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sion of the photon flux stronger than in the presence of conventional physics. Nevertheless, from Fig. 4 one infers that the cases in which T_γ is enhanced at high energies are much more probable.

Conclusions—We have studied the conversions of VHE photons into ALPs proposed as a mechanism to reduce the absorption onto EBL, using for the first time more realistic models of extragalactic magnetic fields, obtained from the largest magnetohydrodynamical cosmological simulations in the literature. We find an enhancement of the magnetic field with respect to what was predicted in the naive cell model, due to the fact that simulated magnetic fields display larger fluctuations, correlated with density fluctuations of the cosmic web. This effect would give a significant boost to photon-ALP conversions. Indeed, using more realistic models of the magnetic field we have found significant conversions also in regions of the parameter space consistent with previous astrophysical bounds. This mechanism would produce a significant hardening of the VHE photon spectrum from faraway sources, and we expect such signature to emerge at energies $E \gtrsim 1$ TeV. Therefore, this scenario is testable with the present generation of the Imaging Atmospheric Cherenkov Telescope, covering energies in the range from ~ 50 GeV to ~ 50 TeV [48, 49].

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SUPPLEMENTAL MATERIAL

Setup of photon-ALP oscillations—Photon-ALP mixing occurs in the presence of an external magnetic field $\mathbf{B}$ due to the interaction term [2]

$$\mathcal{L}_{a\gamma} = -\frac{1}{4}\, g_{a\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu} a = g_{a\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a \ , \tag{2}$$

where $g_{a\gamma}$ is the photon-ALP coupling constant (which has the dimension of an inverse energy).

We consider throughout a monochromatic photon/ALP beam of energy E propagating along the x_3 direction in a cold ionized and magnetized medium. It has been shown that for very relativistic ALPs and *polarized* photons, the beam propagation equation can be written in a Schrödinger-like form in which x_3 takes the role of time [2, 36]

$$i\frac{d}{dx_3}\begin{pmatrix} A_1(x_3) \\ A_2(x_3) \\ a(x_3) \end{pmatrix} = \left(\mathcal{H}_{\rm disp} - \frac{i}{2}\mathcal{H}_{\rm abs}\right)\begin{pmatrix} A_1(x_3) \\ A_2(x_3) \\ a(x_3) \end{pmatrix} \ , \tag{3}$$

where $A_1(x_3)$ and $A_2(x_3)$ are the photon linear polarization amplitudes along the x_1 and x_2 axis, respectively, $a(x_3)$ denotes the ALP amplitude. The Hamiltonian $\mathcal{H}_{\rm disp}$ represents the photon-ALP dispersion matrix, including the mixing and the refractive effects, while $\mathcal{H}_{\rm abs}$ accounts for the photon absorption effects on the low-energy photon backgrounds. We denote by $T(x_3, 0; E)$ the transfer function, namely the solution of Eq. (3) with initial condition $T(0, 0; E) = 1$.

The Hamiltonian $\mathcal{H}_{\rm disp}$ simplifies if we restrict our attention to the case in which $\mathbf{B}$ is homogeneous. We denote by $\mathbf{B}_T$ the transverse magnetic field, namely its component in the plane normal to the beam direction and we choose the x_2-axis along $\mathbf{B}_T$ so that B_1 vanishes. The linear photon polarization state parallel to the transverse field direction $\mathbf{B}_T$ is then denoted by $A_\parallel$ and the orthogonal one by $A_\perp$. Correspondingly, the mixing matrix can be written as [2, 36]

$$\mathcal{H}_{\rm disp} = \begin{pmatrix} \Delta_\perp & 0 & 0 \\ 0 & \Delta_\parallel & \Delta_{a\gamma} \\ 0 & \Delta_{a\gamma} & \Delta_a \end{pmatrix} \ , \tag{4}$$

