WG1: State of the Art
Top-down approach

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String compactifications

- String theory lives in 10D and needs SUSY for consistency
- Compactification: $X_{10D} = M_{4D} \times Y_{6D}$
- 4D EFT for $E \ll M_{\rm KK} \approx 1/{\rm Vol}\left(Y_{6D}\right)^{1/6}$
- Geometrical and topological properties of Y_{6D} determine 4D physics
- N=1 SUSY in 4D if Y_{6D} is a Calabi-Yau manifold → chiral theory → realistic!
- Y_{6D} can de deformed in size and shape

i) maths: deformations parameterised by moduli

ii) 4D physics: moduli are new scalar particles with gravitational couplings

- Moduli ϕ massless at classical level → flat potential $V(\phi)=0$ → $<\phi>$ unfixed!
- 2 problems:

i) Unobserved long-range fifth forces (for $m < 1$ meV)

ii) Unpredictability as $g_{YM} = g_{YM}(\phi)$, $Y_{ijk} = Y_{ijk}(\phi)$, mass spectrum, SUSY breaking, Λ depend on ϕ

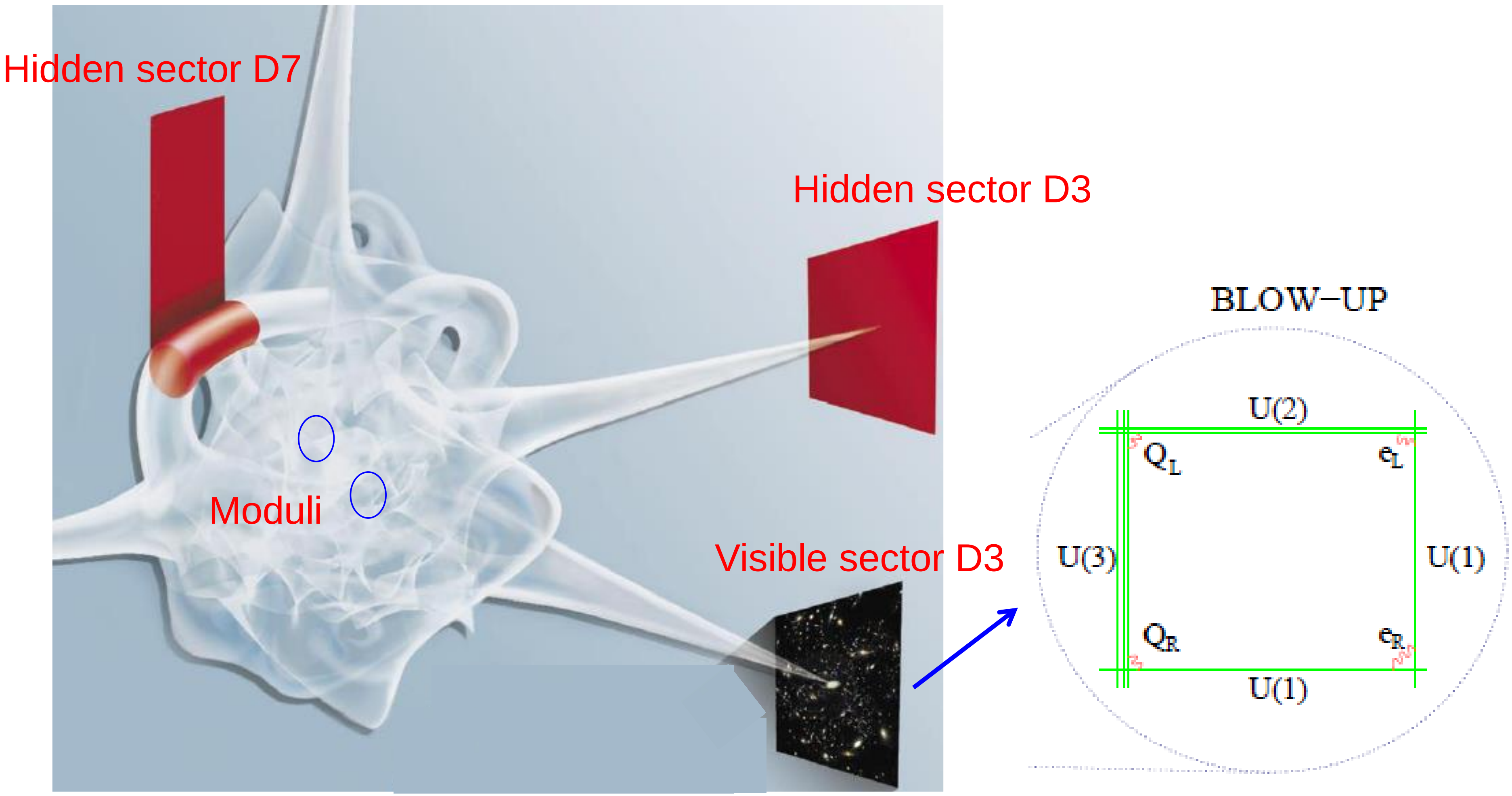
→ develop $V(\phi) \neq 0$ via fluxes/quantum corrections → fix $<\phi>$

