CA21106

LEVERHULME TRUST

KING'S College LONDON

String Axions & Associated Relics

Nicole Righi

Based on

[2110.02964] with Cicoli, Guidetti and Westphal

[2411.18496] with Leedom, Putti and Westphal

[2412.12012] with Sheridan, Carta, Gendler, Jain, Marsh, McAllister, Rogers and Schachner

PLANCK 25, 27/05/25

Axions in the Universe

- Axions are a common product of string theory
- Their presence could affect the cosmological history
- We want to draw statistical features by studying the largest known ensemble of EFTs

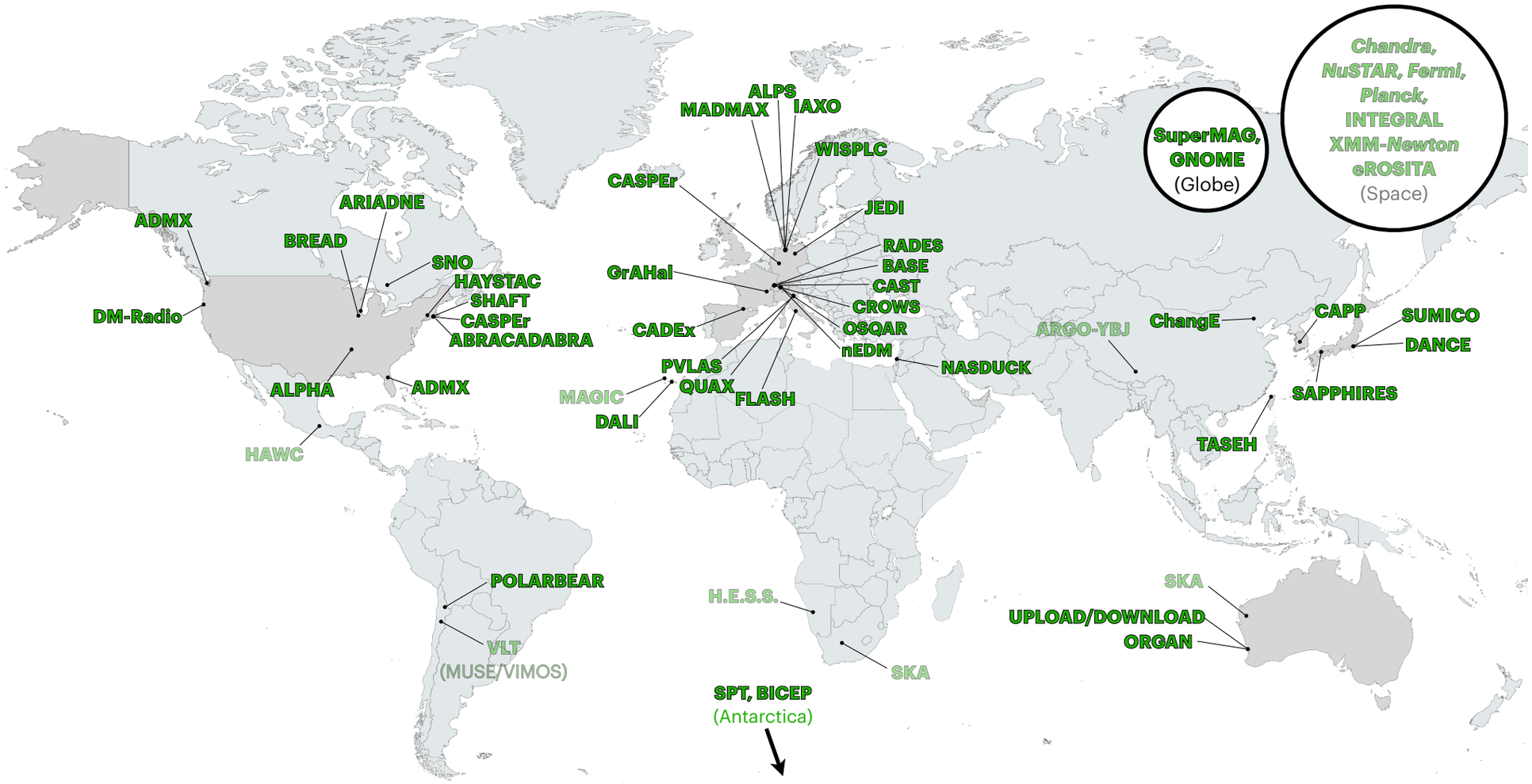
Axions in the Universe

- Axions are a common product of string theory
- Their presence could affect the cosmological history
- We want to draw statistical features by studying the largest known ensemble of EFTs

The string axiverse can be realised in our universe and *detected*, but at a **price**

The Search for Axions

1) Great experimental effort ⇒ great opportunity

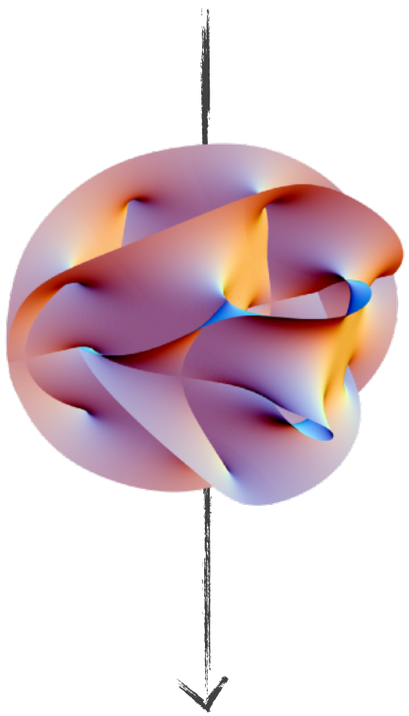


[O'Hare Website *AxionLimits*]

The Search for Axions

2) Axions arise naturally in string theory

10d superstring theory



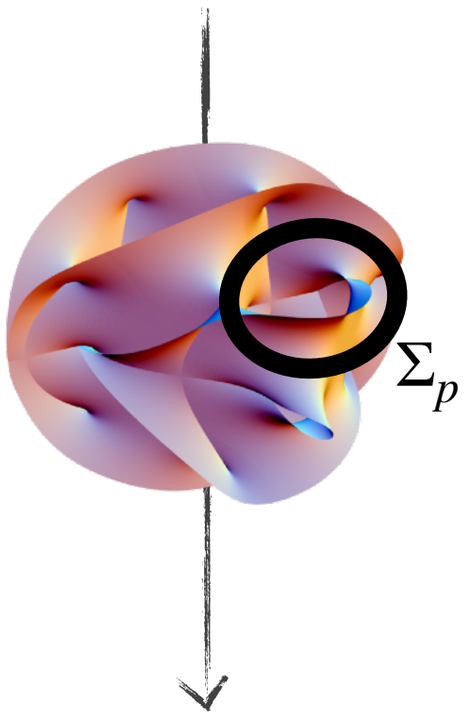
4d EFT

The Search for Axions

2) Axions arise naturally in string theory

10d superstring theory

$$S_{10D} \supset \int_{\mathscr{M}_{9,1}} \mathrm{d}C_p \wedge \star \mathrm{d}C_p$$



$$\int_{\Sigma_p} C_p \equiv \theta(x)$$

4d EFT

$$S_{EFT} \supset -\int_{\mathscr{M}_{3,1}} d^4x \, \frac{f^2}{2} \left(\partial\theta(x)\right)^2$$

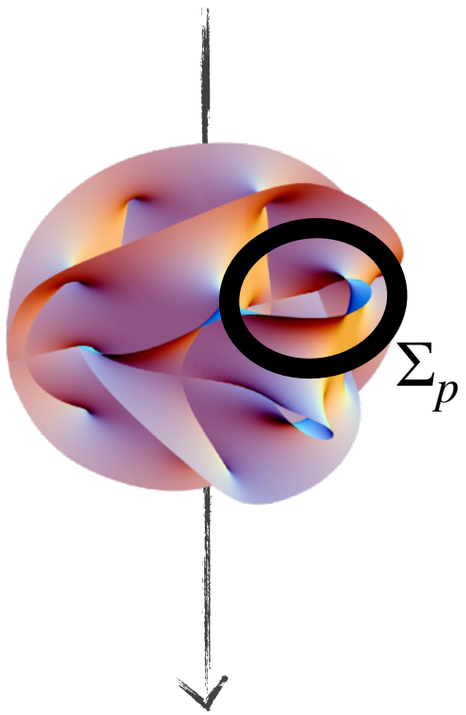
The Search for Axions

2) Axions arise naturally in string theory

10d superstring theory

$$S_{10D} \supset \int_{\mathscr{M}_{9,1}} \mathrm{d}C_p \wedge \star \mathrm{d}C_p$$

$$C_p \to C_p + 2\pi \sum_i n_i \, \omega_p^i$$



$$\int_{\Sigma_p} C_p \equiv \theta(x)$$

$$\int_{\Sigma_p^i} \omega_p^j = 2\pi\delta_j^i$$

4d EFT

$$S_{EFT} \supset -\int_{\mathscr{M}_{3,1}} d^4x \, \frac{f^2}{2} \left(\partial\theta(x)\right)^2$$

$$\theta(x) \to \theta(x) + 2\pi n$$

$\Rightarrow$ string axions are pre-inflationary

The Search for Axions

3) Axion physics is sensible to UV input

$$\mathscr{L}_{\text{EFT}} \supset -\frac{1}{2} K_{ij} \partial_\mu \theta^i \partial^\mu \theta^j + \frac{Q^i_{\text{QCD}} \theta_i}{32\pi^2} G \wedge G + \sum_\alpha \Lambda_\alpha^4 \left(1 - \cos(2\pi Q^i_\alpha \theta_i)\right)$$

The Search for Axions

3) Axion physics is sensible to UV input

$$\mathscr{L}_{\text{EFT}} \supset -\frac{1}{2} K_{ij} \partial_\mu \theta^i \partial^\mu \theta^j + \frac{Q^i_{\text{QCD}} \theta_i}{32\pi^2} G \wedge G + \sum_\alpha \Lambda_\alpha^4 \left(1 - \cos(2\pi Q^i_\alpha \theta_i)\right)$$

K_{ij} = metric on moduli space $\quad \Rightarrow \quad \text{eig}_i(K) \sim f_i^2$

The Search for Axions

3) Axion physics is sensible to UV input

$$\mathscr{L}_{\text{EFT}} \supset -\frac{1}{2} K_{ij} \partial_\mu \theta^i \partial^\mu \theta^j + \frac{Q^i_{\text{QCD}} \theta_i}{32\pi^2} G \wedge G + \sum_\alpha \Lambda_\alpha^4 \left(1 - \cos(2\pi Q^i_\alpha \theta_i)\right)$$

