Axion Couplings as UV probes

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w/ Prateek Agrawal and Mario Reig

arxiv/2206.07053 + ongoing work

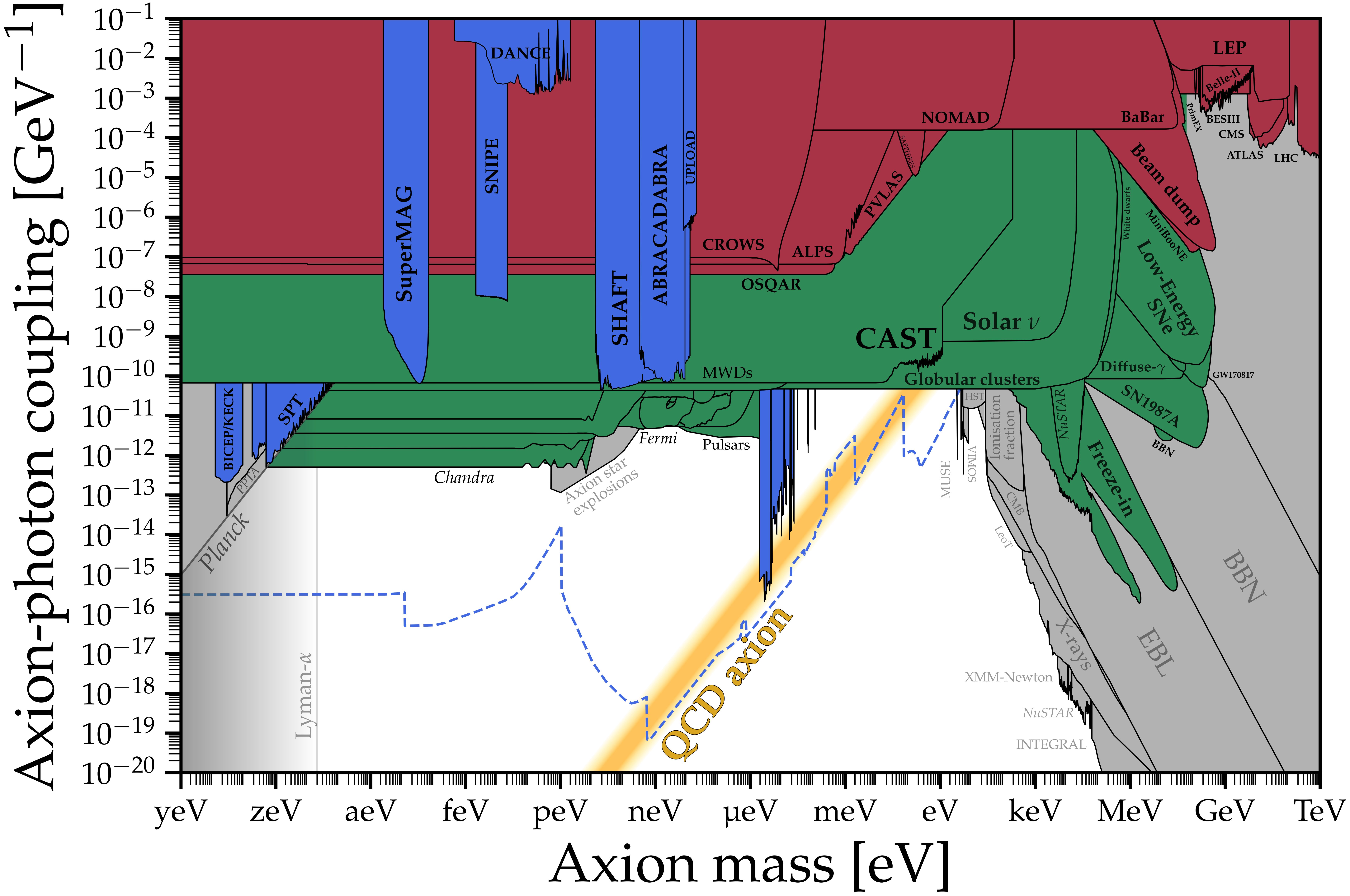
Motivation

What could axion searches teach us about physics in the far UV (grand unification, string theory)?

Axion-gauge bosons couplings are topological so are matched from the UV to the IR

See also: Agrawal, Hook & Huang: arxiv/1912.02823; Cordova, Hong & Wang: arxiv/2309.05636; Reece: arxiv/2309.03939; Choi, Forslund, Lam & Shao: arxiv/2309.03937

Axion Experimental Landscape



Ciaran O'Hare: 'AxionLimits' https://cajohare.github.io/AxionLimits/

Overview

- Axions: definition and allowed couplings
- Axions in GUTs: QCD axion and axion mixing
- GUT-like theories (flipped SU(5), trinification and Pati-Salam)
- Axions in heterotic string models
- Axions in Orbifold GUTs

Axion Couplings

Axions

- Scalar with discrete shift symmetry:

$$a \sim a + 2\pi F_a$$

- Arise naturally as:

  1. PNGBs of broken U(1) symmetries
  2. Higher form fields on compact dimensions
  3. Generically appear in string compactifications

- Solve strong CP problem, quintessence, dark matter, inflation, …

Axion Lagrangian

- Shift symmetry dictates allowed interactions

$$\frac{\partial_\mu a}{F_a} \bar{\psi} \gamma^\mu \gamma_5 \psi \qquad V(a) = \Lambda^4 \cos(a/F_a) \qquad \frac{a}{F_a} G\tilde{G}$$

Manifestly shift-symmetric terms

Coupling must be quantised

- Quantised (topological) couplings unaffected by RG flow

Quantised couplings

- Euclidean action is:

$$S[a] = i\int d^4x\, \mathcal{A} \frac{a}{F_a} \frac{\alpha}{8\pi} G^a_{\mu\nu} \widetilde{G}^{\mu\nu,a}$$

- Consider theory on S_4, then

$$\frac{\alpha}{8\pi} \int_{S_4} d^4x\, G^a_{\mu\nu} \widetilde{G}^{\mu\nu,a} = n \in \mathbb{Z}$$

- In presence of background gauge field:

$$S[a + 2\pi F_a] = S[a] + 2in\mathcal{A}\pi$$

- $\mathcal{A}$ must be an integer so that e^{-S} is invariant under axion shift

QCD Axion Review

- Strong CP problem:

$$\mathscr{L}_\theta = \bar{\theta}\,\frac{\alpha_s}{8\pi}\,\tilde{G}_{\rm QCD}G_{\rm QCD}$$

