X-ray polarimetry detectors

Laboratory proposal

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Luca Latronico

Outline

- Detectors - GPD
- Scientific context - astrophysical X-ray polarimetry
- Laboratory Proposal

Gas Pixel Detectors - a long development

letters to nature

An efficient photoelectric X-ray polarimeter for the study of black holes and neutron stars

Enrico Costa*, Paolo Soffitta*, Ronaldo Bellazzini†, Alessandro Brez†, Nicholas Lumb† & Gloria Spandre†

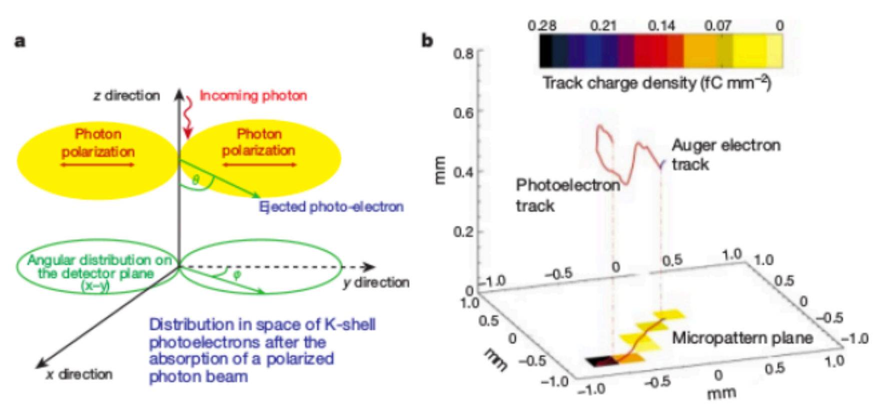
* *Istituto di Astrofisica Spaziale del CNR, Via Fosso del Cavaliere 100, 1-00133, Rome, Italy*
† *Istituto Nazionale di Fisica Nucleare-Sezione di Pisa, Via Livornese 1291, I-56010 San Piero a Grado, Pisa, Italy*

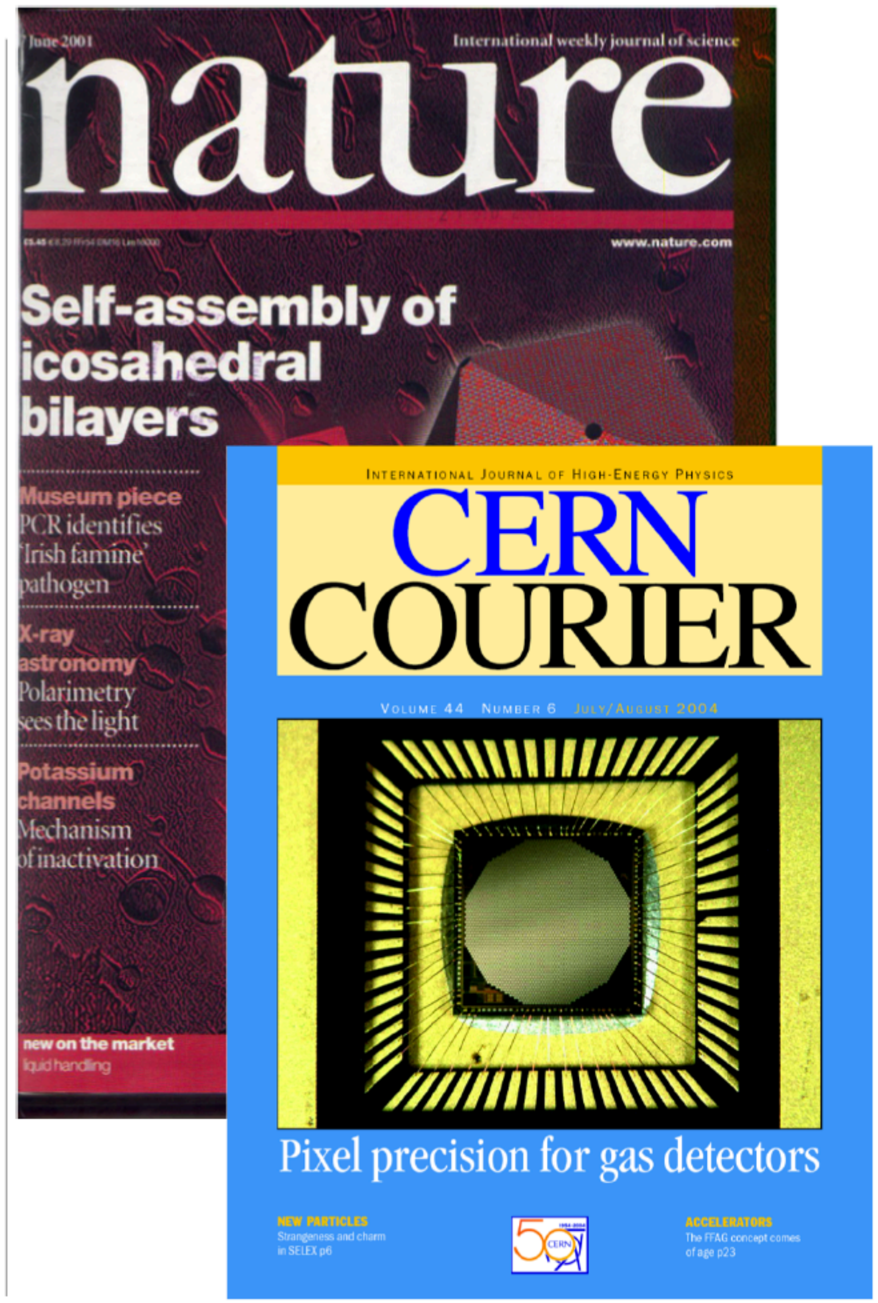
The study of astronomical objects using electromagnetic radiation involves four basic observational approaches: imaging, spectroscopy, photometry (accurate counting of the photons received) and polarimetry (measurement of the polarizations of the observed photons). In contrast to observations at other wavelengths, a lack of sensitivity has prevented X-ray astronomy from making use of polarimetry. Yet such a technique could provide a direct picture of the state of matter in extreme magnetic and gravitational fields[1–6], and has the potential to resolve the internal structures of compact sources that would otherwise remain inaccessible, even to X-ray interferometry[7]. In binary pulsars, for example, we could directly 'see' the rotation of the magnetic field and determine if the emission is in the form of a 'fan' or a 'pencil' beam[1,8]. Also, observation of the characteristic twisting of the polarization angle in other compact sources would reveal the presence of a black hole[9–12]. Here we report the development of an instrument that makes X-ray polarimetry possible. The factor of 100 improvement in sensitivity that we have achieved will allow direct exploration of the most dramatic objects of the X-ray sky.

The main advantage of the proposed polarimeter is its capability of investigating active galactic nuclei (quasars, blazars and Seyfert galaxies) for which polarization measurements have been suggested, crucial to understand the geometry and physics of emitting regions. We can separate synchrotron X-rays from jets[13,14] from the emission scattered by the disk corona or by a thick torus. The effects of relativistic motions and of the gravitational field of a central black hole have probably been detected by iron line spectroscopy on the Seyfert-1 galaxy MCG-6-30-15 (ref. 15) but this feature is not ubiquitous in active galactic nuclei. Polarimetry of the X-ray continuum provides a more general tool to explore the structure of emitting regions[16,17], to track instabilities and to derive direct information on mass and angular momentum[12] of supermassive black holes.

