Dark Sector Science in 2019

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This talk is intended as a primer on the motivation for dark sectors (and dark photons) and to explain the important contributions of Jefferson Lab experiments to this science in 2019

- Dark matter, dark sectors, and the broadening of the US dark matter search program
- Dark photons in the MeV-GeV mass range
- Dedicated dark photon experiments at Jefferson Lab in 2019 (APEX & HPS)
- The future
We know there is new physics in the form of dark matter!

But what is it?
Dark Matter Hints

- **Old** – dark matter imprint in Cosmic Microwave Background → made during or before big bang
- **Cold** – dark matter must have been non-relativistic to form small cosmological structures
- Can’t have strong- or electromagnetic-strength interactions with familiar matter (even weak interactions are significantly constrained by data)

This leaves a lot of room for speculation…
A Strong Candidate: WIMP DM

Simple, familiar particle content

Simple, predictive cosmology

Motivated mass range

DM with thermal freeze-out origin

Motivated mass range

MeV  GeV  TeV

WIMP
Moving Beyond WIMPs

Developing simple ideas beyond the WIMP hypothesis — in response to powerful limits from LHC and direct detection experiments — has arguably been one of the most important developments in particle phenomenology over the last 10 years!

US Cosmic Visions: New Ideas in Dark Matter 2017

Moving Beyond WIMPs

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Dark Sector Candidates, Anomalies, and Search Techniques

US Cosmic Visions: New Ideas in Dark Matter 2017
Lessons From Data

The ingredients most at odds with data underlying WIMPs is that they are heavy (~GeV and up) and their interactions are mediated by the W/Z bosons!

Direct detection and LHC experiments have very good sensitivity to DM interacting through W/Z/h bosons!

The ingredients most at odds with data underlying WIMPs is that they are heavy (~GeV and up) and their interactions are mediated by the W/Z bosons.
Lessons From History

Known ~5% of Universe is rather interesting. If history is any guide, expect the next ~25% to have surprises in store for us!
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Lessons From History

Simple, familiar particle content

weak force
new matter

gw
gsm
Lessons From History

Simple, familiar particle content

So, what if dark matter (like all other known matter) is charged under its own forces?
New Forces Interacting with The Standard Model

Simple, familiar particle content

Standard Model symmetries allow two types of (dim. 4) interactions with new force carriers at low-energy

Vector Mixing \( \frac{1}{2} \epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu} \)

Higgs Mixing \( \epsilon_h |h|^2 |\phi|^2 \)

+ a few other closely related possibilities…(see 1707.04591)
New Forces Interacting with The Standard Model

Simple, familiar particle content

Standard Model symmetries allow two interactions with new force carriers at low-energy

Vector Mixing
\[ \frac{1}{2} \epsilon_Y F_{\mu\nu}^Y F'_{\mu\nu} \]

Higgs Mixing
\[ \epsilon_h |h|^2 |\phi|^2 \]

Increasingly constrained by LHC
(though other scalar couplings less constrained)

Most compatible with cosmology & simple dark matter models, and illustrates much of the essential physics

focus of this talk
Hidden Sector Dark Matter & Dark Photons

Simple, familiar particle content

Dark Matter charged under a new force

“Dark Photons” are the simplest realization of this broad idea (captures much of the essential phenomenology!)
A Strong Candidate: Hidden Sector DM
(interacting through dark photon)

Simple, familiar particle content

Provides a familiar and simple explanation for dark matter stability (i.e. lightest charged particle is stable!)
**A Strong Candidate: Hidden Sector DM**

Simple, familiar particle content

Simple, predictive cosmology

DM with thermal freeze-out origin
A Strong Candidate: Hidden Sector DM

Simple, familiar particle content

Simple, predictive cosmology

Motivated (broader) mass range

DM with thermal freeze-out origin
Planning Next Steps

Significant planning efforts under way in 2016-2018 to define and launch a new (small-scale) program of dark matter studies to capture the broader landscape of well-motivated possibilities.

