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# Progress and prospects in the underground laboratories' search for dark matter

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Dark matter constitutes approximately 85% of the universe's total mass, yet its nature remains a mystery. Beyond its gravitational effects, little is known about its fundamental properties. Various technologies sensitive to different types of dark matter particles have been developed to explore the vast parameter space and cross-check each other's results. In this perspective, we review the progress of past and current dark matter experiments in underground laboratories and discuss the improvements needed for future detectors and their sensitivity prospects.

Invisible astrophysical objects have always been a compelling topic among physicists. The concept of dark matter emerged in the late 19th century when astronomical photography showed that stars are not distributed uniformly in the sky, with dark regions appearing between them[1]. At that time, astronomers discussed invisible matter in the form of dark stars, dark planets, or dark nebulae. However, the term "dark matter" as used in modern physics literature today refers to a hypothetical non-baryonic matter component that constitutes approximately 85% of the total mass in the universe[2]. The nature of dark matter remains unknown, but its existence is necessary to explain a wide range of astronomical and cosmological observations, including the flat rotation curves of spiral galaxies[3], evidence of dark matter distribution in the Bullet Cluster[4], and dark matter density derived from Cosmic Microwave Background (CMB) anisotropies and the Baryon Acoustic Oscillation (BAO) survey[2,5,6].

There are three complementary strategies for searching dark matter, as illustrated in Fig. 1. The first strategy, known as "direct detection", is the main focus of this perspective. It aims to observe the interactions between dark matter particles and Standard Model particles directly, using highly sensitive detectors to measure the recoil energy of nuclei or electrons scattered by dark matter particles. The second approach involves using high-energy colliders to produce dark matter in association with Standard Model particles, and inferring their presence through signatures of missing energy and momentum. These accompanying particles can be detected and used to infer the presence of dark matter[7]. The third strategy, known as "indirect detection", seeks to observe secondary particles such as gamma rays, neutrinos, or cosmic rays etc., produced when dark matter particles annihilate or decay. These signals can be detected using telescopes or other astronomical instruments[8].

Hypothetically, the Milky Way Galaxy is embedded in a spherical, nearly homogeneous halo of dark matter, and there is a large variety of dark matter candidates that could be directly detected on Earth. As shown in Fig. 2, the theoretical mass range for dark matter candidates extends from $10^{-22}$ eV/c$^2$ to beyond the Planck scale. Those above $\sim 1$ eV/c$^2$ of mass are referred to as "particle-like" while those below are considered "wave-like" dark matter. Particle-like dark matter searches are significantly impacted by cosmic ray backgrounds, making underground experimental locations crucial. In contrast, wave-like dark matter searches seek to detect coherent oscillations of fields, such as low-mass axions, rather than individual particle hits. As a result, they are less susceptible to cosmic ray interference and can be conducted in facilities on the surface. This perspective will exclusively address the former class of experiments, which require underground environments for optimal sensitivity.

Among various theories, Weakly Interacting Massive Particles (WIMPs) are one of the most promising dark matter particle candidates[1,9–14]. WIMPs have masses between about 1 GeV/c$^2$ and about 100 TeV/c$^2$, while candidates with sub-GeV/c$^2$ masses are referred to as light dark matter. Both are the primary focus of many direct detection experiments in underground laboratories. As will be described below, these experiments can probe dark matter primarily through two interaction channels: with nuclei or with electrons. In the case of dark matter-nucleon interactions, a further distinction is made based on whether the interaction depends on the nuclear spin. Significant progress has been made in probing the parameter space in both cases, but the experimental sensitivity towards smaller cross sections will be challenged by the "neutrino fog" – a range in the cross section versus dark matter mass space where a dark matter discovery becomes increasingly challenging due to astrophysical neutrino backgrounds[15,16].

In this article, we will provide a brief review of the past and current status of experiments in underground laboratories that attempt to detect the dark matter candidates mentioned above, categorized by technology. We will then discuss the prospects of future detectors based on existing technology, as well as potential new strategies for pushing experimental sensitivity into uncharted dark matter parameter space.

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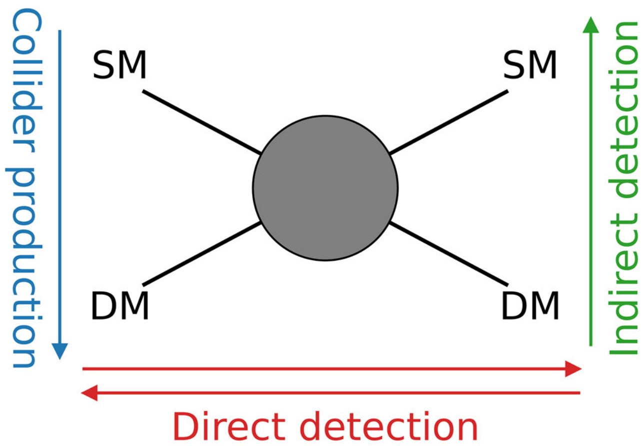


**Fig. 1 | Three types of dark matter particle search methods and their interplay.** "SM" stands for standard model particles, and "DM" represents dark matter particles.

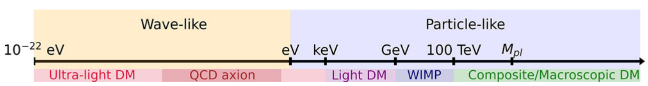


**Fig. 2 | Mass range of dark matter (DM) candidates.** The lightest possible DM mass is constrained by the fact that its wave-like nature can prevent the formation of kiloparsec-scale cusps and substructure in DM halos if the DM mass is below $10^{-22}$ eV/$c^2$ [142]. The heaviest DM mass could exceed the Planck scale ($M_{pl}$) if DM exists as a composite or macroscopic object rather than as a particle. Underground experiments are primarily designed to search for WIMPs in the range of 1 GeV/$c^2$ to 100 TeV/$c^2$, as well as sub-GeV/$c^2$ light DM.

## State-of-the-art dark matter detectors in underground laboratories

### Noble liquid time projection chambers

The noble liquid Time Projection Chamber (TPC) shown in Fig. 3 is a highly effective technology for dark matter detection thanks to its position reconstruction capability, its demonstrated signal-to-background discrimination ability, and its scalability. Position reconstruction in the TPC enables the definition of a low-background fiducial volume for dark matter searches. It detects charge and light signals from particle interactions in the noble liquid, distinguishing between nuclear recoil (NR) and electronic recoil (ER) interactions based on their distinct light-to-charge signal ratios[17,18]. Currently, TPCs made from noble liquids are primarily used to search for WIMPs in the GeV/$c^2$ to TeV/$c^2$ range by detecting their interactions with nuclei. They are, however, also sensitive to other types of new physics through their ER interactions[19–22].

The current best upper limits on the WIMP-nucleon cross section for WIMPs with masses above 9 GeV/$c^2$ are obtained using a tonne-scale dual-phase liquid/vapor xenon TPC, by the LUX-ZEPLIN (LZ) experiment located in the Sanford Underground Research Facility (SURF) in the US[23]. Other tonne-scale xenon-based dark matter experiments, including XENONnT in the Laboratori Nazionali del Gran Sasso (LNGS) in Italy[24] and PandaX-4T in the China Jinping Underground Laboratory (CJPL)[25] present competitive sensitivity for WIMPs within the same mass range. Besides scalability and ER/NR discrimination capability, xenon TPCs' success can be attributed to liquid xenon's exceptional properties for dark matter searches: high scintillation yield and transparency to its own scintillation light, large density providing effective self-shielding against environmental backgrounds, isotopic diversity making it sensitive to different types of WIMP couplings with nuclei (i.e., spin-dependent or spin-independent), and a potentially large spin-independent cross section with WIMPs due to its high atomic mass.

