TESTING THE FAR UV WITH LOW-E AXION EXPERIMENTS*

*: together with P. Agrawal (OXF), M. Nee (Harvard)

based on: 2206.07053 + 24XX.YYYYY

DARK MATTER BEYOND THE WEAK SCALE

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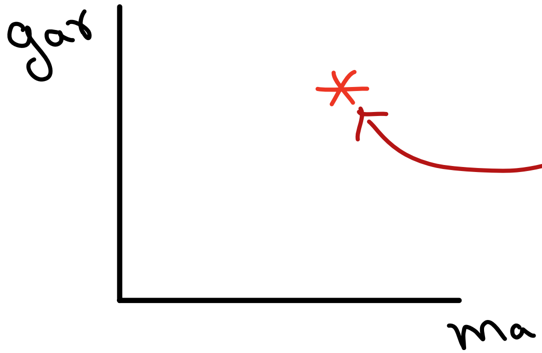
WHY TOPOLOGICAL COUPLINGS?

Or... what can we learn with $(g_{a\gamma}, m_a)$?



Imagine we find this tomorrow!

Dark matter? Strong CP?

A) Is the SM unified in the UV?

B) Can we test / distinguish different String theories at low-E?

AXION REVIEW

- Axion: periodic (compact) scalar with discrete shift-symmetry.

AKA axion-like particle (ALP)
NOT NECESSARILY COUPLED TO QCD

$$\boxed{a \longrightarrow a + 2\pi f_a}$$

- (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

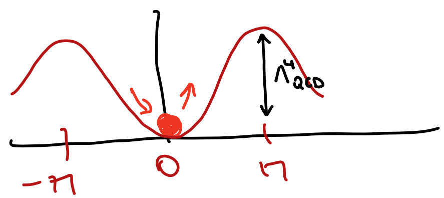
* Dark energy, or even inflation (?)

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

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

$\longrightarrow$ 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!

surge in interest recently...
[Reece; Agrawal+; Cordova+; Choi+, 23]

* One possible caveat to claims: AXION MIXING!

topological nature

axion-pion mixing

(e.g. QCD axion)

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

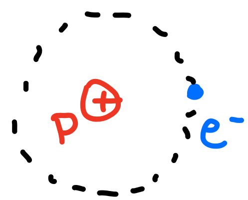
$\boxed{\text{APPLICATION 1}}$

Is the SM unified in the UV?

HINTS FOR UNIFICATION

* GUTs explain charge quantisation (integers of q_{e^-})

$$\frac{|Q_p + Q_{e^-}|}{q_{e^-}} < 10^{-21}$$



* Anomaly freedom:

e.g. $\mathrm{Tr}\, Y^3 = 2\left(-\frac{1}{2}\right)^3 + 6\left(\frac{1}{6}\right)^3 + 3\left(-\frac{2}{3}\right)^3 + 3\left(\frac{1}{3}\right)^3 + 1^3 = 0$

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

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

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

AXIONS AS PROBES OF UNIFICATION

[see: Agrawal, Nee, MR: 2206.07053]

UV gauge group
SU(5), SO(10)...

$$G_{GUT} \xrightarrow{SSB} SU(3) \times SU(2) \times U(1)$$

* Topological, quantised couplings to gauge bosons:

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

* Anomaly matching: $\mathcal{A}_{UV} = \mathcal{A}_{IR}$
* Gauge invariance of G_{GUT}

Strong constraints for axion couplings!

↳ Based on topology: independent of SSB and physics @ intermediate scales

AXIONS AS PROBES OF UNIFICATION

* 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: $\underbrace{U(1)_B \text{ and } U(1)_L}$

weak interaction SU(2)

$U(1)_{B-L}$ anomaly-free

$U(1)_{B+L}$ ANOMALOUS!

applications for baryogenesis etc.

* After symmetry redefinition:

$$G_{GUT} \times U(1)_{PQ} \times \prod_i \underbrace{\tilde{U}(1)_i}_{\text{non anom.}}$$

Important!!

$[G_{GUT}]^2 \times U(1)_{PQ} = \mathcal{A} \neq 0$

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

ONLY ONE AXION COUPLED THROUGH THE ANOMALY!

exact or decoupled Goldstone bosons

$\mathcal{A} = 0$

AXIONS AS PROBES OF UNIFICATION

(see: 2206.07053)

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

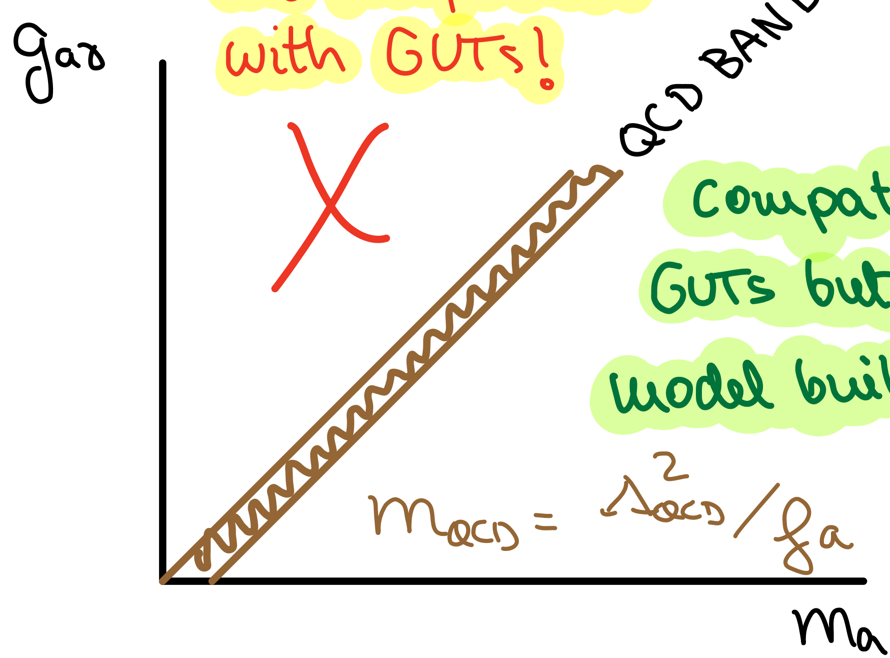
unavoidable QCD potential

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

↳ zero order statement:

Single axion coupled to photons: QCD axion

not compatible with GUTs!



Compatible with GUTs but requires model building!

