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Directional dark matter searches

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Abstract

The importance of directly detect and experimentally probe the nature of Dark Matter (DM) is universally and incontrovertibly recognised as one of the most compelling tasks of today's fundamental physics. Directional DM searches aim at developing experimental techniques that can give access to the measurement of the incoming direction of the DM particle. This can provide a correlation with an astrophysical source that no background whatsoever can mimic and offers an unique key for a positive, unambiguous identification of a DM signal.

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Contents

1 Setting the stage

The presence of DM in the Universe is nowadays an established, yet still mysterious, paradigm: deciphering its essence is one of the most compelling tasks for fundamental physics today [1]. While in the last 20 years the scientific community focused mainly on the search for Weakly Interacting Massive Particles (WIMPs) in the 1 GeV/c^2 to 1 TeV/c^2 range, the present lack of DM evidences from indirect, direct and collider searches [2] has renewed the attention to low WIMP masses below the GeV limit, leading to new approaches looking also for DM scattering off bound electrons.

In this panorama, the latest years have seen several experiments reporting a significant number of observed excesses of unexpected low-energy events. This anomalies pertain very different experimental approaches and both nuclear recoil (NR) and electron recoil (ER) signatures, such as Xenon1T [3], DAMIC [4], SuperCDMS [7], CRESST-III [5], and EDELWEISS [6] among the many. These deviations from expectation are been actively tackled down by the various collaborations, in some cases by demonstrating the disappearance of the excess in larger detector with reduced backgrounds [8], and in others by joining forces and sharing the knowledge about the individual observations [9]. This present scenario is complemented by the long-standing claim of the detection of an annual NR yield modulation compatible with the WIMP hypothesis by the DAMA/LIBRA experiment [10], and the observed excesses of COGENT [11], CREST-II [12] and CDMS-Si [13] in 2013 compatible with the DAMA claim.

Direct DM search has hence (and is still) been hampered by many false promises, since all the experimental approaches discussed so far lack the capability of a positive identification of a DM signature. In addition to this, current Xe-based [14, 15] and several next generation [16] experiments will be sensitive to a new background coming from 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* [17], is nowadays considered a soft limit (*Neutrino Fog*), 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 [18].

All these considerations consequently advocate for the development of experimental approaches able to provide a positive and unambiguous identification of a DM signal, even in presence of (unknown) backgrounds. This is the goal of directional DM searches, whose methods and reasons will be discussed in Sec.2, and of the innovative detector techniques under development towards this goal, that will be illustrated in Sec.3 and Sec.4.

2 Directional Dark Matter search experimental challenge

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 measured 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, with a change in direction of $\sim 90^o$ for every 12 sidereal hours, due to Earth's axis orientation with respect to the solar motion. A detector sensitive to direction and sense of the arrival of particles can therefore hold the key to an unambiguous, positive observation of a DM signal. This holds true even in presence of an unknown amount of neutral isotropic background [19] or neutrinos [18]. Moreover, once detection will be confirmed, this will be the only approach able to provide unbiased constraints on DM properties and to perform DM astronomy [20, 21].

The difficulty in measuring the direction of a NR induced by a WIMP scattering resides in the very low momentum exchanged in the interaction, that for O(keV) recoils produces

