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# Results from the second science run of ZEPLIN-III

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**Abstract.** We present preliminary results from the second run of ZEPLIN-III, a two-phase xenon WIMP experiment which operated at the Boulby Mine (UK). The instrument was upgraded with low background photomultipliers; a new veto detector, featuring a tonne of plastic scintillator, was retrofitted around the WIMP target. Data from 319 days of science exposure rule out a scalar WIMP-nucleon cross-section above  $4.2 \times 10^{-8}$  pb at  $50 \text{ GeV}/c^2$  mass with 90% confidence.

**Keywords:** ZEPLIN-III; dark matter; WIMPs; liquid xenon detectors

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## INTRODUCTION

The ZEPLIN-III dark matter experiment operated at the Boulby Underground Laboratory (UK) between 2006 and 2011. This xenon emission detector measures scintillation and ionisation responses from particle interactions in its 12 kg liquid xenon target. The ionisation signal is transduced via electroluminescence in a thin vapour phase above the liquid [1]. We denote the two optical signals S1 and S2, respectively. A detailed account of the detector design and construction can be found in Ref. [2]. First science run (FSR) data placed world class upper limits on WIMP scattering cross-sections in several interaction models [3, 4, 5].

Two major upgrades were planned for Phase II of the experiment: the replacement of the 31 photomultipliers (PMTs), which dominated the  $\gamma$ -ray and neutron background budgets in the FSR by a large factor, and the addition of an anti-coincidence veto detector, which was retrofitted around the WIMP target. Figure 1 (left) shows a schematic diagram of the experiment. The new PMT model (ETEL D766Q), developed in collaboration with the manufacturer, delivered a 40-fold improvement in  $\gamma$ -ray activity, allowing an 18-fold reduction in overall electron recoil background [6]. The optical performance of the new PMTs was, however, not as good as that of the previous array.

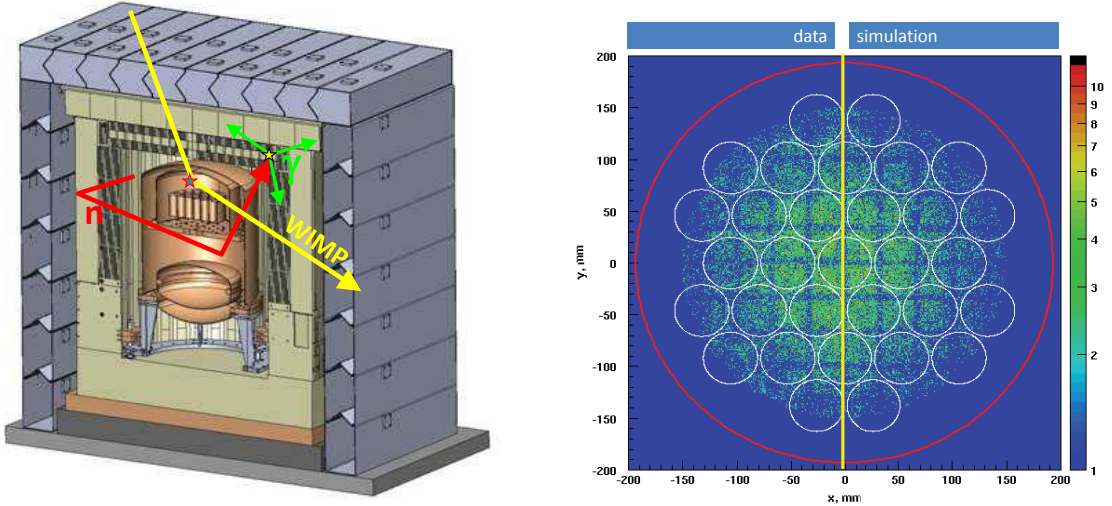
A 52-module veto, containing  $\sim 1$  tonne of plastic scintillator enveloping a Gd-loaded polypropylene structure, was fitted between the instrument and the  $\gamma$ -ray shield [7]. Internal neutrons are captured with a mean time delay of  $\sim 10 \mu\text{s}$ , with the  $^{158}\text{Gd}$   $\gamma$ -rays providing 60% tagging probability. The veto efficiency for  $\gamma$ -rays in a prompt coincidence window was 28% [8].

