

Direct Detection of Dark Matter

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This article is a brief overview of the status of direct detection experiments of the dark matter, especially searching for WIMPs (Weakly Interacting Massive Particles) at deep underground laboratory, when it was discussed at 37th international conference on high energy physics (ICHEP2018) in Seoul, Korea.

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1. Introduction

There is compelling evidences for the dominant matter component of the universe is not made of ordinary matter, but rather non-baryonic dark matter [1, 2, 3]. Cosmological observations tell us that approximately 26% of the mass and energy in the universe is the dark matter while ordinary matter is only approximately 5% [4, 5, 6, 7, 8]. The remained 69% is homogeneous dark energy. Although the underlying nature of dark matter remains elusive, there are a number of particle dark matter candidates [9, 10] that describe the observed structure of the universe as one can see in Fig. 1. One of the most stringent candidate is super-symmetric WIMPs (Weakly Interacting Massive Particles) [11, 12, 13].

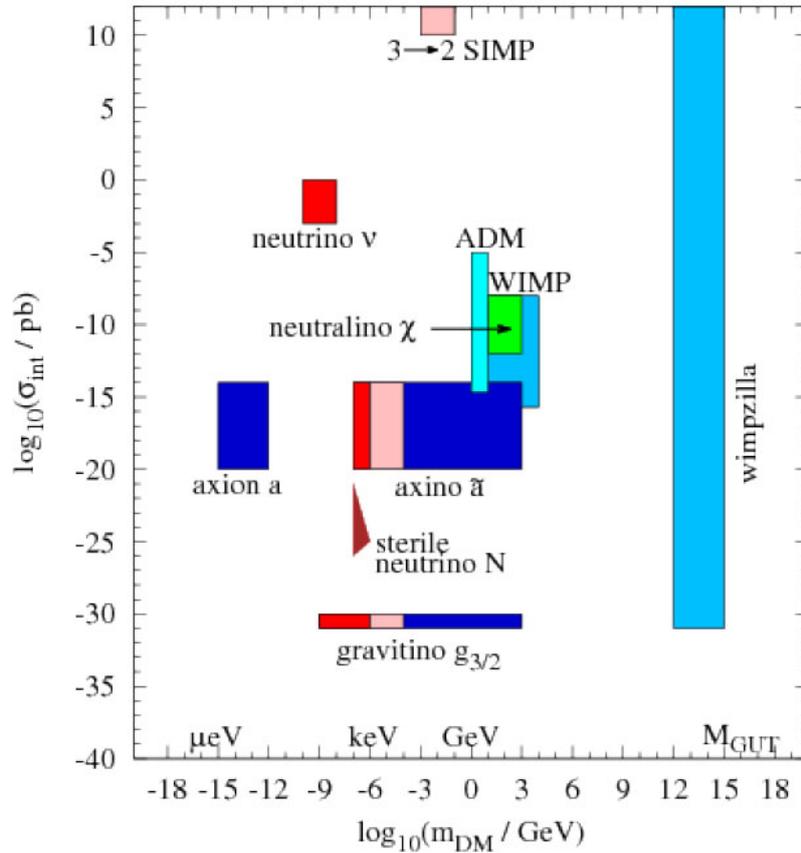


Figure 1: A variety of well motivated particle dark matter candidates are shown in the log-log plane of dark matter mass and interaction cross section. This plot is taken from Ref. [10]

WIMP dark matter has been searched in three different ways consisting of direct [14, 15, 16], indirect [17, 18, 19], and collider production [20, 21] with no clear success [22]. Direct searches of the WIMP dark matter in deep underground laboratory have been performed by searching for the scattering process of the WIMP dark matter with ordinary matter, which deposits tiny energy in target material scattered off nuclei [12, 23, 24]. In this article, we present current status of direct detection experiments for WIMP dark matter.

2. Current status of direct detection

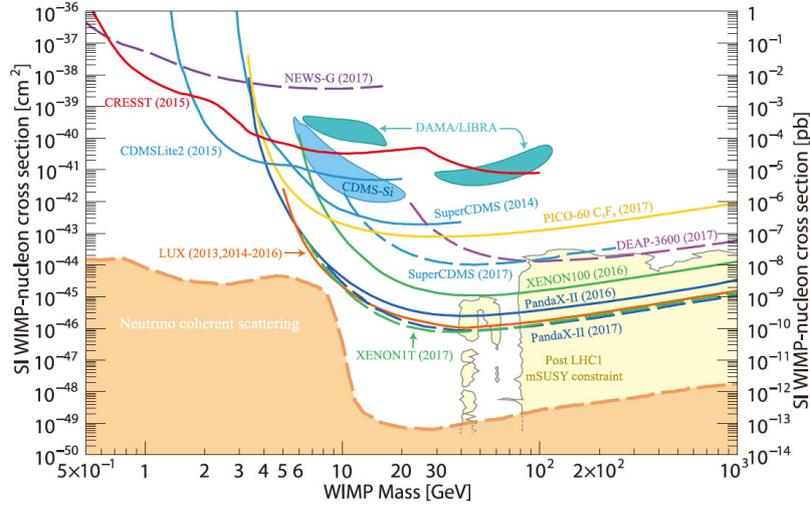


Figure 2: Limits on WIMP-nucleon cross-section for spin-independent coupling as a function of WIMP masses are presented. This plot is taken from Ref. [22]

