PROCEEDINGS OF SCIENCE

Dark radiation: 21cm signals and laboratory tests

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It is entirely possible that our Universe is filled with dark radiation, such as SM neutrinos or new physics states, that are sourced by the decay of dark matter with cosmologically long lifetime. If non-thermal neutrinos produced such way carry sufficient energy, they can leave a detectable imprint in experiments designed to search for very weakly interacting particles: dark matter and underground neutrino experiments. Conversely, a very soft non-thermal population of dark photons sourced this way is allowed to exceed the number density of CMB photons by many orders of magnitude without being in conflict with current bounds. Equipped with a small probability of conversion into ordinary photons, the scenario becomes testable through the cosmological 21cm signal.

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[†] The talk reports on two separate papers [1] and [2].

1. Late Dark Radiation

Observational cosmology over the past decade has resulted in a very sensitive constraint on the number of extra degrees of freedoms that remained radiation-like during the CMB epoch. Phrased in terms of neutrino-like radiation species it reads as: $N_{\rm eff} = 3.04 \pm 0.33$ [3] which translates into a limit on the energy density in additional dark radiation (DR), $\rho_{\rm DR}$, when measured relative to the one in photons, $\rho_{\rm DR}/\rho_{\rm CMB} < 0.15$. This bound has a wide degree of applicability, and is most effectively used to constrain models with "early" DR, or models with extra light degrees of freedom that were in thermal contact with the SM, but decoupled at some point in the history of the early Universe. However, the constraint would not be applicable to models where DR is created much later than the cosmic microwave background (CMB) epoch. Indeed, late decays of a sizable fraction of dark matter (DM) into dark radiation are allowed, and, moreover, $\rho_{\rm DR}$ can be much larger than $\rho_{\rm CMB}$ today.

Two logical possibilities in the late generation of $\rho_{\rm DR}$ arise: either the number density of DR particles, $n_{\rm DR}$, is smaller than that of CMB photons, $n_{\rm CMB}$, while their kinetic energy, $E_{\rm DR}$, on average is much larger than the energy $E_{\rm CMB}$ of individual CMB quanta,

$$n_{\rm DR} \ll n_{\rm CMB}, \;\; E_{\rm DR} \gg E_{\rm CMB}, \;\; \rho_{\rm DR}(\sim E_{\rm DR} n_{\rm DR}) \leq 0.1 \rho_{\rm DM}, \tag{1.1}$$

or DR quanta are energetically much softer, but more numerous than CMB photons,

$$E_{\rm DR} \ll E_{\rm CMB}, \quad n_{\rm DR} > n_{\rm RJ}, \quad \rho_{\rm DR}(\sim E_{\rm DR} n_{\rm DR}) \leq 0.1 \rho_{\rm DM}. \tag{1.2}$$

In the last relations of (1.1) and (1.2) we require that the amount of DR does not exceed 10% of the DM energy density, in accordance with recently updated constraints [4]; $n_{\rm RJ}$ represents the low-energy Rayleigh-Jeans (RJ) tail of the standard CMB Planck distribution up to an energy $E_{\rm max} \ll T_{\rm CMB}$, $n_{RJ} \approx T_{\rm CMB} E_{\rm max}^2/(2\pi^2)$. Such set of inequalities leaves, of course, a lot of freedom for what DR can be, but restricts a number of possibilities for how the non-thermal DR can be created. The most efficient mechanism for populating DR radiation states is the decay of DM, and if it happens at a redshift after CMB decoupling, a per-cent fraction of DM is allowed to decay to DR.

There are then two principal components of the DR flux, either originating from DM decay within the galaxy or from extragalactic distances. The former is obtained from a standard line-of-sight integral over the galactic DM distribution, the latter is obtained as a redshift integral over the cosmological DM density. Focusing on a mono-chromatic injection of a pair of new particles X where X is either assumed to be SM neutrino $X = \nu$ or $\bar\nu$ or a dark photon $X = A'$, the cosmological energy spectrum at redshift z is given by

$$\frac{dn_X(E,z)}{dE} = \frac{2\Omega_{\rm dm}\rho_c(1+z)^3}{m_{\rm dm}\tau_{\rm dm} E H(\alpha-1)}\Theta(\alpha-1-z). \tag{1.3}$$

Here, limits of cosmologically long DM lifetime $\tau_{\rm dm} > t_0^{-1}$ and of relativistic injection energy $E_X \gg m_X$ have been taken. Furthermore, ρ_c is the critical density, $\Omega_{\rm dm}h^2 = 0.12$ the DM density parameter [3], and the Hubble rate, $H(z)$, is evaluated at redshift $\alpha - 1$, where $\alpha \equiv m_{\rm dm}(1+z)/(2E)$; $H_0 = H(t_0)$ and t_0 is the current age of the Universe.

2. Energetic Neutrino Dark Radiation: Laboratory Tests

In this scenario [1] DM gives rise to DR in the form of SM neutrinos with initial energies of several tens of MeV. This can occur directly by DM decay to $\nu(\bar{\nu})+Y$, where Y stands for the rest of the decay products, or in two steps: first through the decay of DM to a nearly massless fermion (*e.g.*, a sterile neutrino), that then oscillates into the SM neutrinos. Models with direct decay to neutrinos are free from potential constraints from $N_{\rm eff}$ measurements, the ν-SM interactions are known, and the model is more minimal/simple. Then, on top of the constraints from dark matter experiments that limit the neutral current interactions of the DR neutrinos with nuclei, there will be additional constraints provided through weak interactions at neutrino detectors such as Super-Kamiokande (SK).

