CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

The Dark Heterotic Axiverse

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Work in progress with
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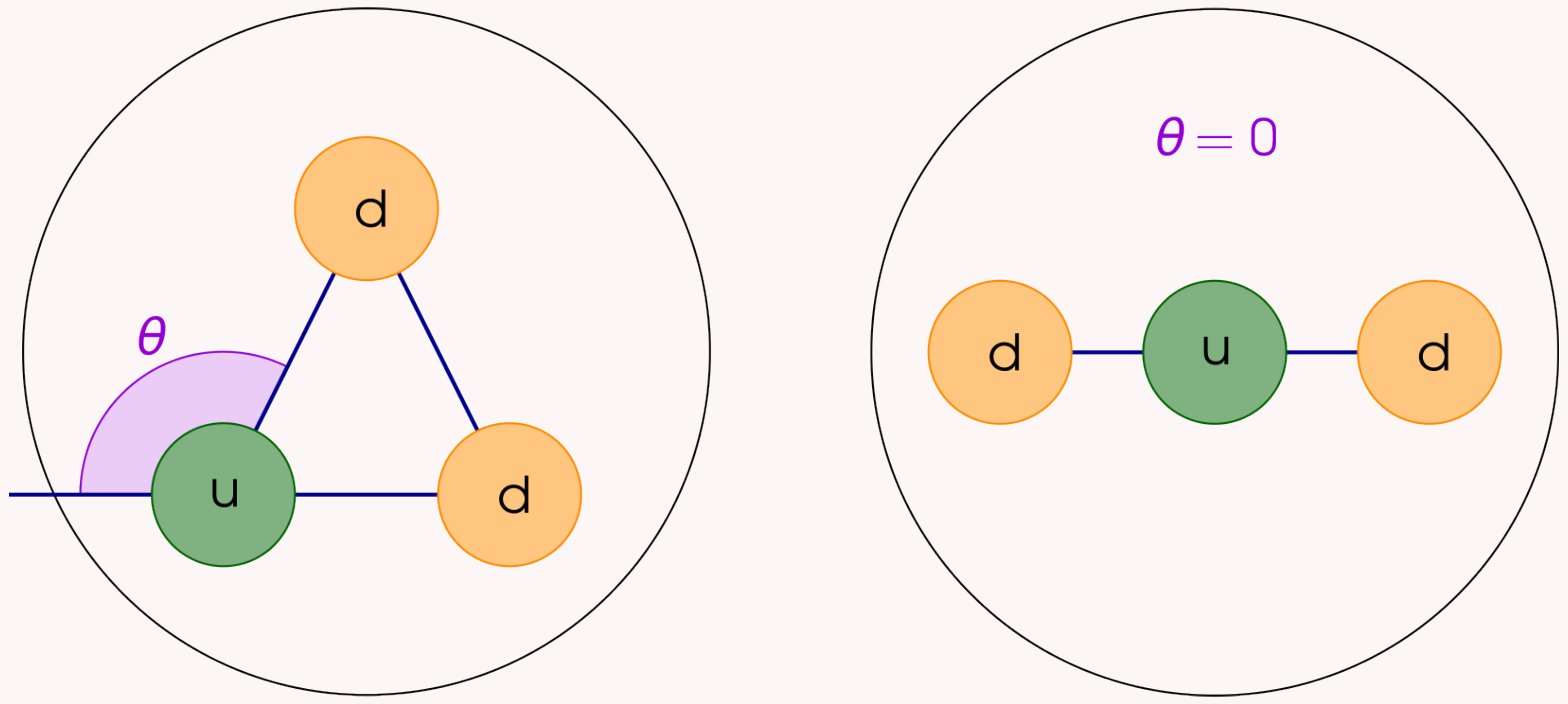
Axions

