

Magnetic monopoles and high frequency gravitational waves from quasistable strings

Rinku Maji^{1,*} and Qaisar Shafi²

¹*Cosmology, Gravity and Astroparticle Physics Group, Center for Theoretical Physics of the Universe, Institute for Basic Science, Daejeon 34126, Republic of Korea*

²*Bartol Research Institute, Department of Physics and Astronomy, University of Delaware, Newark, Delaware 19716, USA*



(Received 6 March 2026; accepted 8 May 2026; published 11 June 2026)

The spontaneous breaking of $SO(10)$ via flipped $SU(5)$ to the Standard Model yields a novel scenario in which the superheavy topologically stable grand unified theory (GUT) monopole carrying a single unit ($2\pi/e$) of Dirac magnetic charge emerges from the merger of a confined but topologically distinct monopole-antimonopole pair that are pulled together by a string. The $SO(10)$ breaking via the subgroup $SU(4)_c \times SU(2)_L \times SU(2)_R$, following a similar reasoning, produces a topologically stable monopole that carries two units ($4\pi/e$) of Dirac charge. We explore the cosmological consequences of this scenario by assuming that the monopoles and strings experience a limited number of inflationary e -foldings, before reentering the horizon and ultimately forming a network of quasistable strings bounded by monopole-antimonopole pairs. We identify regions of the parameter space that yield an observable number density of the GUT monopole from the collapse of the appropriate string segments. The gravitational waves emitted by these quasistable cosmic strings lie in the Hz to kHz range, which can be tested in a number of proposed and ongoing experiments.

DOI: [10.1103/nz1z-xszk](https://doi.org/10.1103/nz1z-xszk)

Introduction. Dirac, nearly a century ago, postulated the existence of magnetic monopoles in order to explain electric charge quantization [1]. Spontaneously broken gauge theories with quantized electric charge predict the existence of topologically stable magnetic monopoles [2,3]. In the framework of grand unified theories such as $SU(5)$ [4] and $SO(10)$ [5,6], the minimal monopole is superheavy and carries a single unit ($2\pi/e$) of Dirac magnetic charge, as well as some color magnetic charge, which is screened [7–9]. Unified theories based on a gauge symmetry such as $SU(4)_c \times SU(2)_L \times SU(2)_R$ [10] predict the existence of a magnetic monopole that carries two units ($4\pi/e$) of Dirac charge as well as color magnetic charge [11,12]. The mass of this monopole can vary over a wide range, as discussed recently [13,14]. For a discussion on how topologically stable monopoles can arise from the decay of a metastable string network, see Ref. [13]. A discussion of how a superheavy monopole may survive primordial inflation can be found in Ref. [15]. For recent studies on metastable and superconducting strings in $SO(10)$ and E_6 , see Refs. [16–19]. High

frequency gravitational waves radiated from composite topological structures such as “walls bounded by strings” [20] along with an observable flux of grand unified theory (GUT) monopoles, have been discussed in Ref. [21]. For other related studies see Refs. [22–30]. For a discussion of the primordial monopole problem, see Refs. [31,32].

In Ref. [33] it was shown that in $SO(10)$, the GUT monopole can arise from the merger of an unrelated monopole-antimonopole pair, which get connected by a string carrying suitable magnetic flux. Our investigation is inspired by this observation and we propose to explore its consequences taking into account the inflationary scenario. We assume that the primordial monopoles experience a limited number of e -foldings and subsequently reenter the horizon. Quantum tunneling of monopole-antimonopole pairs on the strings is exponentially suppressed, but the strings, referred to as quasistable strings, eventually disappear because they end up connecting monopole-antimonopole pairs [34,35]. A subset of these structures yields the topologically stable GUT monopoles. The quasistable strings also emit gravitational waves in the Hz to kHz range. We identify regions of the parameter space that yield an observable number density of the GUT monopole as well gravitational waves that can be measured in a variety of experiments.

The detection of very high frequency gravitational waves (kHz to GHz) from quasistable strings with an observable number density of topologically stable magnetic monopoles,

*Contact author: rinkumaji9792@gmail.com

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

as discussed here, can provide a unique probe of $SO(10)$ symmetry breaking, namely via flipped $SU(5)$ or $SU(4)_c \times SU(2)_L \times SU(2)_R$ subgroups. A wide variety of detector concepts (see Ref. [36] and the references therein) aim to probe such a very high frequency regime of the gravitational wave spectrum. However, the proposed detector sensitivities still remain weaker [36] than the integrated bound inferred from big bang nucleosynthesis (BBN) and the CMB data [37–41]. A stronger sensitivity of resonant electromagnetic cavities has been proposed in Refs. [42,43].

