The Electroweak Horizon Problem

Fulvio Melia

Abstract

Spontaneously broken symmetries in particle physics may have produced several phase transitions in cosmology, e.g., at the GUT energy scale ($\sim 10^{15}$ GeV), resulting in a quasi-de Sitter inflationary expansion, solving the background temperature horizon problem. This transition would have occurred at $t \sim 10^{-36} - 10^{-33}$ seconds, leading to a separation of the strong and electroweak forces. The discovery of the Higgs boson confirms that the Universe must have undergone another phase transition at the electroweak (EWPT) scale $159.5 \pm 1.5$ GeV, about $10^{-11}$ seconds later, when fermions and the $W^\pm$ and $Z^0$ bosons gained mass, leading to the separation of the electric and weak forces. But today the vacuum expectation value ($vev$) of the Higgs field appears to be uniform throughout the visible Universe, a region much larger than causally-connected volumes at the EWPT. The discovery of the Higgs boson thus creates another serious horizon problem for $\Lambda$CDM, for which there is currently no established theoretical resolution. The EWPT was a smooth crossover, however, so previously disconnected electroweak vacua might have homogenized as they gradually came into causal contact. But using the known Higgs potential and $vev$, we estimate that this process would have taken longer than the age of the Universe, so it probably could not have mitigated the emergence of different standard model parameters across the sky. The EWPT horizon problem thus argues against the expansion history of the early Universe predicted by standard cosmology.

Keywords: FLRW spacetime, electroweak phase transition, horizon problem

1. John Woodruff Simpson Fellow. E-mail: fmelia@email.arizona.edu
1. Introduction

The impact of particle-physics-induced phase transitions on cosmology was recognized over four decades ago, e.g., via the proposal in the early 1980’s of solving the cosmic microwave (CMB) temperature horizon problem using the quasi-de Sitter expansion produced when the strong and electroweak forces separated at the grand unified (GUT) scale \( \sim 10^{15} \text{ GeV} \) \cite{1, 2, 3, 4}. But this could not have been the only spontaneously broken symmetry impacting the expansion of the Universe. Aside from this well-studied case, which was actually originally motivated by missing magnetic monopoles, there should have been at least one more associated with the separation of the electric and weak forces \cite{3, 6, 7}.

We know this with confidence following the discovery of the Higgs particle \cite{8}, whose existence confirms the widely held belief that inertial mass in the standard model is at least partially due to the Higgs mechanism \cite{9, 10}. Thus, a second well-motivated transition (the electroweak phase transition, EWPT) must have occurred at a critical temperature of \( 159.5^{\pm 1.5} \) GeV. But as we shall see, this creates a problem because in \( \Lambda \)CDM this temperature would have been reached \( \sim 10^{-11} \) seconds after the Big Bang, when causally-connected regions were still too small to eventually fill the Universe we see today. On the other hand, the EWPT would have occurred well past the first (inflationary) transition at \( t \sim 10^{-36} - 10^{-33} \) seconds, so its impact could not have been mitigated by the quasi-de Sitter expansion completed earlier.

In the standard model of particle physics, the EWPT is a ‘crossover’ (always close to equilibrium), rather than first order (marked by a discontinuity). In principle, the latter could have produced the baryon asymmetry observed in matter left over after particle annihilations ended as the Universe cooled (see, e.g., ref. \cite{11} for a recent summary). The promise of such a scenario motivates possible extensions to the standard model in order to circumvent the implied limitations of a crossover. These include the introduction of additional Higgs fields \cite{12}, that could also generate gravitational waves (see, e.g., \cite{13}) detectable with LISA \cite{14, 15}. The search for hints of a Higgs self-interaction consistent with these models thus continues with the High-Luminosity Large Hadron Collider (LHC) (see, e.g., \cite{16, 17, 18}), and will be featured in future particle accelerator experiments. Currently, however, a primary focus on Higgs tends to be the aforementioned generation of fermionic, \( W^\pm \) and \( Z^0 \) mass, believed to have separated the electric and weak forces—a crucial event in the history of the Universe.
Of course, if the standard model is correct, a third phase transition should have occurred at $\sim 100$ MeV, some $10^{-6}$ seconds after the EWPT. In quantum chromodynamics (QCD), such an event would have ensued following the condensation of free quarks in a quark-gluon plasma into the confined states representing baryons and mesons as the Universe continued to expand and cool.