whose elements are [2] $\Delta_\perp \equiv \Delta_{\rm pl} + \Delta_\perp^{\rm CM} + \Delta_{\rm CMB}$, $\Delta_\parallel \equiv \Delta_{\rm pl} + \Delta_\parallel^{\rm CM} + \Delta_{\rm CMB}$, $\Delta_{a\gamma} \equiv g_{a\gamma} B_T/2$ and $\Delta_a \equiv -m_a^2/2E$, where m_a is the ALP mass. The term $\Delta_{\rm pl} \equiv -\omega_{\rm pl}^2/2E$ accounts for plasma effects, where $\omega_{\rm pl}$ is the plasma frequency expressed as a function of the electron density in the medium n_e as $\omega_{\rm pl} \simeq 3.69\times 10^{-11}\sqrt{n_e/{\rm cm}^{-3}}\,{\rm eV}$. The terms $\Delta_{\parallel,\perp}^{\rm CM}$ describe the Cotton-Mouton effect, i.e. the birefringence of fluids in the presence of a transverse magnetic field. A vacuum Cotton-Mouton effect is expected from QED one-loop corrections to the photon polarization in the presence of an external magnetic field $\Delta_{\rm QED} = |\Delta_\perp^{\rm CM} - \Delta_\parallel^{\rm CM}| \propto B_T^2$, but this effect is completely negligible in the present context. Recently it has been realized that also background photons can contribute to the photon polarization. At this regard a guaranteed contribution is provided by the CMB radiation, leading to $\Delta_{\rm CMB} \propto \rho_{\rm CMB}$ [47]. We will show how this term would play a crucial role for the development of the conversions at high energies. An off-diagonal Δ_R would induce the Faraday rotation, which is however totally irrelevant at

VHE, and so it has been dropped. For our benchmark values corresponding to the HM point, numerically we find

$$\begin{aligned}
\Delta_{a\gamma} &\simeq 1.5\times 10^{-2}\left(\frac{g_{a\gamma}}{10^{-11}\mathrm{GeV}^{-1}}\right)\left(\frac{B_T}{10^{-9}\,\mathrm{G}}\right)\mathrm{Mpc}^{-1}\,,\\
\Delta_{a} &\simeq -3.2\times 10^{1}\left(\frac{m_a}{2\times 10^{-8}\mathrm{eV}}\right)^2\left(\frac{E}{\mathrm{TeV}}\right)^{-1}\mathrm{Mpc}^{-1}\,,\\
\Delta_{\mathrm{pl}} &\simeq -1.1\times 10^{-7}\left(\frac{E}{\mathrm{TeV}}\right)^{-1}\left(\frac{n_e}{10^{-3}\,\mathrm{cm}^{-3}}\right)\mathrm{Mpc}^{-1}\,,\\
\Delta_{\mathrm{QED}} &\simeq 4.1\times 10^{-9}\left(\frac{E}{\mathrm{TeV}}\right)\left(\frac{B_T}{10^{-9}\,\mathrm{G}}\right)^2\mathrm{Mpc}^{-1}\,,\\
\Delta_{\mathrm{CMB}} &\simeq 0.80\times 10^{-1}\left(\frac{E}{\mathrm{TeV}}\right)\mathrm{Mpc}^{-1}\ . \qquad (5)
\end{aligned}$$

VHE photons undergo pair production absorption by EBL low energy photons $\gamma_{\mathrm{VHE}}\gamma_{\mathrm{EBL}}\to e^+e^-$, dominated by the interactions with optical/infrared EBL photons. The absorptive part of the Hamiltonian can be written in the form

$$\mathcal{H}_{\mathrm{abs}}=\begin{pmatrix}\Gamma & 0 & 0\\ 0 & \Gamma & 0\\ 0 & 0 & 0\end{pmatrix}\ , \qquad (6)$$

where Γ is the photon absorption rate (see [45] for details). Several realistic models for the EBL are available in the literature, which are basically in mutual agreement. Among all possible choices, we employ the EBL model [46] as our benchmark. For crude numerical estimates at zero redshift we use for the absorption rate [45]

$$\Gamma = 1.1\times 10^{-3}\left(\frac{E}{\mathrm{TeV}}\right)^{1.55}\mathrm{Mpc}^{-1}\ . \qquad (7)$$

Single magnetic domain—Considering the propagation of photons in a single magnetic domain with a uniform **B**-field with $B_1=0$, the component $A_\perp$ decouples away, and the propagation equations reduce to a 2-dimensional problem. Its solution follows from the diagonalization of the Hamiltonian through a similarity transformation performed with an orthogonal matrix, parametrized by the (complex) rotation angle Θ which takes the value [2, 36]

$$\Theta=\frac{1}{2}\arctan\left(\frac{2\Delta_{a\gamma}}{\Delta_\parallel-\Delta_a-\frac{i}{2}\Gamma}\right)\ . \qquad (8)$$

Note that $\Delta_a<0$ and $\Delta_\parallel>0$. Therefore, these two contributions always sum and must be separately small to achieve large mixing angle. When $\Delta_{a\gamma}\gg\Delta_\parallel-\Delta_a$ the photon-ALP mixing is close to maximal, $\Theta\to\pi/4$ (if the absorption is small as well). On the other hand, from Eq. (5) one sees that Δ_{CMB} grows linearly with the photon energy. Therefore at sufficiently high energies $\Delta_{a\gamma}\ll\Delta_\parallel-\Delta_a$ and the photon-ALP mixing is suppressed.

