TESTING THE FAR UV WITH LOW-E AXION EXPERIMENTS*

*: together with Prateek Agrawal (OXF), Michael Nee (Harvard)

based on: 2206.07053 + 2410.03820

COSMIC WISPERS WG1 MEETING

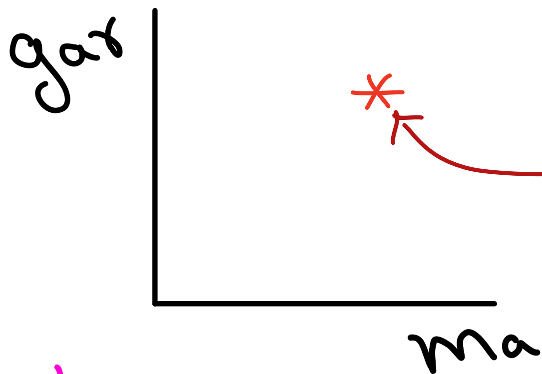
MARIO REIG

mario.reiglopez@physics.ox.ac.uk

UNIVERSITY OF OXFORD

WHY TOPOLOGICAL COUPLINGS ?

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



Imagine we find this tomorrow!

THIS TALK!

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

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

* **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 (?)

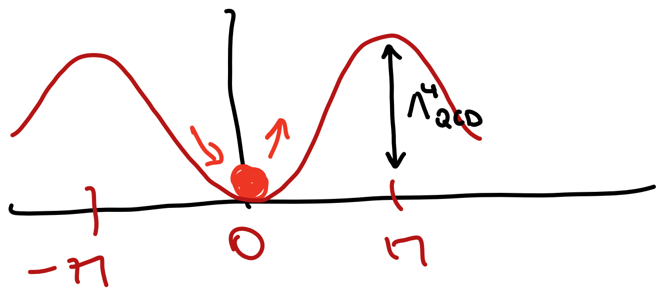
Ex: QCD AXION

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

* 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

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



WHY AXIONS - MOTIVATION

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

$$\mathcal{L}_a = \frac{(\partial a)^2}{2} + \mathcal{A} \frac{a}{F_a} \frac{\alpha_{EM}}{8\pi} F\tilde{F} \rightsquigarrow \text{e.g. field strength of EM.}$$

(Canonically normalised)

→ 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!

Axion as 0-form gauge field
F_a "depending" on scale but
$\mathcal{A}$ "unaffected" by RGE

≡ ANALOGY

Photon as 1-form gauge field
α_{EM} "running" but e^-
charge being "quantised"

IDEA:

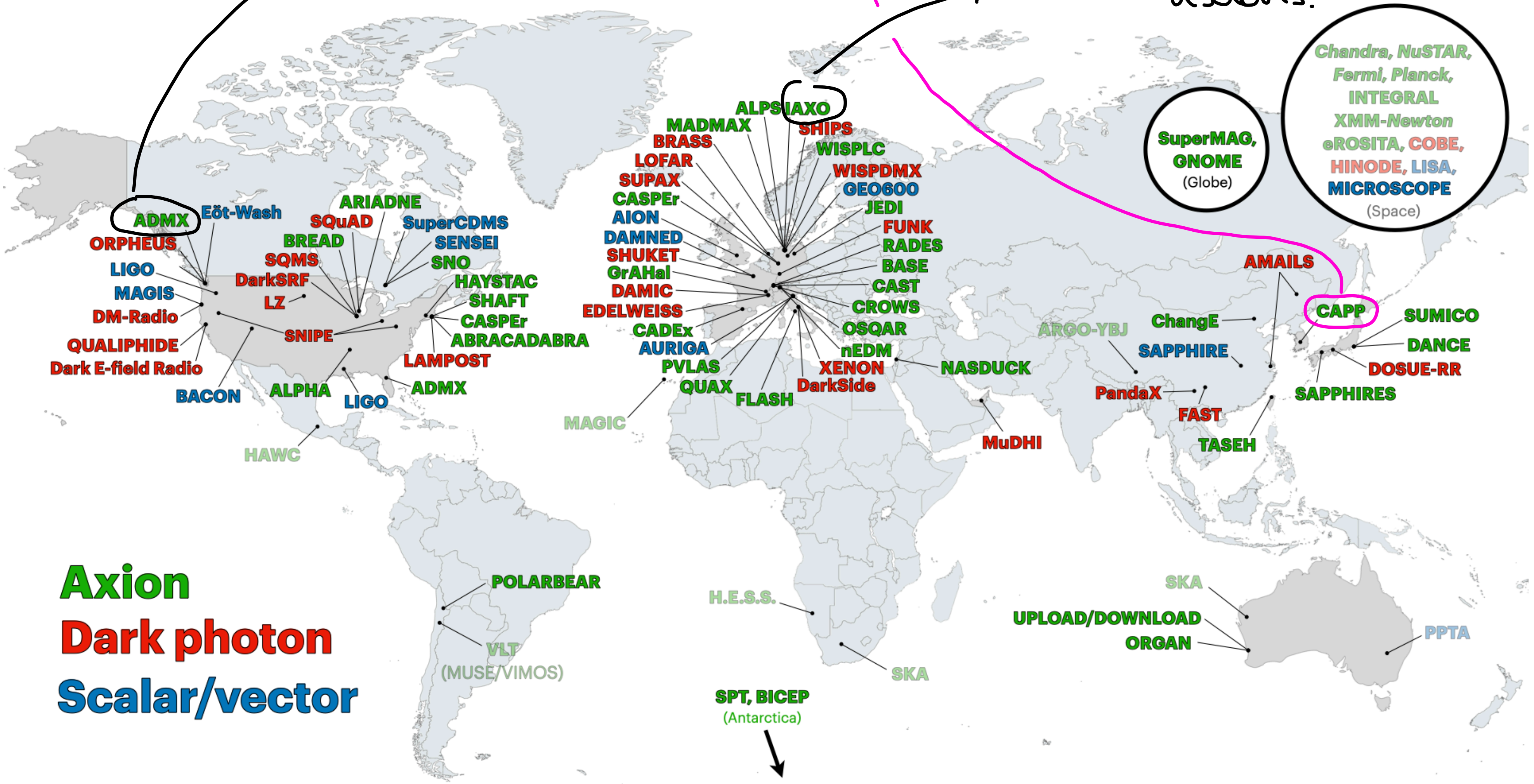
The axion-photon coupling is the BEST motivated channel to learn about UV physics otherwise INACCESSIBLE!

