Development of a Next-Generation Focal Plane Photoelectron Track X-ray Polarimeter with Timepix3 Readout

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High Precision X-ray Measurements 2025
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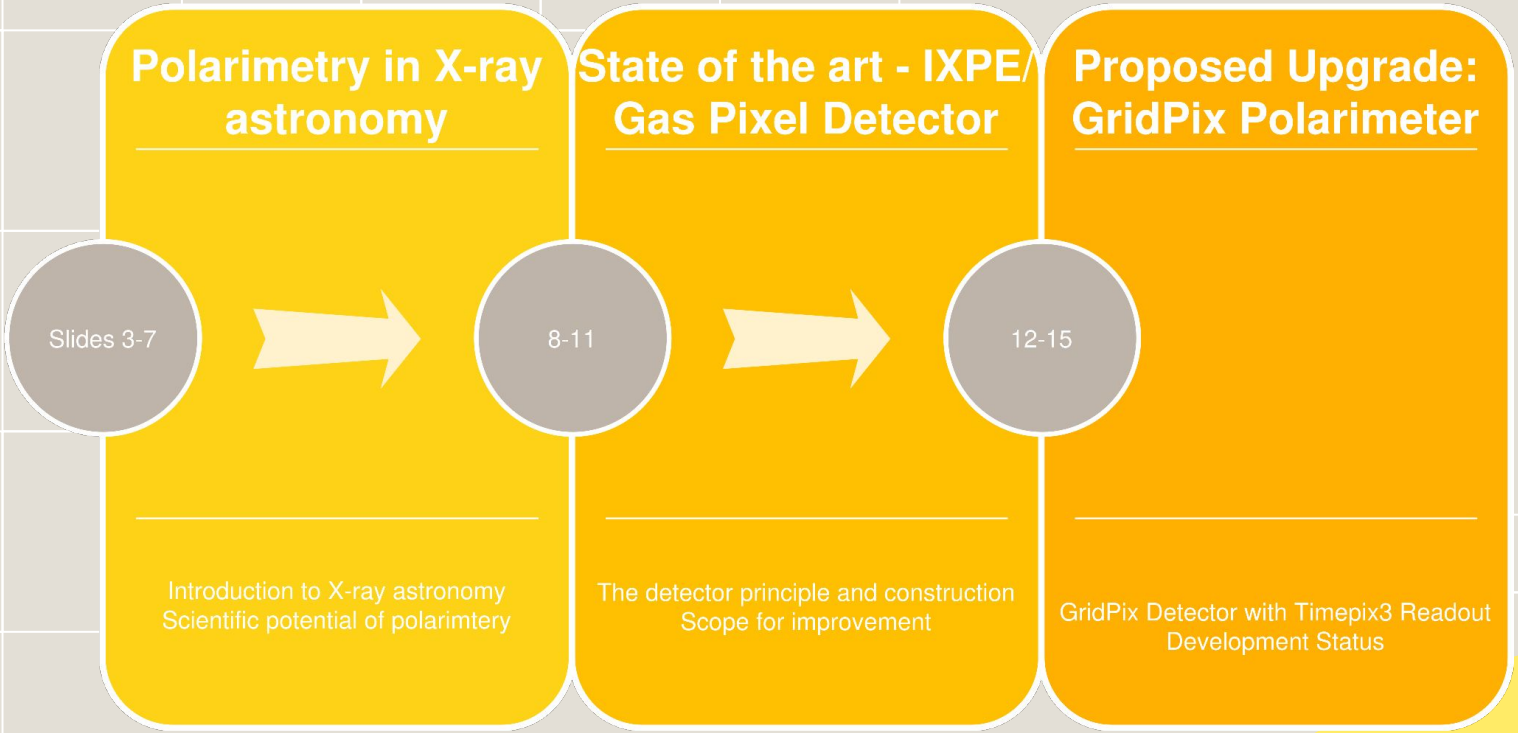
On behalf of the Hype-X collaboration

Enrico Costa, Klaus Desch, Alessandro Di Marco, Sergio Fabiani, Riccardo Ferrazzoli Markus Gruber, Daniel Heuchel, Saba Imtiaz, Jochen Kaminski, Dawoon Kim, Alessandro Lacerenza, Carlo Lefevre, Fabio Muleri, Vladislavs Plesanovs, John Rankin, Ajay Ratheesh, Alda Rubini, Paolo Soffitta