Liquid argon (LAr) has also demonstrated excellent ability in probing dark matter in both scintillator detectors like DEAP-3600 at SNOLAB in Canada[26] and TPC detectors like DarkSide-50 at LNGS[27]. Natural argon contains $^{39}$Ar, which undergoes beta decay, producing a continuous background in the keV energy range. This is one of the primary background sources for LAr-based experiments. DarkSide-50 implements underground Argon (UAr), which contains approximately 1400 times less radioactive $^{39}$Ar compared to atmospheric argon, and has proven to achieve outstanding sensitivity to dark matter between 1.2-3.6 GeV/$c^2$[228], as well as to light dark masses using ionization signals[21]. The accomplishment of argon detectors can be attributed to their high purity achievable in the low-temperature LAr, the demonstrated electron recoil background discrimination power based on scintillation light pulse shapes, and the relatively light argon nucleus, which could provide higher sensitivity to low-mass WIMPs compared to xenon[29,30]. The dark matter mass range to which argon and xenon TPCs are sensitive, as well as their existing limits, are shown in Figs. 4–6. All three figures are adapted from ref. 31.

### Cryogenic solid state detectors

Solid-state materials cooled to cryogenic temperatures exhibit sub-keV nuclear recoil equivalent energy thresholds, with state-of-the-art technologies reaching the $O$ (10) eV range. They can be more sensitive to light dark matter than currently operating noble liquid detectors through both NR and ER channels.

The detection mechanisms for solid-state detectors depend on the target material used. Some experiments measure heat and scintillation light induced by particle interactions in the detector, such as the CRESST-III experiment at LNGS, which uses cryogenic single crystals including $CaWO_4$, Si, $LiAlO_2$, $Al_2O_3$ (sapphire), and Silicon-On-Sapphire (SOS) as the target material[32–34]. Both light and heat signals are measured in the form of phonons using transition edge sensors (TES) operated at ~15 mK.

Other experiments measure phonon and ionization signals, such as the EDELWEISS-III experiment at the Laboratoire Souterrain de Modane (LSM) in France[35], and the SuperCDMS experiment at the Soudan Underground Laboratory in the US[36], both of which used cryogenic semiconductors (germanium) as the target material and have concluded their operations. The ratio between the phonon and ionization signals in these detectors is an efficient discriminator for particle interactions with nuclei or electrons. In EDELWEISS-III, charge signals were measured with a set of interleaved electrodes, while heat was measured by neutron transmutation doped (NTD) thermistors. In SuperCDMS Soudan, the phonon signal was measured using TES arrays, and the ionization signal was measured with charge electrodes. The detector was operated in two modes: the first one was the regular interleaved Z-dependent Ionization and Phonon (iZIP) mode, where a low voltage bias was applied on the electrodes, which also served as charge collectors. In the iZIP mode, the detector could measure both prompt phonons and ionization charge signals, which were used to perform ER and NR discrimination. In the second mode, called CDMSlite[37], a higher bias voltage was applied across the detector to generate additional phonons in proportion to the number of drifting charges and the magnitude of the bias voltage through the Neganov-Trofimov-Luke (NTL) effect[38,39]. This mode achieved a lower energy threshold and better sensitivity to lighter dark matter particles, but it lost the ER/NR discrimination capability.

The above solid state detectors, as shown in Fig. 7, need to be operated at temperatures as low as a few tens of millikelvin using dilution refrigerators. The extremely low temperatures are needed to limit thermal noise, which would otherwise obscure the phonon signals of particle interactions. However, there are also experiments that measure ionization signals only, such as the CDEX-10 experiment at CJPL, which uses High Purity Germanium (HPGe) detectors (point-contact p-type germanium) immersed in liquid nitrogen as the detection target[40]. The current reach of these experiments to dark matter-nucleon cross sections is shown in Figs. 4–5, and to dark matter-electron cross sections in Fig. 6.

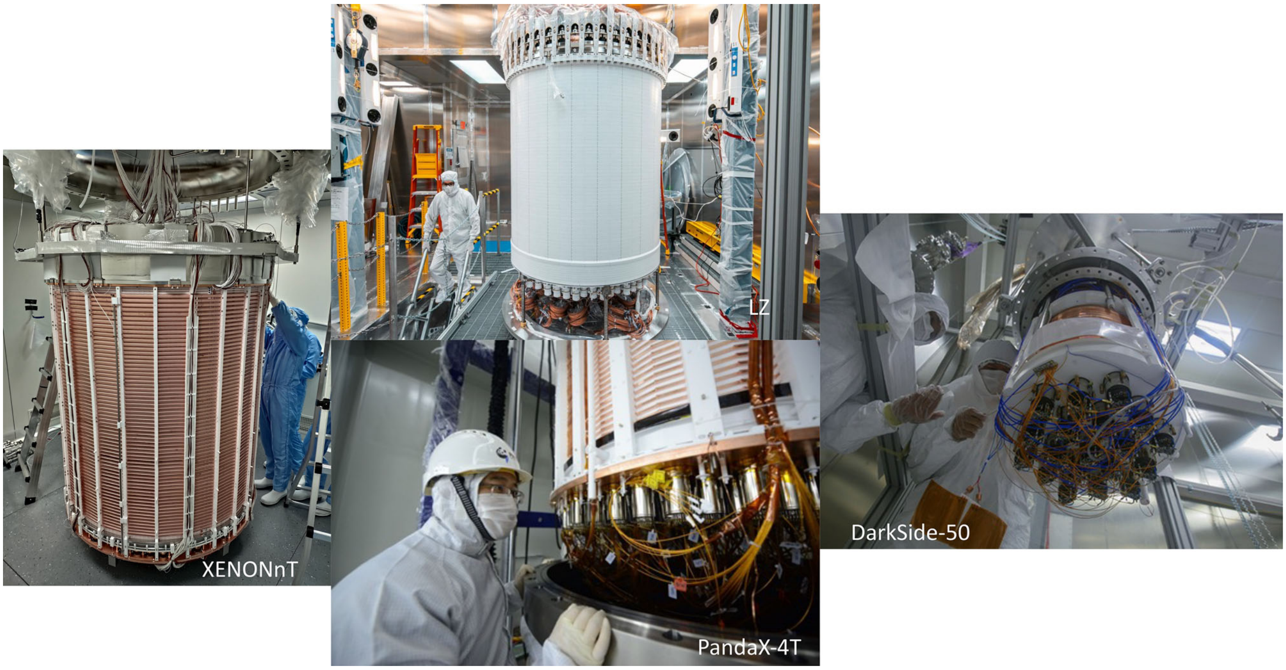


**Fig. 3 | Selection of past and currently operating noble liquid TPCs used in the search for dark matter.** Shown here are some of the leading experiments employing liquid xenon or liquid argon as a detection target. These detectors operate deep underground to shield them from cosmic rays, and use arrays of photomultiplier tubes (PMTs) to detect scintillation light and ionization signals from particle interactions in the liquid. Featured in the images are: LZ at SURF (Credit: Matthew Kapust/SURF[143]), XENONnT at LNGS (Credit: XENON Collaboration[144]), PandaX-4T at CJPL (Credit: PandaX Collaboration[145]), and DarkSide-50 at LNGS (Credit: ©Yura Suvorov/LNGS-INFN[146]).

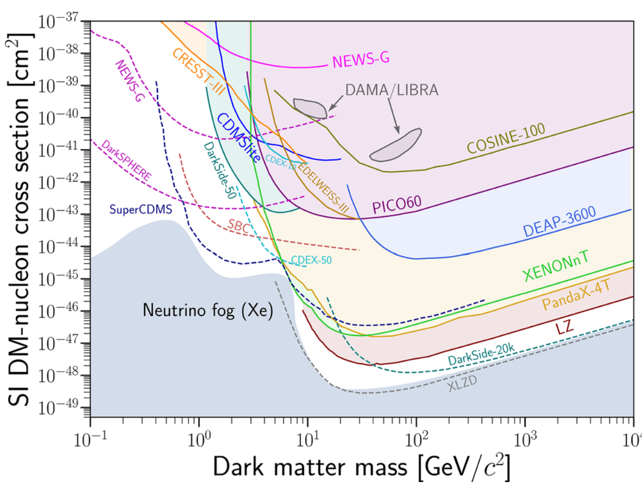


**Fig. 4 | Present limits and future sensitivities to spin-independent (SI) dark matter-nucleon cross section.** Solid lines are limits at 90% confidence level (C.L.) from previous or currently running dark matter direct detection experiments[28,32,37,49,51,54,120,147–156]. Dashed lines are projected 90% C.L. exclusion sensitivity of future experiments[77,78,88,92,122,157–159]. The shaded gray region is the neutrino fog for a xenon target.

