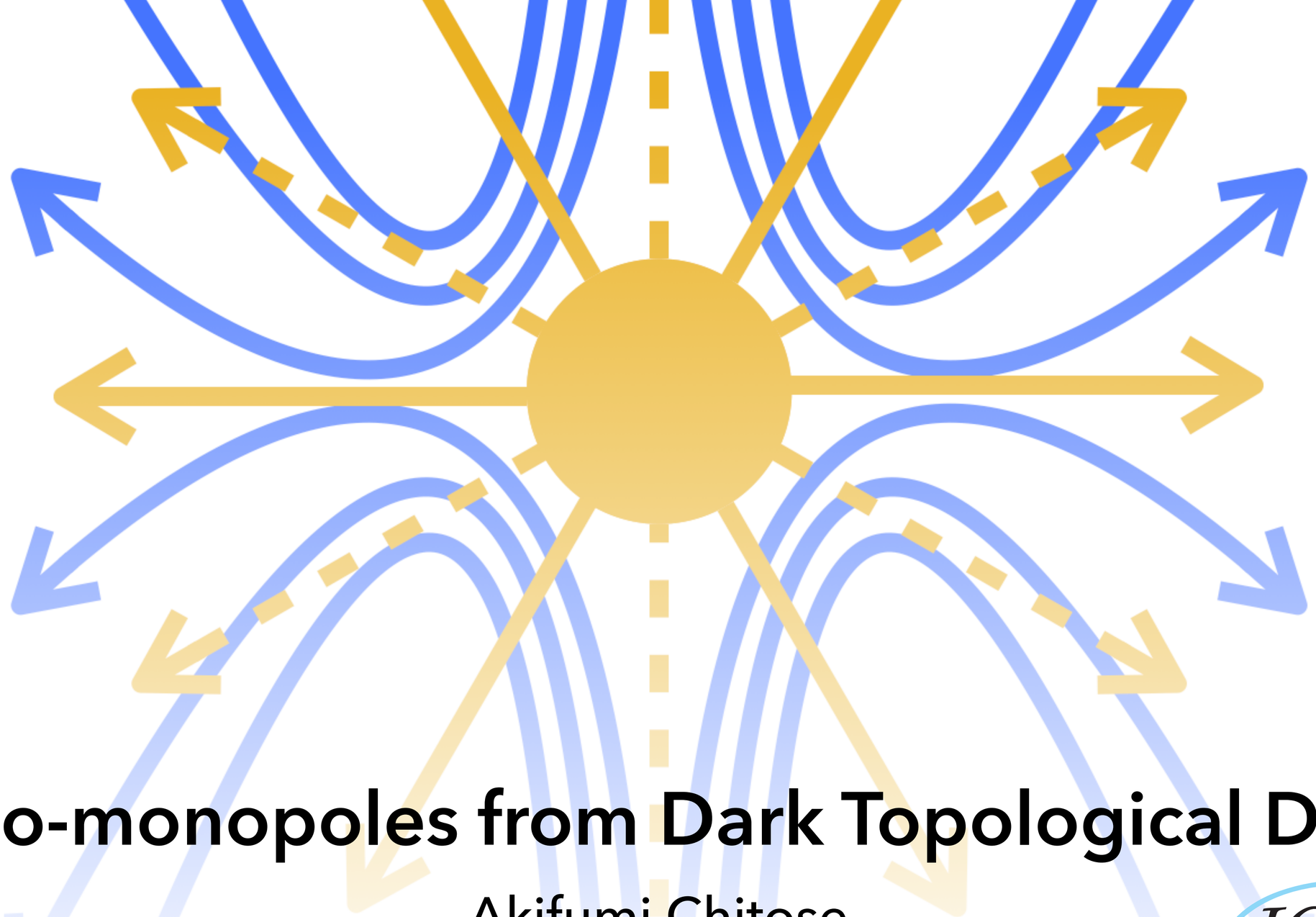

Pseudo-monopoles from Dark Topological Defects

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Introduction

Dark Photon

- $\mathrm{U}(1)_{\mathrm{D}}$ gauge boson
  - Possibly Higgsed to be massive → DM candidate
  - Interacts with photon ($\mathrm{U}(1)_{\mathrm{QED}}$) through kinetic mixing $\epsilon F_{\mu\nu} F^{\mu\nu}_{\mathrm{D}}$

