AXION COUPLINGS IN GRAND UNIFIED THEORIES*

*: together with P. Agrawal, M. Nee

based on: 2206.07053 + 23XX.YYYYY

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WHAT DO WE LEARN ?

i) Quantization of axion-photon coupling allows knowledge about UV: charge quantization, GUTs, ...

ii) In (all ??) unified theories the only axion* coupled to photons is the QCD axion.

* Minimal prediction = QCD band

* Any other axion (ALP) necessarily has $\frac{g^{ALP}_{a\gamma}}{m_{alp}} < \frac{g^{QCD}_{a}}{m^{a}_{QCD}}$

coupling vs mass plane

(SOME) STANDARD MODEL PUZZLES

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

* Unexplained phenomena: DM, baryogenesis, CC problem, hierarchy problem ...

* 3 independent (?) interactions @ low E

Quarks, leptons, LH, RH fields, 3 families .... !?

* Plethora of independent charges & quantum numbers

but still:

CHIRALITY
+
ANOMALY FREEDOM

g_{strong}, g_{weak}, g_Y $\sim \mathcal{O}(1)$ @ TeV

very different from Yukawa couplings

$$Y_{1st} \ll Y_{2nd} \ll Y_{3rd}$$

THE STANDARD MODEL

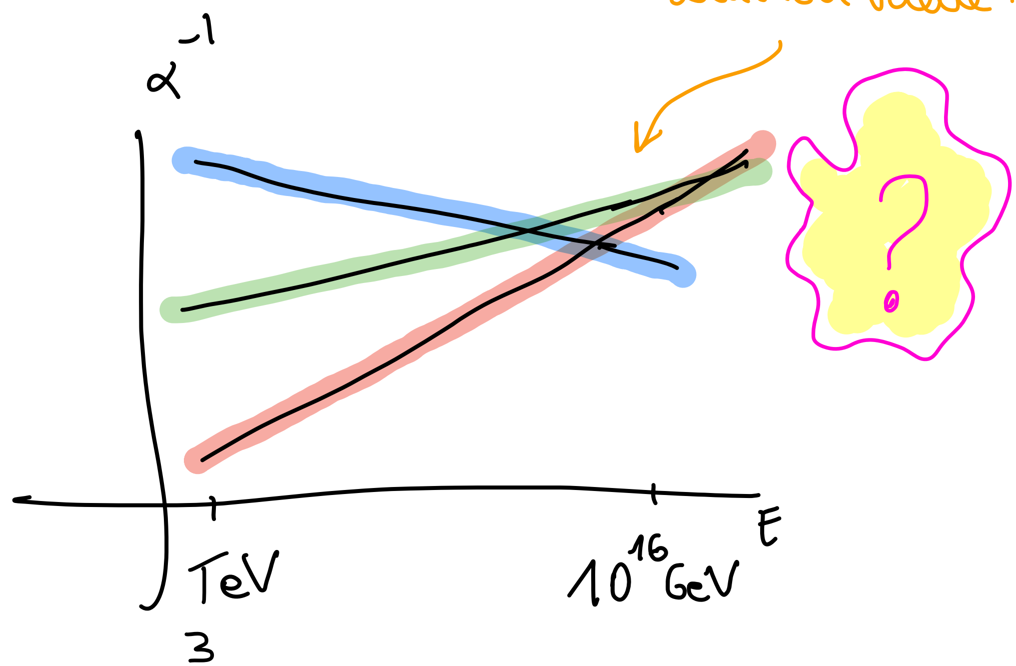
$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

Gauge couplings:

$g_s, g_{weak}, g_Y \sim \mathcal{O}(1)$ at low energies $\rightarrow$

approach a common value?!

↳ looks even better at high E!



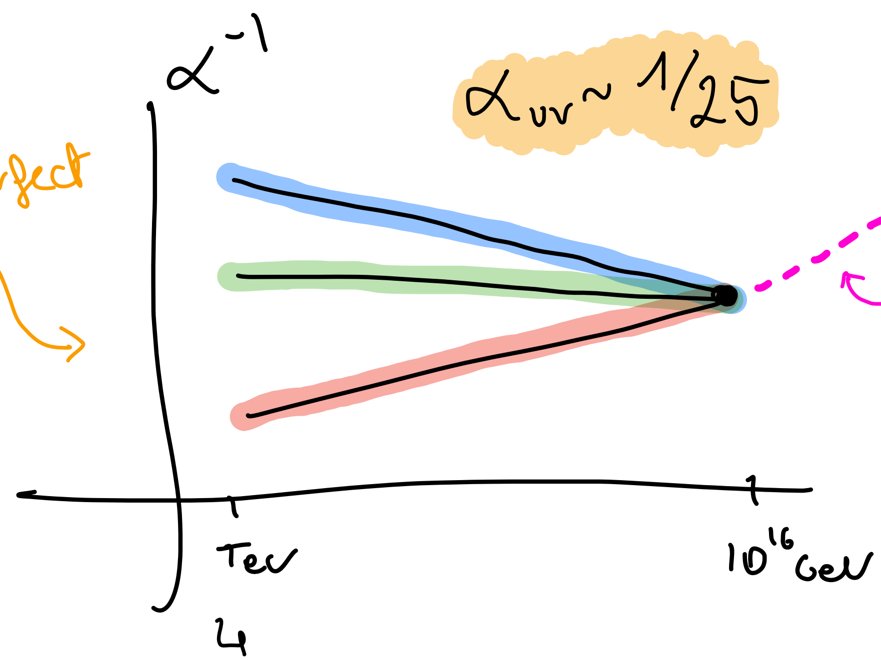
THE STANDARD MODEL

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

* To keep couplings together we need a SIMPLE GROUP! G_{GUT}

(what I'll call GUT here)

Unification almost perfect in MSSM!



unified theory!

