Development and Preliminary Results of a Large-Volume Time Projection Chamber for X-ray Polarimetry

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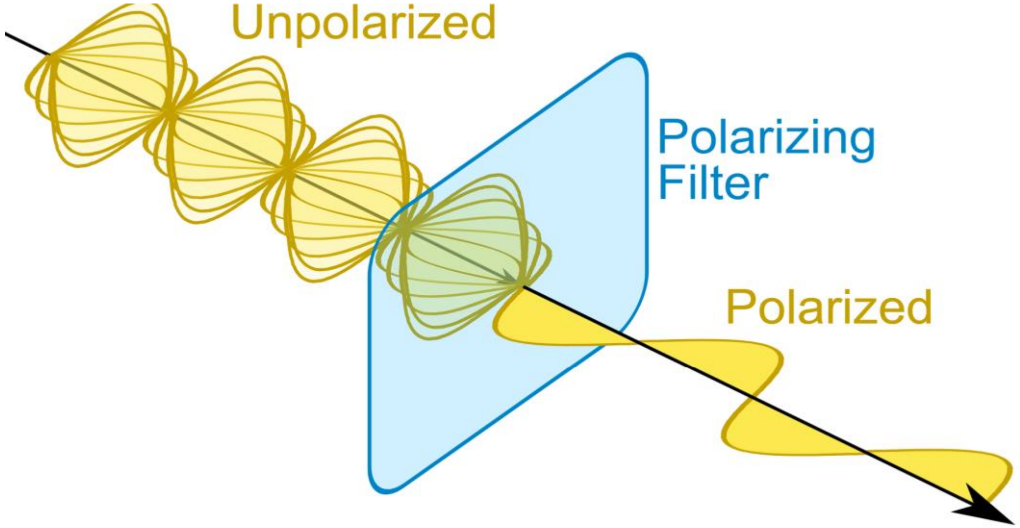
Polarization in Astrophysics

The polarization of a photon refers to the orientation of the oscillating electric field vector perpendicular to its propagation direction.

→ Polarization of photons has always been an important dimension to study astronomical sources

→ In around 50 years of Xray astronomy, only one positive detection of X-ray Polarization: the Crab nebula Novick et al. 1972, Weisskopf et al.1976, Weisskopf et al. 1978



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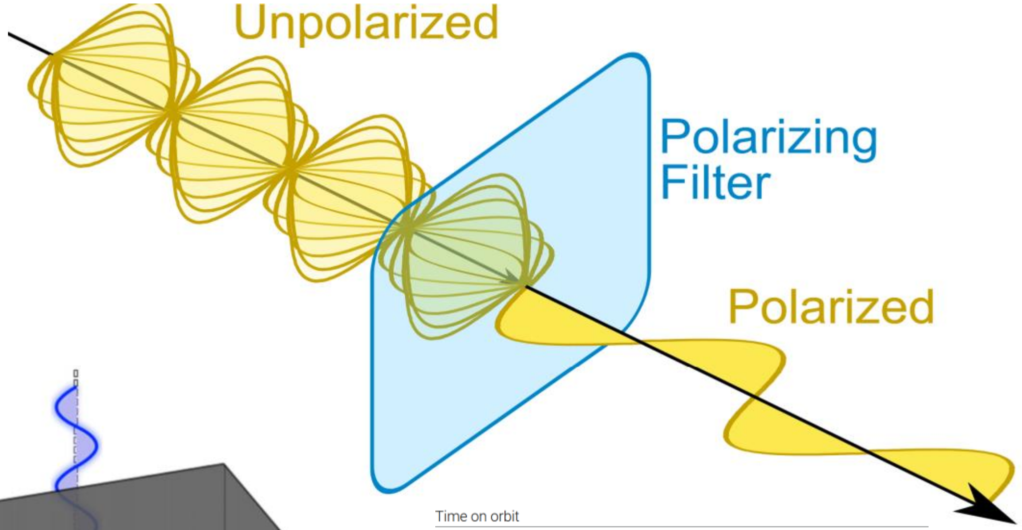
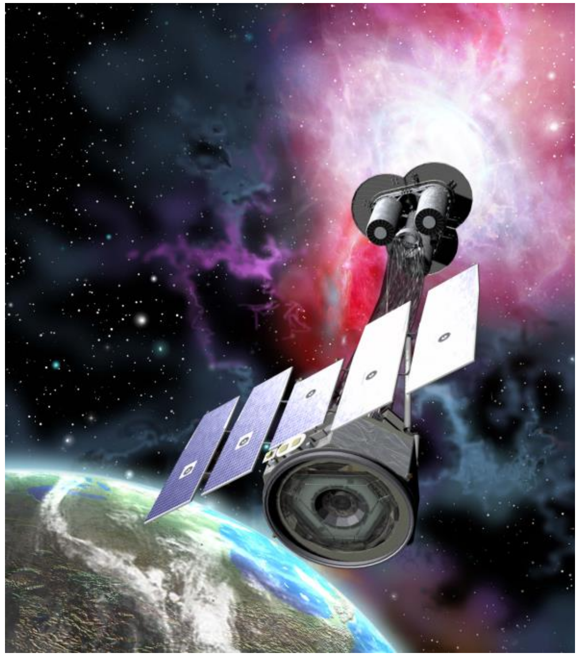




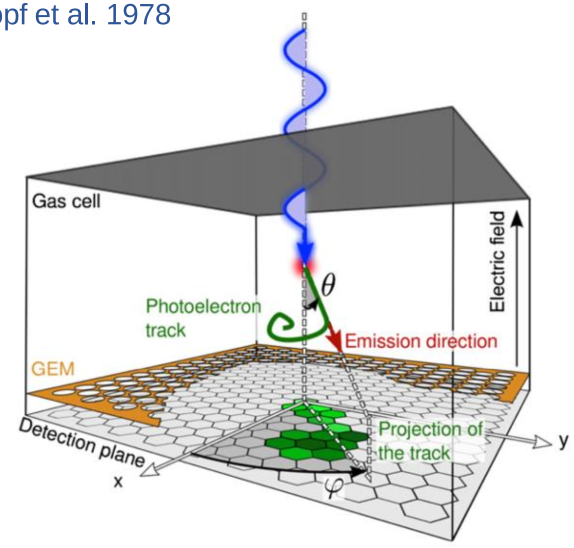
Then **IXPE** arrived equipped with **3x Gas Pixel Detector**

10x15x15mm DME 800 mbar

Single GEM – Pad readout

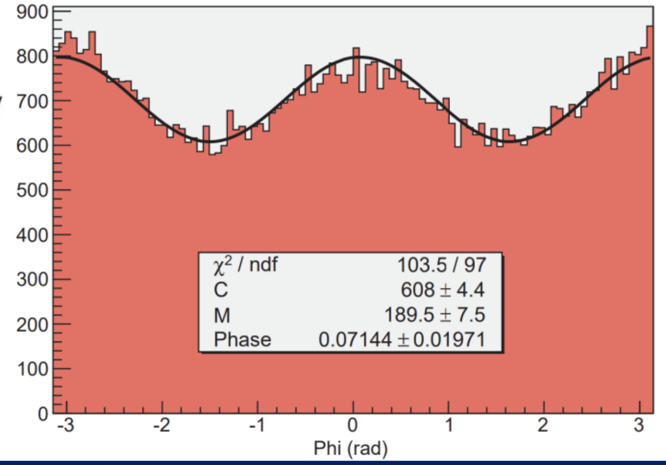
- **Energy range 2-8 keV**
- Angular resolution: better than 30 arcsec, field of view larger than 9 arcmin
- **Energy resolution: better than 25%**

Launched 9 Dec 2021 → 164 papers



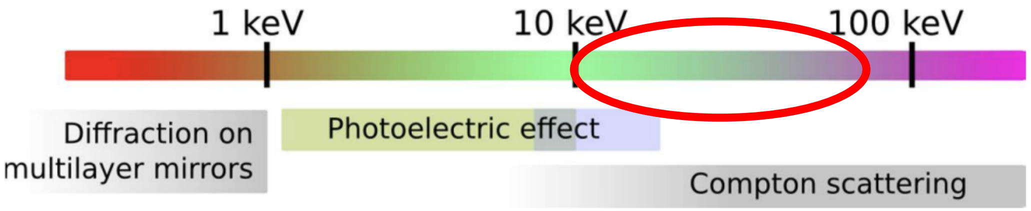
Time on orbit

1034	4	31	32
Days	Hours	Minutes	Seconds



Physics and polarimetry

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

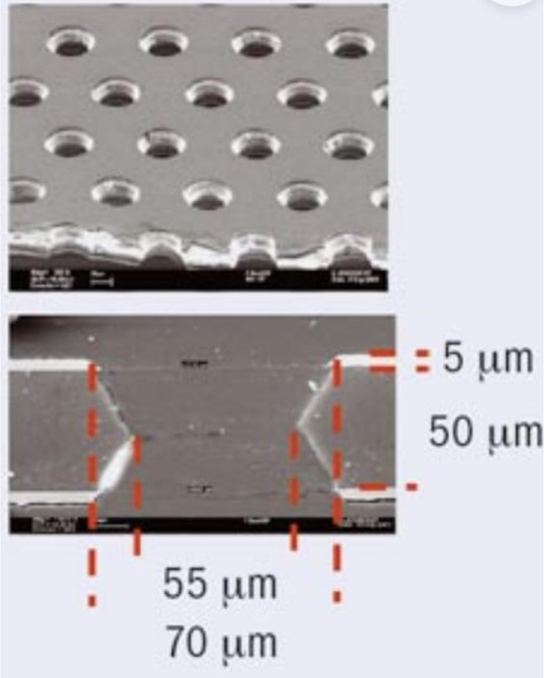


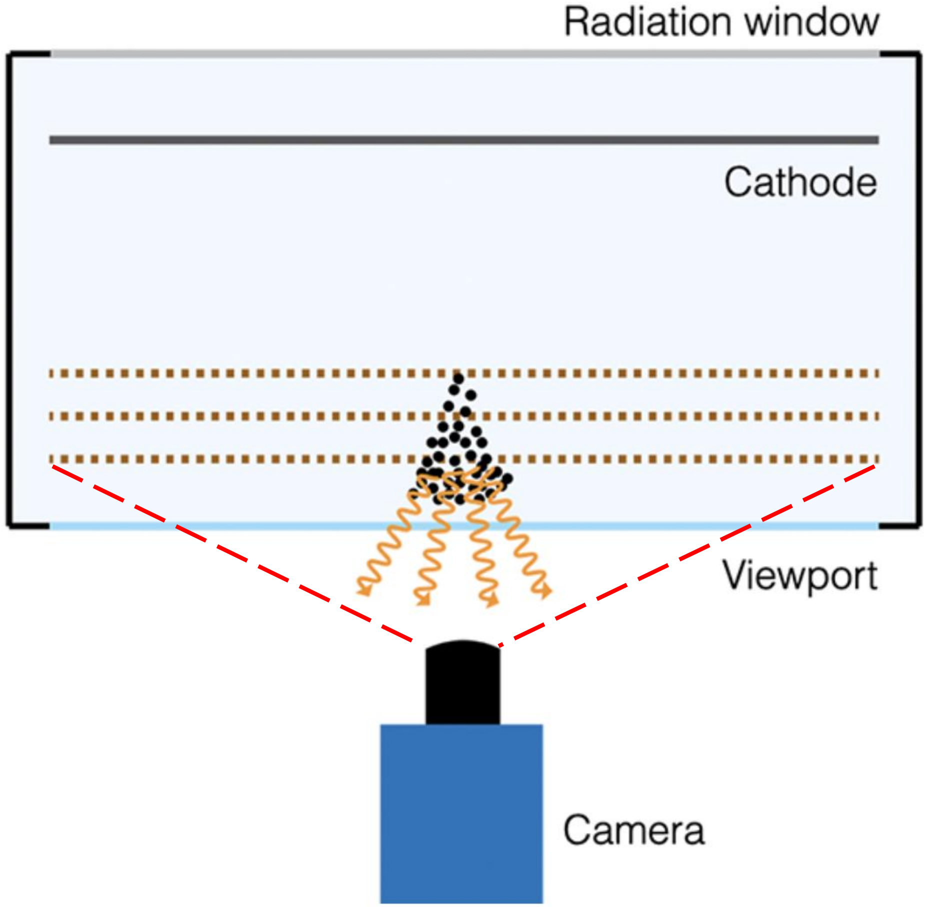
Develop a Detector capable of Measure **Polarization** through **photoelectric effect** for energies >10keV

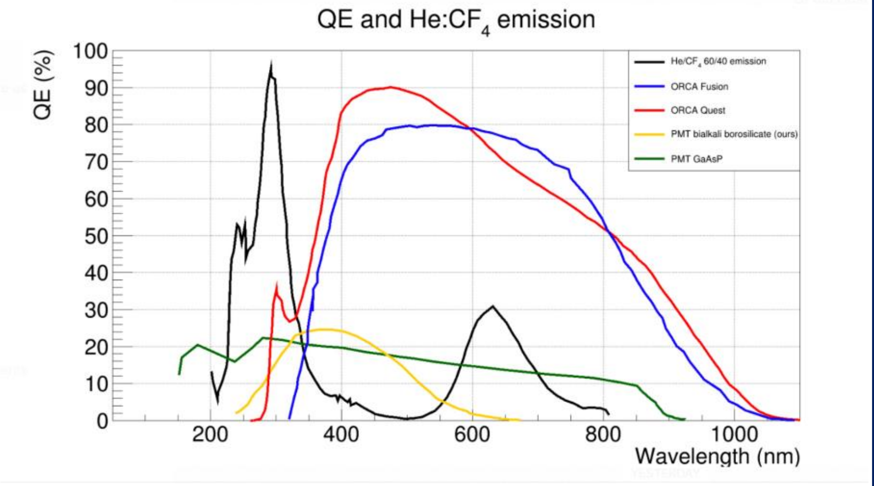
[XIPE: the x-ray imaging polarimetry explorer (unipa.it)](#)

Detector overview

Gas volume filled with
He/CF_4 60/40
1atm



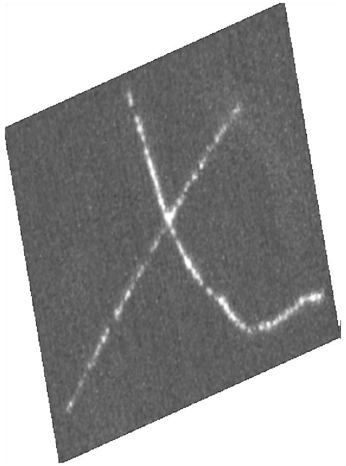




CMOS

Hamamatsu ORCA Quest (2)

