The profile of non-standard cosmic strings

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Más allá del Modelo Estándar y Astropartículas
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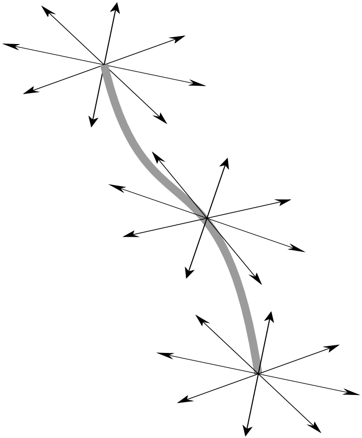
Kibble Mechanism

It is believed that phase transitions occurred in the early universe (10^{-11} s-10^{-5} s for electroweak and $\sim 10^{-33}$ s for GUT). These transitions could have formed topological defects.

Examples:

- $\pi_0(\mathcal{M}) \neq I \Rightarrow$ Domain wall
- $\pi_1(\mathcal{M}) \neq I \Rightarrow$ Vortex (2d), cosmic strings (3d)
- $\pi_2(\mathcal{M}) \neq I \Rightarrow$ Monopole

Cosmic Strings



2-dimensional vortices stacked on top of each other, forming a cosmic string in three dimensions

$\mathrm{U}(1)_{B-L}$ exact local symmetry

In the Standard Model $\mathrm{U}(1)_{B-L}$ is an **exact** global symmetry. B baryon number, L lepton number.

This is strange, an exact symmetry is only natural when it is local.

Gauge symmetry

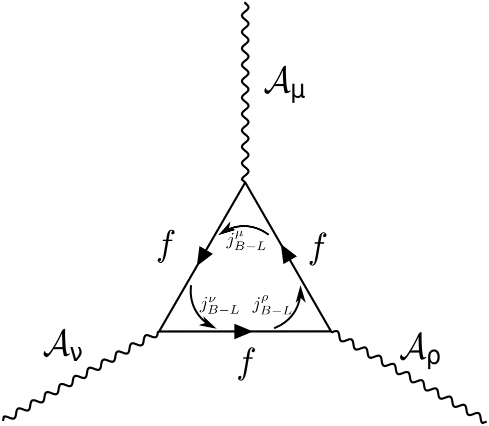
We promote $U(1)_{B-L}$ to a local symmetry and combine it with $U(1)_Y$.

We introduce a new gauge coupling and define a new charge as

$$Y' = 2hY + \frac{h'}{2}(B - L).$$

We take the gauge group to be $U(1)_{Y'}$.

Gauge Anomaly



In each vertex the quarks of one generation contribute with $B = 4$, and leptons with $L = 3$.

$B - L \neq 0$.

Gauge anomaly. It is cured by adding a ν_R $(L = 1)$ to each generation.

We can give mass to the neutrino with a Dirac mass term

$$f_\nu \left[\bar{\nu}_R \begin{pmatrix} -\Phi_0 & \Phi_+ \end{pmatrix} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \begin{pmatrix} \bar{\nu}_L & \bar{e}_L \end{pmatrix} \begin{pmatrix} -\Phi_0^* \\ \Phi_+^* \end{pmatrix} \nu_R \right],$$

where f_ν is a Yukawa coupling.

Without promoting $\mathrm{U}(1)_{B-L}$ to a gauge symmetry we can give mass to the neutrinos with a Majorana mass term

$$M\bar{\nu}_M\nu_M.$$

However, in our scenario, this term is forbidden since it breaks the $\mathrm{U}(1)_{Y'}$ symmetry.

To add a mass term solely for ν_R, independently of ν_L, we add a new Higgs field $\chi \in \mathbb{C}$

$$f_{\nu_R} \nu_R^T \chi \nu_R + \text{c.c.},$$

where f_{ν_R} is a Yukawa coupling.

To preserve gauge invariance, the field χ must have a charge $B - L = 2$.

We generate the Majorana mass with the Higgs mechanism using the new Higgs field $\chi \in \mathbb{C}$.

We denote the vacuum expectation value of χ as v'.