Monopoles connected by strings in $SO(10)$ symmetry breakings. The $SO(10)$ breaking via flipped $SU(5)$ that we consider is as follows:

$$\begin{aligned} SO(10) &\rightarrow SU(5) \times U(1)_X \\ &\rightarrow SU(3)_c \times SU(2)_L \times U(1)_Z \times U(1)_X \\ &\rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y. \end{aligned} \quad (1)$$

We normalize the $U(1)$ generators, following Ref. [44], such that they have the minimal integer charges compatible with a period of 2π . For example, we use the decompositions

$$\begin{aligned} SO(10) &\rightarrow SU(5) \times U(1)_X: 16 = 10(-1) + \bar{5}(3) + 1(-5); \\ SU(5) &\rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y: \\ 10 &= (3, 2)(1) + (\bar{3}, 1)(-4) + (1, 1)(6), \\ \bar{5} &= (\bar{3}, 1)(2) + (1, 2)(-3). \end{aligned} \quad (2)$$

The first breaking produces “green” monopoles that carry $U(1)_X$ and $SU(5)$ fluxes. The second breaking produces “pink” monopoles carrying $U(1)_Z$ as well as $SU(2)_L$ and $SU(3)_c$ fluxes. A minimally charged “green” monopole carries the flux associated with $-\frac{X+Z}{5}$, and a “pink” monopole has fluxes associated with $\frac{Z}{6} + \frac{1}{2}T_L^3 + \frac{1}{3}T_c^8$. Here $T_c^8 = \text{diag}(1, 1, -2)$ is a diagonal generator of $SU(3)_c$, and $T_L^3 = \text{diag}(1, -1)$ is the diagonal generator of $SU(2)_L$. Following the last breaking of Eq. (1), the unbroken and broken generators are given by [18,33]

$$Y = -\frac{Z + 6X}{5}, \quad \tilde{Y} = \frac{-4Z + X}{5}. \quad (3)$$

Note that the Z_5 subgroups of $U(1)_Y$ and $U(1)_{\tilde{Y}}$ coincide. The breaking $U(1)_X \times U(1)_Z \rightarrow U(1)_Y$ produces a $U(1)_{\tilde{Y}}Z_5$ flux tube that connects a pink and a green monopole, as shown in Fig. 1, as well as monopoles to their respective antimonopoles. Also note that $Y + \tilde{Y} = -(X + Z)$ and $Z/6 = -(Y + 6\tilde{Y})/30$. The merger of the green and pink monopoles produces the topologically stable monopole. The broken generator orthogonal to the electric charge generator $Q = Y/6 + T_L^3/2$ is given by [18]

$$B = T_L^3/2 - Y/10. \quad (4)$$

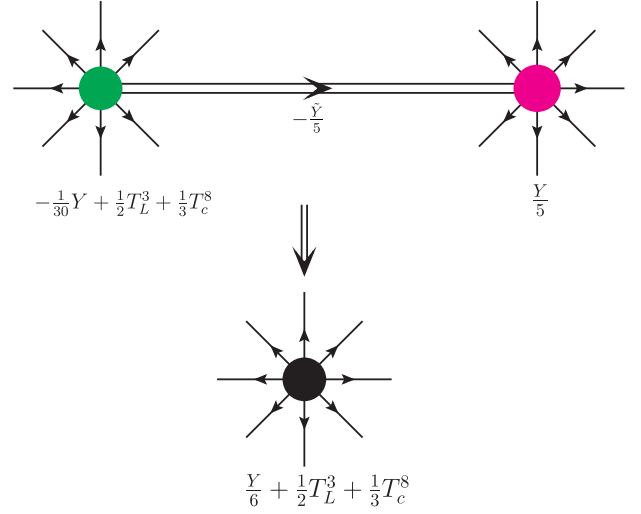


FIG. 1. Merger of $U(1)_X$ and $U(1)_Z$ monopoles before the electroweak symmetry breaking.

After electroweak symmetry breaking there are unconfined fluxes since $-Y/30 + T_L^3/2 = Q/4 + 3B/4$ as shown in Fig. 2. The GUT monopole after electroweak symmetry breaking carries a single unit ($2\pi/e$) of Dirac magnetic charge.

For completeness, following Ref. [12], we briefly summarize here the appearance of a topologically stable monopole carrying two units of Dirac magnetic charge from the following $SO(10)$ breaking:

$$\begin{aligned} SO(10) &\rightarrow SU(4)_c \times SU(2)_L \times SU(2)_R \\ &\rightarrow SU(3)_c \times SU(2)_L \times U(1)_{B-L} \times U(1)_R \\ &\rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y. \end{aligned} \quad (5)$$

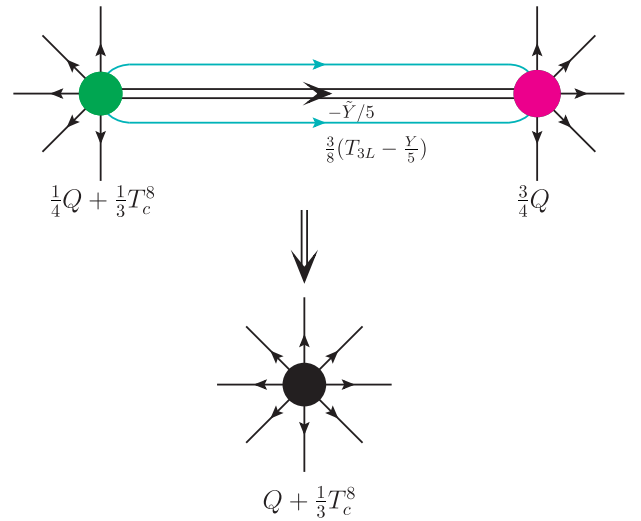


FIG. 2. Emergence of $SO(10)$ GUT monopole with magnetic charge $2\pi/e$ from the merger of a $U(1)_X$ monopole and a $U(1)_Z$ antimonopole following the electroweak symmetry breaking.