## CCD detectors

Charge-coupled devices (CCDs) are widely used in high-quality digital imaging and can also be adapted for use as particle detectors. The $O(1\text{ eV})$ band gap of CCD silicon allows for ionization signals from light dark matter to be detected through eV-scale electronic recoils. The charge produced by a nuclear or electronic recoil, induced by a particle interaction in the CCD, drifts towards the pixel gates where it is read out. The new skipper CCD technology enables accurate charge measurements of pixels with single electrons. This is accomplished by performing multiple non-destructive readouts of the charge in the same pixel and reducing readout noise to sub-electron levels through averaging the results of these repeated measurements[41]. Experiments using skipper CCDs, therefore, have an energy threshold of a few eV and are particularly sensitive to light dark matter. Thanks to recent advances in skipper CCD technology and the increased purity of silicon, thicker (675 $\mu$m) devices have been fabricated to improve sensitivity for light dark matter searches[42].

The currently running skipper CCD detectors, including the prototype DAMIC-M at LSM[43,44] and SENSEI at SNOLAB[45], both employ large-area, thick CCDs to search for dark matter-electron scattering interactions via both light and heavy mediators. Their experimental results are presented in Fig. 6, where the original limit from SENSEI[46] has been recast for a consistent comparison by using the same dark matter halo parameters[47] and charge yield model[48], as detailed in ref. 43.

## Bubble chambers

Bubble chambers are used to search for dark matter through detecting bubble formation induced by their nuclear recoil interactions in superheated liquid, using cameras and piezoelectric sensors. In the bubble chambers, nucleation from electron recoil backgrounds is basically fully suppressed at low energy, thus providing a unique capability of signal and background discrimination power[49,50]. The low energy threshold (a few keV or lower for nuclear recoils), background discrimination capability, and scalability of this technology make it advantageous for dark matter detection.

The PICO experiment at SNOLAB, shown in Fig. 8 – formed through the merger of the PICASSO and COUPP Collaborations, uses a freon($C_3F_8$)-filled bubble chamber to detect dark matter, with an NR energy threshold of a few keV[49,51]. The $^{19}$F nucleus in freon has an unpaired proton and is ideal for measuring spin-dependent WIMP-nucleon cross sections. Because freon presents high spin-dependent and low spin-independent cross sections, it allows for the exploration of orders-of-magnitude more parameter space for WIMPs within the GeV/$c^2$ and TeV/$c^2$ range before reaching the neutrino fog than can be achieved in solid state and noble-

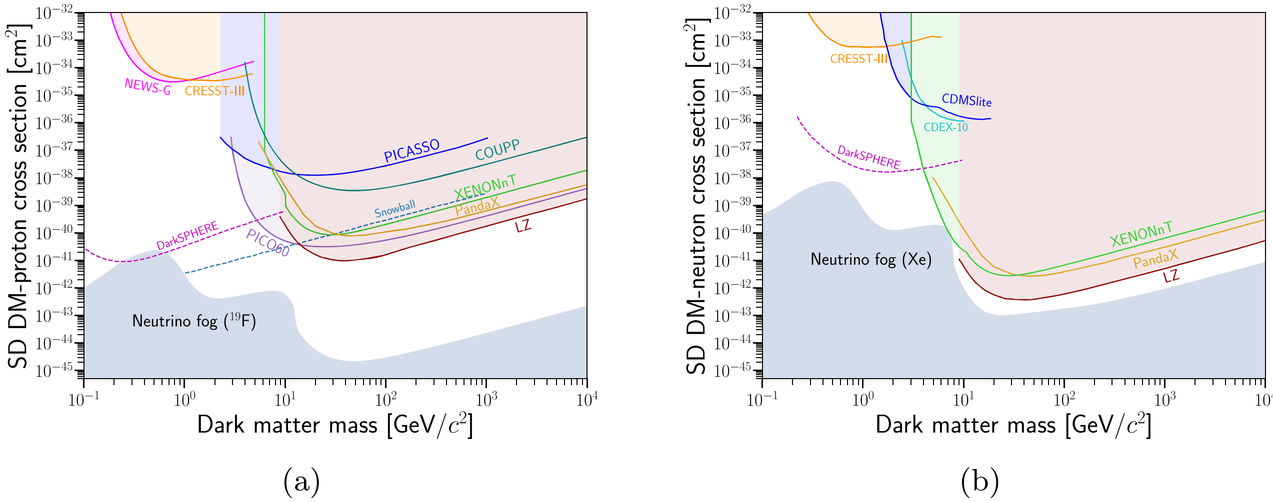


**Fig. 5 | Present limits and future sensitivities to the spin-dependent (SD) dark matter cross section.** (**a**) for protons and (**b**) for neutrons. Solid lines are limits at 90% confidence level (C.L.) from previous or currently running dark matter direct detection experiments[33,49,148,151,152,155,156,159–163]. Dashed lines are projected 90% C.L. exclusion sensitivity of future experiments[122]. The shaded gray region is the neutrino fog for a $^{19}$F target in the dark matter-proton scattering case, and a xenon target in the dark matter-neutron scattering case.

liquid detectors. The dark matter mass range to which PICO is sensitive, along with its existing limits on spin-independent and spin-dependent dark matter-nucleon cross sections, are shown in Figs. 4 and 5a, respectively.

### NaI detectors

The thallium-doped sodium iodide (NaI(Tl)) crystal shown in Fig. 9 is a well-known scintillator technology. While NaI detectors do not have ER/NR discrimination ability, highly radiopure NaI(Tl) crystals with high light yield and an O(1) keV electron equivalent energy threshold can be used in dark matter experiments to search for the annual modulation signature of dark matter-nuclei interactions. This modulation arises from the variation in the detector's velocity relative to the dark matter halo as the Earth orbits the Sun. Due to Earth's annual revolution, a maximal flux of dark matter particles is expected in June, and a minimal one is expected in December[52].

The DAMA/LIBRA experiment at LNGS reported a detection of the annual modulation signal of dark matter using ~250 kg of highly radiopure NaI crystals[53]. This result is model-independent, but it is in tension with the non-modulation searches by the noble liquid and cryogenic detectors, which yield null results. Experiments like COSINE-100 at the Yangyang underground laboratory in South Korea[54,55], and ANAIS-112 at the Canfranc Underground Laboratory in Spain[56,57], which use an array of 106 kg and 112.5 kg of NaI(Tl) crystals, respectively, have also searched for the annual modulation signature, aiming to test DAMA/LIBRA's claim of dark matter discovery. Both experiments have obtained negative test results, which are inconsistent with DAMA/LIBRA's observation at about $3-4\sigma$ confidence level[58–60]. COSINE-100 concluded data taking in 2023, while ANAIS is expected to operate until the end of 2025.

A key challenge in directly comparing different NaI experiments is the uncertainty in quenching factors (QFs) – the ratio of light yield from a nuclear recoil to that of an electron recoil of the same energy – which impacts our understanding of the true nuclear recoil energy deposition[61,62]. Both COSINE-100 and ANAIS-112 have conducted measurements of the QFs for their crystals[63,64]. After accounting for significantly different QF scenarios in their analyses, the results remain incompatible with DAMA/LIBRA[58,65]. However, further work is essential to improve the understanding and modeling of the scintillation QF in all three experiments. On the other hand, several scenarios have been proposed suggesting that the modulation signal detected by DAMA/LIBRA might be caused by variations in the detector's environment or by their specific analysis methods[66–68], but none of these hypotheses have successfully reproduced the amplitude and phase of the signal or provided a satisfactory account of the observed modulation[69,70].

