A Particle Physicist’s Perspective on EDGES

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with Asher Berlin, Dan Hooper, & Gordan Krnjaic
1803.02804, PRL
EDGES

Experiment to Detect the Global Epoch of reionization Signature

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Detects the absorption strength of the spin flip transition of neutral H in the 1s state

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\[ T_{21} \sim \frac{(T_s - T_{CMB,0})}{(1+z)} \]
EDGES

Experiment to Detect the Global Epoch of reionization Signature

Detects the absorption strength of the spin flip transition of neutral H in the 1s state

\[ T_{21} \sim (T_s - T_{CMB,0})/(1+z) \]

\[ T_{21,SM} > -200 \text{ mK} \]

EDGES

Cohen et al, 1609.02312
EDGES

Cohen et al, 1609.02312

(Putative) EDGES Signal
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\[ \sigma(v=1\, \text{km/s}) \, [\sigma_{\text{np}}] \]

\[ 10^4 \]
\[ 10^5 \]
\[ 10^6 \]
\[ 10^7 \]
\[ 10^8 \]
\[ 10^9 \]

\[ m_\chi \, (\text{GeV}) \]

Barkana
Nature 555
(2018)
Millicharge Scattering

\[ \frac{d\sigma_{Xf}}{d\Omega} = \frac{\alpha_{EM}^2 \epsilon^2}{4\mu_X^2 v_{\text{rel}}^4 \sin^4\left(\frac{\theta}{2}\right)} \rightarrow \]

\[ \rightarrow \sigma_t \approx \frac{2\pi \alpha_{EM}^2 \epsilon^2}{\mu_X^2 v_{\text{rel}}^4} \left[ 60 + \ln \left( \frac{x_e \epsilon^2}{10^{-12}} \right) \right] \]
(Putative) EDGES Signal
(Putative) EDGES Signal

Millicharged Dark Matter Fraction $f_{DM} = 1$

see also:
Muñoz & Loeb 1802.10094 (forthcoming in Nature)

Barkana et al., 1803.03091

Liu & Slatyer, 1803.09739
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Outline

1. Astrophysical & Cosmological Implications
2. Future Directions
Early Univ. Production

\[ A' \bar{\chi} \gamma X \]

\[ \chi \bar{\chi} f \]

\[ X \leftrightarrow Y \]

\[ f \]

\[ X \leftrightarrow f \]

\[ X \leftrightarrow \bar{f} \]
Early Univ. Production

Annihilation: $\sigma v = \pi \alpha^2 \epsilon^2 / m x^2$

Diagram of particle interactions with arrows indicating $\epsilon \epsilon$, $e$, and $X$.
Annihilation: $\sigma v = \pi \alpha^2 \varepsilon^2/m_x^2$

Thermalized: $n_x \sigma v(T=m_x) \sim H(T=m_x) \Rightarrow \varepsilon > 10^{-7}(m_x/\text{GeV})^{1/2}$
Annihilation: $\sigma v = \pi \alpha^2 \epsilon^2 / m_X^2$

Thermalized: $n_X \sigma v(T=m_X) \sim H(T=m_X) \Rightarrow \epsilon > 10^{-7} (m_X/\text{GeV})^{1/2}$

Relic abundance: $\sigma v \approx \sigma_{\text{th}} (\epsilon/10^{-3})^2 / (m_X/\text{GeV})^2$
Early Univ. Production

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Thermalized: $n_X \sigma v(T=m_X) \sim H(T=m_X) \Rightarrow \epsilon > 10^{-7} (m_X/\text{GeV})^{1/2}$

Relic abundance: $\Omega_{\text{DM}} h^2 \approx 0.1 (m_X/\text{GeV})^2 / (\epsilon/10^{-3})^2$
Relic Density

Millicharged Dark Matter Fraction $f_{DM} = 1$

Relic Density

$\epsilon$ $10^{-5}$ $10^{-6}$ $10^{-7}$ $10^{-8}$ $10^{-9}$ $10^{-10}$ $10^{-11}$ $10^{-12}$