THE AXION-EXP LANDSCAPE

See WG4 !

Haloscope: resonant cavity looking for axion DM

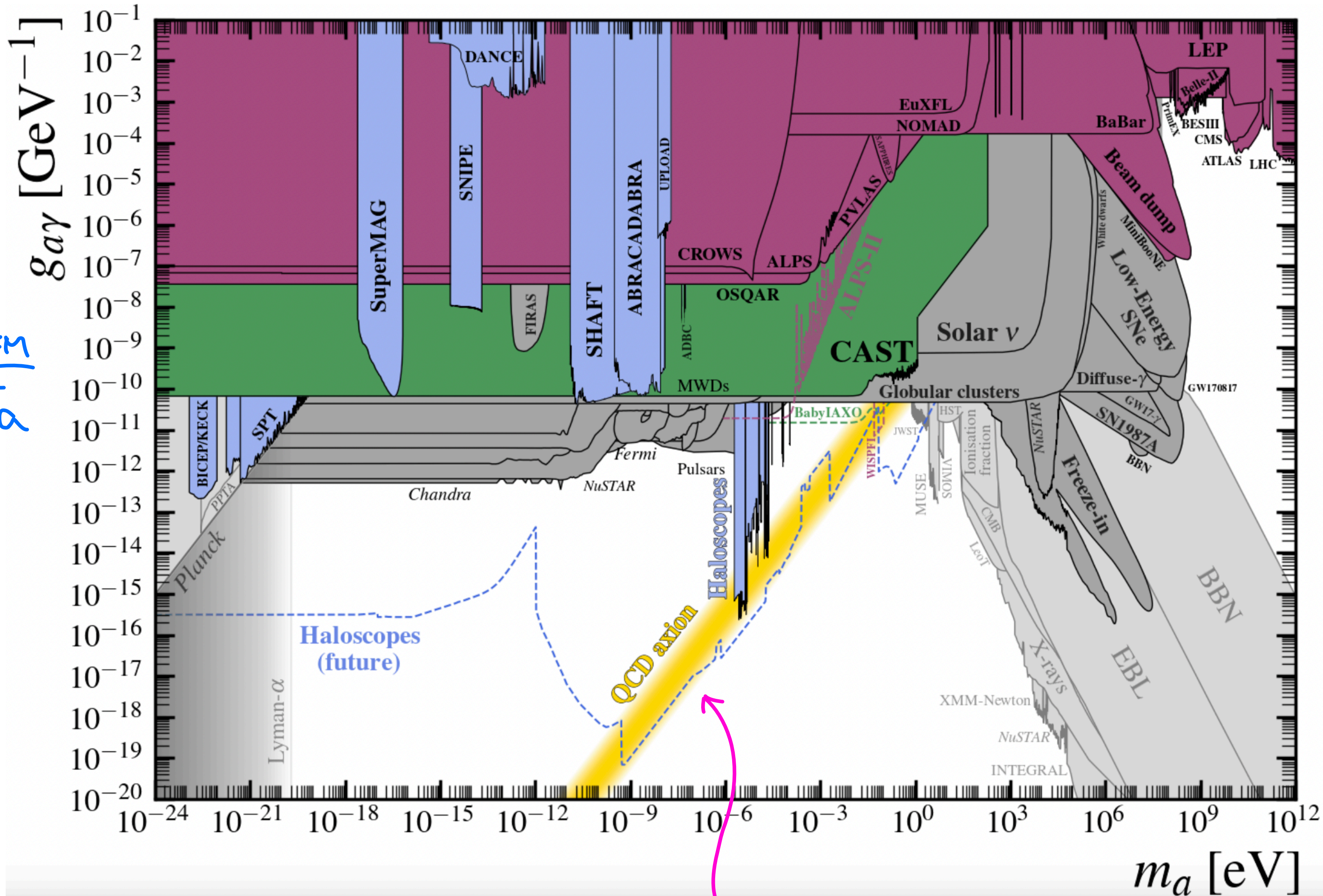
Helioscope: searches for solar axions.



