Feasibility of a directional solar neutrino measurement with the CYGNO/INITIUM experiment

Samuele Torelli on behalf of the CYGNO collaboration

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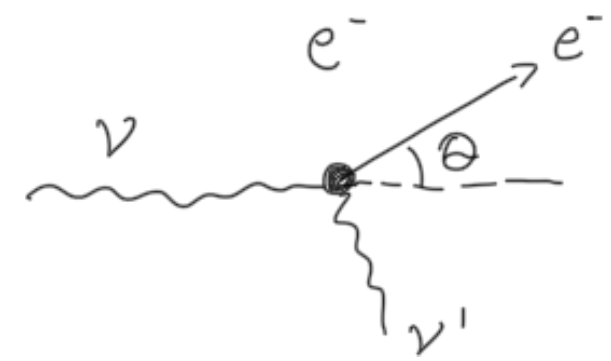
CYGNUS collaboration meeting - 2023

Solar neutrino directional detection



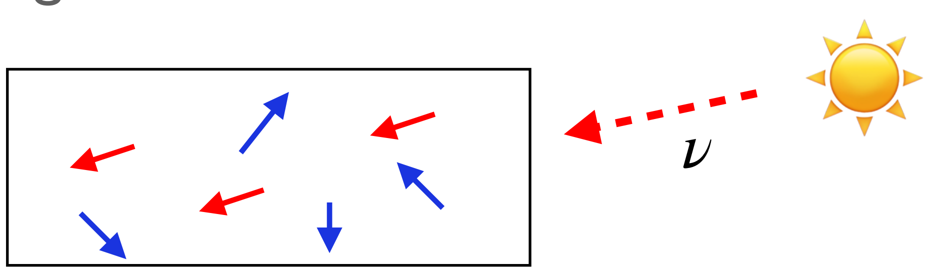
Neutrino from the Sun can be object of study with large TPC through $\nu - e^-$ elastic scattering as proposed in the '90:

Seguinot, Jacques & Ypsilantis, Thomas & Zichichi, Antonino. (1992). A high rate solar neutrino detector with energy determination.

In CYGNO gas mixture:
1 $ev/y/m^3$

Directional detection

Capability of discriminating signal from background from source direction

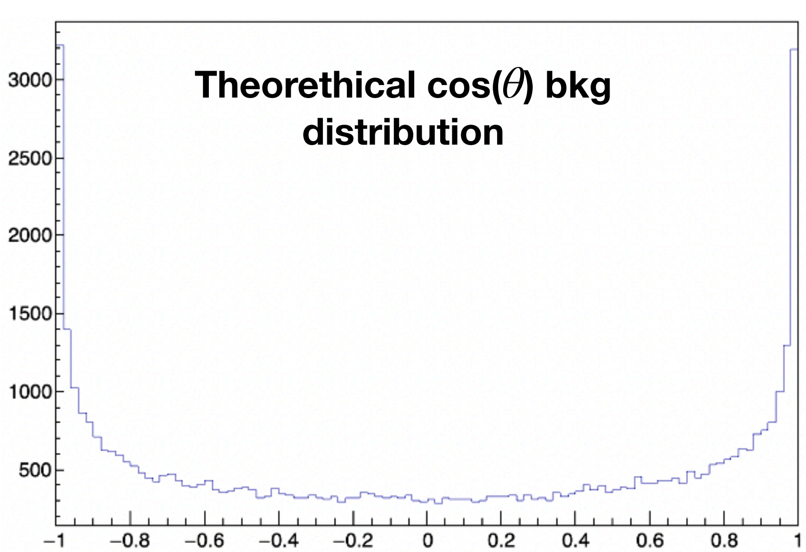


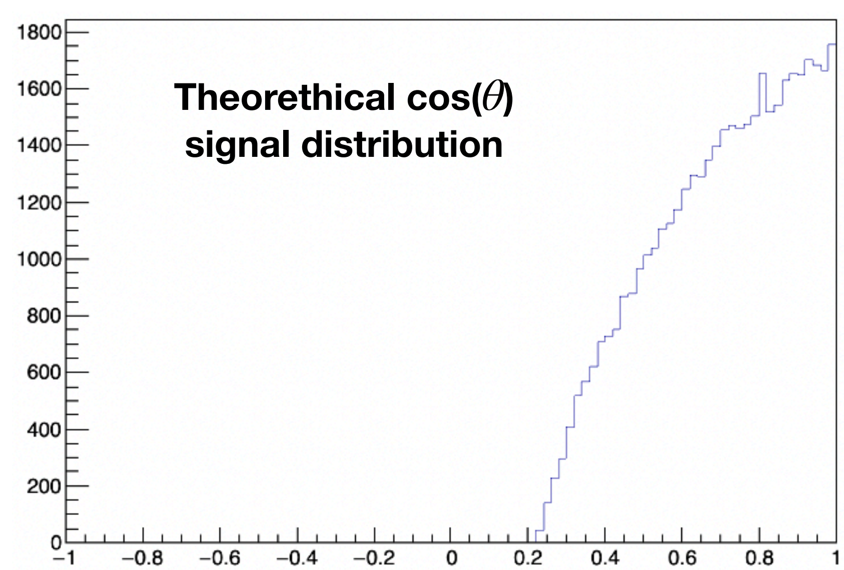
Possibility of event by event neutrino energy reconstruction (closed kinematic)

$$E_{\nu,Reco} = \frac{-m_e T_e - \sqrt{T_e^2 m_e^2 \cos(\theta)^2 + 2T_e m_e^3 \cos(\theta)^2}}{(T_e - T_e \cos(\theta)^2 - 2m_e \cos(\theta)^2)}$$

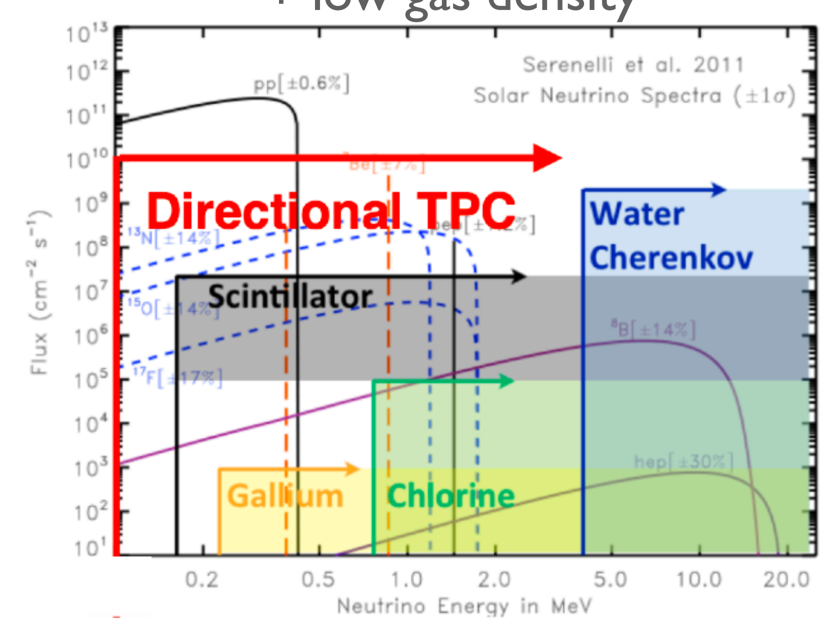
Much stronger signature than energy spectrum