RESULT:

$$\frac{g_{a\gamma}^{ALP}}{m_{ALP}} < \frac{g_a^{QCD}}{m_{QCD}^a} = \frac{\alpha_{em}}{m_\pi f_\pi}$$

- axion mixing
- "charged axions" (pion-like fields)
- Dark photon models
- Extra dim. GUTs..

APPLICATION 2

WHAT CAN AXIONS SAY ABOUT STRING THEORY ?

(or at least some of them)

Work in progress w/ P. Agrawal & M. Nee

AXIONS IN STRING THEORY

GENERIC, KNOWN RESULTS...

* Multiple sources of axions in ST: B_{MN}, C_p, ... ~ gauge fields

  "Axions from p-form fields wrapping p-cycles" $\theta_p = \int_{W_p} C_p$

* Appear in large number: # axions ~ "complexity" of compact space

  AXIVERSE! [Arvanitaki et al., '09]

* Exponentially good PQ (moduli stabilisation might spoil this) CAVEAT!

  [Conlon, '06; McAllister & Quevedo, 23]

* F_a tends to be large! Observability? Overabundance?

  (although avg. decreases with # axions) [Gendler et al., 23]

WHAT'S NEW HERE?

[Huge amount of papers since Witten et al in '80s]

* UV consistency fixes UV gauge group in some ST.
* Axion couplings are topological in ST.

MATCH 10D AXION COUPLINGS $\rightsquigarrow$ 4D EFT @ R^{-1} $\rightsquigarrow$ 4D EFT @ low-E !

compactify 6D space

match couplings from R^{-1} to IR

ADMX, or similar experiment

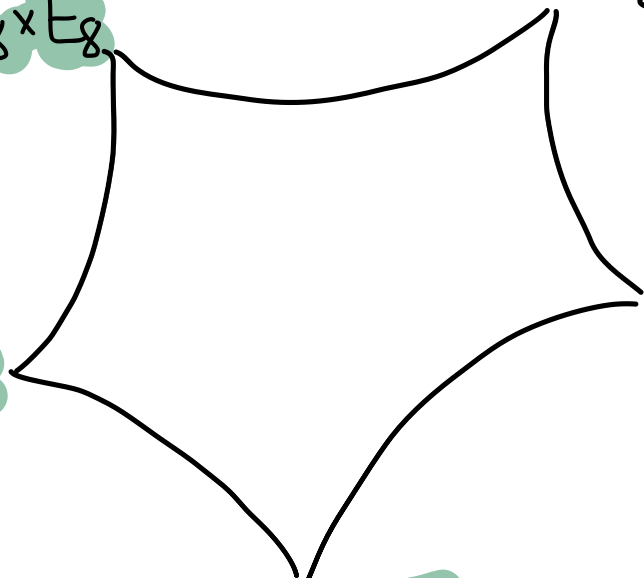
↳ well defined axion predictions independent of details associated to: compactification & obtaining SM spectrum

$$\boxed{\text{In some ST: } g_{a\gamma}/m_a < \frac{\alpha_{em}}{2\pi}\frac{1}{f_\pi m_\pi} \text{ holds!}}$$

DIFFERENT STRING THEORIES

HETEROTIC $E_8 \times E_8$

Type IIA



Type IIB

theories of intersecting branes!

HETEROTIC SO(32)

Gauge group may change

10D consistency

$\parallel$

RR tadpole cancellation

Gauge group fixed by UV consistency

1 to 1 relation with axion couplings

Type I

HETEROTIC STRINGS

* Theory of closed (super)strings in 10D

metric + moduli

dilaton

* Massless states: $\begin{cases} - \; g_{MN}, \; B_{MN}, \; \phi \\ - \; A^{ij}_{M} \end{cases}$

Gauge boson + gauginos

"charged" matter

Source of axions!

EFFECTIVE ACTION:

S_{10}

10D N=1 SUGRA

* Green-Schwarz anomaly cancellation $\longrightarrow$ $E_8 \times E_8$ or $SO(32)$

Focus on

$\hookrightarrow \quad B \wedge \operatorname{tr} F^2 \wedge \operatorname{tr} F^2$

$\hookrightarrow \quad \int_{X_6} \{ \dots \} \longrightarrow a\, G\tilde{G}$

AXION COUPLING IN 4d!

[See Svrcek, Witten for a review]

HETEROTIC STRINGS

"Problem"

$\boxed{\text{UV simplicity vs IR richness}}$

$E_8 \times E_8$ in 10d

↳ compactifying on Calabi-Yau or toroidal orbifold

+

(discrete) Wilson lines

⊛ MANY 4D EFT become available!

$SU(5)$, $SO(10)$, E_6, trinification, etc...

CONNECTING FAR UV TO IR

Energy scale

Fully fledged ST

10D SUGRA
$E_8 \times E_8$

4D EFT @ R^{-1}

↳ E_6, $SO(10)$, $SU(5)\times U(1)$
$SU(5)$, Pati-Salam, SM-like ...

↳ chiral fermions depend on topology of compact space

LHC

EWSB

Axion Experiment

Axions offer pristine window into UV physics!

Independent of intermediate scale physics!

Results will only depend on SM embedding into $E_8 \times E_8$

AXIONS FROM HIGHER-D GAUGE FIELDS

↳ Baby version: $QCD \times U(1)$ in 5D

↳ Compactify: $S_1 / \mathbb{Z}_2$: $\begin{cases} \text{- gluons: } A_\mu^{a\,(0)} \\ \text{- pseudo-scalar: } B_5^{(0)} \end{cases}$

\# REMARKS:

"cost of moving particle around": $e^{-\int M d\tau}$

i) Particle worldline Non-local potential $\quad e^{i\theta} = e^{i\int B_5 dx_5}$ $\rightsquigarrow V(B_5) = R^{-4} e^{-S} \cos(B_5^{(0)} R)$

$$S = 2\pi M R$$

~ UV instanton from 4D point of view!

ii) Chern-Simons interaction $\quad \int K_{cs} \epsilon^{MNPQR} B_M G_{NP} G_{QR} \to B_5^{(0)} G\tilde{G}$ in 4D!

AXIONS IN HETEROTIC STRINGS

[see Svrcek, Witten for a review]

↳ B_{MN} : 2-index antisym. tensor

$(\equiv B_2)$ $\qquad B_2 \to B_2 + d\Lambda_1$

$B_6 \equiv$ dual of B_2 !

* Model-independent axion (a): $\quad a = \int_{X_6} B_6$

(MI)

* Model-dependent axions (MD) (b_i): zero modes of B_{mn} wrapping 2-cycles (W_i)

↳ "internal dimensions"

$$b_i = \int_{W_i} B_2$$

SHIFT SYMMETRY BREAKING EFFECTS:

Instantons in $E_8 \times E_8$, worldsheet instantons, NS5-branes...

