A cosmologically consistent millicharged dark matter solution to the EDGES anomaly

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Abstract

- Analysis of EDGES data shows an absorption signal of the redshifted 21-cm line of atomic hydrogen at z~17 which is stronger than expected from the standard ΛCDM model. The absorption signal interpreted as brightness temperature T_{21} of the 21-cm line gives an amplitude of -500^{+200}_{-500} mK at 99% CL.
- We present a particle physics model for the baryon cooling where a fraction of the dark matter resides in the hidden sector with a U(1) gauge symmetry and a Stueckelberg mechanism operates mixing the visible and the hidden sectors with the hidden sector consisting of dark Dirac fermions and dark photons. The Stueckelberg mass mixing mechanism automatically generates a millicharge for the hidden sector dark fermions providing a theoretical basis for using millicharged dark matter to produce the desired cooling of baryons seen by EDGES by scattering from millicharged dark matter.

EDGES Anomaly

- The Experiment to Detect the Global Epoch of Reionization Signature (EDGES) reported an absorption profile centered at the frequency $\nu = 78$ MHz in the sky-averaged spectrum. [1]
- The analysis by Bowman *et al* finds that the temperature of the 21-cm line is -500^{+200}_{-500} mK at 99% CL which is a 3.8σ deviation from the ΛCDM prediction of $\simeq -200$ mK. [1]

$$T_{21}(z) \simeq 0.023\, x_{\rm HI}(z) \left[\frac{0.15}{\Omega_m}\frac{(1+z)}{10}\right]^{\frac{1}{2}} \left(\frac{\Omega_B h^2}{0.02}\right) \left[1 - \frac{T_\gamma(z)}{T_s(z)}\right] \mathrm{K}.$$

- The observed absorption line at 78 MHz corresponds to a redshift z~17. If confirmed, it indicates that the baryonic temperature is ~ 4K (nearly half the expected value). [2]
- Possible explanations of the anomaly include:
  - Colder DM interacting with baryons causing it to cool down. [3]
  - CMB background radiation temperature was hotter than expected.
  - Astrophysical phenomena such as radiation from stars and star remnants (deemed less likely). [1,2]

The model

- The Stueckelberg extension of the Standard Model (SM) with mass mixing provides a natural candidate for a millicharged DM. The full Lagrangian is [4]

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm hid} + \mathcal{L}_{\rm SM-hid},$$

where

$$\mathcal{L}_{\rm hid} = -\frac{1}{4}C_{\mu\nu}C^{\mu\nu} + i\bar{D}\gamma^\mu\partial_\mu D - m_D\bar{D}D - \frac{1}{2}(\partial_\mu\phi\partial^\mu\phi) + \mathcal{L}^{\rm int}_{\rm hid},$$

$$\mathcal{L}_{\rm SM-hid} = -\frac{\delta}{2}C_{\mu\nu}B^{\mu\nu} - \frac{1}{2}(\partial_\mu\sigma + M_1 C_\mu + M_2 B_\mu)^2,$$

and

$$\mathcal{L}^{\rm int}_{\rm hid} = g_X Q_X \bar{D}\gamma^\mu D C_\mu + \lambda D\bar{D}\phi.$$

- After EWSB and Stueckelberg mass growth:
  - *DDZ* & *DDγ* couplings: $\mathcal{L}^{\rm m}_{\rm hid} = \bar{D}\gamma^\mu\left[\epsilon^D_Z Z_\mu + \epsilon^D_\gamma A^\gamma_\mu\right] D.$

$$\epsilon^D_Z \simeq e\epsilon Q_X g_X \sin\theta_W,$$

$$\epsilon^D_\gamma \simeq -e\epsilon Q_X \frac{g_X}{g_Y},$$

  - DM millicharge: $\epsilon_D = \dfrac{g_X Q_X}{g_Y}\epsilon$.

DM yield and temperature evolution at early and late times

Boltzmann equations for the dark particles' comoving number density

The dark sector (DS) initially has negligible particle number density. DS particles are produced out-of-equilibrium via energy injection from the SM.