Exponential Signal over exponential bkg	vs	Peaked distribution over flat bkg

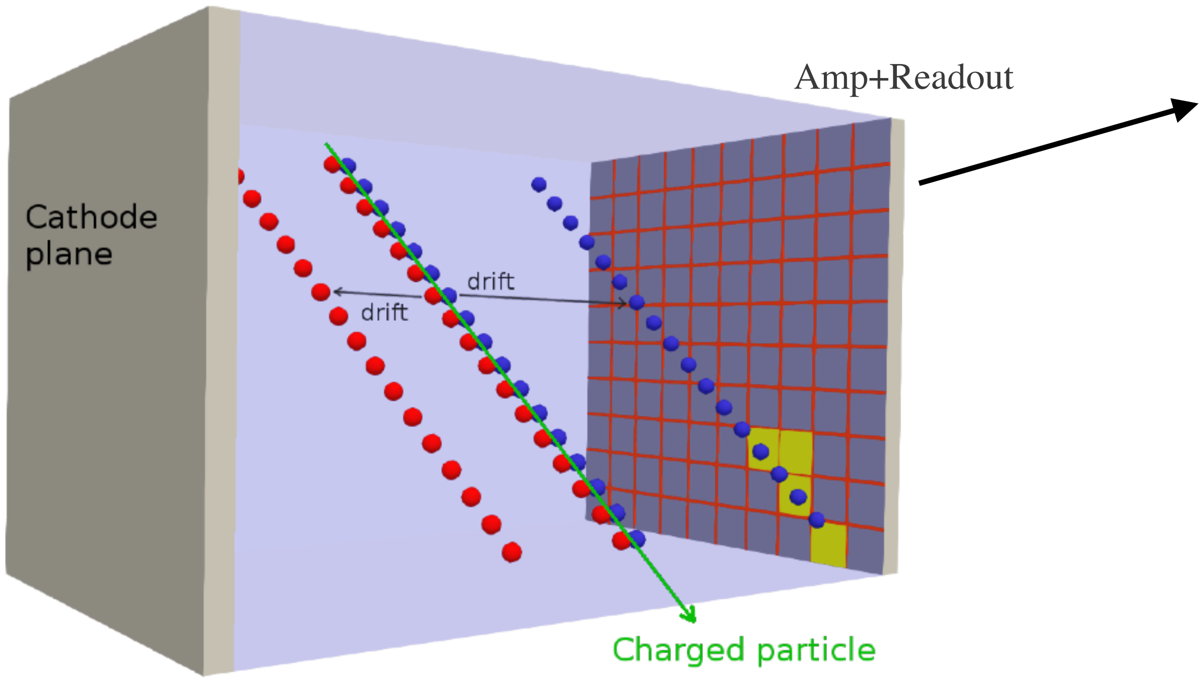


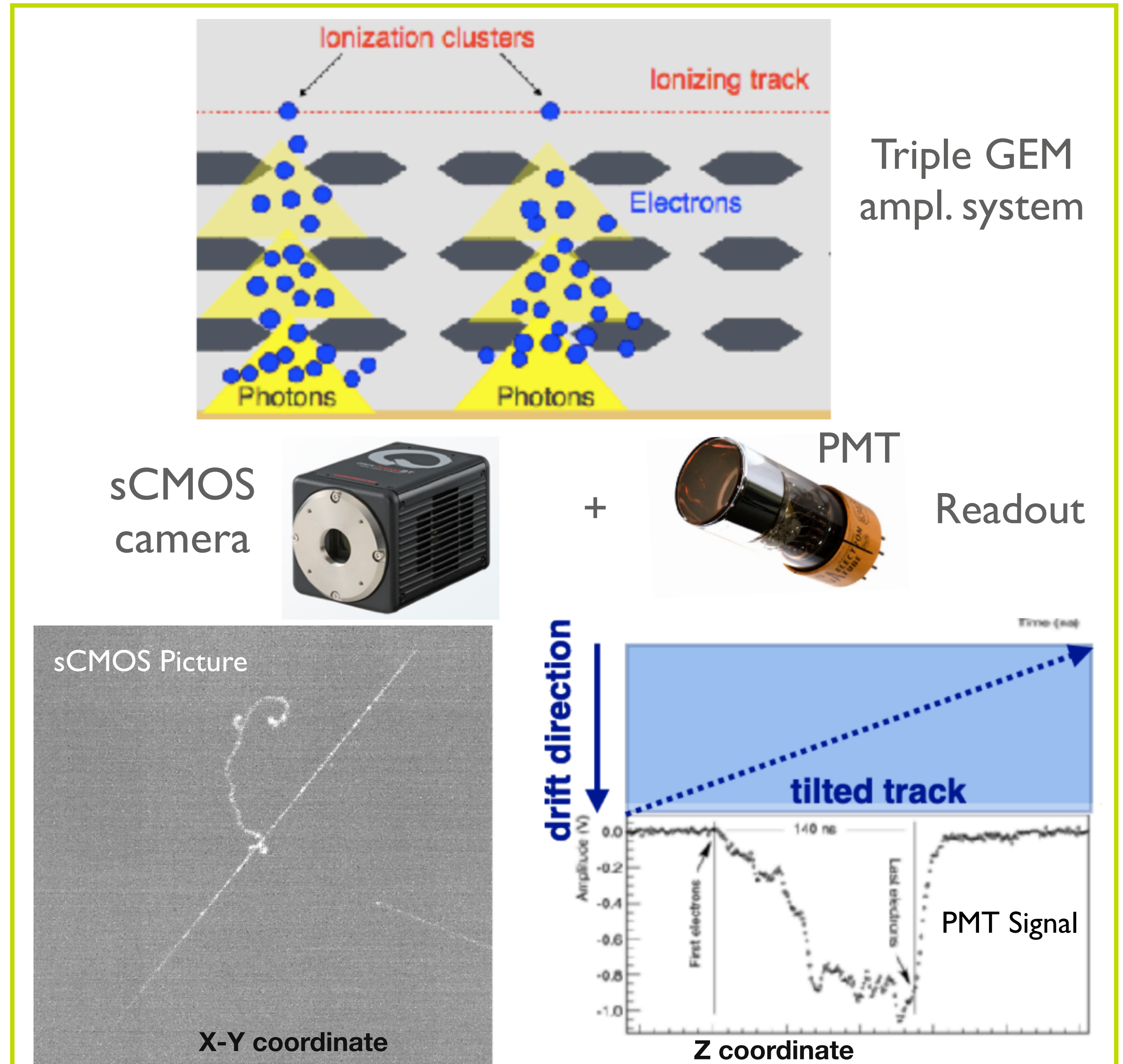


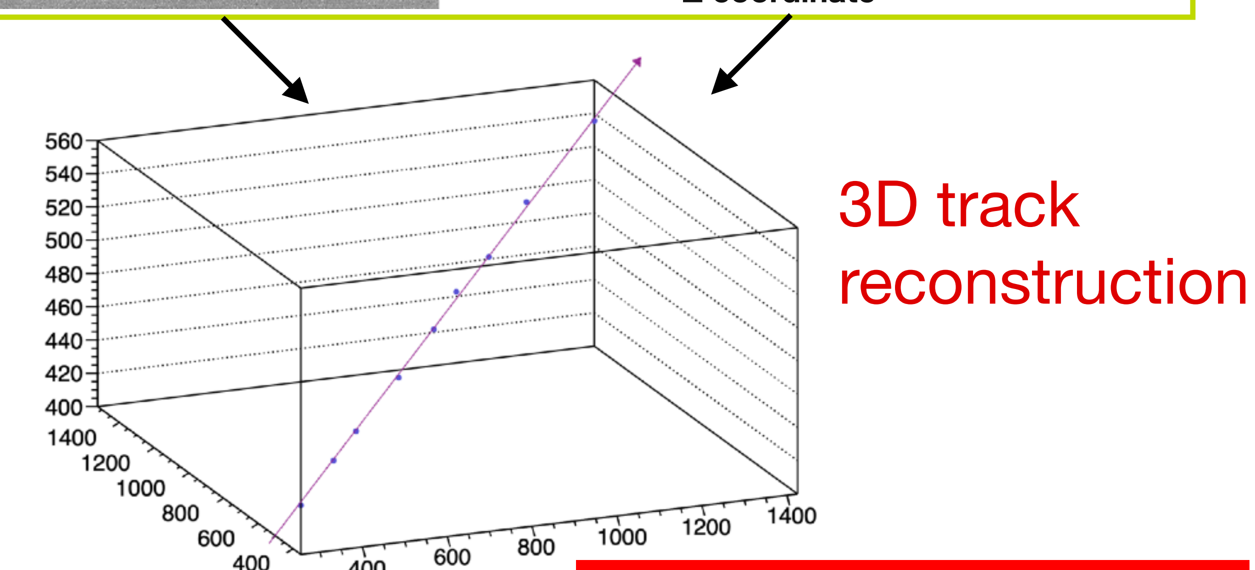
+ low gas density



The CYGNO technique



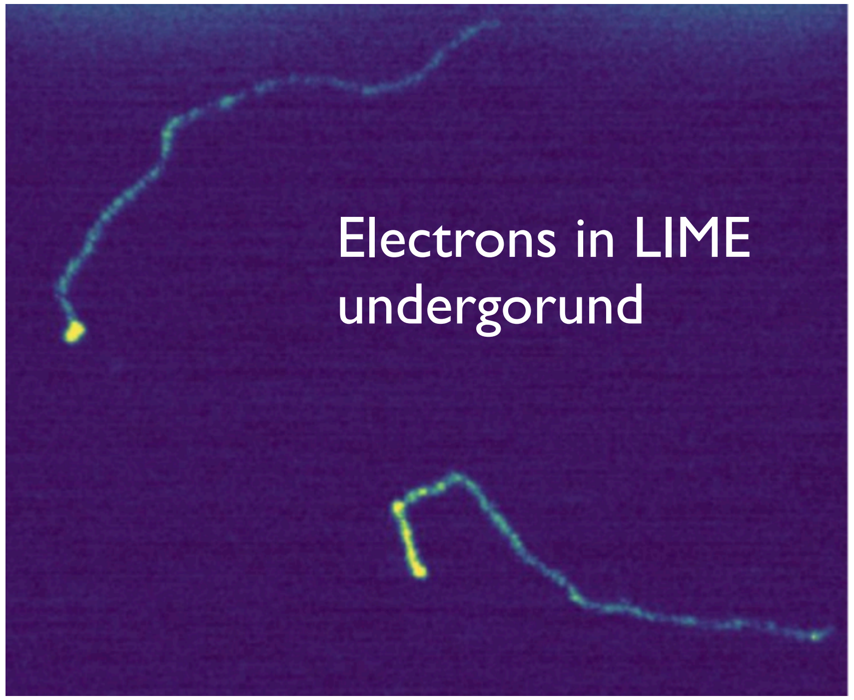


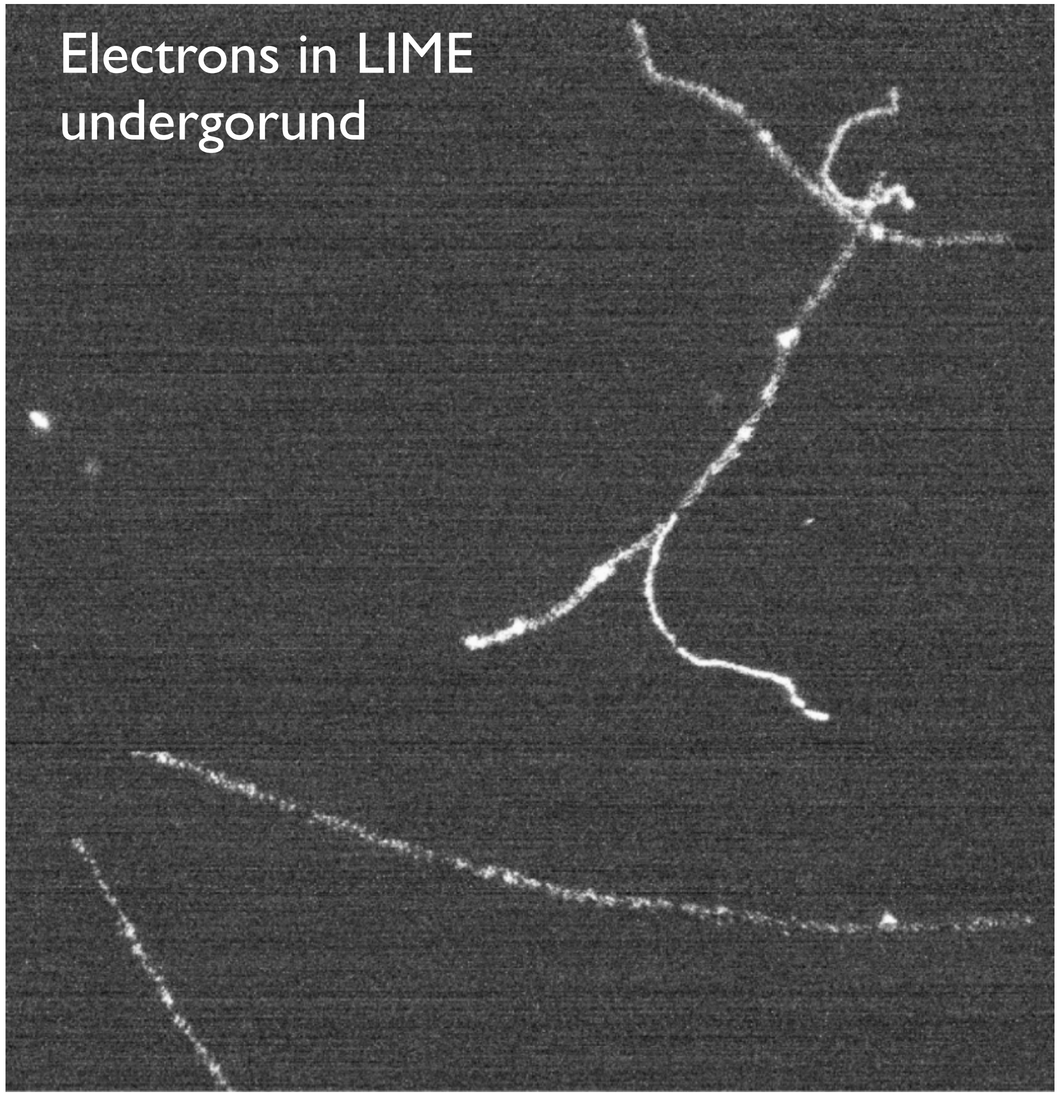


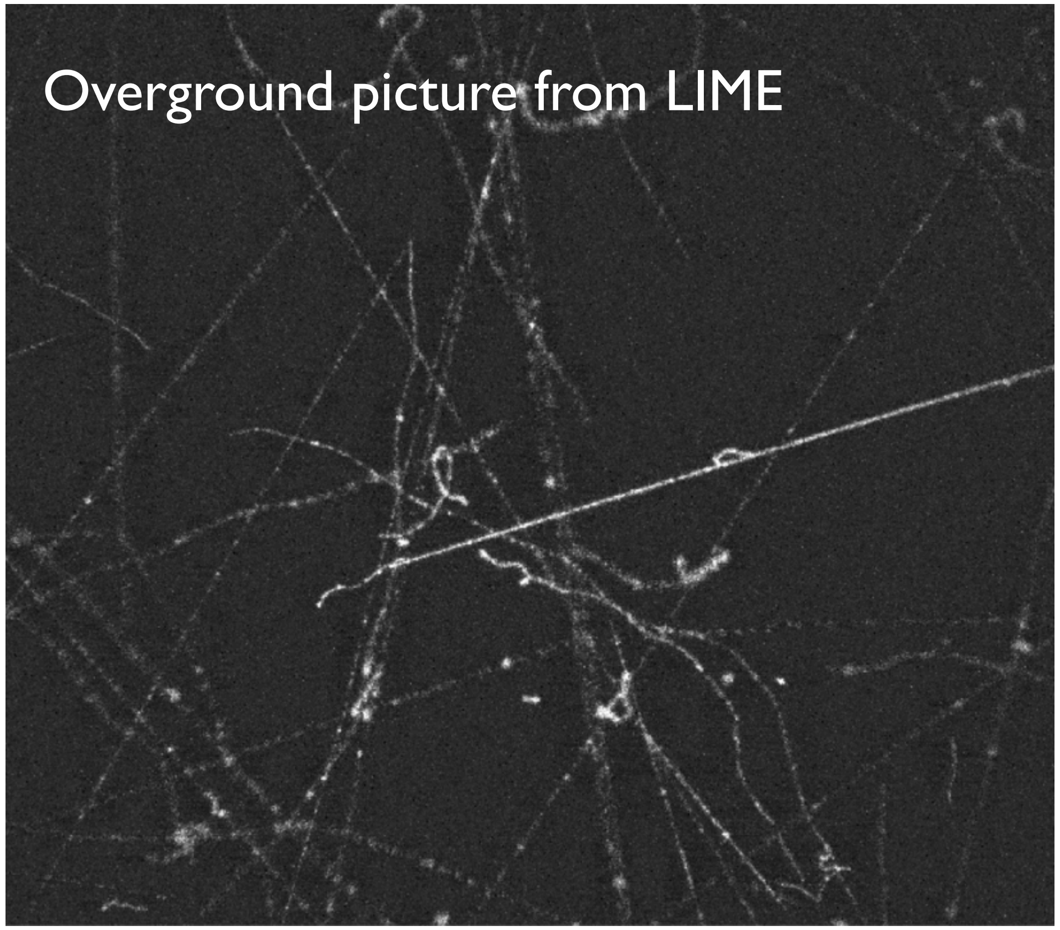
- Time projection chamber filled with He:CF_4 (60:40) at atmospheric pressure
- The trail of electrons produced in the TPC is transported to the readout
- Primary ionisation electrons are amplified by triple thin GEMs, where light is produced together with electron avalanches (0.07 photon/electron)
- Light is readout from a sCMOS and a PMT

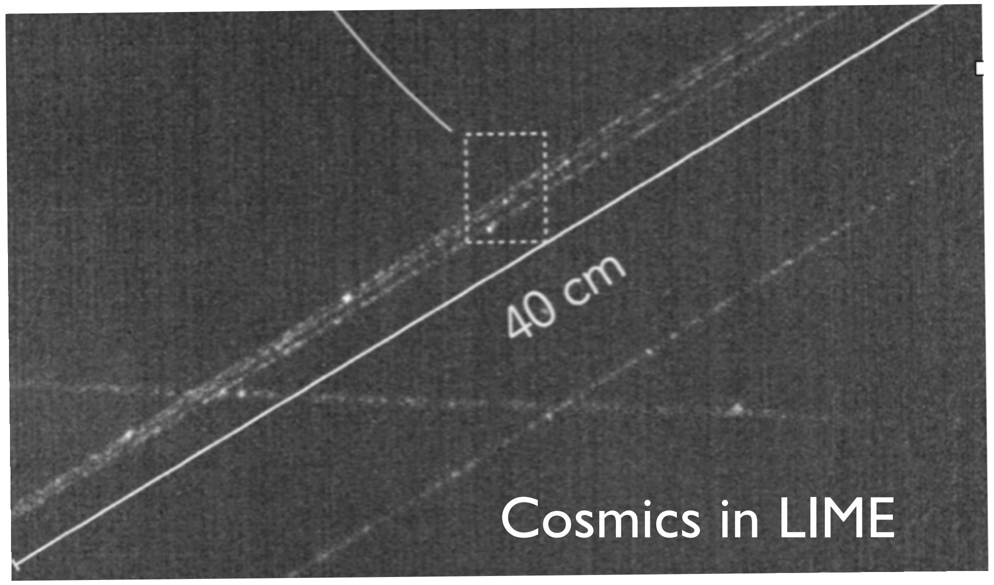
JINST 13 (2018) no.05, P05001

Particle tracks in CYGNO



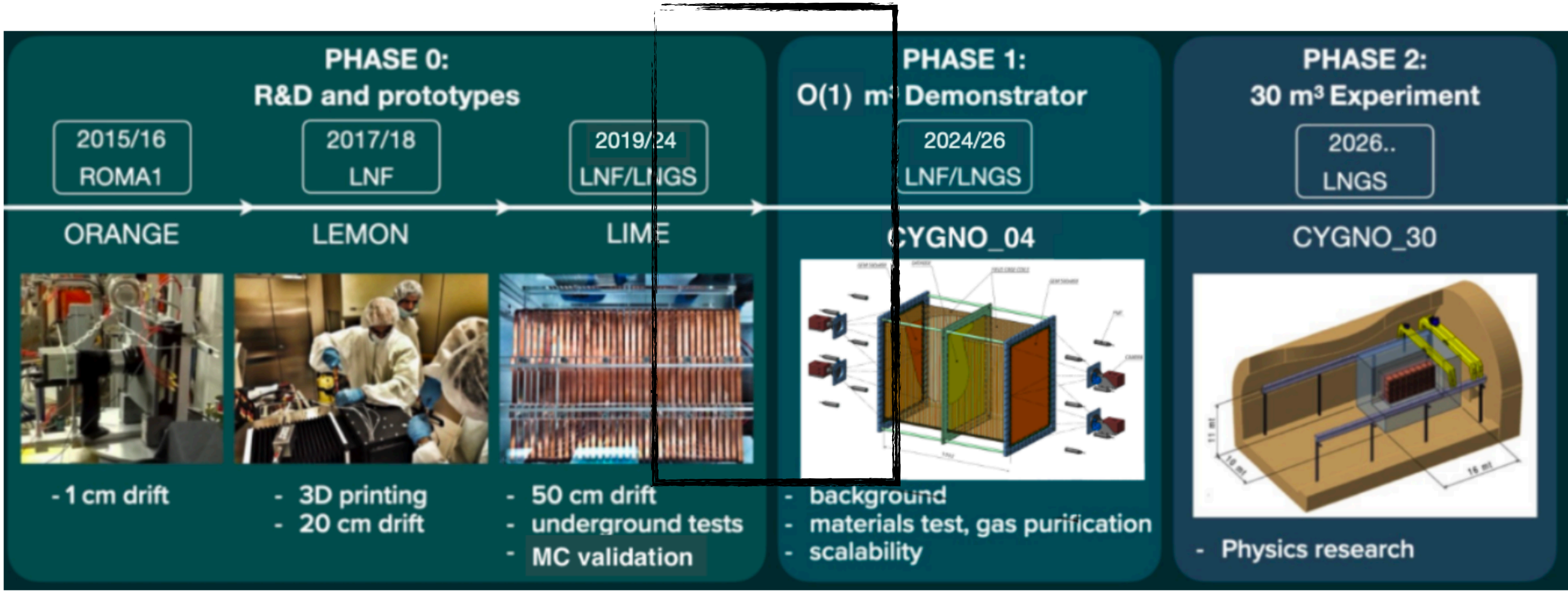






The CYGNO timeline

We are here



- Results in this presentations are from the LIME prototype
- CYGNO-04 will be employed to demonstrate the scalability
- CYGNO-30 used for physics research, composed by many CYGNO-04 modules

Multipurpose apparatus:
originally developed for DM searches

↓

Can be employed for:

- Directional neutron flux measurement
- Solar neutrino
- Supernova pointing

Study of LIME prototype response characterization

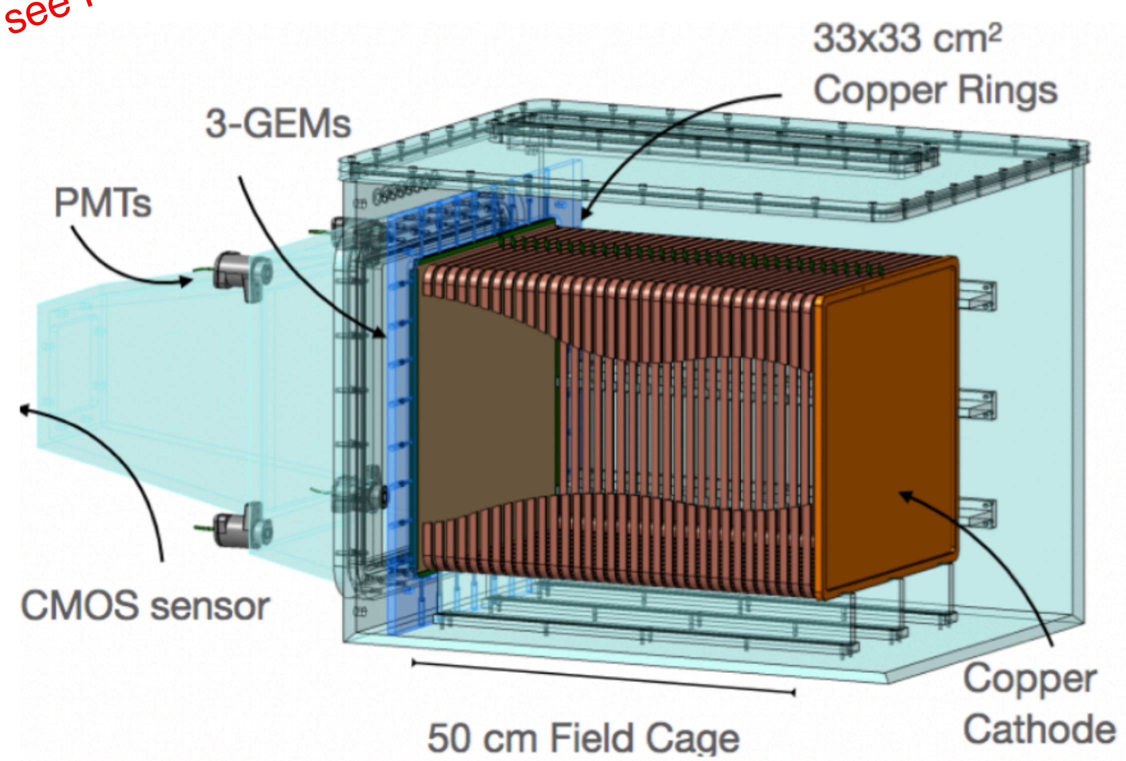
The LIME prototype: CYGNO Phase 0

see Piacentini's talk on Wednesday

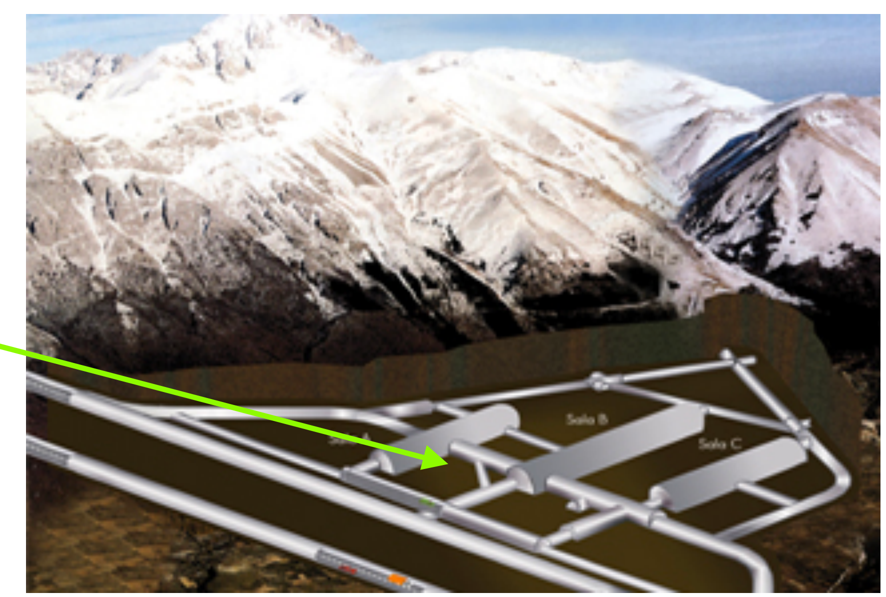
- Directionality studies performed with LIME prototype
  - Basic module for larger detector
- Last prototype developed:
  - 50 cm drift
  - 33 x 33 cm^2 GEMs
  - 50 litres sensitive volume (0.05 m^3)
  - 1 sCMOS camera (ORCA Fusion)
  - 4 PMTs

HIGH RESOLUTION
2304 × 2304
5.3 Megapixels

READOUT NOISE
0.7 electrons rms
Ultra-quiet Scan

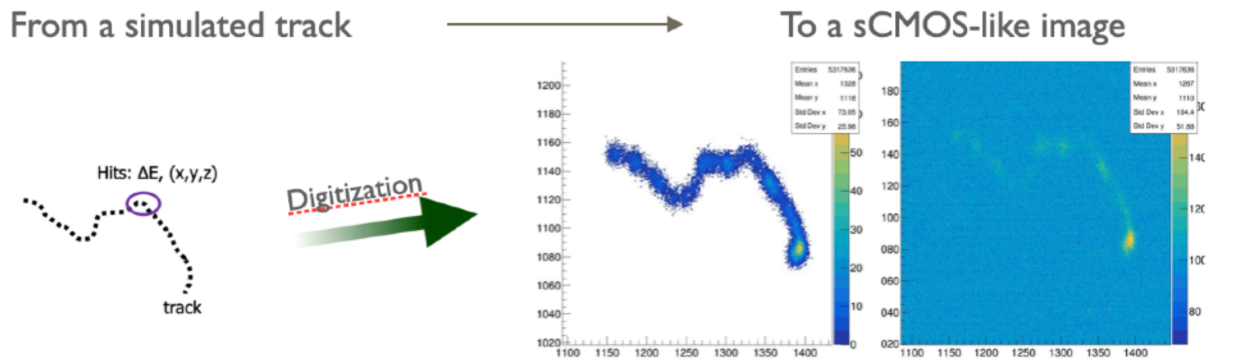


- Light response of 650 ph/keV
- Full detection efficiency in the whole 50 l
- <1 keV$_{ee}$ threshold with the new camera
- LIME is currently taking data underground at LNGS



Amaro, F.D. et. al The CYGNO Experiment. Instruments 2022, 6, 6.

