Cosmic Strings in the Dark Sector

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With Andrew Long and Tanmay Vachaspati, arXiv:1312.4573

Introduction / Outline

- Standard Model extended to include a spontaneously broken "dark" U(1)
- Cosmic strings ("dark strings") would form as topological defects
- Dark strings interact with Standard Model particles

- Constraints on SM extensions? (Andrew's talk)

Model

SM + a "Dark Sector" consisting of a scalar S (singlet under SM $U(1)_Y$) and a gauge boson X_μ

Dark Sector $U(1)_X$ broken at some scale $\sigma \sim$ TeV, S gets a vev

This leads to cosmic strings that are topological defects.

$$\mathcal{L} = |D_\mu \Phi|^2 + |D_\mu S|^2 - U(\Phi, S) - \frac{1}{4} \sum_{a=1,2,3} (W^a_{\mu\nu})^2 - \frac{1}{4} (Y_{\mu\nu})^2 - \frac{1}{4} (\hat{X}_{\mu\nu})^2 - \frac{s_\epsilon}{2} \hat{X}_{\mu\nu} Y^{\mu\nu}$$

$$D_\mu \Phi = \left(\partial_\mu - i\tfrac{g}{2}\,\sigma^a W^a_\mu - i\tfrac{g'}{2} Y_\mu\right)\Phi$$
$$D_\mu S = \left(\partial_\mu - i\tfrac{g_X}{2} \hat{X}_\mu\right) S$$

$$U(\Phi, S) = \lambda\left(\Phi^\dagger \Phi - \eta^2\right)^2 + \kappa\left(S^* S - \sigma^2\right)^2 + \alpha\left(\Phi^\dagger \Phi - \eta^2\right)\left(S^* S - \sigma^2\right)$$

Higgs Portal and Gauge Kinetic Mixing

$$\mathcal{L}_{\mathrm{HP}} = -\alpha \Phi^\dagger \Phi S^* S$$

$$\mathcal{L}_{\mathrm{GKM}} = -\frac{\sin \epsilon}{2} \hat{X}_{\mu\nu} Y^{\mu\nu}$$

Dark Sector “talks to SM” via these two operators.

Higgs Portal term α and GKM $\sin(\varepsilon)$ are well constrained below O(TeV), but no constraints above this scale.

String Ansatz

In terms of cylindrical polar coordinates with scaled radial coordinate $\xi = \sigma\rho$,

Standard Model fields:

