Recoil imaging for dark matter, neutrinos, and physics beyond the Standard Model

Snowmass 2021 inter-frontier white paper:
CF1: Particle-like dark matter
NF10: Neutrino detectors
IF5: Micro-pattern gas detectors

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Abstract

Recoil imaging entails the direct measurement of one or more components of a recoiling particle's direction. This is a capability highly sought-after in detectors, with applications across particle and astroparticle physics. However, currently it seems to only be a practical goal for micro-pattern gas detectors (MPGDs). This white paper outlines the physics case for directional recoil detection, and puts forward a decadal plan to advance towards high definition recoil imaging, in the context of the MPGD topical group of the Snowmass 2021 Instrumentation Frontier community study. The science case covered includes the discovery of DM into the neutrino fog, directional detection of neutrino-electron scattering, the precision study of coherent-elastic neutrino-nucleus scattering, the measurement of the Migdal effect, as well as several other applied physics goals. We also describe several ongoing R&D projects that will test crucial ideas such as the use of negative ion drift in MPGDs, the possibility for sub-mm tracking in gaseous argon time projection chambers, as well as the readout and electronics systems needed for detector scale-up to the ton-scale and beyond.

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Contents

1 Executive summary

The direction in which future particle physics discoveries lie is unknown. Yet it is clear that whatever these discoveries may be, novel approaches for measurement will be what facilitates them. This white paper describes progress towards a general class of particle physics measurement that could potentially lead us to a broad range of discoveries. This measurement involves the direct imaging of keV–MeV energy particle tracks. Primarily driven by technological development in astroparticle physics, *recoil imaging* is most noteworthy for providing *directional* information about recoils from a range different sources.

One of the driving motivations behind developing approaches to image low-energy recoils of nuclei and electrons is the search for dark matter (DM). A direct DM signal in an Earth-bound experiment is generically expected to be directional in a highly characteristic way (see Ref. [1] for a review). This potential smoking-gun signature should underlie the signal of whichever DM candidate is eventually discovered—the only problem is that, at present, very few direct DM detection experiments are designed with the ability to measure it. A large-scale recoil imaging detector not only provides an opportunity to discover DM, but also represents the *only* way to conclusively confirm the DM nature of a signal if it were seen. A corollary to this statement is that recoil imaging presents the optimal way to subtract known sources of background that could mimic a putative DM signal. This turns out to be precisely the problem the field now faces, with the imminent arrival of the neutrino fog [2,3]. As such, the case for developing a directional DM experiment is stronger than it has ever been.

Working towards a competitive large-scale time projection chamber (TPC) for a directional DM search is the central goal of the Cygnus collaboration for the next decade. Initially, the Cygnus collaboration will attempt to converge on the TPC design that optimises directional sensitivity low energy nuclear and electron recoils at the keV scale and above. Obtaining good directional sensitivity is essential not just to realise the central aim of directional detection, but also to enhance nuclear/electron recoil discrimination, which as discussed in a recent feasibility study [4], is the main hurdle for lowering the threshold below ∼10 keV, as is needed to probe into the neutrino fog. The result of this study was the tentative conclusion that a strip-based readout in a negative ion drift TPC operating under atmosphric conditions with a He:SF$_6$, is a cost-effective choice. Scaling up such an experiment to the 1000 m^3 scale is a daunting task, however the modular and multi-site design envisioned for Cygnus should mean that once a smaller scale 10 m^3 are demonstrated, the full-scale experiment can follow. As is discussed in this paper, as well as in Ref. [4], there are in fact many shorter-term physics goals that can be reached even in a much smaller experiment than the final Cygnus-1000 that will probe into the neutrino fog.

The motivation behind the concept of recoil imaging becomes even more powerful when we expand the scope beyond DM. A large number of sources of particle are inherently directional in some way, and many physics processes themselves also have interesting or useful angular dependencies. Since directional detectors are proposed as a way to see through the neutrino fog, the most obvious argument to make is to promote the neutrino background to a signal. With the right optimization, recoil imaging detectors like Cygnus could be sensitive to natural sources of neutrino such as solar neutrinos via both electronic and nuclear recoil channels, achieving directional sensitivity at energies out of reach to many other dedicated neutrino observatories.

A recoil imaging detector could also be used in conjunction with a human-made source of neutrinos to test the nature of the coherent neutrino-nucleus scattering (CEνNS). Novel searches for neutrino physics beyond the Standard Model (SM), as well as the existence of light dark sectors could both be probed via CEνNS, which today remains one of the lesser studied neutrino interactions predicted by the SM. Preparations for experiments to investigate the potential for directional detection of CEνNS recoils are being undertaken under the name νBDX-DRIFT. A 1 m^3 negative ion TPC is planned to be placed near the NuMI proton beam dump, with the eventual goal being to put an experiment at the DUNE Near Detector Complex at Fermilab. A detector of this scale would be able to detect a substantial number of CEνNS events in a timescale of a year, and thanks to its directional sensitivity will be subject to a much lower background than other CEνNS measurements.

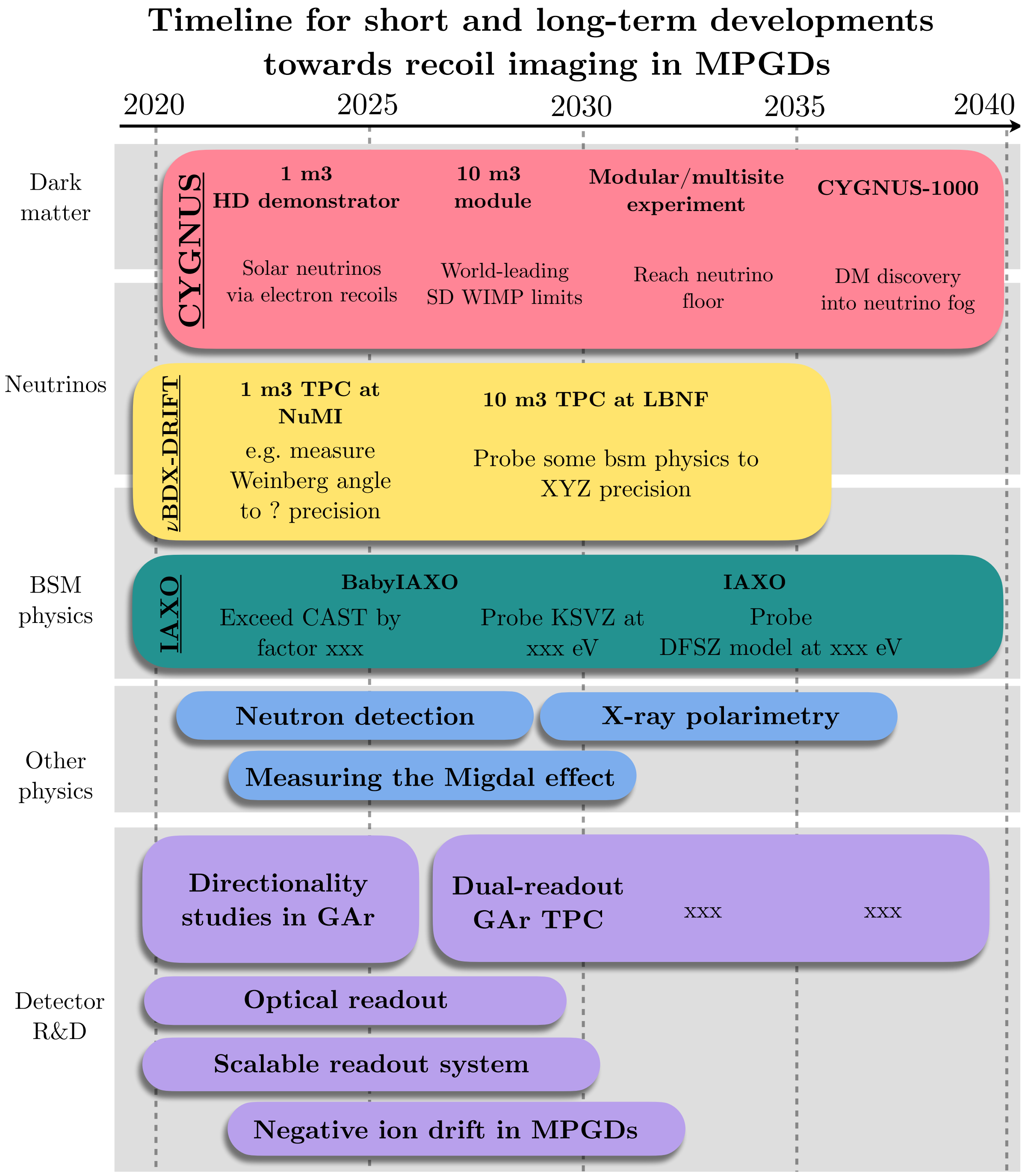
The case for recoil imaging can also be appreciated from a purely experimental point of view. At the most basic level, a complete particle track contains more information than energy-dependent measurements of say absolute quantities of ionisation, or scintillation. As mentioned above, this is advantageous in the context of nuclear/electron recoil discrimination, or for disentangling signals from one another like DM and neutrinos, but this statement can be made far more generally. Imaged recoils of different particle types and energies are far more inter-distinguishable than if their total energy-losses were simply counted, this is due the physical mechanisms that govern the energy-losses of those nuclei and electrons in a medium. This leads to recoil imaging being a desirable strategy for background rejection as well as signal identification in applications totally apart from those listed already—neutron detection, the measurement of the Migdal effect, X-ray polarimetry, and the detection of rare nuclear decays, to name just a few.

A notable application of recoil imaging in MPGDs beyond DM and neutrinos, is for the International Axion Observatory (IAXO). IAXO will be an axion helioscope, an experiment that aims to detect the keV-scale photons generated when the flux of axions coming from the Sun enters a large static magnetic field. IAXO is the proposed successor to the CAST experiment, and its intermediate stage BabyIAXO is already under construction. A range of X-ray detectors are planned to be tested for IAXO, including MPGDs... **Text:** 3-4 more sentences on IAXO

With such a diverse substantial physics case, it is clear that field should devote considerable effort towards developing the technologies needed to do recoil imaging in large-scale detectors over the next ten years. In this paper we make several key recommendations, as well as highlight exciting ongoing projects that will help test several important concepts. For instance, recoil imaging via optical readout currently stands out as a particularly promising strategy with several groups conducting R&D right now. To complement these developments, investigation into the potential for using negative ion drift in MPGDs, scalable readout electronics systems, as well as the construction of high definition pixelized TPC readouts should also begin. Another concept that has attracted significant interest recently, and is outlined in this paper, is the use of gaseous argon. There are several groups looking into the TPC designs that can provide the necessary sub-mm resolution with such a fill gas. This could be achieved via the use of a 'dual readout' TPC which can detect both the positive ions as well as the electrons generated by a recoil event. TPCs using gaseous argon could have many potential advantages, especially for the neutrino sector for example τ-tracking for the study of $\nu_\tau \tau$ charged current interactions.

2 Introduction

Recoil imaging entails directly observing one or more components of a recoiling particle's trajectory. As discussed in a recent review on the subject of directional recoil detection more generally, Ref. [5] argued that real-time measurements of this directional information is only a realistic in gas targets currently. The reason is that a measurement of some component of a track requires that the readout segmentation scale be smaller than both the initial tracks themselves, and the diffusion scales. The



Timeline for short and long-term developments towards recoil imaging in MPGDs

Figure 1: **Ciaran:** PLACEHOLDER, details to be filled in. The plan for developments towards recoil imaging for the next decade and beyond. We have divided the physics undertaken in terms of DM, neutrinos, BSM physics, other physics, detector R&D.

need for *real-time* measurements of these quantities, on the other hand, results from the fact that the Earth rotates with respect to many sought-after fluxes of incoming particles [6], and that timing information itself is often used as a further discriminant in many other searches. The first of these requirements makes recoil imaging impractical in liquid targets, and the second makes it extremely demanding in solids as well (although see Refs. [7,8] for proposed workarounds).

Direct recoil direction measurements in real-time seems to be a goal feasible only via drifting ionization distributions in gas, and should therefore be one of the major motivations for pursuing further development of micropattern gas detectors (MPGDs).[1] The early sections of this paper will argue why such measurements are desirable. This rest of the paper will then focus itself on ongoing and future experimental work under the umbrella of recoil imaging in gas detectors. We have presented our vision for the future of this field pictorially in Fig. 1, which gives a tentative timeline for several major advances. Before we begin, however, we must first lay out the basic physics that underpins all of the measurement strategies that we will discuss, as well as describe what has come before.

2.1 Physics of the ionization process

We start with the most basic question one can ask in this context: what low-energy physics drives the ionization process that eventually leads to recoil tracks. This physics by itself is already of great interest and it turns out that many of the technologies that will be discussed later may elucidate this subject beyond our current knowledge. For now we can summarize a few of the key well-known aspects, which will also allow us to introduce terminology that will appear frequently throughout the rest of the paper.

The energy loss processes of recoils in the energy regime we are interested in were first described by Lindhard et al. [11] (see also the review Ref. [12]). The energy loss as a function of distance, $\mathrm{d}E/\mathrm{d}x$, of a charged particle in a medium has a maximum value at some distance called the Bragg peak. At low energies this energy loss follows the stopping (or falling) side of this Bragg peak, i.e. the energy loss is decreasing with time eventually coming to a stop. The energy loss of fast particles is caused by the excitement and ionisation of other atoms along the path initially, but eventually becomes dominated by elastic processes as they slow down. How much of $\mathrm{d}E/\mathrm{d}x$ is caused by electronic over nuclear scattering varies not just as function of recoil energy but also with the composition of the medium, a feature that is important to understand in all low-energy recoil detectors, but especially when the goal is to measure those recoils' *directions*. For example, the decrease of $\mathrm{d}E/\mathrm{d}x$ along the recoil track can provide a means to measure the vector sign of the recoil track direction, otherwise known as head/tail (see e.g. Refs. [13,14]), but is also essential to understand to obtain good angular resolution and to infer the initial recoil energy.

Understanding energy loss in a medium is also important if we want to discriminate electronic and nuclear recoils, which each have characteristic $\mathrm{d}E/\mathrm{d}x$. In this context, however, we arrive at one of the major advantages of recoil imaging, and this in doing particle identification. Notably, the $\mathrm{d}E/\mathrm{d}x$ of electrons appears to grow as they slow down, which gives the opposite sign to that of nuclear recoil tracks. This is due to a rapid increase in the rate of scattering towards the end of electron trajectories, which also causes their tracks to curl up at the end. This distinction is important for any recoil imaging detector that aims to identify electron recoils and nuclear recoils such as a DM (Sec. 3) or a neutrino detector (Sec. 4). But it also turns out to be one of the critical aspects for plans to measure the Migdal effect via recoil imaging (see Sec. 6.1).

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[1] Other methods of directional detection that could be described as recoil imaging, are solid state detectors relying on nuclear emulsions [7] and crystal defect spectroscopy [8], as well as the proposed DNA detector [9,10], however since this paper focuses on gas detectors they will not be discussed here.

