Dark matter from Kalb-Ramond gauge symmetry

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- Kalb-Ramond couplings and string gauge symmetry
- A $U_Y(1)$ portal to electroweak dipole dark matter
- Abundance constraints on electroweak dipole dark matter
- Electron recoil cross sections and comparison with direct search constraints
- Conclusions

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Background I:

Dark matter with electromagnetic dipole couplings

$$\mathcal{L} = \frac{i}{4M_d} F^{\mu\nu} \bar{\chi} \cdot \left[\gamma_\mu, \gamma_\nu\right] \cdot (a_m + i a_e \gamma_5) \cdot \chi$$

and mass m_χ in the MeV or low GeV range has been introduced by Sigurdson *et al.* in 2004 and shown to be consistent with direct searches in nuclear recoils and with astrophysical constraints.

The non-relativistic limit of the photon coupling term yields magnetic and electric Pauli terms

$$\mathcal{L} = \frac{1}{M_d} \psi^+ (a_m \boldsymbol{B} + a_e \boldsymbol{E}) \cdot \boldsymbol{\sigma} \psi$$

Background II:
Contributions from our recent paper

- Extend to $U_Y(1)$ portal
- Take into account direct searches in electron recoils (SuperCDMS, SENSEI, XENON)
- Propose and explore a stringy origin through induction of dark electroweak dipoles from Kalb-Ramond dipoles

Conventions: Field strengths for
1-form potential B_μ: $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$
2-form potential $C_{\mu\nu} = -C_{\nu\mu}$:

$$C_{\mu\nu\rho} = \partial_\mu C_{\nu\rho} + \partial_\nu C_{\rho\mu} + \partial_\rho C_{\mu\nu}$$

Gauge interactions between strings can be described in analogy to electromagnetic interactions if the string action is amended with a coupling term to the Kalb-Ramond field $C_{\mu\nu} = -C_{\nu\mu}$ and a $U(1)$ gauge field B_μ. The $U(1)$ gauge field B_μ couples to the boundaries of open strings (with $x_a^\mu \stackrel{\text{def}}{=} x^\mu(\tau_a, \sigma_a)$ describing the embedding of the a-th string):

$$S = \sum_a \int d\tau_a \int_0^\ell d\sigma_a \left(\frac{T}{2} (\dot{x}_a^2 - x_a'^2) + \frac{\mu_s}{2} (\dot{x}_a^\mu x_a'^\nu - \dot{x}_a^\nu x_a'^\mu) C_{\mu\nu}(x_a) \right)$$

$$+ \sum_a g \int d\tau_a \left[\dot{x}_a^\mu B_\mu(x_a) \right]_{\sigma_a=0}^{\sigma_a=\ell}$$

→ Equations of motion on the string world sheet

$$2T\left(\ddot{x}_{a\mu} - x''_{a\mu}\right) = \mu_s\left(\dot{x}_a^\nu x_a'^\rho - \dot{x}_a^\rho x_a'^\nu\right) C_{\mu\nu\rho}(x_a),$$

and on the boundary

$$\left[T x'_{a\mu} + \left(g B_{\mu\nu}(x_a) - \mu_s C_{\mu\nu}(x_a) \right) \dot{x}_a^\nu \right]_{\sigma_a \in \{0,\ell\}} = 0.$$

The equations of motion on the world sheet and on the boundaries are Kalb-Ramond (KR) gauge symmetric under

$$C_{\mu\nu} \to C'_{\mu\nu} = C_{\mu\nu} + \partial_\mu f_\nu - \partial_\nu f_\mu,$$
$$B_\mu \to B'_\mu = B_\mu + (\mu_s/g) f_\mu,$$

and also have the usual $U(1)$ gauge symmetry

$$B_\mu \to B'_\mu = B_\mu + \partial_\mu f\,.$$

The coupling terms in the string action imply that strings are sources of $C_{\mu\nu}$ and B_μ, and we need kinetic terms which respect the gauge symmetries:

$$\mathcal{L}_K = -\frac{1}{6} C^{\mu\nu\rho} C_{\mu\nu\rho} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} + \frac{\mu_s}{2g} C^{\mu\nu} B_{\mu\nu} - \frac{\mu_s^2}{4g^2} C^{\mu\nu} C_{\mu\nu}$$

