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Study of the PMTs signals during the first underground run of the LIME prototype for the CYGNO experiment

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Abstract

This thesis focuses on the commissioning and the data analysis of the LIME prototype of the CYGNO experiment, which aims at developing a detector for direct detection of dark matter. The LIME prototype was installed this year (2022) at Laboratori Nazionali del Gran Sasso, in order to characterize the detector response in the underground environment and in site background.

The CYGNO experiment aims at exploiting the optical readout approach of multiple-GEM structures in large volume gaseous Time Projection Chambers (TPCs) for the study of rare events as interactions of low mass DM or solar neutrinos. The combined use of high-granularity sCMOS cameras and fast light sensors allows the reconstruction of the 3D direction of the tracks, offering good energy resolution and very high sensitivity in the few keV energy range.

During the underground commissioning, my main contributions were to help improve the data acquisition system and characterize PMTs response.

The main goal of the analysis on the PMTs waveforms was to reconstruct the event position and energy. Having these quantities it is possible to match the PMTs signals with the sCMOS sensor pictures. Utilizing the charge collected by the 4 PMTs it is in fact possible to reconstruct the spot position on the GEMs plane and the light of the event. After a loose selection on the waveforms, a Bayesian fit was performed to fit the (x, y) position and the light L , produced after the amplification stage of the detector. The position and light are reconstructed with 10% and 11% resolution respectively, and then compared with the picture-reconstructed variables, obtaining encouraging results.

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Introduction

As suggested by astronomical observation since 1930, approximately the 80% of the whole matter of the Universe is possibly made of “dark matter”, whose nature is still unknown. Weakly interactive particles (or WIMPs) are the favored candidates, but more exotic options cannot be excluded.

In the last decades the scientific community has shown a growing interest in the detection of possible dark matter particles, but, until now, no incontrovertible evidence of dark matter particles has been found. Different experimental techniques have been developed in order to detect dark matter on Earth, and can be divided in three categories: “indirect detection”, “direct detection” and production of dark matter particles (e.g. in accelerators).

In the direct detection search many experimental approaches have been developed, giving different performances for different possible values of dark matter particle mass. These experiments try to observe the transferred energy-momentum of dark matter particles scattering off ordinary matter. In this framework, the best results produced in the mass $\mathcal{O}(1 \text{ GeV}/c^2 - 1 \text{ TeV}/c^2)$ region, are based on Time Projection Chambers (TPC). These detectors are characterized by very strong sensitivity, being able to detect incredibly small recoil energies.

The sensitivity of the current direct detection experiments is limited by the extremely low energy threshold needed to detect possible lighter dark matter particles combined with the extremely small cross sections still allowed for these interactions. In order to reject the background sources one of the possibilities is to exploit the directionality of the interactions.

In this contest, I had the opportunity to collaborate with the CYGNO collaboration. The CYGNO collaboration has the goal to develop a gaseous TPC detector with an optical readout for a high precision 3D tracking of dark matter induced nuclear recoils. The aim of this collaboration is the enhancement of the sensitivity in the $\mathcal{O}(1 \text{ GeV}/c^2)$ and sub-GeV mass region for dark matter particles. For this reason, the TPC will be based on a gas mixture of light atoms, like helium and fluorine. The detector will be based on an optical readout performed by a high precision sCMOS sensor, coupled with a Gas Electron Multipliers (GEMs), allowing a precise measurement of the directionality of the recoil. This approach can potentially discriminate signal from the irreducible coherent neutrino scattering background, by confirming the astrophysical source of the event.

The CYGNO collaboration is concluding its R&D phase, and it is currently taking underground data with its last prototype (LIME) placed underground at Laboratori Nazionali del Gran Sasso (LNGS).

During my thesis project I had the possibility to help in the DAQ optimization

overground at Laboratori Nazionali di Frascati (LNF), reducing the dead time and improving the acquisition of PMTs signals. We carried out an analysis on the diffusion for the ^{55}Fe cluster in the data taken last year, for the characterization of the detector.

During the LIME LNGS campaign, I helped the underground commissioning of this prototype, tuning the trigger and the PMTs.

Finally we performed one of the first analyses on the PMTs signals, implementing a Bayesian fit in order to reconstruct events position on the GEMs plane and energy release. These results were then matched with the picture reconstructed information, giving encouraging results.

The thesis is structured as follows.

In Chapter 1 the most significant evidences, possible particle candidates and the current model for dark matter are introduced, together with a brief description of the main features of the direct detection searches.

In Chapter 2 the CYGNO experimental approach is described. It begins describing the performances obtained with the previous prototypes. Then particular emphasis is given to the description of the current prototype LIME, its operation underground at LNGS, and a first analysis of the collected data.

Chapter 3 focuses on the calibration of the PMTs readout performed underground.

Finally, Chapter 4 describes the analysis performed on the PMTs data, carried out in the Bayesian approach. Moreover here there is a first comparison between the camera and PMTs readouts, fundamental for the 3D reconstruction of the events.

Chapter 1

Dark matter

The Universe consists of matter and energy. Approximately 80% of the whole matter of the Universe is possibly made of an unknown source called dark matter (DM), as suggested by recent astronomical and cosmological observations [1].

The nature of dark matter is still a mystery, it does not find an explanation in the framework of the Standard Model of particle physics. Its existence is postulated only by its gravitational effects, such as: effects on galaxy rotation curves, galaxy clusters, gravitational lensing, Cosmic Microwave Background (CMB) and large-scale structure [2].

Also in the realm of particle physics, evidence is accumulating for the existence of physics beyond the Standard Model, based on theoretical and experimental arguments [2].

1.1 Dark matter evidences

1.1.1 Galaxy rotation curves

One of the most known evidences for the existence of DM on galactic scales comes from the observation of the *rotation curves* of spiral galaxies [3, 4].

Rotational curves are usually defined as the relation between the circular speed of the galaxy's stars, measured by the Doppler shift of the 21 cm Hydrogen line, and the distance of these from the galaxy's center.

In Newtonian dynamics the circular velocity is expected to be:

$$v = \sqrt{\frac{GM(R)}{R}}, \quad (1.1)$$

where:

- R is the distance from the galactic center
- G is the gravitational constant
- $M(r) = \int_{|r|<R} \rho(r) dr$, $\rho(r)$ is the visible mass density profile.

At large R , where the mass density ρ is expected to be zero, v should decrease as $v \propto 1/\sqrt{r}$, as it is observed for example in the Solar System.

Most of the observed rotation curves on galactic scales however usually exhibit a characteristic *flat* behaviour at large distances from the center, as shown in Fig. 1.1.

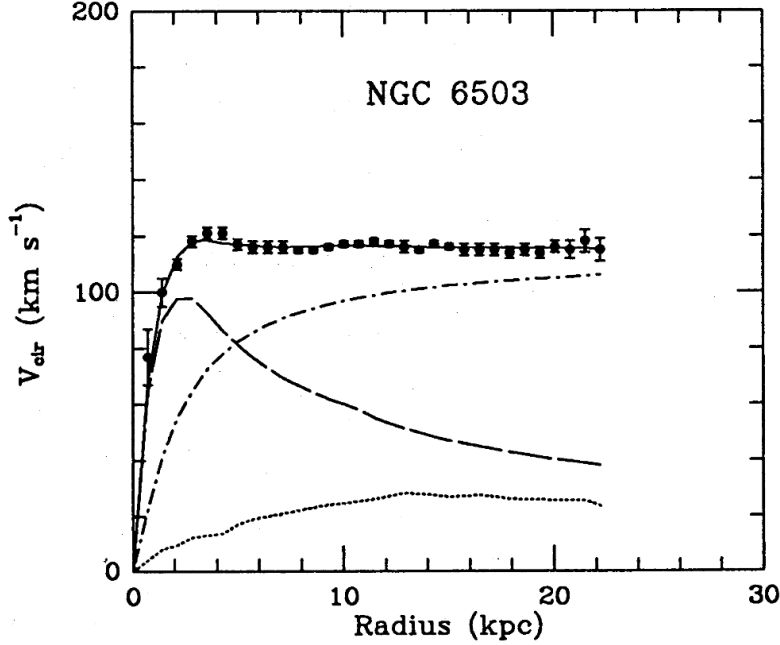


Figure 1.1. Rotation curve of NGC 6503. The dotted, dashed and dash-dotted lines are the contributions of gas, disk and dark matter, respectively. Figure from Ref.[5]

The observation of $v(r)$ approximately constant can be explained by the existence of an halo with $M(r) \propto r$ and $\rho(r) \propto r^{-2}$ of invisible matter which permeates the spiral galaxies called DM.

Although there is a consensus about the shape of dark matter halos at large distances, it is unclear whether galaxies present cuspy or shallow profiles in their innermost regions, in fact the DM halo density profile dependence on r can be different from r^{-2} at small or very large radii [6–8].

1.1.2 Galaxy clusters

Another gravitational evidence of DM comes from galaxy clusters. Those are the biggest gravitationally bound structures of the Universe, formed by $\mathcal{O}(10^{2\div 3})$ galaxies and hot stars. In 1933, Zwicky [9] found a mass-to-light ratio of around 400 solar masses per solar luminosity with the measurements of the velocity dispersion of galaxies in the Coma cluster:

$$\frac{M_C}{L_C} \sim 400 \frac{M_\odot}{L_\odot}, \quad (1.2)$$

where M_C and L_C , are the mass and luminosity of the Coma cluster, and $M_\odot$ and $L_\odot$ are the mass and the luminosity of the Sun.

It is possible to get this ratio for a typical cluster; in fact for a rough estimation

of the total mass of the cluster we can use the virial theorem [10]

$$M = R_G \frac{\langle v^2 \rangle}{G}, \quad (1.3)$$

where $\langle v^2 \rangle$ is the mean square velocity of the cluster, measured with Doppler effect, and R_G is the gravitational radius defined as

$$R_G = 2 \left(\sum_i m_i \right)^2 \left(\sum_i \sum_{j \neq i} \frac{m_i m_j}{r_{ij}} \right)^{-1}, \quad (1.4)$$

measured by reconstructing the position of the galaxies in the cluster. It is found that for a typical cluster this ratio is

$$\frac{M}{L} \sim 10^2 \frac{M_\odot}{L_\odot}. \quad (1.5)$$

The large $O(10^2)$ factor found by Zwicky can be explained with the presence of invisible matter widespread within the cluster, and it is equivalent to a total mass density of $\rho_m \sim 0.3\rho_c$ [11], where ρ_c is the critical density

$$\rho_c = \frac{3H_0^2}{8\pi G}, \quad (1.6)$$

with H_0 being the Hubble constant today.

Another evidence of the presence of an invisible mass that can be studied with galaxy clusters is the baryon fraction f_b , defined as

$$f_b \equiv \frac{M_{gal} + M_{gas}}{M_{tot}}, \quad (1.7)$$

where M_{gal} (the mass in the galaxies of the cluster) can be estimated by multiplying the optical luminosity of the cluster by a representative mass-to-light ratio, and M_{gas} (the mass of hot intercluster gas) can be estimated with spectral data and the X-ray surface brightness. Finally, the cluster binding mass M_{tot} , can be inferred by assuming the cluster in hydrostatic equilibrium. The fraction is then estimated as $f_b \sim 0.144 \pm 0.005$. This proves that there is a different form of mass than the baryon one, and that is $\sim 86\%$ of the total mass of the galaxy clusters [12].

Gravitational lensing

Gravitational lensing can be used to estimate masses of clusters. In fact, according to General Relativity, massive objects modify the local geometry of space-time, causing photons traveling in the curved space around massive objects to be deflected, and therefore causing a distortion of the images. Being a pure gravitational effect, both DM and baryonic matter contribute to it. The distorted images can be used to infer the shape of the (gravitation) potential and the mass of the cluster; such observation, when compared to the mass of visible matter, indicates a lot of missing mass. The mass of stars and gas is hence not sufficient to explain the observed gravitational lensing of bullet clusters, supplying strong evidence of DM.

Bullet Cluster

Another strong evidence of dark matter is the physical system called Bullet Cluster [13], that is two clusters of galaxies colliding. In this system one can study the different behaviour of the various components of the clusters - stars, gas and the hypothetical DM. In Fig 1.2 are shown two clusters after collision. Stars, as observed, were not greatly affected by the collision, and most passed right through, gravitationally slowed but not otherwise altered. Intergalactic gas - most of the ordinary matter of the clusters - on the other hand, interacted electromagnetically, slowing down significantly and we can detect the resulting X-ray emission (pink halo in the picture). If we consider only those two components of the clusters we would expect the gravitational lensing effect to follow the baryonic mass distribution, but, as we can see, it appears unchanged by the collision. This strongly supports the idea that most of the cluster's mass is in the form of dark matter (blue halo in the picture), which interacts very weakly, except for gravity.

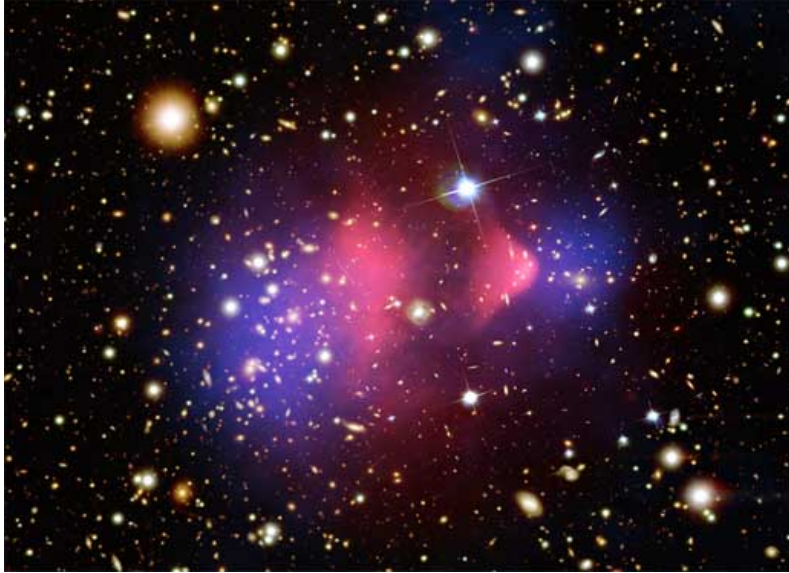


Figure 1.2. Picture of the cluster merger 1E0657-558 ($z = 0.296$) named Bullet Cluster. The pink halo represents the X-ray emission, caused by the intergalactic gas; the blue halo is the matter distribution calculated by gravitational lensing. Figure from Ref. [14]

1.1.3 Cosmic Microwave Background

Despite the evidences discussed in the previous sections, those observations do not allow us to determine the total amount of DM in the Universe. In this section we will briefly discuss how that information can be extracted from the Cosmic Microwave Background (CMB), one of the fundamental observation bases of the Λ CDM model.

The Λ CDM is the current most used parameterization of the Big Bang cosmological model. In this parameterization the Universe contains three major components:

- a cosmological constant (denoted by Λ) related to dark energy,

- the postulated cold dark matter (CDM, we will see it in Sec. 1.1.4),
- the ordinary matter.

To understand the importance of CMB as evidence for dark matter it is useful to make a brief description of the Universe's evolution.

The expansion of the universe is parameterized by a dimensionless scale factor $a = a(t)$ by means of the Friedmann equation, that relates the expansion of the universe to its energy content, as

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3}, \quad (1.8)$$

where $H(t)$ is the Hubble constant at a certain time (t) , ρ is the total energy density, k/a^2 is the spatial curvature of the Universe and Λ is the cosmological constant. In a flat Universe (as the current astronomical observations suggest [1]), namely $k = 0$, the total energy density is called critical density (ρ_c) and is defined as Eq. 1.6. It is standard to define the density parameter Ω

$$\Omega = \frac{\rho}{\rho_c}, \quad (1.9)$$

which in a flat Universe is equal to 1. We can define the density parameter for the various species of the Universe as

$$\Omega_i = \frac{\rho_i}{\rho_c}, \quad (1.10)$$

where i indicates the respective component:

- the energy density of relativistic particles, ρ_r ;
- the energy density of matter ρ_m that can be divided in:
 - baryonic matter energy density ρ_b ,
 - cold dark matter energy density ρ_{CDM} ;
- the energy density of the cosmological constant Λ , ρ_Λ

According to the current Big Bang cosmological model, for significant periods of time the total energy density of the Universe has been dominated by one component [15]. At the beginning it was dominated by radiation, which, as the Universe expands, dilutes as $\rho_r \propto a^{-4}$. The scale factor in this first period evolved as $a \sim \sqrt{t}$. After $\sim 10^4$ y after Big Bang, the Universe started to be dominated by matter, with ρ_m getting bigger than ρ_r , with the matter that dilutes as $\rho_m \propto a^{-3}$ and the scale factor going as $a \sim t^{2/3}$. Finally the cosmological constant became dominant as the matter dilutes, and during this period the scale factor began to grow exponentially. Defining the redshift z with the relation

$$a = \frac{1}{1+z}, \quad (1.11)$$

the Friedmann equation can be written as

$$H^2 = H_0^2 \left(\Omega_{r,0}(1+z)^4 + \Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0}(1+z)^0 \right), \quad (1.12)$$

where the Ω_k term accounts for the curvature term in Eq. 1.8.

Now we can understand the origin of CMB. At the beginning the Universe was hot and dense, with radiation as the predominant component. When matter domination started the Universe was a plasma of baryons and electrons in thermal equilibrium, opaque to photons. As the temperature decreases and neutral atoms started to form, the Universe began transparent to the photons. At $z \sim 1100$ radiation and matter were essentially decoupled and photons started to travel in space. Those photons are still streaming in the Universe today, and they are called Cosmic Microwave Background.

CMB follows with extraordinary precision the spectrum of a black body corresponding to a temperature of $T_0 = (2.7255 \pm 0.0006)$ K. It is not perfectly uniform, but has small fluctuations of order 10^{-5} (Fig. 1.3). Today the analysis of CMB anisotropies enables accurate testing of cosmological models, putting stringent constraints on cosmological parameters.

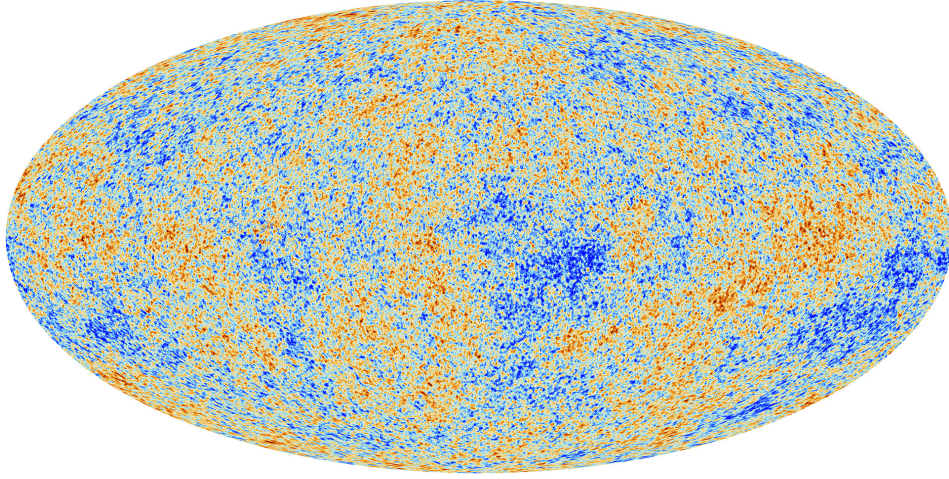


Figure 1.3. CMB temperature fluctuation from the Planck satellite. All the distortions caused by Earth's motion with respect to the CMB galactic frame have been subtracted and corrected. Figure by ESA https://www.esa.int/ESA_Multimedia/Images/2013/03/Planck_CMB

The observed temperature anisotropies of CMB are usually expanded as [2]

$$\frac{\delta T}{T}(\theta, \phi) = \sum_{l=2}^{+\infty} \sum_{m=-l}^{+l} a_{lm} Y_{lm}(\theta, \phi), \quad (1.13)$$

where $Y_{lm}(\theta, \phi)$ are spherical harmonics and a_{lm} are the expansion coefficients. Now it is possible to compute the power spectrum, function of l , as

$$C_l = \left\langle |a_{lm}|^2 \right\rangle_m, \quad (1.14)$$

with the brackets indicating a simple average (result shown in Fig. 1.4). The fit of CMB temperature power spectrum to the Λ CDM parameters performed by the Planck collaboration [1] gives

$$\begin{aligned} \Omega_b h^2 &= 0.02237 \pm 0.00015, \\ \Omega_{CDM} h^2 &= 0.1200 \pm 0.0012. \end{aligned} \quad (1.15)$$

As we can see Ω_{CDM} is different from zero, and, as suggested from the other observations discussed, dark matter is the main ingredient of matter in the Universe.

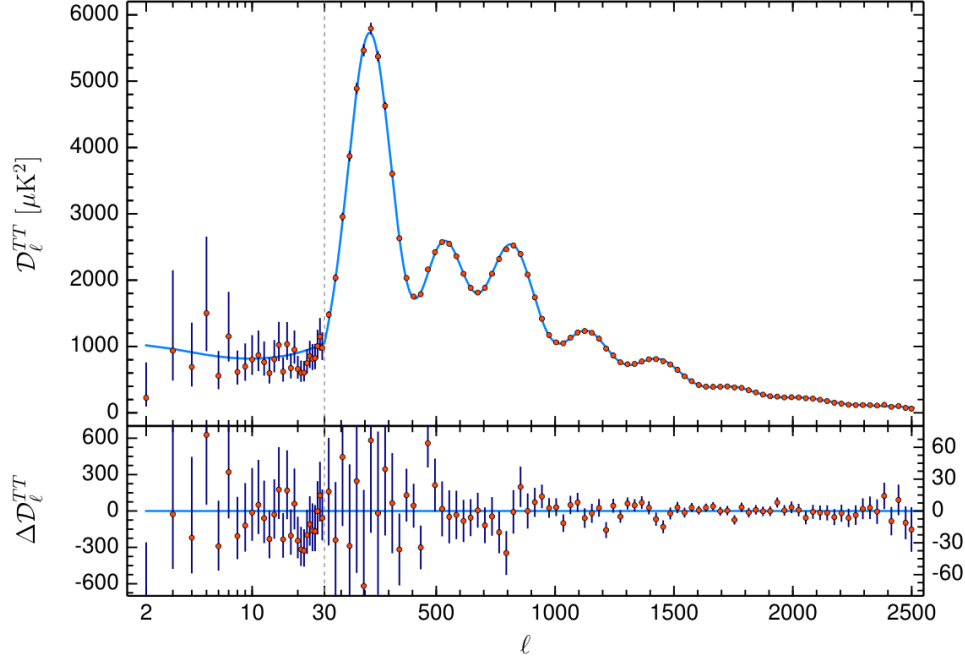


Figure 1.4. Planck 2018 power spectrum (TT) [1]. The relative height of the peaks depends on the abundance of the different components of the Universe at the photon decoupling, and can therefore be used to estimate the total amount of DM. The ratio between odds and even peaks is instead influenced by the baryon matter density. The blue solid line is the fit to the Λ CDM theoretical prediction, and the dashed grey line denotes a change of horizontal scale at $l = 30$.

1.1.4 Large scale structure

The Universe exhibits structures over a wide range of length scales, up to very large scales as filaments and voids that span significant fractions of the observable Universe. These structures seem to organize in a hierarchical model, which is in agreement with the hypothesis of cold DM [8]. A completely homogeneous universe would not have, in fact, stars, galaxies, or planets.

The study of these structures can provide, combining different datasets, constraints on the cosmological parameters. The latest results from DES (Dark Energy Survey) [16], combining observations from galaxy-galaxy lensing, galaxy clustering and weak lensing, provide $\Omega_m = 0.34 \pm 0.03$. This result, combined with other datasets such as Planck, BAO (Baryonic Acoustic Oscillation) or BBN (Big Bang Nucleosynthesis), yields $\Omega_m = 0.306^{+0.004}_{-0.005}$.

1.2 Dark matter local properties

In the Λ CDM Model, the model describing the properties of the DM halo is called Standard Halo Model (SHM)[17]. Here the dark matter is collisionless and its evolution is therefore given by the collisionless Boltzmann equation

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{x}} - \frac{\partial \Phi}{\partial \mathbf{x}} \cdot \frac{\partial f}{\partial \mathbf{v}} = 0, \quad (1.16)$$

where Φ denotes the gravitational potential, and with $f = f(\mathbf{x}, \mathbf{v}, t)$ being the distribution function, defined such that $f(\mathbf{x}, \mathbf{v}, t) d^3\mathbf{x} d^3\mathbf{v}$ gives the number of dark matter particles in an infinitesimal phase space volume $d^3\mathbf{x} d^3\mathbf{v}$, located at time t , with speed $\mathbf{v}$ at position $\mathbf{x}$. If the DM halo can be considered self-gravitating, then the potential is generated by its density distribution, therefore Φ can be obtained by the Poisson's equation

$$\nabla^2 \Phi = 4\pi G \rho. \quad (1.17)$$

Direct dark matter detection experiments aim to probe DM signature; we therefore need to know how dark matter is distributed in density and speed on the Earth, where the direct detection experiments are located. The Earth is in the Solar System, situated at $R_\odot = 8.2 \text{ kpc}$ from the galactic center of our galaxy, the Milky Way (MW). In the MW, the Standard Halo Model assumes an isotropic, isothermal and spherical DM halo, with density profile $\rho(\mathbf{r}) \propto r^{-2}$. The solution of Eq. 1.16, in this case, is the Maxwell velocity distribution[17]

$$f(v) = \frac{1}{N} \left(\frac{3}{2\pi\sigma^2} \right)^{3/2} e^{-\frac{3|v|^2}{2\sigma^2}}, \quad (1.18)$$

where N is a normalization factor and σ the root-mean-square velocity dispersion. The density distribution assumed by the SHM formally extends up to infinity, hence the velocity distribution does it too. However the DM halo of the MW is finite, therefore exist a velocity $v_{esc} = \sqrt{2|\Phi(r)|}$ at which the DM particle is no more gravitationally bound to the MW. As a consequence of the isothermal hypothesis, the halo has a flat rotation curve, and the velocity dispersion σ is dependent on the velocity of rotation of object around the Galactic center, as $\sigma = \sqrt{3/2}v_c$.

