Gravitational Waves and Proton Decay: Complementary Windows into Grand Unified Theories

Stephen F. King,[1,§] Silvia Pascoli,[2,†] Jessica Turner,[3,2,‡] and Ye-Ling Zhou[1,*]
[1]*School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, United Kingdom*
[2]*Institute for Particle Physics Phenomenology, Department of Physics, Durham University, South Road, Durham DH1 3LE, United Kingdom*
[3]*Theoretical Physics Department, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510, USA*

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Proton decay is a smoking gun signature of grand unified theories (GUTs). Searches by Super-Kamiokande have resulted in stringent limits on the GUT symmetry-breaking scale. The large-scale multipurpose neutrino experiments DUNE, Hyper-Kamiokande, and JUNO will either discover proton decay or further push the symmetry-breaking scale above 10^{16} GeV. Another possible observational consequence of GUTs is the formation of a cosmic string network produced during the breaking of the GUT to the standard model gauge group. The evolution of such a string network in the expanding Universe produces a stochastic background of gravitational waves which will be tested by a number of gravitational wave detectors over a wide frequency range. We demonstrate the nontrivial complementarity between the observation of proton decay and gravitational waves produced from cosmic strings in determining SO(10) GUT-breaking chains. We show that such observations could exclude SO(10) breaking via flipped $\mathrm{SU}(5) \times \mathrm{U}(1)$ or standard SU(5), while breaking via a Pati-Salam intermediate symmetry, or standard $\mathrm{SU}(5) \times \mathrm{U}(1)$, may be favored if a large separation of energy scales associated with proton decay and cosmic strings is indicated. We note that recent results by the NANOGrav experiment have been interpreted as evidence for cosmic strings at a scale of $\sim 10^{14}$ GeV. This would strongly point toward the existence of GUTs, with SO(10) being the prime candidate. We show that the combination with already available constraints from proton decay allows us to identify preferred symmetry-breaking routes to the standard model.

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Introduction.—Grand unified theories (GUTs) combine the strong, weak, and electromagnetic forces of the standard model (SM) into a simple gauge group under which the fermions transform. In such a framework, a larger underlying gauge symmetry is broken to the SM gauge group, $G_{\mathrm{SM}} = \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$, either directly or via some symmetry-breaking pattern. Following the Pati-Salam [1] and SU(5) [2] proposals, many models have been considered. Of particular interest are the SO(10) GUTs [3], which predict neutrino masses and mixing and are based on a simple gauge group.

A well-known phenomenological prediction of GUTs is proton decay [4–10]. Super-Kamiokande has set stringent constraints on typical decay channels such as $p \to \pi^0 e^+$ and $K^+ \bar{\nu}$ with the proton lifetime exceeding 10^{34} yr [11,12]. There are even more exciting prospects during the current decade thanks to the upcoming large-scale neutrino experiments, namely, DUNE [13], Hyper-Kamiokande [14], and JUNO [15].

Another generic consequence of GUTs is the production of topological defects when the GUT undergoes spontaneous symmetry breaking (SSB) [16]. Some of these, such as monopoles, need to be inflated away in order not to overclose the Universe. However, cosmic strings associated with the breaking of a U(1) symmetry, which can be a gauged subgroup of the GUT [17], can remain until late times and have observational consequences. These cosmic strings (cs) are expected to produce gravitational waves (GWs) via the scaling of the string network [17–19]. These signals form a stochastic GW background (SGWB) today with an abundance proportional to the square of the U(1) SSB scale, Λ_{cs}. The observation of such events provides a unique probe of physics at remarkably high scales and has been recently considered in the context of leptogenesis [20] and GUTs [21].

In this Letter, we discuss the nontrivial complementarity between observing proton decay and GWs produced from cosmic strings in GUTs. In particular, we focus on the implications for determining possible SO(10) GUT-breaking chains. While searches for proton decay (pd) set a lower bound on the associate scale Λ_{pd} of new physics, the GW observations will place an upper bound on Λ_{cs}.

Moreover, we assume an inflationary epoch, at scale Λ_{inf}, to eliminate unwanted topological defects. We explore the role of experimental searches in determining these three scales: Λ_{cs}, Λ_{pd}, and Λ_{inf}.

