AXION PHOTON COUPLINGS IN TYPE IIB STRING THEORY

based on [2308.xxxxx] with Naomi Gendler, Doddy Marsh, and Liam McAllister

07/07/2023 at String Phenomenology 2023

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AXIONS AND STRING THEORY

Axions are a hallmark of weak coupling limits in string theory:

$$\tau = \frac{\theta}{2\pi} + i\frac{4\pi}{g^2} \quad \text{and} \quad \delta V \sim e^{2\pi i \tau} + c.c.$$

Perturbative shift symmetry $\theta \to \theta + const$
forbids large non-derivative couplings:

- naturally light
- evade fifth force constraints

And: can solve strong CP problem via PQ mechanism!

[Peccei, Quinn'77]

Unique portal to UV physics via dimension five coupling

$$g_{a\gamma\gamma}\,\varphi\,\frac{1}{2}F \wedge F$$

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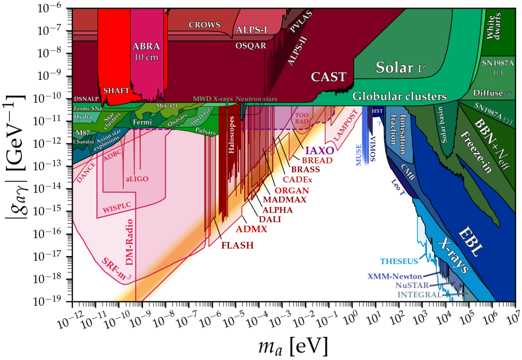
Axions are actively being searched for: [https://github.com/cajohare]



In Calabi-Yau compactifications, usually get large number of axions, the famous axiverse.

[Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell'09]

Important goal: Understand axiverse predictions!

[Demirtas, McAllister, Rios-Tascon'18][Demirtas, Gendler, Long, McAllister, JM'21]

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+see Michele's & Sang Hui's talks!

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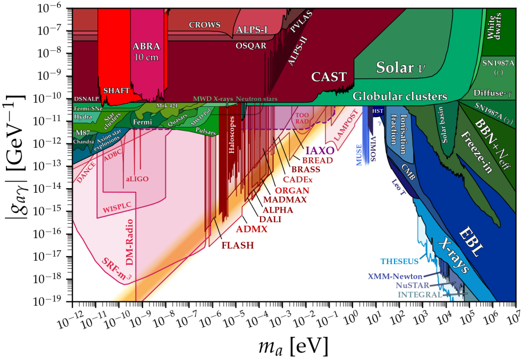

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KEY TAKE AWAYS

We develop machinery to compute axion-photon and axion-axion couplings in generic regime of hierarchical axion masses, at large number of axions.

Key lesson: The axiverse is hard to see. Most (non-)abelian gauge groups couple at most to a few axions.

Two effects conspire:

- Exponential mass hierarchies suppress axion couplings.

[cf. Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell'09]

[cf. Agrawal, Nee, Reig'22]

- Sparse graph of divisor intersections in CY threefolds suppresses couplings (in type IIB axiverse of C_4-axions).

[cf. Halverson, Long, Nelson, Salinas'19]

Also: we apply our tools to the type IIB axiverse of C_4 axions, to study astrophysical constraints and cosmic birefringence.

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PLAN

1. Hierarchies in axion interactions (in type IIB string theory)
2. Astrophysical bounds in an ensemble of semi-realistic models
3. Conclusions

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DIAGONAL TOYMODEL

Start with an oversimplified toymodel. Assume an EFT of

- N axions $\phi^a \simeq \phi^a + 2\pi$, with diagonal kinetic terms

$$\mathcal{L} \supset -\sum_{a=1}^{N} \frac{f_a^2}{2} (\partial \phi_a)^2 \,.$$

- N “basis” instantons generating a potential

$$V(\phi) = \sum_a \Lambda_a^4 \left(1 - \cos(\phi_a)\right) \,, \quad \Lambda_a \geq \Lambda_{a+1} > 0 \,.$$

