Development of the grade selection of X-ray events using machine learning for a CubeSat application

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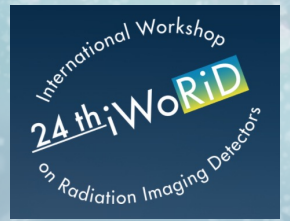
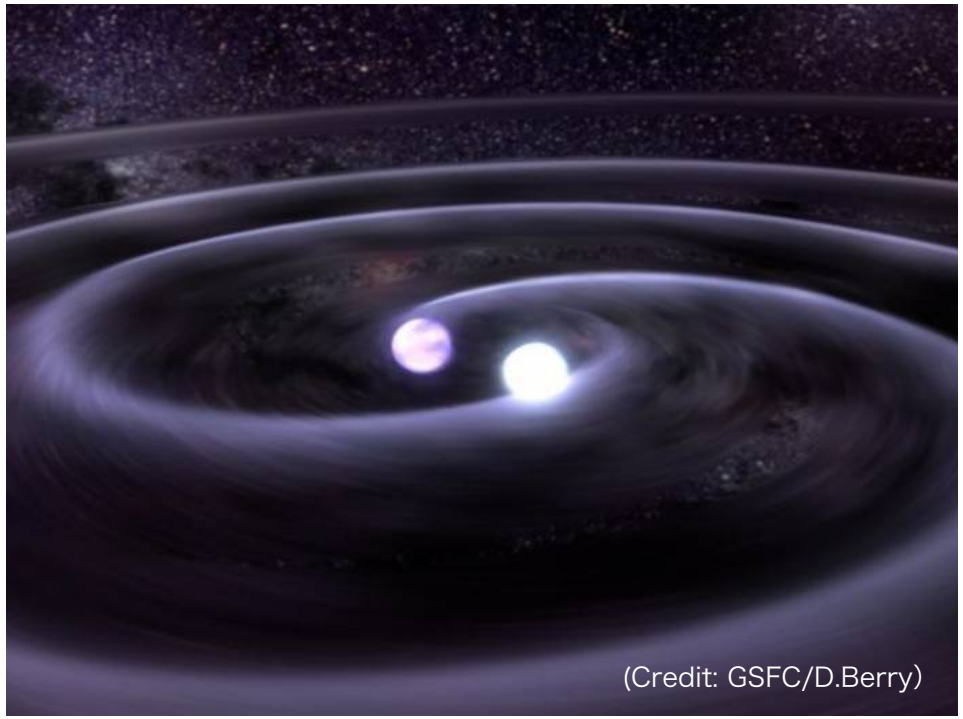
Naoki Ogino, Makoto Arimoto (Kanazawa U.)



Oslo Science Park (25 ~ 29 June 2023)

Binary star merger



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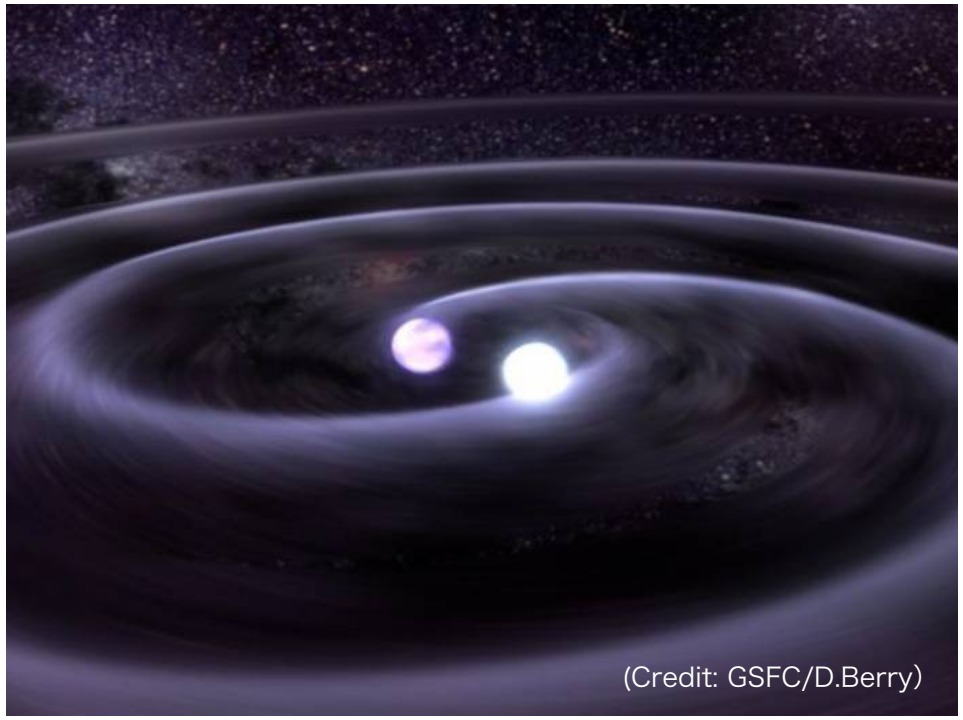
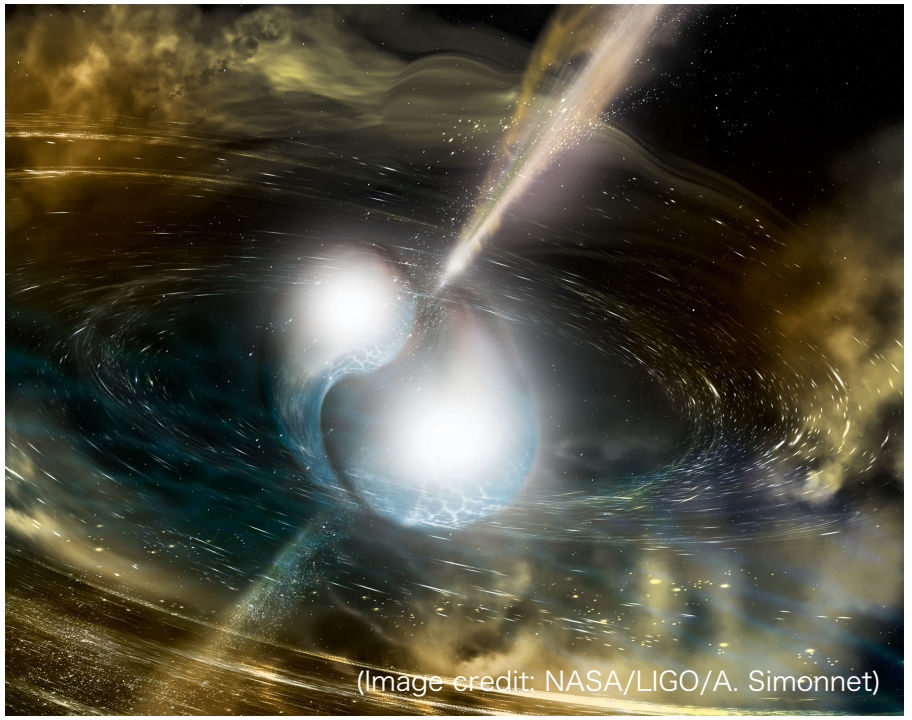
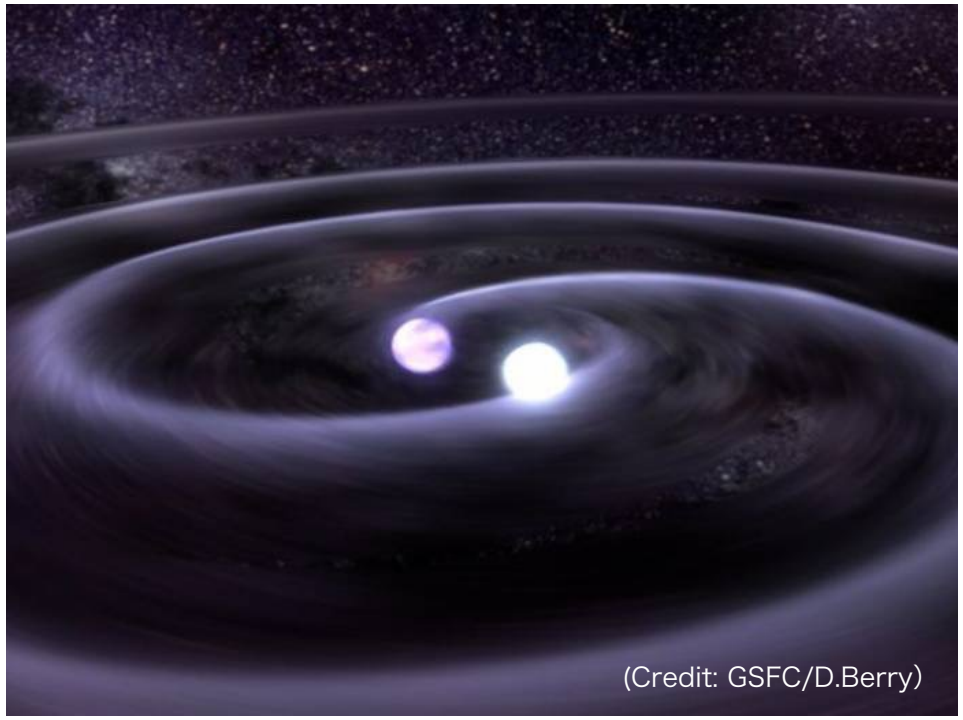


