Status and plans for the study of X-ray polarimetry

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1) GSSI & INFN

2) INAF/IAPS

3) LNF

High Yield Polarimetry Experiment in X-rays

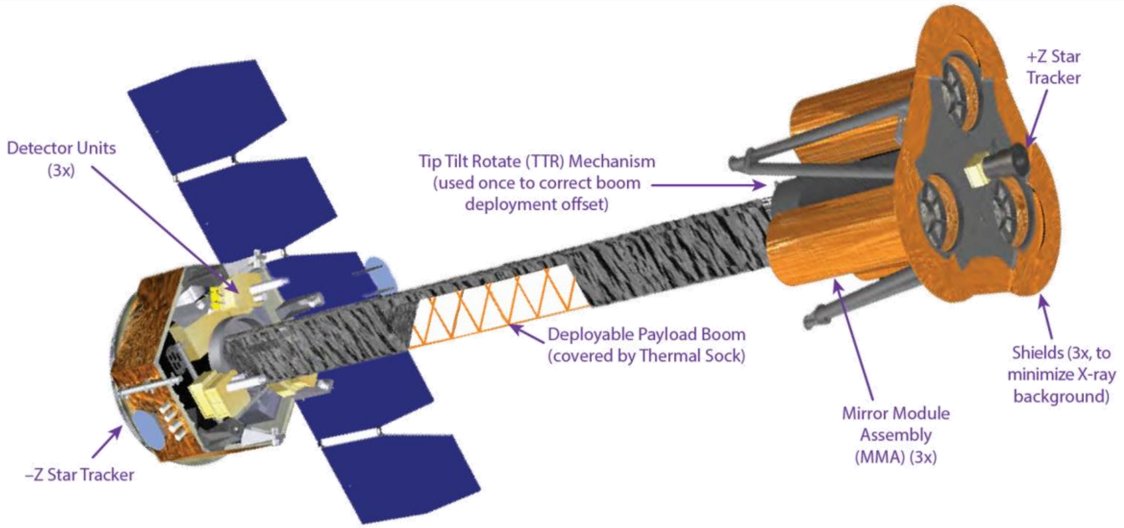
HypeX - Funded by PRIN2020

- Collaboration with INAF
- **Goal**
  → Use a CYGNO-like detector to measure the polarization of Xray from cosmic sources **– GSSI & LNF**
  → Use different readout methods (TimePix) to improve GDP (IXPE GEM currently on data taking) performances - **INAF/IAPS**

Summary:

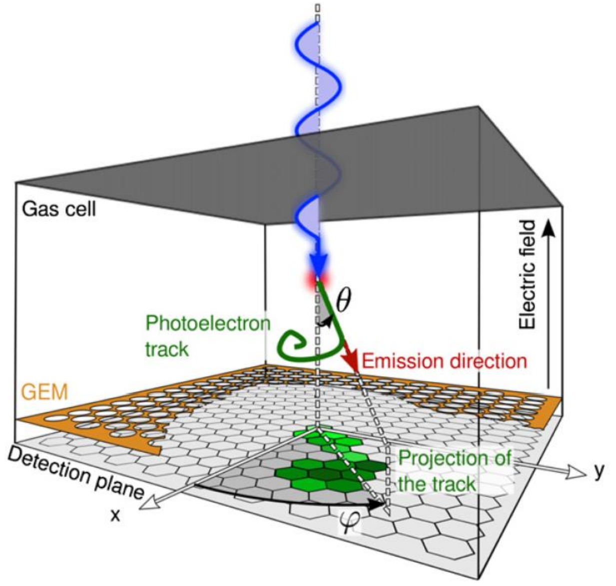
- IXPE
- Xray polarimetry & methods
- Directionality capability of CYGNO-like TPC
- Future plan

IXPE mission



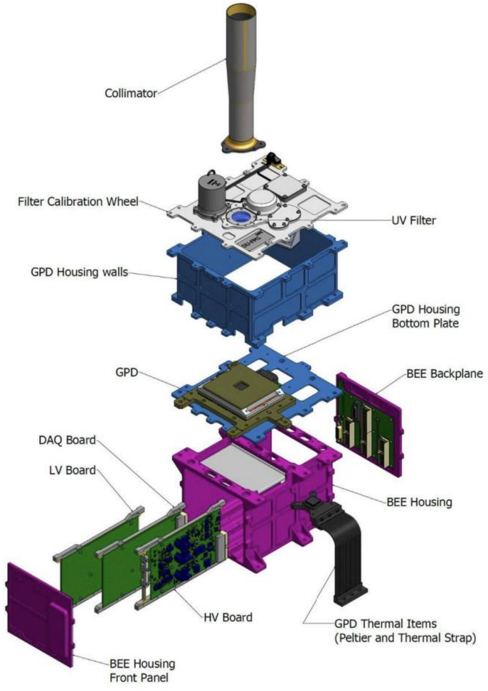
First dedicated satellite to Xray polarimetry

- 3x Telescopes
- 3x Mirror Units (MUs) + 3x Detector Units (Dus)
- A Detectors Service Unit (DSU) with built-in redundancy
- 4 m focal length, deployable boom, and X-ray shield
- GPD is a single GEM detector operated in pure DME 800mbar



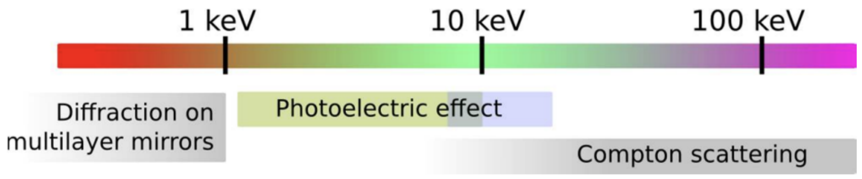
Performance :

- Polarization sensitivity: $MDP_{99\%}$<5.5% in 1 day for flux 10^{-10} ergs/cm^2/s
- **Energy range 2-8 keV**
- Angular resolution: better than 30 arcsec, field of view larger than 9 arcmin
- UTC synchronization: better than 250 μs
- Energy resolution: better than 25%



Astronomical Sources and Physics sectors

Scientific goal	Sources	< 1keV	1-10	> 10 keV
Acceleration phenomena	PWN	yes (but absorption)	yes	yes
	SNR	no	yes	yes
	Jet (Microquasars)	yes (but absorption)	yes	yes
	Jet (Blazars)	yes	yes	yes
Emission in strong magnetic fields	WD	yes (but absorption)	yes	difficult
	AMS	no	yes	yes
	X-ray pulsator	difficult	yes (no cyclotron ?)	yes
	Magnetar	yes (better)	yes	no
Scattering in aspherical geometries	Corona in XRB & AGNs	difficult	yes	yes (difficult)
	X-ray reflection nebulae	no	yes (long exposure)	yes
Fundamental Physics	QED (magnetar)	yes (better)	yes	no
	GR (BH)	no	yes	no
	QG (Blazars)	difficult	yes	yes
	Axions (Blazars, Clusters)	yes ?	yes	difficult



[SOFFITTA_XPE_TEXAS_2015.pdf (cern.ch)]

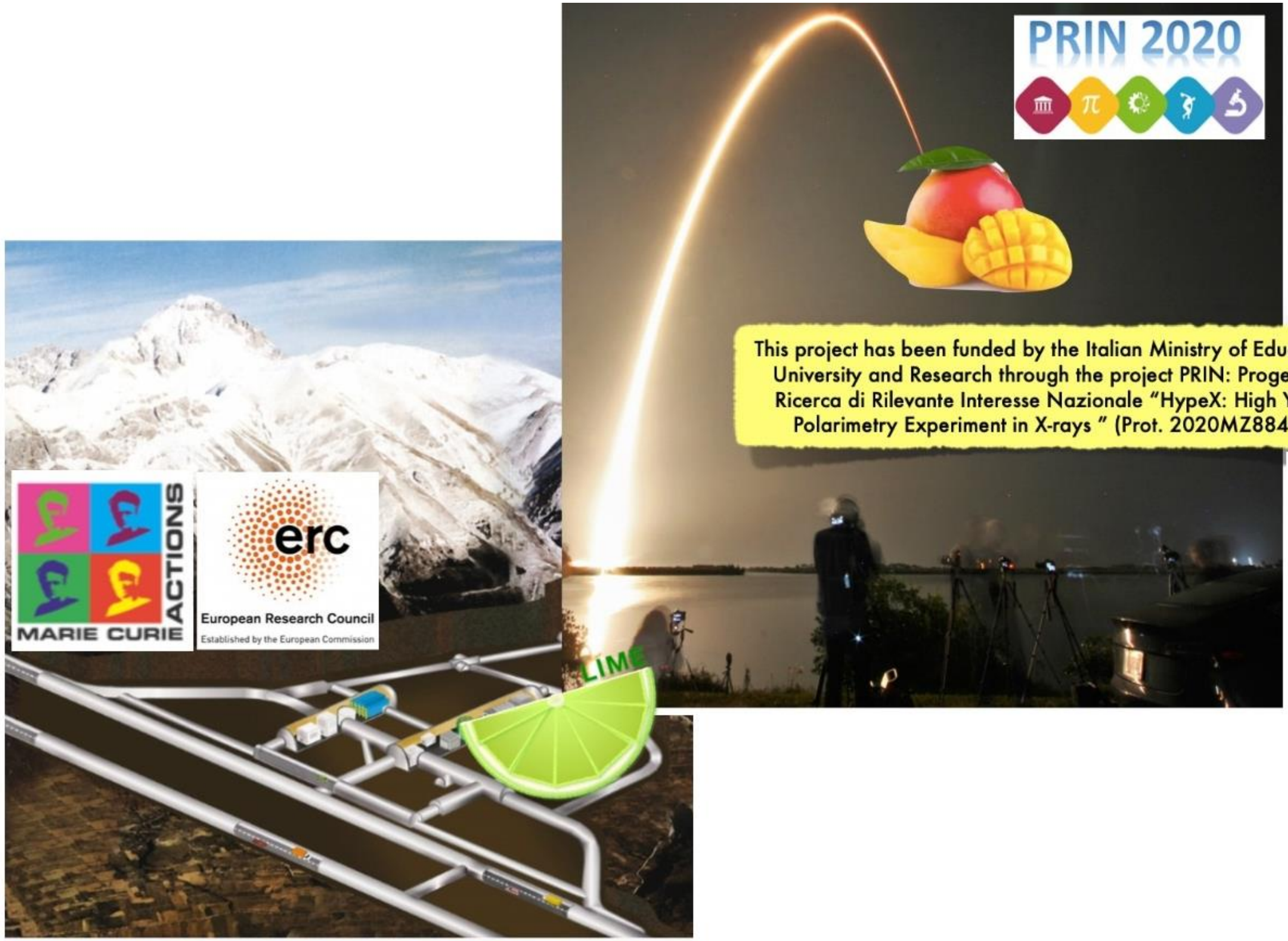
[IXPE - Imaging X-ray Polarimetry Explorer (inaf.it)]

