CF1: Particle-Like Dark Matter

Conveners: Jodi Cooley, Hugh Lippincott, Tracy Slatyer, Tien-Tien Yu*

March 31, 2022

*Replaced Tongyan Lin after restart

“Big Questions” white papers

~150 LOIs submitted to CF1 (including cross lists) - huge amount of community interest and ideas, the most of any topical group!

In the months before the pause, we realized we needed to corral the science in the many LOIs. Based on the LOIs and the discussion at CPM, we identified a few broad science themes split into 8 “Big Question” white papers.

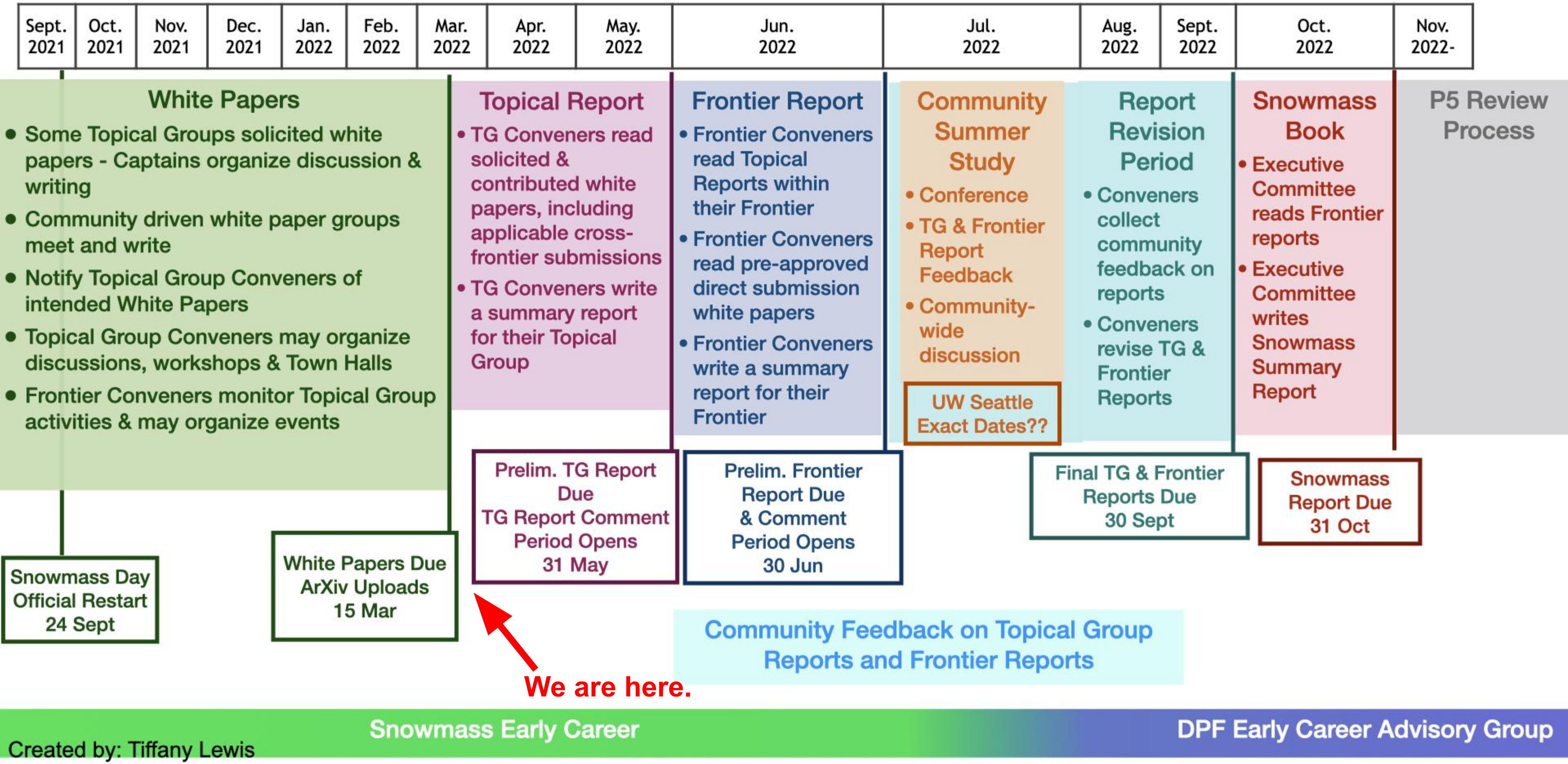
The CF1 summary white paper will be prepared by conveners based **primarily** on these “Big Questions” white papers as well as the 20 additional white papers that were submitted to CF1/CF.

