TESTING THE FAR UV WITH LOW-E AXION EXPERIMENTS*

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

based on: 2206.07053 + 2410.03820

IBS-IFT WORKSHOP 2024

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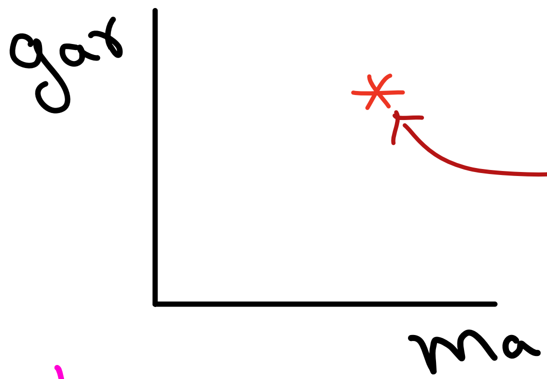
WHY TOPOLOGICAL COUPLINGS?

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



Imagine we find this tomorrow!

Dark matter? Strong CP?

THIS TALK!

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

$$a \to a + 2\pi f_a$$

* **Interactions** shaped by shift-symmetry:

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

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

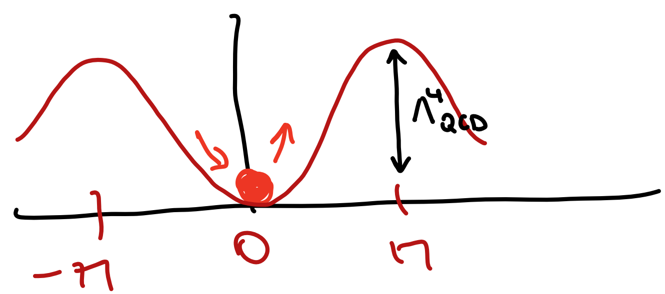
Ex: QCD AXION

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

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

RELIC ABUNDANCE

$$\Omega_a h^2 \simeq 0.1 \left(\frac{F_a}{10^{12}\,\text{GeV}}\right)^{7/6} \theta_i^2$$



WHY AXIONS - MOTIVATION

- 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

$$\mathcal{L}_a = \frac{(\partial a)^2}{2} + \mathcal{A} \frac{a}{F_a} \frac{\alpha_{EM}}{8\pi} F\tilde{F}$$

⤳ e.g. field strength of EM.

$\mathcal{A}$ → QUANTISATION:

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

TOPOLOGICAL COUPLINGS TO GAUGE BOSONS

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

$$\mathcal{A}_{UV} = \mathcal{A}_{IR}$$

→ directly probing the far UV!

* "$\mathcal{A}$" unaffected by RGE but "f_a" depending on scale $\equiv$ α_{EM} "running" but e^- charge being "quantised"

IDEA:

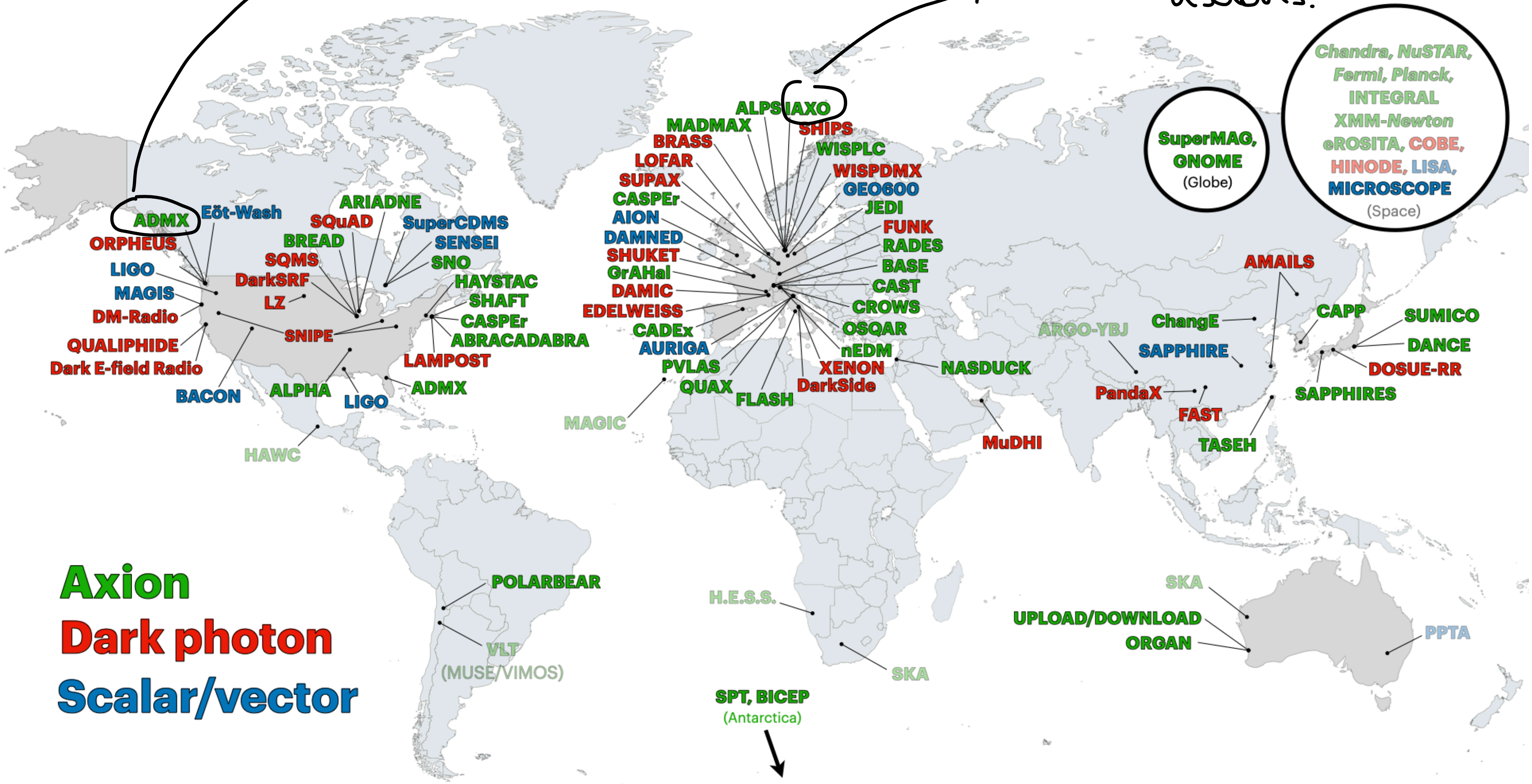
The axion-photon coupling is the BEST motivated channel to learn about UV physics otherwise INACCESSIBLE!

