Direct Detection of Dark Matter: A Critical Review

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Direct Detection of Dark Matter: A Critical Review

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Abstract: The nature of dark matter in the Universe is one of the hardest unsolved problems in modern physics. Indeed, on one hand, the overwhelming indirect evidence from astrophysics seems to leave no doubt about its existence; on the other hand, direct search experiments, especially those conducted with low-background detectors in underground laboratories all over the world, seem to deliver only null results with a few debated exceptions. Furthermore, the lack of predicted candidates on the LHC energy scale has made this dichotomy even more puzzling. We will recall the most important phases of this novel branch of experimental astro-particle physics, analyzing the interconnections among the main projects involved in this challenging quest, and we will draw conclusions slightly different from how the problem is commonly understood.

Keywords: dark matter; dark matter direct search; low-background experiments; gravity modification; science philosophy

1. Introduction

According to Standard Cosmology, the visible Universe emerged from a space–time singularity with infinite temperature and density about 13.8 billion years ago. After a very short phase of rapid inflation, it continued to expand, and its evolution from that moment was determined by the distribution of its energy content among its distinguished constituents: namely, visible (or baryonic) matter (4.9%), dark (non-visible) matter (26.5%), and dark (non-visible) energy (68.5%) [1].

In addition to dark energy, whose physical nature is still a subject of intense debate, dark matter offers more specific clues. These clues have led the scientific community to strongly believe in its existence and even to consider possible ways to experimentally detect its presence when it passes through the Earth.

The dark matter hypothesis fills the gap in the explanation of many astrophysical observations—from the gravitational collapse of structures in the early Universe to patterns in cosmic microwave background, anomalous dynamics, and the gravitational lensing of astronomical objects from small-sized galaxies to large superclusters, with some exceptional cases, such as the Bullet Cluster, considered by some as an incontrovertible smoking gun. This strong experimental evidence seems to converge toward the existence of a given amount of invisible massive particles piled up around massive astronomical objects with some rudimentary properties.

In the dominant paradigm, this matter should have had a negligible velocity at the time of early structure formation, and for this reason, it is called cold, as stated by the widely accepted Lambda Cold Dark Matter (ΛCDM) paradigm [2]. This scenario can be easily realized with the existence of heavy and collisionless particles, e.g., massive particles with mass comparable to or larger than typical atomic nuclei (tens of GeV/c² or more). If massless or much lighter, dark matter should have some interaction properties, or some coherent aggregation, that is sufficient to simulate a non-relativistic gravitational clustering...
capable of speeding up the structure formation, as observed after the matter–radiation decoupling epoch in the early Universe [3].

Alternative theories, such as Modified Newtonian Dynamics (MOND) [4], superfluid dark matter [5], or even the full General Relativity approach [6,7], have been showing waves of interest in the scientific literature. It is worth mentioning, even though it is not the main topic of this article, that some empirical evidence, such as the Tully–Fisher relation [8] and the Renzo rule [9] for galaxies, are hardly explainable by standard cold dark matter galactic halos, and these issues, which are very well addressed by the MOND theories, seem sometimes completely ignored when considering whatever particle explanation of the missing mass of the Universe. Along with this, many issues related to the ΛCDM model are still unsolved, such as the missing satellites problem, the cusp-core problem, and the too-big-to-fail problem (see, e.g., [1] and references therein). Finally, it is worth mentioning that interestingly, MOND theories can be tested with wide binary galaxy dynamics available from the GAIA R3 data release, even though preliminary results look controversial and contradictory [10,11].

Nevertheless, the particle hypothesis for dark matter, even if strongly weakened by the astonishing absence of super-symmetry (SUSY) at the Higgs scale in the LHC accelerator [12], still shows a constant interest in the scientific community, mostly for its experimental feasibility. In other words, the costs and technology for the direct dark matter search in underground laboratories are still so affordable that the biggest part of the experimental community believes that it is still worth trying as the main goal in scientific programs for the forthcoming decades.

Since the early 1990s, when the hypothesis of dark matter began to be taken seriously by scientists, many candidates have been proposed, with masses ranging from axions with masses starting from $10^{-22}$ eV/c² to primordial black holes with masses up to $5 M_\odot = (10^{16} \text{ eV/c}^2)$ [1]. This wide range of 89 orders of magnitude is filled almost homogeneously with many variants of the proposed models and is basically limited by astrophysical constraints related to the observed macrostructures. Within this range, it is worth mentioning the most important candidates with increasing mass: axions, with sub-eV/c² mass, detectable in haloscopes or low-background detectors [1]; sterile neutrinos [13], with mass of the order of 1 keV/c², evergreen candidates for many presumed anomalies, but never detected; weakly interacting massive particles (WIMPs) [14,15], with mass in the range $1-10^3$ GeV/c², predicted by the SUSY extension of the particle Standard Model (SM) and considered the top reference model almost up to the first null results by the LHC [16] and with some monster extensions up to the Grand Unification scale (GUT) of $10^{15}$ GeV/c², often called WIMPzillas [17] yet never detected; finally, dark objects (MACHOs) with the size of a planet ($\sim 10^{24}$ kg) or so [18] and primordial black holes, with huge mass, up to $5 M_\odot$ [19,20]. Finally, it is also worth mentioning the Mirror Matter model [21], conceptually different from WIMPs but predicting the existence of dark matter candidates with mass comparable to the mass of visible chemical elements (1–100 GeV/c²).

Another problem is the cross section scale between visible and dark matter. If one assumes that the typical cross section of the weak interaction ($\sigma \sim 10^{-44}$ cm², or so), is already experimentally at reach, the range of possible interaction cross sections is actually really large. If one takes the squared Planck length as lower bound $\sigma \sim 10^{-66}$ cm², there are 20 possible orders of magnitude, even though not all of them are actually testable.

All the models discussed above basically agree on the invisible (electrically neutral) nature of the dark matter candidate: astrophysical observations constrain its possible electric charge and self-interaction, and they require temporal stability with a lifetime comparable to the age of the Universe [1].

Indirect dark matter searches, such as hidden channels in accelerators or annihilation/decay in visible diffused particle backgrounds in the Galaxy, have also yielded no results [1].

Table 1 summarizes the known physical properties of dark matter particle candidates. The table is essentially empty except for some naïve properties inferred by indirect astrophysical observations. The absence of experimental evidence of dark matter in either
direct or indirect searches has sometimes induced the literature to hide or rename some of the historical candidates, often with fancy names, such as “axion-like” particles (ALPs) or “WIMP-like” [22], just because the original proposed theory seemed not to hold any more in upgraded experimental contexts. Furthermore, there are often unconscious biases, such as the belief that if dark matter is not found in the range of WIMPs, it might be really important to search for somelight WIMP-like dark matter particle with mass below 1 GeV/c$^2$, down to a few tens of MeV/c$^2$. This kind of suggestion is, of course, much weaker if one considers that the theoretical prior on some plausible model from $10^{-22}$ eV/c$^2$ to $5 \, M_\odot$ is currently basically uniform.

Table 1. Properties of the dark matter particle candidate to date. The choice of symbol $\chi$ is not universal, but is assumed in the present article as a reference for a generic dark matter candidate. From the top: composition, Bose or Fermi statistics, particle generation or family, fundamental interaction, symbol, antiparticle, mass, half-life, electric charge, self-interaction, magnetic moment, spin, weak isospin, weak hypercharge, and other characteristics. The symbol “–” stands for not available.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>–</td>
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<tr>
<td>Statistics</td>
<td>–</td>
</tr>
<tr>
<td>Family</td>
<td>–</td>
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<tr>
<td>Generation</td>
<td>–</td>
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<tr>
<td>Interaction</td>
<td>–</td>
</tr>
<tr>
<td>Symbol</td>
<td>$\chi$</td>
</tr>
<tr>
<td>Antiparticle</td>
<td>–</td>
</tr>
<tr>
<td>Mass</td>
<td>$10^{-22}$ eV $\div 5 , M_\odot$</td>
</tr>
<tr>
<td>Half-life</td>
<td>$\gtrsim 10^{10}$ y</td>
</tr>
<tr>
<td>Electric charge</td>
<td>$\lesssim 10^{-7}$ e [at 1 GeV]</td>
</tr>
<tr>
<td>Self interaction</td>
<td>$&lt; 0.5$ cm$^2$ [at 1 GeV]</td>
</tr>
<tr>
<td>Magnetic Moment</td>
<td>–</td>
</tr>
<tr>
<td>Spin</td>
<td>–</td>
</tr>
<tr>
<td>Weak isospin</td>
<td>LH: –, RH:–</td>
</tr>
<tr>
<td>Weak hypercharge</td>
<td>LH: –, RH:–</td>
</tr>
<tr>
<td>Others</td>
<td>–</td>
</tr>
</tbody>
</table>

The discussion about the details and the status of the direct dark matter search will proceed as follows: Section 2 outlines the reason, according to the authors, why direct dark matter detection is so popular and is increasingly supported and financed; in Section 3, the basic ideas about the direct detection of dark matter are reviewed; in Section 4, important and often undervalued aspects of direct dark matter analysis are highlighted; in Sections 5 and 6, the case of both NaI-based and noble gas detectors (xenon and argon) are largely reviewed, respectively. Finally, in Section 7, the evolution of dark matter search in the new millennium is critically reviewed and analyzed.

