Application of Micro Pattern Gaseous Detectors in Space X-ray Polarimetry

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on behalf of the eXTP–PFA Consortium and WXPT Group

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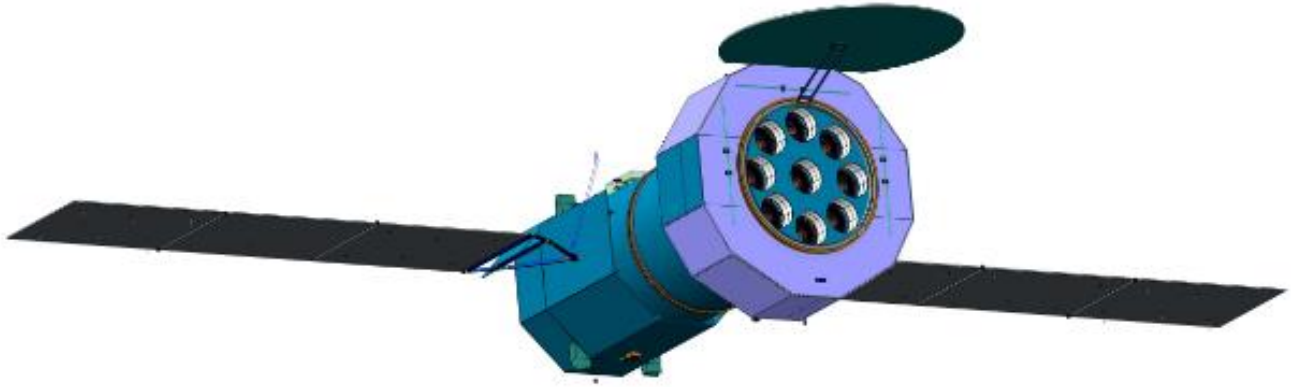
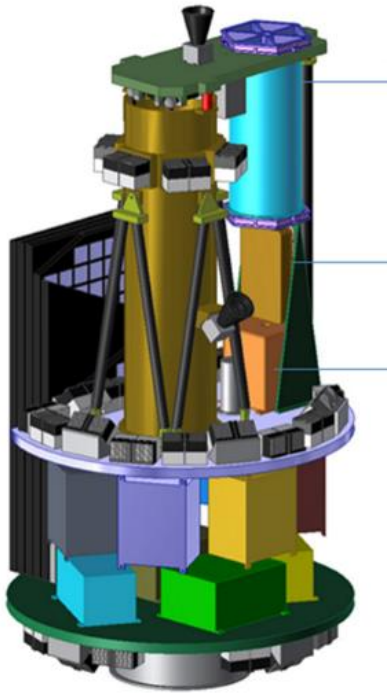
Outline

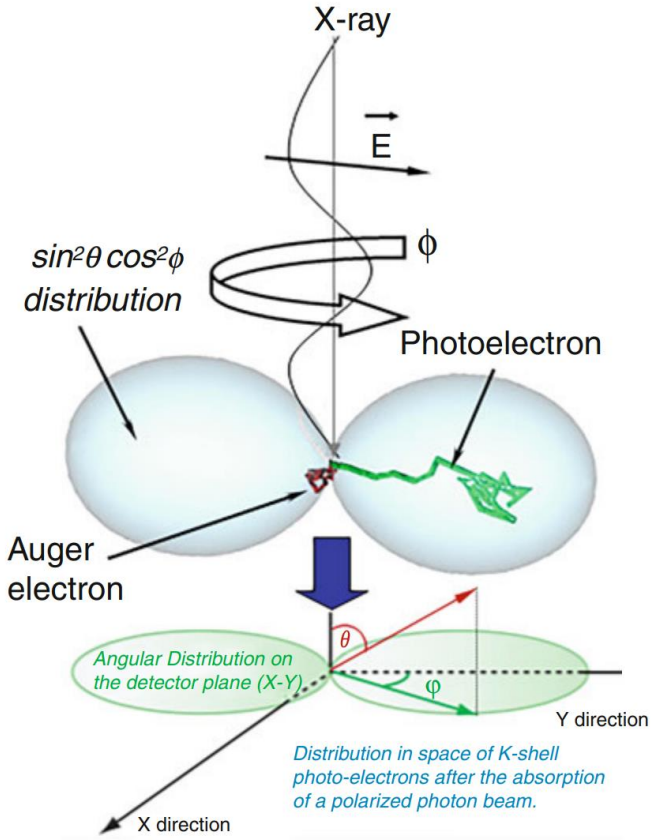
1. Overview of Space X-ray Polarimetry
2. GPD in eXTP mission
3. TPC in WXPT mission
4. Summary



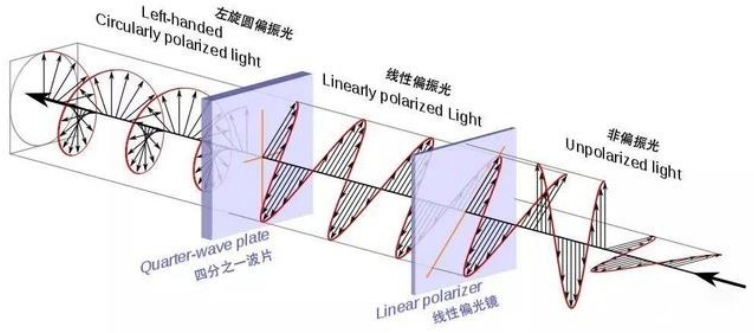


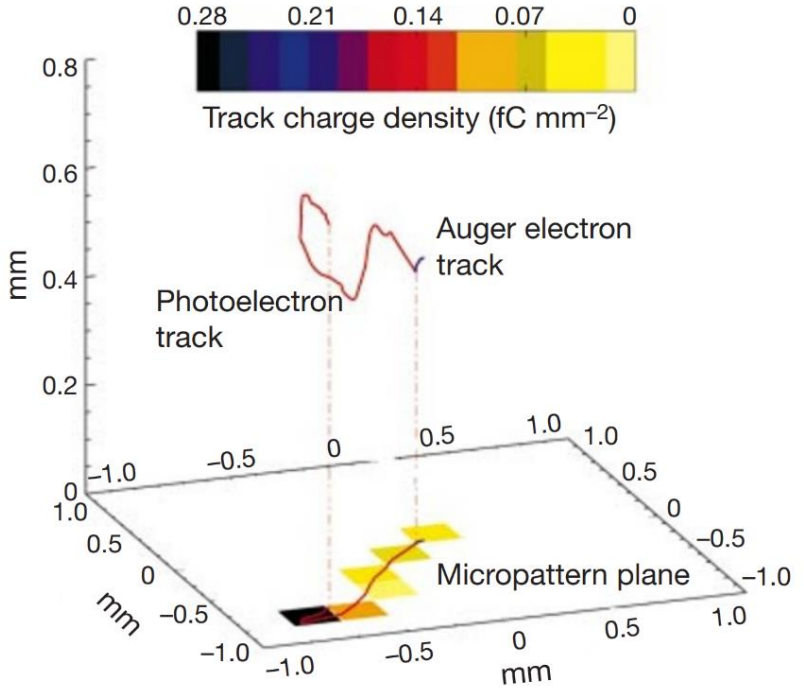
X-ray Polarimetry

$$\frac{\partial\sigma}{\partial\Omega} = r_0^2 \frac{Z^5}{137^4}\left(\frac{mc^2}{h\nu}\right)^{7/2} \frac{4\sqrt{2}\sin^2\theta\cos^2\varphi}{(1-\beta\cos\theta)^4}$$

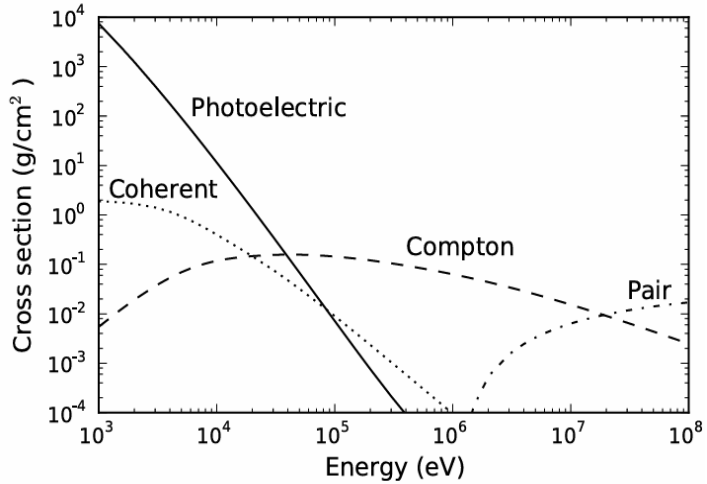


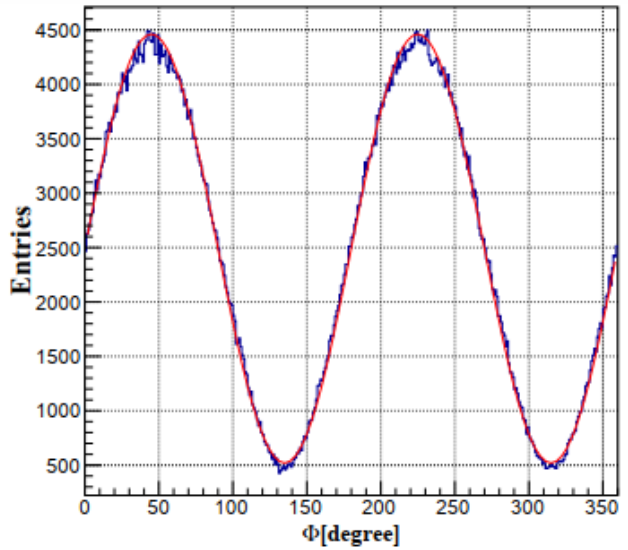
Feng, H. & Bellazzini, R., NatAs, 4, 547 (2020)





Costa, E., et. al, Nat 411, 662(2001)





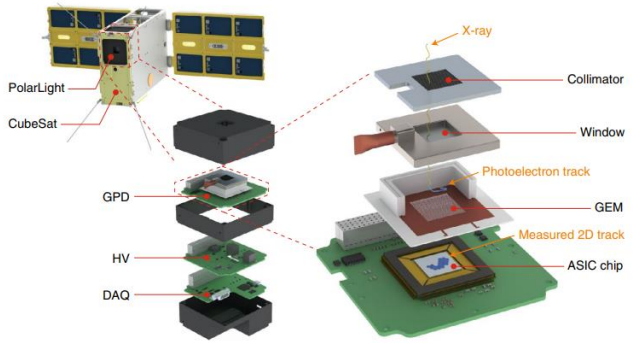
Modulation factor $\mu = \frac{S_{\max} - S_{\min}}{S_{\max} + S_{\min}}$

Timeline of Space X-ray Polarimetry Missions

1969 — Aerobee 350
Crab Nebula
15.4%±5.2%
Novick, R. et al., ApJ, 174, L1 (1972)

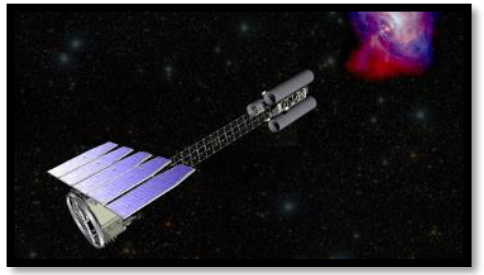
1975 — OSO-8
Crab Nebula
19.2%±1.0%
Crab
15.7%±1.5%
Weisskopf, M. C. et al, ApJ, 208, L125 (1976)
Weisskopf, M. C. et al., ApJ, 220, L117(1978)

2018 — PolarLight
Crab
$15.3\%^{+3.1\%}_{-3.0\%}$
Feng, H. et al., NatAs, 4, 511 (2020)

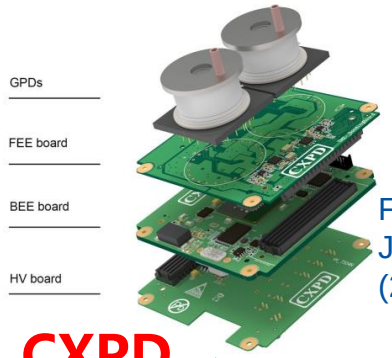


Feng, H. & Bellazzini, R., NatAs, 4, 547 (2020)

2022 — PolarLight2 / IXPE

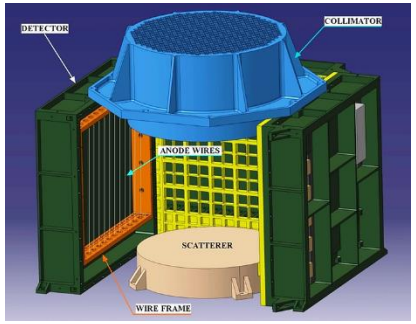


2023 — CXPD



Feng, HB. et al., JINST, 19, 4039 (2024)