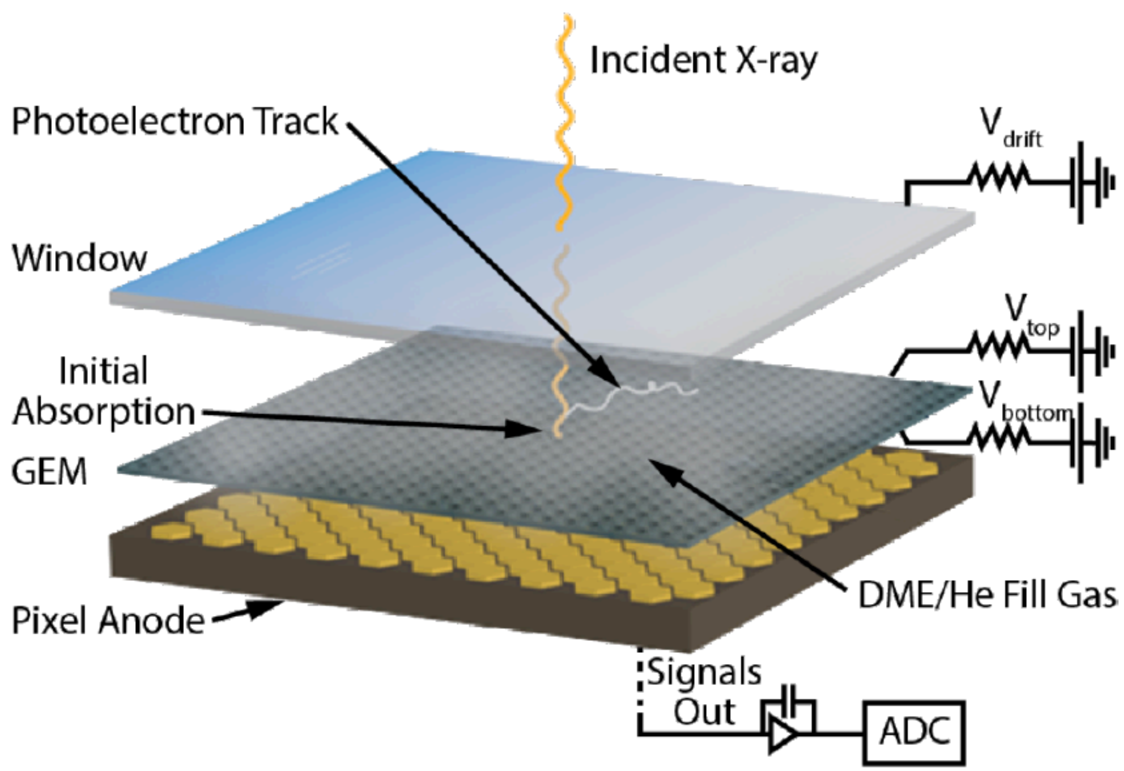
In spite of this wealth of expectations, the important but only positive result until now is the measurement, by the Bragg technique, of the polarization of the Crab nebula[18,19]. The Stellar X-ray Polarimeter[20] (SXRP) represents the state of the art for conventional methods based on Bragg diffraction and Thomson scattering. However, Bragg polarimetry[21] is dispersive (one angle at one time) and very narrow-band. Thomson polarimetry[22] is non-imaging and band-limited (>5 keV). This limits the sensitivity of SXRP to a few bright, galactic sources only.

The photoelectric effect is very sensitive to polarization. The electron is ejected from an inner shell with a kinetic energy which is the difference between the photon energy and the binding energy. The direction of emission is not uniform but is peaked around that of the electric field of the photons (see Fig. 1a). This photoelectron





Gas Pixel Detectors - principle of operation



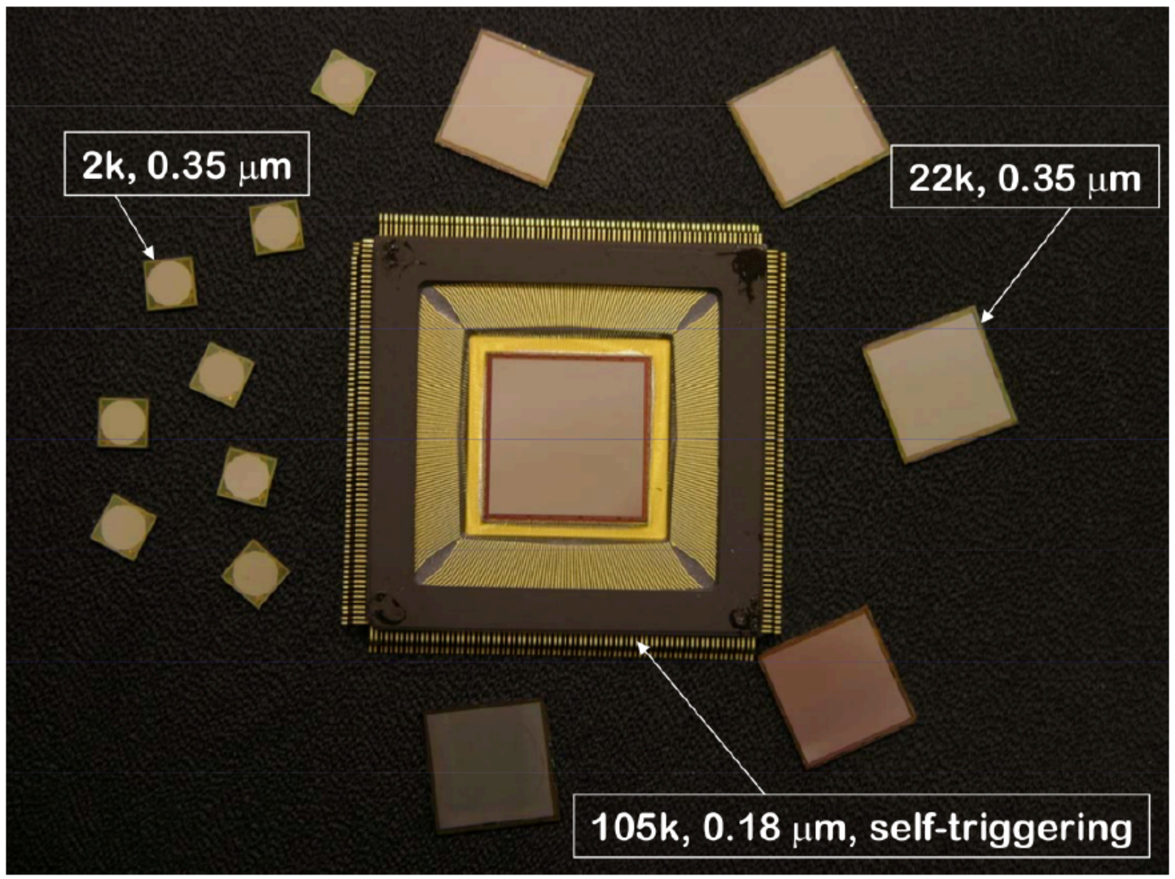
- ▷ Photoelectric effect dominant for soft (< 10 keV) X-rays
- ▷ K-shell photo-electron emission 100% modulated for linearly ploarized radiation:

$$\frac{d\sigma_C^K}{d\Omega} \propto Z^5 E^{-\frac{7}{2}} \frac{\sin^2\theta\cos^2\phi}{(1+\beta\cos\theta)^4}$$

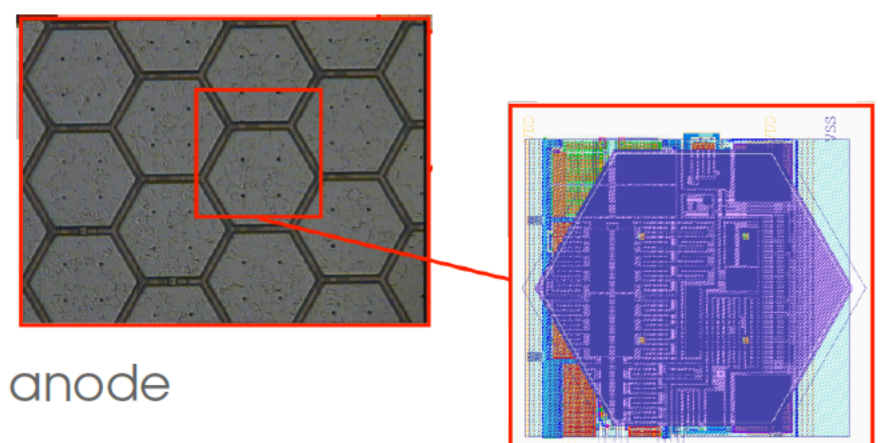
- ▷ Typical track length ∼ few µm in solid: a gaseous medium is needed!