2. A Simple Theory

The direct dark matter search has received an increasing consensus in the recent decades also thanks to its simplicity, and then to the (apparent) solidity of its foundations, invoking some principle invented in the context of theology such as Occam’s razor. The possibility of such a detection is enclosed in simple equations that are understandable at the level of an average high school student. Three basic formulas, concerning the dark
matter hypothesis and its possible detection, are hidden among a list of seemingly simple equations. Here is the list:

\[ \exists A : \aleph_0 < \#A < 2^{\aleph_0} \]  
(1)

\[ v = \sqrt{GM/r} \]  
(2)

\[ \nabla \cdot \mathcal{F} = 0, \nabla \times \mathcal{F} = i\partial_t \mathcal{F} \]  
(3)

\[ \mathcal{H}u = -\frac{\partial u}{\partial t}, \mathcal{H}v = \frac{\partial v}{\partial t} \]  
(4)

\[ E_A = \frac{4}{(M_A + M_b)^2} E_X \]  
(5)

\[ x^3 + x = 1 \]  
(6)

\[ R = n\sigma\Phi \]  
(7)

\[ \int_{\Omega} d\omega = \int_{\partial\Omega} \omega \]  
(8)

\[ (i\hbar \gamma^\mu \partial_\mu - mc)\psi = 0 \]  
(9)

\[ e^{i\pi} + 1 = 0 \]  
(10)

An expert reader has immediately recognized that the relevant three equations are Equations (2), (5) and (7). In the following subsections, an explanation for each of the three equations is discussed (For the sake of completeness, the explanation why the rest of the listed equations look simple, but they are not, is hereby reported. The expression (1), both simple and deeply complicated, represents in symbols the Continuum Hypothesis, which is partially still the subject of discussion among modern mathematicians. The Equations in (3) represent the Maxwell equation in vacuum, just taking the electric and magnetic fields as the real and imaginary parts of \( \mathcal{F} \). Whereas, Equation (4) displays the Shrödinger equation, but this time with two real functions \( u \) and \( v \). Equation (6) is really simple, but it has “complex” solutions, which are definitely not easy to find if one ignores some algebraic technicalities. Equation (8), usually called the Stokes theorem within the k-form formalism, is probably the most beautiful theorem in advanced calculus, as it encloses the Fundamental Theorem of Calculus, the 3D Green and Stokes theorems, their 4D version in the Riemann space–time and so on. Equation (9) is the famous Dirac equation, whose correct interpretation in Quantum Field Theory predicts the existence of antiparticles for fermions. Finally, Equation (10), the Euler identity, often advertised by Richard Feynman for its beauty, is a complex number identity that is much more tricky than its apparent simplicity, as it involves the top five numbers in mathematics).

2.1. Existence–Equation (2)

A spiral galaxy contains about two-thirds of its mass (\( M \)) in the galactic core (or bulge) [23,24]. Assuming for the latter a spherical shape with spherically symmetric density \( \rho(r) \), the Gauss theorem predicts, outside the bulge, a gravitational pull \( \propto M/r^2 \), where \( r \) is the distance from the center of the sphere and \( M \) is the enclosed galactic mass (see Figure 1). More precisely, the profile of the visible matter depends on the galaxy type, but its specific realization does not invalidate this general argument. This force provides centripetal acceleration \( \propto v^2/r \) for all objects gravitating around the galaxy center. Here, one has implicitly assumed the Newtonian weak field approximation of General Relativity at the galactic scale and at the galactic speed (this point has been recently debated; see [6] already anticipated above).

The model described so far immediately implies that the velocity of stars as a function of \( r \) should follow the so-called “Keplerian fall” described by Equation (2). But this is not what is observed [25]: rotation curves always lie largely above the expected behavior coming from the independent quantification of the visible galactic mass from mass-to-luminosity ratio of stars and nonluminous (gaseous or solid) mass. Sometimes, it is somewhat inaccurate to say that the observed rotation curves are flat. Those curves are actually exceeding the Keplerian fall but with a family of universal curves that depends on the visible size of the galaxy, upon which the ratio between visible and dark matter
also depends \cite{23,24}. Dark matter distributed in a spherically symmetric halo, present in the interstellar space inside each galaxy, fills this discrepancy between predictions and observations.

![Figure 1](image)

**Figure 1.** Schematic view of the expected Keplerian fall. The behavior of the rotation curve \( v(r) \) (top) is shown both inside and outside the galaxy bulge with its cross-section displayed at the bottom.

There is considerable debate about the profile of the radial dependence of the spherically symmetric matter distribution in the hypothetical dark matter halo, depending on whether it is inferred from numerical simulations of collision-less particle clustering or from observed rotation curve analysis. The majority of the proposed profiles can be described by the generic formula:

\[
\rho_s(r) = \frac{\rho_0}{\sum_{i=0}^{3} a_i \left( \frac{r}{r_s} \right)^i},
\]  

(11)

where \( \rho_0 \) is a normalization constant and \( r_s \) is a characteristic size scale. According to the choice of dimensionless coefficients \( a_i \), the profile can be more “cuspy” (as in the Navarro–Frenk–White model \cite{26}) or more “cored” (as in the pseudo-isothermal or Burkert models \cite{27}); or something different, but in any case, these are traceable by approximation to Equation (11), as shown in the Einasto profile family \cite{28}.

To conclude this section, it is worth mentioning that interestingly, the absence of the Keplerian fall has been recently questioned—at least from some interpretation of accurate observations of the Milky Way by GAIA \cite{29,30}. The correctness and the implications of such results have yet to be validated and fully understood.

### 2.2. Kinematics–Equation (5)

A typical dark matter candidate \( \chi \) of mass, say, \( M_\chi = 50 \text{ GeV}/c^2 \), hitting a target (visible) nucleus \( A \) with mass of about \( M_A = 50 \text{ GeV}/c^2 \) in laboratories, has a typical velocity \( v_\chi \) in the galaxy of the order of a few hundreds of km/s \((v_\chi \ll c)\). As a consequence, the kinematics of the collision \( \chi - A \) is not different from two billiard balls with masses \( M_\chi \) and \( M_A \) hitting each other (in a non-relativistic regime, actually \( \beta = v_\chi/c \sim 10^{-3} \)). The classical conservation of energy and momentum leads to Equation (5) in case of linear collision; otherwise, the decrease in the cosine of the scattering angle must be included. The kinetic energy of the target recoil \( E_A \) is a *kinematic fraction* of the dark matter kinetic energy \( E_\chi \). Based on the given numbers, it can be calculated that the anticipated recoil energy in an Earth-based detector is approximately less than 10 keV. This energy level is quite challenging to detect, although it is not entirely impossible using current technologies.

### 2.3. Rate–Equation (7)

Lastly, Equation (7) represents the interaction rate \( \mathcal{R} \) expected in a given detector on Earth exposed to the dark matter wind caused by the Solar System’s relative motion inside
the Milky Way: the rate is given by the target density \( n \) times the \( \chi - A \) cross-section per nucleon \( \sigma \), which is typically assumed to be spin-independent (SI), and the dark matter flux \( \Phi \). In detail, assuming a Maxwell distribution of the dark matter particle velocities inside the gravitational potential “box” of the Galaxy, and the experimental features of the detector, Equation (7) has to be integrated over the velocity distribution, taking into account the detector energy threshold. Then, all the data have to be combined with the experimental resolution, normalized to the energy quenching for nuclear recoils, and finally scaled according to the detector acceptance [31]. In the SI case, the full formula can be summarized as follows.

\[
\frac{dR}{dE} = \rho_{\chi} A^2 \sigma F^2(E) \int_{v_{\text{esc}}}^{v_{\text{0}}} \frac{f(v,v_0)}{v} dv \otimes G(E)
\]  

where \( \sigma \) is the cross-section per nucleon of the target \( A \), \( F(E) \) is the nuclear form factor, and \( \mu \) is the reduced mass between the target and the dark matter mass. Whereas, assuming the standard (galactic) halo model (SHM) [32,33], \( \rho_{\chi} = 0.3 \text{ GeV/cm}^3 \) represents the local dark matter density in the Solar System, \( v_{\text{min}} \) represents the minimum detectable velocity (given the experimental energy threshold), \( v_0 = 220 \text{ km/s} \) represents the circular rotation velocity, and \( v_{\text{esc}} = 544 \text{ km/s} \) is the Milky Way escape velocity, which is taken as the cut-off point for the Maxwellian velocity distribution. The Sun’s velocity is \( v_{\odot} = 232 \text{ km/s} \). Those parameters have been slightly updated recently, but those small variations go beyond the basic purpose of this article. It is worth noticing that the notion of SHM could be criticized as non-realistic, and one can imagine a vast zoology of monster halos with local density anisotropies and streams: this can slightly change the result interpretation (as the rate normalization can change), but it cannot create specific detection anomalies out of nothing. Ultimately, the convolution operation, denoted by \( \otimes \), incorporates the energy-dependent function \( G(E) \) in a symbolic manner, taking into account various experimental characteristics such as resolution, nuclear quenching, and acceptance within the specified region of interest.

Equation (12) can be integrated within the experimental energy window and represented explicitly as \( \sigma_{\text{SI}}(M_{\chi}) \). An experimental limit, such as the absence of events at the 90% confidence level (CL), typically takes the form of an asymmetric hyperbolic branch, as shown in Figure 2 (greenish region): the left branch represents the experimental threshold, while the right branch corresponds to the loss of sensitivity due to the reduced density of targets for heavier dark matter masses. The maximum sensitivity of an experiment is typically achieved for \( M_{\chi} \approx M_A \), which corresponds to the minimum of the green curve. The violet region in the figure represents the so-called “neutrino floor”, where neutrinos from the Sun, atmosphere, and diffused supernova background produce nuclear recoils through coherent scattering, which is similar to the expected interaction of dark matter with a given mass. This experimental limitation can only be overcome by future experiments that exploit the “directionality” of the dark matter wind, which refers to the preferred direction along the galactic plane caused by the relative motion of the Sun with respect to the galactic center, in contrast to the assumed uniform and isotropic neutrino background. This specific aspect will be discussed further in Section 7.
Figure 2. The green region represents the typical excluded region of dark matter experiment with a null result in the SI $\sigma$–$M_\chi$ plot. The violet region represents the so-called neutrino floor. Finally, the red curve, with a cusp, represents a limit in case of annual modulation analysis; see Section 4.