χ gives a Majorana mass to the right-handed neutrino $M = f_{\nu_R} v'$.

χ is added to the Lagrangian as

$$V' = \frac{m'^2}{2}\chi^*\chi + \frac{\lambda'}{4}(\chi^*\chi)^2.$$

It is natural to include

$$\frac{\kappa}{2}\Phi^\dagger\Phi\chi^*\chi.$$

We assume that $v' \gg v$ and $f_{\nu_R} \simeq O(1)$ in order to give a large mass to the right-handed neutrino.

Lagrangian

$$\begin{aligned}\mathcal{L} \;=\; & \frac{1}{2}(D^\mu\Phi)^\dagger D_\mu\Phi - \frac{m^2}{2}\Phi^\dagger\Phi - \frac{\lambda}{4}(\Phi^\dagger\Phi)^2 - \frac{\lambda}{4}v^4 \\ & + \frac{1}{2}(D^\mu\chi)^* D_\mu\chi - \frac{m'^2}{2}\chi^*\chi - \frac{\lambda'}{4}(\chi^*\chi)^2 - \frac{\lambda'}{4}v'^4 \\ & - \frac{\kappa}{2}\Phi^\dagger\Phi\chi^*\chi - \frac{\kappa}{2}v^2 v'^2 - \frac{1}{4}\mathcal{F}^{\mu\nu}\mathcal{F}_{\mu\nu},\end{aligned}$$

- $\Phi = (\phi_+, \phi_0)^\mathsf{T} \in \mathbb{C}^2$
- $D_\mu\Phi = (\partial_\mu + ih\mathcal{A}_\mu)\Phi$
- $D_\mu\chi = (\partial_\mu + ih'\mathcal{A}_\mu)\chi$

For the potential to be bounded from below, we need

$$\lambda > 0, \quad \lambda' > 0, \quad \kappa^2 < \lambda\lambda',$$

and for spontaneous symmetry breaking to occur

$$m^2 = -\kappa v'^2 - \lambda v^2 < 0,$$
$$m'^2 = -\kappa v^2 - \lambda' v'^2 < 0.$$

Equations of motion

$$
\begin{aligned}
D^\mu D_\mu \Phi &= -m^2\Phi - \lambda(\Phi^\dagger\Phi)\Phi - \kappa\Phi\chi^*\chi \\
D^\mu D_\mu \chi &= -m'^2\chi - \lambda'(\chi^*\chi)\chi - \kappa\chi\Phi^\dagger\Phi \\
\partial^\lambda \mathcal{F}_{\lambda\nu} &= -\frac{ih}{2}\left[(D_\nu\Phi)^\dagger\Phi - \Phi^\dagger(D_\nu\Phi)\right] \\
&\quad -\frac{ih'}{2}\left[(D_\nu\chi)^*\chi - \chi^*(D_\nu\chi)\right]
\end{aligned}
$$

Ansatz

$\mathcal{M} = \mathrm{U}(1) \Rightarrow \pi_1(\mathrm{U}(1)) = \mathbb{Z} \Rightarrow$ cosmic strings.

We only consider ϕ_0 of the Higgs field Φ.

Cylindrically symmetric ansatz

$$
\begin{aligned}
\phi_0(r,\varphi) &= \phi(r)e^{in\varphi} \\
\chi(r,\varphi) &= \xi(r)e^{in'\varphi} \\
\mathcal{A}(r) &= \frac{a(r)}{r}\hat{\varphi}.
\end{aligned}
$$

Equations of motion

$$\partial_r^2\phi + \frac{1}{r}\partial_r\phi - \frac{(n+ha)^2}{r^2}\phi - m^2\phi - \lambda\phi^3 - \kappa\phi\xi^2 = 0$$

$$\partial_r^2\xi + \frac{1}{r}\partial_r\xi - \frac{(n'+h'a)^2}{r^2}\xi - m'^2\xi - \lambda'\xi^3 - \kappa\xi\phi^2 = 0$$

$$\partial_r^2 a - \frac{1}{r}\partial_r a - h(n+ha)\phi^2 - h'(n'+h'a)\xi^2 = 0.$$