THE AXION-EXP LANDSCAPE

[see talk by Sung Woo]

Haloscope: resonant cavity looking for axion DM

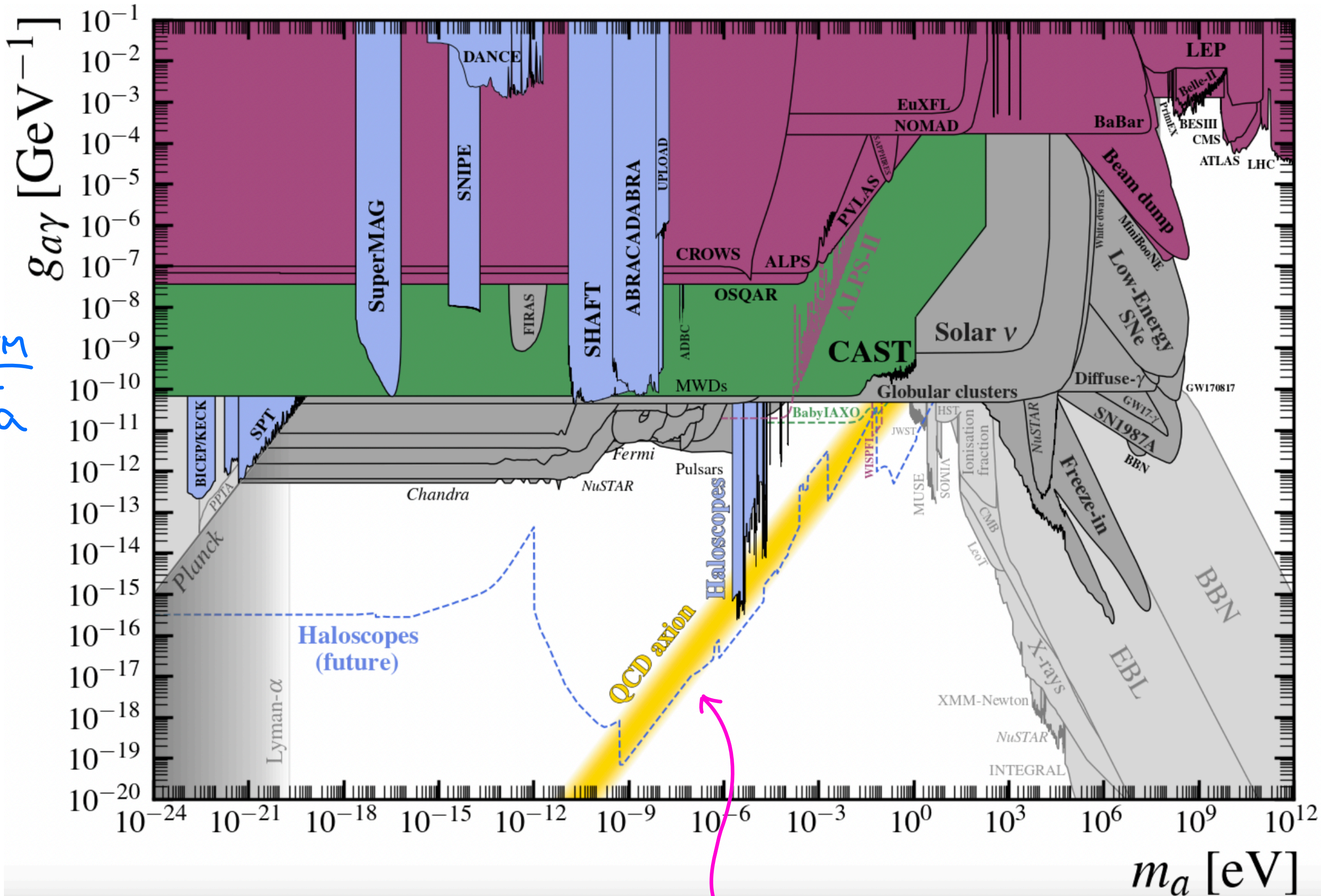
Helioscope: searches for solar axions.



THE AXION-PHOTON LANDSCAPE

many ongoing & planned searches: lab., astro., cosmo.

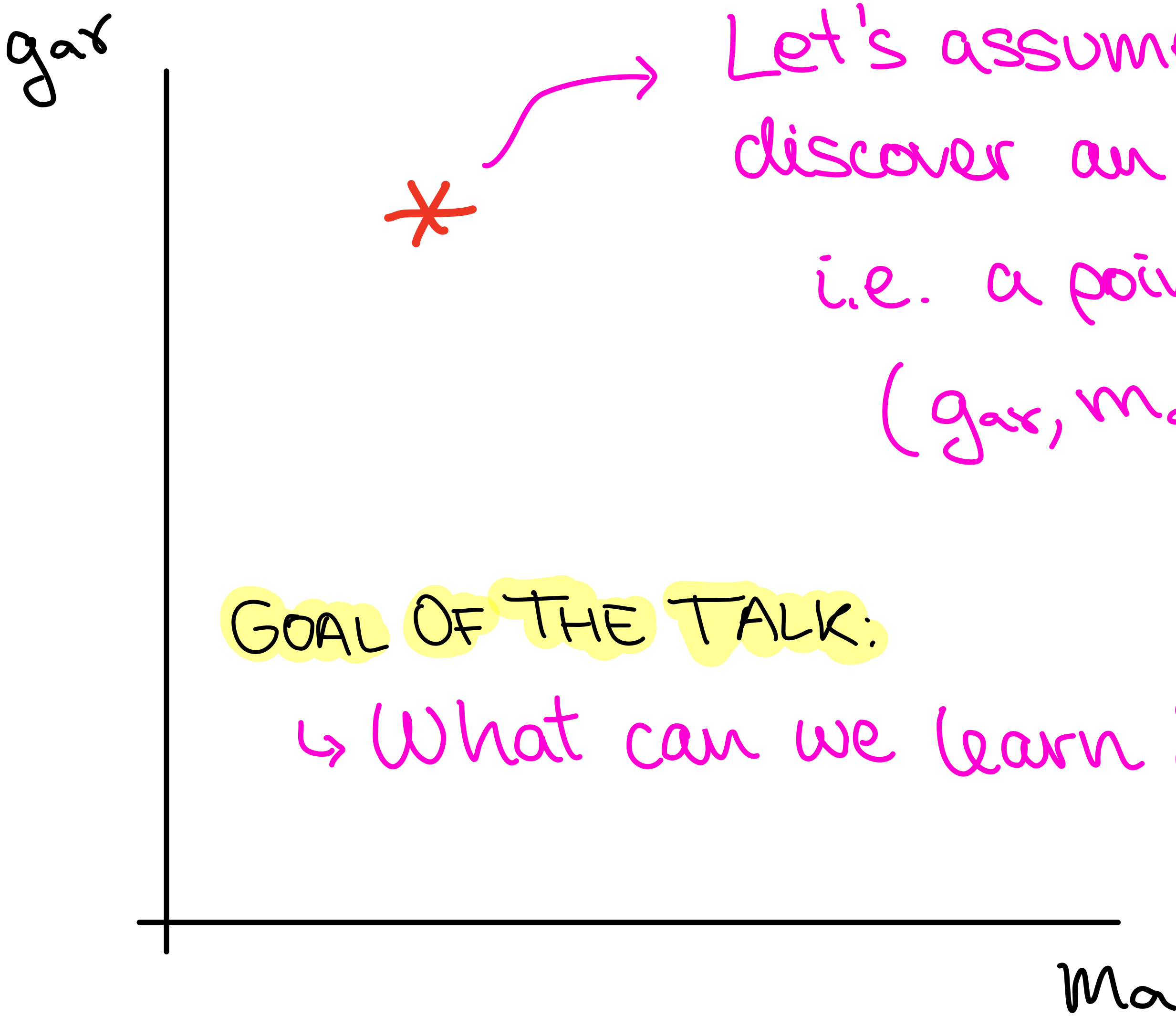
$g_{a\gamma} \sim \mathcal{A}\, \frac{\alpha_{EM}}{F_a}$



Ciaran O'Hare, AxionLimits

$\frac{g_{a\gamma}}{m_a} \sim \frac{\alpha_{EM}}{f_\pi m_\pi}$; QCD AXION PREDICTION

LET ME BE OPTIMISTIC!



Let's assume we discover an axion i.e. a point $(g_{a\gamma}, m_a)$

GOAL OF THE TALK:

↳ What can we learn?

APPLICATION 1

Is the SM unified in the UV ?

UNIFIED THEORY

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

$SU(3)$: quantum chromodyn.

$SU(2) \times U(1)$: electroweak interaction

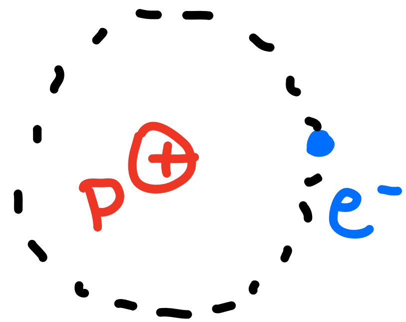
Examples $SU(5)$, $SO(10)$, ⋮

"All SM generators come from non-abelian simple gauge group"

HINTS FOR UNIFICATION

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

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



Why is the H atom neutral?