“Big Questions” white papers

Title	Editors	Arxiv
Dark Matter Direct Detection to the Neutrino Fog	P. Cushman, B. Loer, R. Gaitskell, C. Galbiati	2203.08084
The landscape of low-threshold dark matter direct detection in the next decade	R. Essig, G. Giovanetti, N. Kurinsky, D. McKinsey	2203.08297
Calibrations and backgrounds for dark matter direct detection	D. Baxter, R. Bunker, S. Shaw, S. Westerdale	2203.07623
Modeling, statistics, simulations, and computing needs for direct dark matter detection	Y. Kahn, M.E. Monzani, K. Palladino	2203.07700
The landscape of cosmic-ray and high-energy-photon probes of particle dark matter	T. Aramaki, S. Profumo, P. von Doetinchem	2203.06894
Puzzling Excesses in Dark Matter Searches and How to Resolve Them	L. Yang, R. Leane, S. Shin	2203.06859
Synergies between dark matter searches and multiwavelength/multimessenger astrophysics	P. Harding, S. Horiuchi, D. Walker	2203.06781
Ultraheavy particle dark matter	D. Carney, N. Raj	2203.06508

Useful link to all Snowmass White Paper database compiled by Kristi Engel and Tiffany Lewis

Post-Break Snowmass Timeline



Community Feedback and Buy-in

- Thank you to everyone who has contributed so far - the papers already look great! But…
- The window between now and end of May is critical for us to make sure the white papers posted to the arXiv do represent the views of our community
- To the community: Please engage and provide feedback
- To the editors: Reach out to your community repeatedly (e.g. Slack, google forms, email)
- Endorse or add your name to author lists as appropriate (additional guidance from Frontier Conveners?)
- Still time between now and June/July to update things, but less and less likely to have new input included in the final reports as time ticks away
- Don’t hesitate to reach out to us or any of the editors

CF1 WP1

Snowmass2021 Cosmic Frontier Dark Matter Direct Detection to the Neutrino Fog - edited by P. Cushman, B. Loer, R. Gaitskell, C. Galbiati

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Snowmass2021 Cosmic Frontier Dark Matter Direct Detection to the Neutrino Fog - edited by P. Cushman, B. Loer, R. Gaitskell, C. Galbiati

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Executive Summary

- There are multiple well-motivated dark matter candidates remaining in the "traditional" ~GeV-scale mass range. The currently-funded suite of searches in this mass range ("Generation 2" experiments) will not have sensitivity to fully test the majority of these candidates.
- A "Generation 3" suite of experiments with an order of magnitude larger exposure would be able to fully test some candidates. Such a suite should include searches for spin-dependent interactions, which can uniquely test some models not probed by spin-0 targets.
- Despite the maturity of the field, novel technologies should not be neglected. Current R&D on new techniques will improve established detector performance and provide new methods to mitigate backgrounds and probe complementary parameter space near the neutrino fog.
- Substantial well-motivated parameter space will yet remain if dark matter signals are not observed by the G3 experiments. Irreducible neutrino backgrounds will cause substantially diminished returns on further increases in exposure. However, if the uncertainties in the neutrino fluxes are reduced, further increases may become feasible. Moreover, light, spin-dependent targets such as fluorine have substantially lower neutrino backgrounds and can therefore scale to larger masses even with current neutrino flux uncertainties.
- Directional detectors are one possible way to reject neutrino backgrounds and thereby reach beyond the neutrino-limited point of current technology. Such detectors will require substantial R&D investment to reach the size and level of background control required to explore this parameter space. Gas TPCs with micropattern gaseous detector (MPGD) readout should be advanced to the 10 m^3 scale.

