Cosmological Implications of Unification: Topological Structures and Gravitational Waves

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Gravitational Waves and the Early Universe: Accelerated Expansion, Dynamical Inhomogeneity, and Beyond

Outline

1 *Introduction*

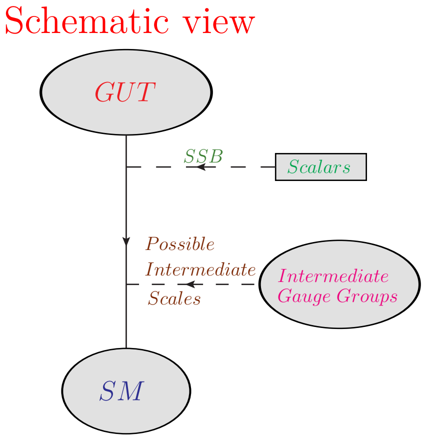
Standard Model $(SU(3)_C \otimes SU(2)_L \otimes U(1)_Y)$

		Fields	Quantum numbers
Spin-$\frac{1}{2}$	Quarks	$Q_g^{i\alpha} = \{ \begin{pmatrix} u^\alpha \\ d^\alpha \end{pmatrix}_L , \begin{pmatrix} c^\alpha \\ s^\alpha \end{pmatrix}_L , \begin{pmatrix} t^\alpha \\ b^\alpha \end{pmatrix}_L \}$	$(3, 2, \frac{1}{6})$
		$u^C_{\alpha\,L},\ c^C_{\alpha\,L},\ t^C_{\alpha\,L}$	$(\overline{3}, 1, -\frac{2}{3})$
		$d^C_{\alpha L},\ s^C_{\alpha L},\ b^C_{\alpha L}$	$(\overline{3}, 1, \frac{1}{3})$
	Leptons	$\ell_g^i = \{ \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \}$	$(1, 2, -\frac{1}{2})$
		$e^C_L,\ \mu^C_L,\ \tau^C_L$	$(1, 1, 1)$
Spin-1	$SU(3)_C$	G^a_μ	$(8, 1, 0)$
	$SU(2)_L$	W^a_μ	$(1, 3, 0)$
	$U(1)_Y$	B_μ	$(1, 1, 0)$
Spin-0	Higgs	$\Phi^i = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	$(1, 2, \frac{1}{2})$

Table: *Fields in the Standard Model.*

Grand Unification Beyond the SM

- The basic idea in a Grand Unified Theory (GUT) is that the SM, $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$, is embedded in a larger simple group, $\mathcal{G}$.



GUT Examples

- $SU(5)$ (rank $= 4$): $\bar{5} + 10 \Rightarrow$ SM fermions.

  Georgi, Glashow, PRL **32**, 438 (1974)

- $SO(10)$ (rank $= 5$): $16 \Rightarrow$ SM fermions $\oplus\ \nu_L^C$.

  Georgi, AIP Conf. Proc. (1975); Fritzsch, Minkowski, Ann. Phys. **93**, 93-266 (1975)

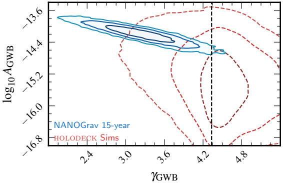
- $E(6)$ (rank $= 6$): $27 \Rightarrow$ SM fermions $\oplus\ \nu_L^C \oplus$

$$\underbrace{(2, \pm\frac{1}{2}, 1) + (1, -\frac{1}{3}, 3) + (1, \frac{1}{3}, \bar{3}) + (1, 0, 1)}_{\text{Exotic fermions}}.$$

  Gursey, Ramond, Sikivie, PLB **60** (1976) 177

  Shafi, PLB **79** (1978) 301

Evidence of GWB in PTA



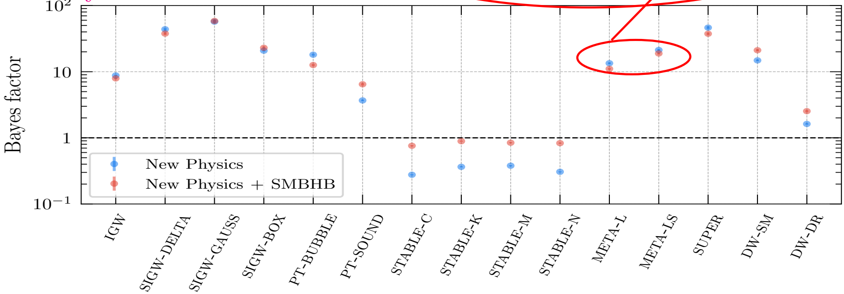
Mergers of SMBHBs?
2306.16213, 2306.16214, 2306.16215...

Cosmological Origin?

New Physics? NG15:2306.16219...

Buchmuller, Domcke, Schmitz (2307.04691);
Antusch, Hinze, Saad, Steiner (2307.04595);
Lazarides, **RM**, Moursy, Shafi (2308.07094);
Fu et. al. (2308.05799); **RM**, Park (2308.11439)
RM, Moursy, Shafi (2409.13584);
Hu, Kamada (2501.18380); ...

Superheavy metastable strings with $G\mu \sim 10^{-6}$ and $\sqrt{\kappa} \sim 8$.