In Sec. II, we compare the scale of proton decay and cosmic string formation for breaking chains of SO(10). The synergy between observation of proton decay and GWs is discussed quantitatively in all possible SO(10)-breaking chains in Sec. III. We summarize and discuss our results in Sec. IV.

Terrestrial and cosmic signatures of GUTs.—SO(10) is the minimal simple GUT which offers the possibility of cosmic string generation. Its breaking to the SM gauge group can proceed along one of the breaking chains shown in Fig. 1, with the additional option of removing intermediate steps. We use the following abbreviations for the symmetries at an intermediate scale:

$$
\begin{aligned}
G_{51} &= \mathrm{SU}(5) \times \mathrm{U}(1)_X, \qquad G_{51}^{\mathrm{flip}} = \mathrm{SU}(5)_{\mathrm{flip}} \times \mathrm{U}(1)_{\mathrm{flip}},\\
G_{3221} &= \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L},\\
G_{3211} &= \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_R \times \mathrm{U}(1)_{B-L},\\
G'_{3211} &= \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_X,\\
G_{421} &= \mathrm{SU}(4)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y,\\
G_{422} &= \mathrm{SU}(4)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R. \qquad (1)
\end{aligned}
$$

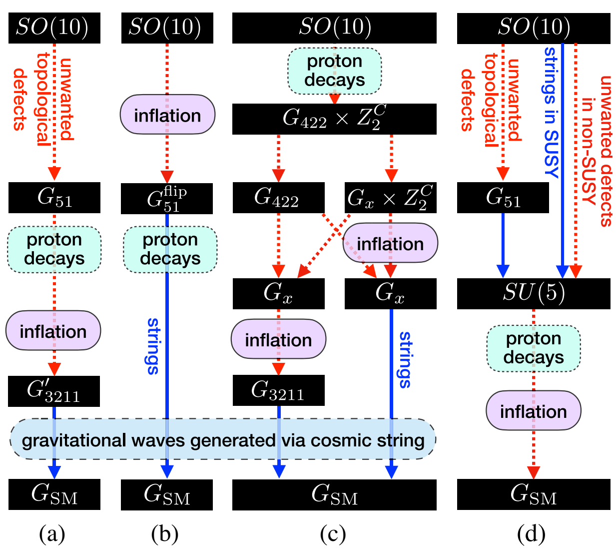


FIG. 1. The breaking chains of SO(10) to G_{SM} are shown along with their terrestrial and cosmological signatures, where G_x represents either G_{3221} or G_{421}. Defects with only cosmic strings (including cosmic strings generated from preserved discrete symmetries) are denoted as blue solid arrows. Those including unwanted topological defects (monopoles or domain walls) are indicated by red dotted arrows. The instability of embedded strings is not considered. Removing an intermediate symmetry may change the type of unwanted topological defect but will not eliminate them. The highest possible scale of inflation, which removes unwanted defects, is assumed in this diagram.

Note that G_{3211} and G'_{3211} are equivalent [22]. All possible SO(10) cases can be classified into four types denoted as (a)–(d) in Fig. 1. Types (a)–(c) are models broken via standard $\mathrm{SU}(5)\times\mathrm{U}(1)$, flipped $\mathrm{SU}(5)\times\mathrm{U}(1)$ [23–26], and Pati-Salam G_{422} [27], respectively. Cases with standard SU(5) [2] as the lowest intermediate symmetry are classified as type (d). The scales of proton decay Λ_{pd} and cosmic strings Λ_{cs} are important testable parameters discussed in the following.

Proton decay in SO(10).—As quarks and leptons are arranged in common multiplets in GUTs, heavy new states which mediate baryon-number-violating (BNV) interactions are introduced. At low energy scales, these heavy states are integrated out, and this induces higher-dimensional BNV operators which lead to proton decay.

In the main body of the text, we will focus on non-supersymmetric contributions, while discussions on additional sources provided by supersymmetric extensions will be discussed in Supplemental Material [28]. In summary, supersymmetry (SUSY) with R parity has similar phenomenological and cosmological consequences (see Fig. 1), with the addition of the $K^+\bar{\nu}$ proton decay channel.

