Polarimetry with Optical Time projection chamber within HypeX project

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High Precision X-ray Measurements 2025

Astrophysical sources in X-rays

- A plethora of astrophysical objects in our Galaxy and outside is known to host extreme conditions in terms of plasma physics, high energy physics, gravity

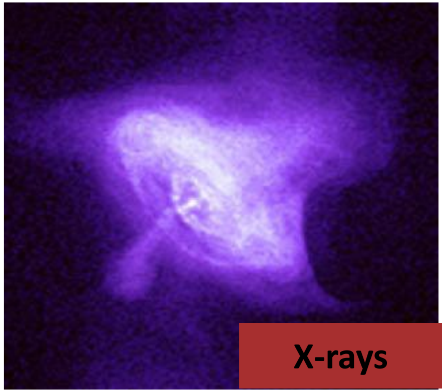
  Black holes, neutron stars, SNR, PWN, AGN, magnetars..

- Excellent case studies for advances in astrophysics and fundamental physics

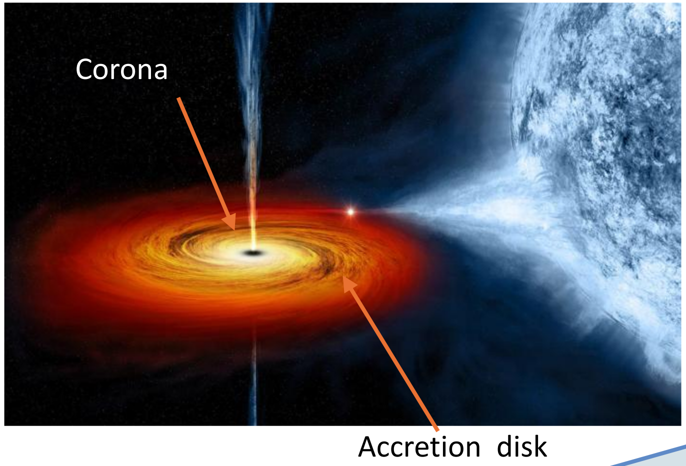
- Non-thermal X-ray emissions from these sources are expected to be polarized (mostly via Inverse Compton, sinchrotron, Bremsstrahlung)

- Plenty of physics cases to study
  - Corona and magnetic field geometries (BH and shock sites)
  - Fundamental physics (Vacuum birefringence, general relativity)
  - Solar flares

- **New physics can be searched too (QG, LIV, ALPs)**



M1-Crab nebula



Why Polarization

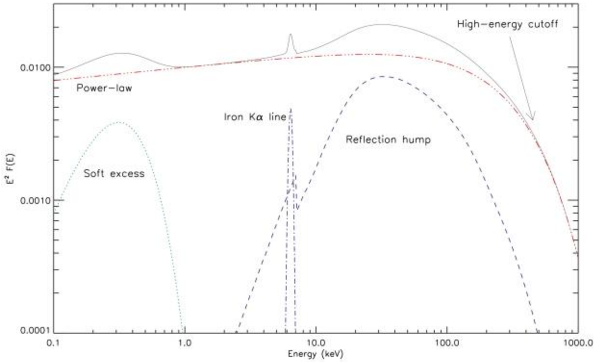
- Typical X-Ray measurements include

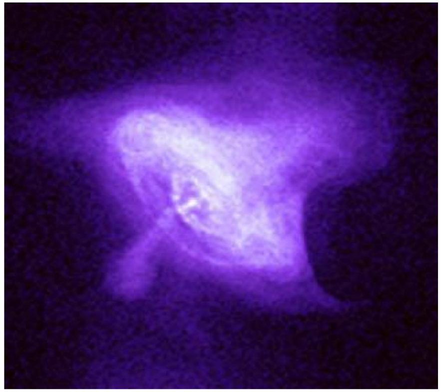
Energy spectrum

Time evolution

Space distribution

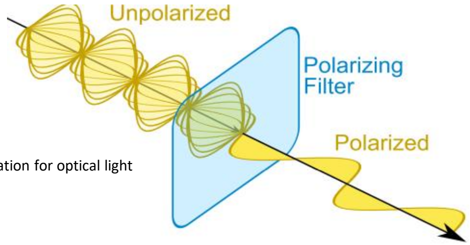
Ricci et al. 2011, PhD thesis





- Polarization measurement can increase the amount of degrees of freedom available to study X-Ray emissions

Meszaros et al. 1988 doi.org/10.1086/165962.



Example of polarization for optical light

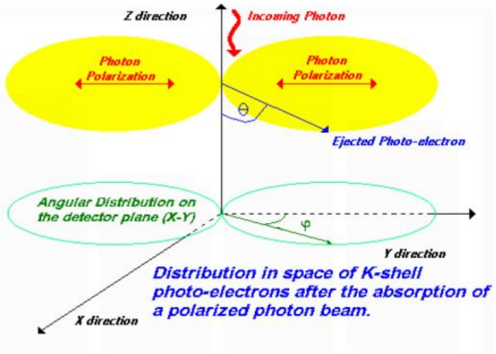
Polarization angle (PA): Direction of the polarization (classically: the orientation of the oscillating electric field)

Polarization Degree (PD): How much of the source X-rays are polarized

All emission mechanisms have polarization characteristics dependent on the geometry of the source

Measure X-Ray Polarisation

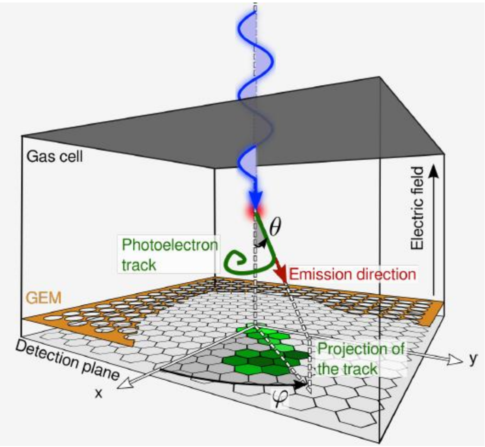
- Combine the photoelectric conversion and imaging of the photoelectron: gaseous Time projection Chamber (TPC)



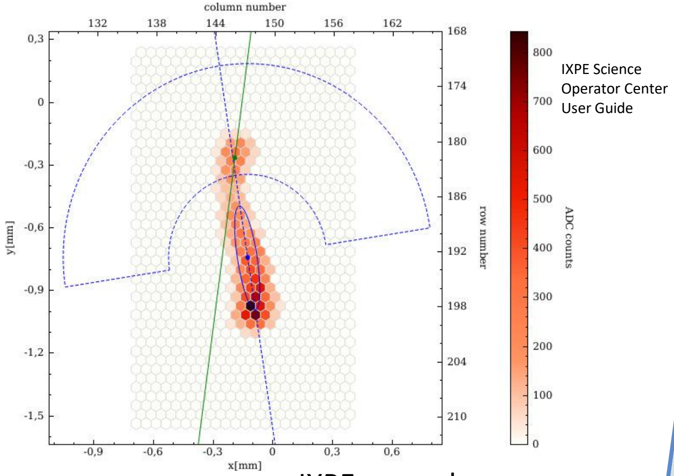
Costa et al., Nature, 2001

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

- Photons convert into the gas producing a photoelectron
- Azimuth distribution is mostly parallel to amplification plane



- TPC detector contains intrinsic 3D information about the electron track
- Combine granular amplification stage and readout to match size of the recoil (and diffusion)



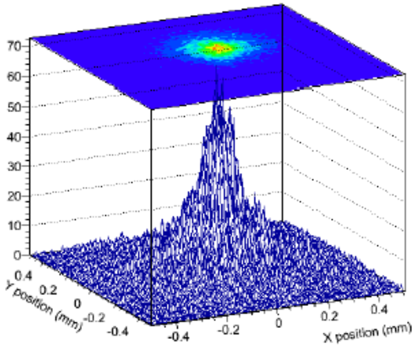
IXPE example

- Readout allows the reconstruction of the track
- Provides Impact point (conversion of the photon) and direction

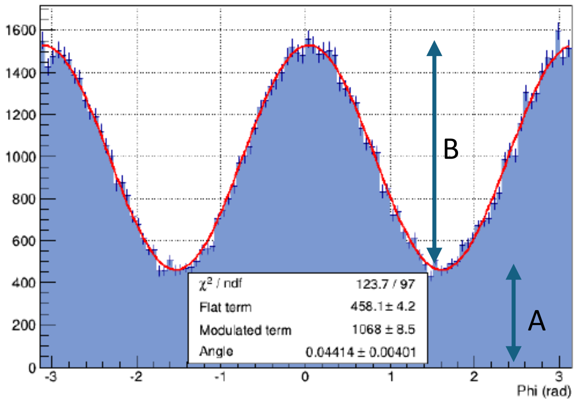
Polarisation Variables

- The impact point distribution returns the image of the emitting source

Angular resolution down to 6.4 arcsec



- The measured direction return the modulation curve



$$\mathcal{M}(\phi) = A + B\cos^2(\phi - \phi_0)$$

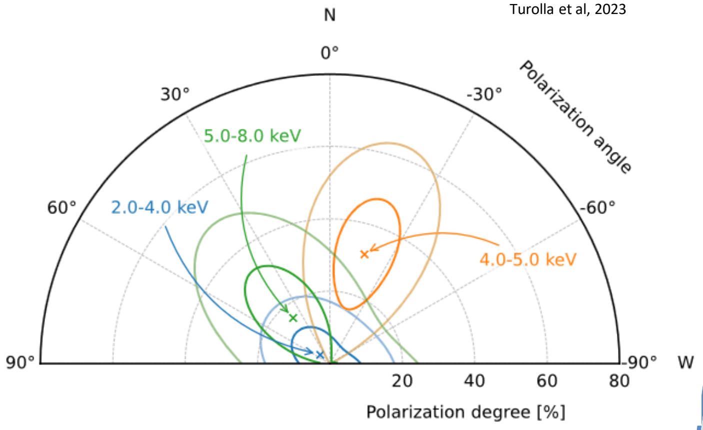
PA

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

PD

Modulation factor (μ):
detector response to 100% polarized source

Turolla et al, 2023



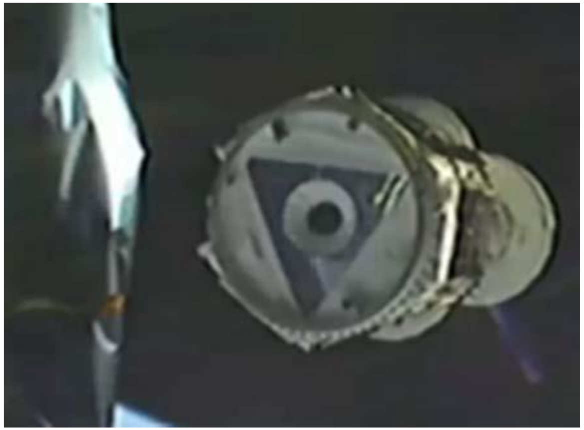
For experts: Actually better passing through Stokes parameters

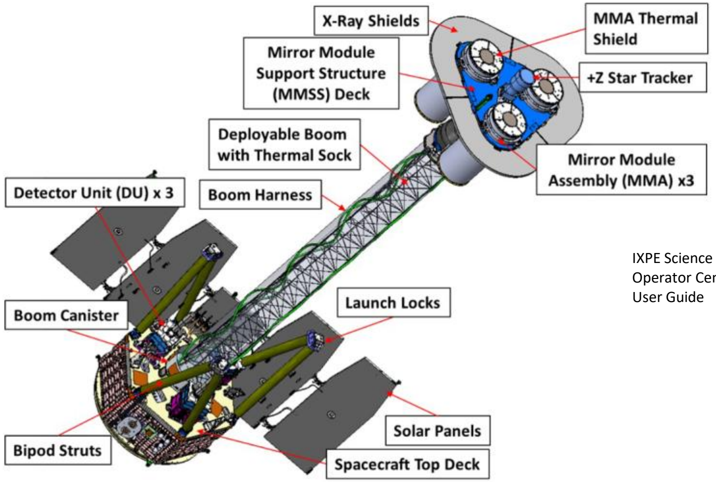
IXPE Mission

- The Imaging X-ray Polarimetry Explorer (IXPE) was launched on December 2021
- 3 Photoelectric detectors (GPD) in the optics of 3 mirror telescopes

  (reduces background, focuses sources)
- GPD: TPC of 1x1x1.5 cm^3 with single GEM and ASIC readout
- On board calibration system with polarized and unpolarized sources

Release from Falcon 9





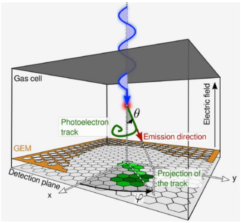
IXPE Science Operator Center User Guide

X-ray mirrors made of 24 concentric reflective Ni-Co alloy shells

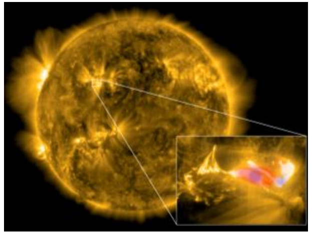
Sensitivity in 2-8 keV range

PRIN Project HypeX

- Despite great results IXPE has limitations



12.9 arcmin



Deadtime of 1 ms per event	Continuous calibrations	2D readout	Limited to focal plane of X-ray optics	Energy range $\leq$ 8 keV
Need to evaluate pedestal after every event	Caused by GEM and ASIC and glue asoption of gas	Lower discrimination power to tracks oriented toward the sensor plane (more background)	Limited field of view Loss to sensitivity to transients (helpful for multimessanger physics)	Higher energies can ✓ increase information on coronas, magnetars ✓ tackle non-thermal bremsstrahlung in Solar flares and NS binaries

Fabiani et al, 2012

Westfold 1959

- **HypeX project** aims to develop innovative detectors and technique for measurement of polarization of X-rays through photoelectic technique