The interesting parameters for direct detection dark matter searches on Earth can be summarized as:

- local circular speed $v_c(R_\odot)$
- local dark matter density $\rho(R_\odot)$,
- local escape speed $v_{esc}(R_\odot)$.

The local circular speed is measured in various manners: from the study of the proper motion of SgrA*, the massive black hole at the center of the MW, recent measures gives $v_c(R_\odot) = (248 \pm 7) \text{ km/s}$ [18], while methods employing tracer stars gives $v_c(R_\odot) = (229.0 \pm 0.2) \text{ km/s}$ [19]. The local density is measured by means of a large set of observation of: nearby stars velocity, MW rotation curves, velocity dispersion of halo stars etc. The standard parameter used for direct detection searches is $\rho(R_\odot) = 0.3 \text{ GeV cm}^{-3} c^{-2}$ [20, 21]. Finally, local escape speed methods based on high velocity stars from the RAVE survey give $v_{esc}(R_\odot) = 553^{+54}_{-41} \text{ km/s}$ [22], while other analysis based on Gaia Data Release 2 give $v_{esc}(R_\odot) = (580 \pm 63) \text{ km/s}$ [23].

1.3 Dark matter candidates

As shown in the previous sections, the evidence for non-baryonic dark matter is compelling at all observed astrophysical scales. It is therefore natural to ask *what is the dark matter made of?*

Various theoretical models have been proposed as a solution for those observations, but, if DM is made of particles, there is a list of properties that it has to satisfy:

- it is not baryonic;
- it is stable on cosmological timescale: we have evidences of existence of DM today;
- it does not interact with electromagnetic force, so it's neutral;
- it has no color charge, because does not feel QCD interactions;
- it has at most weak interaction with the SM particles (except for gravity interactions).

In addition, most of the DM has to be “cold”, i.e. non-relativistic to explain large scale structure, see Sec. 1.1.4. None of the known Standard Model particles have all the previous properties at the same time, so many DM candidates have been proposed.

1.3.1 WIMPs

WIMPs (Weakly Interacting Massive Particles) are one of the most attractive candidates for DM; they have mass in the range $\mathcal{O}(1 \text{ GeV} - 10 \text{ TeV})$, they are stable and neutral, usually named with χ , they interact with SM particles at weak scale and were not relativistic at the photon decoupling.

They are the most studied dark matter candidates both from theoretical and experimental point of view. The reason of this interest is due to the so-called “WIMP miracle”, i.e. the fact that they arise in a natural way in many theories with the correct cosmological properties.

Various candidate particles have been proposed as WIMPs [24], but analyzing deeper the candidates is beyond the scope of this work.

The WIMP miracle

Dark matter may be produced as a thermal relic of the Big Bang [25] in a simple and predictive manner. The early Universe was a dense and hot plasma of particles assumed to be in thermal equilibrium. The Universe then started to cool down, when the Universe temperatures T decreased below the WIMP particle's mass m_χ , the number of DM particles became exponentially suppressed, since it depends on the temperature as $e^{-m_\chi/k_B T}$.

In the early universe there was enough abundance of DM particles so that the generally assumed process for WIMP χ and SM particles ϕ

$$\chi + \bar{\chi} \leftrightarrow \phi \phi^* \quad (1.19)$$

proceed in both directions. Then, as the temperature drops, this process is disfavoured in the direction $\phi \phi^* \rightarrow \chi + \bar{\chi}$. Finally when the Universe has expanded enough, the DM particles become so dilute that the annihilation process turns irrelevant, with their number asymptotically approaching a constant. This transition is called “freeze out”. Note that the freeze out, also known as chemical decoupling, is distinct from the kinetic decoupling; after thermal freeze out, interactions that change the number of dark matter particles become negligible, but interactions that mediate energy exchange between dark matter and other particles may remain efficient.

This process is described by the Boltzmann equation

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle \sigma_A v \rangle (n_\chi^2 - n_{\chi,eq}^2) \quad (1.20)$$

where n_χ is the number density of DM, H is the Hubble parameter, $\langle \sigma_A v \rangle$ is the thermally averaged annihilation cross section, and $n_{\chi,eq}^2$ is the DM number density in equilibrium. On the RHS of Eq. 1.20 the first term accounts for the dilution from the Universe’s expansion, the n^2 term arises from the process $\chi + \bar{\chi} \rightarrow \phi \phi^*$ that annihilate χ particles, and finally n_{eq}^2 accounts for the reverse process, which creates χ particles.

Usually in literature is useful referring to DM yield Y_χ , or comoving number density, defined as

$$Y_\chi \equiv \frac{n_\chi}{s} \quad (1.21)$$

where s is the entropy density. In Fig. 1.5 is shown the evolution of the comoving number density for a WIMP of mass $m_\chi = 100 \text{ GeV}$, where is it visible the exponential fall which, after the freeze out, turns into a constant behavior.

To determine the thermal relic density we need to solve the Boltzmann equation numerically. A rough estimation [24] is however highly instructive. From a quantitative point of view, we can define the freeze out as the moment in which the production and the dilution terms in Eq. 1.20 are comparable

$$n_\chi^{FO} \langle \sigma_A v \rangle \simeq H \quad (1.22)$$

where the superscript FO denotes quantities at freeze out.

We can write the DM density parameter as

$$\Omega_\chi h^2 \equiv \frac{\rho_\chi^0}{\rho_c} h^2 = \left(\frac{s_0 h^2}{\rho_c} \right) m_\chi Y_\chi^0 \quad (1.23)$$

where with the index 0 we denote the present day quantities. Using the freeze out assumption, $Y_\chi^0 = Y_\chi^{FO}$, and the Eq. 1.22 into Eq. 1.23 we obtain

$$\begin{aligned} \Omega_\chi h^2 &= \left(\frac{s_0 h^2}{\rho_c} \right) m_\chi Y_\chi^{FO} = \left(\frac{s_0 h^2}{\rho_c} \right) m_\chi \frac{n_\chi^{FO}}{s^{FO}} \simeq \\ &\simeq \left(\frac{s_0 h^2}{\rho_c} \right) m_\chi \frac{H^{FO}}{s^{FO} \langle \sigma_A v \rangle} \propto \frac{1}{\langle \sigma_A v \rangle}, \end{aligned} \quad (1.24)$$

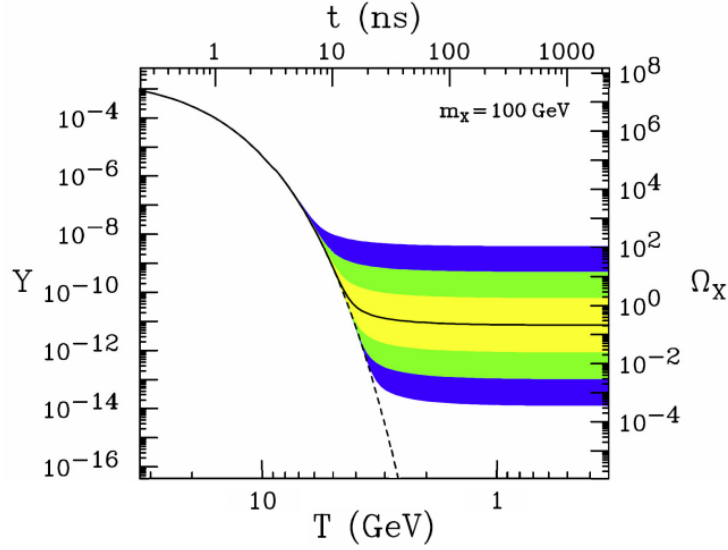


Figure 1.5. The comoving number density Y (left) and resulting thermal relic density Ω_χ (right) for a WIMP mass $m_\chi = 100$ GeV as a function of temperature T (bottom) and time t (top). The solid black line is for an annihilation cross section that yields the observed relic density, and the colored regions are for cross sections that differ by 10, 10^2 , and 10^3 from this value. The dashed black line is the evolution of an equivalent particle's number density that remains in thermal equilibrium. From Ref.[24]

calculating the last equality we obtain

$$\Omega_\chi h^2 \simeq \frac{3 \cdot 10^{-27} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma_{Av} \rangle} \quad (1.25)$$

Although m_χ does not enter Ω_χ directly, in many theories it is the only mass scale that determines the annihilation cross section [24]. Neglecting phase space and other order one factors the cross section can be written as

$$\langle \sigma_{Av} \rangle \sim \frac{g_W^4}{16\pi^2} \frac{1}{m_\chi^2} \quad (1.26)$$

The relic density is therefore determined as a function of m_χ , and using this estimation in Eq. 1.25, solving for m_χ and assuming the desired Ω_χ , we obtain $m_\chi = \mathcal{O}(1 \text{ TeV})$. This is the “WIMP miracle”: weak-scale particles are dark matter candidates with the desired density factor.

Currently there are no signal discovered for WIMP in the expected $\mathcal{O}(1 \text{ GeV} - 10 \text{ TeV})$ mass region - except for the DAMA/LIBRA experiment [26–28]. The WIMP miracle, however, does not necessarily imply the existence of WIMPs. More precisely there are well motivated models [24] in which particles naturally have the desired thermal relic density, but they do not have weak-scale masses (nor weak force interactions). Although lower DM mass particles seems to not reproduce the right relic density, with the steps showed in this section, there exists theories in which the dependence of the cross-section, and consequently Ω_χ , on the DM particle mass is weakened [29, 30].

1.4 Direct detection of dark matter

Direct detection experiments consist in attempting to observe the effect of interaction of dark matter particles on baryonic matter. In the hypothesis in which the DM interacts with the SM particles not only gravitationally (as discussed in Sec. 1.3.1), we can imagine observing the transferred energy-momentum of DM particles scattering off ordinary matter. This scattering process could, for instance, happen off an electron or an atomic nucleus. The challenge of the direct detection experiments is, therefore, measure the transferred energy-momentum of the scattering of DM particles.

The theoretical framework that will be used in this work is:

- heavy dark matter, with mass in the order $\mathcal{O}(\text{GeV} - \text{TeV})$;
- elastic scattering of DM with SM particles as dominant effect;
- the Standard Halo Model.

1.4.1 Dark matter scattering kinematics

Starting from Eq. A.19, that is

$$E_R = \frac{\mu^2 v^2}{m_N} (1 - \cos \theta), \quad (1.27)$$

is possible to find that the possible maximum energy that a DM particle can provide to a target nucleus at rest is

$$E_R^{max} = 2 \frac{\mu^2 v^2}{m_N}, \quad (1.28)$$

i.e. when the DM particles bounces backwards. This is also the case when the transfer moment is higher, in fact, from Eq. A.4, in the non-relativistic limit

$$q^2 = 2\mu v^2 (1 - \cos \theta) \stackrel{\theta=\pi}{=} 4\mu^2 v^2. \quad (1.29)$$

The non-trivial dependence of the scattering kinematics on m_N can be better understood analysing

$$\frac{dE_R^{max}(v)}{dm_N} = \frac{E_R^{max}(v)}{m_N} \frac{m_{DM} - m_N}{m_{DM} + m_N}, \quad (1.30)$$

which implies that $E_R^{max}(v)$ at fixed m_{DM} and v has a single maximum for $m_N = m_{DM}$, and thus increases (decreases) with m_N for $m_N < m_{DM}$ ($m_N > m_{DM}$). If we consider E_R as a fixed quantity, once fixed m_{DM} and v , we can compute the minimum DM velocity required as

$$v_{min}(E_R) = \sqrt{\frac{m_N E_R}{2\mu^2}}. \quad (1.31)$$

The quantity v_{min} is, therefore, the minimum speed a dark matter particle must have in the Earth's rest frame to produce a recoil energy E_R on a target nucleus.

These relations have interesting implications, depicted in Fig. 1.6. Since the SHM constrains the velocity distribution of DM particles, the experiment sensitivity strongly depends on m_{DM} . In fact, lighter dark matter particles need a larger v_{min} to generate the same recoil energy, with respect to heavier particles. In modern direct detection noble liquids experiments, the typical energy threshold is of $\mathcal{O}(1 \text{ keV})$. Assuming the usual DM particle velocity $v \sim 200 \text{ km/s}$, modern direct detection noble liquids experiments will lose sensitivity for $m_{DM} \lesssim 1 \text{ GeV}/c^2$.

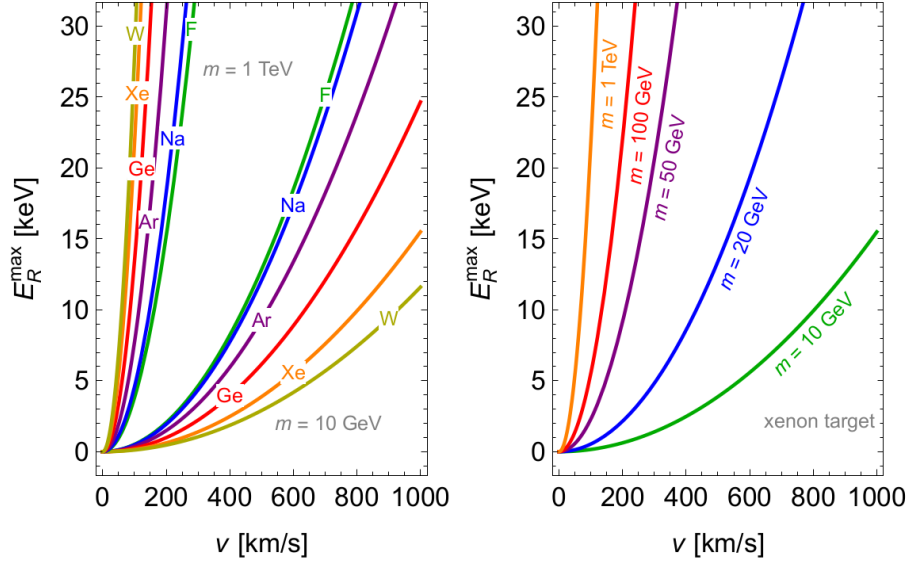


Figure 1.6. E_R^{max} as a function of v , as in Eq. 1.28. Alternatively those plots can be read as v_{min} , on the horizontal axis, as a function of E_R^{max} , on the vertical axis, thanks to Eq. 1.31. **Left:** E_R^{max} for different target nuclei at fixed $m_{DM} = 10 \text{ GeV}/c^2$ or $m_{DM} = 1 \text{ TeV}/c^2$. **Right:** the relation assuming Xenon target for different values of m_{DM} . Figure from Ref. [31].

1.4.2 Event rate

The event rate R is defined as the number of events per unit target mass per unit time, so the differential event rate for a WIMP of mass m_χ and nucleus with mass m_N is given by [32]

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_N} \int_{v_{min}(E_R)}^{v_{esc}} v f(v) \frac{d\sigma}{dE_R} dv, \quad (1.32)$$

with ρ_0 the local WIMP density, $\frac{d\sigma}{dE_R}$ the differential cross-section for the WIMP-nucleus elastic scattering and $f(v)$ the WIMP speed distribution in the detector frame (see Sec. 1.2).

According to the SHM there is an upper limit in the maximum velocity *in the Galactic rest frame*, determined by the Milky Way escape velocity (v_{esc}). The lower limit of the integration (v_{min}), is instead derived with 1.31, and is the minimum DM particle's speed which can cause a recoil of energy E_R .

The total event rate is then found by integrating the differential event rate $\frac{dR}{dE_R}$ over all the possible recoil energies

$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_\chi m_N} \int_{v_{min}(E_R)}^{v_{esc}} v f(v) \frac{d\sigma}{dE_R} dv, \quad (1.33)$$

with E_T as the threshold energy, namely the smallest recoil energy which the detector is capable of measuring.

The quantity that must be determined is then the differential cross-section that encodes the particle dynamics. Since we do not know the nature of the DM-nucleus interaction, its cross-section is usually written as the sum of a spin-independent (SI) contribution, due to scalar or vector DM coupling to quarks in nuclei, and a spin-dependent (SD) contribution, this due to axial-vector coupling to quarks forming the nuclei [32]

$$\frac{d\sigma}{dE_R} = \left[\left(\frac{d\sigma}{dE_R} \right)_{SI} + \left(\frac{d\sigma}{dE_R} \right)_{SD} \right]. \quad (1.34)$$

The total WIMP-nucleus cross-section is then calculated using nuclear form factors:

$$\frac{d\sigma}{dE_R} = \frac{m_N}{2\mu^2 v^2} \left[\sigma_0^{SI} F_{SI}^2(q^2) + \sigma_0^{SD} F_{SD}^2(q^2) \right], \quad (1.35)$$

with $\sigma_0^{SI,SD}$ are the spin-independent and dependent cross section at zero momentum transfer, and $F_{SI,SD}$ are the nuclear form factors. They encode the dependence on momentum transfer q^2 and the nuclear structure: since we are in the non-relativistic case, q^2 is low enough that can be approximated to their values at zero-momentum. We have then $F_{SI,SD} \approx F_{SI,SD}(q^2 = 0) = 1$ [32].

For the cross-sections we can use the following parameterization [31]

$$\sigma_0^{SI} = \frac{\mu^2}{\pi} [Z f_p + (A - Z) f_n]^2, \quad (1.36)$$

$$\sigma_0^{SD} = \frac{\mu^2}{\pi} \frac{J+1}{J} [a_p \langle S_p \rangle + a_n \langle S_n \rangle]^2, \quad (1.37)$$

where Z is the atomic number, f_p (f_n) is the proton (neutron) coupling constant; J is the nuclear angular momentum, a_p (a_n) is the proton (neutron) effective coupling constant and $\langle S_p \rangle$ ($\langle S_n \rangle$) is the proton (neutron) spin expectation value.

For the SI case, the standard assumption is the isosinglet condition, namely $f_p = f_n$. At low momentum transfer, with σ_p being the DM-proton cross section and μ_p being the DM-proton reduced mass, we can write Eq 1.36 as [31]

$$\sigma_0^{SI} = \sigma_p \frac{\mu^2}{\mu_p^2} A^2. \quad (1.38)$$

We have then found that, with our assumptions, the differential event rate, using Eq. 1.32 and 1.35, can be expressed as

$$\frac{dR}{dE_R} \propto \int_{v_{min}(E_R)}^{v_{esc}} v f(v) \frac{1}{v^2} dv, \quad (1.39)$$

assuming $v_{esc} \rightarrow \infty$ for simplicity, we can find the dependence of the event rate on E_R . Using Eq. 1.18 and taking into account the speed of the Earth v_E with respect to the DM halo we have

$$\frac{dR}{dE_R} \propto \int_{v_{min}(E_R)}^{\infty} \frac{\exp\left\{-\frac{|v+v_E|^2}{v_0^2}\right\}}{v} dv, \quad (1.40)$$

where $v_0 \equiv 2\sigma/3$. We now introduce an additional simplification: since we are in fact interested in the general behaviour as a function of E_R , we neglect v_E . Through a change of variables using Eq. 1.31, we obtain

$$\frac{dR}{dE_R} \propto \int_{E_R}^{\infty} \exp\left\{-\frac{E}{rE_0}\right\} dE, \quad (1.41)$$

where we defined

$$\begin{aligned} E_0 &\equiv \frac{1}{2}m_\chi v_0^2, \\ r &\equiv 4\frac{m_\chi m_N}{(m_\chi + m_N)^2}. \end{aligned} \quad (1.42)$$

We find that, following our simplified count, we can express the event rate as [33]

$$\frac{dR}{dE_R} = \frac{R_0}{rE_0} \exp\left\{-\frac{E_R}{rE_0}\right\}, \quad (1.43)$$

with R_0 being the total event rate, namely

$$R_0 = \int_0^{\infty} \frac{dR}{dE_R} dE_R. \quad (1.44)$$

We found that, with this simplistic approach, the event rate is featureless and exponentially falling. Even using a less simplistic calculation the situation remains the same, as represented in Fig. 1.7. Due to the featureless behaviour of the event rate, it is generally difficult to isolate the signal over the background noise. Furthermore the total rate is very small, $\mathcal{O}(1 \text{ evt kg}^{-1} \text{ y}^{-1})^1$, making DM direct detection even more challenging.

1.4.3 Modulation of event rate

To overcome those difficulties, existing DM direct detection experiments are characterized by a large exposure (both in time and size) and very low background rate. Drukier, Freese and Spergel [34] realized that Earth's motion relative to the galactic halo provides a distinctive signal for WIMP detection. In fact Earth's motion produces a seasonal variation in the laboratory's velocity relative to the halo; this motion then provides a distinctive temporal modulate of the observed event rate.

¹ Assuming an ^{40}Ar target, $\rho_0 = 0.3 \text{ GeV cm}^{-3} c^{-2}$, $m_\chi = 10 \text{ GeV}/c^2$ and $\sigma_\chi^{SI} \sim 10^{-38} \text{ cm}^2$.

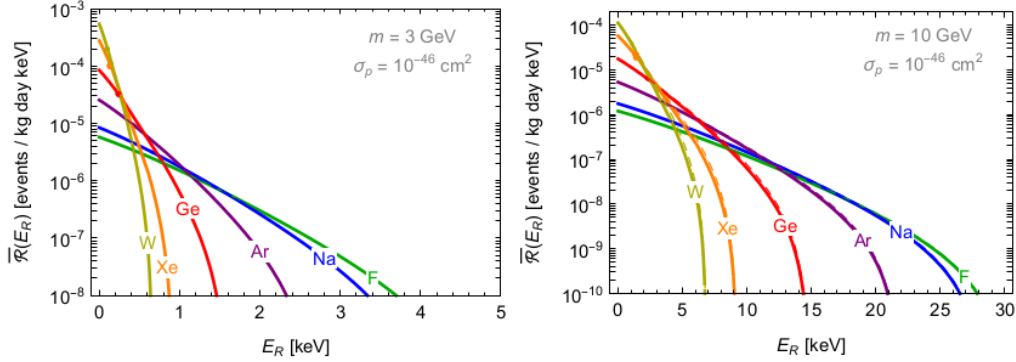


Figure 1.7. Annual average of the SI (solid lines) and total (dashed lines) DM-nucleus scattering rate, for a DM mass $m_\chi = 3 \text{ GeV}/c^2$ (left) and mass $m_\chi = 10 \text{ GeV}/c^2$ (right), assuming a DM-proton scattering cross-section $\sigma_p = 10^{-46} \text{ cm}^2$. Different lines correspond to different target nuclei. Figure from Ref. [33].

Time dependence

The Earth's orbit about the Sun leads to an annual modulation in the differential event rate [34, 35].

The motion of the Sun through the DM halo is expected to be in the direction of the Cygnus constellation, on the plane of the galaxy; in addition, the Earth's orbit is tilted by $\sim 60^\circ$ with respect to the galactic rotation plane. This means that the Earth's speed component parallel to the galactic rotation changes with time, with a period of 1 year. In fact the Earth's speed with respect to the DM halo is larger in Summer when the component of the Earth's orbital velocity is in the same direction of solar motion around the galaxy. Therefore the number of WIMPs with high speeds in the detector rest frame is larger in Summer.

This is a small effect since the velocity v_{orbit} of the Earth in its motion around the Sun is quite smaller than the velocity v_{sun} around the galactic center, namely $v_{orbit}/v_{sun} \sim 0.07$. For this reason the amplitude of the modulation is small and, with a first order Taylor expansion, the differential event rate can be written as [32]

$$\frac{dR(t)}{dE_R} \simeq \frac{dR}{dE_R} \left[1 + \Delta(E_R) \cos \left(\frac{2\pi(t - t_0)}{T} \right) \right], \quad (1.45)$$

with $T = 1 \text{ year}$ and $t_0 \sim 150 \text{ days}$, such as the maximum is on June 2nd, and $\Delta(E_R)$ is expected to be of the order of 1 - 10% [32].

Direction dependence

The detector motion with respect to the Galactic rest frame also produces a directional signal. Since the Earth is rotating on its axis, we should be able to see variations in the number of nuclear recoil events along a particular direction in the laboratory frame, with a period of 1 day. Assuming the SHM the direction

dependence is approximately given by [32, 36]

$$\frac{dR}{dE_R d\cos(\gamma)} \propto \exp \left[-\frac{\left[(v_{orbit}^{\parallel} + v_{sun}) \cos \gamma = v_{min} \right]^2}{v_0^2} \right], \quad (1.46)$$

where $v_{orbit}^{\parallel}$ is the component of the Earth's speed around the Sun parallel to the Cygnus direction, γ is the angle between the observed nuclear recoil and the Cygnus-Sun line. The event rate in the forward direction is roughly an order of magnitude larger than that in the backward direction [36], see Fig 1.8. With a directional detector capable of measuring the 3D nuclear recoil direction with head-tail discrimination, it would be possible to distinguish a WIMP signal from the isotropic background relatively easily.

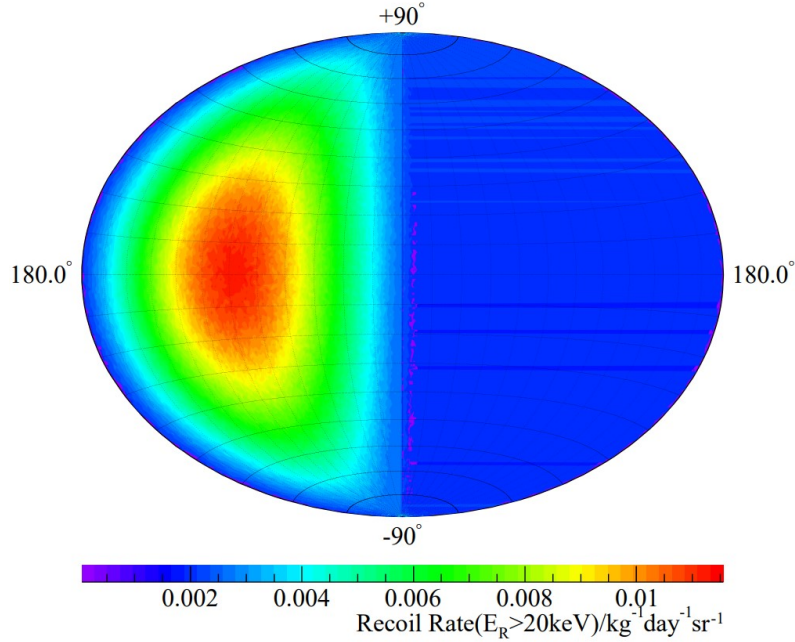


Figure 1.8. Directional recoil rate as a function of the nuclear recoil direction for a standard halo of WIMPs with $m_\chi = 100 \text{ GeV}/c^2$ and $E_R > 20 \text{ keV}$. Figure from Ref. [32].