Our principal concern in this paper is the inevitable horizon problem created by the Higgs mechanism in the context of $\Lambda$CDM, analogously to the earlier horizon problem associated with the CMB temperature. This time, however, the pertinent physical quantity is the vacuum expectation value ($vev$) of the Higgs field, which is apparently uniform throughout the Universe, even on scales greatly exceeding regions that could not have been causally-connected at the time of the EWPT. As we shall see, while inflation might have mitigated the temperature horizon problem, its implied de Sitter expansion would have occurred well before the EWPT, and would thus have been largely irrelevant to the emergence of the Higgs $vev$.

Currently, there is no established solution to this problem, which has slowly gained in prominence over the past half century, culminating with the recent experimental confirmation of the Higgs mechanism. In one of its earliest guises, the EWPT was thought to create sub-horizon features, manifested as observable anisotropies in the CMB. For example, Zel’dovic, Kobzarev & Okun [19] and Kibble [20] assessed the possibility that ‘domain walls’ might have been created from such phase transitions in the early Universe. Some measurable features in the CMB could in principle be associated with these ‘topological defects’ [21, 22, 23]. Five decades later, however, we have a much more detailed understanding of the CMB temperature fluctuations, and we have seen no evidence of domain walls created by the EWPT [21, 22, 23].

Below, we shall first provide a brief background on the Higgs mechanism, followed by a quantitative demonstration of the EWPT horizon problem. We will conclude with a discussion of some attempts made thus far to address this quandry which, however, is now much more serious and better established than ever before following the discovery of the Higgs boson.

2. Background

With the recent discovery of the Higgs boson, the Higgs mechanism for generating the inertia of fermions, and the $W^\pm$ and $Z^0$ bosons is now widely accepted [9, 10]. The two principal issues in this process are (i) when did
the Higgs field acquire a non-zero vev, commonly referred to as ‘turning on the Higgs field’? and (ii) how strong is the Higgs coupling to the various elementary particles? The electroweak symmetry is unbroken at asymptotically high temperatures because all of the ‘messenger’ particles ($W^\pm$, $Z^0$ and photons) mediating the electroweak force transfer the same momentum per unit energy from one fermion to the next. From the relativistic expression for energy, $E^2 = m^2c^4 + p^2c^2$, one can see that the value of $p/E$ becomes independent of $m$ in the regime where $p \gg mc$.

This symmetry is spontaneously broken, however, and the electric and weak forces separate, when $p/E$ becomes dependent on the particle type due to the emergence of a non-zero mass. In the absence of a Higgs mechanism, this would happen gradually as the Universe cooled to a temperature $T \sim m_\alpha c^2/k_B$, where $m_\alpha$ is the $W^\pm$ or $Z^0$ mass and $k_B$ is the Boltzmann constant. If the particle rest-mass energy is directly due to the Higgs coupling, however, the transition would have happened when the Higgs field acquired a non-zero vev. The viability of the Higgs mechanism makes the spontaneous symmetry breaking cleaner and more precisely localized in temperature and time. And as noted earlier, we now know that the EWPT must have occurred at $k_B T = 159.5 \pm 1.5$ GeV, the temperature to which the ΛCDM universe would have cooled by $t \sim 10^{-11}$ seconds.

Clearly, whether the EWPT created a horizon problem or not thus depends on the value at which the Higgs field finally settled. But we have no reason to believe that the vev is specified uniquely. In principle, it could have been anything. What we can say for certain, however, is that whatever conditions established the vev, it would have been created uniformly only throughout a causally-connected region of spacetime. There is no known initial constraint that could otherwise have forced the Higgs field to emerge with the same value even at distances exceeding our causal horizon. Note in particular, that the vev is in fact associated with an operator which, in quantum mechanics would be independent of the observer only if ‘hidden variables’ were to establish its magnitude in terms of preset physical conditions. But many modern tests of Bell’s theorem have compellingly shown that hidden variables almost certainly do not exist [27, 28, 29].

An interesting approach to this question is based on an anthropic constraint for the existence of atoms [30], which allows one to estimate the likelihood function for the Higgs vev. The fermionic masses are proportional to the Higgs vev, the argument goes. Thus, since nuclei and atoms could only exist if the light-quark and electron masses were close to their actual
measured values \[31, 32, 33\], the anthropically permitted bounds constitute constraints on the *vev* distribution producing observers, subject to the other parameters in the standard cosmological model.