↳ Only e^{-S} effects!

[see Choi 9706171]

MATCHING AXION COUPLINGS

$$S_{10d} \supset \int_{X_6} B_6 \wedge [\mathrm{tr}_1 F^2 + \mathrm{tr}_2 F^2] + \int_{X_6} B_2 \wedge X_8^{(YM)}$$

MI couplings

MD couplings

* MI axion couplings : $\mathcal{L}^{4d} \supset a/f_a \, (\mathrm{tr}_1 F^2 + \mathrm{tr}_2 F^2)$

universally coupled to gauge bosons

$\mathrm{tr}_1 F^2 = \sum_i \mathrm{tr}\, F_i^2$ unbroken gauge groups in 1st E_8

* MD axion couplings : $\sum k_i^{(1)} \int_{M_4} b_i \, \mathrm{tr}_1 F^2 + \sum k_i^{(2)} \int_{M_4} b_i \, \mathrm{tr}_2 F^2$

depend on compact space

CALCULABLE!

10d SUGRA

$S_{10d} \longleftrightarrow$ Axion couplings @ R^{-1} in 4d EFT

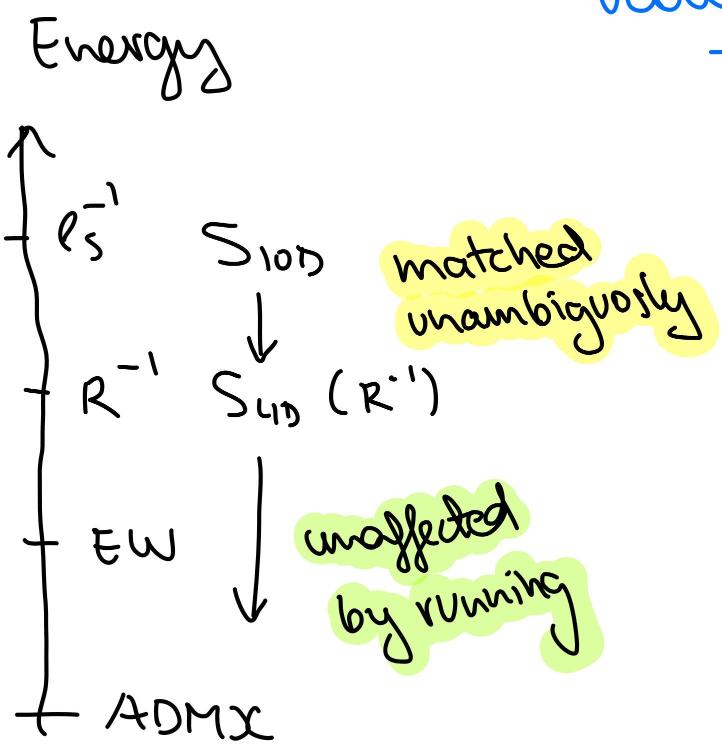
EMBEDDING THE SM

@ R^{-1} :

$$\mathcal{L}_{4D} \supset \underbrace{\int_{M_4} \theta_1 \, \mathrm{tr}_1 F^2 + \int_{M_4} \theta_2 \, \mathrm{tr}_2 F^2}_{}$$

axion couplings at low-E only depend on how we embed the SM!

* θ_1, θ_2 : different linear combinations of a & b_i !



OPTIONS

i) $E_8 \supset G \supset SM$; second E_8 "untouched"

ii) SM non-trivially embedded in $E_8 \times E_8$

EMBEDDING THE SM

$$\mathcal{L}_{4D} \supset \int_{M_4} \theta_1 \, \mathrm{tr}_1 F^2 + \int_{M_4} \theta_2 \, \mathrm{tr}_2 F^2$$

Hidden sector

$$\mathrm{tr}_1 F^2 = \{ QCD + EW + \text{Hypercharge} \}$$

Energy

ℓ_s^{-1} S_{10D}

matched unambiguosly

R^{-1} $S_{4D}(R^{-1})$

EW

unaffected by running

ADMX

$$\theta_1 = a + \sum_i k_i^{(1)} b_i$$

Model independent

model dependent

value of $k_i^{(1)}$ depends on compact space

STANDARD SM EMBEDDING

* 4D EFT → @ R^{-1} scale:

SM from first E_8

$$\mathcal{L} = \frac{\theta_1}{8\pi}\left(\alpha_1 B\tilde{B} + \alpha_2 W\tilde{W} + \alpha_3 G\tilde{G}\right) + \underbrace{\frac{\theta_2}{8\pi} H\tilde{H} + \sum_{\text{world-sheet}} V(b_i)}_{\text{axions other than those in } \theta_1 \text{, not important for } g_{a\gamma}!}$$

$$\theta_1 = a + \sum_i k_i^{(1)} b_i$$

* 4D EFT → below EWSB scale:

$$\mathcal{L} = \frac{\theta_1}{8\pi}\left[\alpha_{em}\left(\frac{E}{N} - 1.92\right)F\tilde{F} + G\tilde{G}\right] + V_{eff}(b_i)$$

source of axion mixing!

Only QCD axion to leading order!

↳ Additional axions satisfy:

$$\boxed{\frac{g_{a\gamma}}{m_a} < \frac{\alpha_{em}}{m_\pi f_\pi}}$$

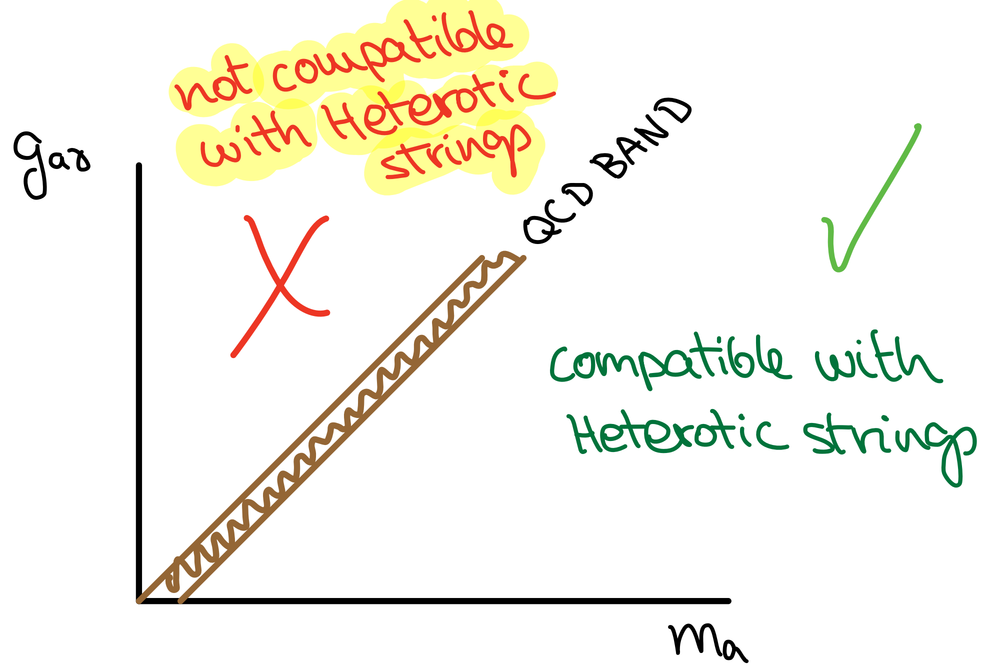
ZERO ORDER STATEMENT

* Find an axion with: $g_{a\gamma}/m_a > \alpha_{em}/m_\pi f_\pi$

For example:

↳ Cosmic birefringence

↳ Ultralight axions coupled to photons



Rule out Heterotic Strings?

↳ ANY LOOPHOLE?!

NON-STANDARD SM EMBEDDING

Possible way out?

$$\mathcal{L}_{4D} \supset \int_{M_4} \theta_1 \, \mathrm{tr}_1 F^2 + \int_{M_4} \theta_2 \, \mathrm{tr}_2 F^2$$

$\theta_1 \to$ ~ QCD axion

$\theta_2 \to$ ~ ALP

* Take: $E_8 \times E_8$

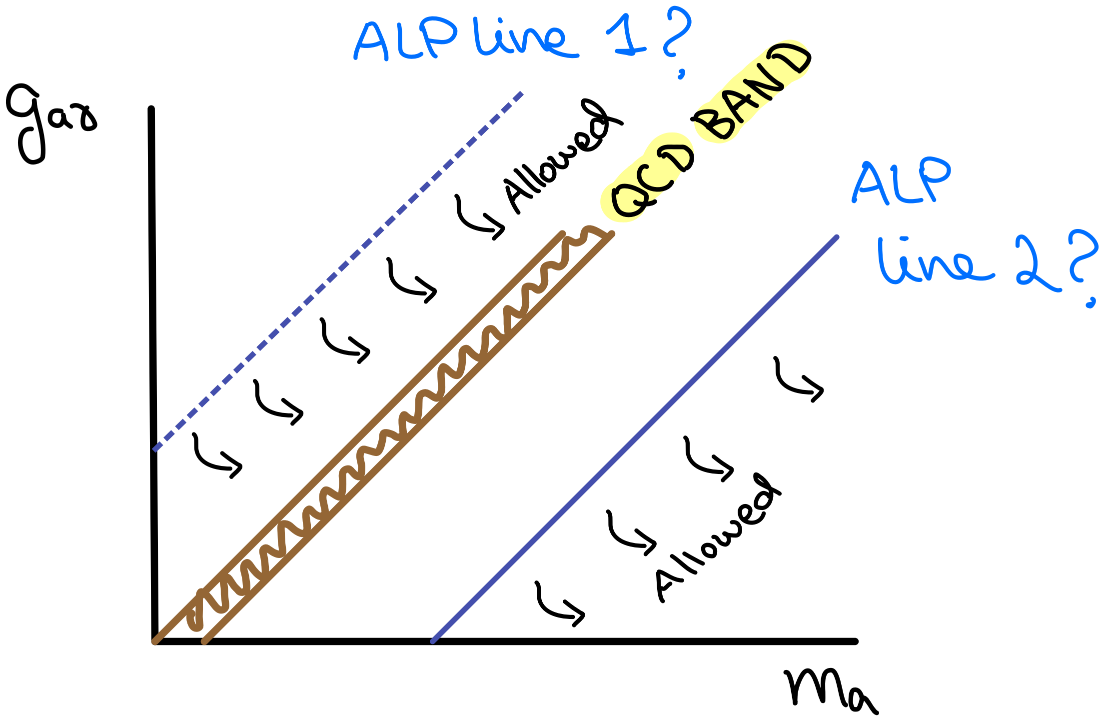
$$[\underbrace{SU(3)\times SU(2)}\times U(1)^n]\times[U(1)^m \times G_h]$$

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

Keep G_h^* instantons under control! subdominant wrt QCD.

$$\left.\begin{aligned} V(\theta_1) &\simeq -\Lambda_{QCD}^4 \cos\theta_1 \\ V(\theta_2) &\simeq -\Lambda_{ALP}^4 \cos\theta_2 \end{aligned}\right\} \to \quad \Lambda_{ALP} \text{ vs } \Lambda_{QCD} \,?$$

WHAT'S THE COST OF THE ALP?



* ALP line 1 or 2?

  Λ_{QCD} vs Λ_{ALP}

  ↳ Model dependent question!

* Irreducible axion potential

  $$V(\theta_{alp}) \sim R^{-4} e^{-2\pi/\alpha_{GUT}} \cos(\theta)$$

MODEL INDEPENDENT IMPLICATIONS

i) Weak mixing angle is modified; $\sin^2\theta_W < 1/3$!

