Dark higher-form portals and duality

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Identification of Dark Matter, Zaragoza, 2026

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Based on:

- *Dark higher-form portals and duality, C. Plantier and C.Smith, Physical review D 112, 2025*
- *Dark higher-form fields and triangle anomalies, C. Plantier and C.Smith, JHEP05, 2026*

Differential forms as dark matter candidates

One can define fields with more than one Lorentz indices. They are antisymmetric and fundamentally tensorial.

Number of indices

$p = 0$	$p = 1$	$p = 2$	$p = 3$
Scalar field ϕ	Vector field A^{μ}	Kalb-Ramond field $B^{\mu\nu}$	Three-form $C^{\mu\nu\rho}$

Formally, these fields are differential forms $\Rightarrow$ Often encountered in string theory

Here we adopt a phenomenological vision: Can these forms be suitable DM candidates?

[1] M. Kalb, P. Ramond, *Classical direct interstring action*, Phys.Rev.D (1974)
[2] T. Curtright, P. Freund, *Massive dual fields*, Nucl.Phys.B (1980)

Theories involving differential forms can exacerbate redundancies, known as *generalized symmetries*.

Like for the vector case, the transformations of the forms depend on gauge parameters.

$$A^\mu \to A^\mu + \partial^\mu \underbrace{\Lambda}_{\text{Zero-form gauge parameter}}$$

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Higher-forms and symmetries

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$$B^{\mu\nu} \to B^{\mu\nu} + \partial^\mu \Lambda^\nu - \partial^\nu \Lambda^\mu$$

$$C^{\mu\nu\rho} \to C^{\mu\nu\rho} + \partial^\mu \Lambda^{\nu\rho} + \partial^\nu \Lambda^{\rho\mu} + \partial^\rho \underbrace{\Lambda^{\mu\nu}}_{\text{Two-form gauge parameter}}$$

Therefore, the strength tensor of a form is gauge-invariant

Theories involving differential forms can exacerbate redundancies, known as *generalized symmetries*.

Like for the vector case, the transformations of the forms depend on gauge parameters.

$$\phi \to \phi + \underbrace{\lambda}_{\text{Shift-Symmetry parameter}}$$

$$A^{\mu} \to A^{\mu} + \partial^{\mu}\Lambda$$

$$B^{\mu\nu} \to B^{\mu\nu} + \partial^{\mu}\Lambda^{\nu} - \partial^{\nu}\Lambda^{\mu}$$

$$C^{\mu\nu\rho} \to C^{\mu\nu\rho} + \partial^{\mu}\Lambda^{\nu\rho} + \partial^{\nu}\Lambda^{\rho\mu} + \partial^{\rho}\Lambda^{\mu\nu}$$

Therefore, the strength tensor of a form is gauge-invariant

What do these forms propagate?

First step is to look at the number of degrees of freedom (*DOFs*) propagated by each form, taking into account for each free-theory:

The equations of motion

The gauge-symmetries

	Scalar field ϕ	Vector field A^{μ}	KR field $B^{\mu\nu}$	Three-form $C^{\mu\nu\rho}$
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Two representations of a massive spin-one particle

[3] A.Hell, *On the duality of massive Kalb-Ramond and Proca fields*, JCAP 01, 2022

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Two representations of a massless spin-zero particle (axion)

[4] F.Quevedo, *Duality Beyond Global Symmetries: the Fate of the $B^{\mu\nu}$ Field* , arXiv: hep-th/9506081 (1995)

A massive vector has two transverses and one longitudinal polarizations. It can be seen explicitly through Stueckelberg decomposition:

$$A^\mu_{\text{massive}} = A^\mu_{\text{massless}} + \frac{\partial^\mu \phi}{m}$$

Unpacking the nature of the DOFs

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2 transverse DOFs (photon like)

1 longitudinal DOF (scalar like)

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<u>In the context of the Higgs mechanism:</u>

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A massive vector can be seen as a massless vector + a scalar « would-be » Goldstone that brings the missing DOF

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1 longitudinal DOF

Nothing!

