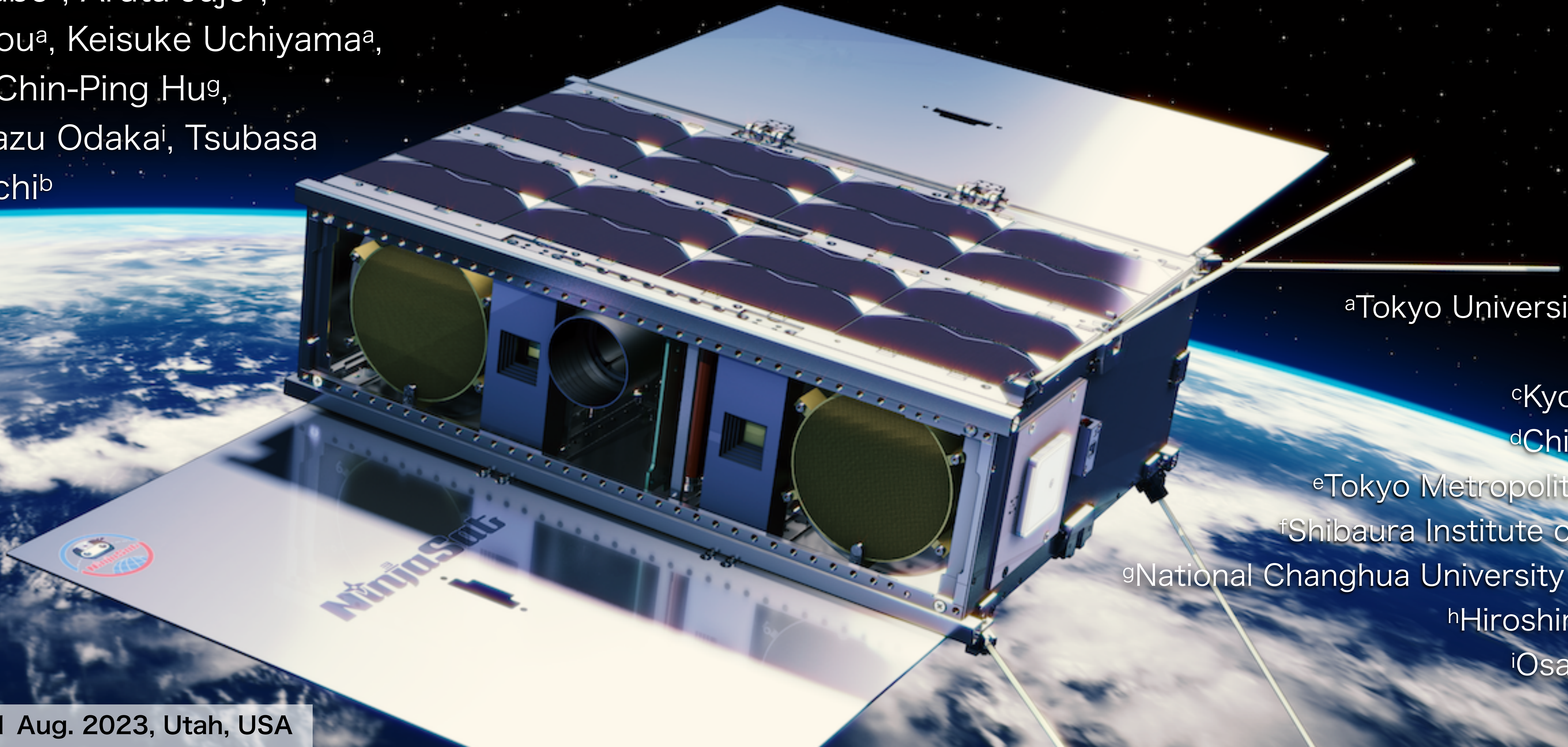
Development of Gas Multiplier Counters (GMCs) onboard the 6U CubeSat X-ray Observatory NinjaSat

SSC23-WIII-01

Tomoshi Takeda[a], Toru Tamagawa[b], Teruaki Enoto[c], Takao Kitaguchi[b], Yo Kato[b], Tatehiro Mihara[b], Wataru Iwakiri[d], Masaki Numazawa[e], Naoyuki Ota[a], Syoki Hayashi[a], Sota Watanabe[a], Arata Jujo[a], Amira Aoyama[a], Yuanhui Zhou[a], Keisuke Uchiyama[a], Yuto Yoshida[a], Hiroki Sato[f], Chin-Ping Hu[g], Hiromitsu Takahashi[h], Hirokazu Odaka[i], Tsubasa Tamba[j], and Kentaro Taniguchi[b]



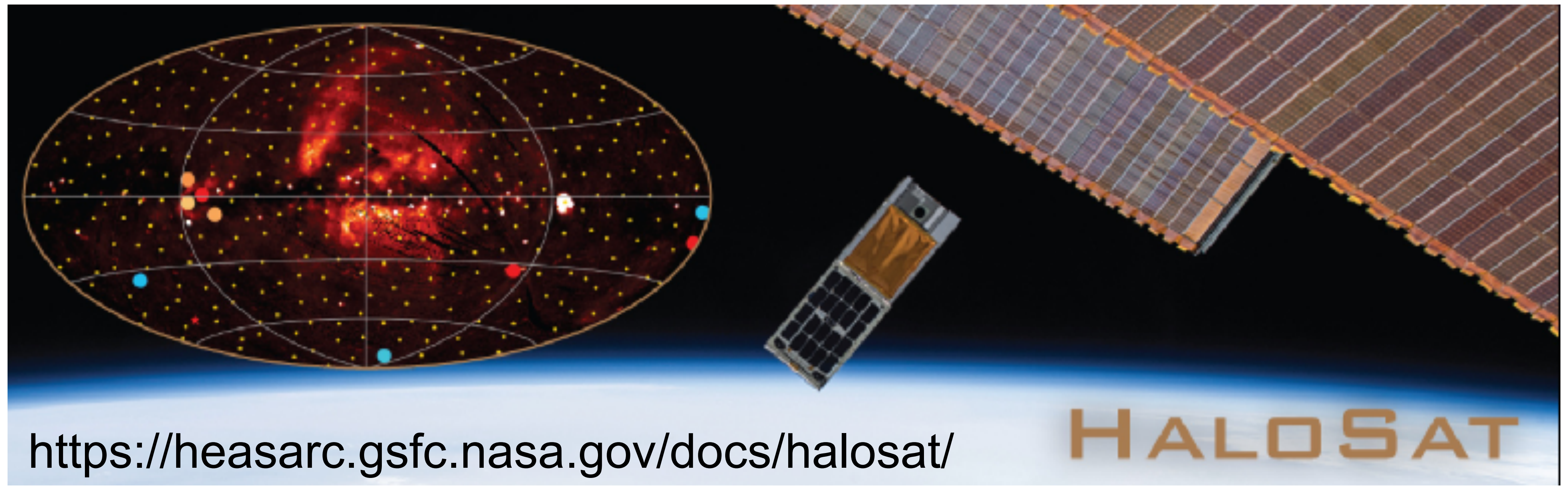
[a]Tokyo University of Science
[b]RIKEN
[c]Kyoto University
[d]Chiba University
[e]Tokyo Metropolitan University
[f]Shibaura Institute of Technology
[g]National Changhua University of Education
[h]Hiroshima University
[i]Osaka University
[j]ISAS/JAXA

Small Satellite Conference 2023, 5–11 Aug. 2023, Utah, USA

Advantages of CubeSat in X-ray Astronomy

- **Cost and time effective means for X-ray astronomy**
  - X-rays from celestial objects are attenuated by the atmosphere.
  - Observations have to be performed in space.
- **Flexibility in observation planning**
  - For large satellites, the obs. time is shared among many users → limited for each object
  - In contrast, CubeSat can conduct a more flexible program (e.g, long-term obs.)

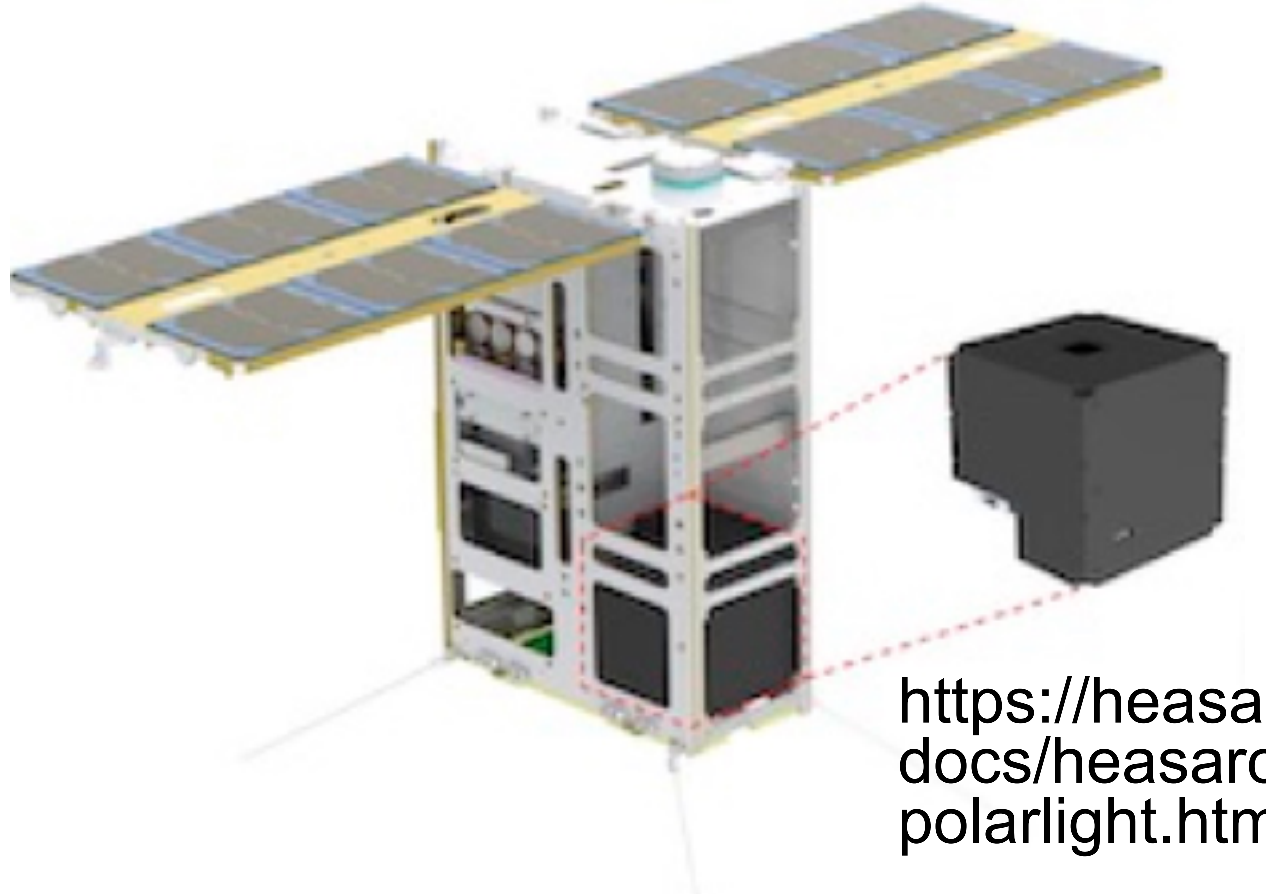
HaloSat (Kaaret et al. 2019)



https://heasarc.gsfc.nasa.gov/docs/halosat/

Examples of successful CubeSat missions
- HaloSat
  - Spatial distribution of hot gas in the Milky Way
- PolarLight
  - X-ray polarimetry of compact objects (e.g, black holes, neutron stars)

PolarLight (Feng et al. 2019)

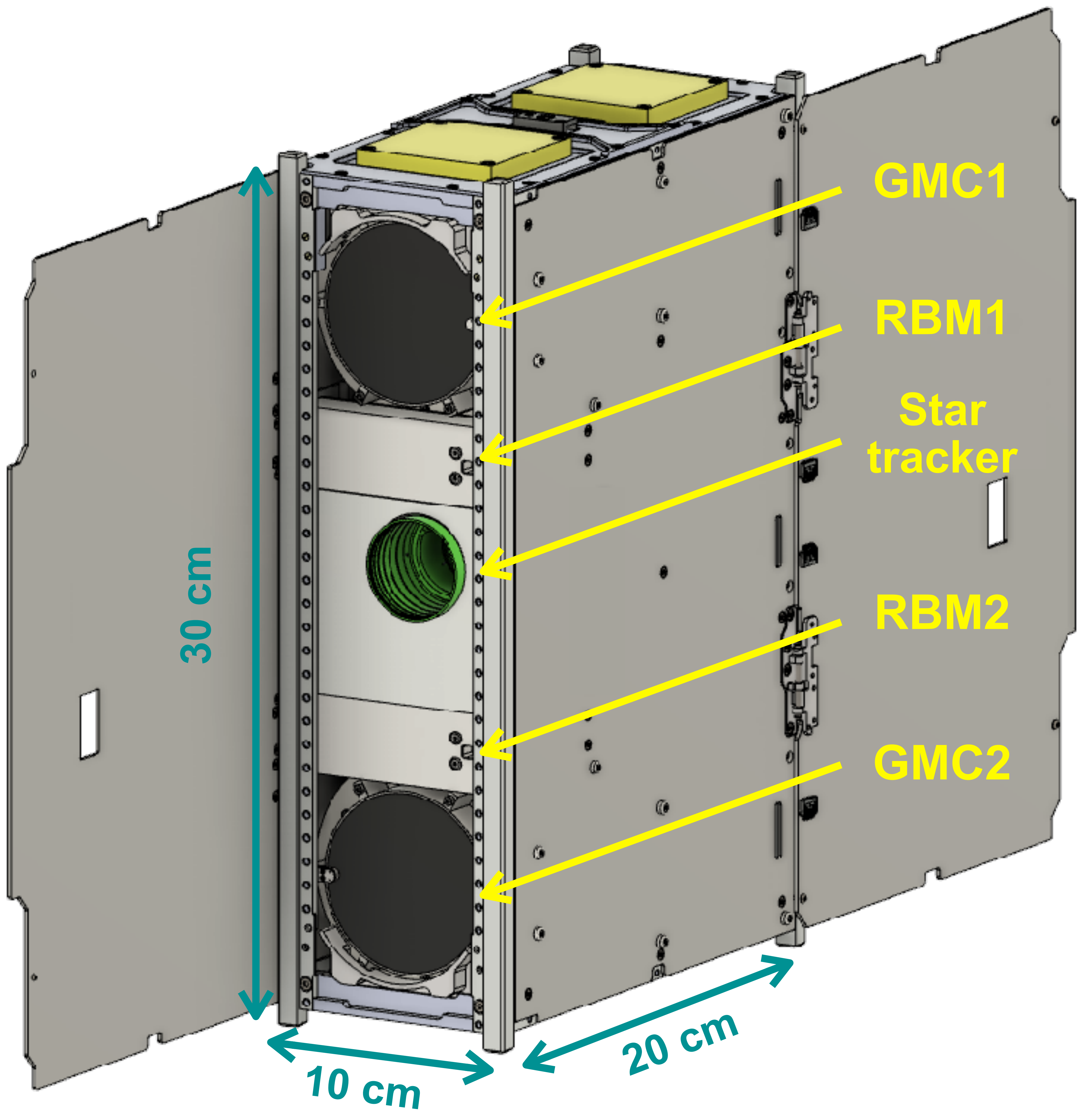


https://heasarc.gsfc.nasa.gov/docs/heasarc/missions/polarlight.html

NinjaSat: 6U CubeSat X-ray observatory

Enoto et al., SPIE proceeding (DOI: 10.1117/12.2561152)

NinjaSat: 6U CubeSat X-ray Observatory

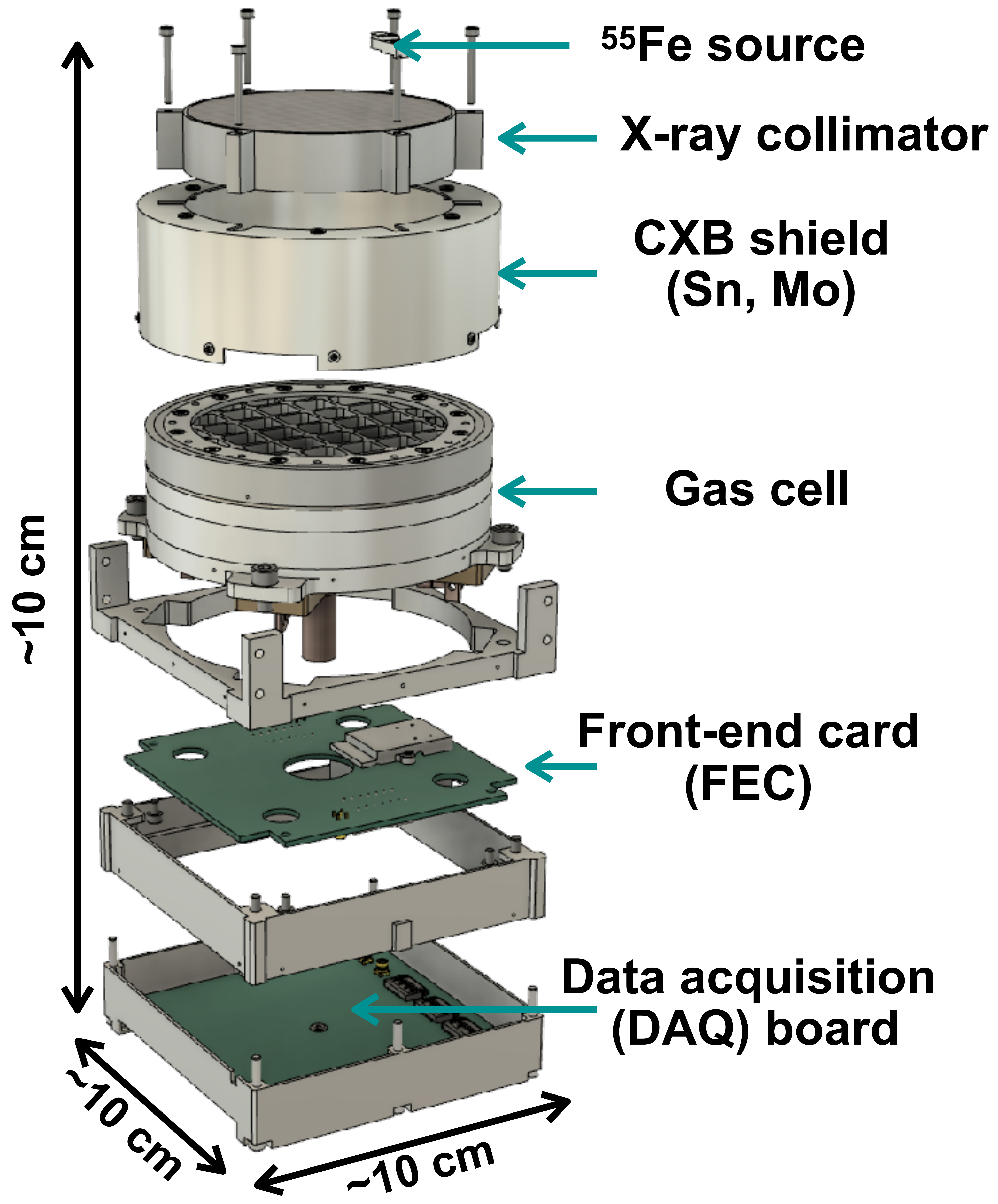


NanoAvionics flight-proven Multi-Purpose 6U platform (M6P)

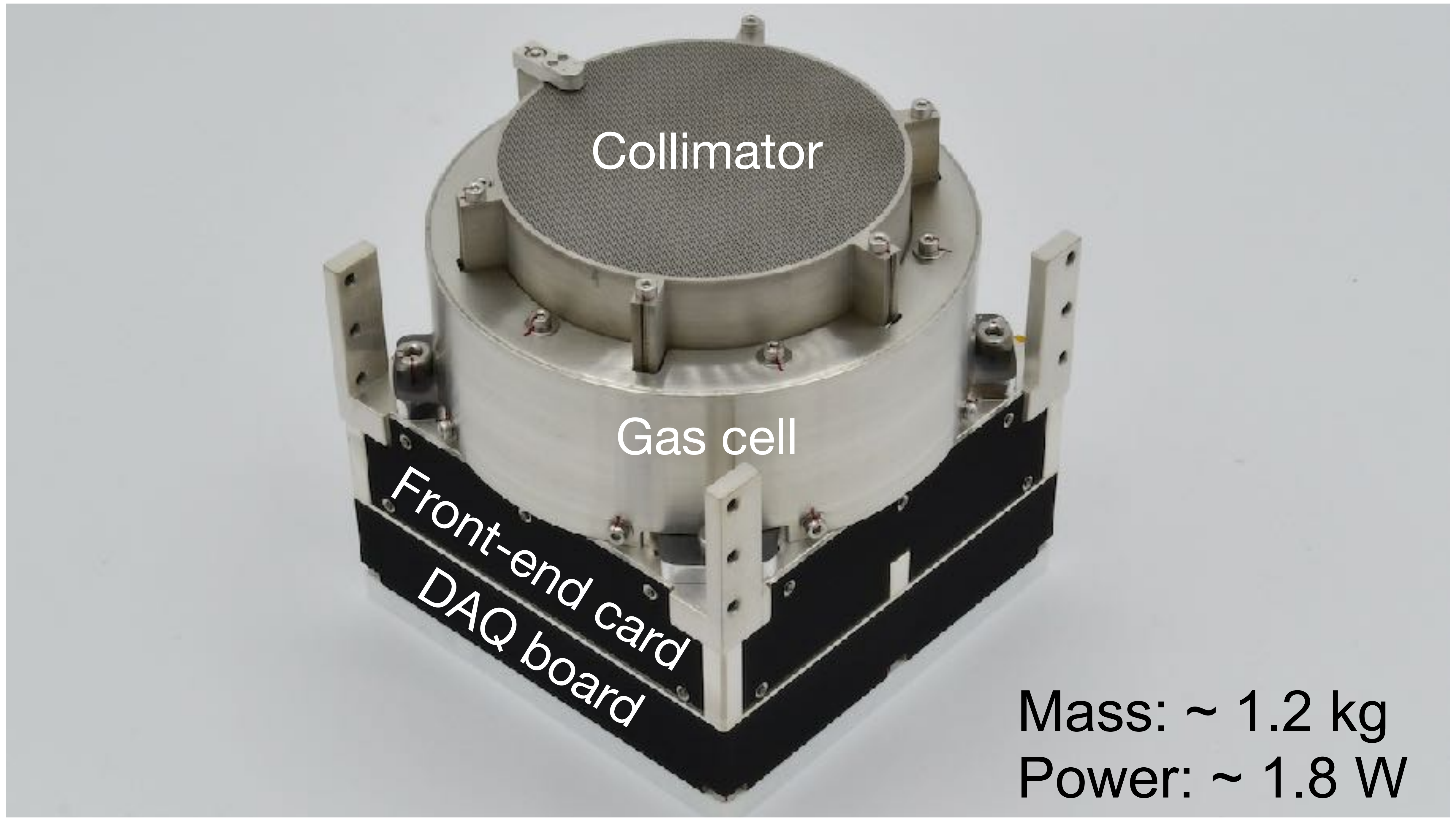
- **6U CubeSat (NanoAvionics)**
  - Scheduled to be launch in October 2023
  - Sun-synchronous orbit (550 km), > 1 year
- **Observation strategies**
  - Long-term multi-wavelength observations of persistently bright X-ray sources
  - Prompt follow-up observations of bright X-ray transients
- **Payloads**
  - Non-imaging Gas Multiplier Counter (GMC) x 2
  - Radiation Belt Monitor x 2