$SU(2)_D \to U(1)_D$ Dark Photon

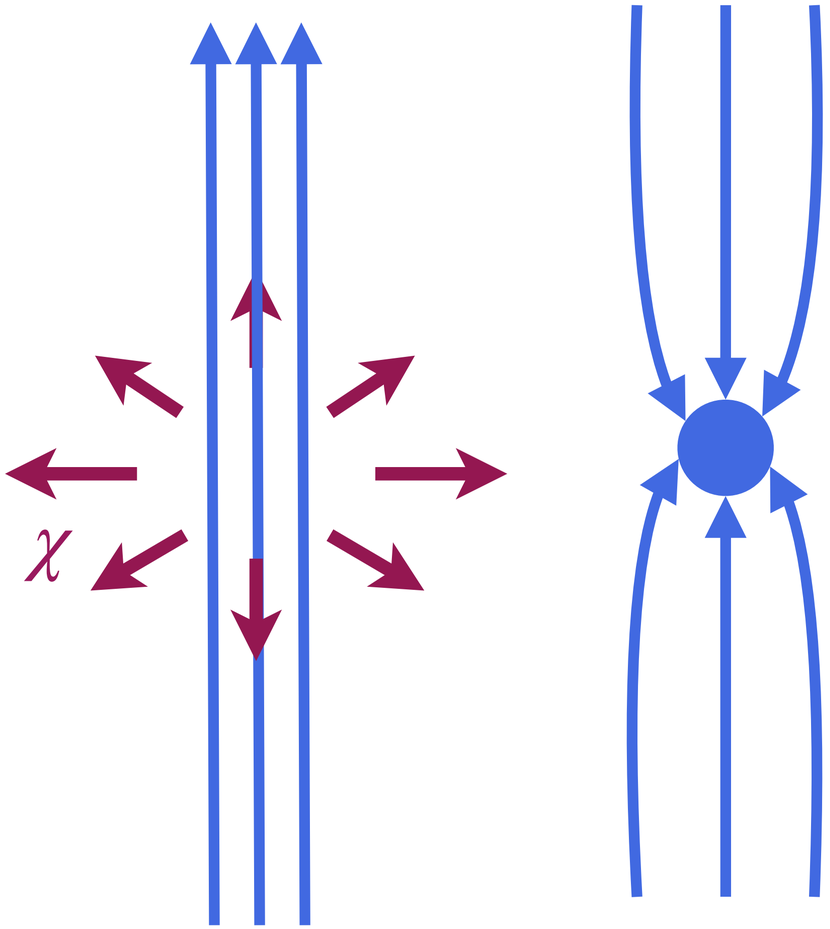
- Embedding: $\mathrm{SU}(2)_\mathrm{D} \to \mathrm{U}(1)_\mathrm{D} \to \mathbb{Z}_2$
  - $V(\phi,\eta) = \frac{\lambda_1}{4}\left(\phi^a\phi^a - v_1^2\right)^2 + \frac{\lambda_2}{4}\left(\eta^a\eta^a - v_2^2\right)^2 + \frac{\kappa}{2}\left(\phi^a\eta^a\right)^2$
  - $v_1 \gg v_2$ is assumed for the SSB pattern $\left(\langle\phi\rangle, \langle\eta\rangle\right) = (0,0) \to (v_1,0) \to (v_1, v_2)$
- Mixing with $\mathrm{U}(1)_\mathrm{QED}$ is naturally small (treated perturbatively here)
  - $\frac{c_1}{\Lambda}\phi^a F_{\mu\nu} F_\mathrm{D}^{a\mu\nu}$: kinetic mixing
  - $\frac{c_2}{\Lambda}\phi^a F_{\mu\nu} \tilde{F}_\mathrm{D}^{a\mu\nu}$: magnetic mixing
- Asymptotically free

Effective $U(1)_{QED} \times U(1)_D$ description

- Effective description in the trivial vacuum of ϕ: $\phi^a = v_1 \delta^a_3$
- $F^{\mu\nu}_{\mathrm{D}} := \dfrac{\phi^a}{v_1} F^{a\mu\nu}_{\mathrm{D}}$: effective $\mathrm{U}(1)_{\mathrm{D}}$ field strength
  - $\dfrac{c_1}{\Lambda} \phi^a F_{\mu\nu} F^{a\mu\nu}_{\mathrm{D}} \to -\dfrac{\epsilon}{2} F_{\mu\nu} F^{\mu\nu}_{\mathrm{D}}$: kinetic mixing
  - $\dfrac{c_2}{\Lambda} \phi^a F_{\mu\nu} \tilde{F}^{a\mu\nu}_{\mathrm{D}} \to -\dfrac{\theta_{\mathrm{mix}}}{16\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu}_{\mathrm{D}}$: magnetic mixing, but total derivative
- $\chi := \dfrac{1}{\sqrt{2}} \left(\eta^1 + i\eta^2 \right)$: $\mathrm{U}(1)_{\mathrm{D}}$ Higgs

Topological Defects

- Associated with spontaneous symmetry breakdown
- Stabilized for topological reasons
- In our case:
  - monopoles at $\mathrm{SU}(2)_{\mathrm{D}} \to \mathrm{U}(1)_{\mathrm{D}}$
  - strings, beads at $\mathrm{U}(1)_{\mathrm{D}} \to \mathbb{Z}_2$
- Question: How do they interact with QED?

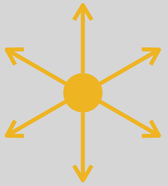
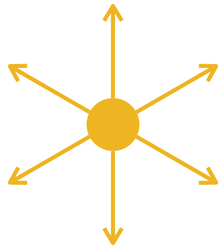
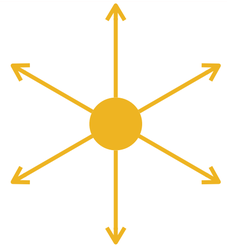
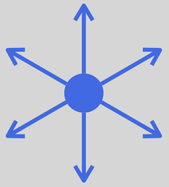
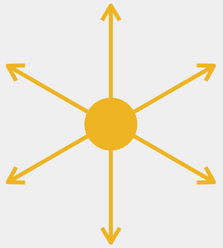
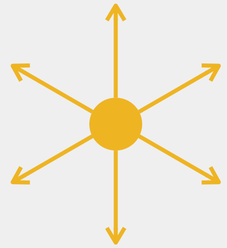
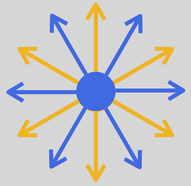
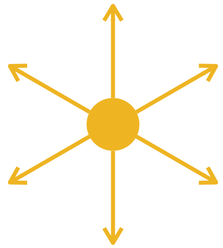
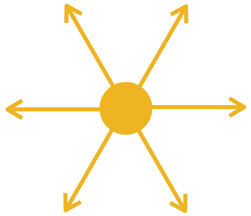
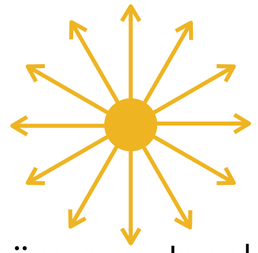