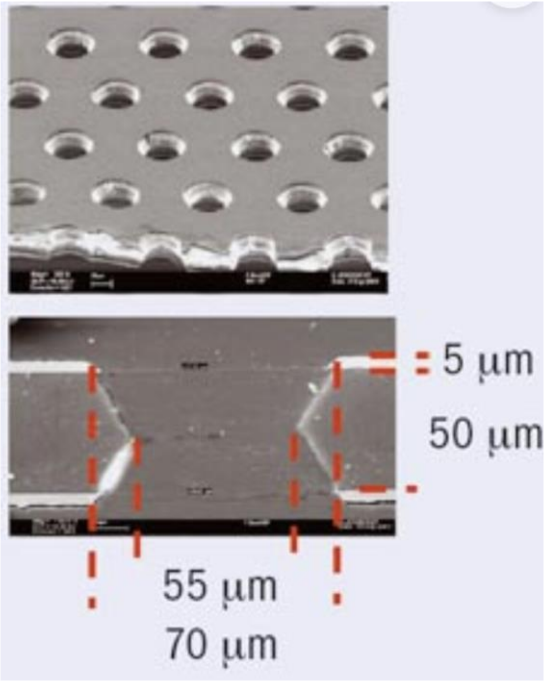
High-granularity X+Y+Energy measurement

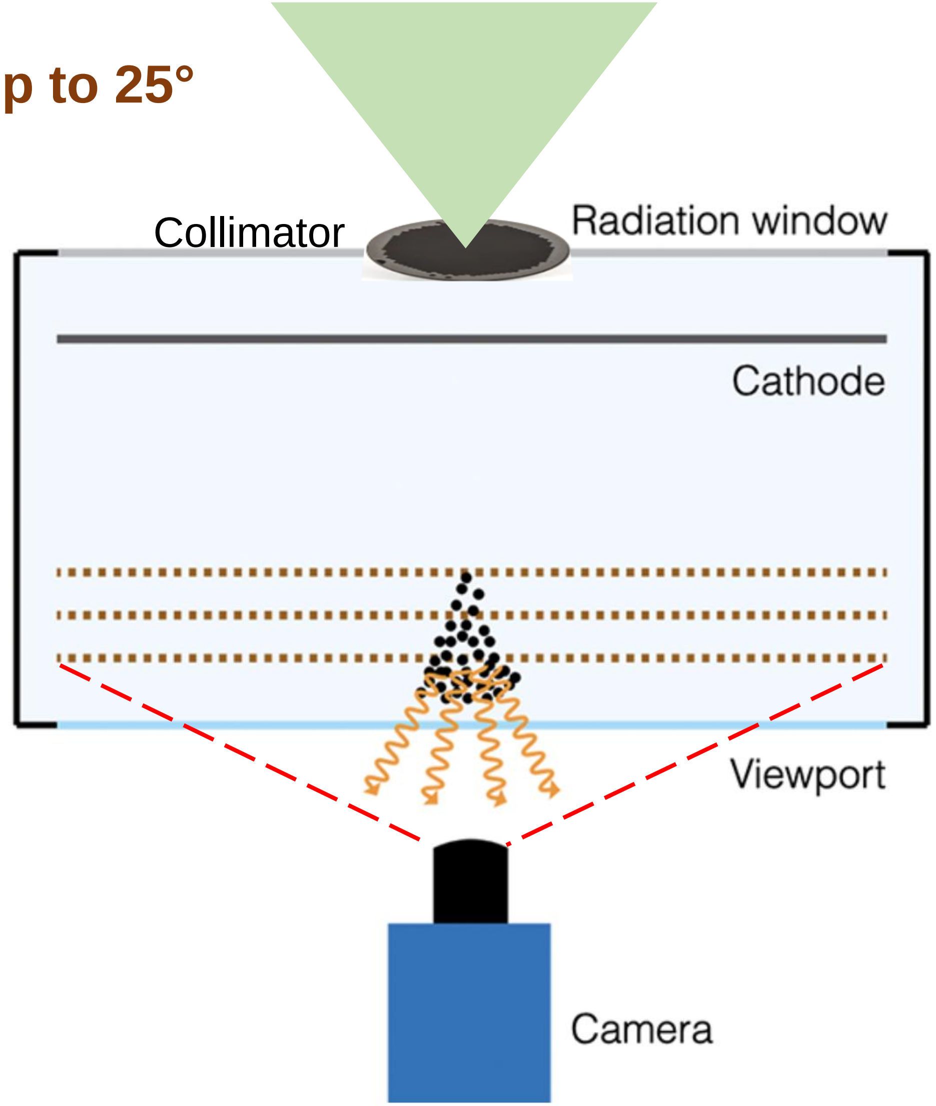


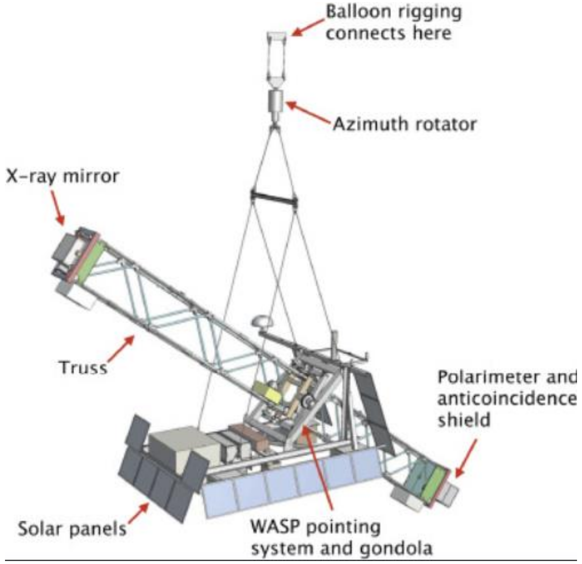
Detector overview

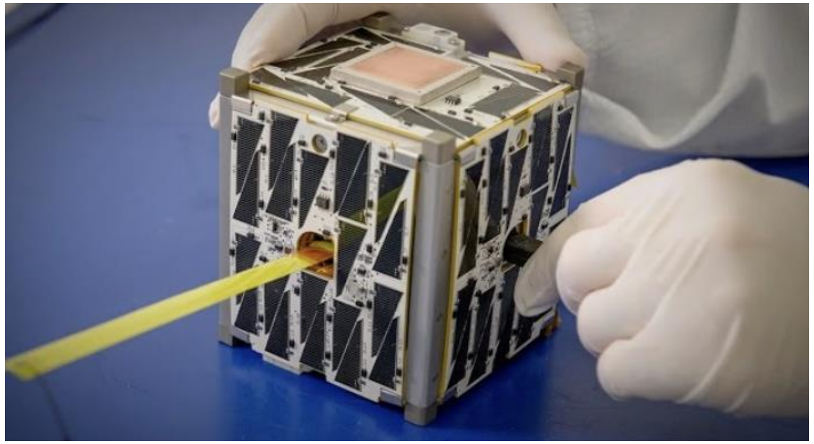
Large FoV up to 25°

Gas volume filled with He/CF_4 60/40 1atm

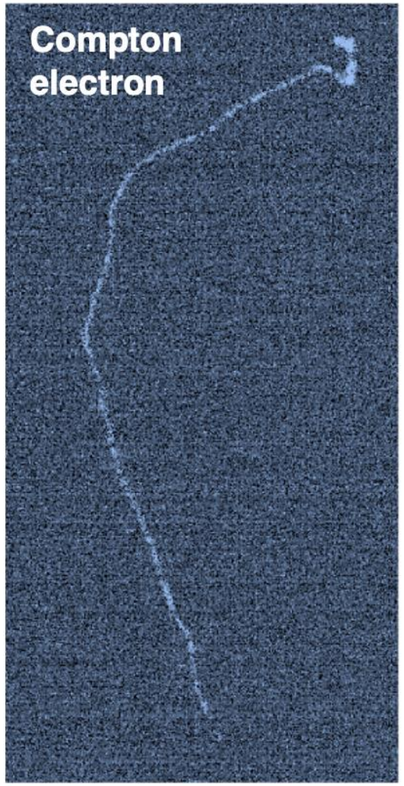


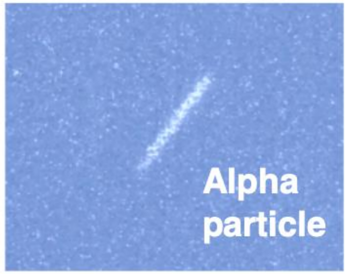




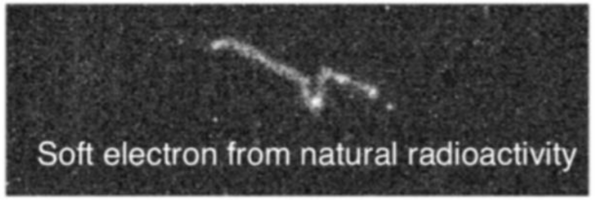


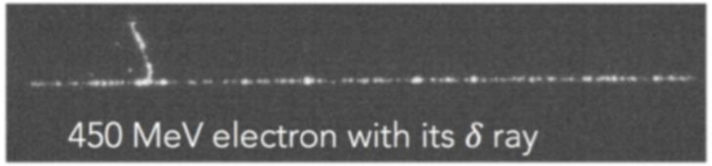
Photographing particle tracks

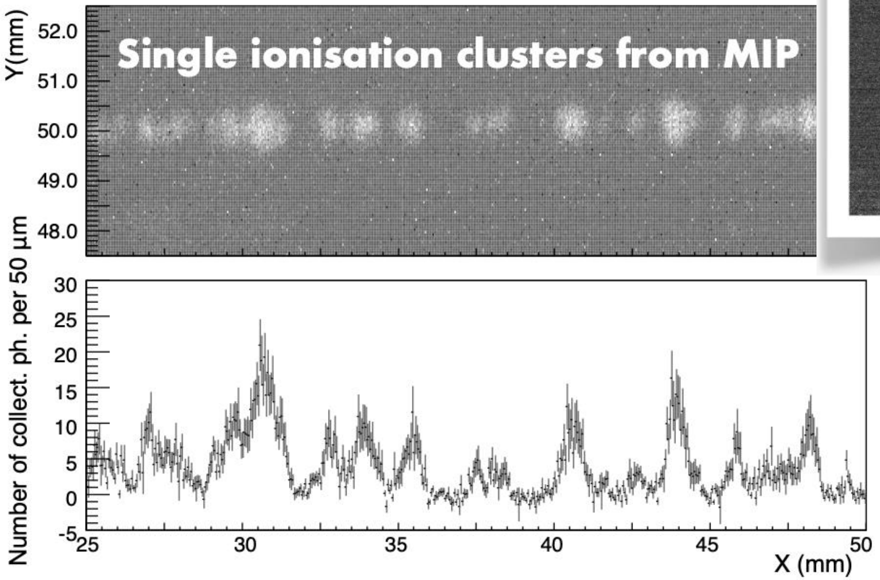


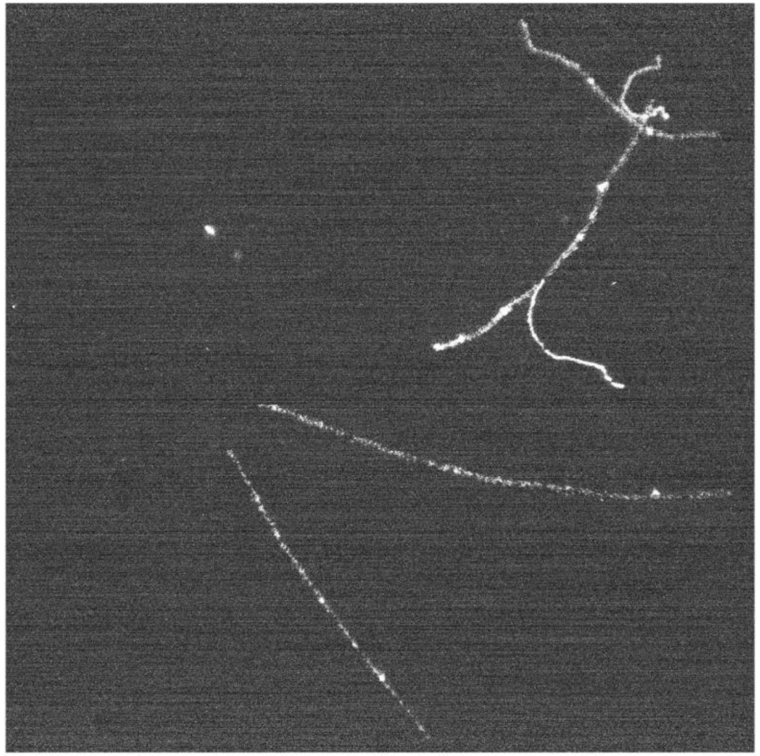


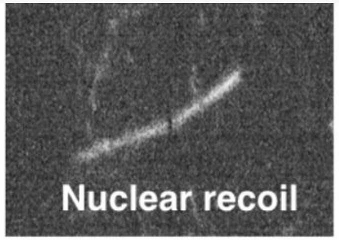
$He:CF_4$ @ 1 atm



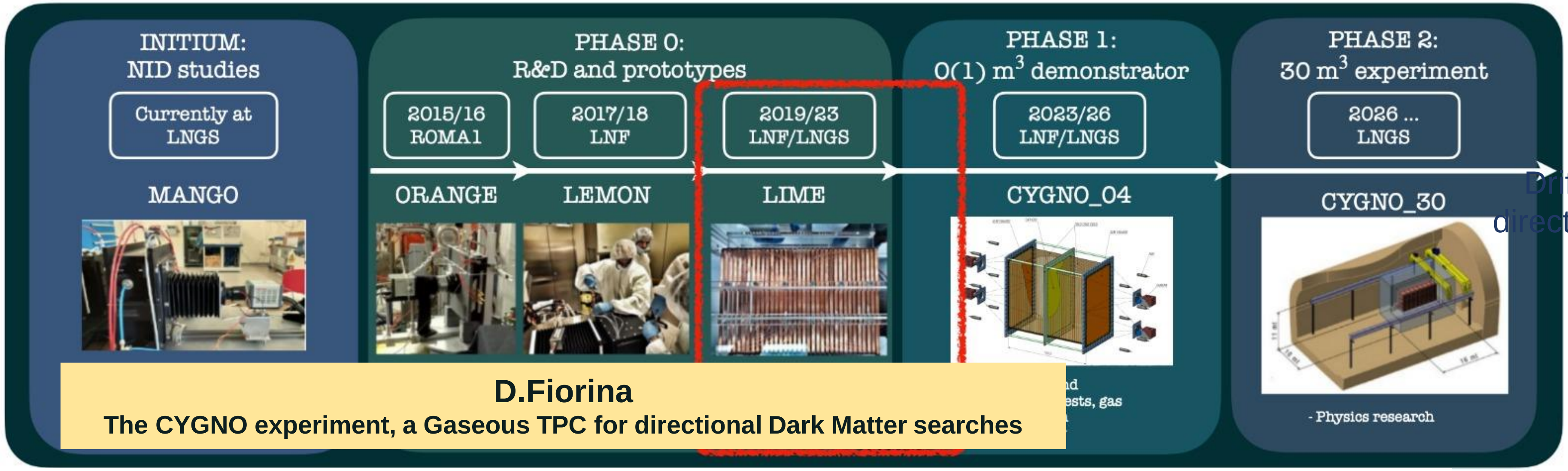








CYGNO Detectors Timeline

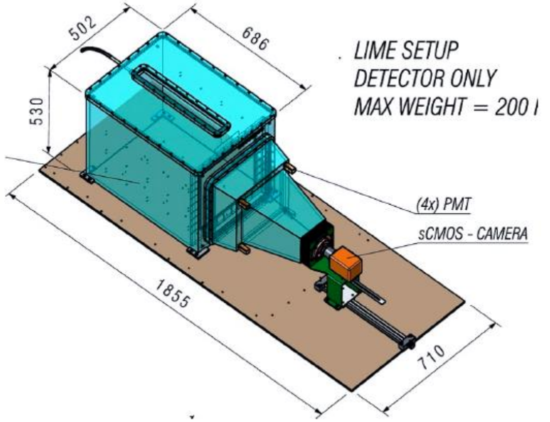


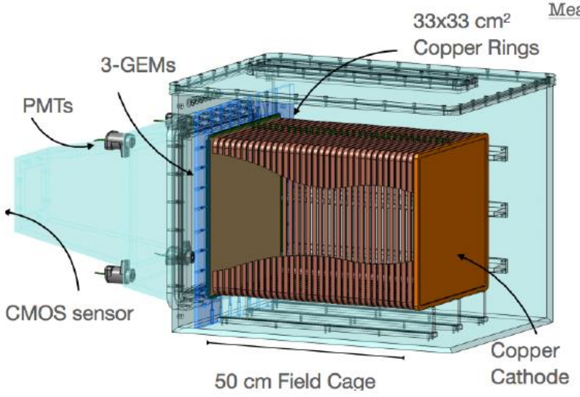
D.Fiorina
The CYGNO experiment, a Gaseous TPC for directional Dark Matter searches

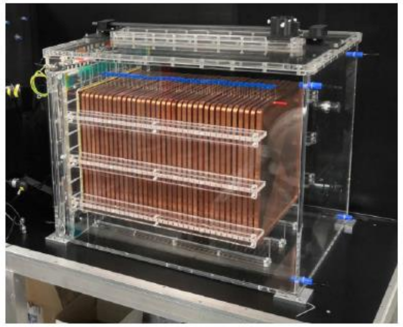
50 L active volume

Instruments 6 (2022) 1, 6
JINST 15 (2020) 12, T12003
JINST 15 (2020) P08018
Measur.Sci.Tech. 32 (2021) 2, 025902

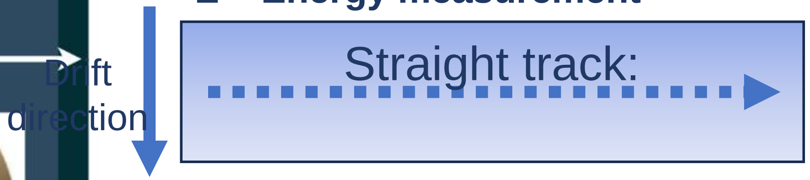
JINST 15 (2020) P10001
2019 JINST 14 P07011
NIM A 999 (2021) 165209

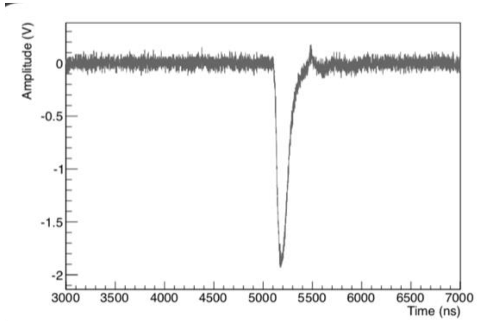


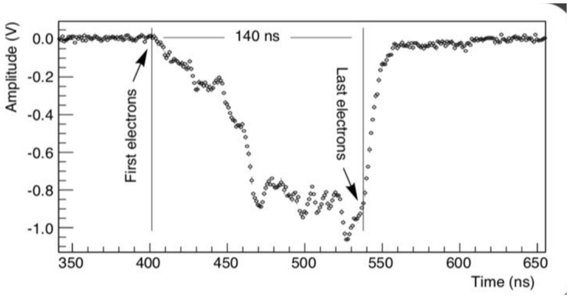




PMT
Integrated
Z + Energy measurement

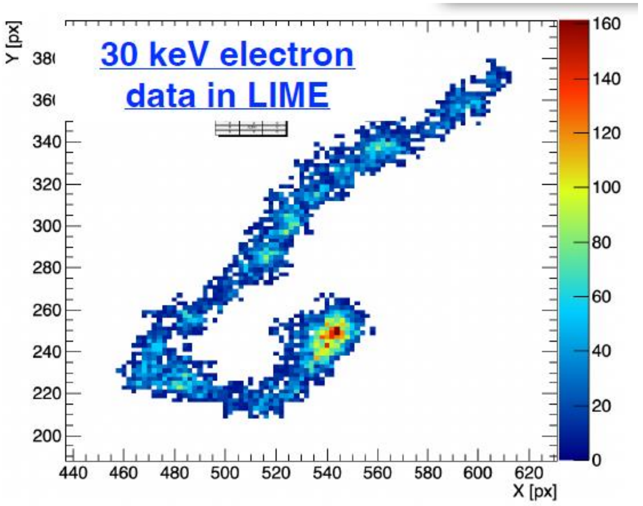






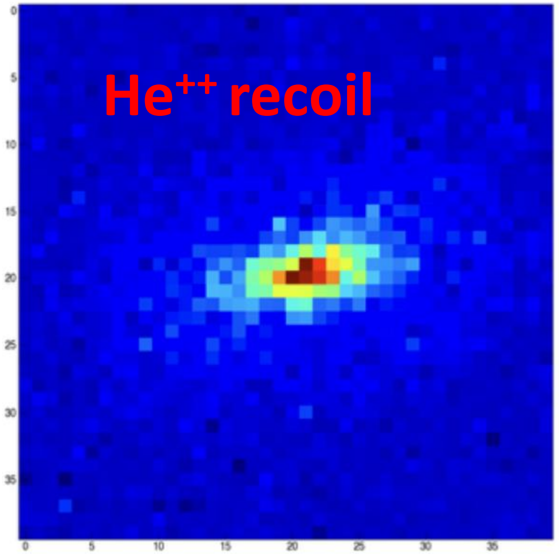
pixels 2304 x 2304 pixels - Imaging 36 x 36 cm2 area Effective - pixel granularity 155 x 155 um2

From Underground to Space



To Electron Recoils

X-rays on atoms



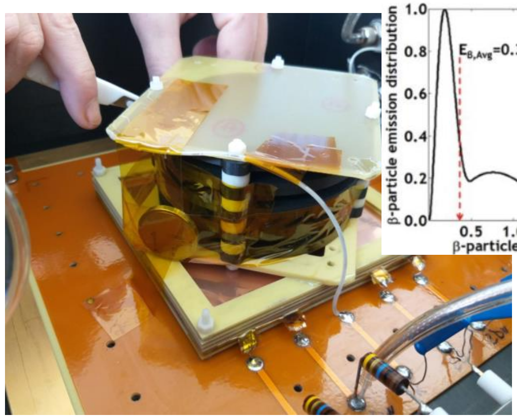
From Nuclear Recoils

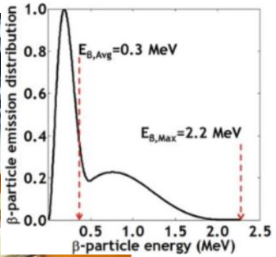
Dark Matter on nuclei

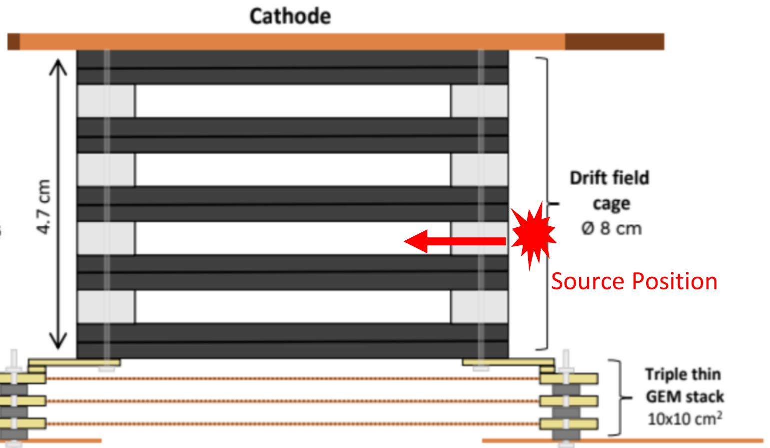
From Underground to Space

Introduction

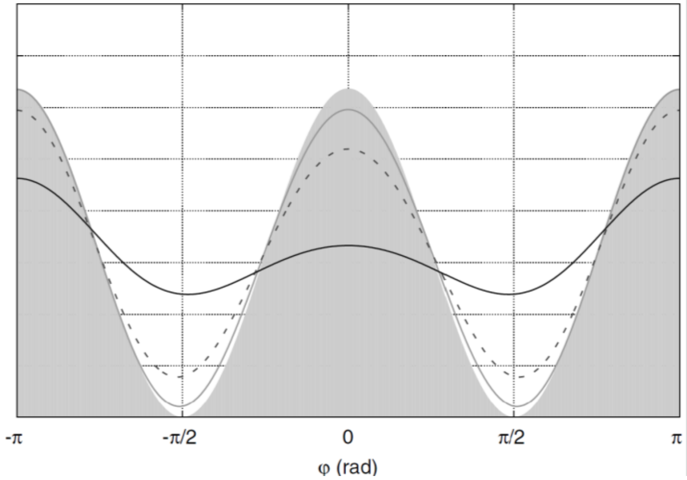
- **Measure the Angular Resolution of our detector to electron**
  - Collimated 90Sr shooting perpendicularly to the GEM surface (and readout plane)
  - **2D tracking** (possibility to have 3D in future) and **energy measurement**







- **Measure the performance of a triple-GEM TPC optically readout for polarimetry in the range [10,60] keV**
  - Infer the expected modulation factor μ → detector response to a fully polarized source
  - Deduce the expected figure-of-merit μ√ε → modulation factor weighted for the efficiency. Related to Minimum Detectable Polarization

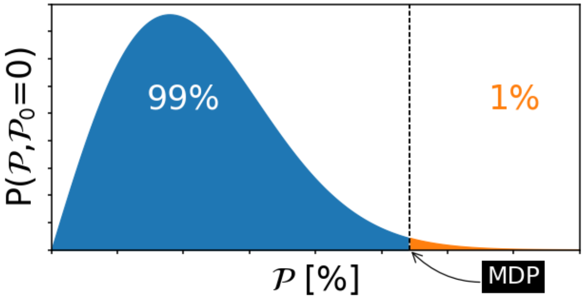


The modulation factor is the ‘efficiency’ of detecting fully polarized photons

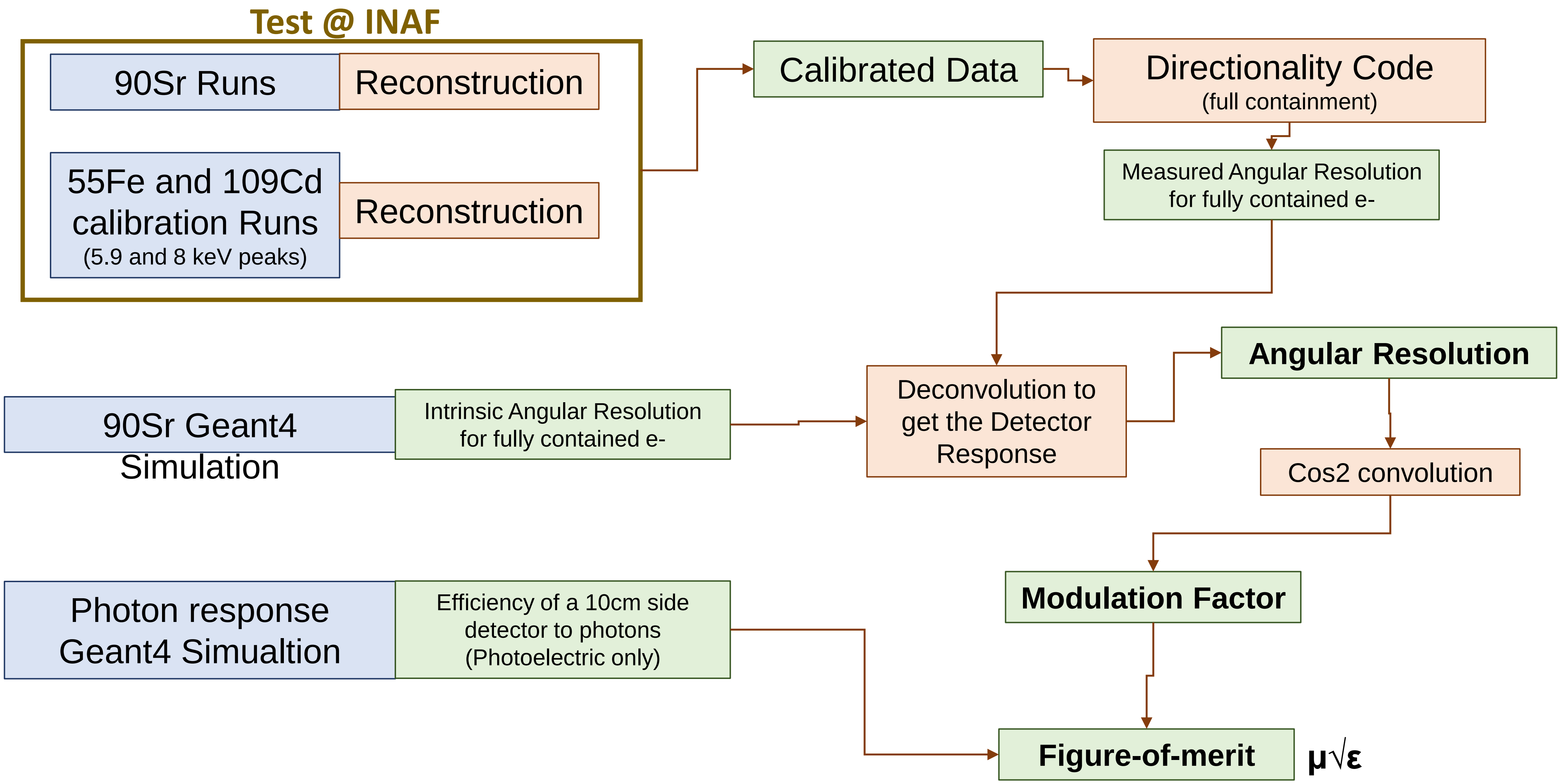
$$\text{no background is: } MDP = \frac{4.29}{\mu\sqrt{N}}$$

N=Flux×efficiency

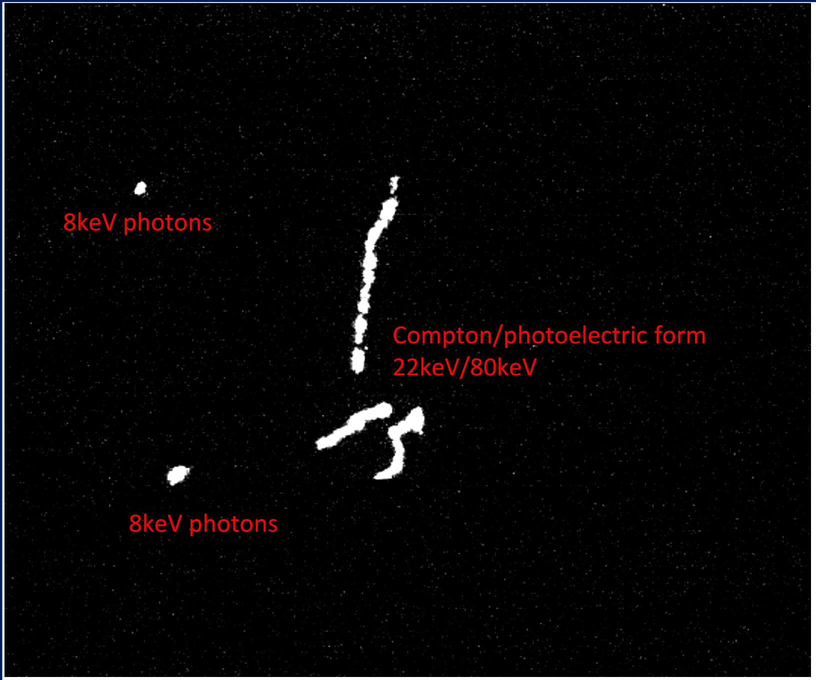
The MDP is the maximum polarization that we expect to measure with a probability of 99% when the true polarization is zero

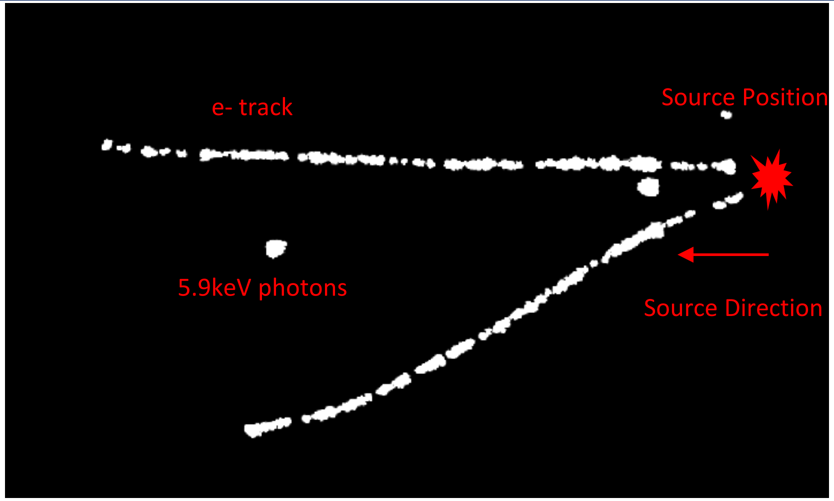


Conceptual Map



Reconstruction and Direction





Tracks reconstructed with the actual reconstruction code used by the CYGNO collaboration

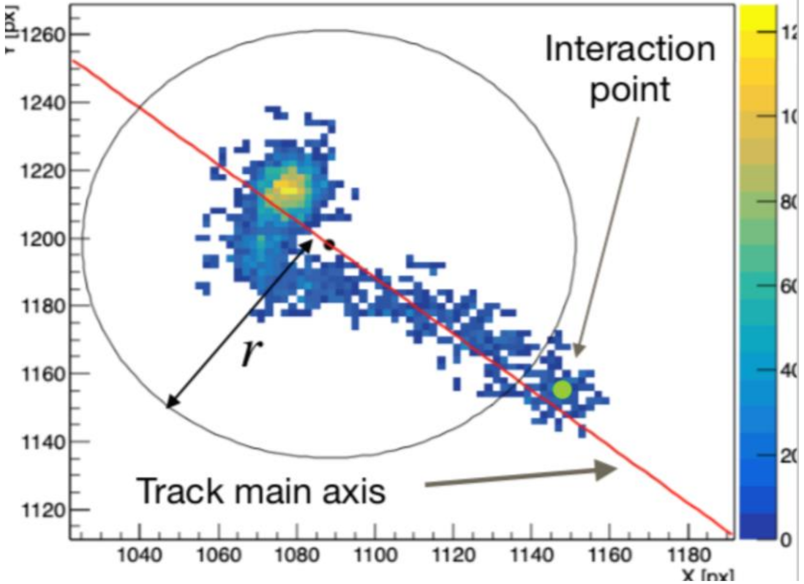
- Low energy electrons <10keV dominated by diffusion in the GEM, limited directionality