- ▷ X-ray absorption in a gas gap
- ▷ Signal amplification via a Gas Electron Multiplier (GEM)
- ▷ Finely pixelized ASIC as readout anode
- ▷ Sensitive in the ∼ 2 – 8 keV band
- ▷ Full two-dimensional imaging and spectroscopy

GPD key components - the ASIC

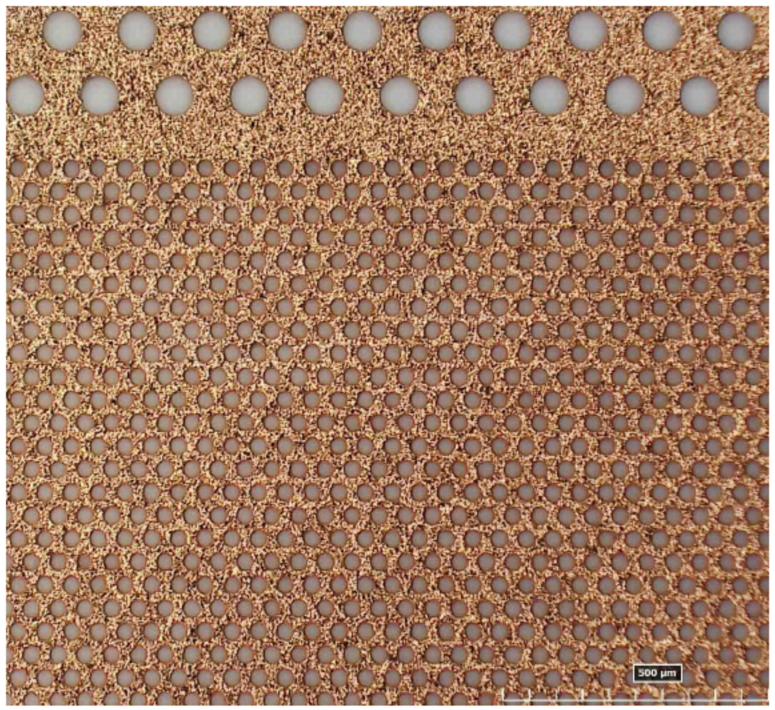


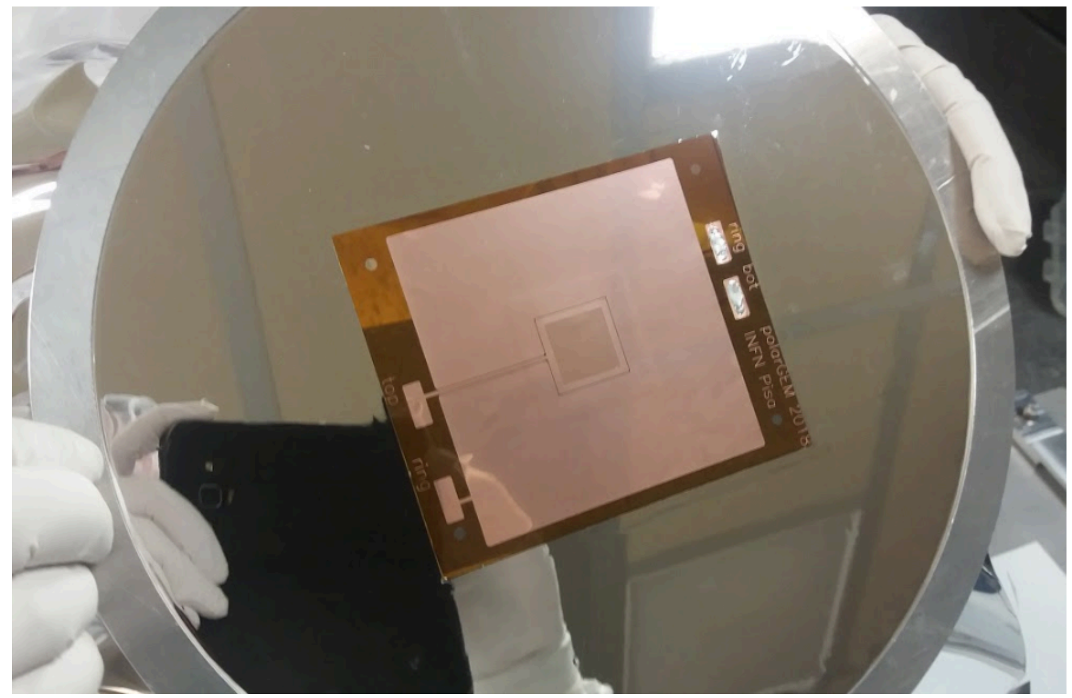
Technology	CMOS 0.18 μm
Active area	$\sim$ 15 $\times$ 15 mm
Fill factor	92 %
Number of pixels	300 $\times$ 352
Pixel pitch	50 μm
Pixel density	$\sim$ 470/mm 2
Pixel noise	$\sim$ 20 ENC
Shaping time amplifiers	3 - 10 μs
Readout clock	typically 5 MHz



- ▷ Self-triggering, with ROI definition
- ▷ Metal top layer acting as a charge collecting anode
- ▷ Integrating preamplifier, shaper, S/H, multiplexer
- ▷ Serial readout via external 14 bits ADC

