Revisiting the Bound on Axion-Photon Coupling from Globular Clusters

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We derive a strong bound on the axion-photon coupling $g_{a\gamma}$ from the analysis of a sample of 39 Galactic Globular Clusters. As recognized long ago, the R parameter, i.e., the number ratio of stars in horizontal over red giant branch of old stellar clusters, would be reduced by the axion production from photon conversions occurring in stellar cores. In this regard, we have compared the measured R with state-of-the-art stellar models obtained under different assumptions for $g_{a\gamma}$. We show that the estimated value of $g_{a\gamma}$ substantially depends on the adopted He mass fraction Y, an effect often neglected in previous investigations. Taking as a benchmark for our study the most recent determinations of the He abundance in H II regions with O/H in the same range of the Galactic Globular Clusters, we obtain an upper bound $g_{a\gamma} < 0.66 \times 10^{-10}$ GeV^{-1} at 95% confidence level. This result significantly improves the constraints from previous analyses and is currently the strongest limit on the axion-photon coupling in a wide mass range.

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Introduction.—Axions are low-mass pseudoscalar particles, somewhat similar to neutral pions. Originally, they were introduced to explain the absence of *CP* violation in the strong interactions (QCD) [1–4], a long-standing puzzle in particle physics known as the strong *CP* problem. Later on, it was also realized that the existence of such particles could account for most or all of the dark matter in the Universe. Specifically, axions with masses in the 10 μeV region would be cold dark matter candidates [5–7], while for $m_a \gtrsim 60$ meV, they would attain thermal equilibrium at the QCD phase transition or later [8,9], contributing to the cosmic radiation density and, subsequently, to the cosmic hot dark matter along with massive neutrinos [10].

A generic property of axions is their two-photon coupling, specified by the Lagrangian $\mathcal{L}_{a\gamma} = g_{a\gamma}\mathbf{E}\cdot\mathbf{B}$, where $g_{a\gamma} = 2\times 10^{-10}$ GeV$^{-1}\zeta(m_a/1$ eV$)$ and ζ is a model dependent parameter of order one in many axion models. This relation defines the "axion line" in the m_a-$g_{a\gamma}$ plane (see, e.g., [11]). However, in recent years, considerable attention has been devoted to the so-called axionlike particles (ALPs) which couple to photons, but do not satisfy the mass-coupling relation defined above for the QCD axions. Such light pseudoscalar particles emerge naturally in various extensions of the standard model (see, e.g., [12]) and are phenomenologically motivated by a series of unexplained astrophysical observations. Among these, the seeming transparency of the Universe to very-high-energy γ rays [13], the larger than expected white dwarf cooling rates [14], and the quest for dark matter candidates (see [15–17] and references therein).

As pointed out in a seminal paper by Sikivie [18], the two-photon coupling $a\gamma\gamma$ allows for efficient experimental searches of axions and ALPs. Indeed, in the presence of an external magnetic field, the $a\gamma\gamma$ coupling leads to the phenomenon of photon-axion mixing [19]. This mechanism is the basis for direct searches of axions in light-shining-through-the-wall experiments (see, e.g., [20]) and axion dark matter in microwave cavity experiments [see, e.g., the Axion Dark-Matter Experiment (ADMX) [21]]. Furthermore, the $g_{a\gamma}$ vertex would also allow for a production of axions via the Primakoff process in stellar plasma [22]. The predicted solar axion spectrum is currently searched by the CERN Axion Solar Telescope (CAST) [23], looking for conversions into x rays of solar axions in a dipole magnet directed towards the sun. CAST searches with vacuum inside the magnet bores achieved a limit of $g_{a\gamma} \lesssim 0.88 \times 10^{-10}$ GeV^{-1} for $m_a \lesssim 0.02$ eV [23], an excellent constraint for very light ALPs. For realistic QCD axions, CAST has explored the mass range up to 1.17 eV, providing the bound $g_{a\gamma} \lesssim (2.3\text{–}3.3) \times 10^{-10}$ GeV^{-1} at 95% C.L., by using ^{4}He [24] and ^{3}He [25,26] as buffer gases.

