Exploring the fuzzy axiverse

Federico Carta

King's College London

24th of October 2024

Based on...

Exploring the fuzzy axiverse

- E. Sheridan, F.C, N. Gendler, M. Jain, D. Marsh, L. McAllister, N. Righi, K. Rogers, A. Schachner. 2024

Motivation

- One of the main goals of String Phenomenology is to make concrete string models which:
  1. Reproduce the esablished low-energy physics (SM, ΛCDM...)
  2. Extend the esablished low-energy physics (**DM**, SUSY, Inflation...)
- In particular, we investigate the possibility of realizing **ultralight axion dark matter** in the fuzzy regime

$$m \sim 10^{-19}\, eV, \quad f \sim 10^{16}\, GeV$$

- Helps solving cusp/core and missing satellites problems.
- Different behaviour than particle-like dark matter.

Fuzzy DM from string theory also previously studied in (Cicoli, Guidetti, Righi, Westphal 2110.02964). Here different approach, large scan, no moduli stabilization, interplay of QCD axion and ALPs.

The setup

- Type II string theory on $\mathbb{R}^{1,3} \times X$, with X compact CY 3-fold.
- Left with a low energy EFT with 8 supercharges. Still too supersymmetric for phenomenology.
- Focus on IIB, with orientifold action allowing for $O3/O7$ planes. Typical setup for the flux landscape (GKP '01. KKLT '03)
- Properties of the CY orientifold fix properties of the low energy 4d EFT.
- In particular, the number of fields we have in the 4d EFT and their type, will depend on the chosen orientifold.
- Known way of constructing orientifolds for a large class of CY manifolds. (J.Moritz '23)

Low energy field content

The orientifold action induces a splitting in cohomology

$$H^{p,q}(X) = H^{p,q}_{+}(X) \oplus H^{p,q}_{-}(X)$$

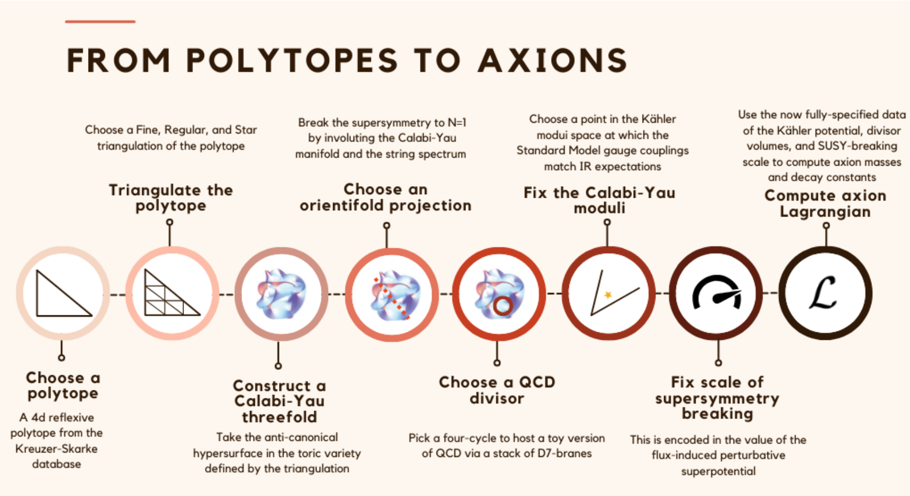
$h^{p,q}_{\pm}$ counts the number of fields in the 4d EFT (Grimm, Louis '04).

- $h^{2,1}_{-}$ complex structure moduli U^i.
- $h^{1,1}_{-}$ C_2 and B_2 axions. (DM? Inflation?)
- $h^{2,1}_{+}$ U(1) vector multiplets. (**Dark photons**?)
- $h^{1,1}_{+}$ Kähler moduli and $\mathbf{C_4}$ **axions**: $T^a = \tau^a + i\theta^a$.