Without such anthropic considerations, there is actually quite a large domain of possible *vev’s*, due to an unknown property of the fundamental theory, extending at least up to the GUT scale, orders of magnitude greater than the current EW scale. Indeed, the present disparity between the GUT and EW scales constitutes a so-called ‘hierarchy problem.’ One may thus explore how the *vev* distribution is shaped by variations in the cosmology, but always mindful of the requirement that nuclei and atoms must appear.

As it turns out, the range of *vev’s* permitted by this anthropic analysis is far smaller than the EW to GUT gap, but it is nevertheless not minute. Rather than the Higgs field being constrained solely to its measured value, referred to as $v_0$, the *vev* distribution actually has a median value of $2.25v_0$, with a $2\sigma$ range extending from $0.10v_0$ to $11.7v_0$. Thus, since fermionic masses are proportional to the *vev*, the nuclear and atomic properties we observe in the real Universe could have varied by over two orders of magnitude, from one causally-connected region to another. As noted earlier, however, we have never seen such variations over the past half-century of observations, culminating with the latest, most precise measurements carried out by Planck \[26\].

3. The Electroweak Horizon Problem

The most straightforward way to see why the EWPT creates a serious horizon problem for standard cosmology is the following. We write the Hubble parameter for flat $\Lambda$CDM in the form

$$H(a) = H_0 \sqrt{\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda},$$  \hspace{1cm} (1)$$

where $a(t)$ is the expansion factor in the Friedmann-Lemaitre-Robertson-Walker (FLRW) metric, and the Hubble constant ($H_0 = 67.8$ km s$^{-1}$ Mpc$^{-1}$) and the scaled densities for matter ($\Omega_m = 0.308$), radiation ($\Omega_r = 5.37\times10^{-5}$) and dark energy ($\Omega_\Lambda = 1 - \Omega_m - \Omega_r$), take on their Planck values \[26\]. For this model, the redshift and age at decoupling were $z_{\text{dec}} = 1089.9$ and $t_{\text{dec}} = 377,700$ years, respectively. Thus,

$$a(t_{\text{dec}}) = (1 + z_{\text{dec}})^{-1} \approx 9.17 \times 10^{-4}. \hspace{1cm} (2)$$
The corresponding Hubble parameter (from Eq. 1) was thus

$$H(t_{\text{dec}}) \approx 4.78 \times 10^{-14} \text{ s}^{-1}.$$  (3)

The gravitational radius (coincident with the size of the Hubble sphere) at that time may thus be calculated as \[34\]

$$R_h(t_{\text{dec}}) \equiv \frac{c}{H(t_{\text{dec}})} \approx 0.20 \text{ Mpc}.$$  (4)

This allows us to infer the expansion factor, $a(t)$, and Hubble parameter, $H(t)$, at any time $t$ prior to decoupling from the definition

$$t_{\text{dec}} - t = \int_{a(t)}^{a_{\text{dec}}} \frac{da}{aH(a)}.$$  (5)

Setting $t = t_{\text{ew}} = 10^{-11}$ seconds, thus allows us to solve for $a(t_{\text{ew}})$ at the EWPT, yielding

$$a(t_{\text{ew}}) \sim 10^{-15},$$  (6)

with a corresponding gravitational radius

$$R_h(t_{\text{ew}}) \sim 1.3 \text{ cm}.$$  (7)

From previous studies \[34, 35, 36, 37\], we know how to determine the proper size of a causally-connected region in terms of $R_h$. Unlike the situation in a static spacetime, like Schwarzschild, $R_h$ in the cosmological context is not an event horizon. In general relativity this quantity represents a so-called ‘apparent’ horizon that separates null geodesics approaching the observer from those that are receding \[34\]. $R_h$ may turn into an event horizon in our distant future, depending on the cosmic equation of state, but for now we recognize that our gravitational (or apparent) horizon is changing with time, so the congruence of null geodesics reaching us at any given time also changes as the Universe expands. Consequently, regions that were beyond our causal horizon in the past, can enter into our current causally-connected portion of the Universe.

In simplest terms, the key physical determinant of whether or not a distant source is causally connected to us is whether or not a light signal it emitted in the past has reached us by today. And in this context, previous studies \[34, 35, 36, 37\] have shown that an observer receiving a light signal at
time $t_{\text{obs}} > t_{\text{max}}$ infers a maximum photon excursion $R_{\gamma}(t_{\text{max}}) \lesssim R_{\text{h}}(t_{\text{obs}})/2$ away from them. The time $t_{\text{max}}$ defines the point on the observer’s past lightcone at which $R_{\gamma}$ is maximized.

