Electroweak Axions

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A shift of paradigm

- To solve: the hierarchy problem

concretely: why the gravitational force is so much weaker than the other fundamental interactions?

Main candidate,

Supersymmetry : -enlarges Poincaré algebra (new energy scale)

-needs many new particles

-can preserve SM gauge group

- To solve: the strong CP puzzle

concretely: why matter and not anti-matter in our universe?

Main candidate,

'Peccei-Quinn' theory : -enforces CP-symmetry

-needs a new global 'no symmetry'

(anomalous+spontaneously broken)

(new energy scale)

-entangled with SM gauge group :

(careful!)

$$[SU(3)_c \otimes SU(2)_L \otimes U(1)_Y]_{local} \times [U(1)_{\mathcal{B},\mathcal{L},PQ}]_{global}$$

the **QCD axion**: « new » Goldstone bosons combination $\perp Z_L$

The Strong CP Puzzle in particle physics

$$\mathcal{L}_{QCD} = \bar{q}(i\gamma^\mu D_\mu - m_q e^{\overset{i\theta_{EW}}{\text{CPV}}})q - \frac{1}{4}G_a^{\mu\nu}G^a_{\mu\nu} - \theta_{QCD}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\underbrace{\tilde{G}^a_{\mu\nu}}_{\text{CPV}}$$

4-component Dirac field

$U(1)_A$ chiral transformation: $q \rightarrow e^{i\gamma^5\theta_{EW}}q$ anomalous symmetry

the measure of the path integral is not invariant under this transformation

axial anomaly shifts quark mass phase to QCD vacuum

$$\mathcal{L}_{QCD} = \bar{q}(i\gamma^\mu D_\mu - m_q)q - \frac{1}{4}G_a^{\mu\nu}G^a_{\mu\nu} - (\overbrace{\theta_{QCD} - \underset{\neq 0}{\theta_{EW}}}^{\bar{\theta}})\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$$

Yukawa coupling to the Higgs are complex $\theta_{CKM} \neq 0$

Why is this strong CP-violation term so puzzling? $\mathcal{L}_{\cancel{CP}} = \bar{\theta}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$

this induces a huge electric dipole moment for the neutron:

Theory: $|d_n| \sim |\bar{\theta}|10^{-16}e.cm$ vs Experiment: $|d_n| \lesssim 10^{-26}e.cm$

$\longrightarrow \bar{\theta} < 10^{-10}$

The strong CP problem
=Why is $\bar{\theta}$ so small?

The strong CP problem is really why the combination of QCD and EW parameters make up should be so small...

The Peccei-Quinn Axion Solution

axial anomaly: $\theta_{EW}^{\text{CPV}} \longleftrightarrow \theta_{QCD}^{\text{CPV}}$

Solution to the strong CP problem of QCD: add fields such that rotate $\bar{\theta}$ to the phase of a complex SM-singlet scalar who gets a VEV and dynamicaly drives $\bar{\theta} \to 0$ Peccei & Quinn

$$\mathcal{L}_{QCD} = \bar{q}(i\gamma^{\mu}D_{\mu} - m_q e^{i\theta_{EW}})q - \frac{1}{4}G_a^{\mu\nu}G^a_{\mu\nu} - \theta_{QCD}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$$

1. Introduce a new global axial $U(1)_{PQ}$ symmetry S.B. at high scale
 $\longrightarrow$ the low-energy theory has a **Goldstone boson** (the **axion** field)

2. Design $\mathcal{L}_{axion}$ such that $Q(q_L) \neq Q(q_R) \longrightarrow$ this makes the $U(1)_{PQ}$ **anomalous** :
 net effect: $\mathcal{L}_{axion} = \mathcal{L}_{QCD} + \frac{a}{v}G_{\mu\nu}\tilde{G}^{\mu\nu} + \ldots$ $\quad \partial_{\mu}J^{\mu} \sim G^a_{\mu\nu}\tilde{G}_a^{\mu\nu}$

3. Non-perturbative QCD effects induce:

$$\mathcal{L}_{axion} = \mathcal{L}_{ChPT}(\partial_{\mu}a, \pi, \eta, \eta', \ldots) + V_{eff}(\bar{\theta} + \frac{a}{v}, \pi, \eta, \ldots)$$
$$\sim -\Lambda^4_{QCD}cos(\bar{\theta} + \frac{a}{v})$$

minimum of the potential: $\bar{\theta} + \frac{<a>}{v} = 0$ CP-violating term cancels!

CP symmetry is dynamically restored!

Two standard axion models

PQWW axion :

Peccei, Quinn '77
Weinberg '78
Wilczek '78

axion identified with a phase in a 2HDM ($f_a \sim v_{ew}$) : **ruled out**

phenomenology calls for $f_a \gg v_{ew}$ (« invisible axion »)

method: mix it with a complex SM singlet with « big » VEV

KSVZ axion :

Kim '79
Shifman, Vainshtein, Zakharov '80

New « heavy » electrically neutral quark, charged under $U(1)_{PQ}$
+ a new complex scalar singlet

$$\mathscr{L}_{KSVZ} = \mathscr{L}_{SM} + \bar{\Psi}_{L,R} \not{D} \Psi_{L,R} + y \bar{\Psi}_L \Psi_R \phi + V(\phi)$$

DFSZ axion :

Zhitnitskii '80
Dine, Fischler, Srednicki '81

2HDM, SM quarks and leptons are charged under $U(1)_{PQ}$
+ a new complex scalar singlet

Axion Like Particles

typical coupling

- QCD axion has couplings correlated to its mass, $m_a \sim \Lambda^2_{QCD} \boxed{\frac{1}{f_a}}$

Non-trivial topology of the QCD vacuum

Current bounds push the mass well below the eV

-ALP: add an explicit mass term to get a new light pseudo scalar state

$$\mathscr{L}_{ALP} = \frac{1}{2}(\partial_\mu a \partial^\mu a - m_a^2 aa) + \text{couplings to SM particles}$$

No longer solve the strong CP problem

May be a DM candidate

Few might arise from string theory

Mass window spans over sub-eV to few GeV

If the mass is greater than a few GeV: LHC could say something!

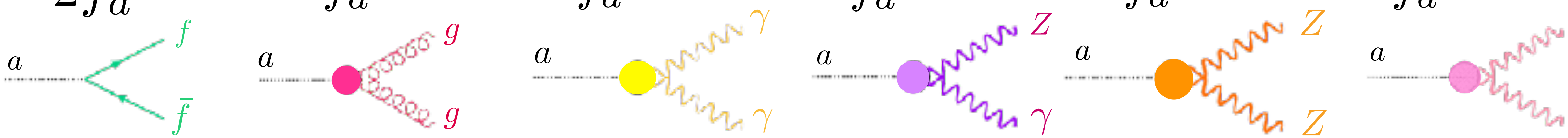
How to tackle ALP-SM couplings?

Axion couplings

Energy

At energies below f_a (SSB):

$$\mathcal{L}_{axion} \supset \frac{\partial_\mu a}{2f_a} j_a^\mu + \#\frac{a}{f_a} G\tilde{G} + \#\frac{a}{f_a} F\tilde{F} + \#\frac{a}{f_a} Z\tilde{F} + \#\frac{a}{f_a} Z\tilde{Z} + \#\frac{a}{f_a} W\tilde{W}$$



electroweak couplings recently computed
do not follow the expected pattern
-J.Q. and C. Smith, arXiv:1903.12559, 2006.06778, 2010.13683;
-J.Q., C. Smith and P.N.H. Vuong , arXiv:2112.00553
-See also Q. Bonnefoy, L. Di Luzio, C. Grojean, A. Paul and A. Rossia, arXiv:2011.10025

LHC regime
free from (complex) low energy QCD effects
probe different couplings than low energy experiments

At energies below Λ_{QCD} : $a - \eta' - \pi^0 - \eta - \ldots$ mixing

axion mass: $m_a = m_\pi \dfrac{f_\pi}{f_a} \dfrac{\sqrt{m_u m_d}}{m_u + m_d} \sim \dfrac{\Lambda^2_{QCD}}{f_a}$

axion couplings to electrons, nucleons, mesons, photons, ...