CF1 WP2

Snowmass2021 Cosmic Frontier: The landscape of low-threshold dark matter direct detection in the next decade - edited by R. Essig, G. Giovanetti, N. Kurinsky, D. McKinsey

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The landscape of low-threshold dark matter direct detection in the next decade

Executive Summary

We live in a galaxy filled with dark matter particles left over from the Big Bang. These particles surround us and continuously stream through us, our laboratories, and the Earth. Yet dark matter particles have never been detected with terrestrial experiments.

Advanced technologies employed in detectors with extremely low energy thresholds may be used to search for rare interactions of the dark matter with ordinary matter. These detectors are surrounded by low-background shielding and placed in underground laboratories to avoid backgrounds from cosmic rays. Historically, such "direct detection" experiments have primarily focused on detecting particles with mass of order $1 - 1000$ GeV/c^2, but a deeper understanding of dark matter theory suggests that dark matter may be part of a dark sector and have a mass below the proton. Direct detection experiments play an essential role in determining the particle nature of such dark matter. Moreover, for many of these theoretical models, such as when dark matter couples to ordinary matter through a light or massless mediator, direct detection provides the *only* opportunity for its detection.

This white paper focuses on new experimental approaches to probe lower mass dark matter ranging from the proton mass to twelve orders of magnitude lighter (i.e. meV/c^2 to GeV/c^2 dark matter particle masses).

The total energy density of dark matter is known. Therefore, as the hypothetical mass of the dark matter particle decreases, the flux of dark matter particles increases in proportion. In addition, the constraints on light dark matter cross-sections with ordinary matter are currently very weak. As a result, current constraints imply that light dark matter candidates could be discovered with very small detector target exposures (as small as 1 gram-day), given sufficiently low energy thresholds and background rates.

Because dark-sector dark matter theories exist in which the dark matter interacts 1) only with nuclei, 2) only with electrons, or 3) only with coherent modes in a target material, experiments are needed to probe each of these interactions. In each case, new parameter space may be probed with cutting-edge experiments that provide lower energy thresholds and/or lower backgrounds than currently are available. At the same time, longer-term research and development (R&D) efforts to lower energy thresholds and lower background rates would allow an even wider range of masses and interaction strengths to be probed.

The search for low-mass dark matter has progressed enormously in the past few years, with significant theoretical and experimental advances. By funding R&D towards improved detector technologies, improved signal and background calibrations and characterizations, and improved theoretical understanding of dark matter interactions in various materials, we can build on these exciting recent developments. These improvements can then be folded into the design of several experiments that are small, relatively inexpensive, and naturally suited to a suite of small projects allowing particle physicists to probe vast regions of well-motivated but unexplored dark matter parameter space in the next decade.

CF1 WP3

[Snowmass2021 Cosmic Frontier White Paper: Calibrations and backgrounds for dark matter direct detection](#) - **edited by D Baxter, R. Bunker, S. Shaw, S. Westerdale**

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Comments requested by April 4

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1.1 Executive Summary

Among the needs discussed below, a few themes arise: a need for more nuclear and atomic data, support for and further development of simulation and modeling codes, and investment in underground infrastructure and advanced detector technologies. These needs become progressively pressing as future direct detection experiments achieve ever-greater sensitivity and search over longer exposures, requiring more precise tools for modeling and mitigating backgrounds and for reconstructing low-energy events.