Related talks
- RBM : Kato (2:15 PM today)
- Mission : Tamagawa (5:30 PM today)

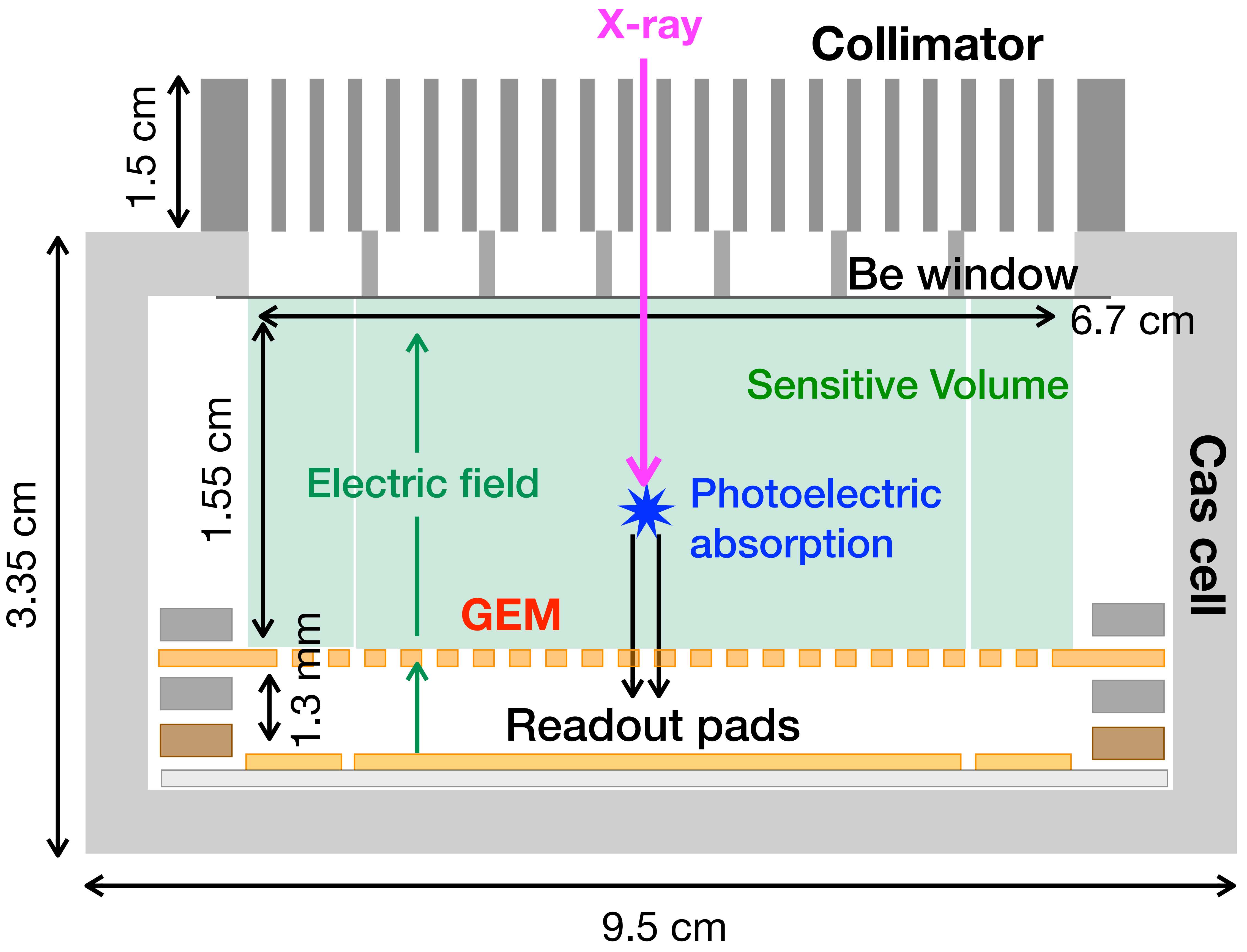
Gas Multiplier Counter (GMC)



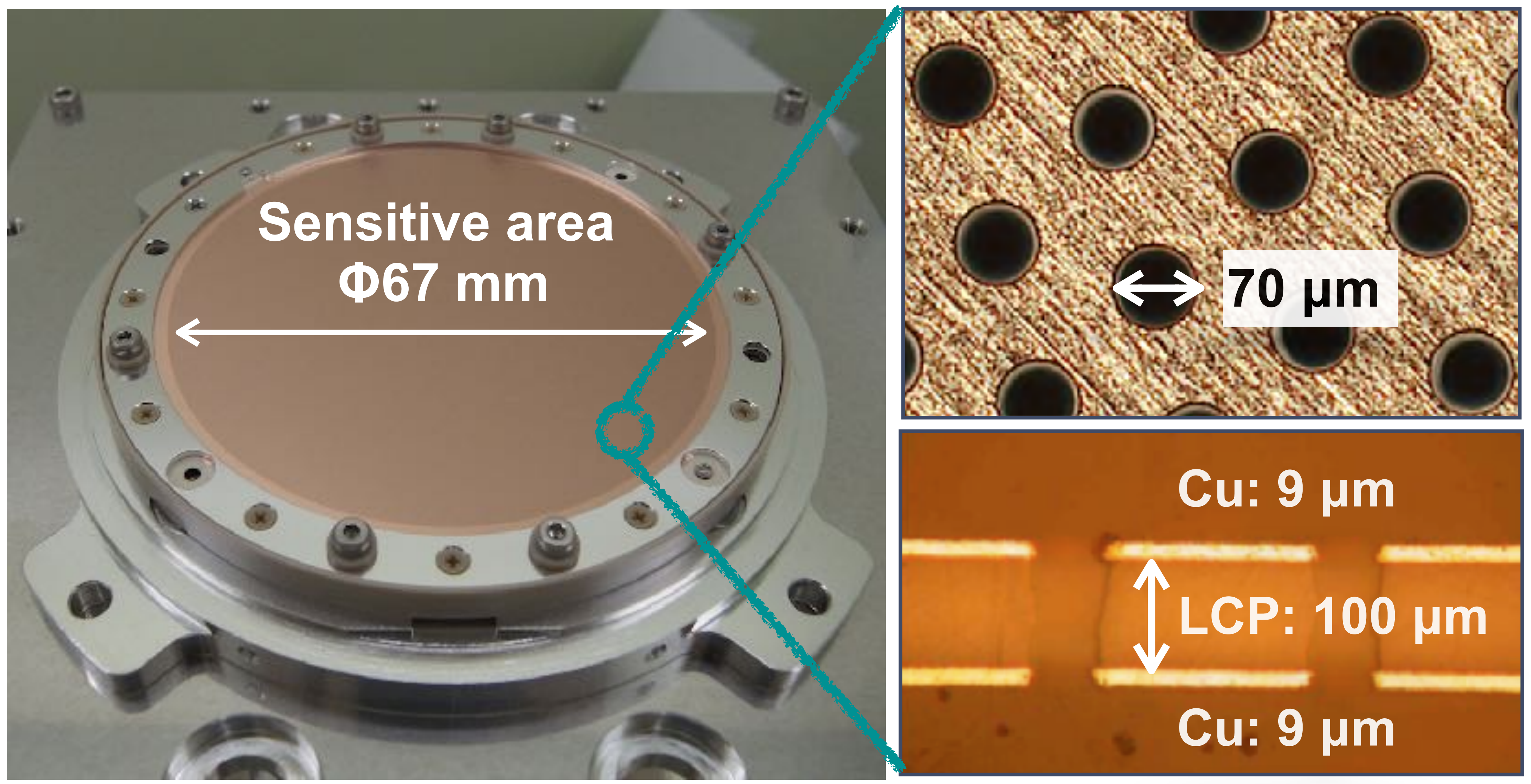
- **1U-size non-imaging gas X-ray detector**
  - Energy bandpass: 2–50 keV
  - Effective area: ~32 cm^2 at 6 keV for 2 GMCs
    - Largest among the previous X-ray detectors onboard CubeSats
  - Field of view: 2.1 deg (FWHM)

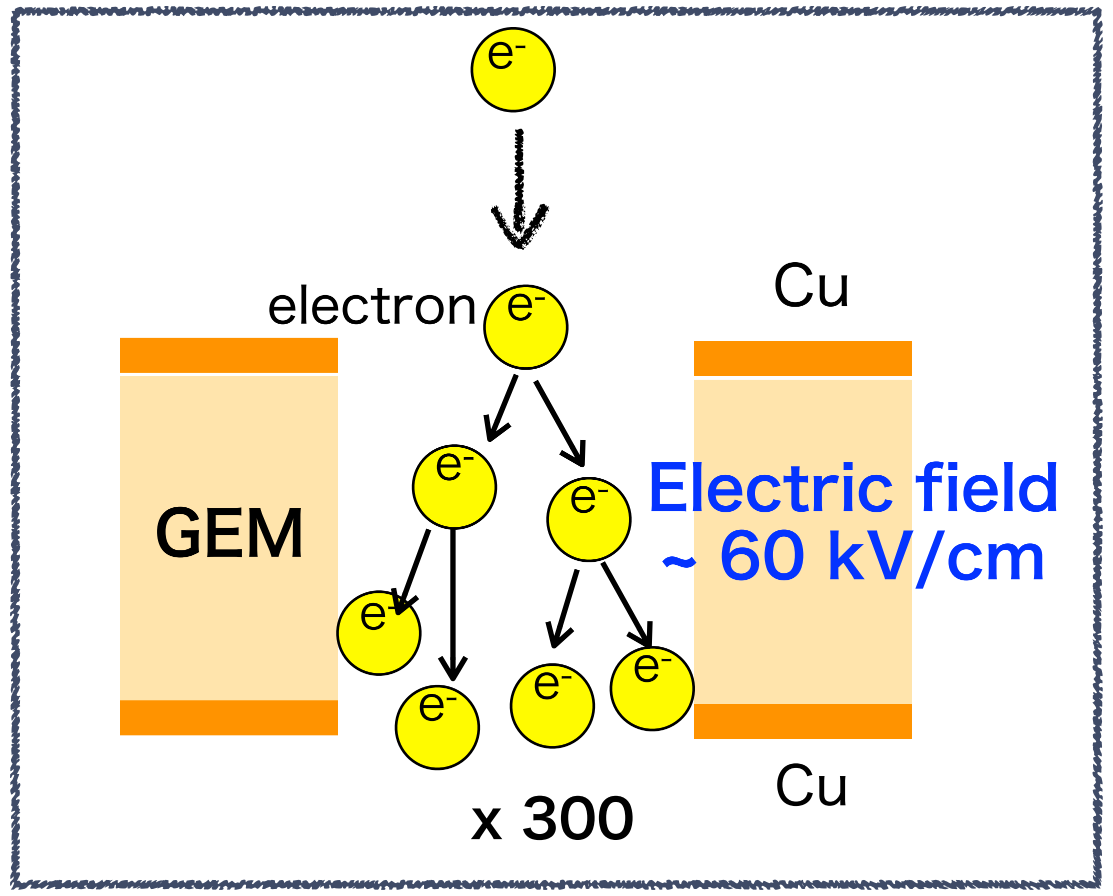


Gas cell equipped with GEM



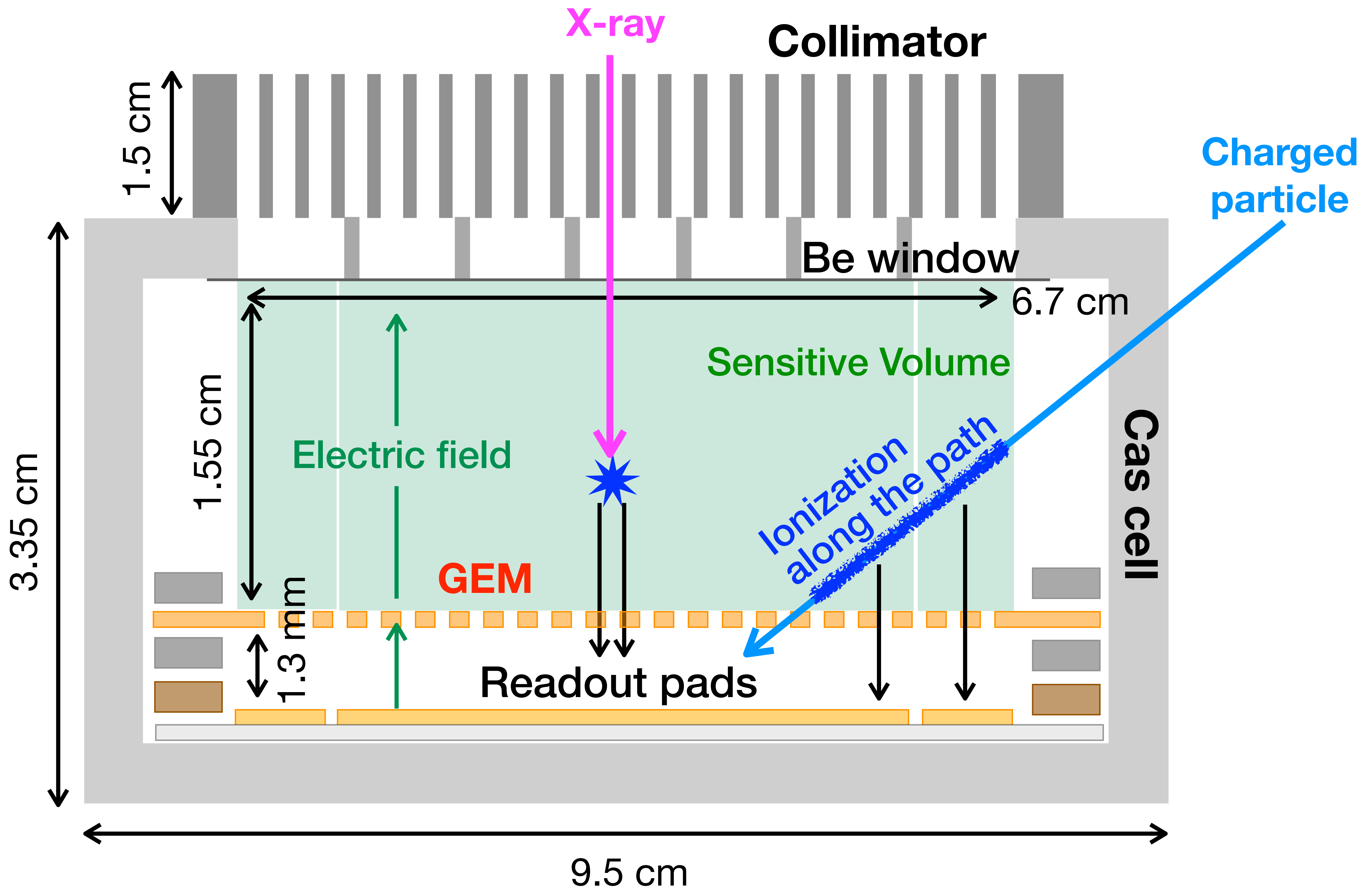
Gas Electron Multiplier (GEM)

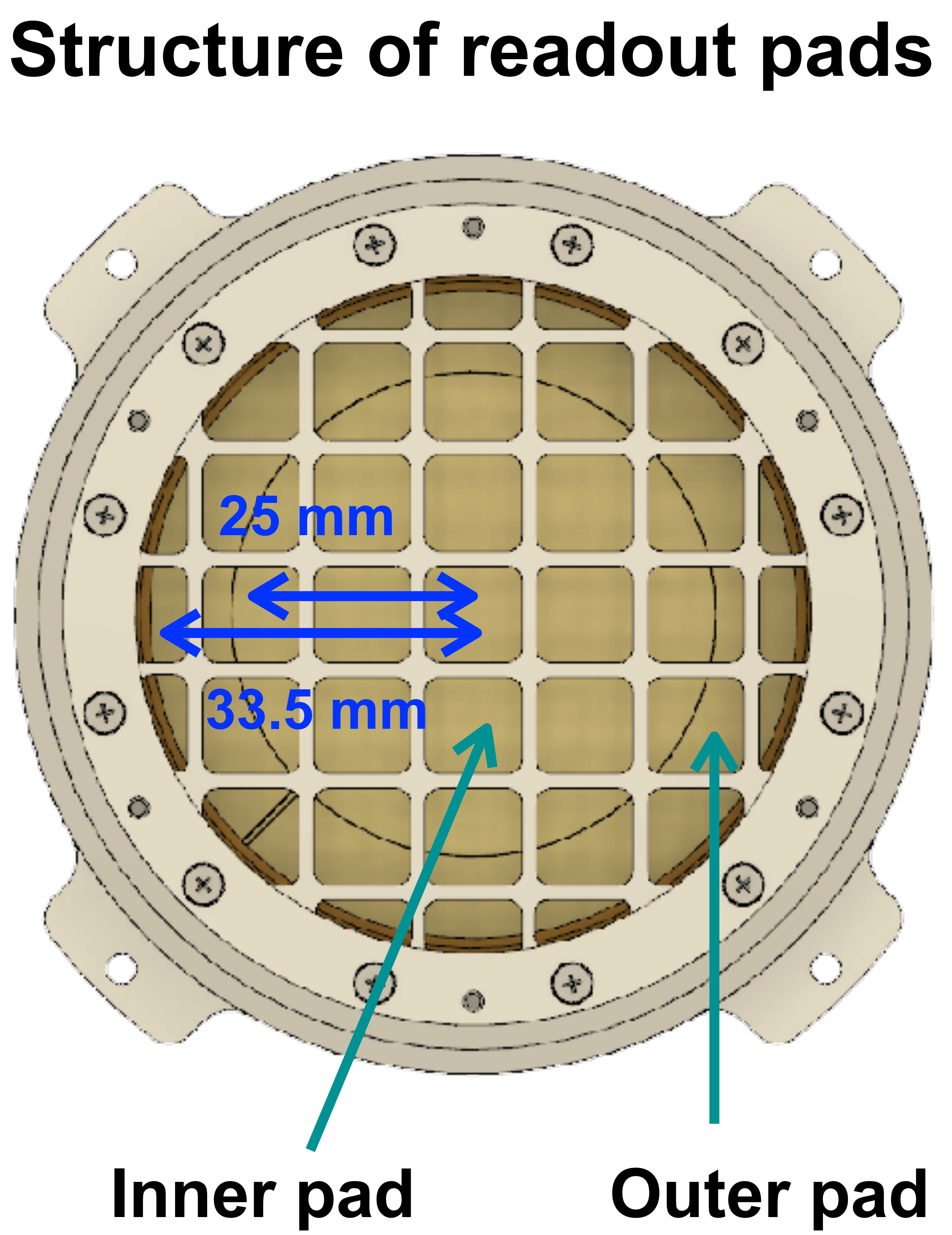




- Role: Converting X-ray energy into an amount of charge
- Sealed gas: XeArDME (75%/24%/1%) @0°C, 1.2 atm
- Gas Electron Multiplier (GEM): amplify #of electrons > 300
- Two readout pads: anti-coincidence for background rejections