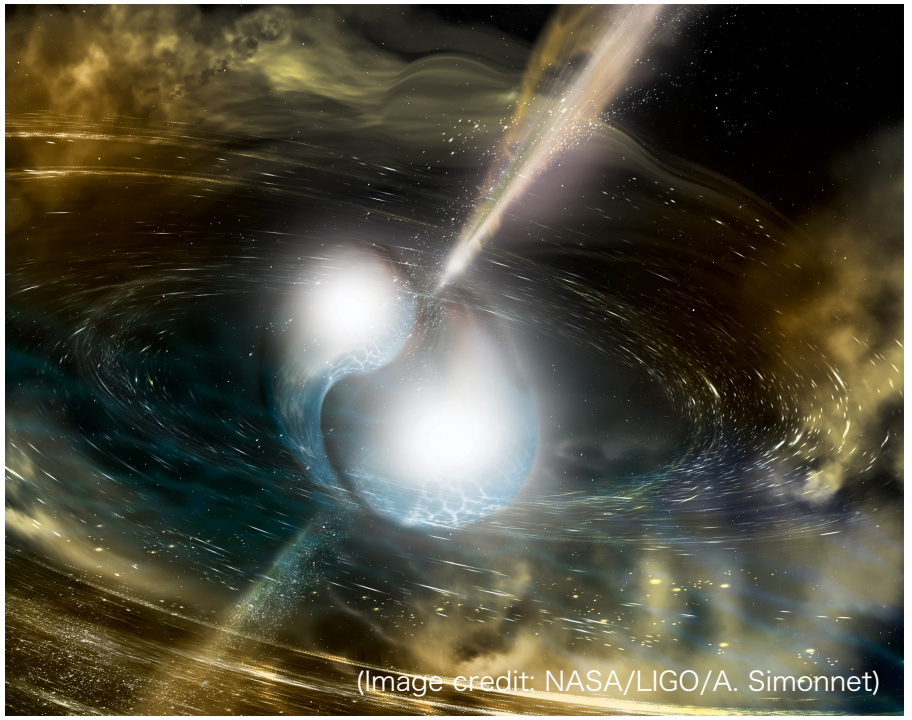


Key Science

- High energy phenomena associated with Gravitational wave (GW)
- The birth of black holes

Binary star merger





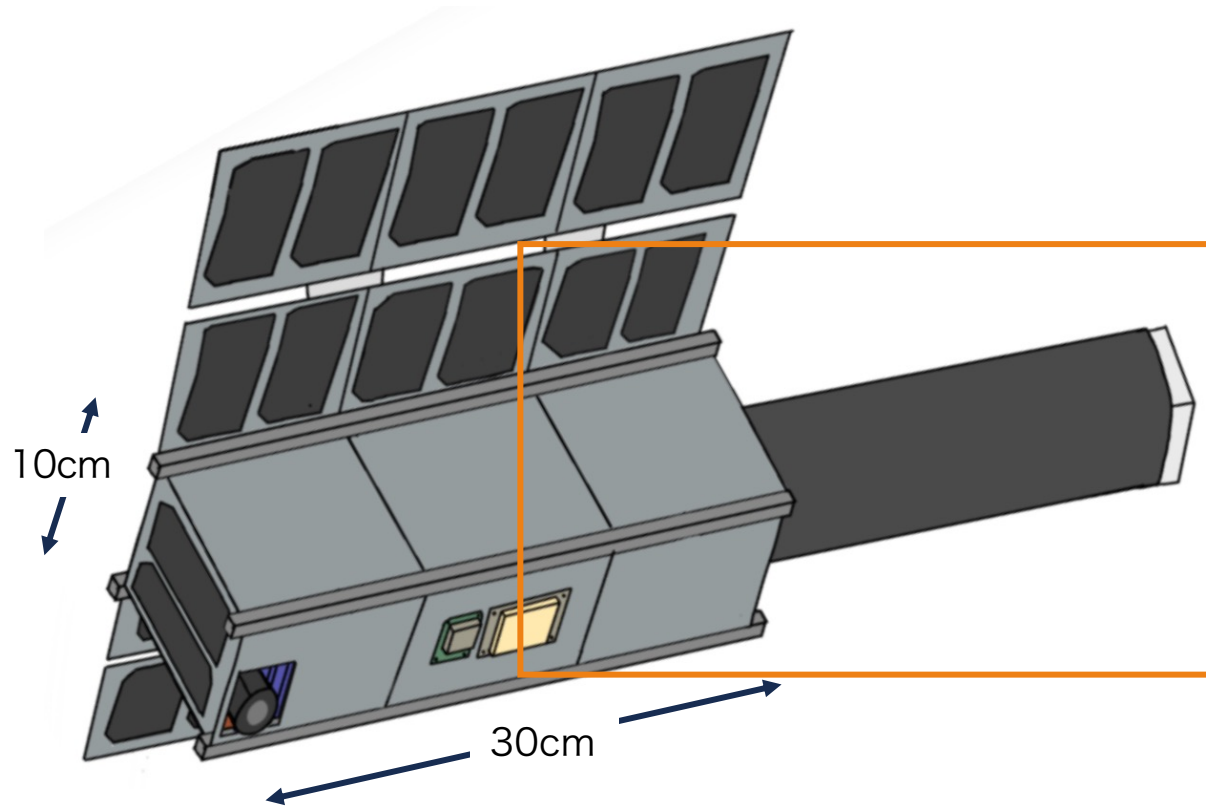
Key Science

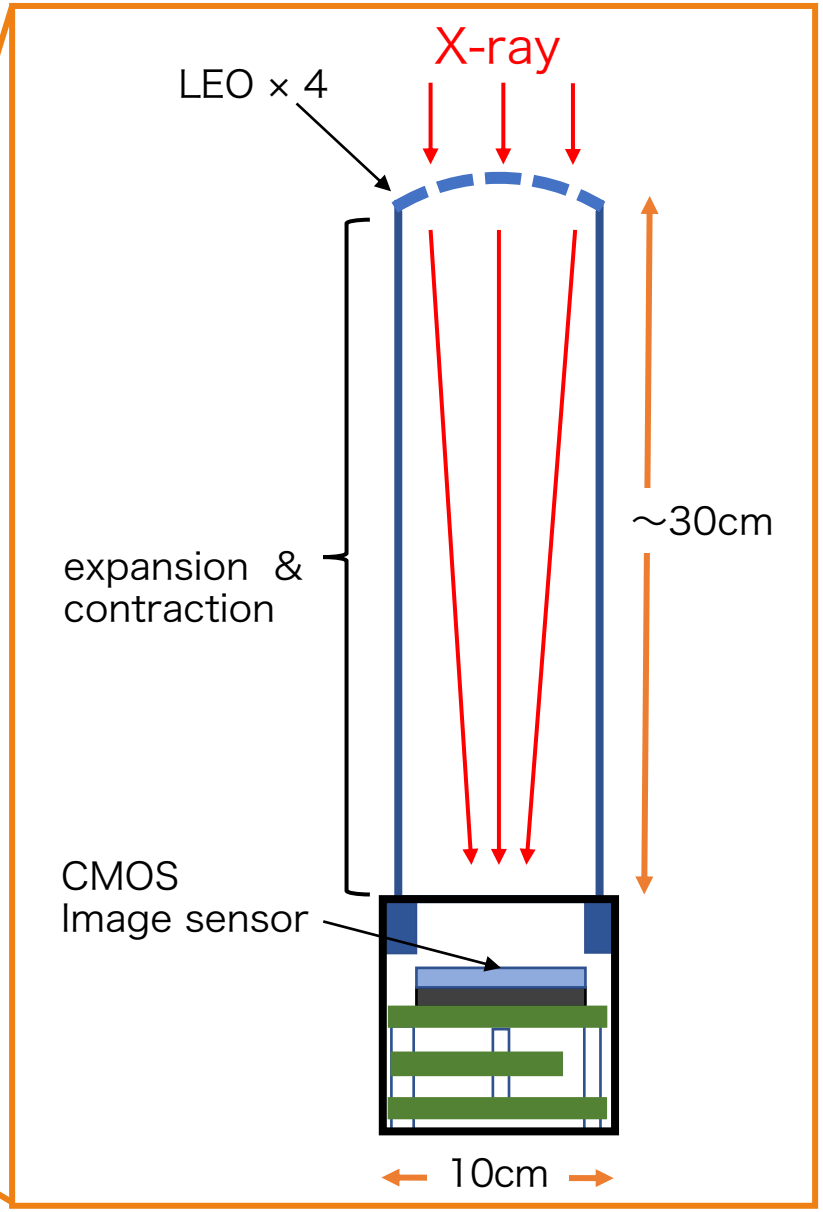
- High energy phenomena associated with Gravitational wave (GW)
- The birth of black holes

To explore this phenomena …
We need a space observatory
with wide FoV & high sensitivity

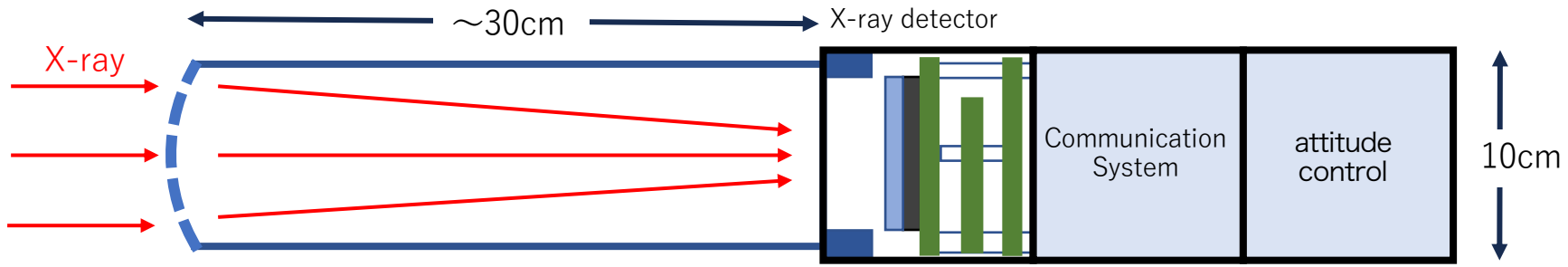
SEAGULL (SEArching origin of Gravitational wave by 3U SateLLite)