* Anomaly freedom:

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

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

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

$g' = \sqrt{\frac{3}{5}}\, g_1$ ⟶

Axions as Probes of Unification

[see: Agrawal, Nee, MR: 2206.07053]

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

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

Axions in GUTs studied since 80s
[Wise, Georgi, Glashow, '81; Nilles, Raby; '82]

- 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

[See: 2206.07053]

TOPOLOGY + GAUGE INVARIANCE ↗

$$\mathcal{L}^{IR} = \frac{a}{f_a}\left[\alpha_{em} E F\tilde{F}_{em} + \alpha_s N G\tilde{G}_{QCD}\right]$$

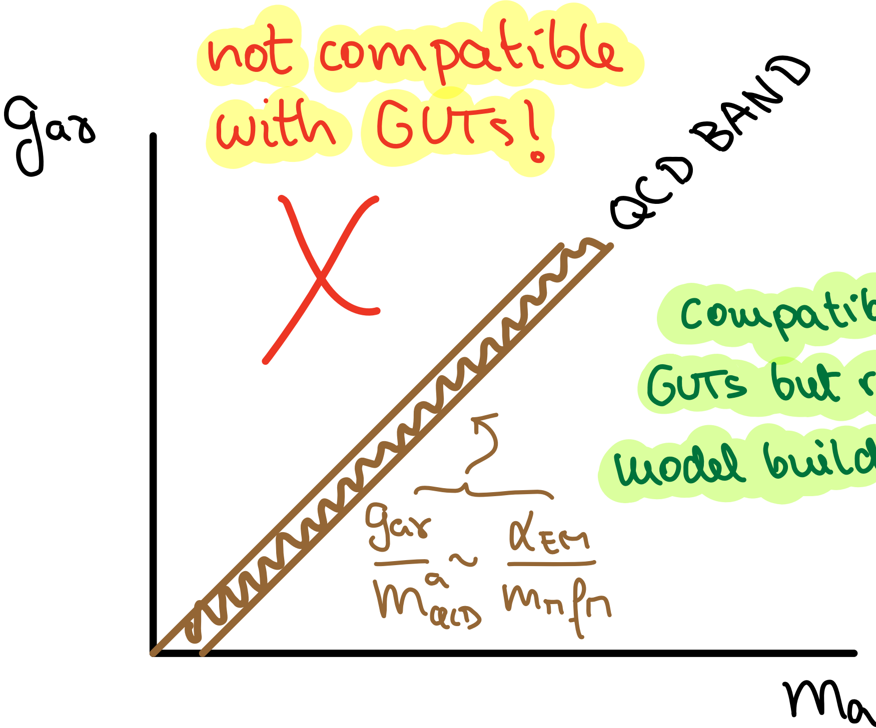
anomaly coeff. (→ E, N)

unavoidable QCD potential (→ $G\tilde{G}_{QCD}$)

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

Single axion coupled to photons:

QCD axion (indep. of f_a) ✓



compatible with GUTs but requires model building! →

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

RESULT:

$$\frac{g^{ALP}_{a\gamma}}{m_{ALP}} < \frac{g^{QCD}_a}{m^a_{QCD}} = \frac{\alpha_{em}}{m_\pi f_\pi}$$

APPLICATION 2

WHAT CAN AXIONS SAY ABOUT STRING THEORY ? (or at least some of them)

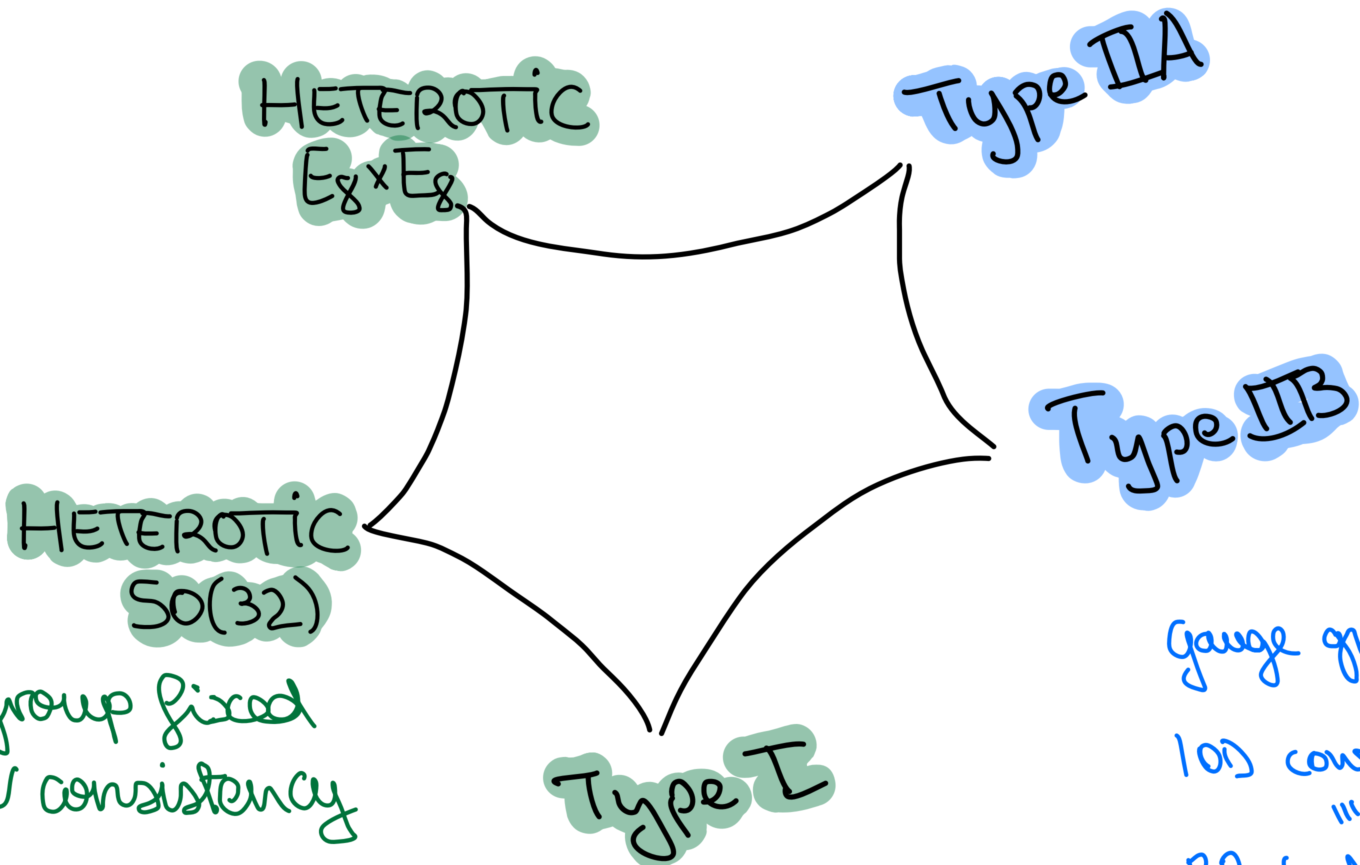
see: 2410.03820 w/ P. Agrawal & M. Nee

DIFFERENT STRING THEORIES

↳ Best understood framework unifying: GR + particle physics

↳ Allows understanding of some BH properties (e.g. entropy)

↳ Different ST related by network of dualities!



theories of intersecting branes!

