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The CYGNUS Galactic Directional Recoil Observatory

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Dark Matter (DM) is nowadays an established, yet still mysterious paradigm: unraveling its nature represents one of the most challenging tasks for fundamental physics today. Direct Dark Matter searches aim at experimentally detect low energy nuclear (or electron) recoils induced by the elastic scattering of Weakly Interactive Massive Particles (WIMPs). In this context, the goal of the CYGNUS Galactic Directional Recoil Observatory is to develop a multi-target ton-scale network of detectors based on gaseous Time Projection Chamber technology, in order to be sensitive not only to the energy deposited by the WIMP scattering but also to the incoming WIMP direction. This information can in fact provide a correlation with an astrophysical source that no background can mimic, hence representing the key for a positive identification of a DM signal.

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1. Introduction

A wide range of astrophysical measurements indicates that about 80% of the Universe gravitating mass is non-luminous and non-absorbing, and its nature and distribution are mostly unknown [1]. All together these observations argue for the existence of at least one quasi-stable Dark Matter (DM) particle, not predicted by the Standard Model of particle physics. Most of direct DM search experiment have been focusing on the possibility to detect Weakly Interactive Massive Particles (WIMPs). The expected signal in the detector is a low energy 1-100 keV nuclear recoil, that needs to be discriminated from interactions induced by ordinary matter with rate typically 10^7-10^8 higher. Current experimental approaches have reached a level of sensitivity for which classical background minimisation (such as underground location, use of radiopure components and shieldings) are not sufficient anymore and powerful background discrimination is needed to reject the remaining backgrounds.

In this panorama, the latest years have seen several experiments reporting observed excesses of unexpected low-energy events difficult to reconcile with the DM hypothesis, both in the nuclear recoil (NR) [2] and electron recoil (ER) [3] channels. This scenario is complemented by the long-standing and still unexplained claim of an annual modulation of NR reported by the DAMA/LIBRA experiment [4]. The present situation is bound to become further convoluted by the Xe-based experiments [5, 6] reaching in the near future the sensitivity to detect solar, atmospheric and diffuse supernovae neutrinos, that will produce NRs hard to distinguish from a DM signal from the energy release point of view. While this phenomenon, previously regarded as an hard limitation to DM searches and hence defined Neutrino Floor [7], is nowadays considered a soft limit (Neutrino Fog) [8], it still holds true that the exposure required for an experiment to surpass this limit could be prohibiting from both the cost and dimensions point of view.

All these considerations advocate for the development of an experimental technique capable to offer a positive and incontestable proof of a DM signal, even in presence of (unknown) backgrounds. This is the goal of the CYGNUS Galactic Directional Recoil Observatory, that will be illustrated in the following.

2. The CYGNUS Galactic Directional Recoil Observatory Project

The measurements of the rotation curve of our Galaxy suggest the presence of high concentrations of DM at the galactic radius of the Sun, although its exact distribution remains still highly unconstrained. The relative velocity between the Solar system motion around the Galactic center and the DM halo distribution implies an apparent WIMP wind for an observer on the Earth, originating from the constellation Cygnus, with an average direction changing of $\simeq 90^o$ for every 12 sidereal hours. Directional DM searches experiments aim at detecting such correlation with an astrophysical source in order to unambiguously and positively establish a DM signal. In the context of the Neutrino Fog, it has been shown [9] that an angular resolution better than 30% with corrected head-tail determination 75% of the time, together with a fractional energy resolution of at least 20%, is required in order to be able to distinguish events induced by neutrinos from a DM signal. In addition, these features need to be achieved below 10 keV$_{nr}$ at the level of individual events and with a timing resolution of few hours. All these requirements imply the development of an experimental technique capable to perform event-by-event recoil imaging. Among all the existing directional searches approaches, the gaseous Time Projection Chambers are the only ones that have demonstrated performances in the ballpark of these prerequisite.

The CYGNUS project sets into this context, with the goal of capitalising on the recent R&D progresses and experimental breakthroughs of TPCs developed for directional DM searches towards the development of a ton-scale multi-site (including the Southern Hemisphere), multi-target Galactic Nuclear and Electron Recoil Observatory to probe Dark Matter inside the Neutrino Fog and measure solar Neutrinos with directionality. CYGNUS key features are the use of an Helium-Fluorine gas mixture at 1 atm with directional threshold and full background rejection at O(keV), in order to extend sensitivity to both Spin Independent (SI) and Spin Dependent (SD) coupling at O(GeV) WIMP masses. In order to achieve these performances at the large volumes needed, CYGNUS is working on the development of gas mixtures that can offer reduced diffusion, via either *cold* gases (such as CF_4) or Negative Ion Drift (NID) [10]. NID is a peculiar modification of TPCs operation obtained by the addition of an highly electronegative dopant to the gas mixture, that captures the primary ionising electrons and act as image carriers to the amplification plane. Thanks to the large anions masses, their diffusion during drift is reduced to the thermal limit, allowing for longer drift distances, combined with improved tracking. Within these gas mixtures choices, CYGNUS aims at achieving full 3D fiducialization, including the drift direction by either coupling *cold* electron drift gases to high granularity readout and fitting for the diffusion [11] or by exploiting the presence of minority charge carriers in the context of NID operations [12]