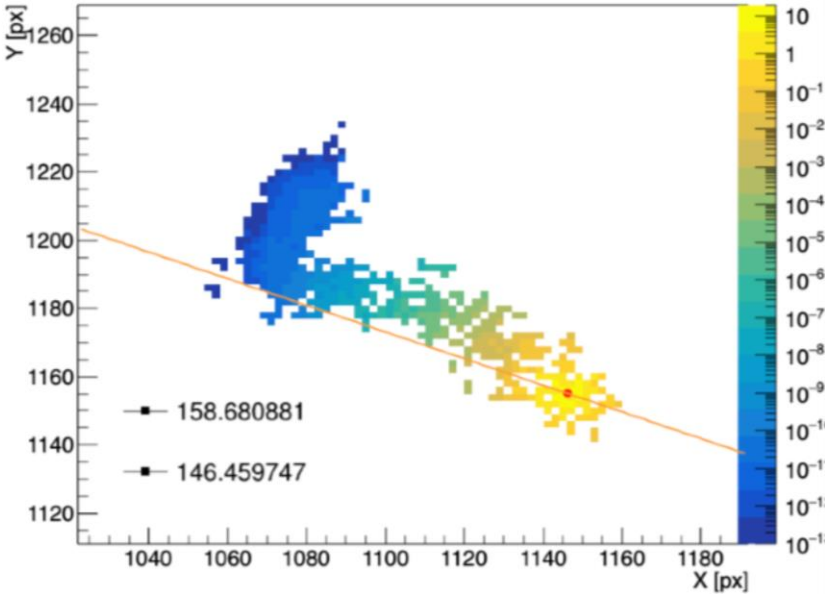
-Journal of Instrumentation 15, T12003
-Measurement Science and Technology 34, 125024

The directionality algorithm is inspired from IXPE:

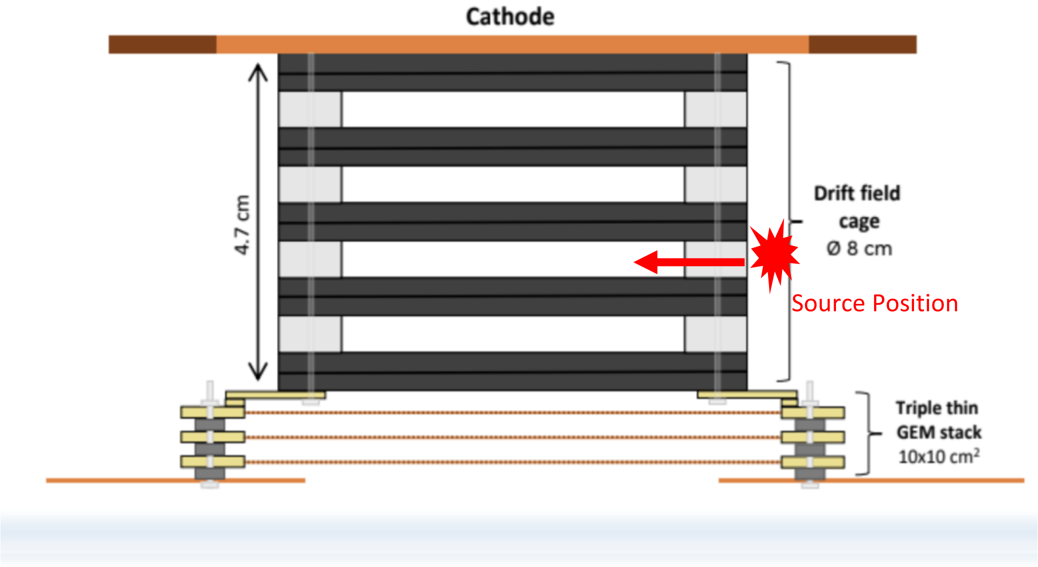
- Optimized for our energy range
- **New strategies under evaluation**

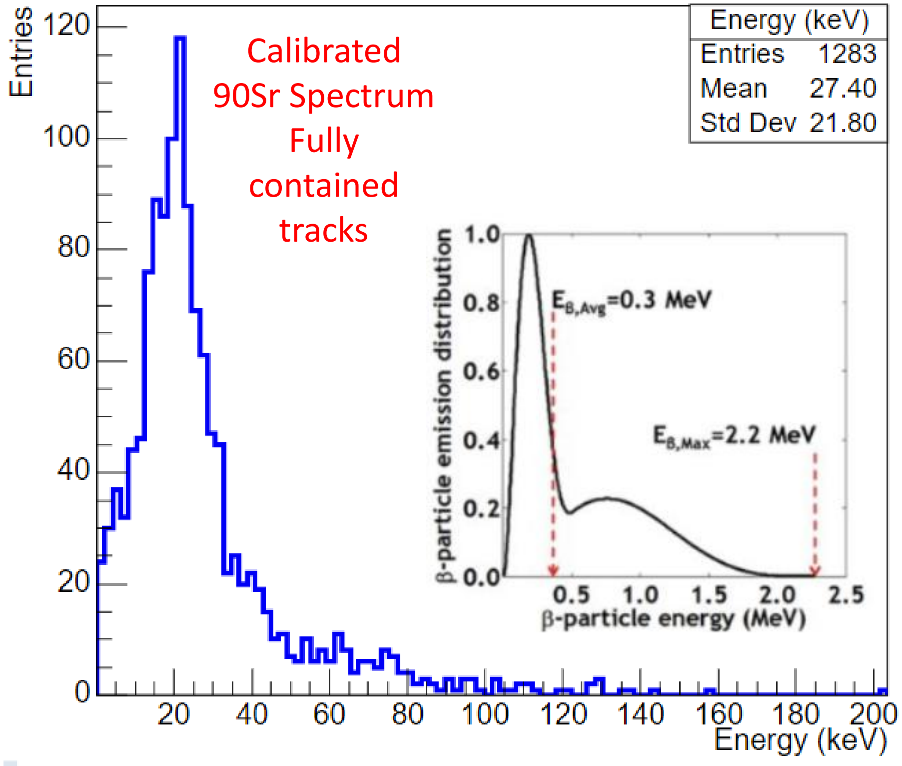
Astroparticle Physics 133, 102628 (2021)



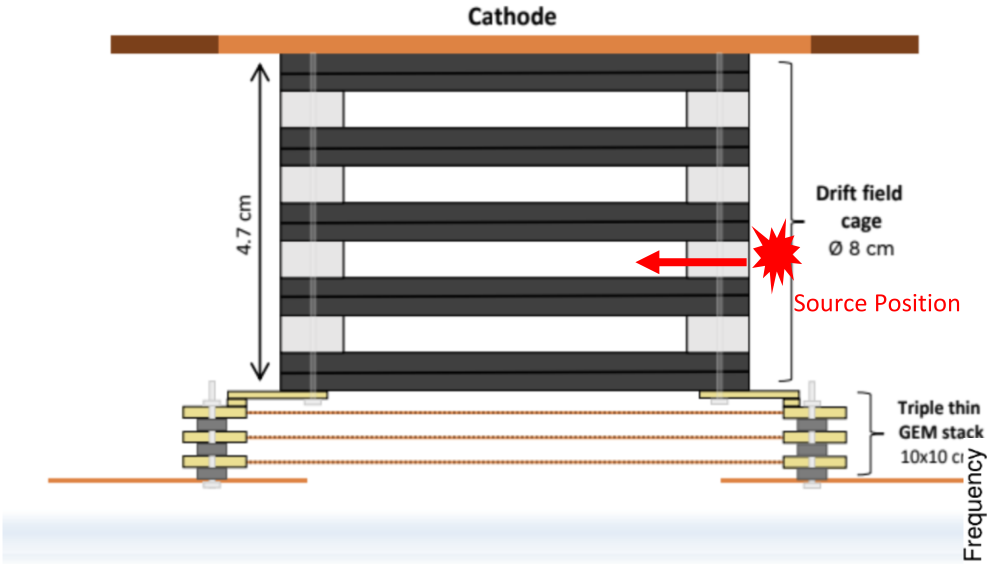


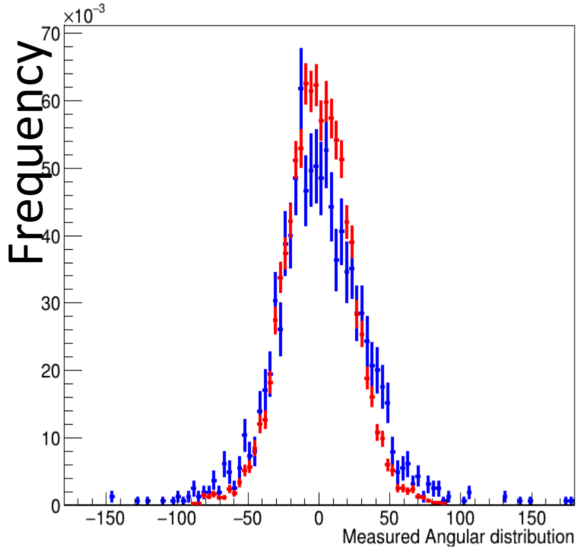
Measurement Results





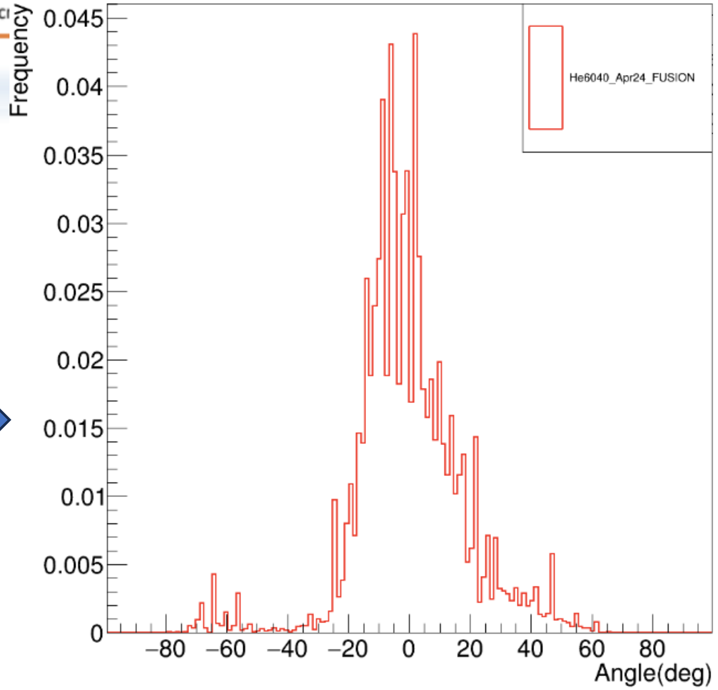
Measurement Results

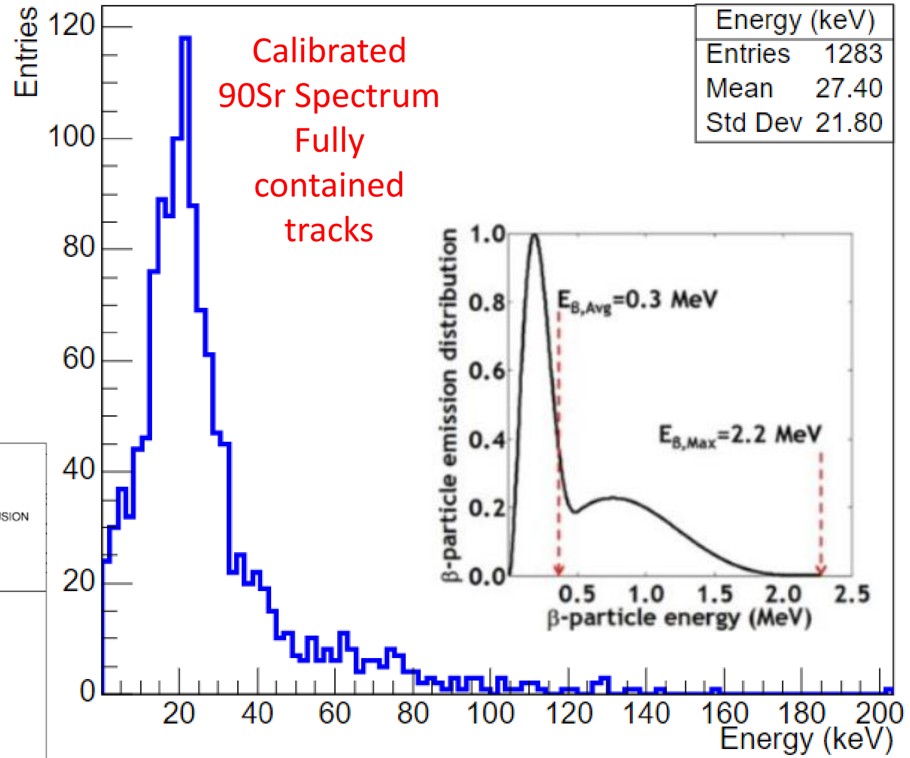




Measured RMS **32.3°**
Simulated RMS **23.6°**

Deconvolution

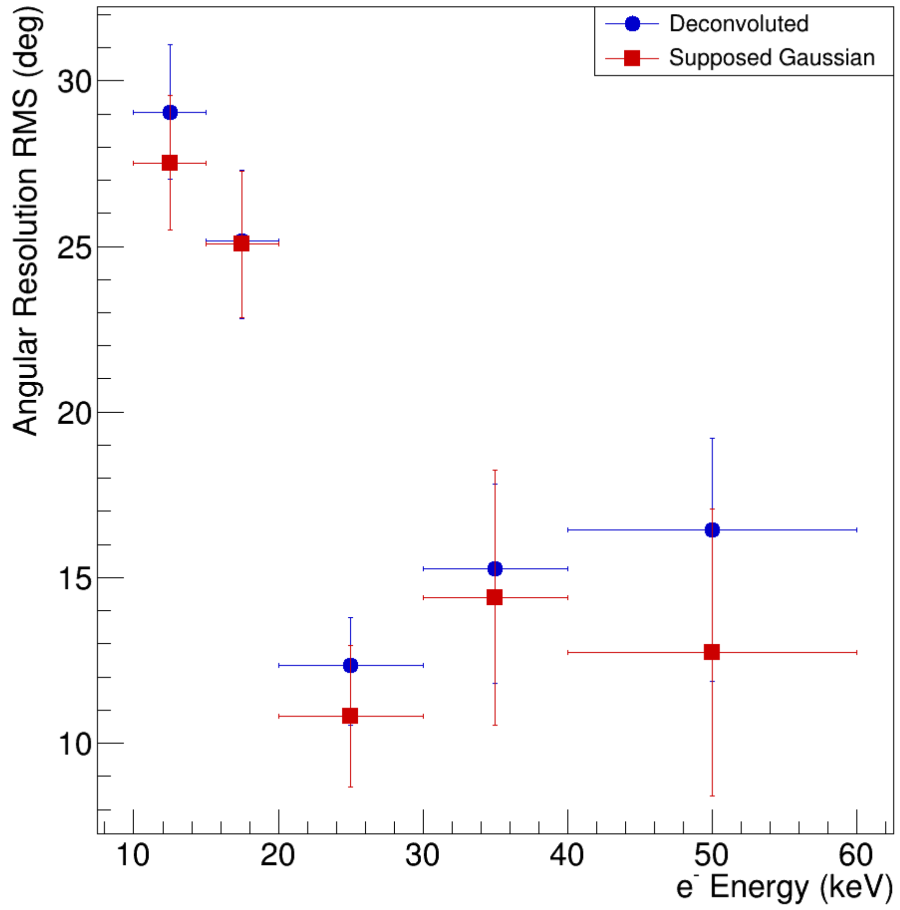




RMS of deconvolved RMS is the angular resolution of the detector

Angular Resolution & Modulation Curve

Using the deconvolved RMS as sigma of a Gaussian, then convolve with a



Distributions are nearly-gaussian

Angular Resolution & Modulation Curve

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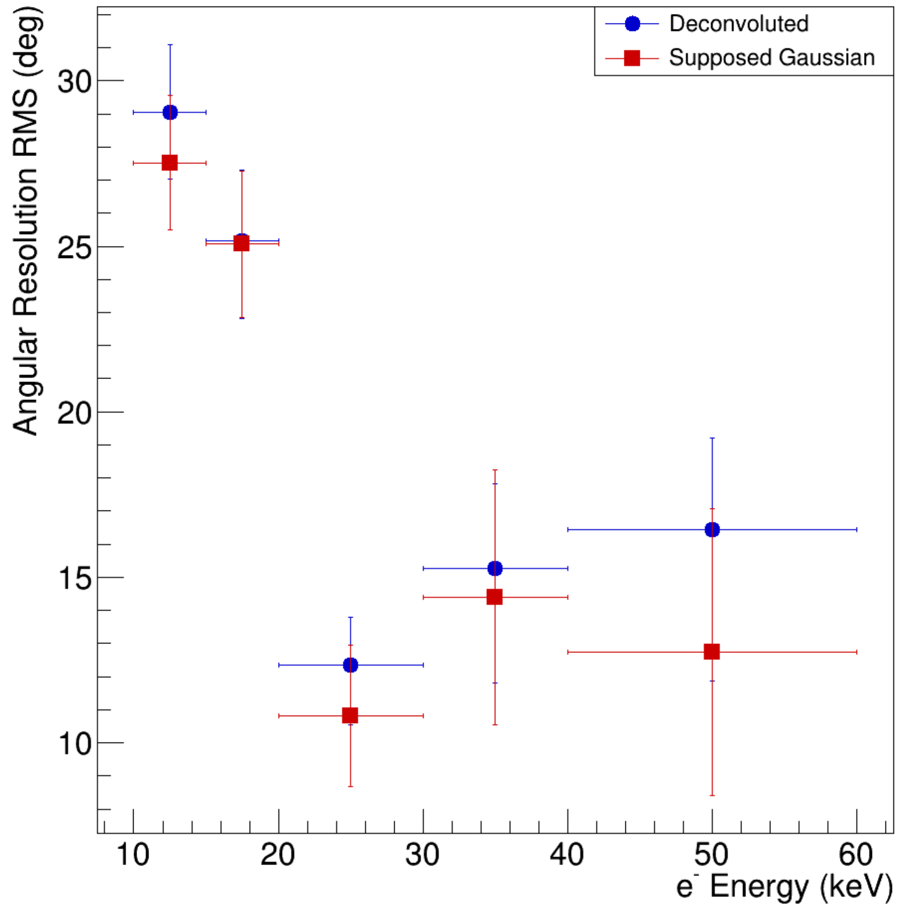
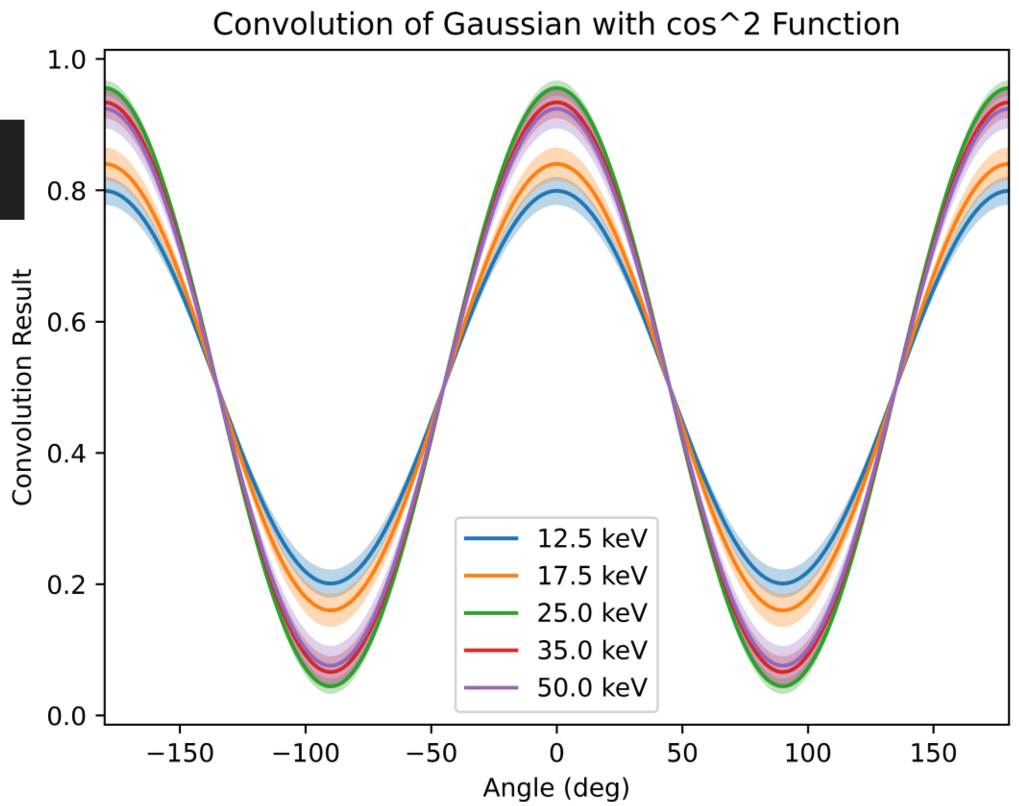
Using the deconvolved RMS as sigma of a Gaussian, then convolve with a



$$(G * \cos^2)(x) = \frac{1}{2}\left(1 + e^{-2\sigma^2}\cos(2x)\right)$$

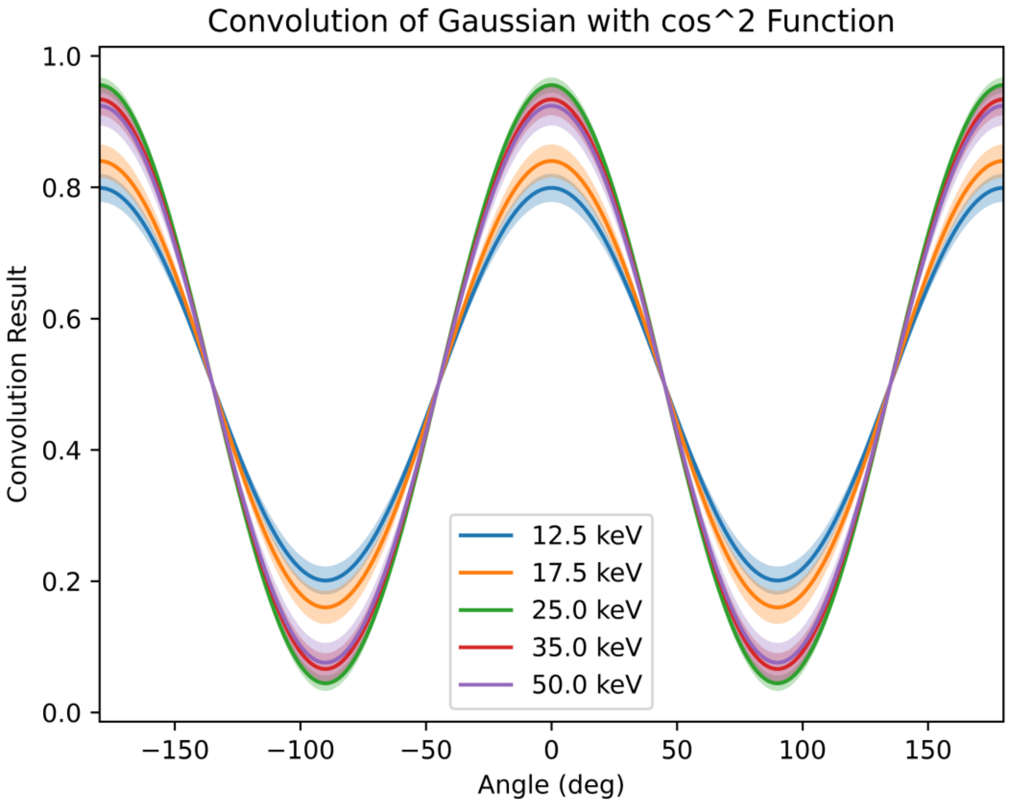
Expected **modulation curves** for a **fully polarized** photon beam <u>if the measured **performance is conserved**</u>!