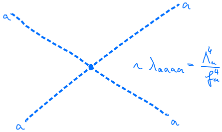
- E&M coupling to a single QED-axion $\theta = \phi_{a^*}$:

$$\mathcal{L} \supset \alpha_{EM} \cdot \frac{\theta}{2\pi} \cdot \frac{1}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} \,.$$

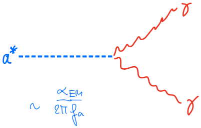
DIAGONAL TOYMODEL (continued)

This theory is almost trivial. We get

- N mass eigenstates $\varphi^a = f_a \cdot \phi_a$ with masses $m_a^2 = \frac{\Lambda_a^4}{f_a^2}$
- only axion self interactions



- a single axion coupling to E&M



This model is of course too naïve!

STRUCTURELESS MODEL

Generically one would expect to find far more general EFTs in string theory, i.e.

- Arbitrary kinetic terms

$$\mathcal{L} \supset -\sum_a \frac{1}{2} K^{ab} \partial\phi_a \partial\phi_b \,.$$

- $N + k$ instantons with generic integer charges $\vec{q}_I$, generating a potential

$$V(\phi) = \sum_{I=1}^{N+k} \Lambda_I^4 \left(1 - \cos\left(2\pi\, \vec{q}_I \cdot \vec{\phi}\right)\right) \,, \quad \Lambda_I \geq \Lambda_{I+1} > 0 \,.$$

- E&M coupling to a general linear combination $\theta_{EM} = 2\pi \vec{q}_{EM} \cdot \vec{\phi}$ with generic integer charge vector $\vec{q}_{EM}$:

$$\mathcal{L} \supset \alpha_{EM} \cdot \frac{\theta_{EM}}{2\pi} \cdot \frac{1}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} \,.$$

STRUCTURELESS MODEL (continued)

Generally, understanding the large N axiverse would seem to be tedious. One has to

- go to canonical normalization, $K^{ab} = e^{ca}e^{cb}$,

$$\hat{\varphi}^a = e^{ab}\phi_b \,.$$

- Numerically find an axion vacuum $\langle\hat{\varphi}^a\rangle$,
- Numerically identify the eigenmodes $\varphi^a = \mathcal{O}^a{}_b\hat{\varphi}^b$ of the Hessian $\mathcal{H}_{ab} = \langle\partial_{\hat{\varphi}^a}\partial_{\hat{\varphi}^b}V\rangle$.
- Compute axion photon couplings by expanding

$$\frac{\theta_{EM}}{2\pi} = \vec{q}_{EM}\cdot\vec{\phi} \equiv \vec{\hat{\mathsf{q}}}_{EM}\cdot\vec{\hat{\phi}} \equiv \vec{\mathsf{q}}_{EM}\cdot\vec{\varphi}\,, \quad g_{a\gamma\gamma} = \alpha_{EM}\mathsf{q}^a_{EM}$$

No particular structure is evident in the $g_{a\gamma\gamma}$ or axion-axion interactions...

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SIMPLICITY AT LARGE N

Somewhat surprisingly, it turns out that type IIB orientifold models are almost like the naïve diagonal model!

The first "emergent" simplification occurs for hierarchical mass scales $\Lambda_a \gg \Lambda_{a+1}$ (Numerically unstable!).

