Searching for the radiative decay of the cosmic neutrino background with line-intensity mapping

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We study the possibility to use line-intensity mapping (LIM) to seek photons from the radiative decay of neutrinos in the cosmic neutrino background. The Standard Model prediction for the rate for these decays is extremely small, but it can be enhanced if new physics increases the neutrino electromagnetic moments. The decay photons will appear as an interloper of astrophysical spectral lines. We propose that the neutrino-decay line can be identified with anisotropies in LIM clustering and also with the voxel intensity distribution. Ongoing and future LIM experiments will have—depending on the neutrino hierarchy, transition and experiment considered—a sensitivity to an effective electromagnetic transition moment $\sim 10^{-12} - 10^{-8} (m_e^2/0.1 \text{eV})^{3/2} \mu_B$, where $m_\nu$ is the mass of the decaying neutrino and $\mu_B$ is the Bohr magneton. This will be significantly more sensitive than cosmic microwave background spectral distortions, and it will be competitive with stellar cooling studies. As a byproduct, we also report an analytic form of the one-point probability distribution function for neutrino-density fluctuations, obtained from the QUIJOTE simulations using symbolic regression.

Considerable efforts are underway to study the properties of neutrinos, including their masses, mixing angles, and nature (e.g., Dirac or Majorana) [1–21]. The stability of neutrinos is also of interest. An active massive neutrino $\nu_i$ can decay into a lighter eigenstate $\nu_j$ and photon, $\gamma$, $\nu_i \rightarrow \nu_j + \gamma$ with a rate determined by electromagnetic transition moments induced via loops involving gauge bosons. The Standard Model (SM) prediction for the lifetime is $\tau_{\nu_i}^{\text{SM}} = 7.1 \times 10^{33} m_{\nu_i}^{-2} \text{s}$ [22–25], where $m_{\nu_i} \equiv m_e c^2 / \text{eV}$ is the neutrino mass in eV/$c^2$ units, significantly longer than the age of the Universe.

However, new physics beyond the SM (BSM) can enhance neutrino magnetic moments [26–34] and such modifications have been considered in connection with experimental anomalies, such a possible correlation of solar neutrinos with Solar activity [14, 35], or more recently [33, 34] the $\sim 3\sigma$ excess reported XENON1T [36]. Although many avenues have been proposed (see e.g., Ref. [37] for a review), the most efficient direct laboratory probe of neutrino electromagnetic couplings involves neutrino-electron scattering [7, 8, 38]. Tighter bounds on neutrino electromagnetic moments come from astrophysics. In particular, the strongest constraint comes from the tip of the red giant branch in globular clusters, which is sensitive to the additional energy loss through plasmon decay into two neutrinos [39–41]. Radiative neutrino decays have also been constrained from measurements of the cosmic microwave background (CMB) spectral distortions [42, 43].

Here we study the use of line-intensity mapping (LIM) to seek photons from radiative decays of neutrinos in the cosmic neutrino background. LIM [44, 45] exploits the integrated intensity at a given frequency induced by a well-identified spectral line to map the three-dimensional distribution of matter in the Universe. Photons from particle decays will appear in these maps as an unidentified line [46] that can be distinguished from astrophysical lines through its clustering anisotropies and through the voxel probability distribution function [47]. We find that LIM has the potential to be significantly more sensitive to radiative decays than current cosmological probes and compete with the strongest bounds to electromagnetic moments coming from astrophysical observations.

While neutrino radiative decays are characterized by the electromagnetic transition moments, LIM experiments are sensitive to the luminosity density $\rho_L$ of the photons produced in each point $x$, which, for the decay between the $i$ and $j$ states, is given by

$$\rho_L^i(x) = (1/6) \rho_{\nu}(x) c^2 \Gamma_{ij} (1 - m_j^2/m_i^2) \ , \quad (1)$$

where $\rho_{\nu}$ is the total neutrino density, $\Gamma_{ij} \equiv \tau_{ij}^{-1}$ is the decay rate, and $m_i$ are the neutrino masses. We assume that the density of each state is 1/3 of the total density, as expected apart from small mass differences and flavor corrections that have negligible consequences for the precision goals of this Letter [48]. The corresponding
The brightness temperature $T$ at redshift $z$ is

$$T^{ij}(z, \mathbf{x}) = \frac{c^3(1+z)^2 \rho_{\ell}^{ij}(z, \mathbf{x})}{8\pi k_B f^3 H(z)} = X_{LT} \rho_{ij}^{0} (z, \mathbf{x}) = \left( \frac{X_{LT}}{6} \right) \rho_c c^2 T_{ij} \left( 1 - m_i^2/m_j^2 \right),$$

where $H$ is the Hubble expansion and $k_B$ is the Boltzmann constant and $f$ is the rest-frame frequency [49]. Thus, the brightness temperature from neutrino decays traces the neutrino density field.

