X-ray polarization from astrophysical sources. Large volume Time Projection Chamber (TPC) from HypeX project

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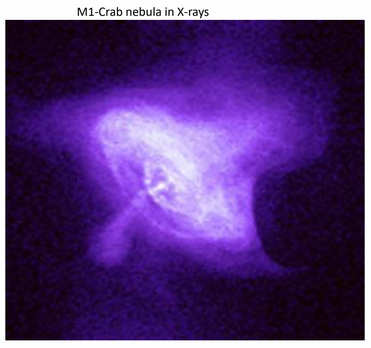
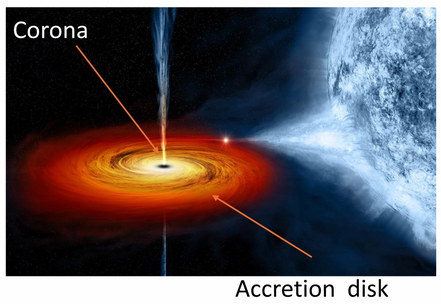
M1-Crab nebula in X-rays





What can we learn

Sources

- Large amount of astrophysical sources are home to extreme physical conditions of plasma shock, gravitational and magnetic field

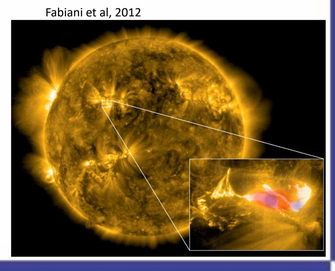
  Black holes, Magnetars, Active Galactic Nuclei, SuperNova Remnant…

- Their non-thermal X-rays emission is foreseen polarized depending on the production mechanism and geometry of the source

Physics with X-ray polarimetry Meszaros et al. 1988 doi.org/10.1086/165962.

- Geometry of the sources (coronas of Black holes, magnetic structure of shocks and jets)
- Fundamental physics (vaccum birifrangence, general relativity, BSM)
- Solar flares above 15 keV (also with space weather applications)

Fabiani et al, 2012



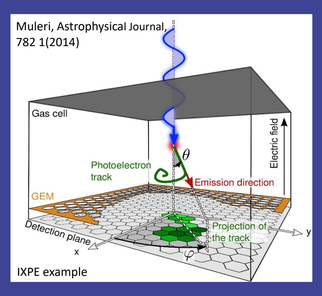
Status now

- IXPE mission (launched in 2021) is leading the scene, featuring:
  - X-ray polarimeter detector in focal point of X-ray mirrors
  - Sensitivity in 2-8 keV range

Wide field of view search at higher energy is still unexplored!

How to measure polarization

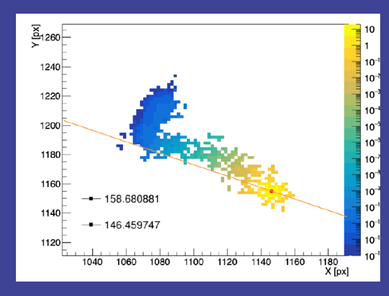
Combine photoelectric effect and an imaging detector like gaseous Time Projection Chambers (TPC)



- Photoelectrons emitted from s-shell follow

$$\frac{d\sigma}{d\Omega} \propto \cos^2\phi \frac{\sin^2\theta}{(1-\beta\cos\theta)^4}$$

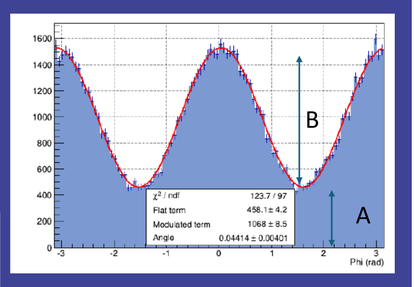
- Their emission direction statistically follows the original polarization of the photon
- Electrons in gas can travel mm (depending on energy, gas density)



- TPCs are intrinsically 3D detectors
- With granular amplification and readout the photoelectron track can be imaged

The reconstructed track provides:

- **Impact point**: conversion of the photon.
  Imaging of the source with ang. resolution down to few arcsec
- **Direction**.
  Its distribution provides polarization angle and degree (P)



$$\mathcal{P} = \frac{1}{\mu}\frac{B}{B+2A}$$

μ : modulation factor.