→ landscape of string vacua ~ 10^{500}

→ $m > 50$ TeV via moduli stabilisation to avoid cosmological problems

4D string models

- Ubiquitous presence of geometric moduli (closed strings)
- Branes provide non-Abelian gauge symmetries and chiral matter (open strings)
- Standard Model (or MSSM/GUT theories) localised on branes (D3/D7 in type IIB)



Axions from strings

- In QFT:

$$\frac{1}{g^2} F_{\mu\nu}F^{\mu\nu} + \vartheta\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

a priori g and ϑ are unrelated parameters

- In SUSY:

$$\mathrm{Re}(f(\Phi))\, F_{\mu\nu}F^{\mu\nu} + \mathrm{Im}(f(\Phi))\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

g and ϑ determined via a single holomorphic function $f(\Phi)$

- $f(\Phi)$ can be either constant or field-dependent

- If $f(\Phi) = \frac{\Phi}{\Lambda}$ with $\Phi = \varphi_1 + i\, \varphi_2$ ⟶ $\frac{1}{g^2} = \frac{\varphi_1}{\Lambda}$ and $\vartheta = \frac{\varphi_2}{\Lambda} \equiv \frac{a}{f_a}$

⟶ Any theory with SUSY and field-dependent couplings has axions!

Main example: string theory — SUSY for consistency and no free parameter

In every string compactifications every gauge field has an associated axion → closed string / open string

Axions from closed strings

- Type II strings: U(N) gauge group realised on N Dp-branes wrapping internal (p-3) cycles Σ_{p-3}
- Closed string spectrum contains p-forms C_p with gauge symmetry

$$C_p \to C_p + d\Lambda_{p-1}$$

- Dp-brane action

$$S_{Dp} = \underbrace{\int_{M^4\times\Sigma_{p-3}} \sqrt{g+F}}_{\text{DBI}} + i \underbrace{\int_{M^4\times\Sigma_{p-3}} \sum_q C_q \wedge e^F}_{\text{Chern-Simons}}$$

- From DBI:

$$S_{\text{DBI}} = \ldots + \int_{M^4} \sqrt{g} F_{\mu\nu} F^{\mu\nu} \underbrace{\int_{\Sigma_{p-3}} \sqrt{g}}_{g^{-2} = \text{Vol}(\Sigma_{p-3}) \equiv \tau}$$

- From Chern-Simons:

$$S_{\text{CS}} = \ldots + \int_{M^4} F \wedge F \underbrace{\int_{\Sigma_{p-3}} C_{p-3}}_{\vartheta}$$