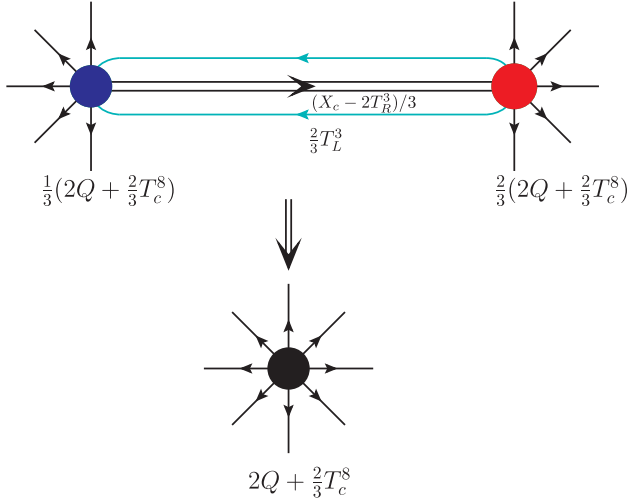


FIG. 3. Emergence of monopole of charge $4\pi/e$ from the merger of confined $U(1)_R$ and $U(1)_{B-L}$ monopoles following the electroweak symmetry breaking.

The second breaking produces a “blue” monopole carrying T_R^3 flux, and a “red” monopole with flux associated with $X_c = (B - L) + \frac{2}{3}T_c^8$. During the third breaking a flux tube associated with a $2\pi/3$ rotation around the broken generator $(B - L) - 2T_R^3$, orthogonal to Y , connects these two monopoles as shown in Fig. 3. Of course, the monopoles can also merge with their respective antimonopoles.

We discuss the simplest symmetry breaking patterns that produce the composite topological structures, namely monopole-antimonopoles connected by strings. The mergers of topologically distinct monopole-antimonopole pairs for the breaking patterns via flipped $SU(5)$ and $SU(4)_c \times SU(2)_L \times SU(2)_R$ produce topologically stable magnetic monopoles carrying a single unit and two units of Dirac magnetic charge, respectively. As given in the examples, the symmetry breaking pattern in Eq. (1) is realized as the component $(1, 0)$ and then $(24, 0)$ in a 45 dimensional Higgs acquires nonzero vacuum expectation values (VEVs). On the other hand, the VEVs $(1, 1, 1)$ followed by $(15, 1, 3)$ from a 210 representation can realize the symmetry breaking pattern in Eq. (5). In both cases, a VEV for the neutrino-like component in the 16 dimensional scalar breaks the diagonal generator orthogonal to the Standard Model (SM) hypercharge Y . It is worth mentioning here that introducing a 126 dimensional scalar in place of 16 leaves a Z_2 lying in the center of $\text{Spin}(10)$ unbroken and leads to the formation of topologically stable cosmic strings [45]. For recent studies on the dependence of the intermediate symmetry breaking scale on the choice of scalar representations, masses of scalar states, and their phenomenological implications, see Refs. [46–50]. Note that the prediction of topological structures is independent of the supersymmetric or non-supersymmetric version of the GUTs. The unification scenarios may rely on the choice of Higgs representations (e.g., 45, 210, etc.), but this does not qualitatively alter the

cosmological imprints such as gravitational waves and flux of monopoles discussed in the next section.

Quasistable string and high frequency gravitational waves. The confined monopoles experience partial e -foldings during inflation and reenter the horizon at a time t_M . After horizon reentry there will be subhorizon monopoles connected by strings carrying unconfined fluxes. Therefore, they decay dominantly by radiating the massless gauge bosons and generate topologically stable magnetic monopoles. The comoving number density of these monopoles can be estimated as [21]

$$Y_M \simeq \frac{1}{V_h s(t_M)} \simeq 10^{-65} \frac{g_*(t_M)^{3/4}}{g_{*s}(t_M)} \left(\frac{\text{sec}}{t_M} \right)^{3/2}, \quad (6)$$

where $V_h = (2t_M)^3$ is the particle horizon volume during radiation domination. The upper bound on the flux of superheavy monopoles from the MACRO experiment [51] can be recast as $Y_M \lesssim 10^{-26}$ for monopole velocity $v_M \sim 10^{-3}$, which gives $t_M \gtrsim 10^{-26}$ sec. using Eq. (6).

Before the horizon reentry of the monopoles, the strings form a network of “stable” strings that we call a quasistable string. The string network experiences friction domination until time $t_F \sim t_{\text{Pl}}/(G\mu)^2$ [52,53], where t_{Pl} is the Planck time. If the horizon reentry time t_M of the monopoles is much later than the timescale of friction domination, the string network can enter the scaling regime at time t_s , which is typically two orders of magnitude higher than t_F [54–57]. The loops, formed after the domination of particle emission era $t_p \sim \frac{t_{\text{Pl}}}{\Gamma^2 (G\mu)^{5/2}}$ [58–60], can radiate gravitational waves.