- Neutron EDM not observed $\implies \bar{\theta} < 10^{-11}$

- Introduce axion with $\mathscr{A}_{\rm QCD} = N \neq 0$ then have

$$\bar{\theta}\,\frac{\alpha_s}{8\pi}\,\tilde{G}_{\rm QCD}G_{\rm QCD} \to \left(\bar{\theta} + \frac{aN}{F_a}\right)\frac{\alpha_s}{8\pi}\,\tilde{G}_{\rm QCD}G_{\rm QCD}$$

QCD Axion review

- QCD potential sets $\theta_{\rm eff} = 0$

$$V(a) \simeq f_\pi^2 m_\pi^2 \left(1 - \cos\left(\frac{a}{f_a} + \bar{\theta}\right)\right)$$

- One parameter (f_a) sets QCD coupling and $m_a \simeq \dfrac{m_\pi f_\pi}{f_a}$

- Have photon coupling: $g_{a\gamma\gamma} = \dfrac{\alpha_{\rm em}}{2\pi f_a}\left(\dfrac{E}{N} - 1.92\right)$

Quantised (rational) piece

Pion mixing contribution

Grand Unification & Axion Couplings

Unification and axions

- Simple gauge group in UV = $\mathbb{G}_{\text{GUT}}$
- Assume set of axions a_i (need more than 1), no potential at this stage
- Only one axion (QCD axion) coupled to gauge bosons:

$$\frac{\alpha_{\text{GUT}}}{8\pi}\left(\sum_i \mathscr{A}_i \frac{a_i}{F_{a_i}}\right) G\widetilde{G} = \mathscr{A}\frac{\alpha_{\text{GUT}}}{8\pi}\frac{a}{F_a} G\widetilde{G}$$

Single gauge group in UV
(Field strength = G)

Unification and axions

- EFT is QCD axion with $E/N = 8/3$

$$\mathscr{A}\frac{\alpha_{\rm GUT}}{8\pi}\frac{a}{F_a}G\widetilde{G} \rightarrow \frac{a}{F_a}\left[\frac{\alpha_{\rm em}}{8\pi}E\,F_{\rm em}\widetilde{F}_{\rm em} + \frac{\alpha_s}{8\pi}N\,G^a_{\rm QCD}\widetilde{G}^a_{\rm QCD} + \dots\right]$$

QED and QCD couplings fixed by E, N
$E/N = 8/3$ for GUTs

- Now add a potential (leads to mixing)

ALP mixing

- Consider 2 axion mixing:

$$V(a_1, a_2) = \left(\frac{a_1}{f_1} + \frac{a_2}{f_2}\right) G\tilde{G} + \frac{1}{2} m_2^2 a_2^2$$

Regime	$m_2 \ll \frac{m_\pi f_\pi}{\max(f_1, f_2)}$	$m_2 \gg \frac{m_\pi f_\pi}{\min(f_1, f_2)}$
QCD axion	$\frac{a}{f_a} \simeq \frac{a_1}{f_1} + \frac{a_2}{f_2}$	$a \simeq a_1$
ALP	$\frac{g_{b\gamma\gamma}}{g_{a\gamma\gamma}} \simeq \frac{m_b^2 \times \max(f_1^2, f_2^2)}{f_\pi^2 m_\pi^2}$	$g_{b\gamma\gamma} = \frac{\alpha_{\rm em}}{2\pi f_2}\left(\frac{E}{N} - 1.92\right)$