$m_X [\text{GeV}]$

EDGES

Equilibrated

$0.001$ $0.01$ $0.1$ $1$ $10$
Baryons should not scatter efficiently with dark matter at the time of CMB: $\Gamma_{Xp} < H_{\text{rec}}$
Baryons should not scatter efficiently with dark matter at the time of CMB:

$$\Gamma_{Xp} < H_{\text{rec}}$$
Rate of change of baryon temperature:

\[
\frac{\langle \frac{d}{dt} \delta T \rangle}{T} = \frac{4}{\sqrt{2\pi}} \frac{\rho_X \sigma_0 \mu_{Xp}^2}{3m_X m_B v_{\text{rel}}} \cdot \frac{1}{T} \approx \frac{4}{3\sqrt{2\pi}} \frac{\rho_X \sigma_0 \mu_{Xp}}{m_X + m_p} \left( \frac{\mu_{Xp}}{T^3} \right)^{1/2} \sim \frac{\epsilon^2}{(m_X + m_p) \sqrt{\mu_{Xp}}}.
\]

Dubovsky et al., hep-ph/0311189
& 1310.2376
McDermott, Yu, & Zurek 1011.2907
Rate of change of baryon temperature:

\[
\frac{\langle \frac{d}{dt} \delta T \rangle}{T} = \frac{4}{\sqrt{2\pi}} \frac{\rho_x \sigma_0 \mu_x^2}{3 m_X m_b v_{\text{rel}}} \cdot \frac{1}{T}
\]

\[
\approx \frac{4}{3} \frac{\rho_x \sigma_0 \mu_x}{m_X + m_p} \left( \frac{\mu_x}{T^3} \right)^{1/2} \approx \frac{\epsilon^2}{(m_X + m_p) \sqrt{\mu_x}}
\]

(warning — new work indicates this is too conservative)
CMB Bound

Millicharged Dark Matter Fraction $f_{DM} = 1$

Relic Density

EDGES

CMB, KD

Equilibrated

$m_x [\text{GeV}]$
$N_\nu > N_{\nu, SM}$ at time of SM nucleosynthesis injects entropy, screws up agreement w/ observation
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Cyburt et al, 1505.01076

Boehm et al, 1303.6270

$N_{\nu}>N_{\nu, SM}$ at time of SM nucleosynthesis injects entropy, screws up agreement w/ observation

Generically rules out $m_X \leq 10$ MeV
BBN

Millicharged Dark Matter Fraction $f_{DM} = 1$

$\epsilon$ vs $m_X$ [GeV]

Relic Density

$\Delta N_{\text{eff}}$

EDGES

CMB, KD

Equilibrated
Crash Course: SN1987A

Core collapse supernova in the LMC detected simultaneously in Jan 1987 with three instruments (Baksan, IMB, and Kamiokande II)

~ 99% of the difference in grav. binding energy radiated away in the form of neutrinos over ~ 10 seconds

(see my talk tomorrow for more details!)
Cooling phase is consistent with analytic expectation

...but wouldn’t be if a new “energy sink” competed with Standard Model processes

Limited amount of luminosity may be diverted to novel particles $\iff$ bounds on new coupling with SM

(see my talk tomorrow for more details!)
Bounds (schematic)

\[
\epsilon_{pr}(m') \quad N_0 \text{ Trapping} \quad \epsilon_{tr}(m')
\]

Efficiently Produced

\[
\epsilon
\]

\[
L_\nu
\]

Efficiently Trapped

Thermal Emission
Bounds (schematic)

\[
\epsilon_{pr}(m') \quad \text{Efficiently Produced}
\]

\[
\epsilon_{tr}(m') \quad \text{Efficiently Trapped}
\]

\[
\text{Luminosity [arb. units]}
\]

\[
L_\nu\]

\[
\epsilon
\]

\[
n_0 \text{ Trapping}
\]

\[
\text{Thermal Emission}
\]

\[
\text{ruled out}
\]

1611.03864
EDGES Constraints

Millicharged Dark Matter Fraction $f_{DM} = 1$

$\epsilon$ vs. $m_\chi$ [GeV]

- Relic Density
- $\Delta N_{eff}$
- EDGES
- CMB, KD
- SN1987A
- Equilibrated
Perhaps only a subdominant component of dark matter has a millicharge (the rest is cold, collisionless, etc)
Caveats?

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\[ f_{\text{DM}} = \frac{\Omega_{\text{millicharge}}}{\Omega_{\text{DM}}} \]

- Preferred region, relic density curve, CMB bounds change
- BBN and SN don’t
Caveats?