One can introduce a generalized (including absorption) photon-ALP oscillations frequency

$$\Delta_{\mathrm{osc}}\equiv\left[(\Delta_\parallel-\Delta_a-\frac{i}{2}\Gamma)^2+4\Delta_{a\gamma}^2\right]^{1/2}\ . \qquad (9)$$

In particular, if absorption effect are small the probability for a photon emitted in the state $A_\parallel$ to oscillate into an ALP after traveling a distance d is given by [2]

$$\begin{aligned}
P^{(0)}_{\gamma\to a} &= \sin^2 2\Theta\,\sin^2\left(\frac{\Delta_{\mathrm{osc}}\,d}{2}\right)\\
&=(\Delta_{a\gamma}d)^2\frac{\sin^2(\Delta_{\mathrm{osc}}d/2)}{(\Delta_{\mathrm{osc}}d/2)^2}\ , \qquad (10)
\end{aligned}$$

where in the oscillation wave number and mixing angle we set $\Gamma=0$.

From Eq. (5) one would realize that for $E\gtrsim 10$ TeV and $B_T\sim 10^{-7}$ G, $\Delta_{a\gamma}\gg\Delta_a,\Delta_{\mathrm{pl}}$. Therefore, neglecting the Δ_{CMB} refractive term one would obtain $P^{(0)}_{\gamma\to a}\simeq(\Delta_{a\gamma}d)^2$, that is energy-independent. However, we see that Δ_{CMB} is not negligible at these energies and would produce peculiar energy-dependent oscillations imprinting significant features in the VHE photon spectra.

So far, we have been dealing with a beam containing polarized photons, but since at VHE the polarization cannot be measured we better assume that the beam is unpolarized. This is properly done by means of the polarization density matrix

$$\rho(x_3)=\begin{pmatrix}A_1(x_3)\\ A_2(x_3)\\ a(x_3)\end{pmatrix}\otimes\begin{pmatrix}A_1(x_3) & A_2(x_3) & a(x_3)\end{pmatrix}^* \qquad (11)$$

which obeys the Liouville equation [36]

$$i\frac{d\rho}{dx_3}=[\mathcal{H}_{\mathrm{disp}},\rho]-\frac{i}{2}\{\mathcal{H}_{\mathrm{abs}},\rho\} \qquad (12)$$

associated with Eq. (3). Then it follows that the solution of Eq. (12) is given by

$$\rho(x_3,E)=T(x_3,0;E)\,\rho(0)\,T^\dagger(x_3,0;E)\ , \qquad (13)$$

where $\rho(0)$ is the initial beam state. Note that for a uniform **B** even if we clearly have

$$T(x_3,0;E)=e^{-i(\mathcal{H}_{\mathrm{disp}}-\frac{i}{2}\mathcal{H}_{\mathrm{abs}})x_3}\ . \qquad (14)$$

Magnetized cosmic web—In the problem discussed in this paper we consider oscillations of VHE photons into ALPs in the extragalactic magnetic fields. Therefore we have to deal with a more general situation than the one depicted in the previous Section. Indeed, as discussed, the extragalactic magnetic field is not constant along the photon line of sight. In the "cell" model the magnetic field can be modeled as a network of a magnetic domains with size set by its coherence length. Although