$$\begin{aligned}\frac{dY_D}{dT_h} = -\frac{\mathfrak{s}}{H}\left(\frac{d\rho_h/dT_h}{4\zeta\rho_h - j_h/H}\right)\Bigg[&\langle\sigma v\rangle_{D\bar{D}\to i\bar{i}}(T)Y^{\rm eq}_D(T)^2 \\ &-\frac{1}{2}\langle\sigma v\rangle_{D\bar{D}\to\gamma'\gamma'}(T_h)\left(Y_D^2 - Y^{\rm eq}_D(T_h)^2\frac{Y^2_{\gamma'}}{Y^{\rm eq}_{\gamma'}(T_h)^2}\right) \\ &-\frac{1}{2}\langle\sigma v\rangle_{D\bar{D}\to\phi\gamma}(T_h)\left(Y_D^2 - Y^{\rm eq}_D(T_h)^2\frac{Y_\phi}{Y^{\rm eq}_\phi(T_h)}\right) \\ &-\frac{1}{2}\langle\sigma v\rangle_{D\bar{D}\to\phi\gamma'}(T_h)\left(Y_D^2 - Y^{\rm eq}_D(T_h)^2\frac{Y_\phi Y_{\gamma'}}{Y^{\rm eq}_\phi(T_h)Y^{\rm eq}_{\gamma'}(T_h)}\right) \\ &-\frac{1}{2}\langle\sigma v\rangle_{D\bar{D}\to\gamma'}(T_h)\,Y_D^2 + \frac{1}{\mathfrak{s}}\langle\Gamma_{\gamma'\to D\bar{D}}\rangle(T_h)\,Y_{\gamma'}\Bigg] \quad [4]\end{aligned}$$

Similar equations can be written for γ' and ϕ .

DM relic density constitutes a fraction $f_{\rm dm} < 0.4\%$ of the observed relic density (Planck 2015 CMB data). [5]
Dark photons decay before BBN.

Evolution of dark sector temperature T_h

Using the Boltzmann equation for the DS energy density, we derive an evolution equation for $\eta = T/T_h$:

$$\frac{d\eta}{dT_h} = -\frac{\eta}{T_h} + \left[\frac{\zeta\rho_v + \rho_h(\zeta - \zeta_h) + j_h/(4H)}{\zeta_h\rho_h - j_h/(4H)}\right]\frac{d\rho_h/dT_h}{T_h(d\rho_v/dT)},$$

where the source term is given by

$$\begin{aligned}j_h = \sum_i &\left[2Y^{\rm eq}_i(T)^2 J(i\,\bar{i}\to D\bar{D})(T) + Y^{\rm eq}_i(T)^2 J(i\,\bar{i}\to\gamma')(T)\right]\mathfrak{s}^2 - Y_{\gamma'}J(\gamma'\to f\bar{f})(T_h)\mathfrak{s} \\ &- \left[\frac{1}{2}Y_D^2\, J(D\bar{D}\to\phi\gamma)(T_h) + Y_D Y_{\gamma'} J(\gamma' D\to\gamma D)(T_h) + Y_\phi Y_D\, J(\phi D\to\gamma D)(T_h)\right]\mathfrak{s}^2\end{aligned}$$

Following kinetic decoupling of *D* fermions, their temperature drops as a^{-2} (*a* = scale factor).

DM and baryon temperature evolution

Since DM is millicharged, then it interacts electromagnetically with baryons. The interaction is parameterized as $\sigma = \sigma_0 v^{-4}$ with

$$\sigma_0 = \frac{2\pi\alpha^2\epsilon_D^2}{\mu^2_{D,t}}\log\left(\frac{9T_B^3}{4\pi\epsilon_D^2\alpha^3 x_e n_{\rm H}}\right) \quad [3]$$

The relative velocity V_{DB} between DM and baryons can produce a drag force $D(V_{DB})$ defined as $D(V_{DB}) = dV_{DB}/dt$

$$D(V_{DB}) = \sum_{t=e,p}\sigma_0\frac{f_{\rm dm}\rho_D + \rho_B}{m_t + m_D}\frac{\rho_t}{\rho_B}\frac{1}{V^2_{DB}}F(r_t).$$

The evolution of the DM and baryon temperatures at late times is done simultaneously with the evolution of the relative velocity and the ionization rate: [3,6]

$$\begin{aligned}(1+z)\frac{\mathrm{d}T_D}{\mathrm{d}z} &= 2T_D + \frac{\Gamma_\phi}{H(z)}(T_D - T_\phi) - \frac{2}{3H(z)}\dot{Q}_D, \\ (1+z)\frac{\mathrm{d}T_B}{\mathrm{d}z} &= 2T_B + \frac{\Gamma_c}{H(z)}(T_B - T_\gamma) - \frac{2}{3H(z)}\dot{Q}_B, \\ H(z)(1+z)\frac{\mathrm{d}x_e}{\mathrm{d}z} &= C\left[n_H\alpha_B x_e^2 - 4(1-x_e)\beta_B e^{-3E_0/4T_\gamma}\right], \\ (1+z)\frac{\mathrm{d}V_{DB}}{\mathrm{d}z} &= V_{DB} + \frac{D(V_{DB})}{H(z)}\end{aligned}$$