→ Gauge kinetic function: $f = T$ with $T = \tau + i\vartheta$ String modulus

→ Axion shift symmetry: $C_p(x,y) = \vartheta(x)\omega_p(y) \xrightarrow[\vartheta(x)\to\vartheta(x)+c]{} C_p + c\omega_p = C_p + d\Omega_{p-1}$

locally in the extra dimensions

Axions from closed strings

- Shift symmetry breaking:

  i) Perturbative level: complete breaking by fluxes which break SUSY

  $$m_{\vartheta,\mathrm{flux}} \sim m_{3/2} \sim M_p / \mathcal{V}$$ e.g. type IIB dilaton and complex structure moduli

  ii) Non-perturbative level: breaking to discrete shift symmetry by stringy instantons

  $$m_{\vartheta,\mathrm{inst}} \sim m_\tau \sim m_{3/2} > 50\ \mathrm{TeV}$$ if τ fixed non-perturbatively as in KKLT models

  $$m_{\vartheta,\mathrm{inst}} \ll m_\tau \sim m_{3/2}$$ if τ fixed perturbatively as in LVS models

- Too get viable QCD axion need to check $m_{\vartheta,\mathrm{inst}} \ll m_{\vartheta,\mathrm{QCD}} \sim \Lambda_{QCD}^2 / f_a$

- f_a from kinetic terms determined by Kahler potential K

$$L_{kin} = \frac{1}{4}\frac{\partial^2 K}{\partial\tau_i \partial\tau_j}\left(\partial_\mu \tau_i \partial^\mu \tau_j + \partial_\mu \vartheta_i \partial^\mu \vartheta_j\right)$$

i) bulk cycles: $K = -3\ln\tau_{bulk}$ → $f_a^2 \sim \frac{M_p^2}{\tau_{bulk}^2} \sim M_{KK}^2$

ii) local cycles (blow-ups): $K = \frac{\tau_{loc}^2}{\mathcal{V}}$ → $f_a^2 \sim \frac{M_p^2}{\mathcal{V}} \sim M_s^2$

→ $U(1)_{PQ}$ always broken in EFT → $f_a > H_{\mathrm{inf}}$

→ $f_a \sim 10^{16}$ GeV unless $M_s \sim 10^{11}$ GeV with $m_{3/2} \sim 1$ TeV for $\mathcal{V} \sim 10^{15}$ but cosmo problems

Axions from open strings

- SM on D-branes at singularities
  → anomalous U(1)

- Local T-modulus gets a U(1) charge
- Axion ϑ eaten up by U(1) while τ yields a field-dependent FI-term

$$\xi \simeq \frac{\partial K}{\partial \tau_{loc}} M_p^2 \simeq \frac{\tau_{loc}}{\mathcal{V}} M_p^2$$

- $M_{U(1)} \sim M_s$ → global $U(1)_{PQ}$ in EFT
- D-term potential for charged open string $\Phi = \rho\, e^{i\zeta}$

$$V_D \simeq g^2 \left(\rho^2 - \xi\right)^2$$

- D = 0 gives $\langle\rho\rangle = \sqrt{\xi} = f_a^{open}$ → spontaneous breaking of $U(1)_{PQ}$

$$\left(f_a^{open}\right)^2 \simeq \tau_{loc} M_s^2 \ll \left(f_a^{closed}\right)^2 \sim M_s^2 \quad \text{for} \quad \tau_{loc} \ll 1$$

→ $U(1)_{PQ}$ spontaneously broken at low energy → $f_a < H_{\inf}$

→ $f_a \sim 10^{11}$ GeV << $M_s \sim 10^{15}$ GeV with $m_{3/2} \sim 10^{11}$ GeV for $\mathcal{V} \sim 10^6$
and $M_{soft} \sim 1$ TeV from sequestered SUSY breaking and no cosmo problems

Summary

- 4D string models:
  - i) closed string axions ϑ (KK zero modes of antisymmetric forms $T = \tau + i\,\vartheta$)
    - $f_a \simeq 10^{16\text{-}17}$ GeV → "stringy" QCD axion, inflation, quintessence, fuzzy DM,…
  - ii) open string axions ζ (phase of a matter field $\phi = \rho\, e^{i\zeta}$)
    - $f_a \simeq 10^{10\text{-}11}$ GeV → "field-theory" QCD axion, astrophysical hints,….