Standard GUT

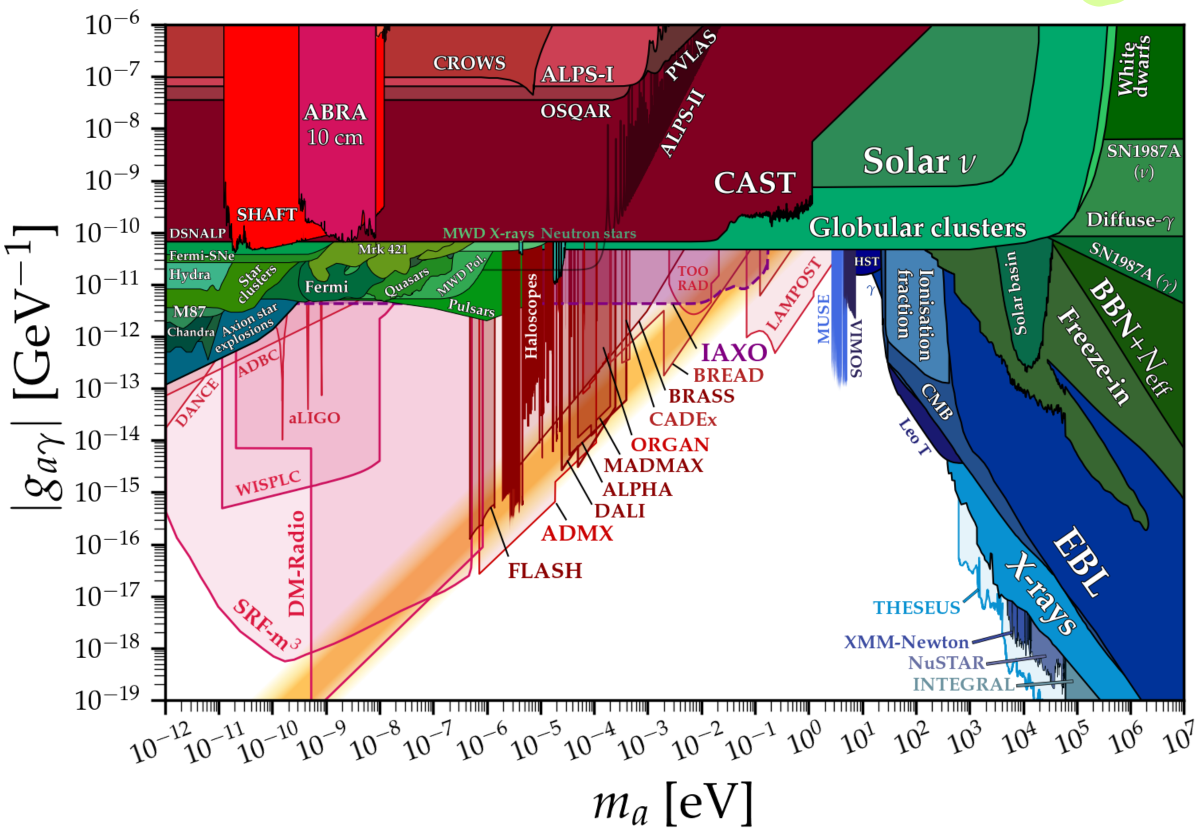
$s^2\theta_W = 3/8$

ii) Fractional charges? Possibly chiral!

UV LESSONS FROM IR EXP

1) On top of Strong CP, Dark Matter, etc axions offer unpolluted UV information: GUTs, Heterotic strings

2) Many experiments searching for axion-photon in near future, specially $g_{a\gamma}/m_a > \alpha_{em}/m_\pi f_\pi$



3) We CANNOT confirm GUTs or Heterotic strings BUT axion searches offer NON-TRIVIAL TESTS of these theories

BACK-UP

FIELD THEORETIC AXIONS?

* Can we get axions from the phase of complex scalars?

$$\phi = \bar{\Phi}\, e^{ic} \quad ; \quad c \to c + q_c \theta$$

YES! BUT only in theories where the lightness is guaranteed by a gauge symmetry: $U(1)_A$

See: Anomalous U(1) scenario

$$\mathcal{O} \sim e^{-S}\, \underbrace{e^{ia}\, \phi^N}$$

phase from ϕ mixes with "a" and inherits axion coupling $\frac{c}{f_{eff}} F\tilde{F}$

↳ Couplings of "c" are the same as MI axion, "a"!

* QUESTION: Can we form cosmic strings?
Do they have "de-compactified" core?

COMPUTING $K_{1,2}^{(i)}$

* $K_{1,2}^{(i)}$ are "anomaly coeff." for model dependent axions.

$$\int B \wedge X_8 = \sum_i K_1^i \int_{M_4} b_i \, \mathrm{tr}_1 F^2 + \sum_i K_1^i \int_{M_4} b_i \, \mathrm{tr}_2 F^2$$

$$K_1^{(i)} = \int_{\Sigma_6} \beta_i \wedge \left(-\mathrm{tr} R^2 + 2 \mathrm{tr}_1 F^2 - \mathrm{tr}_2 F^2\right)$$

Field strength subject to topological constrain:

$$dH = -\mathrm{tr}_1 F^2 - \mathrm{tr}_2 F^2 + \mathrm{tr} R^2 \longrightarrow [\mathrm{tr} R^2] = [\mathrm{tr}_1 F]^2 + [\mathrm{tr}_2 F]^2$$

Same cohomology class

TWISTED STATE CONTRIBUTIONS

* Compactification on non-simply connected manifold

$$K = K_0 / G$$

↳ Fractionally charged states appear! ⇝ Do they modify $g_{a\gamma}/m_a < \alpha_{em}/m_\pi f_\pi$

↳ Ψ, do they induce $g_{a\gamma}$?

* EFT

$$\mathcal{L} = -\mu \bar{\Psi} e^{i\gamma_5 a} \Psi - m_\Psi \bar{\Psi}\Psi \longrightarrow g_{a\gamma} \sim \frac{\alpha_{em}}{f_a} z$$

↳ Calabi-Yau compactification: $z = e^{-S}$; $S \sim 2\pi/\alpha$

↳ Orbifold: $z = \frac{m_a}{m_\Psi} e^{-S/2}$

P-FORM FIELDS

* Antisym. tensor field (~ generalised gauge potential)

$$C_{p+1} \to C_{p+1} + d\Lambda_p$$

p-form gauge parameter

* Field strength: $F_{p+2} = dC_{p+1}$

* p-branes = electric objects $\longleftrightarrow$ $S_{elec} = Q \int_{W_{p+1}} C_{p+1}$

* Duals:

↳ $F_{p+2} = F_{d-p-2} \longleftrightarrow F_{d-p-2} = dC_{d-p-3}$

↳ $(d-p-4)$-branes electrically charged under C_{d-p-3} and magnetically charged under C_{p+1}.

AXIONS IN HETEROTIC STRINGS

If time allows...

MD axions $b_i = \int_{W_i} B_2$

MI axion $a = \int_{X_6} B_6$

$$
\begin{tikzcd}[column sep=huge, row sep=huge]
B_2 \arrow[rr, leftrightarrow, "\text{10D dual object}"] \arrow[d, leftrightarrow, "\text{electrically charged under...}"'] \arrow[drr, leftrightarrow, "\text{magnetically charged}" near start] & & B_6 \arrow[d, leftrightarrow, "\text{electrically charged under...}"] \arrow[dll, leftrightarrow] \\
\text{superstring} & & \text{NS5-branes}
\end{tikzcd}
$$

↳ 4D point of view, superstring ≡ axion string!

4D GUT: ONE AXION COUPLED TO GAUGE BOSONS

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

field redef.