[5] G. Dvali, *Three-Form Gauging of Axion Symmetries and Gravity*, hep-th/0507215 (2005)

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A constraint on exotic fields: Duality

A massive spin zero particle (1 DOF) can be described by a scalar field ϕ or a three-form field $C^{\mu\nu\rho}$

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Same thing for the massive vector field A^{μ} and Kalb-Ramond field $B^{\mu\nu}$ that both describe a massive spin-one particle (3 DOFs) or for a massless scalar field ϕ and Kalb-Ramond field $B^{\mu\nu}$ that both describe a massless spin-zero particle (axion).

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$$L_\phi = \frac{1}{2} F^\phi_\mu F^\mu_\phi - \frac{m^2}{2}\phi^2 \xrightarrow{\text{dualization}} L_C = -\frac{1}{48} F^C_{\mu\nu\rho\sigma} F^{\mu\nu\rho\sigma}_C + \frac{m^2}{12} C_{\mu\nu\rho} C^{\mu\nu\rho}$$

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What are the characteristics of this mapping? At what extent are two dual couplings equivalent?

Duality at the level of effective operators

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→ Despite its rich Lorentz structure, a three-form field $C^{\mu\nu\rho}$ has the same number of effective operators as a scalar field ϕ

Duality at the level of effective operators

Duality establishes a one-to-one correspondence between the two basis of effective operators.

However, this correspondence itself does not preserve:

- Mass scaling
- Gauge invariance
- Parity

[6] D. Dalmazi, R. C. Santos, *Spin-1 duality in D-dimensions*, Phys. Rev. D 84 (2011)
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Mass dimension: four
(dominant operator)

Gauge breaking

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$\bar{\psi}_L \psi_R \phi$	$\frac{1}{M} \bar{\psi}_L \psi_R \varepsilon_{\mu\nu\rho\sigma} F_C^{\mu\nu\rho\sigma}$
Mass dimension: four (dominant operator)	Mass dimension: five (suppressed operator)
Gauge breaking	Gauge invariant
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$$\bar{\psi}_L \psi_R \phi$$

Yukawa-like coupling

$$\bar{\psi}_L \gamma^\sigma \psi_L \varepsilon_{\mu\nu\rho\sigma} C^{\mu\nu\rho}$$

Vector-like coupling

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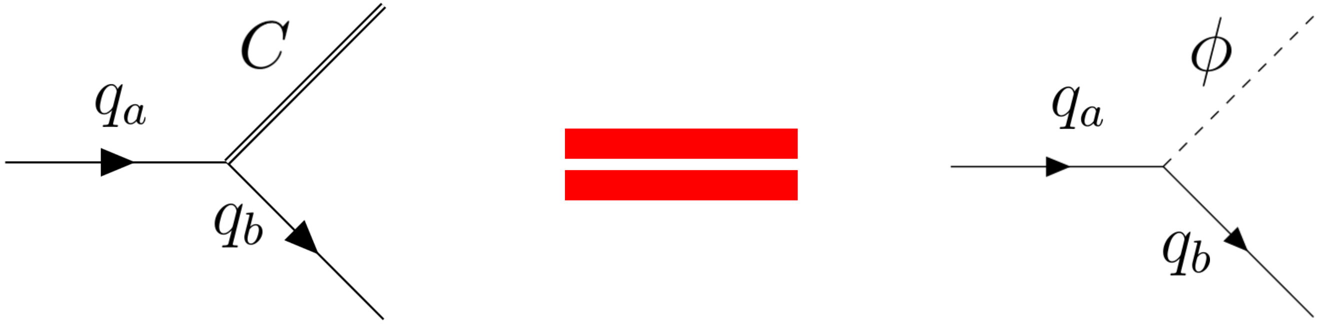
Ex: emission of a real spin-zero field by a fermion:



When both couplings are related through duality

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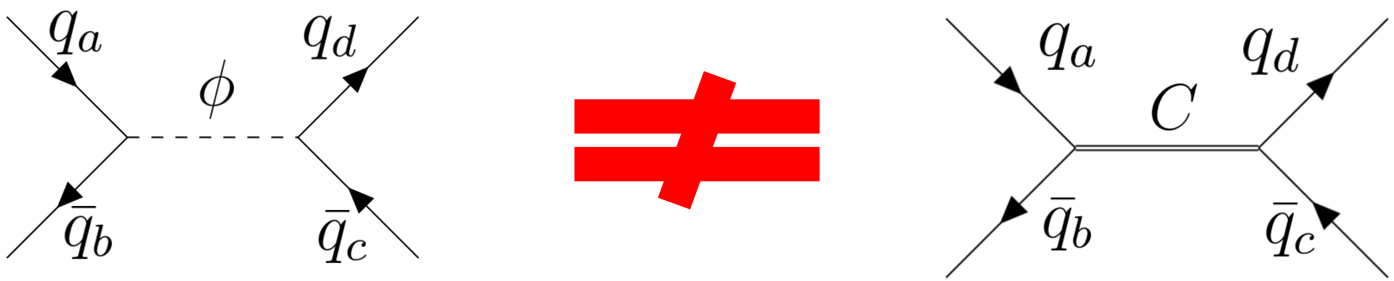
Ex: scattering of fermions though a spin-one field



Even when both couplings are related through duality

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Higher-forms extend the playground

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4) Using higher-forms as propagators breaks duality at the squared amplitude level

Different three-body decays

For every form, the leading operator coupling two dark fields with fermions involves the same structure

$$\boxed{\bar{\psi}_L \psi_R \phi^2} \quad \boxed{\bar{\psi}_L \psi_R A_\mu A^\mu} \quad \boxed{\bar{\psi}_L \psi_R B_{\mu\nu} B^{\mu\nu}} \quad \boxed{\bar{\psi}_L \psi_R C_{\mu\nu\rho} C^{\mu\nu\rho}}$$

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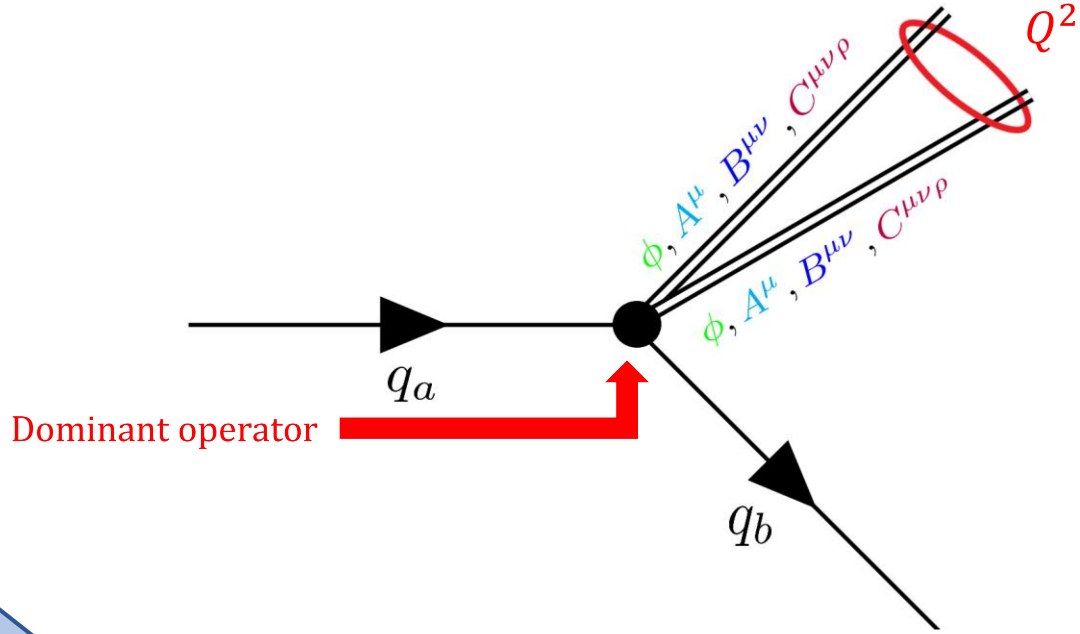

$q_a \to q_b XX$ with $X = \phi, A^\mu, B^{\mu\nu}, C^{\mu\nu\rho}$

We look at the pair production of dark form fields:
$\Gamma(q_a \to q_b XX)$ with $X = \phi, A^\mu, B^{\mu\nu}, C^{\mu\nu\rho}$.