Outline of the talk

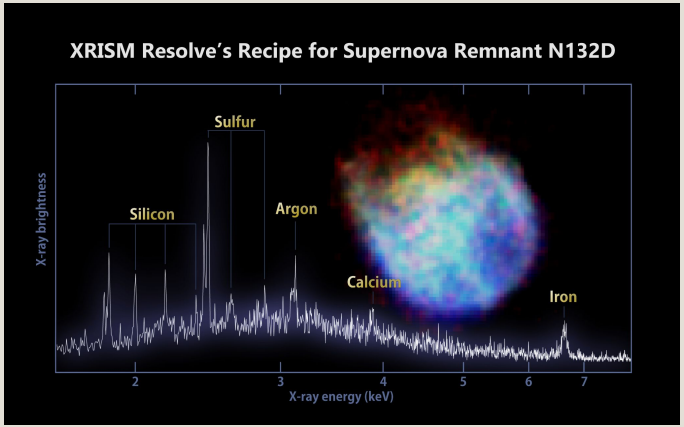


X-ray Polarimetry in Astrophysics

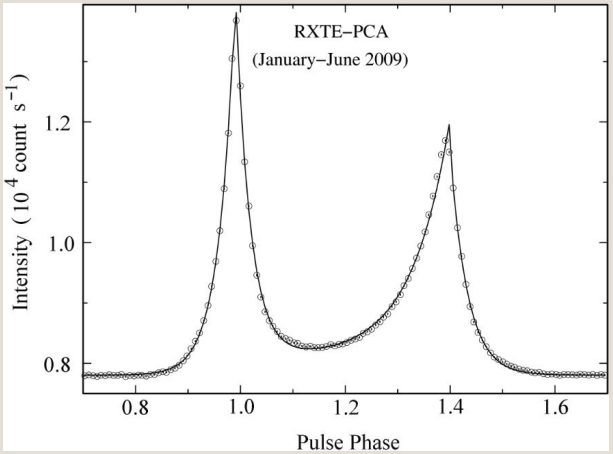
X-ray astronomy

- Emission conditions and geometry of astrophysical objects inside (within 10^5 ly) and outside Milky Way (up to 10^{10} ly)
- Usually in 1–100 keV
- Space borne detectors

  X-ray astronomical detectors measures **for each photon** (1) toa (2) energy (3) position on sky (4) *linear polarization*



Courtesy: JAXA/NASA/XRISM Resolve and Xtend

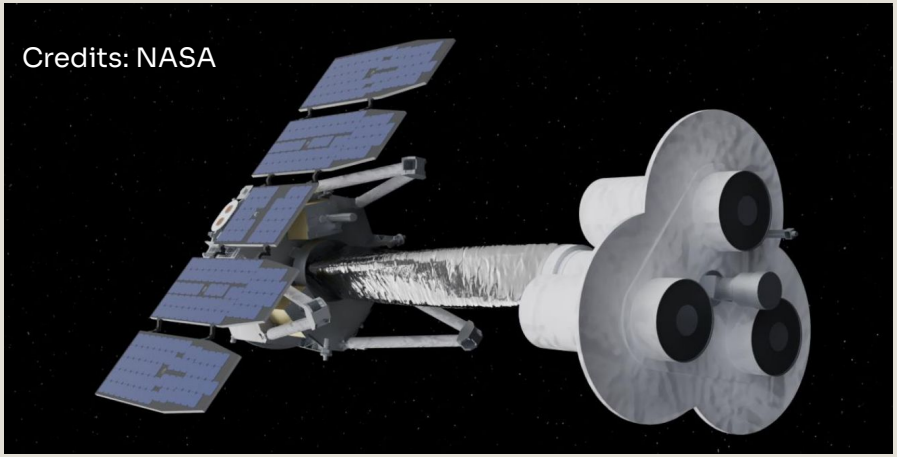


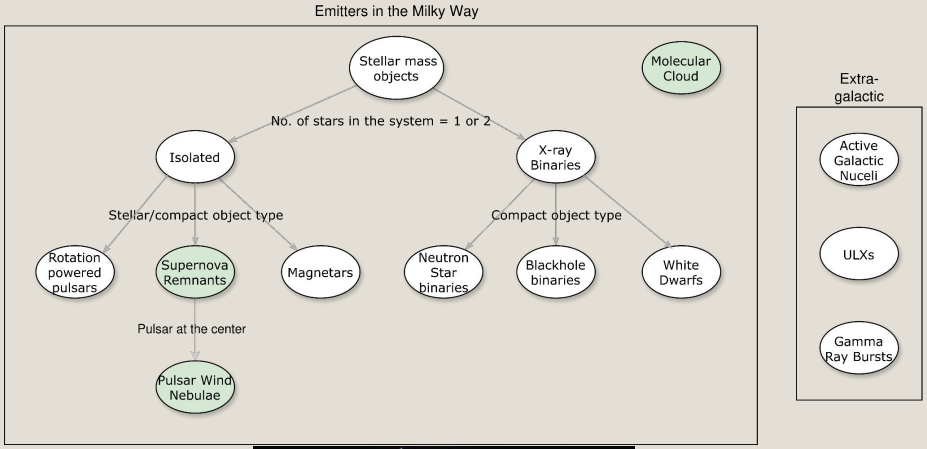
Jain et al (2011) : stability of X-ray pulses from the X-ray pulsar in Crab Nebula