Gas cell equipped with GEM





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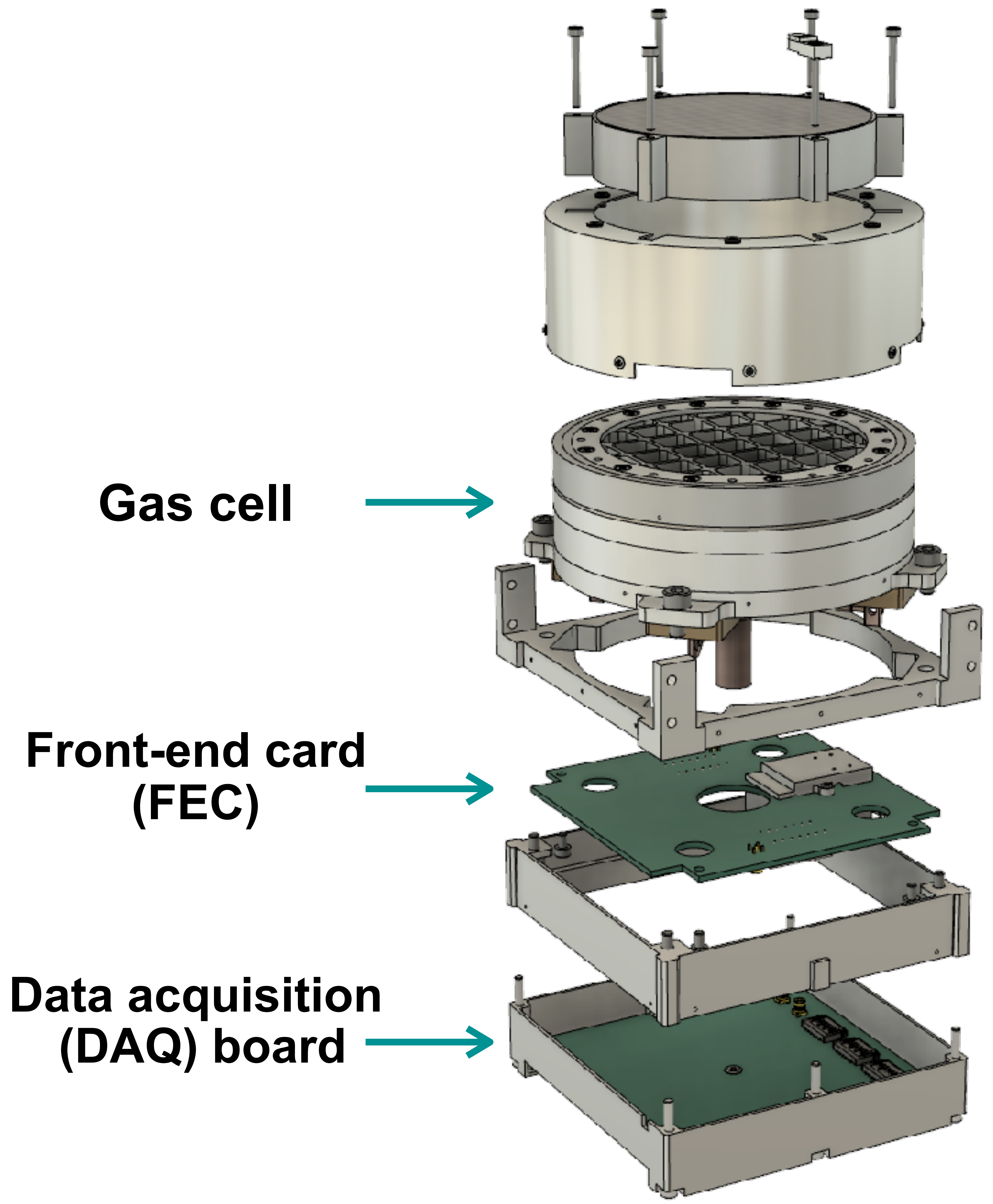
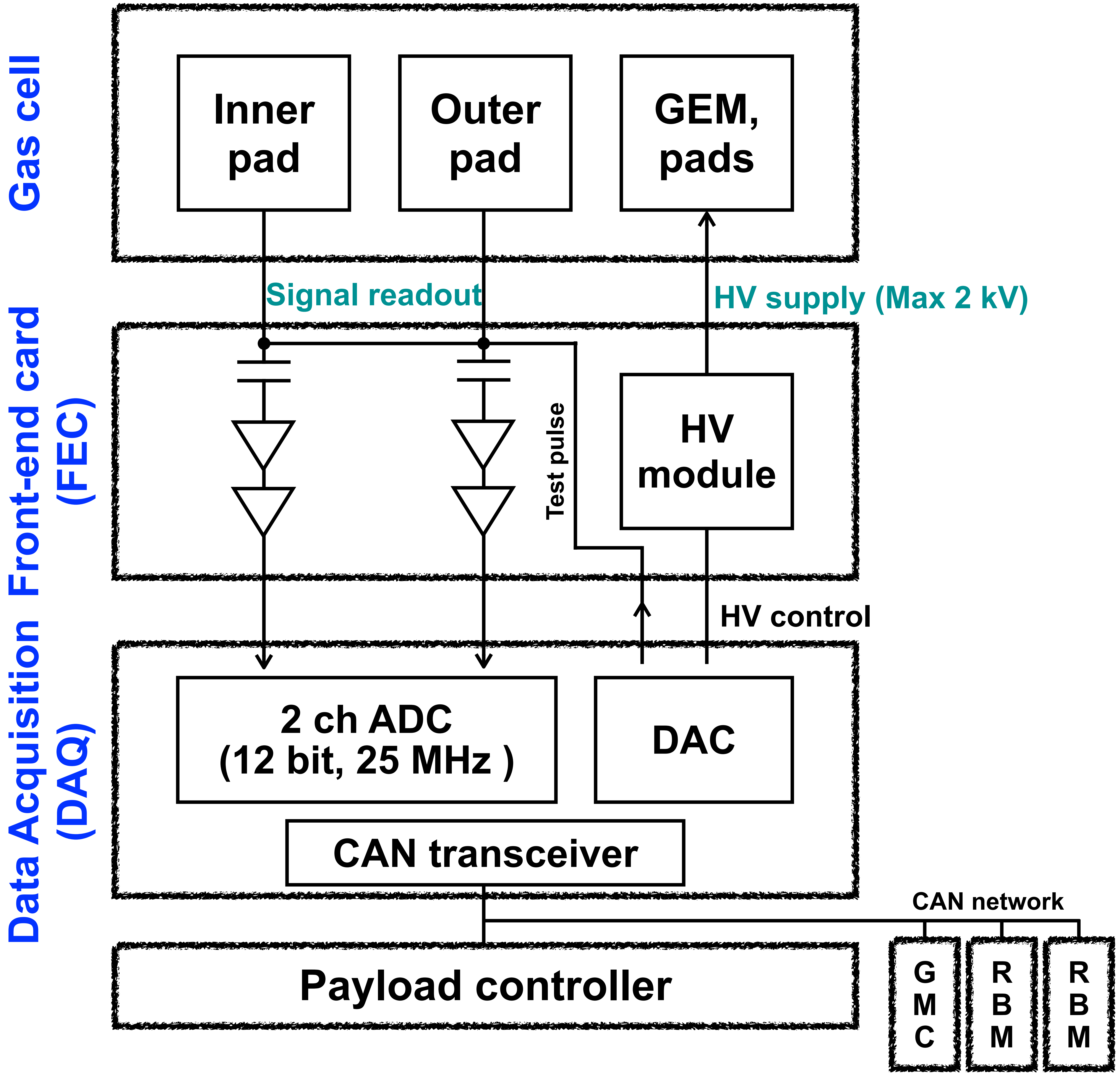
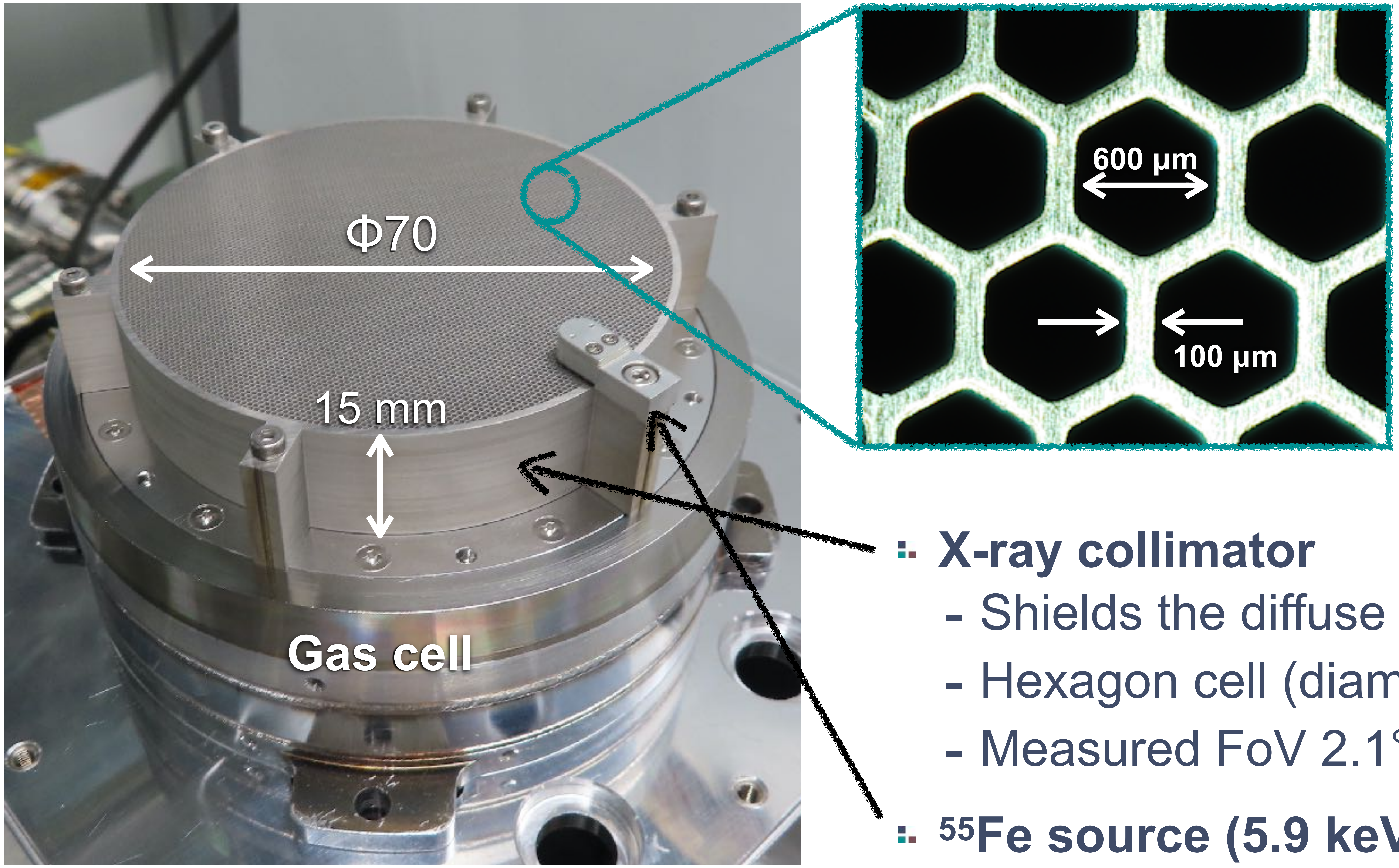
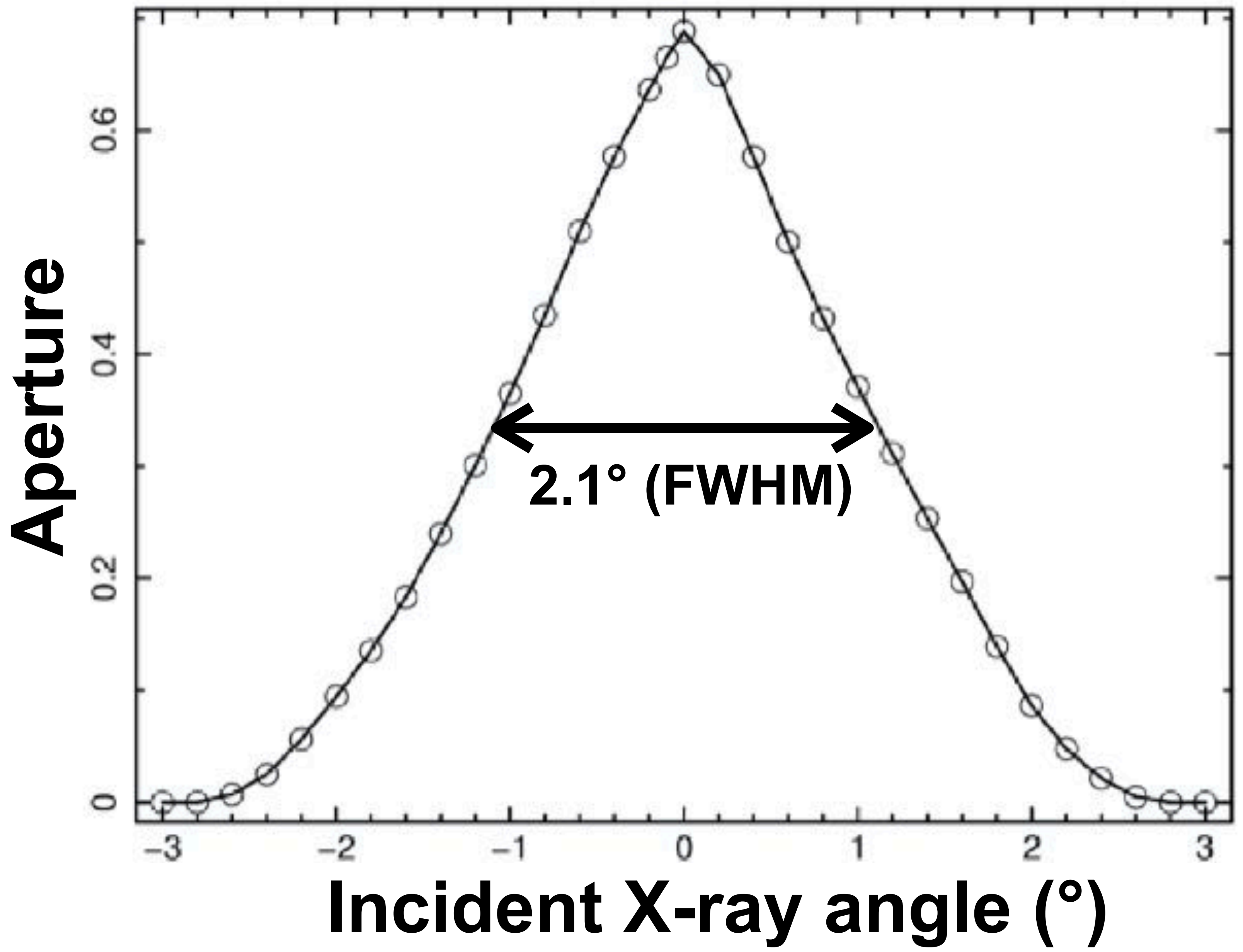
FEC & DAQ — Diagram of the GMC signal flow





X-ray collimator & ^{55}Fe source

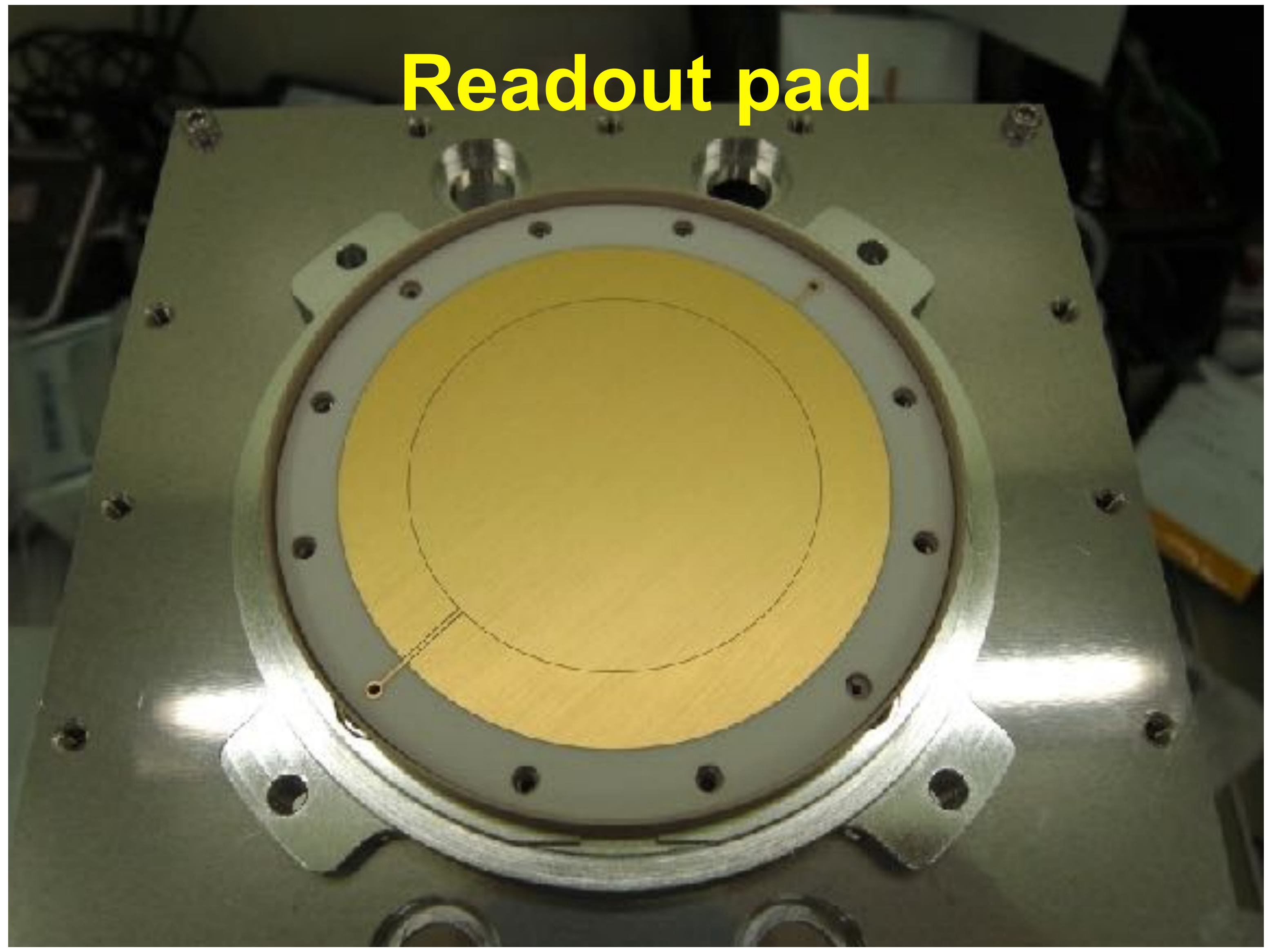


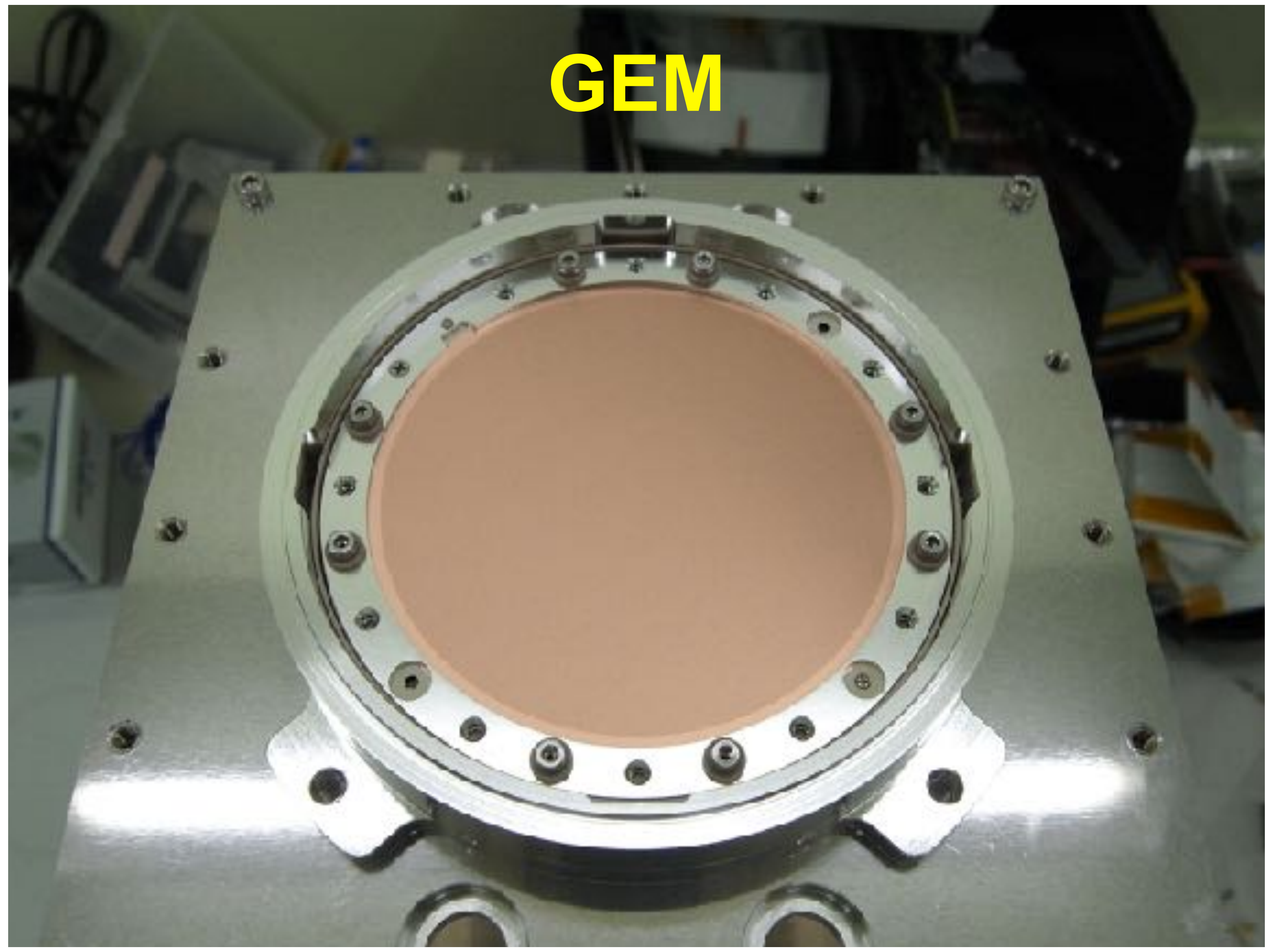


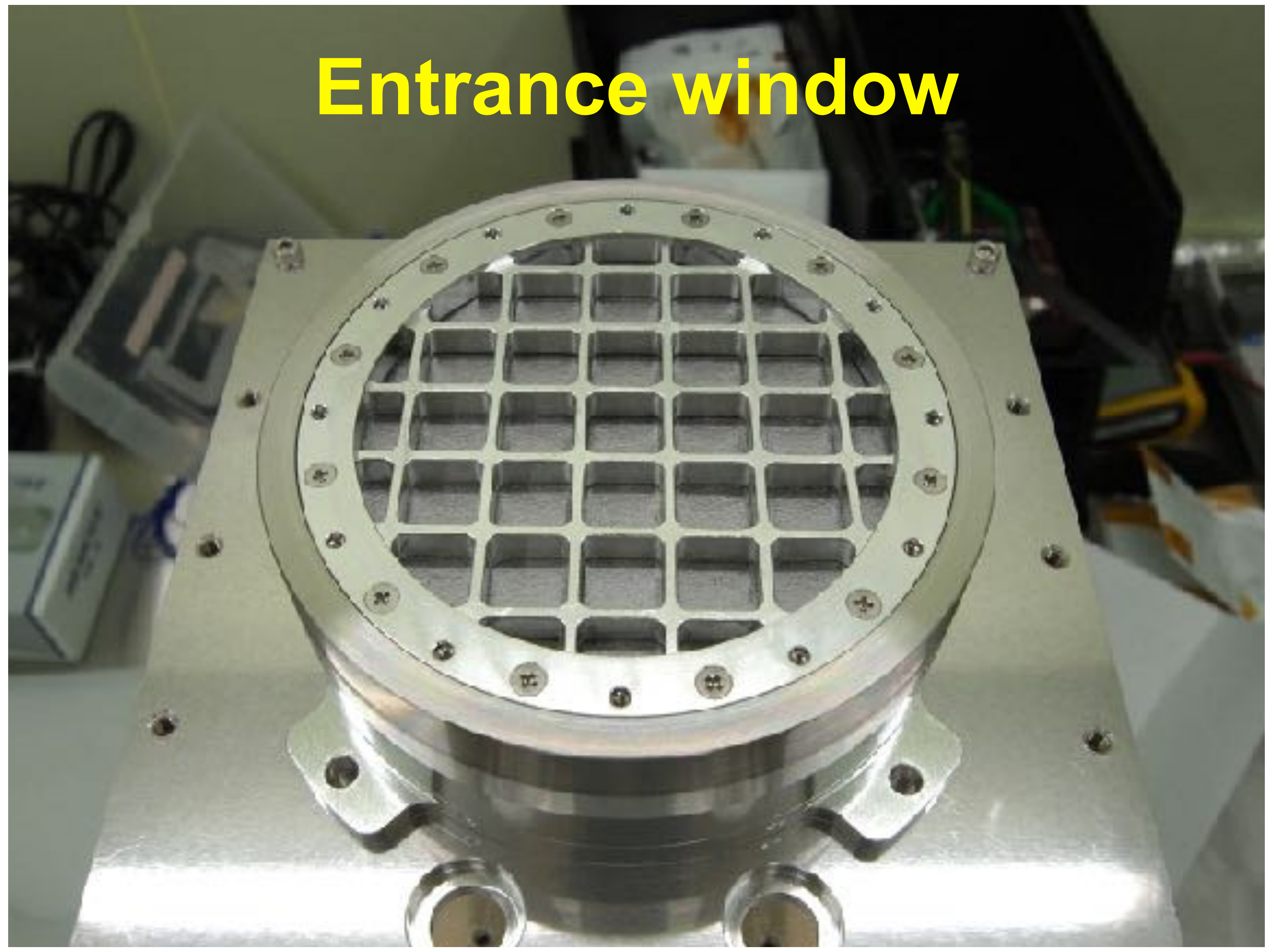
- **X-ray collimator**
  - Shields the diffuse X-ray background
  - Hexagon cell (diameter 600 µm)
  - Measured FoV 2.1° (FWHM), aperture fraction 69%
- **^{55}Fe source (5.9 keV)**
  - 1 counts/sec after the collimator
  - In-orbit energy calibration using 5.9 keV line