Simulation and comparison

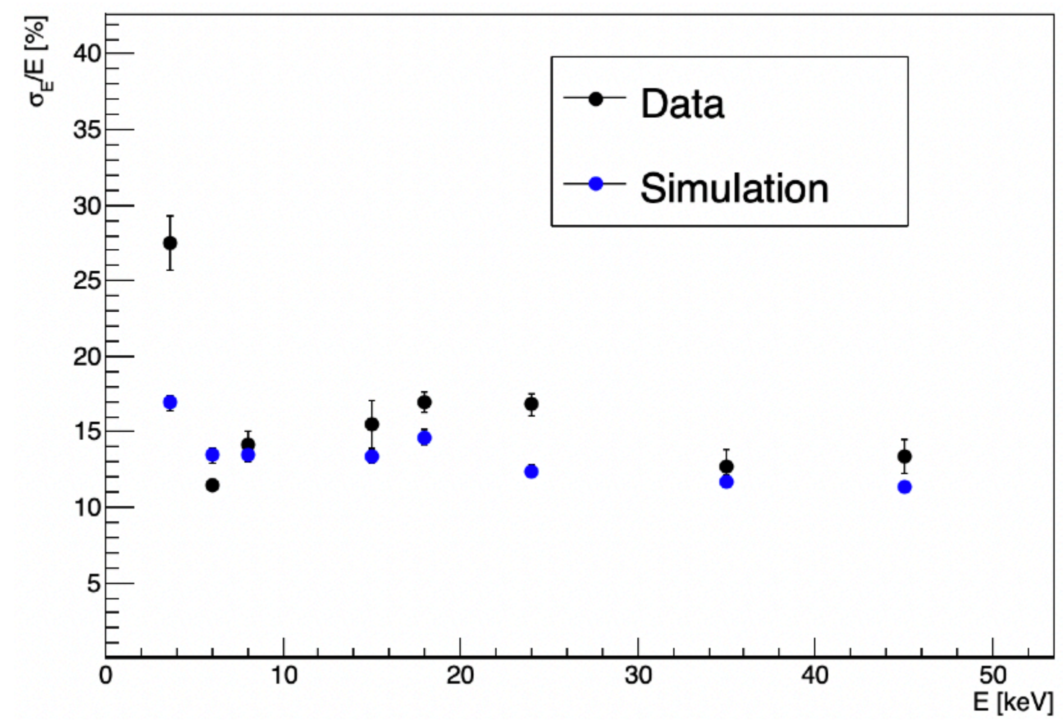


- Digitization of simulated tracks into sCMOS pictures

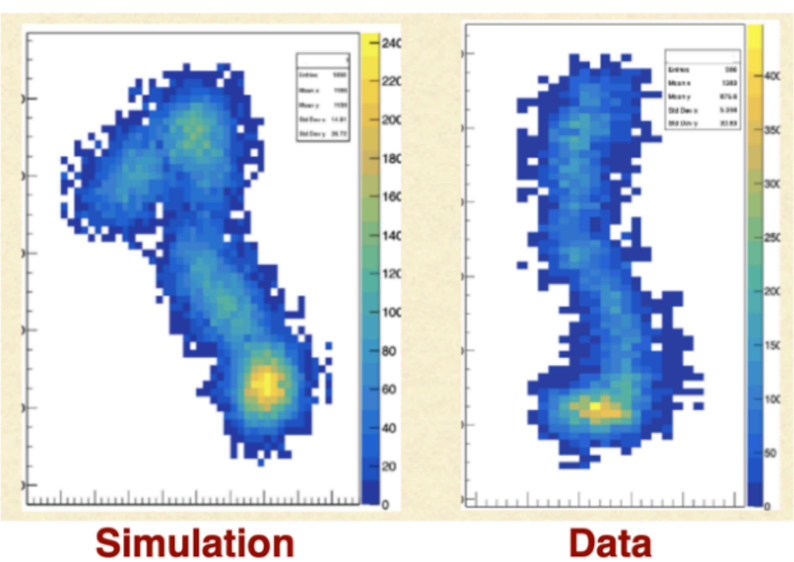
Developed taking into account detector effect:

- Fluctuation in primary electrons production (poiss.)
- GEM gain fluctuation (expo.)
- Gain dependence on electron density
- Electron diffusion from measured coefficients
- Fluctuation in photon production (poiss.)
- Light collection efficiency
- Vignetting effect with track produced in different x-y
- Addition of noise from a real sCMOS picture

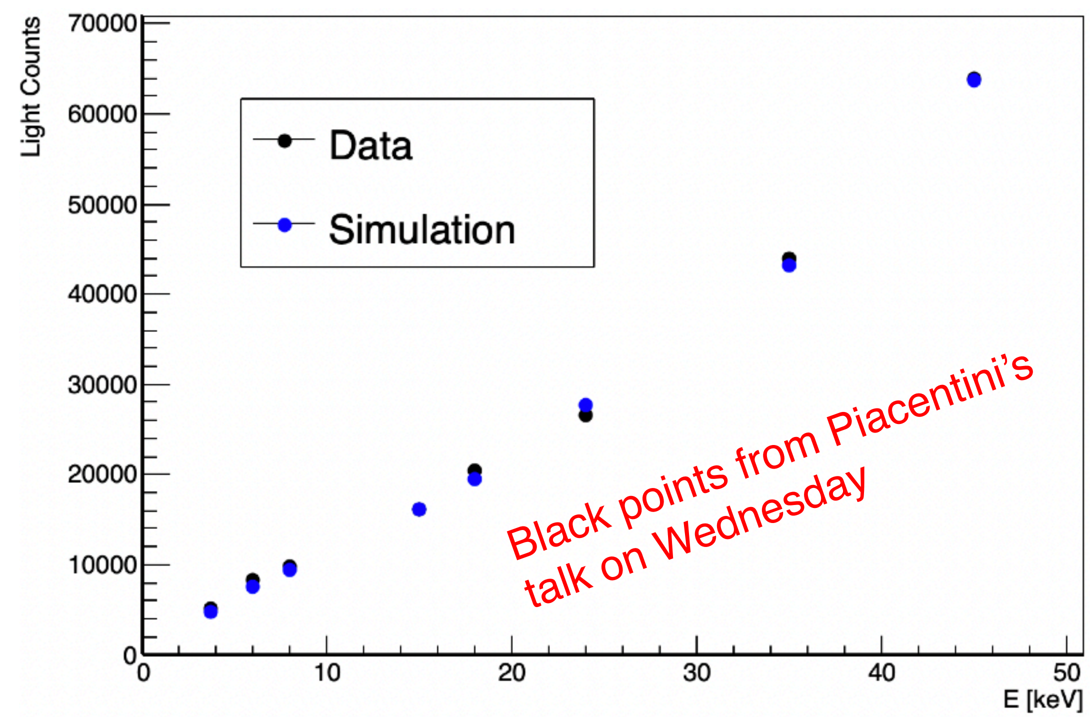
Paper out soon



30 keV electron



- Simulated tracks will be used to study 2D electron directionality
- Work in progress for the third coordinate



Track shape variables comparison

- Simulation in agreement with data in response, and energy resolution
- Directionality studies based on simulated tracks → deeper comparison on tracks needed with respect the response only
- 9 track shape variables have been compared between data and MC:
  - Length: lenght of the main axis of the ellipse that surround the track
  - Width: lenght of the shorter axis of the ellipse that surround the track
  - Slimness: ratio length over width
  - Track desnity: ratio between the total light and the number of pixels
  - $\Delta E/\Delta X$: ratio energy over length
  - Mean of the gaussian that fit the track transverse profile
  - Sigma of the gaussian that fit the track transverse profile
  - Number of Pixels
  - Size of the track cluster without zero suppression

sPlots: a statistical tool to unfold data distributions

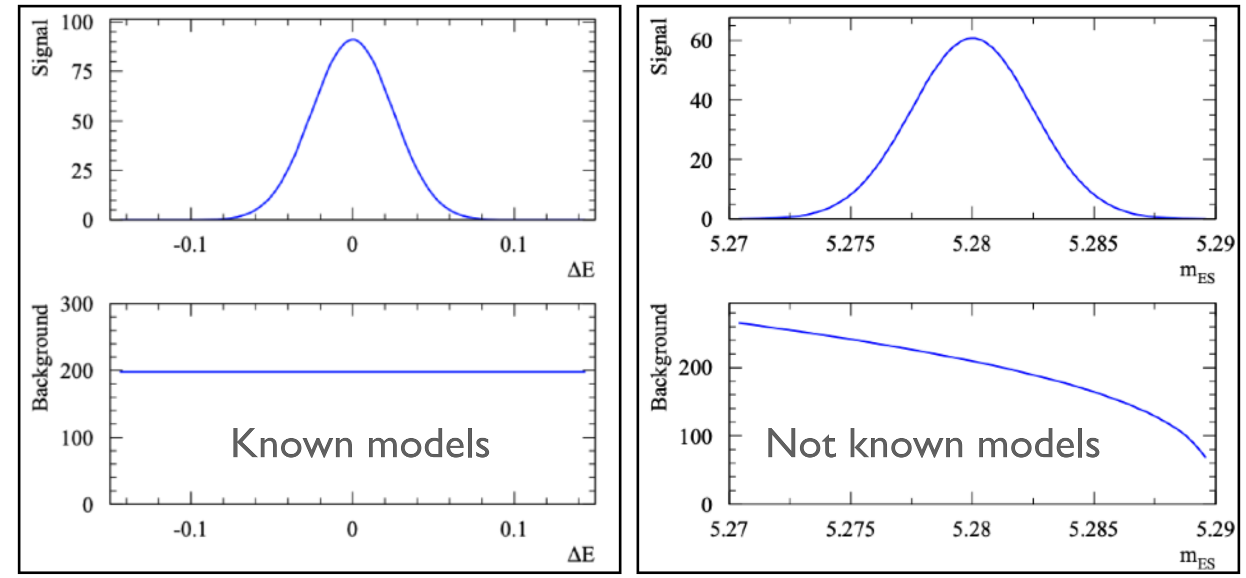
- Dataset containing two variables (consisting of signal S and background B)
- By fitting one distribution (with S + B model)

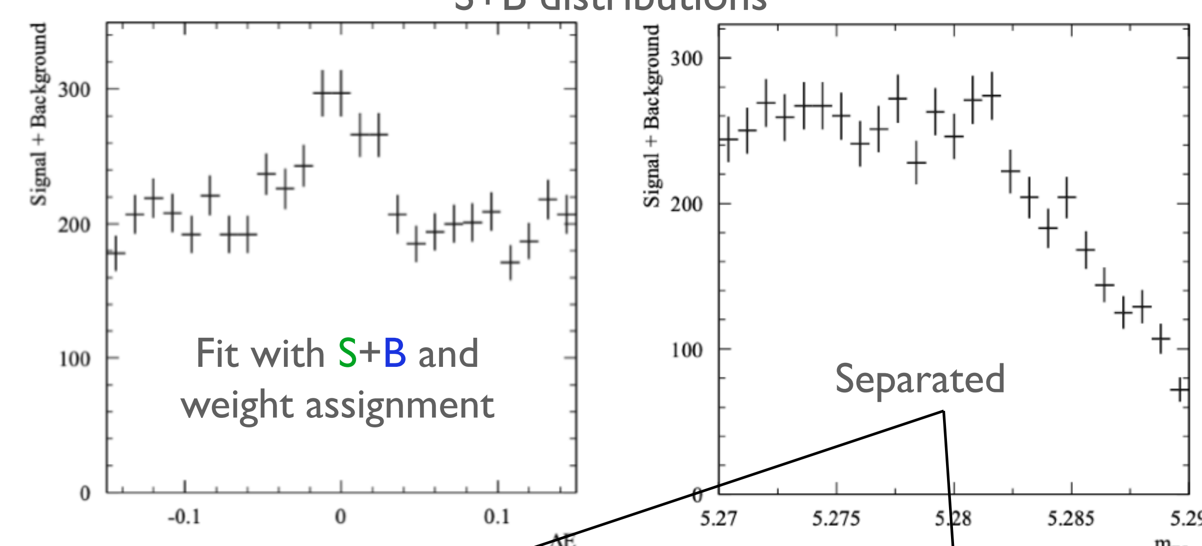
  ↓

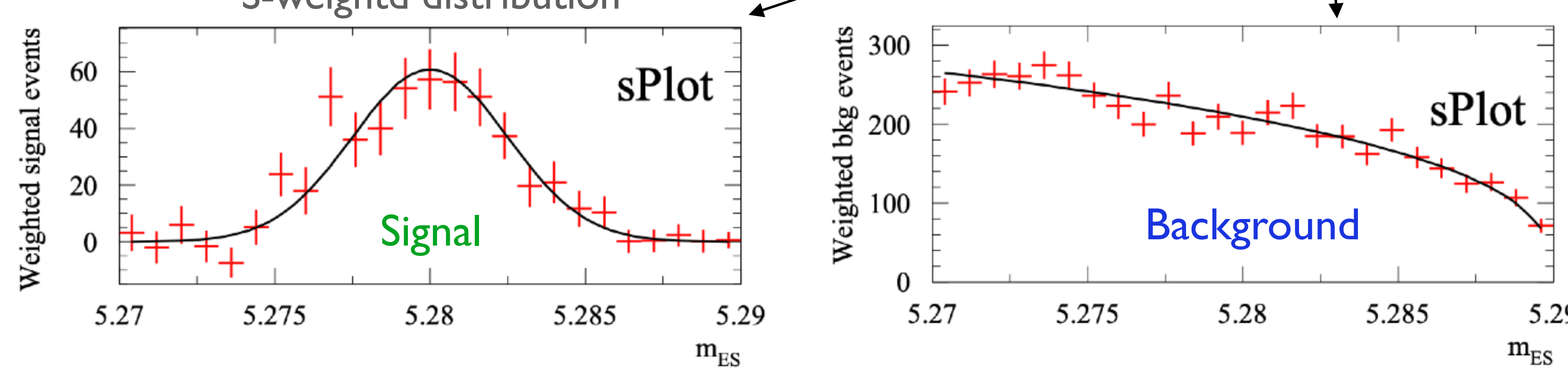
  S weight and B weight assigned to each event proportional to probability of being S and B

- The pure S and pure B distribution can be unfolded by weighting each event by the weight of being S and B
- Since the weight can be positive or negative plotting the pure signal distribution the negative weight cancels the background part

