Executive Summary

MITP workshop

Dark Matter in the Milky Way

Organizers:

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Summary of original workshop proposal and goals

The science case around which this workshop was built in the first place was to bring together the three communities involved in the effort of unveiling the distribution of Dark Matter (DM) in the Milky Way (MW), a timely endeavour today in light of the dramatic developments that DM searches have undergone in the last decade.

We are glad that astronomers, simulators and astroparticle physicists have interacted fruitfully during the workshop and have tackled successfully the original science questions that the workshop aimed at addressing:

- How do hydrodynamical simulations contribute to our understanding of the Milky Way? And reversely, how to design future simulations in view of the available astronomical data?
- How to use the astronomical data soon to be available in constraining the DM distribution in the Milky Way?
- What are the consequences of both simulations and astronomical observations for the phenomenology of dark matter searches?

We will go in detail through the Science discussed during the two weeks, after few considerations on the logistics and format of the workshop.

Format

We identify in the following some elements of the format of the workshop as functional to the productive yet amiable atmosphere we have perceived, and that several participants have praised in their feedback.

- Small number of participants. The relatively small size (no more than 25 per week) of the participant's pool has been very useful to avoid fragmentation in subgroups.
- Balanced sessions. The choice of keeping the program of official meetings very light –with no more than two scheduled sessions per day– has been extremely successful to both concentrate the energies and obtain maximal attention and participation during the events (we are very happy that our invitation to leave laptops out of the meeting room has been mostly attended). This feature also permitted to leave enough time for collaborations and exchange of ideas to take place.
- Original interactive sessions. Besides the usual talks (both review and topical), we have introduced few elements (Q&A session, 1-slider highlighter of a "hot" problem, general discussion, and project brainstorming) which have required active energy from all participants. We are glad that all participants have reacted enthusiastically, and these "unusual" sessions have been successful.

Logistics

The location of the institute and the comfortable setting of offices and common spaces are functional to the creation of the right atmosphere. We thank MITP for giving us the chance to organize the workshop in such a perfect setting. We would also like to add special acknowledgements to the MITP staff, who has taken care of all practicalities: the feeling of welcome we have perceived during the entire two weeks has been invaluable for all participants. For the organizers, the absence of any effort related to practical problems has made it possible to fully concentrate on the Science content.

Science

The three communities have interacted virtuously over the two weeks of the workshop, generating discussions and clarifications. Here we group the subjects addressed during the workshop by main topic, but we would like to stress that it has not been uncommon that a discussion on cogent issues related to one community's work has been first prompted by members of another community. The practical projects stemmed from discussions and brainstorming are listed on the webpage together with the rest of material: slides, Q&A summary, 1–sliders, journal club overview.

Simulations of Milky Way Galaxy analogues

The simulation community was the most represented at the workshop, with members of several different groups (i.e. MaGICC, NIHAO, EAGLE, ILLUSTRIS) offering diverse points of view, thus playing a pivotal role in addressing the main questions of the workshop. Firstly, it emerged that the identification of a MW like galaxy in simulations currently does not follow a unique criterion: while most of the groups use the stellar mass or the halo mass to select a MW candidate in simulations, others rely upon its rotation curve as a better estimator. Ideally, with the refinement of feedback implementations and more resolution, one should converge into reproducing several MW observables at once. It has been suggested to develop a compact, unique nomenclature for the different criteria adopted.

- One of the key issues that has been discussed is whether or not simulations can univocally predict the distribution of DM within our Galaxy, being this a quantity of vital importance for both direct and indirect DM searches. Members of all simulations groups agree on the fact that the inclusion of baryonic physics effects is crucial in any simulation which wants to properly capture the DM distribution. Yet, the innermost region ($<$1 kpc) of a MW-like simulated galaxy poses some questions due to the lack of resolution of current simulations below such scale. At scales just above 1 kpc it is clear, instead, that most simulations codes give a similar answer predicting a contracted distribution of DM with respect to the pure DM only case.
- One of the most cogent topics discussed is the impact of feedback mechanisms, such as stellar feedback or Active Galactic Nuclei (AGN) ones, on the MW's DM distribution. It has been shown that while stellar feedback does not have a considerable impact in such a massive spiral like the MW, the feedback from AGN could, in principle, modify the central region of our Galaxy. The impact of AGN feedback on MW-like galaxies is at the moment unclear, as the simulations that include such type of feedback are only a few and currently at a very early stage.

Aside from the DM distribution within our Galaxy, a few other topics directly connected to the satellite population of the MW have been discussed, such as the missing satellite problem, the too-big-to-fail one, the cusp-core discrepancy: the discussions lead to the clear conclusion that the baryonic physics has a strong impact on the solution of the mentioned problems, to the point that the implementation of different "recipes" can give very different conclusions.

While most of the workshop has been devoted at exploring the formation scenario of MW galaxies within the standard Cold Dark Matter (CDM) universe, other possibilities for DM candidates have been brought up. Particularly, the topic of simulations performed within a Warm Dark Matter (WDM) or a Self-Interacting Dark Matter (SIDM) context has been discussed. The effect of baryonic feedback is often degenerate with that of WDM at the scale of interest for MW studies, making the discrimination between the two mechanisms hard, while in the case of SIDM some recent work highlighted how self-interactions could modify the DM profile already at scales of 20 kpc.

As of future perspectives, during the workshop it has been highlighted that the increase in computer power will permit to increase the simulation's resolution, allowing to look not only at the DM distribution within the inner kpc of MW galaxies, but also at detailed physical processes, that have been neglected so far, important for galaxy formation: magnetic fields, thermal conduction, cosmic rays and radiative transfer are a few examples of these processes.