$$\Phi^+(x) = 0$$

$$H(x) = \eta\,\mathrm{h}(\xi)e^{in\varphi}$$

$$W_\mu^\pm = A_\mu = 0$$

$$Z_\mu(x) = \frac{1}{\rho_0}\frac{\mathrm{z}(\xi)}{\xi}V_\mu(\varphi)$$

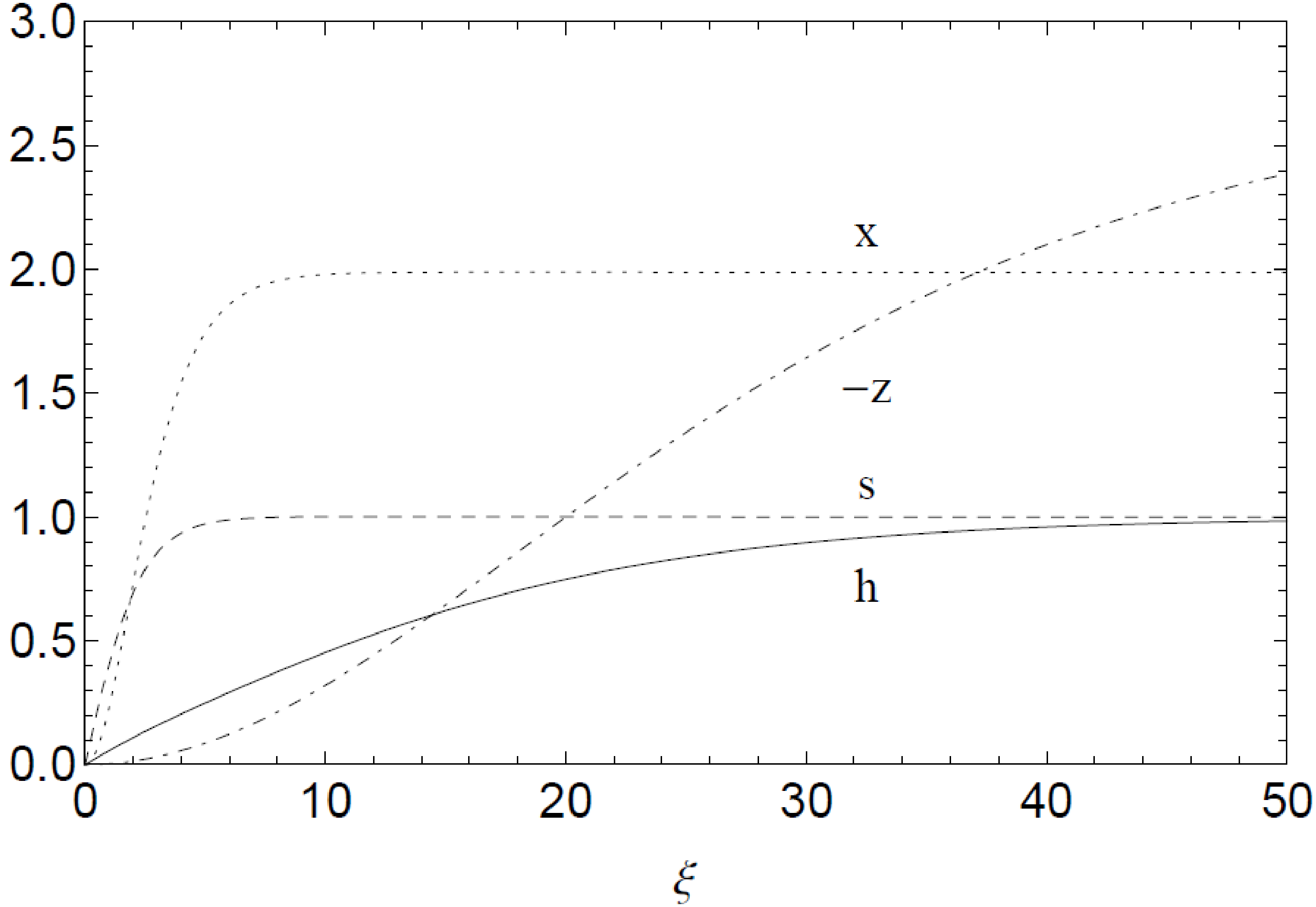
Dark Sector fields:

