New Aspects of Millicharged Dark Matter at 21-cm

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Dark Matter-Baryon Scattering
First measurement of the 21-cm global signal. Larger absorption than expected! Suggests a lower baryon temperature than expected at $z \sim 17$: at most 5.2 K instead of the conventional expectation, 6.8 K.
Dark Matter-Baryon Scattering

100% Millicharged DM, 10 MeV, $Q = 1.5 \times 10^{-7} e$

Significant impact on thermal history of the universe. Interesting target for CMB and 21-cm experiments.

Blum+1311.2937, Xu+ 1802.06788, Slatyer+ 1803.09734, de Putter+ 1805.11616, Boddy+, 1808.00001, ...

EDGES

$\Lambda$CDM Baryon
Baryon
Millicharged DM

Redshift $(1+z)$

Temperature [K]

$n = -4$ [TT]

$\frac{C_{l} - C_{l}^{k-\text{independent}}}{C_{l}}$

Boddy+, 1808.00001
All thermal history calculations here performed using **modifications to DarkHistory**!
Baryon Cooling Requirements

High heat capacity: $m_{\text{DM}} \lesssim \text{GeV}$.

Large scattering cross section. Constraints favor $\sigma \propto v^{-4}$ enhancement, i.e. light mediator exchange.

Mediator must be light compared to momentum transfer, i.e. $m_{\phi} \lesssim \text{keV}$. **Severe constraints** favor identifying $\phi$ with the photon, i.e. millicharged dark matter!
Millicharged Cooling

100% Millicharged DM, 10 MeV, $Q = 1.5 \times 10^{-7}e$

100% millicharged dark matter can do the job. **However**...
CMB Constraints

Constrained by cosmic microwave background power spectrum: dark matter-baryon scattering affects the acoustic oscillations and the sound speed.

Millicharged dark matter limited to less than 0.4% of all dark matter by mass density.
Constraints on $N_{\text{eff}}$ from CMB power spectrum are important, as millicharged particles can thermalize in the early universe. Closes all available parameter space.
Millicharged + Cold Dark Matter
Scattering with neutral H and He are important. Can be up to TeV in mass! 

\( \lesssim 0.4\% \) of dark matter. Relatively light (\( \lesssim 20\text{ GeV} \)) for high heat capacity. 

\( \gtrsim 99.6\% \) of dark matter.
Initial **tight coupling** between millicharged DM and baryons.
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Temperature Evolution

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Millicharged DM **cools baryons**. Also scatters off neutral H and He!
Constraints on Dark Sector?

Self-interaction constraints set very weak limits on $g_C$. 
Constraints on Dark Sector?

Same CMB constraints on dark matter-baryon interactions now limits both millicharged fraction ($f_m \lesssim 0.4\%$) and $g_C g_m$ from limits on momentum transfer to dark matter.
Requiring **tight coupling** between millicharged dark matter and baryons sets limits on $g_m g_C$ as a function of $Q$. 
Millicharged Dark Matter Constraints

EDGES 99% C.L. $m_C=100$ MeV

$Q$ vs $m_\chi$ [MeV]

No bath $f_m=10^{-3}$

Colliders $f_m=10^{-6}$

Rocket $f_m=10^{-8}$

Balloon $f_m=10^{-4}$

Ground $f_m=10^{-2}$

Direct Detection $f_m=4\times10^{-3}$

ArgoNeut

Numi–Fermini

DUNE

CMB $N_{\text{eff}}$

MilliQan

SHIP

LDMX

Preliminary
Millicharged Dark Matter Constraints

Pure millicharged model: ruled out by $N_{\text{eff}}$ constraints.
Millicharged Dark Matter Constraints

Our work: millicharged + cold dark matter model.
Small millicharged fraction of $10^{-8} \lesssim f_m \lesssim 4 \times 10^{-3}$ allowed.
Millicharged dark matter **annihilate in the early universe to light mediators**: $N_{\text{eff}}$ limits require $\gtrsim$ GeV mass for millicharged dark matter.
Millicharged Dark Matter Constraints

Relatively independent of cold dark matter mass, as long as $m_C \lesssim 10$ GeV.
Millicharged Dark Matter Constraints

Change in $Q - m_m$ behavior at $m_m \sim \text{GeV}$ due to growing importance of scattering with neutral H and He.
Millicharged Dark Matter Constraints

Direct detection (e.g. SENSEI) sets lower limits. Must be above ground due to large $Q$, and suppressed by small fraction.
**Millicharged Dark Matter Constraints**

![Graph showing constraints on millicharged particles](image)

**Beam experiment limits** on millicharged particles from combination of SLAC milliQ, CMS, LSND and MiniBooNE.
Millicharged Dark Matter Constraints

Future beam experiments will be very important, e.g. Numi-Fermini and DUNE.
Cold dark matter has a model dependent interaction with baryons at one-loop. Most naive implementation a prime target for upcoming direct detection experiments.

Cold Dark Matter Constraints

Cold dark matter has a model dependent interaction with baryons at one-loop. Most naive implementation a prime target for upcoming direct detection experiments.
1. Millicharged + cold dark matter can consistently produce striking 21-cm signatures, and can explain the EDGES observation.

2. Broad range of parameter space allowed: GeV \( \lesssim m_m \lesssim \) TeV with \( f_m \lesssim 0.4 \% \), and \( m_C \lesssim 10 \) GeV.