Component fabrication (2021~2022)

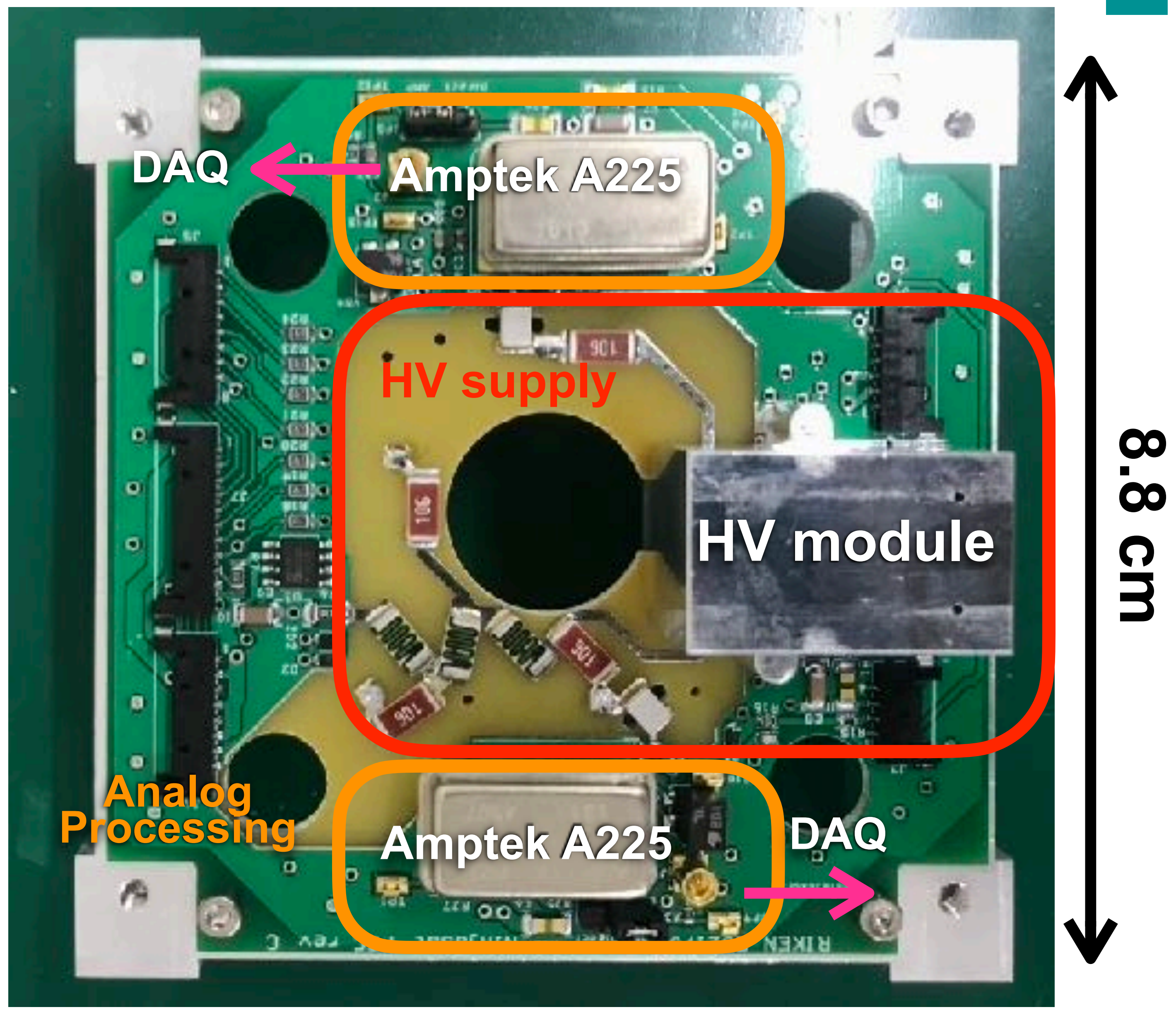
Gas cell



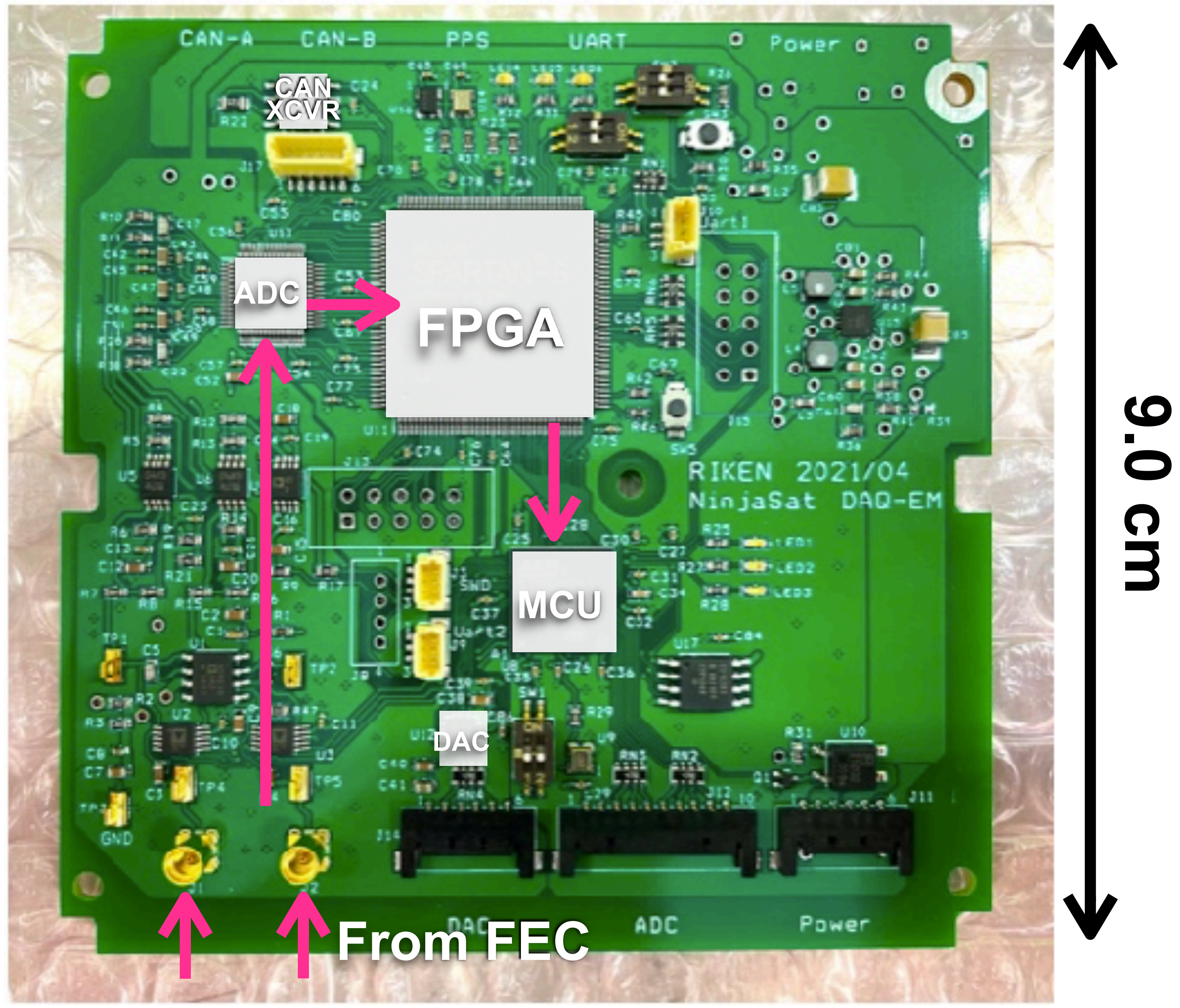




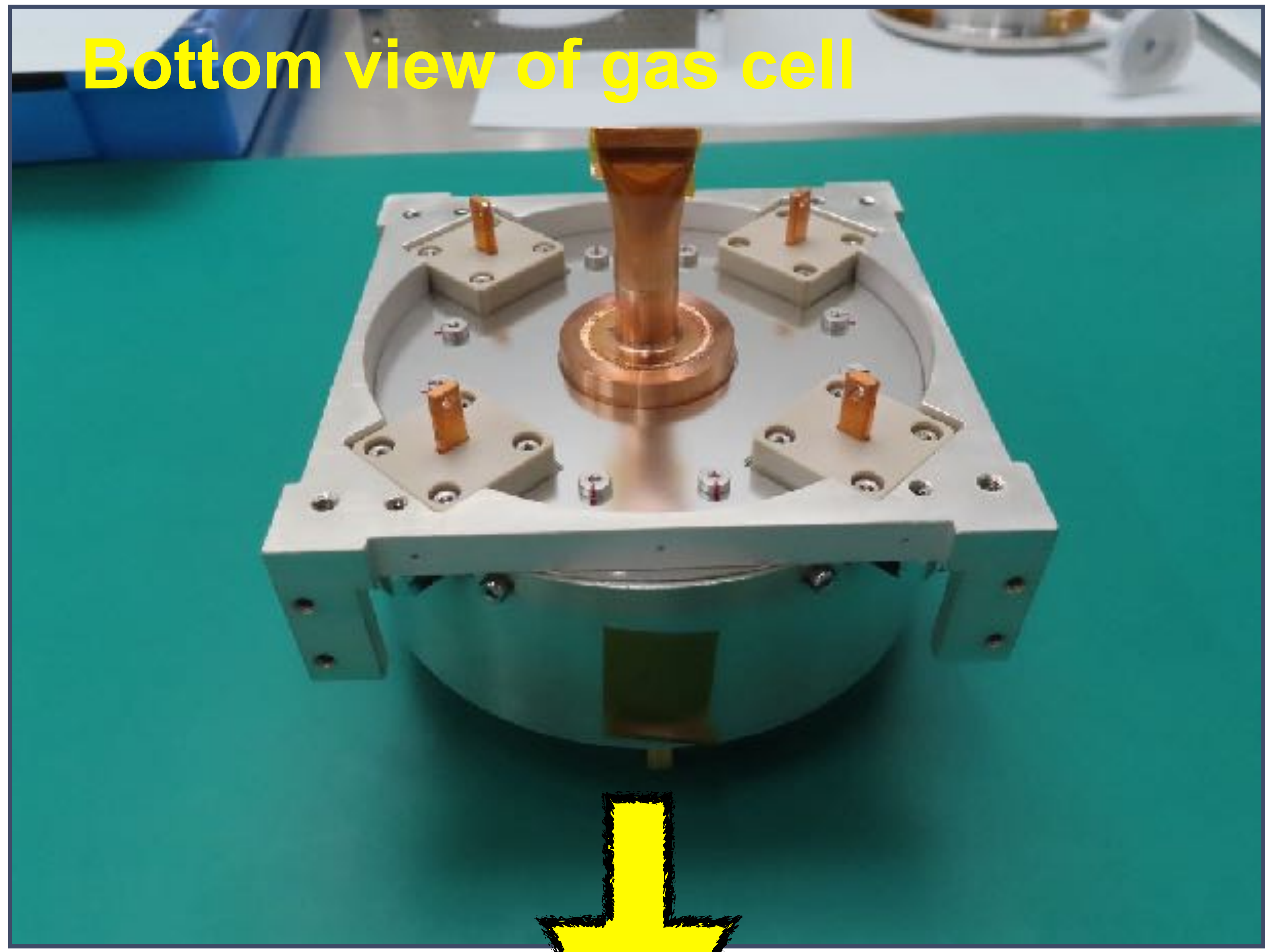
FEC

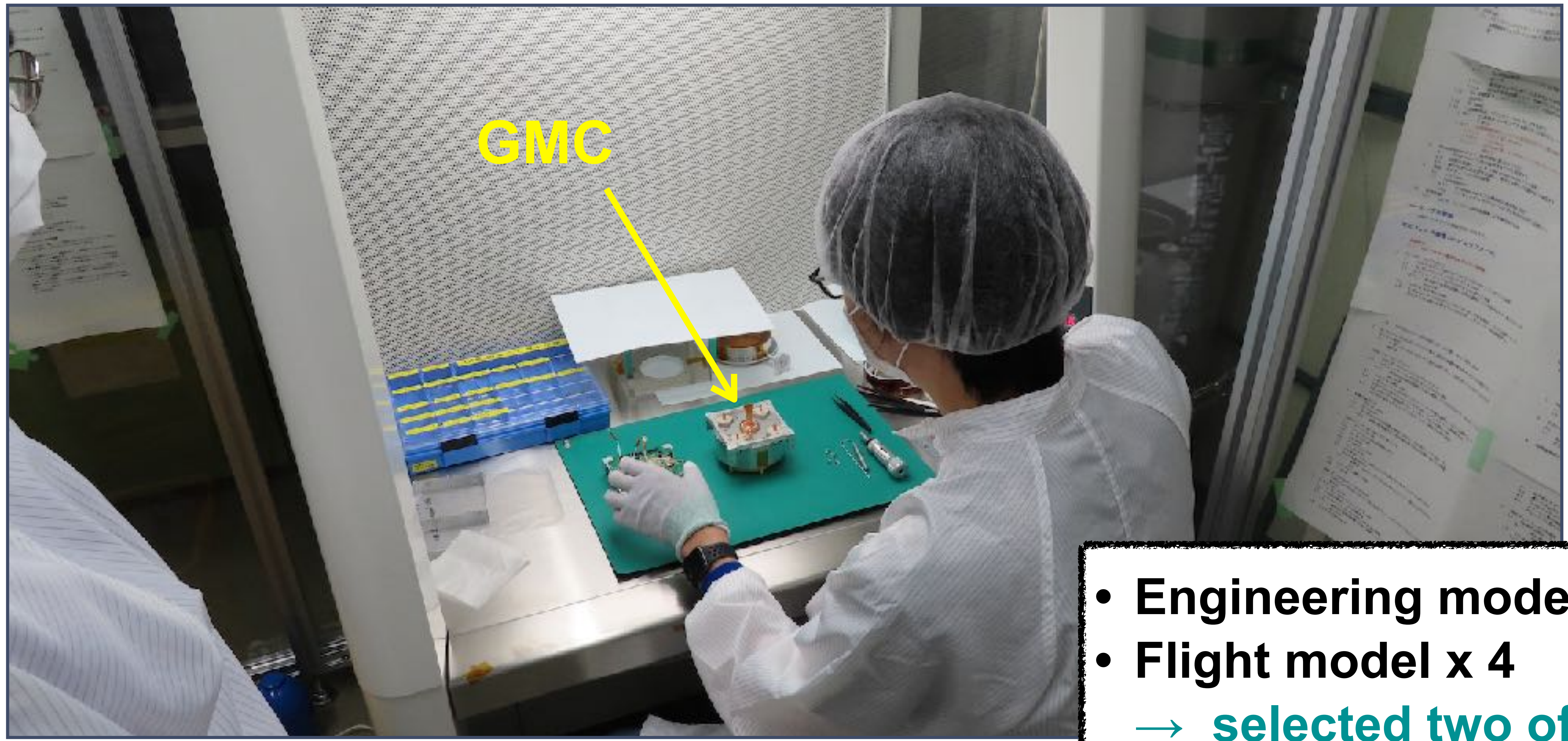


DAQ board

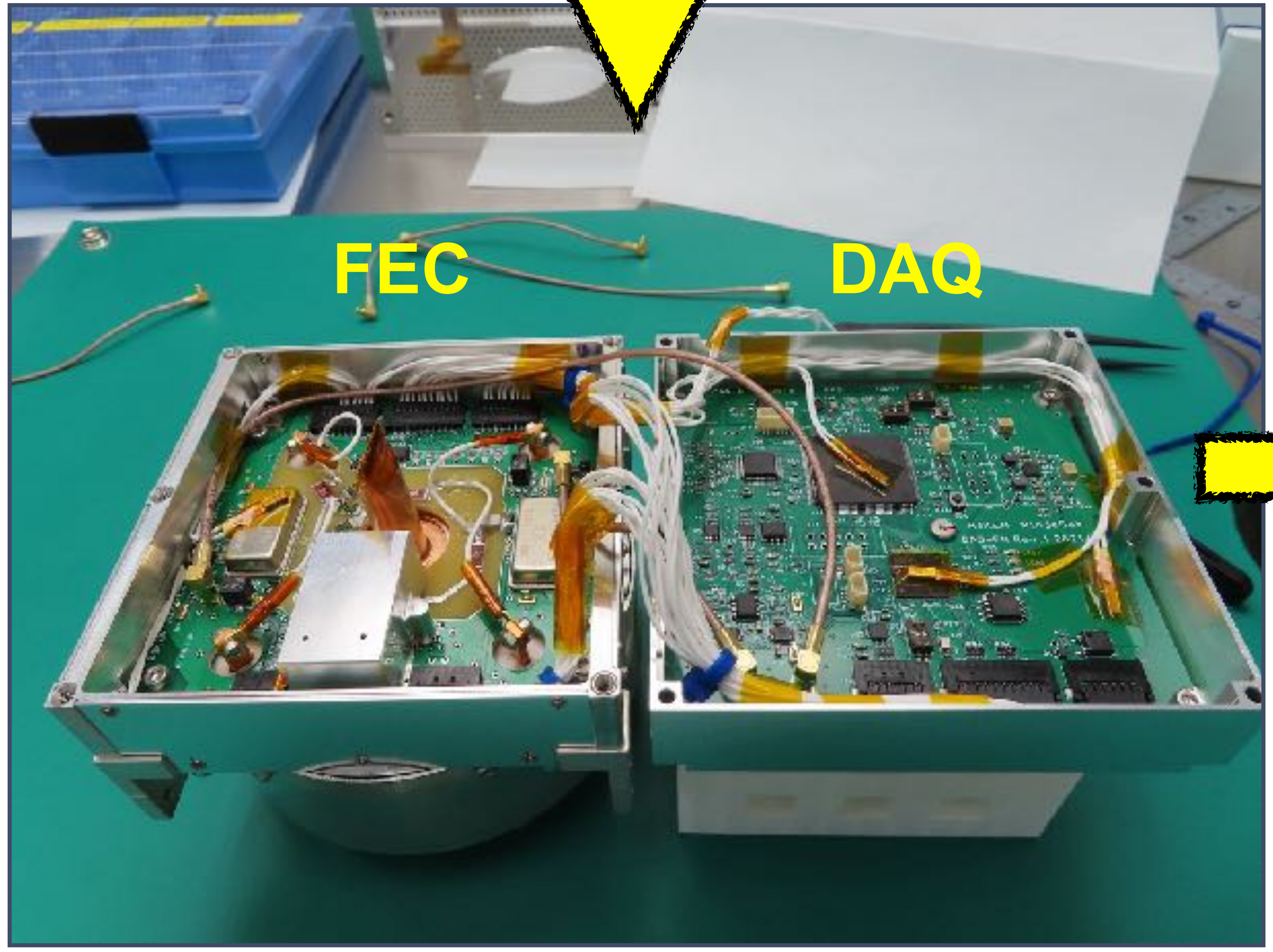


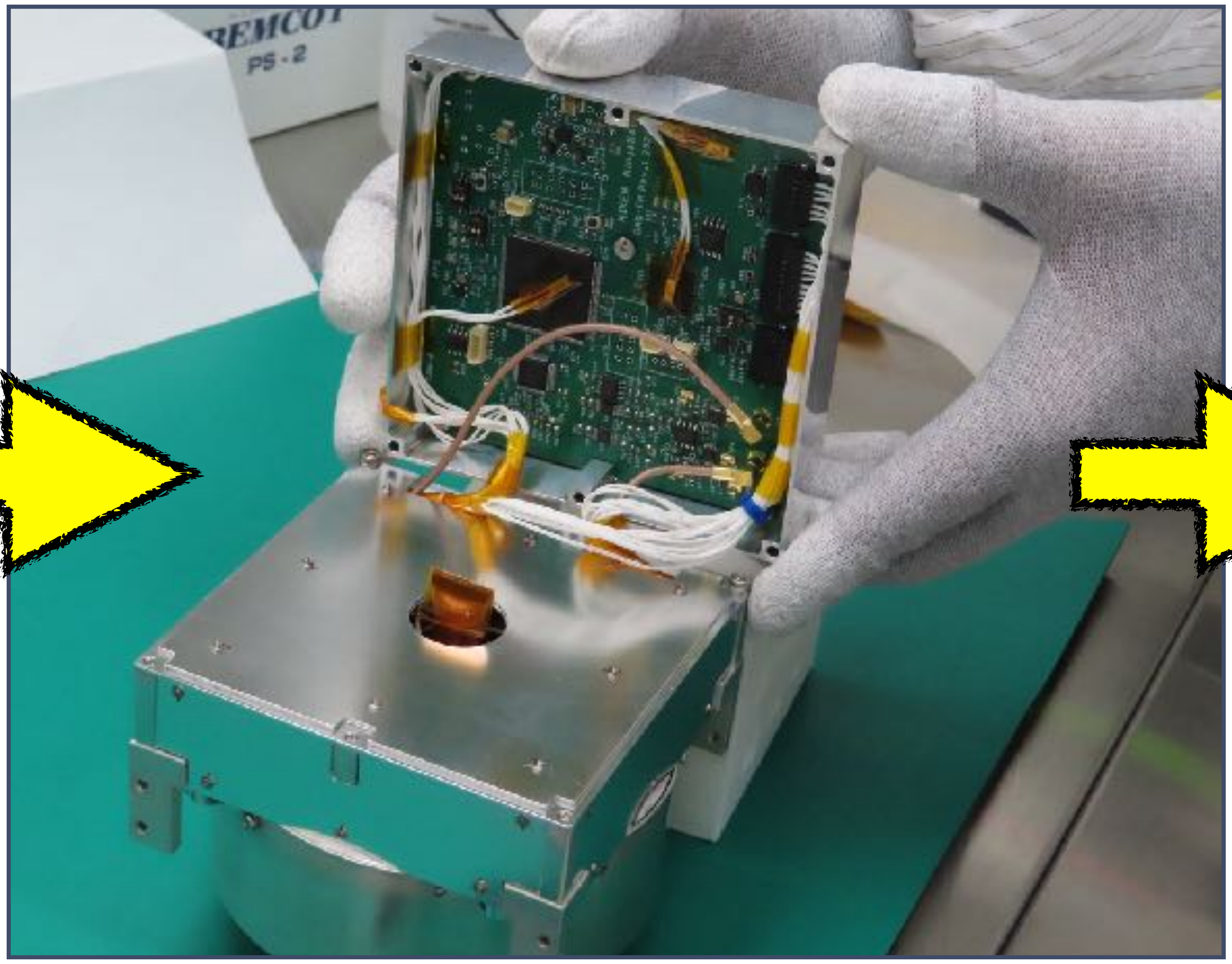
Flight model assembly (2021~2022)

