The Price of Tiny Kinetic Mixing

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Based on work in progress with
Tony Gherghetta, Keith Olive, and Maxim Pospelov

1 Introduction

2 Bottom-Up Models

3 Top-Down Models

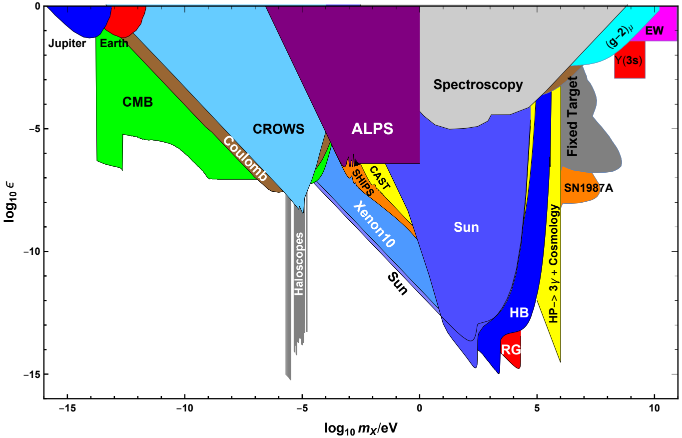
Dark Photons with Kinetic Mixing

- No new physics at LHC $\rightsquigarrow$ hiding at low energies?
- One candidate: gauge boson X^μ of new $U(1)_X$ (dark photon)
- Mass m_X from Brout-Englert-Higgs or Stückelberg mechanism
- Applications: dark matter candidate, mediator of dark matter self-interactions, $(g-2)_\mu$, ...
- Possibly part of dark sector
- Simplest way to couple to Standard Model: kinetic mixing with $U(1)_Y$ gauge boson B^μ

$$\mathcal{L}_{\text{km}} = -\frac{1}{2}\,\epsilon\, B_{\mu\nu} X^{\mu\nu}$$

$\rightsquigarrow$ kinetic mixing with photon ($\epsilon \cos\theta_W$) and Z ($\epsilon \sin\theta_W$)

Constraints on Kinetic Mixing

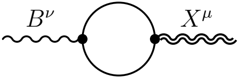


Redondo, personal communication (2018)

- $\epsilon \lesssim 10^{-15} \ldots 10^{-7}$ for μeV $\lesssim m_X \lesssim$ GeV
- How to get such a small number from a model?

Generic One-Loop Expectation

- Vanishing kinetic mixing at high scale
- Field with mass M charged under $U(1)_X$ and $U(1)_Y$



$$\rightsquigarrow \epsilon \sim \frac{g' g_X}{8\pi^2} \ln \frac{M}{\mu} \sim 10^{-4} \dots 10^{-3} \gg 10^{-7}$$

Holdom, PLB **166** (1986)

- Non-decoupling effect $\rightsquigarrow$ large M does not help

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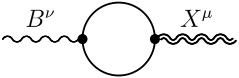

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Holdom, PLB **166** (1986)

- Non-decoupling effect $\rightsquigarrow$ large M does not help
- Known option: $g_X \ll 1$ from LARGE volume string compactifications (or other stringy scenarios)

Burgess et al., JHEP **07** (2008)
Cicoli, Goodsell, Jaeckel, Ringwald, JHEP **07** (2011)

$\rightsquigarrow$ How to get $\epsilon \lesssim 10^{-7}$ for $g_X \sim g' \sim 1$?

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Higher Loop Order

- Additional gauge group $U(1)_M$, broken above TeV-scale
- Vectorlike fermions ψ and χ

	Mass	Charge		
		$U(1)_Y$	$U(1)_M$	$U(1)_X$
ψ	heavy	1	1	0
χ	heavy	0	1	1
B^μ	0	0	0	0
M^μ	heavy	0	0	0
X^μ	light	0	0	0

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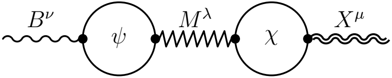
$\rightsquigarrow$ Kinetic mixing at 2-loop order?

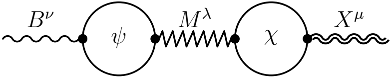
Higher Loop Order



$$\sim \Pi^{\nu\rho}_{YM}(k^2)\, D^{\rho\sigma}_{M}\, \Pi^{\sigma\mu}_{MX}(k^2) \sim \frac{k^4}{m_M^2}$$

- ⇝ Operator with derivatives of $B^{\mu\nu}$ and $X^{\mu\nu}$
- ⇝ Does not contribute to kinetic mixing

Higher Loop Order



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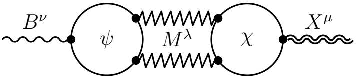
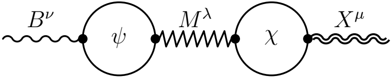
- Operator with derivatives of $B^{\mu\nu}$ and $X^{\mu\nu}$
- Does not contribute to kinetic mixing
- Kinetic mixing at 3-loop order?



