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Gauge kinetic mixing and dark topological defects

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"Gauge kinetic mixing and dark topological defects"

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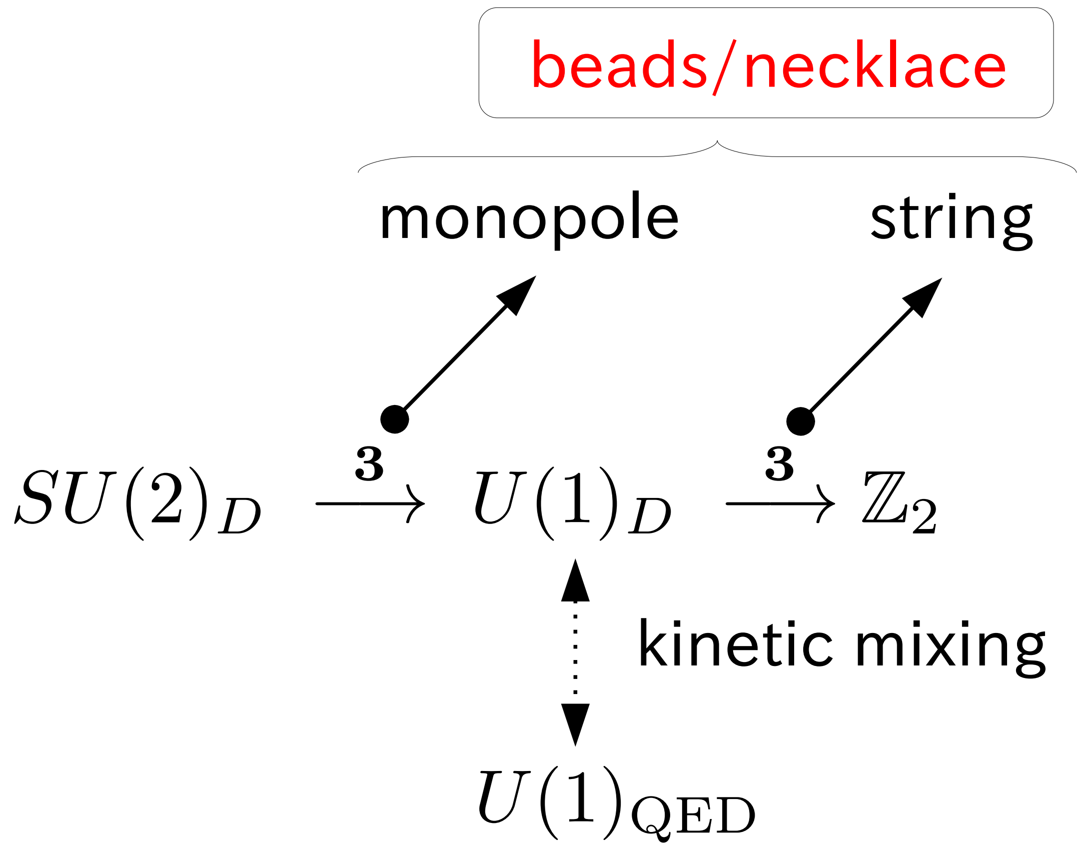
Submitted to JHEP, arXiv:2109.12771

Goal


beads/necklace
monopole
string
SU(2)_D
3
U(1)_D
3
Z_2
kinetic mixing
U(1)_QED

Motivation / Goal

Consider $SU(2)_D \xrightarrow{\mathbf{3}} U(1)_D \xrightarrow{\mathbf{3}} \mathbb{Z}_2$ in the presence of gauge kinetic mixing with $U(1)_{\mathrm{QED}}$, and discuss the effect of the defects.

A hidden U(1) gauge field with the kinetic mixing to SM

- SIDM can resolve the small-scale structure problems (core-cusp/diversity/missing satelites/TBTF) Tulin, Yu, Phys.Rep.730 (2018) 1; Kaplinghat, Tulin, Yu, PRL 116 (2016) 041302
- $U(1)_{B-L}$ provides the small neutrino mass through the seesaw mechanism and its residual discrete symmetry stabilises DM. e.g., Ibe, Matsumoto, Yanagida, PLB 708 (2012) 112
- Transferring large entropy in dark sector to SM

Ibe, Kamada, Kobayashi, Nakano, JHEP 11 (2018) 203

Spontaneously breaking of non-Abelian gauge symmetry to U(1) :

- Non-Abelian theories are UV complete thanks to the asymptotically-free nature, while U(1) is not.