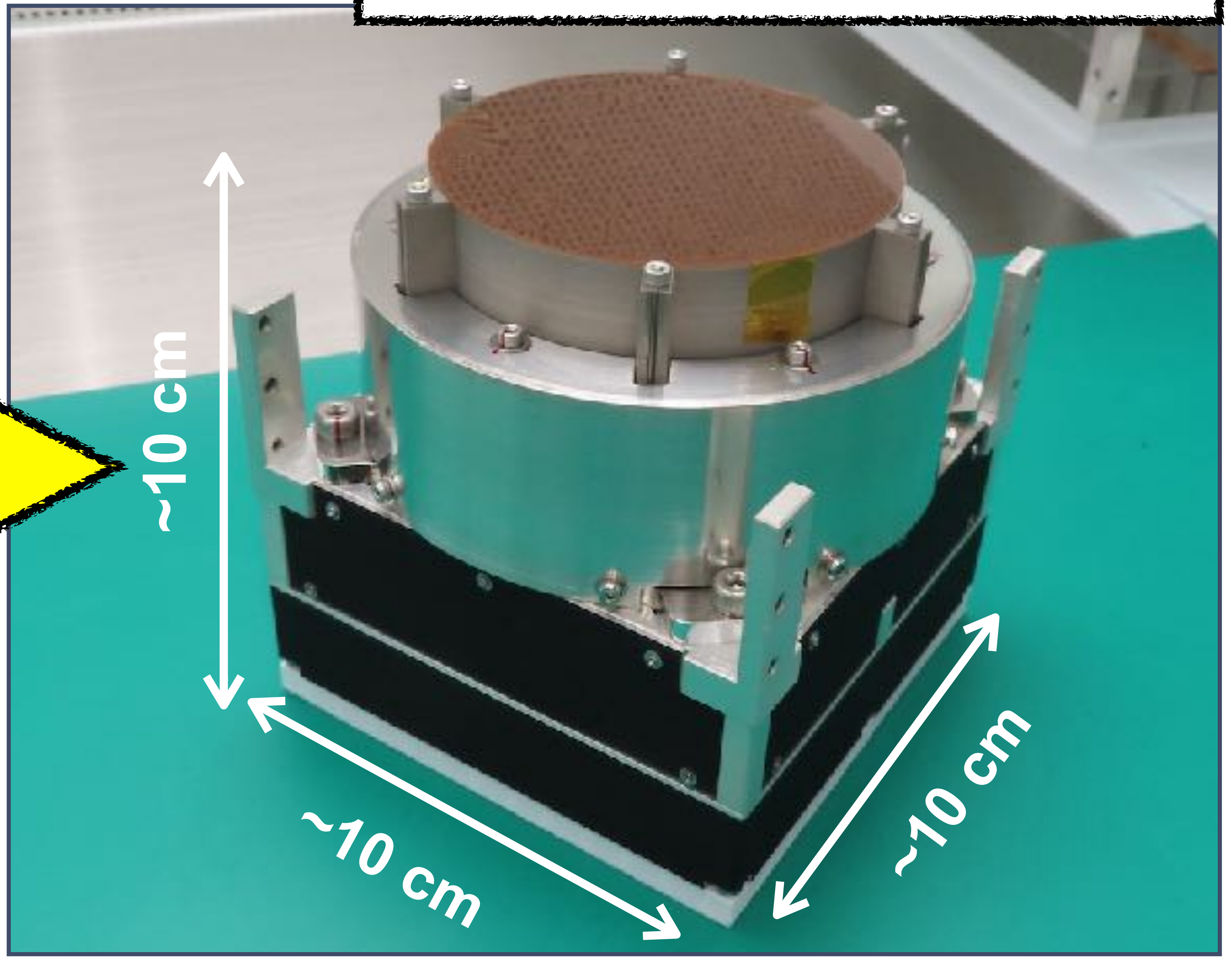




- Engineering model x 1
- Flight model x 4
  → selected two of them



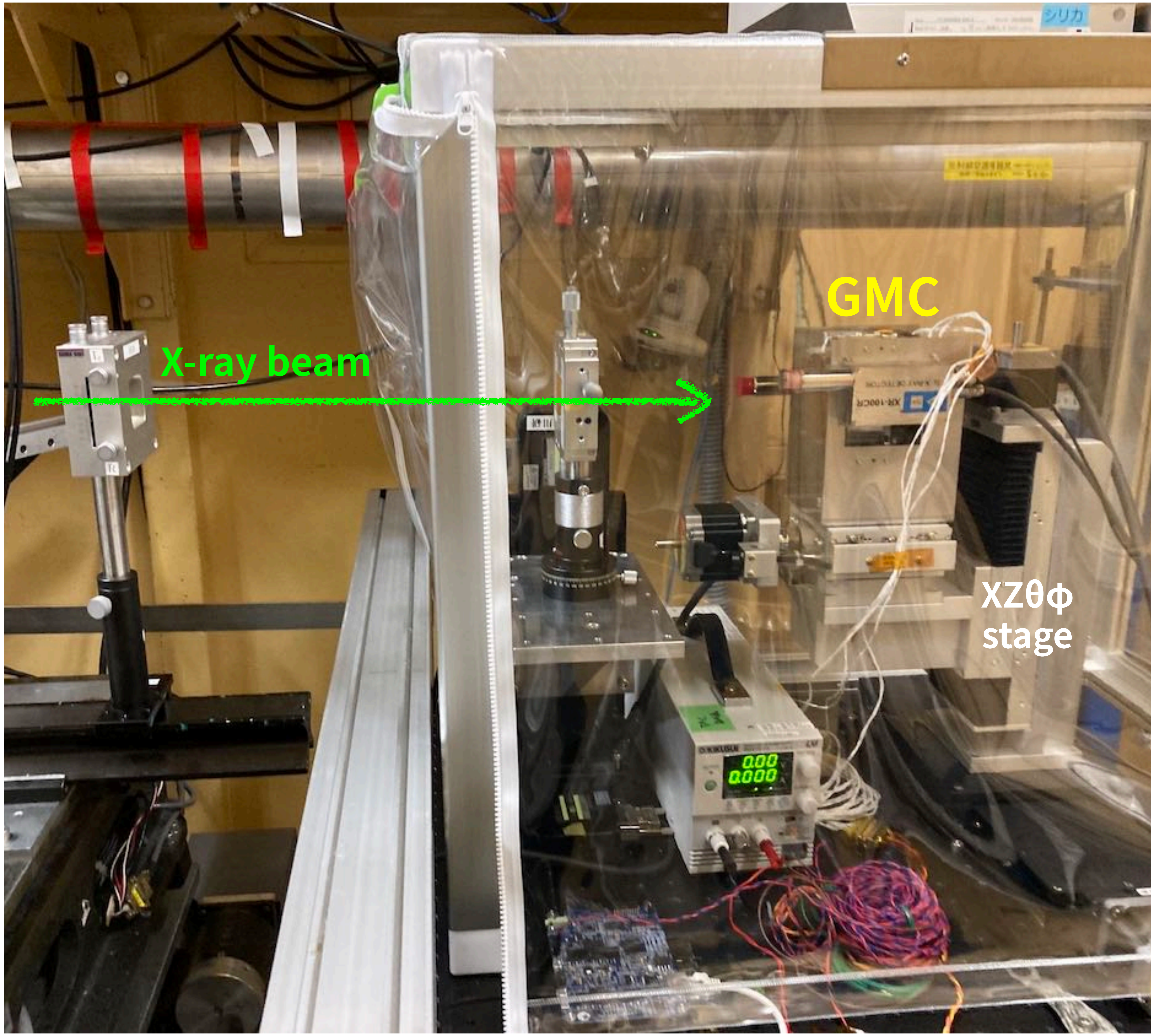




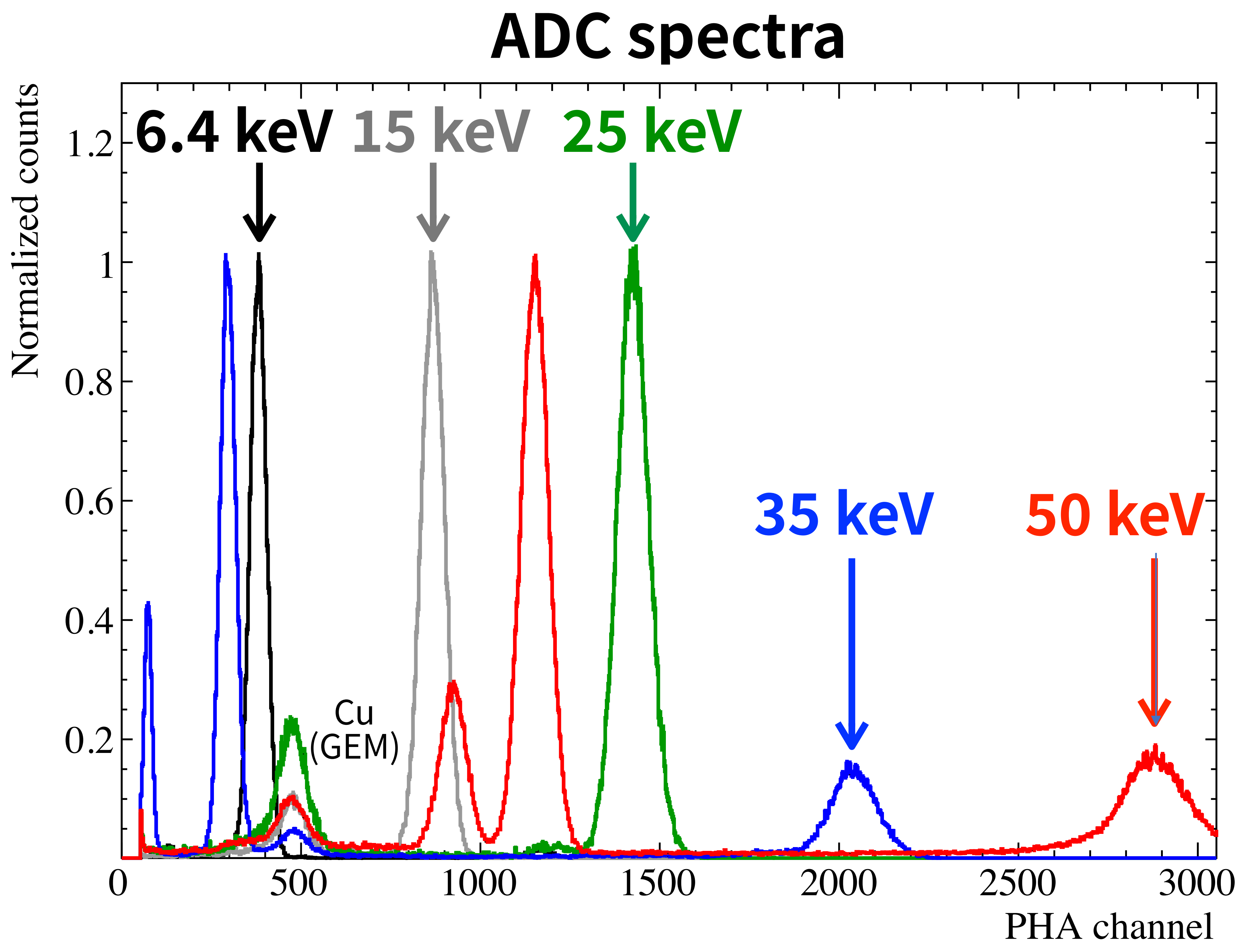
Performance verification with synchrotron X-rays

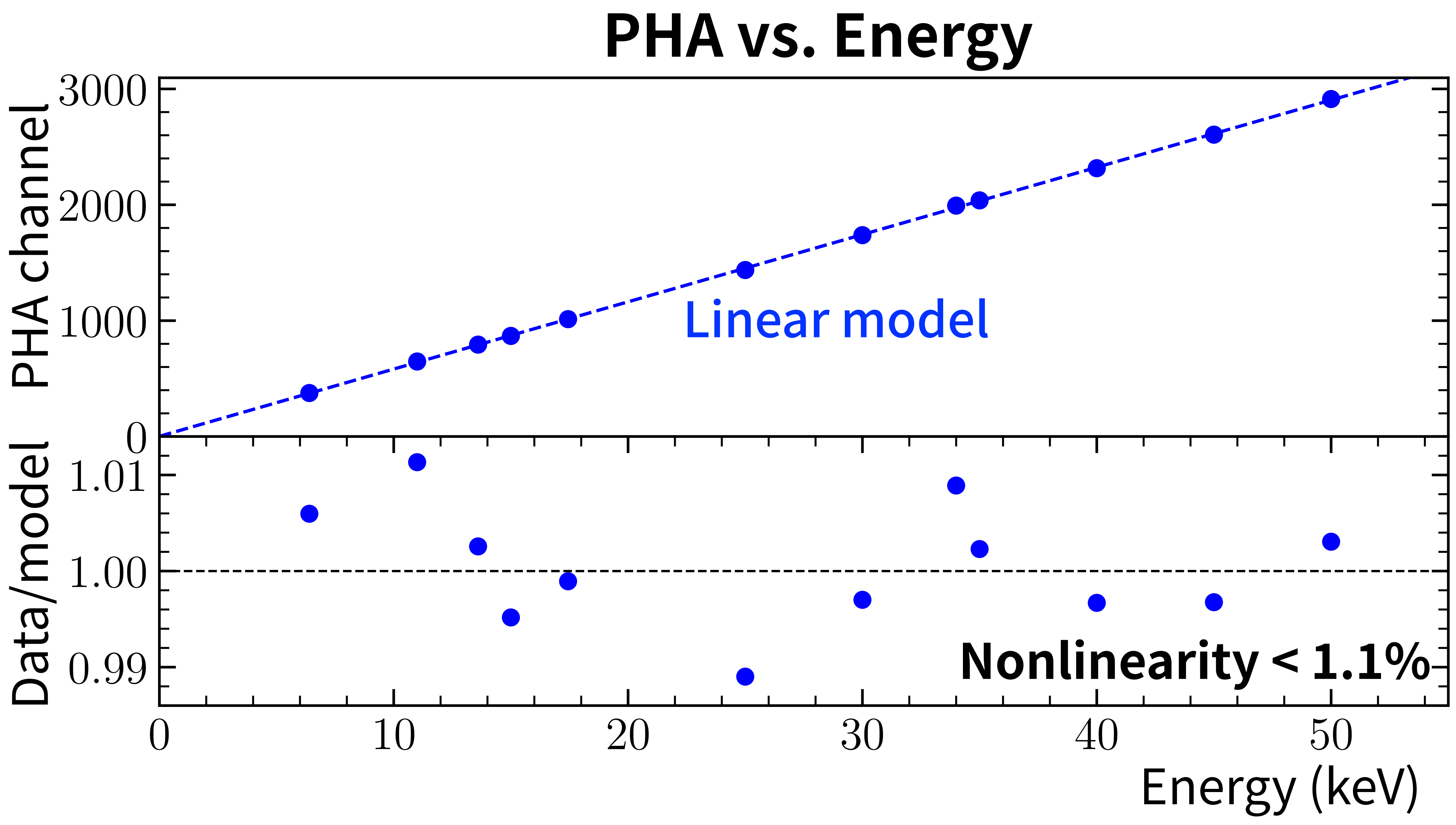
- **Synchrotron radiation facility KEK PF BL-14A**
  - 12 different energies: 6.4–50 keV
  - Beam size: 20×20 μm²

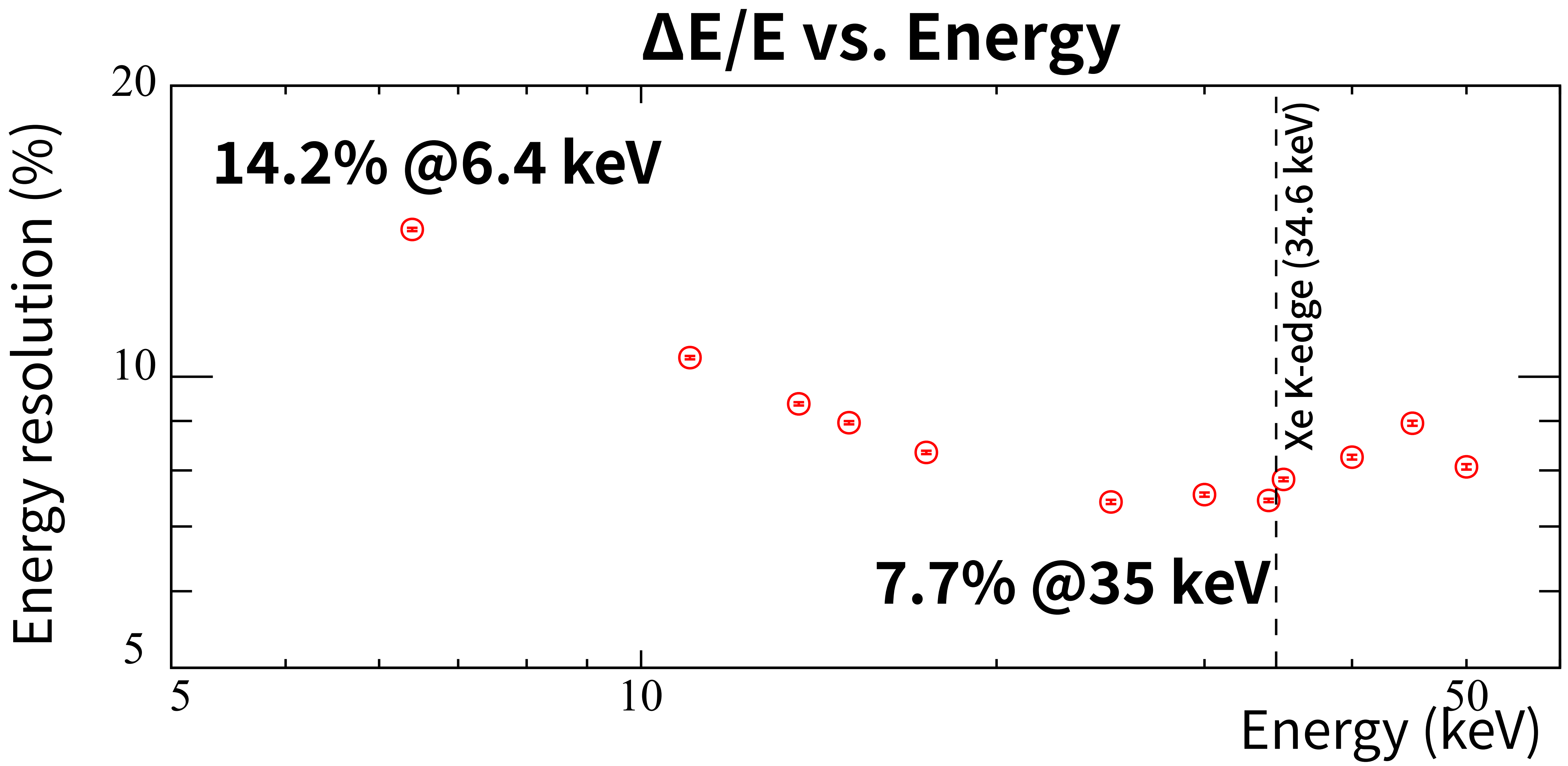
- **Test items**
  - Energy-PHA relation
  - Energy resolution
  - Detection efficiency