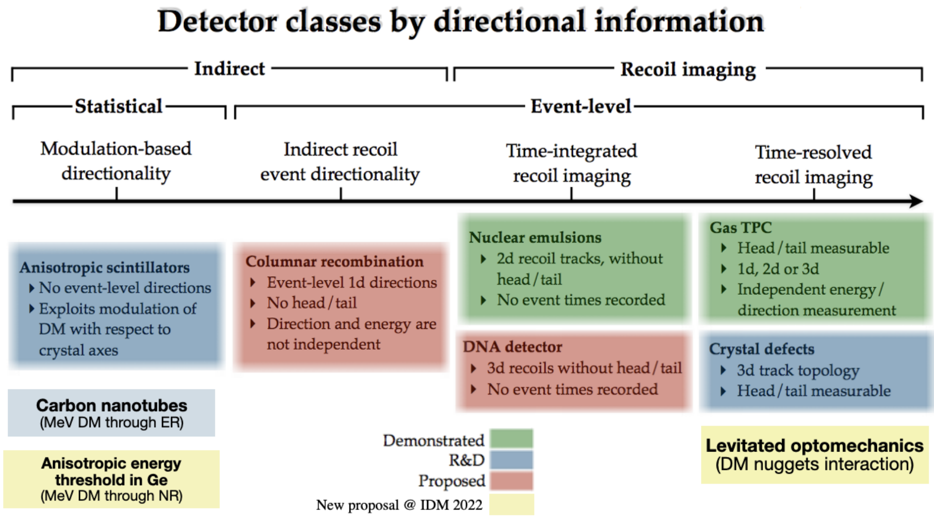

Figure 1: Classification of different directional detection strategies, freely adapted from Ref [22] to include the latest developments. Whenever the target searches are not WIMPs at the GeV scale through classical NR, we indicate in parenthesis the searched DM type and interaction.

tracks of the order of nm in solids, um in liquids and mm in gaseous media. Generally speaking, we can distinguish two main experimental approaches: detectors that can perform recoil imaging and detector sensitive to a direction-depended response of the target material to a scattering interaction. We can refine this categorization even further according to whether the detector can sense recoil directions at the event level or with only statistical distributions of events. These are schematically shown in Figure 1, freely adapted from Ref [22] to include the latest developments. Given the limited space available, in this proceeding we will review the peculiarities and the latest developments only of the two approaches that have so far experimentally demonstrated directional sensitivity in the keV range of interest for DM searches, that is gaseous Time Projection Chambers (TPCs) and solid nuclear emulsions. We refer the reader to the literature for the other experimental approaches presented at the 14^{th} International Conference on Identification of Dark Matter (anisotropic crystals [23], carbon nanotubes [24], anisotropic Ge energy threshold [25], optically levitated sensors [26]).

3 Nuclear Emulsions for WIMP Search project: NEWSdm

Nuclear emulsions are composed of silver halide (AgBr) crystals (2.7 eV semiconducting band gap) working as sensors of charged particles dispersed in a polymer, typically gelatine. When an interaction takes place, several nanometer sized silver clusters are created on the crystals and successively developed with a catalytic process. The two-dimensional track trajectory can be reconstructed with an optical microscope by connecting all the silver grains produced after development. The spatial and angular resolution are then set by the final silver crystal size and density after development and the capability of optical devices to distinguish such small images.

The Nuclear Emulsions for WIMP Search project (NEWSdm) aims at directional detection of Dark Matter with nanometric nuclear emulsions with mean crystal size between 20 nm and 40 nm [27] and a fully automated innovative scanning systems [28], with improved optical technologies. In order to access track length of O(100) nm expected for a WIMP interaction, NEWSdm developed an improved optical technique to overcome the diffraction limit by exploiting the plasmon resonance effect [29]. Plasmon resonance occurs when a light wave gets trapped within conductive nanoparticles smaller than its wavelength and generate a plasmon frequency dependent on the track orientation w.r.t. the light incident direction. With such technique a track length accuracy of 28 nm has been recently achieved [30]. Since December 2020 the NEWSdm collaboration has started the underground production of their emulsion in a dedicated setup in Hall F of Laboratori Nazionali del Gran Sasso (LNGS) with a production capacity of about 100-200 gr/day, in order to further minimise the internal emulsion radioactivity. Since March 2021 a NEWSdm demonstrator setup of 10 gr is running in Hall C of LNGS, with 40 cm of high density polyethylene plus 10 cm of lead shielding. With an overground setup dedicated to the study of neutron background, NEWSdm observed 0.5 MeV proton tracks with precise energy and direction definition.

4 Gaseous Time Projection Chambers

Time Projection Chambers (TPCs) can potentially provide the best observables and architecture for directional DM searches. The total ionisation measured in a TPC indicates the energy of the recoil. Track topology and specific ionisation provide excellent background discrimination. The track itself indicates the axis of the recoil and the charge distribution along its path allows to infer the sense.

Achieving all these features at the low energy of interest for DM searches implies two detector requirements. First, the readout segmentation must be smaller than the recoil length of interest (0.1-1 mm), so that multiple space points along the track can be measured. While experimentally challenging, this is nowadays achievable via multiple technologies [31]. Secondly, any potential diffusion of the recoil trajectory information must also be small compared with the recoil length, in order to not wash out the directionality. This can be obtained with the use of mixtures containing *cold* gases (such as CO_2 or CF_4) or by exploiting Negative Ion Drift (NID). NID is a peculiar modification of the TPC principle induced by the addition to the gas mixture of an highly electronegative dopant (such as CS_2 or SF_6) [32–34]. In this configuration, primary electrons liberated by the track while ionising the gas are captured at very short distances $\leq$ 10 um by the electronegative molecules, creating negative ions. These anions act as image carrier and drift to the anode, where their additional electron is stripped and gives rise to a standard avalanche. Thanks to the anions mass being much larger than electrons, their diffusion is reduced to the thermal limit. This characteristic improves the detector tracking performances and allows for the use of longer drift distances, enhancing the total active mass and easing the detector scalability. Figure 2 summarises the main characteristics of all the existing gaseous directional DM TPCs, together with the proposed CYGNUS project.