(EDMs)

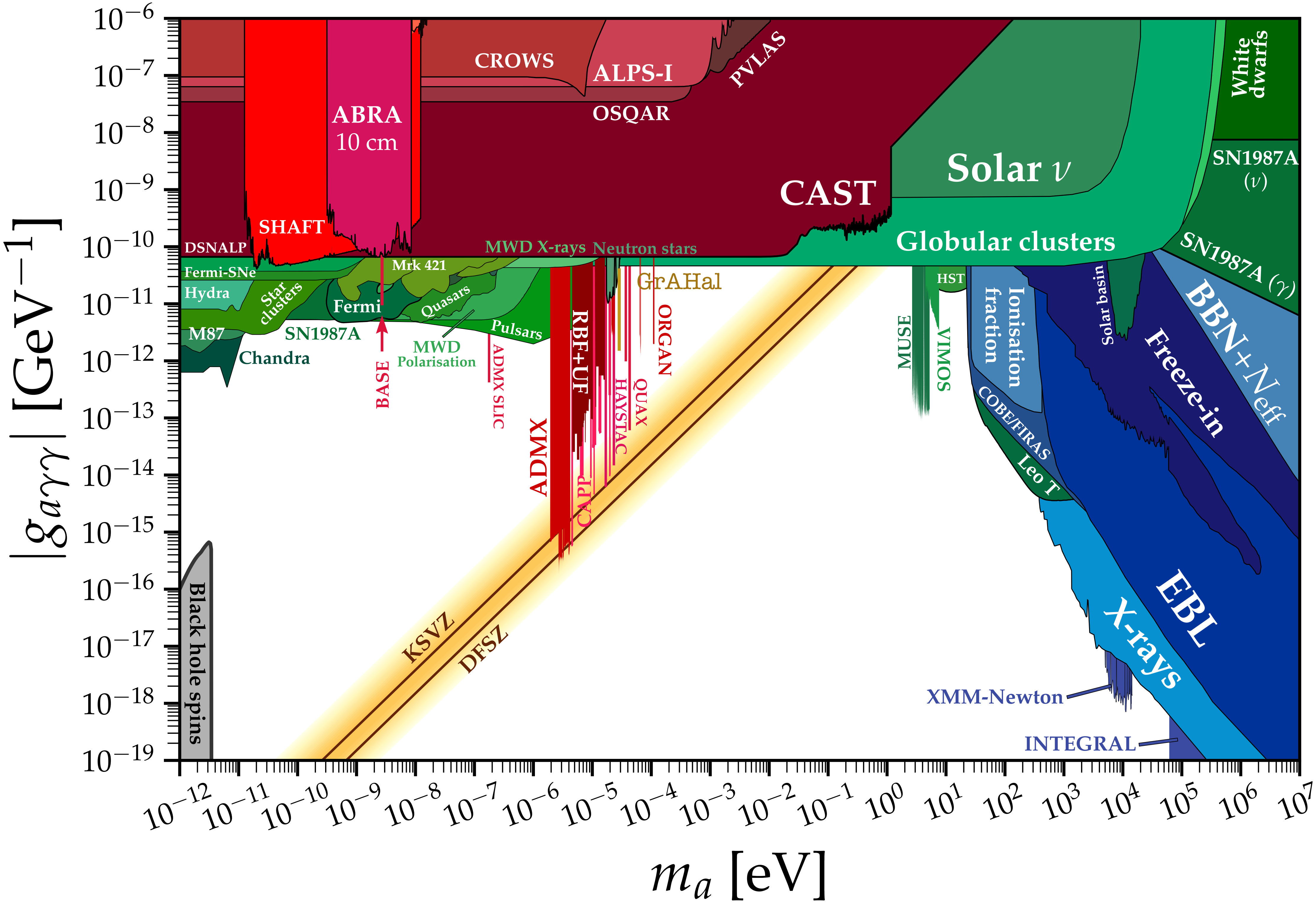
mostly explored:

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - \boxed{1.92}\right)$$

model dep.

model indep.
below confinement

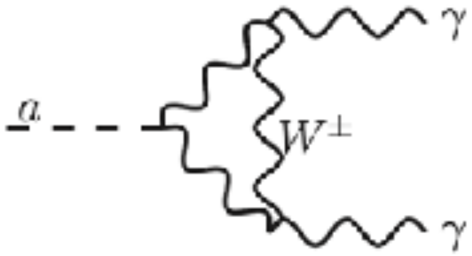
ALP searches from the axion-photon scope



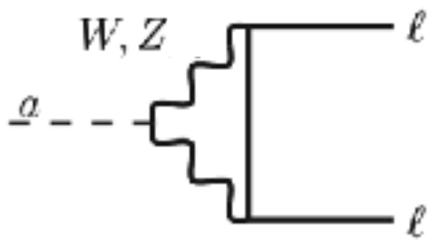
Axion couplings to massive gauge bosons

Axion electroweak couplings

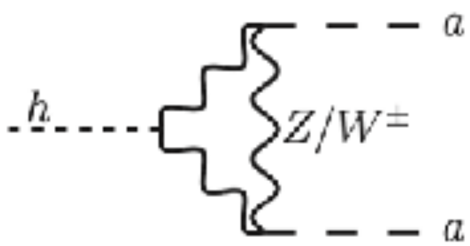
- $a \to \gamma\gamma$:



- $a \to ll$:

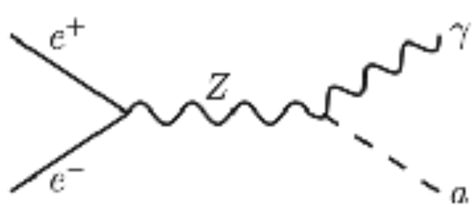


- $h \to aa$:

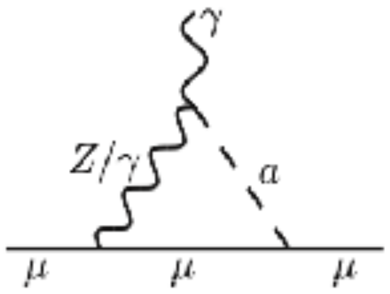


...

- $e^+e^- \to a\gamma$:



- Muon anomalous magnetic moment:



ALP electroweak couplings matters

They need to be crucially explored at the LHC and beyond!

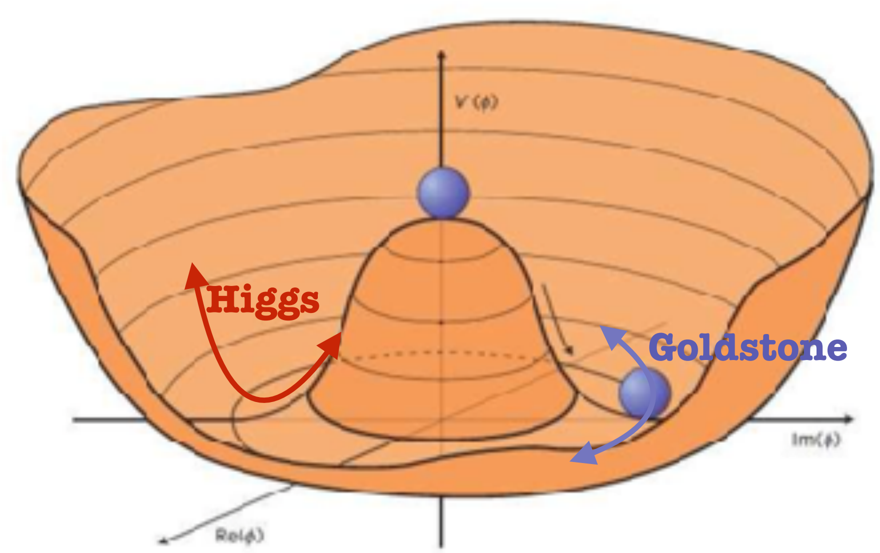
Why axions « have » derivative couplings?

An axionic toy model: simple QED extension

- local $U(1)_{em}$, new scalar field ϕ:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}_L(i\not{D})\psi_L + \bar{\psi}_R(i\not{D})\psi_R + (y\phi\bar{\psi}_L\psi_R + h.c.) + \partial_\mu\phi^\dagger\partial^\mu\phi - V(\phi)$$

$\longrightarrow$ Goldstone boson (**axion**) remnant of $U(1)_{PQ}$ S.S.B.



Linear representation: $\phi(x) = v + \sigma(x) + i a(x)$

$x + iy$

Polar representation: $\phi(x) = \frac{1}{\sqrt{2}}(v + \sigma(x))e^{-ia(x)/v}$

$\rho^{i\theta}$

Linear representation

$$\phi(x) = v + \sigma(x) + i\boxed{a(x)}$$

$$\mathcal{L}_{\text{Linear}} \supset \frac{1}{2}\partial_\mu a^0 \partial^\mu a^0 + \frac{m}{v}\boxed{a \; \bar{\psi} i \gamma_5 \psi}$$

(no tree-level couplings to gauge fields)

→The axion is a usual pseudo-scalar with no derivative couplings to fermions

Polar representation

$$\phi(x) = \rho e^{-ia(x)/v}$$

To remove « a » from the Yukawa terms $(y\phi\bar{\psi}_L\psi_R + h.c.)$

One **reparametrizes** fermion fields:

$$\psi_L(x) \to \exp(i\alpha a^0(x)/v)\psi_L(x)\ ,\ \ \psi_R(x) \to \exp(i(\alpha+1)a^0(x)/v)\psi_R(x)$$

→Fermion kinetic term induce **derivative interactions**

$$\bar{\psi}_L(i\not{D})\psi_L + \bar{\psi}_R(i\not{D})\psi_R$$

$$\boxed{\delta\mathcal{L}_{\rm Der}} = -\frac{\partial_\mu a^0}{v}(\alpha\bar{\psi}_L\gamma^\mu\psi_L + (\alpha+1)\bar{\psi}_R\gamma^\mu\psi_R) = -\frac{\partial_\mu a^0}{2v}((2\alpha+1)\bar{\psi}\gamma^\mu\psi + \bar{\psi}\gamma^\mu\gamma_5\psi)$$

$$\longrightarrow\ \mathcal{L}_{\rm Polar} \supset \frac{1}{2}\partial_\mu a^0\partial^\mu a^0 + \boxed{\delta\mathcal{L}_{\rm Der}} + \boxed{\ ?\ }$$