✦ Potential solution to the Strong CP problem

$$\mathscr{L}_{SM} \supset \frac{1}{32\pi^2}\theta F^{A}_{\mu\nu}\tilde{F}^{A\mu\nu}$$

$$|d_n| \simeq 10^{-16}\,\theta\, e\ \text{cm}$$

$$\theta \lesssim 10^{-10}$$



$$\theta \to \frac{\vartheta}{f} \implies \theta = 0$$

Axions

- ✦ Pseudo-scalar particles with perturbative continuous shift symmetry

$$\vartheta \to \vartheta + c \qquad c \in \mathbb{R}$$

Broken by non-perturbative effects

$$V(\vartheta) \sim \Lambda^4(1 - \cos(\vartheta/f_\vartheta))$$

To discrete shift symmetry

$$\vartheta \to \vartheta + 2\pi n f_\vartheta \quad n \in \mathbb{Z}$$

- ✦ QFT axions arise as massless modes after SSB

P-form axions

Unified QG theories have p-form gauge potentials

10D Type IIB

$$C_4,\ C_2,\ B_2,\ C_0$$

Compactification: $M_{10} \to M_4 \times X_6$

Gives rise to axions $C_4 = \rho_\alpha \omega^\alpha + ..$ $\alpha \in \{1,2,...h^{1,1}\}$

Axions

Few - $\mathcal{O}(10^2) \to$ axiverse

- ✦ Gauge symmetry protects shift symmetry
- ✦ Inflation models / quintessence
- ✦ …

Axiverse among the best prospects to tie string theory to experiments

Arvanitaki, Dimopolous, Dubovsky, Kaloper, March-Russel arXiv:0905.4720
Cicoli, Goodsell, Ringwald arXiv:1206.0819
Acharya, Bobkov, Kumar arXiv:1004.5138
…