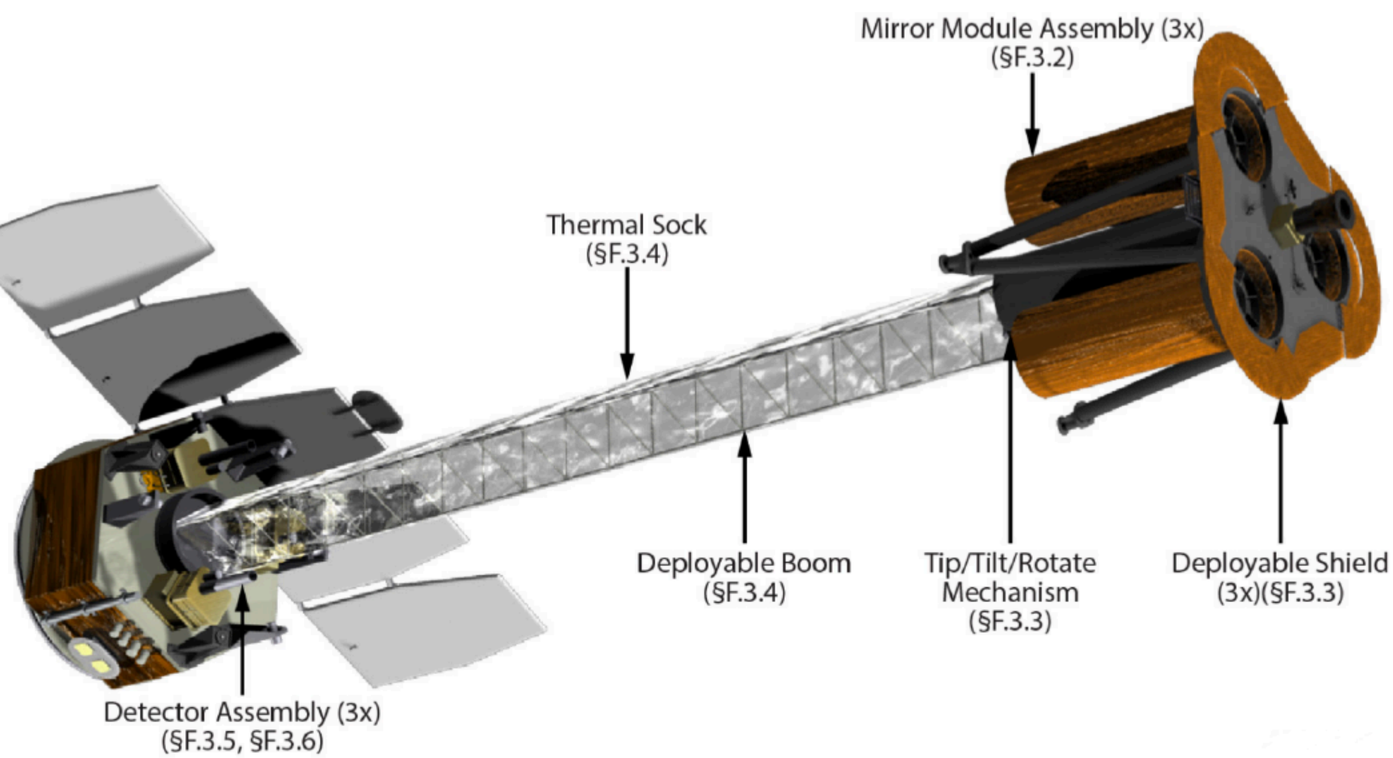
GPD key components - the GEM





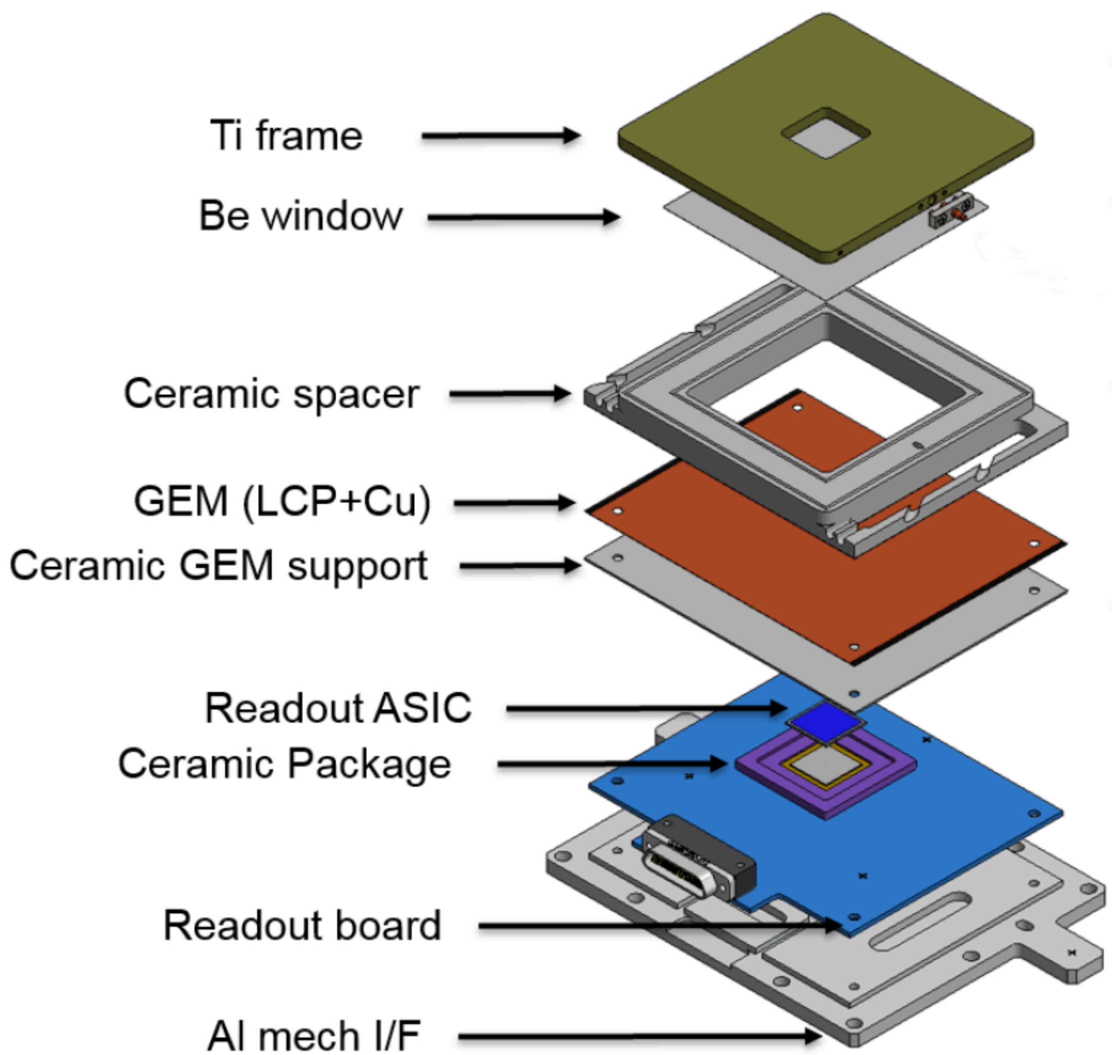
- Produced by RIKEN and SciEnergy in Japan
  - photo-lithographic copper etching + CO_2 laser drill + wet etching
- 50 µm thick Liquid Crystal Polymer (LCP) insulator
- 5 µm copper layer
- Hexagonal hole pattern, with 50 µm pitch, diameter of 30 µm
- Typical operating voltages 400 - 500 V

Scientific context - the IXPE mission

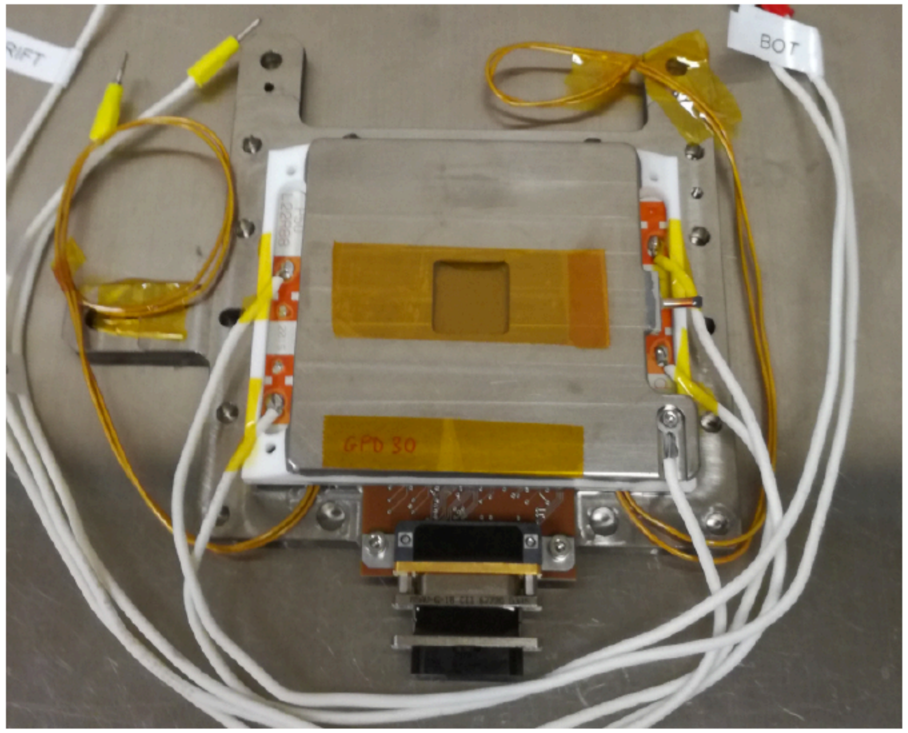


- Selected by NASA as its next SMEX (SMall EXplorer) mission, to be launched in April 2021
- 2 + 1 years of on-orbit operations
- Three identical telescopes dedicated to x-ray polarimetry
- 4 m focal length
- 0° inclination orbit, 540-620 Km altitude