$|\mathbf{B}| \equiv B_0$ is supposed to be the same in every domain, its direction changes randomly from one domain to another. Therefore the propagation over many magnetic domains is clearly a truly 3-dimensional problem, because – due to the randomness of the direction of $\mathbf{B}$ –the same photon polarization states play the role of either $A_\parallel$ and $A_\perp$ in different domains. Therefore the Hamiltonian $\mathcal{H}_{\rm disp}$ entering propagation equation cannot be reduced to a block-diagonal form similar to Eq. (4) in all domains. Rather, we take the x_1, x_2, x_3 coordinate system as fixed once and for all, and – denoting $\mathbf{b}_k$ a random unit vector inside each cell, during their path with a total length L along the line of sight, the beam crosses $n = L/l_c$ domains, where l_c is the size of each domain: The set $\{\mathbf{B}_k\}_{1\le k\le n} = \{B_0\,\mathbf{b}_k\}_{1\le k\le n}$ represents a given random realization of the beam propagation. Accordingly, in each domain the Hamiltonian $\mathcal{H}_{\rm disp}$ takes the form [50]

$$\mathcal{H}^k_{\rm disp} = \begin{pmatrix} \Delta_{xx} & \Delta_{xy} & \Delta_{a\gamma}\,\sin\phi_k \\ \Delta_{yx} & \Delta_{yy} & \Delta_{a\gamma}\,\cos\phi_k \\ \Delta_{a\gamma}\,\sin\phi_k & \Delta_{a\gamma}\,\cos\phi_k & \Delta_a \end{pmatrix} , \tag{15}$$

where $\phi_k \in [0, 2\pi)$ is the azimuthal (random) angle between the projection of $\mathbf{b}_k$ on the (x_1, x_2) plane and the x_2 axis, and

$$\Delta_{xx} = \Delta_\parallel\,\sin^2\phi_k + \Delta_\perp\cos^2\phi_k\ , \tag{16}$$

$$\Delta_{xy} = \Delta_{yx} = (\Delta_\parallel - \Delta_\perp)\sin\phi_k\,\cos\phi_k\ , \tag{17}$$

$$\Delta_{yy} = \Delta_\parallel\cos^2\phi_k + \Delta_\perp\sin^2\phi_k\ , \tag{18}$$

while $\Delta_{a\gamma}$ is given by the first of Eqs. (5) with $B_T = B_0\sin\theta_k$, where θ_k is the zenith angle chosen randomly in $\theta_k \in [0, \pi)$.

Working in terms of the Eq. (12), after the propagation over n magnetic domains the density matrix is given by repeated use of $\mathcal{H}^k_{\rm disp}$, namely

$$\rho_n = T(\mathbf{b}_n, \ldots, \mathbf{b}_1)\,\rho_0\,T^\dagger(\mathbf{b}_n, \ldots, \mathbf{b}_1)\ , \tag{19}$$

where we have set

$$T(\mathbf{b}_n, \ldots, \mathbf{b}_1) \equiv \prod_{k=1}^{n} T_k\ , \tag{20}$$

with

$$T_k = e^{(i\mathcal{H}_{\rm disp} - \frac{i}{2}\mathcal{H}_{\rm abs})l_c}\ , \tag{21}$$

which is the transfer function in the k-th domain. In a cosmological context however we should remember that B_0 and l_c are no longer fixed but scale as $B_0\,(1+z_k)^2$ and $l_c/(1+z_k)$ where z_k is the redshift of the cell.

In the realistic case we solve the same equations, but the field $\mathbf{B}$ is no longer a random vector but its three components are calculated from the numerical model for every realization.

The effect of the $\Delta_{\rm CMB}$ *term* —We briefly comment on the role of $\Delta_{\rm CMB}$ term on the ALP-photon conversions at high energies. This term due to VHE photon refraction on CMB photons been recently calculated in [47]. From Eqs. (9) and (10) it results that assuming $\Delta_{\rm CMB} = 0$, when $\Delta_{a\gamma} \gg \Delta_a, \Delta_{\rm pl}$ $P_{a\gamma}$ would become energy-independent. Conversely, including $\Delta_{\rm CMB}$ this term can mimic a mass term, producing peculiar energy-dependent features. In order to illustrate this effect, in Fig. 5 we show the transfer function T_γ as a function of energy for a source at redshift $z = 0.3$ for $m_a = 10^{-10}$ eV and $g_{a\gamma} = 4\times10^{-12}$ GeV^{-1} (LM case) in presence of ALP oscillations including the $\Delta_{\rm CMB}$ effect (continuous curve) and without it (dashed curve). For comparison it is also shown T_γ with only absorption on EBL (dotted curve). As predicted $\Delta_{\rm CMB}$ is responsible for the energy-dependent "wiggles" in the $T_\gamma(E)$ which are absent when $\Delta_{\rm CMB} = 0$. Another important consequence of $\Delta_{\rm CMB}$ is to suppress the transfer function at high energies when $\Delta_{\rm CMB} \gtrsim \Delta_{a\gamma}$ (at $E > 30$ TeV in Fig. 5).

