Lightening the dark matter from its viscosity and explanation of EDGES anomaly

Arvind Kumar Mishra

Theoretical Physics Division, Physical Research Laboratory,
Navrangpura, Ahmedabad, 380009, India
Indian Institute of Technology Gandhinagar,
Palaj, Gandhinagar, 382355, India
E-mail: arvind@prl.res.in

Received August 1, 2019
Revised March 11, 2020
Accepted April 14, 2020
Published May 18, 2020

Abstract. In this work, we study the visible photon production from the viscous dissipation of the dark matter (DM) fluid. The generation of visible photons depends on the magnitude of the dark matter viscosity and becomes important at the late time. We argue that for sufficiently large dark matter viscosity, the number of resonantly converted visible photons becomes large which populates the Rayleigh-Jeans (RJ) tail of the Cosmic Microwave Background (CMB) radiation. Consequently, these excess visible photons can explain the anomaly in the 21 cm signal observed by the EDGES collaboration. Further, we explore the parameter space for which the 21 cm signal can provide the region to probe the dark radiation and the DM viscosity.

Keywords: CMBR theory, dark matter theory, particle physics - cosmology connection

ArXiv ePrint: 1907.04238
Contents

1 Introduction 1

2 Viscous dark matter and energy dissipation 2
   2.1 Dark matter viscosity and coldness condition 3
   2.2 Energy dissipation from the viscous DM fluid 6

3 Production of visible photons from the viscous dark matter dissipation 6
   3.1 When DM directly dissipates into photons 7
   3.2 When DM dissipates into DR which convert into photon via kinetic mixing 7

4 EDGES anomaly in 21 cm signal 9

5 Viscous DM dissipation into the photons as an explanation of EDGES anomaly 10
   5.1 Production of visible photons from the viscous dissipation 10
   5.2 Constraining the parameter space for $\epsilon$, $m_{A'}$ and $m_\chi$ 12
   5.3 Constraining the DM viscosity 13
   5.4 DM energy dissipation and its contribution in total DM energy density 13

6 Conclusion 14

1 Introduction

The different astronomical and cosmological observations confirm a new kind of matter, called dark matter [1–6], which contribute $\sim 25\%$ to the Universe energy budget. Rest $\sim 75\%$ of the energy budget is constituted by the dark energy and the baryonic matter. Till date, the presence of DM is dictated only through its gravitational interaction. In the current ongoing DM searches — direct, indirect, and at colliders, a finite non-gravitational interaction between the DM and the visible matter is considered. But the results suggest no sign of any non-gravitational interaction with the DM. For reviews on the DM candidates and the DM searches, we refer to refs. [7–10].

In the standard cosmological description, the dark matter is considered as a perfect fluid, but any deviation from the perfect fluid approximation can lead to some interesting consequences. It has been argued that the viscous DM can explain the early time [11–14] and late-time cosmic acceleration [15–29] and also ameliorate the tension between the Planck and local measurements [30]. In our previous work [31], we show that the Self Interacting Dark Matter (SIDM) can lead to viscosity in the DM fluid and at the late time of the cosmic evolution, the SIDM viscosity is strong enough to create the accelerated expansion and account for the present observed cosmic acceleration. Also, the SIDM viscosity can explain the low redshift observations without the dark energy component, as shown in our other works [32, 33]. For more recent work on the cosmic viscosity, see refs. [34–41].

In this work, we explore the consequences of the DM viscosity that can lead to an observational signal and thus can be used to understand the properties of the DM. In particular, we study the visible photons (standard model photon) production from the viscous
DM dissipation. It has been argued that the viscous dark matter contributes to the entropy production and in energy dissipation in the cosmic medium [42, 43]. The produced energy depends on the DM viscosity parameters and if the DM viscosity is large enough, it increases the DM temperature. We calculate the analytic expression for the DM temperature in the presence of the DM viscosity and find that it depends on its mass and viscosity parameters. For large DM mass and viscosity, the DM temperature becomes large and hence can conflict with the DM coldness paradigm. To keep the success of the cold dark matter paradigm, we derive the condition on the DM viscosity parameters so that the viscous DM could not violate the DM coldness criteria.

Here we consider that the DM dissipates into the visible photons in two possible ways. First, when the DM dissipates directly into visible photons, and second, when the dark matter dissipates into the Dark Radiation (DR) which can further convert into the visible photons via a kinetic mixing. In the case of kinetic mixing, the visible photon conversion will peak at the time of resonance, when the plasma mass of the visible photon equals the dark radiation mass. We find that in both the cases, the number density of the generated photon crucially depends on the dark matter temperature (which depends on the DM mass and viscosity) and increases as the DM temperature increases.

We check a possibility whether the photons produced from the viscous dissipation can address the anomaly in the 21 cm signal as reported by the EDGES collaboration [44]. A possible explanation of the EDGES anomaly requires a large number of CMB photons in the Rayleigh-Jeans limit of the CMB spectrum [45–49]. Considering the DM as a viscous fluid, we calculate the number of RJ photons produced from the DM dissipation. We find that the photons produced through the kinetic mixing can significantly increase the number density of CMB photons in the RJ limit and hence address the EDGES anomaly. But when the DM directly dissipates into the photons, it does not produce sufficient low energy RJ photons and fails to explain the EDGES anomaly. Further, we constrain the parameter space for the mixing parameter, DM mass, dark radiation mass and DM viscosity parameters which can explain the reported EDGES anomaly.

The arrangement of this work is as follows: in section 2, using the power-law form of the DM viscosity, we calculate an analytic expression of the DM temperature as a function of the redshift. Further we derive the condition on the DM viscosity that respect the DM coldness criteria. In section 3, we discuss the two different possible mechanisms for the photon production from the viscous DM dissipation. Further, in section 4, we discussed the anomaly observed in the 21-cm signal reported by EDGES collaboration. Then in section 5, we propose a new explanation of 21 cm signal by assuming the viscous energy dissipations in photons and explored the parameter space for different quantities involved. Lastly in section 6, we conclude our work.

2 Viscous dark matter and energy dissipation

In this section, we derive the expression of entropy generation from the DM viscosity and then using this, we study the temperature evolution of the dark matter. Since the presence of DM viscosity increases the DM temperature, hence for large DM viscosity the viscous DM may no longer be cold. Considering this fact in mind, we further derive the condition on the DM viscosity parameters for which the DM respect the coldness paradigm.
2.1 Dark matter viscosity and coldness condition

In the standard cosmology (ΛCDM model), DM is assumed to be cold and an ideal fluid (with no viscosity). But whenever a fluid is expanded, (or compressed) the fluid may deviate from the local thermodynamic equilibrium, then the relaxation process like viscosity can attempt to restore the local equilibrium. Here we assume that the dark matter is a viscous fluid having a bulk viscosity (the possibility of the shear viscosity can be ruled out from the homogeneity and the isotropy of the large scale). In this work, we consider DM bulk viscosity as a power-law form in its energy density as \[ \zeta_\chi(z) = \zeta_0 \left( \frac{\rho_\chi(z)}{\rho_\chi(0)} \right)^\alpha, \] (2.1)

where \( \zeta_0 \) and \( \alpha \) are the viscosity parameters. Here \( \rho_\chi(z) \) and \( \rho_\chi(0) \equiv \rho_\chi(0) \) represent the DM energy density at any redshift, \( z \) and at present, \( z = 0 \), respectively. Since the DM energy density decreases at a late time, the evolution of the DM viscosity depend on the sign of \( \alpha \). It is clear that for \( \alpha > 0 \), \( \zeta_\chi \) is large at large redshift and decreases at small redshift but for \( \alpha < 0 \), \( \zeta_\chi \) is small at large redshift and increases on small redshift. For \( \alpha = 0 \) case, the viscosity is independent on DM energy density and hence does not varies with the redshift.