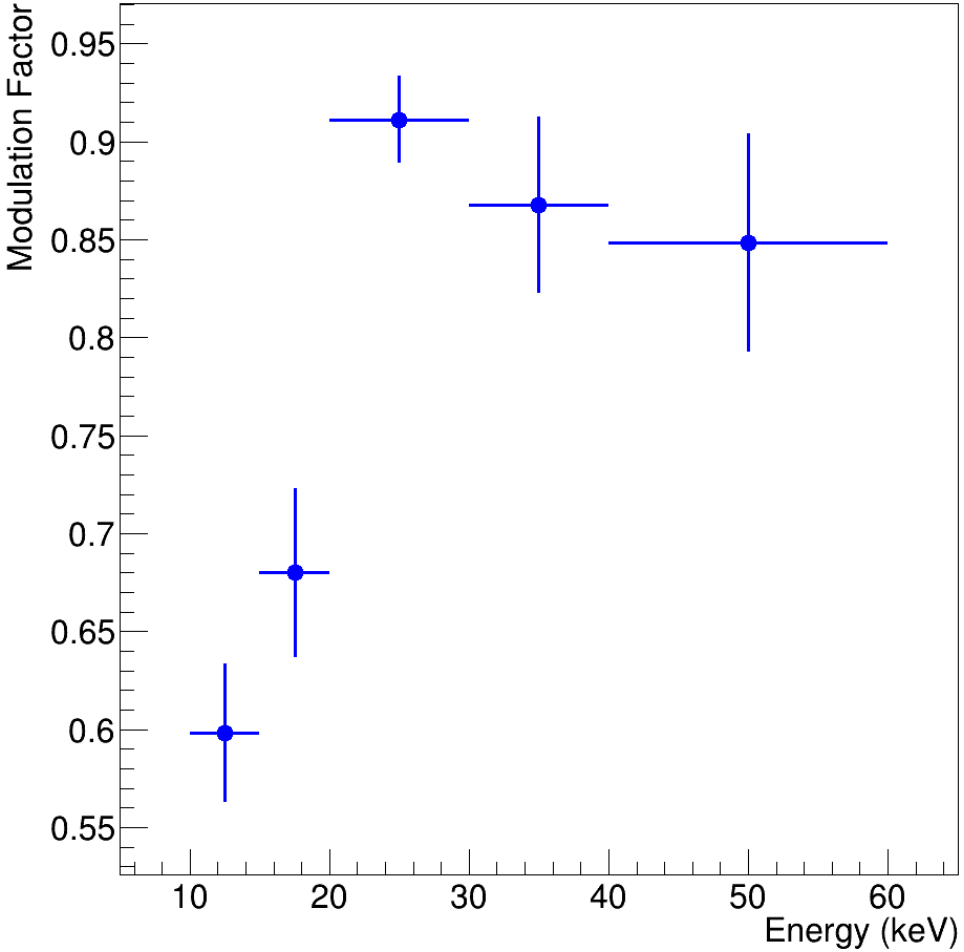
Distributions are nearly-gaussian

Modulation Factor

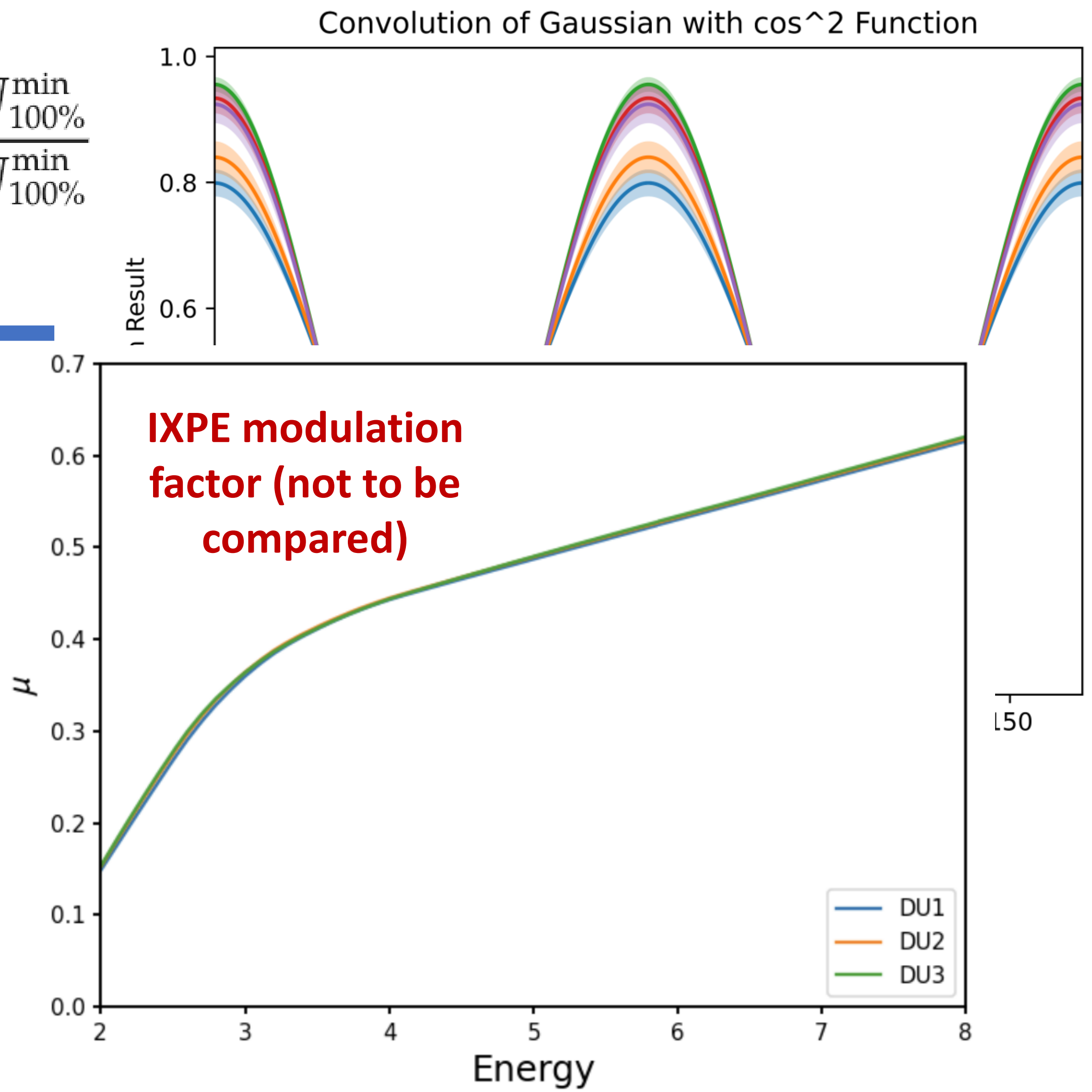
$$\mu = \frac{N^{\max}_{100\%} - N^{\min}_{100\%}}{N^{\max}_{100\%} + N^{\min}_{100\%}}$$



Modulation Factor



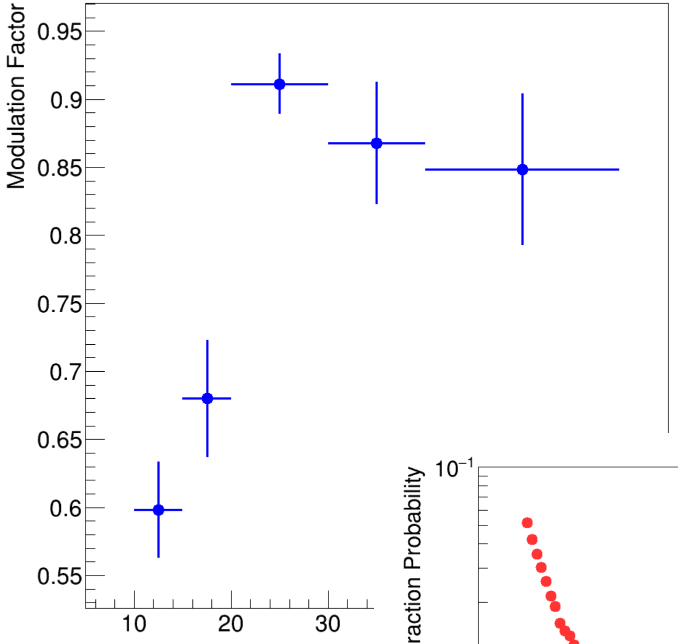
$$\mu = \frac{N^{max}_{100\%} - N^{min}_{100\%}}{N^{max}_{100\%} + N^{min}_{100\%}}$$



A good modulation factor is expected!

In particular for energies above 20 keV >0.8

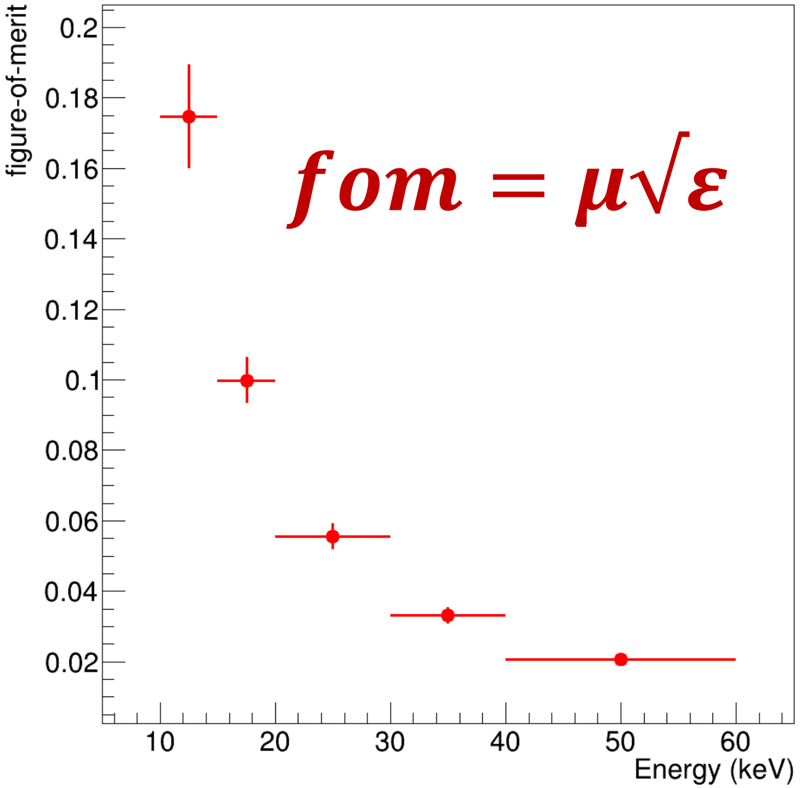
Figure-of-merit



no background is: $MDP = \frac{4.29}{\mu\sqrt{N}}$

N=Flux×efficiency

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



The probability for a photon to interact photoelectrically and be fully contained in the detector

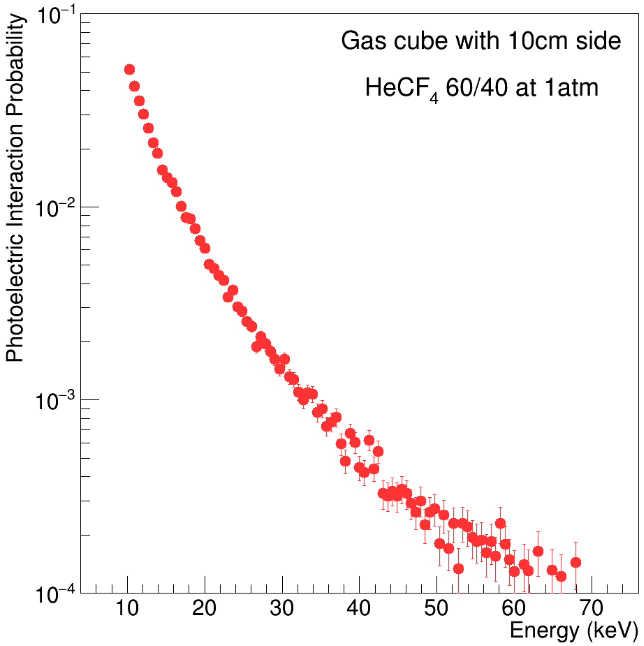
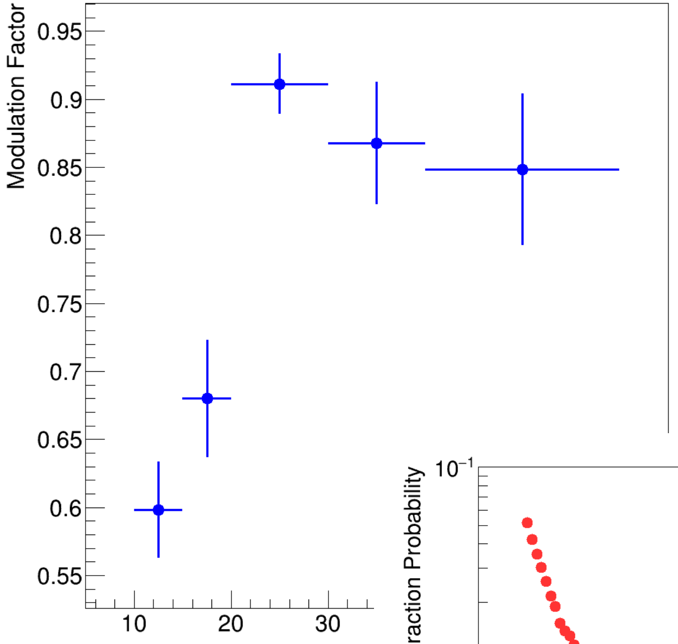


Figure-of-merit



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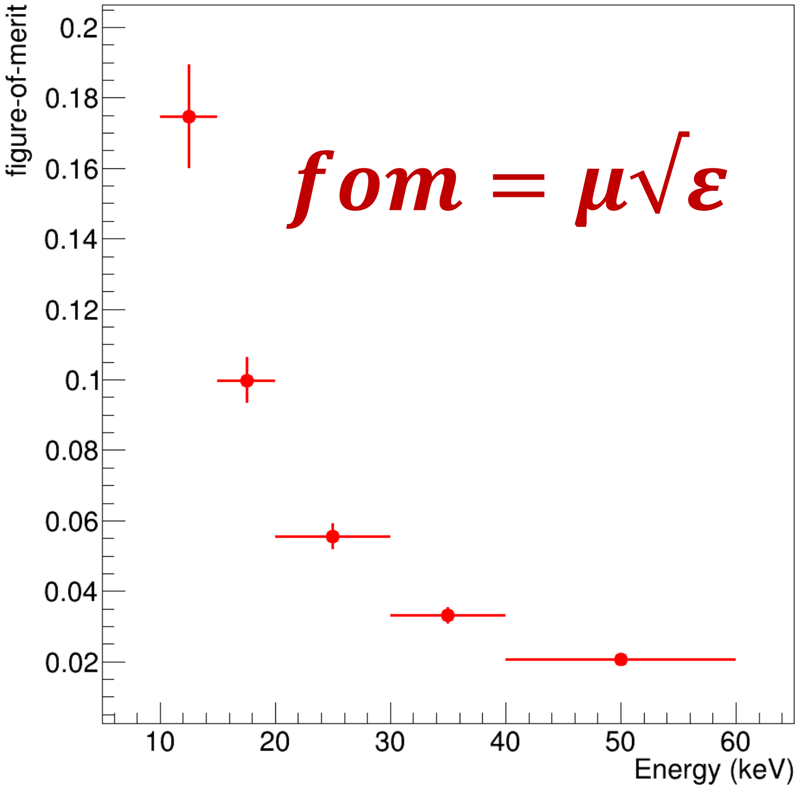
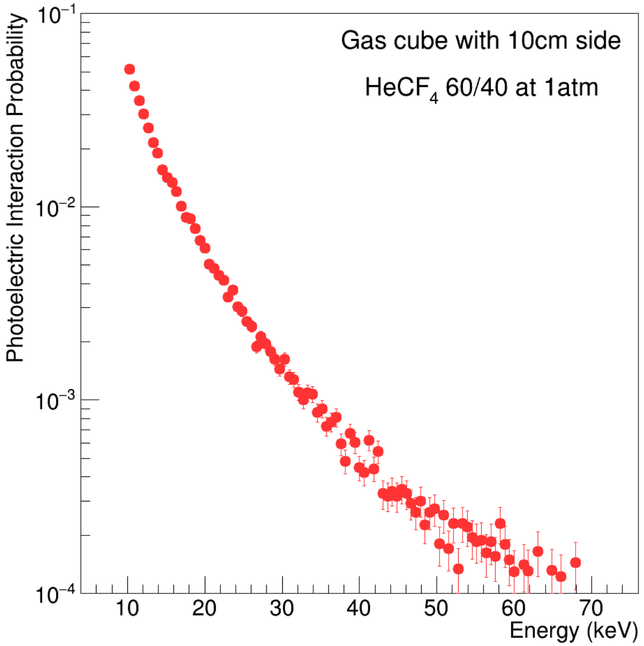


$fom = \mu\sqrt{\varepsilon}$



The probability for a photon to interact **photoelectrically** and be **fully contained** in the detector

He/CF_4 is a very good mixture for Dark Matter searches, but it may not be the perfect one for X-ray imaging!

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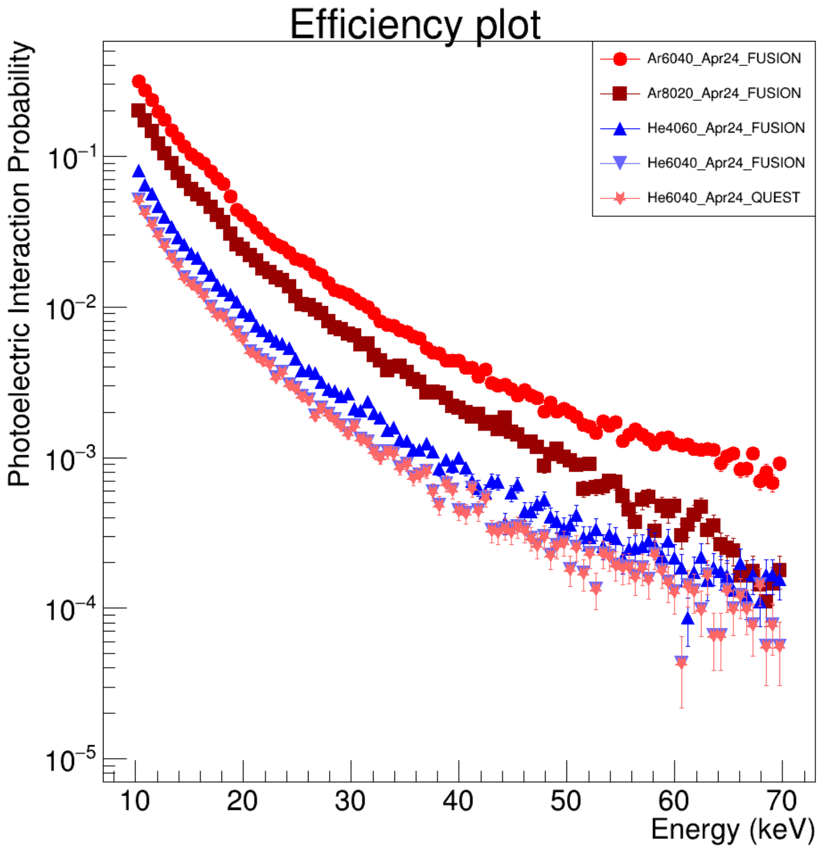
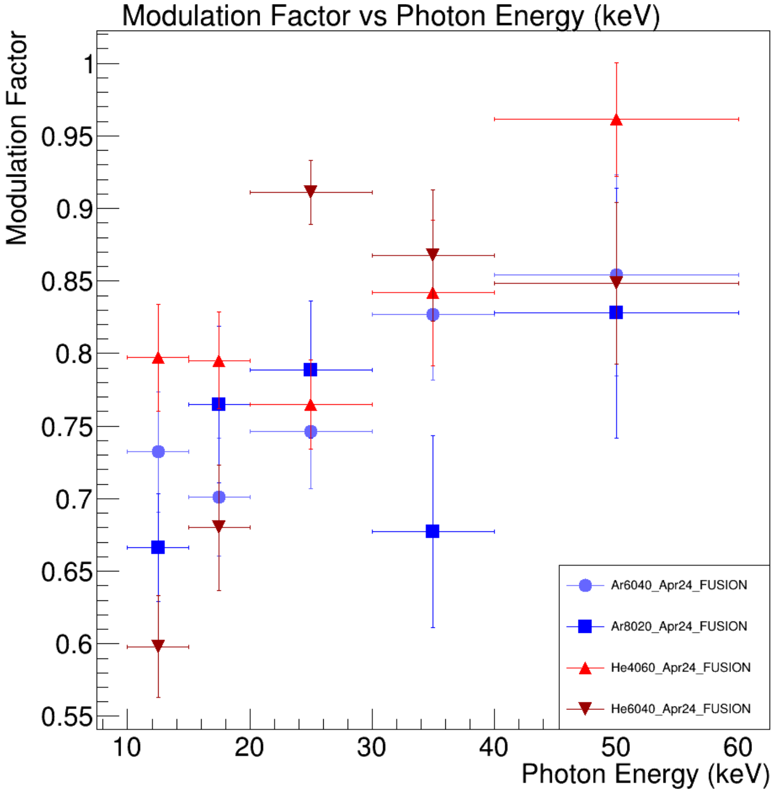
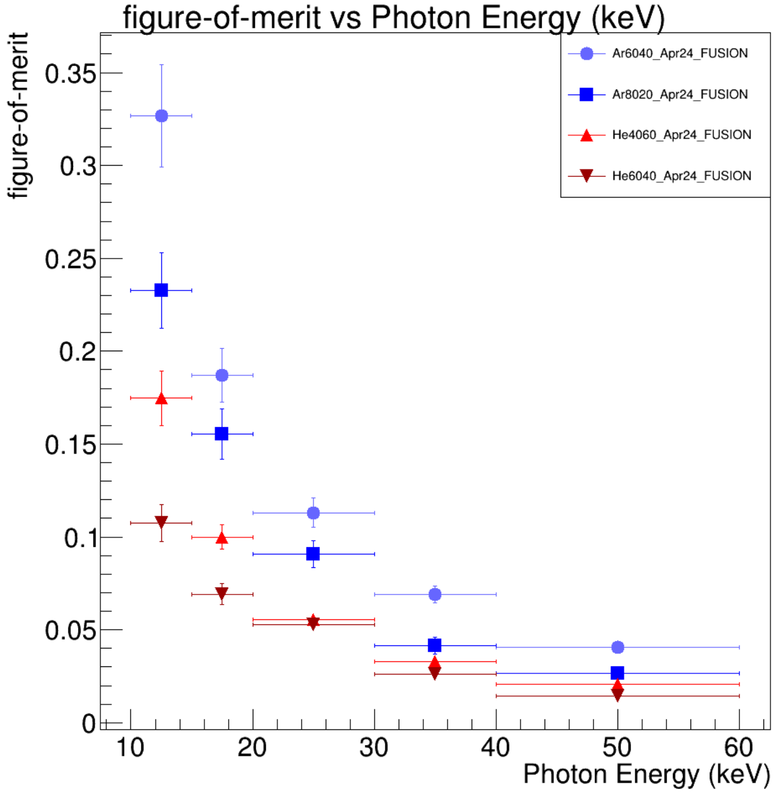
Other Gases

INFN LNGS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Gran Sasso



More CF4 helps because of larger density, but photoelectric interaction probability scales linearly with density but scales with Z^5!!!





While Angular resolution is almost th same (depending on the sCMOS and software), the figure-of-merit can be increased by more than a factor 3-4 in Ar-based mixtures!

He/CF_4 60/40 - He/CF_4 40/60 - Ar/CF_4 60/40 – Ar/CF4 80/20

Other Gases tested!

Conclusions

We proudly operate a triple-GEM with optical Readout for Dark Matter Search, and we want to apply our detector concept to X-ray polarimetry.