Boundary conditions

$$\phi(0) = 0, \qquad \lim_{r\to\infty}\phi(r) = v$$

$$\xi(0) = 0, \qquad \lim_{r\to\infty}\xi(r) = v'$$

$$a(0) = 0, \quad \lim_{r\to\infty} a(r) = -\frac{n}{h} = -\frac{n'}{h'}.$$

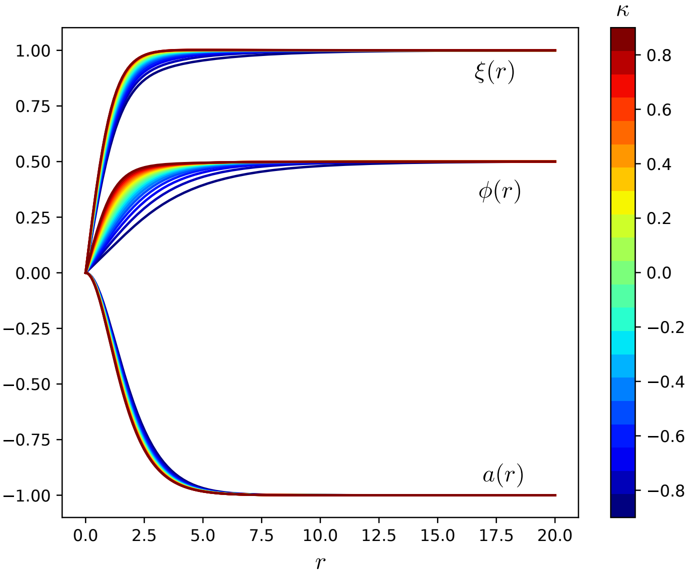
Boundary value problem, numerical solutions with the damped Newton method.

Solutions uniquely defined by inserting v, v', λ, λ', h, h', n and n'.

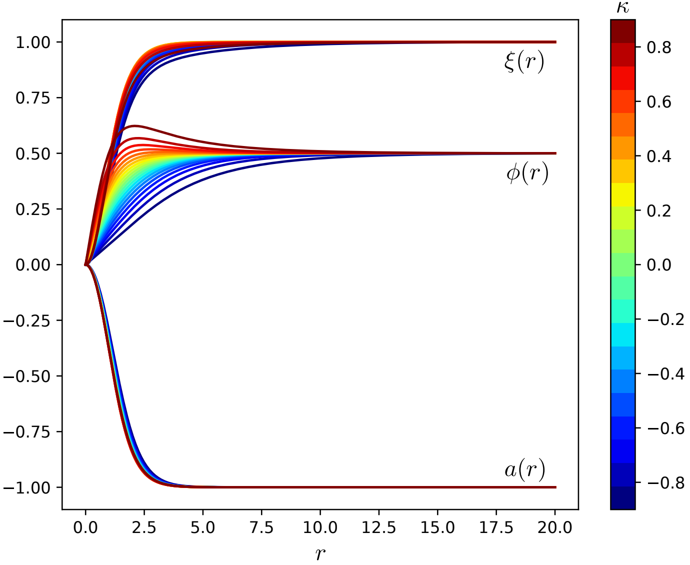
We choose $v' \gg v$.

$v = 246$ GeV is used to convert all dim'less variables to physical units. We display the profile radius r in units of

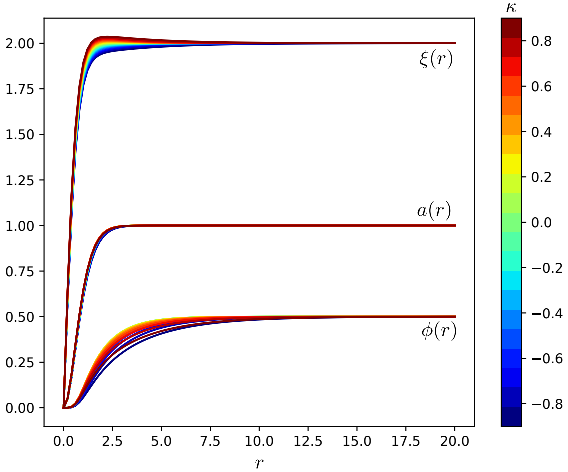
$$v_{\text{dim'less}} \cdot 0.0008 \text{ fm}.$$



