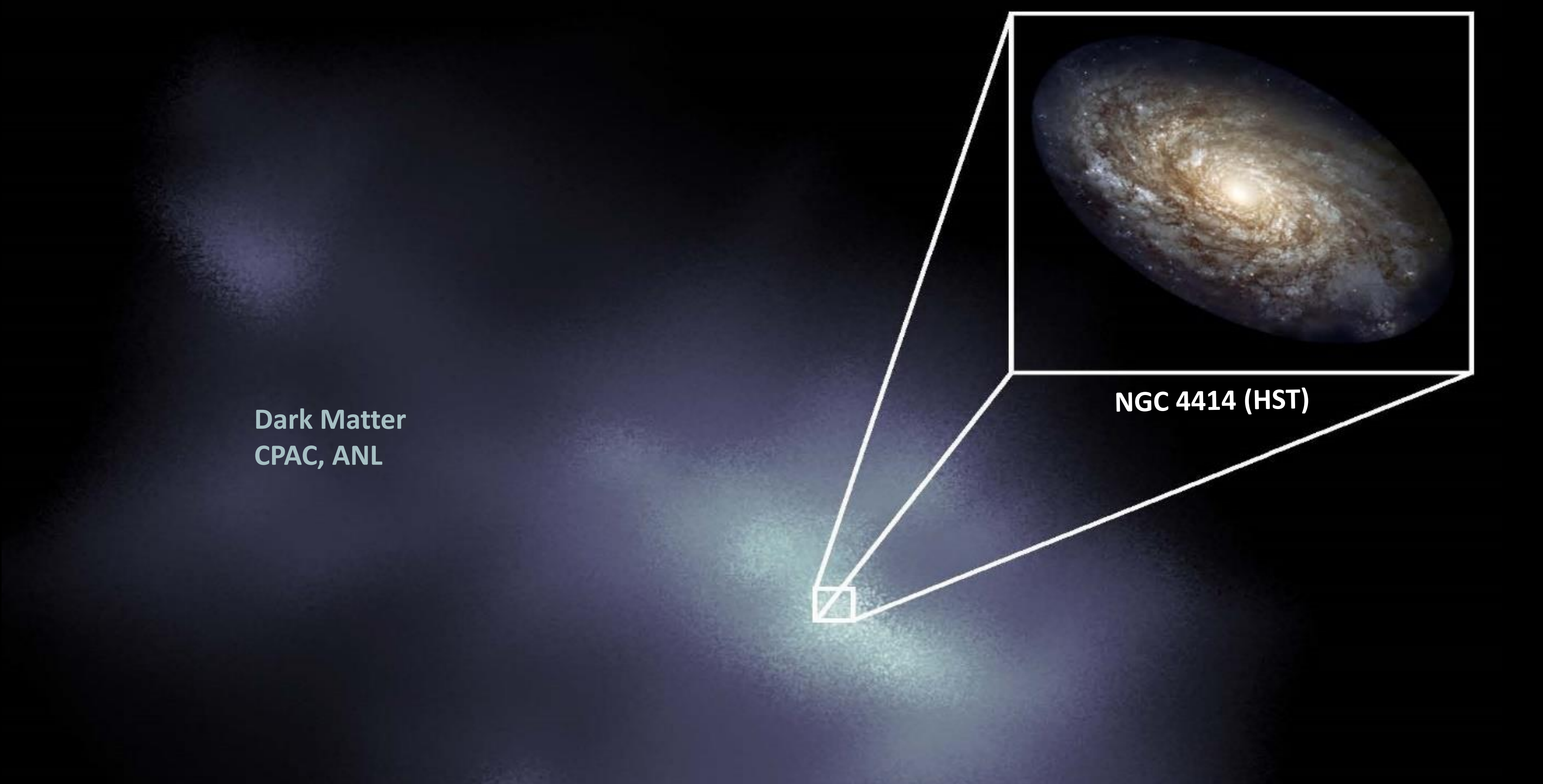
Basic Research Needs (BRN) Study for Dark-Matter Small Projects

(<u>preliminary</u> report to HEPAP 30 November 2018)



Summary of the High Energy Physics Workshop on

Basic Research Needs for Dark-Matter Small Projects New Initiatives

October 15 – 18, 2018

Basic Research Needs (BRN) Study for Dark-Matter Small Projects
(preliminary report to HEPAP)

On behalf of co-chair Harry Weerts, 10 panel leads (conveners), 27 panel members

Co-chairs:
- Rocky Kolb (Chicago)
- Harry Weerts (Argonne)

Accelerator Panel Leads:
- Natalia Toro (SLAC)
- Richard Van de Water (LANL)

Direct Detection Panel Leads:
- Rouven Essig (Stony Brook)
- Dan McKinsey (Berkeley)
- Kathryn Zurek (LBNL)

Ultralight Panel Leads:
- Aaron Chou (FNAL)
- Peter Graham (Stanford)

Cross Cut Panel Leads:
- Juan Estrada (FNAL)
- Joe Incandela (Santa Barbara)
- Tim Tait (Irvine)

Accelerator Panel Members:
- Marco Battaglieri (INFN)
- Brian Batell (Pitt)
- Stefania Gori (Santa Cruz)
- Gordon Krnjaic (FNAL)
- Tim Nelson (SLAC)
- Adam Ritz (Victoria)
- Philip Schuster (SLAC)
- Rex Tayloe (Indiana)
- Nhan Tran (FNAL)

Direct Detection Panel Members:
- Adam Bernstein (LLNL)
- Jodi Cooley (SMU)
- Eric Dahl (Northwestern)
- Sunil Golwala (Caltech)
- Scott Hertel (U Mass)
- Reina Marayama (Yale)
- Matt Pyle (Berkeley)
- Javier Tiffenberg (FNAL)

Ultralight Panel Members:
- Karl van Bibber (Berkeley)
- Kent Irwin (SLAC)
- Tim Kovachy (Northwestern)
- Surjeet Rajendran (Berkeley)
- Gray Rybka (U Washington)
- Alex Sushkov (Boston U)
- Lindley Winslow (MIT)

Cross Cut Panel Members:
- Roni Harnik (FNAL)
- Yoni Kahn (Chicago)
- Mariangela Lisanti (Princeton)

Balance Important

University/ National Lab	University Lab	25 (64%) 14 (36%)
Geography	California Midwest East Coast West Coast (non-CA) Mountain Europe	15 (38%) 13 (33%) 7 (18%) 2 (5%) 1 (3%) 1 (3%)
Gender	Male Female	32 (82%) 7 (18%)
Experimentalist/ Theorist	Experimentalist Theorist	24 (62%) 15 (38%)

BRN Workshops

- Started by BES in 2001-2002
- First report 420 pages with 37 Proposed Research Directions
  (DMBRN will be ca. 100 pages and 3 Priority Research Directions)
- Over 20 subsequent BES BRNs
- Very prescribed BES process
  Two pages of planning task list with target dates
  Detailed tasks for co-chairs, speakers, panel leads, panelists, writers, webmaster, …
  Agenda for of BRN workshops
  Templates for panel-generated closing sessions and chair closing session presentations
  Invitation only

  We followed process where possible.

