Snowmass2021 - Letter of Interest

The Exploitation of Xe Large Scale Detector Technology for a Range of Future Rare Event Physics Searches

Topical Group(s): (check all that apply by copying/pasting ☐/☑)

- ☑ **(CF1) Dark Matter: Particle Like**
- ☑ **(CF2) Dark Matter: Wavelike**
- ☑ **(NF4) Neutrinos from Natural Sources**
- ☑ **(NF5) Neutrino properties**
- ☑ **(Other)** ***[Please specify frontier/topical group]***
- ☑ **Computational Frontier**
- ☑ **Instrumentation Frontier**
- ☑ **Underground Facilities**

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Abstract:

Xenon-based detectors have demonstrated their world-leading scalability and sensitivity to a wide array of novel physics signals. There have been many successful deployments covering over 4 orders of magnitude in scale over the last twenty years, with significant improvements in both the backgrounds and the energy resolution/thresholds. This bodes well for future deployment of even larger and more sensitive detectors. This physics spans SNOWMASS working groups and Funding Agency divisions, and should prompt us to devise flexible metrics of evaluation, and greater coordination among programs. U.S. leadership in the field will be aided with R&D funding opportunities to match those already available in Europe including the UK.

Many of the core technologies are mature. We can implement a 40-100-tonne scale detector and multiple smaller ones optimized to particular low-mass dark matter and neutrino signals. Groups around the world have significant experience in successful Xe experiments. Increasing cooperation among these groups is ideal for future Xe observatories, and the wider detector community. Goals include threshold reduction, background reduction, sensors/readout electronics, calibrations, and isotopic separation. These areas of study build on proven successes in earlier detectors, and the Xe-detector community is eager to pursue such R&D enhancements en route to a future observatory.

The specific LOIs to which this additional letter is attached cover proposals to make a significant range of new physics measurements in particle physics, nuclear physics, astrophysics, and cosmology possible. The capabilities of Xe detectors may be enhanced further by new initiatives that are also mentioned below.

CF01	Particle dark matter searches with a G3 liquid-xenon detector
CF02	Wave-like searches with a G3 liquid xenon detector
NF04	Extracting Physics from Natural Neutrinos with G3 Liquid Xenon Detector
NF05	A 3rd generation liquid xenon TPC dark matter experiment sensitivity to neutrino properties: magnetic moment and $0\nu\beta\beta$ decay of ^{136}Xe
CompF2	Fast simulations for Noble Liquid experiments
CompF3	The Future of Machine Learning in Rare Event Searches
(CF,NF,IF,Comp)	NEST, The Noble Element Simulation Technique: A Multi-Disciplinary Monte Carlo Tool and Framework for Noble Elements
CommF3	Creating inclusive collaborations
InstrF	Solid / crystalline Xenon
InstrF	HydroX - Using hydrogen doped in liquid xenon to search for dark matter
InstrF	Reaching the solar CEvNS floor with noble liquid bubble chambers
InstrF	Charcoal based Radon Reduction Systems for Ultra-clean Rare-event Detectors

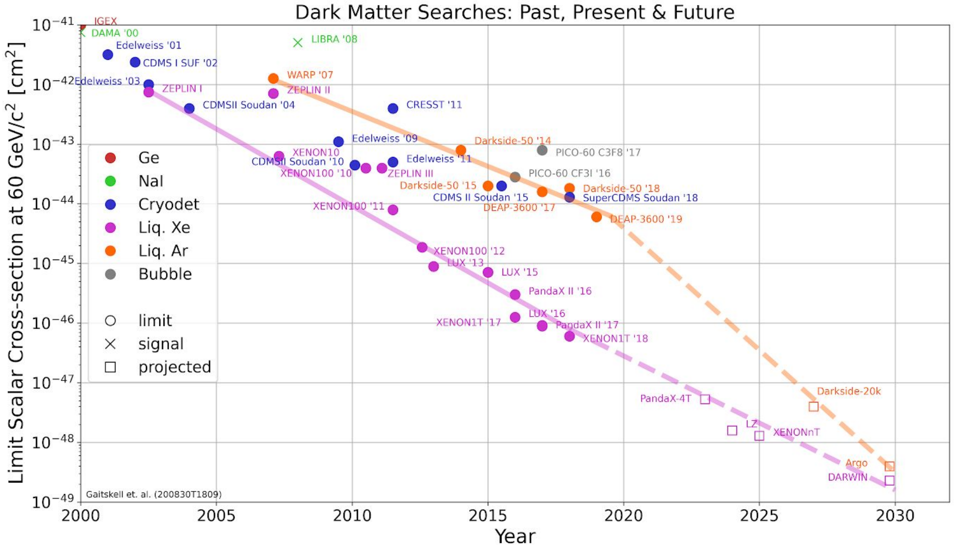

Figure 1: An example of the historical development and future search sensitivity of dark matter direct detection experiments (using a range of technologies) for 60 GeV/c^2 particle candidates with spin-independent nuclear couplings. The primary improvement in sensitivity has come from increased target masses, lower backgrounds, and in some cases improved energy thresholds.