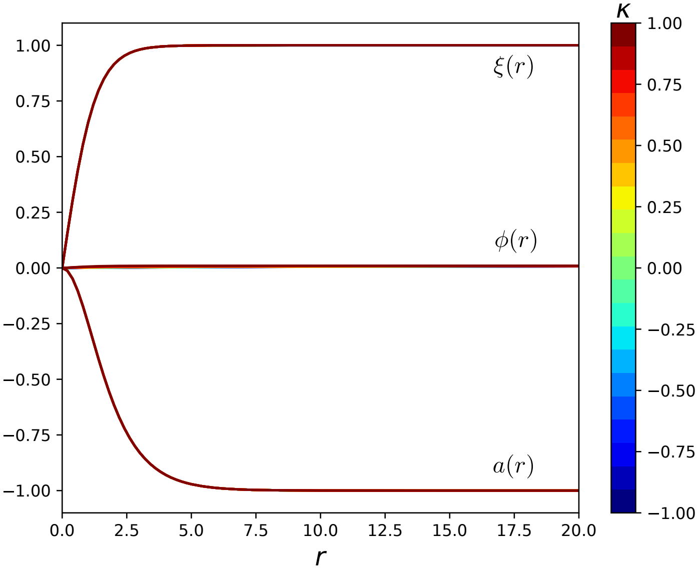
$$v = 0.5,\ v' = 1,\ n = n' = h = h' = \lambda = \lambda' = 1.$$



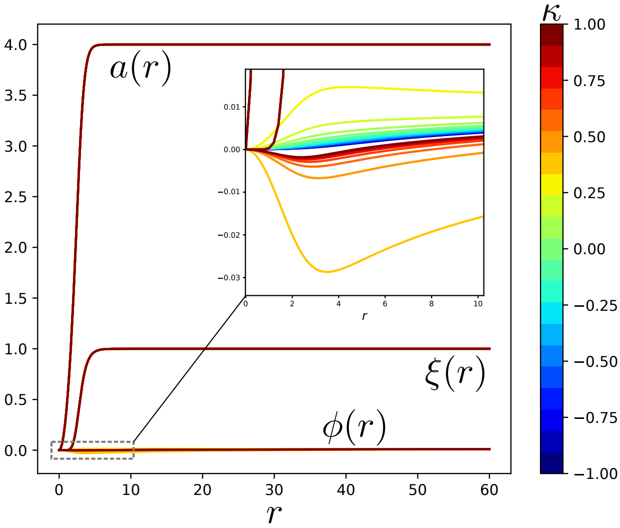
$$v = 0.5,\ v' = 1,\ n = 1,\ n' = 2,\ h = 1,\ h' = 2,$$
$$\lambda = \lambda' = 1.$$



$v = 0.5$, $v' = 2$, $n = -5$, $n' = -1$, $h = 5$, $h' = 1$, $\lambda = \lambda' = 1$. This is an example from the SO(10) GUT [Buchmüller/Greub/Minkowski, '91].



$$n = h = n' = h' = \lambda = \lambda' = 1,\ \ v = 0.01,\ \ v' = 1$$



Coaxial string solution with $n = -2,\ h = 0.5,\ n' = 10,\ h' = -2.5,\ \lambda = 1,\ \lambda' = 1,\ v = 0.01,\ v' = 1$

Summary

In this BSM model, we added

- A new gauge coupling h'
- A right-handed neutrino ν_R
- A new Higgs field $\chi \in \mathbb{C}$

A non-standard type of cosmic strings is possible.
At large distances, they do not affect known physics.

Not observed but detectable, in principle. Like gravitational wave detection, gravitational lensing, CMB anisotropies etc.

No contradictions with SM physics, motivated from the exactness of $\mathrm{U}(1)_{B-L}$.