PROCEEDINGS OF SCIENCE

Future 21cm constraints on dark matter energy injection: Application to ALPs

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The redshifted 21cm signal from the Cosmic Dawn is expected to provide unprecedented insights into early Universe astrophysics and cosmology. Here, we briefly summarize how decaying dark matter can heat the intergalactic medium before the first galaxies, leaving a distinctive imprint in the 21cm power spectrum. We have derived the first Fisher matrix forecasts on the sensitivity of the Hydrogen Epoch of Reionization Array telescope (HERA) and we have shown that HERA can improve by up to three orders of magnitude previous cosmology constraints. In these proceedings, we project these future bounds in the plane of the Axion like particles (ALP) coupling to photons as a function of the ALP mass. We focus on the ALP mass range between $\sim$ 10 keV and 1 MeV where the 21cm signal power spectrum probes are expected to improve on any other current dark matter searches. This illustrates how 21cm cosmology can be expected to help in probing uncharted regions of the dark matter parameter space beyond the reach of existing astro-particle and cosmology experiments.

Corfu Summer Institute 2023 "School and Workshops on Elementary Particle Physics and Gravity" (CORFU2023)
23 April - 6 May , and 27 August - 1 October, 2023
Corfu, Greece

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[*] Speaker

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1. Introduction

Dark matter (DM) is a crucial component of our Universe that shapes its evolution. Cosmological probes are amongst the powerful tools at our disposal to shed light on the nature of DM. In particular, the Cosmic Microwave Background (CMB) [1] currently provides the strongest constraints on DM properties probing its energy density today to the percent level. The CMB can also constrain DM annihilation or decay into SM particles [1, 2]. Both scenarios result in an exotic injection of energy into the intergalactic medium (IGM). Late time probes (sensitive at $z \ll 1000$), including the Lyman-α forest in Quasi-Stellar Objects (QSO) spectra and the 21cm signal of the hyperfine HI transition, are expected to be particularly efficient in testing late time energy injection. They are sensitive to the IGM temperature, T_k, and, consequently, to exotic energy injections transferred to the IGM in the form of heating [3, 4]. In particular, the Lyman-α forest sensitivity to T_k at redshifts $z \sim 4-6$ disfavors [5] lifetimes $\tau \sim 10^{-25}$ s for DM decays into electron-positron pairs for $m_\mathrm{DM} < \mathrm{MeV}/c^2$. On the other hand, the 21cm signal will be sensitive to T_k at even earlier times, during the so-called Cosmic Dawn (CD) of galaxies ($z \sim$ 10-20) and the epoch of reionisation (EoR, $z \sim$ 5-10). Interestingly, the relative dearth of galaxies during the CD should make it easier to isolate an additional heating contribution from DM decay or annihilation.

In these proceedings we briefly summarize our recent work [6] on the imprint of DM decays on the cosmological 21cm signal and the first Fisher matrix forecasts on DM lifetime constraints for the Hydrogen Epoch of Reionisation Array (HERA) telescope. The latter was designed to measure the 21cm power spectrum at a high signal to noise ratio (S/N). HERA has completed deployment [7] and is currently analysing data from an extended observational campaign. An initial observational result performed with 71 antennas (out of the total 331) and only 94 nights of measurement has already provided the most constraining upper bounds on the 21 cm power spectrum at redshifts $z = 8$ and 10. [8]

Our results, obtained with `exo21cmFAST` [9] and `21cmCAST` [10], clearly indicate that 21cm cosmology will soon be mature enough to quantitatively probe exotic heating scenarios like decaying DM models.

2. 21cm signal and DM decay imprint

The redshifted cosmic 21cm signal, arising from the hyperfine spin-flip transition of neutral hydrogen, can be seen in emission or in absorption compared to the radio background. Here we fix the latter to the CMB whose temperature is denoted by T_CMB. The differential brightness temperature of the 21cm signal, δT_b, shows the following dependence

$$\delta T_\mathrm{b} \propto 20\mathrm{mK}\left(1 - \frac{\mathrm{T_{CMB}}}{T_\mathrm{S}}\right) x_\mathrm{HI} \tag{1}$$

in the the spin temperature, denoted as T_S, and in the neutral fraction, x_HI. The spin temperature quantifies the relative occupancy of the two hyperfine levels of the ground state of neutral hydrogen. At the redshifts of interest for our study ($z \sim 6-30$) and our assumed astrophysics model, it is obtained from the equilibrium balance of absorption/emission of 21cm photons from/to the CMB background, coupling T_S to T_CMB, and resonant scattering of Lyman-α photons, coupling T_S to the

