Two surprises in axion and hidden photon physics

Martin Bauer

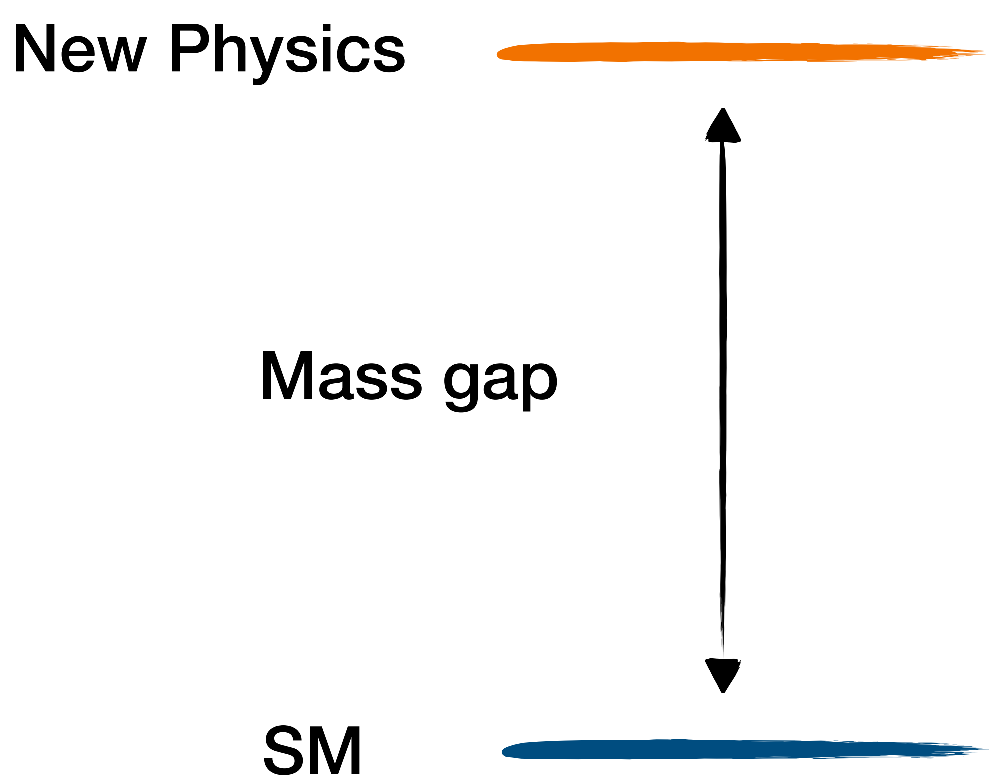
MB, Guillaume Rostagni, hep-ph/2307.09516

MB, Patrick Foldenauer, Phys. Rev. Lett. 129, 171801 (2022).

