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CYGNO Conceptual Design Report

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Abstract

The conceptual design of the experiment named CYGNO (a CYGNUs module with Optical readout) is presented here. CYGNO aims to make significant advances in the technology of single phase gas-only time projection chambers (TPC) for the specific application of rare scattering events detection. In particular it will focus on a read-out technique based on the GEM amplification of the ionisation and on the visible light collection with a sub-mm position resolution by sCMOS camera. This type of readout - in conjunction with a fast light detection - will allow to reconstruct three dimensional (3D) images of the recoiling particles with high precision, offering new ways to distinguish the electron and nuclear recoils. The recoil direction resolution is also being investigated as a further tool to reject neutral background in the detection of Galactic Dark Matter (DM) particles. The final goal is to build and operate a high resolution gas TPC detector at the 50 kg scale for the directional search of a DM signal, in underground Laboratori Nazionali del Gran Sasso. In order to achieve this very demanding goal, we are going to develop firstly a 1 m^3 volume, 1 kg mass detector based on these concepts, to assess on a real underground experiment the design performances and capabilities of our approach, while at the same time testing innovative techniques and methods to reach the 50 kg scale. This project is part of the world-wide effort of the CYGNUS collaboration to define an optimal DM detection scheme sensitive to DM direction, towards a one-ton gas TPC nuclear recoils observatory.

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1 Introduction

Galactic DM particles are being searched for by a variety of terrestrial experiments, all located in underground labs and all characterised by an accurate selection of the detector materials with the aim to reduce the radioactivity background, especially the γ emission. A passive or partially active shielding can reduce the background originated by fast and thermal neutrons: fast neutrons, in particular, could mimic the WIMP[1] DM experimental signature. A precise knowledge of the *neutron flux* in various locations of the underground labs and in different seasons is therefore an important element in assessing the level of such irreducible background in DM searches.

Ton-scale and multi-ton scale dual phase TPCs based on liquid Ar or liquid Xe as WIMP targets are effectively exploring WIMP masses M_χ with M_χ larger than 10 GeV. Lighter nuclei and very low threshold, on the other hand are needed in order to extend the searches in the range of *lower DM mass*, down to few GeV.

Therefore we propose to build a *gas-only TPC chamber* that can be operated at *room temperature* and *atmospheric pressure* using a gas mixture of *He* and CF_4 with the possible *addition of* SF_6. The particles recoiling after a scattering in the active gas volume drift region leave a trail of ionisation that is drifted to the anode where it is amplified by a Gas Electron Multiplier (*GEM*) stage. In this last process visible scintillation light is emitted in the electron amplification process. This light is then partially collected by a fast detector (PMT or SiPM) and focused on a *sCMOS camera* featuring high granularity and extremely low noise per pixel. The underground commissioning of such detector (in absence of passive neutron shielding) will be able to provide a precise seasonal, spectral and directional measurement of the LNGS fast and thermal neutron flux, of great interest for any current or future DM experiment in this location. After commissioning, with the proper water or polyethylene shielding, it will serve as demonstrator for the development of a large scale directional DM detector at the 50 kg scale.

While a gas-only detector has a low density (kg/m^3) compared to liquid or solid target (ton/m^3), calling for large volumes to be competitive, it can however feature a very low detection threshold (down the level of the gas molecule ionisation potential) and new ways to reject charged backgrounds, based on the *ionisation density* and the *topological* information present in the recoiling particle image. Moreover, this can be used to infer the *DM original direction*, that is a powerful constraint in the Galactic DM searches and an additional mean for neutral background rejection (that is expected to be isotropic). The possibility to operate at room temperature and atmospheric pressure moreover requires minimal infrastructures, compared to cryogenic detectors, hence a relatively inexpensive technology to be scaled to the 100-1000 kg mass.

The aim of CYGNO - in the context of the CYGNUS experimental effort is to investigate how this technology with the proposed optical readout can be effective to reach

[1] Weakly Interacting Massive Particle

the longer term goal. CYGNO will contribute to assess the different threshold levels at which the electron rejection capability and the directional sensitivity are effective with this gas-only TPC technology.

2 Physics Objectives

2.1 Current status of direct DM searches

Figure 1 shows the current status of the direct DM search, for Spin Independent (SI, on the left) and Spin Dependent proton (SD, on the right) WIMP-nucleon coupling, with superimposed the expected CYGNO sensitivities. Four pre-eminent features can be observed:

- The DAMA/LIBRA observation of the annual modulation of the nuclear recoils rate has nowadays more than 11.9 σ significance with 2.17 ton year exposure [2]. Still, it is difficult to reconcile such result with the several exclusion limits produced by other experiments [3], including the most recent one by COSINE-100, obtained with the same target nuclei [4]. While it is true that its crystals purity is still unsurpassed nowadays, not even by COSINE-100, the DAMA/LIBRA experiment is not background free, detecting about 1 background count/day/kg/keV above 2 keV (annual modulation observed between 2-6 keV).

- The so-called "Neutrino Bound" [5]. Current Xe-based experiment (and several next generation detectors) [3] will be sensitive to a new background coming from solar, atmospheric and diffuse supernovae neutrinos, for which they do not possess at the moment any discrimination capability. Any observed signal in this region by these experiments will be difficult to interpret unambiguously as DM signal.

- The region between 1 and 10 GeV DM mass still remains theoretically well motivated and largely unexplored up-to-date for both Spin-Independent (SI) and Spin-Dependent (SD) coupling, as also recognised by the US Cosmic Vision report [6], due to the need for very low energy thresholds combined with light target nuclei. The latest result from the Darkside experiment [7] has significantly improved the current SI limits in this region, but at the price of renouncing to background discrimination, vetos and Z coordinate determination in the low mass analysis.

- The sensitivities reached in the SD coupling (Fig. 1 right) are between 10^5-10^7 times weaker than for the SI coupling. This is mainly due to the restricted availability of spin-odd target nuclei sensitive to axial vector currents.

The currently most effective way to actively discriminate electrons from nuclear recoils is to exploit the different partition of the energy deposition into the heat, scintillation and ionisation channels. A simultaneous measurement of the relative yield of at least two out of these three contributions offers particle identification, due to the different energy release mechanism of these two classes of events.

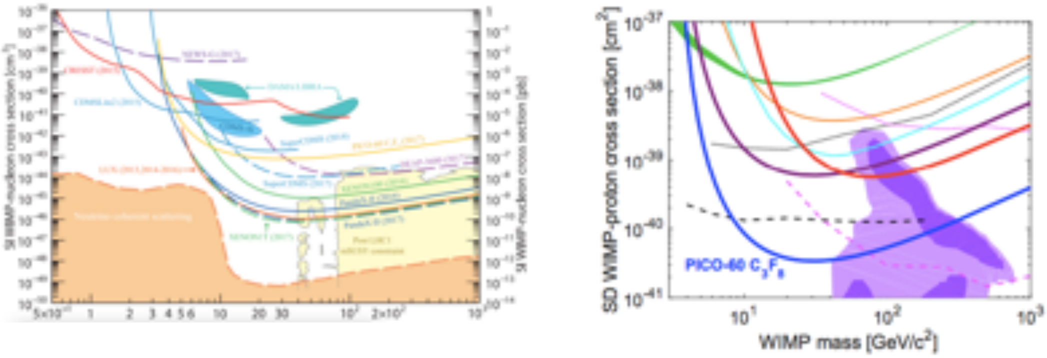

Figure 1: Left: WIMP cross section limits (normalized to a single nucleon) for Spin-Independent coupling versus mass, as from Particle Data Group 2017 [1]. Right: WIMP cross section limits (normalized to a single nucleon) for Spin-Dependent coupling versus mass as from the latest PICO-60 result [3].

Most of the current experimental efforts with the best sensitivities are based on this approach, as for example SuperCDMS [8] and Edelweiss [9] (phonons and ionisation), CRESST [10] (heat from low energy phonons and scintillation) or XENON and LUX [3] (ionisation and scintillation).

Neutrons, on the other hand, produce a detector response nearly identical to WIMPs, unless some additional topology or directional handle is employed for further discrimination. In large detectors with heavy dense targets, fast neutron with O(cm) mean free path can be suppressed by rejecting multiple scattering events (which is anyway only a statistical feature) and defining an internal fiducial volume, but at the price of reducing the active material sometimes even of 50%. This is effectively an additional internal shielding and does not lead to a straightforward scaling. Neutrinos, on the other hand, can not be shielded, nor are expected to multiple scatter. This implies no discrimination or suppression possibilities, unless a correlation with their source is employed, that requires the determination of the nuclear recoil track direction. None of the current experimental approaches discussed or shown above possess this capability at the moment.

The low WIMP mass region between 0.1 GeV and 10 GeV has recently received renewed attention, given the lack of detection claim at higher masses and by indirect searches. Several efforts with cryogenic detectors based on semiconductors (as SuperCDMS [8] or Edelweiss [9]) or scintillating crystals (CRESST [10]) have demonstrated with prototypes capability for electron/nuclear discrimination down to few keV threshold. Nonetheless, all of them are now adopting different modes of operation that, while lowering the energy threshold down to O(100) eV, strongly reduce the discrimination power. Similarly, alternative approaches as NEWS-G [11], with a spherical 1-channel gaseous TPC, are able to reach even lower energy threshold (down to single electron, i.e. 30 eV), but lack of highly efficient active electron/nuclear recoil rejection at this energies. Each of these approaches implies stricter requirements on the detector materials radio-purity.

Therefore, all experiments currently active in the direct DM search field need to rely on a precise estimation of the expected background, since none of them is able to completely reject it, especially at low energies. Moreover, none of the current experiments or foreseen upgrades has the capability to unambiguously establishing a clear galactic signature for the DM signal with a directional correlation: this is the reason why we believe that a high-resolution gaseous Time Projection Chamber at atmospheric pressure and with sCMOS optical readout is the radical change in technology needed nowadays to solve these issues.

2.2 The case for directional gaseous TPC approach

The expected WIMP scattering in the detector is due to the Earth's relative motion with respect to the galactic halo, that is believed to contain high concentration of DM from measurement of the rotational curves of our Galaxy. This implies that an apparent WIMP wind coming from the Cygnus constellation is expected to be observable on our planet. The determination of the incoming direction of the WIMP particle can provide a correlation with an astrophysical source that no background whatsoever can mimic, and therefore it offers an unique key for a positive identification of a DM signal [12]. This holds true even in presence of an unknown amount of isotropic background, such as neutrons from environmental or detector materials radioactivity [12], but also neutrinos. It has been shown that, while about 10^4 DM events are needed for a 90% confidence level discovery with a non-directional detector operating below the neutrino floor, a directional detector can achieve the same confidence with as few as 10 events, since the Sun never occupies the same position of the Cygnus in galactic coordinates over the year. Moreover, once (and if) detection will be confirmed, this will be the only approach able to provide constraints on DM properties and to perform DM astronomy [12,**?**].

