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# Future of Dark Matter Search with Time projection chamber and bubble chamber detector experiments

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***Abstract:*** **Dark matter is one of the long-standing problems in different sectors of physics. In this present paper, we will report the current scenario of dark matter candidate's searches. Also, we will focus on the different detection techniques used for their detection. Such as detection through time projection chamber (TPC), detection using super heated liquid by bubble formation. Also, we will focus on their current status and proposed future plan.**

***Index Terms:*** **TPC, Rare Event Search, Dark Matter, WIMP, Detector Technology,**

## I. Introduction

Dark matter is one of the most intriguing mysteries in the nature. Also, it is currently one of the core problems in many branches of physics. In 1933 Fritz Zwicky first observed some discrepancy in coma cluster, the mass observed by luminous objects is less than the observed mass by gravitational interaction (Zwicky, 2009). In 1970 Vera Rubin and others have looked for the rotation curves of 10 spiral galaxies and reported a flat rotation curve was observed and they have concluded the presence of the extra nonluminous mass (Rubin, 1978). With these observations and other observation like Big Bang nucleosynthesis, cosmic microwave background, and other it is now well established that percentage of the total luminous matter in universe is very much low compared to the total mass content of our universe. All over the world, various experiments are running to find the particle content of the dark matter. Various candidates have proposed to account for the dark matter. Among which Weakly Interacting Massive Particles (WIMPs) is a superior candidate, also Kaluza-Klein particle, Axion and particle arising from supersymmetry, etc are viable candidates. From bullet cluster observation it suggests that dark matter candidate is basically not interactions. The bottom-up structure suggests the presence of non-relativistic cold dark matter (CDM) in the universe (Rezaei et al., 2020) Cosmic microwave background along with big bang nucleosynthesis are suggested the non-baryonic nature of dark matter (Popolo et al. 2017, Rau et al. 2011, Profumo et al. 2019, Baltz et al. 2004). Detection of WIMPs is basically on the basis of direct and indirect searches. For indirect detection, experiments will focus on the annihilation of WIMPs with themselves. In the case of direct detection, we will basically look at the nuclear recoil produced by the dark matter particles. Here we will discuss some of the next generation experiments based on direct detection with a time projection chamber and using superheated liquid. These two techniques are very useful in dark matter.

## II. Time Projection Chamber based experiment

### *A. PANDA-X*

PANDA-X is one of the famous liquid xenon dual-phase time projection chamber (TPC) detector based dark matter Search experiments. This collaboration is situated in China JinPing Deep Underground Laboratory. PandaX-1 collaboration has published limits with their full exposure

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for 80.1 live exposure. They have operated their TPC with a fiducial mass of 54 kg. With this data they have also excluded the WIMP interpretation of DAMA/LIBRA, CoGeNT etc (Xiao et al., 2015). PandaX-II collaboration have published in 2016, reported limits using dual phase (TPC) with 500 kg liquid xenon. The best reported cross section (CS) upper limit for spin independent(SI) scattering is $2.5 \times 10^{-46}$ $cm^2$ in case of 40 $GeV/c^2$ WIMP at 90% C.L. (confidence level) (Tan et al., 2016). With $3.3 \times 10^4$ kg day exposure PandaX-II experiment published SD WIMP-neutron CS of $4.1 \times 10^{-41}$ $cm^2$ at a WIMP mass of 40 $GeV/c^2$ (Fu et al., 2017). With added data taken with low background they have able to improve their previous result and give the CS upper limit for SI WIMP-nucleon to be $8.6 \times 10^{-47}$ $cm^2$ at same mass. For galactic axion like particle limit for coupling $g_{Ae}$ was set $\leq 4 \times 10^{-13}$ for 1 - 25 $keV/c^2$ mass range which is slightly improved from LUX previous results. Recently they have published their PandaX-4T result which is operating with 3.7 tonne of liquid Xe located at CJPL-II. With 0.63 tonne yr exposure they were able to put SI scattering CS at $3.3 \times 10^{-47}$ $cm^2$ for 30 $GeV/c^2$. Now they are looking to remove tritium basically leftover of PandaXII collaboration (Meng et al., 2021). The PandaX-4T employs liquid xenon detector to measure the flux of solar $^8B$ neutrinos by searches neutrinos by its coherent scattering with xenon nuclei. The coincidence of scintillation and ionization signals (referred to as paired) as well as unpaired ionization-only signals, with energy thresholds of approximately 1.1 keV for paired signals and 0.33 keV for unpaired signals. The total exposures of 1.25 tonne-years of three events and 1.04 tonneyears of 332 events for the paired and unpaired samples respectively is given, with background events of $2.8 \pm 0.52$ and $251 \pm 32$. The background hypothesis was rejected with a significance level of 2.64 σ. The combined analysis revealed a $^8B$ neutrino signal of 3.5 events in the paired sample and 75 events in the unpaired sample, with an uncertainty of approximately 37% (Bo et al., 2024). The analysis determined a solar $^8B$ neutrino flux of $(8.4 \pm 3.1) \times 10^6$ $cm^{-2}s^{-1}$, consistent with the predictions of the standard solar model.