Padua, Sept 6, 2023

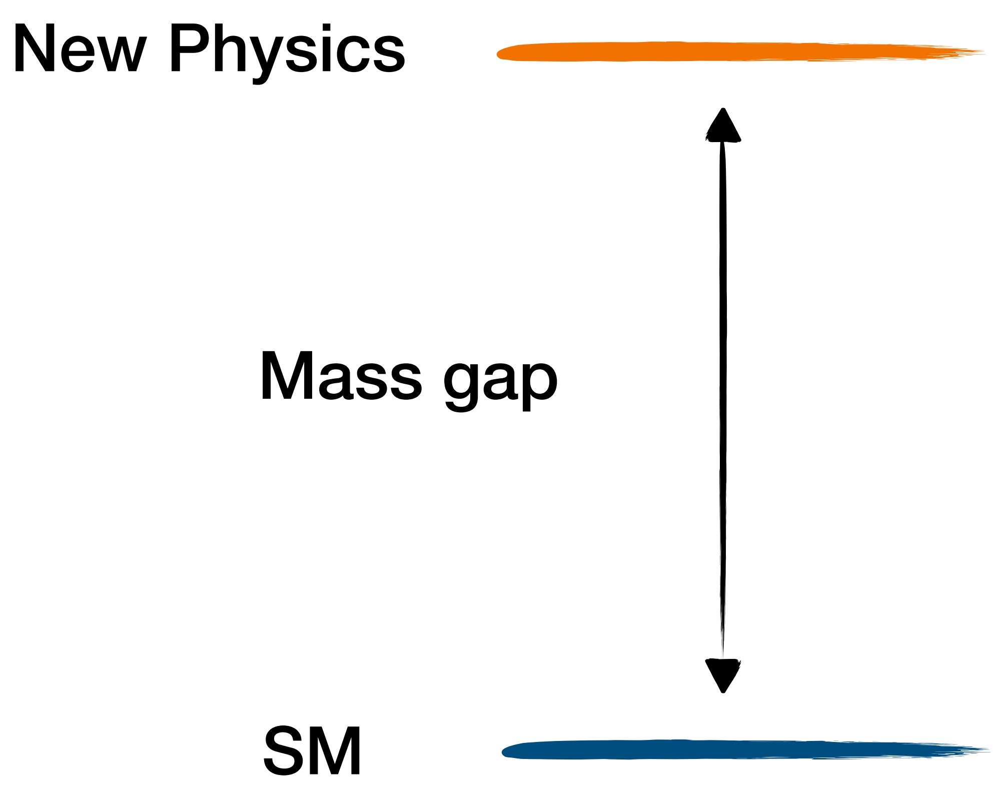
Durham University

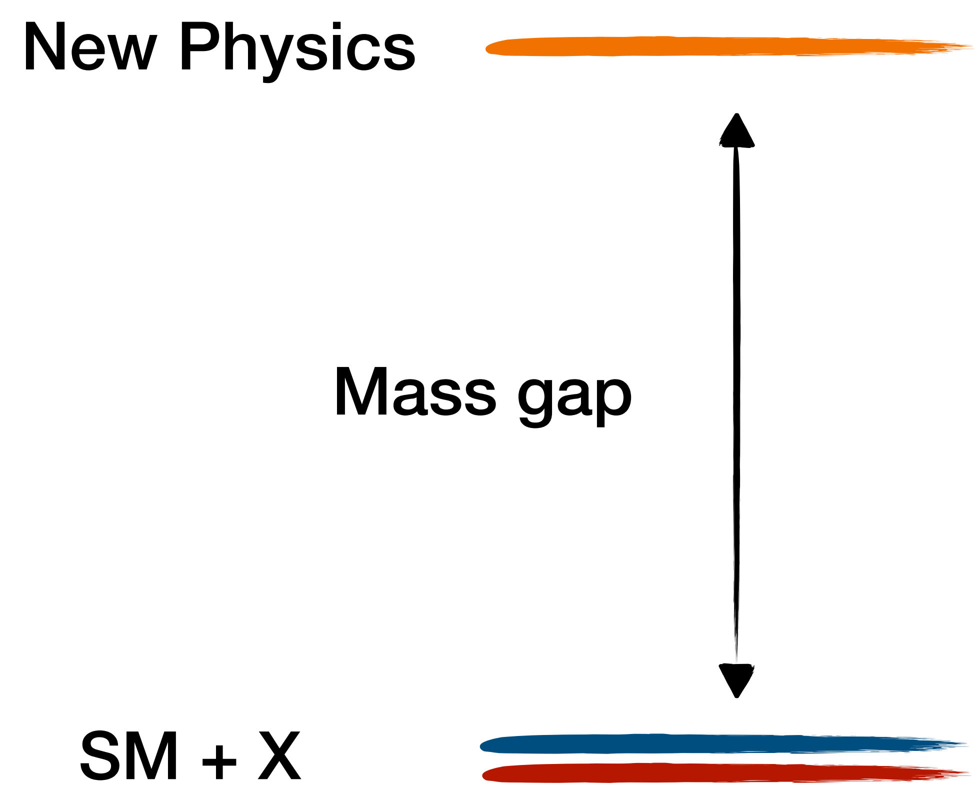
Landscape of new physics



$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}^5 + \dots$$

Landscape of new physics





$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}^5 + \ldots$$

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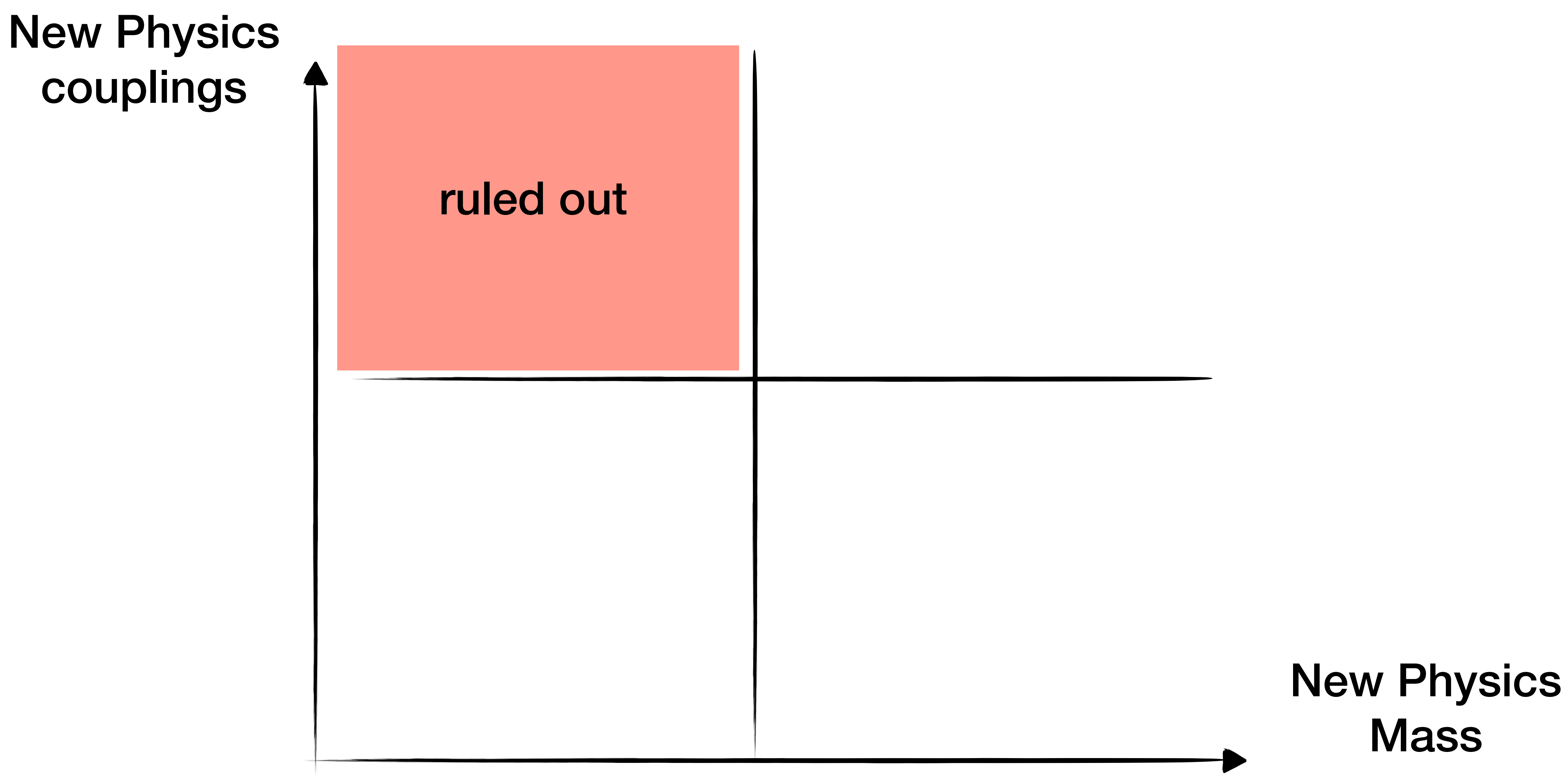
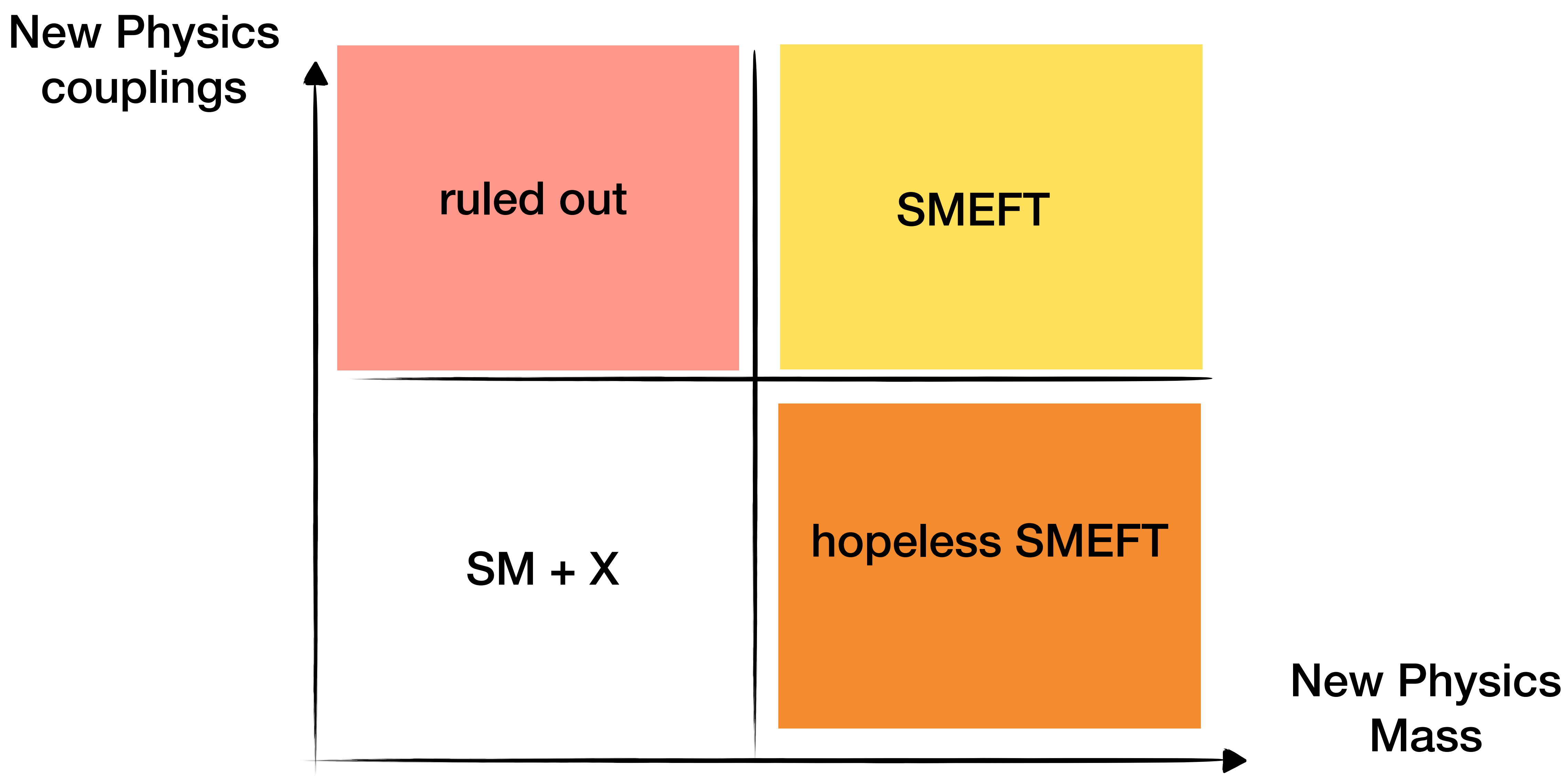
Landscape of new physics



Landscape of new physics



If these states are light they can be DM or mediators

But why should there be *any* new physics that is light and weakly coupled?

Light new physics ?

First example: Goldstone bosons

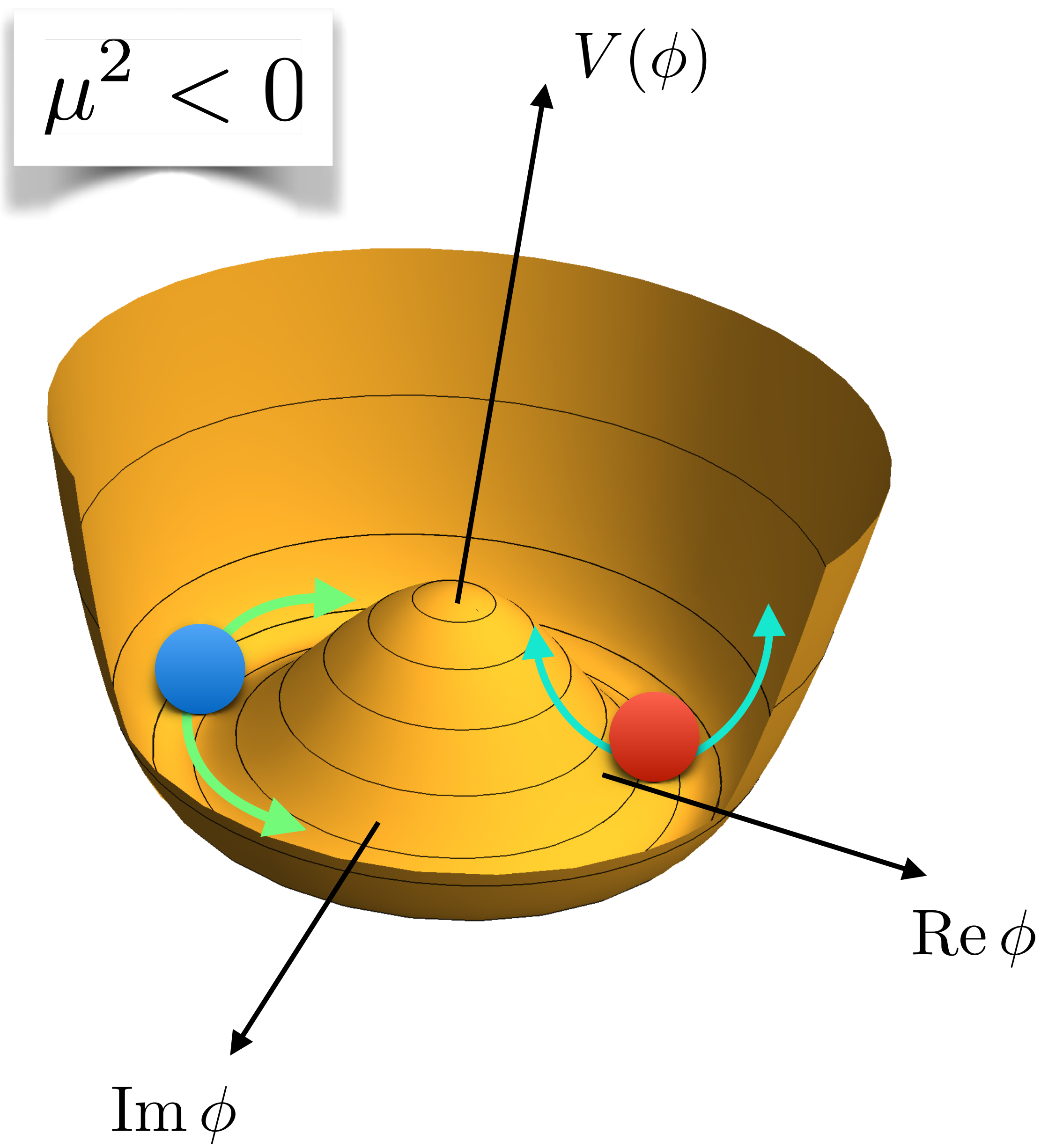
Every spontaneously broken continuous symmetry gives rise to massless spin-0 fields.

$$V(\phi) = \mu^2 \phi\phi^\dagger + \lambda\,(\phi\phi^\dagger)^2$$

$$\phi = (f+s)e^{ia/f}$$

$$m_s^2 = 4\lambda f^2 = |\mu^2|$$

$$m_a^2 = 0$$



Goldstone bosons

Since the GB corresponds to the phase of a complex field, it is protected by a shift symmetry

$$\phi = (f + s)e^{ia/f}$$

it is protected by a shift symmetry

$$e^{ia(x)/f} \rightarrow e^{i(a(x)+c)/f} = e^{ia(x)/f} e^{ic/f}$$

This symmetry forbids a mass term, and all couplings are suppressed by the UV scale

$$\mathcal{L} = \frac{1}{2}\partial_\mu a\, \partial^\mu a + c_\mu \frac{\partial^\nu a}{4\pi f}\, \bar{\mu}\gamma_\nu \mu + \ldots$$

