

Astrophysical consequences of an electroweak η_w pseudoscalar

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(Received 17 October 2025; accepted 8 January 2026; published 21 January 2026)

Recently, it has been suggested that the spectrum of physical states in the Standard Model may include an ultralight pseudoscalar, denoted by η_w , in analogy with the η' state arising from the strong interactions. We find that typical expectations for the properties of η_w get challenged by astrophysical constraints on the couplings of ultralight bosons. Our strongest limit sets a lower bound of $\mathcal{O}(100 \text{ TeV})$ on the decay constant of the hypothesized pseudoscalar. We also briefly discuss whether η_w could be a dark matter candidate, or the origin of dark energy, but conclude that those identifications appear unlikely. Given the important implications of a potentially overlooked η_w state for a more complete understanding of the electroweak interactions and a fundamental description of nature, further theoretical and phenomenological investigations of this possibility and its associated physics are warranted.

DOI: [10.1103/qm4d-1n3d](https://doi.org/10.1103/qm4d-1n3d)

It has recently been proposed that the dynamics of the electroweak sector leads to the emergence of an ultralight pseudoscalar, denoted by η_w , whose mass arises from the anomaly of the global $U(1)_{B+L}$ symmetry of the $B + L$ charge, where B and L are the baryon and lepton numbers, respectively [1,2]. The gist of this proposal is that, since the vacuum angle θ_w associated with the $SU(2)$ gauge interactions of the Standard Model (SM) is not physical [3–5], there must exist a pseudoscalar, the aforementioned η_w , that is responsible for its removal. This is akin to the same effect in the strong interactions governed by the SM quantum chromodynamics (QCD), in the presence of a massless quark that would make the analogous angle θ_{QCD} unphysical. Within QCD, this effect would be ascribed to the infrared contribution of the observed pseudoscalar η' [6], whose relatively large mass $\sim 1 \text{ GeV}$ originates from the anomaly of the axial $U(1)_A$ symmetry.

It is fair to say that the status of η_w as a firm prediction of the SM is not well established and some of its fundamental properties, like mass and coupling, remain to be confidently predicted [2]. It has also been suggested that perhaps this state is not ultralight and is in fact a superposition of hydrogen and antihydrogen [7]. This is an interesting idea which may play a role in the phenomenology of the relevant physics. However, as pointed out

in Ref. [2], it does not seem to fit the assumed features of a particle associated with the removal of θ_w from the electroweak interactions. This association would make sense if one could treat η_w as a phase, i.e., a Goldstone mode, and it is not obvious that a composite atomic state can fulfill this role.

We find that the theoretical arguments put forth in Refs. [1,2]—in order to support the presence of η_w within the SM—provide good motivation for examining this intriguing hypothesis further. The emergence of η_w from the SM electroweak interactions would have significant import for our understanding of fundamental physics. In light of this circumstance, it is interesting to examine the feasibility of this hypothesis from various angles. Here, we will simply assume that the η_w pseudoscalar described in Refs. [1,2] is a prediction of the SM. We will then examine to what extent current astrophysical bounds, in particular those related to stellar emission of new light particles, can constrain the basic properties of η_w .

Let us denote the mass of η_w by m_{η_w} and its decay constant by f_{η_w} . What do we expect for the value of m_{η_w} ? This mass scale is assumed to be generated by electroweak instantons due to the $B + L$ anomaly in the SM. Therefore, it seems reasonable to take the Higgs vacuum expectation value $v = 246 \text{ GeV}$ as the typical mass scale M of the relevant dynamics. However, the associated instanton effects are suppressed by $e^{-2\pi/\alpha_2(v)} \sim 10^{-80}$, where $\alpha_2 \equiv g_2^2/(4\pi)$ and $g_2 \approx 0.65$ is the SM $SU(2)$ coupling at the weak scale $\sim v$. On general grounds, we may then expect

$$m_{\eta_w}^2 \lesssim e^{\frac{-2\pi}{\alpha_2(M)}} M^2 \quad (1)$$

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which for $M \sim v$ yields $m_{\eta_w} \lesssim 10^{-29}$ eV. This is a very tiny mass, making η_w a genuine ultralight scalar. Note that even for an unlikely value $M \sim M_P \sim 10^{19}$ GeV, i.e., near the Planck scale, we get $m_{\eta_w} \sim 10^{-39}$ eV, which is even deeper in the ultralight regime, due to the falling value of α_2 with energy in the SM. Here, we have used $\alpha_2(M_P) \approx 1/50$, given by the one-loop running formula,

$$\frac{1}{\alpha_2(\mu)} = \frac{1}{\alpha_2(\mu_0)} + \frac{\beta_0}{2\pi} \ln(\mu/\mu_0), \quad (2)$$

where $\beta_0 = 19/6$ in the SM (see, Ref. [8], for example). We thus conclude that, under any reasonable assumptions consistent with the assumed origin of the η_w state, m_{η_w} is extremely small and within the kinematic reach of stellar physical processes.

