Stable Magnetic Monopoles from Metastable Cosmic Strings

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New Horizons in PBH Physics

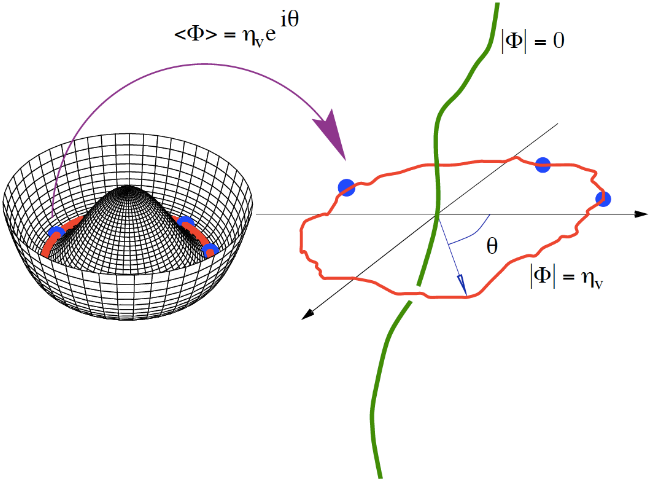
Outline

1. *Topological Defects in BSM symmetries*

Prediction of Topological Defects

- 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.

Cosmic String



Vachaspati et. al. arXiv:1506.04039

Cosmic String Network

- String tension $\mu \simeq \pi v^2$, v 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.

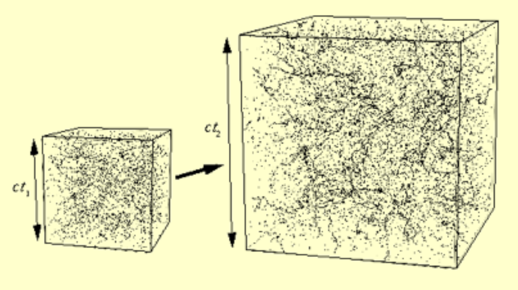


Image source: ctc.cam.ac.uk

Kibble, NPB 252 (1985) 227; Bennett, Bouchet, PRL 60 (1988) 257 ...

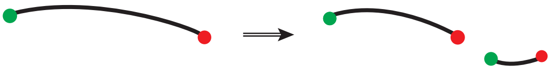
2. *Formation of Metastable Strings*

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 $t_s = 1/\sqrt{\Gamma_d}$.

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

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

3 *SO(10) symmetry breaking and monopoles*

SO(10) symmetry breaking and monopoles

$$
\begin{aligned}
SO(10) &\xrightarrow{M_{\rm GUT}} SU(4)_c \times SU(2)_L \times SU(2)_R \\
&\xrightarrow{M_I} SU(3)_c \times U(1)_{B-L} \times SU(2)_L \times U(1)_R \\
&\xrightarrow{M_{II}} SU(3)_c \times SU(2)_L \times U(1)_Y .
\end{aligned}
$$

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

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

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

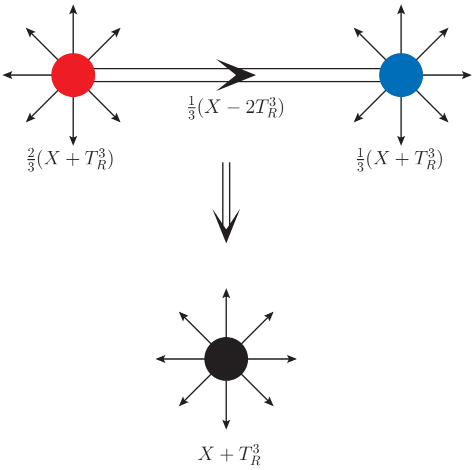
$$T_R^3 = diag(1, -1).$$

Lazarides, Shafi, JHEP 10 (2019) 193

Strings connecting monopoles

- $U(1)_R \times U(1)_{B-L} \to U(1)_Y$ generates topologically unstable strings.

- These strings connects
  1. a blue monopole to a red monopole: $\mathbf{M_R S M_B}$,
  2. a monopole to its anti-monopole.



