New $e^-$ Beam Dump Experiments to Search for Light Dark Matter

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New Perspectives on Dark Matter
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Where Are We Now?

The LHC has found (only) the Higgs

Issues remain: one, two, many? ... natural or not? etc.
But defining question “what triggers EWSB?” is answered

New priority: what is 85% of stuff?

Strong evidence: rotation curves, CMB, lensing, galaxy surveys...
Null LHC results undermine theoretical prejudices

DM is a fishing expedition, so how do we discover it?
Overview

• a “light” dark sector?

• why electron beams?

• what can be done today?

• ... tomorrow?

• sneak preview
Overview

• a “light” dark sector?

• why electron beams?

• what can be done \textit{today}?

• \ldots \textit{tomorrow}?

• sneak preview
“Light” MeV-GeV Dark States?

Are everywhere (in theory space):

asymmetric dark matter, (in)direct detection anomalies, missing satellites, self-interacting dark matter, Sommerfeld enhancement, non-thermal dark matter, hidden valleys, gamma/X-ray lines, “Goodenough Hooperon” annihilation, muon anomalous mag. moment ...

\[
A' \triangleleft 3.5 \sigma \text{ discrepancy}
\]

... yet remain experimentally elusive

Need new ideas
Q: Does “Light” Make Sense?

Naive expectation: overclosure? (Lee/Weinberg)

\[ \langle \sigma v \rangle \sim \frac{\alpha \alpha_D m_X^2}{M_{\text{med}}^4} \implies \Omega_X \gg (\Omega_{DM})_{\text{obs}}. \]

Merely implies light mediator

\[ m_X > M_{\text{med}}, \quad \langle \sigma v \rangle \sim \frac{\alpha \alpha_D}{m_X^2} \implies \frac{\Omega_X}{\Omega_{DM}} \sim 10^{-3} \left( \frac{\alpha}{\alpha_D} \right)^2 \left( \frac{m_X}{100 \text{ MeV}} \right)^2 \]

CMB: Dirac DM (s-wave) annihilation to leptons?

\[ \Omega_X = \Omega_{DM} \implies \sigma_{\chi \chi \rightarrow \ell \ell} < 10^{-5} \left( \frac{m_X}{\text{MeV}} \right) \sigma_{\text{thermal}} \]

\[ \Omega_X < \Omega_{DM} \implies \left( \frac{\Omega_X}{\Omega_{DM}} \right) < 10^{-3} \left( \frac{m_X}{100 \text{ MeV}} \right) \]

**Highly model dependent, more later...**
Q: Does “Light” Make Sense?

A: Yes! (too) many possibilities...

If there are light particles, let’s find them!
Simplified Model

Familiar starting point

$$\frac{\epsilon}{2} F_{\mu \nu} F'_{\mu \nu} + \frac{m_{A'}}{2} A'^{\mu} A'_\mu + \bar{\chi} (i \slashed{D} + m_\chi) \chi + \cdots$$

Most of this talk

$$m_\chi, m_{A'} \sim \text{MeV} - \text{GeV}$$

$$\epsilon \sim 10^{-5} - 10^{-2}$$

$$\alpha_D \sim 10^{-2} - 1$$

Great for fixed target searches
Simplified Model

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Most of this talk

\[ m_\chi, m_{A'} \sim \text{MeV} - \text{GeV} \]
\[ \epsilon \sim 10^{-5} - 10^{-2} \]
\[ \alpha_D \sim 10^{-2} - 1 \]

Great for fixed target searches

\[ U(1)_D \text{ breaking sector always there!} \]

Generic \( O(1) \) DM mass splitting

\[ H_D \bar{\chi}^c \chi \rightarrow v_D \bar{\chi}^c \chi \]
\[ \Delta \sim m_\chi \]

Identical model, Rich pheno, CMB 100% OK!