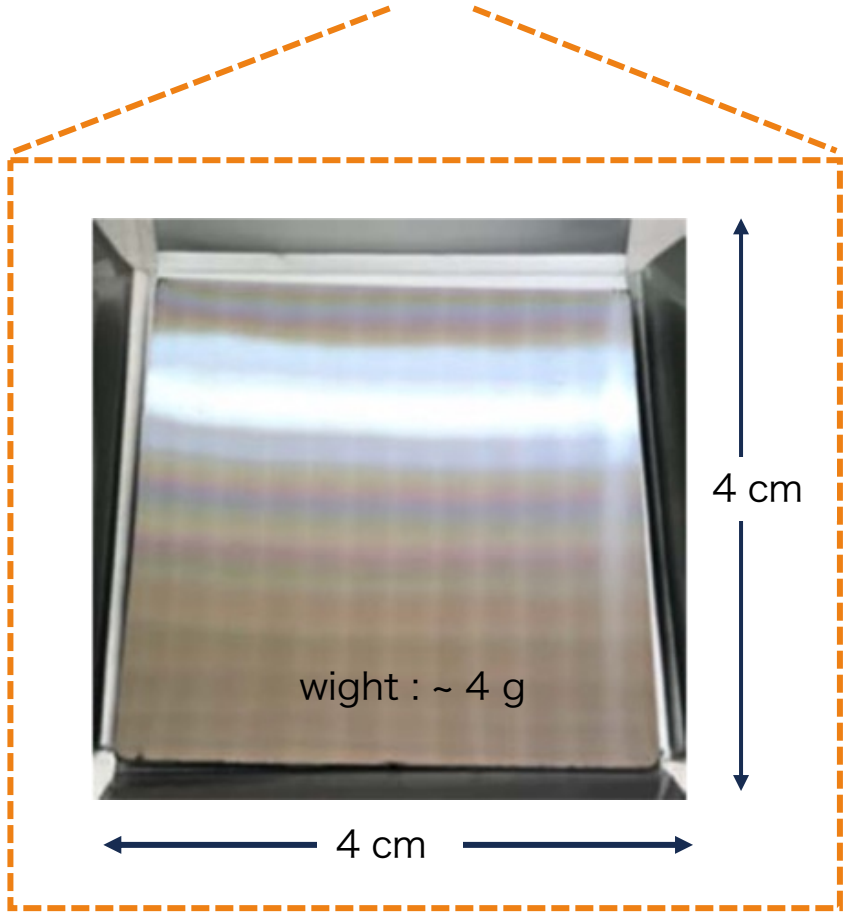
- 4 Lobster-eye optics (LEO) + 1 CMOS image sensor
- Soft X-ray band : 0.4 ~ 4.0 keV
- Field of view : 64 deg^2
- Automatic attitude control

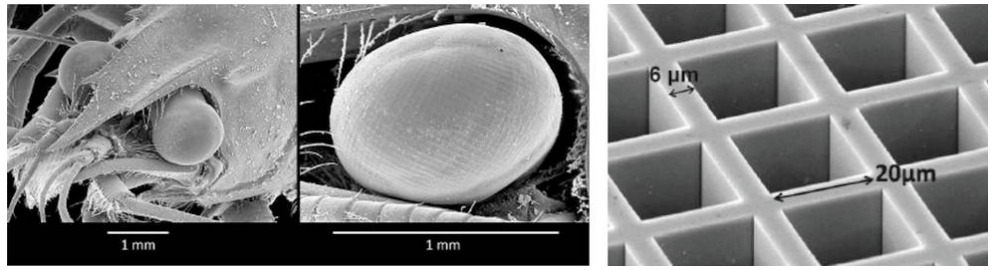


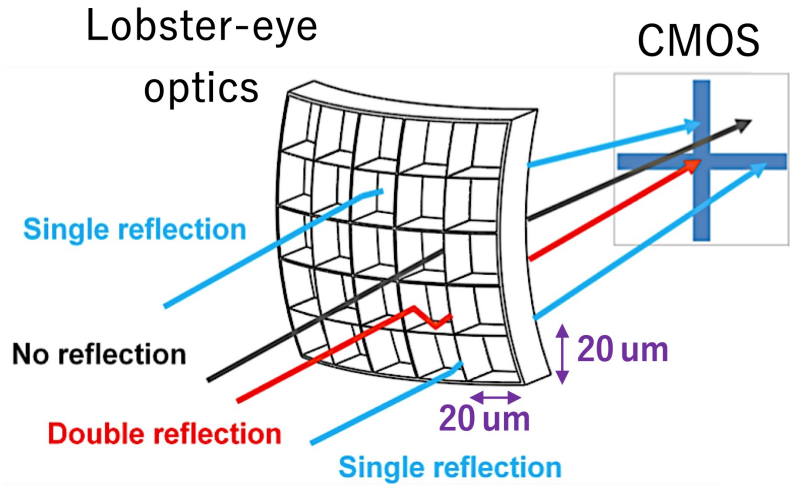


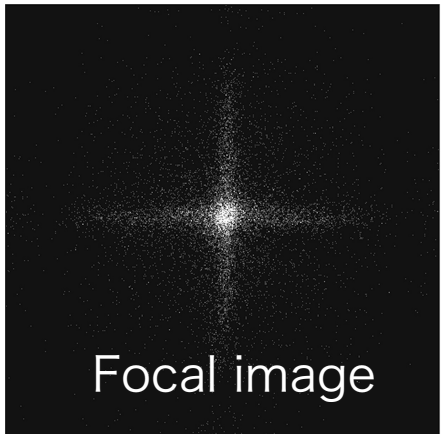
Lobster-eye optics (LEO)



