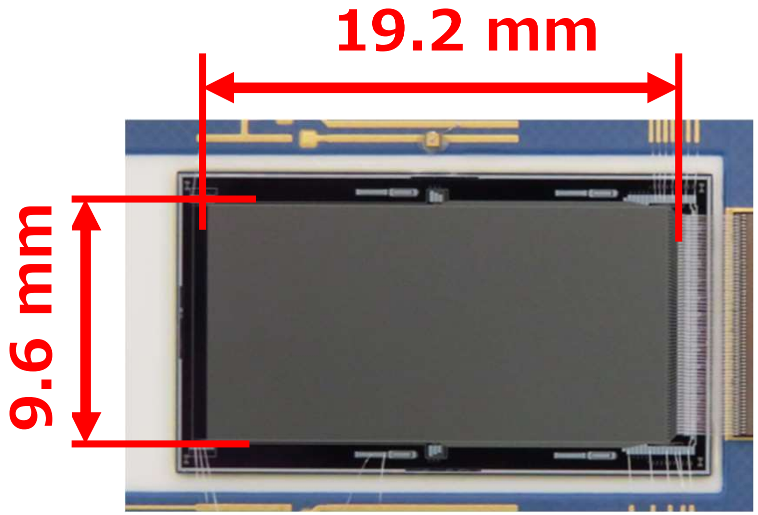
Items	Parameter
lower detectable energy	0.1 keV
frame rate	any
temperature	any

pnCCD operating range
after irradiation

Items	Parameter
lower detectable energy	≤ 0.4 keV
frame rate	**≥ ??? frame/s**
temperature	**≤ ??? ℃**

Detector used in this study

- The focal plane detector of FM requires 55 mm × 55 mm sensitive area, but a small pnCCD image sensor was used for this study to test radiation tolerance.

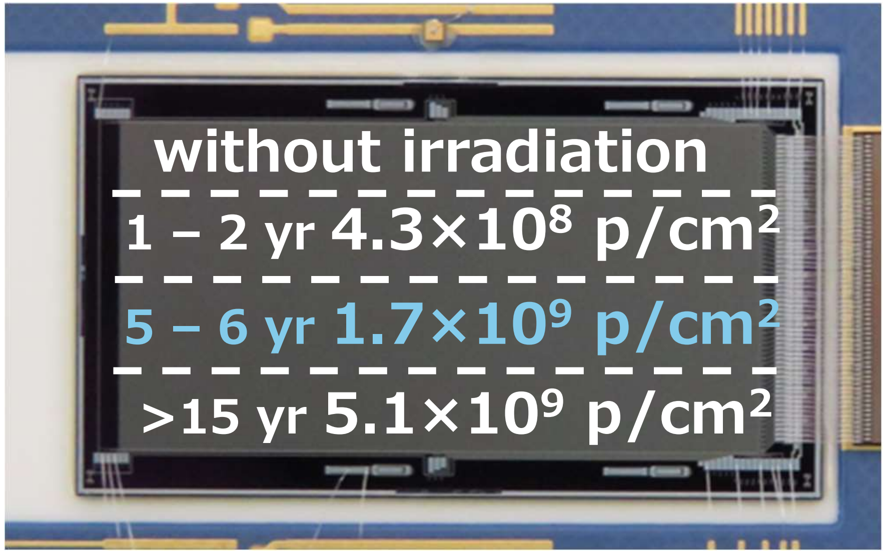


Item	small-pnCCD
sensitive area	9.6 × 19.2 mm^2
pixel size	75 um
pixel number	128 × 256
depletion thickness	450 um

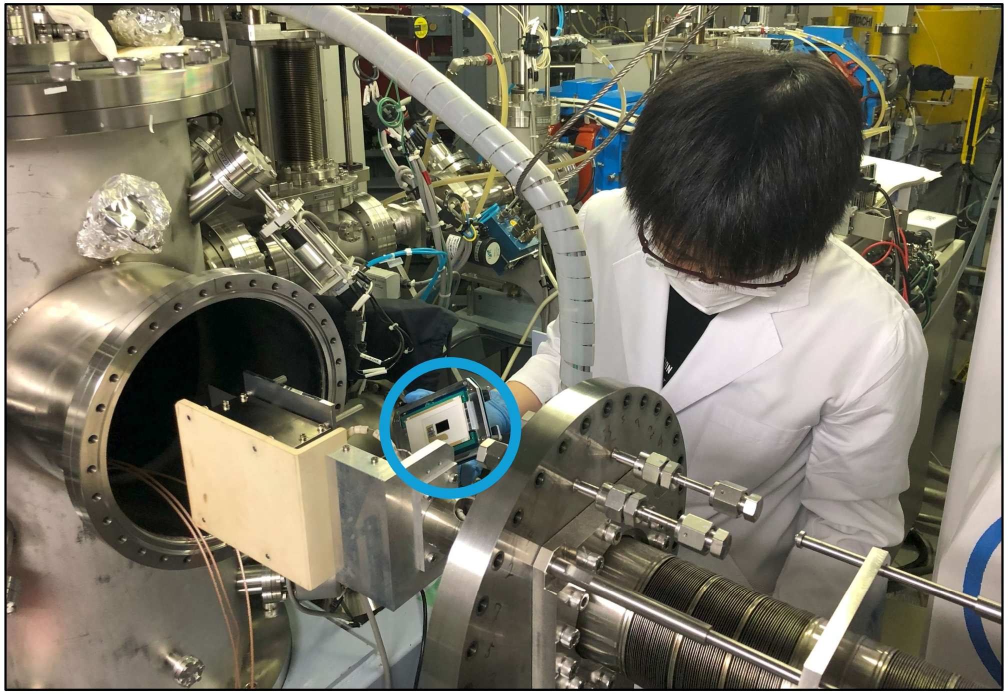
Radiation Tolerance Test

@ Wakasa-wan Energy Research Center (WERC)

The exposure received in orbit was represented by 10 MeV proton beams.
The pnCCD is divided into four irradiated areas, each of which is irradiated with a different number of protons.



pnCCD with separate irradiation area
(number of years in orbit in the WORST case corresponding to the irradiation dose → Actual deterioration could be much less.)