Liquid Xe targets have been deployed in a range of particle detection schemes for dark matter detection [1-14] and neutrinoless double beta decay[15-18]. They have delivered optimal performance in rare event searches that demand ultra-low radioactive backgrounds in electron recoil (ER) and nuclear recoil (NR), often benefiting from low energy thresholds (below 100 eV ER and 1 keV for the NR) and/or requiring a premium on the energy resolution. The Xe detectors have shown a well-controlled and reproducible ability to measure both the light and charge signals from events. The combined signals can be exploited to determine event position and details of the type of particle event interaction. This can be crucial in the clear identification of signals and the rejection of radioactive and other more idiopathic backgrounds.

A healthy Xe instrumentation development community will likely encompass detectors optimized for particular signals, low thresholds and low-mass dark matter, reactor and natural neutrino sources, alongside a larger, general-purpose observatory. The capabilities of Xe detectors developed over the past 30 years make the technology suited to many areas of future study[19-24]. Such diversity can bring economies of scale with lower project risks as advancements are shared across platforms, as well as new physics results at a reliable pace. There will need to be studies of the optimal configurations for target mass, low-background goals, and sensor readouts across the many planned physics search objectives.

Other factors that must be considered include the need to better synchronize the R&D efforts of the U.S. with other major centers of development of Xe detector technology including the European, Japanese, and Chinese efforts. European funding into next-generation (beyond XENONnT, LZ, PandaX-4T) Xe-based experiments already exists. There are also challenges ahead that need to be addressed concerning the requirements of research groups with respect to the location of detectors at specific national underground laboratories.

In the field of dark matter direct detection over the last 16 years (see Fig. 1) experiments based on liquid Xe detectors have improved their sensitivity by over four orders of magnitude, healthily outstripping Moore's Law in that time. Importantly as an indicator of Xe-detector technology, many of those experiments delivered (and in some cases exceeded) their design sensitivities for their mass-time exposures. There is now considerable experience in the U.S. and worldwide concerning the design and operation of Xe-based detectors. This reduces the uncertainties associated with the optimization of their future designs and reduces the project and physics risks associated with future deployment.

From their outset, liquid-Xe detectors have most often been operated at quantum thresholds where single photons and electrons can be counted. The characteristic energy associated with the exciton and ion creation is O(10) eV. The efficiency of detection for electrons in liquid Xe can be close to 100% - this is worth noting - that single free electrons from a particle interaction from the center of a multi-tonne Xe target can be detected. Photons are typically detected at efficiencies closer to 10%. Technologies to improve this efficiency are sought. The investigation and reduction of the prime background sources of unwanted single or low multiplicity electron and photon signals is a bountiful area of research since reducing these rates will permit further significant gains in coherent neutrino and low-mass dark matter event detection.

So far separate procurements of xenon targets up to masses of 10 tonnes have been readily accommodated by conventional purchase contracts with the rare gas production industry. It is a misnomer to cite the cost of Xe gas as a significant obstacle to large Xe-based detectors since strategies of purchasing over extended periods of time can be very effective in controlling costs. Natural Xe targets can be subsequently sold as a commodity, significantly reducing the net costs to experiments. Investigations of future strategies and techniques to reduce the net acquisition/production costs of Xe are warranted.

The very low intrinsic radioactive background of natural Xe means that the event rate due to residual ^{136}Xe is only 0.004 Bq per tonne. Event rates in large Xe detectors are dominated by events from the radioactivity of construction materials, with the events being concentrated around the edge of the detector due to effective self-shielding. Even a 100-tonne target is manageable with respect to event pileup and allows for lower-cost detector readout and acquisition.

Xe detector-response physics is also well understood with precision models of the liquid xenon response to particle events from 100 eV to ~10 MeV for ionization and scintillation responses in Xe over more than two orders of magnitude of applied electric fields[25-26].

Advancements in a number of technical areas can aid Xe detectors in maximizing their physics reach. Some notable areas include:

- Further development of calibration neutron sources with kinetic energies in the range 1 keV-14 MeV. These are required for CEvNS and dark matter searches and can be deployed in dedicated labs, and also *in situ* to ensure direct efficiency measurements of detectors.
- Further development of intrinsic electron recoil calibration sources for detailed study of detector response. This includes development of techniques for the sources' subsequent removal at high efficiencies, or the development of appropriate short-lived isotopes.
- Xe target doping with light elements, such as H_2, or He, can potentially be used to improve overall detector sensitivity in measurements of nuclear recoil events from low mass/energy particles.
- Optimized sensor choice and deployment for scintillation and ionization signal detection. Trade-offs between efficiency, detector noise (such as single electron noise), radioactivity and cost per unit area need to be made.
- Development/deployment of reduction techniques for intrinsic Kr and Rn to ensure that the low-energy electron recoil event rates in the Xe fiducial are dominated by pp-solar neutrinos.
- Understanding (including costing) of techniques available for isotopic separation focusing primarily on ^{136}Xe rich and poor targets, and also targets with predominantly odd- and even-neutron Xe isotopes.

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