THE AXION-PHOTON LANDSCAPE

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

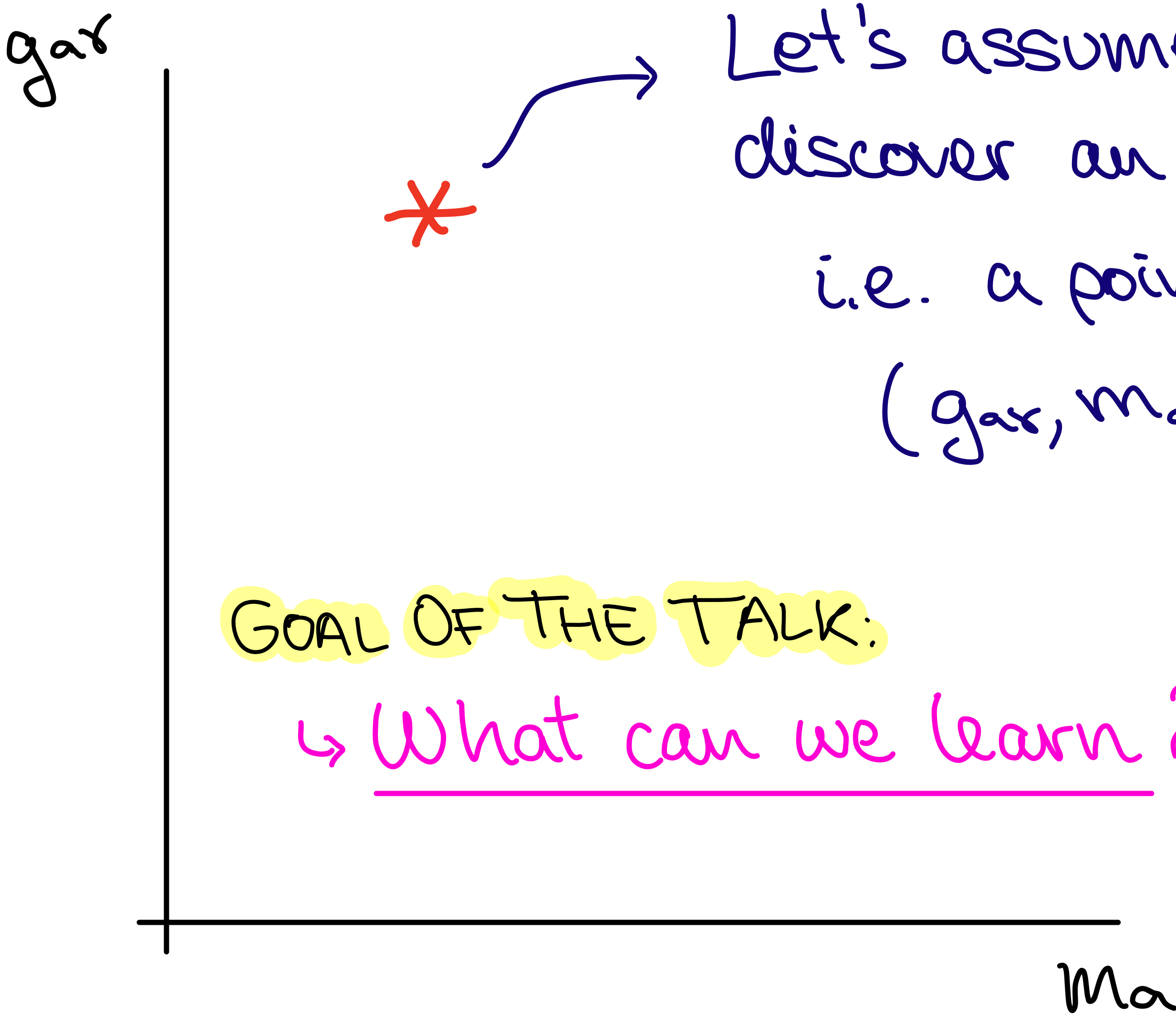
$g_{a\gamma} \sim \mathcal{A}\, \frac{\alpha_{EM}}{F_a}$



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

$$G_{GUT} \xrightarrow{SSB} \underbrace{SU(3)}_{\text{quantum chromodyn.}} \times \underbrace{SU(2) \times U(1)}_{\text{electroweak interaction}}$$

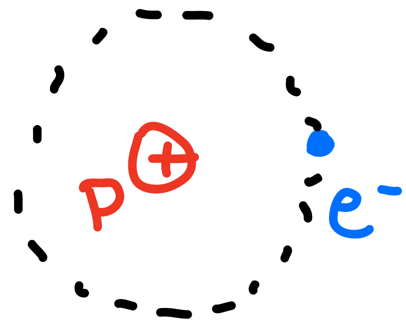
Examples $SU(5)$, $SO(10)$, E_6, ...

"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 cancellation:**

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]

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

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

  - G_{GUT}: simple gauge group, e.g. SU(5), SO(10)...
  - $\prod_i U(1)_{PQ\,i}$: Set of commuting, global unbroken symmetries

↳ Analogy with SM: $U(1)_B$ and $U(1)_L$ anomalous wrt $SU(2)_{weak}$ →
- $U(1)_{B-L}$ anomaly-free
- $U(1)_{B+L}$ ANOMALOUS!

applications for baryogenesis etc.

* After symmetry redefinition:

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

- $U(1)_{PQ}$: ONLY ONE AXION COUPLED THROUGH THE ANOMALY!
- $\tilde{U}(1)_i$: Decoupled Goldstone bosons, $\mathcal{A} = 0$

Important!!

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

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

Axions as Probes of Unification

[See: 2206.07053]

TOPOLOGY + GAUGE INVARIANCE →

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

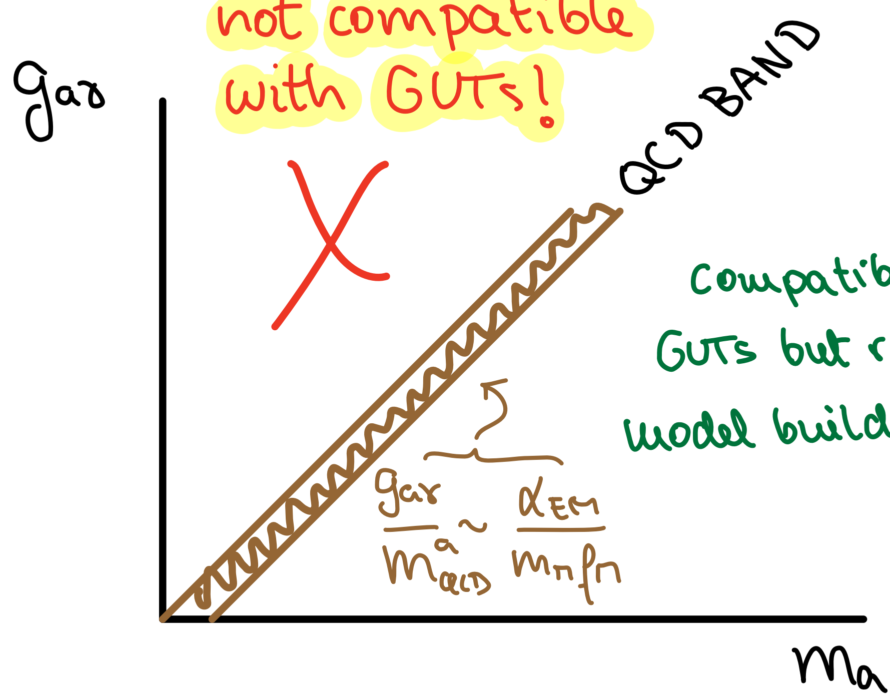
anomaly coeff. (E, N)