Time on orbit

725 Days | 0 Hours | 58 Minutes | 28 Seconds

Nr. 115	PUBLICATIONS
6	The high polarisation of the X-rays from the Black Hole X-ray Binary 4U 1630-47 challenges standard thin accretion disc scenario **Ratheesh et al.** *Submitted to Nature Astronomy*
16	Simultaneous space and phase resolved X-ray polarimetry of the Crab Pulsar and Nebula **N. Bucciantini et al.** *Submitted to nature Astronomy - Includes Supplementary material, 2022*
21	An efficient photoelectric X-ray Polarimeter for the study of Black Holes and Neutron Stars **E. Costa et al.** *2001, Nature, 411, 662*
52	Polarized Blazar X-rays imply particle acceleration in shocks **I. Liodakis et al.** *Accepted for publication in Nature*
113	A space-borne X-ray imaging polarimeter **M. C. Weisskopf et al.** *Nature Astronomy volume 7, page 635 (2023)*
115	Vela pulsar wind nebula X-rays are polarized to near the synchrotron limit **Xie F. et al.** *Nature 612, 658–660 (2022)*

From a LIME Underground to a MANGO in space

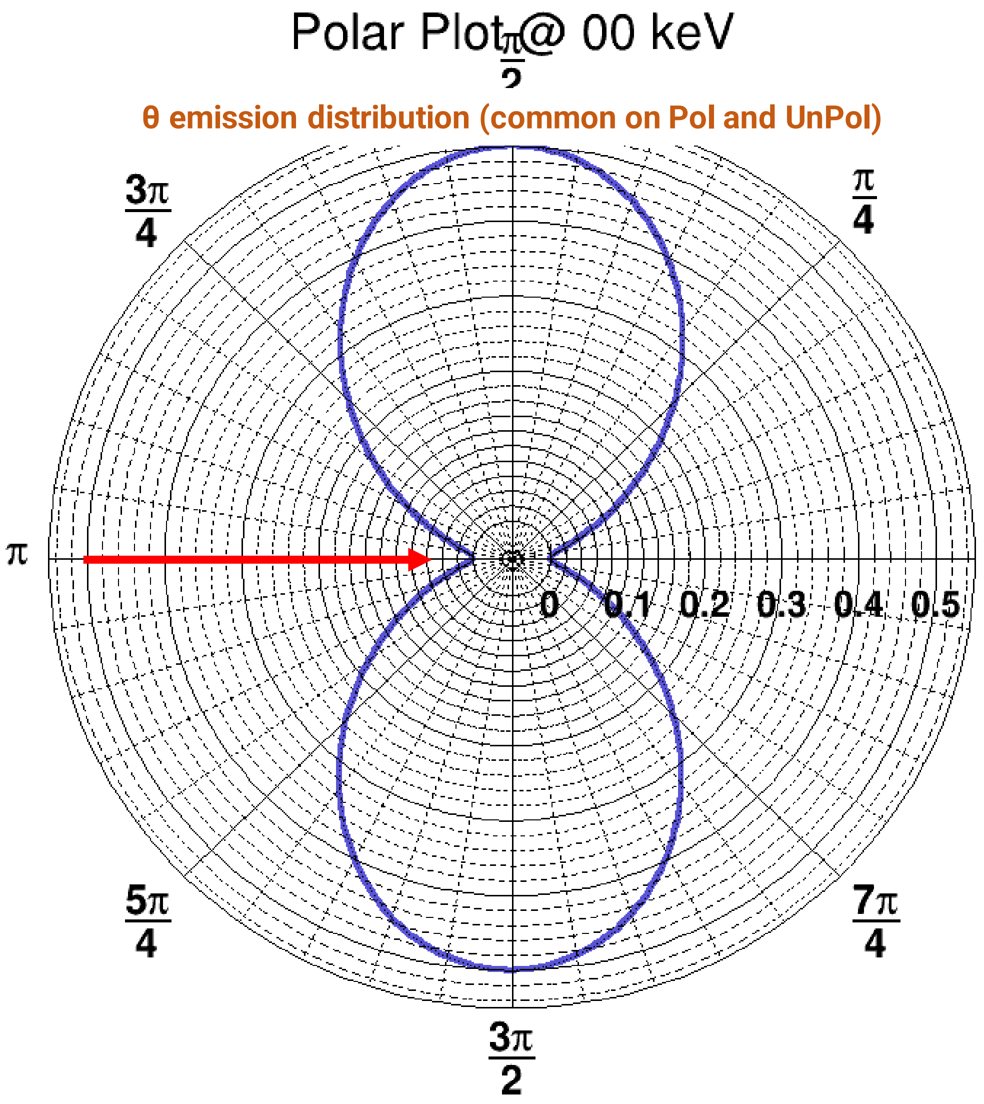


This project has been funded by the Italian Ministry of Education, University and Research through the project PRIN: Progetti di Ricerca di Rilevante Interesse Nazionale "HypeX: High Yield Polarimetry Experiment in X-rays " (Prot. 2020MZ884C)

This project has received fundings under the European Union's Horizon 2020 research and innovation programme from the Marie Sklodowska-Curie grant agreement No 657751 and from the European Research Council (ERC) grant agreement No 818744

Photoelectric effect

θ emission distribution (common on Pol and UnPol)



fiorotto8/AngularProbabilityPhotoelectric (github.com)

Valid only for spherical symmetric shells!

Usually true since PE is dominant on inner shells that are spherical

$$\frac{d\sigma_{\mathrm{Ph}}}{d\Omega} = r_0^2 \alpha^4 Z^5 \left(\frac{m_e c^2}{E}\right)^{\frac{7}{2}} \frac{4\sqrt{2}\sin^2\theta\ \cos^2\phi}{(1-\beta\cos\theta)^4}$$

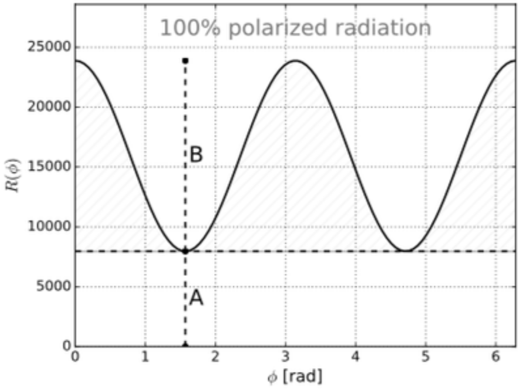
Unpolarized photons

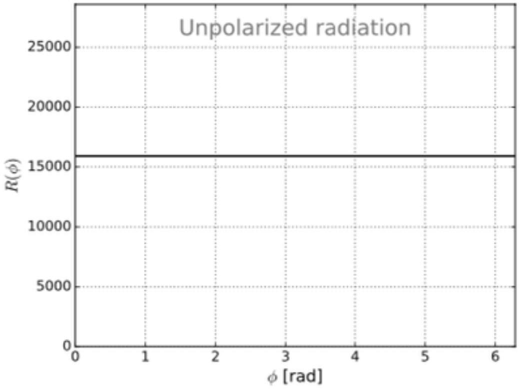
$$\mathcal{D}_{\mathrm{Ph}}^{\mathrm{UnP}}(\phi,\theta) = \frac{1}{2}\frac{\sin^2\theta}{(1-\beta\cos\theta)^4}.$$

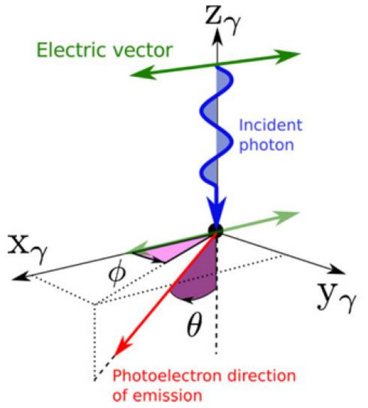
Linearly polarized photons

$$\mathcal{D}_{\mathrm{Ph}}^{\mathrm{Pol}}(\phi,\theta) = \frac{\sin^2\theta\ \cos^2\phi}{(1-\beta\cos\theta)^4},$$

Φ emission distribution modulated on Xray Polatization







Photoeletron directionality and Xray polarimetry

- **Doing X-ray Polarimetry means doing electron directionality!** (also, energy is essential)
- Reconstruct the photoelectron angular distribution to get some modulation in the **azimuthal angle**