In this talk, **we focus on axions** θ^a.

$$\theta^{\mathbf{a}} := \int_{\mathbf{D_a}} \mathbf{C_4}$$

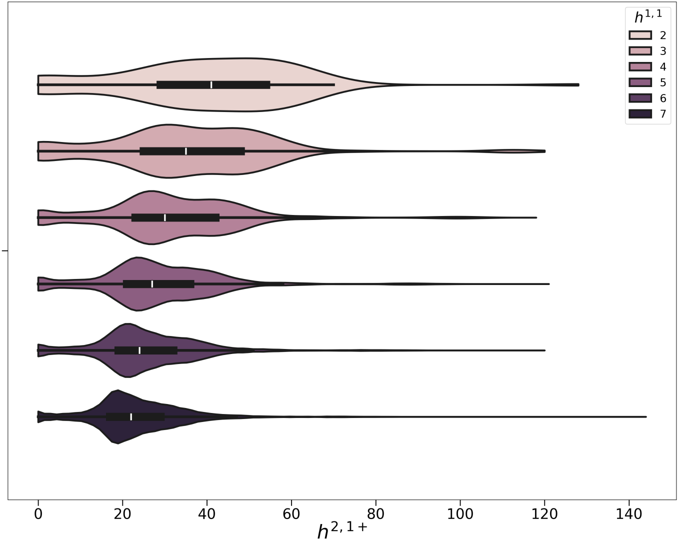
Flowchart on string side



CY orientifolds

- Generically the larger $h^{1,1}$, the smaller f at tip of KC.
  For fuzzy, prefer small $h^{1,1}$.
- In KS $h^{1,1} \in [1, 491]$. We restrict to $h^{1,1} \in [1, 7]$.
- We are exhaustive in scanning all polytopes, all triangulations.
- Orientifolds are classified. Turns out that in the chosen $h^{1,1}$ range:
  1. Only 67% of CYs admit an orientifold. (Throw away 1/3 of them)
  2. Orientifolds with $h^{1,1-} \neq 0$ are rare. 3%
  3. Orientifold with $h^{2,1+} \neq 0$ are ubiquitous. 98%
- $\implies$ **fuzzy DM** realized from string theory with single hypersurface CY generically **implies dark photons**
- $\implies$ **2-form axions are not generic** in the fuzzy axiverse.

How many dark photons



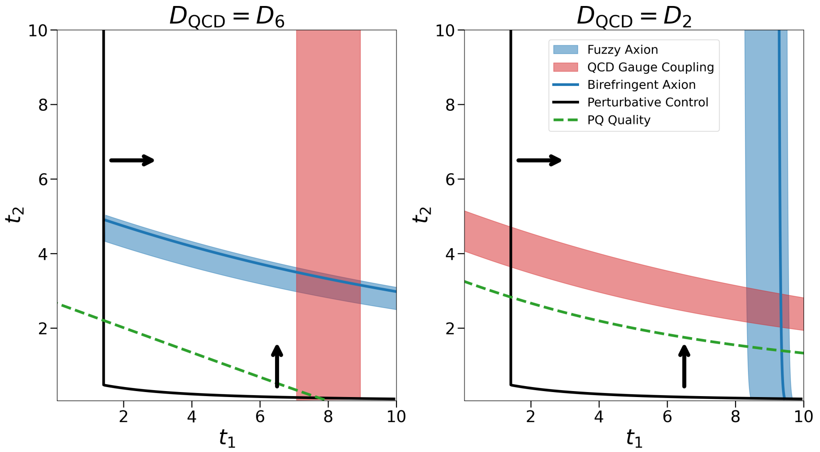
Model building assumptions and schematic procedure

- $K = -2\log(\mathcal{V}) = -2\log\left(\frac{1}{6}k^{ijk}t_i t_j t_k\right)$.
  No corrections to K at this stage.
- $W = W_0 + \sum_i A_i e^{-aT}$. Sum over all prime toric divisors.
- $W_0 = A_i = 1,\ a = 2\pi$.
  This is, euclidean D3s on all prime toric divisors.
- Assume absence of 7-branes
  Don't address yet tadpole cancellation and SM sector
- $V = e^K\left(K^{a\bar{b}}D_a W D_{\bar{b}}\bar{W} - 3W\bar{W}\right)$
- Numerically compute (f, m) from the eigenvalues of Kahler metric $K_{a,\bar{b}}$, and the scalar potential V.

Picking position in the kahler cone

- We do not do moduli stabilization. Evaluate masses and decay constants sampling various points inside the Kahler cone (KC).
- Stay in region of perturbative control, vol$(D_i) = \frac{1}{2}k^{ijk}t_j t_k > 1$. More practically, safe enough to inside the stretched kahler cone (EKC). (vol$(C_i) > 0$).
- Identify region that realizes fuzzy axions.
- We **also want a QCD axion** from C_4 on a 4-cycle D_{QCD} which would also wrapped by a stack of D7s.
- The UV gauge coupling $g^2_{UV} \sim \frac{1}{\text{vol}(D_{QCD})}$. Need vol$(D_{QCD}) \sim 40$ to match observed coupling at Z_0 mass scale. $\implies$ Look for regions in the Kahler cone where a divisor has such volume.