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

Lazarides, Shafi, JHEP 10 (2019) 193

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

Radiation of massless gauge bosons

- Unconfined Y magnetic flux of the red and blue monopoles:

$$g_{mR} = \frac{2}{3}\left(\frac{4\pi}{g_1}\right) \quad \text{and} \quad g_{mB} = \frac{1}{3}\left(\frac{4\pi}{g_1}\right).$$

- Acceleration of a monopole its instantaneous rest frame: $a = \mu/m_M$. Berezinsky, Martin, Vilenkin, PRD **56** (1997)

- Rate of energy loss from both monopoles:

$$\frac{dE}{dt} = -\frac{1}{6\pi}(g_{mR}^2 + g_{mB}^2)a^2 = -\frac{10}{27\kappa}\frac{1}{\alpha_1(t)}\mu \equiv -j(t)\mu,$$

where $\alpha_1 = g_1^2/4\pi$, $\kappa = m_M^2/\mu$ and $j = \frac{10}{27\kappa}\frac{1}{\alpha_1(t)}$.

- After including the radiation of gravitational wave:

$$\boxed{\frac{dl}{dt} = -\tilde{\Gamma}G\mu - j(t),}$$

where $\tilde{\Gamma}$ is a numerical factor.

Sub-horizon $M_R S M_B$ from metastable strings

- Sub-horizon string bounded by monopoles segments are produced after time t_s from the decay of long strings and loops.
- Half of the first generation segments from long strings will constitute of $M_R S M_B$ structures.
- The first generation of string segments from loops will connect monopoles to their antimonopoles.
- The first generation of segments decay very quickly via the radiation of massless gauge bosons.
- The second generations of the monopoles connected by strings will be highly suppressed.

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Monopoles from $M_R S M_B$ Structures

- The segments at time $t \geqslant t_s$ from the long strings after a 'scaling regime' is given by

$$\boxed{\tilde{n}^{(s)}(l,t) = \frac{4}{\xi^2}\frac{\Gamma_d^2}{4}\frac{(t+t_s)^2}{\sqrt{t^3 t_s}} e^{-\Gamma_d\left[l(t+t_s)+\frac{1}{2}(\tilde{\Gamma}G\mu+j)(t-t_s)(t+3t_s)\right]},}$$

where $\xi = 0.27$ in RD universe.

- Present day monopole number density is

$$\boxed{n_{\rm TSM} = \sum_{i\in\{s,l\}} \int_{t_s}^{t_e} dt \frac{n_{\rm TSM}^{(i)}(t)}{(1+z(t))^3},}$$

where superscripts s, l are for long strings and loops respectively.

- t_e the time at which the monopole generation ceases to operate.

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Monopole Flux and Observational Bounds

Experiment	Monopole mass (m_{TSM}) in GeV	Velocity (v_{TSM})	Flux $\mathcal{F}_{\text{TSM}} = \frac{n_{\text{TSM}} v_{\text{TSM}}}{4\pi}$ in $\text{cm}^{-2}\text{sec}^{-1}\text{sr}^{-1}$
MACRO	$5 \times 10^8 - 5 \times 10^{13}$	> 0.05	3×10^{-16}
	$> 5 \times 10^{13}$	$> 4 \times 10^{-5}$	1.4×10^{-16}
IceCube	$> 10^8 - 10^{10}$	$0.8 - 0.995$	2×10^{-19}

Upper limits on monopole flux from MACRO and IceCube experiments.
MACRO EPJC **25** (2002) 511, IceCube PRL **128** (2022) 051101...

- We estimate v_{TSM} by [Kolb, Turner]

$$v_{\text{TSM}} \simeq \min\left[3 \times 10^{-3}\left(\frac{m_{\text{TSM}}}{10^{16}\ \text{GeV}}\right)^{-1/2}, 1\right].$$

- Threshold for observability: $\mathcal{F}_{\text{TSM}} \gtrsim 10^{-24}\ \text{cm}^{-2}\text{sec}^{-1}\text{sr}^{-1}$.