Next, we will focus on the decay constant f_{η_w} . In Ref. [2], no definitive value is derived, but $f_{\eta_w} \lesssim v$ is considered as reasonable, in light of theoretic considerations. In the scenario where the physics of η_w is entirely contained in the SM, this scalar is associated with a condensate that emerges from the dynamics of the 't Hooft vertex through the electroweak $SU(2)$ instantons [1,2]. This condensate is made up of quark Q and lepton ℓ doublets,

$$\langle (QQQ\ell)^{N_f} \rangle \propto e^{\frac{-2\pi}{\alpha_2(v)}} v^{6N_f}, \quad (3)$$

where $N_f = 3$ is the number of generations in the SM [1,2]. The above condensate corresponds to the order parameter for the spontaneous breaking of the global $U(1)_{B+L}$ symmetry and, hence, the decay constant f_{η_w} depends on its size. This is in analogy with the QCD chiral condensate $\langle \bar{q}_L q_R \rangle$ that sets the pion decay constant f_π . Hence, given the instanton suppression in Eq. (3), it is reasonable to assume that $f_{\eta_w} \lesssim v$ from electroweak non-perturbative dynamics, which we will adopt as the typical expectation, consistent with arguments put forth in Ref. [2].

No matter what the actual value of f_{η_w} is, it sets the coupling of η_w to the SM $SU(2)$ gauge fields, through the anomaly, by

$$\frac{\alpha_2}{8\pi} \frac{\eta_w}{f_{\eta_w}} W_{\mu\nu}^a \tilde{W}^{a\mu\nu}, \quad (4)$$

where $W_{\mu\nu}^a$ is the field strength tensor, $\tilde{W}_{\mu\nu}^a$ is its dual, and $a = 1, 2, 3$ is the adjoint index of $SU(2)$. Upon electroweak symmetry breaking, the above yields an interaction between η_w and the weak gauge bosons, $W^\pm$ and Z . A similar coupling to photons is vanishing due to anomaly cancellation, and the direct coupling to fermions is exponentially suppressed by the electroweak instanton rate [1].

The interaction in Eq. (4) leads to a loop-induced coupling to quarks and leptons, which can potentially

provide missing energy signals in meson decays [1]. The $W^\pm$ interaction also generates a one-loop coupling to photons, however this coupling is proportional to $m_{\eta_w}^2/m_W^2$, where $m_W = 80.4$ GeV is the $W^\pm$ boson mass and, hence, extremely suppressed; see Ref. [9] for an effective field theory derivation (see also Ref. [10]; a similar result has been reported for the two-loop Majoron coupling to photons in Ref. [11] as well). Therefore, we will only consider the interactions of η_w with fermions, in relation to the astrophysical bounds below. However, first we need to make an estimate of the coupling strengths. Given the uncertainty regarding the precise form of the physics that describes η_w , it suffices to use estimates that are correct up to $\mathcal{O}(1)$ factors, in what follows.

Let us consider the class of diagrams represented in Fig. 1. Here, V is a heavy electroweak vector boson $W^\pm, Z$ and f is a fermion of the SM. We will use the result of Ref. [9], where the contribution of such processes to the coupling between an axionlike particle and fermions was calculated. Let us parametrize the coupling to a charged lepton l by

$$c_{ll} \frac{m_l}{f_{\eta_w}} \eta_w \bar{l} \gamma_5 l, \quad (5)$$

where c_{ll} is a numerical coefficient and m_l is the charged lepton mass. From the results of Ref. [9], we have

$$c_{ll} = \left(\frac{3\alpha_2}{8\pi} \right)^2 \ln \left(\frac{\Lambda^2}{m_W^2} \right), \quad (6)$$

where Λ is a cutoff scale which we set by $\Lambda \gtrsim m_W$, given that the loop momenta corresponding to the process in Fig. 1 are governed by scales of the order of the W mass. We may require that

$$\Lambda = 4\pi f_{\eta_w}, \quad (7)$$

as a natural cutoff scale for the η_w dynamics. In this case, we find $f_{\eta_w} \gtrsim 6$ GeV, in a regime that may be suggested by the general arguments in Ref. [2].