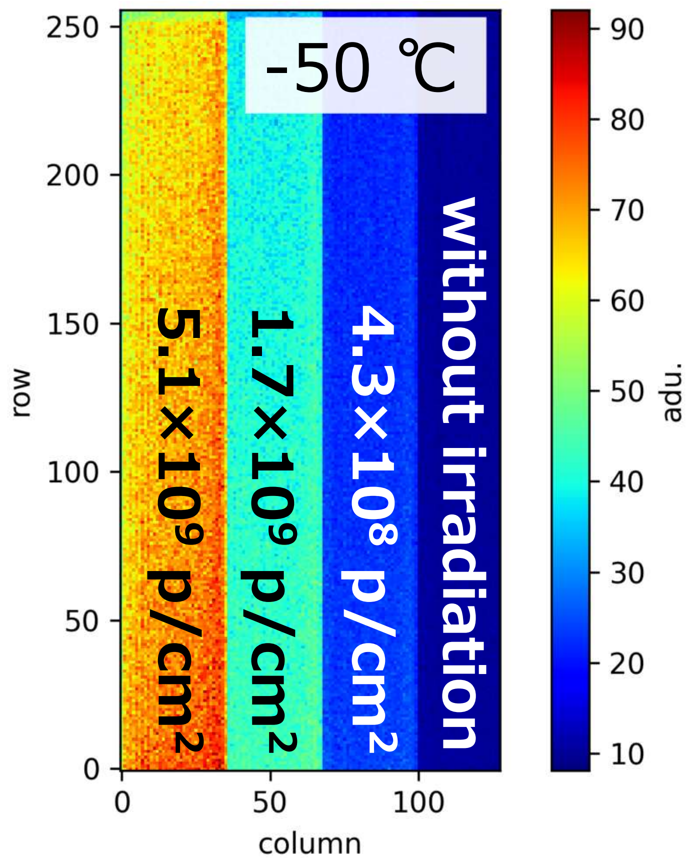


assembling the experimental setup

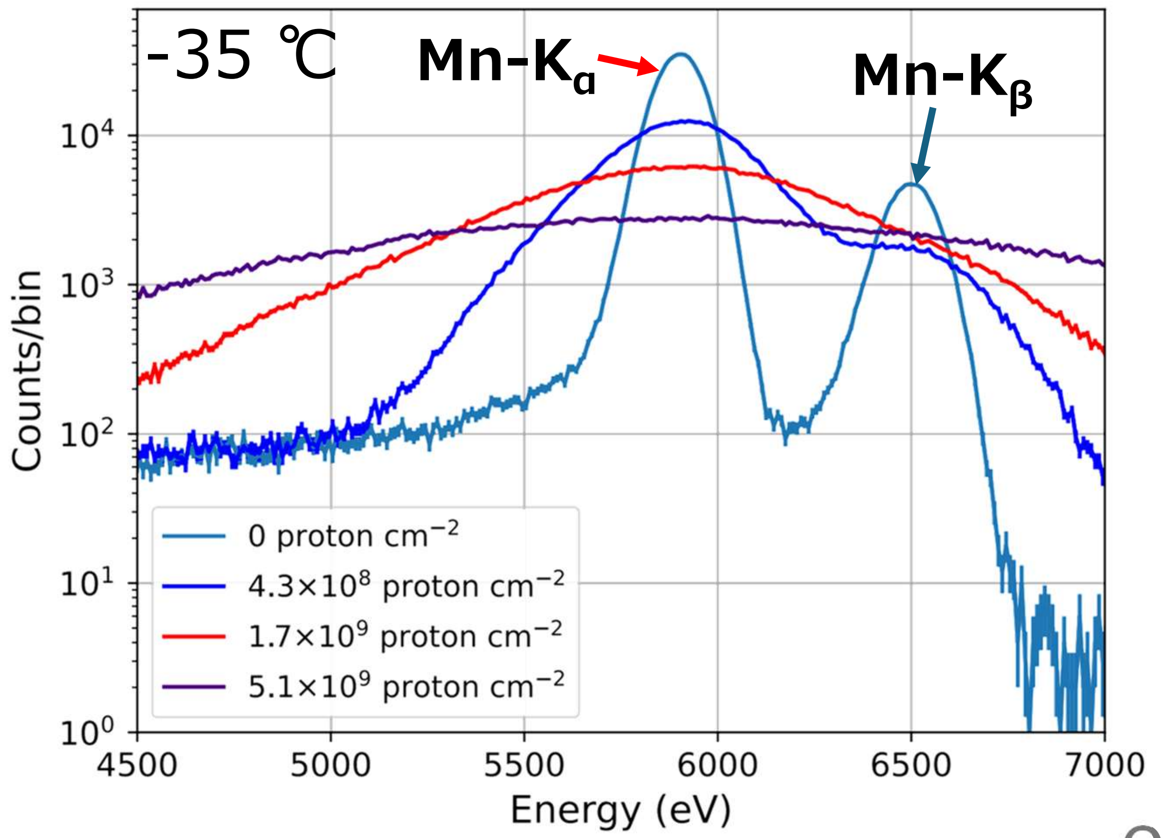
Image data after irradiation

frame rate: 33 frames/second
temperature: -20℃,-35℃,-50℃,-70℃,-90℃

Dark noise (e^-)