## Prospects of future dark matter detection

Over the past few decades, significant progress has been made in advancing the limits of dark matter detection using various technologies. Figure 10 illustrates the improvement in sensitivity in the search for a 60 GeV/c$^2$ dark matter candidate. Although the figure does not capture the growing diversity of experimental approaches or the broadening range of dark matter masses over the years, it highlights the rapid pace of progress in the search for classic WIMPs.

The common goal of all dark matter experiments is to enhance future sensitivity and probe more unexplored parameter space. Achieving this will primarily depend on increasing exposure, reducing background levels in current experiments, reducing the energy threshold and/or developing new detector technologies. Scaling up the detector size poses technical challenges, even for mature technologies that have already deployed multiple generations of detectors. A common issue is that backgrounds from radioactive contaminants or instrument noise tend to increase with detector size, making it difficult to improve sensitivity proportionally to exposure. For dual-phase TPCs, which read out light and charge signals with a time delay between them, another significant challenge in scaling up the detector size is the increased likelihood of accidental coincidences between unrelated charge and light signals that could mimic real particle events. Additionally, calibrating large detectors and understanding their response at very low energies is challenging and requires technical advancements[71].

In this section, we discuss the future sensitivity prospects of the technologies described in the "State-of-the-art Dark Matter Detectors in Underground Laboratories" section, using representative examples of experiments that are either currently under construction or in the planning stages (a list of recent and future experiments discussed in this perspective is presented in Table 1). We will also describe improvements in detector design, target and detector material cleanliness, and the assembly process, all aimed at overcoming the challenges of scaling up existing experiments. In addition, we will cover some newly developed or proposed detection strategies.

### Noble liquid time projection chambers

The ultimate goal of the noble liquid dark matter experiments is to either detect WIMPs or explore all the parameter space accessible for WIMPs that is constrained by the neutrino fog.

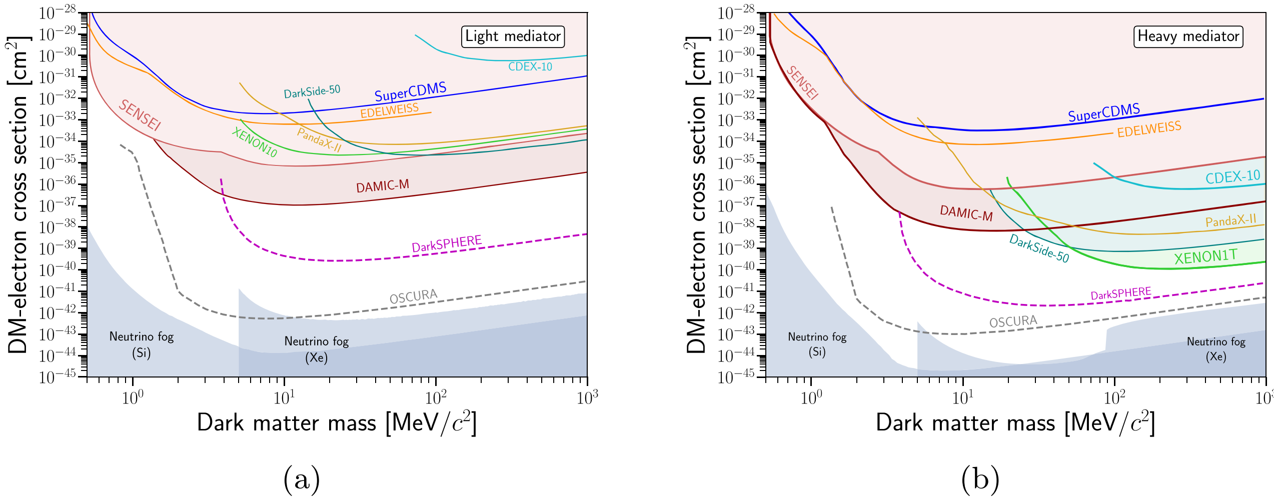


**Fig. 6 | Existing limits at 90% C.L. on DM-electron cross section.** **a** for light mediators and **b** for heavy mediators from various experiments[21,44,46,148,164–170]. The limits from SuperCDMS and SENSEI have been adjusted to have consistent halo model and charge yield models from DAMIC-M[43]. The projected sensitivity at 90% C.L. of future experiments[95,122], and the neutrino fog for dark matter-electron scattering in Xe and Si targets[16] are also shown.

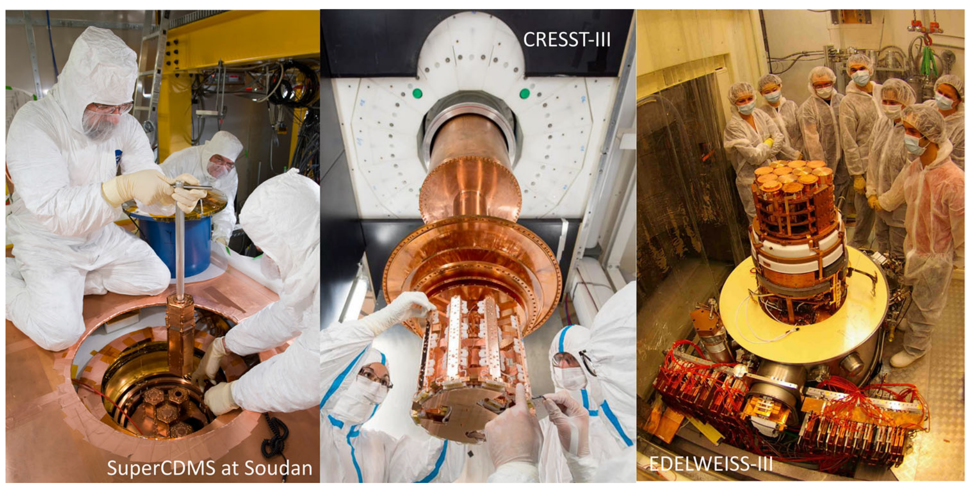


**Fig. 7 | Selection of past and currently operating cryogenic solid-state detectors developed for direct dark matter searches.** These experiments employ ultrapure crystals operated at millikelvin temperatures to achieve high sensitivity to the tiny signals produced by potential dark matter interactions. Shown here are: SuperCDMS at Soudan (Credit: Reidar Hahn, Fermilab[171]), CRESST-III (Credit: A. Eckert/MPP[172]), and EDELWEISS-III (Credit: EDELWEISSS Collaboration[173]).


**Fig. 8 | Bubble chambers used in the PICO experiment.** When a nuclear recoil from a potential dark matter particle interaction occurs in the superheated liquid, it deposits localized energy that triggers the formation of a bubble. Acoustic sensors and cameras record the event, allowing discrimination between NR signals and ER backgrounds. Operated deep underground at SNOLAB, the PICO series of detectors has achieved world-leading sensitivity to spin-dependent WIMP-proton interactions. Shown here are PICO-60 (Credit: Eric Vázquez Jáuregui from the PICO Collaboration[174]) and PICO-40L (Credit: PICO Collaboration[175]).


**Fig. 9 | Selection of past and currently operating NaI(Tl) detectors.** These experiments probe annual modulation signatures expected from Earth's motion through the dark matter halo. DAMA/LIBRA at LNGS has reported such a signal for about two decades. Independent efforts, including COSINE-100 at the Yangyang Underground Laboratory and ANAIS-112 (not shown in the figure) at the Canfranc Underground Laboratory, aim to test DAMA/LIBRA's claim. Image credits: ©DAMA/LIBRA Collaboration[176]; Changhyon Ha for the COSINE-100 Collaboration[177].