At low energy, the most important operators which respect G_{SM} are the dimension-six ones arising from gauge contributions:

$$
\begin{aligned}
&\frac{\epsilon_{\alpha\beta}}{\Lambda_1^2}[(\overline{u_R^c}\gamma^\mu Q_\alpha)(\overline{d_R^c}\gamma_\mu L_\beta) + (\overline{u_R^c}\gamma^\mu Q_\alpha)(\overline{e_R^c}\gamma_\mu Q_\beta)]\\
&+\frac{\epsilon_{\alpha\beta}}{\Lambda_2^2}[(\overline{d_R^c}\gamma^\mu Q_\alpha)(\overline{u_R^c}\gamma_\mu L_\beta) + (\overline{d_R^c}\gamma^\mu Q_\alpha)(\overline{\nu_R^c}\gamma_\mu Q_\beta)], \qquad (2)
\end{aligned}
$$

where α and β denote $\mathrm{SU}(2)_L$ indices and Λ_1 and Λ_2 are the UV-complete scales of the GUT symmetry [4–8]. For types (a) and (d), Λ_1 and Λ_2 correspond to the SU(5)- and SO(10)-breaking scales, respectively, and thus $\Lambda_1 < \Lambda_2$. For type (b), $\Lambda_2 < \Lambda_1$, and $\Lambda_1 = \Lambda_2$ for type (c). In general, the lower of these two scales will mediate the dominant proton decay channel, and we indicate it as Λ_{pd}.

These operators induce a series of proton decay channels. The most stringently constrained is $p \to \pi^0 e^+$ as determined by Super-Kamiokande, $\tau_{\pi^0 e^+} > 1.6 \times 10^{34}$ yr (90% C.L., 100% branching ratio assumed) [12]. This bound translates to the lower limits of $\Lambda_1 > 6.7 \times 10^{15}$ GeV and $\Lambda_2 > 3.9 \times 10^{15}$ GeV, respectively, using $\tau_{\pi^0 e^+} \simeq 8 \times 10^{34}\ \mathrm{yr} \times (\Lambda_1/10^{16}\ \mathrm{GeV})^4$ [50] or $7 \times 10^{35}\ \mathrm{yr} \times (\Lambda_2/10^{16}\ \mathrm{GeV})^4$ [51], respectively. Hyper-Kamiokande offers at least an order of magnitude improvement [14], which will further push the lower bound of Λ_1 above 10^{16} GeV.

Gravitational waves from cosmic strings.—The cosmological consequence of SSB from the GUT to the SM gauge group is the formation of topological defects. These defects generically arise from the breaking of a group G to its subgroup H such that a manifold of equivalent vacua, $M \simeq G/H$, exists. Monopoles form when the manifold M

contains noncontractible two-dimensional spheres, cosmic strings when it contains noncontractible loops, and domain walls when M is disconnected. Different GUT-breaking chains result in different combinations of topological defects forming at various scales; these have been comprehensively categorized in Ref. [16], where it was shown that the vast majority of GUT-breaking chains produce cosmic strings. In Fig. 1, we summarize all possible symmetry-breaking chains and associated defects as derived in Sec. 4.2 of Ref. [16]. We note that embedded strings can be generated if a Z_2 symmetry is preserved [52]; however, we do not distinguish them from topological strings, and both scenarios are indicated by the blue lines in Fig. 1.

Cosmic strings are a source of GWs, as they actively perturb the metric at all times. If cosmic strings form after inflation, they exhibit a scaling behavior where the stochastic GW spectrum is relatively flat as a function of the frequency and the amplitude is proportional to the string tension μ. We refer to the string formation scale as $\sqrt{\mu} \equiv \Lambda_{cs}$ as, without fine-tuning, all gauge coefficients in GUTs are of the order of one. We note that this scale is identical to the symmetry-breaking scale up to an order-one coefficient. This scale, if it exists, is the lowest intermediate scale of SO(10) GUT breaking, as indicated in Fig. 1. The GWs are sourced when the cosmic strings intersect to form loops. Cusps on these strings emit strong beams of high-frequency GWs, or *bursts*, that constitute a SGWB if unresolved over time [53,54]. An inflationary period can suppress the SGWB in high frequencies [55]. However, it was recently shown that cosmic string network regrowth can occur to the extent that its associated GW signal is observable [56], contrary to what was naively expected. This string regrowth is contingent upon the initial number of cosmic strings per Hubble volume and the number of e-folds into inflation that the string formation occurs. A detailed discussion of these initial conditions and up-to-date sensitivities of the GW observatories on the string tension are provided in the aforementioned reference.