K_{ij} = metric on moduli space $\Rightarrow$ $\text{eig}_i(K) \sim f_i^2$

Q^i_α = instanton charges

The Search for Axions

3) Axion physics is sensible to UV input

$$\mathscr{L}_{\text{EFT}} \supset -\frac{1}{2} K_{ij} \partial_\mu \theta^i \partial^\mu \theta^j + \frac{Q^i_{\text{QCD}} \theta_i}{32\pi^2} G \wedge G + \sum_\alpha \Lambda_\alpha^4 \left(1 - \cos(2\pi Q^i_\alpha \theta_i)\right)$$

K_{ij} = metric on moduli space $\Rightarrow$ $\text{eig}_i(K) \sim f_i^2$

Q^i_α = instanton charges

$\Lambda^4_\alpha \sim e^{-\text{vol}(\Sigma_4^\alpha)}$ = instanton scales

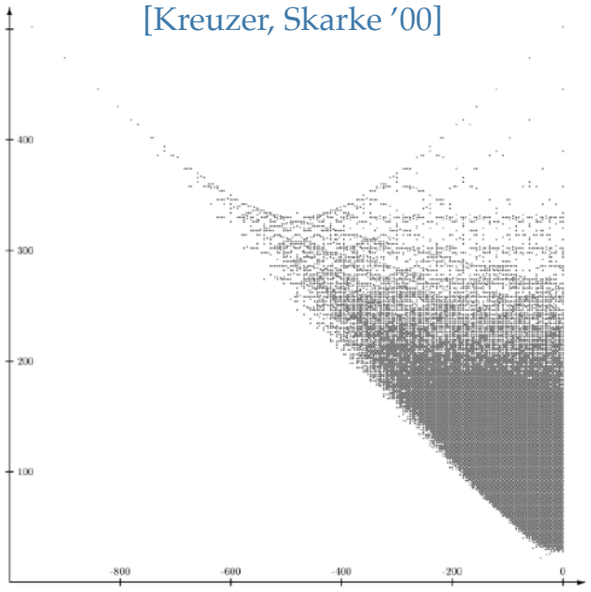
geometric quantities

can be computed in
(a subset of) the landscape

The String Axion Landscape

The subset we focus on:

[Kreuzer, Skarke '00]



+

[Demirtas, Rios-Tascon, McAllister '22]

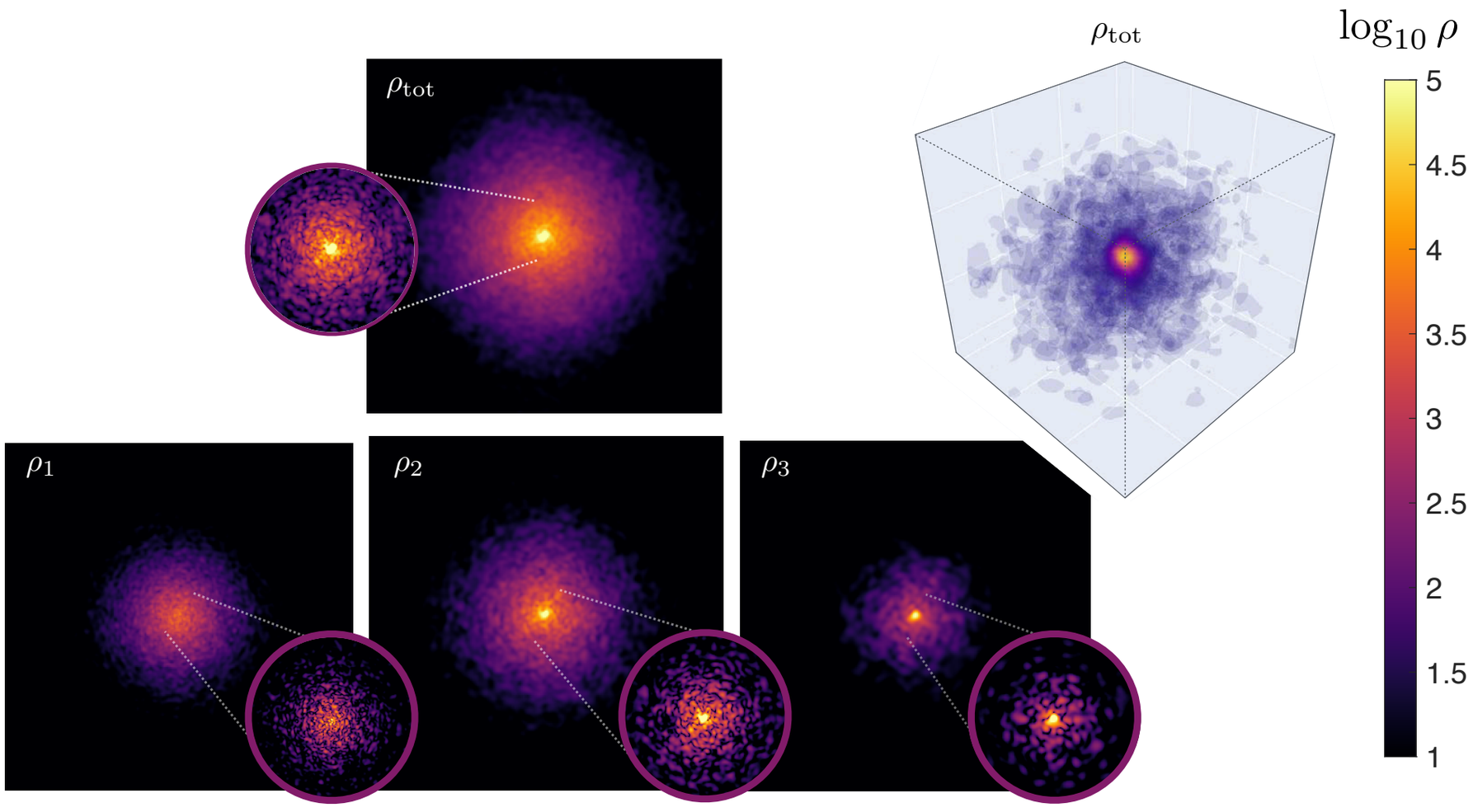
which means:
- work with a *stringy* axion from C_4 potentials
- scan over $\lesssim 10^{428}$ Calabi-Yau manifolds
- work with concrete geometric data
- use optimization methods

We leave behind: axions from other 10D elements, full SM implementation, positive Λ, etc…

— see **Margherita Putti**'s parallel this afternoon —

String Axions as Dark Matter

Let us test the string axiverse:
Can we accomodate Fuzzy Dark Matter in string theory?



[Sheridan, Carta, Gendler, Jain, Marsh, McAllister, NR, Rogers, Schachner '24]

String Axions as Dark Matter

Generate EFTs such that

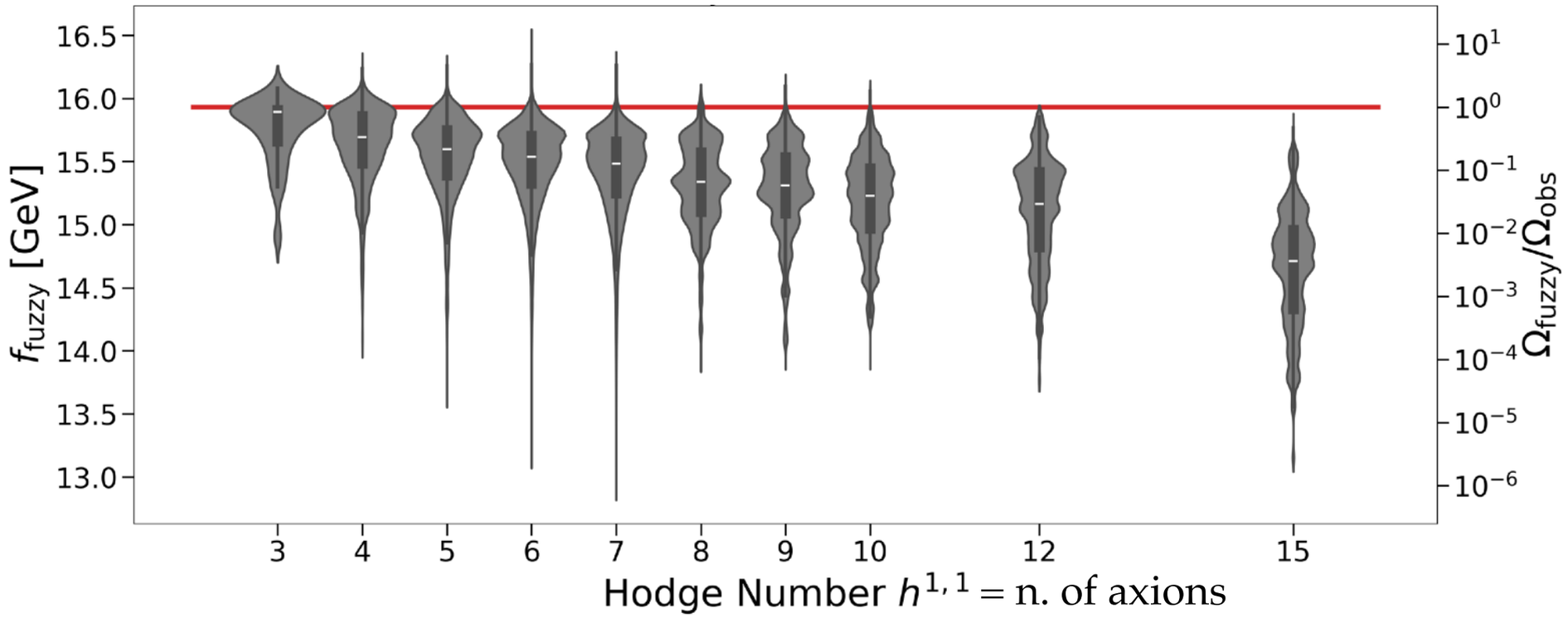
- $f_{fuzzy} \gtrsim 10^{16}\,\mathrm{GeV}$

String Axions as Dark Matter

Generate EFTs such that

- $f_{fuzzy} \gtrsim 10^{16}\,\text{GeV} \;\Rightarrow\;$ focus on $2 \leq$ axions ≤ 7