Minor upgrades were implemented to aid calibration: an automated radioactive source delivery system was installed; a copper structure ('phantom' grid) was positioned internally above the anode mirror to cast a shadow from  $^{57}\text{Co}$   $\gamma$ -rays onto the liquid surface for calibration of the position reconstruction algorithms; a fibre-coupled LED gun was fitted to help with calibration of the PMT responses.

## RESULTS FROM THE SECOND RUN

The second science run (SSR) took place between 24<sup>th</sup> Jun 2010 and 7<sup>th</sup> May 2011, giving a fiducial exposure of 1,344 kg-days from 319 live days of operation. This was the longest continuous WIMP run of a xenon detector to date. A daily operational duty cycle of 96% was achieved consistently, with 1 hr/day reserved for  $^{57}\text{Co}$  calibration and cryogen re-filling; these tasks were automated and controlled remotely.

Waveforms were digitised with 2 ns sampling, triggered above a threshold of  $\approx 5$  electrons in electroluminescence. Following data reduction [9], the data were searched for single scatter events and several corrections applied (free electron lifetime in liquid, electronics gain drift, detector tilt and pressure variations). A vertex reconstruction algorithm estimates the energy and position of the interaction, with a maximum likelihood method operating on the S1 response and a least squares fit on the S2 channel. Figure 1 (right) confirms the excellent performance of the vertex algorithm. A central fiducial region of 140 mm radius containing 5.1 kg of liquid xenon is retained for further analysis.



**FIGURE 1.** LEFT: Schematic representation of the ZEPLIN-III experiment; a copper cryostat contains liquid xenon (upper internal chamber) cooled by liquid nitrogen (lower chamber). The 12-kg WIMP target is located above an array of 31 PMTs. Gd-loaded plastic envelops the instrument, providing neutron moderation and capture. The capture  $\gamma$ -rays are detected by the scintillator modules. A 20-cm thick lead castle completed the shield. RIGHT: Position reconstruction of  $^{57}\text{Co}$   $\gamma$ -ray interactions in data and simulation (point-like vertex in this instance). The spatial resolution thus achieved is 13 mm in S1 and 1.1 mm in S2 (FWHM).

A WIMP search region was defined in the range 2–12 keVee (7.4–29 keV recoil energy [10]) and including approximately the lower half of signal acceptance (2–45%) in the  $\log(S2/S1)$  discrimination parameter. The nuclear recoil response is calibrated by elastic scatters from an Am-Be neutron source. Considering all recoil detection efficiencies and the above signal acceptance fraction, the effective exposure was 251.0 kg-days for a 50 GeV/ $c^2$  WIMP.