$$S(x) = \sigma\,\mathrm{s}(\xi)e^{im\varphi}$$

$$X_\mu(x) = \frac{1}{\rho_0}\frac{\mathrm{x}(\xi)}{\xi}V_\mu(\varphi)$$

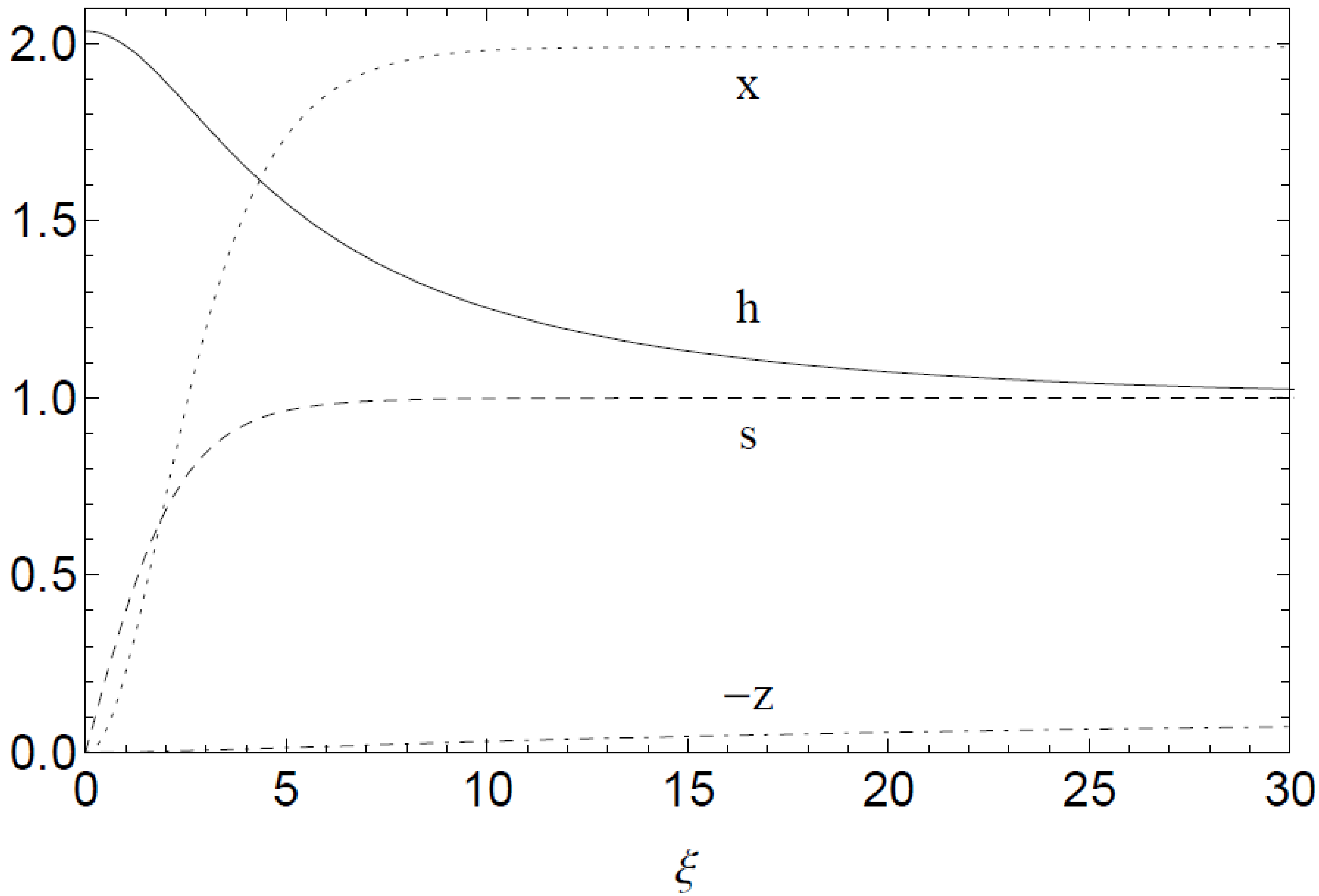
$$\mathrm{z}(\infty) = \frac{g_\mathrm{X}^\mathrm{S} n - g_\mathrm{X}^\mathrm{H} m}{g_\mathrm{X}^\mathrm{S} g_\mathrm{Z}^\mathrm{H} - g_\mathrm{X}^\mathrm{H} g_\mathrm{Z}^\mathrm{S}} \qquad \mathrm{z}(0) = \mathrm{x}(0) = 0 \qquad \mathrm{x}(\infty) = \frac{g_\mathrm{Z}^\mathrm{H} m - g_\mathrm{Z}^\mathrm{S} n}{g_\mathrm{X}^\mathrm{S} g_\mathrm{Z}^\mathrm{H} - g_\mathrm{X}^\mathrm{H} g_\mathrm{Z}^\mathrm{S}}$$