Chandra 2–10 keV (false color) image of Crab Nebula

Only polarization measurement was from Crab Nebula by OSO-8 (Weisskopf M. C. et al, ApJ, 1976)

Novel powerful X-ray polarimetry observational window with focal plane polarimeter Imaging X-ray Polarimeter Explorer (IXPE)

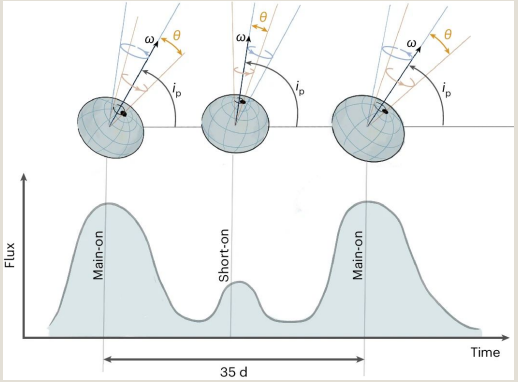




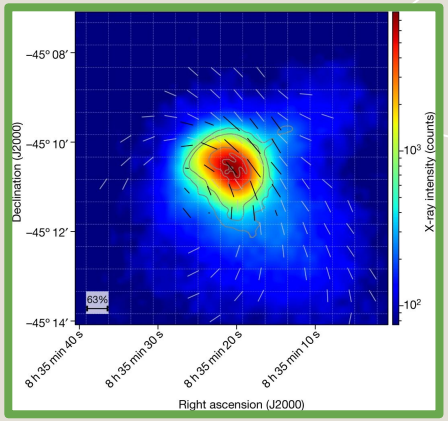
NASA-ASI mission
2–8 keV polarimeter
2021 December – **

- First in 1978 (OSO-8)
- Second in 2021 (IXPE)

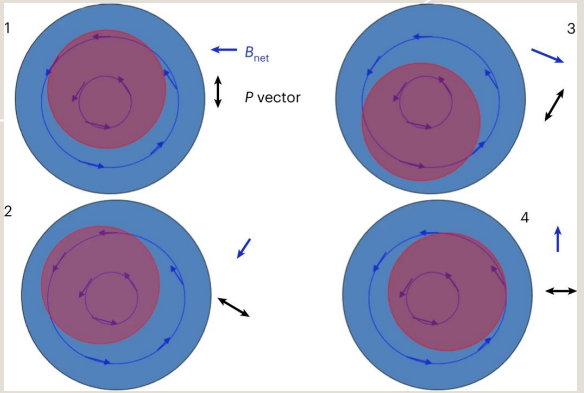
Potential of X-ray polarimetry: Emission mechanisms and Asymmetry in environment



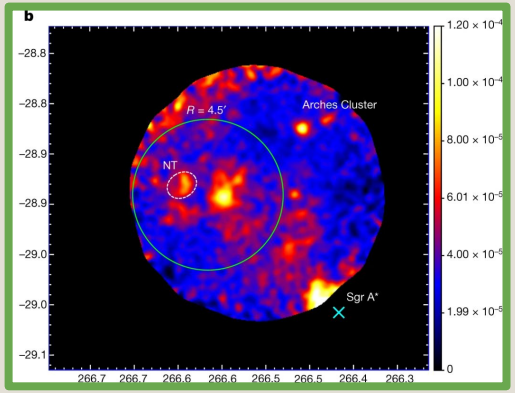
Precession of NS; J. Heyl et al., Nature Astronomy, 2024



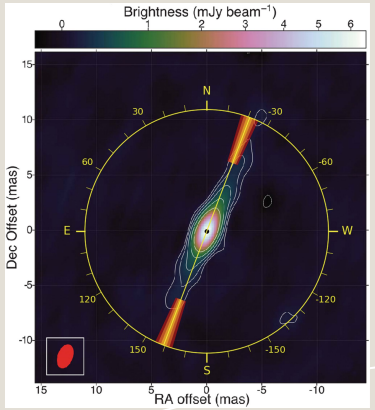
Magnetic Field map of PWNe; F. Xie et al., Nature, 2022