The form of bulk viscosity, as discussed in eq. (2.1) has been widely used to study the cosmological evolution. The bulk viscosity of form \( \zeta = \kappa \rho \) (\( \alpha = 1 \)), has been used to show that the viscous model can avoid the singularity [51] and assuming the same form the stability of de Sitter Universe has been checked [52]. Further, power law form of the DM viscosity has been also been used to investigate the cosmic evolution (using \( \alpha \geq 1 \) and also \( \alpha < 1 \)), the large scale structure formation (\( \alpha = 0, 1/4 \) [53, 54], 21-cm signal (\( \alpha = 0 \) and \(-1/2 \)) [43]. However\( \alpha \) values considered in the above studies were phenomenological.

It is important to note that the bulk viscosity is a relaxation phenomenon, so it is related to its microscopic properties. In refs. [31–33], using kinetic theory, we have calculated the DM bulk viscosity contributed from its self-interaction and checked its effect on late time of cosmic evolution. In refs. [16, 17], it has been shown that as the DM decays into the relativistic particles, the extra pressure will be produced and hence as a effect the bulk viscosity will be naturally arise in cosmic fluid. The form of the bulk viscosity is given by [16, 17]

\[
\zeta = \frac{4}{3} \rho_{d\chi} \tau_e \left( 1 - \frac{\rho_R + \rho_{CMB}}{\rho_T} \right)^2, \] (2.2)

where, \( \rho_{d\chi} \) is the energy density of decaying DM and \( \tau_e \) is the equilibration time. Here \( \rho_R, \rho_{CMB} \) and \( \rho_T \) represents the energy density of relativistic particles (produced from the DM decay), CMB and total cosmic fluid, respectively. Since \( \rho_T > \rho_R + \rho_{CMB} \), thus one finds \( \zeta \propto \rho_{d\chi} \), which implies \( \alpha = 1 \). Thus inspired by the cosmological studies and non-equilibrium thermodynamics, as discussed above, we assume \( \alpha = 1 \) as a representative value of viscosity evolution and discuss its effect on evolution of the Universe.

In order to calculate the viscous dark matter temperature evolution, first we need to estimate the entropy generation from the DM viscosity. The entropy production per unit volume due to the bulk viscous dark matter is given by [42]

\[
\nabla_\mu S^\mu = \frac{\zeta_\chi}{T_\chi} \left( \nabla_\mu u^\mu \right)^2, \] (2.3)
where, $T_\chi$ is DM temperature and $S^\mu$ is the entropy four-vector. The $S^\mu$ is defined as
\[ S^\mu = n_\chi s_\chi u^\mu , \tag{2.4} \]
where $s_\chi$, $n_\chi$ and $u^\mu$ represents the entropy per unit particle, number density and the four-velocity of the dark matter, respectively. Further, from the Second Law of Thermodynamics, the heat energy per unit time per unit volume generated by the viscous dark matter fluid is given by
\[ \frac{dQ_v}{dV dt} = T_\chi \nabla_\mu S^\mu , \tag{2.5} \]
where $\nabla_\mu S^\mu$ is given from the eq. (2.3). In order to estimate the heat energy generation, we consider the homogeneous and isotropic expansion of the Universe, given by Friedmann-Lamaitre-Robertson-Walker (FLRW) metric in flat ($k = 0$) spacetime as
\[ ds^2 = -dt^2 + a^2(t) \delta_{ij} dx^i dx^j , \tag{2.6} \]
where, $a(t)$ is the scale factor of the Universe. In the comoving frame, $u^\mu = (1, 0, 0, 0)$ and using eq. (2.5), the expression for the energy generation per unit time per unit volume becomes
\[ \frac{dQ_v}{dV dt} = 9 \zeta_\chi H^2 . \tag{2.7} \]
The presence of the dissipative effect in the DM modifies the DM temperature evolution equation. The temperature of the viscous DM evolves as \[ \frac{dT_\chi}{dz} = 2 \frac{T_\chi}{1 + z} - \frac{2}{3(1 + z)H} \left( \frac{m_\chi}{\rho_\chi} \right) \left( \frac{dQ_v}{dV dt} \right) , \tag{2.8} \]
where $m_\chi$, $\rho_\chi$ represents the mass and energy density of the dark matter respectively. The term $\frac{dQ_v}{dV dt}$ is obtained from eq. (2.7). In the matter dominated era, the Hubble expansion rate is given by $H(z) \approx H_0 (\Omega_{M0})^{1/2} (1 + z)^{3/2}$, where $\Omega_{M0}$ and $H_0$ ($H_0 = 100h \text{ km-s}^{-1}\text{MPc}^{-1}$) correspond to the present value of total matter content (DM and baryon) and the Hubble expansion rate, respectively. Here, we consider $h = 0.674$, $\Omega_B h^2 = 0.0224$, $\Omega_M h^2 = 0.142$ from the Planck 2018 data \[55\]. The first term in eq. (2.8) corresponds to the Hubble dilution which decrease the DM temperature throughout the cosmic evolution. The second term in eq. (2.8) is because of the DM viscous dissipation and the negative sign indicates that due to the viscous dissipation, the dark matter temperature increases.

Further, using eq. (2.8), the analytic solution for DM temperature is obtained as
\[ T_\chi(z) = A (1 + z)^2 - \frac{4.2}{24\pi} \left( \frac{H_0^2 m_{\text{Pl}}^2}{\rho_c} \right) \left( \frac{m_\chi \bar{\zeta}}{\alpha - 1.16} \right) \left[ 1 + z \right]^{3(\alpha - \frac{3}{2})} , \tag{2.9} \]
where $A$ and $\rho_c$ represent the constant of integration and the present critical energy density of the Universe, respectively. Further, $\bar{\zeta} = \frac{24\pi G \zeta_0}{H_0}$ is dimensionless viscosity parameter and $m_{\text{Pl}} = \sqrt{G}$ is the Planck mass. From the equation (2.9), it is clear that the DM temperature depends on the viscous parameter, $\bar{\zeta}$ and $\alpha$ and there is a singularity corresponding to $\alpha = 1.16$. In order to calculate $A$, we take the initial condition of DM temperature at the redshift, $z_i$, where we assume $T_\chi(z_i) = 0$. Using the initial condition in eq. (2.9), we obtain
\[ A = \frac{4.2}{24\pi} \left( \frac{H_0^2 m_{\text{Pl}}^2}{\rho_c} \right) \left( \frac{m_\chi \bar{\zeta}}{\alpha - 1.16} \right) \left[ 1 + z_i \right]^{3\alpha - \frac{3}{2}} . \tag{2.10} \]
Furthermore, as the DM viscosity increases, the DM starts heating up. In the case of sufficiently large DM viscosity, the DM temperature becomes high and may conflict with the DM coldness paradigm. The condition that DM will be cold in the redshift interval $z_{\text{dec}} \geq z \gg 1$, is given by [56]

$$\frac{T_{\chi}}{m_{\chi}} \leq 1.07 \times 10^{-14} (1 + z)^2,$$  \hspace{1cm} (2.11)

where $z_{\text{dec}}$ is the redshift at which the DM decouples from the rest of the thermal plasma kinematically. This allows us to find a condition on the DM viscosity parameter for which the DM behaves as cold. Then using eq. (2.9) and eq. (2.11), the condition on the DM viscosity at the redshift, $z_{f}$ for which the DM is dictated as a cold fluid, is given as

$$\bar{\zeta} \leq 1.92 \times 10^{-13} \left(\frac{\rho_c}{H_0^2 m_{\text{Pl}}^2}\right) \left(\alpha - 1.16\right) \left[(1 + z_i)^{3a - \frac{7}{2}} - (1 + z_f)^{3a - \frac{7}{2}}\right]^{-1},$$  \hspace{1cm} (2.12)

where $z_{\text{dec}} \gg z_i > z_f \gg 1$. If the above inequality does not satisfy, then the viscous DM fluid will not be cold. The above DM coldness criteria hold for the linear regime of the structure formation and do not hold for the late time where the structures are formed and found in form of the collapsed object (such as galaxies and clusters). Thus, assuming $z_i = 1300$ and $z_f = 17$, the maximum allowed viscosity that respect the DM coldness paradigm is, $\bar{\zeta} \sim 10^{-14}$ for $\alpha = 1$ case.