Experiments for dark photon search Bauer, Foldenauer, Jaeckel, JHEP 07 (2018) 094

Model : w/o kinetic mixing

$$\mathcal{L} = -\frac{1}{4}F'^{a}_{\mu\nu}F'^{a\mu\nu} \ -\frac{1}{2}D_\mu\phi_1^a D^\mu\phi_1^a - \frac{1}{2}D_\mu\phi_2^a D^\mu\phi_2^a - V(\phi_1,\phi_2)$$

dark SU(2) triplet scalars in SU(2)

$$V(\phi_1,\phi_2) = \frac{\lambda_1}{4}(\boldsymbol{\phi}_1\cdot\boldsymbol{\phi}_1 - v_1^2)^2 + \frac{\lambda_2}{4}(\boldsymbol{\phi}_2\cdot\boldsymbol{\phi}_2 - v_2^2)^2 + \frac{\kappa}{2}(\boldsymbol{\phi}_1\cdot\boldsymbol{\phi}_2)^2$$

$$D_\mu\phi^a = \partial_\mu\phi^a - ig\epsilon^{abc}A'^b_\mu\phi^c$$

Breaking pettern : $SU(2)_D \xrightarrow{\mathbf{3}} U(1)_D \xrightarrow{\mathbf{3}} \mathbb{Z}_2 \quad (v_1 \gg v_2)$

monopole: $\pi_2(SU(2)_D/U(1)_D) = \mathbb{Z}$

$\mathbb{Z}_2$ string: $\pi_1(U(1)_D/\mathbb{Z}_2) = \mathbb{Z}_2$

Monopole solution

Ansatz for a static monopole

$$\phi^a = vH(r)\frac{x^a}{r} \qquad A'^a_i = \frac{1}{g}\frac{\epsilon^{aij}x^j}{r^2}F(r) \qquad \begin{array}{l} H(r), F(r) \to 0 \ \ (r \to 0) \\ H(r), F(r) \to 1 \ \ (r \to \infty) \end{array}$$

Magnetic charge carried by a monopole

$$\mathcal{F}'_{\mu\nu} \equiv \frac{1}{v}\phi^a F'^a_{\mu\nu} \qquad Q'_M = \frac{1}{2}\int_{r\to\infty} dS_{ij}\mathcal{F}^{ij} = -\frac{4\pi}{g}$$

Maxwell equation and Bianchi identity

$\partial_\mu \mathcal{F}'^{\mu\nu} = 0$ everywhere

$\partial_\mu \widetilde{\mathcal{F}}'^{\mu\nu} \approx 0$ only for $r \gg (gv)^{-1}$ → Dark photon defined in this way cannot be defined grobally

String solution

After the transition of $SU(2)_D \xrightarrow{\mathbf{3}} U(1)_D$ ($\phi_1^a = v_1 \delta^{a3}$)

$$\mathcal{L} \longrightarrow -\frac{1}{4} F'^3_{\mu\nu} F'^{3\mu\nu} - \frac{1}{2} D_\mu \phi_2^a D^\mu \phi_2^a - V(v_1, \phi_2)$$

(other two gauge fields are massive)

Ansatz for a static string

$$\phi^a = v h(\rho) e^{in\varphi} \qquad A'^a_i = -\frac{n}{g} \frac{\epsilon_{ij} x^j}{\rho^2} f(\rho) \qquad \begin{array}{l} h(r), f(r) \to 0 \;\; (\rho \to 0) \\ h(\rho), f(\rho) \to 1 \;\; (\rho \to \infty) \end{array}$$