Dark Sectors 2016 Workshop: Community Report


Marco Battaglieri (SAC co-chair), Alberto Belloni (Coordinator), Aaron Cheung (WG2 Convener), Priscilla Cushman (Coordinator), Bertrand Echenard (WG3 Convener), Rouven Essig (WG1 Convener), Juan Estrada (WG1 Convener), Jonathan L. Feng (WG4 Convener), Breuna Flaugher (Coordinator), Patrick J. Fox (WG4 Convener), Peter Graham (WG2 Convener), Carter Hall (Coordinator), Ronni Harnik (SAC member), JoAnne Hewett (Coordinator), Joseph Incandela (Coordinator), Eder Izaquique (WG3 Convener), Daniel McKinsey (WG1 Convener), Matthew Pyle (SAC member), Natalie Roe (Coordinator), Gay Rybska (SAC member), Pierre Sikive (SAC member), Tim M.P. Tait (SAC member), Natalia Toro (SAC co-chair), Richard Van De Water (SAC member), Neal Wein, Joseph Lykken, John Jaros, Stephen Derenzo, Antonia Di Crescenzo, Matthew Echenard, Eric Dahl, Milind Diwan, David Mark Asner, Jessica Catmir, Andre Rubbia, Mario Stockinger.

Dark Sectors 2016 report — Establish the community and scope of science

2017 US Cosmic Visions report — Sharpen the science case and ideas for new experiments.

arXiv:1707.04591

arXiv:1608.0832

arXiv:1608.08632

arXiv:1608.08632

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Basic Research Needs study for Dark-Matter Small Projects

Shaped by formal DOE oHEP charge:

- Identify priority science opportunities and high impact parameter space targets
- Identify high impact opportunities which can be pursued by small projects
- Suggest opportunities that could be pursued by future small projects

HEPAP Brochure

Rocky Kolb’s November 2018 HEPAP talk
An Emerging Program

Three Priority Research Directions

Create & Detect Dark Matter at Accelerators

Detect Galactic Dark Matter Underground

Detect Wave Dark Matter in the Laboratory

Rocky Kolb’s November 2018 HEPAP talk
An Emerging Program

Priority Research Directions (alphabetical 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.
  
  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 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:** Detect wave dark matter using innovative technologies with emphasis on resolving a decades-old mystery of the physics inside the nucleus, the so-called “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.

HEPAP Brochure

An Emerging Program

Priority Research Directions (alphabetical 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...
All three PRD’s are extremely interesting, but in the interest of time I will focus on PRD#1, as this relates directly to ongoing Jefferson Lab efforts.
An Emerging Program

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 also 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.

Rocky Kolb’s November 2018 HEPAP talk
Future Goals
(in my own words!)

Key goals for accelerator experiments:

• Produce and detect sub-GeV dark matter directly

• Produce and detect sub-GeV mediator particles directly

• Test coupling-mass combinations directly relevant to thermal origin dark matter, in addition to broad exploration

For sub-GeV dark matter and dark forces, achieving these goals requires experiments with low to moderate energy beams over a range of beam intensities
Key goals for accelerator experiments:

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Physics of Dark Photons

Nicest (common) example is vector-photon kinetic mixing $\frac{1}{2} \epsilon Y F_{\mu\nu}^{Y} F'_{\mu\nu}^{\prime}$

Vector mixing effectively gives matter of electric charge $q e$ a vector $A'$ coupling $\propto q \epsilon e$

⇒ Wherever there are photons (and sufficient phase space), there are “dark” photons

Annihilation:
$e^+ \rightarrow A' \rightarrow e^-$

Decay:
$\pi^0 \rightarrow \gamma \rightarrow A' \rightarrow e^-$

Radiation:
$e^- \rightarrow A' \rightarrow e^-$
Organizing the Physics

(Vector kinetic mixing as an example — most models work similarly)

DM and Mediator Production

- Contact operator DM production (off-shell $A'$)
- Resonant DM production (on-shell $A'$)
- Visibly decaying mediator; Near-threshold DM production (off-shell mediator)

Search for both the mediator and DM itself!
**Organizing the Physics**

(Vector kinetic mixing as an example — most models work similarly)

[Diagram showing Dark photon mass and Dark matter mass, with points for Contact operator DM production (off-shell A'), Resonant DM production (on-shell A'), and Visibly decaying mediator; Near-threshold DM production (off-shell mediator).]