In Fig. 2, we show sensitivities of current and future GW experiments alongside the predicted SGWB for cosmic strings undiluted (solid curves) and diluted (dashed curves) by inflation. The U(1) symmetry-breaking scale $\Lambda_{cs} = 10^{10,11,\ldots,15}$ GeV corresponds to $G\mu \simeq 0.7 \times 10^{-18,-16,\ldots,-8}$, respectively, where G is Newton's constant. We provide formulations of SGWB in both the undiluted and diluted cosmic string scenarios in Supplemental Material [28], following Refs. [57,58] and [56], respectively. Furthermore, for a comprehensive review on cosmic strings, see Ref. [59] and references therein.

Applying these standard assumptions, a large range of Λ_{cs} can be explored using GW detectors. LIGO O2 [60] has excluded cosmic string formation at $\Lambda_{cs} \sim 10^{15}$ GeV in the high-frequency regime 10–100 Hz, while in the low-frequency band, 1–10 nHz, the null result of European

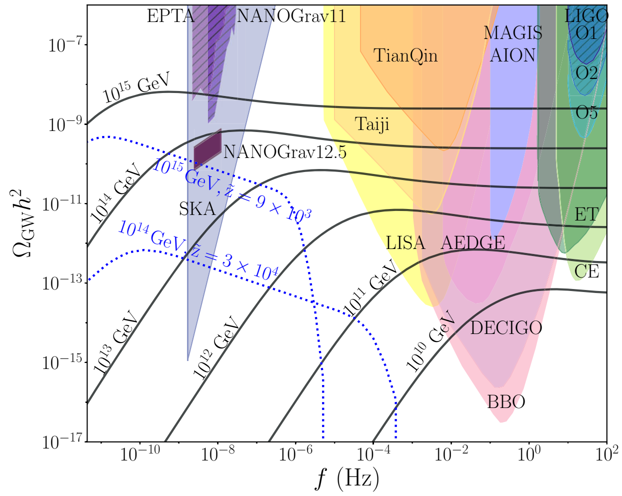


FIG. 2. SGWB predicted from undiluted (solid black lines) and diluted (dashed blue lines) cosmic string networks, where $\Lambda_{cs} = 10^{10,11,\ldots,15}$ GeV are input. $\tilde{z}$ denotes the redshift when strings return to the horizon, namely, $H(\tilde{z})L(\tilde{z}) = 1$. Current (hatched) and future (colored) experimental limits are shown as a comparison.

Pulsar Timing Array [61] and NANOGrav 11-yr data [62] constrains the upper bound of Λ_{cs} below 10^{15} and 10^{14} GeV, respectively. (These constraints could be relaxed due to the choice of prior as recently pointed out in Ref. [63].) Planned pulsar timing arrays Square Kilometre Array [64], space-based laser interferometers LISA [65], Taiji [66], TianQin [67], Big Bang Observer [68], and DECi-hertz Interferometer Gravitational wave Observatory [69], ground-based interferometers Einstein Telescope [70] and Cosmic Explorer [71], and atomic interferometers MAGIS [72], AEDGE [73], and Atom Interferometer Observatory and Network [74] will probe Λ_{cs} values in a wide regime 10^{10-14} GeV. As the spectrum of GWs produced via diluted cosmic strings decreases rapidly for $f > 10^{-6}$ Hz, this allows them to be distinguished from the undiluted cosmic strings as shown in Fig. 2.