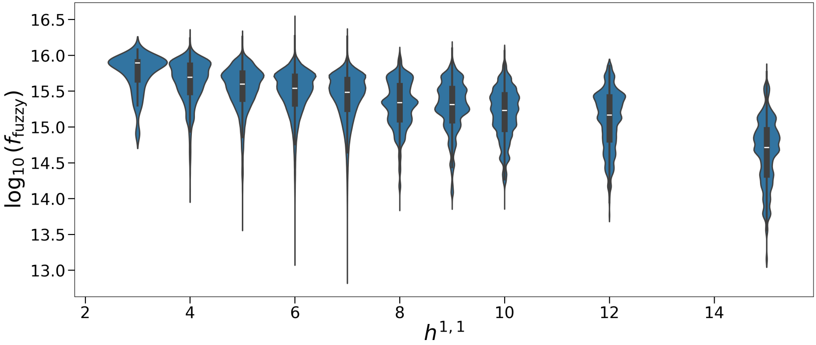
Two models at $h^{1,1} = 2$



The scan

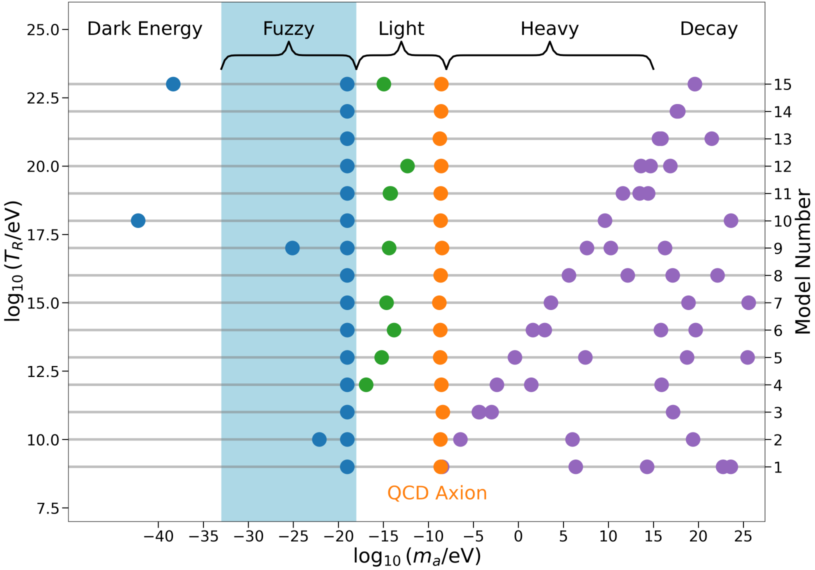
- Can't sample the full EKC for all 500000 geometries in KS with $h^{1,1} < 11$. Restrict to points in a line connecting the tip of the KC to that of the EKC.
- For each model, sample in this line until an axion of mass exactly $m = 10^{-19}\,eV$ is found.
- Then check if at least one one prime toric divisor D has vol$(D) \in [40-\epsilon, 40+\epsilon]$
- If no, reject model.
- If yes, compute masses and decay constants of all $h^{1,1}_{+}$ axions (not just the fuzzy one and QCD one).
- For QCD axion, compute f from the Kahler metric, but compute m using chiral perturbation theory result.
- Couple of weeks time on a modern laptop $\implies$ big space for optimization (see Andreas Schachner talk)

Results: decay constants



- Decay constants of all axions (not only fuzzy ones) are approximately $10^{15} \sim 10^{16}$GeV
- This poses the QCD axion at $m_{QCD} \sim 10^{-9}$ eV

Fifteen selected models



How much DM is produced?