One proceeds as follows:

- Canonically normalize kinetic terms.
- Select the leading N instantons $\vec{\hat{\mathsf{q}}}_a$, by deleting those with charges $\vec{\hat{\mathsf{q}}}_I$ contained in the linear span of the $\vec{\hat{\mathsf{q}}}_{1,\ldots,I-1}$.
- Apply the Gram-Schmidt process to the $\vec{\hat{\mathsf{q}}}_a$ to find an axion basis, s.t. instanton charge matrix is lower triangular:

$$\mathsf{q}_{ab} = \begin{pmatrix} \mathsf{q}_{11} & 0 & 0 & \ldots & 0 \\ \mathsf{q}_{21} & \mathsf{q}_{22} & 0 & \ldots & 0 \\ \vdots & & \ddots & & \\ \mathsf{q}_{N1} & & \ldots & & \mathsf{q}_{NN} \end{pmatrix}$$

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SIMPLICITY AT LARGE N (continued)

Now the instanton term with smallest action depends only on the first axion φ^1:

$$\mathcal{L} = -\frac{1}{2}\partial\varphi^a\partial\varphi^a - \Lambda_1^4\left(1-\cos\left(2\pi \mathsf{q}_{11}\varphi^1\right)\right) + \ldots$$

In limit $\frac{\Lambda_2}{\Lambda_1} \to 0$ the axion φ^1 is a mass eigenstate.

Integrating out φ^1, get EFT of $N-1$ axions with upper triangular instanton charge matrix, so by induction:

"Gram-Schmidt" basis = Mass eigenbasis$+\mathcal{O}\left(\frac{\Lambda_a^4}{\Lambda_{a+1}^4}\right)$.

SOME CONSEQUENCES

- Axion masses: $m_a^2 \approx \frac{\Lambda_a^4}{f_a^2}$ with $f_a := (2\pi \mathfrak{q}_{aa})^{-1}$.

$$V(\varphi) = \sum_{a=1}^{N} \Lambda_a^4 \left(1 - \cos\left(\sum_b \theta_{ab} \frac{\varphi^b}{f_b}\right)\right)$$

with hierarchical mixing angles θ_{ab}:

- Mass suppressed mixing angles

$$\theta_{ab} \approx \frac{\mathfrak{q}_{ab}}{\mathfrak{q}_{bb}} \quad \text{for} \quad b \leq a$$

$$\theta_{ab} \approx -\frac{\Lambda_b^4}{\Lambda_a^4}\frac{\mathfrak{q}_{ba}}{\mathfrak{q}_{aa}} \ll 1 \quad \text{for} \quad b > a$$

Light axions do not mix into “heavy” theta angles.

SOME CONSEQUENCES (continued)

- If $\vec{\mathsf{q}}_{EM}$ also contributes an instanton term to potential,

$$V(\varphi) \supset \Lambda_{\rm EM}^4 \left(1 - \cos(2\pi \vec{\mathsf{q}}_{EM} \cdot \vec{\varphi})\right) ,$$

axions lifted by instantons with $\Lambda_a \ll \Lambda_{EM}$ do not couple to EM:

$$g_{a\gamma\gamma} f_a = \mathcal{O}\left(\frac{\Lambda_a^4}{\Lambda_{EM}^4}\right)$$

- Mixed quartics suppressed by lightest mass scale:

$$\lambda_{a \le b \le c < d} \sim \frac{\Lambda_d^4}{f_a f_b f_c f_d} \theta_{da} \theta_{db} \theta_{dc}$$

Axions preferentially decay to their mass neighbors.

KINETIC DECOUPLING IN TYPE IIB AXIVERSE

So far: discussed suppression of couplings in ratios of mass scales Λ_a.

$\Rightarrow$ pure QFT effect

Next: Planck-suppression of axion interactions from kinetic decoupling at large $N \equiv h^{1,1}_+$

We will study Calabi-Yau hypersurfaces X in toric fourfolds V at large $h^{1,1}$, i.e. the KS-database.

Axions given by $h^{1,1}_+$ zero modes of C_4, lifted by D3-brane instantons wrapped on four-cycles.