One of the major goals for the near future of MPGD R&D is to understand how to push electron/nuclear track discrimination to very low energies. This is a challenge as all possible discriminating characteristics between the two become unusable when tracks shrink beneath either the diffusion or readout segmentation scale. This issue is crucial most of all for a potential directional DM and neutrino detector, since nuclear recoils from both are generated mostly at energies below 10 keV. It turns out that one of the major obstacles for reducing the energy threshold of a detector is limiting the electron background, and hence electron/nuclear recoil discrimination is essential for opening up searches for light DM particles and solar neutrinos. Work is underway in the CYGNUS collaboration to try and address these issues and will be discussed in Sec. 3.3.

Text: Dinesh - What more needs to be understood and investigated regarding the physics of the ionisation process, and who will do it?

2.2 Current status of directional recoil detection using MPGDs

One of the driving motivations behind low-energy, especially nuclear, recoil imaging has been the search for DM. Gas TPCs provide tremendous flexibility in operating pressure and gas mixture that allows optimisation for varying DM mass ranges and interaction type. Readouts available for TPCs can provide reconstructed tracks with up to 3-dimensions, and a granularity of ~200 μm or better. For the lateral components of the track parallel to the drift direction this has only become possible thanks to the advent of MPGD technologies (with the drift direction coming via pulse-shape timing).

A number of advances over the past decade have improved the sensitivity of TPCs for directional DM searches that are now finding new relevance in the context of other physics. One example is negative ion drift (NID) achievable by the addition of electronegative components of the gas mixture [15], which allows for very low diffusion and a factor 10^3 slower drift speeds compared to the alternative, i.e. drifting electrons. This allows for low cost and potentially exquisite resolution of the drift direction to complement the potential resolution already achievable along the readout plane. Validating the use of NID in MPGDs is therefore one of the directions for future blue-sky R&D that we advocate for in this paper, and will be discussed in Sec. 8.1.

The DRIFT experiment [16] pioneered the use of NID, and were the first directional DM search to take data underground, which they did over several generations of detector. Over time, the advances in MPGDs then allowed many other directional DM searches to be possible. For example the US-based DMTPC collaboration built several CCD-based optical readouts [17] for DM searches. And more recently the Italian CYGNO collaboration are also employing an optical readout using CMOS cameras, which they plan to augment via pulse-shaping using PMTs to also measure the drift direction.

Electronic readouts using Micromegas, GEMs and other novel MPGDs for gas amplification combined with strips or pixels are also being used both for R&D and in underground experiments. The Japanese NEWAGE collaboration for instance has deployed several generations of TPC detectors based on a micro pixel chamber (μ-PIC) combined with GEMs and strip readouts [18] whereas the French MIMAC experiment is using a Micromegas pixel readout TPC [19]. An LBNL and U. Hawaii R&D project, D^3 instead has constructed small prototypes with HD pixel charge readout based on ASIC chips, which have been deployed for directional neutron background measurements at the SuperKEKB collider [20].

While considerable cost and effort is required to scale up such high-definition detectors to competitive sizes, larger-scale pixel based readout planes are already being fabricated and tested for tracking detectors in future colliders. This is an R&D synergy that could prove useful for the field. In fact, GridPix detectors [21], based on pixel ASICs that are directly combined with a gas amplification MPGD structure, have already demonstrated exquisite imaging of nuclear recoils [22]. Given the abundance of available TPC charge readout technologies, it is not straightforward to determine the best strategy for a large-scale detector. The recent CYGNUS design study [4] is the first attempt at such a technology comparison in the context of a future DM search, and will be described in Sec. 3.3.

3 Dark matter

3.1 Directionality for dark matter discovery

It has been known since the 1980s that the flux of DM on Earth should be anisotropic in a way that is characteristic only of particles originating from the galactic halo. This fact is simply a result of our Sun's motion through the galaxy which points us along a path towards the constellation of Cygnus. This velocity vector is now pinned down rather precisely thanks to the Gaia satellite and other Milky Way surveys, so the only caveats to the statement that the DM flux should point back towards Cygnus are if the halo model were not the homogeneous, roughly isotropic sphere that is expected under the Standard Halo Model [23]. These caveats were discussed in Ref. [4], but in general it seems that only very radical and little-motivated halo formation scenarios could lead to a notable suppression of the DM flux anisotropy[2], and even more radical modifications are needed to change its preferred direction [24].

Therefore, it is not unreasonable to state that the directionality of the DM flux is only of the only broad predictions one can make about a terrestrial DM signal that is independent of the assumed particle candidate. So even though this characteristic signal is not searched for in any of the most competitive DM searches currently, it is still spoken of as a 'smoking gun'. In contrast, the annual modulation of the flux, which is also due to the relative motion of the Earth with respect to the DM halo, *is* searched for (and apparently observed [25]) but has proven unreliable. In a recoil-based particle-like DM experiment, the predicted dipole anisotropy in the flux is slightly washed out in the scattering process, but it generally persists at the $\mathcal{O}(10)$ level in the rate. This is also robust against all realistic DM-nucleus interaction models [26, 27]. This startlingly low number has been what has driven the majority of the interest in directional DM experiments to date.

Under the conditions that DM nuclear recoil-based searches currently operate (i.e. roughly isotropic backgrounds) a set of well-measured recoil directions would be enough to make a non-parametric *discovery* of DM with as few as tens of events [1, 4, 28–31]. One of the key capabilities that these numbers assume however is the ability to measure the head/tail of each recoil, and this will be reiterated several more times later in this paper as an important technical hurdle that all proposed directional DM experiments must overcome.

Under *anisotropic* background conditions, as long as the background is generally well separated from Cygnus[3], then the numbers of required events are even smaller. This turns out to be the case for solar neutrinos, which appear to us to originate from a single point, so are as anisotropic a source of background as it is possible to be.

Therefore directionality seems to be the way forward if we want to have a reliable discovery of

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[2] In fact many of these modifications would harm nondirectional DM experiments as much as they would harm directional ones

[3] and generally any background originating within the Solar System will be since the DM flux is stationary with respect to the fixed background of stars, whereas anything else would be fixed with respect to either the geocentric or heliocentric coordinates.

DM, and that should remain true even if a DM-like signal is first seen in another nondirectional experiment. While it is certainly true that the most competitive DM searches have trustworthy background models, signal reconstruction, and statistical analyses, a signal that does not possess any unique characteristics befitting a galactic particle—as is case in the majority of experiments—will need to await some confirmation before it is widely accepted. Indeed, a history of purported signals, hints, and excesses (see Ref. [32] for the most recent cause for excitement) would certainly affirm any reasons one might have to doubt even a high-significance excess of events. Only with directionality can we be sure that we have captured the same mysterious substance that we have observed across our galaxy, the Universe, and throughout cosmic time [33]. Ultimately, the distant-future goal of detecting DM is to transport us to an era in which we possess a brand new messenger to study new physics beyond the SM, and to unravel the history and structure of our galaxy. A directionally sensitive detector would have an unmatched capability to do this [1, 29, 30, 34–37].

3.2 Directionality and the neutrino fog

While the search for DM has inspired much advancement in low-energy recoil imaging detectors for nuclear recoils, over the last several decades the broader direct detection community has devoted much of its effort in different directions. Most notably, the largest collaborations have focused on the scale up experiments to large target masses, with the latest generation, especially of liquid-noble detectors, being already beyond the ton-scale [38, 39]. While these kinds of experiment lead the field right now, it has been known for some time that this rapid progress cannot continue indefinitely. Even it were possible to keep making detectors larger, improvements in sensitivity to particle-like DM[4] would eventually stall due to the presence of the neutrino background [40–44]. Neutrinos scatter with nuclei via the recently measured SM process of coherent elastic neutrino-nucleus scattering. The scattering kinematics dictates that for typical direct detection targets 1–100 keV-scale nuclear recoils will be generated by 1–100 MeV scale neutrinos, which unfortunately is precisely where there is a huge flux of solar and atmospheric neutrinos. Worse still is the fact that the CEνNS recoil spectra are extremely similar to those generated by DM. For a wide range of models, the neutrino background is therefore not just an unshieldable source of noise, but a source of noise that looks remarkably like the signal being searched for. The DM scattering cross section at which this the CEνNS signal was expected to drown out a potential DM signal was labelled the "neutrino floor", see e.g. Refs. [45–61] for discussion.

One of the more recent shifts in language however has been the softening of the term neutrino floor to the "neutrino fog" [3]. The reason is simply to more accurately reflect the statistical nature of the problem. As long as all sources of background are properly characterised and any systematic uncertainties accounted for, then there can only be a "floor" if a background mimics the signal perfectly. This is not the case for the neutrino background. Hence there is no hard neutrino floor, but instead a fog: a region of parameter space where a conclusive identification or exclusion of a signal requires many more events (sometimes even orders of magnitude more) than would naively be expected under Poisson statistics. The neutrino fog for the most familiar spin independent DM-nucleon scattering cross section is visualised in Fig. 2, where the colour indicates how badly the neutrino background inhibits the exclusion or discovery of a DM signal.

The advantage of directionality then is made quite clear in the context of the neutrino fog: the anisotropy of the incoming DM flux is a feature that only it should possess, so if the directional signals of both the DM and neutrino-induced nuclear recoils can be fully measured then this should

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[4] i.e. DM in the form of weakly interacting massive particles (WIMPs), or similar

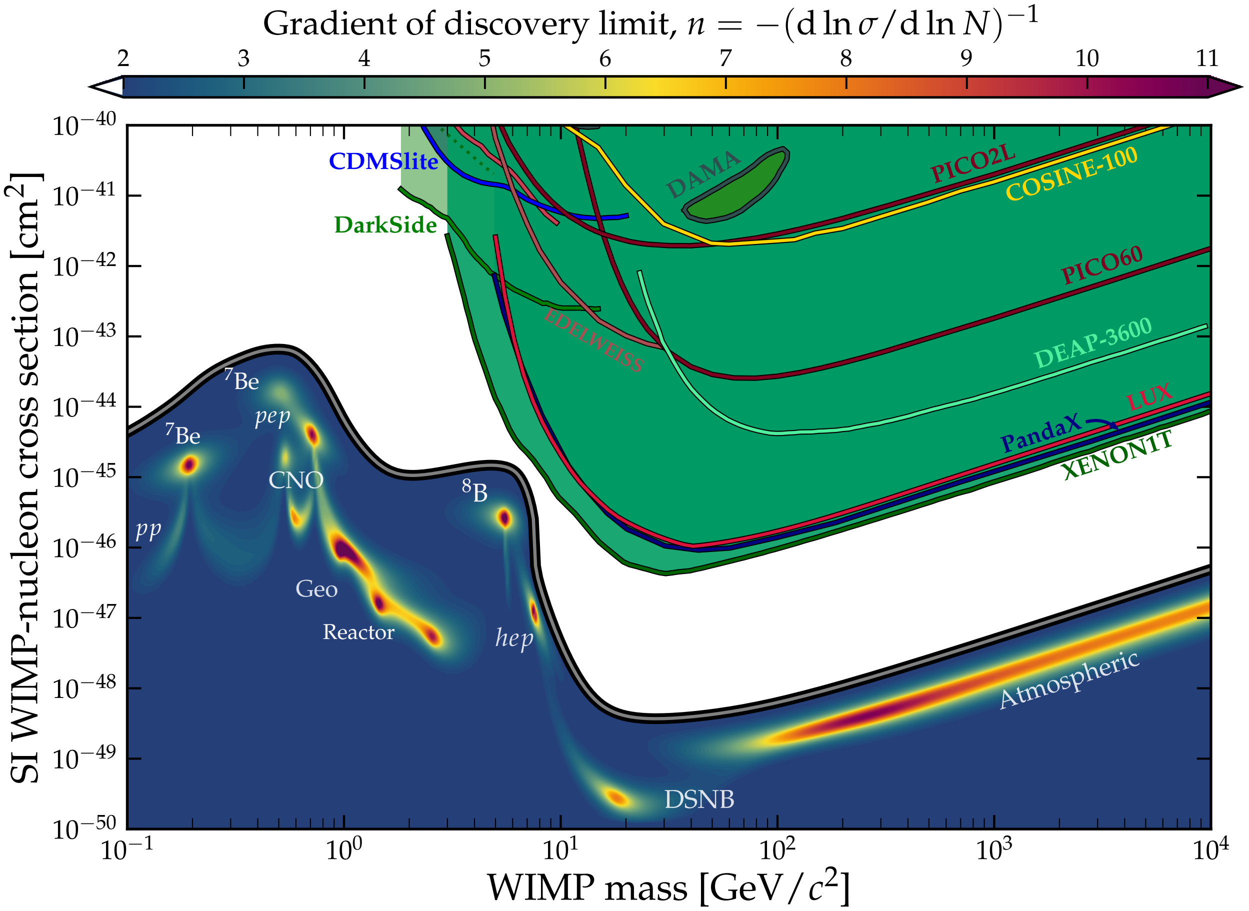


Figure 2: A graphical description of the neutrino fog and plot its boundary. we show the spin-independent DM parameter space, colouring the section below the neutrino floor by the value of n, defined as the index with which a discovery limit scales with the number of background events, i.e. $\sigma \propto N^{-1/n}$. The neutrino fog is defined to be the regime for which $n > 2$, with the neutrino floor being the cross section for a given mass where this transition occurs. For a highly-performing directional detector this entire region would be white, as the value of n would never exceed two.

be the information required to disentangle the two signals and eliminate the problem. In other words, a directional detector should be able to "see-through" the neutrino fog [1, 4–6, 56, 62–64].

Interestingly, compared against the scenario described in the previous subsection, directional detectors should in principle fair against the neutrino background much better than against other isotropic backgrounds. The key reason is that *both* the neutrino and DM signals are highly distinct, meaning it is easier to distinguish DM from solar neutrinos, than it is from other isotropic sources of background [62]. As a result, the sensitivity of a fully directional experiment that has access to full 3-d vectorial (as opposed to axial, i.e. without head-tail) information about every single event scales very favourably with with exposure. In the case of a non-directional experiment, this scaling becomes worse than the Poissonian expectation $\sim 1/\sqrt{MT}$ due to the fact that the neutrino signal mimics a DM signal for certain DM masses. This leads to the so-called neutrino floor, or increasingly, neutrino "fog" [3], that makes probing small DM cross sections extremely challenging, and perhaps totally impractical. A directional experiment circumvents this theoretical boundary entirely, and sensitivity scales almost as the background-free expectation of $\sim 1/MT$ at the low-mass end [62].

The key issue that remains to be understood is to determine if an gas-based experiment can achieve, firstly, the energy thresholds and target volumes needed to *reach* the neutrino fog, but also the angular and head-tail performance necessary to discriminate the two signals. Answering these questions is the primary goal of the CYGNUS collaboration.

