DIRECT SEARCHES FOR DARK MATTER: THE WORLD CONTEXT

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1. Introduction

The field of dark matter (DM) direct detection is experiencing a significant expansion in this decade, with many new experiments coming on board and exploring new avenues to increase sensitivity to dark matter particles, in particular to Weakly Interacting Massive Particles (**WIMPs**).

All of these experiments are trying to identify dark matter by detecting its possible interaction with ordinary matter in specialized, low-background detectors deployed in underground laboratories. A typical dark matter signature would be an anomalous rate of low-energy (<100 keV) nuclear recoils induced by WIMP elastic scatterings.

Given the very low rate of interactions (few events per ton per year, at the interaction cross-section of O(10^{-47}cm^2)), large target masses are required and backgrounds must be highly suppressed and controlled. Backgrounds are classified in radiogenic, from the detector materials and the environmental hall of the experiment, and cosmogenic, surviving to the underground locations where experiments are usually installed. Backgrounds can also be classified on the basis of the interaction mode: electron recoils (ERs), the most abundant class induced by gammas and beta, and nuclear recoils (NRs), induced mostly by neutrons, extremely dangerous since they can perfectly mimic WIMP signals. In addition, future experiments will have to face a new and irreducible class of NR background, induced by coherent scattering of solar and atmospheric neutrinos, the so called "neutrino floor".

Detection techniques employed in the direct dark matter search mainly exploits three types of observables: heat (phonons), charge (ionization electrons), and light (scintillation photons). The simultaneous detection of two observables is a tool to distinguish ERs to NRs, thanks to the dependence of the energy sharing in the different channels on the interaction mode.

The direct dark matter search strategy depends on the WIMP mass. At the GeV/c^2 scale, the NR energy is expected in the sub-keV/few keV range. Detection requirements are then very low energy threshold, light target nuclei, and low quenching factors. The most sensitive technologies are Germanium bolometers detecting phonons and light (CRESST) or charge (EDELWEISS and SuperCDMS), Silicon CCD to record particle tracks (DAMIC), and gaseous proportional counters (NEWS-G). The higher mass region, above the multi-GeV/c^2 scale, is probed by experiments using heavier targets, such as liquefied Argon (DEAP, DarkSide) or Xenon (XENON, Panda-X, LUX, XMASS), with very low background rates and much larger target masses.

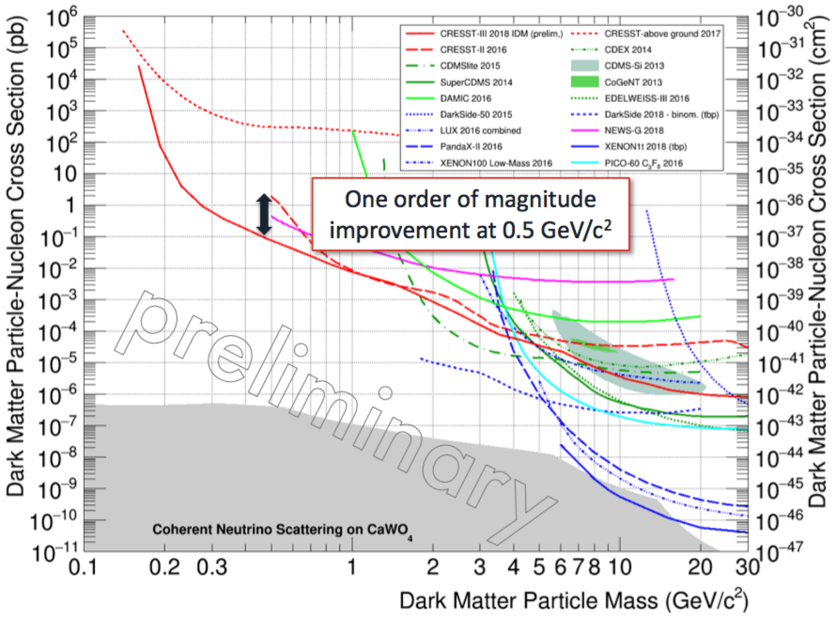

Figure 1: Upper limits on spin-independent WIMP-nucleus interaction cross-sections, in the low mass region. From [5].