DMBRN Provenance

In 2014 the Particle Physics Project Prioritization Panel (P5) identified the search for dark matter as one of the five priority science drivers for the High-Energy Physics Program.

There are many well-motivated ideas for what the dark matter should be. These include weakly interacting massive particles (WIMPs), gravitinos, axions, sterile neutrinos, asymmetric dark matter, and hidden sector dark matter.

It is therefore imperative to search for dark matter along every feasible avenue.

Some of these scenarios – including WIMP searches— are the purview of larger experiments. However, much of the well-motivated parameter space for dark matter can be explored by small experiments in the near future.

This corresponds to another recommendation of P5, namely that

The HEP program should contain a portfolio of small projects to enable an uninterrupted flow of high-priority science results.

DMBRN Timeline

23-25 March 2017:

“U.S. Cosmic Visions: New Ideas in Dark Matter“ workshop, focusing “… on the science case for additional new small-scale projects in dark-matter science that complement the G2 program …” Comprehensive (exhaustive) report.

10 SAC members (Marco Battaglieri and Natalia Toro, co-chairs)

(4 SAC members were BRN panel leads, 4 others were panel members)

9 conveners in 4 areas

(5 conveners were BRN panel leads)

14 July 2017:

Cosmic Visions Report published (1707.04591). 113 pages. 254 signatories from 112 Institutions (US, Australia, Austria, Canada, Denmark, Germany, Israel, Italy, Japan, Korea, Russia, Switzerland, Taiwan, UK).

1 May 2018:

Request from Karen Byrum to co-chairs for a DOE basic needs workshop for future dark matter small projects.

May/June:

Co-chairs work with DOE on charge and workshop dates and logistics. Weekly co-chairs Turner/Byrum phone.

June/July:

Decide on panels, invite panel leads.

July/August:

Core group weekly zoom conferences to discuss charge, deliverables, and membership of panels.

August/September:

Panel membership settled, panels start calls on charge.

15-18 October:

Workshop in Gaithersberg. All 39 panel leads and panel members attended.

Day 1, Monday 10/15

9:00am – 10:45am PLENARY

- 15 minutes: Logistics, purpose and organization of the BRN – DOE and Chairs
- 25 minute each reports from Direct + Accelerator+ Ultralight panels
  - Brief review of CV workshop filtered through our charge
  - What's new since CV
  - Report on pre-workshop phonecons
    - Where there is consensus
    - Key questions and areas of contention

  15 minutes: Discussion all

11:00am – 1:00pm

- WG breakout sessions

1:00pm – 2:00pm (working lunch for core group members)

2:00pm – 5:00pm

- WG breakout sessions

Day 2, Tuesday 10/16

9:00am – 11:00am PLENARY

- 30 minute each reports from Direct + Accelerator + Ultralight panels
  - 15min report on previous day's work
  - 15min all participant discussion
- 30 minute presentation and discussion of cross-cut opportunities

11:15am – 1:00pm

- WG breakout sessions

1:00pm – 2:00pm (working lunch for core group members)

2:00pm – 5:00pm

- WG breakout sessions

Day 3, Wednesday 10/17:

9:00am – 11:00am PLENARY

- 30 minute each reports from Direct + Accelerator + Ultralight panels
  - Present draft PRD for discussion
  - 15min all participant discussion
- 30 minute participation and discussion of cross-cut opportunities

11:15am – 1:00pm

- WG breakout sessions

1:00pm – 2:00pm

- Core group meeting

2:00pm – 3:00pm

- Final WG wrap up breakout sessions

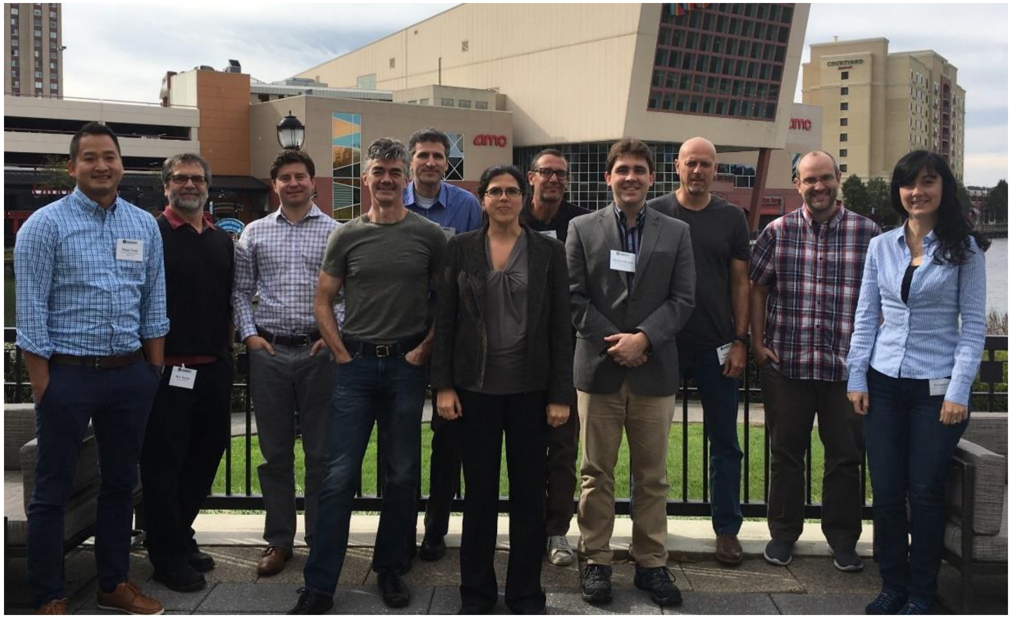
3:00pm – 6:00pm PLENARY

- 30 minute each reports from Ultralight+Direct+Accelerator WG's
  - Outline final WG findings and discuss final science opportunities
  - Discuss technology roadmaps
- 30 minute report and discussion of cross-cut opportunities
- 60 minute group discussion about Priority Research Directions