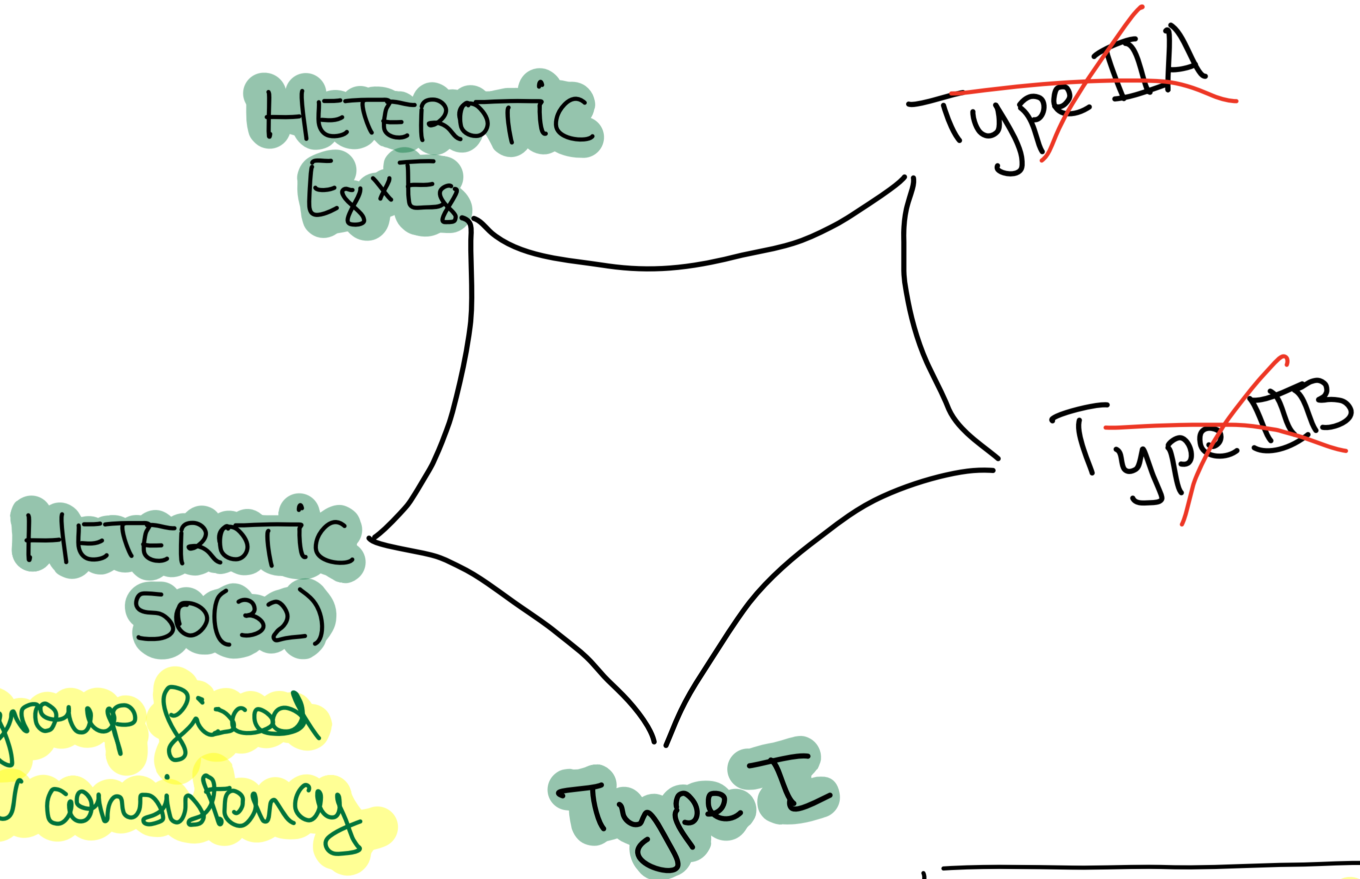
Gauge group fixed by UV consistency

Gauge group may change

10D consistency
≡
RR tadpole cancellation

DIFFERENT STRING THEORIES

↳ I will restrict myself to Heterotic strings...



Not today...

Gauge group fixed by UV consistency

↔ 1 to 1 relation with axion couplings

→ **Well defined predictions for axion-photon coupling!**

STRINGY AXIONS: KNOWN RESULTS...

[Many papers since Witten; Choi and Kim; et al in 80s]

* Multiple sources of axions in ST: B_2, 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

  STRING AXIVERSE! [Arvanitaki et al., '09]

* Exponentially good PQ (moduli stabilisation might spoil this) CAVEAT! [Conlon, 0602233]

  ↳ Nicely explained by higher-form symmetries!

* Fa tends to be large! Observability? Overabundance?

See however: [Im et al. 1906.11851; Choi et al. 1104.3274; and many others...]

[Gendler et al, 2309.13145] "axiverse statistics"

WHAT'S NEW HERE?

i) UV consistency fixes UV gauge group in some ST

ii) Axion couplings are topological in ST: fixed at 10D level!

TAKE 10D AXION COUPLINGS ⇝ MATCH TO 4D EFT @ R^{-1} ⇝ OBTAIN 4D EFT @ low-E ! ADMX, or similar experiment

(compactify 6D space) (match couplings from R^{-1} to TR)

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

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

HETEROTIC STRINGS

* CY and toroidal orbifold compactif.

* Theory of closed (super)strings in 10D*

metric + moduli

* Massless states: { – g_{MN}, B_{MN}, ϕ ← dilaton
– A_M^{ij}

Gauge boson + gauginos

"charged" matter

Source of axions!

EFFECTIVE ACTION: S_{10} = 10D N=1 SUGRA

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

Crucial for axions!

↳ e.g. $B \wedge trF^2 \wedge trF^2$

↳ $\int_{X_6} \{\dots\} \rightarrow$ $a G\tilde{G}$

Focus on

AXION COUPLING IN 4d!

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HETEROTIC STRINGS

"Problem"? UV simplicity vs IR complexity

$E_8 \times E_8$ in 10d (I won't consider SO(32), but results apply)

↳ compactifying on Calabi-Yau or toroidal orbifold (compact spaces with different topological properties)

+

(discrete) Wilson lines

⇒ MANY 4D EFT become available!

Examples: SU(5), SO(10), E_6, trinification, etc...

CONNECTING FAR UV TO IR

Energy scale

$$S_{10} = \int d^{10}x\, e^{-\phi}\left[\sqrt{-g}R + (d\phi)^2 - |H|^2 - \mathrm{tr}|F|^2\right]$$

$+ S_{GS}$ → important for anomaly cancellation

Fully fledged ST

M_P

10D SUGRA
$E_8 \times E_8$

Axions offer pristine window into UV physics!

4D EFT @ R^{-1}

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

↳ chiral fermions depend on topology of compact space...

Independent of intermediate scale physics!

LHC

EWSB

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

Axion Experiment

STRINGY AXIONS:

HOW DO THEY LOOK LIKE?

?

AXIONS IN HETEROTIC STRINGS

[see Svrcek, Witten for a review]

↳ B_2: 2-index antisym. tensor ↳ $B_6 \equiv$ 10d dual of B_2

$$B_2 \to B_2 + d\Lambda_1$$

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

6-form integrated over 6d space → 0-form in 4d EFT

$X_6 \equiv$ 6d compact space

* Model-dependent axions (b_i): zero modes of B_2 wrapping 2-cycles (W_i) (MD) $b_i = \int_{W_i} B_2$

※ and decay const depends on compact space

* Field theoretic axions: $\phi = \bar{\phi} e^{i c(x)}$ → complex phase

↳ Relevant in scenarios with anomalous U(1). Do not add new ingredients wrt MI, MD.

After dim. reduction...