The Primakoff process induced by the photon-axion coupling would also allow for indirect axion searches, via effects on stellar evolution. In this context, additional constraints on the axion-photon coupling have been obtained from astronomical observations of helium burning low and intermediate mass stars [27–30]. A recent analysis showed that a sufficiently large axion emission would affect the very existence of Cepheids variables in the mass range $M \sim (8\text{–}12)M_\odot$, providing the bound $g_{a\gamma} < 0.8 \times 10^{-10}$ GeV^{-1} [30]. On the other hand, photometric studies of Globular Cluster (GC) stars provided the long-standing strong bound $g_{a\gamma} \lesssim 10^{-10}$ GeV^{-1} for an axion mass lower than about 10 keV [27–29].

Globular Clusters are gravitationally bound systems of stars populating the Galactic Halo. They are among the oldest objects in the Milky Way. Hence, only low mass stars ($M \lesssim 0.85 M_\odot$) are still alive and, therefore, observable. A typical GC harbors a few million stars, so that the various evolutionary phases are well populated and distinguished from each other. In particular, one can easily locate the main sequence, corresponding to the core H burning phase, the red giant branch (RGB), during which the stellar luminosity is supported by the H burning shell, and the horizontal branch (HB), corresponding to the core He burning phase. The number of stars observed in a particular evolutionary phase is proportional to the corresponding lifetime, which is determined by the efficiency of all the relevant sources and sinks of energy. As early recognized, axions coupled to photons would significantly reduce the lifetime of stars in the HB, while producing negligible changes on the RGB evolution [27]. (The RGB phase has been recently exploited to set a bound on the neutrino dipole moment and on the axion-electron coupling [31].) Therefore, $g_{a\gamma}$ can be constrained by measurements of the R parameter, $R = N_{\rm HB}/N_{\rm RGB}$, which compares the numbers of stars in the HB ($N_{\rm HB}$) and in the upper portion of the RGB ($N_{\rm RGB}$).

The previous analyses were based on the assumption that the measured R parameter is well reproduced, within 30%, by extant models of GC stars, without including axion cooling. Although it was recognized long ago (see, e.g., [32–35]) that the R parameter is sensitive to the helium mass fraction Y, which mainly affects the number of RGB stars, in the context of the axion bounds, this dependence has so far been neglected. Indeed, even a considerable decrease of the HB lifetime caused by a large value of $g_{a\gamma}$ could be compensated by a suitable increase of the assumed He content. Because of this degeneracy, a proper evaluation of the axion constraints from the R parameter relies on our knowledge of the He abundance in the GCs. He abundance measurements are particularly difficult for Globular Clusters stars. However, since they are among the first stars that appeared in the Universe, it is commonly assumed that the original He content of Galactic GCs practically coincides with the primordial one (Y_p). In this regard, in the last 20 years, the estimation of Y_p has improved significantly, changing from ~0.23 [36] to ~0.25 [37]. Furthermore, the large amount of new photometric studies of GCs accumulated over the last 20 years by exploiting Earth and space based telescopes allows a more accurate determination of the R parameter [38].

In light of these improvements and of the great importance of the GC bound for the current experimental efforts, we provide, here, a new analysis of this astrophysical constraint including, for the first time, the effects of the helium mass fraction. Our result, $g_{a\gamma} < 0.66 \times 10^{-10}\ {\rm GeV}^{-1}$ at 95% confidence level, improves significantly the bound from the previous analyses and is currently the strongest constraint on the axion-photon coupling in a wide mass range.

Analysis.—Salaris *et al.* [38] reported measurements of the R parameter for a sample of 57 Galactic Clusters. As discussed below, for the star's total metal abundance $[M/{\rm H}] < -1.1$, the R parameter is practically independent of the cluster age and metallicity. (Here, we are using the standard spectroscopic notation for the relative abundances, $[M/{\rm H}] = \log_{10}(Z/X) - \log_{10}(Z/X)_\odot$, where X is the hydrogen mass fraction and Z is the total mass fraction of all the elements except H and He, i.e., $Z = 1 - X - Y$.) At larger metallicity, however, the so-called RGB "bump" (The bump is an intrinsic feature appearing as a peak in the differential luminosity function of GCs. It originates when the H-burning shell crosses the chemical discontinuity left over by the convective envelope soon after the first dredge up, slowing down the evolutionary time scale.) is too faint to enter into the RGB star count and, in turn, the resulting R is definitely larger. Therefore, in our analysis, we considered only the 39 clusters with $[M/{\rm H}] < -1.1$, for which we obtain a weighted average $R_{\rm av} = 1.39 \pm 0.03$, and assumed that all the stars of the 39 clusters sample share the same original He abundance. The small statistical error (about 2%) supports this hypothesis.