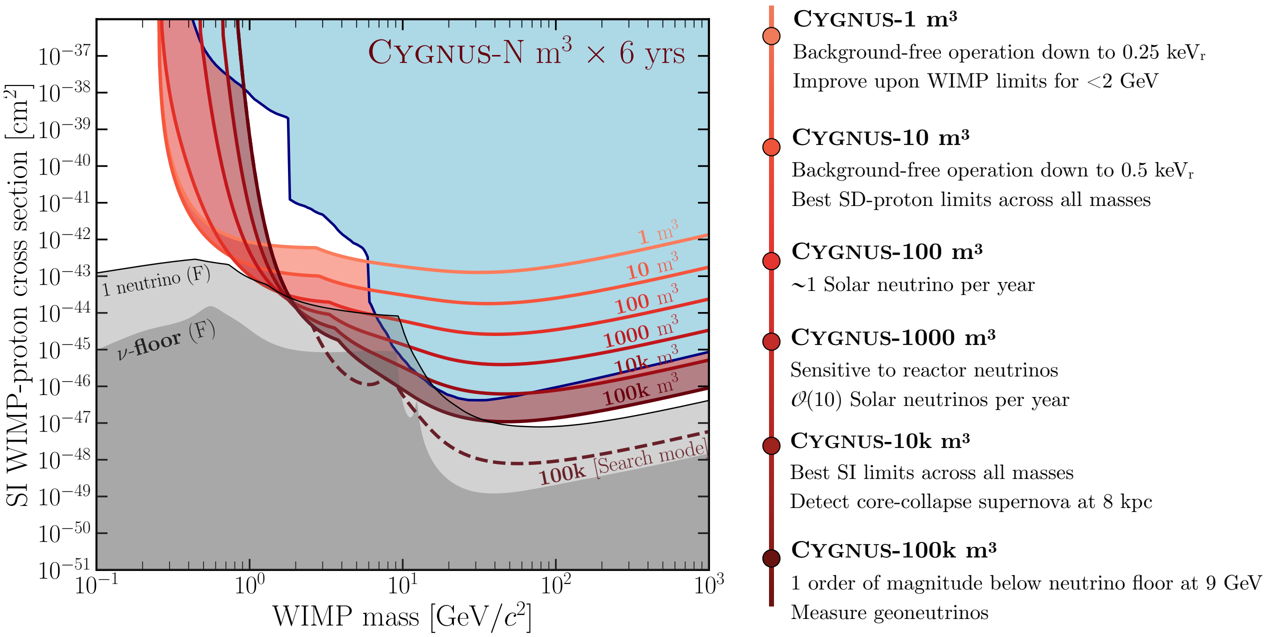
3.3 CYGNUS

Though there are several proposed techniques for realising directional detection experimentally, it is safe to say that the majority of the community is converging around the gas TPC as the optimum technology, both in terms of the potential directional performance, but also in terms of the scale-up needed to be create a competitive experiment. Proponents of the gas TPC as the preferred technique for doing a directional DM search have grown in recent years. The most recent development has been the formation of the CYGNUS proto-collaboration [4], which is the joint venture of several international groups [16, 18, 65, 66] who have successfully run small-scale directional TPC experiments in the past. These groups are now utilizing the continual advancements in advanced readout technologies, that should be capable of detecting the nuclear and electron recoil events down at low energies, whilst also providing excellent direction reconstruction and discrimination between the two. This acceleration in interest and technological capability has caused the vision of the CYGNUS collaboration to expand beyond simply the discovery of DM, but into a range of other fundamental and applied physics goals, perhaps most notably in the context of neutrino physics, which will be subject of the following section of this paper.

We point the reader to the recent feasibility study of Ref. [4] for details on the potential feasibility of the ton-scale 'recoil observatory' that is put forward there. Here we will simply summarise the key results from this paper and highlight some of the directions that future simulation and detector R&D should move towards.

To reach the solar neutrino shoulder of the neutrino fog for masses , a detector must have a total target exposure around the ton-year scale, but potentially lower if nuclear recoil energy thresholds can be lowered significantly. Bear in mind that for a typical TPC fill gasses like SF_6 or CF_4, all solar neutrino recoils will be below 10 keV (true recoil energy). For lighter nuclei such as helium, ^{8}B neutrinos generate recoils at much higher energies, but the CEνNS rate scales with the number of neutrons squared, so this gas would suffers a factor 25 in the event rate compared to a fluorine-based one. Another consideration that has to balance this statement is the fact that recoil directions, are better preserved in a gas mixture containing a light target like helium than in, say, pure SF_6. So even if a TPC were filled with a high density target that allows it to observe the neutrino background, that same gas could have such poor angular resolution, head-tail recognition and electron discrimination, that it would provide no benefit over a non-directional experiment. This is one of the key issues that needs to be resolved

One possible baseline configuration for a directional experiment that would reach the neutrino fog is the proposed 'CYGNUS-1000' detector outlined in Ref. [4]. CYGNUS-1000 would have a fiducial target volume of 1000 m^3, filled with a 755:5 He:SF_6 gas mixture at room temperature and atmospheric pressure, and with 1–3 keV$_\mathrm{r}$ event detection thresholds though this depends critically on the chosen readout, as will be discussed below. This mixture has multiple advantages: it improves the directionality of all recoil species, permits fiducialization in the drift direction via minority carriers, whereas atmospheric pressure provides a high event rate while also avoiding the need for a vacuum vessel. This baseline configuration would observe 10–40 solar neutrino events, and already have a non-directional sensitivity to DM-nucleon cross sections extending significantly beyond existing limits. For spin-independent nucleon interactions this sensitivity could extend into presently unex-



Cygnus-1 m³
Background-free operation down to 0.25 keV$_r$
Improve upon WIMP limits for <2 GeV

Cygnus-10 m³
Background-free operation down to 0.5 keV$_r$
Best SD-proton limits across all masses

Cygnus-100 m³
∼1 Solar neutrino per year

Cygnus-1000 m³
Sensitive to reactor neutrinos
$\mathcal{O}(10)$ Solar neutrinos per year

Cygnus-10k m³
Best SI limits across all masses
Detect core-collapse supernova at 8 kpc

Cygnus-100k m³
1 order of magnitude below neutrino floor at 9 GeV
Measure geoneutrinos

Figure 3: Summary of the projected 90% CL spin-independent DM-nucleon cross section exclusion limits as a function of the total fiducial volume of the detector-network comprising Cygnus, along with a few key physics measurement benchmarks that could be achieved at each stage. Target masses are multiplied by a running time of six years so that Cygnus-1000 corresponds to a 1 ton year exposure, assuming a 755:5 Torr He:SF$_6$ gas mixture. The achievable threshold is dependent crucially on the electron rejection factor, and as a consequence on the readout, gas mixture, and track reconstruction algorithms all of which are under further investigation. Hence the thresholds for the limits shown here are increased evenly between 0.25 and 8 keV$_r$ and for each increasing volume to illustrate a possible range. Below the final volume an additional "search mode" limit is shown, which would have 1520 Torr of SF$_6$ (as opposed to 5 Torr), but would have no directional sensitivity. Reproduced from Ref. [4].

plored sub-10 GeV parameter space, whereas for spin dependent-proton interactions it would beat the most stringent limit set by PICO-60 [67] by several orders of magnitude.

To achieve good directional sensitivity and electron/nuclear recoil discrimination at energies below 10 keV$_r$ Cygnus will require a highly segmented charge readout. This must also be complemented by a drift length that minimizes diffusion of the ionization as much as possible while ensuring a decent fiducial volume and readout planes that are not excessively large. A high electron rejection factor is critical to ensure that the detector can operate free of internal background and allow the detector to discriminate DM from CEνNS events as promised by the directional detection concept. The most cost-effective way to achieve a highly segmented readout, low diffusion, and excellent directional sensitivity simultaneously seems to be to use a strip-based readout with NID.[5] Limiting the drift direction to 50 cm and using a back-to-back configuration as in Fig. 4, Cygnus-1000 would require a 2000 m^2 readout plane. Large strip micromegas planes from CERN meeting these segmentation requirements are already available at a cost of order \$12,500 /m^2. If a radiopure version of these detector as well as preamps with integration time appropriate for NID are developed, then Cygnus-

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[5] Importantly though, electron drift used in combination with other readouts such as optical are not thoroughly ruled out for a large-scale DM/neutrino observatory at this stage, and work to demonstrate their feasibility should be encouraged, as we will discuss in Sec. 7.4.

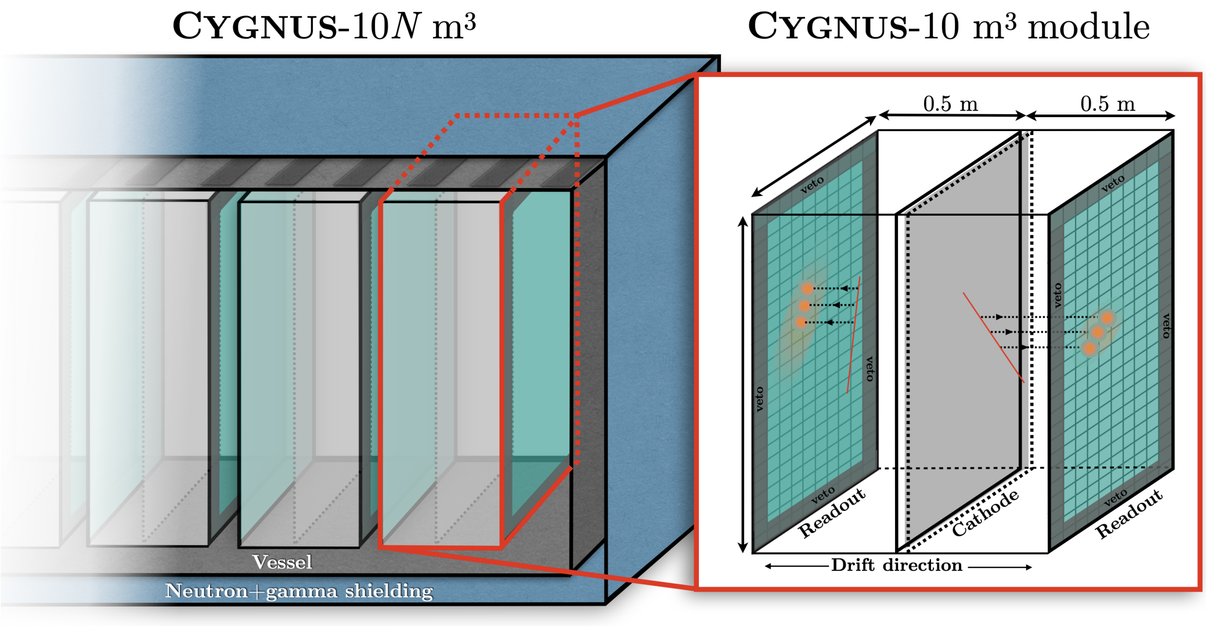

Figure 4: Schematic of the modular scheme envisioned to implement a Cygnus recoil observatory at a large scale. A $N \times 10$ m^3 detector could be comprised of N back-to-back NID TPC modules. Each module would have a central cathode and two readout planes so as to limit the maximum drift distance to 50 cm and thereby minimize diffusion. Reproduced from Ref. [4].

1000 could be constructed relatively soon and at quite reasonable cost. Assuming 20 million readout channels at an electronics cost of US \$1/channel for mass production, the total charge readout cost of Cygnus-1000 would then amount to US \$45 million. Downstream DAQ, gas vessels and shielding would add to the cost, but due to the ability of Cygnus to operate with low noise at room temperature and atmospheric pressure, these costs could be kept reasonable.

Unlike most other direct detection experiments, Cygnus is not envisioned to be a monolithic experiment. Instead a scheme of modularity would have to be implemented, such as in Fig. 4. An even larger experiment could be realized by distributing further modules across multiple sites; formal and informal agreements with LNGS, Boulby, Kamioka, and Stawell, have all been made for the development of directional experiments, and could host the eventual network of Cygnus detectors. As well as simply facilitating a large scale gaseous experiment while maintaining low pressure operation, the modularity and distribution of the experiment provides several additional benefits: systematics could be controlled by comparison between detectors, and importantly, the modularity allows for flexibility in the size and shape of the detector and allows for expansion at each site. Utilizing multiple detectors would allow also the use of multiple target gases and pressures to explore different ranges of DM mass, different DM-nucleon interactions, and potentially optimize for the detection of electron recoils rather than nuclear recoils in a fraction of the total volume. The latter optimisation could be essential if Cygnus is to serve a dual-purpose as a DM and neutrino observatory, as we will discuss in the following section.

While a low-density gas such as 755:5 torr He:SF$_6$ is essential to maintain low-mass WIMP and neutrino sensitivity with directionality, the planned segmentation of Cygnus naturally enables operation of parts of the detector with a higher-density "search mode" gas. If we choose a vacuum-capable gas vessel design, then this would be capable of withstanding a 1 atmosphere pressure differential. In that case the search mode could utilize 1520 torr of SF_6 for a factor 300 boost in exposure, and around a factor of ∼17 boost in sensitivity at high masses . The beauty of Cygnus is that the exact partitioning of the target volume into low-density and search mode running can be optimized and varied even after construction, and be responsive to new developments in the field. This flexibility may prove particularly important for larger volume detectors, e.g. a Cygnus-100k with a total volume similar to that of DUNE [68], which will required a substantial investment of time and funding but could utilize directionality to penetrate deep into the neutrino fog perhaps even at high masses.

An exciting physics program will be possible with the anticipated network of Cygnus detectors, as illustrated in Fig. 3. To move forward, after a fully optimized technical design is outlined, all of the energy-dependent performance parameters of that design including energy resolution, angular resolution, head-tail recognition, and electron rejection, must all be validated experimentally. A Cygnus HD1 Demonstrator listed in Fig. 1 would be a 1 m^3 prototype with full drift length and high readout resolution and should be achievable within the tentative timescale of XXX years. This experiment would already be sensitive to neutrinos if placed near to a reactor or spallation source, and would allow optimisation for a next-stage solar neutrino search to begin. If along with this development, the intrinsic radioactivities of the components of the suggested strip readout can be reduced to a level consistent with the measured electron rejection capabilities, then progress towards a large-scale Cygnus detector network would be well underway.