4d AXION COUPLINGS

* MI axion couplings (a): $\mathcal{L}^{4d}_{MI} = a/f_a \left(\mathrm{tr}_1 F^2 + \mathrm{tr}_2 F^2 \right)$ universally coupled to gauge bosons

$\mathrm{tr}_1 F^2 = \sum_i \mathrm{tr}\, F_i^2$ ← unbroken 4d gauge groups from 1st E_8

* MD axion couplings (b_i): $\mathcal{L}^{4d}_{MD} = \sum k_i^{(1)} b_i \,\mathrm{tr}_1 F^2 + \sum k_i^{(2)} b_i \,\mathrm{tr}_2 F^2$

↑ depend on compact space ↑ CALCULABLE!

[see Choi, Kim in '80s]

CRUCIAL POINT: Only 2 linear comb. θ_1, θ_2 !

MOST GENERAL AXION COUPLINGS

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

EMBEDDING THE SM IN $E_8 \times E_8$

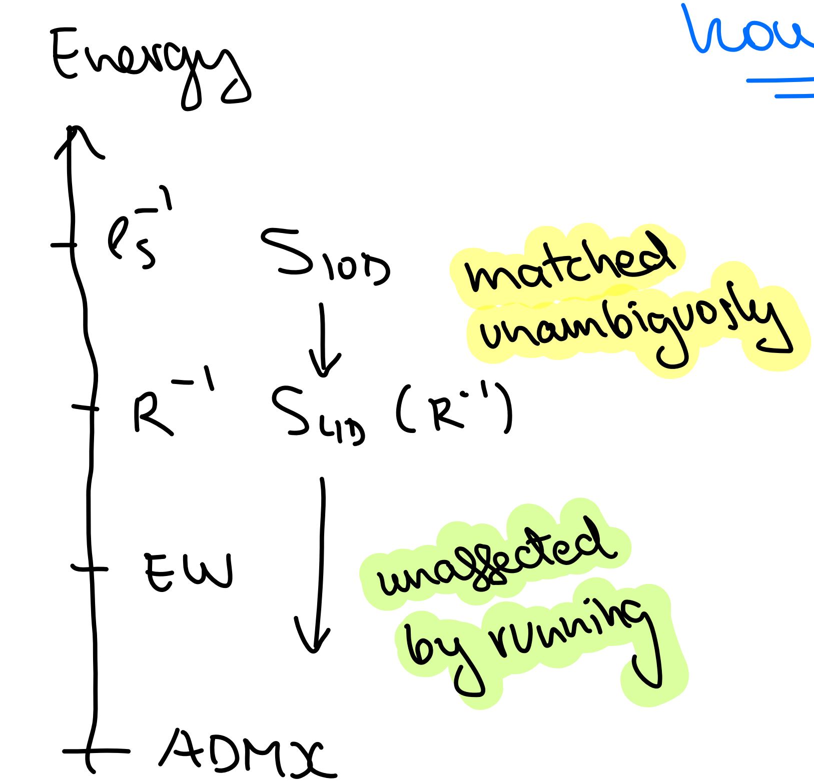
@ R^{-1}:

$$\mathcal{L}_{4D} \supset \underbrace{\int_{M_4} \theta_1 \, \mathrm{tr}_1 F^2 + \int_{M_4} \theta_2 \, \mathrm{tr}_2 F^2}_{\text{axion couplings at low-E only depend on how we embed the SM!}}$$

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

E.g.

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



ONLY 2 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 IN $E_8 \times E_8$

$$\mathcal{L}_{4D} \supset \int_{M_4} \theta_1 \, tr_1 F^2 + \int_{M_4} \theta_2 \, tr_2 F^2$$

The same result holds for SO(32)

$\theta_2 \, tr_2 F^2$ → Hidden sector

$$tr_1 F^2 = \{QCD + EW + Hypercharge\}$$

"VISIBLE AXION"

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

- a ← Model independent axion
- $k_i^{(1)}$ ← value of $k_i^{(1)}$ depends on compact space
- b_i ← model dependent axions

Energy

- ℓ_s^{-1}: S_{10D} — matched unambiguosly
- ↓
- R^{-1}: $S_{4D}(R^{-1})$
- ↓ unaffected by running
- EW
- ADMX

SM EMBEDDING IN A SINGLE E_8

* 4D EFT → @ R^{-1} scale:

SM from first E_8

$$\mathcal{L} = \frac{\theta_1}{8\pi}\left(\alpha_1 B\tilde{B} + \alpha_2 W\tilde{W} + \alpha_3 G\tilde{G}\right) + \frac{\theta_2}{8\pi} H\tilde{H} + \sum_{\text{world-sheet}} V(b_i)$$

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

axions other than those in θ_1, only couple through mixing!

* 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:

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

SM EMBEDDING IN A SINGLE E_8

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

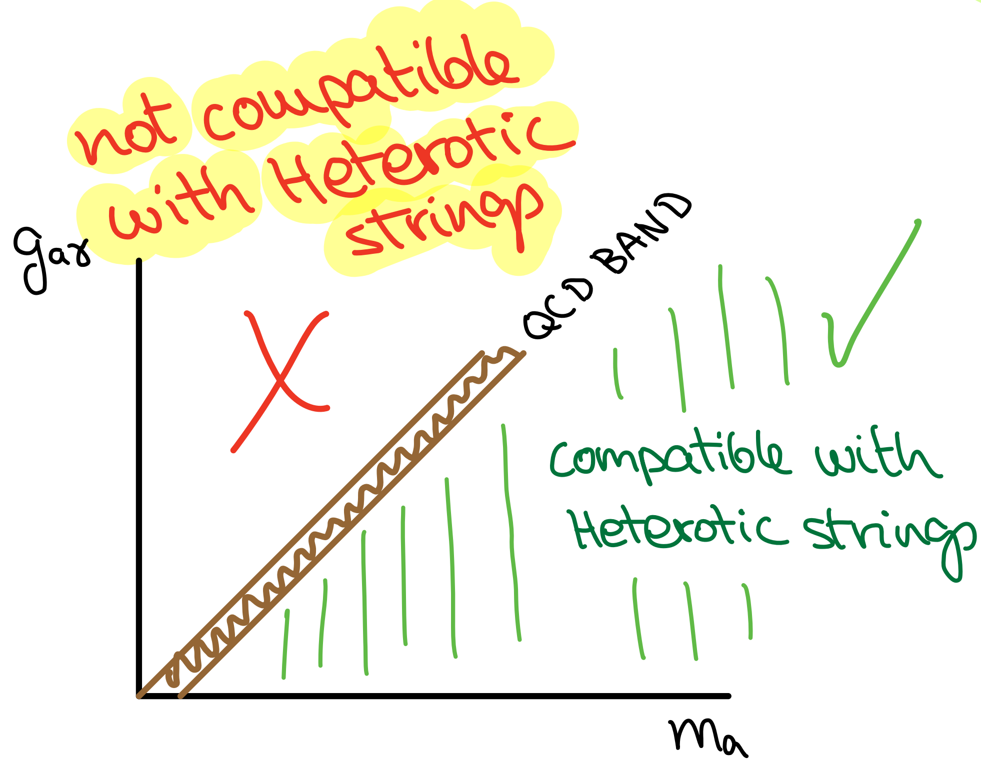
For example:

↳ Cosmic birefringence

$m_a \sim 10^{-30}$ eV, $f_a \sim 10^{18}$ GeV

↳ Ultralight axions coupled to photons

$m_a \sim 10^{-20}$ eV, $f_a \sim 10^{16}$ GeV



Rule out Heterotic Strings !

INDEPENDENT OF THE DECAY CONSTANT!