ALP mixing

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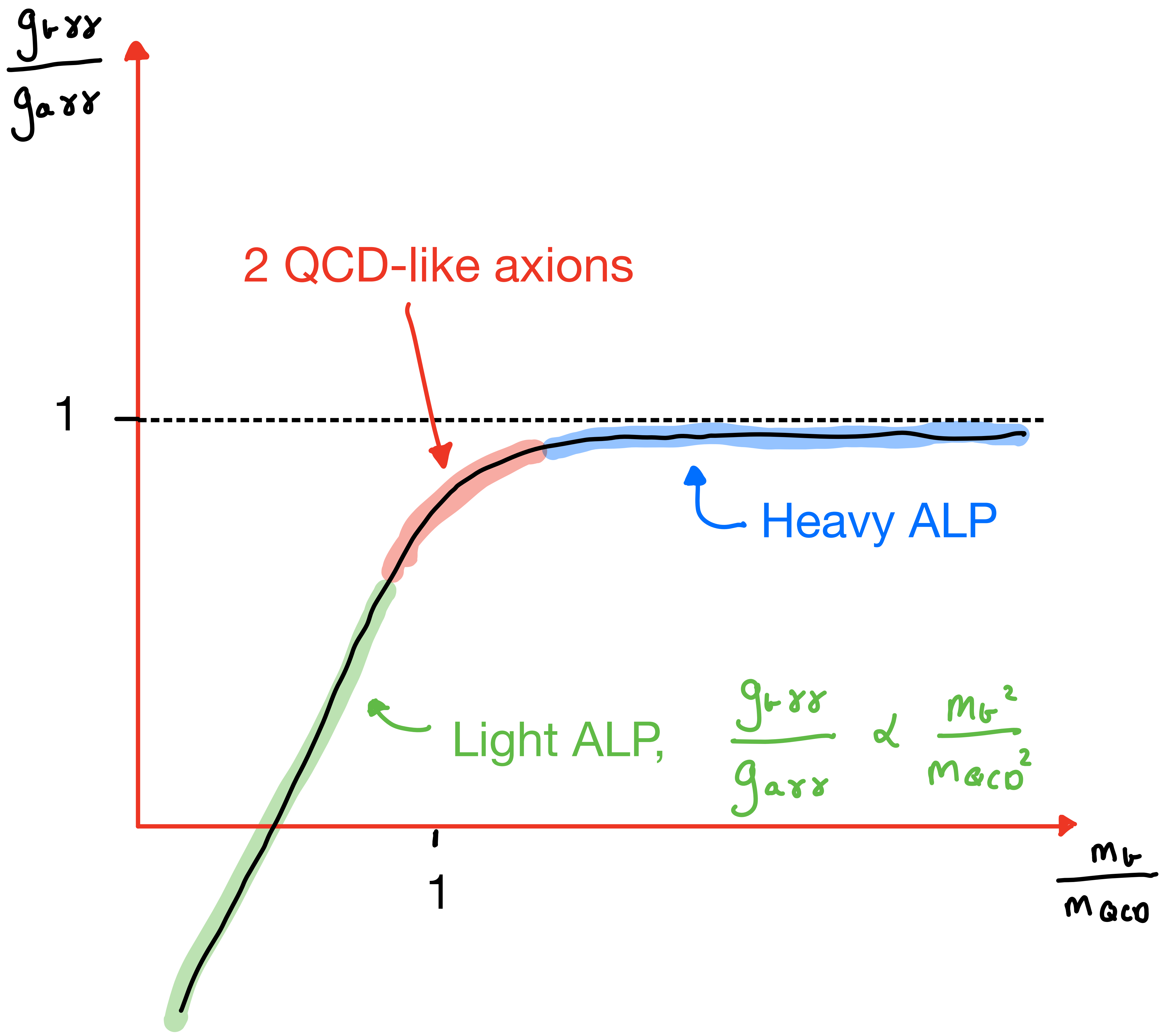
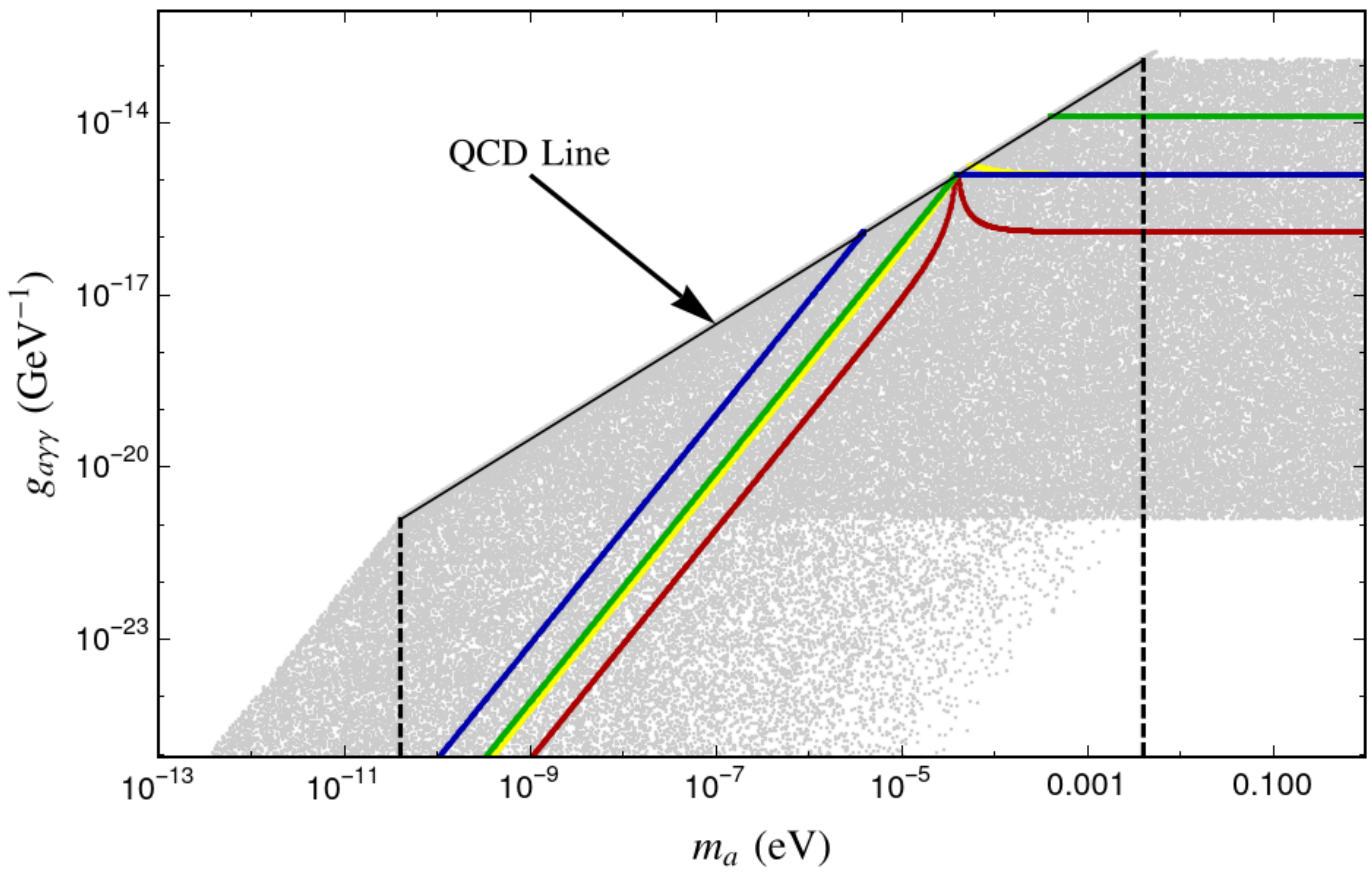
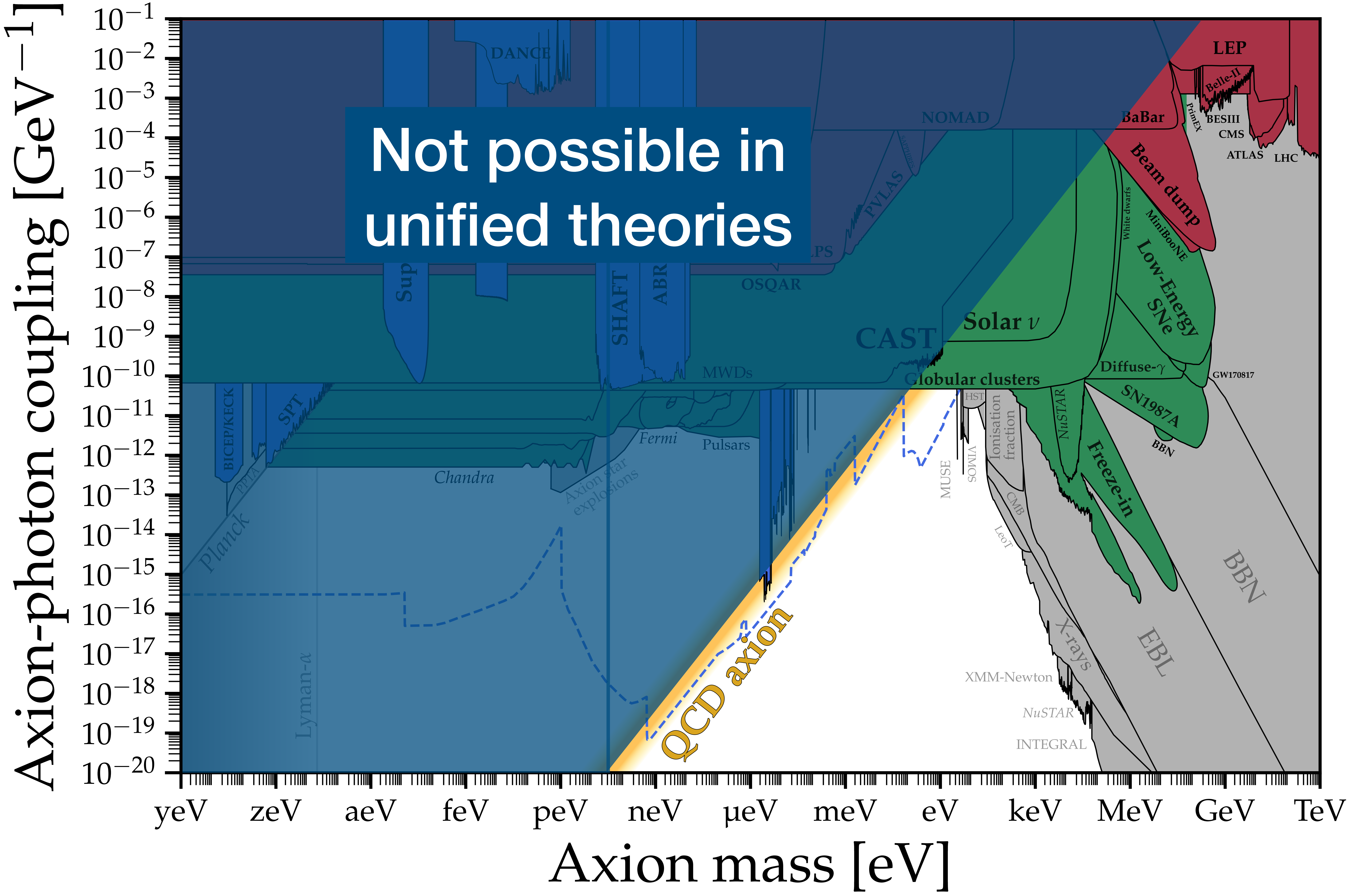