Up to this point our analysis is general but for the rest of the paper we consider the initial condition for DM temperature at $z_i = 1300$, i.e. $T_{\chi}(1300) = 0$. We have checked that changing the initial condition for DM temperature from 1300 to 1700 does not change our results significantly.

In order to see the effect of the DM viscosity on its temperature, we plot the DM temperature as a function of the redshift for different values of the viscosity parameters in figure 1. We fix $\bar{\zeta} = 10^{-15}$, $m_{\chi} = 0.1$ GeV and plot $T_{\chi}(z)$ for $\alpha = 1$ (red line), $\alpha = 0$ (black line), $\alpha = -1$ (blue line). We see that for $\alpha = -1$, DM temperature increases at low redshifts. This happens because the DM viscosity in inversly proprtional to the DM energy density, which decreases at late times (small redshift) and hence increases the DM viscosity contribution on late times. Further, for $\alpha = 0$ (viscosity is constant with the redshift), the
DM temperature increases at a small redshift but slightly lower rate in comparison with the \( \alpha = -1 \) case. But for \( \alpha = 1 \), the DM temperature firstly increases on large redshift and decreases below redshift \( \sim 500 \), which is evident because the DM viscosity decreases with the redshifts. Thus we conclude that for a fix value of \( \bar{\zeta} \) and increasing the viscosity parameter \( \alpha \), causes to increases the DM temperature.

Further, using eq. (2.9) we point out that the ratio of DM temperature to DM mass, \( \frac{T}{m_\chi} \) is independent of the DM mass and only depends on the viscosity parameters, \( \bar{\zeta} \) and \( \alpha \).

### 2.2 Energy dissipation from the viscous DM fluid

In terms of redshift, the dissipated energy density by viscous DM from eq. (2.7) is given by

\[
q_{\text{vis}}(z_s \rightarrow z_e) = \int_{z_s}^{z_e} \left( \frac{dQ_v}{dVdz} \right) dz = -9 \int_{z_s}^{z_e} \zeta_\chi(z) \frac{H(z)}{(1+z)} \frac{dz}{(1+z)} . 
\]

(2.13)

Here \( z_s \) and \( z_e \) represent the starting and ending redshift between which the DM dissipates its energy. After integrating eq. (2.13), we get

\[
q_{\text{vis}}(z_s \rightarrow z_e) = 5.36 \times 10^{-34} \left( \frac{H_0 \, m_\chi^2}{24 \pi} \right) \left( \frac{\bar{\zeta}}{2\alpha + 1} \right) \left[ (z_s + 1)^{3(\alpha + \frac{1}{2})} - (z_e + 1)^{3(\alpha + \frac{1}{2})} \right].
\]

(2.14)

Thus the dissipated energy density depends on the dark matter viscosity parameters, \( \bar{\zeta} \) and \( \alpha \). Also, the viscous DM dissipation becomes prominent when the viscosity is large. From eq. (2.14), it is clear that \( \alpha \neq -0.5 \), otherwise the expression on r.h.s. will blow. We point out that the viscous energy dissipation becomes large at late time and increases with the DM viscosity.

### 3 Production of visible photons from the viscous dark matter dissipation

In this section, we discuss the production of visible photons from the dissipation of viscous DM fluid. Note that we will use the terms visible photon and photon interchangeably unless specified explicitly. We assume that a small fraction of the DM is viscous and its contribution is very small to the total DM energy density. The DM viscosity leads to entropy generation and energy dissipation in the cosmic medium due to which visible photons can be produced. This can take place in two ways: (1) when the DM directly dissipates into the visible photons and (2) when the DM firstly dissipates into the dark radiation (DR) which then convert into the visible photons via a kinetic mixing.

Further, to study photon generation from the viscous energy dissipation, we need to estimate the bulk viscosity of DM fluid, which requires the particle physics description of the DM decay (e.g., to calculate \( \tau_e \) in eq. (2.2)). So to keep our analysis model-independent, here, we do not discuss the explicit particle physics motivated mechanism for viscous dissipation and leave it as a future exercise. For completeness, several models for the DM energy dissipation into the visible particles are studied in the literature. In ref. [48], it has been discussed the complete realization of the unstable scalar field, which decays to dark photons via dimensional five operators and then generates the visible photons from the kinetic mixing. In other refs. [57–59], the DM dissipation in the standard model particles has been discussed in the context of two-component hidden sector dark matter.
3.1 When DM directly dissipates into photons

In this case, we assume that the viscous dissipation directly produces visible photons. We also consider that these photons are in thermal equilibrium with the DM and follow the Bose-Einstein distribution. Then the number of photons generated from DM viscous dissipation is given as

\[ n_{\chi \to A} = \frac{1}{\pi^2} \int_0^\infty \frac{\omega_A^2}{\exp \left( \frac{\omega_A}{T_A} \right) - 1} \, d\omega_A . \]  

(3.1)

Therefore the number of photons generated up to a small frequency limit \( \omega_{\text{max}} \) is given as

\[ n_{\chi \to A} = \frac{1}{\pi^2} \int_0^{\omega_{\text{max}}} \frac{\omega_A^2}{\exp \left( \frac{\omega_A}{T_A} \right) - 1} \, d\omega_A . \]  

(3.2)

In the low energy limit, \( \omega_A \) is small and we can approximate, \( e^{\frac{\omega_A}{T_A}} - 1 \approx \frac{\omega_A}{T_A} \). Further, as photons are in thermal equilibrium with the DM, therefore they follow the same temperature as dark matter, \( T_A = T_\chi \). Thus using the above assumptions and integrating eq. (3.2), we get

\[ n_{\chi \to A} \approx \frac{T_\chi}{2\pi^2} \frac{\omega_{\text{max}}^2}{2}. \]  

(3.3)

This shows that the number density of the low energy photons is proportional to the DM temperature. The greater is the DM temperature, the larger is the photon production.

At large redshift (at the time of CMB release), due to small DM viscosity, the energy dissipation and the DM temperature were small and hence the photons generation was less. But at low redshift, due to increment in the DM viscosity, the energy dissipation hence the DM temperature becomes large and contribute more in the photons production rate. If the DM temperature is small then the produced photons contribute to the low energy frequency limit of CMB radiation but if the DM temperature is large, the produced photons increase the number of photons of large frequency limit of the CMB radiation also. Thus for sufficiently large DM viscosity, the photons generation will large which increase the radiation component and Hubble expansion rate of the Universe at the time of decoupling. This modifies the baryon to photon ratio and decreases the sound horizon \( r_s \), because \( r_s \propto 1/H \) (see, refs. [60, 61] and references therein), which is well constraint from the CMB measurement [55]. In our whole analysis, the DM viscosity is considered to be small and consequently the viscous energy dissipation is small in comparision with the CMB radiation. For example, in case of \( \alpha = 1 \) and \( \bar{\zeta} = 3 \times 10^{-15} \), \( q_{\text{vis}}^{(1300-17)} \rho_{\text{CMB}} = 10^{-15} \). Thus such a small energy density produced via the viscous dissipation will not affect \( H \) and \( r_s \).