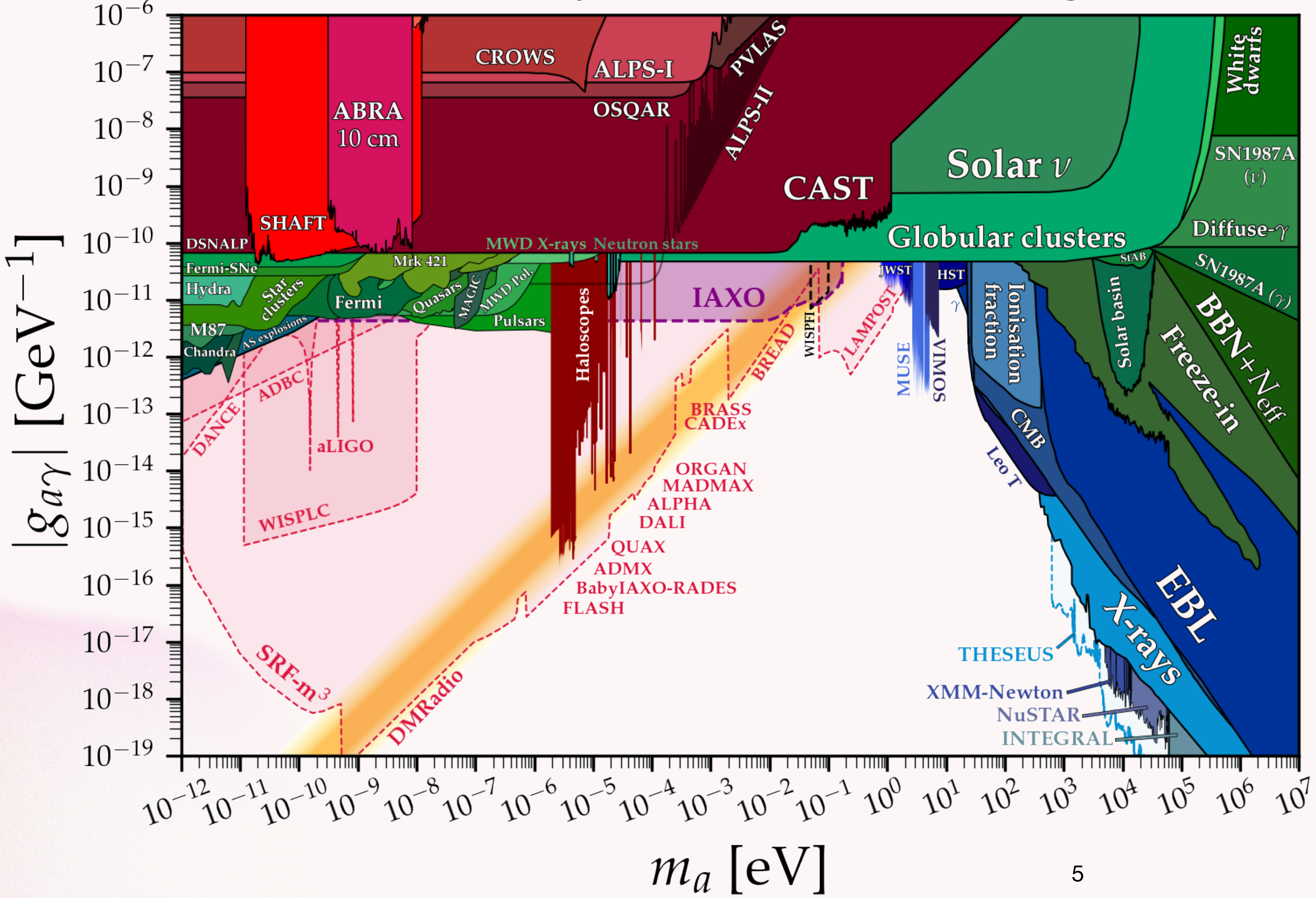
Detecting the Axiverse

If axions couple to SM →

- ✦ Axion - photon coupling $g_{a\gamma}$
- ✦ Axion - nucleon coupling g_N

O'Hare Github

Constraints and future projections of axion-photon coupling experiments.



Assumptions:
axion is very light,
makes up DM.

Detecting the Axiverse

If axions couple to SM →

- ✦ Axion - photon coupling $g_{a\gamma}$
- ✦ Axion - nucleon coupling g_N

However, string axions may not be:

- ✦ Light enough
- ✦ DM
- ✦ Coupled to SM

Naively:

- ✦ One QCD axion
- ✦ One for inflation
- ✦ One for quintessence

What about the rest of the axiverse?

How can we detect string axions that don't necessarily couple to the Standard model

Axion in type IIB

Type IIB on 6d Orientifold

$$M_{10} \to M_4 \times \tilde{X}_3$$

X_3 CY 3-fold

$\tilde{X}_3 = X_3/\Omega$

- $H^{(1,1)}$ p-form axions

$$C_4,\ C_2,\ B_2,\ C_0 \ \to\ \rho_\alpha,\ c^a,\ b^a,\ C_0$$

- 4d $\mathcal{N} = 1$ theory

$$S = C_0 + ie^{-\phi}$$

$$G^a = c^a - Sb^a$$

$$T_\alpha = \tau_\alpha - i(\rho_\alpha - \kappa_{abc} c^b b^c) + \frac{i}{2} S \kappa_{abc} b^b b^c$$

c^a 2-form axion

ρ_α 4-form axion

Axion candidates

The type IIB axiverse

✦ Axion decay constants: kinetic terms $\mathscr{L} \supset K_{i\bar{j}} \partial T^i \partial T^{\bar{j}}$, $K_{i\bar{j}} = \partial_{T^i} \partial_{T^{\bar{j}}} K$

✦ Axion masses: ED3, ED1, or Gaugino condensation

ED3 brane wrapping 4-cycle of $\tilde{X}_3$ $W_{ED3} \sim A e^{-2\pi T}$ $\rightarrow \delta V_{ED3} \simeq e^{-2\pi\tau} \cos(\vartheta/f)$