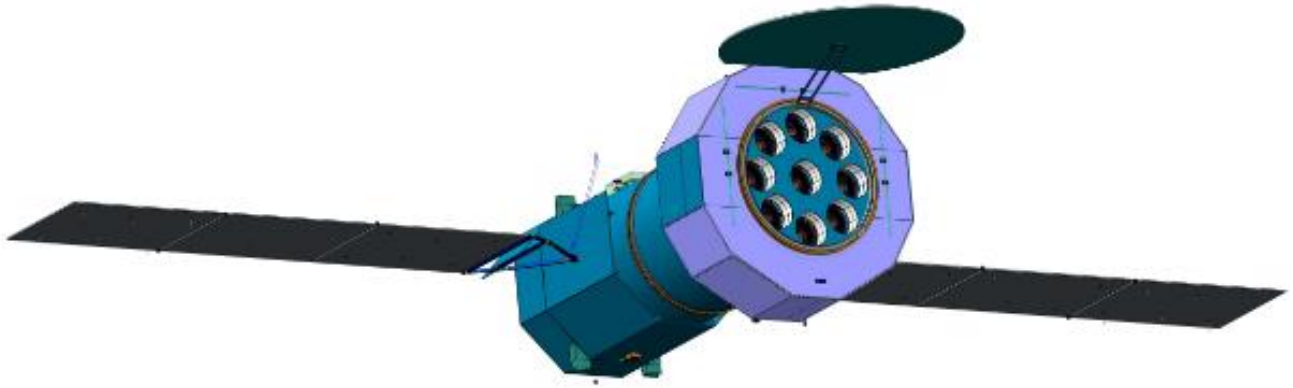
2024 — XPoSat



enhanced X-ray Timing and Polarimetry Mission（eXTP）

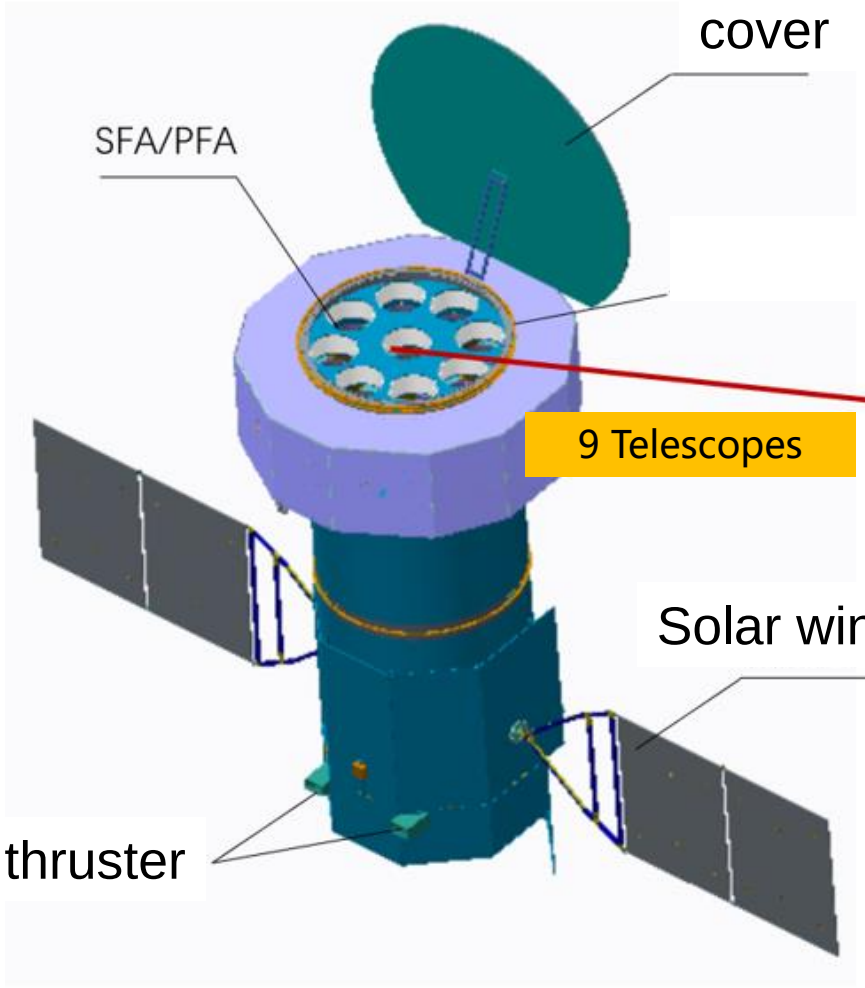
- Scientific Objectives：Understanding the extreme laws of astrophysics under conditions of extreme gravity, extreme magnetic fields, and extreme density through the observation of black holes, neutron stars, or quark stars.
- Detection Capability：0.5-10 keV，~2700 cm^2@6 keV；High time resolution, high energy resolution, and high precision polarization detection

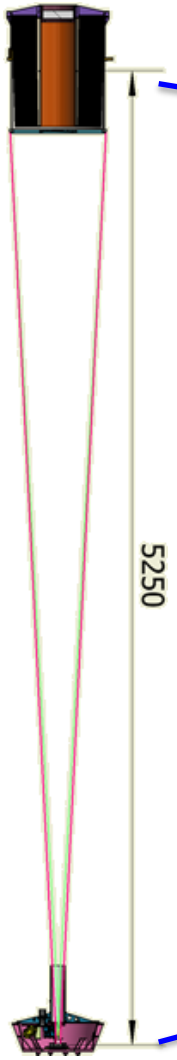
- Satellite Design：
  - Apogee altitude of 110,000 km, highly elliptical orbit.
  - Total weight of 4.0 tons
  - designed lifespan of 5 (goal 8) years.



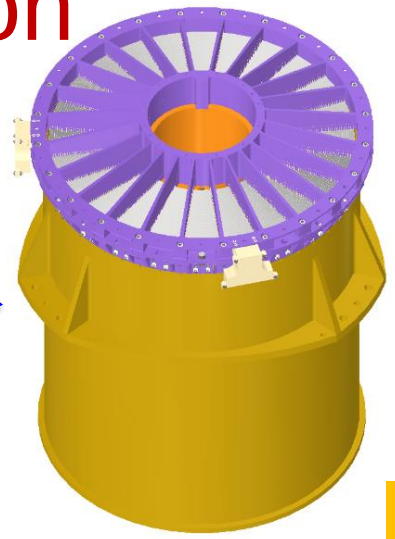
- Status：
  - The next-generation flagship X-ray space observatory of China,
  - Scheduled for launch in 2030.

eXTP payload and satellite configuration

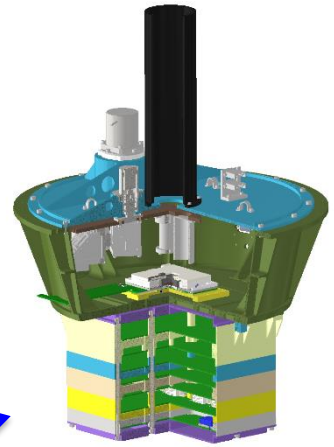




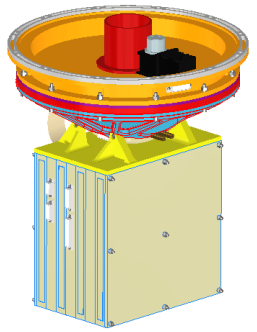
Focal length 5250mm



Wolter I Mirrors (9)



PFA (3)



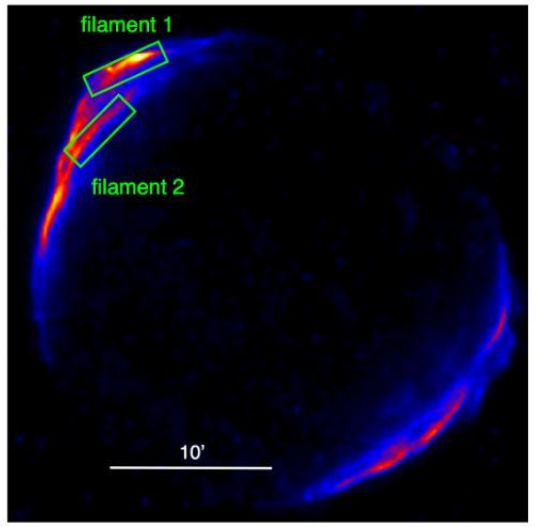
SFA (6)

GPD is Designed by the INFN-Pisa group (Bellazzini et al.)

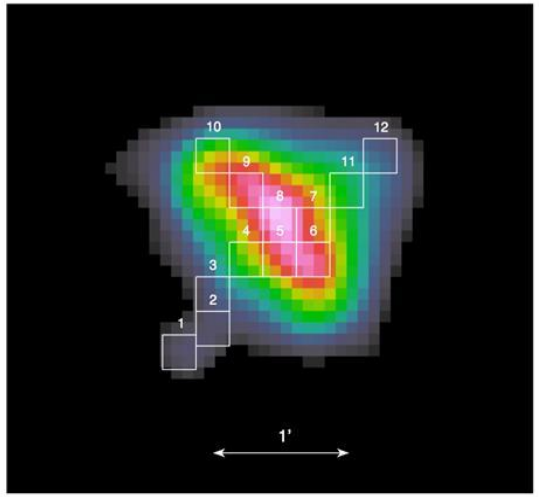
Polarimetry Focusing Array(PFA) onboard eXTP

What can PFA do:

- Imaging
- Polarimetry
- Timing
- Spectrometry



Simulating results of the imaging polarization for the SN1006



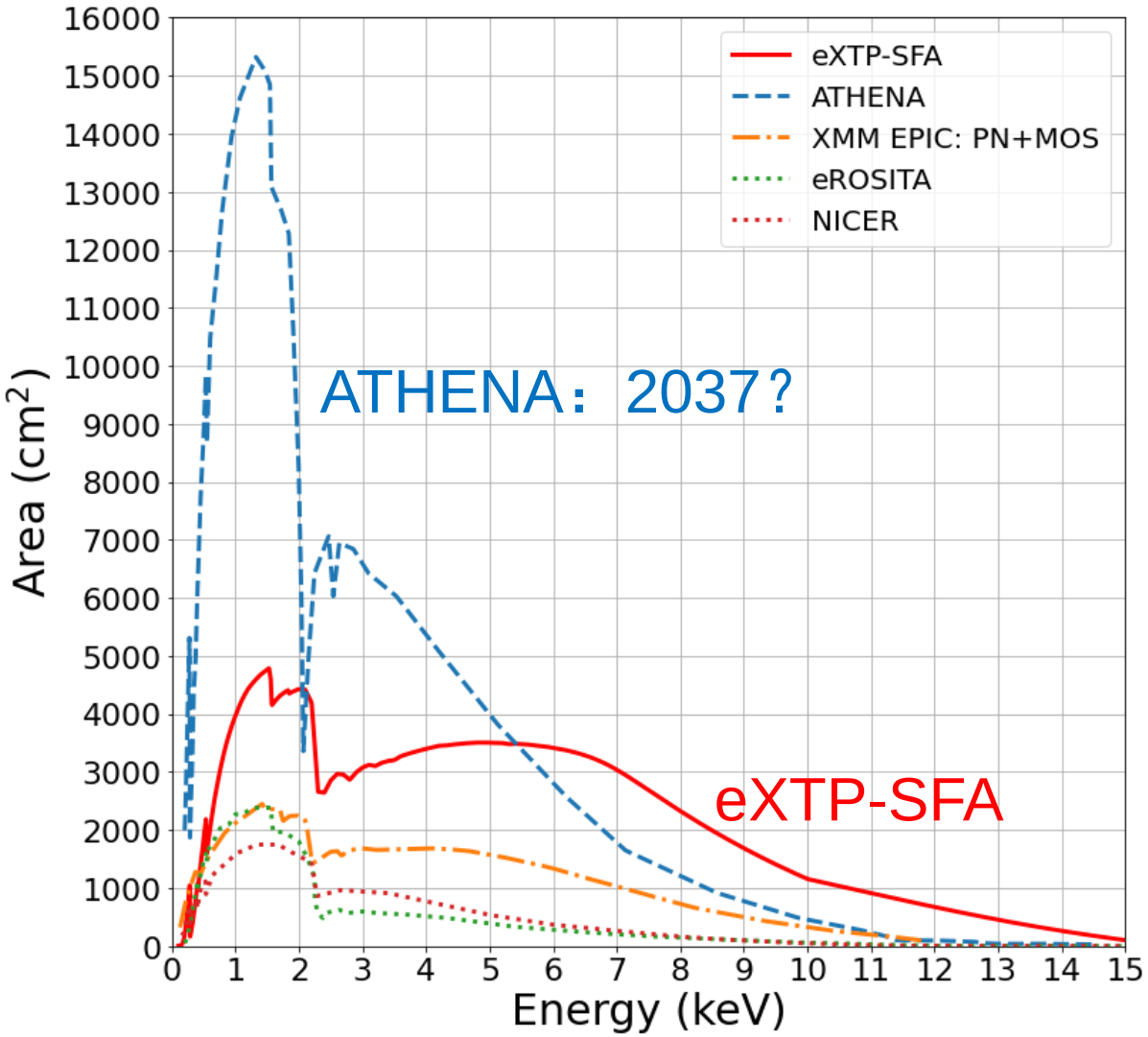
Simulating results of the imaging polarization for crab

