

**Bounds on Dark-Matter Annihilations from 21-cm Data**

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The observation of an absorption feature in the 21-cm spectrum at redshift  $z \approx 17$  implies bounds on dark-matter (DM) annihilations for a broad range of masses, given that significant heating of the intergalactic medium would have erased such a feature. The resulting bounds on the DM annihilation cross sections are comparable to the strongest ones from all other observables.

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*Introduction.*—The EDGES experiment recently reported the first measurement of the global 21-cm spectrum [1], which is an observable sensitive to the temperature of the gas at redshift  $z \approx 17$ . This allows us to constrain the dark-matter (DM) annihilation cross section, as the annihilation products would heat the gas [2–6].

The signal seen by EDGES is the absorption of light at energy equal to  $\Delta E = 0.068 \text{ K} = 2\pi/(21 \text{ cm})$  in the rest

frame of the gas. This is the energy difference between the ground states of hydrogen with total spin  $S = 0$  or 1 (depending on the relative spin between electron and proton). Cosmological redshifting brings the signal to radio frequencies of order  $\sim 100 \text{ MHz}$ . The signal is reported in terms of the average of the difference between the brightness temperature and that of the background radiation, given by [7,8]

$$T_{21}(z) \approx 23 \text{ mK} \left(1 - \frac{T_\gamma(z)}{T_S(z)}\right) \left(\frac{\Omega_b h^2}{0.02}\right) \left(\frac{0.15}{\Omega_m h^2}\right)^{1/2} \sqrt{\frac{1+z}{10}} x_{\text{HI}}. \quad (1)$$

Here,  $x_{\text{HI}}$  is the number fraction of neutral hydrogen, very close to 1. Next,  $T_\gamma(z)$  is the background photon temperature, expected to be dominated by the low-energy tail of cosmic microwave background (CMB) photons, so that  $T_\gamma = T_{\text{CMB}} = 2.7 \text{ K}(1+z)$ .  $T_S$  is the “spin temperature,” which defines the relative population of the two spin levels of the hydrogen ground state as  $n_1/n_0 \equiv 3e^{-\Delta E/T_S}$ .

According to standard cosmology, the gas, composed mainly of neutral hydrogen, is thermally decoupled from CMB at  $z \approx 150$ . After thermal decoupling, the gas cools like any nonrelativistic particle, such that  $T_{\text{gas}}/T_{\text{CMB}} \propto (1+z)$ . At  $z \lesssim 20$ , the first light from stars (re)couples the 21-cm two-state system to gas, such that its spin temperature becomes  $T_S = T_{\text{gas}}$ . This is a sensible assumption, in the limit of a large Ly- $\alpha$  radiation rate and no

heating of the gas due to x-ray radiation from first stars. In any case, using detailed balance, the spin temperature has to be higher than  $T_{\text{gas}}$ , as any other source of radiation is hotter. At even lower redshifts,  $z \lesssim 15$ , star light heats the gas to temperatures higher than the CMB, and the  $T_{21}$  signal goes to zero. EDGES measured an absorption feature centered at a frequency of  $\approx 78 \text{ MHz}$ , translating to a redshift  $z = 17.2$ , at which

$$T_{21} \approx -500_{-500}^{+200} \text{ mK} \quad (99\% \text{ C.L.}). \quad (2)$$

The expectation from standard astrophysics with noninteracting DM is  $T_{21} \approx -200 \text{ mK}$ . Thereby, the gas temperature inferred from Eq. (2) is about a factor of 2 lower than what is expected. The statistical significance of the anomaly is claimed to be  $3.8\sigma$ . This could be due to systematic issues, astrophysical processes increasing  $T_\gamma$  [9,10], or maybe, to new physics [11–13]. In our Letter, we will not address the possible origin of the anomaly. Rather, we use the fact that an absorption feature is observed to set bounds on DM annihilations.

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*Bound on DM annihilations.*—DM annihilation products can heat the gas considerably, therefore, suppressing the observed absorption feature, even erasing it if DM heating is too large. To give bounds on DM annihilations, we will not rely on the actual value of the strong absorption signal, but we conservatively impose that DM heating does not erase the absorption feature observed down to  $z \approx 16$ .