3. Very testable at beam experiments and direct detection, both current and future.
If neutral hydrogen were in equilibrium with a background source of 21-cm radiation, e.g. the CMB,

\[ T_S = T_R \]
21-cm Processes

21-cm Photons

$T_S \rightarrow T_R$

Collisional Excitation/De-Excitation

important at $z \sim 30 - 70$

$T_S \rightarrow T_m$

Wouthuysen-Field Effect:
Lyman-Alpha Radiation
important at $z \sim 20$

$T_S \rightarrow T_m$
Measure the brightness of the sky in MHz, relative to CMB temperature. Constrains the ratio of **baryon temperature** $T_m$ to **21-cm radiation temperature** $T_R$ in the early universe, $T_m/T_R$. 

Pritchard & Loeb, 1109.6012

**blue - in absorption**

**red - in emission**
Evolution Equations

\[
\frac{dT_b}{d \log a} + 2T_b = \frac{2 f_m \rho_{\rm DM}}{3H(1 + x_e + \mathcal{F}_{\rm He})} \sum_j \frac{x_j \mu_{jm}}{m_m + m_j} \left[ I_{jm}^D + \frac{T_m - T_b}{m_m u_{jm}^2} I_{jm}^T \right] + \frac{\Gamma_{\text{Comp}}}{H} (T_\gamma - T_b),
\]

\[
\frac{dT_C}{d \log a} + 2T_C = \frac{2 f_m \rho_{\rm DM}}{3H} \frac{\mu_{mC}}{m_m + m_C} \left[ I_{mC}^D + \frac{T_m - T_C}{m_m u_{mC}^2} I_{mC}^T \right],
\]

\[
\frac{dT_m}{d \log a} + 2T_C = \frac{2 (1 - f_m) \rho_{\rm DM}}{3H} \frac{\mu_{mC}}{m_m + m_C} \left[ I_{mC}^D + \frac{T_C - T_m}{m_C u_{mC}^2} I_{mC}^T \right] + \frac{2}{3H} \sum_j \frac{n_j m_j \mu_{jm}}{m_m + m_j} \left[ I_{jm}^D + \frac{T_b - T_m}{m_i u_{jm}^2} I_{jm}^T \right],
\]

\[
\frac{dV_{bm}}{d \log a} + V_{bm} = - \left( \frac{\rho_m}{\rho_b} + 1 \right) \sum_j \frac{\rho_j}{m_m + m_j} \frac{I_{jm}^D}{H V_{bm}} + \frac{\rho_C}{m_m + m_C} \frac{I_{mC}^D}{H V_{mC}},
\]

\[
\frac{dV_{mC}}{d \log a} + V_{mC} = - \frac{\rho_m + \rho_C}{m_m + m_C} \frac{I_{mC}^D}{H V_{mC}} + \sum_j \frac{\rho_j}{m_m + m_j} \frac{I_{jm}^D}{H V_{bm}},
\]

\[
\frac{d x_e}{d \log a} = - \frac{C}{H} \left( n_H A_B x_e^2 - 4 (1 - x_e) B_B e^{3 E_0 / (4 T_\gamma)} \right).
\]
Rates Plot

- Temperature $[K]$ vs. Redshift $(1+z)$
- Ionization Fraction $x_e$ vs. Redshift $(1+z)$
- Lines and symbols represent:
  - $\Lambda$CDM Baryon
  - Baryon
  - Millicharged DM
  - Cold DM

- Processes:
  - Compton Heating
  - Adiabatic Cooling
  - $e, p$ Cooling
  - H,He Cooling
  - Born (H, He)

- Preliminary
Rates Plot

![Graphs showing temperature, relative velocity, and ionization fraction as functions of redshift.](image)

Preliminary
CMB and SI Limit

CMB:

\[
\sigma_T^{mC} (V_{\text{rel}}) V_{\text{rel}}^4 \lesssim \frac{m_C + m_m}{m_p} \left( 1 + \frac{\Omega_b}{f_m \Omega_{DM}} \right) \times 1.7 \times 10^{-41} \text{ cm}^2
\]

Self-Interaction:

\[
\frac{\alpha_C^2}{m_C^3} \lesssim 10^{-11} \text{ GeV}^{-3}
\]
Scattering

Momentum Transfer Cross Section

\[
\sigma_{T}^{bm} \approx \frac{2\pi Q^2 \alpha_{em}^2}{\mu_{m}^2 v_{rel}^4} \log \left( \frac{T_b m_p \mu_{b}^2 v_{rel}^4}{Q^2 \alpha_{em}^3 \rho_b} \right)
\]

\[
\sigma_{T}^{mc} = \frac{2\pi \alpha_C \alpha_{m}}{\mu_{mc}^2 v_{rel}^4} \log \left( \frac{\mu_{mc}^2 v_{rel}^4}{\alpha_C \alpha_{m} m_{\phi}^2} \right)
\]
Non-Minimal Cold DM

\[ \sigma_{\text{ee}} \] vs. \( m_C \) for different masses of the mediator \( m_m \):
- \( m_m = 100 \text{ GeV} \)
- \( m_m = 10 \text{ GeV} \)
- \( m_m = 1 \text{ GeV} \)
- \( m_m = 100 \text{ MeV} \)

XENON-10T, SENSI 1g, SENSI 100g, DAMIC 1 Kg, Super-CDMS 1 Kg, EDGES 99% C.L. 

(\( f_m = 10^{-4}, \Delta m/m = 1\% \))
Dependence on mDM-CDM Coupling

![Graph showing dependence on mDM-CDM Coupling]