3.2 When DM dissipates into DR which convert into photon via kinetic mixing

In this case, we assume that the DM dissipates into the dark radiation, \( A' \). We consider that the DR is in thermal equilibrium with the DM and follows the Bose-Einstein distribution. Then the number density of the produced dark radiation can be given by

\[ n_{A'} = \frac{g_{A'}}{2\pi^2} \int_{m_{A'}}^\infty \frac{\omega_{A'}^2}{\exp \left( \frac{\omega_{A'} - \mu_{A'}}{T_{A'}} \right) - 1} \sqrt{\omega_{A'}^2 - m_{A'}^2} \, d\omega_{A'} , \]  

(3.4)

where \( m_{A'} \) is the DR mass and \( g_{A'}, \mu_{A'} \) represent the relativistic degree of freedom and the chemical potential of the dark radiation, respectively. The energy associated with DR,
\[ \omega_{A'} = \sqrt{m_{A'}^2 + p_{A'}^2}, \] where \( p_{A'} \) is the momentum of the dark radiation. Since the produced dark radiation is in thermal equilibrium with the DM, therefore \( T_{A'} = T_\chi \). Thus considering \( \mu_{\chi} = 0 \), the differential number density of the DR is given as

\[ \frac{dn_{A'}}{d\omega_{A'}} = \frac{g_{A'}}{2\pi^2} \exp \left( \frac{\omega_{A'}}{T_\chi} - 1 \right) \sqrt{\omega_{A'}^2 - m_{A'}^2}. \]  

(3.5)

Further, we point out that the production of extra relativistic particles, DR can increases the Hubble expansion rate and create the problems at decoupling (as discussed in subsection 3.1). The energy of extra relativistic particles is quantified in terms of effective degree of freedom \( \Delta N_{\text{eff}} \), defined as

\[ \Delta N_{\text{eff}} = \frac{\rho_{\text{REL}}}{\rho_{\text{CMB}}}. \]  

(3.6)

where \( \rho_{\text{REL}} \) is the energy density of the extra radiation component (excluding the CMB and standard model neutrino) present in the Universe. We use the Planck 2018 data \cite{55} to constraint the maximum energy contained in extra DR which demands \( \Delta N_{\text{eff}} \leq 0.33 \). Here, we consider that the viscous energy dissipation leads to the radiation generation, hence \( \rho_{\text{REL}} = \rho_{\text{vis}} \). In case of DM dissipates in to the DR, for the DM viscosity parameter considered in this work \( \alpha = 1 \) and \( \zeta = 3 \times 10^{-15} \), \( \Delta N_{\text{eff}} = 10^{-15} \). This implies that energy generated from the DM viscous dissipation into the DR is within the limits allowed from the Planck 2018 data (i.e. \( \Delta N_{\text{eff}} \leq 0.33 \)) and hence it will not modify the CMB observations.

Further, we assume that the DR can convert into the photons via a kinetic mixing, in a similar mechanism as the Standard Model neutrinos change their flavors \cite{62}. In this realization, the Lagrangian density is given by \cite{48}

\[ \mathcal{L}_{A'A} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{\epsilon}{2} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu. \]  

(3.7)

In the above Lagrangian density, the first and second term corresponds to the kinetic term for photon and DR. The third term corresponds for mixing between the DR and visible photon and \( \epsilon \) is the kinetic mixing parameter. The last term is the mass term for the DR. The maximum probability for a conversion of DR to photons occurs at the time of resonance, when the DR mass is equal to the photon plasma mass, i.e. \( m_{A'} = m_A(z) \), where \( m_A(z) \) is the plasma mass of the photon at redshift \( z \). The plasma mass is defined as \cite{63, 64}

\[ m_A(z) \simeq 1.7 \times 10^{-21} (1 + z)^{3/2} x_e^{1/2}(z) \text{ GeV}, \]  

(3.8)

where \( x_e(z) \) is the electron fraction which we calculate from the \textsc{recfast} code \cite{65} using \textsc{ camb} \cite{66}. The resonance condition can happen for a range of DR mass between, \( 10^{-23} - 10^{-18} \) GeV. The conversion probability of DR \( (A') \) into the SM photon \( (A) \) at the resonance is given by \cite{63}

\[ P_{A' \rightarrow A} = P_{A' \rightarrow A} = \frac{\pi \epsilon^2 m_{A'}^2}{\omega_{A'}} \left| d \log m_{A}^2 \right|^{-1} \left. \frac{d \log m_{A}^2}{dt} \right|_{t=t_{\text{res}}}, \]  

(3.9)

where \( t_{\text{res}} \) is the time of the resonance. In terms of the redshift, the conversion probability given in the above equation can be written as

\[ P_{A' \rightarrow A} = \frac{\pi \epsilon^2 m_{A'}^2}{\omega_{A'}} \left| (1 + z) H(z) \frac{d m_{A}^2}{dz} \right|^{-1} \left. \frac{d m_{A}^2}{dz} \right|_{z=z_{\text{res}}}. \]  

(3.10)
where $z_{\text{res}}$ is the redshift corresponds for $t_{\text{res}}$. For the low energy photons, the free-free (bremsstrahlung) absorption effect should be taken into consideration. Then the above probability should be multiplied by the photon survival probability, $P_S(x, z) \approx e^{-\tau(x, z)}$. Hence, $P_{\Lambda \to \Lambda' \to \Lambda} \approx P_{\Lambda \to \Lambda'} \times P_S(x, z)$. The absorption will be effective when $z > z_{\text{abs}} = 1700$ [67], but here we are interested in $z < 1700$.

Therefore, the differential number density of the visible photon produced from the viscous dissipation of DM into DR and further to photons is given by

$$
\frac{dn_{\Lambda' \to \Lambda}}{d\omega_{\Lambda'}} = \left( \frac{dn_{\Lambda'}}{d\omega_{\Lambda'}} \right) P_{\Lambda \to \Lambda'}.
$$

(3.11)

Using eq. (3.5) and eq. (3.10) in eq. (3.11), we get

$$
n_{\Lambda' \to \Lambda} = \frac{\pi \epsilon^2 g_{\Lambda} m_{\Lambda}^2 T_X}{2} \left( 1 + z \right) H \left( \frac{dm_{\Lambda}^2}{dz} \right)_{t = z_{\text{res}}}^{-1} \int_{m_{\Lambda'}}^{\infty} \frac{\sqrt{\omega_{\Lambda}^2 - m_{\Lambda}^2}}{\omega_{\Lambda'}} \ d\omega_{\Lambda'}.
$$

(3.12)

In order to estimate the number density of the photons in the low energy limit, we need to integrate the energy interval in the above equation up to a small frequency limit, $\omega_{\text{max}}$. Thus in this approximation, on integrating eq. (3.12) we obtain

$$
n_{\Lambda' \to \Lambda} = \frac{\epsilon^2 g_{\Lambda} m_{\Lambda}^2 T_X}{2\pi} \left[ \sqrt{\omega_{\text{max}}^2 - m_{\Lambda}^2} + m_{\Lambda} \tan^{-1} \left( \frac{m_{\Lambda}^{\Lambda'}}{\sqrt{\omega_{\text{max}}^2 - m_{\Lambda}^2}} \right) - \frac{\pi m_{\Lambda}^{\Lambda'}}{2} \right] \times \left( 1 + z \right) H \left( \frac{dm_{\Lambda}^2}{dz} \right)_{t = z_{\text{res}}}^{-1}
$$

(3.13)

where $g_{\Lambda'} = 2$. It is clear from the above equation that the number of the produced photons depend on the DM temperature, DR mass, and the mixing parameter.

The effect of these extra photons produced from the DM dissipation may be applied to explain the EDGES anomaly, which we will discuss in the next section.

