A Fuzzy Axiverse from String Theory

based on upcoming work with F. Carta, N. Gendler, M. Jain, D. Marsh, L. McAllister, N. Righi, K. Rogers and E. Sheridan

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Upshot

We find explicit string theory models for dark matter (DM) with multiple fuzzy axions and the QCD axion.

For these models, we …

- … compute the DM abundance of axions from vacuum realignment,
- … investigate the required T_{reh} and SUSY breaking scale to avoid DM overabundance, and
- … find extra dark vector fields (=dark radiation?).

Outline

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1 **INTRODUCTION**

2 AXION EFTS FROM STRING THEORY

3 A FUZZY AXIVERSE IN STRING THEORY

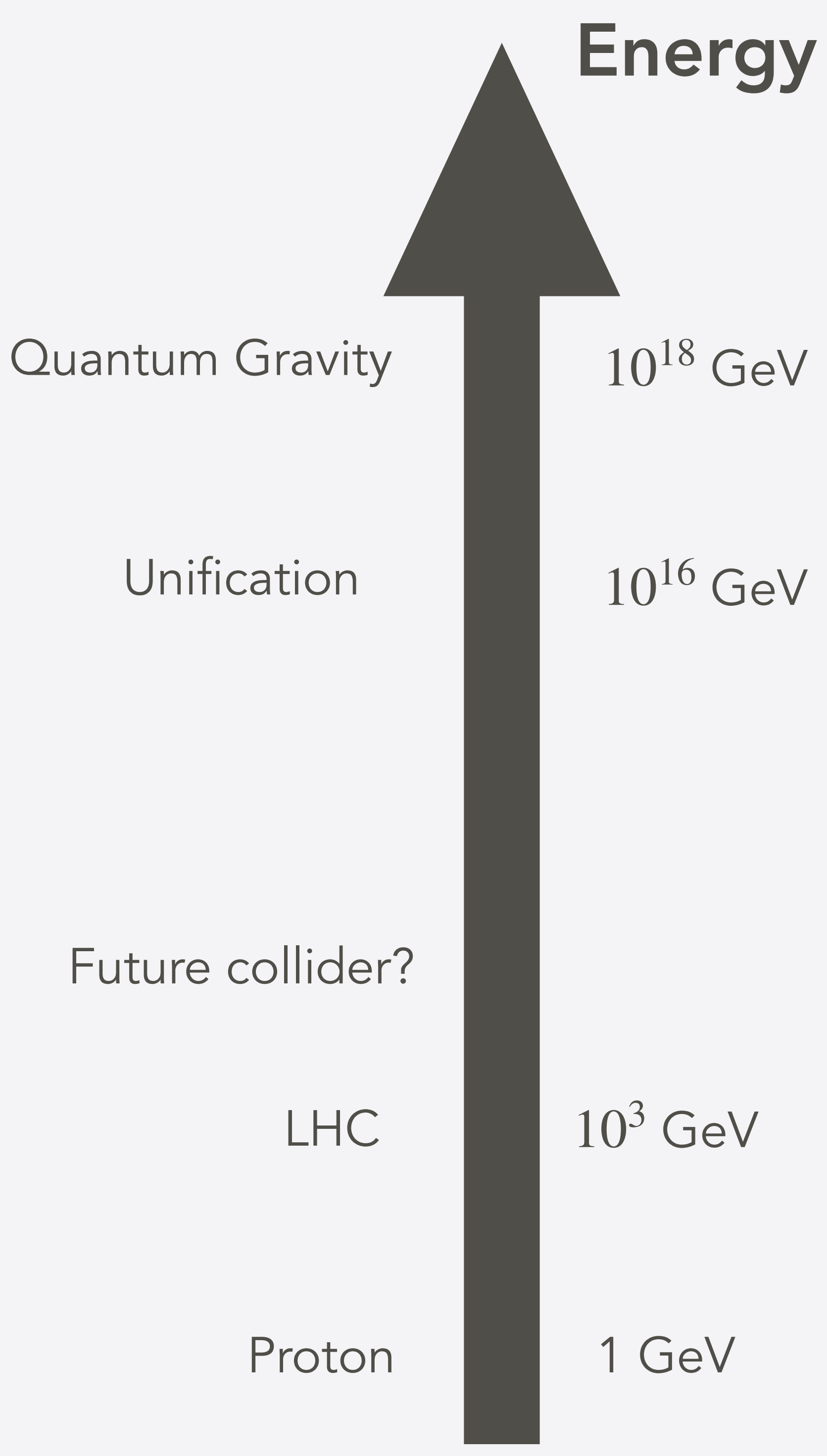
4 RESULTS

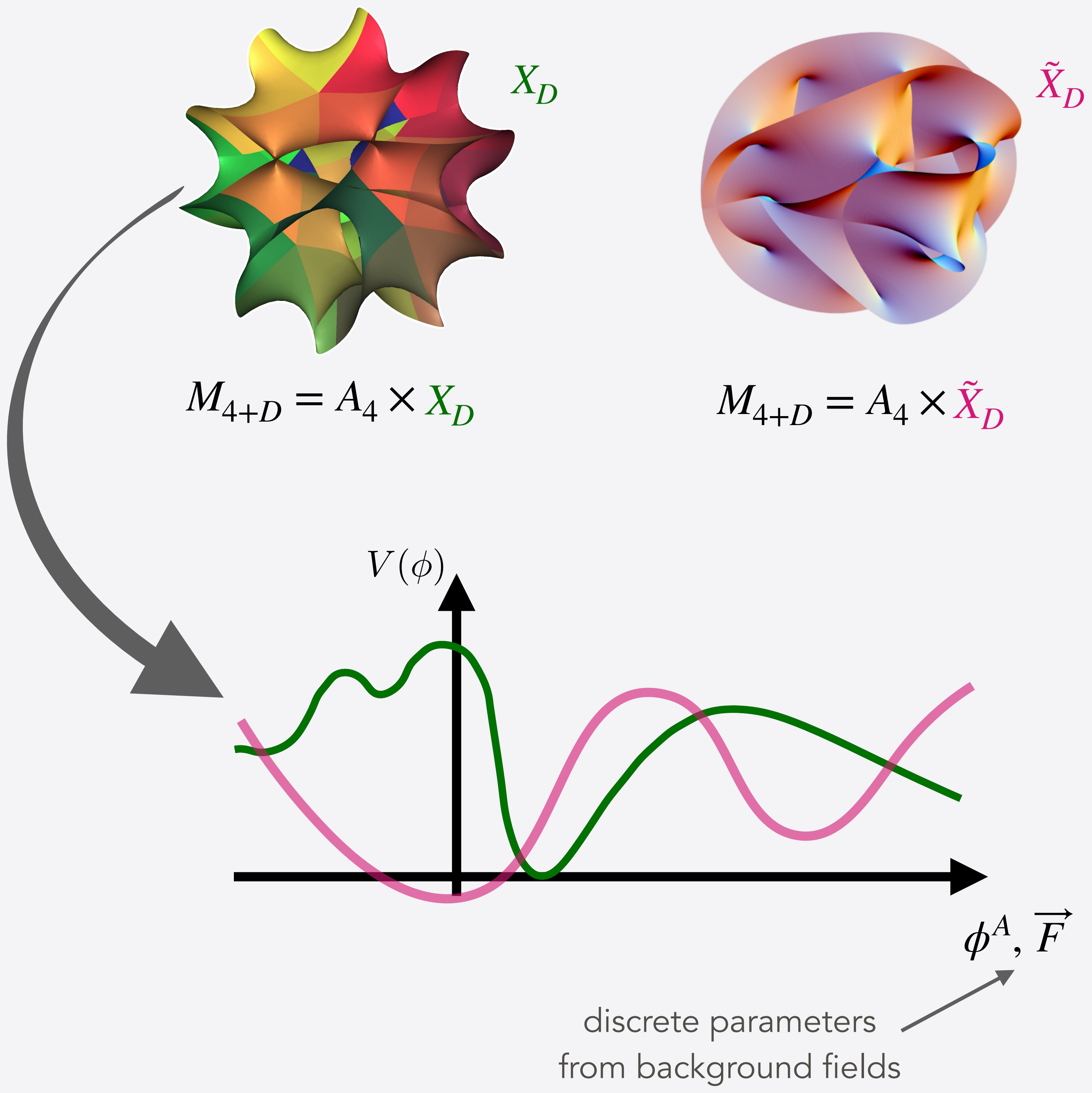
5 CONCLUSIONS

Introduction and Motivation

The String Theory Landscape

MOTIVATION: WHICH BSM PHYSICS DOES STRING THEORY PREDICT?





String theory predicts **extra dimensions** which need to be **compactified** to describe a four-dimensional universe at low energies.

Generic features:

- Different compact manifolds lead to varying physics at low energies (spectra, scales, cosmological evolutions, …).
- Additional light scalar fields associated with compact geometry (=**moduli**).
- Plethora of **axion-like particles (ALPs)** from higher-dimensional gauge fields.

The **string landscape** is the space of all such 4D EFTs from string theory.

Question:

What can we say about models of **axion dark matter** in these theories?

Introduction and Motivation

The String Axiverse

See also talk by J. Leedom, A. Westphal

Typical string compactifications contain $\mathcal{O}(100)$ axion-like particles ϕ^a with a rich phenomenology [Arvanitaki et al. 0905.4720] → **String Axiverse**

The general Lagrangian in string compactifications

$$\mathcal{L} = -\frac{1}{2} K_{ab}(\partial_\mu \phi^a)(\partial^\mu \phi^b) - V(\phi) - g_{a\gamma\gamma}\, \phi^a \frac{\alpha}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} + \dots$$

naturally contains axionic couplings to

- moduli parametrising the compact geometry,
- SM degrees of freedom like photons or gluons, and
- other hidden sectors.