Polarimetry with our concept appears very promising in the range [10,60] keV

From preliminary measurement, we may infer for X-ray energy above 20 keV

- **μ > 0.8 (IXPE <0.8 *not to compare*)**
- **ε : [1E-4, 5E-2] (IXPE [2E-1,1E-2] *not to compare*)**

Future tests:

- **Hamamatsu ORCA Quest qCMOS**
  - **With 3D implementation**
- **Different gas mixtures, pressures and ratios**

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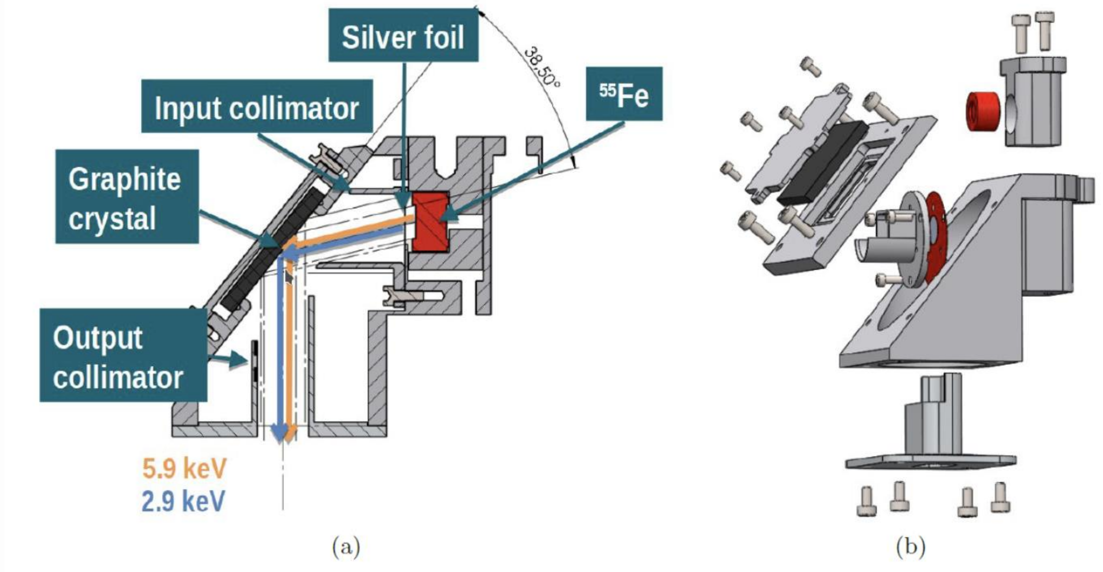


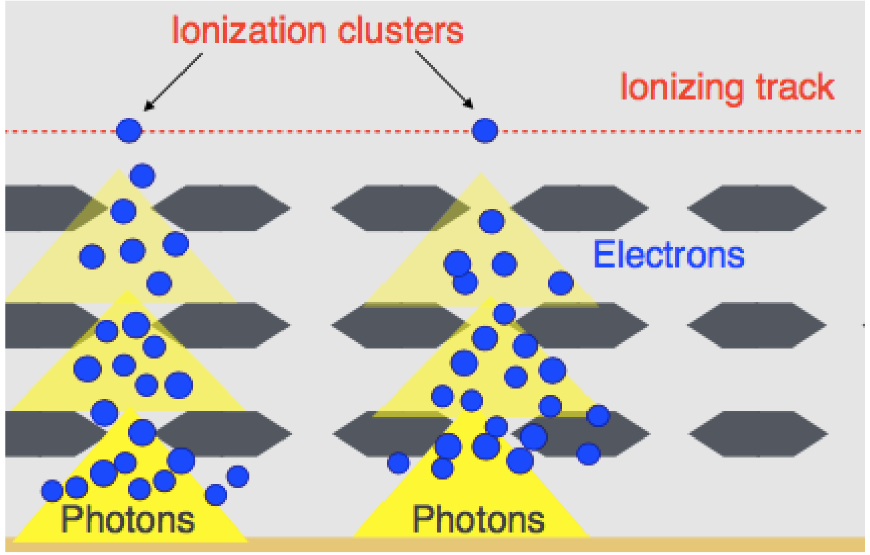
Future tests:

- **Hamamatsu ORCA Quest qCMOS**
  - **With 3D implementation**
- **Different gas mixtures, pressures and ratios**
- **Polarized X-ray Beam test @ INAF TorVergat**
  - **Validate Simulation**
  - **Provide full simulation on an astronomical physics case**

BACKUP

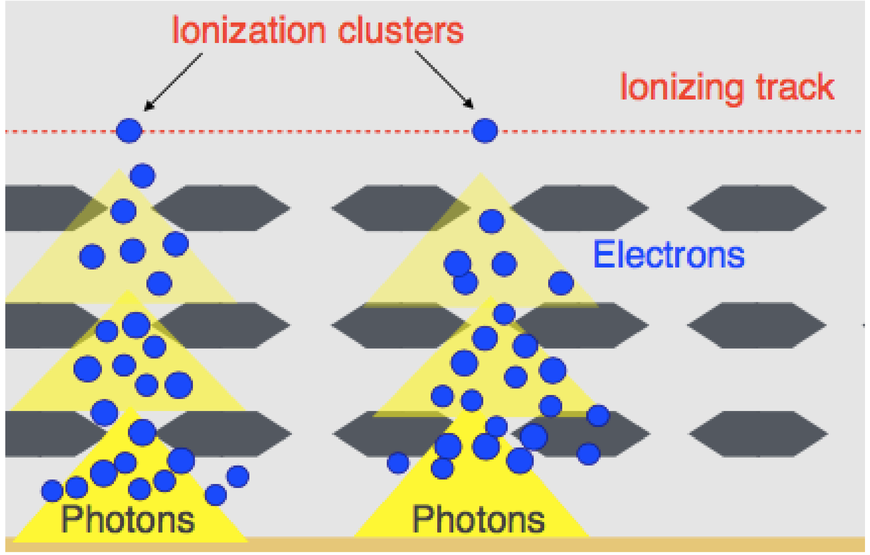
High-precision 3D TPC with optical readout via PMT + sCMOS

JINST 13 (2018) no.05, P05001



High-precision 3D TPC with optical readout via PMT + sCMOS

JINST 13 (2018) no.05, P05001

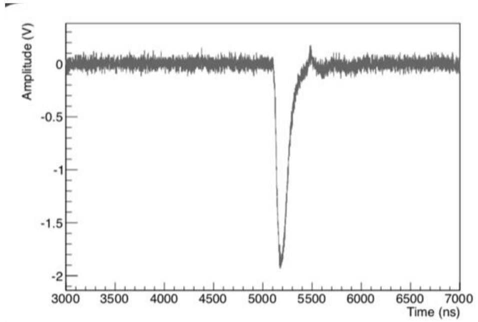


PMT

Integrated
Z + Energy measurement

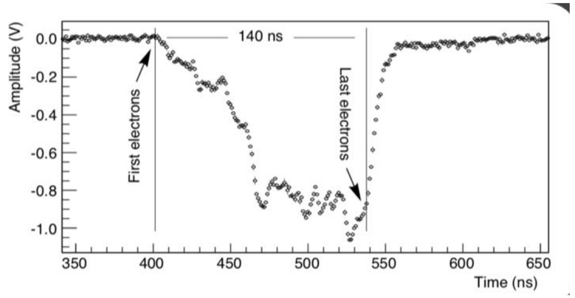
Drift direction

Straight track:



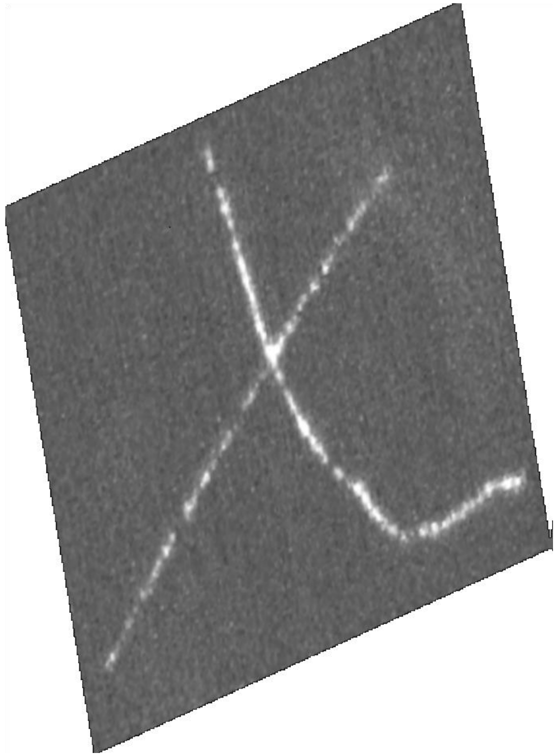
Drift direction

Tilted track:

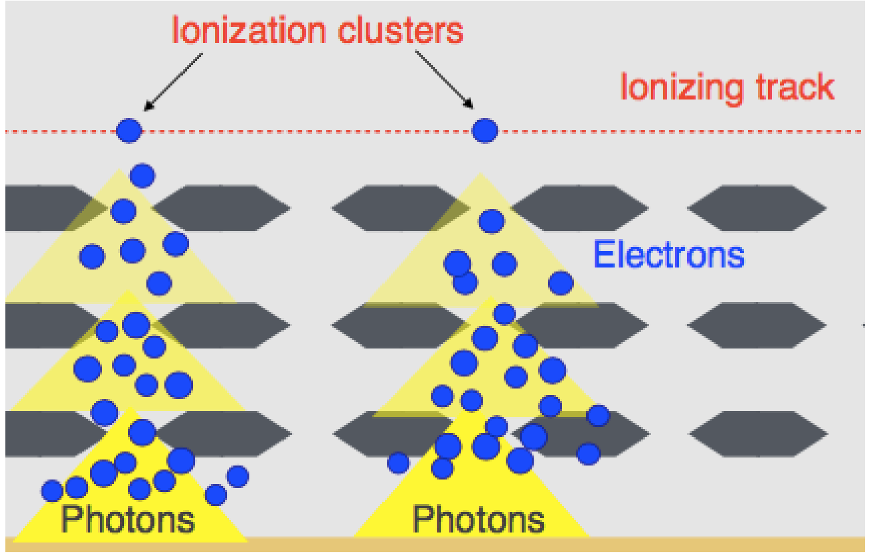


High-precision 3D TPC with optical readout via PMT + sCMOS

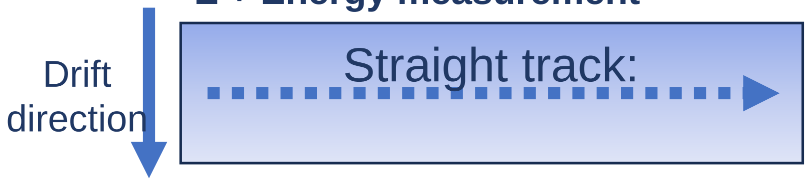
sCMOS
High-granularity X+Y+Energy measurement

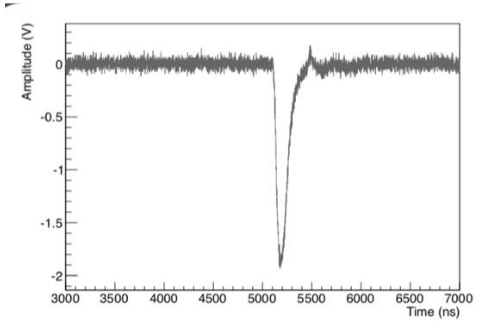


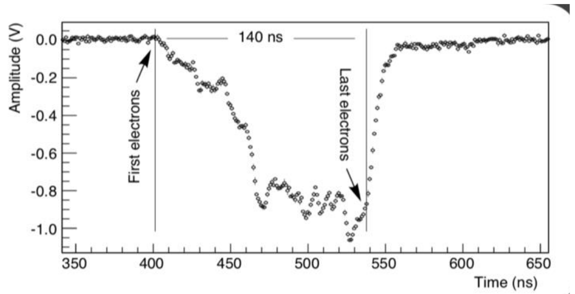
JINST 13 (2018) no.05, P05001



PMT
Integrated Z + Energy measurement



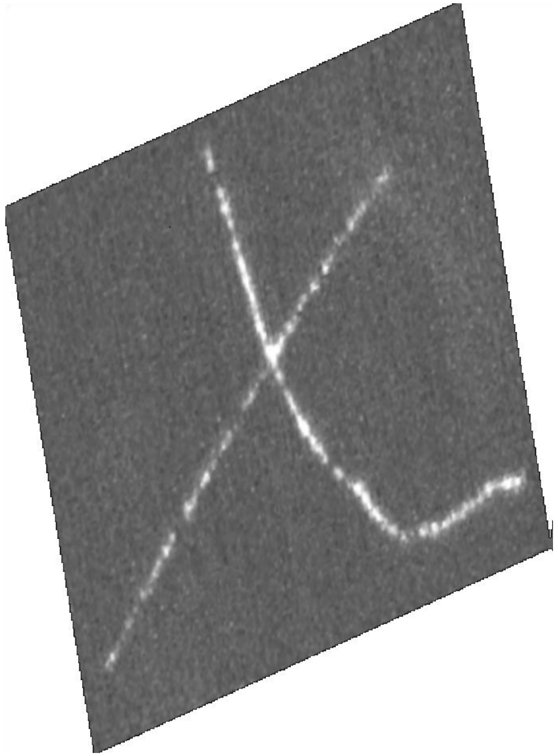




High-precision 3D TPC with optical readout via PMT + sCMOS

sCMOS

High-granularity
X+Y+Energy measurement



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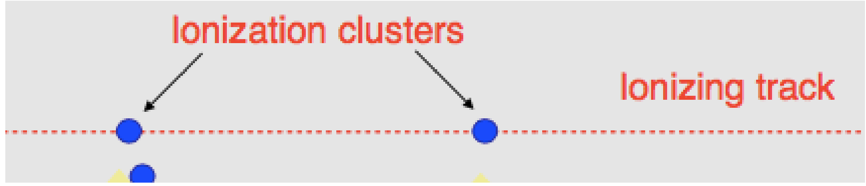
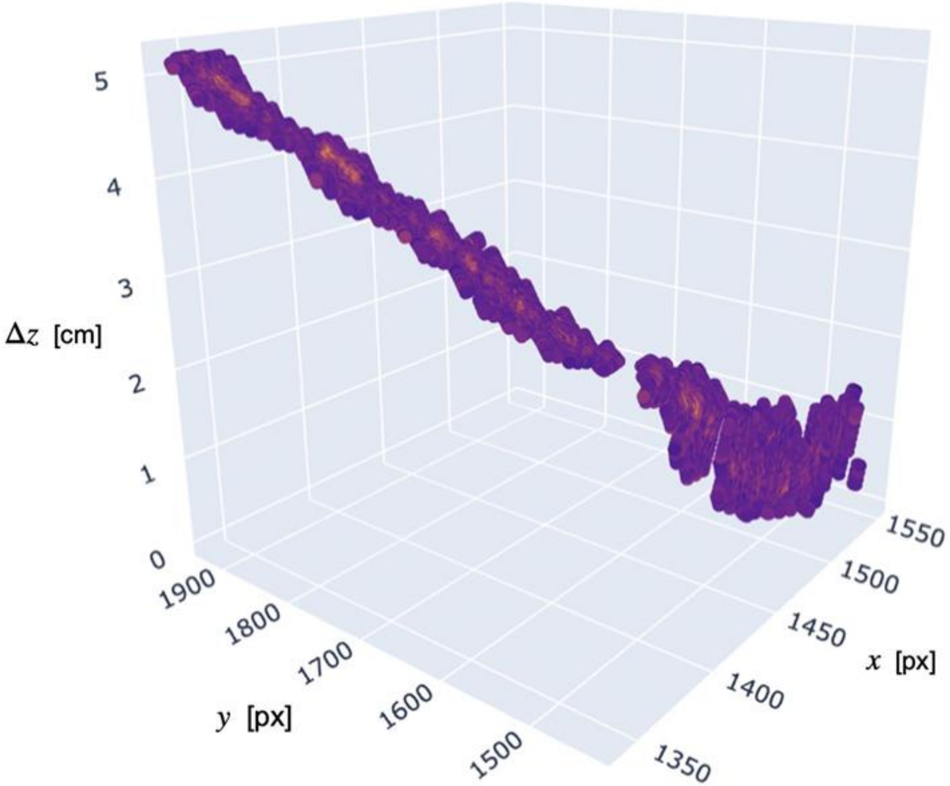
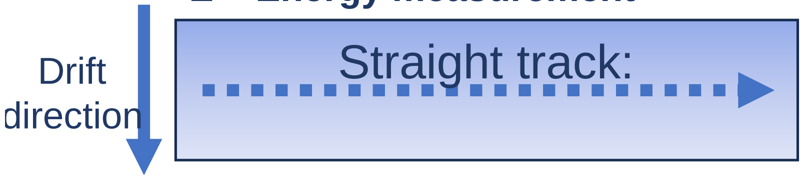
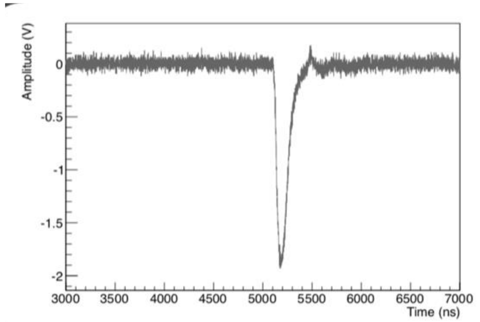


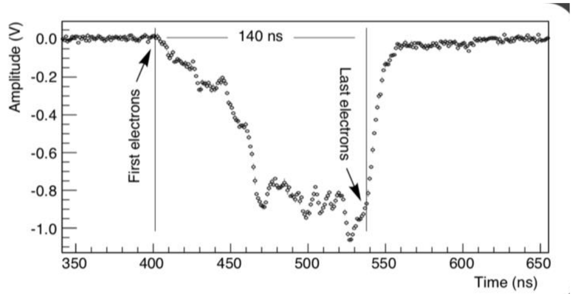


PMT

Integrated
Z + Energy measurement



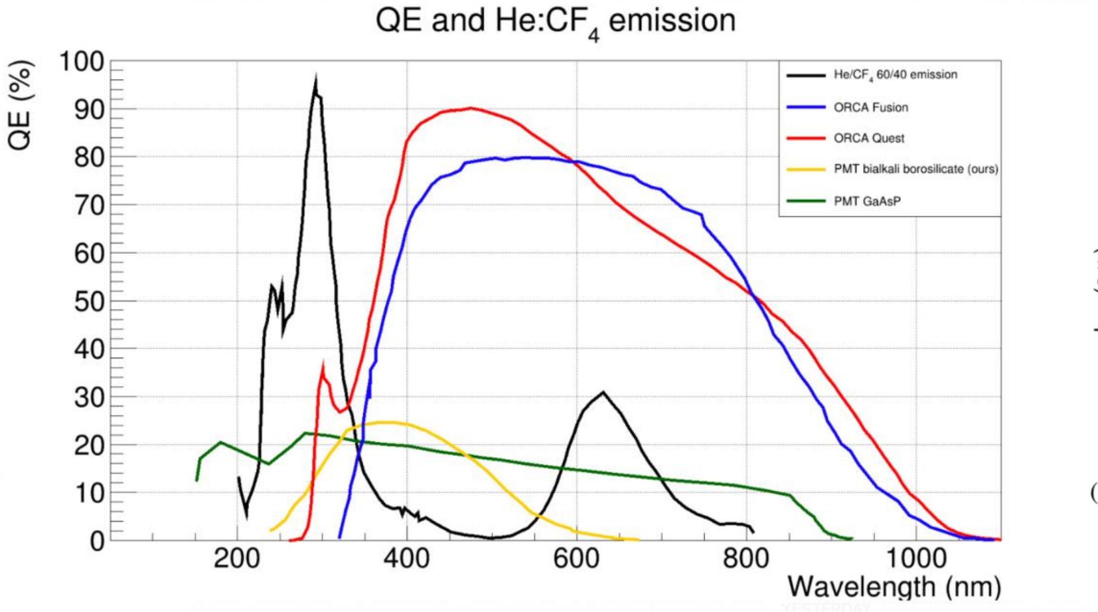


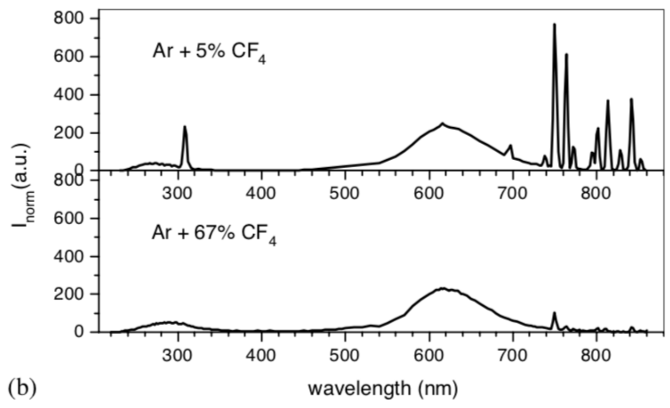


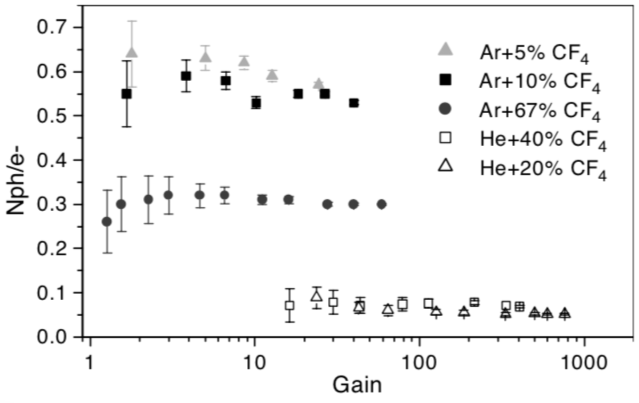
sCMOS characteristics & He/Ar:CF4 emission spectra