ALP mixing



QCD Line
$g_{a\gamma\gamma}$ (GeV^{-1})
10^{-14}
10^{-17}
10^{-20}
10^{-23}
10^{-13}
10^{-11}
10^{-9}
10^{-7}
10^{-5}
0.001
0.100
m_a (eV)

The search for GUTs?



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Cosmic Birefringence

Minami & Komatsu, arxiv/2011.11254; Eskilt & Komatsu arxiv/2205.13962;

- Some possible evidence already for light ALP from cosmic birefringence
- Measured CMB rotation: $\beta = 0.35^\circ \pm 0.14^\circ \sim 6 \times 10^{-3}$
- Contribution from ALP φ is: $\beta = \frac{c_{a\gamma\gamma}\alpha_{\rm em}}{2\pi F_a}\left(\varphi(t_0) - \varphi(t_{\rm cmb})\right)$
- Need: $H_{\rm cmb} > m_\varphi > H_0$

$$10^{-28} > m_\varphi/eV > 10^{-33}$$

GUT-like theories

"GUT-like" theories

- Now allow UV gauge group to be non-simple but preserve some GUT features
- All can arise as subgroups of $SO(10)$:
  - Flipped $SU(5)$: $SU(5) \times U(1)_X$,
  - Pati-Salam: $SU(4)_c \times SU(2)_L \times SU(2)_R$
- Or of E_6:
  - Trinification: $SU(3)_c \times SU(3)_L \times SU(3)_R$

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

Barr, Phys. Lett. B 112 (1982); Derendinger, Kim, & Nanopoulos Phys. Lett. B 139 (1984)

- Breaks to SM by Higgs transforming as $\mathbf{10}_1$
- At M_{GUT} have matching condition:

$$25\alpha_1^{-1} = \alpha_5^{-1} + 24\alpha_X^{-1}$$

- Can have axions a, b:

$$\mathscr{L} = \alpha_5 \frac{a}{f_a} G\tilde{G} + \alpha_X \frac{b}{f_b} F_X \tilde{F}_X$$

QCD axion

ALP

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

Barr, Phys. Lett. B 112 (1982); Derendinger, Kim, & Nanopoulos Phys. Lett. B 139 (1984)

- Weak mixing angle prediction: $\sin^2(\theta_w) = \dfrac{3/8}{1 + 3/5\left(\frac{\alpha_5}{\alpha_X} - 1\right)}$

- $\alpha_5 = \alpha_X$ if $SU(5), U(1)_X$ come from unified group in the UV

- Fractionally charged states, i.e. fermion in $\mathbf{1}_1$ rep has electric charge $q = 1/5$

- ALP couplings depend on whether the model is embedded into a GUT or not

Heterotic String Models

UV gauge group

Green & Schwartz Phys. Lett. B (149) 1984; Gross, Harvey, Martinec & Rohm Phys. Rev. Lett. (54) 1985

- Anomaly cancellation + SUSY restricts the UV gauge group to 2 possibilities:

$$E_8 \times E_8 \text{ or } SO(32)$$

- Breaking mechanisms: wilson lines, orbifolds, background gauge fields (vector bundles) leave only a subgroup massless in 4d

- Fermions in reps of low energy gauge group, expect fractionally charged states, $E/N \neq 8/3$ (model's don't appear unified)

- Notation: K= internal manifold, $\mathrm{tr}G^2 = \mathrm{tr}(G \wedge G) = \frac{\alpha}{8\pi}\mathrm{tr}(G\tilde{G})$

Heterotic Axions

Choi & Kim: Phys.Lett.B 154 (1985) & Phys.Lett.B 165 (1985); Svrcek & Witten hep-th/0605206