(Embedding into a single E_8)

NON-STANDARD SM EMBEDDING

See orbifold papers:

* Font et al. '90
* Ibañez et al. '87

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

QCD → $\mathrm{tr}_1 F^2$; (part of) EM → $\mathrm{tr}_2 F^2$

θ_1 → ~ QCD axion

θ_2 → ~ ALP

* Take: $E_8 \times E_8$

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

$$\downarrow$$

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

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

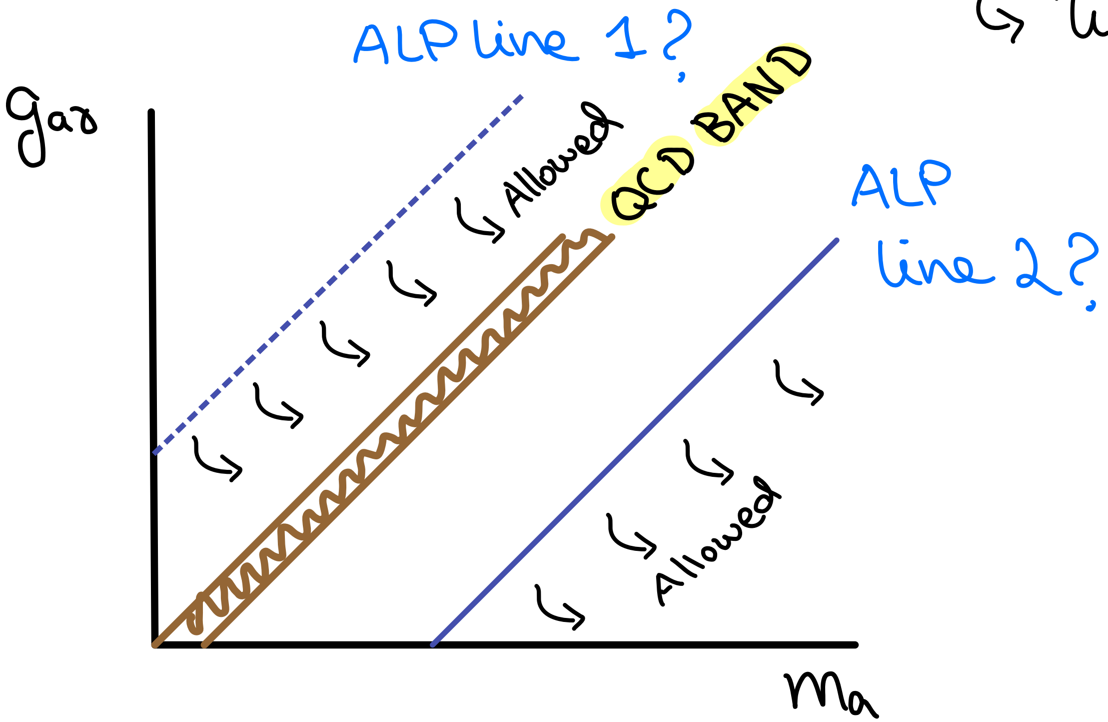
No known "realistic" model with non-standard embedding?!

$$V(\theta_1) \simeq -\Lambda_{QCD}^4 \cos\theta_1$$

$$V(\theta_2) \simeq -\Lambda_{ALP}^4 \cos\theta_2$$

→ Λ_{ALP} vs Λ_{QCD} ?

WHAT'S THE "COST" OF THE ALP?



↳ "line" means: $\frac{g_{ALP}}{m_{ALP}} \sim \frac{\alpha_{EM}}{\Lambda^2_{ALP}}$

* ALP line 1 or 2?

Λ_{QCD} vs Λ_{ALP}

↳ Model dependent question!

* Irreducible axion potential

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

MODEL INDEPENDENT IMPLICATIONS

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

Standard GUT

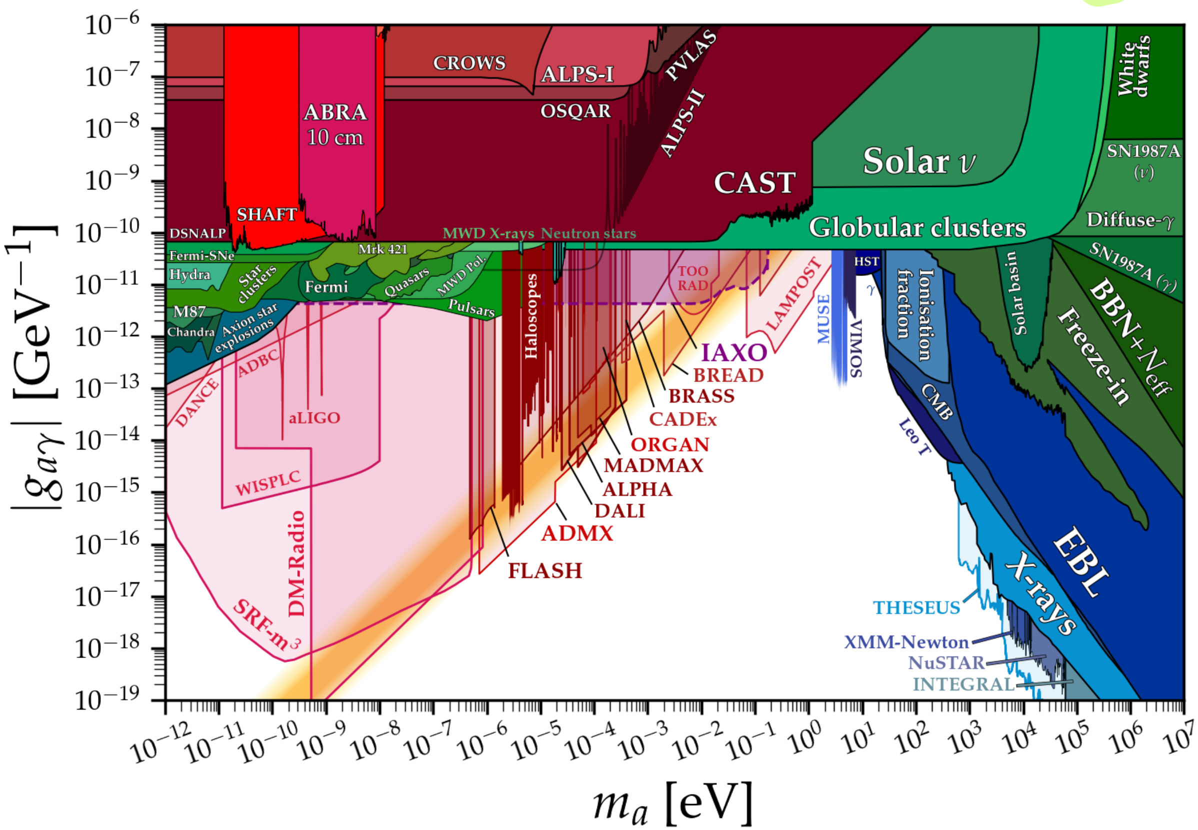
$s^2\theta_W = 3/8$

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, ... others?

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

AXIONS AS PROBES OF UNIFICATION

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

simple gauge group (e.g. SU(5), SO(10)...) → G_{GUT}

Set of commuting, global unbroken symmetries → $\prod_i U(1)_{PQ\,i}$

↳ Analogy with SM: $U(1)_B$ 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:

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

non anom. $\prod_i \tilde{U}(1)_i$ ← exact or decoupled Goldstone bosons, $\mathcal{A} = 0$

$U(1)_{PQ}$ ← ONLY ONE AXION COUPLED THROUGH THE ANOMALY!

Important!!

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

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

4D GUT: ONE AXION COUPLED TO GAUGE BOSONS

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

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: $\mathcal{A}^{UV} = \mathcal{A}^{IR}$

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}

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

→ 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!

