Snowmass2021 - Letter of Interest

Neutrino physics with the DARWIN Observatory

NF Topical Groups: (check all that apply □/■)

□ (NF1) Neutrino oscillations
□ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
□ (NF6) Neutrino cross sections
□ (NF7) Applications
□ (TF11) Theory of neutrino physics
□ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
□ (Other) *[Please specify frontier/topical group(s)]*

Contact Information:
Laura Baudis (University of Zurich) [lbaudis@darwin-observatory.org]
Marc Schumann (University of Freiburg) [schumann@darwin-observatory.org]
Collaboration: DARWIN

Authors: The author list is placed after the text and references

Abstract: The DARWIN collaboration (`www.darwin-observatory.org`) aims at building the ultimate underground-based direct detection dark matter detector, with a WIMP dark matter sensitivity limited by irreducible neutrino backgrounds. The core of the detector will have a 40 ton 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 for a diversification of the physics program beyond the search for dark matter particles. In particular, DARWIN will also be a neutrino observatory: it will search for the neutrinoless double beta decay of ^{136}Xe, will measure the solar pp and ^{7}Be neutrino flux via neutrino-electron scattering with high statistics, as well as the ^{8}B solar neutrino flux via coherent elastic neutrino-nucleus scattering, it will be sensitive to supernovae neutrinos, and will search for a neutrino magnetic moment. Here we elaborate on the neutrino physics capabilities of DARWIN.

1 DARWIN neutrino physics goals: overview

The goal of the DARWIN project is to construct and operate a low-background, low-threshold observatory for astroparticle physics with a liquid xenon target that features a background that is only 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 3D-reconstruction of the interaction position with mm precision as well as the identification of multiple 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 based on the S1 and the S2 signal ($\sigma/E = 0.8\%$ at $E = 2.46$ MeV[4]). The target-intrinsic backgrounds ^{222}Rn and ^{85}Kr can be suppressed to extremely low levels by xenon purification, material selection, detector design as well as S2/S1 discrimination.

The main *neutrino physics channels*, the focus of this Letter of Intent, in DARWIN are the following

- The low energy threshold, ultra-low background levels and excellent target fiducialization will allow for a precise measurement of the **solar pp-neutrino** flux at the 1% level through elastic neutrino-electron scattering. It will provide access to **solar neutrinos** from other production channels as well and constrain the oscillation probability P_{ee} at lowest energies[1;5]. DARWIN will also measure the ^{8}**B solar neutrino** flux via coherent elastic neutrino-nucleus scattering and could distinguish between vector and scalar interactions[6].

- Even without isotopic enrichment, DARWIN will contain more than 3.5 tons of ^{136}Xe, a double beta decaying isotope with Q-value of 2.46 MeV. This will enable the search for the **neutrinoless double beta decay** ($0\nu\beta\beta$) in an ultra-low background environment to investigate the Majorana nature of neutrinos and lepton number violation[1]. The projected half-life sensitivity of 2.4×10^{27} yr is competitive to dedicated $0\nu\beta\beta$ searches[7].

- Other **rare decays** accessible to DARWIN are double electron capture processes in ^{124}Xe. XENON1T has recently observed the 2-neutrino double electron capture for the first time – it is the slowest process in the Universe ever measured directly[8]. The increased target mass of DARWIN will allow to probe the neutrinoless decay mode as well (Q-value=2.79 MeV)[9]. A target depleted in ^{136}Xe would also allow exploring double beta decays of ^{134}Xe and ^{126}Xe[10].

- DARWIN will be a continuous monitor for **supernova neutrinos**, with sensitivity to all (active) neutrino species. A galactic supernova will generate hundreds of events in the target through coherent scattering off xenon nuclei[11]. Such a measurement will help to determine the supernovae properties, as well as the intrinsic properties of neutrinos. Thanks to its sensitivity to all neutrino flavours and uniquely low energy threshold, DARWIN will be fully complementary to the much larger neutrino detectors. It would also be sensitive to neutrinos from galactic Type Ia and failed core-collapse supernovae[12].

- With an energy threshold of 1 keV for ERs, DARWIN can search for an enhanced neutrino magnetic moment using solar neutrinos, as recently demonstrated by XENON1T[13].

2 Project overview, ongoing R&D and timeline

DARWIN will operate ∼50 t of liquid xenon in a low-background cryostat, surrounded by nested shielding structures. The core of the experiment is a dual-phase LXe TPC[14] containing 40 t of instrumented xenon target mass. 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 liquid xenon target. The TPC is a cylinder of 260 cm diameter and height, with a target volume containing 40 t of xenon, as illustrated in Figure 1. It is enclosed in a low-background, double-walled titanium cryostat equipped with several stiffening rings to reduce its total mass. The cryostat is surrounded by a Gd-doped (0.2% by mass) water Cherenkov shield - as in XENONnT - to mitigate the radiogenic neutron background from materials. The outermost layer is a water Cherenkov muon shield also acting as a passive shield against the radioactivity of the laboratory environment.