Perhaps only a subdominant component of dark matter has a millicharge (the rest is cold, collisionless, etc)

\[ f_{DM} \sim \Omega_{\text{millicharge}} / \Omega_{DM}^{3/4} \]

(Munoz and Loeb, 1802.10094)

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$$f_{DM} = \frac{\Omega_{\text{millicharge}}}{\Omega_{\text{DM}}} \sim f^{1/2}$$

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- BBN and SN don’t

http://www.solstation.com/x-objects/darkhalo.htm
EDGES Constraints

Millicharged Dark Matter Fraction $f_{DM} = 0.1$

- Relic Density
- $\Delta N_{\text{eff}}$
- EDGES
- CMB, KD
- SN1987A
- Equilibrated
EDGES Constraints

Millicharged Dark Matter Fraction $f_{DM} = 0.1$

$10\%$ of $\Omega_{DM} \sim 50\%$ of $\Omega_b$
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This is too large to be absorbed in the baryon budget at time of CMB...
Can some values of $f_{DM}$ be accommodated?

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This is too large to be absorbed in the baryon budget at time of CMB… Can some values of $f_{DM}$ be accommodated?
$\Omega_b$: BBN vs. CMB

Cyburt et al, 1505.01076
$\Omega_b$: BBN vs. CMB

If this is the true number of baryons
This can "secretly" include millicharged particles if this is the true number of baryons.
\( \Omega_b: \text{BBN vs. CMB} \)

Cyburt et al, 1505.01076

- If this is the true number of baryons, this can "secretly" include millicharged particles.

Approximately: \( 10\% \Omega_b = 2\% \Omega_{DM} \)
$\Omega_b$: BBN vs. CMB

$\sim 10\%$ $\Omega_b = \sim 2\%$ $\Omega_{DM}$

If this is the true number of baryons, this can "secretly" include millicharged particles. No CMB bound below $f_{DM} \sim 2\%$.
\( \Omega_b: \text{BBN vs. CMB} \)

Cyburt et al, 1505.01076

\[
\rho_b = \frac{\Omega_b}{\Omega_{DM}} = \frac{2\%}{\sim 2\%} = 10\%
\]

If this is the true number of baryons, this can "secretly" include millicharged particles.

No CMB bound below \( f_{DM} \sim 2\% \)

1805.11616, de Putter et al.: “we derive a new upper limit on the fraction of tightly coupled dark matter...<0.6%”
EDGES Constraints

Millicharged Dark Matter Fraction $f_{DM} = 0.01$

$\epsilon$ vs $m_x [\text{GeV}]$

$\Delta N_{\text{eff}}$

SN1987A

Equilibrated
EDGES Constraints

Millicharged Dark Matter Fraction $f_{DM} = 0.001$

$\epsilon$

$\Delta N_{\text{eff}}$

SN1987A

Equilibrated

$m_{\chi} \text{[GeV]}$
Outline

1. Astrophysical & Cosmological Signatures
2. Future Directions
EDGES, $f_{DM} = 1\%$

Millicharged Dark Matter Fraction $f_{DM} = 0.01$

$\epsilon$ vs $m_x [\text{GeV}]$

$\Delta N_{\text{eff}}$ and SN1987A regions on the graph.
EDGES, $f_{DM}=1\%$

What do we need to do to make this region work?
Implications of $f_{DM}=1\%$

1. Relic density via QED alone is problematic — how else to deplete thermal abundance?
Couple to New Force

Many possibilities, but some guidelines:
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• Shouldn’t couple to electrons
Couple to New Force

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- Shouldn’t inject too much energy during cosmic dark ages
Couple to New Force

Many possibilities, but some guidelines:

• Shouldn’t couple to electrons
• Shouldn’t inject too much energy during cosmic dark ages
  • neutrinos
  • $p$-wave suppression
Couple to $L_{\mu}-L_{\tau}$

Scalar Millicharge $\chi$ with $L_{\mu} - L_{\tau}$, $g_{\chi} = 1$, $m_{V} = 3m_{\chi}$

$y = (g_{\chi}g_{\mu-\tau})^2(m_{\chi}/m_{V})^4$

$\chi\chi^* \rightarrow \bar{\nu}\nu, \mu^+\mu^-$

$(p -$ wave)
Implications of $f_{DM} = 1\%$

1. Relic density via QED alone is problematic — how else to deplete thermal abundance?

2. Thermal population introduced to SN1987A — how does this affect the eqn of state?
Muon creation in supernova matter facilitates neutrino-driven explosions

R. Bollig,¹ ² H.-T. Janka,¹ A. Lohs,³ G. Martínez-Pinedo,³ ⁴ C.J. Horowitz,⁵ and T. Melson¹
Muon creation in supernova matter facilitates neutrino-driven explosions

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Inclusion of muons significantly effects explodability (Bollig et al. 2017)

Kotake et al 1801.02703
Implications of $f_{\text{DM}}=1\%$

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2. Thermal population introduced to SN1987A — how does this affect the eqn of state?