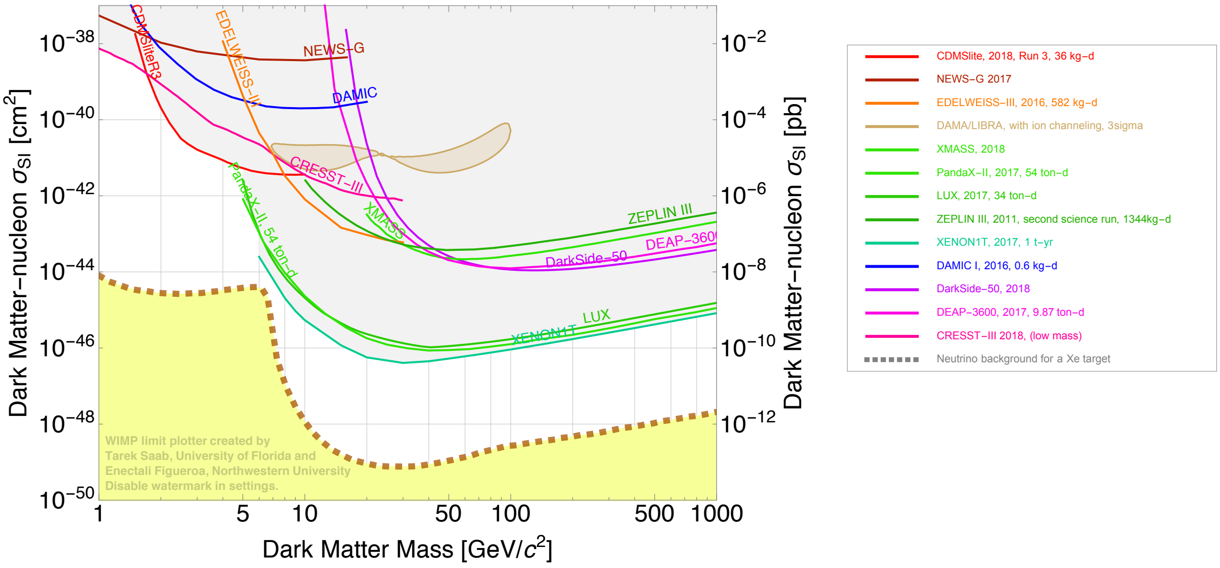

Figure 2: Upper limits on spin-independent WIMP-nucleus cross-sections in the high mass region, for a selection of current experiments [1].

The current status of upper limits on spin-independent (SI)[1] WIMP-nucleon cross-sections is summarised in Fig. 1 and Fig. 2 for the low- and high-mass regions, respectively. The anomalies observed in the few GeV/c^2 region are ruled out by other experiments.

In case of a positive signal, stronger evidence is needed that it is actually due to DM. Using different target materials is essential to confirm the evidence and to have information on WIMP mass, as the scattering rate as a function of DM mass scales differently with different materials, in particular with the ratio Z/(A-Z). The spectral features of the signal will provide information on the nature of the interactions. Recoils induced by DM collisions should have a directional feature, due to the rotation of our solar system in the galaxy: experiments capable of directional measurements (MIMAC) will provide a powerful method to confirm the origin of a signal. Finally, annual and daily modulations should be observed. These considerations provide the guidelines for the future strategy.

Most of these experiments are also sensitive to the interactions on electrons that would be induced by alternative candidates of dark matter, namely **axions** or **axion-like particles** (ALPs) or **baryonic DM**, such as Dark Photons (DP). Fig. 3 shows recent exclusion limits on ALP-electron coupling parameters and on the mixing parameter of DP with ordinary photons.