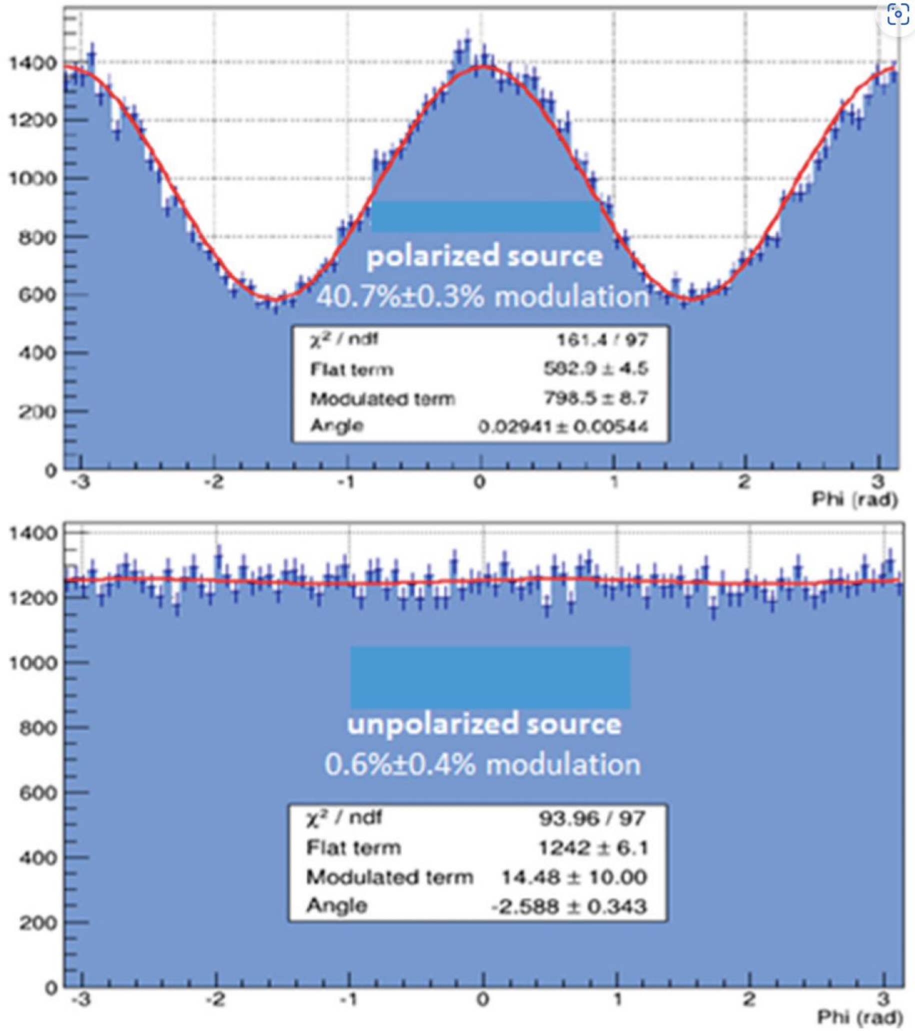
$$R(\phi) = A + B\cos^2(\phi - \phi_0)$$

- **Modulation factor**: response to 100% polarized radiation:

$$\mu = \frac{R_{\max} - R_{\min}}{R_{\max} + R_{\min}} = \frac{B}{B + 2A}$$

- **Minimum Detectable Polarization** (MDP) with no background:

$$\mathrm{MDP} = \frac{4.29}{\mu\sqrt{N}} \quad (99\% CL)$$



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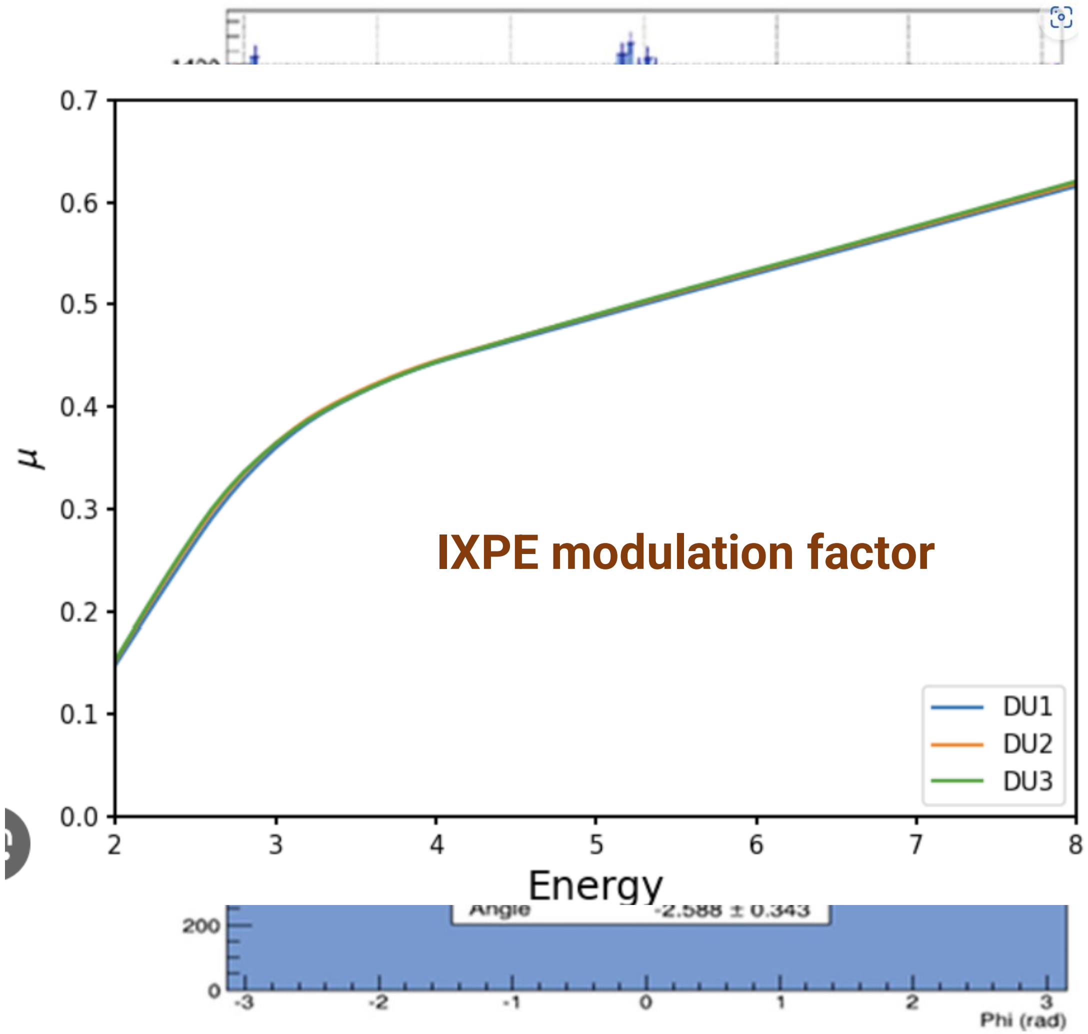


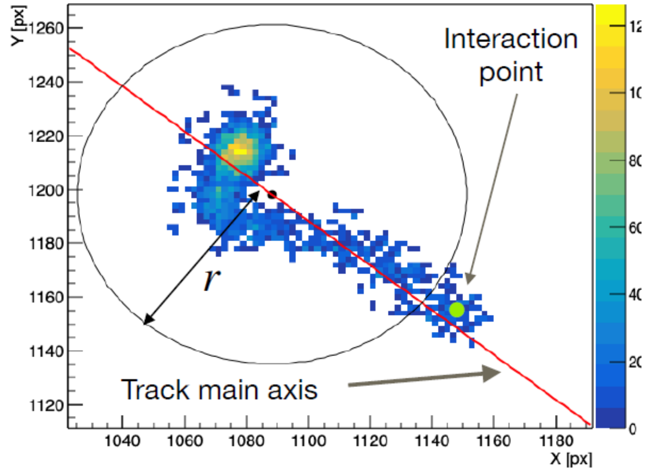
Reconstruction & Directionality

- To do X-ray polarimetry, you need to reconstruct the **impact point** of the X-ray and its **direction**!
- Let's start with CYGNO simulation
- **Samuele** applied the IXPE algorithm for directionality to **electrons simulated and digitized in LIME**

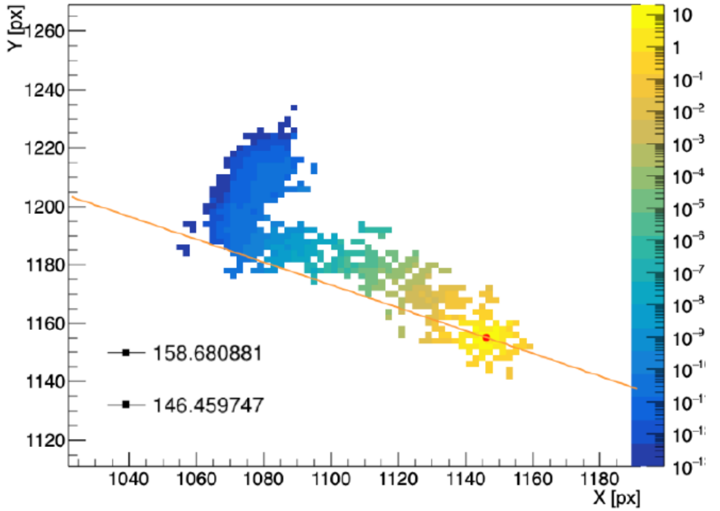
- Algorithm adapted from X-ray polarimetry:

"Measurement of the position resolution of the Gas Pixel Detector"
Nuclear Instruments and Methods in Physics Research Section A, Volume 700, 1 February 2013, Pages 99-105

- First part of the algorithm: searching for the beginning of the track with:
  - Skewness
  - Distance of pixels from barycenter (farthest pixels)
  - Selection of a region with fixed number of points N_{pt}



