Light Dark Matter search using electron beams

M. Battaglieri
INFN-GE Italy
Dark matter proofs

Galaxies rotation curve shows constant velocity despite visible mass is concentrated at the center

Big portion of invisible mass in the outer regions (halo)

The mass of galaxy clusters can be estimated in different ways:

- **X-ray emission**: Hydrostatic equilibrium links pressure, temperature, density (mass)

  Hydra A galaxy cluster. Chandra X-ray observations reveal a large cloud of hot gas that extends throughout the cluster.

- **Gravitational lensing**: A mass in between the source and the observer distorts the light propagation acting as a lens

  Mass balance
  Total mass $10^{14} - 10^{15} \, M_\odot$
  Gas fraction $\sim 16\%$ ($\sim 13\%$ ICM, $\sim 3\%$ galaxies).
  Remaining $84\%$ of the mass is in dark matter

  DM in CMB
  Clusters of galaxies
  Cluster collisions
  …

  Compelling astrophysical indications about DM existence
**Dark Matter (DM) vs Baryonic Matter (BM)**

★ How much DM w.r.t. BM?

![Iceberg diagram](image)

.. even worse if we consider the total balance

Only ~4% of the Universe is explained by the Standard Model of the elementary particles

★ Is DM undergoing to other interactions? is the DM made by ‘particles’ (such as the ones in the Standard Model)?

★ Constraint on DM mass and interactions

- should be ‘dark’ (no em interaction)
- should weekly interact with SM particles
- should provide the correct relic abundance
- should be compatible with CMB power spectrum

★ We can use what we know about standard model particles to build a DM theory

*Use the SM as an example:  \( SM = U(1)_{EM} \times SU(2)_{Weak} \times SU(3)_{Strong} \)*

... assuming that the gravity is not modified and DM undergoes to other interactions
4 fundamental interactions known so far: strong, electromagnetic, weak and gravitational

**Particles, interactions and symmetries**

- **Known particles & new force-carriers**
  - Particles: quarks, leptons
  - Force-carriers: gluons, $\gamma$, $W$, $Z$, graviton (?), Higgs, ...

**Two options:**
- ★ **New matter** interacting through the same forces
- ★ **New matter** interacting through new forces

**Dark Matter**
- New particles & new force-carriers
  - Spin-1: U bosons (‘hidden’ or ‘dark’ photons)
  - Spin-0: Axions (or axion-like particles)
  - Spin-0 (scalars): Higgs-like
Any guess about the DM mass and interaction?

Yes, if we do a couple of assumptions:

★ DM thermal origin
  in the early Universe DM was in thermal equilibrium with regular matter (via annihilation)

★ DM as thermal relic from the hot early Universe
  Minimal DM abundance is left over to the present day

Correct DM density for an annihilation xsec:

\[ \langle \sigma v \rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{s} \sim 1/(20 \text{ TeV})^2 \]

WIMPs (Weakly Interacting Massive Particles)

• Massive DM with massive mediator
• For \( \sim 100 \text{ GeV} \) DM mass, weak-scale mediators provide reasonable annihilation rate and range of DM-scattering rates

Thermal origin suggests DM interactions and mass in the vicinity of the weak-scale
Exploring the WIMP’s option

★ Experimental limits

**Slow-moving cosmological weakly interacting massive particles**

- DM detection by measuring the (heavy) nucleus recoil
- Constraints on the interaction strength from the DM Direct Detection limits

  - Scattering through Z boson ($\sigma \sim 10^{-39} \text{cm}^2$): ruled out
  - Approaching limits for scattering through the Higgs ($\sigma \sim 10^{-45} \text{cm}^2$)
  - Close to irreducible neutrino background

★ No signal in direct detection
★ Experiments have (almost) no sensitivity to (light) DM (<1 GeV)
Introducing a new force in nature

- Hidden sector (HS) present in string theory and super-symmetries
- HS not charged under SM gauge groups (and v.v.) no direct interaction between HS and SM
- HS-SM connection via messenger particles

A simple way to go beyond the SM (not yet excluded!):

\[ SU(3)_C \times SU(2)_L \times U(1)_Y \times \text{extra } U(1) \]

Color Electroweak Hypercharge Hidden sector

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\chi}{2} X_{\mu\nu} F_{\mu\nu}^{\text{Visible}} + \frac{m_{\gamma'}^2}{2} X_{\mu} X^{\mu} \]