The CYGNUS proto-collaboration has recently produced an extensive concept paper on a 1000 m^3 gaseous NID TPC detector focused on technical feasibility and WIMP searches through NRs [13]. In this Whitepaper a detailed simulation of seven readout options with negative ion drift in He:SF_6 755:5 Torr at 1 atm is carried out, to compare planar, wires, pads, strips and pixels charge readout and 2D optical readout in terms of a cost benefit figure of merit. For each of these simulated options, the energy resolution, the angular resolution and the head/tail recognition is studied and from these the mean number of WIMP-induced Helium and Fluorine NRs to reject isotropy (i.e. to establish the galactic origin of a DM signal) or to reject the neutrino hypothesis (i.e. to breach the Neutrino Fog) is evaluated as a function of the energy threshold. A cost-benefit figure of merit is produced from such performances, by comparing estimated detector costs at equal directional sensitivity. The conclusions of this study show that, while pixels readout are able to extract the entire directional information that is left after diffusion NID during drift, the strips are capable to perform almost at pixels but with a significant reduction of costs of nearly a factor 4.

Electron background rejection is also analysed in [13], since it effectively determine the energy threshold if zero background operations are pursued. The results of this study show that about 10^3 rejection can be achieved at 5 keV$_{nr}$, exponentially rising to above 10^6 at 10 keV$_{nr}$. These results can be significantly improved by the use of Machine Learning

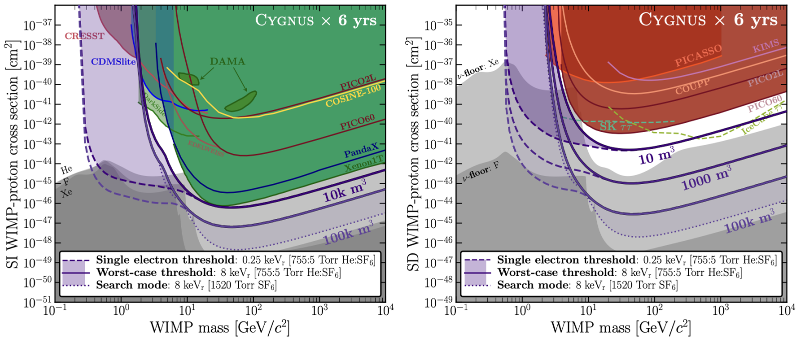


Figure 1: Constraints on the spin-independent WIMP-nucleon (left) and spin-dependent WIMP-proton (right) cross sections. In purple solid and dashed lines are the projected 90% CL exclusion limits for operating six years with 10 m^3 up to 100,000 m^3 of He:SF6 gas at 755:5 Torr. The reader is referred to [13] for additional details

algorithms, as will be illustrated in Sec.3.

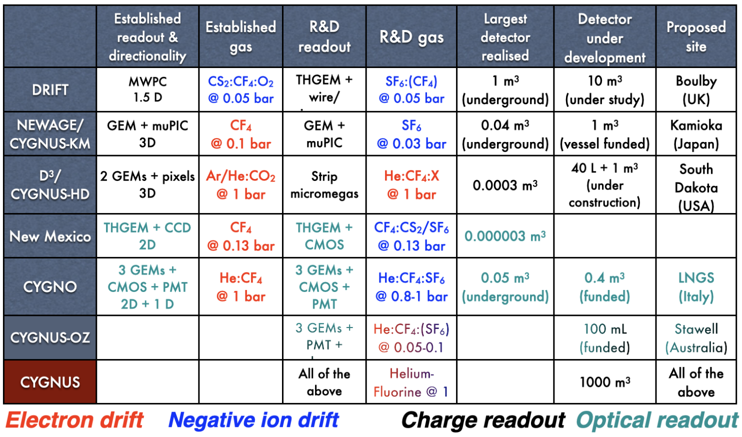
These simulated performances evaluations are accompanied in [13] with an engineering study for the realisation of a 1000 m^3 detector and with a detailed simulation of all internal and external backgrounds emerging from such design. The design optimisation goal is to limit the overall rate from internal and external backgrounds in order to achieve zero ER background with rejection capabilities discussed above and limit nuclear recoils from neutrons to less than a sixth of the solar neutrino signal. The most challenging aspect results in the readout and amplifications internal contributions, that, while not representing an immediate showstopper, will require further R&D to establish the optimum choice for CYGNUS from a background standpoint.

The expected sensitivity emerging from this study for a 1000 m^3 CYGNUS detector operated for 6 years is shown in Figure 1 for two possible thresholds, ranging from the worst-case scenario of electron-background-free operation at 8 keV$_{nr}$ to a very best-case minimum energy threshold corresponding to a single electron, 0.25 keV$_{nr}$.

