# Snowmass2021 - Letter of Interest

# *Cosmic Probes of Dark Matter Interactions: Challenges for Theory and Analysis*

**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
■ (TF09) Theory frontier/Astro-particle physics and Cosmology
■ (TF08) Theory Frontier/BSM Model Building

**Contact Information:**
Vera Gluscevic (University of Southern California) vera.gluscevic@usc.edu
Kimberly K. Boddy (University of Texas at Austin) kboddy@physics.utexas.edu

**Authors:** (names and institutions)

Vera Gluscevic (University of Southern California), Kimberly Boddy (UT Austin), Yacine Ali-Haïmoud (New York University), Keith Bechtol (University of Wisconsin-Madison), Simon Birrer (Stanford University), Torsten Bringmann (University of Oslo), Jens Chluba (University of Manchester), Djuna Croon (TRIUMF), Francis-Yan Cyr-Racine (University of New Mexico), Caterina Doglioni (Lund University), Cora Dvorkin (Harvard University), Nicolas Fernandez (University of Illinois at Urbana-Champaign), Daniel Grin (Haverford College), Benjamin V. Lehmann (UC Santa Cruz), Julien Lesgourgues (RWTH Aachen University), Ethan Nadler (Stanford University), Julian B Munoz (Harvard-Smithsonian), Ashley Perko (University of Utah), Annika Peter (The Ohio State University), Vivian Poulin (LUPM, CNRS U. de Montpellier), Katelin Schutz (Massachusetts Institute of Technology), Sarah Shandera (Pennsylvania State University), Tracy Slatyer (Massachusetts Institute of Technology), Yu-Dai Tsai (Fermilab), Benjamin Wallisch (IAS & UC San Diego), Zihui Wang (New York University), Samuel D. McDermott (Fermilab)

**Abstract:** Cosmological and astrophysical observations uniquely capture signatures of many compelling theoretical scenarios for new dark matter physics, often surpassing or complementing the reach of terrestrial and other experiments. We focus on signals from dark matter interactions with baryons, neutrinos, and dark radiation, and their effects on the cosmic microwave background, large-scale structure, Lyman-$\alpha$ forest, the cosmological 21-cm signal, dwarf galaxy abundances, and probes of structure at extremely small physical scales. We identify key theoretical advancements that will play a pivotal role in realizing the potential of cosmological and astrophysical searches for the evidence of dark matter interactions, using data from surveys such as the Nancy Grace Roman Space Telescope, Vera C. Rubin Observatory, Simons Observatory and CMB-S4, James Web Space Telescope, and other next-generation facilities.

Observations of the Universe testify to the existence of dark matter (DM) that sources gravitational potentials and underpins structure on a variety of observable physical scales, but whose fundamental nature remains unknown. The existence of DM implies new physics whose investigation centrally drives research at the intersection of astrophysics, cosmology, and particle physics. Here we focus on observational probes of DM interactions with known particles (baryons, photons, and neutrinos), interactions within the DM sector itself, and DM annihilations and decays.

**Interactions with baryons.** For example, elastic scattering between DM and visible particles is commonplace in some of the best-motivated DM models, including weakly interacting massive particles (WIMPs), WIMP-like particles, and DM that strongly couples to baryons. These scattering processes can occur in a cosmological setting and lead to an exchange of heat and momentum between DM and baryons in pre-recombination Universe, or during Dark Ages and Cosmic Dawn, affecting both the thermal history and the distribution of matter throughout cosmic history. In particular, DM-baryon scattering tends to erase structure below a certain critical scale, set by the interaction cross section. Observations of the cosmic microwave background (CMB), Lyman-$\alpha$ forest, as well as the abundance of the Milky Way satellite galaxies have all been used to constrain these scenarios[1–15]. Observational probes typically access nuclear-scale cross sections for scattering with protons, and effectively probe sub-GeV DM masses, complementing the reach of current direct detection experiments[16].

**Interactions with neutrinos.** An intriguing possibility is that DM may communicate with visible matter through interactions with neutrinos—the least well understood part of the Standard Model of particles. If neutrinos efficiently scatter with DM seconds after the Big Bang, the DM-neutrino fluid undergoes acoustic oscillations and diffusion damping. As a result, CMB anisotropy power spectra and the matter power spectrum are suppressed, and acoustic peaks shifted towards smaller angular scale; all of these effects have been used to put observational bounds on DM-neutrino scattering[17–21].

**Interactions with dark radiation.** Models in which the dark sector is complex and contains not only DM, but also a thermal bath of dark radiation (DR) that interacts with DM, are motivated in several ways[22]. They also represent a specific case of self-interacting DM (SIDM) models, proposed as a possible solution for putative anomalies in DM structure on sub-galactic scales[23–29]. Similar to how photon pressure prohibits the growth of baryon fluctuations until recombination, DM interacting with DR in the early Universe experiences suppressed growth of structure, as compared to a scenario with no DR. The resulting suppression of power is captured by all tracers of large-scale and small-scale structure, with some of the best current bounds coming from the CMB anisotropy[30–32].