Decay photons are then an emission line with rest-frame frequency given by $f_{ij} = (m_i^2 - m_j^2) c^2 / (2h_P m_i)$, where $h_P$ is the Planck constant. For $m_i / c^2 \gg T_{\nu} / k_B \sim 10^{-4} (1 + z) \text{eV}$ (where $T_{\nu}$ is the cosmic neutrino temperature), which holds true for our cases of interest, the neutrinos are non-relativistic and we can neglect the linewidths due to their velocity dispersion. The rest-frame frequency of the emission lines is then uniquely characterized by the neutrino hierarchy and the sum $\sum m_i$ of neutrino masses, as shown in Fig. 1, with the observed frequency redshifted accordingly. The transitions not included in the figure have a very similar frequency than one of the other two (e.g., $f_{31}$ for the normal hierarchy) and are not distinguished hereinafter.

We now consider two LIM observables: the power spectrum and the voxel intensity distribution (VID). The observed anisotropic LIM power spectrum associated to the neutrino decay between $i$ and $j$ states is [47, 50]

$$P_{ij}(k, \mu) = W(k, \mu) X_{LT}^2 \langle \rho_{\ell}^{ij} \rangle^2 F_{\text{rsd}}^2(k, \mu) P_{\nu}(k),$$

where $k$ is the modulus of the Fourier mode, $\mu \equiv k \cdot k_{\parallel} / k^2$ is the cosine of the angle between the Fourier mode and the line of sight, $W$ is a window function modeling the effects from instrumental resolution and finite volume observed, the brackets $\langle \rangle$ denote the spatial mean, $F_{\text{rsd}}$ is a redshift-space distortions factor [50], $P_{\nu}$ is the neutrino power spectrum, computed using CAMB [51], and all redshift dependence is implicit. We consider the Legendre multipoles of the LIM power spectrum with respect to $\mu$ up to the hexadecapole.

Similarly, the VID is related to the probability distribution function (PDF) $P_{\bar{\rho}}$ of the normalized total neutrino density $\bar{\rho}_{\nu} \equiv \rho_{\nu} / \langle \rho_{\nu} \rangle$, as $P_{ij}(T) = P_{\bar{\rho}}(\bar{\rho}_{\nu}) / (T^{ij})$. We estimate the neutrino density PDF from high-resolution simulations of the QUIJOTE simulation suite [52], that model the gravitational evolution of more than 2 billion cold dark matter and neutrino particles in a comoving box of $(1 \, h^{-1}\text{Gpc})^3$ volume. Degenerate neutrino mass eigenstates are assumed.

First, neutrino particle positions are assigned to a regular grid with 1500$^3$ voxels employing the cloud-in-cell mass-assignment scheme. Next, the 3D field is convolved with a Gaussian kernel of a given width. Then, the PDF is estimated by computing the fraction of voxels with a given $\bar{\rho}_{\nu}$. We do this for $\sum m_{\nu} c^2 = \{0.1, 0.2, 0.4\} \text{eV}$, at $z = \{0, 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9\}$ and for 6 smoothing scales $\{2, 3, 4, 5, 7.5, 10\} \, h^{-1}\text{Mpc}$. We have checked that the computed PDFs, in the range of interest for this study, are converged in our simulations. Note that all dependences can be condensed in the root-mean square $\sigma$ of smoothed density field, which depends on $\sum m_{\nu}$, $z$ and the smoothing scale. Finally, we use symbolic regression to approximate this grid of PDFs using the Eureqa package (https://www.datarobot.com/nutonian/) finding

$$P_{\bar{\rho}} / A = \exp \left\{ \frac{0.2 \mathcal{G}(0.6^2 z^2) + 2.5 \mathcal{G}^{1.6}(1.1 + \frac{z}{2} - 2.3 \sigma)}{s + 0.05 \mathcal{G}(0.65^2 z^2)} - 2.5 \mathcal{G}^{1.6}(1.1 + \frac{s}{\sigma} - 2.3 \sigma) \right\} - 1,$$

where $\mathcal{G}(x) \equiv e^{-x^2}, \sigma \equiv \log \bar{\rho}_{\nu}, s \equiv \log (1 + \sigma)$, and $A$ is