- But axions can be:
  - i) removed from the spectrum by orientifold projection
  - ii) eaten up by anomalous U(1)s
    - a) open string axions eaten up for branes wrapping bulk cycles
    - b) closed string axions eaten up for branes at singularities
  - iii) too heavy if fixed supersymmetrically (saxion τ has to get a mass $m > 50$ TeV)

- Axion masses:
  - i) axions are heavy ($m_\vartheta \simeq m_\tau > 50$ TeV) if saxions are fixed non-perturbatively
  - ii) axions are light ($m_\vartheta << m_\tau$) if saxions are fixed perturbatively

Generic prediction: ultra-light axions unavoidable in controlled EFT with $\mathcal{V} \gg 1$

Generic feature: relativistic axions from saxion decay → extra dark radiation $\Delta N_{eff} \neq 0$

- Applications: QCD axion, axion DM diluted from saxion decay, DR, astrophysics, inflation, quintessence, fuzzy DM,….

- Need to develop explicit models + statistical analysis + UV correlations among observables

State of the art:
ALPs from the bottom up

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ALP Effective Field Theory - above the EW scale

- ALPs defined as generic pseudo-Goldstone bosons → naturally lighter than other UV states
- can be described in an **EFT** where the UV sector they originate from is integrated out → model-independent!

ALP EFT ingredients

Georgi,Kaplan,Randall PLB169B(1986)73

- **fields**: SM states + a. **symmetries**: SM gauge + ALP shift symmetry $(a(x) \mapsto a(x) + \alpha)$ + CP
- EFT cutoff: ALP characteristic scale f_a (reminiscent of f_π)

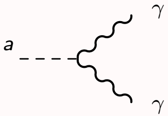
$$\mathscr{L}_{ALP\ EFT} = \mathscr{L}_{SM} + \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{m_a^2}{2} a^2 + \sum_i \frac{C_i}{f_a} O_i + \mathcal{O}(f_a^{-2})$$

dimension-5, CP-conserving operator basis

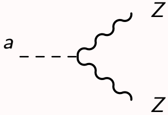
$$O_{\tilde{B}} = -a\, B_{\mu\nu} \tilde{B}^{\mu\nu} \qquad O_{\tilde{W}} = -a\, W^I_{\mu\nu} \tilde{W}^{I\mu\nu} \qquad O_{\tilde{G}} = -a\, G^A_{\mu\nu} \tilde{G}^{A\mu\nu}$$

$$O_{u,\alpha\beta} = ia\,(\bar{Q}_\alpha \tilde{H} u_\beta) \qquad O_{d,\alpha\beta} = ia\,(\bar{Q}_\alpha H d_\beta) \qquad O_{e,\alpha\beta} = ia\,(\bar{L}_\alpha H e_\beta)$$

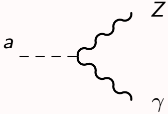
ALP couplings



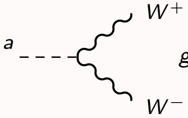
$g_{a\gamma\gamma} \sim (s_\theta^2 \, C_{\tilde W} + c_\theta^2 \, C_{\tilde B})$



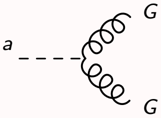
$g_{aZZ} \sim (c_\theta^2 \, C_{\tilde W} + s_\theta^2 \, C_{\tilde B})$



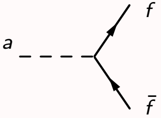
$g_{a\gamma Z} \sim s_{2\theta} (C_{\tilde W} - C_{\tilde B})$



$g_{aWW} \sim C_{\tilde W}$ $\quad (+aWWZ, aWW\gamma)$



$g_{aGG} \sim C_{\tilde G}$ $\quad (+aG^3, aG^4)$



$g_{aff} \sim C_f$

for 3 (1) fermion generations:
29 (6) free parameters + m_a

Chala et al 2012.09017
Bauer et al 2012.12272
Bonilla et al 2107.11392

coupling to Higgs only at

$d = 6 \ (\partial_\mu a \partial^\mu a)(H^\dagger H)$

$d = 7 \ (\partial_\mu a)(H^\dagger i \overleftrightarrow{D}^\mu H)(H^\dagger H)$