- Calibration measurements are needed of detector responses to electronic and nuclear recoils, for a wider range of targets and at lower energies (eV–keV scale and in the "UV-gap" of solid-state detectors), including measurements of inelastic and atomic effects (*e.g.* the Migdal effect) and coherent excitations, both using established techniques and with new ones (see Secs. 2.1–2.2).
- Optical and atomic material-property measurements are needed, including atomic de-excitation cascades, electronic energy levels, and energy-loss functions, both for modeling detector response and for simulating transport of low-energy particles. Similarly, improved models and simulations of detectable-quanta production and propagation are needed (see Secs. 2.3, 3.1, 4.1.1, 4.1.3, 4.2).
- Measurements to decrease neutrino uncertainties are needed, including nuclear-reaction and direct-neutrino measurements that improve simulation-driven flux models (see Secs. 3.1 and 4.1.2).
- Elastic and inelastic nuclear reaction measurements—(α,n), (n,γ), (n,n), (ν,x), *etc.*—are needed to improve particle transport codes, background simulations, and material activation calculations, and to validate and improve models/evaluations used in these codes; exclusive cross-section measurements are particularly needed to model correlated ejectiles, and codes should provide a full treatment of uncertainties (see Secs. 2.1, 2.2, 3.1, 3.2, 3.3, 4.1.1, 4.1.2).
- Increased support for development of simulations (*e.g.* `FLUKA`, `Geant4`, `MCNP`, `NEST`, `G4CMP`) is needed, both for software codes and models (see Secs. 4.1–4.2).

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[Snowmass2021 Cosmic Frontier White Paper: Calibrations and backgrounds for dark matter direct detection](#) - edited by D Baxter, R. Bunker, S. Shaw, S. Westerdale

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Comments requested by April 4

- Increased collaboration with nuclear, atomic, and cosmic-ray physics communities is recommended to improve detector response and background models (see Secs. 2.2, 3.2, 3.3, 3.5.1, 4.1.2).
- *In situ* measurements of backgrounds are valuable for validating and improving models in various codes, especially for neutrons and muons and material activation measurements, both on surface and underground. Likewise, uncertainties on model predictions for these backgrounds need to be quantified by model codes, informed by this validation (see Secs. 3.2, 3.3, 3.5.1, 3.5.3, 4.1.2)
- Improved material cleaning and screening procedures are needed for dust, radon progeny, cosmogenically activated radioisotopes, and other bulk radioisotopes. New procedures are needed to avoid such contamination, and improved *ex situ* models of residual background levels are needed (see Secs. 3.4, 3.5.2, 3.5.3)
- Additional R&D is needed to characterize and mitigate near-threshold backgrounds, such as from secondary emission processes (see Secs. 3.6.1–3.6.3).
- Same-location, multi-method radioassay facilities are needed to simplify measurements of decay chains and reduce systematic errors, alongside greater precision across techniques and increased assay throughput/sensitivity (see Sec. 5.1). Also, development of software infrastructure to track large-scale assay programs across the community is needed (see Sec. 5.5).
- Finally, investment in underground infrastructure and detector technology (e.g., vetoes) will be needed to mitigate backgrounds such as from radon, dust, cosmogenic activation, and neutrons (see Secs. 3.3, 3.5.1, 5.3, 5.4).

CF1 WP4

Snowmass2021 Cosmic Frontier: Modeling, statistics, simulations, and computing needs for direct dark matter detection - edited by M.E. Monzani, K. Palladino, Y. Kahn

Collecting feedback via email

1 Modeling

- Framework for updating choices of ρ_χ and $f_\chi(\mathbf{v})$ which incorporate the best current astrophysical knowledge, rather than just a standard benchmark which may be based on outdated parameters (WIMP DM and sub-GeV DM)
- Data-driven detector response functions including many-body effects (sub-GeV DM)
- Many-body response functions for DM-SM interactions beyond the spin-independent benchmark (sub-GeV DM)
- Compendium of material properties for optimal DM detectors which could facilitate selection of future detector material (sub-GeV DM)

2 Statistics and Analysis

This was one of the main topics that was addressed at the 2019 PHYSTAT-DM workshop. Participants from DAMIC, DarkSide, DARWIN, DEAP, LZ, NEWS-G, PandaX, PICO, SBC, SENSEI, SuperCDMS, and XENON collaborations achieved a consensus on a number of important topics, mostly centered around the PLR method but not exclusively. The results of this work were summarized in Ref. [13]. We endorse the common standards presented in that reference, which, if they are widely adopted in the direct detection community, will facilitate the comparison of statistical claims amongst different collaborations. In