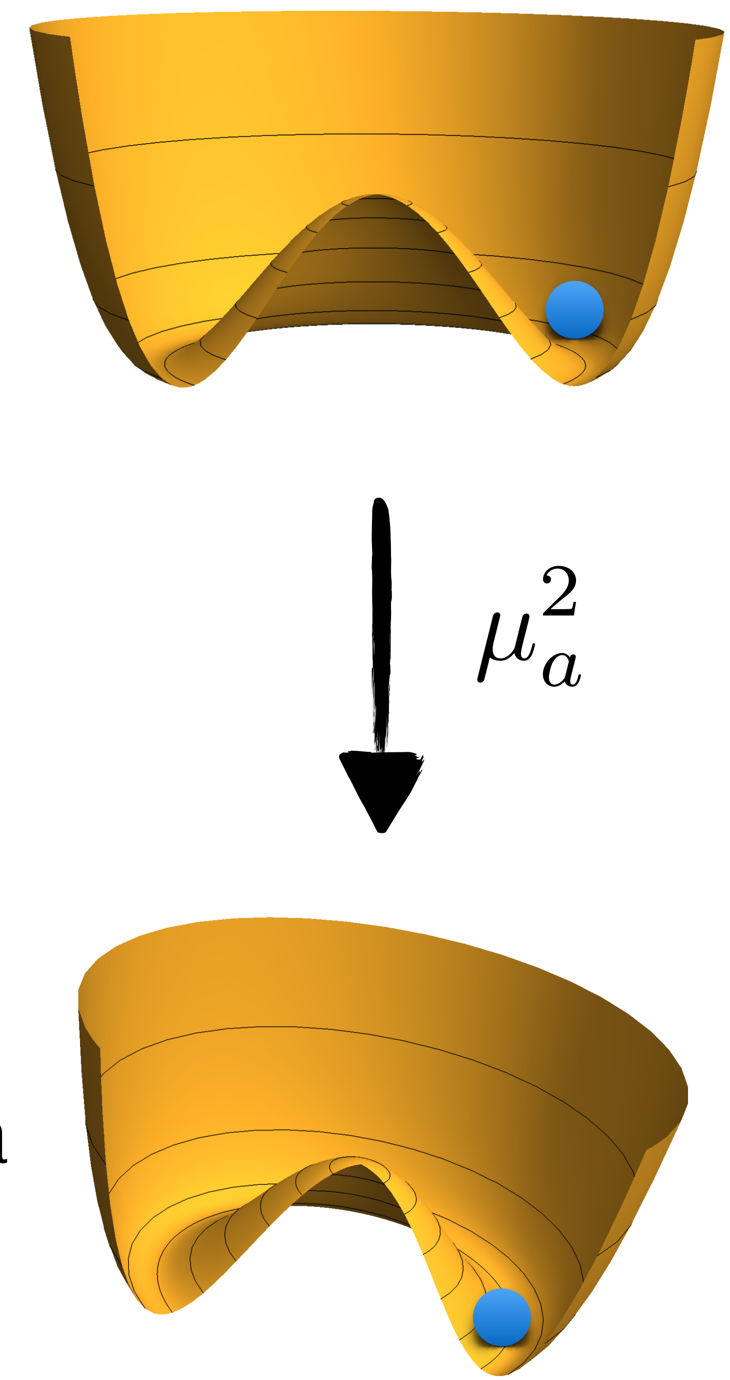
Goldstone bosons

An exactly massless boson is very problematic.

The global symmetry can be broken by
explicit masses or anomalous effects

$$\mathcal{L} = \frac{1}{2}\partial_\mu a\, \partial^\mu a + c_\mu \frac{\partial^\nu a}{4\pi f}\, \bar{\mu}\gamma_\nu \mu + \ldots + \frac{1}{2} m_a^2 a^2$$

$$m_a = \frac{\mu_a^2}{f}$$



Small couplings correspond to small masses and a
decoupled NP sector.

Goldstone bosons

The most famous example is the pion

$$\mathcal{L}_{\rm QCD} = \bar{q}_L i\not{D}\, q_L + \bar{q}_R i\not{D}\, q_R + m_q \bar{q}_L q_R$$

$$\langle \bar{q}_L q_R \rangle = \Lambda^3_{\rm QCD} \approx {\rm GeV}^3$$

The pion mass is controlled by the explicit breaking through light quark masses

$$m_\pi^2 = \frac{m_u + m_d}{f_\pi^2} \Lambda^3_{\rm QCD} \approx (140\,{\rm MeV})^2$$

Goldstone bosons

NP at f

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axion

Axionlike particles

Most general dimension five Lagrangian at the UV scale

$$\mathcal{L}_{\rm eff}^{D\le 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{f}\,\sum_F\,\bar\psi_F\,\boldsymbol{c}_F\,\gamma_\mu\,\psi_F + c_\phi\frac{\partial^\mu a}{f}\,\big(\phi^\dagger iD_\mu\phi + \text{h.c.}\big)$$

$$+\, c_{GG}\,\frac{\alpha_s}{4\pi}\,\frac{a}{f}\,G_{\mu\nu}^a\,\tilde G^{\mu\nu,a} + c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W_{\mu\nu}^A\,\tilde W^{\mu\nu,A} + c_{BB}\,\frac{\alpha_1}{4\pi}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde B^{\mu\nu}\,.$$

All couplings are suppressed by the UV scale f

Georgi, Kaplan, Randall, Phys. Lett. 169B, 73 (1986)

Axionlike particles

Most general dimension five Lagrangian at the UV scale

coupling to the Higgs current

explicit mass term

couplings to fermions

F=Q,u,d,L,e

$$\mathcal{L}_{\rm eff}^{D\le 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{f}\,\sum_F\,\bar\psi_F\,\boldsymbol{c}_F\,\gamma_\mu\,\psi_F + c_\phi\,\frac{\partial^\mu a}{f}\,\big(\phi^\dagger i D_\mu\phi + \text{h.c.}\big)$$

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coupling to gluons

coupling to $SU(2)_L$ gauge bosons

coupling to hypercharge

All couplings are suppressed by the UV scale f

Georgi, Kaplan, Randall, Phys. Lett. 169B, 73 (1986)

Axionlike particles

For the purpose of this talk I will focus on the fermion couplings

$$\mathcal{L}_{\text{eff}}^{D\leq 5} \supset \frac{\partial_\mu a}{2f} \sum_\psi c_\psi \bar{\psi} \gamma_\mu \gamma_5 \psi$$

The derivative coupling can be rewritten as a pseudoscalar coupling using the anomaly equation for the axial-vector current (or the equations of motion)

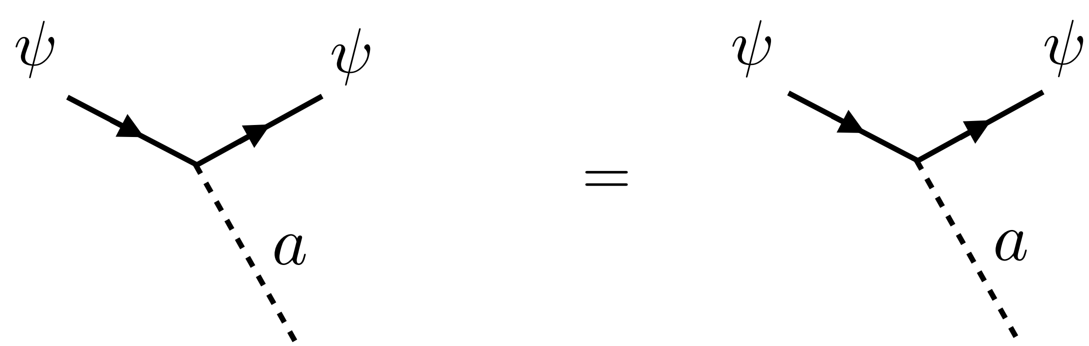
$$\frac{c_\psi}{2} \frac{\partial_\mu a}{f} \bar{\psi} \gamma_5 \gamma^\mu \psi = -c_\psi i m_\psi \frac{a}{f} \bar{\psi} \gamma_5 \psi + c_\psi \frac{\alpha Q_\psi^2}{4\pi} \frac{a}{f} F_{\mu\nu} \tilde{F}^{\mu\nu} .$$

Axionlike particles

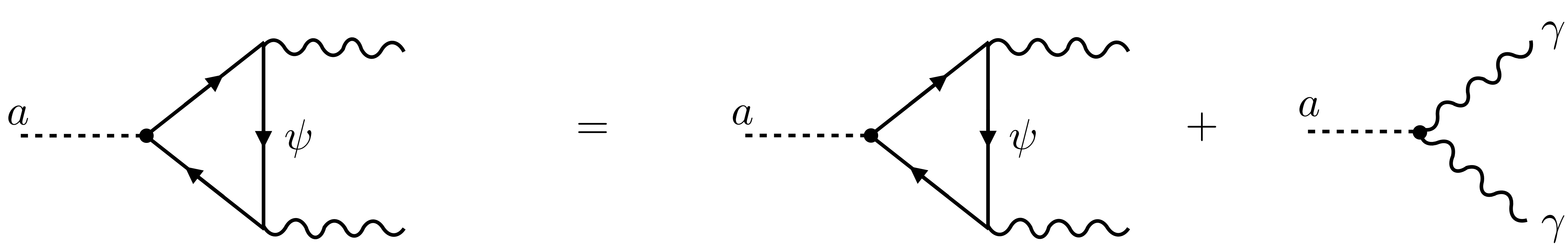
If you calculate axion production, these two bases are equivalent

$$\frac{c_\psi}{2}\frac{\partial_\mu a}{f}\bar{\psi}\gamma_5\gamma^\mu\psi = -c_\psi i m_\psi \frac{a}{f}\bar{\psi}\gamma_5\psi \; + c_\psi \frac{\alpha Q_\psi^2}{4\pi}\frac{a}{f}F_{\mu\nu}\tilde{F}^{\mu\nu} \, .$$