Monopoles from Scaling String Network

- Scaling regime is possible for string network with $t_s > t_{\rm Pl}/(G\mu)^2$:

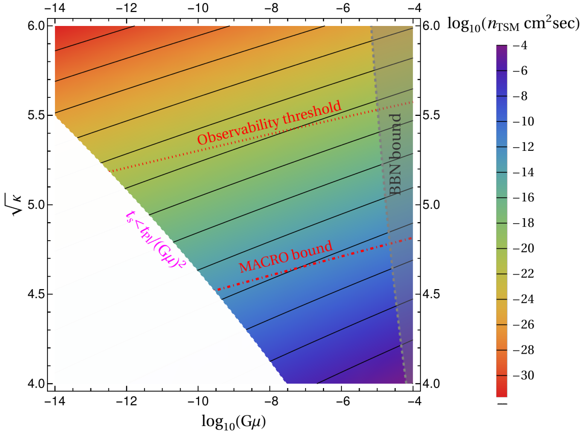
$$\sqrt{\kappa} > (-2.19\log_{10}(G\mu) - 0.58)^{1/2}.$$

Vilenkin, PRD 1991

- Monopoles could be observed for $G\mu \in [10^{-9}, 10^{-5}]$, $\sqrt{\kappa} \in [4.55, 5.53]$.

- Monopole masses $10^{15} - 10^{17}$ GeV.

- BBN bound from GWs for $G\mu \gtrsim 10^{-5}$.



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Strings and Gravitational Waves

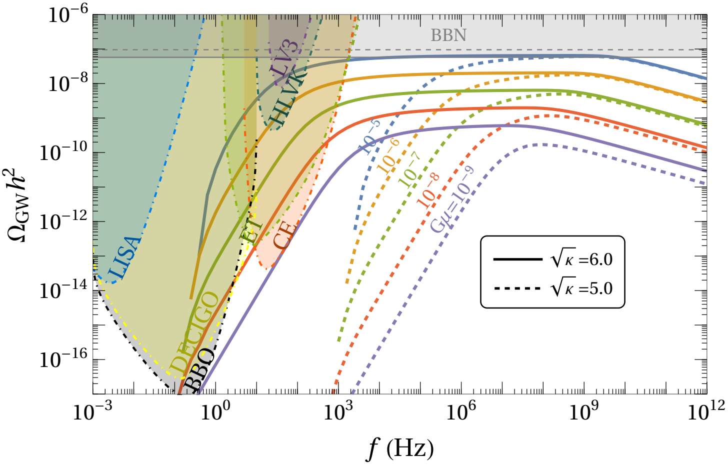
- Loops of initial length $l_i = \alpha t_i$ decay via emission of gravity waves.

$$\frac{dE_{\rm GW}^{(k)}}{dt} = \Gamma_k G\mu^2; \quad \Gamma_k \propto k^{-n} \quad \text{with } n = \begin{cases} 4/3 & \text{cusps} \\ 5/3 & \text{kinks} \\ 2 & \text{kink-kink collisions.} \end{cases}$$

- The redshifted frequency of a normal mode k, emitted at time $\tilde{t}$, as observed today, is given by Vilenkin, Shellard, 1994, CUP

$$f = \underbrace{\frac{a(\tilde{t})}{a(t_0)}}_{\text{Redshift}} \frac{2k}{\underbrace{\alpha t_i - \Gamma G\mu(\tilde{t} - t_i)}_{\text{Loop size at time } \tilde{t}}}, \quad \text{with} \quad \Gamma = \sum \Gamma_k$$

High Frequency GWs from String Network in Scaling



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Monopoles in Friction Dominated Era

- For $t_s < t_F = t_{\mathrm{Pl}}/(G\mu)^2$, sub-horizon segments do not oscillate in the friction dominated era.

- The length of a string segment at time t_F is given by

$$l \sim \frac{1}{\Gamma_d t_F} = \frac{t_s^2}{t_F}.$$

- We expect a total length of the string network pt_F within particle horizon at t_F.

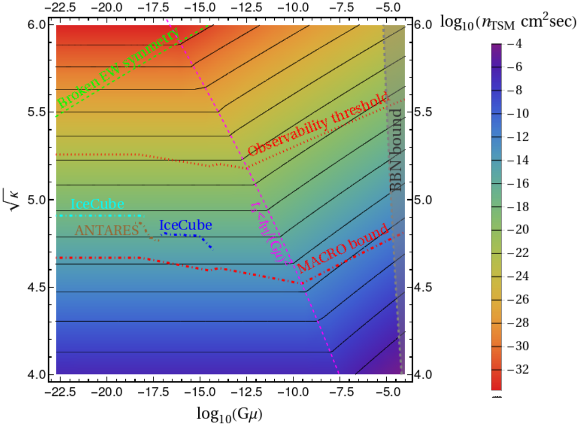
- Present day number density of TSM is

$$n_{\mathrm{TSM}} \sim \frac{p}{t_s^2 t_F} \frac{1}{(1+z_F)^3}.$$

Monopoles from String in Friction Era

- Intermediate mass monopoles with masses $\lesssim 10^{11}$ GeV can be relativistic.

