Metastable strings from supersymmetric $U(1)_{B-L}$ flat direction and NANOGrav 15 year data

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Outline

1. *Formation of Topological Defects*

Prediction of Topological Defects

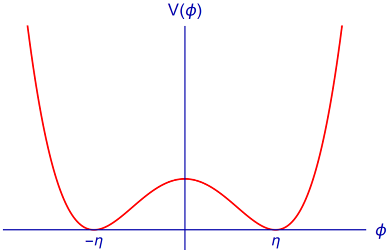
$$\mathcal{G} \xrightarrow[\text{SSB}]{\langle S \rangle} \mathcal{H}$$

- Topological defects may appear during the SSB of a group $\mathcal{G}$ down to its subgroup $\mathcal{H}$.

- Non-trivial homotopy group $\Pi_k(\mathcal{M})$ of the vacuum manifold $(\mathcal{M} = \mathcal{G}/\mathcal{H})$ implies formation of topological defects.

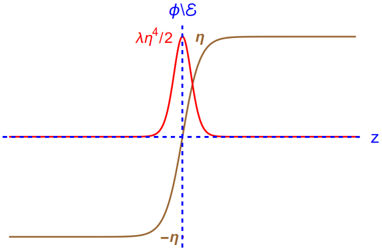
- Various types of topological defects which can be formed are : domain walls (k = 0), cosmic strings (k = 1), monopoles (k = 2) etc

Example : Domain wall

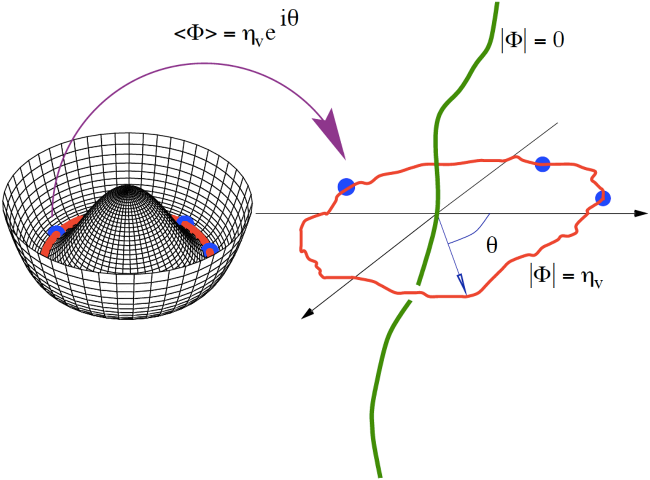


- $\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{\lambda}{4}(\phi^2 - \eta^2)^2$
- Vacuum manifold consists of two disconnected elements : $\langle\phi\rangle = \pm\eta$: $\Pi_0(\mathcal{M}) = \mathbb{Z}_2$.
- Boundary conditions: $\phi \to \pm\eta$ as $z \to \pm\infty$.

- Stationary solution : $\phi(z) = \eta \tanh\left(\sqrt{\frac{\lambda}{2}}\eta z\right)$.
- Energy density : $\mathcal{E} = \frac{\lambda\eta^4}{2}\text{sech}^4\left(\sqrt{\frac{\lambda}{2}}\eta z\right)$.
- Energy per unit area : $\frac{2\sqrt{2}}{3}\frac{m^3}{\lambda}$ on xy plane ⇒ Wall!



String



Vachaspati et. al. arXiv:1506.04039

2 *Gravitational Waves from Strings and Observational Prospects*

String Loops and Gravitational Waves

- 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.