Although inherently challenging, gaseous TPCs constitute the natural approach to directional DM searches and can potentially provide the best architecture and the best observables for the following reasons:

- A measurement of the *total ionisation* indicates the *energy* of the recoil. α particles and electrons can be easily identified comparing their *track topology* to the energy released along the path (i.e. dE/dx), providing excellent background rejection;

- The track itself indicates the axis of the recoil and the charge measured along its path encodes the track orientation, providing an additional powerful observable (usually referred to *"head-tail" asymmetry*, given that most charge is released at the start of the track at these energies). It has been in fact demonstrated how this information improves by a factor 10 the directional sensitivity of a detector, while a pure axial signal (the track orientation via 2D or 3D reconstruction) can in practice be washed-out by the WIMP velocity distribution [12];

- The active target volume can be made free of background-producing material: it contains only the gases, which can be purified of Radon (Rn) and recirculated. Large choice of gases can be employed in a TPC, from light to heavy nuclei, with both odd and even spins, therefore sensitive to both SI and SD interactions also in the low WIMP mass region;

- Only one wall of the detector needs to be instrumented with an amplification and readout systems, and the other with a cathode, leading to favourable cost-volume scaling and to reduced radioactive contamination due to the detector materials. Radon Progeny Recoils (RPRs) from such sources constitute, indeed, one of the most dangerous backgrounds for direct DM searches [14]. This happens when ^{222}Rn from internal detector radioactivity decays into ^{218}Po and the unstable positively charged ion ^{218}Po^{+} (80% of times), drifts and plates out on the cathode with the emission of a 6.11 MeV α particle. The geometry of this process implies an high probability for the α to be completely embedded in the cathode, leaving only the ^{218}Po recoiling in the fiducial volume and mimicking a WIMP interaction. In order to reject these events, the full 3D position of the track, including along the drift direction, needs to be reconstructed (a technique usually referred to as *"fiducialization"*);

- The operational and economical advantages of a room-temperature and atmospheric-pressure instrument, with no need for cooling or vacuum sealing. These choices allow for a much more compact experiment realization and straightforward scaling when comparing to cryogenic experiments, that are currently dominating the DM direct search scene, both in the low and high WIMP mass region;

- TPCs up to 100 m^3 of active volume have already been sucessfully operated at the ALICE LHC experiment [15] and up nearly 20000 m^3 approved for construction in the neutrino field [16], showing the feasibility of very large detectors with large active masses;

2.3 Directional Dark Matter experiments - state of the art

The main experimental challenges of DM detectors aiming at directional sensitivity are to instrument a *large volume* with *high enough granularity* to infer recoiling tracks direction down to low energy, while staying background-free. The spatial resolution required is ultimately set by the density of the target material, since it determines the characteristic length of a WIMP induced recoil, which in turn fixes the minimum energy threshold for which the track direction and orientation can be inferred and the electrons discriminated from nuclear recoils using topology information. The development of directional DM detectors has therefore mainly concentrated on low-pressure <100 torr TPCs, in order to produce O(mm) tracks whose direction could be determined. Given the reduced total target mass compared to liquid or solid detectors, these experiment focused on nuclei with

Table 1: Summary of the main characteristics of all the existing directional DM search project based on gaseous TPC approach, together with the proposed CYGNO PHASE-1.

Experiment	Amp. + Readout	Press. [mbar]	Vol. [L]	Mass [g]	E Thr. [keV]	e^- rej.
DRIFT	MWPC	55	800	33 CF_4	20	1.9×10^5 [21]
NEWAGE	μ-PIC	100	37	11.5 CF_4	50	2.5×10^5 [25]
MIMAC	Micromegas	50	6	1 CF_4	2	10^5 [27]
DMTPC	Meshes + CCD + PMT	55	30-100	50-100 CF_4	40	6×10^6 [30]
D^3	GEM + Charge pixels	1000	0.025-0.05	0.01 He/0.06 Ar, 15 CO_2	5300 [33]	n.a.
PHASE-1	GEM + sCMOS + PMT	1000	1000	100 He, 900 CF_4	1 He, 2 C, 3 F	10^5

non-vanishing spin (i.e. ^{3}He, CF_4 or CS_2) in order to explore the less constrained SD parameter space. None of them has sensitivity to SI interactions. The only noticeable exception is the NEWS-dm project, based on microscopic inspection of nuclear emulsions [17]. Nonetheless, its limited track range capability and the use of medium-heavy target nuclei make this approach sensitive only to high > 50 GeV WIMP masses.

The mean features of all existing projects for directional DM searches based on TPC detectors are summarised, together with CYGNO PHASE-1 demonstrator expected performances and features, in Table 1 and hereafter discussed:

- The *DRIFT* collaboration [18] at the Boulby Underground Laboratory has pioneered since 2001 the construction and operation of the only existing directional DM TPC at 1 m^3 scale. The DRIFT II detector currently taking data is composed of 2 back-to-back TPCs, each with 50 cm drift length, separated by 0.9 μm thick texturised mylar cathode, conveniently shaped to minimise recoils induced by materials radioactivity [19]. Gas amplification and readout is obtained with Multi Wire Proportional Chambers technique. DRIFT employs a 30:10:1 torr CS_2:CF_4:O_2 gas mixture to obtain negative ion drift and exploit the minority carriers for fiducialization purposes [20]. Thanks to this, DRIFT demonstrated track directional and head-tail sensitivity at ~20 keV threshold [21]. The combination of the complete electron rejection (2×10^{-5} at 20 keV) with the fiducialization offered by the minority charge carriers in a negative ion TPC, allowed DRIFT to put the most stringent constraint from a directional detector on SD WIMP-nucleon proton coupling [22]. Nonetheless, having a total of 33.2 g of F target over 54 live-days, this limit is $\sim 10^{-36}$ cm^2 at 50-100 GeV WIMP mass, several order of magnitude weaker than the most recent result by PICO 60-C_3F_8 at 5×10^{-40} cm^2 in the same region [23].

- *NEWAGE* chooses to use micro-pixels chambers (μ-PIC) coupled to GEM to amplify and detect the track ionisation cloud [24]. The μ-PIC peculiar features are the possible development on monolithic printed circuit boards (allowing easy scalability) and the gas amplification structures acting also as a 2D pixel readout. The data acquisition system measures the analog signals from the cathodes and the charge collected by each pixel. NEWAGE demonstrated directional capability down to $\sim$ 50 keV (with head-tail sensitivity in the range 70-400 keV on a statistical basis) and $\sim 2.5 \times 10^{-5}$ gamma rejection at the same energy [25]. Their latest underground run with 0.327 kg day was limited mainly by μ- PICs internal radioactivity, since unfortunately NEWAGE does not possess yet any fiducialization technique to suppress such events, as opposite to DRIFT. NEWAGE is working on the development of low radioactivity μ-PICs and on the possibility of using negative ion charge carriers to improve its background budget and rejection [26].

- The MIcro-tpc MAtrix of Chambers (*MIMAC*) experiment employs Micromegas (for amplification and readout), a self-triggering electronics with a 50 MHz sampling, and the use of the gas mixture 70% CF_4 + 28% CHF_3 + 2% C_4H_{10} (specifically developed to control the gain and velocity of the primary drifting electrons). MIMAC demonstrated 10^5 electron/nuclear recoil discrimination at 5 keV [27], but have not produced yet a DM search result from an underground run. They are attempting to develop a fiducialization technique by measuring the diffusion accumulated by the ionisation cloud in its drift toward the readout plane. Unfortunately, the precision reached (10 cm over 20 cm drift distance) does not make this approach profitable yet [27].

- *Dark Matter Time Projection Chamber (DMTPC)* experiment is the most similar to the CYGNO conceptual design. It was developed to work with pure CF_4 between 30 and 100 torr and equipped with CCD-cameras, PMTs and a mesh charge amplification readout systems [28]. With a 20ℓ prototype, DMTPC demonstrated directional capability at $\sim$ 40 keV, with an axial angular resolution of 40 degrees [29]. Moreover, they showed a 6×10^6 electron recoil rejection, combining the charge signal from the meshes with the CCD images [30]. DMTPC is finalising the construction and commissioning of a 1 m^3 detector at SNOLAB since 2016 [31], but have not produced any physics results since then.

- *The D^3 project* is based on the use of a double (or more recently triple) thin GEM charge amplification coupled to ATLAS FE-I3 ASIC pixels readout (50 x 400 um^2 pixel size) [32]. Preliminary results with very small prototypes and Ar/He:CO_2 gas mixtures show the possibility of 150-200 um single point resolution, few degrees angular resolution for 5-10 mm tracks and gain resolution of $\sim$ 15% at 2.9 keV, indicating the possibility of head-tail discrimination for keV scale nuclear recoils [33]. More recently, they demonstrated the capability of extracting absolute z measurement from charge cloud topology with $\sim$ 1 cm uncertainty over 15 cm drift distance [34].

- *The CYGNUS-TPC project* is a new international collaboration formed by nearly all the members of the experiments described above (including CYGNO collaborators). The aim of CYGNUS-TPC is to develop a large modular Galactic Recoil Observatory that could test the DM hypothesis beyond the Neutrino Floor and measure the coherent scatter of galactic Neutrinos. The key features of the proposed experiment is a modular design of recoil sensitive TPCs filled with He:SF_6(:CF_4) (low and high pressure operations envisaged, as well as electron or negative ion drift) with installation in multiple underground sites (including the Southern Hemisphere) to minimise location systematics and improve sensitivity. A coordinated R&D (of which the CYGNO group is part) to optimise technologies and gas mixture choices is currently undergoing in several laboratories in the participating countries.

The CYGNO project fits into this context, as part of the multi-site network of CYGNUS modules development and with the aim of establishing the proof-of-principle and scalability of our chosen optical sCMOS + PMT readout.

2.4 CYGNO 3D optical readout approach

When the ionising track cloud is amplified, not only electrons but also photons are produced, with the ratio of the two highly depending on the gas mixture. CYGNO key aspect resides in detecting the ionisation cloud through these photons, rather than through the electrons with a charge measurements, thanks to the recent advances in light detectors. CYGNO innovative choice is to couple an high granularity 2D projection of the track detected by highly sensitive, relatively slow sCMOS cameras with the fast, integrated measurement of all the light emitted offered by more common photomultipliers (PMT). We recently demonstrated how the combination of these two information can provide high resolution 3D tracking, that will be discussed in more details in Sec.3.

Given this, CYGNO approach peculiarities and distinctive traits with respect to all the above discussed experiments will be:

- the use of *sCMOS sensors* which offers a high granularity along with *very low noise* and a very high sensitivity (>80% of quantum efficiency at 600 nm). These provide larger number and smaller pixels with respect to the DMTPC choice (2048 $\times$ 2048 pixels versus 1024 $\times$ 1024, with dimensions 6 $\times$ 6 μm^2 versus 12 $\times$ 12 μm^2) and a much lower cost per channel compared to charge pixels readout. Moreover, while it is already possible to envisage a 1 m^2 area read out by sCMOS cameras, charge pixels are still at the mm^2-cm^2 stage;

- the addition of fast light sensors (PMTs or SiPM) to exploit the signal time structure in order to infer tracks extension along the drift direction (Δ Z) with O(100) μm precision (while several mm where obtained by DMTPC) ;

- the use of Gas Electron Multipliers (*GEM*) coupled to light sensor, that provide very high granularity not only at the readout, but also at the amplification stage;

- atmospheric pressure and room temperature operation, to minimise infrastructures needed and for reduced overall experiment dimensions, costs and material budget (thin vessel compared to all other low pressure TPC approaches, no need for cryogenic as noble liquids or HPGe-Si detectors);
- the decoupling of the readout sensor from the gas target volume (not possible with charge TPC readouts) for lower intrinsic detector radioactivity;
- the use of a Helium-Fluorine based gas mixture, to improve the total light yield, to maintain sensitivity to SD interactions while gaining also the possibility to explore SI (in particular in the low mass WIMPs region) and to reach atmospheric pressure operation while maintaining a low density target gas;
- the fit to the ionisation cloud diffusion to extract the track coordinate along the drift direction, to be used for fiducialisation purposes;
- the *possibility* to improve all the performances with the use of *negative ion* drift gas mixture based on a small addition of SF_6.