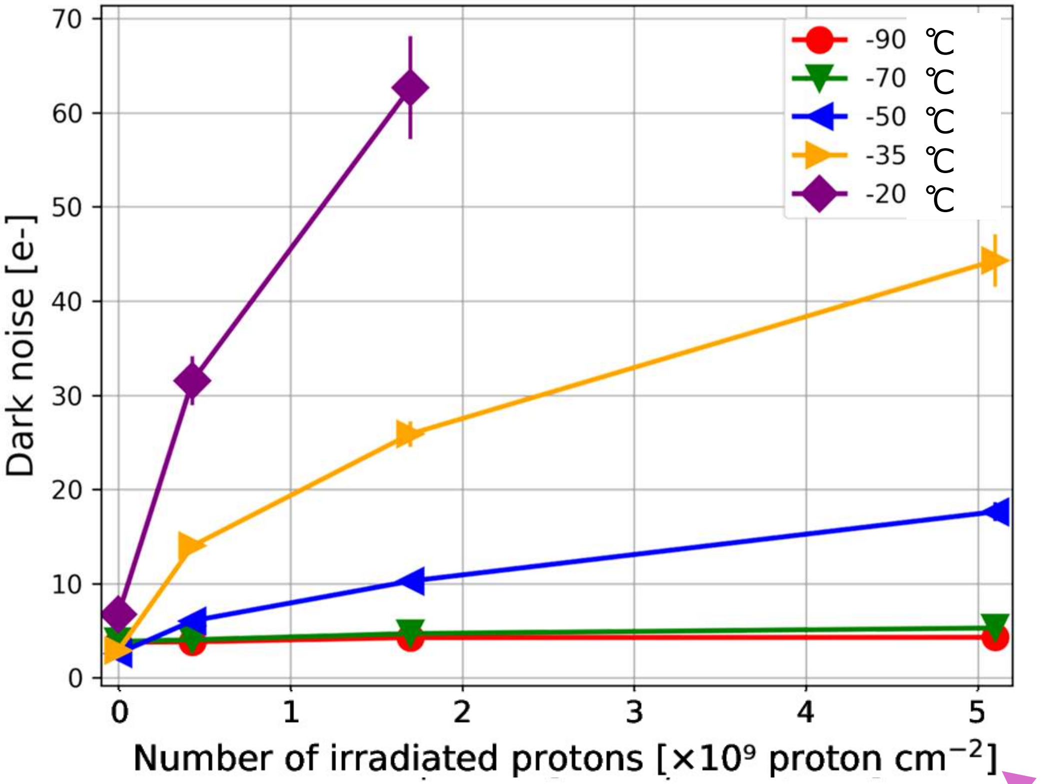


^{55}Fe(Mn-Kα:5.9 keV, Mn-Kβ:6.5 keV)

