The Price of Tiny Kinetic Mixing

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Based on Tony Gherghetta, JK, Keith Olive, and Maxim Pospelov,
arXiv:1909.00696

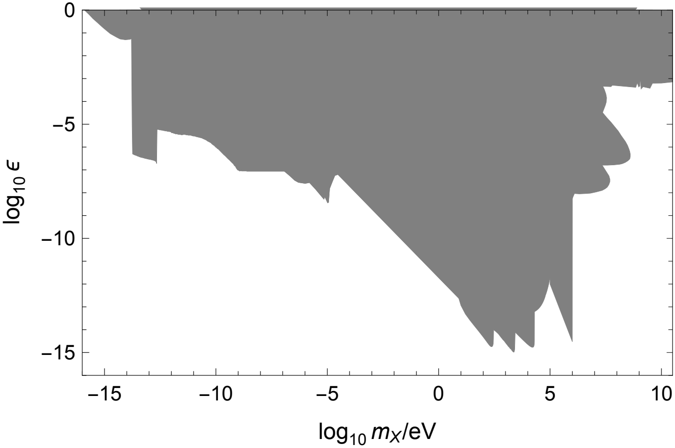
Dark Photons with Kinetic Mixing

- 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; Beacham et al., `arXiv:1901.09966`

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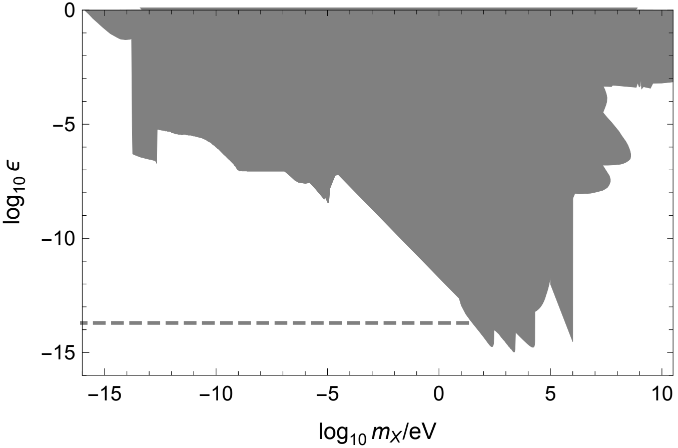

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Dark photon mass from dark Higgs: $g_X \epsilon \lesssim 10^{-14}$ for $m_X \lesssim 10\,\mathrm{keV}$

Ahlers, Jaeckel, Redondo, Ringwald, PRD **78** (2008)

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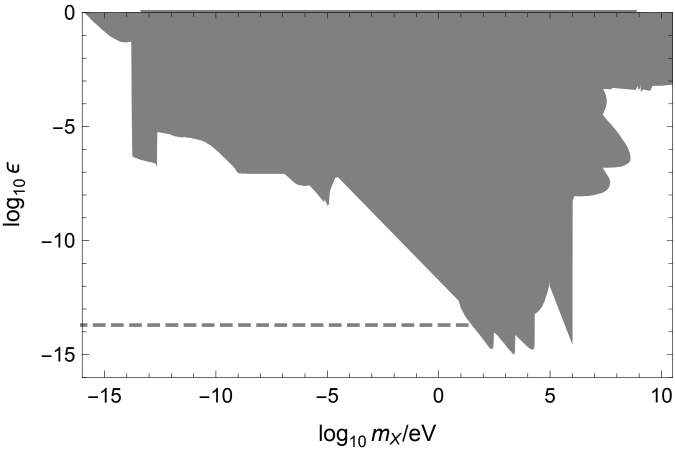

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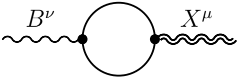
- $\rightsquigarrow$ $\epsilon \lesssim 10^{-15} \ldots 10^{-7}$ for $\mu\mathrm{eV} \lesssim m_X \lesssim 10\,\mathrm{MeV}$
- $\rightsquigarrow$ How to get such a small number from a model?