- Improvements on IXPE expertise

- Winner of 2020 PRIN fund subdivided in subprojects

Funds of about 1 M€ until last May

GPD3D

Focused on improvements of:
- charge sensor
- energy range
- Amplification stage

Team INAF-IAPS:
Soffitta
Costa
Muleri
Fabiani

Xray-CMOS

Focused on:
- optical readout
- Amplification stage
- field of view and energy range

Team LNF-GSSI:
Baracchini
Mazzitelli
Fiorina
Dho

Renamed X-POT after PRIN expired

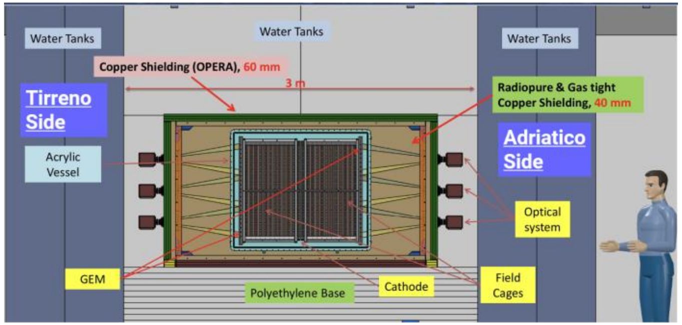
MUR
Ministero dell'Università e della Ricerca

PRIN 2020

X-POT Concept

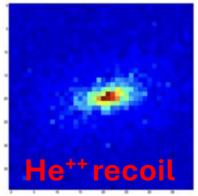
- Main effort guided by E. Baracchini
- Technology inherited by CYGNO (3D rare event searches)
- Gas TPC with large area optical readout

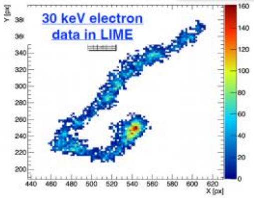
CYGNO-04 demonstrator under construction



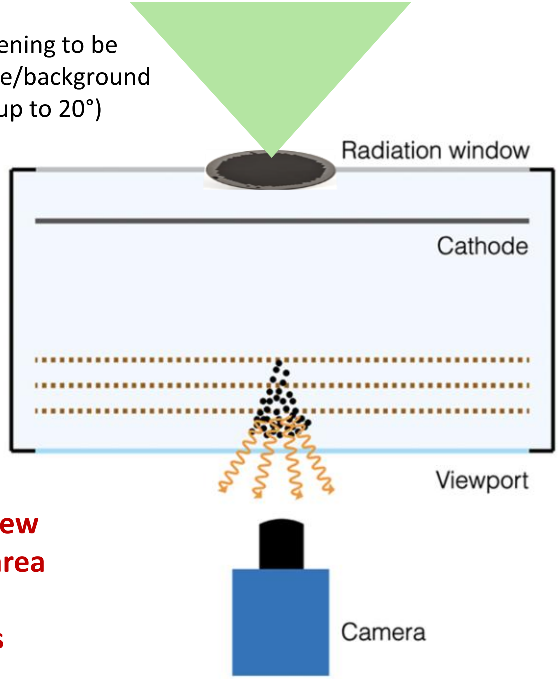
Amaro et al, CYGNO experiment 2022

- TPC of 0.4 m^3 double sided with 50 cm drift
- Readout area 50x80 cm^2





Field of view opening to be optimized on source/background fluxes (ideally up to 20°)



Energy range 8-40 keV

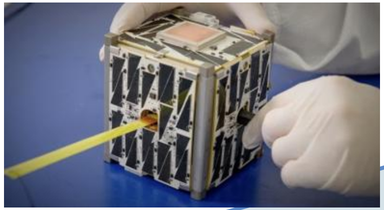
10x10x10 cm^3

Amplification stage

Tackle

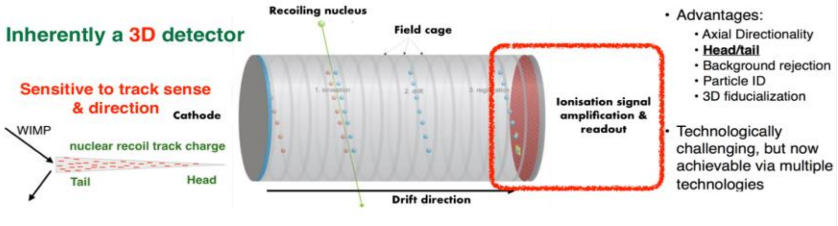
- **Large field of view**
- **Wide imaging area**
- **3D tracking**
- **Higher energies**

Could be hosted on small missions on balloons or cubesat

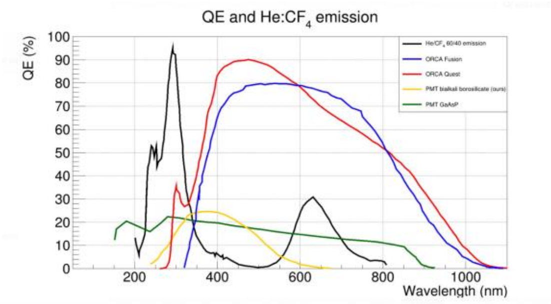


Detector Principle

Time Projection Chamber



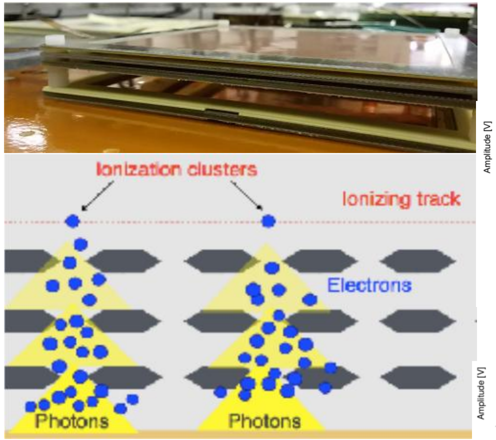
- Intrinsic 3D capable detector
- He/Ne/Ar:CF_4 60/40 gas mixture
- Low diffusion in gas (about 100 $\frac{\mu m}{\sqrt{cm}}$)



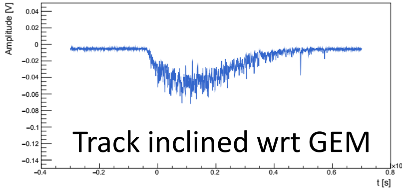
GEM amplification optically readout

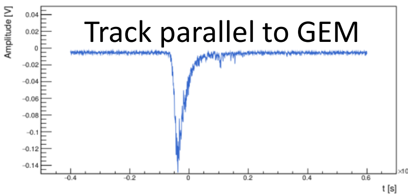
sCMOS camera

- Single photon sensitivity
- High granularity (2304x2304 pixels)
- Nice match with CF_4 emission

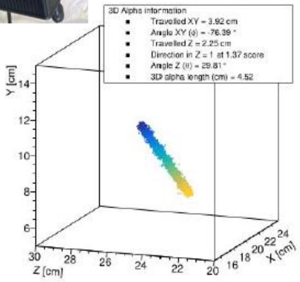


PMT





Energy
x-y coordinate



Energy
z coordinate

Detector Principle

Time Projection Chamber

optically readout

Recoiling nucleus

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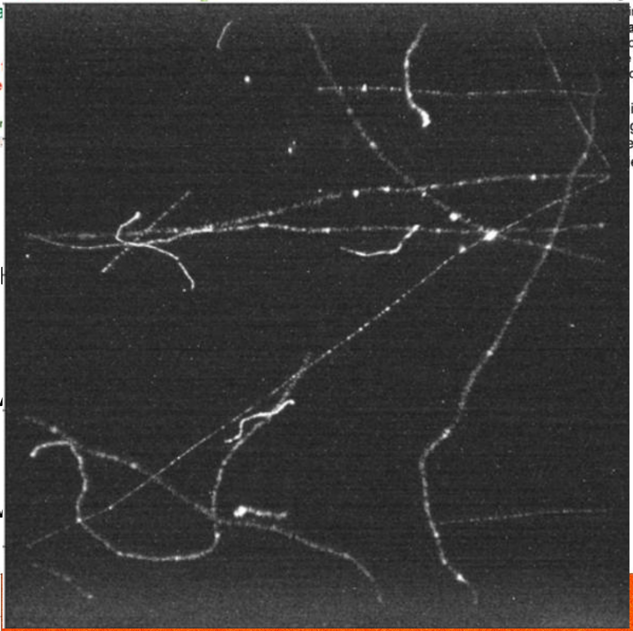

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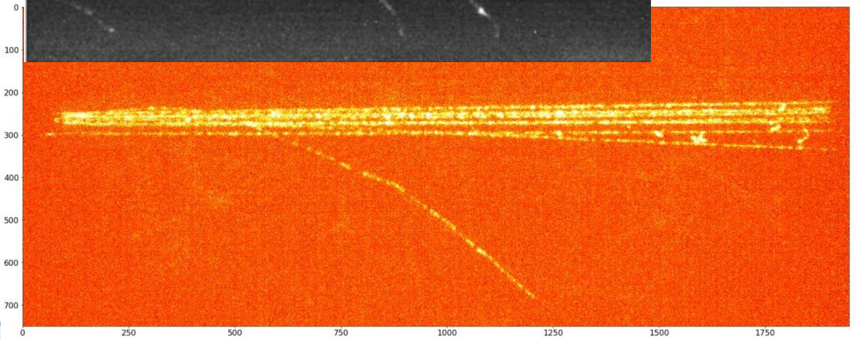

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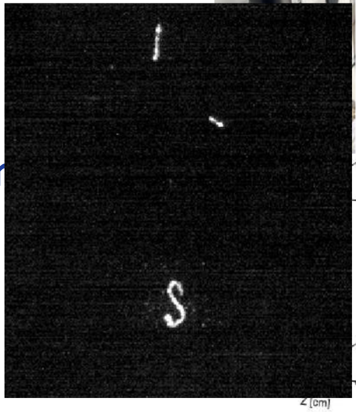
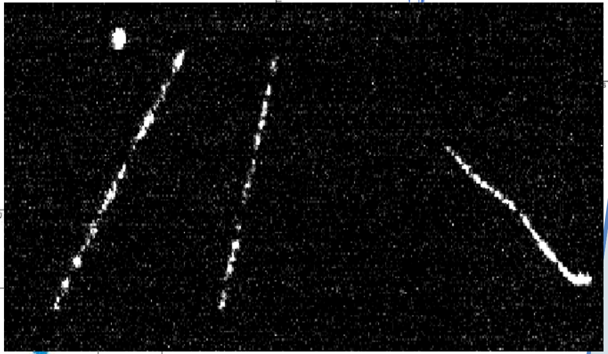
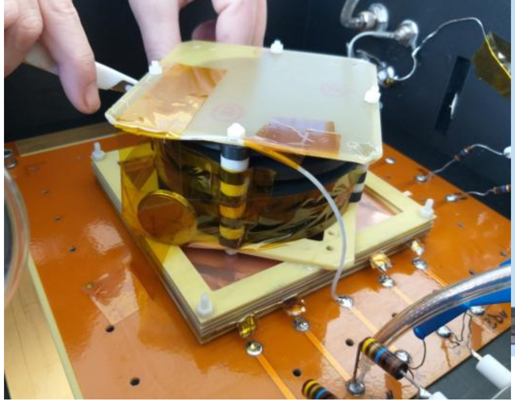
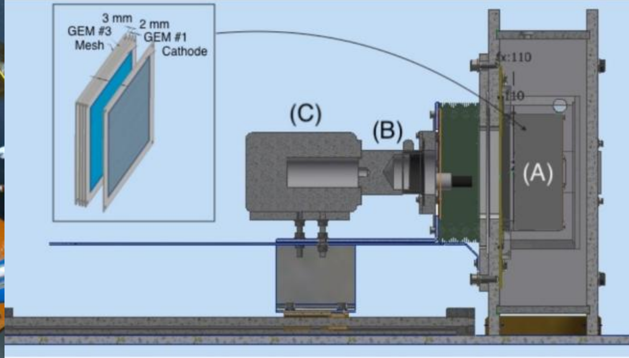


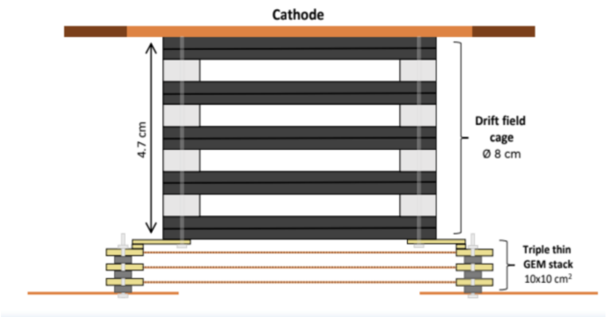


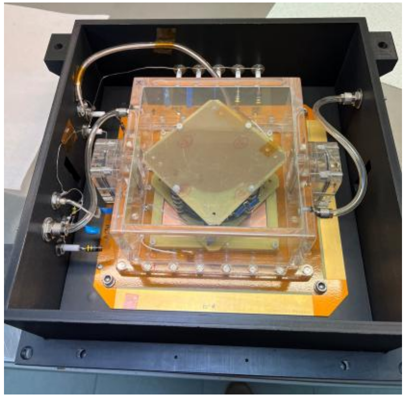
MANGO Prototype

- Prototype in use for early tests is of the potential dimensions for a polarimetry mission
- Drift gap 4.7 cm with cylindrical field cage of 4 cm radius (40.24 cm^2 readout area)
- ORCA Fusion camera (1.49x1.49 cm^2 sensor size)
- Effective granularity of image sensor 48x48 μm^2 (can image with same granularity 10x10 cm^2 area)
- Intrinsic diffusion from amplification stage about 300 μm in standard deviation
- Both Ar and He used as noble gas