DM annihilations will heat the gas in two ways. First, DM annihilations around the period of thermal decoupling from the CMB can increase the amount of free

electrons above the value predicted by the Standard Model,  $x_e = n_e/n_b \approx 2 \times 10^{-4}$ . A higher  $x_e$  delays hydrogen/CMB decoupling, increasing  $T_{\text{gas}}$  at lower redshifts since the gas has less time to cool adiabatically. More importantly, DM annihilations directly heat the hydrogen gas through energy injection, increasing  $T_{\text{gas}}$ . A higher  $T_{\text{gas}}$  will result in a modification of the  $T_{21}$  spectrum [5,6,14].

In the presence of DM annihilations, the temperature of the gas  $T_{\text{gas}}$  and the free electron fraction  $x_e$  evolve as dictated by the following equations:

$$\frac{dx_e}{dz} = \frac{\mathcal{P}_2}{(1+z)H(z)} [\alpha_H(T_{\text{gas}})n_H x_e^2 - \beta_H(T_{\text{gas}})e^{-E_\alpha/T_{\text{gas}}}(1-x_e)] + \frac{1}{(1+z)H(z)} \frac{dE}{dVdt} \Big|_{\text{inj}} \frac{1}{n_H} \left( \frac{f_{\text{ion}}(z)}{E_0} + \frac{(1-\mathcal{P}_2)f_{\text{exc}}(z)}{E_\alpha} \right), \quad (3a)$$

$$\frac{dT_{\text{gas}}}{dz} = \frac{1}{1+z} \{2T_{\text{gas}} - \gamma_C[T_\gamma(z) - T_{\text{gas}}]\} + \frac{1}{(1+z)H(z)} \frac{dE}{dVdt} \Big|_{\text{inj}} \frac{1}{n_H} \frac{2f_{\text{heat}}(z)}{3(1+x_e+f_{\text{He}})}. \quad (3b)$$

The upper line in each equation describes standard cosmology:  $E_\alpha = 3E_0/4$  is the Lyman- $\alpha$  energy, and  $E_0 = 13.6$  eV is the binding energy of hydrogen in its ground state,  $\beta_H$  is the effective photoionization rate for an atom in the  $2s$  state, and  $\alpha_H$  is the case *B* recombination coefficient. We defined the dimensionless coefficient

$$\gamma_C \equiv \frac{8\sigma_T a_r T_\gamma^4}{3Hm_e c} \frac{x_e}{1+f_{\text{He}}+x_e}, \quad (4)$$

where  $\sigma_T$  is the Thomson cross section,  $a_r$  the radiation constant,  $m_e$  the electron mass and  $f_{\text{He}}$  the number fraction of helium. The coefficient  $\mathcal{P}_2$  represents the probability for an electron in the  $n=2$  state to get to the ground state before being ionized, given by [15]

$$\mathcal{P}_2 = \frac{1 + K_H \Lambda_H n_H (1-x_e)}{1 + K_H (\Lambda_H + \beta_H) n_H (1-x_e)}, \quad (5)$$

where  $\Lambda_H = 8.22 \text{ s}^{-1}$  is the decay rate of the  $2s$  level, and the factor  $K_H = \pi^2/[E_\alpha^3 H(z)]$  accounts for the cosmological redshifting of the Ly- $\alpha$  photons. We solve the above equations starting from an initial redshift  $z_M$  before recombination, imposing  $x_e(z_M) = 1$  and  $T_{\text{gas}}(z_M) = T_{\text{CMB}}(z_M)$ . We use  $z_M = 1400$ , and we have checked that solutions do not change using a different starting point.