Magnetic flux carried by a string

$$\Phi(n) = \frac{1}{2} \int dS_i \epsilon_{ijk} F'^{3jk} = \frac{2\pi n}{g}$$

Beads solution

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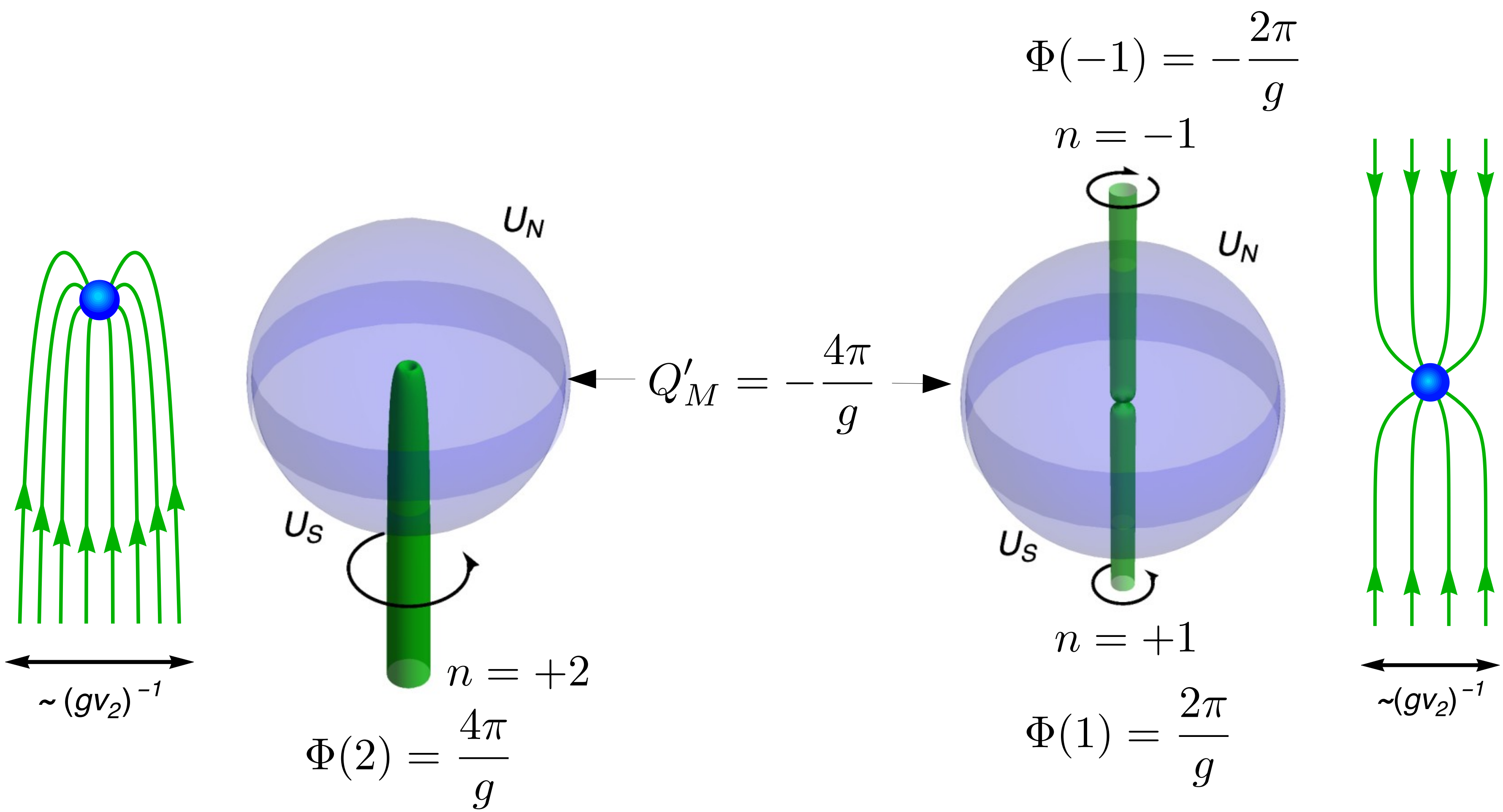
Kibble, Vachaspati, J. Phys. G 42 (2015) 094002 [arXiv:1506.02022]

Asymptotic behaviour of magnetic flux around a monopole



Topologically trivial configuration

Beads solution

Relevant winding number of string is $\{0, 1\} \cong \mathbb{Z}_2$

Cosmological simulation of beads network (= "necklace")

grid size	384
$aL/H^{-1}\|_{\rm in}$	60
$aL/H^{-1}\|_{\rm fin}$	2
Background	Radiation dominant
$\epsilon = v_1/\Lambda$	0.2
$\lambda_{1,\rm in}$	1.0
$\lambda_{2,\rm in}$	1.0
κ	2.0
v_2/v_1	0.3
$g_{\rm in}$	$1/\sqrt{2}$

Use Press-Ryden-Spergel algorithm

$$\lambda_i(\eta) = \frac{\lambda_{i,\rm in}}{a^2}$$

$$g(\eta) = \frac{g_{\rm in}}{a}$$

to maintain the size of monopole/string

Necklace has the scaling property.

Hindmarsh, Rummukainen, Weir, PRD 95 (2017) 063520 [arXiv:1611.08456]

