CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

EFT of axions and gauge bosons (in the light of UV models)

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Based on ongoing work with
L. Di Luzio, C. Grojean, A. Paul and A. Rossia

PLAN

In this talk :

- **anomalous** nature of **axion couplings to gauge fields**

- connection with **UV models** and **PQ anomaly matching**

- **phenomenological consequences** for the electroweak sector of the SM

[Mimasu, Sanz '14, Jaeckel, Spannowsky '15, Izaguirre, Lin, Shuve '16, Brivio, Gavela, Merlo, Mimasu, No, del Rey, Sanz '17, Bauer, Neubert, Thamm '17 x2, + Heiles '18, Alonso-Alvarez, Gavela, Quilez '18, Ebadi, Khatibi, Mohammadi Najafabadi '19, ...]

STEP 1 : ABELIAN MODELS

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How to couple a pseudoscalar to a pair of gauge fields in a CP-invariant way ? **A single EFT coupling at dimension 5** :

$$\mathcal{L} \supset -\frac{\mathcal{C}}{16\pi^2}\frac{a}{f}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

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Signals a **heavy sector** :

Heavy matter

Energy

Axion, Gauge fields

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Usually : **this EFT term reproduces the UV anomaly**

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What if I wrote the coupling as follows ?

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$$\mathcal{L} \supset \frac{\mathcal{C}}{8\pi^2}\frac{\partial_\mu a}{f}A_\nu\tilde{F}^{\mu\nu}$$

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No shift anymore : **anomaly matching is only motivated and unambiguous for local (PQ) symmetries**

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How to split the EFT:

$$\mathcal{L} \supset -\frac{\mathcal{A}}{16\pi^2}\frac{a}{f}F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{\mathcal{C}-\mathcal{A}}{8\pi^2}\frac{\partial_\mu a}{f}A_\nu\tilde{F}^{\mu\nu}$$

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UV anomaly coefficient

(computed from the UV charges)

$$\mathcal{A} = \sum_{LH} q^{\mathrm{PQ}} q^2 - \sum_{RH} \ldots$$

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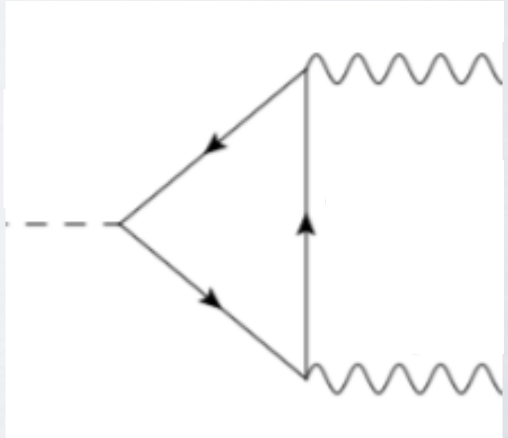
EFT coefficient (obtained from UV-IR matching)



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Non-anomalous coefficient

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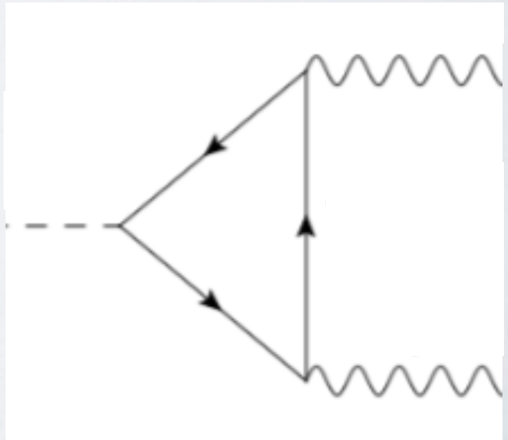

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This picture is justified when **gauging the PQ symmetry** :

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- for a massive (chiral) gauge field : $\mathcal{A} \neq \mathcal{C}$ **[Quevillon, Smith '19]**