Nucl.Instrum.Meth.A 555 (2005), 356-369

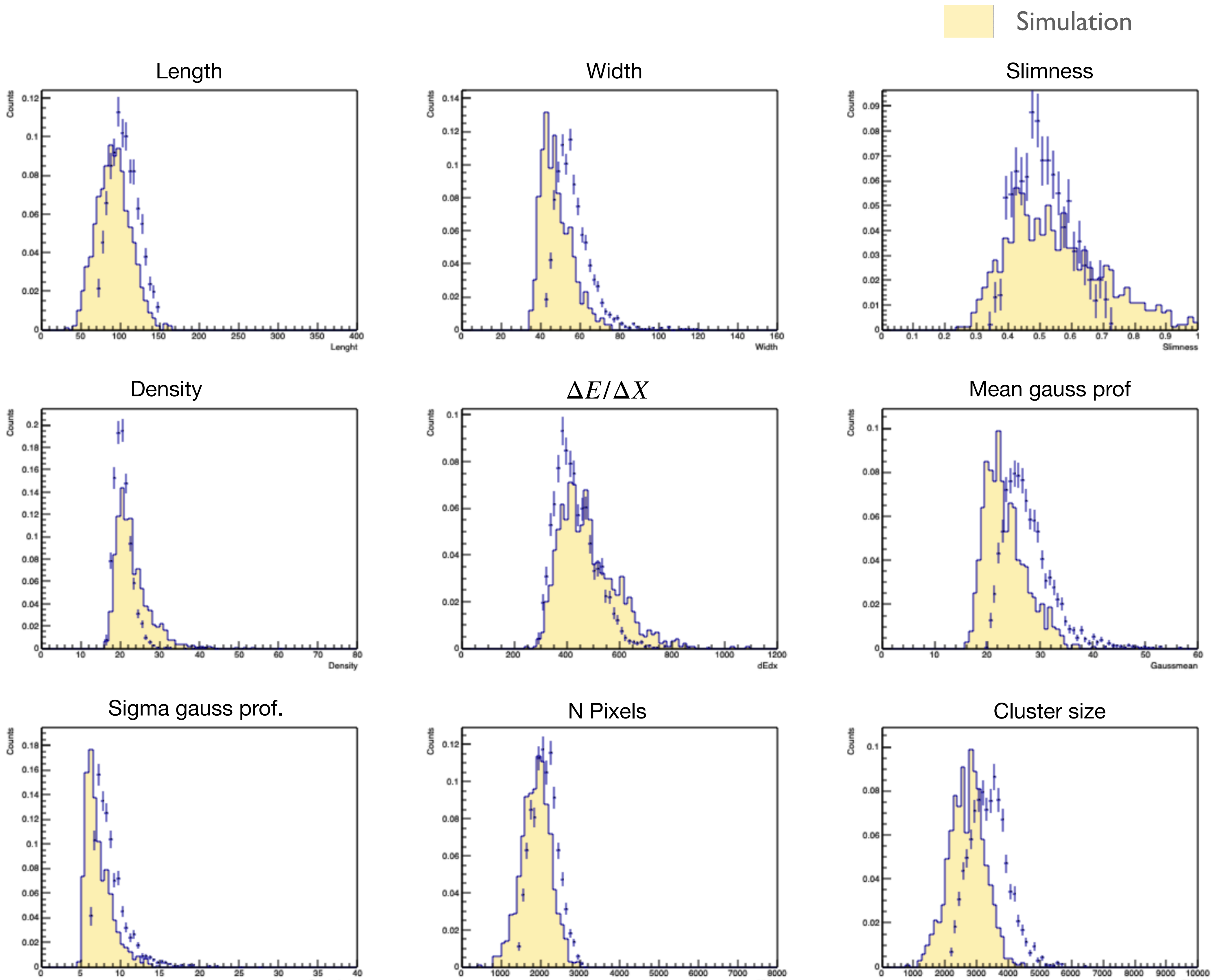






Track shape parameters comparison

Barium data



Study of the directionality performances

Directionality algorithm in a nutshell

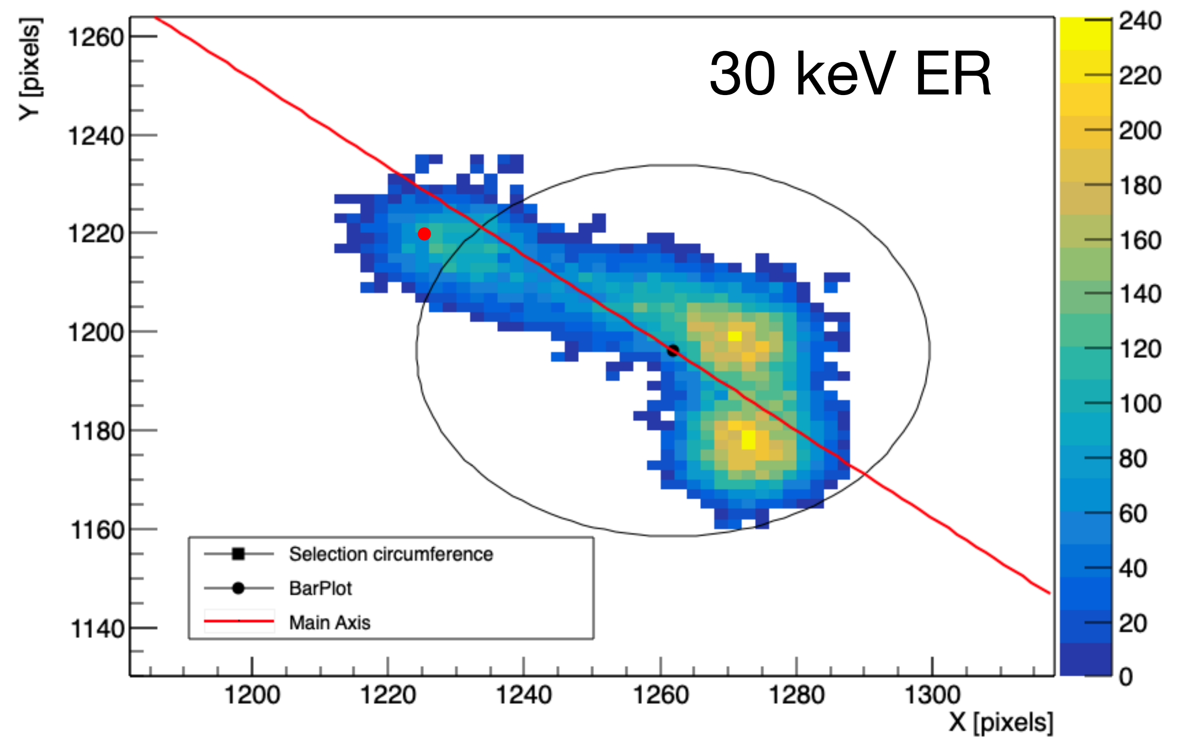
- Algorithm adapted from X-ray polarimetry:

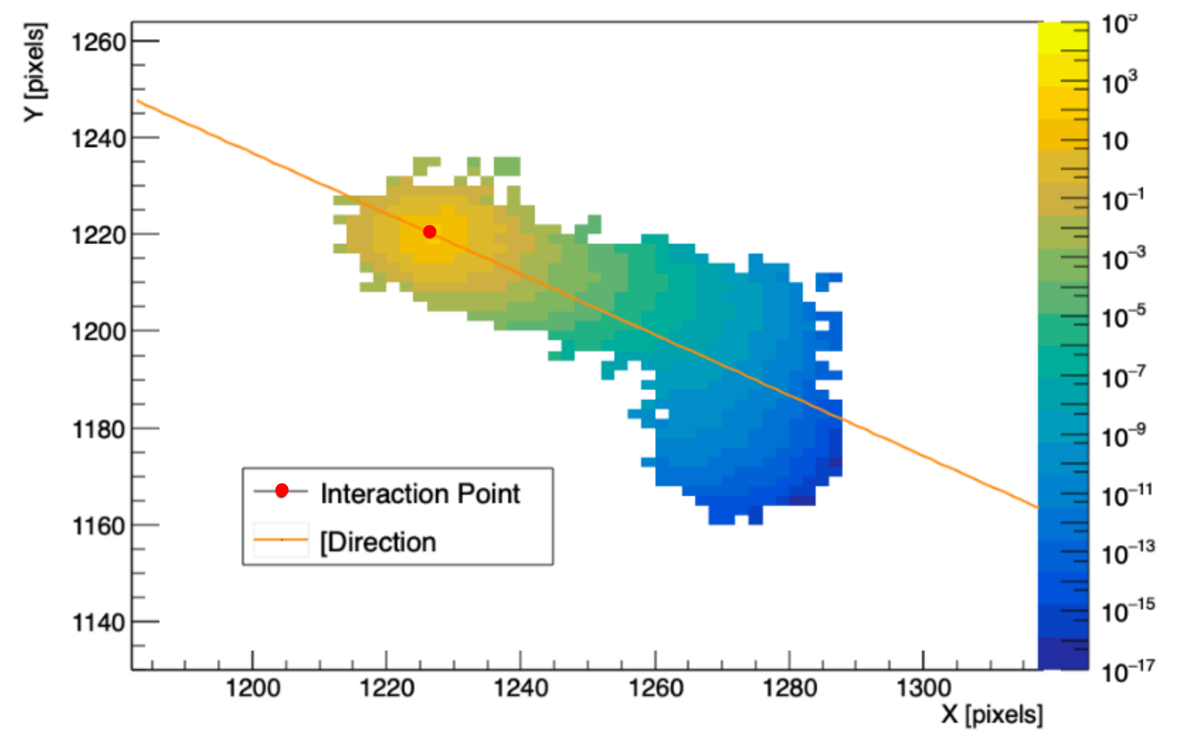
"Measurement of the position resolution of the Gas Pixel Detector" Nuclear Instruments and Methods in Physics Research Section A, Volume 700, 1 February 2013, Pages 99-105

- 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

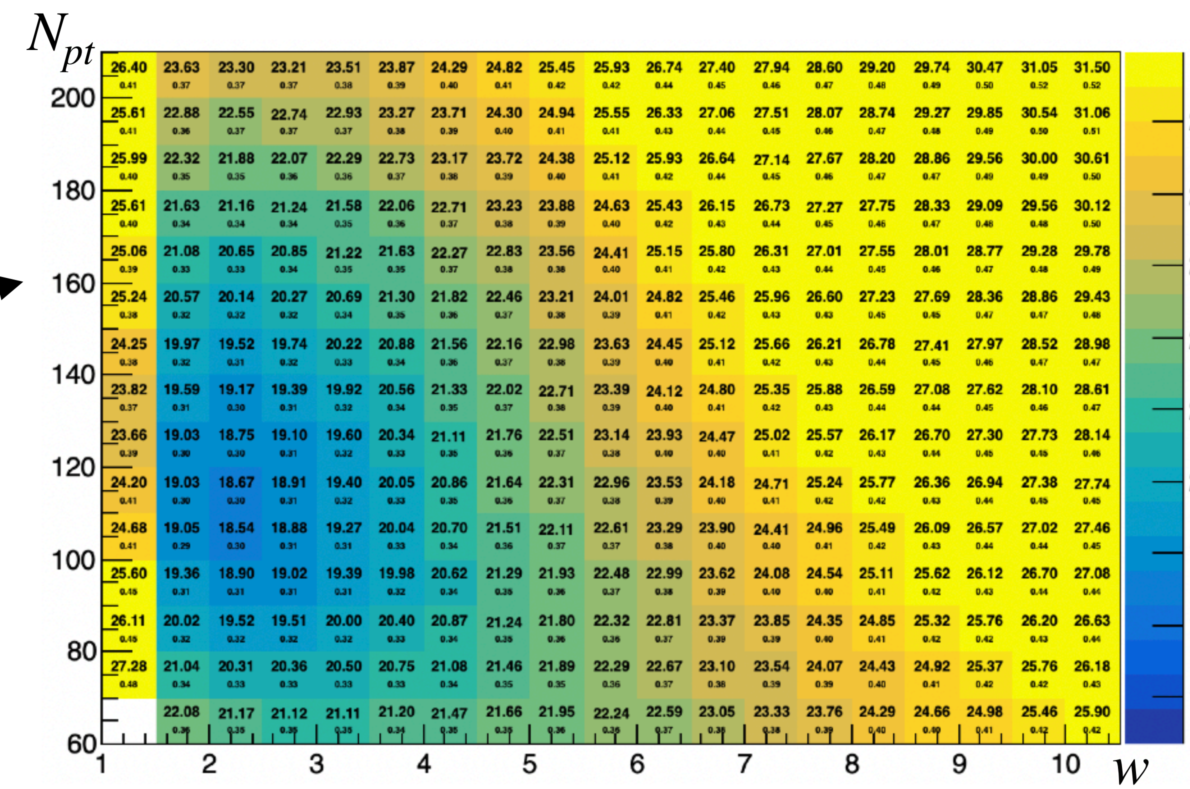
- Two parameters of the algorithm: N_{pt} and w

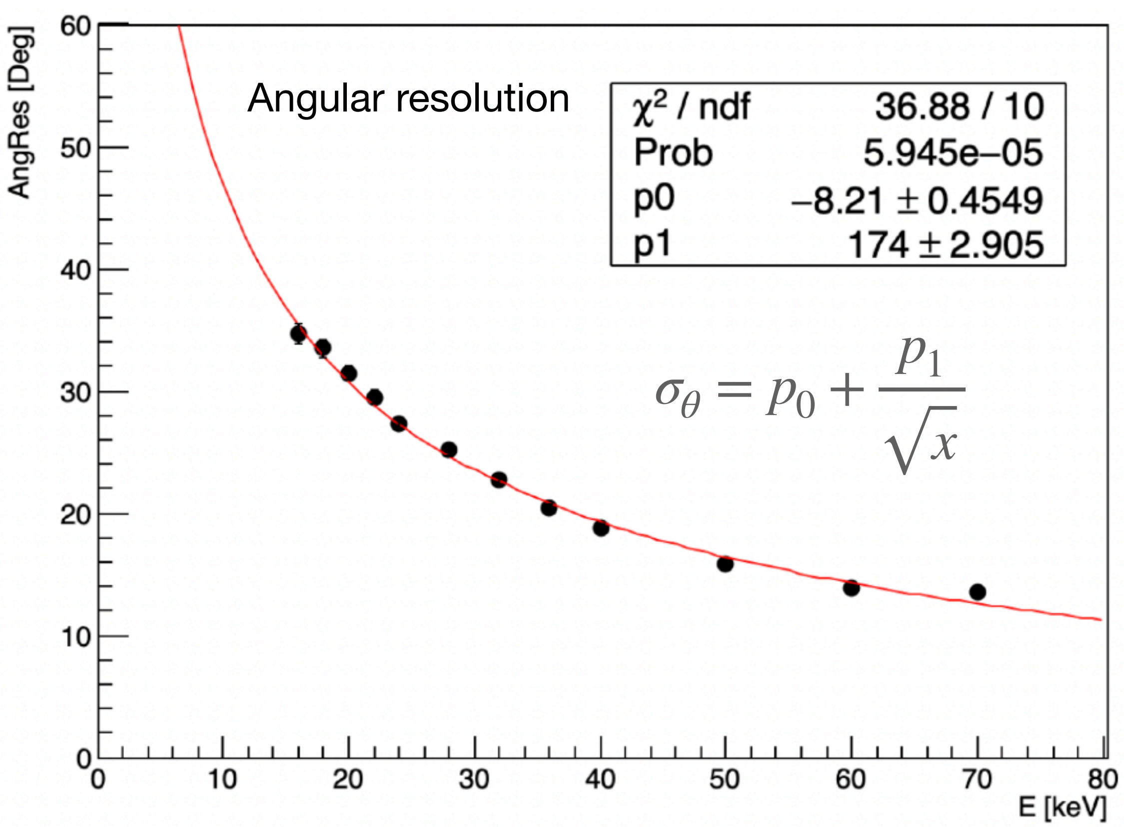


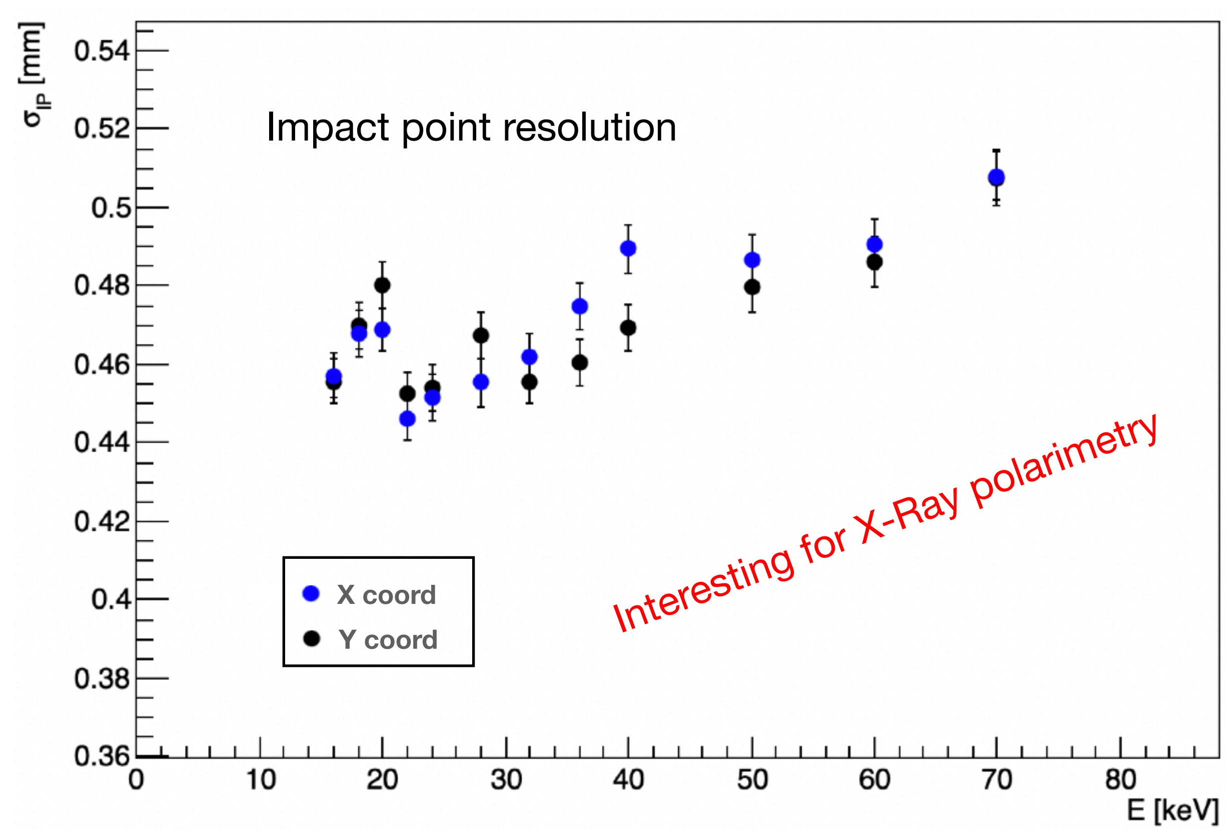


Parameters optimization and results

- Optimization & performances on simulated tracks
- Tracks simulated isotropically in direction and in the whole detector volume (5-45 cm diffusion)
- Scan of angular resolution vs N_{pt} and w
- Parameters which provide the best angular resolution used
- Resolution as the sigma of $\theta_{meas} - \theta_{true}$ distrib.