2. *Monopoles Connected by Strings in SO(10) and Metastable Strings*

Monopoles connected by strings with no unconfined flux

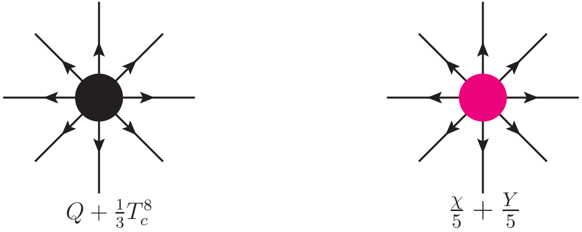
$$SO(10) \to SU(5) \times U(1)_\chi$$
$$\xrightarrow{v_{\rm GUT}} H = SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_\chi$$
$$\xrightarrow[\langle 16_H \rangle]{v_s} SU(3)_c \times SU(2)_L \times U(1)_Y \xrightarrow{v_{\rm EW}} SU(3)_c \times U(1)_{\rm em}$$

- We normalize the $U(1)$ generators such that they have the minimal integer charges compatible with a period of 2π.
- For example, we use the decompositions Slansky (1981)

$$SO(10) \to SU(5) \times U(1)_\chi : \ 16 = 10(-1) + \bar{5}(3) + 1(-5);$$
$$SU(5) \to SU(3)_c \times SU(2)_L \times U(1)_Y :$$
$$10 = (3,2)(1) + (\bar{3},1)(-4) + (1,1)(6), \ \bar{5} = (\bar{3},1)(2) + (1,2)(-3).$$

- During electroweak symmetry breaking:
  - Charge operator: $Q = T_L^3/2 + Y/6, \quad T_L^3 = diag(1,-1).$
  - Broken generator: $\mathcal{B} = T_L^3/2 - Y/10$

Monopoles in $SO(10) \to H$

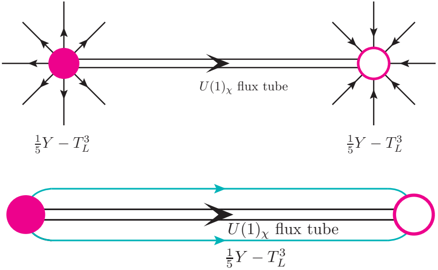


- Topologically stable superheavy GUT monopole arises from $SU(5)$ which contains the electric charge generator Q.
- $U(1)_\chi$ intersect with $SU(5) \supset SU(3)_c \times SU(2)_L \times U(1)_Y$ at its center Z_5, lying on $U(1)_Y$.
- Minimally charged χ monopole (would be confined) carries a flux $\frac{\chi}{5} + \frac{Y}{5}$.

RM, Shafi JHEP 06 (2025) 217

Monopole-antimonopole connected by a string

- The χ monopole-antimonopole pair is connected by a flux tube (string) following the breaking of $U(1)_\chi$, but the electroweak magnetic flux is still unconfined.



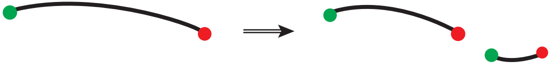
- Spontaneous breaking of the electroweak symmetry squeezes this flux because it corresponds to the broken generator orthogonal to the electric charge Q.
- This dumbbell configuration does not carry any unconfined flux.

RM, Shafi JHEP 06 (2025) 217

Metastable strings (MSS)

- Magnetic monopoles, created prior to the cosmic strings, experience inflation.

- Strings are topologically unstable: $\Gamma_d = \frac{\mu}{2\pi} \exp\left(-\pi m_M^2/\mu\right)$ with $\mu \sim \pi v_s^2$ and $m_M \sim (4\pi/g) v_{\rm GUT}$.



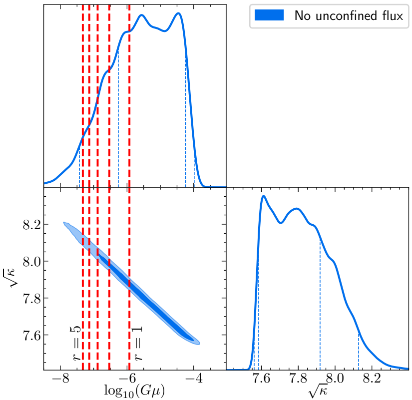
Witten (1985), Preskill, Vilenkin (1993)

- The lifetime of decay, $t_s = 1/\sqrt{\Gamma_d}$, of the strings via quantum mechanical tunneling is much smaller than the age of Universe $\Rightarrow$ Metastable.

- The strings are metastable if $v_s \sim v_{\rm GUT}$, i.e., they necessarily have to be superheavy in this case. **RM**, Shafi JHEP 06 (2025) 217

MSS and NANOGrav 15 year data

- The string tension ($\mu \simeq \pi v_s^2$) of the metastable strings get constraint from the proton lifetime bound.
- The proton lifetime ($p \to \pi^0 e^+$): $\tau_p \simeq 1.72 \times 10^{45} (G\mu)^2 r^4$ yrs. where the ratio $r = v_{\rm GUT}/v_s$.
- $\tau_p > 2.4 \times 10^{34}$ yrs from the Super-Kamiokande data (2021) can be recast as: $G\mu \gtrsim 10^{-6}/r^2$.



RM, Shafi, JHEP 06 (2025) 217

3 *GWB from Quasi-stable Strings and PTA Data*

Formation of quasi-stable strings

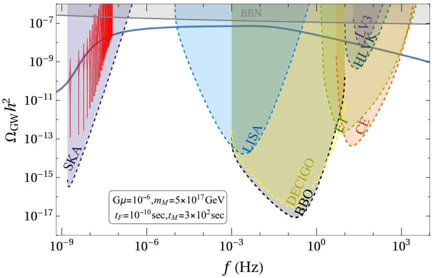
- Magnetic monopoles, created prior to the cosmic strings, experience "partial" inflation.
- The lifetime of decay of the strings via quantum mechanical tunneling is larger than the age of Universe.
- The strings make random walks with step of the order of the horizon, and form a network of stable strings before the horizon reentry of the monopoles.
- The strings inter-commute and form loops which decay into gravitational waves. $\boxed{f = \frac{1}{1+z(t)} \frac{2k}{l(t)},}$ $k \in Z^+$.
- As monopoles reenter the horizon at a cosmic time t_M, we obtain monopoles connected by string segments which eventually decay.