Day 4, Thursday 10/18:

Morning Core Group

- Incorporate workshop initial conclusions for final document



Accelerator Panel:

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Rex Tayloe
Gordan Krnjaic
Tim Nelson
Adam Ritz
Natalia Toro
Marco Battaglieri
Philip Schuster
Richard Van de Water
Brian Batell
Stefania Gori

(Panel leads in bold)

Direct Detection Panel:

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Lindley Winslow
Karl van Bibber
Alex Sushkov
Tim Kovachy
Peter Graham

(Panel leads in bold)

Cross Cutting Panel:

Mariangela Lisanti
Tim Tait
Yoni Kahn
Juan Estrada
Roni Harnik
Joe Incandela

Co Chairs:

- Harry Weerts
- Rocky Kolb

DOE:

- Kathy Turner
- Glen Crawford (eyes closed)
- Jim Siegrist (looking at phone)
- Karen Byrum (not pictured—the photographer)

DMBRN Timeline

October, November, December:
Core Group continues weekly zoom meetings.

30 November:
Preliminary report to HEPAP.

NLT 31 December 2018:
Final report delivered to DOE.

DMBRN Preliminary Report

CONTENTS

DMBRN Charge

- Identify science opportunities for new directions and areas of parameter space that will provide high impact science return and advancement for DM particle detection.

- Determine the high impact science opportunities which could be pursued by small projects (approximately $5M to $15M in Total Project Cost) that could be ready to start within the next few years, and in which DOE's laboratory infrastructure and/or technology capabilities are required to be realized.

- Suggest opportunities that could be pursued by future small projects, which also require DOE capabilities, but need further technology development before project initiation.

Note that the priority opportunities should not include significant upgrades of current large projects or development of new large projects in the HEP program, nor small contributions to large projects supported by other sources. While not the focus of the study, it may be useful to summarize the parameter space and science reach of existing or planned experiments in program and globally, and relevant future directions that may be addressed by significant upgrades or next steps for the large projects. If applicable, the study can also develop a technology R&D roadmap, along with a notional timeline and schedule, identifying key technical milestones relevant to enabling future DM searches.

The BRN <u>does not</u>:

- Recommend anything
- Advise DOE
- Prioritize projects
- Rank PRD opportunities

The BRN <u>does</u>:

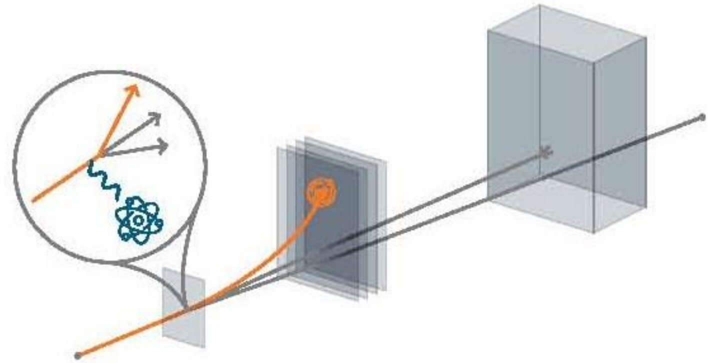
- Describe SCIENCE OPPORTUNITIES

Issues not completely resolved:

- What is an upgrade?
- Glossiness of report, brochures, etc.

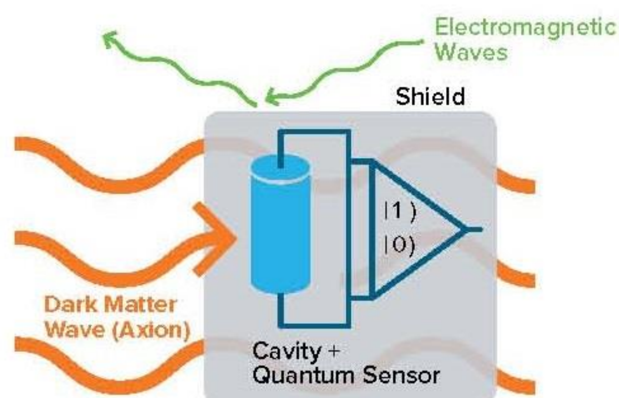
Three Priority Research Directions

Create & Detect Dark Matter at Accelerators



Detect Galactic Dark Matter Underground

Detect Wave Dark Matter in the Laboratory



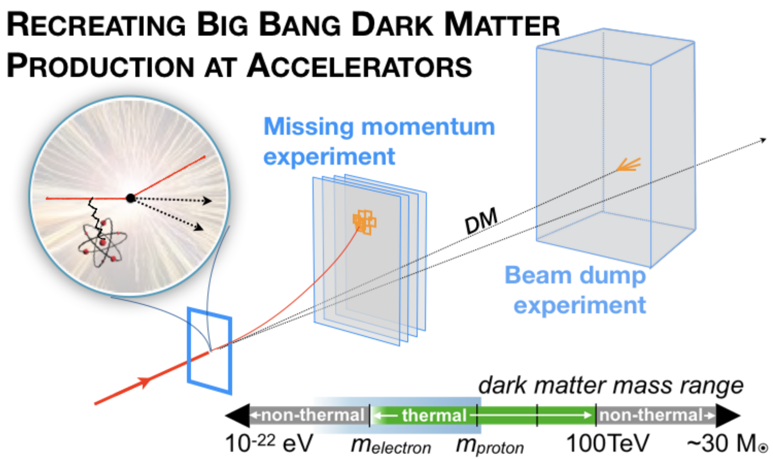
Priority Research Directions (alphabetical, not priority order)

PRD #1: Create and detect dark-matter particles and associated forces below the proton mass, 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 individual galactic dark-matter particles below the proton mass through interactions with advanced, ultra-sensitive detectors. 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 ranging from the proton mass to twelve-orders-of-magnitude below, through their interactions with electrons and nuclei in advanced detectors. New small projects leveraging these theoretical and technological advances would be carried out by using DOE laboratories, infrastructure, personnel, and underground facilities, such as the Sanford Underground Research Facility.

PRD #3: Observe wave dark matter using innovative technologies with emphasis on a target which resolves a decades-old mystery of the physics inside the nucleus, the QCD axion." Recent theoretical advances and developments in quantum sensors enable the search for dark-matter waves over twenty-two orders of magnitude in the ultralight mass range, previously inaccessible to observation. Discovery of these dark-matter waves would provide a glimpse into the earliest moments in the origin of the universe and the laws of nature at ultrahigh energies, far beyond what can be probed in particle colliders. DOE resources, infrastructure, technology capabilities, and personnel are required to achieve maximum impact.