GEORGI-GLASHOW SU(5)

* minimal GUT : $SU(5) \longrightarrow SU(3) \times SU(2) \times U(1)$

$$\underbrace{5 + \overline{10}}_{\text{anomaly free}} \longrightarrow \underbrace{q,\ \ell,\ u^c,\ d^c,\ e^c}_{\text{SM family}}$$

* $\sin^2\theta_W = \dfrac{g'^2}{g^2 + g'^2} = \dfrac{3}{8}$ @ M_{GUT} $\longrightarrow$ @ low E $\sim$ $\sin^2\theta_W \simeq 0.23$

$g' = \sqrt{\frac{3}{5}}\, g_1$

* Other GUTs : $\overbrace{SO(10),\ SO(18),\ E_6,\ E_8 \ldots}^{\text{contain } SU(5) \text{ as subgroup}}$

spinor unification

particularly appealing : CHIRAL + ANOMALY FREE

SO(10) spinor : $16 \rightarrow q + u^c + d^c + \ell + e^c + \nu^c$

DISCLAIMER

I will be talking about general features of GUTs but will be using all the time SU(5) as particular example.

THE GOOD: HINTS FOR UNIFICATION

* **Charge quantisation**: ALL isolated states have integer electric charge.

$$\frac{|Q_p + Q_{e^-}|}{e} < 10^{-21} \text{ [PDG]}$$

* **Anomaly freedom**: SM quantum numbers "conspire" to cancel gauge anomalies.

* **Unification of couplings**: $\sin^2\theta_W$ & $\frac{m_b}{m_\tau}$

$$\sin^2\theta_W = \frac{g'^2}{g^2 + g'^2} = \frac{3}{8} \quad , \quad \frac{m_b}{m_\tau} \simeq 3 \text{ at low } E$$

$g' = \sqrt{\frac{3}{5}}\, g_1$

THE BAD: PROTON DECAY

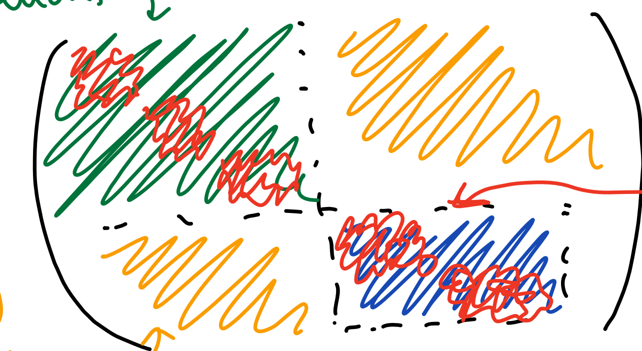
* Generic GUT prediction

SU(5) ADJOINT MATRIX: 24

* GUT bosons:

gluons

mediate proton decay



hyperchange boson
$\propto \mathrm{diag}\left(-\frac{1}{3}, -\frac{1}{3}, -\frac{1}{3}, \frac{1}{2}, \frac{1}{2}\right)$

5×5

$X \sim (3, 2, -5/6)$

Weak bosons

$\mathcal{O}_6 \sim \frac{1}{M_{GUT}^2} qqq\ell$

$$\boxed{\Gamma_{p \to \pi e^+} \sim \frac{m_p^5}{M_{GUT}^4}} \rightarrow$$

$M_{GUT} \gtrsim 10^{16}$ GeV

$\tau_{proton} > 1.6 \times 10^{34}$ yr.

Current limits from Super-K

Hyper-K expected to improve by factor of 10!

(data-taking ~ 2027)

THE UGLY: GUT DRAWBACKS

* Doublet-triplet splitting:

$$\bar{5} \sim \begin{pmatrix} H_3 \\ H_{SM} \end{pmatrix}$$

lead to proton decay unless $m_{H_3} \sim M_{GUT}$

* Mass ratios: $\frac{m_b}{m_\tau}$ is OK... but $\frac{m_s}{m_\mu}$ or $\frac{m_d}{m_e}$?!..

NOT EVERYTHING IS LOST...

↳ requires model building effort: orbifold GUTs, flavor sym...

! Our results will be independent of GUT model building details...

↳ Only depend on having a simple group G_{GUT}

Axion Review

* Axion: periodic (compact) scalar with discrete shift-symmetry. $\boxed{a \to a + 2\pi f_a}$

AKA axion-like particle (ALP)

* (periodic) Interactions shaped by shift-symmetry

$$\frac{\partial_\mu a}{f_a} \bar{f} \gamma^\mu \gamma^5 f \; ; \; \frac{a}{f_a} F\tilde{F} \; ; \; V(a) = \Lambda^4 \cos(a/f_a)$$

* Field theory language: pNGb of (anomalous) symmetries

↳ $U(1)_{PQ}$ for QCD axion

$$[SU(3)_c]^2 \times U(1)_{PQ} = \mathcal{A}_{QCD}$$

anomaly coefficient

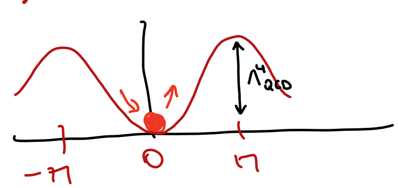
WHY AXIONS?

* Appear BSM models & string Theory (i.e. AXIVERSE)
* solve strong CP problem: QCD axion
* Dark matter candidates
* Dark energy, or even inflation (?)

Ex: QCD AXION

$$\theta_{QCD}\, G\tilde{G} \longrightarrow \frac{a}{F_a}\, G\tilde{G}$$

* solves strong CP: $\frac{\langle a \rangle}{F_a} = 0$
* $V(a) = \Lambda_{QCD}^4 \left(1 - \cos\left(\frac{a}{F_a}\right)\right) \Rightarrow m_a \sim \frac{\Lambda_{QCD}^2}{F_a}$



WHY AXIONS?

- Appear in many BSM constructions
- solve strong CP problem: QCD axion
- Dark matter candidates
- Dark energy, or even inflation (?)

- Topological, quantized couplings to gauge bosons

$$\mathcal{L}_a = \frac{(\partial_\mu a)^2}{2} + \mathcal{A} \frac{a}{F_a} \frac{\alpha_{GUT}}{8\pi} G_{GUT} \tilde{G}_{GUT}$$

QUANTISATION:

Anomaly coefficient $\mathcal{A} \in \mathbb{Z}$, an integer!

TOPOLOGICAL COUPLINGS TO GAUGE BOSONS

- Anomaly coeff. unaffected by renormalization [see anomaly matching]

$$\boxed{\mathcal{A}_{UV} = \mathcal{A}_{IR}}$$ → directly probing the far UV!