### 4 EDGES anomaly in 21 cm signal

The EDGES collaboration has announced the detection of a global signal of the 21 cm wavelength at the redshift $z \sim 17$ [44]. The observed intensity of the 21 cm signal is represented by the brightness temperature, $T_{21}$, which is defined as [68, 69]

$$
T_{21} \approx \frac{3\lambda_{21}^2 A_{10nH} T_S}{16(1 + z)H(z)} \left( 1 - \frac{T_{\text{CMB}}}{T_S} \right),
$$

(4.1)

where $T_S$ and $T_{\text{CMB}}$ represents the spin and the gas temperature, respectively. $\lambda_{21}$ and $n_H$ are the wavelength of the 21 cm line at rest and the neutral hydrogen number density, respectively. The reported strength of the signal, $T_{21}^{\text{EDGES}} \approx -500^{+200}_{-300} \text{ mK}$ [44], which is approximately two times larger than the standard cosmological prediction and termed as EDGES anomaly. It has been argued that the EDGES anomaly can be addressed via the DM-baryon interaction [68] or by increasing the photons in the low-frequency limit of the CMB tail [45–49], etc. For other possible EDGES explanations, see refs. [70–73].

The EDGES signal has been used to constrain the DM microphysics such as DM annihilation and decay [74, 75], DM cross-section with the light degree of freedom [76] and
ultra-light DM hidden photon \cite{77} etc. Further, using the viscous DM-gas interaction in the light of the reported EDGES 21 cm signal, we have obtained the constraints on the DM viscosity in ref. \cite{43}. In ref. \cite{78}, using the EDGES signal the authors have constrained the strength of the magnetic field.

In this work, we focus on the explanation of EDGES anomaly that requires an increase in the photons in the Rayleigh-Jeans limit of the CMB radiation. The photons in the low energy limit of the RJ tail of the CMB radiation is given by

\[
    n_{\text{RJ}} = \frac{g_{\text{CMB}}}{2\pi^2} \int_0^{\omega_{\text{max}}} \frac{1}{\exp \left( \frac{\omega}{T_{\text{CMB}}} \right) - 1} \omega^2 \ d\omega \approx \frac{T_{\text{CMB}} \omega_{\text{max}}^2}{2\pi^2},
\]

where \( g_{\text{CMB}} = 2 \).

5 Viscous DM dissipation into the photons as an explanation of EDGES anomaly

Here, we propose a new mechanism to explain the EDGES anomaly by the viscous DM dissipation into the photons. As we have seen in section 3 that the viscous dissipation leads to the photon production and can increase the photon number density in the RJ frequency limit of the CMB and hence possibly address the reported EDGES anomaly. In this section, we will estimate the number density of photons produced from the viscous DM and constrain the parameter space of the different quantities involved.

5.1 Production of visible photons from the viscous dissipation

In this subsection, we estimate the photon production via the DM energy dissipation. In figure 2, we plot the differential number density of the photons obtained from the direct dissipation of the dark matter (black region), through kinetic mixing with the DR (red region), as discussed in section 3 and from the CMB (blue region). To generate this plot, we consider the DM viscosity parameters, \( \alpha = 1, \bar{\zeta} = 10^{-15} \), DM mass, \( m_\chi = 0.1 \text{ GeV} \) and kinetic mixing parameter, \( \epsilon = 2.1 \times 10^{-7} \) \cite{48}.

From figure 2 it is clear that the photons obtained from the kinetic mixing with the DR (red region) can significantly increase the number density of the CMB photons in the small frequency region, but does not alter the number density of the high-frequency photons by an appreciable amount. For the case of directly produced photons (black region), there is an increase in the CMB photons only at large frequency region and hence this case is inappropriate to address the EDGES anomaly.

In order to see the dependency of the photon production through the kinetic mixing on the DM viscosity, we plot the \( n'_{A' \rightarrow A} / n_{\text{RJ}} \) (using equations (3.13) and (4.2)) as a function of the redshift for different values of the DM viscosity in figure 3(a). In this plot the red line, black line and blue line correspond to \( \bar{\zeta} = 10^{-14}, \bar{\zeta} = 10^{-15} \) and \( \bar{\zeta} = 10^{-16} \), respectively. We take \( \epsilon = 2.1 \times 10^{-7} \) \cite{48}, \( \alpha = 1 \) and \( m_{A'} = 6.12 \times 10^{-19} \text{ GeV} \), and for this DR mass the resonant condition happens at \( z_{\text{res}} = 1268 \). From figure 3(a), we find that increasing the DM viscosity increases the photon production rate.

Further, to understand the dependency of \( n'_{A' \rightarrow A} / n_{\text{RJ}} \) on the DR mass, we plot it as a function of redshift for different values of the DR mass in figure 3(b). The DR masses \( 10^{-20} \text{ GeV} \) (blue line), \( 10^{-19} \text{ GeV} \) (black line) and \( 6.12 \times 10^{-19} \text{ GeV} \) (red line) corresponds
Photons via direct conversion
Photons via mixing
CMB photons
$\omega_{21} \approx 10^{-15}$, $10^{-14}$, $10^{-13}$, $10^{-12}$, $10^{-11}$
$10^{-27}$, $10^{-26}$, $10^{-25}$, $10^{-24}$, $10^{-23}$

$\omega$ (GeV) $dn_A/ d\omega$ (GeV$^2$)

Figure 2. The spectrum of the photon produced by the viscous dissipation and the CMB photons. We consider $\alpha = 1$, $\bar{\zeta} = 1.5 \times 10^{-14}$, $m_\chi = 0.1$ GeV and $\epsilon = 2.1 \times 10^{-7}$ [48]. Here brown dashed vertical line, $\omega_{21}$ represents the energy of $21$ cm signal. The blue region corresponds to the CMB photons and the black region corresponds for the spectrum of photons via direct conversion from the DM dissipation. The red region corresponds to the spectrum when the DM dissipate into the DR and then convert into the photons via kinetic mixing. It is clear that the photons obtained from the kinetic mixing populate the numbers of RJ photons but directly converted photons fail to do so.

Figure 3. Ratio of photon obtained from viscous dissipation with the CMB photon in the RJ limits. We consider, $\epsilon = 2.1 \times 10^{-7}$ [48] and $\alpha = 1$. In figure 3(a), DR mass $m_{A'} = 6.12 \times 10^{-19}$ GeV ($z_{\text{res}} = 1268$) and DM viscosity increases. In figure 3(b) DM viscosity is fixed and DR mass increases. The plot suggest that the photon production becomes large for the large DM viscosity and DR mass.

to the resonance redshift $z_{\text{res}} = 637$, 973, 1268, respectively. From figure 3(b) we see that the photon number density increases as the DR mass, $m_{A'}$ increases. This happens because for a large $m_{A'}$, the resonance condition is met earlier (i.e. at large redshift) and thus the probability of conversion of DR to photon becomes large. Therefore we conclude that photon production becomes large for large DM viscosity and DR mass.
Figure 4. Constraining the dark matter parameters that explain the EDGES observed 21 cm signal, i.e. \( n'_{\chi\rightarrow A}/n_{RJ} = 1 \) [48]. We assume the viscosity parameters, \( \alpha = 1 \) and \( \bar{\zeta} = 3 \times 10^{-15} \). In figure 4(a), keeping \( m_{A'} = 6.12 \times 10^{-7} \), \( \epsilon \) is plotted as a function of \( m_\chi \). In figure 4(b), keeping \( m_\chi = 0.1 \) GeV, \( \epsilon \) is plotted as the function of the \( m_{A'} \). In figure 4(c), keeping \( \epsilon = 2.1 \times 10^{-7} \) [48], \( m_\chi \) is plotted as function of \( m_{A'} \).