### B. LUX

The Large Underground Xenon (LUX) is also one of the leading experiments in dark matter detection as well for neutrinoless double beta decay sector. The detector is a twophase xenon TPC operating with liquid Xenon (Xe) of nearly 300 kg. The experiment was started its underground operation in 2012 end. The detector setup of LUX is placed at Sanford Underground Research Facility (SURF) at 4850 feet below underground (Fig 1). Which provides 4300 m.w.e. (meter water equivalent) and due to this muon flux is reduced heavily. They have published their first work in 2014. In this, LUX detector contained Liquid Xe of 250 kg in the dual phase TPC. Events were recorded by two means one is the prompt scintillation (S1) and the other one is electroluminescence (S2) (Akerib et al., 2014). Both of these signals are used to get the deposited energy and their ratio enables to separate the nuclear recoils from the electron recoil which is one of the keys to operating dark matter experiment. S2 signal gives the X,Y axis information of the events and the time difference of S2 and S1 gives the Z axis information. They have achieved minimum $7.6 \times 10^{-46}$ $cm^2$ SI WIMP-nucleon elastic scattering CS for a WIMP mass 33 $GeV/c^2$. In 2016 they have reanalyzed their 2013 data (Akerib et al., 2016) with several upgrades. These update includes the algorithm for event reconstruction, background model is revised have improved the zero efficiency for nuclear recoil event under 3 keV. These upgrades have increased the active volume, and also helped to achieve a good sensitivity for low WIMP mass (Akerib et al., 2016).

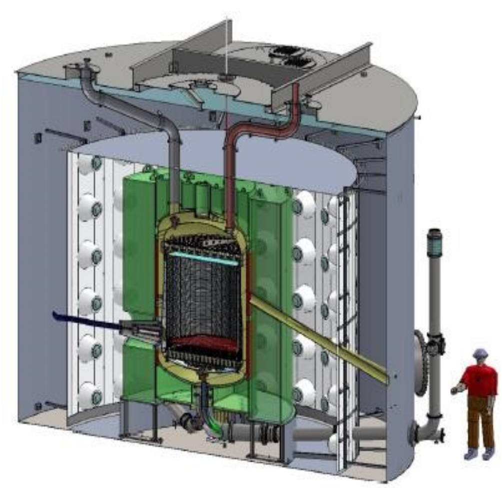

Fig 1. Detector sketch of LZ experiment (Akerib et al., 2017).

Improved CS for SI WIMP-nucleon elastic scattering at WIMP mass of 33 GeV/$c^2$ is 0.6 zb. They have also provided the limit for CS of spin-dependent(SD) WIMP-nucleon elastic scattering. The achieved limit is $9.4 \times 10^{-41}$ $cm^2$ and $2.9 \times 10^{-39}$ $cm^2$ for SD WIMP-neutron and spin-dependent WIMP-proton elastic scattering respectively (Akerib et al., 2017). In 2017 they have published their full exposure result for both SD and SI CS of WIMP-nucleon scattering. For LUX exposure with the previously reported data, this brings the exclusion limit for WIMP-nucleon SI CS to $1.1 \times 10^{-46}$ $cm^2$ at 50 GeV/$c^2$ (Akerib et al., 2017). For WIMP-nucleon SD interaction the achieved limit is $1.6 \times 10^{-41}$ $cm^2$ and $5 \times 10^{-40}$ $cm^2$ for WIMP-neutron and spindependent WIMP-proton elastic scattering respectively at 35 GeV/$c^2$. They have also provided constraints on sub-GeV WIMPs for 0.4 – 5 GeV/$c^2$ using $1.4 \times 10^4$ kg day of exposure (Akerib et al., 2017). They have also provided limits on axion and axion like particles as these particles are a viable candidate for dark matter. It excludes $g_{Ae}$ larger than $3.5 \times 10^{-12}$ for solar axions and axion mass greater than 0.12 or 36.6 eV/$c^2$. Also excludes $g_{Ae}$ greater than $4.2 \times 10^{-13}$ over the axion mass rang 116 keV/$c^2$ for axion-like particles, also see (Akerib et al., 2017). LUX-ZEPLIN (LZ) is of one the next generation experiment and a merger of the LUX and ZEPLIN-III experiments. Seven tonnes for liquid Xe will act as target for the WIMPs. This collaboration has made several upgrades from their predecessor (Akerib et al., 2020). One of the most important upgrade is the Xe skin. It acts as scintillator veto and a dielectric insulation between field cage and inner cryostat veto. They are expecting to reach $1.4 \times 10^{-48}$ $cm^2$ CS for SI interaction at 90% C.L. for mass 40 GeV. scattering CS of ~$10^{-43}$ and $10^{-42}$ is expected for neutron WIMP and proton WIMP SD interaction (Akerib et al., 2020).

