Snowmass2021 - Letter of Interest

Dark matter physics with the DARWIN Observatory

Thematic Areas:

■ (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)

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Abstract: The DARWIN collaboration (`www.darwin-observatory.org`) aims at building the ultimate liquid xenon-based, underground direct detection dark matter detector, with a WIMP dark matter sensitivity limited only by irreducible neutrino backgrounds. The core of the detector will have a 40 tonne liquid xenon target operated as a dual-phase time projection chamber. The unprecedented large xenon mass, the exquisitely low radioactive background and the low energy threshold will allow us to search for WIMP dark matter and cover a large mass range, from $\mathcal{O}(100)$ MeV/c^2 to multi-TeV/c^2, while testing various coupling scenarios. DARWIN will also be able to probe other dark matter candidates, such as axion-like-particles and dark photons, and will search for solar axions. While these do not constitute dark matter, the detection of QCD axions would strengthen the case for axion cold dark matter. Here we elaborate on the dark matter physics capabilities of DARWIN.

1 DARWIN dark matter physics goals: overview

The goal of the DARWIN project (*DA*rk matter *WI*mp search with liquid xeno*N*) is to construct and operate a low-background, low-threshold observatory for astroparticle physics with a liquid xenon (LXe) target that features a background limited by irreducible neutrino interactions[1–3]. The technology selected for DARWIN's inner detector is the xenon dual-phase (liquid and gas) time projection chamber (TPC). Some of the main advantages of this technology are: a very low energy threshold of $\sim$1 keV$_{ee}$ and $\sim$5 keV$_{nr}$ when reading out both light (S1) and charge signals (S2); a further reduced energy threshold by conducting a search using only the charge signal[4]; 3D-reconstruction of the interaction position with mm precision as well as the identification of multiply scattered events; rejection of electron recoil (ER) backgrounds at the 10^{-3} level at 50% nuclear recoil (NR) acceptance down to the low energy threshold based on the charge-over-light (S2/S1) ratio; a good energy resolution using S1 and S2 ($\sigma/E = 0.8\%$ at $E = 2.46$ MeV[5]).

Over the last decade, the lowest background levels for the dark matter search were achieved by dual-phase LXe detectors, with rates *before* ER rejection as low as 76 events în the 1-30 keV$_{ee}$ range[6]. Apart from the very long-lived isotopes ^{124}Xe[7] and ^{136}Xe[8], which constitute no significant background for the dark matter search[2], there is no long-lived radioactive Xe isotope. The target-intrinsic backgrounds ^{85}Kr and ^{222}Rn can be suppressed to extremely low levels: The removal of $^{\mathrm{nat}}$Kr from Xe to levels required for DARWIN has already been demonstrated[9]. Rn will be removed by a combination of xenon purification[10], material selection and surface treatment, detector design as well as S2/S1-based discrimination.

The main *dark matter (DM) physics channels*, the focus of this Letter of Interest, in DARWIN are summarized here. DARWIN's other science channels, e.g., in neutrino physics[1;8;11;12], are described elsewhere:

- **WIMPs**: weakly interacting massive particles as dark matter candidates will be searched for via DM-nucleus and DM-electron scattering. The search will cover a large range of masses, from $\sim$100 MeV/c^2 up to $\sim$10 TeV/c^2, using the S1-S2 and S2-only channels. Regarding DM-nucleus scattering, xenon is sensitive to spin-independent WIMP-nucleon interactions, to spin-dependent interactions thanks to the combined $\sim$50% abundance of ^{129}Xe and ^{131}Xe with nonzero nuclear spins and to a number of models of inelastic WIMP-nucleus scattering. Dark matter-electron scattering will explore the mass regime below 100 MeV/c^2.

- **ALPs**: Axion-like-particles are pseudo-scalar bosons which could make up the dark matter in the Universe. They would interact in the LXe target via the axio-electric effect or the inverse Primakoff process, generating a mono-energetic line at their rest mass m_a. DARWIN will be able to explore the mass range from $\sim$0.2 keV/c^2 to $\sim$1 MeV/c^2. It will also be sensitive to solar axions. While these do not constitute dark matter, their detection would strengthen the case for axion cold dark matter.

- **Dark Photons** are vector bosonic DM candidates, which could couple to the Standard Model photons via kinetic mixing. As in the case of ALPs, the detection signature would be a mono-energetic peak at their rest mass m_v, broadened by the energy resolution of the detector. DARWIN will probe dark photons with masses m_v between 0.2 keV/c^2 and $\sim$1 MeV/c^2.