Sensitivity studies

Sensitivity studies

- Sensitivity studies on solar neutrino detection performed with a Bayesian framework:

Posterior probability — Likelihood — Prior probabilities — Normalization

$$p(\mu_s, \mu_b | D) = \frac{p(D | \mu_s, \mu_b) \cdot \pi(\mu_s) \cdot \pi(\mu_b)}{p(D)}$$

Binned likelihood

$$L = \prod_{i,j} \frac{\lambda_{i,j}^{n_{i,j}} e^{-\lambda_{i,j}}}{n_{i,j}!}$$

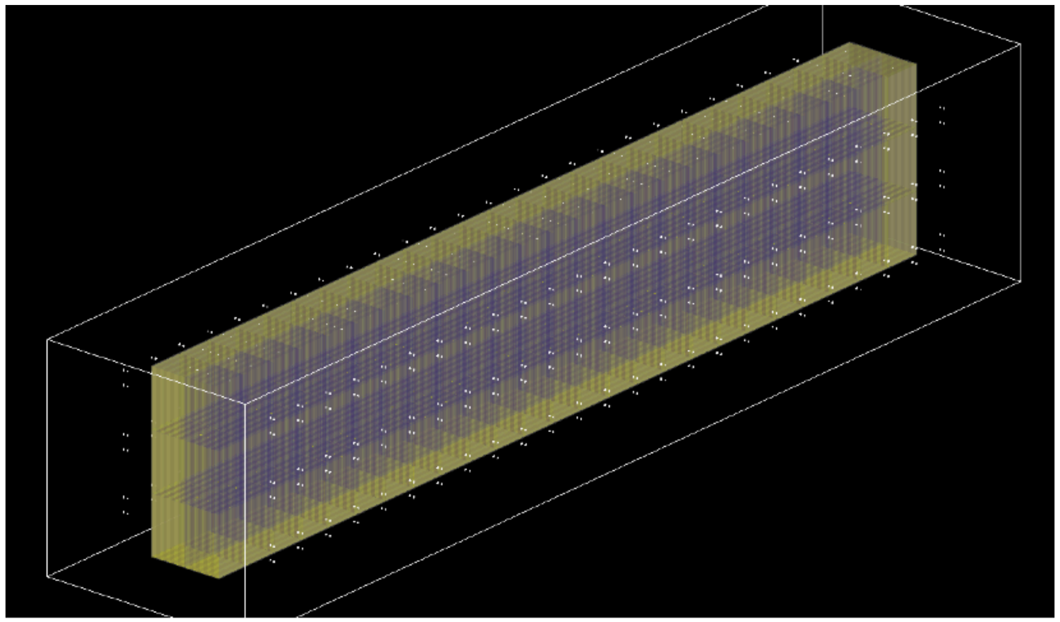
- Assumptions:
  - Same resolution in both theta (on the GEM plane) and phi (respect to the perpendicular to the GEM plane) given the PMT time resolution.
  - Isotropic gamma background
  - Energy and angular resolution taken from data and MC respectively (shown before)
  - Threshold on electron energy of 10 keV (55 keV on ν energy)

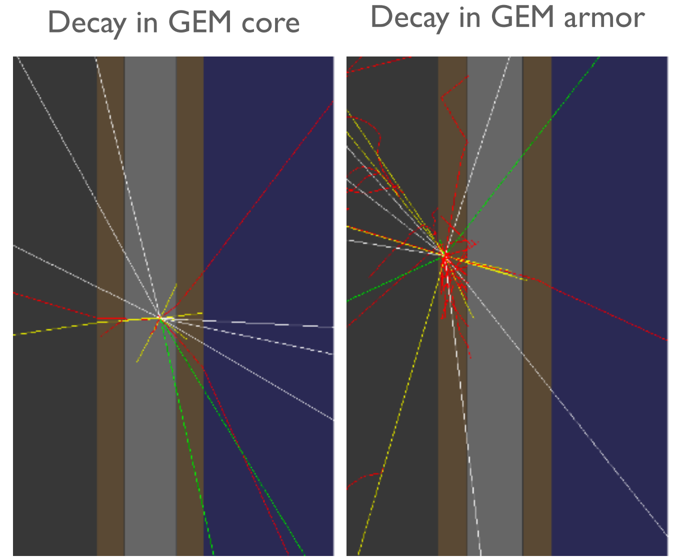
- Strategy:
  - Model for signal and background
  - ToyMC production
  - Likelihood fit for S+B model (H_1) and only B model (H_0)
  - Calculation of the Bayes factor and discovery probability vs exposure

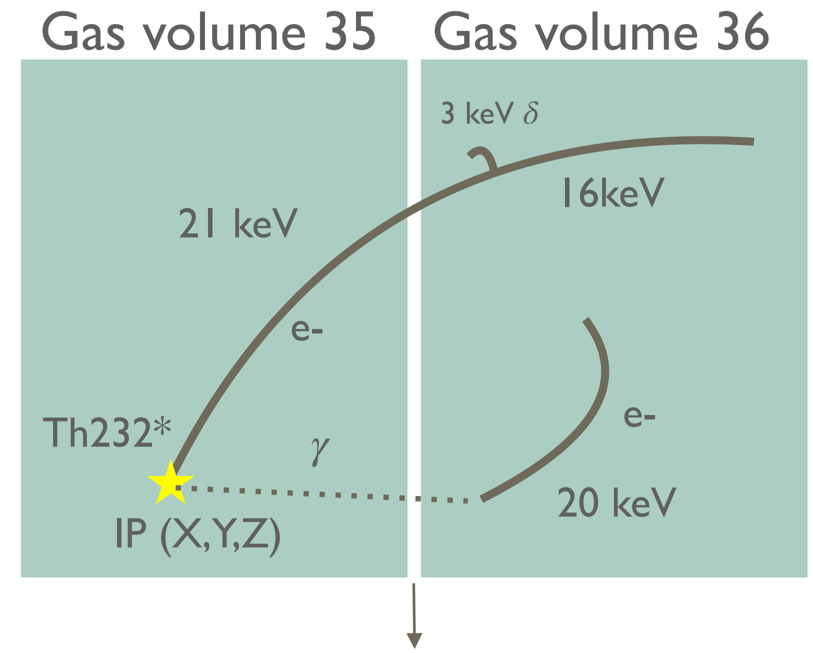
$$p(H_1 | D) = \frac{\mathscr{L}(D | H_1) \cdot \pi(H_1)}{p(D)} \qquad p(H_0 | D) = \frac{\mathscr{L}(D | H_0) \cdot \pi(H_0)}{p(D)}$$

$$\frac{p(H_1 | D)}{p(H_0 | D)} = \frac{\mathscr{L}(D | H_1) \cdot \pi(H_1)}{\mathscr{L}(D | H_0) \cdot \pi(H_0)} = B_f \frac{\pi(H_1)}{\pi(H_0)}$$

Background studies





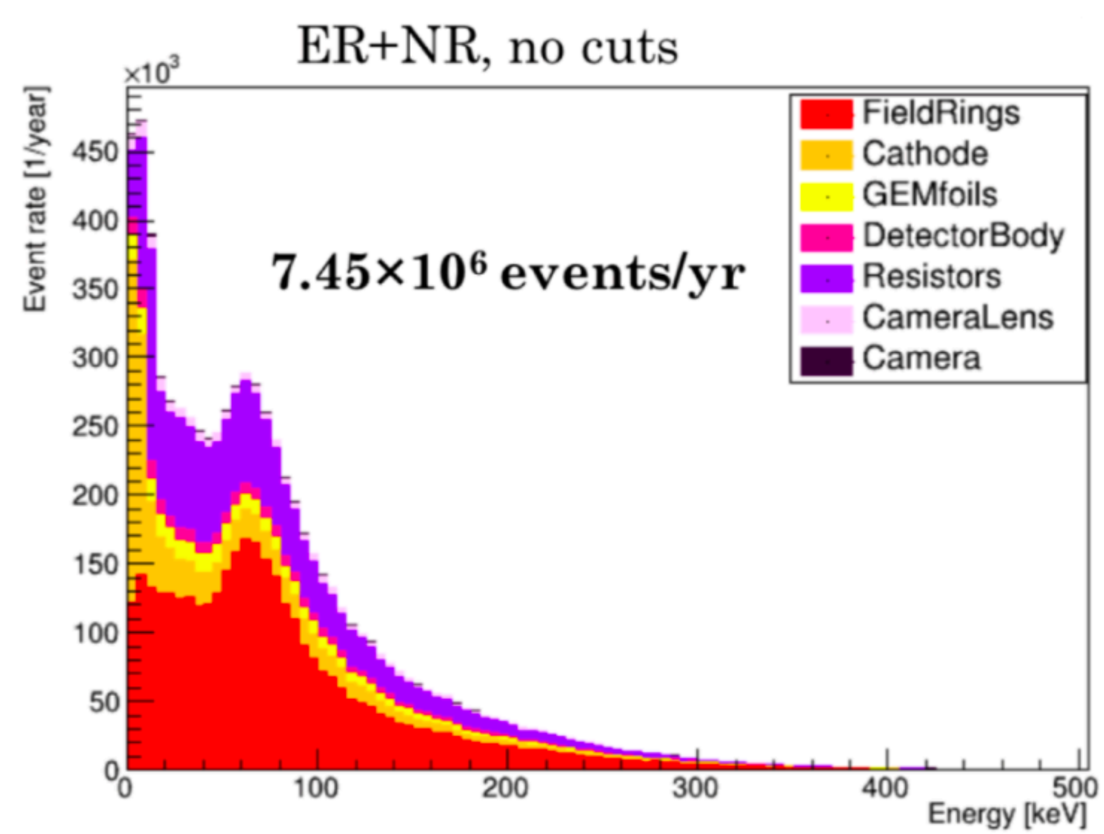


40 keV electron +20 keV electron in the final spectrum

- Bkg simulation of the full detector geometry → 3x25 CYGNO-04 modules

- Most crytical detector element from LIME background studies icluded in the simulation:
  - Field cage
  - Cathode
  - GEMs
  - Detector body (Vessel)
  - Resistors
  - Camera lenses
  - Camera sensor

- Simulation done with most ultrapure materials avealiable now → detector to be realized in ~ 6y



Material choise

Reference:

- Electroformed copper by Majorana Collaboration: MAJORANA Collaboration • N. Abgrall (LBNL, NSD and Shanghai Jiao Tong U.) et al. Nucl.Instrum.Meth.A 828 (2016), 22-36
- Acrylic insulator from SNO: Systematic study of trace radioactive impurities in candidate construction materials for EXO-200 D.S. Leonard (Alabama U.), et al. Nucl.Instrum.Meth.A 591 (2008), 490-509
- SMD Resistors from XENON-1T: Material radioassay and selection for the XENON1T dark matter experiment. XENON Collaboration • E. Aprile (Columbia U.) et al. Eur.Phys.J.C 77 (2017) 12, 890
- Suprasil lenses and camera sensor: Measurement performed @ LNGS - low radioacitvity lab.

Detector element	Material	^{238}U	^{232}Th	^{40}K	^{235}U	^{226}Ra	^{228}Th
GEM core	Acrylic	< 296.0 μBq/Kg	< 56.9 μBq/Kg	< 71.2 μBq/Kg	x	eq	eq
GEM armor	EFCu	0.131 μBq/Kg	0.034 μBq/Kg	x	x	eq	eq
Field cage support	Acrylic	< 296.0 μBq/Kg	< 56.9 μBq/Kg	< 71.2 μBq/Kg	x	eq	eq
Field cage strip	EFCu	0.131 μBq/Kg	0.034 μBq/Kg	x	x	eq	eq
Cathode	EFCu	0.131 μBq/Kg	0.034 μBq/Kg	x	x	eq	eq
Vessel	EFCu	0.131 μBq/Kg	0.034 μBq/Kg	x	x	eq	eq
Camera sensor	Silicon	2 mBq/Kg	2.8 mBq/Kg	9 mBq/Kg	x	eq	eq
Camera lenses	Suprasil	123 μBq/Kg	40.7 μBq/Kg	0.3 mBq/Kg	x	eq	eq
Resistors	Al_2O_3	1 μBq/pc	0.14 μBq/pc	1.2 μ Bq/pc	0.04 μ Bq/pc	0.18 μ Bq/pc	0.13 μ Bq/pc

- Purest material avealiable employed for detector realization
- Materials emplyed at the moment on LIME $\mathcal{O}(10^2 - 10^4)$ times more radioactive.
- GEMs with acrylic core from: CYGNUS: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos S.E. Vahsen(Hawaii U.), et. Al. ADS Abstract Service

Comparison with current materials for CYGNO-04

- Materials forseen for CYGNO-04

GEM	Activity (Bq/kg)
U238	1.63E-01
U235	1.58E-02
Th232	3.09E-02
K40	3.58E-01
Cs137	8.13E-03
Co60	7.48E-03

Camera Lens	Activity (Bq/kg)
U238	4.22E+00
U235	1.45E-01
Th232	3.61E-01
K40	5.15E+01
Cs137	2.67E-02
Co60	4.64E-02
La138	2.44E+00

Field Cage	Activity (Bq/kg)
238U	1.84E-02
232Th	7.77E-03
40K	1.12E-01
60Co	2.54E-03

Cathode	Activity (Bq/kg)
238U	9.01E-01
234U	4.07E-05

Sensor	Activity (Bq/kg)
U238 (Ra226)	8.13E-01
U235	1.81E-01
Th232	9.49E-01
K40	8.59E-01
Cs137	4.07E-02
Co60	5.42E-03

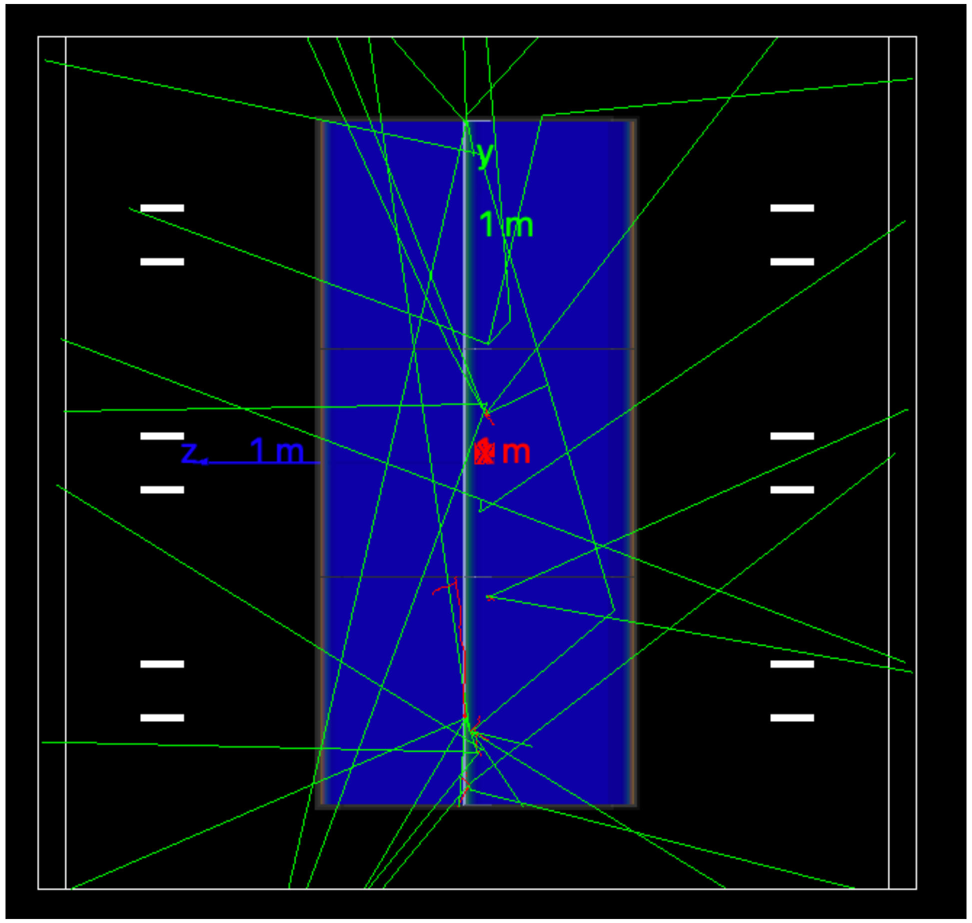
- Materials used in the CYGNO-30 simulation

Detector element	Material	^{238}U	^{232}Th	^{40}K	^{235}U	^{226}Ra	^{228}Th
GEM core	Acrylic	< 296.0 μBq/Kg	< 56.9 μBq/Kg	< 71.2 μBq/Kg	x	eq	eq
GEM armor	EFCu	0.131 μBq/Kg	0.034 μBq/Kg	x	x	eq	eq
Field cage support	Acrylic	< 296.0 μBq/Kg	< 56.9 μBq/Kg	< 71.2 μBq/Kg	x	eq	eq
Field cage strip	EFCu	0.131 μBq/Kg	0.034 μBq/Kg	x	x	eq	eq
Cathode	EFCu	0.131 μBq/Kg	0.034 μBq/Kg	x	x	eq	eq
Vessel	EFCu	0.131 μBq/Kg	0.034 μBq/Kg	x	x	eq	eq
Camera sensor	Silicon	2 mBq/Kg	2.8 mBq/Kg	9 mBq/Kg	x	eq	eq
Camera lenses	Suprasil	123 μBq/Kg	40.7 μBq/Kg	0.3 mBq/Kg	x	eq	eq
Resistors	Al_2O_3	1 μBq/pc	0.14 μBq/pc	1.2 μ Bq/pc	0.04 μ Bq/pc	0.18 μ Bq/pc	0.13 μ Bq/pc