Hammamatsu	# of pixels	Pixel size [um]	Sensor area [cm²]	Dynamic range	Readout noise (enc)	Mix exposure	
Orca Flash	2048 x 2048	6.5 x 6.5	1.33 x 1.33	37000:1	1.4 (1.6) rms	33 (10) us	
Orca Fusion	2304 x 2304	6.5 x 6.5	1.498 x 1.498	21400:1	0.7 (1.4) rms	280 (17) us	**Used for the reasult shown**
Orca Quest	4096 x 2304	4.6 x 4.6	1.884 x 1.060	25900:1	0.27 (0.43) rms	200 (7.2) us	Tested
Orca Quest2	4096 x 2304	4.6 x 4.6	1.884 x 1.060	25900:1	0.27 (0.43) rms	200 (7.2) us	Under Procurement

improving performances

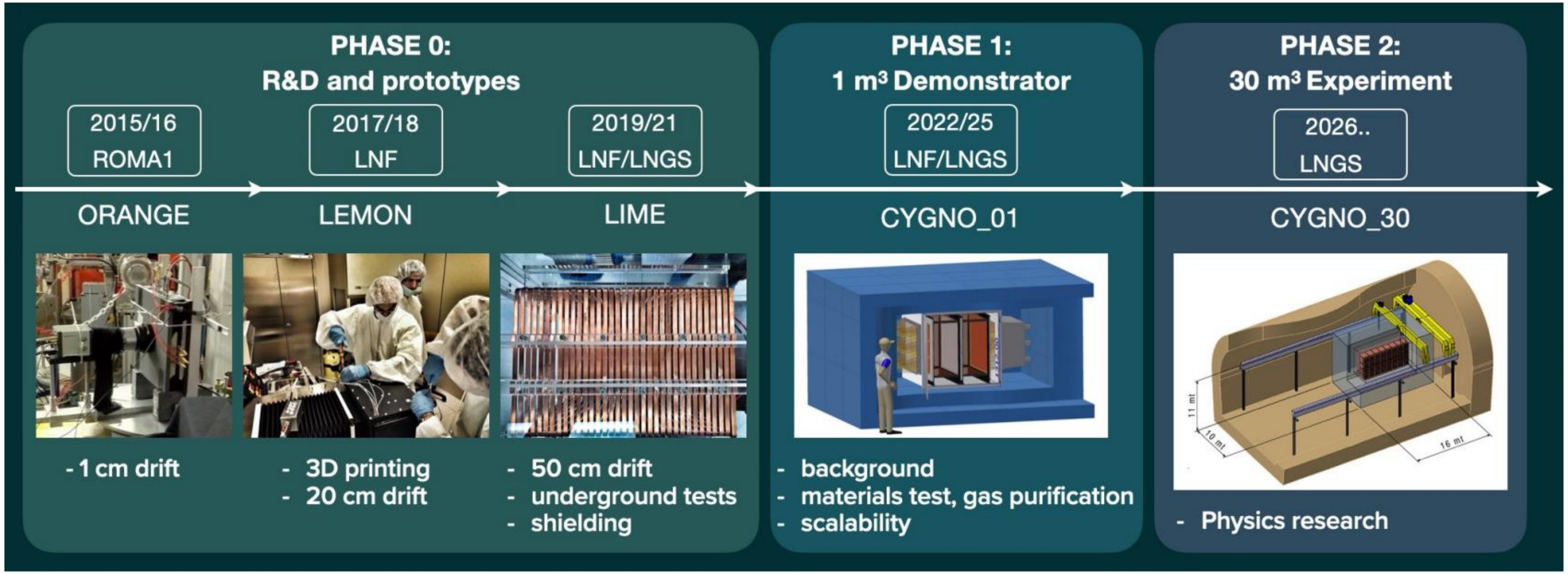






NIM A 504 (2003) 88-92

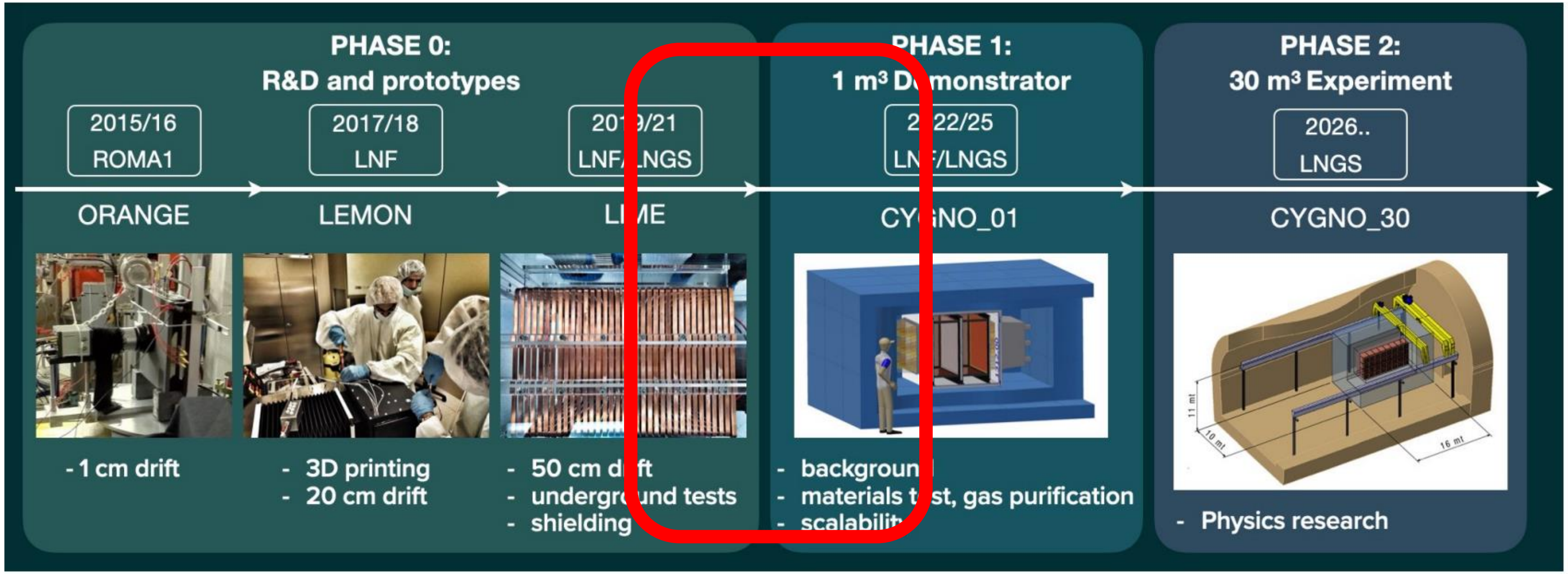
CYGNO ectors and timeline



low-energy (1–100 keV) nuclear recoils

10^5 beta/gamma rejection

CYGNO ectors and timeline



low-energy (1–100 keV) nuclear recoils
10^5 beta/gamme rejection

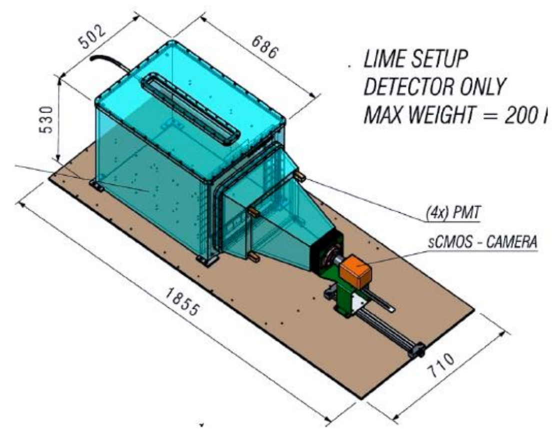
LIME
- The first large-size prototype
- Currently taking data

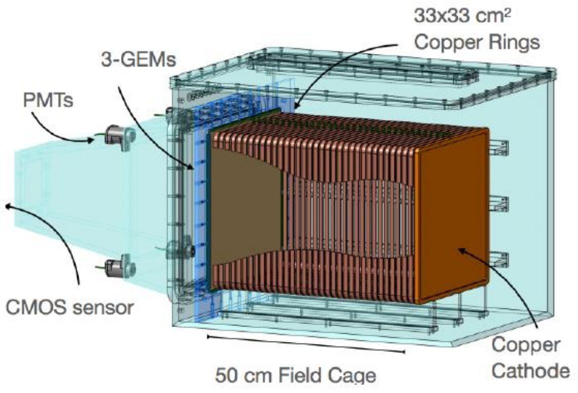
CYGNO04
- The first detector for physics runs
- Currently under design

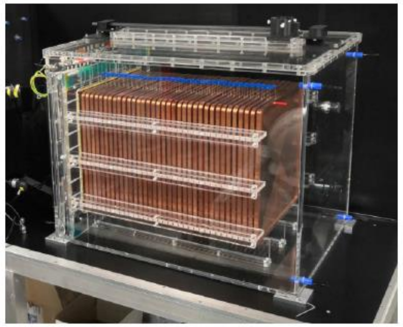
Long Imaging ModulE

INFN LABORATORI NAZIONALI DEL GRAN SASSO

50 L active volume

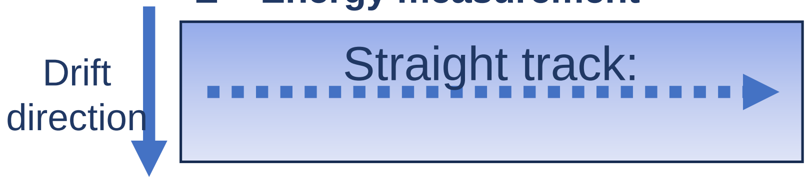


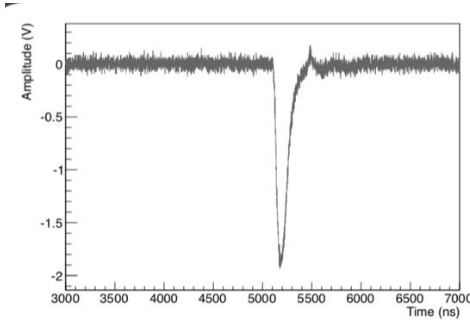


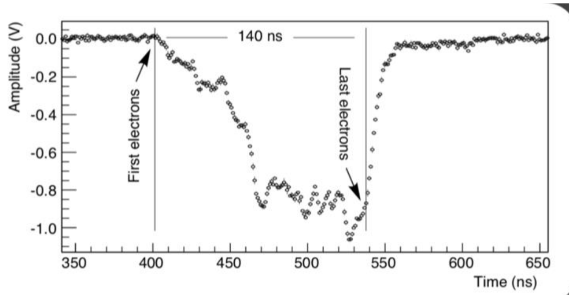


PMT

Integrated
Z + Energy measurement







Successfully Running since 2022 at the underground laboratory of Gran Sasso, Italy

1 sCMOS + 4 PMT + 3 GEMs 33 x 33 cm2 readout area 50 cm drift length

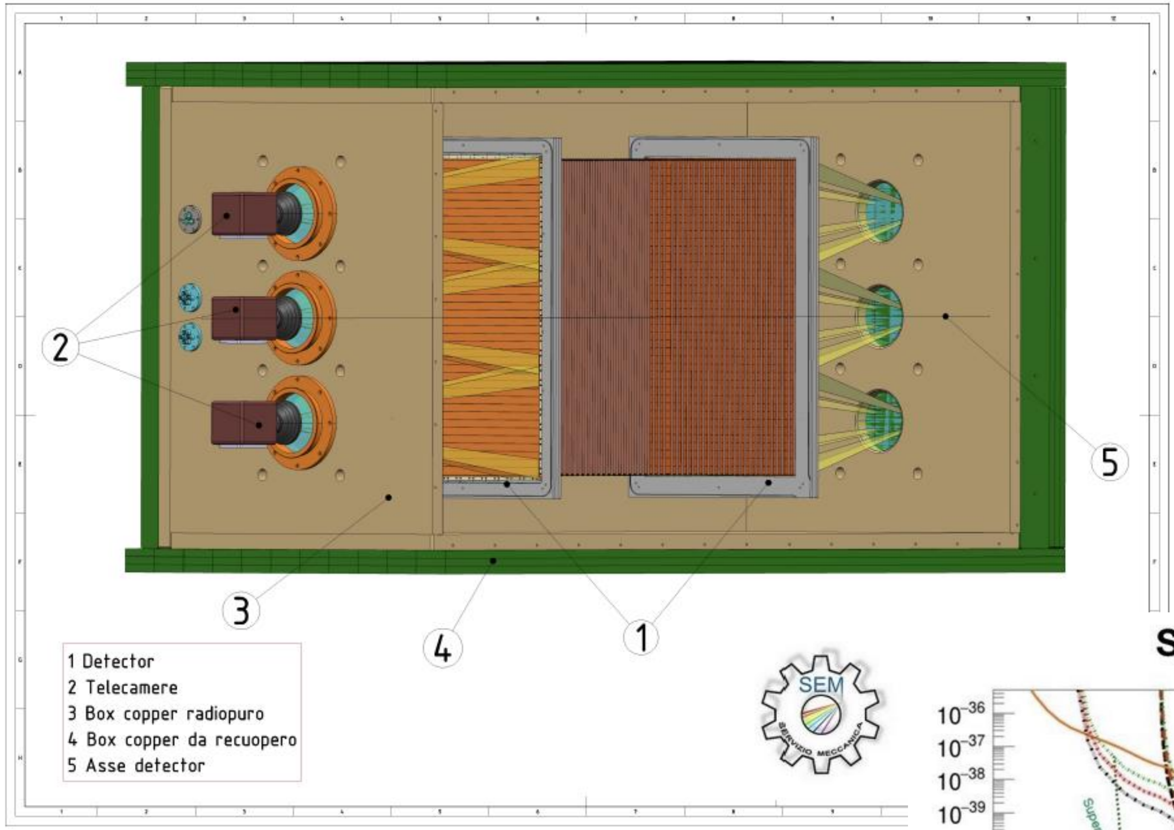
1.498 x 1.498 cm^2 sensor 6.5 x 6.5 um^2
pixels 2304 x 2304 pixels
Imaging 36 x 36 cm^2 area Effective
pixel granularity 155 x 155 um^2
Sensor geometrical acceptance Ω =1.1 x 10^{-4}

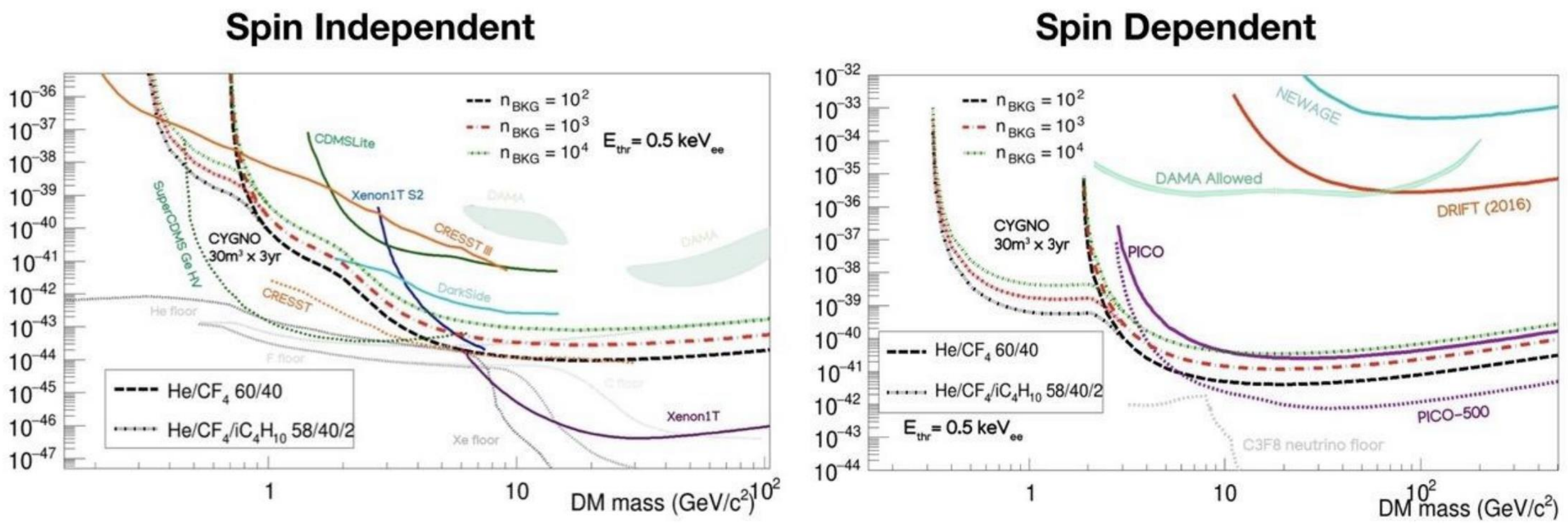
CYGNO04

Common Cathode TPC

2x 3 sCMOS + 8 PMT + 3 GEMs 80 x 50 cm2 readout area 50 cm drift length

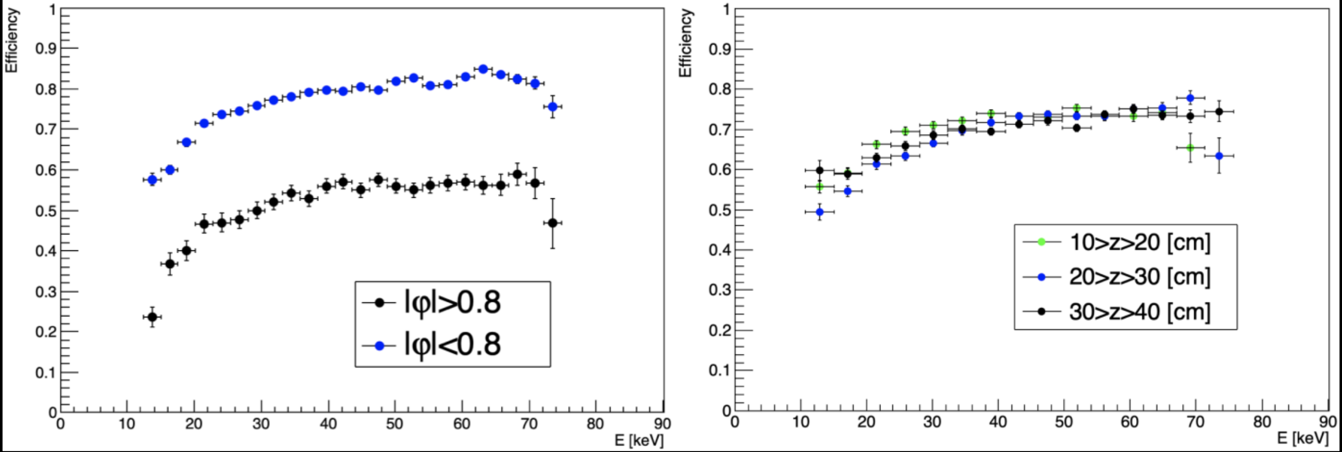
- **$0.4m^3$ Volume**
- **Last generation sCMOS**
  - **Better granularity**
  - **Lower noise**
- **More radiopure materials**





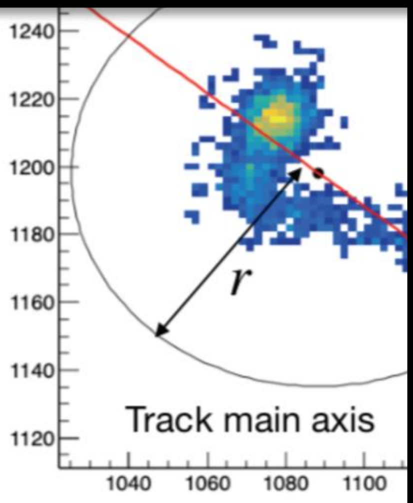
Reconstruction and Direction

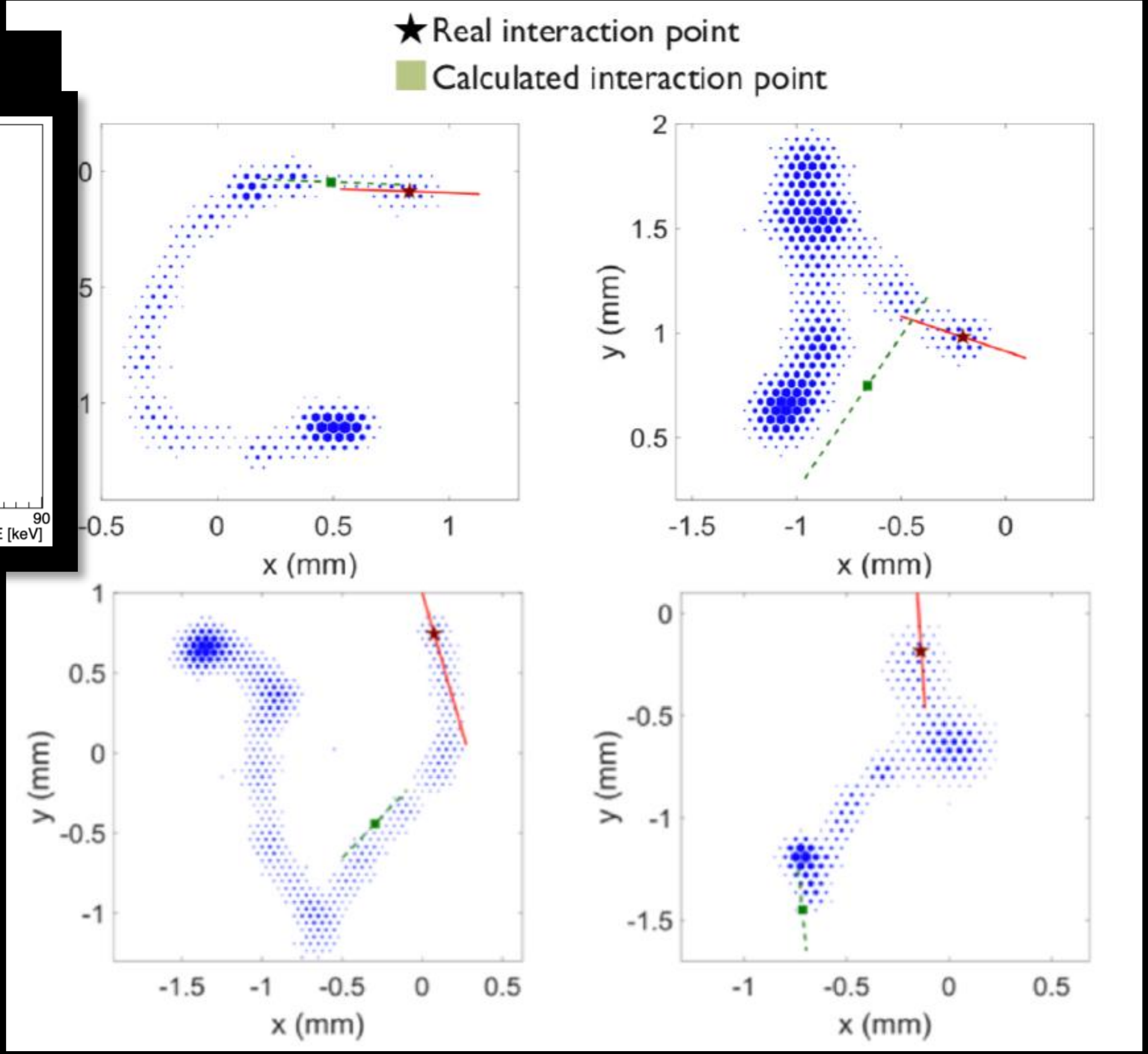
From LIME (underground detector) Simulation



The directionality algorithm is entirely derived from IXPE:

- Optimal for short, almost straight track (IXPE energy range)
- **May fail in case of long zigzaggy tracks**
- **New strategies under evaluation**





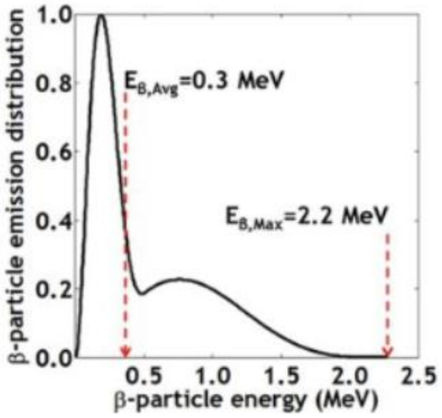
Introduction

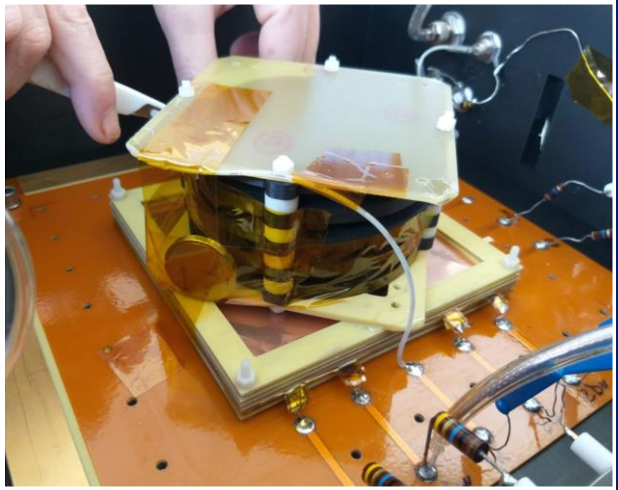
- **Measure the performance of a triple-GEM TPC optically readout for polarimetry in the range [10,50] keV**
  - Measure the expected modulation factor μ → detector response to a fully polarized source (if 1 is perfect if 0 is non sensible)
  - Measure the expected figure-of-merit μ√ε → modulation factor weighted for the efficiency. Related to Minimum Detectable Polarization