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

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

Single axion coupled to photons: QCD axion (indep. of f_a) ✓

not compatible with GUTs!



compatible with GUTs but requires model building! →

RESULT:

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

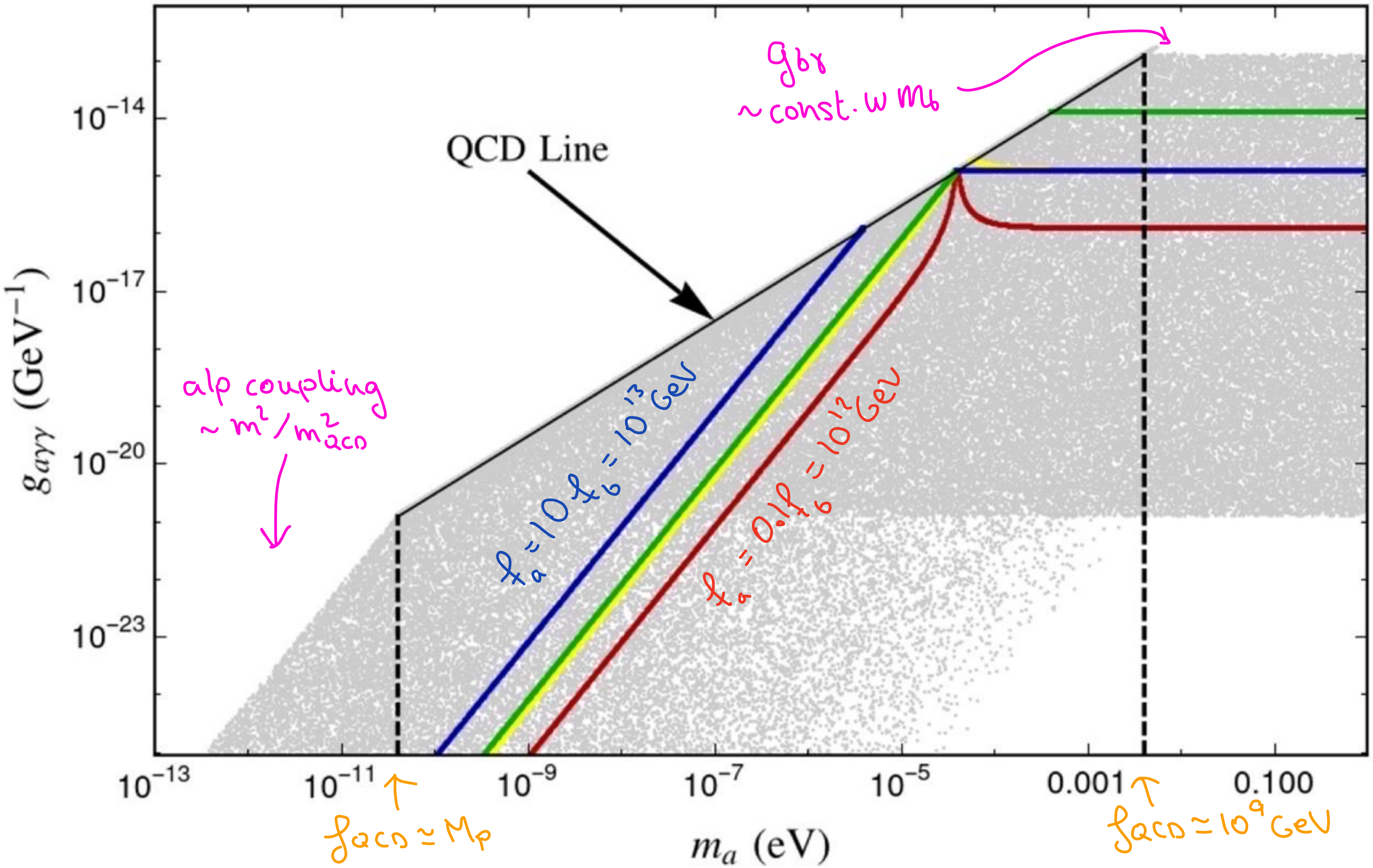
- axion mixing
- "charged axions" (pion-like fields)
- Clockwork
- Dark photon models
- Extra dim. GUTs..

ALP-photon coupling via mixing

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

behaviour depends on m_b / m_{QCD} !