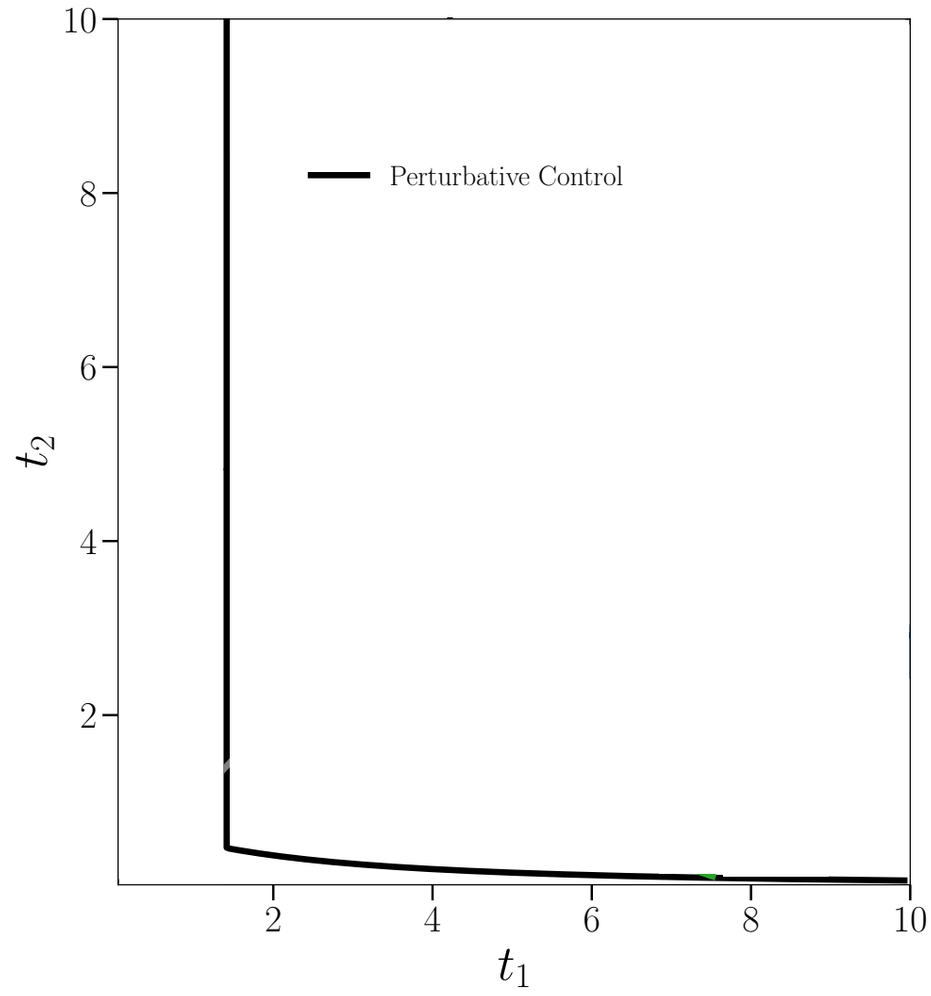
mean f decreases with the number of axions



String Axions as Dark Matter

Generate EFTs such that

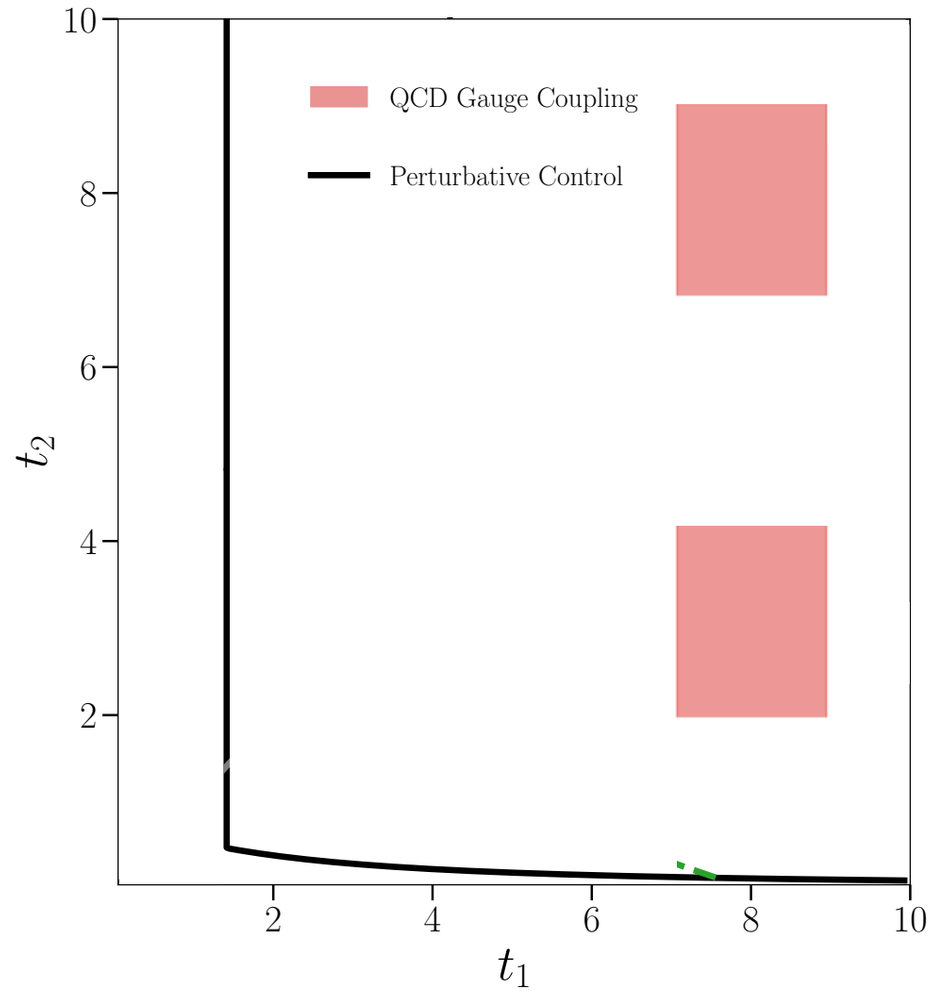
- $f_{fuzzy} \gtrsim 10^{16}\,\text{GeV} \Rightarrow$ focus on $2 \leq$ axions ≤ 7
- all volumes $> \ell_s$



String Axions as Dark Matter

Generate EFTs such that

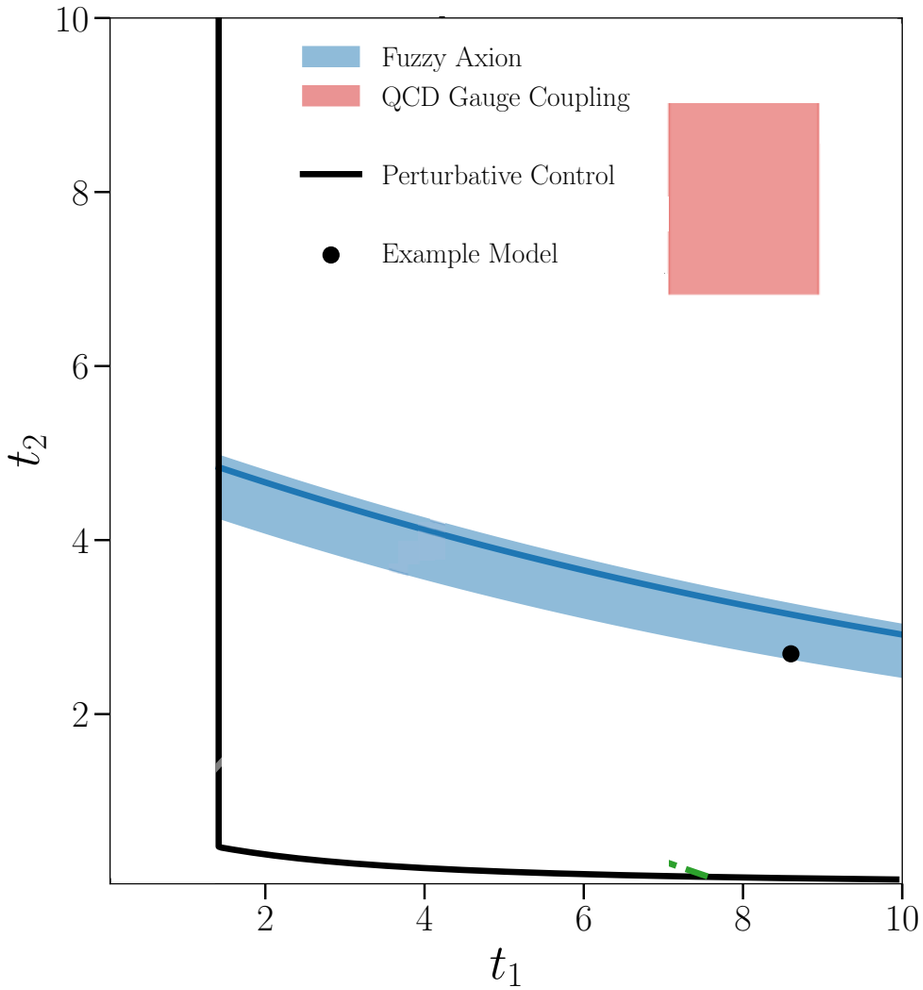
- $f_{fuzzy} \gtrsim 10^{16}\,\text{GeV} \;\Rightarrow\;$ focus on $2 \leq$ axions ≤ 7
- all volumes $> \ell_s$
- one QCD axion



String Axions as Dark Matter

Generate EFTs such that

- $f_{fuzzy} \gtrsim 10^{16}\,\text{GeV} \;\Rightarrow\;$ focus on $2 \leq$ axions ≤ 7
- all volumes $> \ell_s$
- one QCD axion
- at least one axion with $m_{fuzzy} \sim 10^{-19}\,\text{eV}$