Necklace = beads network

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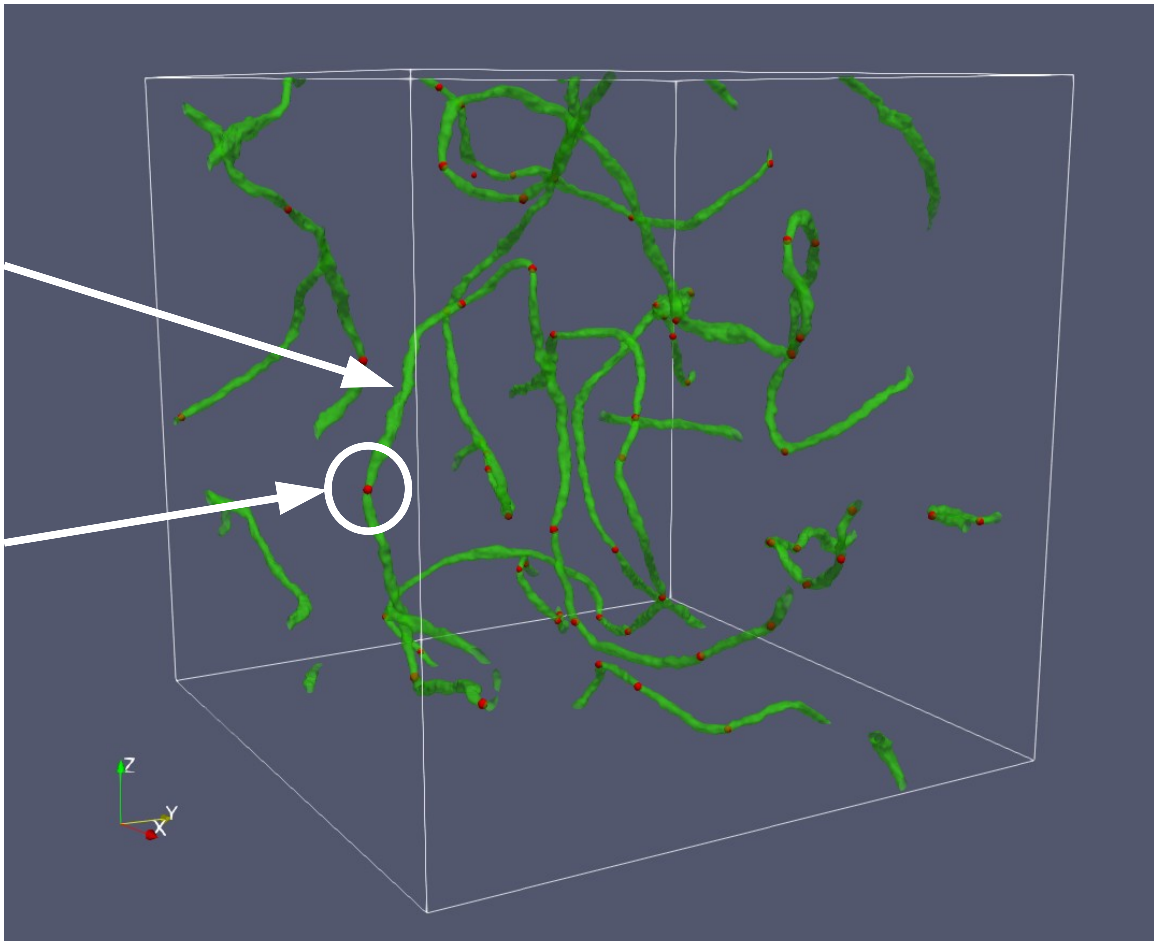
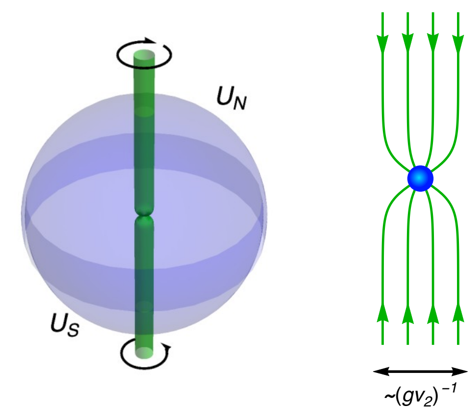
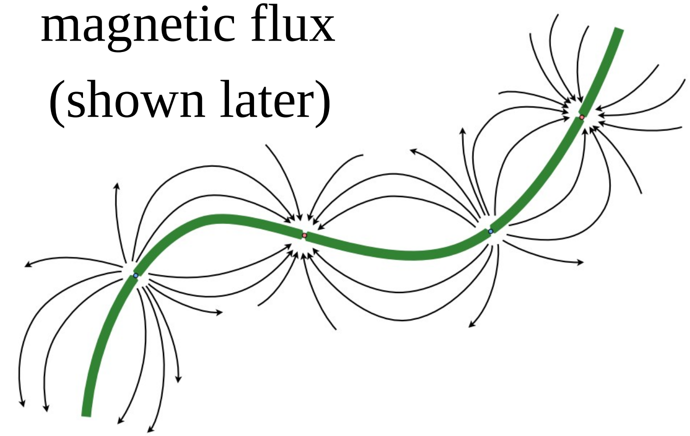
string

monopole





magnetic flux
(shown later)



There are no $n=2$ strings, which rapidly decay by their tension and the annihilation of monopoles.

Model : + kinetic mixing

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$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'^a_{\mu\nu}F'^{a\mu\nu} + \frac{\phi_1^a}{2\Lambda}F'^a_{\mu\nu}F^{\mu\nu}$$

visible U(1) hidden SU(2) mixing

$$-\frac{1}{2}D_\mu\phi_1^a D^\mu\phi_1^a - \frac{1}{2}D_\mu\phi_2^a D^\mu\phi_2^a - V(\phi_1,\phi_2)$$