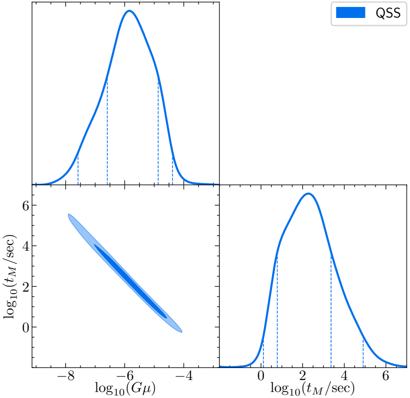
Lazarides, **RM**, Shafi, JCAP 08 (2022) 042

GWs from QSS and NANOGrav 15 year data

- Large string loops and segments ($> 2t_M$) are absent.
- Gravitational wave spectrum in the low frequency region $f \lesssim 1/t_M(1 + z(t_M/\Gamma G\mu))$ is suppressed.

Parameters	Bayesian Credible Intervals	
	68%	95%
$\log_{10}(G\mu)$	$[-6.59, -4.87]$	$[-7.58, -4.38]$
$\log_{10}(t_M/\text{sec})$	$[0.78, 3.36]$	$[0.12, 4.91]$





Lazarides, **RM**, Shafi, Phys. Rev. D **108** (2023) 095041

4 *Monopoles connected by strings with unconfined fluxes*

$SO(10)$ breaking via Pati-Salam

$$SO(10) \xrightarrow[M_U]{\langle 210 \rangle} SU(4)_c \times SU(2)_L \times SU(2)_R$$
$$\xrightarrow[M_U]{\langle (15,1,3) \in 210 \rangle} SU(3)_c \times U(1)_{B-L} \times SU(2)_L \times U(1)_R$$
$$\xrightarrow[M_R]{\langle (1,1,1,-\frac{1}{2}) \in 16 \rangle} SU(3)_c \times SU(2)_L \times U(1)_Y.$$

- Symmetry breaking $SU(4)_C \to SU(3)_C \times U(1)_{B-L}$ produces 'Red' monopoles with magnetic fluxes

$$X_c \equiv B - L + 2T_c^8/3 = diag(1, 1, -1, -1).$$

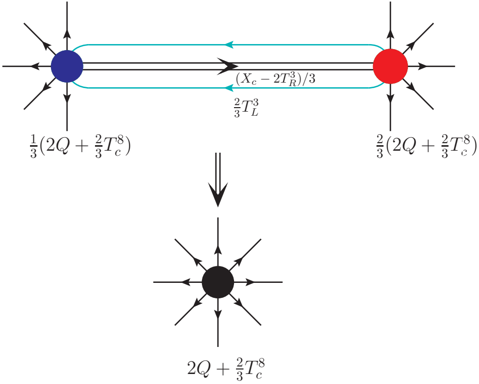
- $SU(2)_R \to U(1)_R$ generates 'Blue' monopoles with fluxes

$$T_R^3 = diag(1, -1).$$

Lazarides, Shafi, JHEP 10 (2019) 193

Strings connecting monopoles with unconfined fluxes

- $U(1)_R \times U(1)_{B-L} \rightarrow U(1)_Y$ generates topologically unstable strings.
- These strings connects
  1. a blue monopole to a red monopole.
  2. a monopole to its anti-monopole.
  3. ends on itself forming a loop.



- Red and blue monopoles combined to form stable Schwinger monopoles.

Lazarides, Shafi, JHEP 10 (2019) 193

Lazarides, **RM**, Shafi, JCAP 05 (2024)

$SO(10)$ breaking via flipped-$SU(5)$

$$SO(10) \to SU(5) \times U(1)_X \to SU(3)_c \times SU(2)_L \times U(1)_Z \times U(1)_X \\ \to SU(3)_c \times SU(2)_L \times U(1)_Y .$$

- Note the embeddings: $16 = 10(-1) + \bar{5}(3) + 1(-5)$; Slansky
  $10 = (3,2)(1) + (\bar{3},1)(-4) + (1,1)(6),\ \bar{5} = (\bar{3},1)(2) + (1,2)(-3)$.
- Symmetry breaking $SO(10) \to SU(5) \times U(1)_X$ produces 'Green' monopoles with magnetic fluxes $-\frac{X}{5} - \frac{Z}{5}$.
- $SU(5) \to SU(3)_c \times SU(2)_L \times U(1)_Z$ generates 'Pink' monopoles with fluxes associated with $\frac{Z}{6} + \frac{1}{2}T^3_L + \frac{1}{3}T^8_c$.
  Lazarides, Tiwari, Shafi, JHEP 05 (2023) 119; **RM**, Shafi JHEP 06 (2025) 217

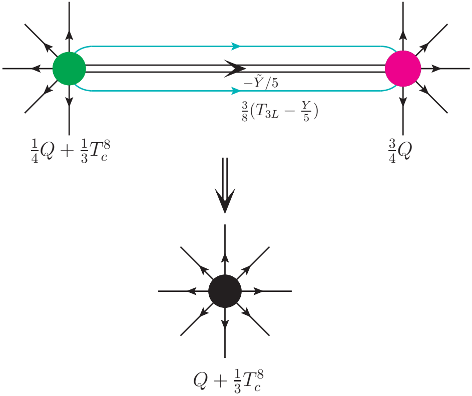
Strings connecting monopoles with unconfined fluxes

- $U(1)_X \times U(1)_Z \to U(1)_Y$ generates topologically unstable strings.