Figure 2 shows the current status of direct detection experiments as limits on WIMP-nucleon cross-section for spin-independent interaction as a function of WIMP masses taken from recent particle data group reports [22]. In summary, liquid noble gas detectors have achieved big progress in sensitivities for the high-mass WIMP searches while many different types of detectors have developed and competed for the low-mass dark matter searches. However, a long debated annual modulation signals observed by DAMA collaboration has still been unresolved.

3. High mass searches

Liquid noble gas (Xe, Ar) dual-phase detectors have lead WIMP dark matter searching for the mass greater than $10 \text{ GeV}/c^2$ (high-mass) last decade with tremendous progress. Liquid and gas two-phase detectors allows one to measure both the primary scintillation and the secondary ionization electrons drifted through the liquid, amplified in the gas stage. The ratio of the primary and secondary signal allow one to discriminate the electron recoil backgrounds from the nuclear recoil signals together with 3-dimensional position reconstruction. This makes the liquid noble gas detectors to search WIMP dark matter with almost background-free conditions in the region of interest. Due to their relatively easy scalability as well as high radiopurity, which has been achieved with extensive works, this type detectors improved detection sensitivities of about three order of magnitudes during last 10 years for high-mass WIMP searches.

XENON collaboration progresses quite fastly and leads high-mass search starting from XENON-10 [25] operated at Gransasso Underground Laboratory since 2006. Its successors have continued with XENON100 [26] and XENON1T [16]. Current best limit for high-mass dark matter searches is obtained from XENON1T with 1 ton-year data exposure obtaining 90% confidence level (CL) upper limit of $4.1 \times 10^{-47} \text{ cm}^2$ for WIMP-nucleon spin-independent cross section in case of WIMP

mass $30 \text{ GeV}/c^2$. Fast upgrade for XENONnT is planned at 2019 with replacement of inner liquid Xenon vessel to accommodate 8-ton liquid Xenon. LZ (Lux-Zeplin), an upgrade of LUX experiment that had an operation since 2014 with a 307 kg liquid xenon at Stanford Underground Research Facility [27], has well prepared to start operation at 2020 spring with 10-ton liquid xenon. With successful operation of PandaX at Jingping Underground Laboratory [28], the collaboration has a plan to upgrade detector as PandaX-4T at 2019-2020.

Liquid Ar experiments have two different approaches of single-phase by DEAP-3600 experiment [29] at SNO Underground Laboratory and two-phase by DarkSide-50 [30] at LNGS (Granssaso) with similar performance. The community of liquid Ar experiments agrees to launch joint collaboration for single future experiment of the DarkSide-20k with 50 ton of underground liquid Ar. It will eventually be upgraded to 300 ton detector. Figure 3 show projected sensitivities of liquid noble gas experiments that are explained here.

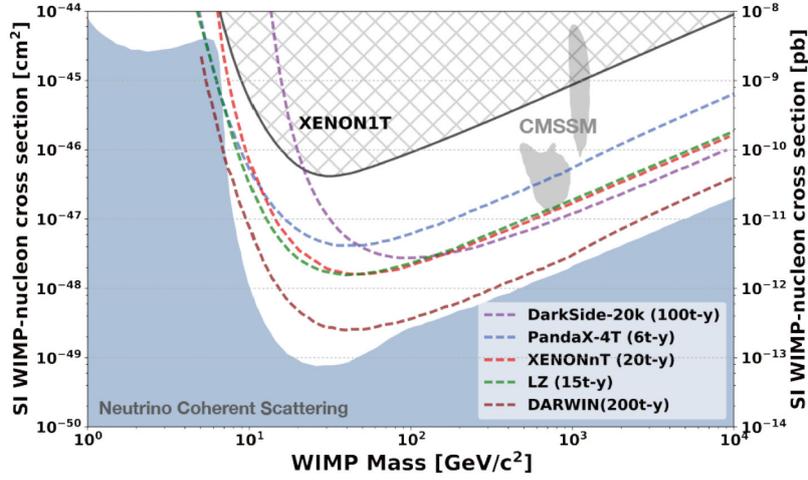


Figure 3: Projected sensitivities of planned liquid noble gas experiments. This plot is taken from Ref. [31]

4. Low mass searches

Various techniques are developed to reach enough sensitivities for low-mass dark matter between few hundreds MeV/c^2 and sub GeV/c^2 . DarkSide-50 produce interesting results by using so called “s2” only analysis [32]. Only using ionization signals, which are amplified in gas stage, makes low energy threshold of 0.1 keV_{ee} (electron-equivalent energy). With this approach, they obtain the best exclusion limit for the WIMP dark matter in the mass range of $1.8\text{--}6 \text{ GeV}/c^2$.