Search for both the mediator and DM itself!

**JLab experiments!**
Visible “Dark Photons”

Natural parameter space is illustrated by coupling on y-axis, mediator mass on x-axis.
Visible “Dark Photons”

Red/green: e,μ anomalous dipole moments

All other colors: Pair resonance searches

Gray: Beam Dump
Recent accelerator experiments have tested interpretation of muon g-2 anomaly from dark photon — if it decays visibly!
Visible “Dark Photons”

Hints from measured structure for DM self-interactions
Visible “Dark Photons”

Mixing in Grand Unified Theories

Tree-level and one-loop forbidden. 2-loop mixing is expected!
Visible “Dark Photons”

Mixing in Grand Unified Theories

sub-GeV mass scale compatible with epsilon magnitude coupling to SM Higgs
Visible “Dark Photons”

Early universe thermal freeze-out cross-section bounded by DM abundance

\[ \sigma v \sim \alpha_D \epsilon^2 \alpha \times \frac{m^2_{\chi}}{m_A'} \]

For part of DM-A’ mass range, provides a lower limit on mediator coupling vs mass!
Incredible progress expected with next round of small-scale experiments

* GUT-level coupling
* well-motivated mass range
* thermal dark matter region of interest
* (not discussed) Be8, EDGES…

Program is multi-purpose — will uniquely test many models beyond kinetic mixing and beyond vector mediators!
Two Jefferson Lab experiments that address dark matter/dark sector physics goals have upcoming runs in 2019!

APEX — “A Prime EXperiment" in Hall A (February-March run!)

HPS — “Heavy Photon Search” in Hall B (June-August run!)

I’ll describe the approach common to these experiments first
Dark Sectors at JLab: 2019

Signal process occurs via A’-emission off beam electron scattering on high-Z target

Kinematically irreducible backgrounds originate from “trident” reactions
Dark Sectors at JLab: 2019

Signal and background peaked at opposite ends of phase space!
Experimental Setup

Approach: Detect narrow (signal) resonance in electron-positron pairs above smooth trident background near the energy endpoint

Symmetric kinematics well matched to maximizing signal to background
Experimental Setup

Good mass resolution requires minimal scattering in target!

Target:
- multiple foil target allows to achieve high rate and good (A') mass resolution while keeping multiple scattering to a minimum;
- such design of the target provides wide A' mass range for each fixed beam energy;
- by using high-Z targets (tungsten and tantalum) we maximize the production rate of electron/positron pairs as compared to pions.

Project led by Silviu Covrig and team!
Experimental Setup

Measuring 100’s of MeV mass range requires forward kinematics

At same time, want relatively high energy electron-positron energy (compared to beam) to avoid potential hadronic backgrounds

New septum:
> allows registration of small-angle $e^+e^-$ pairs in HRS;
> provides operation for full momentum range of the experiment (up to 2.2 GeV);
> has a good magnetic shielding of the beam line.

Project led by collaborators at Carnegie Mellon, NCCU, Cal State LA, Perimeter, Stony Brook, UVA, Rutgers, Hebrew University
Experimental Setup

**SciFi (Scintillator Fibers hodoscopes):**
- with 8.8 cm x 10.3 cm active area in front of Septum Magnet SciFi will allow optics calibration to 0.1 mrad precision;
- makes possible HRSR optics calibration without change of HRS polarity.