\( \gamma' / A' \) couples to SM via electromagnetic current (kinetic mixing)

\( \Rightarrow A_\mu = A_\mu + \epsilon a_\mu \quad \chi = \epsilon \sim 10^{-6} - 10^{-2} \) (\( \alpha e_{\text{SM}} + \eta_{\text{HS}} = \epsilon^2 \alpha_{\text{SM}} \))

\( \Psi \) can be a huge mass scale particle (\( M_{\Psi} \sim 1 \text{EeV} \)) coupling to both SM and HS
Light Dark Matter

Light Dark Matter with a (almost) weak interaction (new force!)
- Direct Detection is (almost) impossible
  - Low mass elastic scattering on heavy nuclei produces small recoil
  - eV-range recoil requires a different detection technology
  - Directionality may help to go behind existing limits at large masses

Accelerators-based DM search
covers an unexplored mass region extending the reach outside the classical DM hunting territory
- **High intensity**
- **Moderate energy**

N.Toro

Want to look here!

Light Dark Matter

Direct Detection

1 MeV 1 GeV \( M_z \) 10 TeV

WIMPs

Dark Sector or Hidden Sector (DM not directly charged under SM interactions)

Can be explored at accelerators!
Dark forces and dark matter
(Light WIMPs - light mediators)

- **Minimal decay**
- **Decay regulated by** $\varepsilon^2$
- **Independent of** $m_\chi$
- **Requires** $m_{A'} < 2m_\chi$

**Visible**

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

**Invisible**

- **Depends on 4 parameters**
- $m_{A'} > 2m_\chi$ (on-shell)
- $\alpha_D = g_\chi^2/4\pi \gg \varepsilon^2\alpha_{EM}$

4 parameters: $m_\chi, m_{A'}, \varepsilon, g_\chi$

$m_\chi \sim m_{A'} \sim \text{MeV} - 5 \text{ GeV}$

Visible

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

Invisible

- $A' \rightarrow \chi$
- $A' \rightarrow \overline{\chi}$

**Visible**

- $\sigma \propto \varepsilon^2$
- $\Gamma_{e^+e^-} \propto \varepsilon^2$

**Invisible**

- $\sigma \propto \varepsilon^2$
- $\Gamma_{\chi\chi} \propto 1$ (not $\varepsilon$-suppressed!)
**Fixed target vs. collider**

**Process**

- Fixed Target
  - $\sigma \sim \frac{\alpha^3 Z^2 e^2}{m^2} \sim O(10 \text{ pb})$
  - $1/M_{A'} \text{ vs. } 1/E_{\text{beam}}$
  - Coherent scattering from Nucleus ($\sim Z^2$)
  - High backgrounds
  - Limited $A'$ mass

- $e^+e^-$ colliders
  - $\sigma \sim \frac{\alpha^2 e^2}{E^2} \sim O(10 \text{ fb})$
  - Low backgrounds
  - Higher $A'$ mass

**Luminosity**

- Fixed Target
  - $10^{11} \text{ e}^-$
  - $\sim 10^{23}$ atoms in target

- $e^+e^-$ colliders
  - $10^{11} \text{ e}^-$
  - $10^{11} \text{ e}^+$
Heavy photon signatures in HPS

1) Bump Hunting (BH)
Narrow $e^+e^-$-resonance over a QED background
➤ good mass resolution: $\sigma_{A'\text{mass}} \sim 1 \text{ MeV}$

2) Secondary decay vertex (vertexing)
Detached vertex from few mm to tens cm
➤ good spacial resolution: $\sigma_{\text{vertex}} \sim 1 \text{ mm}$

BH + Vertexing = enhanced experimental reach
e+e- Colliders Recent & future results - visible -

- 1 gamma + 2 opposite leptons
- Di-lepton mass fit to a bg
- Mass resolution: 1.5 MeV - 8 MeV
- Int (L) = 514 fb⁻¹


- Events with μ+μ- detected
- L ~ 240 pb⁻¹

J.P. LEEs et al. (The BABAR Collaboration) - PRL 113, 201801 (2014)
Hunting for A’ at accelerators