Bauer,Neubert,Thamm 1704.08207,1708.00443

ALP Effective Field Theory – below the EW scale

at energies $E \lesssim m_W$: → one can integrate out the **top** quark and the $\boldsymbol{W, Z, H}$ **bosons**

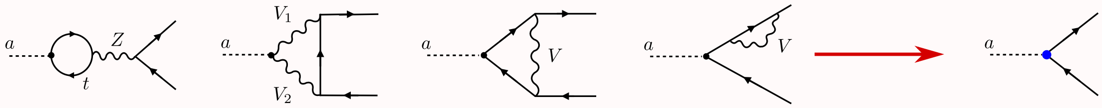
→ the symmetry is reduced to $U(1)_{em} \times SU(3)_c$

dimension-5 operator basis

$$O_\gamma = -a\, F_{\mu\nu} \tilde{F}^{\mu\nu} \qquad O_{\tilde{G}} = -a\, G^A_{\mu\nu} \tilde{G}^{A\mu\nu} \qquad O_f = i\partial_\mu a\, (\bar{f}\gamma^\mu\gamma_5 f)\,, \; f \neq t$$

EFTs above and below the EW scale can be **matched**

Bauer,Neubert,Renner,Schnubel,Thamm 2012.12272
Chala,Guedes,Ramos,Santiago 2012.09017

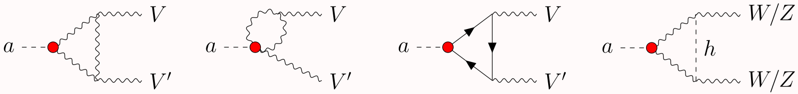


Some recent theory developments in ALP EFT

significant progress made on ALP EFT recently, borrowing from SMEFT technology. some highlights:

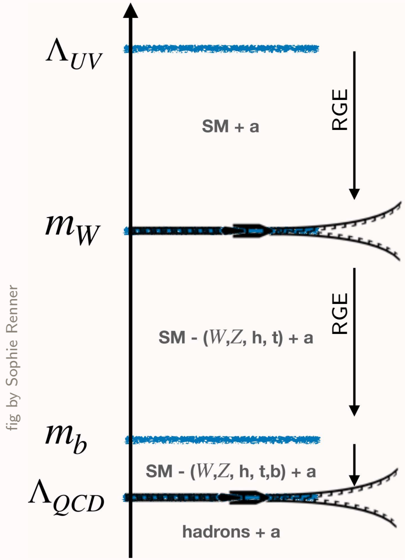
- complete RG equations above m_W Choi,Im,Park,Yun, 1708.00021, Bauer,Neubert,Renner,Schnubel,Thamm 2012.12272, Chala,Guedes,Ramos,Santiago 2012.09017
- complete RG equations below m_W Bauer,Neubert,Renner,Schnubel,Thamm 2012.12272, Chala,Guedes,Ramos,Santiago 2012.09017
- RGE mixing of ALP EFT **into SMEFT** Galda,Neubert,Renner 2105.01078

- **finite 1-loop** corrections to all ALP couplings Bauer,Neubert,Thamm 1708.00443, Bonilla,IB,Gavela,Sanz 2107.11392. . .



- perturbative **unitarity** bounds on Wilson coefficients IB,Éboli,González-García 2106.05977
- flavor-invariant analysis of shift-symmetry invariance conditions Bonnefoy,Grojean,Kley 2206.04182

The bottom-up paradigm



UV theory

ALP EFT above m_W

ALP EFT below m_W

chiral Lagrangian + ALP Bauer et al. 2102.13112

ALP coupling measurements at LHC

ALP coupling measurements in low-E experiments

reconstruct ALP properties

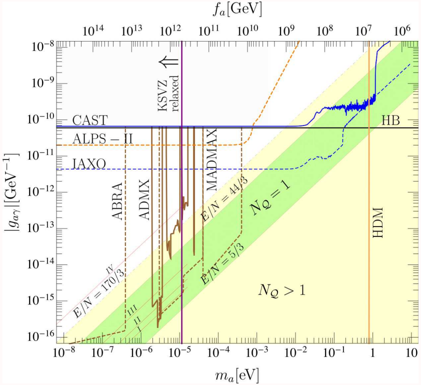
An agnostic approach

ALPs form a vast class of hypothetical particles.
specific states live on subsets of the parameter space

e.g.:

invisible QCD axion $\to f_a \sim 1/m_a$
QCD axion from exotic UV scenarios $\to f_a \not\sim 1/m_a$
Majoron $\to c_{\tilde{G}} \simeq 0$
Flavon $\to$ fixed flavor structure
DM-ALP $\to$ specific couplings range