↳ Together with gauge invariance offers info about gauge group.

WAIT!!

WHAT ABOUT MIXING?

- AXION-PHOTON COUPLING (QCD axion case)

topological nature

axion-pion mixing

$$\frac{\alpha_{em}}{F_a}\left(E/N - 1.92\right) a F\tilde{F}$$

↳ we obtain solid information in the massless axion limit:

MIXING EFFECTS VANISH IN THIS LIMIT → $m^2 \ll m^2_{QCD} \sim \Lambda^4_{QCD}/f_a^2$

WILL BE SHOWN LATER...

MINIMAL 4dim GUT

* Starting point: $G_{GUT} \times \prod_i U(1)_{PQ\,i}$

simple gauge group

e.g. SU(5)

Set of commuting, global unbroken symmetries

↳ Analogy with SM: $\underbrace{U(1)_B \text{ and } U(1)_L}_{\text{weak interaction } SU(2)}$ → $U(1)_{B-L}$ anomaly-free; $U(1)_{B+L}$ ANOMALOUS! applications for baryogenesis etc.

* After symmetry redefinition:

$$G_{GUT} \times U(1)_{PQ} \times \prod_i U(1)_i$$

axion

non anom.

exact or decoupled Goldstone bosons

Important !!

$$[G_{GUT}]^2 \times U(1)_{PQ} = \mathcal{A}$$

$$[G_{GUT}]^2 \times U(1)_i = 0$$

4D GUT: ONE AXION COUPLED TO GAUGE BOSONS

$$\prod_i U(1)_{PQ_i} \xrightarrow{} \underbrace{U(1)_{PQ}}\times \overset{\text{non-anom}}{\prod_i} \tilde{U}(1)_i$$

field redef.

↳ only this linear combination gives an axion coupled to gauge bosons.

$$\left.\begin{array}{l} \mathcal{A}_{PQ} \neq 0 \\ \\ \mathcal{A}_i = 0 \end{array}\right\} \text{ and due to quantisation } \underline{\underline{\mathcal{A}^{UV} = \mathcal{A}^{IR}}}$$

↳ CURRENTS:

Above PQ & GUT SSB scales

$$\begin{cases} U(1)_{PQ}: & \partial^\mu J_\mu^{PQ} = \mathcal{A}_{PQ}\,\dfrac{\alpha_{GUT}}{8\pi}\,\underbrace{G\tilde{G}_{GUT}} \\ \tilde{U}(1)_i: & \partial^\mu J_\mu^{\tilde{U}(1)_i} = 0 \end{cases}$$

↳ This axion couples to both, photons and gluons!!

decoupled Goldstones! (from gauge bosons)

SINGLE AXION – DEPENDENCE ON PQ SCALE?

PQ current above F_a, M_{GUT}

$$\boxed{\partial^\mu J_\mu^{PQ} = \mathcal{A}_{PQ} \frac{\alpha_{GUT}}{8\pi} G\tilde{G}_{GUT}}$$

→ What if $F_a < M_{GUT}$!?

A) $F_a > M_{GUT}$: effects of anomaly captured by dim-5 op.

$$\mathcal{A}_{PQ} \frac{a}{F_a} \frac{\alpha_{GUT}}{8\pi} G\tilde{G}_{GUT}$$

axion couples to both photons and gluons!

k_3, k_2, k_1 levels of embedding of $SU(3)$, $SU(2)$, $U(1)$ in G_{GUT}

B) $F_a < M_{GUT}$:

$$\partial^\mu J_\mu^{PQ} = \mathcal{A}_{PQ} \left\{ k_3 \frac{\alpha_3}{8\pi} G\tilde{G}_{QCD} + k_2 \frac{\alpha_2}{8\pi} W\tilde{W} + k_1 \frac{\alpha_1}{8\pi} B\tilde{B} \right\}$$

↓ After PQ breaking...

$$\mathcal{A}_{PQ} \frac{a}{F_a} \left\{ k_3 \frac{\alpha_3}{8\pi} G\tilde{G}_{QCD} + k_2 \frac{\alpha_2}{8\pi} W\tilde{W} + k_1 \frac{\alpha_1}{8\pi} B\tilde{B} \right\}$$

↳ Again, axion couples to both photons & gluons!

RESULT: MINIMAL 4dim GUT

TOPOLOGY
+
GAUGE INVARIANCE $\rightarrow$ $\frac{a}{f_a}\left[\alpha_{em}\, E\, F_{em}\tilde{F}_{em} + \alpha_s\, N\, G\tilde{G}_{QCD}\right]$

$\hookrightarrow$ generates QCD potential!

$V(a) \simeq \Lambda_{QCD}^4 \left(1-\cos(a/f_a)\right)$

* Generic GUT prediction:

EM & QCD anom. coef.
$\hookrightarrow$ $\frac{E}{N} = \frac{k_1 + k_2}{k_3}$

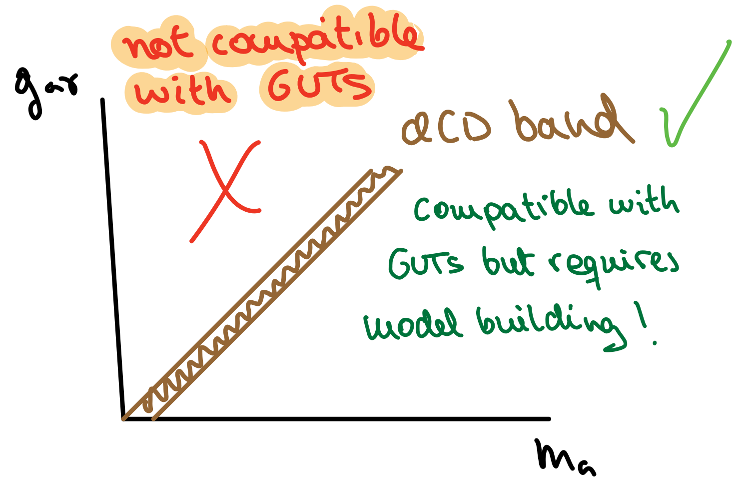
k_i : level of embedding of i-th SM group: 3, 2, 1

Standard embedding $\begin{cases} k_3 = k_2 = 1 \\ k_1 = 5/3 \end{cases}$

$E/N = 8/3$

$\hookrightarrow$ Only one axion coupled to photons: the QCD axion!