Fixed target: e N → N γ’ → N Lepton⁻ Lepton⁺ → JLAB, MAINZ

Fixed target: p N → N γ’ → p Lepton⁻ Lepton⁺ → FERMILAB, SERPUKHOV

Annihilation: e⁺e⁻ → γ’ γ → μ⁺μ⁻ γ → BABAR,BELLE,KLOE

Meson decays: π⁰, η, η’, ω’ → γ’ γ → Lepton⁻ Lepton⁺ γ → KLOE, BES3, NA48, HC

coupling vs mass
Hunting for A’ at accelerators

Fixed target: $e\,N \rightarrow N\,\gamma' \rightarrow N\,\text{Lepton}^{-}\,\text{Lepton}^{+}$
$\rightarrow$ JLAB, MAINZ

Fixed target: $p\,N \rightarrow N\,\gamma' \rightarrow p\,\text{Lepton}^{-}\,\text{Lepton}^{+}$
$\rightarrow$ FERMILAB, SERPUKHOV

Annihilation: $e^+ e^- \rightarrow \gamma' \gamma \rightarrow \mu\mu\,\gamma$
$\rightarrow$ BABAR, BELLE, KLOE

Meson decays: $\pi^0, \eta, \eta', \omega \rightarrow \gamma' \gamma \rightarrow \text{Lepton}^{-}\,\text{Lepton}^{+}\,\gamma$
$\rightarrow$ KLOE, BES3, NA48, HC

No positive signal (so far) but limits in parameter space coupling vs mass
Dark forces and dark matter  
(Light DM - light mediators)

Visible

- Minimal decay
- Decay regulated by $\epsilon^2$
- Independent of $m_X$
- Requires $m_{A'} < 2m_X$ (on-shell)

Invisible

- Depends on 4 parameters
- $m_{A'} > 2m_X$ (on-shell)
- $\alpha_D = g^2_X/4\pi \gg \epsilon^2 \alpha_{EM}$

4 parameters: $m_X, m_{A'}, \epsilon, \alpha_D$

$m_X, \sim m_{A'}: \text{MeV - GeV}$
Particle physics search of A’
- invisible -

Fixed target:  e N → N γ’ → N Lepton⁻ Lepton⁺
  → JLAB, MAINZ
Fixed target:  p N → N γ’ → p Lepton⁻ Lepton⁺
  → FERMILAB, SERPUKHOV
Annihilation:  e⁺e⁻ → γ’ γ → μ⁺μ⁻
  → BABAR, BELLE, KLOE
Meson decays:  π⁰, η, η’, ω → γ’ γ → Lepton⁻ Lepton⁺ γ
  → KLOE, BES3, NA48, HC

No positive signal (so far) but limits in parameter space coupling vs mass
**e^+ annihilation on fixed (thin) target - invisible -**

**Fixed-target config**

- Independent of A' decay mechanism
- Bump hunt (monophoton@collider)
- Need a positron beam
- Limited M_{A'} accessible
  - 1 GeV beam: M_{A'} < 31 MeV
  - 5 GeV beam: M_{A'} < 71 MeV
  - 11 GeV beam: M_{A'} < 106 MeV

**Missing mass search:**

- LNF
  - e^+ = 550 MeV
  - EOT ~ 10^{13} - 10^{14} year^{-1}

- Cornell
  - E_{e^+} = 5.3 GeV
  - EOT ~ 10^{17} - 10^{18} year^{-1}
  - \(a_{\mu2}\) favored

- JLab
  - E_{e^-} = 11 GeV
  - EOT ~ 10^{18} - 10^{19} year^{-1}

- VEPP3
  - E_{e^+} = 500 MeV
  - EOT ~ 10^{15} - 10^{16} year^{-1}

- Novosibirsk
- LNF
- Cornell
- Jefferson Lab

**Invisibility**

- a_{\mu2}, a_{\mu32} favored
- New analysis: longer e+ pulses e+ front veto
- \(750 \text{ MeV } e^+\)

**Invisibly Decaying Dark Photon \(A' \to \gamma \gamma\)**

- DarkLight
- Ballar
- NA64
- VEPP3
- MNSAPs
- Belle II
- LDMX

**PRELIMINARY**

- I = 10 nA
- I = 100 nA
The BDX experiment

Two step process

I) An electron radiates an A’ and the A’ promptly decays to a \( \chi \) (DM) pair

II) The \( \chi \) (in-)elastically scatters on a e/nucleon in the detector producing a visible recoil (GeV)

Experimental signature in the detector:

\[ \chi \text{-electron} \rightarrow \text{EM shower} \sim \text{GeV energy} \]
BDX @ JLab

approved by JLab 2018
PAC with max rate (A)