Measurement campaigns

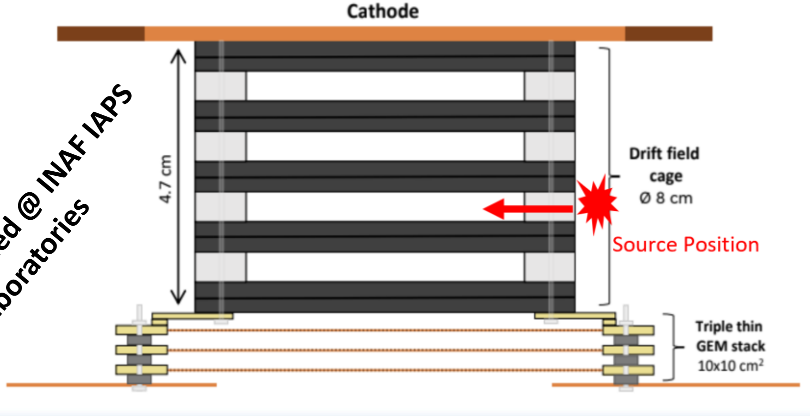
- **^{90}Sr source to estimate angular resolution**
- **Polarized source to measure modulation factor**

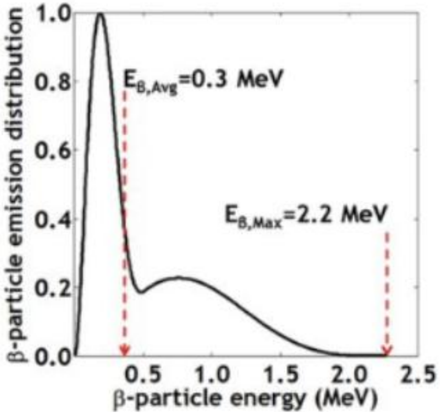
^{90}Sr Campaign

- Beta^{-} emitter with a wide range of energies
- Source collimated placed (~ 2 mm radius)

  close to the field cage rings

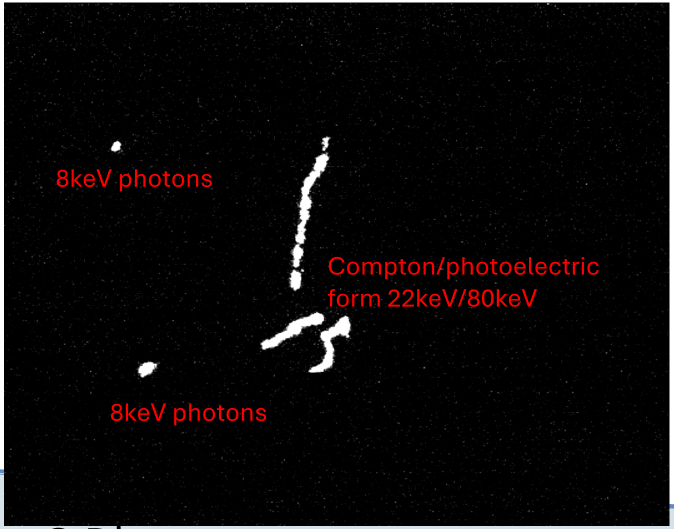
Tests performed @ INAF IAPS laboratories

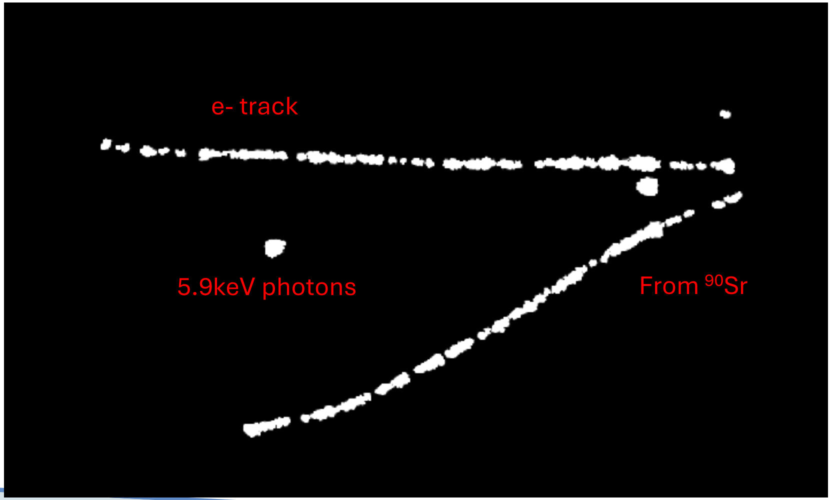


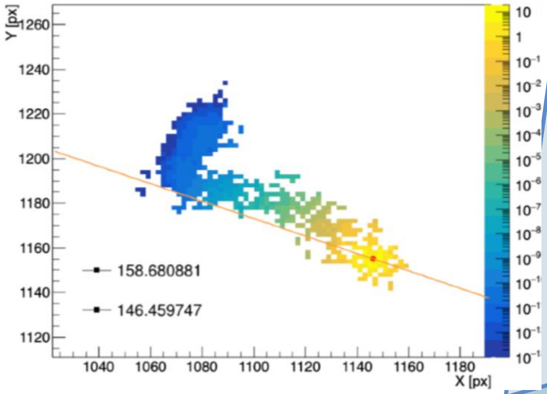


^{90}Sr e^{-} spectrum

- Electrons emitted mostly parallel to the amplification plane (2D measurements)
- Energy calibration performed with ^{55}Fe (5.9 keV) and ^{109}Cd (22 and 80 keV) sources (and 8.1 keV from Cu fluorescence)

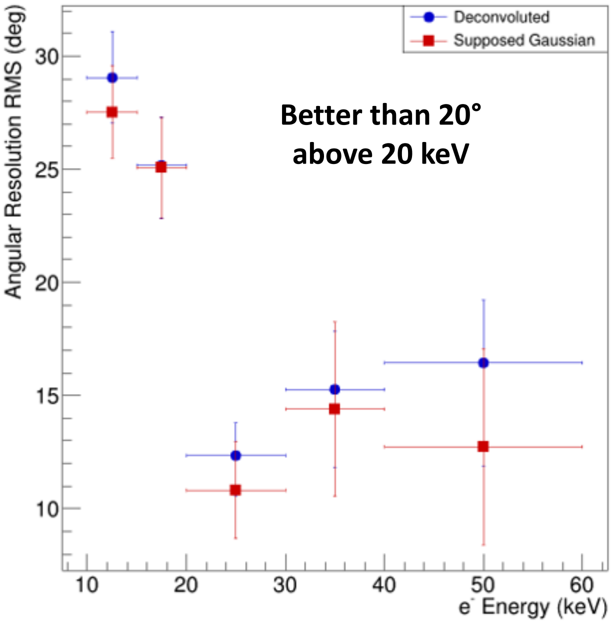






Modulation factor and Efficiency

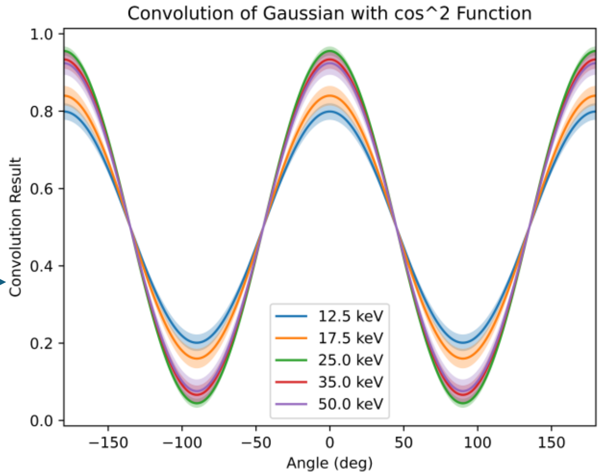
- Interesting angular resolution are found as a function of energy



Deconvolution with simulation of ^{90}Sr emission

Could we just convolve the resolution with a $\cos^2$ function and get the modulation?

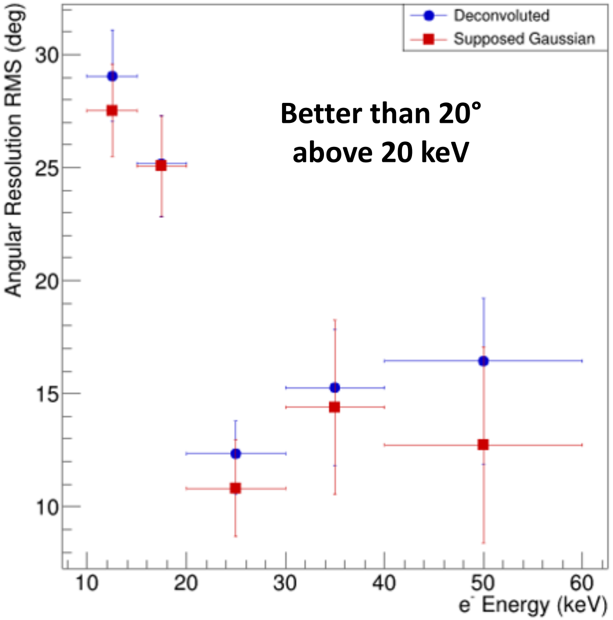
Controversy in the community if this is a ''legal move''



Modulation factor up to 70% achieved

Modulation factor and Efficiency

- Interesting angular resolution are found as a function of energy

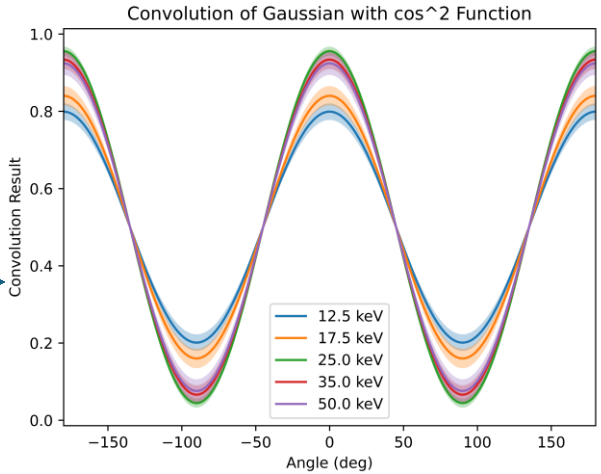


Better than 20° above 20 keV

Deconvolution with simulation of ^{90}Sr emission

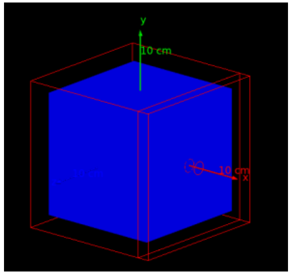
Could we just convolve the resolution with a $\cos^2$ function and get the modulation?

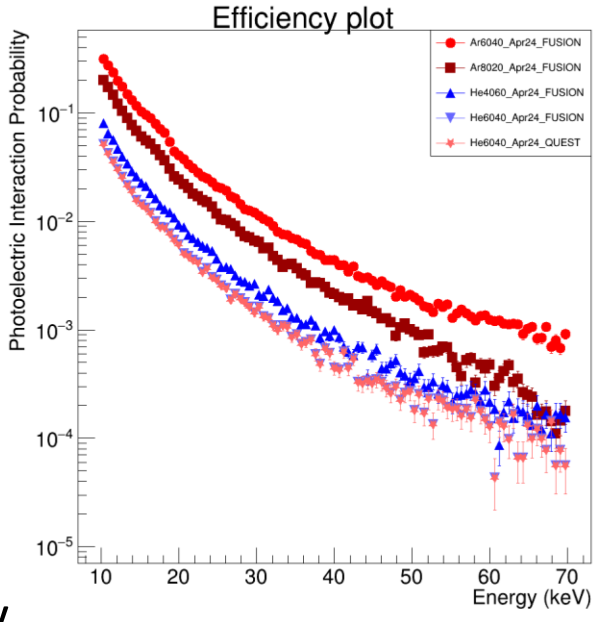
Controversy in the community if this is a ''legal move''



What about efficiency??

- GEANT4 simulation of converted e^-





As expected high Z dominates efficiency

Figure of Merit

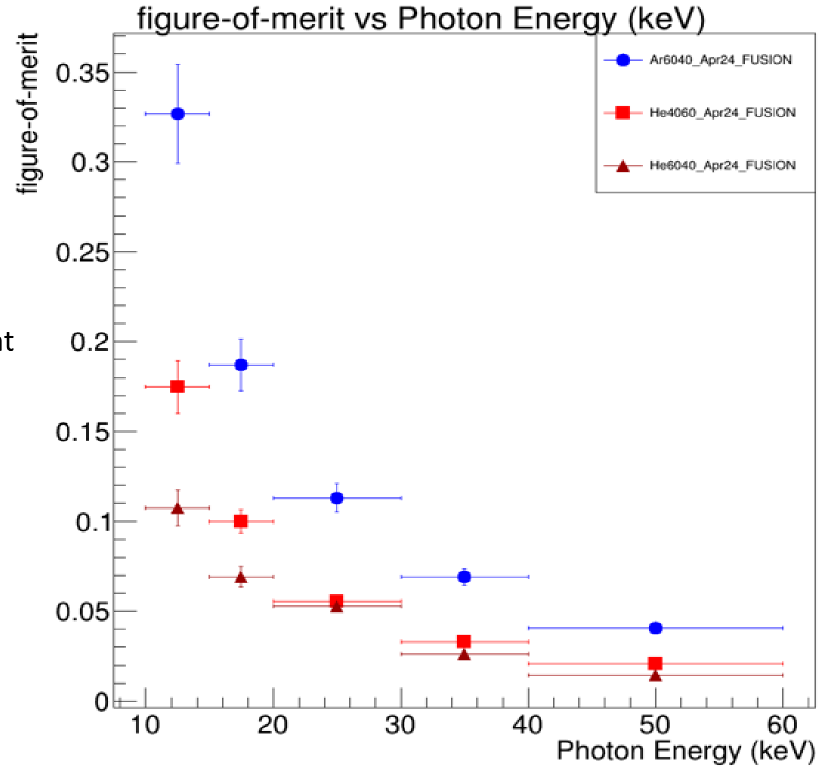
- When no measurements are available, the Minimum Detectable Polarisation (MDP) can describe how well you expect your detector to be

$$\mathrm{MDP} = \frac{4.29}{\mu\sqrt{N_{ph}}}$$

With negligible background

- Square root of Efficiency multiplied by modulation factor is a valid parameter for goodness of detector

X error bars represent energy resolution



IXPE values:
0.11 @ 2.6 keV
0.074 @6.4 keV

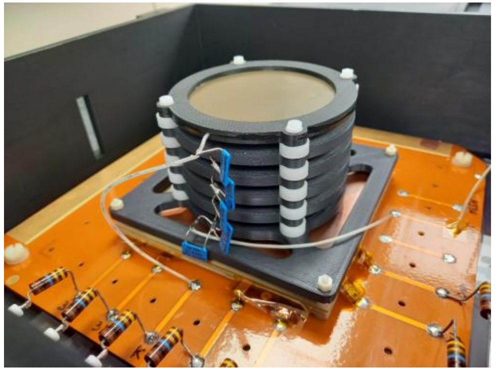
Our value are in the ballpark.