The present day (t_0) frequency of the gravitational waves in a normal mode k , radiated at time $\tilde{t}$ from a loop formed at time t_i with an initial size αt_i , is expressed as

$$f = \frac{a(\tilde{t})}{a(t_0)} \frac{2k}{\alpha t_i - \Gamma G\mu(\tilde{t} - t_i)}, \quad k \in \mathbb{Z}^+, \quad (7)$$

where $a(t)$ denotes the scale factor, $\Gamma \simeq 50$, and $\alpha \simeq 0.1$ for a string network in the scaling regime [61,62]. The gravitational wave background is given by

$$\Omega_{\text{GW}}(f) = \sum_{k=1}^{\infty} \Omega_{\text{GW}}^{(k)}(f), \quad (8)$$

with

$$\Omega_{\text{GW}}^{(k)}(f) = \frac{1}{\rho_{c,0}} \int_{t_F}^{t_0} d\tilde{t} \left(\frac{a(\tilde{t})}{a(t_0)} \right)^5 \frac{\mathcal{F}C_{\text{eff}}(t_i)}{(\Gamma G\mu + \alpha)\alpha t_i^4} \left(\frac{a(t_i)}{a(\tilde{t})} \right)^3 \times \frac{\Gamma k^{-n}}{\zeta(n)} G\mu^2 \frac{2k}{f} \Theta(t_M - t_i) \Theta(t_i - \max[t_s, t_p]). \quad (9)$$

Here $n = 4/3$ assuming the gravitational wave emission is dominated by the bursts from the cusp [63], $\rho_{c,0}$ denotes the

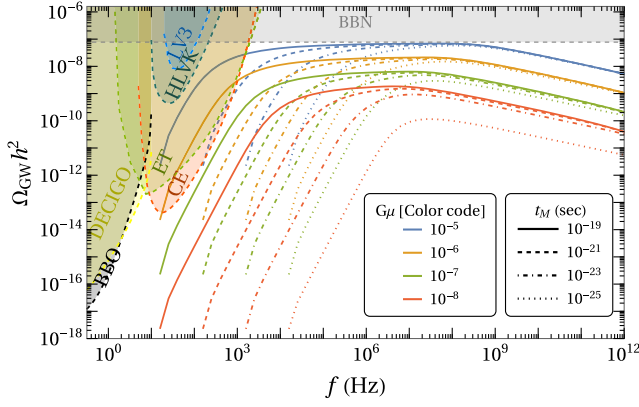


FIG. 4. Gravitational wave background from the quasistable string network for $G\mu = 10^{-8}$ – 10^{-5} with a varying monopole horizon reentry time $t_M = 10^{-25}$ – 10^{-19} sec, which can give rise to a comoving monopole number density $Y_M \sim 10^{-27} - 10^{-37}$. We have depicted the power-law integrated sensitivity curves [75,76] for planned experiments near the Hz to kHz frequency region, namely, HLVK [77], ET [72], CE [73], DECIGO [78], and BBO [79,80]. The gray shaded region shows the bound for a scale-invariant gravitational wave spectrum for $f_{\text{high}}/f_{\text{low}} = 10^7$ arising from the bound on ΔN_{eff} in the BBN and CMB data.

critical energy density of the universe at present, $\mathcal{F} \simeq 0.1$, and $C_{\text{eff}} = 5.7$ in the radiation dominated era [64–70].

At this stage, it is worth mentioning that the right-handed neutrinos achieve a Majorana mass $m_R \sim \mathcal{O}(v_s^2/\Lambda)$ (Λ represents the UV cutoff scale) from the dimension five operators $\mathcal{C}_W 16_F 16_H^\dagger 16_H^\dagger 16_F$ ($\mathcal{C}_W$ represents the Wilson coefficient), since the SM singlet in 16_H acquires a VEV v_s [47,71]. For $\Lambda \sim 10^{17}$ GeV and $\mathcal{C}_W \sim 1$, we have $v_s \gtrsim 10^{15}$ GeV in order to obtain the heaviest right-handed neutrino mass $m_R \gtrsim 10^{12}$ GeV. The associated string has a dimensionless tension $G\mu \simeq \frac{1}{8}(v_s/m_{\text{Pl}})^2 \gtrsim 10^{-8}$, where m_{Pl} is the reduced Planck mass.

In Fig. 4 we display the gravitational wave background for $G\mu = 10^{-8}$ – 10^{-5} with the monopoles horizon reentry time $t_M = 10^{-25}$ – 10^{-19} sec, which can give rise to a comoving monopole number density $Y_M \sim 10^{-27} - 10^{-37}$. The gravitational waves from GUT scale strings with $G\mu \sim 10^{-6}$ can be observed in the proposed experiments such as the Einstein Telescope (ET) [72] and Cosmic Explorer (CE) [73] for $t_M \gtrsim 10^{-20}$ sec, along with a comoving monopole number density $Y_M \lesssim 10^{-36}$. The gravitational wave background with the monopole horizon reentry time $t_M > 10^{-15}$ sec is ruled out by the third observing run data of LIGO and VIRGO [74].