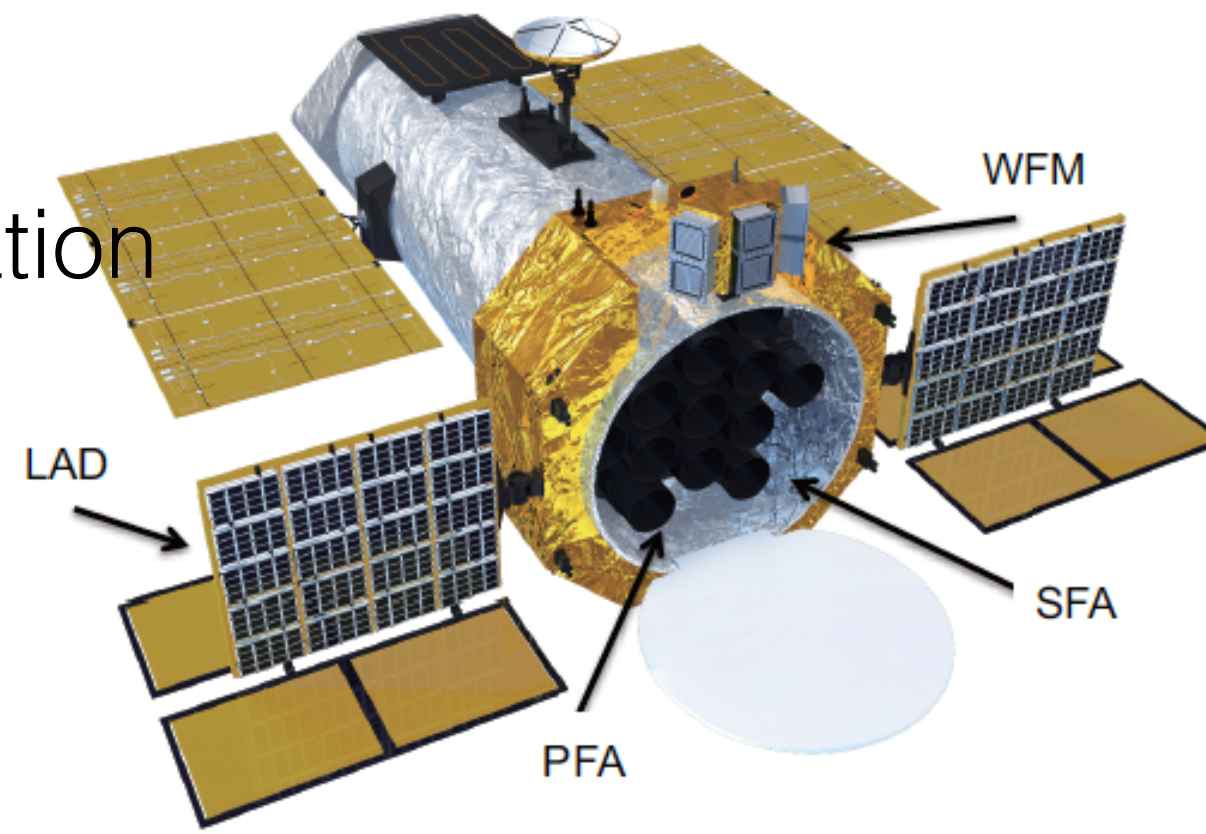
IXPE GPDs



- ▷ Sealed detector, no gas system needed
- ▷ Gas cell thickness 1 cm
- ▷ Gas mixture DME @ 0.8 bar
  - ▷ Optimized for 2-8 keV energy range
- ▷ X-ray window in Be, 50 μm thick



Scientific context - the eXTP mission



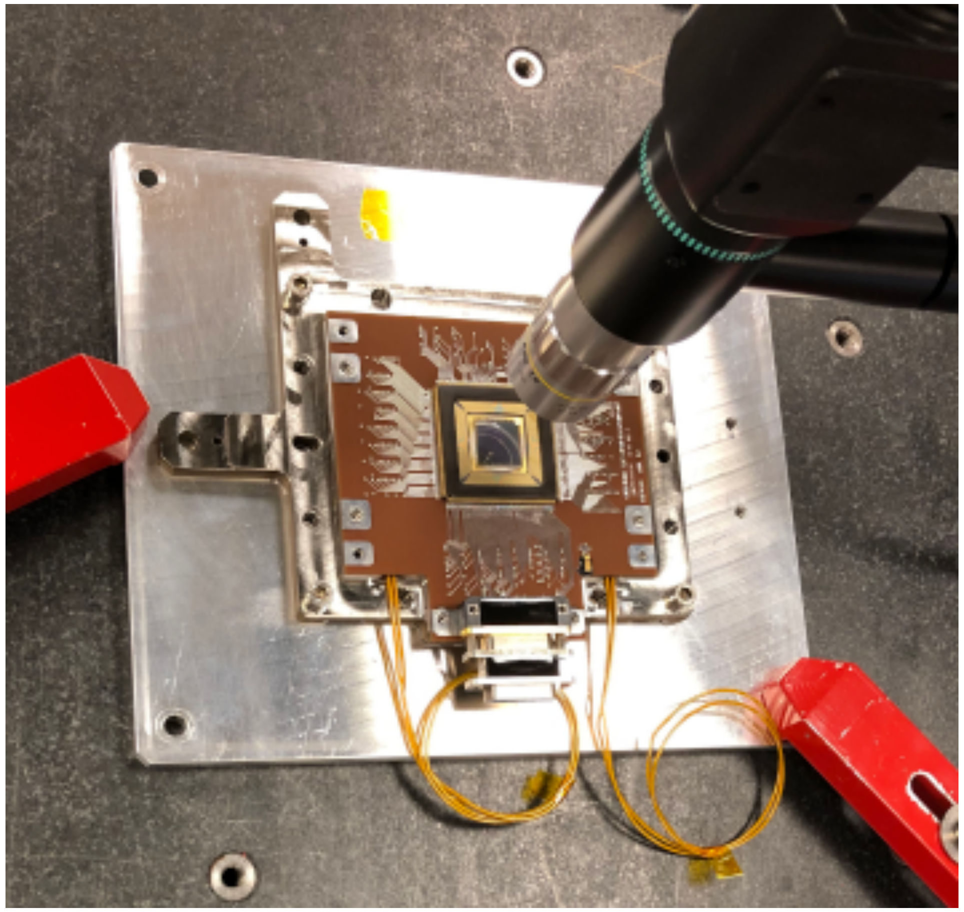
- China and Europe collaboration
- Launch in 2025
    - in phase B until 2022
- Multiple instruments for concurrent X-ray timing, imaging, spectroscopy, polarimetry
- GPD with new of ASIC and GEM to be developed