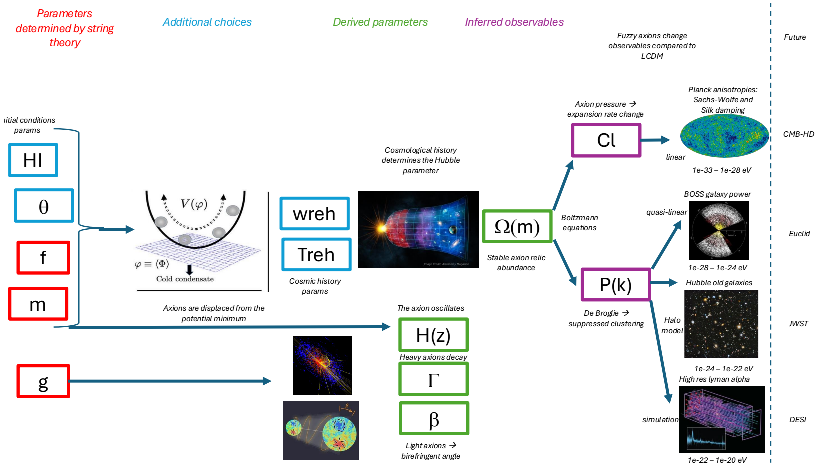
- Production mechanism is **misalignement**:
  1. Scalar field stuck in a potential at θ
  2. When $H < m$ it starts oscillating.
  3. ρ dilutes with a^{-3} like matter.
- No SM sector, no axion-photon couplings
- No Primakoff thermal production
  - Ok approximation for fuzzy mass range, unavoidable thermal production is small.
- For QCD axion the story is a bit different. $m_{QCD}(T)$. Only $m_{QCD}(0) \sim 10^{-9}$ eV. For this mass, $H_{\text{osc}} \sim 10^{-11}$ eV
- $H_{BBN} \sim 10^{-16}$ eV

Do we overproduce/underproduce?

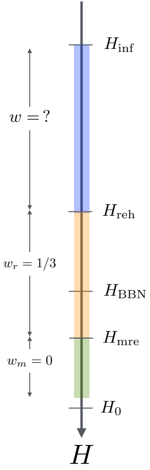
It depends a lot on

1. θ tuning
2. Pre-reheating cosmology

Flowchart on cosmo side



Abundance

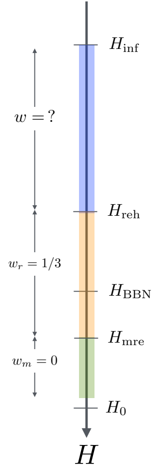


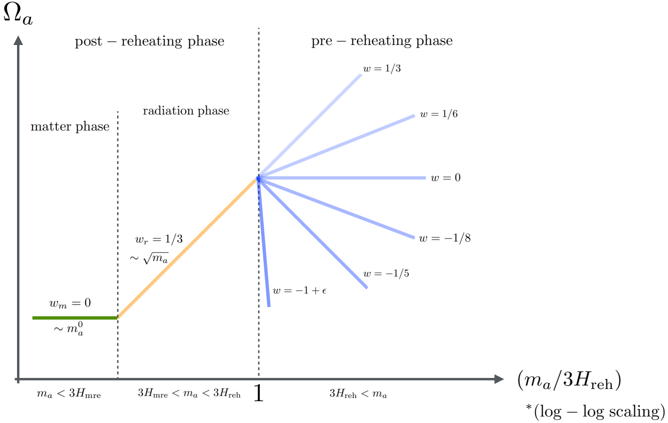
$$\Omega_a \approx \eta(g_{\rm reh}) \left(\frac{f_a}{10^{15.5}\,{\rm GeV}}\right)^2 \left(\frac{3H_{\rm reh}}{10^{-8}\,{\rm eV}}\right)^{1/2} \left(\frac{\theta_i}{10^{-2}}\right)^2 \left(\frac{m_a}{3H_{\rm reh}}\right)^{\frac{2w}{1+w}}$$