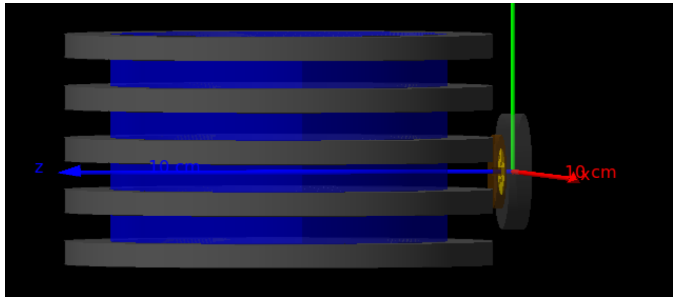
- **Measure the Angular Resolution of our detector to electron**
  - Source is 90Sr shooting perpendicularly to the GEM surface (and readout plane)
  - Ionization tracks are multiplied by a triple-GEM structure, and the scintillation light from the CF4 gas is read by a CMOS camera
    - 2D tracking (possibility to have 3D in future) and energy measurement
- **I will elaborate on the measurement with the standard gas mixture <u>He/CF4 60/40 1atm</u>, but other gases have been tested**

no background is: $\text{MDP} = \frac{4.29}{\mu\sqrt{N}}$

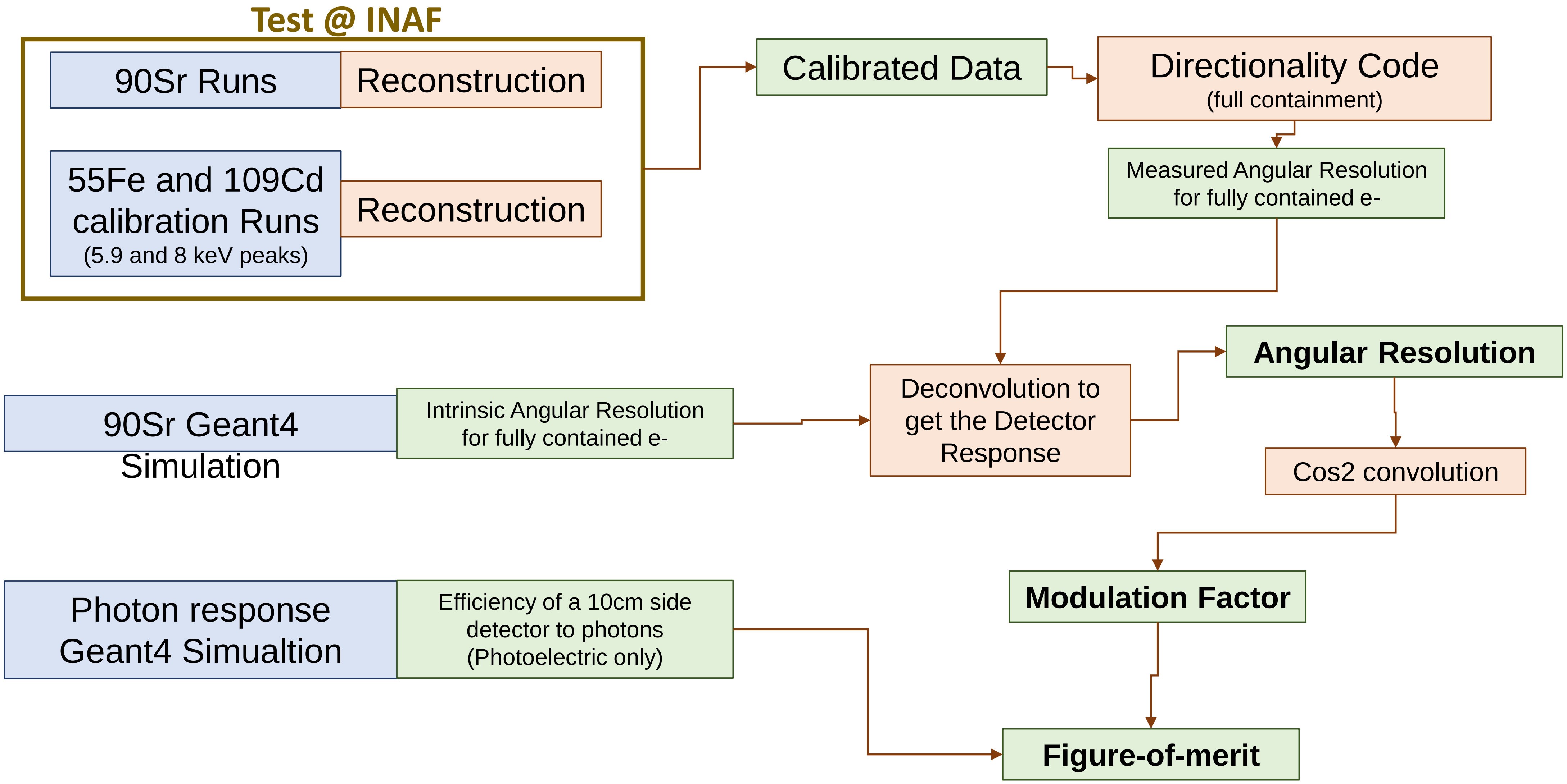
N=Flux×efficiency







Conceptual Map

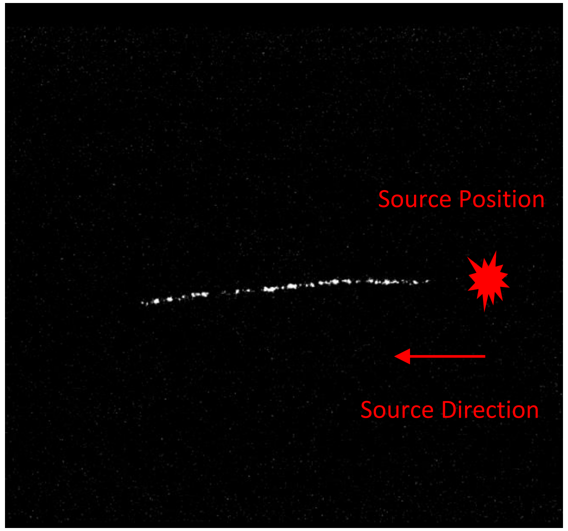


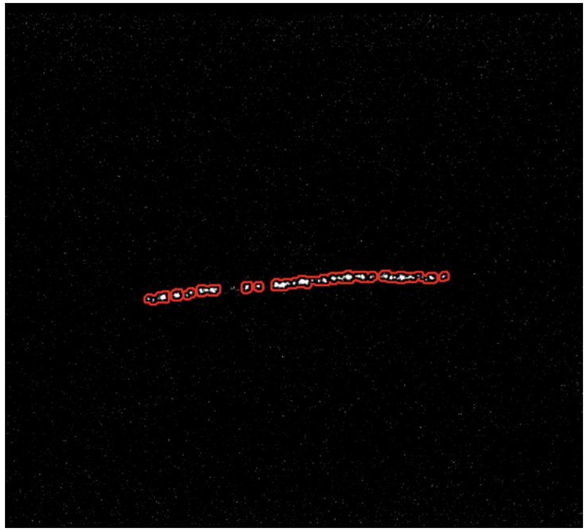
Measurements

Test @ INAF

- 90Sr Runs → Reconstruction
- 55Fe and 109Cd calibration Runs (5.9 and 8 keV peaks) → Reconstruction

→ Calibrated Data → Directionality Code (full containment) → Measured Angular Resolution for fully contained e-





Example of e- track from 90Sr

- DBSCAN is used to find clusters of pixels over the threshold
- Directional DBSCAN is used to aggregate clusters that came from the same track

[CYGNUS-RD/reconstruction: Camera and scope analysis tools (github.com)](CYGNUS-RD/reconstruction)

Measurements

Test @ INAF

90Sr Runs → Reconstruction

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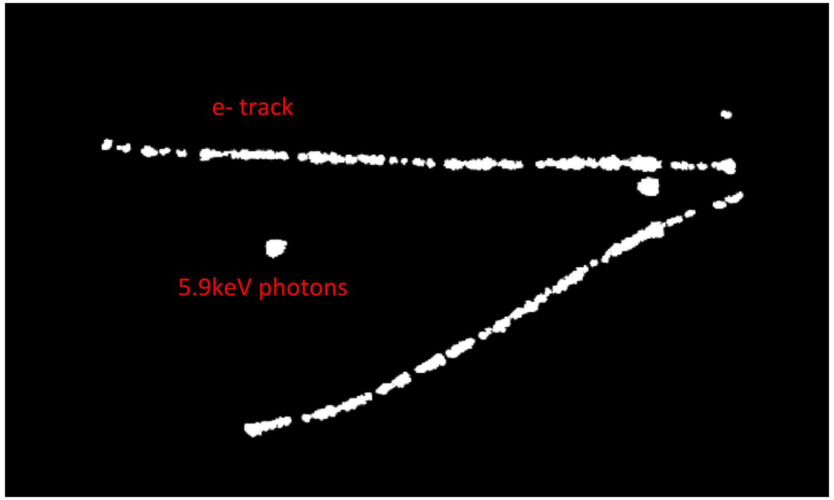
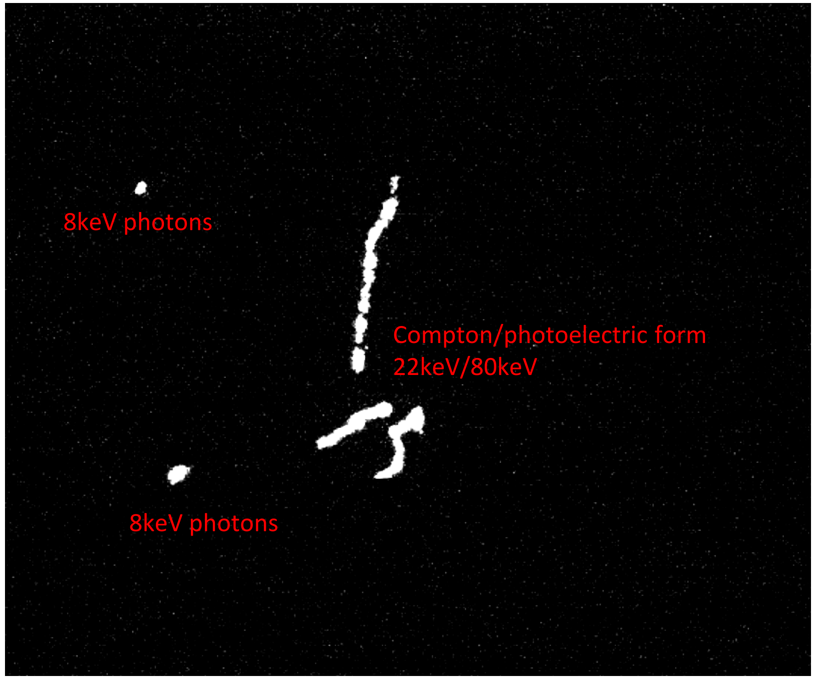




Measurements

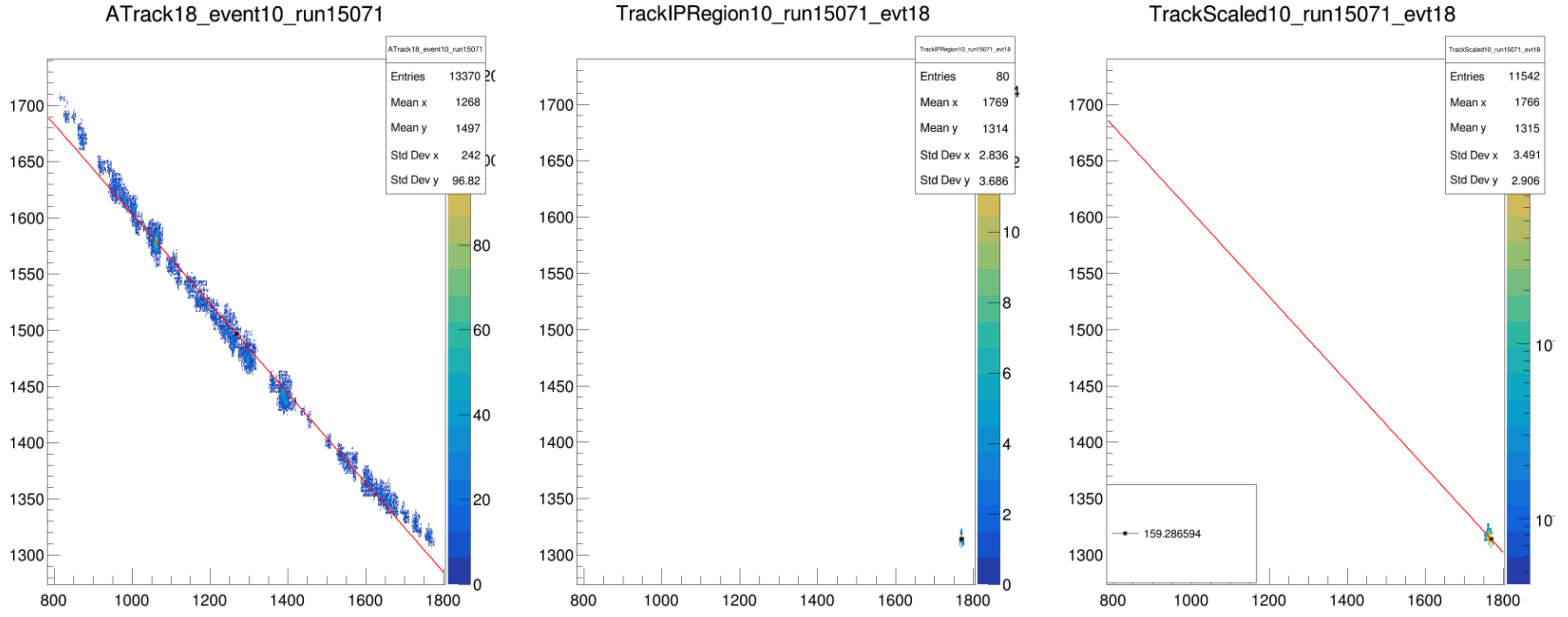
Test @ INAF

- 90Sr Runs → Reconstruction
- 55Fe and 109Cd calibration Runs (5.9 and 8 keV peaks) → Reconstruction

→ Calibrated Data → Directionality Code (full containment) → Measured Angular Resolution for fully contained e-

The directionality algorithm is entirely derived from IXPE (main developer S.Torelli)

- IP→moving circularly where skewness is positive far away from Barycenter
- DIR→maximizes RMS of selected points around IP with exponentially scaled intensity



fiorotto8/CygnoAnal (github.com)

Measurements

Test @ INAF

- 90Sr Runs → Reconstruction
- 55Fe and 109Cd calibration Runs (5.9 and 8 keV peaks) → Reconstruction

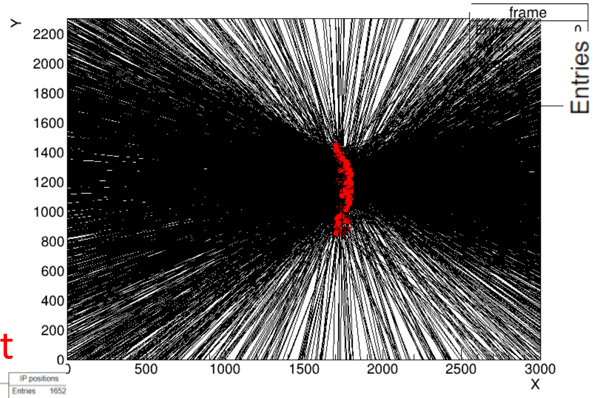
→ Calibrated Data → Directionality Code (full containment) → Measured Angular Resolution for fully contained e-

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

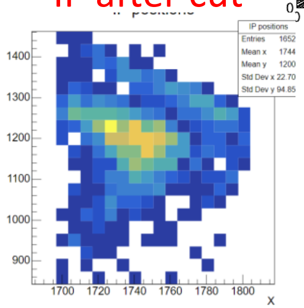
Full containment is defined as:

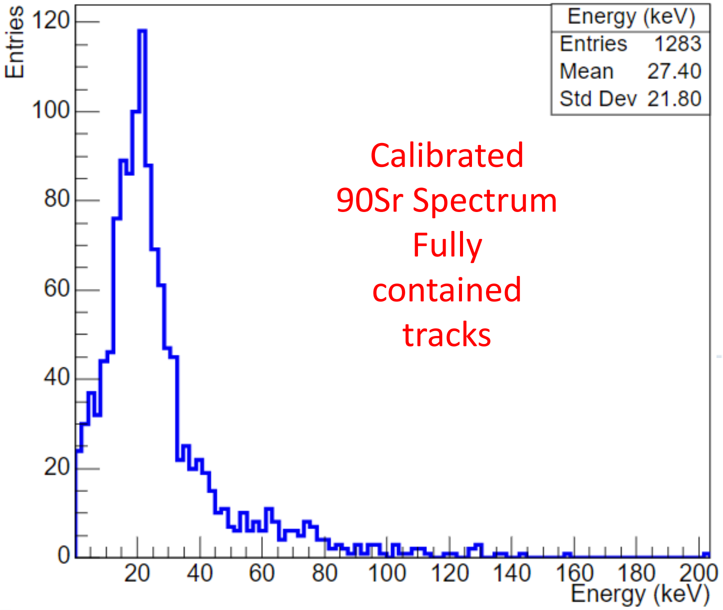
- IP region
  - 'X_ImpactPoint' > 1700 &
  - 'X_ImpactPoint' < 1800 &
  - 'Y_ImpactPoint' > 850 &
  - 'Y_ImpactPoint' < 1450 &
- Camera containment:
  - 'Ymin' >500 &
  - 'Ymax' <2304-500 &
  - “Xmin">500

IP with direction line

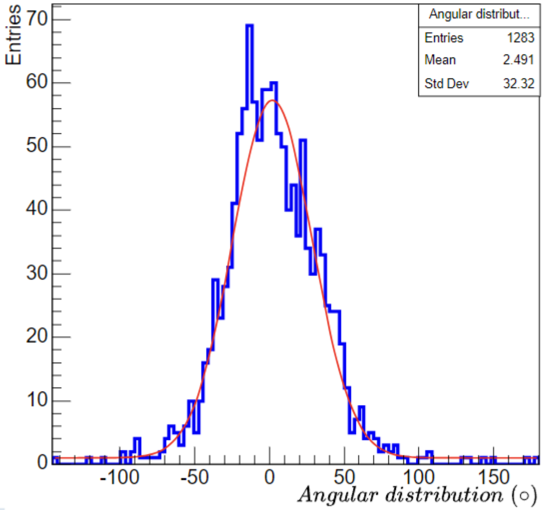


IP after cut





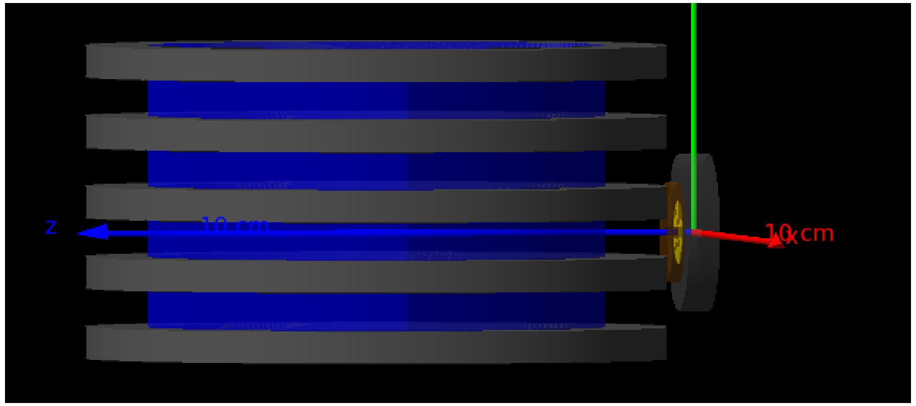
Calibrated 90Sr Spectrum Fully contained tracks



Angular resolution

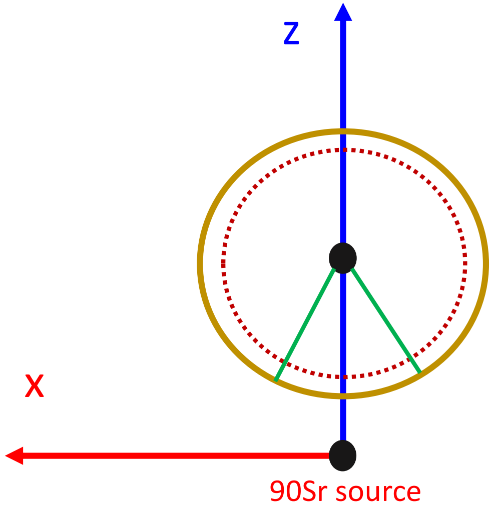
Intrinsic Angular spread simualtion

90Sr Geant4 Simulation → Intrinsic Angular Resolution for fully contained e- → Deconvolution to get the Detector Response → **Angular Resolution**



Simulation with a simple geometry:
- Cylindrical gas volume h=5cm, r=3.7cm
- Field cage rings, 1cm with SS ring 0.1cm radius
- 90Sr Source with r=1mm tungsten collimator
- 90Sr decay, electrons tracked only in the gas volume!
  - Deposited energy measurement in sensitive volume

Full containment:
- Track without hits in 5mm from the border or the circle
- But allowed if the hit is in the +/- 30° region of the entering angle
- No containment in cylinder height (we are only 2D for now)

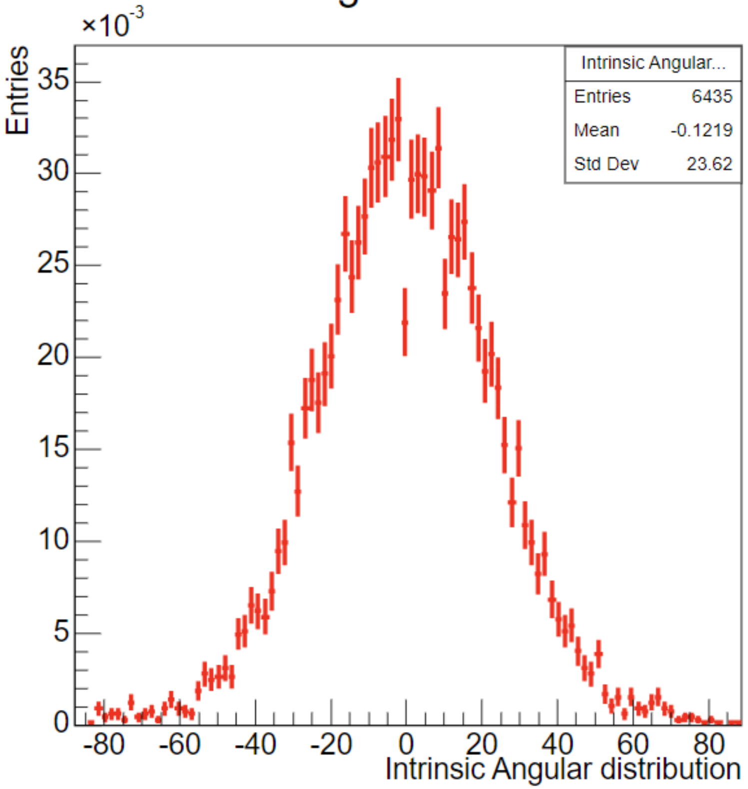


fiorotto8/MANGO_RadioactiveSource: Simulation of Cd-109 Radioactive source in MANGO (github.com)

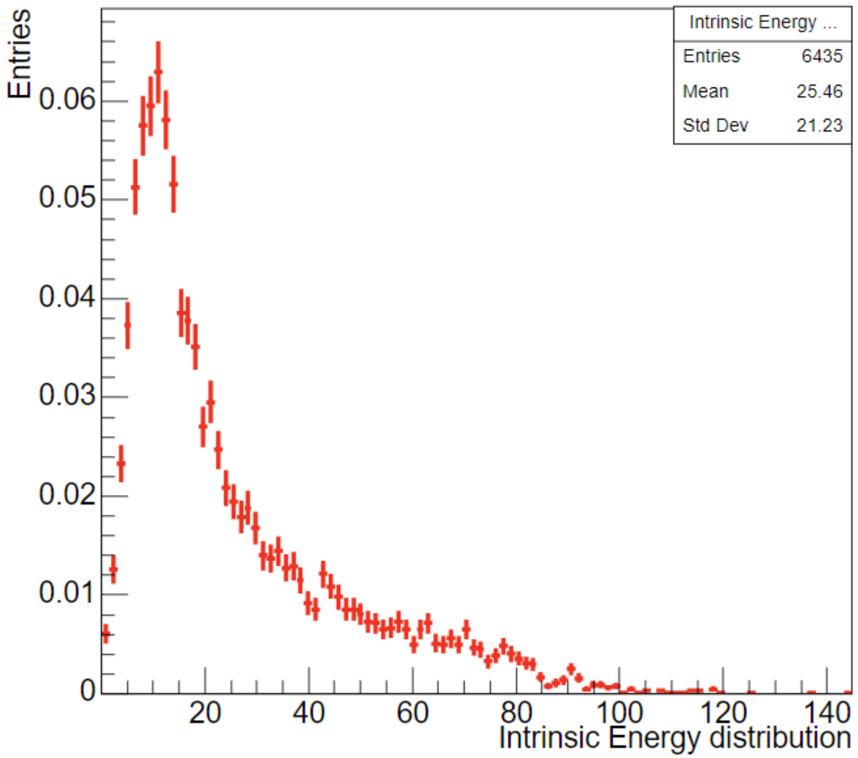
Intrinsic Angular spread simualtion

90Sr Geant4 Simulation → Intrinsic Angular Resolution for fully contained e- → Deconvolution to get the Detector Response → **Angular Resolution**

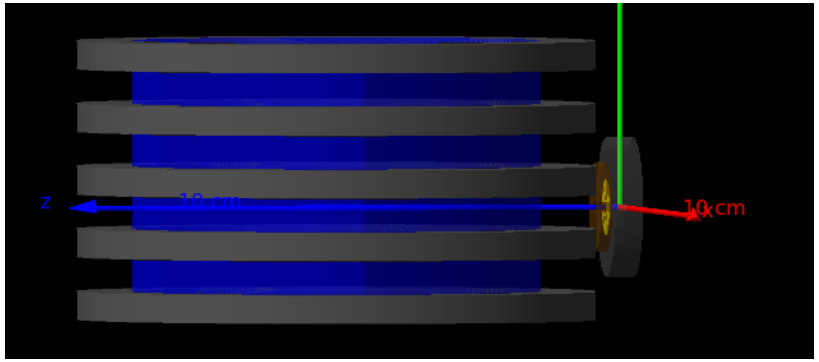
Intrinsic Angular distribution



Intrinsic Energy distribution



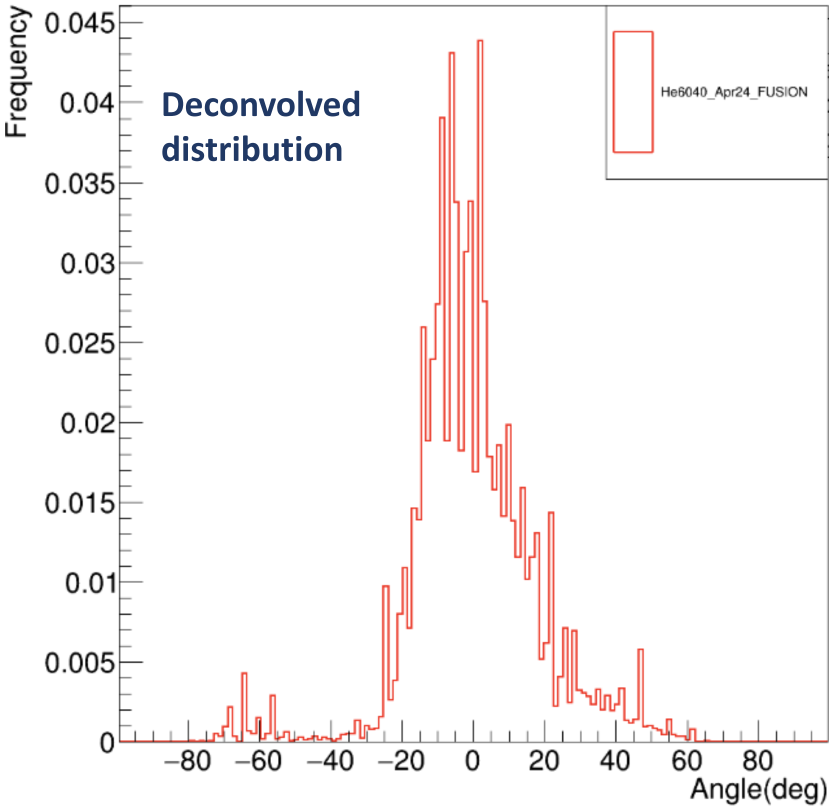
Fully contained Simulated Tracks!