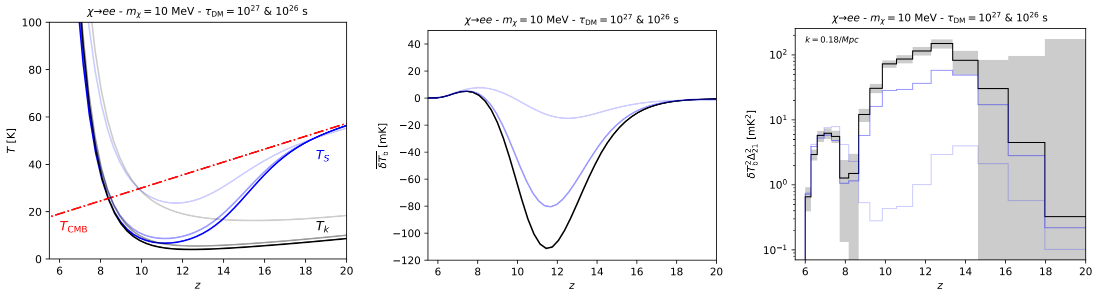

Figure 1: Imprint of DM decays into a pair of electron positrons with 10 MeV/c^2 mass and decay rates of $\tau = 10^{27}$ and 10^{26}s (lightest colored line correspond to longest lifetime) compared to a fiducial scenario considering a single population of galaxies (darkest lines). In the figures, the temperatures (left), the global 21cm signal (central) and the power spectrum (PS, right) are shown as a function of the redshift z in the redshift range of interest. The PS, displayed in z bins compatible with HERA specificities, is shown at a scale of $k = 0.18$/Mpc. The gray area represents the 2 sigma error expected from HERA on the fiducial model (black line).

gas temperature T_k. When the spin temperature is coupled to IGM gas kinetic temperature through the latter process, T_S can differ from the CMB temperature T_CMB in eq. (1) and the redshifted 21cm signal is seen in absorption or emission w.r.t. the CMB, see e.g. the left and central plots of Fig. 1. The spatial variation of IGM properties leads to fluctuations in the 21cm signal. In what follows, we refer to the 21cm global signal, $\overline{\delta T_b}$, as the sky averaged brightness temperature while the 21cm power spectrum (PS), $\overline{\delta T_b^2}\Delta_{21}^2$, that we will use to derive our sensitivity curves, is obtained from:

$$\overline{\delta T_b^2}\Delta_{21}^2(k,z) = \overline{\delta T_b^2}(z) \times \frac{k^3}{2\pi^2} P_{21}(k,z) \tag{2}$$

where P_{21} is defined as $\langle \tilde{\delta}_{21}(\mathbf{k},z)\tilde{\delta}_{21}(\mathbf{k}',z)\rangle = (2\pi)^3\delta^D(\mathbf{k}-\mathbf{k}')P_{21}(k,z)$ with $\langle\rangle$ the ensemble average, $\mathbf{k}$ the comoving wave vector, and $\tilde{\delta}_{21}(\mathbf{k},z)$ the Fourier transform of $\delta_{21}(\mathbf{x},z) = \delta T_b(\mathbf{x},z)/\overline{\delta T_b}(z) - 1$. An example of 21cm PS is shown in the right panel of Fig. 1.

Dark matter energy injection in the IGM, from e.g. annihilations or decays, induces extra heating, ionization and excitation of the IGM that leave a footprint in the 21cm signal. In the case of dark matter decays, the fraction of energy *injected* per redshit per unit volume and baryons, is given by:

$$\frac{1}{n_b}\left(\frac{dE}{dVdz}\right)_\mathrm{injected} = \frac{\rho_\mathrm{DM}c^2}{n_b(1+z)H}\frac{1}{\tau}, \tag{3}$$

where we have assumed that the lifetime satisfy $\tau \gg t_U$, with t_U the age of the universe, c is the speed of light, n_b the baryon number density, ρ_DM the DM energy density and H the Hubble rate. Below we also use the DM decay rate, $\Gamma \equiv 1/\tau$, to characterize DM energy injection. The fraction of energy injected of eq. (3) scales as $(1+z)^{-5/2}$ in a matter ($(1+z)^{-3}$ in a radiation) dominated era. From the negative powers of $(1+z)$ one can expect that DM decays shall leave a stronger impact on cosmological observables at relatively late times (at $z \ll 1000$) including e.g. 21cm Cosmology probes. In contrast, DM annihilation through s-wave annihilations is already strongly constrained by CMB observations [1]. For this reason, we focus on DM decays instead of DM annihilation for a first forecast of 21cm constraints on DM energy injection in the IGM.