It has been suggested that some GCs may harbor He enhanced stellar populations (see [39]). Indeed, the presence of He-rich stars would lead to a certain overestimation of the R parameter. However, He enhanced stars would be less massive than coeval stars with primordial He content, so that they would be located in the bluer part of the HB. We have tested this possibility by restricting the cluster sample, considering only 18 clusters whose HB is not dominated by blue stars. (The selection has been made by including only clusters with $(n_B - n_V)/(n_B + n_V + n_R) < 0.8$, where n_B, n_V, and n_R represent the number of HB stars bluer than the RR Lyrae instability strip, within the strip, and redder than the strip, respectively [40].) The new weighted average $R_{\rm ave} = 1.39 \pm 0.04$, practically coincides with the one obtained for the whole sample, thus, supporting the usual assumption that the bulk of the stars in our GC sample shares a unique He abundance.

Axions or ALPs with mass below a few keV could be produced in stellar interiors via the Primakoff process—the conversion of a photon into an axion in the fluctuating electric field of nuclei and electrons in the stellar plasma [22]. Being weakly interacting, axions would efficiently carry energy outside the star, much like neutrinos do, providing an effective cooling mechanism. In the following, we will neglect other possible couplings of axions with nucleons and electrons, since these are rather model dependent (see, e.g., [11]). If present, these interactions would also contribute to the energy loss. In this respect, our limit on $g_{a\gamma}$ should be considered conservative.

In order to asses the axion effects on stellar evolution and derive a bound on $g_{a\gamma}$, we have computed several evolutionary sequences of stellar models, from the premain sequence to the asymptotic giant branch, with different initial mass (M), RGB mass loss rate, metallicity (Z), helium mass fraction (Y), and axion coupling ($g_{a\gamma}$). The models were computed by means of the "full network stellar evolution" (FUNS) code, a hydrostatic 1D stellar evolution code [41–43]. Axion effects have been introduced as an additional energy sink following the procedure in [27] which includes the effects of electron degeneracy and of nonzero plasma frequency, relevant for the evolution during the RGB phase.

Besides axion induced effects, proportional to $g_{a\gamma}^2$, variations of R may be caused by changes of the parameters characterizing the cluster, such as age, metallicity or He content. Our numerical analysis shows negligible variations of R for initial stellar masses in the range $0.82 \leq M/M_\odot \leq 0.84$ and metallicities in $0.0002 \leq Z \leq 0.001$, which correspond to cluster ages between 11.1 and 13.3 Gyr and $-1.9 \leq [M/\mathrm{H}] \leq -1.1$, respectively. On the other hand, we find a linear dependence of R on the He mass fraction of the cluster. The relation

$$R_{\mathrm{th}}(g_{a\gamma}, Y) = 6.26Y - 0.41g_{10}^2 - 0.12, \qquad (1)$$

describes very well our numerical results and shows the mentioned degeneracy between Y and $g_{a\gamma}$. Evidently, an accurate determination of the He mass fraction in GCs is necessary to appropriately constrain the axion-photon coupling. As mentioned above, measurements of helium abundance in GC stars are challenging. Indeed, ultraviolet data are needed to perform He abundance analysis in stars, a spectroscopic window not achievable from Earth. In addition, convection, rotational induced mixings, and other secular phenomena, such as gravitational settling, modify the He abundance in the atmospheres of these stars. For this reason, the primordial He is often adopted for GC stars. Actually, Y_p represents a lower bound for the GC He mass fraction. For our purpose, we prefer to use direct measurements of Y in low metallicity environments which may be considered representative of the chemical composition of the early Galaxy. In this context, optical spectra of low-metallicity H II regions show several He I lines which allow a quite accurate He abundance determination. The most recent independent studies of low-metallicity H II regions are those published by Izotov *et al.* [37] and by Aver *et al.* [44]. These two groups use very similar procedures and tools, but different data sets. In particular, Aver *et al*. use high accuracy spectra of 16 blue compact dwarfs galaxies with $1.5 < \mathrm{O/H}(\times 10^5) < 13$. Note that this range of O/H is approximately the same as the 39 GCs we have used to derive the R parameter. The 111 H II regions used by Izotov *et al.* [37] extend to larger metallicity, even though most of them have O/H in the same range as Aver *et al.* [44]. In spite of the different data sets, the resulting weighted average values for the He abundance are very similar, namely: $Y = 0.2535 \pm 0.0036$ and 0.255 ± 0.003 for Aver *et al.* [44] and Izotov *et al.* [37], respectively. (These average values shouldn't be confused with the extrapolated values at 0 metallicity calculated by both groups, which represent an estimation of the primordial He.) Since the result obtained by Izotov *et al.* could be slightly higher, because of the few high Z H II regions included in their data set, in the following, we will use the weighted average value reported by Aver *et al.* [44] for the same metallicity range of the 39 GCs of our sample.