3. Detectors

A gran piano is made up of hard and raw materials. Specifically, this music instrument is primarily composed of hard substances such as wood, cast iron, steel, and felt. Each individual string is under a tension of approximately 80 kg, and many of the 88 keys have two or three strings, resulting in a total tension of 15,000 kg-force. However, it is only through careful assembly and precise tuning that this remarkable musical instrument is able to produce a soft and profound sound, as exemplified in the renowned Chopin’s Nocturnes. Similarly, a particle detector is also composed of hard and raw materials, such as metals, crystals, liquids, and electronic components. It provides insights into fundamental questions in particle physics and cosmology. Nevertheless, this process is not straightforward, and a limited understanding of its functioning can mislead both the astute experimentalist and the brilliant theoretician who may be inclined to prematurely draw conclusions.

Consider a simple example. A typical particle detector is made of a scintillating target (solid or liquid) coupled with a light sensor, for example a photo-multiplier tube (PMT) [34]. When an ionizing particle hits the target, a given number of electromagnetic field quanta are excited, and part of them (depending on detection efficiency) collapse to form what is known as a “photo-electron” on the light detector. The corresponding electric pulse output is then shaped and amplified and eventually converted into a binary number and finally stored on a computer hard drive. The corresponding data are retrieved and analyzed by numerical algorithms or passed to some black box artificial intelligence; see Figure 3.

A real detector is, of course, sensitive to internal and external radioactive backgrounds, as well as hypothetical dark matter particles, whose foreseen amount plays a crucial role in the goodness of the proposed experimental setup. Furthermore, the electronic (non-physical) noise, intrinsic and/or picked up from the environment, can mimic, to some extent, the signal produced by particle interactions. As a matter of fact, only a very deep knowledge of all those effects described above can enable a good investigation. And sometimes, as happens in most of the experiments, part of those effects are not known a priori and can be addressed properly only after a lot of years of calibrations, analysis, and hardware improvements. Even a seemingly simple device like a PMT can produce a wide variety of noise pulse signals that might not be distinguishable by a basic classifier and require a deep characterization, sometimes using novel techniques based on multidimensional mathematical algorithms such as multivariate likelihood ratios or support vector machines, or even nonlinear methods based on boosted decision trees or multilayer perceptrons, and machine learning in general.
Figure 3. Example of a simple detector made of a scintillating crystals optically coupled to a PMT. The scintillation signal is converted into a series of photo-electrons producing an electrical pulse related to the time distribution of the scintillation light emission.

Finally, the optimal detector has some properties capable of discriminating not only between signal and noise but also between the physical characteristics of the primary interaction, as between electron and nuclear recoils (ER–NR, hereafter), which is especially useful for addressing the nature of a possible dark matter candidate. In the example mentioned above, the discrimination could be enabled by the time distribution of the scintillation light. Typically, a classifier, i.e., a parameter defined through, e.g., a likelihood ratio or an artificial neural network, shows a characteristic distribution depending, in general, on the particle energy and exhibiting a partial overlap (inefficiency) in the region of interest. Usually, after deep training with known sources, an acceptance region, in which the dark matter candidate is expected, is defined (see Figure 4 as an example). If a statistically significant group of events emerges over the expected background, one can reasonably claim evidence of new physics, which should later be confirmed by other equally sensitive experiments or complementary techniques.

Dark matter detectors commonly use different phenomena to create classifiers. When a charged particle collides with a material, it can generate scintillation, ionization, or phonon excitation. Depending on the state and temperature, several detectors can use one or more of these signals, allowing for better particle discrimination capabilities.[35]

The high-level standard of low-background detection requires the choice of highly radio-pure target materials to be operated in shielded and, possibly, actively vetoed detectors, which are located in underground laboratories far enough from the atmospheric muons and cosmogenic-induced radiations. These materials are usually not available on the market and require a long and accurate R&D program, sometimes with no predictable outcome.

Lastly, an important experimental aspect to consider is nuclear quenching. An NR indeed releases only a portion of its actual kinetic energy due to non-radiative excitation. For that reason, the observable energy is less than that released by an equivalent ER. This relative ratio is important for the final interpretation of the experimental result; for this reason, results are usually presented in electron-equivalent energy (e.g., keVee), and the quenching factor is given independently by dedicated calibrations with neutrons.

In addition to the counting of outliers in the expected acceptance region, direct dark matter detection in underground laboratories can also be pursued through the detection of annual modulation. This signal arises from the relative motion of the Earth around the Sun with respect to the center of the Galaxy. In addition, tracking detectors sensitive to the directionality of dark matter can be employed.

With these basic concepts in mind, one can now move on to the present experimental situation.
Figure 4. Classifier distribution for NR (gray) from calibration and ER (blue) from a physics data collection. The acceptance region (red box) for NR candidates can be defined, e.g., as the median of the NR distribution. The observed three events in the NR band are to be interpreted according to event/noise understanding and expected physical background.

4. Analysis

Imagine that we have a few (unsuspected) points in the square box of Figure 4. Can one claim for the dark matter discovery based on that? A wise response might be that the number and the distribution (e.g., in energy and space) of the expected background has to be declared in advance. For example, if an experiment observes four events out of two (expected), one may argue that the Poissonian fluctuation of two can likely give four in a reasonable number of cases. But if one has eight out of two, the story becomes more intriguing, as the fluctuation of two can hardly return eight.

4.1. Which Statistics?

The way in which these naive words “likely” or “hardly” are converted into some quantitative parameters is not universally accepted by a common procedure, and there are multiple approaches based on different statistical interpretations, often with heated debates, like the ones between Frequentists (e.g., Feldman–Cousin [36]) or Bayesians [37] statisticians.

Of course, this is a fundamental and longstanding controversial debate that cannot be solved for sure here, and sometimes, the solution is not unique but depends on the specific situation. Therefore, for an experimentalist, it is more convenient to quote results (whether it is a measurement or a limit) in more than one approach just to delegate some possible controversial matters to others.

The real challenge might be how to properly combine the results from different approaches. However, it is also true that as long as the results are just limits, the process itself is not really harmful, and the nuances in the results stemming from different philosophies are basically hidden by the line width in the $\sigma$–$M_\chi$ exclusion plot. For real positive results, the problem could be more delicate.

4.2. How Many $\sigma$’s?

If some statistical procedure is assumed, it becomes important to show how many sigmas (actually, the $p$-value over the background fluctuation) are necessary to claim for a discovery. Among physicists, there is a common (questionable) practice to associate a naive meaning to a certain number of sigmas, such as mild indication ($1\sigma$), indication ($2\sigma$), evidence ($3\sigma$), never quote that, it’s bad luck! ($4\sigma$) and discovery ($5\sigma$). The real problem here is that all of them are only indicators: forgotten systematic uncertainties and mistakes
are always possible and may unexpectedly arise, and unfortunately, there are plenty of such examples in the literature.

In addition to these folkloristic topics, to claim a scientific discovery, the way is much harder, as is explained in the following subsection.

4.3. No Background

Given that background fluctuations can deceive experimentalists, it would ideally be preferable not to have any background at all. In other words, when planning a detector, it is ideal for the expected background events to be significantly fewer than the expected signal to avoid being misled by fluctuations. This has created the fashion of having high-sounding names as background-free experiments or even zero-background experiments.

What is the difference between “Cola Light” and “Cola Zero”? In reality, there is no difference: both contain chemical sweeteners instead of sugar, but in marketing, names really matter. Some people might choose a drink labeled as “zero” but would avoid the one labeled “light”, as the word light might have negative connotations for some. The same concept applies to the background in dark matter experiments: it is primarily marketing. The honest name should be “low-background”, where the adjective “low” should go with some objective quantifier.

In a popular, and absolutely interesting, review on neutrinoless double beta decay, a footnote reads [38]:

“For a truly zero background experiment, one event is enough to claim a discovery. In a similar fashion, encountering a unicorn is enough to claim its existence, provided that we have a template of a unicorn to which to compare the observed candidate”.

When the authors asked GPT-4 [39] to comment on this statement, its response was notably insightful. Here is its reply:

“A single observation of an event can suggest that something exists, but in a scientific context, such conclusions are usually considered weak evidence. Scientists value repeatability and reliability of data, meaning that multiple, consistent, and independent observations are necessary to establish existence.

In the case of a unicorn sighting, a single observation would likely not be considered sufficient proof of their existence. Scientists would need to examine the evidence, conduct additional observations, and demonstrate that these observations are indeed consistent and repeatable. For rare or extraordinary phenomena like unicorns, scientists may be more cautious and require even more evidence to accept their existence.

In summary, a single observation can lead to the belief that something exists, but scientists typically rely on repeatable, reliable, and independent data. A lone unicorn sighting would likely be insufficient, and further research and observations would be needed to confirm their existence”.

If one ignores this genuine reasoning, one can easily be fooled and forget the basic principles of good science. Indeed, continuing with the metaphor, the unicorn is quite an unfortunate example not only because of our prior of its existence but also because there are plenty of alicorns (unicorn’s horns) in museums, coming from the Middle Ages [40], sometimes made of bone. Yes, but many people, even today as in the Middle Ages, ignore the existence of narwhals.