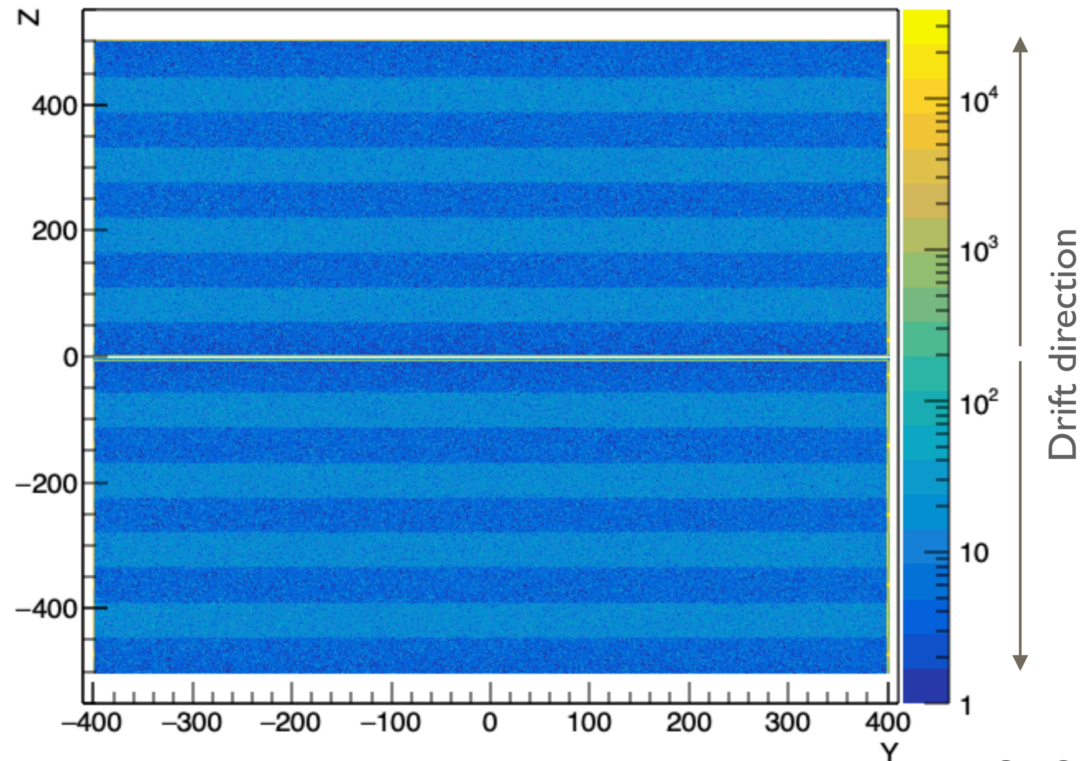
Event production

- For every detector element (GEMs in/out, Cathodes, Rings, ecc…):
  - For every contaminant (U238,U235,K40, ecc…):

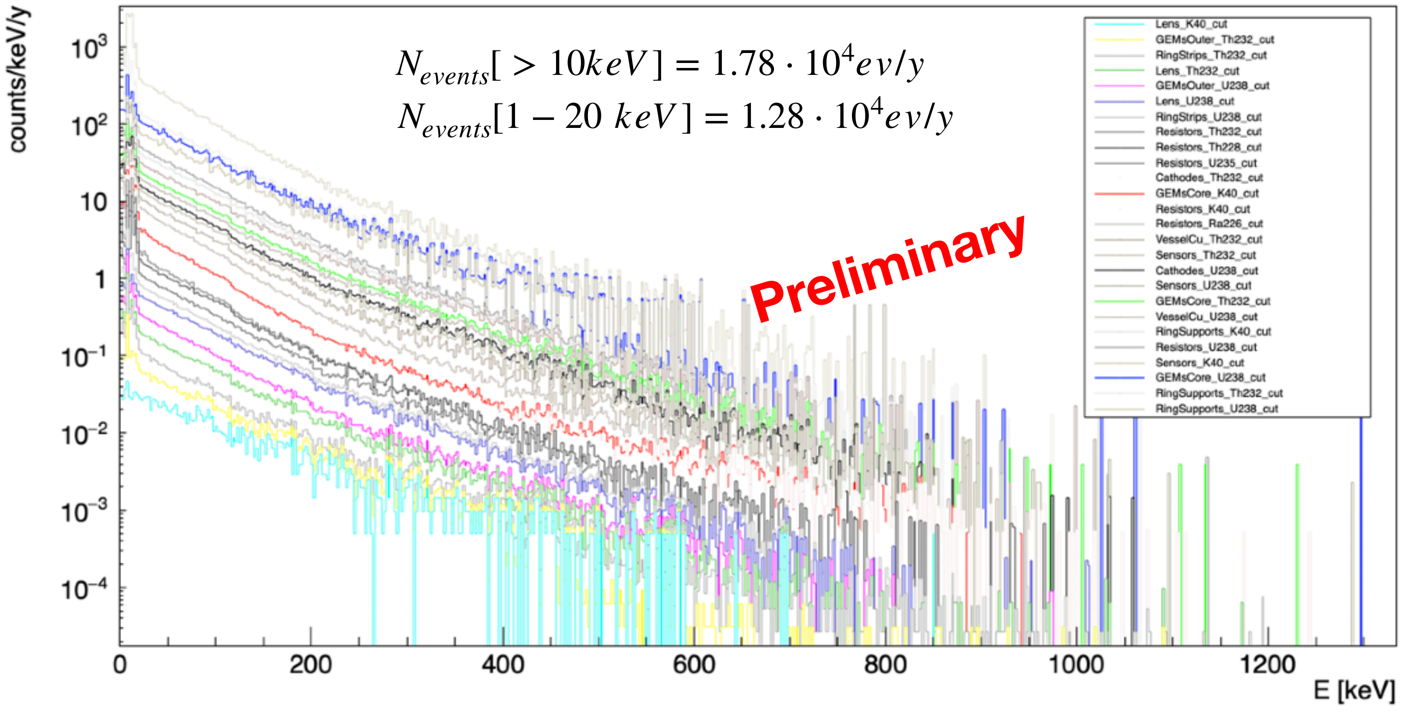
1. Extraction of a random detector element (GEM_34, GEM_75)
2. Extraction of a random point on the element volume
3. Simulation of the whole decay chain of the element, taking into account also atomic excited states (ps Life), until the chain break if not in secular equilibrium



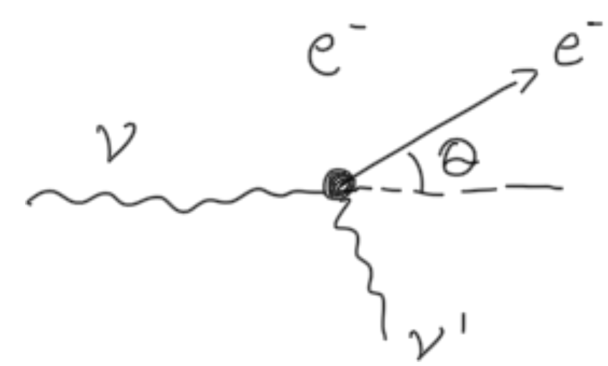
$$Norm = \frac{1}{N_{ev}} \cdot A\left[\frac{dec}{s \cdot kg}\right] \cdot M[kg] \cdot 3.15 \cdot 10^{7}\left[\frac{s}{y}\right]$$



Fiducialization cutting 1 mm from the edge of each gas volume



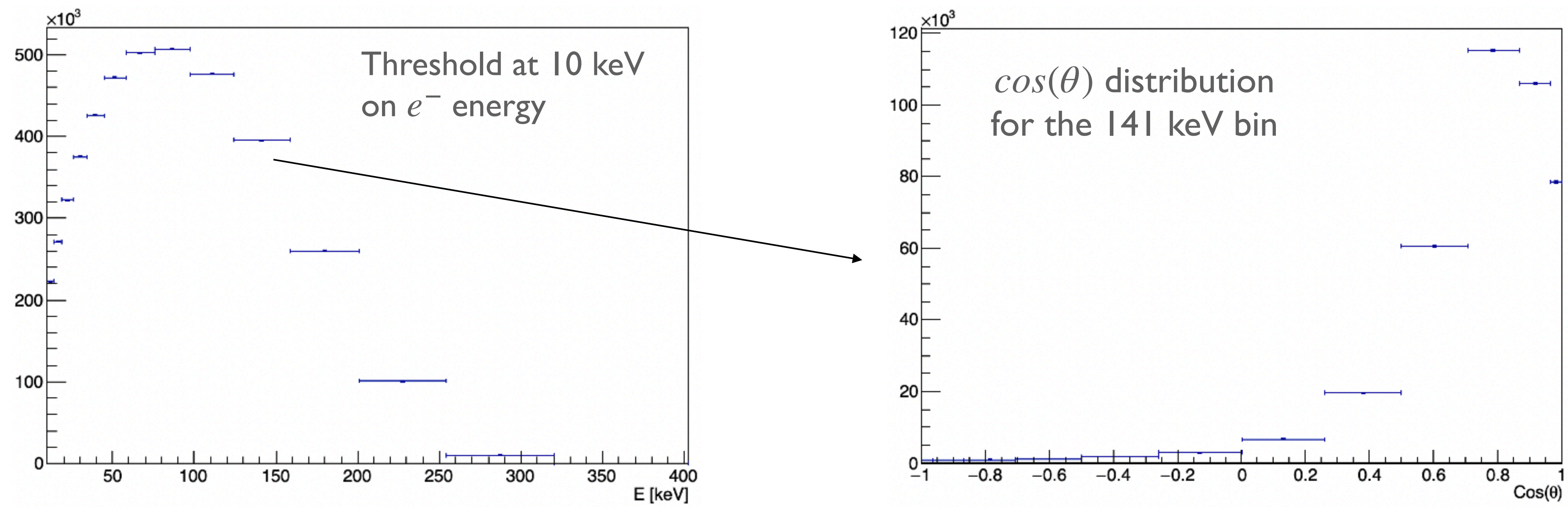
Template production



- Template produced starting from the expected distribution adding the detector resolution
  - For each energy bin the cos(θ) distribution is produced

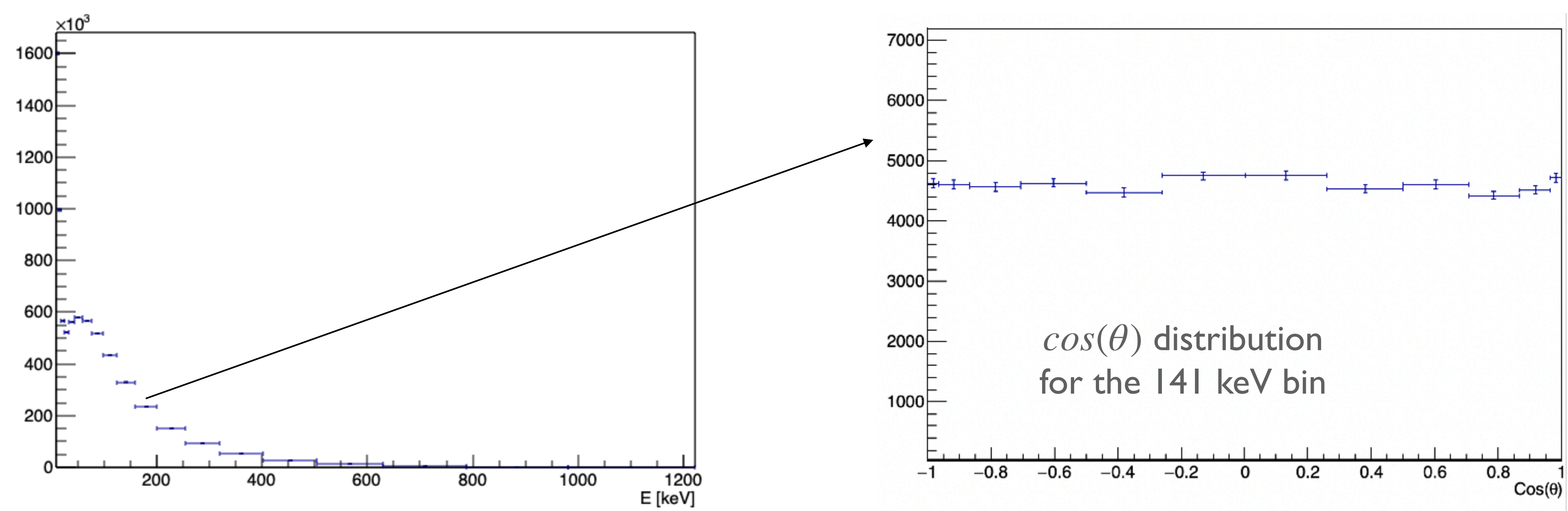
- Signal

Produced starting from the pp cycle neutrino, simulating the interaction and adding the detector resolution



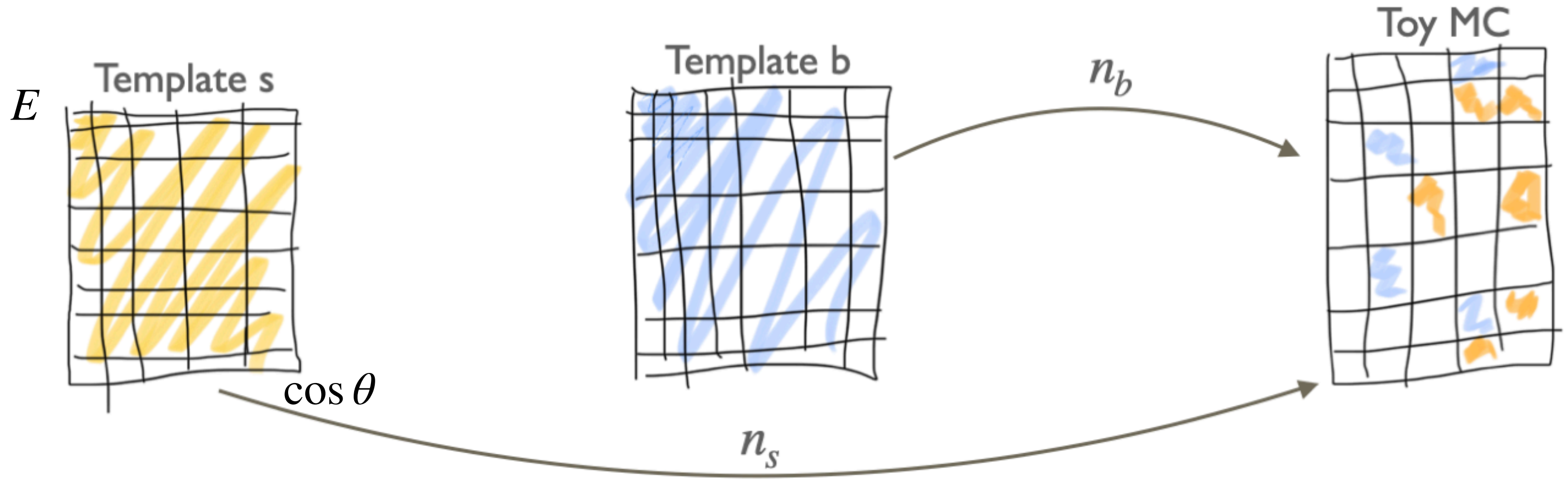
- Background

From CYGNO_30 background simulation



Toy-MC analysis

- Toy-MC generated by a hypothesis on of $\bar{N}_s$ and $\bar{N}_b$, extracting poissonianly the values of n_s and n_b, and filling an E-cos(θ) histogram with the extracted events from the templates



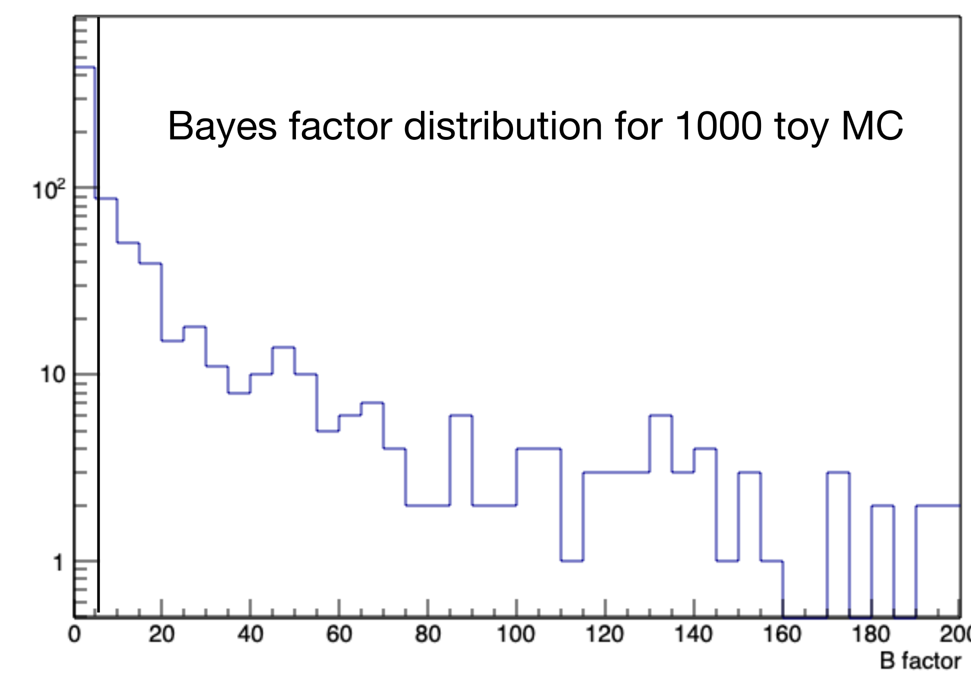
- 1000 toy MC produced for different exposure have been produced: Exposure from 6 to 120 months in step of 6 months
- Tested also different hypothesis of background reduction: R_f = x1, x2, x5, x10, x15, x20, x30, x50
  - $\bar{N}_s = 30 ev/y \cdot exp$ $\qquad$ $\bar{N}_b = 1.78 \cdot 10^4 ev/y \cdot exp/R_f$
- Each toy fit with B (H_0) model and S+B (H_1) model
- Calculation of the Bayes factor:

$$\frac{p(H_1|D)}{p(H_0|D)} = \frac{\int \mathscr{L}(D|\mu_b, \mu_s, H_1)\pi(\mu_b)\pi(\mu_s)d\mu_b d\mu_s}{\int \mathscr{L}(D|\mu_b, H_0)\pi(\mu_b)d\mu_b} \cdot \frac{\pi(H_1)}{\pi(H_0)} = B_f \frac{\pi(H_1)}{\pi(H_0)}$$