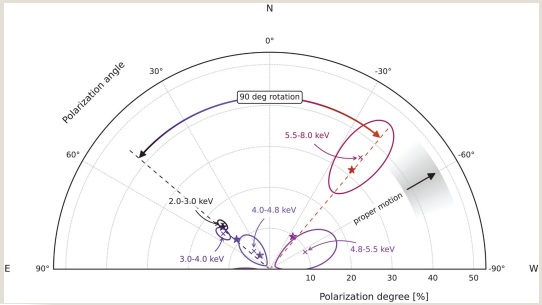
Helical magnetic field in an AGN jet; Laura Di Gesu et al., Nature Astronomy, 2023



Outburst history of Sgr A*; F. Marin et al., Nature, 2023



Accretion Disk and Jet geometry in accreting binary Black hole; H. Krawczynski et al., Science, 2022



Emission mechanism and scattering region geometry in Magnetar; R. Taverna et al., Science, 2022

Bruno Rossi Prize 2024 awarded to **Martin Weiskopff (NASA), Paolo Soffitta (INAF)** and the **IXPE team**

American Astronomical Society (AAS)
@AAS_Office

.@AAS_HEAD is awarding 2024 Rossi Prize to Martin Weisskopf, Paolo Soffitta & the Imaging X-ray Polarimetry Explorer (IXPE) team for the instrument & the revelations it is producing about the physics of neutron stars & black holes & their environments. 🏆 aas.org/posts/news/202...

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Antonio Feltrinelli 2025 for Physics awarded to **Ronaldo Bellazzini (INFN), Enrico Costa (INAF) and Martin Weisskopf (NASA)**

INFN - Istituto Nazionale di Fisica Nucleare and **INAF - Istituto Nazionale di Astrofisica**
1d ·

🏅 Premio Feltrinelli 2025 all'Astrofisica dei raggi X
L'**Accademia Nazionale dei Lincei**, alla presenza del Presidente della Repubblica Sergio Mattarella, ha conferito il Premio Internazionale Antonio Feltrinelli per le Scienze Fisiche a
✨ Ronaldo Bellazzini (INFN)
✨ Enrico Costa (INAF)
✨ Martin Weisskopf (NASA)
per il loro straordinario contributo alla missione spaziale IXPE – Imaging X-ray Polarimetry Explorer, lanciata nel 2021 e ancora oggi operativa. Un riconoscimento prestigioso per una missione rivoluzionaria!

IXPE ha aperto una nuova finestra sull'universo, rendendo possibile – per la prima volta – lo studio sistematico della polarizzazione dei raggi X provenienti da buchi neri, stelle di neutroni, AGN e altre sorgenti cosmiche estreme. Un traguardo scientifico e tecnologico frutto di oltre 20 anni di lavoro, che vede l'Italia protagonista grazie al contributo di INAF, INFN, **Agenzia Spaziale Italiana** e OHB Italia, in collaborazione con la NASA.

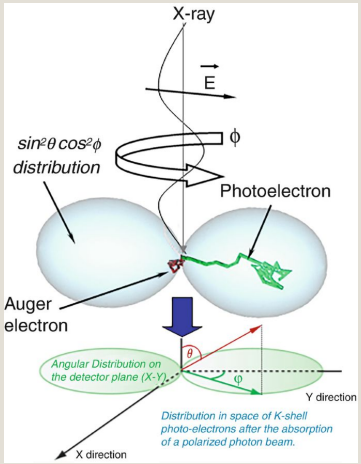
Per saperne di più, leggi il comunicato stampa.
👉 **https://www.infn.it/a-ronaldo-bellazzini-enrico-costa-e.../**
👉 **https://www.media.inaf.it/.../06/13/premio-feltrinelli-2025/**

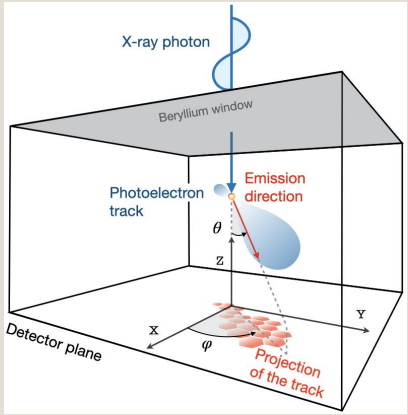
📷 In copertina, la missione spaziale IXPE in preparazione prima del lancio. ©NASA