- The unbroken and broken generators are given by

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

- Green and Pink monopoles combine to form stable monopoles.



RM, Shafi, arxiv:2603.02996

5 *Magnetic monopoles and high frequency gravitational waves from quasi-stable strings*

Monopole number density

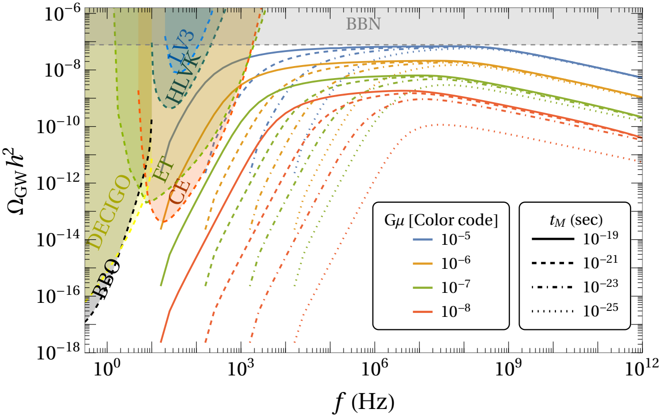
- The confined monopoles experience partial e-foldings during inflation and re-enter the horizon at a time t_M.
- Subhorizon monopoles connected by strings, carrying unconfined fluxes, decay dominantly by radiating the massless gauge bosons.
- Mergers generate topologically stable magnetic monopoles: $(4\pi/e)$ for Pati-Salam and $(2\pi/e)$ for flipped-$SU(5)$.
- Comoving number density of such monopoles:

$$Y_M \sim \frac{H(t_M)^3}{s(t_M)} \sim 10^{-65} \frac{g_*(t_M)^{3/4}}{g_{*s}(t_M)} \left(\frac{\text{sec}}{t_M}\right)^{3/2} .$$

- Upper bound on comoving monopole number density: $Y_M = n_M/s \lesssim 10^{-27}$.

  MACRO: EPJC 25 511, IceCube: PRL 128 (2022) 051101, ANTARES: JHEAp 34 (2022) 1, ...

GWs with a flux of monopoles



- GWs from QSS for $G\mu = 10^{-8} - 10^{-5}$ with monopole horizon re-entry time $t_M = 10^{-25} - 10^{-19}$ sec.
- Can give rise to a comoving monopole number density $Y_M \sim 10^{-27} - 10^{-37}$. **RM**, Shafi, arxiv:2603.02996

6 *Summary*

Summary

- $SO(10)$ GUTs predicts formation of strings which connects monopoles.

- Metastable strings in the breaking $SO(10) \to SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_\chi$ necessarily have to be superheavy and the string tension is related with the proton decay. **RM**, Shafi JHEP 06 (2025) 217

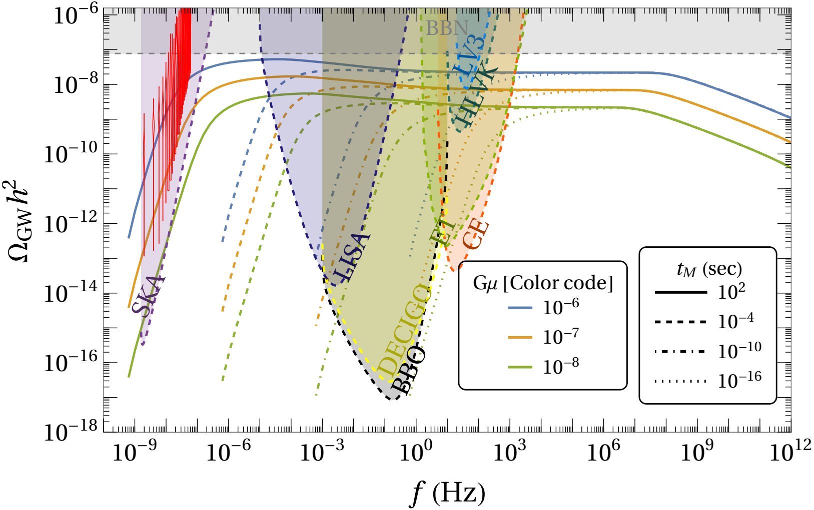
- The GWs from superheavy QSS and WBS with $G\mu \sim 10^{-6}$ can explain the evidence of GWs in recent PTA data.
  Lazarides, **RM**, Shafi, PRD (2023) 095041

- $SO(10)$ breakings can give rise to a **high frequency GWs** with an observable flux of topologically stable monopoles carrying Dirac magnetic charge of two units for breaking via Pati-Salam and that of single unit for flipped-$SU(5)$. Lazarides, **RM**, Shafi, JCAP 05 (2024); **RM**, Shafi, arxiv:2603.02996

Thank You

Back up slides

GWs with heavily diluted monopoles



RM, Shafi, arxiv:2603.02996

Prediction of topological defects

- Topological defects may appear during the SSB of a group $\mathcal{G}$ down to its subgroup $\mathcal{H}$.
- GUTs predict topologically stable magnetic monopole that carries one unit $(2\pi/e)$ of Dirac magnetic charge. 't Hooft 74; Polyakov 74
- SO(10) GUTs with scalars only in tensor reps. predict topologically stable strings. Kibble, Lazarides, Shafi PLB 1982
- $SO(10)$ predicts formation of composite structures depending on the symmetry breaking patterns to the SM.

