

# Pseudodyons from dark topological defects

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## Dark photon by $SU(2) \rightarrow U(1) [\rightarrow Z_2]$

### Setup

#### Field Contents

$A_D^a$ :  $SU(2)_D$  Gauge Field

$A$ :  $U(1)_{\text{QED}}$  Gauge Field

$\phi^a, \eta^a$ :  $SU(2)_D$  Adjoint scalar

#### Symmetry breaking

$$V(\phi, \eta) = \frac{\lambda_1}{2} (\phi^a \phi^a - v_1^2)^2 + \frac{\lambda_2}{2} (\eta^a \eta^a - v_2^2)^2 + \kappa (\phi^a \eta^a)^2$$

$(\lambda_1 v_1^4 \gg \lambda_2 v_2^4)$   
 $(\kappa > 0)$

$SU(2)_D \xrightarrow{\langle \phi^a \rangle = v_1 \delta_3^a} U(1)_D \xrightarrow{\langle \eta^a \rangle = v_2 \delta_1^a} Z_2$

#### Gauge field mixing

Kinetic mixing:  $-\frac{c_1}{2\Lambda} \phi^a F_{\mu\nu} F_D^{a\mu\nu}$

Magnetic mixing:  $-\frac{c_2}{16\pi^2 \Lambda} \phi^a F_{\mu\nu} \tilde{F}_D^{a\mu\nu}$

↑ dimension 5 → naturally suppressed  
(cf.  $U(1)_{\text{QED}} \times U(1)_D \rightarrow [eF_{\mu\nu} F_D^{\mu\nu}] = 4$ )

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

$\frac{\epsilon}{2} F_{\mu\nu} F_D^{\mu\nu}$

$-\frac{\theta_{\text{mix}}}{16\pi^2} F_{\mu\nu} \tilde{F}_D^{\mu\nu}$  (total derivative)

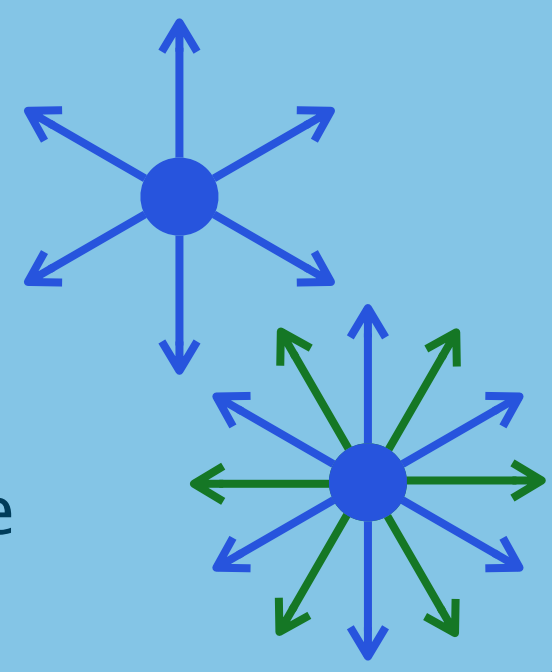
$F_{D\mu\nu} := \frac{\phi^a}{v_1} F_{D\mu\nu}^a$ : Effective  $U(1)_D$  field strength

Valid away from monopoles

## Topological Defects in the Dark Sector

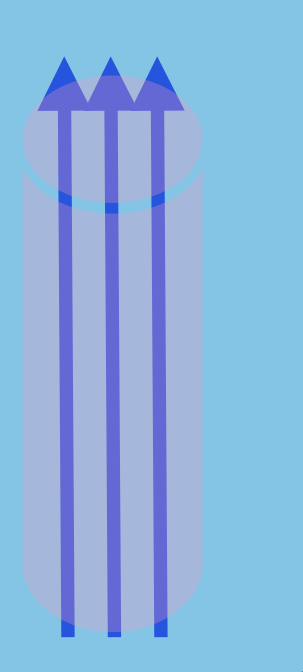
### Monopoles / Dyons

Formed at  $SU(2)_D \rightarrow U(1)_D$   
Stabilized by  $\pi_2(SU(2)/U(1)) = \mathbb{Z}$   
 $\theta$ -term quantizes the electric charge