✦ Gauge theory and axion couplings

D7-brane wrapping divisor $\tilde{\mathcal{D}}$ of $\tilde{X}_3$ Worlvolume theory: $\mathcal{N} = 1$ gauge theory

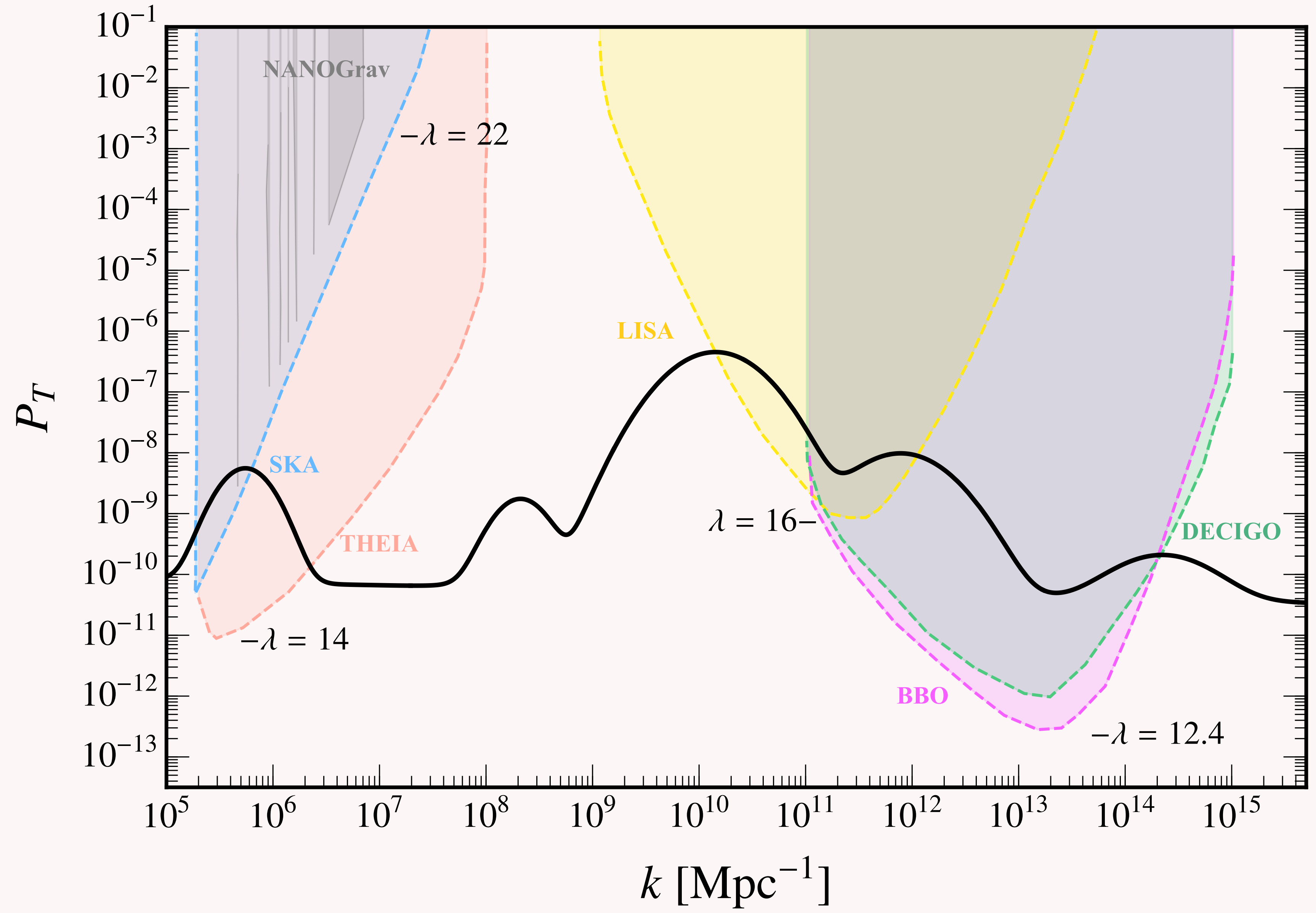
$$\mathscr{L}_{gauge} \supset -\frac{1}{4} Re[f_{\tilde{D}}] F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} Im[f_{\tilde{D}}] F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Automatically coupled to ρ_α

$$f_{\tilde{D}} = \frac{T}{2\pi} = \frac{\tau_\alpha - i\rho_\alpha + ..}{2\pi}$$