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

$\mathcal{A}_{PQ} \neq 0$

$\mathcal{A}_i = 0$

and due to quantisation $\underline{\underline{\mathcal{A}^{UV} = \mathcal{A}^{IR}}}$

Above PQ & GUT SSB scales

↳ CURRENTS:

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

↳ 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!

How does axion mixing change the result?

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

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

only possible if unbroken!

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

↳ Do we get additional light ALPs with $g_{a\gamma}$?

MASS MIXED AXIONS?

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

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

AXION MIXING!

↳ No longer freedom to rotate away axions!

SPECTRUM OF ADDITIONAL ALPs

- 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 : $a_{QCD} \simeq a$

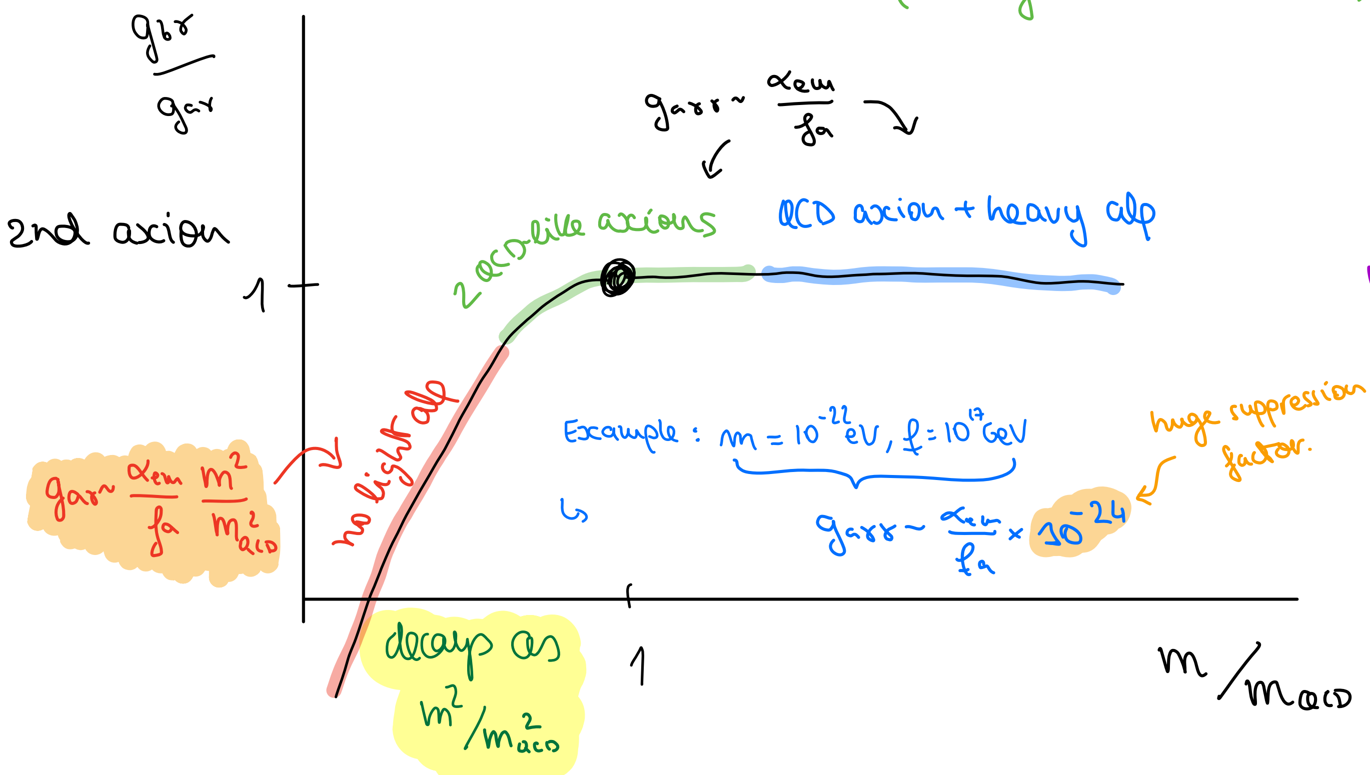
heavy ALP b : mass m_b , coupling $g_{a\gamma} \sim \frac{\alpha}{f_b}$

↳ 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.)