DARWIN is designed such that the main backgrounds for the ER and NR DM channels are solar neutrinos via elastic neutrino-electron interactions and coherent neutrino-nucleus interactions, respectively[3], both allowing for a 200 t·y exposure before becoming relevant. Neutrino-induced nuclear recoils from coherent neutrino-nucleus scatters cannot be distinguished from a WIMP-induced signal, and solar ^{8}B neutrinos yield up to 10^3 events/(t·y) at NR energies below 4 keV. NRs from atmospheric neutrinos and the diffuse supernovae neutrino background will yield event rates which are orders of magnitude lower but at higher recoil energies[1]. These will dominate the measured spectra at WIMP-nucleon cross sections around 10^{-49} cm^2 for DM masses above ∼10 GeV/c^2.

2 Project overview, ongoing R&D and timeline

The core of DARWIN is a dual-phase LXe TPC[3;13;14]. In the baseline design scenario the prompt (S1) and proportional scintillation signals (S2) are recorded by two arrays of photosensors installed above and below the LXe target. The selection of the photosensor is subject to ongoing R&D. The TPC is a cylinder of 260 cm diameter and height, with a target volume containing 40 t of LXe, as illustrated in Figure 1. A light-weight TPC design minimizes material backgrounds. It is enclosed in a low-background, low-mass double-walled titanium cryostat which itself is surrounded by a Gd-doped (0.2% by mass) water Cherenkov shield - as in XENONnT[15] - to mitigate the radiogenic neutron background from materials. The outermost layer is a water Cherenkov muon veto also acting as a passive shield against the radioactivity of the laboratory environment.

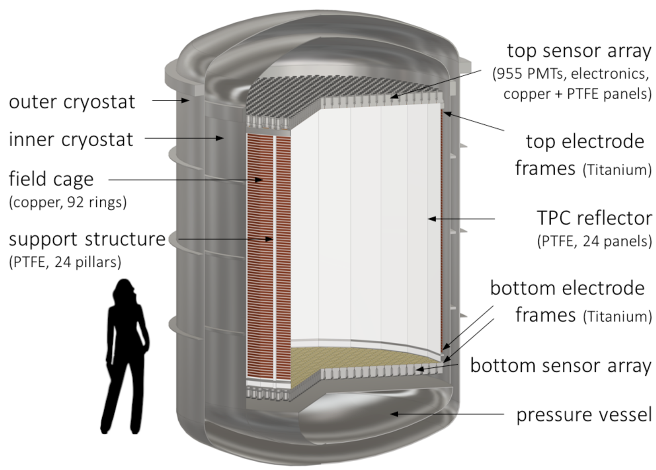

Figure 1: The DARWIN time projection chamber instruments about 40 tons of LXe as active dark matter target. The sketch shows the baseline realisation with two photosensor arrays made of 1910 PMTs of 3″ diameter. This geometry was optimized in sensitivity studies[8].

The design of the DARWIN detector follows the successful concepts of XENON10/100/1T/nT, also considering the experience obtained by LUX/LZ and PandaX as well as from the single-phase LXe project XMASS. However, several technical aspects require R&D studies such as the TPC design, the VUV-sensitive photosensors, low-background materials, neutron veto, cryogenics and target purification, and calibration systems. The R&D effort is supported by two European ERC grants, a significant startup grant by DFG/SIBW (Germany), the German Ministry for Education and Research (BMBF), the Swiss National Science Foundation (SNF) as well as by smaller grants at various collaborating institutions. Two large-scale demonstrators to develop and test components and operation methods for DARWIN at the real scale of ∼2.6 m are under construction: one full scale demonstrator for the xy-dimension, and a second one in the full z-dimension, facilities which will be used by the entire collaboration. By using about 400 kg of LXe each, the platforms will allow for testing full-scale DARWIN electrodes in LXe/GXe, the drift of electrons over the full TPC length, the HV feedthrough, large-scale photosensor arrays, efficient LXe purification, the slow control system, etc. The R&D efforts aim at a conceptual design report by the end of 2021, followed by a technical design report in 2023. Construction of DARWIN would start in 2024, while the XENONnT experiment is still taking data. Commissioning will begin after the completion of XENONnT in 2026. After calibrations, a first science run would start in 2027. At present, after a successful LoI submission to the Laboratori Nazionali del Gran Sasso (LNGS) of INFN, the collaboration was invited to prepare and submit a CDR to LNGS.

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