3-rep. in SU(2)

$$V(\phi_1,\phi_2) = \frac{\lambda_1}{4}(\boldsymbol{\phi}_1\cdot\boldsymbol{\phi}_1 - v_1^2)^2 + \frac{\lambda_2}{4}(\boldsymbol{\phi}_2\cdot\boldsymbol{\phi}_2 - v_2^2)^2 + \frac{\kappa}{2}(\boldsymbol{\phi}_1\cdot\boldsymbol{\phi}_2)^2$$

$$D_\mu\phi^a = \partial_\mu\phi^a - ig\epsilon^{abc}A'^b_\mu\phi^c$$

Breaking pettern : $SU(2)_D \xrightarrow{\mathbf{3}} U(1)_D \xrightarrow{\mathbf{3}} \mathbb{Z}_2$

beads → U(1) flux

$$\frac{\phi^a}{2\Lambda}F'^a_{\mu\nu}F^{\mu\nu}$$

Induced U(1) magnetic field

Around a monopole, we have

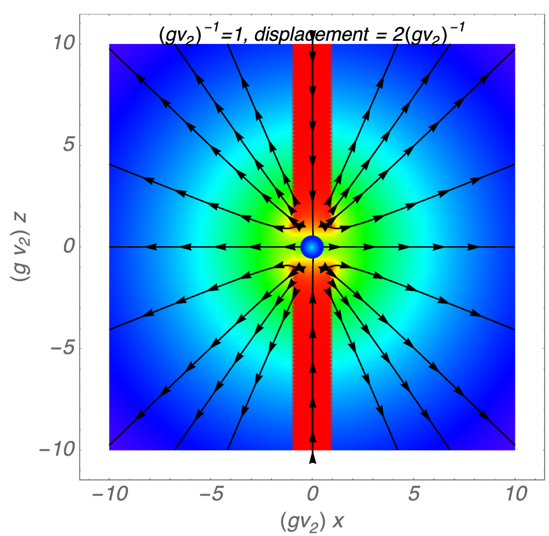
$$\partial_\mu \mathcal{F}'^{\mu\nu} = 0$$

$$\partial_\mu F^{\mu\nu} - \epsilon \partial_\mu \mathcal{F}'_{\mu\nu} = e J^\nu_{\rm QED} \qquad \epsilon \equiv \frac{v_1}{\Lambda}, \mathcal{F}'_{\mu\nu} \equiv \frac{1}{v} \phi^a F'^a_{\mu\nu}$$

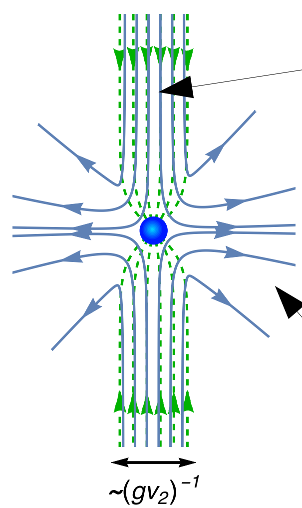
$$\partial_\mu \widetilde{F}^{\mu\nu} = 0$$

→ monopole cannot induce QED magnetic field.

Instead, strings can do it. Defining $B^{(\rm QED)}_\mu \equiv \frac{1}{2} \epsilon_{\mu\alpha\beta} F^{\alpha\beta}$, we expect the resultant field would look like two glued solenoids.



(schematic picture)



induced magnetic field parallel to string

escaping from string and monopole

Effective field strength of dark sector

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We'd like to see the field strength around monopoles.

But, $\mathcal{F}'_{\mu\nu} \equiv \frac{1}{v_1}\phi_1^a F'^a_{\mu\nu}$ is relevant only for $r \gg (gv)^{-1}$.

New effective field strength

$$F'^{(\mathrm{eff})}_{\mu\nu} = \frac{1}{|\phi|}\phi^a(\partial_\mu A'^a_\nu - \partial_\nu A'^a_\mu + g\epsilon^{abc}A'^b_\mu A'^c_\nu) - \frac{1}{g|\phi|^3}\epsilon_{abc}\phi^a D_\mu\phi^b D_\nu\phi^c$$

'tHooft, NPB 79 (1974) 276

$$A'^1_\mu = A'^2_\mu = 0, A'^3_\mu \neq 0, \phi^1 = \phi^2 = 0, \phi^3 \neq 0$$

$$\longrightarrow \quad F'^{(\mathrm{eff})}_{\mu\nu} = \partial_\mu A'^3_\nu - \partial_\nu A'^3_\mu$$ looks like U(1)

Effective magnetic field / QED magnetic field

$$B'^{(\mathrm{eff})}_i = \frac{1}{2}\epsilon_{ijk}F'^{(\mathrm{eff})}_{jk} \qquad B^{(\mathrm{QED})}_i = \frac{1}{2}\epsilon_{ijk}F_{jk}$$

Numerical simulation

Cosmological simulation of beads network (=Necklace)

grid size	256
$aL/H^{-1}\|_{\rm in}$	30
$aL/H^{-1}\|_{\rm fin}$	0.2
Background	Radiation dominant
$\epsilon = v_1/\Lambda$	0.2
λ_1	1.0
λ_2	1.0
κ	2.0
v_2/v_1	0.3
g	$1/\sqrt{2}$

Use Press-Ryden-Spergel algorithm

$$\lambda_i(\eta) = \frac{\lambda_{i,\rm in}}{a^2}$$

$$g(\eta) = \frac{g_{\rm in}}{a}$$

to maintain the size of monopole/string

Perform simulations for longer time than before so that box size becomes smaller than horizon size.