The lower terms in Eqs. (3) describe the additional effect of DM annihilations. The energy injection rate per unit volume due to DM is

$$\frac{dE}{dVdt} \Big|_{\text{inj}} = \rho_{\text{DM}}^2 f_{\text{DM}}^2 \frac{\langle \sigma v \rangle}{M_{\text{DM}}}, \quad (6)$$

with  $f_{\text{DM}}$  the fraction of the dark matter which annihilates. The dimensionless factors  $f_c(z)$  take into account the efficiency of deposition in the gas of the injected energy in three different channels *c*, namely, ionization (ion), excitation (exc), and heating (heat), as defined in [16,17]. In our calculations, we computed them according to [17]. The  $f_c(z)$  depend on the primary annihilation channel and on the DM mass and take into account the delay between the injection and the deposition of energy. An important ingredient which needs to be considered at low redshifts is the effect of structure formation, which enhances the injected energy due to the DM annihilation with respect to the smooth background. This can be estimated by replacing, in Eq. (6),  $\rho_{\text{DM}}^2 \rightarrow \langle \rho_{\text{DM}}^2 \rangle = B(z) \rho_{\text{DM}}^2$ . The boost factor  $B(z)$  is the variance of the DM power spectrum, which is subject to considerable uncertainty (see, for instance, Fig. 2 of [18]). Since the  $f_c(z)$  functions depend on the history of the energy injection at redshifts previous to  $z$ , they will involve the time integral of the boost factor.

In our results, we show constraints for two different boost factors. A conservative choice, denoted as ‘‘Boost 1’’ in our plots, is the smallest boost factor from [5],

$$B(z) \approx 1 + \frac{1.6 \times 10^5}{(1+z)^{1.54}} \text{erfc} \left( \frac{1+z}{20.5} \right), \quad (7)$$