3.4 CYGNUS Internationally

The US groups in the CYGNUS collaboration have converged on advancing high-definition (HD) recoil imaging using TPCs with electronic charge readout. This effort is referred to as CYGNUS HD. Previous and ongoing precision studies using ultra-high-resolution (pixel ASIC and optical) charge readout in small prototypes [?, ?] have shown that excellent particle identification capabilities, axial recoil directionality and head/tail sensitivity can be achieved even below 10 $\mathrm{keV_{ee}}$. Importantly, these studies have also taught us how to model recoil imaging detectors, and validated that our simulation tools can reliably predict recoil directional performance from the ground up, based on detector specifications. A large simulation study comparing different readout options revealed strip readout as a very promising strategy [4]. By combining custom CERN Micromegas amplification planes with x/y strip readout and off-the-shelf CERN SRS readout systems, we expect directionality in the sub-10-$\mathrm{keV_{ee}}$ regime can be achieved at substantially reduced (two orders of magnitude lower) cost, with components that can be readily mass produced. This should enable large-scale recoil imaging facilities at realistic cost. The initial target is to demonstrate the performance goals using electron drift gases, with which we have already previously achieved single-electron sensitivity. Construction of a 40l fiducial volume CYGNUS HD prototype is well underway, and will be used to optimize the gas mixture and choose between several Micromegas types. A 1000l fiducial volume CYGNUS HD1 Demonstrator, a unit cell prototype that will demonstrate the critical ingredients of a large-scale facility, has also been designed and construction will begin this year. This detector will use bi-directional drift and two two $1\mathrm{m}^2$ Micromegas x/y strip charge readout planes. While both CYGNUS HD detectors will operate with electron drift gases as a baseline, the natural blue-sky R&D goal is to increase the gas gain with negative ion drift gases (where gain is typically much lower) until individual primary electrons can be counted. Since the single-electron showers are due to electron avalanching and have the time-scale associated with electron drift gases, this electron-counting approach would allow re-using the existing SRS readout electronics (designed for electron-drift timescales) also for negative ion gases where drift velocities are much lower. Beyond negating the need to develop custom electronics, this would results in two very significant advances: substantially reduced diffusion due to negative ion drift (which drastically improves directionality at the lowest recoil energies), and substantially improved energy resolution because electron counting removes the contribution of avalanche variance to the energy resolution.

To fully explore all options, both NID and design approaches based on electron drift should be pursued. Electron drift allows much higher avalanche gains than NID gases, but at the cost of increased diffusion. For electron drift, fiducialization would be performed via measurements of diffusion, rather than via observation of minority carriers. The higher gain with electron drift gases could also be a good match for optical readout, and hence the CYGNO experiment in Italy [69,70] will pursue that option in parallel with the wider Cygnus collaboration.

CYGNO will use a CMOS camera coupled to a TPC with triple thin GEMs for gas amplification in a 60:40 He:CF_4 mixture at 1 bar [71]. This configuration provides the necessary high gas gain of $\mathcal{O}(10^6)$, with about one photon produced for every ten electrons [72]. In LEMOn, the largest CYGNO prototype, the drift length is 20 cm, achievable thanks to the low electron diffusion in He:CF_4. Fiducialization may also be possible because the high spatial granularity can allow the diffusion of ionization cloud to be measured, which in turn is dependent on the absolute track position along the drift direction. Preliminary measurements with LEMOn have demonstrated directional and head/tail sensitivity down to about $20\,\mathrm{keV_{ee}}$.

The Australian contribution to Cygnus is currently focused on the CYGNUS-1 prototype. This TPC contains a 1.5 L fiducial volume with a maximum drift length of 20 cm. The prototype's gas control system can supply arbitrary tertiary mixtures of gases and is able to operate between atmospheric pressure and 10 Torr. There is currently a dual charge-optical readout using a multi-wire proportional counter and a photomultiplier tube to readout signals from the GEM gain stage. There are near-term plans to add an intensified camera optical readout, which will permit the triggered acquisition of images and superb signal-to-noise ratios. The avalanche scintillation yields of negative ion gas mixtures are poorly studied, and CYGNUS-1 is intended to study the charge and light signals of a variety of gas mixtures, with a focus on those containing SF_6, a negative ion gas. In addition to detailed detector studies, the prototype will be used as a test-bed for technical challenges associated with operating a larger gas TPC, making use of the trace element analysis facilities at the Australian National University, which hosts the prototype. These include studies of gas capture, recirculation, and impurities, and the screening of detector components for radioactivity.

Text: Sven, Dinesh, Kentaro, Neil, Lindsey/Greg

4 Neutrinos

So far we have discussed the role played by recoil imaging detectors as instruments to detect and study DM interactions. However many of the same techniques, and even the same experiments as those that have been discussed are extremely well suited to studying neutrino interactions leading to nuclear and electron recoils. Although neutrinos, in particular CEνNS, has been introduced as a crucial background for DM searches, one experiment's noise can be a different experiment's signal. As a result, the sizeable physics case for underground dark matter experiments to use their eventual neutrino background as a signal has been explored extensively over the last few years [49,54,73–90]. In the case of a directional experiment we may even have the situation in which which source of events is a background and which is a background is nothing more than a matter of perspective. In this section we will discuss the ways in which recoil imaging in MPGDs and directional detection more broadly could be a route towards new discoveries in the neutrino sector.

4.1 Coherent elastic neutrino-nucleus scattering

Elastic scattering between nuclei and neutrinos is one of the more active frontiers of study into neutrino physics that has appeared recently. After COHERENT's first detection of CEνNS using a stopped pion source [91, 92], many more dedicated experiments have been proposed to test this prediction of the SM [93–95]. As discussed above, the importance of CEνNS in the context of natural sources of neutrino is well-appreciated, being a crucial background to the upcoming generation of direct dark matter searches. However, the physics case for precision studies of CEνNS using an artificial neutrino source, such as a spallation source in the manner of COHERENT [96] or a reactor [97–104], are extensive. As far as it is currently measured the CEνNS cross section as measured with both CsI [91] and LAr [92] targets appears to be consistent with a Z boson exchange as predicted by the SM. However, as a flurry of recent theoretical studies have shown, this channel is potentially promising as one for studying the nature of neutrino-nucleus interactions, the structure of nuclei, or even to discover the existence of new mediator particles. The latter could thus opening up doors to probe undiscovered dark sectors of particle physics, as will be discussed in the following Sec. 5. Nevertheless, even in the absence of any signal for new physics, simply measuring SM process itself also has important implications for high-energy physics, astrophysics, nuclear physics, as well as safeguard applications. Hence new experiments to test the fundamental nature of CEνNS in new ways are important. A notable instance of this that although the angular dependence of CEνNS is well-predicted, it has never been measured in any form. We highlight here the ways in which a direction-sensitive search could be fruitful.

One immediate reason why detecting the direction of the nuclear recoil in CEνNS is crucial is because it provides information that cannot be extracted from the energy spectrum alone. Moreover if combined with timing information, a directional detector could provide valuable additional information in searches for new physics whilst simultaneously subtracting the SM background. Since the direction dependence of CEνNS has never been measured, such an experiment could be agnostic about any reasons why it would depart from the SM. However, one example could be if there exists new light, GeV-scale mediators that contribute to the CEνNS process. These could generate distinct and prominent spectral features in both the angular and the recoil energy spectrum [105] which a recoil imaging detector would be able to disentangle even for nuclear recoil thresholds as high as 50 keV. The same principle could allow a directional experiment to make precise measurements of SM quantities involved in CEνNS, such as the Weinberg angle or the neutron distribution inside nuclei [106].

4.2 νDX-DRIFT

The idea to detect CEνNS directionally using a next-generation neutrino facility is currently being pursued for νBDX-DRIFT experiment [106]. An initial proposal was put forward to place a negative-ion TPC behind the NuMI proton beam dump at Fermilab, with the longer-term goal of operating a TPC at the DUNE Near Detector Complex.

There are several proposals for experiments that would build upon two the successful implementation of NID in a TPC done by the DRIFT experiment. As discussed in the previous section, NID allowed DRIFT to have the lowest energy threshold and best inherent directional sensitivity of any limit-setting, directional dark matter detector, including background-free limits [107]. With its unique directional and background rejection capabilities, the DRIFT's negative ion TPC technology is ideally suited to search for nuclear recoils in beam dump experiments, and a proposal was developed to search for light DM recoils behind an electron beam-dump at JLab. Preliminary work, including a test run at SLAC, suggests that a Beam Dump experiment using a DRIFT detector, BDX-DRIFT,

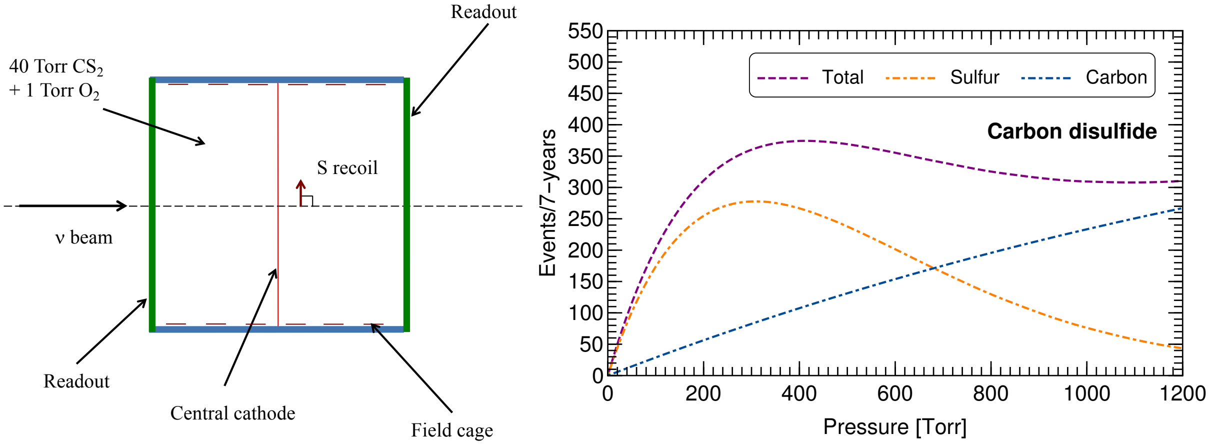

Figure 5: Left: Sketch of the back-to-back NID TPC design of the νBDX-DRIFT detector, with a central cathode and two readouts along the plane perpendicular the neutrino beam direction. Right: CEνNS event yield in a 10 m^3 experiment over 7 years for each nucleus present in CS$_2$, and as a function of the vessel pressure/energy threshold.

would have sensitivity rivaling the best limits on light dark matter and provide an unequivocal directional signature in the event of discovery [108]. The νBDX-DRIFT experiment then would extend this idea and place a detector behind a proton beam dump, such as in the DUNE Near Detector Complex.

The Near Detector Complex is 100 m underground. The beam timing structure at the NuMI beam is such that backgrounds are expected to be reduced to negligible levels. Proton beam-dumps produce a plethora of neutrinos, particularly the Long Baseline Neutrino Facility (LBNF) beam, which is optimized for neutrino production. Thus, in addition to traditional beam-dump searches for light dark matter we can also search for beyond the standard model (BSM) neutrino interactions. A 1 m^3 detector run for several years at the DUNE Near Detector Complex would detect several coherent neutrino-nucleus elastic scatters, potentially confirming recent CEνNS detection results [91, 92], but with minimal background. Off-axis and directional sensitivity will provide νBDX-DRIFT signatures to search for physics even in the presence of a neutrino background and opening up a new window to search for BSM physics.

A recent study [106] evaluated the event rates, backgrounds, and performance on the sensitivity to a number of physics measurements of a 10 m^3 experiment placed at LBNF. The design under consideration, shown in Fig. 5 (left), was a back-to-back NID TPC filled with a 40:1 Torr CS$_2$:O$_2$ gas mixture. This design is similar to the that used by the DRIFT collaboration for DM, and to the design proposed for 10 m^3 CYGNUS module shown in Fig. 4. The use of the LBNF is interesting in this context as it provides a way to probe CEνNS in the higher energy $E_\nu \sim 100$ MeV window, compared to reactor and SNS sources using Ge or CsI targets respectively. Usually this window is thought to be challenging to the need for sufficiently low backgrounds, however this challenge can be addressed by the inclusion of directional sensitivity. For the high energy neutrinos in the LBNF beamline, one can optimise the pressure to balance the need for high target mass, but also a low energy threshold which is not possible if the gas density is too high. As can be seen in Fig. 5 (right), a pressure of $\sim$ 400 Torr, corresponding to maximises the event rate to around 370 events over seven years—at higher pressures (i.e. thresholds) the event rate is suppressed due to the nuclear form factor of sulfur. Such a configuration could provide percent-level measurements of the Weinberg angle in the [0.1,0.4] GeV renormalization scale window. The directionality allows for a suppression in the neutrino-induced neutron background relative to the CEνNS signal of a factor around 20, potentially facilitating many other novel BSM searches not possible in other detectors.

In the near term a 1 m^3 νBDX-DRIFT detector is available to be deployed in the NuMI beam at Fermilab on a year or two timescale. Knowledge gained from those runs will inform proposed a proposed experiment in DUNE in the future.

4.3 Solar neutrinos

The Sun produces several well-understood fluxes of neutrinos from a variety of processes involved in nuclear fusion. Most CEνNS recoils will be from the $E_\nu \sim 10$ MeV neutrinos from the decay of ^{8}B nuclei. These are not the highest energy neutrinos emitted by the Sun—those being the neutrinos from ^{3}He-proton fusion—but they are the only ones that can generate a sizeable rate of nuclear recoils at keV energies. For electron recoils however, the kinematics result in much higher recoil energies at constant neutrino energy than in the case of nuclear recoils. This makes the electron recoil signature a very promising target for the directional detection community. In this case, the most substantial contribution will be from *pp* fusion which generates the vast majority of the total solar flux.

As well as DM, even for the worst-case scenario of an 8 keV$_\mathrm{r}$ nuclear recoil threshold, Cygnus-1000 would observe around 13 CEνNS events over six years from ^{8}B and *hep* solar neutrinos. This would be a significant achievement, given that CEνNS will not become an appreciable signal in conventional direct detection experiments until LZ or XenonNT have taken data. For a threshold of 1 keV$_\mathrm{r}$ this number increases to 37 which would already be enough to begin to characterize the neutrino spectrum.

Unfortunately, *pp* and ^{8}B neutrinos are not the most interesting type of solar neutrino astrophysically, since both fluxes are known rather precisely [109, 110]. Instead, one of the most sought-after solar fluxes are the neutrinos emitted in the Sun's "CNO cycle". Three fluxes of neutrinos labeled, ^{13}N, ^{15}O and ^{17}F, have only just been observed by Borexino after a heroic background modeling effort [111]. CNO neutrinos are almost entirely hidden under backgrounds, both from their fellow and more abundant solar neutrinos, as well as from radioactive contaminants. Yet they are a highly prized signal from a solar physics standpoint. A firm measurement of the CNO flux would help understand a long-standing disagreement between two models for the Sun's heavy element content [112]. This quantitative issue is subtle but has far-reaching consequences for astronomy since almost all determinations of astronomical elemental abundances rely upon the solar abundances.

The measurement of low energy solar neutrinos via directional electron recoils is, surprisingly, not a new idea. Largely-forgotten work from the 1990s [113, 114], proposed the use of a TPC filled with high densities of gases like He and CF$_4$ to detect solar-neutrino electron recoils $\gtrsim$100 keV. While most fluxes generating high numbers of electron recoils are now well-measured, the detection of CNO neutrinos is an intriguing possibility.