Response to a fully polarized source

The Detector

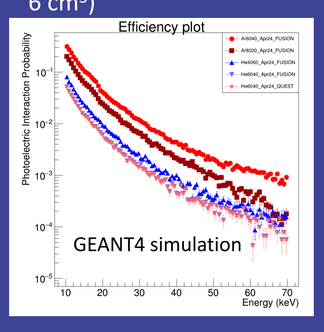
Amaro et al., https://arxiv.org/abs/2406.05713 (accepted and reviewed by EPJ C)

- Large field of view collimator combined with gaseous TPC with optical readout (inherited from CYGNO experiment)
- 8-40 keV energy range of interest

Part of PRIN project HYPEX, now renamed X-POT

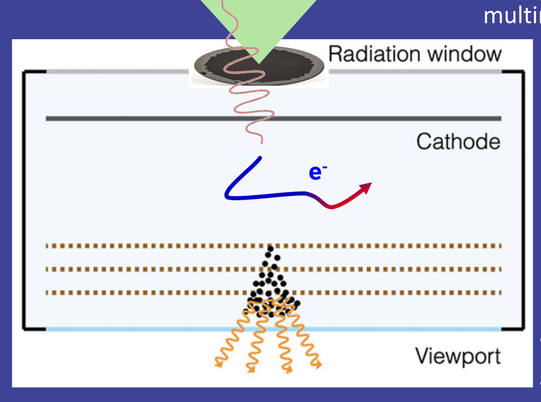
GAS

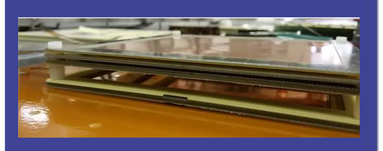
- Mixture of He/Ar:CF_4 @ 1 bar
- Density between 1.5 and 2.2 kg/cm^3
- Scintillating mixtures in visible and UV
- 10^3 cm^3 volume to enhance conversion of X-rays (IXPE has 6 cm^3)



LARGE FOV

- Simple collimator to reduce backgound
- Aperture up 20 deg to comply with transient phenomena for multimessanger



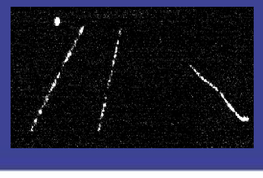


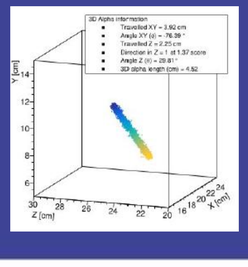
AMPLIFICATION

- Gas Electron Multiplier stack
- High gain (10^5)
- Granular (300 μm RMS diffusion)

CAMERA qCMOS

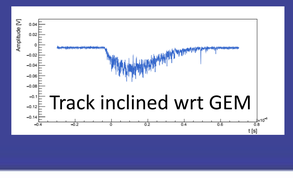
- Extremely sensitive (0.3 e$^-$ RMS = photon counting)
- Highly granular: 44x44 μm^2 imaging 10x10 cm^2



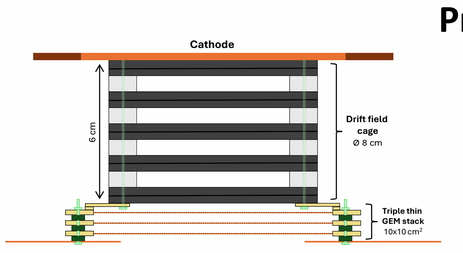


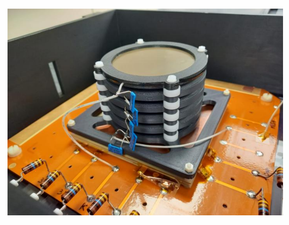
PMT

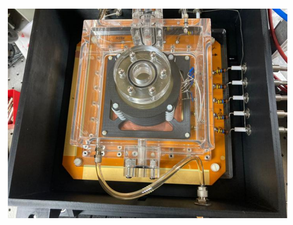
- Fast detector
- Provides missing coordinate to camera for 3D tracking