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1 The widening would only be relevant if larger than the instrumental spectral resolution $f_{\text{obs}} / df$, where $f_{\text{obs}}$ is the observed frequency and $df$ is the channel width. In such case, we would take the line width as the spectral resolution for the neutrino decay line.
In the Fisher-matrix analysis, the variation of $\sum m_\nu$ and the change of the neutrino hierarchy are included in our fiducial model: we only consider deviations due to the neutrino decay and not to the varying neutrino masses.

\footnote{2 In the Fisher-matrix analysis, the variation of $\sum m_\nu$ and the change of the neutrino hierarchy are included in our fiducial model: we only consider deviations due to the neutrino decay and not to the varying neutrino masses.}
bounds to date: \( \mu_{\nu}^{\text{eff}} < 4.5 \times 10^{-12} \mu_B \) at 95\% confidence level [41].

This demonstrates the great potential that LIM surveys have to unveil neutrino properties: on top of having a sensitivity competitive to and in some cases even improving current strongest limits, LIM experiments may probe neutrino decays in a very different context than the rest of experiments and observations discussed above. Instead of neutrinos produced in the interior of stars, LIM will be sensitive to the cosmic neutrino background (as CMB studies are, but at very different redshifts). Moreover, the energy of the neutrinos involved in each probe also varies, which may inform about a potential energy dependence of the electromagnetic transition moments [76]. These synergies are very timely, since an enhanced magnetic moment may explain the \( \sim 3\sigma \) excess observed by XENON1T [36], but the values require are close to the limits found by Borexino and in tension with stellar cooling constraints.

Finally, LIM may provide additional information about the cosmic neutrino background beyond the effect of \( \sum m_\nu \) in the growth of perturbations: combining the information about \( \sum m_\nu \) with the frequency of the photons produced in the decay, LIM might be the only cosmological probe sensitive to individual neutrino masses and their hierarchy [77].

The complementarity between different probes of neutrino decays will also help as a cross-check for eventual caveats or systematic uncertainties in the measurements. In the case of LIM experiments, these are the same as for the search for radiative dark matter decays, which are discussed in Ref. [47]. In summary, astrophysical uncertainties are already accounted for in our analysis, there are efficient strategies to deal with known astrophysical line interlopers [53–61], and galactic foregrounds are expected to be under control at the frequencies of interest. Moreover, the neutrino decay contribution to the LIM power spectrum and VID is very characteristic, and the combination of both summary statistics will not only improve the sensitivity but also the robustness of the measurement.\(^3\) Finally, we have assumed that the neutrino decay line is a delta function, and neglected any widening due to the neutrino velocity distributions. While this is a good approximation for the regime of interest at this stage, it is also possible to model the neutrino decay emissivity with a generic momentum distribution [43]; this

\(^{3}\text{Here we consider the LIM power spectrum and VID constraints separately, but they could be combined if the covariance between them is available [78].} \)
will allow to adapt our analysis to neutrino production models that alter their momentum distribution [79]. The neutrino decay contribution might be confused with other exotic radiation injection such as dark matter decay. However, the shape of the neutrino power spectrum and density PDF is different. Moreover, while the contribution from dark matter decays will appear in LIM cross-correlations with galaxy clustering [46] and lensing [80], the contribution from neutrino decays will barely do, since galaxy surveys do not trace the neutrino density field.

In this letter we have proposed the use of LIM for the detection of a possible radiative decay of the cosmic neutrino background, focusing on its contribution to the LIM power spectrum and VID. We have also provided a first parametric fit of the neutrino density PDF using N-body simulations and symbolic regression, that was required to compute the contribution to the VID. Our results show that LIM have the potential to achieve sensitivities competitive to current limits, improving other cosmological probes by several orders of magnitude. The complementarity of LIM and other existing probes of neutrino decays opens exciting synergies, as well as checks for systematics, that will lead the way to new studies of neutrino properties.

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