PROCEEDINGS OF SCIENCE

DARWIN: dark matter to the limits

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This paper reviews the main scientific goal of the DARWIN experiment: the 40 ton dual-phase Xenon TPC for WIMP dark matter search. Dark matter experiments with target masses beyond the ton scale are already a reality: the XENONnT detector is currently taking its first science run data. DARWIN will reach spin-independent WIMP-nucleon scattering cross section values of a few 10^{-49} cm^2, where coherent neutrino interactions with atomic nuclei become the dominating and irreducible background. In this paper the other important science channels that can be explored by DARWIN are discussed, including solar neutrinos, axion and axion-like particles, supernova neutrinos and neutrinoless double-beta decay of ^{136}Xe.

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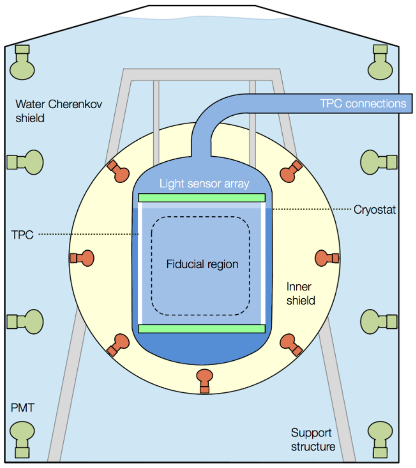

Figure 1: Pictorial view of the DARWIN baseline detector design. Picture from [2].

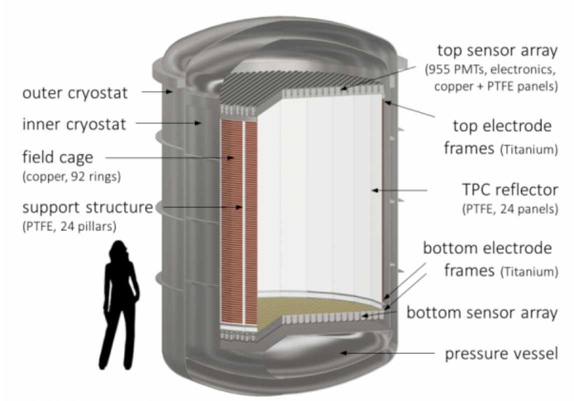

Figure 2: Detailed view of the DARWIN TPC detector components. Picture from [2].

1. The DARWIN experiment

The DARWIN (DARk matter WImp search with liquid xenoN) detector concept is based on a 50 t (40 t target and 30 t fiducial) dual-phase LXe (liquid xenon) TPC (Time Projection Chamber) inside a Water Cherenkov veto and a neutron veto, with the main goal of probing a large fraction of the parameter space for WIMPs (Weakly Interacting Massive Particles). The current baseline detector design is based on a LXe TPC (~2.6 m high and 2.6 m large) with photosensor arrays, made of 3" or 4" Hamamatsu R11410-21 photomultipliers (PMTs) placed on the top and bottom of the chamber. These PMTs were also implemented in the XENONnT detector [1] and represented a good choice in terms of high quantum efficiency, low dark count rate and high gain. On the other hand they represent a significant (~40%) fraction of the total background budget, therefore a huge effort of R&D activities is being carried on within the collaboration to find alternative photosensor solutions that would give a reduced radioactivity contribution.
The electric field required to drift electrons across the liquid towards the gas phase must be $O(0.1)$ kV/cm, with the cathode located at the bottom of the TPC biased with voltages larger than $\sim$100 kV. The field homogeneity will be ensured by oxygen-free high conductivity (OFHC) copper field shaping rings. Drifted electrons are extracted into the gas phase by a stronger electric field ($O(1)$ kV/cm). This is generated by placing an additional electrode (the gate) at the liquid/gas interface between the cathode and the anode. The realization of very large dimension electrodes represents one of the most relevant challenges for the experiment, therefore the collaboration is also commited on several R&D activities focused on the identification of the best electrode design. The energy is reconstructed from the combination of the two signals, S1 and S2, generated from the scintillation in the liquid phase and from the electroluminescence in the gas phase, respectively. The position can be inferred from the x-y pattern over the photosensor arrays and the time difference (vertical coordinate z) between S1 and S2. Scatters of WIMPs off electrons or nuclei can be discriminated by the charge-to-light ratio S2/S1. Powerful event selection can be obtained by the combination of position, energy and discrimination [2].