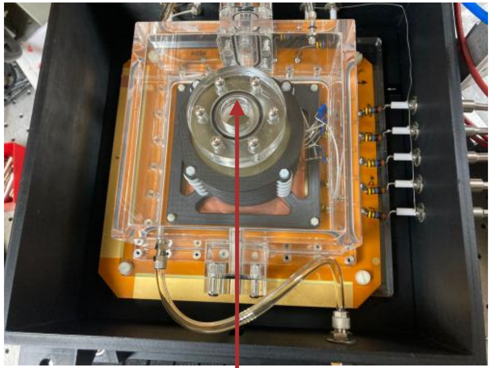
This does not mean we are similarly good

Measure modulation!

Polarised Source

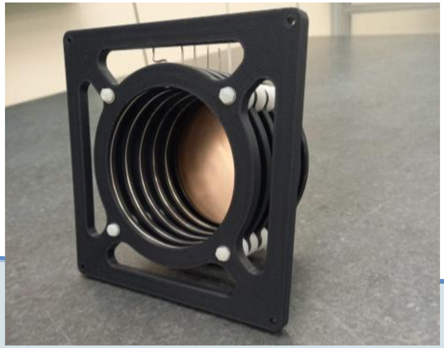
- X-ray polarised source available at INAF-IAPS (Tor Vergata)
- Modification required (thanks to LNF design and technical support!)





New Field cage adapter to GEM stack
now 6 cm drift

New opening in the plexiglass box to allow X-rays in
(15 μm PET)



New cathode foil
45 μm of Kapton
35 μm of deposited Cu

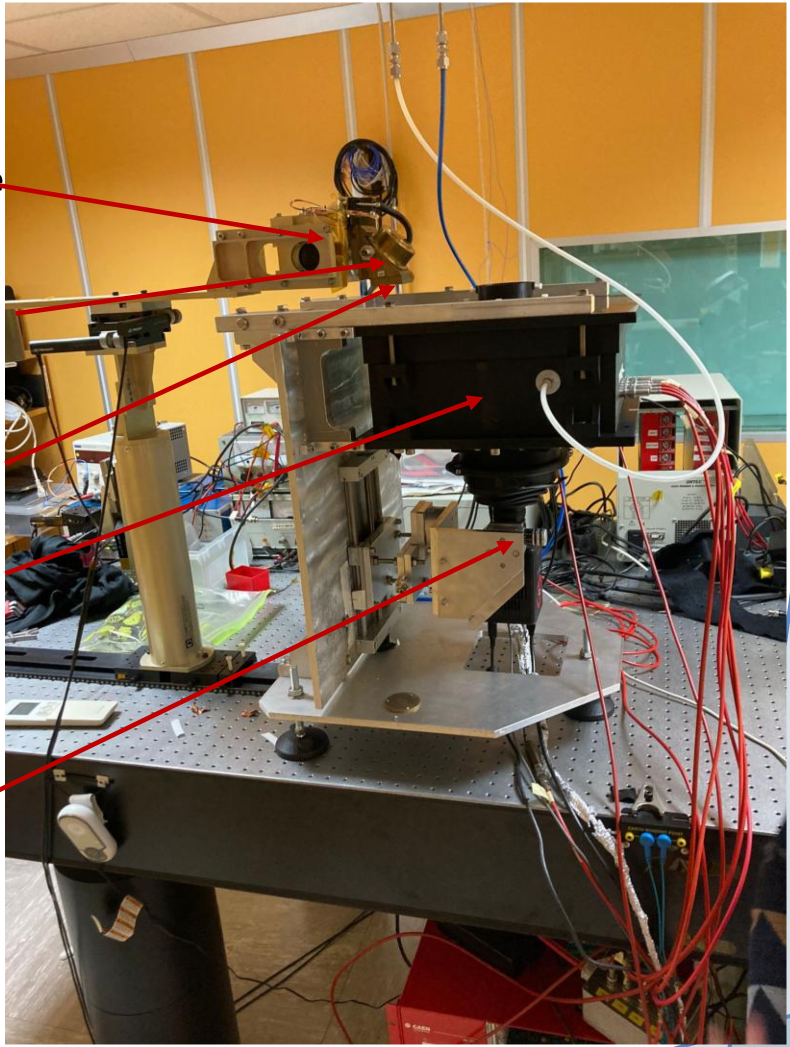
X-ray tube

Diffractor crystal

Collimator

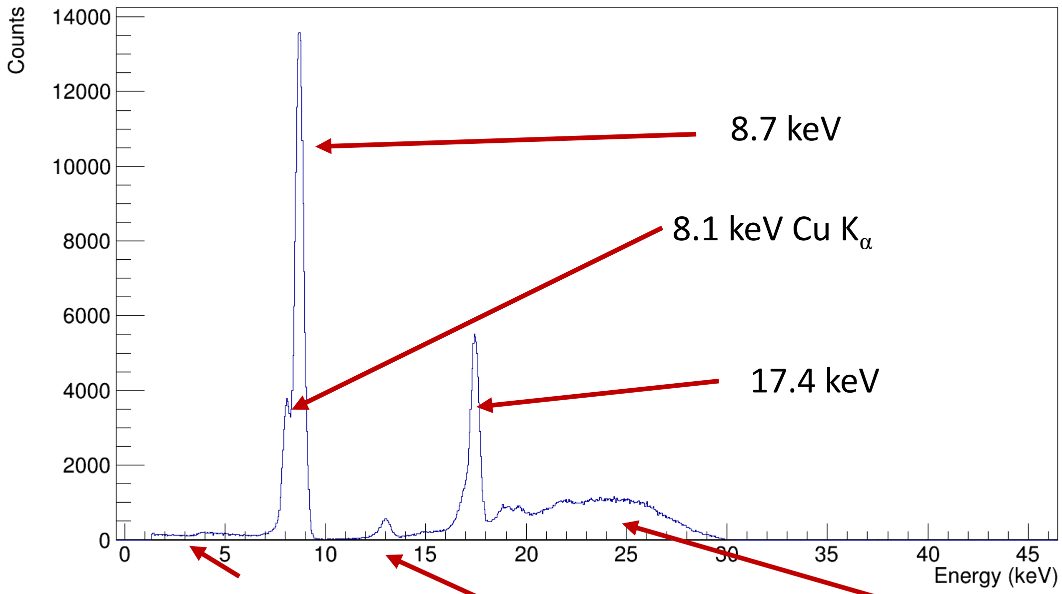
Gas volume

Camera and lens



Data Sets and Source

- Spectrum of the source measured with a solid state CdTe detector positioned below a piece of foil of our cathode



8.7 keV

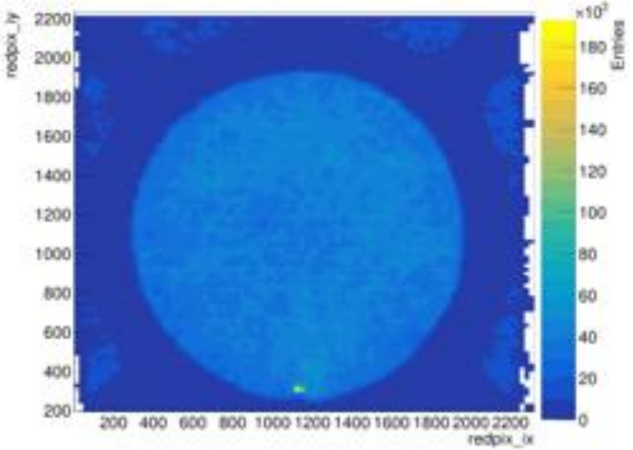
8.1 keV Cu K_{α}

17.4 keV

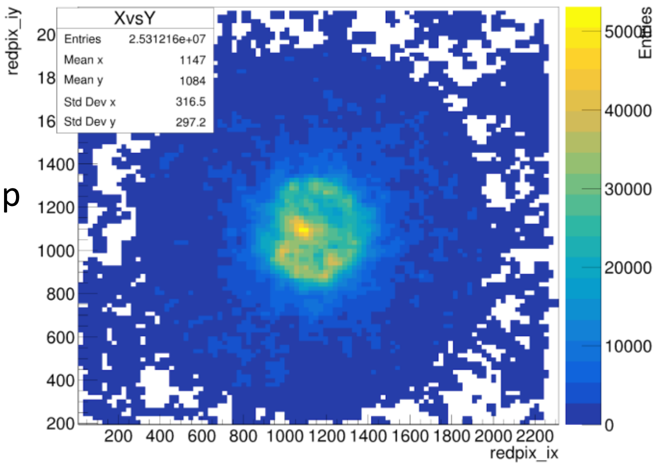
4.3 keV
Completely absorbed by Cu

Bremsstrahlung bump

13 keV
Almost completely absorbed by Cu (K_{edge} =8.9 keV)



Cosmic map
FC uniformity



Source map

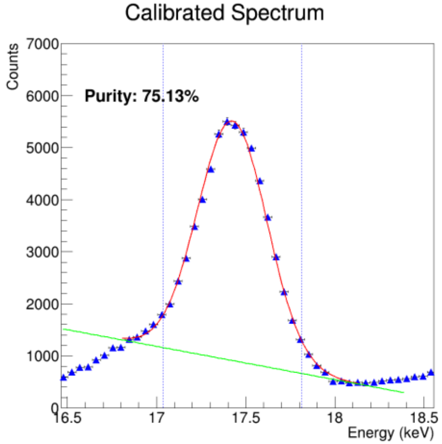
Concentrated in 1 cm radius

Concern: Pile up

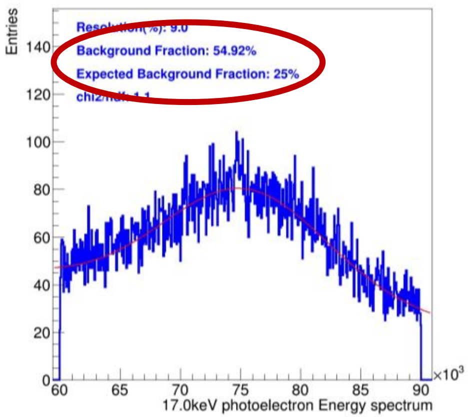
Exposure time 200 ms
Rate ~ 30 Hz

Data Analysis (He:CF_4 Fusion camera)

- Energy spectrum calibrated with ^{55}Fe (5.9 keV) and ^{109}Cd (22 and 80 keV)
- Background contamination estimated from CdTe spectrum



Simple trapezoidal method
(can be improved)

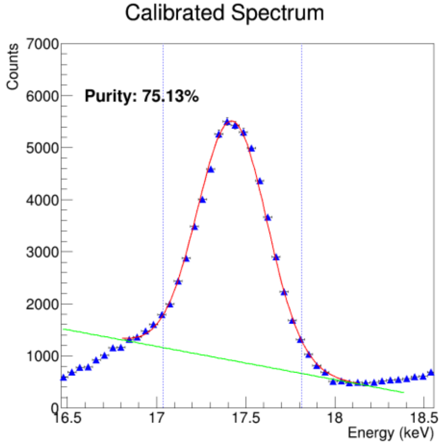


Measured 17.4 keV peak

Data Analysis (He:CF_4 Fusion camera)

PRELIMINARY

- Energy spectrum calibrated with ^{55}Fe (5.9 keV) and ^{109}Cd (22 and 80 keV)
- Background contamination estimated from CdTe spectrum



Simple trapezoidal method
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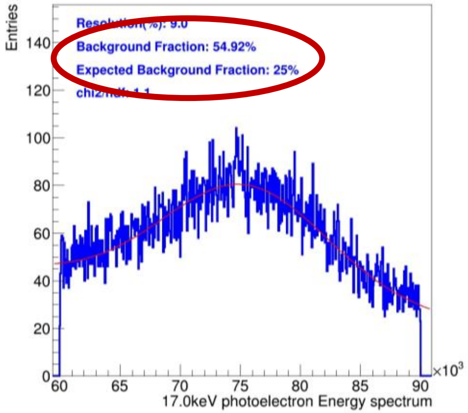
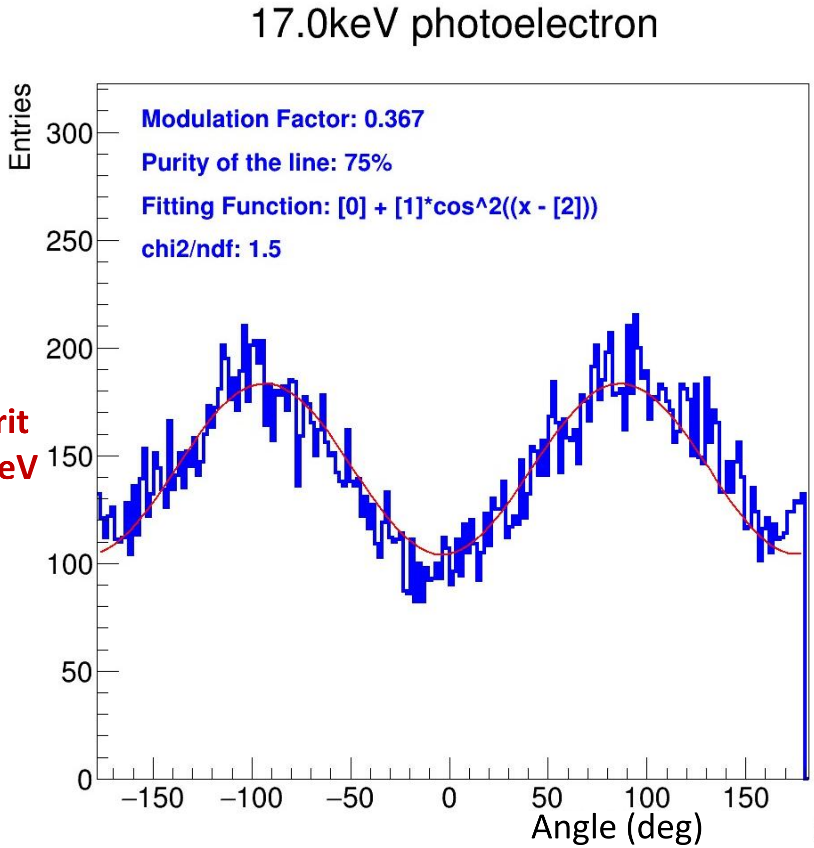