4.1 MIcro-tpc MAtrix of Chambers: MIMAC

The peculiar features of the MIcro-tpc MAtrix of Chambers (MIMAC) experiment [36] are the amplification via Micromegas with Flash ADC on the grid, a pixelated strip-based anode with 424.3 um granularity, self-triggering electronics with 50 MHz sampling, and a 70% CF_4 + 28% CHF_3 + 2% i-C_4H_{10} gas mixture at 50 mbar. In an high gain configuration employing a 50% i-C_4H_{10} + 50% CHF_3 mixture at 30 mbar they recently discovered a distortion of the grid signal due to the movement of the ions released in the amplification gap. While these feature can in principle hamper the track reconstruction, they noticed that, if properly treated, it can actually improve the detector directional sensitivity. A procedure to analytically deconvolve the ionic signal on the grid from the measured charge was hence developed, that allows to access the time distribution of the primary electrons cloud at the grid before the avalanche [37], lead-

	Established readout & directionality	Established gas	R&D readout	R&D gas	Largest detector realised	Detector under development
MIMAC	Micromegas + FADC 3D	CF_4:CHF_3:C_4H_{10} @ 0.05 bar		CHF_3:C_4H_{10} @ 0.03 bar	0.05 m^3 (underground)	1 m^3 (under study)
DRIFT	MWPC 1.5 D	CS_2:CF_4:O_2 @ 0.05 bar	THGEM + wire/ micromegas	SF_6:(CF_4) @ 0.05 bar	1 m^3 (underground)	10 m^3 (under study)
NEWAGE	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)
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	0.04 m^3 (under construction)
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)
CYGNUS			All of the above under consideration	Helium-Fluorine @ 1 bar		1000 m^3 (concept paper)

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

Figure 2: Summary of the main characteristics of all the existing gaseous directional DM TPCs, together with the proposed CYGNUS project.

ing to a new method to access directionality and head-tail complementary to the traditional one. Thanks to this innovative approach, MIAMC reconstructed the spectra of 27 keV and 8 keV neutrons impinging parallel to the detector drift direction with an angular resolution of about 15^o.

4.2 Directional Recoil Identification From Tracks: DRIFT

The DRIFT collaboration [38] 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. Currently, they are focusing on the study of innovative amplification structures and improved means of gas purification towards the development of a larger scale detector in the context of the CYGNUS project (Sec.4.4). In order to overcome the typical low gains of NID operation, they are testing an original Multi-Mesh Thick Gas Electron Multipliers (GEMs) device (MMTHGEM), that adds additional stages of amplification to a classical thick GEM by embedding mesh layers within it. The meshes improve the amplification field uniformity and the avalanche characteristics, and reduce the ion back flow that can hinder the gain. A systematic study of the field strength ratio between meshes and GEM electrodes has been carried out in order to maximise their transparency for the avalanche electrons. The optimisation, carried out in pure CF_4 in order to precisely measure the signals, revealed a 200 V/cm tansfer field to be the most advantageous for gas amplification. Future works will employ pure SF_6, for which the MMTHGEM already demonstrated a gain $\geq 6 \times 10^4$ in an unoptimised configuration. In parallel with this studies, DRIFT is developing a gas purification system based on low radioactivity molecular sieves [39].