CAN WE TEST GUTs WITH AXIONS?

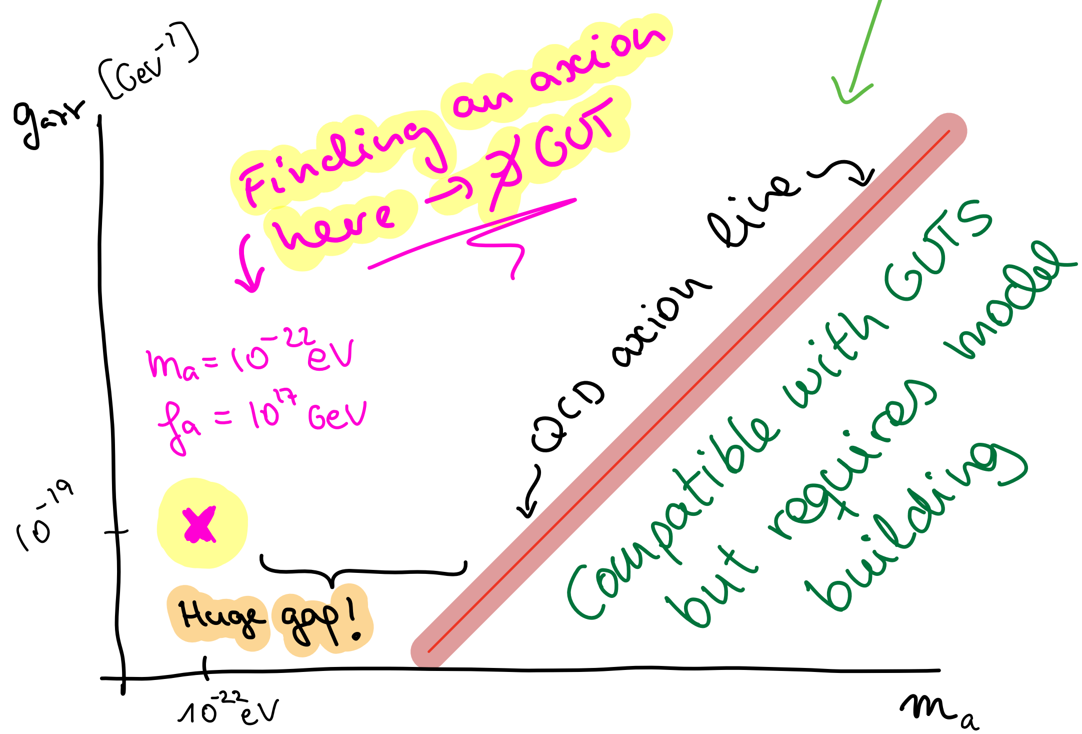


TESTING GUTs WITH AXIONS

LO: In GUTs the axion couples to EM & QCD with comparable strength

NLO: ALPs can appear BUT have $g_{a\gamma}^{alp}/m_a^{alp} < g_{a\gamma}^{QCD}/m_a^{QCD}$ [Shown later...]

NOTE! We cannot really predict m_{QCD}
this depends on F_a (non-topological quantity)



EXAMPLE 1

* Ultralight axion coupled to photons,
  $m_a \sim 10^{-22}$ eV ; $F_a \sim 10^{17}$ GeV

EXAMPLE 2

* Rotation of CMB polarisation by light axion coupled to photons
* Requires: $\begin{cases} H_{CMB} > m_{alp} > H_0 \\ F_a \sim M_P \end{cases}$

INCOMPATIBLE WITH GUTs

ASSUMPTIONS MADE SO FAR...

* Axion is a GUT singlet. See $U(1)_{PQ}$ SSB

* Axions have no mass mixing

* GUT group is simple (e.g no $U(1)$ factors)

* 4D GUTs

Does the main GUT result change if we relax these assumptions ??

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Does the main GUT result change if we relax these assumptions??

How does axion mixing change the result?

* In the absence of mixing: 1 anomalous $U(1)_{PQ}$ $\updownarrow$ 1 axion coupled to photons

$$\prod_i U(1)_{PQ\,i} \longrightarrow U(1)_{PQ} \times \prod_i^{\text{non-anom}} \tilde{U}(1)_i$$

only possible if unbroken!

* Small explicit breaking of shift symmetries may turn on non-quantised mixing... (see a-π^0 mixing)

↳ Does it change the result?

MASS MIXED AXIONS?

$$\mathcal{L} = \delta_{ij} \frac{\partial a_i \partial a_j}{2} + a_{QCD} G\tilde{G} + m_{ij} a_i a_j$$

$\det(m_{ij}) \stackrel{!}{=} 0$ or small to solve strong CP

AXION MIXING!

↳ No longer freedom to rotate away axions!