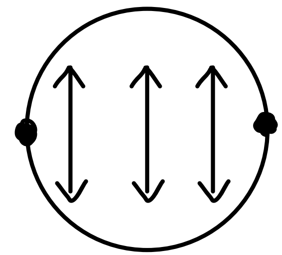
AXIONS FROM HIGHER-D GAUGE FIELDS

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

"1-form gauge field" → ↪ $B_M = (B_\mu, B_5)$

↪ Compactify: $S_1/\mathbb{Z}_2$: { - gluons: $A_\mu^{a\,(0)}$; - pseudo-scalar: $B_5^{(0)}$ }

$S_1/\mathbb{Z}_2$



REMARKS:

i) Chern-Simons couplings $\int K_{cs}\, \epsilon^{MNPQR} B_M G_{NP} G_{QR} \rightarrow$ $B_5^{(0)} G\tilde{G}$ in 4D

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

ii) Particle worldline Non-local potential

$$e^{i\theta} = e^{i\int B_5\, dx_5} \rightsquigarrow V(B_5) = R^{-4} e^{-S} \cos(B_5^{(0)} R)$$

$$S = 2\pi M R$$

~ UV instanton in 4d

AXIONS IN HETEROTIC STRINGS

[see Svrcek, Witten for a review]

SHIFT SYMMETRY BREAKING EFFECTS: [see also Choi 9706171]

* Instantons in $E_8 \times E_8$: additional confining interactions in 4d

* Worldsheet instantons: euclidean closed string worldsheet wrapping 2-cycles

* NS5-branes: non-pert. states (5+1)d, coupled magnetically to B_2

  Can be deformed into UV YM instantons

↳ Only e^{-S} effects, GOOD QUALITY AXIONS!

GREEN-SCHWARZ ANOMALY CANCELLATION

* N=1 10d SUPERGRAVITY ACTION

Ricci scalar — dilaton — Field strength of B_2 — YM

$$S_{10} = \frac{1}{2\kappa_{10}^2}\int e^{-2\phi}\left[d^{10}x\sqrt{-g}R + 4\,d\phi\wedge * d\phi - \frac{l_s^4}{2}H\wedge * H - \frac{\alpha'}{4}F\wedge * F\right]$$

$$- \frac{1}{768\pi^3}\int B\wedge X_8 \,;$$

$\int B\wedge X_8$ → GREEN-SCHWARZ COUNTERTERM

NOTATION

$$\frac{\kappa_{10}^2}{g_{10}^2} = \frac{\alpha'}{4}$$

$$g_{YM}^2 = g_{10}^2 e^{2\phi}$$

The eight-form: X_8 (for $E_8\times E_8$)

$$X_8 = -\left(tr_1F^2 + tr_2F^2\right)trR_2^2 + 2\left[(tr_1F^2)^2 + (tr_1F^2)^2 - tr_1F^2\, tr_2F^2\right]$$

↳ Integrating $\int B\wedge X_8$ over compact space → 4d Axion COUPLINGS !

MATCHING AXION COUPLINGS

* Take 10d SUGRA action:

Green-Schwarz mech.

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

↳ Contains: $\mathrm{tr}_i F^2 \, \mathrm{tr}_j F^2, \ldots$

MI axion couplings

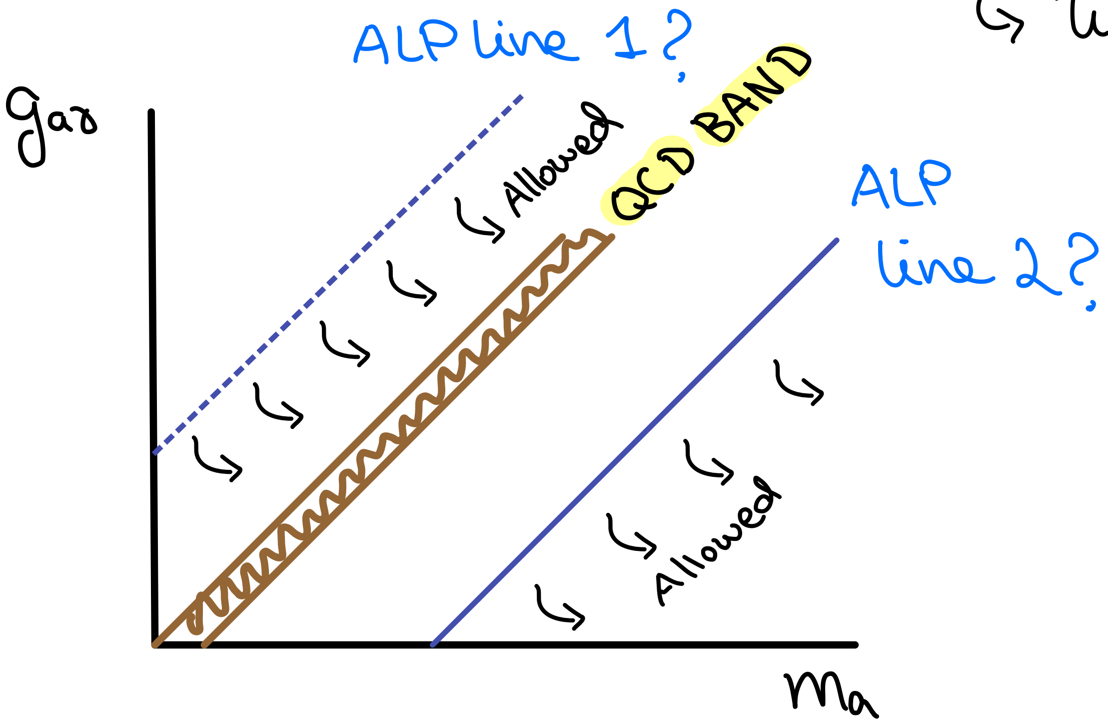
MD axion couplings

e.g. $K_i = \int B_2 \wedge \mathrm{tr}_i F^2 \rightarrow$ quantised

* Consistency of the 10d SUGRA gives couplings of B_2 and B_6 to gauge bosons.

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

WHAT'S THE "COST" OF THE ALP?



↳ "line" means: $\frac{g_{ALP}}{m_{ALP}} \sim \frac{\alpha_{EM}}{\Lambda^2_{ALP}}$

* ALP line 1 or 2?

Λ_{QCD} vs Λ_{ALP}

↳ Model dependent question!

* Irreducible axion potential

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

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!

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

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

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.

$$\int B\wedge X_8 = \sum_i K_1^i \int_{M_4} b_i \, tr_1 F^2 + \sum_i K_1^i \int_{M_4} b_i \, tr_2 F^2$$

$$K_1^{(i)} = \int_{\Sigma_6} \beta_i \wedge \left(-tr R^2 + 2 tr_1 F^2 - tr_2 F^2\right)$$

Field strength subject to topological constrain:

$$dH = -tr_1 F^2 - tr_2 F^2 + tr R^2 \longrightarrow [tr R^2] = [tr_1 F]^2 + [tr_2 F]^2$$