- High energy beam available: 11 GeV
- The highest available electron beam current: ~65 uA
- The highest integrated charge: $10^{22}$ EOT (41 weeks)
- New experimental hall (~2$M$) at JLab
- BDX detector (recycling BaBar CsI crystals) ~$1M$
- Expected to run in ~2y

Expected BDX reach

Accumulating $10^{22}$ EOT in ~1y BDX sensitivity is 10-100 times better than existing limits on LDM

BDX detector: E.M. Calorimeter + Veto
- 8 modules 10x10 crystals each
- 800 CsI(Tl) crystals (from BaBar EMCal)
- 6x6 mm$^2$ Hamamatsu SiPM readout
- Plastic scintillator + WLS fibres, sips RO

BDX prototype to assess cosmic bg
Missing energy/momentum BD experiments

Present ...

- E137 and NA64: null results interpreted as invisible decay search
- No showering effects included

... and future BD experiments

- LDMX: missing momentum exp proposed at SLAC-LCLS-II 4 GeV e-beam, (Active beam-dump)
- BDX: beam-dump exp proposed at JLAB 11 GeV e-beam with $10^{22}$ EOT in 1y run
## Status and perspectives

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Lab</th>
<th>Production</th>
<th>Detection</th>
<th>Vertex</th>
<th>Mass (MeV)</th>
<th>Mass Res. (MeV)</th>
<th>Beam</th>
<th>Ebeam (GeV)</th>
<th>Dose or Lumi</th>
<th>Machine</th>
<th>1st Run</th>
<th>Next Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>APEX</td>
<td>JLab</td>
<td>e-brem</td>
<td>1+1</td>
<td>no</td>
<td>65 – 600</td>
<td>0.5%</td>
<td>e(^+)</td>
<td>1.1–4.5</td>
<td>150 (\mu)A</td>
<td>CEBAF(A)</td>
<td>2010</td>
<td>2018</td>
</tr>
<tr>
<td>A1</td>
<td>Mainz</td>
<td>e-brem</td>
<td>e(^+)e(^-)</td>
<td>no</td>
<td>40 – 300</td>
<td>?</td>
<td>e(^-)</td>
<td>0.2–0.9</td>
<td>140 (\mu)A</td>
<td>MAMI</td>
<td>2011</td>
<td>–</td>
</tr>
<tr>
<td>HPS</td>
<td>JLab</td>
<td>e-brem</td>
<td>e(^+)e(^-)</td>
<td>yes</td>
<td>20 – 200</td>
<td>1–2</td>
<td>e(^-)</td>
<td>1–6</td>
<td>50–500 nA</td>
<td>CEBAF(B)</td>
<td>2015</td>
<td>2018</td>
</tr>
<tr>
<td>DarkLight</td>
<td>JLab</td>
<td>e-brem</td>
<td>e(^+)e(^-)</td>
<td>no</td>
<td>&lt; 80</td>
<td>?</td>
<td>e(^-)</td>
<td>0.1</td>
<td>10 mA</td>
<td>LERF</td>
<td>2016</td>
<td>2018</td>
</tr>
<tr>
<td>MAGIX</td>
<td>Mainz</td>
<td>e-brem</td>
<td>e(^+)e(^-)</td>
<td>no</td>
<td>10 – 60</td>
<td>?</td>
<td>e(^-)</td>
<td>0.155</td>
<td>1 mA</td>
<td>MESA</td>
<td>2020</td>
<td>–</td>
</tr>
<tr>
<td>NA64</td>
<td>CERN</td>
<td>e-brem</td>
<td>e(^+)e(^-)</td>
<td>no</td>
<td>1 – 50</td>
<td>?</td>
<td>e(^-)</td>
<td>100</td>
<td>(2 \times 10^{11}) EOT/yr</td>
<td>SPS</td>
<td>2017</td>
<td>2022</td>
</tr>
<tr>
<td>Super-HPS</td>
<td>SLAC</td>
<td>e-brem</td>
<td>vis</td>
<td>yes</td>
<td>&lt; 500</td>
<td>?</td>
<td>e(^-)</td>
<td>4–8</td>
<td>1 (\mu)A</td>
<td>DASEL</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>(TBD)</td>
<td>Cornell</td>
<td>e-brem</td>
<td>e(^+)e(^-)</td>
<td>?</td>
<td>&lt; 100</td>
<td>?</td>
<td>e(^-)</td>
<td>0.1–0.3</td>
<td>100 mA</td>
<td>CBETA</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>VEPP3</td>