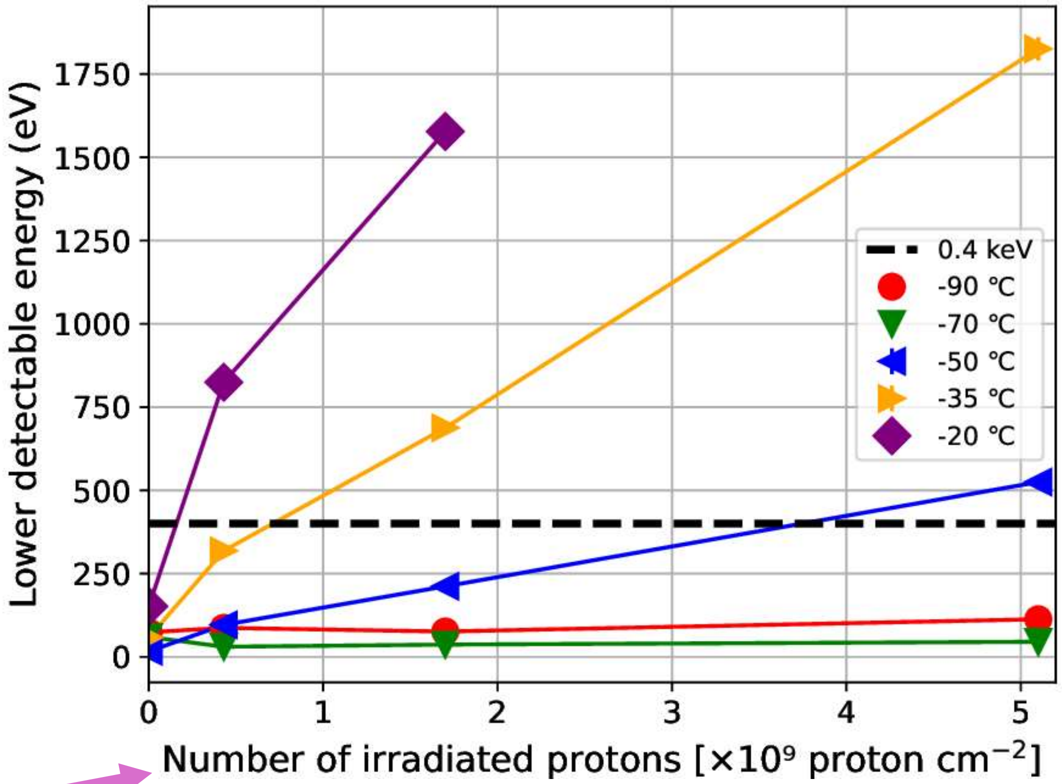


Dark Noise and Lower Detectable Energy

Dark Noise



Lower Detectable Energy

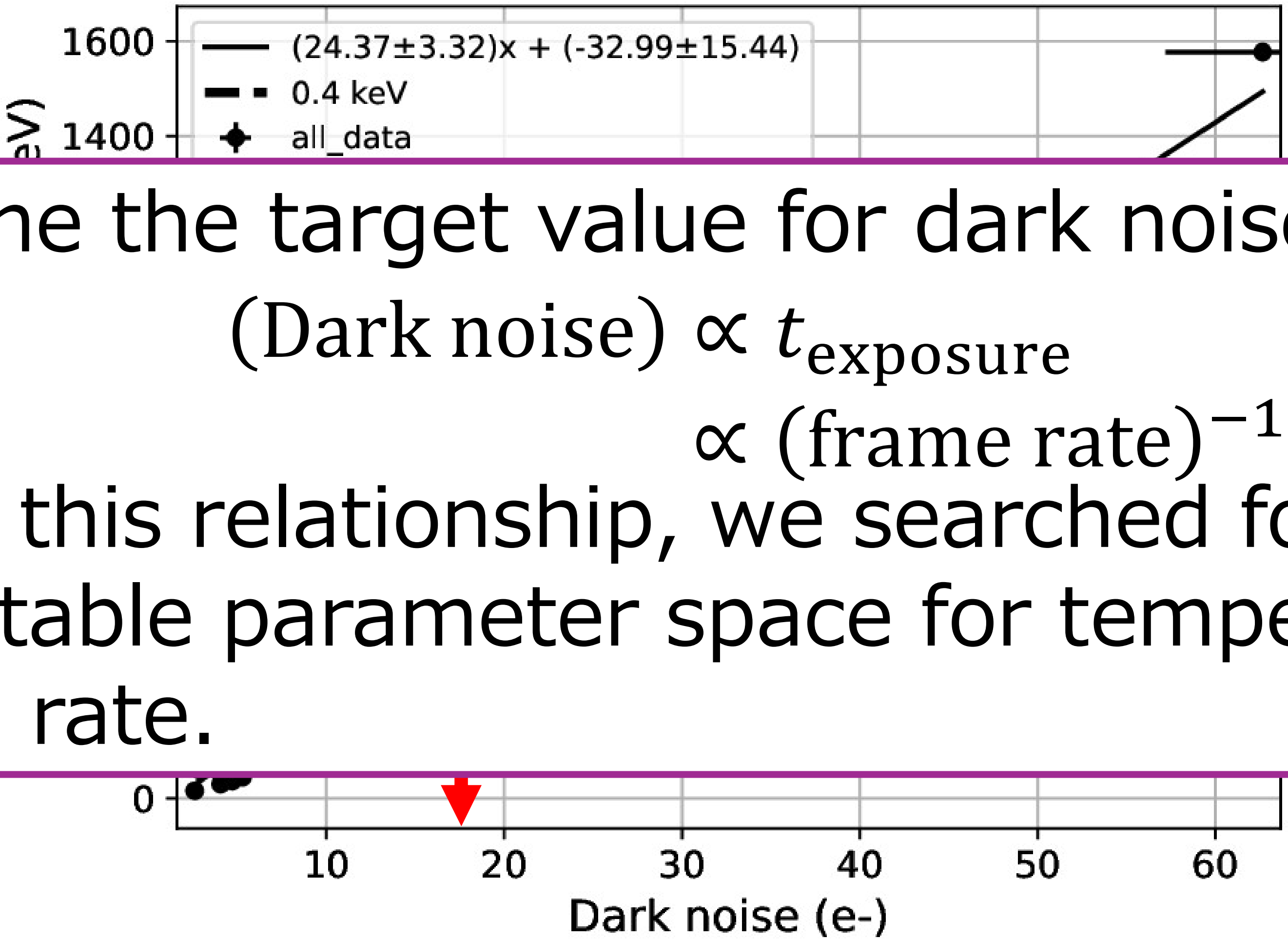


identical

Frame rate: 33 Hz

A correlation can be plotted between dark noise and lower detectable energy.