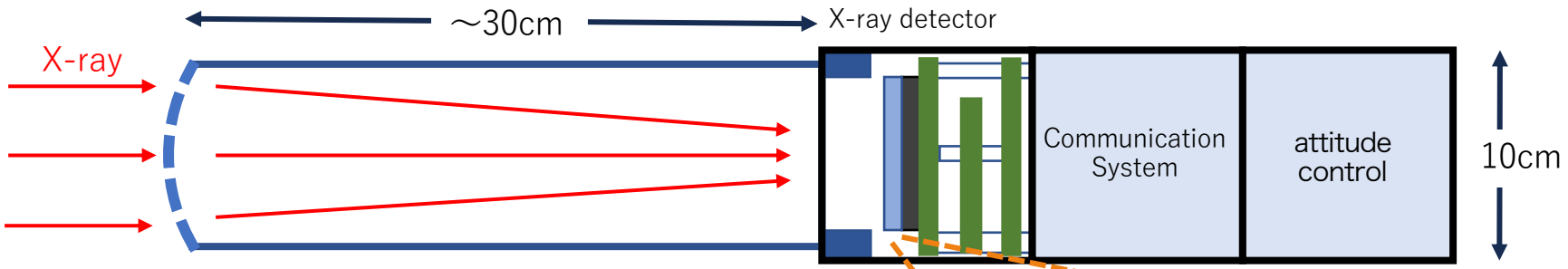






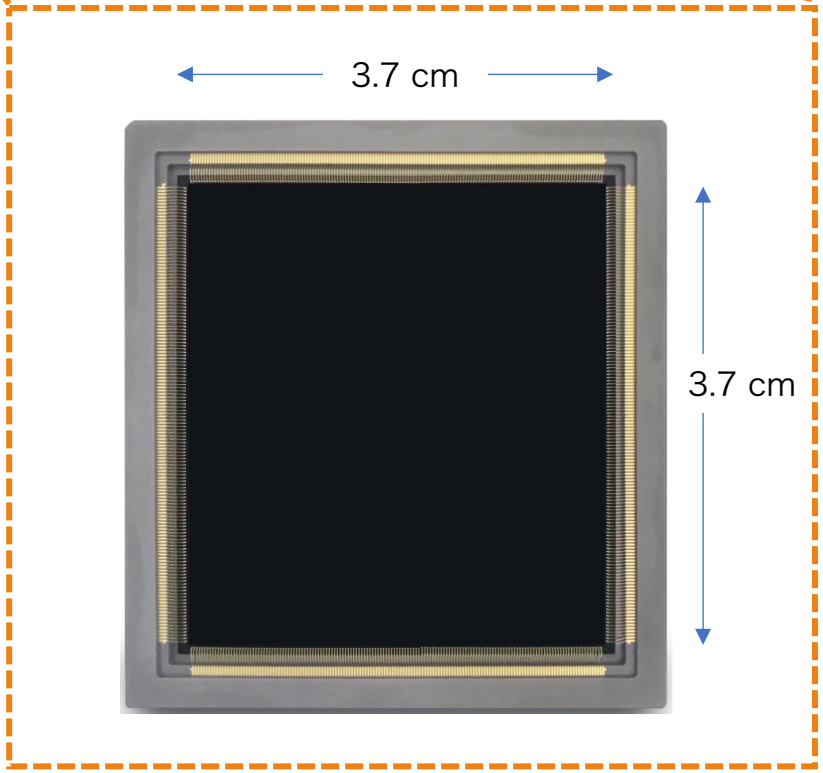


CMOS Image Sensor

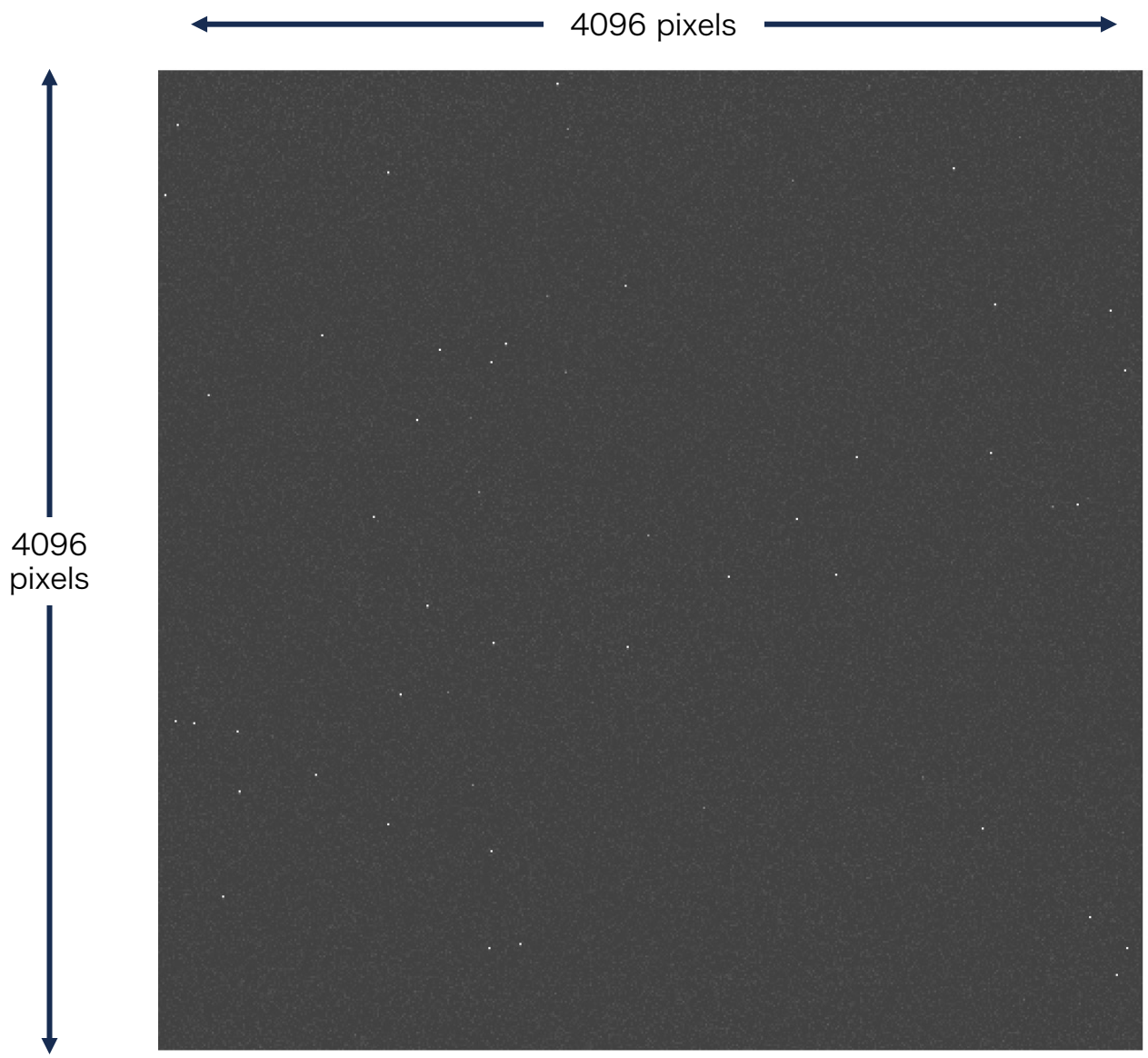


- Back Side Illuminated type CMOS
- Performance verification

Gpixel.Inc GSENSE 4040BSI	
Active image size	36.9 x 36.9 mm^2
Pixel size	9 μm x 9 μm
Number of pixels	4096 (H) x 4096 (V)
Power consumption	< 1.4 W
Frame Rate	24 fps(max)



^{55}Fe X-ray Image



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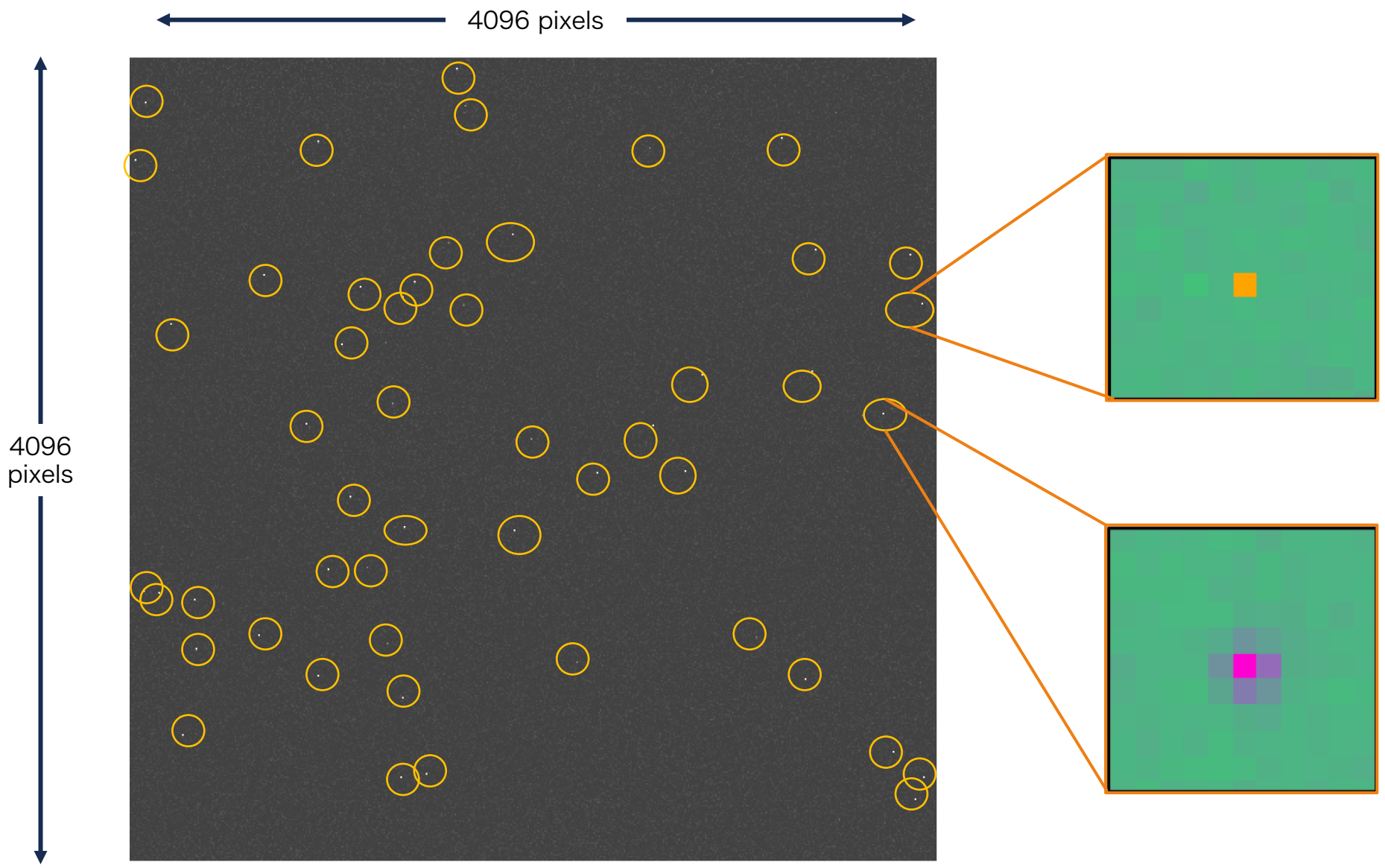
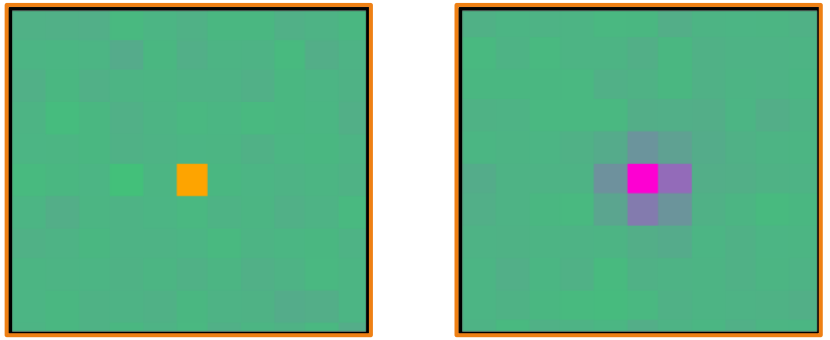


X-ray Observation in Astronomy

- Only few X-ray photons / 1 sec.
- 1 X-ray photon = 1 X-ray event
- We want the time, energy, and location information of X-ray events

X-ray events



Problem

- Image data is too large
- Remove the background noise like cosmic ray

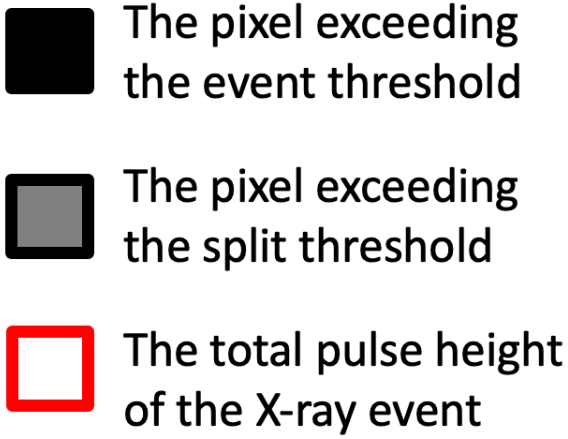
➡ How to extract the X-ray events from the image ?

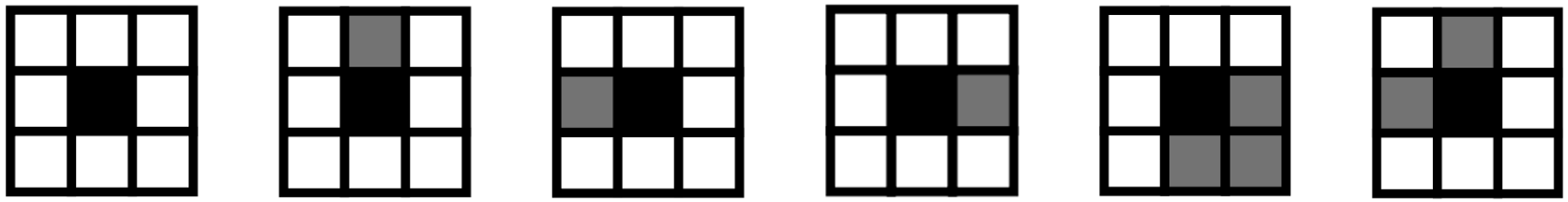
Grade discrimination method (GDM)

- Two types of thresholds : an event threshold and a split threshold.
- All the pixel values which exceed two thresholds in 3×3 pixels are summed up to obtain the total deposit energy.