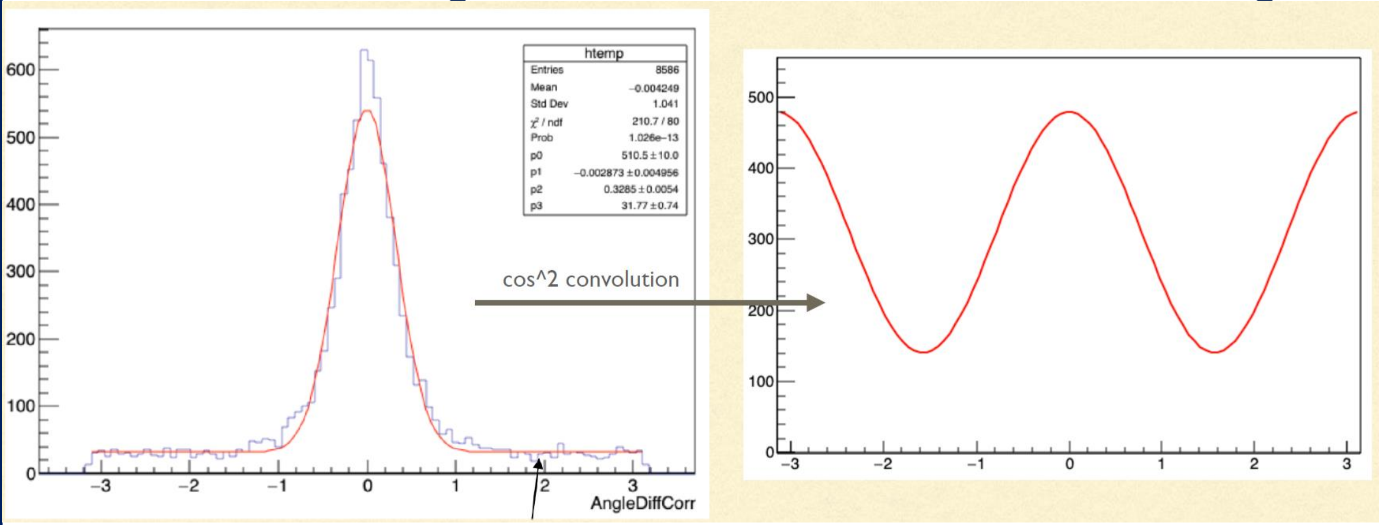
- Second part of the algorithm aims to find the direction:
  - Track point intensity rescaled with the distance from the interaction point: $W(d_{ip}) = exp(-d_{ip}/w)$
  - Direction taken as the main axis of the rescaled track passing from the interaction Point
  - Orientation given following the light in the Pixels



- Two parameters of the algorithm: N_{pt} and w

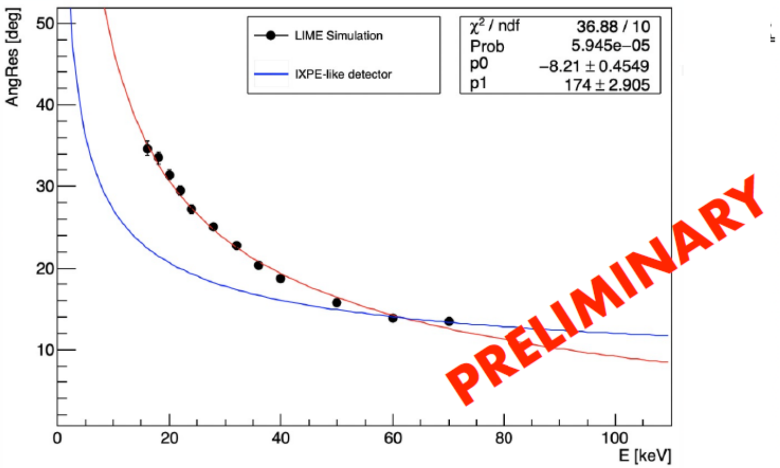
Reconstruction & Directionality

Simulated and digitized Electron tracks in LIME range of 15-70 keV **(Samuele's Thesis)**

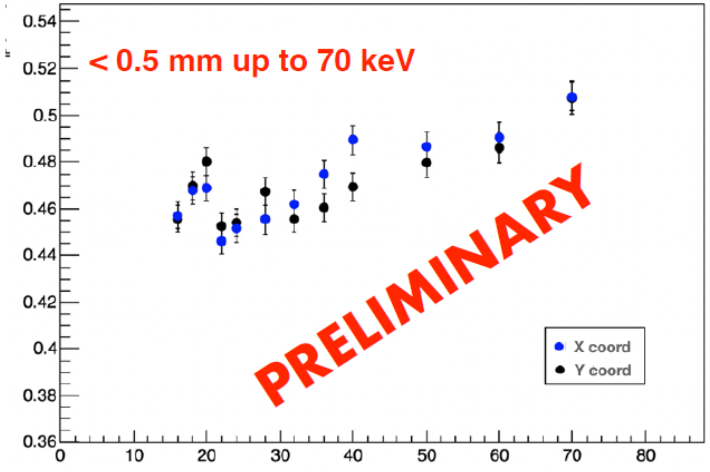


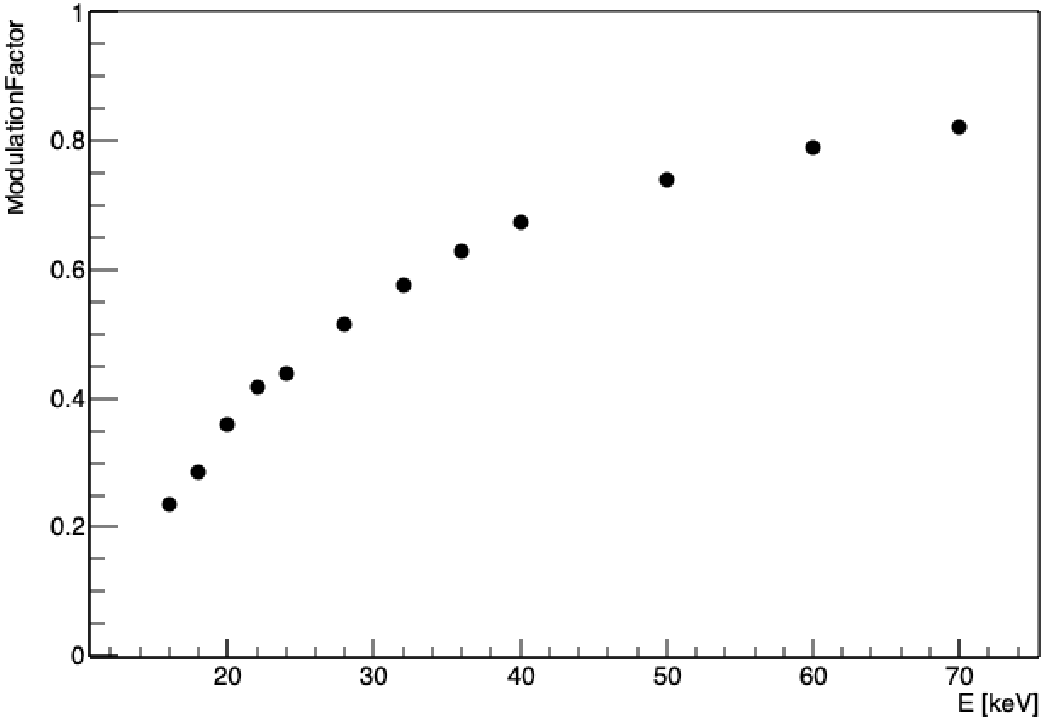
- Directionality code for **IP and direction**
- From angular distribution, you may apply a **cos^2 convolution** to simulate **linearly polarized Xrays**
- Then you can measure the **Modulation factor!**