5.2 Constraining the parameter space for \( \epsilon, m_{A'} \) and \( m_\chi \)

In this subsection, we will constrain the range of parameter space for \( \epsilon, m_{A'} \) and \( m_\chi \) which can explain the EDGES anomaly. To address the EDGES anomaly it requires \( n'_{\chi\rightarrow A}/n_{RJ} = 1 \) [48]. Here we take the viscosity parameters \( \alpha = 1 \) and \( \bar{\zeta} = 3 \times 10^{-15} \). In figure 4(a), we fix \( m_{A'} = 6.12 \times 10^{-19} \) GeV and plot \( \epsilon \) as a function of \( m_\chi \) that satisfy the condition \( n'_{\chi\rightarrow A}/n_{RJ} = 1 \). We see that as \( m_\chi \) increases, \( \epsilon \) decreases. In figure 4(b), on fixing \( m_\chi = 0.1 \) GeV, we plot \( \epsilon \) as a function of \( m_{A'} \). Here also we find that \( \epsilon \) decreases as \( m_{A'} \) increases. Thus it is clear from 4(a) and figure 4(b) that in order to address the EDGES anomaly from the small DM or DR mass, the mixing parameter should be sufficiently large and vice-versa.

Further, in figure 4(c) on fixing \( \epsilon = 2.1 \times 10^{7} \), we plot \( m_\chi \) as function of \( m_{A'} \). We see that as the DR mass increases, in order to produce the sufficient photons that satisfy the condition \( n'_{\chi\rightarrow A}/n_{RJ} = 1 \), the DM mass decreases.
Figure 5. The DM viscosity parameter space that explain the EDGES 21 cm anomaly and consistent with the DM coldness. We fix $m_\chi = 0.1 \text{GeV}$, $\epsilon = 2.1 \times 10^{-7}$ and $m_{A'} = 6.12 \times 10^{-19} \text{GeV}$ and also mention that $\alpha = -1/2$ is not allowed from eq. (2.14). The blue region respect the DM coldness criteria and also explain the EDGES anomaly. The red region explain the EDGES anomaly but is disallowed from the DM coldness condition.

5.3 Constraining the DM viscosity

In this subsection, we explore the parameter space for the DM viscosity that address the EDGES anomaly and also is consistent with the DM coldness paradigm. In figure 5, fixing $m_\chi = 0.1 \text{GeV}$, $\epsilon = 2.1 \times 10^{-7}$ and $m_{A'} = 6.12 \times 10^{-19} \text{GeV}$, we show the $\tilde{\zeta} - \alpha$ parameter space. The blue region corresponds for a parameter space which respect the DM coldness condition and also explains the EDGES anomaly and the red region represents the space which explain the EDGES anomaly but is forbidden from the DM coldness paradigm. We see that small $\alpha$ (more negative $\alpha$ value) needs large $\tilde{\zeta}$ and large value of $\alpha$ (for less negative $\alpha$ value) requires small $\tilde{\zeta}$. Here we find that a majority of the parameter space towards the large $\alpha$ values is ruled out due to the DM coldness criteria, but corresponding to a small $\alpha$ value, a large parameter space is still allowed.

Further, we also point out that the DM viscosity considered in our analysis $\tilde{\zeta} = 3 \times 10^{-15}$ at $z = 17$ is less than the maximum limit allowed from the cold dark matter paradigm given in eq. (2.12), i.e. $\tilde{\zeta} = 5 \times 10^{-15}$. Thus the viscous effect of the DM is not large and the DM is cold.

5.4 DM energy dissipation and its contribution in total DM energy density

In this subsection, we estimate the amount of the energy dissipation from the DM fluid which can explain the observed EDGES anomaly. We estimate the ratio of DM dissipational energy which produces the required number density of the photons, $q_{\text{vis}}$ from eq. (2.14) to the present DM energy density, $\rho_\chi 0$. In our analysis, we have considered $z_s = 1300$ and $z_e = 15$. For the viscosity parameters, $\alpha = 1$ and $\tilde{\zeta} = 3 \times 10^{-15}$, we get $q_{\text{vis}}/\rho_\chi 0 \sim 10^{-17}$, which implies that only a small part of the total DM dissipates into the visible photons.
6 Conclusion

The viscous dark matter contains rich physics and hence it is crucial to study its effects on the evolution of the Universe. The presence of the DM viscosity increases its temperature through the viscous dissipation and this effect becomes prominent at the late time. If DM viscosity is sufficiently large, then the DM fluid may no longer behave like a cold fluid. In this work, we have derived the condition on the DM viscosity parameters for which the DM behaves like a cold fluid.

The viscous effect of DM can be realized when DM produces any observable signal. In this study, we have discussed one of the possible scenarios where the DM viscosity leads to the generation of visible photons. We consider the visible photon production in two ways. First, when the dark matter dissipates directly to the visible photons and second when the dark matter dissipates into the dark radiation which further convert into the visible photons through the kinetic mixing.

Further, the production of extra relativistic particles such as the photons or dark radiation from the DM viscous dissipation may affect the cosmological observations. Although in the case of small DM viscosity, the relativistic particles do not affect the cosmic evolution but for sufficiently large DM viscosity, it can increase the Hubble expansion rate and create the problems at decoupling. We show that for the DM viscosity parameters considered in this work, the production of the relativistic particles is not large enough (lie within the limit allowed from the Planck 2018 observations) to increase the Hubble expansion rate. Hence it will not modify the CMB observations.

We find that the photons produced via the DM viscous dissipation populate the low frequency range of the CMB radiation and hence can explain the 21 cm anomalous signal reported by the EDGES collaboration. In particular, we point out that the resonantly produced photons increase the number density of the RJ tail of the CMB radiation and are sufficient to explain the reported EDGES anomaly but the directly produced photons fail to do so. We also explore the range of the values of the mixing parameter, $\epsilon$, the DM mass, $m_\chi$, the DR mass, $m_{A'}$ and DM viscosity parameters in the light of EDGES 21 cm anomaly. These parameter space can further provide a useful probe for DR and DM viscosity from the upcoming precise 21 cm cosmological observations.

Acknowledgments

I would like to thank Prof. Jitesh R. Bhatt, Prof. Subhendra Mohanty and Prof. Namit Mahajan for providing valuable comments during the development of this paper. I would also like to thank Richa Arya for fruitful suggestions and helping in the modification of CAMB code. I am also thankful to the anonymous referee for providing critical and insightful comments.

References

[1] F. Zwicky, Die Rotverschiebung von extragalaktischen Nebeln, Helv. Phys. Acta 6 (1933) 110 [arXiv:SPIRE].

[2] V.C. Rubin and W.K. Ford, Jr., Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions, Astrophys. J. 159 (1970) 379 [arXiv:SPIRE].

[3] M. Persic, P. Salucci and F. Stel, The Universal rotation curve of spiral galaxies: 1. The Dark matter connection, Mon. Not. Roy. Astron. Soc. 281 (1996) 27 [astro-ph/9506004] [arXiv:SPIRE].
[4] A. Borriello and P. Salucci, *The Dark matter distribution in disk galaxies*, *Mon. Not. Roy. Astron. Soc.* **323** (2001) 285 [astro-ph/0001082] [SPIRE].

[5] H. Hoekstra, H. Yee and M. Gladders, *Current status of weak gravitational lensing*, *New Astron. Rev.* **46** (2002) 767 [astro-ph/0205205] [SPIRE].

[6] L.A. Moustakas and R.B. Metcalf, *Detecting dark matter substructure spectroscopically in strong gravitational lenses*, *Mon. Not. Roy. Astron. Soc.* **339** (2003) 607 [astro-ph/0206176] [SPIRE].

[7] M. Klasen, M. Pohl and G. Sigl, *Indirect and direct search for dark matter*, *Prog. Part. Nucl. Phys.* **85** (2015) 1 [arXiv:1507.03800] [SPIRE].