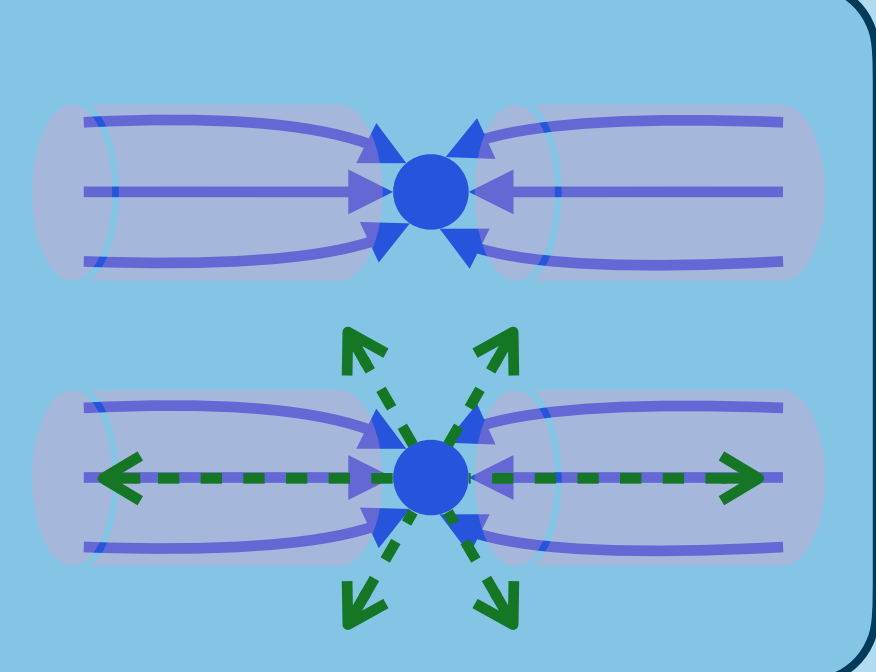
### Strings

Formed at  $U(1)_D \rightarrow Z_2$   
Stabilized by  $\pi_1(SU(2)/Z_2) = Z_2$   
Magnetic field goes through it



### Beads

Formed at  $U(1)_D \rightarrow Z_2$   
Monopoles with the magnetic fields confined in strings



## Q: How do dark topological defects interact with QED?

## Induced electromagnetic fields

→ [Dark] magnetic field  
→ [Dark] electric field

### $U(1)_D$ symmetric phase

#### QED Noether charge

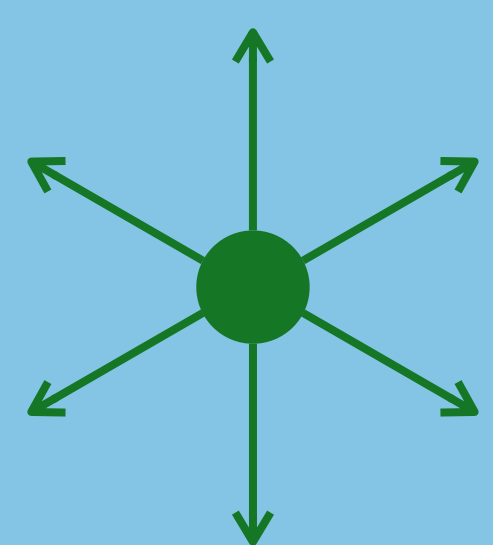
EoM:

$$\partial_\mu F^{\mu\nu} - \epsilon \partial_\mu \left( \frac{\phi^a}{v_1} F_D^{a\mu\nu} \right) + \frac{\theta_{\text{mix}}}{8\pi^2} \partial_\mu \left( \frac{\phi^a}{v_1} \tilde{F}_D^{a\mu\nu} \right) = e J_{\text{QED}}^\nu$$

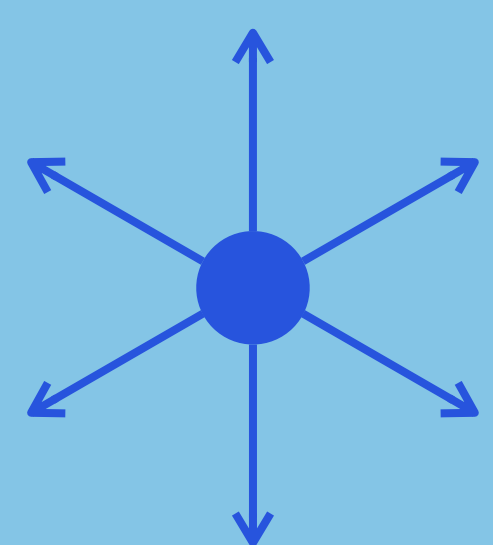
$$\rightarrow N_{\text{QED}} = \frac{1}{e} Q_{\text{QED}}^e - \frac{\epsilon}{e} Q_D^e + \frac{\theta_{\text{mix}}}{8\pi^2} Q_D^m$$