Angular resolution

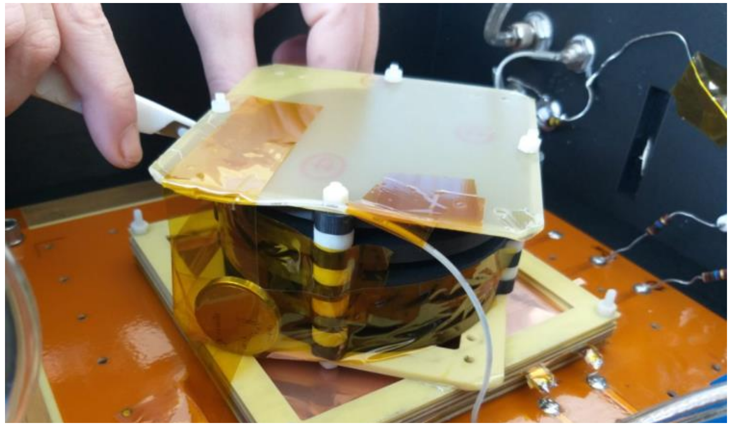


Impact point resolution



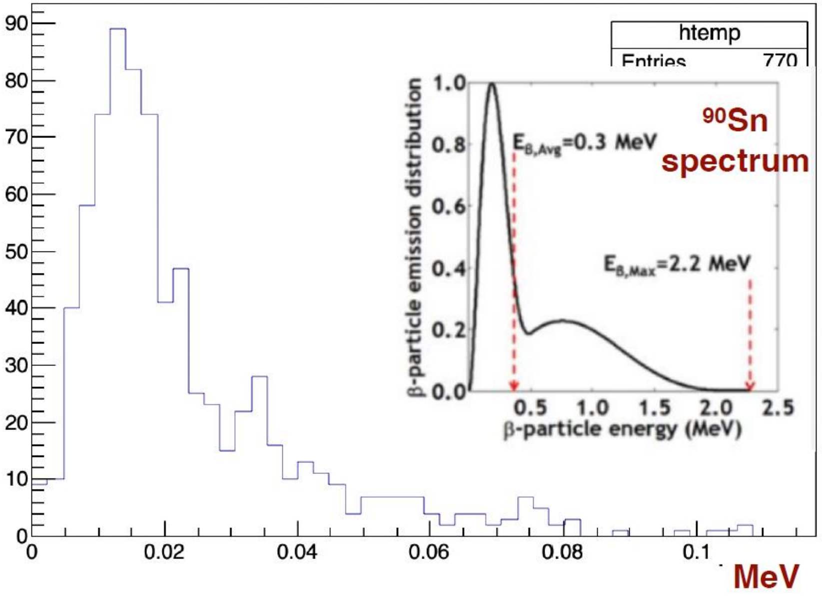


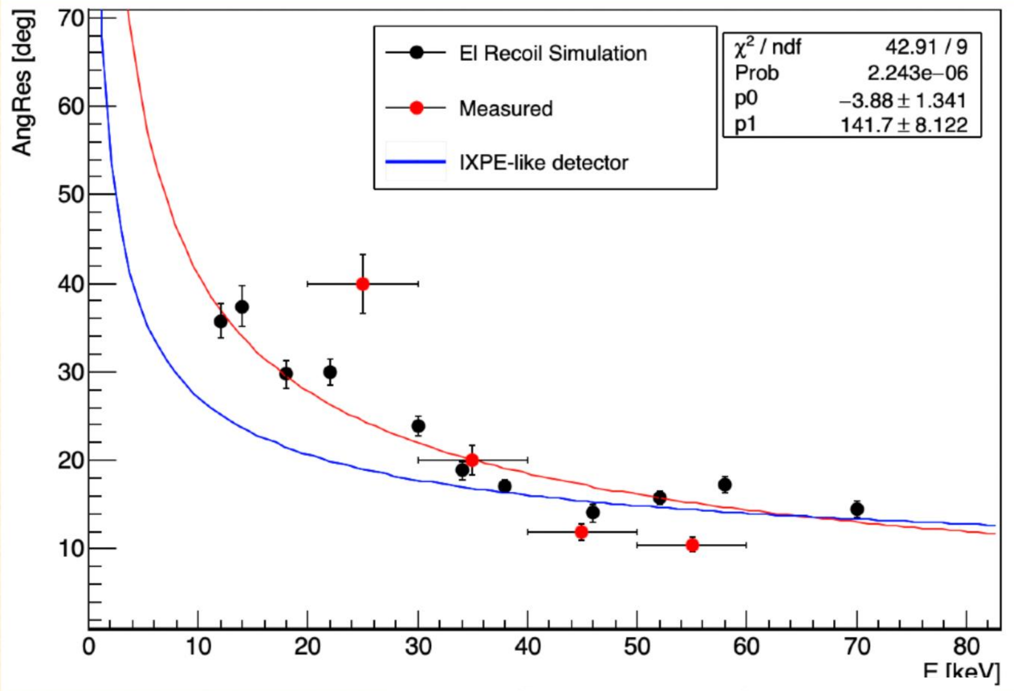
First test @ INAF



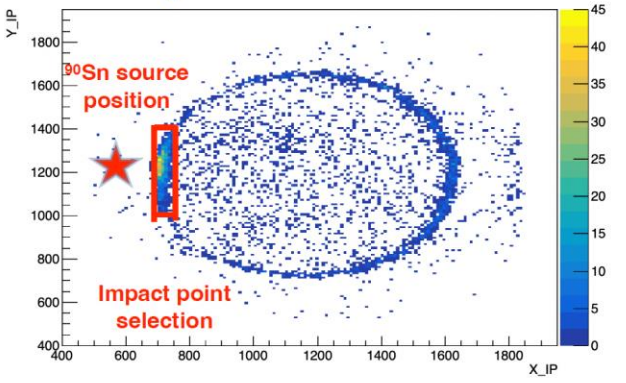
- Collimated ^{90}Sr source
- Simulation and measurement of electron tracks

Spectrum of contained tracks from simulation





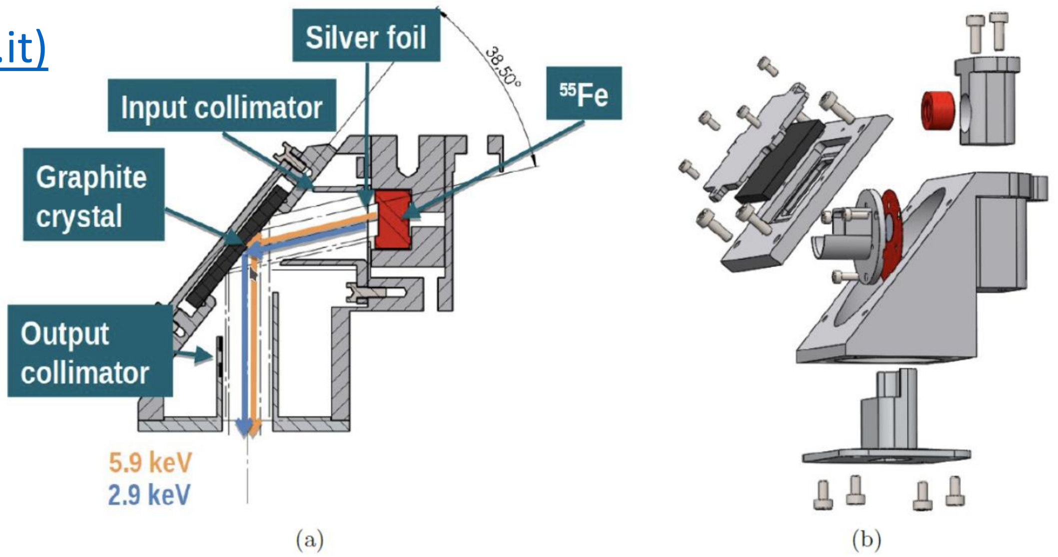
Reconstructed impact point of all tracks



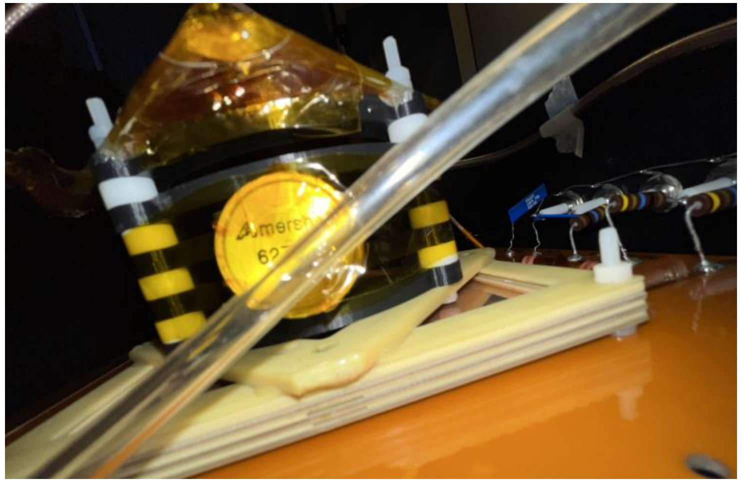
- The detector was not operated in the appropriate condition (**Gain saturation**)
- However, there is **quite a good agreement with the simulation**
- **PRELIMINARY!**

Future Plan

- **Collimated 90Sr source** (with a good working detector!)
- **Polarized Xray source** [Di Marco et al. Calibration.pdf (inaf.it)]
  - Source/crystal can be changed and determine the energy of the emitted Xrays (both Xray gun and source)
  - In crystals, Bragg diffraction ≈45°→ the direction of linearly polarized Xrays
  - We would need sources with higher energies → to be discussed with INAF colleagues

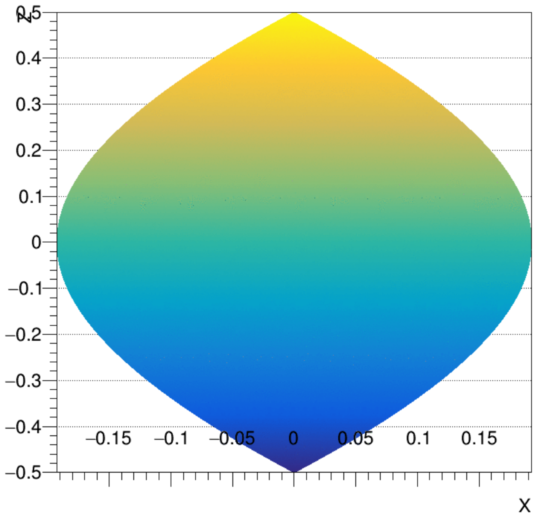


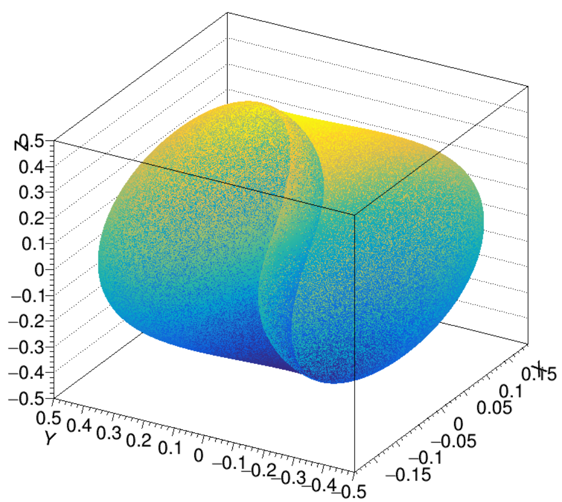
- **Gas Studies** (Ar, Ne, He with CF4 comparison)
  - Diffiuson measurement with different gases
  - Simulation & measurement
- **Different Amplification Stages:**
  - Minimize the diffusion and extend the energy range
  - MMGEM (THGEM with embedded mesh) – Available
- **Other approaches to directionality**