The equations of motion for the gauge fields

$$\partial_\mu C^{\mu\nu\rho}(x) + \frac{\mu_s}{2g} B^{\nu\rho}(x) - \frac{\mu_s^2}{2g^2} C^{\nu\rho}(x) = -\sum_a j_a^{\nu\rho}(x)$$

$$\partial_\mu \left(B^{\mu\nu}(x) - \frac{\mu_s}{g} C^{\nu\rho}(x) \right) = -\sum_a j_a^{\nu}(x)$$

contain source terms

$$j_a^{\mu\nu}(x) = \frac{\mu_s}{2} \int d\tau_a \int_0^\ell d\sigma_a \left(\dot{y}^\mu(\tau_a,\sigma_a) y'^\nu(\tau_a,\sigma_a) - \dot{y}^\nu(\tau_a,\sigma_a) y'^\mu(\tau_a,\sigma_a) \right)$$
$$\times\, \delta\big(x - y(\tau_a,\sigma_a)\big)$$

$$j_a^{\mu}(x) = g \int d\tau_a \left[\dot{y}^\mu(\tau_a,\sigma_a) \delta\big(x - y(\tau_a,\sigma_a)\big) \right]_{\sigma_a=0}^{\sigma_a=\ell}$$

which satisfy the consistency conditions

$$\partial_\mu j_a^{\mu\nu}(x) = (\mu_s/2g) j_a^{\nu}(x), \qquad \partial_\mu j_a^{\mu}(x) = 0.$$

Induction of a dark $U_Y(1)$ dipole portal from Kalb-Ramond dipoles:

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{\chi}\left(i\gamma^{\mu}\partial_{\mu} - m_{\chi}\right)\chi$$
$$- \frac{i}{4} g_{C\chi} C^{\mu\nu} \bar{\chi}\left[\gamma_{\mu}, \gamma_{\nu}\right](a_m + i a_e \gamma_5)\chi$$
$$- \frac{1}{6} C^{\mu\nu\rho} C_{\mu\nu\rho} - g_{BC} m_C C^{\mu\nu} B_{\mu\nu} - \frac{m_C^2}{2} C^{\mu\nu} C_{\mu\nu}$$

is KR gauge symmetric for $g_{BC} = 1/\sqrt{2}$. However, moduli stabilization (e.g. dilaton stabilization and an internal KR flux) will likely break KR gauge symmetry in the low energy sector. Elimination of the Kalb-Ramond field for energies much smaller than m_C induces a $U_Y(1)$ dipole portal to dark matter:

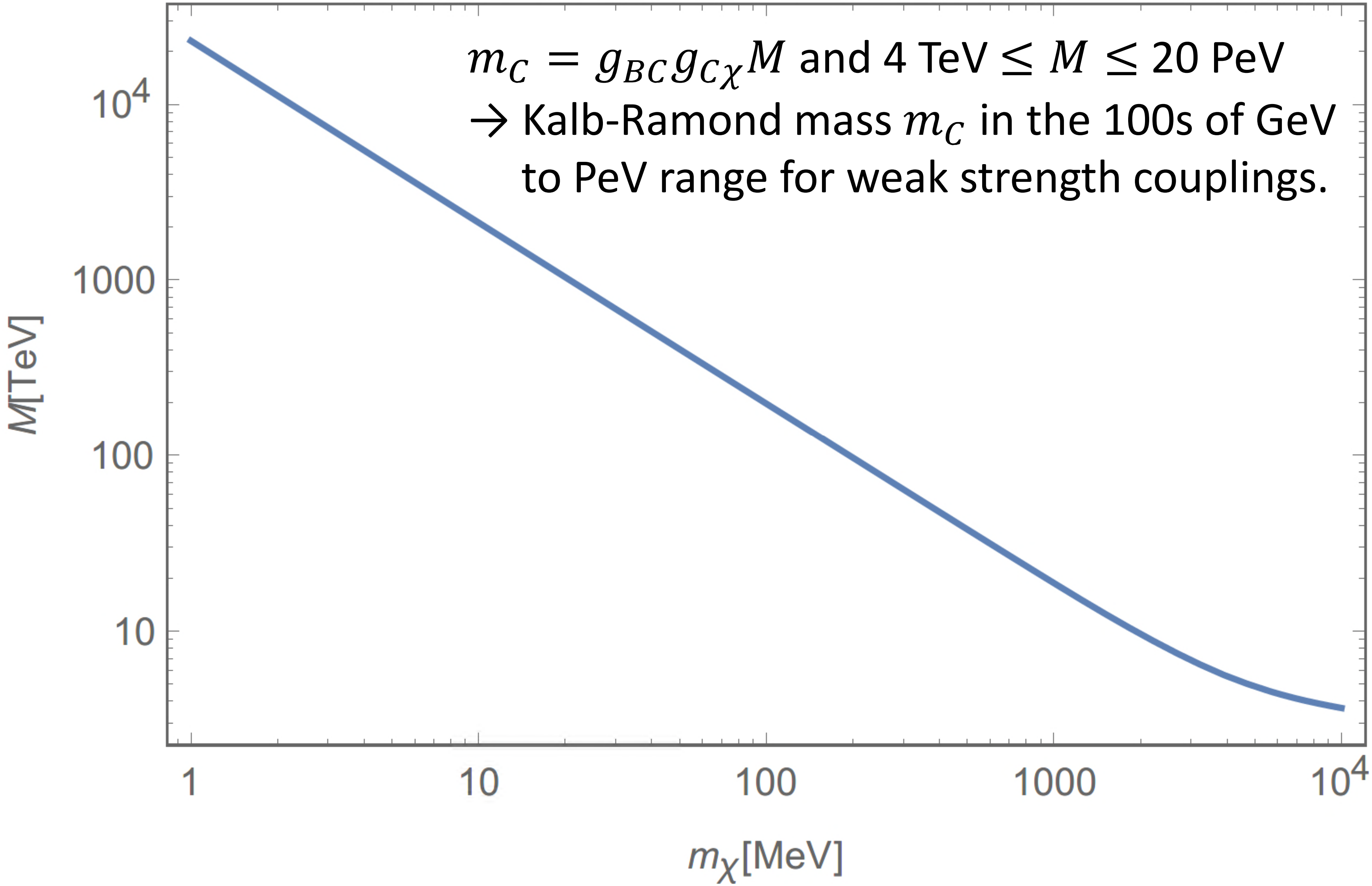
$$\mathcal{L}_{B\chi} = \frac{i}{4m_C} g_{BC} g_{C\chi} B^{\mu\nu} \bar{\chi}\left[\gamma_{\mu}, \gamma_{\nu}\right](a_m + i a_e \gamma_5)\chi$$