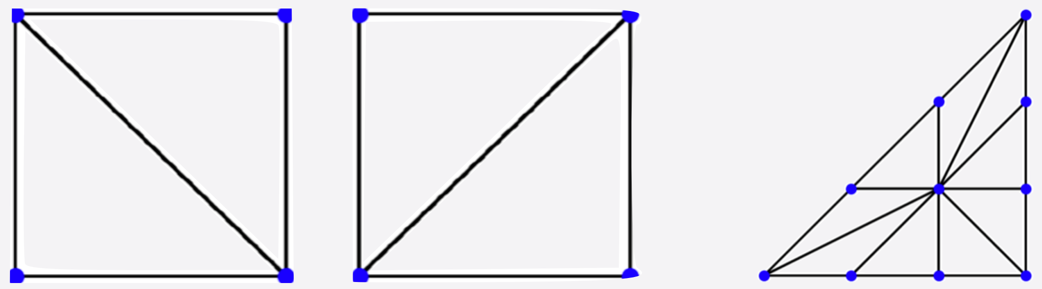
Outline

Axion EFTs from Type IIB String Theory

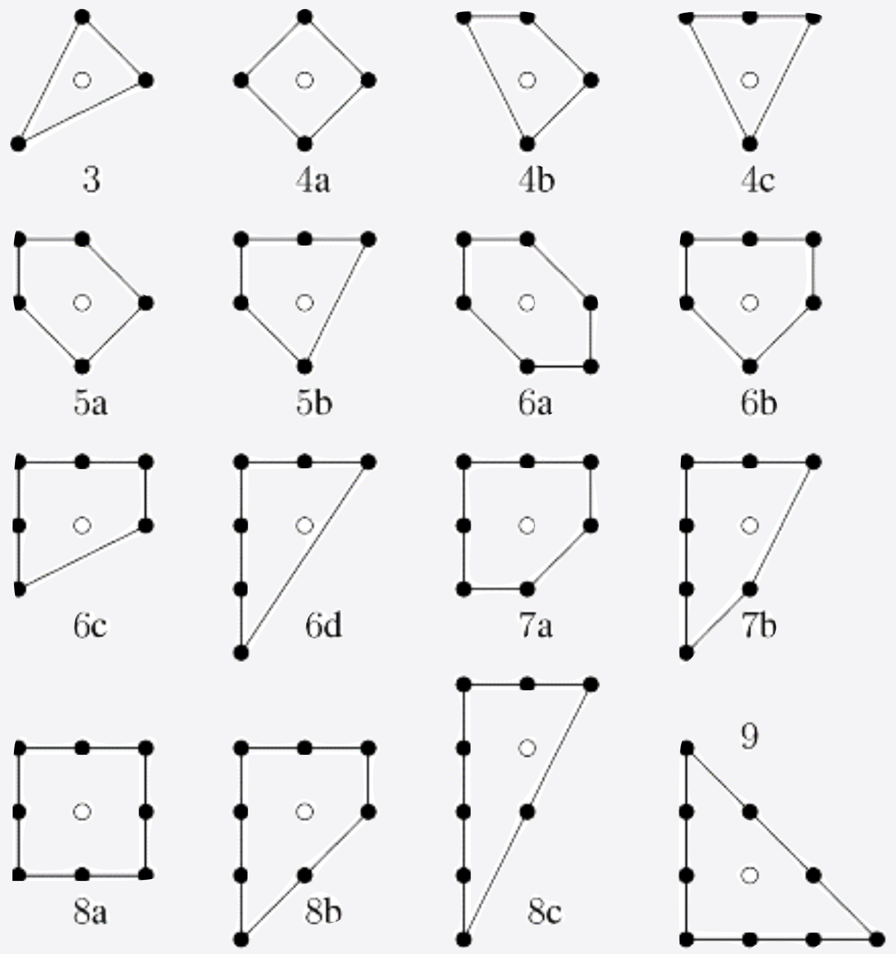
Setup and Geometries

We will focus on the **Kreuzer-Skarke (KS) Axiverse** [Demirtas et al. 1808.01282] for C_4-axions as a corner of the **Type IIB Axiverse** [Cicoli et al. 1206.0819].

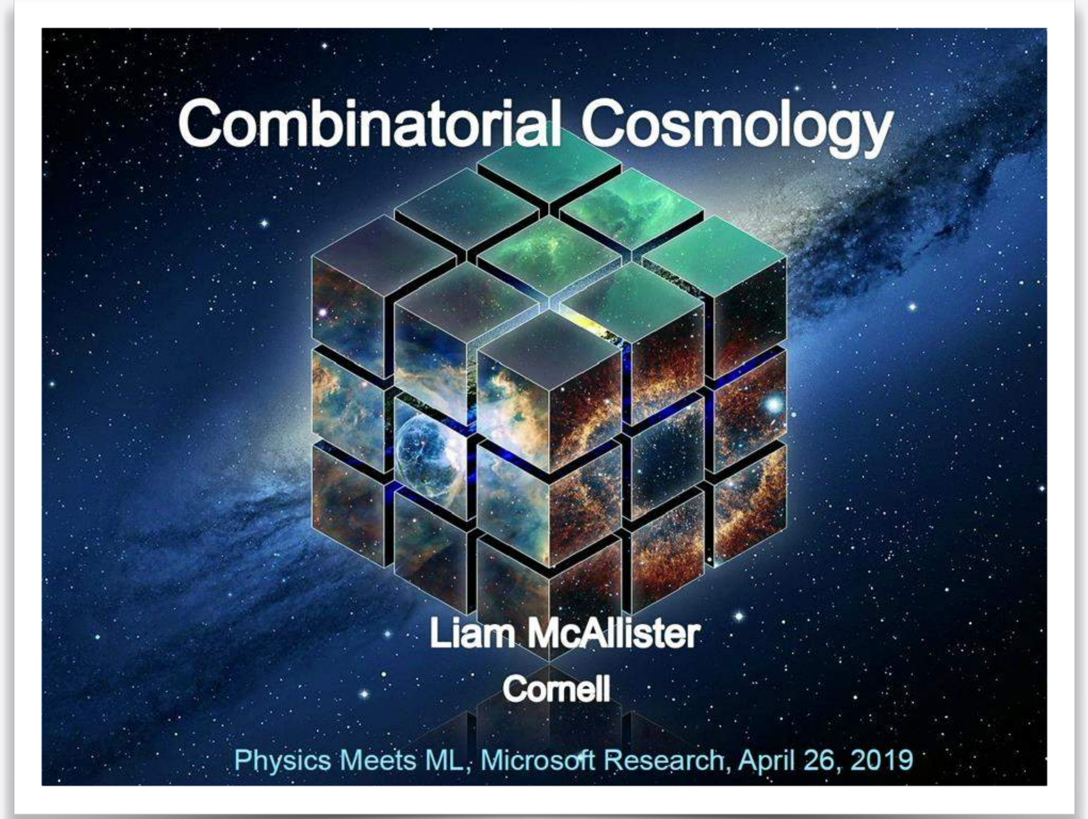
That is, we will work with CY_3 hypersurfaces X in toric varieties V obtained from triangulations of 4D polytopes Δ.



Demirtas, Rios-Tascon, McAllister 2211.03823



473,800,776 reflexive polytopes in 4D
Kreuzer, Skarke (KS) [hep-th/0002240]



In this KS axiverse, previous works studied e.g.

- BH superradiance [Mehta et al. 2011.08693, 2103.06812]
- PQ quality problem [Demirtas et al. 2112.04503]
- Axion-photon couplings [Gendler et al. 2309.13145]

Axion EFTs from Type IIB String Theory

The Type IIB Axiverse

See also talk by J. Leedom, A. Westphal

In the 4D EFT, the **(F-term) scalar potential** for the Kähler moduli $T^a = \tau^a + \mathrm{i}\,\phi^a$, $a = 1,\ldots,h^{1,1}$, is of the form

$$V(\tau^a,\phi^a) = V(\tau^a) + \sum_I \Lambda_I^4(\tau^a)\cos\left(-2\pi\mathcal{Q}_b^I\phi^b + \delta^I\right) + \ldots\ ,\quad \Lambda_I^4 \sim m_{3/2}\,\mathcal{Q}_b^I\tau^b\,\exp\left(-2\pi\mathcal{Q}_b^I\tau^b\right)\ ,\quad m_{3/2}\sim\frac{W_0}{\mathcal{V}^2}\,.$$

The masses m_a and decay constants f_a for axions **depend on values of moduli** τ^a

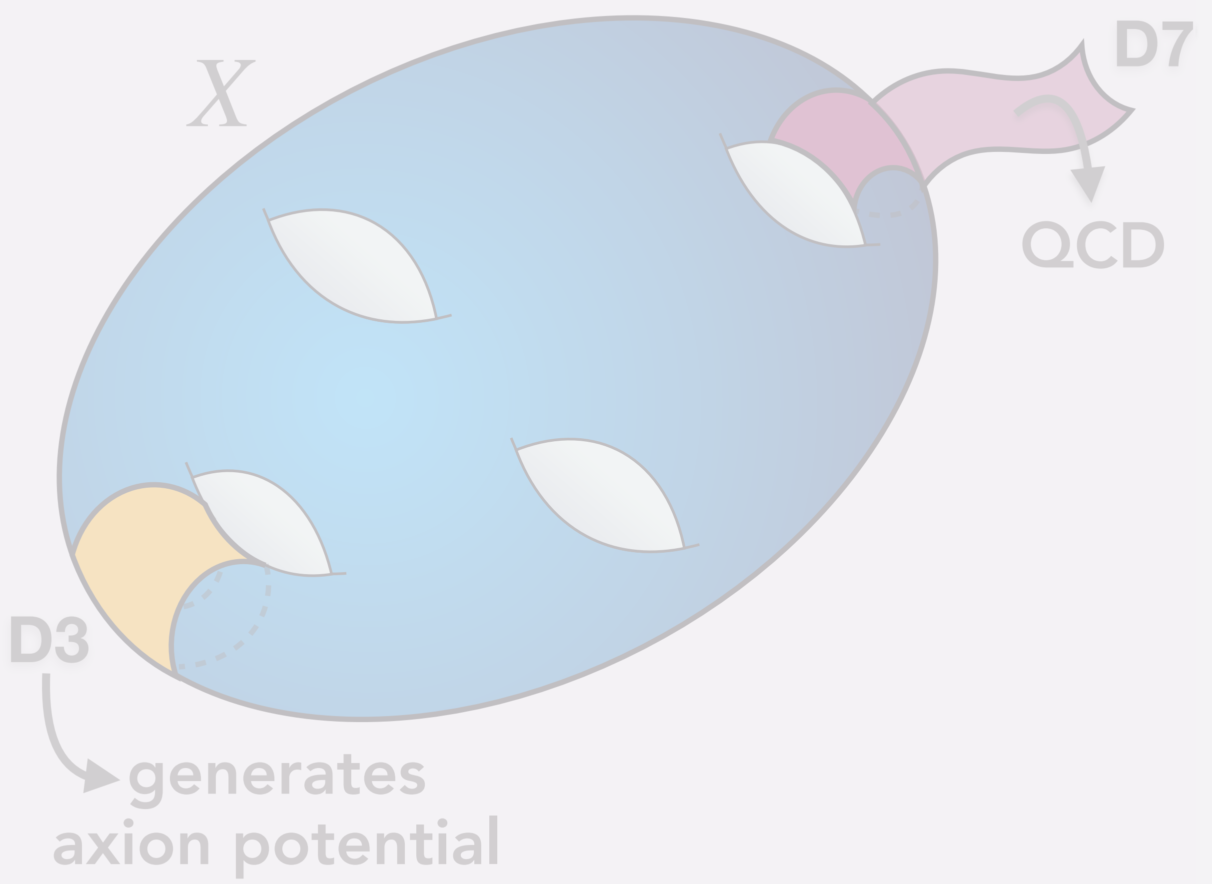
$$f_a \sim \frac{1}{\tau^a}\ ,\qquad m_a^2 \sim m_{3/2}\,\tau^a\,\frac{\mathrm{e}^{-2\pi\tau^a}}{f_a^2}\,.$$

Exponential suppression of m_a^2 naturally leads to **ultra-light ALP** in the regime $\tau^a \gg 1$.