Friday, May 2, 14
If $A'$ Decays to the SM

Many experiments (arXiv:1209.2558), see Matt’s talk

Much harder for invisible decays
If $A'$ Decays Invisibly

**NB:** Only the $g-2$ curves are model independent.
A’ Decays Invisibly: Neutrino Factories

π^+ \rightarrow \mu^+ \nu_\mu \quad \mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu
\rho + p(n) \rightarrow V^* \rightarrow \chi \chi
\pi^0, \eta \rightarrow V\gamma \rightarrow \chi \chi \gamma

(detector)

χ + N \rightarrow χ + N

Pioneering searches w/ MiniBooNE, LBNE, MINOS NOvA...
DM produced via nuclear physics, scatters downstream
(Batell, Pospelov, de Niverville, McKeen, Ritz, Dharmapalan, Frugiulele, Dobrescu, Yu, Jackson, Soper ...)

However:

Designed to make neutrinos = large NC backgrounds
Large \sim 100 \text{ m - km} baseline degrades acceptance
Proper search expensive, requires dedicated beam time
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Why Electron Beams?

Beam related backgrounds: negligible

Parasitic running: existing beams & detectors

Discount physics: small & cheap

High acceptance: nearby detector & forward kinematics

Cosmic backgrounds: beatable & reducible

Complementary to proton beam searches
How to Search

0. Ingredients

Already exist

Electron beam (few-100) GeV, continuous or pulsed
Beam dump & dirt ~ 10 m, range out beam BG

Just need

Small Detector for NC scattering: oil, plastic, LAr-TPC...
1. Production

$m_{A'} > 2m_\chi \implies$ on-shell $A'$-strahlung

$m_{A'} < 2m_\chi \implies$ off-shell radiative

\[ \sigma \sim \frac{\epsilon^2}{m_{A'}^2} \]

\[ \sigma \sim \frac{\alpha_D \epsilon^2}{m_{\chi}^2} \]

$A'$ gets large fraction of beam energy. Same as APEX/HPS, (see Matt Graham’s) talk
How to Search

2. Detection $\Delta = 0$

Coherent Nuclear
Low recoil energies, light mediator
$Z^2$ enhancement, form factor

Inelastic hadro-production
High Q transfer (e.g. David Soper’s talk)

Electron Scattering
Low recoil energies, light mediator

Quasi-elastic Nucleon
Higher recoil energies $> 10s$ MeV,
How to Search

3. Inelastic DM: $\Delta \neq 0$

**A' produces both eigenstates (beam dump)**

**DM upscatters into excited state**

**Excited state decays promptly**

**Releases ~ GeV energy**

$$\Gamma(\psi \to \chi e^+ e^-) = \frac{8\epsilon^2\alpha\alpha_D\Delta^5}{15\pi m_{A'}^4} + \mathcal{O}(\Delta^6)$$

$$\ell = c\tau \simeq 0.01\text{cm} \left(\frac{\gamma}{2}\right) \left(\frac{10^{-3}}{\epsilon}\right)^2 \left(\frac{0.1}{\alpha_D}\right) \left(\frac{50 \text{ MeV}}{\Delta}\right)^5 \left(\frac{m_{A'}}{50 \text{ MeV}}\right)^4$$
“Benchmark” Setup

1. Layout

12 GeV pulsed

Average current $\sim 80\mu A$

$10^{22}$ EOT ($\sim 1$ yr.)

Duty cycle $\sim 10^{-4}$, live-time $\sim 10^3 s$

Fiducial volume $= 1 m^3$

Oil based detector (CH$_2$)*

Depth $= 15$ m.w.e.
Neutrinos from beam $\pi/\mu$

Nuclear recoil cut $E_{\text{recoil}} > 10$ MeV

$(0.1 - 1)$ BG event per $10^{22}$ $e^-$

Consistent with SLAC mQ rates

Ejected “Fast” Neutrons

$E_n < 10$ MeV, below cuts

$\implies$ Beam backgrounds very small
3. Beam Unrelated Backgrounds

**Cosmic muons**

Decays in flight $\sim 0.005 \text{ Hz (veto)}$
Stopped decays $\sim 100 \mu\text{s cut (veto)}$

**Cosmic neutrons**

$\Phi(E > 10 \text{ MeV}) \approx 2 \times 10^{-2}\text{m}^{-2}\text{s}^{-1}$
Consistent with CDMS-SUF ($\sim 10 \text{ m.w.e}$)