The relic abundance calculation requires the annihilation cross section of the $U_Y(1)$ dipole dark matter. The annihilation at thermal freeze-out is dominated by the annihilation cross sections into $f\overline{f}$ states for $s \geq 4m_f^2$,

$$\sigma_{\chi\overline{\chi}\to f\overline{f}} = N_c \frac{\alpha \cos^2\theta}{48 M_d^2} (Y_{f,+}^2 + Y_{f,-}^2) \sqrt{\frac{s-4m_f^2}{s-4m_\chi^2}} \times (s-m_f^2)\left[a_m^2(s+8m_\chi^2) + a_e^2(s-4m_\chi^2)\right] \times \left(\frac{1}{s^2} + \frac{2}{s}\frac{(s-m_Z^2)\tan^2\theta}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2} + \frac{\tan^4\theta}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2}\right).$$

$Y_{f,\pm}$ are the weak hypercharges of the right- and left-handed fermions, respectively, and $N_c = 1$ for leptons, $N_c = 3$ for quarks.

Required coupling scale $M = M_d/a_m$ for $\Omega_\chi = \Omega_d$



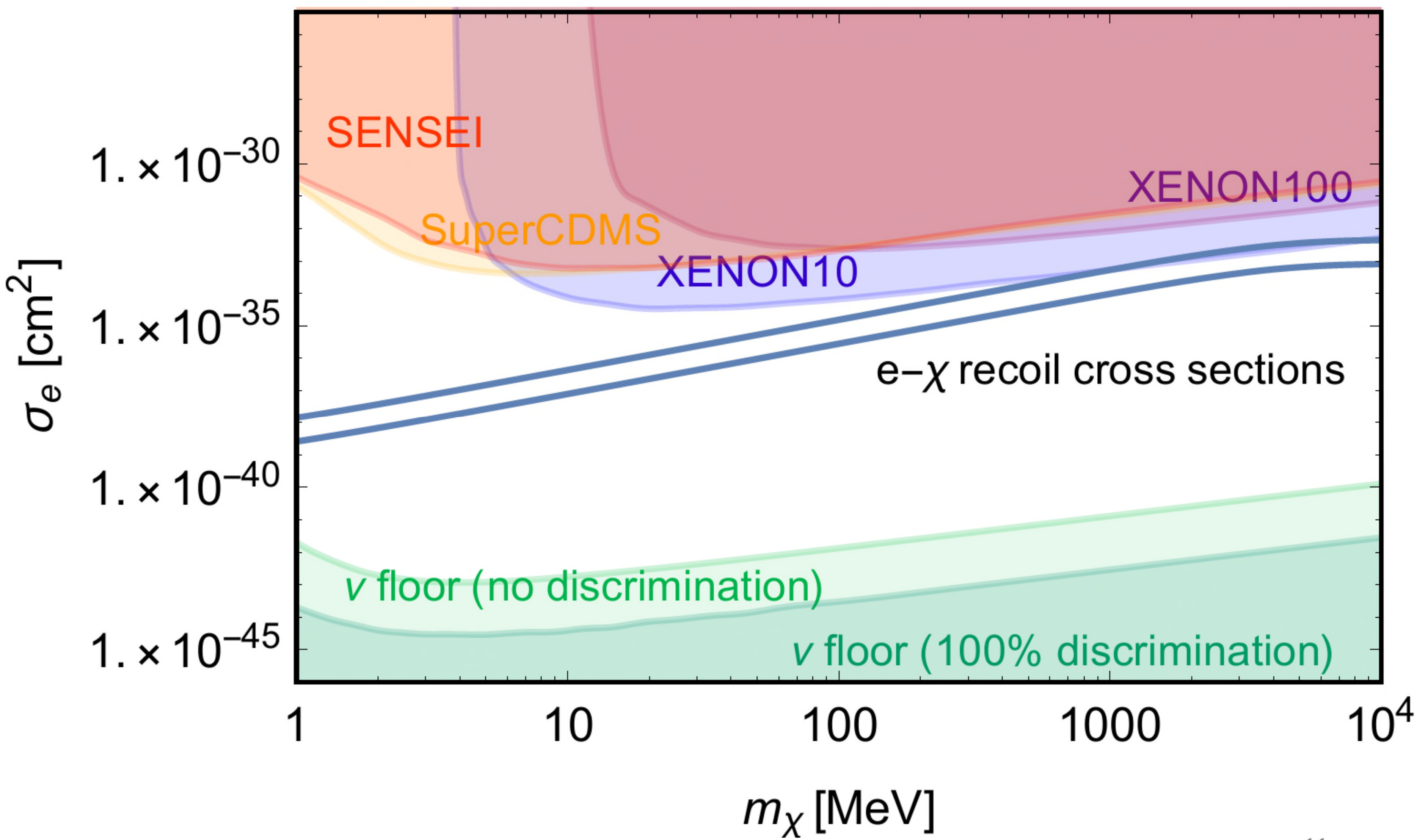
The differential electron recoil cross section is

$$\frac{d\sigma_e}{d\Omega} = \sum_{\pm} \frac{\alpha \cos^2\theta}{8\pi M^2} \frac{m_e m_\chi^3}{(m_e + m_\chi)^2} \frac{1}{(\Delta \boldsymbol{k})_\pm^2} \left(1 + \frac{9a_e^2}{2a_m^2}\right) \times \frac{\left(\cos\varphi \pm \sqrt{(m_e/m_\chi)^2 - \sin^2\varphi}\right)^2}{\sqrt{(m_e/m_\chi)^2 - \sin^2\varphi}},$$

with momentum transfers for each scattering angle φ, $\varphi \leq \varphi_{max} = \arcsin(m_e/m_\chi)$,

$$\frac{(\Delta \boldsymbol{k})_\pm^2}{\boldsymbol{k}^2} = 1 + \frac{\left(\cos\varphi \pm \sqrt{(m_e/m_\chi)^2 - \sin^2\varphi}\right)^2}{[1 + (m_e/m_\chi)]^2} - 2\cos\varphi \frac{\cos\varphi \pm \sqrt{(m_e/m_\chi)^2 - \sin^2\varphi}}{1 + (m_e/m_\chi)}.$$

Interestingly, the electron recoil cross section for $|a_e/a_m| \leq 1$ complies with constraints from SuperCDMS, SENSEI, XENON (and also DarkSide), and should be testable above the neutrino floor.



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Conclusions

- Kalb-Ramond dipoles provide an interesting option to induce a dark $U_Y(1)$ dipole portal.
- Electron recoil cross sections have been calculated and comply with experimental constraints.
- Electron recoil cross sections are above the neutrino floor and should therefore be detectable.
- The dark $U_Y(1)$ dipole portal would not only yield an interesting portal to dark matter, but could also open a new window into string phenomenology.