SPECTRUM OF AXIONS

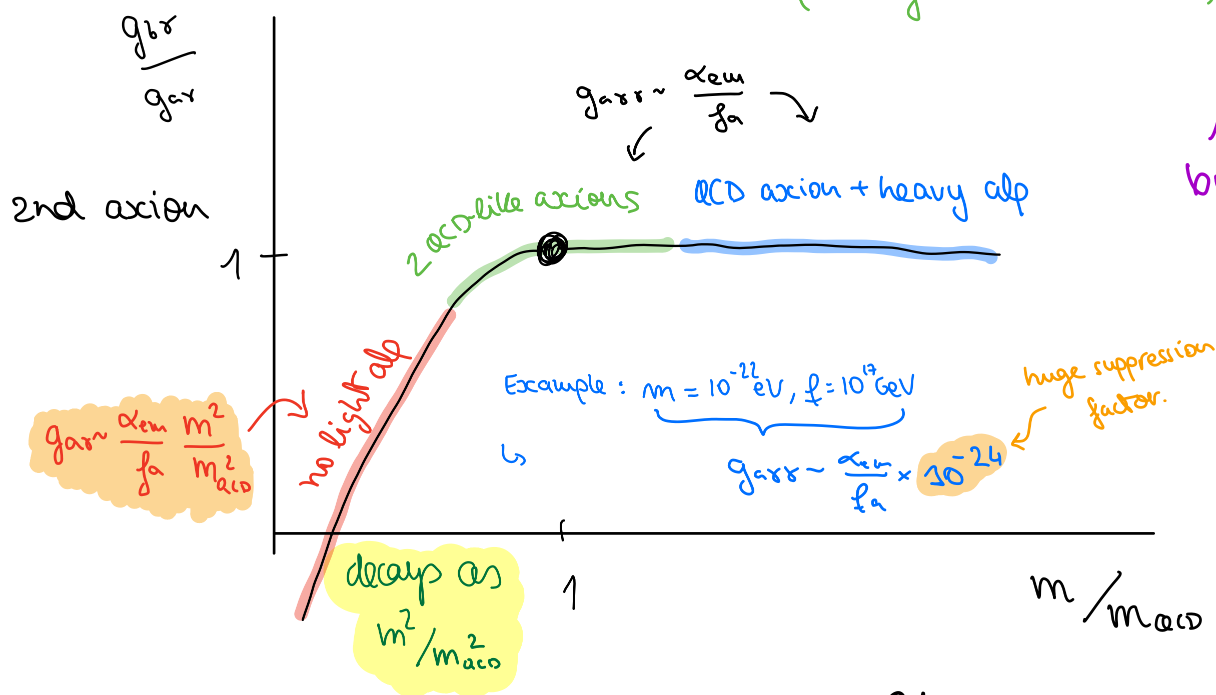
- Heavy (decoupled) axions $m_i^2 \gg m_{QCD}^2$
- LIGHT AXIONS WITH $m_i^2 \ll m_{QCD}^2$

TOY MODEL WITH 2 AXIONS

$$\mathcal{L} = \left(\frac{a}{f_a} + \frac{b}{f_b}\right) G\tilde{G} + \frac{1}{2} m_b^2 b^2$$ ← explicit breaking of b shift-symmetry

↳ a) $m_b \gg \Lambda_{QCD}^2 / f_a$ → { QCD axion: $a_{QCD} \simeq a$
heavy ALP b: mass m_b, coupling $g_{a\gamma} \sim \frac{\alpha}{f_b}$ }

↳ b) $m_b \ll \Lambda_{QCD}^2 / f_a$ → { QCD axion: $\frac{a_{QCD}}{F} = \frac{a}{f_a} + \frac{b}{f_b}$
decoupled light ALP: (orthogonal linear comb.) $g_{a\gamma} \sim \frac{m_b^2}{m_{QCD}^2} \times \frac{\alpha_{em}}{f}$ }



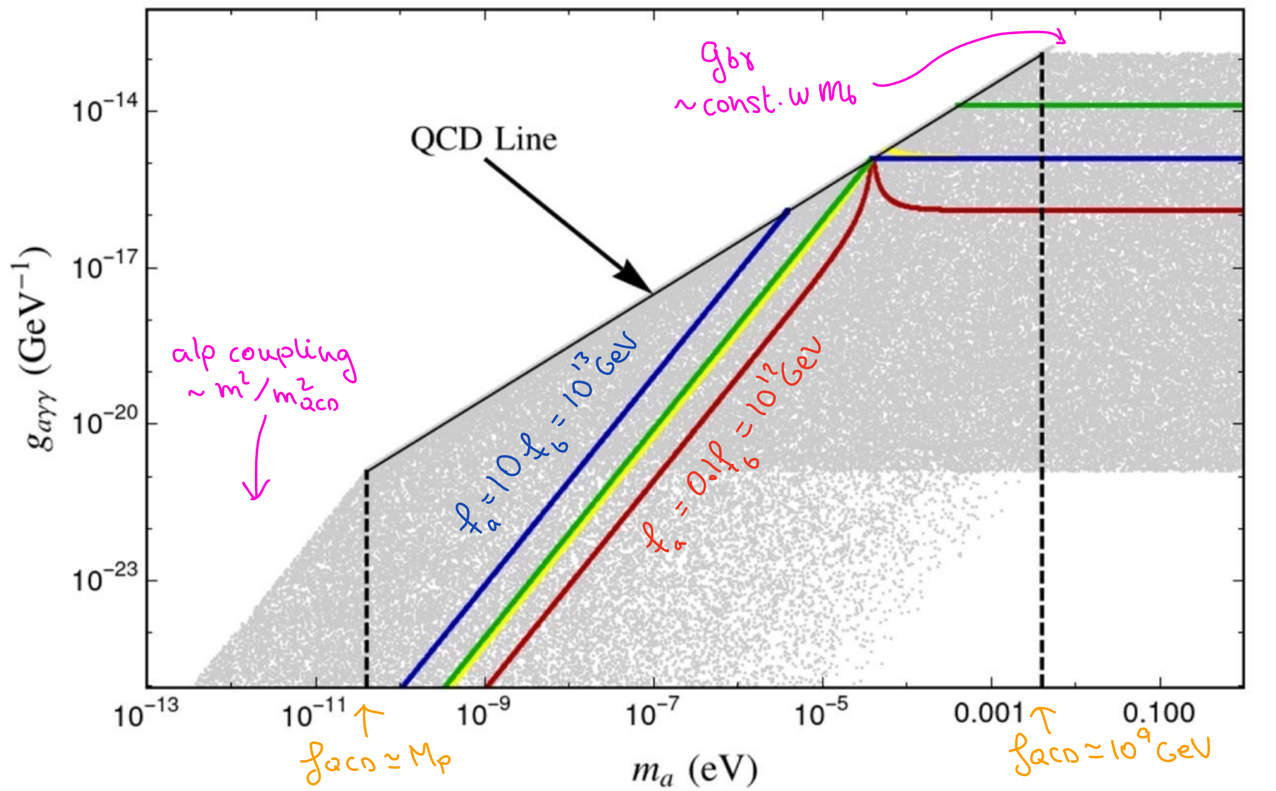
ALP-photon coupling induced by mixing effects vanishes in the massless limit!