The SM sector can e.g. be realised on wrapped branes with $T^{QCD} = \tau^{QCD} + \mathrm{i}\,\phi^{QCD}$ where

- ϕ^{QCD} is the **QCD axion**, and
- τ^{QCD} sets the **QCD gauge coupling** in the UV (see talk by J. Leedom)

$$g_{QCD}^2 \sim \frac{1}{\tau^{QCD}} \quad\Rightarrow\quad \tau^{QCD}\approx 40\ \text{ s.t. }\ \alpha_s(M_Z^2)\approx 0.118\,.$$



Axion EFTs from Type IIB String Theory

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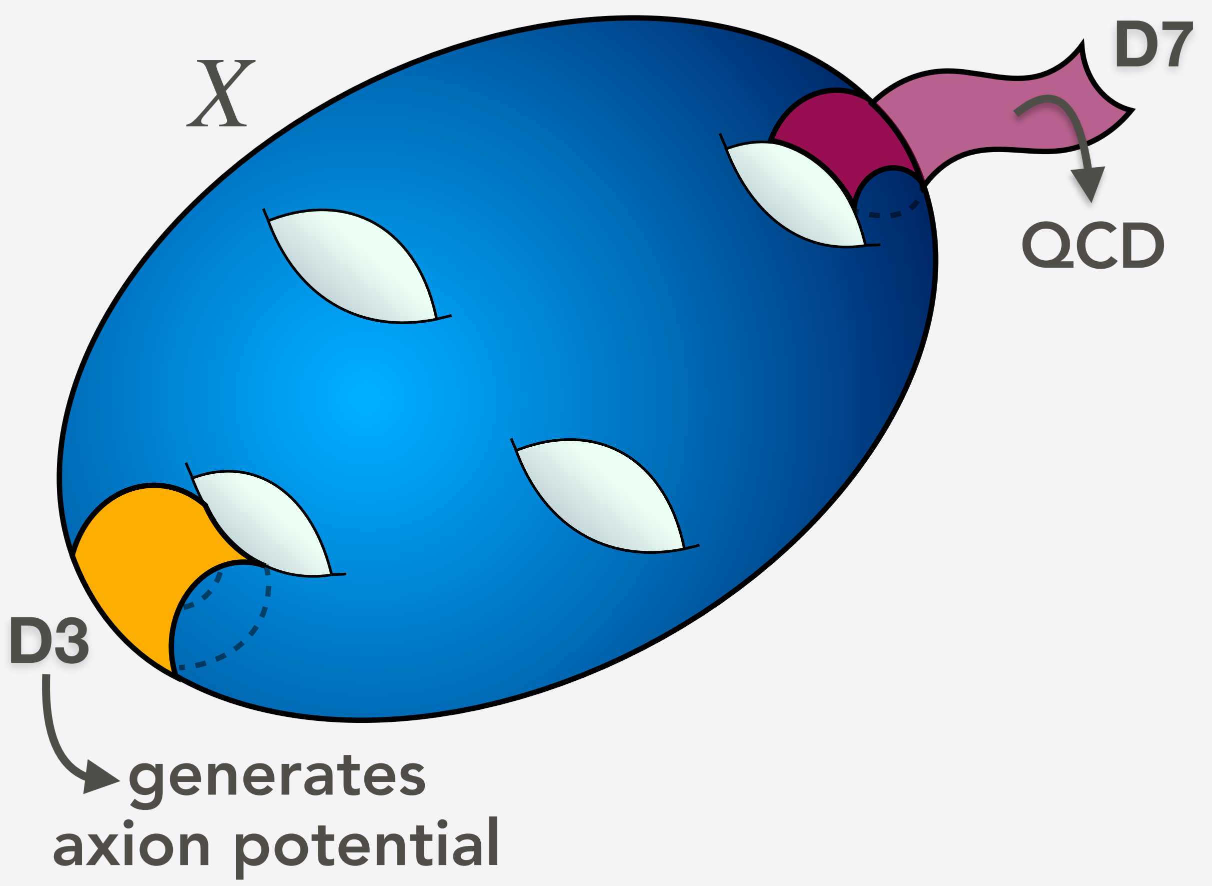

Axion EFTs from Type IIB String Theory

From Polytopes to Axions — Summary

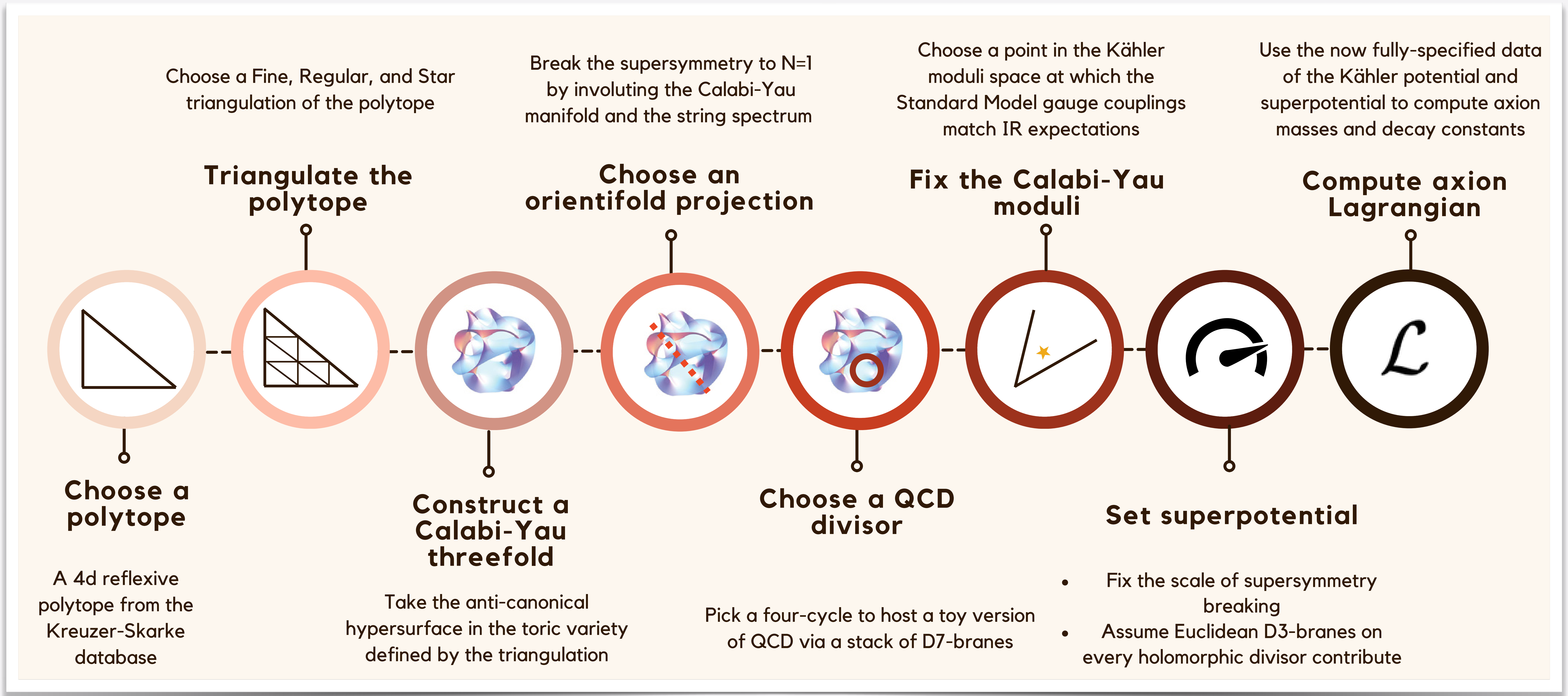

Figure credit: N. Gendler

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A Fuzzy Axiverse in String Theory

Stringy assumptions

See also talk by A. Westphal

Fuzzy Axiverse from ChatGPT

We construct all CY orientifolds in KS with $2 \leq h^{1,1} \leq 7$ using [Moritz 2305.06363] with $h^{1,1}_{-} = 0$ (i.e., only C_4-axions).

Our ensemble is then generated as follows:

A. sample $\tau^a \geq 1$ for computational control,

B. assume moduli can be stabilised by perturbative effects,

C. need a divisor with volume close to 40 hosting QCD,

D. require $m_a \sim 10^{-19}\,\mathrm{eV}$ for at least one axion for large DM abundance,

E. heaviest axion has mass below KK-scale.

Throughout this talk, we refer to axions with $m_a \lesssim 10^{-18}\,\mathrm{eV}$ as ***fuzzy axions***.

Related work: Fuzzy DM + moduli stabilisation [Cicoli et al. 2110.02964]

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A Fuzzy Axiverse in String Theory

Cosmology assumptions

Vacuum realignment mechanism for DM production:
see e.g. [Marsh 1510.07633, O'Hare 2403.17697].

We assume inflation is described by 4D EFT with axions ϕ^a in the pre-inflation regime with initial misalignment angle θ_a.

We compute the abundance assuming

- standard phases of radiation, matter, and c.c. domination,
- a possibly unknown pre-heating phase after inflation, and
- that moduli are much heavier than the axions.

E.g. the relic density for axions with $10^{-28}\,\text{eV} \lesssim m_a \lesssim 10^{-15}\,\text{eV}$ is

$$\Omega_a h^2 \approx 0.12\,\theta_a^2 \left(\frac{m_a}{4.8\cdot 10^{-17}\,\text{eV}}\right)^{1/2}\left(\frac{f_a}{10^{15.5}\,\text{GeV}}\right)^2$$

To solve overabundance problem, we can 1) tune θ_a, 2) couple axions to e.g. photons, 3) lower H_I or modify cosmology.