10	7	4	0	7
5	13	5	0	7
0	0	3287	0	0
0	3	0	3	2
0	2	0	1	0

18	-9	-5	0	5
16	21	37	9	10
13	28	1490	220	4
-11	9	493	135	-3
-5	-3	-6	-15	-7





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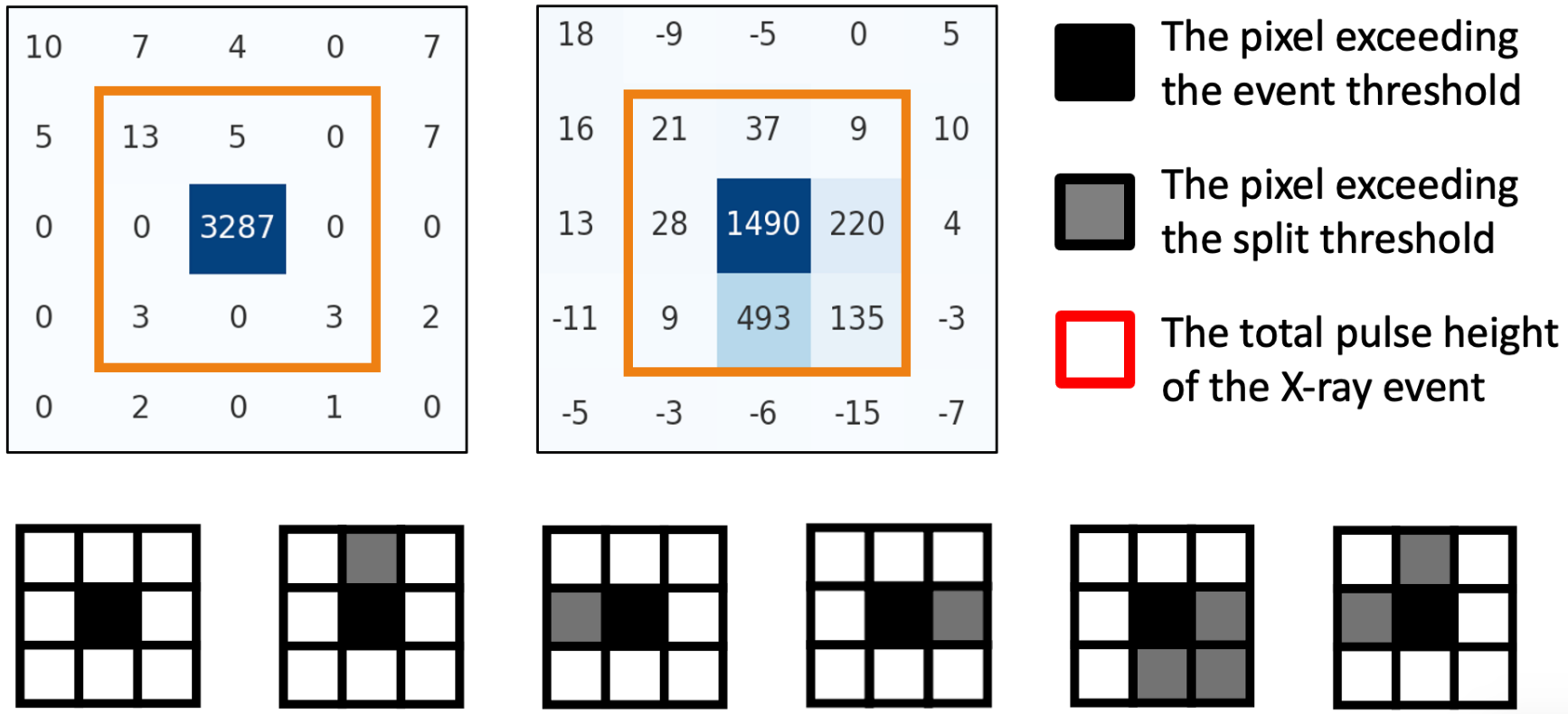

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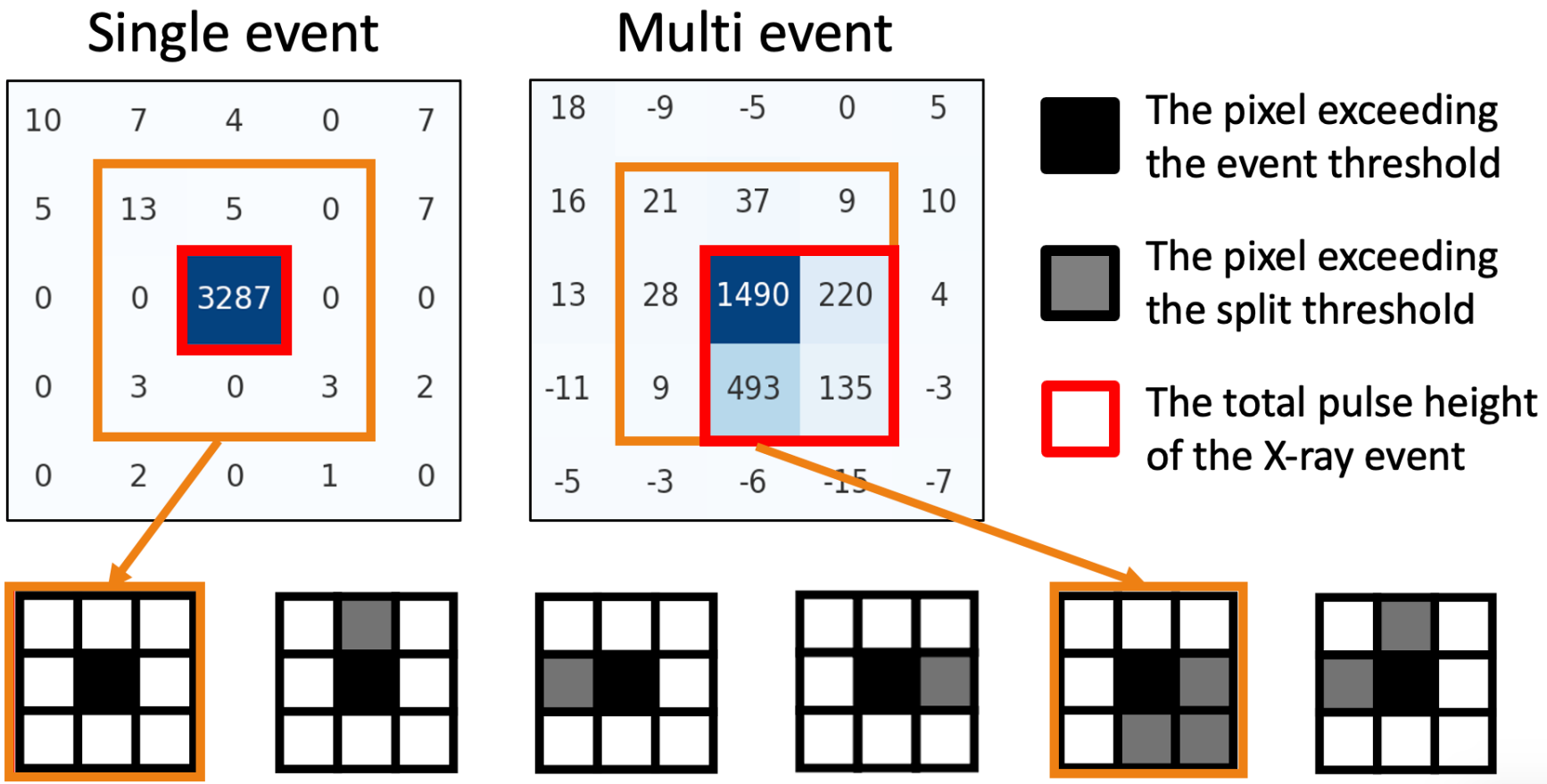


Machine learning method (MLM)

- GDM is unable to discriminate charged particles such as cosmic rays

X-ray events

23	15	11
16	1702	664
-4	95	56

21	37	9
28	1490	220
9	493	135

-18	0	-3
51	1573	22
37	499	10

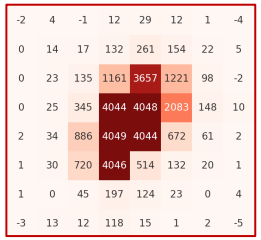
43	268	9
7	1532	32
-15	-10	0

-29	-13	1
-3	2550	7
-9	7	42

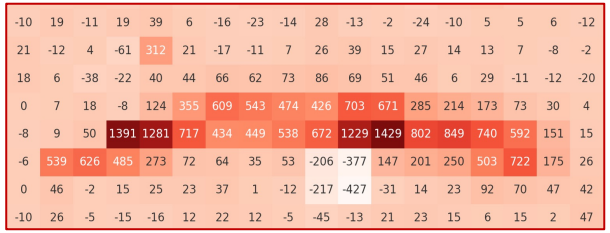
119	91	4
859	1383	-12
22	8	13

Charged particle events

α particle



Proton



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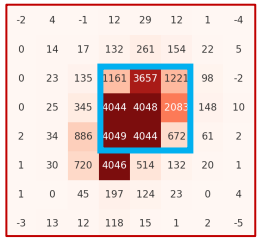

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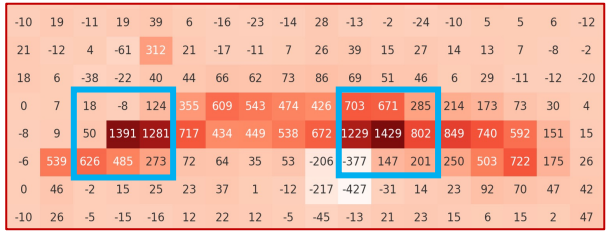