To conclude, what one sees in a detector is not a unicorn anyway, if for a unicorn one means something completely weird and different from ordinary events. In a real particle detector, what one records is nothing else other than a pure electronic signal, digitized and analyzed as a discrete waveform, that resembles either physical events and/or noise artifacts more often than expected.
4.4. Annual Modulation

A “model-independent” approach, which in principle can ignore the nature of the $A$–$\chi$ interaction, involves detecting an annual modulation signal from a shielded detector over a prolonged (multi-annual) exposure period. In this case, the ER–NR discrimination is not necessary, as one is interested only in the typical signature of such a signal. The Earth, indeed, revolves around the Sun at 30 km/s while the Solar System, tilted 60° with respect to the galactic plane, moves altogether around the center of the Galaxy at about 232 km/s, as depicted in Figure 5. As a result of this simple geometry, the expected signal is

$$R(t) = R_0(t) + S_m \cos(\omega(t - t_0)),$$

(13)

Here, $R_0(t) = S_0 + B(t)$ is the total trend given by the sum of a constant part $S_0$, due to the unmodulated dark matter component, and the detector background $B(t)$ that in principle can depend upon time, as, e.g., in the presence of radioactive decaying contamination or time-varying cosmogenic background; $S_m$ is the modulation amplitude of the (expected) dark matter signal, basically given by the relative speed of Earth with respect to the local dark matter velocity distribution in the Galaxy, and therefore of the order $30/232 \times \cos(60^\circ) \simeq 6.5\%$ with respect to $S_0$; $\omega$ is the annual angular velocity corresponding to $2\pi/(365 \text{ d}) \simeq 0.0172 \text{ rad}^{-1}$; finally, $t_0$ is the time (phase) corresponding to the maximum rate, i.e., to the date at which Earth and Sun go toward the same direction (on June 2nd). If one builds up a radio-pure and shielded setup, acquires data for some years and performs a temporal regression analysis in which $S_m$, $\omega$ and $\phi$ are free parameters returned simultaneously in the expected ranges, one can in principle claim that such a signal is compatible with the presence of a diffused dark matter gas in the interstellar space at the Earth distance from the Galaxy center. Indeed, Freese et al. [41] clearly state:

“We argue that a modulation can itself be used as primary means of detecting WIMPs [more in general dark matter (A.N.)] (rather than as a confirmation) even in presence of a large background”.

This sentence is for common sense correct but actually theoretical and practically wrong. First of all, assuming the SHM hypothesis, the correct logical sentence should be the material implication “IF the dark matter exists THEN a modulation is visible”, that is

$$\text{DARK MATTER} \rightarrow \text{MODULATION},$$

and not its vice versa. Therefore, looking at the truth table, the fact that one can see modulation even if dark matter does not exist is still a valid possibility: one can argue, for example, that a time-varying background related to some possible seasonal (or seasonal-induced) signal is still possible [42,43]; moreover, a time-varying background $B(t)$, if not properly accounted for, can bias the final results [44], as is discussed later. Then, a robust modulation analysis must show the consistency of all terms of Equation (13), no one excluded at the very least. As a further example, it is also worth mentioning that the literature is full of apparent violations of the exponential law with annual modulation components in radioactive decays, opportunely criticized; see [45] and references therein.

Finally, in case of annual modulation, the limit in Figure 2 has a cusp around the minimum (red curve). This is an artifact of integrating each time bin over a limited energy window. It is possible, indeed, that the distribution of the target recoil spectrum is distorted between June 2nd ad December 2nd in such a way that the shape changes, but the total area does not: in this case, there is a specific dark matter mass for which the sensitivity is lost; see Figure 6. The same accurate analysis also leads to the so-called phase inversion phenomenon, happening in the very low-energy region, that should be present in the experimental data, but sometimes is not visible because of a too high experimental threshold with respect to the inversion point that depends also on the specific dark matter mass.
Figure 5. Diagram of the Earth and Sun velocity vectors with respect to the galactic plane.

Figure 6. Two limit cases of distortion: June 2nd (orange), with maximum relative velocity of the Earth with respect to the dark matter halo, and the opposite case on December 2nd (cyan). Finally, the red lines mark a possible experimental integration interval.

4.5. Blind Analysis

Blind analysis, consisting, for example, of closing, completely or in part, the red box in Figure 4, is a good practice that is adopted by other disciplines such as medicine to avoid biases in the analysis—especially in low-rate critical conditions. A collaboration that decides to apply this practice usually closes the box for physical data taking, training the event reconstruction and the selection criteria only on a subset of data that is possibly not used in the final analysis. The collaboration decides to freeze the dataset and eventually to open the box. The scenario is significantly different when the “un-blinding” is completed in public with journalists. With a few exceptions, this usually takes place behind closed doors, and no one knows what happens inside. In this case, one can only rely on the honesty and professionalism of colleagues.
4.6. Data Sharing

It is worth citing what Wikipedia [49] says about the important item of “data sharing”:

“When additional information is needed before a study can be reproduced, the author of the study might be asked to provide it. They might provide it, or if the author refuses to share data, appeals can be made to the journal editors who published the study or to the institution which funded the research”.

Raw data are usually not understandable for non-experts. However, all physically reconstructed events and procedures must be available. The dark matter community should, sooner or later, converge toward an open data policy, especially if large amounts of funding are going to be spent on reproducing some experiments.

5. The NaI Case

Sodium iodide crystals doped with thallium NaI(Tl) are largely used as particle detectors, exploiting their scintillation properties. The light produced when an ionizing particle hits the crystal is usually detected by PMTs, which is based on a very well-known and consolidated technology, which nowadays can be easily manufactured with highly radio-pure materials [46].

The possibility of using these crystals for dark matter direct detection was first explored by the DAMA collaboration (see [50] and references therein for a detailed review). DAMA, since its smaller version, has been detecting a modulation signal compatible with period and phase with the one expected by the presence of the dark matter halo in the Milky Way, rejecting the no-oscillation hypothesis at 12.9σ (20 annual cycles) in the 2–6 keVee energy interval. These interesting results, already released in its first and less massive version at the turn of the new millennium, have become a media event, and have pushed, to some extent, the direct dark matter search in the first decade of 2000s, as will be detailed in Section 7. The signal detected by DAMA is significantly incompatible, in the framework of the SI interaction with SHM, with the absence of a corresponding signature in detectors with higher sensitivity, such as those based on noble gases, which will be discussed in Section 6, and with other detectors that exploit a wide variety of different techniques, which are briefly reviewed in Section 6.4. In other words, in practical terms, the DAMA signal is so intense that the same WIMP-like interactions should be visible in a cup of liquid xenon. Instead, xenon-based detectors, as discussed later, are currently operating multi-ton targets with no results. The remote explanation that the sodium and iodine nuclei have some “special feature”, not met by other target nuclei, has in general strongly motivated the scientific community to reproduce the DAMA experiment using similar NaI crystals independently, as will be discussed later.

Figure 7 shows approximately the genealogy of experiments born after DAMA to accomplish this goal. At the moment, COSINE-100 [51] (originating from the merging of KIMS-Nal [52] and DM-Ice [53]) and ANAIS-112 [54] are the only two experiments that are already collecting data for dark matter search. SABRE [55] and PICOLON [56] are taking data in a R&D stage to basically prove the detection principle and quantify intrinsic contamination. COSINUS [57] is the only detector that uses NaI crystals with a bolometric technique and therefore exploits both scintillation and temperature signals for the discrimination ER—NR. After some preliminary results in small crystal samples [58], the COSINUS collaboration is building a larger and complete setup. The major experiments in this genealogy are discussed below.

Finally, the interpretation of the NaI iodide results in terms of SI solution on the $\sigma$–$M_\chi$ parameter space could depend on the quenching factor for both Na and I nuclei separately, which could in principle depend on the specific crystal. There is a lot of debate on this issue and a lot of controversial measurement of these important parameters [59].
Figure 7. Genealogy of the NaI-based detectors. In addition to COSINUS, which is planning to deploy a cryogenic crystal with ER–NR discrimination, all the others are using the model-independent approach exploiting the annual modulation expected signal. The grey diagrams refer to future projects.

5.1. The DAMA Experiment

The impressive radiopurity of the DAMA crystals, as low as one count per day per kg per keV (cpd/kg/keV), with a threshold of 1 ÷ 2 keVee, made it possible to achieve a sensitivity in the $A-\chi$ cross-section better than $10^{-42}$ cm$^2$ for the model-independent annual modulation in the energy region $\lesssim 10$ keV. However, the typical NaI(Tl) light yield of the order of $\sim 10$ PE/keV does not allow for statistically sensible ER–NR discrimination. The DAMA collaboration had been operating a 100 kg detector in the early phase called DAMA/NaI. The target was replaced with 250 kg of high-purity NaI crystals in the subsequent Phase-I and Phase-II. In the latter case, the energy threshold has been lowered from 2 to 1 keV. The DAMA collaboration is currently operating an empowered Phase-II with threshold as low as 0.5 keV with the aim of adding an additional extreme low-energy point in the analysis. This region is extremely important because it could show the phase inversion described above, which is not yet present in the recoil spectrum published so far by the DAMA collaboration.

The modulation measured by DAMA is $S_m \simeq 0.01$ cpd/kg/keVee in the 2–6 keVee energy interval, which is extracted by a time fit of the residual single-hit (non coincident) rate as reported in Figure 8 of Ref. [50].
Figure 8. Experimental residual rate of the single-hit scintillation events measured by DAMA/LIBRA in the combined Phase-I and Phase-II in the (2–6) keV energy intervals as a function of time. Data are taken from [50]. The superimposed curve (red) represents the modulation as in Equation (13), with period fixed to one year, phase fixed to 152 days (June 2nd) and amplitude equal to the central value obtained by best fit on the data as reported in [50].