The brightness temperature of the 21-cm line

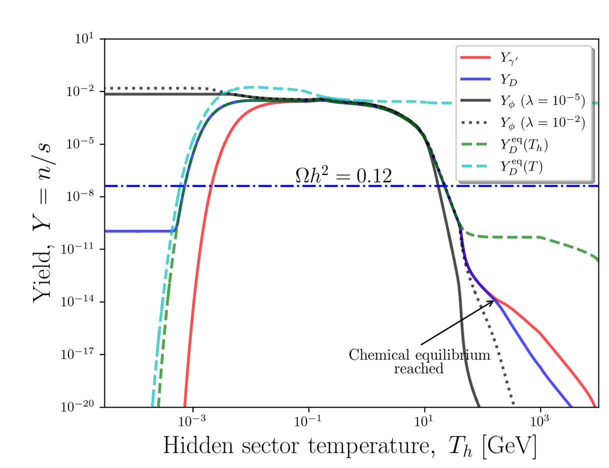
The brightness temperature T_{21} of the 21-cm line is defined by [6]

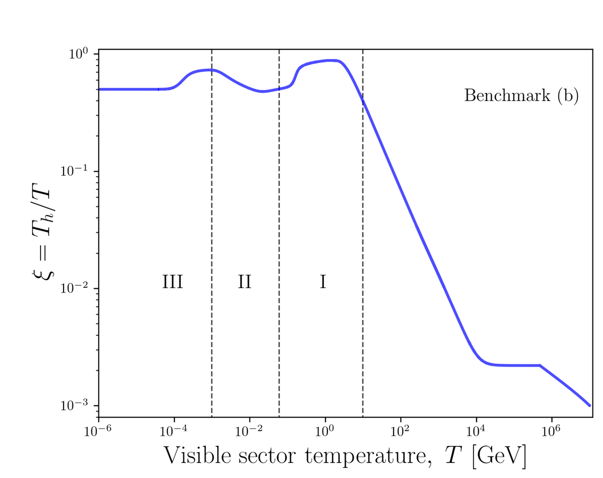
$$T_{21}(z) = \frac{T_s - T_\gamma}{1+z}(1 - e^{-\tau})$$

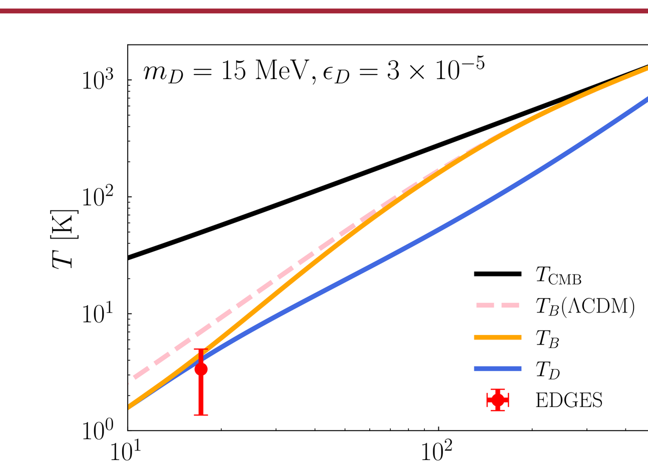
The sky-averaged 21-cm temperature is

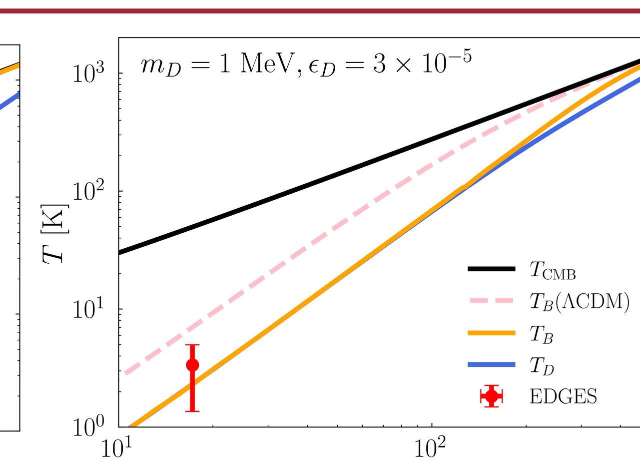
$$\overline{T}_{21} \equiv \int \mathrm{d}V_{DB}\,\mathcal{P}(V_{DB})\,T_{21}[T_B(V_{DB})]$$

