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Dark matter searches: Interdisciplinary aspects of theoretical developments

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Abstract

Progress in the understanding of dark matter–its behavior on all astrophysical scales up to assessing its very nature–should optimally be based on interdisciplinary approaches, which it is crucial to strengthen in France. This contribution provides arguments to support more efficiently the works that develop at the frontiers of different fields (and/or different CNRS institutes). The IN2P3 could play a major role in supporting theory development in this field where the existence of new physics is clearly established. This concerns networking, funding, and hiring aspects.

1 Introduction

Unveiling the nature of dark matter is an exciting observational/experimental and theoretical challenge. This unambiguously calls for new physics beyond the known frontiers, which is one of the raisons d'être of IN2P3.

In this field, high-energy particle physics beyond the standard model (BSM) has long led the scientific debates by promoting some classes of dark matter candidates and focusing the experimental searches on specific targets. One of the most popular candidates is (still) the WIMP/FIMP (weakly/feebly interacting massive particle), which arises in particle theories willing to address the so-called electroweak hierarchy problem, and which is motivated independently by its simple production mechanism in the early universe. Other popular candidates are the QCD axion, which relies on BSM extensions aiming at solving the strong CP problem, and a long-lived sterile neutrino, which can derive from BSM neutrino mass generation mechanisms. Other candidates are inferred from effective approaches where one tries to get the correct cosmological abundance out of a minimal BSM field content (these approaches are based on the introduction of a couple of new matter fields and new interactions, where the free parameters can be the spins, masses, and interaction coupling constants).

These popular candidates have served as beacon targets for experimental searches. At the IN2P3, a lot of effort has been invested on WIMP searches, and most of the theoretical developments have concerned the calculation of interaction cross sections in UV-complete models (supersymmetry, extra-dimensions/composite theories, etc.), which are important inputs for predictions of the cosmological abundance and of detection signals. These calculations are similar to what is needed for collider physics, hence the collider phenomenology community could easily participate in this useful and challenging task. Comparing cross section predictions to some data, at colliders or in indirect/direct searches, has then been the routine of the field in the last two decades, with the French high-energy community (IN2P3 and INP) not investing much on the astrophysical/cosmological details (a few exceptions of course). The positive aspect of this routine is that it allowed theorists and experimentalists/observers to start collaborate with each other (the GDR/IRN Terascale has played an active role). Several meetings were also organized specifically around direct dark matter searches of WIMPs and axions, where most discussions focused on model-building aspects and detection methods. At INSU laboratories, on the other hand, scientists have long developed knowledge on cosmological and astrophysical aspects (matter power spectrum, structure formation, galactic dynamics, etc.) without paying much attention to the potential dark matter candidates. The links between the astrophysical and cosmological expertise and the high-energy expertise are still poorly developed in France (with a few exceptions distributed between small IN2P3, INP, and INSU groups), which may hinder our ability to propose and develop original search strategies with a leading position at the international level.

With the absence of discovery of new physics at the LHC, astrophysics and cosmology are becoming more and more central to the scientific discussion about dark matter. Cards have been reshuffled significantly since 10-20 years, and new ideas are more bottom-up than before. Particle theory, which is reassessing the relevance of the electroweak hierarchy problem and reconsiders the best ways to embed the SM in a more fundamental picture, is no longer the driving force in setting the stage. Examples are given by the rising of the self-interacting dark matter (SIDM) or ultra-light (scalar) dark matter (ULDM) proposals, which were motivated by observational issues regarding the distribution of dark matter on small scales. Particle theory is still involved, but at the level of effective models where the technical difficulty is no longer to implement multi-loop corrections to some interaction predictions, nor to consider the complete spectrum of a UV-complete model, but more to come with a proof of principle as simple as possible. Studying consequences on UV completion or refining predictions is still fruitful, but this is less of an issue in the absence of strong guiding principle beside dark matter itself (as the hierarchy problem used to be, independently of dark matter). Another example is that of the renew of activity in the study of primordial black holes (PBHs) as valid non-particle dark matter candidates—even if a tiny fraction of dark matter is made of PBHs, this would very strongly constrain the allowed properties of the other candidates. Other examples may stem from interpretation of cosmological tensions, such as the H_0 one (see contributions of some of the authors to the cosmo GT). Investigating the effects of these new views, and participating in proposing motivated alternatives, is where some effort should be invested in the coming years. This demands a stronger participation of scientists with expertise in astrophysics and cosmology. This also demands to form young theoretical researchers to work on advanced topics at the frontiers of particle physics, cosmology, and astrophysics, much better skilled in the latter domains than before. Forming young scientists able to be innovative at the frontiers of different theoretical fields also implies a specific attention when it comes to opening new permanent positions. IN2P3 has recently demonstrated that it was able to react positively to such evolution in the field of dark matter searches, and it is important that is effort is confirmed in the coming years.