Analysis: $U(1)_D$ symmetric phase

dark electric charge / monopole and mixing terms

- EoM: $\partial_\mu F^{\mu\nu} - \epsilon \partial_\mu \left(\frac{\phi^a}{v_1} F_{\rm D}^{a\mu\nu} \right) + \frac{\theta_{\rm mix}}{8\pi^2} \partial_\mu \left(\frac{\phi^a}{v_1} \tilde{F}_{\rm D}^{a\mu\nu} \right) = e J^\nu_{\rm QED}$
  - $\rightarrow N_{\rm QED} = \frac{1}{e} Q^e_{\rm QED} - \frac{\epsilon}{e} Q^e_{\rm D} + \frac{\theta_{\rm mix}}{8\pi^2} Q^m_{\rm D}$
    - Q's: charge measured by field flux
- $N_{\rm QED} = 0$ for both dark electric charge / monopole
  - $\rightarrow Q^e_{\rm QED} = \epsilon e_{\rm D}$ for dark electric charge, $Q^e_{\rm QED} = -\frac{e\theta_{\rm mix}}{8\pi^2} Q^m_{\rm D}$ for monopole

QED charge in $U(1)_D$ symmetric phase

Dark Sector	Kinetic Mixing	Magnetic Mixing	Total
Electric Charge 	 [Holdom (1986)]	None [Brümmer, Jaeckel, Khoze (2009)]	 [Brümmer, Jaeckel, Khoze (2009)]
Monopole 	None [Brümmer, Jaeckel (2009)]	 [Brümmer, Jaeckel, Khoze (2009)]	 [Brümmer, Jaeckel, Khoze (2009)]
Dyon 	 [Brümmer, Jaeckel, Khoze (2009)]	 [Brümmer, Jaeckel, Khoze (2009)]	 [Brümmer, Jaeckel, Khoze (2009)]

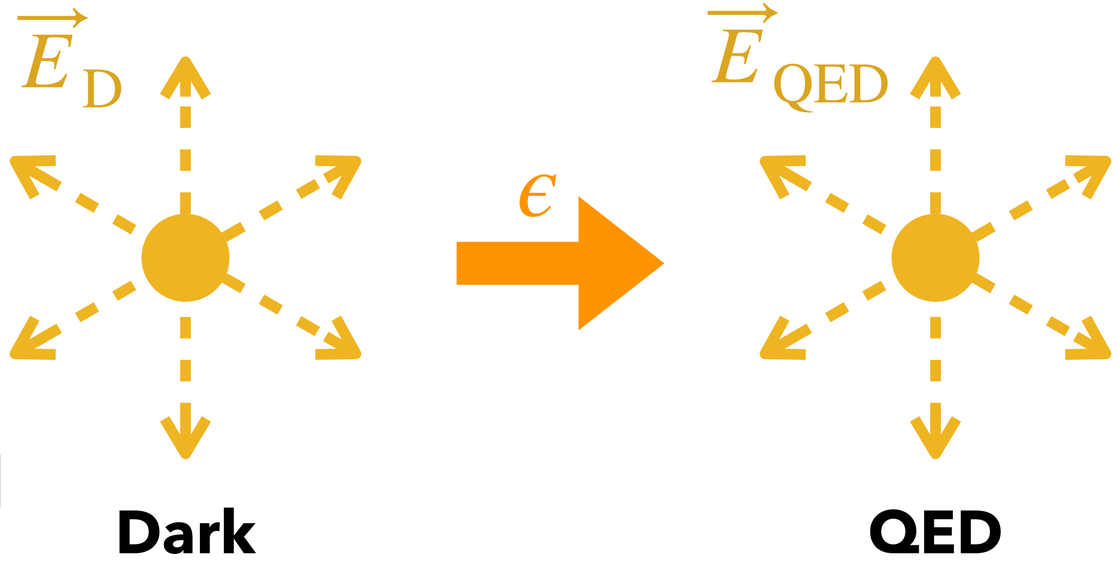
Analysis: $U(1)_D$ broken phase

Basis change in $U(1)_{QED} \times U(1)_D$

- "Decoupled basis": $\begin{pmatrix} 1 & \frac{\epsilon}{1-\epsilon^2} \\ 0 & \frac{1}{1-\epsilon^2} \end{pmatrix} \begin{pmatrix} A' \\ A'_D \end{pmatrix} := \begin{pmatrix} A \\ A_D \end{pmatrix}$
  - EoMs: $\begin{cases} \partial_\mu F'^{\mu\nu} = e J^\nu_{QED} \\ \partial_\mu F'^{\mu\nu}_D - m'^2_D A'^\nu_D = \frac{e_D}{\sqrt{1-\epsilon^2}} J^\nu_D + \frac{\epsilon e}{\sqrt{1-\epsilon^2}} J^\nu_{QED} \end{cases}$
- reminder: θ_{mix} does nothing in the absence of monopoles