**Pulsed beam** $\sim$ livetime $10^3 \text{ s}$, $\mathcal{O}(10)$ cosmic BG events

$\implies$ **Small, Measurable**
Sensitivity $\sim 10$ event signal yield
"Benchmark" Setup

$E = 12 \text{ GeV}, \ 10^{22} \text{ EOT}, \ \text{Dist.} = 20 \ m, \ \text{Det} = 1 \ m^3$

**Electrophilic** \( \Delta = 0 \)

**Quasi-elastic nucleon**

$E = 12 \text{ GeV}, \ 10^{22} \text{ EOT}, \ \text{Dist.} = 20 \ m, \ \text{Det} = 1 \ m^3$
Overview

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What Can Be Done Today?

1. SLAC FACET-Beam

30 GeV, pulsed
Tungsten dump
Current $\mathcal{O}(\mu A) \implies \sim 10^{20} e^- / \text{Yr.}$
Negligible cosmic BG
Sensitivity $\sim 10$ signal events

Oil based detector $(\text{CH}_2)^*$
Depth = 15 m.w.e.
What Can Be Done Today?

1. SLAC FACET-Beam

\[ E = 30 \text{ GeV}, \ 10^{20} \text{ EOT}, \ \text{Dist.} = 100 \text{ Ft.}, \ \text{Det} = 1 \text{ m}^3 \]

Quasi-elastic nucleon, pulsed

\[ \Delta = 0 \]
What Can Be Done Today?

1. SLAC FACET-Beam

\[ E = 30 \text{ GeV}, \ 10^{20} \text{ EOT}, \ \text{Dist.} = 100 \text{ Ft.}, \ \text{Det} = 1 \text{ m}^3 \]

\[ \epsilon^2 \]

\[ m_{A^*} (\text{MeV}) \]

\[ \alpha_D = 1 \]

\[ \Delta = 0 \]

electrophilic scattering, pulsed beam
Continuous wave 12 GeV

Aluminum beam dump

80μA $\rightarrow \sim 10^{22}$ Electrons/Yr.

No neutron rejection (veto muons)
$N_n \sim 400,000$, Systematics $\sim 2.5\%$

Sensitivity $\sim 20,000$ signal events

Oil based detector $(\text{CH}_2)^*$
Depth = 15 m.w.e.
What Can Be Done Today?

2. JLab CEBAF

$E = 12 \text{ GeV}, \ 10^{22} \text{ EOT}, \ \text{Dist.} = 20 \text{ m}, \ \text{Det} = 1 \text{ m}^3$

Quasi-elastic nucleon, CW beam

$\Delta = 0$

$2 \times 10^4$ events, $m_\ell = 10 \text{ MeV}$
What Can Be Done Today?

2. JLab CEBAF

$E = 12\text{ GeV} (\text{JLab}), \ 10^{22}\text{ EOT}, \ \text{Dist.} = 20\text{ m}, \ \text{Det} = 1\text{ m}^3$

Electrophilic scattering, CW beam

$\Delta = 0$

JLab $2 \times 10^4$ events, $m_\chi = 10\text{ MeV}$

$\alpha_D = 1$

BaBar

$(g-2)_\mu$

$(g-2)_e$

$\epsilon^2$

$m_{A'}\ (\text{MeV})$

$1\ 5\ 10\ 50\ 100\ 500$
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Around the Corner 1

Some BG reduction (JLab)

Goal:

95% cosmic neutron reduction
Comparable to CDMS-SUF
2.5 % systematics ($n$ flux)
Sensitivity $\sim 1000$ event signal yield

Need one/some:
- Active neutron veto
- Neutron moderator
- Directional information
- Oil-based, cubic-meter fiducial
  Depth $\sim 15$ m.w.e
Some BG reduction (JLab)