(QCD axion "portal")

ALP-photon coupling via mixing

$$\mathcal{L} = \left(\frac{a}{f_a} + \frac{b}{f_b}\right) G\tilde{G} + \frac{1}{2} m_b^2 b^2$$

Generate sets of "points" $(a, g_{a\gamma}) + (b, g_{b\gamma})$



Ranges:

- $m_b = [10^{-11}, 1]$ eV
- $f_a, f_b = [10^9, 10^{18}]$ GeV

* $\frac{g_{alp}^{\gamma}}{m_{alp}}$ is always smaller than QCD axion $\frac{g_{a\gamma}}{m_{QCD}}$

[Does not depend on number of axions]

ASSUMPTIONS & RESULTS

see: 2206.07053

* Turn on mass/kinetic mixing for alps:

↳ GUT-alp constraint: $\frac{g_{\gamma}^{alp}}{m_{alp}} < \frac{g_{a\gamma}^{QCD}}{m_{QCD}}$ ("to the right of QCD band")

* Axion is NOT a GUT singlet:

↳ "charged" axions get large perturbative mass

* Higher-D GUTS ↝ stringy axions which avoid gluons get mass from D-instanton.

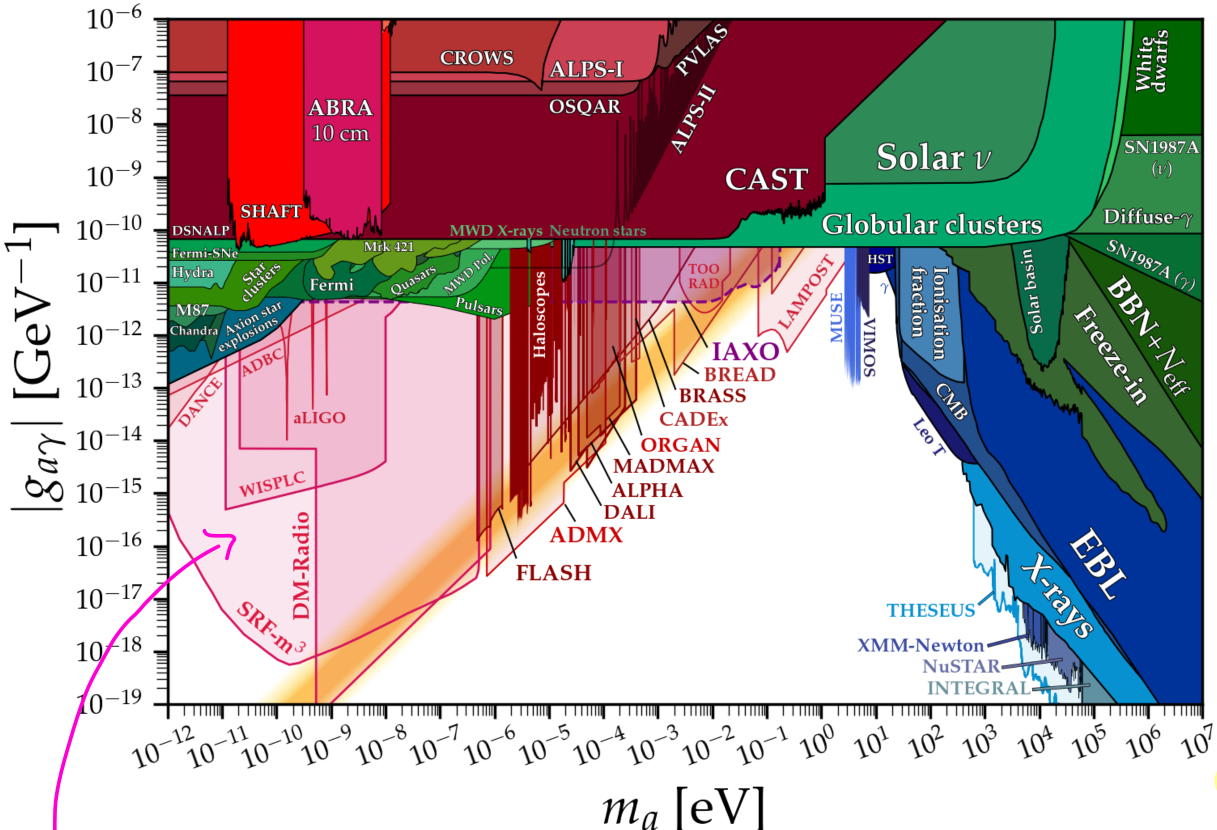
Others: clockwork, mirror worlds, dark photons...

ASK ME! :)

Axion-Photon Coupling: a bright future...

... or why I think all this is exciting!

* lab & haloscopes * astrophysics * cosmology



see: 2206.07053

Incompatible with GUTs

* Many ongoing and planned experiments looking for axions coupled to photons!

2 SIDES OF THE SAME COIN

i) no hope for exp? :(

ii) TESTING GUTs WITH TABLE-TOP EXP! :)

BACK-UP

KINETICALLY MIXED AXIONS?

$$\underbrace{K_{ij}}_{\text{Axion kinetic mixing matrix}} \frac{\partial a_i \partial a_j}{2} + \hat{a}\, G\tilde{G}_{GUT}$$

Axion kinetic mixing matrix

$\hat{a}$ ↪ linear combination coupled to GUT

Remember about redef. of "anomalous" $U(1)$'s

* Massless limit: freedom to rotate away K_{ij} ✓

$[E F\tilde{F} + N G\tilde{G} \ldots]$

$$\hookrightarrow \frac{\delta_{ij}}{2} \partial a_i \partial a_j + a_{QCD}\, G\tilde{G}_{GUT} + \left\{ \begin{array}{l} \text{bunch of massless} \\ \text{decoupled axions} \end{array} \right\}$$

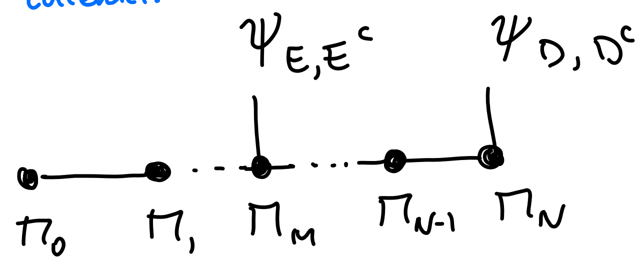
SINGLE AXION COUPLED TO PHOTONS: QCD AXION!