For $z < 30$, DM energy injection can dominate the IGM heating at early times. In Fig. 1 we illustrate the imprint of DM decays into a pair of electron positrons with 10 MeV$/c^2$ mass and decay rates of $\tau = 10^{27}$ and 10^{26}s (lightest colored line corresponds to longest lifetime) on the gas (blue lines) and spin temperatures (gray lines) in the left plot, on the global 21cm signal (blue lines) in the central plot and on the PS (blue lines) in the right plot. In all cases we consider an astrophysics model involving a single type of galaxies, refered to as atomic-cooling galaxies (ACGs), that we have observed at late times.

For the scenarios displayed in Fig. 1, the DM heating dominates for $z > 10$–15. From eq. (3), DM decays shall give rise to a stronger energy injection in the IGM for shorter lifetimes (lighest blue colored curves). At fixed mass, a shorter lifetime is then expected to induce a stronger heating or a larger increase of T_k and T_S at $z > 10$–15 for the scenario illustated in in Fig. 1. This also implies a shallower absorption trough in the global signal. Both effects are well visible in the left and central panels of Fig. 1. DM decays also induce a more uniformly heated IGM at early times, which can decrease the large-scale 21cm power during Cosmic Dawn compared to galaxy-only heating [3, 4] as illustrated in the right panel of Fig. 1. Let us mention that the impact of DM decay on the late-time 21cm power ($z < 9$ for our scenario displayed in Fig. 1) is far more modest compared to astrophysics sources of X-rays. [6] Given that experiments such as HERA will be able to probe a large range of redshifts and scales, we expect them to be able to disentangle these two sources of heating. From the HERA sensitivity estimate shown in Fig. 1 with a light gray area, we can expect that HERA shall be able to probe lifetimes up to $10^{27} - 10^{28}$ s, surpassing the sensitivity from CMB and Lyman-α probes.

3. Results

We have performed the first Fisher matrix analysis [6] to evaluate the best lower limits that are expected to be set on the dark matter lifetime τ by the HERA experiment within two possible astrophysics scenarios and fixed dark matter mass m_χ. The first scenario considers only radiation from PopII-dominated ACGs. ACGs have been observed and their stellar to halo mass relation is well constrained by UV luminosity functions. On the other hand, we have also considered the case of a more complete, yet more complex, astrophysics model where we consider both ACGs and molecular-cooling galaxies (MGCs). The latter scenario involves more sources of uncertainties as MGCs properties are yet to be determined. MGCs would correspond to the very first galaxies, hosted by so-called minihalos (with a virial mass $< 10^8 M_\odot$) that are expected to predominately host Population-III stars. In particular, MGCs can heat the medium earlier than AGCs and the DM imprint becomes less easy to untangle from astrophysics. This is expected to mitigate the constraints on exotic sources of heating.

The Fisher matrix analysis including AGCs only (AGCs+MGCs) involves a set of 8 (11) astrophysical parameters and one dark matter parameter which is the decay rate, Γ. In the case of AGC only (AGC& MGCs), it appears that one of the most degenerate parameter with Γ is the integrated soft-band luminosity per star formation rate from AGCs (from MGCs), denoted with L_X^{II} (L_X^{III}). The latter essentially determines the amplitude of X ray heating from cosmic dawn galaxies.

Our main results, presented in Fig. 2, display the lower bound at a 95% confidence level (CL) on the lifetime of dark matter derived from our Fisher matrix forecasts based on HERA specifications.