Generic One-Loop Expectation

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



$$\rightsquigarrow \epsilon \sim \frac{g' g_X}{8\pi^2} \ln \frac{M}{\mu} \sim 10^{-3} \ldots 10^{-1} \gg 10^{-7}$$

Holdom, PLB **166** (1986)

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

Known Suppression Mechanisms

- Fine-tuned cancellation between tree level and loop correction
- $g_X \ll 1$ from LARGE volume string compactifications
  Burgess et al., JHEP **07** (2008)
  Cicoli, Goodsell, Jaeckel, Ringwald, JHEP **07** (2011)
- Cancellation due to mass degeneracy
  - SUSY, string theory Dienes, Kolda, March-Russell, NPB **492** (1997)
  - GUTs Arkani-Hamed, Weiner, JHEP **12** (2008)
- Type-II string theory with warped extra dimensions and fluxes
  Abel et al., JHEP **07** (2008)
- 4-loop suppression in mirror-symmetric twin Higgs model
  Chacko, Goh, Harnik, PRL **96** (2006)
  Koren, McGehee, `arXiv:1908.03559`
- 2 additional options to be mentioned later

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

Higher Loop Order

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

	Charge		
	$U(1)_Y$	$U(1)_M$	$U(1)_X$
ψ	1	1	0
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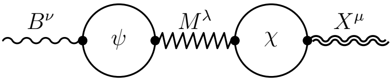
$\rightsquigarrow$ Kinetic mixing at 2-loop order?



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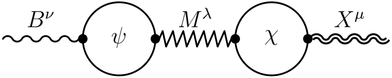


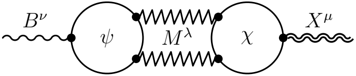
$\sim \Pi^{\nu\rho}_{YM}(k^2)\, D^{\rho\sigma}_M\, \Pi^{\sigma\mu}_{MX}(k^2) \sim \dfrac{k^4}{m_M^2}$

$\rightsquigarrow$ Operator with derivatives of $B^{\mu\nu}$ and $X^{\mu\nu}$

$\rightsquigarrow$ Does not contribute to kinetic mixing

Higher Loop Order

$\rightsquigarrow$ Kinetic mixing at 3-loop order?



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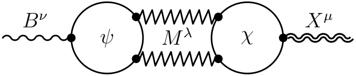

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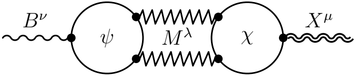

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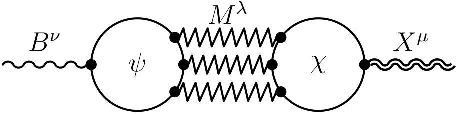

$$\rightsquigarrow \epsilon \sim \left(\frac{1}{16\pi^2}\right)^4 \sim 10^{-9}$$

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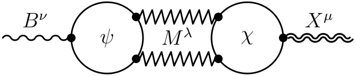

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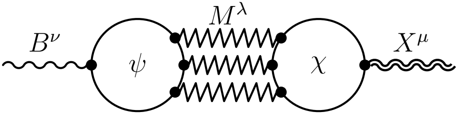

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Similar model with $U(1)_M \to SU(3)_c$: Dunsky, Hall, Harigaya, JHEP **07** (2019)

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_μ^i
- 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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- Diagonalize gauge boson mass matrix
  $\rightsquigarrow$ zero mode $=$ dark photon $=$ linear combination of all A^i_μ
- Field charged only under $U(1)_N$:

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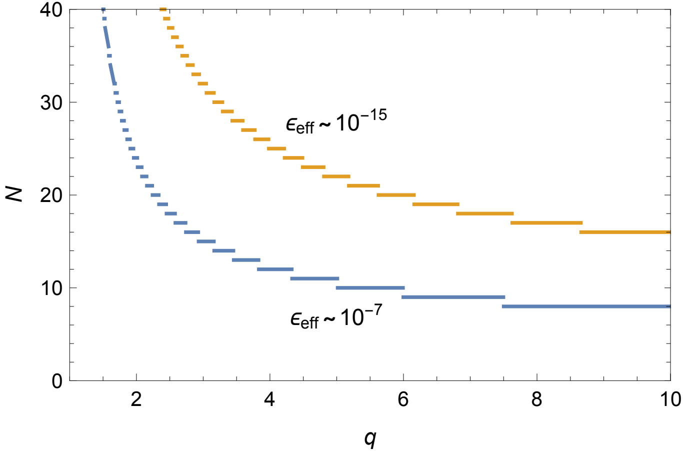
- Continuum limit $N \to \infty$: equivalent to 5D theory, $g_{\text{eff}} \sim e^{-kR}$

Clockwork-Suppressed Kinetic Mixing

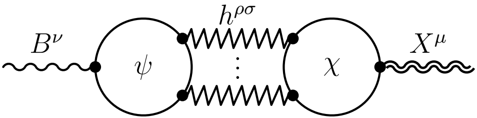
Kinetic mixing of B_μ only with A_μ^N

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



Gravity-Mediated Kinetic Mixing

- Visible and dark sector only connected via gravity
- No separate C conservation in dark sector
- Divergent graviton loops $\rightsquigarrow \epsilon \sim \left(\frac{\Lambda}{M_{\mathrm{Pl}}}\right)^n$ unsuppressed if $\Lambda \sim M_{\mathrm{Pl}}$



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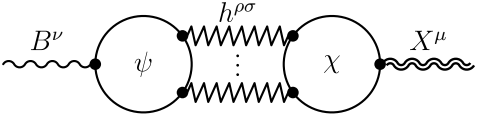
- $\sum Y_i = \sum Y_i^3 = 0 \rightsquigarrow$ need non-universal couplings in loops



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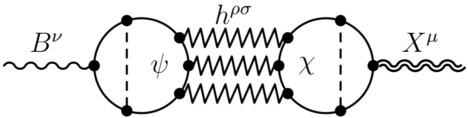

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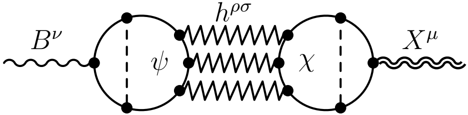

$$\rightsquigarrow \epsilon \sim \left(\frac{1}{16\pi^2}\right)^6 \left(\frac{\Lambda}{M_{\text{Pl}}}\right)^6 \sim 10^{-13}$$

Embedding Light and Dark Photons in a Single Group

- $G_{\mathrm{SM}} \times U(1)_X \subset$ non-Abelian group G
  $\rightsquigarrow \epsilon = 0$ at breaking scale of G
  $\rightsquigarrow$ Stückelberg mass excluded $\rightsquigarrow g_X \epsilon \lesssim 10^{-14}$ or $m_X \gtrsim 10\,\mathrm{keV}$

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- Light particles charged under both $U(1)_Y$ and $U(1)_X$
  $\rightsquigarrow$ generic $\epsilon \sim 10^{-3} \ldots 10^{-1}$
- 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: $E_8 \to E_6 \times SU(3) \to E_6 \times U(1)_X$

Only Standard Model Embedded in Simple Group

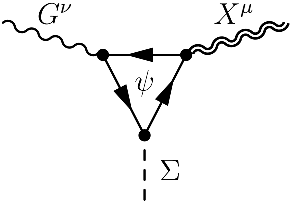
- $G_{\text{SM}} \times U(1)_X \subset G_{\text{GUT}} \times U(1)_X \rightsquigarrow G^{\mu\nu} X_{\mu\nu}$ not gauge-invariant
- Effective operator $\frac{1}{\Lambda} \Sigma \, G^{\mu\nu} X_{\mu\nu}$ with scalar Σ can be gauge-invariant