Abundance

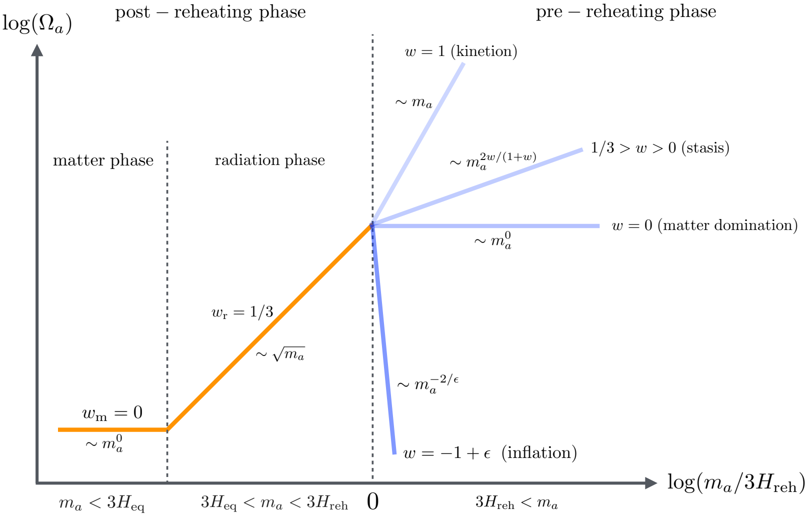
$$\Omega_a \approx \eta(g_{\rm reh}) \left(\frac{f_a}{10^{15.5}\,\mathrm{GeV}}\right)^2 \left(\frac{3H_{\rm reh}}{10^{-8}\,\mathrm{eV}}\right)^{1/2} \left(\frac{\theta_i}{10^{-2}}\right)^2 \left(\frac{m_a}{3H_{\rm reh}}\right)^{\frac{2w}{1+w}} < 1$$

$\mathcal{O}(1)$





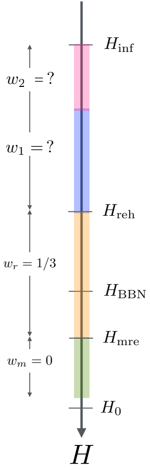
Abundance

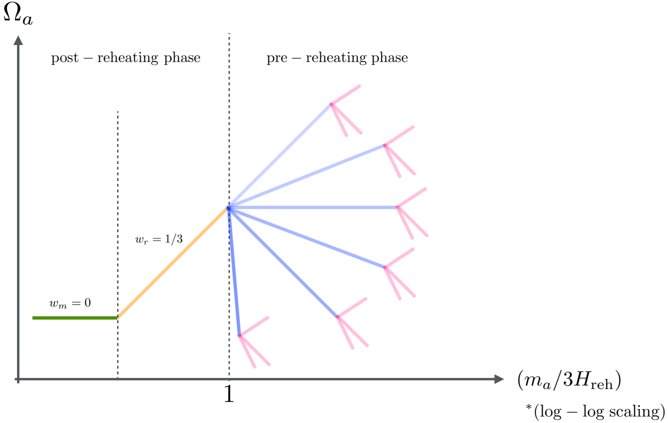


$\log(\Omega_a)$
post − reheating phase
pre − reheating phase
$w = 1$ (kinetion)
$\sim m_a$
matter phase
radiation phase
$\sim m_a^{2w/(1+w)}$
$1/3 > w > 0$ (stasis)
$w = 0$ (matter domination)
$\sim m_a^0$
$w_\mathrm{r} = 1/3$
$\sim \sqrt{m_a}$
$\sim m_a^{-2/\epsilon}$
$w_\mathrm{m} = 0$
$\sim m_a^0$
$w = -1 + \epsilon$ (inflation)
$\log(m_a/3H_\mathrm{reh})$
$m_a < 3H_\mathrm{eq}$
$3H_\mathrm{eq} < m_a < 3H_\mathrm{reh}$
0
$3H_\mathrm{reh} < m_a$

Abundance

$$\Omega_a \approx \eta(g_{\rm reh}) \left(\frac{f_a}{10^{15.5}\,{\rm GeV}}\right)^2 \left(\frac{3H_{\rm reh}}{10^{-8}\,{\rm eV}}\right)^{1/2} \left(\frac{\theta_i}{10^{-2}}\right)^2 \left(\frac{m_a}{3H_{\rm reh}}\right)^{\frac{2w_1}{1+w_1}} < 1$$





Conclusions and future directions

Summarizing the results: **Summarizing the results:**

- Fuzzy in KS $\implies$ must deal with dark photons.
- Can rse two. Generically have axions with $m > m_{QCD}$. Without tuning misalignement angles they overclose if they start oscillating in $w = 1/3$ era.
- Propose oscillation in $w = -1$ scenarios to have right abundance.

For the future: **For the future:**

- Implement moduli stabilization.
- Check if the EFT is under control.
- Scan over more parameters.
- How dark photons change the story?

The end

Thanks for the attention.

Comparing with observations