String Solution



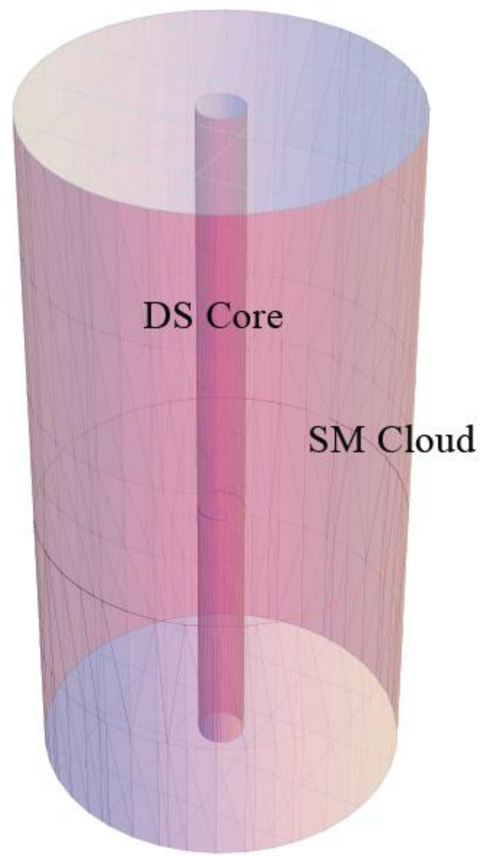
$$(\text{SM winding, DS winding}) = (1,1), \quad \sigma = 1.4 \text{ TeV}, \quad \alpha = 0.1, \quad \sin\epsilon = 0.1$$

String Solution



$$(\text{SM winding, DS winding}) = (0,1), \quad \sigma = 1.4\ \text{TeV}, \quad \alpha = 0.1, \quad \sin\epsilon = 0.1$$

Structure of Dark String



Effective Couplings

Fluctuations of the light fields (H and Z) about the string solution → linear source terms.

In terms of the mass eigenstate $\phi_H = \cos\theta\,\bar{h} - \sin\theta\,\bar{s}$

the equation of motion becomes

$$(\Box + M_H^2 + \delta M_H^2)\phi_H + \delta\mu^2\phi_S = \mathcal{S} + O(\phi_H^2, \phi_H\phi_S)$$

If we think of the string as a delta-function source, i.e.

$$\mathcal{S} \approx g_{\rm str}^{\rm H}\,\eta\sigma^2\,\delta(\sigma x)\delta(\sigma y)$$

then the effective coupling constant would be

$$g_{\rm str}^{\rm H} \equiv \eta^{-1}\int dxdy\,\mathcal{S}$$

Effective Couplings

Similarly for the Z, the equation of motion becomes

$$\partial_\nu \bar{Z}^{\nu\mu} + M_Z^2 \bar{Z}^\mu + \delta M_Z^2 \bar{Z}^\mu = \mathcal{J}^\mu$$

and the current can be written in the form $\mathcal{J}^\mu = \eta^2 \, \epsilon^{\mu\alpha\beta\gamma} \partial_\alpha \Big(k(\xi) T_\beta L_\gamma \Big)$

