Snowmass2021 - Letter of Interest

Particle dark matter searches with a G3 liquid-xenon detector

Thematic Areas: (check all that apply ☐/■)
■ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

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Abstract:

The unknown nature of dark matter continues to pose one of the greatest mysteries in modern physics. The dual-phase liquid-xenon time-projection chamber has been demonstrated to exhibit leading sensitivity to a range of possible dark matter signatures and is able to cover the largest phase space for Weakly Interacting Massive Particle (WIMP) dark matter. A third-generation, xenon-based detector of mass 40-100 tonnes will be a multi-purpose instrument that can probe a myriad of dark matter candidates, capitalizing on xenon's unique abilities as a dark matter target.

Introduction: Over the past three decades, the search for signatures of particle-like dark matter (DM) interactions in terrestrial laboratories has made astounding leaps in sensitivity for a broad range of DM candidates. At the forefront of that progress are experiments which use the dual-phase, liquid-xenon (LXe) time projection chamber (TPC), as illustrated in Fig. 1. The LXe TPC technology has demonstrated robust sensitivity to a myriad of potential DM candidate signatures, the most prominent being the Weakly Interacting Massive Particle (WIMP). Concomitant with its strides in sensitivity is the demonstration of this technology's capacity for scalability, with the current generation (G2) of detectors containing on the order of 10 tonnes of total LXe target. Dual-phase xenon detectors have shown unparalleled low-background rate in the 1-200 keV energy range, have the ability to discriminate nuclear from electronic recoils, and contain isotopes both with and without spin, allowing tests of a great variety of dark matter models. Beyond the reach of G2 experiments there will remain open WIMP parameter space to the neutrino floor [1], where one begins to encounter the irreducible background from coherent elastic neutrino-nucleus scattering from astrophysical sources. The third-generation (G3) instrument considered in this LOI is designed to cover that remaining parameter space and probe the signals at the neutrino floor. The total LXe mass is expected to be in the range of $40 - 100$ tonnes.

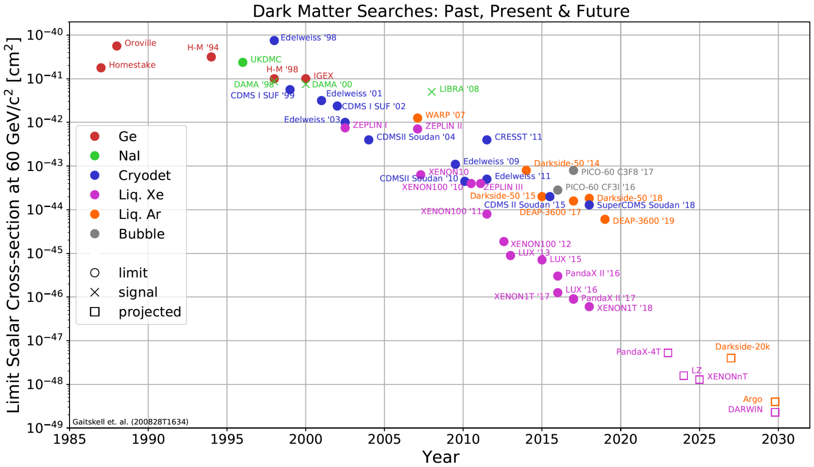

FIG. 1: Sensitivity for spin-independent 60 GeV WIMP DM-nucleon scattering vs. time.

WIMPs and Other DM Candidates: The WIMP model [2, 3] for particle dark matter remains a singularly well-motivated hypothesis. The hierarchy problem continues to strongly motivate searches for new physics (and new particles) at the $\mathcal{O}(100)$ GeV scale of the electroweak force [4]. Through a simple thermal freeze-out process, a stable particle in this mass range with electroweak scale interactions can give rise to the current dark matter density in the Universe [5, 6]. This concept, known as the "WIMP miracle," remains an exceptional motivation for WIMP dark matter searches. Xenon is particularly well-suited to searches for WIMP dark matter for several reasons described later. Additionally, a G3 LXe TPC will be sensitive to the potential signatures from a large variety of DM models such as:

Asymmetric DM: Present-day visible matter exists due to an early-universe asymmetry between baryons and antibaryons. The Asymmetric DM hypothesis suggests the same is true of the present-day DM density: it exists due to a particle-antiparticle asymmetry. These models connect the DM number density to the baryon number density, often requiring them to be equal, resulting in particles of masses 1-15 GeV, detectable through low-energy nuclear recoils [7].