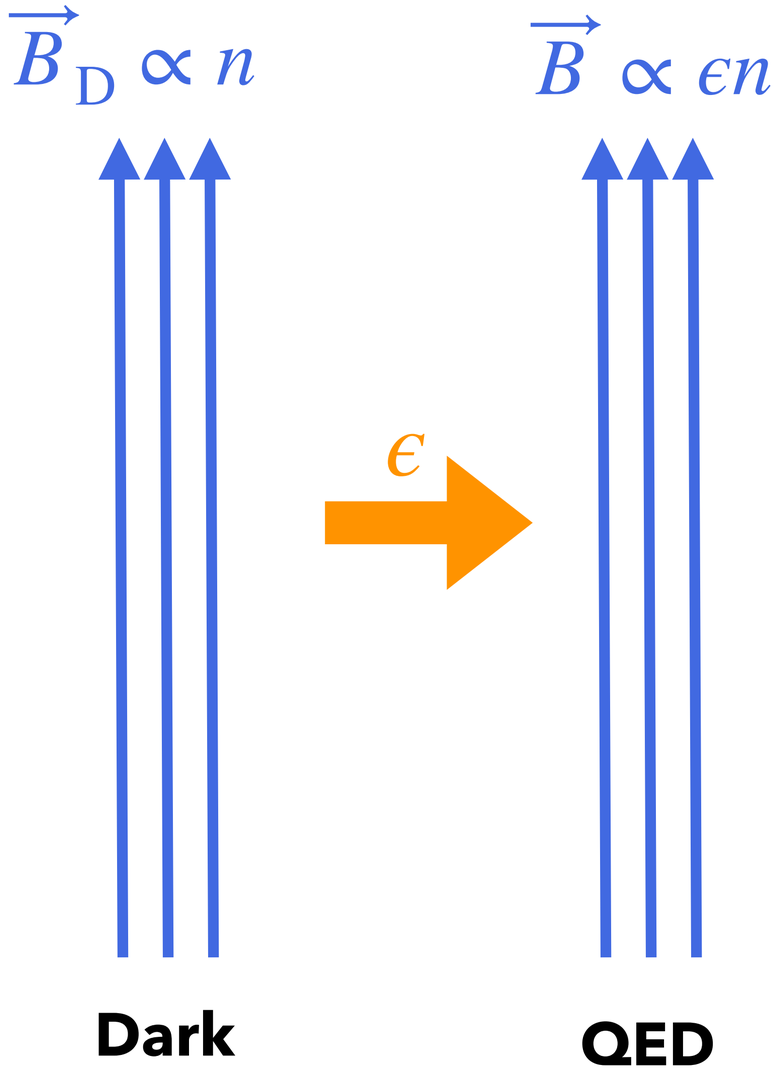
Dark electric charge and kinetic mixing

- $\partial_\mu F'^{\mu\nu}_{\mathrm{D}} - m'^2_{\mathrm{D}} A'^{\nu}_{\mathrm{D}} = \dfrac{e_{\mathrm{D}}}{\sqrt{1-\epsilon^2}} J^{\nu}_{\mathrm{D}}$
  - $\rightarrow A'_{\mathrm{D}}$: Yukawa Potential
  - $\rightarrow A \sim \epsilon A'_{\mathrm{D}}$: also Yukawa potential

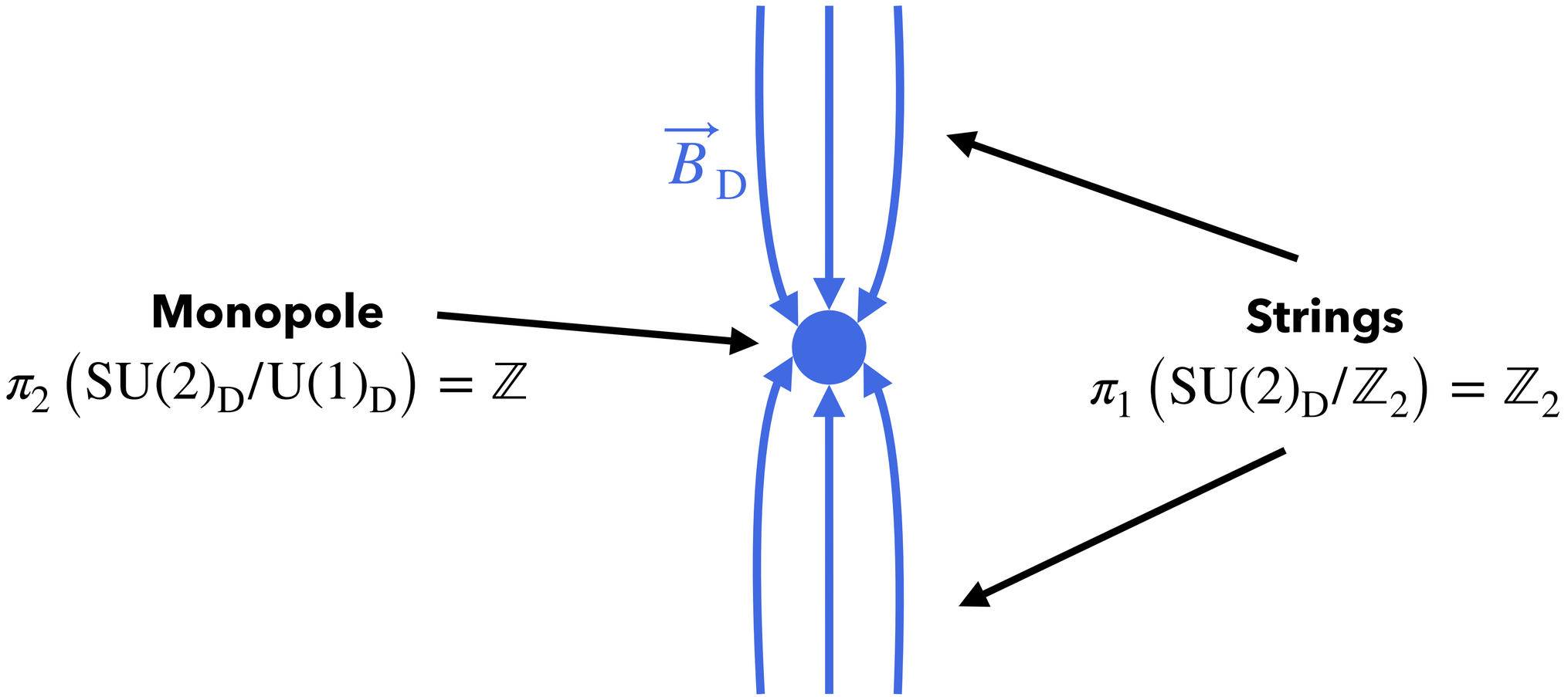


Strings and kinetic mixing

- Stabilized by $\pi_1\left(\mathrm{SU}(2)_\mathrm{D}/\mathbb{Z}_2\right) = \mathbb{Z}_2$
  - subgroup of $\pi_1\left(\mathrm{U}(1)_\mathrm{D}/\mathbb{Z}_2\right) = \mathbb{Z}$
    (corresponds to assuming $\phi^a = v_1\delta_3^a$)
- $$\int \vec{B}'_\mathrm{D} \cdot d\vec{S} = \frac{1}{e'_\mathrm{D}} \oint i\chi^{-1} d\chi = -\frac{2\pi n}{e'_\mathrm{D}}$$
  (n: winding number)
  - $B \sim \epsilon B_\mathrm{D}$ → magnetic flux induced