( $Q$ : electric / magnetic charge defined by field flux)

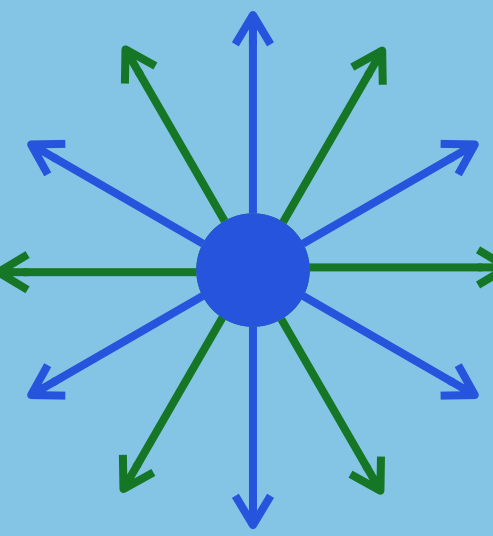
#### Dark Sector



$$N_{\text{QED}} = 0, Q_D^e = e_D$$

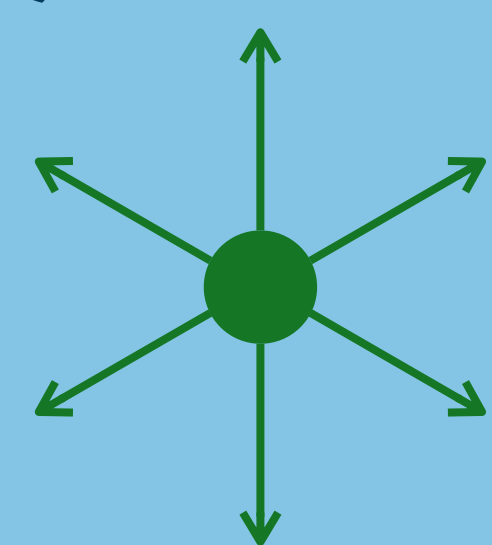


$$N_{\text{QED}} = 0, Q_D^m = -\frac{4\pi n}{e_D}$$



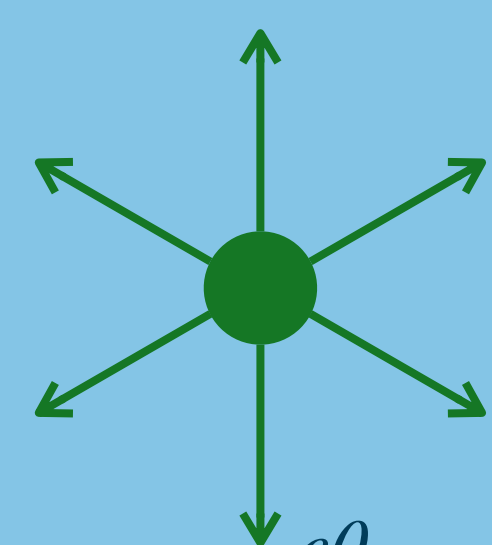
$$N_{\text{QED}} = 0, Q_D^m = -\frac{4\pi n}{e_D}, Q_D^e \neq 0$$

#### QED Sector



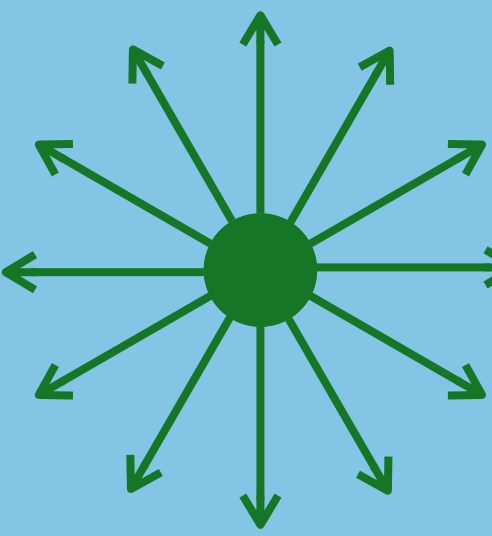
$$Q_{\text{QED}}^e = \epsilon e_D$$

[Holdom ('86)]



$$Q_{\text{QED}}^e = -\frac{e\theta_{\text{mix}}}{8\pi^2} Q_D^m$$

[Brümmer, Jaeckel, Khoze ('09)]