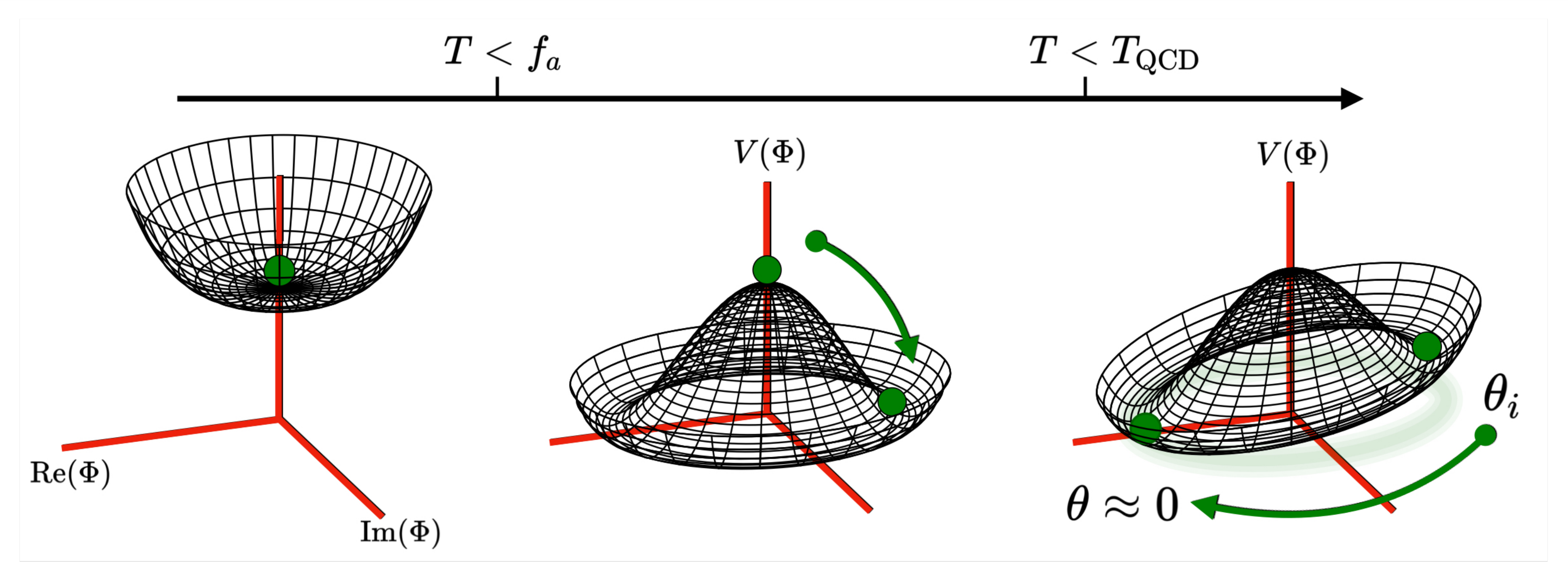

Figure credit: O'Hare 2403.17697

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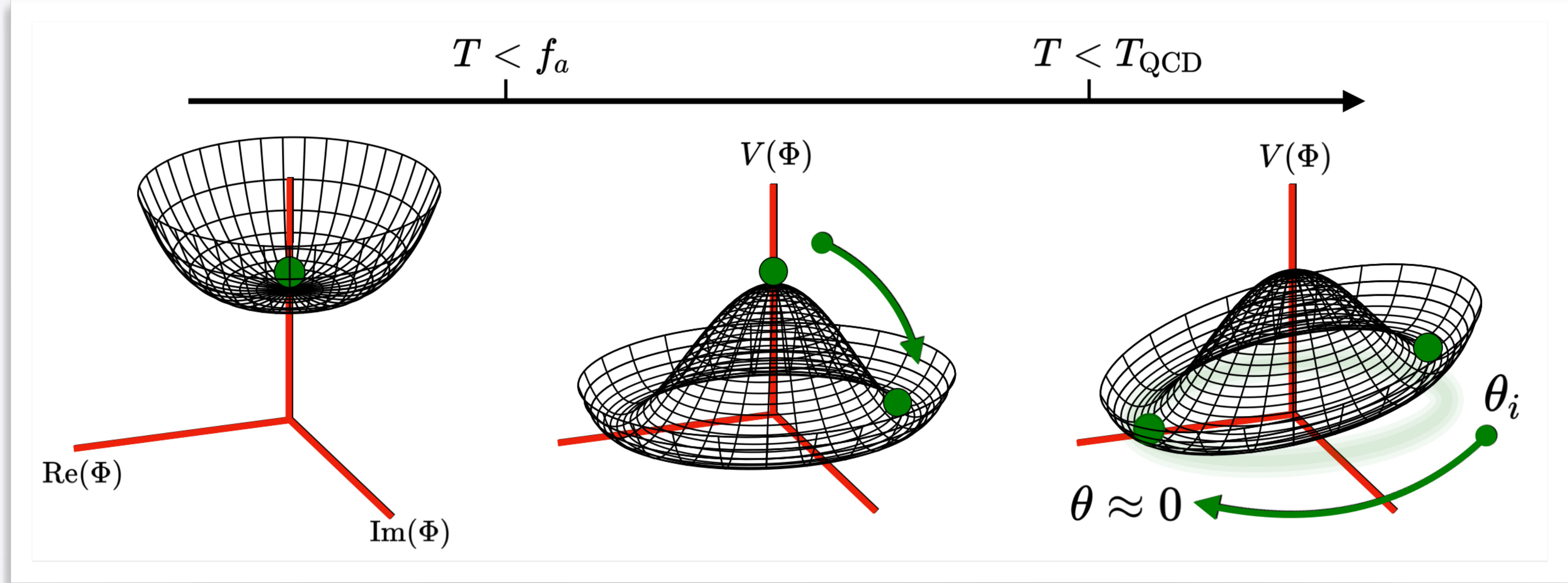

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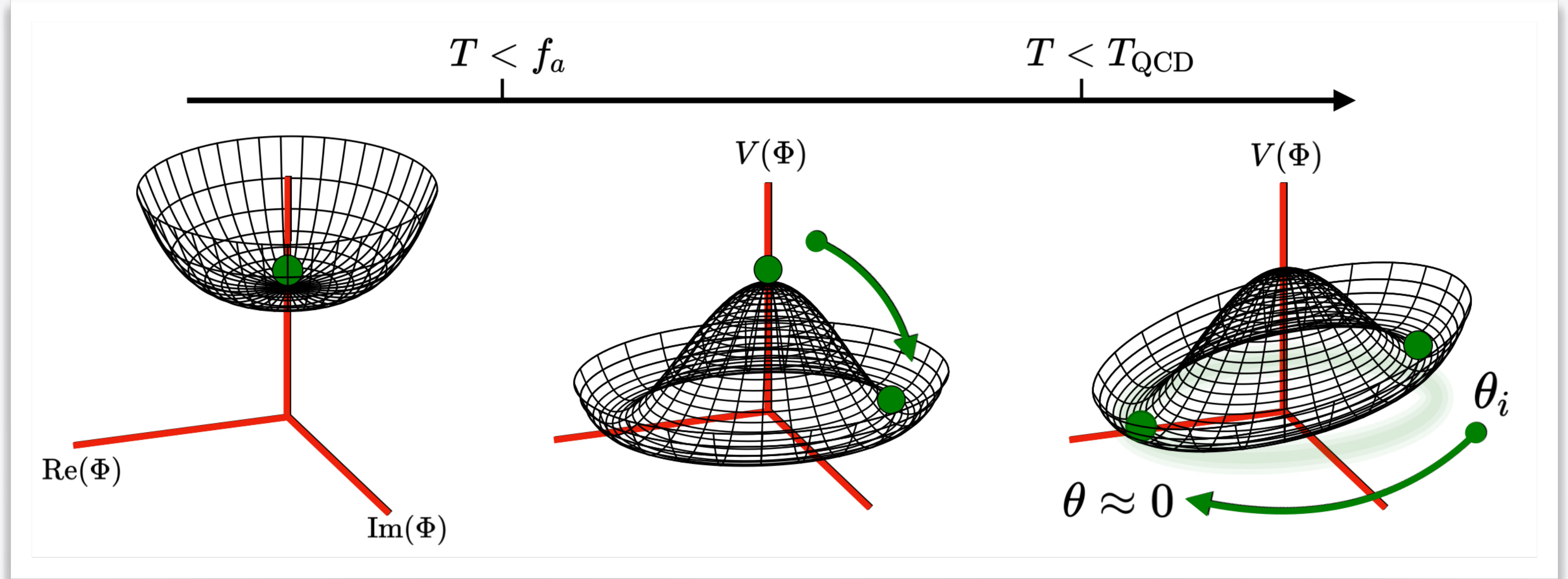

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Outline

Results

Simple example — $h^{1,1} = 2$

Our model contains two axions for which we compute m_a, f_a at

$$(t_1, t_2) \approx (16.96\,, 2.74) \in \mathcal{K}(X)\,.$$

We find that at this point in $\mathcal{K}(X)$

$$\log_{10}(m_{QCD}/\text{eV}) = -8.74\,, \quad \log_{10}(f_{QCD}/\text{GeV}) = 15.49\,,$$

$$\log_{10}(m_{fuzzy}/\text{eV}) = -19.23\,, \quad \log_{10}(f_{fuzzy}/\text{GeV}) = 16.07\,.$$

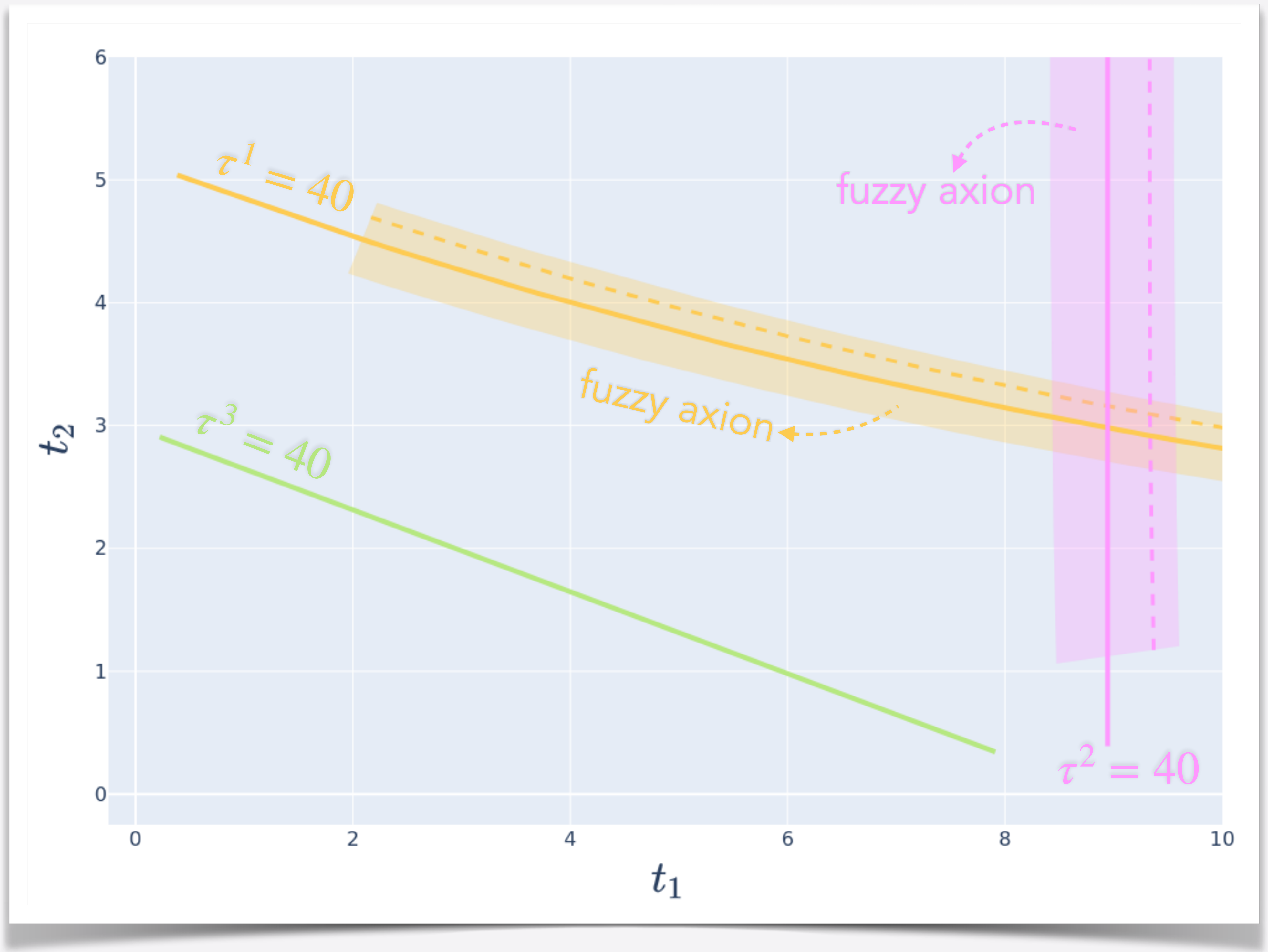
The misalignment abundance for the fuzzy axion is

$$\frac{\Omega_{fuzzy}}{\Omega_{DM}} \approx 0.458\,.$$

For the QCD axion to account for remaining DM, we need

$$\theta_{QCD} \approx 0.0079\,.$$

Kähler cone $\mathcal{K}(X) = \{(t_1, t_2) \in \mathbb{R}^2 : \ t_1 \geq 0\,, \ \ t_2 \geq 0\}$



Moduli values are given by $2\tau^a = \kappa^{ajk}\, t_j t_k$ for some topological numbers $\kappa^{ajk} \in \mathbb{Z}$.