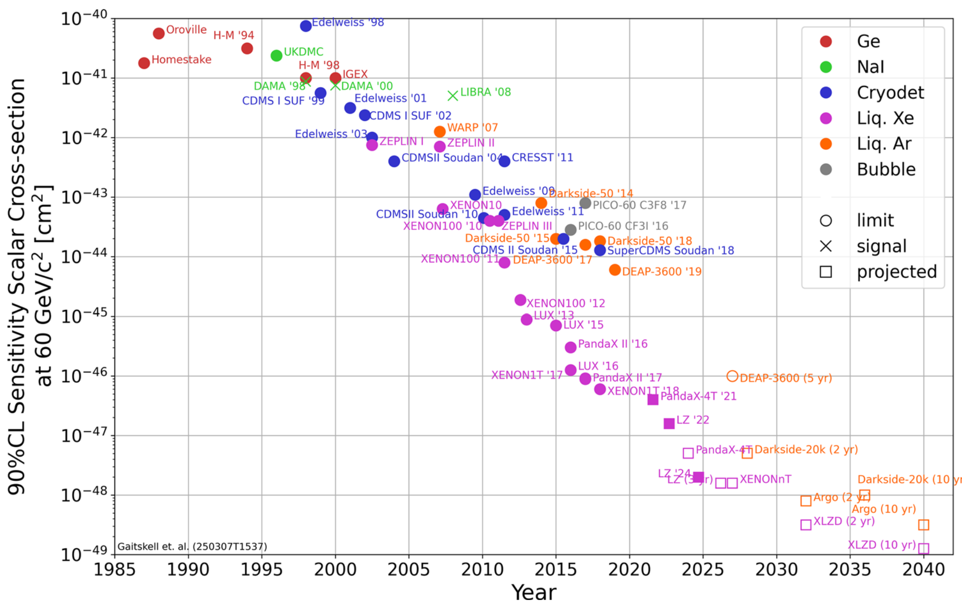


**Fig. 10 | Improvement in sensitivity to spin-independent WIMP-nucleon coupling for a dark matter mass of 60 GeV/c² using various detector technologies over the years[178].** The solid points represent achieved limits, while the empty points indicate projected sensitivities.

Xenon TPCs have proven to be a powerful and reliable technology for probing dark matter, and the current generation of tonne-scale xenon experiments has made impressive progress on pushing the limits on WIMP detection. The PandaX Collaboration is building a multi-ten-tonne liquid xenon TPC, with the aim of reaching the neutrino fog, detecting neutrinos from astrophysical sources, and searching for other types of rare events[72]. The LZ experiment is currently operational and is considering potential upgrades to be implemented after reaching its sensitivity goal. These include doping xenon with lighter nuclei, as in HydroX[73,74], and freezing xenon into a solid form, as in CrystaLiZe[75]. HydroX may extend LZ's sensitivity to dark matter in the $O(1)$ GeV/$c^2$ range, as doped nuclei such as hydrogen are more kinematically favorable for scattering with low-mass WIMPs, resulting in larger signals. CrystaLiZe aims to significantly enhance LZ's sensitivity by using solid xenon (SXe) as a target medium, which has demonstrated exceptional effectiveness in preventing radioactive radon ingress – a dominant background in LZ. Meanwhile, a future xenon detector, with a fiducial mass of multi-ten-tonne and capable of reaching an exposure of 1 ktonne-year, is being planned by the XLZD Collaboration[76]. This next generation experiment will be useful under two scenarios: if the current generation of xenon experiments discovers dark matter, a larger detector will be needed to gather more statistics for a better characterization of its properties; if the current generation does not detect dark matter, the future detector will be able to reach the neutrino fog for WIMPs within the GeV/$c^2$ to TeV/$c^2$ mass range. Furthermore, a xenon TPC with 1 ktonne-year of exposure can serve as an effective observatory for various rare events beyond WIMPs. A broad physics program, involving searches for non-WIMP dark matter, neutrinoless double beta decay, and neutrinos from astrophysical sources, among others, are detailed in the white paper[77].

The DarkSide-20k (DS-20k) experiment of the Global Argon Dark Matter Collaboration (GADMC) will search for dark matter using a dual-phase argon TPC with 20 tonne fiducial mass and is currently under construction at LNGS[78]. The detector builds on successful elements of previous argon experiments, including the use of UAr. Equipped with high chemical purity and demonstrated background discrimination power, DS-20k is expected to measure less than 0.1 background events over a planned ten year run and achieve a sensitivity for WIMPs above ~100 GeV/$c^2$ beyond any other currently funded experiment, as indicated in Fig. 4. A key challenge is scaling up from the ~50 kg argon TPC used in DarkSide-50 to a 20-tonne fiducial mass detector within a short timeframe in order to remain competitive with xenon-based dark matter experiments. The final goal of the GADMC is to build an argon TPC with 300 tonne fiducial mass named Argo[79], which will push the experimental sensitivity into the neutrino fog for argon. Similar to XLZD, Argo can also become an observatory for neutrinos from the sun and supernovae. In order to successfully construct Argo, longer-term operation of the UAr extraction and purification plants, as well as their storage and assay facilities are needed.

A new experiment called ALETHEIA is conducting R&D on a liquid helium (LHe) TPC to probe low-mass dark matter. The LHe TPC faces several challenges, one of which is the very low electron mobility due to the formation of "electron bubbles" in LHe[80–82]. A one-meter-high TPC requires

**Table 1 | Summary of recent and future direct dark matter detection experiments discussed in this paper**

| Name | Technique | Target | Target Mass | Detection Channel | Location | Status |
|---|---|---|---|---|---|---|
| XENONnT | TPC | LXe | 5.9 tonnes | scintillation, ionization | LNGS | running |
| LZ | TPC | LXe | 7 tonnes | scintillation, ionization | SURF | running |
| PandaX-4T | TPC | LXe | 3.7 tonnes | scintillation, ionization | CJPL | running |
| LZ HydroX | TPC | $LXe+H_2$ | 7 tonnes | scintillation, ionization | SURF | R&D |
| LZ CrystaLiZe | TPC | SXe | ~8 tonnes | scintillation, ionization | SURF | R&D |
| PandaX-xT | TPC | LXe | 43 tonnes | scintillation, ionization | CJPL | construction |
| XLZD | TPC | LXe | 60−80 tonnes | scintillation, ionization | TBD | proposed |
| DEAP-3600 | scintillator | LAr | 3600 kg | scintillation | SNOLAB | running |
| DarkSide-50 | TPC | LAr | ~50 kg | scintillation, ionization | LNGS | completed |
| DarkSide-20k | TPC | LAr | ~50 tons | scintillation, ionization | LNGS | construction |
| Argo | TPC | LAr | ~400 tonnes | scintillation, ionization | TBD | proposed |
| ALETHEIA | TPC | LHe | $O(1)$ ton | scintillation, ionization | TBD | R&D |
| CRESST-III | cryogenic solid state | $CaWO_4$, $LiAlO_2$, Si, $Al_2O_3$ | $O(10)$ g | scintillation, heat | LNGS | running |
| EDELWEISS-III | cryogenic solid state | Ge | ~20 kg | ionization, heat | LSM | completed |
| EDELWEISS CRYOSEL | cryogenic solid state | Ge | ~20 kg | ionization, heat | LSM | R&D |
| SuperCDMS Soudan | cryogenic solid state | Ge | ~9 kg | ionization, heat | Soudan | completed |
| SuperCDMS SNOLAB | cryogenic solid state | Ge, Si | ~30 kg in total | ionization, heat | SNOLAB | construction |
| CDEX-10 | HPGe | Ge | 10 kg | ionization | CJPL | completed |
| CDEX-50 | HPGe | Ge | 50 kg | ionization | CJPL | R&D |
| DAMIC-M | skipper CCD | Si | ~700 g | ionization | LSM | prototype running |
| SENSEI | skipper CCD | Si | ~100 g | ionization | SNOLAB | 40 g of target running |
| OSCURA | skipper CCD | Si | ~10 kg | ionization | SNOLAB | awaiting funding for construction |
| PICO-60 | bubble chamber | $CF_3I$ or $C_3F_8$ | 37 kg or 52 kg | acoustic signals | SNOLAB | completed |
| PICO-40L | bubble chamber | $C_3F_8$ | ~70 kg | acoustic signals | SNOLAB | running |
| PICO-500 | bubble chamber | $C_3F_8$ | ~250 kg | acoustic signals | SNOLAB | construction |
| SBC-LAr10 | bubble chamber | LAr | 10 kg | scintillation, acoustic signals | Fermilab, SNOLAB | construction |
| Snowball | supercooled liquid | $H_2O$ | $O(1)$ kg | nucleation | TBD | R&D |
| DAMA/LIBRA | scintillator | NaI(Tl) | 250 kg | scintillation | LNGS | completed |
| COSINE-100 | scintillator | NaI(Tl) | 106 kg | scintillation | YangYang | completed |
| COSINE-200 | scintillator | NaI(Tl) | 200 kg | scintillation | YangYang | R&D |
| ANAIS-112 | scintillator | NaI(Tl) | 112.5 kg | scintillation | Canfranc | running |
| COSINUS | cryogenic solid state | NaI | 34.8 g−2 kg (phase 1) | scintillation, heat | LNGS | construction |
| PICOLON | scintillator | NaI(Tl) | 250 kg | scintillation | Kamioka | R&D |
| SABRE South | scintillator | NaI(Tl) | 35 kg or 50 kg | scintillation | SUPL | construction |
| SABRE North | scintillator | NaI(Tl) | 45 kg | scintillation | LNGS | construction |
| TESSERACT SPICE | cryogenic solid state | GaAs, $SiO_2$, $Al_2O_3$, Si, Ge | between 10 $g^{-1}$ kg | scintillation, heat | LSM | R&D |
| TESSERACT HeRALD | superfluid He | $^4He$ | $O(10)$ g | scintillation, heat | LSM | R&D |
| DELight | superfluid He | $^4He$ | $O(1)$−$O(10)$ kg | scintillation, heat | La Vue-des-Alpes | R&D |
| QUEST-DMC | superfluid He | $^3He$ | ~0.1 g | scintillation, heat | TBD | R&D |
| NEWS-G SEDINE | SPC | $Ne+CH_4$ | 282 g | ionization | LSM | completed |
| NEWS-G S140 | SPC | $Ne+CH_4$ | 114 g | ionization | SNOLAB | running |
| NEWS-G ECuME | SPC | $Ne+CH_4$ | TBD | ionization | SNOLAB | R&D |
| NEWS-G DarkSPHERE | SPC | $He+C_4H_{10}$ | 27 kg | ionization | Boulby | proposed |
| NEWSdm | nuclear emulsion | AgBr | 10 kg | nuclear recoil | LNGS | R&D |
| DRIFT-II | directional gas TPC | $CS_2+CF_4$ | ~140 g | ionization | Boulby | completed |
| DMTPC | directional gas TPC | $CF_4$ | 3.3 g | ionization | WIPP | completed |
| CYGNUS | directional gas TPC | $He+SF_6$ | 100−1000 kg | ionization | TBD | R&D |