The stochastic gravitational wave background from quasistable strings contributes to the effective number of relativistic degrees of freedom before BBN. The constraint on the gravitational wave spectra from BBN and CMB [37,81,82] can be expressed as [83],

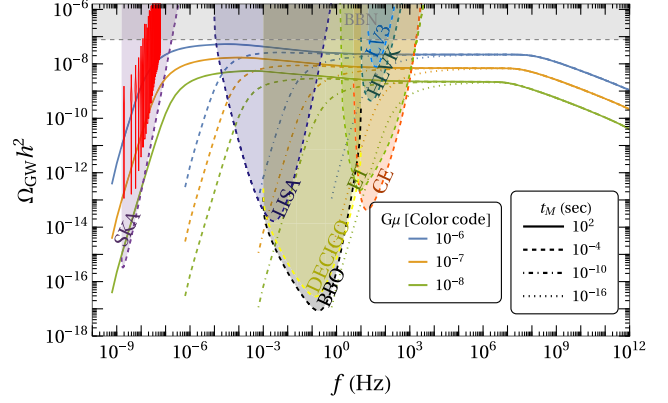


FIG. 5. Gravitational wave background from the quasistable string network for $G\mu = 10^{-8}$, 10^{-7} , and 10^{-6} with a varying monopole horizon reentry time $t_M = 10^{-16}$, 10^{-10} , 10^{-4} , and 10^2 sec. We also display the power-law integrated sensitivity curves [75,76] for proposed experiments, namely, HLVK [77], ET [72], CE [73], DECIGO [78], BBO [79,80], LISA [84,85], and SKA [86]. The gray shaded region shows the bound for a scale-invariant gravitational wave spectrum for $f_{\text{high}}/f_{\text{low}} = 10^7$ arising from the bound on ΔN_{eff} in the BBN and CMB data. The red violin plots represent the Bayesian free-spectral periodogram from the NANOGrav 15 year data [87,88].

$$\frac{\rho_{\text{GW}}}{\rho_c} = \int_{f_{\text{low}}}^{f_{\text{high}}} \Omega_{\text{GW}}(f) d \ln f \lesssim \Omega_{\gamma,0} \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} \Delta N_{\text{eff}}, \quad (10)$$

where the present day relic energy fraction in photons, $\Omega_{\gamma,0} h^2 \simeq 2.5 \times 10^{-5}$, and $\Delta N_{\text{eff}} \lesssim 0.22$ is the combined upper bound from BBN and CMB data [37–41]. The lower limit on the frequency f_{low} is dictated by the gravitational radiation before BBN, whereas f_{high} is the highest frequency of the spectrum that could be taken as infinity without loss of the generality. Assuming a scale invariant spectrum $\Omega_{\text{GW}} = \Omega_0$ for $f_{\text{low}} \leq f \leq f_{\text{high}}$, we can express the BBN bound as $\Omega_0 h^2 \lesssim 5.6 \times 10^{-6} \Delta N_{\text{eff}} / \log(f_{\text{high}}/f_{\text{low}})$.

For completeness, we have depicted the gravitational wave spectra for $G\mu = 10^{-8}$, 10^{-7} , and 10^{-6} with the monopoles horizon reentry time $t_M = 10^{-16}$, 10^{-10} , 10^{-4} , and 10^2 sec in Fig. 5. We have adopted $Y_M \gtrsim 10^{-36}$ as a threshold for observability. For $t_M > 10^{-20}$ sec monopoles will be heavily diluted to be observed.

It is worth mentioning at this point that the quasistable strings can explain the evidence of a gravitational wave background in the recent NANOGrav 15 year data [87,88] for $G\mu \in [2 \times 10^{-8}, 7 \times 10^{-6}]$ and $t_M \in [2 \times 10^1, 1 \times 10^5]$ sec (95% Bayesian credible intervals) [48,89]. The gravitational waves for $G\mu = [10^{-8}, 10^{-7}]$ can be detected in all the proposed experiments depending on the horizon reentry time of the monopoles. The constraint from the third observing run data from LIGO and VIRGO experiments for $G\mu > 10^{-7}$ can be alleviated if the strings experience a certain number of e -foldings during inflation for high t_M

values. For example, $G\mu = 10^{-6}$ and $t_M = 10^{2.5}$ sec can explain the NANOGrav data and satisfy the LV3 bound for $t_s = 10^{-10}$ sec, as shown in Ref. [48].

Conclusions. We have explored a novel symmetry breaking pattern of $SO(10)$ via its subgroup flipped $SU(5)$, which yields the topologically stable GUT monopole with a minimal Dirac charge of $2\pi/e$ arising from the merger of a monopole with an unrelated antimonopole. The breaking of $SO(10)$ via the subgroup $SU(4)_c \times SU(2)_L \times SU(2)_R$ produces, on the other hand, an intermediate to superheavy scale monopole with a Dirac magnetic charge of $4\pi/e$, also from the merger of a topologically distinct pair of monopoles. In both cases, the strings responsible for these mergers form a quasistable string network and emit gravitational waves over a wide range of frequencies with a scale-invariant spectrum up to GHz frequencies. We explore the parameter space that simultaneously yields

observable gravitational waves and primordial magnetic monopoles. We also find that the IR tail of the gravitational waves emitted by the superheavy quasistable cosmic strings can lie in the Hz to kHz range, which can be tested in a number of proposed experiments such as the Einstein Telescope and Cosmic Explorer. In the case with heavily diluted primordial monopoles, the predicted gravitational wave spectrum can explain the recently reported evidence by the pulsar timing array experiments for a gravitational wave background in the nHz frequency range.

Acknowledgments. R. M. is funded by IBS under the Project No. IBS-R018-D3.