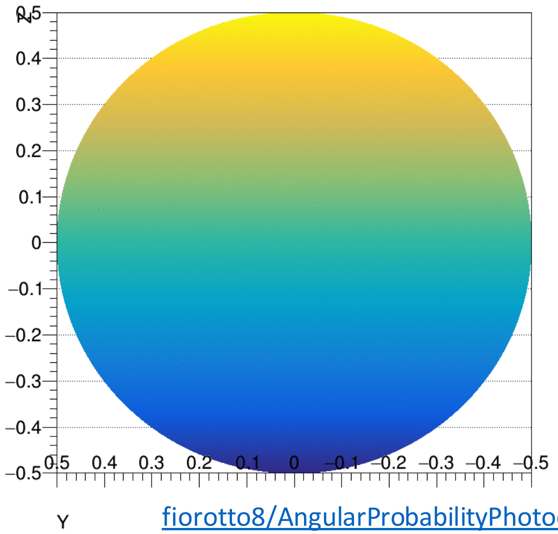


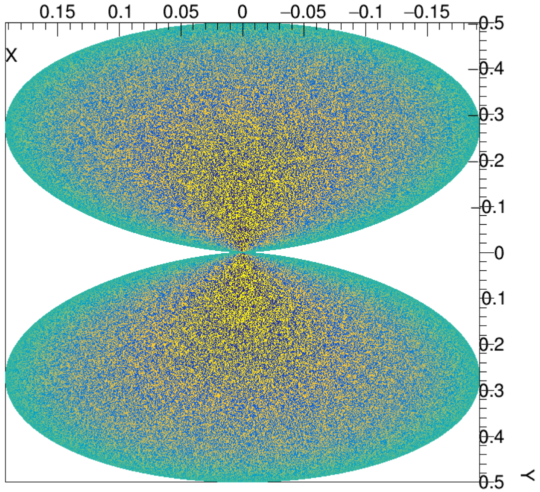
BACKUP

Photoelectric Effect - UNPOLARIZED
Spherical coordinates

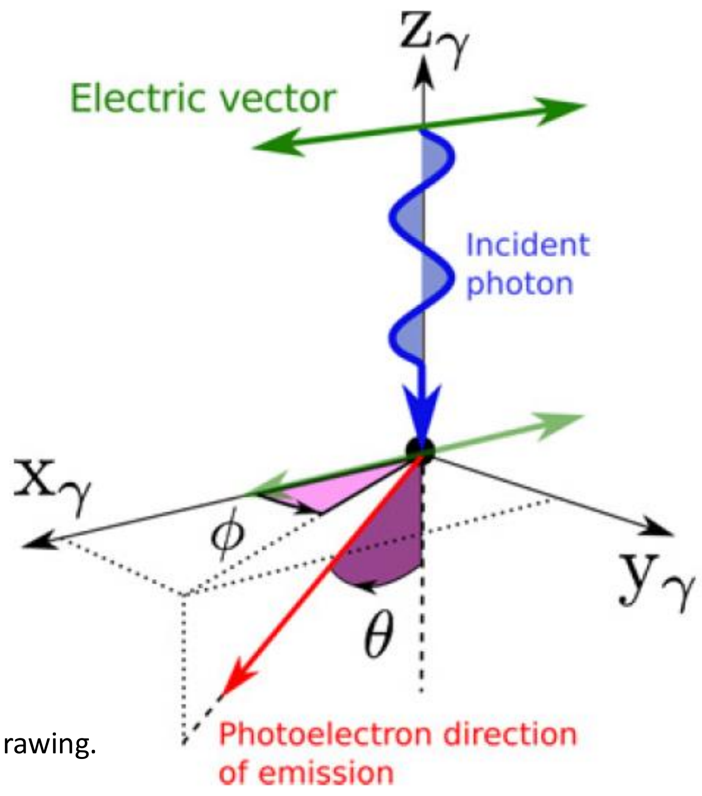








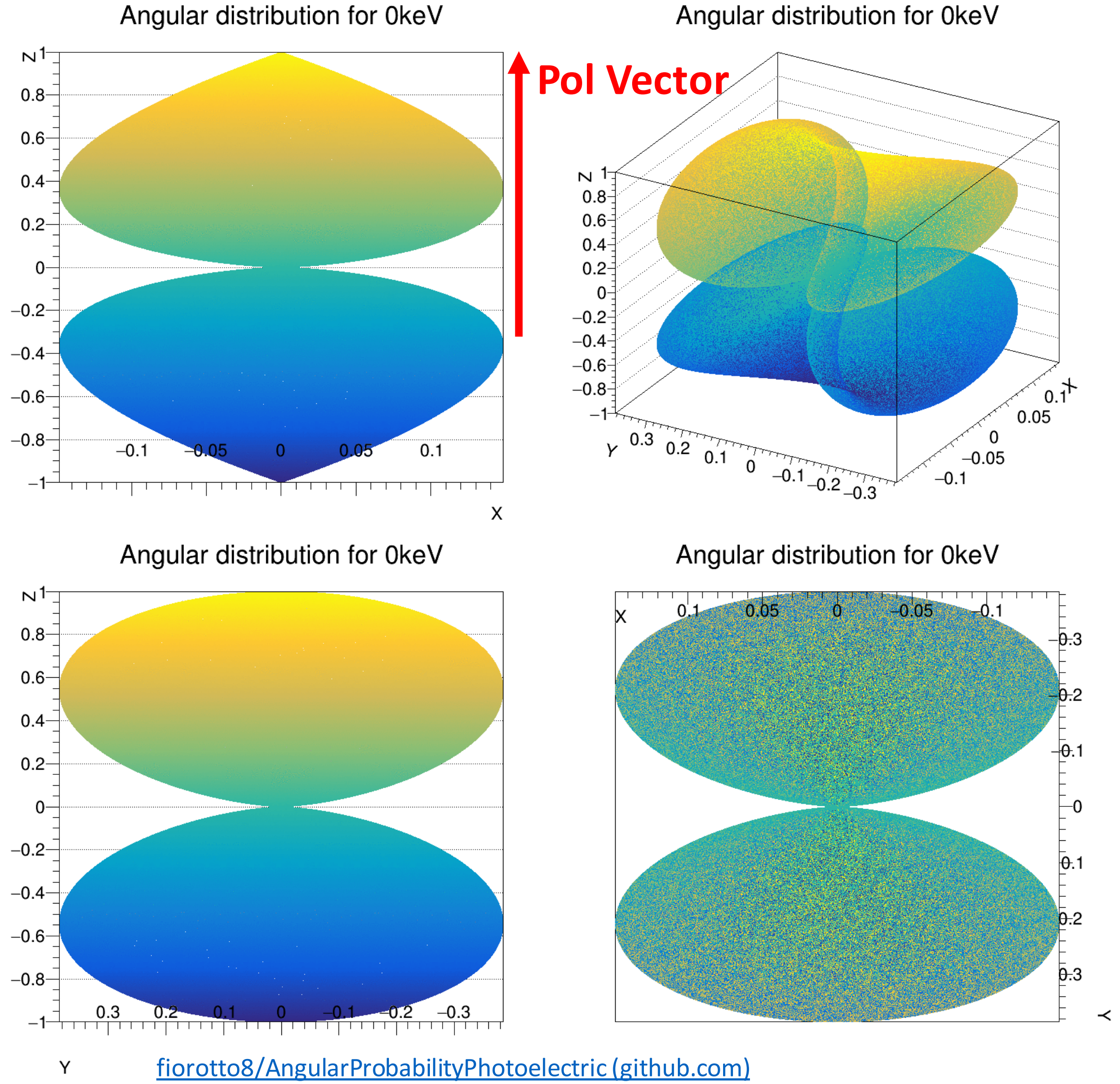
$$\mathcal{D}^{\mathrm{UnP}}_{\mathrm{Ph}}(\phi,\theta) = \frac{1}{2}\frac{\sin^2\theta}{(1-\beta\cos\theta)^4}.$$



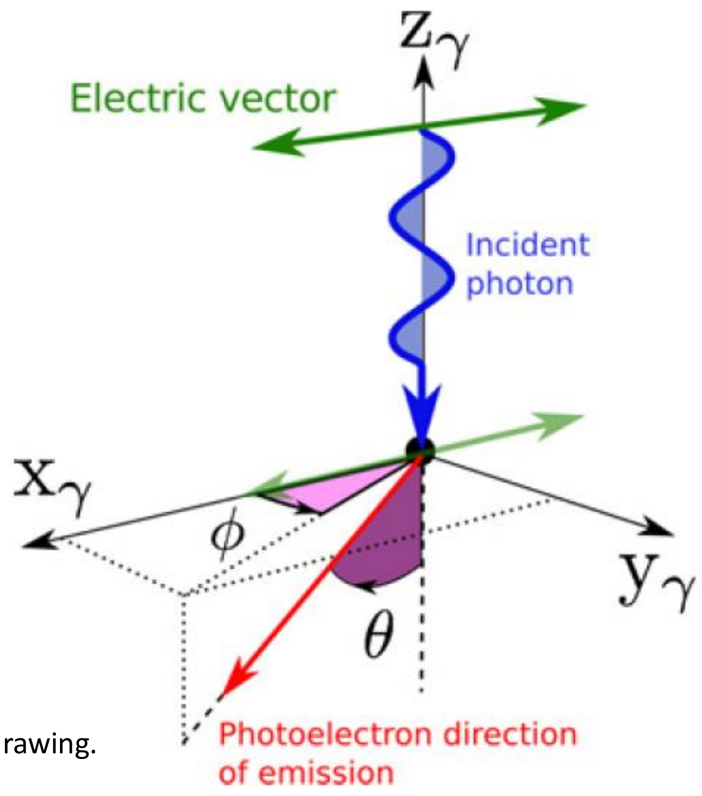
The blue-yellow color is just for the sake of drawing.
No physical sense is associated

fiorotto8/AngularProbabilityPhotoelectric (github.com)

Photoelectric Effect – LINEARLY POLARIZED
Spherical coordinates



$$\mathcal{D}^{\text{Pol}}_{\text{Ph}}(\phi,\theta) = \frac{\sin^2\theta\ \cos^2\phi}{(1-\beta\cos\theta)^4},$$



The blue-yellow color is just for the sake of drawing.
No physical sense is associated

[fiorotto8/AngularProbabilityPhotoelectric (github.com)](https://github.com/fiorotto8/AngularProbabilityPhotoelectric)

Cosmic Xray Background

Xray Cosmic BackGround Power Flux measurement

X-ray and gamma-ray limits on the primordial black hole abundance from Hawking radiation

[X-ray and gamma-ray limits on the primordial black hole abundance from Hawking radiation - ScienceDirect]

$$\Phi_{\mathrm{AGN}} = \frac{\mathrm{d}N}{\mathrm{d}E\,\mathrm{d}t} = \frac{A}{(E/E_b)^{n_1} + (E/E_b)^{n_2}} \,. \tag{4}$$

For instance, assuming zero contribution to the data from PBH evaporation, the best fit is: $E_b = 35.6966$ keV, $A = 0.0642$ $\mathrm{keV^{-1}s^{-1}cm^{-2}sr^{-1}}$, $n_1 = 1.4199$ and $n_2 = 2.8956$; see the black dashed line in Fig. 1.