The type IIB dark axiverse

How can we detect string axions that don't couple to the Standard model

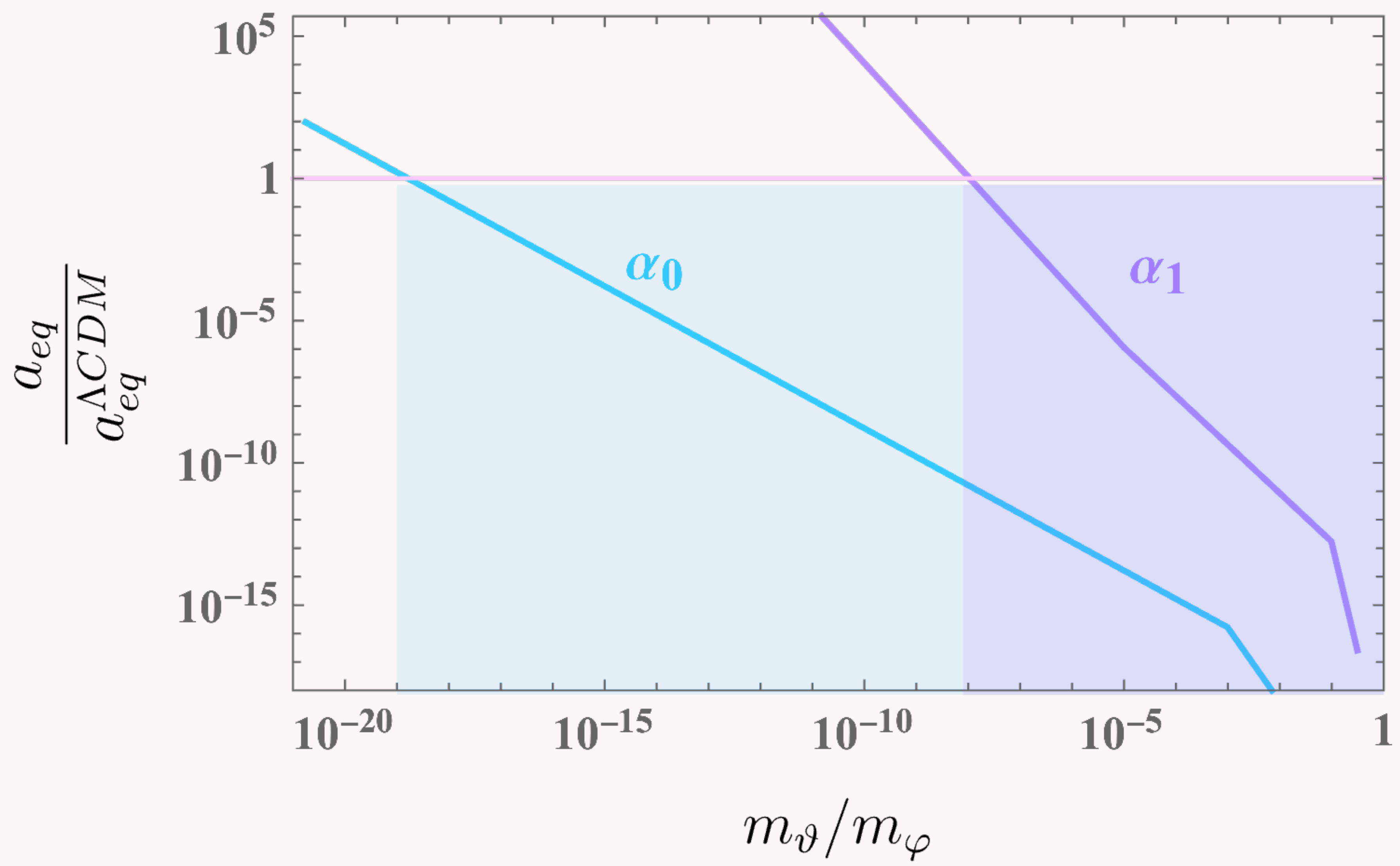


Dimastrogiovanni, Fasiello, Leedom, MP, Westphal

arXiv:2312.13431

Gravitational Waves

...



Leedom, MP, Righi, Westphal

arXiv:2411.18496,

Dark Matter

Heterotic Axions

- Heterotic string theory has gauge fields
- $E_8 \times E_8$ or SO(32) gauge group
- Gauge bundle with G s.t. $E_8 \to G \times H$
- H commutant: 4D gauge content

- Take G_1 in $E_{8,1}$ s.t. 4D GUT
- Then $E_{8,2}$: dark sector

If G contains U(1): there will be an anomalous U(1) in 4D

What is the (dark) axiverse in heterotic string theory?

Heterotic Axions

B_2

$$a = \int_{CY} B_6\,, \quad dB_6 = \star\, dB_2$$

Universal axion

$$b_i = \int_{\Sigma_i} B_2 \qquad B_2 = \sum_{i=1}^{h_{11}} b_i \beta_i$$

Model dependent axions

- ✦ Heterotic string theory has gauge fields
- ✦ E_8 x E_8 or SO(32) gauge group
- ✦ Gauge bundle with G s.t. $E_8 \to G \times H$
- ✦ H commutant: 4D gauge content

- ✦ Take G_1 in $E_{8,1}$ s.t. 4D GUT
- ✦ Then $E_{8,2}$: dark sector

If G contains U(1): there will be an anomalous U(1) in 4D

Axion couplings

✦ Axion decay constants: kinetic terms

