Snowmass2021 - Letter of Interest

A simulation program to discover dark matter physics in the sky

Thematic Areas: (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
■ (Other) *[Please specify frontier/topical group]*
(CompF2) Theoretical Calculations and Simulation
(TF09) Astro-particle physics & cosmology

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Abstract: Since the last Snowmass process, the landscape of plausible and serious particle dark matter models has expanded dramatically. Just as the models lead to predictions for observational signatures of dark matter in the laboratory, so too may they lead to observable signatures in the cosmos. To date, the only non-null measurements of dark matter and its particle properties come from detailed study of its distribution in space and time. Powerful new telescope facilities are coming online within the next decade, which can lead to ever-sharper measurements of dark matter properties – but only if paired with a well-matched theoretical and simulation program. Here, we lay out the requirements for a simulation program to fully realize the potential of this decade's cosmic observatories.

In the past three decades, cosmologists revealed that matter composed of Standard Model particles is but lightly sprinkled across the universe, atop the structures shaped by the yet-unidentified dark energy and dark matter. To date, all positive statements about the nature of either comes from the interpretation of data from telescopes, despite a massive effort to detect dark matter in the laboratory. Because of cosmological observations of the expansion of the universe and the clustering of matter in time, we know that dark matter cannot carry (much) electromagnetic charge, must be non-relativistic at its time of decoupling in the early universe, and must be stable on cosmic timescales. And still, there is so much more we want to know about dark matter – its couplings to the Standard Model as well as to other particles in a possible hidden sector, its particle properties, and the fundamental theory that describes it. This decade, in addition to the expanding portfolio of laboratory experiments to probe a growing space of dark matter models, there will switch on a number of powerful telescopes, like the Vera C. Rubin Observatory[1], that can probe the clustering of dark matter to high statistical significance across an unprecedented range of scales. Realistic and precise simulations of the clustering of dark matter across cosmic time – including the physics of galaxies – are the essential keys to translating these highly precise measurements of cosmic dark matter to constraints on dark matter microphysical parameters. Here, we describe the requirements for a simulation program to reveal dark matter physics with next-generation observational facilities.

Need #1: Collaboration between cosmological simulators and particle theorists. The space of possible dark matter models is so vast that it is nearly impossible to directly simulate even a modest fraction of the allowed parameter space. Collaboration between simulators and particle theorists is needed in order to prioritize models and to develop classification schemes that divide dark matter models into broad classes according to their structure formation properties, enabling a single simulation to represent models that might have very different particle origins. This is powerful as it allows simulators to cover a broad range of dark matter parameter space with a computationally realistic number of simulations. An example of such an approach is the ETHOS effective theory, enabling a unified simulation approach to warm (WDM) and self-interacting (SIDM) dark matter models[2]. It is of great interest to incorporate other dark matter models, such as the class of fuzzy dark matter (FDM)[3], with and without self-interactions[4–6], in this framework.

Need #2: Algorithm development and code comparison tests. The community recognizes the need to develop and validate algorithms for dark matter physics beyond the collisionless cold dark matter (CDM). In the galaxy evolution community, the many codes with various implementations of the hydrodynamics governing star formation are regularly tested against each other[7]. New algorithms for the gas physics and for the analysis of simulation data are in continual development in order to solve specific problems identified in previous code comparison tests, and to incorporate more physics (e.g., gas cooling)[8;9]. We need a similar approach for dark matter physics. First, we need to run performance and validation tests of existing algorithms for, and code implementations of, WDM[10;11] and SIDM[12–15]. Second, we need new algorithms for FDM and QCD axions, especially to probe the existence and survivability of tiny microhaloes in these models[4;16–18]. The latter has significant consequences for the detectability of QCD axions and axion-like particles in terrestrial direct detection experiments. Again, close collaboration between simulators and particle theorists is necessary to ensure that the microphysical properties of dark matter are properly implemented in the fundamentally macroscopic approach to solving the collisional Boltzmann equation in simulations, and that the simulations target the most interesting parts of dark matter parameter space[19;20].