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Charged particle events

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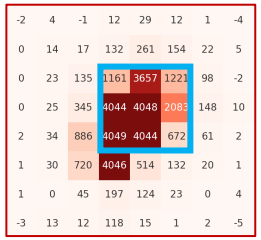

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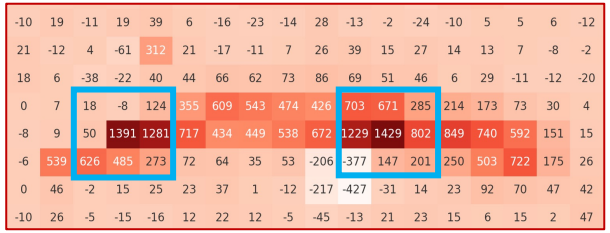
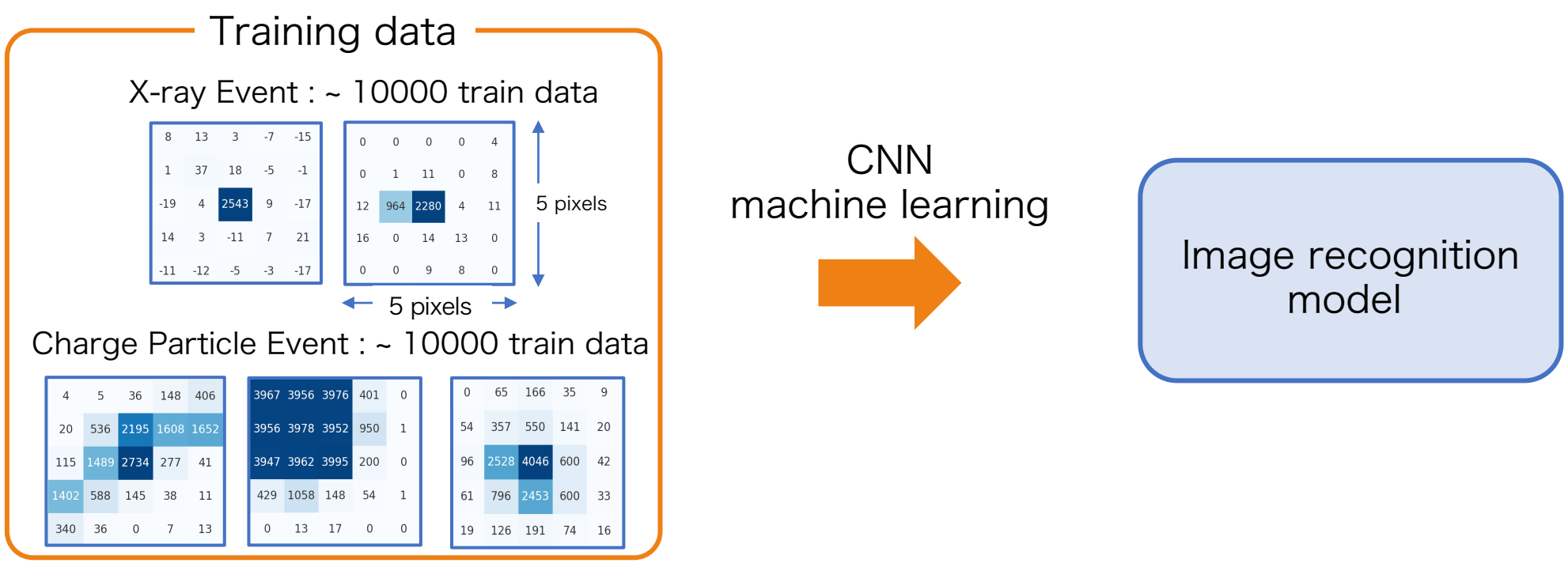


β particle

Utilize one of the machine learning models of convolutional neural network (CNN) to identify X-ray events & charged particle events.

Machine learning method (MLM)

① Train an image recognition model with the data of X-ray events & charged particle events.



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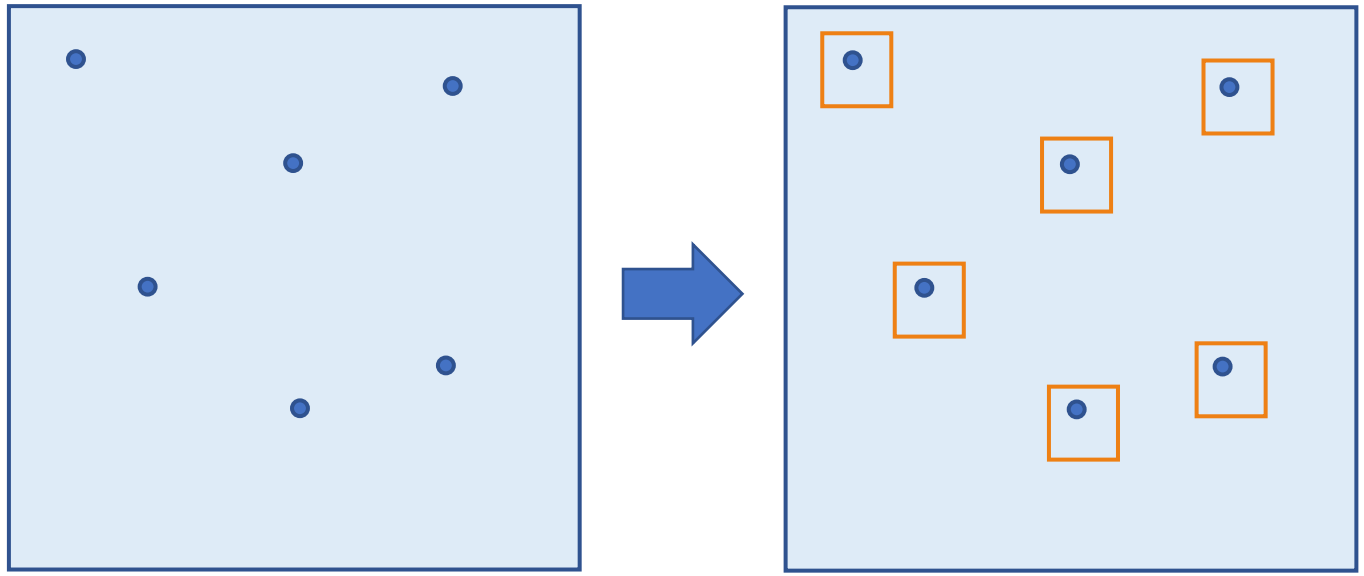
① Train an image recognition model with the data of X-ray events & charged particle events.
② Use a threshold identifies a center pixel of X-ray from the image.



Machine learning method (MLM)

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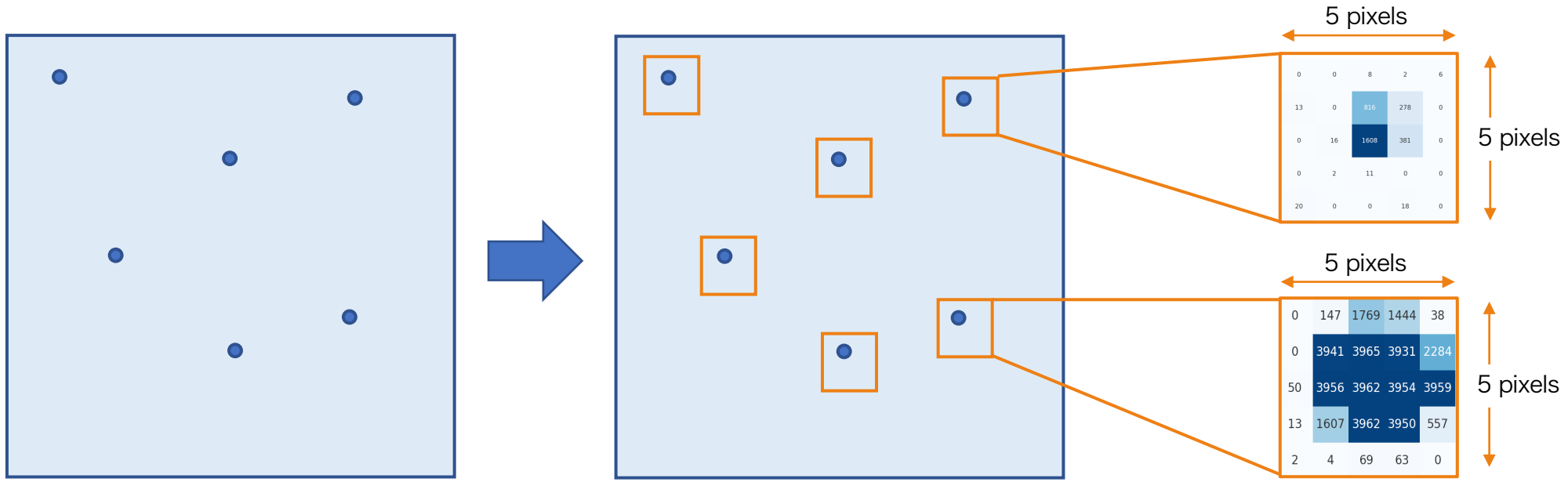
② Use a threshold identifies a center pixel of X-ray from the image.
③ Clip adjacent 5×5 pixels around the center pixel and recognize this range by the machine learning model.