This behavior of null geodesics, in terms of the proper distance $R_{\gamma}(t)$ in FLRW, is not difficult to understand \cite{37}. de Sitter space is the only well known FLRW model with a time-independent metric and no initial singularity. All other models, including $\Lambda$CDM, began their expansion at a specific time (i.e., the Big Bang), and therefore could not have had pre-existing, detectable sources lying away from the observer’s location prior to the Big Bang. Except in de Sitter, all of the photons detected by the observer at time $t_{\text{obs}}$ from the most distant, observable locations were emitted after their sources had reached the edge of visibility—at a proper distance of roughly $R_{\text{h}}(t_{\text{obs}})/2$. This defines the proper size of the visible Universe at any given time $t_{\text{obs}}$ (see ref. \cite{34} for a more detailed description).

Some authors have claimed that today (at time $t_{0}$) we can see sources beyond $R_{\text{h}}(t_{0})$ (see, e.g., ref. \cite{38}). But these papers are confusing the location of the sources today with where they were when they emitted the light we are just now receiving. We certainly cannot expect that our causally-connected region is defined by light signals we shall receive in our future. Causal contact must be established within the proper size $R_{\gamma}(t_{\text{max}})$ by light signals that have actually already been exchanged between the emitter and the observer.

Shifting forward to the present, we estimate that

$$R_{\text{ew}}(t_{0}) \equiv \left[ \frac{a(t_{0})}{a(t_{\text{ew}})} \right] R_{\text{h}}(t_{\text{ew}}) \approx 10^{-3} \text{ lyr} . \tag{8}$$

Thus, to within a factor $\sim 2$ \cite{37}, this is the size today of the region that was causally-connected at the EWPT. It therefore represents the largest region within which the Higgs $v_{\text{ew}}$ ought to be uniform. The horizon problem arises because the gravitational radius of the Universe is now $R_{\text{h}}(t_{0}) \approx 4,424$ Mpc—many orders of magnitude larger than this. If the expansion history in $\Lambda$CDM were correct, the fermionic and atomic properties we observe around us should thus be varying spatially across the Universe, as one would expect from the aforementioned topological defects discussed by Zel’dovic, Kobzarev & Okun \cite{19} and Kibble \cite{20} half a century ago.
4. Discussion

To place the radius $R_{\text{ew}}(t_0)$ in context, compare $R_h(t_{\text{ew}})$ in Equation (7) with the corresponding gravitational radius at the start of inflation, presumably at $t_{\text{inf}} \sim 10^{-36}$ seconds after the Big Bang. The Universe would have been dominated by radiation for $t \lesssim t_{\text{ew}}$, so we can put $a(t) \propto t^{1/2}$ and $H(t) \propto t^{-3/4}$ during this epoch. This yields $R_h(t_{\text{inf}}) \sim 1.6 \times 10^{-25}$ cm. Of course, with the hypothesized subsequent 60 e-folds of expansion before the Universe settled back into its hot Big Bang dynamics, this radius would have increased almost instantaneously to $\sim 16$ cm, already larger than the electroweak horizon radius $R_h(t_{\text{ew}}) \sim 1.3$ cm about $10^{-11}$ seconds later. One can easily estimate from this that the inflated causally-connected volume at the end of inflation would thus have been larger than the whole Universe we see within our gravitational radius today, i.e., $R_{\text{inf}}(t_0) \equiv \left[ a(t_0)/a(t_{\text{inf}}) \right] R_h(t_{\text{inf}}) > R_h(t_0)$.

4.1. A Second Inflationary Expansion

The obvious question is therefore whether an analogous spurt of inflated expansion could have happened a second time to rescue the glaring inconsistency implied by Equation (8). A milder, delayed inflationary phase has in fact been proposed on several occasions, for various reasons not necessarily having to do with the EWPT itself [39, 40, 41, 42, 43, 44]. For example, models of supersymmetry breaking contain many possible scalar and fermionic fields, loosely referred to as ‘moduli,’ characterized by masses of order the weak scale and gravitational-strength couplings to the visible sector. Their corresponding quanta could have posed a serious problem to cosmology, however, if produced in the early Universe. They would have behaved like non-relativistic matter, decaying very slowly, and dominating the cosmic energy density past the end of nucleosynthesis. Their decay products could have destroyed $^4$He and D nuclei by photodissociation, thus ruining any hope of a working BBN model within standard cosmology [45, 46, 47, 48]. An example of such a relic is the supersymmetric partner of the graviton, called the spin-3/2 gravitino.