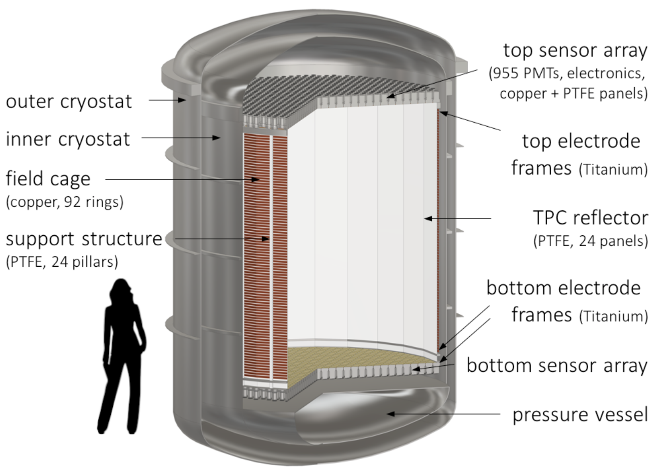

Figure 1: The DARWIN time projection chamber instruments about 40 tons of LXe as active target. The sketch shows a realisation with two photosensor arrays made of 1910 PMTs of 3″ diameter.

The baseline design of the DARWIN detector follows the successful concepts of XENON1T/nT, also considering the experience obtained by LUX/LZ and PandaX as well as from the single-phase 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, as well as the 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) 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 for various tests. 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 collaboration will follow the successful experience from the XENON project, where the more sensitive instrument was always designed and built while the current stage of the project was under operation and collecting data. 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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The DARWIN Collaboration:
Senior scientists: Elena Aprile[aa], Francesco Arneodo[z], Laura Baudis[1][y] (*spokesperson*), Amos Breskin[q], Ethan Brown[af], Ranny Budnik[q], Auke-Pieter Colijn[u], Jan Conrad[x], Patrick Decowski[u], Guido Drexlin[g], Klaus Eitel[g], Ralph Engel[g], Alfredo Ferella[o], Walter Fulgione[m], Horst Fischer[f], Peter Fischer[j], Michelle Galloway[y], Luca Grandi[ae], Stephanie Hansmann-Menzemer[j], Bernhard Holzapfel[g], Michele Iacovacci[p], Yoshitaka Itow[s], Shingo Kazama[s], Ben Kilminster[y], Lawrence Krauss[ag], Belina von Krosigk[k], Rafael Lang[ab], Manfred Lindner[e], Teresa Marrodán Undagoitia[e], José A. Matias-Lopes[v], Carla Macolino[b], Kai Martens[t], Kentaro Miuchi[r] Kaixuan Ni[ad], Uwe Oberlack[h], Igor Ostrovskiy[ah], Mila Pandurovic[t], Gabriella Sartorelli[n], Hans-Christian Schultz-Coulon[j], Marc Schumann[2][f] (*co-spokesperson*), Luca Scotto Lavina[c], Marco Selvi[n], Hardy Simgen[e], Christopher Tunnell[ac], Dominique Thers[a], Roberto Trotta[l], Kathrin Valerius[g], Marc Weber[g], Yuehuan Wei[ad], Christian Weinheimer[e], Michael Wurm[h], Masaki Yamashita[s], Kai Zuber[i].

[a]SUBATECH, Université de Nantes (France)
[b]Université Paris-Saclay (France)
[c]LPNHE, Sorbonne Université, Paris (France)
[d]Westfälische Wilhelms-Universität Münster (Germany)
[e]Max-Planck-Institute für Nuclear Physics, Heidelberg (Germany)
[f]University of Freiburg (Germany)
[g]Karlsruhe Institute of Technology (Germany)
[h]Johannes Gutenberg-Universität Mainz (Germany)
[i]TU Dresden (Germany)
[j]Heidelberg University (Germany)
[k]University of Hamburg (Germany)
[l]Imperial College London (Great Britain)
[m]INFN (Italy), Sezione Laboratori Nazionali del Gran Sasso (LNGS)
[n]INFN (Italy), Sezione di Bologna
[o]University of L'Aquila (Italy)
[p]University of Naples (Italy)
[q]Weizmann Institute of Science (Israel)
[r]Kobe University (Japan)
[s]Nagoya University (Japan)
[t]Kavli IPMU, The University of Tokyo (Japan)
[u]Nikhef, Amsterdam (The Netherlands)
[v]University of Coimbra (Portugal)
[w]Vinca Institute of Nuclear Sciences, University of Belgrade (Serbia)
[x]Stockholm University (Sweden)
[y]University of Zürich (Switzerland)
[z]New York University at Abu Dhabi (NYUAD, UAE)
[aa]Columbia University (USA)
[ab]Purdue University (USA)
[ac]Rice University (USA)
[ad]University of California San Diego (UCSD, USA)
[ae]University of Chicago (USA)
[af]Rensselaer Polytechnic Institute (USA)
[ag]Origins Foundation (USA)
[ah]University of Alabama (USA)

[1]lbaudis@darwin-observatory.org [2]schumann@darwin-observatory.org