3 Simulations

- The continuation of Geant4 [78] support and training within the community.
- Continued support for event generators, including those developed as part of a national security program.
- Detector-specific simulation packages, such as: NEST [79,80], which simulates noble elements detector response, and Opticks [81], which tracks optical photons.
- Opportunities for cross-collaboration communication, in order to reduce duplication of effort and maximize return on investment.

For low-threshold (sub-keV) experiments in particular, a further essential need is:

- Consistent incorporation into existing codes of solid-state effects such as directionally-dependent displacement energy, modifications to the Lindhard ionization yield model, and realistic atomic binding energies.

CF1 WP4

Snowmass2021 Cosmic Frontier: Modeling, statistics, simulations, and computing needs for direct dark matter detection - edited by M.E. Monzani, K. Palladino, Y. Kahn

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4 Computing

Current dark matter experiments are approaching data volumes of order 1 PB/year [103]. This is not an unusual scale for HEP, however it presents a significant challenge in the direct detection community, which until recently hasn't prioritized the development of a scalable computing infrastructure in support of its scientific ambition. Moreover, a fragmentation of funding sources and a climate of competition between experiments, have hindered the opportunities for cooperation and tool sharing in the computing and software domain, leading to unnecessary duplication of efforts across the field. Key strategic goals to ensure success for the experiments of the next decade include:

- Lower the barrier of entry to national supercomputing facilities, by providing common tools and shared engineering. Solicit community input on architecture evolution, while providing access to specialized resources, such as GPU and TPU clusters.
- Support scalable software infrastructure tools across HEP, avoiding duplication of effort. These tools run the gamut of data management and archiving, event processing, reconstruction and analysis, software management, validation and distribution.
- Enhance industry collaborations on machine learning techniques and provide access to external experts. Foster community-wide efforts to understand uncertainties and
- Expand training and career opportunities for computing-inclined physicists, both within academia and in cooperation with industry. Ensure that academic and national laboratory positions are viable career options for a diverse group of people.

CF1 WP5

Snowmass2021 Cosmic Frontier: The landscape of cosmic-ray and high-energy photon probes of particle dark matter - edited by T. Aramaki, S. Profumo, P. von Doetinchem

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Snowmass2021 Cosmic Frontier: The landscape of cosmic-ray and high-energy photon probes of particle dark matter

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Snowmass2021 Cosmic Frontier: The landscape of cosmic-ray and high-energy photon probes of particle dark matter

Executive Summary

This white paper discusses the current landscape and prospects for experiments sensitive to particle dark matter processes producing photons and cosmic rays. Much of the γ-ray sky remains unexplored on a level of sensitivity that would enable the discovery of a dark matter signal. Currently operating GeV–TeV observatories, such as Fermi-LAT, atmospheric Cherenkov telescopes, and water Cherenkov detector arrays continue to target several promising dark matter-rich environments within and beyond the Galaxy. Soon, several new experiments will continue to explore, with increased sensitivity, especially extended targets in the sky. This paper reviews the several near-term and longer-term plans for γ-ray observatories, from MeV energies up to hundreds of TeV. Similarly, the X-ray sky has been and continues to be monitored by decade-old observatories. Upcoming telescopes will further bolster searches and allow new discovery space for lines from, e.g., sterile neutrinos and axion-photon conversion.

Furthermore, this overview discusses currently operating cosmic-ray probes and the landscape of future experiments that will clarify existing persistent anomalies in cosmic radiation and spearhead possible new discoveries.

Finally, the article closes with a discussion of necessary cross section measurements that need to be conducted at colliders to reduce substantial uncertainties in interpreting photon and cosmic-ray measurements in space.