[8] T. Marrodán Undagoitia and L. Rauch, *Dark matter direct-detection experiments*, *J. Phys.* **G 43** (2016) 013001 [arXiv:1509.08767] [SPIRE].

[9] B. Penning, *The pursuit of dark matter at colliders — an overview*, *J. Phys.* **G 45** (2018) 063001 [arXiv:1712.01391] [SPIRE].

[10] A. Boveia and C. Doglioni, *Dark Matter Searches at Colliders*, *Ann. Rev. Nucl. Part. Sci.* **68** (2018) 429 [arXiv:1810.12238] [SPIRE].

[11] T. Padmanabhan and S.M. Chitre, *Viscous universes*, *Phys. Lett.* **A 120** (1987) 433 [SPIRE].

[12] O. Gron, *Viscous inflationary universe models*, *Astrophys. Space Sci.* **173** (1990) 191 [SPIRE].

[13] B. Cheng, *Bulk viscosity in the early universe*, *Phys. Lett.* **A 160** (1991) 329 [SPIRE].

[14] W. Zimdahl, *Bulk viscous cosmology*, *Phys. Rev.* **D 53** (1996) 5483 [astro-ph/9601189] [SPIRE].

[15] J.C. Fabris, S.V.B. Goncalves and R. de Sa Ribeiro, *Bulk viscosity driving the acceleration of the Universe*, *Gen. Rel. Grav.* **38** (2006) 495 [astro-ph/0503362] [SPIRE].

[16] J.R. Wilson, G.J. Mathews and G.M. Fuller, *Bulk Viscosity, Decaying Dark Matter and the Cosmic Acceleration*, *Phys. Rev.* **D 75** (2007) 043521 [astro-ph/0609687] [SPIRE].

[17] G.J. Mathews, N.Q. Lan and C. Kolda, *Late Decaying Dark Matter, Bulk Viscosity and the Cosmic Acceleration*, *Phys. Rev.* **D 78** (2008) 043525 [arXiv:0801.0853] [SPIRE].

[18] A. Avelino and U. Nucamendi, *Can a matter-dominated model with constant bulk viscosity drive the accelerated expansion of the universe?*, *JCAP* **04** (2009) 006 [arXiv:0811.3253] [SPIRE].

[19] S. Das and N. Banerjee, *Can neutrino viscosity drive the late time cosmic acceleration?*, *Int. J. Theor. Phys.* **51** (2012) 2771 [arXiv:0806.3666] [SPIRE].

[20] B. Li and J.D. Barrow, *Does Bulk Viscosity Create a Viable Unified Dark Matter Model?*, *Phys. Rev.* **D 79** (2009) 103521 [arXiv:0902.3163] [SPIRE].

[21] O.F. Piattella, J.C. Fabris and W. Zimdahl, *Bulk viscous cosmology with causal transport theory*, *JCAP* **05** (2011) 029 [arXiv:1103.1328] [SPIRE].

[22] H. Velten and D.J. Schwarz, *Constraints on dissipative unified dark matter*, *JCAP* **09** (2011) 016 [arXiv:1107.1143] [SPIRE].

[23] J.-S. Gagnon and J. Lesgourgues, *Dark goo: Bulk viscosity as an alternative to dark energy*, *JCAP* **09** (2011) 026 [arXiv:1107.1503] [SPIRE].

[24] B.D. Normann and I. Brevik, *General Bulk-Viscous Solutions and Estimates of Bulk Viscosity in the Cosmic Fluid*, *Entropy* **18** (2016) 215 [arXiv:1601.04519] [SPIRE].

[25] B.D. Normann and I. Brevik, *Characteristic Properties of Two Different Viscous Cosmology Models for the Future Universe*, *Mod. Phys. Lett.* **A 32** (2017) 1750026 [arXiv:1612.01794] [SPIRE].
[26] N.D.J. Mohan, A. Susidharan and T.K. Mathew, Bulk viscous matter and recent acceleration of the universe based on causal viscous theory, *Eur. Phys. J. C* 77 (2017) 849 [arXiv:1708.02437] [nSPIRE].

[27] N. Cruz, E. Gonzáles, S. Lepe and D. Sáez-Chilló Gómez, Analysing dissipative effects in the $\Lambda$CDM model, *JCAP* 12 (2018) 017 [arXiv:1807.10729] [nSPIRE].

[28] C.M.S. Barbosa, J.C. Fabris, O.F. Piattella, H.E.S. Velten and W. Zimdahl, Viscous Cosmology, in Proceedings of 12th International Conference on Gravitation, Astrophysics and Cosmology (ICGAC-12), Moscow Russia (2015) [arXiv:1512.00921] [nSPIRE].

[29] S. Floerchinger, N. Tetradis and U.A. Wiedemann, Accelerating Cosmological Expansion from Shear and Bulk Viscosity, *Phys. Rev. Lett.* 114 (2015) 091301 [arXiv:1411.3280] [nSPIRE].

[30] S. Anand, P. Chaubal, A. Mazumdar and S. Mohanty, Cosmic viscosity as a remedy for tension between PLANCK and LSS data, *JCAP* 11 (2017) 005 [arXiv:1708.07030] [nSPIRE].

[31] A. Atreya, J.R. Bhatt and A. Mishra, Viscous Self Interacting Dark Matter and Cosmic Acceleration, *JCAP* 02 (2018) 024 [arXiv:1709.02163] [nSPIRE].

[32] A. Atreya, J.R. Bhatt and A.K. Mishra, Viscous Self Interacting Dark Matter Cosmology For Small Redshift, *JCAP* 02 (2019) 045 [arXiv:1810.11666] [nSPIRE].

[33] A.K. Mishra, Exploring the Self Interacting Dark Matter Properties From Low Redshift Observations, *arXiv:2002.11652* [nSPIRE].

[34] I. Brevik, Ø. Grøn, J. de Haro, S.D. Odintsov and E.N. Saridakis, Viscous Cosmology for Early- and Late-Time Universe, *Int. J. Mod. Phys. D* 26 (2017) 1730024 [arXiv:1706.02543] [nSPIRE].

[35] R.-G. Cai, T.-B. Liu and S.-J. Wang, Gravitational wave as probe of superfluid dark matter, *Phys. Rev. D* 97 (2018) 023027 [arXiv:1710.02426] [nSPIRE].

[36] S. Anand, P. Chaubal, A. Mazumdar and P. Parashari, Bounds on Neutrino Mass in Viscous Cosmology, *JCAP* 05 (2018) 031 [arXiv:1712.01254] [nSPIRE].

[37] B.-Q. Lu, D. Huang, Y.-L. Wu and Y.-F. Zhou, Damping of gravitational waves in a viscous Universe and its implication for dark matter self-interactions, *arXiv:1803.11397* [nSPIRE].

[38] I. Brevik and S. Nojiri, Gravitational Waves in the Presence of Viscosity, *Int. J. Mod. Phys. D* 28 (2019) 1950133 [arXiv:1901.00767] [nSPIRE].

[39] S. Bravo Medina, M. Nowakowski and D. Batic, Viscous Cosmologies, *Class. Quant. Grav.* 36 (2019) 215002 [arXiv:1901.09787] [nSPIRE].

[40] W. Yang, S. Pan, E. Di Valentino, A. Paliathanasis and J. Lu, Challenging bulk viscous unified scenarios with cosmological observations, *Phys. Rev. D* 100 (2019) 103518 [arXiv:1906.04162] [nSPIRE].

[41] J.R. Bhatt, P.K. Natwariya and A.K. Pandey, Viscosity in cosmic fluids, *arXiv:1907.03445* [nSPIRE].

[42] S. Weinberg, *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity*, John Wiley and Sons, New York U.S.A. (1972).