Higher Loop Order



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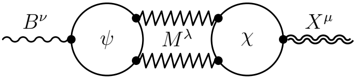
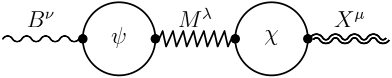


$= 0$ by Furry's theorem



$$\sim \Pi_{YM}^{\nu\rho}(k^2)\, D_M^{\rho\sigma}\, \Pi_{MX}^{\sigma\mu}(k^2) \sim \frac{k^4}{m_M^2}$$

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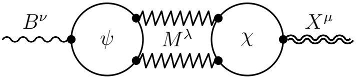

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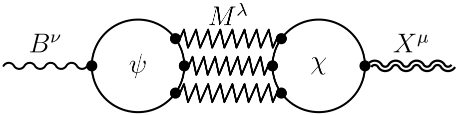
- Kinetic mixing at 4-loop order



$$\rightsquigarrow \epsilon \sim \left(\frac{1}{16\pi^2}\right)^4 \sim 10^{-9}$$

More Gauge Groups

Gauged Clockwork

Giudice, McCullough, JHEP **02** (2017); Lee, PLB **778** (2018)

- $N + 1$ gauge symmetries $U(1)_i$, $i = 0, \ldots, N$
- Equal gauge coupling g
- Corresponding gauge fields A^i_μ
- N Higgs fields ϕ_j, $j = 0, \ldots, N - 1$, each with charges $(1, -q)$ under $U(1)_j \times U(1)_{j+1}$ (and charge 0 under the other groups)
- $\langle \phi_j \rangle = f$ for all $j \rightsquigarrow U(1)^{N+1} \to U(1)_X$

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- $\langle \phi_j \rangle = f$ for all $j \rightsquigarrow U(1)^{N+1} \to U(1)_X$
- Diagonalize gauge boson mass matrix
  $\rightsquigarrow$ zero mode = dark photon = linear combination of all A_μ^i
- Field charged only under $U(1)_N$:

  coupling to dark photon $g_{\text{eff}} \sim \dfrac{g}{q^N}$ exponentially suppressed

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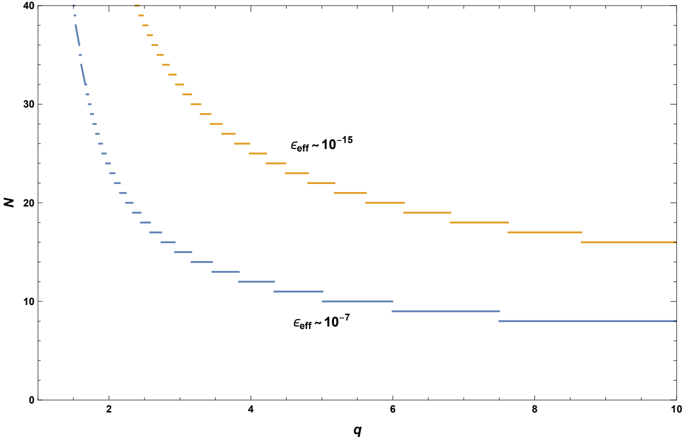
  coupling to dark photon $g_{\text{eff}} \sim \dfrac{g}{q^N}$ exponentially suppressed
- Continuum limit $N \to \infty$: equivalent to 5D theory, $g_{\text{eff}} \sim e^{-kR}$

Clockwork-Suppressed Kinetic Mixing

Kinetic mixing of B_μ only with A_μ^N

$\rightsquigarrow$ mixing with dark photon $\epsilon_{\text{eff}} \sim \dfrac{\epsilon}{q^N}$ can be tiny even for $\epsilon \sim 1$



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Embedding Light and Dark Photons in a Single Group

- SM gauge group $\times$ $U(1)_X \supset$ non-Abelian group G
  $\rightsquigarrow$ no kinetic mixing at breaking scale of G
- Light particles charged under both $U(1)_Y$ and $U(1)_X$
  $\rightsquigarrow$ generic $\epsilon \sim 10^{-4} \ldots 10^{-3}$
- Heavy particles charged under both $U(1)_Y$ and $U(1)_X$ fill complete GUT multiplets
  $\rightsquigarrow$ $\epsilon = 0$ for exact mass degeneracy
  $\rightsquigarrow$ Expect $\epsilon \sim 10^{-6} \ldots 10^{-4}$
  Arkani-Hamed, Weiner, JHEP **12** (2008)