Measured 17.4 keV peak

Figure of Merit
0.037 @17 keV



First ever modulation measured with our detector

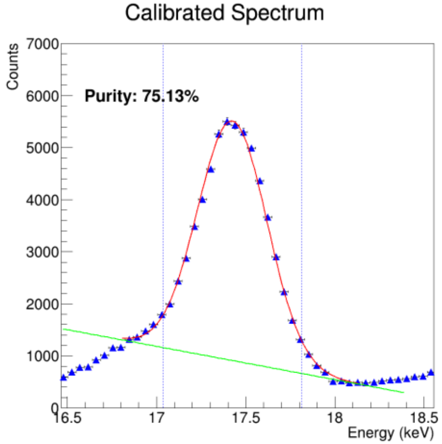
Half of our prediction with angular resolution

Large background. **Can definetely improve**

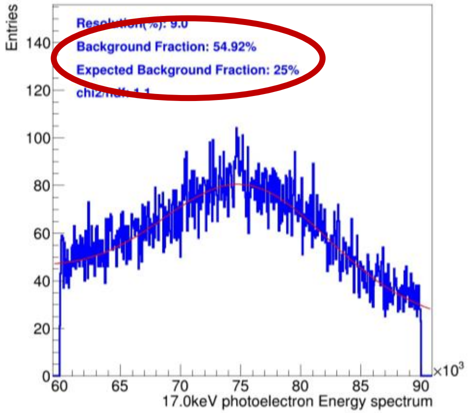
Data Analysis (He:CF_4 Fusion camera)

PRELIMINARY

- Energy spectrum calibrated with ^{55}Fe (5.9 keV) and ^{109}Cd (22 and 80 keV)
- Background contamination estimated from CdTe spectrum

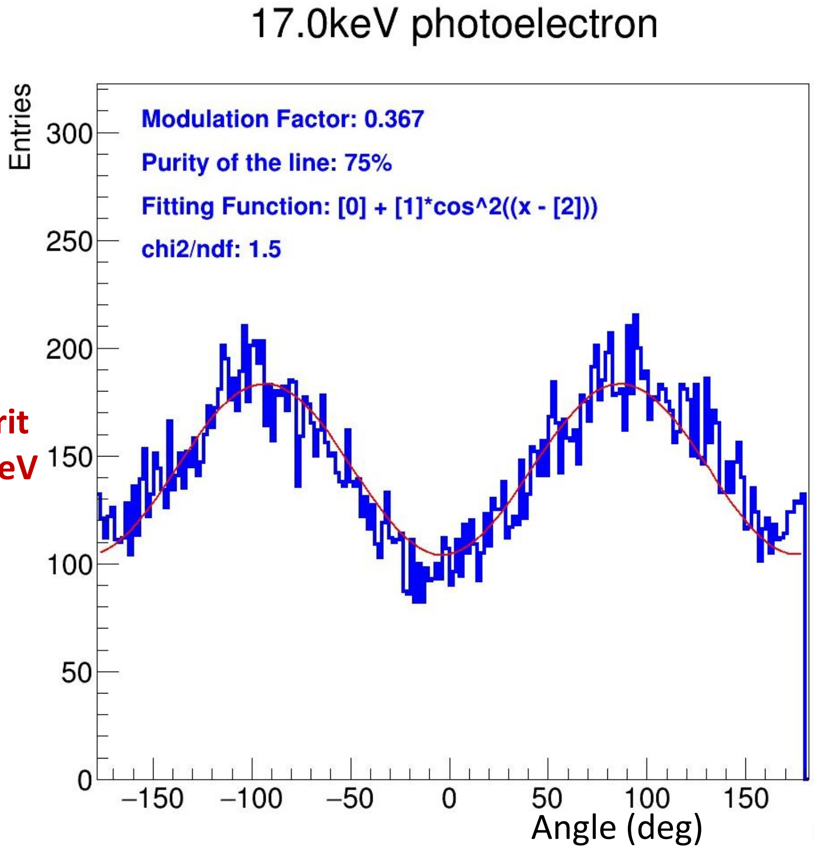


Simple trapezoidal method
(can be improved)



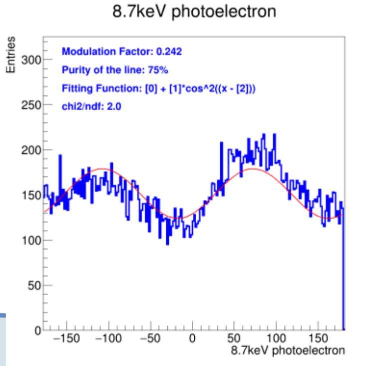
Measured 17.4 keV peak

Figure of Merit
0.037 @17 keV



Positive hints for 8.7 keV too

Big background due to Cu fluorescence



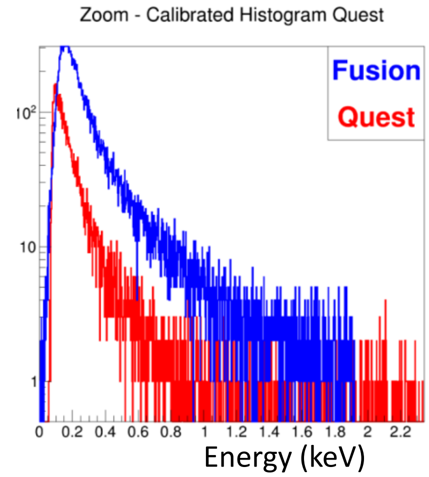
First ever modulation measured with our detector

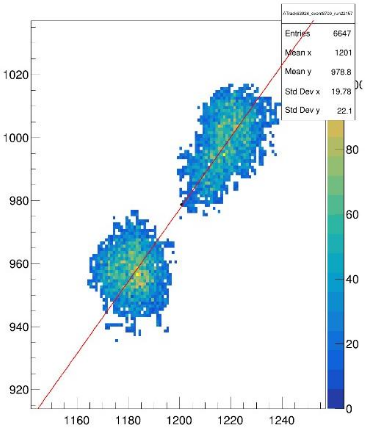
Half of our prediction with angular resolution

Large background. **Can definetely improve**

Data Analysis (Ar:CF_4 Quest camera)

- New camera with much lower noise
- Pile-up still present
- Exposure of camera reduced to cope with higher conversion in gas





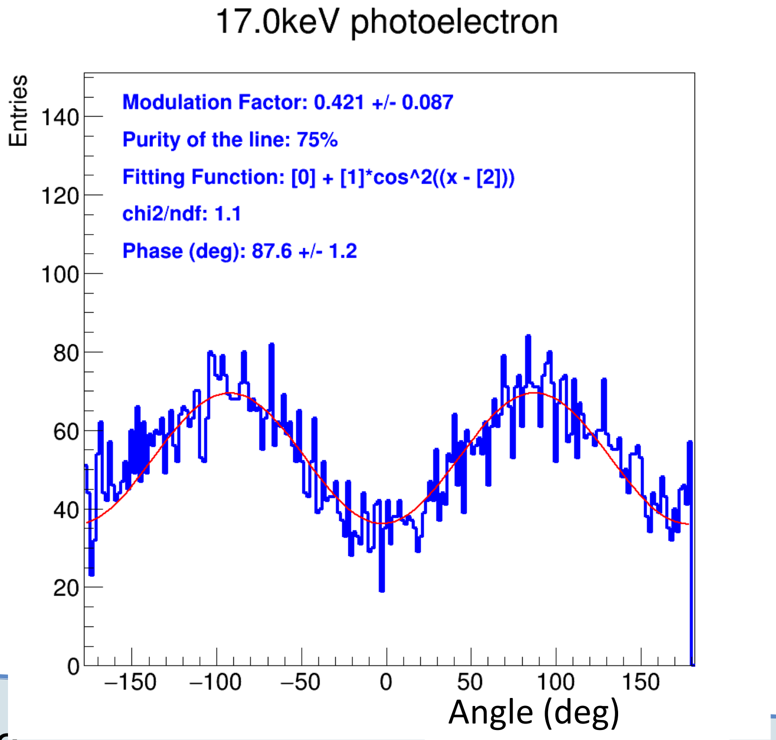


Figure of Merit
0.12 @17 keV

Possible improvements on:

- pileup
- Background
- Directional code

PRELIMINARY

Conclusions

- Astrophysical sources in our Universe are home of extreme events many of which still elude our comprehension
- Measurement of X-ray polarization can help unveil unknown physics from acceleration mechanisms to fundamental physics
- IXPE is providing incredible amount of information measuring polarization in the 2-8 keV range
- HypeX aimed to improve the detection technique for the measurement of polariation of X-rays via photoelectric effect
- The X-POT project inherits the detector concept from the CYGNO experiment and adapts it to image and detect X-ray polarization in the range 8-40 keV with a large area and field of view concept
- Early measurement of angular resolution and response to polarized sources yield promising results
- Next steps clear in our group

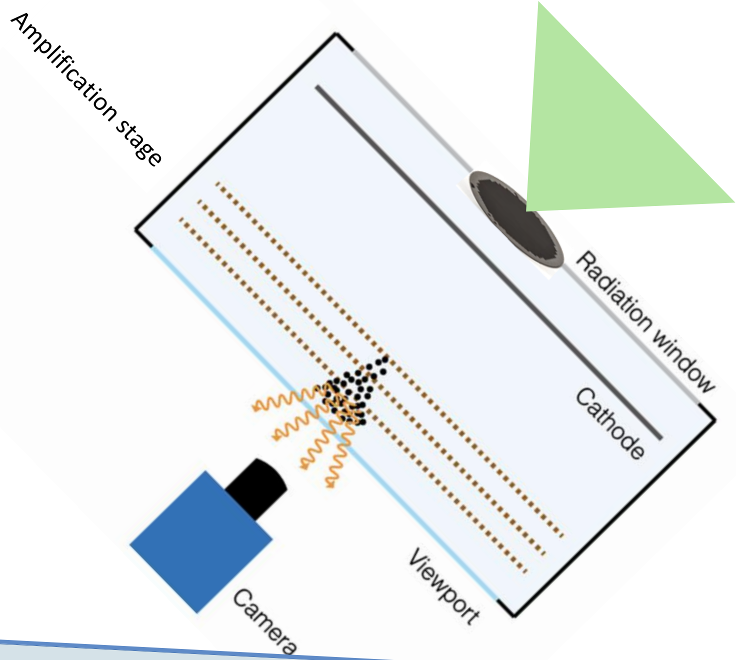
Model astrophysical background | Data reduction | Amplification stage improvement

BACKUP

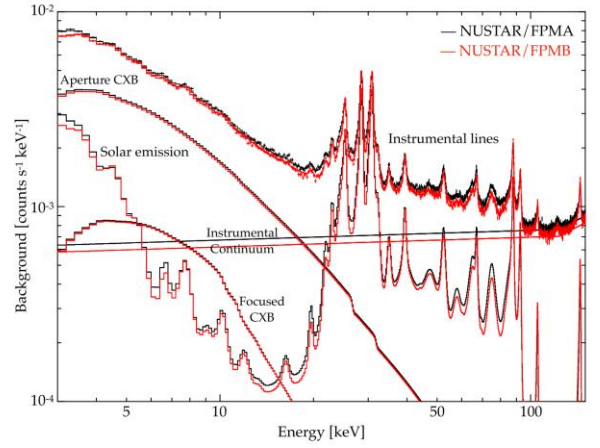
Next Steps

Astrophysics

- Produce realistic background and source fluxes to optimize collimation geometry
- Better define feasibility parameters



NUSTAR X-ray background



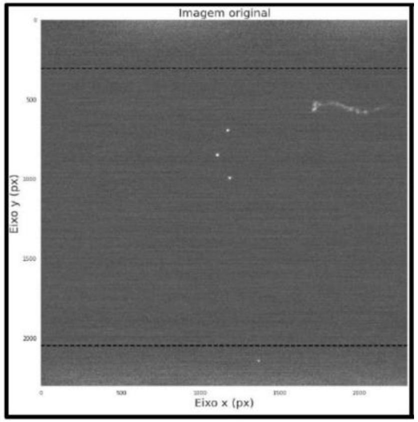
Next Steps

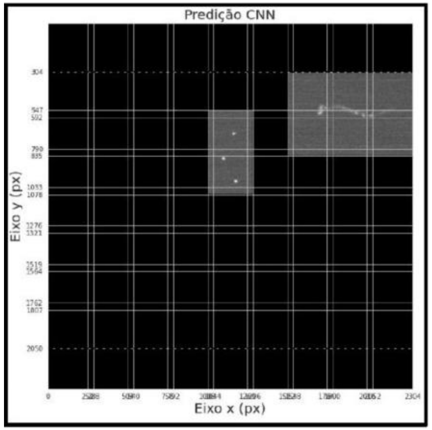
Astrophysics

- Produce realistic background and source fluxes to optimize collimation geometry