The CRESST-III experiment upgrade their detector module consisted to a 24 g CaWO_4 crystal that is connected to transition-edge-sensors for signal readout of phonons [33]. A silicon-on-sapphire disc is used for a light absorber. The mass of CRESST-III is significantly lower than that of CRESST-II about 300 g [34]. Main goal is to achieve lower energy threshold for lower mass dark matter search. The CRESST-III achieved less than 100 eV energy threshold while CRESST-II was 307 eV. Results from single module for 2.39 kg-days exposure already obtain compatible limits

with CRESST-II 52 kg-days exposure for WIMP mass less than $20 \text{ GeV}/c^2$ and much better results for WIMP mass below $1 \text{ GeV}/c^2$.

The CDEX experiment has developed p-type point-contact germanium detector to reach low-energy threshold. The CDEX-10 experiment with a 10 kg germanium detector array immersed in liquid nitrogen at the China Jinping Underground Laboratory can reach to 160 eV_{ee} analysis threshold improving the exclusion limit significantly [35]. The CDEX has plan for upgrade detectors up to 1-ton scale that may be grown in the Jinping Underground Laboratory for low background.

The NEWS-G experiment has developed gases spherical proportional detector with light noble gases to search for low-mass WIMP. A 60 cm diameter prototype detector operated with a mixture of Ne and CH_4 at 3.1 bars for a total exposure of 9.6 kg-days [36]. Achieved low energy threshold of 150 eV_{ee} allows the best limit for WIMP mass around $0.5 \text{ GeV}/c^2$.

The observed upper limits from various low-mass dark matter search experiments are shown in Fig. 4.

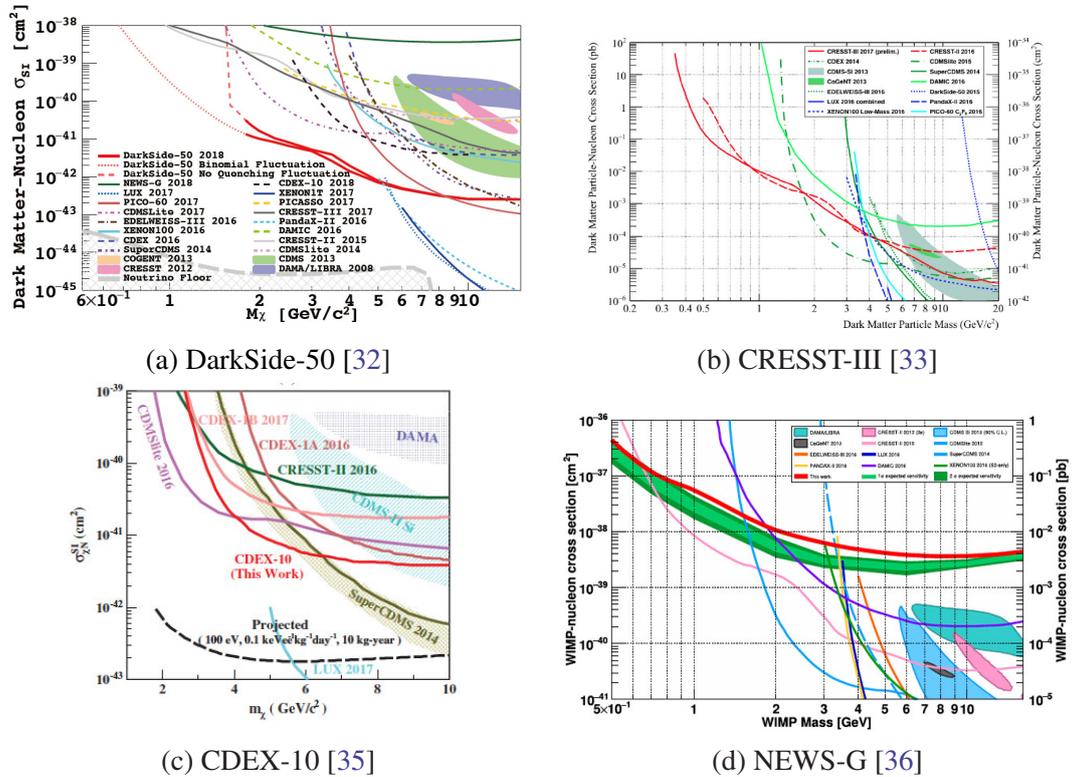


Figure 4: Measured 90% CL upper limits on the WIMP-nucleon spin-independent cross sections from various low-mass dark matter search experiments. Plots are taken from each reference.