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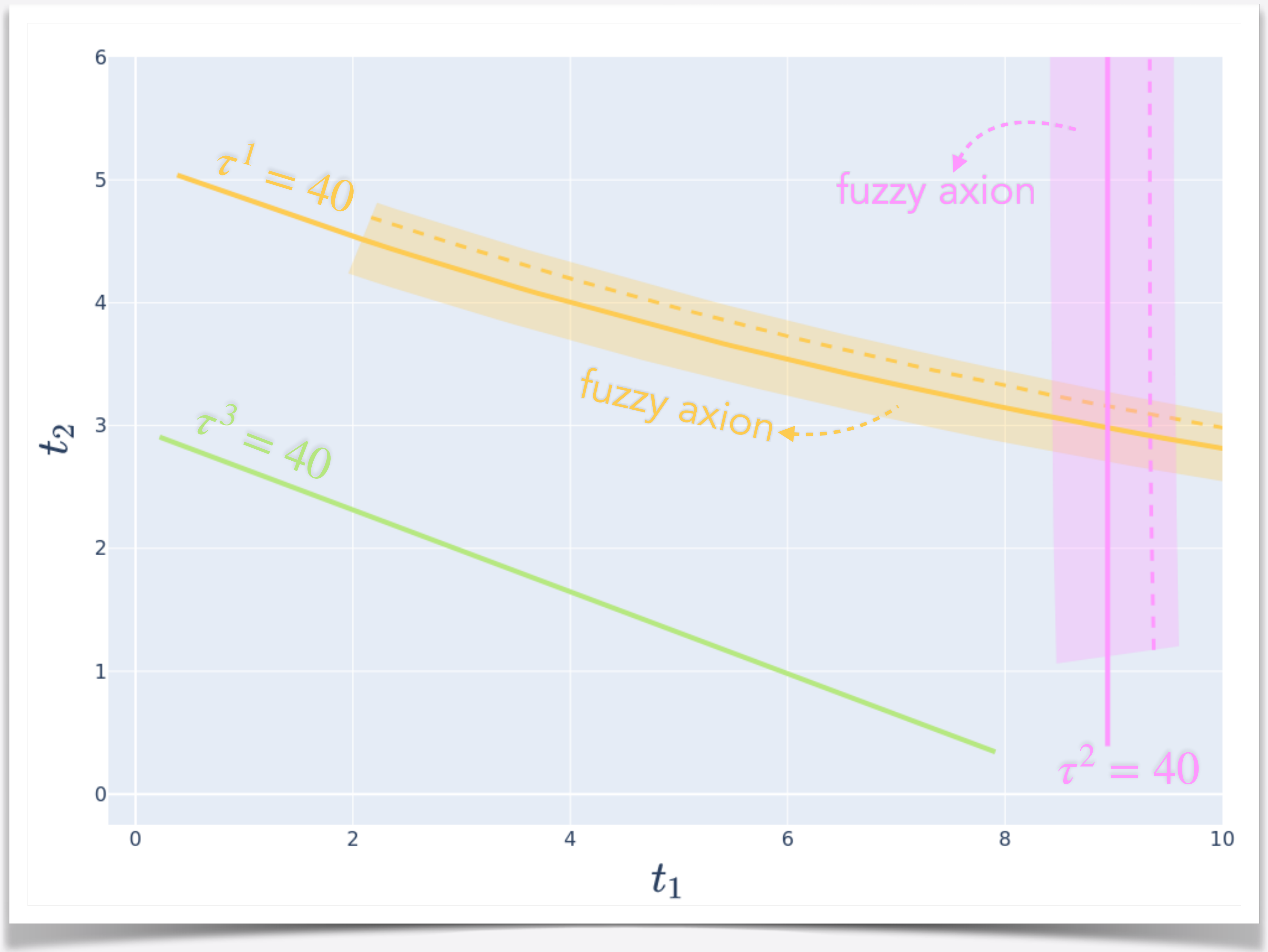

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Results

Best abundance model — $h^{1,1} = 7$

This model contains $h^{1,1} = 7$ axions which at one point in $\mathscr{K}(X)$ have

$$\log_{10}(m_{QCD}/\mathrm{eV}) = -8.91\,, \quad \log_{10}(f_{QCD}/\mathrm{GeV}) = 15.67\,,$$

$$\log_{10}(m_{fuzzy}/\mathrm{eV}) = -19.43\,, \quad \log_{10}(f_{fuzzy}/\mathrm{GeV}) = 16.29\,,$$

plus five heavier axions with

$$\log_{10}(m_a/\mathrm{eV}) = (22.21, 8.50, 7.42, 1.13, -3.43)\,,$$

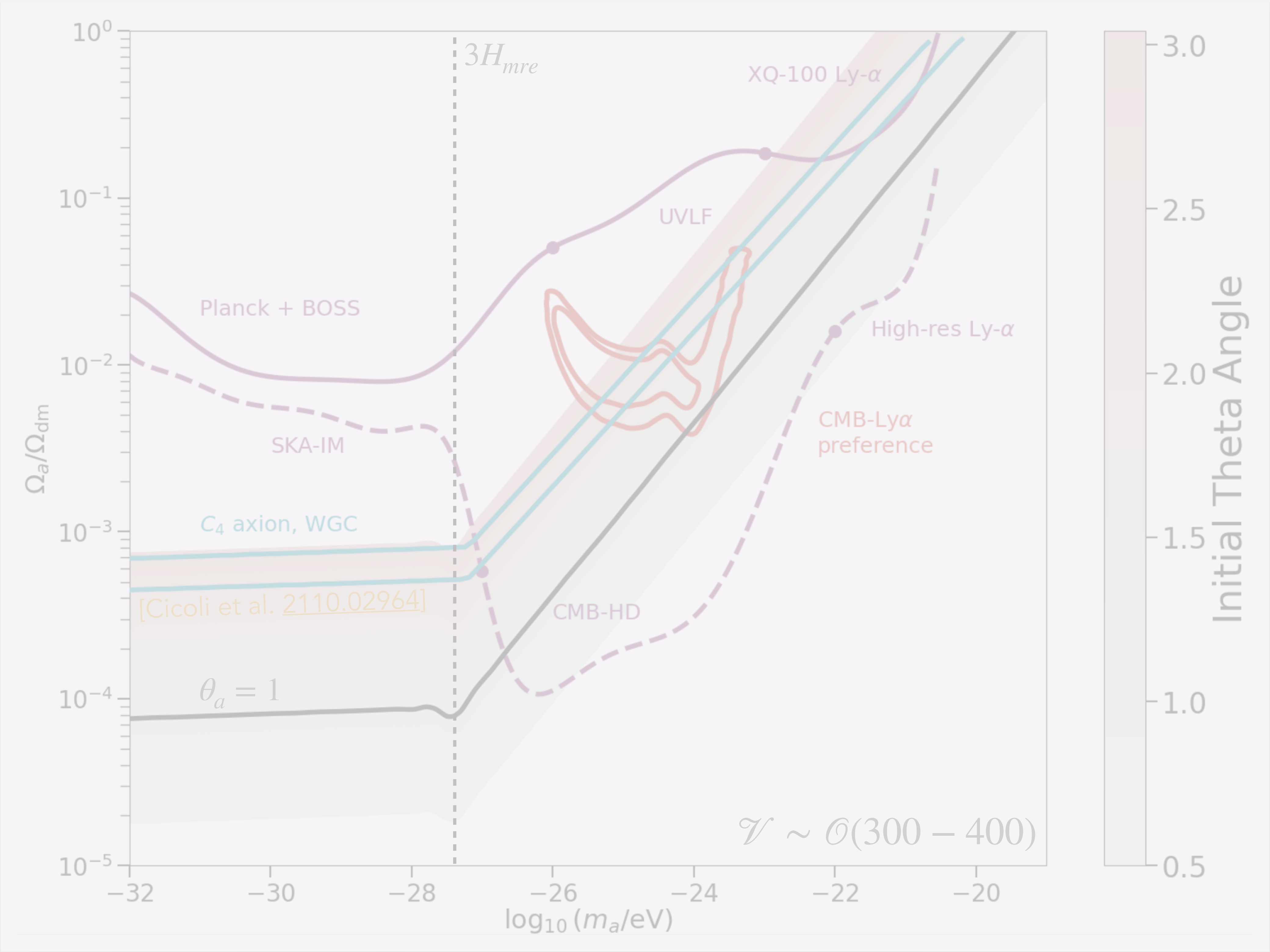
$$\log_{10}(f/\mathrm{GeV}) = (15.69, 15.64, 15.52, 15.51, 15.45)\,.$$

To dilute these axions through entropy production, we need to have

$$T_{reh} \leq 2.99 \cdot 10^{11}\,\mathrm{eV}.$$

The misalignment abundance for $\theta_a = 1$ for the fuzzy axion is

$$\frac{\Omega_{fuzzy}}{\Omega_{DM}} \approx 1\,.$$



DM abundance from varying the misalignment angle and the point in Kähler cone $\mathscr{K}(X)$ along a given ray.

Tuning of θ_a and anthropics [Kaloper, Westphal: 2404.02993]