String Axions as Dark Matter

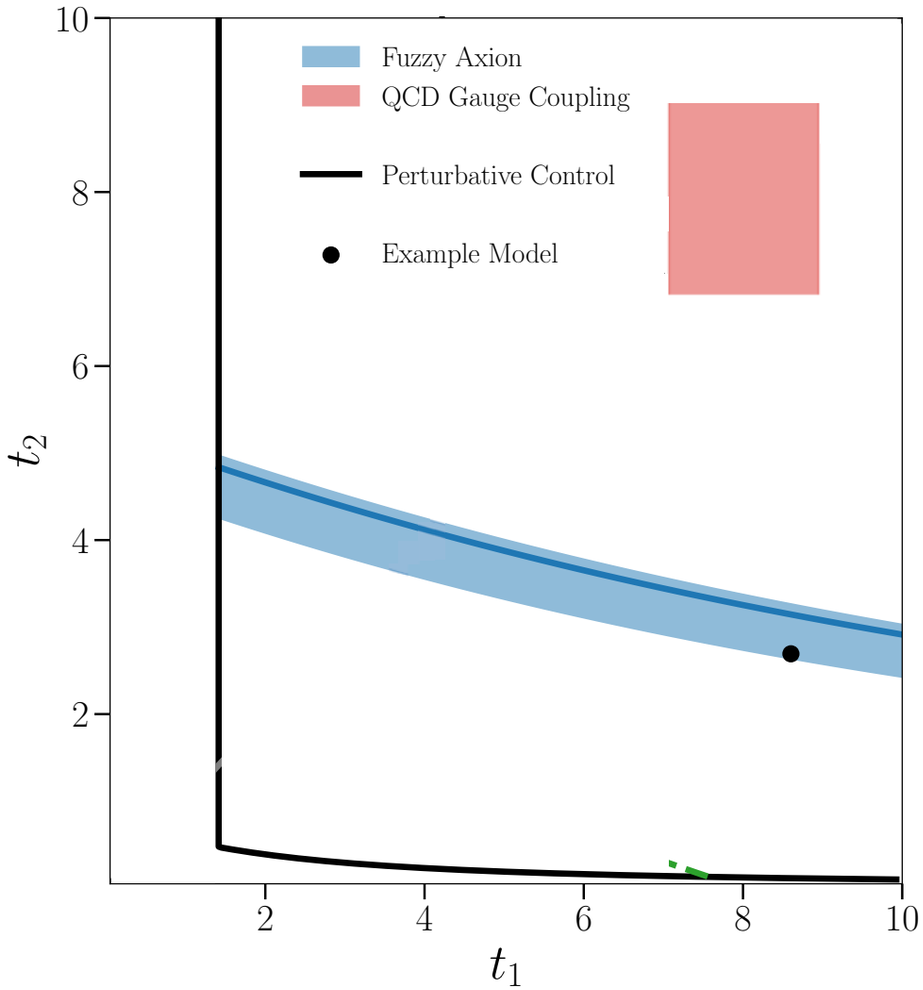
Generate EFTs such that

- $f_{fuzzy} \gtrsim 10^{16}\,\text{GeV} \;\Rightarrow\;$ focus on $2 \leq$ axions ≤ 7
- all volumes $> \ell_s$
- one QCD axion
- at least one axion with $m_{fuzzy} \sim 10^{-19}\,\text{eV}$

$m_{QCD} \sim 10^{-9}\,\text{eV}$ $\qquad$ $f_{QCD} \sim 10^{15}\,\text{GeV}$

$m_{fuzzy} \sim 10^{-20}\,\text{eV}$ $\qquad$ $f_{fuzzy} \sim 10^{16}\,\text{GeV}$

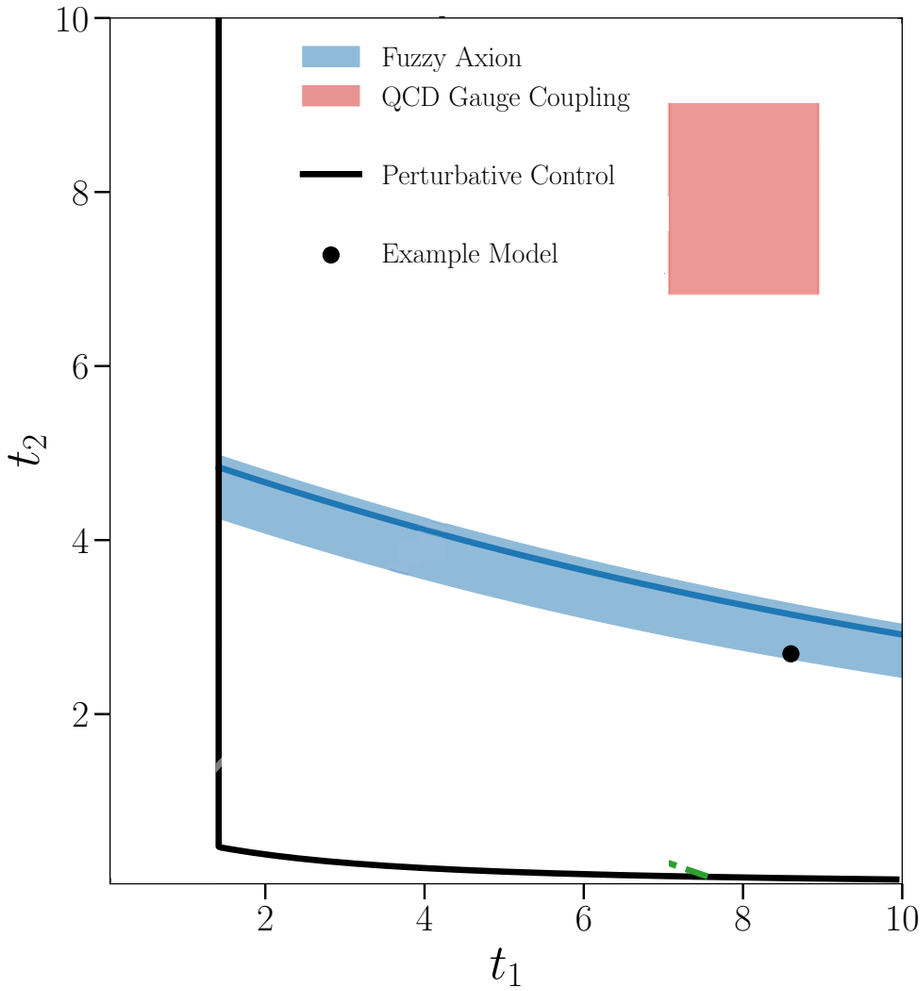
$\dfrac{\Omega_{QCD}}{\Omega_{DM}} \sim 0.5$ $\qquad$ $\dfrac{\Omega_{fuzzy}}{\Omega_{DM}} \sim 0.5$



String Axions as Dark Matter

Generate EFTs such that

- $f_{fuzzy} \gtrsim 10^{16}\,\text{GeV} \;\Rightarrow\;$ focus on $2 \leq$ axions ≤ 7
- all volumes $> \ell_s$
- one QCD axion
- at least one axion with $m_{fuzzy} \sim 10^{-19}\,\text{eV}$



$m_{QCD} \sim 10^{-9}\,\text{eV}$ $\qquad$ $f_{QCD} \sim 10^{15}\,\text{GeV}$

$m_{fuzzy} \sim 10^{-20}\,\text{eV}$ $\qquad$ $f_{fuzzy} \sim 10^{16}\,\text{GeV}$

$\dfrac{\Omega_{QCD}}{\Omega_{DM}} \sim 0.5$ $\qquad$ $\dfrac{\Omega_{fuzzy}}{\Omega_{DM}} \sim 0.5$

in general, things are not that clean!

String Axions and Relics

Relic 1: AXIONS

$$\Omega_a h^2 \sim f_a^2 \, \theta_0^2 \sqrt{m_a}$$

String Axions and Relics

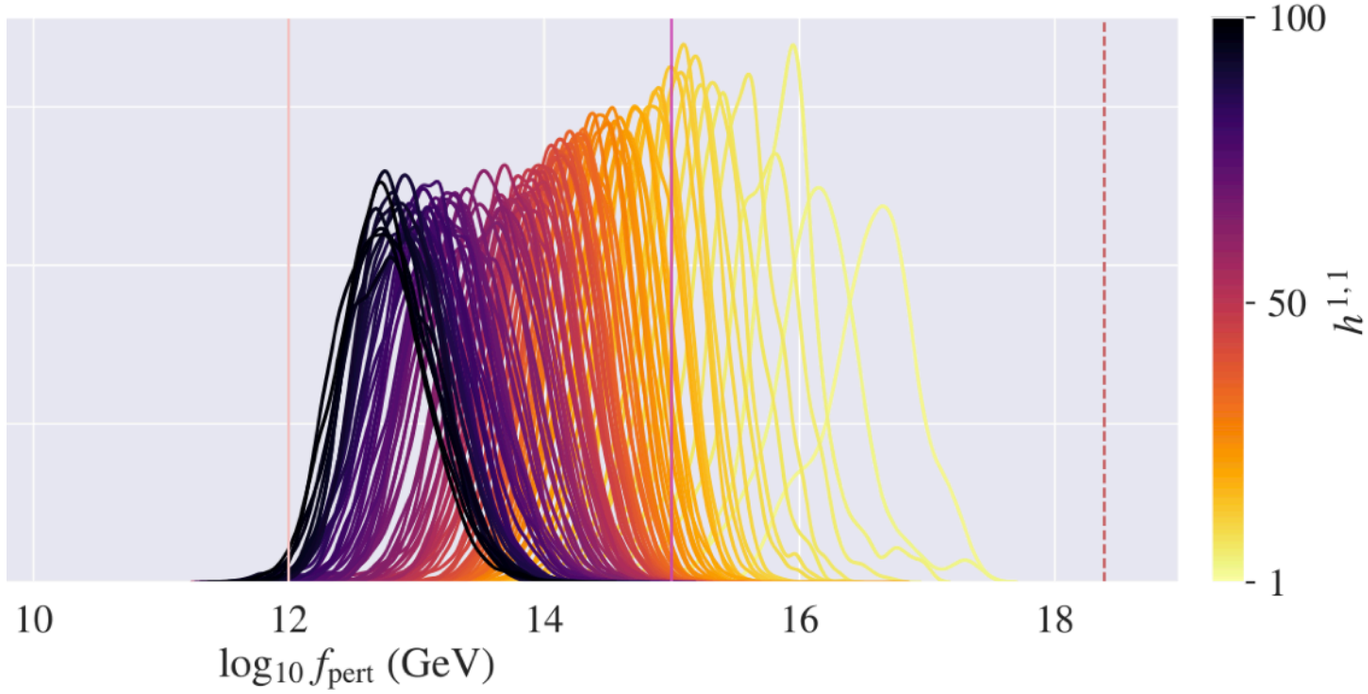
Relic 1: AXIONS

$$\Omega_a h^2 \sim f_a^2\, \theta_0^2 \sqrt{m_a}$$

$$\Omega_{a,\text{total}} h^2 = \Omega_{\text{QCD}} h^2 + \sum \Omega_i h^2 \Big|_{\text{m}} + \sum \Omega_j h^2 \Big|_{\text{r}} + \sum \Omega_k h^2 \Big|_{w_R} \leq \Omega_{\text{DM}} h^2 \approx 0.12$$

typical distributions:

- masses log flat
- decay constants clustered



[Mehta, Demirtas, Long, Marsh, McAllister, Stott '21]