This so-called cosmological moduli problem may be solved, however, with a period of weak-scale inflation [39, 40, 42], which could have diluted the density of moduli below their destructive level. In this proposal, the hot Big Bang may not have persisted uninterrupted through the electroweak scale if one or more of these hypothesized scalar fields had a sufficiently large
vacuum expectation value to temporarily dominate the energy density with an almost flat potential. In other words, this inflationary process would have arisen ‘naturally’ from the same assumptions that lead to the cosmological problem in the first place.

But unlike the GUT inflationary phase invoked to solve the CMB temperature horizon problem, this late-time, weak-scale inflation would have produced a mere $\sim 10$ e-folds of inflation, growing the size of a typical, causally-connected electroweak region to $\sim 2.2 \times 10^4 R_{ew}(t_0) \approx 22 \text{ lyr}$—still many orders of magnitude below the gravitational radius of the Universe today.

A similar mechanism for a late-time inflationary phase has also been proposed at the QCD phase transition [43]. In this scenario, the phase transition would have signaled the transformation in the early Universe from a quark-gluon plasma to a hadron gas at a critical temperature $T_{QCD} \approx 150 - 200 \text{ MeV}$, corresponding to a time $\sim 10^{-6} - 10^{-4}$ seconds in the standard model. But this scenario, it turns out, is very similar to the late-time weak-scale inflation, with a length of only $\sim 10$ e-foldings. Thus, while it may have mitigated other cosmological problems, it cannot even come close to solving the electroweak horizon problem.

Finally, a more generic form of late-time inflation has been proposed to account for the fact that dark matter candidates today, such as the weakly interacting massive particles (WIMPs) or the QCD axion [49, 50], appear to have a much lower density than one might expect from their overproduction in the early Universe [44]. To ‘fix’ this particular problem, an imprecisely defined scenario referred to as ‘inflatable dark matter’ has been proposed, in which a brief period of late-time inflation could have occurred with an energy scale from several MeV to hundreds of GeV.

As noted earlier, however, such an inflationary event would require a source of vacuum energy exceeding the radiation energy density in the early Universe, at least briefly. We know of at least some possible candidates, including those associated with the QCD and electroweak phase transitions. But as we have seen, these cases could not have provided a sufficient number of e-foldings to mitigate our problem. And it now appears that these fields transitioned to their broken phase before they could dominate the energy density, so they probably could not have provided the late-time inflation anyway [44]. Thus, to conceive of a second inflationary event that might also have solved the electroweak horizon problem, one would need to postulate a period of inflation triggered by the potential energy density of fields beyond
the Standard Model.

It remains to be seen whether such extensions can eventually be made to work, however. Unlike ‘standard’ inflation that may have possibly occurred very early in the Universe’s history, late-time inflation would have been uncomfortably close to other physically important events—such as BBN—requiring a fine tuning of conditions to fix the electroweak horizon problem, while not breaking other aspects of the cosmic expansion that seem to be currently viable. We note, in this regard, that the new inflationary field would need to have had a potential dominating the energy density for more than 30 e-foldings in order to solve the electroweak horizon problem. But such a dramatic expansion just prior to (or during) baryogenesis and BBN would probably have broken the concordance model, not to mention overly diluting any dark matter candidates to densities below observationally relevant levels, defeating the purpose for which such fields were proposed in the first place.

4.2. Homogenization of causally disconnected electroweak vacua

If not another inflationary spurt, one might contemplate the mitigation of the EWPT horizon problem via the homogenization of different electroweak vacua as they gradually came into causal contact. Since the EWPT is now known to have been a crossover, one would not expect topologically stable domain walls to have formed, allowing different vacua to be mutually accessible. Gradients in the Higgs field could thus have affected the Higgs-field dynamics, possibly establishing a uniform vev across the observable Universe.