5. Tests of the DAMA annual modulation signal

It has been a long time since DAMA reported an annual modulation in their event rate first time at 1998 [37] with an array of low-background NaI(Tl) crystals. Experiment has been upgraded and performed with much longer period of exposure and keeps reports about similar positive seasonal

modulation [38, 39, 40]. The most recent result from DAMA/LIBRA-phase2 [41] shows a consistent annual modulation with more than 13σ statistical significance as one can see in Fig. 5. Even though DAMA/LIBRA-phase2 data itself is inconsistent with canonical spin-independent WIMP dark matter model [42, 43] in the context of standard halo model, but it still has consistent phase and period with previous DAMA/NaI and DAMA/LIBRA-phase1 results.

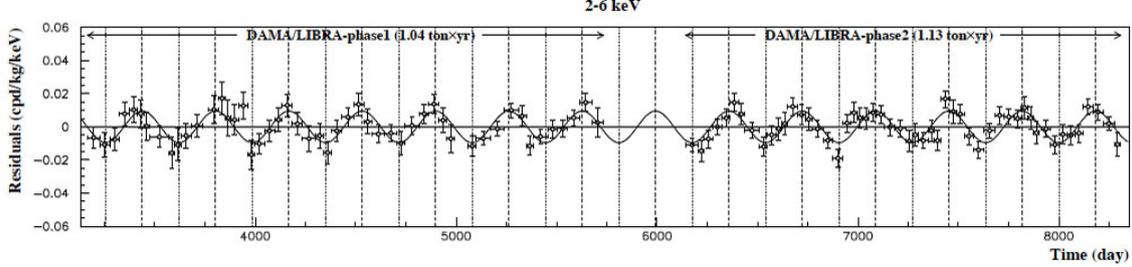


Figure 5: Observed annual modulation of event rates (residual spectrum) measured by DAMA/LIBRA-phase1 and phase2 in 2-6 keV energy region. This plot is taken from Ref. [41]

If the annual modulation signal observed by DAMA is interpreted in the context of the standard halo WIMP dark matter model, i.e. interpretation of DAMA/LIBRA-phase1 result [44], the favored regions of WIMP-nucleon cross section have been already excluded by other direct search experiments [22, 16]. It is also been studied for the annual modulation of event rates by other experimental searches with liquid Xenon [45, 46, 47], but they clearly found contradictory results with DAMA. Therefore, it is important to devise experiments that search for the DAMA signal using the same technique of NaI(Tl) crystals with higher sensitivity.

To reproduce the DAMA observation, several experiments [48, 49, 50, 51, 52, 53] have attempt to search WIMP dark matter using the same NaI(Tl) crystals. ANAIS [54] and COSINE [50, 55] experiments start physics data taking with approximately 100 kg scale detectors. Interesting result from COSINE-100 with 59.5 days data indicate that DAMA's annual modulation signal is in tension with typical dark matter interpretation of spin-independent interaction with the standard halo model based on their precise background understanding [56]. This is consistent with all other null results experiments but, it is first time with same NaI(Tl) detector. It will be more interesting to compare the modulation amplitudes observed by the ANAIS and COSINE experiments that will be available in near future.

Even though ANAIS and COSINE take physics data, crystal backgrounds achieved by those experiments [55, 57, 58, 59, 60] are still higher than those of the DAMA/LIBRA's crystals [41]. It has potential leak to resolve all possible scenarios of the DAMA's modulation signals due to poorer detector performances. COSINE, SABRE, and PICO-LON experiments independently have developed ultra-low background NaI(Tl) detectors with a goal of lower background level than DAMA/LIBRA's crystals. Each experiment has proper progress of crystal growing. It is expected to have conclusive understanding of the DAMA's signal within a few years.

6. Summary

The WIMP dark matter direct searches in deep underground are actively ongoing with

significant progress last few decades even though we did not find crucial evidence of the WIMP dark matter. In high-mass region, liquid Xe experiments made leading role in the field. Near future project are well prepared in liquid Xe and liquid Ar with significant improvement on the sensitivities of the search regions. In the low-mass region that requires a lower threshold, several new techniques are being developed to reach extremely low energy threshold. The DAMA conundrum is still persistent but, new NaI(Tl) experiments will resolve this issue in near future.

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