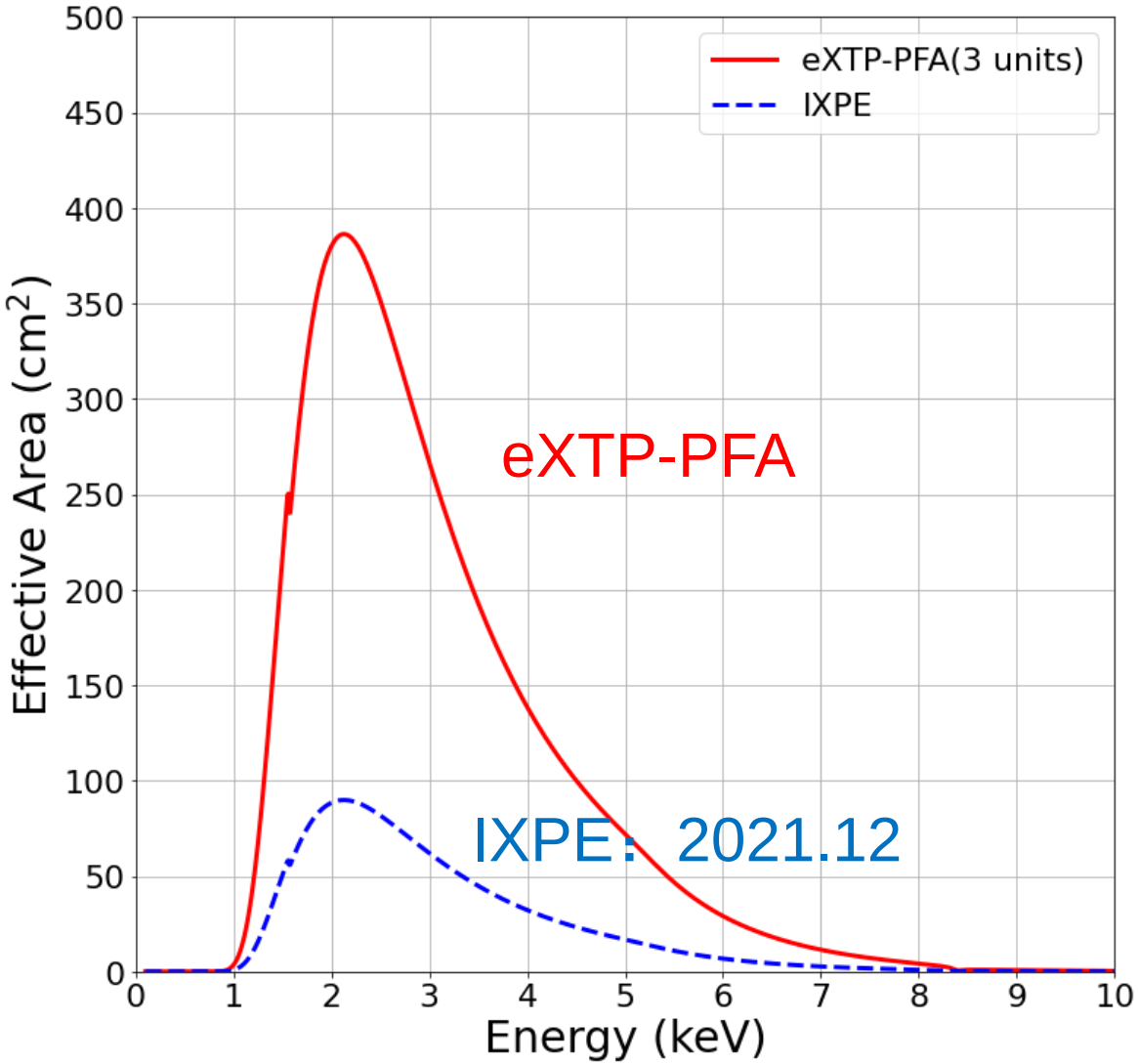
eXTP payload configuration

Payload	Configuration	Technical performances
Spectroscopy Focusing Array (SFA)	6 focusing telescopes. Focal length：5.25m Focal plane detector： multi pixels SDD array	Effective Area：≥ 3300 (4000) cm^2 (1-2keV)；≥ 2000 (2700) cm^2 @ 6 keV Energy range：0.5~10 (0.3-10) keV；Energy resolution：≤ 180 (150) eV@ 6 keV FOV：≥ ϕ12 arcmin； Angular resolution：HPD ≤ 1 arcmin，W90 ≤ 3 arcmin Timing resolution：≤ 10 μs；Timing accuracy ≤ 1 (0.5) μs Dead time：≤ 6% @ 1 Crab
Polarimetry Focusing Array (PFA)	3 focusing telescopes. Focal length：5.25 m Focal plane detector： Gas pixel detector(GPD)	Effective Area：≥ 180 (220) cm^2@3 keV Energy range：2~8 keV；Energy resolution：≤ 1.8 (1.5) keV@ 6 keV FOV：8 arcmin (square)，Angular resolution：HPD < 30 (15) arcsec Minimum detectable polarization（MDP）：≤ 3% (1mCrab, 10^6s) Timing resolution：≤ 10 μs；Timing accuracy ≤ 4 μs

The PFA is a China-Italy joint payload led by CAS/IHEP.

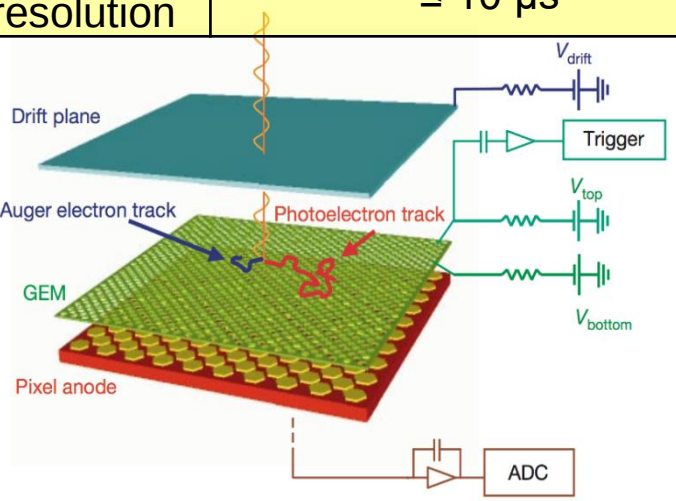
Effective Area of eXTP



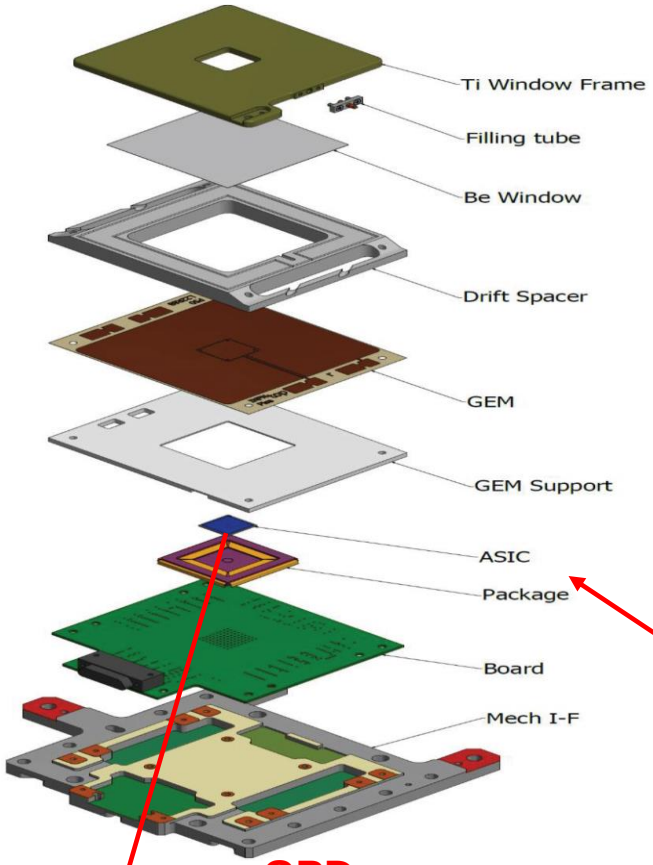


PFA focal plane camera design

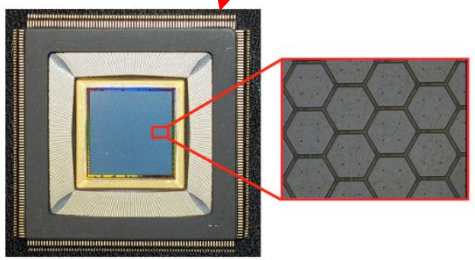
	PFA
Detector	GPD
Det Aera	≥ 12×12 mm^2 (8′)
Position resolution	≤ 0.2 mm (8″)
Energy range	2-8 keV
Energy resolution	≤1.8 keV @ 6 keV
Modulation factor	≥ 50% @ 6keV
Timing resolution	≤ 10 μs



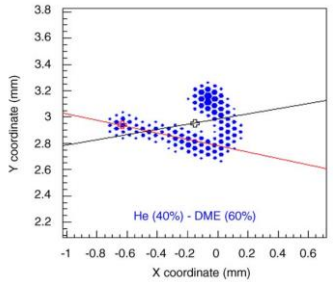
GPD configuraion



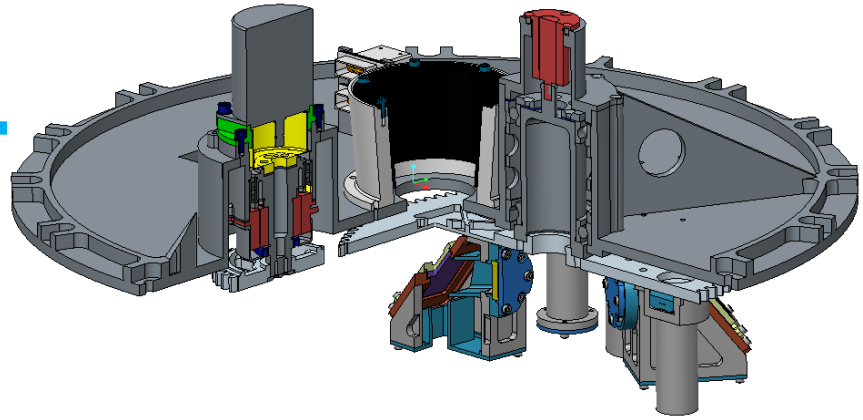
GPD



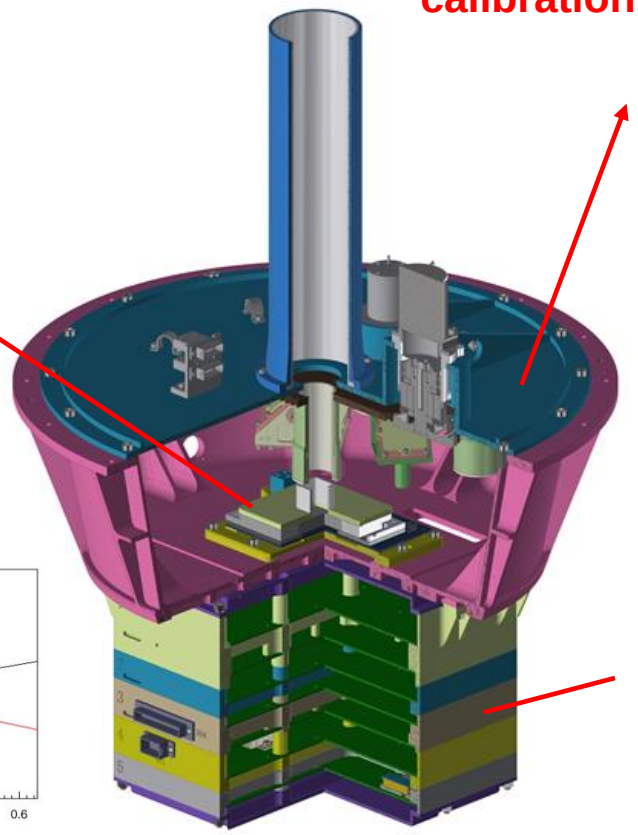
ASIC



Baldini, L., et. al, Astro Phys, 133 (2021)



Filter and calibration Wheel



PFA focal plane camera

Technical specification of GPD

Parameter	Value
Thickness of the absorption gap	10 mm
Thickness of the transfer gap	0.7 mm
Thickness of the Be window	50 μm
Active area	15×15 mm^2
Readout pitch	50 μm
Gas Volume	$60 \times 60 \times 10$ mm^3
Gas mixture	Pure DME
Filling pressure	800 mbar

Parameter of GPD

Parameter	Value
Number of pixels	105600 (300×352)
Horizontal pitch	50.00 μm
Vertical pitch	43.30 μm
Shaping time	4 μs
Pixel gain	$\sim$ 400 mV fC^{-1}
Pixel Noise	22.5 e^- ENC
Dynamic range	1 V ($\sim$ 30k e$^-$)

Parameter of ASIC

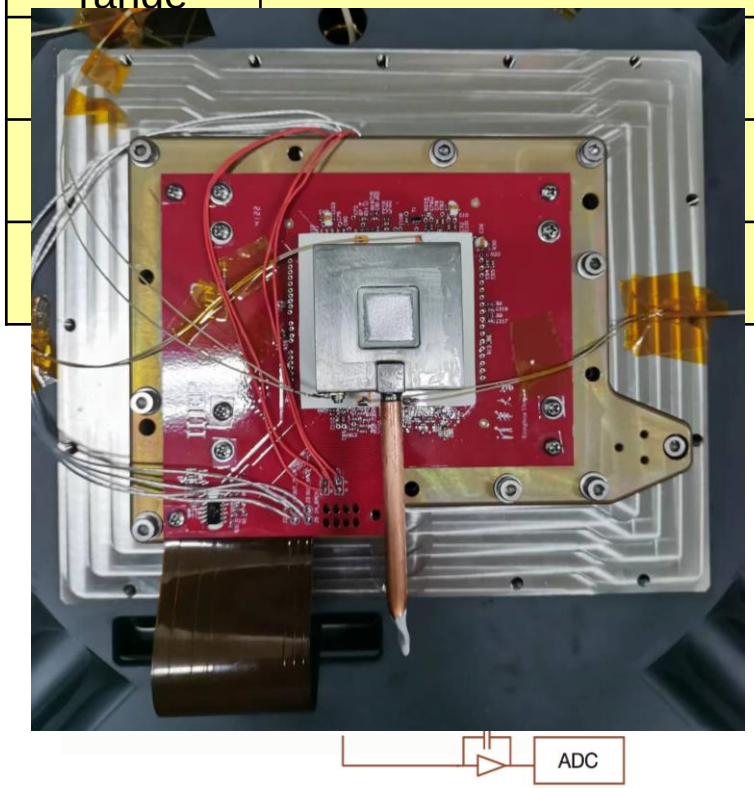
Parameter	Value
Number of holes	112008 (359×312)
Horizontal pitch	43.30 μm
Vertical pitch	50.00 μm
Hole diameter	30 μm
Hole diameter dispersion	$\sim$ 1 μm (typical)
Top-bottom alignment	$\sim$ 2 μm (typical)
Metal coating	Copper
Coating thickness	5 μm
Substrate	Liquid crystal polymer (LCP)
Substrate thickness	50 μm
Manufacturing process	Laser etching
Typical operating voltage	$\sim$ 470 V
Gain gain scaling	$\propto$ exp($\sim$ 0.03 V)
Working effective gain	$\sim$ 200