WARNING

OVERCLOSURE

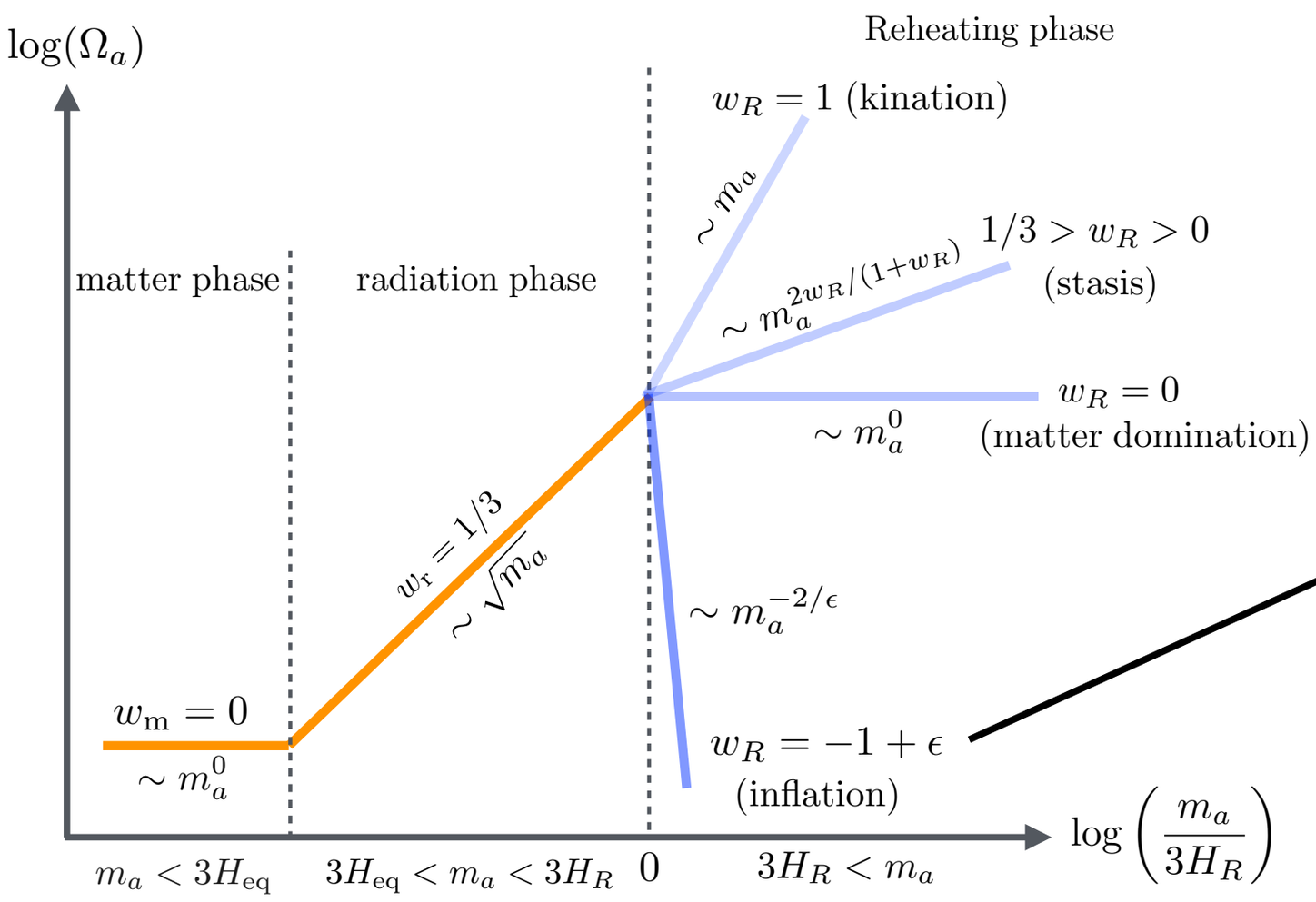
String Axions and Relics

Relic 1: AXIONS

$$\Omega_a h^2 \sim f_a^2\, \theta_0^2 \sqrt{m_a}$$

$$\Omega_{a,\text{total}} h^2 = \Omega_{\text{QCD}} h^2 + \sum \Omega_i h^2 \Big|_{\text{m}} + \sum \Omega_j h^2 \Big|_{\text{r}} + \sum \Omega_k h^2 \Big|_{w_R} \leq \Omega_{\text{DM}} h^2 \approx 0.12$$

- Dilution



the relics are diluted away for appropriate (low) T_R

String Axions and Relics

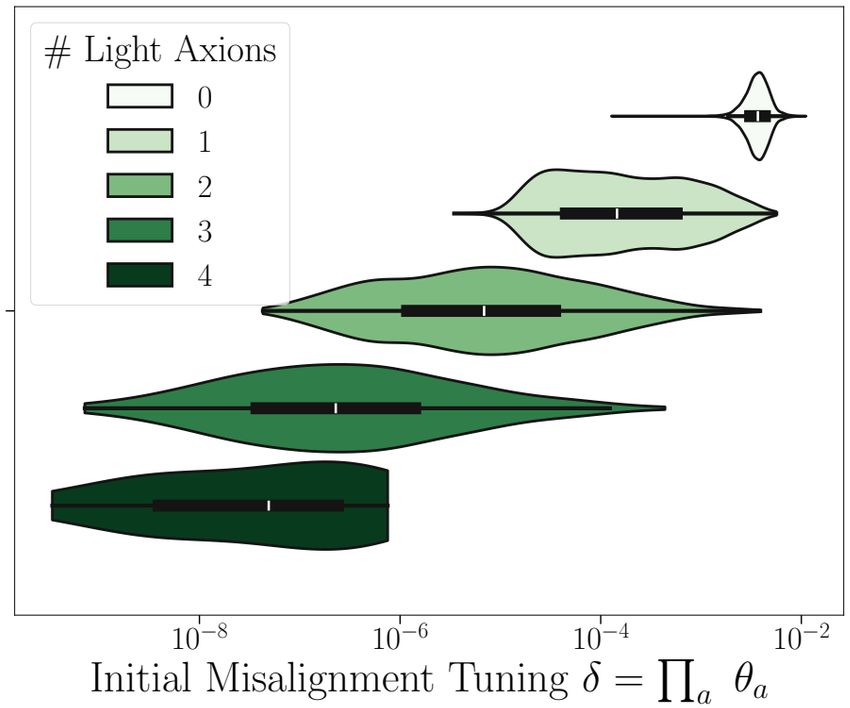
Relic 1: AXIONS

$$\Omega_a h^2 \sim f_a^2\, \theta_0^2 \sqrt{m_a}$$

$$\Omega_{a,\text{total}} h^2 = \Omega_{\text{QCD}} h^2 + \sum \Omega_i h^2 \Big|_{\text{m}} + \sum \Omega_j h^2 \Big|_{\text{r}} + \sum \Omega_k h^2 \Big|_{w_R} \leq \Omega_{\text{DM}} h^2 \approx 0.12$$

- Initial misalignment ⇓

$$\Omega_{a,\text{total}} h^2 = \Omega_{\text{QCD}}(\theta_0) h^2 + \sum_i \Omega_i(\theta_0) h^2 \Big|_{\text{m}} + \sum_j \Omega_j(\theta_0) h^2 \Big|_{\text{r}} + \sum_k \Omega_k(\theta_0) h^2 \Big|_{w_R} \leq \Omega_{\text{DM}} h^2 \approx 0.12$$



String Axions and Relics

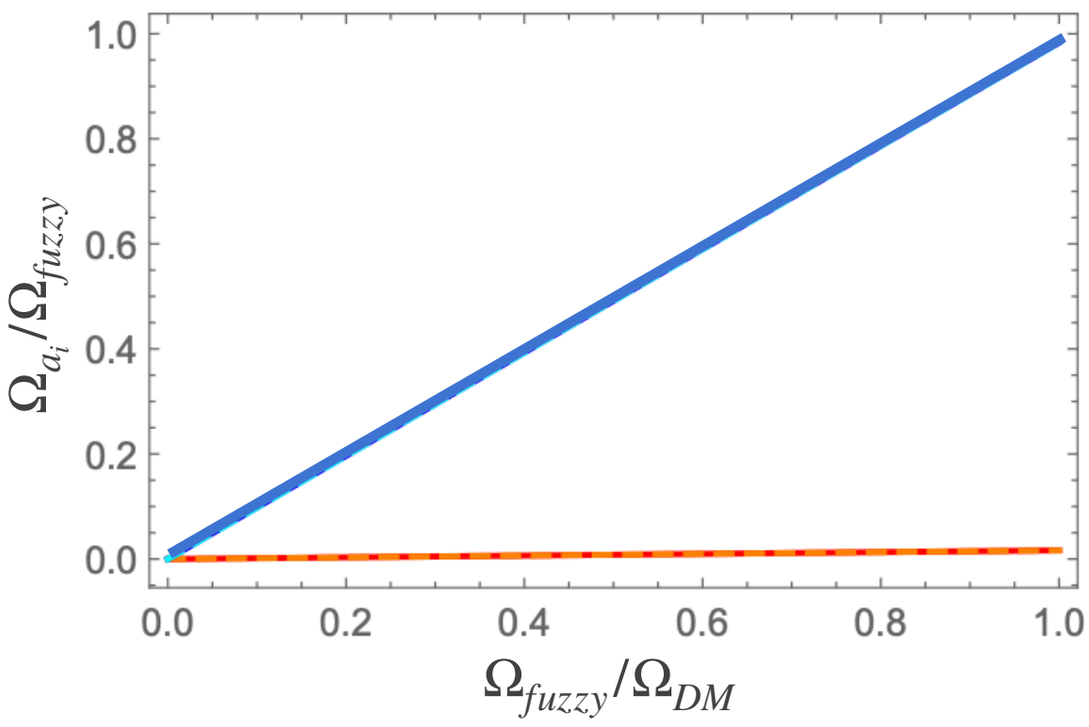
Relic 1: AXIONS

$$\Omega_a h^2 \sim f_a^2\, \theta_0^2 \sqrt{m_a}$$

$$\Omega_{a,\text{total}} h^2 = \Omega_{\text{QCD}} h^2 + \sum \Omega_i h^2 \Big|_{\text{m}} + \sum \Omega_j h^2 \Big|_{\text{r}} + \sum \Omega_k h^2 \Big|_{w_R} \leq \Omega_{\text{DM}} h^2 \approx 0.12$$