Inelastic DM: For models in which a dark matter excited state is separated by a small energy from the ground state, the elastic scattering cross-section can be suppressed to below the neutrino floor. But if the dark matter scatters inelastically, exciting the dark matter, then the recoil energy spectrum can exhibit a peak. As a result, the testing of these models is not fundamentally limited by neutrino backgrounds. Models include Higgsino dark matter, magnetic inelastic dark matter, and inelastic models with dark photon exchange [8].

Self-Interacting DM: Standard ΛCDM models usually assume collisionless DM; self-interacting models differ in that DM-DM interactions are possible through a light mediator and have been used to explain astrophysical observations [9]. The signature of such a particle in a dual-phase LXe detector is a nuclear recoil spectrum with enhancement at low energies [10].

Mirror DM: This is the concept that the dark sector is an exact copy of the Standard Model, with an unbroken symmetry between the two [11, 12] – each SM particle has a mirror partner with the same masses, lifetimes, and self interactions [13]. The dark matter exists as a plasma halo, with free electrons and nuclei that can generate both ER and NR signals in a liquid xenon experiment [14, 15].

Leptophilic DM: Motivated by leptonic astrophysical excesses, leptophilic DM models predict the DM-Standard Model interactions to be through leptons only [16]. This would produce an electron recoil signal.

Dark photons: Dark sector models can include DM interactions through a dark photon mediator [17]. This dark photon can interact with standard model photons through kinetic mixing, providing a route to detect them through interactions with atomic electrons. An ionization (S2)-only search in a dual-phase xenon TPC would provide sensitivity to this model.

Axion-like Particles (ALPs): Axions arise as a consequence of a global U1 symmetry introduced by Peccei & Quinn to explain the absence of charge-parity violation in strong interactions [18]. Numerous string-theory driven models predict axion-like particles (ALPs) [19–22], which could be excellent dark matter candidates [23]. Axioelectric absorption of cold galactic ALPs leads to electron recoil line features. G3 searches will provide the most stringent constraints on axion – electron coupling, g_{ae}

Superheavy DM: If DM particles cluster together through their own self-attraction, then the combined particle mass may be much higher than the $\sim$ 200 TeV upper limit for thermally produced WIMPs [24]. These particles (known as "dark blobs" [25] or "dark nuggets" [26]) may scatter multiple times in a dual-phase xenon TPC, producing a line of easily resolved nuclear recoils. Sensitivity to much of the unexplored Multiply Interacting Massive Particle (MIMP) parameter space is therefore possible [27].

Xenon as a DM Target: Liquid xenon provides a multitude of powerful advantages over other DM target materials. First, in the low momentum-transfer regime of direct detection, a generic spin-independent scattering will interact with the whole nucleus coherently, with the scattering cross section scaling roughly as the square of the number of nucleons. Therefore, a heavy nucleus like xenon is significantly favored over lighter options. A second advantage is the large number of common natural xenon isotopes, giving xenon significant sensitivity to various interaction models, be it spin-independent, spin-dependent, or other couplings which are systematically explored using effective field theories (EFTs) [28].

Furthermore, LXe TPCs can observe recoil energies as low as a few keV, due to xenon's low intrinsic radioactivity, high yield of detectable quanta (photons and electrons) per unit energy deposited, and, in the case of nuclear recoil signals, powerful discrimination between signal and background down to the few keV level [29]. The threshold can be further lowered to a few hundreds of eV by exploiting signals that produce ionization only [30]. Low threshold, as well as searching for signals through the Migdal effect or Bremsstrahlung [31, 32], enables xenon detectors to search for particle DM with masses below a GeV, where many of the candidates referenced in the previous section may reside.

Backgrounds: Both past and current experimental sensitivity has been limited by terrestrial backgrounds (radioactivity of detector components and dispersed contaminants, namely radon). As control of these backgrounds continues to improve it is expected that for the instrument here the dominant electron recoil background will be from pp solar neutrinos. Recent studies [29] suggest that the discrimination between electron and nuclear recoils will allow a LXe G3 experiment to reach the neutrino floor in spite of this. This includes the low-energy region pertinent for WIMPs with mass $\lesssim 10$ GeV.

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