  $$\rightsquigarrow \epsilon \sim \frac{\langle \Sigma \rangle}{\Lambda} \ll 1$$

  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

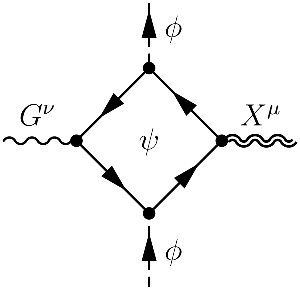


$$\rightsquigarrow \epsilon \sim \frac{y_\Sigma}{16\pi^2}\frac{\langle\Sigma\rangle}{\Lambda} \gtrsim \frac{y_\Sigma}{16\pi^2}\frac{M_{\mathrm{GUT}}}{M_{\mathrm{Pl}}} \sim 10^{-4}\, y_\Sigma$$

$\rightsquigarrow$ Ok for moderately small Yukawa coupling y_Σ

Example 2: Non-Adjoint Scalar in $SU(5)$

- Scalar $\phi \sim (\mathbf{75}, 0)$ under $SU(5) \times U(1)_X$
- Vector-like fermion $\psi = \chi \sim (\mathbf{10}, q)$, mass Λ

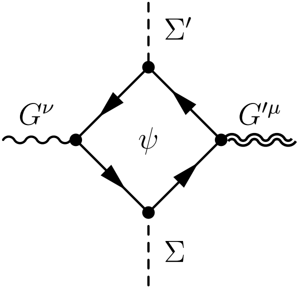


$$\rightsquigarrow \epsilon \sim \frac{y_\phi^2}{16\pi^2}\frac{\langle\phi\rangle^2}{\Lambda^2} \sim \frac{y_\phi^2}{16\pi^2}\left(\frac{M_{\mathrm{GUT}}}{M_{\mathrm{Pl}}}\right)^2 \sim 10^{-6}\, y_\phi^2$$

$\rightsquigarrow$ Ok

Non-Abelian Groups in Both Sectors

- $G_{\mathrm{SM}} \times U(1)_X \subset G_{\mathrm{GUT}} \times G'$
- Adjoint scalars Σ, Σ'



$$\rightsquigarrow \epsilon \sim \frac{y_\Sigma y_{\Sigma'}}{16\pi^2} \frac{\langle\Sigma\rangle \langle\Sigma'\rangle}{\Lambda^2}$$

- $\langle\Sigma'\rangle \ll M_{\mathrm{GUT}} \rightsquigarrow$ tiny ϵ

Goldberg, Hall, PLB **174** (1986)

Conclusions

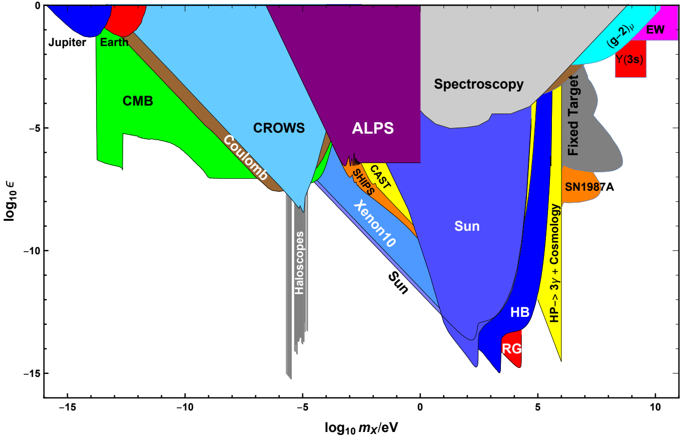
Kinetic mixing between visible and dark photon severely constrained: $\epsilon \lesssim 10^{-15} \ldots 10^{-7}$

$\rightsquigarrow$ Scenarios to explain such a small mixing

- Fine-tuning
- String theory
- Generation at high loop order $\rightsquigarrow \epsilon \sim 10^{-13} \ldots 10^{-9}$
- Suppression by gauged clockwork
- Gravity mediation $\rightsquigarrow \epsilon \sim 10^{-13}$
- 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

Constraints on Kinetic Mixing



Redondo, personal communication (2018)

Collider limits (BaBar etc.) not included