- Model-independent (a): Dual of 2-form field $B_{\mu\nu}$ (indices in 4d directions)
- Model-dependent (b_i): Expand B_{ab} (indices in internal dimensions) in basis of harmonic 2-forms

$$B = \frac{1}{2\pi} \sum_i b_i \beta_i$$

- Couplings fixed by 10d anomaly cancellation

Model Independent Axion

Witten Phys.Lett.B 149 (1984); Svrcek & Witten hep-th/0605206

- Couplings from Bianchi Identity of $H = dB$
- Add Lagrange multiplier to 10d action:

$$\int \tilde{B}_6 \wedge \left(dH - \frac{\alpha'}{4}\mathrm{tr}R^2 - \mathrm{tr}_1 G^2 - \mathrm{tr}_2 G^2 \right)$$

- Do path integral over H to get Lagrangian for $\dfrac{a}{f_a} = \displaystyle\int_K \tilde{B}_6$
- a then couples universally to G: $\dfrac{a}{f_a}\left[\mathrm{tr}_1 G^2 + \mathrm{tr}_2 G^2\right]$

Model Dependent Axions

Witten Phys.Lett.B 149 (1984); Svrcek & Witten hep-th/0605206

$$B = \frac{1}{2\pi}\sum_i b_i \beta_i$$

- Couplings fixed by anomaly cancellation:

$$S_4 = \sum_i \int_{M_4} b_i \left(k_i^{(1)} \mathrm{tr}_1 G^2 + k_i^{(2)} \mathrm{tr}_2 G^2 \right)$$

Different couplings to each E_8

$$k_i^{(1)} = \int_K \beta_i \wedge \left(-\mathrm{tr} R^2 + 2\mathrm{tr}_1 G^2 - \mathrm{tr}_2 G^2 \right) \in \mathbb{Z}$$

Depends on β_i, background fields on K

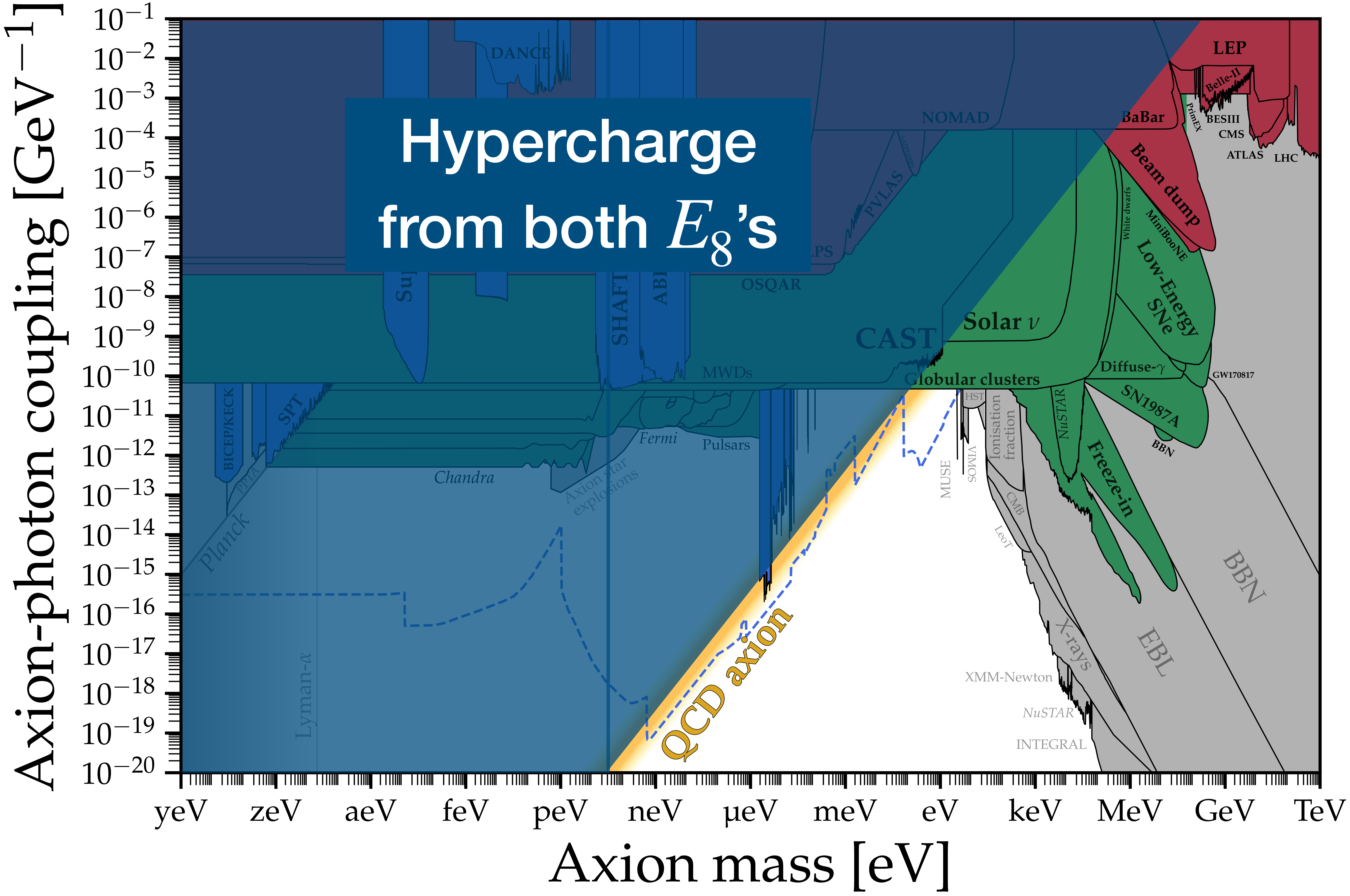
4d EFT picture

$$S_4 = \int_{M_4} \frac{a_1}{f_1} \text{tr}_1 G^2 + \int_{M_4} \frac{a_2}{f_2} \text{tr}_2 G^2$$

$$= \int_{M_4} \frac{a}{f_a} \text{tr}\, G^2_{\text{QCD}} + \int_{M_4} \frac{b}{f_b} F^2$$

- Can get light ALPs if a, b are different linear combinations
- Requires non-trivial embedding of either QCD or QED into both E_8 subgroups
- This is not the case for most models
- SM fermion reps. mean both need to have a contribution from the same E_8

Tests of Heterotic String theory?