Parameter of GEM

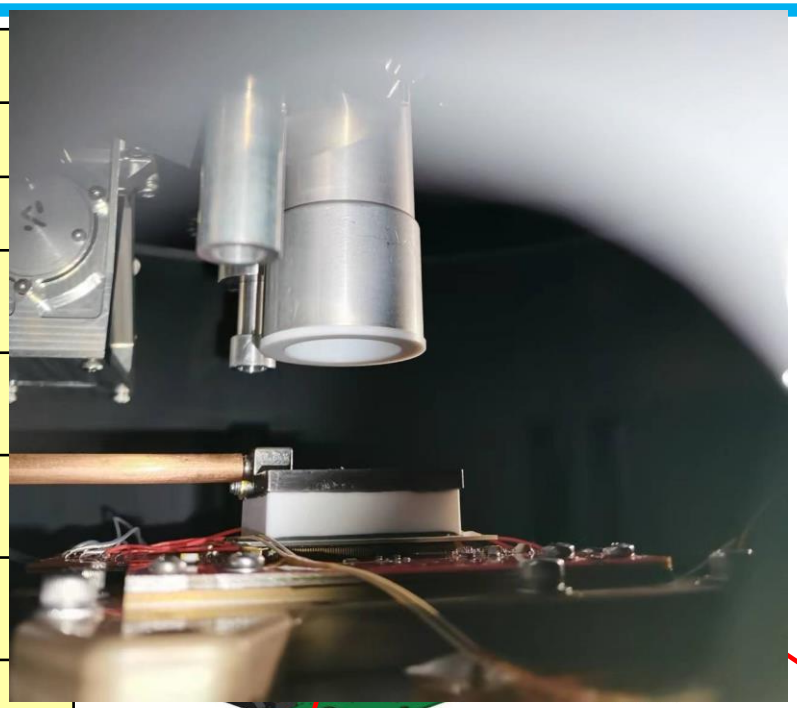
Baldini, L., et. al, Astro Phys, 133 (2021)

PFA focal plane camera design

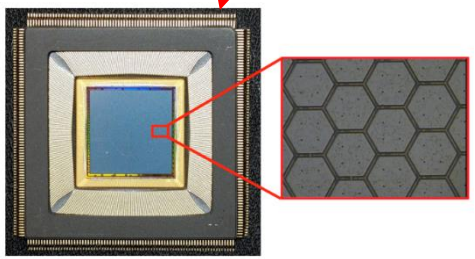
	PFA
Detector	GPD
Det Aera	≥ 12×12 mm^2 (8′)
Position resolution	≤ 0.2 mm (8″)
Energy range	2-8 keV



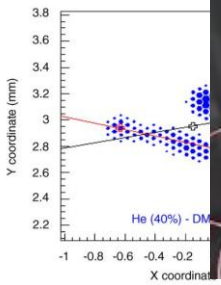
GPD configuraion



GPD



ASIC



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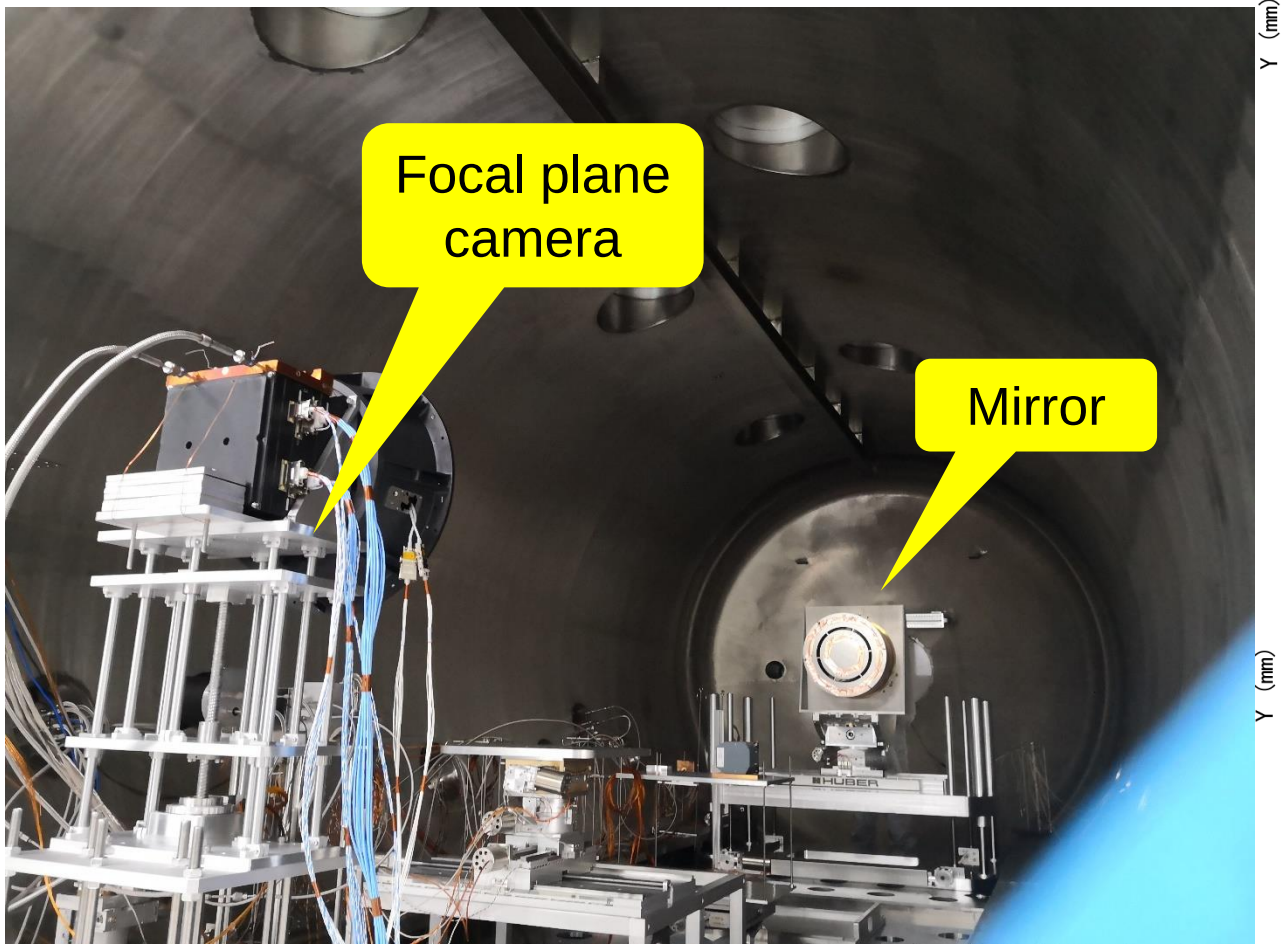
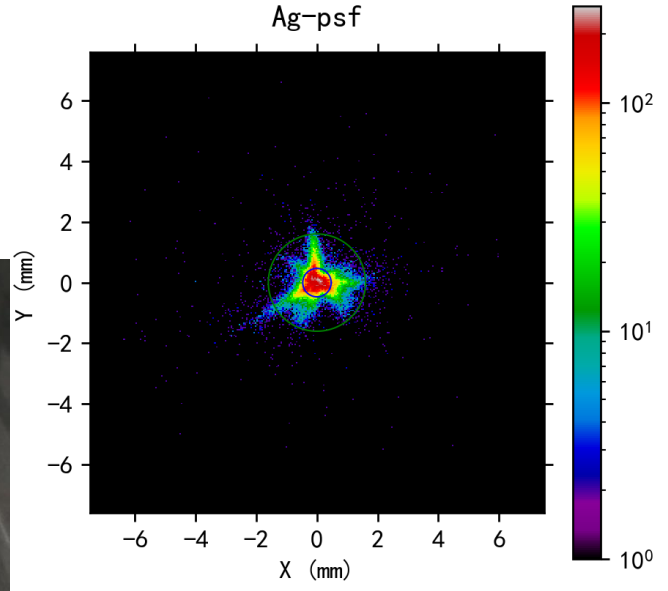
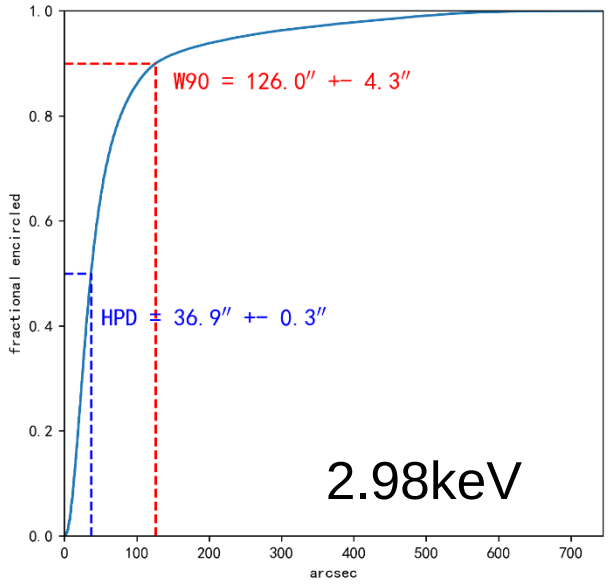
PFA focal plane camera

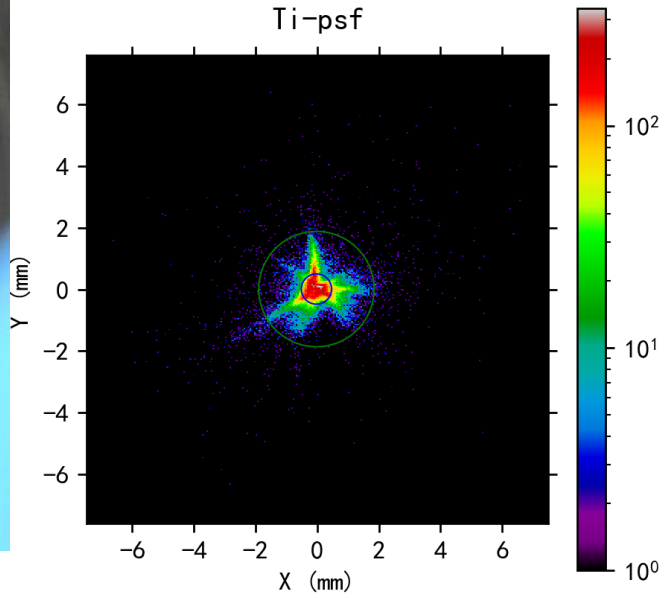
PFA telescope "end-to-end" testing (mirror + detector).

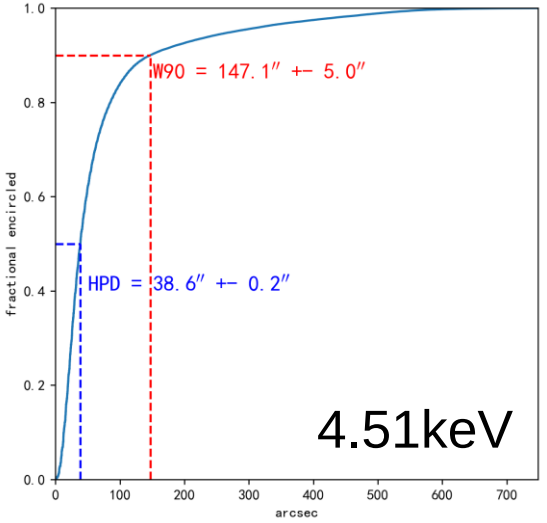
- Completed "end-to-end" testing at the 100-meter beamline in IHEP.
- Latest angular resolution of Mirror: 26’ (HPD).



