# Astrophysical Consequences of an $\eta_{\rm w}$ Pseudoscalar

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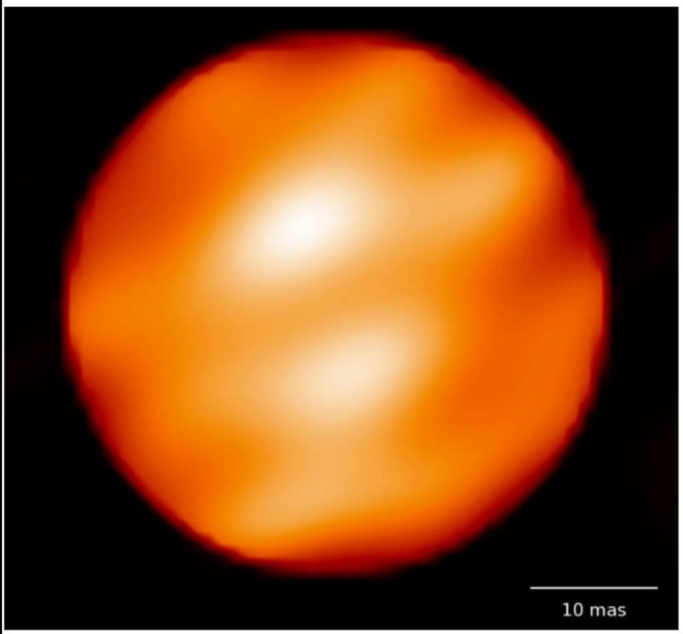


Credit: Observatoire de Paris/Xavier Haubois et al

Based on: H.D., Phys.Rev.D 113 (2026) 2, 023039, arXiv:2510.02310

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# $\theta$ angles

- An interaction allowed by all known symmetries: $\frac{\alpha_s \theta_{\text{QCD}}}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$

- Breaks $P$ and $T$, hence $CP$

- $CP$ is not a preserved symmetry of Nature (electroweak interactions)

- Neutron EDM bounds: $\theta_{\text{QCD}} \lesssim 10^{-10}$ (Why? Strong $CP$ problem)

- One can rotate $\theta_{\text{QCD}}$ into the quark mass matrix $M_q$

$\Rightarrow$ physical parameter $\bar{\theta}_{\text{QCD}} \equiv \theta_{\text{QCD}} + \arg|M_q| \Rightarrow$ Why $\bar{\theta}_{\text{QCD}} \lesssim 10^{-10}$

- New physics solutions: *E.g.*, Peccei-Quinn (1977), Nelson (1984)-Barr (1984)

- Obvious solution: one massless quark would allow to rotate $\bar{\theta}_{\text{QCD}}$ away

  - Introduces a classical chiral symmetry

  - Not favored by low energy hadronic data (lattice, phenomenology)

- For $m_q \to 0$, theoretical arguments imply $\eta'$ would dynamically remove $\bar{\theta}_{\text{QCD}}$

*E.g.*, Witten, 1979

  - Peccei-Quinn axion can accomplish this, but requires new physics

# The electroweak sector

- Analogous $SU(2)_L$ angle: $\dfrac{\alpha_2\,\theta_{\rm W}}{8\pi} W^a_{\mu\nu}\tilde{W}^{a\mu\nu}$

$a = 1, 2, 3$; $\alpha_2 = g_2^2/(4\pi)$

- A classically good symmetry $U(1)_{\rm B+L}$ (good quality)
- However $B + L$ broken by an anomaly at quantum level $\partial_\mu J^{\mu B+L} \propto W^a_{\mu\nu}\tilde{W}^{a\mu\nu}$
- One can be removed $\theta_{\rm W}$ away by rotating quark and lepton fields

$$Q \to e^{i\alpha/6} Q \quad \text{and} \quad \ell \to e^{i\alpha/2}\ell$$

See, *e.g.*, Fileviez Pérez, Patel, 2014

$$\theta_{\rm W} \to \theta_{\rm W} + N_f\,\alpha$$

($N_f = 3$ number of families)

- Akin to the massless quark case for QCD

# The case for $\eta_{\rm W}$

- Recent work has raised the question: is $\theta_{\rm W}$ removed dynamically by an $\eta_{\rm W}$?
  - Analogy with $\eta'$ for QCD with $|M_q| = 0$

Dvali, Kobakhidze, Sakhelashvili (DKS), 2408.07535, 2509.16043

- DKS argue $\eta_{\rm W}$ can emerge from the Standard Model (SM) electroweak dynamics
- Theoretical arguments for this require more careful examination
- No firm prediction for the properties (mass $m_{\eta_{\rm W}}$, decay constant $f_{\eta_{\rm W}}$) of $\eta_{\rm W}$
- Nonetheless, the emergence of this state can have significant import
  - A deeper understanding of electroweak (EW) dynamics and phenomenology
- One may ask: can the typical expectations for $\eta_{\rm W}$ be consistent with data?
  - This can be complementary to formal investigations
  - The answers may challenge the underlying assumptions and arguments