Superposition

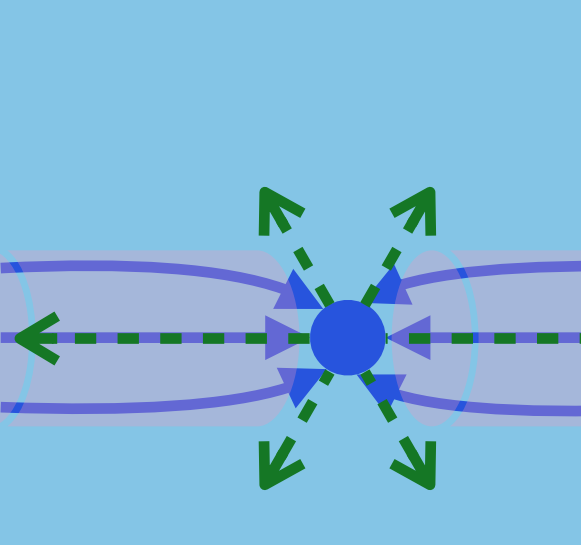
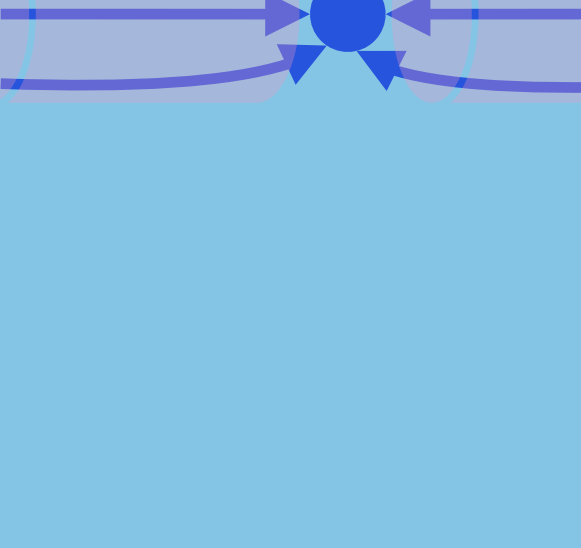
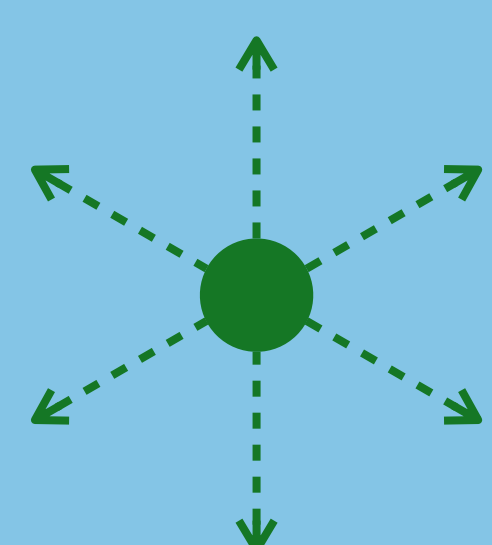
[Brümmer, Jaeckel, Khoze ('09)]