one million volts to achieve a reasonable electron drift velocity[83]. However, if these challenges are overcome and the technology is successfully developed, the experiment could be sensitive to dark matter in the ~10 MeV/$c^2$−10 GeV/$c^2$ range, which argon or xenon detectors cannot fully explore.

Using TPCs with different noble gas elements as targets helps cross-verify dark matter signals and rule out false positives. For example, if WIMPs are detected by a xenon-based experiment in the coming years, detecting them with another target, such as argon, would allow for a more precise measurement of the WIMP mass and serve as a valuable test to distinguish the signal from potential background misinterpretations.

### Cryogenic solid state detectors

A common challenge for cryogenic solid-state detectors with low energy threshold is the "low energy excess (LEE)" – the observation of a significantly higher number of registered events below a few hundred eV than predicted from known background sources. The shape and rate of the LEE vary across different experiments, and a common origin to explain all excess – such as a dark matter signal – is inconsistent with the data[84,85]. The LEE is the main limiting factor for further sensitivity improvement of cryogenic solid state dark matter experiments towards lighter dark matter masses and is therefore intensively studied by the community. For example, some experiments have found hints that a stress-induced phonon burst may be one source contributing to this excess[86,87]. However, the source of the LEE is not fully understood yet, and an overview of the observed LEE in experiments including CRESST, EDELWEISS, SuperCDMS, as well as experiments using CCDs such as DAMIC and SENSEI can be found in ref. 84. In the coming years, significant improvement to the cryogenic solid state detectors will be needed to increase their sensitivity to < 10 GeV/$c^2$ WIMPs, as shown in Fig. 4.

The SuperCDMS experiment at SNOLAB is currently under construction and will utilize both cryogenic germanium and silicon crystals as targets. The experiment will use two types of detectors: iZIP and HV, optimized to be operated at different bias voltages[88]. The iZIP detectors are equipped with both phonon sensors and ionization sensors and will operate at a bias of ~5–10 V. They have the ability to distinguish ER backgrounds from dark NR signals through the ratio of ionization production to the total recoil energy. The HV detectors, on the other hand, are instrumented with phonon sensors only. They will operate at a bias of up to ~100 V, which will generate additional phonons in proportion to the number of drifting charges through the NTL effect. Thanks to low-radioactivity shielding and the depth of SNOLAB, most backgrounds will be reduced compared to SuperCDMS Soudan. The HV detectors, with high energy resolution and low thresholds, are expected to improve the existing limits on 1 GeV/$c^2$ dark matter by more than three orders of magnitude[88]. The iZIP detectors, which are relatively insensitive to variations in backgrounds due to their advanced ER/NR discrimination capability, will have better sensitivity for dark matter particles with masses ≥5 GeV/$c^2$. The initial design of SuperCDMS SNOLAB does not allow its sensitivity to reach the neutrino fog, but the experiment has the potential to achieve greater sensitivities and probe even smaller dark matter masses through R&D, such as using lower-background materials and improving detector fabrication and assembly techniques to reduce surface radon contamination.

The CRESST experiment is planning a major upgrade to the experimental setup at LNGS. The primary objective is to enhance the detector exposure and improve the experimental sensitivity by increasing the number of readout channels by approximately an order of magnitude. Thanks to the flexibility of cryogenic calorimetry technology and the ability to operate a large number of detectors, CRESST expects to achieve a substantial improvement in its physics reach. Ongoing data-taking efforts using different thermal sensor designs – such as various TES layouts – and detector configurations aim to identify the setup with the best operational performance, which will be adopted in the planned upgrade[89].

The EDELWEISS Collaboration is developing a new detector design, called CRYOSEL, which incorporates a Superconducting Single Electron Device (SSED) sensor to tag phonons emitted via the NTL effect by individual charges drifting through a nearby high-field region[90,91]. Such kind of tagging could suppress backgrounds at low energy with no ionization signal, which limits the sensitivity of the detector.

The CDEX Collaboration is preparing for the next-generation of the experiment, CDEX-50, which will feature 50 kg of germanium detectors with enhanced material purity and improved shielding to reduce the background level. The experiment aims to achieve the most sensitive limits on WIMPs in the mass range of 2.2 − 8 GeV/$c^2$ [92].

A new experimental collaboration, TESSERACT, is aiming at detecting MeV/$c^2$ to GeV/$c^2$ dark matter with a variety of cryogenic detectors[93]: solid state targets including polar crystals ($Al_2O_3$, $SiO_2$) and scintillating crystals (GaAs) in the case of the SPICE experiment, and superfluid helium in the case the HeRALD experiment which will be discussed in the "Superfluid Helium Detectors" subsection. Another detector based on cryogenic semiconducting (Ge, Si) bolometers may also be added to the TESSERACT experiment. In the SPICE experiment, the solid state detectors will be instrumented with TES-based athermal phonon sensors with eV-scale energy thresholds to probe both NR and ER dark matter interactions. As the authors write this paper, TESSERACT has published its first limits on light dark matter using a low threshold, two-channel athermal phonon detector on the surface, which can sense phonon bursts in the silicon substrate from dark matter NR interactions. The two-channel design helps distinguish dark matter signals, which would produce roughly equal responses in both channels, from sensor-coupled backgrounds, which would primarily be confined to a single channel. The experiment has achieved the best energy resolution to date for athermal phonon detectors, enabling it to reach the lowest-mass sensitivity of any dark matter NR search and set the most stringent limits on dark matter masses between 44−87 MeV/$c^2$ [94].