so that the coupling is found by

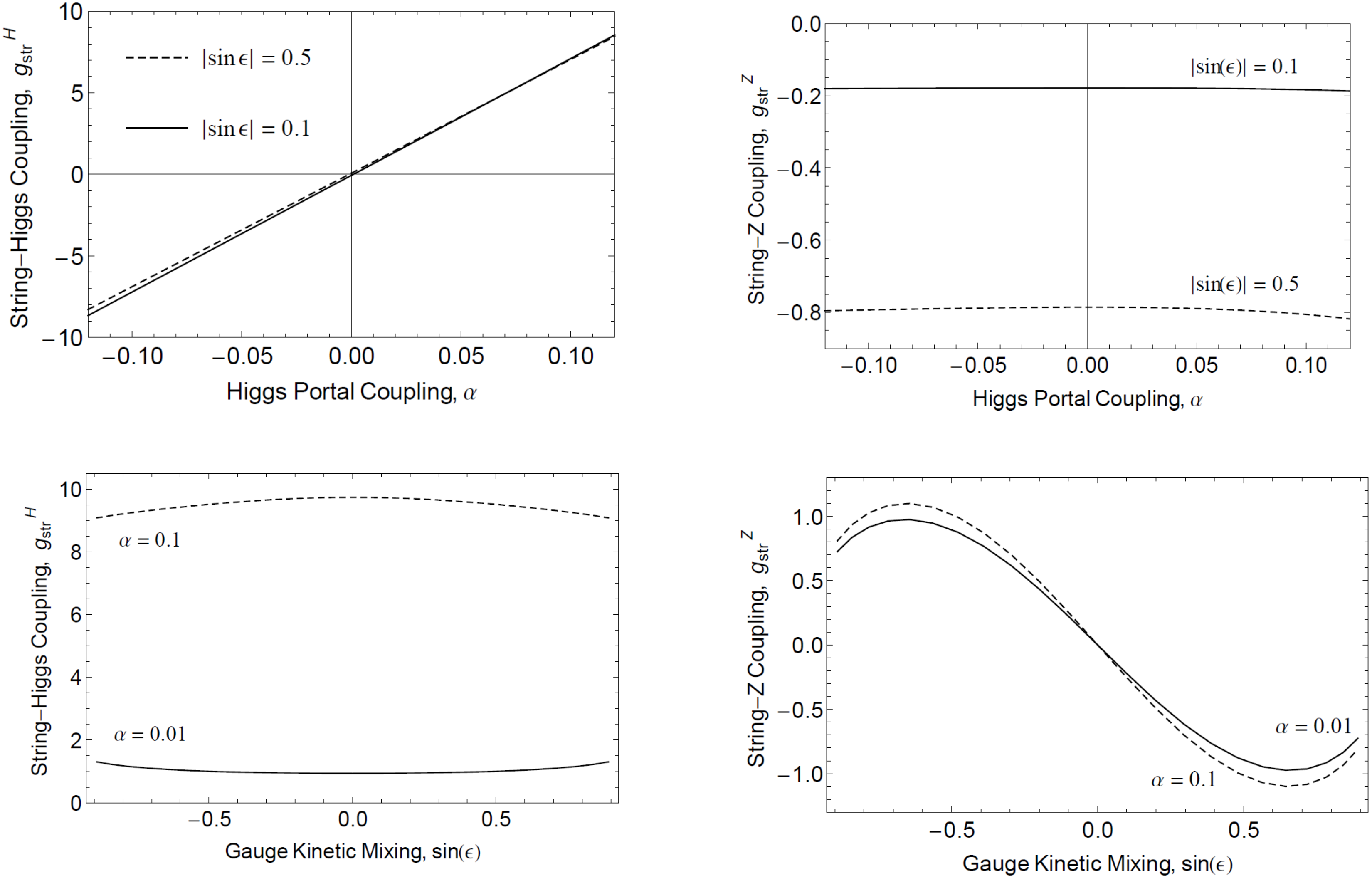
$$k(\xi) \approx g^{\mathrm{Z}}_{\mathrm{str}} \, \sigma^{-2} \, \delta(x)\delta(y) \qquad\qquad g^{\mathrm{Z}}_{\mathrm{str}} \equiv 2\pi \int_0^\infty \xi d\xi \; k(\xi)$$

These source terms can be derived from terms in the action:

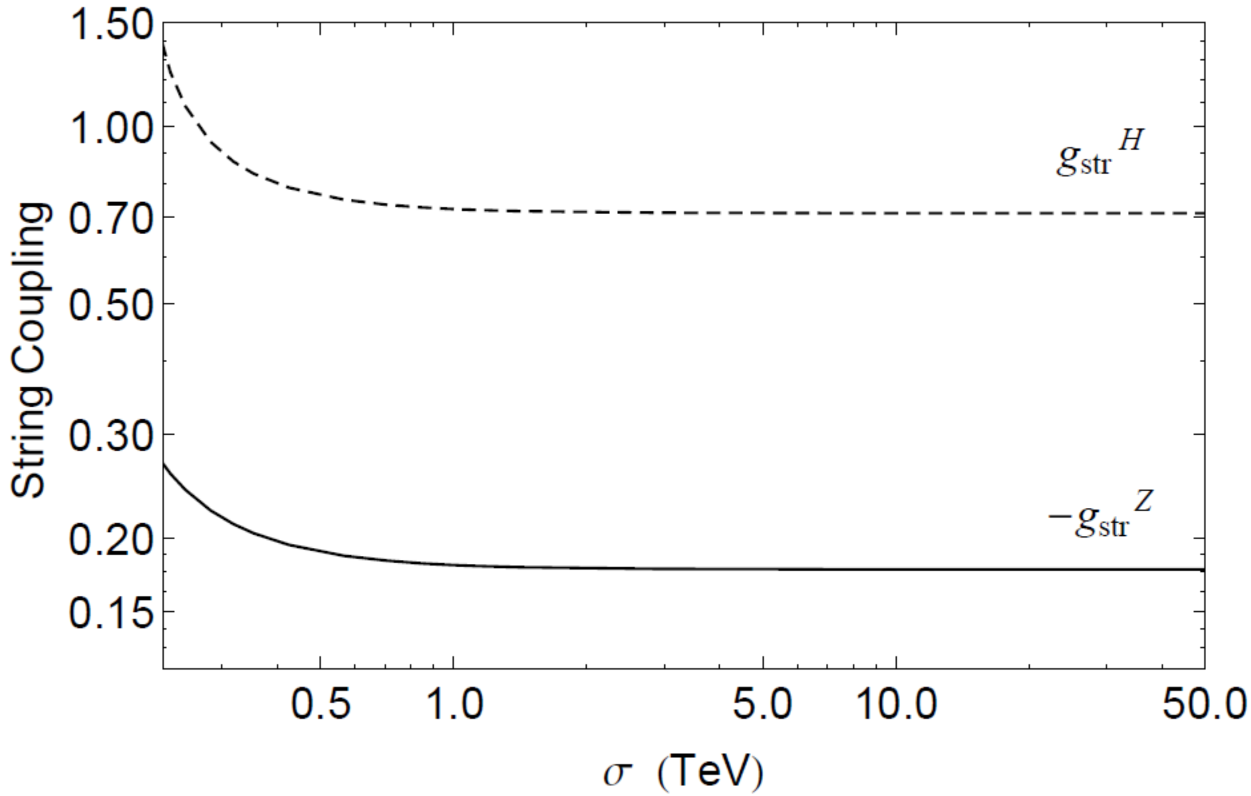
$$S^H_{\mathrm{str}} = g^{\mathrm{H}}_{\mathrm{str}} \, \eta \int d\tau d\zeta \sqrt{-\gamma} \; \phi_H(\mathbb{X}^\mu)$$

$$S^Z_{\mathrm{str}} = \frac{g^{\mathrm{Z}}_{\mathrm{str}}}{2} \left(\frac{\eta}{\sigma}\right)^2 \int d\sigma^{\mu\nu} Z_{\mu\nu}(\mathbb{X}^\mu)$$

Effective Couplings



Couplings at Large Scales



The couplings scale with the electroweak vev η and asymptote to constants as σ >> η

Aharonov-Bohm Coupling

Interior of dark string contains flux of X and/or Z magnetic fields → charged fermions scatter via Aharonov-Bohm interaction.

Cross section for this scattering depends on total flux as well as the couplings g_X and g_Z; all of these depend on the kinetic mixing.

For the (0,1) string, the AB phase is

$$\theta_i = q_i \Theta \qquad \text{with} \qquad \Theta \equiv -2\frac{c_w s_\epsilon}{g_{\mathrm{X}}}$$

and the transport cross-section is

$$\sigma_t\Big|_i = \frac{2}{|\mathbf{p}|} \sin^2 \pi\theta_i$$

Summary

- A common extension of the SM contains strings as topological defects
- These dark strings may interact with SM particles in various ways
- Andrew will discuss cosmological implications.