E.g. an axion radiated off an electron

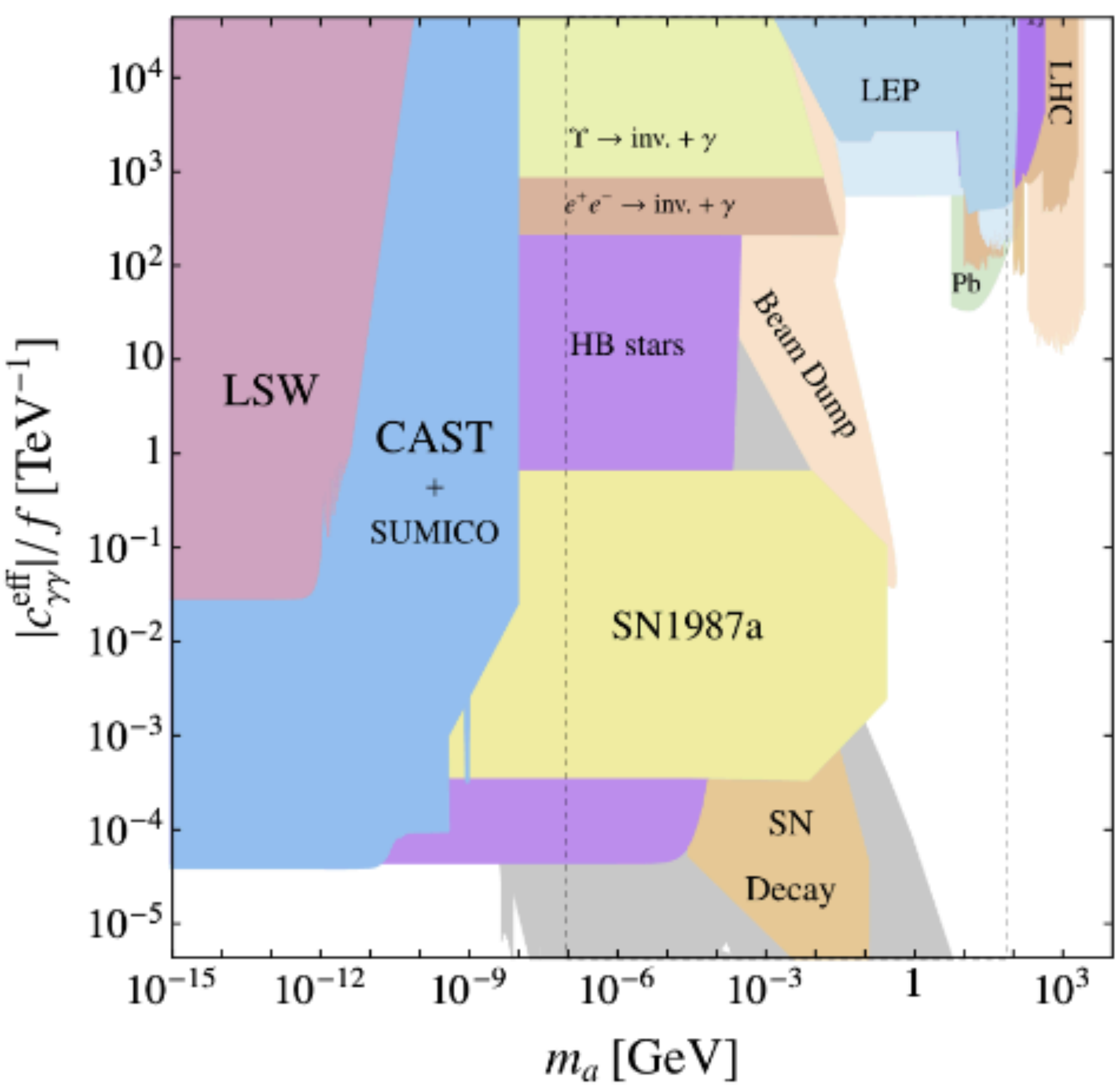


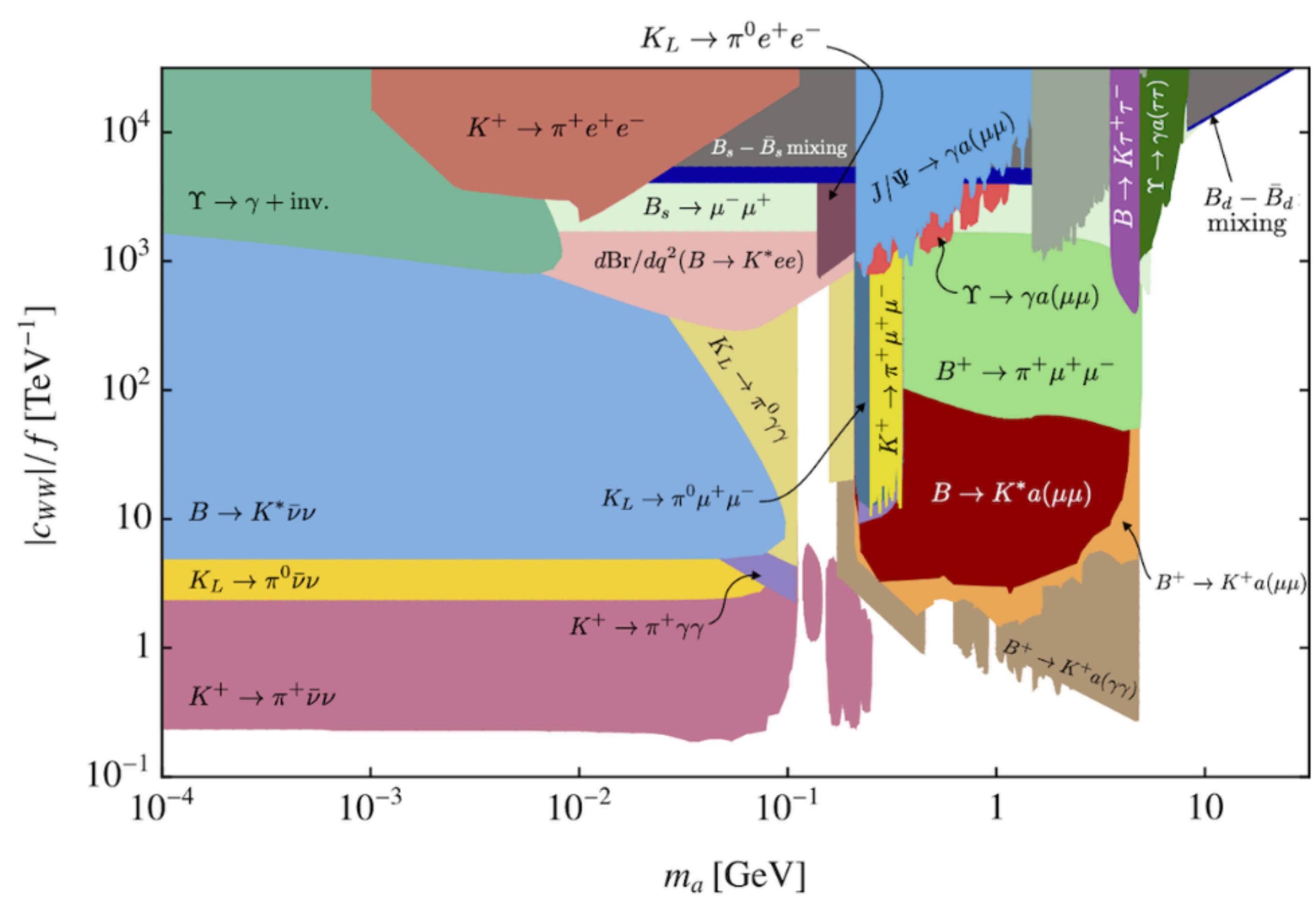
Same for the axion decay rate into photons



Axionlike particles

There are many ways to search for axions…





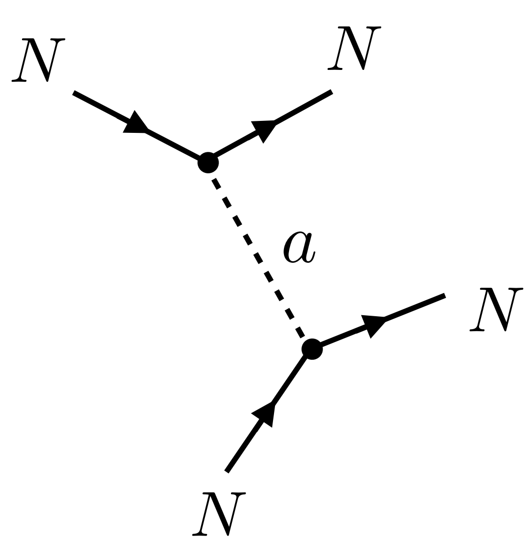
MB, Neubert, Renner, Schnubel, Thamm, *JHEP* 09 (2022) 056

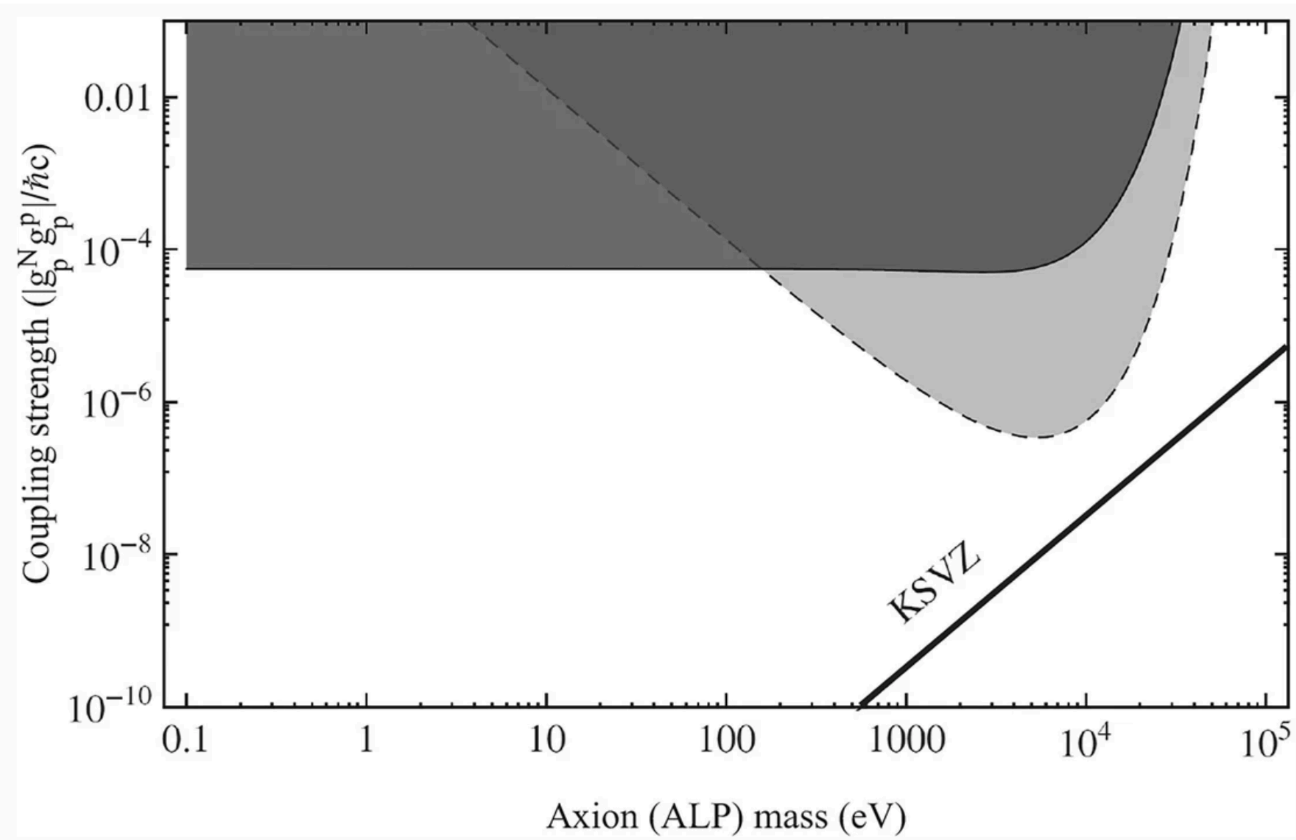
Axionlike particles

At very low energies, axion exchange induces a spin-dependent force

$$V(r)=\frac{g_P^1 g_P^2}{16\pi M_1 M_2}\left[(\hat{\sigma}_1\cdot\hat{\sigma}_r)\left[\frac{m_\varphi}{r^2}+\frac{1}{r^3}+\frac{4\pi}{3}\delta^3(r)\right]-(\hat{\sigma}_1\cdot\hat{r})(\hat{\sigma}_2\cdot\hat{r})\left[\frac{m_\varphi^2}{r}+\frac{3m_\varphi}{r^2}+\frac{3}{r^3}\right]\right]e^{-m_\varphi r}$$