3 R&D towards the CYGNO experiment

Gas represents an interesting target for directional DM searches. Thanks to the low density, nuclear recoils can in fact give rise to tracks long enough to be reconstructed pertaining the information about the track direction and sense, differently than in other medium states.

In order to amplify the ionisation cloud produced by particles crossing the gas, we propose the use of Micro-Pattern Gas Detectors (MPGD), that have proven very versatile devices for high resolution particle tracking. Gas Electron Multipliers (GEMs), in particular, introduced in 1996 at CERN [35], have demonstrated to be one of the most successful micro-pattern technologies. The stacking of a multiple GEM foils allows moreover to reach high gas gain and efficiency, while improving detector stability.

In the past few years, we have been working on an alternative approach to the GEM readout, where the light emitted by the molecular de-excitation in the avalanche processes is detected by high sensitivity sCMOS cameras, rather than the electric signal produced by the movement of free charges in gas. This technique, compared to classical charge readout, offers several advantages, since sCMOS optical sensors:

1. are developed for a large commercial market, allowing for quick performances improvements over short period of time;
2. feature high integrated granularity and sensitivity;
3. are mechanically decoupled from the gas volume, for reduced intrinsic detector internal radioactivity;
4. can be easily scaled to sense large volumes with adequate optics.

The main limitation may only be represented by the low acquisition frequency of the order of the kHz.

Between 2015 and 2018 we developed an R&D to study possible application of the described approach to high precision large gaseous TPC at room temperature and atmospheric pressure for direct Dark Matter searches. We manufactured a small (10×10 cm^2 readout area, 1 cm drift gap) and a large (20×24 cm^2 readout area, 20 cm drift gap)) prototype, respectively named ORAnGE (Optically ReAdout GEm) and LEMOn (Large Elliptical Module Optically readout), and tested their performances with He:CF_4 gas mixtures at atmospheric pressure at Laboratori Nazionali di Frascati ([36], [37], [38], [39] and [40]). In both prototypes we employed triple thin standard GEMs from CERN for the ionisation cloud amplification, and collected the light by means of ORCA-Flash 4.0 sCMOS camera[2]. In ORAnGE, the 2D sCMOS information is complemented by an Hamamatsu H10580 PMT positioned on the same side of the camera, while in LEMOn

[2]http://www.hamamatsu.com/jp/en/C13440-20CU.html

by a HZC Photonics XP3392 PMT looking at the light produced only by the first GEM from the cathode side.

3.1 Photon efficiency, energy threshold and energy resolution

We performed a preliminary evaluation of photon efficiency and energy threshold by means of the 450 MeV electron tracks at the BTF of Laboratori Nazionali di Frascati and ^{55}Fe radioactive source with both ORAnGE and LEMOn.

With ORAnGE we detected about 330 photons in each millimeter of the 450 MeV minimum ionizing track in a He:CF_4 60:40 gas mixture, with an applied voltage on the GEM of V_{GEM} = 440 V (see Fig.2 left). By using a Garfield[41] simulation of a minimum ionizing particle (mip) in this gas mixture a release of 230 eV per mm is estimated and therefore 1.4 photons are detected per eV released in the gas.

Very similar results were found with a ^{55}Fe source (see Fig.2 right): 0.9×10^4 photons are detected per impinging 5.9 keV photon (1.5 photons/eV). ^{55}Fe electron recoil events appear as 1 mm long bright spots. The pedestal fluctuation due to the sCMOS camera noise is about 60 photons for this event topology: this translates into a 5 σ detection threshold of 200 eV. Since the measured energy resolution for ^{55}Fe electron recoil events is about 1.3 keV, we conclude that a fully efficient detection of ^{55}Fe with such threshold is possible. Moreover, the energy resolution was also estimated with mip events to be few hundred eV down to 1 keV.

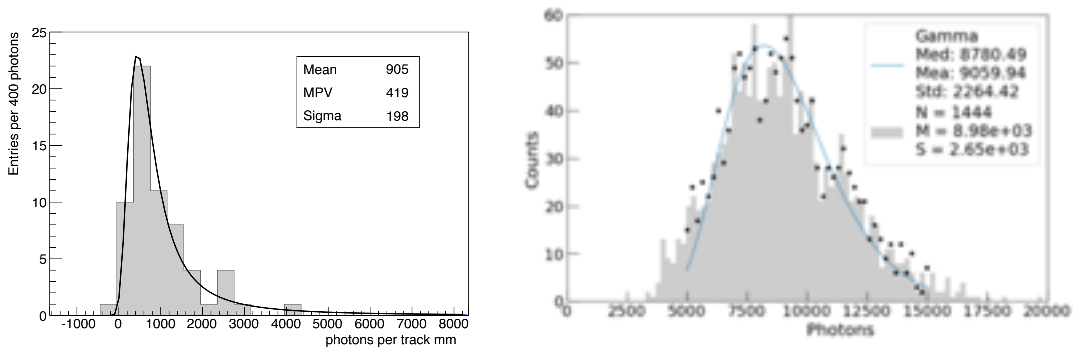

Figure 2: Distribution of the amount of light collected in 1 mm track slices (left) and in ^{55}Fe events (right).

With LEMOn we studied the same features over a larger volume and longer drift distances. By studying the distribution of the light collected in slices of different widths, the energy resolution was evaluated for tracks at different Z. Fig.3 shows that, already for energy releases of few keV, a resolution of about between 200 and 300 eV can be achieved even on a longer drift distance.

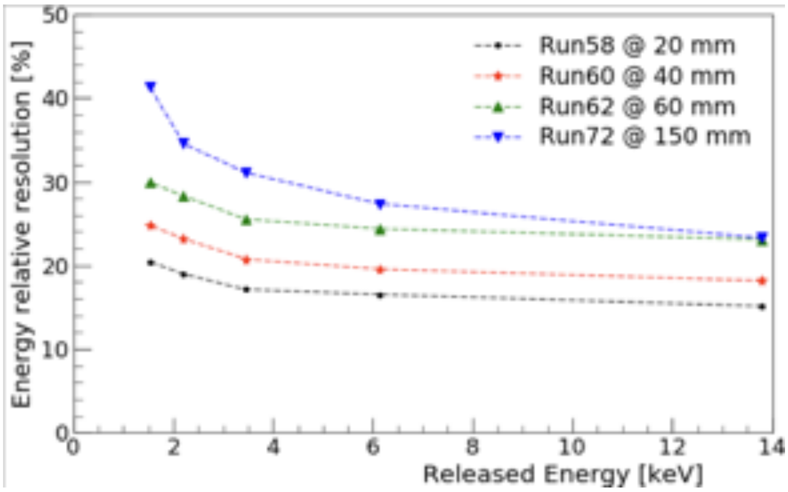

Figure 3: Energy resolution for different distances from the GEM.

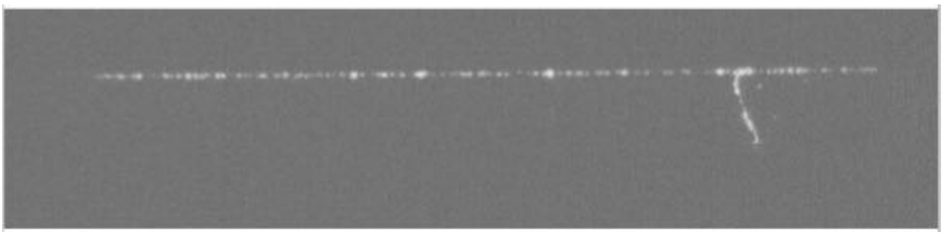

Figure 4: Image of a 450 MeV electron with a δ ray emitted on a side.

3.2 Tracking performances and spatial resolution on minimum ionising particles

Fig. 4 shows an example of the sCMOS image of a single 450 MeV electron crossing ORAnGE sensitive volume. Figure 5 shows a portion of the same track of Fig. 4 and the corresponding longitudinal profile (pedestal subtracted) of the detected light: the ionization cluster structure is well visible.

Figure 5 shows a portion of the track of Fig. 4 and the corresponding longitudinal profile (pedestal subtracted) of the detected light: the ionization cluster structure is well visible.

For the same track the distribution of the light on the plane orthogonal to the track direction is shown in Fig. 6 and resulted to be well described by a Gaussian function with a σ width of about 230 μm.

The distribution of the residuals of the reconstructed clusters to the fitted track for 20 events is shown in Fig. 7 with a superimposed Gaussian fit. From the obtained width (σ) it was possible to evaluate a space resolution of 35 μm in ORAnGe.

In 2017 we performed additional tests on the LEMOn prototype, in order to assess the above discussed features on a larger volume and longer drift distances. These tests showed that, even with a moderate drift field of 450 V/cm, a 300 μm space resolution can be achieved for 20 cm drift paths.

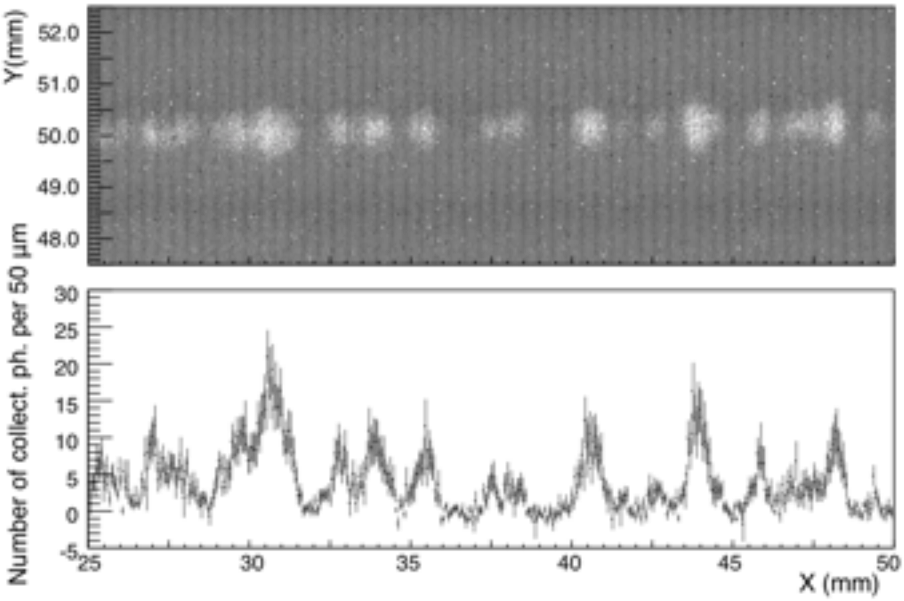

Figure 5: Longitudinal profile, pedestal subtracted, of the detected light for a portion of the track shown in Fig. 4.