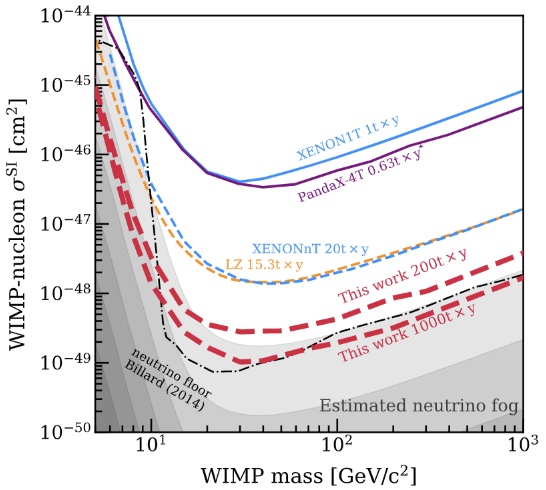

Figure 3: Projections for DARWIN spin-independent WIMP-nucleon cross-section, together with projected and current leading 90%upper limits. The dashed line shows one definition of the "neutrino floor" [5], the shaded gray area indicates where more than one, 10, 100, etc. neutrino events are expected in the 50% most signal-like S1/S2 region. Plot from [4].

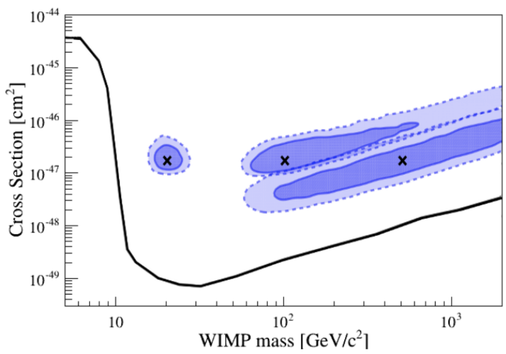

Figure 4: The 1σ and 2σ credible regions of the marginal posterior probabilities for simulations of WIMP signals assuming three different WIMP masses of 20 GeV/c^2, 100 GeV/c^2 and 500 GeV/c^2 and a cross section of $2{\times}10^{-47}$cm^2, after a 200 t×y exposure.

A pictorial view of the DARWIN detector concept is shown in Fig. 1: the neutron veto surrounding the TPC is a system based on the detection of radiogenic neutrons from detector materials. The expected neutron tagging efficiency is larger than 85%. The different detector components of the DARWIN TPC are shown in Fig. 2.

The DARWIN detector construction will follow a staged approach, in order to overcome the different challenges related to the realization of such a large dimension TPC.

2. WIMP search sensitivities

The DARWIN sensitivity goal for WIMP search can be reached if the background budget is decreased to the level at which coherent neutrino-nucleus scattering (CNNS) interactions from pp and ^{7}Be solar neutrinos and higher energy atmospheric neutrinos dominate. The other contributions to the background come from detector materials(γ-radiation, neutrons), β-decays of ^{85}Kr (0.1 ppt of ^{nat}Kr) and the progeny of ^{222}Rn (assuming 0.1 μBq/kg) in the xenon target, two-neutrino double beta decays ($2\nu\beta\beta$) of ^{136}Xe. The expected background rates are listed in Tab. 1. The biggest challenge on the background is related to achieving a very low radon level (concentration of $\sim$0.1μBq/kg). An intensive R&D program is taking place within the collaboration: the use of coating materials as radon barriers, the development of radon detectors and an online removal distillation system are being considered. The latter has been already implemented in XENONnT and showed already very good capabilities in terms of radon reduction down to $\sim$1 μBq/kg [3].

The expected sensitivity to the spin independent WIMP-nucleon cross-section with 200 t×yr exposure is shown in Fig. 3. At a WIMP mass m_χ=40 GeV/c^2 the upper limit of the spin-independent

WIMP-nucleon cross-section is 2.5×10^{-49} cm^2, assuming an electron recoil rejection at 99.98% and 30% acceptance of nuclear recoil events. Under the same assumptions and an increased exposure of 500 t × y the sensitivity reaches $\sim 1 \times 10^{-49}$cm^2.
As for the spin-dependent scattering of WIMPs with the two non-zero spin isotopes of xenon, ^{129}Xe and ^{131}Xe at a ~50% combined abundance, the DARWIN sensitivity is complementary to LHC searches with 14 TeV center of mass energy [6]. From the measured recoil spectrum both mass and cross-section of WIMPs can be inferred with very good precision for a large part of the explorable parameter space. Fig. 4 shows the expected mass measurement precisions for a cross-section value of 2×10^{-47} cm^2 and 200 t × y exposure, with uncertainties on the dark matter halo parameters being marginalised over the mass and cross-section parameters. The masses of 20, 100 and 500 GeV/c^2 correspond to 154, 224 and 60 events, respectively [2].