Observational constraints from defects

- Stable domain walls contradict standard cosmology.

  Zeldovich, Kobzarev, Okun, Zh. Eksp. Teor. Fiz. **67**, 3-11 (1974)

- Upper bound on comoving monopole number density:
  $Y_M = n_M/s \gtrsim 10^{-27}$. MACRO: EPJC 25 511, IceCube: PRL 128 (2022) 051101, ANTARES: JHEAp 34 (2022) 1, ...

- CMB constraint on stable strings: $G\mu \lesssim 10^{-7}$.

  PhysRevD.93.123503, ...

- LIGO-VIRGO O3 data constraint on "undiluted" strings:
  $G\mu \lesssim 10^{-7}$ around decaHz frequencies. PhysRevLett.126.241102

- PTA experiments put a constraint on stable cosmic strings :
  $G\mu \lesssim 10^{-10}$ around the nanoHertz frequencies.

  arXiv:2306.16219,...

Cosmic string network

- String tension $\mu \simeq \pi v_s^2$, v_s is the VEV that form the string.

- Strings inter-commute, form loops, radiate GWs and the evolution of the network enters a 'scaling' regime.

- Scaling energy density $\rho_s \sim \mu/t^2$. Critical density: $\rho_c \sim 1/Gt^2$ in RD and MD.

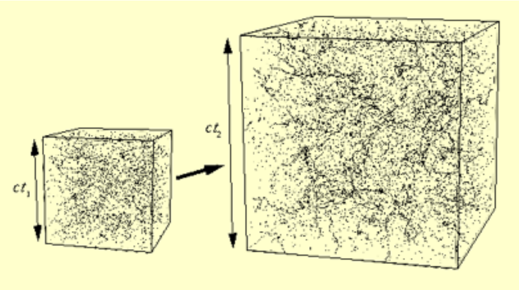
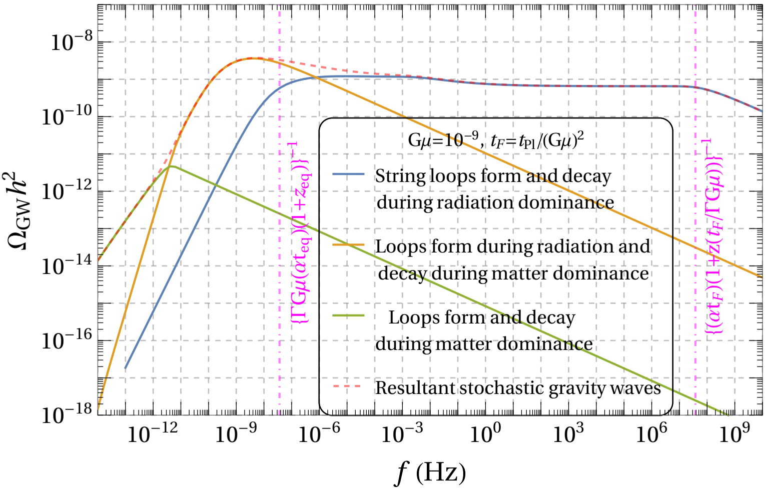


Image source: ctc.cam.ac.uk

Kibble, NPB 252 (1985) 227; Vachaspati, Vilenkin PRD 31 (1985) 3052; Bennett, Bouchet, PRL 60 (1988) 257 ...

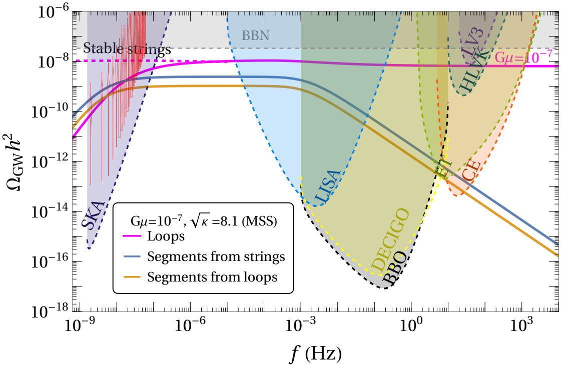
Stochastic gravitational wave background



Cusp and Kink

Metastable Strings and GWs

- String loops larger than αt_s are absent.
- The strings network disappear at a time $t_e \sim 1/\sqrt{\Gamma_d \Gamma G\mu}$.
- Gravitational wave spectrum in the low frequency region, $f \lesssim 1/\Gamma G\mu t_e(1+z_e)$, becomes suppressed.



Buchmuller, Domcke, Schmitz, JCAP **12** (2021) 006

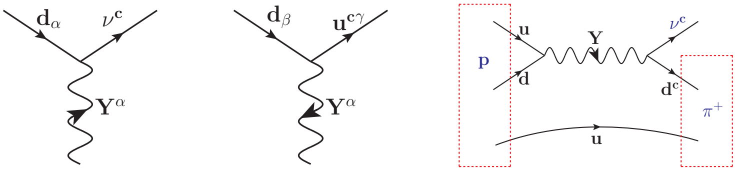
- If the strings are metastable $\sqrt{\kappa} \lesssim 9$, i.e., $v_s \sim v_M \equiv v_{GUT}$.

Prediction of GUTs: Proton Decay

- Mediation of lepto-quark gauge bosons⇒ proton decay into meson plus antilepton :

  $\boxed{p \to M + \bar{l}}$ $\quad M \in \{\pi^+, \pi^0, K^+, K^0, \eta\}$, $l \in \{e, \mu, \nu_{e,\mu,\tau}\}$.