#PremioFeltrinelli #INFN #NASA #SergioMattarella #IXPE #Raggix

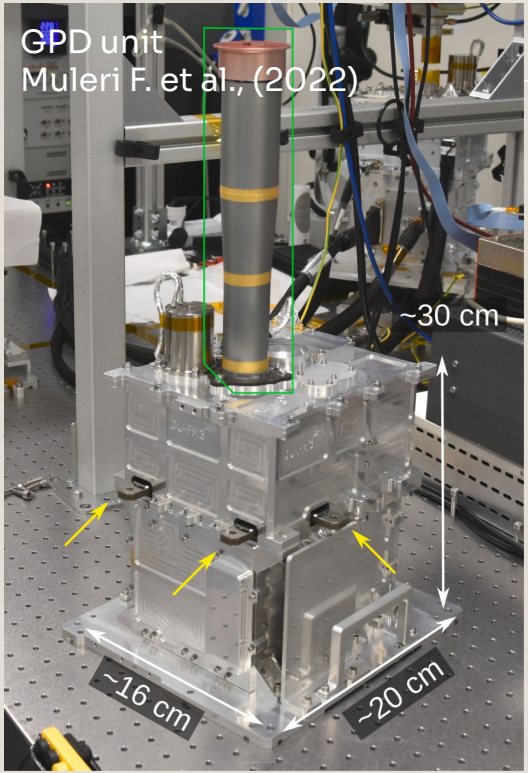
Gas Pixel Detector (GPD) on board Imaging X-ray Polarimeter (IXPE)