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$$-\frac{\mathcal{C}-\mathcal{A}}{8\pi^2 g}\left(\frac{\partial_\mu a}{f} - g_{\mathrm{PQ}}A_\mu^{\mathrm{PQ}}\right)\left(\frac{\partial_\nu \theta_A}{m_A} - gA_\nu\right)\tilde{F}^{\mu\nu}$$

[see e.g. Dudas, Mambrini, Pokorski, Romagnoni '09]

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Still, **a single coefficient captures the phenomenology**

$\longrightarrow$ step 2

STEP II : THE SM

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[D'Hoker, Fahri '84]

$$\mathcal{L} \supset \frac{\mathcal{C}}{8\pi^2}\frac{\partial_\mu a}{f}\mathrm{Tr}\left(A_\nu \tilde{F}^{\mu\nu} + \frac{i}{3}\epsilon^{\mu\nu\rho\sigma}A_\nu A_\rho A_\sigma\right)$$

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With a longitudinal component and a PQ gauge field :

$$\frac{\mathcal{C}}{8\pi^2}\left(\frac{\partial_\mu a}{f} - A_\mu^{\mathrm{PQ}}\right)\mathrm{Tr}\left(\left[A_\nu - \frac{\partial_\nu \theta_A}{m_A}\right]\tilde{F}^{\mu\nu} + \ldots\right)$$

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More generally : write **all the possible** (dimension 5) **terms using a non-linear realization of the SM gauge group**

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[Brivio et al '17]

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$$+\frac{i}{8\pi^2}\frac{\partial_\mu a}{f}\left(\frac{g'c_1}{2}\mathrm{Tr}(TV_\nu)\tilde{B}^{\mu\nu} + gc_2\mathrm{Tr}(V_\nu\tilde{W}^{\mu\nu})\right.$$

$$\left.+gc_3\mathrm{Tr}(TV_\nu)\mathrm{Tr}(T\tilde{W}^{\mu\nu})\right)$$

$$\left(\begin{array}{ll} U = e^{i\frac{\pi^a}{v}\sigma^a} \;, & D_\mu U = \partial_\mu U - igW_\mu U + ig'B_\mu U\frac{\sigma_3}{2} \\ V_\mu = D_\mu U U^\dagger \;, & T = U\sigma_3 U^\dagger \end{array}\right)$$

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Result : **new structures in axion couplings**

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$$-\frac{c_2 g}{16\pi^2 f}a(gW^a\tilde{W}^a - g'B\tilde{W}^3) - \frac{c_3 g}{16\pi^2 f}a(gW^3 - g'B)\tilde{W}^3 \ ,$$

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A term beyond the SU(2) trace

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Pheno impact : **breakdown of sum rules**

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$$\left[\frac{\Gamma(a\to ZZ)}{\Gamma(a\to\gamma\gamma)} - 1 - \frac{\left(t_W^2-1\right)^2}{2t_W^2}\frac{\Gamma(a\to Z\gamma)}{\Gamma(a\to\gamma\gamma)}\right]^2 - \frac{2\left(t_W^2-1\right)^2}{t_W^2}\frac{\Gamma(a\to Z\gamma)}{\Gamma(a\to\gamma\gamma)} = 0$$

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When does this happen ? $\longrightarrow$ step 3

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UV completion of the non-anomalous operators ? Examples :

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$$\mathcal{L} \supset -\overline{\psi}(\partial_\mu - ig(\alpha + \beta\gamma_5)A_\mu + m)\psi$$