1.4.4 Event signatures

Radiation entering the detector can interact with the sensitive volume, producing two classes of signatures. For example, photons and electrons will tend to scatter with the atomic electrons, producing an electronic recoil (ER); while for example neutrons will interact exclusively with the atomic nucleus, producing a nuclear recoil (NR). Alpha particles will predominantly ionize atomic electrons, but can also interact with the atomic nucleus. All those kinds of interactions can be detected by the experiment, with the NR induced by the interaction of neutrons being the trickiest to discriminate from a possible dark matter signal.

The electronic recoils are predominantly generated by gamma rays or by the interaction of electrons, positrons etc. In these interactions a significant amount of energy can be released, in the form of free electrons, in the material, making them easily distinguishable from DM-like interaction.

Nuclear recoils, on the other hand, are exactly the kind of interactions expected from a WIMP particle with our detector. Neutron interactions will appear like a 1 GeV WIMP striking on a nucleus. Eq. 1.27 and 1.32 can in fact be applied using the neutron mass and its nuclear interaction cross section as inputs. In the case of NR the scattered atom can release energy in the form of electrons, photons or phonon inside the detector.

Different detectors will have different responses to those kinds of interaction, especially depending on the material chosen. The signatures for the interactions can be summarized as follows:

- **Ionization:** electrons are extracted from the atoms as a consequence of the interaction. Electrons and ions can be read out using modern electronics. From the number of extracted electrons, the energy release of the interaction can be extracted.
- **Light:** the interaction with the incoming particle can induce scintillation. By appropriate detector design it is possible to observe and capture this light providing a measurement of a portion of the energy release.
- **Heat:** in regular structured systems phonons can be induced by the interaction and after be revealed. These kinds of detectors must be kept extremely cold, to reduce thermal noise as much as possible. Furthermore the energy released in terms of phonons is a high fraction of the total event released energy. Another class of detectors employ high pressure liquid system, in which the interaction will cause the material to boil, generating small bubbles that can be imaged.

In general, detectors respond differently to ER and NR, allowing potential discrimination methods for these kinds of interactions. In this context, the so-called “quenching factor” (QF) is an important parameter that describes the difference in the amount of visible energy in a detector for these classes of events. The ER signal will then be measured in keVee (keV *electron equivalent*), while the NR signal will be measured in keVnr (keV nuclear recoil). These two energy scales can, in principle, be calibrated one to the other. In literature, the QF is usually defined as:

$$E_{detected}(\text{keVee}) = \text{QF} \cdot E_{recoil}(\text{keVnr}). \quad (1.47)$$

The employment of a well-defined radiation source, can be used to determine the QF relating those two scales.

1.4.5 Backgrounds for direct detection experiments

Due to the small rate ($\mathcal{O}(1 \text{ evt kg}^{-1} \text{ y}^{-1})$) and the absence of peculiar features, the discrimination of a possible DM signal from the backgrounds events is very challenging. Those experiments are therefore generally located underground, where cosmic rays background is reduced [37]. Another prominent background source is

environmental radioactivity, including airborne radon and its daughters, as well as radio-impurities in the materials used for the detector and shielding construction. It is therefore important to find ways to reduce these background sources, as well as determine the expected background event rate in a precise way.

Cosmic rays and environmental backgrounds

Cosmic rays are the first background source that experiments have to deal with. These rays are usually divided in two categories:

- primary: high energy particles, mostly protons and light nuclei, coming from astrophysical sources;
- secondary: X-rays, muons, pions, electrons, protons, neutrons, produced in the interaction of primary cosmic rays with the atmosphere particles.

The rate of those rays decreases by approaching the Earth's surface, and it decreases even more below the Earth surface. That effect is shown in Fig. 1.9, where can be seen how the Earth surface acts as a shield from the cosmic rays.

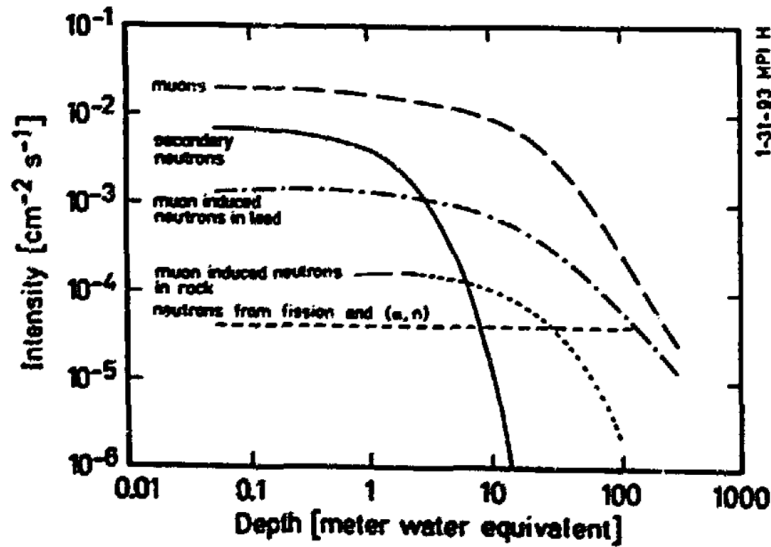


Figure 1.9. Flux of secondary cosmic rays versus shielding depth. Figure from Ref. [38].

Many dark matter direct detection experiments are therefore located in laboratories beneath the Earth's surface. The CYGNO project is, in fact, programming to install the future detector in the Laboratori Nazionali del Gran Sasso (LNGS), situated below ~ 1400 m the Gran Sasso, a mountain in the center of Italy. This year (2022) the CYGNO project has installed the last prototype underground at LNGS, in order to evaluate the performance of its approach in an underground environment. Many of the experiments situated in the underground laboratories equip additional shielding and active veto systems, in order to remove the external background.

Internal radioactivity

Besides the external background sources as cosmic rays and natural radioactivity, another important contribution is given by the internal radioactivity. In fact, the radioactivity of the detector components generates background events themselves. For example, any uranium, thorium, potassium, cesium, cobalt, argon or krypton atoms embedded either in the active detector material or nearby shielding can result in radioisotope decays that can produce background events. The contamination of detector materials from these unstable isotopes is almost inevitable. A lot of detector-dependent techniques are developed by the different collaborations, in order to reduce the internal radioactivity. However, the elimination of these radioactive isotopes from the construction process can be very challenging. In fact, during different phases of the detector construction the cosmic rays can activate unstable isotopes via nuclear interaction [37].

Because of difficulty in the elimination of the internal background, especially in very sensitive dark matter direct detection, a lot of work is spent in the characterization of the employed materials. By screening the materials it is possible to estimate a radioisotope contamination of small samples of the detector. It is however impossible to monitor the whole detector while it is operating. For this the development of a very detailed Monte Carlo (MC) simulation of the geometry, materials and response of the detector is needed.

1.4.6 Status of DM direct detection

The status of spin-independent WIMP-nucleon interaction coupling scattering for the various experiments is usually summarized with the plot in Fig 1.10. It represents the SI cross-section constraints of the experiments as a function of the mass of the DM candidate, assuming the SHM. The open lines represent the exclusion limits for the different experiments, with the green shaded area corresponding to the 90% C.L. excluded region.

For masses $m_\chi \gtrsim 1 \text{ GeV}/c^2$ the strongest constraints come from noble liquids experiments, as XENON1T [40, 41], LUX [42] and PandaX-II [43]. On the other hand, for masses $m_\chi \lesssim 1 \text{ GeV}/c^2$ there is a general loss of sensitivity. In fact, in this mass region the nuclear recoil DM energy typically goes under the experimental thresholds, usually $\mathcal{O}(1 \text{ keV})$. In order to explore this region detectors with single-electron sensitivity are needed or new possible signatures that can contribute to the signal rate can be considered.

The two brown closed lines represent the constraints coming from possible signal observation by the DAMA/LIBRA experiment [26, 27]. The DM nature of this observation is, however, in tension with a large number of results [39].

The orange dashed line of the plot represents the so-called “neutrino floor”. In order to increase the overall sensitivity of the experiment, it is possible to simply improve the exposure, i.e. the total mass of the target, the exposure time or both. As the experiment becomes more sensitive, neutrinos become an important source of background. In fact, coherent neutrino scattering on nuclei has the same signature of the searched DM-nucleus interaction, making it virtually impossible to differentiate them. In order to reject the neutrino background, a possible solution is to use the

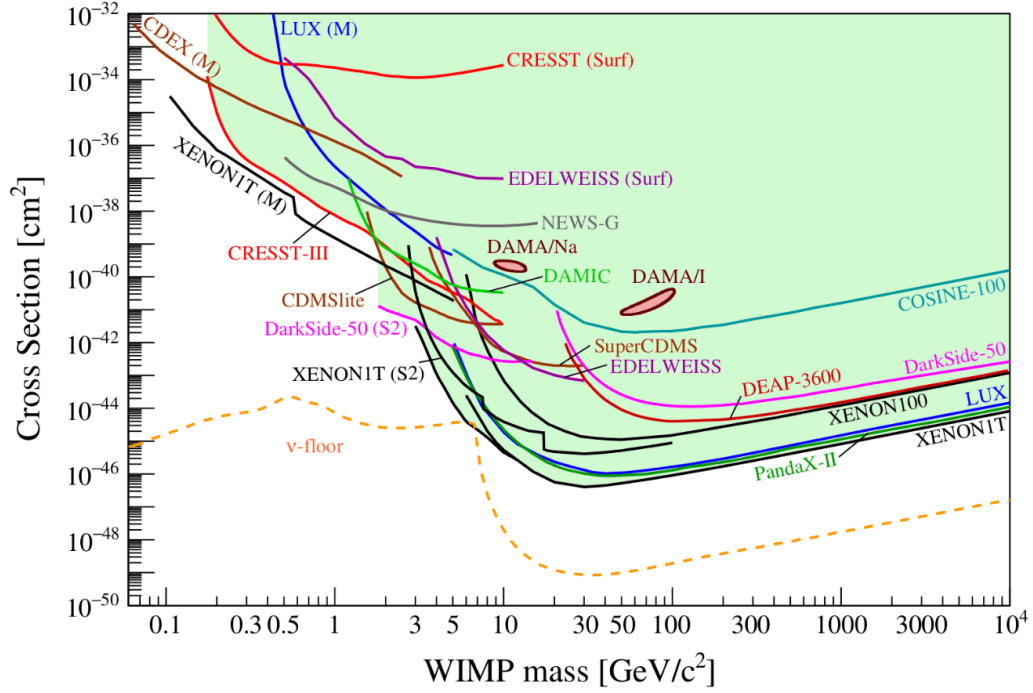


Figure 1.10. The state-of-the-art of DM direct detection, for spin-independent DM cross-section. The curves are obtained assuming $\rho_0 = 0.3 \text{ GeV cm}^{-3}$, $v_0 = 220 \text{ km s}^{-1}$, $v_{esc} = 544 \text{ km s}^{-1}$ as the DM halo parameters. The open lines represent the exclusion limits by the different experiments, with the green shaded area representing the correspondent excluded region. The closed lines correspond to possible signal observations. Figure from Ref. [39].

directional information of the scatter. In this sense, many projects are working on directional detection, and during my thesis I had the possibility to contribute to the CYGNO project [44].

Chapter 2

The CYGNO experiment (a CYGNus module with Optical readout)

While in the last decades there were enormous advances in direct DM detection of masses greater than 10 GeV, leading to an improvement of many orders of magnitude, the $\mathcal{O}(1 \text{ GeV})$ is still largely unexplored, although been theoretically well motivated [45–47].

Given the rarity of NR induced by DM particles (see Sec. 1.4), one of the main experimental challenges in the GeV mass region is the discrimination between NR and ER induced by other particles with significantly higher rates. In fact, by lowering the energy threshold in search of lighter DM particles, it is harder to reduce background sources. Since the experiment is located on Earth, there is an apparent DM wind crossing the detector. The main contribution to the wind velocity is produced by the motion of the Solar System around the galactic center. Since the Cygnus constellation comes before the Solar System roughly on the same orbit, the wind appears to come from the Cygnus direction.

Both this and the directional modulation already outlined in Sec. 1.4.3 can be exploited to positively identify the DM signal. The seasonal modulation (claimed to be observed by the DAMA collaboration [26–28, 48, 49]) is induced by the Earth’s motion around the Sun, and contributes to the signal by a few percent. The diurnal modulation would instead be a more robust signature, due to the Earth’s rotation along its axis; an observer (on Earth) would see the average incoming DM direction changing of $\sim 96^\circ$ every 12 sidereal hours, with the amplitude depending on the angle between the laboratory frame and the Earth axis.

The ability to reconstruct the direction of the incoming DM particle could, therefore, highly improve discrimination of the signal from the background.

2.1 A TPC with optical readout

The goal of the CYGNO experiment is to deploy an underground high-resolution Time Projection Chamber (TPC) with optical readout, based on Gas Electron Multipliers (GEMs), working at atmospheric pressure and using an helium/fluorine

based gas mixture, for the study of rare events with an energy release in the range of tens of eV to tens of keV.

Gaseous TPCs constitute a promising approach to directional DM detection. These detectors consist of a gas or liquid filled sensitive volume combined with electric or magnetic fields in order to perform a three-dimensional reconstruction of an interaction. In order to reconstruct the position of the interaction, TPCs usually employ a position sensitive electron collection system. Electrons are generated as a result of the interaction between the gas or the liquid and a charged particle crossing it. Charged particles ionize the active material along their path of flight, producing a number of ion-electron pairs that will be collected by the cathode and the anode respectively. In Fig 2.1 is depicted a typical TPC. In order to be able to measure

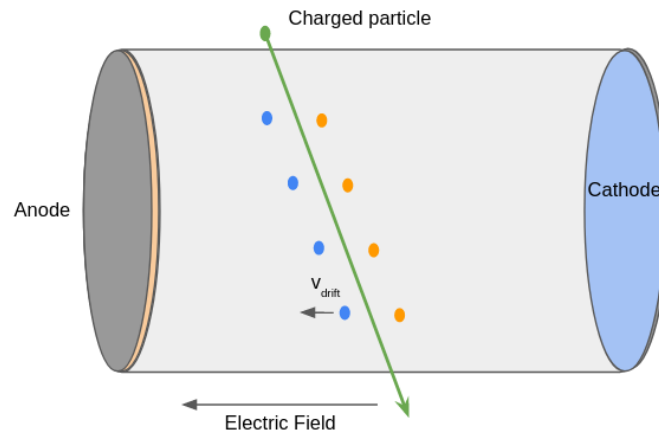


Figure 2.1. Drawing of a cylindrical TPC. The electrons produced in the interaction are drifted towards the anode, where they will be amplified and then collected.

the position of the interaction or the particle's trajectory as accurately as possible, the electric field inside the sensitive volume has to be homogeneous. This is usually achieved by means of a field cage that allows dividing the potential from the cathode stepwise down to the anode. The electrons produced in the interaction are then drifted towards the anode. Since the electron signal from the primary ionization process is too low, an amplification stage is needed in order to detect the interaction. The readout chosen to detect the electron signal gives information on the projection of the track on the readout plane. To reconstruct the z position of the track the drift time is generally used. Charge or optical readout are generally utilized, with the former also giving timing information, while with the latter an external readout that gives timing information is needed.

The CYGNO collaboration has chosen to use a triple stack of GEMs as an amplification stage, acquiring the light produced at the end of the multiplication. The GEM is a micro-pattern gas detector that can be used for high resolution particle tracking [50]. Usually it is made of a kapton foil of thickness of about $50\,\mu\text{m}$, clad on each side by a thin copper layer, usually $5\,\mu\text{m}$ thick, perforated with holes with a high surface density. In Fig. 2.2 it is shown a GEM foil seen under an electron microscope. By applying a voltage difference between the two copper sides a strong electric field is produced within the holes. Primary electrons produced in

the interaction of a particle in the sensitive volume, are led towards the GEM by an electric field. The high field inside the holes induces an avalanche process that multiplies the primary electrons generating secondary electrons, Fig. 2.3.

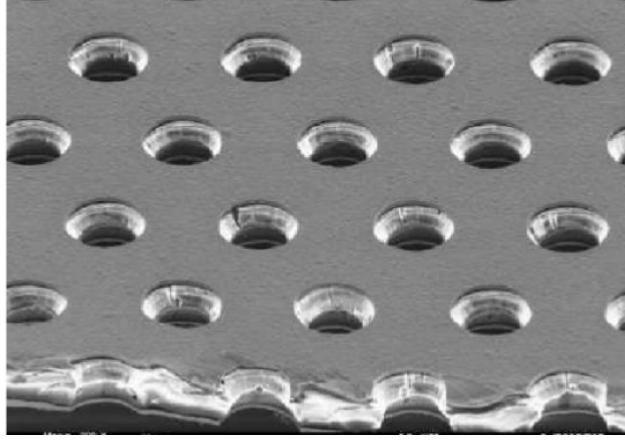


Figure 2.2. A GEM foil seen under the electron microscope, figure from Ref. [51].

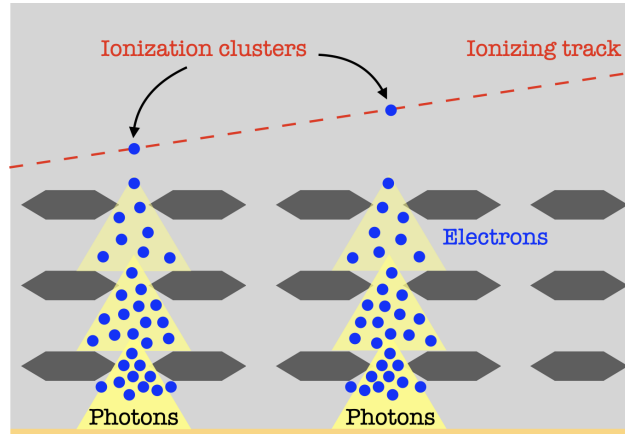


Figure 2.3. Schematic drawing of the multiplication process that takes place in the three stack GEMs employed by the CYGNO collaboration.

The most important features of TPCs for directional dark matter direct detection can be summarized with the following:

- TPCs are 3D detectors capable of acquiring large sensitive volumes with a lower amount of readout channels, with respect to other high-precision 3D tracking systems;
- gaseous detector allows very low energy detection thresholds: a single electron cluster can be produced by an energy release of a few tens of eV, that, in gasses, has a very good chance of reaching the multiplication stage and therefore being detected;
- the measurement of the total ionization gives information on the energy releases, and, if the readout granularity is enough, the profile of the energy

deposit can be measured with high precision, providing an important tool for signal/background discrimination;

- the track itself provides the axis of the recoil, while the charge profile along it allows us to access the track orientation (*head-tail*), supplying another powerful observable for DM search;
- a large choices of gasses can be used to fill the TPC, including gas light nuclei with even or odd number of nucleons (such as fluorine), sensitive to SI or SD dark matter interactions, respectively, in the $\mathcal{O}(\text{GeV})$ mass region;
- operating at room-temperature and atmospheric-pressure results in great economical and operational advantages, with no need for cooling or vacuum sealing, allowing for a simpler technology and a better scalability;
- although using a gaseous target at atmospheric pressure reduces the interaction probability with respect to solid or liquid targets, very large TPCs can be built: in fact TPCs up to 100m^3 of active volume have been already successfully operated, showing the feasibility of gaseous detector with large active mass.

2.1.1 The optical readout

In recent years, an increasing number of tracking detectors started to employ MPGDs (micro-pattern gaseous detectors). These detectors are characterized with a very high achievable granularity and rate capability, and, the modern MPGDs, provides by now stable and uniform operation. The GEMs, in particular, have already been used to equip very large areas, reaching high spatial and time resolution, and they have also been employed coupled to pixelised sensors, showing really good performances.

Gas luminescence is a well-studied and established mechanism: charged particles traveling in the gas can ionize atoms and molecules but can also excite them. As a consequence of the de-excitation process photons are emitted. The spectrum and the amount of this light strongly depends on the gas mixture, its density and the presence and strength of an electric field.

The idea of the CYGNO collaboration is to detect the light produced during the multiplication process with an sCMOS-based optical device. The possibility of installing the light sensor outside of the TPC volume, reducing possible issues related with gas contamination and high-voltage operations is one of the advantages offered by this type of readout. In addition highly performing sensors can be easily procured, since they are being developed for commercial use, and the use of a proper lens allows the acquisition of large areas ($\mathcal{O}(1)\text{m}^2$) while maintaining a great spatial resolution, with a $\mathcal{O}(100)\mu\text{m}$ effective pixel size. Because the currently available frame rate for sCMOS is still low compared to the duration of a typical TPC signal, to obtain a 3D reconstruction of the tracks, the CYGNO experiment will utilize additional fast light sensors (PMTs or SiPMs), that can provide the track profile along the drift direction.

The high sensitivity obtained by the implementation of this technique results in an excellent performance at particle detection, not only at energies of DM searches, but also for cosmic rays and high energy electrons.

2.1.2 Gas mixture

The overall detector performance is significantly dependent on the gas characteristics; with the main properties affected being:

- ionization statistics,
- transport properties (drift velocity and diffusion),
- electron multiplication,
- light production;

for this reason the CYGNO project extensively studied different gas mixtures [44]. In the context of DM searches with an optical TPC, CF_4 -based mixtures are particularly interesting. CF_4 is indeed a well-known efficient scintillator, and, furthermore, the electro-luminescence spectra of these mixtures have a large peak at 600 nm [52], where Si sensor have their highest quantum efficiency, as can be seen in Fig. 2.4.

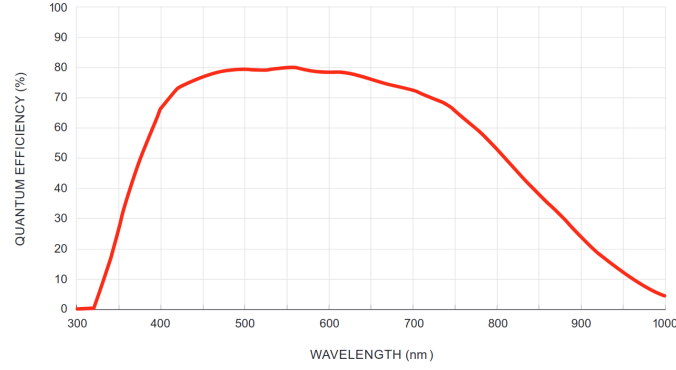


Figure 2.4. Quantum efficiency for the Hamamatsu ORCA-Fusion camera, the camera employed in the LIME prototype. Figure from Ref. [53].

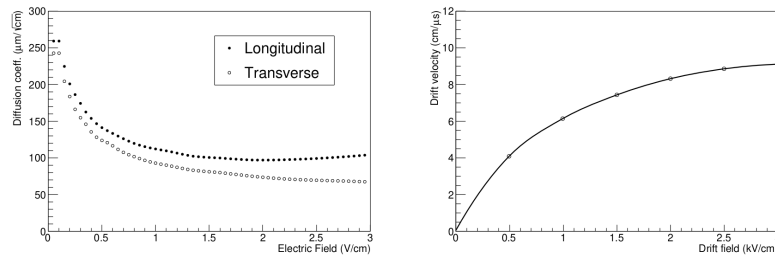


Figure 2.5. Transverse and longitudinal diffusion coefficients (**left**) and electron drift velocity (**right**) as a function of drift field, for He/ CF_4 60/40 mixture. Figure from Ref. [44].

As explained in [54], He- CF_4 mixture was chosen by the CYGNO collaboration. While the light yield increases for larger amounts of CF_4 , the detector stability improves for higher amounts of He, and the best compromise was found to be a

mixture with 60% He and 40% of CF₄. Diffusion coefficients and drift velocity were calculated with GARFIELD [55, 56] by the CYGNO collaboration, showing the behaviors represented in Fig 2.5.

For this mixture, an average of 42 eV energy loss per single ionization was estimated, and for a minimum ionizing particle are expected 3 ionization/mm, with 2 electrons per cluster, resulting in a 250 eV/mm energy loss [44].

2.1.3 CYGNO roadmap

After an initial phase where the techniques outlined before have been proven to work, a staged plan has been developed:

- PHASE_0: installation of a 50 L prototype underground at Laboratori Nazionali del Gran Sasso (LNGS), to study the performance in a low background environment, and validate MC simulations;
- PHASE_1: developing a $\mathcal{O}(1) \text{ m}^3$ demonstrator to test the scalability of the experiment, while studying and minimizing the internal background due to radioactivity of the apparatus materials;
- PHASE_2: propose a larger scale experiment $\mathcal{O}(30 - 100) \text{ m}^3$, depending on the results of the previous phases, to explore the 1 – 10 GeV DM mass region. This kind of apparatus will have competitive sensitivity to both SI and SD couplings, and will also have the possibility of performing low-energy solar neutrinos measurement. For both those purposes, the directional capability of the CYGNO approach will provide useful information for astrophysical studies of incoming particles.

In the next sections, the different stages of the project will be explained. The CYGNO project is now in the PHASE_0, with the LIME prototype installed underground and taking data to characterize the background and the detector response.

2.2 CYGNO's approach performances

The CYGNO approach was widely tested and validated by means of small prototypes in the last years. The Long Elliptical Module (LEMON) represents the most comprehensive example currently available of the performance achievable with this approach [44].

2.2.1 The LEMON prototype

The detector, visible in Fig. 2.6 has an $24 \times 20 \text{ cm}^2$ readout area and 20 cm drift length. The 7 litres of sensitive volume are enclosed by a cylindrical field cage with an elliptical base (A). On one side the elliptical cylinder is closed by a stack of 3 GEMs, while on the other side is closed by a mesh-based semitransparent cathode. Behind the cathode is placed a Photo Multiplier Tube (PMT) (B). Facing the GEMs is placed the Orca-Flash 4.0 by Hamamatsu (D), optically coupled by a black bellow (C). The Orca-Flash 4.0 is based on a $1.33 \times 1.33 \text{ cm}^2$ sCMOS sensor comprising

2048 × 2048 pixels, with a readout noise of 1.4 electrons rms and a quantum efficiency of 70% at 600 nm. The PMT information complements the camera picture, providing three dimensional reconstruction capabilities. The sCMOS sensor was placed at 52.6 cm distance from the GEMs, resulting in a geometrical acceptance of photons of 1.6×10^{-4} . The PMT chosen by the collaboration is a Photonics XP3392 PMT.