Create and detect dark-matter particles and associated forces below the proton mass, leveraging DOE accelerators.



Two thrusts: The first thrust exploits dark-matter production reactions to fully explore the range of dark-matter interaction strengths that could generate the observed abundance of dark matter through thermal reactions in the early Universe. The second thrust calls for broad exploration of the production of particles related to light dark matter (i.e. a dark sector) and their subsequent decays into familiar matter.

Thrust 1 (near-term): Use particle beams to explore interaction strengths singled out by thermal dark matter through 10-1000-fold improvements in sensitivity over current searches.

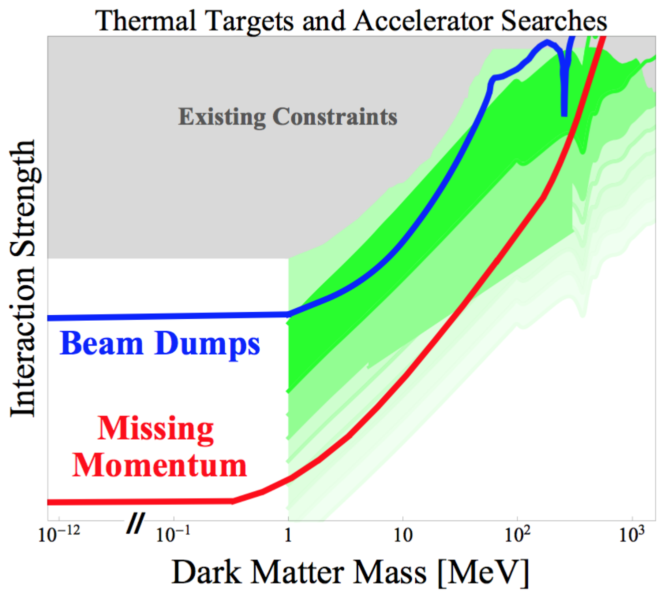
By improving particle-beam measurements of dark-matter's interactions with leptons and hadrons by a factor of 10–1000, most of the predictive milestones for thermal dark matter below the proton mass can be thoroughly explored.

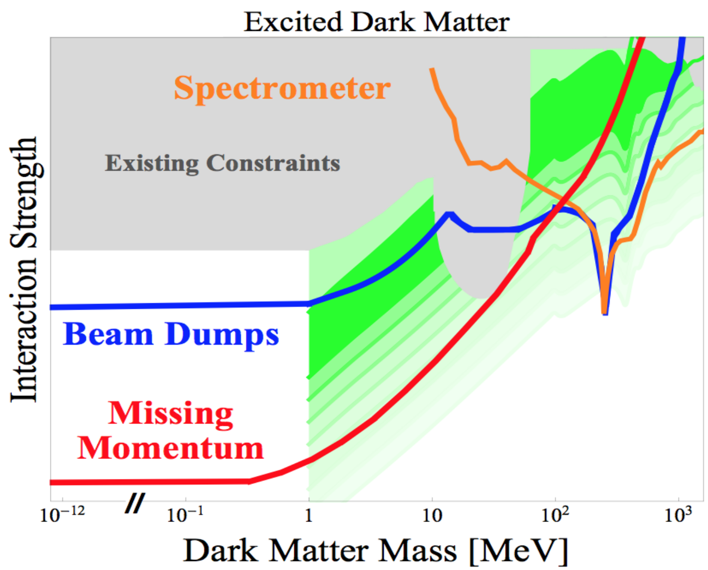
Thrust 2 (near-term and long-term): Explore the structure of the dark sector by producing and detecting unstable dark particles.

Accelerator-based missing-momentum and beam-dump experiments are capable of producing not only dark matter, but other related particles (the "dark sector"). Such a dark sector is needed for thermal dark matter lighter than the proton.

> The science described in this PRD is motivating new efforts at laboratories around the world, including CERN, KEK, Mainz, and INFN. In this global landscape, the capabilities of the US DOE accelerator infrastructure – in particular, multi-GeV CW electron beams and high-intensity proton beams – provide unique opportunities. By leveraging existing DOE accelerator infrastructure, US small projects can provide world leading contributions to this important and vibrant new science.

Create and detect dark-matter particles and associated forces below the proton mass, leveraging DOE accelerators.



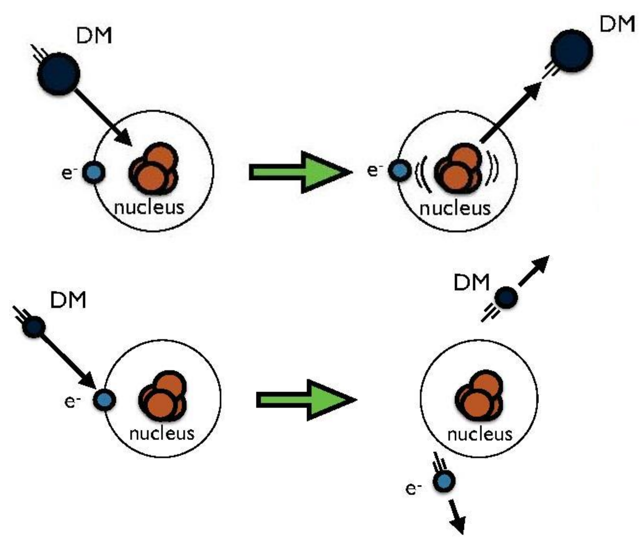


Green areas are high priority parameter space identified at BRN, singled out by thermal models for the origin of dark matter – many are uniquely explored at accelerators

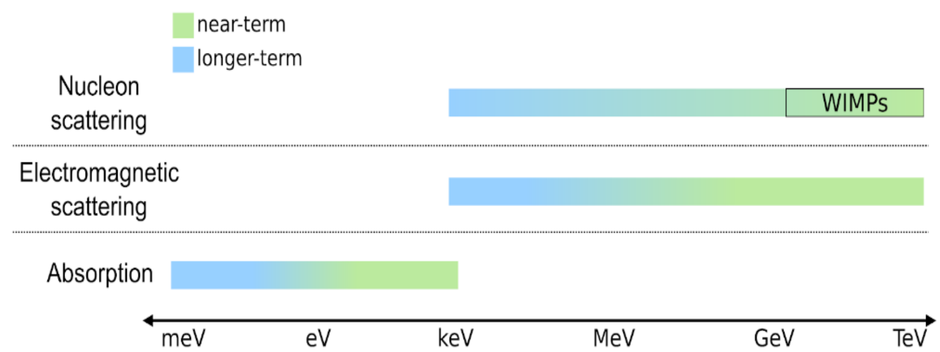
The science described in this PRD is motivating new efforts at laboratories around the world, including CERN, KEK, Mainz, and INFN. In this global landscape, the capabilities of the US DOE accelerator infrastructure – in particular, multi-GeV CW electron beams and high-intensity proton beams – provide unique opportunities. **By leveraging existing DOE accelerator infrastructure, US small projects can provide world leading contributions** to this important and vibrant new science.