<td>Budker</td>
<td>annih</td>
<td>invis</td>
<td>no</td>
<td>5 – 22</td>
<td>1</td>
<td>e(^+)</td>
<td>0.500</td>
<td>(10^{33}) cm(^{-2})s(^{-1})</td>
<td>VEPP3</td>
<td>2019</td>
<td>?</td>
</tr>
<tr>
<td>PADME</td>
<td>Frascati</td>
<td>annih</td>
<td>invis</td>
<td>no</td>
<td>1 – 24</td>
<td>2–5</td>
<td>e(^+)</td>
<td>0.550</td>
<td>(&lt; 10^{14}) e+OT/yr</td>
<td>Linac</td>
<td>2018</td>
<td>?</td>
</tr>
<tr>
<td>MMAPS</td>
<td>Cornell</td>
<td>annih</td>
<td>invis</td>
<td>no</td>
<td>20 – 78</td>
<td>1–6</td>
<td>e(^+)</td>
<td>6.0</td>
<td>(10^{34}) cm(^{-2})s(^{-1})</td>
<td>Synchr</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>KLOE 2</td>
<td>Frascati</td>
<td>several</td>
<td>vis/invis</td>
<td>no</td>
<td>(&lt; 1.1) GeV</td>
<td>1.5</td>
<td>e(^+)e(^-)</td>
<td>0.51</td>
<td>(2 \times 10^{32}) cm(^{-2})s(^{-1})</td>
<td>DA(\phi)NE</td>
<td>2014</td>
<td>–</td>
</tr>
<tr>
<td>Belle II</td>
<td>KEK</td>
<td>several</td>
<td>vis/invis</td>
<td>no</td>
<td>(&lt; 10) GeV</td>
<td>1–5</td>
<td>e(^+)e(^-)</td>
<td>4 \times 7</td>
<td>1 \sim 10 ab(^{-1})</td>
<td>Super-KEKB</td>
<td>2018</td>
<td>–</td>
</tr>
<tr>
<td>SeaQuest</td>
<td>FNAL</td>
<td>several</td>
<td>(\mu^+\mu^-)</td>
<td>yes</td>
<td>(&lt; 10) GeV</td>
<td>3–6%</td>
<td>p</td>
<td>120</td>
<td>(10^{18}) POT/(y)</td>
<td>MI</td>
<td>2017</td>
<td>2020</td>
</tr>
<tr>
<td>SHIP</td>
<td>CERN</td>
<td>several</td>
<td>vis</td>
<td>yes</td>
<td>(&lt; 10) GeV</td>
<td>1–2</td>
<td>p</td>
<td>400</td>
<td>(2 \times 10^{20}) POT/5(y)</td>
<td>SPS</td>
<td>2026</td>
<td>–</td>
</tr>
<tr>
<td>LHCb</td>
<td>CERN</td>
<td>several</td>
<td>(l^+l^-)</td>
<td>yes</td>
<td>(&lt; 40) GeV</td>
<td>\sim 4</td>
<td>pp</td>
<td>6500</td>
<td>\sim 10 fb(^{-1})</td>
<td>LHC</td>
<td>2010</td>
<td>2015</td>
</tr>
</tbody>
</table>

* The table represents various experiments and their dark matter search parameters, including the laboratory where the experiment was conducted, the production method, detection methods, and relevant masses and luminosities. The table is intended to provide an overview of the status and perspectives of dark matter searches using electron beams as of the date indicated.

---

**Dark Sectors 2016 Workshop**  
ArXiv:1608.08632
Conclusions

✴ Existence of Dark Matter is a compelling reason to investigate new forces and matter over a broad range of mass

✴ Accelerator-based (Light)DM search provides unique feature of distinguish DM signal from any other cosmic anomalies or effects

✴ Extensive experimental plans at high intensity e-facility: JLab, LNF, Cornell, Mainz, SLAC (+ p beam at FNAL and CERN)

✴ A new generation of dedicated and optimised experiments at high intensity frontier will test the relic (light) dark matter scenario

✴ Many experiments run at electron-beam facilities excluding a significant fraction of parameter space

✴ … and more are expected in the future

✴ Discovery or decisive tests of simplest scenarios will possible in the next ~5-8 years!