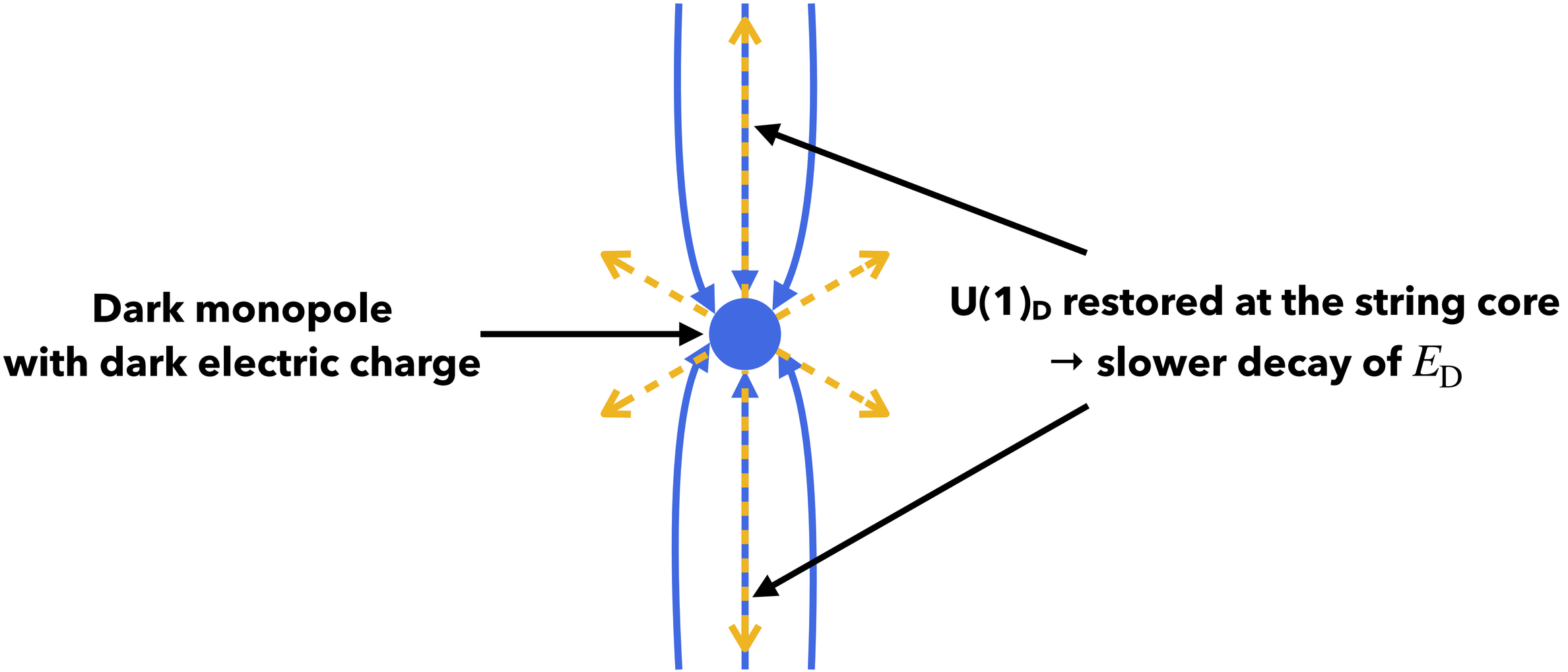
Dark Bead



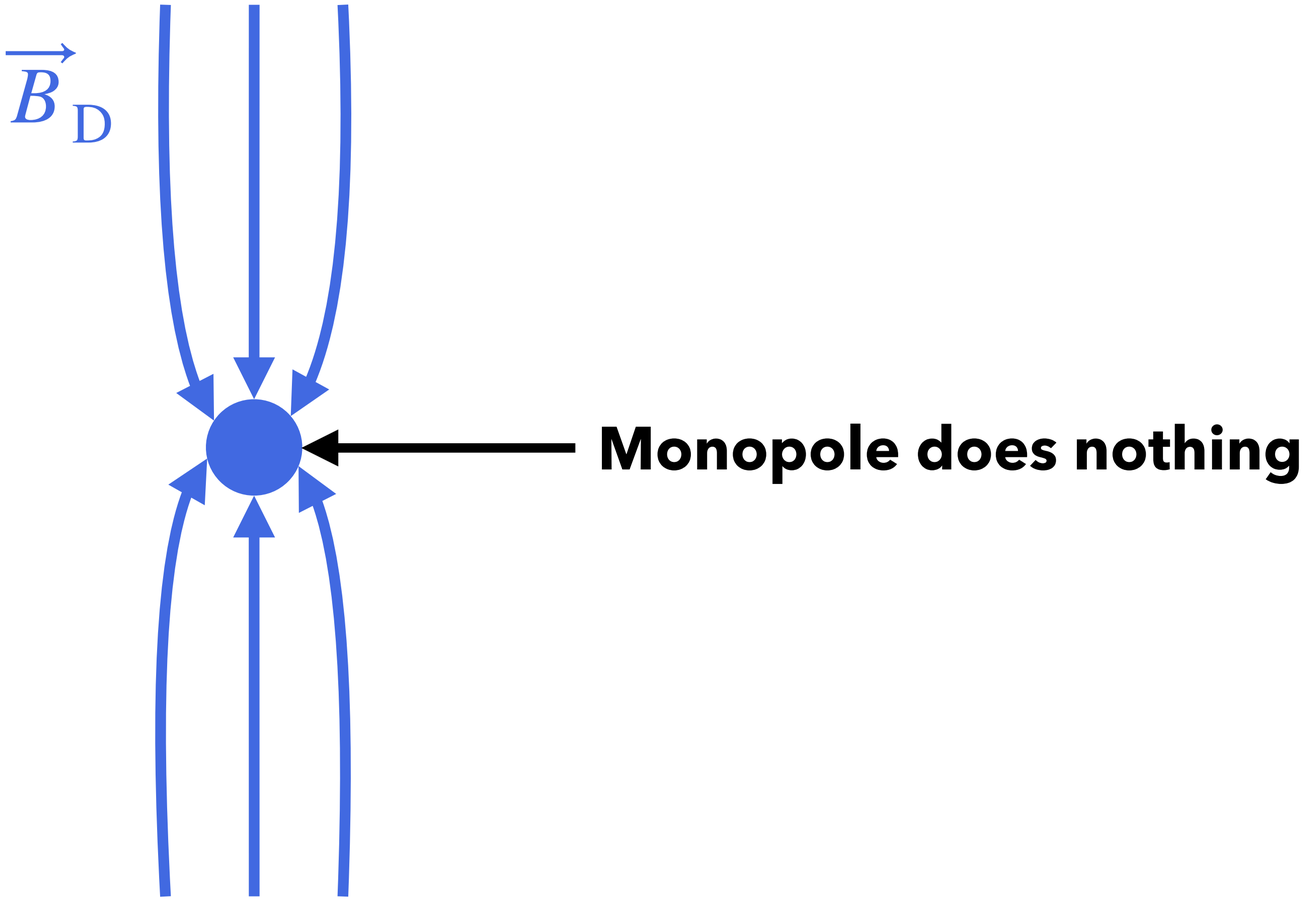
(magnetic flux of a monopole) = 2 × (magnetic flux through a string)