The most obvious novel aspect of directionality is background rejection. Unfortunately, in the case of CNO neutrinos, the major backgrounds will be *other* solar neutrinos. However, directionality is novel in another way when dealing with a signal originating from a single direction. Given the known position of the Sun and the combined measurement of recoil energy and direction, in theory, this information permits event-by-event reconstruction of the neutrino energy spectrum. In practice, this places high demands on the energy resolution and tracking of the detector, but the payoff is potentially substantial for distinguishing the different solar fluxes. A modern gas TPC with a

1000 m^3 volume at atmospheric pressure or higher could make *directional* measurements down to $\mathcal{O}(10)$ keV energies, much lower than the current threshold of Borexino of ∼160 keV. Borexino's current measurement of CNO neutrinos is not sufficient to resolve the solar abundance problem, so this novel and important physics measurement therefore makes a compelling case for ton-scale gas TPCs.

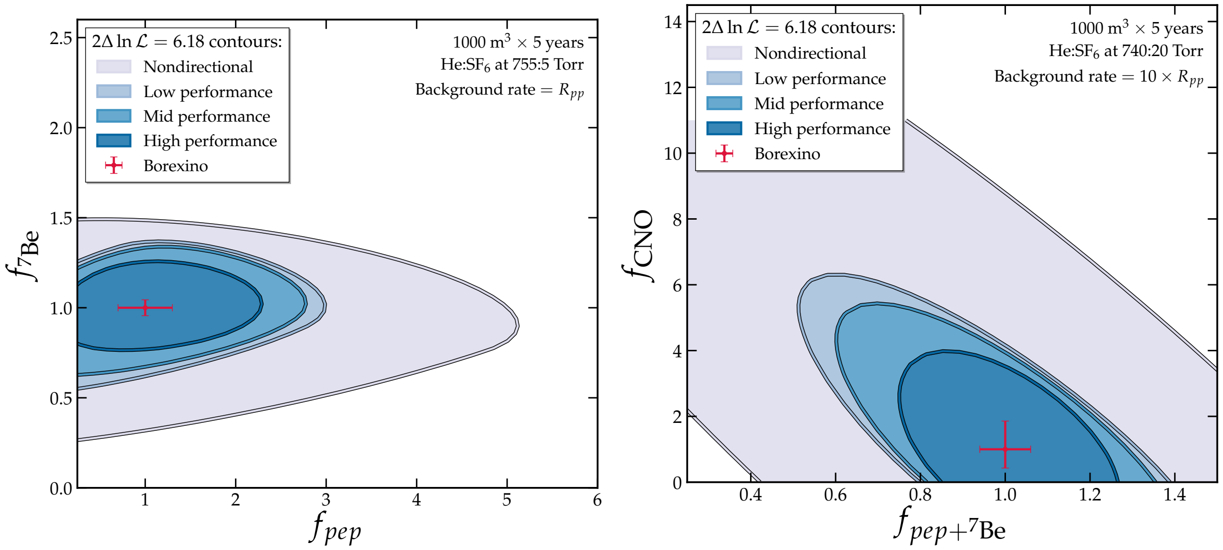

Figure 6: Forecasted 95% C.L. sensitivity to neutrino flux parameters, normalised to the B16 high-Z standard solar model of Ref. [109]. The various colours correspond to different levels of directional sensitivity, ranging for a best-case scenario based on optimistic projections for electron recoil energy/angular resolution, down to a worst-case scenario corresponding to an already demonstrated projection. The key observation is that the directionality provides a means to distinguish these different fluxes of neutrino that would otherwise provide very similar spectra in recoil energy.

The potential to do solar neutrino spectroscopy was evaluated in Ref. [115] in the context of the Cygnus collaboration as described earlier. In particular the goal of this study was to evaluate the detector requirements needed to address the aforementioned physics goals. In particular the key issues that must be addressed are 1) the electron recoil energy and angular resolutions and 2) the electron recoil background. Prospects can be seen in Fig. 6.

4.4 Non-solar neutrinos

For nuclear recoils, the most interesting source apart from the Sun are the possibility of a nearby burst of 10 MeV-scale neutrinos coming from a Galactic supernova. An explosion occurring at a distances closer than 3 kpc would be sufficient to produce a measurable number of highly energetic nuclear recoil events in a 1000 m^3 scale detector operating at atmospheric pressure. Of course if a SN occurred much closer than this then neutrino events would be guaranteed, possibly even in small-scale prototype experiments.

For electron recoils on the other hand, which can typically allow keV-scale and above sensitive detectors to access MeV neutrino energies, the most interesting source beyond solar neutrinos would be the constant flux of $\bar{\nu}_e$ coming from the Earth known as geoneutrinos. The energies are typically very low $\lesssim 4.5$ MeV, and so is the expected flux. The physics case backing a potential dedicated geoneutrino are substantial from the point of view of geophysics, in particular if such an experiment had directional sensitivity. For instance a 10 ton-scale gas detector operating for 10 years would be capable of a 95% CL measurement of the ^{40}K flux [116] and go some way to understanding the radioactive contribution to the Earth's surface heat flow [117, 118]. However ensuring good directionality of electron recoils at such a large scale will likely be something that must be evaluated further in the future.

4.5 Tau neutrinos

Another opportunity brought via recoil imaging, specifically in the context of noble gas experiments is the study of ν_τ interactions. Another major goal for the next decade of particle physics, the value of studying tau neutrinos is clear: precise measurement of neutrino oscillations in the ν_τ appearance and disappearance channels would directly test the unitarity of the neutrino mixing matrix [119, 120]. Any deviation from unitarity would suggest a portal into physics beyond the Standard Model. Yet, with a global sum of 21 identified ν_τ candidates [121,122], tau neutrinos remain the least experimentally probed particles in Standard Model. The Super-Kamiokande [123, 124] and IceCube [125] experiments have developed statistical methods to separate the tau neutrino component in the atmospheric flux; upcoming experiments such as DeepCore [126] or DUNE [127] plan to use similar techniques. Yet, the only technology deployed to select ν_τ charged current interactions via the tau identification at accelerator neutrino energies is nuclear emulsion. This guarantees excellent tracking (1µm in the active volume), but the long timescales and awkward data acquisition methods involved in emulsion readout makes scalability of such techniques impractical.

Experiments addressing DM searches with directional techniques and experiments aiming to detect taus in ν_τ charged current interactions face some similar challenges. In order to overpower the small cross section for neutrinos interactions or to compete with the current stringent limits on DM scattering, they must utilize a large target mass, requiring a detection medium with the highest possible density. Additionally, this large mass needs to be instrumented with an extremely fine-granularity tracking capability of order of tens of microns, to reconstruct directions of very low energy recoils or to identify the short-lived tau particle. This capability must, furthermore, be employed in such a way that the extreme channel density does not become a prohibitive technological hurdle for a large detector. This is why an MPGD using a gas such as argon may be the optimal approach. Achieving the required sub-mm track resolution, while also instrumenting the entire however will be a key challenge for the next decade if recoil imaging is to be feasible. Some specific R&D directions along these lines that have already been planned will be discussed in Sec. 7.6 and 7.7.

5 Beyond the SM

5.1 Searches for BSM physics using a neutrino source

Measurements using artificial neutrino sources such as reactor, stopped pions, or beam dumps all offer a potential gateway to beyond-the-SM physics measurements. These could include the detection of up-scattered heavy neutrinos, axion-like particles [128,129], and light DM candidates [130], which may produce novel signatures in angular spectra. With even higher statistics, constraining and disentangling a wide range of additional mediators that could be involved in CEνNS could also greatly benefit from additional information present in the angular distribution [105, 106]. Though the measured CEνNS cross section is consistent with the SM, there is still room for beyond-the-SM corrections below experimental bounds [131]. In the context of DM detectors, the effects of new mediators taking part in CEνNS have been considered, for example, in Refs. [49, 54, 81, 84, 132]. As well as providing opportunities for discovery, the added uncertainty in the CEνNS background also presents problems for conventional recoil detectors. As we discussed earlier, the height of the neutrino floor is controlled by the neutrino event rate, and its uncertainty. Non-standard interactions and additional mediators have the potential to increase both. In particular, the event rate at low energies relevant for GeV and sub-GeV WIMP searches is precisely where there is substantial room for large deviations from the SM. Conducting a directional search to unravel these subtleties and distinguish them from a potential DM signal, is therefore even more warranted.

Recently, several neutrino experiments have performed searches for sub-GeV dark matter-like particles produced in bremsstrahlung processes at beam dumps, with a putative experimental signature being a nuclear recoil [130,133–136]. The primary concern of such an interesting laboratory produced dark particle appearance search is the SM neutrino background. However when this idea is applied to potential searches at neutrino experiments, e.g. COHERENT [137], CCM [138], JSNS^2 [139], it is envisioned that timing and energy spectra could be used to isolate the SM background on the basis that the SM neutrinos should come from the prompt decays of π^+ and delayed decays of μ^+ [130,136]. For various types of new feeble interactions via scalar/gauge boson mediators, a signal could be distinguished from the SM background even in the absence of timing measurements, by measuring the recoil spectra and angular distribution with a direction sensitive detector.

Other BSM searches made possible by placing a directional recoil detector near to a neutrino source involve the search for up-scattered heavy neutrinos. Nuclear scattering from neutrinos or some other feebly interacting species could produce both additional particles such as heavier sterile neutrinos [140, 141], or perhaps a heavier state of the original particle, if the new physics existed in a spectrum similar to inelastic DM scenarios []. These heavy particles may decay within or outside the detector. If they decay occurs within the detector, the angular and recoil energy spectra would be able to distinguish this scenario from the SM background. However, if the heavier state decays into electrons or photons *within* the detector[6], then the angular and energy spectra of the electrons or photons would provide important additional handles.

5.2 Axion-like particles

Axions and axion-like particles (ALPs) are a general class of light, pseudoscalar particle that have several well-motivated interaction channels with SM particles [146]. One of the most important of these interactions is the axion to 2 photon conversion, also known as Primakoff conversion, that facilitates many dedicated experimental strategies (see for instance the one detailed in the next section). However axions are expected to also have derivative couplings to fermions, permitting their detection in recoil-based searches.

For example, recently it has been realized that photons produced in beam dumps at neutrino experiments may be able to create ALPs via the Primakoff (and/or Compton-like) processes [128,129,147]. The ALPs would then travel to the neutrino detectors and could be detected after they decay, or via their scattering induced by the inverse Primakoff or Compton-like processes. The ALP can produce two photons or electrons when it decays in the detector, which provides the best constraint of the ALP parameter space. The angular and energy spectra of the electrons and photons, as in the up-scattered case, would be very important to distinguish this signal from the background.

As well as a pure search for physics beyond the SM, ALPs may also play a role as the DM that makes up the galaxy. However in this case, a direct search for keV-scale nuclear recoils is no longer viable. ALPs, (or light bosonic DM candidates more generally, such as dark photons [148, 149]), would instead undergo absorption processes in atoms [150], resulting in the emission of electrons

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[6] this is one possible explanation [142–144] for the low energy excess in the MiniBooNE data [145]

with energies equal to the DM mass [151]. Therefore electrons from keV-scale mass particles are readily observable in most DM searches. The key issue is how to separate these signal electrons from all other sources of electron recoils. A major advantage of directional detectors in this context is the ability to not just discriminate electrons from nuclear recoils, but to discriminate many sources of electron recoil from each other. The event rate of electron recoils will essentially follow the angular dependence of the photoelectric cross section of the target atom or molecule. Since high-pressure gas TPCs optimised to detect solar neutrinos (see Sec. 4.3) will have good angular sensitivity to electrons with energies between $\mathcal{O}(10)$ to a few hundred keV, then the main competitors for bosonic DM searches will be neutrinoless double-beta decay experiments such as GERDA [152], who have set the most competitive limits so far using a 58.9 kg-year exposure. Assuming atmospheric pressure operation is possible, achieving a competitive scale will likely entail TPC volumes of a few tens of m^3 or above, making bosonic DM searches a longer term goal of recoil imaging.

5.3 MPGD development for IAXO

Axions are hypothetical particles appearing in extensions of the Standard Model (SM) of particle physics [153–158], proposed in the late 70s to solve the strong charge-parity (CP) problem [153,154]. Moreover, axions could be copiously produced in the early Universe and are a leading candidate for comprising the Dark Matter of the Universe [159–163]. Axion-like particles (ALPs) appear in a number of extensions of the SM (a prime example being string theory [146, 164–169]) could also have important roles in astrophysics and cosmology. The experimental search for these particles constitutes one of the main quests of modern particle physics and has a high potential for a new breakthrough in our understanding of the Universe, opening an entirely new window to physics beyond the SM.

These particles have very low mass and extremely weak interactions with ordinary matter. Axion search techniques rely on its omnipresent, although weak, interactions with photons. This interaction gives rise to the Primakoff effect, i.e. the conversion of axions into photons (and vice versa) in the presence of electromagnetic fields [170–172]. In practice, strong magnetic fields are used to trigger the conversion for detection, therefore axion experiments are usually linked to the use of powerful and large magnets. Depending on the source of axions, experiments can be conceptually divided into three categories. Those looking for the axions supposedly composing the galactic dark matter halo, those looking for axions produced in the sun ("helioscope"), and those looking for axions (or axion signatures) produced entirely in the laboratory. A comprehensive and recent review on experimental axion searches can be found in Ref. [173]. An overview of current, future, experimental and observational limits is given in figure 7.

Here we will concentrate on the helioscope technique which could potentially facilitate many interesting physics discoveries related to axions [174].