**Observations.** All DM interaction scenarios discussed above suppress matter density fluctuations, affecting all visible tracers of structure, with the most prominent effects occuring on small scales. The next-generation surveys such as the Nancy Grace Roman Space Telescope, Vera C. Rubin Observatory, Simons Observatory and CMB-S4, James Web Space Telescope, and others, will unveil the details of matter distribution throughout cosmic history, with a broad range of observables: CMB temperature, polarization, and lensing anisotropy, galaxy clustering and weak lensing, Sunyaev-Zeldovich effect and galaxy-cluster number counts, abundance of the Milky Way satellite galaxies and other luminous tracers of low-mass halos, strong gravitational lensing, and cosmological 21-cm signal. By capturing structure on progressively smaller scales, where the effects of DM interactions are most prominent, the upcoming surveys will enable a tremendous leap in sensitivity to DM microphysics—in some cases, by many orders of magnitude in terms of DM mass and interaction cross sections.

**Immediate Challenges for Theory and Analysis.**

Robust observational tests of DM will rely on our ability to model relevant signals and disentangle them from uncertainties on other unknown parameters and systematic effects, and perform consistency checks between data sets[33;34]. To enable successful observational searches for evidence of DM interaction physics, it is critical that the following theory and analysis challenges are addressed in the coming years:

**Challenge 1: Modeling the effects of DM interactions on semi-nonlinear and nonlinear scales.**

The most promising observables in the context of DM interactions are those that trace the matter power spectrum on small, semi-nonlinear and nonlinear scales, most affected by DM particle physics. The challenge here is that nonlinear scales are difficult to accurately model, even without inclusion of complicated galaxy-formation physics, and often require computationally expensive forward modeling through structure formation simulations, sometimes supplemented by various machine learning methods and semi-analytic modeling to capture the galaxy-halo connection. To date, efforts to forward model small scales have mainly focused on collisionless cold or warm DM scenarios, or classes of SIDM models. To probe DM interactions more broadly, modeling of nonlinear scales must be done self-consistently in the context of appropriate DM cosmology and include the effects of the interaction physics (both the appropriate initial conditions and late-time effects). For some observables, it is possible to begin these exercises without the need to model galaxy formation physics, and only focus on DM, but for others, inclusion of baryonic physics is also needed; both approaches (modeling of DM and joint modeling of DM+galaxies) are thus recommended.

**Challenge 2: Disentangling DM from baryons.**

Galaxies trace structure, while their baryons also influence properties of their DM halos, through feedback processes, star formation, etc. To recognize evidence of DM interaction physics and confidently separate it from baryonic physics, it is important to model this interconnection reliably, through dedicated hydrodynamical simulations and semi-analytic models, adapted to the context of interacting-DM cosmologies. It is also important that astrophysical modeling is guided by particle physics theory, to ensure that the most interesting parts of the DM particle parameter space are addressed.

**Challenge 3: Analysis frameworks for all observables.**

Many observables ultimately probe the same underlying physics, and the process of ruling out cold collisionless DM and establishing a discovery of new DM physics will critically rely on joint analyses and cross comparisons of all relevant observations. Frameworks for such analyses are still scarce and incomplete; while individual collaborations focus on constructing very specific analysis pipelines, separate efforts to combine distinct observables in a self-consistent manner are likewise valuable. Combining distinct observational probes ensures maximal return of information about DM physics, but it also helps to mitigate systematics and sources of bias that plague individual analyses. Importantly, to enable such efforts and to learn about the physics of DM from observations through (likelihood-based and likelihood-free) statistical inferences, we need tools for *fast* and self-consistent predictions of all relevant observables, beyond what can be accomplished with computationally-expensive simulation efforts. Emulators and analytic modeling trained on simulations are the preferred approach to this problem.

**Challenge 4: Forecasting and comparing sensitivity of individual probes.**

There is a growing need for frameworks to forecast the sensitivity of individual probes to DM interaction physics. Detailed forecasts related to individual observations can help to identify the most promising observations and also determine which aspects of modeling uncertainties present a bottleneck to uncovering DM physics.

The next decade of observations will open avenues to broadly probe DM interactions in the context of compelling theoretical scenarios, complementing terrestrial experiments. Many individual probes will reach sufficient raw sensitivity to potentially uncover DM signals that are invisible to the present-day searches. Their robustness demands the development of theoretical, simulation, and analysis tools for self-consistent modeling of DM signals across different surveys, as well as joint analyses of all available data.

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