Constraints e.g. from hyperfine splitting corrections





J. E. Moody and F. Wilczek, Phys. Rev. D 30 (1984), 130
Ledbetter, Romalis, Kimball, Phys. Rev. Lett. **110**, 040402 (2013)

Axionlike particles

If there is a theta angle the axion has a tiny scalar coupling as well

$$H_{\text{int}} = \frac{a}{F}\frac{m_u m_d}{m_u + m_d}\theta(\bar{u}u + \bar{d}d + \bar{s}s)$$

Any such force would depend on the size of the theta angle, which acts like a spurion for the shift symmetry

monopole²

$$V(r) = \frac{-g_S^1 g_S^2 e^{-m_\varphi r}}{4\pi r}$$

$$\sim(\theta/F)^2$$

monopole x dipole

$$V(r) = (g_S^1 g_P^2)\frac{\hat{\sigma}_2\cdot\hat{r}}{8\pi M_2}\left[\frac{m_\varphi}{r} + \frac{1}{r^2}\right]e^{-m_\varphi r}$$

$$\sim\theta/F^3$$

dipole²

$$V(r) = \frac{-g_P^1 g_P^2}{16\pi M_1 M_2}(\hat{\sigma}_1\cdot\hat{r})(\hat{\sigma}_2\cdot\hat{r})\left[\frac{m_\varphi^2}{r} \ldots\right.$$

$$\sim 1/F^4$$

J. E. Moody and F. Wilczek, Phys. Rev. D 30 (1984), 130

Axionlike particles

This can have interesting effects in situations where the nuclear density is large, because finite density effects change the axion potential

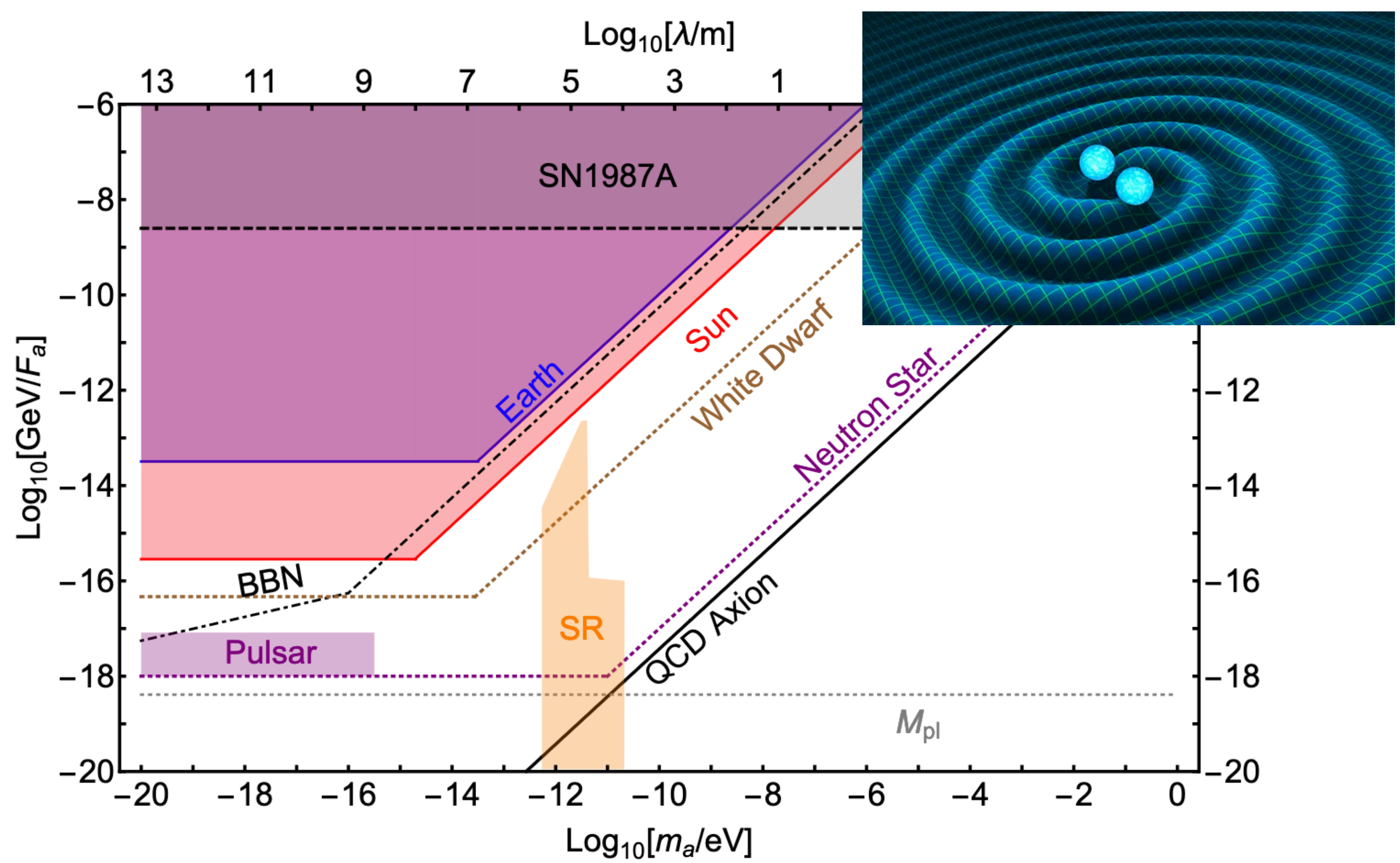
nucleon number density

$$V = -m_\pi^2 f_\pi^2 \left\{ \left(\epsilon - \frac{\sigma_N n_N}{m_\pi^2 f_\pi^2} \right) \left| \cos\left(\frac{a}{2 f_a} \right) \right| + \mathcal{O}\left(\left(\frac{\sigma_N n_N}{m_\pi^2 f_\pi^2} \right)^2 \right) \right\},$$

and then one can have

theta ~ pi

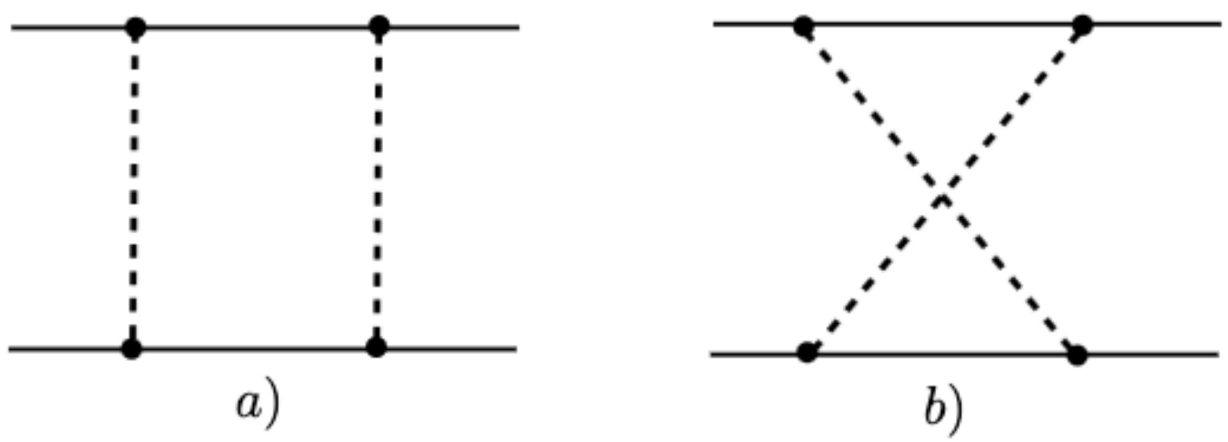
and a large force at small distances



A. Hook and J. Huang, JHEP 06 (2018), 036

Axionlike particles

The axion also mediates spin-independent forces via 2-axion exchange that is completely theta independent



If you calculate the potential you find

$$V_{ab}(r) = -\frac{c_{\psi_1}^2 c_{\psi_2}^2}{64\pi^3 f^4} \frac{m_{\psi_1} m_{\psi_2}}{r^3}$$ for $$: -c_\psi i m_\psi \frac{a}{f} \bar{\psi}\gamma_5\psi$$

MB, Rostagni, hep-ph/2307.09516

Axionlike particles

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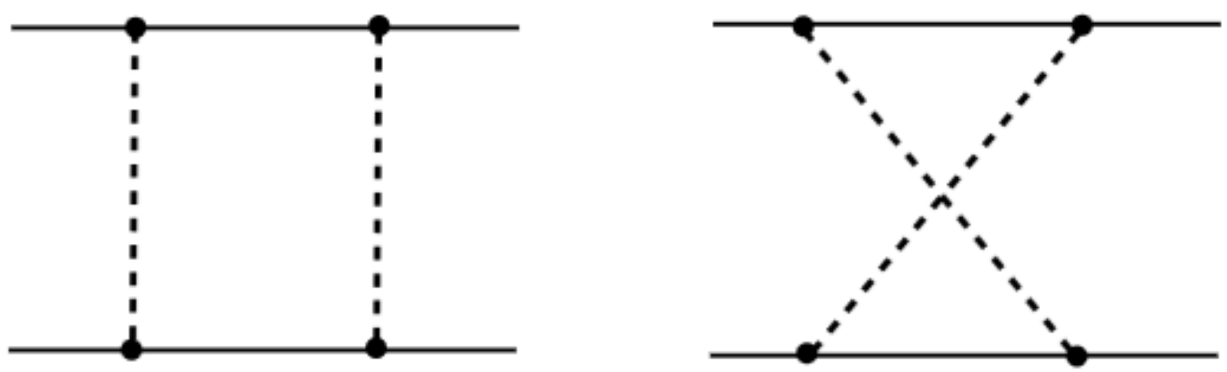

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$$V_{ab} = \frac{3c_{\psi_1}^2 c_{\psi_2}^2}{128\pi^3 f^4}\frac{1}{r^5}$$ for $\frac{c_\psi}{2}\frac{\partial_\mu a}{f}\bar{\psi}\gamma_5\gamma^\mu\psi$

This result can’t possibly depend on the basis!