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

$z := \mu / m_\psi$

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

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

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

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}

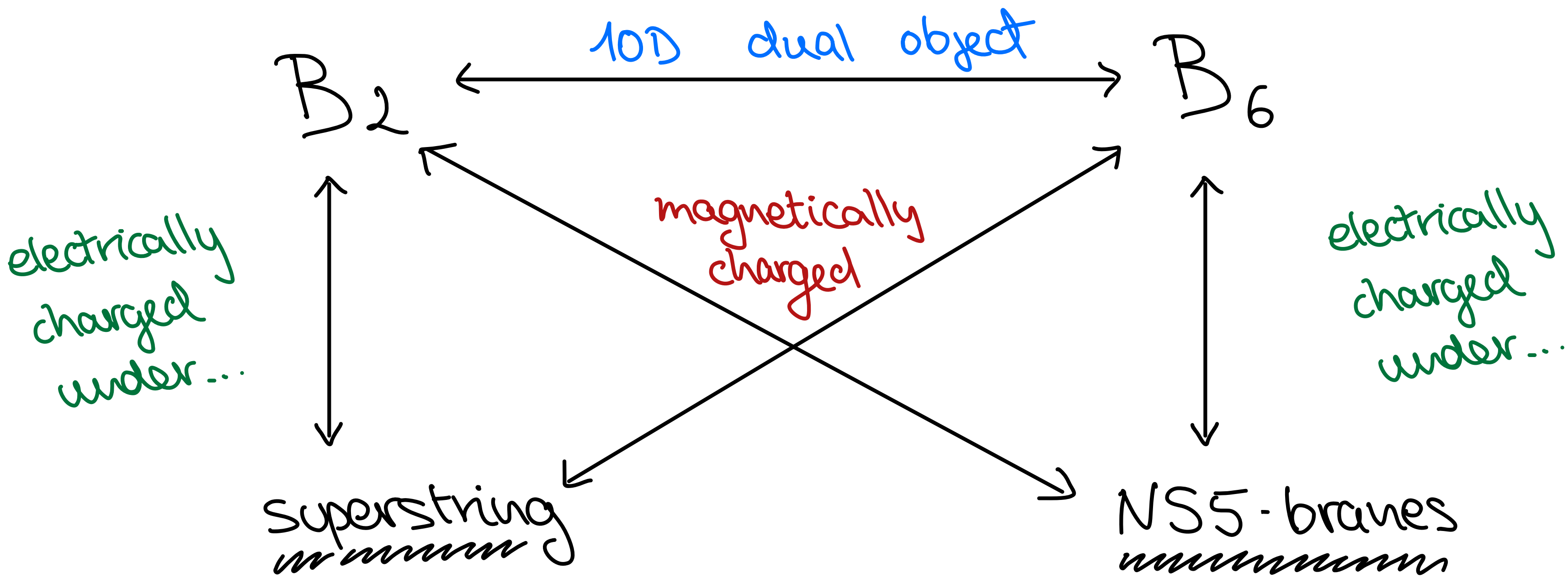
and magnetically charged under C_{p+1}.

Axions in Heterotic Strings

If time allows...

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

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

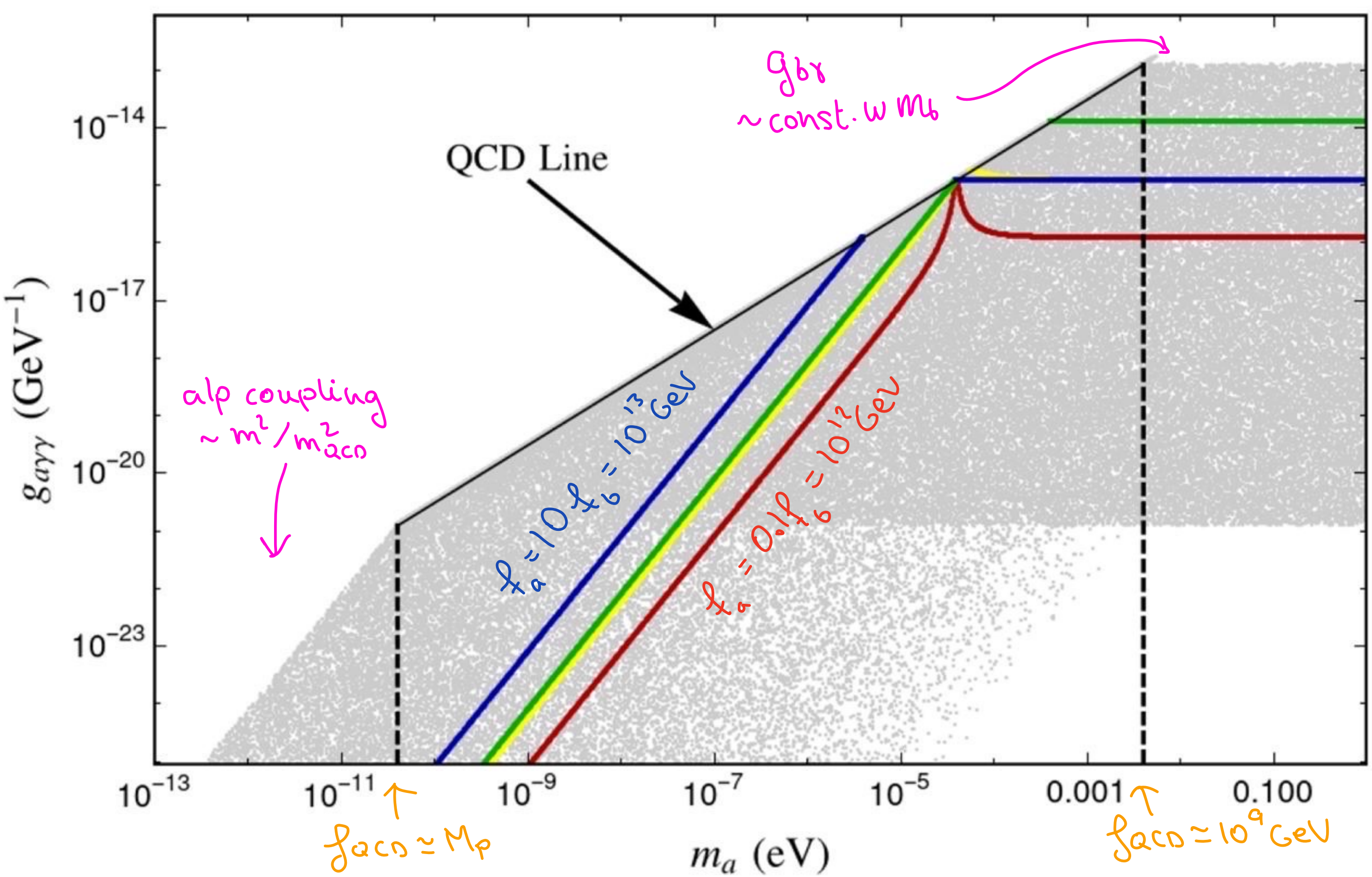


↳ 4D point of view, superstring ≡ axion string!

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

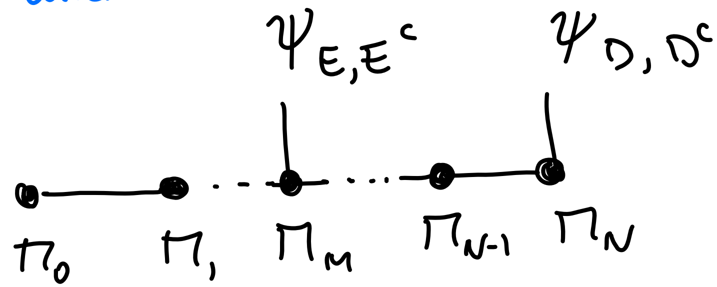
[Does not depend on number of axions]

Clockwork axions

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

[1611.09855]

*



↳ 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

$$\mathbb{Z}_N : SM_k \to SM_{k+1}$$
$$a \to a + \frac{2\pi k}{N} f_a$$

} N copies of SM

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

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

} Need: $N \sim 100$ copies of SM

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 $\sin^2\theta_W$!

} ← $\alpha_5 \neq \alpha_X$

↑ price to pay... :(

KINETICALLY MIXED PHOTONS ?

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

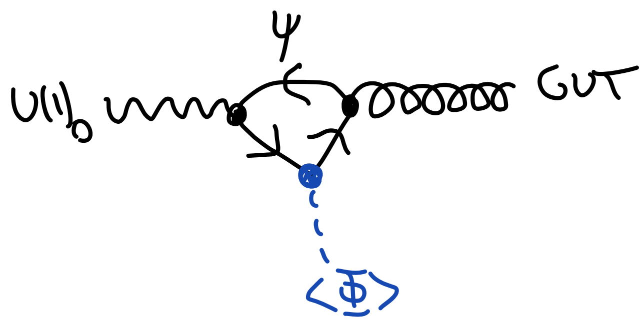
dark photon

QCD axion → $\alpha_{GUT} \frac{a}{f_a} G\tilde{G}_{GUT} + \frac{\alpha_D}{f_b} b_D F\tilde{F}_D$ ← axion coupled to dark sector

- 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!

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