Beyond discovery, offers ample opportunities to corroborate a signal, understand its physical origin, and measure dark-matter particle properties

Detect individual galactic dark-matter particles below the proton mass through interactions with advanced, ultra-sensitive detectors



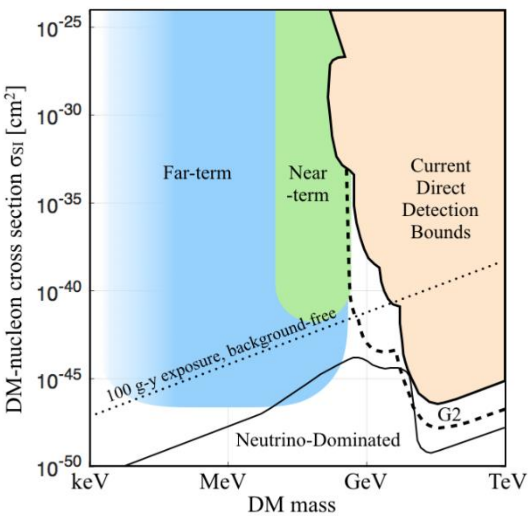
Two thrusts: The first involves dark-matter interactions with nuclei. The second thrust probes dark-matter interactions with electrons. Both thrusts cover possible thermal and non-thermal origins, and both thrusts have near-term and longer-term goals.



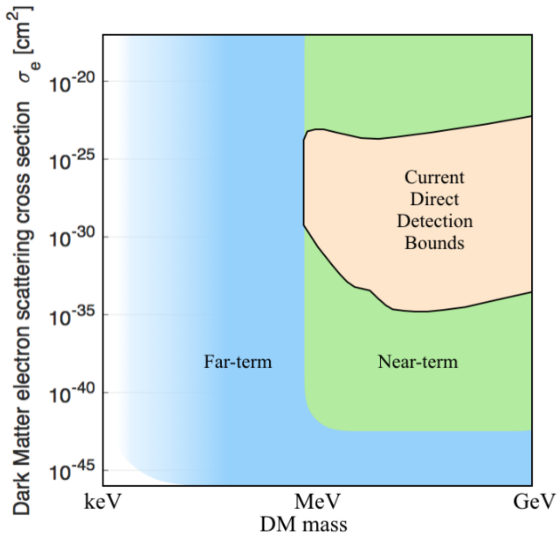
<u>Thrust 1:</u> Probe dark-matter interactions with nuclei, as motivated by theoretical ideas for the nature of light dark matter, including its possible thermal and non-thermal origins. Near-term experiments probes dark-matter masses between 50 MeV to 1 GeV; medium/longer term probes masses down to 1 keV; absorption of dark matter probes masses as light as 1 meV.

<u>Thrust 2:</u> Probe dark-matter interactions with electrons, as motivated by theoretical ideas for the nature of light dark matter, including its possible thermal and non-thermal origins. Near-term probes dark-matter masses between 1 MeV to 1 GeV; absorption of dark matter with masses 1 eV to 1 keV. Medium-to-longer term experiments can be sensitive to the scattering of dark matter with masses 1 keV and 1 MeV and the absorption down to masses of 1 meV.

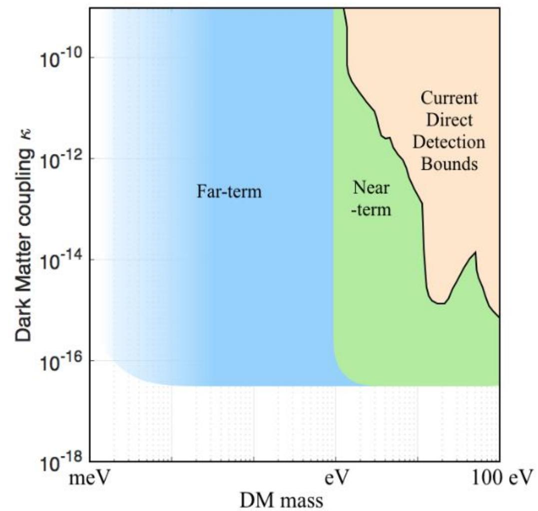
Detect individual galactic dark-matter particles below the proton mass through interactions with advanced, ultra-sensitive detectors



Galactic dark matter scattering off nuclei



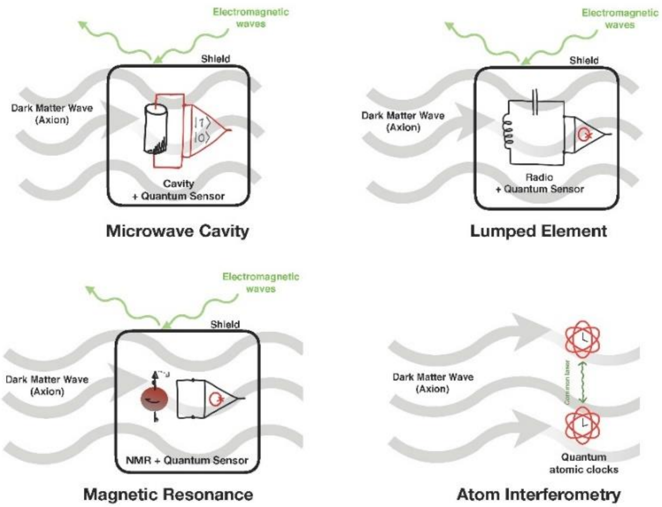
Galactic dark matter scattering off electrons