ASSUMPTIONS AND APPROXIMATIONS

- All BPS D3-brane instantons contribute to W.
- SUSY is broken at low enough scales s.t. BPS instantons dominate over non-BPS instantons, i.e.

$$m_{\frac{3}{2}} \ll M_P$$

- The Kähler and CS moduli of X are stabilized at high scales compared to the axion masses $m_a = \Lambda_a^2/|f_a|$.
- No two-form axions, i.e. $h^{1,1}_{-} = 0$.
- Standard model realized on (intersecting) 7-branes.
- Approximate the cone of effective divisors by the one inherited from toric ambient variety.

AXION FIELD SPACE METRIC

The smallest irreducible divisors in a CY X are the prime toric divisors:

$$D_i := \{x_i = 0\} \cap X\,, \quad i = 1, \ldots, h^{1,1}(X) + 4$$

Letting D_a be basis of $H^2(X)$ furnished by subset of smallest linearly independent $h^{1,1}$ prime toric divisors:

$$q_{ab} = \delta_{ab}$$

Their overlap, measured by inverse Kähler metric is

$$K_{ab} = \langle D_a, D_b \rangle = 2\mathcal{V}\left(c_{ab} + \frac{\mathrm{Vol}(D_a)\mathrm{Vol}(D_b)}{\mathcal{V}}\right)$$

with $c_{ab} = 0$ if $D_a \cap D_b = \emptyset$.

Off-diagonal terms K_{ab} from non-intersecting divisors are Planck-suppressed, i.e. $\propto 1/\mathcal{V}$.

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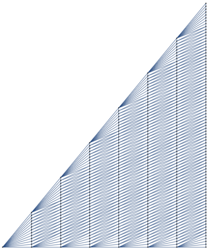
AXION FIELD SPACE METRIC (continued)

Crucial: At large $h^{1,1}$ divisor intersections are sparse!

[cf. Halverson, Long, Nelson, Salinas'19]

Reason: Toric ambient variety arises from triangulating reflexive polytope Δ°. A pair of divisors (D_a, D_b) intersects iff points (p_a, p_b) in Δ° are in same two-face of Δ° and connected by triangulation:



(largest two-face of Δ° with $h^{1,1} = 491$, Delaunay triangulation)

LOCALIZATION OF AXION WAVEFUNCTION

In absence of off-diagonal terms we would be back to our naïve toy model with trivial mixing angles $\theta_{ab} = 0$ for $a \neq b$. Every mass eigenstate overlaps precisely with one basis divisor.

This gets corrected by

- Cross terms c_{ab} for intersecting divisors
  $\Rightarrow$ Local in intersection graph.
- Planck suppressed off-diagonals $\frac{\mathrm{Vol}(D_a)\mathrm{Vol}(D_b)}{\mathcal{V}}$
  $\Rightarrow$ Non-local in intersection graph,
  negligible for small pairs of divisors.

Mixing angles θ_{ab} are

- localized around $a = b$ in intersection graph,
- and mass suppressed for $a < b$.

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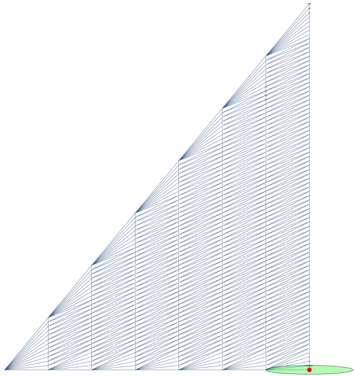
LOCALIZATION OF AXION WAVEFUNCTION

Example at $h^{1,1} = 491$,
at "tip of the stretched Kähler cone": $\mathcal{V} \approx 1.7 \times 10^{12}$
QED on smallest divisor: $\mathrm{Vol}(D) = 0.5$



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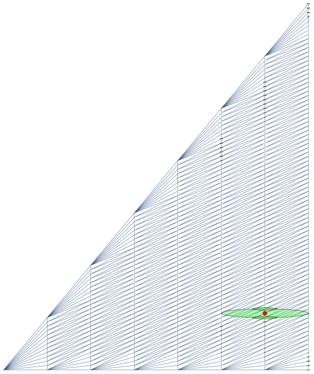
QED on 20th divisor: $\mathrm{Vol}(D) = 11$