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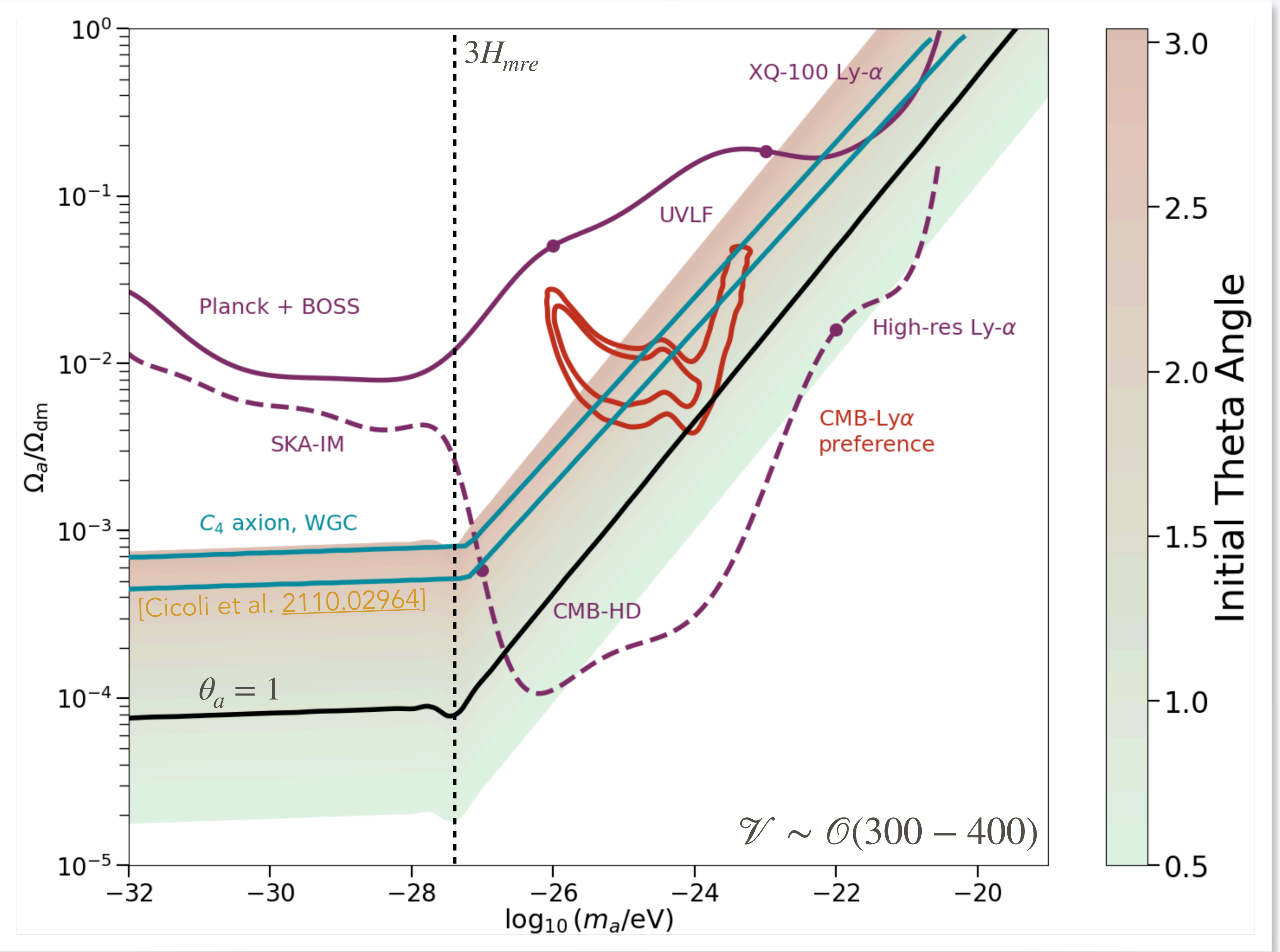
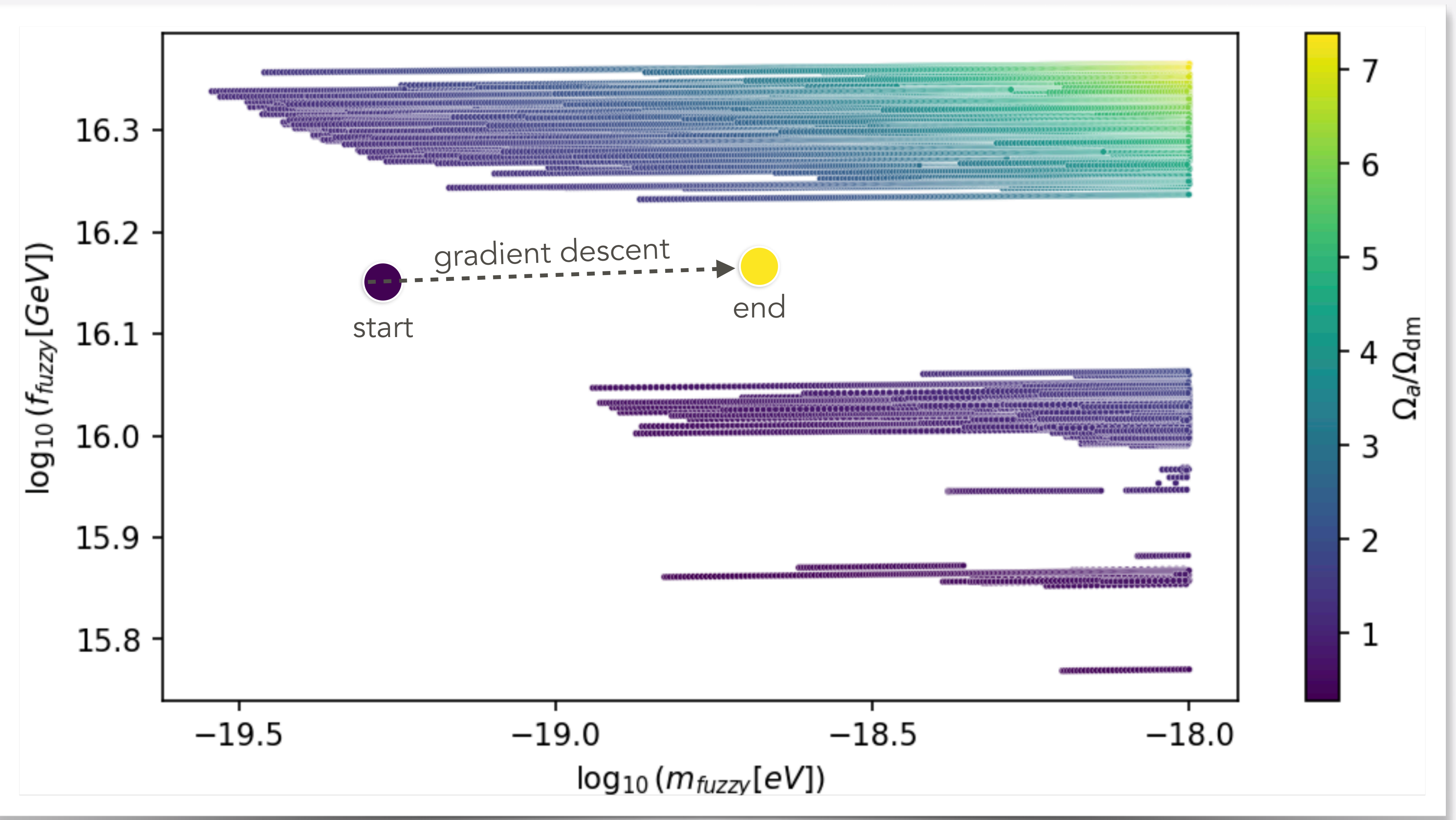


DM abundance from varying the misalignment angle and the point in Kähler cone $\mathcal{K}(X)$ along a given ray.

Tuning of θ_a and anthropics [Kaloper, Westphal: 2404.02993]

Future explorations of the Axiverse

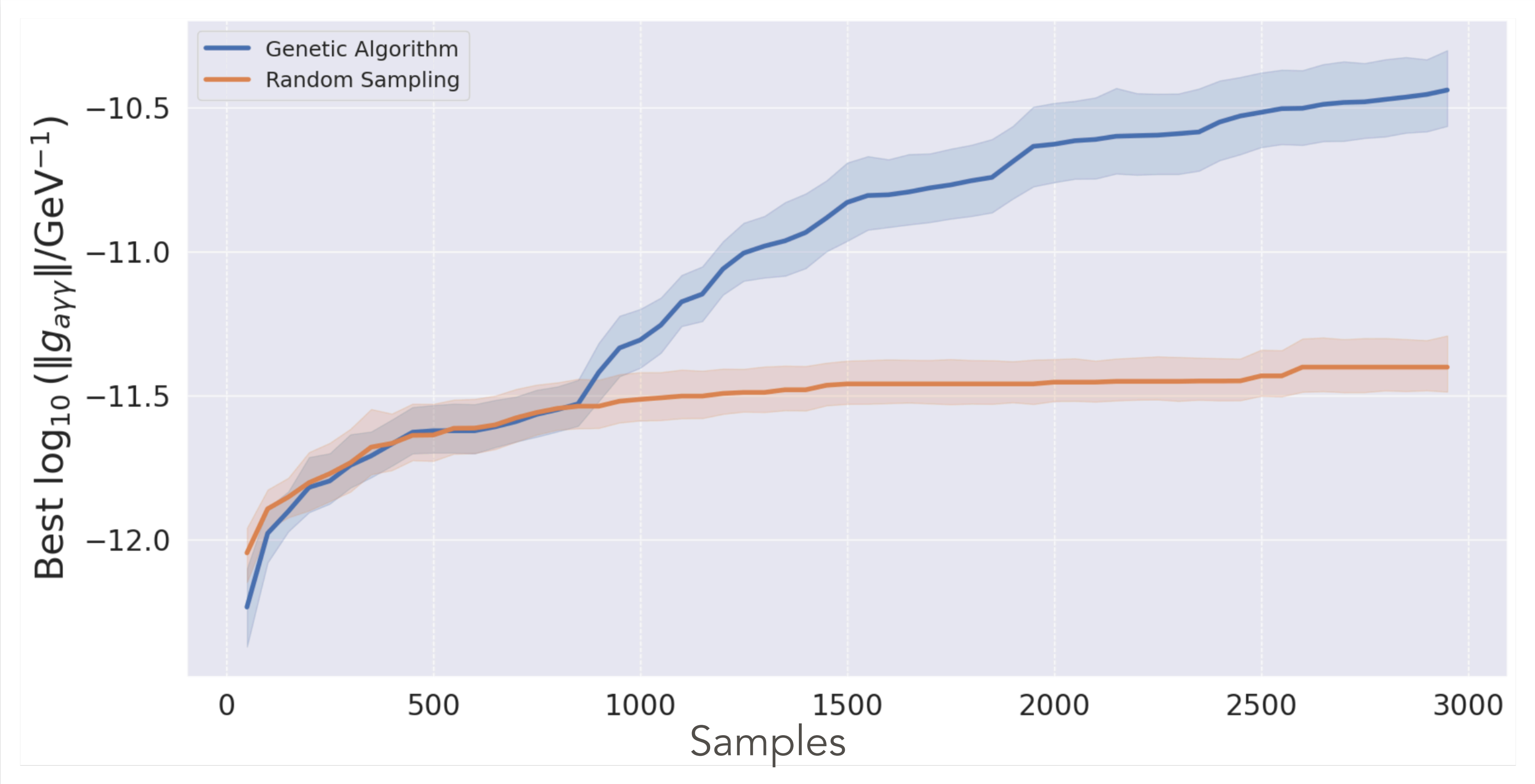
Pipeline for sampling stringy axion models



We used **optimisation methods** from `scipy.optimize`, `jax`, `optax` to obtain models with e.g. large DM abundance.

In the future, develop pipeline to sample models more efficiently.

Genetic Algorithms (GAs) for polytope triangulations



[MacFadden, **AS**, Sheridan: 2405.08871]

We were able to perform optimisation **across different compact geometries**.

Can GAs be used to explore the axiverse globally?

Conclusions

Main takeaway:

We uncovered regimes for fuzzy DM from C_4-axions in explicit Type IIB compactifications.

Summary:

- Systematic scan over Calabi-Yau orientifolds with $2 \leq h^{1,1} \leq 7$.
- Resulting DM is a mix of (multiple) fuzzy axions, the QCD axion, and potentially heavier axions.
- Fine tuning of initial displacements is necessary to avoid DM overproduction.

Open issues and future directions:

1. Combine with moduli stabilisation in explicit setups (see [Cicoli et al. 2110.02964] for initial attempts)
2. Make construction of SM sector more explicit (F-theory, Branes at singularities [Cicoli, **AS** et al. 2106.11964], …)
3. Study different axionic sectors (C_2/B_2-axions [Cicoli, Shukla, **AS**: 2109.14624], open-string axions, …)


Thank you!