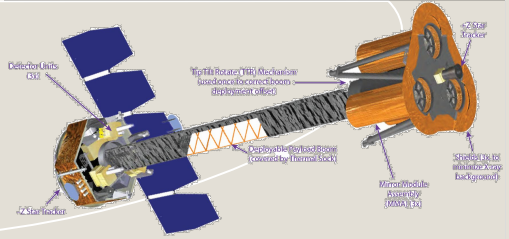
IXPE/GPD focal plane polarimeter



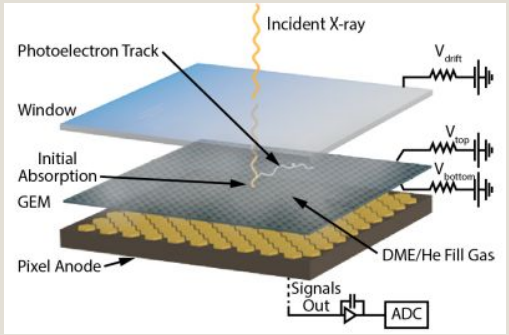


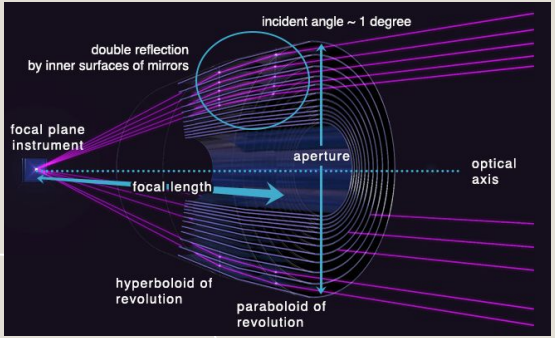
Costa E. et al., Nature, 2001





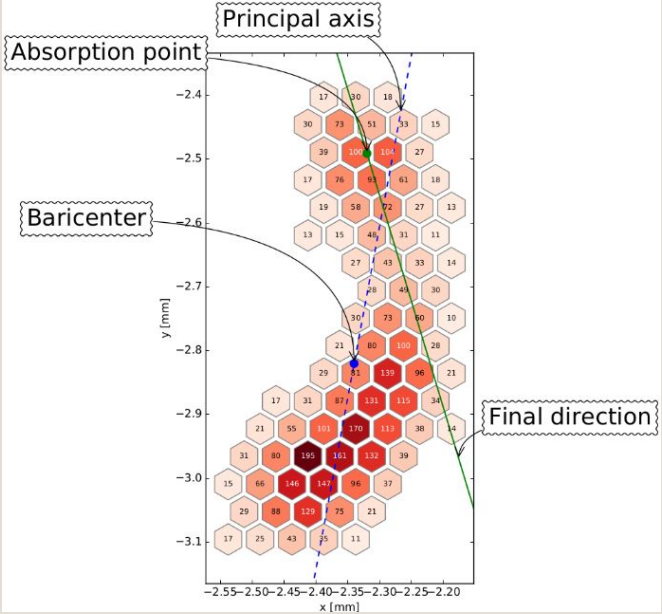
Courtesy: JAXA/NASA/XRISM





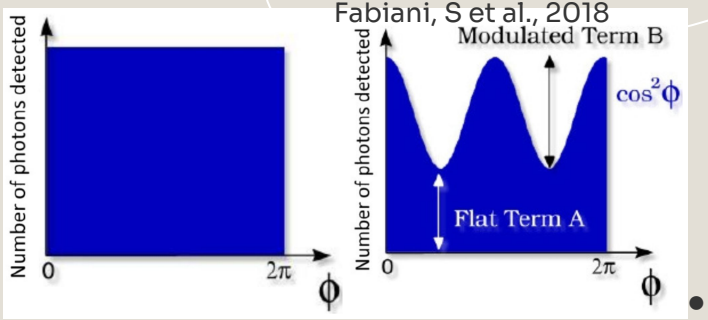
Photoelectron track imaging feasible in gas

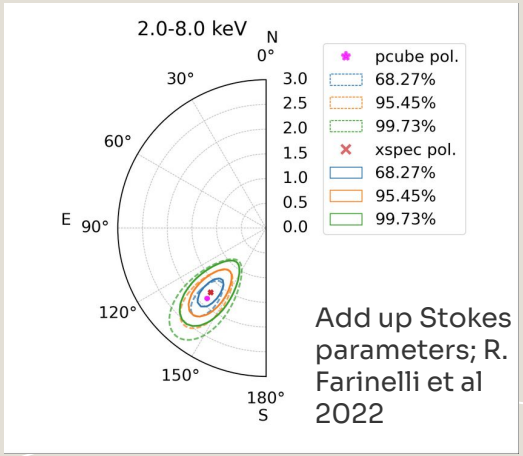
Extraction of polarization from photoelectron tracks



- Photoelectron + Auger electron / Fluorescence photon
- Bragg peak exclusion
- Extraction of absorption point and direction

Fit with $\cos^2(\phi)$ function
Fabiani, S et al., 2018

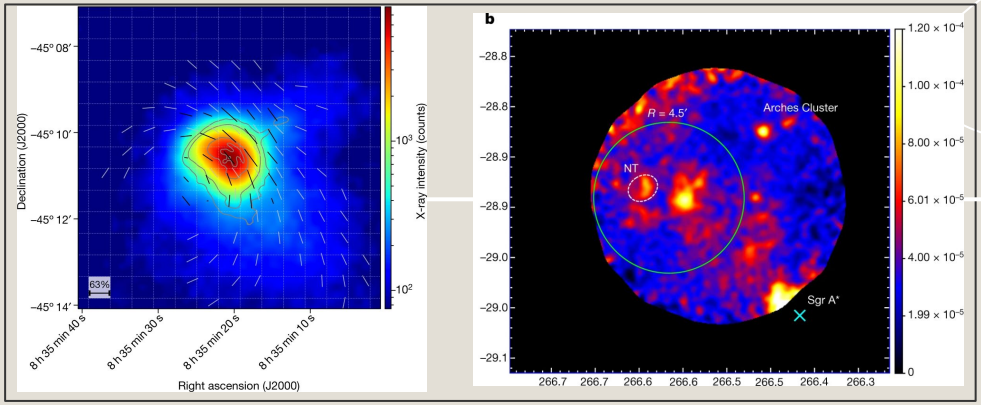


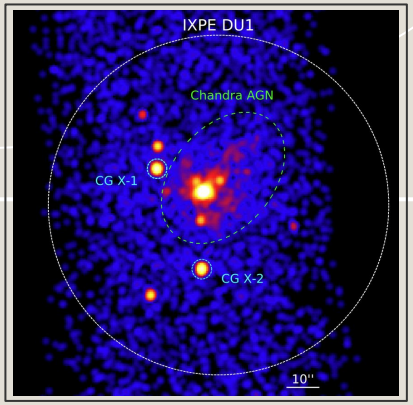


Add up Stokes parameters; R. Farinelli et al 2022

- Response to 100% polarized source: modulation factor (μ)
- Figure of merit: Minimum Detectable Polarization
- MDP $\propto \mu\sqrt{\varepsilon}$

Requirement of focal plane detector and necessary upgrade to GPD specifications





Spatially resolved polarimetry of extended sources

High SNR observations of point sources
Small active area samples low background

Characteristic	IXPE/GPD (existing)	Requirement	Way forward
Energy Range	2–8 keV	Science goals: Higher energy (6–30 keV)	High Z gas / high pressure
Modulation factor	20% at 2 keV (low E)	Reduced exposure operations: Improved μ at low E	3D track
Deadtime	1 ms	High count rate operability with future optics like AXIS: ~ μs	New ASIC
Charged particle veto (Minimum ionizing particle)	Low gas gain (x100)	High gas gain (x1000)	New Gas Multiplication stage