→ strings straighten

Magnetic field on necklace

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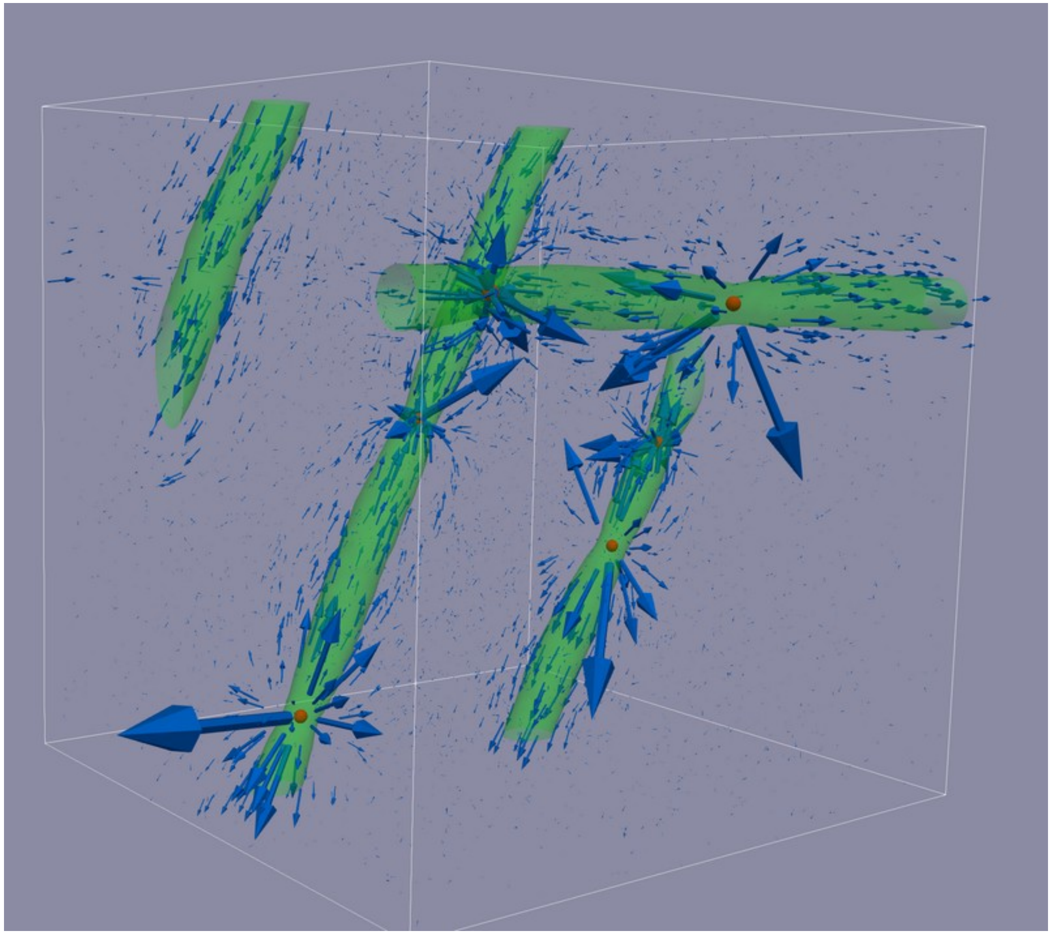
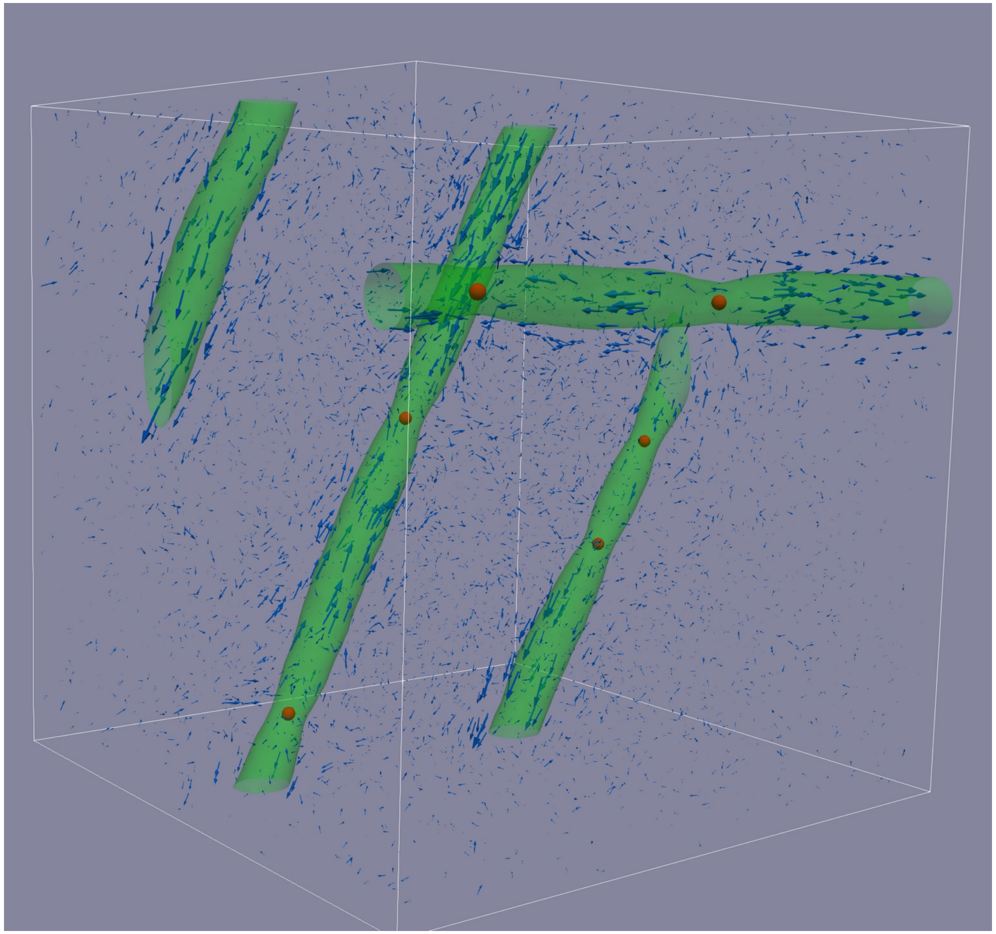
$B_i'^{(\mathrm{eff})}$