Dark noise v.s. Lower Detectable Energy



Assume the target value for dark noise is **18 e-**,

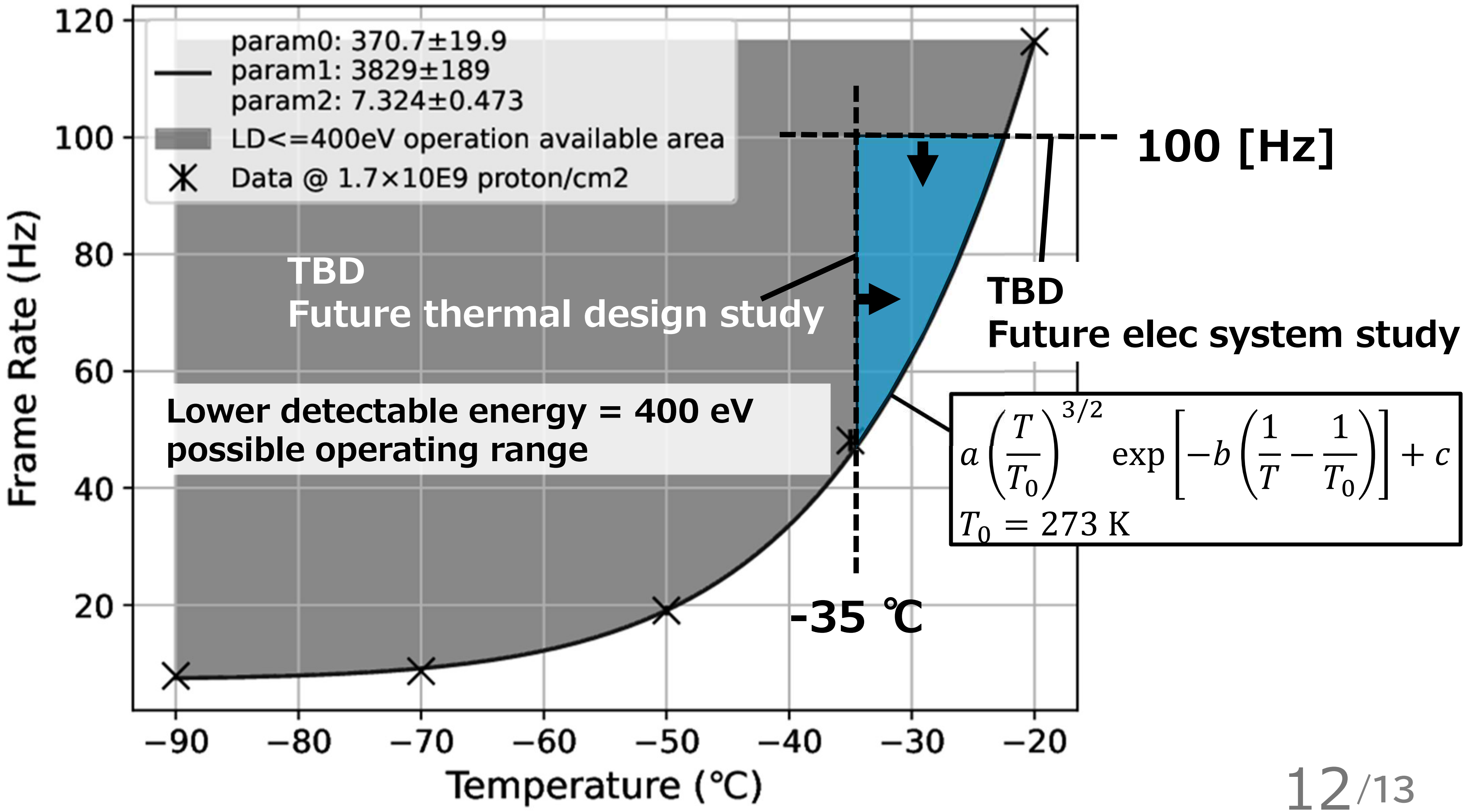
$$(\text{Dark noise}) \propto t_{\text{exposure}}$$
$$\propto (\text{frame rate})^{-1}$$

Using this relationship, we searched for an acceptable parameter space for temperature and frame rate.

Dark noise, where lower detectable energy is 400 eV of the required value, is **~18 e-**.

Temperature v.s. Frame Rate

$@1.7 \times 10^9\ \mathrm{p/cm^2}$(5 – 6 years)



Summary and Future

Summary

- In this study, radiation tolerance tests were conducted on pnCCDs equipped with *HiZ-GUNDAM*.
- For four different exposures and arbitrary temperatures (-90°C to -20°C), the range of frame rates over which a pnCCD can operate with lower detectable energy = 0.4 keV requirement was investigated.
- The results show that *HiZ-GUNDAM* can operate with lower detectable energy = 0.4 keV for the mission duration.

Future

Starting with thermal design and electrical system considerations, operating temperatures and frame rates will be discussed.

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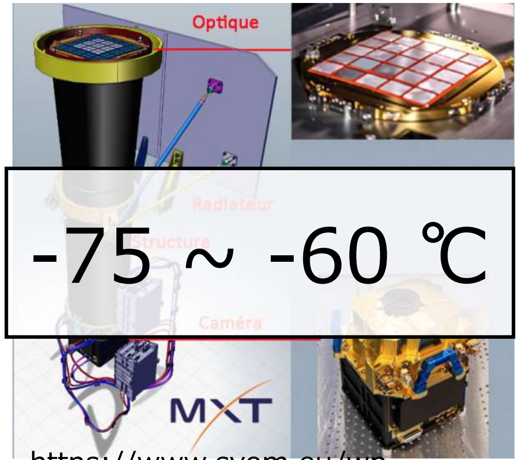
APPENDIX

Achievements of pnCCD in Spacecrafts

SRG/eROSITA(Germany)

https://heasarc.gsfc.nasa.gov/docs/srg/erosita/inc/erosita_banner.png

SVOM/MXT(France)



https://www.svom.eu/wp-content/uploads/2021/06/4922_5-1024x926.jpg

XMM-Newton(Europe)

http://sci.esa.int/xmm-newton/18015-xmm-newton-spacecraft/

Einstein Probe/FXT(China)