GridPix X-ray Polarimeter with Timepix3 readout ASIC

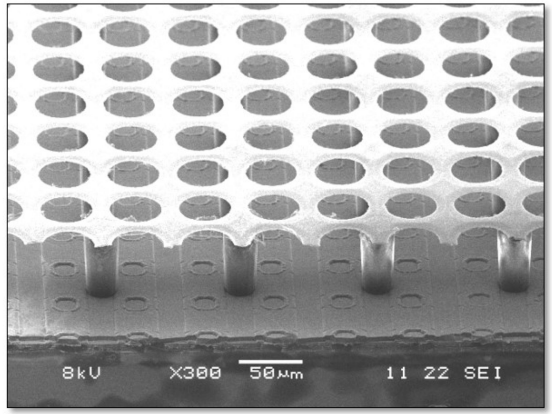
GridPix: Hybrid Micro-pixel Gas Detector with Timepix3 Readout

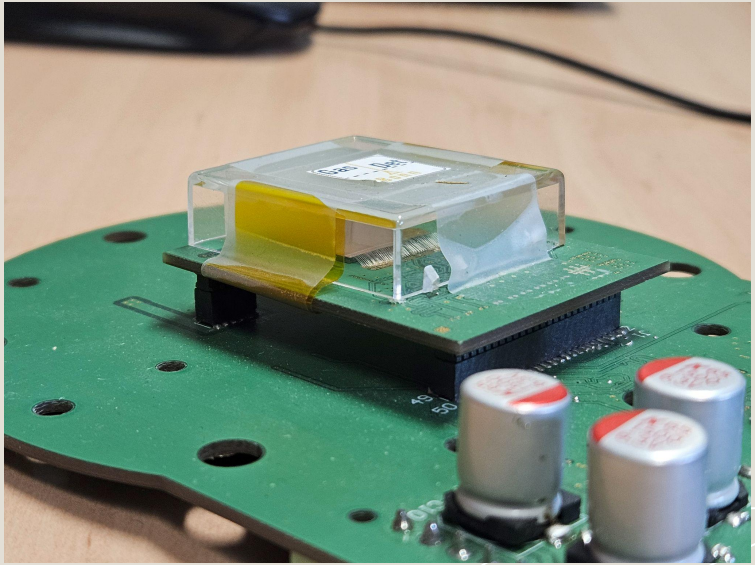
GridPix = Gas Cell + InGrid

ASIC

- 256 x 256 (55 µm pitch) pixels
- Active Area 1.4 x 1.4 cm^2
- 1.5625 ns time resolution
- Simultaneous TOA/TOT
- Sparse readout
- Dead time 475 ns + TOT

InGrid gas multiplication stage Micromegas structure fabricated on top of Timepix3 ASIC





Gas Cell

- Beryllium window
- Argon (6–30 keV) or DME (2–8 keV) gas
- Thickness: 1-2 cm
- Pressure: 1-2 atm

Major Improvements facilitated by GridPix

<u>3D track with relative time difference</u>

Simulations show improved polarimetric sensitivity (μ) with 3D tracks

<u>Sparse Readout and Low Deadtime</u>

Count rates compatible with next generation X-ray optics

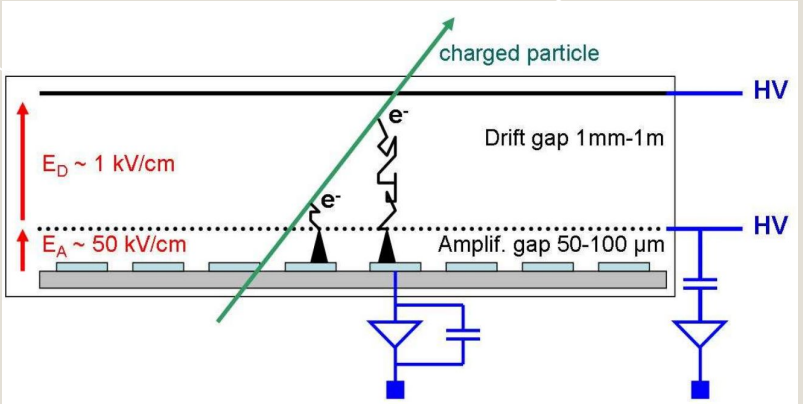
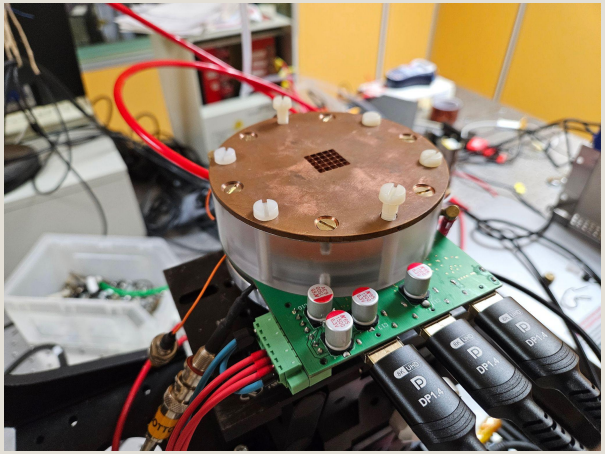