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

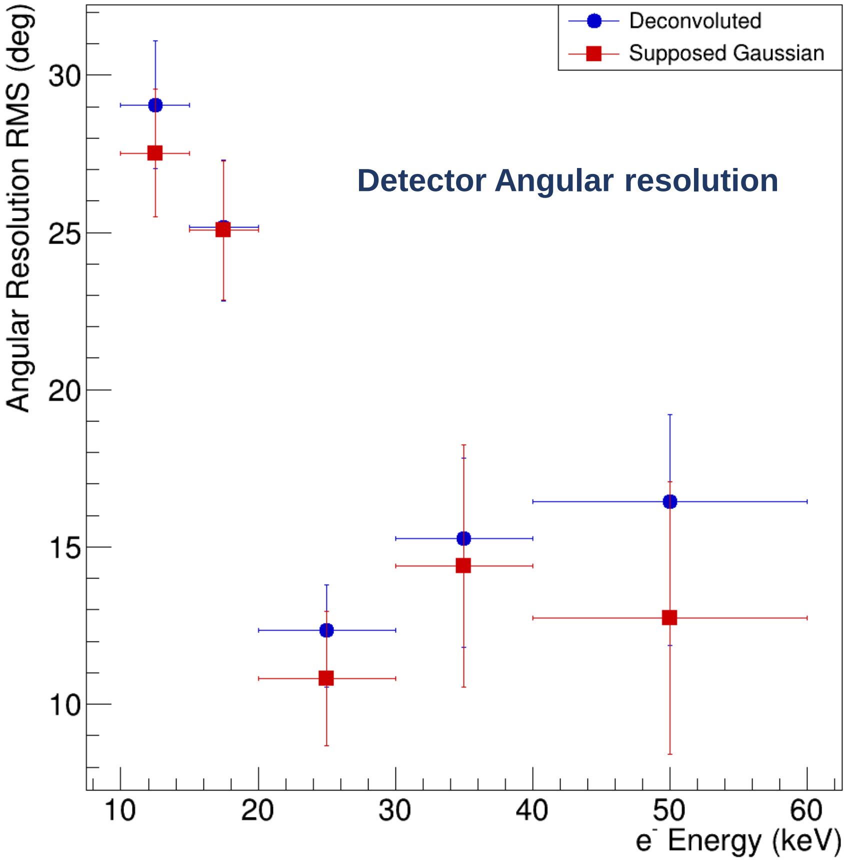
Detector Resolution

90Sr Geant4 Simulation → Intrinsic Angular Resolution for fully contained e- → Deconvolution to get the Detector Response → **Angular Resolution**



Richardson-Lucy deconvolution to get the Detector Angular resolution:

- Deconvolution and Subtraction in quadrature give very similar results
- Errors are calculated by bootstrapping the measured and intrinsic distributions and deconvolving many times
- With these bins: np.linspace(-100, 100, 151)



Modulation factor and figure-of-merit

Photon response Geant4 Simualtion

Efficiency of a 10cm side detector to photons (Photoelectric only)

Modulation Factor

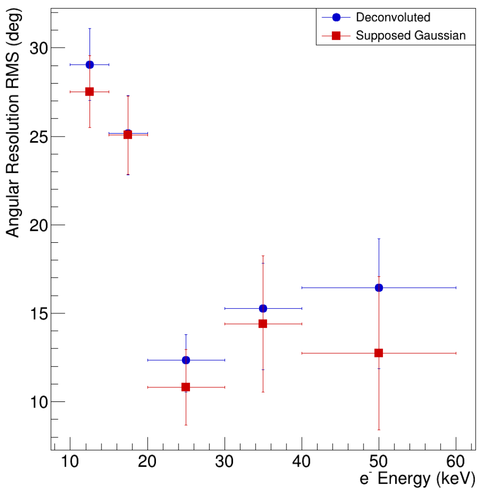
Angular Resolution

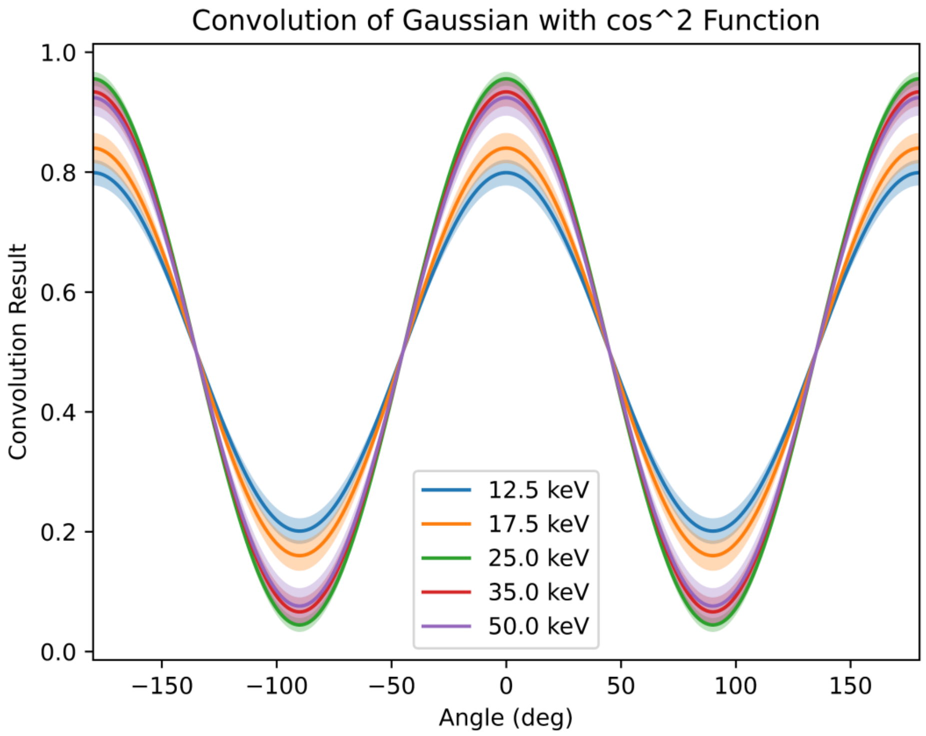
Cos2 convolution

Figure-of-merit

Using the deconvolved RMS as sigma of a Gaussian, then convolve with a $\cos^2$

$$(G * \cos^2)(x) = \frac{1}{2}\left(1 + e^{-2\sigma^2}\cos(2x)\right)$$





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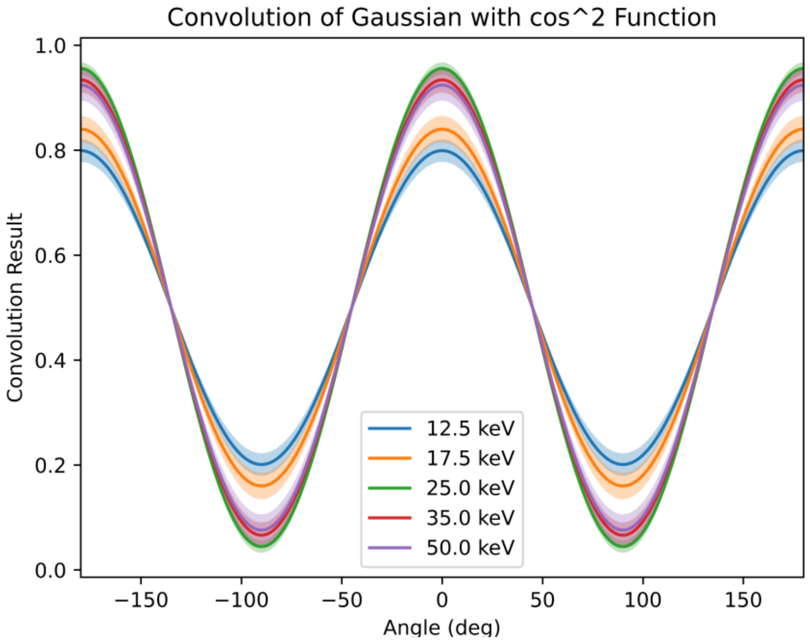
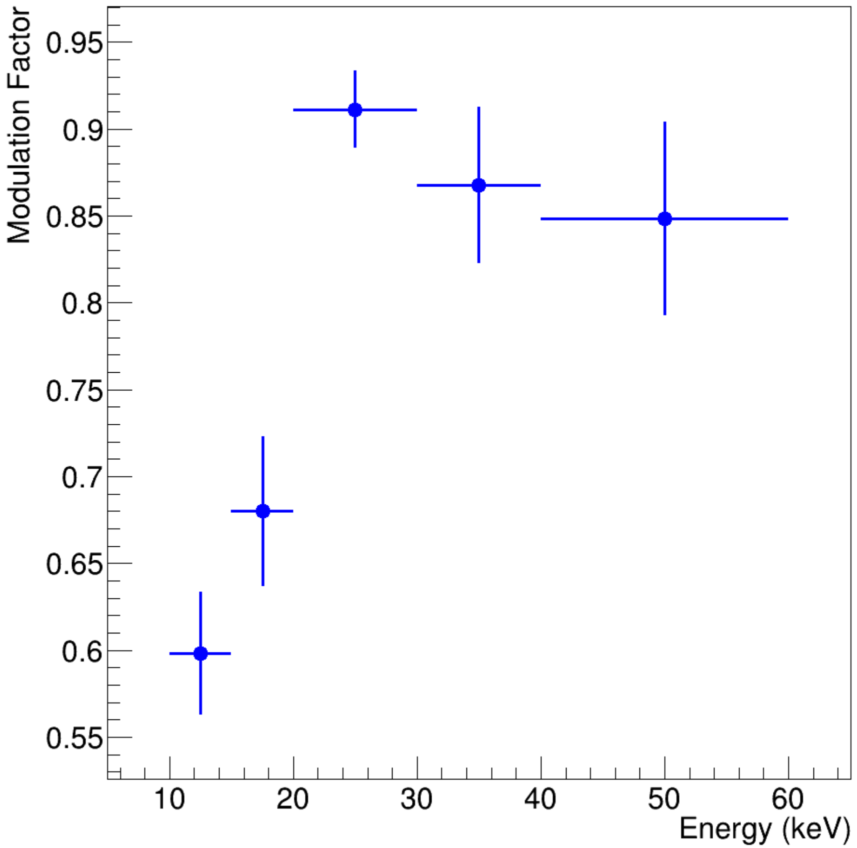




fiorotto8/Directionality (github.com)

$$\mu = \frac{N^{max}_{100\%} - N^{min}_{100\%}}{N^{max}_{100\%} + N^{min}_{100\%}}$$

Modulation factor and figure-of-merit

Photon response Geant4 Simualtion

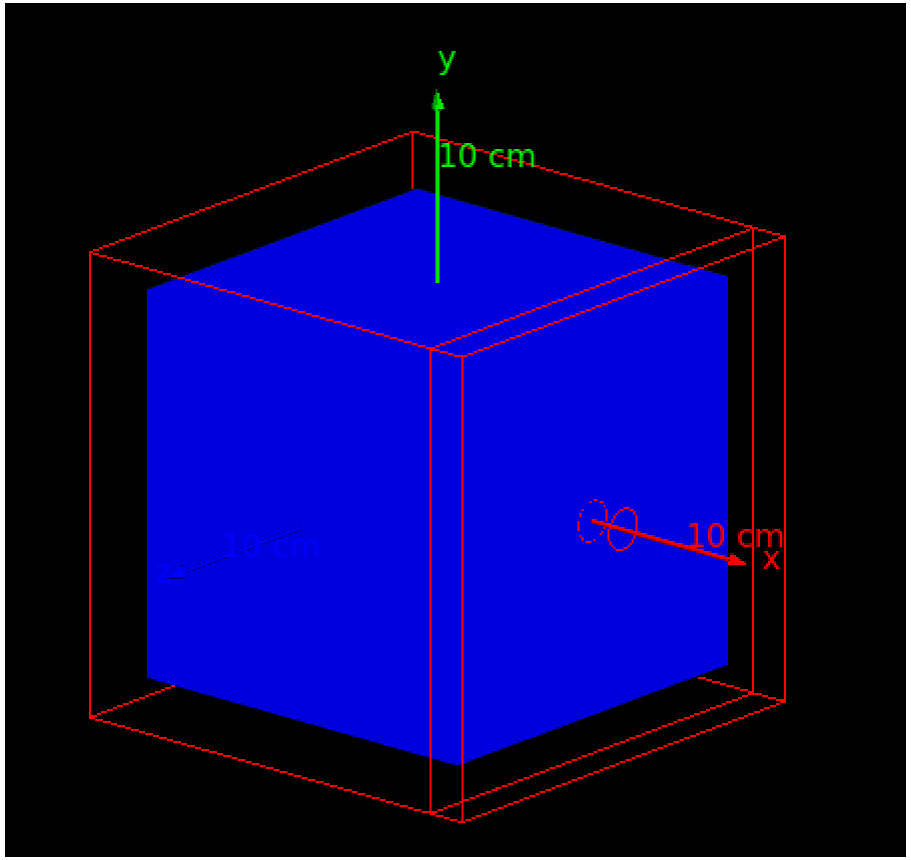
Efficiency of a 10cm side detector to photons (Photoelectric only)

Modulation Factor

Angular Resolution

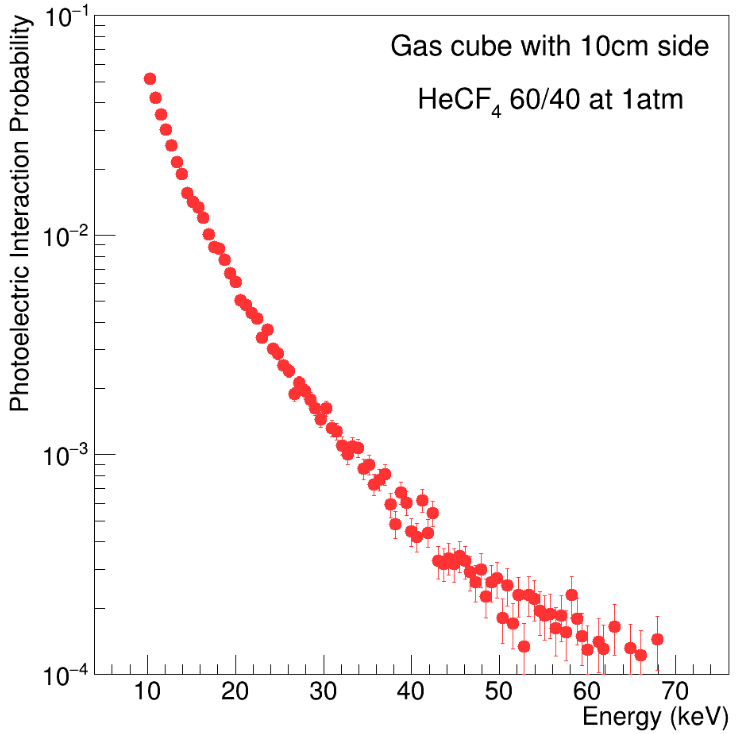
Cos2 convolution

Figure-of-merit



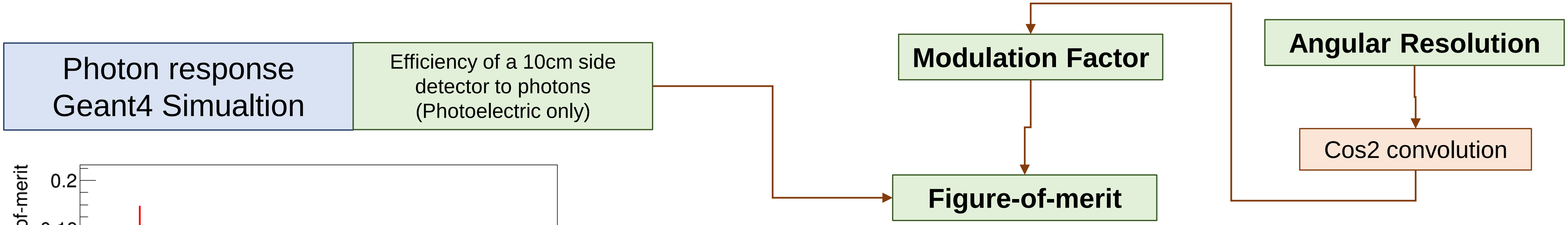
Geant4 simulation of a gas cube of 10cm side with 2cm of Al shielding

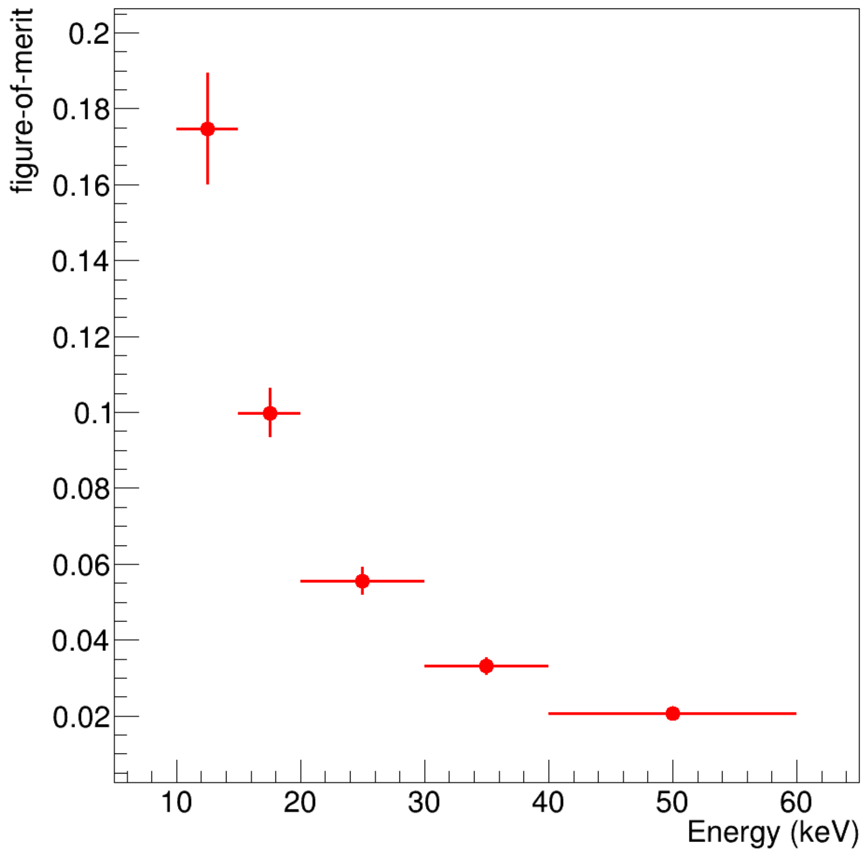
- Hole of 10.6mm to put an eventual [MCP plate]
- Shooting photons [10,70]keV through the hole
- Photon is considered detected if:
  - The total energy deposited is its primary energy (with 200eV clearance)
  - It did only one interaction (photoelectric selection) in the gas



fiorotto8/MANGOspaceG4 (github.com)

Modulation factor and figure-of-merit





no background is: $MDP = \frac{4.29}{\mu\sqrt{N}}$

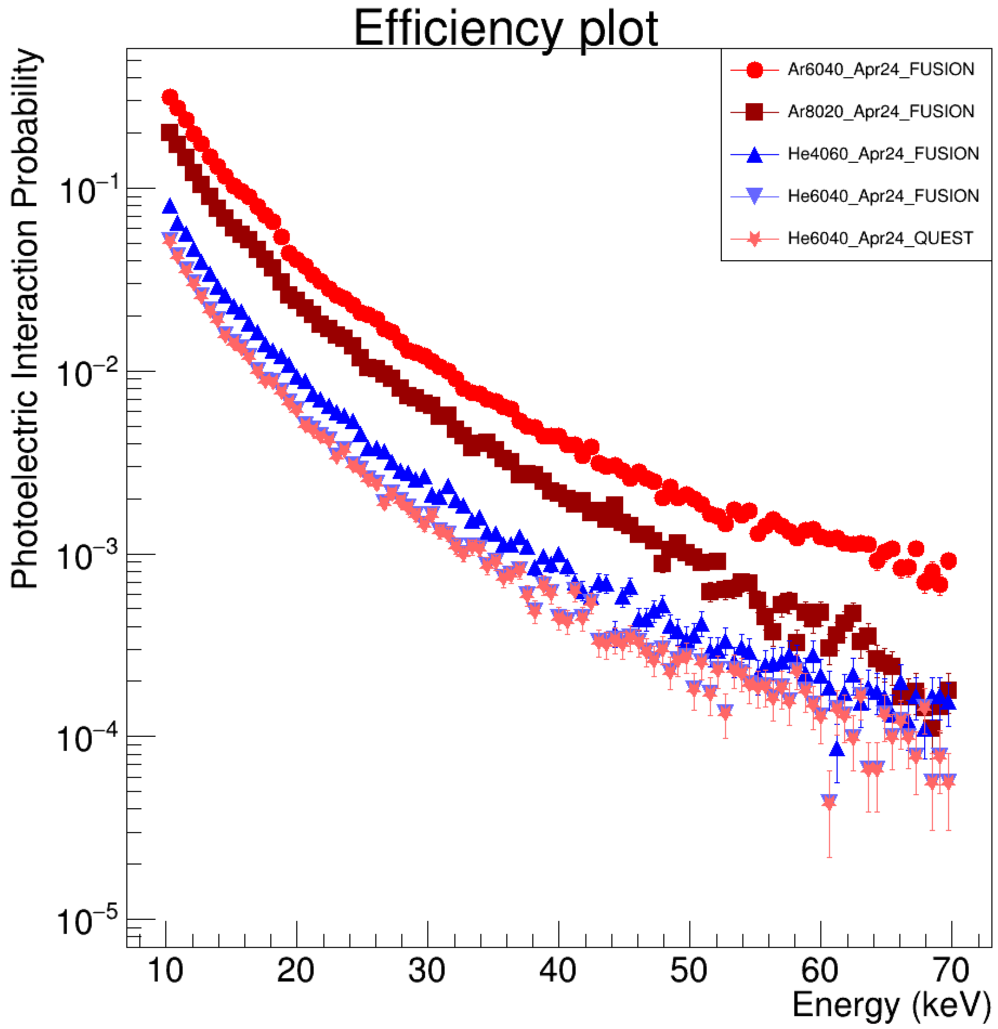
N=Flux×efficiency

Huge quenching of the good modulation factor is caused by very low efficiency!

This is the best possible condition! We are not considering the reconstruction efficiency and possible background!!

Other results

He/CF4 at atmospheric pressure is great for DM searches. However, it ~~may~~should be optimized for polarimetry



- Argon ensures up to an order of magnitude of efficiency
- More CF4 helps because larger density, but photoelectric

Iteraction probability scales linearly with density but scale with Z^5!!!

Modulation Factors and figure-of-merits