Performance verification with synchrotron X-rays

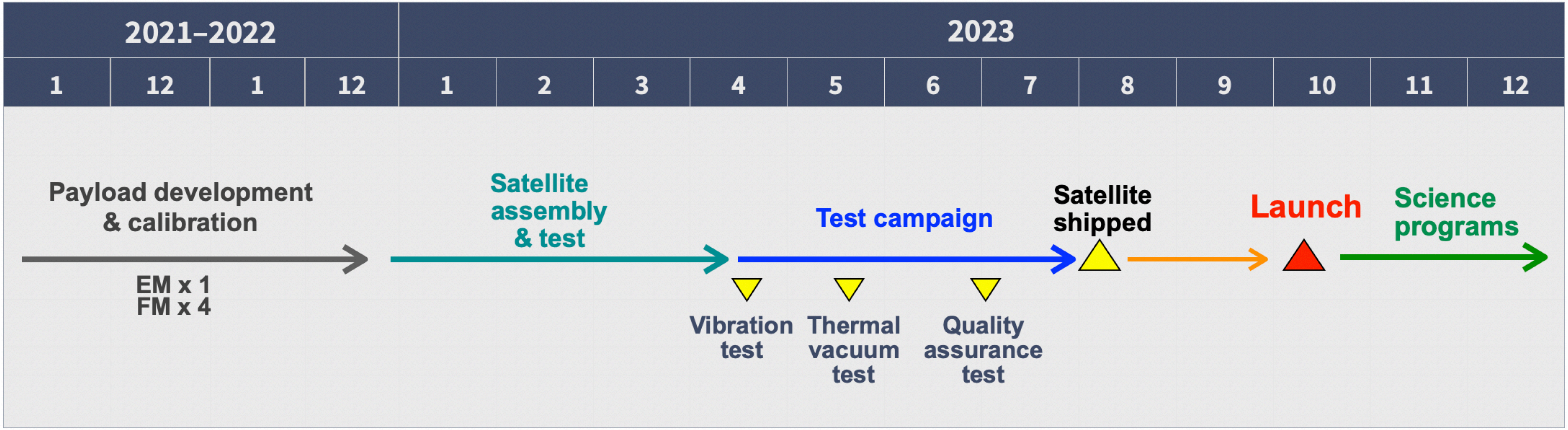


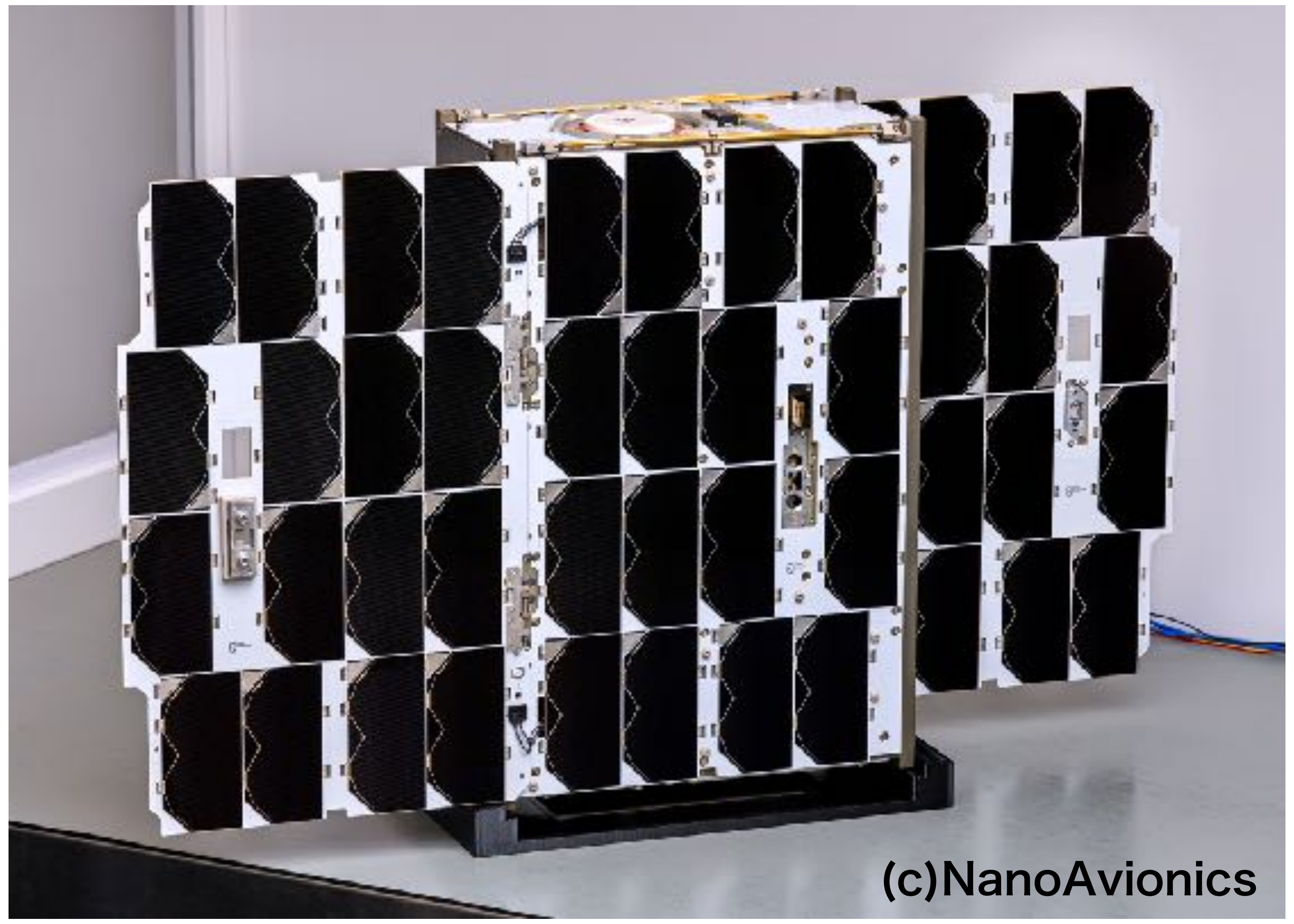




- **Energy-PHA relation**
  - Nonlinearity < 1.1% @6.4–50 keV
- **Energy resolution (FWHM)**
  - 14.2% @6.4 keV
  - 7.7% @35 keV

NinjaSat schedule





Summary

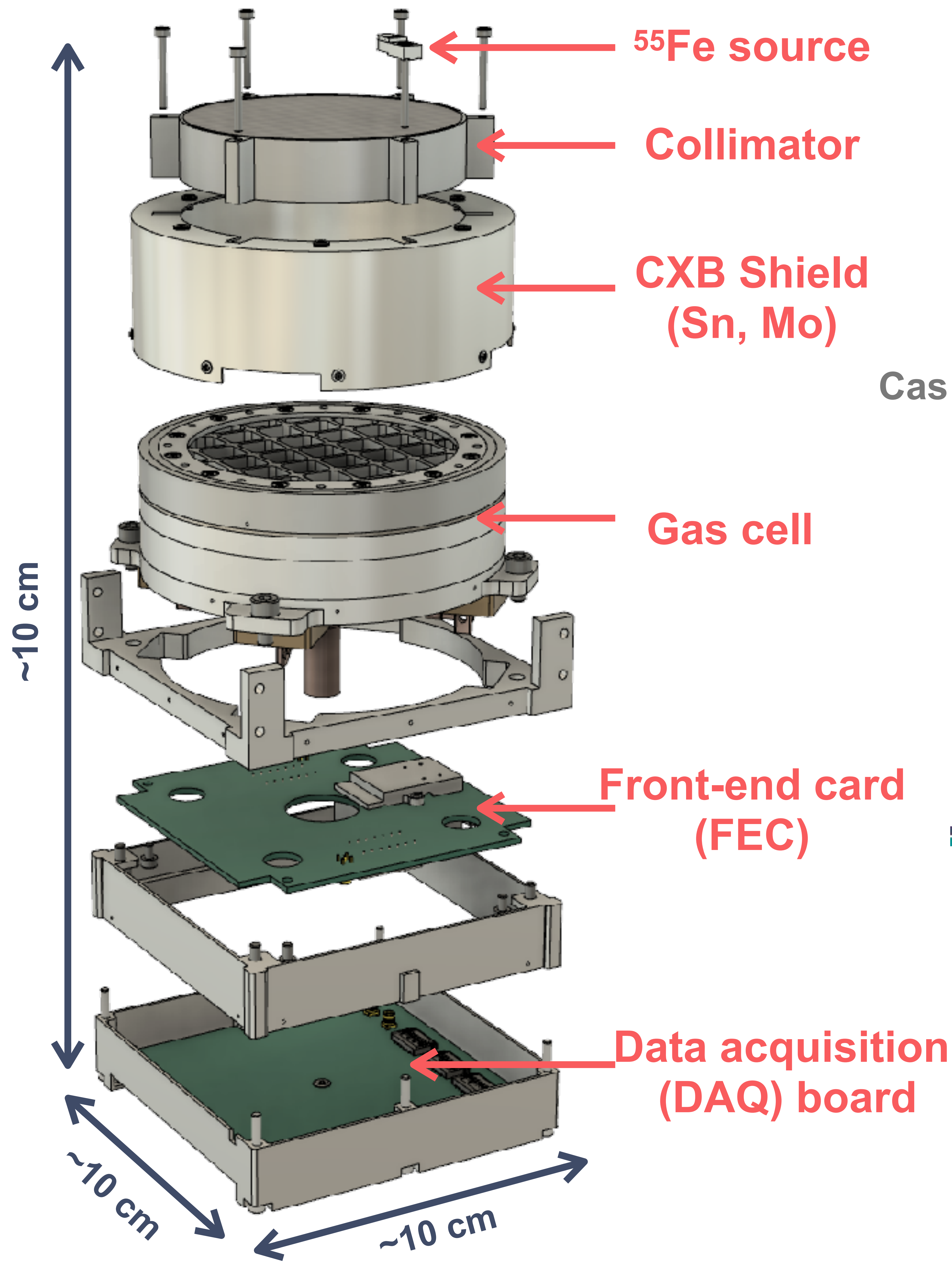
[SSC23-WIII-01]

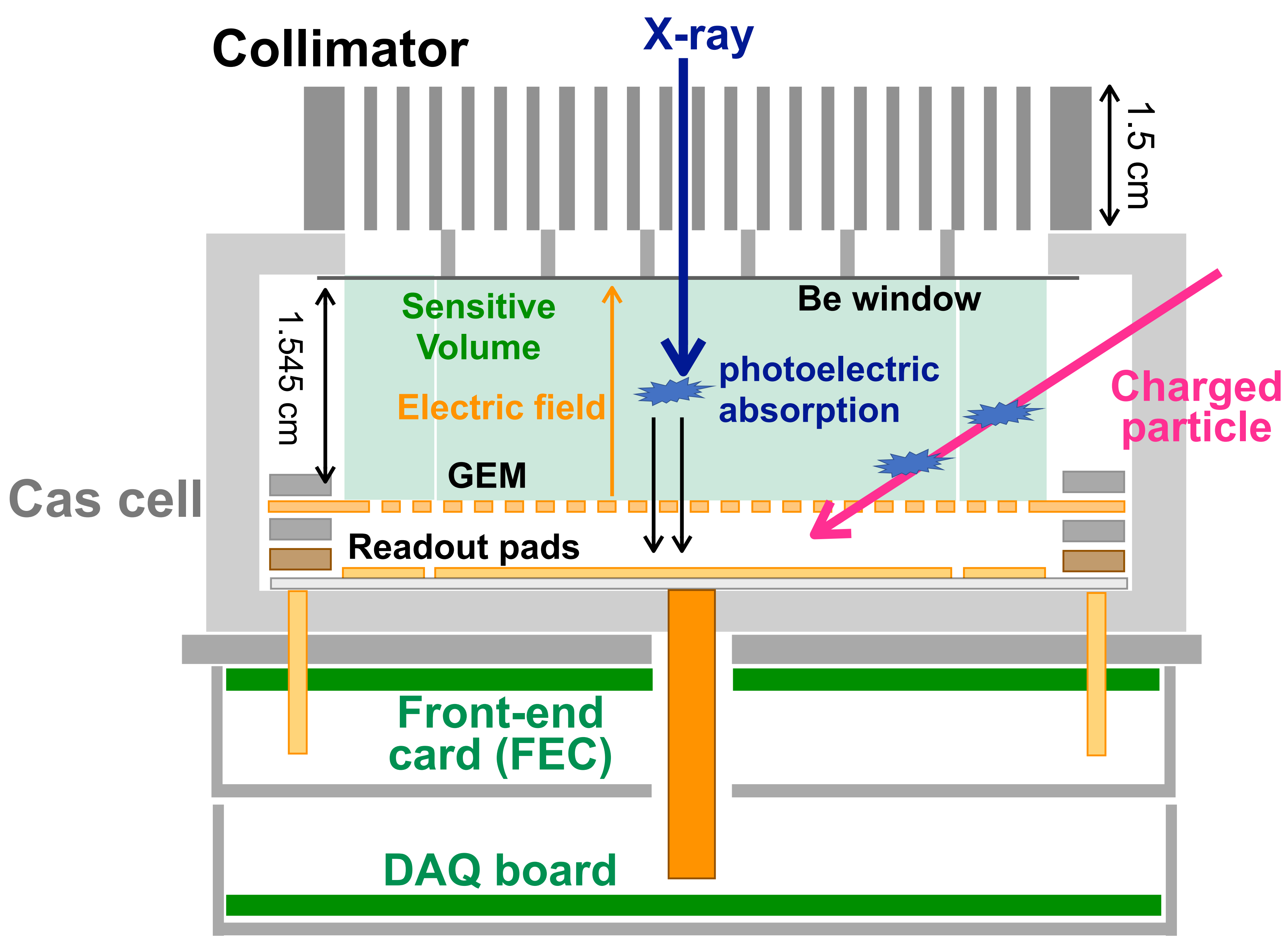
- In X-ray astronomy, agile and flexible CubeSat can play a complementary role to large satellites.
- NinjaSat is a 6U CubeSat X-ray observatory to be launched in October 2023.
- The NinjaSat science payload is Gas Multiplier Counter (GMC), sensitive in the 2–50 keV band. GMCs has a largest effective area (32 cm^2 at 6 keV) compared to the previous X-ray detector onboard CubeSats.
- The satellite has passed the performance verification test and space environmental test and is ready for launch.

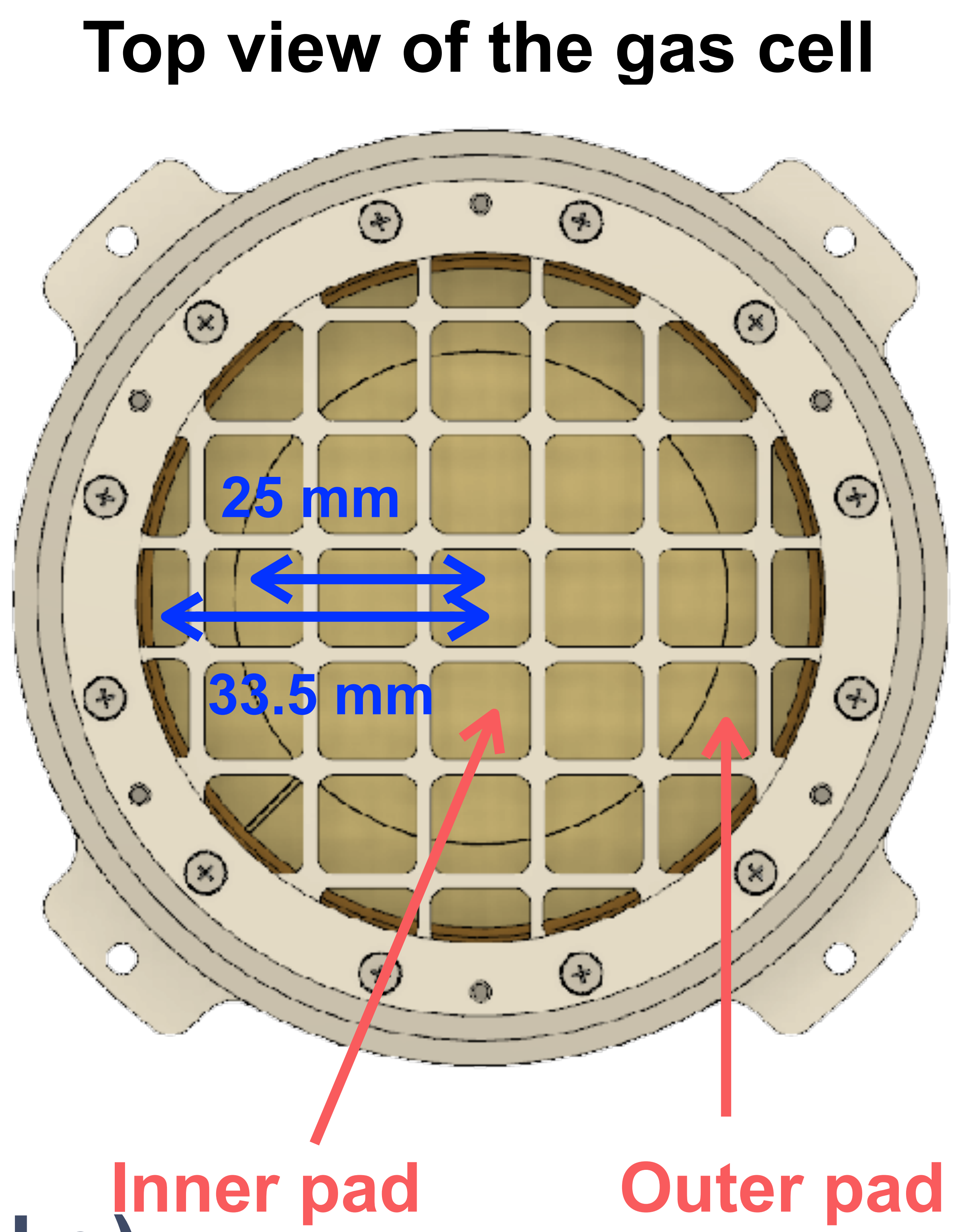
Related talks
- RBM : Kato (2:15 PM today)
- Mission : Tamagawa (5:30 PM today)

Backup slides

Gas Multiplier Counter (GMC)







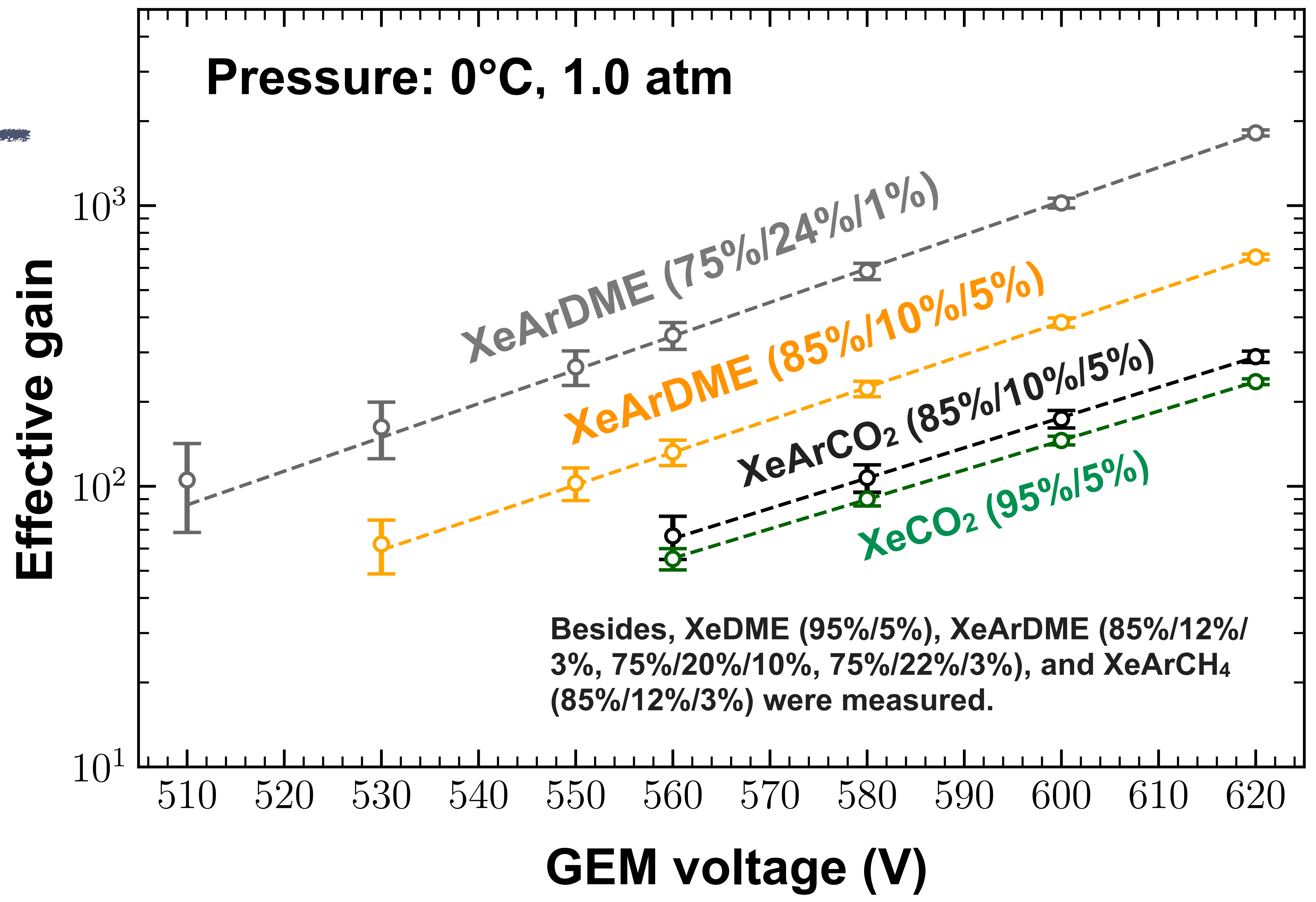
- **1U-size gas X-ray detector (1.2 kg)**
  - Energy bandpass 2–50 keV
  - Sealed gas: XeArDME (75%/24%/1%) @0°C, 1.2 atm
  - Gas Electron Multiplier (GEM): amplify #of electrons > 300
  - Two readout pads: anti-coincidence for background rejections