Polar representation

$$\phi(x) = \frac{1}{\sqrt{2}}(v + \sigma^0(x))e^{-ia^0(x)/v}$$

- Fermionic path integral measure is not invariant under the **fermion reparametrisation**: [Fujikawa]

new local interaction (**anomaly** - Jacobian of the transformation)

$$\boxed{\delta\mathcal{L}_{\text{Jac}}} = \frac{e^2}{16\pi^2 v} a^0 (\underbrace{\alpha - (\alpha+1)}_{Q(q_L) \;-\; Q(q_R)}) F_{\mu\nu}\tilde{F}^{\mu\nu} = -\frac{e^2}{16\pi^2 v} a^0 F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\longrightarrow \mathcal{L}_{\text{Polar}} \supset \frac{1}{2}\partial_\mu a^0 \partial^\mu a^0 + \boxed{\delta\mathcal{L}_{\text{Der}}} + \boxed{\delta\mathcal{L}_{\text{Jac}}}$$

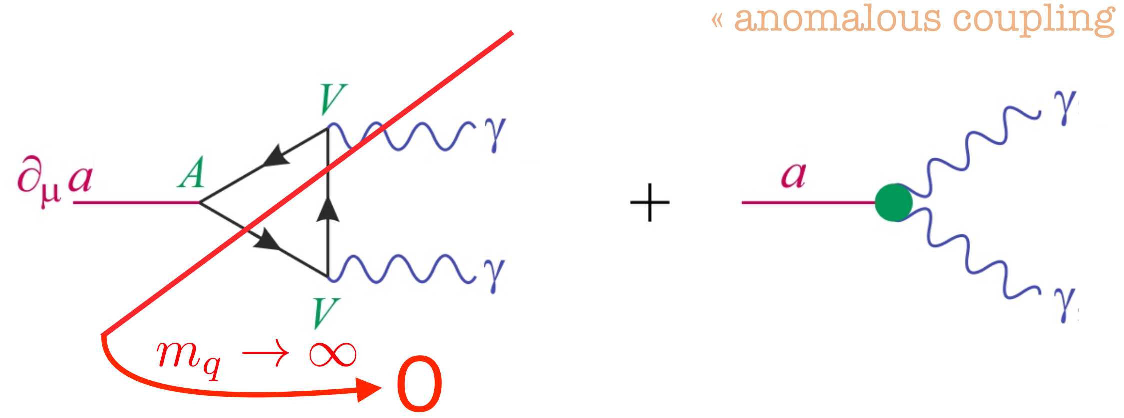
DFSZ axion couplings to SM gauge fields

Axion with derivative couplings to fermions

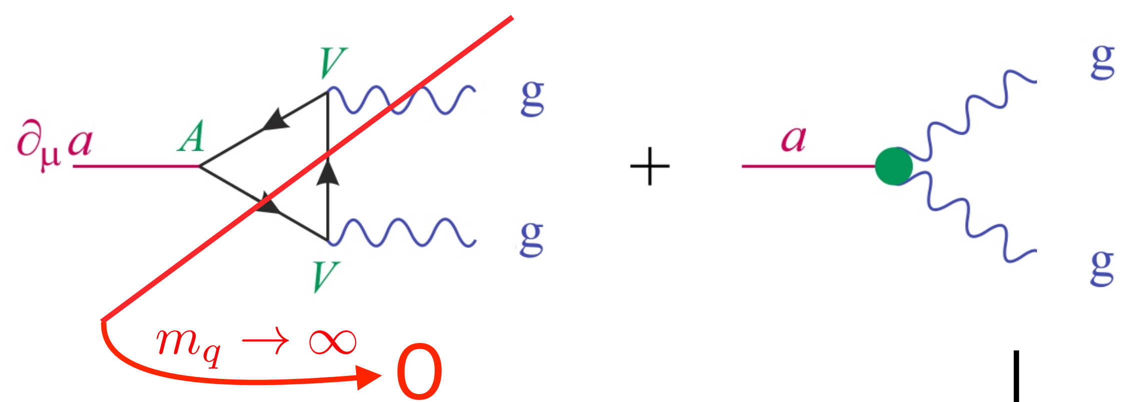
Effective couplings to SM gauge bosons at one loop:

« anomalous coupling »

Axion-photons :



Axion-gluons:



Convenient book-keeping of the effect of heavy fermions

« Polar = Linear »

Polar representation:

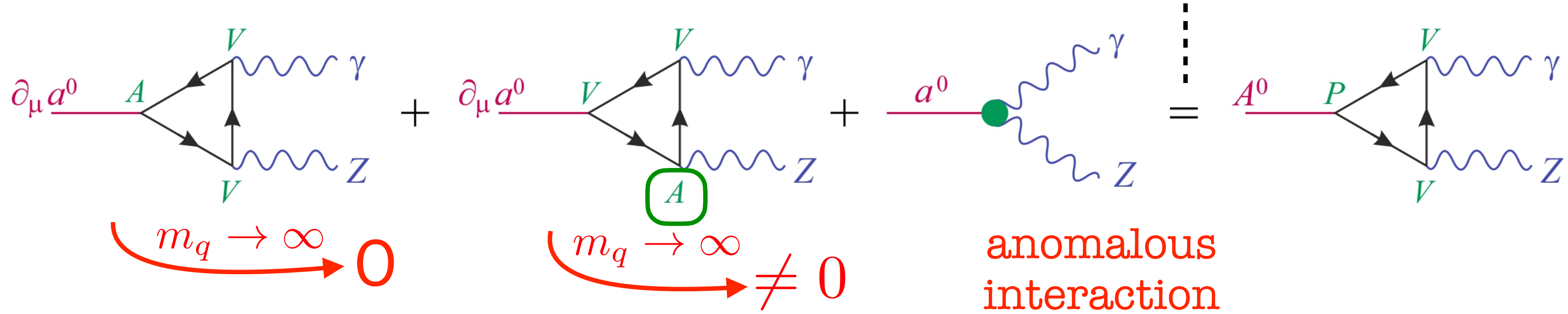
Axial current $A = \bar{\psi}\gamma^\mu\gamma_5\psi$

Vector current $V = \bar{\psi}\gamma^\mu\psi$

Linear representation:

Pseudo-scalar current $P = \bar{\psi}\gamma_5\psi$

- $a \to \gamma Z$:



Vector current is not conserved

One has to consider both couplings:

$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma^5\psi$ **and** $(\partial_\mu a)\bar{\psi}\gamma^\mu\psi$

not a reliable **book-keeping** of the effect of heavy fermions

- idem for ZZ and WW

Several interesting phenomenological aspects

Baryon & Lepton number, Seesaw, GUTs

Axion and Baryon & Lepton number

2HDM of type II: $\mathcal{L}_{\text{Yukawa}} = -\bar{u}_R \mathbf{Y}_u q_L \Phi_1 - \bar{d}_R \mathbf{Y}_d q_L \Phi_2^\dagger - \bar{e}_R \mathbf{Y}_e \ell_L \Phi_2^\dagger + h.c.$

$$\boxed{U(1)_{\mathcal{B}} \otimes U(1)_{\mathcal{L}}} \otimes \boxed{U(1)_1 \otimes U(1)_2} \otimes SU(2)_L \otimes SU(3)_C \xrightarrow[x = v_2/v_1]{\text{EWSB}} U(1)_{\mathcal{B}} \otimes U(1)_{\mathcal{L}} \otimes U(1)_{em} \otimes SU(3)_C$$

2 neutral Goldstone bosons: a, Z_L

$a \perp Z_L$

$$PQ(\Phi_1, \Phi_2, \underset{\text{DFSZ}}{\phi}) = \left(x \; , \; -\frac{1}{x} \; , \; \frac{1}{2}\left(x + \frac{1}{x} \right) \right)$$

$$\Rightarrow PQ(q_L, u_R, d_R, \ell_L, e_R) = (\alpha, \alpha + x, \alpha + \frac{1}{x}, \beta, \beta + \frac{1}{x})$$

2 parameters ambiguity

At this stage no way to fix α & β

Ambiguity due to the invariance of the Yukawa couplings under $\mathscr{B}$ & $\mathscr{L}$

$\Rightarrow$ to be used to accommodate $\mathscr{B}, \mathscr{L}$ violation

Axion and the seesaw mechanism

Majorana mass term: $\mathcal{L}_{\nu_R} = -\frac{1}{2}\bar{\nu}_R^C \mathbf{M}_R \nu_R + \bar{\nu}_R \mathbf{Y}_\nu \ell_L \Phi_i + h.c.\,.$

$$\Rightarrow \begin{cases} \bar{\nu}_R \mathbf{Y}_\nu \ell_L \Phi_1 : PQ(\nu_R) = \beta + x = 0\,, \\ \bar{\nu}_R \mathbf{Y}_\nu \ell_L \Phi_2 : PQ(\nu_R) = \beta - \frac{1}{x} = 0\,. \end{cases}$$

still: $PQ(q_L, u_R, d_R, \ell_L, e_R) = (\alpha, \alpha + x, \alpha + \frac{1}{x}, \beta, \beta + \frac{1}{x})$

- No ambiguity on β since $U(1)_{\mathscr{L}}$ has never been a symmetry: β is fixed
- Introduce operator and then set β, **not the contrary!**

ν**DFSZ:** $\mathcal{L}_{\nu_R} = -\frac{1}{2}\bar{\nu}_R^C \mathbf{Y}_R \nu_R \phi + \bar{\nu}_R \mathbf{Y}_\nu \ell_L \Phi_i + h.c.\,.$

$$\Rightarrow \quad PQ(\nu_R) = -PQ(\phi)/2 \;\neq 0$$

$$\Rightarrow \begin{cases} \bar{\nu}_R \mathbf{Y}_\nu \ell_L \Phi_1 \Rightarrow \beta = -\frac{1}{4}\left(5x + \frac{1}{x}\right) \\ \bar{\nu}_R \mathbf{Y}_\nu \ell_L \Phi_2 \Rightarrow \beta = -\frac{1}{4}\left(x - \frac{3}{x}\right) \end{cases}$$

still: ....