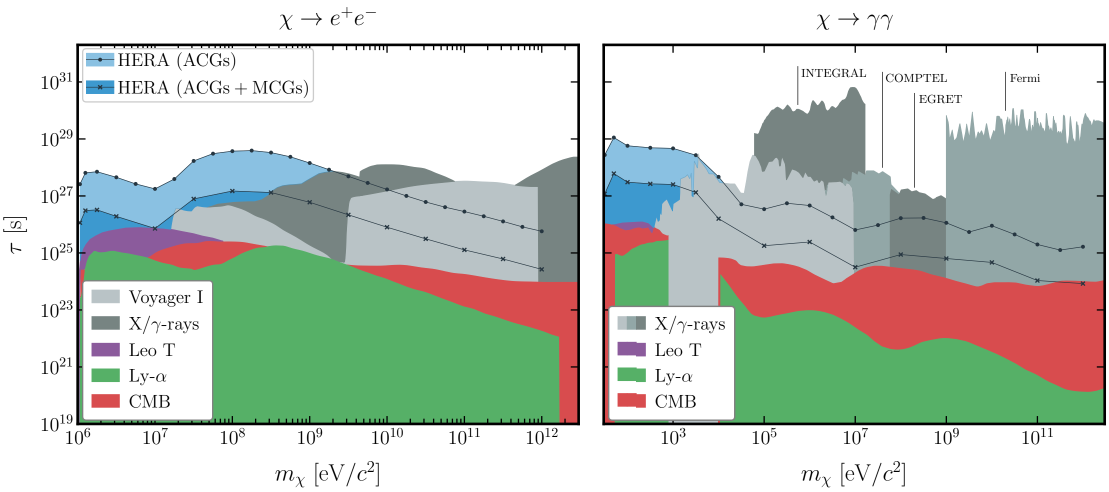

Figure 2: Updated constraints on the dark matter lifetime (at 95% level) for decay into an electron/positron pair (left panel) and photons (right panel). We superpose the forecasts for the HERA telescope assuming PopII-dominated ACGs only (solid dark line with round markers), or PopII-dominated ACGs + PopIII-dominated MCGs with $\log_{10}(L_X^{\mathrm{II,III}}) = 40$ (solid dark line with crosses) with existing cosmological constraints.

Black lines with bullets are obtained for one single population of galaxies (AGCs) while black lines with crosses assume ACGs+MCGs. The blue area below these curves are excluded at 95% CL. When considering the ACGs+MCGs scenario, heating from galaxies competes with DM heating earlier and the DM heating parameters become more difficult to constrain. The lower bound on the DM life time becomes thus less stringent in ACGs+MCGs scenario (crosses) than in the AGCs only case (bullets). For decays into e^+e^-, a few 100 MeV/c^2 DM gets the most stringent 21cm bounds on Γ while, for decays into photons, it is the case for the lowest DM masses (with $m_\chi <$MeV/c^2).

In Fig. 2, we also show the lower bounds arising from cosmology and astrophysics probes such as Lyman-α forest (green), CMB (red) and Leo T (purple). 21-cm measurements with HERA could improve by up to 3 orders of magnitude the current limits on the DM lifetime, when considering PopII-dominated ACGs only (black line with bullets). In addition, we also show the existing bounds from indirect dark matter searches including constraints from the Voyager I observation of cosmic rays, and from X- or γ-ray experiments such as INTEGRAL/SPI, COMPTEL, EGRET and Fermi.[1] We have found that existing constraints for dark matter heavier than 1 GeV/c^2 (or 100keV/c^2) for decays into e^+e^- (or photons) remain competitive and our 21cm forecast for 1000 hours of HERA observation is unlikely to improve these limits in the higher DM mass range.

In Fig. 3, we project the HERA sensitivity for $\chi \to \gamma\gamma$ in the plane $(m_a, g_{a\gamma\gamma})$ corresponding to the mass and coupling to photons of DM, in the form of an axion like particle (ALP) decaying to two photons. For the latter purpose we have assumed that the axion decay rate scales as $\Gamma_a = \frac{g_{a\gamma\gamma}^2}{64\pi} m_a^3$. The red region is excluded at 95% CL by Planck 2018 data assuming a tanh reionization model [2] while the blue region illustrates the 95% CL sensitivity of HERA. The later can probe $g_{a\gamma\gamma}$ couplings smaller by more than order of magnitude than Planck data and can also

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[1] More competitive constraints from XMM Newton have recently been published [11], see talk of P. De la Torre Luque in Moriond VHEPU talks.

