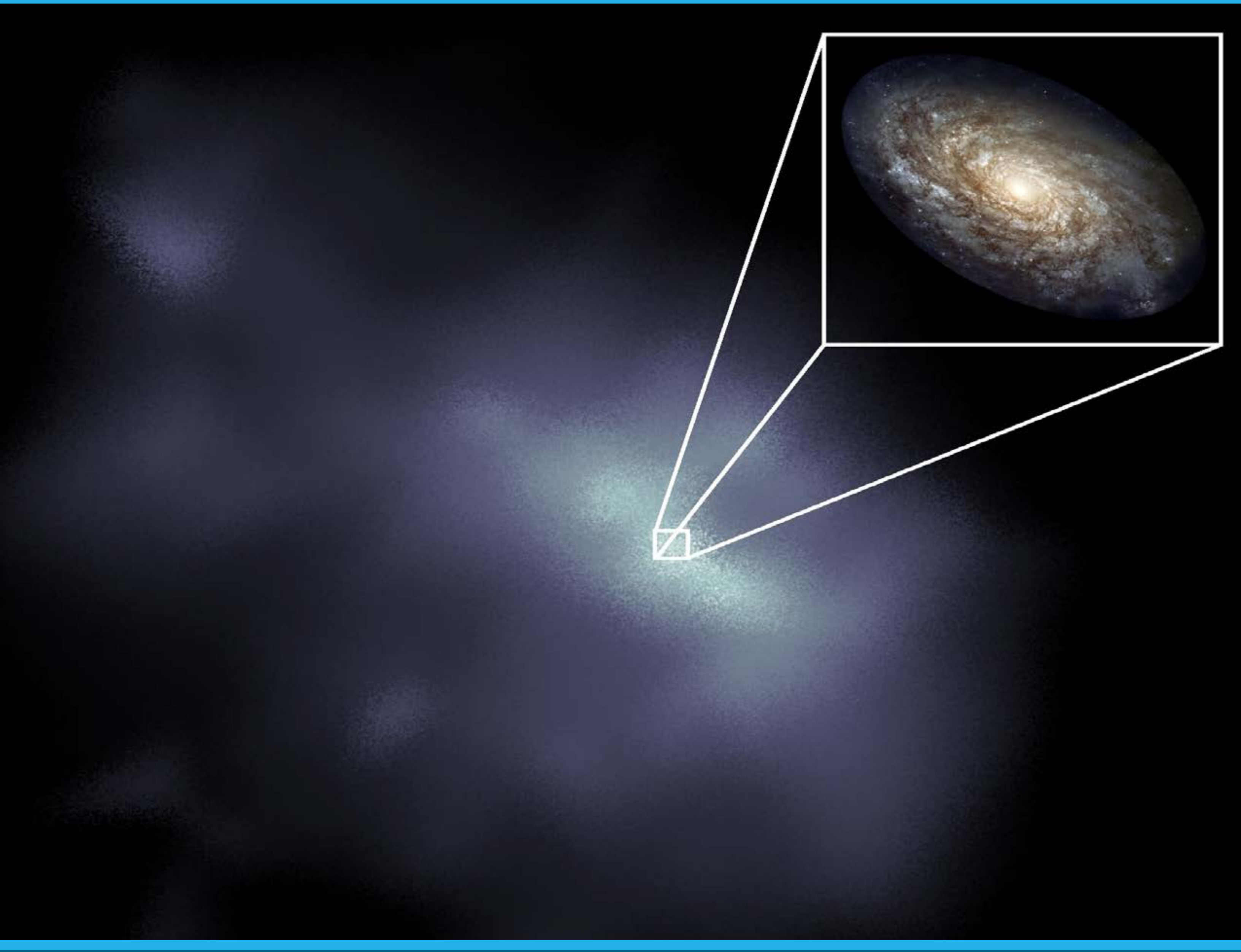
Basic Research Needs for
Dark Matter Small Projects New Initiatives