- Example: With $Y^\alpha = (3, 1/3) \in (3, 2, 5/6)$



Lepto-quark vertex | Di-quark vertex | $\mathbf{p} \to \pi^+ \overline{\nu}$

- Selection rules : $\boxed{\Delta B = \Delta L = -1}$ and $\boxed{\Delta S = 0, 1}$.

Machacek, NPB **159** (1979) 37. Langacker, Phys. Rept. **72** (1981) 185.

Gravitational waves from quasi-stable strings

- The stochastic gravitational wave background receives contributions from the oscillating string loops before t_M:

$$\boxed{n_r(l, t < t_M) = \frac{0.18\ \Theta(0.1t - l)}{t^{3/2}(l + \Gamma G\mu t)^{5/2}}.}$$

Blanco-Pillado, Olum, Shlaer, Phys. Rev. D **89** (2014) 023512

- After t_M, the contributions mainly come
  1. from the decaying string loops formed before t_M:

$$\boxed{n_r(l, t > t_M) = \frac{0.18\ \Theta(0.1t_M - l - \Gamma G\mu(t - t_M))}{t^{3/2}(l + \Gamma G\mu t)^{5/2}}},$$

  2. from the oscillating $MS\bar{M}$ structures:

$$\boxed{\tilde{n}(z) = (2t_M)^{-3}\left(\frac{1+z}{1+z_M}\right)^3.}$$

Pulsar Timing Arrays

- Pulsars are rapidly spinning neutron stars with a strong magnetic field ⇒ Radiate beam of radio waves.
- Repeating pulses are observed as the radio beam intersects the observers periodically.
- Millisecond pulsar (MSP) produces exceedingly stable and regular pulse profile ⇒ "Perfect Clock".

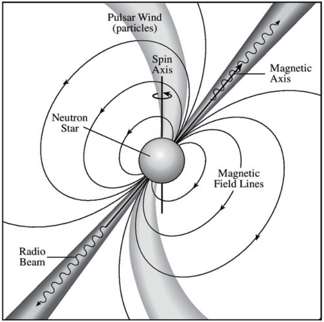
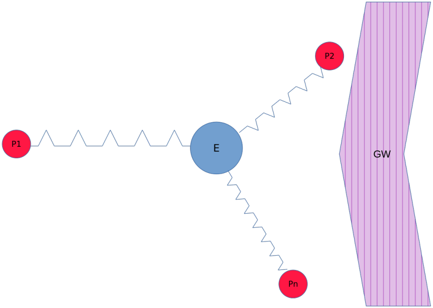


Image source: K.R. Lang, NASA's Cosmos

Pulsar Timing Arrays



- Measurement of the time of arrival (ToA) of pulses can reveal tiny distortion of spacetime fabric due to gravity waves (GWs) $\Rightarrow$ Pulsar timing!

Image source: Wikipedia

- Difference between observed ToA and the expected ToA from timing model gives time residual.
- Time residual contains information about other signals like GWs.

Pulsar Timing Arrays

- Impossible to distinguish between GWs signal and other source of signal in the timing residual of a single pulsar.
- Need correlations between the timing residuals of different pulsars $\Rightarrow$ Pulsar Timing Array (PTA).
- Gravity waves generate unique quadrupolar correlations between timing residuals of pulsar pairs.
- Correlations depend on the angular separations between the pulsar pairs and follow the Hellings and Downs correlation curve. **APJ. 265, L39 (1983)**

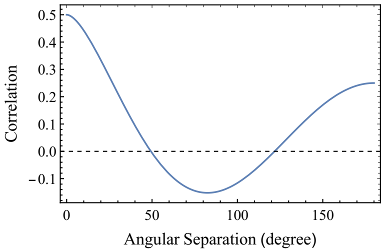
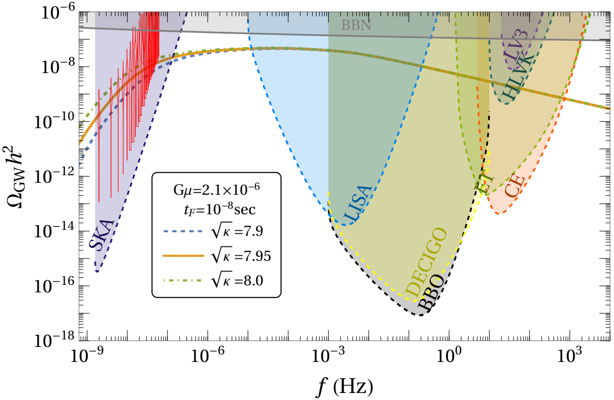


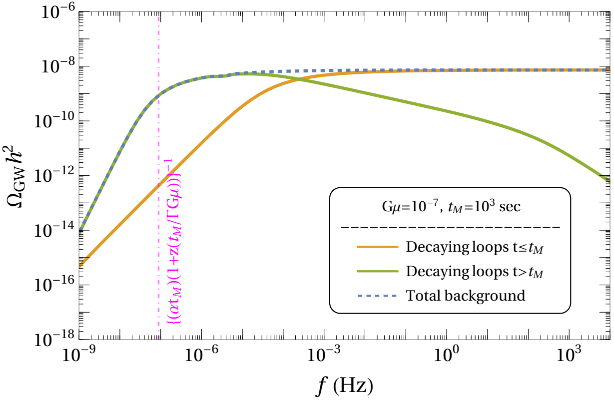
Figure: Hellings and Downs curve.