Data reduction

- Large amount of data from the 8 Mpixel camera when only a fraction contain information
- Fast preprocessing could shrink data output of 100 times
- In line with CYGNO needs





Next Steps

Astrophysics

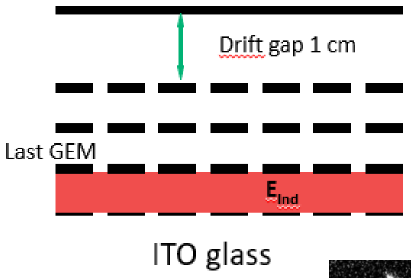
- Produce realistic background and source fluxes to optimize collimation geometry

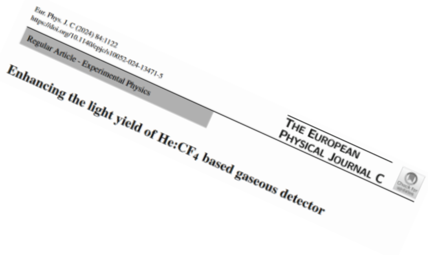
Data reduction

- Smarter approach to save and store only relevant pixels

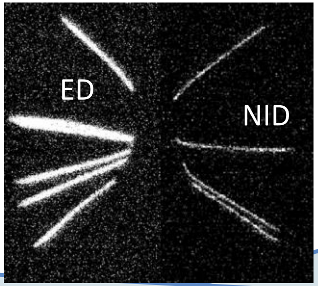
Tweak amplification stage

- Reducing the intrinsic diffusion will improve tracking
- New camera and lens collect more light
- Found new ways to enhance light yield
- Amplification can be milder.. Reduce GEM number?
- Negative ion drift to reduce diffusion could also help





Negative Ion Drift



Next Steps

Astrophysics

- Produce realistic background and source fluxes to optimize collimation geometry

Data reduction

- Smarter approach to save and store only relevant pixels

Tweak amplification stage

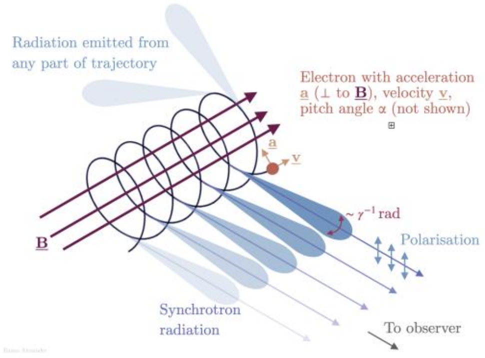
- Play with amplification structure and gas to reduce diffusion without losing too much light

New prototype

- Thinking toward space detectors
  - Sealed detector
  - Be window
  - More compact object

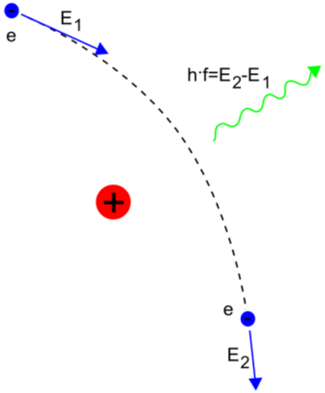
X-Rays Emission Mechanism

Synchrotron emission



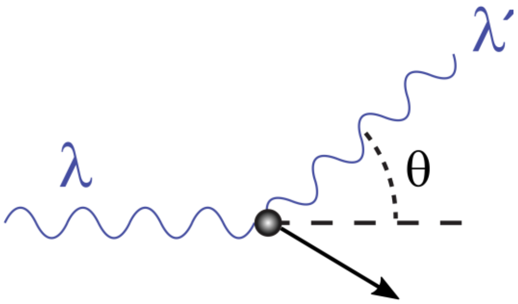
- Polarization orthogonal to the projection on the sky of the magnetic field
- Predictable polarization degree for power law electron distribution

Bremsstrahlung emission



- Polarization of 100% orthogonal to the plane of interaction
- Geometries in anisotropic electron fluxes can be studied

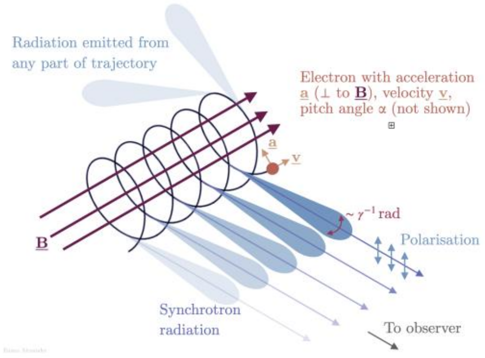
Inverse Compton



- Polarization degree survives the scattering (energy-dependent)
- Predictable polarization degree for power law electron distribution

X-Rays Emission Mechanism

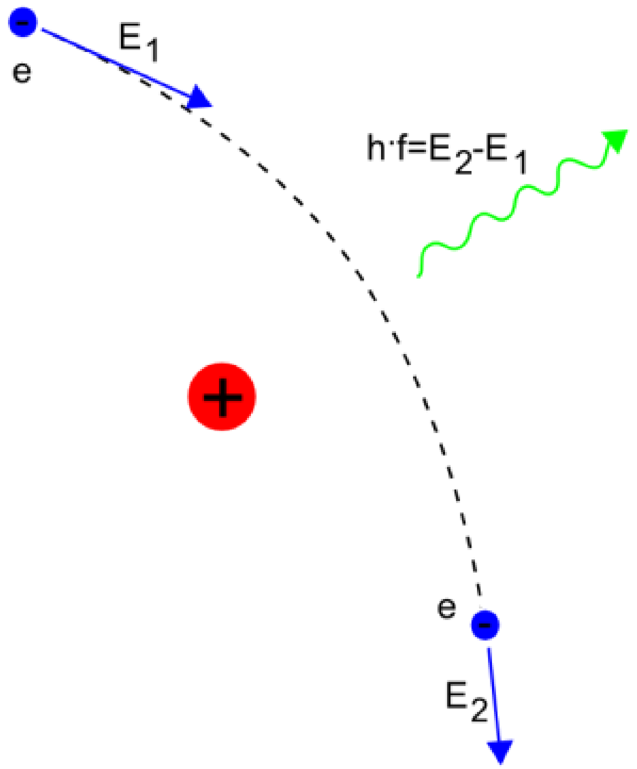
Synchrotron emission



- Emission frequency $$\nu_0 = \frac{3\gamma^2 eB\sin\alpha}{4\pi mc}$$
- At X-Rays mostly non-thermal emission
- Polarization orthogonal to the projection on the sky of the magnetic field
- If electrons follow an energy power law distribution with index p, the X-Rays will too
  - Power law with index (p-1)/2
  - For typical p=2.2 and uniform magnetic field PD can reach 70%

X-Rays Emission Mechanism

Bremsstrahlung emission



- Emission due to deflection of electron caused by protons or other atoms
- Emission over wide range of energies and angles with respect to the deflection
- Polarization of 100% orthogonal to the plane of interaction
- Usually, especially thermal Bremsstrahlung, the randomness of the interaction planes makes the polarization null
- Anisotropic distributions of electrons can induce polarization degrees (for example hard X-rays emitted in Solar flares caused by e^- and ions moving from corona to photosphere)

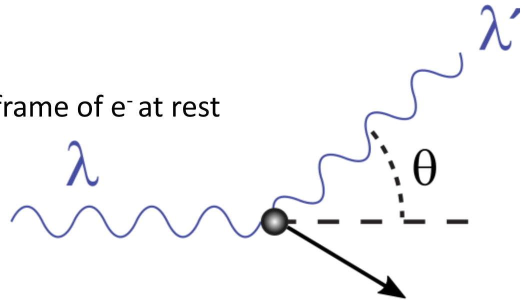
X-Rays Emission Mechanism

Inverse Compton Scattering

Scatter of relativistic e⁻ with photon

Photons can pick up some of the electron energy

In the reference frame of e⁻ at rest

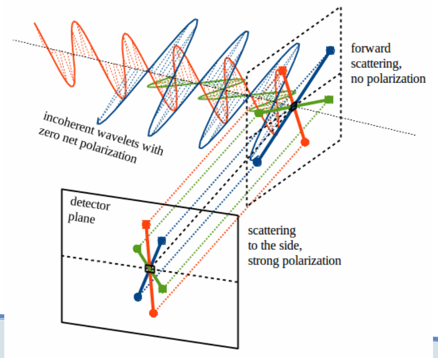


Low energy photon:

Thomson scatter behaviour

Medium-high energy photon:

Classic Compton scatter behaviour

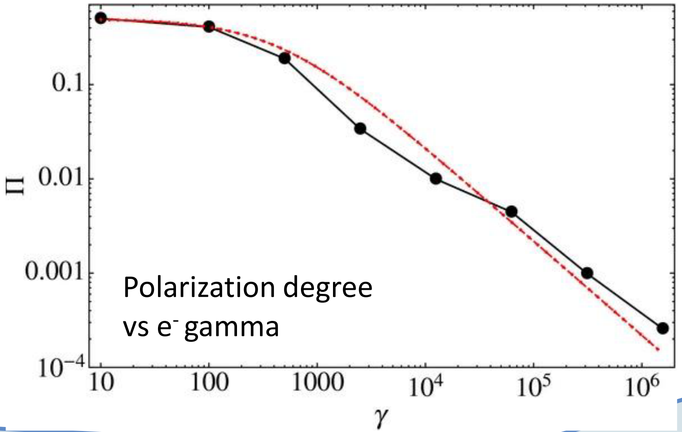


$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_e^2 \left(\frac{\lambda}{\lambda'}\right)^2 \left[\frac{\lambda}{\lambda'} + \frac{\lambda'}{\lambda} - 2\sin^2(\theta)\cos^2(\phi)\right]$$

- Emission frequency $\nu \propto \gamma^2 \nu_0$
- Far infrared emission can be transformed in X-Rays (non-thermal emission)
- Polarization: 100% kept in Thomson behaviour

  Dependent on energy with Compton behaviour

  (at larger energies polarized photons are scattered more forward)



Krawczynski 2011

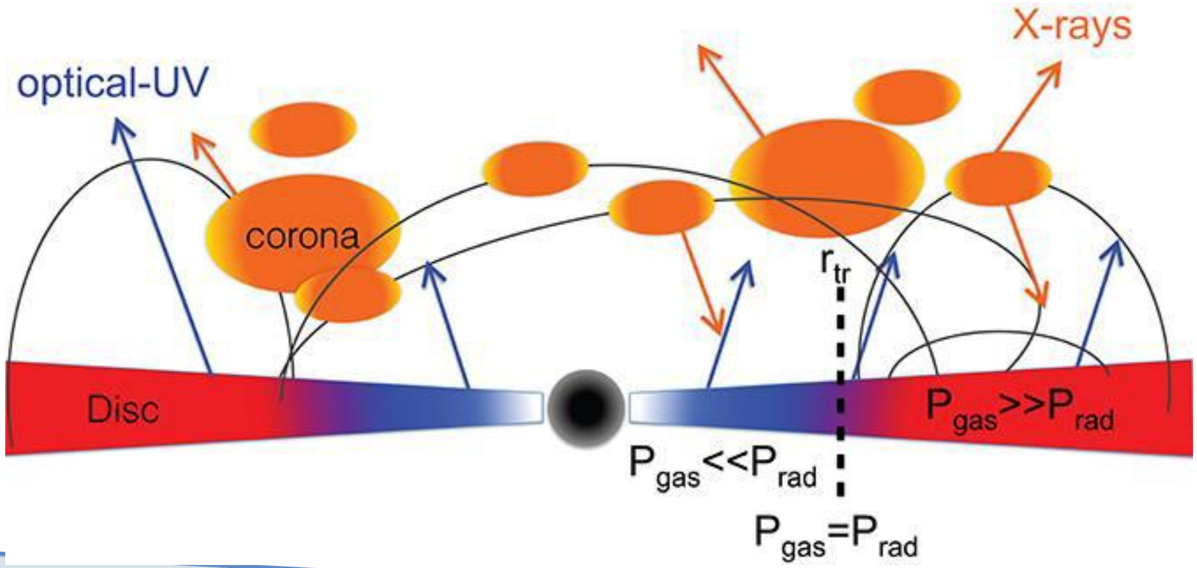
G.Dho

X-Rays Emission Mechanism: Comptonization

- Inverse Compton is extremely relevant for reflections out of gas clouds (like coronas)

- Emission of synchrotron and thermal from parts of the astrophysical object could be reflected through inverse Compton to us

- Polarization would depend on original polarization, geometry of the reflector

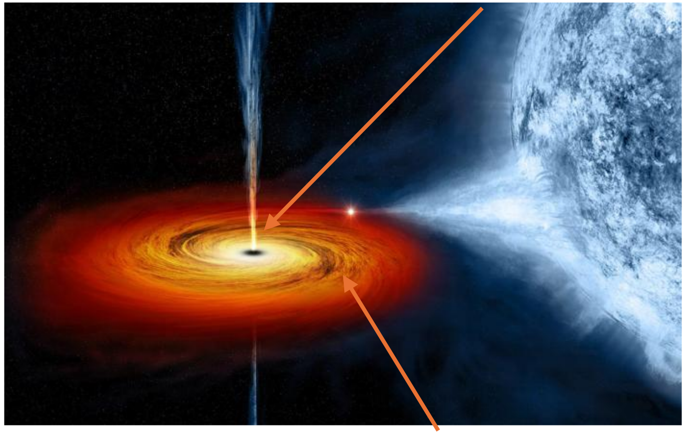


So Why Polarized X-Rays

- The polarization of X-Rays depends on magnetic field structures, geometry of gas clouds and fundamental interactions