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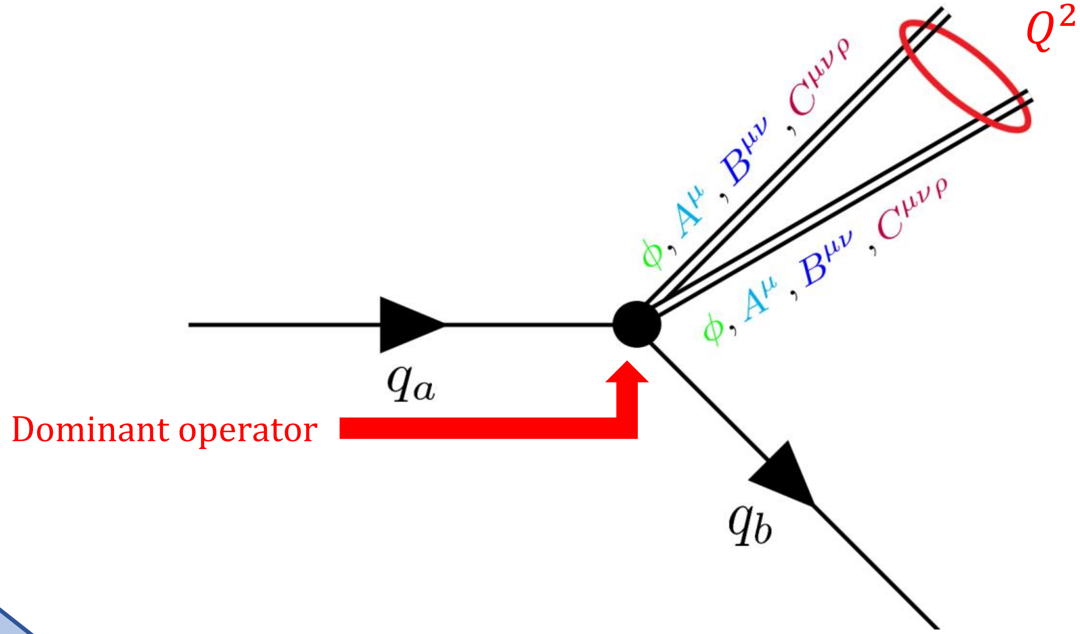

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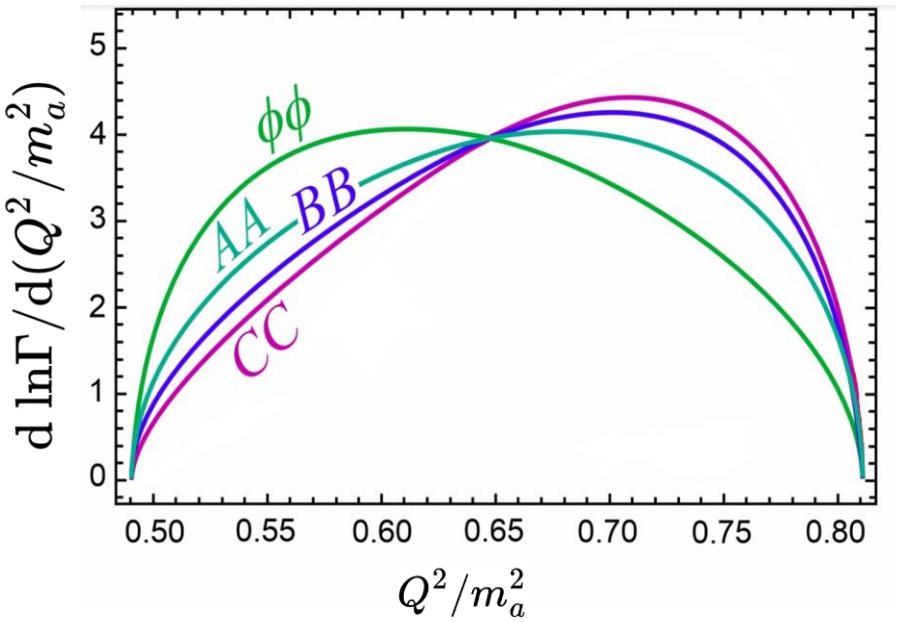

Normalized differential decay rates for $q_a \to q_b XX$, in function of the squared impulsion Q^2 normalized by m_a^2. Here, $\frac{m_b}{m_a} = 0{,}1, \frac{m_X}{m_a} = 0{,}35$.