Metastable Strings: PTA and LIGO-VIRGO



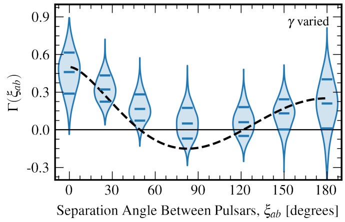
- The GWs from MSS explain PTA data at nanoHertz frequency, but violate the bound from LIGO-VIRGO third observing run!
- An early matter domination or partial inflation can reduce the spectra at high f.
  Lazarides, **RM**, Moursy, Shafi, JCAP 03 (2024) 006
  RM, Park, JCAP 01 (2024) 015

Gravitational waves from quasi-stable strings



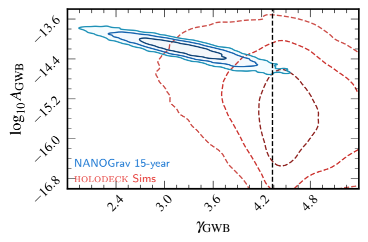
- Large string loops and segments ($> 2t_M$) are absent.
- Gravitational wave spectrum in the low frequency region $f \lesssim 1/t_M(1 + z(t_M/\Gamma G\mu))$ is suppressed.

Evidence of GWB in PTA

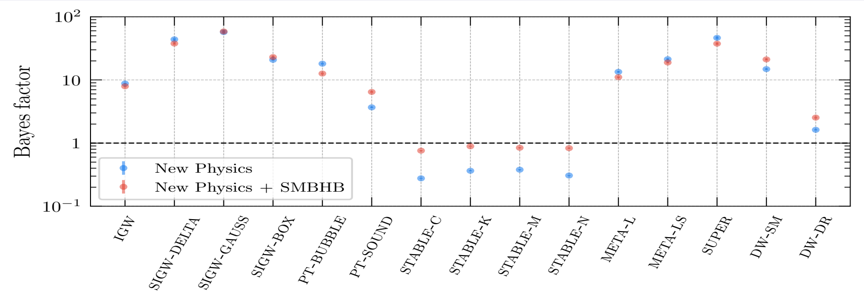


NG15:2306.16219,...

Mergers of SMBHBs?

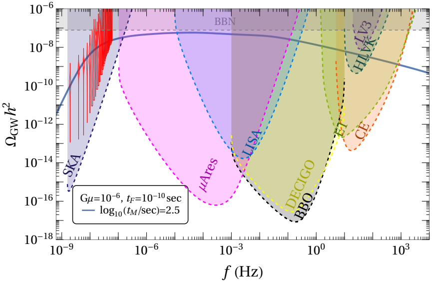


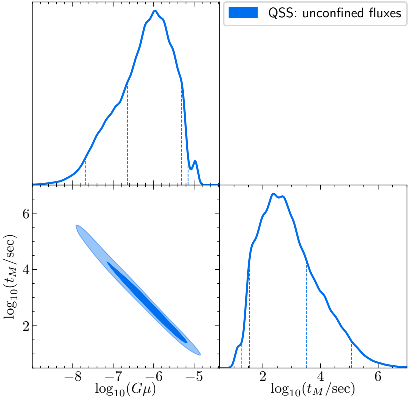
Cosmological Origin? New Physics?



Gravitational waves and NANOGrav 15 year data

Parameters	Bayesian Credible Intervals	
	68%	95%
$\log_{10}(G\mu)$	$[-6.65, -5.31]$	$[-7.68, -5.15]$
$\log_{10}(t_M/\mathrm{sec})$	$[1.53, 3.51]$	$[1.27, 5.08]$





RM, Shafi, JHEP 10 (2024) 157

Dim-5 operators and kinetic mixing of $U(1)_{B-L} \times U(1)_R$

- $F^p_{\mu\nu} = \partial_\mu A^p_\nu - \partial_\nu A^p_\mu$ $(p = X, R;\ X \equiv B - L)$ mixes as:

$$-\frac{1}{4} F^X_{\mu\nu} F^{X\mu\nu} - \frac{1}{4} F^R_{\mu\nu} F^{R\mu\nu} - \frac{\epsilon}{2} F^X_{\mu\nu} F^{R\mu\nu},$$

  ϵ is the mixing parameter. Holdom, PLB 166 (1986)

- Dim-5 operator suppressed by the cut-off scale Λ:

$$\frac{\mathcal{C}}{\Lambda} G^{a\mu\nu} \Phi_{ai} G^i_{\mu\nu}, \quad \Phi_{ai} \equiv (15, 1, 3) \in 210_H$$

  induces $\boxed{\epsilon \sim \mathcal{O}(M_U/\Lambda)}$ at the GUT scale as Φ_{ai} gets a VEV $\sim M_U$. **RM**, Shafi, JHEP 10 (2024) 157

- The canonical form is obtained through change of basis $A^p \to B^p$:

$$\begin{pmatrix} A^X_\mu \\ A^R_\mu \end{pmatrix} = \begin{pmatrix} 1 & \frac{-\epsilon}{\sqrt{1-\epsilon^2}} \\ 0 & \frac{1}{\sqrt{1-\epsilon^2}} \end{pmatrix} \begin{pmatrix} B^X_\mu \\ B^R_\mu \end{pmatrix}.$$