We shall adopt a highly simplified approach to estimate the timescale over which this process could have acted, starting with the equation of motion for the Higgs field in the FLRW metric (see, e.g., ref. [9, 10, 49, 51]):

\[ \ddot{\phi} + 3H(t)\dot{\phi} + V'(\phi) = 0 , \] (9)

where \( H(t) \) is the Hubble parameter and the Higgs potential may be written

\[ V(\phi) = \frac{\lambda}{4} (\phi^2 - v^2)^2 , \] (10)

in terms of the self-interaction coupling of the Higgs boson, \( \lambda \), and the vev, \( v \), which today has a measured value of 246 GeV. The Higgs boson mass itself is given by \( m \equiv \sqrt{2\lambda v} \).

We focus on small background Higgs field values, near the minimum of the potential, so that we may neglect the quadratic term. In addition, we
ignore for simplicity the contribution from local spatial gradients in $\phi$ itself, though these would clearly contribute to the global evolution in the $vev$ (see Eq. 13 below). It is not difficult to see that, in this case, we may approximate the potential with the simpler expression

$$V(\phi) \approx \frac{1}{2} m^2 (\phi - v)^2 ,$$  

(11)

which then gives

$$V'(\phi) \approx m^2 (\phi - v) .$$  

(12)

We suppose that gradients in the $vev$ (within regions where previously disconnected vacua come into causal contact) would manifest themselves via a time-dependent $v$, but always follow the field near the minimum of $V(\phi)$, as described above. In that case, $\dot{\phi} \sim \dot{v}$, and Equation (9) simplifies to

$$\ddot{v} + 3H \dot{v} + m^2 kv \approx 0 ,$$  

(13)

where we take $k$ to be a constant of order $\lesssim 1$.

In the standard model, $H(t)$ averaged over a Hubble time is remarkably close to $1/t$, an odd coincidence that no doubt points to some fundamental physics [51], though we do not need to explore that here. It does, however, allow us to simplify Equation (13) even further, so that

$$\ddot{v} + 3 \frac{v}{t} \dot{v} + m^2 kv \approx 0 ,$$  

(14)

which has the trivial solution $v(t) = v_{\text{init}}/t$, with $v_{\text{init}} \equiv 1/\sqrt{2k\lambda}$.

Suppose then that adjacent electroweak vacua had a $vev$ mismatch by a factor $n \lesssim 10$, consistent with our expectation from the anthropic principle discussed in § 2 above. At what time, $t_{\text{init}}$, would the homogenization process need to have started in order for us to see a uniform $v = 246$ GeV today? According to the simple solution to Equation (14),

$$t_{\text{init}} \sim \frac{1}{\sqrt{knm}} .$$  

(15)

Both $k$ and $n$ are of order 1, so $t_{\text{init}} \sim 0.008$ GeV$^{-1}$, which translates to a time $\sim 5 \times 10^{-23}$ seconds. But the EWPT must have occurred much later, at $t \sim 10^{-11}$ seconds, so the Higgs $vev$ probably could not have become homogenized across the observable Universe today.
5. Conclusion

No reliable evidence has ever been found of a breakdown in the physical properties of atomic and nuclear matter on cosmic scales (see, e.g., ref. [26]). Moreover, all of the structure we have seen throughout the visible Universe appears to be made of matter, not antimatter. So if the baryon asymmetry is due to the EWPT, as some have suggested via the introduction of additional Higgs fields, its uniformity affirms the measurement of a uniform Higgs $v_{ev}$ throughout our causally-connected spacetime.

But correspondingly, no viable solution to the electroweak horizon problem has been proposed either. Given the recent discovery of the Higgs boson, and its implied confirmation of the Higgs mechanism for generating inertia in the Standard Model, there is no question now that the culpability for any conflict between the EWPT and cosmology must be placed squarely upon the latter. It is becoming increasingly clear that the most likely resolution of this problem is to avoid it altogether, calling for a major overhaul of the physical basis for predicting the expansion history in $\Lambda$CDM [51].

Acknowledgments

I am very grateful to the anonymous referee for an excellent suggestion to improve the presentation in this manuscript.

References

[1] A. A. Starobinskii, Soviet Journal of Experimental and Theoretical Physics Letters, 30 (1979) 682.

[2] D. Kazanas, ApJ Lett, 241 (1980) L59.

[3] A. H. Guth, PRD 23 (1981) 347.

[4] A. Linde, PLB 108 (1982) 389.

[5] S. L. Glashow, Nucl Phys 22 (1961) 579.

[6] S. Weinberg, Phys Rev Lett 19 (1967) 1264.