Table 1: Expected background rates for the WIMP search with DARWIN. Background sources are divided into nuclear (NR) or electron recoil (ER) type according to the scattering with xenon.

Source	Rate [cts/(t·keV·yr)]	Interaction type
γ-rays from materials	0.054	ER
neutrons	$3.8 \cdot 10^{-5}$	NR
intrinsic ^{85}Kr	1.44	ER
intrinsic ^{222}Rn	0.35	ER
$2\nu\beta\beta$ of ^{136}Xe	0.73	ER
pp and ^{7}Be neutrinos	3.25	ER
CNNS neutrinos	0.0022	NR

3. Other main science channels

DARWIN is a multi-purpose experiment and it will probe alternative dark matter hypotheses and additional fundamental physics channels.
DARWIN is sensitive to the search for bosonic dark matter, primarily including axion-like particles (ALPs) and dark photons and solar axions. Galactic ALPs and solar axions can be detected thanks to the axio-electric effect, i.e. the coupling with the electrons of the target xenon atoms and induce atomic ionisation, analogously to the photo-electric effect. The experimental search for ALPs consists therefore in the search for monoenergetic peaks in the electron recoil energy spectrum between 0 and few hundreds of keV. The projected sensitivity to the ALPs coupling versus the axion mass is shown in Fig. 5. For this channel, the dominant background contribution is represented by the $2\nu\beta\beta$ decays of ^{136}Xe and solar neutrino interactions.
Solar neutrinos represent the dominant background component for DARWIN and, at the same time, their flux can be detected with good precision [7]. The high statistics measurement of pp and ^{7}Be neutrinos spectrum through the elastic neutrino-electron scatterings, can improve our knowledge of their production mechanism in the Sun and the study of neutrino properties. Fig. 6 shows the sensitivity of DARWIN to the survival probability of solar electron neutrinos. With 1 t×y, DARWIN would reach the precision on the pp flux (10%) already set by the Borexino experiment. With 20 t×y the precision would be below 1% and would reach the ultimate value of 0.15% with 20 t×y.

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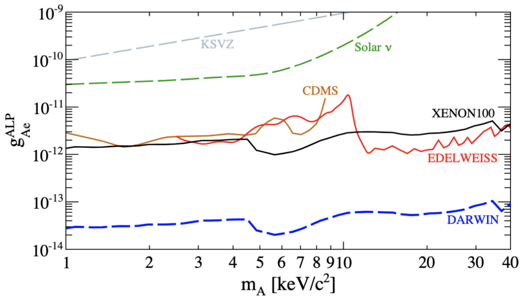

Figure 5: Sensitivity to axion-like-particles (ALPs) coupling as a function of the ALP mass. Direct upper limits from the dark matter experiments, indirect limits from solar neutrinos and red giants and two generic axion models are also shown. Plot from [2].

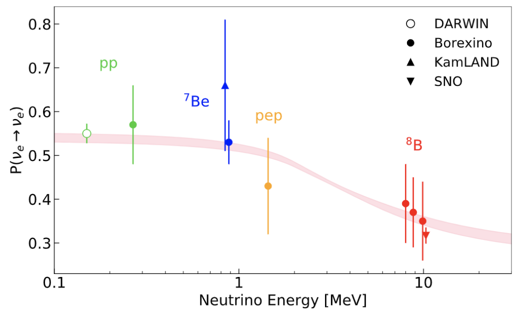

Figure 6: The electron-neutrino survival probability versus energy under the high-Z SSM (Solar Standard Model). The open point indicates the DARWIN expected precision of the survival probability to 0.02 below 420 keV with pp events. The pink band represents the 1σ prediction of the MSW-LMA (Mikheyev Smirnov Wolfenstein - Large Mixing Angle) solution. Picture from [7].

