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The EDGES 21 cm anomaly and properties of dark matter

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ABSTRACT

The recently claimed anomaly in the measurement of the 21 cm hydrogen absorption signal by EDGES at $z \sim 17$, if cosmological, requires the existence of new physics. The possible attempts to resolve the anomaly rely on either *(i)* cooling the hydrogen gas via new dark matter-hydrogen interactions or *(ii)* modifying the soft photon background beyond the standard CMB one, as possibly suggested also by the ARCADE 2 excess. We argue that solutions belonging to the first class are generally in tension with cosmological dark matter probes once simple dark sector models are considered. Therefore, we propose soft photon emission by light dark matter as a natural solution to the 21 cm anomaly, studying a few realizations of this scenario. We find that the signal singles out a photophilic dark matter candidate characterised by an enhanced collective decay mechanism, such as axion mini-clusters.

1. Introduction

The 21 cm signal of atomic hydrogen from the dark ages and cosmic dawn provides important information on the thermal and ionization history of the Universe. Recently, the low-band antenna of the Experiment to Detect the Global EoR Signature (EDGES) has reported an anomalously strong absorption in the measured 21 cm signal at redshifts in the range of $z \approx 13.2$–27.4 [1]. The anomaly could be a new signal of baryon-dark matter (DM) interaction [2,3], as scattering processes may over-cool the hydrogen gas with respect to the standard expectations from the Cosmic Microwave Background (CMB) measurements. Alternatively, the anomaly may be related to, or even be a consequence of [4], the excess in the radio background observed by ARCADE 2 [5]. Most radical explanations advocate instead for a purely baryonic Universe [6] and, regardless of the actual mechanism behind the 21 cm anomaly, it is clear that the signal offers new probes for the physics beyond the standard model of particle interactions. In this paper we therefore analyse new physics scenarios that explain the EDGES 21 cm absorption anomaly, pointing out important complementary implications.

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On general grounds, the intensity of the observable 21 cm signal is proportional to [1]

$$I_{21} \propto 1 - \frac{T_R(z)}{T_S(z)}, \tag{1}$$

where T_S is the spin temperature of the gas and T_R is temperature of radiation for a fiducial $z \sim 17$. The form of Eq. (1) suggests that, if the EDGES result is indeed cosmological, there are *only two* potential ways for new physics to resolve the anomaly.

Firstly, the introduction of new interactions can lower the hydrogen spin temperature while keeping $T_R = T_{\rm CMB}$. This approach has been followed in recent papers [7–10] which introduce a new baryon-DM velocity-dependent interaction [7,8] or a milli-charged DM fraction [9,10]. As we argue below, addressing the 21 cm anomaly in this way forces to confront cosmological measurements that bound the scenario severely [11–13].

Alternatively, it is possible to consider new physics scenarios that increase T_R by emission of extra soft photons in the early Universe, which add to the standard CMB background. This explanation is also in line with the ARCADE 2 excess, requiring that only a few percent of the ARCADE 2 photons must be of cosmological origin to explain also the EDGES anomaly. A first example of this approach was given in the recent paper [14], where the photon emission by accreting intermediate mass black holes is analysed.

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Light WIMP annihilations or decays that might be consistent with the ARCADE 2 excess [15] also belong to this class of scenarios.

In the following, to be as general as possible, we first address the above mentioned solutions to the 21 cm anomaly and then propose new ones. In agreement with Ref. [10], we demonstrate that the proposed simple scenarios relying on extra gas cooling typically face generic and robust constraints. This motivates us to study scenarios where DM couples to photons producing a new soft radiation component with $T_R > T_{\rm CMB}$. In particular, we show that the scenarios which produce a hard photon background in addition to the soft counterpart are also severely constrained. In light of this, axions [16,17], axion-like particles (ALPs) [18,19], light oscillating spin-2 DM [20] and light excited DM [21] seem to be the DM candidates favoured by the 21 cm anomaly. Nevertheless, we find that even these scenarios need to be augmented by an enhanced collective decay mechanism, such as the decay via parametric resonance, in order to explain the signal.

2. Hydrogen cooling from DM scattering

We start by reviewing the possibility that hydrogen-DM elastic scatterings may cool the gas and improve the consistency with data [7–9]. To model the case, Ref. [7,8] *assumed* a velocity-dependent elastic cross section of the form

$$\sigma(v) = \sigma_1 \left(\frac{v}{1\,{\rm km\,s^{-1}}}\right)^{-n}, \tag{2}$$

where the reference value $\sigma_1 > 3.4 \times 10^{-21}$ cm$^2 = 3.4 \times 10^3$ b is taken at the velocity $v = 1$ km s^{-1}, and the value of n reflects the velocity dependence of the scattering cross section. It is crucial to notice that dependences as strong as $n = 4$ are needed in order to suppress the cross section at the recombination epoch and comply with the existing CMB and cosmological bounds [12,13]. The choice $n = 4$ in Eq. (2) can be motivated by the non-relativistic Rutherford cross section, i.e. by the QED of point-like particles. However, only a tiny fraction of the hydrogen, $x_e \approx 10^{-4}$, is in the ionized form at the epoch the 21 cm signal is generated. Thus, the dominant fraction of the atomic hydrogen gas possess only dipole interactions (see for example Ref. [22] for explicit computations) which, instead of the assumed v^{-4} behaviour, predicts scattering processes with $n = 2$. The latter are firmly excluded by the CMB alone. We stress that this argument is completely general. The simplified approaches to the 21 cm anomaly seem then to face equally simple constraints, and more detailed scenarios must be formulated to study their actual consistency with data.