https://ep.bao.ac.cn/ep/cms/files/W020210609570525377403.png

4ページ目の
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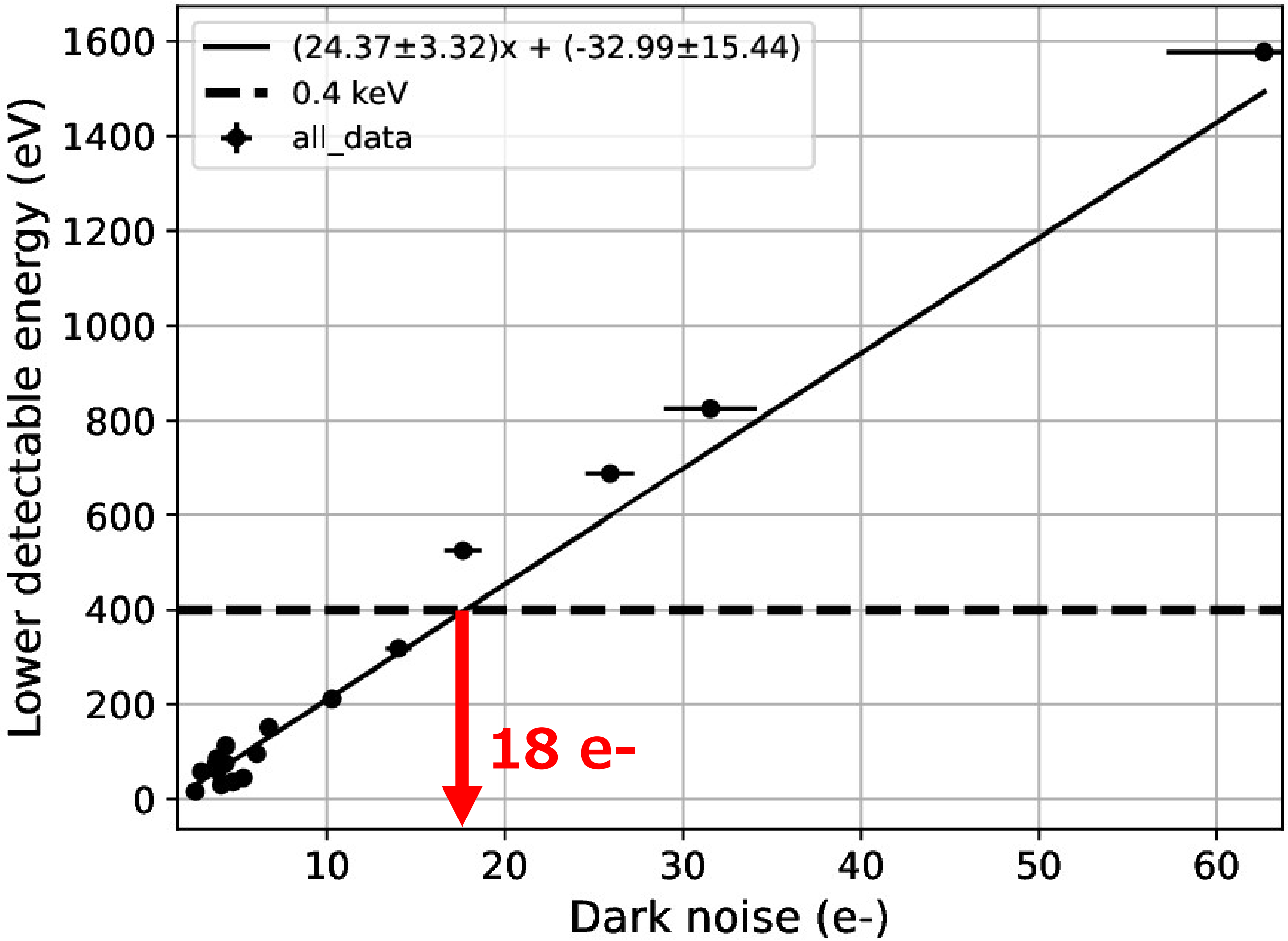
Dark noise v.s. Lower Detectable Energy



HiZ-GUNDAM Requirement: 0.4 keV

11ページ目の
隠れている部分

Dark noise, where lower detectable energy is 400 eV of the required value, is **~18 e-**.

5σにした理由

X線バックグラウンドレート

- HiZ-GUNDAMでは宇宙X線背景放射によるバックグラウンドレートは露光時間を0.1s で

$$\mathbf{0.355\ counts/frame}$$

ノイズ誤検知

- 5σ の有意度で信号を検出する場合、ノイズ成分を信号 として誤検出する確率が、

$$3 \times 10^{-5}\mathrm{event/s} \times 700^{2}\ \mathrm{pixels/frame}\ \times 0.1\ \mathrm{s} \simeq \mathbf{0.1\ event/frame}$$

ノイズの誤検知率がバックグラウンドレートと同等以下となるため
5σを採用している。

モデル関数の導出

33 HzでのダークノイズとフレームレートのH関係

$$(\text{Dark noise\_@33 Hz}) \propto (\text{Frame rate} = 33\ \text{Hz})^{-1}$$

400 eVを満足するダークノイズとフレームレートの関係

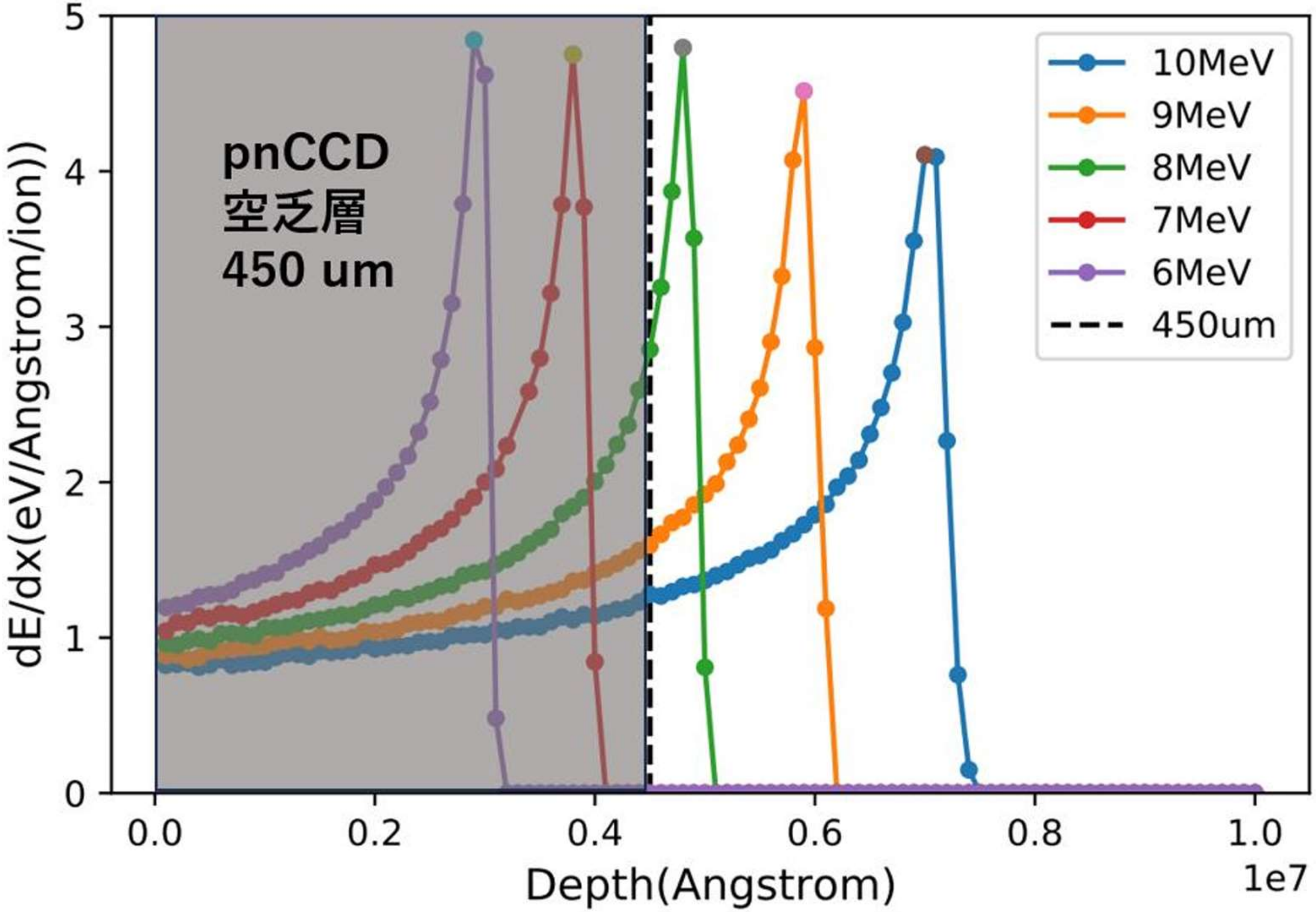
$$(\text{Dark noise\_@400 eV}) \propto (\text{Frame rate\_@400 eV})^{-1}$$