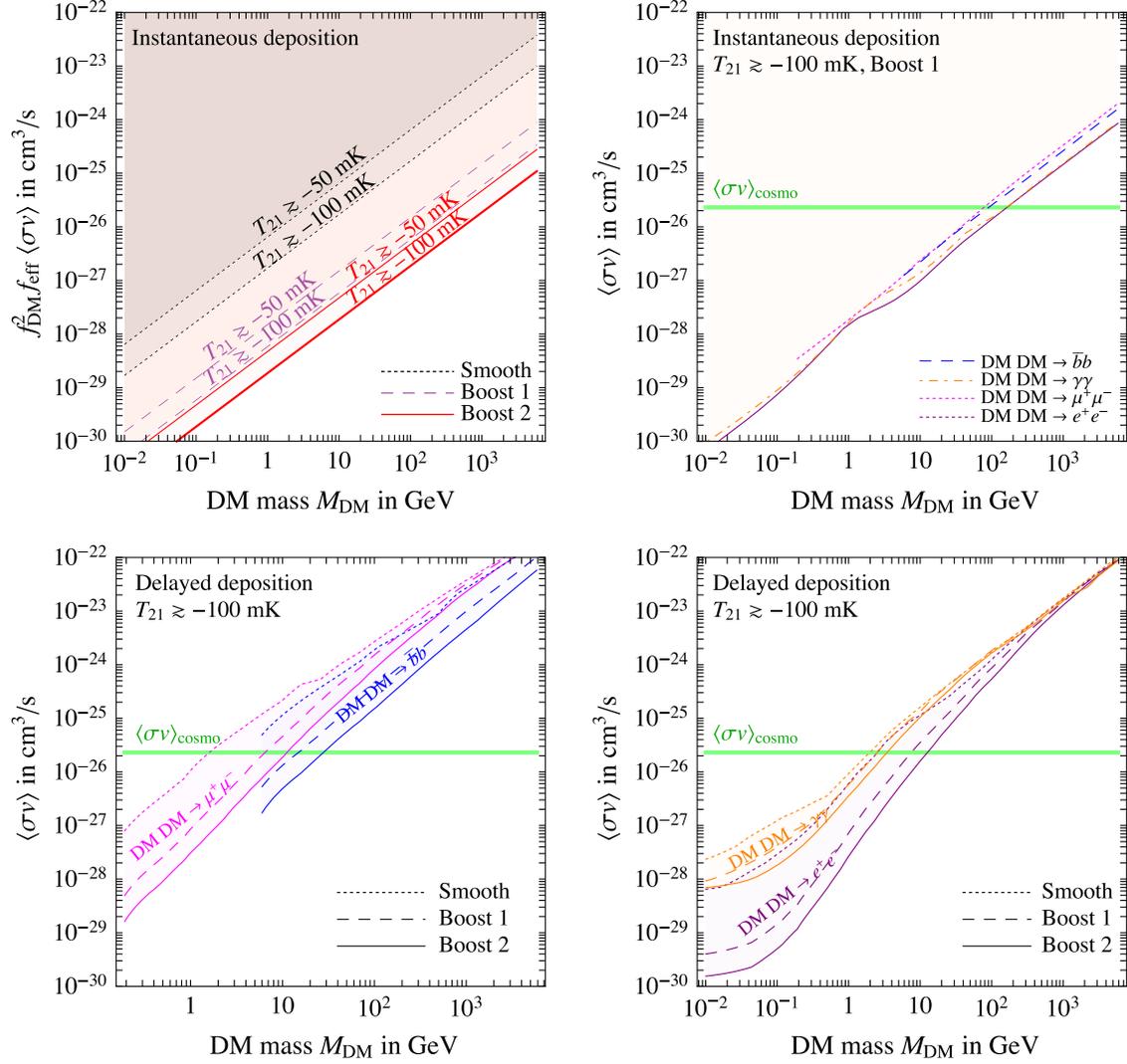


FIG. 1. Upper row: Bounds on DM annihilation cross sections in the instantaneous deposition approximation. The left panel shows bounds on the cross section times efficiency factor  $f_{\text{eff}}$  and fraction of annihilating DM  $f_{\text{DM}}^2$ , obtained by demanding that the 21-cm absorption feature is not depleted from the value of standard cosmology ( $-200$  mK in our computation) down to  $-100$  or  $-50$  mK because of DM heating. We take into account two different cosmological boost factors, and also show the weaker bound obtained by (unrealistically) ignoring DM clustering. The right panel shows bound on the cross section for a few main annihilation channels (bottoms, photons, muons, and electrons), using the  $f_{\text{eff}}$  described in the text, the mild boost factor of Eq. (7) and demanding that  $T_{21} \gtrsim 100$  mK. Bottom row: Bounds on DM annihilation cross sections using delayed energy deposition and numerical primary spectra as described in the text. We demand that  $T_{21} \gtrsim 100$  mK, showing the results for two different boost factors, as well as ignoring DM clustering. The left (right) panel shows DM decaying into bottom quarks or muons (photons or electrons).

which evaluates to  $B \approx 217$  at  $z \approx 20$  and roughly agrees with the smallest boost factor in Fig. 19 of [19]. Higher boost factors are considered in the literature. To illustrate the effect that the boost factor has on the constraints, we also plot results for a less conservative choice, denoted as “Boost 2,” obtained from a halo model calculation, considering an Einasto profile with substructures and minimum halo mass of  $10^{-6} M_{\odot}$  (Fig. 2 of [18]).

We notice that the use of the cosmological boost factor is justified for the  $T_{21}$  observable at hand. Indeed, the first starlight induces a 21-cm signal from roughly all baryons in the universe, not only from those in over-dense regions

close to structures that contain the first stars, as x-ray photons lead to a roughly uniform radiation flux. DM annihilations dominantly happen in many small overdensities, enhanced by the boost factor, but annihilation products produce a broad spectrum of radiation which will spread the heat leading to a roughly uniform heating [5].

In Fig. 1, we show the constraints on DM annihilations obtained by imposing that the DM correction to  $T_{21}$  does not suppress by more than a factor of 2 or 4 the  $T_{21}$  resulting from standard astrophysics, close to  $-200$  mK as inferred by solving Eqs. (3) without the DM contribution.

We show bounds for a few different cases, as follows. In the upper row of Fig. 1, we consider the instantaneous deposition approximation. This means that we assume that a fraction  $f_{\text{eff}}$  of the energy produced by DM annihilation at some redshift is immediately transferred to the plasma, using a simplified approach (“SSCK” approximation) proposed in [20], based on earlier work by [21]

$$f_{\text{ion}}^{\text{SSCK}} = f_{\text{exc}}^{\text{SSCK}} = f_{\text{eff}} \frac{1 - x_e}{3}, \quad f_{\text{heat}}^{\text{SSCK}} = f_{\text{eff}} \frac{1 + 2x_e}{3}. \quad (8)$$