- $U(1)_{\mathscr{L}} \subset U(1)_1 \times U(1)_2$ does not correspond to the usual Lepton number
- $U(1)_{\mathscr{L}}$: never occurs at low energy
- **axion = majoron** and still solve the strong CP-problem

Axion and GUT

- Let's embed the axion into $SU(5)$ $\begin{cases} \mathscr{B} - \mathscr{L} \text{ conserving} \\ \underline{\mathscr{B} + \mathscr{L} \text{ violating}} \end{cases}$

$\longrightarrow$ one of the ambiguity immediately <u>disappears</u>:

$$3\alpha + \beta = -\left(x + \frac{1}{x}\right) \equiv 2\underbrace{\mathcal{N}_{SU(5)}}_{\text{anomaly coefficients}}$$

Rq: constraint not compatible with instanton requirement: $3\alpha + \beta = 0$

$\mathscr{L}^{\text{eff}}_{\text{inst}} \propto l_L^3 q_L^9$

- In axion models, PQ charges of the 2 Higgs doublets and the fermions are the same up to the value of α and β

$\rightarrow$ this comes from the orthogonality condition among Goldstone bosons (Yukawa couplings)

$\Rightarrow$the low energy phenomenology of the axion is the same in all these models since axions couplings are independent of α and β!

often obscured by the normalisation of the PQ charges

Axion-Like Particle Effective Field Theories

BSM Higgs strategy

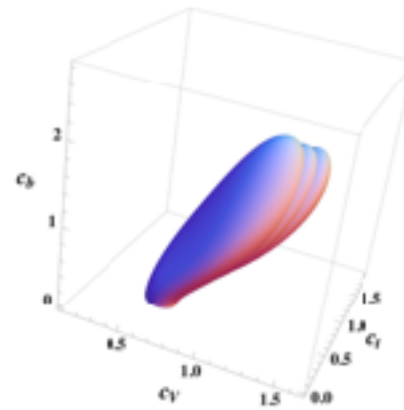
Toy model

(simple, intuitive, model independant, etc.)

Ex: Higgs kappa-framework

$$\mathscr{L}^{BSM}_{Higgs} \supset \kappa_W g^{SM}_{hWW} hW^+W^- + \kappa_Z g^{SM}_{hZZ} hZZ + \kappa_t g^{SM}_{htt} h\bar{t}t + \ldots$$

experimental data ⟶

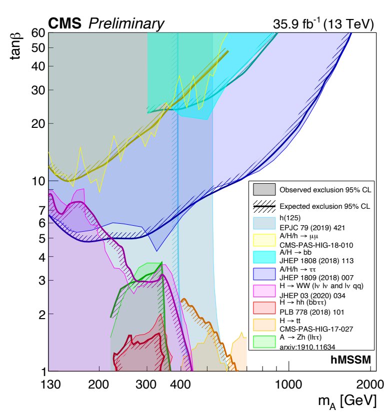


Ultra-Violet model

(solve problems, complicated, many parameters, etc.)

Ex: MSSM

experimental data ⟶



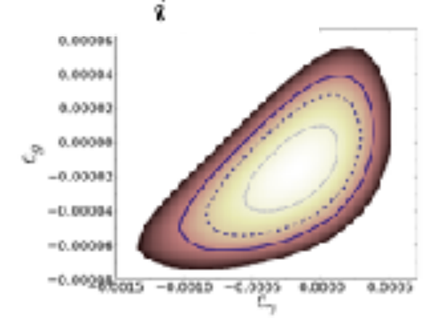
Effective Field Theory

(phenomenological QFT, model independant, etc.)

Ex: SMEFT

$$\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{SM}} + \sum_i c_i \mathcal{O}_i$$

experimental data ⟶



BSM Axion strategy

Ultra-Violet model

Ex: PQWW axion

KSVZ invisible axion

DFSZ invisible axion

} QCD axion

ALP models

etc.

On going theoretical effort

ALP Effective Field Theory

$$\mathscr{L}_{SM-ALP-EFT} = \mathscr{L}_{SM} + \mathscr{L}_{a} + \mathscr{L}_{a-SM}$$

Ex:

$$\mathscr{L}^{D=5}_{a-SM} \supset \sum_f C_{ff} \frac{\partial^\mu a}{\Lambda} \bar{f}\gamma_\mu\gamma_5 f + C_{GG}\frac{a}{\Lambda}G_{\mu\nu}\tilde{G}^{\mu\nu} + C_{\gamma\gamma}\frac{a}{\Lambda}F_{\mu\nu}\tilde{F}^{\mu\nu} + C_{\gamma Z}\frac{a}{\Lambda}F_{\mu\nu}\tilde{Z}^{\mu\nu} + C_{ZZ}\frac{a}{\Lambda}Z_{\mu\nu}\tilde{Z}^{\mu\nu} + C_{WW}\frac{a}{\Lambda}W_{\mu\nu}\tilde{W}^{\mu\nu}$$

$$\mathscr{L}^{D\geq 6}_{a-SM} \supset \frac{C_{ah}}{\Lambda^2}(\partial_\mu a)(\partial^\mu a)H^\dagger H + \ldots$$

Which basis for ALP-SM couplings?

On going theoretical effort

Useful for model independent searches

Several independent Wilson coefficients : Is this always reasonable from a UV point of view?

Implication for ALPs searches

How to construct a truly **axion-like** basis?

F. Arias-Aragón, J.Q., C. Smith, arXiv:2211.04489

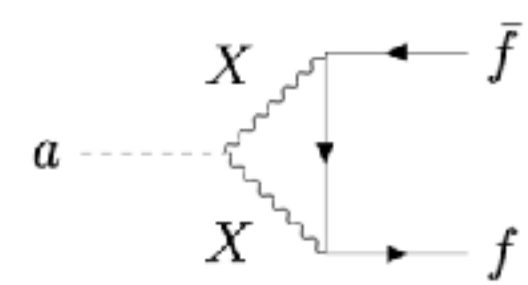
$$\mathcal{L}^{\text{eff}}_{ALP} = \frac{1}{2}(\partial_\mu a^0 \partial^\mu a^0 - m_a^2 a^0 a^0) + \mathcal{L}_{\text{KSVZ}-\text{like}} + \mathcal{L}_{\text{DFSZ}-\text{like}}$$

KSVZ like: New, heavy, electrically neutral quark, charged under $U(1)_{\text{PQ}}$

$$\mathcal{L}^{\text{eff}}_{\text{KSVZ-like}} = \frac{a^0}{16\pi^2 f_a}\left(g_s^2 \mathcal{N}_C G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} + g^2 \mathcal{N}_L W_{\mu\nu}\tilde{W}^{\mu\nu} + g'^2 \mathcal{N}_Y B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

$$\begin{aligned} g_{agg} &= \alpha_s \mathcal{N}_C \ , \\ g_{a\gamma\gamma} &= \alpha\left(\mathcal{N}_L + \mathcal{N}_Y\right) \ , \\ g_{a\gamma Z} &= 2\alpha\left(-\mathcal{N}_L/t_W + t_W \mathcal{N}_Y\right) \ , \\ g_{aZZ} &= \alpha\left(\mathcal{N}_L/t_W^2 + t_W^2 \mathcal{N}_Y\right) \ , \\ g_{aWW} &= \frac{2\alpha}{s_W^2}\mathcal{N}_L \ . \end{aligned}$$

- Typically assuming some heavy **vector-like** fermions
- Manifestly symmetric under $SU(3)_C \otimes SU(2)_L \otimes U(1)_L$
- No direct coupling to SM fermions, but one loop induced:



$$\mathcal{L}^{eff}_{fermion} = \sum_{f=u,d,e} \frac{m_f}{v_a} c_{af}\, a \bar{f}\gamma_5 f$$