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]

APPLICATION 2

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

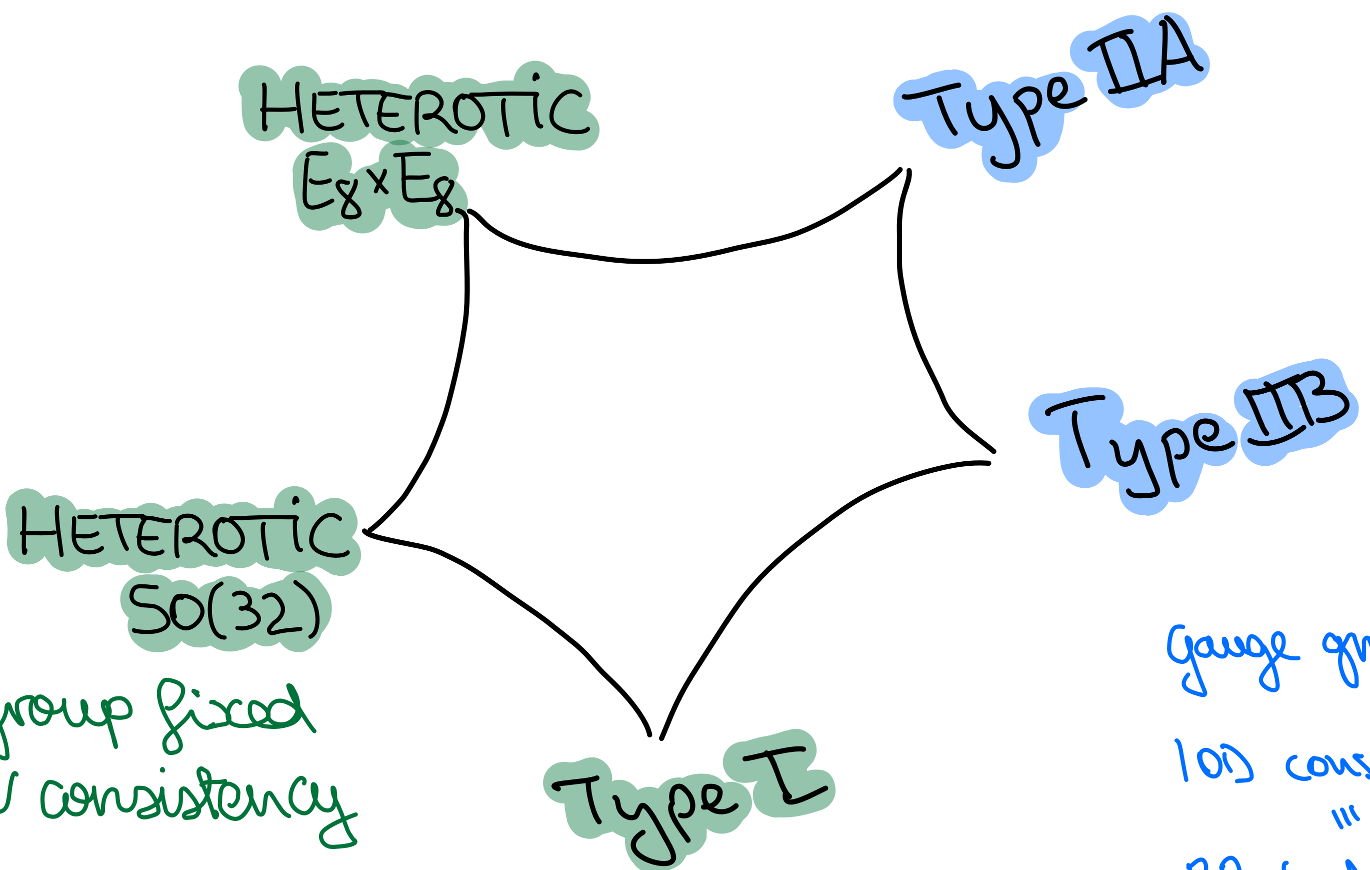
see: 2410.03820 w/ P. Agrawal & M. Nee

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!