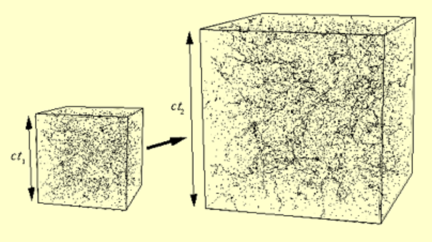


Image source: ctc.cam.ac.uk

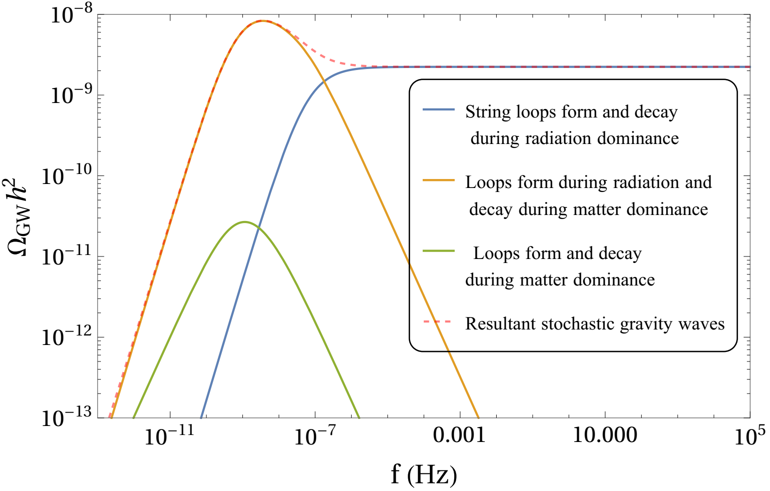
- Loops of initial length $l_i = \alpha t_i$ decay via emission of gravity waves.

$$\frac{dE_{\rm GW}^{(k)}}{dt} = \Gamma_k G\mu^2 \quad \text{with} \quad k = 1, 2, 3, \ldots$$

- The redshifted frequency of a normal mode k, emitted at time $\tilde{t}$, as observed today, is given by

$$f = \frac{a(\tilde{t})}{a(t_0)} \frac{2k}{\alpha t_i - \Gamma G\mu(\tilde{t} - t_i)}, \quad \text{with} \quad \Gamma = \sum \Gamma_k$$

Stochastic Gravitational Wave Background



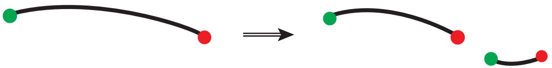
Sousa, Avelino, Guedes, PRD 101 (2020) 10, 103508

Topologically Unstable Cosmic Strings

- Consider $G \xrightarrow{M_I} H \otimes U(1) \xrightarrow{M_{II}} H$ with G being simply connected and $\Pi_1(G/H) \cong \Pi_0(H) = I$.

- Strings formed at M_{II} connect monopole-antimonopole $(M\bar{M})$ pairs formed at M_I.

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



- However, strings are practically stable unless two breaking scales are very close ($\sqrt{\kappa} \equiv (m_M^2/\mu)^{1/2} \lesssim 9$).

Preskill, Vilenkin, Phys. Rev. D **47** (1993)

Formation of Metastable Strings (MSS)

- Intermediate scale 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

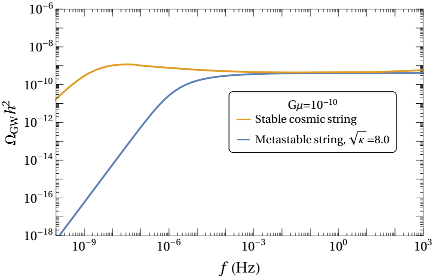
Example in GUT

$$
\begin{aligned}
SO(10) &\xrightarrow{M_{\rm GUT}} SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\
&\xrightarrow{M_R} SU(3)_c \times U(1)_{B-L} \times SU(2)_L \times U(1)_R \\
&\xrightarrow{M_{BL}} SU(3)_c \times SU(2)_L \times U(1)_Y .
\end{aligned}
$$

- Symmetry breaking $SU(2)_R \to U(1)_R$ produces monopoles.
- $U(1)_R \times U(1)_{B-L} \to U(1)_Y$ generates cosmic strings which are not topologically stable. These strings connects a monopole to its antimonopole.

Metastable Strings and GWs

- 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.

Observational Constraints on Defects

- Stable domain walls contradict standard cosmology.