- Its measurements can unlock knowledge on astrophysical objects no other method is able to

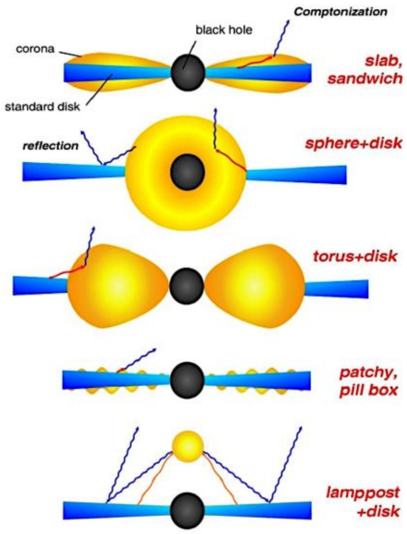
Shape of coronas and accretion geometry (Accreting black hole (BH), neutron stars (NS), active Galactic Nuclei (AGN))



Depending on polarization angle, energy and degree different geometries can be tested of

Coronas' shape

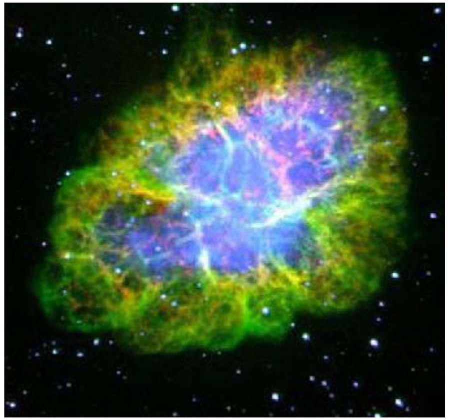
BH, NS spin measurements



From Matt presentation (ASI school 2024)

So Why Polarized X-Rays

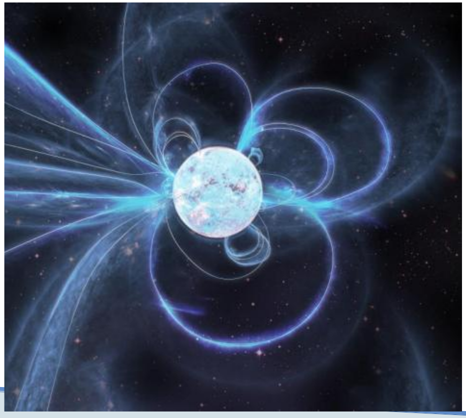
Acceleration mechanisms (SuperNova Remnant (SNR), Pulsar Wind Nebulae (PWN), Blazars)



How is magnetic field oriented at shocks?

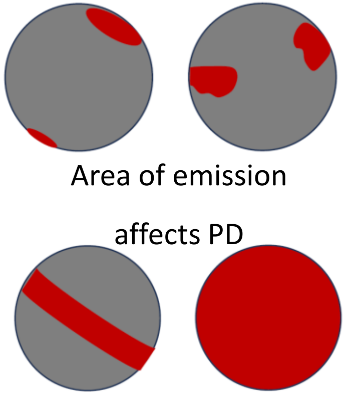
Can we dive deeper into mechanisms of acceleration in Jets?

Fundamental physics (Magnetars)



How is polarization in strong magnetic field conditions (B>10^{12} G)

Vacuum birefringence and atmosphere interaction?



Area of emission affects PD

From Taverna presentation (ASI school 2024)

Some of IXPE Scientific Output

- More than 200 published papers

Corona

Serafinelli et al, 2023

Veledina & Zdziarski 2018

Tagliacozzo 2023

- In binaries and AGN it extends horizontally

- In BH and NS large variability among classes of source

Veledina 2023

Farinelli 2023

- Relevance of reflection contribution

Veledina 2024

Extended sources

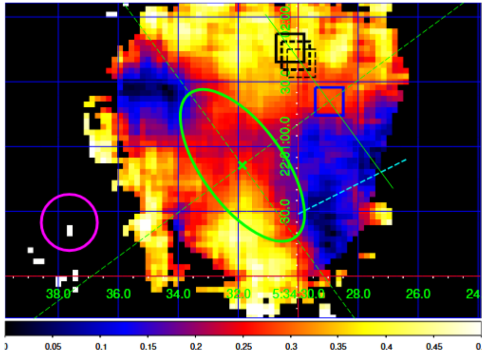
- Tycho SNR polarization found tangent to shock (compatible with radial magnetic field and synchrotron emission)

Bykov et al, 2024

Ferrzzoli et al, 2024

- Crab Nebula polarization map in X-ray performed

Mizuno et al, 2023



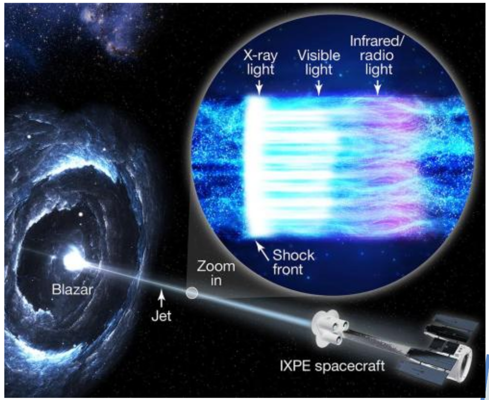
Blazars jets

Marshall et al, 2024

- Low synchrotron peak Blazar IXPE favours leptonic acceleration models

- For high peak, IXPE is providing new clues provided, most probably due to stratified shocks (MRK-501)

DiGesu et al, 2023

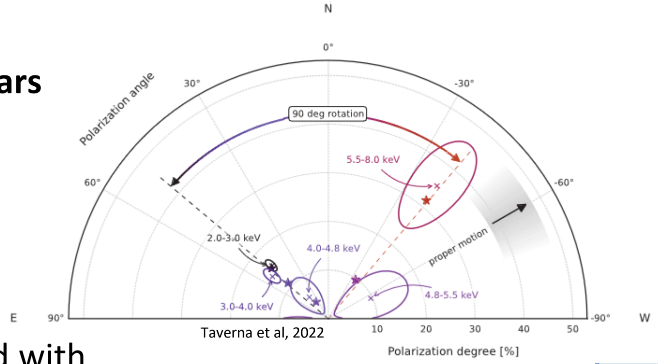


Magnetars

Variation of polarization in energy

Hinting:

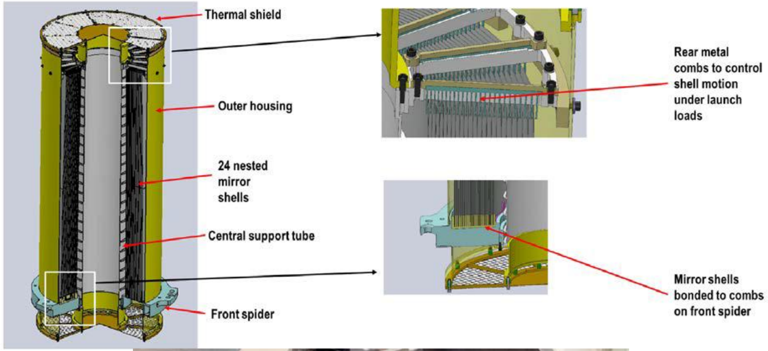
- Different regions of NS emitting
- twisted magnetosphere embedded with electron-positron flowing plasma which scatters low energy radiation produced by the NS surface



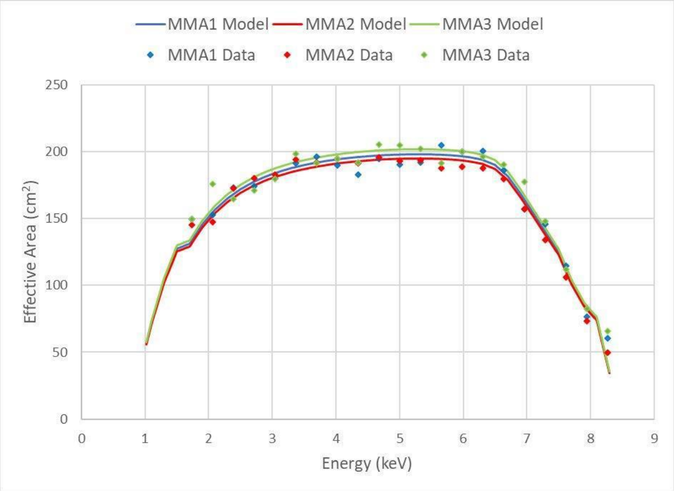
Taverna et al, 2022

IXPE: Telescope

- 3 Mirror modules (1 per GPD)
- X-ray mirrors made of 24 concentric reflective Ni-Co alloy shells
- 3 Photoelectric detectors (GPD) in the optics of 3 mirror telescopes
- Angular resolution better than 30 arcsec (Half Power Diameter)
- Focal length 4m
- Effective area accurately measured



Ramsey, B. et al, JATIS, 2022

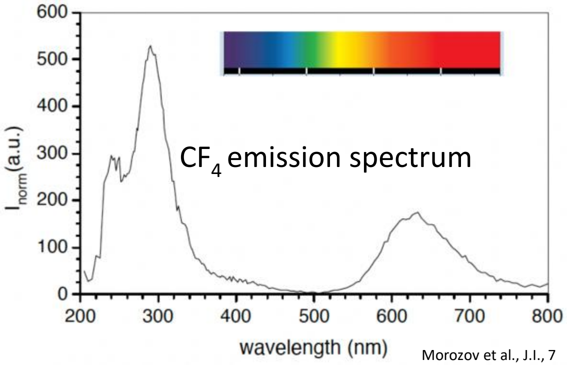


IXPE Science Operator Center User Guide

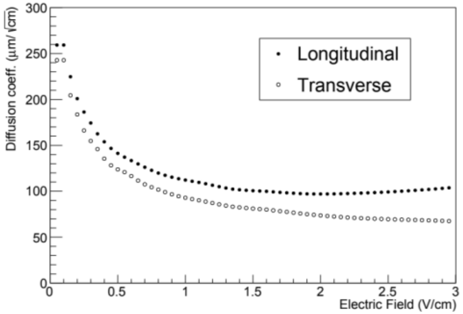
TPC: Gas and Amplification

Gas composition: He:CF4 (60/40)

- CF_4 has scintillation properties and is *cold* (diffusion below 110 $\frac{\mu m}{\sqrt{cm}}$ above 1 kV/cm of drift field)
- W-value 35 eV, density ~1.5 kg/m^3 (ambient pressure)
- He noble buffer gas. Optimized for dark matter searches due to kinematic match for elastic recoils

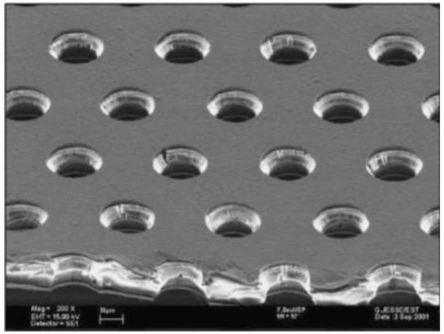


Morozov et al., J.I., 7 (02) (2012)

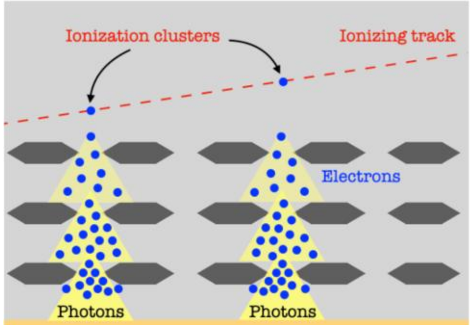


Veenhof 9306149 (1993)

Amplification stage: Triple thin standard GEM



Sauli et al, 2016



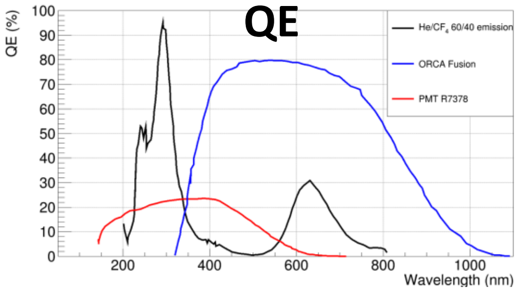
- Triple structure of thin GEMs to grants high gains (up to 10^6)
- Typical CERN thin GEM: 50 -70 -140 μm (internal diameter hole – extermal diameter hole –pitch)
- Production of photons during amplification due to neutral and charged fragmentation of CF_4 (0.07 ph/e-)

TPC: Optical readout

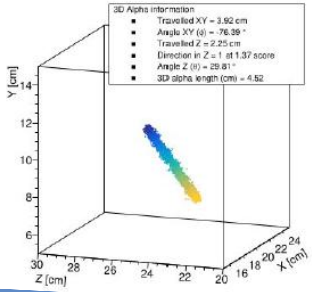
sCMOS Camera

- Highly sensitive and granular sensor
  (1 camera can image a 35x35 cm^2 area 62 cm away from the amplification pane with 155x155 μm^2 granularity)
- Low noise per pixel (modern below 0,7 e^- RMS)
- Market pulled

- <u>Provides</u>
- Energy information from number of photons
- dE/dx on X-Y plane
- X-Y positionand topology



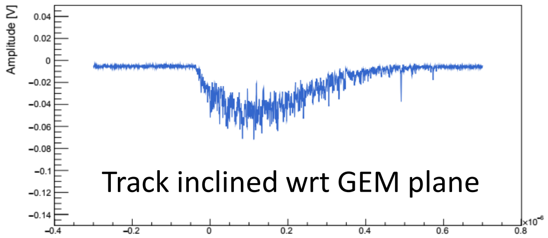
The combination allows energy and 3D topological measurement of each track