MB, Rostagni, hep-ph/2307.09516

Axionlike particles

The problem is that applying the equations of motion only accounts for a linear shift in the fermion fields. Since we have an $1/f^4$ effect we need to shift up to quadratic order

$$\psi \;\rightarrow\; \exp\left(i\frac{a}{f}\right)\psi = i\frac{a}{f}\psi - \frac{a^2}{2f^2}\psi + \ldots$$

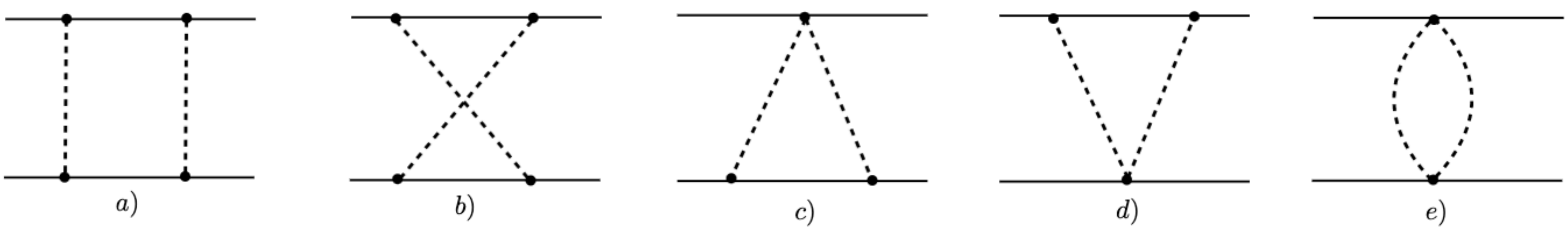
EoM account only for this term

or in terms of the anomaly equation

$$\frac{c_\psi}{2}\frac{\partial_\mu a}{f}\bar{\psi}\gamma_5\gamma^\mu\psi = -c_\psi i m_\psi \frac{a}{f}\bar{\psi}\gamma_5\psi + c_\psi^2 m_\psi \frac{a^2}{f^2}\bar{\psi}\psi + c_\psi \frac{\alpha Q_\psi^2}{4\pi}\frac{a}{f}F_{\mu\nu}\tilde{F}^{\mu\nu} + \mathcal{O}\Big(\frac{a^3}{f^3}\Big)$$

Axionlike particles

As a result the full calculation in the pseudoscalar basis has additional contributions



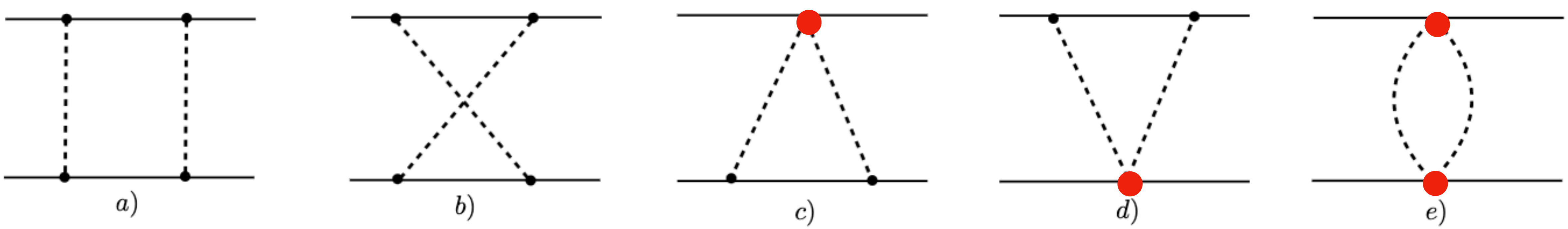
And the result agrees with the derivative basis

$$
\begin{aligned}
V(r) &= V_{ab}(r) + V_c(r) + V_d(r) + V_e(r) \\
&= \frac{3c_{\psi_1}^2 c_{\psi_2}^2}{128\pi^3 f^4}\frac{1}{r^5}\left[\left(x_a + \frac{x_a^3}{6}\right)K_1(x_a) + \frac{x_a^2}{2}K_0(x_a)\right] \\
&= \frac{3c_{\psi_1}^2 c_{\psi_2}^2}{128\pi^3 f^4}\left[\frac{1}{r^5} - \frac{1}{3}\frac{m_a^2}{r^3} + O(m_a^4)\right]
\end{aligned}
$$

MB, Rostagni, hep-ph/2307.09516

Axionlike particles

A delicate cancellation between the linear and quadratic interactions makes the spin-independent axion force extremely suppressed ~1/r⁵



But there is a quadratic spurion in the ALP Lagrangian

$$\mathcal{L}_{\rm ssb} \ni \sum_{\psi} c_m \frac{m_a^2 a^2}{f^3} \bar{\psi}\psi$$

For a generic ALP this shift-symmetry breaking scales like ~1/f⁵

MB, Rostagni, hep-ph/2307.09516

Axionlike particles

But the QCD axion is special, because the shift symmetry is broken by the quark masses

The relevant interactions of the QCD axion in the chiral 2-flavor Lagrangian can be written as

$$\mathcal{L}^{(1)} = \bar{N}\left(i\not{D} - m_N + \frac{g_A}{2}\gamma^\mu\gamma^5 u_\mu + g_0\gamma^\mu\gamma^5 a_\mu^{(s)}\right) N$$

and

$$\mathcal{L}^{(2)} = c_1 \mathrm{tr}[\chi_+]\bar{N}N - \frac{c_2}{4m^2}\mathrm{tr}[u_\mu u_\nu](\bar{N}D^\mu D^\nu N + \mathrm{h.c.}) + \frac{c_3}{2}\mathrm{tr}[u_\mu u^\mu]\bar{N}N - \frac{c_4}{4}\bar{N}\gamma^\mu\gamma^\nu[u_\mu, u_\nu]N$$

MB, Rostagni, hep-ph/2307.09516

Axionlike particles

All terms are shift symmetric apart from

$$c_1 \mathrm{tr}[\chi_+]\bar{N}N = c_N \frac{a^2}{f^2}\bar{N}N + \ldots$$

with $$\chi_+ = 2B_0\big(\xi^\dagger m_q(a)\xi^\dagger + \xi m_q^\dagger(a)\xi\big) \qquad \tau_a = m_a^2/m_\pi^2$$

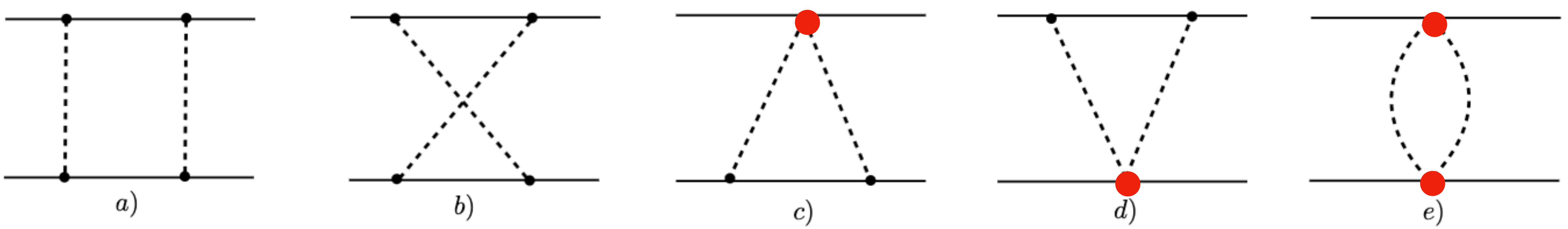
and the coefficient $$c_N = c_1 \frac{m_\pi^2}{2}\frac{4c_{GG}^2(1-\tau_a)^2 + (c_u - c_d)^2\tau_a^2}{(1-\tau_a)^2}$$

This term breaks the shift symmetry at the same order in 1/f as the leading shift-invariant interactions even though it's induced by a higher order operator

MB, Rostagni, hep-ph/2307.09516

Axionlike particles

The leading contributions to the potential read



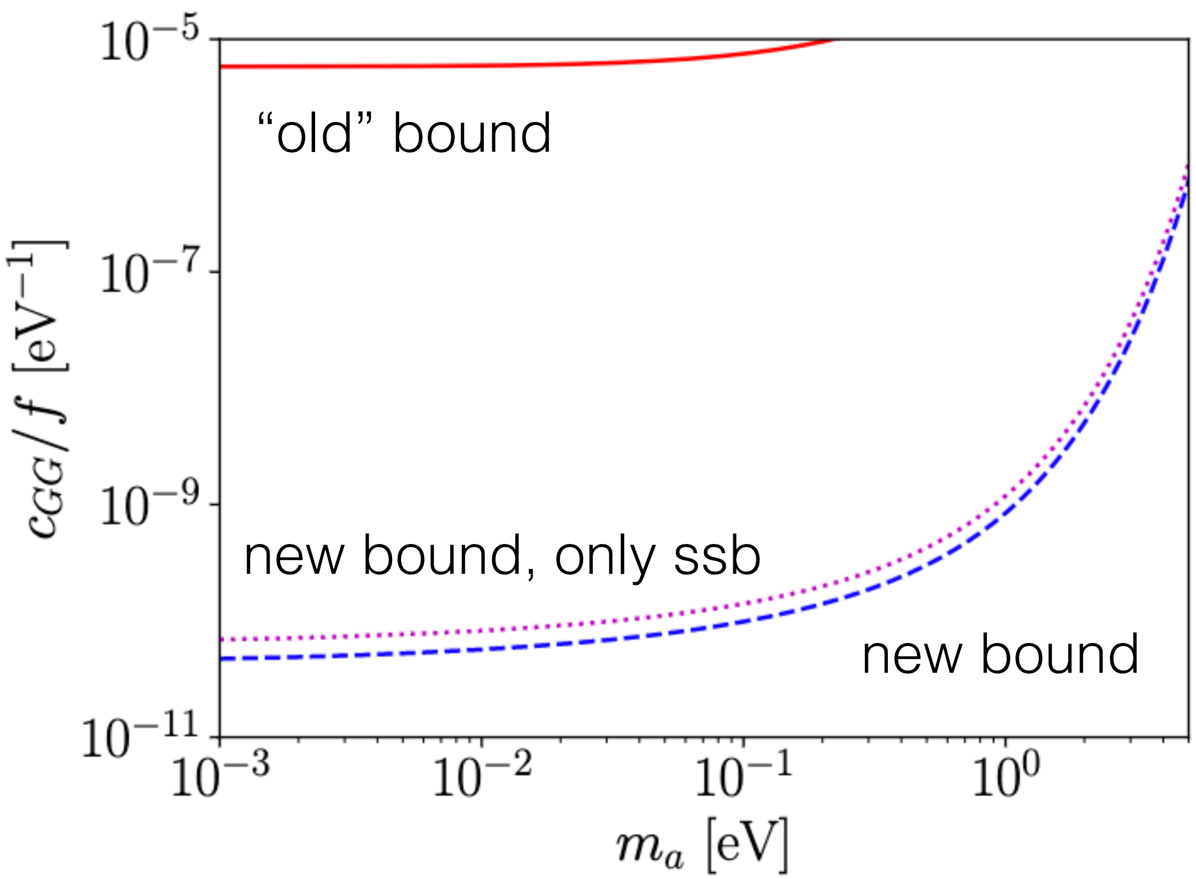
$$V_{\rm sp.}(r) = -\frac{c_{N_1} c_{N_2}}{64\pi^3 f^4}\frac{1}{r^3} + O\left(\frac{m_a^2}{r^3}, \frac{1}{r^5}\right)$$