2 Current situation of theoretical developments and expected developments

Particle theory: The French expertise in particle model building and phenomenology is well established, and is spread among several INP and IN2P3 groups. Starting with the GDR Supersymmetry in the early 2000, there has been significant efforts to develop contacts with experimental scientists involved in dark matter search experiments (indirect/direct WIMP searches, axion searches). Many numerical codes have been developed and offered to the community to test a diversity of UV-complete models against data, a real *tour de force* (e.g. DarkSUSY, Micromegas, SuperIsoRelic, MadDM, PPPC4DM, etc.), and some even comprise bayesian analysis packages (e.g. Gambit). Now, with the recent evolution of the field and in the context of the current LHC results, theoretical particle physics efforts to unveil the origin of dark matter would strongly benefit from closer contacts with theoretical astrophysics and cosmology. It is still important that a significant (even growing) part of the particle theory community participates in assessing the relevance and/or consequences of scenarios driven by astrophysical or cosmological arguments with respect to UV completion patterns.

Theoretical astrophysics: The expertise in the astrophysics of dark matter at the IN2P3 is scarce (also scarce at the INP, more concentrated at the INSU). It includes high-energy astrophysical aspects, like cosmic-ray propagation relevant to indirect WIMP searches with antimatter cosmic rays, and more generally predictions for multimessenger signals (gamma rays, and neutrinos). It also includes dynamical/kinematic studies to infer the distribution of dark matter in phase space and its inhomogeneities in relevant targets (useful to direct/indirect searches, or to infer capture by stars), the formation of axion clusters, gravitational lensing, etc. There are also topics mixing a variety of expertises, like studying the accretion of matter around PBHs at different epochs in the universe. Theoretical astrophysics is therefore gaining importance and will be instrumental to tackle the coming challenges in the near future: precision astrometry (Gaia, LSST) that will strongly impact in dynamical/kinematic studies and lensing (distribution of dark matter, searches for subhalos or dark compact objects, disentangling SIDM/ULDM/CDM, etc.), high-energy astrophysical signatures and related foregrounds or backgrounds (multimessenger/multiwavelength astrophysics to look for dark matter annihilation/decay, anomalous stellar evolution, accretion around PBHs, etc.). A pressing topic in which theoretical astrophysics is expected to play a significant role is the census of cusps in the centers of galactic halos and searches for subhalos. More generally, the connection of specific scenarios of dark matter with specific astrophysical environments is a rich and promising topic for which the expertise is quite scarce in France, and is worth being more and more supported in the near future. Progress in these topics is crucial to assess the exploratory power of direct and indirect searches (of whatever dark matter candidate). Finally, the opening of the gravitational wave window also offers opportunities to constrain or detect signatures of non-conventional scenarios of the early universe (from the PBH production and mergers to early phase transitions) which are possibly related to dark matter production (or more generally to a dark sector). A synergy between ground-based (Virgo, LIGO) and space-based (LISA) interferometers, as well as the development of pulsar timing arrays is the best tool to offer a more complete cartography of the gravitational wave sky, as well as to draw implications for the early universe. A new generation of theorists who are familiar with the particle physics aspects and the gravitational wave phenomenology, while at the time well aware of the astrophysical backgrounds, is probably needed to fully exploit these probes.

Theoretical cosmology: Theoretical cosmology relevant to dark matter searches concerns several topics, and has obviously somes links with the other aspects discussed above. The most common topic in this field deals with the production and possibly decoupling of dark matter in the early universe (assuming an expanding homogeneous universe), which depends on dark matter particle properties; this part has been widely explored in the past decades, and novelties in this area mostly come at the level of details – the expertise in this topic is well distributed among the INP, IN2P3, and INSU. Conversely, the expertise on PBH production is very scarce, but interestingly enough, a significant part of it is hosted by IN2P3. Further works study dark matter through its imprints on big bang nucleosynthesis (BBN) and the CMB power spectrum—in the latter case, cosmological perturbations come into play. Finally, structure formation is another important avenue to study and constrain dark matter scenarios, again with extremely rare expertise at the IN2P3. Structure formation can also somewhat be related to the inflationary era that specifies the shape of the primordial power spectrum (crucial for the PBH scenario too). Specific studies on how to probe the matter power spectrum on small scales are particularly important to distinguish between CDM, SIDM, axion particles (in particular when the Peccei-Quinn symmetry is broken after inflation), PBHs, etc. The potentially strong imprints present at the linear level can in some cases persist after the non-linear evolution of structures, which offers ways to explore both dark matter and inflation scenarios. This intimate connection between properties of dark matter on small scales and the primordial power spectrum induced by inflation is likely something to develop more deeply in the future, which should rely on growing interactions between the relevant experts. A closer interaction between "hardcore" theorists and numerical simulators is a typical area where major progress is possible, in order to test alternative models on non-linear scales, or to make emerge new techniques to approach some challenging problems.