Data availability. The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

-
- [1] P. A. M. Dirac, Quantised singularities in the electromagnetic field, *Proc. R. Soc. A* **133**, 60 (1931).
 - [2] G. 't Hooft, Magnetic monopoles in unified gauge theories, *Nucl. Phys.* **B79**, 276 (1974).
 - [3] A. M. Polyakov, Particle spectrum in quantum field theory, *JETP Lett.* **20**, 194 (1974).
 - [4] H. Georgi and S. L. Glashow, Unity of all elementary particle forces, *Phys. Rev. Lett.* **32**, 438 (1974).
 - [5] H. Georgi, The state of the art—gauge theories, *AIP Conf. Proc.* **23**, 575 (1975).
 - [6] H. Fritzsch and P. Minkowski, Unified interactions of leptons and hadrons, *Ann. Phys. (N.Y.)* **93**, 193 (1975).
 - [7] M. Daniel, G. Lazarides, and Q. Shafi, $SU(5)$ monopoles, magnetic symmetry and confinement, *Nucl. Phys.* **B170**, 156 (1980).
 - [8] C. P. Dokos and T. N. Tomaras, Monopoles and dyons in the $SU(5)$ model, *Phys. Rev. D* **21**, 2940 (1980).
 - [9] G. Lazarides, Q. Shafi, and W. P. Trower, Consequences of a monopole with Dirac magnetic charge, *Phys. Rev. Lett.* **49**, 1756 (1982).
 - [10] J. C. Pati and A. Salam, Lepton number as the fourth color, *Phys. Rev. D* **10**, 275 (1974); **11**, 703(E) (1975).
 - [11] G. Lazarides, M. Magg, and Q. Shafi, Phase transitions and magnetic monopoles in $SO(10)$, *Phys. Lett. B* **97**, 87 (1980).
 - [12] G. Lazarides and Q. Shafi, Monopoles, strings, and necklaces in $SO(10)$ and E_6 , *J. High Energy Phys.* **10** (2019) 193.
 - [13] G. Lazarides, R. Maji, and Q. Shafi, Quantum tunneling in the early universe: Stable magnetic monopoles from metastable cosmic strings, *J. Cosmol. Astropart. Phys.* **05** (2024) 128.
 - [14] T. W. Kephart and Q. Shafi, Magnetic monopoles and exotic states in $SU(4)_c \times SU(2)_L \times SU(2)_R$, *Phys. Rev. D* **112**, 075013 (2025).
 - [15] A. Moursy and Q. Shafi, Primordial monopoles, black holes and gravitational waves, *J. Cosmol. Astropart. Phys.* **08** (2024) 064.
 - [16] A. Afzal, Q. Shafi, and A. Tiwari, Gravitational wave emission from metastable current-carrying strings in E_6 , *Phys. Lett. B* **850**, 138516 (2024).
 - [17] R. Maji, Q. Shafi, and A. Tiwari, Topological structures, dark matter and gravitational waves in E_6 , *J. High Energy Phys.* **08** (2024) 060.
 - [18] R. Maji and Q. Shafi, Superheavy metastable strings in $SO(10)$, *J. High Energy Phys.* **06** (2025) 217.
 - [19] R. Maji and Q. Shafi, Superconducting strings in E_6 , *Phys. Rev. D* **112**, L101903 (2025).
 - [20] T. W. B. Kibble, G. Lazarides, and Q. Shafi, Walls bounded by strings, *Phys. Rev. D* **26**, 435 (1982).
 - [21] R. Maji and Q. Shafi, C-parity, magnetic monopoles, and higher frequency gravitational waves, *Phys. Rev. D* **111**, 075027 (2025).
 - [22] W. Buchmuller, V. Domcke, H. Murayama, and K. Schmitz, Probing the scale of grand unification with gravitational waves, *Phys. Lett. B* **809**, 135764 (2020).
 - [23] W. Buchmuller, V. Domcke, and K. Schmitz, Stochastic gravitational-wave background from metastable cosmic strings, *J. Cosmol. Astropart. Phys.* **12** (2021) 006.
 - [24] D. I. Dunskey, A. Ghoshal, H. Murayama, Y. Sakakihara, and G. White, GUTs, hybrid topological defects, and gravitational waves, *Phys. Rev. D* **106**, 075030 (2022).
 - [25] G. Senjanović and M. Zantedeschi, Minimal Pati-Salam theory: From cosmic defects to gravitational waves and colliders, *Phys. Rev. D* **112**, 055018 (2025).
 - [26] I. Jeong, J. Kersten, S. Scopel, and L. Velasco-Sevilla, Gravitational wave signals in a promising realization of $SO(10)$ unification, *Phys. Rev. D* **113**, 075017 (2026).