Need #3: Simulations with full hydrodynamics for observational targets. The distribution of cosmic dark matter is traced and shaped by galaxies. Thus, accurate predictions for the growth and properties of dark matter halos depend on accurate modeling of galaxy physics. The properties of galaxies and halos depend strongly on the adopted modeling for baryonic processes in simulations such as star formation and feedback. However, different implementations of galaxy evolution physics can lead to different predictions for galaxies even within the CDM framework[21–24], and arguably none so far exactly match observed properties of galaxy populations (although the matching is rapidly improving)[25]. Thus a critical study of implementations of feedback processes is required, and an emphasis on finding the most promising ways to disentangle possible modifications to dark matter halos induced by the baryons versus effects driven by non-CDM models for dark matter. Moreover, these studies should focus on the types of cosmic systems that are the most promising targets for observations in the coming decade. In other words, we should go beyond the Milky Way (although simulations of the Milky Way, including its stellar halo, are still essential) and simulate isolated dwarf galaxies, strong lens systems, the first generation of stars and galaxies, and satellite systems of a variety of different hosts, for example.

Need #4: Comparison of observations and simulations should be carried out in the space of observables. Simulation results have to be translated into image/spectral data to be directly compared with telescope data. The interplay between simulations and observations has reached a high level of maturity due to the increased resolution of simulations, and the wealth of observational data. Using simulations, we can, for example, correlate the phase space distribution of stars with that of dark matter, and then use observations of kinematics of stars (for example Gaia) to build a first map of the dark matter in the Milky Way[26;27]. This is crucial in obtaining robust direct detection results. More broadly, translating simulation data into observable space can lead to dramatic reassessments as to whether the data indicate problems with CDM or not, which is particularly notable in the case of the rotation curves or velocity dispersion profiles of dwarf galaxies[28;29].

Need #5: Fast realization of observed systems for dark matter parameter constraints. Quantifying statistical observables (e.g., distributions of halos as a function of mass, density, and spatial location) within different dark matter models requires large numbers of high-resolution simulations. To set parameter constraints on dark matter models from observed systems, comparisons with observations (e.g., strong gravitational lenses) also often require $\sim 10^5$ or more model realizations of a given system *for each dark matter model*[30]. Such numbers are not achievable via direct simulation at the resolutions needed. Rapid computation of statistical observables that enable likelihood evaluations on the space of dark matter parameters requires the development of fast semi-analytic and emulator approaches which can be applied across the dark matter macro model parameter space. These tools must be calibrated with simulations. The challenge is to simulate enough systems, for enough dark matter models, that interpolation among simulations is well-defined and accurate.

Need #6: Provide guidance to observers about promising new signatures of dark matter physics. Simulations have long played a role in identifying new possible signatures of novel dark matter physics in astronomical systems[15;18;31–34], or in refining interesting features in standard direct and indirect particle dark matter searches[27;35]. This is truly an area where cross-discipline collaboration plays an important role in making progress. New ideas and methods from the collider community, thanks to the inflow of particle physicists into astronomy, are being tested on simulations as well as in real astronomical data[26;36]. Simulators are highlighting new areas of dark matter parameter space that can be tested observationally, and observers give guidance as to what is possible to measure with telescopes. This cross-disciplinary work to use simulations to find new probes of dark matter physics should be strengthened going forward.

The time is now. As laboratory experiments for an ever-wider set of dark matter candidates proliferate, and as unprecedentedly powerful telescopes come online, we must have cosmological structure simulations, with full galaxy-formation physics, to connect the two. Cosmological simulations, testing a wide variety of non-CDM candidates, are essential to fully utilizing astronomical data to measure the microphysical properties of dark matter, and connect them to searches in the lab. While the astronomical community has long supported cosmological simulation work in the context of CDM, there is much work to be done to simulate non-CDM models. The particle physics community can play an important role in supporting simulation work for non-CDM candidates. Astronomical observations have a high discovery potential for the identity of dark matter – but only if we understand what the data are telling us.

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