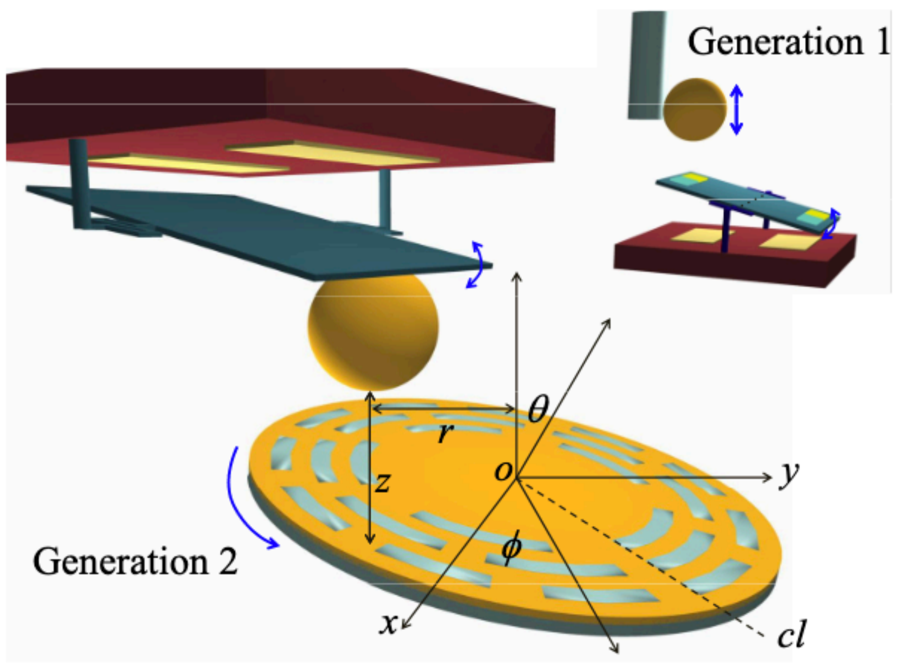
This force acts only between nuclei, because the shift-symmetry breaking quadratic coupling doesn't exist for leptons

MB, Rostagni, hep-ph/2307.09516

Axionlike particles

The leading constraints arise from “Casimir-less” fifth force searches and the force is purely attractive for an axion only coupled to gluons





Chen, Tham, Krause, Lopez, Fischbach, Decca, Phys. Rev. Lett. 116 (2016) no.22, 221102

MB, Rostagni, hep-ph/2307.09516

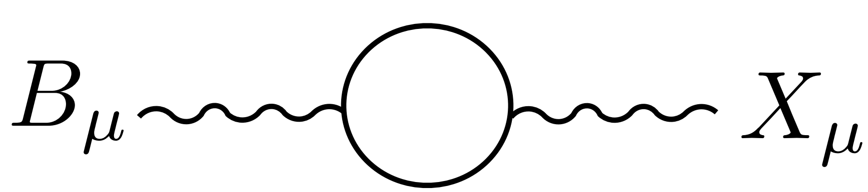
Hidden Photons

Second example: gauge bosons (local symmetry breaking)

$$\mathcal{L} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}D_\mu\phi D^\mu\phi - V(\phi) + g_X\bar{\psi}\gamma_\mu\psi X^\mu$$

$$\phi = (f+s)e^{ia/f} \quad \longrightarrow \quad m_X = g_X f$$

Interactions with the SM are either directly set by the gauge coupling or through kinetic mixing



$$\epsilon \propto \frac{g_X e}{8\pi^2}\log\frac{\Lambda^2}{m^2}$$

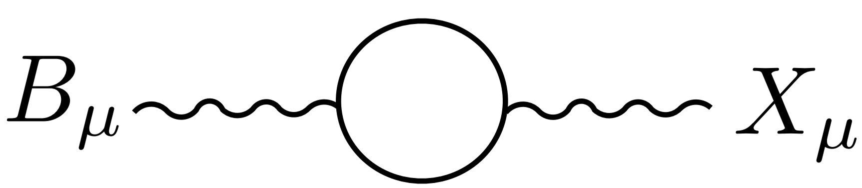
Small gauge couplings imply small masses

Hidden Photons

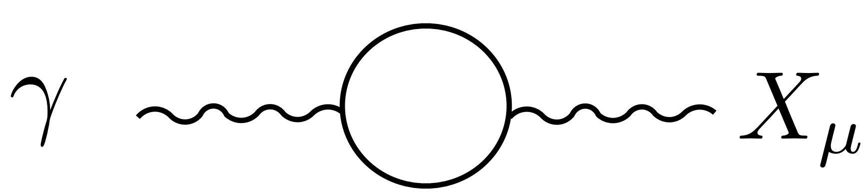
The hidden photon can be either a secluded gauged group, or one of the anomaly free global symmetries of the SM (unless you add more matter fields)

$$U(1)_{B-L} \quad U(1)_{L_\mu - L_e} \quad U(1)_{L_\tau - L_e} \qquad U(1)_{L_\mu - L_\tau}$$

If you calculate the kinetic mixing between the photon and the hidden photon

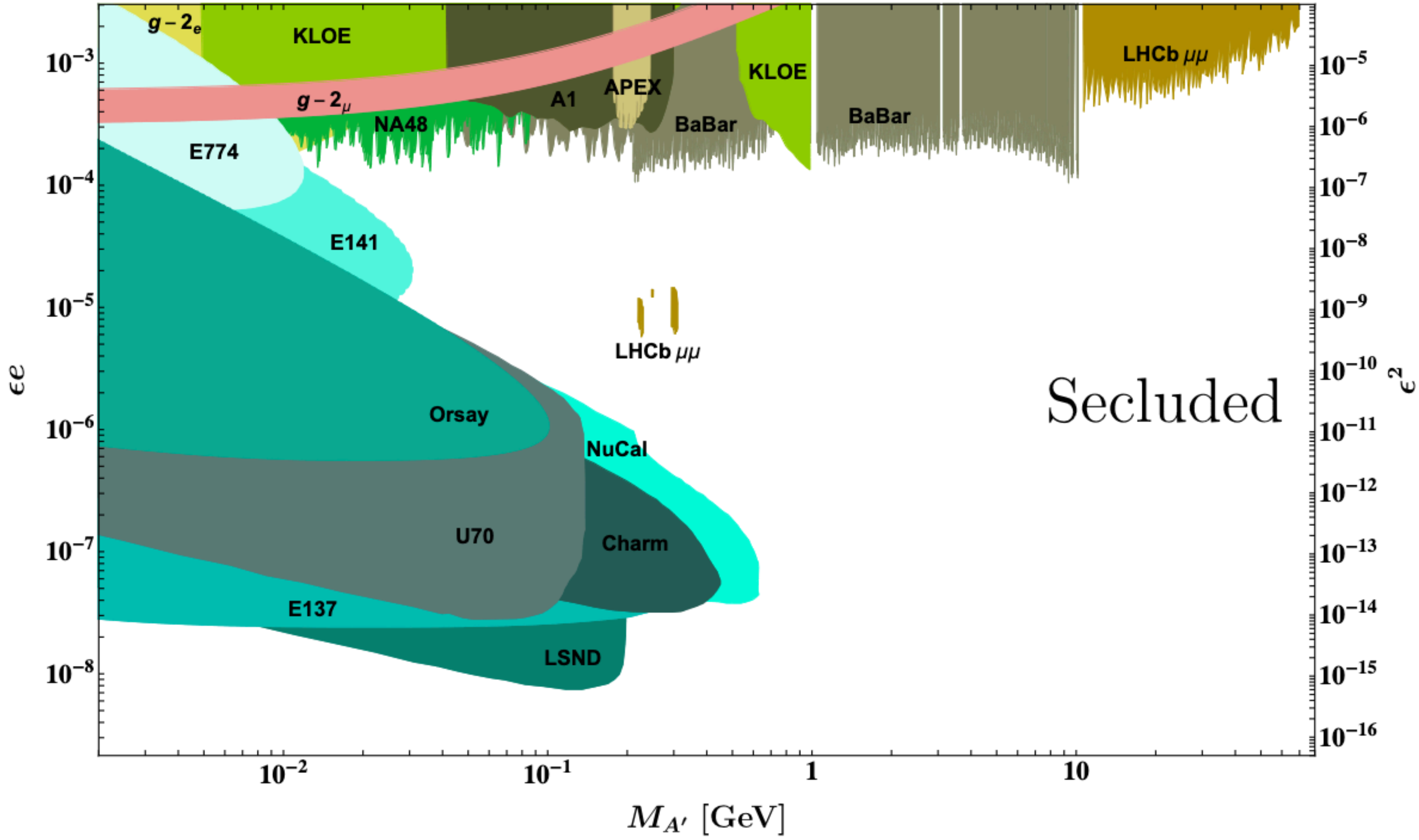


$$\epsilon_B = \frac{g' g_{\mu-\tau}}{24\pi^2}\left[3\log\left(\frac{m_\mu}{m_\tau}\right) + \log\left(\frac{m_{\nu_\mu}}{m_{\nu_\tau}}\right)\right]$$



$$\epsilon \propto \frac{e g_{\mu-\tau}}{12\pi^2}\log\left(\frac{m_\mu}{m_\tau}\right)$$

Bounds on hidden photons



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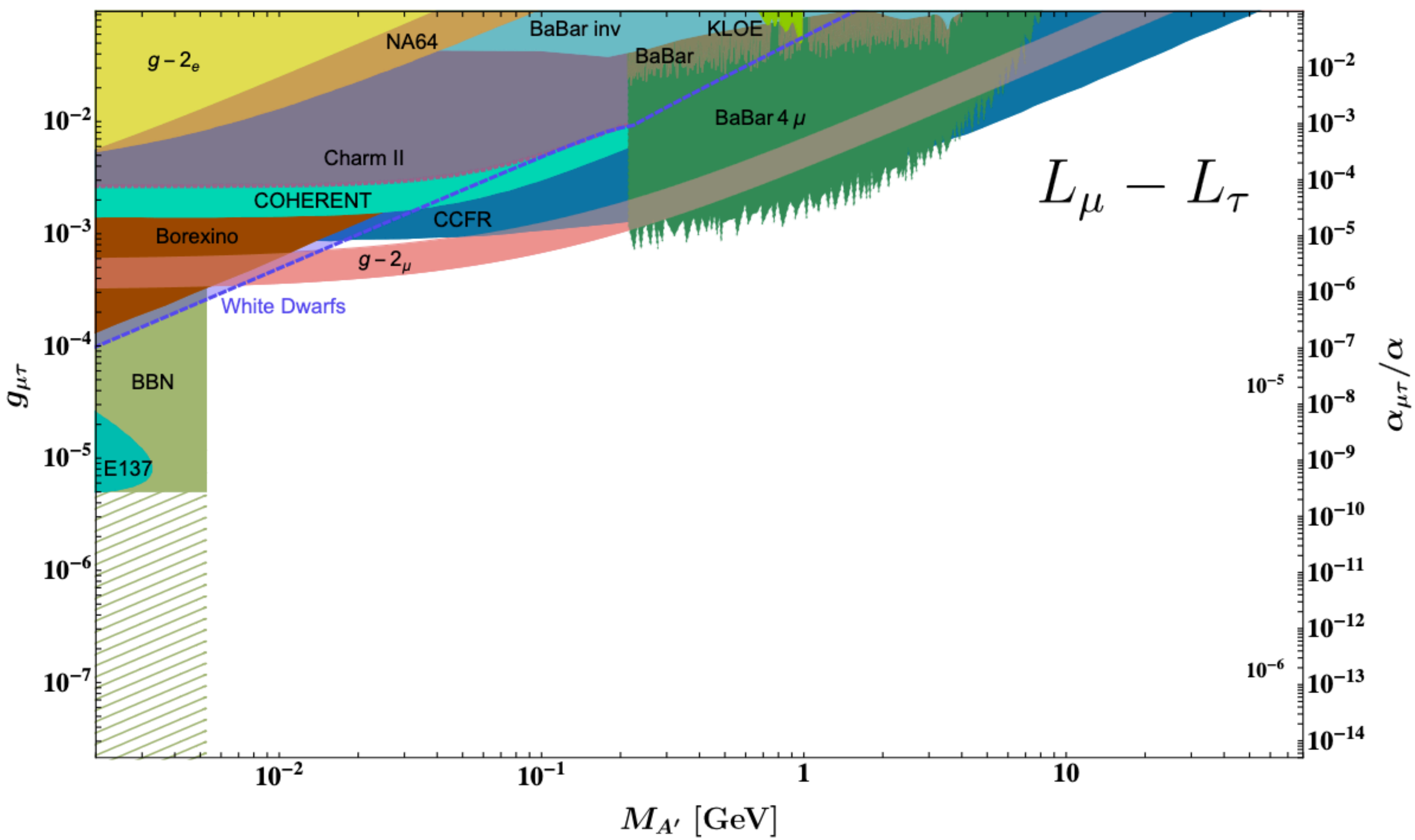