### $U(1)_D$ broken phase

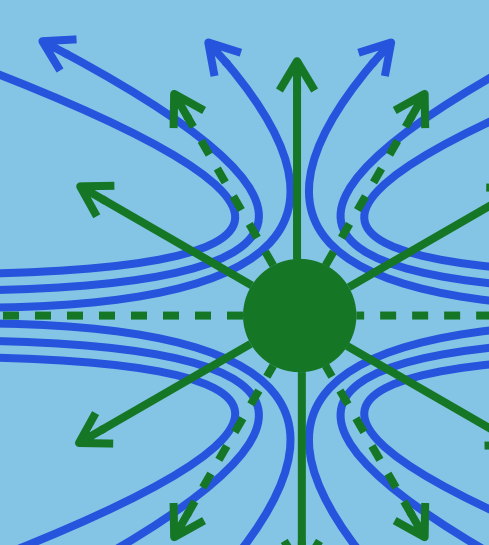
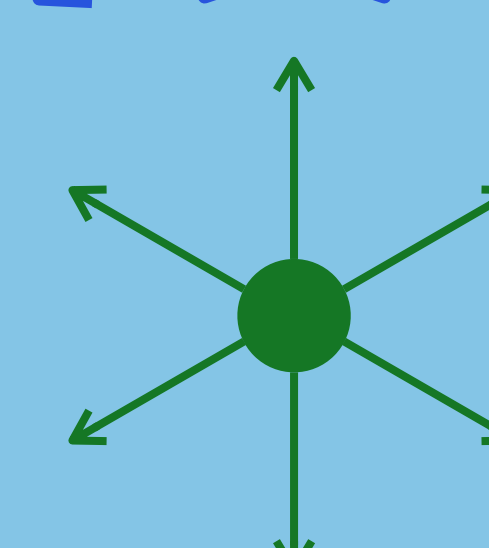
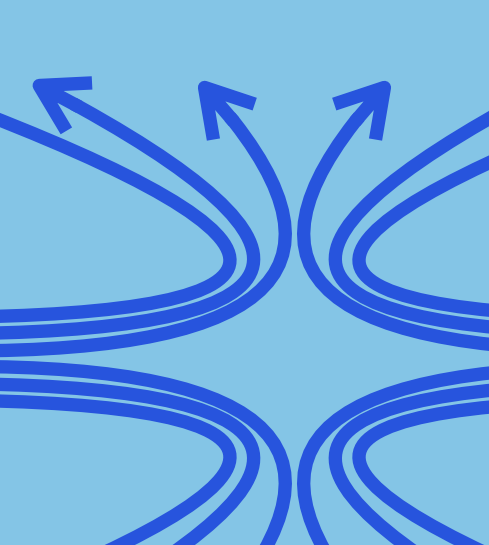
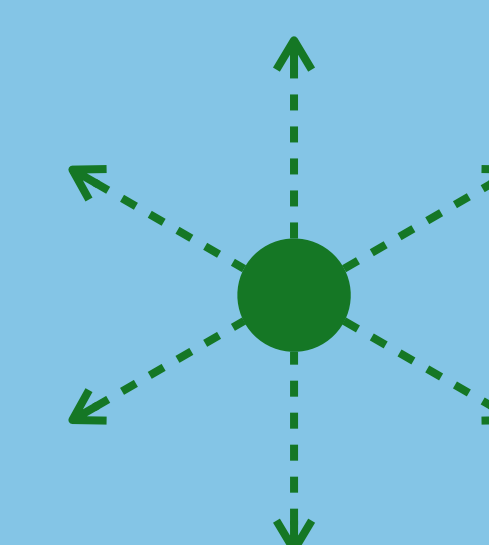
#### Decoupled basis

$$\begin{pmatrix} 1 & \frac{\epsilon}{1-\epsilon^2} \\ 0 & \frac{1}{1-\epsilon^2} \end{pmatrix} \begin{pmatrix} A' \\ A_D \end{pmatrix} := \begin{pmatrix} A \\ A_D \end{pmatrix} \rightarrow \begin{cases} \partial_\mu F'^{\mu\nu} = e J_{\text{QED}}^\nu & \leftarrow \text{involves only } A' \\ \partial_\mu F_D^{\mu\nu} - m_D^2 A_D^\nu = \frac{\epsilon_D}{\sqrt{1-\epsilon^2}} J_D^\nu + \frac{\epsilon e}{\sqrt{1-\epsilon^2}} J_{\text{QED}}^\nu & \leftarrow \text{involves only } A_D \end{cases}$$

#### Dark Sector



#### QED Sector



$$\langle \phi^a \rangle: \text{trivial} \rightarrow F_{\mu\nu} = e F_{D\mu\nu}$$

[Alford, Wilczek ('89)  
[Vachaspati ('09)]

Magnetic field from cosmic strings leaks at the joint  
→ "Pseudomonopole"

[Hiramatsu, Ibe, Suzuki, Yamaguchi (2021)]

$$\text{EoM: } \partial_i E^i = \frac{\theta_{\text{mix}}}{8\pi^2} \partial_i B_D^i$$

→ "Pseudodyon"

Superposition of all the above