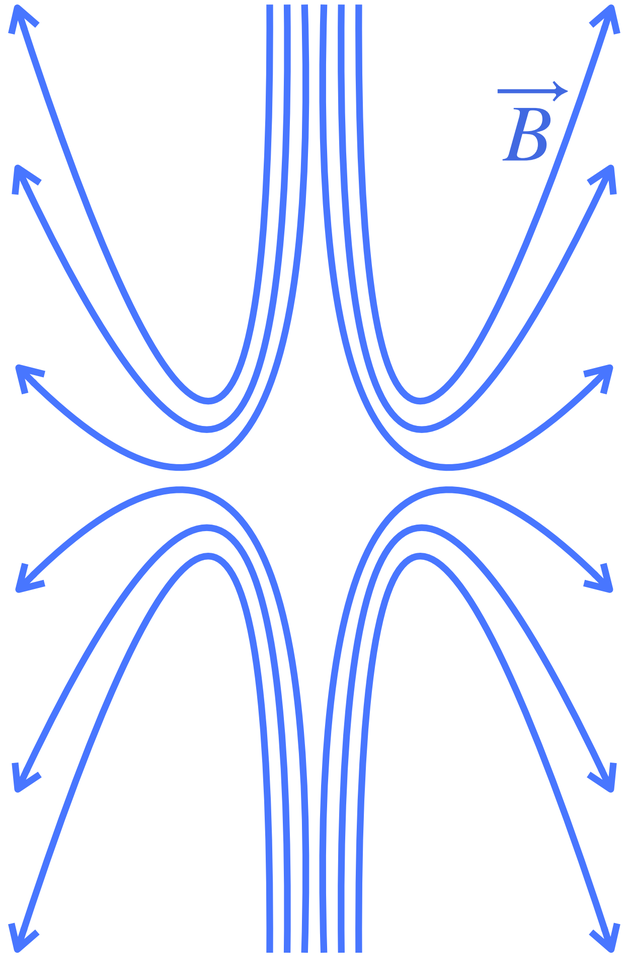
→ Two strings must attach to the monopole

Dyonic bead


Dark monopole
with dark electric charge
U(1)D restored at the string core
→ slower decay of E_{D}