LOCALIZATION OF AXION WAVEFUNCTION

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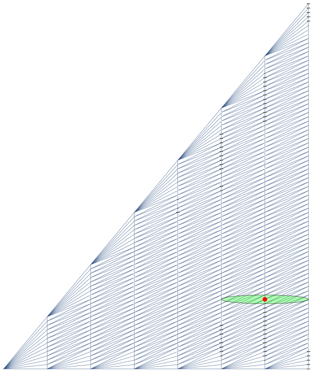
QED on 50th divisor: $\mathrm{Vol}(D) = 23$



LOCALIZATION OF AXION WAVEFUNCTION

Example at $h^{1,1} = 491$,
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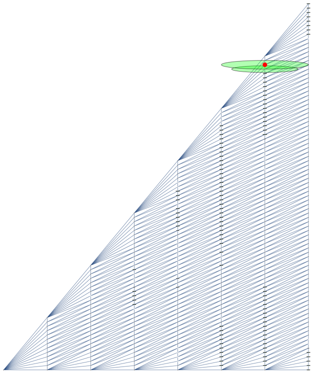
QED on 100th divisor: $\mathrm{Vol}(D) = 63$



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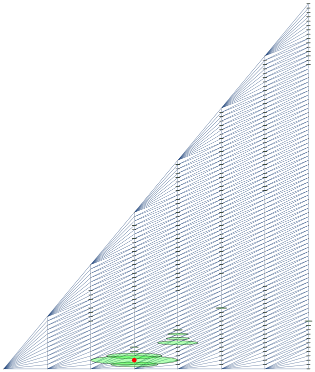
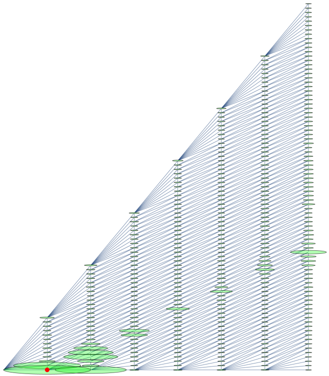
QED on 200th divisor: $\mathrm{Vol}(D) = 655$



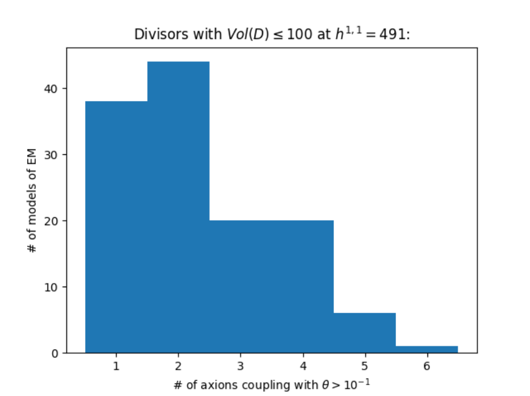
LOCALIZATION OF AXION WAVEFUNCTION

Example at $h^{1,1} = 491$,
at "tip of the stretched Kähler cone": $\mathcal{V} \approx 1.7 \times 10^{12}$
QED on 343th divisor: $\mathrm{Vol}(D) = 6.8 \times 10^{6}$



IS AN AXIVERSE INVISIBLE ?

Even at very large $h^{1,1}$ most standard models realized on (intersecting) seven-branes couple to few axions:



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AXION HELIOSCOPES

How relevant are the suppression effects for real world experiments?