$$g_{b\gamma} \sim \frac{m_b^2}{m_{QCD}^2} \times \frac{\alpha_{em}}{f_b}$$

$$m_{alp} \sim m_b$$

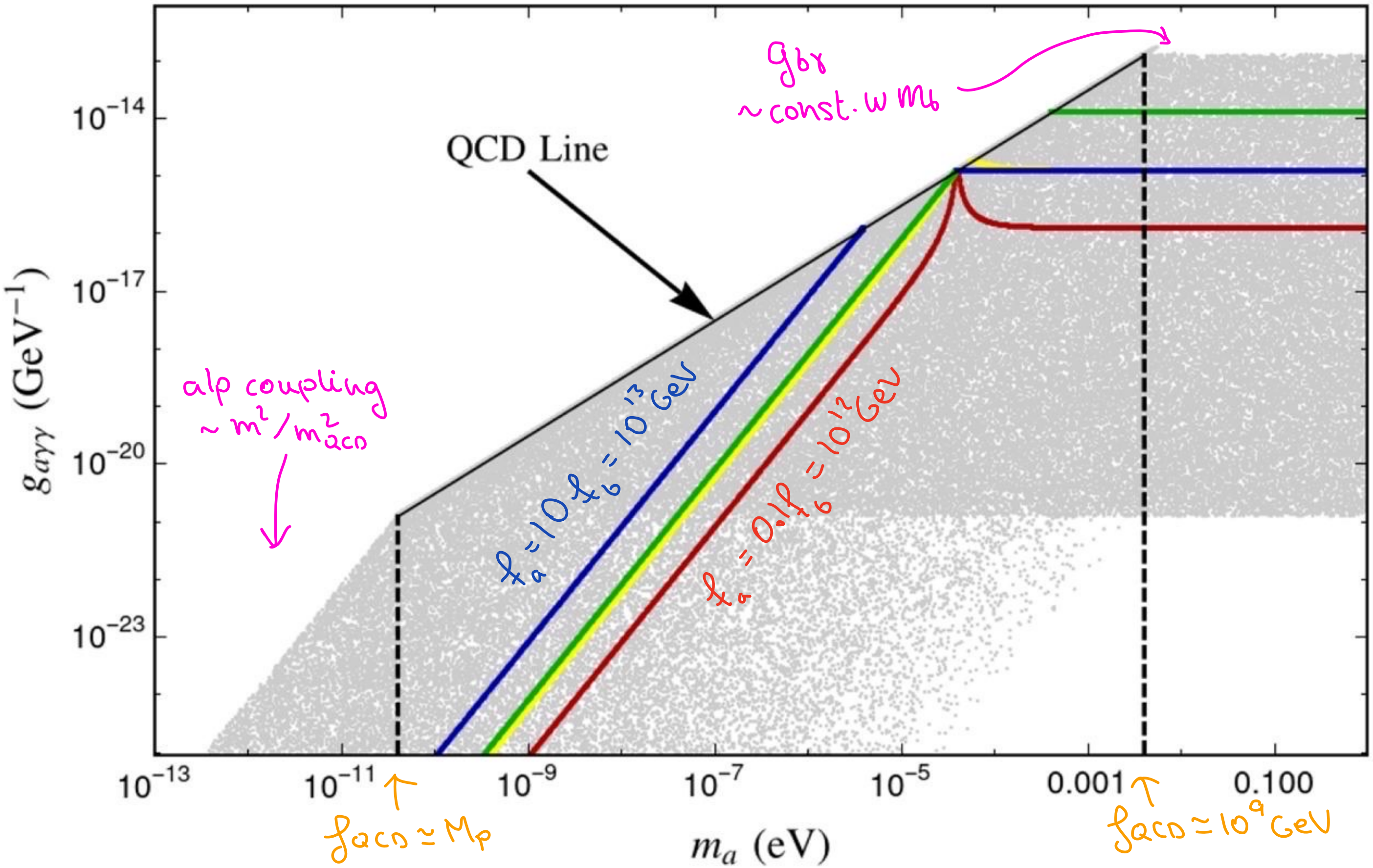


ALP-photon coupling induced by mixing is smaller than the coupling of the QCD axion

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

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

[Does not depend on number of axions]

STRING AXIONS & GUTs

* SM is embedded in higher dim. simple gauge group:

GUT symmetry is exact everywhere in extra dimension

CS-like coupling (e.g. 5D)

4-dimensions

$$S_{CS}^{(5)} = \frac{K}{16\pi^2} \int d^5x \, \epsilon^{MNPQR} B_M \, \mathrm{Tr}[G_{NP} G_{QR}] \simeq \frac{a}{F_a} G_{GUT} \tilde{G}_{GUT} \rightarrow$$

4d result trivially extended to higher D!

→ CS level ~ anom. coeff.

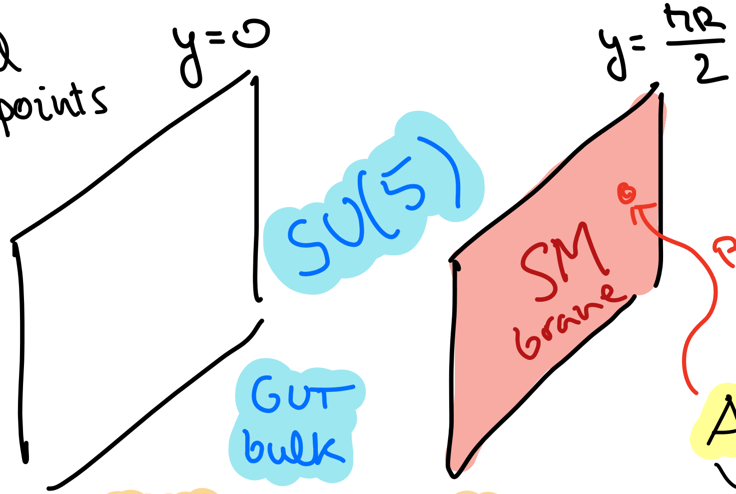
→ $B_5 \equiv$ axion "a"

* String theory offers richer possibilities: orbifold GUTs

"position dependent" gauge symmetry

↓ leading to: APPARENT UNIFICATION

branes @ orbifold fixed points



Brane localized axion

ALP without QCD coupling ?!

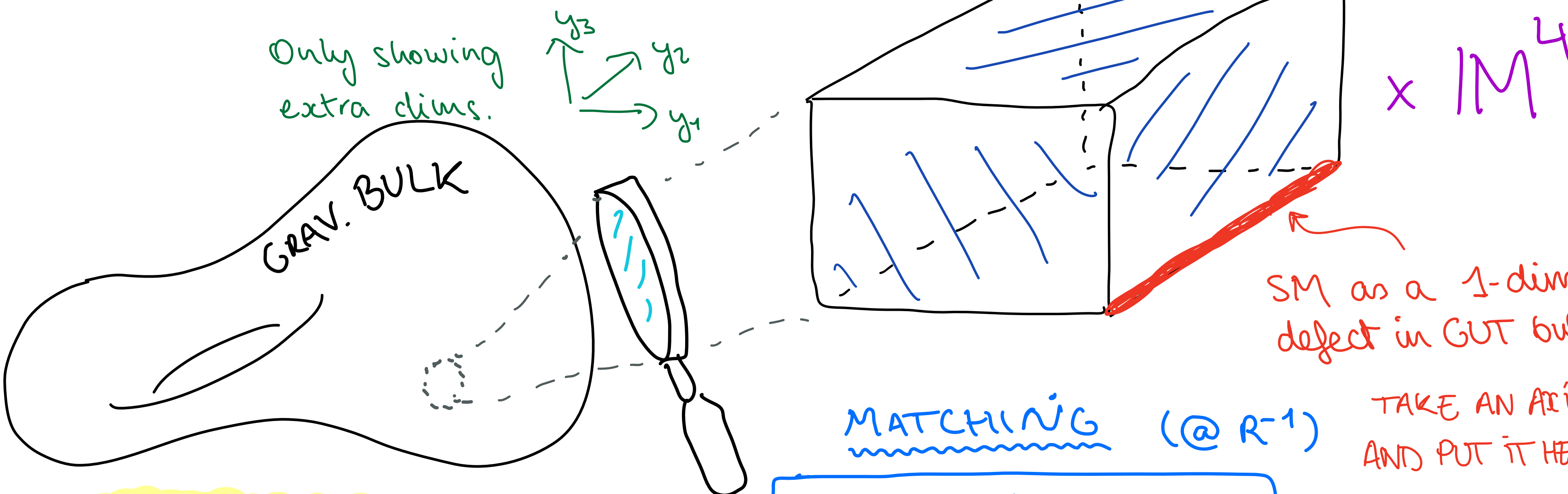
EXAMPLE: $S_1/\mathbb{Z}_2 \times \mathbb{Z}_2'$ orbifold

[See: AH, JMR 0106166]

TOY MODEL OF "APPARENT UNIFICATION"

- General GUT-symmetric bulk with SM-like defect

[see: 0212134 for a review]



TAKE AN AXION AND PUT IT HERE?