Unwanted topological defects are generated in all SO(10)-breaking chains, as indicated in Fig. 1, and inflation is a promising means to remove them. Consistent hybrid inflation models have been achieved via GUT breaking [75,76]. The shape and magnitude of the inflaton potential are imprinted in the primordial density perturbations which are characterized by the spectral index and the tensor-to-scalar ratio in cosmic microwave background (CMB) measurements, from which the upper limit on inflation is $\Lambda_{inf} < 1.6 \times 10^{16}$ GeV (95% C.L., Planck) [77]. Future CMB measurements can improve the tensor-to-scalar ratio upper limit to 0.001 (95% C.L., CMB-S4) [78], corresponding to $\Lambda_{inf} < 5.7 \times 10^{15}$ GeV.

Synergy between proton decay and GW measurements.—Planned future proton decay searches will either put a more stringent lower bound on Λ_{pd} or, in the presence of a signal, provide further insight into the GUT symmetry structure. Because of the relatively model-independent nature of the operators shown in Eq. (2), the following experimental results are of particular interest: (i) Proton decay is observed in the $\pi^0 e^+$ channel. This provides an explicit link between $\Lambda_{\rm pd}$ and $\tau_{\pi^0 e^+}$. (ii) Proton decay is observed in the $K^+\bar{\nu}$ channel. This case provides a weaker connection to $\Lambda_{\rm pd}$ due to the involvement of the unknown SUSY-breaking scale.

The observation of GWs from cosmic strings is crucially dependent on the scale of inflation. We consider two possibilities: (i) the case of string formation after inflation, namely, $\Lambda_{\rm cs} < \Lambda_{\rm inf}$, for which a SGWB is generated from undiluted strings; and (ii) the case of GWs from diluted cosmic strings, if $\Lambda_{\rm cs} \sim \Lambda_{\rm inf}$. The case $\Lambda_{\rm cs} > \Lambda_{\rm inf}$ will not be considered, as there are no associated cosmological signatures of GUTs.

From the synergy of experimental data discussed in Sec. II ($\Lambda_{\rm pd} \gtrsim 10^{15}$ GeV, $\Lambda_{\rm inf} < 10^{16}$ GeV, and $\Lambda_{\rm cs} < 10^{14}$ GeV), certain orderings of scales are already excluded such as $\Lambda_{\rm inf} > \Lambda_{\rm cs} \sim \Lambda_{\rm pd}$ and $\Lambda_{\rm inf} \gtrsim \Lambda_{\rm cs} > \Lambda_{\rm pd}$. [The latter is not predicted in SO(10) but in enlarged symmetries such as E_6 [16].] We first discuss the various scales for the type (a) chain and then examine the remaining breaking chains.

Type (a) is characterized by $\Lambda_{\rm pd} > \Lambda_{\rm cs}$. The main source of proton decay is provided by Λ_1-suppressed operators in Eq. (2) [4,5]. A cosmic string network is produced at $\Lambda_{\rm cs}$. However, the observational signal of associated GWs depends on $\Lambda_{\rm inf}$ as follows.

As discussed, inflation must be introduced to remove unwanted defects produced in the first and second steps of the breaking. To achieve this, the inflationary scale $\Lambda_{\rm inf}$ should not be higher that the second-step breaking scale $\Lambda_{\rm pd}$. Therefore, there are three possible orderings of the relevant scales. (i) $\Lambda_{\rm pd} \gtrsim \Lambda_{\rm inf} > \Lambda_{\rm cs}$; proton decay may be observed in conjunction with an undiluted GW signal, which is an ideal possibility from the experimental perspective. (ii) $\Lambda_{\rm pd} > \Lambda_{\rm inf} \sim \Lambda_{\rm cs}$; proton decay may be observed in combination with a diluted GW signal. (iii) $\Lambda_{\rm pd} > \Lambda_{\rm cs} > \Lambda_{\rm inf}$; proton decay could be observed, but no associated GW signal is detected.