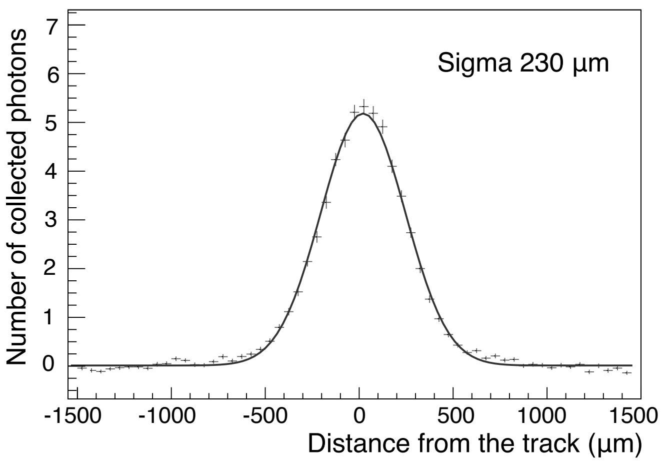

Figure 6: Transversal profile (pedestal subtracted) of the detected light for the track shown in Fig. 4.

3.3 3D reconstruction exploiting the fast and integrated PMT light detection

In order to acquire the time structure of the signals, light can be concurrently readout by a fast light detector (PMT or SiPM) placed close to the camera lens. Tests on ORAnGe, performed with a 25-mm diameter PMT[3] and the 450 MeV electron beam, demonstrated that the analysis of the signal waveform provides information very useful to reconstruct not only the slope of the track with respect to the GEM plane and the relative Z of main

[3]Hamamatsu H10580

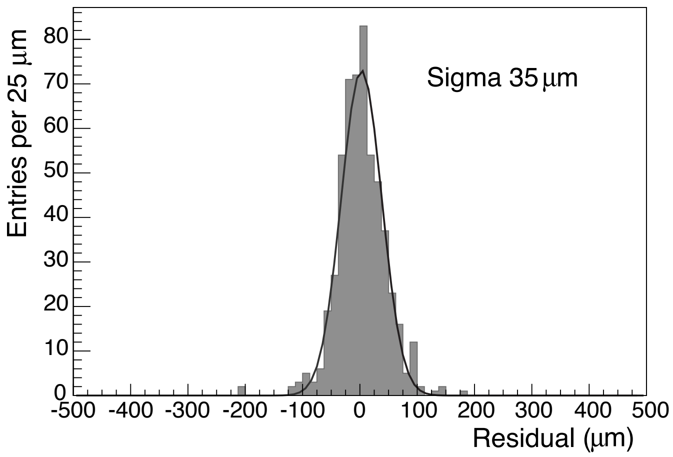

Figure 7: Distribution of the residuals of the reconstructed cluster positions from 20 fitted tracks with a superimposed Gaussian fit with a σ = 35 μm

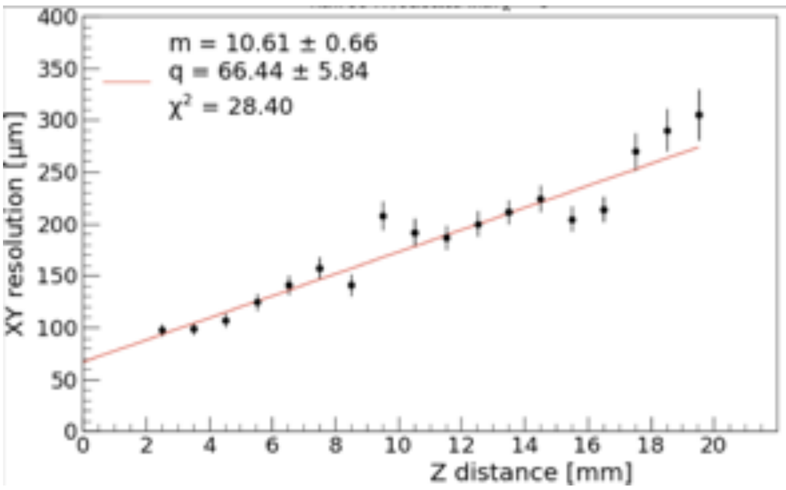

Figure 8: Space resolution as a function of the track distance from the GEM. The extrapolated value at zero distance (q) is 66.4 $\pm$ 5.8 μm while the linear coefficient (m) is 10.6 $\pm$ 0.7 $\frac{\mu m}{mm}$.

cluster, but also the relative positions of the main clusters.

In Fig. 9, the PMT signal is shown for an inclined electron crossing the 1 cm drift gap at an angle of 0.1 rad (almost 6°) with respect to the GEM foils.

The arrival time of the main clusters is clearly visible, allowing an independent reconstruction of their absolute position in z. Taking into account the gap width (1 cm) and the width of the signal (about 135 ns), an electron drift velocity of 72 μm/ns is found in agreement with the value evaluated with Garfield.

3.4 Response to neutrons and discrimination between nuclear and electron recoils

We performed tests with neutron particles in order to assess the capability of our prototype to detect nuclear recoils and the feasibility of discrimination between them and electron

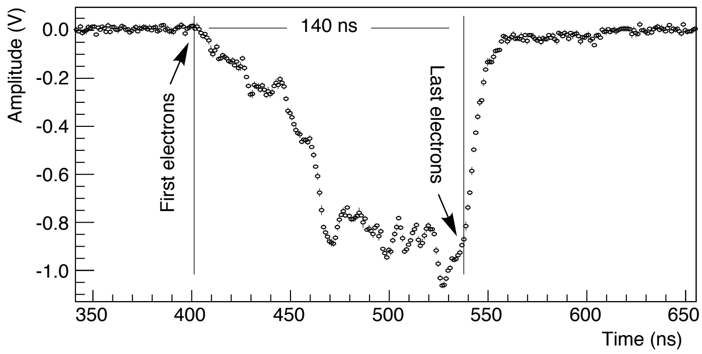

Figure 9: PMT waveform for a track crossing the drift gap inclined with respect to the GEM plane.

recoils.

ORAnGE was exposed to an Am-Be source (Fig.10), emitting 1-10 MeV neutrons along with 4 MeV and 60 keV photons. A 0.2 T magnetic field due to a permanent magnet was applied within the drift field. By evaluating the average light density, the three species are very well separated.

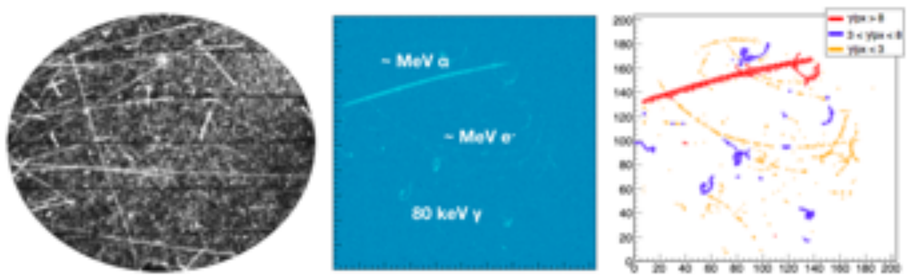

Figure 10: Particle identification - left: log time exposure (5 seconds) AmBe neutron source; center: short time exposure (0.01s) where tree component of the AmBe source are identifiable; PID clustering track analysis reconstruction

Recently, the LEMOn prototype was exposed to the Frascati Neutron Generator (ENEA) beam of 2.5 MeV neutron. Neutrons were clearly identified even in presence of a diffuse soft X-ray background.

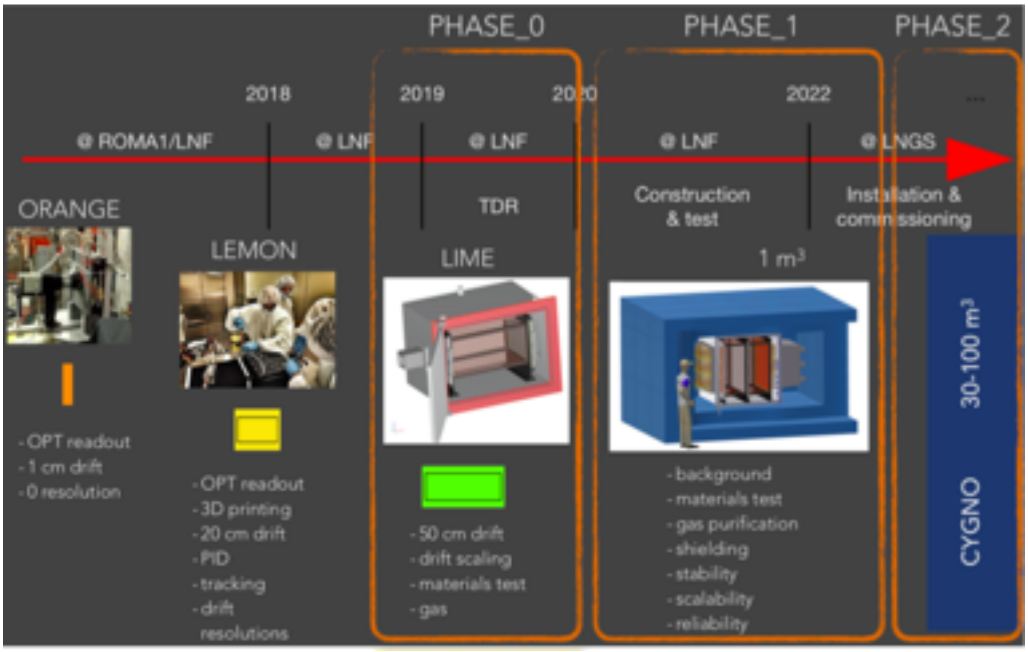

Figure 11: Roadmap to 10-100 m^3

4 CYGNO road-map

4.1 PHASE-0 and the LIME prototype

The detector development road map (Fig. 11) has already started with the design of a new prototype, named *LIME*, in PHASE-0. While ORANGE and LEMOn [42] prototypes were aimed to demonstrate both the validity of the readout performances, and its limitations and scalability, the LIME prototype will be the PHASE-0 of CYGNO roadmap to the development of a large scale detector. For this reason, LIME *materials radiation budget* and its test are crucial component of the experiment's validation, with special attention to the vessel, field cage, GEMs, and optical windows. The LIME prototype (fig. 12) is under design at the LNF and its realization is planned during the 2019 with the aim to develop a gas vessel and a *50 cm* long field cage with a low gas chemical contamination and a low radiation budget. The cathode will been realised using an ATLAS MicroMegas mesh, glued on the last ring of the field cage and ensuring an adequate light transmission ($\simeq 70\%$). This will allow to equip the detector with a photomultiplier to read the light time-shape from the GEM amplification stage ("secondary light") but also the primary gas scintillation. A SiPM will also be tested to detect the secondary light on the camera side. LIME dimensions have been chosen to be nearly identical to those of each optical module of CYGNO PHASE-1 (see Sec.5), with the aim of demonstrating on this final prototype the 1 m^3 expected performance on a single module.

LIME main goal is to allow us to understand and tackle the following detector optimisation and constructive issues, for the finalisation of CYGNO PHASE-1 Technical Design Report by the end of 2019:

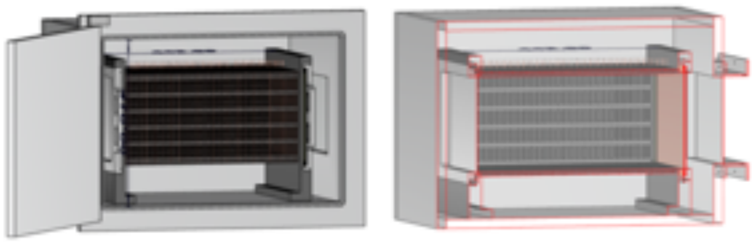

Figure 12: Left: LIME Cat 3D design; Right: LIME cross section. The overall length of the LIME prototype is about 50 cm.