- Relativistic and ultra-relativistic monopole fluxes can be observed in future experiments such as IceCube, Pierre Auger, ANITA and KM3NeT.



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4 *Summary*

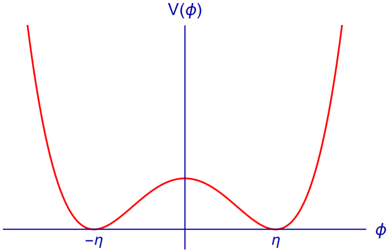
Summary

- Decay of metastable cosmic strings can generate topologically stable monopoles.
- Experimentally observable flux of superheavy ($\sim 10^{15} - 10^{17}$ GeV) monopoles produced from string network in scaling regime for $G\mu \approx 10^{-9} - 10^{-5}$ and $\sqrt{\kappa} \sim 5$.
- Very high frequency gravitational wave spectra are generated.
- $G\mu \lesssim 10^{-14}$ can generate relativistic and ultra-relativistic monopole fluxes which can be observed in future experiments such as IceCube, Pierre Auger, ANITA and KM3NeT.

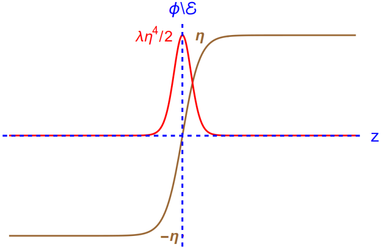
Thank You

Back up slides

Example : Domain wall

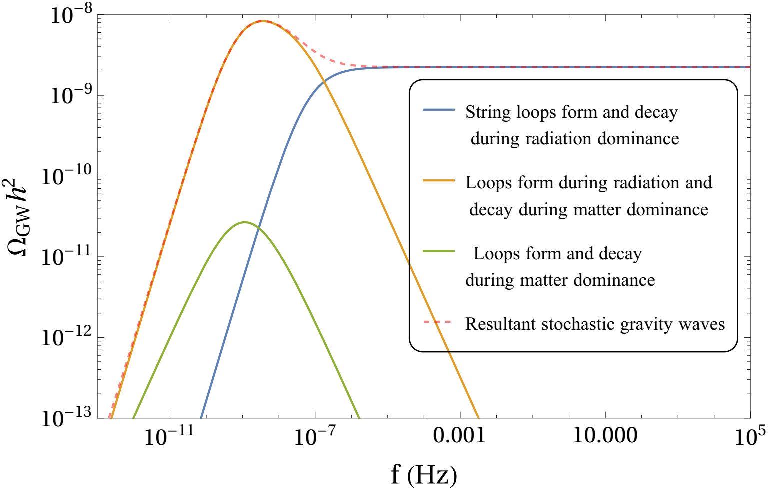


- $\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{\lambda}{4}(\phi^2 - \eta^2)^2$
- Vacuum manifold consists of two disconnected elements : $\langle \phi \rangle = \pm\eta$: $\Pi_0(\mathcal{M}) = \mathbb{Z}_2$.
- Boundary conditions : $\phi \to \pm\eta$ as $z \to \pm\infty$.



- 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 : $\frac{2\sqrt{2}}{3}\sqrt{\lambda}\eta^3$ on xy plane $\Rightarrow$ $\boxed{\textit{Domain Wall}}$

Stochastic Gravitational Wave Background

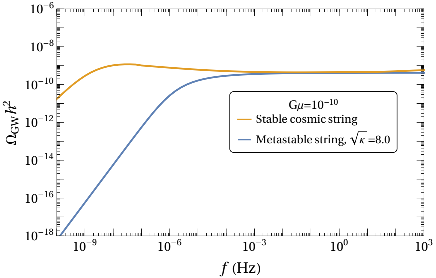


Sousa, Avelino, Guedes, PRD 101 (2020) 10, 103508

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 ($f \lesssim 1/t_e(1+z_e)$) becomes suppressed.