Summary of the High Energy Physics Workshop on Basic Research Needs for Dark Matter Small Projects New Initiatives

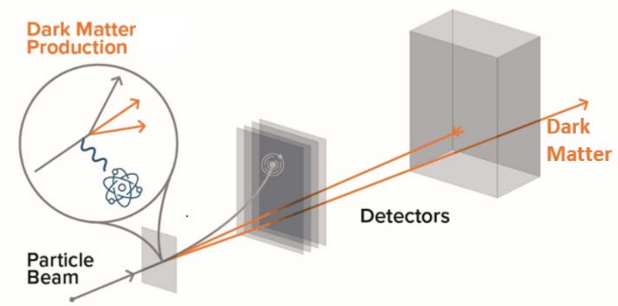
October 15 – 18, 2018

Opening New Areas of Discovery Concerning the Nature of Matter in the Universe

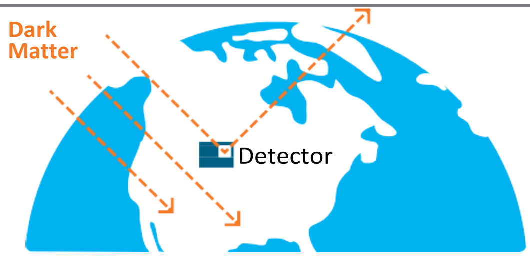
Only one-sixth of the matter in our Universe is made of the fundamental particles we understand. Understanding what the remaining “dark” matter is made of is one of the most important fundamental goals in modern science. It connects such disparate scientific areas as the formation of stars and galaxies, the earliest moments of our Universe, and the constituents of matter at the smallest length scales. Astronomical evidence for dark matter has built steadily for eight decades, though the elementary particles or waves that constitute dark matter remain a mystery. Recent theoretical developments have highlighted the importance of searching for dark matter particles in the range from as heavy as a single hydrogen atom to the lightest mass consistent with galactic structure (30 orders of magnitude lighter). Remarkably, small projects at the $5M–15M scale can explore key milestones throughout this range. By seizing these opportunities, we are now in a position to finally discover the nature of dark matter.

The Particle Physics Project Prioritization Panel (P5) identified the search for dark matter as one of the five priority science drivers for the Department of Energy (DOE) High-Energy Physics Program. The 2014 P5 report also recommended a portfolio of small projects to enable an uninterrupted flow of high-priority results. Guided by the P5 report recommendation, a Basic Research Needs Workshop held in October 2018 identified three Priority Research Directions (PRDs). The PRDs would make use of current DOE facilities (in laboratories above and below ground and in accelerators) and complement the ongoing Generation-2 (G2) dark-matter program. The G2 program is mostly focused on dark matter particles with mass larger than the proton and also explores wave-like dark matter. Looking beyond the current G2 program, we propose complementary searches for dark matter particles with mass less than the proton. The overarching goal is finally understanding the nature of the matter in the Universe. The full report will be available at https://science.energy.gov/hep.

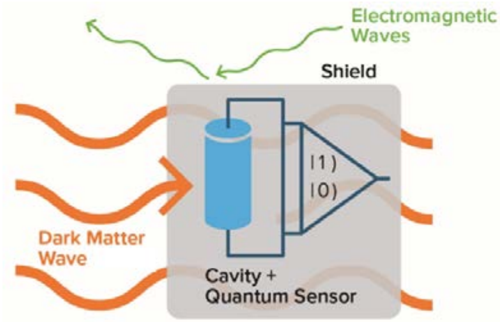
Create & Detect Dark-Matter Particles at Accelerators



Detect Galactic Particle Dark Matter Underground



Detect Galactic Wave Dark Matter in the Laboratory



Priority Research Directions (alphabetical order)

- **PRD #1: Create and detect dark-matter particles below the proton mass along with associated forces, leveraging DOE accelerators that produce beams of energetic particles.**