- [27] A. Moursy and Q. Shafi, Waterfall phase in supersymmetric hybrid inflation, *J. High Energy Phys.* **01** (2026) 162.
- [28] D. Bandyopadhyay, D. Borah, N. Das, and R. Samanta, High-quality axion dark matter at gravitational wave interferometers, [arXiv:2509.14323](#).
- [29] Y. Bao, T. Boybeyi, V. Mandic, and L.-T. Wang, Searching stochastic gravitational wave background landscape across frequency bands, [arXiv:2511.19590](#).
- [30] L. Tranchedone, E. Carragher, E. Hardy, and N. K. van IJcken, Metastable cosmic strings are broken at the start, [arXiv:2601.04320](#).
- [31] Y. B. Zeldovich and M. Y. Khlopov, On the concentration of relic magnetic monopoles in the universe, *Phys. Lett.* **79B**, 239 (1978).
- [32] J. Preskill, Cosmological production of superheavy magnetic monopoles, *Phys. Rev. Lett.* **43**, 1365 (1979).
- [33] G. Lazarides, Q. Shafi, and A. Tiwari, Composite topological structures in $SO(10)$, *J. High Energy Phys.* **05** (2023) 119.
- [34] X. Martin and A. Vilenkin, Gravitational wave background from hybrid topological defects, *Phys. Rev. Lett.* **77**, 2879 (1996).
- [35] G. Lazarides, R. Maji, and Q. Shafi, Gravitational waves from quasi-stable strings, *J. Cosmol. Astropart. Phys.* **08** (2022) 042.
- [36] N. Aggarwal *et al.*, Challenges and opportunities of gravitational wave searches above 10 kHz, *Living Rev. Relativity* **28**, 10 (2025).
- [37] Planck Collaboration, Planck 2018 results. VI. Cosmological parameters, *Astron. Astrophys.* **641**, A6 (2020); **652**, C4 (E) (2021).
- [38] M. Escudero Abenza, Precision early universe thermodynamics made simple: N_{eff} and neutrino decoupling in the Standard Model and beyond, *J. Cosmol. Astropart. Phys.* **05** (2020) 048.
- [39] K. Akita and M. Yamaguchi, A precision calculation of relic neutrino decoupling, *J. Cosmol. Astropart. Phys.* **08** (2020) 012.
- [40] J. Froustey, C. Pitrou, and M. C. Volpe, Neutrino decoupling including flavour oscillations and primordial nucleosynthesis, *J. Cosmol. Astropart. Phys.* **12** (2020) 015.
- [41] J. J. Bennett, G. Buldgen, P. F. De Salas, M. Drewes, S. Gariazzo, S. Pastor, and Y. Y. Y. Wong, Towards a precision calculation of N_{eff} in the standard model II: Neutrino decoupling in the presence of flavour oscillations and finite-temperature QED, *J. Cosmol. Astropart. Phys.* **04** (2021) 073.
- [42] N. Herman, A. Füzfa, L. Lehoucq, and S. Clesse, Detecting planetary-mass primordial black holes with resonant electromagnetic gravitational-wave detectors, *Phys. Rev. D* **104**, 023524 (2021).
- [43] N. Herman, L. Lehoucq, and A. Füzfa, Electromagnetic antennas for the resonant detection of the stochastic gravitational wave background, *Phys. Rev. D* **108**, 124009 (2023).
- [44] R. Slansky, Group theory for unified model building, *Phys. Rep.* **79**, 1 (1981).
- [45] T. W. B. Kibble, G. Lazarides, and Q. Shafi, Strings in $SO(10)$, *Phys. Lett.* **113B**, 237 (1982).
- [46] J. Chakraborty, G. Lazarides, R. Maji, and Q. Shafi, Primordial monopoles and strings, inflation, and gravity waves, *J. High Energy Phys.* **02** (2021) 114.
- [47] A. Preda, G. Senjanovic, and M. Zantedeschi, $SO(10)$: A case for hadron colliders, *Phys. Lett. B* **838**, 137746 (2023).
- [48] R. Maji and Q. Shafi, Kinetic mixing, proton decay and gravitational waves in $SO(10)$, *J. High Energy Phys.* **10** (2024) 157.
- [49] A. Preda, G. Senjanović, and M. Zantedeschi, Minimal $SO(10)$ near the edge: The importance of being effective, *Phys. Rev. D* **111**, 015036 (2025).
- [50] A. Preda, G. Senjanović, and M. Zantedeschi, $SO(10)$ theory on the plateau: The importance of being renormalizable, [arXiv:2502.21180](#).
- [51] MACRO Collaboration, Final results of magnetic monopole searches with the MACRO experiment, *Eur. Phys. J. C* **25**, 511 (2002).
- [52] A. Vilenkin, Cosmic string dynamics with friction, *Phys. Rev. D* **43**, 1060 (1991).
- [53] J. Garriga and M. Sakellariadou, Effects of friction on cosmic strings, *Phys. Rev. D* **48**, 2502 (1993).
- [54] C. J. A. P. Martins and E. P. S. Shellard, String evolution with friction, *Phys. Rev. D* **53**, R575 (1996).
- [55] C. J. A. P. Martins and E. P. S. Shellard, Quantitative string evolution, *Phys. Rev. D* **54**, 2535 (1996).
- [56] C. J. A. P. Martins and E. P. S. Shellard, Extending the velocity dependent one scale string evolution model, *Phys. Rev. D* **65**, 043514 (2002).
- [57] Y. Gouttenoire, G. Servant, and P. Simakachorn, Beyond the standard models with cosmic strings, *J. Cosmol. Astropart. Phys.* **07** (2020) 032.
- [58] J. J. Blanco-Pillado and K. D. Olum, Form of cosmic string cusps, *Phys. Rev. D* **59**, 063508 (1999); **103**, 029902(E) (2021).
- [59] D. Matsunami, L. Pogosian, A. Saurabh, and T. Vachaspati, Decay of cosmic string loops due to particle radiation, *Phys. Rev. Lett.* **122**, 201301 (2019).
- [60] P. Auclair, D. A. Steer, and T. Vachaspati, Particle emission and gravitational radiation from cosmic strings: Observational constraints, *Phys. Rev. D* **101**, 083511 (2020).
- [61] T. Vachaspati and A. Vilenkin, Gravitational radiation from cosmic strings, *Phys. Rev. D* **31**, 3052 (1985).
- [62] A. Vilenkin and E. P. S. Shellard, *Cosmic Strings and Other Topological Defects* (Cambridge University Press, Cambridge, England, 2000).
- [63] T. Damour and A. Vilenkin, Gravitational wave bursts from cusps and kinks on cosmic strings, *Phys. Rev. D* **64**, 064008 (2001).
- [64] V. Vanchurin, K. D. Olum, and A. Vilenkin, Scaling of cosmic string loops, *Phys. Rev. D* **74**, 063527 (2006).
- [65] C. Ringeval, M. Sakellariadou, and F. Bouchet, Cosmological evolution of cosmic string loops, *J. Cosmol. Astropart. Phys.* **02** (2007) 023.
- [66] K. D. Olum and V. Vanchurin, Cosmic string loops in the expanding Universe, *Phys. Rev. D* **75**, 063521 (2007).
- [67] S. Olmez, V. Mandic, and X. Siemens, Gravitational-wave stochastic background from kinks and cusps on cosmic strings, *Phys. Rev. D* **81**, 104028 (2010).