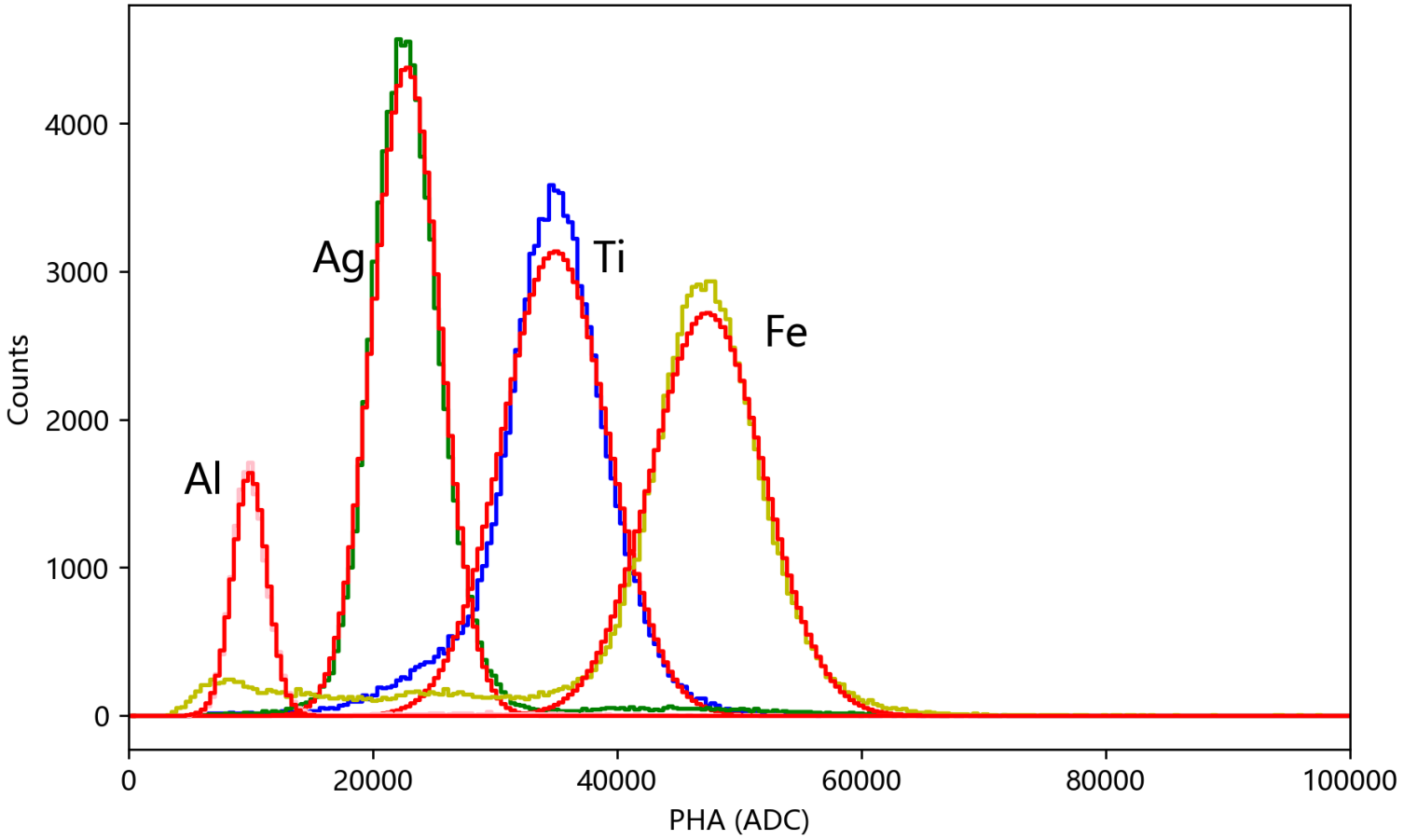






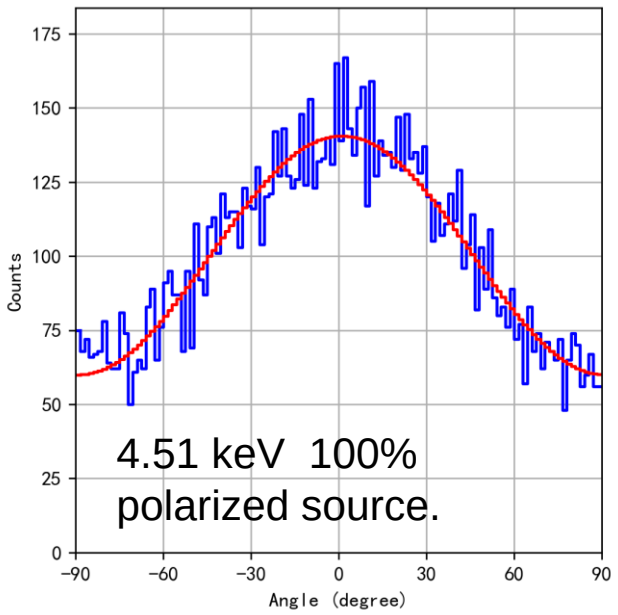


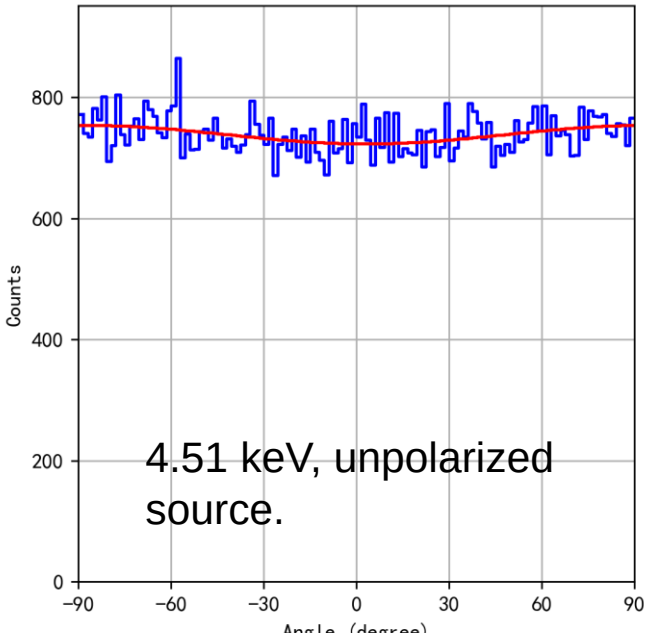
PFA telescope "end-to-end" testing: energy resolution

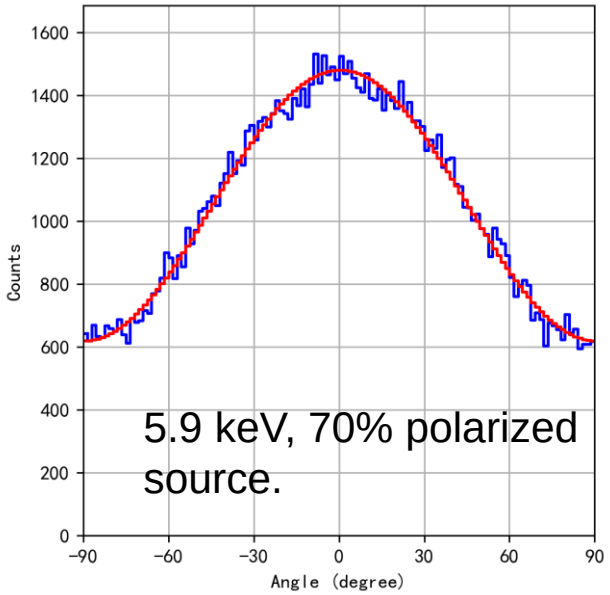


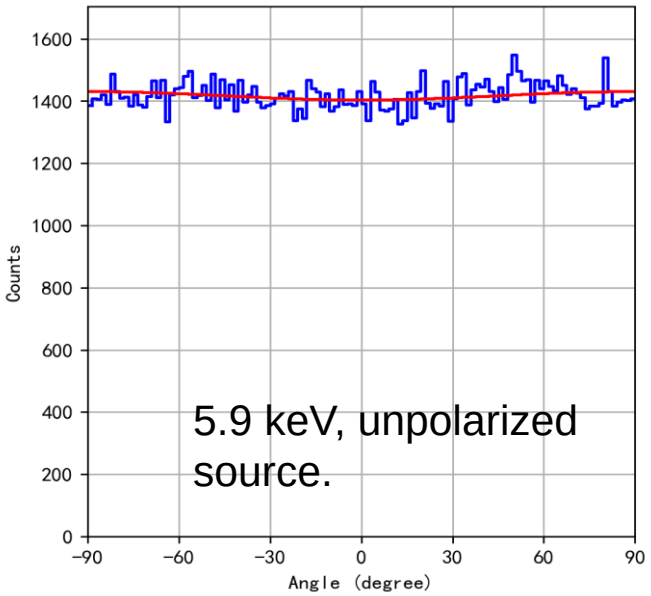
Line	Energy（keV）	Resolution（keV）
Al-K	1.49	0.47
Ag-L	3	0.85
Ti-K	4.51	1.28
Fe-K	6.40	1.47

PFA telescope "end-to-end" testing: polarization









4.51 keV :

Polarized: $\mu = 0.41 \pm 0.01$

unpolarized: $\mu = 0.021 \pm 0.005$

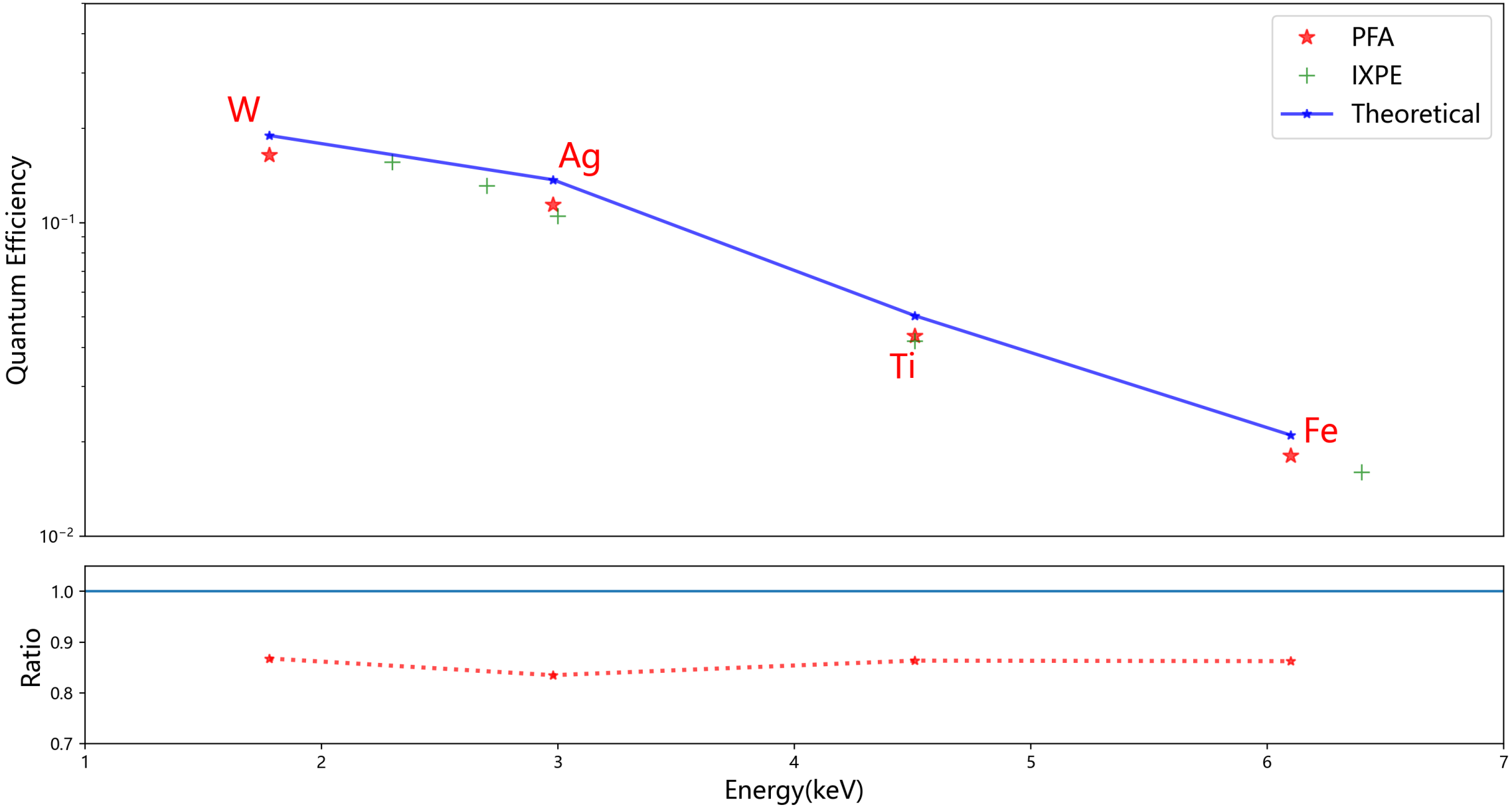
5.9 keV :