Transfer function in the $(g_{a\gamma}, m_a)$ *space*—In Fig. 6 we show, superposed to the exclusion regions of Fig. 1, curves iso-T_γ for a source at $z = 0.3$ and at energy $E = 20$ TeV. Left panel refers to the cell model while right panel is for realistic magnetic field. Each contour corresponds to the 95th percentile of the distribution of T_γ. In other words, there is a 5% probability that T_γ is larger than the indicated value. From these curves is evident the enhancement of the area probed with the realistic model at a fixed value of T_γ.

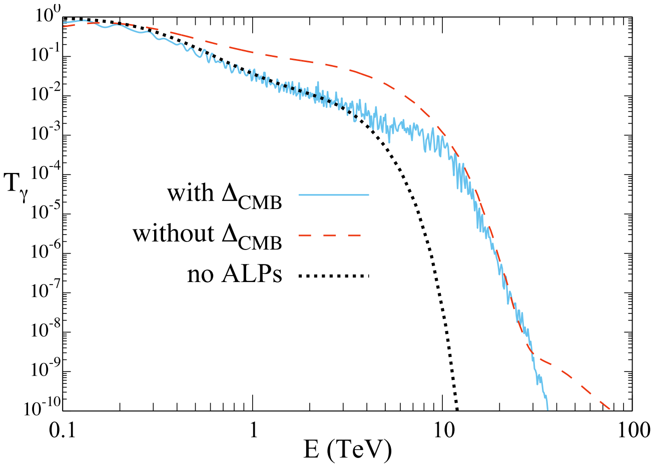

FIG. 5. The photon transfer function T_γ as a function of energy for a source at redshift $z = 0.3$ for $m_a = 10^{-10}$ eV and $g_{a\gamma} = 4\times10^{-12}$ GeV^{-1} (LM) for a particular realization with (continuous blue curve) and without (dashed red curve) $\Delta_{\rm CMB}$. The dotted curve corresponds to the case of only absorption onto EBL.

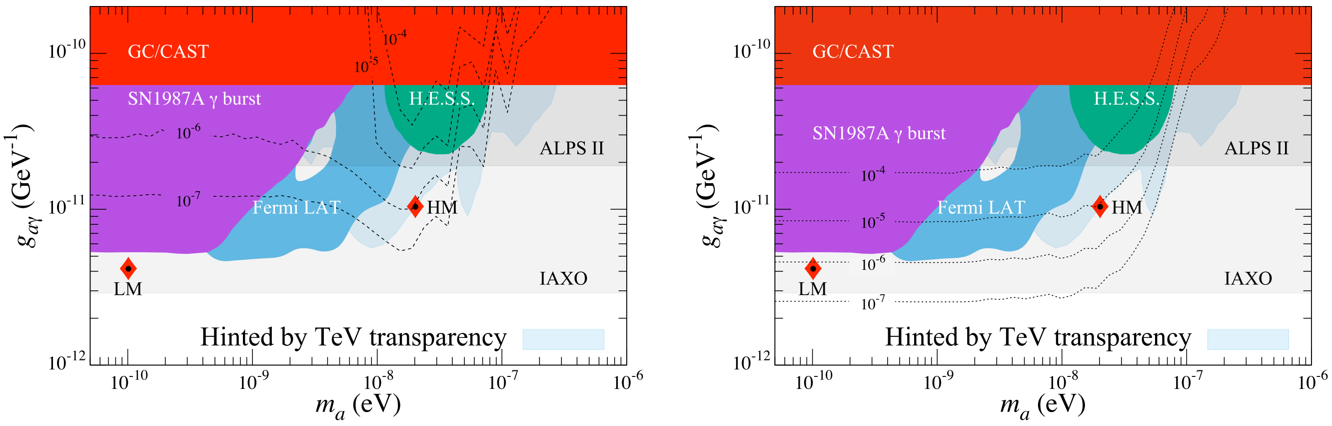

FIG. 6. Iso contour lines for transfer function T_γ for a source at $z = 0.3$ and at an energy $E = 20$ TeV for cell model (left) and realistic model (right) of B-field. Se the text for more details.