### CCD Detectors

Built on the successful experience of probing electron recoils from light dark matter with prototype skipper-CCDs detectors, SENSEI plans to install a 100 g detector at SNOLAB, while DAMIC plans to install a ~1 kg detector at LSM. In the future, an even larger experiment, OSCURA, is planning to deploy 10 kg of skipper-CCD sensors, which will reach unprecedented sensitivity to light dark matter through both nuclear and electronic interactions. OSCURA is expected to have a threshold of two electrons and measure less than one event in the 30 kg-yr exposure in the 2–10 electron signal region. This will allow it to probe dark matter-electron scattering for masses down to ~500 keV/$c^2$ (as shown in Fig. 6) and dark matter being absorbed by electrons for masses down to ~1 eV/$c^2$ [95].

### Bubble Chambers

Bubble chambers are a scalable technology and the next generation of the PICO detector, PICO-500, will have an active volume of 420 kg of $C_3F_8$. It is expected to reach an exposure of tonne-years and a spin-dependent WIMP-proton sensitivity around $10^{-42}$ cm$^2$ for WIMP masses around 60 GeV/$c^2$. However, PICO-500's sensitivity is still four-orders-of-magnitude above the $C_3F_8$ neutrino fog[96]. In order to achieve a kiloton-year exposure and reach the atmospheric neutrino sensitivity, a larger inner vessel with low radioactivity that can contain 50 tons of freon needs to be built[71]. Studies and tests on materials with suitable mechanical and surface chemistry are ongoing.

The Scintillating Bubble Chamber (SBC) is a new experiment that uses noble liquid as the detection target[97]. Compared to freon used in the PICO experiment, noble liquids can be superheated to a far greater degree, making them sensitive to sub-keV nuclear recoils while remaining completely insensitive to ER backgrounds in the acoustic channel due to the suppression of ER-induced bubble nucleation. The scintillation signal in SBC enables energy reconstruction and can also be used to reject high-energy backgrounds. This technology offers greater sensitivity to 1–10 GeV/$c^2$ WIMPs than noble liquid TPCs, as indicated in Fig. 4. A 10-kg LAr scintillating bubble chamber, SBC-LAr10, has been built at Fermilab, and a twin bubble chamber has also been funded and will be built at SNOLAB. The target nuclear recoil energy threshold of the detector is 100 eV, but the exact value is not known yet and will be measured with the upcoming calibration run at Fermilab. If the target energy threshold is proven achievable, the scalability and background discrimination power of this technology could enable a future larger bubble chamber experiment, with ~1-ton-year exposure, to reach the neutrino fog for Ar at 1 GeV/$c^2$ WIMP mass[98].

### NaI detectors

To date, the annual modulation signal reported by DAMA/LIBRA has not been replicated in other NaI(Tl)-based experiments such as COSINE-100 and ANAIS-112. A combined analysis instead disfavors a dark matter interpretation of the DAMA/LIBRA result[60], warranting further investigation. DAMA/LIBRA stopped data-taking in 2024 and accumulated approximately 3 tonne-years of exposure[99]. Given the widespread dispute concerning the validity of their results[65,67,68,100], we believe it is important to perform and publish a detailed background analysis of the experiment. This will help ascertain if the observed annual modulation stems from time-dependent backgrounds.

In the meantime, other NaI(Tl)-based experiments will continue testing DAMA/LIBRA's results. The ANAIS-112 experiment is expected to achieve a 5$\sigma$ sensitivity in ruling out the DAMA/LIBRA signal by 2025[59], and the collaboration is developing new strategies to improve the experiment's sensitivity even further, such as replacing the PMTs with SiPMs in the ANAIS+ project, which can reduce the background level[101]. COSINE-100 is upgrading its detector by directly attaching the crystals to PMTs, which can improve the light collection efficiency by approximately 35%. The new COSINE-100U detector will be installed at Yemilab in South Korea, which provides a deeper underground environment with enhanced shielding from cosmic rays. It is expected to probe previously unexplored parameter spaces for spin-dependent WIMP-proton interactions[102]. Because the background level in COSINE-100 is 2-3 times higher than in DAMA/LIBRA, it could not draw a definitive conclusion regarding DAMA/LIBRA's claimed observation. There has been R&D into a mass production process of ultra-pure NaI powder to grow kilogram-scale NaI crystals for the next phase COSINE-200 experiment, with the goal of definitively confirming or refuting DAMA/LIBRA's reported signal[103].

In parallel, future programs involving NaI(Tl)-based detectors are being developed to test the DAMA/LIBRA results, including the COSINUS experiment at LNGS[104], the PICOLON experiment at Kamioka[105], and the SABRE experiment, which will deploy two detectors – SABRE North at LNGS in Italy and SABRE South in the Stawell Underground Physics Laboratory (SUPL) in Australia respectively[106,107]. Among all NaI experiments, COSINUS will be the only one using NaI without Tl doping and featuring a measurement of nuclear recoil energy per event. It will develop NaI into a cryogenic detector that measures both the heat channel signal and scintillation light. This will be crucial in resolving uncertainties in light quenching factors for nuclear recoils, which impact the interpretation of physics outcomes from NaI experiments relying solely on scintillation readout. COSINUS is expected to have a lower energy threshold and better resolution than DAMA/LIBRA, and it can perform particle identification based on the measured light-to-phonon signal ratio. Therefore, in addition to providing a cross-check of the DAMA/LIBRA result, COSINUS's sensitivity could be competitive to other direct dark matter searches in the 1–10 GeV/$c^2$ range[108,109]. The PICOLON experiment is making significant efforts to remove radioactive impurities from NaI powder through multiple recrystallizations and the use of ion exchange resins. Its final goal is to construct a 250 kg highly radiopure NaI(Tl) detector to verify the result of the DAMA/LIBRA after one year of continuous data collection. The SABRE experiment's deployment of two similar detectors, one in the Northern Hemisphere and the other in the Southern Hemisphere, will allow the disentangling of seasonal effects, such as those from cosmic muons, which exhibit opposite seasonal modulation in the two hemispheres. The SABRE South experiment will implement a liquid scintillator veto and muon detection system surrounding NaI crystals to reject a large fraction of backgrounds[110], while SABRE North will instead utilize passive shielding, based on tests demonstrating that its background goal can be achieved without an active veto[106].

### New technologies

**Superfluid helium detectors**. A number of experiments are exploring the use of superfluid helium for detecting light dark matter through NR interactions. The DELight experiment and the HeRALD experiment (as part of TESSERACT) will use superfluid $^4$He as a target to study light dark matter[111,112], while the QUEST-DMC Collaboration proposes to build a superfluid $^3$He-based detector with a sub-eV NR energy threshold to improve on the sensitivity to dark matter in the same mass range[113].

Energy deposits in superfluid helium can be detected calorimetrically through both scintillation photons and quasiparticle-induced "quantum evaporation". Here, quasiparticles refer to low-momentum phonons and higher-momentum "rotons"[114]. The quantum evaporation signal arises when single quasiparticles liberate single helium atoms from the liquid surface into the vacuum above. When the evaporated helium atoms reach the calorimetric quantum sensors installed above the liquid, the energy detected is not their relatively small kinetic energy but rather the much larger van der Waals potential of helium adsorption at the calorimeter surface[115]. Combining the scintillation channel with the quasiparticle channel could provide event-by-event information on the ER or NR nature of interactions.

The TESSERACT Collaboration has made good progress in the HeRALD experiment on instrumenting a superfluid $^4$He target with TES-based calorimeters with an energy threshold of 145 eV, allowing sensitivity to dark matter masses down to 220 MeV/$c^2$ [111]. Their energy threshold is expected to be further reduced in the future. The DELight experiment will be equipped with magnetic microcalorimeters (MMCs), which have demonstrated good energy resolution, paving the way for the search for dark matter with masses below 100 MeV/$c^2$ using superfluid $^4$He[116]. The QUEST-DMC detector consists of a bolometer box filled with superfluid $^3$He and instrumented with a nanomechanical resonator (NEMS) designed to detect thermal quasiparticle production in $^3$He[113]. The experiment is projected to expand searches in the parameter space of light dark matter candidates and complement experiments using superfluid $^4$He by offering sensitivity to spin-dependent dark matter-nuclei interactions.