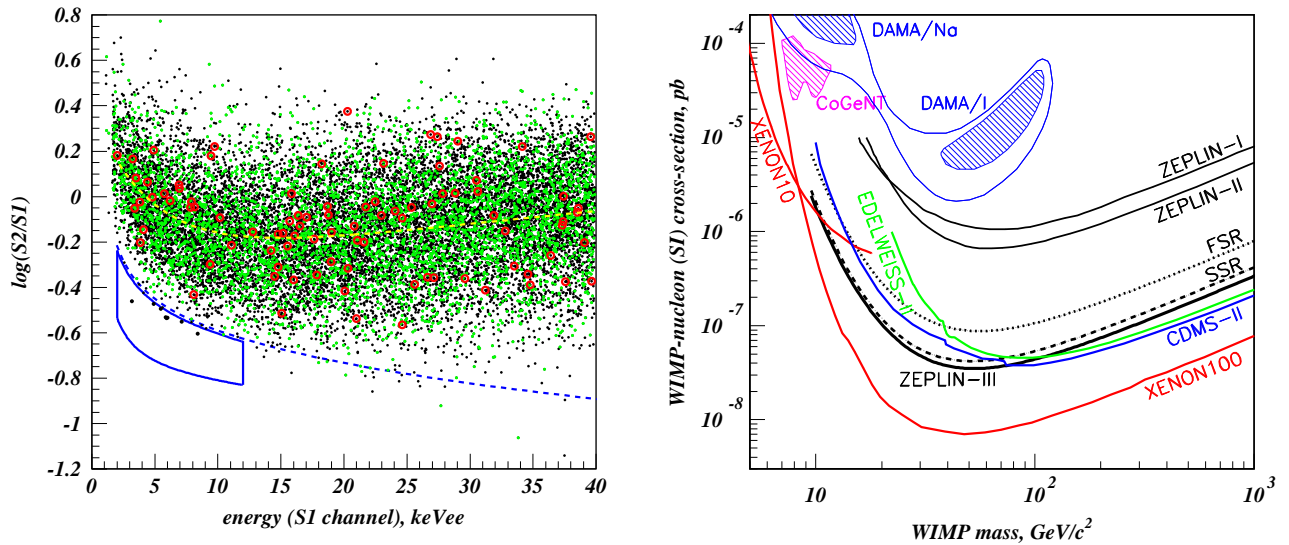
The result of the SSR exposure is shown in Figure 2 (left). Eight candidate events were observed in the search region. No delayed coincidences were observed below the nuclear recoil median and the number registered above it is consistent with random coincidences with the expected probability – indicating successful mitigation of the neutron background. Only  $0.06 \pm 0.02$  neutron events were predicted for this effective exposure [6]. Leakage from the electron recoil population is estimated from  $^{137}\text{Cs}$  data ( $9 \pm 3$  events expected in the search region). This was confirmed by fitting to that population as in FSR data [3] ( $6.5 \pm 2.6$  events predicted). Therefore, the SSR observation (8) is entirely consistent with leakage from the electron recoil band. This implies a degraded discrimination power relative to the FSR brought about by the new phototubes.

A preliminary statistical analysis, using a Feldman-Cousins calculation [11] which accounts for the distribution of background in  $\log(S2/S1)$ , yields a two-sided confidence interval of 0 – 4.35 signal events (90% CL). The corresponding upper limits on the WIMP-nucleon scalar cross-section are shown in Figure 2 (right), calculated for a standard halo model. A peak sensitivity of  $4.2 \times 10^{-8}$  pb is reached at 51 GeV/ $c^2$  WIMP mass. A FSR+SSR combined result is also shown; this has a minimum at  $3.5 \times 10^{-8}$  pb.

## CONCLUSION

Analysis of 1,344 kg-days of fiducial exposure acquired by ZEPLIN-III between June 2010 and May 2011 provide a 90% CL upper limit on the scalar WIMP cross-section of  $4.2 \times 10^{-8}$  pb/nucleon near 50 GeV/ $c^2$  mass. The combined result for the two runs of the experiment is  $3.5 \times 10^{-8}$  pb. These are based on a preliminary statistical analysis, and final results will be published soon.

The ZEPLIN programme comes thus to its conclusion at Boulby, having built, deployed and exploited three liquid xenon WIMP experiments of increasing sensitivity since the mid 1990s [16, 17]. We look forward to continuing the search with next-generation detectors in the LUX-ZEPLIN programme [21].



**FIGURE 2.** LEFT: Fiducial events in full SSR exposure. Green markers label prompt veto coincidences (mostly  $\gamma$ -rays); events in the delayed window (mostly accidental coincidences) are in red. There are 8 unvetoes events in the WIMP acceptance region. RIGHT: Preliminary 90%-CL limits on WIMP-nucleon scalar cross-sections from ZEPLIN-III as well as from XENON-10 (low energy analysis [12]), XENON100 [13], CDMS-II [14] and EDELWEISS-II [15]. Previous results from the ZEPLIN programme are also indicated [16, 17]. In blue we represent the 3- and 5- $\sigma$  DAMA/LIBRA contours (2008 data, no ion channelling [18, 19]). The magenta contour is the fit to CoGeNT data under a light WIMP hypothesis [20].

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