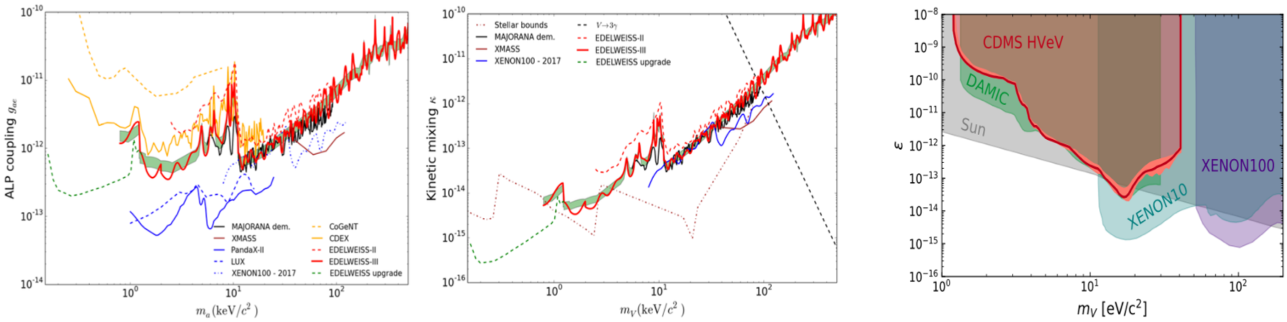

Figure 3: Limits on the coupling of axion-like particles with electrons (left) and on the mixing parameters of dark photons (center and right). From [15] and [16].

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[1] If WIMPs have a spin, a target nucleus with uneven total angular momentum is required or observe spin-dependent (SD) interactions. This report will not discuss experiments specifically designed to search for SD WIMP interactions by using a superheated liquid target containing ^{19}F, such as PICASSO, COUPP, SIMPLE, etc.

2. Solid-state detectors

Solid-state bolometers operated at mK temperature are characterised by low energy thresholds, yielding sensitivity to low-mass WIMPs, and excellent energy resolution. The extension to large masses is limited by the size of single crystals (10^1-10^3 g) and the need to operate the detector in a cryostat.

Phonon and light signals are used by the **CRESST** experiment [2], located al LNGS, based on scintillating calcium tungstate ($CaWO_4$) crystals with a mass of 249g each, operated as cryogenic calorimeters. In the CRESST-II phase, based on 18 target crystals and a total exposure of 52 kg*day, limits were established on the DM-nucleon cross section below 1.7 GeV/c^2 and the reach of direct searches was extended down to DM-particle masses below 1GeV/c^2.
For CRESST-III [3], whose Phase 1 started in July 2016, detectors have been optimised for low-mas WIMP searches, using crystals with radically reduced size (˜24 g) with the goal of a very low energy threshold. Preliminary results [4] from this phase, with a threshold as low as 30 eV on nuclear recoils and an exposure of 5.7 kg*d, have improved the previous limit by one order of magnitude at 0.5 GeV/c^2 and have extended the reach down to 0.16 GeV/c^2. Phase-2 of the experiment, with upgraded detectors, has just started.

The **EDELWEISS** experiment [5], installed at LSM, looks at phonon and charge signals, using high-purity Germanium bolometers at 18 mK. The latest generation of such detectors, equipped with a set of Fully InterDigitized electrodes (FID detectors), provides the possibility to select interactions taking place inside a large fiducial fraction of each detector. During the EDELWEISS-III phase, a ten-month run in low-background conditions was carried out with an array of 24 FID detectors of ˜800 g each, for a total exposure of 582 kg*day. The most recent results [6], using a threshold of 900 eV on NR energy, include precise data-driven modelling of backgrounds and a full likelihood analysis, to set limits in the 4-30 GeV/c^2 mass range. The sensitivity to low-mass WIMPs is limited by the presence of an intense background of heat-only events, whose origin is not yet fully understood.
Current developments of EDELWEISS [7][8] are towards GeV-range mass WIMPs by means of a of lower threshold on the heat signals (EDELWEISS-LT), by operating the detector at a higher bias voltage, and towards better heat energy resolution, using smaller (32g) detectors. On the other hand, sensitivity down to the neutrino floor and the possibility to measure ^{8}B solar neutrinos (EDW-DMB8) can be achieved with a 100-kg scale array of bolometers with improved ionization resolution and NR discrimination.