Prototype and Setup



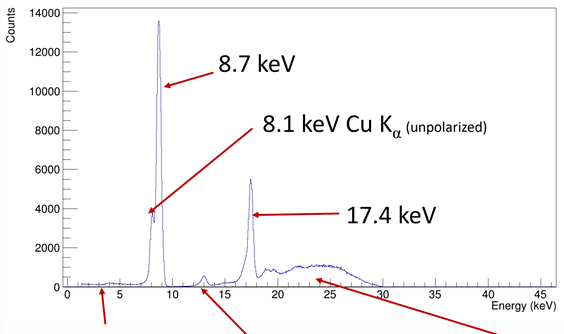




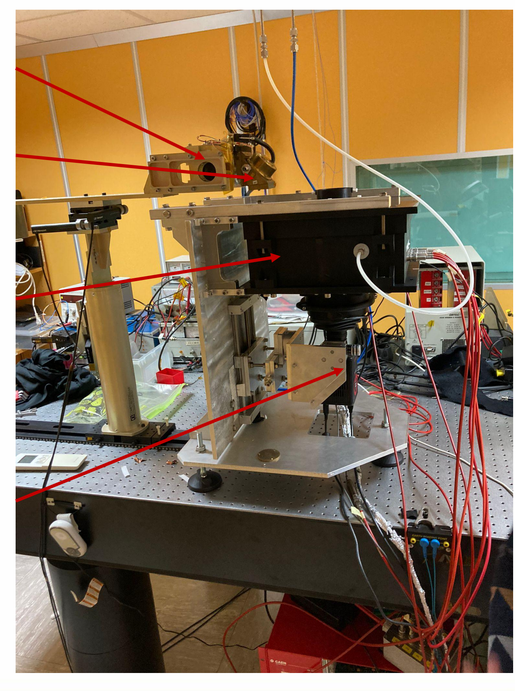
- 6 cm long field cage made with silver wires
- Thin cathode: Kapton (40 μm) and Cu (35 μm)
- PMMA gas tight box with 15 μm thick PET window
- He:CF_4 and Ar :CF_4 mixtures (60/40)
- Only camera used at the moment

Polarized lines generated by diffractor crystal

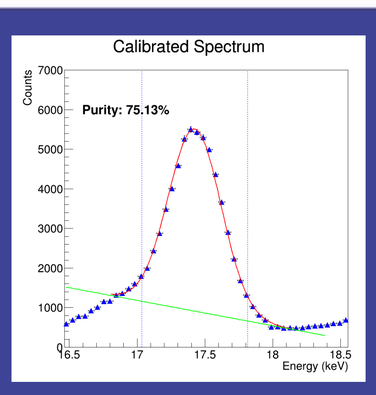
Energy spectrum of X-ray crossing cathode (measured with CdTe detector)



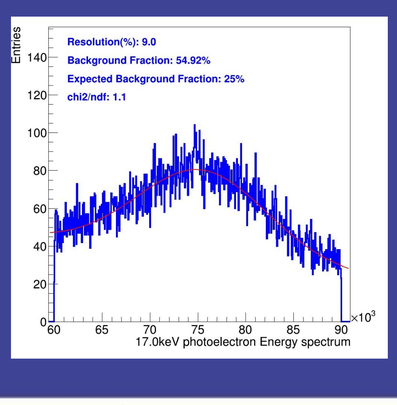
Setup at INAF IAPS for polarized measurements



Modulation factor measurement at 17 keV



Unpolarized background estimated from the CdTe

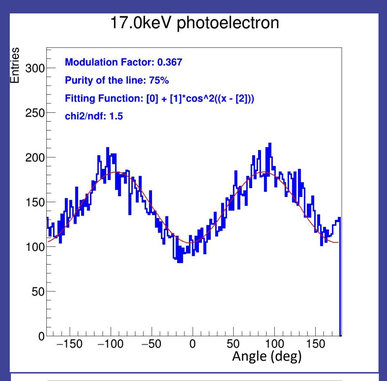


Larger background fraction due to lower energy resolution of gas detector

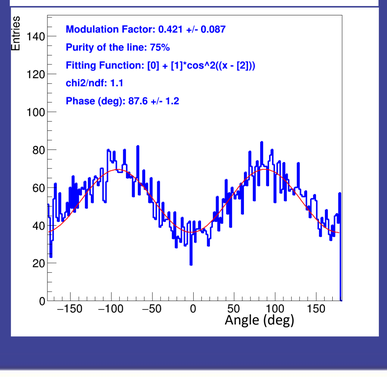
First ever modulation factor measurement with our detector

Polarization angle consistent with expectation

He:CF_4



Ar:CF_4



FoM @ 17 keV

0.037

FoM @ 17 keV

0.12

Figure of Merit *(FoM)*

- The Minimum detectable polarization of a source is inversely proportional to the Figure of Merit (FoM)

$$FoM = \mu\sqrt{\varepsilon}$$

- The larger this number the better the performance of the detector
- IXPE FoV in their energy range is 0.07 – 0.11

While still at early stages, our detector concept has similar FoM than IXPE in a higher unexploredenergy range

Conclusion

- Measuring the polarization of X-rays from astrophysical sources can unveil mysteries on unknown physics
- X-POT detector concept exploits an optical TPC for a wide field of view measurement of polarized X-rays in the 8-40 keV energy range
- The first ever measurement of modulation factor suggests the detector concept is competitive with state of the art technology

Next

- Optimize the concept design simulating background and source fluxes
- Tweak the amplification stage to reduce intrinsic diffusion
- Improve data reduction and dead time