4.3 CYGNus module with Optical readout: CYGNO

The CYGNO experiment peculiarities are the amplification stage composed of 3 thin GEMs, an He:CF_4 gas mixture at 1 bar, and the optical readout of the light produced by CF_4 scintillation in the electron avalanche with a scientific CMOS camera (sCMOS) and photomultipliers (PMTs) [40]. The synergic INITIUM project ambitious goal is to develop NID at atmospheric pressure in He:CF_4:SF_6 within the CYGNO optical readout approach. The largest prototype manufactured so far LIME, has a 33 × 33 cm^2 readout area with 50 cm drift length for 50

L active volume. LIME has been characterised with multiple X-ray lines and demonstrated a linear response between 3.5 keV and 35 keV with 13% energy resolution and a solid data/MC agreement. LIME has been recently installed at underground LNGS, with data taking started in Summer 2022. After an initial unshielded commissioning, LIME will be shielded by 10 cm of Cu to study the external background and perform a directional measurement of LNGS underground neutron flux. Subsequently, 40 cm of H_2O will be added in order to minimise the external background to study the internal material radioactivity and verify on a realistic dimensions and environment the performances expected for the 0.4 m^3 CYGNO-04 detector (that will be composed of LIME-like modules). CYGNO-04 goal is to prove the capability and scalability of the optical readout approach towards a large O(30) m^3 experiment. Its Technical Design Report was recently submitted and the detector is expected to be hosted in LNGS Hall F. Within the INITIUM project, NID with optical readout at LNGS atmospheric pressure (880 mbar) was recently demonstrated, showing a mobility compatible with previously published results and an impressive reduction of the diffusion during drift w.r.t. the He:CF_4 gas mixture (paper in preparation).

4.4 CYGNUS

CYGNUS [41] is a newly formed international proto-collaboration, aimed at developing a multi-modular Galactic Directional Recoil Observatory of TPCs at the ton-scale that could test the Dark Matter hypothesis beyond the *Neutrino Fog* and measure Sun neutrino with directionality. CYGNUS key features are the use of an Helium-Fluorine gas mixture at 1 atm with reduced diffusion (via either *cold* gases or NID) and directional threshold and full background rejection at O(keV). The proto-collaboration produced an extensive concept paper on a 1000 m^3 gaseous NITPC detector focused on technical feasibility and WIMP searches through NRs [42]. More recently CYGNUS started investigating the potentialities of ER directionality measurement, than can enable solar neutrino spectroscopy through neutrino-electron elastic scattering on an event-by-event basis [43]. Preliminary studies show how an O(10) m^3 detector could extend Borexino detection of the *pp* cycle to lower energies ($\sim$ 50 keV), while a 1 ton detector could measure the CNO cycle by breaking the degeneracy with *pep* and ^{7}Be fluxes through directionality. In this context, an improved model for electron multiple scattering in gases has been worked out starting from DEGRAD simulation [44]. In parallel, within the CYGNO collaboration, an algorithm inspired from X-ray polarimetry [45] has been optimised on LIME simulated sCMOS images (see Sec.4.3) and demonstrated the possibility to reach 30^o angular resolution for 20 keV ERs (uniformity distributed in orientation and drift distance from the amplification plane in the whole 50 L volume), improving to 12^o at 70 keV (paper in preparation).

5 Conclusions and Outlook

Experimental direct DM searches have reached a level of maturity and complexity for which the detectors response to signal and the experiment backgrounds needs to be understood and controlled at unprecedented levels, in order to avoid the appearance of unexplained excesses. In addition to this, the experiments sensitivity will soon reach the *Neutrino Fog*, beyond which their sensitivity will start to be limited by the uncertainties on the neutrino fluxes backgrounds and the return on investment in increasing the exposure will not be anymore favourable. The measurement of the DM scattering directionality provides a powerful handle to deal with both these problems, offering an unique key for a positive unambiguous identification of a DM interaction, together with the opportunity to promote neutrinos from background to a signal with attractive physics cases.

The directional DM search experimental field appears lively and fervid, with several new R&D proposal for DM candidates alternative to GeV WIMPs appearing in the last few years, such as the use of carbon nanotubes with an anysotropic response to MeV DM scattering off electrons [24] or directional dependence of the ionisation threshold in Ge crystal [25]. The most mature technologies in the field, that is gaseous TPCs and nuclear emulsions, have demonstrated imaging capability in the keV region with solid background rejection capabilities. The gaseous TPC landscape in particular, is moving towards establishing scalability at the O(1) m^3 scale towards O(50) m^3 experiments, with most of the projects working together in the CYGNUS proto-collaboration to eventually form a ton-scale Galactic Recoil Observatory.

For all these reasons, a large scale directional experiment with competitive sensitivity for both Spin Dependent and Spin Independent couplings appears today not only technologically feasible, but also the only viable option to venture into the *Neutrino Fog* and to eventually establish beyond any doubt the nature of Dark Matter.

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