70%Polarized: $\mu = 0.410 \pm 0.004$

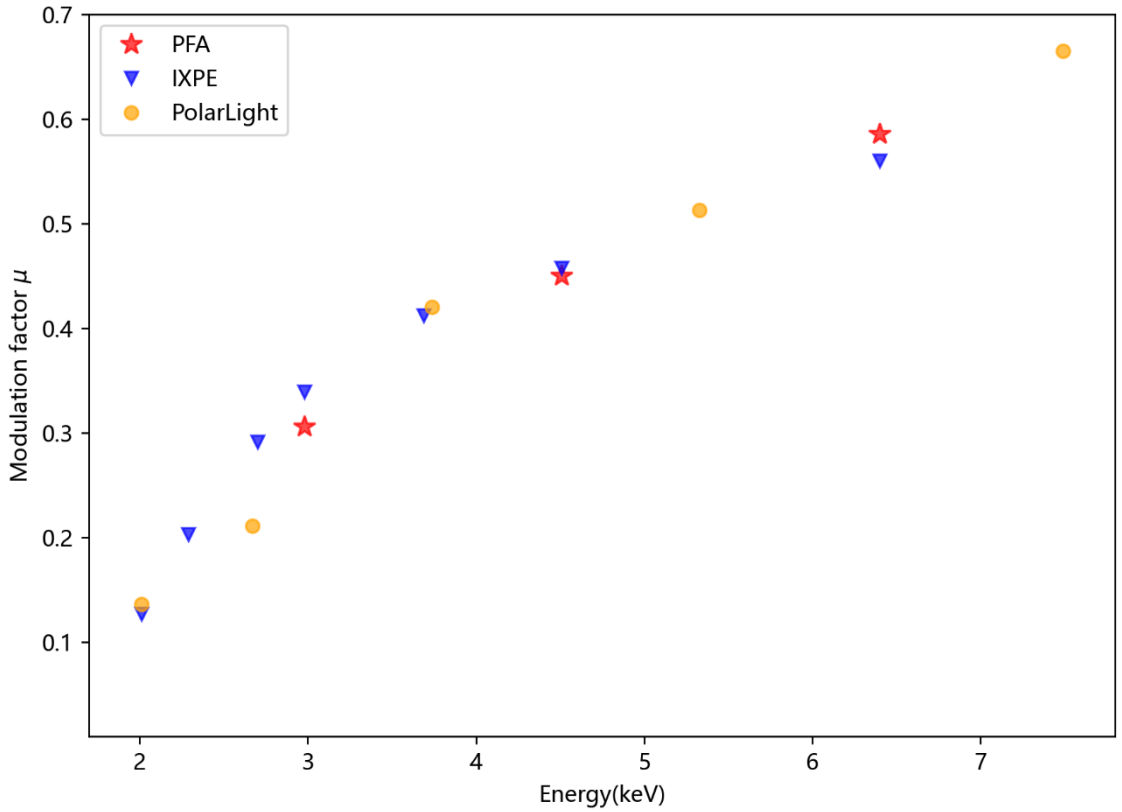
- Modulation factor： 0.59

unpolarized: $\mu = 0.0095 \pm 0.0038$

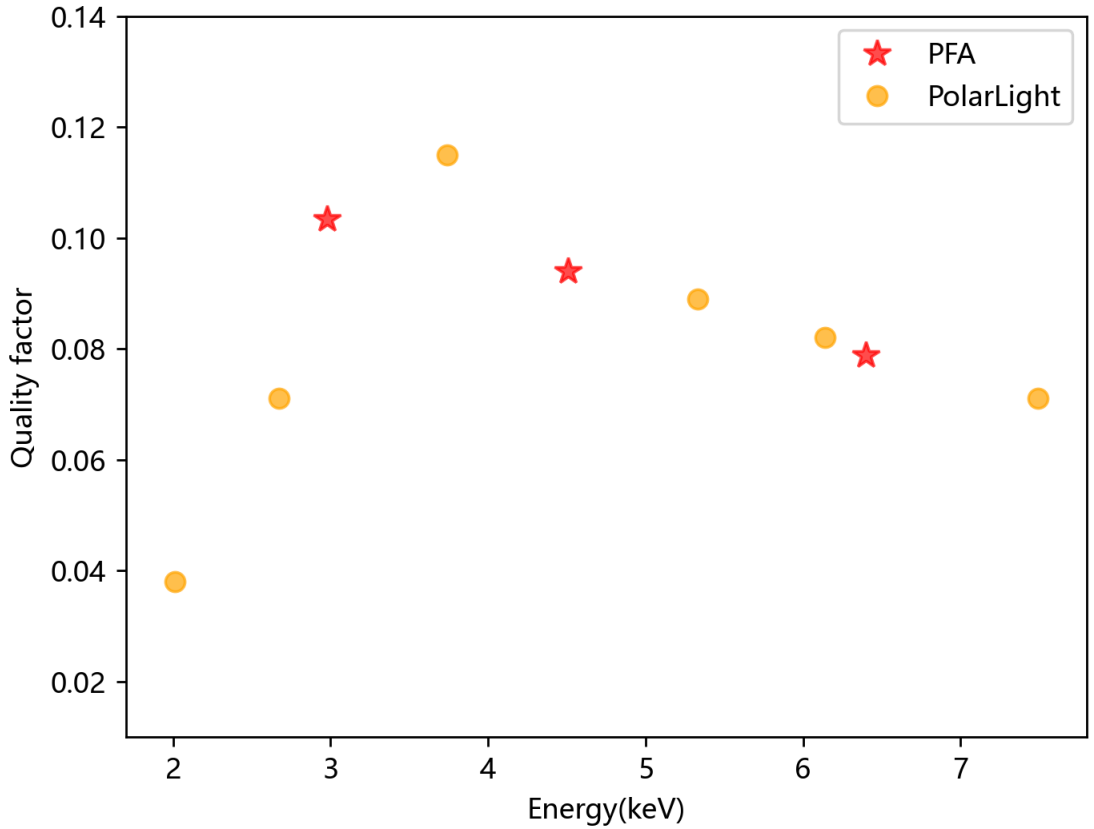
Detection efficiency of the GPD(standard detector: SDD).



Modulation factor and Quality factor of GPD



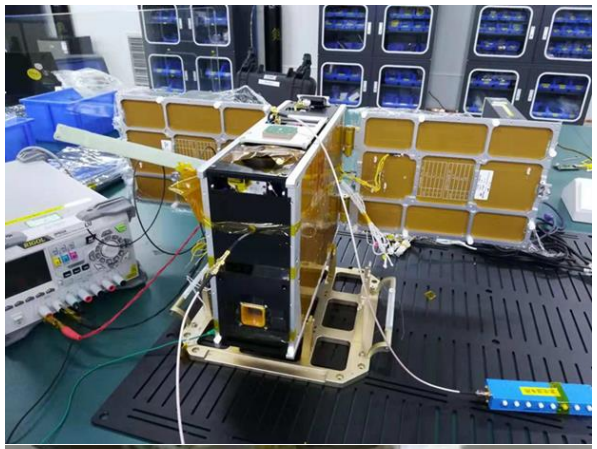
Modulation factor of GPD

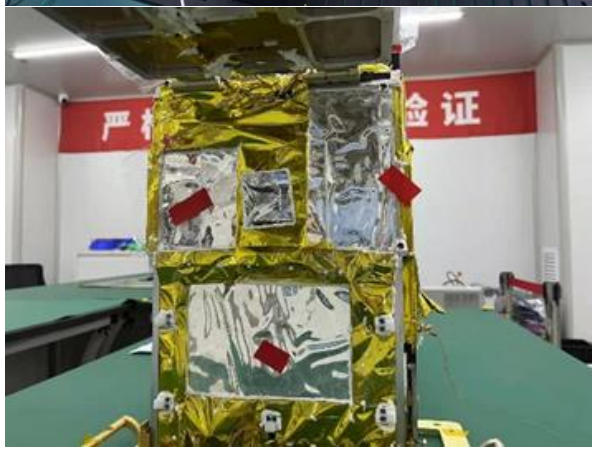


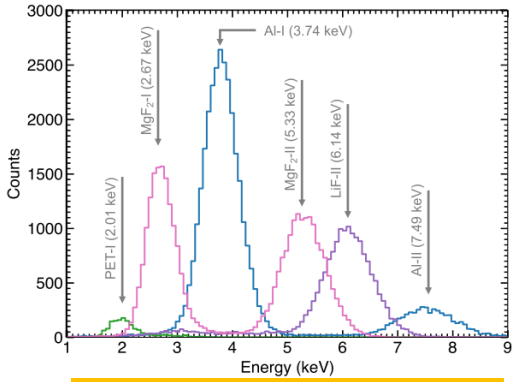
Quality factor of GPD

In-orbit flight verification of GPD on CubeSats

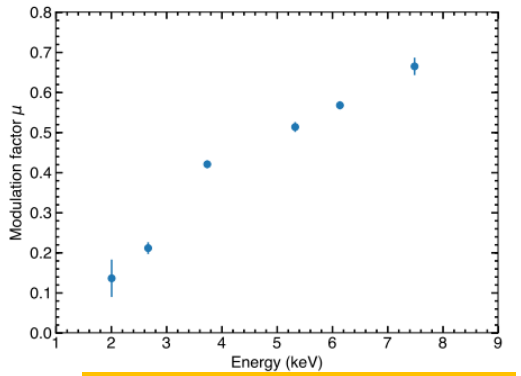
- “Polar light 1”: Launched in October 2018 aboard the "Tongchuan-1" CubeSat.
- “Polar light 2”: Launched in February 2022 aboard the "Changxing Leishen" CubeSat.



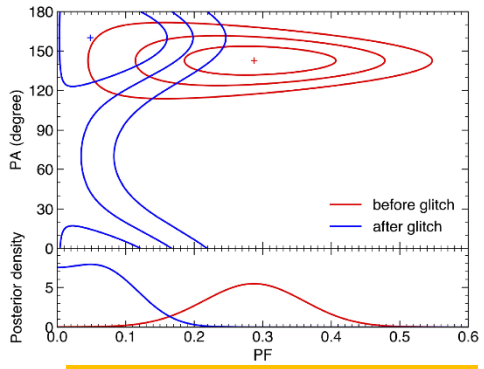




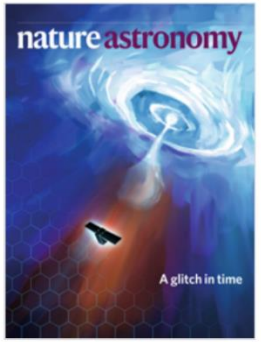
Energy resolution



Modulation factor



On-orbit observation



Volume 4 Issue 5, May 2020

A glitch in time

A CubeSat hosting the PolarLight payload has made i to conduct polarimetry in the soft X-ray band from s than 40 years after this opportunity was last availabl astronomers. Hua Feng and colleagues observed the fortunately catching the pulsar during a glitch.

See Feng et al.

The Astrophysical Journal Letters, 912:L28 (4pp), 2021 May 10 https://doi.org/10.3847/2041-8213/abf600

X-Ray Polarimetry of the Crab Nebula with PolarLight: Polarization Recovery after the Glitch and a Secular Position Angle Variation

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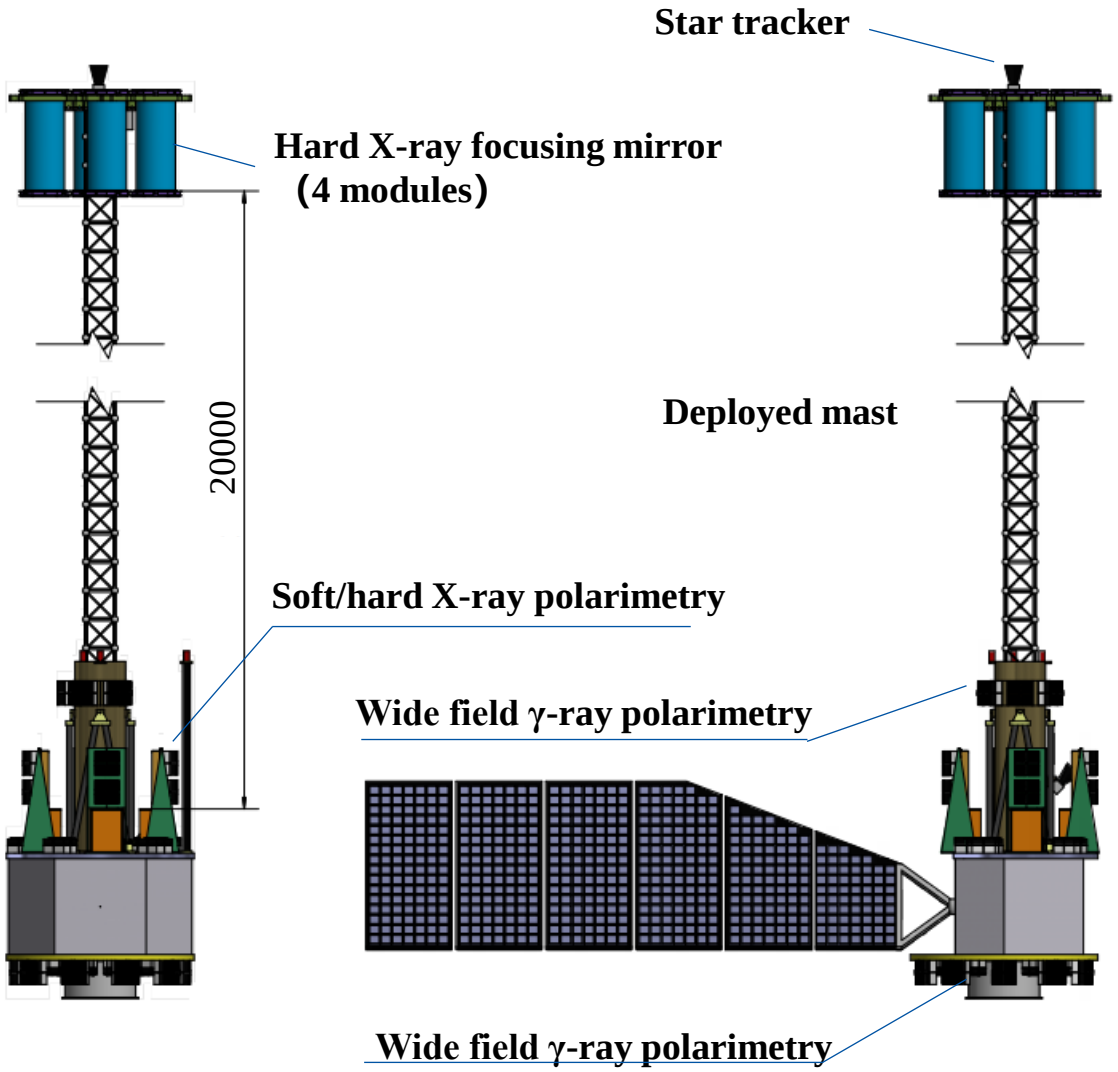
Abstract

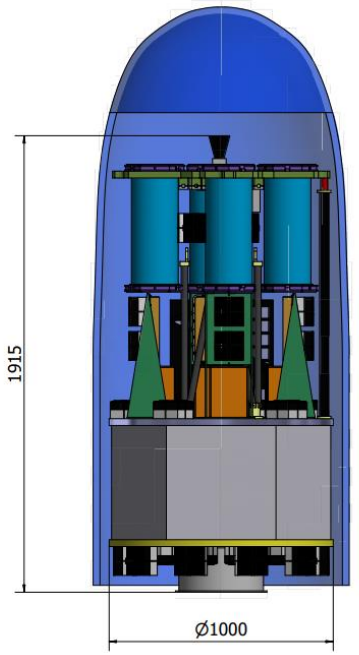
We report follow-up observations of the Crab Nebula with the PolarLight X-ray polarimeter, which revealed a possible variation in polarization associated with a pulsar glitch in 2019. The new observations confirm that the polarization has recovered roughly 100 days after the glitch. With the new observations, we find that the polarization angle (PA) measured with PolarLight from the total nebular emission has a difference of 18°.0 ± 4°.6 from that measured 42 yr ago with OSO-8, indicating a secular evolution of polarization with either the Crab Nebula or pulsar. The long-term variation in PA could be a result of multiple reconnection, or movement of synchrotron emitting structures in the nebula, magnetic geometry.