0.5/0.5

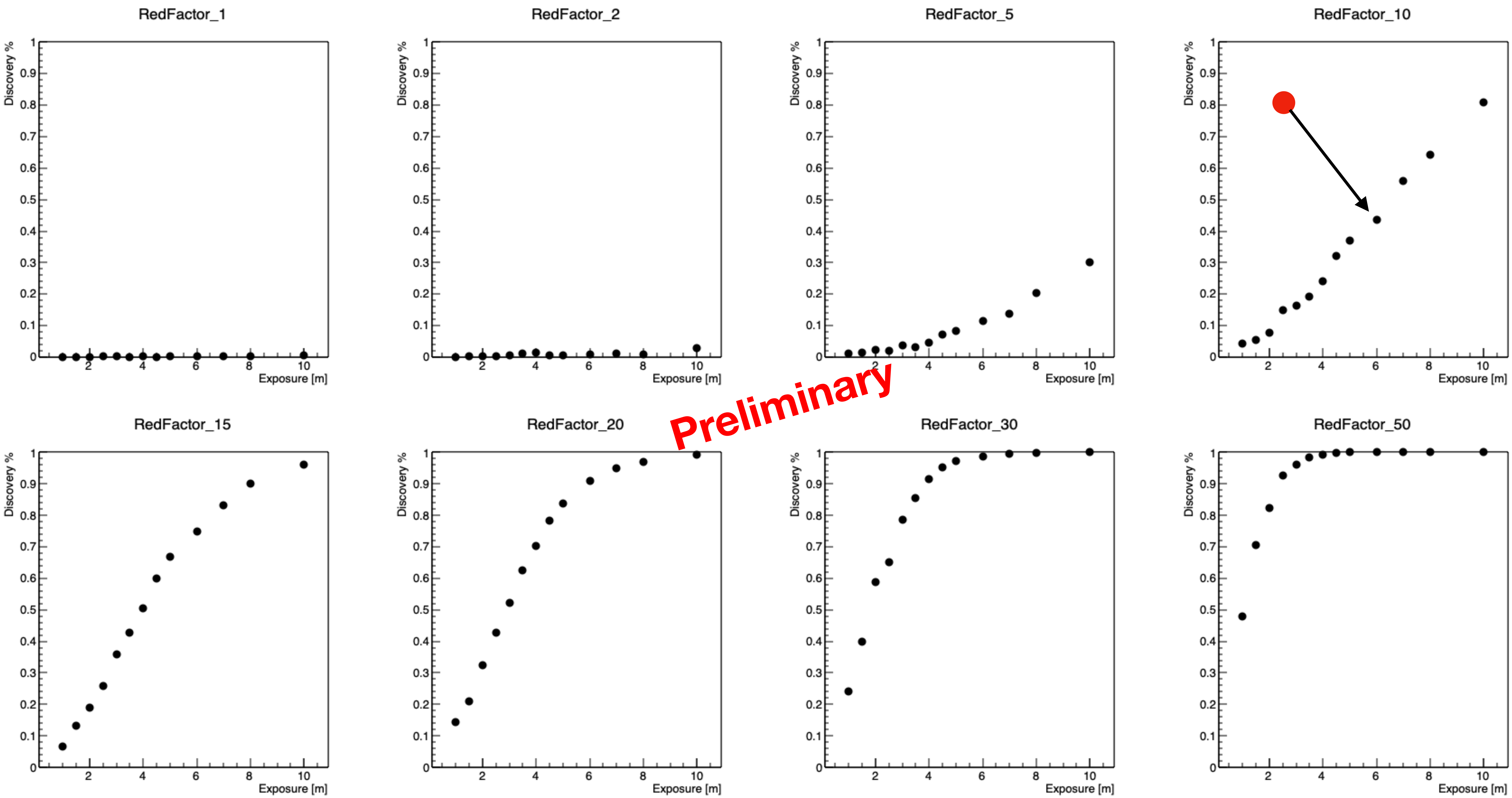
- Discovery probability with a BF>5:

$$DP(exp, R_f) = \frac{N_{toy}(BF > 5)}{N_{toy}}$$



Sensitivity results

- Plot of the discovery probability with BF>5 as a function of the exposure for different further background reduction



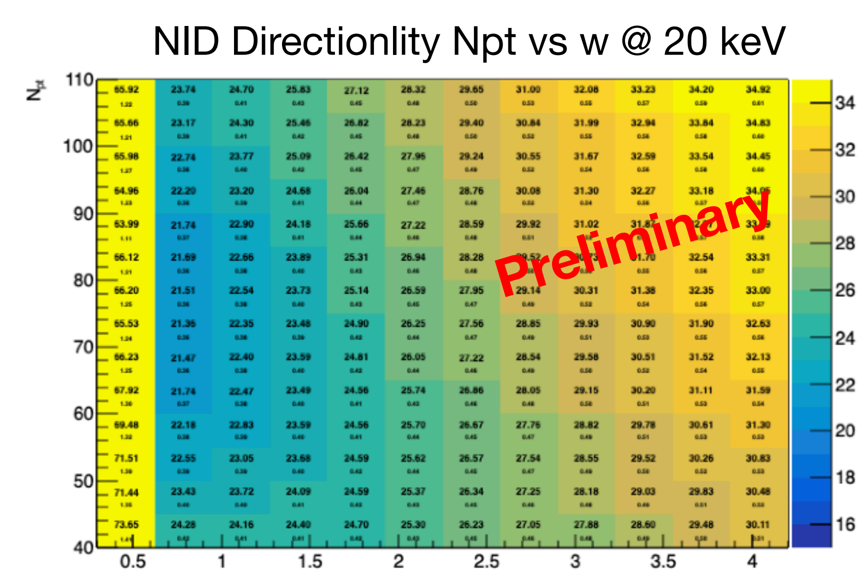
- With a bkg reduction of a factor 10 there are 45% probability of collecting data for which the S+B model is at least 5 times more probable than the only B model → 180 neutrino signal over 10680 ev. of background

Conclusions of feasibility of directional solar neutrino measurement

- Solar neutrino can be object of study with directional TPC approach
- Directionality can increase the bkg toleration and can lead to a spectroscopic measurement of the solar pp flux
- The energy response and resolution of the 50L prototype have been studied and a simulation able to reproduce the data has been developed
- In this context an algorithm to measure directionality of low energy electrons has been developed and optimised for CYGNO
- CYGNO-30 can perform a solar neutrino measurement at 10 keV threshold in a reasonable amount of time if the background can be constrained down to ~10^4 events/y (same requirement to make a meaningful DM search)

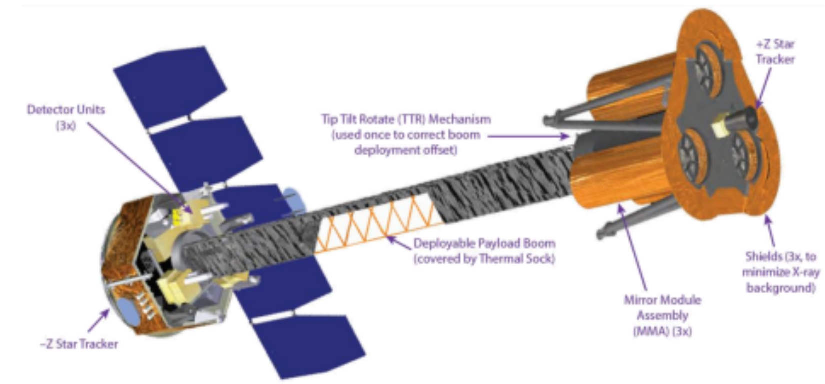
To do…

- Study the angular resolution for NID diffusion
- Repeat the sensitivity study with the new resolution found and study the impact of a better directionality on this measurement



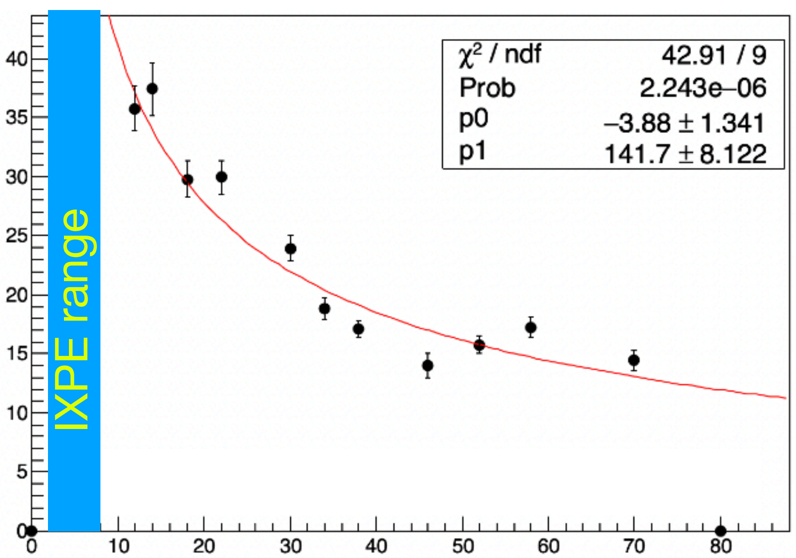
Bonus slide: X-Ray polarimetry

- Doing X-Ray polarimetry means doing electron directionality
- Same directionality studies done on MANGO 10x10x10 cm^3 detector with granularity 0.049mm/pixel
- The detector can be employed in the x-ray polarimetry with large field of view (IXPE must point towards the source)

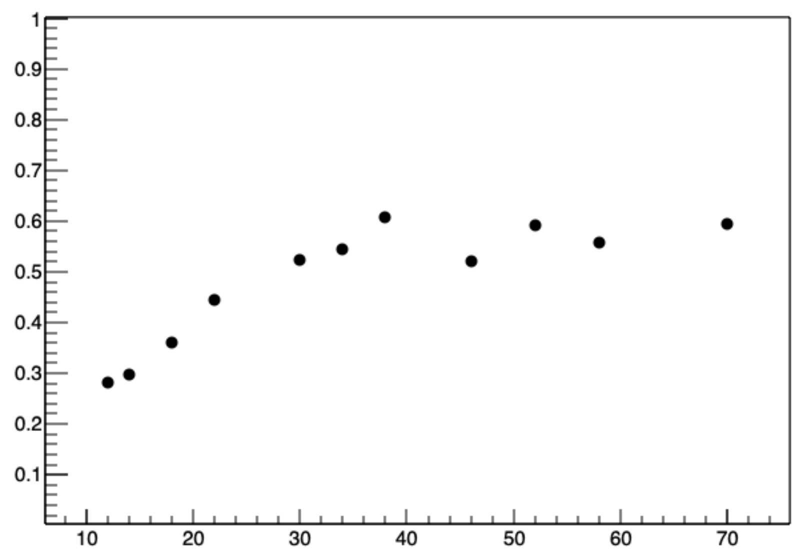


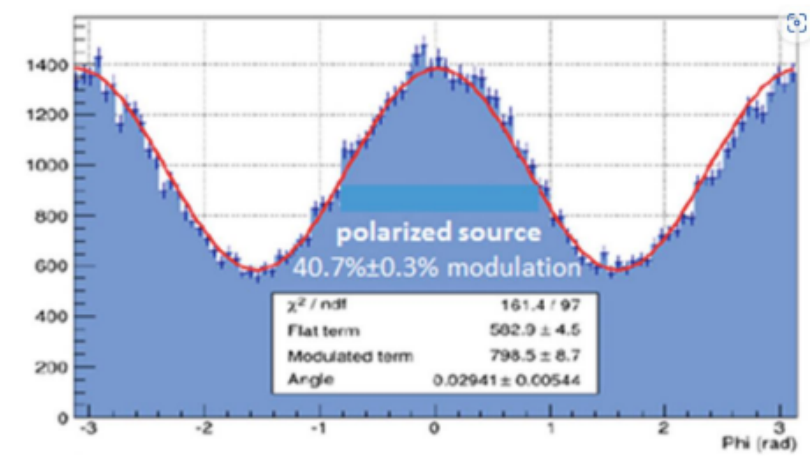
Sensitive volume 1.5x1.5x 1 cm^3

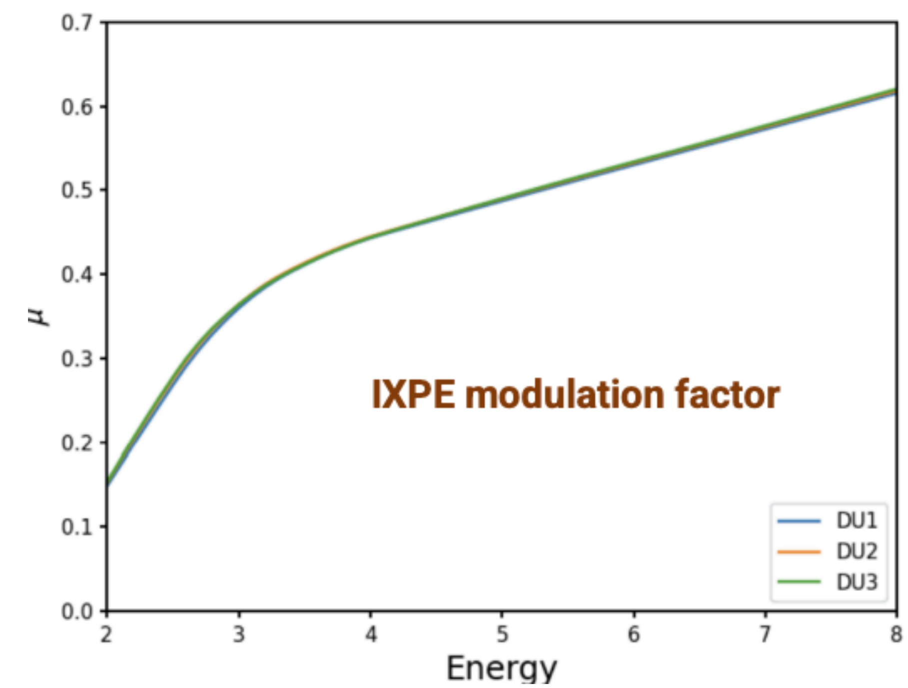
Angular resolution MANGO



Modulation factor MANGO







- Performances competitive in 15-30 keV range and tracks fully contained
- A MANGO-like detector can be competitive and complementary in the field

Backup slides

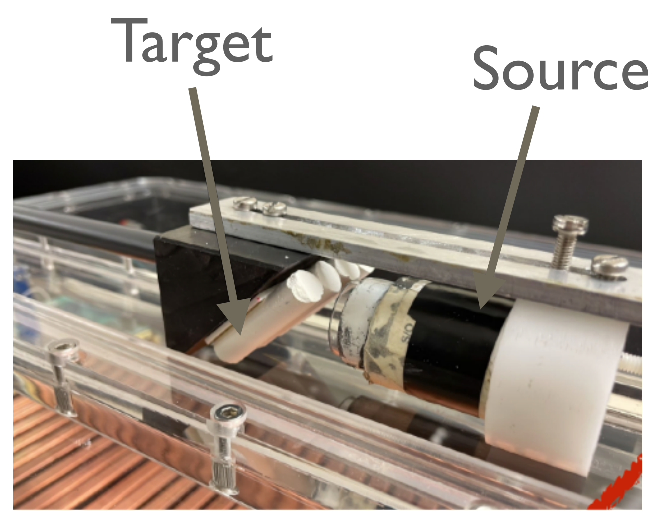
Multi-source X-Ray runs

- Study of linearity and energy resolution overground performed with different X-Ray source

- Gamma @ 6 keV produced using a ^{55}Fe source

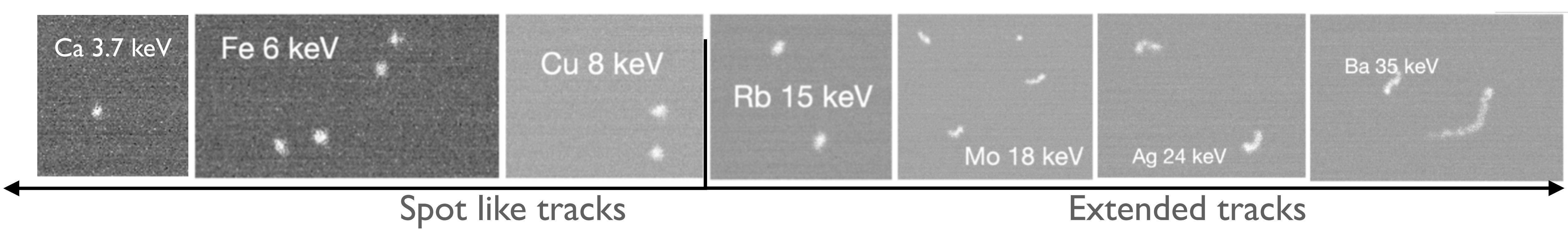
Target	Energy (keV)		Photon Yield
Selected	K_alpha	K_beta	(#/sec/steradian)
Cu	8.04	8.91	2,500
Rb	13.37	14.97	8,800
Mo	17.44	19.63	24,000
Ag	22.10	24.99	38,000
Ba	32.06	36.55	46,000
Tb	44.23	50.65	76,000