- cathode and field cage materials and their radiation budget
- design of the HV feed-thru and HV distribution
- design of the gas system distribution to operate the detector with an appropriate mixture
- GEM material radiation budget and its framing to install them in the vessel
- GEM operational stability
- Low radioactivity glasses (fused silica) and lenses
- design of an image multiplexing optical system
- CMOS camera: noise reduction with cooling, operational stability
- choice of the vessel material to be a proper γ shielding
- PMT or SiPM choice

4.2 PHASE-1 goals and expected results

The aim of CYGNO PHASE-1 is to prove the potentials of a high resolution gaseous TPC with sCMOS optical readout for near future, direct Dark Matter searches at low 1-10 GeV WIMP masses down to and beyond the Neutrino Floor in both SI and SD couplings. For these reasons, two run will be performed: firstly, without the neutron shielding, in order to measure the LNGS Halls environmental neutron flux and to demonstrate in an underground, cosmic-ray shielded run CYGNO approach sensitivity to nuclear recoils. Secondly, with about 50 cm water shielding, a Dark Matter search run that will prove on the 1 m^3 scale CYGNO expected performances and capabilities.

4.2.1 PHASE-1 neutron flux measurement at LNGS

Precise knowledge of the expected neutron flux in underground laboratories is critical in both designing new large-scale detectors, and analysing current experimental data. While fast neutrons are already a background in present experiments, thermal neutrons will become so for future experiments when activation of detector materials will become an issue *per se*. Table 2 summarises most of the neutron flux measurements performed at LNGS, all evaluated in presence of significant backgrounds. Although very different energy binning were used (reflecting the different experimental techniques), results vary very widely and only two of them [44,**?**] give information on the spectral shape. While recent measurements of the thermal flux exist, the publications regarding fast neutrons are more than 20 years old. All the measurements in Tab. 2 were performed in Hall A, except for one in Hall C [48]. Sensible variations in the backgrounds levels are possible even between different location in the same lab, due to the varying contents of U, Th and Rn in the underground environment, as well as of the humidity of the surrounding concrete walls (thanks to the moderation capability of water). This feature could partially vary with season, and therefore requires a long-term monitoring in order to be ruled out [51]. CYGNO will provide a new, background-free, seasonal measurement of the neutron flux intensity and spectrum at LNGS, information presently highly needed in order to check the current results and reduce the experimental errors. CYGNO expected features (discussed in Sec.5.1), will in fact allow:

- Excellent sensitivity to both fast and thermal neutron flux. The addition of 0.5% ^{3}He can make CYGNO sensitive to both thermal neutrons through capture on ^{3}He and fast neutrons through He (C, F and S) nuclear recoils. The characteristic signature of a neutron capture event, with the emission of a proton and a triton back-to-back in the center of mass frame and a total energy fixed at 764 keV, makes this process easily detectable with CYGNO experimental approach. This has already been shown feasible with a conventional TPC and a 2D CCD readout in ^{3}He:CF$_4$ gas at 600:40 torr[52]. None of the experiments in Tab. 4.2.1 could simultaneously detect both components, since the ^{3}He-based detectors employed by [44] needed a shielding to moderate and detect the fast neutron flux.

- Fig. 10 center panel shows a He recoil in He:CF$_4$ 450:200 torr as seen by ORANGE exposed to an ^{241}AmBe neutron source (about 4 MeV average neutron energy). Given the expected performances of CYGNO, we believe 3D tracking reconstruction and track sense determination to be possible for O(keV) energy neutron recoils. None of the measurement in Tab. 2 provides directional information.

- Precise spectral measurement of the fast neutron flux. With a spectral deconvolution analysis similar to[48], CYGNO can in fact extract not only the intensity but also the fast neutron spectrum from the observed events. From the expected rate inside the detector (see below), CYGNO be able to largely reduced the uncertainties with respect to the result reported by [44,**?**].

- Background free measurement (i.e. electron/nuclear recoil rejection down to <1 bkg event/year) of neutron flux. The background contributions discussed in Sec. 5.10, together with the expected performances shown in Sec. 5.1, demonstrate the possibility for CYGNO to suppress all the gamma backgrounds induced by cosmogenic, natural and detector radioactivity. Moreover, DRIFT recently produced the first background-free measurement of Boulby Underground Laboratory fast neutron flux[53], proving such feasibility on the 1 m^3 scale. None of the measurement in Tab. 2 was background free.

- Seasonal measurement of both fast and thermal neutron flux. A preliminary evaluation of the expected neutron yields from LNGS walls and concrete activity developed within our group, shows an expected rate of about 5000 recoils induced by fast neutrons per month, after basic selection cut and with a 30 keV energy threshold (thanks to the nice kinematic match between neutron and He masses). Since neutron capture cross section on ^{3}He is about 600 times higher than the elastic scattering cross section on He, a 0.5% ^{3}He addition, combined with similar detection efficiency (as demonstrated feasible by [52]), provides a similar thermal neutron yield. The expected event rate indicates therefore the feasibility of a precise seasonal measurement, to possibly investigate any temporal variation of the neutron flux. None of the measurement in Tab. 2 was able to study such potential fluctuations.

4.2.2 PHASE-1 Direct Dark Matter search at LNGS

The goal of PHASE-1 Dark Matter search run at LNGS with a 1 m^3 demonstrator will be to prove on a realistic detector scale and in an underground environment the following expected performances and capabilities:

- *O(keV) energy threshold on nuclear recoil tracks*. This goal is backed by DRIFT (demonstrated sensitivity to 2 keV Carbon atoms recoils in CS_2 at 40 torr, with a gas gain of about 10^3)[21] and MIMAC (2 keV nuclear recoil tracks in 70% CF_4 +28% CHF_3+ 2% C_4H_{10} at 50 mbar with 10^4 gain [55]) results. Our prototypes, described in Sec. 3, already performed with high GEMs gains of 10^6 that, combined with the sCMOS granularity and low noise per pixel and the characteristic single photon sensitivity of PMTs, demonstrated sensitivity of our readout approach to 1 keV energy deposition by minimum ionising particles (see Fig.3).

- *3D tracking reconstruction with head-tail determination* at O(keV) energy. This will be possible thanks to the 2D X-Y sCMOS readout, complemented by the time

E interval (eV)	Thermal Neutron Flux (10^{-6}cm^{-2}s^{-1})			
	Ref. [43]	Ref. [44]	Ref. [45]	Ref. [46]
0 - 0.05	5.3 ± 0.9	1.08 ± 0.02 (1.07 ± 0.05)	0.54 ± 0.13	0.32 ± 0.09
0.05 - 1000		1.84 ± 0.20 (1.99 ± 0.05)		

Table 2: Thermal and epithermal (top) and fast (bottom) neutron flux measurements at the Gran Sasso laboratory reported by different authors. In analyzing their experimental data with Monte Carlo simulations, Belli et al. [44] have used two different hypothetical spectra: flat, and flat plus a Watt fission spectrum. This leads to the upper and lower data sets shown for ref.[44] respectively.

<table>
<tr><th rowspan="2">E interval (MeV)</th><th colspan="6">Fast Neutron Flux (10^{-6}cm^{-2}s^{-1})</th></tr>
<tr><th>Ref. [47]</th><th>Ref. [48]</th><th>Ref. [44]</th><th>Ref. [43]</th><th>Ref. [49]</th><th>Ref. [50]</th></tr>
<tr><td>$0.1 - 1$</td><td rowspan="3"></td><td></td><td rowspan="2">0.54±0.01
(0.53±0.08)</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="5">2.56±0.27</td></tr>
<tr><td>$1 - 2.5$</td><td>0.14±0.12</td></tr>
<tr><td>$2.5 - 3$</td><td rowspan="2">0.13±0.04</td><td rowspan="2">0.27±0.14
(0.18±0.04)</td><td rowspan="5">3.0±0.8</td><td rowspan="5">0.09±0.06</td></tr>
<tr><td>$3 - 5$</td><td rowspan="4">0.78±0.3</td></tr>
<tr><td>$5 - 10$</td><td>0.15±0.04</td><td>0.05±0.01
(0.04±0.01)</td></tr>
<tr><td>$10 - 15$</td><td>$(0.4 \pm 0.4)\cdot 10^{-3}$</td><td>$(0.6 \pm 0.2)\cdot 10^{-3}$
($(0.7 \pm 0.2)\cdot 10^{-3}$)</td><td rowspan="2"></td></tr>
<tr><td>$15 - 25$</td><td></td><td>$(0.5 \pm 0.3)\cdot 10^{-6}$
($(0.1 \pm 0.3)\cdot 10^{-6}$)</td></tr>
</table>

profile from PMTs for the third coordinate along the drift direction (see Fig.9). The independent photon counting of each sCMOS pixel allows dE/dx measurement along track path (i.e. track orientation determination). This information can be improved by the independent measurement of the asymmetry of the PMT signal, that is expected to show the typical head-tail feature as shown by DRIFT with wires charge readout [56].

- *Full 3D detector fiducialization* to suppress neutrons and RPR-induced recoils to zero. This will be achieved with the exploitation of the expected diffusion of the track ionisation cloud, as demonstrated on minimum ionising particles with 20% uncertainty over 20 cm drift with LEMOn prototype (Fig.8).

- *Electron rejection power of 10^5* at O(keV) energy threshold. This claim is supported by the experimental results obtained by MIMAC[55] and with a 2D CCD optical readout by our collaborators at University of New Mexico [57]. The preliminary background rejection results obtained with the ORANGE and LEMOn prototypes discussed in Sec.5.9 demonstrate the very good particle identification capabilities of our design. These were obtained exploiting only the number of detected photons per pixel, hence dE/dx. The combination of this information with the total energy released, the track length and the topology can further significantly improve the background rejection. This is also supported by the preliminary simulation developed within the CYGNUS collaboration down to 1-10 keV, that are also confirming the persistency of head-tail signature at this energies [58].

- *Goal of less than 1 count per year of data taking*. This goal will be guaranteed by the fiducialization and electron power rejection, combined with the minimisation of detector and environmental radioactivity through materials selection, passive shielding and possibly muon vetos, as discussed in Sec. 5.10.
- *The use of He*, to reach atmospheric operations and SI sensitivity at low WIMP masses, with only a modest increase of the total gas target density. As an example, a 1 atm He:CF_4 80:20 gas mixture is only a factor 1.7 more dense than 100 torr pure CF_4, a typical pressure for gas TPC DM detectors. This will result in nuclear He recoils in CYGNO long enough to be detected and discriminated from electron recoils at comparable lower energies (10 keV for 100 torr of pure CF_4 with CCD readouts see [57]).
- *Very favourable mass-to-sensitivity ratio in the 1-10 GeV WIMP mass region.* This is possible thanks to the use of low target nuclei as He, C and F, that provide very good kinematic matches to low mass WIMP, combined with the O(keV) energy threshold and high background rejection capabilities of our detector design (see Sec. 5.1).

Sec. 3 will illustrate all the results obtained with our prototypes, that support all the above claims for our experimental approach.