Cosmological Simulations of Extragalactic Magnetic Fields—The simulation used in this work belongs to a dataset of large cosmological simulations produced with the grid-MHD code ENZO [43], presented in detail [38] and [39] and designed to study the evolution of extragalactic magnetic fields under different physical scenarios. This simulation employed non-radiative physics to evolve a comoving volume of 200^3Mpc^3, assuming a cosmology with $H = 67.8$ km/(s $\cdot$ Mpc), $\Omega_b = 0.0478$, $\Omega_{\rm tot} = 1.0$, $\Omega_\Lambda = 0.692$. The magnetic field has been initialized to the uniform value of $B_0 = 1$ nG along each coordinate axis at the begin of the simulation ($z = 38$). With its 2400^3 cells/dark matter particles (for the fixed spatial resolution of 83.3 kpc per cell) this dataset represents the largest magnetohydrodynamical simulation in the literature so far.

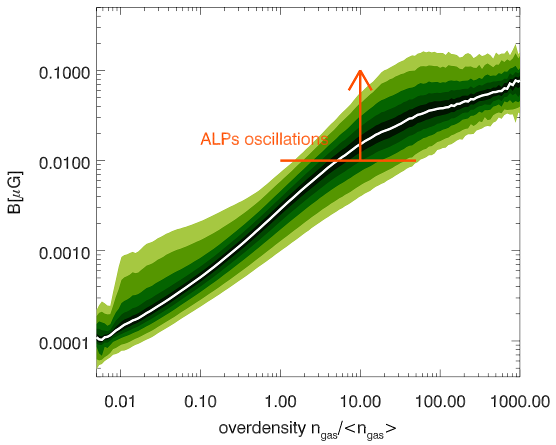

FIG. 7. Distribution of typical magnetic field strength as a function of gas overdensity for a representative samples of line of sights through our simulated volume. The different lines mark the percentiles of the distribution at each overdensity, tenfold from 10 to 90%. The additional orange arrow approximately marks the regime in which we observe significant photon-ALPs conversion in the energy range investigated in the paper.

Fig. 7 shows the distribution of magnetic fields as a function of cosmic environment in our simulation. The majority of the investigated volume presents a magnetisztion level that follows the compression/rarefaction of gas: $|\mathbf{B}| \propto (n_{\rm gas}/\langle n_{\rm gas}\rangle)^{2/3}$, i.e. the frozen-field approximation. The additional scatter on the relation is due structure formation dynamics; in particular the larger fluctuations at the high-density end of the distribution are a product of small-scale dynamo amplification acting within virialized halos.

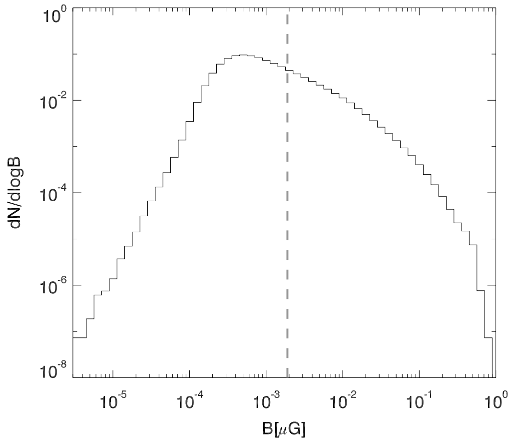

FIG. 8. Volume distribution of typical magnetic field strength for the same set of simulated lines of sight as in Fig. 7 (black). The additional dashed line show the r.m.s. magnetic field value for the same distribution.

Fig. 8 gives the volume distribution of magnetic field strength for the same set of lines of sight. The majority of the volume has a magnetization level slightly below the initial seed field (as an effect of adiabatic expansion in voids), yet a pronounced tail with magnetic fields up to $\sim \mu$G is present, largely exceeding the r.m.s. magnetic field measured within the volume, i.e. 1.9×10^{-9}G (as shown with the vertical grey line). The distribution of extragalactic magnetic fields reproduced in this simulation is a first, important step towards the simulation of possible scenarios for the origin of cosmic magnetic fields, which is presently limited by the constraints from the cosmic microwave background [22], and it will also possibly include the magnetization from astrophysical sources, like radio galaxies, starburst winds and jets from active galactic nuclei. The impact of such mechanisms on the conversion of ALPs will be subject of forthcoming work.

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