Unified Astronomy Thesaurus concepts: Polarimetry (1278); Rotation powered (1815); X-ray sources (1822)

ApJ 2021

WXPT:Wide band X-ray Polarization and imaging Telescope



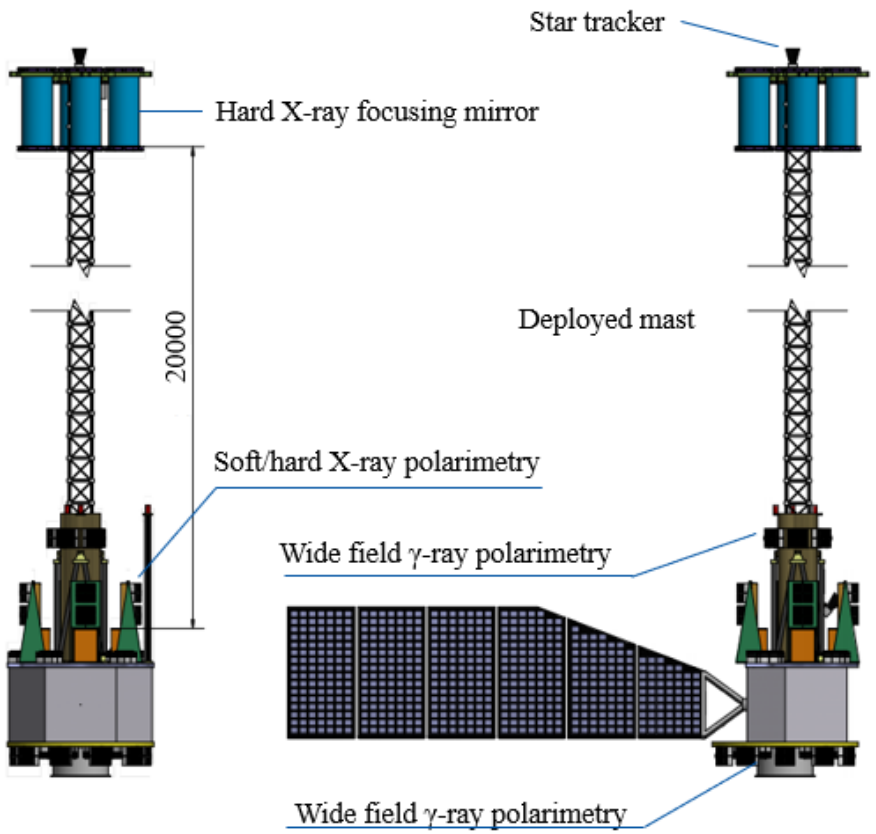


Total Mass：	≤ 500 kg
Orbit inclination：	28°
Hard X-ray Optics：	4 module
Focal length：	20m

- Detailed design small satellite for X/γ ray polarimetry
- Broad energy coverage： 3-60keV（focusing optics）
  50-500keV（Large field of view）
- Highest polarimetry sensitivity at hard X-ray

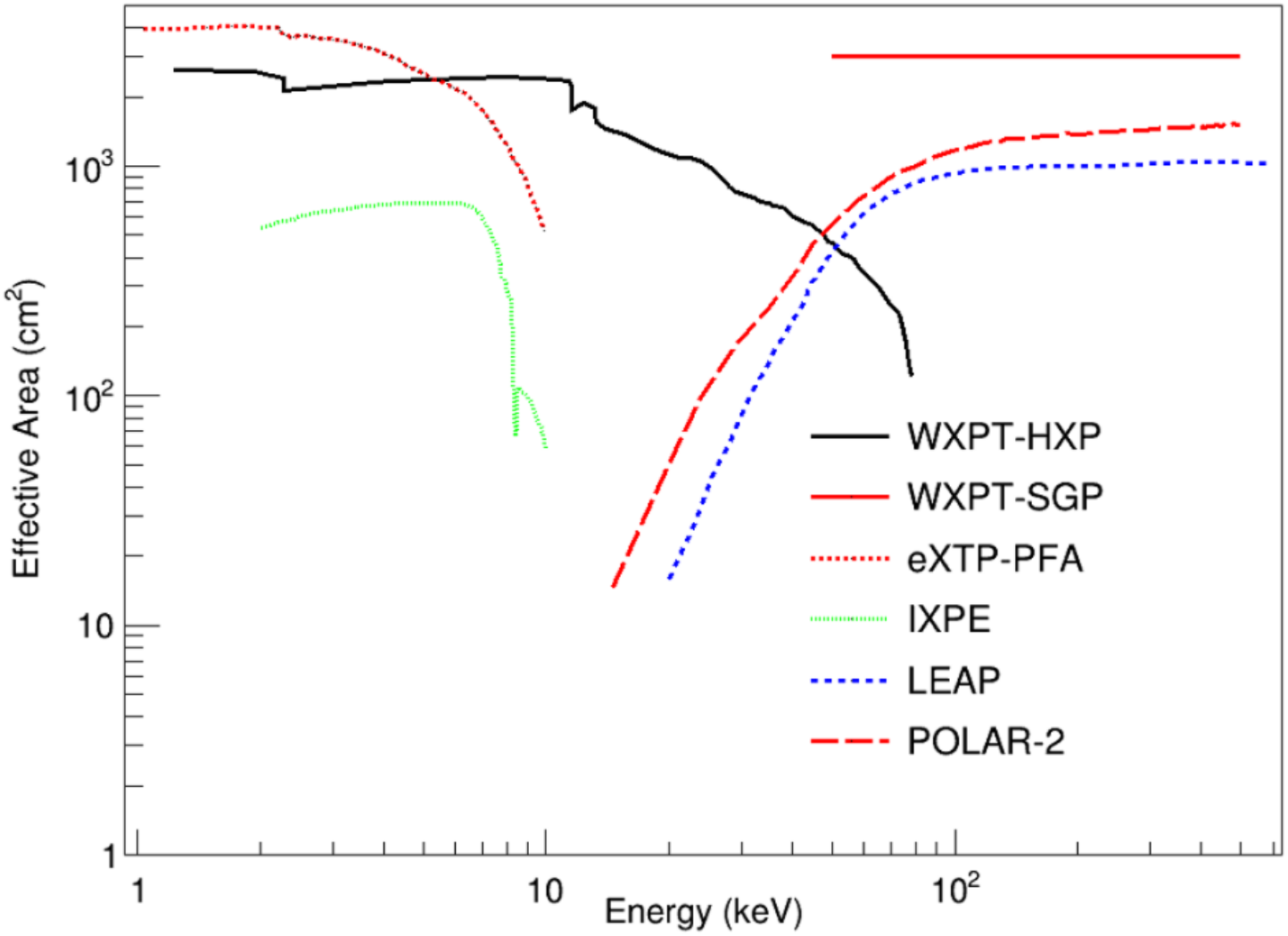
Preliminary design of the WXPT

WXPT: 3-60keV （focusing optics）
50-500keV（large FOV）



Payload	Configuration	Specification
Soft/hard X-ray Polarimetry(HXP)	3 focusing hard X-ray optics mirrors; Focal plane: TPC detector（3~10keV） Scintillator + Multi-layer stacked TES array（8~60keV）	Sensitive area：>3*100cm^2@60keV; Energy：3~60 keV Angular resolution：≤30”(HPD)@10keV MDP：<1.5%@（100ks，1mCrab，3~10keV），<7%@(100ks，1mCrab，10~60keV）
Hard X-ray imaging telescope	1 focusing hard X-ray optics mirror; Focal plane: Silicon based detector(soft X-ray) CdTe pixel detector array(hard X-ray) or layer stacked TES array	Energy: 3~60keV Energy resolution: 400eV@8keV 2keV@60keV Angular resolution:≤30”(HPD)@10keV Sensitivity(1Ms, 10~30keV):5×10^{-15}erg/cm^2/s
Wide-field Soft γ-ray Polarimetry(SGP)	Plastic scintillator +CsI calorimeter	Sensitive area：≥3000cm^2 Energy：50~500keV Pointing accuracy：≤1° MDP：<10%(10^{-6}erg*cm^{-2})

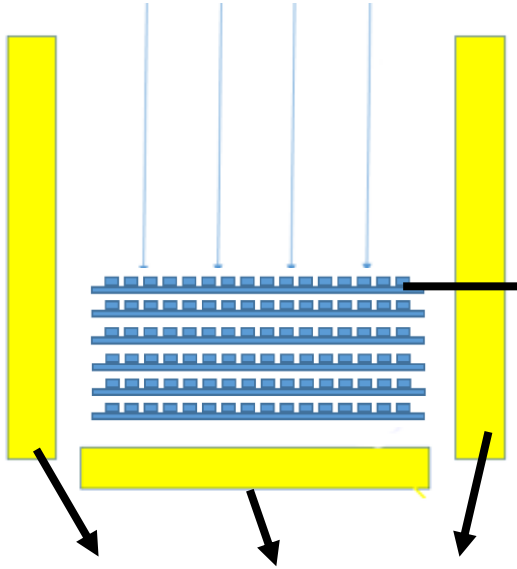
WXPT:Wide band X-ray Polarization and imaging Telescope



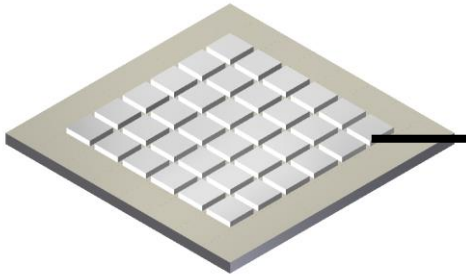
- **Broad energy coverage:from soft X-ray to gamma ray**
- **Highest sensitivity at hard X-ray**
- **Large sensitive area and field of view at soft γ-ray**

- **To be launched 2035**

3. Preliminary design of the WXPT Soft/hard X-ray polarimetry

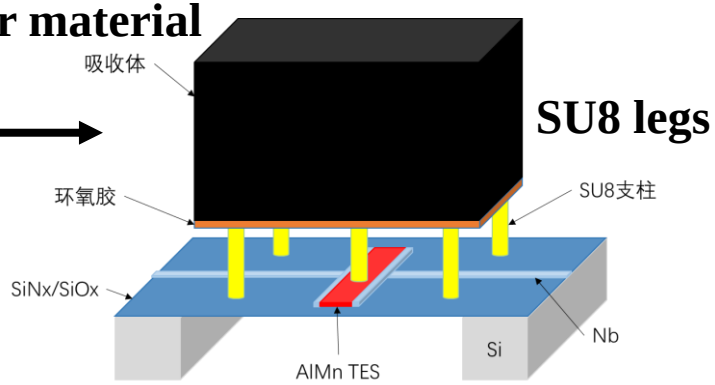


Anti-concidence detector: CsI

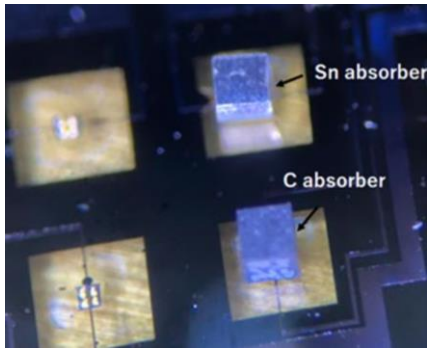


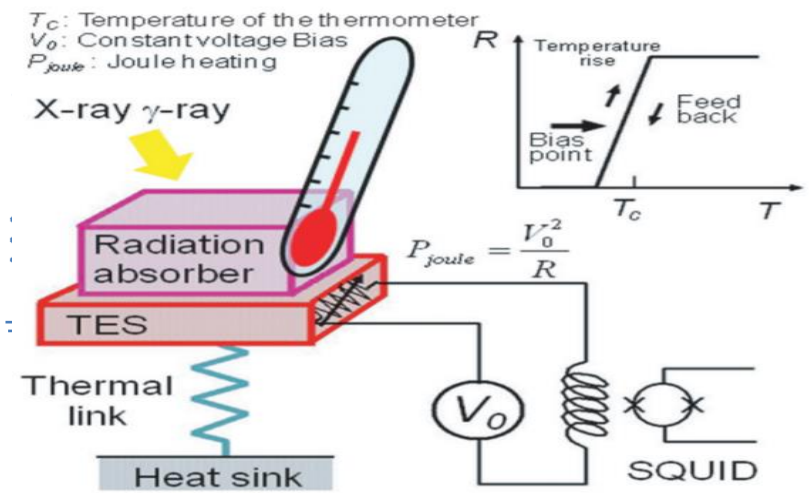
Layer stacked Transition Edge Sensor TES