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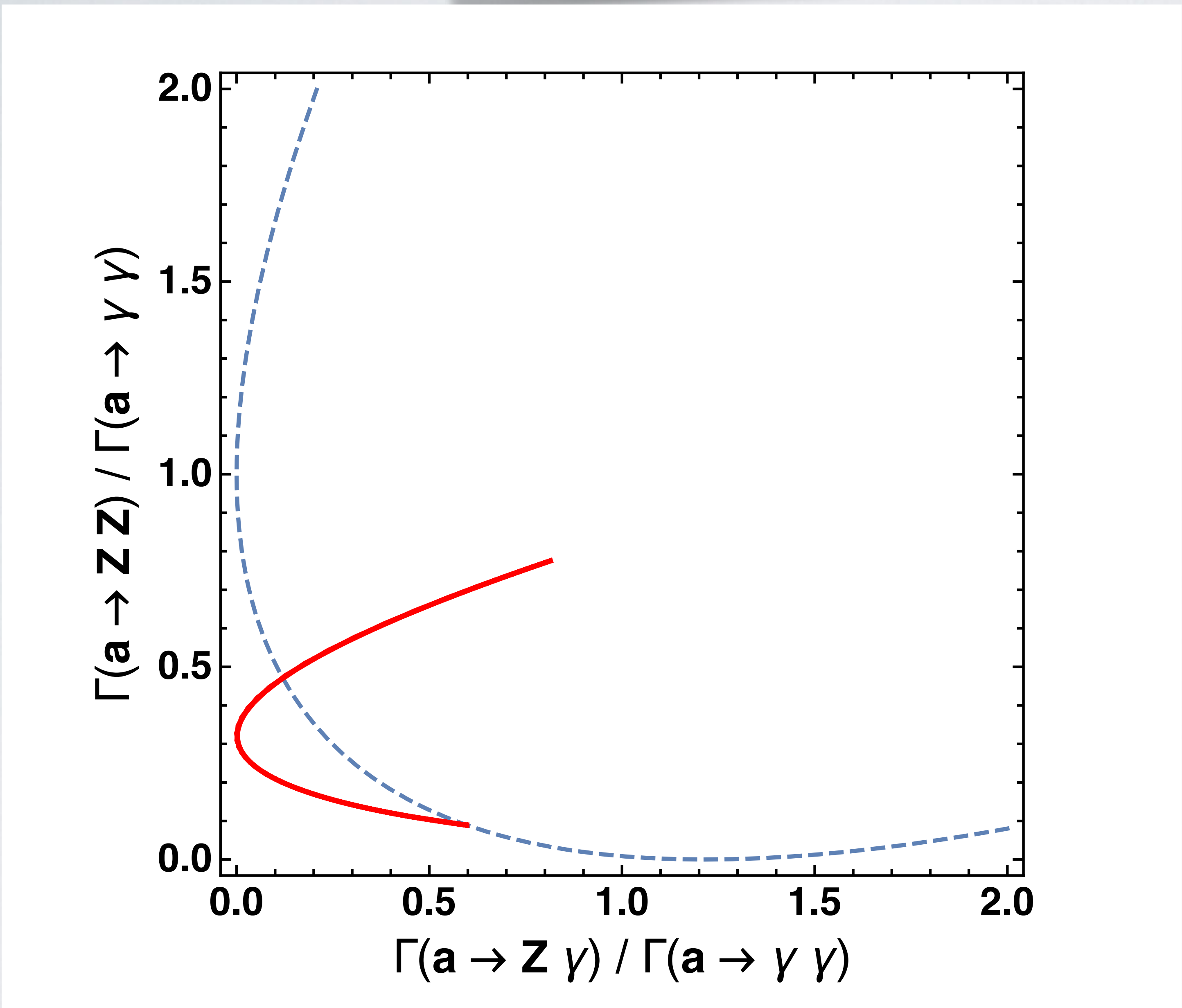
- **Chiral extensions of the SM**

$$\mathcal{L} \supset -\overline{\psi}(\partial_\mu - ig(\alpha + \beta\gamma_5)A_\mu + m)\psi$$