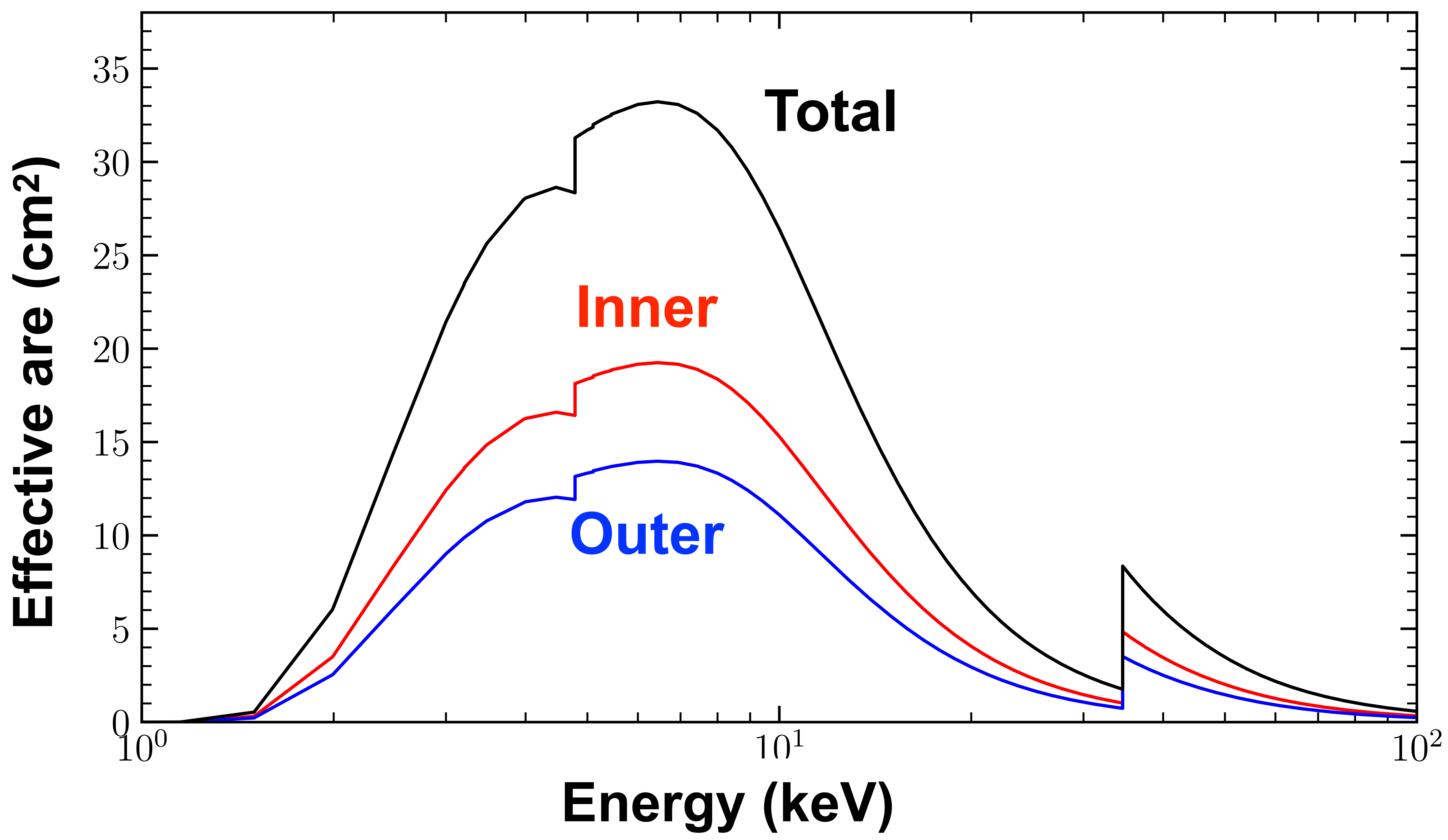
Selection of the sealed gas

- **Requirements**
  - Sensitivity to the high energy X-rays >10 keV => candidate: Xe gas mixtures @0°C, 1.2 atm
  - GEM gain > 300 to improve S/N ratio
  - **In the case of GEM, no gases met these requirements in previous studies.**

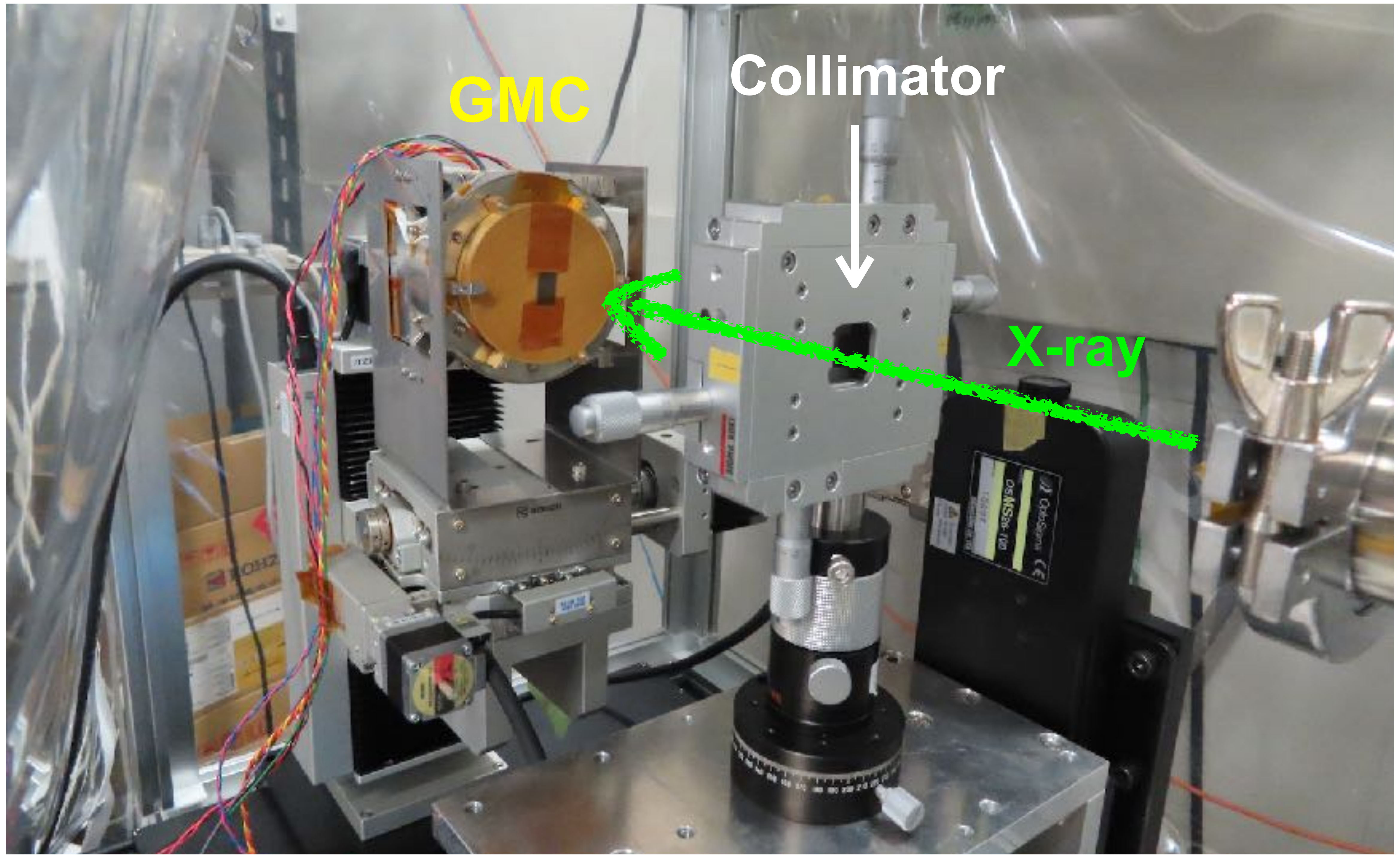
- **Gain measurements**
  - for 9 gases, gains were measured @0°C, 1 atm
  - XeArDME mixture can achieve high gain
  - We selected XeArDME (75%/24%/1%)

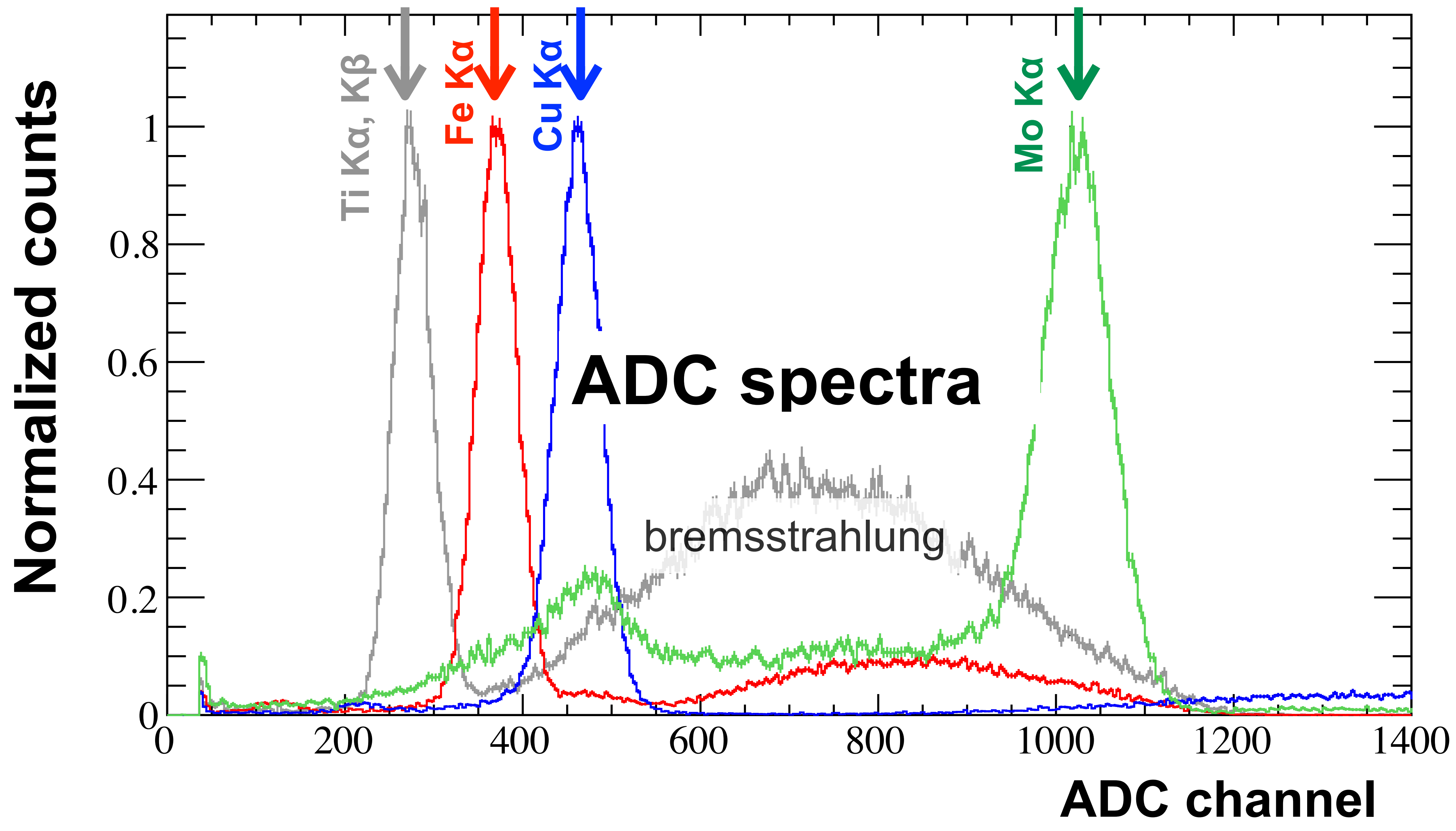
- **Effective area**
  - Total ~ 32 cm² @6 keV for 2 GMCs
    - Largest effective area in the 2-50 keV band compared to previous CubeSats
  - Expected 2-20 keV rate for Crab: ~80 cps

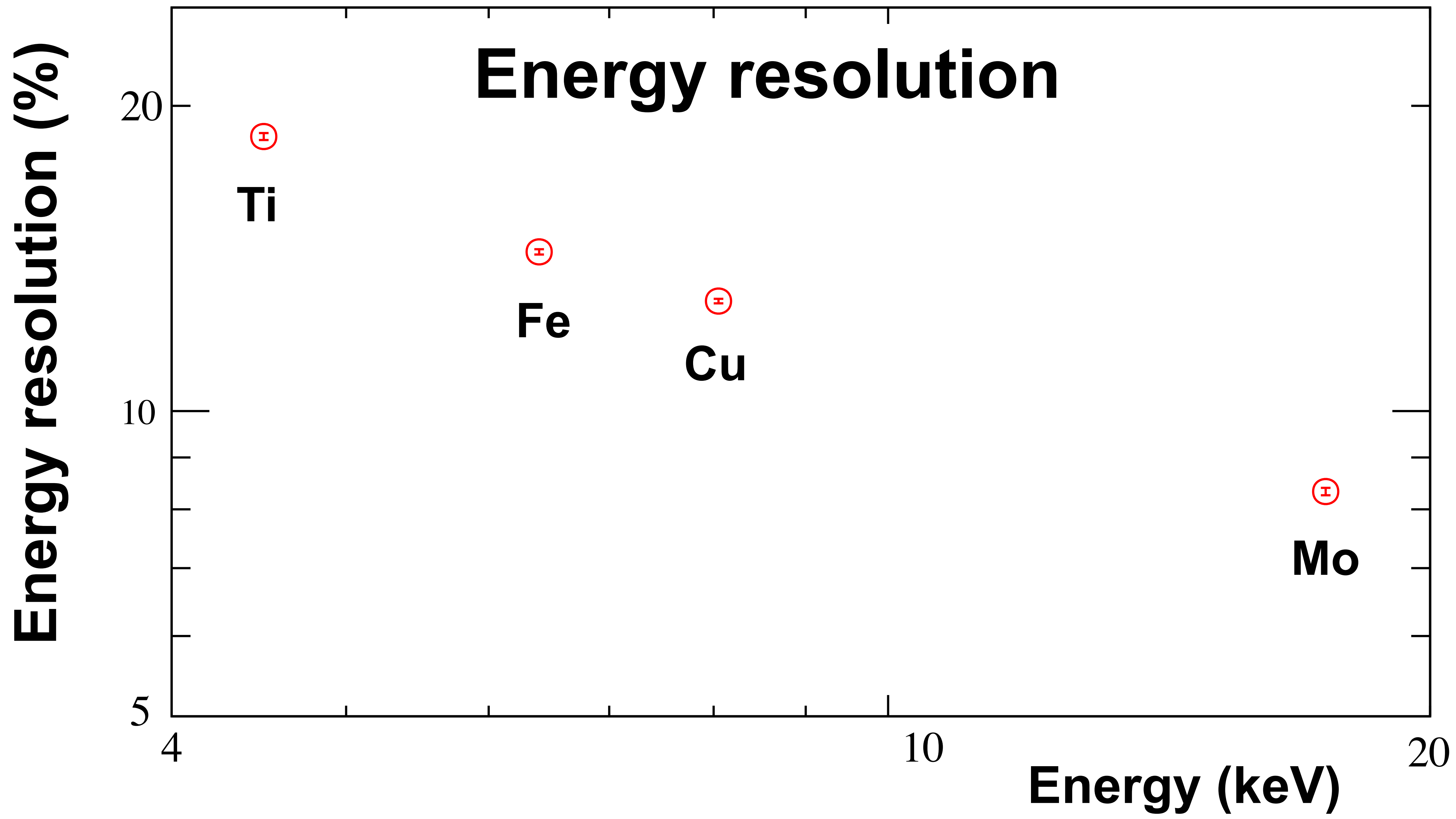




Performance test with an X-ray generator



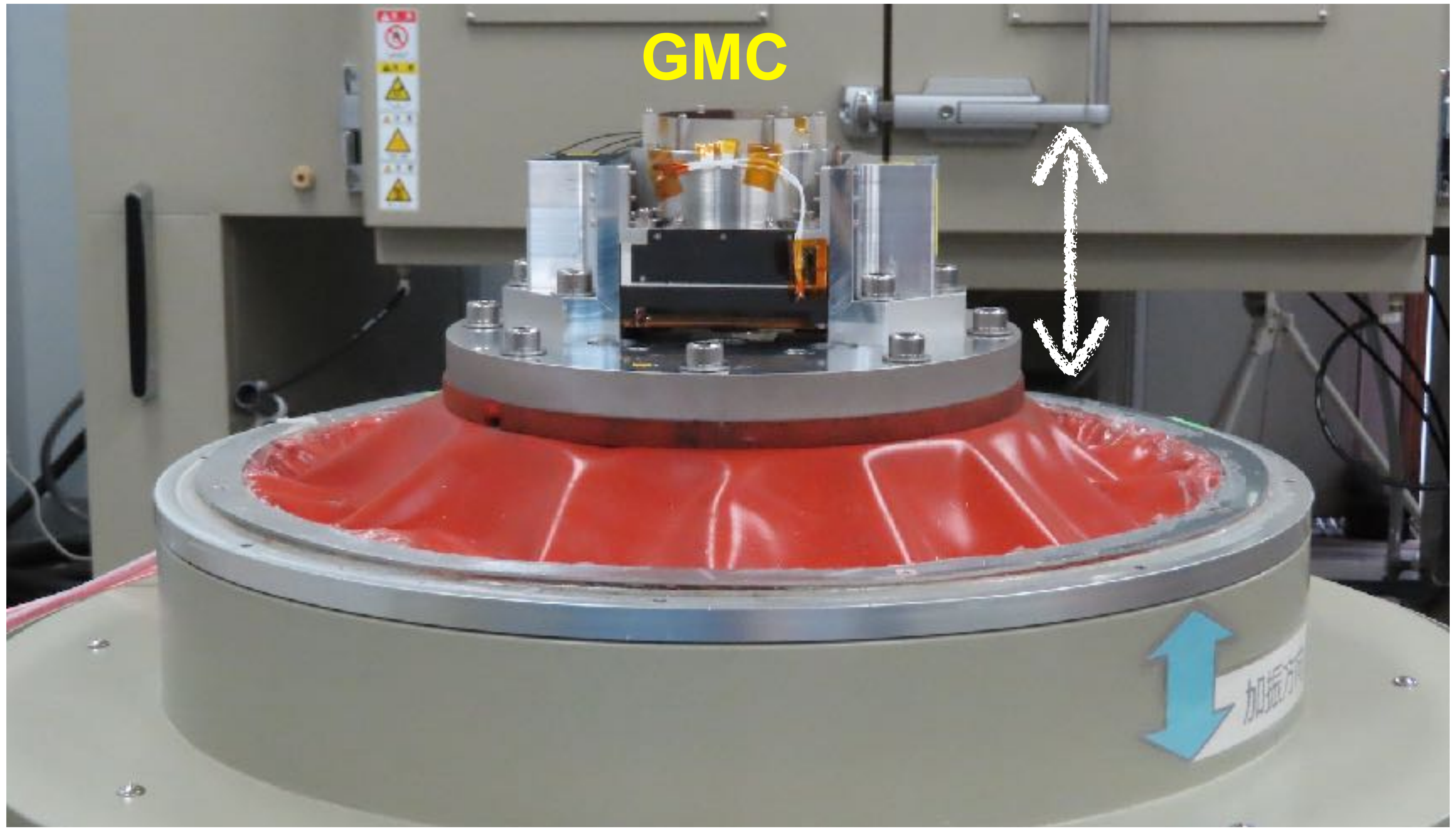




- X-ray generator
  - 4 energy: 4.5 (4.9), 6.4, 8.0, and 17.5 keV
  - Beam size: 40 x 40 um^2
- **Energy resolution**
  - almost proportional to $E^{-1/2}$
  - ~ 14.4% @6.4 keV (FWHM)

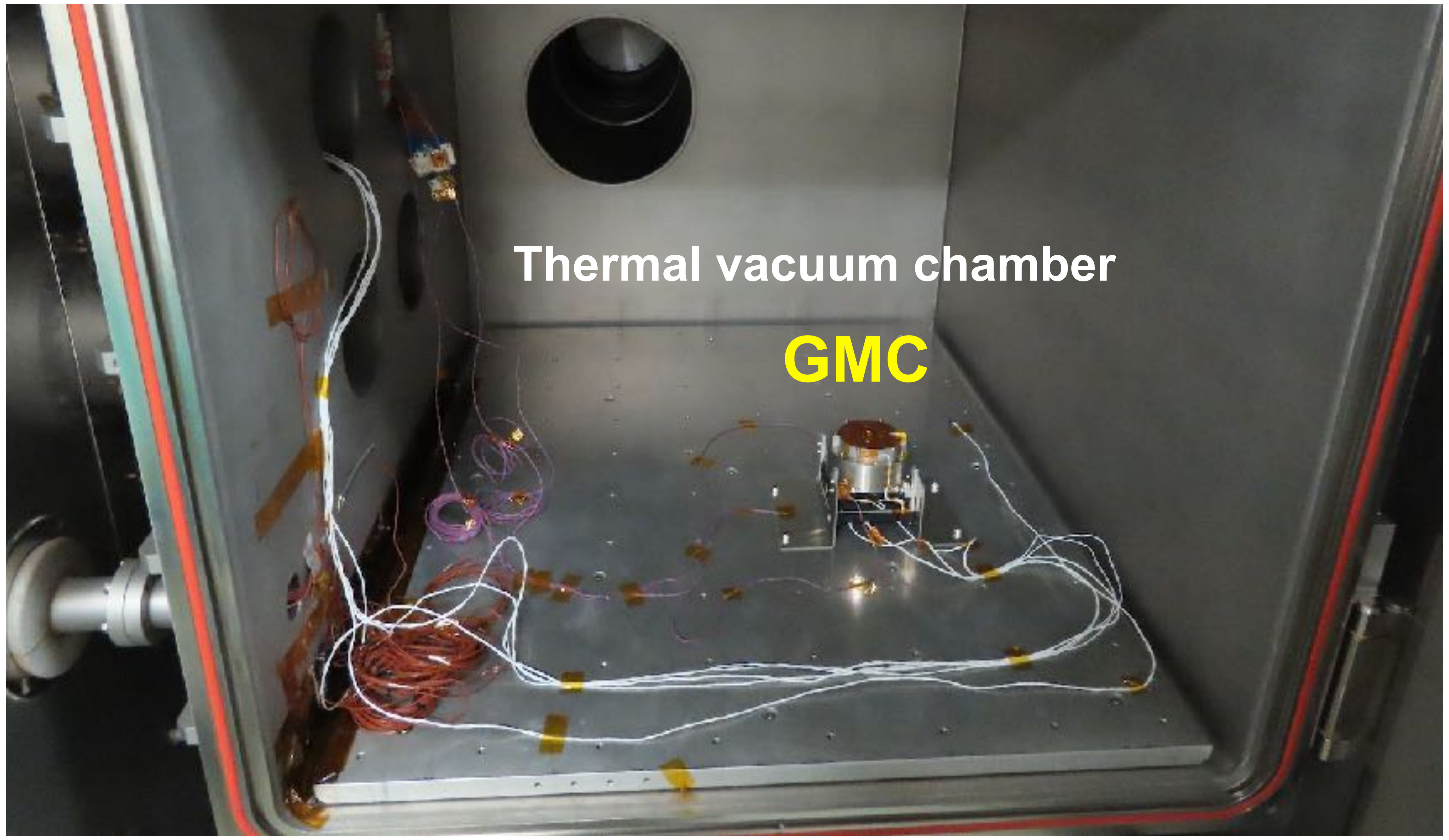
Space environmental testings

Vibration test



- Performed for the 3 axes (XYZ)
- Resonance survey
  - Resonance frequency > 1250 Hz
- Random vibration
  - SpaceX falcon9 acceptance level (5.13 Grms)