- [68] J. J. Blanco-Pillado, K. D. Olum, and B. Shlaer, The number of cosmic string loops, *Phys. Rev. D* **89**, 023512 (2014).
- [69] J. J. Blanco-Pillado and K. D. Olum, Stochastic gravitational wave background from smoothed cosmic string loops, *Phys. Rev. D* **96**, 104046 (2017).
- [70] Y. Cui, M. Lewicki, D. E. Morrissey, and J. D. Wells, Probing the pre-BBN universe with gravitational waves from cosmic strings, *J. High Energy Phys.* **01** (2019) 081.
- [71] E. Witten, Neutrino masses in the minimal O(10) theory, *Phys. Lett.* **91B**, 81 (1980).
- [72] G. Mentasti and M. Peloso, ET sensitivity to the anisotropic stochastic gravitational wave background, *J. Cosmol. Astropart. Phys.* **03** (2021) 080.
- [73] T. Regimbau, M. Evans, N. Christensen, E. Katsavounidis, B. Sathyaprakash, and S. Vitale, Digging deeper: Observing primordial gravitational waves below the binary black hole produced stochastic background, *Phys. Rev. Lett.* **118**, 151105 (2017).
- [74] LIGO Scientific, Virgo, and KAGRA Collaboration, Constraints on cosmic strings using data from the third Advanced LIGO–Virgo observing run, *Phys. Rev. Lett.* **126**, 241102 (2021).
- [75] E. Thrane and J. D. Romano, Sensitivity curves for searches for gravitational-wave backgrounds, *Phys. Rev. D* **88**, 124032 (2013).
- [76] K. Schmitz, New sensitivity curves for gravitational-wave signals from cosmological phase transitions, *J. High Energy Phys.* **01** (2021) 097.
- [77] KAGRA, LIGO Scientific, and VIRGO Collaborations, Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA, *Living Rev. Relativity* **21**, 3 (2018).
- [78] S. Sato *et al.*, The status of DECIGO, *J. Phys. Conf. Ser.* **840**, 012010 (2017).
- [79] J. Crowder and N. J. Cornish, Beyond LISA: Exploring future gravitational wave missions, *Phys. Rev. D* **72**, 083005 (2005).
- [80] V. Corbin and N. J. Cornish, Detecting the cosmic gravitational wave background with the big bang observer, *Classical Quantum Gravity* **23**, 2435 (2006).
- [81] E. Aver, K. A. Olive, and E. D. Skillman, The effects of He I $\lambda 10830$ on helium abundance determinations, *J. Cosmol. Astropart. Phys.* **07** (2015) 011.
- [82] A. Peimbert, M. Peimbert, and V. Luridiana, The primordial helium abundance and the number of neutrino families, *Rev. Mex. Astron. Astrofis.* **52**, 419 (2016), https://www.astrosca.unam.mx/rmaa/RMxAA..52-2/PDF/RMxAA..52-2_apeimbert.pdf.
- [83] M. Maggiore, Gravitational wave experiments and early universe cosmology, *Phys. Rep.* **331**, 283 (2000).
- [84] N. Bartolo *et al.*, Science with the space-based interferometer LISA. IV: Probing inflation with gravitational waves, *J. Cosmol. Astropart. Phys.* **12** (2016) 026.
- [85] P. Amaro-Seoane *et al.*, Laser interferometer space antenna, [arXiv:1702.00786](https://arxiv.org/abs/1702.00786).
- [86] G. Janssen *et al.*, Gravitational wave astronomy with the SKA, *Proc. Sci. AASKA14* (2015) 037 [[arXiv:1501.00127](https://arxiv.org/abs/1501.00127)].
- [87] NANOGrav Collaboration, The NANOGrav 15 yr data set: Evidence for a gravitational-wave background, *Astrophys. J. Lett.* **951**, L8 (2023).
- [88] NANOGrav Collaboration, The NANOGrav 15 yr data set: Search for signals from new physics, *Astrophys. J. Lett.* **951**, L11 (2023).
- [89] G. Lazarides, R. Maji, and Q. Shafi, Superheavy quasistable strings and walls bounded by strings in the light of NANOGrav 15 year data, *Phys. Rev. D* **108**, 095041 (2023).