Abelian mixing and matching of gauge couplings

- In the covariant derivative part, the diagonal gauge coupling $diag[g_X, g_R] \to G$:

$$G = \begin{pmatrix} g_{XX} & g_{XR} \\ 0 & g_{RR} \end{pmatrix},$$

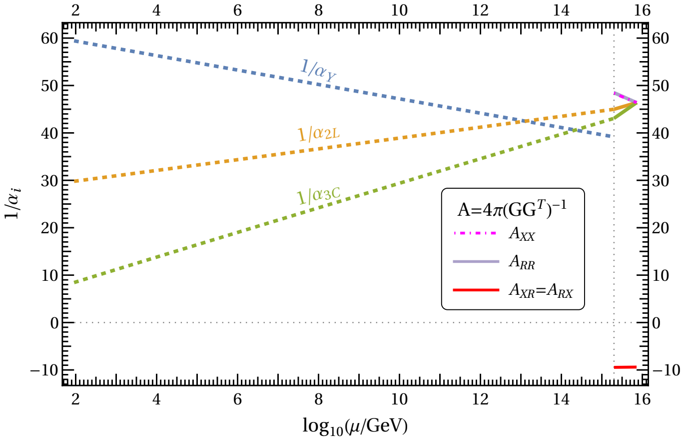
$$\text{with} \quad g_{XX} = g_X, \quad g_{XR} = -\frac{\epsilon g_X}{\sqrt{1-\epsilon^2}}, \quad g_{RR} = \frac{g_R}{\sqrt{1-\epsilon^2}}.$$

- At the GUT scale M_U: $g_X = g_R \equiv g_U$.
- We have the matching condition at the breaking scale M_R given by

$$\frac{1}{\alpha_Y(M_R)} = 4\pi P(GG^T)^{-1}P^T \quad \text{with } P = (\sqrt{\frac{2}{5}}, \sqrt{\frac{3}{5}})$$

$$\Rightarrow \frac{1}{g_Y^2} = \frac{3g_{XX}^2 - 2\sqrt{6} g_{XX} g_{XR} + 2\left(g_{XR}^2 + g_{RR}^2\right)}{5 g_{XX}^2 g_{RR}^2}.$$

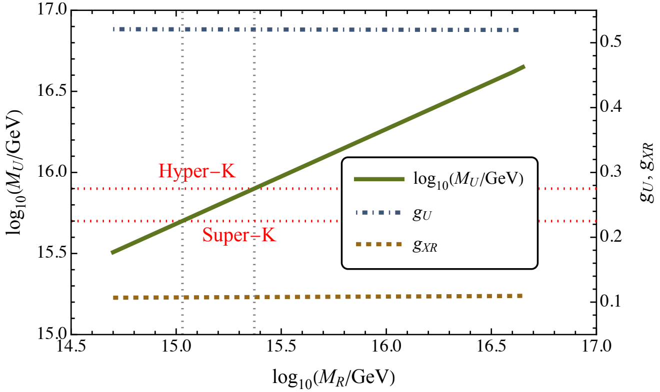
Unification solution



- The unification occurs for $\epsilon \sim M_U/\Lambda \sim 0.1$

RM, Shafi, JHEP 10 (2024) 157

Unification solution



- The unification occurs for $\epsilon \sim M_U/\Lambda \sim 0.1$.
- String tension ($\mu \sim \pi M_R^2$): $\log_{10}(G\mu) \in [-7.7, -4.7]$
- Seesaw scale $\sim \epsilon M_R^2/M_U \sim 10^{14}$ GeV.

RM, Shafi, JHEP 10 (2024) 157

Formation of Metastable Strings (MSS)

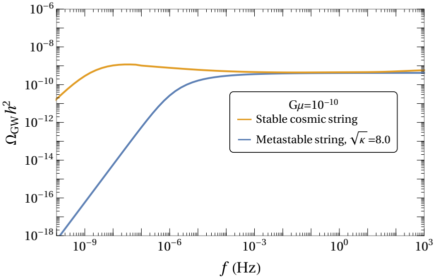
- Magnetic monopoles, created prior to the cosmic strings, experience inflation.
- The lifetime of decay of the strings via quantum mechanical tunneling is much smaller than the age of Universe.
- The strings form a network of stable strings before the time $t_s = 1/\sqrt{\Gamma_d}$.
- The strings network disappear at a time $t_e \sim 1/\sqrt{\Gamma_d \Gamma G\mu}$.

Leblond, Shlaer, Siemens, PRD **79** (2009) 123519

Buchmuller, Domcke, Schmitz, JCAP **12** (2021) 006

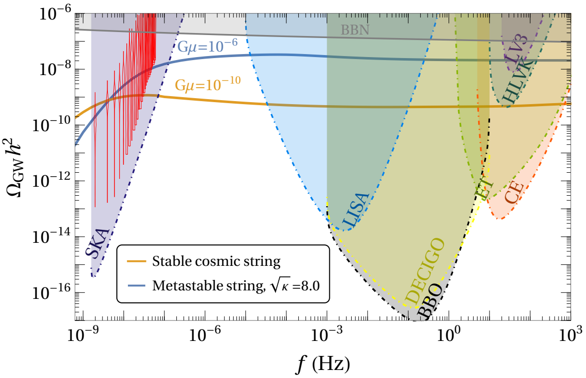
- The strings inter-commute and form loops which decay into gravitational waves.

- String loops larger than αt_s are absent.



- Gravitational wave spectrum in the low frequency region, $f \lesssim 1/\Gamma G\mu t_e(1+z_e)$, becomes suppressed.

PTA and Observational Prospects of Strings



- Pulsar Timing Arrays (PTAs)
  1. found evidence of a stochastic background which can be explained by superheavy "metastable" strings $G\mu \sim 10^{-6} - 10^{-5}$.
  2. put a contraint "undiluted stable" cosmic strings : $G\mu \lesssim 10^{-10}$.

in the nanoHertz frequencies. arXiv:2306.16219,...