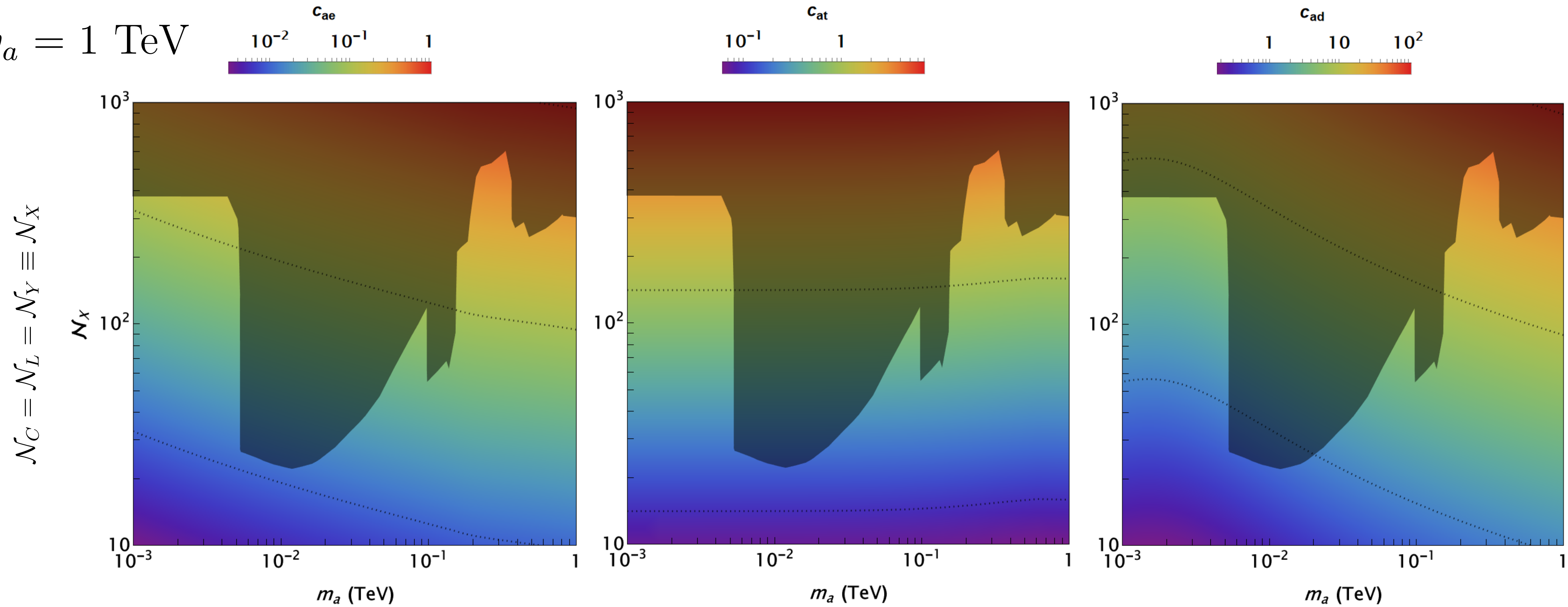
$$\begin{aligned} c_{af} =& 16\left(\alpha^2 Q_f^2\left(\mathcal{N}_L + \mathcal{N}_Y\right) + \alpha_s^2 \frac{4}{3}\mathcal{N}_C\right) I_0 - \frac{\alpha^2(\mathcal{N}_L/t_W^2 + t_W^2 \mathcal{N}_Y)}{s_W^2 c_W^2} I_{ZZ} \\ &+ \frac{16\alpha^2 Q_f (T_f^3 - 2Q_f s_W^2)(-\mathcal{N}_L/t_W + t_W \mathcal{N}_Y)}{s_W c_W} I_{\gamma Z} - \frac{4\alpha^2 \mathcal{N}_L}{s_W^4}\sum_{f'} V_{ff'} I_{WW} \end{aligned}$$

coupling to heavy quarks $\Rightarrow \mathcal{N}_X \Rightarrow c_f \equiv f(\mathcal{N}_X)$

KSZV-like ALPs

- Parameter space easy to bound, with for example, limits on $g_{a\gamma\gamma}$:

$v_a = 1$ TeV



F. Arias-Aragón, J.Q., C. Smith, arXiv:2211.04489

Implication for ALPs searches

How to construct a truly **axion-like** basis?

$$\mathcal{L}^{\text{eff}}_{ALP} = \frac{1}{2}(\partial_\mu a^0 \partial^\mu a^0 - m_a^2 a^0 a^0) + \mathcal{L}_{\text{KSVZ}-\text{like}} + \mathcal{L}_{\text{DFSZ}-\text{like}}$$

DFSZ like: 2HDM plus extra scalar, SM quarks and leptons are charged under $U(1)_{\text{PQ}}$

$$\mathcal{L}^{\text{eff}}_{\text{DFSZ-like}} = -\frac{1}{2f_a}\partial_\mu a \sum_{f\,=\,\text{chiral fermions}} \chi_V^f \bar{\psi}_f \gamma^\mu \psi_f + \chi_A^f \bar{\psi}_f \gamma^\mu \gamma^5 \psi_f$$

$$+ \frac{a}{16\pi^2 f_a}\left(g_s^2 \mathcal{N}_C G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} + g^2 \mathcal{N}_L W_{\mu\nu}\tilde{W}^{\mu\nu} + g'^2 \mathcal{N}_Y B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

- **Vector currents do contribute** to physical observables
- Spurious $\mathscr{B}$ and $\mathscr{L}$ violation included
- Axion-like $\Rightarrow$ **need to impose anomaly cancellation**!

Implication for ALPs searches

How to construct a truly **axion-like** basis?

$$\mathcal{L}^{\rm eff}_{ALP} = \frac{1}{2}(\partial_\mu a^0 \partial^\mu a^0 - m_a^2 a^0 a^0) + \mathcal{L}_{\rm KSVZ-like} + \mathcal{L}_{\rm DFSZ-like}$$

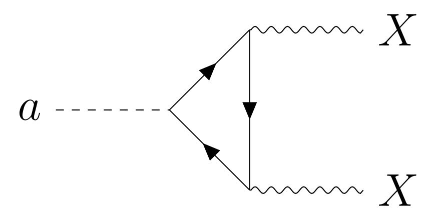
DFSZ like: 2HDM plus extra scalar, SM quarks and leptons are charged under $U(1)_{\rm PQ}$

$$\mathcal{L}^{\rm eff}_{\rm DFSZ\text{-}like} = -\frac{i}{f_a} a^0 \sum_{f=u,d,e} m_f \chi_A^f (\bar{\psi}_f \gamma_5 \psi_f)$$

Anomaly cancellation
taken into account!
Simple pseudo-scalar couplings

- One should not build EFTs with both **anomalous couplings** and **vectorial-axial fermion couplings** : because of **anomaly cancellations**!
- Effective interactions are not always equal to anomalous interactions!

- One loop induced couplings to gauge fields :



$$\mathscr{L}^{eff}_{gauge} = \frac{a}{4\pi v_a}\left(g_{agg} G^{a\mu\nu}\tilde{G}^a_{\mu\nu} + g_{a\gamma\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu} + g_{aZ\gamma} Z_{\mu\nu}\tilde{F}^{\mu\nu} + g_{aZZ} Z_{\mu\nu}\tilde{Z}^{\mu\nu} + g_{aWW} W^{+\mu\nu}\tilde{W}^-_{\mu\nu}\right)$$

$$g_{aV_1V_2} = -2i\pi\sigma \sum_{f=u,d,e} m_f \chi_f \left(g^f_{V_1} g^{f'}_{V_2} \mathcal{T}_{PVV}(m_f) + g^f_{A_1} g^{f'}_{A_2} \mathcal{T}_{PAA}(m_f)\right)$$

$$\mathcal{T}_{PVV}(m) = \frac{-i}{2\pi^2} m C_0(m^2)\ ,$$

$$\mathcal{T}_{PAA}(m) = \frac{-i}{2\pi^2} m (C_0(m^2) + 2C_1(m^2))$$

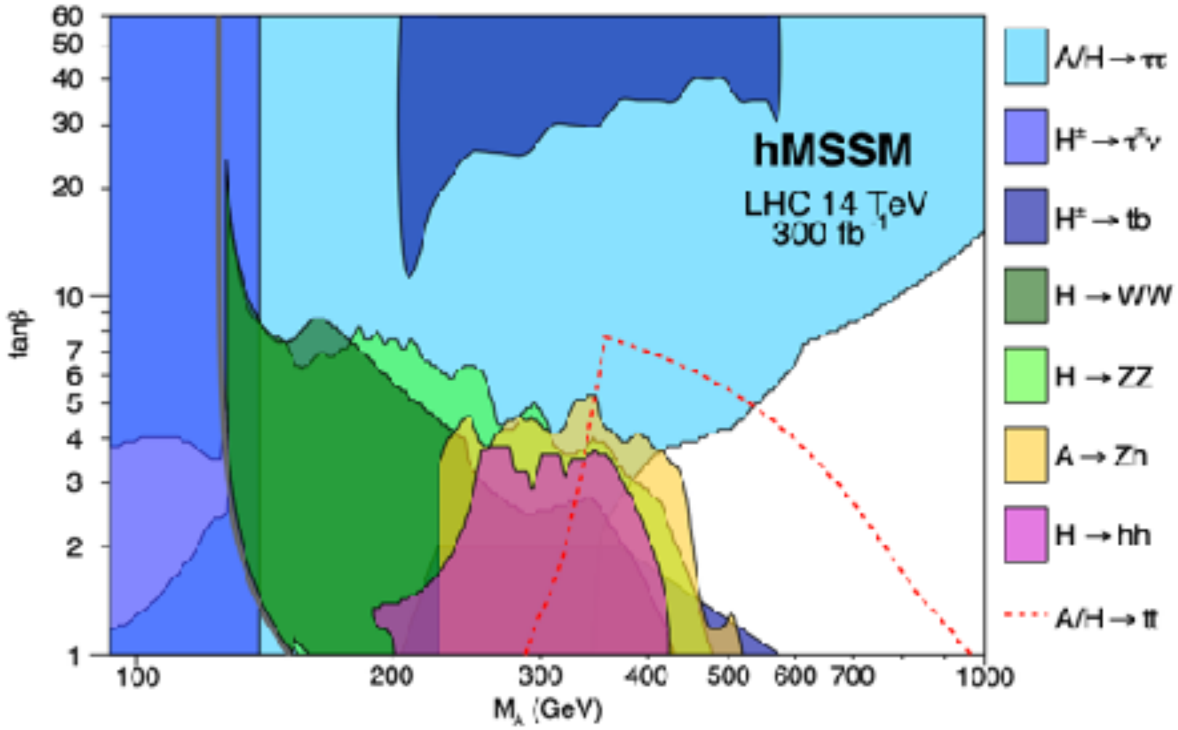
$g_{aXX} \equiv f(\chi_f)$

DFSZ-like ALPs - a more constrained case

- Mimicking the 2HDM type-II pseudoscalar couplings:

$$\chi_u = \frac{x^2}{1+x^2}, \; \chi_d = \chi_e = \frac{1}{1+x^2} \qquad \text{with} \qquad x = \tan\beta = v_u/v_d$$