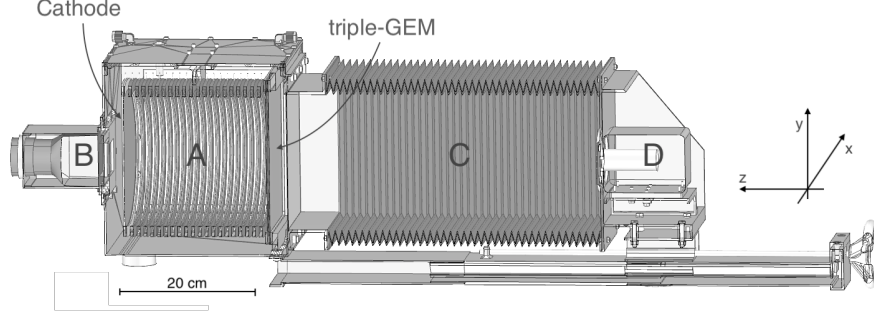


Figure 2.6. The LEMON prototype. The elliptical sensitive volume (A), the PMT (B), the optical bellow (C) and the sCMOS camera (D) are indicated. Figure from Ref. [57].

The performance of LEMON has been tested at LNF overground, by means of radioactive sources (^{55}Fe , AmBe), high energy (450 MeV) electrons from a Beam Test Facility (BTF [58]) and cosmic rays.

Energy resolution and detector efficiency

To evaluate the light production and the detector response interactions of 5.9 keV X-rays produced by a ^{55}Fe source were used. The source was placed inside the gas, at 20 cm far from the GEMs [54]. The sCMOS images were acquired in a free-running mode (i.e. without using any trigger signal) with an exposure of 100 ms. Figure 2.7 shows on the left the light spectrum of the ^{55}Fe events reconstructed from the sCMOS pictures, and on the right the integral of the charge signal measured by the PMT. For the sCMOS camera an average light yield of 514 ± 63 photons per keV

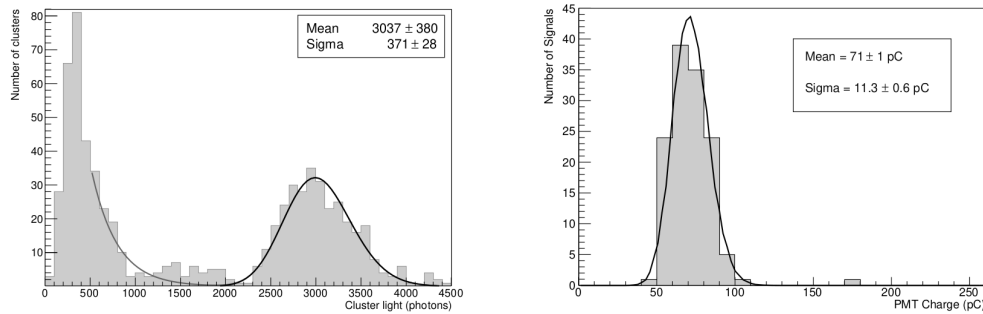


Figure 2.7. **Left:** distribution of the light content of the ^{55}Fe events reconstructed by the sCMOS pictures. **Right:** charge distribution measured by the PMT signals of the same events. Fig from Ref. [44].

[44] is found, with an energy resolution of 12%. For the PMT were obtained similar

results, with an average of (12.0 ± 0.2) pC per keV [44], and an energy resolution of 16%. The results for the sCMOS sensor confirm that his noise is well beyond 400 eV and the detector can be operated with an energy threshold of 1 keV.

The detector efficiency was studied varying the drift electric field, finding a plateau for electric field values larger than 300 V/cm [54]. The left panel of Fig. 2.8 shows the number of reconstructed ^{55}Fe spots in the sCMOS pictures as a function of the drift field E_D , normalized to the value obtained for $E_D = 600$ V/cm. The right panel of Fig. 2.8 shows the dependency of the number of reconstructed spots, normalized to its average value, on the source distance from the amplification stage. This effect was studied showing no significant change in the detection efficiency [54].

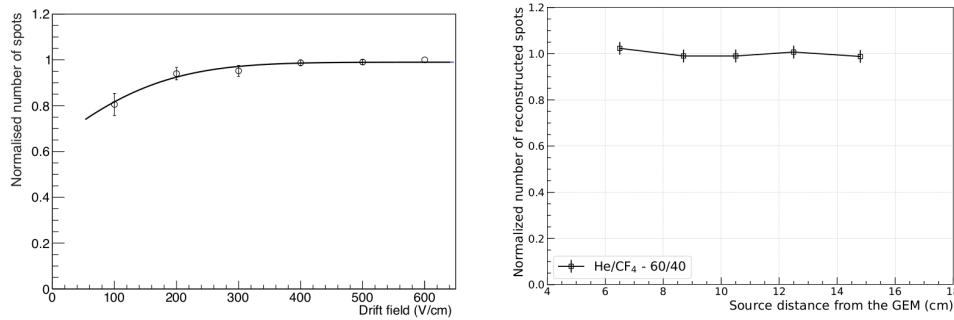


Figure 2.8. Behaviour of number of ^{55}Fe spots (normalized) as a function of the drift electric field (**left**) and source distance from the GEM plane (**right**). Fig from Ref. [44].

Position reconstruction

The ability to reconstruct the event's z position was studied with 450 MeV electrons from the LNF-BTF facility [59]. Using the transverse diffusion it is, in fact, possible to extract the drift length and thus infer the z position of the ionization cluster [57]. The $x - y$ resolution was measured as a function of z , finding $100 \mu\text{m}$ close to the GEM, increasing to $300 \mu\text{m}$ at 20 cm far from them. As described in [57], the light profile transverse to the track direction possess a Gaussian shape. The total light L is proportional to $\sigma \times A$, where the light amplitude A decreases with longer drift distances, while the width σ increases as $\sqrt{z}$. Therefore, the ratio $\eta = \sigma/A$ is expected to increase quadratically with z [59]. Using this technique a 15% resolution was obtained on the z position over the 20 cm length [59].

Discrimination between Nuclear and Electron Recoils

Thanks to the high granularity of the optical sensor all the track properties can be exploited to identify and separate ER, surely due to background process, from NR, possible candidates of DM signals.

The need to access track information such as shape, length, width, light density and others, is the reason for a deployment of an advanced clustering algorithm for the CYGNO experiment. This algorithm, called iDBSCAN [60], is briefly described in

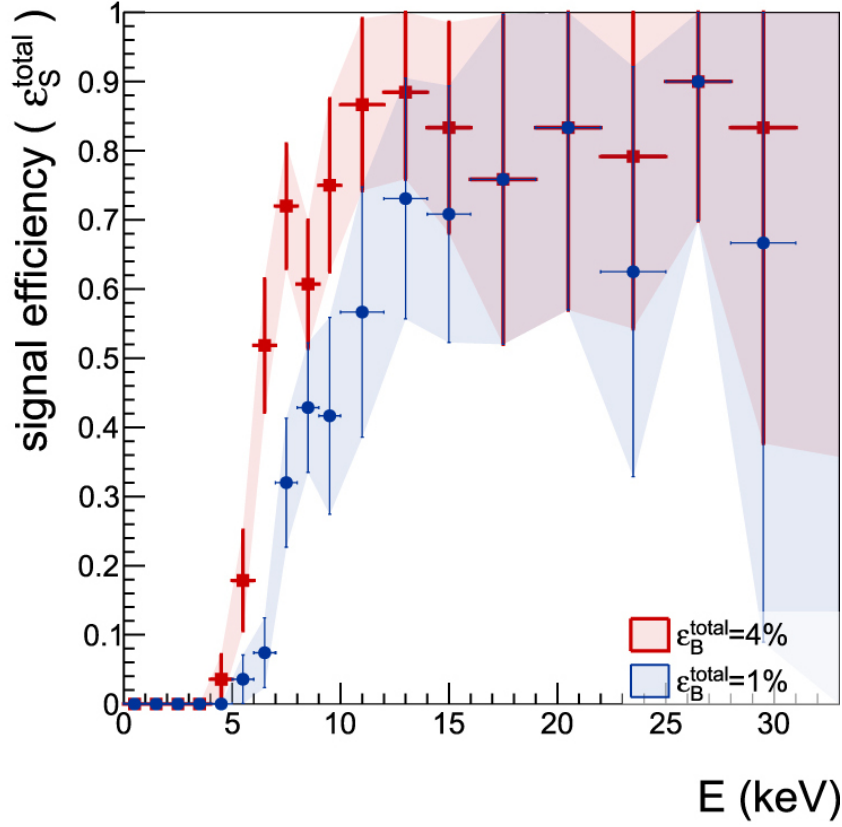


Figure 2.9. Detection efficiency for nuclear recoils as a function of their detected energy. The different points correspond to an electronic recoil rejection efficiency of 4% (squares) and 1% circles. Fig from Ref. [44].

Sec. 2.3.6. Its performances were tested using ER produced by 5.9 keV X-ray coming from ^{55}Fe and NR produced by an AmBe neutron source [61]. The 59 keV photons produced by the AmBe source were almost completely shielded by means of a lead shield surrounding the detector. However, since the data were taken overground at LNF, there was a significant presence of cosmic background.

In order to select a sample of pure NR induced by the AmBe's neutrons, several cluster observables were exploited. Among them the slimness (ξ), defined as the ratio of the width of the track in the transverse direction and the projected path length, was used in order to discriminate cosmic rays. On the other hand, the light density (δ) i.e. the ratio between the total number of photons of the cluster and the cluster pixel size, was used for the NR/ER discrimination.

Using a simple cut on the observable δ , a 50% (40%) nuclear recoil discrimination efficiency is obtained in correspondence to an ER background rejection of 96.5% (99.2%) in the 5.9 keV_{ee} energy region [61], as can be seen in Fig 2.9.

This simplistic cut can be improved for example including more sophisticated analyses combining topological variables together with the PMT data. However, it provides a promising rejection factor of 10^2 for ER with an energy of 5.9 keV with a gas detector at atmospheric pressure, while retaining a high fraction of NR events.

2.3 PHASE_0: the Long Imaging Module

The Long Imaging ModuleE (LIME) detector is the prototype foreseen to conclude the R&D phase of the Cygno project, in Fig. 2.10 there are two pictures of it. It consists on a squared-box TPC, with the same drift length as the future demonstrator (50 cm), and a $33 \times 33 \text{ cm}^2$ transverse area, for a 50 L of total active volume. The gas volume, a mixture of He (40%) and CF₄ (60%) at atmospheric pressure, is enclosed in a plexiglass box that provides gas tightness. The field cage is composed of square copper rings that delimits laterally the active volume. On the transverse side, the gas chamber is delimited by the copper cathode on one side and a stack of three GEMs on the other one. The ionization electrons, produced in the interactions, drift towards the anode. Once they have reached the GEMs, they produce an avalanche of electrons and ions that will produce light. A scientific CMOS camera is used to collect the light produced, with an integration over time that can be set between 30 ms and 10 s. As described in Sec. 2.1.1, to complement the information given by the camera, a set of 4 PMTs is installed around it to detect the same light but with a much faster response.

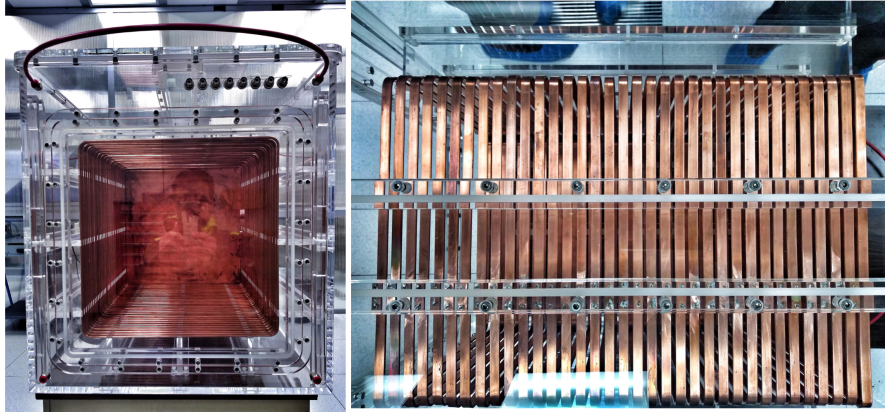


Figure 2.10. Pictures of the LIME detector. On the **left** there's a front view of the field cage, while on the **right** the field cage copper rings are shown. Figure from Ref. [44].

The detector has been designed, built and commissioned at Laboratori Nazionali di Frascati (LNF) overground. It is now collecting data, without shielding, underground at LNGS, to study the detector performance in low radioactivity and low pile-up, and to characterize the radioactive background in site. In Fig. 2.11 two pictures collected during the underground campaign can be seen, showing tracks induced by natural radioactivity. Its final configuration will have a shielding of 10 cm of copper and an additional 40 cm of water externally. Data taken with the different shield configurations will be crucial to validate the Monte Carlo (MC) simulation of the LIME setup.

This is the detector I have worked on during my thesis project. I have worked in particular on the DAQ optimization and on the PMTs signal analysis (as will be described in Chap. 3 and Chap. 4).

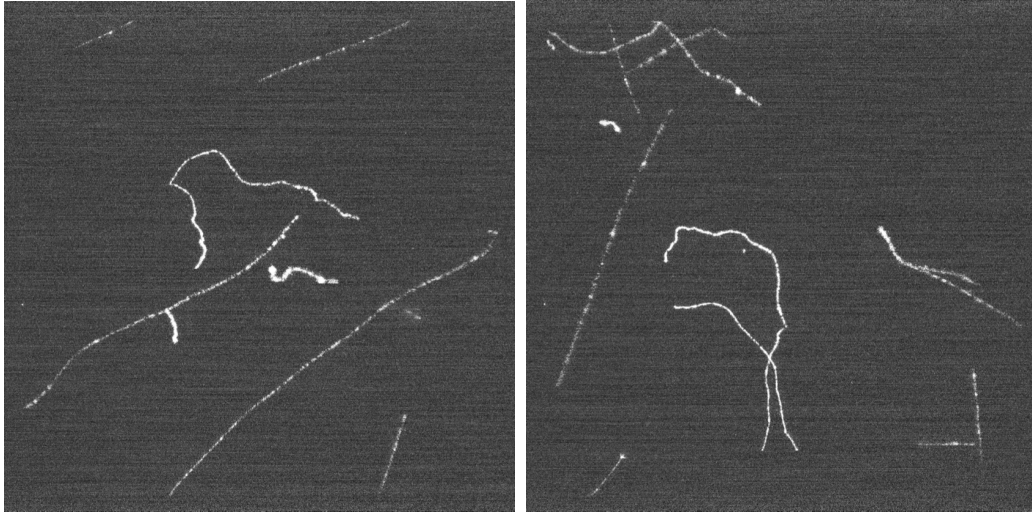


Figure 2.11. Two pictures collected by the sCMOS camera in the underground campaign of LIME at LNGS.

2.3.1 Gas vessel and field cage

The gas vessel is realized with a 10 mm thick PMMA box. Inside it there is the field cage, consisting of 34 square 10 mm thick coils, placed at 4 mm distance from each other, with an effective pitch of 14 mm. The dimensions of this square field cage are 330×330 mm side, with 488 mm length. The cathode is made of a 0.5 mm thin copper slab, with the same squared dimension as the rings. The anode is composed of a stack of 3 GEMs, that have $50 \mu\text{m}$ diameter holes with a pitch of $140 \mu\text{m}$, placed at 2 mm from each other and at 7 cm from the first coil. The field cage produces an uniform electric field that drifts the primary ionization electrons towards the amplification stage.

As described in Sec. 2.1.2 the gas mixture usually contained is a 60/40 He/CF₄.

In the upper part of the plexiglass box there is a thin window, sealed by a $150 \mu\text{m}$ thick EFTE layer, 5 cm wide and 50 cm long. This window allows low energy photons, down to the keV, to enter the gas volume from external radioactive sources, allowing the calibration of the detector response. A plastic trolley that can be moved back and forth along the drift direction is mounted over the window. This serves as a source holder and has a 5 mm diameter hole in the base, in order to collimate the photon beam.

2.3.2 Readout system

On the same side of the vessel where the GEMs are placed, a black PMMA conical structure is installed, allowing the housing of the optical sensors. The readout of this prototype relies on a water-cooled Hamamatsu Orca-Fusion sCMOS camera, and 4 Hamamatsu R7378 PMTs symmetrically-arranged, placed on the GEMs side with a 22 mm diameter. The Orca-Fusion camera sensor is a matrix of 2304×2034 pixels, with a quantum efficiency of 80% at 600 nm and a dark noise of 0.7 electrons per pixel. This sensor is able to acquire the whole GEM surface by means of a

Schneider Xenon 0.95/25-0037 lens, with a 25.6 mm focal length and a 0.95 aperture. The lens is placed at 62.3 cm far from the GEMs, in order to image the $33 \times 33 \text{ cm}^2$ GEM surface. In this configuration the geometrical acceptance for the camera is $\epsilon_{\Omega} = 1.2 \times 10^{-4}$. While the camera can easily provide a 2D projection of the tracks, the profile along the drift direction can be obtained by the 4 PMTs, to achieve a precise 3D track reconstruction.

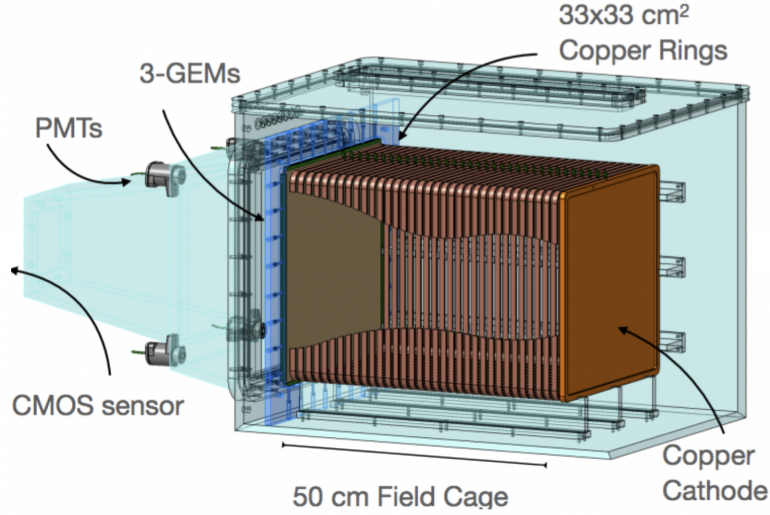


Figure 2.12. A schematic drawing of the LIME experimental setup.

2.3.3 Faraday cage

The detector is placed inside a 3 mm thick aluminum metal box. This box acts as a Faraday cage, and guarantees light tightness of the detector. It is equipped with connection for the high voltages required by the field cage and the PMTs, and for the gas system. To operate the source holder, a rod is connected, free to enter the cage from a hole in the rear face. On the front side there is a square hole, where the optical bellow is mounted, at which the sCMOS camera system can be coupled.

2.3.4 High voltage and gas supply system

Electrical voltages are supplied by 2 generators:

- an ISEG HPn 500, provides up to 50 kV and 7 mA, with negative polarity and ripple $< 0.2\%$ directly to the cathode,
- a CAEN A1515TG board with Individual Floating Channels, that supplies the voltages to the GEMs, up to 1 kV, with 20 mV precision.

The usual configurations at which LIME is operated are:

- an electric field inside the sensitive volume with a standard value of $E_{Drift} = 0.8 \text{ kV/cm}$,

- an electric field in the transfer gaps between the GEMs about $E_{Transf} = 2.5 \text{ kV/cm}$
- the voltage difference across the two sides of the GEM is usually set at 420 V

The gas mixture is continuously flushed into the detector at a rate of 200 cc/min. The fresh gas is obtained from cylinders of pure gasses, and the output is sent to an exhaust line.

2.3.5 DAQ and trigger system

The data acquisition is realized by means of a Linux server through an integrated system within the Midas framework. The camera is acquired via USB 3.0 connection, while the PMTs and GEMs signal are acquired via USB 3.0 to a VME crate that houses I/O register modules for trigger and controls.

The PMTs signals are sent into a leading edge discriminator and a logic module that produces a trigger signal when at least two of the PMTs waveform cross a set threshold. Furthermore, the trigger is vetoed for $10 \mu\text{s}$ after every trigger in order to avoid trigger on afterpulses.

The camera is generally operated in Global Exposure (GE), i.e. every pixel is exposed for the same amount of time. The reading and activation of the sCMOS sensor in this configuration is done sequentially by rows, starting from the top of the sensor. The readout employed is the “*ultra-quiet scan*” mode, in which the readout of each row takes $80 \mu\text{s}$, for a total time of $\sim 180 \text{ ms}$ for the whole sensor. Therefore, to have the same exposure for every pixel the exposure start is delayed by the same amount in respect to the previous row, in Fig. 2.13 there is a graphical description. Usually the camera is operated with an exposure of 200 ms. The DAQ system has

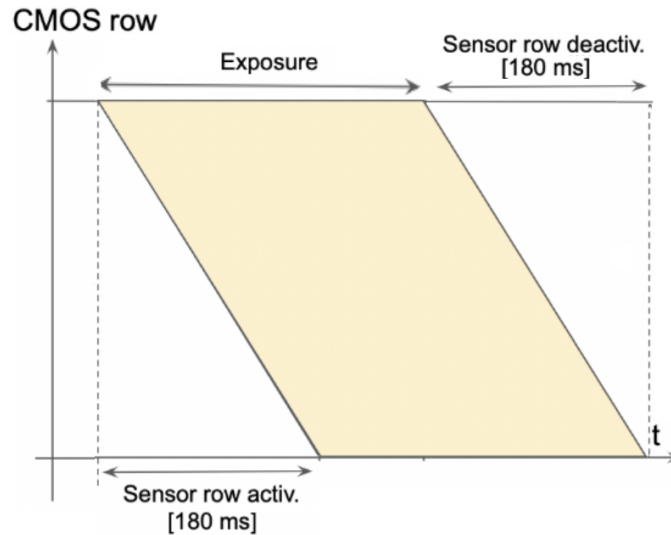


Figure 2.13. Graphical description of the camera operation mode normally used. In the horizontal axis there is the time, while in the vertical axis the rows of the sCMOS sensor. The exposure of each row is represented by the yellow box. Using the usual exposure (200 ms) we would have a global exposure, i.e. all the pixels are exposed at the same time, of 20 ms.

been designed to acquire simultaneously the sCMOS picture and the PMTs signal. In this way a 3D reconstruction of the event in the sensitive volume is possible.

The acquisition of the picture is triggered via software, every time that:

- the camera is ready to acquire, i.e. it is not already acquiring or reading the sensor,
- the digitizer is ready, i.e. the DAQ system is not downloading waveforms from it.

From the start of the exposition to the end of the sensor reading, waveforms for every PMTs trigger are acquired. Every event saved is therefore formed by a picture and n PMTs waveforms. In the Global Exposure configuration not all the PMT events are captured by the sCMOS sensor. In fact, as described above, the army of each row is at different times. The total exposure of the picture acquired will therefore be of $\Delta t + 180$ ms, where Δt is the set global exposure, and the 180 ms is the sensor readout time. The PMTs acquired events can occur in two different conditions:

- the camera is *globally exposed* (i.e. all the rows are exposed): the light produced by these events is collected also from the sCMOS sensor;
- the camera is not *globally exposed*: there is a non-zero probability that those events happened when the corresponding sensor portion was not yet exposed or already deactivated. In this case the event may not be observed by the sCMOS sensor.

In Fig 2.14 there is a schematic drawing that describes when the PMTs triggers can occur.

2.3.6 Pictures analysis

The acquisition system provides images captured by the sCMOS sensor. Each pixel provides a response proportional to the number of collected photons, that we will call intensity, added to a baseline, called pedestal, that can be defined as the intensity value corresponding to zero photons collected. The pedestal average, in principle, can vary from pixel to pixel. Another important parameter is the noise level, that can also vary from pixel to pixel, and it is calculated as the standard deviation of the pedestal distribution of the single pixel. To account for such variations, both the pedestal (μ_i) and the average noise (σ_i) are estimated before the event reconstruction procedure. The reconstruction algorithm consist of four steps:

1. a zero suppression, in order to reject electronic noise of the sensor;
2. an optical correction to equalize light yield, as a function of the distance from the camera focus;
3. a super-clustering step, to reconstruct long tracks;
4. a small clustering step to find short deposits.

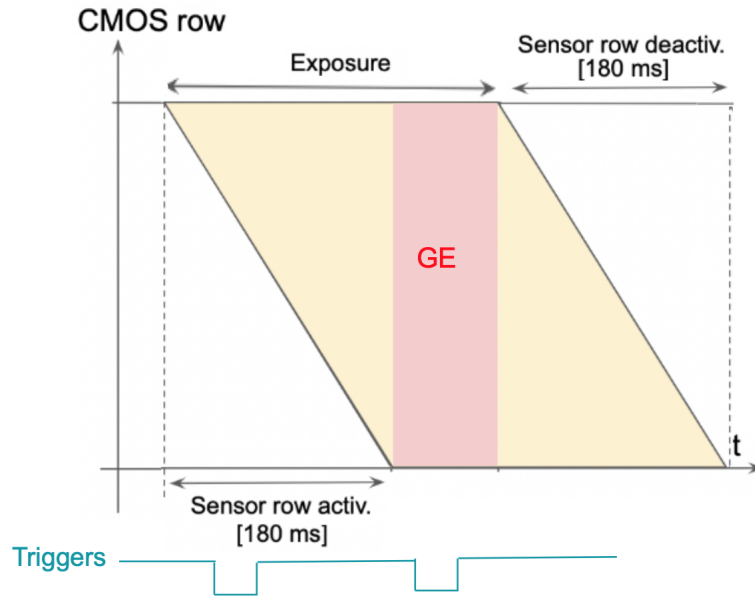


Figure 2.14. Graphical description of the two possibilities for the timing of the PMTs triggers. As we can see, the first trigger occurs when not all the rows of the camera are exposed, therefore in this case the event may not be observed in the picture, or can be cut (some rows could have seen it, others could not). The second trigger, instead, occurs when the camera is *globally exposed*, therefore the event will be captured by the sCMOS sensor.