Axions can be produced in the solar core by the Primakoff conversion of plasma photons into axions giving rise to a solar axion flux at the Earth surface with a distribution around 1-10 keV. The helioscope technique was first applied in [175] and later by the Tokyo helioscope [176–178]. Today the concept has been used by the CAST Collaboration [179–185]. The CAST experiment has been using a 10 m long decommissioned LHC test dipole magnet providing a magnetic field of 9 T along its two parallel pipes of $2 \times 14.5\,\mathrm{cm}^2$. The CAST magnet point and track the Sun 3 h per day thanks to its rotating platform. The rest of the day is devoted to background measurement. Different X-ray detectors have been used since the beginning of the experiment: a conventional Time Projection Chamber (TPC) [186], a CCD [187], gaseous Micromegas-based TPCs [188] and an Ingrid TPC [189]. CAST was the first helioscope that applied low background techniques to X-ray detectors, previously

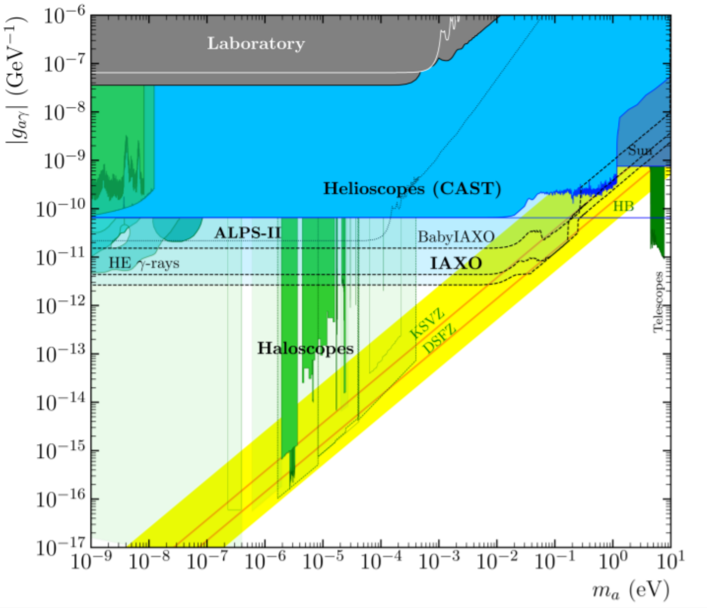

Figure 7: Sensitivity plot of axions experiments in the primary $g_{a\gamma} - m_a$ parameter space. Current (solid) and future (dashed) experimental and observational limits. The yellow band represents the standard QCD axion models and the orange line the benchmark KSVZ model.

employed in other rare event searches (dark matter, double beta decay…). A second originality is the use of X-ray focusing mirror systems, which increased the signal-to-noise ratio and the sensitivity of the experiment: a mirror from the X-ray astronomy mission ABRIXAS [190] coupled to the CCD or Ingrid TPC, and a mirror specially designed for axion detection using NUSTAR tooling, which was coupled to a Micromegas detector [191].

The CAST experiment has been taking data since 2003 providing the most stringent experimental limits on the axion-photon coupling for a broad range of axion masses. In the first phase of the experiment, the CAST magnet operated in vacuum to probe masses $m_a < 0.2$ eV. No signal was observed and an upper limit on the axion coupling constant $g_{a\gamma} < 0.66 \times 10^{-10}\,\mathrm{GeV}^{-1}$ at 95% CL was derived reaching similar levels to the most restrictive astrophysical bounds. The CAST experiment extended its sensitivity by operating the magnet with ^{4}He and ^{3}He at different pressure settings to obtain high continuous sensitivity up to $m_a = 1.17\,\mathrm{eV}$ [192]. The International AXion Observatory [174, 193, 194], IAXO, a new generation of axion helioscope, aims to improve on the CAST sensitivity by 1–1.5 orders of magnitude. The conceptual design consists of an 8-coil toroidal magnet with 60 cm diameter bores equipped with optics focusing X-rays into 0.20 cm^2 spots coupled to ultra-low background detectors. The magnet will be on a platform that would allow solar tracking for 12 hours per day.

BabyIAXO [195] is an intermediate scale experiment with a single bore magnet with similar dimensions to full IAXO bores. It will allow to improve all the systems and to mitigate the risks for IAXO. BabyIAXO will be a test bench for the magnet, optics and detectors providing a relevant physics outcome with an expected data taking for 2024.

The Micromegas detectors developed for the CAST experiment are the baseline technology for the X-ray detectors of IAXO. The background levels achieved result from a global approach where the improvement has come from different fronts: from a new manufacturing technique, Microbulk, leading to highly intrinsically radiopure detectors with high performance; from the optimization of the passive and active shielding thanks to an understanding of the background; and from the refinement of the background rejection algorithms. The Micromegas detectors of CAST have been in continuous evolution since 2002 with different Micromegas technologies and shieldings. At the start of CAST, only one detector out of the four installed was a Micromegas. Since 2004 and thanks to the achieved performances, the four X-ray detectors of CAST are based on Micromegas technologies. The detector installed since the 2014 CAST data taking campaign on the "sunrise side" presented major novelties: it was the first time a Micromegas detector is operated with an X-ray optics that has been specially designed and built purposely for an axion application. The total efficiency of the detector, taking into account all the losses due to thin windows, is 75% in the energy range of 2-8 keV. The background level of the detector has been improved over previous designs, reaching a value of $(1 \pm 0.2) \times 10^{-6}$counts keV^{-1} cm^{-2} s^{-1} [191] the lowest achieved at CAST. Thanks to this result, the best experimental limit on $g_{a\gamma}$ was achieved [192]. This system can be considered as a technological pathfinder for IAXO with a series of improvements as the background level needs to be improved by a factor 10. A substantially improved muon veto system should allow to bring the detector background to a level of $\sim 1 \times 10^{-7}$counts keV^{-1} cm^{-2} s^{-1} , and we consider this a realistic target for the BabyIAXO detectors. Additional improvements beyond this level are possible, following improvements in shielding and veto extensions towards the pipe to the magnet, moving to a Xe-based operation and new electronics. The final effect of these improvements in the background level remains to be quantified, but could potentially lead to the $\sim 1 \times 10^{-8}$counts keV^{-1} cm^{-2} s^{-1} levels.

GridPix detectors are an evolution of the Micromegas technology where the Micromegas mesh is produced by photolithographic postprocessing techniques on top of a pixelized readout chip allowing small feature sizes and precise alignment [189]. Each grid hole of the mesh is aligned to one pixel allowing single electron detection. A GridPix detector was developed installed and operated in the CAST experiment in 2014–2015 with an energy threshold of 300 eV and achieving background levels of $\sim 1 \times 10^{-5}$counts keV^{-1} cm^{-2} s^{-1} [189,196]. Background levels were improved by in the last data taking by introducing an active cooling in order to avoid performance dependence with temperature, introducing and active muon veto and recording the mesh for triggering purposes and for signal shape background discrimination. These improvements should lead to an improved background reduction. The final background levels are being finalised.

In order to further improve background levels for BabyIAXO, the radiopurity of the GridxPix detector will be optimised by developing new polyimide PCBs and finding radiopure materials for the mounting of the detector on the beamline. In addition the successor of the TimePix, TimePix3 will allow a fully three-dimensional reconstruction of the charge cloud associated with the X-ray conversion can be exploited for improved background rejection. Furthermore, dead-time free readout can be achieved. With the combination of all these efforts, background levels similar to the ones obtained with the Micromegas detector should be at reach.

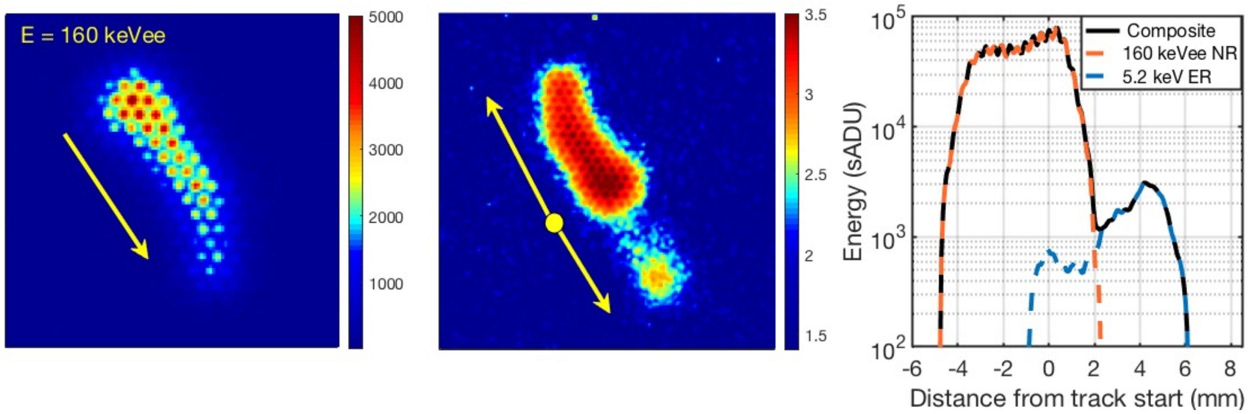

Figure 8: *Left panel*: a 160 keV$_{\mathrm{ee}}$ nuclear recoil track, showing the reconstructed direction (arrow) derived from its dE/dx profile. *Middle panel*: An example Migdal event constructed by taking a composite of the 160 keV$_{\mathrm{ee}}$ nuclear recoil image with that of a ∼5.2 keV electron track with their interaction points overlaid. Due to the large difference in the dE/dx of the electron and nuclear recoil, the intensity along the electron track was scaled up by a factor 5 for visualization purposes, before co-adding to produce the image. The reconstructed directions (arrows) derived from the dE/dx profiles are used to identify each particle in the Migdal event and its interaction point (yellow dot). *Right panel*: The dE/dx profile of the full Migdal event. Here we show projected intensity along the major axis of the reconstructed track for both electron (blue dashed) and nuclear (orange dashed) recoils, as well as their sum (black solid). Here the true scaling between the electron and nuclear recoils was used.

6 Other applications

6.1 Migdal effect

When performing a naive two-body nuclear scattering calculation, it is typically assumed that the electron cloud follows the recoiling nucleus instantaneously. This approximation implies that for low enough energies, at some point the resulting ionization signal is unobservably small. However, the nucleus and the atomic electron cloud are distinct entities, and taking the so-called "Migdal approach" of treating them as such reveals a potentially interesting new source of ionization for very low energy nuclear recoils [197–202], as well as other detectable signals [203, 204]. If we model the nucleus and electron cloud separately, the electrons will lag behind the nucleus during a scattering event. In the frame of the nucleus, the electron cloud is seen to experience a small boost, which can excite or ionize an electron. The effect is small but can become the dominant source of ionization at very low recoil energies. For example, in xenon or germanium, the maximum kinetic energy of a recoiling atom from, say, a 1 GeV DM particle would be ∼0.1 keV—far below experimental thresholds [202]. Nuclear quenching will reduce the measurable energy further, compounding the problem.[7]. Yet the Migdal prediction of the rare emission of a ∼keV electron would clearly be detected. So in the context of DM searches, simply invoking this effect can improve bounds for sub-GeV DM masses [205]. Most remarkable amongst these are EDELWEISS [206] and XENON [207], who lowered their mass reach down to 45 and 85 MeV, respectively. XENON's sensitivity to WIMP masses was lowered by almost 2 orders of magnitude, which, together with EDELWEISS's result, effectively rules out a large area of unexplored parameter space targeted by future experiments being

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[7] At these low energies this is further compounded by quenching, where only ∼10% or less of the energy lost by the recoil goes into a form accessible to the detectors, e.g., scintillation or ionization.

developed to explore the sub-GeV mass range.

While calculations of the Migdal effect exist [202, 208, 209], the process itself has never been measured.[8] This raises doubts about the validity of the effect, especially since theoretical atomic physics calculations are performed under specific assumptions, which may break down in liquids or molecular targets. A possible route towards a first experimental verification could involve a directional measurement, as has been recently proposed by the MIGDAL collaboration [213]. Such a measurement would be advantageous for a conclusive identification of the effect because of the additional handle on the kinematic relationship between the Migdal electron and the recoiling nucleus that directional information provides. Of the available directional technologies we have discussed, recoil imaging with HD gas TPCs stands out as the ideal strategy for the study of the Migdal effect. A low pressure TPC with a highly segmented ionization detector could provide both the high signal-to-noise and fine-granularity 3d track reconstruction needed to give detailed information on the low energy tracks. In contrast to DM or neutrino searches, an experiment sensitive to this rare effect (with a probability of $10^{-5} - 10^{-4}$ per nuclear recoil), would not require large volumes. Instead, one could focus on designing the best technology without the worry of scaling-up and the associated cost and complexity.

To detect and fully reconstruct a Midgal event in a dedicated gas TPC experiment, the $\mathrm{d}E/\mathrm{d}x$ measured along the track could be used to identify the electron and nuclear recoil emerging from a common vertex, and then to measure the direction of each particle along its track.

The challenge for such a measurement is to fully detect the low $\mathrm{d}E/\mathrm{d}x$ electron tracks, which requires high resolution and signal-to-noise approaching single primary electron detection. The detection of electron tracks down to a few keV has been demonstrated in Ref. [214] using a small TPC operating in 25–100 Torr of CF_4, with an optical readout consisting of a CCD camera coupled to a fast lens. The TPC consisted of a double-THGEM (thick gas electron multipliers) gas amplification device with a 9.5×9.5 cm^2 active area and a similar sized copper mesh cathode placed 2 cm below. An electron and nuclear recoil track imaged with this TPC with the CCD replaced by a more sensitive EMCCD are shown in Fig. 8. One can see how the order of magnitude lower $\mathrm{d}E/\mathrm{d}x$ of the electron ($<\mathrm{keV_{ee}/mm}$) relative to that of the nuclear recoil ($>10\ \mathrm{keV_{ee}/mm}$) could be used to distinguish them. The directionality of each particle can also be deduced from the $\mathrm{d}E/\mathrm{d}x$ profile, with the nuclear recoil's falling towards the head of the track, and the electron's rising. This is a fortuitous difference that can be used to reconstruct the common vertex of the two particles.

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For a recoil imaging Migdal experiment, either optical or electronic MPGD-based readouts could work since most atoms of interest for DM searches can be found in scintillating gases. What is more important is that the detector has the highest 3d track resolution possible to measure the effect

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[8] The Migdal effect covers a broad range of phenomena, from α- and β-decay, to neutron scattering. Although experiments have measured it in the former two processes [210–212], they have not done so for the latter, which best approximates the light DM interaction.

down at the energies relevant for DM searches. In this regard, an ideal detector would be a TPC with fine-granularity MPGD readouts operating with NID.

6.2 Directional Neutron detection

Recoil imaging can also be used to achieve direction-sensitive neutron detection. In the case of the most common application — directional detection of *fast* neutrons by imaging nuclear recoils resulting from elastic neutron-nucleus scattering — the recoil-energies involved are typically higher (up to order 100 keV) than those expected from dark matter scattering (up to order 10 keV). Therefore, directional fast-neutron detection is slightly less challenging and a good stepping stone on the way towards directional dark matter detection. At the same time, both directional neutron and dark matter detection benefit from lower energy thresholds, so that many of the technological challenges are shared. Several groups working towards directional dark matter detection with gas TPCs have already successfully demonstrated smaller-scale directional neutron detectors based on optical readout [215], strip-based charged readout [216], and charge readout via pixel ASICs [20]. Such TPCs are relatively portable, compact, tolerant of high signal and background rates, and capable of measuring both the energy spectrum and directional distribution of a neutron field. So far such detectors are not in wide use, but a large number of diverse applications appear feasible and have been proposed, including directional neutron background monitoring at underground labs, directional detection of special nuclear material, fuel rod monitoring, monitoring of atmospheric neutrons, and possibly even monitoring of neutrons in space. Focusing on US efforts, the BEAST TPC detectors developed at the University of Hawaii [20] have been operating for several years in an extreme background environment at the SuperKEKB electron-positron collider in Japan, and have been successfully used to characterize the rate, spectrum, and directional distribution of neutrons there [217–220].