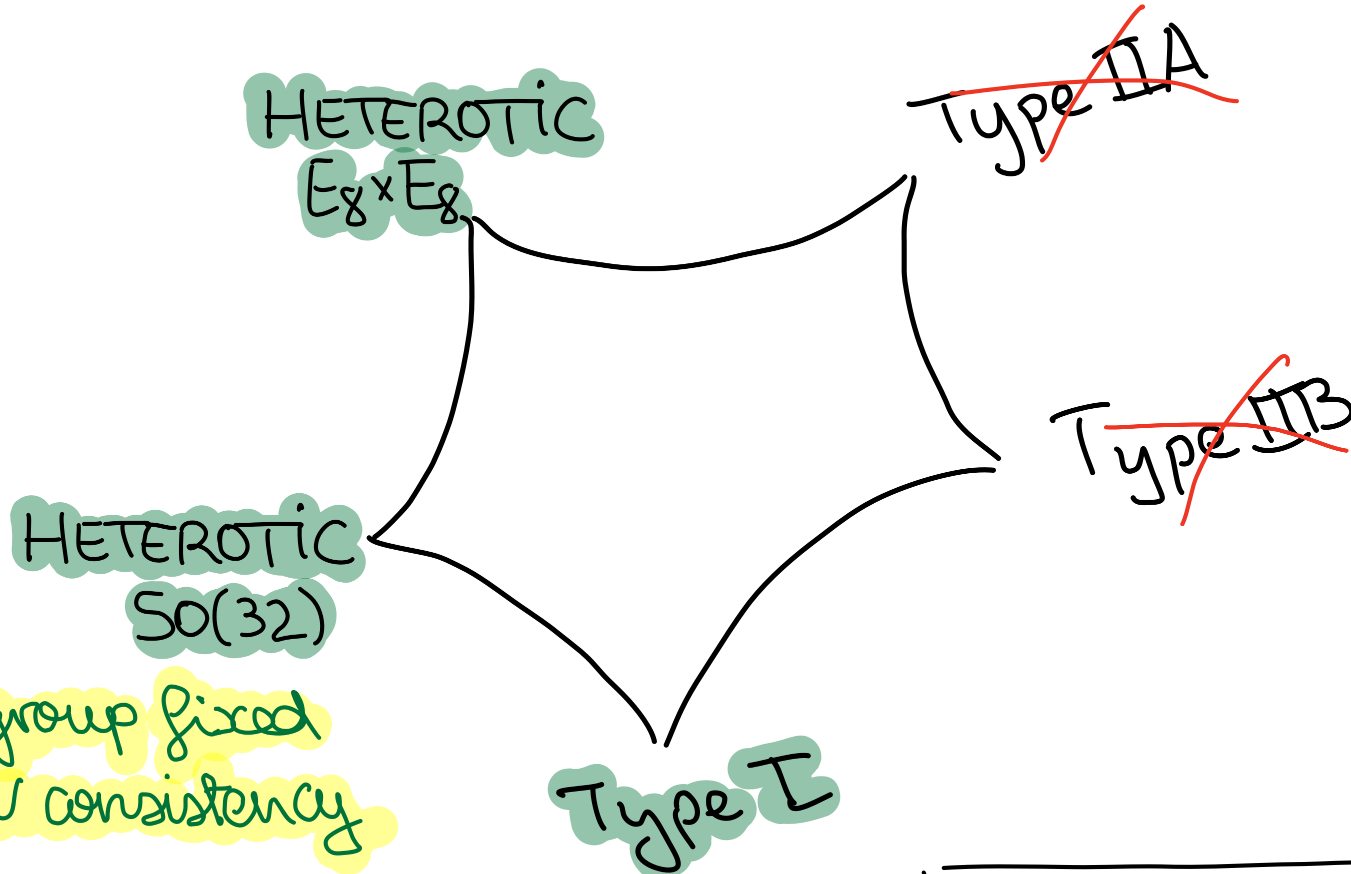
Gauge group fixed by UV consistency

Gauge group may change

10D consistency
⫴
RR tadpole cancellation

DIFFERENT STRING THEORIES

↳ I will restrict myself to Heterotic strings...



Not today... (work in progress)

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]

  CAVEAT! [Conlon, 0602233]

* Exponentially good PQ (moduli stabilisation might spoil this)

  ↳ Nicely explained by higher-form symmetries! [Brennan, Hong; 2306.00912]

* F_a tends to be large! Observability? Overabundance?

  [Gendler et al, 2309.13145]

  "axiverse statistics"

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

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 IR)

↳ 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 ↘ dilaton ↙

* Massless states: { – g_{MN}, B_{MN}, ϕ
  – A^{ij}_M

Gauge boson + gauginos ↗ ; "charged" matter ↑

B_{MN} → Source of axions!

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

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

Focus on ↑ ($E_8 \times E_8$)

Crucial for axions!

↳ e.g. $B \wedge trF^2 \wedge trF^2$

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

AXION COUPLING IN 4d!

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, SM, etc...

CONNECTING FAR UV TO IR

Energy scale

Fully fledged ST

M_P

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

Strategy: match mixed anomalies of GLOBAL higher-form symmetries to 4d axion anomalies!

Independent of intermediate scale physics!

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

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: $\phi = \bar{\phi} e^{ic(x)}$ → complex phase

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

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

(see Bianchi id. $dH = \mathrm{tr} F^2 - \mathrm{tr} R^2$)

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.

Alternative: match higher form anomalies

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

4d AXION COUPLINGS

After dim. reduction ...

* MI axion couplings : $\mathcal{L}^{4d}_{MI} = a/f_a \left(tr_1 F^2 + tr_2 F^2 \right)$ universally coupled to gauge bosons

$tr_1 F \wedge F \equiv tr_1 F^2 = \sum_i tr\, F_i^2$ ← unbroken 4d gauge groups from 1st E_8

* MD axion couplings : $\mathcal{L}^{4d}_{MD} = \sum k_i^{(1)} b_i\, tr_1 F^2 + \sum k_i^{(2)} b_i\, tr_2 F^2$
(b$_i$)

↑ depend on compact space ↑
CALCULABLE!

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

MOST GENERAL AXION COUPLINGS

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

EMBEDDING THE SM IN $E_8 \times E_8$

@ R^{-1} :

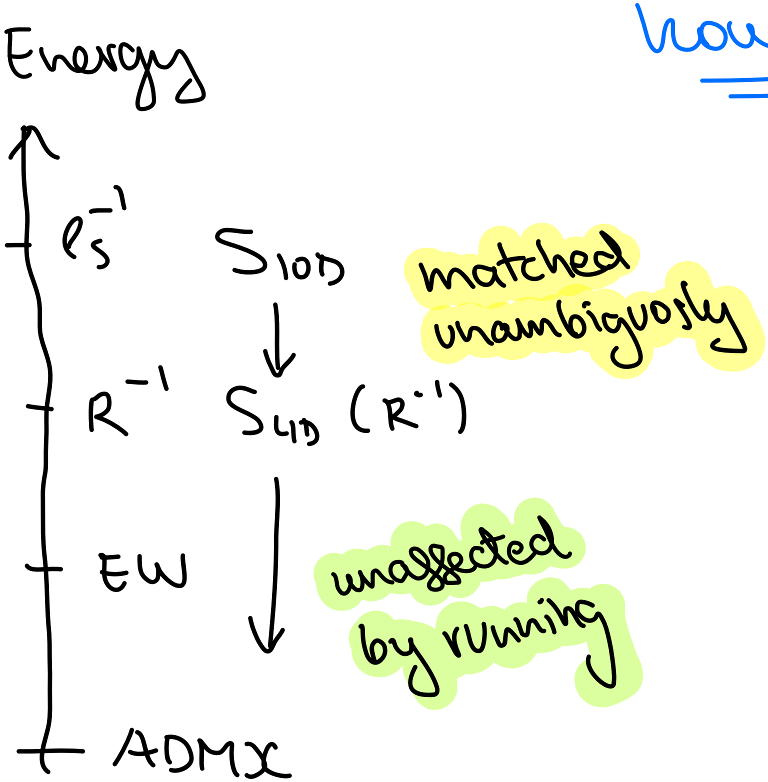
$$\mathcal{L}_{4D} \supset \int_{M_4} \theta_1 \, \mathrm{tr}_1 F^2 + \int_{M_4} \theta_2 \, \mathrm{tr}_2 F^2$$