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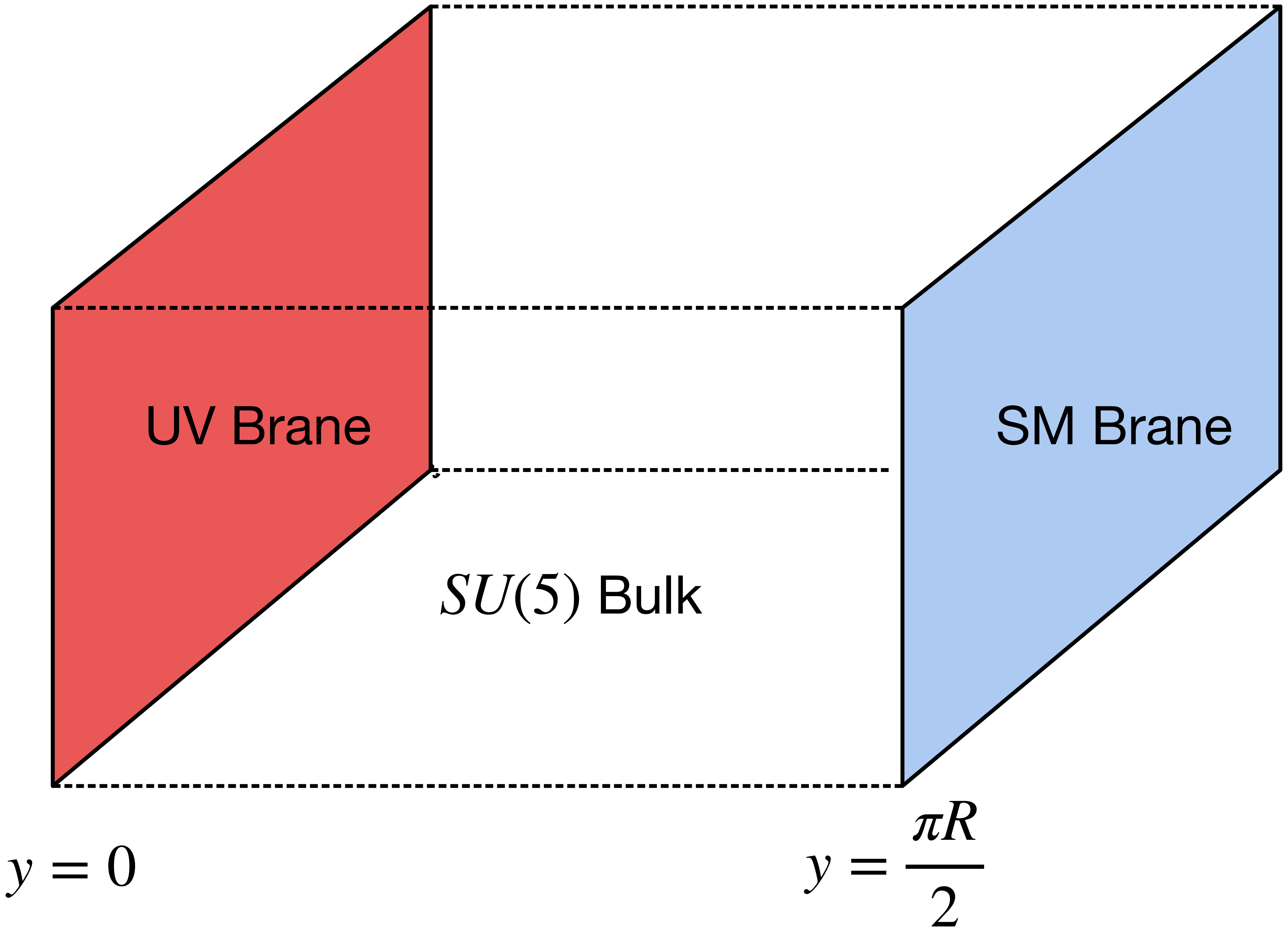
Orbifold GUTs

Orbifold GUTs

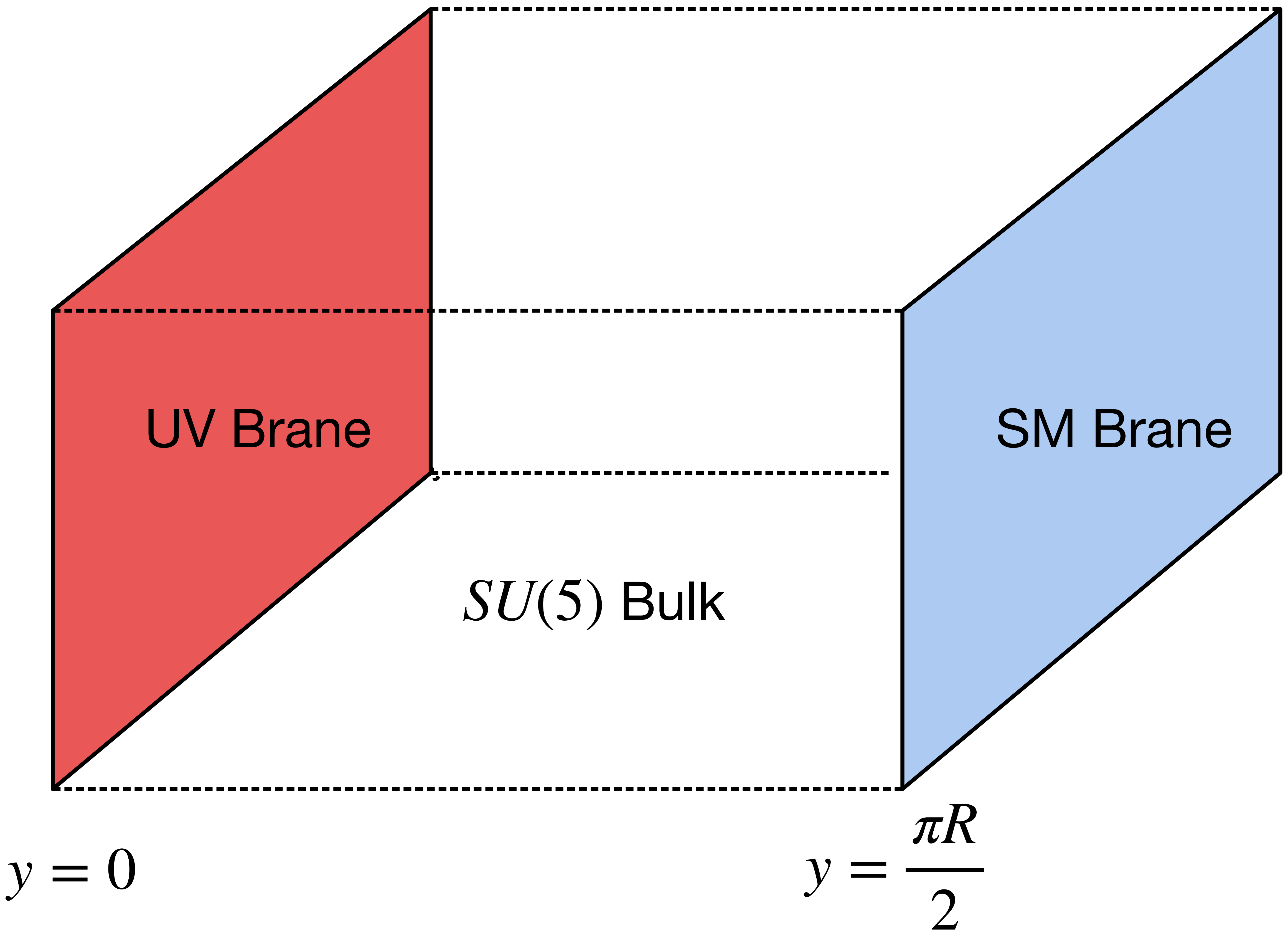
Kawamura: hep-ph/9902423 & hep-ph/0012125; Hall & Nomura: hep-ph/0103125; Hebecker & March-Russell: hep-ph/0106166