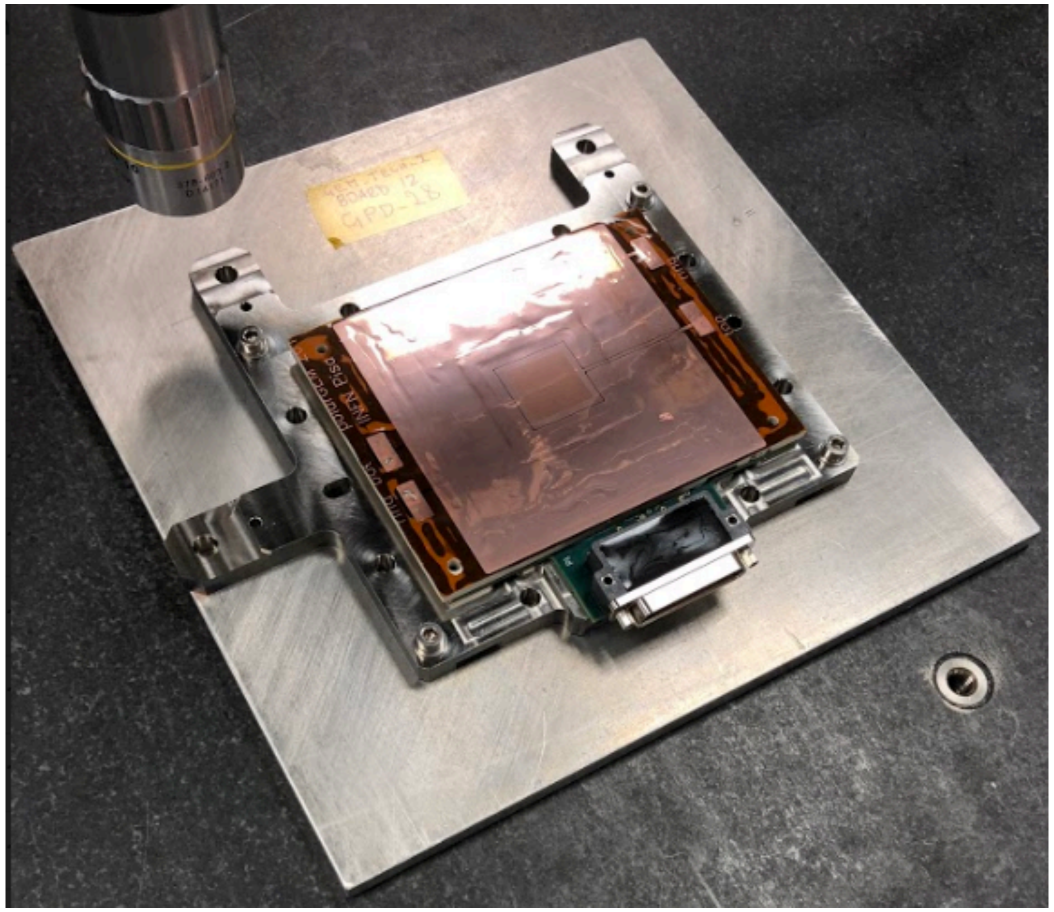
X-ray polarimetry lab - goals

1. Familiarize with the GPD components
2. Measure basic GPD performances
3. Experience impact of event reconstruction on performance
4. Learn (maybe see) systematic effects
5. Setup a GPD lab in Torino (for me)

Xpol lab - hands-on

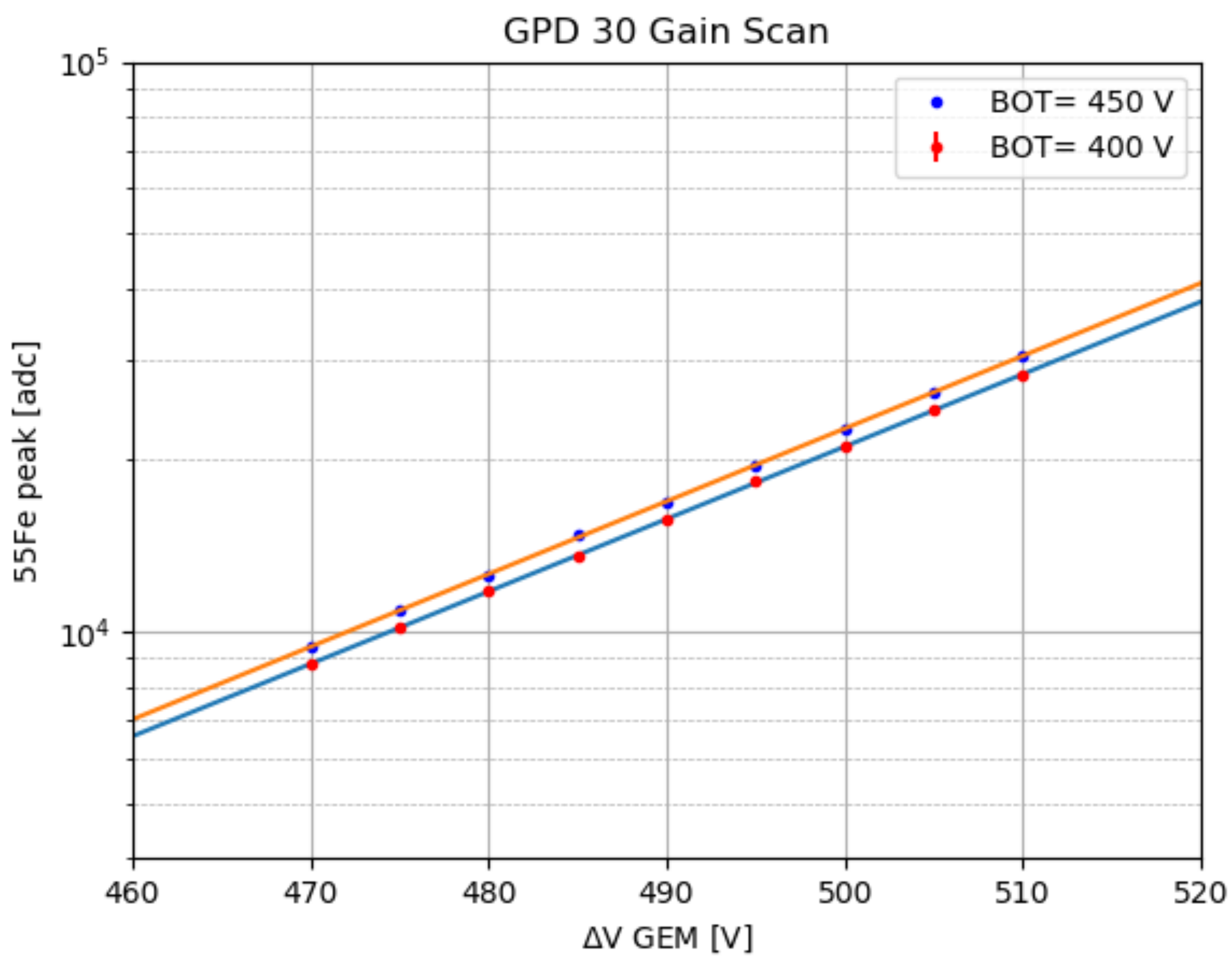
- **Hands on the hardware**: see, touch, feel a demonstration GPD and its main components (GEM, ASIC) under a lens / microscope and learn about mechanical integration