[43] J.R. Bhatt, A.K. Mishra and A.C. Nayak, Viscous dark matter and 21 cm cosmology, *Phys. Rev. D* 100 (2019) 063539 [arXiv:1901.08454] [nSPIRE].

[44] J.D. Bowman, A.E.E. Rogers, R.A. Monsalve, T.J. Mozdzen and N. Mahesh, An absorption profile centred at 78 megahertz in the sky-averaged spectrum, *Nature* 555 (2018) 67.

[45] A. Ewall-Wice, T.C. Chang, J. Lazio, O. Dore, M. Seiffert and R.A. Monsalve, Modeling the Radio Background from the First Black Holes at Cosmic Dawn: Implications for the 21 cm Absorption Amplitude, *Astrophys. J.* 868 (2018) 63 [arXiv:1803.01815] [nSPIRE].
[46] S. Fraser et al., The EDGES 21 cm Anomaly and Properties of Dark Matter, Phys. Lett. B 785 (2018) 159 [arXiv:1803.03245] [SPIRE].

[47] Y. Yang, Contributions of dark matter annihilation to the global 21 cm spectrum observed by the EDGES experiment, Phys. Rev. D 98 (2018) 103503 [arXiv:1803.05803] [SPIRE].

[48] M. Pospelov, J. Pradler, J.T. Ruderman and A. Urbano, Room for New Physics in the Rayleigh-Jeans Tail of the Cosmic Microwave Background, Phys. Rev. Lett. 121 (2018) 031103 [arXiv:1803.07048] [SPIRE].

[49] T. Moroi, K. Nakayama and Y. Tang, Axion-photon conversion and effects on 21 cm observation, Phys. Lett. B 783 (2018) 301 [arXiv:1804.10378] [SPIRE].

[50] W.-H. Huang, Anisotropic cosmological models with energy density dependent bulk viscosity, J. Math. Phys. 31 (1990) 1456 [gr-qc/0308059] [SPIRE].

[51] G.L. Murphy, Big-bang model without singularities, Phys. Rev. D 8 (1973) 4231 [SPIRE].

[52] J.D. Barrow, The Deflationary Universe: An Instability of the de Sitter Universe, Phys. Lett. B 180 (1986) 335 [SPIRE].

[53] H. Velten, D.J. Schwarz, J.C. Fabris and W. Zimdahl, Viscous dark matter growth in (neo-)Newtonian cosmology, Phys. Rev. D 88 (2013) 103522 [arXiv:1307.6536] [SPIRE].

[54] H. Velten, T.R.P. Caramés, J.C. Fabris, L. Casarini and R.C. Batista, Structure formation in a \( \Lambda \) viscous CDM universe, Phys. Rev. D 90 (2014) 123526 [arXiv:1410.3066] [SPIRE].

[55] Planck collaboration, Planck 2018 results. VI. Cosmological parameters, arXiv:1807.06209 [SPIRE].

[56] C. Armendariz-Picon and J.T. Neelakanta, How Cold is Cold Dark Matter?, JCAP 03 (2014) 049 [arXiv:1309.6971] [SPIRE].

[57] R. Foot and S. Vagnozzi, Dissipative hidden sector dark matter, Phys. Rev. D 91 (2015) 023512 [arXiv:1409.7174] [SPIRE].

[58] R. Foot and S. Vagnozzi, Diurnal modulation signal from dissipative hidden sector dark matter, Phys. Lett. B 748 (2015) 61 [arXiv:1412.0762] [SPIRE].

[59] R. Foot and S. Vagnozzi, Solving the small-scale structure puzzles with dissipative dark matter, JCAP 07 (2016) 013 [arXiv:1602.02467] [SPIRE].

[60] Z. Hou, R. Keisler, L. Knox, M. Millea and C. Reichardt, How Massless Neutrinos Affect the Cosmic Microwave Background Damping Tail, Phys. Rev. D 87 (2013) 083008 [arXiv:1104.2333] [SPIRE].

[61] M. Archidiacono, E. Giusarma, S. Hannestad and O. Mena, Cosmic dark radiation and neutrinos, Adv. High Energy Phys. 2013 (2013) 191047 [arXiv:1307.0637] [SPIRE].

[62] T.-K. Kuo and J.T. Pantaleone, Neutrino Oscillations in Matter, Rev. Mod. Phys. 61 (1989) 937 [SPIRE].

[63] A. Mirizzi, J. Redondo and G. Sigl, Microwave Background Constraints on Mixing of Photons with Hidden Photons, JCAP 03 (2009) 026 [arXiv:0901.0014] [SPIRE].

[64] K.E. Kunze and M.A. Vázquez-Mozo, Constraints on hidden photons from current and future observations of CMB spectral distortions, JCAP 12 (2015) 028 [arXiv:1507.02614] [SPIRE].

[65] S. Seager, D.D. Sasselov and D. Scott, How exactly did the universe become neutral?, Astrophys. J. Suppl. 128 (2000) 407 [astro-ph/9912182] [SPIRE].

[66] A. Lewis, A. Challinor and A. Lasenby, Efficient computation of CMB anisotropies in closed FRW models, Astrophys. J. 538 (2000) 473 [astro-ph/9911177] [SPIRE].
[67] J. Chluba, Green’s function of the cosmological thermalization problem – II. Effect of photon injection and constraints, Mon. Not. Roy. Astron. Soc. 454 (2015) 4182 [arXiv:1506.06582][SPIRE].

[68] R. Barkana, Possible interaction between baryons and dark-matter particles revealed by the first stars, Nature 555 (2018) 71 [arXiv:1803.06698][SPIRE].

[69] R. Barkana, N.J. Outmezguine, D. Redigolo and T. Volansky, Strong constraints on light dark matter interpretation of the EDGES signal, Phys. Rev. D 98 (2018) 103005 [arXiv:1803.03091][SPIRE].

[70] G. Lambiase and S. Mohanty, Hydrogen spin oscillations in a background of axions and the 21-cm brightness temperature, arXiv:1804.05318 [SPIRE].

[71] N. Houston, C. Li, T. Li, Q. Yang and X. Zhang, Natural Explanation for 21 cm Absorption Signals via Axion-Induced Cooling, Phys. Rev. Lett. 121 (2018) 111301 [arXiv:1805.04426][SPIRE].

[72] A. Auriol, S. Davidson and G. Raffelt, Axion absorption and the spin temperature of primordial hydrogen, Phys. Rev. D 99 (2019) 023013 [arXiv:1808.09456][SPIRE].

[73] J.C. Hill and E.J. Baxter, Can Early Dark Energy Explain EDGES?, JCAP 08 (2018) 037 [arXiv:1803.07555][SPIRE].

[74] H. Liu and T.R. Slatyer, Implications of a 21-cm signal for dark matter annihilation and decay, Phys. Rev. D 98 (2018) 023501 [arXiv:1803.09739][SPIRE].

[75] G. D’Amico, P. Panci and A. Strumia, Bounds on Dark Matter annihiliations from 21 cm data, Phys. Rev. Lett. 121 (2018) 011103 [arXiv:1803.03629][SPIRE].

[76] L. Lopez-Honorez, O. Mena and P. Villanueva-Domingo, Dark matter microphysics and 21 cm observations, Phys. Rev. D 99 (2019) 023522 [arXiv:1811.02716][SPIRE].

[77] E.D. Kovetz, I. Cholis and D.E. Kaplan, Bounds on ultralight hidden-photon dark matter from observation of the 21 cm signal at cosmic dawn, Phys. Rev. D 99 (2019) 123511 [arXiv:1809.01139][SPIRE].

[78] J.R. Bhatt, P.K. Natwariya, A.C. Nayak and A.K. Paudey, Baryon-Dark matter interaction in presence of magnetic fields in light of EDGES signal, Eur. Phys. J. C 80 (2020) 334 [arXiv:1905.13486][SPIRE].