# General features of $\eta_{\mathrm{W}}$

- We follow DKS in general description of the main points
- $\eta_{\mathrm{W}}$ as a pseudo-Nambu-Goldstone boson (pNGB): spontaneous $U(1)_{B+L}$ breaking
- Mass generation from EW $SU(2)$ anomaly of $B+L$ current

$$m_{\eta_{\mathrm{W}}}^2 \lesssim e^{\frac{-2\pi}{\alpha_2(M)}} M^2$$

  - $M$ is the relevant scale
  - We take $M \sim v$, with $v \approx 246$ GeV the Higgs vev $\Rightarrow e^{-2\pi/\alpha_2(v)} \sim 10^{-80}$

$$\boxed{m_{\eta_{\mathrm{W}}} \lesssim 10^{-29}\ \mathrm{eV}}$$

  - Too light for "fuzzy" dark matter (de Broglie wavelength $\gg$ Mpc)

- DKS: spontaneous $U(1)_{B+L}$ breaking via the 't Hooft vertex of the EW instantons

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

Quark $Q$ and lepton $\ell$ doublets

  - Analogy with QCD chiral condensate $\langle \bar{q}_L q_R \rangle$, setting the pion decay constant $f_\pi$.

- This suggests typical expectation (also consistent with DKS arguments)

$$\boxed{f_{\eta_{\mathrm{W}}} \lesssim v}$$

# Interactions of $\eta_{\mathrm{W}}$ with SM

- To constrain $\eta_{\mathrm{W}}$, we need to find its couplings to matter
- Couplings to $SU(2)$ and $U(1)_Y$ gauge bosons via anomalies

$$\frac{\eta_{\mathrm{W}}}{f_{\eta\mathrm{W}}}\left(\frac{\alpha_2}{8\pi}W^a_{\mu\nu}\tilde{W}^{a\mu\nu} - \frac{\alpha_1}{8\pi}B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

- Since $B+L$ is not anomalous under EM/QCD, no coupling to $\gamma\gamma/gg$
- However, there is a 1-loop coupling to fermions $\boxed{i\xi\, m_\psi \frac{\eta_{\mathrm{W}}}{f_{\eta\mathrm{W}}}\bar{\psi}\gamma_5\psi}$, where

$$\xi = \frac{3\alpha^2}{16\pi^2}\left[\frac{3}{4\sin^4\theta_W} - \frac{Y_L^2+Y_R^2}{\cos^4\theta_W}\right]\ln\left(\frac{\Lambda^2}{m_W^2}\right)$$

See, *e.g.*, Bauer, Neubert, Thamm, 2017

Fermion mass $m_\psi$, $\alpha$ EM fine structure constant, $\theta_W$ weak mixing angle, $Y_L$ and $Y_R$ hypercharges of the doublet and singlet $\psi$, respectively.

$W^\pm$ mass $m_W \approx 80.4$ GeV, $\Lambda > m_W$ a cutoff scale, $\sin^2\theta_W(m_Z) \approx 0.231$, $Z$ mass $m_Z \approx 91.2$ GeV, $\alpha(m_Z^2) \approx 1/127.9$

# Coupling to electrons

- We may derive a coupling electrons $y_e \, \eta_{\mathrm{W}} \, \bar{e}\gamma_5 e$ based on the above
- One could set $\Lambda = 4\pi f_{\eta\mathrm{W}}$ and get

$$y_e \approx 3 \times 10^{-5} \ln\left(\frac{16\pi^2 f_{\eta\mathrm{W}}^2}{m_W^2}\right) \frac{m_e}{f_{\eta\mathrm{W}}}$$

- Globular cluster red giant anomalous energy loss: $y_e \lesssim 10^{-13}$ Caputo, Raffelt, 2024

$$\boxed{\Rightarrow f_{\eta\mathrm{W}} \gtrsim 10^3 \ \mathrm{TeV}}$$

Similar result, in a different context: Cacciapaglia, Sannino, Turner, 2510.14104

- The above lower bound in tension with an EW origin for $\eta_{\mathrm{W}}$

# Conclusions

- Recent suggestion for emergence of a light pseudoscalar $\eta_{\mathrm{W}}$ from EW dynamics warrants examination

- If present, it has significant implications for non-perturbative EW interactions

- One may ask whether the expected properties of such a state are accommodated by data

- We considered this question and found that red giant cooling bounds strongly disfavor values of couplings for $\eta_{\mathrm{W}}$ suggested by theoretical considerations

- This can be interpreted as a challenge to theory arguments for its emergence from SM interactions

- Further theoretical investigations regarding $\eta_{\mathrm{W}}$ seem warranted, given its potential impact on a fundamental description of the EW sector