Quasi-elastic nucleon, CW beam
$\Delta = 0$

$E = 12$ GeV, $10^{22}$ EOT, Dist. = 20 m, Det = 1 $m^3$

$2 \times 10^4, 1 \times 10^3$ events, $m_\chi = 10$ MeV

$E = 12$ GeV, $10^{22}$ EOT, Dist. = 20 m, Det = 1 $m^3$

$2 \times 10^4, 1 \times 10^3$ events, $m_\chi = 10$ MeV
Around the Corner 1
Some BG reduction (JLab)

\[ E = 12 \text{ GeV (JLab)} , \ 10^{22} \text{ EOT} , \ \text{Dist.} = 20 \text{ m.} , \ \text{Det} = 1 \text{ m}^3 \]

Electrophilic scattering, CW beam \( \Delta = 0 \)

Friday, May 2, 14
Around the Corner 2

Aggressive BG reduction (JLab)

Goal:
99.9% background reduction \(\sim 400\) events
Statistics dominated uncertainty
Sensitivity \(\sim 40\) event signal yield

Need all (?) of these:
Active neutron veto
Neutron moderator
Directional information

Oil-based, cubic-meter fiducial
Depth \(\sim 15\) m.w.e
Around the Corner 2
Aggressive BG reduction (JLab)

$E = 12 \text{ GeV} \ , \ 10^{22} \text{ EOT} \ , \ \text{Dist.} = 20 \text{ m} \ , \ \text{Det} = 1 \text{ m}^3$

Quasi-elastic nucleon , CW beam

$\Delta = 0$

$2 \times 10^4, 1 \times 10^3, 40 \text{ events}, \ m_x = 10 \text{ MeV}$

$E = 12 \text{ GeV} \ , \ 10^{22} \text{ EOT} \ , \ \text{Dist.} = 20 \text{ m} \ , \ \text{Det} = 1 \text{ m}^3$

$\alpha_D = 0.1$

$\alpha_D = 1$
Around the Corner 2
Aggressive BG reduction (JLab)

\[ E = 12 \text{ GeV (JLab)}, \quad 10^{22} \text{ EOT}, \quad \text{Dist.} = 20 \text{ m}, \quad \text{Det} = 1 \text{ m}^3 \]

\[ 2 \times 10^4, 1 \times 10^3, 40 \text{ events, } m_\chi = 10 \text{ MeV} \quad \alpha_D = 1 \]

electrophilic scattering, CW beam \( \Delta = 0 \)
Side Comment

Vary DM Mass

$m_X = 250$ MeV

$m_X = m_X/2 = 68$ MeV

$m_X = 10$ MeV

$e^-$ Beam

$\alpha_D = 1$

40 event yield contours
Variations

Our work only a proof of concept, not optimal!
Detector size, material, location may all vary in a smarter setup

Exploit high acceptance?
JLab setup cosmics limited. Run smaller, closer w/ more shielding?

Different dump?
Beam related BG may not be negligible! May need deflectors

Different beam?
CW: JLab, Mainz, DESY...
Pulsed: SLAC, SuperKEKB, ILC (?)...

Different cuts/signals (electron, inelastic...)?
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Existing Detector:

CORMORAD prototype
CORMORINO
scale (1:3)³ ~3% m³

Prototype cell
★ 4 30x5x5 cm³ NE110 bars
★ 1 5x10x10 cm³ NE110 block
★ 12.5 µm Gd foils wrapping

Light read-out:
18 Photonis XP2312 3” PMTs

Size: 40 x 30 x 30 cm³

Test run w/ ~ 10¹⁹ EOT with a smaller detector. Can it cover new ground?
JLab Test Run Sensitivity

Letter of intent ~ Summer 2014
Hall D test run, CORMORINO
See $e^\pm$, recoil irrelevant!
Sensitive to NP w/ only $\sim 10^{19} e^-$
Summary

Electron fixed-target searches are powerful
High acceptance, negligible beam BG, reducible cosmic BG

Probe almost entire, viable MeV – GeV range
Dedicated experiment can extend sensitivity by orders of magnitude
Definitively cover (g-2)µ, complement proton and visible A’ searches

Can run parasitically at existing facilities
JLab, SLAC, Mainz, DESY, Super KEK-B

Small & cheap
Parasitic running, meter-scale (or smaller) detector

Only the beginning
Letter of intent for either test run or full experiment @ JLAB
(summer 2014, stay tuned)
Thanks!