If one considers that this quantity represents only 6.5% of the total rate detected in the crystals, one can naively assume, by scaling, that in the same energy window, the unmodulated component of the total rate is about $S_0 \approx 0.15 \text{ cpd/kg/keV}$ and then smaller than the total rate, i.e., $\ll 1 \text{ cpd/kg/keV}$.

From Figure 8, the modulation reported by DAMA is extracted on the experimental residual rate of single scintillation hits, i.e., $S(t) - \hat{S}(t)$ where $\hat{S}(t)$ is the detrend function. The detrend function used by DAMA is a piecewise function made up of the average annual cycles of the total rate for each crystal. It should be noted that this method applies without bias if and only if the total rate of a single hit is constant; in all other cases, in which there is an explicit dependence on the time of the total rate, amplitude, and phase, are biased as described in [44]. Basic signal processing theory, indeed, warns about the fact that injecting a periodical manipulation in time series will make the injected frequency itself appear in the final periodogram. The total and explicit rate $S(t)$ is never reported by the collaborations (see always [50] and references therein) even if, from the same publications, it is evident that this rate is different in the two experimental phases, is time dependent because of the presence of decaying contaminants, and is presumably affected by many discontinuities because of hardware operations.

One is not saying that the DAMA signal is a complete artifact from an incorrect analysis, but one is only suggesting that the result in phase and amplitude could be biased and, consequently, the interpretation in terms of dark matter is not exactly correct.

5.2. Reproducing DAMA

At present, SABRE is the only R&D project that was able to manufacture high-purity crystals with a counting rate close to 1 keV/kg/keV comparable to DAMA [60], and plans to deploy two different detectors in both Earth’s hemispheres, to factor out all possible systematics due to unaccounted seasonal effects. PICOLON R&D also plans to deploy a target of 250 kg of NaI crystals in the coming years. Finally, the COSINUS collaboration has proved that the combined scintillation and temperature signals in the bolometric usage of the NaI can feature the ER–NR separation, and it is building the first real experiment for a counting experiment with a relatively small crystal. Furthermore, it plans, after the first data collection, to increase the target and exploit the annual modulation analysis as well.

In summary, the NaI case is not yet solved. The experiments trying to reproduce DAMA have not yet definitively clarified this debated result; therefore, the funding agencies should strongly support all the attempts to independently clarify the question as soon as possible with substantial resources and manpower. If there is a physical explanation for the DAMA signal, this explanation would be extremely interesting.

6. Noble Gases

At present, noble gas-based experimental setups are the most promising dark matter detectors in terms of sensitivity in a wide dark matter mass range, from 1 GeV/$c^2$ to 1 TeV/$c^2$ [46,47,61–63], and recently even for masses lower than 1 GeV/$c^2$ [46,64]. Liquid
targets made of these special elements can reach high levels of radiopurity and, thanks to their scalability, in terms of target mass, they represent a realistic technology and a candidate for the ultimate experiment in dark matter search, which is capable of reaching the optimal sensitivity, as will be discussed in Section 7.

Among the known noble elements, argon and xenon are the sole gases, permitting a feasible realization in terms of reliable technology and sustainable costs. Both gases can be exploited in single phase (liquid) detectors or double phase (liquid and gas) time projection chambers (TPCs).

Table 2 summarizes the main properties of the two noble elements, making the two technologies complementary in terms of pros and cons. All details will be discussed in the two following subsections dedicated to xenon and argon, respectively.

Figure 9 sketches the genealogy of both technologies, showing weak (dashed) and strong (solid) relationships in terms of collaborators and/or merging of the corresponding experimental groups, while the gray block represents future projects. Basically, the two technologies have a common origin in large noble gas neutrino detectors, such as the ICARUS project [65]. Two distinct branches originated from some preliminary R&D projects: the argon and xenon communities, even if this nomenclature is not formally shared among all collaborators. The genealogy includes neither the DAMA/Xe project [66], a single-phase small scintillation not upgraded by the collaboration, nor XMASS [67], another single phase xenon-based detector that has anyway set a fair limit on WIMP-like dark matter. Some of the experimental aspects of the two approaches will be discussed in the following.

![Genealogy of noble gas detectors](image_url)

Figure 9. The genealogy of the noble gas detectors can be traced back to a shared ancestor from which the xenon (green) and argon (red) communities diverged, forming two distinct branches. The dashed lines point to some weak connection between different projects, while the solid line represents the natural evolution of different detector scales. Finally, the grey diagrams represent future projects. The xenon is divided into three main projects: ZEPLIN, XENON, and PandaX. The first two will possibly evolve in a common final project. The argon community, started with three projects (ArDM, WArP and DarkSide), are currently reunited in the common project DarkSide-20k (GADMC). Interactions between XENON and DarkSide collaborators have already begun, and therefore, one can speculate about a final Grand Unified TPC (GUT) in which all communities eventually converge in a common highly performing strategy.
Noble gases can be operated in single-phase detectors (liquid) or in double-phase (liquid and gas) TPCs. In the first case, the sole scintillation signal (S1) can be used for position reconstruction and pulse shape where possible. In the second case, for each primary interaction in the liquid target, two signals are exploited: scintillation in the liquid (S1) and electroluminescence in the top gas pocket due to ionization electrons accelerated and extracted by strong electric fields (S2). Exploiting both S1 and S2 can help in volume fiducialization, background rejections, and particle identification when S1 alone, as in the case of the xenon, is not capable of performing the ER–NR separation. A single-phase detector, indeed, is easier from a technical point of view, but in general, it does not allow for a high performance in event reconstruction. S1 and S2 are usually correlated through the ion recombination process (see Figure 10); therefore, to improve the performances, the energy estimator is defined as a linear combination of the two, whose parameters are calculated from accurate energy calibrations. A scheme of the single and double-phase noble gas detectors is shown in Figure 11.

Figure 10. Scheme of the noble gas signals S1 and S2 in double-phase TPCs. A collision of an ionizing particle with the noble gas (dashed brown) produces both scintillation light and ions. In the presence of an electric field, part of the ions does not recombine producing additional light (S1), but it is extracted and produces the secondary signal (S2). As a consequence, S1 and S2 are partially correlated.

Recently, the possibility of using an ionizing-only signal (S2-only) has been exploited both by argon and xenon detectors, allowing one to set a limit, after an accurate low-energy background modeling, and considering the shape of Equation (12) for the expected dark matter signature. These technologies have confirmed a competitive performance also for the light dark matter detection with a mass below 1 GeV [46,64].

Table 2. Comparison between xenon and argon in dark matter detectors. From the top: atomic number, atomic weight, density, boiling point, scintillation wavelength, singlet decay, triplet decay, light yield, ER–NR classifier.

<table>
<thead>
<tr>
<th>Property</th>
<th>Argon</th>
<th>Xenon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>18</td>
<td>54</td>
</tr>
<tr>
<td>A</td>
<td>39.9</td>
<td>131.9</td>
</tr>
<tr>
<td>ρ</td>
<td>1.4 g/cm³</td>
<td>3 g/cm³</td>
</tr>
<tr>
<td>T_B</td>
<td>87 K</td>
<td>165 K</td>
</tr>
<tr>
<td>λ</td>
<td>128 nm</td>
<td>178 nm</td>
</tr>
<tr>
<td>τ_fast</td>
<td>6 ns</td>
<td>5 ns</td>
</tr>
<tr>
<td>τ_slow</td>
<td>1.6 µs</td>
<td>24 ns</td>
</tr>
<tr>
<td>LY</td>
<td>40 PE/keV</td>
<td>46 PE/keV</td>
</tr>
<tr>
<td>ER–NR Classifier</td>
<td>S1(t)</td>
<td>S2 / S2</td>
</tr>
</tbody>
</table>
Figure 11. (Left): Single-phase detector in which the light emission from the scintillation process is collected by PMT’s instrumented all around the detector. (Right): Double-phase TPC. A primary scintillation signal (S1) is produced in the liquid. The drift electric field between the cathode (K) and the grid (G) moves the ionization electrons upward, which are finally extracted by another electric field between the grid and the anode (A). The accelerated electrons in the gas produce a second and stronger light signal (S2).

6.1. Xenon

The xenon has a high atomic number and thus an optimal self-shield from an external background. Xenon-based detectors can search for both spin-dependent and spin-independent dark matter interactions. Even if the nuclear form factor is not that favorable \[31\], the xenon-based detectors can be smaller than the argon-based detectors by a factor of 5–7, which was mostly because of the factor $A^2$ in the cross-section.

Because of the relatively higher boiling point (165 K), the xenon does not present technical issues, which is typical of electronic components at very low cryogenic temperatures: PMTs and the electronics chain usually work smoothly with high performance. Even though the scintillation wavelength is in the near-UV region (178 nm), the corresponding light can be easily detected by commercial photo-cathodes. It does not require a wavelength shift, resulting in high performance in event reconstruction. Since the two decay components of the scintillation light are very close to each other, S1 alone cannot discriminate between ER and NR, while the S2/S1 ratio is usually used. Typically, the discrimination power of this classifier is 1 over 300. For this reason, xenon-based detectors require high accuracy in the background control through deep purification systems and high accuracy in material screening and selection. If not, there is a real risk of saturating the detector sensitivity in a very short exposure and creating puzzling results. Investing in the S1-only discrimination with digitizers with a high sampling rate, of the order of 1 GSa/s, could be valid: even a mild preference in the NR–ER discrimination could be enough to improve the separation when combined with S2/S1 and other observables in a multivariate approach, but at present, no progress has been made in this direction.