(non-decoupling, HEFT) **[see e.g. Cohen, Craig, Lu, Sutherland '20]**

STEP III : UV MODELS



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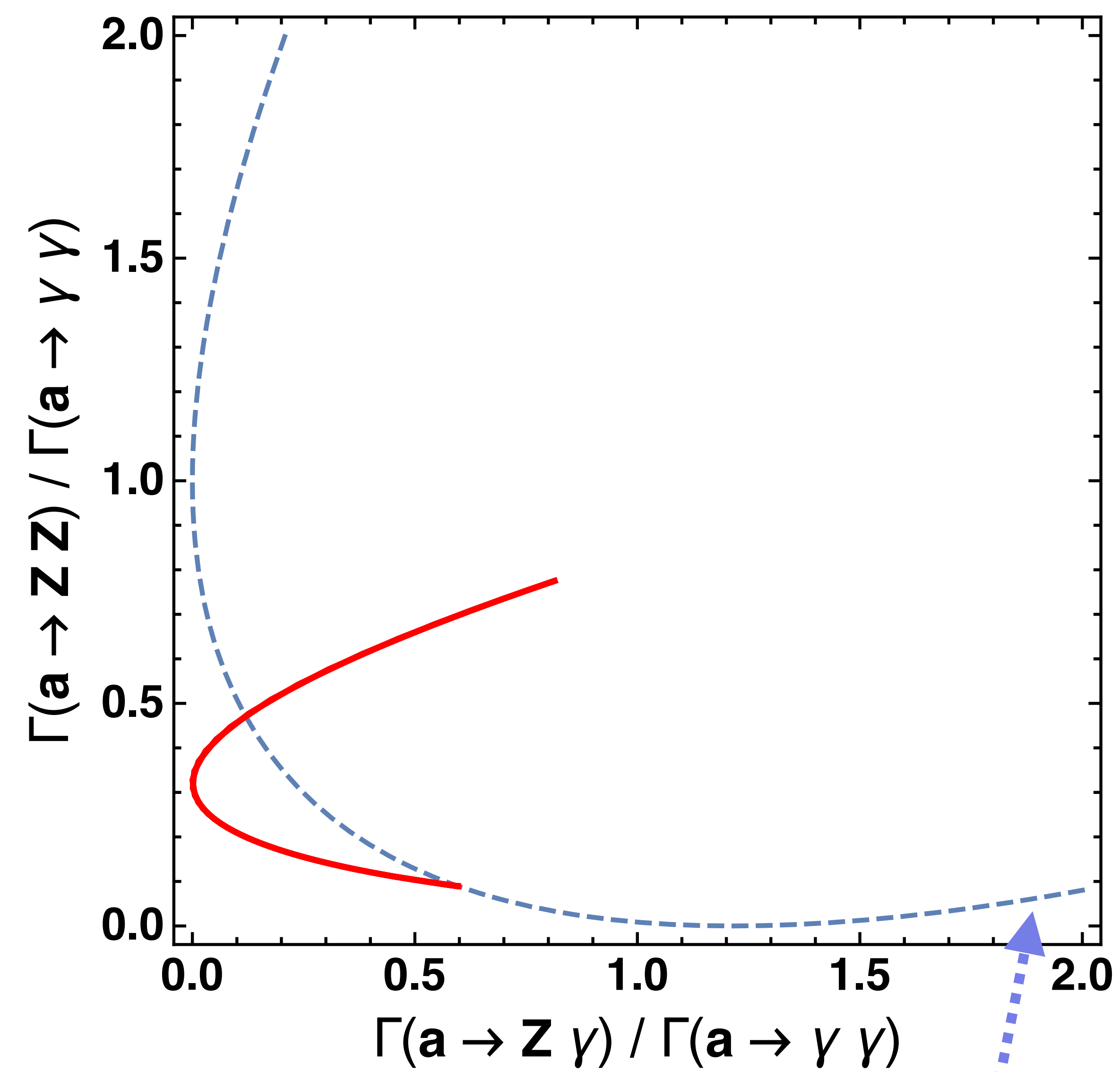

$$\left[\frac{\Gamma(a\to ZZ)}{\Gamma(a\to\gamma\gamma)}-1-\frac{\left(t_W^2-1\right)^2}{2t_W^2}\frac{\Gamma(a\to Z\gamma)}{\Gamma(a\to\gamma\gamma)}\right]^2-\frac{2\left(t_W^2-1\right)^2}{t_W^2}\frac{\Gamma(a\to Z\gamma)}{\Gamma(a\to\gamma\gamma)}=0$$