4.3 PHASE-2 features and prospects for direct Dark Matter searches

A 50 kg scale CYGNO detector will be able to give a significant contribution to direct DM searches in the low 1-10 GeV WIMP mass region for both SI and SD coupling and to possibly pave the way for a directional DM experiment at the ton-scale, distributed over several underground laboratories (see Sec.2.3). A development of a such larger scale detector (compared to any other directional experiment) in terms of intrinsic background minimisation and tracking performances, would of course require an improved scalable design in terms of active volume versus readout area and costs. The possible improvements include, but are not limited to, the following:

- development custom, fast sCMOS sensors, capable to image larger areas with similar performances to the current employed. With an in-house development, we believe we could also reduce the intrinsic material radioactivity, that from preliminary studies is very likely due to the camera packaging rather than the sCMOS sensors. With a faster sensor acquisition we could moreover sample the collected light and from this being able to determine the relative, ΔZ track measurement along the drift direction from the sCMOS camera alone (studies with the Engineering Department of UNIVAQ are already ongoing);

- improvements to the amplification stage (in terms of number of detected photon per primary electrons per cost per area), thanks to optimised gas mixture in terms of helium to fluorine ratio and/or improved MPGD approaches. These could include the use of less expensive and less radioactive GEMs from new emerging companies or alternative techniques, like for example μ-RWELL. The μ-RWELL have been operated with an increased gain and with a higher stability, but they would require a different light collection approach (on the side of the drift region) with a different rearranging of the detector active volume;

- improvements to the optical configuration, to possibly strongly reduce the costs. Due to the very low rate the probability to have multiple events in different area of the detector is very low. This implies that many areas of the GEMs active surface can be observed simultaneously by the same sensor by multiplexing the image with mirrors or collecting different area in on the same focus point with collimators. Study in collaboration whit INAF-Osservatorio Astronomico di Roma are ongoing to find the best solution;

- control the electron diffusion over longer drift paths (e. g. 1 m) by increasing the drift field and/or developing Negative Ion Drift [20, 59, 60] at atmospheric pressure. Negative Ion Drift (NID) is a peculiar TPC variation for which a small quantity of highly electronegative dopant is added to the gas mixture. In such configuration, the free primary electrons resulting from gas ionisation by a charged track would quickly attach at less than 100 μm distance to the electronegative molecules, transforming them into negative ion. The track image, transported to the amplification plane by these anions, would then suffer a much smaller diffusion thanks to the heavy anions thermalising with the other gas molecues, providing much crispier and defined track reconstruction;

- reduce the intrinsic detector material radioactivity, with the lesson learned after the results obtained with PHASE-1.

Given the recent fast developments in both MPGD and sCMOS sensor fields, we believe the availability of improved configurations of detectors and gas mixtures not to be unreasonable already by the end of PHASE-1 (2022-2023). Given this and all the lessons we will learn from the development and underground operation of a 1 m^3 detector, we consider feasible a CYGNO 30 m^3 to be operational in about 7-8 years from now (PHASE-2, 2025-2026).

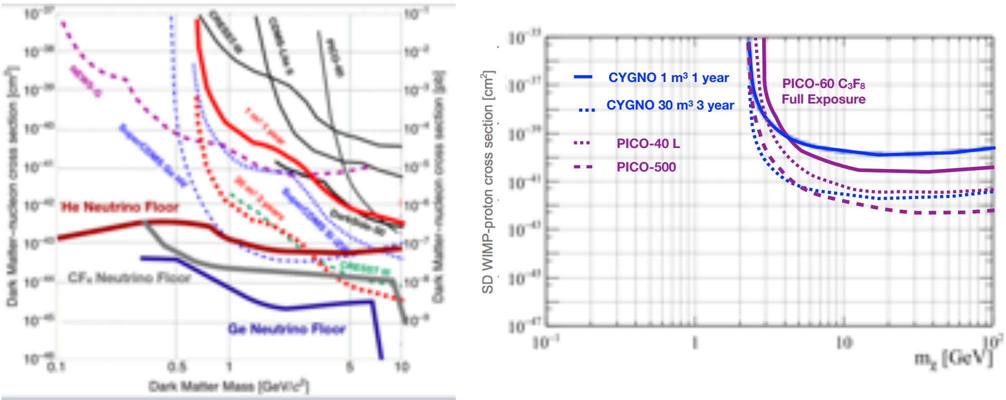

Figure 13: Preliminary expected PHASE-1 and PHASE-2 Spin Independent (left) and Spin Dependent (right) 90%C.L. exclusion limit for a 1 m^3 (30 m^3) 80:20 He:CF_4 at atmospheric pressure with 1 keV threshold in 1 (3) year livetime, compared to current best limits and expected sensitivities of future experiments, including CYGNUS-TPC.

4.4 CYGNO expected sensitivites and comparison to other experiments

We anticipate an expected SI (left) and SD (right) 90%C.L. exclusion limit for a PHASE-1 (PHASE-2 dashed line) 80:20 He:CF_4 at atmospheric pressure in one (three) year livetime with 1 keV threshold on He, 2 keV on C and 3 keV on F and zero background, as shown in Fig.13. In the SI plot, full black lines show current published experimental limits, while all the other reported curves represent the predicted expected sensitivity for the upgrade of each experiment. The following considerations can be drawn from Fig.13:

- All the shown experiments in the SI plot require cryogenics operations, leading to much larger infrastructures need and a much less straightforward scaling than a simple atmospheric pressure, room temperature gaseous TPC like CYGNO;
- All the current published experimental limits in the SI plot (with the exception of DarkSide) were produced with a demonstrators of O(100) g of the experimental technique and approach of each collaboration, while PHASE-1 aims at 1 kg operation;
- Comparison with SuperCDMS prospects: the SuperCDMS upgrade to reach such limits requires an improvement of a factor 10 in both phonon and charge resolutions, accompanied by a factor 10 reduction of the energy thresholds. The SuperCDMS HV (CDMS-lite) limit is obtained with a peculiar modification of the IZiP modules, that gives up electron recoil background rejection (i.e. charge signal) in order to reach lower energy thresholds. The shown upgrade limits are for 5 years of data-taking;
- Comparison with CRESST prospects: the CRESST upgrade requires a reduction of a factor 100 in the intrinsic crystal background contamination, to be obtained in the

development of 100 crystals (reached factor 10 on only one crystal for the moment). The shown upgrade limit is for 2 years of data-taking;

- Comparison with NEWS-G prospects: the shown limit is for a 100 kg day with 30 eV energy threshold and zero background. CYGNO-I limit is for 50 kg day of He, showing a similar mass to sensitivity ratio in the region 1-5 GeV. NEWS-G first result show the presence of a very large intrinsic radioactive background [11];

- The CYGNO-I project demonstrator has the capability to reach current sensitivity in both SI and SD direct WIMP search by 2023 (one year of data-taking).

- The CYGNO-30 expected sensitivity for 3 years of data-taking is comparable with the planned upgrade of current experimental approaches, that nonetheless still need to be fully proved, similarly to the possible scale of CYGNO-I;

- Among all the shown expected limits for SI coupling, CYGNO expects background rejection capabilities much more efficient than any other experimental approach;

- Among all the shown experimental approaches, CYGNO technique (if proved feasible with the expected performances) is and will be the only one able to continue DM searches beyond the Neutrino Floor for both SI and SD couplings.

CYGNO development fits and is part of the CYGNUS-TPC international effort, to identify the best technological and operational choices for a ton-scale directional Dark Matter detector.

5 CYGNO PHASE-1 Detector Design

The CYGNO PHASE-1 detector will comprise a $\simeq$ 1 m^3 gas vessel, with two back-to-back TPC separated by a central 1 m^2 aluminised mylar cathode following DRIFT example (Fig. 14). While the best standard will be employed to ensure the highest hermeticity possible and operation in sealed conditions, the vessel will not be designed to be vacuum tight, since we expect to operate at room temperature and atmospheric pressure. Two (100$\times$ 100 $\times$ 50) cm^3 field cages, made of plastic holders surrounding field wires, will guarantee the stability of a drift field towards the anode amplification plane up to 2 kV/cm. Wires materials and thickness are under study to evaluate the field uniformity and radioactivity budget, and are expected to be first tested in LIME in order to evaluate all the performances on a real prototype. Gas amplification at the anode plane will be provided by GEM foils [4] (possibly stacked with two 2 mm wide transfer field gaps). On the other side of the GEM foils, the vessel will be closed by large synthetic quartz windows, transparent to the light produced in the gas and collected by nine sCMOS cameras on each side. The cameras will be located at about 66 cm from the GEMs planes, that, assuming the same sensor we used for our prototypes (ORCA-Flash 4.0[5]) will imply an effective area of 165$\times$165 μm^2 imaged by each pixel.

The PMTs (or alternatively a collection of SiPM, under study in LIME) will be located on the same side of the sCMOS cameras, to detect the secondary light produced by the GEMs amplification, to reconstruct the time-shape of the avalanche signal. This fast signal will be used for triggering, to aid the head-tail identification and to determine the track extension along the drift direction of detected recoils (see Sec.3). The baseline solution includes six PMTs per side

The detector vessel will be equipped with all the necessary services, as gas and HV distribution systems, and a number auxiliary devices (pressure, temperature, humidity sensors) needed to monitor the quality of data taking and the stability of the apparatus (see section 5.4) . Moreover, removable ^{55}Fe and ^{252}Cf radioactive sources will be used to periodically calibrate the detector (see section 5.7).

Finally, the vessel volume will be surrounded by a neutron shielding systems made of removable tanks filled with purified water and muon veto system, composed by plastic scintillator slabs read by PMT.

5.1 GEMs foils

The 1 m^3 meter apparatus we propose is sub-divided in two symmetric sensitive volumes by a 1 m^2 central cathode. The two parts will, therefore, have a 50 cm depth and a 1 m^2 surface. The two 1 m^2 surfaces will be equipped with a 3 $\times$ 3 matrix of 33 $\times$ 33 cm^2

[4] Currently, CERN-produced GEM with 70 μm diameter holes at a 140 μm pitch are used in the prototypes, but alternative versions with different dimensions are expected to be tested for the finalisation of PHASE-1 design

[5]http://www.hamamatsu.com/jp/en/C13440-20CU.html

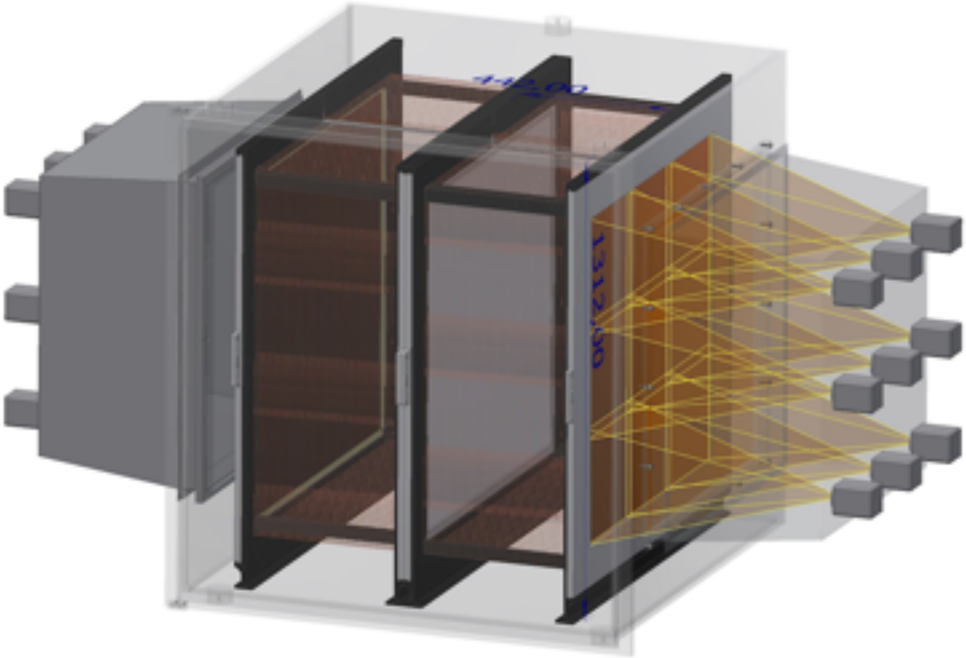

Figure 14: CYGNO PHASE-1 schematic design (shielding and veto not shown). The drift region is designed to have a 1 m^3 volume.