CF1 WP6

Snowmass2021 Cosmic Frontier White Paper: Puzzling Excesses in Dark Matter Searches and How to Resolve Them - edited by R. Leane, S. Shin, L. Yang

Collecting feedback via email

Puzzling Excesses in Dark Matter Searches and How to Resolve Them

1 Introduction

A number of indirect and direct dark matter experiments have observed excess signals above background over the years. They have provided tantalizing hints but no definitive proof of a dark matter discovery. Understanding the origin of these puzzling excesses is an important task for the community in the coming decade, as it will provide insights and guidance on the future direction of the field. In this solicited white paper, we summarize the status of the observed signal excesses from astrophysical observations and direct detection experiments, and discuss the efforts and prospects in resolving the puzzles.

2. Astrophysical Signals
    - 2.1. Galactic Center Gamma Ray Excess
    - 2.2. AMS Antiproton excess
    - 2.3. AMS Positron Excess
    - 2.4. 511 keV line
    - 2.5. 3.5 keV line
3. Direct Detection Signals
    - 3.1. Annual Modulation in NaI
    - 3.2. XENON1T Electronic recoil excess
    - 3.3. Solid state detectors

CF1 WP7

Snowmass2021 Cosmic Frontier: Synergies between dark matter searches and multiwavelength/multimessenger astrophysics - edited by P. Harding, S. Horiuchi, D. Walker

Collecting feedback via email

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CF1 WP7

Snowmass2021 Cosmic Frontier: Synergies between dark matter searches and multiwavelength/multimessenger astrophysics - edited by P. Harding, S. Horiuchi, D. Walker

Collecting feedback via email

Snowmass2021 Cosmic Frontier: Synergies between DM searches and multiwavelength/multimessenger astrophysics

Executive Summary

This whitepaper focuses on the astrophysical systematics which are encountered in dark matter searches. Oftentimes in indirect and also in direct dark matter searches, astrophysical systematics are a major limiting factor to sensitivity to dark matter. Just as there are many forms of dark matter searches, there are many forms of backgrounds. We attempt to cover the major systematics arising in dark matter searches using photons—radio and gamma rays—to cosmic rays, neutrinos and gravitational waves. Examples include astrophysical sources of cosmic messengers and their interactions which can mimic dark matter signatures. In turn, these depend on commensurate studies in understanding the cosmic environment—gas distributions, magnetic field configurations—as well as relevant nuclear astrophysics. We also cover the astrophysics governing celestial bodies and galaxies used to probe dark matter, from black holes to dwarf galaxies. Finally, we cover astrophysical backgrounds related to probing the dark matter distribution and kinematics, which impact a wide range of dark matter studies. In the future, the rise of multi-messenger astronomy, and novel analysis methods to exploit it for dark matter, will offer various strategic ways to continue to enhance our understanding of astrophysical backgrounds to deliver improved sensitivity to dark matter.

CF1 WP8

[Snowmass2021 Cosmic Frontier White Paper: Ultraheavy particle dark matter] - edited by D. Carney, N. Raj

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CF1 WP8

Snowmass2021 Cosmic Frontier White Paper: Ultraheavy particle dark matter - edited by D. Carney, N. Raj

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V. SUMMARY

Ultraheavy dark matter presents an exciting and relatively unexplored regime of possible dark matter candidates. A rich variety of production mechanisms and DM models are viable in this

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parameter space. Existing direct and indirect detection programs already exhibit significant sensitivity to a number of potential candidates. In the future, we encourage these experiments to display the constraints on the entire range of DM mass sensitivity up to the ultraheavy scales considered here. We have presented a few example searches in order to encourage other experimental collaborations to consider analyses of these heavy DM candidates. Moreover, a number of technologies in current development are quickly coming online and will continue to explore swathes of open parameter space. We look forward to continuing rapid developments in this exciting frontier in the search for dark matter.