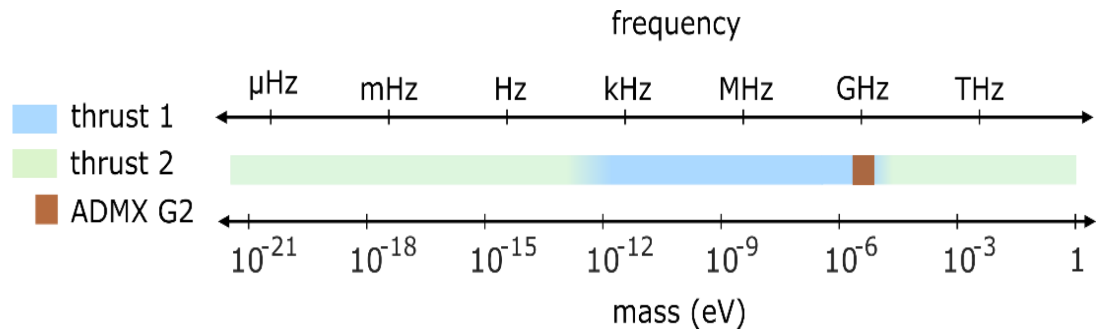
Galactic dark-photons absorbed by electrons

Beyond known sharp theory targets, new direct-detection experiments can probe orders of magnitude of dark-matter parameter space that is well-motivated but without a sharp target. This includes the scenario in which dark matter results from thermal freeze-out by annihilating into a hidden sector (the “secluded-annihilation dark-matter scenario”), from the misalignment mechanism, and others. Direct detection uniquely probes models with an ultralight mediator.

Observe wave dark matter using innovative technologies



Recent theoretical developments motivate very light dark-matter particles that interact more like waves. Improvements in our understanding of cosmology, especially the period of inflation, show these very light particles to be excellent dark-matter candidates. Techniques required to search for very light particles differ from those for previous dark-matter searches and rely heavily on advances in quantum sensing.



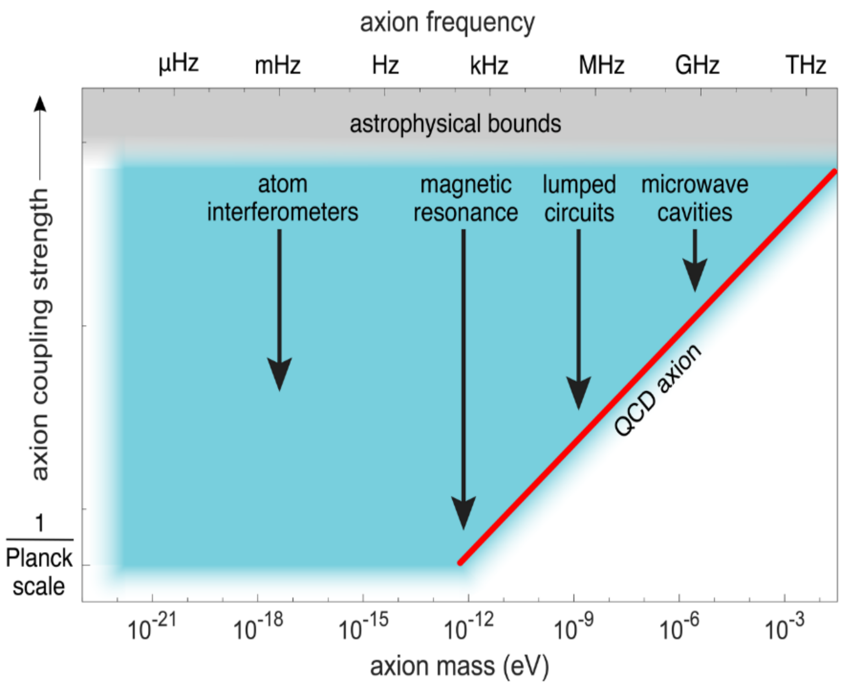
Thrust 1: Utilize new detector technologies to explore large parts of dark-matter parameter space covering a broad range of mass from 100 Hz to 10 GHz (roughly 10^{-12} eV - 10^{-4} eV), and targeting sensitivity to the QCD axion where possible.

Thrust 2: Develop or transfer new detector technologies to enable experiments to cover the remaining parameter space for well-motivated dark-matter models spanning the entire 20 orders of magnitude in mass and also targeting complete coverage of QCD axion models.

This high-impact science opportunity could be pursued by small projects ($5M to $15M Total Project Cost) which could be ready to start within the next few years, and in which DOE resources, infrastructure, technology capabilities, and personnel are required to achieve maximum impact.

Observe wave dark matter using innovative technologies

The goal of the dark-matter community is complete coverage of the entire mass range of possible wave dark-matter candidates.



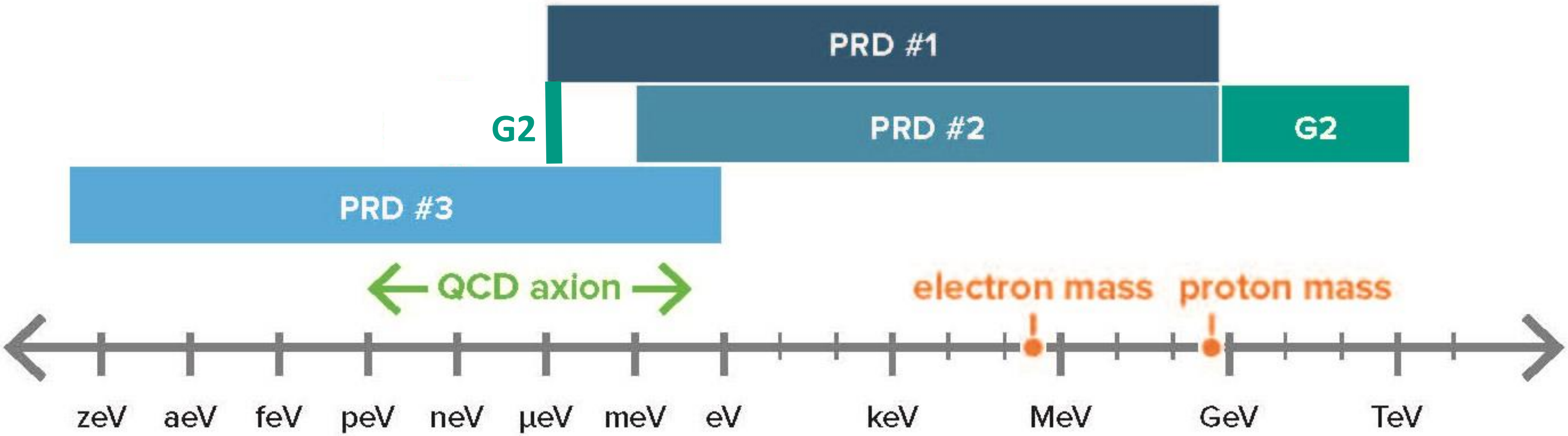
Extremely sensitive quantum sensors will be developed, which can be applied to fields interested in single photon detection. These sensors include CCDs with extremely low dark current, as well as calorimetric detectors with 100% quantum efficiency and excellent energy resolution for individual photons.