Illustration from M. Chefdeville, 2009

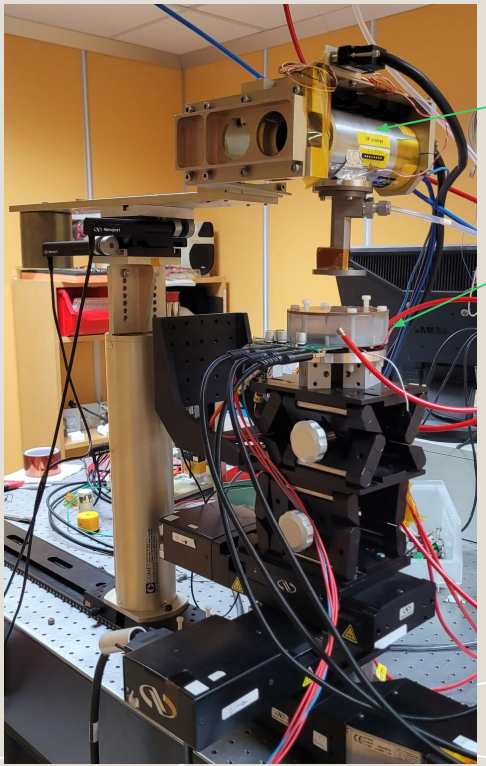
GridPix prototype with Ar/DME 1 cm 1 atm

6.4, 17 keV polarized and unpolarized sources

Ar/DME (4:1)
Mylar window
2 cm drift gap
E field 500 V/cm

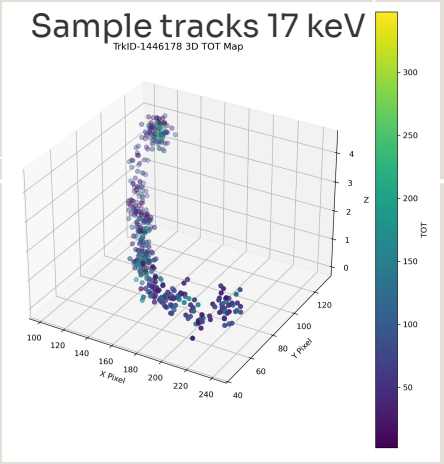


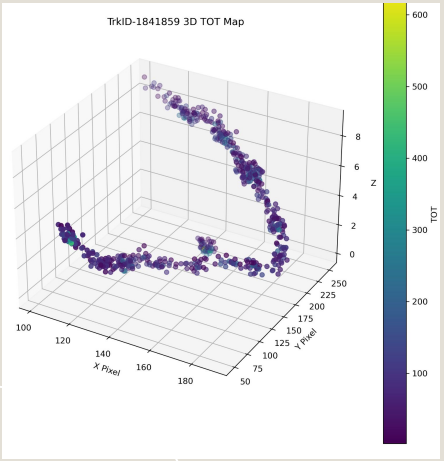
GridPix Detector



X-ray generator

GridPix





Development Status

- ✓ Thermal-Vacuum tests of InGrid (4–40 deg C)
- ✓ General Environment Vibration Test (Random vibrations)
- ✓ Geant4 simulation setup
- ✓ Generalized 3D track reconstruction algorithm
- ✓ 3D photo electron track from prototype
- ✓ High count rates operability (30,000 tracks per sec)
- ✓ Higher energy range (17 KeV tested with Ar/DME)
- ❑ Uniform electric field with Field-forming rings
- ❑ Gas flow detector (test gas mixtures)
- ❑ Beryllium window
- ❑ Optimization of Generalized 3D photoelectron track algorithm
- ❑ Heavy ion beam tests (Cosmic rays dose for 20 years) planned July 2025

Summary

- Huge scientific potential of X-ray polarimetry demonstrated by the success of IXPE
- Imaging Polarimeter in higher energy band with better polarimetric sensitivity is necessary
- GridPix detector serves a potential upgrade
- Construction of detector and Characterization with X-rays ongoing at University of Bonn and INAF/IAPS, Roma