- Allows to recast pseudoscalar searches for 2HDM on the DFSZ-like ALP parameter space



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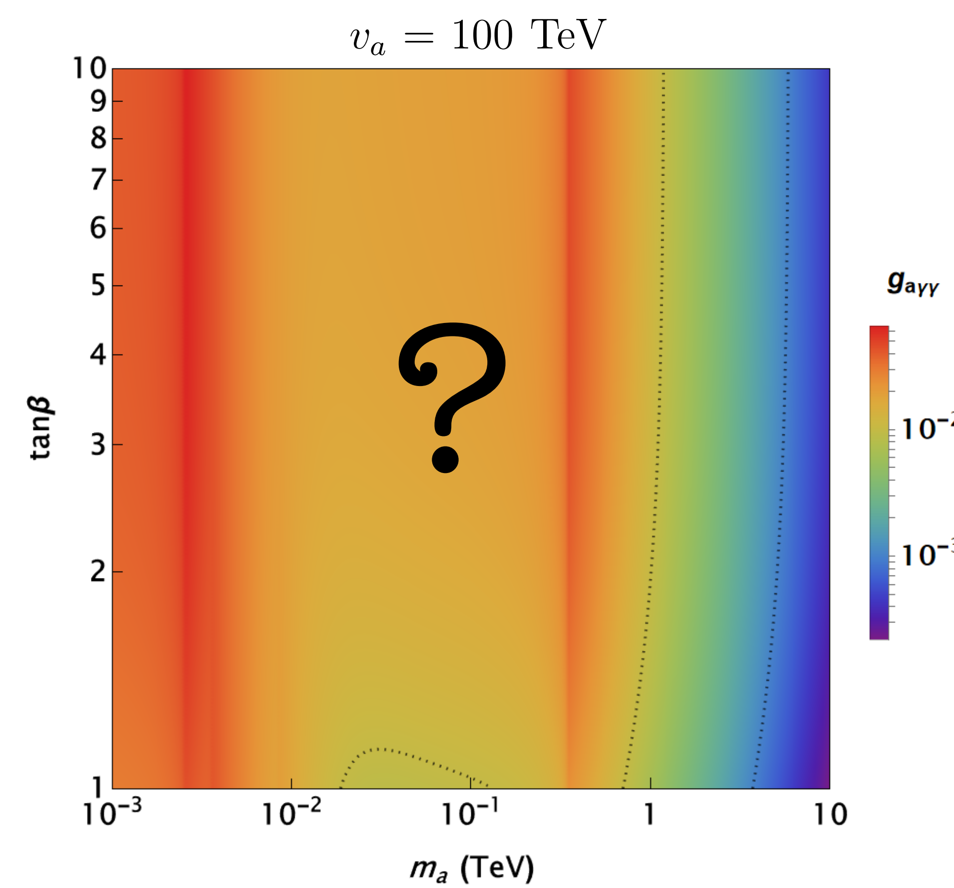


For $v_a \gtrsim 100$ GeV the parameter space is completely unconstrained by the ALP-photon coupling

Conclusion

- Axion-electroweak couplings are mostly unexplored yet
- Axion-electroweak couplings do not always follow the expected pattern $\rightarrow$ must be kept in mind for ALP searches
- Axion with fermion pseudoscalar couplings is safer (no ambiguity)
- DFSZ-like and KSZV-like benchmarks presented
- Different set of parameters identified, reduced with respect to generic ALP EFT with totally different correlations
- Generic ALP EFT does not « incorporate » DFSZ and KSVZ-like benchmarks
- Scenarios easy to constrain, in particular DFSZ-like through 2HDM searches
- Full dedicated analysis with all bounds required for LHC and beyond!

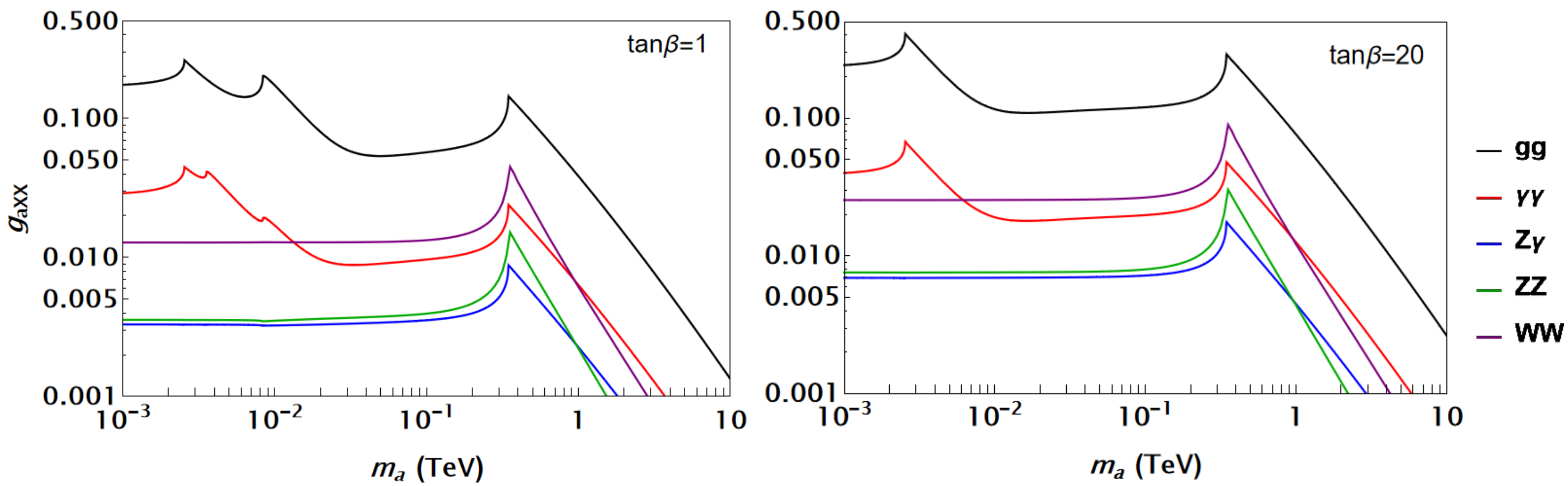
Spare slides

DFSZ-like ALPs

- 4 physical parameters $(\chi_f / v_a, m_a)$ as opposed to 7 in the generic ALP EFT

- g_{aXX} is now a function of the ALP mass :

F. Arias-Aragón, J.Q., C. Smith, arXiv:2211.04489



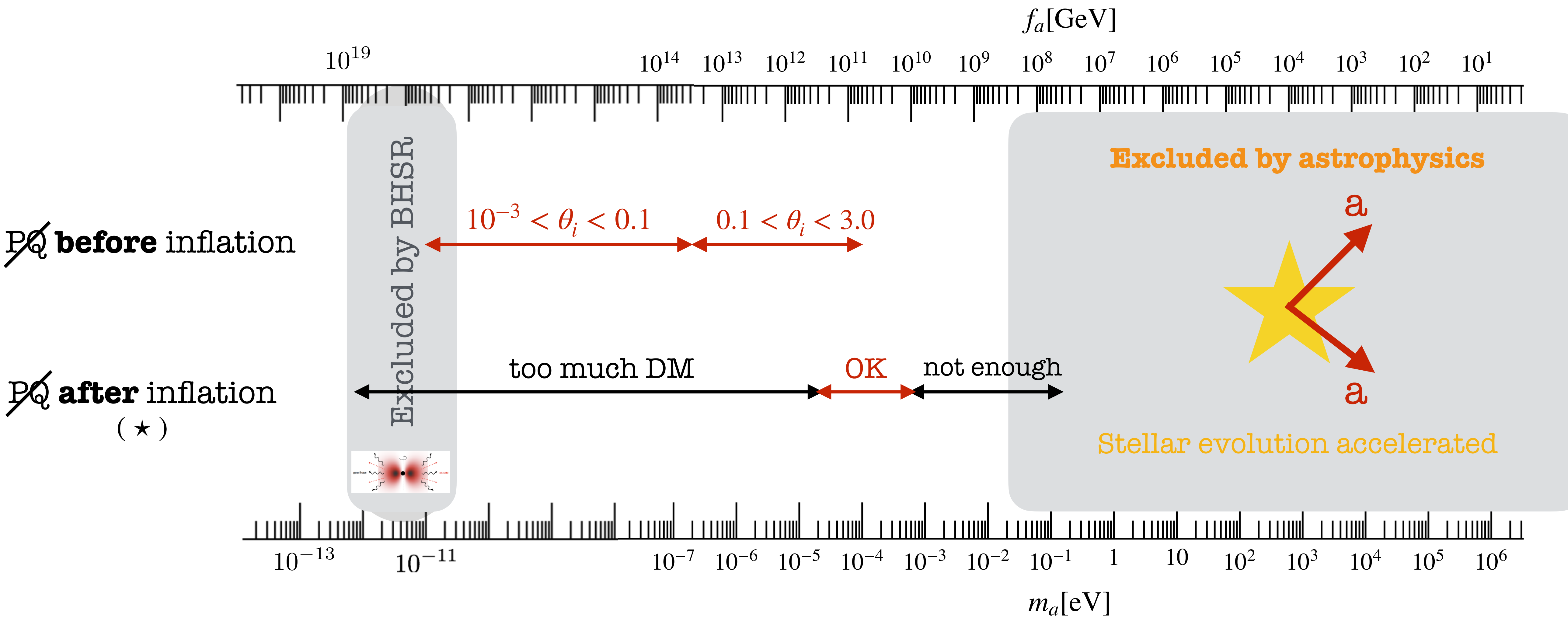
- Non-linear correlations among EW g_{aXX} in the Higgs broken phase