Three PRDs Cover Entire Range Below Proton Mass

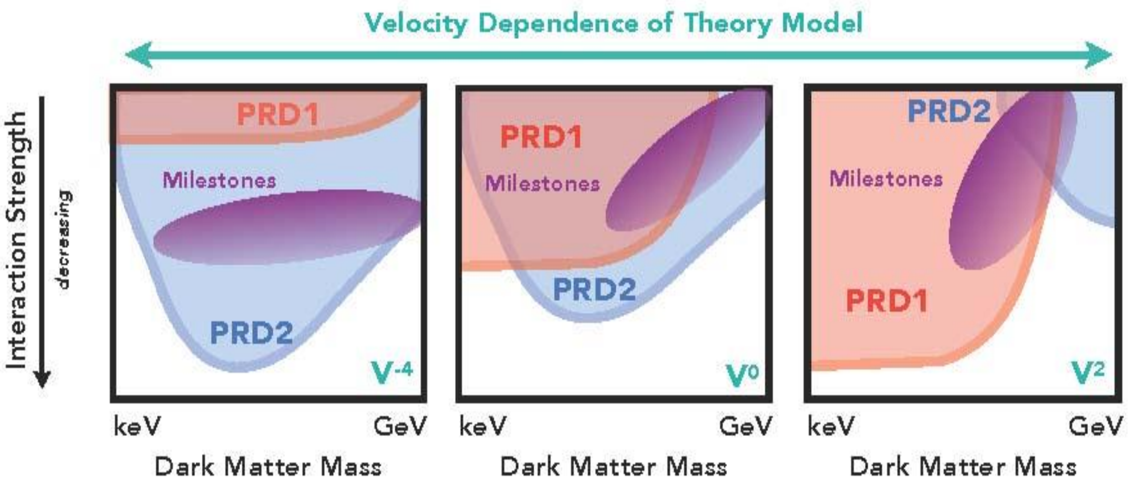
- Thermally produced dark matter must have mass larger than a keV from astrophysical considerations
- Accelerator searches (PRD 1) are sensitive to much lower masses; can produce dark sector particles even if not dark matter
- Direct detection (PRD 2) can also probe lower-mass galactic particles that can be sub-dominant component to dark matter

- Thermal particle dark-matter (freeze-out) particles must have mass less than about $200\ \mathrm{TeV}$

- Dark matter must have mass larger than $10^{-22}\ \mathrm{eV}$ so that its Compton wavelength is smaller than the size of the galaxy



PRDs Provide Complementary Information

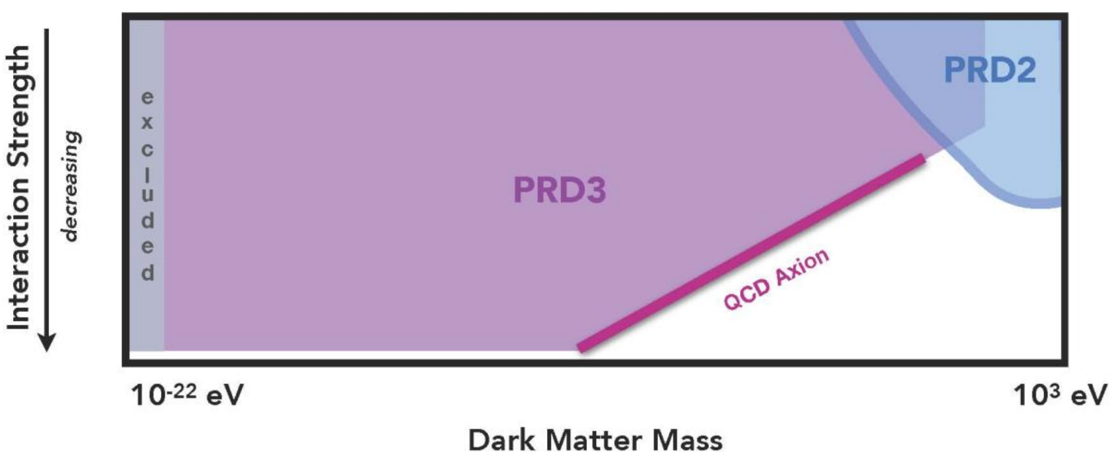


Mediator □ DM
Freeze-in

Mediator ≈ DM
Freeze-out
DM-S, Med.-V

Mediator ≈ DM
Freeze-out
Majorana DM

- Accelerators can produce dark-sector particles, not only dark matter.
- Direct detection directly probes the galactic dark matter.
- Together, they provide an extremely powerful diagnostic tool for dark-matter physics.



Discovery of dark-matter waves provides a glimpse into the earliest moments in the origin of the universe and the laws of nature at ultrahigh energies, far beyond what can be probed in colliders.

Complementary with G2

HEP Next Generation (G2) Dark-Matter Experiments

Direct detection focused on weak-scale WIMPS

- LUX-Zeplin (LZ): seven tons of active liquid xenon to search for xenon nuclei that recoil in response to collisions caused by an impinging flux of dark matter particles
- SuperCDMS use of low-temperature solid-state detectors to search for the rare scattering of dark-matter particles with atomic nuclei.

Narrow mass range: 2.4–8 eV (600 MHz—2 GHz)

- ADMX-Gen 2: large microwave cavity resonator located inside a high-field solenoid magnet.

BRN does not evaluate the science opportunities specific to G2 experiments, nor consider upgrades to suite of G2 experiments.

Emphasis of this BRN is to extend the reach for discover of dark-matter particles below the proton mass (e.g., hidden sector dark matter—modest generalization of WIMP paradigm), and extend the reach of wave dark-matter searches beyond the G2 range (e.g., generalized axion and dark photons).

Create and detect dark-matter particles and associated forces below the proton mass, leveraging DOE accelerators

Scientific challenges

Particle collisions at accelerators can reproduce the conditions under which dark matter was created in the early universe and create dark matter lighter than the proton. The challenge is to extend the sensitivity of current experiments to reach well-motivated theoretical milestones.

Summary of research direction

The first thrust is to use missing-momentum and beam-dump experiments to search for dark-matter production at rates expected if thermal reactions in early Universe generate the observed abundance of dark matter. The second thrust is to explore broadly production of unstable particles related to light dark matter, also using spectrometer experiments.