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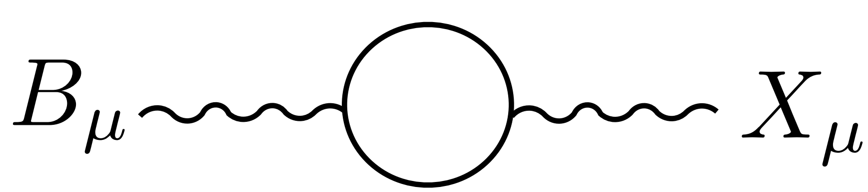

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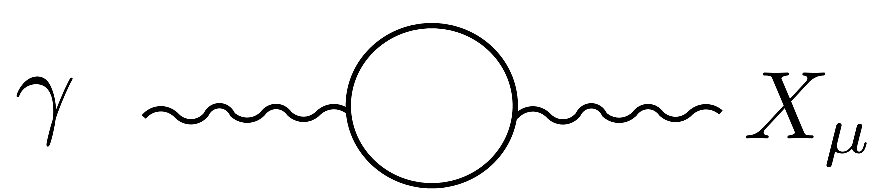
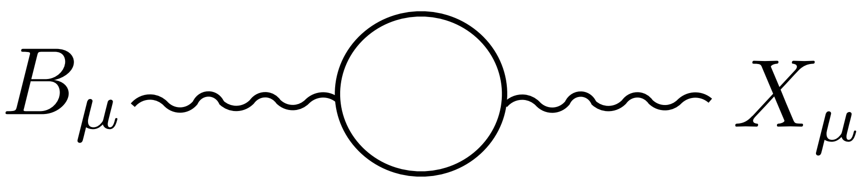


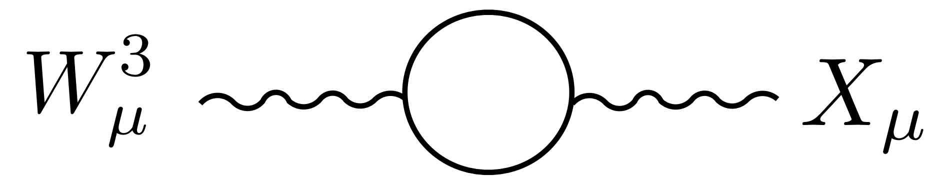
$$\epsilon \propto \frac{e g_{\mu-\tau}}{12\pi^2} \log\left(\frac{m_\mu}{m_\tau}\right)$$

Hidden Photons

In some cases the loop induced mixing is finite, e.g. $U(1)_{L_\mu - L_\tau}$

In this case the muon, tau and the corresponding neutrinos are charged under a new gauge group





$$-\frac{\epsilon_B}{2} B_{\mu\nu} X^{\mu\nu}$$

$$\mathcal{O}_{WX} = \frac{c_{WX}}{\Lambda^2} H^\dagger \sigma^i H \, W^i_{\mu\nu} X^{\mu\nu}$$

$$\supset -\frac{\epsilon_W}{2} W^3_{\mu\nu} X^{\mu\nu}$$

With the result

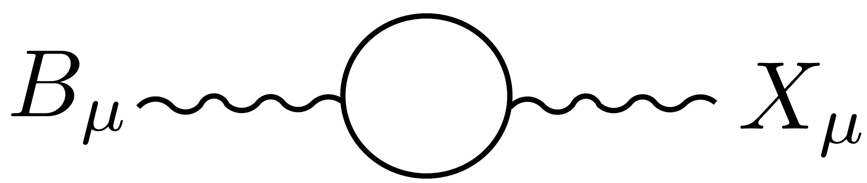
$$\epsilon_B = \frac{g' g_{\mu-\tau}}{24\pi^2} \left[3 \log\left(\frac{m_\mu}{m_\tau}\right) + \log\left(\frac{m_{\nu_\mu}}{m_{\nu_\tau}}\right) \right]$$

$$\epsilon_W = \frac{g g_{\mu-\tau}}{24\pi^2} \left[\log\left(\frac{m_\mu}{m_{\nu_\mu}}\right) - \log\left(\frac{m_\tau}{m_{\nu_\tau}}\right) \right]$$

MB, Foldenauer, Phys. Rev. Lett. 129, 171801 (2022)

Hidden Photons

But this is not always the case, e.g. for a charged B-L group



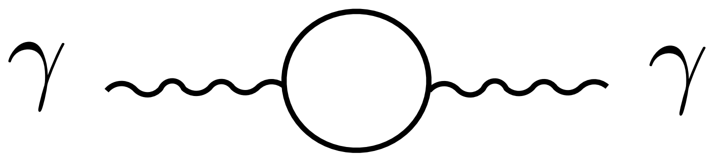
$$\epsilon \propto \frac{g_X e}{8\pi^2} \log \frac{\Lambda^2}{m^2}$$

So some hidden photon gauge groups have finite kinetic mixing, others are sensitive to a UV scale

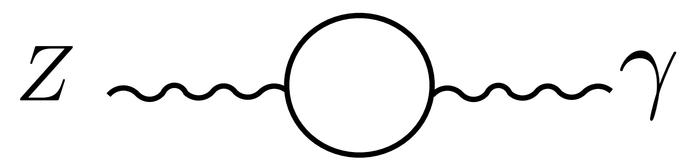
What’s the implication of this UV divergence in kinetic mixing?

Hidden Photons

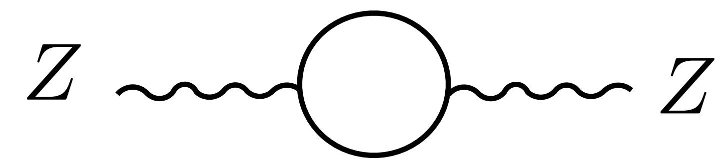
Consider the photon-Z mixing in the SM



$$\log \frac{\Lambda^2}{m^2}$$



$$\log \frac{\Lambda^2}{m^2}$$



$$\log \frac{\Lambda^2}{m^2}$$

Needs 3 counterterms:

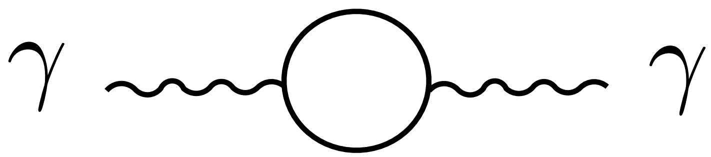
$$\mathcal{L} \supset \frac{1}{4} Z_{AA} F^{\mu\nu} F_{\mu\nu} + \frac{1}{4} Z_{ZZ} Z^{\mu\nu} Z_{\mu\nu} + \frac{1}{2} Z_{ZA} F_{\mu\nu} Z^{\mu\nu}$$

But there can be only 2:

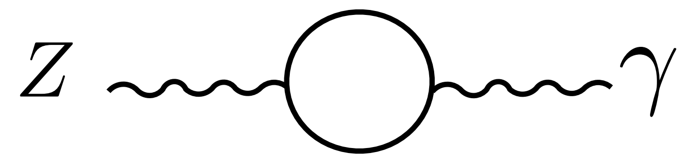
$$\mathcal{L} \supset \frac{1}{4} Z_{BB} B^{\mu\nu} B_{\mu\nu} + \frac{1}{4} Z_{WW} W^{a,\mu\nu} W^{a}_{\mu\nu}$$

Hidden Photons

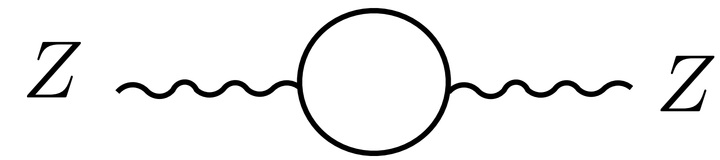
Consider the photon-Z mixing in the SM



$$\log \frac{\Lambda^2}{m^2}$$



$$\log \frac{\Lambda^2}{m^2}$$



$$\log \frac{\Lambda^2}{m^2}$$

The only way 3 divergences can be absorbed in 2 counterterms is when the couplings aren't independent

$$R(\theta) \begin{pmatrix} Z_{AA} & Z_{ZA} \\ Z_{ZA} & Z_{ZZ} \end{pmatrix} R(\theta)^{-1} = \begin{pmatrix} Z_{BB} & 0 \\ 0 & Z_{WW} \end{pmatrix}$$

Hidden Photons

If the kinetic mixing term is UV divergent there must be a symmetry breaking in the UV that mixes the gauge bosons

Without knowing anything else we know that G_{UV} can't be a direct product

$$G_{UV} \quad \to \quad SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

Whereas for $U(1)_{L_\mu - L_\tau}$ it must be possible to find a direct product

$$\begin{array}{ccc} G_{\text{SM}} & \times & G_{L_\mu - L_\tau} \\ \downarrow & & \downarrow \\ SU(3)_C \times SU(2)_L \times U_Y(1) & \times & U(1)_{L_\mu - L_\tau} \end{array}$$

Two Surprises

1. For QCD axions interacting with quarks and gluons the leading term in the spin-independent force is induced by higher-order shift-symmetry breaking operators

2. The divergence of any loop-induced kinetic mixing term for hidden photons tells us whether the underlying gauge group in the Uv can be written as a direct product or must be a GUT