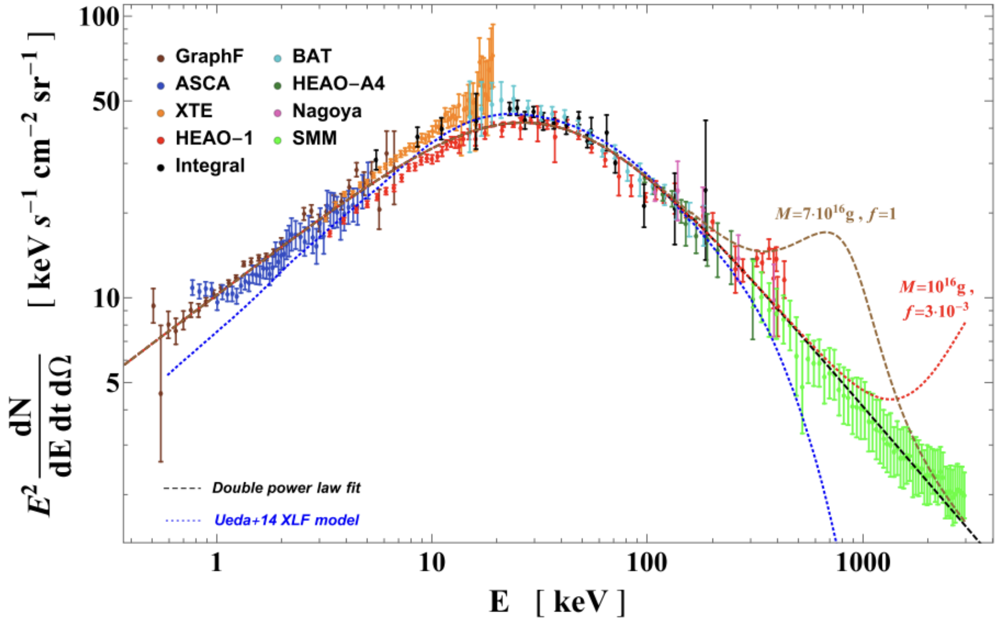
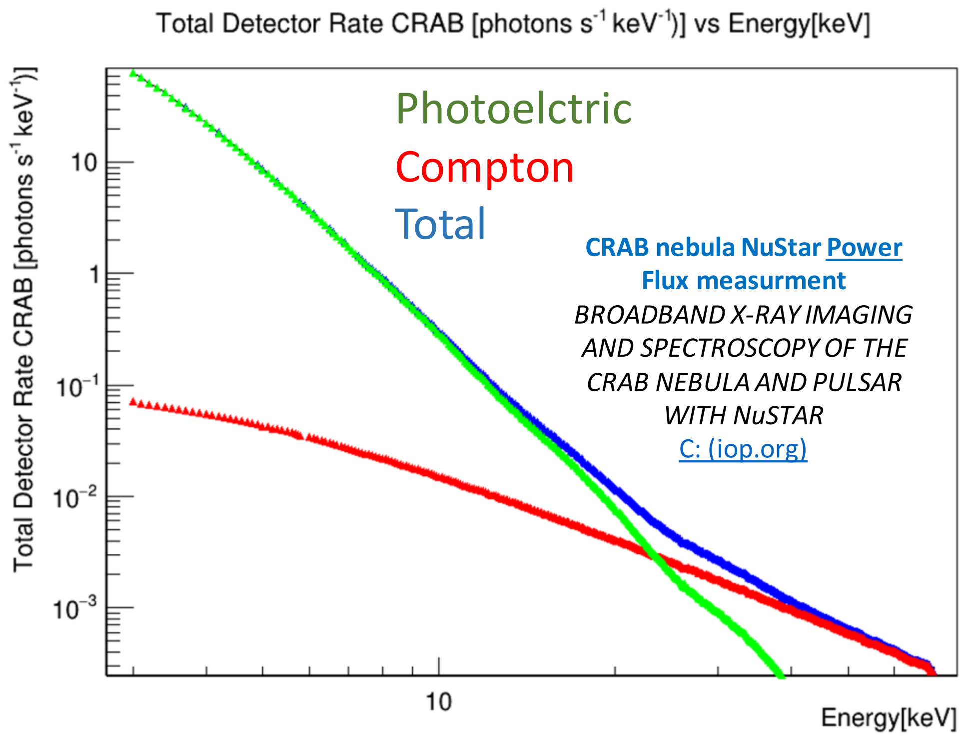


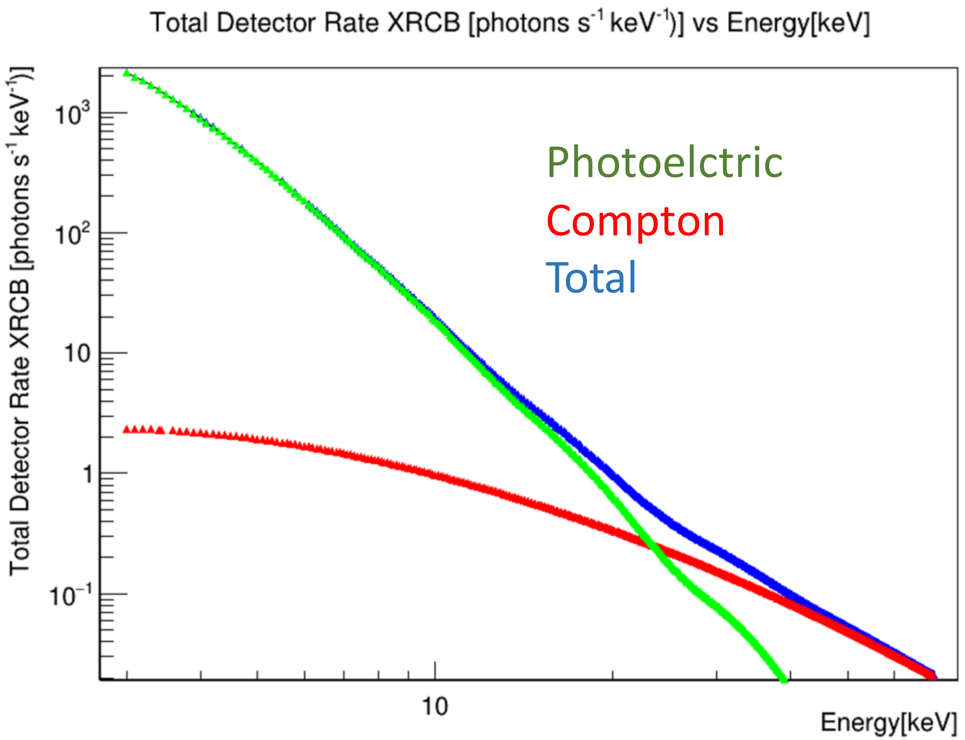
Fig. 1. Cosmic X-ray background spectrum, as measured by various experiments. Overimposed are the Ueda+14 model (blue dashed line), the fit to a double power-law (black dashed line) of Eq. (4), and the corrections to the latter due to two hypothetical monochromatic PBH distributions with different masses M and cosmological abundances $f = \Omega_{PBH}/\Omega_{DM}$.

- In "hard" X-rays, E = 3 - 300 keV, the emission is remarkably uniform across the sky, except for a narrow "ridge" of emission in the plane of the galaxy. (qui)
- Superimposition of many far point-like sources (AGNs) so uniform. Nearer to us the things are different so on the galactic plane the intensity is larger (no idea how much…)

Expected hit Rate on 100cm2 detector

- Every energy bin is multiplied by the sensitity data from [NIST XCOM: Element/Compound/Mixture]
  - Sensitity and CRAB flux evaluated with Eval with Tspline (very small difference with linear interpolation)





Addendum:

- **XRCB flux is computed supposing all the 4π flux impining on a single 10x10cm^2 side (overestimation of the flux but underestimation of the active area)**
- **For CRAB this is not the case**

Cosmic Xray background rate: 2700 Hz
Crab Nebula Rate: 70 Hz

Code and data available:

fiorotto8/RateCalc_CRAB-XRCB (github.com)