Type (b) is associated with flipped $\mathrm{SU}(5) \times \mathrm{U}(1)$, and proton decay proceeds dominantly via the pion channel. Similarly to (a), string formation occurs in the final breaking step. This case is characterized by $\Lambda_{\rm pd} \sim \Lambda_{\rm cs}$. Given the current limits on proton decay and GWs (which imply $\Lambda_{\rm pd} \gtrsim 10^{15}$ GeV and $\Lambda_{\rm cs} \lesssim 10^{14}$ GeV for the undiluted cosmic string scenario), it may appear that $\Lambda_{\rm pd} \sim \Lambda_{\rm cs}$ is already excluded. However, as before, the observability of GWs depends on the scale of inflation $\Lambda_{\rm inf}$ as we now discuss.

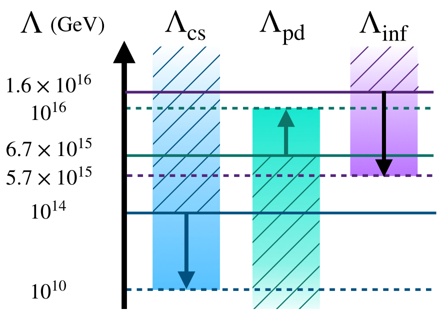
If the scale of inflation is high, then indeed the scale ordering $\Lambda_{\rm inf} > \Lambda_{\rm pd} \sim \Lambda_{\rm cs}$ can already be excluded. However, $\Lambda_{\rm inf} \sim \Lambda_{\rm pd} \sim \Lambda_{\rm cs}$ remains viable, as the SGWB produced from diluted strings is suppressed relative to the undiluted case. Given the sensitivities, this ordering can be tested in the next-generation experiments.

Type (c) represents a class of cases which have the common feature that proton decay is associated with the breaking of $\mathrm{SO}(10)$ to the Pati-Salam gauge group where cosmic strings are generated by the last step of breaking. Hence, $\Lambda_{\rm pd} > \Lambda_{\rm cs}$ as in type (a). As before, the observability of GWs depends on the scale of inflation $\Lambda_{\rm inf}$, to which we turn. The breaking of G_{422} results in the production of unwanted defects at each stage of SSB prior to the final breaking that produces the string network. Therefore, $\Lambda_{\rm inf}$ must occur below the breaking of G_{422}. Notwithstanding, the scale ordering of this class of models can be determined in a similar way to type (a).

To distinguish between types (a) and (c), further specification of the model is required. From this, predictions of nucleon decay branching ratios could be used to differentiate between the breaking chains (see, e.g., Ref. [79]). Furthermore, $\Lambda_{\rm pd}$ in type (c) chains can be significantly higher than 10^{16} GeV if there are threshold corrections from intermediate symmetries at a low scale, e.g., $10^{10\text{–}12}$ GeV [80,81]. Such low-scale SSB may be linked to the origin of neutrino masses and leptogenesis [82,83]. An observation of low-scale GWs may favor some specific breaking chains of this type.

Type (d) has the same SU(5) intermediate symmetry as type (a) and, therefore, similar predictions for proton decay as in type (a) but with $\Lambda_{\rm cs} > \Lambda_{\rm pd}$. However, the inflation scale must be lower than the proton decay scale $\Lambda_{\rm pd} > \Lambda_{\rm inf}$, since monopoles generated in the final step of symmetry breaking must be inflated away. Unfortunately, this also inflates away the cosmic strings. Hence, any associated GW detection via cosmic strings (diluted or undiluted) would exclude this class of breaking chains under our assumption that the GW signal is associated to the SO(10) breaking.

Our analysis is summarized in Fig. 3. In the right panel, we tabulate how observing proton decay via the pion channel in conjunction with GWs can be used to exclude or favor certain breaking chains and also provide information on the scale ordering. The consequences of null observations are not given in Fig. 3. In the event proton decay is not observed in the upcoming neutrino experiments, the limit on the UV-complete scale $\Lambda_{\rm pd}$ will be pushed even higher. On the other hand, future nonobservation of cosmic-string-induced GWs would suggest an inflationary era occurred after cosmic string formation. In addition, improved CMB measurements will allow a more stringent upper bound for $\Lambda_{\rm inf}$ to be placed, which will, in turn, be an upper bound for $\Lambda_{\rm cs}$ if cosmic strings are to be observed. This is schematically shown in the left panel in Fig. 3, where colored and hatched regions indicate current and future experimental limits, respectively, to probe these scales. For example, future experiments may constrain $\Lambda_{\rm pd} > \Lambda_{\rm inf}$. In SUSY $\mathrm{SO}(10)$, the same scale orderings between $\Lambda_{\rm pd}$ and $\Lambda_{\rm inf}$ can