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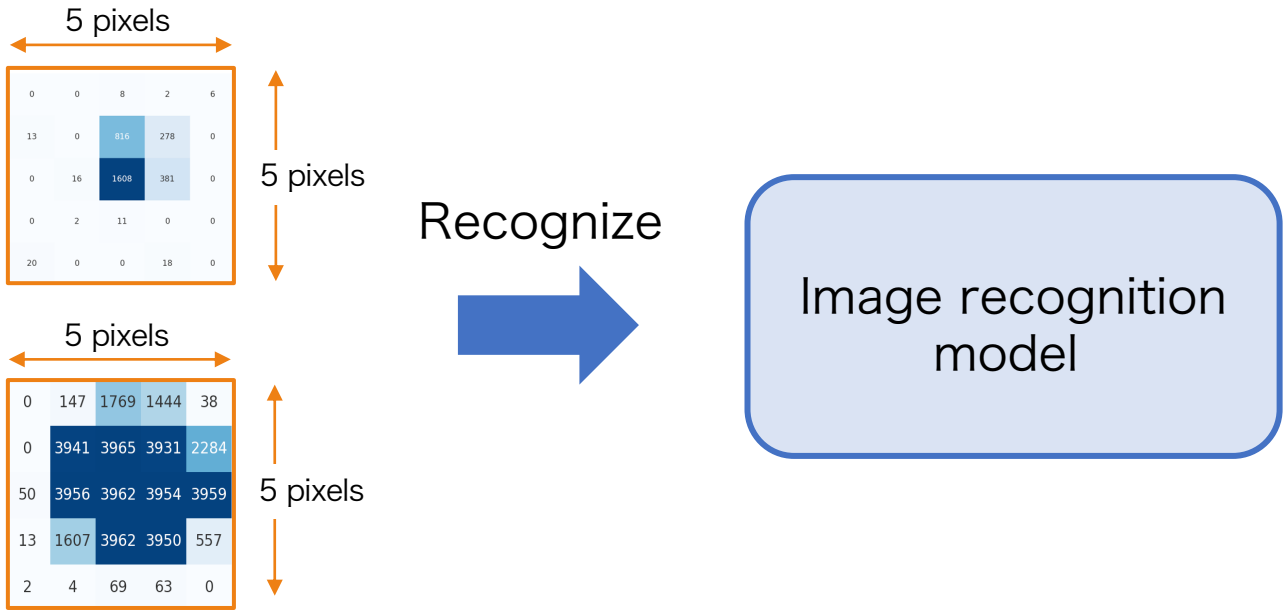
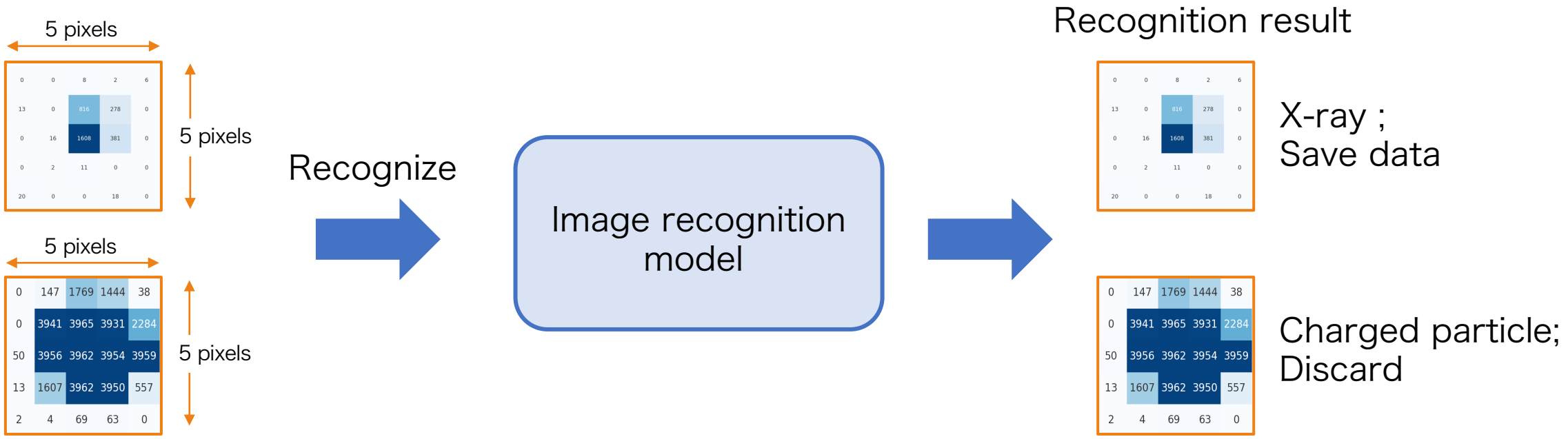


Machine learning method (MLM)

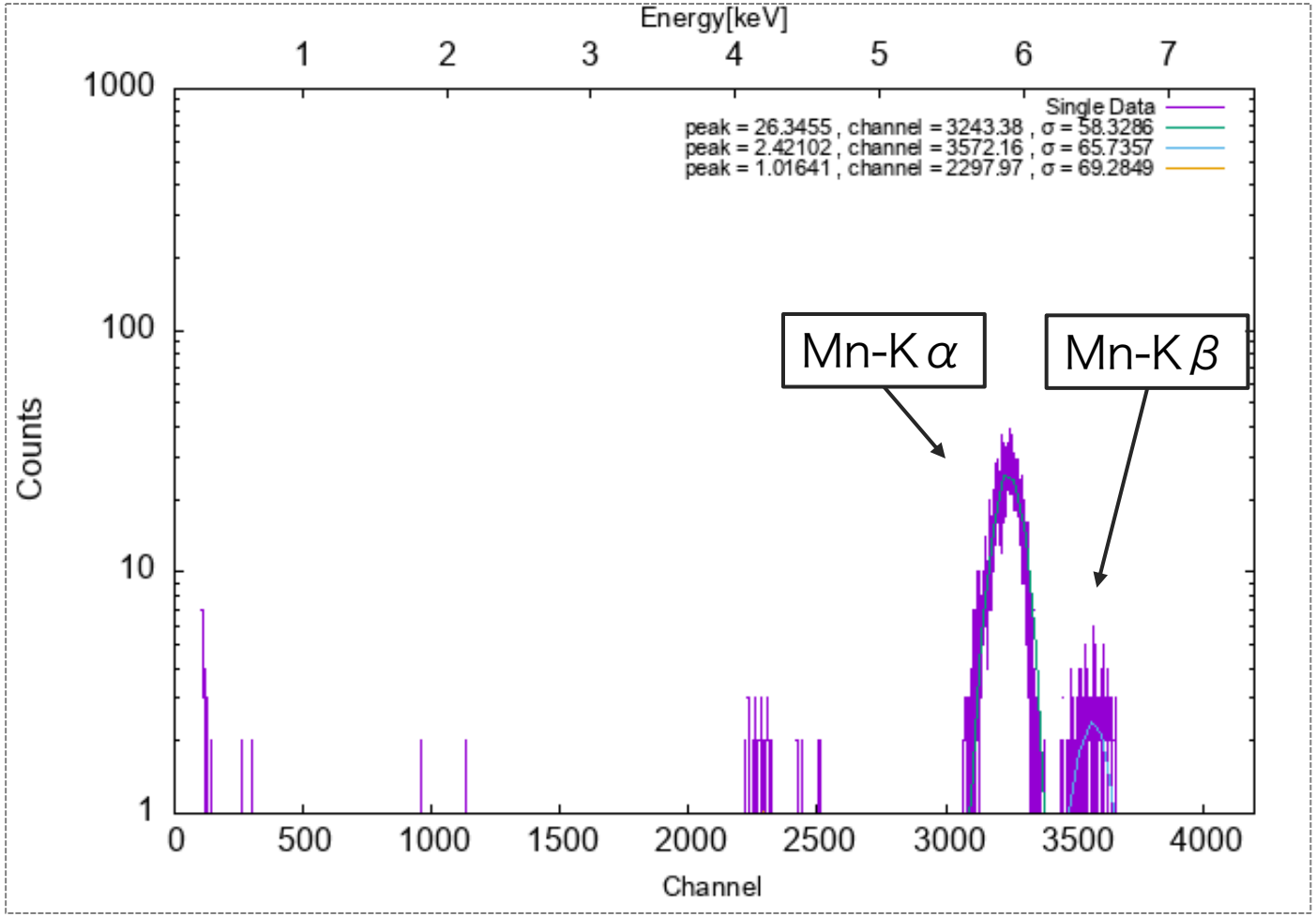
① Train an image recognition model with the data of X-ray events & charged particle events.
② Use a threshold identifies a center pixel of X-ray from the image.
③ Clip adjacent 5×5 pixels around the center pixel and recognize this range by the machine learning model.
④ If the event is categorized as an X-ray, the data will be saved. On the contrary, the data will be discarded.