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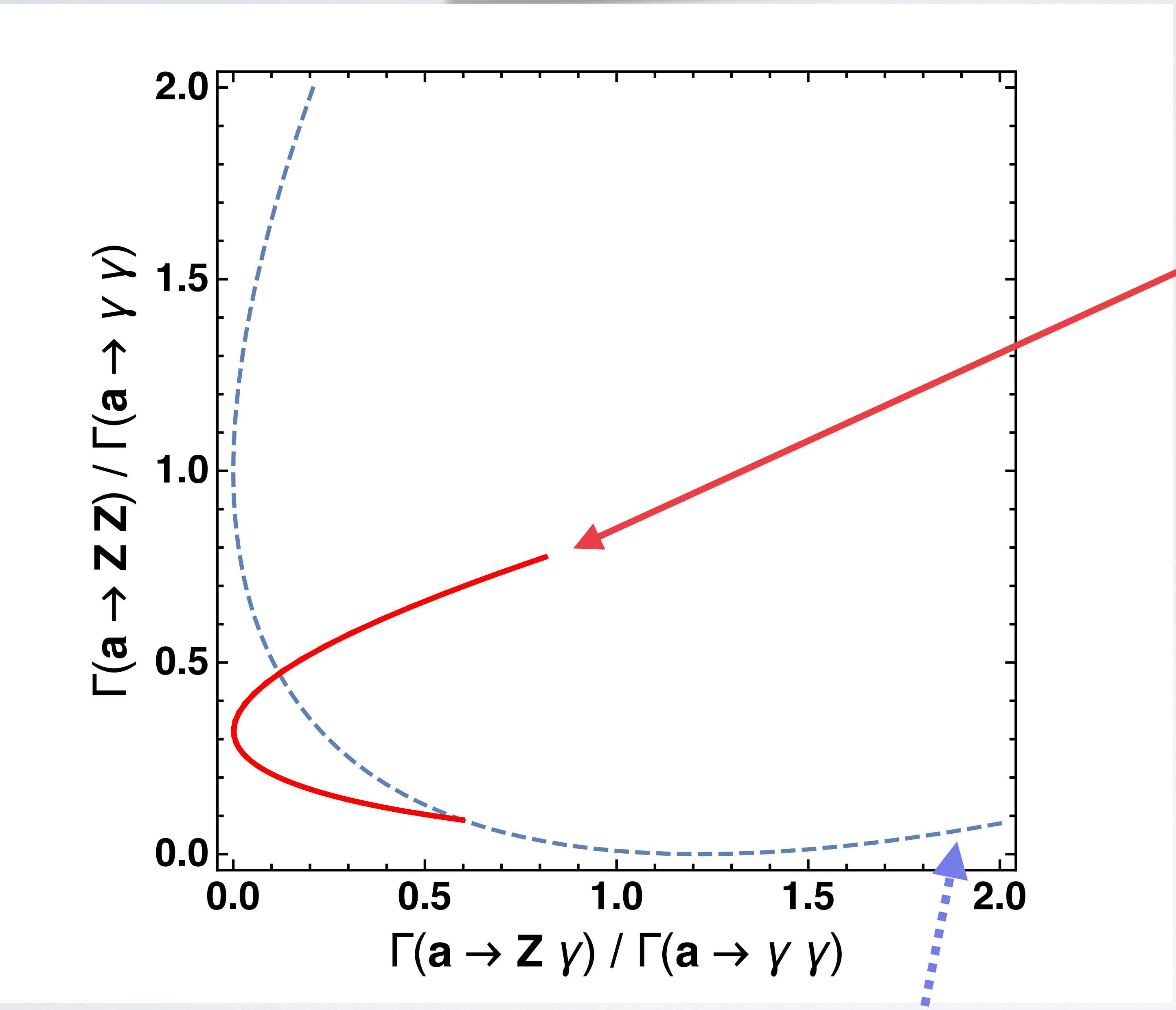