The new bound for the axion-photon coupling.—In order to constrain the axion-photon coupling, we compare the average value of R (R_{av}) with the theoretical prediction (R_{th}). Assuming that the R measurements are distributed as Gaussian variables, one can determine confidence levels for the different quantities. Our results are shown in Fig. 1. The vertical lines indicate, respectively, 68% C.L. (short-dotted curves) and 95% C.L. (long-dashed curves) uncertainties of Y. The other bent curves correspond to the determination of $g_{a\gamma}$ as a function of Y from R_{th} [Eq. (1)]. In particular, the solid black curve has been obtained with $R_{\mathrm{th}} = R_{\mathrm{av}}$, while the short-dashed and the long-dashed black lines indicate, respectively, the 1σ and the 2σ ranges.

Combining the confidence levels of Y and R_{th}, we find

$$g_{a\gamma} = (0.45^{+0.12}_{-0.16}) \times 10^{-10}\ \mathrm{GeV}^{-1}\ (68\%\ \mathrm{C.L.}), \qquad (2)$$

(the best-fit point is indicated with a star in Fig. 1) while

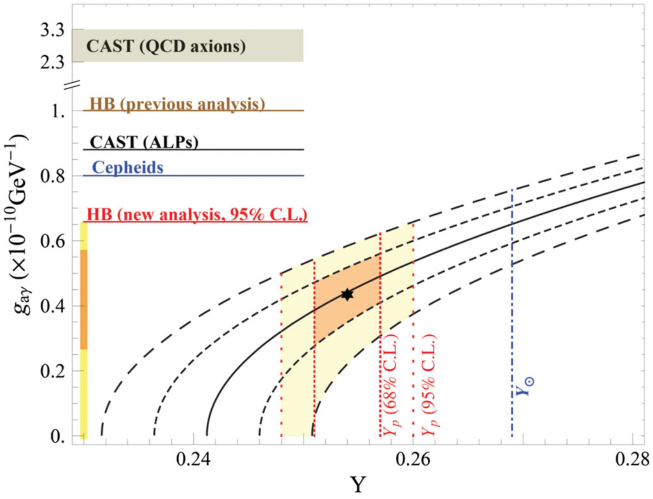

FIG. 1 (color online). R parameter constraints to Y and $g_{a\gamma}$. The vertical lines indicate, respectively, the 1σ (short-dotted curves) and 2σ (long-dotted curves) of Y. The dotted-dashed vertical line indicates the preferred value of $Y_\odot$. The other bent curves correspond to the determination of $g_{a\gamma}$ as a function of Y from R_{th} [Eq. (1)]. Specifically, the continuous curve corresponds to $R_{\mathrm{th}} = R_{\mathrm{av}}$, while the short and long-dashed lines indicate, respectively, the 1σ and the 2σ ranges. The star represents the best fits for $Y = 0.254$. The shaded area delimits the combined 68% C.L. (dark) and 95% C.L. (light) for Y and R_{th}. The vertical rectangles indicate the 68% C.L. (dark) and 95% C.L. (light) for $g_{a\gamma}$. Previous bounds from HB lifetime [27], from the Cepheids observation [30], from CAST for light ALPs [25,26] and for QCD axions [23] are also shown.

TABLE I. Axion-photon coupling bounds

		R	Y	g_{10}
Bounds from low-Z II regions	up 95%	1.33	0.260	0.66
	up 68%	1.36	0.257	0.57
	central value	1.39	0.254	0.45
	low 68%	1.42	0.251	0.29
	low 95%	1.45	0.248	0.00
Bounds from SBBN	up 95%	1.33	0.2478	0.50
	up 68%	1.36	0.2475	0.42
	central value	1.39	0.2472	0.31
	low 68%	1.42	0.2469	0.15
	low 95%	1.45	0.2466	0.00
Bounds from $Y_{\odot}$	up 95%	1.33	0.269	0.76
	up 68%	1.36	0.269	0.71

$$g_{a\gamma} < 0.66 \times 10^{-10}\ \mathrm{GeV}^{-1}\ (95\%\ \mathrm{C.L.}). \qquad (3)$$

Note that in the standard physics scenario, $g_{a\gamma} = 0$, we find $Y = 0.241 \pm 0.005$ which is compatible with the measured Y at 2σ.