- Small decay constants: $f_{fuzzy} \gg f_{\text{others}}$

$f_{fuzzy} \gg f_a$



String Axions and Relics

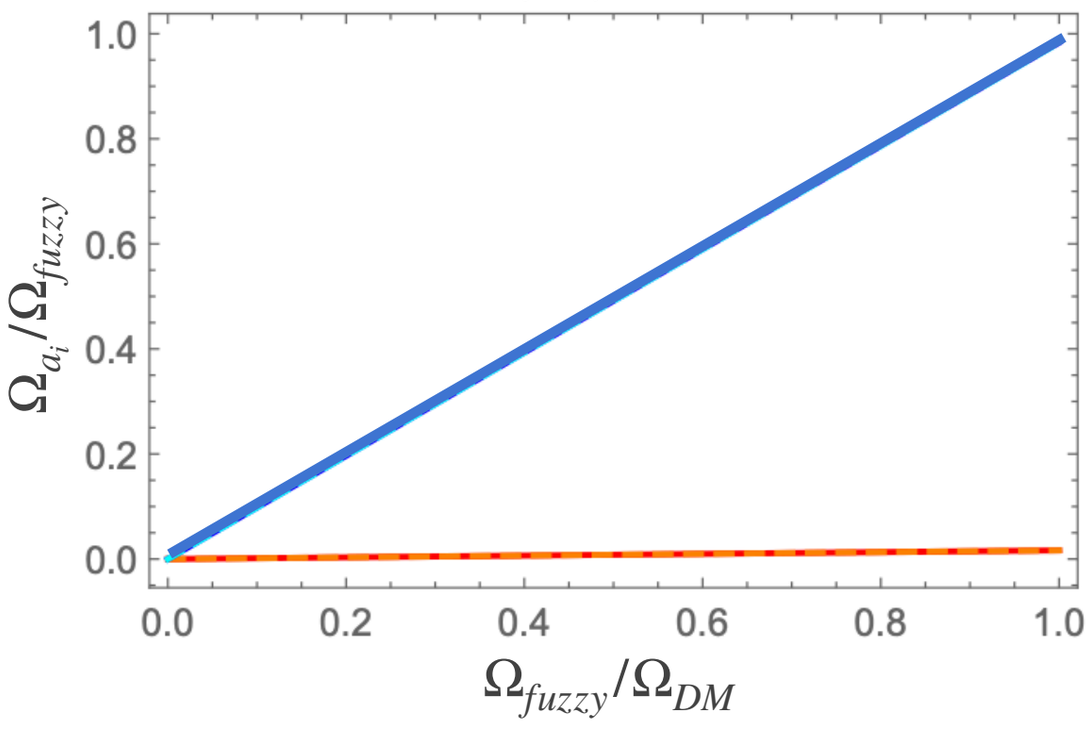
Relic 1: AXIONS

$$\Omega_a h^2 \sim f_a^2\, \theta_0^2 \sqrt{m_a}$$

$$\Omega_{a,\text{total}} h^2 = \Omega_{\text{QCD}} h^2 + \sum \Omega_i h^2 \Big|_{\text{m}} + \sum \Omega_j h^2 \Big|_{\text{r}} + \sum \Omega_k h^2 \Big|_{w_R} \leq \Omega_{\text{DM}} h^2 \approx 0.12$$

- Small decay constants: $f_{fuzzy} \gg f_{\text{others}}$

$f_{fuzzy} \gg f_a$



not generic!

$$f_{fuzzy} \sim 10^7 f_{QCD}$$

$$\Downarrow$$

$$\det(K)\Big|_{fuzzy} \sim 10^{-14} \det(K)\Big|_{QCD}$$

K metric on moduli space

String Axions and Relics

Relic 2: Moduli

4D $\mathcal{N} = 1$ chiral multiplet: $T_i = \mathrm{vol}\left(\Sigma_4^i\right) + i\theta_i \;\Rightarrow$ at least as many moduli as axions!

must be stabilised at the right scale

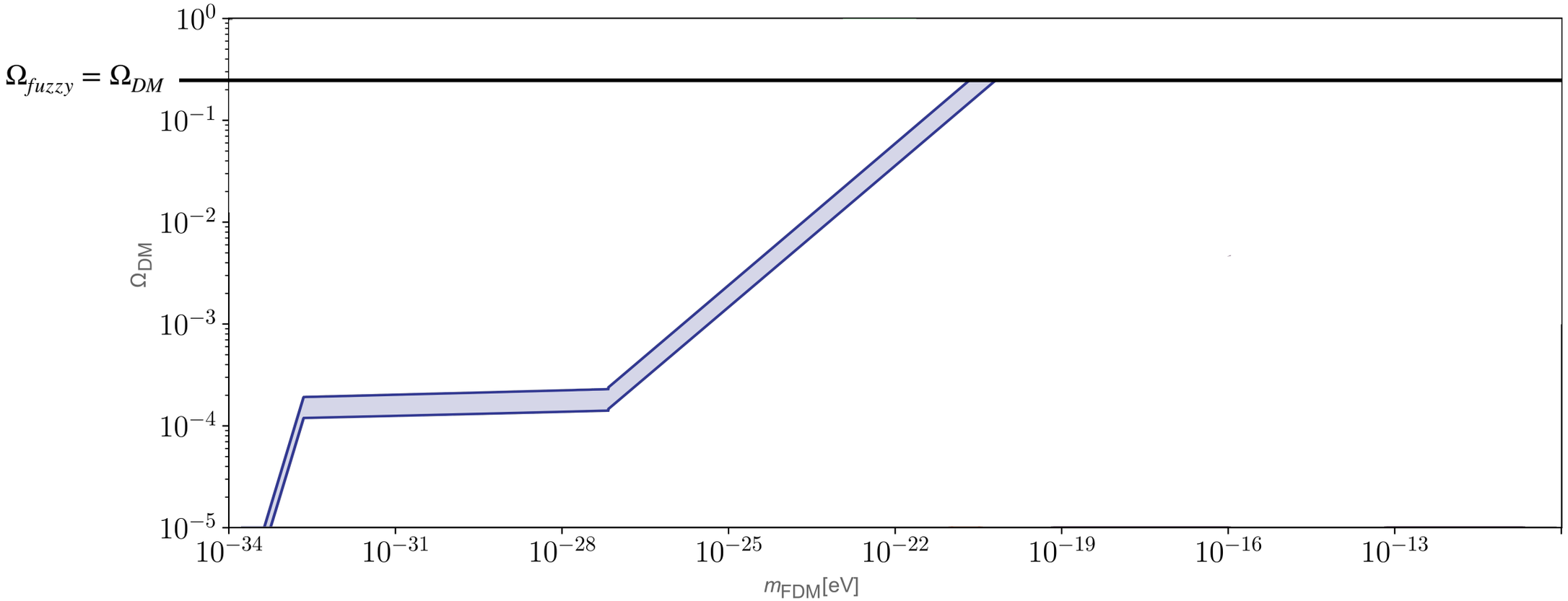
String Axions and Relics

Relic 2: Moduli

4D $\mathcal{N}=1$ chiral multiplet: $T_i = \mathrm{vol}\left(\Sigma_4^i\right) + i\theta_i \;\Rightarrow$ at least as many moduli as axions!
must be stabilised at the right scale

1) Implement moduli stabilisation properly [Cicoli, Guidetti, NR, Westphal '21]

ensure ⟨moduli⟩, *then* compute axions EFT



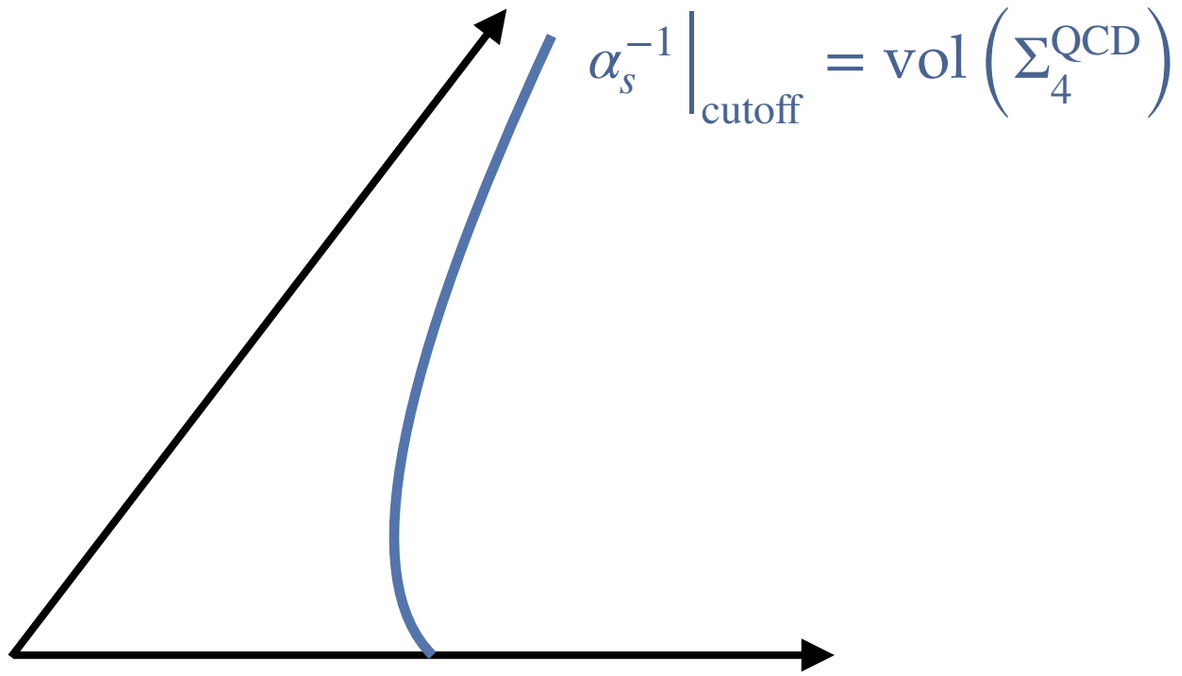
String Axions and Relics

Relic 2: Moduli

4D $\mathcal{N}=1$ chiral multiplet: $T_i = \mathrm{vol}\left(\Sigma_4^i\right) + i\theta_i \;\Rightarrow$ at least as many moduli as axions!
must be stabilised at the right scale