Zero suppression

Before begin the CYGNO's event reconstruction some pre-processing steps are made, to reject electronic noise:

1. Pedestal subtraction is carried out pixel by pixel, subtracting μ_i from the original intensity values, generating new intensity values defined as I_i .
2. Upper threshold is applied: it allows to remove pixels with a too large intensity, produced mainly due to leakage currents that go into sensor wells, also known as hot-pixels.
3. Lower threshold is applied: this was optimized to be just above the noise level, to ensure a good detection efficiency, but not too low in order not to overload the event-reconstruction algorithm with noise dominated pixels. It is set as $n \cdot \sigma_i$. Pixels outside these limits have their intensities reset to zero.
4. Acceptance cuts are custom cuts in x and y , that allows the user to remove noise edges of the images.
5. Images are then rescaled for CPU reasons, so that at the $res \times res$ matrix, called macro-pixel, is assigned an intensity value corresponding to the average of the intensities I_i of the $res \times res$ pixels of the macro-pixel.
6. Finally the rescaled image goes through a filtering stage, based on a 2×2 median

filter, that replaces a given macro-pixel intensity by the median intensity of all macro-pixels in its neighborhood.

Clustering

After the pre-processing steps, the coordinates (x, y) and the respective intensities z of non-zero I_i values are sent to the clustering algorithm, whose output is used to extract clusters' features. The principal clusters' features derived are: integrated light, size, length, width and others. To determine integrated light, and therefore energy, another step is applied: a vignette correction. This correction is needed because the sensor response to light can differ from pixel to pixel.

In the first step small-radius energy deposit are formed with iDBSCAN [60], a modified version of Density-Based Spatial Clustering of Application with Noise (DBSCAN) [62]. DBSCAN is one of the most known algorithms for clustering analysis. Given a set of elements distributed over a hyper-plane, the algorithm seeks for areas of high density to form clusters. The functionality of this algorithm can be understood with his two parameters: the radius of the hyper-sphere (ϵ), applied to over each element to count the number of neighboring elements around it, and the minimum number of points inside each hyper-sphere (N_{min}), used to decide if those elements make a cluster. The modified version used by the CYGNO collaboration is called intensity-based DBSCAN, or iDBSCAN. This version has shown to be able to improve detector performance when compared to the previously used algorithm based on the Nearest Neighbor Clustering (NCC) technique [63]. Furthermore, as described in Ref. [60], the adapted version iDBSCAN can achieve with respect to NCC an enhancement of 57% for natural radioactivity background, and a factor of few thousands less for the number of electronic-noise clusters per image. Again Ref. [60] shows how iDBSCAN has obtained similar results for the background rejection with respect to DBSCAN; in addition, iDBSCAN was able to significantly reduce the number of electronic-noise clusters, when compared with DBSCAN.

The effective gathering radius for pixels around a seed pixel is of few pixels. Small clusters are therefore formed, even if they could belong to long tracks. After this clustering a super-clustering algorithm begins. It searches, iteratively, for possible trajectory candidates compatible with polynomials. For polynomials of orders from 1 to 3 several fits are performed with RANSAC [64]. If one of the performed fits is good then the super-cluster is formed and all the seed basic clusters are removed from the image. When no other super-clusters can be found the super-clustering algorithm stops, and the remaining pixels are passed to a final clustering step that searches for small clusters.

2.3.7 First results with LIME overground

LIME was operated for several months overground at LNF, to study the long term stability and to characterize the detector response. A preliminary calibration of ER response has been performed using different X-ray sources. For this calibration campaign only images collected by the sCMOS sensor were analyzed. The data was taken in free-running, i.e. without any physics-derived trigger, acquiring images of 200 ms exposure. Those images were analyzed using the clustering algorithm

described in Sec. 2.3.6, in order to derive cluster information such as the cluster's total number of photons, xy position, photon density etc.

In Fig. 2.15 the ER calibration curve is shown on the left, while on the right it is shown the observed spectrum for the copper 8 keV X-ray line. The data points for the ER calibration curve are obtained as results of a Cruijff function fit to the observed spectrum, expressed as the photon counts of the entire cluster. For each signal model 2 lines were fitted (K_α, K_β). The background was modelled with a Bernstein polynomial of order n (with n up to 5), with the parameters fixed to the values obtained on no-source data.

The response curve shows a good linearity, and an energy resolution of 13% across the whole 50 cm drift length has been measured with the ^{55}Fe source.

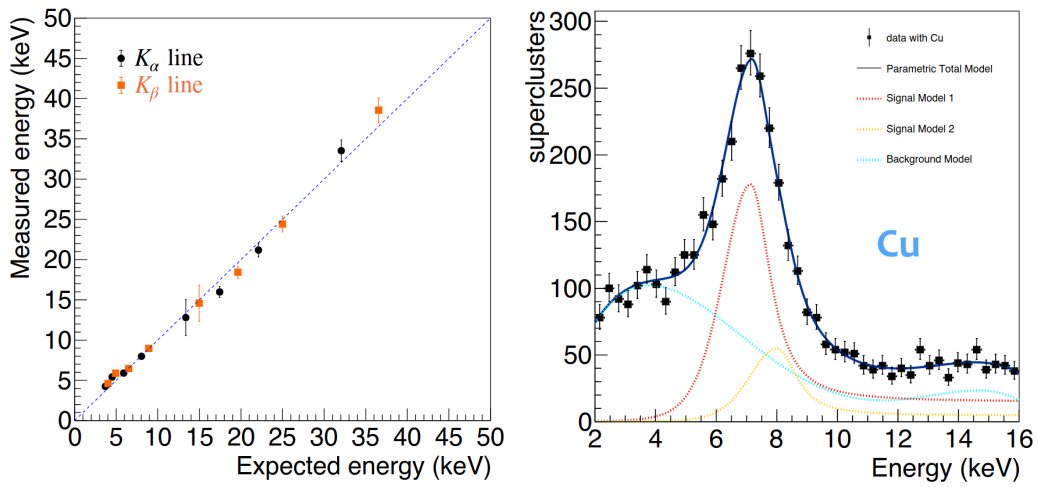


Figure 2.15. **Left:** LIME preliminary ER energy calibration curve. The fit has been performed on images collected overground at LNF using different X-ray sources. **Right:** energy spectrum and fit of the 8 keV Cu X-ray line. Preliminary studies from the CYGNO collaboration.

As already discussed in Sec. 1.4.4, the events that can possibly be caused by a DM-nucleus interaction are the nuclear recoil. In order to learn how to discriminate NR from electron recoil a deep knowledge of the detector response is needed, as well as a possible low background. For the LIME prototype, this kind of study is still in progress. This thesis will focus on the ER events, with the purpose of characterizing them. The X-rays produced by the ^{55}Fe were chosen by the collaboration as the main calibration source for this prototype. In the following I present a study I conducted on the picture clusters produced by the interaction of those X-rays, that will be helpful also for the matching between sCMOS and PMTs information.

^{55}Fe cluster analysis

The first analysis I did with the CYGNO dataset was for the ^{55}Fe clusters. The analyzed runs were taken overground at LNF, with a ^{55}Fe source positioned at different positions, varying from 5.5 to 45 cm far from the GEMs plane. The data were taken in free-running, with a camera exposure of 200 ms, and without acquiring

PMTs waveforms. The aim of the analysis was to understand the diffusion and the energy resolution for the ^{55}Fe spots. The typical energy spectrum is represented in Fig. 2.16, and shows different distances of the source with respect to the GEMs plane. The amount of total collected light depends on the distance of the interaction site inside the TPC from the GEM plane in a non-trivial way, see Fig. 2.16. In particular, at low distance, the density of the primary ionization cloud is enough to saturate the GEM gain, with an overall reduction of the light yield.

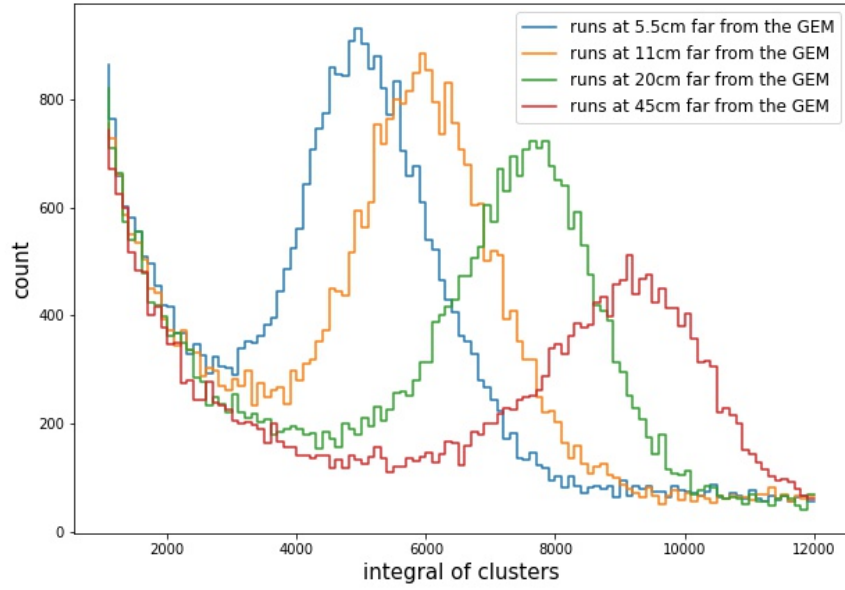


Figure 2.16. Energy spectrum of LIME runs with ^{55}Fe source overground. The different colors represents different source distances from the GEM.

The first step of the analysis was the cluster selection. The ^{55}Fe source produces bichromatic X-ray emission, with the two line separation being smaller than the detector resolution. Therefore, the correspondent clusters collected by the camera will appear to have the same integral, within the detector energy resolution. Furthermore we expect the clusters to be sufficiently small circles, with the dimension dependent on the diffusion. The fastest approach was discarding all the clusters which did not satisfy these conditions:

- cluster photon count (from now on called *integral*) < 1000 & > 15000 ;
- outside of a chosen zone in *integral* vs *size* plot, represented in Fig. 2.17.

The result of this cluster selection is visible in Fig. 2.18, in blue there is the spectrum of the uncut *integral*, while in orange is the *cut integral* of the same dataset.

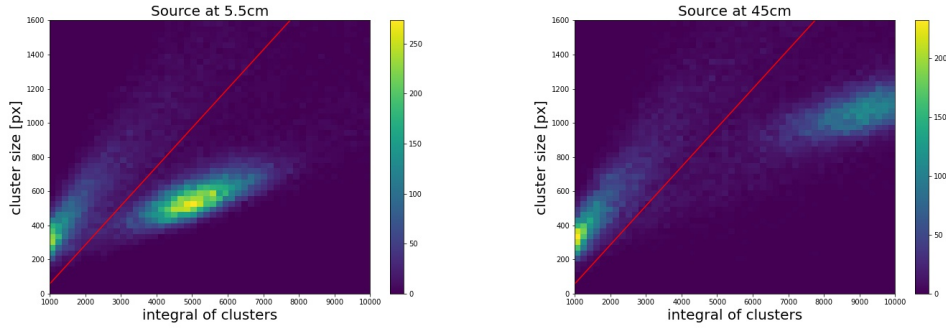


Figure 2.17. Representation of the chosen zone in the *size* vs *integral* of the clusters. All the clusters placed above the red line were discarded. **Left:** runs with the source 5.5 cm far from the GEM, **Right:** runs with the source 45 cm far from the GEM

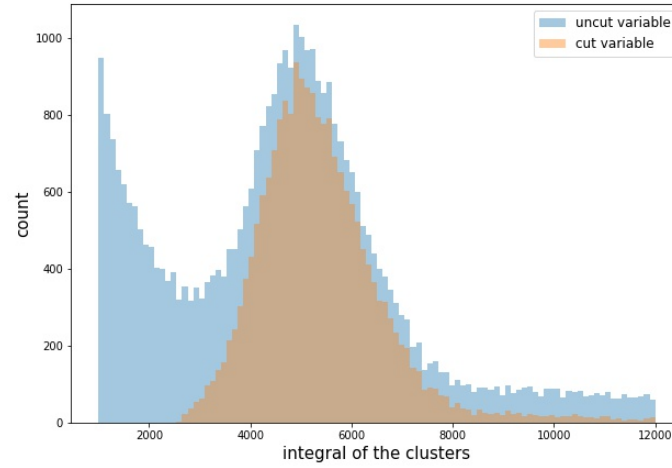


Figure 2.18. Energy spectrum for runs with the source 5.5 cm far from the GEM. **Blue:** uncut energy spectrum, **orange:** cut energy spectrum.

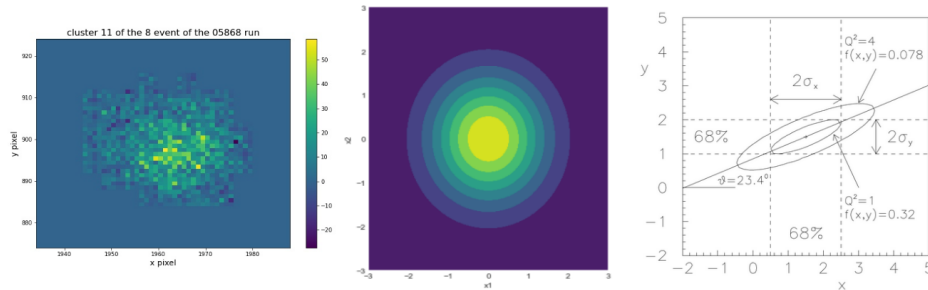


Figure 2.19. **Left:** typical ^{55}Fe cluster. **Center:** an example of a bivariate gaussian. **Right:** bivariate gaussian equidensity ellipse, from Ref. [65].

The next step was to understand how to treat the ^{55}Fe clusters. These can be seen as bivariate Gaussians, see Fig. 2.19, it is therefore possible to find σ_x , σ_y and ρ , respectively the diffusion along the x or y axis and the correlation coefficient, of every cluster to evaluate its shape. With the cluster's shape it is then possible to evaluate the directionality of the e^- recoil. In fact, using σ_x , σ_y and ρ it is possible to find θ with [65]:

$$\tan 2\theta = \frac{2\rho\sigma_x\sigma_y}{\sigma_x^2 - \sigma_y^2}. \quad (2.1)$$

Once we find θ it is possible to retrieve width and height of the equidensity ellipse, respectively σ_a and σ_b [65].

It is possible to find σ_x , σ_y and ρ using an MCMC fit for every cluster. Since the bivariate fit gave similar results of the sample quantities for a fast approach we used the latter, being faster to compute.

Once we find θ it is possible to find σ_a and σ_b , i.e. the semi-major and semi-minor axes of the ellipse. We expect that σ_a , i.e. the longitudinal diffusion, to depend on the distance from the GEMs plane as:

$$\sigma(z) = \sqrt{\sigma_0^2 + D^2 z}. \quad (2.2)$$

The same can be computed for the height of the ellipse, which will have a different σ_0 , but should depend in the same manner from D .

After computing the mean σ_a and σ_b for the different distances we fitted the results, finding the values reported in Tab. 2.1. The fit is shown in Fig. 2.20. The fits obtained are adequate, although some correlation in the residuals is visible. Moreover the dependence on z should be the same for both, but the found values differ more than three sigmas.

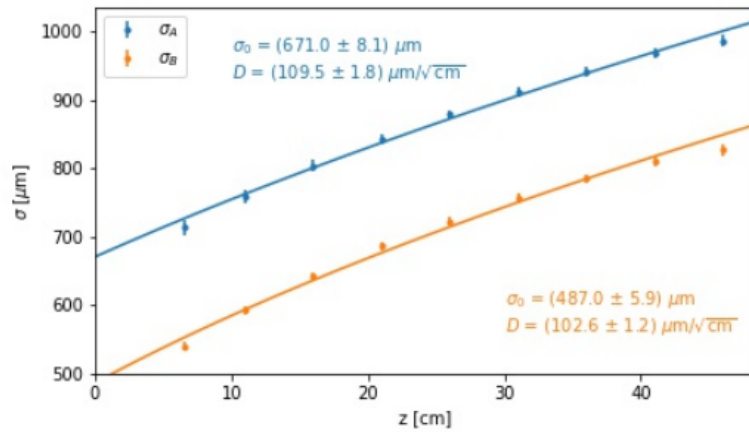


Figure 2.20. Fit for the transverse diffusion in the ^{55}Fe clusters.

2.3.8 LIME commissioning at LNGS

The performance of the LIME prototype in an underground environment will be crucial to validate the CYGNO's approach. The analysis of the environmental

	σ_a		σ_b
σ_0	671.0 ± 8.1	σ_0	487.0 ± 5.9
D	109.5 ± 1.8	D	102.6 ± 1.2

Table 2.1. Fitted parameters for the transverse diffusion of the ^{55}Fe clusters.

and internal background will be essential in order to verify the goodness of the MC simulations. Those simulations, in fact, will be used to determine how the future detectors will perform. Because of this, a great effort was made to simulate both the environmental and the internal background by the CYGNO collaboration.

The plan for the underground campaign of LIME is to perform different shielding configuration measurements, in view of the final low background setup with the full shielding. The configurations that will be studied are:

- No shield: this is the just concluded run, it consisted in background measurement and a periodic calibration with the ^{55}Fe source;
- 6 cm of copper: background measurement, periodic calibration and also a measure with the AmBe neutron source will be performed;
- 10 cm of copper: will consist in background measurement, periodic calibration and the measurement of the *fast neutron flux* underground
- 10 cm of copper + 40 cm of water: this will be the final test of the LIME operation, and this will be the shielding operation condition of the future experiment.

The expected backgrounds are summarized in Sec. 1.4.5.

The external spectra used to perform the simulation are the ones measured in Hall C at LNGS by the Sabre Collaboration for the gamma flux, and by P. Belli et al. [66] for the neutron flux. In Fig. 2.21 and 2.22 external and internal backgrounds are represented respectively.

During my thesis project, I had the possibility to contribute to the commissioning of LIME underground. The main purpose of my contributions were:

- try different readout configuration;
- improve data acquisition, by reducing dead time and optimizing PMTs and sCMOS acquisition;
- characterize in site background rates, primarily with PMTs response.

The first step was to try to improve data acquisition, mainly reducing the dead time. To do this we must understand how the previous acquisition scheme worked for LIME, depicted in Fig. 2.23:

- the start of the camera exposure is triggered via software, by the MIDAS framework;

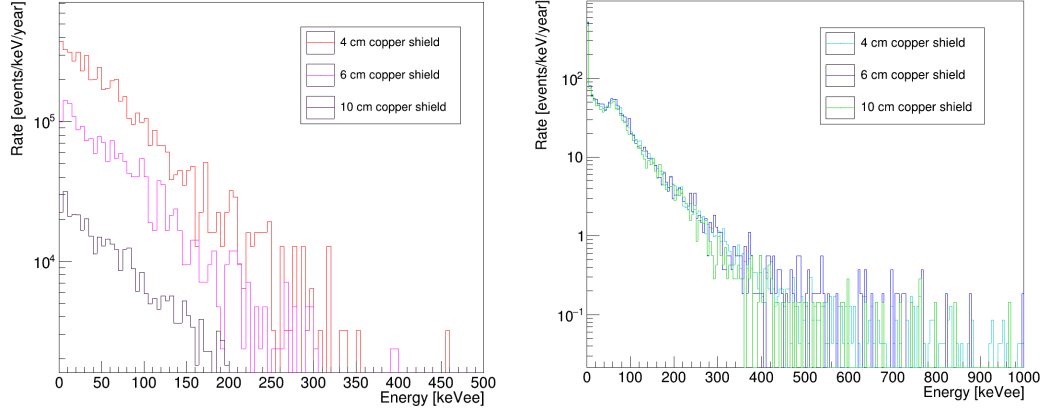


Figure 2.21. Simulation of the expected external background. **Left:** rate of external gammas for different shielding configurations. **Right:** rate of external neutrons for different shielding configurations. Simulations performed by Flaminia Di Giambattista for the CYGNO collaboration.

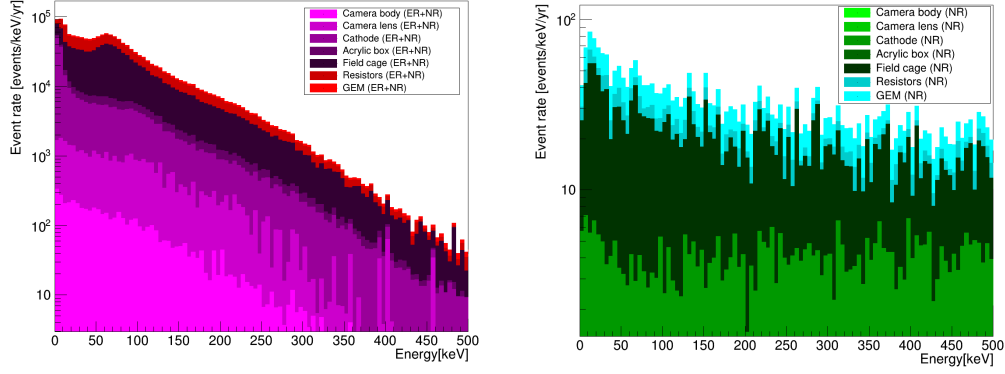


Figure 2.22. Simulation of the expected internal background. **Left:** event rate produced by internal radiation, both electron recoil and nuclear recoil. **Right:** event rate of internal produced nuclear recoil. Simulations performed by Flaminia Di Giambattista for the CYGNO collaboration.

- PMTs trigger is accepted only if the camera is in “Global Exposure”, i.e. all the pixels are exposed at the same time;
- when a trigger is accepted, MIDAS creates an *event*, where it will store the picture and the waveforms collected during the “Global Exposure”.

Setting the camera exposure to 200 ms, the one used before for the LIME data-taking, we find that the time acceptance for PMTs signal is of 20 ms, that is only $\sim 5\%$ of the exposure time of the experiment.

In the new acquisition scheme, instead, the time acceptance of the PMTs is now all the exposure of the camera, from the beginning of the first row, to the end of the last row, for a total time of $\Delta t + 180$ ms, where Δt is the set exposure, see Fig. 2.24. If the triggered signal occurred in GE then we are sure that they are acquired also by the sCMOS sensor. We therefore acquire the GE status of the camera for every triggered waveform, to understand if the spot is necessarily in the picture.

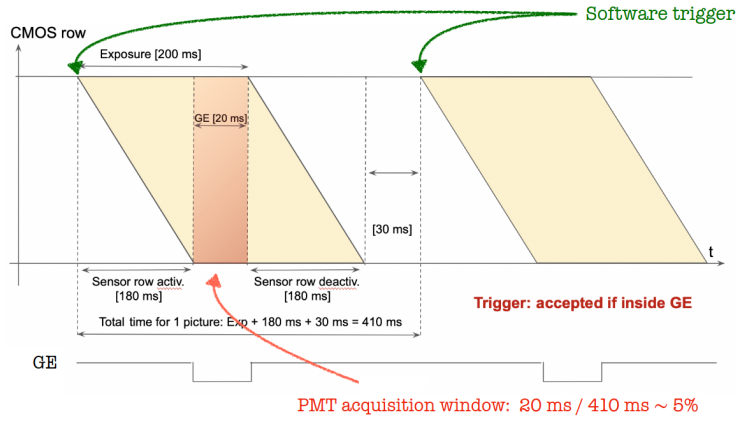


Figure 2.23. Old acquisition scheme for the LIME prototype.

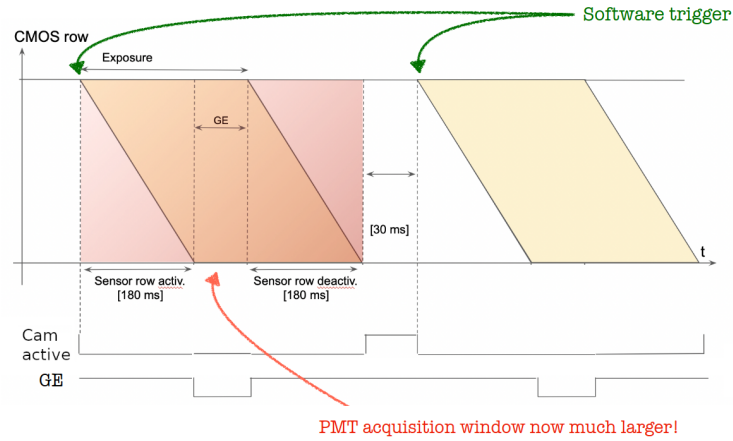


Figure 2.24. New acquisition scheme used for LIME data acquisition.

Another addition to the DAQ, meant for future versions of the DAQ system where PMTs and sCMOS acquisition will be decoupled, was to synchronize timing information from waveforms and pictures. In order to do that, we acquire trigger time stamps (defined as “Trigger Time Tag”) reset at every picture. The reset impulse is given from the camera “in exposure” signal, and therefore we will have trigger synchronized timing for every trigger acquired in the picture.

A lot of data were collected in the autumn campaign by the LIME prototype, acquiring $\sim 4 \times 10^5$ pictures for background and $\sim 3 \times 10^5$ for runs with the ^{55}Fe source.

In order to validate the quality of the data acquired, we did an analysis of rates both for background and for the ^{55}Fe source, for different PMTs thresholds. The rates are represented in Tab. 2.2 and 2.3. The background measured rate is in good agreement with the MC simulated one, which expects ~ 37 Hz of background rate without any shielding. By the analysis of the pictures similar rates were found, indicating that the DAQ is working as expected.

	2 mV thr (Hz)	3 mV thr (Hz)	5 mV thr (Hz)
Trg lvl 2	33.88 ± 0.58	27.10 ± 0.52	26.22 ± 0.51
Ch1	442.0 ± 2.1	333.8 ± 1.8	243.5 ± 1.6
Ch2	361.4 ± 1.9	269.0 ± 1.6	210.2 ± 1.4
Ch3	354.0 ± 1.9	287.4 ± 1.7	246.6 ± 1.6

Table 2.2. Rates of background for LIME campaign at LNGS at various PMTs threshold.

	2 mV thr (Hz)	3 mV thr (Hz)	5 mV thr (Hz)
Trg lvl 2	42.36 ± 0.65	36.74 ± 0.61	34.10 ± 0.58
Ch1	471.5 ± 2.2	363.3 ± 1.9	254.8 ± 1.6
Ch2	379.3 ± 1.9	290.9 ± 1.7	228.0 ± 1.5
Ch3	374.0 ± 1.9	310.9 ± 1.8	260.6 ± 1.6

Table 2.3. Rates of runs with ^{55}Fe source for LIME campaign at LNGS at various PMTs threshold.