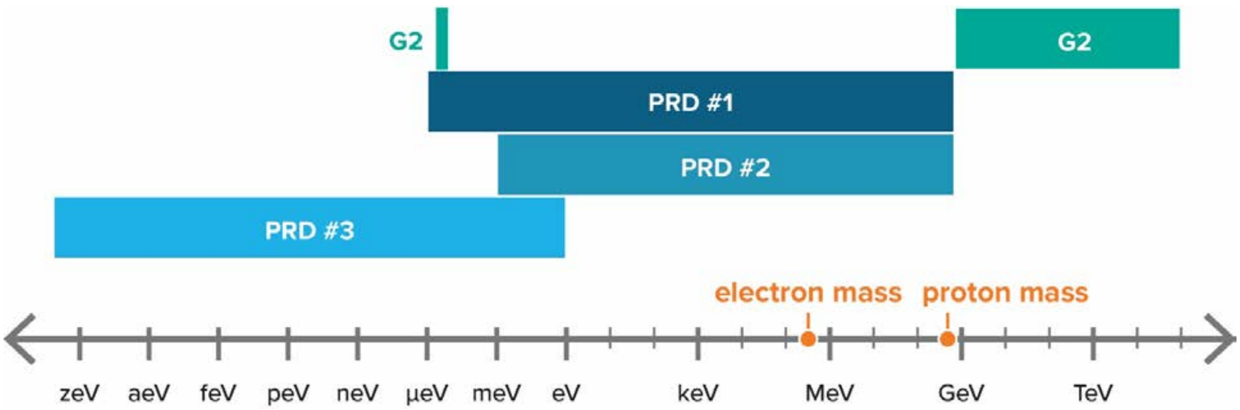
  The interactions of energetic particles recreate the conditions of dark- matter production in the early Universe. Small experiments using established detector technology can detect dark- matter production with sufficient sensitivity to test compelling explanations for the origin of dark matter and explore the nature of its interactions. These experiments draw on the unique capabilities of multiple DOE accelerators (Continuous Electron Beam Accelerator Facility, Linac Coherent Light Source-II, Spallation Neutron Source, Los Alamos Neutron Science Center, and the Fermilab complex) to enable transformative new science without disrupting their existing programs.

- **PRD #2: Detect galactic dark- matter particles below the proton mass through interactions with advanced, ultra-sensitive detectors.**

  Galactic dark matter passes through the earth undetected every second. Recent advances in particle theory highlight new compelling paradigms for the origin of dark matter and its detection. Revolutionary technological advances now allow us to discover individual dark matter particles with a mass ranging from the proton mass to twelve orders of magnitude below, through their interactions with electrons and nucleons in advanced detectors. New small projects leveraging these theoretical and technological advances are needed and can be carried out by using DOE personnel, laboratories, and infrastructure, especially the underground infrastructure already built using DOE support.

- **PRD #3: Detect galactic dark-matter waves using advanced, ultra-sensitive detectors with emphasis on the strongly-motivated QCD axion.**

  Recent technological and theoretical advances finally allow the detection of dark matter over the entire 20 orders of magnitude of the ultralight mass range, previously inaccessible to observation. Discovery of these dark matter waves also provides a glimpse into the earliest moments in the origin of the universe and the laws of nature at ultrahigh energies and temperatures, far above what can be created in terrestrial laboratories. DOE resources, infrastructure, technology capabilities, and personnel are required to achieve maximum impact.



Mass range explored by the three PRDs in search for dark matter spans roughly thirty orders of magnitude, from zepto to giga electron volts. Range for each PRD indicates regions accessible with existing technologies and regions requiring more R&D to increase detection sensitivity. All three PRDs are needed to achieve broad sensitivity and, in particular, to reach different key milestones. Mass range for G2 program included for comparison.