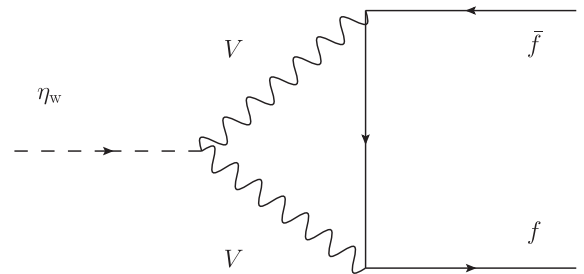


FIG. 1. A representative one-loop process that couples η_w to a fermion f . Here, V denotes a heavy $SU(2)$ gauge boson.

Using the above relations, we can estimate the coupling of η_w to electrons

$$y_e \eta_w \bar{e} \gamma_5 e. \quad (8)$$

Setting $\ln(\Lambda^2/m_w^2) \sim 1$ in Eq. (6), we find

$$y_e \sim (2 \times 10^{-5}) \frac{m_e}{f_{\eta w}}, \quad (9)$$

where $m_e \approx 0.511$ MeV is the electron mass. Given the ultralight nature of η_w , stellar cooling bounds apply. Here, the most stringent bound comes from globular cluster red giant energy loss, with $y_e \lesssim 10^{-13}$ [12–15], which implies

$$f_{\eta w} \gtrsim 100 \text{ TeV}. \quad (\text{Red giants}) \quad (10)$$

This bound pushes $f_{\eta w}$ 3 orders of magnitude above the weak scale and seems to be in tension with an electroweak origin for η_w [1,2].¹

In recent years, the coupling of light bosons to muons has been considered in the context of astrophysics, in particular core collapse supernova explosions. The investigations in Refs. [17,18] suggest that the coupling of muons to a light pseudoscalar is constrained by the supernova 1987A to be $y_\mu \lesssim \text{few} \times 10^{-9}$. Following the treatment applied to the electron coupling before, this would imply $f_{\eta w} \gtrsim 1$ TeV, which is not competitive with the above red giant bound. In general, the derivation of preceding bounds could be affected by the trapping of axions in the stellar environment. However, that regime of parameters is generally ruled out by other considerations [14].

In the case of first generation quarks, $f = u, d$, the diagram in Fig. 1 provides a coupling between η_w and nucleons N ,

$$y_N \eta_w \bar{N} \gamma_5 N, \quad (11)$$

of strength y_N . Along the lines of the preceding discussion, we may roughly estimate y_N by

$$y_N \sim \left(\frac{3\alpha_2}{8\pi} \right)^2 \frac{m_q}{f_{\eta w}}, \quad (12)$$

where $m_q \sim 5$ MeV is a typical valence quark mass inside a nucleon. Note that the above estimate is at the level of quarks, but we expect that up to $\mathcal{O}(1)$ effects this can be

¹We have ignored the log enhancement in the above estimate, which effectively removes the dependence on the unknown cutoff scale, but should in principle be accounted for. Including that effect would result in a lower bound on $f_{\eta w}$ that is $\mathcal{O}(1000 \text{ TeV})$ (similar to the result in Ref. [16], which however assumes a different context, based on physics beyond the SM), leading to more severe tension with $f_{\eta w}$ values suggested in Ref. [2].

taken as the nucleon coupling. For nucleon couplings, we have $y_N \lesssim 10^{-9}$ [12,14,15]. Using the above estimate for y_N , we thus find that $f_{\eta w} \gtrsim 100$ GeV would be sufficient, which may fit within a weak scale scenario for η_w , but is quite a bit less stringent than the one in Eq. (10).

Here, we note that the nonperturbative nature of the dynamics governing the properties of η_w could in principle defy naive expectations for the size of $f_{\eta w}$. Nonetheless, the above astrophysical constraints seem to suggest that, if η_w is present in the SM spectrum of states, its underlying dynamics may be more involved than what may be inferred from straightforward arguments.