3. Gaseous TPCs project within CYGNUS

Figure 2 summarises the main characteristics of all the existing gaseous directional DM TPCs projects working towards the development of CYGNUS, together with the proposed CYGNUS experiment features. Given the space constraints, here we report only some of the most recent highlights from R&Ds of such projects in the context of CYGNUS.

Operation with SF$_6$ With an innovative hybrid THGEM-Micromegas structure (where two sets of meshes are embedded inside a GEM) the DRIFT team demonstrated the possibility of achieving a gas gain larger than 6 $\times 10^4$ at 5.9 keV within a NID CF$_4$:SF$_6$ 39.0:1.8 gas mixture [18], the larger gain ever measured with SF$_6$ and comparable to CF$_4$. The NEWAGE collaboration demonstrated for the first time full 3D tracking of alpha particles with the detection of absolute z coordinate through NID minority carriers in pure SF$_6$ at 20 Torr with GEMs amplification and μPIC readout with a spatial resolution of 130 μm [15].



	Established readout & directionality	Established gas	R&D readout	R&D gas	Largest detector realised	Detector under development	Proposed site
DRIFT	MWPC 1.5 D	CS_2:CF_4:O_2 @ 0.05 bar	THGEM + wire/	SF_6:(CF_4) @ 0.05 bar	1 m^3 (underground)	10 m^3 (under study)	Boulby (UK)
NEWAGE/ CYGNUS-KM	GEM + muPIC 3D	CF_4 @ 0.1 bar	GEM + muPIC	SF_6 @ 0.03 bar	0.04 m^3 (underground)	1 m^3 (vessel funded)	Kamioka (Japan)
D^3/ CYGNUS-HD	2 GEMs + pixels 3D	Ar/He:CO_2 @ 1 bar	Strip micromegas	He:CF_4:X @ 1 bar	0.0003 m^3	40 L + 1 m^3 (under construction)	South Dakota (USA)
New Mexico	THGEM + CCD 2D	CF_4 @ 0.13 bar	THGEM + CMOS	CF_4:CS_2/SF_6 @ 0.13 bar	0.000003 m^3		
CYGNO	3 GEMs + CMOS + PMT 2D + 1 D	He:CF_4 @ 1 bar	3 GEMs + CMOS + PMT	He:CF_4:SF_6 @ 0.8-1 bar	0.05 m^3 (underground)	0.4 m^3 (funded)	LNGS (Italy)
CYGNUS-OZ			3 GEMs + PMT +	He:CF_4:(SF_6) @ 0.05-0.1		100 mL (funded)	Stawell (Australia)
CYGNUS			All of the above	Helium- Fluorine @ 1		1000 m^3	All of the above

Electron drift *Negative ion drift* *Charge readout* *Optical readout*

Figure 2: Summary of the main characteristics of all the existing gaseous directional DM TPCs working towards the development of CYGNUS, together with the proposed CYGNUS experiment features.

The CYGNO/INITIUM collaboration demonstrated for the first time NID operation with an ^{241}Am source at LNGS atmospheric pressure (900 mbar) with He:CF_4:SF_6 59.2/39.2/1.6 and an optical readout composed by a PMT and an Hamamatsu Orca Fusion camera, obtaining results consistent with already published data with same mixture and charge pixel readout [16]. The undergoing diffusion measurements appears very promising. The New Mexico team measured thermal diffusion in NID operation with CF_4:SF_6 between 20 and 50 Torr with an optical TPC readout by a CCD camera [17].

Large Detectors Realisations and Projects The NEWAGE team has manufactured a 1 m^2 vacuum vessel able to host of 18 modules of 30 × 30 cm^2 readout area and 50 cm drift length each, towards the development of CYGNUS-KM. A single module is under commissioning at Kobe University in pure SF_6, with the goal of detecting SF_6^- NID, together with SF_5^- minority carriers. After this commissioning, the structure will be moved to underground Kamioka Mine. The CYGNO/INITIUM collaboration has commissioned during the summer the 50 L active volume LIME prototype (33 × 33 cm^2 readout area for 50 cm drift length, readout out by one sCMOS and 4 PMTs) at underground Laboratori Nazionali del Gran Sasso and the prototype is currently taking data. LIME represent the base module for the 0.4 m^3 detector CYGNO-04, whose Technical Design Report has been submitted to funding agency and LNGS Administration. The D^3 team has designed a 33 × 33 cm^2 readout area for 50 cm drift length detector to be readout with Micromegas strips and CERN SRS system, and this is currently under construction, with the goal to evaluate components for a follow-on 1 m^3 detector for CYGNUS-HD.

Simulation and Analyses The NEWAGE team developed the first simulation of gas gain for NID in pure SF_6 at 100 Torr with a GEM amplification plane with Garfield++ and Magboltz and was able to reproduce experimental data within a factor 2 difference [19]. The D^3 team studied the possibility of improving ER background rejection by exploiting track shape variables [20] and combining them with a Machine Learning approach [21], obtaining an improvement of nearly 3 orders of magnitude with respect to the use of track length versus track energy.

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