6.3 X-ray polarimetry

Text: Elisabetta

X-ray polarimetry is recognised as a fundamental tool to study the origin of cosmic rays in the Universe, the nature and the role of black holes in the evolution of galaxies, and the interaction of radiation and matter within the highest physically possible magnetic fields [1]. Polarization fraction and angle are in fact powerful observables for probing the emission mechanism of exotic astrophysical objects, characterized by strong gravitational and magnetic fields, highly asymmetric geometries and explosive phenomena [1]. Polarimetry can also improve our understanding of solar flares, with implications in space weather science [2]. The lack of suitable sensitive instrumentation in the X-ray energy band has been the limiting factor for its development in the last 40 years. This was mainly due to the limitation of the experimental techniques used, based on Bragg diffraction (too narrow energy band) or on Thomson scattering (loss of efficiency for energies $\lesssim$ 10 keV due to photoelectric absorption). Moreover, contrary to imaging, spectroscopy and timing, these techniques are not suited to be combined with X-ray optics, a feature that effectively allowed the study of a few galactic sources only. Nonetheless, recent developments in highly-performing imaging and tracking devices make today Gas Pixel Detectors (GPDs) and Time Projection Chambers (TPCs) exploiting the photoelectric effect a promising basis for innovative sensitive X-ray polarimeters [3,4,5,7]. In photoionization, in fact, the s-photoelectron is ejected preferentially in the direction of the electric field of the incident photon, with a probability distribution of $\cos 2\phi$, where ϕ is the polarization dependent azimuthal angle correlated with the photon momentum direction. By reconstructing the impact point and the original direction of the photoelectrons, a high resolution gas detector can measure the linear polarization of X-rays, while preserving the information on the absorption point, the energy and the time of individual photons. The exploitation of such effect to measure X-ray polarization with a gas proportional counter was first proposed in 1992 [8]. From this first proposal, in the past years the first Gas Pixel Detector (GPD) optimized for x-ray polarimetry measurements in space was produced [4,5,9] and launched on the IXPE mission in December 2021. The GPD is a 1 cm drift distance TPC with He:DME gas mixture, single Gas Electron Multiplier (GEM) amplification and innovative charge pad readout, a finely subdivided custom VLSI ASIC, realized in 0.35 um CMOS technology. This allows full 2D imaging capability over an area of 15 x 15 mm2 covered by 105k hexagonal pixels down to about 3-4 keV energy for the photoelectron track produced in the absorption of the X-ray. The GDP proved the possibility to nicely operate a high-resolution gas detector in space in sealed condition, opening the doors for the full exploitation of this technology.

The combination of the GDP concept with recent developments in imaging techniques for high-resolution TPCs can significantly contribute to the next generation of X-ray polarimetry detectors.

Advances in commercial CMOS processes have led to the availability of highly segmented sensors with $\gg$ 100k pixels, each operating as an independent element. Such sensors can be used to detect either the electrons (i.e. charge), or photons (i.e light) produced in the amplification stage of a gas detector. This will open the doors for two lines of advances:

- improved performances for detectors on a focal plane (X-ray incidence perpendicular to the drift field), thanks to the use of highly performing pixel chips such as the Timepix3 [10] for next generation optics. Timepix3 can provide single electron sensitivity and 3D tracking, allowing to discriminate photoelectrons emitted out of the plane from the ones suffering high Rutherford scattering, and therefore with limited information on polarization. The Timepix3, thanks to its 5.12 Gbps output bandwidth, will allow to perform time resolved X-ray polarimetry with planned or very high throughput future telescopes with virtually no dead time;
- development of large area/volume detector for the measurement sources brighter than the background, especially transients, (with no requirement on X-ray focusing, hence compatible with mini/micro and even nano-satellites), with the use of CMOS cameras, following recent developments by the CYGNO collaboration within directional Dark Matter searches[11,12], possibly also exploiting negative ion drift operation [13]. With this second approach, new transient sources with unpredictable orientation could be studied, opening a new window on a completely still unexplored territory of observation, not accessible to the detectors installed on IXPE or eXTP missions [14].

We are today witnessing the dawn of X-ray polarimetry, with the first measurements coming from the GDP installed on IXPE. The two new observables that will become available (i.e. the polarisation fraction and angle) encode crucial information not only on the geometry of the studied system, but also on the structure of the magnetic and gravitational fields, and will result in a breakthrough for Astronomy, Astroparticle, Particle Physics and Fundamental Physics.

X-ray polarimetry can not only test models of X-ray emission and propagation, but also provide qualitatively new and independent ways to measure intrinsic properties of black holes as well as significantly improve the comprehension of the mechanisms fuelling the most powerful cosmic particle accelerators, such as supernova remnants and pulsar wind nebulae, and the mechanism responsible for the prompt emission and the structure of gamma ray burst jets.

Fundamental physics tests can be performed with polarimetry measurements, exploiting the Universe as a laboratory of extreme phenomenology [40], such as measuring QED vacuum birefringence or test General Relativity in extreme gravity fields [40] thourgh the measurement of rotation of the polarization angle and degree of Black Holes.

Polarimetric measurements allow moreover to search also for Axion Like Particles (ALPs), that could be produced via nucleon-axion bremsstrahlung in the core of Neutron Stars [47]. ALPs travelling through the magnetosphere will convert into photons polarized parallel to the plane containing the electric field and the external magnetic field of the Neutron Star, inducing an overall high degree of parallel polarisation that could lead to a clear detection signal.

Finally, X-ray polarimetry allows for the study of Solar flares, that can not only help us to better understand our star magnetic field behaviour, but it can be significantly valuable for space weather science, with a substantial impact on society and economics. The occurrence of these events is in fact known to strongly influence the space surrounding Earth, with dangers for military, commercial and communication systems. Solar flares polarisation measurements can therefore greatly impact society and economics by adding to space weather information on the Sun activity in the soft and hard X-ray energy bands, that incorporates some of the prime diagnostics for these hazards.

6.4 Rare nuclear decays

Text: Dinesh

7 Near-future detector development

Having focused so far mostly on the physics case that motivates the general concept of recoil imaging via MPGDs, we now come to talking more specifically about certain experimental R&D directions that must be followed for this physics case to be realised. In particular we will highlight some of the *requirements* that will be needed by future large-scale and high-resolution imaging detectors, for example scalability. This section focuses itself with developments that are either ongoing, or with plans for the near future. With more blue sky R&D covered in the following section.

7.1 Recoil imaging performance requirements

The performance required for a directional recoil detector targeting both solar neutrinos and $\mathcal{O}(10\text{ GeV})$ DM masses is reviewed in detail in Ref. [5]. These applications require event-level directionality with angular resolution $\leq 30^\circ$ and excellent head/tail sensitivity, ideally down to recoil energies of $\mathcal{O}(5\text{ keV})$. A 1000 m^3 detector volume would require that internal electron backgrounds be reduced by factors of at least $\mathcal{O}(10^5)$, also down to $\mathcal{O}(5\text{ keV})$. Fractional energy resolution of order 10% at 5.9 keV appears sufficient, and even poor timing resolution, of order 0.5 h, should suffice. These requirements are consistent what was considered an optimistic performance scenario at the conclusion of a previous optimization study [221], which focused on fluorine recoils in CF_4. The main difference in our requirements is the need for good energy resolution, which would be needed to reconstruct neutrino spectra, but which is likely also required to achieve sufficient electron background rejection suitable for large detectors.

7.2 Performance in practice

Gas TPCs are now close to meeting these performance requirement. Yet the optimal operating configuration in terms of gas mixture, pressure, readout segmentation, and drift length needs further study. One promising approach is high definition (HD) charge readout, meaning electronic readout with high spatial segmentation via MPGDs. High segmentation will almost certainly be required to achieve sufficient discrimination between nuclear and electron recoils.

In practice, angular performance of gas TPCs is strongly energy dependent. For example, the Cygnus simulation of optimized gas TPCs [4] suggests an angular resolution of 10° and a head/tail efficiency of nearly 100% is feasible for helium recoils $\gtrsim 50$ keV$_\mathrm{r}$. At lower energies, even a highly idealized detector is limited by the primary ionization distribution of the recoils to about 28° resolution and 70% head/tail efficiency. A realistic gas TPC with diffusion loses most directional sensitivity at 1 keV$_\mathrm{r}$. Since solar neutrinos and $\mathcal{O}$(GeV) mass WIMPs generate most nuclear recoils below 10 keV$_\mathrm{r}$, the greatest challenge for future detectors will be to extend good directional performance to low energies.

In designing future detectors, the contribution of TPC readout performance to angular resolution can be reliably predicted, see Equation 5 in Reference [222]. For mm-length nuclear recoils, this leads to the requirement of highly segmented detectors, with feature size $\mathcal{O}(100\,\mu\mathrm{m})$, and low diffusion. The contribution from the spatial shape of the primary ionization distribution, especially below 10 keV$_\mathrm{r}$ has, however, large uncertainties, and the same is true for the head/tail efficiency. Because these directly affect the designs of future detectors, it is imperative for the field to validate the commonly used simulation tools at the lowest energies. Validation work using helium nuclei for energies above 50 keV$_\mathrm{ee}$ and carbon and fluorine above 10 keV$_\mathrm{ee}$ can be found in Reference [14]. Fluorine recoil measurements going down to 6 keV$_\mathrm{r}$, can be found in Reference [223]. For progress in this direction, recoil imaging detectors with low pressure, high definition (HD) readouts and minimal diffusion are required.

7.3 Electronic readout

Given the abundance of available TPC charge readout technologies, it is not straightforward to determine the best strategy for a large-scale detector. The recent Cygnus design study [4] is the first attempt at such a technology comparison, and suggested that x/y strips with $\mathcal{O}(100\,\mu\mathrm{m})$ segmentation provide the best cost/performance tradeoff. An optimized strip readout should enable HD charge readout near the resolution obtained with pixel ASICs, but at substantially reduced cost and complexity. Based on this, two (40 liter and 1000 liter) “Cygnus HD demonstrator” detectors, utilizing CERN strip Micromegas readout and CERN SRS DAQ systems, are now under construction [224] in the US.

In the optimal case, a HD TPC would count every single electron in 3d with near unity efficiency, 100 μm-scale segmentation, and the smallest possible diffusion—implying NID. Pixel ASIC readouts are already close to achieving this [21], but probably not cost-effective for detectors beyond the m^3 scale. For larger detectors, strip readout appears more realistic, but if NID is used, this may first require development of optimized readout electronics.

7.4 Optical readout

Recording scintillation light emitted during avalanche multiplication in amplification structures such as GEMs or Micromegas offers an alternative way to visualise events and exploit highly pixellated and sensitive photon sensors. Optical readout of MPGDs is being explored for and used in a number of applications from radiation imaging to event reconstruction in optical TPCs. The intuitive visualisation of event topologies and the high granularity offered by modern imaging sensors are also important features for nuclear recoil imaging and enable detailed measurements of event topology, directionality and deposited energy distributions. Current examples include the CYGNO project aiming at the detection of directional dark matter and solar neutrinos with a low energy threshold [225] in a large optical TPC, the MIGDAL project combining optical and electronic readout for the observation of nuclear recoils and electrons as signature for the Migdal effect [226] and the ARIADNE dual-phase LAr TPC [227].

Optical readout can offer an attractive way to profit from the latest developments in imaging sensors including high granularity pixel sensors, increasing frame rate capabilities, wide dynamic range and low noise characteristics and is thus a good candidate for imaging short recoil tracks while maintaining the possibility to extract directionality information and operate in the presence of events with highly variable energy deposits. While suitable optics and detector windows offer great flexibility in the placement of imaging sensors and allow relatively simple adaption of the readout system for different detection areas, spectral sensitivity is a crucial challenge and requires careful considerations to match emission characteristics of detector gases with the sensitivity of recording devices. CF4 has been a popular choice due to its strong visible scintillation band which can be picked up by many standard imaging sensors but may not match experimental requirements due to detector operation or investigated interaction processes. In addition, future restrictions on the availability of CF4 are expected due to its greenhouse warming potential. Investigations of scintillation spectra of alternative gas mixtures, optimisations of wavelength shifters and adaptation of imaging sensors to cover wide spectral ranges and allow direct recording of light emitted by other scintillation gases and mixtures will be important to extend the optical readout approach to a more applications and make it compatible with a wider range of experimental requirements and constraints. The use of image intensifiers with different photocathode materials to extend spectral sensitivity is already explored and can offer a modular way to adapt optical readout systems to varying experimental requirements.

While imaging sensors offer highly detailed 2D visualisations of tracks, slow frame rates on the order of tens to hundreds of frames per second have conventionally limited optical readout to an integrated imaging approach. For the case of track reconstruction in optical TPCs, this means that an additional fast detector such as a PMT is required to provide depth information which can then be merged with 2D images. Alternative approaches such as the extraction of depth information from diffusion or the use of semi-transparent readout anodes for simultaneous optical and electronic readout can be used to increase reconstruction capabilities in 3D for intricate track topologies. In addition, the latest generation of ultra-fast CMOS sensors may overcome previous frame rate limitations and allow for direct reconstruction of drift processes from sequences of images with µs-level inter-frame intervals. Currently limited by resolution and sensitivity, future developments towards even faster and more sensitive CMOS cameras may be used for track visualisation in optical TPCs. Hybrid readout devices like Timepix-based cameras as well as other fast photon detection technologies like SiPMs may offer alternative ways to obtain depth information while profiting from high granularity 2D images.

Technical advances in photon detection devices towards increasing pixel counts, single-photon sensitivity and an extension of the accessible range of spectral sensitivity as well as higher readout speeds make optical readout a highly flexible and versatile approach for detailed visualisation of particle tracks and recoil processes.

7.5 Scalable readout electronics

The scalable readout system (SRS) is a widely used readout system [228] for high channel count detectors, e.g. MPGDs, with up to several MHz per channel readout rates [229]. It consists of a crate-resident backend and a detector-resident frontend with integrated readouts ASICs. The most recent

SRS frontend is based on the VMM3a ASIC [230] which includes zero-suppression and configuration settings for a wide range of detectors. The SRS paradigm splits the backend and frontend into fully functional, independent DAQ slices of minimum 128 channels, allowing to start detector R&D with a single, 128- channel "hybrid" to be read out by a crate-based SRS backend and dedicated online software. The addition of more hybrids is in principle unlimited, requires however addition of SRS hardware. Larger systems require more performant PCs or Server-level technology. SRS comes with professional DAQ and controls software associated with default particle physics data analysis tools (ROOT). Channel hit rates in the 1 MHz range may require fast trigger selections in order to reduce bandwidth or alternatively to enhance the physics content of events.

PBX is a short acronym for "Power Box with X for cross-linked trigger FPGAs". Optionally inserted into the frontend HDMI links of SRS, the PBX modules allow for implementation of fast triggers in Spartan-7 FPGAs. Bi-directional, high-bandwidth LVDS cable rings can be connected via the PBX front-panels to generate ring topologies for FPGA algorithms working over larger regions. Apart from the trigger extensions, the PBX is an SRS system module which provides local power to a VMM frontend and which operates in one of 4 possible readout modes. Only the ART (Address in Real Time) mode of the PBX is subject of this LoI.