^{55}Fe Spectrum

Check the X-ray extraction performance

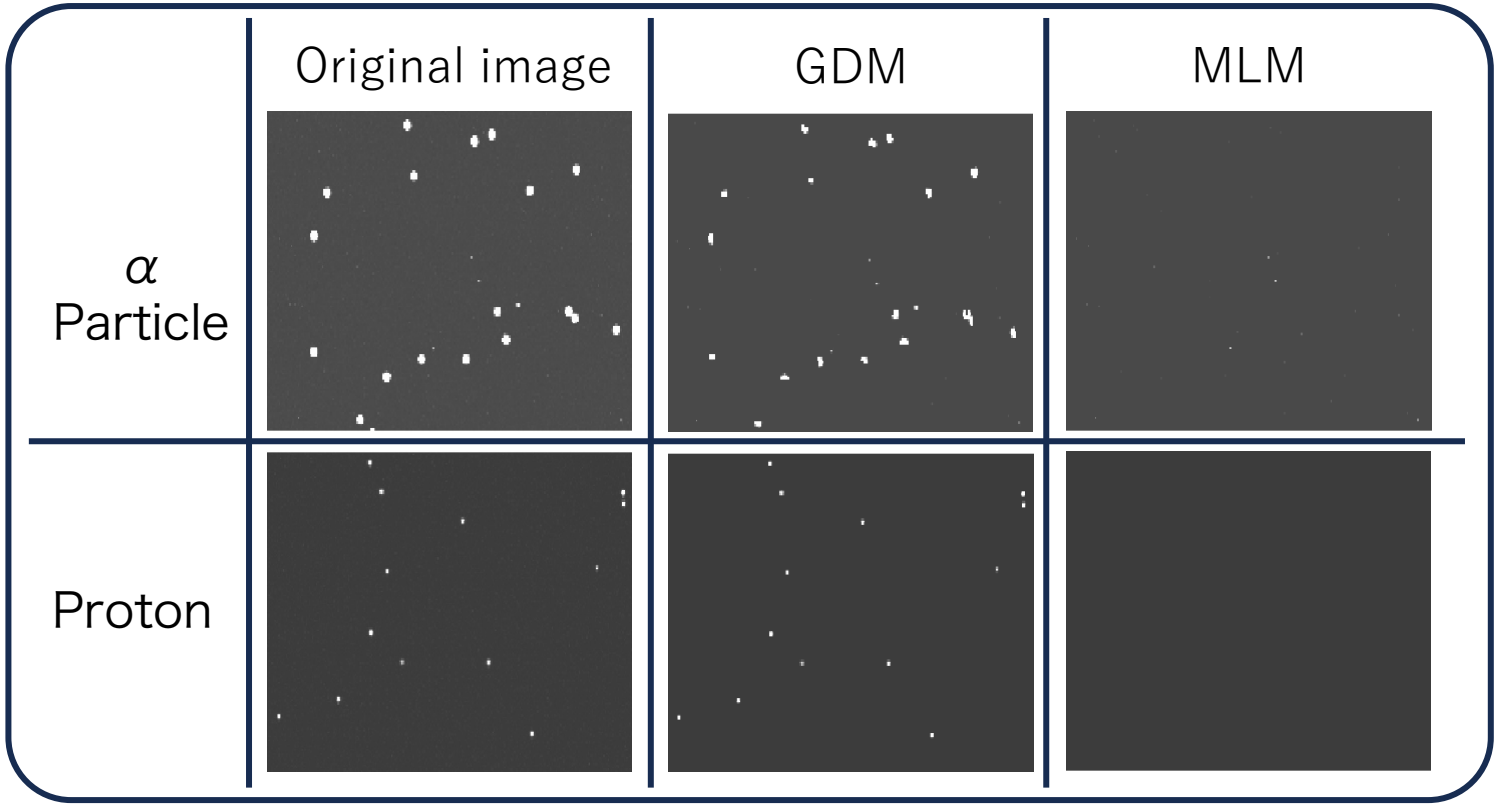
- CMOS pixels : 4096 (H) x 4096 (V)
- Processing speed : 0.71 s/frame
- Energy Resolution
  - Mn-Kα : 241.2 eV @ 5.89 keV
  - Mn-Kβ : 258.9 eV @ 6.49 keV



MLM can extract the X-ray events in high speed

The judgment accuracy of charged particles

- Identify the charged particles event from the image data using both the GDM & the MLM.
- Create an event map based on the location information of the event.



The accuracy for recognizing charged particles:

- α particles : ~ 100%
- Proton : ~ 98 %

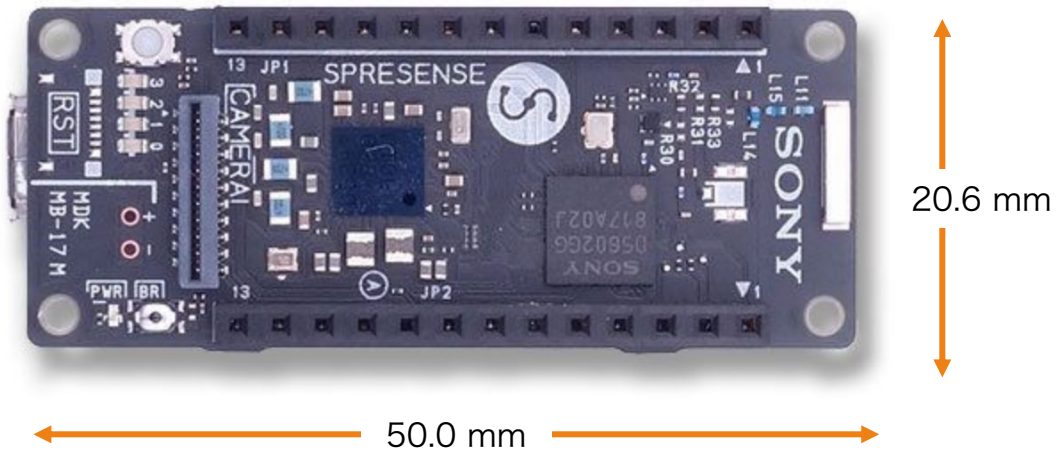
The charged particle events could be recognized and removed from the event map by using the MLM.

How to install MLM on a CubeSat ?

Spresense

- Sony's single-board computer
- Low power consumption
- Compact size
- Machine learning support library
- Space qualified : Adopted by JAXA's RAISE-2 mission (2021)

Spresense	
Size (Main board) Size (Extension board)	50.0 mm × 20.6 mm 68.6 mm × 53.3 mm
Typical Operating Power	100 mW (Main Board:30 mW)
processor	ARM®Cortex®-M4F × 6 cores
Clock speed	156 MHz
RAM	1.5 MB
FLASH	8 MB

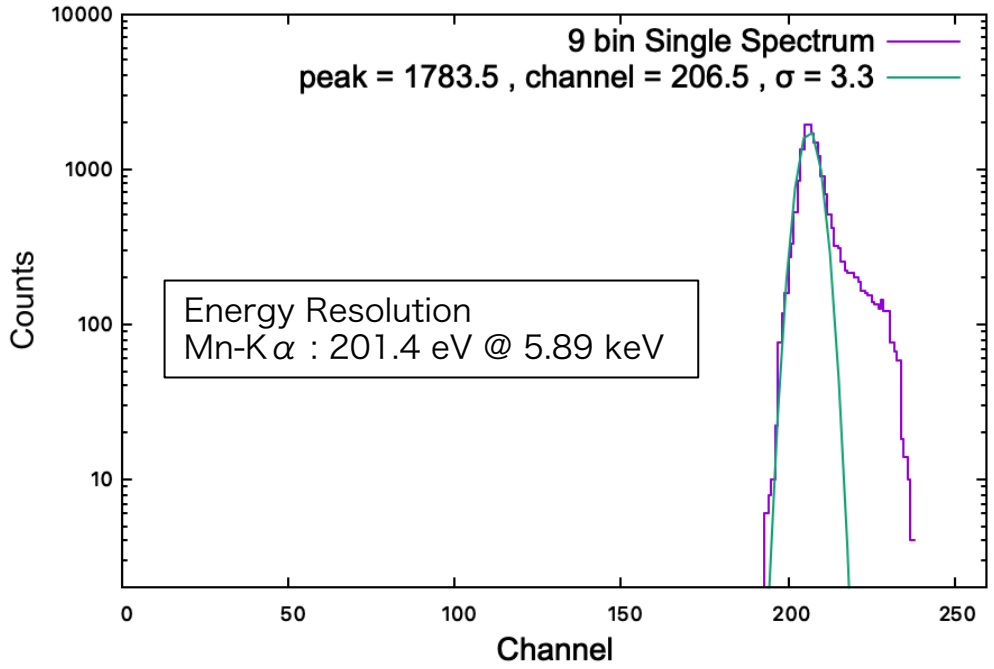


Implement the MLM in Spresense

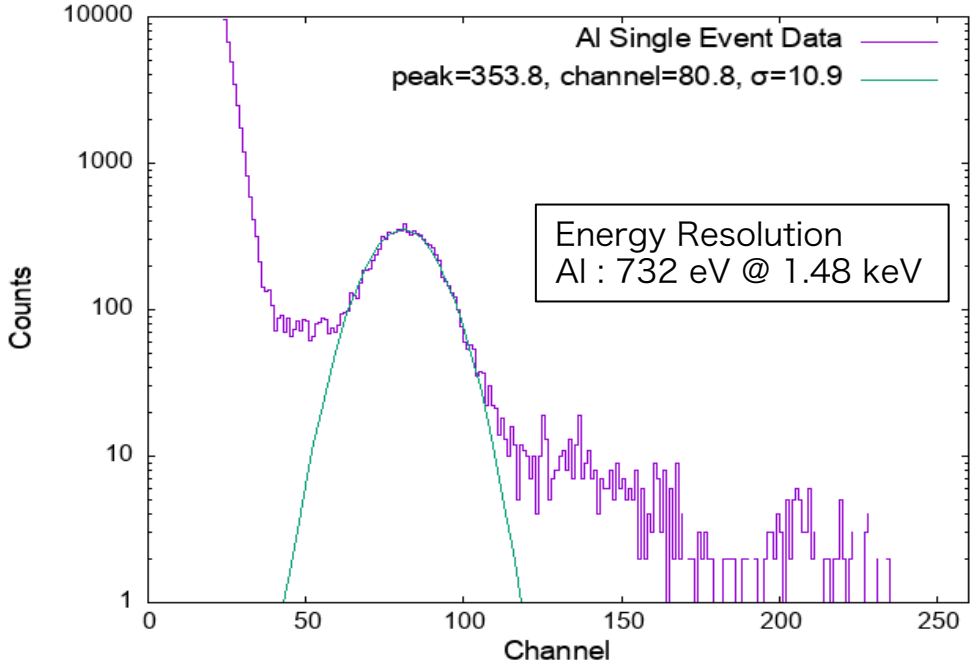
- 1.5 Mbyte RAM limit
- Compressed ADU : 12 bit → 8 bit
- Binning the pixels : 4096^2 pixels → 456^2 pixels

- X-ray lines were clearly detected
- Operating speed was about 3 s/frame.

^{55}Fe (5.9 keV & 6.5 keV) spectrum



Al (1.5 keV) spectrum



Summary

- SEAGULL will explore the origin of GW events in soft X-ray band.
- MLM can identify X-ray events & charged particle events
- High processing speed
- We implement MLM in Spresense.