Clockwork axions

[1611.09855]

- Each site ≡ scalar field
- links ≡ nearest neighbor interact.

*



↳ Crucially relies on having "incomplete" multiplets @ each site.

* coupling to photons gets exp. enhancement

$$g_{a\gamma} \simeq \frac{\alpha_{em}}{F_a}\left(E/N - 1.92\right)$$

with $E/N = q^{N-M}$

↳ GUT-like constructions are expected to get back to $\frac{E}{N} = \frac{k_1+k_2}{k_3}$

N mirror sectors?

See 1802.10093, 2102.00012

$$Z_N : SM_k \longrightarrow SM_{k+1}, \quad a \longrightarrow a + \frac{2\pi k}{N} f_a$$

N copies of SM

$$m^2 \sim m_{QCD}^2 \times \frac{1}{2^N}$$

E.g. to get $m \sim 10^{-22}$ eV; $F_a \sim 10^{17}$ GeV

Need: $N \sim 100$ copies of SM

What if the axion is NOT a GUT singlet?

* We've assumed a is pNGB from $U(1)_{PQ}$:

$$\Phi = \rho(x)\, e^{i\, a(x)/F_a}$$

* Photon coupling from: $[G_{GUT}]^2 \times U(1)_{PQ}$ anomaly

Anomaly matching: GUT anomaly $\longrightarrow$ EM anomaly

* Example: $U(1)_{PQ}$ does not commute with G_{GUT}

↳ axion coupled to $U(1)_{EM}$ without QCD coupling.

Avoids anomaly matching argument ?!

WARM UP: THE PION CASE

* QCD provides an example of an "alp" coupled to photons!

Flavor symmetry $N_f = 2$ → $SU(2)_L \times SU(2)_R \xrightarrow[\langle \bar{q} q \rangle]{} SU(2)_V$

+ pions as NGb
$\pi^a(x) \sim 3$ of $SU(2)_V$

GAUGE EM!

* Conseq. 1: gauging $U(1)_{EM} \subset SU(2)_V$ induces an anomaly for neutral pion current!

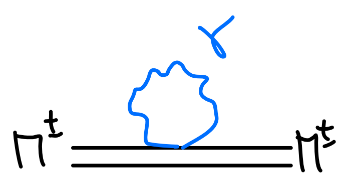
Triangle anomaly!

$$\partial^\mu J^{\pi^0}_\mu = \frac{N_c}{16\pi^2} F \tilde{F} \, \mathrm{Tr}\left[\frac{\sigma^3}{2} Q^2_{EM} \right]$$

$$\left\{ \begin{array}{l} Q_{EM} = \begin{pmatrix} 2/3 & 0 \\ 0 & -1/3 \end{pmatrix} \\ \sigma^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \end{array} \right.$$

$$\pi^0 \longrightarrow \gamma\gamma$$

* Conseq. 2: $\pi^\pm$ receive a mass from EM effects



$$\boxed{\Delta m^2_{\pi^\pm} \simeq \alpha_{EM} f_\pi^2}$$

generators of $\pi^\pm$ do not commute with Q_{EM}!

Pion-like GUT-charged AXIONS ?!

$SU(5)_{GUT} \times SU(N)_{HC}$ → confining interaction: $\Lambda_{HC} \simeq f_a \gg EW$

* Fermions: $SM + \Psi \sim (5, N) + \psi \sim (1, N)$

$\langle \bar{\Psi}\Psi \rangle = \Lambda_{HC}^3$

* Flavor symmetry: $SU(6)_L \times SU(6)_R \longrightarrow \underbrace{SU(6)_{L+R}}$

Let's gauge a subgroup of the flavor symmetry

pion-like field: $\pi^a \sim 35$

Is there an ALP here?

In this GUT case:

* SU(5) is gauged!

$\pi^a \sim 35 \to 24 + 5 + \bar{5} + 1$ → QCD-like axion: $m_a \sim \frac{\Lambda_{QCD}^2}{f_a}$

contains SM singlet!

$24 \to (8,1,0) + (1,3) + (3,2,5/6) + (\bar{3},2,-5/6)$

$+ (1,1,0)$

↳ COMPOSITE ALP

Large perturbative mass! $M \sim \alpha_{SM} \Lambda_{HC}$

COUPLED TO PHOTONS WITHOUT QCD ?!

Pion-like GUT-charged Axions ?!

* What happens to $(1,1,0)$?

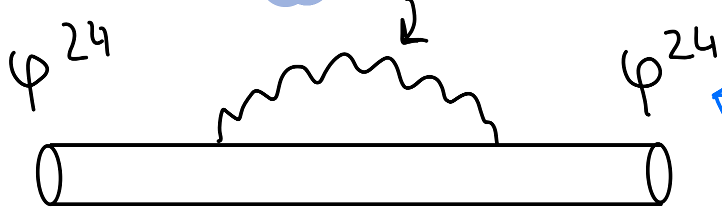
φ^{24}: aligned in "hyper-charge direction"

$T_{24} \sim \mathrm{diag}(-2,-2,-2,3,3)$

coupled to photons

$$\alpha_{em} \frac{\varphi^{24}}{\Lambda_{HC}} F\tilde{F} \; \underbrace{\mathrm{Tr}[T_{24} Q_{EM}^2]}_{\text{non-zero!}}$$

$X_{GUT} \sim (\bar{3},2,5/6)$



COMPOSITE ALP

$(\simeq$ equiv. to π^0 in QCD$)$

SM singlet BUT gets mass from heavy GUT bosons $\rightarrow$

Mass prediction:

$$m^2_{\varphi^{24}} \sim \alpha_{GUT} \frac{\Lambda^4_{HC}}{M^2_{GUT}}$$

$\langle \bar{\Psi}\Psi \rangle = \Lambda^3_{HC} \longrightarrow F_a \sim \Lambda_{HC}$ for pion-like axions!