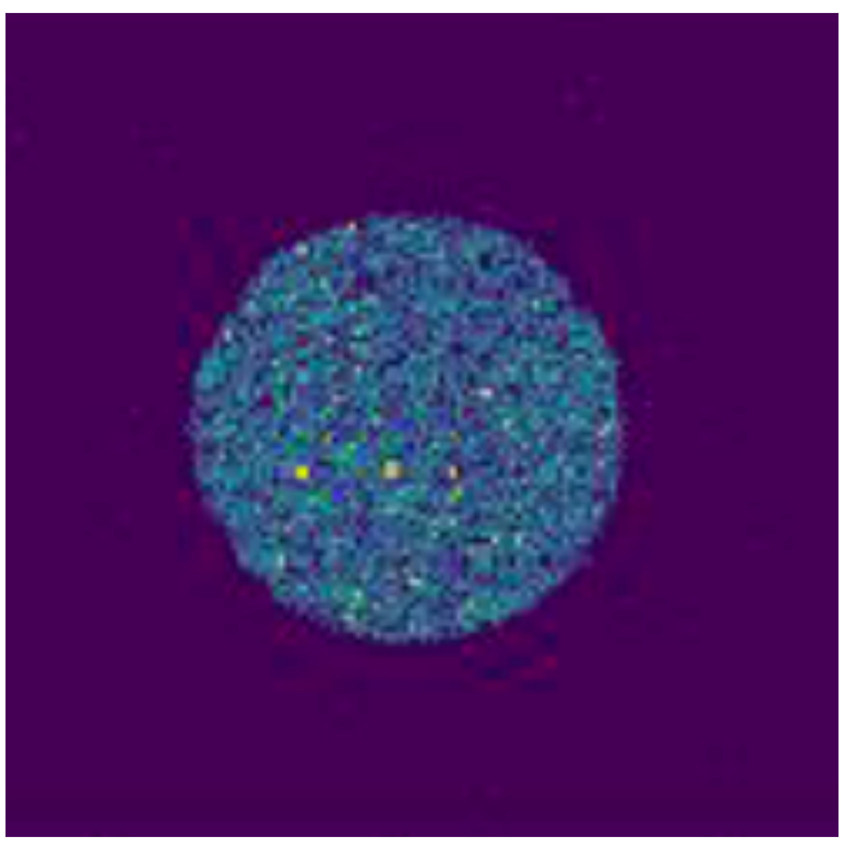
Xpol lab - hands-on

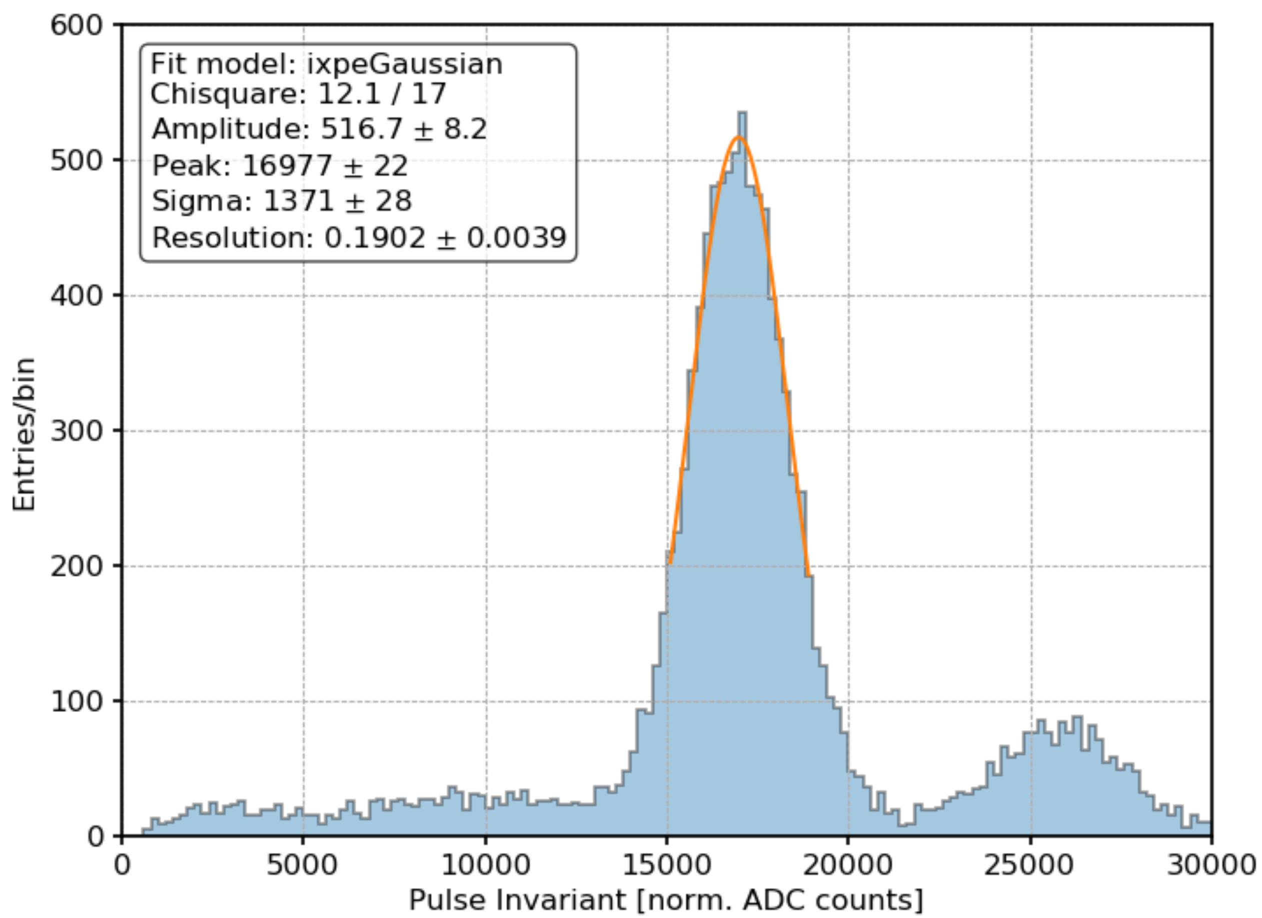
- **Power up a GPD**: understand the role of the three HV electrodes and verify the standard exponential dependence of the signal with the voltage across the GEM



Xpol lab - hands-on

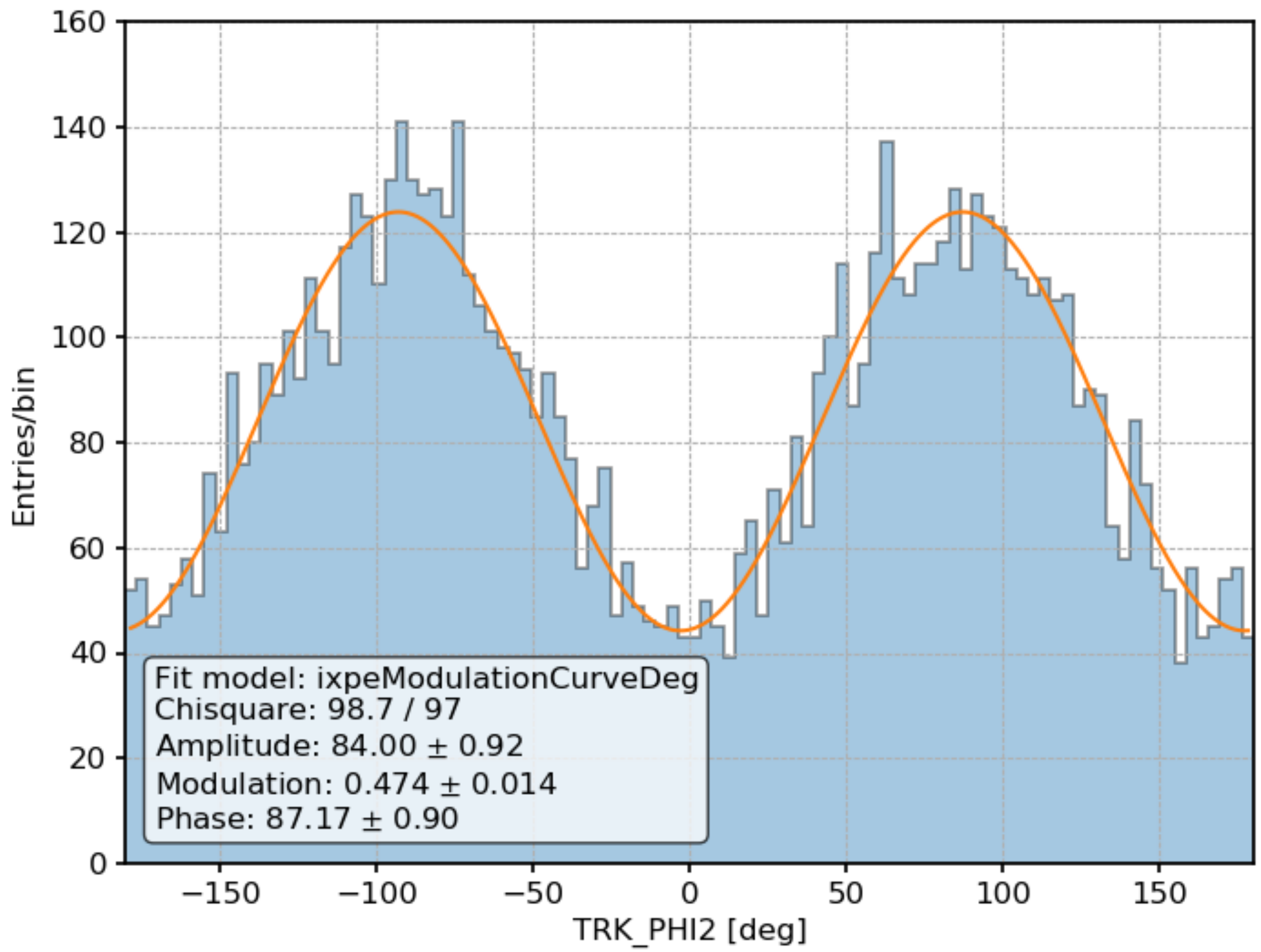
- **Gauge the basic GPD performance:** verify the imaging capabilities of the detector and understand its energy resolution