MATCHING (@ R^{-1})

APPARENT UNIFICATION

$$\frac{1}{\alpha^{\text{bulk}}_{\text{GUT}}} \gg \frac{1}{\alpha^{\text{loc}}_{i}}$$

$$\boxed{\frac{1}{\alpha^{4D}_{i}} = \frac{1}{\alpha^{\text{bulk}}_{\text{GUT}}} + \frac{1}{\alpha^{\text{loc.}}_{i}}}$$

4D EFFECTIVE COUPLING

↳ localized axion: $a_{\text{loc.}} F_{em} \tilde{F}_{em}$
(ALP)

MINIMAL ALP MASS...

In some sense is the usual "PQ quality problem" applied to ALPs.

MINIMAL ALP POTENTIAL

$$V(a) \sim T\!\!\!\!\Lambda \times R^{-4}\, e^{-S_{D(p-1)}} \cos(\theta^i)$$

CHIRAL SUPPRESSION?

- Zero modes saturated by m_{SUSY} insertions
- Charged chiral matter highly constrained! (e.g. Z decays, Higgs properties...)

D-instanton action

$$\boxed{S_{D(p-1)} \sim 2\pi / \alpha_i}$$

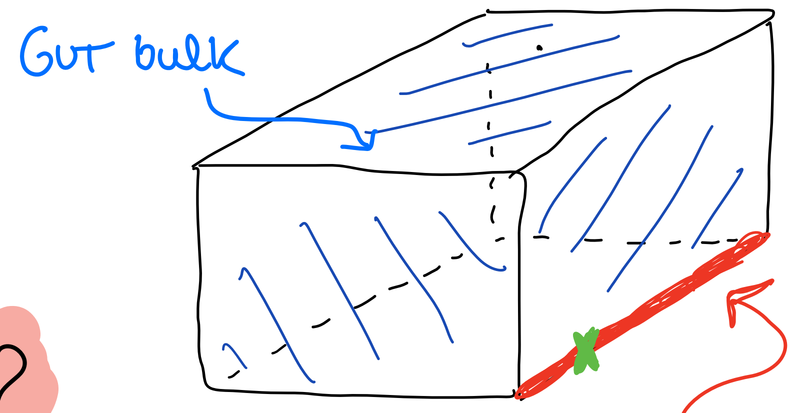
- Dominates $V(a)$
- axion massless ($m_a \ll H_0$) if $\alpha_i \lesssim 1/45$

Although $\exists$ minimum mass, it may well be orders of magnitude below H_0.

AN APPLICATION: APPARENT UNIFICATION

MATCHING $(@\, R^{-1})$

$$\boxed{\frac{1}{\alpha_i^{4D}} = \frac{1}{\alpha^{bulk}_{GUT}} + \frac{1}{\alpha_i^{loc.}}}$$



localized axion coupled to photons $\frac{a_i}{F_{a_i}} F_i \tilde{F}_i$?

Example: SM as a 1-dim defect in GUT bulk

KEEP PREDICTIONS

* Gauge coupling unification $\alpha^{bulk} \sim 1/25$
* $\sin^2\theta_W$ prediction.

needs

$$\boxed{\frac{1}{\alpha^{bulk}} \gg \frac{1}{\alpha_i^{loc}}}$$

implies

LARGE MASS FOR LOCALISED AXIONS !!

LOCALISED D-INSTANTON ACTION

$S_D \sim \mathcal{O}(1)$!

$$V(\theta^i_{loc}) \sim K R^{-4} e^{-2\pi/\alpha_i^{loc}} \cos(\theta^i)$$

KINETICALLY MIXED AXIONS?

$$K_{ij}\frac{\partial a_i \partial a_j}{2} + \hat{a}\, G\tilde{G}_{GUT}$$

Axion kinetic mixing matrix

linear combination coupled to GUT

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

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

$[EF\tilde{F} + NG\tilde{G} \ldots]$

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

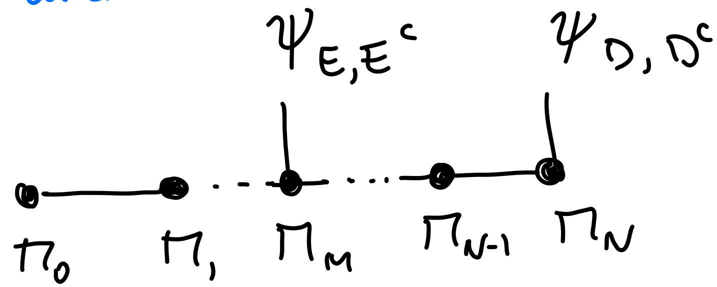
SINGLE AXION COUPLED TO PHOTONS: QCD AXION!

Clockwork axions

[1611.09855]

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

*



* coupling to photons gets exp. enhancement

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

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

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

↳ 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 }

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

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

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 $\alpha_5 = \alpha_X$ →
- Standard GUT prediction
- All couplings meet @ GUT scale
- Embeddable in simple group

SO(10), E6, ...

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

axion coupled to dark sector

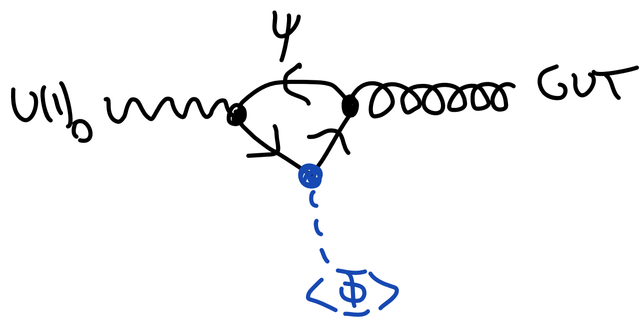
QCD axion

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

* 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!

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

CHARGE QUANTISATION IN GUTS

(see Polchinski ST vol. 2)

↳ Define $Q' = Q_{em} + \frac{T_{color}}{3}$ ⇝ accounts for triality

* Isolated states have $T_{color} = 0 \mod 3$

↳ All particles in 5-plet of SU(5) have integer Q'.

↳ All SU(5) reps. are obtained by tensor prod. of 5-plet.

↳ $Q' =$ integer $\longrightarrow$ $Q_{em} =$ integer for isolated states, too!