[7] A. Salam. Proc 8-th Nobel Symp, ed. N. Svartholm (Almqmst and Wlk- sell, Stockholm, 1968) p 367.
[8] G. Aad et al. (ATLAS collaboration), PLB 716 (2012) 1.
[9] F. Englert & R. Brout, PRL 13 (1964) 321.
[10] P. Higgs, PRL 13 (1964) 508.
[11] J. M. Cline, Philos Trans A 376 (2018) 20170116.
[12] P. P. Fileviez & H. H. Patel, PRD 79 (2009) 055024.
[13] D. J. Weir, Phil. Trans. R. Soc. A 376 (2018) 20170126.
[14] C. Caprini et al., JCAP 04 (2016) 001.
[15] P. Amaro-Seoane, H. Audley et al., e-print 1702.00786 (2017).
[16] A. Noble & M. Perelstein, PRD 78 (2008) 063518.
[17] M. J. Dolan, C. Englert & M. Spannowsky, HEP 1210 (2012) 112.
[18] A. J. Barr, M. J. Dolan, C. Englert, D. E. Ferreira, D. E. Lima & M. Spannowsky, HEP 1502 (2015) 016.
[19] Y. B. Zel’dovic, I. Y. Kobzarev & L. B. Okun, Sov. Phys. JETP 40 (1975) 1.
[20] T.W.B. Kibble, J. Math. Phys. 9 (1976) 1387.
[21] A. Vilenkin & E.P.S. Shellard, “Cosmic Strings and other Topological Defects,” (1994) Cambridge: Cambridge University Press.
[22] A. Lazanu, C.J.A.P. Martins & E.P.S. Shellard, PLB 747 (2015) 426.
[23] L. Sousa & P. P. Avelino, PRD 92 (2015) 083520.
[24] G. Hinshaw, A. J. Branday, C. L. Bennett et al., ApJ Lett 464 (1996) L25.
[25] C. L. Bennett, R. S. Hill, G. Hinshaw et al., ApJ Sup 148 (2003) 97.
[26] Planck Collaboration VII, Y. Akrami et al., A&A 641 (2020) A7.
[27] B. Hensen et al., Nature 526 (2015) 682.
[28] M. Giustina et al., PRL 115 (2015) 250401.
[29] L. K. Shalm et al., PRL 115 (2015) 250402.
[30] J. F. Donoghue, K. Dutta, A. Ross & M. Tegmark, PRD 81 (2010) id.073003.
[31] V. Agrawal, S. M. Barr, J. F. Donoghue & D. Seckel, PRD 57 (1998) 5480.
[32] C. J. Hogan, Rev. Mod. Phys. 72 (2000) 1149.
[33] T. Damour & J. F. Donoghue, PRD 78 (2008) id.014014.
[34] F. Melia, Am. J. Phys. 86 (2018) 585.
[35] O. Bikwa, F. Melia & A.S.H. Shevchuk, MNRAS 421 (2012) 3356.
[36] F. Melia, JCAP 09 (2012) 029.
[37] F. Melia, CQG 30 (2013) 155007.
[38] T. M. Davis & C. H. Lineweaver, AIP Conference Proceedings 555 (2001) 348.
[39] L. Randall & S. Thomas, Nuc. Phys. B 449 (1995) 229.
[40] D. H. Lyth & E. D. Stewart, PRD 53 (1996) 1784.
[41] L. Randall, M. Soljacic & A. H. Guth, Nuc. Phys. B 472 (1996) 377.
[42] G. Germán, G. Ross & S. Sarkar, Nuc. Phys. B 608 (2001) 423.
[43] T. Boeckel & J. Schaffner-Bielich, PRL 105 (2010) 041301.
[44] H. Davoudiasl, D. Hooper & S. D. McDermott, PRL 116 (2016) 031303.
[45] G. Coughlan, W. Fischler, E. Kolb, S. Raby & G. Ross, PLB 131 (1983) 59.
[46] J. Ellis, D. V. Nanopoulos & M. Quiros, PLB 174 (1986) 176.
[47] B. de Carlos, J. A. Casas, F. Quevedo & E. Roulet, PLB 318 (1993) 447.
[48] T. Banks, D. Kaplan & A. Nelson, PRD 49 (1994) 779.

[49] S. Weinberg, PRL 40 (1978) 223.

[50] F. Wilczek, PRL 40 (1978) 279.

[51] F. Melia, The Cosmic Spacetime, Taylor & Francis, Oxford, 2020.