$$\begin{aligned}\mathcal{L}_Y = & - y_{E_1} \bar{L}_1 E_1 H_1 \\ & - y_{E_2} \bar{L}_2 E_2 \tilde{H}_2 \\ & - y_{N_1} \bar{L}_1 N_1 \tilde{H}_2 \\ & - y_{N_2} \bar{L}_2 N_2 H_1 + \text{h.c.}\end{aligned}$$

$$\left[\frac{\Gamma(a\to ZZ)}{\Gamma(a\to\gamma\gamma)} - 1 - \frac{\left(t_W^2-1\right)^2}{2t_W^2}\frac{\Gamma(a\to Z\gamma)}{\Gamma(a\to\gamma\gamma)}\right]^2 - \frac{2\left(t_W^2-1\right)^2}{t_W^2}\frac{\Gamma(a\to Z\gamma)}{\Gamma(a\to\gamma\gamma)} = 0$$

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Anomalous properties of axion EFTs are easily analysed with **a gauged PQ symmetry**.

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It allows for a consistent identification of the role played by the **non-linear realisations of the gauge symmetries**.

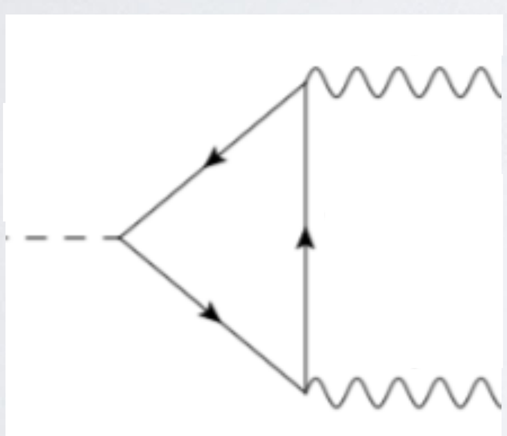
Non-anomalous couplings are tied to the presence of **heavy chiral matter** which obtains its mass from a Higgs-like field. Low-energy probes such as **violations of sum rules** are smoking guns of such UV completions.

THANK YOU !

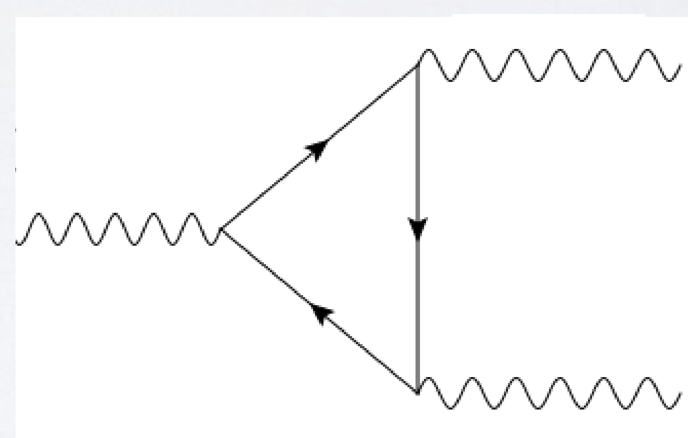
PQ ANOMALY MATCHING

EFT terms **with a PQ gauge field** :

$$\mathcal{L} \supset -\frac{\mathcal{C}}{16\pi^2}\frac{a}{f}F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{\mathcal{C}-\mathcal{A}}{8\pi^2}A_\mu^{\mathrm{PQ}}A_\nu\tilde{F}^{\mu\nu}$$