Backup slides

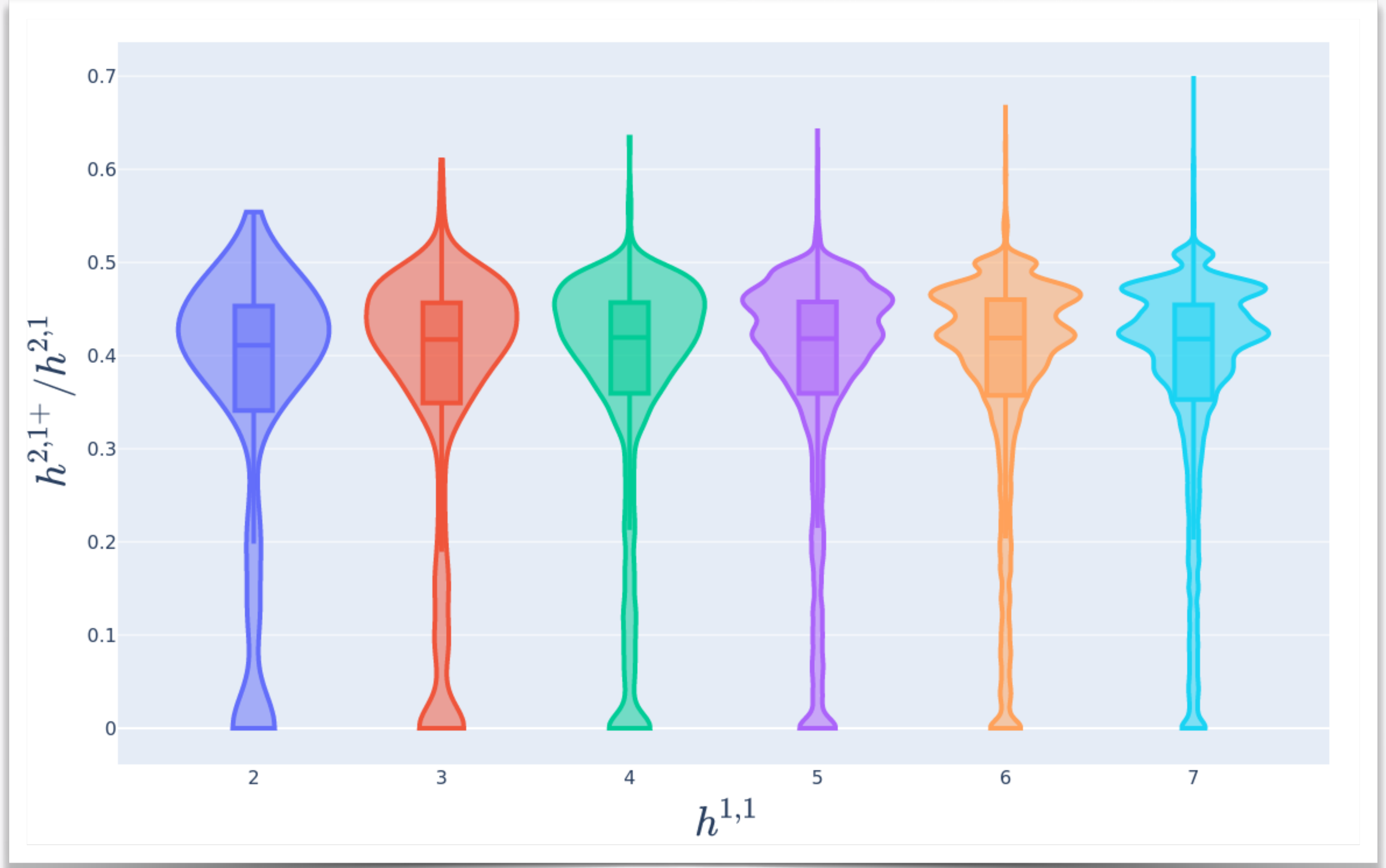
Statistics of the fuzzy axiverse

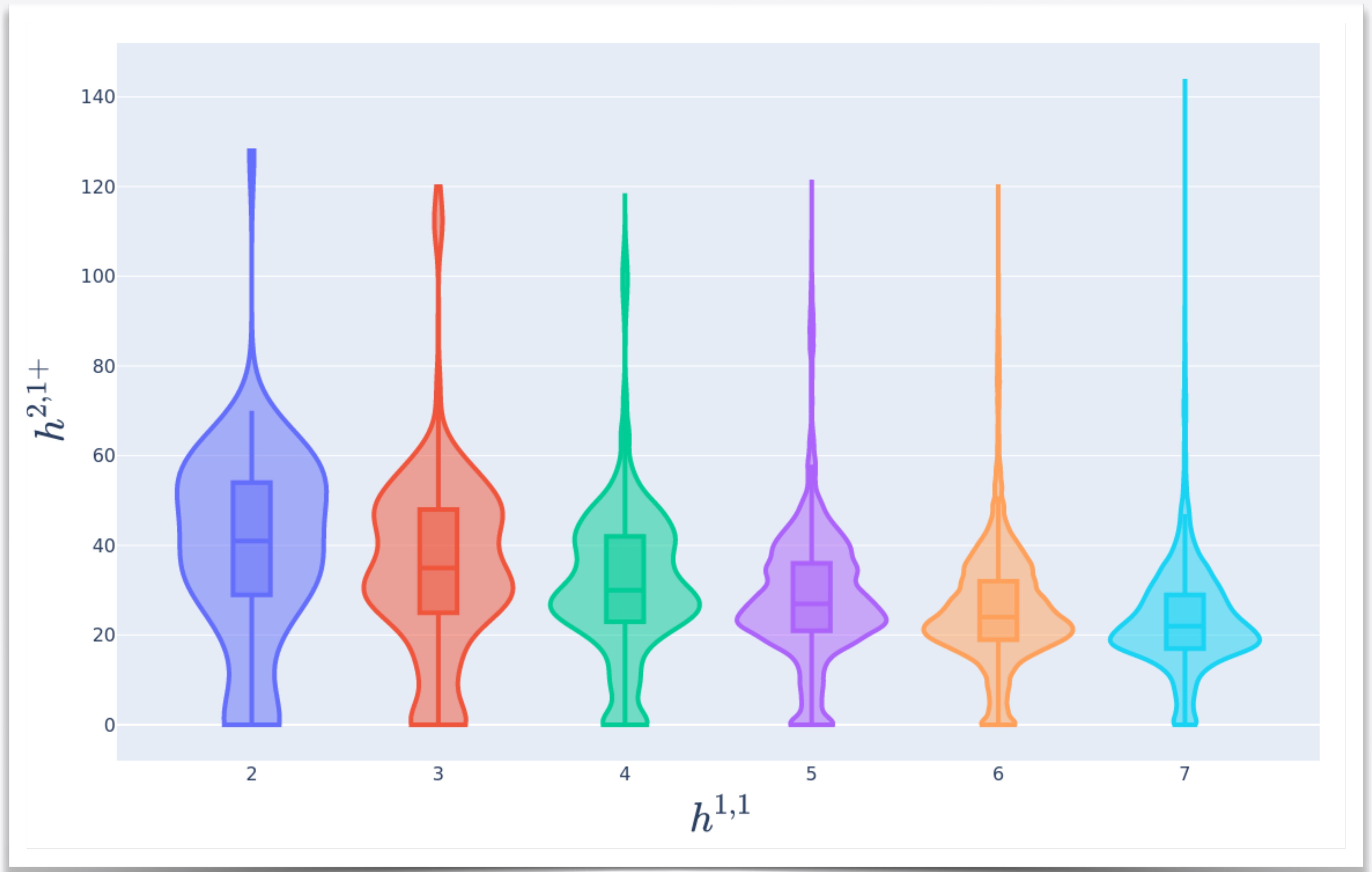
Dark vector fields

Around 98% of our orientifolds contain extra vector multiplets counted by $h_+^{1,2} \neq 0$

$$\int_X F_5 \wedge \star_{10} F_5 \supset \mathrm{d}\phi^a \wedge \star_4 \mathrm{d}\phi_a + \mathrm{d}A^I \wedge \star_4 \mathrm{d}A_I$$

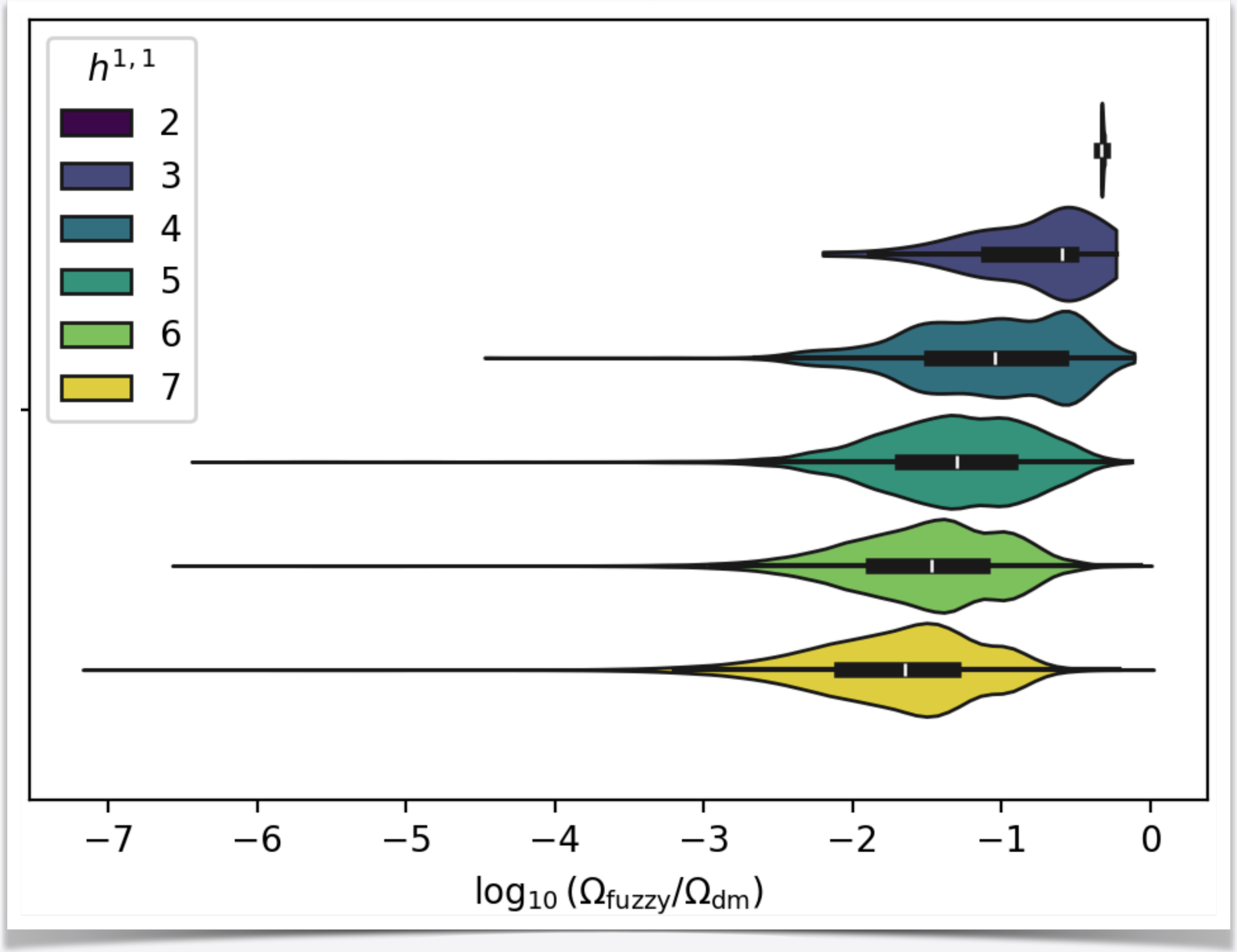
These dark vector fields might contribute to dark radiation.