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

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

  M. Ambrosio et al. [MACRO Collaboration], EPJC 25, 511 (2002)

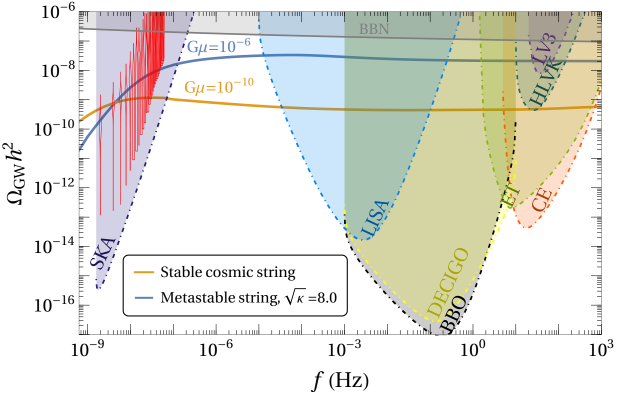
- Pulsar Timing Arrays (PTAs)
  1. found evidence of a stochastic background which can be explained by superheavy "metastable" strings $G\mu \sim 10^{-6} - 10^{-5}$.
  2. put a contraint "undiluted stable" cosmic strings : $G\mu \lesssim 10^{-10}$.

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

- LIGO-VIRGO O3 data rules out $G\mu \gtrsim 10^{-7}$ around decaHz frequencies.

  PhysRevLett.126.241102

Observational Prospects of Cosmic Strings



- The GWs from MSS explain PTA data at nanoHertz frequency, but violate the bound from LIGO-VIRGO third observing run!
- An early matter domination can reduce the spectra at high frequencies.

3. *Type I Metastable Strings from D-flat $U(1)_{B-L}$ and GWs*

MSS from Breaking of SUSY $U(1)_{B-L}$ D-flat Direction

$$
\begin{aligned}
& SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\
& \xrightarrow{M_R} SU(3)_c \times U(1)_{B-L} \times SU(2)_L \times U(1)_R \\
& \xrightarrow{M_{BL}} SU(3)_c \times SU(2)_L \times U(1)_Y .
\end{aligned}
$$

- Two $SU(2)_R$ doublet chiral superfields Φ_1 and Φ_2 with $B-L$ charges ± 1.
- $U(1)_{B-L}$ is broken along D-flat direction of the potential with the scalar components $|\phi_1| = |\phi_2| \equiv \phi/\sqrt{2}$.
- Before SSB there will be 'thermal inflation' from the flat potential.
- The strings formed after inflation will experience an early matter dominated era after thermal inflation.

Type I String from the Breaking of D-flat $U(1)_{B-L}$

- The scalar mass m_ϕ is much smaller than the vev (ϕ_0), and hence $m_\phi << m_V$, the vector boson mass.
- The correlation lengths for scalar (m_ϕ^{-1}) is much larger than that for gauge field (m_V^{-1}).
- There is an attractive force between the strings, they can zip together and can form energetically favorable higher winding strings.

String Tension

- String tension for a winding number N_w is expressed as:

$$\frac{\mu_s(N_w)}{\pi \phi_0^2} \approx c_1(1 + c_2 \ln N_w)$$

with the coefficients:

$$c_1 \approx \frac{4.2}{\ln(R)} + \frac{14}{\ln^2(R)},$$
$$c_2 \approx \frac{2.6}{\ln(R)} + \frac{57}{\ln^2(R)}.$$

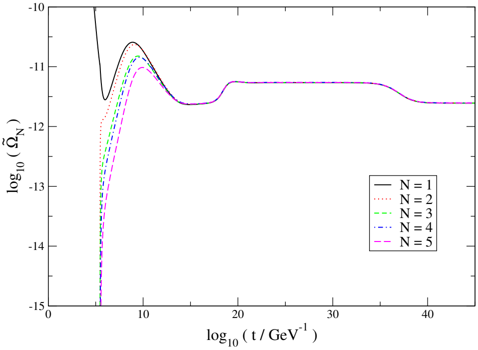
where, $R = m_V^2/m_\phi^2 >> 1$.