- Other energies done using an ^{243}Am impinging on different Materials



Data taken overground at LNF: High pileup

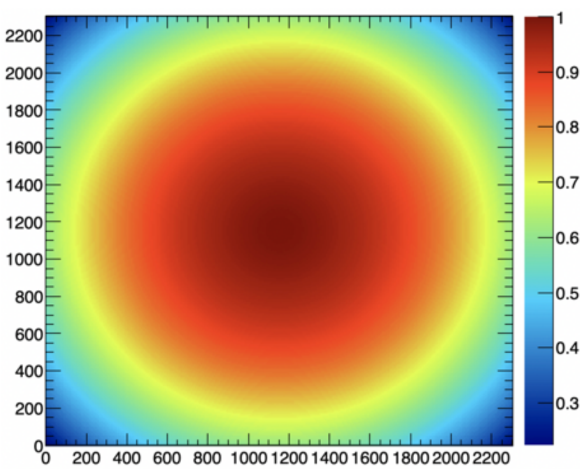
- How tracks appear:

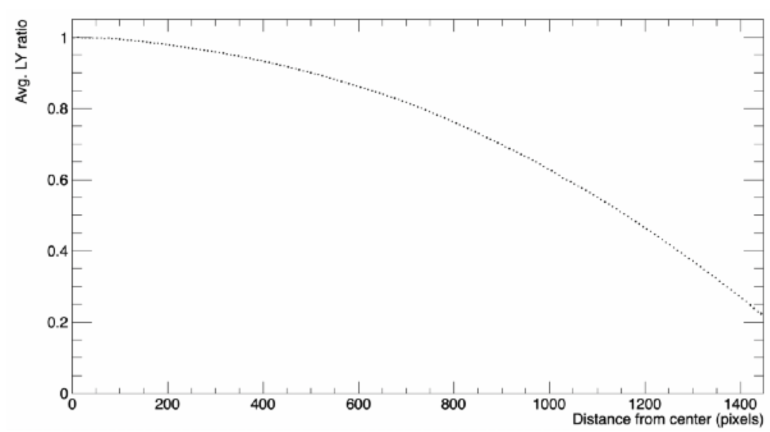


Track reconstruction code

- High quantity of tracks with overlapping due to large sensitive volume
- First iteration of directional iDBSCAN to reconstruct long and straight tracks
- Remaining tracks reconstructed with iDBSCAN

+ Vignetting correction:





- Light Collection down up to 20% on the border of the images
- Saved information: pixels of the tracks

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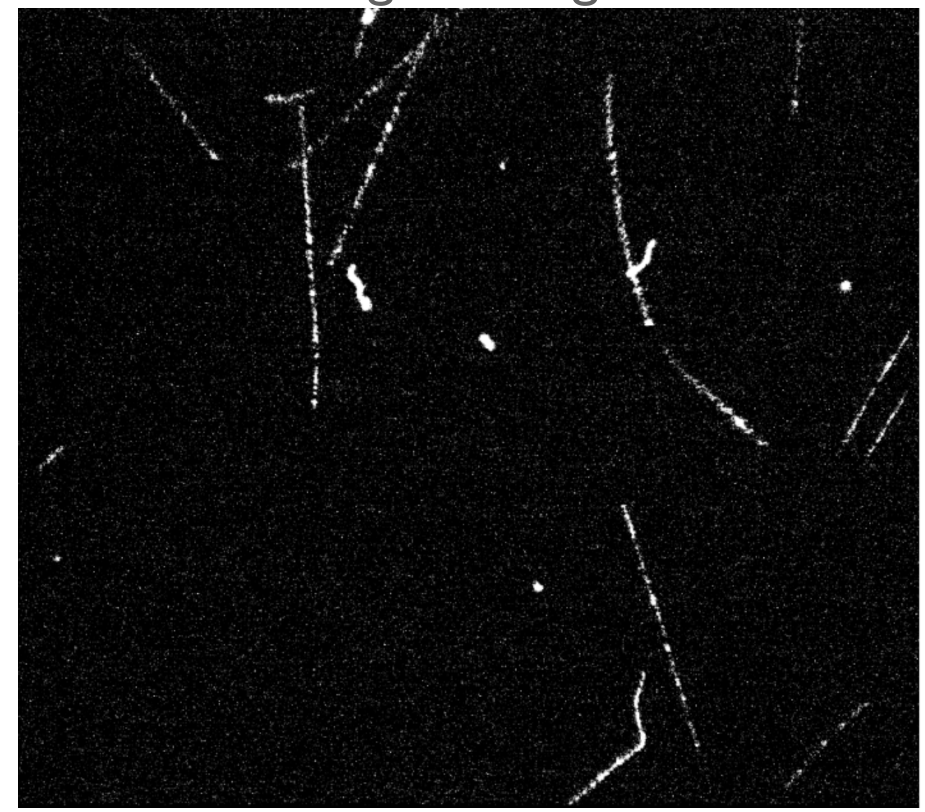
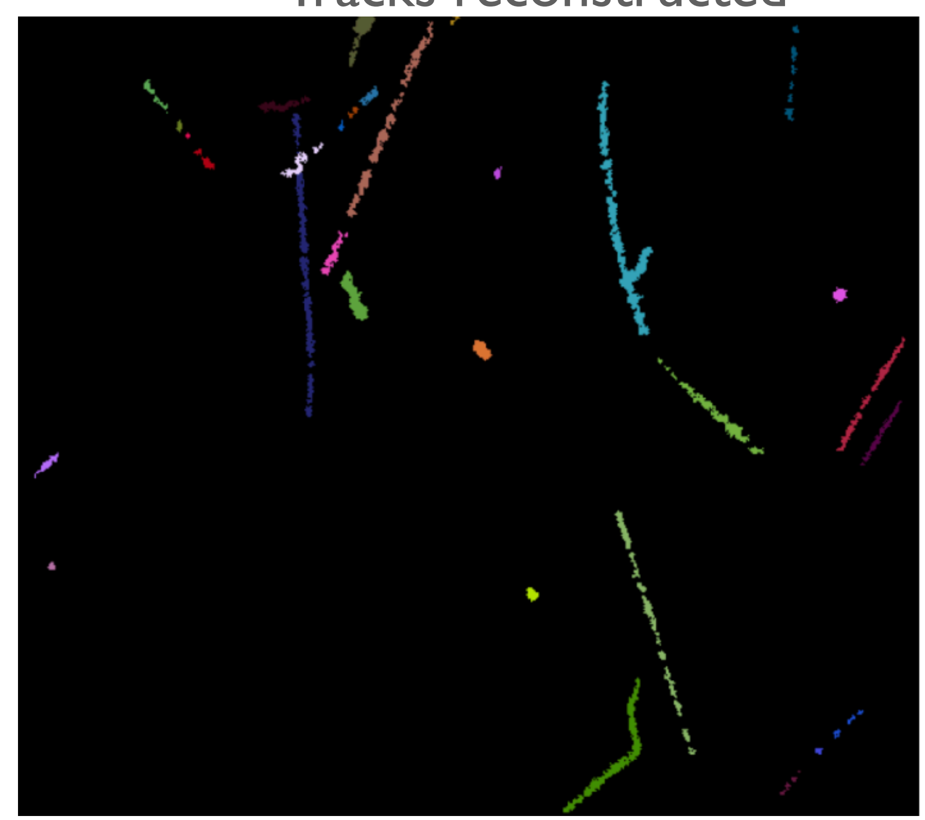
Original image

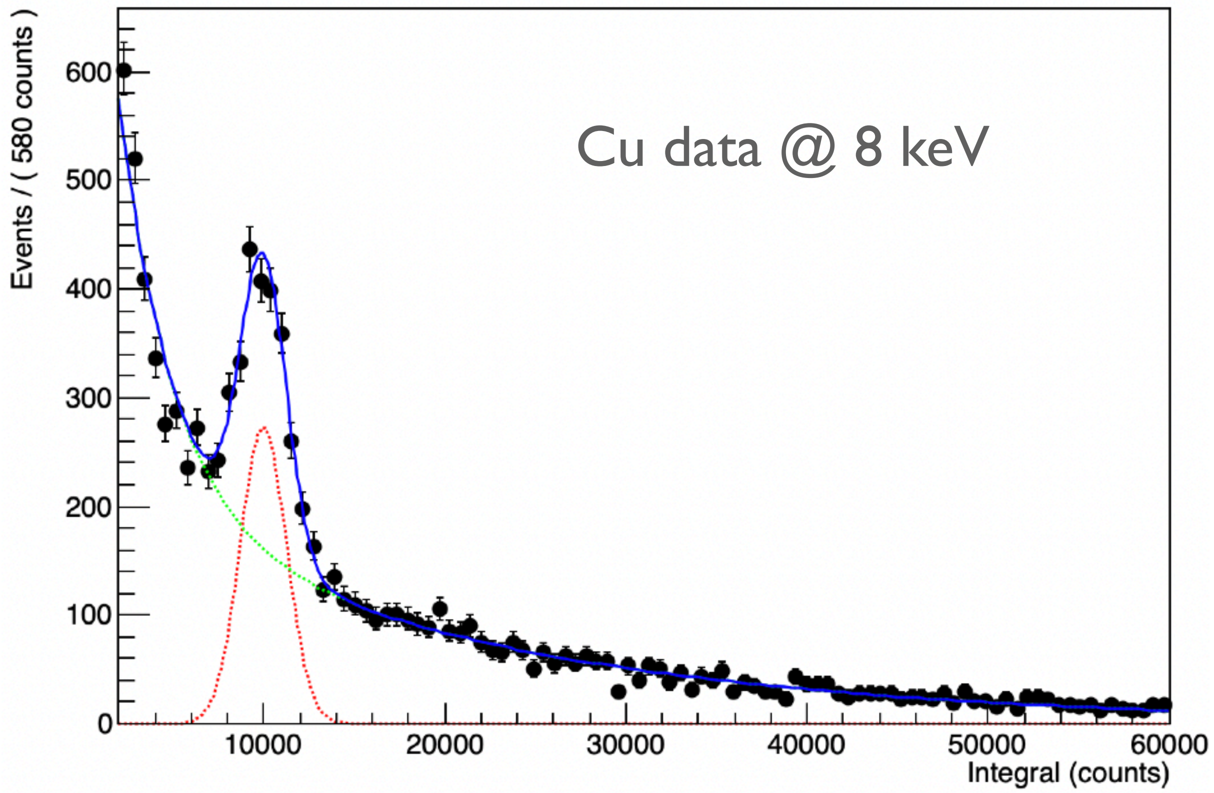


Tracks reconstructed



Energy response and resolution on data

- Fit with 2 exponential (B) + 1 gaussian (S)

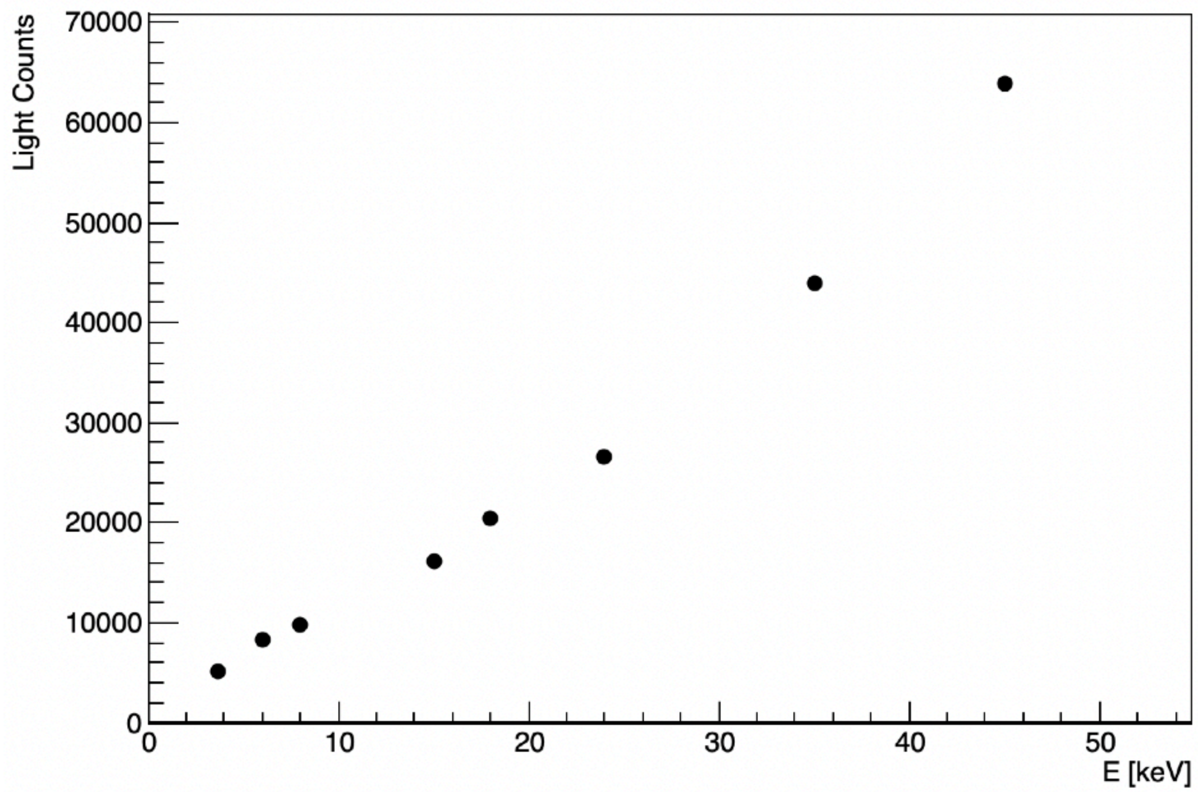


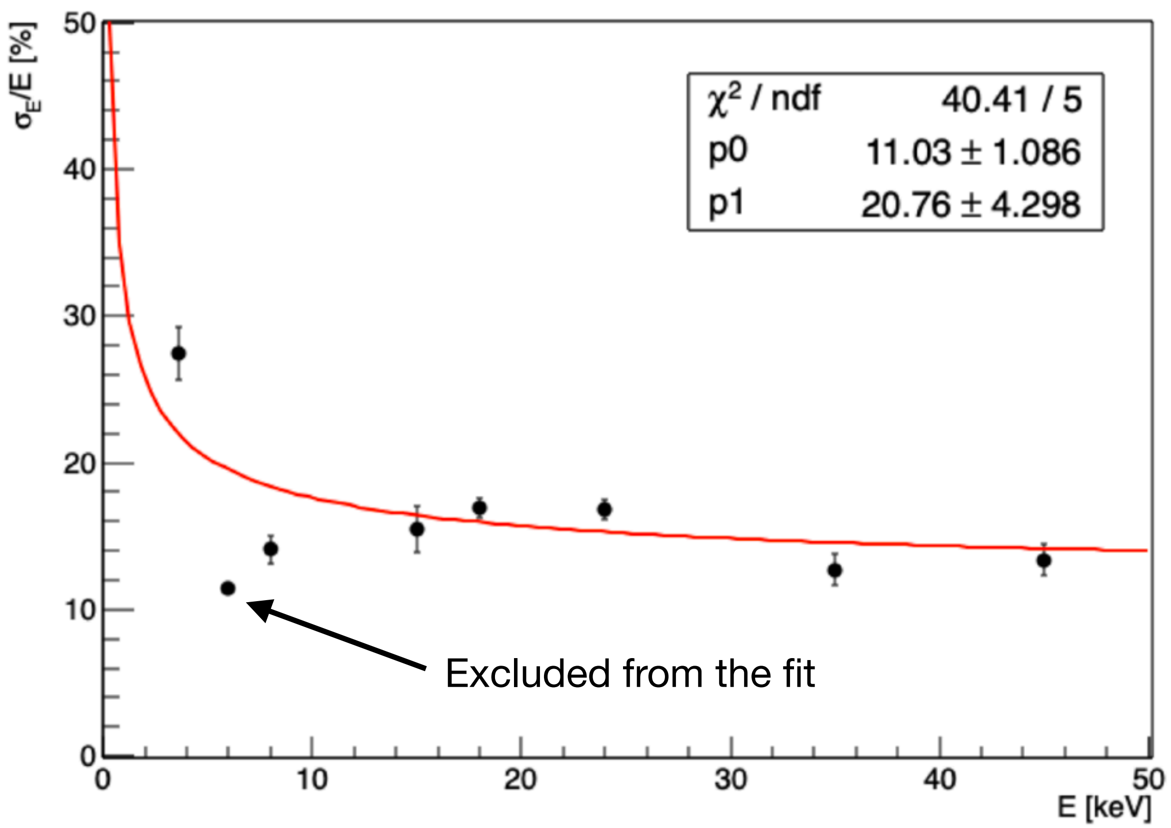
- Model fit well the data

- Data shows good linearity in [6-35] keV

- Energy resolution $\sigma_E/E \propto 1/\sqrt{E}$

Same kind of tracks expected from ν scattering





SI and SD sensitivity for DM