Comprehensively Exploring Dark Matter

The three Priority Research Directions constitute a comprehensive program of small projects to explore dark matter below the mass of the proton. This program is achievable at modest cost because it leverages existing and planned large-scale DOE investments and expertise in accelerators, under-ground laboratories, detector research and development, novel quantum sensing, and theoretical physics.

Together, all three directions cover the key range of possibilities for dark matter across this mass range. Successfully unravelling the nature of dark matter, its interactions, and its origin in the Universe can only be achieved by combining results from projects spanning these new directions. In the event of a discovery, each provides a unique and essential piece of the puzzle.

Extraction from cosmological simulation of dark matter halo hosting a Milky Way-type galaxy.

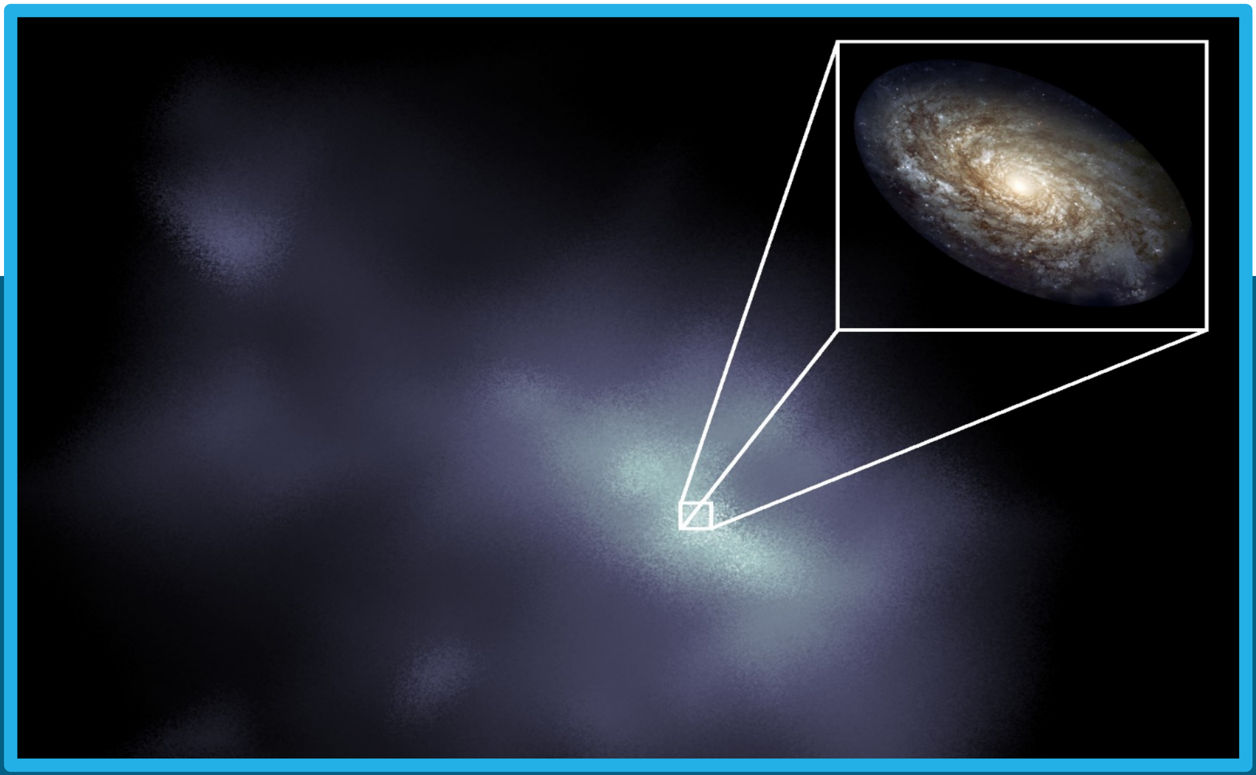


Image credits: Cosmological Physics and Advanced Computing Group, Argonne National Laboratory.
Halo from the Outer Rim simulation, galaxy image (NGC 4414) from the Hubble Space Telescope Key Project.

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