Cui, Martin, Morrissey, Wells, Phys. Rev. D **77** (2008) 043528

Scaling Regime for Type I Strings

- Scaling energy density $\rho_s \sim \mu/t^2$. Critical density: $\rho_c \sim 1/Gt^2$ in RD and MD.
- String with winding number N enters the 'scaling regime': $\tilde{\Omega}_N = \frac{\mu_s(1)}{\mu_s(N)} \frac{\rho_s(N)}{\rho_c}$ becomes constant with time.
- Maximum value of winding number at time t:

$$N_w^{\max} \sim \left(\frac{t}{t_c}\right)^{0.22}.$$



Cui, Martin, Morrissey, Wells, Phys. Rev. D **77** (2008) 043528

String-loop Distribution

- The loop distribution in a radiation dominated universe:

$$n(l, t < t_s) = \frac{0.18\ \Theta(0.18t - l)}{t^{3/2}(l + \Gamma G\mu_{s,c} t)^{5/2}},$$

$$n(l, t > t_s) = \frac{0.18\ \Theta(0.18t - l - \Gamma G\mu_{s,c}(t - t_s))}{t^{3/2}(l + \Gamma G\mu_{s,c} t)^{5/2}} e^{\left[-\Gamma_d \left(l(t - t_s) + \frac{1}{2} G\mu_{s,c}(t - t_s)^2\right)\right]}$$

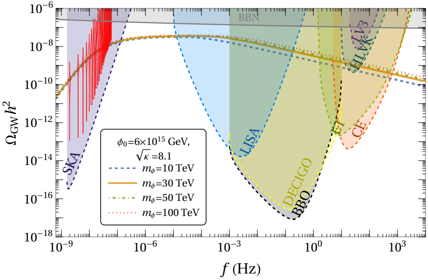
- Early matter domination era continues from t_c till $t_d = \Gamma_\phi^{-1}$.
- Early matter era:

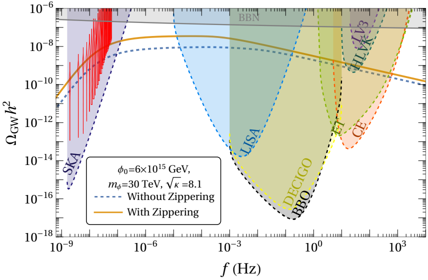
$$n_m(l, t < t_d) = \frac{0.27 - 0.45(l/t)^{0.31}}{t^2(l + \Gamma G\mu t)^2} \Theta(0.18t - l).$$

- $t_s = 1/\sqrt{\Gamma_s}$, and $\Gamma \simeq 50$.

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

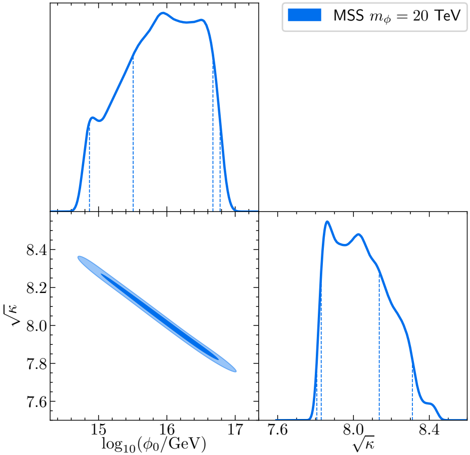
Gravitational Waves from Meta-stable Strings





RM, Park, arxiv:2308.11439

MSS from D-flat breaking and NANOGrav 15 year data



- $\log_{10}(\phi_0/\mathrm{GeV}) = 15.90 \pm 0.55,\ \sqrt{\kappa} = 8.04 \pm 0.15$

4 *Summary*

Summary

- The topology of BSM symmetry can be probed via GWs from the defects.
- Gravitational wave spectrum from MSS from D-flat breaking of $U(1)_{B-L}$ can explain the PTA data around nanoHertz frequencies.
- Early matter domination after the thermal inflation suppresses the GWs around the decaHertz frequencies and satisfy third run LIGO-VIRGO bound.

Thank You

Back up slides