In xenon detectors, it is easy to remove volatile radioactive contaminants such as $^{85}$Kr, but it is more difficult to remove radon with comparable atomic mass, even if significant progress has been recently achieved in distillation techniques \[46\].

Figure 12 reports the most updated comparison between the leading dark matter detectors LZ, XENONnT (5.9 tons) and PandaX-4t (3.7 tons) with the same order target, as reported in \[46\]: LZ, originating from the merger of the ZEPLIN and LUX groups, is a double-phase TPC, which has been in operation since 2022 with a target of 5.5 ton \[63\]. XENONnT, coming from a long preceding history of versions with increasing mass (XENON10, XENON100 and XENON1T), has shown an unprecedented low-background level \[46\] and is currently taking data with a 5.9 ton target; PandaX-4t is
an independent collaboration that, after different preceding versions, is currently operating a 3.7 ton version [62].

![Graph showing WIMP-nucleon cross-section vs. WIMP mass](image)

**Figure 12.** Comparison of the three leading xenon-based dark matter detectors, as reported in [46], which is the publication referred to as “this work”.

From the experience of experiments described above, a gradual difficulty in the scaling process is evident: a working prototype can prove the detection principle, but cannot prove the increasing technical complication coming from the increase of the target mass and the detector volume. Only a step-by-step scaling, with intermediate stages, can guarantee a solid progression of the project and success against a highly probable failure.

The current generation of projects can reach a sensitivity very close (even a logarithmic decade above) to the neutrino floor. All collaborations are planning future projects with targets larger of an order of magnitude (30–50 ton) to reach a sensitivity that will basically touch the neutrino floor as ultimate experiments on this research field. In particular, PandaX is moving independently toward a multi-ton detector, while LZ and XENON (with a possible middle scale DARWIN [68]) are discussing a possible joint venture in a project called XLZD [69].

### 6.2. Argon

Argon is lighter than xenon; therefore, self-shielding is less effective. Its boiling point is 87 K, with a corresponding technical difficulty such as the one observed in PMT electronics at this temperature [70] (even if this argument is a kind of myth: a failure of a specific PMT batch does not mean that a possible R&D with the PMT producer would not have solved the observed problems). The scintillation light of 128 nm is hardly matching the photo-cathode sensitivity; for this reason, typically, a wavelength shifter (such as the TPB at 420 nm [70]) is used, with a corresponding degradation of the event reconstruction, due to the extra diffusion of light. Nevertheless, the argon shows an excellent ER–NR discrimination using S1 only: a very large separation (three orders of magnitude) in the fast and slow scintillation components permits discriminating ER from NR as one over ten billion [61]. It is worth mentioning that the argon nucleus has spin equal to zero; therefore, the spin-dependent search cannot be performed, and the non-relativistic expansion of all possible relativistic operators can be completed only for a reduced subset [71].

Contrary to xenon, argon from the atmosphere is highly contaminated with the long-lived beta emitter $^{39}\text{Ar}$. For this reason, part of the argon community has moved toward the usage of deep underground argon in which this contaminant is reduced by a factor greater than one of over 1000 [72].
For the reasons described above, the argon-based detectors have a different story. Indeed, two independent lines have emerged over the years: single-phase TPCs such as DEAP-3600 [61] and double-phase TPCs such as DarkSide-50 (and marginally ArDM [75]). DEAP, operating 3.6 tons of atmospheric argon, has set the strongest limit to date for this technology, showing its intrinsic limitations.

The double-phase liquid argon TPC has a more complex history. Before DarkSide-50 with atmospheric argon (A-Ar) [70], a smaller prototype of WArP had the only result for this technology using 2.3 L of A-Ar [74]. This limit was further improved by the first data of underground ultra-pure argon (U-Ar) distilled from the deep Earth mantle CO$_2$ [72]. After this result, DEAP-3600 currently holds the best limit for argon-based detectors (in single phase).

DarkSide-50, DEAP-3600, and ArDM are now joining a common project called GADMC (Global Argon Dark Matter Community) [75]. The first instance of this joint venture is DarkSide-20k, a giant TPC containing about 50 tons of U-Ar, which is currently under construction [76]. Furthermore, the GADMC is also planning a futuristic version with 300 tons of active target mass, which is called ARGO-300.

DarkSide-20k presents a lot of challenging aspects and many technological novelties compared with the existing TPCs for dark matter: first, the use of SiPM-based photodetector modules instead of standard PMTs to overcome the issue of cold electronics, with quite a few critical issues discussed in the literature [77,78]; second, extraction and distillation of more than 100 tons of U-Ar (in total), and preservation of its radio-purity; third, the realization of a very big multi-ton acrylic-based TPC with many challenges for high voltage, purity, and event pile-up handling; fourth, the use of multi-ton acrylic vessels; finally, a multi-ton gadolinium-doped acrylic veto. Even in the case of DarkSide-20k, it is not clear why the funding agency panels have not supported intermediate scale detectors (like e.g., 1-ton scale) with the intermediate physics goal of exploring the light dark matter mass, pushing instead for something bigger, just to fill the gap in a phantom competition with the xenon-based detectors. This choice is anyway questionable: even in the case that argon technology was left behind the xenon, the unknown behavior in terms of radiopurity of multi-ton xenon-based detectors is enough to justify an alternative, even smaller but solid, with high background rejection capability, as featured by argon.

In conclusion, as a matter of fact, the xenon-based technology has always been criticized, but in the real world, it continues to be the most advanced branch of the noble gas-based detectors. Liquid argon, on the contrary, is struggling to keep up, and future stages are not completely clear.

### 6.3. Solar Neutrinos

Before moving ahead, it is worth mentioning that the multi-ton noble gas detectors have some promising by-product purposes. The very low achievable background, high target and high scintillation light yield can make them optimal detectors for the precision measurement of solar neutrino fluxes coming from the proton–proton chain and the CNO cycle [79], which are the two processes responsible for hydrogen fusion in the Sun.

The current precision measurements, produced by detectors such as GALLEX/GNO [80], Super Kamiokande [81], SNO [82] and especially Borexino [83–87], have helped to better understand solar physics and neutrino oscillation. However, further improvement in precision can address plenty of other open problems, such as the solar metallicity abundance [86], the tensions on the solar $\Delta m^2$ with reactor experiments [1], the precision constraint of the total solar luminosity in the low-energy spectrum as an extra source of energy in the Sun’s (as dark matter decay, indeed) search for solar axions [88], and non-standard neutrino interaction as a smoking gun of new physics beyond SM [89]. In other words, trying to build large dark matter detectors with some multi-purpose possibility, such as solar neutrino and also neutrino-less double beta decay detection, could in principle be reasonably acceptable.
6.4. Others

In addition to NaI-, xenon- and argon-based detectors, there is plenty of other experiments and R&D’s using a big variety of target nuclei and techniques. Some of those, which are less sensitive to the WIMP-like particles (or sensitive only to light masses), are not discussed for the purpose of present article. It is interesting to mention some of them, which are playing an important role in direct dark matter search: CRESST using a target with CaWO$_4$ [90], CDMSLite and SuperCDMS [91] using germanium, DAMIC using silicon [92], PICO-60 using C$_3$F$_8$ [93], and NEWS-G using neon [94].

If one may think that DAMA, made of sodium (light nucleus, $A \simeq 23$) and iodine (heavy nucleus, $A \simeq 127$), cannot be compared to xenon (heavy nucleus, $A \simeq 131$), because the origin of the annual modulation comes from the interaction with sodium rather than iodine, one should also think about what happens with a large variety of other atoms, used by other experiments, with null results. And they are made of carbon ($A \simeq 12$), oxygen ($A \simeq 16$), fluorine ($A \simeq 19$), calcium ($A \simeq 40$), argon ($A \simeq 40$), tungsten ($A \simeq 183$), germanium ($A \simeq 73$), silicon ($A \simeq 28$) and neon ($A \simeq 20$). Results do not easily reconcile even in the case of spin-dependent (SD) interactions, such as, e.g., the xenon contains approximately the same percentages of isotopes with nuclear spin 0, 1/2 and 3/2. Given the extensive range of nuclei that have been examined in the context of the SI (and SD) interaction with SHM, it is challenging to accept the notion that sodium holds a uniquely significant position among all the elements in the periodic table.

6.5. Other Laboratory Detections and Indirect Searches

This review focuses primarily on direct searches for dark matter in underground laboratories. The analysis critically examines the evolution of these searches over time, particularly in relation to potential candidates such as WIMPs, WIMP-like particles, or light–dark matter. However, it is important to briefly mention other types of laboratory searches (such as axion-like detectors, accelerators, and colliders) and indirect detection methods (such as astrophysics). For a comprehensive overview, ref. [1] can be consulted as a general reference.

The search for axion-like particles has received increasing interest over recent years. Starting from the original Peccei–Quinn theory for explaining the absence of strong CP violation in SM, the nature and properties of the axion have been changing over time, making it today a class of hypothetical models whose features are updated and adapted to the present experimental situation. Axion-like particles can be searched in laboratories with different complementary techniques, e.g., as photon conversion with electromagnetic fields (e.g., OSQAR [95]), or as fifth long-range force detection. Furthermore, the existence of axion-like particles can be proved with specific reactions in solar neutrino detectors [88] and studied in indirect astrophysical phenomena, such as significant effects on stellar evolution or cosmic rays. The results are combined and compared in the mass-coupling parameter space. Currently, no reasonable evidence for its existence has been found.