An example of more detailed scenario is presented by millicharged DM [9,10]. In this case the momentum transfer cross-section is given by

$$\bar{\sigma}_t = \frac{2\pi\alpha^2\epsilon^2\xi}{\mu_{\chi,t}^2 v^4}, \tag{3}$$

where ϵ is the millicharge of the DM particle, $\mu_{\chi,t}$ is the DM-target reduced mass, α is the fine-structure constant, v is the relative velocity between the two particles and ξ is the Debye logarithm. The cross-section (3) arises from scattering with the ionized fraction $x_e(z = 20) \approx 10^{-4}$ of hydrogen atoms. With $\epsilon = 10^{-6}$ and $\mu_{\chi,t} \approx m_e = 0.5$ MeV, the cross section is about $\bar{\sigma}_t = 4 \times 10^{-12}$ cm^{-2} at $z \approx 20$. The fraction of milli-charged DM is taken to be $f_{\rm DM} \approx 0.1$. However, at the time of photon decoupling ($z \approx 1100$) we have $x_e(z = 1100) \approx 1$, so the full cross-section at that time $\sigma = x_e(z = 1100)\, f_{\rm DM}\, \bar{\sigma}_t \approx 5 \times 10^{-20}$ cm^{-2}, while the CMB bound is $\sigma \approx 10^{-26}$ cm^{-2} for $m_\chi = 10$ MeV.

Our result agrees with the one in Ref. [10], where the authors state that the millicharged DM is allowed only in the small range $m_\chi \sim 10$–80 MeV, $\epsilon \sim 10^{-6}$–10^{-4} and $f_{\rm DM} \sim 0.003$–0.02.

Although these types of arguments cannot exclude all possible solutions of hydrogen cooling based on new DM interactions, they demonstrate that these scenarios are severely constrained and that their assessment requires a careful study. For these reasons, we prefer to study here another class of solutions to the 21 cm anomaly, which relies on $T_R > T_{\rm CMB}$ in Eq. (1).

3. Soft vs hard photon background

Most of the conventional DM candidates predict that DM processes inject charged cosmic rays as well as photons into the Universe. Light, sub-GeV WIMPs represent the most well-known type of DM with such properties that has excited our community in last few years. Sub-GeV dark matter in the keV to MeV range can in the future be probed by detectors based on Fermi-degenerate materials [23], superconductivity [24], superfluid helium [25,26], semiconductors [27] or Dirac materials [28]. Superconducting detectors [29] or detectors based on resonant dark matter absorption in molecules [30] could bring the detectable mass range down to eV range. Even the LHC monojet [31,32] and monophoton [33,34] searches, which are typically insensitive for such a low mass range, may still constrain these scenarios significantly.

In our case, to explain the 21 cm anomaly, the WIMP mass must be precisely in the sub-GeV range in order for their annihilations or decays to be compatible with the charged cosmic ray [35] and extra-galactic gamma-ray [36,37] backgrounds. These processes were regarded as compatible with the ARCADE 2 excess [15], although later measurements tended to disfavour this interpretation [38]. In fact, the predicted photon spectrum is generally broad and includes energetic photons in addition to the soft spectrum needed to explain the 21 cm anomaly, which makes it necessary to address the constraints on the hard part of the spectrum.

Similarly, if a fraction of the DM consists of primordial black holes [39], which is constrained to be below unity for most of the parameter space [40],[1] the accretion of matter onto these systems may indeed explain the 21 cm anomaly [14]. However, also in this case the photon spectrum is broad, leading to a hard radiation part that needs to be addressed.

As stated above, any mechanism which injects photons into the cosmic medium has to be such that it does not lead to an extra heating of the gas by the hard radiation. In fact, assuming that the heating of gas is negligible, reproducing the required 21 cm absorption feature requires the standard radiation field temperature $T_{\rm CMB}$ to be increased by a factor of $\sim 7/4$. In practice, extra photons are needed to provide $\sim 3/4\, T_{\rm CMB}$. Thus, the amount of background soft photons must be doubled in the frequency range $(65$–$90) \times (1+z)$ MHz of the absorption feature, for $z \approx 17$. For example, if the injection spectrum has a spectral index $\alpha = 1$, i.e. $I_\nu \propto \nu^{-\alpha}$, the energy density of the extra photons in the $(65$–$90) \times 18$ MHz band corresponds to $\sim 3 \times 10^{-6}$ eV/cm^3, while the CMB photons provide $\sim 4 \times 10^{-6}$ eV/cm^3. The kinetic energy density ρ_k of the gas at $z = 17$, where the gas temperature is $T_g \sim 7$ K, can be estimated as $\rho_k \sim 1.5 \times 10^{-6}$ eV/cm^3, and therefore is approximately two times lower than the energy density of the injected photons in the narrow energy band considered. As the most relevant absorption process for the soft photons injected after

[1] Light wormholes or other horizonless objects can form all the DM [41]. However, such light objects are expected to radiate a hard spectrum, thus intermediate mass black holes are more appropriate to explain the soft photon excess [14].