Statistics of the fuzzy axiverse

Fuzzy abundance for different $h^{1,1}$



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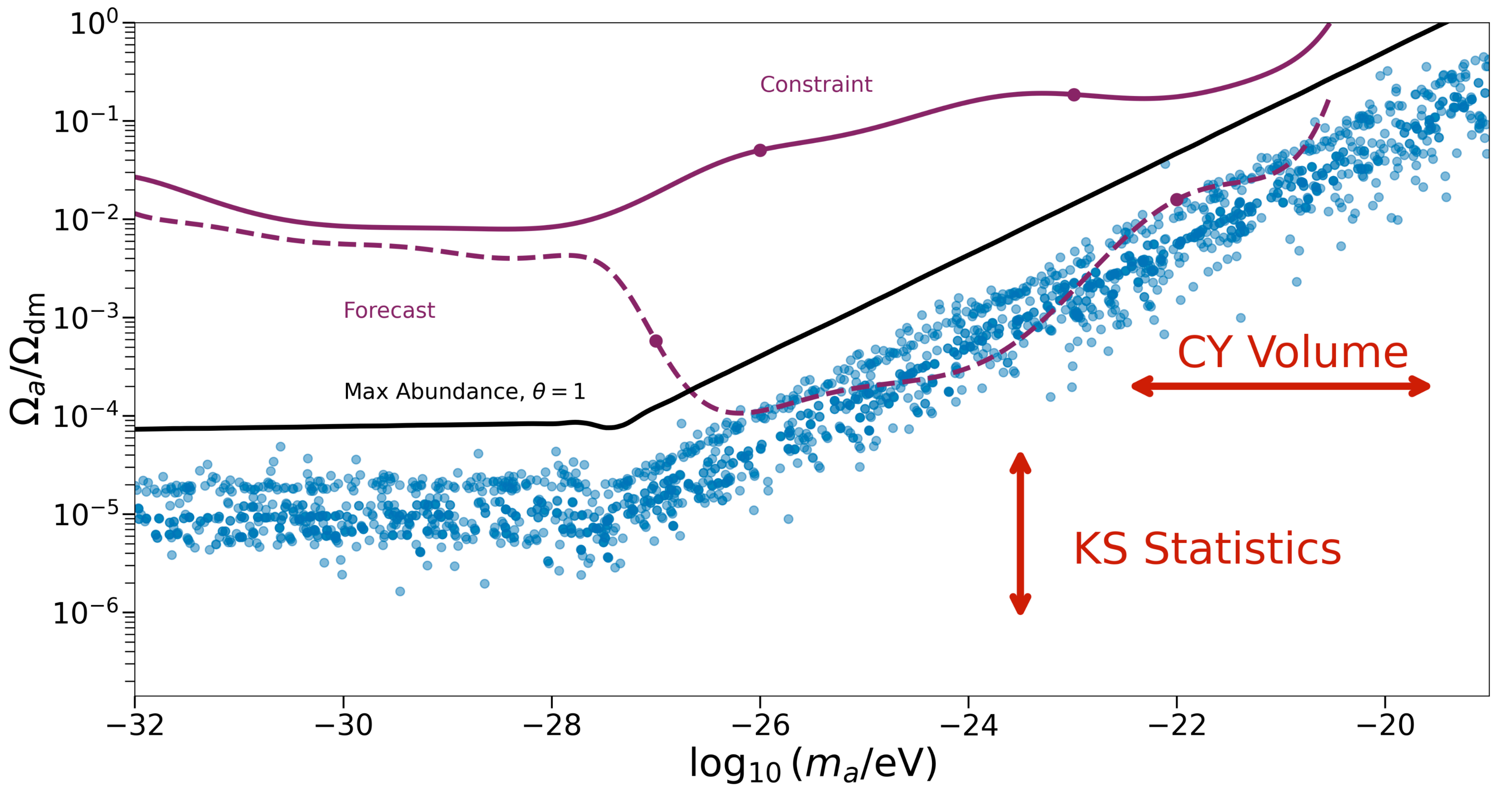
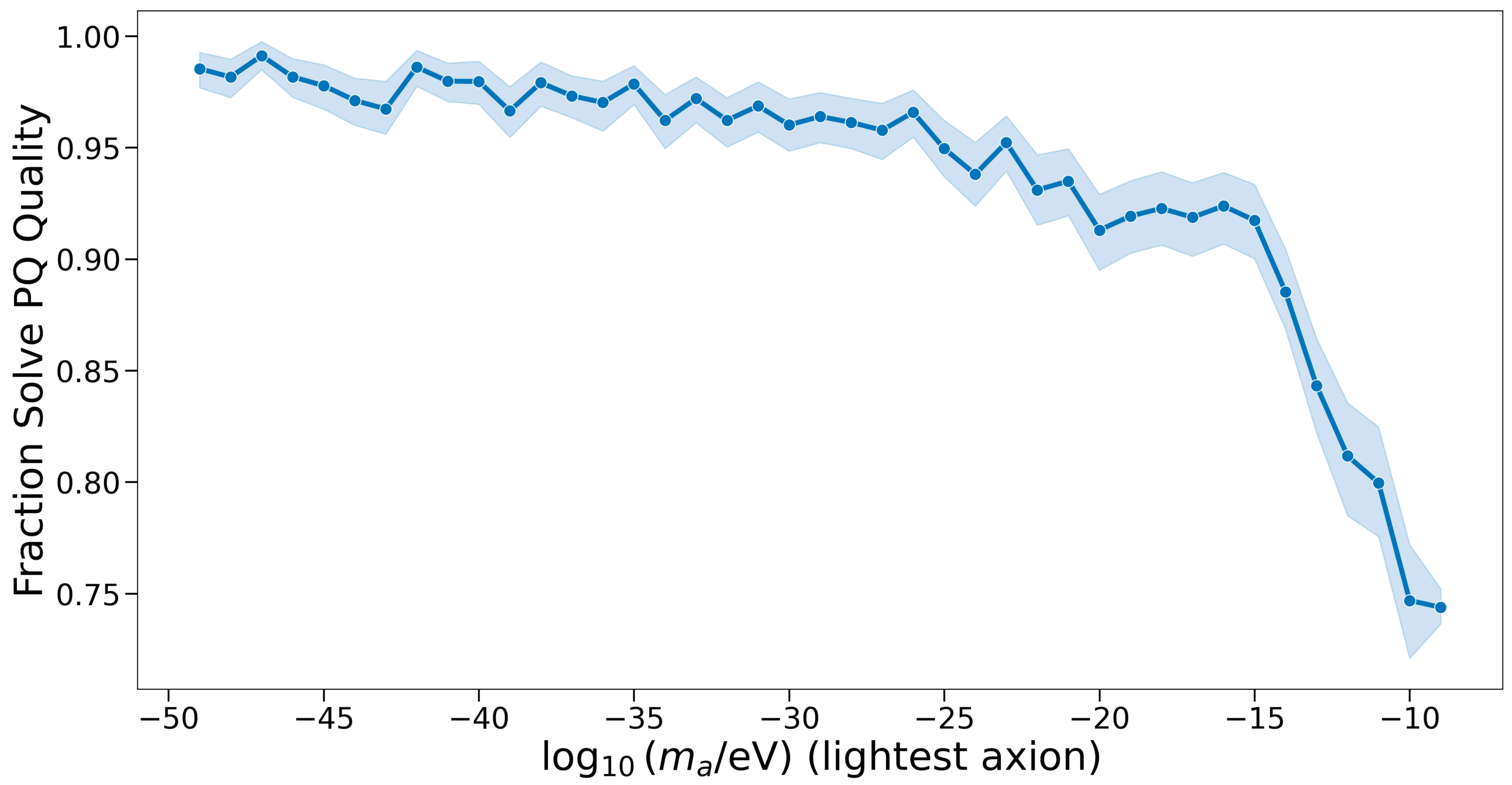
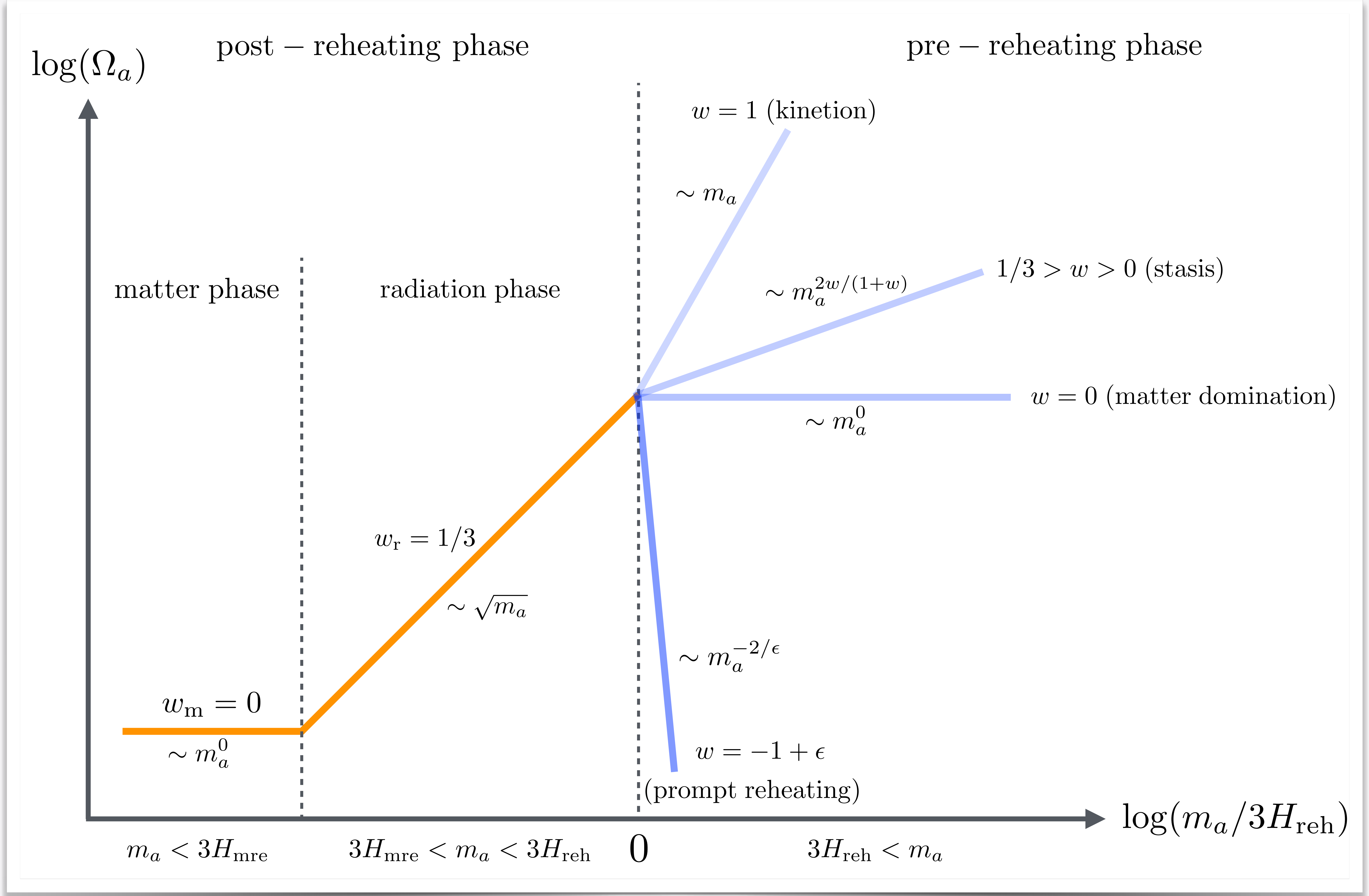


Statistics of the fuzzy axiverse

PQ quality problem solutions



Cosmological Scenarios



Cosmological Scenarios

The abundance of an axion that starts rolling in any pre-heating w phase is

$$\Omega_a\Big|_w \sim \left(\frac{\theta_a}{2.4\times10^{-2}}\right)^2\left(\frac{3H_{reh}}{4.45\times10^{-10}\,\mathrm{eV}}\right)^{1/2}\left(\frac{f_a}{10^{15.5}\,\mathrm{GeV}}\right)^2\left(\frac{m_a}{3H_{reh}}\right)^{\frac{2w}{1+w}}$$

Without tuning of the initial misalignment angles θ_a, a necessary requirement to keep heavier axions from overclosing the universe is that $w \leq 0$. We consider two scenarios:

Scenario 1: Prompt reheating: push reheating temperature as high as possible without tuning of θ_a for the axions heavier than the QCD axion, by having the inflationary Hubble scale H_I just below the mass of the lightest axion above the QCD axion. These heavy axions are in a $w \approx -1$ pre-heating phase, thereby inflating them away.

Scenario 2: Modulus (matter) domination: This is the borderline $w = 0$ pre-heating phase. Imposing a prior constraint on how much tuning one tolerates, dictates the reheating temperature. We use as tuning measure an upper bound on the product $\prod_a \theta_a$. This will pull Hubble at reheating closer to the QCD axion mass.