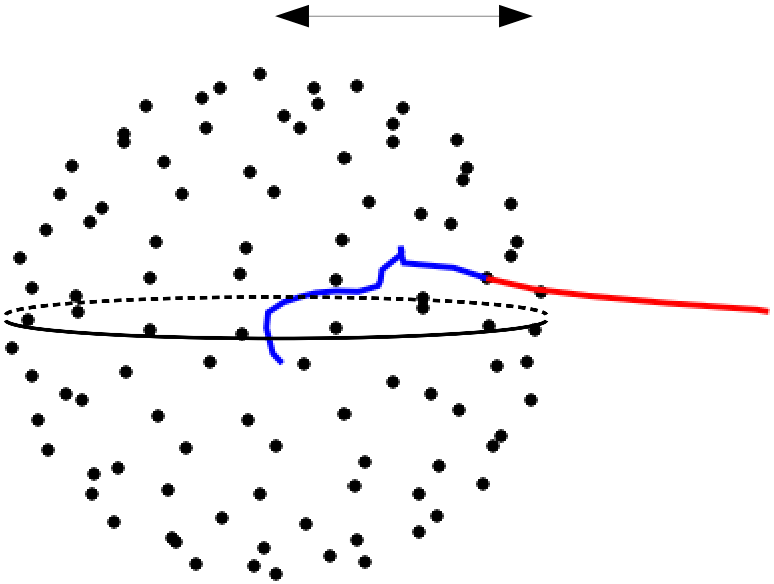


$B_i'^{(\mathrm{QED})}$



How to draw a stremline

$$r_* = \alpha_* \left(\frac{3V}{4\pi}\right)^{1/3}$$



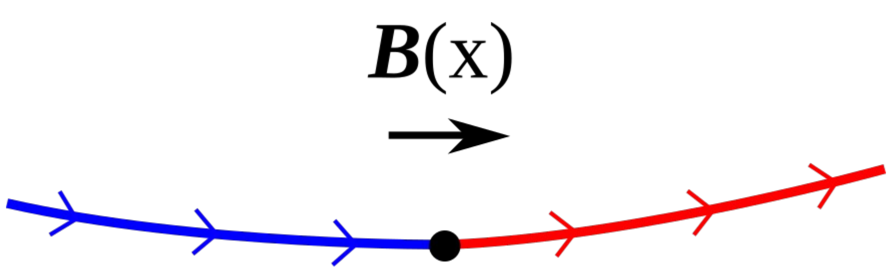
1. Identify the volume, V, satisfying $|\phi_1| < \frac{v_1}{2}$ centred at a monopole.

2. Generate starting points on a 2-sphere with radius r_* .

3a. Solve the following equation from $\zeta = 0$ to $\zeta > 0$ (red line)

$$\frac{d\boldsymbol{x}_s}{d\zeta} = \boldsymbol{B}(\boldsymbol{x}_s(\zeta))$$

3b. Solve it from $\zeta = 0$ to $\zeta < 0$ (blue line)