One of the most stringent bounds on axion photon couplings: axion helioscopes

CAST EXPERIMENT

Effective coupling probed:

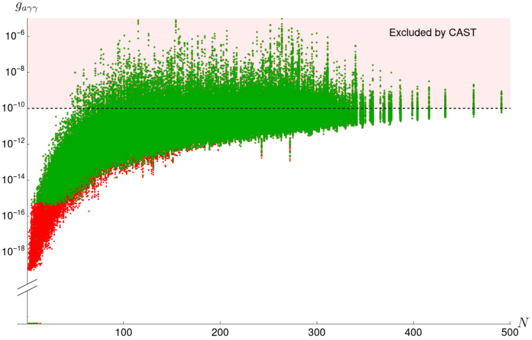
$$g_{\text{eff}} = \sqrt{\sum_{m_a < 1\text{eV}} (g_{a\gamma\gamma})^2} = \sqrt{\sum_{m_a < 1\text{eV}} \left(\frac{\alpha_{EM}}{2\pi f_a} \theta_{\text{EM},a} \right)^2}$$

Bound from CAST: $g_{\text{eff}} \lesssim 10^{-10} (\text{GeV})^{-1}$.

Without mixing suppression, i.e. $\theta_{\text{EM},a} = \mathcal{O}(1)$, get dominated by smallest f_a.

TYPE IIB AXIVERSE EXCLUSIONS (naïve)

Under this assumption, significant part of the type IIB axiverse would seem to be excluded: [Demirtas, Gendler, Long, McAllister, JM'21]



Key fact: f_a vary over a few orders of magnitude

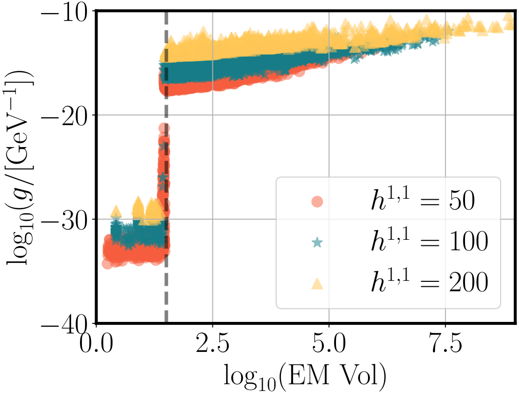
[Demirtas, McAllister, Rios-Tascon'20]

But: With significant mixing suppression, expect

$$g_{eff} \sim \frac{\alpha_{\rm EM}}{2\pi\langle f_a\rangle} \ll \frac{\alpha_{\rm EM}}{2\pi\,\min_a(f_a)}$$

MASSES AND COUPLINGS

Including mixing suppression, bounds are significantly relaxed:



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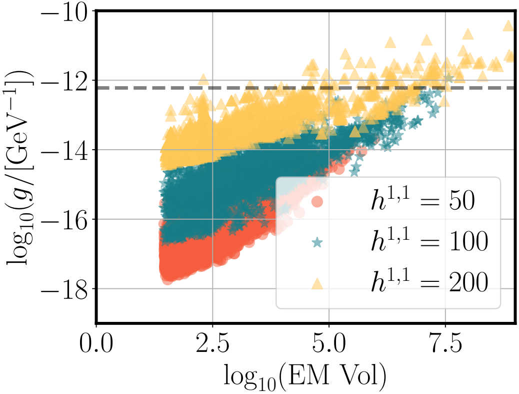

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COSMIC BIREFRINGENCE

Currently there is $\sim 3.6\sigma$ evidence for

cosmic birefringence in CMB := non-zero rotation of polarization plane by angle β between CMB and today.

$$\beta = (6.0 \pm 1.6) \times 10^{-3}$$

[Minami, Komatsu'20][Eskilt, Komatsu'22] +Donghui's talk!