Bead and kinetic mixing

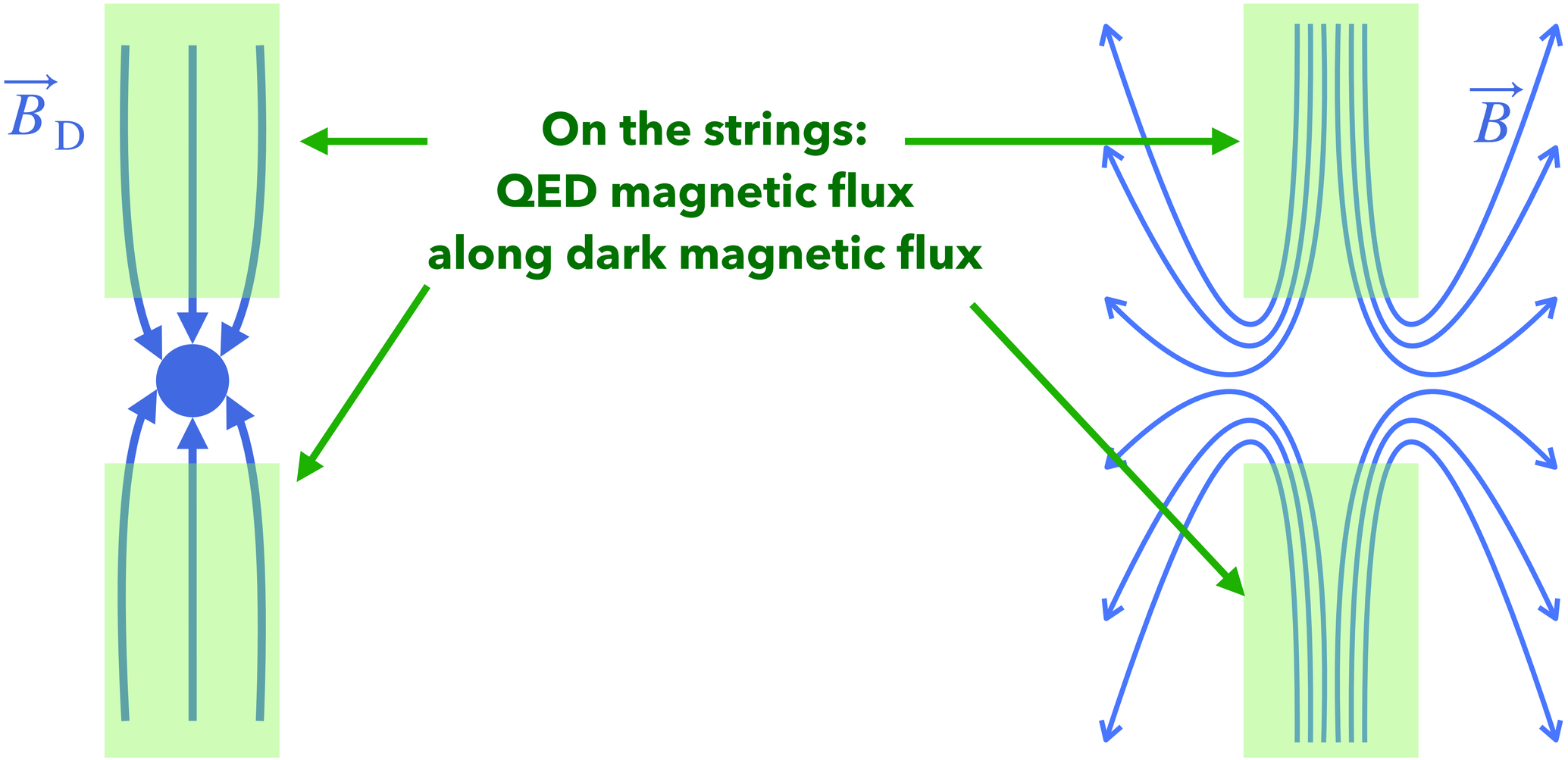




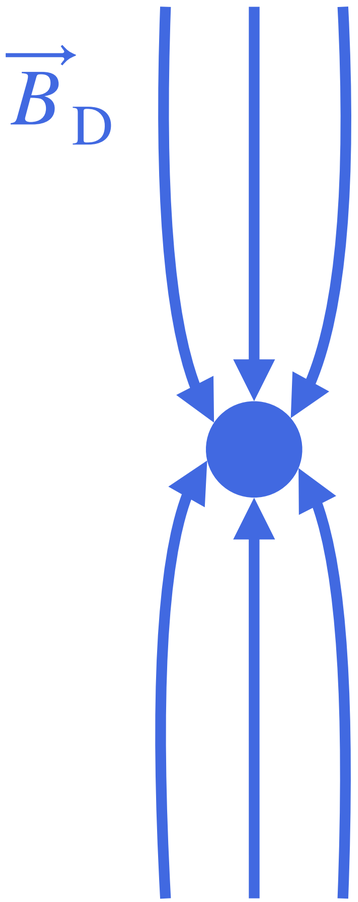
Dark sector

QED sector

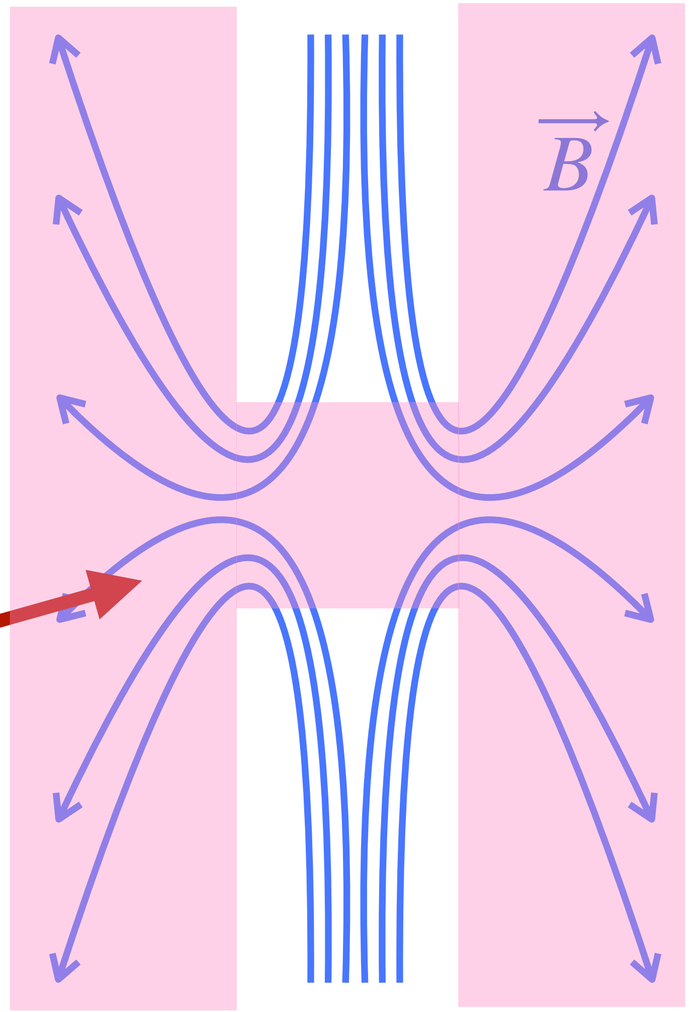
Bead and kinetic mixing



Bead and kinetic mixing



Outgoing magnetic field
"Pseudo-Monopole"