Heavier dark matter candidates, in the mass region of WIMPs, have been largely searched at LHC (in ATLAS and CMS) as hidden channels detectable in collision events with high missing momentum. Up until now, there has been no detection of such signals in the LHC experiments. Typically, these $M_{\chi}\sigma$ limits can be compared with results from direct detection experiments, albeit in a model-dependent manner. Dark matter candidates, especially in the region of sub-GeV light dark matter, can be alternatively searched in fixed target accelerators, such as PADME [96] or LDMX [97].

Dark matter, despite being weakly interacting at the microscopic level, can influence astrophysical systems on a larger scale, such as stellar evolution. Thet indirect detection of dark matter involves searching for the products of dark matter particle annihilation or decay, such as photons, fermion pairs, and neutrinos. The rate at which these particles are produced depends on factors like the annihilation (or decay) rate, the density of particles in a certain galactic region, and the quantity of final-state particles generated in each process. There are specific satellite detectors capable of performing such measurements.
such as, e.g., PAMELA [98] and AMS-02 [99]. The upper limits in the parameter space mass−⟨σv⟩ are increasingly updated, and the results are compared with the limits from other detection strategies. Even in this case, no results have ever been reported in favor of specific candidates.

In conclusion, complementary to direct dark matter searches, there are numerous other strategies to indirectly constrain the parameter space of potential dark matter scales across a wide mass interval. Indirect dark matter searches are undoubtedly useful in addressing the dark matter problem and assisting the scientific community in focusing on a restricted set of potential candidates. However, the indirect dark matter search cannot definitively claim a discovery without direct confirmation in laboratories, as potential effects can be misinterpreted and affected by systematic errors.

As anticipated and discussed in detail in the following section, the very wide range of possible candidates requires wisely devising plans to refine the understanding of dark matter. Unfortunately, the region of the parameter space is wide enough and cannot be explored randomly. There is a compelling need to converge in synergy on a restricted number of models, and the indirect search, especially through astrophysical observations, can play a crucial role in this respect, as further detailed in the next section.

7. Evolution of Results

A good way to explore the evolution of results on direct detection of dark matter is by reading the dark matter review as reported by the Particle Data Group (PDG) [100]. Downloading old versions from 1996 to the latest update (2022) (see [1,101–113] and references therein), one can see that the review has increasingly dedicated a larger and larger number of pages, growing from about 4 to more than 30 in about 25 years. This fact, of course, is related not only to the increasing interest in dark matter but also to the overall increase of the space dedicated to physics reviews in PDG. A correct comparison should be normalized somehow.

The first SI σ=Mχ plot appeared only in 2010 and was updated in 2011 [108]. In this paradigm, one can immediately see the strong tension of the two DAMA solutions (as interpreted in the SI framework by [32]), made of two islands (one for the sodium solution and one for the iodine solution), with the other experiments, such as XENON-100, EDELWEISS, and CMDSSi. Together with DAMA, another small-scale detector based on germanium called CoGeNT [114] shows a similar solution close to the DAMA sodium regions. The plots show the potential discovery region for SUSY candidates, which could be hidden channels, at the LHC.

In 2012, nothing changed much, but in the 2013 update [109] (see Figure 13), persisting also in 2014 [110], new islands appeared, which were very close to DAMA: both CDMS-Si and CRESST had an excess over the predicted background. All these positive results appeared singularly close to the discovery of the Higgs boson in July 2012 at LHC [115,116]. At the same time, the absence of evidence of SUSY candidates started to be digested by the scientific community, but it was still not widely consolidated [117].

In 2015, CRESST-II did not observe excess, and then the previous islands due to CaWO4 were removed from the updated PDG [110]. In 2016, nothing changed much except for some improvement in the limits of many experiments [111]. In the 2017 update [111], from null results from further upgraded versions of CoGeNT, the corresponding island was removed, and new limits, such as PICO-60 and DEAP-3600, were added. In the 2018 update [112], coinciding with important releases of ANAIS-112 and COSINE-100 [51,118], the DAMA islands were removed from the PDG. Notice that the DAMA SI islands are almost never presented in the official DAMA publications, and they recently survived mainly in the publications of the NaI-based experiments trying to reproduce DAMA. Hereafter, up to the last upgrade in 2022 [1], the PDG SI σ=Mχ plot reports only upgraded limits (see Figure 14), closer and closer to the neutrino floor, for both low and high masses.
Figure 13. Cross-section as a function of the WIMP-like mass in the SI framework as reported in PDG 2013. In the same plot, limits (solid curves) and positive results (islands with a given CL) are reported for various experiments; see text.

Figure 14. Cross-section as a function of the WIMP-like mass in the SI framework, as reported in PDG 2022. Only limits (solid curves) are reported by various experiments; see text.

Recently, since the statistical fluctuations of the neutrino floor are becoming important in the present and next generation of dark matter experiments, the name has been changed to neutrino fog or mist, considering the real impact of how this expected background grows with the experimental exposure [119].

The common practice of focusing on the SI $\sigma - M_\chi$ plot has received some criticisms. One may think that comparing all experimental results in the same SI $\sigma - M_\chi$ plot could not be a comprehensive and accurate way to address the dark matter problem, and it would be only a generally subjective, limited and imprecise action. One can reasonably accept this criticism, but it remains unexplained how a unique positive result (from DAMA) can be compatible, independently of the model, with tens of other null results made by experiments of comparable or larger sensitivity and using even nuclei similar to those discussed above. Those experiments are not detecting any positive signal anyway regardless of the fact that nature has chosen a SI interaction, or whatever, for visible and dark matter particles.
As has happened many times in the history of physics, research is going through a hard period in which knowledge is stuck and experiments are becoming more and more challenging and expensive. The whole scientific community is moving by inertia after the thrust of a strong theory that has now been left behind and becomes everyday fuzzier and fainter. Moreover, this motion proceeds so smoothly that no one could even realize how it happened.

Furthermore, the belief is so strong that people are already thinking about a future consisting not only of bigger and bigger detectors capable of reaching the neutrino floor but also of how to drive into the neutrino fog with a huge detector capable of exploiting the directionality of the dark matter. The latter in particular looks very futuristic given the present status of results.

From recent history, it is clear that there was some original enthusiasm, supported by a very appealing theory as SUSY, and close to Higgs discovery, there was a cluster of experimental “excesses”, led by the DAMA result that has probably amplified the expectation that dark matter particles could be really detectable.

It is anyway commonly accepted that reaching at least the neutrino floor is a kind of “moral duty” for the scientific community before trashing completely WIMPs and all WIMP-like paradigms all at once, in favor of other particle or non-particle solutions of the problem of the missing mass of the Universe.

Finally, to conclude with another interesting sociological case, one can recall when XENON1T published a presumed excess above the threshold as reported in Figure 15 [120] and later XENONnT did not confirm it with a lower overall background [46]. The collaboration also warned that such a spectrum could even come from an unaccounted tritium beta spectrum. Regardless of whether or not some trained eyes see these two outlier points above the event threshold as an excess, it is curious that these two points have received about 600 citations to date, which are mostly from theorists and phenomenologists.

What can one do as a particle physicist? The choice of spending some more time in this kind of search will surely pay back, as advances in knowledge and technological implications are granted by basic research. Anyway, one should not exaggerate, because if the main purpose of an experiment is its secondary goals, in this case one can propose to search for whatever non-falsifiable theory, and this would make the science become a practical paradox.

![Figure 15. Excess of events above the threshold reported by XENON1T compared with their background model (red).](image-url)
7.1. A Drake Equation

The Drake equation is a probabilistic argument used to estimate the number of active, communicative extraterrestrial civilizations in the Milky Way galaxy [121]. Of course, this equation is more useful for “understanding” rather than “quantifying”, as its parameters are affected by large uncertainty and sometimes supported by naive arguments.

One can imagine following the same approach for the probability $P_\chi$ that dark matter is made of WIMP-like (or light WIMP) particles and can be detected by experiments on the Earth.

A possible ansatz, containing the main terms, is:

$$P_\chi = f_e \cdot f_s \cdot f_{th} \cdot f_{exp} \cdot f_{det} \cdot f_\Omega$$

where

- $f_e$ = fraction of energy in the full mass interval for candidates for dark matter. As there is no actual reason to prefer one candidate to another, one can estimate this ratio as $5/89$, where 5 corresponds in the logarithmic scale to the 0.1–10,000 GeV/c$^2$ interval over the full range of 89, as discussed above, from axions to massive primordial black holes.

- $f_s$ = fraction of the possible cross-section available for a WIMP-like interaction. If one considers the full range, from the already reached ($\log(\sigma) = -46$) down to the squared Planck mass ($\log(\sigma) = -66$) of 20 orders of magnitude, and that this kind of candidate cannot be much lower than the neutrino floor ($\log(\sigma) = -50$) for experimental reasons, this factor has to be taken as 4/20.

- $f_{th}$ = probability that the missing mass of the Universe is explained by particles or by some acceleration anomaly, i.e., the failure in extrapolating the Newton law (General Relativity) for the Solar System ($10^8$ km) to the galactic scale (kpc), or something else. There is no real reason why this fraction should not be at least 1/2 or even lower (1/3).

- $f_{exp}$ = probability that only one experiment (DAMA) has detected dark matter over about 10 with comparable sensitivity, that is about 1/10.

- $f_{det}$ = probability that the dark sector cannot exchange information with the visible sector with other (weak) interaction but gravity, as in some versions of the so-called Mirror Matter models [122]. This probability can be set to 1/2, since there is no real reason why dark matter should share the same interaction properties of visible matter.