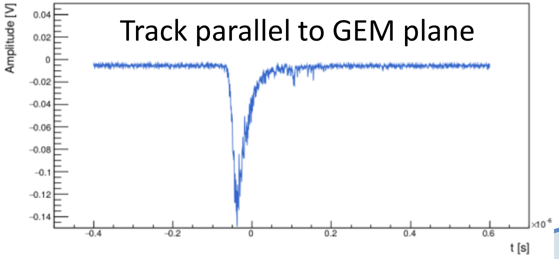


PMT

- Fast light detector O(100s) ns

- <u>Provides</u>
- Energy information from number of photons
- Z direction topology and development



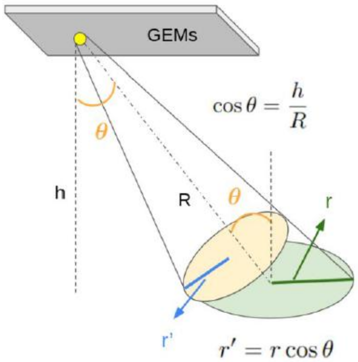


G.Dho

3D Reconstruction CYGNO

- Merging the two detector allows 3D reconstruction
- LIME has 4 PMTs whose distance from the event changes their intensity
- Important to match the signals of the detectors: multivariate Bayesian fit

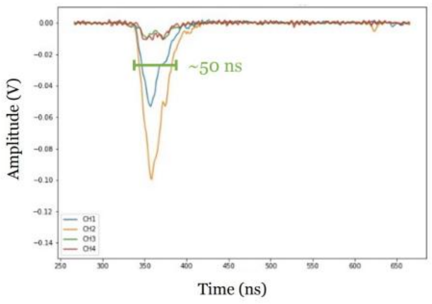
- $L'_{ji} = c_i \dfrac{L_j}{R_{ij}^{\alpha}}$
- $R_{ji} = \sqrt{x_{ji}^2 + y_{ji}^2 + z^2}$

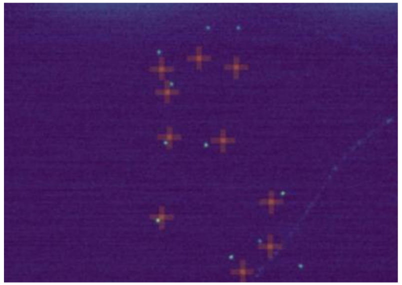


$$p(\{x_{ij}\}\,|\,\theta) = \prod_{j=1}^{N_{points}} \prod_{i=1}^{4} \mathcal{N}(\{x_{ij}\}\,|\,L'_{ij}(\theta))$$

One can retrieve from PMT signals x,y coordinate and L (light yield at GEM)

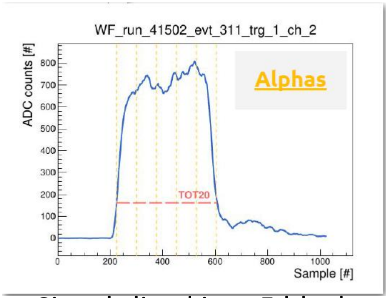
1. Calibrated with iron signal with known x,y position from camera





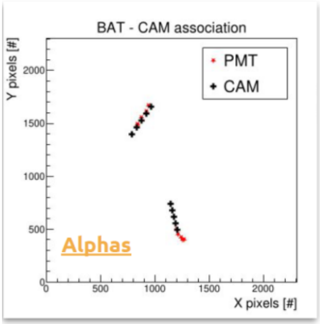
Resolution of about 1 cm

2. Applied to alpha signal



Signal sliced into 5 blocks

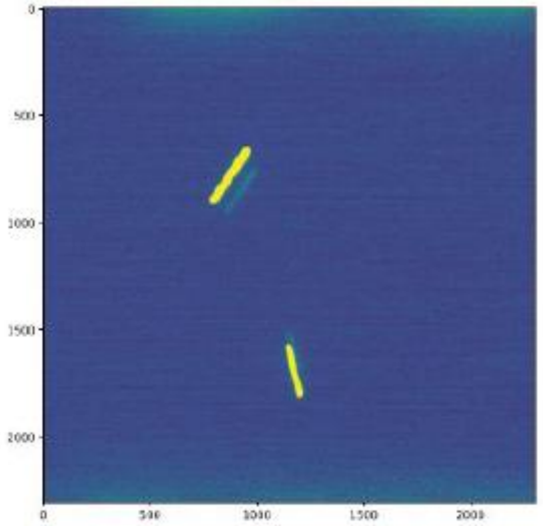
Accuracy within 2 cm

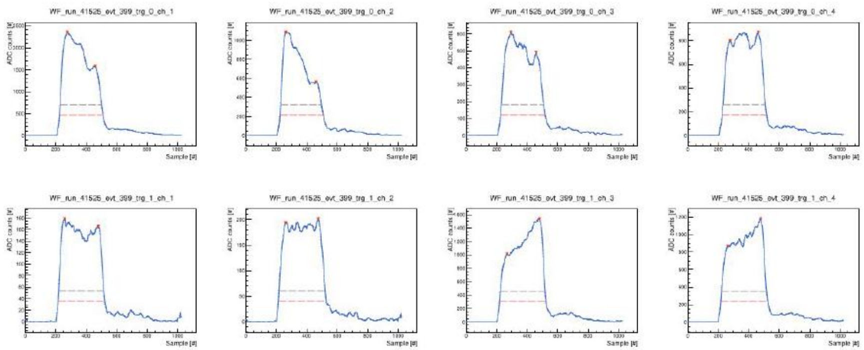


Enough for association purposes

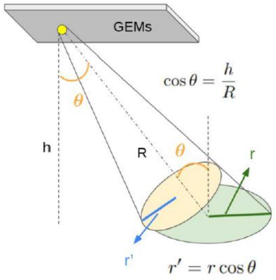
G.Dho

3D Reconstruction CYGNO





- Different response of the 4 PMTs in LIME

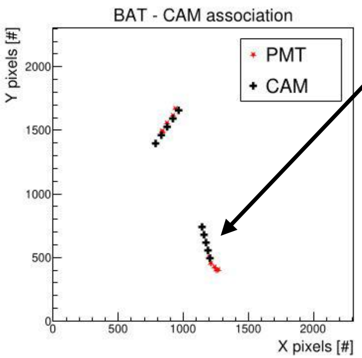


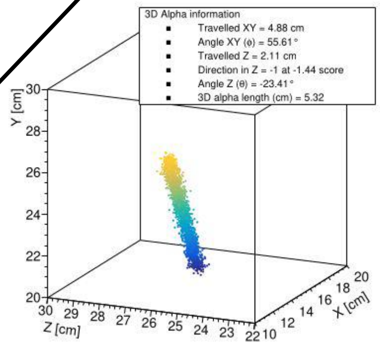
- Multivariate Bayesian fit procedure

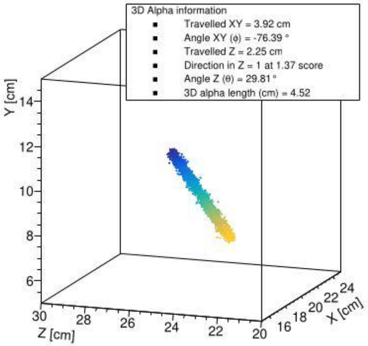
$$p(\{x_{ij}\}\,|\,\theta) = \prod_{j=1}^{N_{points}} \prod_{i=1}^{4} \mathcal{N}(\{x_{ij}\}\,|\,L'_{ij}(\theta))$$

- Calibrated on ^{55}Fe source
- **Precision of ~1 cm**

(e)

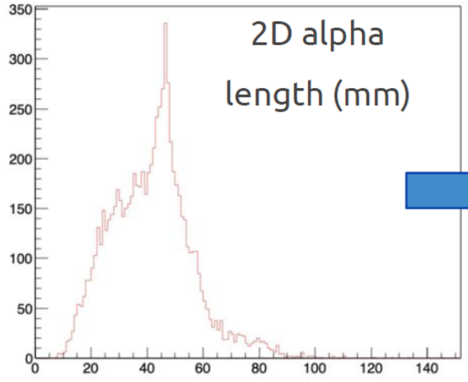


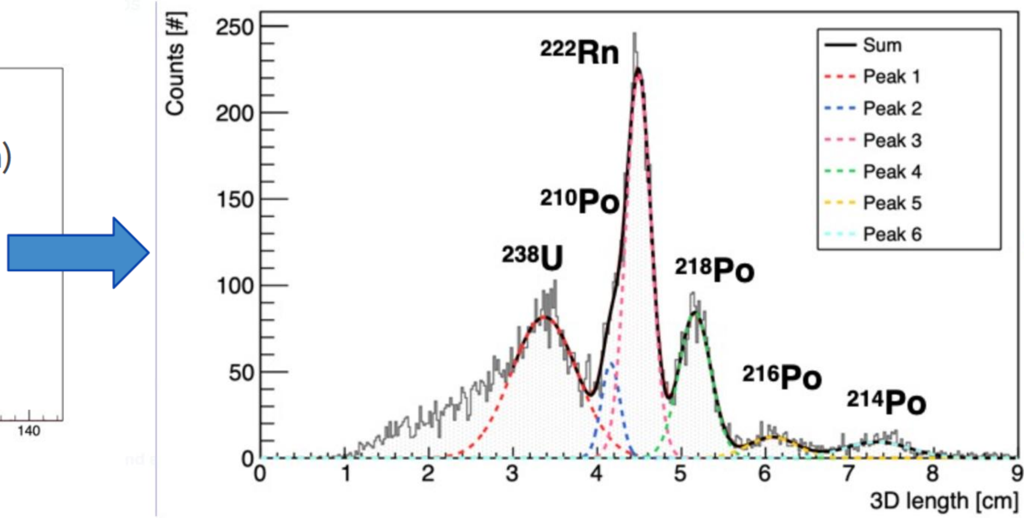




3D Reconstruction CYGNO

- With 3D recoed tracks we can look at lengths



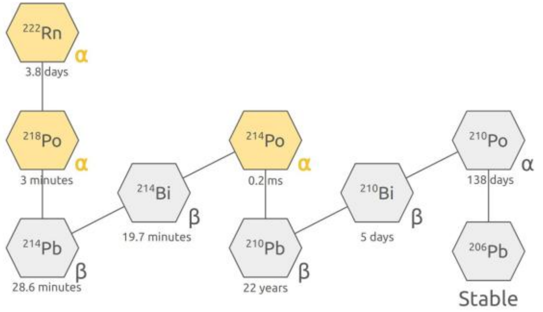


Theory + *detector effect* (7% error)

- ^{238}U -> 4.17 MeV -> 33.7 mm
- ^{216}Po -> 6.78 MeV -> 61.6 mm
- ^{210}Po -> 5.30 MeV -> 43.1 mm

Measured (5% error)

- 33 mm
- 61 mm
- 41.6 mm



Theory + *detector effect* (7% error)

- ^{222}Rn -> 5.50 MeV -> 45.7 mm
- ^{218}Po -> 6.00 MeV -> 51 mm
- ^{214}Po -> 7.69 MeV -> 71 mm

Measured (1% error)

- 44.3 mm
- 51.2 mm
- 72.9 mm

Reconstruction and Direction

- Standard reconstruction code of CYGNO experiment employed (recognition of clusters via custom DBSCAN algorithm)

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- Directional algorithm inspired by IXPE's one and optimized to our setup

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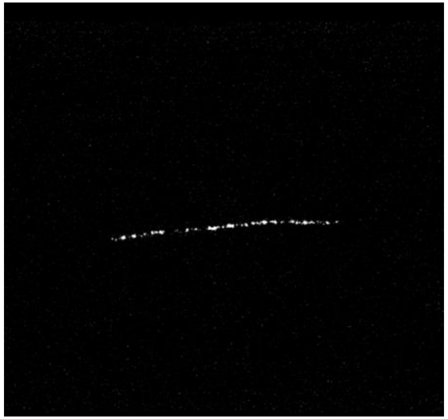
Exposure time 300 ms

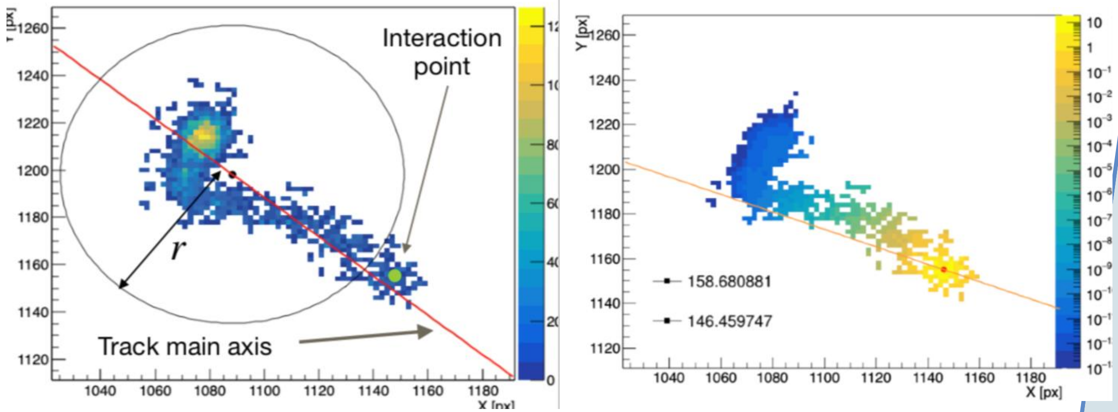
Raw data



After reco

Selection of interesting pixels
Separation of different tracks
Energy estimation

Direction evaluation



Determination of impact point
Determination of sense of direction

Fit weighted on distance from impact point
Determination of direction

Polarized Source Measurements

- Polarized source and measurements taken @ INAF IAPS

  - ✓ X-ray tube powered at 30 kV with tens of microamperes to adjust flux
  - ✓ Molybdenum target K_{α} emission 17.4 keV (λ = 0.7107 A°)
  - ✓ Bragg diffractor crystal of LiF (800)
  - ✓ reflects @ 45° λ_{Mo} and integer multiples with 100% polarization
  - ✓ Polarized energies: 4.3, 8.7, 13, 17.4 keV