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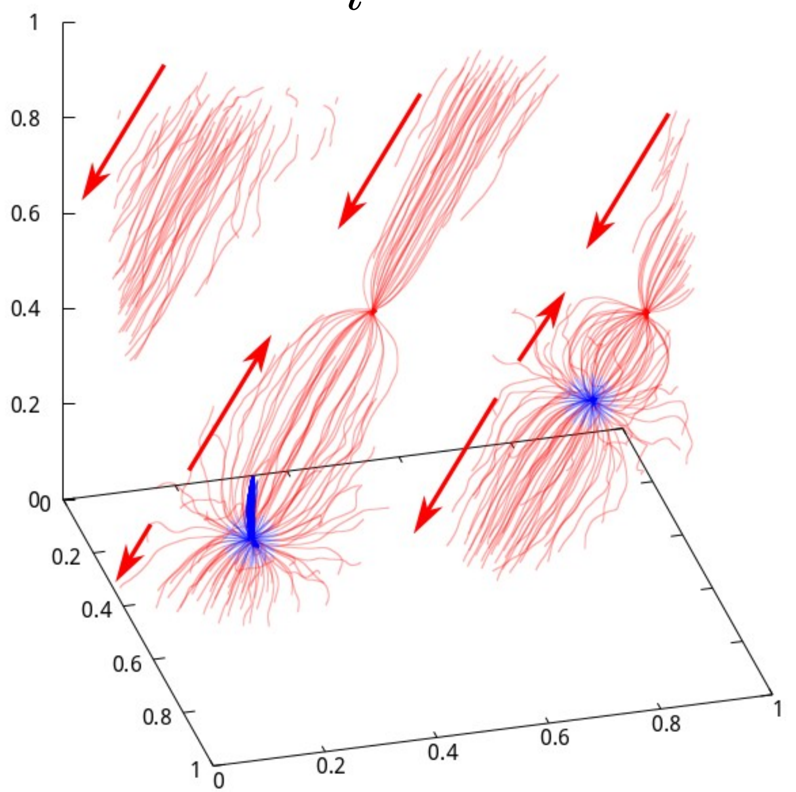
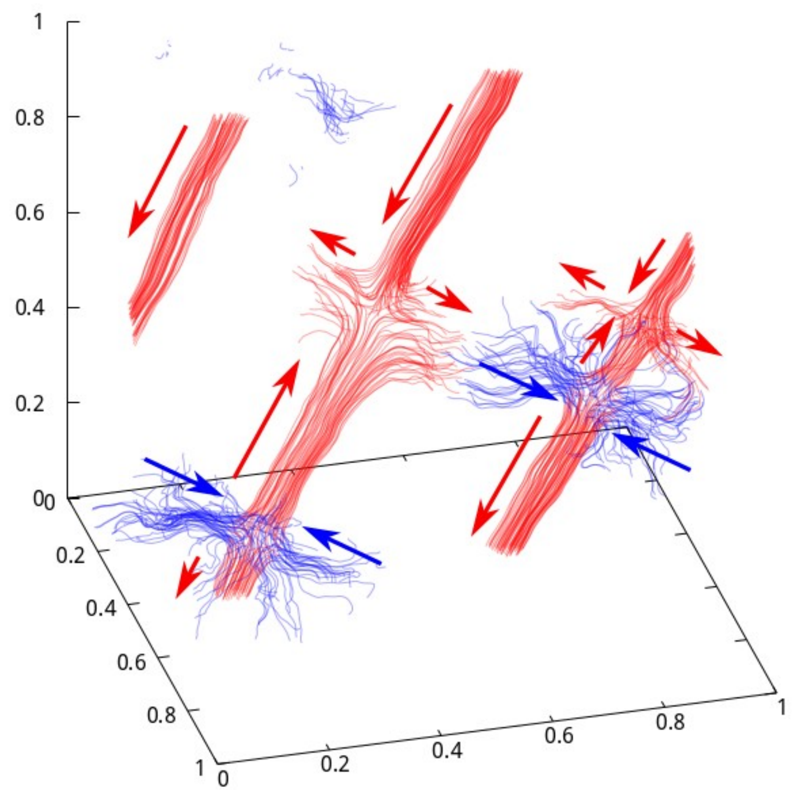
Effective field strength

$B_i'^{(\mathrm{eff})}$



$B_i^{(\mathrm{QED})}$



The dark magnetic flux is well confined into a string, while the associated QED magnetic flux imitates the Hedgehog configuration like a monopole.

Discussion

Dark monopoles are always connected to strings.

→ Monopoles can move only along strings.

(if the string network in this model has the scaling property,...)

The number of strings is only a few in the cosmological horizon.

→ Only a few dark monopoles would exist in our Universe.

→ evading the astrophysical bounds like Paker's bound

(upper limit from Galactic magnetic field)

Summary

We study the topological defects in a non-abelian model realising $SU(2)_D \xrightarrow{\mathbf{3}} U(1)_D \xrightarrow{\mathbf{3}} \mathbb{Z}_2$ with gauge kinetic mixing.

- Hybrid defect ‘necklace’ (beads network) appears.

- Necklace confines dark magnetic flux from ‘t Hooft-Polyakov monopoles

- Dark U(1) gauge field can induce QED magnetic flux through the kinetic mixing, mimicking QED monopoles.