- Orbifold extra dimension $S^1/\left(\mathbb{Z}_2 \times \mathbb{Z}_2'\right)$
- Leads to incomplete multiplets in zero mode spectrum
    - Suppressed proton decay from scalar partners
    - Solves doublet-triplet splitting
    - Can explain yukawa relations

Orbifold GUTs

Kawamura: hep-ph/9902423 & hep-ph/0012125; Hall & Nomura: hep-ph/0103125; Hebecker & March-Russell: hep-ph/0106166



- Gauge kinetic terms:

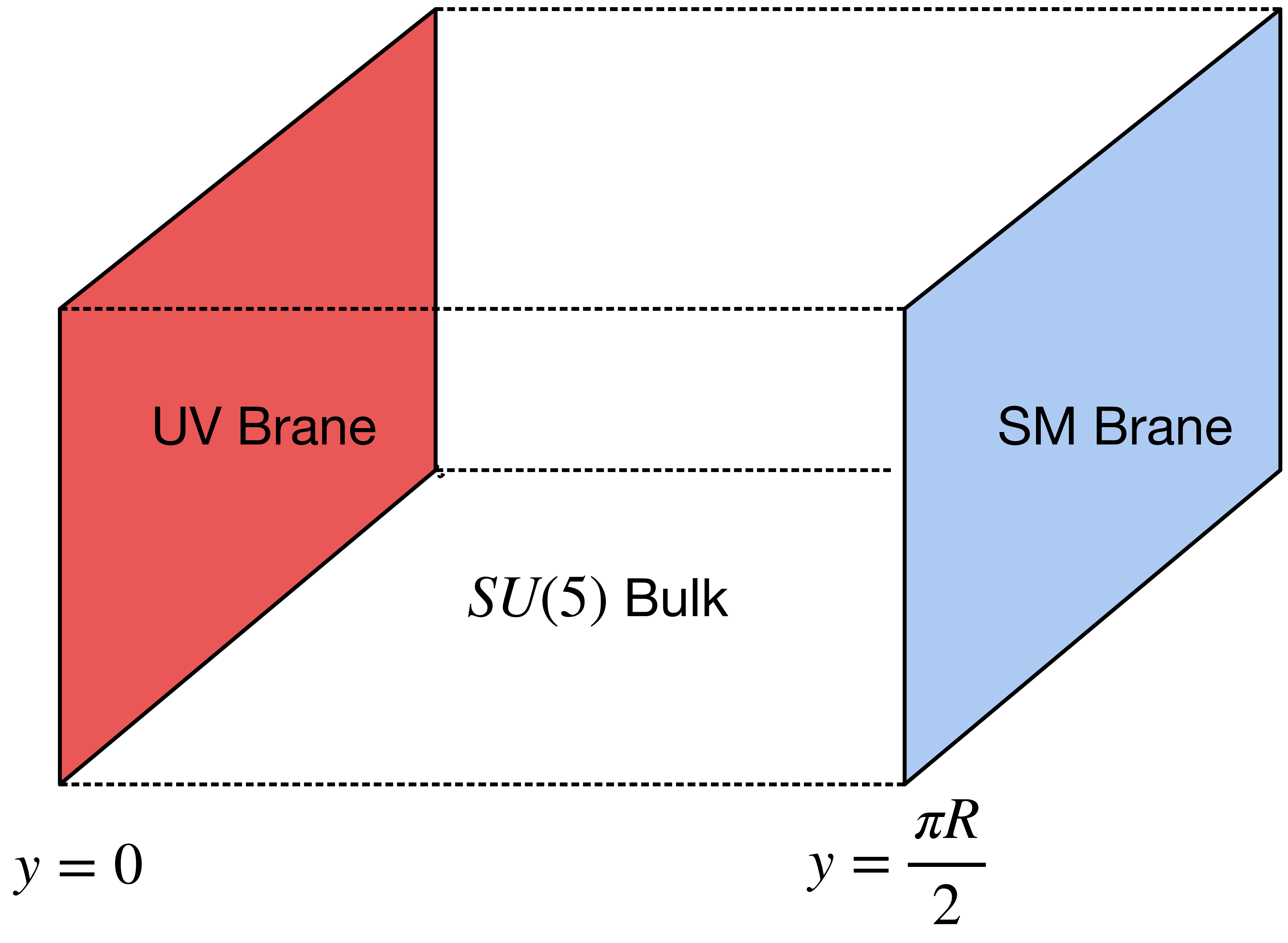
$$\mathscr{L}_{\text{eff}} = \int dy \left[-\frac{1}{2g_5^2}\text{Tr}[G^{MN}G_{MN}] - \sum_i \frac{\delta(y-\pi R/2)}{2g_{brane,i}^2}\text{Tr}[F_i^{\mu\nu}F_{i\,\mu\nu}] \right]$$