Observables		Proton decays
		$p \to \pi^0 e^+$ observed ⇒ non-SUSY contribution indicated
GWs	Observed	• types (a) and (c) favoured • types (b) and (d) excluded
	Marginal	• types (a) and (c) favoured • type (d) excluded • type (b) allowed if $p \to K^+\bar{\nu}$ not observed and $\Lambda_{pd} \sim \Lambda_{cs}$

FIG. 3. GUTs constrained by observations of GWs and proton decays. Left: Current (hatched) and future (solid) exclusion limits of energy scales of cosmic string formation, proton decays, and inflation. $\Lambda_{pd} \sim \Lambda_1$ is approximated, and the exclusion limit of Λ_{cs} is shown in the undiluted case only. Right: Potential conclusions of GUT properties based on observations of GWs and proton decays in next-generation experiments.

be obtained, although a less precise value of Λ_{pd} can be inferred from an observation $p \to K^+\bar{\nu}$; see Supplemental Material [28].

Very recently, NANOGrav 12.5-yr data found strong evidence of SGWB with a power law spectrum in the frequency band 2.5–12 nHz [84], as shown in Fig. 2. It has been explained in the framework of string network scaling with $G\mu \sim (2 \times 10^{-11}, 2 \times 10^{-10})$ at 95% C.L. [85], corresponding to $\Lambda_{cs} \sim (0.5, 1.7) \times 10^{14}$ GeV. (Variations of string models such as small loops [86] and metastable strings [87] would point to an even higher string formation scale.) As we explained above, if confirmed, the combination with already available constraints from proton decay excludes the type (b) and type (d) breaking chains. Moreover, it does not support a large class of type (c) ones. As indicated in Refs. [80,81], type (c) with one or two intermediate scales predicts the lowest intermediate scale either below or marginally consistent with the NANOGrav lower bound 5×10^{13} GeV. Therefore, a preference for type (a) emerges, and future information from proton decay experiments would crucially allow one to further strengthen this conclusion.

Summary and conclusion.—We propose a strategy to use both proton decay and GWs as a means of identifying possible breaking chains of GUTs. We focus on SO(10) GUT models and categorize them according to their symmetry-breaking patterns as shown in Figs. 1(a)–1(d), corresponding to standard $SU(5) \times U(1)$, flipped $SU(5) \times U(1)$, Pati-Salam, and standard SU(5), respectively.

For each pattern of breaking, we compare the scale of proton decay, Λ_{pd}, with the cosmic string formation scale Λ_{cs}. These scales can have important testable consequences, as they are related to the proton lifetime and the generation of GWs via cosmic strings. The determination of these scales, in particular, their ordering, provides useful information in assessing the viability of a given class of breaking chains within SO(10) GUTs.

Our results are summarized in Fig. 3. In particular, such observations could exclude SO(10) breaking via flipped $SU(5) \times U(1)$ or standard SU(5), while breaking via a Pati-Salam intermediate symmetry, or standard $SU(5) \times U(1)$, may be favored if a large separation of energy scales associated with proton decay and cosmic strings is indicated.

We note that recent evidence of a stochastic background of gravitational waves by the NANOGrav experiment can be interpreted as due to cosmic strings at a scale of $\sim 10^{14}$ GeV. This result would strongly point toward the existence of GUTs, with SO(10) being the prime candidate. Our results show that the combination with already available information from proton decay can identify the symmetry-breaking pattern down to the standard model, with a strong preference for type (a) or a subset of type (c).

In conclusion, we have entered an exciting era where new observations of GWs from the heavens and proton decay experiments from under Earth can provide complementary windows to reveal the details of the unification of matter and forces at the highest energies.

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*Corresponding author.
ye-ling.zhou@soton.ac.uk
†silvia.pascoli@durham.ac.uk
‡jessica.turner@durham.ac.uk
§king@soton.ac.uk

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