As we have shown, the largest source of systematic error is the adopted helium mass fraction. Certainly the primordial He provides a lower bound to the GC He. For instance, by taking the latest standard big bang nucleosynthesis (SBBN) prediction, as obtained after the Planck results [45], we would obtain a more stringent constraint for the axion-photon coupling, i.e., $g_{a\gamma} < 0.50 \times 10^{-10}\mathrm{GeV}^{-1}$ (95% C.L.). On the other hand, the He content of the Solar System provides a very conservative upper bound for the GC He. The He abundance in the early Solar System is an input parameter of standard solar models and its value is mostly constrained by the present Solar System age, as derived by means of radioactive dating techniques of terrestrial and meteoritic materials. Piersanti *et al.* [46] found $Y_{\odot} = 0.269$ (vertical dotted-dashed line in Fig. 1) in good agreement with other extant standard solar models. (Serenelli *et al.* [47], by adopting the helioseismic determination of the present-day solar surface He abundance, found a slightly larger value, i.e., $Y_{\odot} = 0.278$.) By using this solar He mass fraction, we find a higher upper bound, namely $g_{a\gamma} < 0.76 \times 10^{-10}\ \mathrm{GeV}^{-1}$ (95% C.L.). However, this is an overly conservative assumption which would imply that no chemical evolution occurred during the 8 Gyr elapsed between the GC and the solar system formation, in contrast with many well-known astronomical evidences.

In Table I, we summarize the various bounds obtained under the different assumptions on Y. Obviously, our analysis relies on the reliability of the adopted stellar models of RGB and HB stars. In the Supplemental Material [48], we will give a short summary of the state of the art. A detailed study of the relevant uncertainties will be extensively presented in a forthcoming paper.

Discussion and conclusions.—We have obtained a new and more stringent bound on the axion-photon coupling constant $g_{a\gamma}$ from an updated analysis of the R parameter in 39 Galactic GCs. Our constraint, given in Eq. (3), represents the strongest limit on $g_{a\gamma}$ for QCD axions in a wide mass range. Only in the case of cold dark matter axions is there a stronger constraint, $g_{a\gamma} \lesssim 10^{-15}\ \mathrm{GeV}^{-1}$ from ADMX, and only for a narrow range around $m_a \sim 1\ \mu\mathrm{eV}$ [59]. As is evident from Fig. 1, our result improves the previous long-standing bound from GCs [27], $g_{a\gamma} \lesssim 10^{-10}\ \mathrm{GeV}^{-1}$ and the more recent one from Cepheid stars, $g_{a\gamma} \lesssim 0.8 \times 10^{-10}\ \mathrm{GeV}^{-1}$ [30]. Moreover, it is a factor ~4 better than the current experimental bound on QCD axions from the CAST experiment (see Fig. 1). This is also the strongest constraint for generic ALPs, except in the extremely low mass region $m_a \lesssim 10^{-10}$ eV. There, a more stringent limit $g_{a\gamma} \lesssim 10^{-11}\ \mathrm{GeV}^{-1}$ [60] or even $g_{a\gamma} \lesssim 3 \times 10^{-12}\ \mathrm{GeV}^{-1}$ [61] has been derived from the absence of γ rays from SN 1987A.

Ultralight ALPs with such a small coupling would play an important role in astrophysics. A particularly intriguing hint for these particles has been recently suggested by very-high-energy gamma-ray experiments [13], even though this problem has also been analyzed using more conventional physics (see, e.g., [62,63]). Indeed, photon-axion conversions in large-scale cosmic magnetic fields would reduce the opacity of the Universe to TeV photons, explaining the anomalous spectral hardening found in the very-high-energy gamma-ray spectra [64]. In particular, for realistic models of the cosmic magnetic field, this scenario would require $g_{a\gamma} \gtrsim 0.2 \times 10^{-10}\ \mathrm{GeV}^{-1}$ and $m_a \lesssim 10^{-7}$ eV [65].

Remarkably, the coupling ranges discussed in this Letter are accessible by new independent laboratory searches, such as the planned upgrade of the photon regeneration experiment ALPS at DESY [20,66] and the next generation solar axion detector International Axion Observatory (IAXO) [67]. This confirms, once again, the nice synergy between astrophysical arguments and laboratory searches to corner axions and axionlike particles.

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