$\vdots$



DiLuzio,Giannotti,Nardi,Visinelli 2003.01100

EFT covers all scenarios simultaneously. space can be restricted *a posteriori*

! mapping **viable parameter space** for each scenario would be valuable, but non-trivial!

ALP EFT: phenomenology

very vast and diverse pheno, depending on ALP mass, width, couplings

- **LEP/LHC** – invisible ALP: $Z \to a\gamma$, $H \to aa$, mono-X, $a +$ VV, $a + \bar{t}t \ldots$ Mimasu,Sanz 1409.4792 IB et al 1701.05379...
  – resonant ALP: $a \to \gamma\gamma, \mu\mu, VV \ldots$ Jäckel et al 1212.3620, 1509.00476, Mariotti et al 1710.01743, Bauer et al 1808.10323, Cacciapaglia et al 1701.11142, Buarque-Franzosi et al 2106.12615, Craig et al 1805.06538...
  – long-lived ALP: $a \to \gamma\gamma$ displaced vertices
  – light, non-resonant ALP: in VV, $\bar{t}t$, VBS Gavela et al 1905.12953, Carrá et al 2106.10085, Bonilla et al 2202.03450

- **Flavor physics** – meson mixing, meson/baryon decays Gavela et al 1901.02031, Carmona et al 2101.07803, Bauer et al 2110.10698...
  – LFV: $\mu \to 3e, e\gamma, ea \ldots$
  – $g-2$

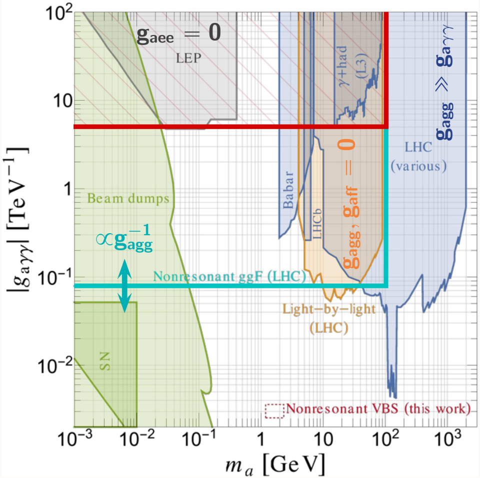
\+ **Astrophysics, Cosmology, Direct searches ...** $\rightsquigarrow$ WG 2, 3, 4

The need for a global approach

constraints often derived on 1-coupling at a time
→ $(m, c/f)$ plane

however

- each process typically affected by several ALP interactions, especially at 1-loop
- RGEs make c_i run and mix
- **gauge invariance** ties together $g_{a\gamma\gamma}, g_{aZ\gamma}, g_{aZZ}, g_{aWW}$
  e.g. $BR_{\gamma\gamma} = 1$ forbidden for $m_a \gtrsim 2m_W$
  Alonso-Àlvarez et al 1811.05466



→ sometimes (at large-ish m_a) bounds in 2D plots can't be directly compared
→ can be worth adopting a **multi-dimensional/global approach**

WG1 Wrap-Up

- a very diverse community, an incredibly broad theory landscape
- top-down and bottom-up approaches are highly complementary
  → crucial to create **a synergic exchange**, to make the most of both worlds
- experimental searches and observations probe entire EFT parameter space
  → aim for a unified, consistent interpretation
  → important to have an accurate **mapping to models** for guidance

attend the parallel session tomorrow morning! [zoom link]

Luca Di Luzio	*QCD axion*
Alexander Westphal	*ALPs from string theory*
Mark Goodsell	*Dark photons and other non-ALP WISPs*

+ plenty of time for discussion