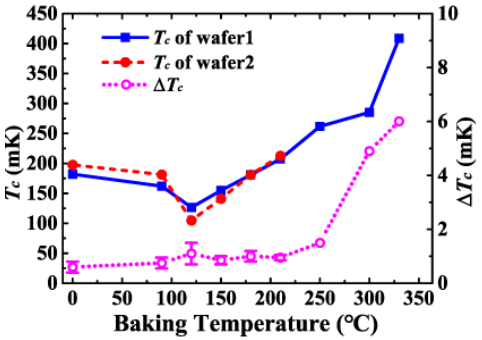
Low Z material : absorber as scatter material



SU8 legs



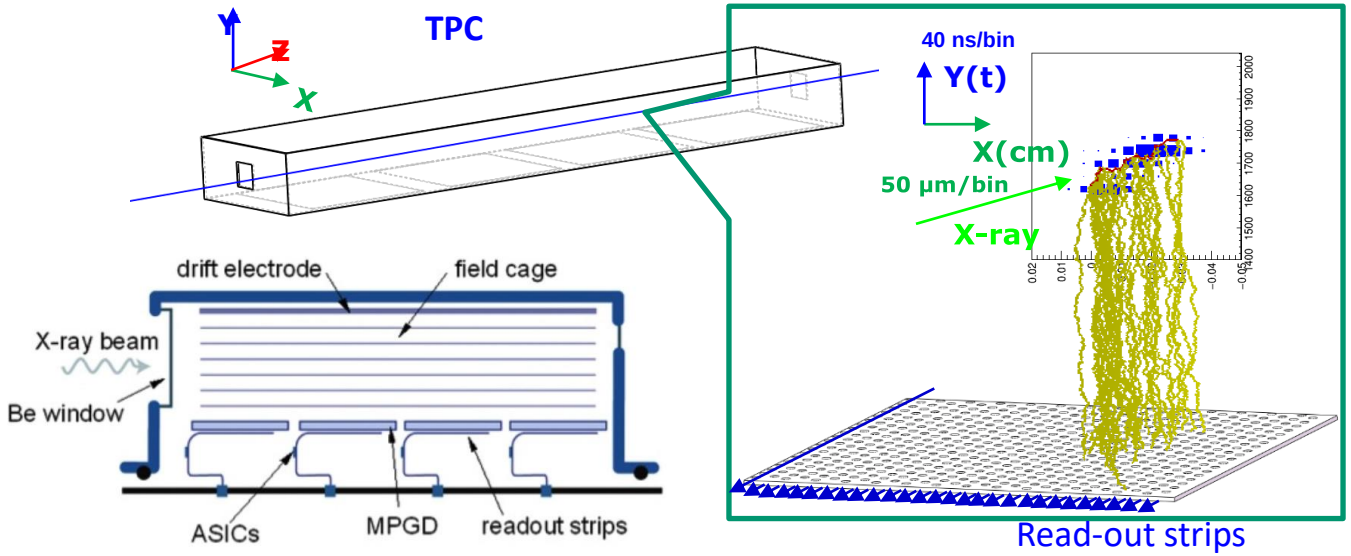




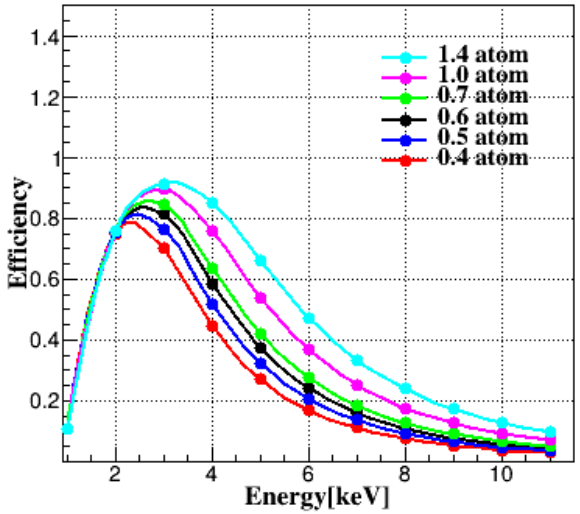
- Superconducting transition temperature ~100mK
- Multilayer stacked: detected efficiency >90%, energy resolution 5eV@5.9keV
- Angular resolution:30”

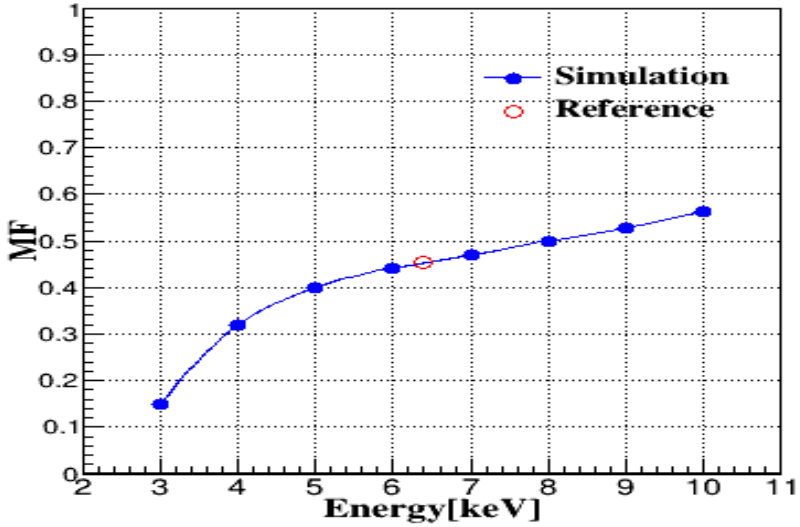
TPC Simulation

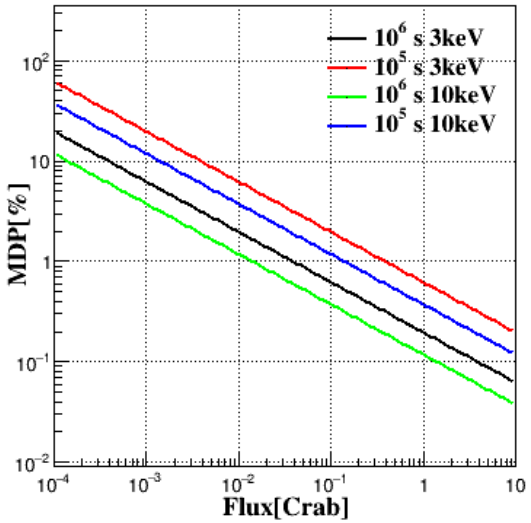
- **GAS：DME or 0.5MDE+0.5Ne：MF>0.4@6 keV**
- **pure DME　< 4 keV**
- **0.5MDE+0.5Ne　4 ~10 keV**



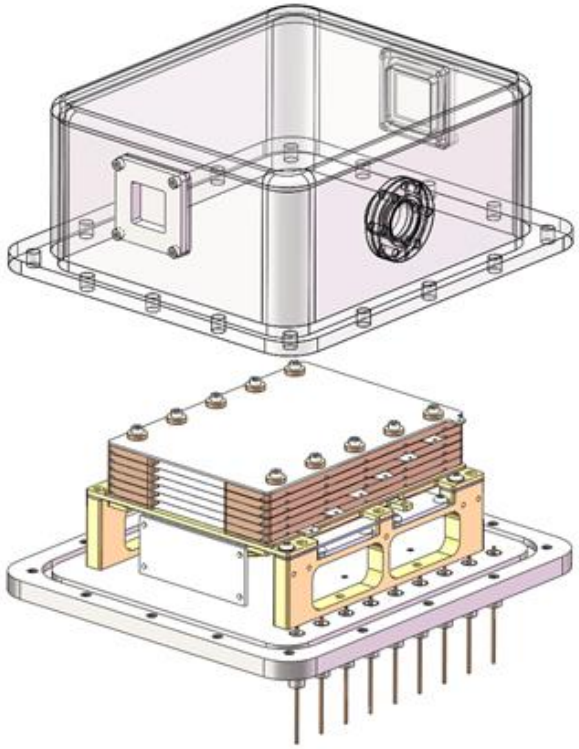
0.5DME+0.5Ne, 10cm, 0.6 atom

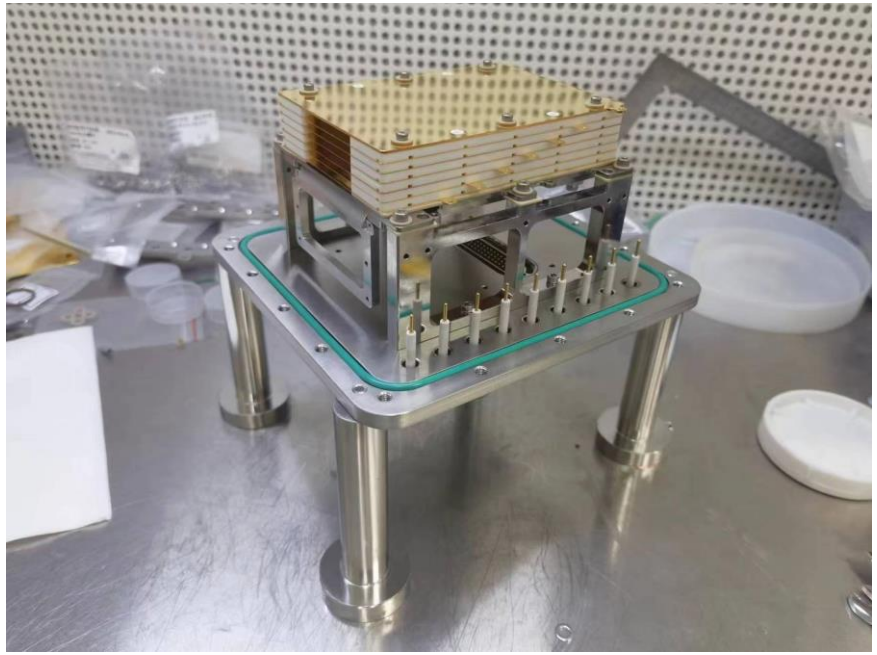


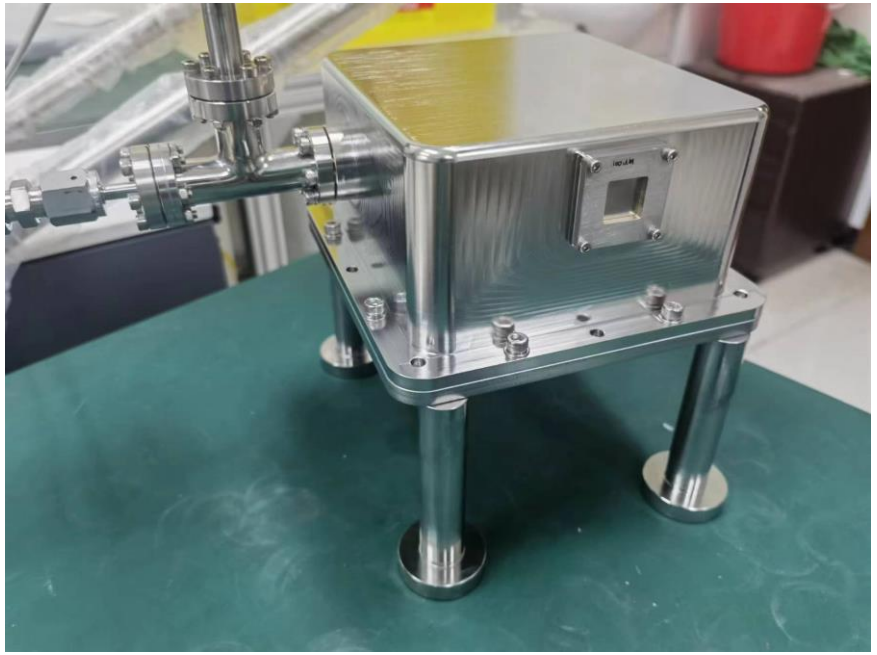


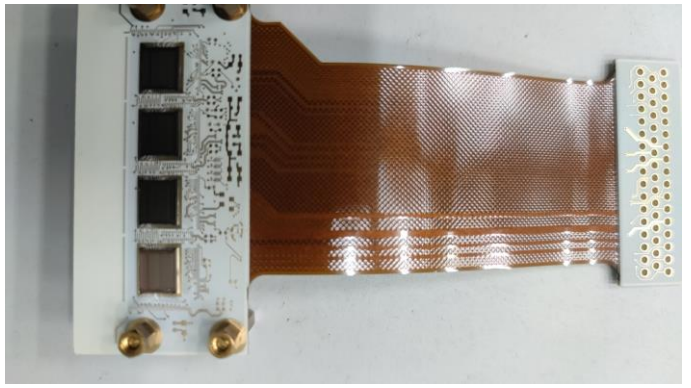


The TPC is currently being under testing









Summary

- MPGD is suitable as a high-sensitivity X-ray polarization detector.
- GPD has been adopted by eXTP-PFA which will be launched in 2030.
- TPC will be applied in WXPT and launched in 2035.

Thanks !