Additional White Papers submitted to CF1

A. Aboubrahim, W.-Z. Feng, P. Nath, Z.-Y. Wang, “Hidden sectors and a multi-temperature universe”

M. Zaazoua, L. Truong, K. A. Assamagan, F. Fassi, “Higgs portal vector dark matter interpretation: review of Effective Field Theory approach and ultraviolet complete models”

Thomas G. Rizzo, “Portal Matter and Dark Sector Phenomenology at Colliders”

Krystal Alfonso, Gabriela R. Araujo, Laura Baudis, Nathaniel Bowden, et al. ”Passive low energy nuclear recoil detection with color centers – PALEOCCENE”

G. Wang, C. L. Chang, M. Lisovenko, V. Novosad, V. G. Yefremenko, J. Zhang. ”Light Dark Matter Detection with Hydrogen-rich Crystals and Low-Tc TES Detectors“

Additional White Papers submitted to CF1

J. Aalbers, K. Abe, V. Aerne), F. Agostini, S. Ahmed Maouloud, D.S. Akerib, et al. ”A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics”

Reza Ebadi, Mason C. Marshall, David F. Phillips, Tao Zhou, Michael Titze, et al. ”Directional Detection of Dark Matter Using Solid-State Quantum Sensing“

C. A. J. O'Hare, D. Loomba, K. Altenmüller, H. Álvarez-Pol, F. D. Amaro, et al. ”Recoil imaging for dark matter, neutrinos, and physics beyond the Standard Model”

A. Abed Abud, B. Abi, R. Acciarri, et al. (DUNE Collaboration). ”DUNE Physics Summary”

Tao Han, Zhen Liu, Lian-Tao Wang, Xing Wang. ”WIMP Dark Matter at High Energy Muon Colliders”

Pouya Asadi, Saurabh Bansal, Asher Berlin, Raymond T. Co, Djuna Croon, Yanou Cui, et al. ”Early-Universe Model Building”

Additional White Papers submitted to CF1

Benjamin Monreal. ”High-pressure TPCs in pressurized caverns: opportunities in dark matter and neutrino physics”

Alaina Attanasio, Sunil A. Bhave, Carlos Blanco, Daniel Carney, Marcel Demarteau,, et al. (Windchime Collaboration). ”The Windchime Project”

Junhui Liao, Yuanning Gao, Zhuo Liang, Zebang Ouyang, Chaohua Peng, Fengshou Zhang, Lei Zhang, Jian Zheng, Jiangfeng Zhou. ”Introduction to a low-mass dark matter project, ALETHEIA: A Liquid hElium Time projection cHambEr In dArk matter”

Andrea Mitridate, Tanner Trickle, Zhengkang Zhang, Kathryn M. Zurek. ”Light Dark Matter Direct Detection at the Interface With Condensed Matter Physics”

Additional White Papers submitted to CF1

M.F. Albakry, I. Alkhatib, D.W.P. Amaral, T. Aralis, T. Aramaki, I.J. Arnquist, I. Ataee Langroudy, et al. ”A Strategy for Low-Mass Dark Matter Searches with Cryogenic Detectors in the SuperCDMS SNOLAB Facility“

Alexander Aryshev, Ties Behnke, Mikael Berggren, James Brau, Nathaniel Craig, et al. ”The International Linear Collider”

A. Avasthi, T. Bezerra, A. Borkum, E. Church, J. Genovesi, J. Haiston, C. M. Jackson, et al. ”Low Background kTon-Scale Liquid Argon Time Projection Chambers”

The ATLAS and CMS Collaborations. ”Physics with the Phase-2 ATLAS and CMS Detectors”

Rouven Essig, Yonatan Kahn, Simon Knapen, Andreas Ringwald, Natalia Toro. ”Theory Frontier: Theory Meets the Lab”

Priorities and Next Steps

- We are considering whether to collect “endorsers” for all of our papers
- Publication is up to authors and journals
- Beginning to write topical group summary - again leaning heavily on solicited white papers. First draft will be completed May 31 and opened for comments.
- Complementarity effort restarting as well - currently driven by EF
  - Discussion tomorrow, Friday April 1, at 10:25-10:50 EST about plots combining results from different experiments
  - Previous discussion about trying to come up with high level plot/summary characterizing importance and interest in dark matter