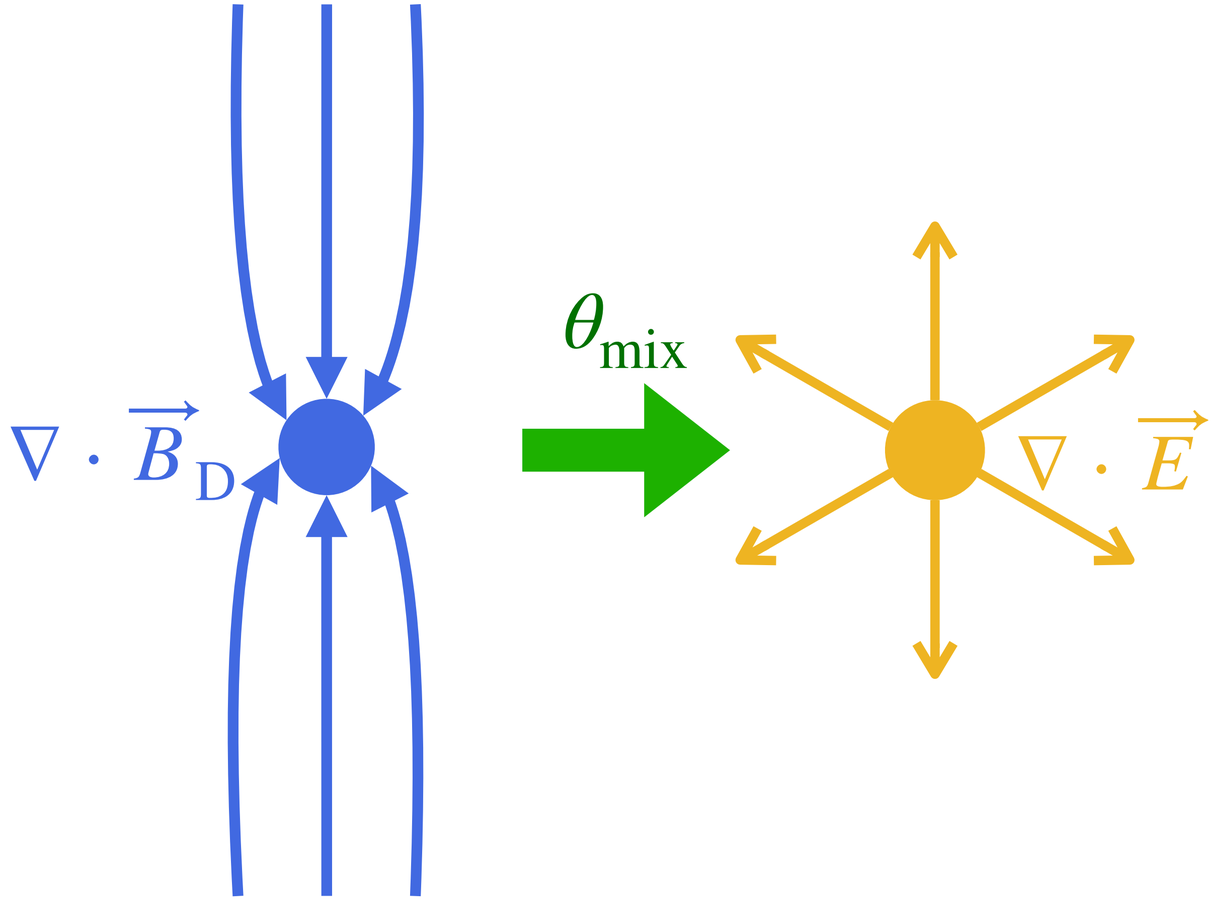


Dark sector

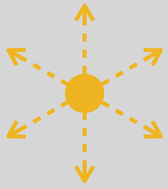
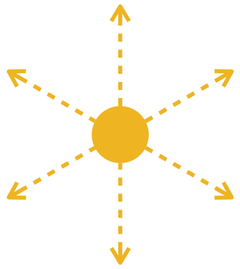
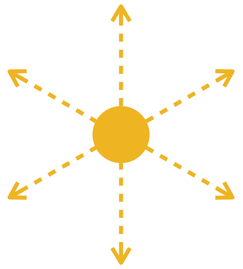
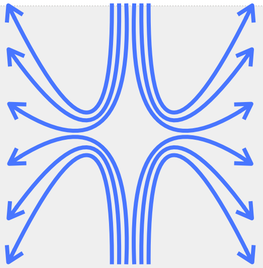
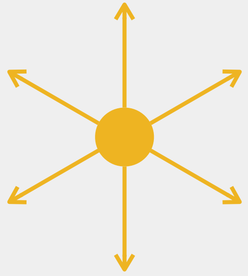
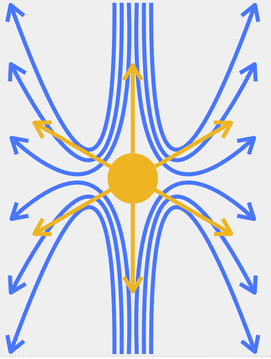
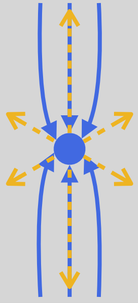
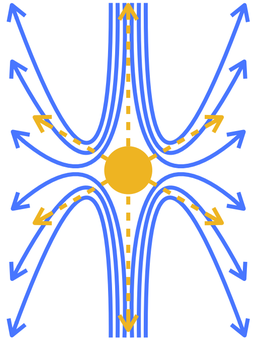
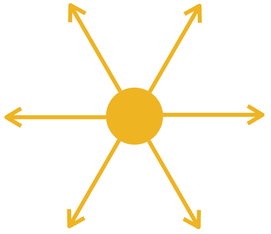
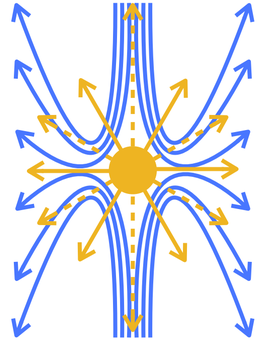
QED sector

Bead and magnetic mixing

- The strings do nothing
- EoM: $\partial_i E^i = \dfrac{\theta_{\rm mix}}{8\pi^2}\partial_i B^i_{\rm D}$
  → QED Coulomb potential
  - ↔ Yukawa (dark electric charge)



Summary: $U(1)_D$ broken phase

Dark Sector	Kinetic Mixing	Magnetic Mixing	Total
Electric Charge 		None	
Bead 	 [Hiramatsu, Ibe, Suzuki, Yamaguchi (2021)]		
Dyonic bead 			

Outlook on phenomenology

- Interaction with the plasma?
- Interaction with / implications on magnetic field in the Universe?
  - Magnetic field can be strong (no Schwinger effect)
- Implications on gravitational wave spectrum?

Conclusions

- Dark monopoles / strings / beads induce peculiar electromagnetic fields through kinetic / magnetic mixing terms
- Dark topological defects are potential probes for the dark sector