### *C. XENON*

The XENON experiment, situated at the Sanford Underground Research Facility (SURF), is dedicated to finding dark matter by using liquid xenon detectors. The project originated in the early 2000s with the goal of creating advanced detectors capable of detecting weakly interacting massive particles (WIMPs), a prime suspect for dark matter. Beginning with the construction of the XENON10 detector at the Gran Sasso National Laboratory in Italy from 2006 to 2007, significant progress was made in setting boundaries on WIMPnucleon interactions. Following this achievement, the team proceeded to develop the XENON100 experiment, which offers improved sensitivity and greater capabilities in rejecting background noise (Fig. 2). From 2009 to 2018, XENON100 made significant progress in the search for dark matter, narrowing down the characteristics of WIMPs. In 2018, the XENON1T experiment marked a major breakthrough with its large liquid xenon target and impressive sensitivity. XENON1T ran until 2020, pushing the boundaries of dark matter research with a larger mass of 2 t as a target aiming to probe spinindependent WIMP-nucleon having cross section scattering of $1.6 \times 10^{-47}$ $cm^2$ at a WIMP mass ($m_\chi$) = 50 GeV/$c^2$ with an exposure of 2.0 t.y (Aprile et al. 2016).

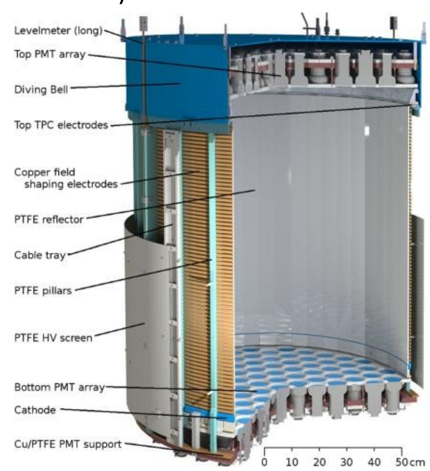


Fig. 2 Schematic diagram of XENON1T TPC (Aprile et al. 2017).

The total electronic recoil background within a 1-tonne fiducial volume and an energy region of (1, 12) keV electronic recoil equivalent, prior to any discrimination between electronic and nuclear recoils, is $(1.80 \pm 0.15) \times 10^{-4}$ $(kg.day.keV)^{-1}$. This background is predominantly attributed to the decay of $^{222}Rn$ daughters inside the xenon target. Furthermore, the nuclear recoil background within the corresponding energy range of (4, 50) keV is composed of $0.6 \pm 0.1$ $(t.y)^{-1}$ from radiogenic neutrons, $(1.8 \pm 0.3) \times 10^{-2}$ $(t.y)^{-1}$ from coherent neutrino scattering, and less than 0.01 $(t.y)^{-1}$ from muon-induced neutrons (Aprile et al. 2016).

The team then focused on the XENONnT project, an upgraded version of XENON1T designed to enhance sensitivity and improve detection methods. This next phase instrument, with a mass of approximately 8 t of Liquid Xe and with target of mass 6 t, was technically designed. It is observed in the recent investigation that the highest significance finding for the chiral effective field theory (ChEFT) models reached 1.7σ for the vector-vector interaction model with a $m_\chi = 70\ GeV/c^2$. For the inelastic dark matter model, the peak significant finding was 1.8σ for a $m_\chi = 50\ GeV/c^2$ with a mass splitting of 100 $keV/c^2$. However, it did not result any significant value in the signal region for any model tested. Instead, the data revealed a minor background over-fluctuation, peaking between 20-50 $keV_{NR}$. The team reported 90% C.L. upper limits over the Wilson coefficients and the interaction scale for each ChEFT model (Aprile et al. 2024).