SuperCDMS [9] at Soudan, also looking at phonons and charge, employs 15 interleaved Z-sensitive Ionization- and Phonon-mediated (iZIP) high-purity germanium detectors (0.6 kg each). Background rejection in the iFID detectors and a fiducialisation procedure allow for a nearly background-free search, with a threshold of 8 keV_{ee}. A total exposure of 1690 kg*day provided a limit on interactions of WIMP with masses in the 10-250 GeV/c^2 range.
In the **CDMSlite** [10] configuration, iZIP detectors are operated at high voltage bias to amplify the signal from the Neganov-Luke effect. Limits are set on interactions of WIMPs with masses down to 2.5 GeV/c^2. The most recent results are from so-called Run3, with an exposure of 36 kg*day.
The next phase of SuperCDMS [11] will be a detector at SNOLAB using both Germanium and Silicium detectors of two types: iZIP for improved background rejection and detectors operated at high voltage to lower the detection threshold. Another improvement will be a large reduction of bulk and surface ER backgrounds and of neutron background. Underground installation is expected to start in 2019 and to be completed by 2020. A sensitivity $<10^{-43}$ cm^2 is expected for 1-10 GeV/c^2 WIMP masses, with a coverage down to 0.4 GeV/c^2.

A different type of approach is the one adopted by the **DAMIC** (Dark Matter in CCDs) experiment [12] at SNOLAB, using fully depleted, high resistivity **Charge-Coupled Devices** to search for recoils of Silicon nuclei off dark matter particles with 1-10 GeV/c^2 masses. The ionization signal is drifted by an electric field and collected on a pixel array, allowing for 3D reconstruction of the position of the energy deposit and for particle identification based on the cluster pattern. An upgrade of the detector using an array of 7 16-Mpixel CCDs (total mass of 40 g) started operation in February 2017, with a threshold of ˜50 eV_{ee} and a significantly reduced background. 13 kg*d of integrated exposure will be collected by the end of 2018, which will improve the current limits from the experiment [13], obtained with 0.6 kg*day of exposure and a threshold of 60 eV_{ee}, by more than one order of magnitude.

The next stage of the experiment, DAMIC-M, envisages 1 kg of large (20g) CCDs with skipper readout, installed at the Modane Underground Laboratory. The expected sensitivity is down to ˜$2x10^{-43}$ cm^2 for the interaction cross-section of few-GeV/c^2 WIMPs.

Solid-state detectors are sensitive to the electron signal induced by **bosonic DM** (see Fig. 3).
In CRESST-II, a dedicated search for dark photons (DP) was performed, which excludes a parameter space for DP masses in the range 300 eV/c^2-700 eV/c^2 [14]. EDELWEISS-III currently sets the best limits from Ge detectors on couplings of ALPs on bosonic DM with masses down to ˜1 keV/c^2. Improved ionization measurement will allow for an extension of the limits down to the mass range 0.1-1 keV/c^2 [15]. A prototype SuperCDMS detector having a charge resolution of 0.1 electron-hole pairs (CDMS HVeV, a 0.93 gram CDMS HV device) has recently obtained first results on inelastic e-DM scattering. Using an exposure of only 0.49 g*day, DM parameter space in the mass range of 0.5-5 MeV/c^2, that was consistent with previous experimental and observational bounds, has been excluded [16].
In DAMIC, a search for hidden-photon dark matter yielded stringent limits in the 3-12 eV/c^2 mass region. DAMIC-M will be able to set limits at the level of 10^{-41} cm^2 on the DM-electron cross-section for a mediator mass of few MeV/c^2.

3. Gaseous detectors

NEWS-G (New Experiments With Spheres-Gas) [17][18] uses light noble gases, such as hydrogen, helium, and neon, as targets, to search for light dark matter down to the sub-GeV/c^2 mass region. The first detector of NEWS-G, is a 60-cm diameter sphere already operated in the Underground Laboratory of Modane. First results 9.7 kg·days of exposure with neon as target exclude at 90% CL cross-sections above $4.4x10^{37}$ cm^2 for WIMP candidates with mass 0.5 GeV/c^2 mass. The next phase of the experiment will consist of a 140-cm diameter sphere, made of extremely low activity copper, that is going to begin operation in SNOLab by summer 2019. It will allow for sensitivities of O(10^{-41} cm^2) for WIMP masses down to 0.1 GeV/c^2.

MIMAC (MIcro-tpc MAtrix of Chambers) [19][20] envisages the use a low-pressure TPC with a CF_4-based mixture, with charge amplification and readout provided by large pixelated Micromegas chambers, to improve the ER/NR discrimination and to observe tracks long enough to provide the **direction of the recoils**. Measurements of quenching and of angular resolutions have been performed. A $1m^3$ detector, validating a new-generation larger detector, installed at MODANE is expected to start taking data in 2019. With an exposure of 30 kg*year, a discovery of spin-dependent interactions will be possible down to 10^{-3}-10^{-4} pb.