This is also common with the community focusing on modified gravity and alternatives to dark energy. All the topics mentioned in this paragraph are associated with a plethora of cosmological observables, e.g. the CMB (power spectrum and energy spectrum), the 21cm signal (SKA, etc.), the galaxy power spectrum (galaxy surveys, Ly-α), down to stellar surveys on galactic and extra-galactic scales (Gaia, LSST), etc. There is some expertise at the IN2P3 on these topics which must be reinforced, similarly to the experimental investments in cosmological projects.

Overall—the need for multidisciplinary expertise: Since most of the relevant expertise to fully address the dark matter problem is spread over the three main CNRS institutes of physics (INP, IN2P3, INSU), it is crucial to promote as much as possible initiatives willing to reinforce links between these communities (particle physics, astrophysics, cosmology). The astrophysical/cosmological efforts dedicated to identify the very nature of dark matter is not very well developed in France, and the IN2P3 could play a major role to strengthen this in the future. At the same time, among astrophysicists working e.g. on galactic scales, there is sometimes a lack of appreciation of the importance of theoretical and cosmological consistency, which is an essential requirement to be able to test a scenario. Based on its expertise, IN2P3 (and INP) could certainly contribute to complement the formation of researchers in these areas, for instance with common thematic schools. This however is one more area where one should question the often too rigid organizational rules, that make it heavier and difficult to manage-also financially-formations and research projects across different CNRS institutes. Flexibility and versatility are keys to success, notably for research at the interface of different domains, and should be promoted by removing barriers which are often administrative ones, but do not reflect the reality of the field. IN2P3 could trigger a change of paradigm by promoting projects involving groups with a good balance between different expertises, and even by creating a more inclusive network on the national level in the form of a GDR (a GDR "Matière noire" or even "Secteurs sombres de l'univers"). Such a change would also imply forming young scientists versatile enough to address challenging issues in a multidisciplinary environment, and consequently a specific attention to such profiles by hiring committees.

Links theory-experiments: There is a good level of interactions in the high-energy particle physics community between experimentalists and theorists, which is nicely exemplified by the long-lived GDR/IRN Terascale (and ancestors). In the near future, astrophysical (including direct WIMP/axion searches) and cosmological probes will become more and more important, which progressively moves the core of the scientific debate toward astrophysics and cosmology. It is important that even with this slight paradigmatic move, the contact between theory and experiment remains regular and constructive. This calls for both the reinforcement of active theoretical forces able to interact with experimentalists on this topic, but also to build an efficient networking environment on the national level where ideas and observational results could meet together. This would again be favored by an independent structure like a GDR, with much more space left to theoretical astrophysics and cosmology.

3 Conclusion

The dark matter problem is a fundamental issue that propagates from subatomic to cosmological scales, and which is unambiguously related to new physics. As such, this topic should be central to the IN2P3 scientific program. While collider physics is the perfect environment to test realizations of BSM particle physics models, many dark matter scenarios can hardly be fully probed there, if e.g. the associated BSM sector is too light or too heavy. On the other hand, any dark matter-related discovery at colliders should have astrophysical counterparts elsewhere. New ideas and new constraints in this field have mostly come from astrophysics and cosmology in the recent years, and associated observations or experiments in these domains are promising avenues to unveil the nature of dark matter in the future, complementary to collider searches. IN2P3 could be a major player there, not only through investment in experimental projects (e.g. CTA, Fermi, LSST, Edelweiss, Xenon, DarkSide, CMB experiments, SDSS, IAXO, etc.), but also in supporting theoretical developments necessary to make progress on these issues. Promoting projects or hirings at the frontier of theoretical astrophysics, cosmology, and particle physics, with a significant weigh on the former domains, is likely to be a successful strategy.

As a final remark, we note that the current organization of the IN2P3 working groups makes it difficult to submit any contribution relevant to the theoretical aspects of dark matter, which basically concerns particle physics but not only at colliders, experimental/observational searches but not only at underground experiments, astrophysics but not only its high-energy (or astroparticle) aspects, cosmology but not necessarily the one relevant to dark energy.