Astrophysics of indirect and direct dark matter searches

Throughout the workshop the genuine interest of simulators and astronomers on the phenomenological aspects of dark matter (theory, indirect and direct searches) triggered many fruitful exchanges toward knowledge often not entirely clear outside the phenomenology community. In that respect, it is worth highlighting two of the most important punchlines of those phenomenological discussions:

- Dark matter is beyond the WIMP paradigm. Feasible candidates include (non-exhaustively) non-thermal particles, primordial black holes, sterile neutrinos, gravitinos or axions, all addressed during the workshop. In particular, warm dark matter was subject of a dedicated session with emphasis on simulations, observations and phenomenology. Also, the possibility of having multiple dark matter components is usually overlooked but it is entirely feasible, just much more difficult to detect and simulate.

- General particle physics frameworks such as supersymmetry are currently not excluded, and will not be even if LHC finds nothing. However, specific models or classes of models within general frameworks are being and will continue to be severely constrained by collider and other searches.

The input of simulations and observations is crucial to direct and indirect searches and thus the expertise shared by the community of simulators and astronomers has been beneficial to the phenomenology community. One of the points most stressed throughout the workshop was that virtually all present hot topics in both indirect and direct dark matter searches need the crucial input of simulations of Milky Way-sized galaxies and/or astronomical observations of our own Galaxy. For indirect searches, two topics were lively debated:

- Galactic center. The gamma-ray emission from the Galactic centre region –detected with the Fermi-LAT instrument– cannot be explained by known astrophysical sources. This excess is significant, very solid against systematics and its morphology and spectrum are well characterised. Our ultimate understanding of the excess relies on the dark matter profile in the very centre of the Galaxy (within hundreds of pc), which is currently unknown. Any input on that regard from either simulations or observations is of paramount importance.

- Dwarf galaxies. These constitute a robust target for indirect searches, where the exact dark matter profile is not critical at the current angular resolution of gamma-ray instruments. Instead, the current limits will be considerably improved with more observed dwarfs and more precise spectroscopy, a feat at the reach of the upcoming generation of astronomical observatories.

For direct searches, the key topics addressed include:

- Velocity distribution. The velocity distribution of dark matter is a crucial input for direct searches that cannot be extracted from current astronomical data (at least not directly). Simulations play here an important role by providing their three-dimensional velocity distribution of dark matter. More than qualitative aspects, for direct searches it is especially important to quantify the differences between different hydrodynamical simulation sets, and the comparison between the dark matter only and the hydrodynamical cases.

- Low-mass WIMPs. The status of claims and limits in the region of the parameter space corresponding to low-mass WIMPs is currently unclear. The potential effect of our lack of knowledge of the local dark matter phase-space distribution is small at these masses. The situation can only be resolved with additional direct detection data.

- Neutrino floor. The coherent scattering of low-energy solar neutrinos off nuclei constitutes an important obstacle for the upcoming generation of direct detection experiments. This is not an ultimate limitation since there is a number of strategies to tackle it (including directionality, modulation, energy spectrum, non-standard scattering interactions), but they all require relatively large amounts of data to put in practice.

Astronomical observations

Astronomical observations were at the centre of the debate during the second week of the workshop. Both simulators and phenomenologists depend greatly on more accurate astronomical data, especially in what refers to our own Galaxy. Fortunately, a batch of new precise data is expected by the end of the decade. The discussion sessions painted a relatively broad overview of this topic and addressed some misconceptions about the extent of usability of some astronomical datasets. We summarise here the most salient points addressed:

- The future of astronomical data is not only Gaia. Upcoming observatories include PanSTARRS, WEAVE, HERMES, 4MOST, MSE, MOONS, WFIRST. Depending on sky footprint, wavelength, magnitude sensitivity, type of data collected and timeline, the most important observatory for a given application might be one of these or a combination thereof. While Gaia will provide a comprehensive collection of six-dimensional information for local stars, it is useful to keep in mind that Gaia alone will not eventually settle all astrophysical uncertainties relevant to the community of simulators and phenomenologists.
- The measurement of the local dark matter density will be tough but possible in near future with an extended collection of kinematics of local stars. The measurement of the local dark matter velocity distribution, instead, is much more difficult given that we cannot see dark matter and thus its velocity distribution can only be constrained indirectly through self-consistent methods. Refinements and generalisations of these methods will be crucial in the coming years to both understand better the structure of our Galaxy and help interpret the results of direct searches.
- The possibility to detect dark matter haloes using stellar stream gaps is exciting and it has potential consequences to disentangle the nature of dark matter (cold vs hot). The capability of current astronomical observatories starts now to be at the level needed to identify such structures accurately. This is certainly a topic to follow closely in the coming years.
- The dark matter profile close to the Galactic centre (inner 2-3 kpc) is currently not possible to measure. This is due to a combination of non-existent or unreliable tracers and the small amount of dark matter compared to baryons. The situation might change with upcoming infrared surveys such as MOONS (2019) and WFIRST (2025-2030?).

On a side note, the role of general relativity on galactic rotation curves was lively discussed during the last week of the workshop. Following recent claims and counter-claims in the literature, it is still unclear whether general relativity actually departs from Newtonian dynamics at galactic scales and, if it really does, whether it is able to reproduce the observed rotation curve using the observed luminous distribution only (i.e., without dark matter).