$$\frac{(\text{Dark noise\_@33 Hz})}{\boxed{18\ e^{-}}} \propto \left(\frac{33\ \text{Hz}}{(\text{Frame rate\_@400 eV})}\right)^{-1}$$

最小検出エネルギー=400 eV に対応する目標値

$$(\text{Frame rate\_@400 eV}) \propto (\text{Dark noise\_@33 Hz})$$
$$\propto T^{\frac{3}{2}} \exp\left(-\frac{Eg}{2k_B T}\right)$$

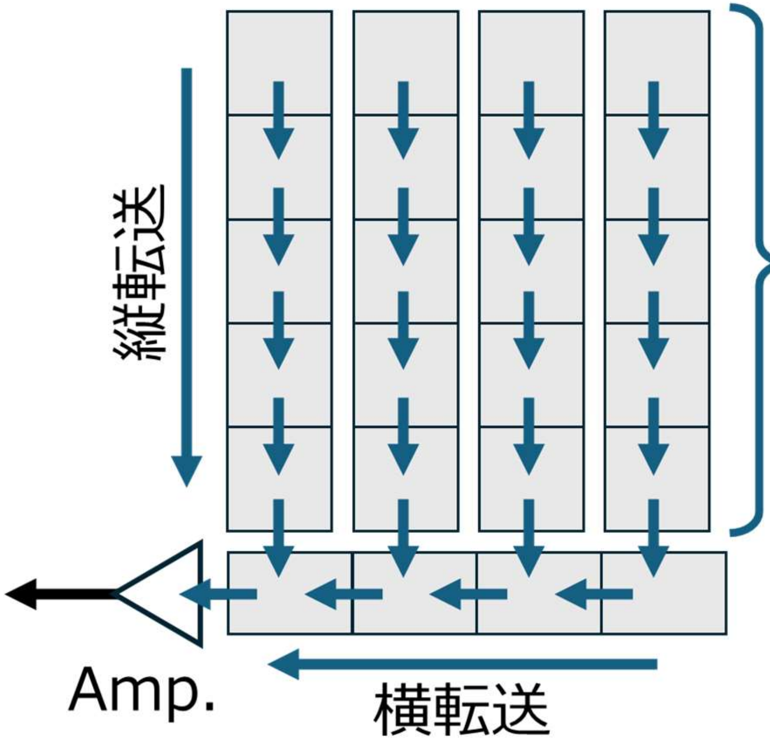
10 MeV陽子線を選んだ理由



一般的なCCDとpnCCDの違い