Possible explanation:

[Carroll, Field, Jackiw'90]

axion φ with $\quad 10^{-33}eV \sim H_{\rm now} < m < H_{\rm CMB} \sim 10^{-28}eV$

relaxes to minimum from generic initial field displacement φ_0

$$\beta \approx g_{a\gamma\gamma}\varphi_0 = \frac{\alpha_{\rm EM}}{2\pi}\theta_{{\rm EM},a}\frac{\varphi_0}{f_a} \approx 3\times 10^{-3}\times\theta_{{\rm EM},a} \quad \text{for} \quad \varphi_0 \sim \pi\cdot f_a$$

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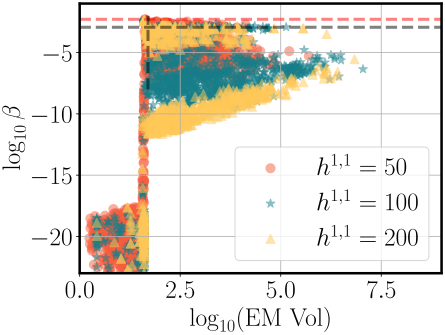
$$\beta \approx g_{a\gamma\gamma}\varphi_0 = \frac{\alpha_{\rm EM}}{2\pi}\theta_{{\rm EM},a}\frac{\varphi_0}{f_a} \approx 3 \times 10^{-3} \times \theta_{{\rm EM},a} \quad \text{for} \quad \varphi_0 \sim \pi \cdot f_a$$

COSMIC BIREFRINGENCE (continued)

To account for this, need axion(s) with $\mathcal{O}(1)$ mixing angle to standard model.

We find this to be possible only if QED-axion itself falls in correct mass window, $\text{Vol}(D_{QED}) \gtrsim 40$:



Incidentally, this gives correct GUT scale $U(1)_Y$ coupling in standard model $\frac{4\pi}{g^2(10^{16}GeV)} \sim 40$...

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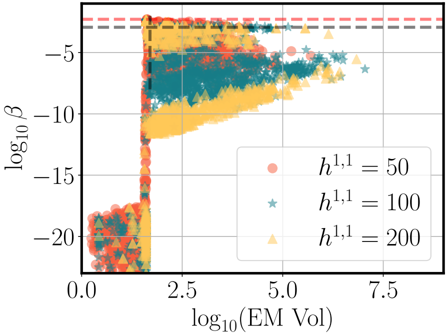

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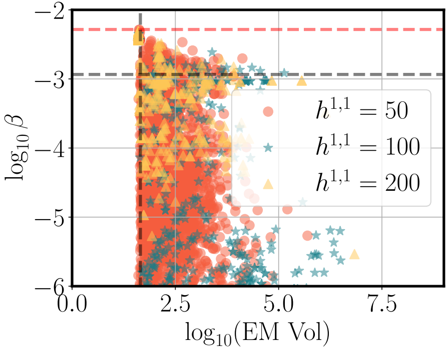
COSMIC BIREFRINGENCE (continued)

To account for this, need axion(s) with $\mathcal{O}(1)$ mixing angle to standard model.

This appears to be possible only if QED-axion itself falls in correct mass window, $\mathrm{Vol}(D_{QED}) \gtrsim 40$:



Incidentally, this coincides with GUT scale $U(1)_Y$ coupling in standard model $\frac{4\pi}{g^2(10^{16}\mathrm{GeV})} \sim 40 \ldots$

CONCLUSIONS

We have developed tools to systematically compute axion photon couplings in large axiverses with large separation of scales.

We have learned that a true axiverse is almost invisible: QED realized on a small divisor couples to $\mathcal{O}(1)$ axions even in models with many axions. This significantly reduces constraints from astrophysical processes.

WIP not mentioned: dark matter abundances from misalignment, freeze-in/out, constraints from decaying dark matter, moduli problem, dark radiation...

Macaulay2, Computational Algebraic Geometry and String Theory

To be held at the University of Utah

May 28th - June 1st, 2024 (School)

June 3rd - June 5th, 2024 (Conference)

CY Tools

May 28-June 5, 2024

Organizers: D. Eisenbud, D. Grayson, A. Leykin, A. Lukas, L. McAllister, K. Schwede, M. Stillman

감사합니다