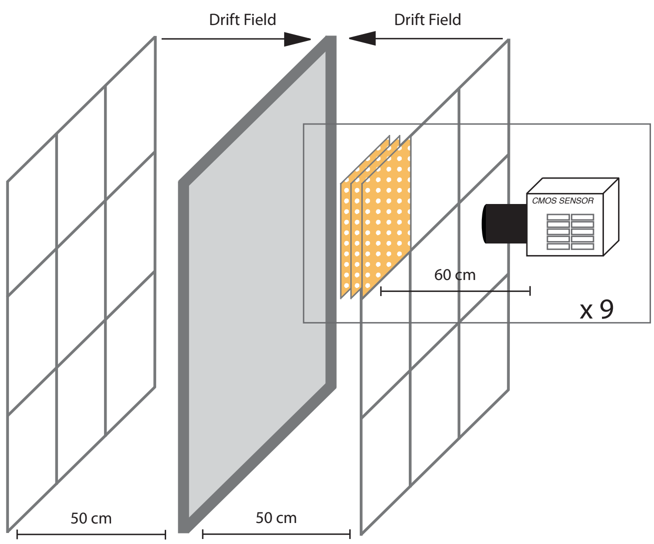

Figure 15: Sketch of the cubic meter module.

Triple-GEM structures, for a total of 18 Triple-GEM.

5.2 sCMOS Camera

An Hamamatsu Orca Flash 4.0 camera[6], based on a CMOS sensor, has been used so far in all our prototypes as image acquisition. The sensor (2048×2048 pixels) provides a noise

[6]For more details visit http://www.hamamatsu.com

level of less than 2 electrons per pixel together with a quantum efficiency of about 70% at 600 nm. The sCMOS response was studied with a calibrated light source ([37]) and resulted to be 0.9 counts per photon. While new and improved version of such camera can be envisaged to be available for purchase at the time of CYGNO PHASE-1 construction, we assume for the moment to employ this version. The baseline proposal is to provide a camera for each Triple-GEM structure. Each camera will be equipped with a Schneider lens[7] providing an aperture $a = 0.95$ with a focal length of 25 mm.

5.3 PMTs and SiPM

Various light detectors (PMT and SiPM) will be tested to optimise light detection and timing performance. In particular, the PMT used so far has a low quantum efficiency in the band where the CF_4 is producing more light. The idea is to equip each Triple-GEM structure with one (or more in case of SiPM) detectors and to record their signal waveforms.

5.4 Trigger and DAQ

The main challenges for trigger and DAQ are the impossibility of building a first level trigger, in a proper sense, using the photo camera, and the synchronous acquisition of digital images from the photo cameras and analogue signals from other devices like PMTs or GEM foils.

Photo camera sensors require to be triggered well in advance (from tens of microseconds to several milliseconds, depending on the operation mode) with respect to the arrival of the light signal. It makes impossible to trigger the camera from the prompt signals coming from PMTs or GEM foils. Instead, the camera needs to be operated in continuous acquisition. On the other hand, cameras require a minimal exposure of a few ms and digital processing of the image is required afterward to determine if the event can be of any interest. Hence, a camera-based first-level trigger would introduce a very long latency which would make very difficult the acquisition of the prompt and fast signals of PMTs and GEM foils. The only viable alternative is a trigger and DAQ scheme where the camera continuously acquire images, the analogue signals are acquired with a trigger logic based on discriminators and coincidences (including the requirement that all camera pixels are exposed when the analogue signals arrive), and data are then combined and analysed by a processing unit (an FPGA, CPU or GPU) to associate the analogue signals to the corresponding image and to determine if data should to be stored.

For test purposes, a trigger and DAQ scheme of this kind has been already implemented with the use of VME electronics for the handling of the analogue signals and the implementation of the trigger logic, and a PC for the photo camera acquisition and data processing. On the other hand, such an implementation is not economically scalable to

[7] For more details visit https://www.edmundoptics.com

a system with many cameras, PMTs and GEMs. Commercial alternatives based on the PXI platform have been investigated and the cost per detector module (1 analogue signal + 1 photo camera) would exceed a few k€ even accepting performances (in terms of analogue signal processing and computing power) which would be barely sufficient, and would reach 15 k€ per module in a high-end configuration.

In order to overcome such difficulties, we plan to develop a custom acquisition board which will combine in a single device analogue signal processing, image acquisition based on the CameraLink protocol and data processing with an on-board FPGA. The development on a VME standard or as a standalone board is under discussion. Each board could host 4 to 8 module readout, with analogue signals digitised at a sampling speed of at least 1 GS/s, and one to three FPGAs for logic implementation, data management and communication handling. Six month FTE work and about 20 k€ are expected for the design and prototyping of the board, with the goal of having a couple of fully operational boards available by the end of 2019. The final expected cost per module would not exceed 2 k€, and it would be driven by the required performances of the digitizer (sampling speed) and the FPGAs (available computing resources).

Slow control systems and environmental monitoring are also crucial for a stable operation of the detector. In particular, the gas system requires active control and/or readout of several devices (flow meters, valves, sensors, etc.) which can be implemented using PLCs or microcontroller-based devices. The high voltage control and the readout of other sensors can be implemented with dedicated hardware and software. It will be important anyway to integrate everything into a single slow control environment. It could be performed within the MIDAS framework, either using or not its native bus system (MSCB). MIDAS would also allow integration with the data acquisition into a unique system.

5.5 HV distribution system

The GEM has been so far operated either with a custom distribution system (HV-GEM) or with a commercial HV. GEM bias and transfer field within GEMs must be controlled carefully and an accurate current reading with nA resolution is required to monitor their stability. Moreover, an interlock system to power off the HV in case of GEMs discharge is needed. Given the low rate, relatively large resistors can be used to protect the GEMs from growing large currents. The field cage field needs to be provided with a HV resistive divider over several tens of cm. This calls for an adequate design of the number of resistors and for an applied total voltage up to 60-100 kV between the cathode and the first GEM. Moreover a solution for the the HV feed-thru being installed in the vessel must be found to provide very good stability in presence of a relatively large amount of He (avoid field cage or cathode sparking).

5.6 Gas system

As mentioned in Sec.5, the baseline detector will be operated with a He:CF_4 mixture at atmospheric pressure, possibly with a minority content (few percent in volume) of SF_6. A continuous gas flow will be provided through the chamber using mass flow controllers to mix pure gases in the desired proportions and to regulate the total flow. This will allow to keep a constant, very small overpressure inside the vessel with respect to the external atmosphere, in order to avoid air from entering the active volume even in presence of small leakages. Moreover, this will allow to remove contaminants due to outgassing from the detector materials. In order to reduce the operating costs, most of the gas mixture will be *recirculated* inside the detector after having been purified from oxygen, moisture, organic compounds and other contaminants in dedicated filters. A few complete changes of the gas volume contained in the detector are envisaged per day, with only a few volumes of fresh gas per week to be externally supplied.

Beside the gas purity required for a good operation of the detector, *Radon removal* is also crucial in order to reach the desired radiopurity when large gas volumes are considered. It has been recently demonstrated [54] that Radon can be removed from SF_6 by means of molecular sieves. Tests with a He:CF_4 mixture will be then performed.

From the technical point of view, a proper handling of greenhouse gases like CF_4 and SF_6 has to be also adopted. Although the adoption of a recirculation system is strongly reducing the amount of released gas to atmosphere, it will be still necessary to store and recycle it according to the current regulations. A commercial or custom gas recovery system will be installed and strategies to separate the different components *in situ* or at external companies are being studied.

5.7 Calibration systems

Detector calibrations are of paramount importance in order to define the energy scale, to control the data quality and the detector stability and performances. For these reasons, we are going to use

- Internal radioactive sources. The deployment of internal γ and α sources is critical, in order to have a constant monitoring of the detector. In order to check the energy scale of the detector we plan to use ^{55}Fe to have a low energy (5.9 keV) calibration point, ^{241}Am to have a 60 keV γ and a 4 MeV α. Additionally, a AmBe or a ^{252}Cf source might be useful to measure neutron induced nuclear recoils. A shutter system and/or a system to move the source in and out of the active volume will be installed to perform calibration runs few times a day. The overall activity, the number and the position of the sources will be tuned to have a good coverage of the target volume, to be compatible with the camera exposure time and not to be harmful for the other experiments. The γ lines will provide the energy scale and resolution (including the relative GEM gain), and a monitoring of the gas properties

(diffusion versus the z scale)

- In order to have a constant monitoring of the camera efficiency and to adjust the focus of the optical system, a few pulsed LED will be installed close to the camera and in the gas volume;
- ^{14}C residual radioactivity: depending on the actual isotope purity of the CF_4 the beta decay of the residual ^{14}C nuclei could provide a two-prong event with a beta and a nitrogen nucleus recoiling in coincidence.
- The muon veto system, composed of slab of scintillators readout by PMTs, will work effectively also as a cosmic ray tracking system. This would in fact provide a calibration of the drift velocity - possible even in presence of a very low rate given the long path length of the cosmic ray in the gas volume (several ionization cluster in the gas volume). Given the reduce specific ionization of a m.i.p. cosmic ray, this can be used to monitor the single ionization cluster formation, drift and detection.

To perform calibration activity during the prototyping phase we plan to access beam facilities as FNG at ENEA, Frascati and the Li+p LNS beam line. This is especially needed to study the energy-angle correlation in the neutron elastic scattering over the gas nuclei. Besides providing a test of our ability to *3D reconstruct nuclear recoils*, this will provide an opportunity to measure the *quenching factor* accurately as a function of the recoiling energy.

5.8 Detector Simulation

A common problem to all the DM experiment is the simulation of very low energy nuclear recoils (down to few keV). In this range the standard high energy physics simulation tools (as Geant4) are not completely validated. This is why it is especially important to compare simulation with the quenching factor measurements. For this purpose, the SRIM package is usually employed in the gas TPC community. This validation in fact would call for a larger effort. Nevertheless Geant4 ensures an easy framework to model the materials and the geometry of a large equipment. It will be then used to create the CYGNO detector model and to simulate the electromagnetic interaction due to the gamma background.

Simulation studies of the ionization and scintillation process in the gas (attachment, recombination, diffusion, drift, GEM amplification process) will come from the international CYGNUS collaborative network.

An evaluation of the CYGNO performance in the term of DM sensitivity and the ultimate CYGNUS performance with a He:CF_4 mixture will be also given.