2.4 Future CYGNO projects

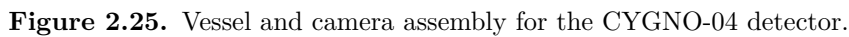
2.4.1 PHASE_1: the CYGNO-04 detector

Once the LIME prototype will be optimised and assessed, the project will move to PHASE_1, with the aim of studying and minimizing material radioactivity on a real experiment scale.

The detector TDR was submitted to INFN. The detector is shown in Fig. 2.25.

The active volume of the detector will be contained in a transparent PMMA vessel, in order to lower the material's intrinsic radioactivity. The vessel wall will be 20 mm thick, and the vessel will ensure gas tightness for the total 0.86 m^3 volume.

The field cage will be made of a kapton foil with printed copper strips to form rings, see Fig. 2.26. It will be supported by an acrylic structure, being able to produce a uniform electric field using low radioactive materials. Two of those field cages will be installed side by side in the gas vessel, with a common cathode in between them. In the other end of the field cages are installed the amplification stages, constituted by a two GEMs stack of $500 \times 800 \text{ mm}^2$, at $\sim 500 \text{ mm}$ from the cathode. The sensitive volume inside of the field cages is 0.4 m^3 .



The DAQ system will be able to collect synchronized data from the sCMOS cameras and PMTs.

A CYGNO detector with a volume of the order of several tens of cubic meters would have the sensitivity needed to contribute to the search and study of DM in the $1 - 10 \text{ GeV}$ mass region, both for SI and SD coupling. In addition, in the case of

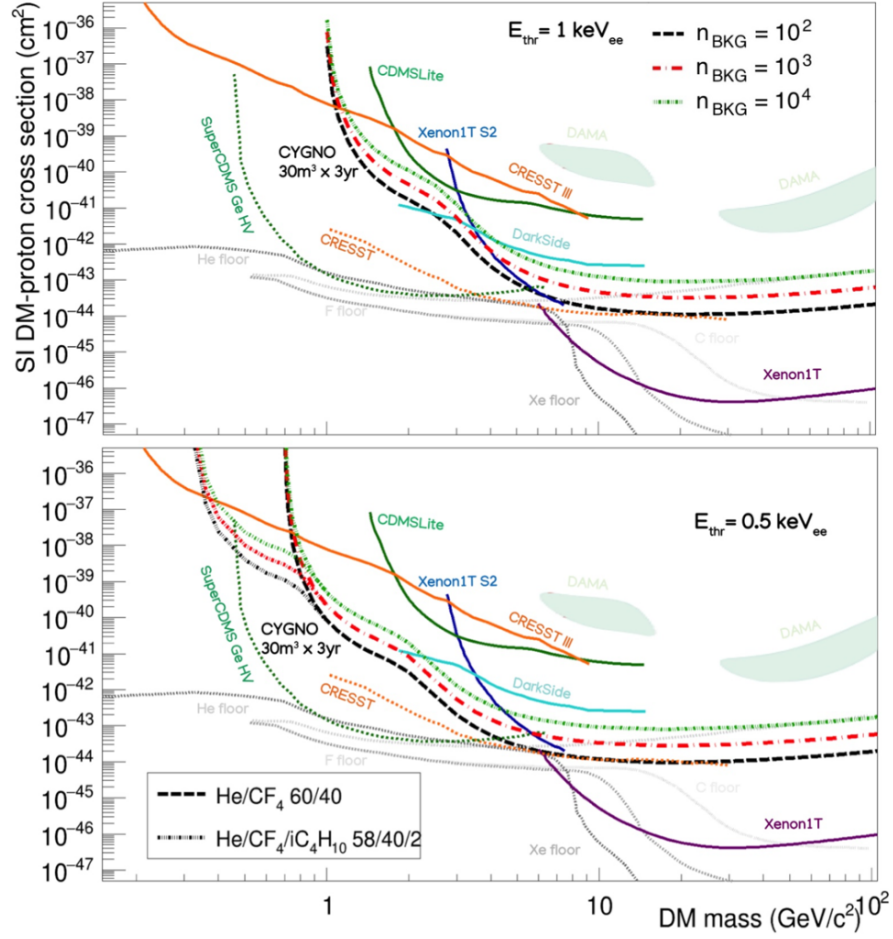


Figure 2.28. Spin-independent sensitivity for WIMP-nucleon cross section for a 30 m² CYGNO PHASE_2 detector for 3 year exposure with different backgrounds assumptions and different operative thresholds. In the top panel an energy threshold of 1 keV is considered, while in the bottom panel for 0.5 keV. The light grey curves shows the neutrino floors for different targets. Figure from Ref. [44].

Chapter 3

PMTs response calibration at LNGS

As discussed in the previous chapter, the main readout of LIME is represented by the sCMOS sensor, which is, however, unable to supply temporal information about the tracks acquired. The use of fast light sensors (PMTs in our case) overcomes this problem, making it possible to access the time information such as the arrival time and the signal duration. The challenge is to associate the temporal information, given by the PMTs, with the cluster reconstructed in the picture.

3.1 PMT geometrical acceptance

Before illustrating what was done to reconstruct the spot position with the PMTs signal, it is useful to describe how the light produced after the GEMs is collected by a PMT.

The two main effects that must be taken into consideration are:

- $\frac{1}{R^2}$ flux dependence,
- PMT geometrical acceptance

In Fig 3.1 there is a schematic drawing of the problem. The intensity of the light produced at the GEMs will decrease with the inverse square of the distance. The PMT sensor, if aligned perpendicular to the light propagation vector, should therefore collect $\propto \frac{1}{R^2}$ times the produced light (with R being the distance from the emission point). However, in principle the PMTs sensors are not necessarily aligned properly. In fact, unless placed exactly in front of the light emitting spot, there will be an intrinsic inclination of the sensor. The effective surface of the sensor will therefore change with respect to the position of the spot in the GEM plane.

Is it possible to demonstrate that the effective surface of the sensor is $\propto \frac{1}{R}$. Fig. 3.1 shows how the radius of the effective surface (r') is related to the real radius of the sensor (r) as

$$r' = r \cos \theta, \quad (3.1)$$

where θ is the angle between the two surfaces. Is possible to derive θ from the emission point, in fact, this is also the angle between R and the perpendicular from

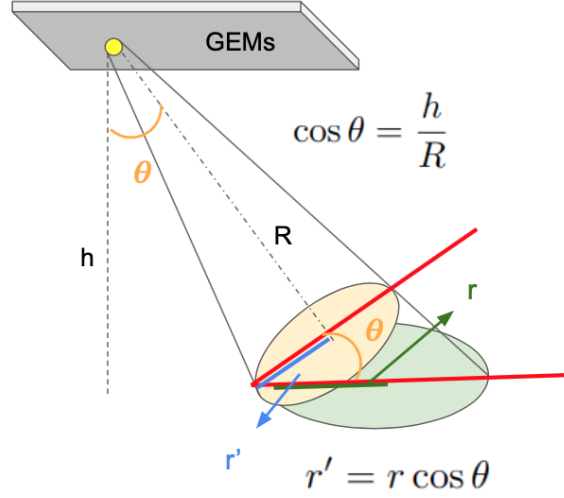


Figure 3.1. A schematic drawing of the PMT geometrical acceptance.

the PMT to the GEM plane. Calling h the distance between the PMTs and the GEM plane, θ is hence given by

$$\theta = \frac{h}{R}. \quad (3.2)$$

Knowing that the sensor surface is a circle, the effective surface can be expressed as

$$A' = \pi r \cdot r' = \frac{\pi r^2 h}{R}, \quad (3.3)$$

and therefore will be different for every PMT every event. We then can find the light collected by each of the PMTs as

$$L_i = \frac{L}{4R_i^2} \frac{r^2 h}{R_i}, \quad (3.4)$$

with $i = 1, 2, 3, 4$ the index of each PMT.

The validation of this geometrical dependence was carried out by specific measurements [67]. The results of this work provided a dependence on R_i much closer to R_i^{-4} , as it can be seen in Fig 3.2, where r is the distance in the (x, y) plane from the PMT, and z is the distance from the plane where the light was situated and the PMTs plane.

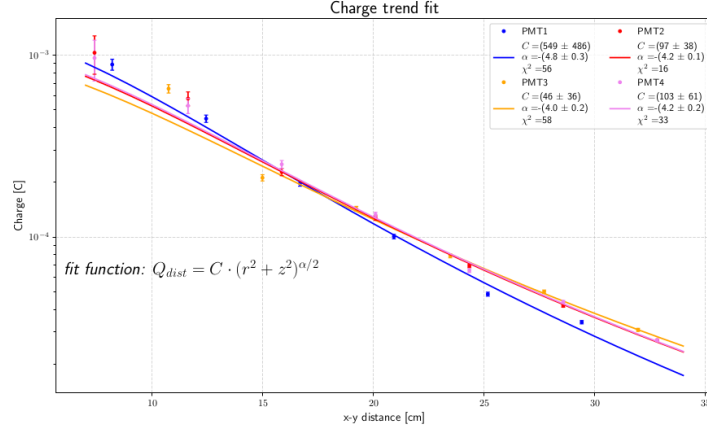


Figure 3.2. Charge variation as a function of the distance for the four PMTs. Figure from Ref. [67].

For this reason, the work carried out on this thesis will account for a dependence:

$$L_i \propto \frac{L}{4R_i^4}. \quad (3.5)$$

Another evaluation carried out to prove this dependence was performed by means of a toy simulation, and it is described in Sec. 4.1.1.

3.2 PMTs

The PMT model chosen by the collaboration is the Hamamatsu Photomultiplier Tube R7378A. It has a photocathode of 20 mm diameter, and a typical gain of 2.0×10^6 [68]. In Fig. 3.3 it is shown a schematic drawing and the spectral response for the PMT model used.

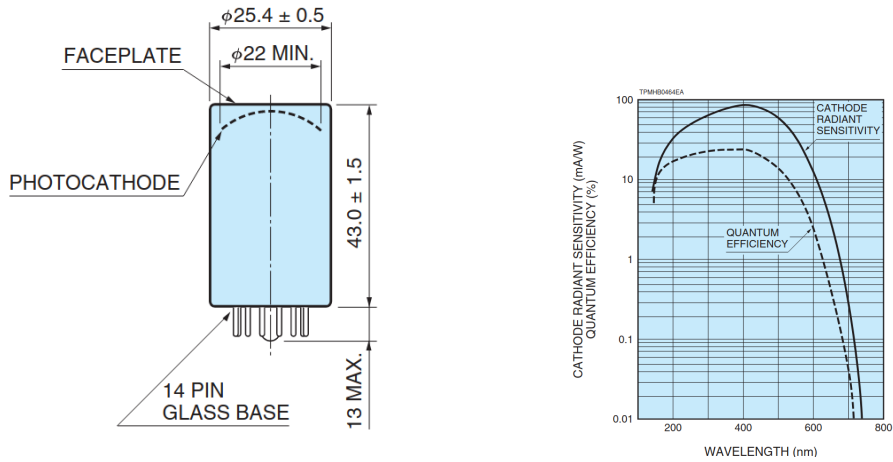


Figure 3.3. Left: a schematic drawing of the PMTs used in the LIME prototype, all the measures are in mm. **Right:** typical spectral response for the PMT model used. Figures from Ref. [68].

The supply voltages for the PMTs were chosen after a calibration. The calibration consisted in the acquisition of the response of every PMT to a fixed intensity of a light pulse generator (LPG). In Fig. 3.4 the gain curves of every PMT are shown. In Tab. 3.1 are shown the possible supply voltages to apply in order to obtain similar PMTs' gain.

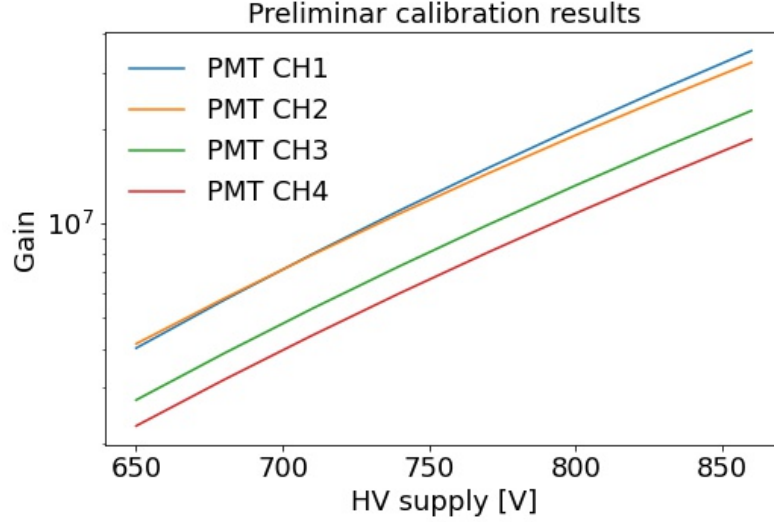


Figure 3.4. PMTs' gains at different voltages.

Supply voltages [V]			
PMT ₁	PMT ₂	PMT ₃	PMT ₄
683	701	647	650
748	769	711	710
813	836	774	770
911	938	870	860

Table 3.1. Equalized supply voltages quadruplets.

3.2.1 PMTs waveforms

The trigger conditions in the analyzed runs of the underground LIME campaign are:

- discrimination threshold = 15 mV,
- 2 or more PMTs over threshold (majority 2),
- signal arrived within the camera sensor activity (in exposure).

The digitizer sample rate is 750 MHz, the samples stored for each triggered signal are 1024, for a total of 1365 ns sampled for every triggered waveform. A

typical waveform is shown in Fig. 3.5. As it can be seen in the figure, the baseline of the four channels is not the same. In order to set a common zero we acquire 270 samples before the trigger, the beginning of each waveform will therefore be used to estimate the pedestal and correct for it on an event by event basis. In Fig. 3.6 two typical waveforms are shown, the first one is the same as Fig. 3.5 but with the offset of each channel subtracted, calculated as the mean of the first 100 samples of every waveform. The second one, is a typical ^{55}Fe signal. In Fig. 3.7 the pedestal distributions for the four channels are shown.

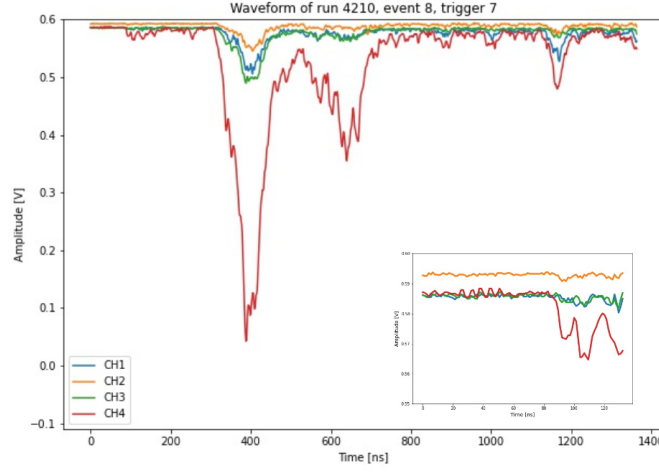


Figure 3.5. A waveform collected by the digitizer. As it can be seen in the inset, each channel has a different zero value, which in this plot is not subtracted.

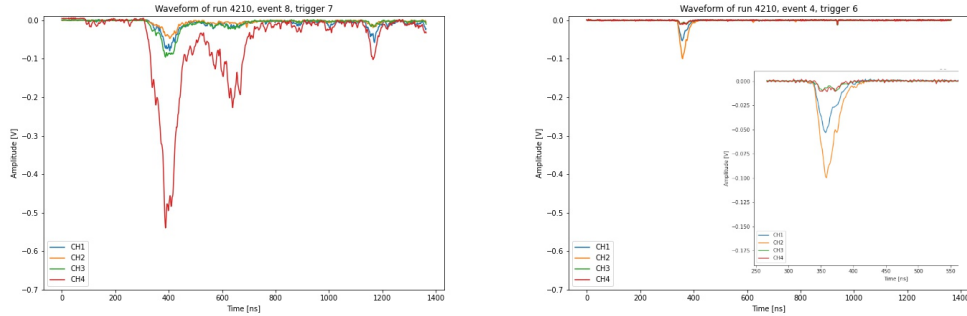


Figure 3.6. Two typical waveforms collected by the digitizer, with the offset subtracted, calculated as the mean of the first 100 samples of every waveform. **Left:** a signal of a mid-energetic event. **Right:** a typical ^{55}Fe event waveform, in the inset the same event but zoomed in is shown.

The PMTs response was characterized using the light produced by the K_α and K_β X-ray lines emitted by a ^{55}Fe source. The K_α is the leading one with an energy of 5.9 keV. As discussed in Sec. 3.1, the light collected by each of the PMT strongly depends on the spot position in the GEM plane and it is given by Eq. 3.5. The selection done on the PMTs signal was on purpose loose, to populate the sidebands

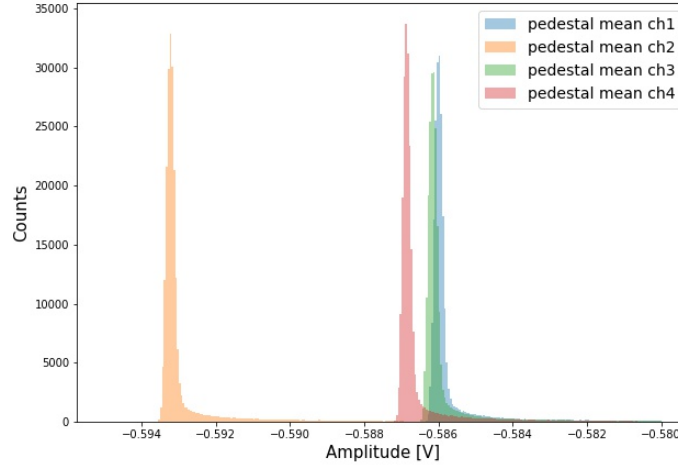


Figure 3.7. Pedestal distribution for the four PMTs, calculated with the first 100 samples of each waveform.

of the spectrum and to avoid possible biases induced by the selection. The selection has two parameters: voltage threshold and minimum length over that threshold. Analyzing the data collected overground at LNF, a reasonable selection was obtained by imposing a threshold of 30 mV on the signal voltage. The LNF dataset was characterized by a more active ^{55}Fe source, resulting in more spots and waveforms per picture to be used in the analysis. The minimum length was instead chosen on the basis of the detector properties: the signal length, in fact, is strictly connected with the drift distance of the produced electrons.

The electrons produced in the interaction will diffuse both longitudinally and transversely. While the transverse diffusion causes the enlargement of the spot size projected on the GEMs plane, the longitudinal diffusion will instead result in different arrival time for the electrons. The temporal distance between the first and the last electrons arrived at the GEMs is given by the longitudinal diffusion of the spot time and the drift velocity of the electrons.

As it can be seen in Fig. 2.5, with a drift field of 0.8 kV we obtain a longitudinal diffusion of $\sim 140 \mu\text{m}/\sqrt{\text{cm}}$. In this configuration, the spot length is expected to be $\sim 700 \mu\text{m}$ when the interaction occurs at 25 cm far from the first GEM. With the source placed at such distance, we therefore expect to have the majority of the interactions in the 15 – 30 cm far from the GEM zone. Using as drift velocity $v_{\text{drift}} = 6 \text{ cm}/\mu\text{s}$, we found $\Delta t \sim 12 \text{ ns}$ for the PMT signal peak duration of an hypothetical ^{55}Fe spot.

The chosen discrimination parameters where:

- voltage threshold: 30 mV,
- minimum peak length: 15 samples ($\sim 20 \text{ ns}$).

With these parameters, $\sim 72\%$ of the waveforms passed the cut for the dataset with the source.

To begin with, an analysis on the peak voltage was made. In Fig. 3.9 there is the distribution of the voltage of the peak (inverted for display purposes). As can be easily seen, the plots for PMTs 1 and 2 are clearly different from PMTs 3 and 4 plots. This depends on the PMTs position with respect to the event position on the GEM plane. The ^{55}Fe source is placed at the top of the TPC, as depicted in Fig. 3.8, and the 1 and 2 PMTs are placed at the top of the TPC; PMTs 3 and 4, instead, are placed at the bottom. Due to the exponential distribution of the interaction spot within the gas, interactions at the top of the TPC (closer to 1 and 2 PMTs) are expected to be more frequent with respect to those at the bottom. Because of this, the upper PMTs have much higher counts in the 25 – 100 mV region.

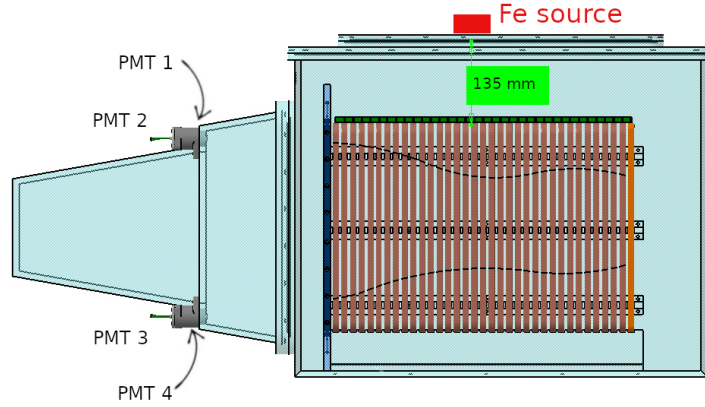


Figure 3.8. A schematic drawing of source and PMTs position in the detector.

3.3 Charge collection

The charge collected by the PMTs gives information on the event energy release in the detector. In fact, the charge collected is related to the light produced after the GEMs amplification, and the light is related to the ionized electrons.

To calculate the charge it is sufficient to integrate the waveform over the signal duration, and then divide for the termination resistance. In fact, using the definition of the electric current

$$I = \frac{V}{R} = \frac{Q}{t}, \quad (3.6)$$

where R is the termination resistance, V is the voltage, Q is the charge, and t is the time. Therefore, the integral of the waveform gives

$$Q \cdot R = \int_{t_0}^{t_1} V(t) dt, \quad (3.7)$$

where $V(t)$ is the waveform amplitude. Finally, the charge

$$Q = \frac{\int_{t_0}^{t_1} V(t) dt}{R}. \quad (3.8)$$

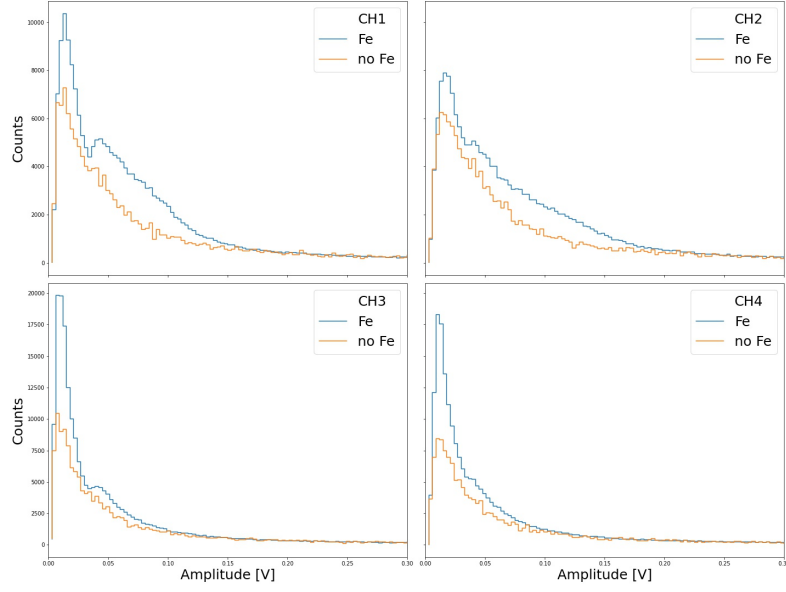


Figure 3.9. Histograms of max amplitude of the waveform for every PMT, data taken at LNGS. The blue line is the data taken with the ^{55}Fe source at 25 cm far from the GEMs, while the orange line is the data taken without the source, normalized to the other histogram using amplitudes > 0.2 V.

The PMTs are connected at the Fan-in/Fan-out of the DAQ, which is terminated with a $50\,\Omega$ resistor, which matches the impedance of the circuit.

Using the charge collected histograms, we can see the differences in data taken with or without the ^{55}Fe source. As already outlined in Sec. 3.2.1, the behavior of the plots is strictly connected to the source position with respect to the GEM plane. In the plot in Fig. 3.10, done using the LNGS dataset, the different shape of the histograms for the upper PMTs is clearly visible with respect to the ones at the bottom. These histograms are made using the full dataset, without any a-posteriori cuts.

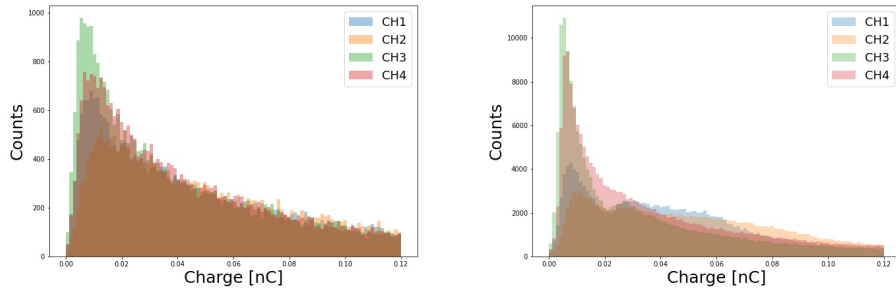


Figure 3.10. Charge histograms for the four PMTs, data taken at LNGS, no cuts applied. **Right:** data taken without the source. **Left:** data taken with the ^{55}Fe source 25 cm far from the GEMs.