The total flux $\phi_{\rm tot}$, integrated over the whole energy spectrum, varies over many orders of magnitude depending on the choice parameters. Nevertheless, one can estimate the maximum possible flux at $\tau_{\rm dm} = 100\,{\rm Gyr}$, while taking $m_X \to 0$, and keeping $m_{\rm dm}$ as a free parameter: $\phi_{\rm tot}^{\rm max} \sim (10\,{\rm MeV}/m_{\rm dm}) \times 10^6\,{\rm cm}^{-2}{\rm s}^{-1}$. Coincidentally, the value of the DR flux may become comparable to that of ^{8}B solar neutrinos at $m_{\rm dm} \sim 10\,{\rm MeV}$, and exceeds the diffuse SN neutrino flux by many orders of magnitude at $m_{\rm dm} \sim 50\,{\rm MeV}$. With regards to the injection of SM neutrinos (and not anti-neutrinos), it turns out that constraints from SK are superior to the current sensitivity of DM direct detection experiments. To pick a specific example, the current constraint on the neutrino flux originating from the decay of a DM particle of $m_{\rm dm} = 50\,{\rm MeV}$ and lifetime $\tau_{\rm dm} \gg t_0 :\ \phi_\nu(E_\nu \simeq 25\,{\rm MeV}) < 5\times 10^2\,{\rm cm}^{-2}{\rm s}^{-1}$. This constraint is more than two orders of magnitude more relaxed compared to the SK limit on a cosmic $\bar{\nu}_e$ flux. Consequently, if this limit is saturated by DR, then the expected scattering rate inside the xenon-based direct detection experiments will be such as to mimic a DM particle with $m_{\rm dm} \sim 30\,{\rm GeV}$ and cross section of $\sigma \sim 10^{-47}{\rm cm}^2$, which is significantly above the traditionally derived “neutrino floor”.

3. Soft dark photon radiation: 21cm signals

Returning to (1.2) and considering the case when typical DR energy is significantly smaller than that of CMB photons [2], one observes that the number of DR quanta may significantly exceed $n_{\rm RJ}$. For example, letting 5% of the DM energy density convert to DR in the frequency range $E_{\rm max}/T_{\rm CMB} = 2\times 10^{-3}$ after CMB decoupling, $n_{\rm DR} \le 3.3\times 10^5\, n_{\rm CMB}$ where $n_{\rm CMB} = 2\zeta(3)/\pi^2\, T_{\rm CMB}^3$ is the full Planckian number density. Thus, soft DR quanta can outnumber the RJ CMB photons by up to 11 orders of magnitude.

For the case for SM neutrinos considered above that have Fermi-type interactions with atomic constituents, this type of DR would be very difficult to see directly. There is, however, one class of new fields that can manifest their interactions at low energies and low densities. These are light vector particles (often called dark photons), A', that develop a mixing with ordinary photons, $\varepsilon F'_{\mu\nu}F_{\mu\nu}$. The apparent number count of CMB radiation can be modified by photon/dark photon oscillation:

$$\frac{dn_A}{dE} \to \frac{dn_A}{dE} \times P_{A\to A} + \frac{dn_{A'}}{dE} \times P_{A'\to A}\ , \tag{3.1}$$

where $P_{A\to A} = 1 - P_{A\to A'}$ is the photon survival probability, while $P_{A'\to A}$ is the probability of $A' \to A$ conversion. The physics of the 21 cm line then provides a useful tool to probe DR through the apparent modification of the low-energy tail of the CMB: at the end of the dark-ages, the strength of the net-absorption signal of 21 cm radiation through the hyperfine transition in neutral hydrogen is expected to be proportional to $1 - T_{\rm CMB}/T_s$. Here $T_{\rm CMB}$ is a proxy that counts the number of CMB photons interacting with the two-level hydrogen hyperfine system, and T_s is the spin temperature. The relevant photons have energy $E_0 = 5.9\,\mu$eV at redshift $z \approx 17$, and therefore reside deep within the RJ tail, $E_0/T_{\rm CMB} \approx 1.4 \times 10^{-3}$. Cosmological $A \leftrightarrow A'$ oscillations that populate photons in the relevant frequency band may therefore enhance the strength of the absorption signal.

Indeed, the EDGES experiment recently presented a tentative detection of 21 cm absorption coming from the interval of redshifts $z = 15-20$ [5], indicating a twice as strong absorption signal than expected. We find that the oscillation of non-thermal DR into visible photons can easily accommodate EDGES consistent with other constraints. For this a resonance condition in the $A' \to A$ conversion must be met, $m_{A'} = m_A(z)$, where $m_A(z)$ is the plasma mass of photons at redshift z. In the course of cosmological evolution $m_A(z) \simeq 1.7 \times 10^{-14}{\rm eV} \times (1+z)^{3/2} X_e^{1/2}(z)$ scans many orders of magnitude where X_e is the free electron fraction, and hence allows a sizable permissible dark photon mass range. For example, for DM decay with $m_{\rm dm} = 10^{-3}$ eV, $\tau_{\rm dm} = 100\,t_0$ and a dark photon mass of $m_{A'} = 5 \times 10^{-12}\,$eV (implying a resonance redshift $z_{\rm res} = 500$), and $\varepsilon = 2.1 \times 10^{-7}$, the number of photons in the relevant frequency interval is doubled at $z = 17$—implying a twice as strong 21 cm absorption signal—while the total energy density of dark photons relative to the energy density of ordinary CMB photons at resonance is 6×10^{-6}, and a fraction 4×10^{-4} of the dark photons oscillate into ordinary photons.

4. Conclusions

A cosmic DR background can be probed through a variety of observational and laboratory tests. SM neutrinos with energy $O(10)$ MeV are tested in direct detection and neutrino experiments [1]. Dark photons with energies well below $T_{\rm CMB}$ are tested through 21 cm cosmology [2].

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