Captures **all** axion terms



Absent without the PQ gauge field

$$\longrightarrow \quad \delta_{\mathrm{PQ}}\mathcal{L} \supset -\epsilon_{\mathrm{PQ}}\frac{\mathcal{A}}{16\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

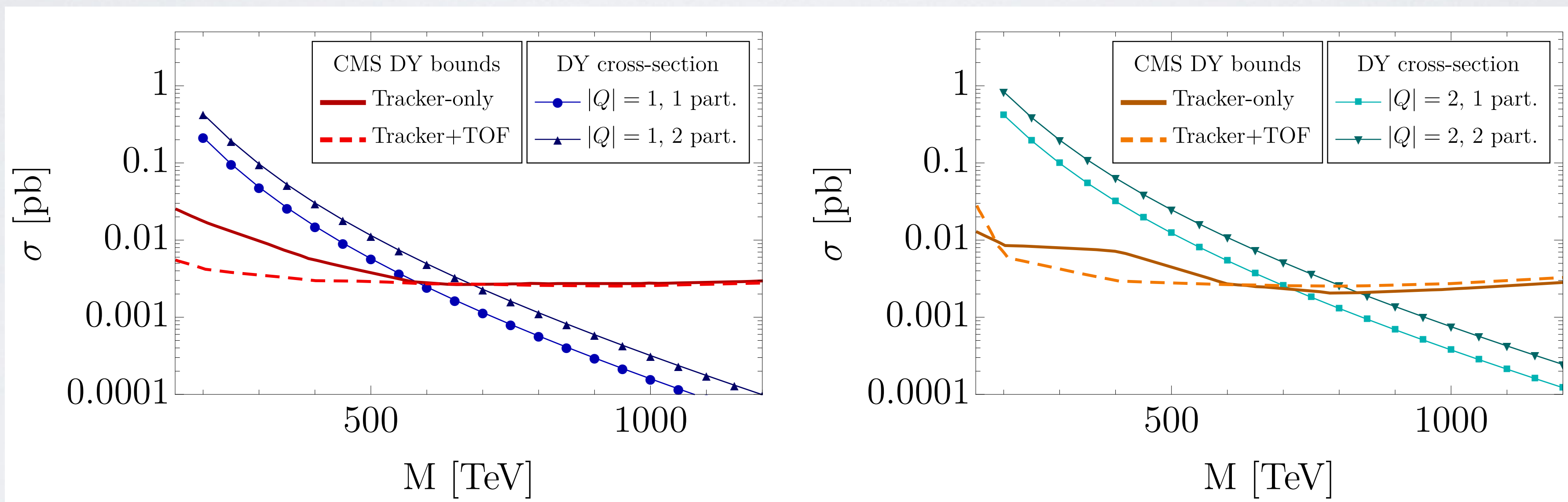
CONSTRAINTS ON THE SIMPLEST CHIRAL MODEL

	$SU(3)$	$SU(2)$	$U(1)$
L_1	1	2	Y
E_1	1	1	$Y - \frac{1}{2}$
N_1	1	1	$Y + \frac{1}{2}$
L_2	1	2	$-Y$
E_2	1	1	$-Y + \frac{1}{2}$
N_2	1	1	$-Y - \frac{1}{2}$

$$\mathcal{L} \supset \bar{L}_1 N_1 H\,, \quad \bar{L}_1 E_1 \tilde{H}\,,$$
$$\bar{L}_2 E_2 H\,, \quad \bar{L}_2 N_2 \tilde{H}$$

CONSTRAINTS ON THE SIMPLEST CHIRAL MODEL

- **electroweak precision tests** : satisfied in the custodial limit
- **direct searches** for stable charged particles :



- **Higgs couplings** :
  (in the alignment limit. No constraints in the wrong-sign limit)