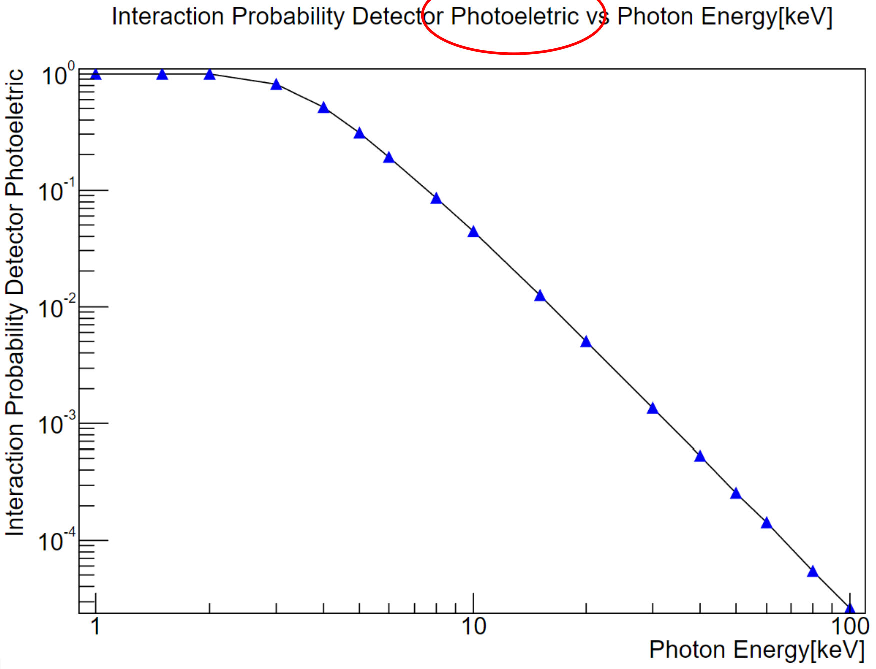
Christmas tree solution

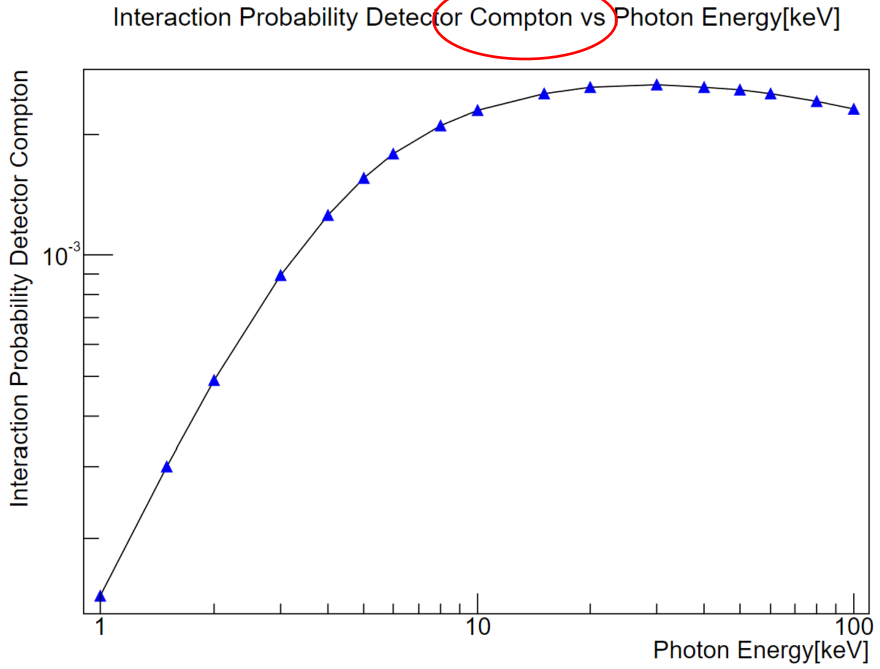
Gas Attenuation factors and Sensitivity

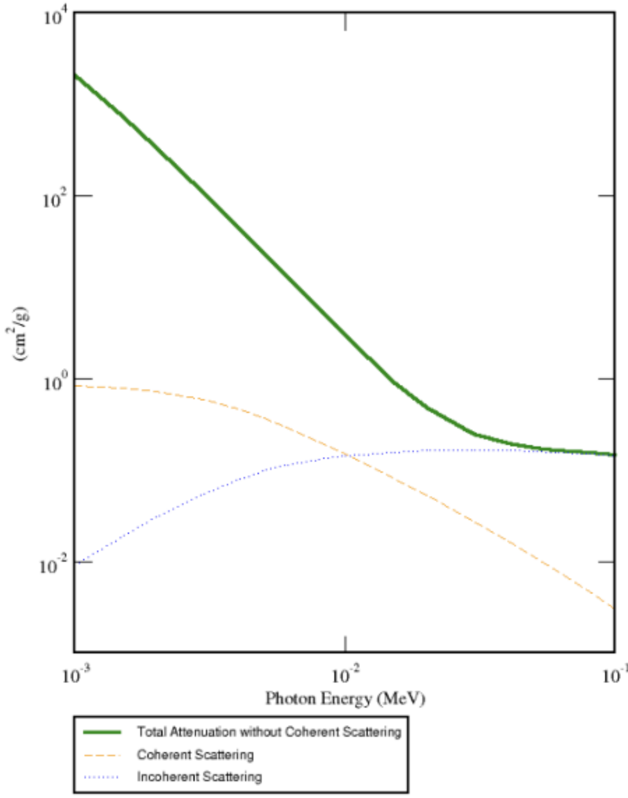
He/CF4 60/40 **μ/ρ** from NIST database [NIST XCOM: Element/Compound/Mixture]

- Interaction probabilility in x=10cm of such gas
- $P = 1 - e^{-\mu x}$

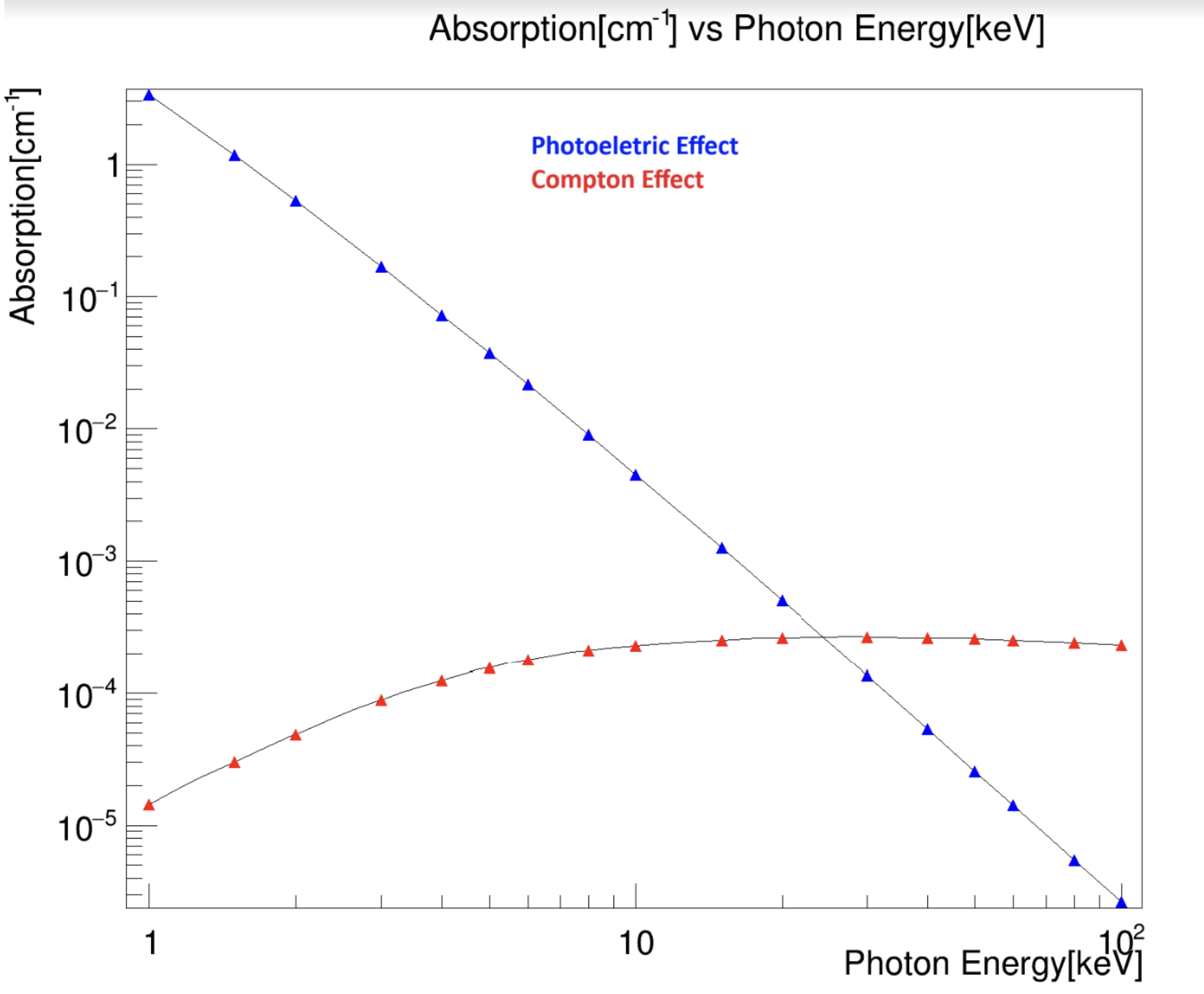
Gas	density (g/L)	density (g/cm3)
He	0.18	0.00018
cf4	3.72	0.00372
Mix density(g/cm3)	0.001596	
detector side (cm)	10	







He/CF4 60/40



Absorption[cm-1] vs Photon Energy[keV]
Photoeletric Effect
Compton Effect
Absorption[cm-1]
1
10−1
10−2
10−3
10−4
10−5
1
10
102
Photon Energy[keV]

Requirements for a CYGNO-like Polarimeter

- Polarimetry is also possible with Xrays not on-axis HERE
- Compton process is also polarization-dependent
- If the background is too large to use a ‘slow’ ORCA-like camera we may switch to Phoebe: The single-photon TPX3CAM – YouTube (Used by ARIADNE experiment)
  - Small area (256x256 pixels) but fast readout (no need of PMT in principle), probably noisy (image intensifier)
- Gas choice is a trade-off of many factors:
  - Quantum efficiency → heavy elements
  - Modulation factor → light elements (straight tracks)
- The K-edge of the chosen gas should be (much) lower than the minimum energy of interest
  - Otherwise, we got contaminated by the Auger electron, which is emitted isotropically
- For HypeX TPC, we foresee good directionality of the photoelectron from 15 keV up to fully contained tracks (He/CF4)
  - Potentially, we can work up to the Argon (K-shell ≈3keV)
  - Larger efficiency with heavier gases (also to the background!)
  - Choice of gas (with fixed dimension) fixes the energy range