Recent efforts led by U. of Glasgow, Andrew Moyer, Toshiyuki Gogami, and many others over past several years!
Experimental Setup

Demonstrated that HRS has up to 5 MHz Rate operation capability with on-line coincidence 20 ns. $e^+e^-$ invariant mass resolution is $\sim0.5\%$.

Many thanks to recent efforts from Florian Hauenstein, Alexandre Camsonne, Bob Michaels, Evan McClellan and other tritium collaborators.
Test run (2010): concept & technical demonstration; weekend run achieved world-record sensitivity, highly cited PRL

Data

QED (no efficiency correction)

Accidental

• Begin exploring GUT range of coupling below muon threshold
• Explore part of the coupling-mass range motivated by thermal DM
• Aim to go to lower mass in future with low energy runs if possible, or altered kinematics configuration

2019 Physics Run (2/7 - 3/13): start with a single 2.2 GeV run configuration to deliver first physics results at high statistics. Focus on mass range below muon threshold to complement CERN LHCb efforts

\[ \frac{\epsilon}{2} \]

\[ a_\mu, 5\sigma \]

\[ a_\mu, 2\sigma \text{ favored} \]

\[ M_A'/M_X = 1.5 \]

lower bound on thermal targets

\[ \alpha_D = 0.5, M_A'/M_X = 1.5 \]

Orsay/E137/CHARM/U70

E141
Fantastic response to anticipated shift needs! Still some shifts left in March!
Key capability — precision tracking of electron/positrons to detect displaced decays

Allows sensitivity to very weak couplings with \( \sim \text{cm} \) decay vertex
Compact $e^+e^-$ spectrometer, immediately downstream of thin target in multi-GeV beam in Hall B.

- Low-mass, high-rate (up to 4 MHz/mm$^2$) silicon tracker (SVT) allows vertexing long-lived $A'$. SVT must suppress SM tridents from target by factor $\sim 10^7$.

- PbWO$_4$ ECal trigger eliminates 10's MHz scattered single $e^-$. Short engineering runs in 2015 (1.7 days) and 2016 (5.4 days).
HPS @ JLab: 2019
No new sensitivity for minimal dark photons, but analyses prove concept in advance of physics runs.
First physics run scheduled for 6/10 — 8/4/2019
8 weeks at 4.55 GeV, \(\approx\) 4 weeks of data = 0.7 C (50% typical duty cycle)

HPS can also discover
True muonium (ortho)!
Two Jefferson Lab experiments that address dark matter/dark sector physics goals have upcoming runs in 2019!

APEX — “A Prime EXperiment" in Hall A (February-March run!)

HPS — “Heavy Photon Search” in Hall B (June-August run!)

Exciting data expected this year!
Still plenty of room to get involved
Organizing the Physics
(Vector kinetic mixing as an example — most models work similarly)

JLab and other efforts in US as well!

Search for both the mediator and DM itself!

DM and Mediator Production

Contact operator DM production (off-shell $A'$)

Resonant DM production (on-shell $A'$)

Visibly decaying mediator; Near-threshold DM production (off-shell mediator)

$2m_e$
Light Dark Matter Searches at Beam Dumps

Dark Matter interacts weakly

⇒ passes through anything!

Produce DM through the portal…

…detect its scattering downstream

Izaguirre, Krnjaic, Schuster & NT PRD.88.114015 and 1403.6826

can use proton beams too!
BDX (parasitic behind JLab Hall A dump)

New sensitivity to dark matter production!

See: arXiv:1712.01518
Conclusions

Testing the dark sector idea is a critical step in our broadening effort to understand the particle nature of dark matter

- Sharp science case with vibrant community
- Important and well-defined parameter space sensitivity milestones (i.e. thermal dark matter, GUT strength couplings, DM self-interactions…)
- **Dedicated “dark force” experiments (APEX & HPS) collecting their first significant data in 2019!**
- Lively activity towards future experimental efforts to produce dark matter in electron beams