Proceeding with the cuts discussed in Sec. 3.2.1 we can do the same histogram, trying to compare data with and without the source. The histograms are normalized to the one with the source, using charges > 0.014 nC. Results are shown in Fig. 3.11

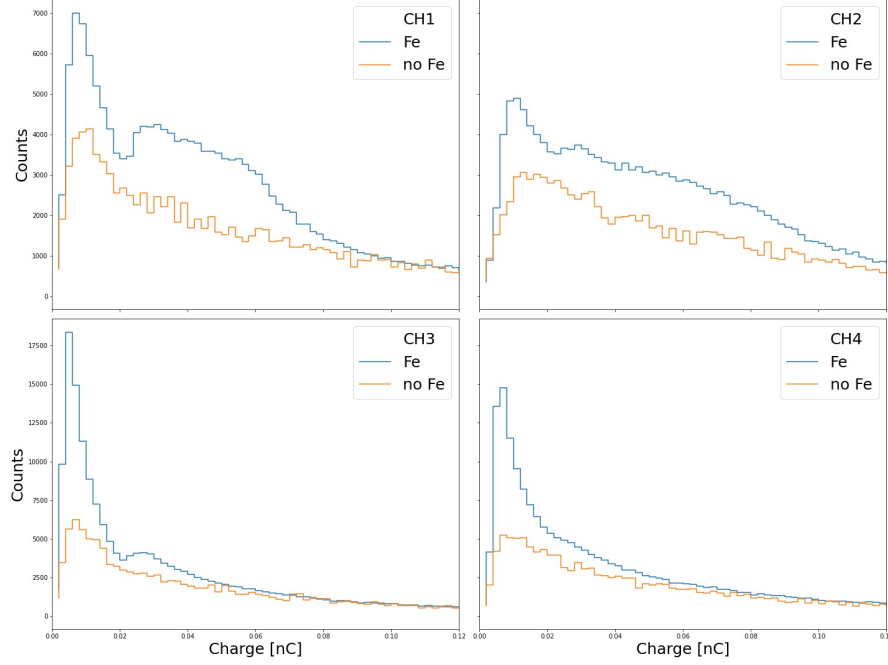


Figure 3.11. Histograms of the charge collected for every PMT, data taken at LNGS. The blue line is the data taken with the ^{55}Fe source 25 cm far from the GEMs, while the orange line is the data taken without the source, normalized to the tail of the blue histogram using charges > 0.014 nC.

A first analysis on the detector performance can be done using the sum of the charge collected by the 4 PMTs. This quantity, in fact, also if not invariant under spot position changes on the GEMs plane, can be used to understand the performance of the gas mixture or the high voltage system (HV). In Fig. 3.12 the histograms for the dataset of LNGS are shown, taken with and without the source. The mean of the peak, that indicates the peak of the ^{55}Fe , will be affected by the detector properties. Having a bad gas mixture (dirty gas, high humidity in the chamber, etc.) will strongly affect the light production, as discussed in Sec. 2.1.2. Furthermore, the HV status will affect the electron gain, and, therefore, the light produced by the event.

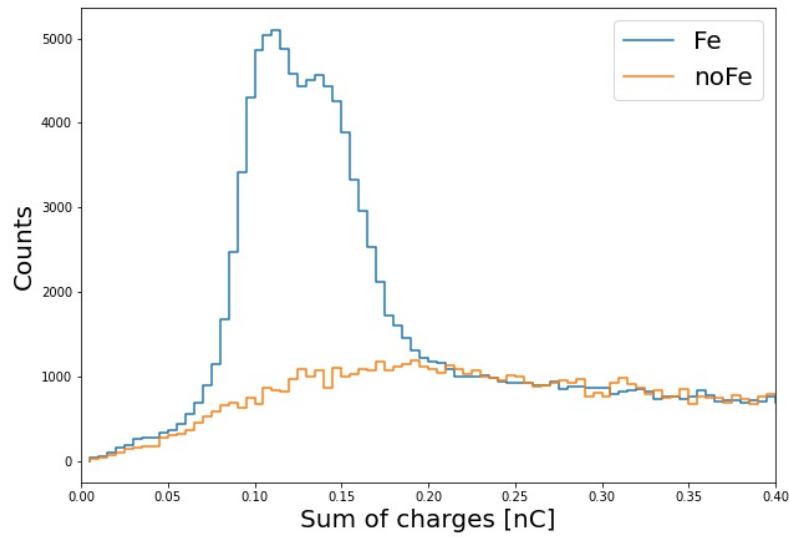


Figure 3.12. Histograms of the sum of the charge collected by the 4 PMTs, data taken at LNGS. The blue line is the data taken with the ^{55}Fe source at 26 cm far from the GEMs, while the orange line is the data taken without the source, normalized to the tail of the blue histogram for sum of charges > 0.25 nC.

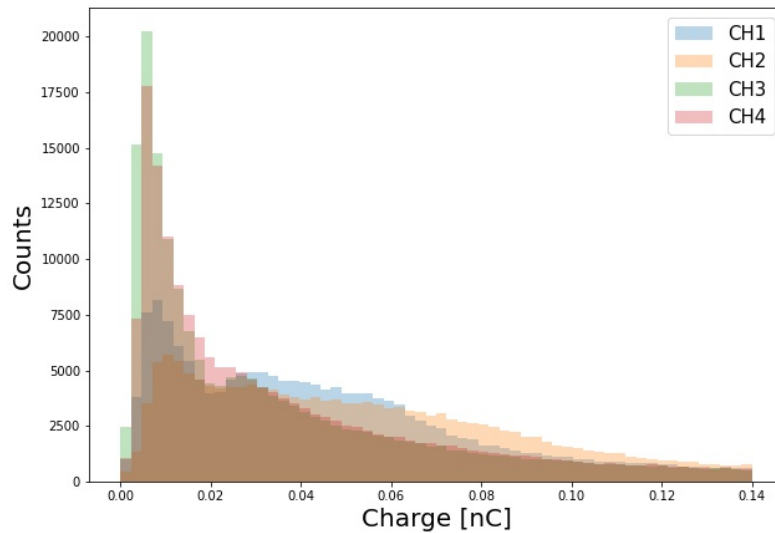


Figure 3.13. Histograms of the charge collected by the 4 PMTs, data taken at LNGS. The selection on the dataset is described in Sec. 3.2.1. The different behaviour of the PMTs in the same position with respect to the source can be attributed to the difference in HV supply voltages, see Fig. 3.4, and PMT misequalization.

Chapter 4

Analysis on PMTs data

As already outlined in Sec. 3.1, the light collected by the PMTs goes as $L_i \propto R_i^{-4}$, with R_i the distance between the spot on the GEMs plane and the PMT. We know that in PMTs the light observed is proportional to the charge collected as

$$L_{observed} = \alpha \cdot Q_{collected}, \quad (4.1)$$

where α depends on the PMT single photon charge. It is therefore possible to interchange $Q_{collected}$ and $L_{observed}$, remembering that relation. From now on we will define

$$L \equiv L_{true} \cdot C, \quad (4.2)$$

with L_{true} being the light produced after the amplification stage, and C a geometrical parameter. Using Eq. 4.1 and Eq. 4.2 we will refer to charge collected and light observed equivalently, and therefore the charge collected by each PMT will be $L_i = L/R_i^4$, where R_i is the distance between the PMT and the spot on the GEMs plane.

4.1 Inferring energy and position from the PMTs data

In order to reconstruct energy and position of the events we implemented a Bayesian fit. The measured quantities used in the fit are the charges collected by the PMTs for every event. It is, in fact, possible to infer the position and the energy release of the event starting from those charges.

With a Bayesian approach it is possible, at least in principle, to compute the probability of any specific proposition, based on a prior knowledge of conditions that might be related to it. Theoretical models and parameters can be intended as an uncertain proposition, connected by probability rules.

In Bayesian inference, the Bayes' theorem is used to update initial probability for a model or a parameter as more evidence or information becomes available, in the form of experimental observation. The posterior *pdf* (probability density function) for the model parameters, which is the result of the Bayesian inference, derives from a prior probability and a likelihood function. The posterior can be computed, by means of the Bayes' theorem as

$$p(\boldsymbol{\theta}|\{x_i\}, \alpha) = \frac{p(\{x_i\}|\boldsymbol{\theta}, \alpha) \pi(\boldsymbol{\theta}|\alpha)}{p(\{x_i\}|\alpha)} = \frac{p(\{x_i\}|\boldsymbol{\theta}, \alpha) \pi(\boldsymbol{\theta}|\alpha)}{\int p(\{x_i\}|\boldsymbol{\theta}, \alpha) \pi(\boldsymbol{\theta}|\alpha) d\boldsymbol{\theta}}, \quad (4.3)$$

where:

- $E = \{x_i\}$ represents the data;
- θ is the parameter list necessary to describe experimental condition or theoretical assumption, in our case (L, x, y) ;
- $\pi(\theta|\alpha)$ the prior *pdf* of the θ , that describes how the θ parameters can vary;
- α a set of parameters controlling the prior itself, also called hyperparameters;
- $p(\{x_i\}|\theta) = \mathcal{L}(\theta)$ is the distribution of the observed data conditional on its parameters, also called the likelihood for the generic θ set of parameters;
- and finally $p(\theta|\{x_i\})$ is the posterior *pdf* for the generic set of parameters θ given the data $\{x_i\}$.

In our case, we want to infer the light and the position of the spot on the GEMs plane, knowing the charge collected by the 4 PMTs. Therefore, our $\{x_i\}$ will be the four charges $(L_1, L_2, L_3 \text{ and } L_4)$, while our set of parameters will be:

$$\theta = (L, x, y), \quad (4.4)$$

for every event.

From Eq. 4.3 it is evident that the posterior *pdf* depends on the choice of the priors on all the parameters. Our choice of priors is rather simple, in fact we can easily restrict x and y parameters to the GEMs plane dimension, i.e. a $33 \times 33 \text{ cm}^2$ phase space. As for L it must be positive, and we can set an upper limit based on the expected light.

The likelihood $\mathcal{L}(\theta)$ is the probability of observing the data given θ . In our case, the likelihood will be defined as

$$p(\{x_i\}|\theta) = \prod_i \mathcal{N}(\{x_i\}|\mu_i(\theta)) \equiv \prod_i \frac{1}{\sqrt{2\pi}\sigma_i} e^{-\frac{(L_i - \mu_i(\theta))^2}{2\sigma_i^2}}, \quad (4.5)$$

where we assumed a normal distribution for the response of the PMTs, i goes from 1 – 4 and is the PMT number, L_i is the charge measured by the PMT, σ_i is set at 10% of μ_i and $\mu_i(\theta)$ is the true value of the light light seen by each PMT. In turn, they are a function of the emitted light L and the emission position (x, y) and thus indicated as:

$$\mu_i = \frac{L}{R_i^4}, \quad (4.6)$$

where $R_i = \sqrt{x_i^2 + y_i^2 + z^2}$.

The integral over all the parameter space is needed in order to compute the posterior on the parameters and thus any summary of it such as the mean value and the standard deviation. This integral is usually computed by means of numerical methods, i.e. a Markov Chain Monte Carlo (MCMC). This reconstruction algorithm was implemented in BAT (Bayesian Analysis Toolkit) [69], a C++ set of libraries to implement a Bayesian analysis. The algorithm chosen to perform the integration is a Metropolis-Hasting MCMC. This package has been largely used in the HEP

fields by many collaborations, such as UFit [70] or HEPfit [71]. The sampling is performed by means of 12 parallel MCMC chains, for a total number of steps equal to 1.2×10^6 . This number is large enough to sample the posterior in a complete way.

We can decide how many events we want to fit at the same time, and also if we want to fix the reconstructed light to be equal for the fitted events or if it can be different. We decided, in order to avoid biases, to perform this fit on a large sample of data, without too strict cut, as described in Sec. 3.2.1. For this reason the reconstructed light will be, in principle, different for every event. To allow a fast convergence of the fit, we decided to fit an event at the time, with a flat prior on L .

Figure 4.1 shows the typical behavior of the MCMC chains.

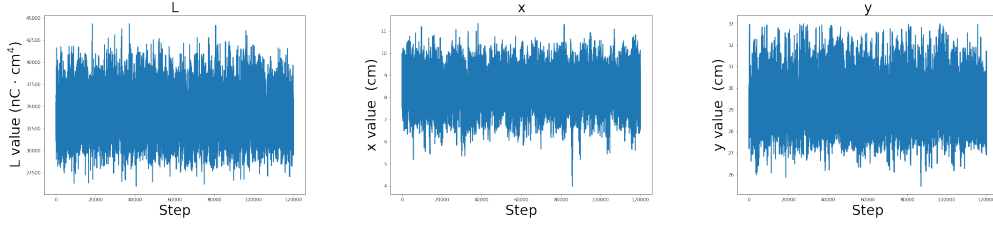


Figure 4.1. Evolution of the MCMC chains for a typical fit run.

In Fig. 4.2 it is reported the posterior *pdf* of the fit, performed over one event.

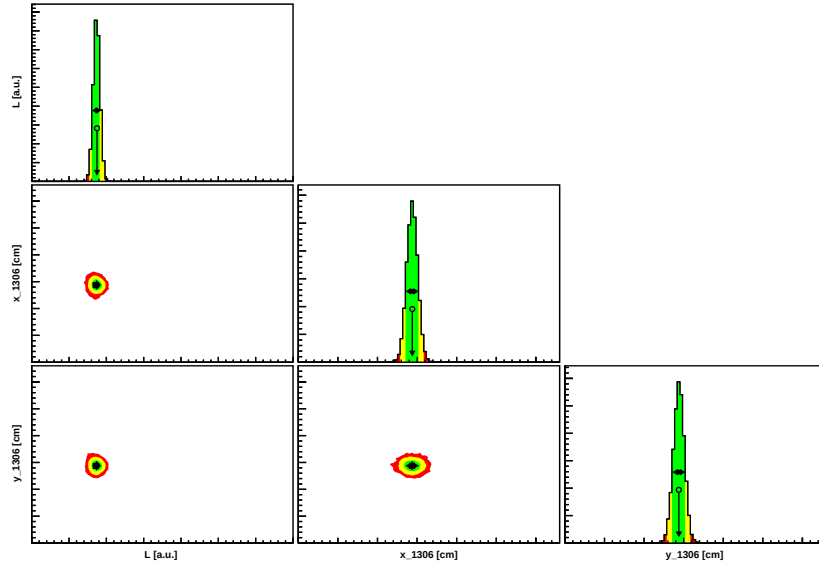


Figure 4.2. Graphical representation of the joint posterior *pdf* of the fit over one event. The plots on the diagonal of the figure are the uni-dimensional *pdf* of each single parameter, obtained by marginalizing all the others. The bi-dimensional *pdfs* in the bottom-left corner are the joint *pdfs* of each pair of parameters. The plots show the credible regions at 68%, 95%, 99.7% solid contour line.

4.1.1 Fit testing

In order to test the fit implementation a toy simulation was created. This simple simulation generates spots uniformly in the GEMs plane, with a Gaussian distributed light. In Fig. 4.3 it is shown the generated light for a set of simulated spots.

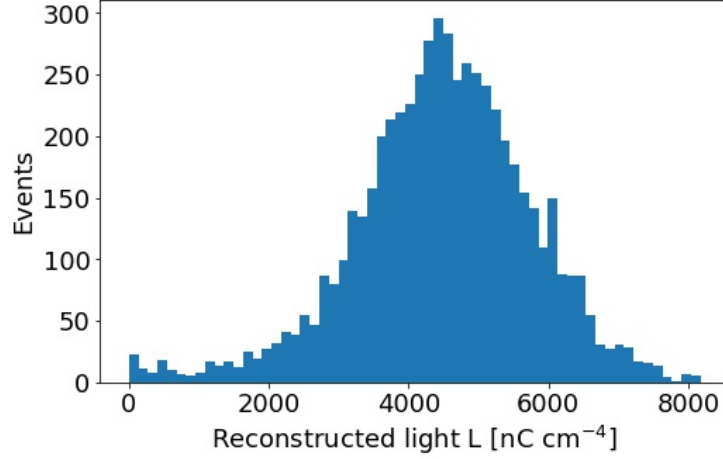


Figure 4.3. Distribution of the light for the generated spots.

Then the light collected by the PMTs is calculated with Eq. 3.5 using the spot position and luminosity generated and the PMT position. The L_i calculated for every spot is then passed to the fit, to reconstruct position and luminosity. In Fig. 4.4 is shown a set of reconstructed spot positions, where the blue points are the ones reconstructed with x and y both within 3 sigma, and the orange ones are the ones outside.

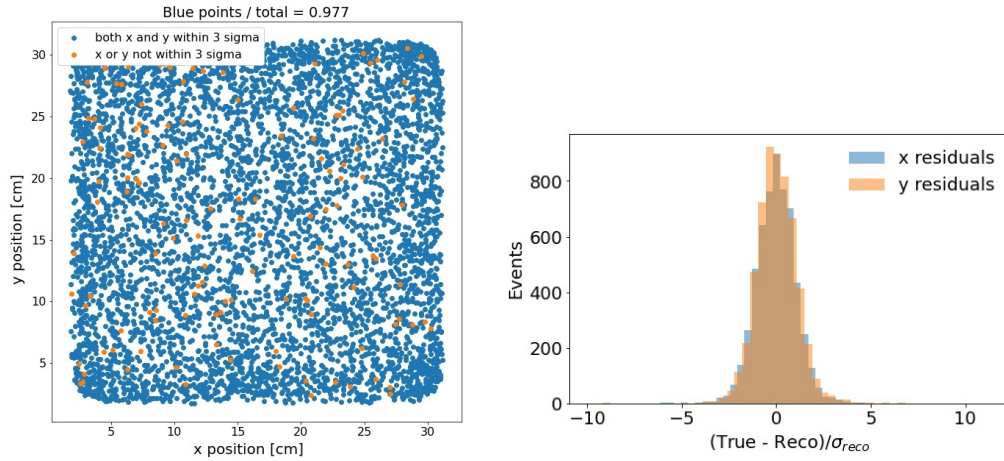


Figure 4.4. Left: Scatter plot of spots reconstructed from the generated ones. The **blue** points are the ones generated within 3 sigma (both in x and y) from the generated one; the **orange** are the ones outside of 3 sigma. **Right:** distribution of the normalized residuals for the reconstructed spots.

Geometrical dependence test

To better understand if the dependence of the light observed by the PMTs is $\propto R^{-4}$ we tested it by means of a toy simulation. This simulation generates spots uniformly in the GEMs plane, with a Gaussian distributed light. The collected light of every PMT is then computed with a R^{-3} and R^{-2} dependence. The reconstruction is carried out in the same manner as before, with a R^{-4} dependence. In this way, we can understand how the fit performs if the assumption of Eq. 3.5 is wrong.

Figure 4.5 shows the results of these simulations, where the green points are the simulated ones, and the red points are the reconstructed ones. It is therefore evident that the fit in these cases is not able to reconstruct the positions, validating the assumption carried out in Ref. [67], with the dependence of the light from the spot position being described by Eq. 3.5.

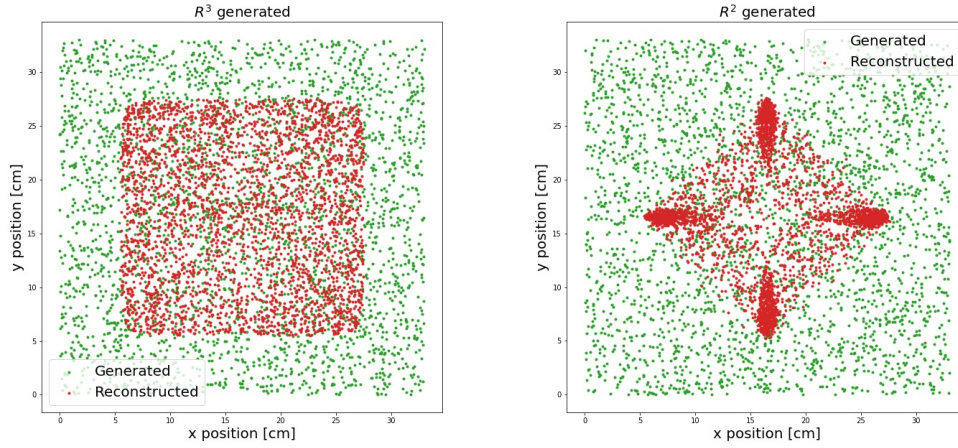


Figure 4.5. Scatter plots of generated and reconstructed spots positions with different distance dependence. The green points are the positions of the generated spots, while the red points are the positions of the reconstructed ones. **Left:** light observed by the PMTs computed with an R^3 dependence. **Right:** light observed by the PMTs computed with an R^2 dependence.

4.2 PMT calibration

By looking at the data taken at LNGS it can be seen that the PMTs respond differently at the same signal (see, for example, Fig. 3.13). An extension of the fit discussed previously allows us to introduce four additional parameters c_{1-4} that accounts as calibration constants as described by the following relation:

$$\mu_i = \frac{L}{R_i^4} \cdot c_i \quad (4.7)$$

with L the light intensity, and c_i our calibration constants. This means to have a total of 7 parameters to infer from the data.

To perform this fit, a tighter selection on the waveforms was made, to ensure that the majority of the events were ^{55}Fe spots. Thanks to the tighter selection, it was

possible to fix L . In fact, L is expected to be the same for every ^{55}Fe spot, needing to fit only calibration constants and positions. The L parameter was therefore fixed to 1 and multiple events at the time were fitted. To select the number of events to fit was taken into consideration the fit performance: using a flat prior *pdf* for every (x, y) pair enlarges the nuisance parameters space, making the fit gradually slower, as events are added. However, adding more events reduces uncertainty on c_i parameters. The number of events chosen to execute the fit was 4, obtaining 4 degrees of freedom (16 measures and 12 parameters to infer). For every fit iteration the parameters obtained were:

- (x_1, y_1) ;
- (x_2, y_2) ;
- (x_3, y_3) ;
- (x_4, y_4) ;
- c_1, c_2, c_3, c_4 .

In Fig. 4.6 are depicted the results obtained by the fit. It is easier to work with these calibration constants if we express them as a ratio over one of them. The ratios are shown in Tab. 4.1. As can be seen, the four PMTs seem to be miscalibrated, suggesting that the supply voltages for the PMTs could still have an offset.

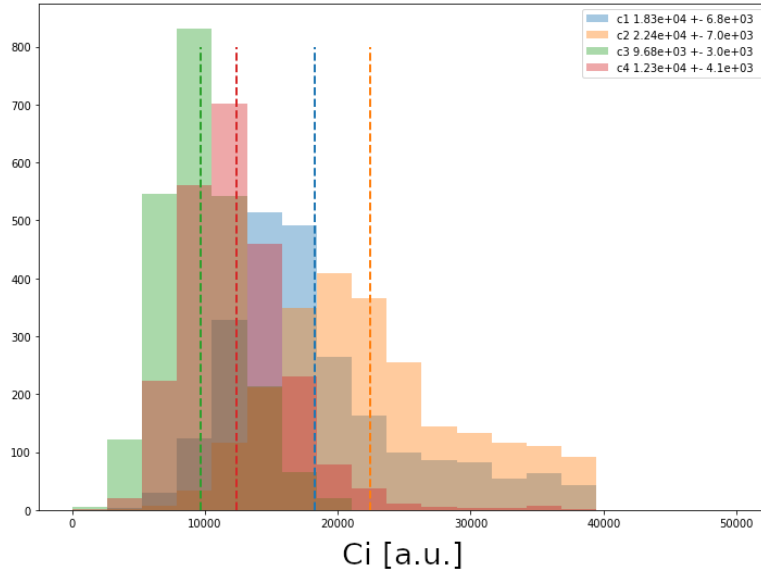


Figure 4.6. Histograms of the fitted calibration parameters for the four PMTs.

4.2.1 New supply voltages proposal

To understand if the fit was working properly, a different supply voltage was set for each PMT. The gain function in a PMT is [68]

$$G_i = A_i \cdot V_i^{k_i \cdot n}, \quad (4.8)$$

	c_i/c_1
c_1	1
c_2	1.22 ± 0.77
c_3	0.529 ± 0.33
c_4	0.672 ± 0.43

Table 4.1. Ratios of PMTs *calibration constants* over c_1 . PMTs 3 and 4 seem to have a lower gain with respect to the other 2.

where i is the PMT index, A_i and k_i are constants dependent on the dynodes structure and material, V_i is the supply voltage and n is the number of dynodes in the PMT. While n is the same for the four PMTs, A_i and k_i can differ within a certain range. Without disassembling the experiment to calibrate again the PMTs, namely find all the A_i and k_i , it is possible to rewrite Eq. 4.8 using the calibration constants found with the fit as

$$G_i = c_i \cdot A_i \cdot V_i^{k_i \cdot n}. \quad (4.9)$$

The new gain curves obtained using this method are shown in Fig. 4.7. Equalizing the gains, is now possible to retrieve a set of voltages, see Tab. 4.2, supply to choose from. To understand if the process work, a new dataset was taken, with the new

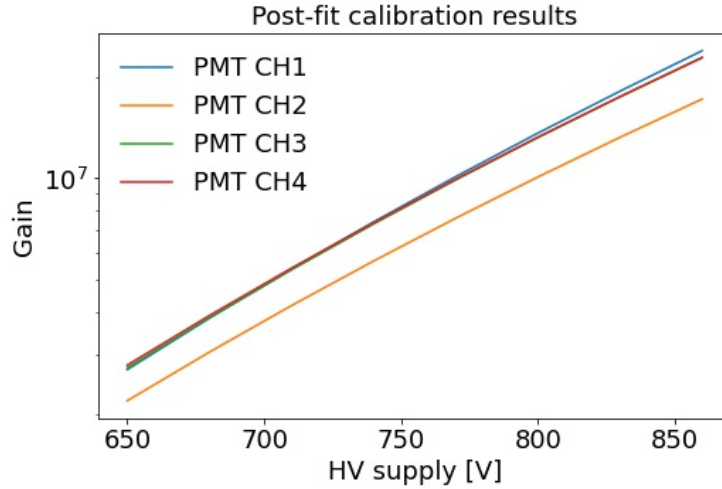


Figure 4.7. New PMTs' gain curves as a function of the supply voltage.

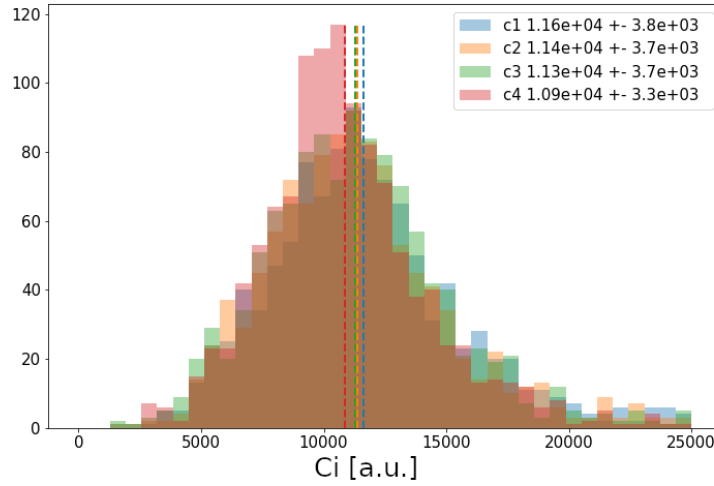
supply voltages being:

- PMT₁: 803 V,
- PMT₂: 803 V,
- PMT₃: 833 V,
- PMT₄: 800 V.