## III. BUBBLE CHAMBER BASED EXPERIMENT

### A. PICO

PICO collaboration used the combined technologies of PICASSO and COUPP experiments. PICASSO, a dark matter search experiment at SNOLAB in Canada, aimed to detect WIMPs. It used superheated droplets of $C_4F_{10}$ in a gel matrix, functioning like tiny bubble chambers that transitioned from liquid to gas when interacted with high-energy particles. This phase change created bubbles, detected acoustically by piezoelectric sensors. PICASSO's unique sensitivity to spindependent WIMP interactions distinguished it in the dark matter search. It can distinguish between various particle interactions, including background radiation and WIMPs, by adjusting the energy threshold for this nucleation by manipulation of the droplet temperature and pressure.

COUPP, originally based at Fermilab and later relocated to SNOLAB, was a bubble chamber experiment similar to PICASSO but utilized a bulk liquid target, initially $CF_3I$ (trifluoroiodomethane), instead of droplets. It was designed to detect WIMPs by observing bubbles formed in superheated liquid, COUPP's approach allowed for scaling up to larger detector volumes, enhancing sensitivity to rare WIMP interactions. The experiment operated in superheated conditions, where minimal energy from particle interactions could trigger bubble formation, which was then photographed and analyzed. By adjusting pressure and temperature, COUPP effectively reduced background noise, focusing on potential WIMP signals.

As PICASSO and COUPP, both working on dark matter detection, employed with similar principles but had distinct methods where PICASSO used droplets, while COUPP used bulk liquid for detection. Their merger into the PICO experiment allowed for a combination of strengths like PICASSO's acoustic sensitivity and COUPP's scalability and background differentiation. This union of these collaboration enabled the creation of larger, more sensitive detectors are crucial for detecting rare WIMP.

Use of super-heated liquid for the detection of the spin dependent dark matter search experiment is proved to be a good detector technology. PICO Collaboration which is the merger of the two DM search experiment PICASSO and COUPP have started data taking of PICO-2L October 2013 with $C_3F_8$ bubble chamber. The experiment was done at SNOLAB in Canada (Fig 3). The 2.9 kg $C_3F_8$ is kept inside a silica jar (Amole et al., 2015). Three lead zirconate (PZT) acoustic transducers in order to accquire acoustic signal from bubble nucleations Also they have used CCD cameras. For PICO-2L have operated in four different temperatures which provides four different Seitz threshold. PICO-2L have able to show the good electron-recoil and alpha rejection capability of $C_3F_8$. This collaboration has also able to supersymmetric parameter space (Amole et al., 2017).

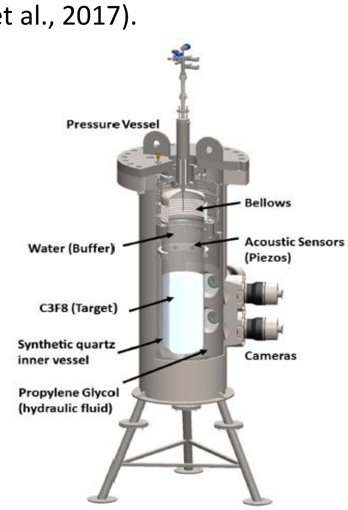


Fig. 3. Detector of PICO-60 experiment (Amole et al., 2016).

Later this collaboration has also used 36 kg of $CF_3I$ bubble chamber (Amole et al., 2016). To extract the free iodine in the $CF_3I$ Some sodium sulfite is added to buffer water so that it can convert the organic iodine to colorless iodine. It is done to prevent the discoloration of fluid. This experiment also has achieved excellent background rejection as the previous one. Further they have used $C_3F_8$ bubble chamber with an increased mass of 52 kg and operated from November 2016 to January 2017. They have analyzed 1167-kg day exposure which is efficiency-corrected having threshold 3.3 keV. They have not registered any sign of no nuclear recoil event. They have produced limits both for spin dependent and spin independent interaction. For a 30 $GeV/c^2$ WIMP the achieved upper limit for the SD WIMP-proton CS is $3.4 \times 10^{-41}$ $cm^2$ (Amole et al., 2017). In 2019 publication they have published 1404-kg-day exposure with threshold of 2.45 keV, lower than the previous one. In their 2016 upgradation they have made several changes like a new cooling system is used to maintain the lower temperature for more see (Amole et al., 2019). They have also claimed the world most stringent limit for WIMP-proton SD, CS to date for a 25 GeV WIMP to be $3.2 \times 10^{-41}$ $cm^2$ (Amole et al., 2019).

## II. Conclusion

In this paper we have seen that Xe time projection chamber have the potential to search for WIMPs in sub GeV regime also which will be key point to watch. LUX and PANDA upgradation have made by increasing the detector mass. Backgrounds have lower to achieve good threshold and limit. We are further looking at their improved result.

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