- Ex: measuring g_{agg}, $g_{a\gamma\gamma}$, $g_{aZ\gamma}$ fixes g_{aWW} & g_{aZZ} in the KSVZ-like scenario (generic EFT)

- In DFSZ-like scenario one degree of freedom remains: curve in the g_{aWW} & g_{aZZ} space

Landscape

Axions should be very light and feebly interacting



(⋆) for $N_{DW} > 1$, predictions spoiled by topological defects

Axion DM constraints from **laboratory** experiments, from **stars** and **cosmos** observations

DFSZ axion summary

$$\mathcal{L}^{\text{eff}} = \frac{a^0}{16\pi^2 v}\left(g_s^2 \mathcal{N}^{gg} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} + e^2\mathcal{N}^{\gamma\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{2e^2}{c_W s_W}\left(\mathcal{N}_1^{\gamma Z} - s_W^2\mathcal{N}_2^{\gamma Z}\right) Z_{\mu\nu}\tilde{F}^{\mu\nu}\right.$$
$$\left. + \frac{e^2}{c_W^2 s_W^2}\left(\mathcal{N}_1^{ZZ} - 2s_W^2\mathcal{N}_2^{ZZ} + s_W^4\mathcal{N}_3^{ZZ}\right) Z_{\mu\nu}\tilde{Z}^{\mu\nu} + 2\mathcal{N}^{WW} g^2 W^+_{\mu\nu}\tilde{W}^{-,\mu\nu}\right)$$

in the limit $m_{u,d,e} \to \infty$

Linear $a^0\bar{\psi}\gamma_5\psi$	Polar			
	Anomalous interactions	$\partial_\mu a^0\bar{\psi}\gamma^\mu\gamma_5\psi$ AVV	AAA	$\partial_\mu a^0\bar{\psi}\gamma^\mu\psi$ VAV
$\mathcal{N}^{gg} = \frac{1}{2}\left(x + \frac{1}{x}\right)$	$\mathcal{N}^{gg}$	0	$-$	$-$
$\mathcal{N}^{\gamma\gamma} = \frac{4}{3}\left(x + \frac{1}{x}\right)$	$\mathcal{N}^{\gamma\gamma}$	0	$-$	$-$
$\mathcal{N}_1^{\gamma Z} = \frac{1}{2}\left(x + \frac{1}{x}\right)$	$\mathcal{N}_L$	0	$-$	$\mathcal{N}_1^{\gamma Z} - \mathcal{N}_L$
$\mathcal{N}_2^{\gamma Z} = \mathcal{N}^{\gamma\gamma}$	$\mathcal{N}^{\gamma\gamma}$	0	$-$	0
$\mathcal{N}_1^{ZZ} = \frac{1}{4}x + \frac{1}{3x}$	$\mathcal{N}_L$	$\frac{\beta}{16}$	$-\frac{1}{2}\mathcal{N}_1^{ZZ} + \frac{\beta}{16}$	$\frac{3}{2}\mathcal{N}_1^{ZZ} - \mathcal{N}_L - \frac{\beta}{8}$
$\mathcal{N}_2^{ZZ} = \mathcal{N}_1^{\gamma Z}$	$\mathcal{N}_L$	0	0	$\mathcal{N}_2^{ZZ} - \mathcal{N}_L$
$\mathcal{N}_3^{ZZ} = \mathcal{N}^{\gamma\gamma}$	$\mathcal{N}^{\gamma\gamma}$	0	0	0
$\mathcal{N}^{WW} = \frac{x}{4} + \frac{3}{8x}$	$\mathcal{N}_L$	$\frac{3}{2}\mathcal{N}^{WW} - \frac{3}{2}\mathcal{N}_1^{\gamma Z} + \frac{\beta}{16}$	$-\frac{1}{2}\mathcal{N}^{WW} + \frac{\beta}{16}$	$\frac{3}{2}\mathcal{N}_1^{\gamma Z} - \mathcal{N}_L - \frac{\beta}{8}$

J.Gunion et al., PRD 46 (1992) 2907

$x = v_2/v_1 = 1/\tan\beta$

J.Q. and C. Smith, arXiv:1903.12559

Effective interactions are not always equal to anomalous interactions!

Remember that $\mathcal{N}_L$ is ambiguous

DFSZ axion couplings

2. in the polar representation

$$\Phi_1 = \frac{1}{\sqrt{2}} \exp\left\{ i \frac{a}{v} x \right\} \begin{pmatrix} \sqrt{2} H_1^+ \\ v_1 + H_1^0 \end{pmatrix}, \quad \Phi_2 = \frac{1}{\sqrt{2}} \exp\left\{ -i \frac{a}{v} \frac{1}{x} \right\} \begin{pmatrix} \sqrt{2} H_2^+ \\ v_2 + H_2^0 \end{pmatrix}$$

Fermion reparametrization: $\psi \to \exp\left\{ i \frac{PQ(\psi)}{v} a \right\} \psi$

Consequence 1 : non-invariance of the kinetic terms

- Axion **derivative** couplings to fermions :

$$\mathcal{L}_{Der} = -\frac{1}{2f_a} \partial_\mu a \sum_{u,d,e,\nu} \chi_V^f (\bar{\psi}_f \gamma^\mu \psi_f) + \chi_A^f (\bar{\psi}_f \gamma^\mu \gamma^5 \psi_f)$$

Freedom/ambiguity in the PQ charge

	u	d	e	ν
χ_V	$2\alpha + x$	$2\alpha + \frac{1}{x}$	$2\beta + \frac{1}{x}$	β
χ_A	x	$\frac{1}{x}$	$\frac{1}{x}$	$-\beta$

Consequence 2 : non-invariance of the fermionic measure

- Anomalous axion couplings to SM gauge fields at **tree-level** :

(Jacobian of the transformation)

$$\begin{aligned} \delta\mathcal{L}_{Jac} = & \frac{a}{16\pi^2 v} g_s^2 \mathcal{N}_C G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} \\ & + \frac{a}{16\pi^2 v} g^2 \mathcal{N}_L W_{\mu\nu}^i \tilde{W}^{i,\mu\nu} \\ & + \frac{a}{16\pi^2 v} g'^2 \mathcal{N}_Y B_{\mu\nu} \tilde{B}^{\mu\nu} \end{aligned}$$

$$\mathcal{N}_C = \frac{1}{2}\left(x + \frac{1}{x} \right)$$

$$\mathcal{N}_L = -\frac{1}{2}(3\alpha + \beta)$$

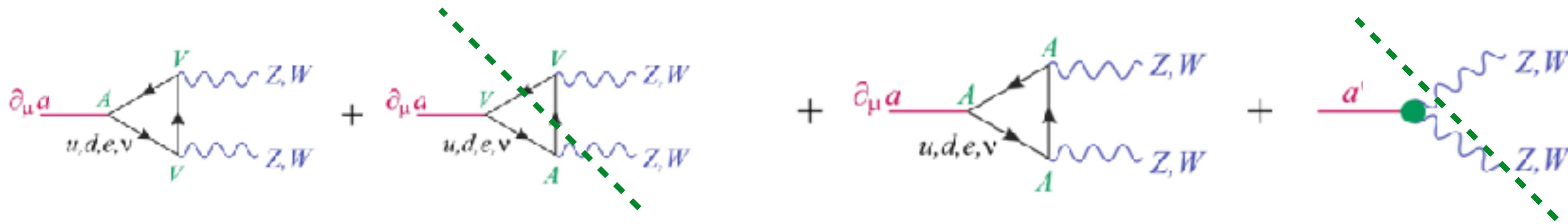
$$\mathcal{N}_Y = \frac{1}{2}(3\alpha + \beta) + \frac{4}{3}x + \frac{1}{3x} + \frac{1}{x}$$

DFSZ axion couplings to SM gauge fields

2. Axion has derivative couplings to fermions

Effective couplings at one loop:

$a \to ZZ, W^+W^-$:



contribute | partially contribute | contribute | **does not** contribute

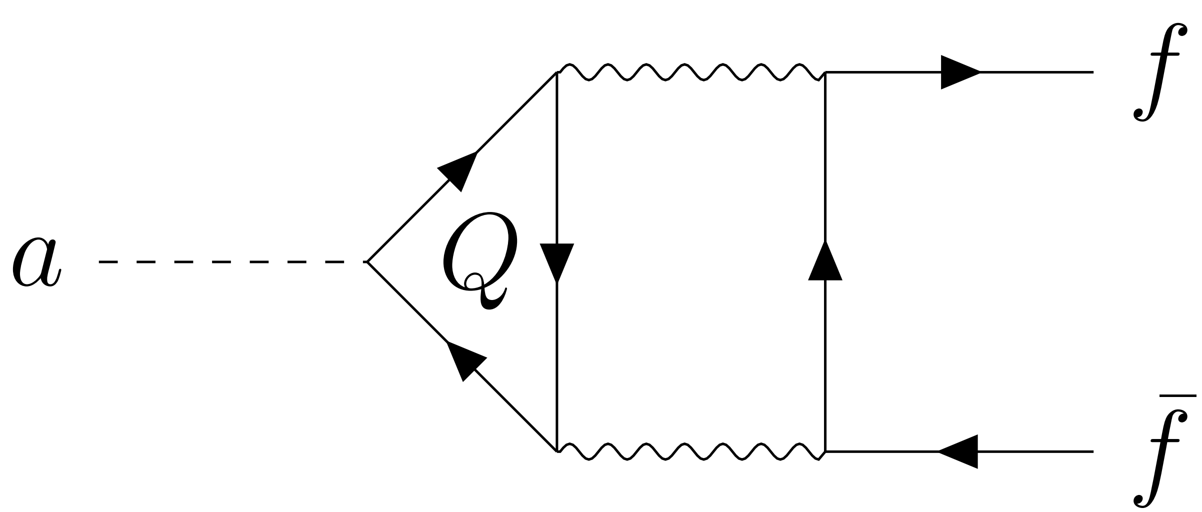
Freedom/ambiguity in the PQ charge cancel exactly

2. The anomalous contact int. does cancel out systematically with the anomalous part to the triangle graphs

$$\mathcal{L}_{\text{axion-gauge}} = \underbrace{\boxed{\delta\mathcal{L}_{\text{Der}}}}_{\cancel{\text{finite+divergence}}} + \underbrace{\boxed{\delta\mathcal{L}_{\text{Jac}}}}_{\cancel{\text{anomaly}}}$$

KSZV-like ALPs

- The fermion one-loop coupling arises from an infinite diagram
- Regularizing this diagram may introduce scheme-dependence due to γ_5
- Dependence removed by projecting fermion pair on the $J^{CP} = 0^{-+}$ state
- This yields a result with more physical meaning than the other schemes
- Renormalization scale $\mu = v_a$ identified from two-loop finite process



Switch to generic ALP EFT

$$\mathscr{L}_{SM-ALP-EFT} = \mathscr{L}_{SM} + \mathscr{L}_{a} + \mathscr{L}_{a-SM}$$

Ex:

$$\mathscr{L}^{D=5}_{a-SM} \supset \sum_f C_{ff} \frac{\partial^\mu a}{\Lambda} \bar{f}\gamma_\mu\gamma_5 f + C_{GG}\frac{a}{\Lambda} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

only 2 d.o.f: $+C_{\gamma\gamma}\frac{a}{\Lambda}F_{\mu\nu}\tilde{F}^{\mu\nu} + C_{\gamma Z}\frac{a}{\Lambda}F_{\mu\nu}\tilde{Z}^{\mu\nu} + C_{ZZ}\frac{a}{\Lambda}Z_{\mu\nu}\tilde{Z}^{\mu\nu} + C_{WW}\frac{a}{\Lambda}W_{\mu\nu}\tilde{W}^{\mu\nu}$

$$\mathscr{L}^{D\geq 6}_{a-SM} \supset \frac{C_{ah}}{\Lambda^2}(\partial_\mu a)(\partial^\mu a)H^\dagger H + \frac{C_{Zh}}{\Lambda^2}(\partial^\mu a)(H^\dagger i D_\mu H + h.c.)H^\dagger H + \dots$$

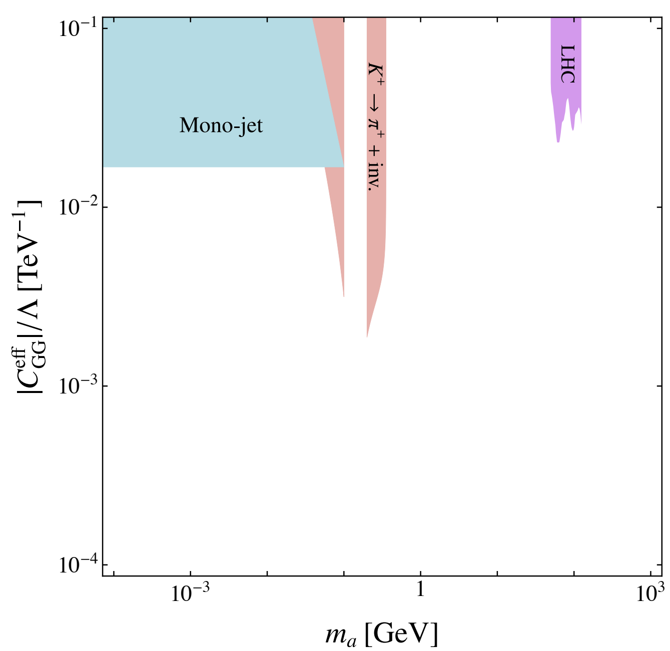
More degrees of freedom

Major difference for analysis: fermionic & gauge sectors are truly secluded here

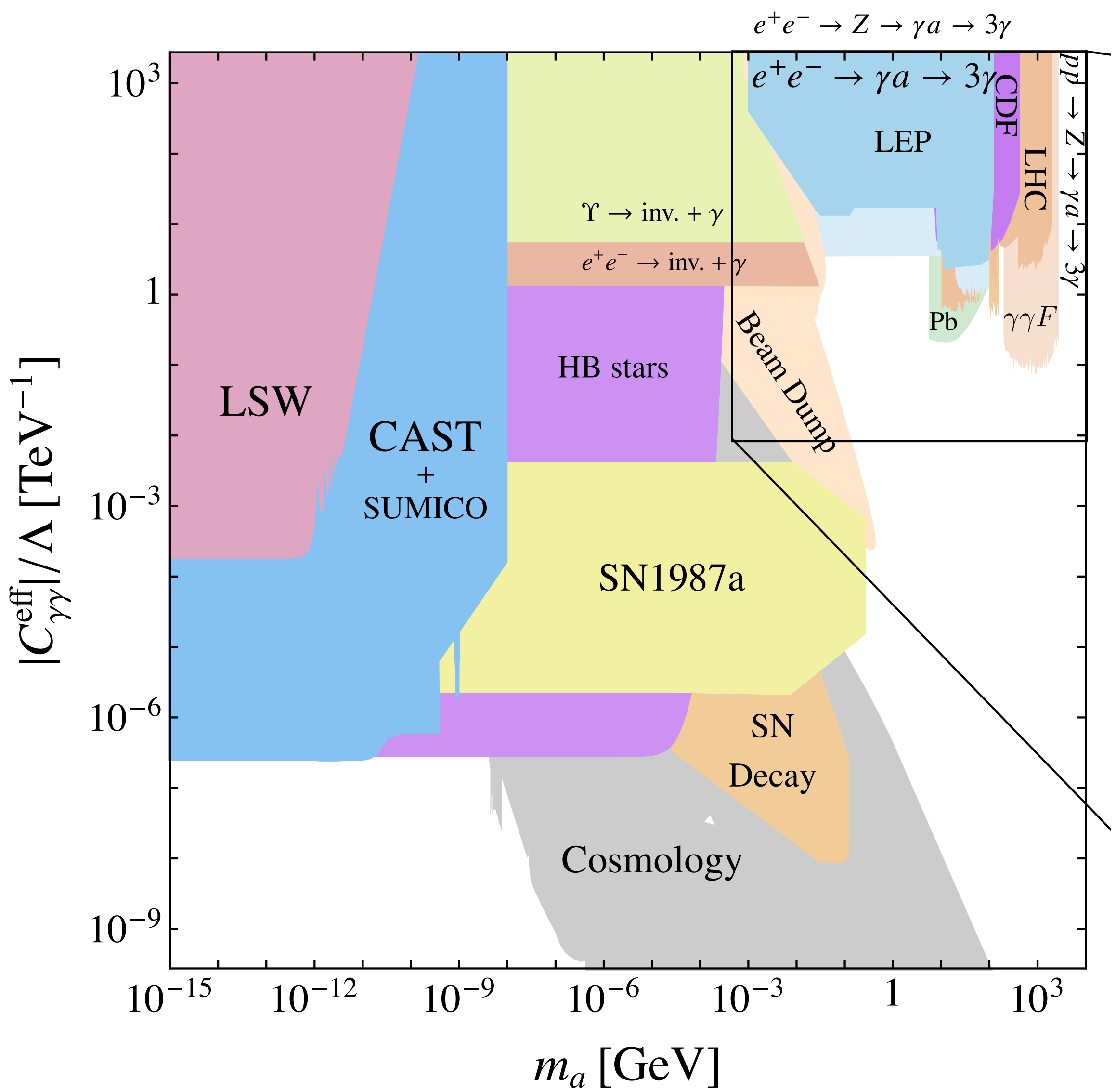
Current constraints on :

M. Bauer, M. Heiles, M. Neubert, A. Thamm, arXiv:1808.10323

C_{gg}^{eff}



$C_{\gamma\gamma}^{eff}$



C_{ee}^{eff}