✦ Gauge couplings from Green Schwarz terms (anomaly cancellation)

$$\mathscr{L} \supset \left(\frac{\vartheta_a}{f_a} + \sum_i \frac{n_i}{f_i}\vartheta_i\right) \mathrm{tr}_1 F \wedge F + \left(\frac{\vartheta_a}{f_a} - \sum_i \frac{n_i}{f_i}\vartheta_i\right) \mathrm{tr}_2 F \wedge F$$

$$n_i = \int_{CY} \beta_i \wedge \left(\mathrm{tr}_1 \overline{F} \wedge \overline{F} - \frac{1}{2}\mathrm{tr}\overline{R} \wedge \overline{R}\right) = \int_{CY} \beta_i \wedge \left(c_2(V_1) - \frac{1}{2}c_2(TX)\right)$$

$$\mathscr{F} = F + \overline{F}, \quad \mathscr{R} = R + \overline{R}$$

Axions are coupled equally to the visible and the hidden sector ($E_{8,1}$ and $E_{8,2}$)

Axion couplings

- ✦ Axion decay constants: kinetic terms
- ✦ Gauge couplings from Green Schwarz terms (anomaly cancellation)

$$\mathscr{L} \supset \left(\frac{\vartheta_a}{f_a} + \sum_i \frac{n_i}{f_i} \vartheta_i \right) \mathrm{tr}_1 F \wedge F + \left(\frac{\vartheta_a}{f_a} - \sum_i \frac{n_i}{f_i} \vartheta_i \right) \mathrm{tr}_2 F \wedge F$$

$$n_i = \int_{CY} \beta_i \wedge \left(\mathrm{tr}_1 \bar{F} \wedge \bar{F} - \frac{1}{2} \mathrm{tr} \bar{R} \wedge \bar{R} \right) = \int_{CY} \beta_i \wedge \left(c_2(V_1) - \frac{1}{2} c_2(TX) \right)$$