The upper left panel shows constraints on  $f_{\text{eff}} \langle \sigma v \rangle$ . It shows the effects of the boost factor, for two different choices of observed  $T_{21}$ , in the instantaneous deposition approximation (with the SSCK prescription). These bounds are well approximated by

$$f_{\text{DM}}^2 f_{\text{eff}} \langle \sigma v \rangle < 10^{-26} \frac{\text{cm}^3}{\text{s}} \frac{M_{\text{DM}}}{100 \text{ GeV}} \times \begin{cases} 0.62 \\ 1.57 \end{cases}, \quad (9)$$

where the two slopes refer to imposing  $T_{21} \gtrsim -100$  mK or  $T_{21} \gtrsim -50$  mK, respectively. In the upper right panel, we specialize the constraints to a few representative channels: electrons, muons, photons, and bottom quarks. We derive the bounds by rescaling Eq. (9) with the  $f_{\text{eff}}$  from [16] extended to lower energies using the formulas and the numerical results given in [16,17].

The bottom row of Fig. 1 again shows the bounds for some representative DM annihilation channels but considering a full calculation by convolving the primary spectra provided in [19] with the delayed transfer functions of [16]. The effects due to the boost factor vary with DM mass and annihilation channel. For DM particles annihilating directly into photons or electrons the boost has little effect on the bounds at high DM masses. This happens because energetic photons and electrons deposit a relevant amount of their energy in the gas only after some time. In particular, for photons, the effect is quite small for the full range of mass we consider. Physically, this can be understood by the fact that the instantaneous deposition approximation becomes poor for highly energetic particles, which were either produced at a redshift in which structures were not already formed and interact with the gas only later, or do not have time to interact with the gas if produced when the boost enhancement becomes important. On the other hand, energy deposition is well approximated as instantaneous for primary annihilation channels (such as quarks,  $\tau$ ,  $W$ ,  $Z$ , and  $h$ ) with a broad low-energy spectrum of secondary products and for primary muons and electrons injected at low energies. The small discrepancy at low masses between the upper right panel and the correct bounds of the bottom row can be attributed to the fact that the  $f_{\text{eff}}$  derived in [16] is the effective deposited fraction relevant for CMB bounds, while here, we are interested in different physics.

The 21-cm bounds are comparable to bounds from the CMB (which rely on global fits which assume standard cosmology) [16,22], and to bounds from indirect detection searches [23], subject to astrophysical uncertainties especially when based on Galactic Center observations [24,25]. With respect to the latter case, our bounds apply to a broader range of DM masses.

*Conclusions.*—We derived strong bounds on DM annihilation cross sections by demanding that heating due to the annihilations does not erase the 21-cm absorption feature observed from sources around  $z \approx 17.2$ . Even imposing this conservative view, adopting a quite mild cosmological boost factor, DM with an  $s$ -wave cross section that reproduces the cosmological DM abundance,  $\langle \sigma v \rangle \approx 2.3 \times 10^{-26} \text{ cm}^3/\text{sec}$ , is excluded for DM masses  $M_{\text{DM}} \lesssim 3\text{--}30 \text{ GeV}$ , depending on the annihilation channel.

The fact that the 21-cm absorption feature seems anomalously stronger than what is expected on the basis of collisionless DM is receiving large attention. In particular, a large baryon-DM interaction in special models of DM with a subleading millicharged component has been immediately considered [11–13] as an explanation for the cooling. We would like to stress, here, that this explanation, if valid at all [26–28], comes from an incomplete analysis which neglects the heating caused by DM annihilation. In these models, in the limit where  $T_{\text{DM}} \ll T_{\text{gas}}$  and where the two components interact strongly enough that they rethermalize, the gas temperature is reduced at most by a factor  $T'_{\text{gas}}/T_{\text{gas}} = n_b/(n_b + n_{\text{DM}})$ , such that a DM lighter than a few GeV is needed to fully explain the anomaly. In our analysis, we point out that annihilations of such a light DM are strongly constrained, as it can inject electrons and low-energy photons, which could heat the gas more than it is cooled. More generally, a large class of models which posit a DM-baryon interaction will feature DM annihilation, whose energy injection must be taken into account.

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