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

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

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 $E_8 \times E_8$

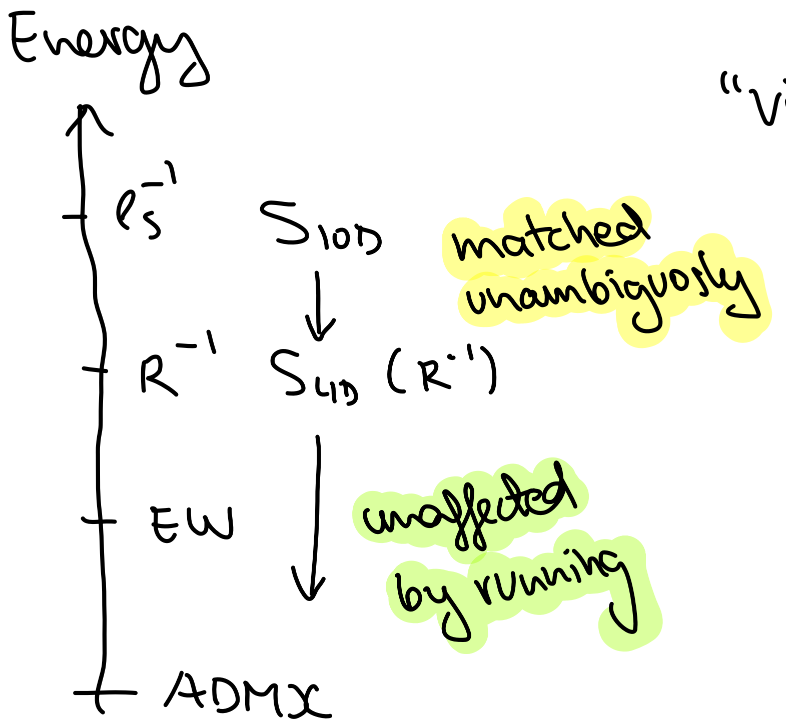
EMBEDDING THE SM IN $E_8 \times E_8$

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

The same result holds for SO(32)

Hidden sector

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



"VISIBLE AXION"

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

Model independent axion

model dependent axions

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

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:

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

SM EMBEDDING IN A SINGLE E_8

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

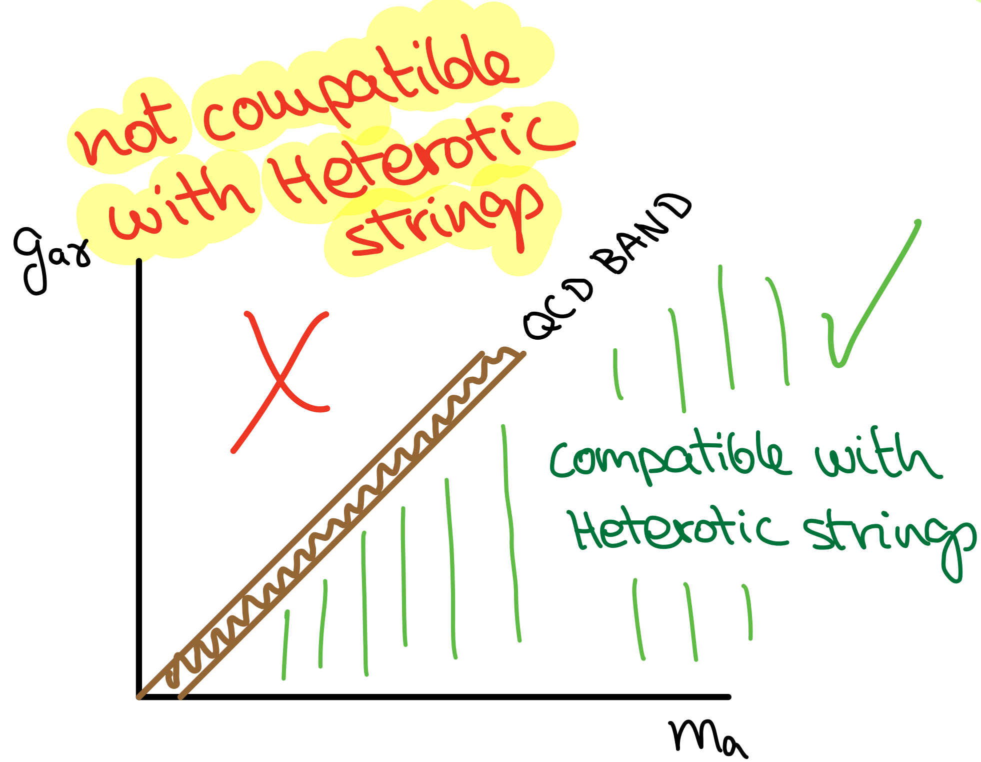
For example:

↳ 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 !!

(Embedding into a single E_8)

INDEPENDENT OF THE DECAY CONSTANT!

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 → θ_1 ↳ ~ QCD axion

(part of) EM → θ_2 ↳ ~ ALP

* Take: $E_8 \times E_8$

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

$$\downarrow$$

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

↳ Instantons generate ALP potential!