- ✦ Axion masses:

$$V_{QCD} = -\Lambda_{QCD}^4 \cos \left(\frac{\vartheta_a}{f_a} + \sum_i \frac{n_i}{f_i} \vartheta_i + \delta \right)$$

$$V_{gc} = -\Lambda_g^4 \cos \left(\frac{\vartheta_a}{f_a} - \sum_i \frac{n_i}{f_i} \vartheta_i \right)$$

$$V_{ws} = -\Lambda_i^4 \cos \left(\frac{\vartheta_i}{f_i} \right)$$

Each anomalous U(1) will eat an axion to cancel anomaly via the GS term

Axion couplings - I

2024: Agrawal, Nee, Reig

φ_1 combination: QCD

φ_2 combination: dark

φ_i light, decoupled axions

✦ Axion masses: V_{QCD} V_{gc} V_{ws}

$$\text{QCD}\ \frac{\varphi_1}{f_1} = \frac{\vartheta_a}{f_a} + \frac{n_i}{f_i}\vartheta_i \quad , \quad \text{Dark}\ \frac{\varphi_2}{f_2} = \frac{\vartheta_a}{f_a} - \frac{n_i}{f_i}\vartheta_i$$

$$\mathscr{L} \supset \left(\frac{\varphi_1}{f_1}\right) \mathrm{tr}_1 F \wedge F + \left(\frac{\varphi_2}{f_2}\right) \mathrm{tr}_2 F \wedge F$$

If $V_{ws} \ll V_{QCD}\,, V_{gc} \ \rightarrow\ h_{11} - 1$ dark decoupled axions with $m_i^2 = \dfrac{\Lambda_i^4}{f_i^2}$

If $V_{ws} \sim V_{QCD}\,, V_g \ \rightarrow$ mass mixing non-negligible

Axion couplings - II

ϑ_a: QCD axion

ϑ_i : coupled to hidden and visible gauge sector with same coupling n_i

✦ Axion masses: V_{QCD} V_{gc} V_{ws}

If $V_{ws} \sim V_{QCD}, V_{gc}$ $\rightarrow$ mass mixing non-negligible

Axions couple to both E8s.

$$\mathscr{L} \supset \left(\frac{\vartheta_a}{f_a} + \sum_i \frac{n_i}{f_i} \vartheta_i \right) \mathrm{tr}_1 F \wedge F + \left(\frac{\vartheta_a}{f_a} - \sum_i \frac{n_i}{f_i} \vartheta_i \right) \mathrm{tr}_2 F \wedge F$$

$V_{ws} > V_{QCD}, V_{gc}$, imposes $\langle \vartheta_i \rangle = 0$ for the $h_{11} - 1$ axions, V_{gc} imposes

$\langle \vartheta_a \rangle \sim -\dfrac{n_1 f_a}{f_1} \langle \vartheta_1 \rangle$, strong CP problem will be solved only by ϑ_a

2023: Choi, Leedom
Related ideas

Axion couplings - III

ϑ_a: QCD axion

ϑ_i : coupled to hidden and visible gauge sector with same coupling n_i

✦ Axion masses: V_{QCD} ~~V_{gc}~~ V_{ws}

No gaugino condensation: G s.t. E8→ $U(1)^m$
NB to stabilize the dilaton we need Kähler stabilization

$$\mathscr{L} \supset \left(\frac{\vartheta_a}{f_a} + \sum_i \frac{n_i}{f_i}\vartheta_i\right) \mathrm{tr}_1 F \wedge F + \left(\frac{\vartheta_a}{f_a} - \sum_i \frac{n_i}{f_i}\vartheta_i\right) \mathrm{tr}_2 F \wedge F$$

Axion couple to both E8s. V_{ws} will force h_{11} axion vevs $\langle \vartheta_i \rangle = 0$.