1) The Stueckelberg decomposition shows that different degrees of freedom will contribute at low or high energy scales

Direct consequence of points 2 and 3:

2) The dominant effective interactions with matter are structurally different

3) The gauge-invariant operators are structurally different

Gauge /Shift invariant dark spin-zero particle

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Examples:

- Gauge/shift invariant dark spin-zero particle
- Gauge invariant dark photon

Gauge /Shift invariant dark spin-zero particle

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Scalar field ϕ

Yukawa interaction forbidden by the shift-symmetry

$$\boxed{\phi\bar{\psi}\psi}$$

The dominant fermion coupling is *axion-like*

$$\boxed{(\partial_\mu\phi)\bar{\psi}\gamma^\mu\psi}$$

$$\boxed{(\partial_\mu\phi)\bar{\psi}\gamma^\mu\gamma^5\psi}$$

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Three-form $C^{\mu\nu\rho}$

$$\boxed{F^C_{\mu\nu\rho\sigma}\varepsilon^{\mu\nu\rho\sigma}\bar{\psi}\psi}$$

The dominant fermion coupling is a Yukawa interaction

$$\boxed{C_{\mu\nu\rho}\varepsilon^{\mu\nu\rho\sigma}\bar{\psi}\gamma_\sigma\psi}$$

No *axion-like* interaction

$$\boxed{C_{\mu\nu\rho}\varepsilon^{\mu\nu\rho\sigma}\bar{\psi}\gamma_\sigma\gamma_5\psi}$$

Embody a dark photon in a vector or a Kalb-Ramond field, you obtain completely different realizations:

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Dark vector A^μ

Kinetic Mixing with SM fermions

$$\boxed{\epsilon' F^A_{\mu\nu} \tilde{F}^{\mu\nu}_\gamma} \quad \boxed{\epsilon F^A_{\mu\nu} F^{\mu\nu}_\gamma}$$

Vector/axial interaction forbidden

$$\boxed{\bar{\psi}\gamma^\mu\psi A_\mu} \quad \boxed{\bar{\psi}\gamma^\mu\gamma^5\psi A_\mu}$$

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EDM/MDM operators are the dominant couplings

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Kalb-Ramond $B^{\mu\nu}$

No kinetic Mixing with SM fermions

$\boxed{\epsilon B_{\mu\nu}F^{\mu\nu}_\gamma}$ $\boxed{\epsilon' B_{\mu\nu}\tilde{F}^{\mu\nu}_\gamma}$

Vector/axial operators are the dominant couplings

$\boxed{F^B_{\mu\nu\rho}\varepsilon^{\mu\nu\rho\sigma}\bar{\psi}\gamma_\sigma\psi}$ $\boxed{F^B_{\mu\nu\rho}\varepsilon^{\mu\nu\rho\sigma}\bar{\psi}\gamma_\sigma\gamma_5\psi}$

$\boxed{B_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi}$ $\boxed{B_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\gamma^5\psi}$

EDM/MDM operators are forbidden

Conclusion

Despite the constraints imposed by duality, higher-forms make compelling and natural candidates for dark matter, as:

Operators that were considered irrelevant in the standard picture are dominant in the dual description

- A reinterpretation of the currents limits on dark photons or ALPs would be needed to account for the higher-form description

Operators that were gauge-breaking in the standard picture are gauge-preserving in the dual description

- We could expect kinetic-mixing and EDM/MDM free dark photons, or Yukawa coupling ALPs

Degrees of freedom do not dominate at the same regimes in the two dual pictures

- Heavy higher-forms (at TeV or above) would have distinct experimental signatures in colliders

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Thank you for your attention and feel free to ask questions!