3. Primordial millicharged particles are evacuated from the disk — is any DD possible?
Reopening the window on charged dark matter

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ABSTRACT: We reexamine the limits on charged dark matter particles. We show that if their mass and charge fall in the range $100(q_X/e)^2 \lesssim m_X \lesssim 10^8(q_X/e)$ TeV, then magnetic fields prevent particles in the halo from entering the galactic disk, while those initially trapped inside are accelerated through the Fermi mechanism and ejected within about 0.1 – 1 Gyrs. Consequently, previous constraints on charged dark matter based on terrestrial non-observation are invalid within that range. ...
EDGES Constraints

Millicharged Dark Matter Fraction $f_{DM} = 0.01$

$\epsilon$ vs. $m_x$ [GeV]

EDGES

$\Delta N_{\text{eff}}$

SN1987A

B field

Equilibrated
DD for 1% of $\Omega_{DM}$

- Such particles are evacuated from the disk…
DD for 1% of $\Omega_{DM}$

- Such particles are evacuated from the disk...
- ...but supernovae are hot!
DD for $1\%$ of $\Omega_{\text{DM}}$

• Such particles are evacuated from the disk…

• …but supernovae are hot!

• Do more appear? What is their phase space? What do they look like at DD experiments?

  • Boosted DM (Agashe et al., 1405.7370)

  • Marques-Tavares et al., in prep
Implications of $f_{\text{DM}} = 1\%$

1. Relic density via QED alone is problematic — how else to deplete thermal abundance?

2. Thermal population introduced to SN1987A — how does this affect the eqn of state?

3. Primordial millicharged particles are evacuated from the disk — is any DD possible?

4. We’ve “already seen” DM in the CMB power spectrum — CMB S4 or BBN improvement?
Different rates, different moments of the Boltzmann equation:

\[ \Gamma \simeq n\langle \sigma v \rangle, \]
\[ \langle \delta \dot{p} \rangle \simeq \mu n\langle \sigma v^2 \rangle, \]
\[ m\langle \delta \dot{T} \rangle \simeq \mu^2 n\langle \sigma v^3 \rangle \]
Changing $T$ (2nd moment of Boltzmann eq):

$$\frac{\langle \frac{d}{dt} \delta T \rangle}{T} = \frac{4}{\sqrt{2\pi}} \frac{\rho X \sigma_0 \mu^2_{Xp}}{3 m_X m_b \nu_{\text{rel}}} \cdot \frac{1}{T_b} \approx \frac{4}{3 \sqrt{2\pi}} \frac{\rho X \sigma_0 \mu_{Xp}}{m_X + m_p} \left( \frac{m_p}{T_p^3} \right)^{1/2}$$

Changing $p$ (1st moment of Boltzmann eq):

$$\frac{\langle \frac{d}{dt} |\delta \vec{p}| \rangle}{\langle |\vec{p}| \rangle} = \frac{2}{3 \sqrt{2\pi}} \frac{\rho X \sigma_0}{m_X + m_p} \left( \frac{m_p}{T_p} \right)^{3/2}$$
Changing $T$ (2nd moment of Boltzmann eq):

Changing $p$ (1st moment of Boltzmann eq):

\[
\begin{align*}
\text{cross section } \sigma_p \text{ [cm}^2]\end{align*}
\]

\[
\begin{align*}
\text{particle mass } m_\chi \text{ [GeV]\end{align*}
\]

V. Gluscevic, private comm.

- Scaling from momentum exchange
- Scaling from heat exchange
- Scaling $(m_p + m_\chi)$
Millicharged particles don’t look exactly like SM fermions — increased precision at high multipoles may be able to distinguish real baryons from DM in the damping tail.
Conclusions

• EDGES has possibly detected evidence of dark matter scattering off baryons during the epoch of structure formation

• If it did, it’s not “minimal” — a rich structure of auxiliary interactions and signals awaits

• We’ll learn (a lot) more (fairly) soon
Conclusions

• EDGES has possibly detected evidence of dark matter scattering off baryons during the epoch of structure formation

• If it did, it’s not “minimal” — a rich structure of auxiliary interactions and signals awaits

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What we find could surprise us!