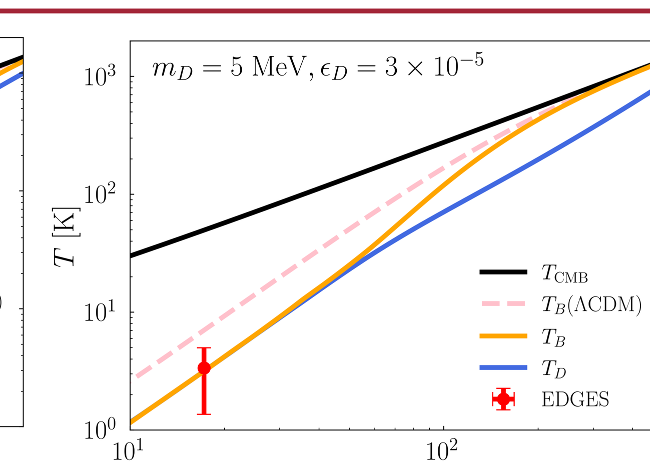
Results









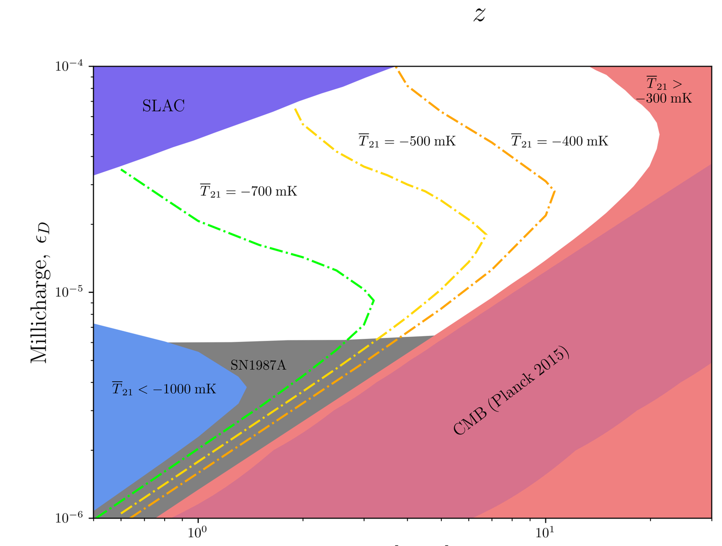


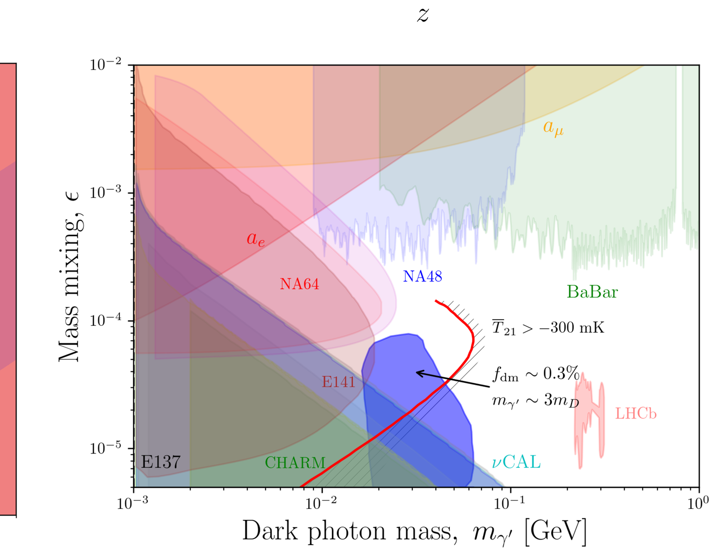
Relic density, $\Omega h^2 \simeq 3\times10^{-4}$

$m_{\gamma'} \sim 3m_D$

$\xi = 0.5$

$$\Delta N_{\rm eff} \simeq \frac{4\Delta n_b}{7}\left(\frac{11}{4}\right)^{4/3}\xi^4 \simeq 0.138 \quad [4]$$





References

[1] J. D. Bowman, A. E. E. Rogers, R. A. Monsalve, *et al*, Nature 555, no.7694, 67-70 (2018)

[2] R. Barkana, Nature 555, no.7694, 71-74 (2018)

[3] J. B. Munoz and A. Loeb, Nature 557, no.7707, 684 (2018)

[4] A. Aboubrahim, P. Nath and Z-Y. Wang [arXiv: 2108.05819 [hep-ph]] (to appear in JHEP)

[5] K. K. Boddy, V. Gluscevic, V. Poulin, E. D. Kovetz, *et al*, Phys. Rev. D 98, no.12, 123506 (2018)

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