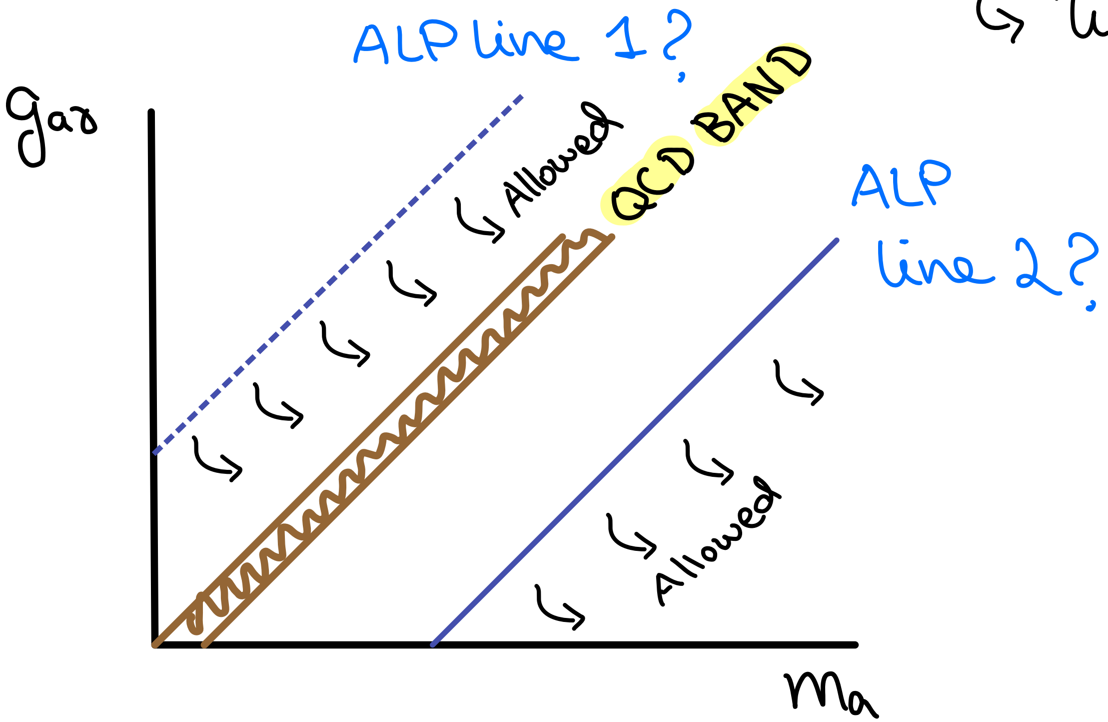
No known "realistic" model with non-standard embedding ?!

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

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

→ Λ_{ALP} vs Λ_{QCD} ?

WHAT'S THE "COST" OF THE ALP?



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

* 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

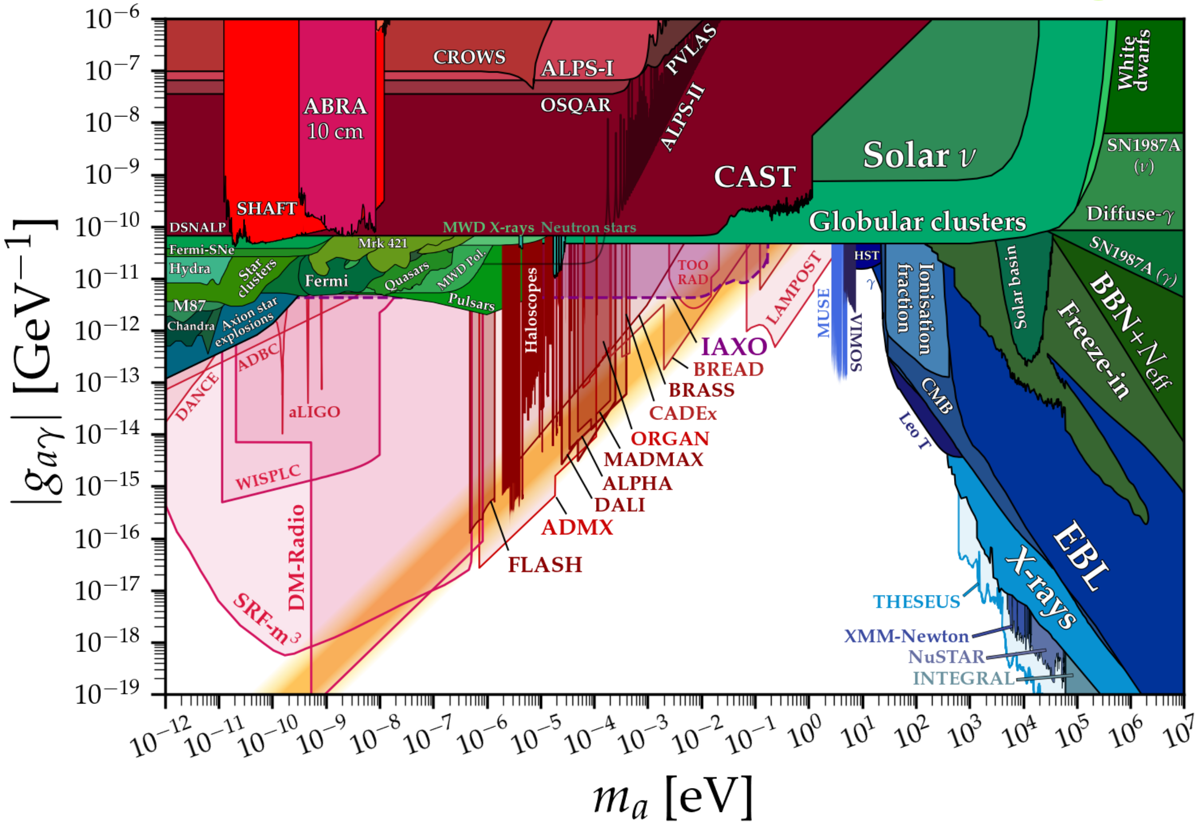
$s^2\theta_W = 3/8$

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