Supply voltages [V]			
PMT ₁	PMT ₂	PMT ₃	PMT ₄
710	709	734	710
741	741	767	740
803	803	833	800
834	834	866	830

Table 4.2. Possible new supply voltages quadruplets.

The waveforms were selected with the same method used before, and the fit was performed in the same manner. The results obtained are shown in Fig. 4.8 and in Tab. 4.3.

**Figure 4.8.** Histograms of the fitted calibration parameters with the new supply voltages, for the four PMTs.

c'_i/c'_1	
c'_1	1
c'_2	0.99 ± 0.64
c'_3	0.97 ± 0.64
c'_4	0.935 ± 0.62

Table 4.3. Ratios of PMTs *calibration constants* for the new supply voltages, over c_1 . This time the PMTs seem to have the same gain.

4.3 Reconstruction of spot position

The main purpose of this thesis is to associate the measurement obtained with the PMTs with that collected by the sCMOS sensor. As already outlined in the previous sections, the sCMOS sensor is able to obtain high precision on the positions and energy release, but without enough temporal information. Frame rates currently available are in fact too low compared to the typical event duration. PMTs are, instead, fast light sensors that can be used to read out the time of arrival and the duration of each signal. The main problem when combining those two signals is to link the four waveforms to a spot in the picture. With the fit described in Sec. 4.1 is possible to reconstruct the event position on the GEM plane, with the information obtained by the waveforms. By means of a coordinate transformation it is, therefore, possible to link the waveform to the picture spot.

To reconstruct the spot position on the GEM plane, the fit was performed over the selected waveforms. In this case the parameters utilized were L and (x, y) . One event at the time was fitted, with the prior being:

- flat prior on $L \in [0, 90000] \text{ nC cm}^4$,
- flat prior on x and y , both $\in [0, 33] \text{ cm}$.

The range for L was chosen to help the fit converge, decreasing the phase space of the parameters, taking into consideration the expected ^{55}Fe peak. On the other hand, the range for x and y include all the possible values, being the GEMs of the LIME prototype a $33 \times 33 \text{ cm}^2$ square. The results are described below.

Reconstructed spot positions

Figure 4.9 represents the reconstructed positions for the dataset taken at LNGS. As it can be seen, the distribution of the reconstructed spots differ largely between runs with or without the iron source. In the background runs the distribution is, as expected, mostly uniform. The peculiar shape of the shower in the runs with the source is due to the source position. As depicted in Fig. 3.8 the source is placed at the top of the TPC.

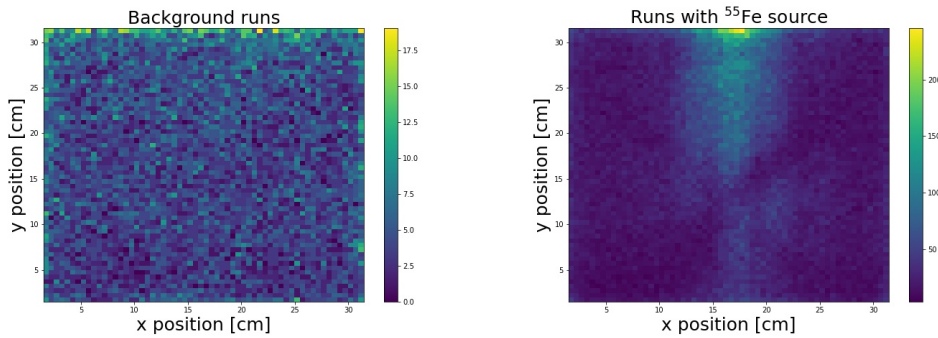


Figure 4.9. 2D histograms for the reconstructed position, LNGS dataset. **Right:** data taken without the source. **Left:** data taken with the ^{55}Fe source at 25 cm far from the GEMs.

Reconstructed light intensity

Figure 4.10 represents the results of the fit. The histogram of the background has been normalized such that the event in the tails for $L > 80 \mu\text{C cm}^4$ have the same yields.

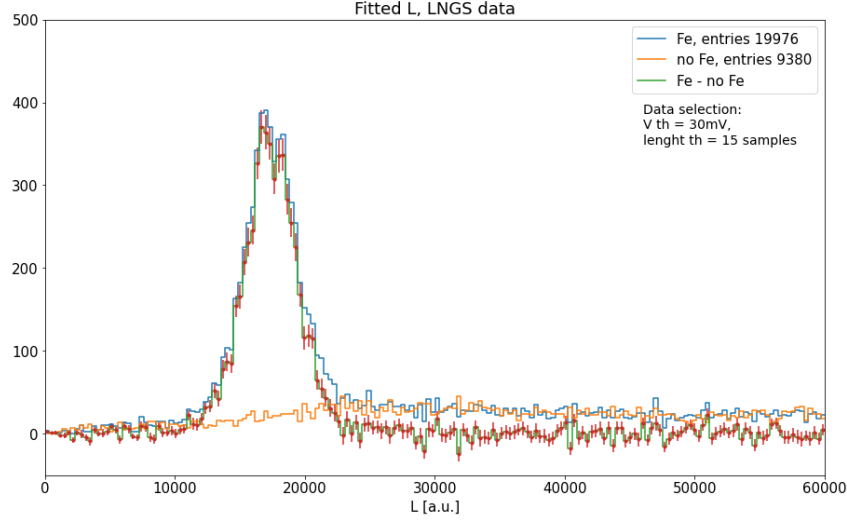


Figure 4.10. Histograms of the fitted light intensity. The blue line represents data taken with the ^{55}Fe source, the orange line instead is the data taken without the source. Finally the green line represents the difference with and without the source. The histograms are normalized to the tail of the one with the source, for $30 \mu\text{C cm}^4 < L < 80 \mu\text{C cm}^4$.

A Gaussian was fitted on the histogram of the difference, giving the results in Fig. 4.11. The results of the fitted Gaussian are reported in Tab. 4.4.

Fit results	
L_{mean}	$(173.5 \pm 0.4) \times 10^2 \text{ nC cm}^4$
L_{std}	$(19.8 \pm 0.4) \times 10^2 \text{ nC cm}^4$
Resolution	0.114 ± 0.002

Table 4.4. Results for the Gaussian fit of Fig. 4.11

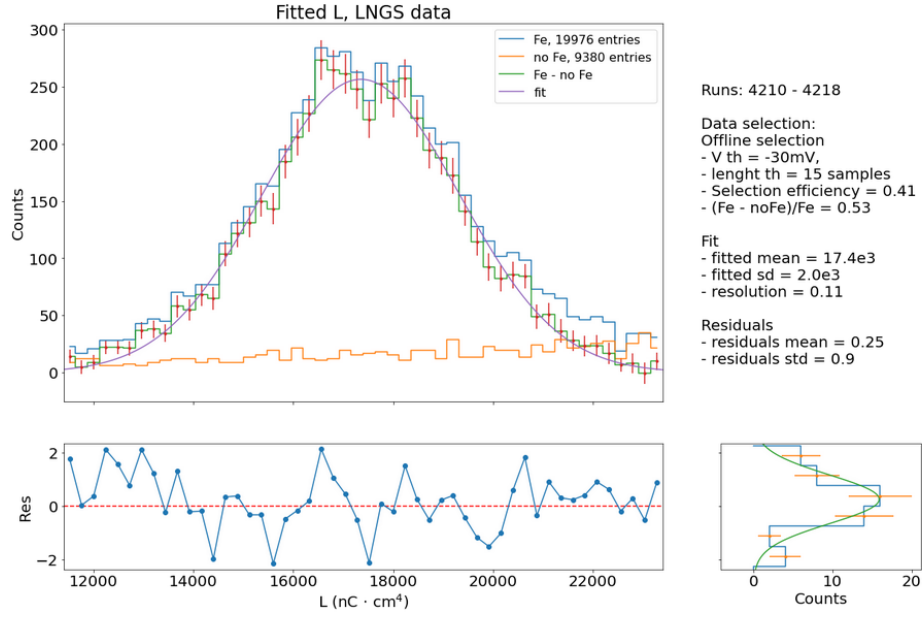


Figure 4.11. Gaussian fit performed on the Fig. 4.10 histogram. In the upper-left panel the histogram of the fitted light for the selected clusters is shown, in the bottom-left the residuals are shown. On the right there is more information on the plot, and below the residual distribution.

4.4 Comparison with picture-reconstructed variables

Now that we have reconstructed the spot position using the PMTs waveforms the last step will be matching the PMT-reconstructed spot with the picture.

In order to match the position as reconstructed with the data from the two readout systems we need to understand how the two position reference systems are related. The camera acquires a surface which is larger than the GEM plane alone, therefore the first step needed was to find the GEMs plane in the picture coordinate. A set of pictures with a led illuminating the interior of the detector were taken, with the typical result being represented by Fig. 4.12. In this figure it is evident how the sCMOS sensor image part of the gas vessel. Using the vertices of the imaged GEM, we can find the appropriate coordinate transformation for the PMT-reconstructed position.

4.4.1 Spot matching with pictures

Our first step consisted in matching the PMT-reconstructed position with the raw image. To reduce possible biases coming from having multiple spots on the same image, we decided to take a set of runs with the camera exposure set at 100 ms. In those pictures we expect ~ 1 ^{55}Fe spot per image. In Fig. 4.13 some examples of the performance in the matching are represented. It is useful to remember that, because of the DAQ system, we can have more PMTs acquired waveform than imaged tracks. In the figure the reconstructed spots are represented by the orange cross, with the uncertainty given by the reconstruction fit.

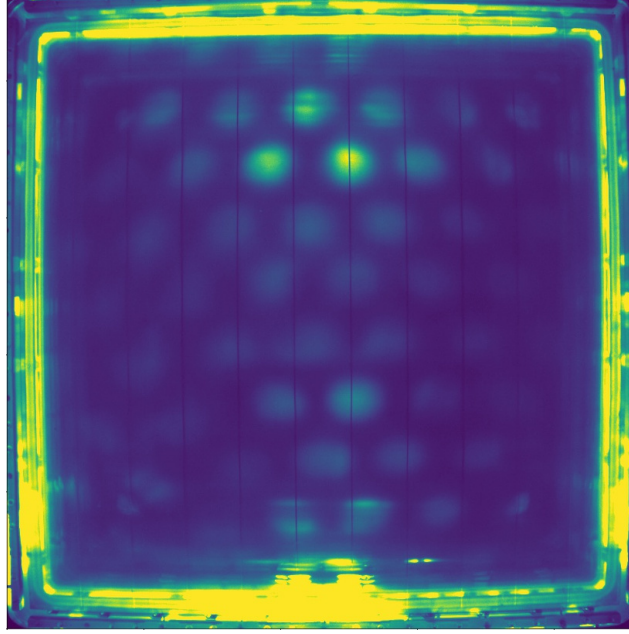


Figure 4.12. A 2D histogram of the sCMOS sensor count for a picture taken while lighting up the inside of the detector.

4.4.2 PMTs vs camera

The whole purpose of this study is to be able to match the acquired waveforms to the reconstructed spot from the picture, in order to add temporal information to the high precision position and energy information obtained by the picture.

A selection on clusters similar to the one described in Sec. 2.3.7 was made, to obtain a cleaner dataset for the pictures. Then a very preliminary algorithm was implemented in order to find the first neighbor for every picture-reconstructed spot.

The matching between the spots is considered only if both Δx and Δy are $< 5 \cdot \sigma_{x/y}$, where $\sigma_{x/y}$ is the uncertainty given by the fit. In Fig. 4.14 there are shown the distributions of the distance between the matched spots and the distribution of Δx and Δy .

These results are encouraging, allowing us to match the event in the PMTs signals with a spot in the picture, providing timing information. There is room for improvements, but it is already working really well.

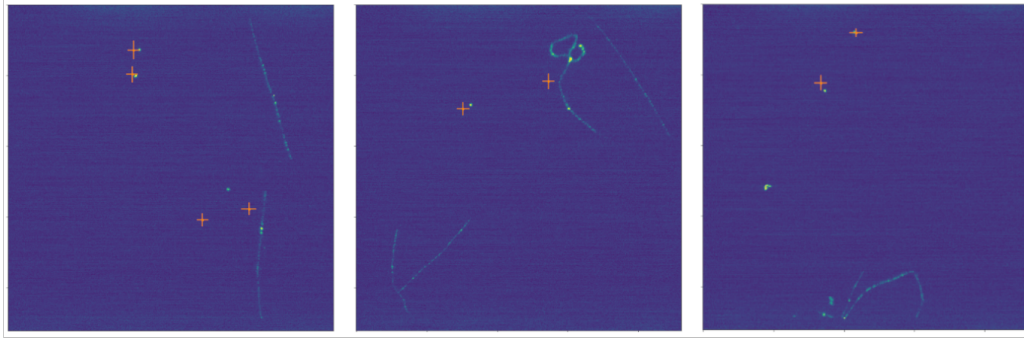


Figure 4.13. Some examples of the performance of the reconstruction fit. The orange crosses are the PMT-reconstructed position, with the uncertainty given by the reconstruction fit. Some of the reconstructed spots are not in the image, as explained in Sec. 2.3.8.

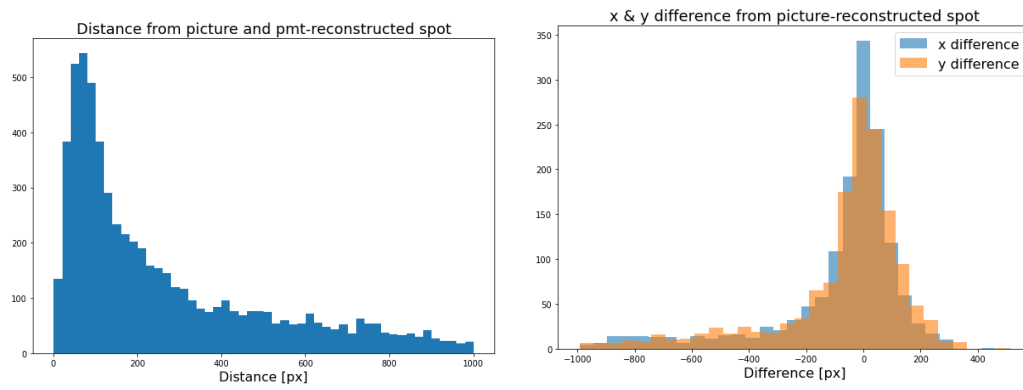


Figure 4.14. Distribution of the first-neighbour between picture-reconstructed and PMT-reconstructed spots distance (**left**) and Δx and Δy distributions (**right**).

Conclusions

The microscopic properties of dark matter are as much of a mystery now as they were in the 1930's, despite establishing its nature is one of the most open and discussed problems for the last decades. Several and very different experimental approaches were developed in order to search for DM signals. Direct detection experiments produced very strong constraints on dark matter interaction cross-section. In this framework directional direct detection is taking hold in order to discriminate possible signals from background.

During my thesis project, I had the opportunity to contribute to the CYGNO collaboration in the commissioning of their last prototype underground at LNGS. Moreover, I carried out an analysis on the PMTs readout in order to enable the 3D reconstruction of the track inside the TPC.

The characterization of the LIME prototype in an underground environment will be crucial to evaluate the CYGNO's approach performance for a directional direct detector for dark matter. In fact, by validating the simulations performed by the collaboration, it will be possible to evaluate the feasibility of the future detector. We focused our effort on the optimization of the DAQ system for the underground environment.

The characterization of the PMTs response will be crucial to the 3D track reconstruction. The high precision information of the sCMOS sensor will, in fact, need temporal information not obtainable from the current camera technology. The waveforms acquired by the PMTs must be matched with the corresponding spots inside the picture. A coarse event reconstruction is then needed for the PMTs waveforms, in order to find the right spot of the picture.

The reconstruction of the event is performed by means of a Bayesian analysis that is able to evaluate the position of the spot in the GEMs plane together with its energy release inside the TPC. This reconstruction algorithm is just in a preliminary phase, with room for improvements, but it has already demonstrated to be a great tool for the matching of the two readouts.

We expect that, with the right tuning, this algorithm will be able to improve the 3D reconstruction of the CYGNO approach for long tracks, increasing the sensitivity of the detector.

Appendix A

Kinematics of the DM-nucleus scattering

A.1 Preliminaries

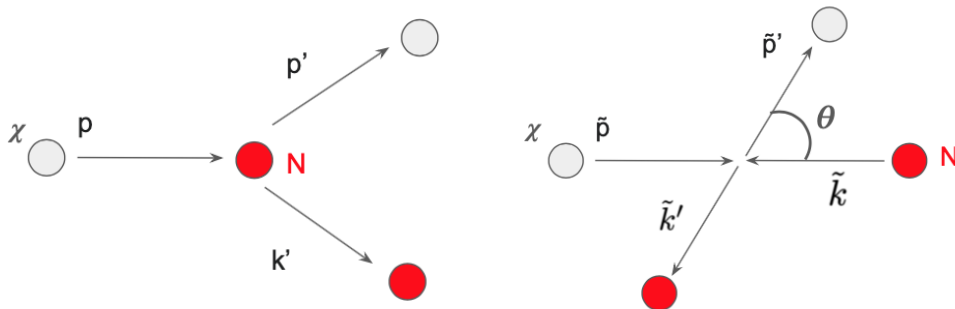


Figure A.1. Elastic scattering of a DM particle (χ) and a nucleus (N) in the nucleus rest frame (**left**) and in the center of mass frame. θ denotes the CM-frame scattering angle.

We start by fixing some notations we will use in this chapter, in Fig A.1 there is a visual reference. **Sans serif** symbols (e.g $\mathbf{p}, \mathbf{k}$) indicates four-vectors, **bold** symbols (as $\mathbf{p}, \mathbf{k}$) indicate three-vectors, and plain symbols (e.g. $p = |\mathbf{p}|$) denote absolute values. The tilde variables, as $\tilde{p}$, are the ones in the center of momentum frame (CM). All the other momenta and velocity refers to laboratory frame (lab), where the target nuclei is at rest. The prime, as p' , indicates quantities after the scattering. Therefore we have, for the initial DM and nucleus

$$\tilde{p}^\mu = \begin{pmatrix} E_{\tilde{p}} \\ \tilde{\mathbf{p}} \end{pmatrix}, \quad \tilde{k}^\mu = \begin{pmatrix} E_{\tilde{k}} \\ \tilde{\mathbf{k}} = -\tilde{\mathbf{p}} \end{pmatrix}, \quad (\text{A.1})$$

and

$$p^\mu = \begin{pmatrix} E_p \\ \mathbf{p} \end{pmatrix}, \quad k^\mu = \begin{pmatrix} E_k \\ \mathbf{k} \end{pmatrix} = \begin{pmatrix} m_N \\ \mathbf{0} \end{pmatrix}, \quad (\text{A.2})$$

with m_N being the nuclear mass. We define the momentum transfer four-vector as:

$$\mathbf{q} \equiv \mathbf{p} - \mathbf{p}' = \mathbf{k}' - \mathbf{k}, \quad (\text{A.3})$$

where the last equality derives from energy-momentum conservation. The nuclear recoil energy is then

$$E_R \equiv \frac{k'^2}{2m_N} = \frac{q^2}{2m_N}, \quad (\text{A.4})$$

because $\mathbf{k}' = \mathbf{q}$. We denote θ the scattering angle in the CM frame, such that $\cos \theta = \hat{\mathbf{p}} \cdot \hat{\mathbf{p}}' = \hat{\mathbf{k}} \cdot \hat{\mathbf{k}}'$.

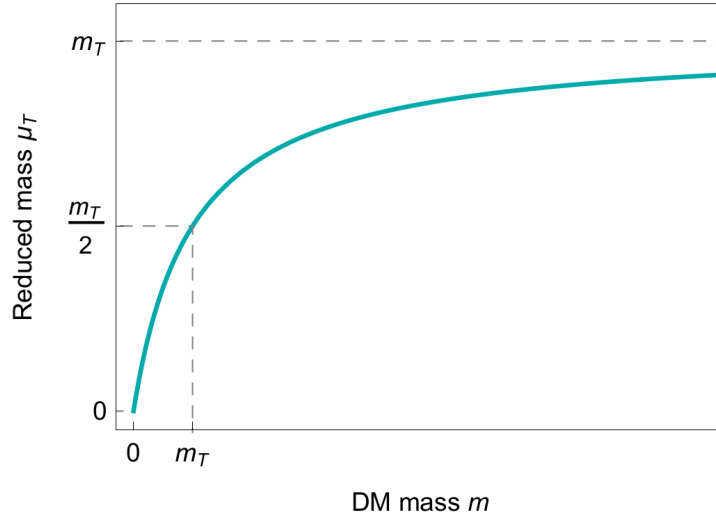


Figure A.2. Reduced mass μ , for fixed m_N as a function of m_χ .

The DM-nucleus reduced mass, defined as

$$\mu \equiv \frac{m_{DM}m_N}{m + m_N} \quad (\text{A.5})$$

has some interesting properties (in Fig. A.2 is represented the behaviour of the reduced mass as a function of m_{DM}):

- symmetric under $m_N \leftrightarrow m_{DM}$ exchange,
- fixed one of the masses μ is an increasing function of the other,
- is smaller than both DM and nuclear mass,
- it approaches the smallest mass of the two when one is much bigger than the other (e.g. $\mu \xrightarrow{m_{DM} \gg m_N} m_N$).

A.2 Elastic scattering

The dynamics of $2 \rightarrow 2$ scattering is defined by two parameters: the energy and the scattering angle (or alternatively the momentum transfer) in the CM frame. Using the relation $\tilde{\mathbf{p}} = -\tilde{\mathbf{k}}$, it is possible to express the energy in the CM frame as

$$s = (\tilde{\mathbf{p}} + \tilde{\mathbf{k}})^2 = (E_{\tilde{p}} + E_{\tilde{k}})^2. \quad (\text{A.6})$$

Knowing that

$$E_{\tilde{p}}^2 - m_{DM}^2 = \tilde{p}^2 = \tilde{k}^2 = E_{\tilde{k}}^2 - m_N^2, \quad (\text{A.7})$$

we find

$$\sqrt{s} - E_{\tilde{p}}^2 = E_{\tilde{k}}^2 = \sqrt{E_{\tilde{p}}^2 - m_{DM}^2 + m_N^2}. \quad (\text{A.8})$$

Squaring we find the solutions

$$E_{\tilde{p}}^2 = \frac{s + m_{DM}^2 - m_N^2}{2\sqrt{s}} \quad E_{\tilde{k}}^2 = \frac{s + m_N^2 - m_{DM}^2}{2\sqrt{s}}, \quad (\text{A.9})$$

we can, therefore, find $\tilde{p}$ as

$$\begin{aligned} \tilde{p}^2 = E_{\tilde{p}}^2 - m_{DM}^2 &= \frac{s^2 + (m_{DM}^2 - m_N^2)^2 - 2s(m_{DM}^2 + m_N^2)}{4s} \\ &= \frac{\lambda(s, m_{DM}^2, m_N^2)}{4s}, \end{aligned} \quad (\text{A.10})$$

where

$$\lambda(s, m_{DM}^2, m_N^2) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz \quad (\text{A.11})$$

is the Källén function. Those equation, written for the initial-state quantities, apply also to final-state masses and momenta.

For our purposes, we will consider an elastic DM-nucleus scattering, which is a good approximation of most cases, and extremely useful to study the kinematics of the process. From A.10 we can see that $\tilde{p}$ depends only on s and the masses. Since s is conserved and m_{DM} and m_N are the same before and after the scattering (we have assumed elastic scattering), $\tilde{p}$ must be equal to $\tilde{p}'$. Therefore we have

$$\tilde{p} = \tilde{p}' = \tilde{k} = \tilde{k}', \quad (\text{A.12})$$

and

$$E_{\tilde{p}} = E_{\tilde{p}'} \quad E_{\tilde{k}} = E_{\tilde{k}'}. \quad (\text{A.13})$$

Being Lorentz invariant, the scalar product in the lab frame

$$\mathbf{k} \cdot \mathbf{k}' = m_N E_{k'} \quad (\text{A.14})$$

is, in the CM frame,

$$\tilde{\mathbf{k}} \cdot \tilde{\mathbf{k}}' = E_{\tilde{k}}^2 - \tilde{p}^2 \cos \theta \quad (\text{A.15})$$

According to the SHM, the mean velocity of a DM particle traveling at our distance from the Galactic center is $\sim 220 \text{ km/s}$, meaning that the hypothetical scattering

process for a dark matter particle and a nucleus happens at a non-relativistic regime. Accordingly, for a non-relativistic particle, in the CM frame we have

$$\tilde{p} = m_{DM}\tilde{v}_{DM} = m_N\tilde{v}_N, \quad (\text{A.16})$$

and therefore

$$\tilde{p} = \frac{m_{DM}\tilde{p} + m_N\tilde{p}}{m_{DM} + m_N} = \frac{m_{DM}m_N}{m_{DM} + m_N}(v_{\tilde{DM}} + v_N) = \mu|\tilde{\mathbf{v}}_{DM} - \tilde{\mathbf{v}}_N|, \quad (\text{A.17})$$

with $\tilde{\mathbf{v}}_{DM}$ and $\tilde{\mathbf{v}}_N$ the DM and target velocities in the CM frame respectively. Thus, Eq. A.15, in the non-relativistic limit becomes

$$\tilde{\mathbf{k}} \cdot \tilde{\mathbf{k}}' = E_k^2 - \tilde{p}^2 \cos \theta \stackrel{\text{non-rel}}{=} m_N^2 + \tilde{p}^2(1 - \cos \theta). \quad (\text{A.18})$$

Using Eq. A.17, and defining $\mathbf{v} \equiv \mathbf{v}_{DM} - \mathbf{v}_N$, Eq. A.4 becomes

$$E_R = \frac{\mu^2 v^2}{m_N}(1 - \cos \theta). \quad (\text{A.19})$$

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