5.9 Data Reconstruction and Analysis

While, conceptually, the analysis of high density images is simple and supported by a large amount of algorithms, the application to the identification of rare events with low signal to noise ratio is not so obvious. This requires deep understanding of the readout system and large computational resources and is fundamental in the design of the DAQ system, evaluate the energy threshold and the ability to identify directionality of dark matters candidates recoil.

The main goals will be to:

- define particle identification algorithms on calibration data and compare with simulation;
- define track shape (head-tail) evaluators and track direction;
- employ Machine Learning technique as neural networks for pattern recognition;

For data Storage and Analysis Infrastructure, CYGNO would like to exploit the INFN Corporative Cloud (INFN-CC) facility as back-end data storage and front-end analysis recurses for our national and international community. The idea is to provide over the INFN-CC Infrastructure As A Service (IaaS) the resources need to study and develop all the software services useful for the data analysis. When services will be clearly defined and tested, software will be provided as a Software Services (SAAS) ready for data analysis.

Data collected and selected by the DAQ will be pushed on the INFN-CC for long term storage, backup and analysis. As done during the R&D the software will be develop mainly in Python and ROOT exploiting the pyROOT faculties.

Thanks to Ricardo Gargana (INFN-LNF), Stefano Stalio (INFN-LNGS) and Giacinto Donvito (INFN-Bari), studies and first tests on the INFN-CC infrastructure have already started.

5.10 Radiation budget

This section is dedicated to the discussion of the expected background contributions from environmental and detector components radioactivity. Ultra-high purity stainless steel and titanium vessels with radio-nuclei impurities <100 ppt have been developed in recent years for rare events searches (and are considered in the context of CYGNUS). Nonetheless, DRIFT demonstrated that 0.81 ppb U and 0.51 ppb Th contamination can be dealt with at the 1 m^3 scale and a 6 mm Acrylic internal HV shielding[22]. The optical readout windows can be made of synthetic quartz, with very low intrinsic radioactivity. Therefore, we do not anticipate these to constitute important contributions to CYGNO backgrounds. The cathode will be made of semi-transparent aluminized mylar foils conveniently shaped to suppress RPRs, as pioneered by DRIFT[19]. Once fiducialization is employed, we believe to be able to identify all the Radon Progeny Recoils (RPRs) background coming from this material and hence to reject them. From DRIFT experience, we predict the internal acrylic shielding, together with an Acrylic/Cu field cage, to contribute for a total of about 1×10^{-6} neutron recoils/year and 1×10^{2} electron recoils/year. From preliminary simulations within the CYGNUS collaboration, we evaluated the larger background contribution to come from the 1.2 x 1.2 m^2 GEMs, with a rate of about 3.7×10^4 gamma/year between 1-100 keV and 2.6 x 10^3 gamma/year between 1-10 keV, plus about 0.04 neutron recoils/year for triple thin GEMs and a lower rate for configurations involving thick GEMs. DRIFT demonstrated with MWPC 1.98×10^5 gamma rejection at 20 keV[22] and [57] similar capabilities with 2D CCD readout and 100 Torr of CF_4 at 10 keV. Preliminary CYGNUS simulations indicate that 3D reconstruction or even only head-tail track determination can further improve particle rejection. The contribution of the sCMOS cameras and PMTs to the total induced background will highly depend on the detector design and the final shielding scheme employed. We are currently already performing a preliminary measurement of the sCMOS intrinsic radioactivity levels, thanks to the LNGS services facilities. This will give us indication on how to deal with this issue. Additional measurements of GEMs, cathode, optical windows and PMTs radioactivity are foreseen before the end of the year.

Given the environmental activity in the LNGS experimental Halls (about 1×10^{-6} cm^{-2} s^{-1} flux, see Tab. 2), a 50 cm polyethylene (or water) shielding around the vessel can suppress any neutron background coming from the surrounding rocks and concrete. In addition, a muon veto with 1 cm thick plastic scintillators on top and the lateral side of the detector can reduce the cosmogenic muon-induced nuclear recoil rate down to about 9×10^{-8} Hz.

Together with our colleagues from DRIFT and Sheffield University, we are developing a preliminary simulation of the expected backgrounds, including their spectrum, starting from the preliminary CYGNO design and material radioactivity measurements from literature. In the next year, we will improve this with the radioactivity measurements we will perform at LNGS and a more detailed detector design.

6 Tasks and financial requests time profile estimation

WORK PACKAGE	ITEM	Task 2018 (CNS5)	assignm. 2018 (k€)	Tasks 2019 (CNS2)	Request 2019 (k€)	Tasks 2020 (CNS2)	Request 2020 (k€)	Tasks 2021 (CNS2)	Request 2021 (k€)	Tasks 2022 (CNS2)	Request 2022 (k€)
		LIME Design & Construction		LIME Test and TDR		CYGNO Construction		CYGNO Construction & run overground		CYGNO Commissioning and preliminary Data Taking	
DETECTOR	Design	LIME		CYGNO		Shielding & Veto					
	Vessel	procurement & assembly	2	material test & radioactivity measurement	2	procurement, assembly & qualification	30	overground test		installation & commissioning	
	Cathode, Field Cage, Feedthrough	procurement	2	material test & radioactivity measurement	2	procurement, assembly & qualification	10	overground test		installation & commissioning	
	GEM	procurement & assembly	10	mechanical test & radioactivity measurement	3	procurement, assembly & qualification	60	overground test		installation & commissioning	
	Windows	procurement & assembly	2	test & radioactivity measurement	1	procurement, assembly & qualification	10	overground test		installation & commissioning	
	Optics			design & test	1						
	Lens							procurement, assembly & qualification	36	installation & commissioning	
	CMOS sensors			camera tests, OEM scouting				procurement, assembly & qualification	140	installation & commissioning	
	PMT & SiPM			performance & low radioactivity test	5			procurement, assembly & qualification	20	installation & commissioning	
	Veto System							procurement and test	10	installation & commissioning	
	Shielding									procurement & installation	10
SERVICES	HV GEM System			procurement of HV crate + 1 HV GEM board	14	full system procurement & test	35	overground test		installation & commissioning	
	HV Field Cage Power Supply			procurement and test	5			overground test		installation & commissioning	
	GAS System			procurement of recirculating filtering system prototype	20	full system procurement & test	60	overground test		installation & commissioning	
	DAQ System			DAQ-custom board prototype	10	preliminary test		procurement, qualification & overground test	50	installation & commissioning	
	Data storage/ backup and Analysis infrastructure	setup of INFN-CC infrastructure		open access to the international community		test of scalability & integration with DAQ		overground test		installation & commissioning	
PHYSICS	LIME & CYGNO Simulation	evaluation of LIME & CYGNO expected sensitivity		fast simulation		full simulation		evaluation of systematics		comparison with first data	
	Background simulation, including natural radioactivity from detector materials	evaluation of CYGNO background radioactivity based on literature measurements		LIME comparison of background simulation with data		integration in the full detector simulation					
	Neutron Simulation & measurements	evaluation of LIME & CYGNO expected sensitivity		fast simulation of expected neutron flux at LNGS/LIME data comparison with simulation		full simulation of expected neutron flux at LNGS		LIME data analysis development for fast and thermal neutron flux		CYGNO data analysis development for fast and thermal neutron flux	
	Data Analysis and pattern recognition	development on prototypes data on ORANGE and LEMON data		fast implementation of algorithms on LIME data		validation algorithms on LIME data		test algorithms on CYGNO overground data		CYGNO data analysis	
	Detector calibration with sources			study of available sources and safety issues		procurement	10	installation & test			
	Test beam & quenching factor measurements	study and development of tools for precise test beam measurements		LIME Test beam at neutron/ion sources & detector performance measurements		LIME underground run					
	Large scale Detector sensitivity	evaluation of CYGNO 30m^3 and 1000m^3 sensitivity		future gas mixture, axions, coherent neutrino, light DM, etc				fast simulation of CYGNO 30m^3		full simulation of CYGNO 30m^3 and 1000^3 sensitivity	
Consumable (k€)			1		5		5		5		5
Gas bottle (k€)		procurement	3		8		4		8		8
Travels (k€)			9		13		13		15		50
Shipping (k€)			0		0		0		0		10
Total/year (k€)			29		89		237		284		83
Total (k€)		CYGNUS-RD (CNS5)	29	TDR (CNS2)	89					CYGNO Project (CNS2)	604

Figure 16: Budget and time scale

Table 3: WP and tasks. Servizio Meccanica DR-LNF, SPCM-LNF , SEA-LNF serviceswill be involved in detector and services Working groups.

Work Package (coordinator)	tasks in 2019	tasks (2020-2022)	Task coordinator
Detector	Mechanical design	CYGNO design	S. Tomassini
(G. Mazzitelli)	Material test		S. Tomassini
	Radioactivity measurements		N. Spooner, B. Baracchini
	LIME construction	CYGNO construction	G. Mazzitelli
	LIME overground run	CYGNO installation, commissioning & run	G. Mazzitelli
	GEM mechanical test	GEM installation & commissioning	L. Benussi
	GEM quality assurance	GEM quality assurance	D. Piccolo
	Fast light sensor selection (PMT/SiPM)	procurement and qualification	M. Marafini
	Camera Test and OEM scouting	Camera procurement	D. Pinci
Services	HV GEM system test	HV system installation & commissioning	D. Pinci
(D. Pinci)	HV Field Cage system test	HV system installation & commissioning	D. Pinci
	GAS system prototype & test	GAS system installation & commissioning	F. Renga
	GAS purification test	GAS purification installation & commissioning	K. Miuchi
	DAQ custom board prototype	DAQ installation & commissioning	A. Messina
	Data stream infrastructure test	Data stream installation & commissioning	G. Mazzitelli
Physics	LIME & CYGNO Simulation	Full detector simulation	E. Baracchini
(E. Baracchini)	Background radioactivity simulation	Integration in full detector simulation	N. Spooner
	Neutron Simulation & measurements	Data collection, qualification and analysis	R. Bedogni
	Data Analysis & pattern recognition	3D reconstruction, particle ID	E. Di Marco
	Calibration with sources	Test & installation	G. Cavoto
	Test beam & quenching factor	Test beam & quenching factor	G. Cavoto
	Large scale sensitivity	Simulation of detector response	S. Vahsen
	Future detector GAS mixture studies		D. Loomba
	Light DM sensitivity		N. Phan
	axions, coherent ν scattering, ecc. evaluation		E. Baracchini

6.1 Personnel

Table 4: People involved in project (*15 people 5.1 FTE in total*)

Name.	Institution	Role	FTE
INFN - LNGS (0.8 FTE)			
E. Baracchini	GSSI	Assistant Prof.	80%
INFN - Roma1 (1.9 FTE)			
G. Cavoto	Sapienza Univ	Assoc. Prof.	30%
E. Di Marco	INFN	Researcher	20%
M. Marafini	Centro Fermi	Researcher	20%
A. Messina	Sapienza Univ	Researcher	30%
D. Pinci	INFN	Researcher	50%
F. Renga	INFN	Researcher	40%
INFN - LNF (2.4 FTE)			
R. Bedogni	INFN	Researcher	20%
E. Benussi	INFN	Researcher	10%
S. Bianco	INFN	Senior Researcher	20%
G. Maccarrone	INFN	Senior Researcher	30%
G. Mazzitelli	INFN	Senior Researcher	100%
D. Piccolo	INFN	Senior Researcher	20%
S. Tomassini	INFN	Engineer	20%
E. Dané	INFN	Engineer	20%

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