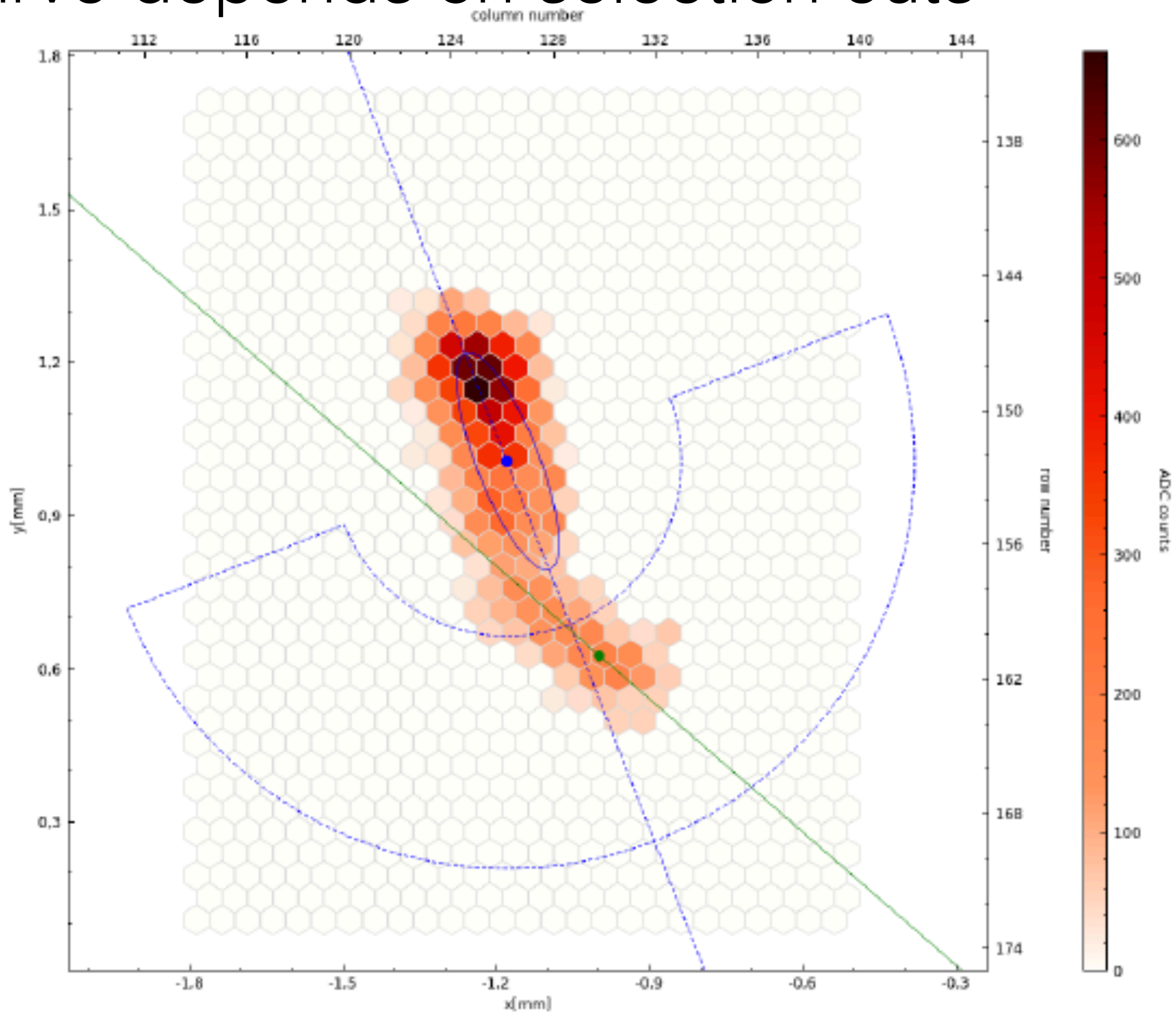
Xpol lab - hands-on

- **Discover X-ray polarization**: compare the response of the GPD to a polarized X-ray source and measure the modulation factor at different energies



Xpol lab - hands-on

- **Reconstruct photoelectrons:** visualize how a photoelectron propagates in gas and how it is reconstructed on the event display, see how their shape changes with the event energy and how the modulation curve depends on selection cuts



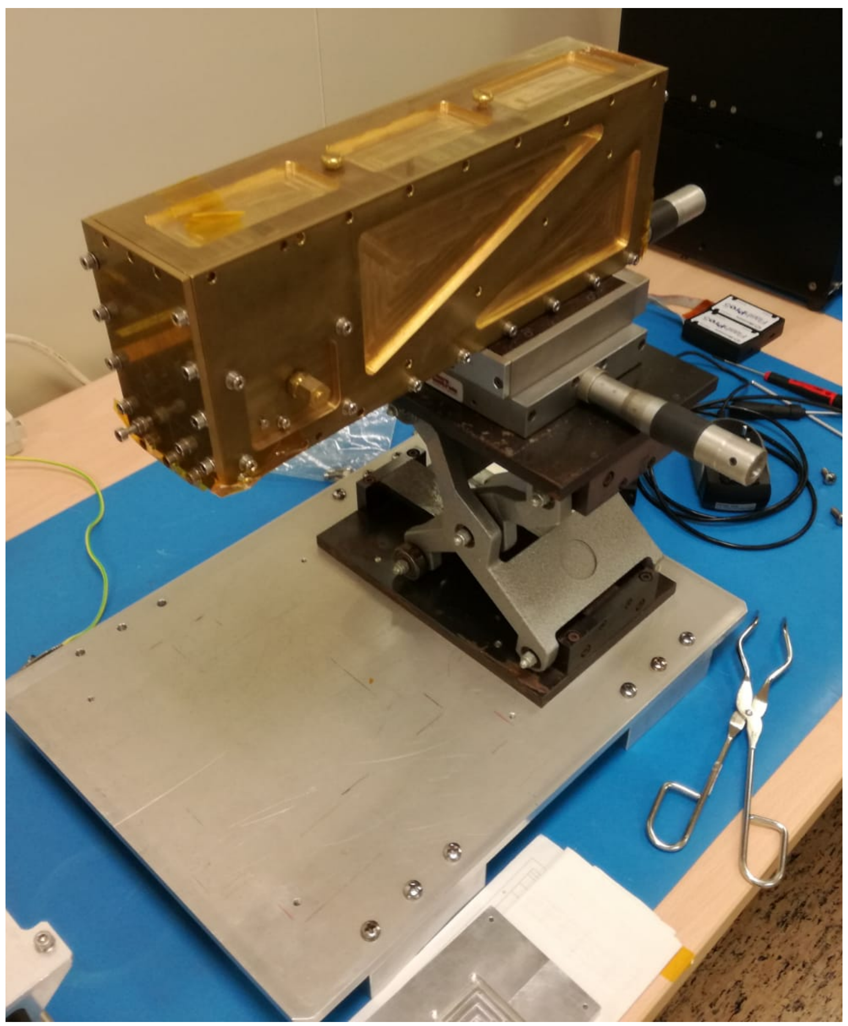
Xpol lab - hands-on

- **Systematic effects:** IXPE GPDs show rate-induced gain variations and residual modulation from unpolarized test sources; these are subtle effects which require availability of specific sources with different rates and energies and fairly long acquisitions to highlight non flat azimuthal distribution of the photoelectron reconstructed directions; it will be challenging, although interesting, to experience these effects during the laboratory

Xpol lab - setup and team

- Table-top setup (detector and electronics)
- Sealed GPDs (ie no need for gas system)
- Custom x-ray tube (can live w/o sources)
- Experienced team
  - Luca Latronico, INFN-Torino (IXPE DU PM)
  - Carmelo Sgro, INFN-Pisa (IXPE DU AIVT Mngr)

Xpol lab - the setup



custom
polarized X-ray
source

GPD and DAQ