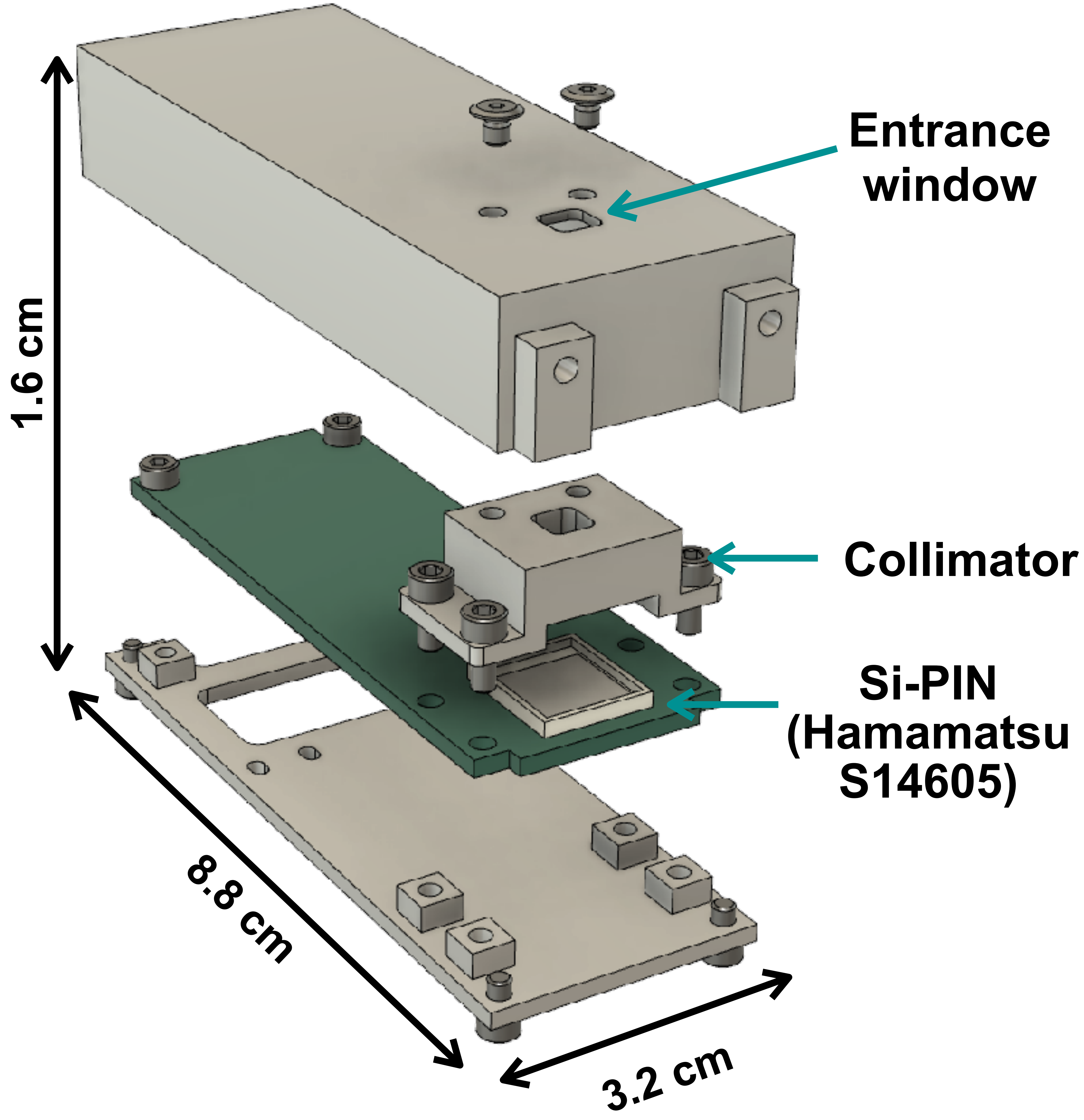
Thermal vacuum test



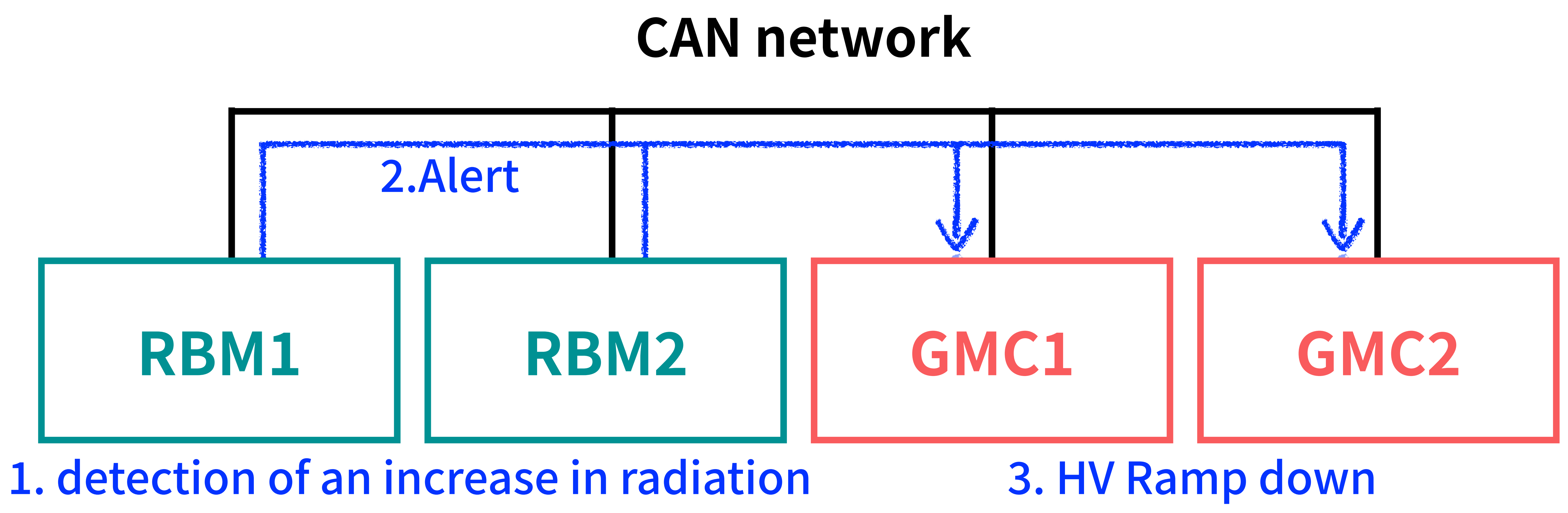
- Pressure: ~10^{-4} Pa
- Temperature range: −30 ~ +60°C (satellite survival temperature)
- 4 cycles

Three flight model GMCs passed both tests

Radiation Belt Monitor (RBM)



- GMCs will ramp down high voltage by the scheduled command when passing through high radiation regions (South Atlantic Anomaly; SAA, aurora belt)
- **Radiation Belt Monitor (RBM) x 2**
  - Role: detect unexpected radiation increase such as solar flares and send alerts to the GMCs
  - use Si-PIN photodiode (9 x 9 cm^2, 500 μm thick) to measure charged particles



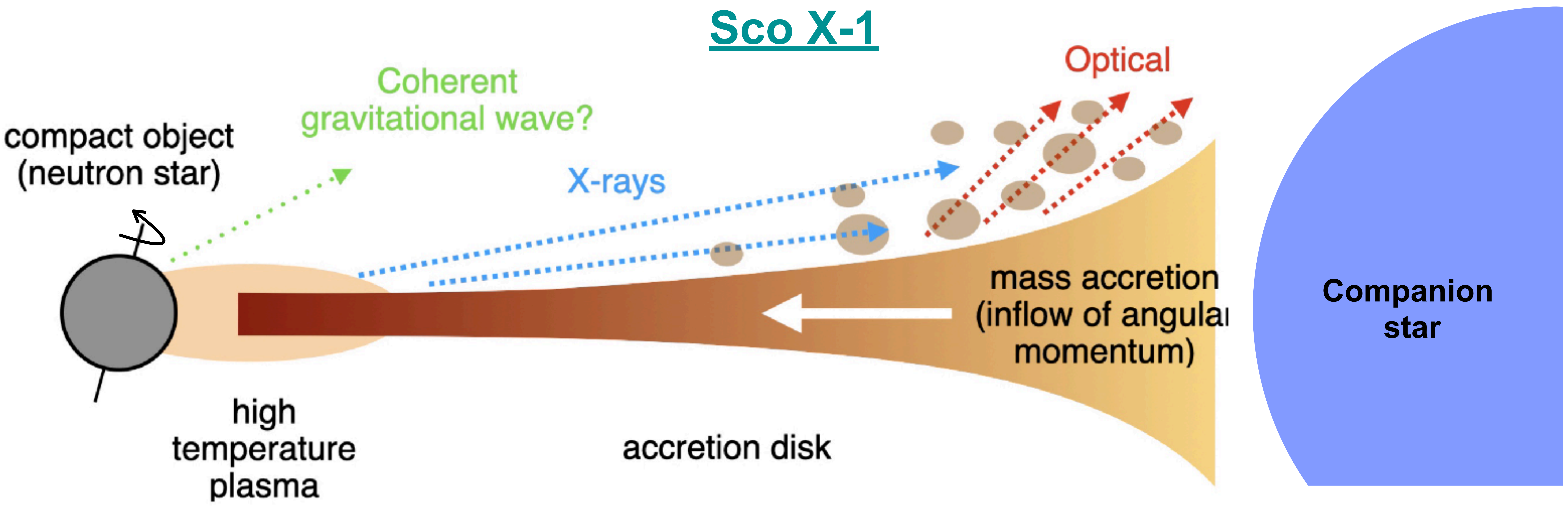
NinjaSat observation strategies

- CubeSat should have different observational strategies from large satellites
- The observation time of large satellites is shared among many users and is therefore limited for each X-ray object.
  In contrast, CubeSat will conduct a more flexible observation program.

- **NinjaSat observation strategies**
  1. **Long-term monitoring** of persistently bright sources simultaneous with high time-resolution optical observation and radio observations (e.g., Scorpius X-1).

  2. **Flexible and prompt follow-up observations** of bright X-ray transient discovered with an all-sky survey such as MAXI (e.g., new blackholes, neutron stars).

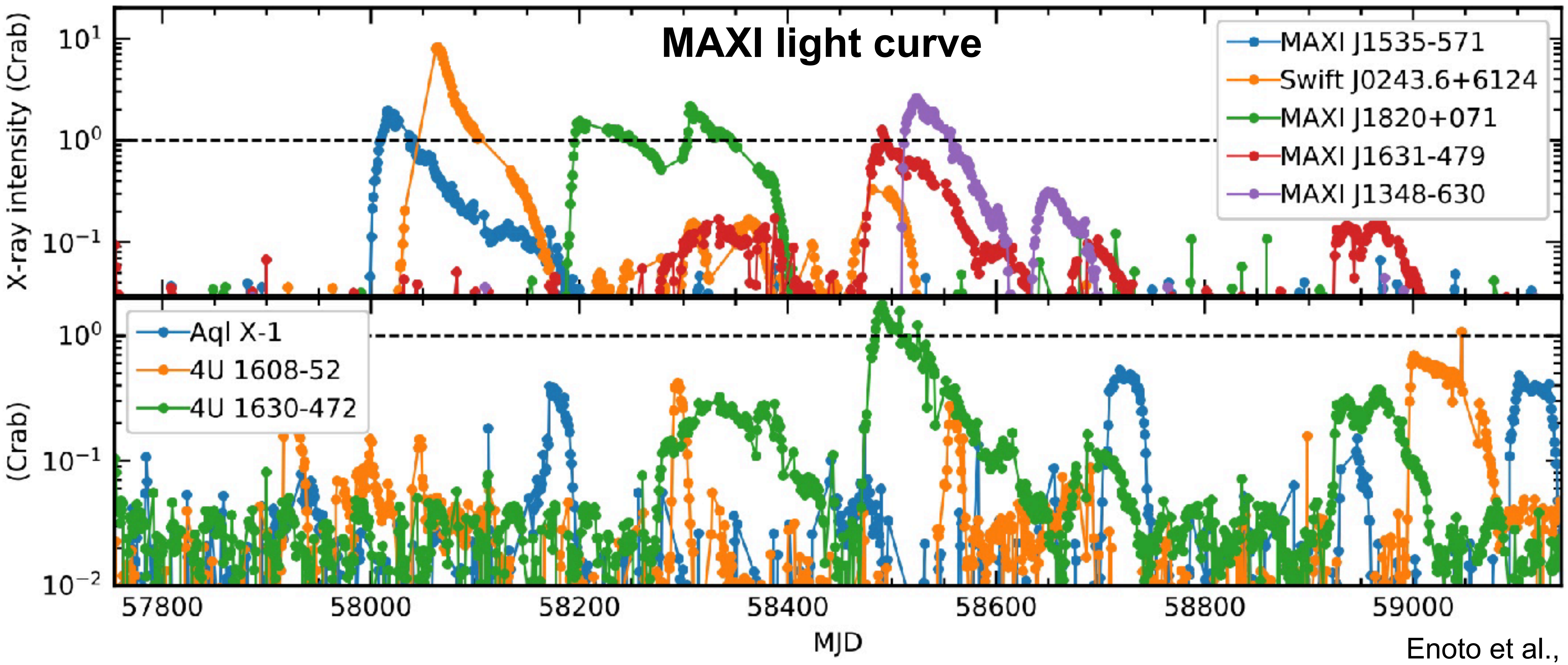
Long-term multi-wavelength observation



Enoto et al., SPIE proceeding (DOI: 10.1117/12.2561152)

- **Fast time-variability has been observed from Sco X-1**
  - Instabilities of mass accretion onto the neutron star
  - Dramatic change of the geometry of the inner accretion flow
  - Sporadic release of magnetic energy
- **Simultaneous multi-wavelength observation for fast time-variability (sec scale)**
- **There are only a few observations due to the lack of dedicated satellites**

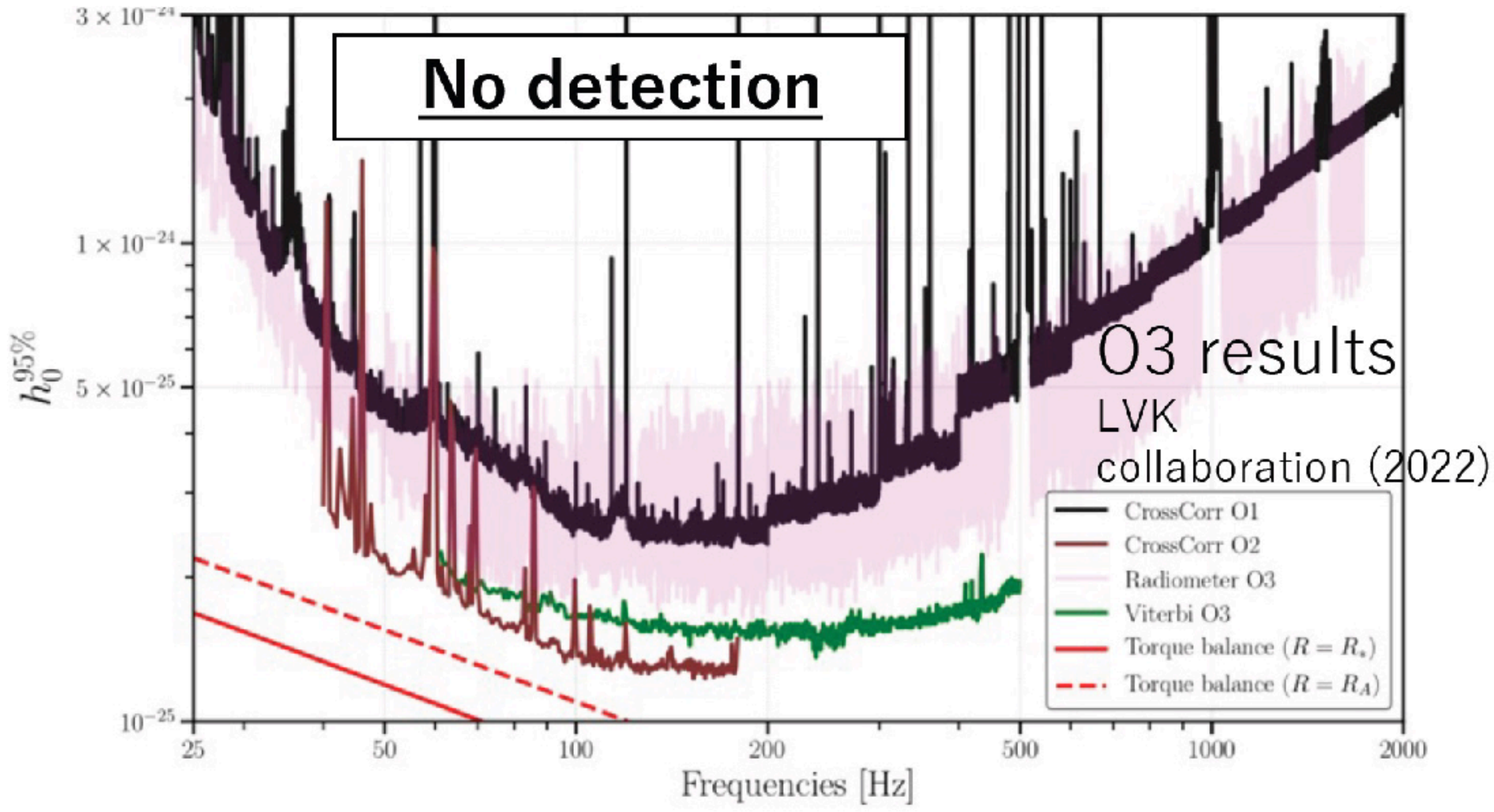
Follow-up observation

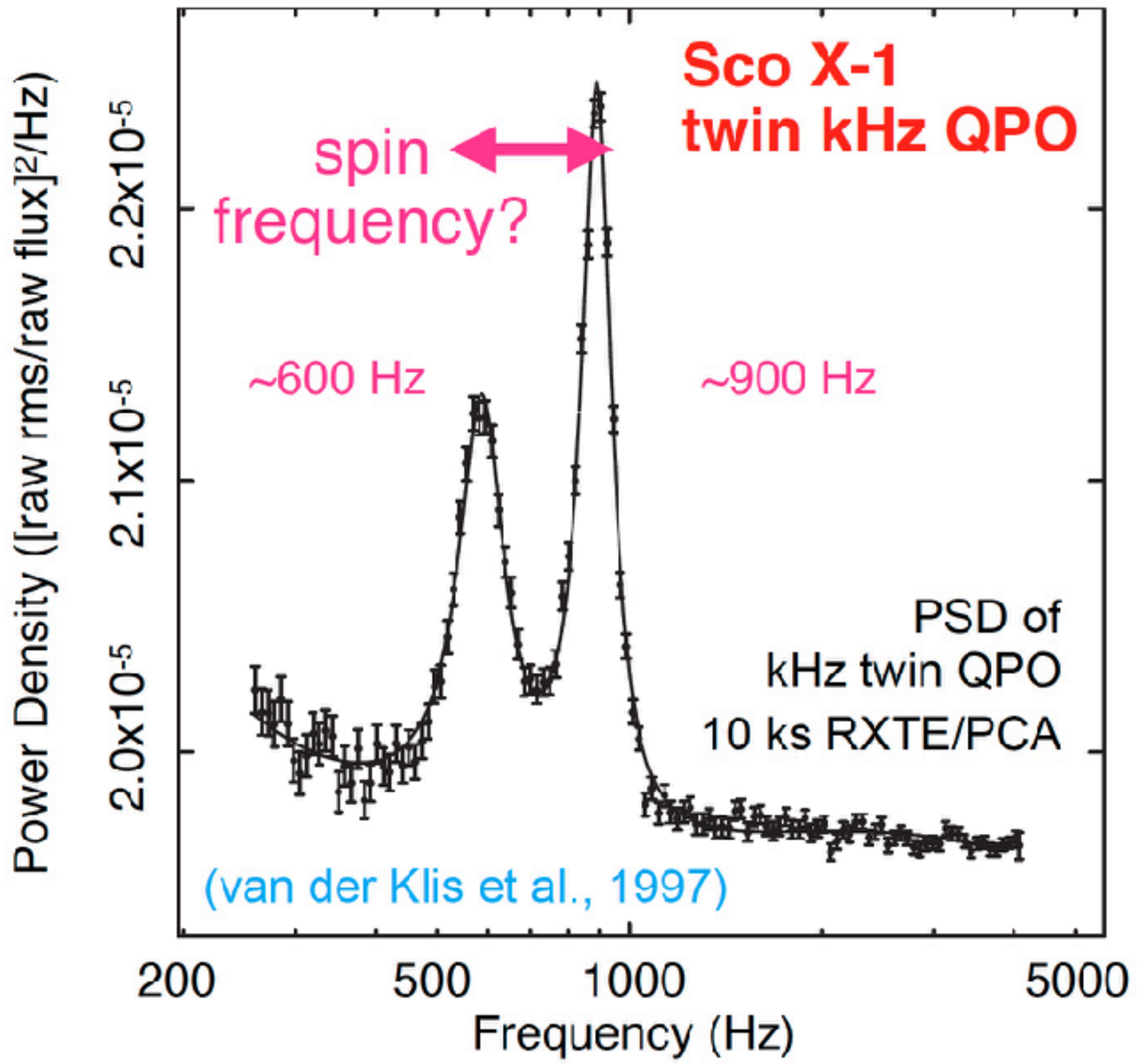


Enoto et al., SPIE proceeding (DOI: 10.1117/12.2561152)

- **The number of transients has been rapidly increasing**
- **Difficulty for large X-ray satellites to observe bright sources**
  - Instrumental (pile ups)
  - Limitation of scheduling
- **Flexible and prompt follow-up observations of transients using CubeSat**

Scorpius X-1 — Continuous gravitational wave (CGW)





- **X-ray variation of Sco X-1 shows the twin kHz Quasi-Periodic Oscillation (QPO)**
  - Frequency difference is proposed to correspond with the spin frequency.
  - But, fluctuate with mass accretion rate…
- Long-term monitoring of QPOs can be useful for CGW search.