- $f_\Omega$ = catastrophic probability that the Big Bang cosmology is wrong. Nobody will ever admit that, but also saying that the Big Bang cosmology is 100% correct would look weird as well. In addition to static or quasi-static physical cosmological models and the like, one could consider alternative and radical views of the Universe, such as the Simulation hypothesis [123] or the Mathematical Universe hypothesis [124]. In this case, one would reasonably accept a 50% chance from a philosophical point of view, even though one may also think that dark matter could anyway be included in this kind of simulation. Furthermore, this probability could be correlated to $f_{th}$ if the modification of gravity can explain the missing mass, assuming that this factor is part of the game, even if it is quite disturbing.

With these basic terms, we obtain about 1:3560 for $P_\chi$. If the equation is empowered with other terms, each of them will be $\lesssim 1$; then, the updated probability is likely to be less than this first estimation. Now, it is time to bet.

7.2. Mala Tempora

Until the early 1980s, new particles came out of accelerators every day, and it was relatively easy to understand the hidden logic among particles and interactions in the frameworks of quantum field theory. Theorists became carried away and fantasized about many extensions of SM, which, although constituting an excellent description of the observed phenomena, left and still leaves indications of a more complete high-energy theory. And SUSY, with its by-product “WIMP miracle” [125], was the most awaited guest at the party.
LHC, close to the discovery of the Higgs boson, has been shown not to be really suitable as a discovery machine for the new physics beyond SM. It is therefore probable that the planned high luminosity stage \[126\] will end up in controversial anomalies and tensions, which will only complete a long list already existing. It would have been probably better to shut down LHC and speed up the construction of the Future Circular Collider, also known as FCC \[127\], with a center-of-mass collision energy of 100 TeV, which is almost one order of magnitude higher than LHC. To be honest, one should also admit that in principle, there is no indication that possible new physics emerges just at 100 TeV rather than at 1 PeV or more. Therefore, it is generally like sailing in the open sea without knowing if and where the next land will be. If one can speak of a possible “crisis in modern particle physics”, now is precisely that moment. The only (weak) hope, in light of the phrase “mala tempora currunt”, is the memory that in similar situations in the history of physics, a significant revolution often followed a deep crisis.

The only serious risk is that in the absence of concrete scientific objectives, experimental collaborations may become inefficient and uncontrollable organizations whose main goals can be something different from scientific research.

7.3. Falsifiable and Scientific

Karl Popper in his book The Logic of Scientific Discovery (1934) suggested that a statement, a hypothesis, or theory, to be considered scientific, should be “falsifiable”, i.e., logically contradicted by an empirical test. The material implication “IF it is scientific THEN it is falsifiable”, i.e.,

\[
\text{SCIENTIFIC} \rightarrow \text{FALSIFIABLE},
\]  

leaves wide room for theories that are falsifiable but not scientific. Proposing a massive particle detectable in underground experiments is certainly falsifiable but not necessarily scientific, especially if there is no theory behind it and no clear motivation regarding why it should be worth searching for. Reading the material implication in the opposite direction (as a basic logical fallacy) has sometimes created a lot of confusion not only for the dark matter case but also for numerous extensions of SM, which are based on aesthetic argument instead of real necessity. This misunderstanding becomes even more threatening when the properties of a given dark matter candidate are updated after the initial dark matter candidate is not found in the place in which it was proposed \[128\].

This is the case for WIMP particles emerging from SUSY. The Minimal Supersymmetric Standard Model (MSSM), introduced to accommodate the problem of the hierarchy of the Higgs mass, should have broken at the Higgs mass scale ($\sim$100 GeV) and should have predicted the existence of stable massive dark matter candidates. The absence of a SUSY particle discovery at the LHC has pushed theorists to abandon the “naturalness” concerns, add other parameters and mechanisms, and increase the SUSY breaking scale, creating a big family of X-MSSM models, where X stands for the acronym of the case; see \[129\] and references therein. The PDG has recently removed those families of allowed regions in SI dark matter parameter space \[1\], being already halved by xenon-based dark matter detectors. Furthermore, saying that there is still a 50%, or so, unexplored region is, for what is discussed, definitely pointless.

What one needs is a change of paradigm, and this is very well summarized by F. Nesti et al. \[130\]:

“In detail, we advocate for a paradigm according to which, after abandoning the failing $\Lambda$CDM scenario, we must be poised to search for scenarios without requiring that: (a) they naturally come from (known) “first principles”; (b) they obey the Occam razor idea; (c) they have the ability to lead us toward the solution of presently open big issues of fundamental physics. On the other side, the proper search shall: (i) give precedence to observations and the experiment results wherever they may lead (ii) consider the possibility that the physics behind the
Dark Matter phenomenon be disconnected from the physics we know and and does not comply with the usual canons of beauty”.

This strategy is quite reasonable. However, the discovery of some elusive particle solution in underground laboratories, not supported by any theoretical framework, will be a big deal from an epistemological point of view but better than nothing.

7.4. The Emperor Is Naked!

The dark matter in the shape of WIMP or WIMP-like or light WIMP particles is widely accepted as true or professed to be plausible because of the unwillingness of the general scientific community to criticize it or be seen as going against the mainstream opinion.

The Emperor’s New Clothes fairy tale by Hans Christian Andersen is a metaphor about logical fallacies that reads in this case: no one believes in such a dark matter, but everyone believes that everyone else believes in it, until some child comes out of the crowd and shouts: “The emperor is naked”! But in this case, such a child, if ever, has yet to be born.

7.5. A Way Out

Even though direct searches have not solved the dark matter problem, there are a few interesting things to do. First, we might need to rethink our understanding of gravity. MOND, or similar, is one idea, essentially saying that our current gravitational laws might not apply on larger scales. Alternatively, one might discover new particles that interact even more weakly than previously thought, making them incredibly difficult to detect.

Another possibility is that something is missing in our theoretical framework. Maybe our understanding of particle physics needs an upgrade. Some theories propose new types of particles, like sterile neutrinos or axions, which could be potential dark matter candidates. These particles would be elusive and might interact with normal matter in ways that are not fully understood yet. For example, an interesting change of paradigm, exploiting the relationships of all objects in the universe, from microscopic to macroscopic, in the mass-radius diagram, is proposed here [131].

On the observational side, upcoming experiments, like the James Webb Space Telescope [132] and Euclid [133], might provide more insight into the cosmic web and the distribution of matter in the Universe. High-energy cosmic-ray observatories and gravitational wave detectors could also provide new clues.

In essence, solving the dark matter puzzle might require a combination of refining our theories, developing more sensitive detection methods, and pushing the boundaries of our observational capabilities.

8. Conclusions

We do not want to spoil the party, so we will conclude by reiterating the conviction that the current direct detection of dark matter in the region of the WIMP-like and light dark matter is absolutely valid, as the cost/benefit is still affordable and justifiable. About the next generation of detectors, the same cannot be said with the same certainty.

However, we want to point out that this quest is currently moved by inertia after the strong thrust impressed a few years ago by a solid theoretical framework that now is becoming farther and fainter. It happened many times in the history of physics that some puzzle has been solved because there was a clear indication where to search for its solution. Now it looks as though it is not the case for dark matter any more.

The missing mass of the Universe, explained as a heavy particle forming a halo all around galaxies is an simple theory, so simple and easy to attract many scientists who may be not so willing to dwell in complicated calculations and ideas. But it is also persisting, because we are led to think that easier solutions are always the ones chosen by nature.

The fact that the presence of the missing mass of the Universe is supported by so many irrefutable pieces of evidence makes the direct search of dark matter a kind of moral duty that we seem to pursue at all costs. But this idea is pointless, and probably dangerous.
In this report, we have seen that the leading role in the dark matter search has been driven first by the DAMA annual modulation result, followed by other results singularly close to the discovery of the Higgs boson. This apparent convergence slowly disappeared in the subsequent years, and was overcome by the liquid noble gas detectors, which are continuing showing null results, and increasing their sensitivity with bigger and bigger targets.

Given the very small chance of detecting such dark matter particle candidates, as inferred by a procedure similar to the Drake equation, we can conclude that the present stage of the quest, without getting sidetracked by science fiction-like projects, is anyway necessary to start rethinking the Universe.


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**Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>LHC</td>
<td>Large Hadronic Collider</td>
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<td>ΛCMD</td>
<td>Lambda Cold Dark Matter</td>
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<td>MOND</td>
<td>Modified Newtonian Dynamics</td>
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<td>SUSY</td>
<td>Super Symmetry</td>
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<td>WIMP</td>
<td>Weakly Interacting Massive Particle</td>
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<td>GUT</td>
<td>Grand Unification Theory</td>
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<td>MACHO</td>
<td>Massive Astrophysical Compact Halo Object</td>
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<td>ALP</td>
<td>Axion-Like Particle</td>
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<td>SI</td>
<td>Spin Independent</td>
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<td>Spin Dependent</td>
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<td>SM</td>
<td>Standard Model</td>
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<td>Standard Halo Model</td>
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<td>CL</td>
<td>Confidence Level</td>
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<td>Photo-Multiplier Tube</td>
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<td>Electron Recoil</td>
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<td>Nuclear Recoil</td>
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<td>Silicon Photo-Multiplier</td>
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<td>Time Projection Chamber</td>
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<td>Primary scintillation light in TPCs</td>
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<td>Secondary scintillation light in TPCs</td>
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<td>Ultra Violet</td>
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<tr>
<td>FCC</td>
<td>Future Circular Collider</td>
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<tr>
<td>MSSM</td>
<td>Minimal Supersymmetric Standard Model</td>
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