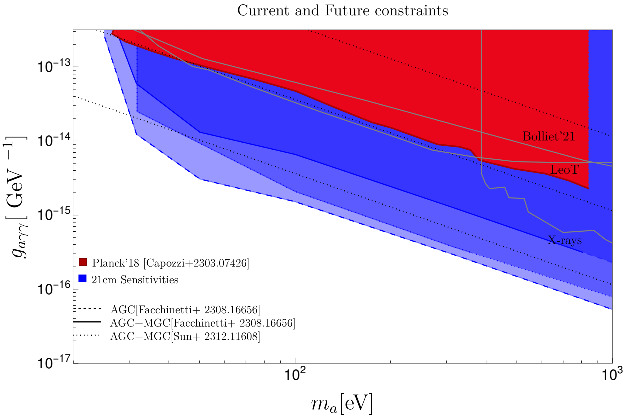

Figure 3: Present and future bounds on the ALP $(m_a, g_{a\gamma\gamma})$ parameter space. These include existing 95% CL cosmology constraints from Planck 2018 assuming a tanh reionization [2] in red and expected future HERA sensitivity estimate in blue from our work [6] and a recent analysis accounting for inhomogeneous injection [12]. The dotted black lines indicate, from top to bottom, axion life times of $\tau = 10^{24}, 10^{26}$ and 10^{28} s.

improve on X-ray searches in the ~ MeV masses (all references for other (astro-)particle bounds in gray colors can be found in [2]). Notice that our results, shown with the continuous and dashed blue contours, were obtained considering an homogeneous DM energy injection. The dashed (continuous) contour corresponds to the ACGs only (AGCs+MGCs) limits represented with solid dark line with round markers (crosses) in the left panel of Fig. 2. Our results can be compared to the dotted blue contours from a more recent analysis accounting for inhomogeneous injection [12] and a yet different astrophysics background involving AGCs+MGCs. It appeared that, when accounting for inhomogeneities, the sensitivity reach of HERA only marginally weakens compared to the homogeneous treatment even though the detailed 21cm fluctuation maps might differ more significantly depending on the decaying DM lifetimes.[2] To conclude, Fig. 3 emphasizes again the improvement in probing decaying DM candidates that can be expected from 21cm cosmology experiments probing the 21cm power spectrum.

4. Conclusion

As is well known, DM decays give rise to a relatively late time ($z \ll 1000$) energy deposition into the medium. This makes late time probes, such as Lyman-α forest or 21cm cosmology, very interesting targets to detect the DM imprint. In this work, we focus on the effect of DM on the 21cm signal power spectrum and prospects for constraints on the DM lifetime by the HERA interferometer. This telescope will enable us to explore a vast range of redshifts, stretching from the Epoch of Reionization to Cosmic Dawn, with exceptional precision. This capability is of paramount importance because DM is not the sole contributor to the heating process, and it is

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[2] This conclusion could be expected as the differential brightness contrast sourced by inhomogeneous DM energy injection is expected to be enhanced but the potential increase in sensitivity is counterbalanced by increasing degeneracies with astrophysics parameters. [12]

crucial to distinguish its distinct signature from that generated by X-rays emitted from the first galaxies.

Our Fisher matrix forecasts for 21cm power spectrum measurements sensitivity to DM decays are very promising. Our results are summarized in Fig. 2 and projected in the case of ALPs in the relevant mass range in Fig. 3 for these proceedings. When considering the minimal astrophysics scenario (AGC only), HERA is expected to improve on existing cosmology constraints (from CMB and Lyman-α probes) on the DM lifetime by up to 3 orders of magnitude. This corresponds to more than one order of magnitude improvement on the ALP photon coupling $g_{a\gamma\gamma}$ in the mass range of $m_a \sim 10$ keV to MeV. We also compare these prospects to the case where the astrophysics model includes both PopII-dominated ACGs and PopIII-dominated MCGs. Similarly to DM, MCGs is expected to give rise to a new source of IGM heating before PopII-dominated ACGs light on, partially drowning the DM signal. Nevertheless, even in the latter case, HERA can improve on existing cosmology constraints by a factor of 10 to 100. Finally, compared to existing γ-ray and cosmic-ray limits, HERA is expected to be a key player in constraining DM candidates decaying to e^+e^- in the mass range $m_\chi < 2$ GeV$/c^2$. For decays into photons, HERA improves on other searches in the low mass range for $m_\chi <$ few MeV$/c^2$.

Acknowledgments

These proceedings mainly summarize the work [6] done in collaboration with G. Facchinetti, Y. Qin and A. Mesinger where all missing details and references (due to restricted number of pages) can be found. LLH thank the organizers of Moriond Electroweak Interactions & Unified Theories 2024 and of the Corfu Summer Institute 2023 for the the invitation and the very nice conferences. She is supported by the Fonds de la Recherche Scientifique F.R.S.-FNRS through a research associate position and acknowledges support of the FNRS research grant number F.4520.19, the ARC program of the Federation Wallonie-Bruxelles and the IISN convention No. 4.4503.15.

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