Potential scientific impact

US small accelerator-based experiments are positioned to play world-leading role in international program: uniquely strong sensitivity provides powerful test of thermal dark matter and enables exploration of the particle properties of dark matter.

Synergies

Unique opportunities leverage capabilities of US DOE accelerator infrastructure – in particular, multi-GeV CW electron beams and high-intensity proton beams. Detectors would use established technology, are synergistic with neutrino program and ongoing detector development across HEP program.

Detect individual galactic dark-matter particles below the proton mass through interactions with advanced, ultra-sensitive detectors

Scientific challenges

Recent advances in particle theory highlight new paradigms for the origin of dark matter in the mass range from the proton mass to twelve orders of magnitude below. Present dark-matter experiments cannot probe deeply into this region. The scientific challenge is to employ new experimental techniques to detect dark matter in this mass range.

Summary of research direction

The first thrust is to probe dark-matter interactions with nuclei, including its possible thermal and non-thermal origins. The second thrust is to probe dark-matter interactions with electrons, as motivated by theoretical ideas for the nature of light dark matter, including its possible thermal and non-thermal origins.

Potential scientific impact

Direct detection plays a unique and essential role in our quest to identify the nature of dark matter, as a discovery of a new particle at an underground direct-detection experiment would constitute direct evidence that such a particle constitutes all or at least part of the galactic dark matter.

Synergies

Extremely sensitive quantum sensors will be developed, which can be applied to fields interested in single photon detection. These sensors include CCDs with extremely low dark current, as well as calorimetric detectors with 100% quantum efficiency and excellent energy resolution for individual photons.

Observe ultralight wave dark matter over 20 orders of magnitude in mass using innovative technologies

Scientific challenges

Our understanding of cosmology show ultralight dark matter (mass in the range 1 eV to 10^{-22} eV) be excellent dark-matter candidates. Very light dark-matter particles interact more like waves. The scientific challenge is to develop and deploy sensors and experiments required to search for wave-like dark matter.

Summary of research direction

The first thrust is to utilize new detector technologies to explore a broad range of mass from 10^{-12} eV – 10^{-4} eV. The second thrust is to develop or transfer detector technologies to cover the remaining parameter space spanning the entire 22 orders of magnitude in mass for ultralight dark matter.

Potential scientific impact

Discovery of dark-matter waves provides a glimpse into the earliest moments in the origin of the universe and the laws of nature at ultrahigh energies, far beyond what can be probed in particle colliders.

Synergies

New quantum sensors allow measurements near the Heisenberg uncertainty principle limits. This leverage works both ways: bringing the unique resources and expertise of the HEP community to bear on the development of quantum sensors will lead to rapid advances to benefit the QIS community.

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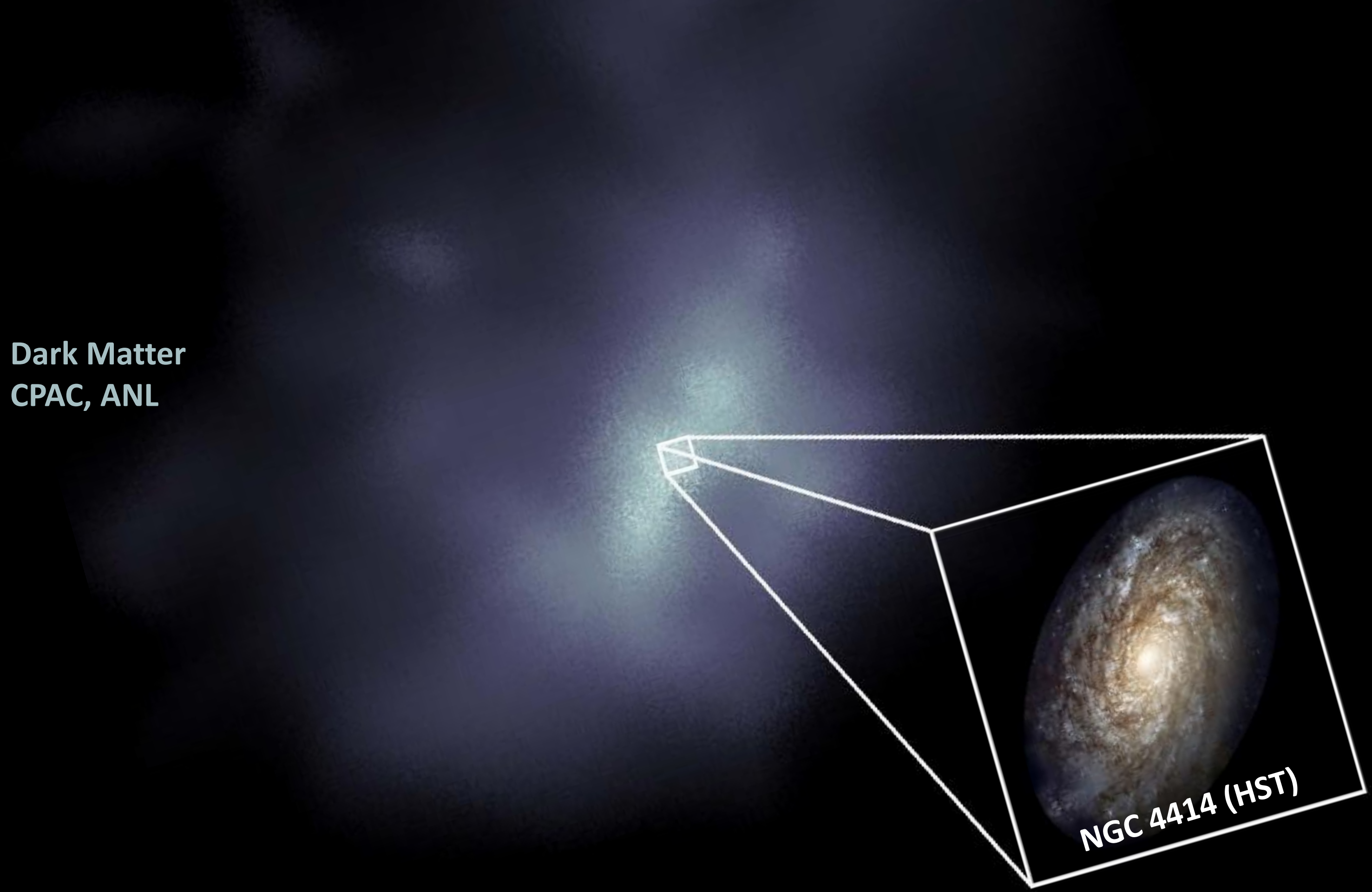

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