Other projects of directional detectors using a CF_4-based gas mixture are DRIFT [21] at Boulby, NEWAGE [22] at Kamioka and DMTPC [23] at SNOLAB. Different detection techniques are also envisaged for directional measurements, such as nuclear emulsions or anisotropic crystals.

4. Detectors based on liquid noble elements

Liquid noble elements such as Liquid Argon (LAr) or Liquid Xenon (LXe) are excellent for building, non-segmented, homogenous and self-shielded detectors, easily scalable to large masses. In response to the passage of radiation, they provide large scintillation and ionization signals. Pulse-shape discrimination (PSD) is a powerful tool for background rejection in LAr[2]. LXe is intrinsically radiopure, while LAr suffers from the contamination from beta-decaying ^{39}Ar due to cosmogenic activation: low-radioactivity Ar, depleted in ^{39}Ar by a factor ~1400, has been extracted from underground sources (UAr). An additional depletion factor (x10-100) will be achieved via cryogenic distillation (DAr).

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[2] In LAr, the half-life of singlet and triplet excitations are very different (7 ns and ˜1600 ns respectively). Electron recoils produce more triplet-state excitation w.r.t. nuclear recoils, resulting in longer scintillation pulses. In LXe the two half-lives are 2ns and 27ns respectively.

Single-phase detectors are only sensitive to the scintillation signal. Reconstruction of the interaction position, allowing for background rejection, is possible with ˜cm resolution based on the light distribution at the photosensors.
The **XMASS** experiment [24] at Kamioka uses 832 kg of LXe viewed by 642 2" PMTs. Not having access to particle identification and discrimination, it searched for an annual modulation signal on a 800 live days data set and set limits both in the multi-GeV (4-20 GeV/c^2) and in the sub-GeV (0.32-1 GeV/c2) region.
DEAP-3600 [25] is a 3600-kg single-phase LAr detector located at SNOLAB. An analysis of 4.44 live days (fiducial exposure of 9.87 ton*days) of data taken during the initial filling phase demonstrated excellent ER rejection using pulse-shape discrimination in argon and yielded a limit on high-mass WIMP interactions ($<1.2\times10^{-44}$ cm^2 at 100 GeV/c^2). The projected sensitivity with 3 live-years of data is 10^{-46} cm^2 for a WIMP mass of 100 GeV/c^2.

Dual-phase time-projection chambers (TPCs) provide simultaneous detection of scintillation and ionization signals, allowing for identification of the interacting particle looking at the scintillation-to-ionization ratio, and for a full topological reconstruction of the event with ˜mm precision.

XENON [26] is a dual-phase Xenon TPC operated at LNGS. The current phase, XENON-1T, with a total mass of 3.2 t (1.3 t fiducial), has been taking data since early 2017. Recently [27], data has been analysed via a profile likelihood method, setting the most stringent limit on WIMPs with masses > 10 GeV/c^2 (4.1×10^{-47} cm^2 at 90% CL at 30 GeV/c^2). Upgrades are expected on purity and background rejection, in view of the next phase, starting physics in 2020, XENON-nT [28], with a total (fiducial) mass of 8 t (5.9 t) and the goal of a sensitivity improved by a factor 20.

LUX (Large Underground Xenon) at SURF, with a total (fiducial) mass of 250 (118) kg, analysed 427 days of live data and set the exclusion limits in the high-mass region [29] similar to those of XENON. The sensitivity is extended down to DM masses of 0. GeV/c^2 using Bremsstrahlung and Migdal effect signals [30] (limit not shown on Fig. 1). LUX recently showed a potential for LXe to reject background with PSD [31].
The next-generation experiment **Lux-ZEPLIN (LZ)** [31] will use a dual-phase LXe TPC with a fiducial mass of 7 ton (5.6 t fiducial). Commissioning is expected to start in 2020. With 1000 lives days of data, the projected 90% CL limit reaches $1.6\text{x}10^{-48}$ cm^2 for SI interaction of WIMPs of 40 GeV/c^2 mass.