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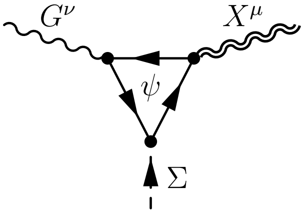
- Light particles charged under both $U(1)$'s hard to avoid
  Example: $SO(10) \to SU(5) \times U(1)_X$
  Standard Model fields in $\mathbf{16} = (\bar{\mathbf{5}}, 3) + (\mathbf{10}, -1) + (\mathbf{1}, -5)$
- … but not impossible for sufficiently large groups
  Example: $E_8 \to E_6 \times SU(3) \to E_6 \times U(1)_X$
  Standard Model fields in $\mathbf{248} = (\mathbf{27}, \mathbf{3}) + \dots$
  $\rightsquigarrow$ can be uncharged under $U(1)_X$ generated by $\lambda_3 \sim \mathrm{diag}(1, -1, 0)$

Only Standard Model Embedded in Simple Group

- $G_{\text{SM}} \times U(1)_X \subset G_{\text{GUT}} \times U(1)_X \rightsquigarrow G^{\mu\nu} X_{\mu\nu}$ not gauge-invariant
- Effective operator $\frac{1}{\Lambda} \Sigma\, G^{\mu\nu} X_{\mu\nu}$ with scalar Σ can be gauge-invariant
  $\rightsquigarrow \epsilon \sim \dfrac{\langle \Sigma \rangle}{\Lambda} \ll 1$
  Arkani-Hamed, Weiner, JHEP **12** (2008)
- Generated via loops with heavy particles (mass Λ)
- Alternative: embed $U(1)_X$ in non-Abelian group

Example 1: Adjoint Scalar

- Scalar Σ in adjoint representation of GUT group, no $U(1)_X$ charge
- Vector-like fermion charged under both groups, mass Λ

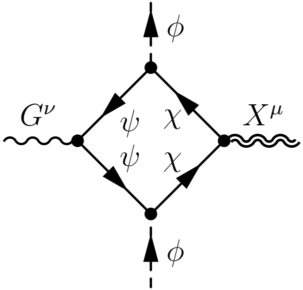


$$\rightsquigarrow \epsilon \sim \frac{1}{16\pi^2}\frac{\langle\Sigma\rangle}{\Lambda} \gtrsim \frac{1}{16\pi^2}\frac{\langle\Sigma\rangle}{M_{\text{Pl}}}$$

$\rightsquigarrow \epsilon \lesssim 10^{-7}$ for $\langle\Sigma\rangle \lesssim 10^{-3}\, M_{\text{GUT}}$ (and $\mathcal{O}(1)$ couplings)

Example 2: Fundamental Scalar in $SU(5)$

- Scalar $\phi \sim (\mathbf{5}, 0)$ under $SU(5) \times U(1)_X$
- Vector-like fermions $\psi \sim (\mathbf{5}, q)$ and $\chi \sim (\mathbf{10}, q)$, mass Λ



$\rightsquigarrow$ effective operator $\frac{1}{\Lambda^2} \phi^\dagger \phi \, G^{\mu\nu} X_{\mu\nu}$

$\rightsquigarrow \epsilon \sim \frac{1}{16\pi^2} \frac{\langle \phi \rangle^2}{\Lambda^2}$

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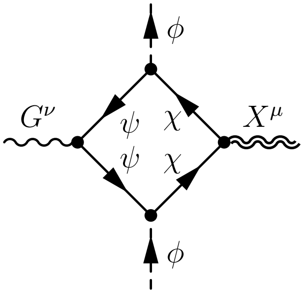

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$\rightsquigarrow \epsilon \sim \frac{1}{16\pi^2}\frac{\langle\phi\rangle^2}{\Lambda^2}$

- $\phi \sim (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{2})$ under $SU(3)_\mathrm{c} \times SU(2)_\mathrm{L}$
  $\rightsquigarrow \langle\phi\rangle \leq v_\mathrm{EW} \rightsquigarrow \epsilon \lesssim 10^{-28}$ for $\Lambda \sim M_\mathrm{GUT}$
- Different representations and GUT groups more promising

Conclusions

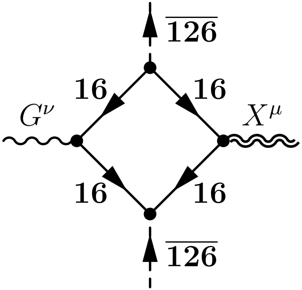
Kinetic mixing between visible and dark photon severely constrained: $\epsilon \lesssim 10^{-15} \ldots 10^{-7}$

$\rightsquigarrow$ Scenarios to explain such a small mixing

- Tiny gauge coupling from string theory
- Generation at high loop order $\rightsquigarrow \epsilon \sim 10^{-9}$
- Suppression by gauged clockwork
- Embedding of both $U(1)$'s in common group $\rightsquigarrow \epsilon \sim 10^{-6} \ldots 10^{-4}$
- Effective operators in GUT $\rightsquigarrow \epsilon \sim 10^{-28} \ldots 10^{-4}$

$\rightsquigarrow$ Tiny kinetic mixing possible, but not for free

Example 3: $SO(10)$



$\langle\phi\rangle \gtrsim 10^{10}$ GeV possible