In the ART mode, the PBX routes hits from up to 1k VMM channels from 8 SRS-VMM hybrids to a single, PBX-resident FPGA. ART is the 5-bit, charge-over-threshold address of the first VMM channel, and preceded by a flag bit. The latency for single-hit addresses from a 1024 channel region arrives in the FPGA over 5 m HDMI links is less than 80ns. Simple local trigger algorithms can complete in O(100-150ns) with trigger outputs both on the front-panels and at the SRS backend. For trigger regions involving multiple FPGAs, and requiring inter-communication over LVDS links, we assume that interlinked regional triggers complete in significantly less than 1us. The current VMM3a version limits the ART feature to single hits per chip and we strongly advocate that next VMM chip revisions should unblock successive ART addresses for multiple hits per chip. Up to 4(8) PBX modules can be stacked in a new PBX Mini(Euro)crate. For triggering purposes, the VMMs are to be configured in the ATLAS mode as opposed to the SRS- default self-triggered mode. Whilst 2D regional triggers, or 3D topology triggers are particularly interesting for confined particle signatures like directional DM events [4], alpha particles counting, or hierarchical triggers in calorimeters [231], basic timing triggers like veto, coincidence, gate, or busy are available through the front-panel. In order to assist the development of standard trigger algorithms the PBX FPGA is mastered by a 32-bit MCU card with USB port. This subsystem allows for development of laptop-based GUIs like already developed for VTC hybrid tester [232] in order to give users or shifters easy access to trigger functionalities and their parameters.

SRS is a very mature readout technology developed since 2009 with resources of the RD51 collaboration and using CERN infrastructure and resources . A large number of RD51 collaborators have contributed to its progress and wide acceptance within the MPGD user community. Following a very successful early period with the analogue APV frontend, newer frontend technologies, like SAMPA, Timepix and in the particular VMM have been interfaced to SRS. Based on the latest VMM3a ASIC version developed by BNL for the ATLAS NSW detector [233], SRS was fully redesigned on all levels for commercial SRS production. Ca. 40% of 120.000 ordered VMM channels for 15 teams have been delivered and reference systems are exploring the possibilities given with SRS-VMM [234]. The new PBX can be optionally get inserted into the SRS frontend links to provide longer distances between backend and frontend with four modes of operation. At the time of writing the PBX module is fully specified from the system level down to the schematics and 3D levels. A first prototype implementation is expected by the end of 2020.

This LoI represents a call for competences to implement FPGA-based region trigger functionality with GUI-based user control on the new PBX SRS platform. PBX hardware will very soon become available for developers for implementing trigger features at the level of firmware, software, testing and commissioning with the following work plan:

- Establish a full set of uPython procedures to access FPGA resources via I2C, SPI and JTAG
- Develop a MAC and/or Windows-based GUI for embedded use of uPython procedures
- Implement the basic set of standard PBX triggers (fast-or, veto, coincidence, busy)
- Add multi-level trigger definitions for region and topology triggers
- Establish a common trigger database for the PBX (binaries and sources)
- Provide GUI-level parameterization of triggers
- Provide a stand-alone, debug-level test environment without SRS backend
- Establish a standard user guide for shifters

7.6 Directionality in gaseous argon

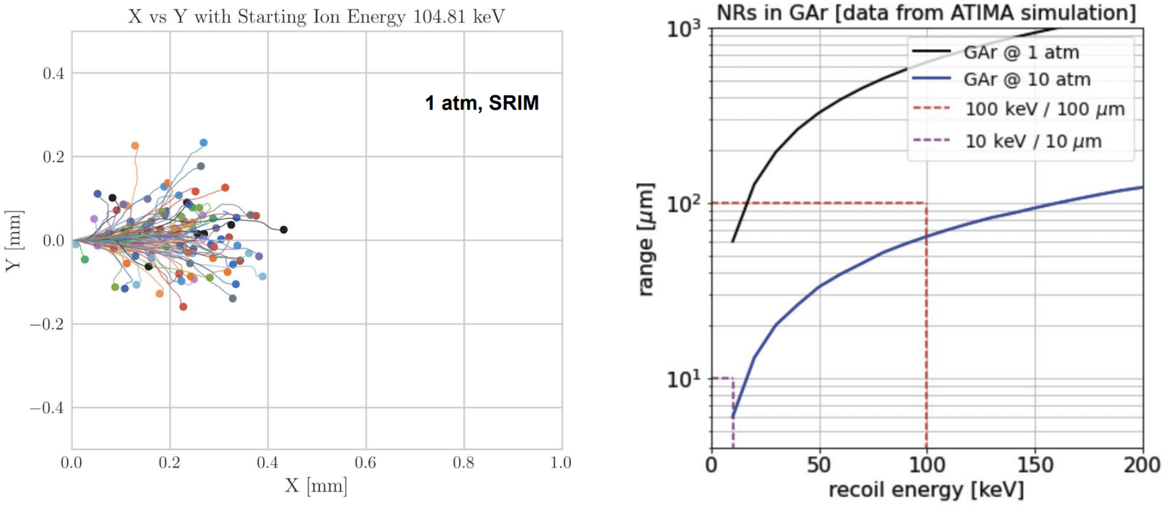

Figure 9: Simulation Studies of NRs in GAr with the SRIM (left) and ATIMA (right) packages.

Noble element TPCs have long been used in both DM and neutrino experiments, and provide a number of desirable properties, such as full homogeneous calorimetry in dense media and 4π tracking, among others. There is now interest in advancing an R&D program to study the feasibility of, and help achieve the measurement of NR directionality by tracking their ionization signatures in gaseous argon TPCs. The ability to measure the direction of NRs, in addition to their energy, allows to fully constrain the kinematics of elastic interactions. In the case of CEνNS interactions, measuring the recoil energy and direction would allow to reconstruct the incoming neutrino's energy, enabling CEνNS measurements to achieve to full spectral measurements which can expand their physics application. Furthermore, directional detection of NRs can help improve background rejection, whether these be neutron-induced recoils in beam CEνNS measurements, or CEνNS backgrounds in future direct DM searches.

The focus now will be to develop detectors capable of tracking the $\mathcal{O}$(10-100) μm ionization tracks produced by $\mathcal{O}$(10-100) keV NRs from CEνNS interactions in gaseous argon employing high-granularity GEM-based GAr TPCs. Fig. 9 left shows example trajectories for 100 keV NRs simulated in argon gas at 1 atmosphere, ranging up to several hundred μm (SRIM simulation), while the right panel shows the expected NR range for different NR energies from the ATIMA simulation. A detector capable of tracking these recoils would enable a broad range of physics measurements in focused neutrino beams of $\mathcal{O}$(100) MeV neutrinos as well as high-intensity stopped pion neutrino sources which are currently available or will be operational in the coming years at facilities such as the SNS at Oak Ridge National Lab and in Fermilab's next-generation neutrino beamline. A particularly interesting scenario would envision augmenting, through this effort, a DUNE-like GAr TPC detector in order to measure CEνNS interactions from sub-100 MeV neutrinos in a future underground near-detector experimental hall at Fermilab. The technological challenges to be addressed in order to ensure the proposed detector's ability to perform physics measurements of CEνNS events in the mentioned beamlines are:

- Achieving O(10s) of keV thresholds in the ionization energy-loss channel in argon.
- Achieving large enough event rates within the limitations of detector size to enable a positive observation of CEνNS events.
- Achieving the spatial resolution needed to track the direction of NRs in GAr.
- The availability of powerful beamlines capable of delivering high intensity neutrino rates with a large duty cycle plays an important role in assessing feasibility.

Achieving these goals requires optimization of several detector components. The R&D effort being proposed aims to address these by optimizing the gas pressure and exact gas mixture for the detector which impact spatial resolution, total event rate, and tracking potential for NRs. Development of GEM design focused on optimizing the detection of NRs in particular is another important aspect of this program.

7.7 Dual readout TPCs

Another interesting new design put forward for a noble element TPC recently is a dual-readout configuration: a high pressure gaseous TPC collecting charge from both the ionization electrons at the anode and the positive ions at the cathode. The intrinsic spatial limitation of noble gas TPCs is driven by the transverse diffusion of the electrons during drift. Unlike electrons, ions remain thermal during their drift, and so their diffusion is much reduced. The use of positive ions collected at the cathode would push the intrinsic physical resolution of such a chamber in the 10-100 micron region. The challenge associated with this scheme is the development of a sensor that can reliably detect slow positive ions with the required granularity. Detection at micron-scale pitches in massive detectors implies major technological challenges. However, there are several emerging technologies that may make micron-scale tracking of ions a reality during the next decade, enabling such a detector to be realized at scale.

The concept is depicted diagrammatically in Fig. 10. In such a dual-readout TPC, the anode sensors would allow a "coarse" (mm to cm) event reconstruction using conventional electron detection methods, while the cathode would push the scale of tracking in the tens of micron region via detection of ions. If the anode readout is pixelated, it would be possible to identify the 3D region of interest (ROI) for the interaction, map it to a cathode equivalent ROI, and trigger the fine cathode readout online. Using the fact that the drift timescales of electrons and ions are orders of magnitude apart

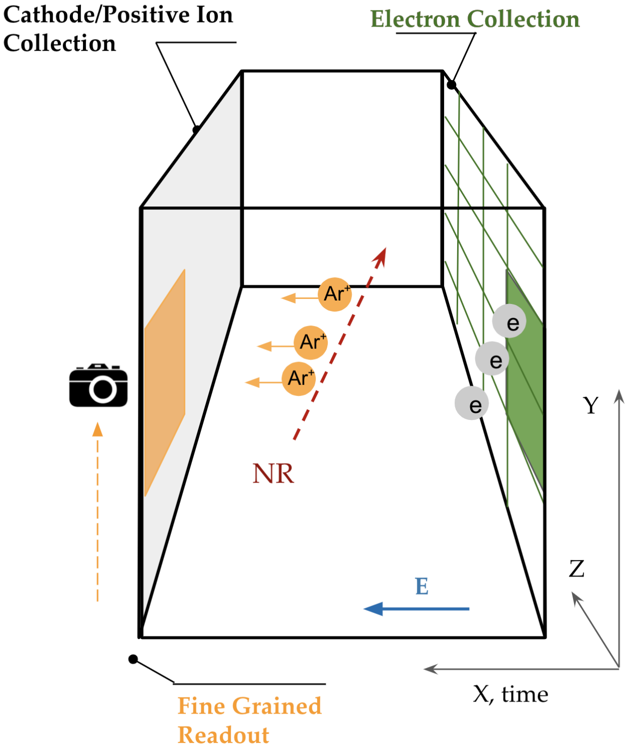

Figure 10: Diagram of the concept behind the dual-readout gas argon TPC.

(microseconds vs seconds, respectively) this approach not only evades problems associated with what may be an unmanageable data rate from a finely granular cathode, but also allows for solutions where readout is triggered in a locally defined region, based on coarse reconstruction of electron positions. For readout of the ion signal, there are at least two distinct but promising technological solutions.

TopMetal: The recently developed Topmetal-II—a CMOS pixel sensitive to direct charge—has demonstrated functionality when embedded in a standard 0.35 µm CMOS Integrated Circuit process. The corresponding sensor made of 72×72 pixel array for charge collection with 83 µm pitch has been successfully read out through time-shared multiplexing. Tests showed that the sensor achieved $< 15e^-$ analog noise and a $200e^-$ minimum threshold for digital readout per pixel, and capability for the detection of both electrons and ions drifting in gas, demonstrating readout device in future TPCs without low background and low rate-density experiments [235].

Ion Microscopy: Techniques for ion sensing and microscopy in gas are under development for neutrinoless double beta decay searches (barium tagging), spearheaded by the University of Texas at Arlington group within the NEXT collaboration. In those systems the target ion is a doubly charged metal dication. However, for noble TPCs with admixtures of certain gases, such as CF4, the positive ions are expected to be sufficiently chemically reactive that novel fluorescent chemosensors could be deployed that exhibit turn-on fluorescence upon reaction with them at the cathode. A system with a fluorescent ion-sensing layer probed by a mobile laser excitation source and EMCCD camera could resolve projected ion tracks with micron precision, seconds to minutes after the original interaction. Positioning of the camera could be realized using similar systems to those being considered for barium tagging in liquid or gaseous xenon, in schemes where the sensor moves to the ion rather than vice versa. Groundwork has demonstrated single ion detection at scanning surfaces with 2 nm spatial resolution [236], and developed bespoke fluorophores with dry fluorescent response to target metal dications [237]. The development of chemosensors for positive ion detection within its host gas, as opposed to metal dications, has been explored conceptually and appears plausible, with several promising chemoreceptors already identified.

8 Blue-sky R&D

8.1 Negative ion drift in MPGDs

8.2 MPGD TPCs at large-scale

9 Conclusions

In this white paper we have outlined the substantial and diverse physics case for the directional detection of recoils via real-time imaging. This physics motivation spans astroparticle physics to pure particle physics as well as applications. We have described the ongoing work of some notable collaborations, namely CYGNUS, νBDX-DRIFT, and IAXO, but have also highlighted the work of smaller groups engaged in various crucial R&D work. To conclude we would like highlight some of the major recommendations that we have reached from undergoing the writing of this paper, as well as some of the important advancements that we anticipate over the next decade.

Key developments expected from collaborations

- **CYGNUS**: Two (40 liter and 1000 liter) "CYGNUS HD demonstrator" detectors, utilizing CERN strip Micromegas readout and CERN SRS DAQ systems, are now under construction [224].
- **CYGNO**:
- **νBDX-DRIFT**: The collaboration is continuing work on understanding backgrounds and mitigation while also strengthening the physics case.
- **IAXO**:
- **MIGDAL**:

Future issues to be studied

- **Physics case:** The physics reach of directional electron recoil detectors should be studied further so that Strawman designs for fully optimised direction electron and nuclear recoil detectors can begin. This physics case should focus on evaluating the potential to detect low-mass and bosonic DM candidates, but also cover neutrino-electron scattering, as is needed to develop the potential for MPGDs to detect solar and geoneutrinos.
- **Performance limits:** The fundamental performance limits of gas TPCs should be experimentally demonstrated: single-electron counting detector with negative ion drift (NID). A single-electron counting NID TPC should be used to validate simulations of keV-scale nuclear and electron recoils. All proponents of new recoil imaging should also demonstrate directional performance versus recoil energy.
- **Simulations and analysis**: Simulation tools that generate the 3d topology of low-energy nuclear recoils should be developed and made publicly available. In particular the nature

of low-energy recoil tracks in GAr should receive dedicated. Dedicated track reconstruction algorithms for electron and nuclear recoils should be developed, for instance via the use of machine learning techniques.

- **Detector R&D**: NID should demonstrated in MPGDs by doing... The steps necessary to scale-up small scale prototypes need to be outlined and investigated to avoid potential show-stoppers along the road to achieving a large-scale DM or neutrino detector. **Text:** something on optical readout

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