2) *Assume* moduli are stabilised properly [Sheridan, Carta, Gendler, Jain, Marsh, McAllister, NR, Rogers, Schachner '24]

$$M_{moduli} > \Lambda_{EFT}$$

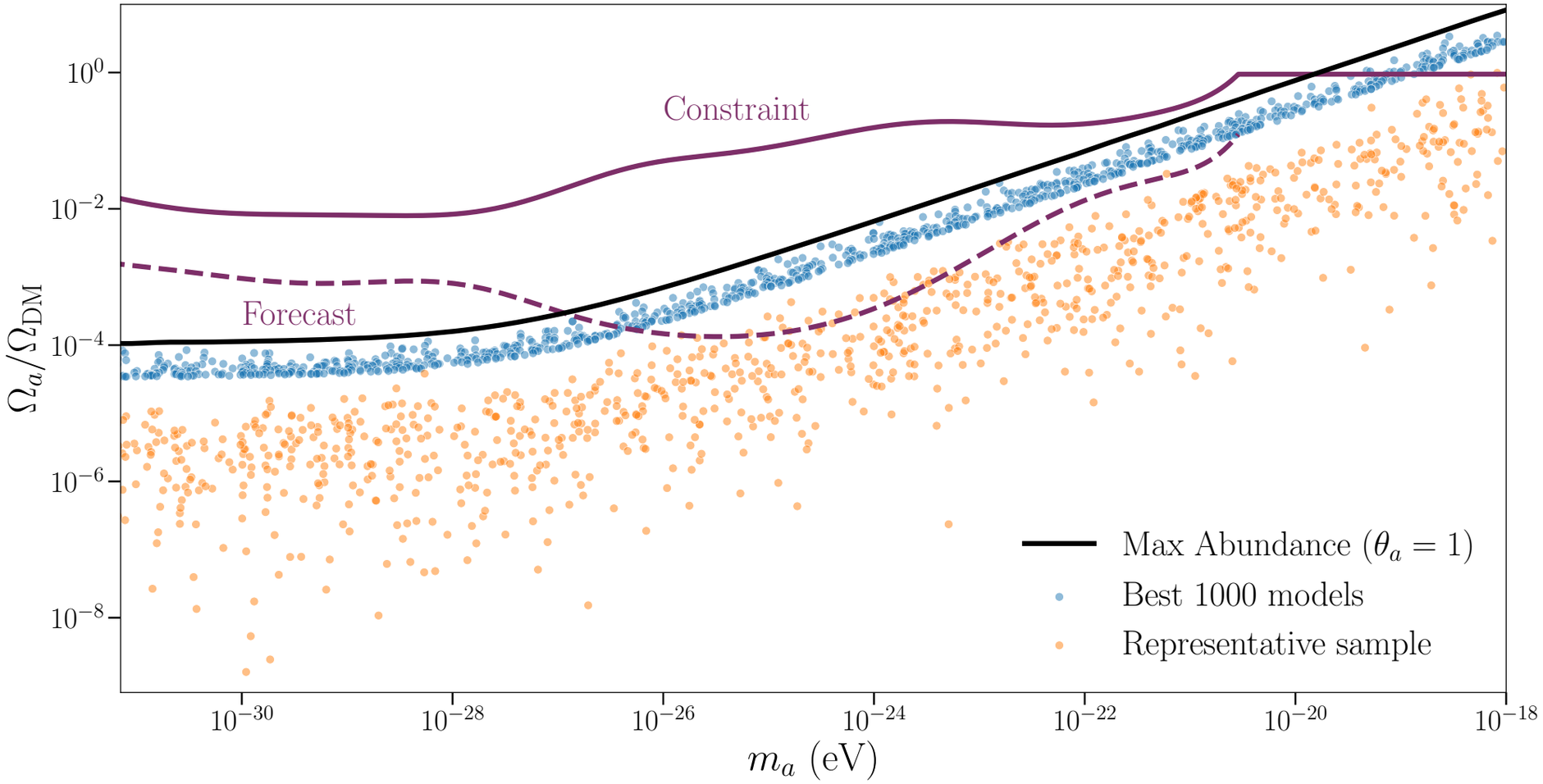


String Axions and Relics

Relic 2: Moduli

4D $\mathcal{N}=1$ chiral multiplet: $T_i = \mathrm{vol}\left(\Sigma_4^i\right) + i\theta_i \;\Rightarrow$ at least as many moduli as axions!
must be stabilised at the right scale

2) *Assume* moduli are stabilised properly [Sheridan, Carta, Gendler, Jain, Marsh, McAllister, NR, Rogers, Schachner '24]

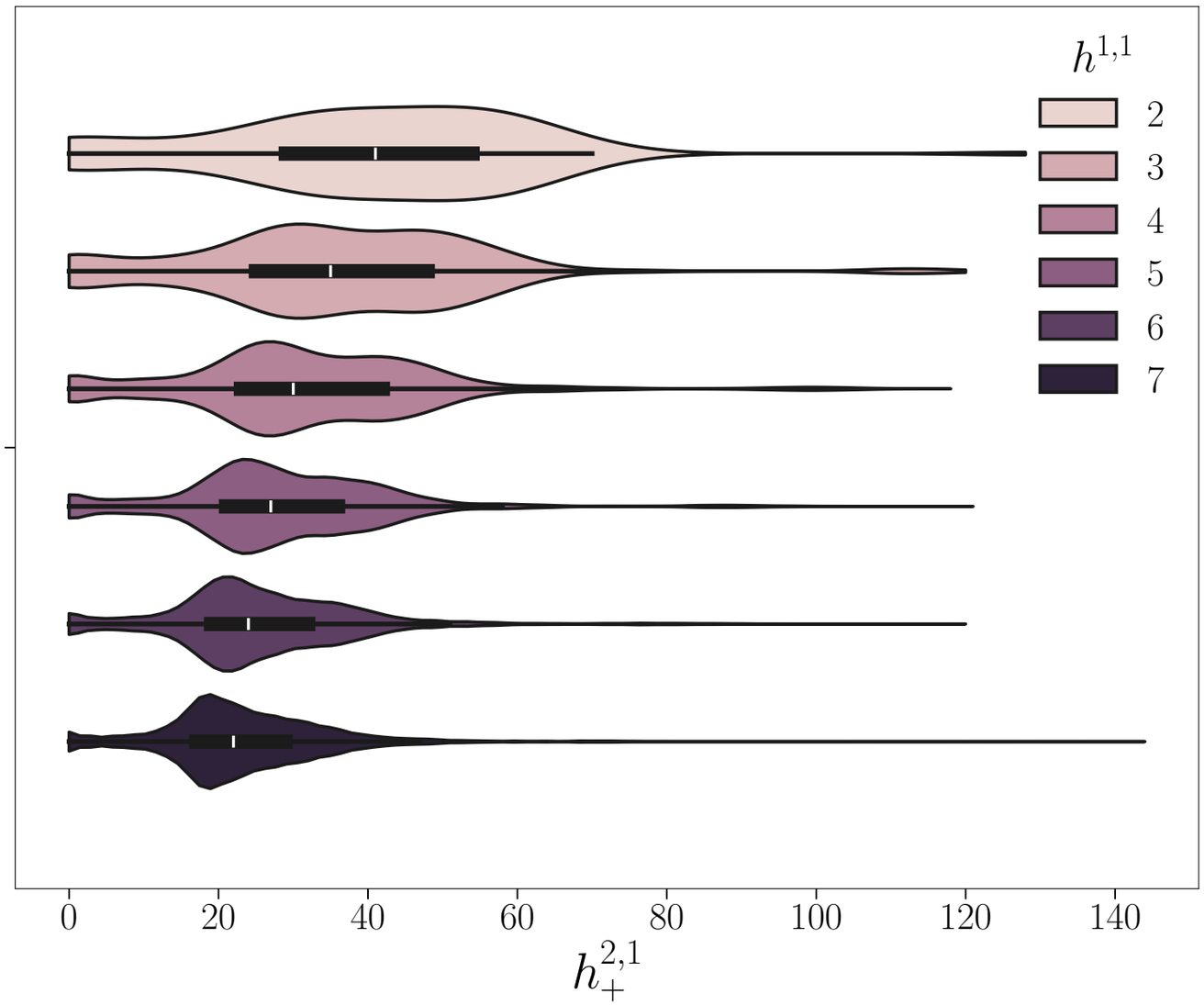


Relic 3: Dark U(1) gauge fields

using [Moritz '23]

$h^{2,1}_{+} \neq 0$ in $\sim 95\,\%$ of orientifolds

$$C_4 = \theta_i \, \omega_4^i + V^a \wedge \alpha_a$$

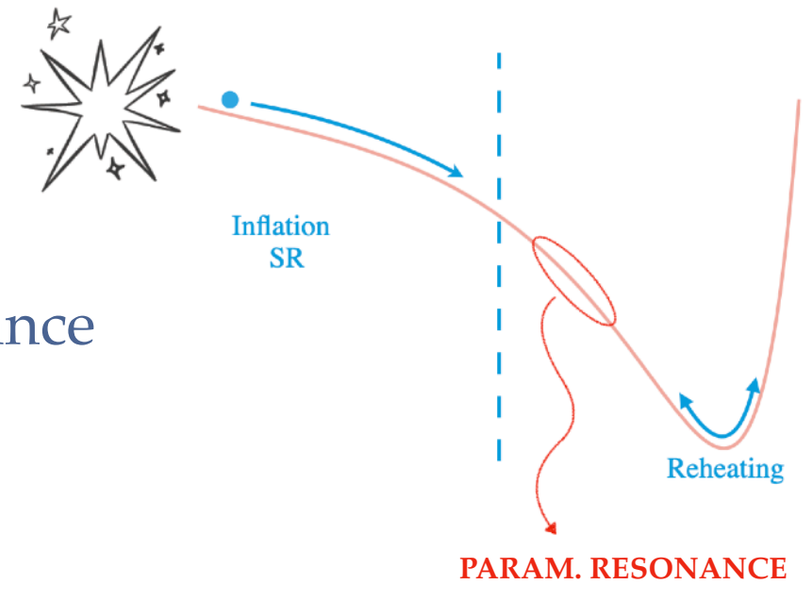


Heavy String Axions form Inflation

String axions are naturally light: $m_a^2 \sim e^{-\mathrm{vol}(\Sigma_4)}$

Heavy String Axions form Inflation

String axions are naturally light: $m_a^2 \sim e^{-\mathrm{vol}(\Sigma_4)}$



A dynamical process can change this: parametric resonance

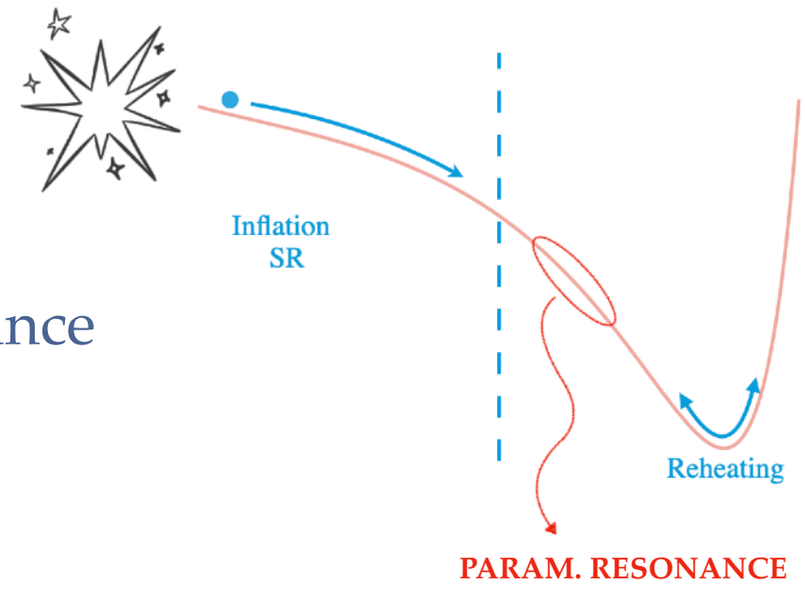
inflaton: $\phi \simeq \langle\phi\rangle + \Delta\phi\, t^{-1} \cos(m_\phi t)$

axion: $\theta(t,\vec{x}) \simeq \langle\theta\rangle + \theta_k(t,\vec{x})$

$$\ddot{\theta}_k + \left(3H - \frac{\partial K_{T\bar{T}}}{K_{T\bar{T}}}\right)\dot{\theta}_k + \left(\frac{k^2}{a^2} + \frac{\partial^2 V}{\partial\theta_k^2}\right)\theta_k = 0$$