Let us now turn to the question of dark matter (DM), which comprises about 25% of cosmic energy density [19]. The identity of DM remains a mystery of great interest to both particle physics and cosmology. A great deal of effort, in theory as well as experiment, is devoted to finding the answer to this question, which is one of the main motivations in searching for new physics beyond the SM. This is because no particle, elementary or otherwise, within the SM domain is believed to account for the DM content of the Universe. While neutrinos are weakly interacting and long lived, they do not have the requisite mass and cosmological properties to establish the observed DM abundance and characteristics. It has also been suggested that there may be a deeply bound long-lived state of six quarks [20]—often called the “dibaryon”—that could be DM [21,22]. However, no such state has been observed and it is quite doubtful that it could be the dominant form of matter in the Universe [23,24].

In light of the above considerations, it is important to ask whether η_w —assuming that it arises without the need for physics outside of the SM—can be a viable DM candidate. As discussed before, a weak scale origin for this particle would suggest $m_{\eta w} \sim 10^{-29}$ eV which is too light. To see this, note that its de Broglie wavelength would be given by

$$\lambda_w \sim (m_{\eta w} v_g)^{-1}, \quad (13)$$

where $v_g \lesssim 10^{-3}$ is a typical galactic virial velocity. The above equation then suggests $\lambda_w \gtrsim 10^{32} \text{ eV}^{-1} \gtrsim \text{Gpc}$, which is several orders of magnitude large than the size of a galaxy. Thus, η_w cannot be confined within galactic structures, as observational data require. Hence, it seems unlikely that η_w could be a viable DM candidate.

A very light scalar could in principle provide an explanation for the observed accelerated expansion of the Universe [19] (see Ref. [8] for an alternative view of the electroweak instanton contribution to the cosmological constant). In this case, the field should be essentially static and not have any significant kinetic energy at the present epoch. This amounts to requiring that $m_{\eta w} \lesssim H_0$, where $H_0 \sim 10^{-33} \text{ eV}$ is the present Hubble constant. Then, the potential energy of η_w could provide the requisite “dark energy” accelerating the expansion of the Universe, which

we may estimate by $\rho_w \sim m_{\eta_w}^2 f_{\eta_w}^2$. However, if we take $f_{\eta_w} \sim 100$ TeV, as close as possible to the weak scale allowed by astrophysical bounds above, we would get $\rho_w \lesssim 10^{-34}$ eV⁴. The dark energy stored in the η_w field is thus expected to be exponentially small compared to the value $\sim 10^{-11}$ eV⁴ [19] inferred from observational data. Getting close to the observed value requires $f_{\eta_w} \sim M_P$ for $m_{\eta_w} \sim H_0$ (see, for example, Ref. [25] for a model of dark energy based on a supersymmetric extension of the SM, where the scalar mass is generated by electroweak instantons).

Summary and concluding remarks. In this work, we have considered the astrophysical implications of a possible ultralight pseudoscalar, the η_w . It has been argued in Refs. [1,2] that this boson can emerge in the SM, without the need for any new ingredients, due to nonperturbative electroweak interactions and the $B + L$ anomaly. The arguments that have led to this conclusion are subtle, but have close kinship with those that relate the observed η' meson to QCD instantons and the axial anomaly. As such, the case for η_w can be considered motivated and worth further scrutiny, as it can have profound implications for the physical spectrum of the SM particles and electroweak dynamics.

Our results indicate that typical assumptions about the basic physical properties of η_w are in tension with astrophysical constraints on ultralight bosons. We found that avoiding excessive cooling of red giants results in the strongest such constraint, providing a lower bound $f_{\eta_w} \gtrsim 100$ TeV on the decay constant of a hypothetical η_w . This is

roughly 3 or more orders of magnitude above the expectation $f_{\eta_w} \lesssim 100$ GeV, assuming an electroweak origin.

While the underlying nonperturbative dynamics of such a particle is nontrivial, the bounds on its coupling, as obtained in this work, challenge typical arguments for the emergence of η_w and its general properties. Nonetheless, we view the possibility of a hitherto-ignored ultralight state of the SM sufficiently intriguing that further investigations of this topic seem well justified. If theoretical evidence for η_w gets more robust and difficult to refute, its detection would become an urgent experimental priority in fundamental physics. In that case, our results suggest that astrophysical observations could provide a promising avenue for discovery of η_w .

Note added. Recently, Ref. [16] appeared that has some overlap with our work.

ACKNOWLEDGMENTS

We thank M. Berbig for pointing out an error in an earlier version of our manuscript, regarding the estimation of the η_w coupling to photons. This work is supported by the U.S. Department of Energy under Grant Contract No. DE-SC0012704.

DATA AVAILABILITY

No data were created or analyzed in this study.

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