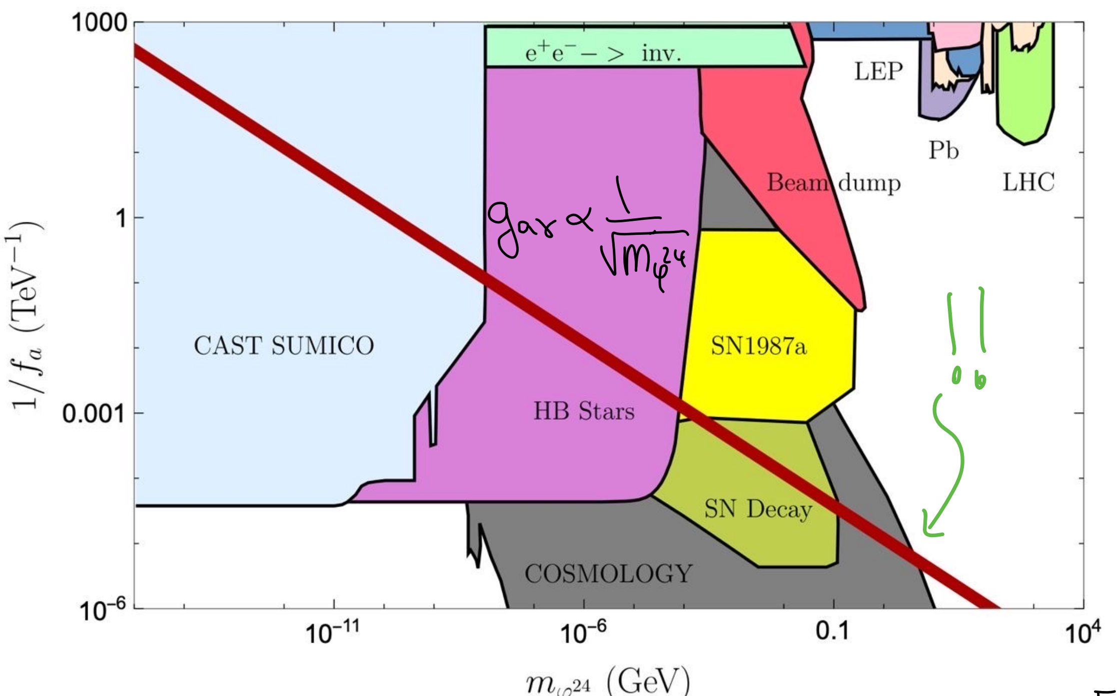
Exp. input $M_{GUT} \gtrsim 10^{16}$ GeV

Pion-like GUT-charged Axions ?!

* Emergent, charged axion does <u>NOT</u> invalidate previous results

No axion parametrically lighter than QCD can arise after GUT breaking.

$m_\varphi \gtrsim 1$ GeV



[Adapted from Bauer et al.: 1708.00443]

$m_{ALP} \sim \frac{F_a^2}{M_{GUT}}$

$g_{a\gamma\gamma} \sim \frac{\alpha_{em}}{F_a}$

qualitatively different to QCD axion!

* $F_a \sim \Lambda_{HC}$ for pion-like ALPs
* Assuming $M_{GUT} \simeq 10^{16}$ GeV

FLIPPED GUTS

what about exotic charges?!

* Theories based on $SU(5) \times U(1)_X$, or more complex groups.

* $U(1)_Y$ comes from T_{24} & X (properly normalizing)

* WEAK MIXING ANGLE (@ GUT scale)

$$\sin^2\theta_w = \frac{3/8}{1+\frac{5}{3}\left(\frac{\alpha_5}{\alpha_X}-1\right)}$$

Only if $\alpha_5 = \alpha_X \rightarrow$
- Standard GUT prediction
- All couplings meet @ GUT scale
- Embeddable in simple group $SO(10), E_6, \ldots$

ONLY QCD AXION IN THIS CASE!

FLIPPED GUTS

* QUANTUM NUMBERS

$SU(5) \times U(1)_X$

$$\underbrace{5_{-3},\ 10_1,\ 1_5}_{\text{SM family} + \nu_R}$$

* WEAK MIXING ANGLE

$$\sin^2\theta_w = \frac{3/8}{1 + \frac{5}{3}\left(\frac{\alpha_5}{\alpha_X} - 1\right)}$$

↳ Axion coupled to $U(1)_X$ without $SU(5)$ → $\nexists$ common origin ↓ $\alpha_5 \neq \alpha_X$

i) $\nexists$ reason for SM charges
eg: fermion with electric charge $+\frac{1}{2}$?

ii) $\nexists$ prediction of $\sin^2\theta_w$!

← price to pay... :(

KINETICALLY MIXED PHOTONS?

* $G_{GUT} \times U(1)_{Dark}$ with 2 axions:

dark photon

QCD axion

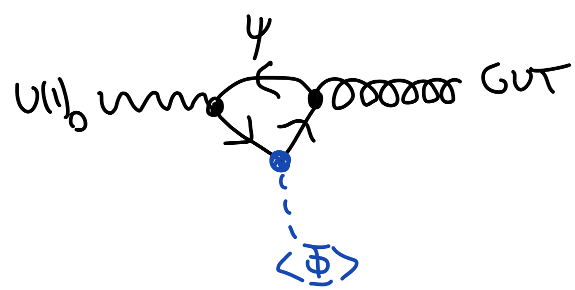
axion coupled to dark sector

$$\alpha_{GUT} \frac{a}{f_a} G\tilde{G}_{GUT} + \frac{\alpha_D}{f_b} b_D F\tilde{F}_D$$

* Gauge invariance forbids tree-level kin. mixing

↳ higher dim: $\frac{1}{M_P} F_D \, \Phi \, G_{GUT}$

$$\epsilon \sim \frac{\alpha_{GUT}\,\alpha_D}{16\pi^2} \frac{M_{GUT}}{M_{Pl}}$$



* After GUT SSB: $\frac{\epsilon^2}{8\pi} \alpha_D \frac{b}{f_b} F\tilde{F}$

expected to give a large suppression!

$\epsilon^2 \lesssim 10^{-8}$