PandaX (Particle and Astrophysical Xenon Experiments) [33], located at the China JingPing Underground Lab, is currently in phase II, operating a 500-kg dual-phase Xe TPC. With an exposure of 54 ton*day, the lowest exclusion limit is 8.6×10-47cm2 at 40 GeV. The future phase, PandaX-xT, envisages a detector with ˜4 t fiducial mass and 10-times improved sensitivity on SI interactions; assembly and commissioning are scheduled in 2019-2020.

LXe can be used for Spin-Dependent (SD) WIMP searches, thanks to the natural occurrence of odd nuclei ^{129}Xe and ^{131}Xe. The most stringent limits are currently provided by PandaX-II using elastic scattering, with a minimum upper limit of 4.1×10^{-41} cm^2 at 90% CL for a WIMP mass of 40 GeV/c^2 [34]. The sensitivity of LZ to SD interactions will be 2 orders of magnitude lower than current limits.

DarkSide-50 [35] at LNGS is dual-phase Argon TPC with an active mass of 46.4 kg of UAr, with a 39Ar contamination 1400 smaller than atmospheric Ar. With an exposure of 1.7 t*day, it obtained an upper limit on the dark matter-nucleon SI cross section with a minimum of 1.14×10^{-44} cm^2 for a WIMP mass of 100 GeV/c^2 [36]. A search for WIMPs with masses below 20 GeV/c^2 was performed using the ionization signal only, allowing to significantly lower the threshold to 100 eV$_{ee}$; the limits on SI DM-nucleon interactions are extended in the range 1.8-6 GeV/c^2 [37]. The next generation detector, DS-20k [38], with a fiducial mass of 20 t of DAr read out by SiPMs, will begin operation in 2021 and reach sensitivities at the level of $2\text{x}10^{-48}$ cm^2 for WIMP masses of O(10 GeV/c^2) with an exposure of 100 ton*year. A dedicated 1-tonne detector to improve the limit in the low-mass region is also envisaged.

Future projects of TPCs based on noble liquids envisage the extension to very large scales, to reach sensitivities to high-mass WIMP interactions down to the neutrino floor. The communities of different experiments based on similar technologies will be brought together. **DARWIN** (DARk matter WImp search with liquid xenoN) [39] proposes a 50-t scale Xe detector, based in Europe. **GADMC** (Global Argon Dark Matter Collaboration) envisages a 300-t LAr detector installed at SNOLAB.

Electron signals induced by non-WIMP particles can be measured in noble-liquid detectors using the ionization signal alone. XENON-100, with 224.6 live days of data and 34 kg of LXe in the fiducial region, set limits in the 8-125 keV/c^2 mass range [40]. LUX [41] and Panda-X [42] currently set the most stringent limits on coupling of axions with 1-20 keV/c^2 masses. XMASS recently set stringent limits [43] (not shown in Figure 2) on ALPs and dark photons with masses of 50-100 keV/c^2. DarkSide [44] set limits on the DM-e interaction cross-section in the 2-100 MeV/c^2 mass range.

5. Scintillating crystals

Inorganic scintillators are characterised by high density (3-5 g/cm^3) providing large stopping power and a large light yield allowing to reach low (˜keV) thresholds. Being sensitive only to the scintillation signal, they rely only on cuts on multiple crystals for background rejection. The crystal size is limited, therefore multiple detectors are needed to achieve a large mass.

The **DAMA/Libra** experiment [44], located at LNGS, is based on high radio-purity NaI(Tl) crystals. With the full exposure over 20 annual cycles (13.3 ton*y + 1.13 ton*y with upgraded apparatus), evidence at 12.9 sigma is obtained for an annually-modulated single-scatter signal that can be interpreted as due to DM particles. The result is in conflict with the upper limit set by the KIMS [46] experiment at the Yangyang underground laboratory, using CsI(Tl) detectors.
Several future projects are envisaged to check the modulation signal with a similar technology: ANAIS [47] at LSC, DM-Ice [48] at the South Pole, SABRE [49] at LNGS.

6. Conclusions

Direct dark-matter search experiments have explored a wide range of parameters using different target materials and complementary detection techniques. Future experiment will extend the sensitivity both to lower masses and to lower interaction cross-section. If a positive signature is observed, its nature should be probed by the signal in different elements and/or with directional information.

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