- Matching condition at R^{-1}:

$$\frac{1}{g_i^2} = \frac{2\pi R}{g_5^2} + \frac{1}{g_{brane,i}^2}$$

- $g_{brane,i}^2 \gg 1$ leads to apparent unification

Bulk axions



- Axion comes from 5-component of $U(1)$ gauge field

Axion

$$B_M \to \left(B_\mu, B_5\right)$$

$$S_{CS} = \frac{k}{16\pi^2} \int d^5x \epsilon^{MNPQR} B_M \,\mathrm{tr}\left[G_{NP} G_{QR}\right]$$

$$\to \frac{k}{8\pi} \int d^4x \frac{b}{f_b} G\tilde{G}$$

- Quantised coefficient + GUT symmetry $\Longrightarrow$ 4d results apply ($f_b \sim R^{-1}$)

Brane-localised axions

- Allowed couplings:

$$\mathscr{L} = \int dy\, \delta\left(y - \frac{\pi R}{2}\right) \frac{b}{f_b} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- Brane-localised instantons generate potential

$$V = KR^{-4} \exp\left(-\frac{8\pi^2}{g^2_{brane,i}}\right) \cos(b/f_b)$$

- Apparent unification implies $g_{brane,i} \gg 1$, so $m_b \sim R^{-2}/f_b$

Chiral Suppression

- Chiral suppression factor from brane-localised fermions:

$$K = (RM_\psi)^{n_f}$$

- Also leads to non-universal running:

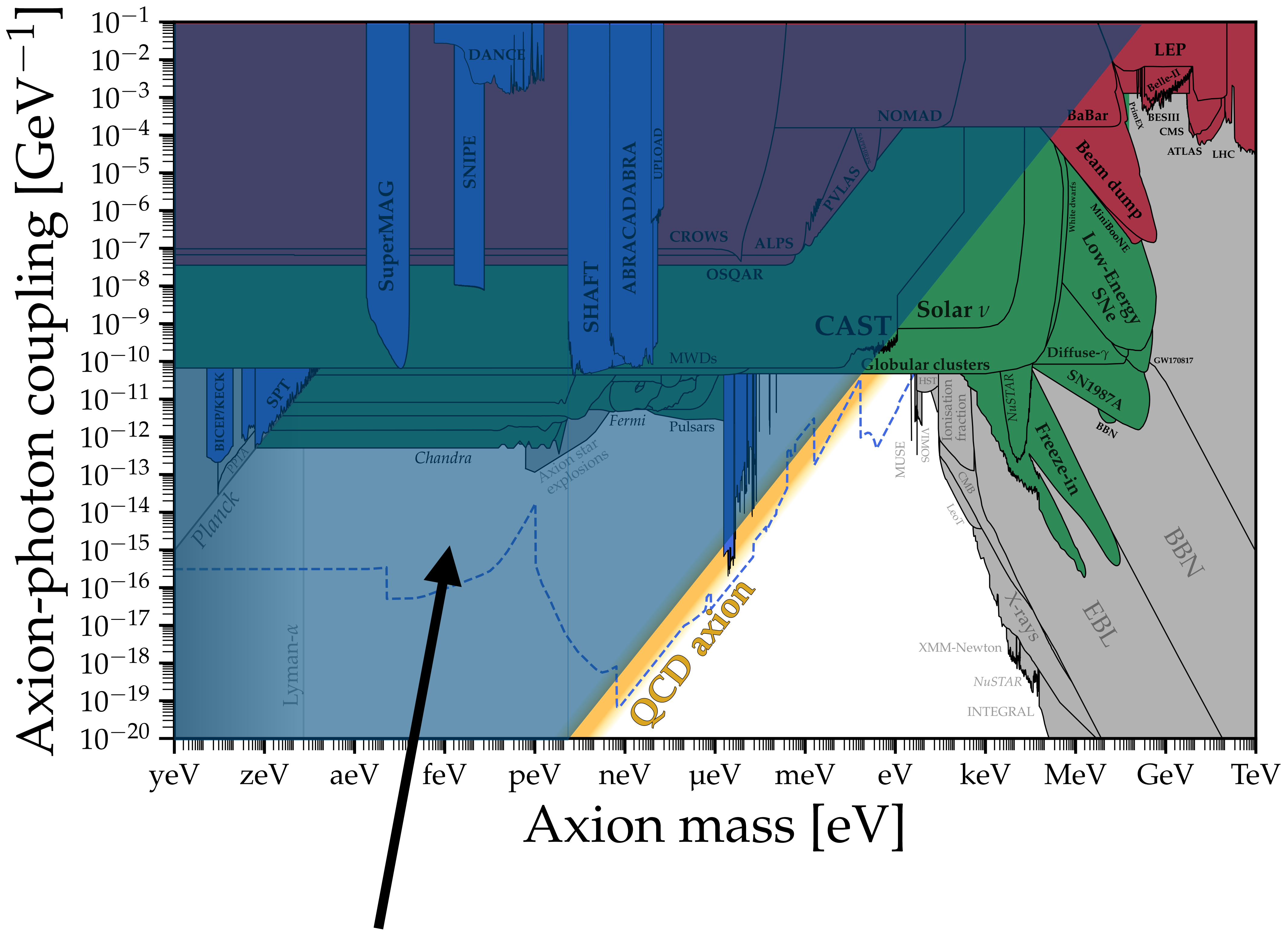
$$\Delta\alpha_i^{-1} = -\frac{2n_f T_i}{3\pi}\log(RM_\psi) \ll \alpha_{\mathrm{GUT}}^{-1} \sim 25$$

- Take $\Delta\alpha_i^{-1} \sim 1, \quad K = e^{-3\pi\Delta\alpha_i^{-1}} \sim 8 \times 10^{-5}$, then get:

$$m_a \simeq \left(\frac{R^{-1}}{10^{14}\,\mathrm{GeV}}\right)^2 \left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right) \times 4 \times 10^{12}\,\mathrm{GeV}$$

Conclusions

- Light axions coupled to photons not compatible with unification
- Result also holds for Heterotic models where SM comes from one E_8 factor
- Light ALP searches offer a way to rule out unification of the SM and some string models



Probe of unification