**Spherical proportional counters**. The Spherical Proportional Counter (SPC) is a detector built from radio-pure materials and filled with high-pressure gas for particle detection[117,118]. The spherical shape of the detector maximizes the volume for a given surface area and provides 4$\pi$ coverage around a particle interaction in the gas. The vessel of an SPC is grounded and acts as the cathode, while the anode located at the center is supported by a metallic rod through which the high voltage is applied. Following an energy deposition in the SPC, ionization electrons drift towards the anode, where they are multiplied by an avalanche process near the anode. The signal's pulse shape depends on the spread in arrival time of electrons and therefore can provide information about the spatial distribution of the charge and the distance of the interaction from the anode. This technology has demonstrated a very low energy threshold – down to single electron detection – and very low electronic noise[118,119]. Combined with the use of gases that are rich in light elements, an SPC can be very sensitive to light dark matter through both NR and ER channels. Another advantage of the SPC is that the detector's gas can be easily exchanged as long as it is chemically compatible with the detector material. If a dark matter signal is detected using one type of target gas, a different target can be deployed afterward to confirm the results without the need for hardware modifications.

First constraints on dark matter using the SPC technology were obtained using a 60 cm in diameter SPC filled with a neon-methane mixture by the NEWS-G experiment at LSM[120]. Since its completion, the NEWS-G Collaboration has built a new detector with 140 cm in diameter and installed it at SNOLAB[121]. A new multi-anode sensor was also developed to ensure a sufficiently high electric field in the larger detector. The dominant background for the current NEWS-G detector is the radioactive contamination of the copper used in the vessel. To address this, the next NEWS-G detector of the same size will be constructed using ultra-pure copper electroformed in an underground lab, eliminating the need for welding and minimizing cosmogenic activation. This new 140 cm diameter SPC will then be installed in the same location. In order to reach the neutrino fog, a future electroformed 3 m in diameter detector named DarkSPHERE in the Boulby Underground Laboratory has been proposed[122]. It will be filled with helium-isobutane (He-$C_4H_{10}$) gas mixture and will be able to reach the neutrino fog for dark matter mass around 0.6 GeV/$c^2$. Due to the natural presence of $^{13}$C in the gas, the detector can also improve the sensitivity to spin-dependent dark matter-nucleon interaction compared to existing experimental constraints for dark matter lighter than 1 GeV/$c^2$.

**Supercooled detectors.** A "snowball chamber" has been proposed as a novel dark matter detector that utilizes supercooled water. When an incoming particle interacts within the chamber, it can induce nucleation in the supercooled water. Similar to bubble chambers, this technique may be sensitive to NR signals while maintaining low sensitivity to ER backgrounds at low energy[123,124]. However, several challenges must be addressed before this detector concept becomes viable. The water must be highly purified to achieve deep supercooling – and thus a low energy threshold – by eliminating potential nucleation sites. Additionally, rapid reheating mechanisms following an event are required to ensure sufficient live time. Furthermore, comprehensive calibrations of the detector's response to different particle types must be conducted. These calibrations should span a range of temperatures and pressures to determine optimal operating conditions.

**Detectors for directional dark matter search.** A key challenge for the detector technologies described in the "State-of-the-art Dark Matter Detectors in Underground Laboratories" section is the irreducible background from neutrinos, whose coherent elastic neutrino-nucleus scattering (CE$\nu$NS) interactions are indistinguishable, on an event-by-event basis, from NRs induced by dark matter. Although the expected number of neutrino events is known, discovering a dark matter signal becomes increasingly challenging as the experimental sensitivity of these detectors approaches the neutrino fog described in the introduction. In order to circumvent the neutrino background, directional dark matter detectors are being developed to utilize the distinct angular recoil distributions of dark matter and neutrinos for optimum discrimination between the two. Due to the motion of the galactic disk relative to the Milky Way's dark matter halo, the angular recoil distribution of dark matter exhibits a fixed dipole shape in galactic coordinates, with a peak pointing back along the Galactic plane, toward the constellation of Cygnus[125,126]. For a detector on the Earth, this effect can manifest as a "dark matter wind", with its direction oscillating over the course of a day. A direct measurement of the dipole feature or the detection of the daily oscillation in the angular distribution could serve as a smoking gun for dark matter, as neither radioactive backgrounds nor solar neutrinos can mimic this anisotropy.

Among the technologies proposed for directional dark matter detection, the low-pressure gas TPC has been regarded as the optimum choice and has demonstrated the ability to achieve directional detection through directly imaging the nuclear recoil trajectory. Prototype experiments like DRIFT-II at the Boulby Underground Science Facility[127] in the UK use a mixture of $CS_2$ and $CF_4$, and DMTPC at the Waste Isolation Pilot Plant (WIPP) in the US[128] uses $CF_4$ to probe spin-dependent WIMP-proton interactions. Both low-pressure gas TPCs are designed to search for 100 GeV/$c^2$ WIMPs, though they have limited directionality for nuclear recoil energies below 50 keV. The CYGNUS Collaboration has proposed the construction of a 1000-$m^3$-scale gas TPC filled with atmospheric pressure helium and $SF_6$, capable of measuring a directional nuclear recoil signal at low energies[129]. The detector is expected to detect individual ionization electrons with a spatial resolution of $O(100\ \mu m)$ and measure the directionality of interactions down to helium nuclear recoil energies of 6 keV. The experiment has planned a staged program and will achieve the target volume by using multiple smaller detectors, potentially located at multiple underground laboratories. Because the neutrino fog can be distinguished from dark matter signals via directionality, the experiment can also exploit neutrino scattering events as a signal as the experiment's sensitivity increases.

While the low-density gas TPC is the most mature technology for directional dark matter detection, there are various other strategies for directional detection as well, including directly imaging the nuclear recoil trajectory or indirectly inferring the direction from anisotropic light or charge yield in the target material[125]. There has been some progress on direct imaging of the nuclear recoil trajectory by the NEWSdm experiment. It is developing a directional recoil detection using nuclear emulsion films with nanometric grains, which can detect sub-micrometric tracks left by low-energy ions in the emulsion films[130,131]. The reduction of the track length threshold is crucial to enhancing the sensitivity of NEWSdm such that it can explore the dark matter parameter space beyond the neutrino fog. In addition to nuclear emulsions, physicists have suggested using crystal defects[132,133], damage features in natural minerals[134,135], 2D materials[136], and even DNA strands[137] to directly image dark matter trajectories, but these ideas still require R&D before they can be developed into a functional dark matter detector. The indirect directional detection strategy involves measuring anisotropic light yield in crystals[138–140] and anisotropic ionization due to columnar recombination in liquid or high-pressure gas[141]. However, these methods have not been demonstrated at energies relevant for dark matter searches.

## Conclusion

The past few decades have witnessed an intriguing shift in physics: from the belief that almost everything could be explained by the Standard Model to the realization that we comprehend only about 5% of the universe's energy density[2]. Uncovering the nature of dark matter poses significant challenges but also offers thrilling opportunities, with the potential to unlock new realms of physics. Current dark matter experiments have pushed the limits on dark matter-normal matter interaction strength to unprecedented levels, but further increasing the sensitivity is not trivial. It is crucial to continue operating and upgrading various types of existing detectors, as well as developing new technologies, for the following reasons:

- A variety of detector technologies are required to ensure complementarity in probing the dark matter parameter space.
- If a dark matter signal is detected in the near future, multiple experiments will be required to confirm the discovery.
- Dark matter experiments can also probe other new physics phenomena, and the technologies developed could benefit other fields such as quantum computing and material science.

Meanwhile, advances in dark matter searches across colliders and indirect detection, including cosmology and astrophysics experiments, could provide valuable guidance for direct detection experiments by identifying the most promising mass ranges to explore. With continued technological improvements and increasing sensitivity in direct detection experiments, we expect to place tighter constraints on dark matter in the coming decades and, with a bit of luck, ultimately detect a signal.

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## Author contributions
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## Competing interests
The authors declare no competing interests.

## Additional information
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