The precise measurement of the pp component allows the inference of the values of the electroweak mixing angle and the ν_e survival probability. The uncertainties on these would be 0.0122(5.1%) and 0.022 (4.0%), respectively, where the latter would be improved by an order of magnitude with respect to the measurement from Borexino [7].
Neutrinoless double-beta ($0\nu\beta\beta$) decay of ^{136}Xe with optimal energy resolution below 1% can be investigated. After 10 years of exposure DARWIN can reach a sensitivity of $2.4{\times}10^{27}$ yr on the 90% C. L. limit on the half-life of the decay. The sensitivity at 3σ on the discovery of $T_{1/2}$ would be $1.1{\times}10^{27}$ yr. At the Q-value for the double-beta decay the energy resolution corresponds to $\sigma(E)/E$=0.8%, as already demonstrated in the XENON1T TPC [8]. The predicted background spectrum for the 5 t fiducial volume around the region of interest (ROI), i.e., between 2435 and 2481 keV, is shown in Fig. 7. In the baseline design scenario and assuming the experiment to be located at Gran Sasso laboratories (LNGS), the background is dominated by material induced external radioactivity, intrinsic contributions given by solar ^{8}B neutrinos, decay of ^{137}Xe (neutron capture from this muon-induced background at LNGS), the two-neutrino double-beta decay of ^{136}Xe and ^{222}Rn decays. The total expected background index at the ROI is 3.96 events/(t·yr·keV), therefore DARWIN will reach a sensitivity that would almost match the one of the tonne-scale $0\nu\beta\beta$ experiments. Considering an adaptation of the baseline design and improvements in the intrinsic background rejection technique, DARWIN will be able to probe the entire inverted hierarchy and hence be competitive with the most sensitive $0\nu\beta\beta$ specific projects [9].
DARWIN is also sensitive to the detection of neutrinos and anti-neutrinos of all species from core collapse supernovæ, via their coherent scattering off xenon nuclei. The detected recoil spectrum would provide important informations on the supernova properties and on the intrinsic properties of the neutrinos. The expected detection significance as a function of the supernova distance is shown in Fig. 8. Between 10 and 20 events per ton are expected from a 10 kpc distant supernova, depending on the supernova neutrino emission model and progenitor mass therefore, with $O(100)$ neutrino events froma Galactic supernova, DARWIN can contribute to the Supernova Early Warning System

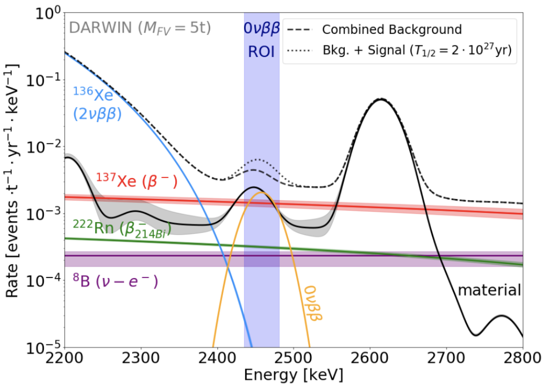

Figure 7: Predicted background spectrum around the ROI for the 5 t fiducial volume. A hypothetical signal of 0.5 $0\nu\beta\beta$ events per year corresponding to $T^{0\nu}_{1/2} \sim 2\times10^{27}$ yr is shown for comparison. Picture from [9].

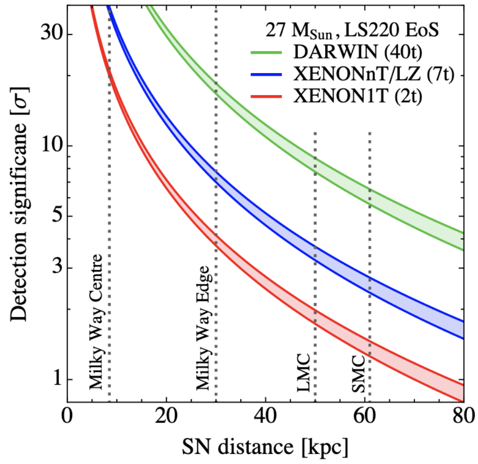

Figure 8: Detection significance as a function of the supernova distance for a 27 $M_\otimes$ progenitor with LS220 [10] EoS (Equation of State). The SN signal has been integrated over [0,7]s. Picture from [11].

(SNEWS) [11].

4. Conclusions

DARWIN is a dark matter experiment that will be able to cover a large fraction of the parameter space for WIMPs. The background will be dominated by the irreducible component of solar and atmospheric neutrinos. In addition to dark matter, DARWIN can probe other fundamental physics channels: bosonics dark matter, solar axions, solar neutrinos, $0\nu\beta\beta$ decay of ^{136}Xe and neutrinos from core-collapse supernovæ.

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