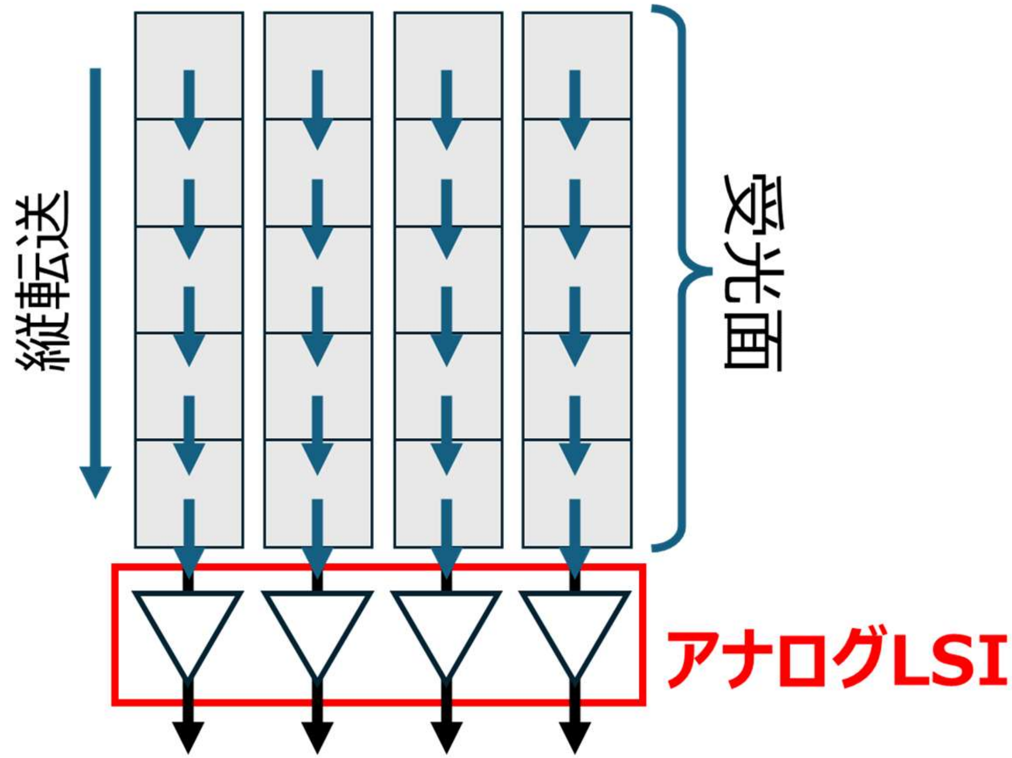
一般的なCCD

1読出しチャネル
→ 遅い (~0.1-1 fps)

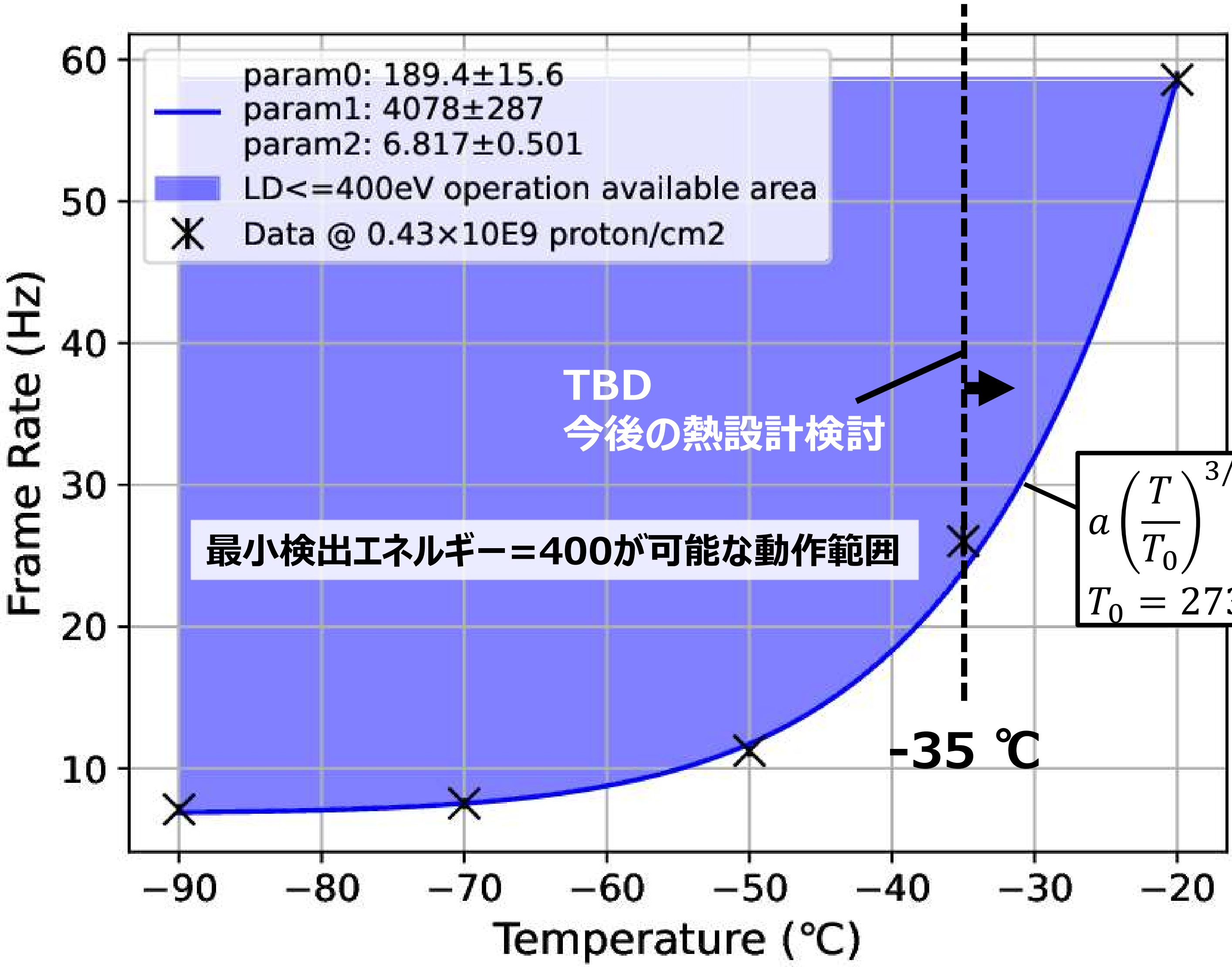


pnCCD

全列に読み出しチャネル
→ **速い！！！（~10-1000 fps)**



温度 v.s. フレームレート@4.3×10^8 p/cm^2(1-2年分)



$$a\left(\frac{T}{T_0}\right)^{3/2} \exp\left[-b\left(\frac{1}{T}-\frac{1}{T_0}\right)\right]+c$$

$T_0 = 273$ K

Temperature v.s. Frame Rate

$@1.7 \times 10^9\ \mathrm{p/cm^2}$(5 – 6 years)