The strong CP problem will automatically be solved only by ϑ_a

4D Gauge group

Embed vector bundle V in the hidden E8 → G x H

Check number of anomalous U(1)s in H: m axions will be eaten → $h_{11} - m$ axions left

$$\mathscr{L} \supset \left(\frac{\vartheta_a}{f_a} + \sum_i \frac{n_i}{f_i} \vartheta_i \right) \mathrm{tr}_1 F \wedge F + \left(\frac{\vartheta_a}{f_a} - \sum_i \frac{n_i}{f_i} \vartheta_i \right) \mathrm{tr}_2 F \wedge F$$

$$n_i = \int_{CY} \beta_i \wedge \left(\mathrm{tr}_1 \overline{F} \wedge \overline{F} - \frac{1}{2} \mathrm{tr} \overline{R} \wedge \overline{R} \right) = \int_{CY} \beta_i \wedge \left(c_2(V_1) - \frac{1}{2} c_2(TX) \right)$$

Take X CY defined via complete intersection in some toric variety with h_{11} Kähler par.

Compute c_2 via cohomology of the bundle monad

What is the axion coupled to? 4D dark gauge sector

Check axion-photon coupling, constraint dark axion couplings.

GW? DM?

Conclusions

Dark string theory axiverse general for all string theories

Probing it would give us info on ST and compactification

For now studied mainly in type IIB

What about Heterotic?

Compactify on a CY. Axions $\vartheta_i,\ i = 1,\ldots,h_{11}$ MD + ϑ_a universal

Axion masses from ED1 world sheet instantons + 4D gauge instantons

Dark heterotic axiverse cannot be completely decoupled from visible sector

Correlated signals between dark sector and visible sector

Backup -Example I

K3 fibred over $\mathbb{CP}^1$

Bianchi identity $dH = \mathrm{tr}R \wedge R - \mathrm{tr}F \wedge F$

$$\int_{K3} (\mathrm{trR} \wedge \mathrm{R} - \mathrm{trF} \wedge \mathrm{F}) = \chi(K3) - \int_{K3} \mathrm{trF} \wedge \mathrm{F} = 24 - \int_{\mathrm{K3}} \mathrm{trF} \wedge \mathrm{F} = 0$$

Instanton number

$$N = \int \mathrm{tr}F \wedge F \geq 0 \qquad N_1 + N_2 = 24$$

$$n = N_1 - \frac{1}{2}\chi(K3) = N_1 - 12 \quad \rightarrow |n| \leq 12$$

Backup -Example II

Quintic CY $\mathbb{CP}^4[5]$ with $W = V_1 + V_2 + L, \quad V_1, L \in G_1$

$\sum_i z_i^5 = 0 \to h_{11} = 1$, one divisor D=H, triple inters. n. $\int_{CY} H^3 = 5$

$$c_2(TX) = 10H^2$$

$$n_i = \int_{CY} \beta_i \wedge \left(\mathrm{tr}_1 \bar{F} \wedge \bar{F} - \frac{1}{2} \mathrm{tr} \bar{R} \wedge \bar{R} \right) = \int_{CY} \beta \wedge \left(c_2(V_2) - \frac{1}{2} c_2(TX) \right)$$

Take e.g. bundle V_2 defined via

$$0 \to \mathcal{O}\Big|_X \xrightarrow{M} \mathcal{O}(1)^{\oplus 5} \oplus \mathcal{O}(3) \xrightarrow{N} \mathcal{O}(8) \to 0$$

$$c(V) = \frac{c(\mathcal{O}(1)^{\oplus 5} \oplus \mathcal{O}(3))}{c(\mathcal{O}|_X)c((\mathcal{O}(8))} = 1 + 25H^2 + .. \quad c_2(V_2) = 25H^2 \to n = \int_{CY} \beta (20H^2) = 100$$