Heavy String Axions form Inflation

String axions are naturally light: $m_a^2 \sim e^{-\mathrm{vol}(\Sigma_4)}$



A dynamical process can change this: parametric resonance

inflaton: $\phi \simeq \langle\phi\rangle + \Delta\phi\, t^{-1} \cos(m_\phi t)$

axion: $\theta(t,\vec{x}) \simeq \langle\theta\rangle + \theta_k(t,\vec{x})$

$$\ddot{\theta}_k + \left(3H - \frac{\partial K_{T\bar{T}}}{K_{T\bar{T}}}\right)\dot{\theta}_k + \left(\frac{k^2}{a^2} + \frac{\partial^2 V}{\partial\theta_k^2}\right)\theta_k = 0$$

$$\ddot{\theta}_k + \left(3H - \frac{\partial K_{T\bar{T}}}{K_{T\bar{T}}}\right)\dot{\theta}_k + \left(\frac{k^2}{a^2} + m_{\theta,0}^2 e^{-\frac{\Delta\phi}{m_\phi t}\cos(m_\phi t)}\right)\theta_k = 0$$

[Leedom, Putti, NR, Westphal '24]

Relics from Heavy Axions

$$\ddot{\theta}_k + \left(3H - \frac{\partial K_{T\bar{T}}}{K_{T\bar{T}}}\right)\dot{\theta}_k + \left(\frac{k^2}{a^2} + \underbrace{m_{\theta,0}^2 e^{-\frac{\Delta\phi}{m_\phi t}\cos(m_\phi t)}}_{m_{\theta,\mathrm{eff}}^2}\right)\theta_k = 0$$

- $\mathscr{L}_{kin} > V \;\Rightarrow$ production of axions, $m_{\theta,\mathrm{eff}} \lesssim 10^{-28}$ eV $\;\Rightarrow\;$ contribution to $\Delta N_{eff} \lesssim 10^{-6}$

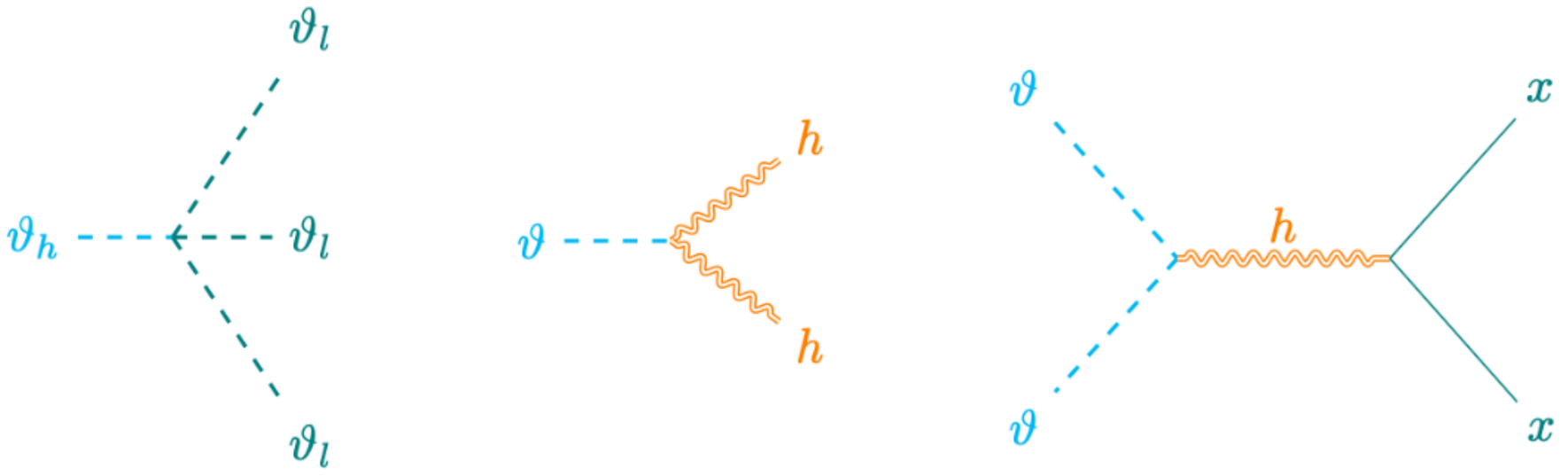
- $\mathscr{L}_{kin} < V \;\Rightarrow$ production of axions, $m_{\theta,\mathrm{eff}} \sim m_\phi \;\Rightarrow$ During radiation domination redshift slower than radiation, might lead to overclosure

$$\Downarrow$$

must decay efficiently

[Leedom, Putti, NR, Westphal '24]

Relics from Heavy Axions



If axion is heavy ($m_\theta \sim H_I$), it can decay into

1. Massless gauge bosons
2. Gravitons
3. SM — MSSM Higgs doublet
4. Lighter axions
5. Condensing gauge group

Conclusions

The string axiverse can be realised in our universe and *detected*, but at a price:

- Presence of a number of relics: moduli, dark photons, decay products…
- Introduction of non-standard cosmology: low T_R
- Tuning of the geometry

String theory p.o.v. is different form pure EFT, e.g. high quality and couplings

Axion detection could inform us about our place in the landscape.

Conclusions

The string axiverse can be realised in our universe and *detected*, but at a price:

- Presence of a number of relics: moduli, dark photons, decay products…
- Introduction of non-standard cosmology: low T_R
- Tuning of the geometry

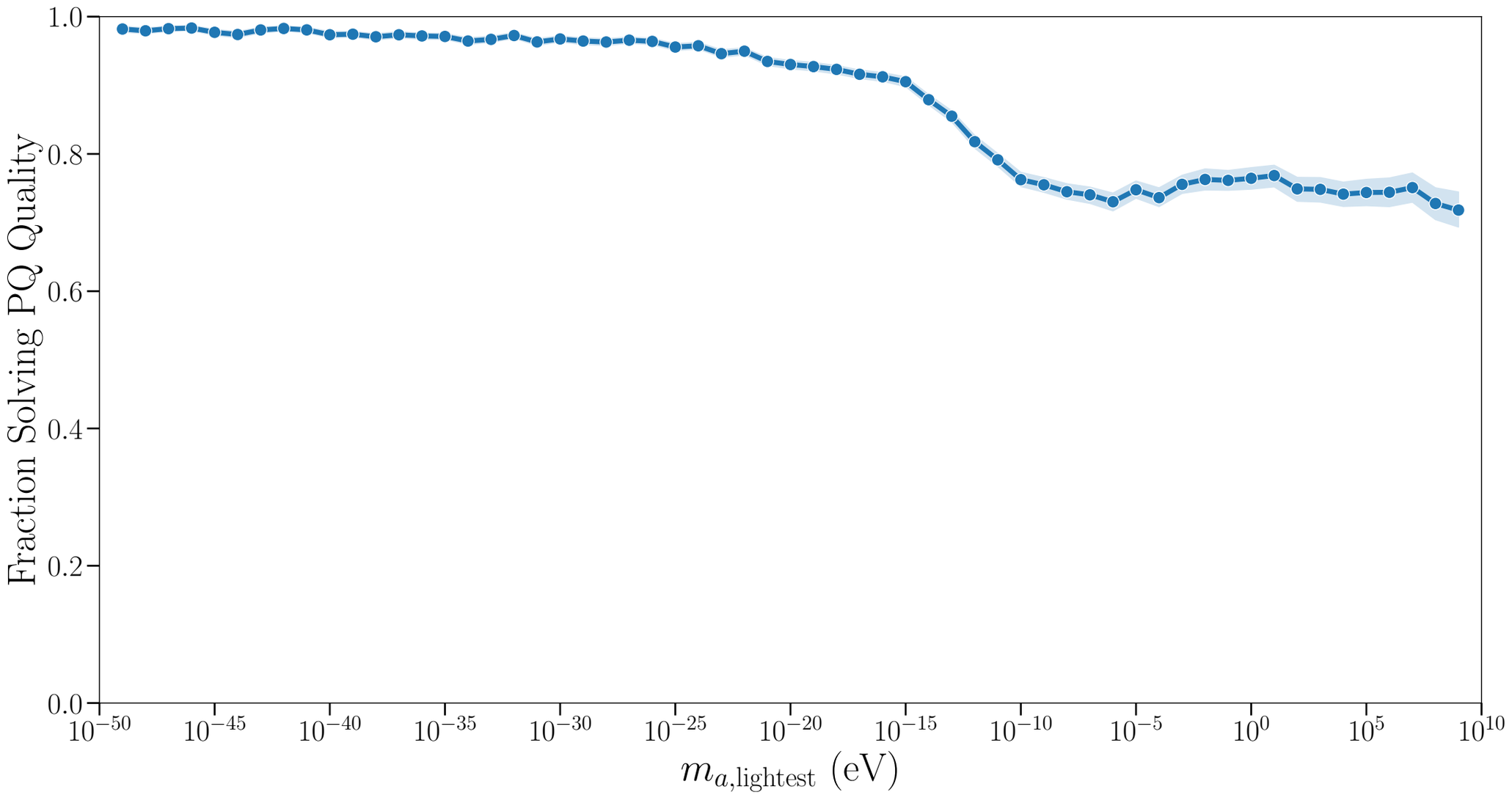
String theory p.o.v. is different form pure EFT, e.g. high quality and couplings

Axion detection could inform us about our place in the landscape.

Thank you

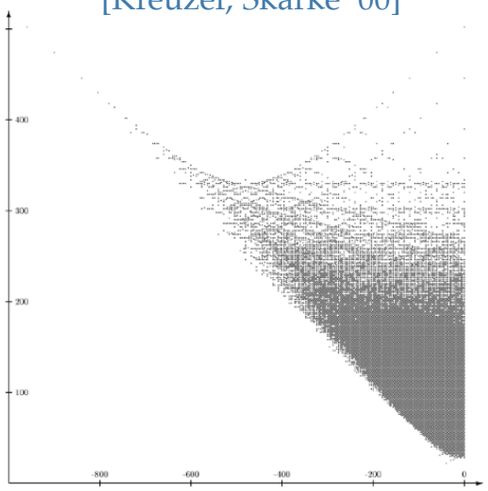
Backup: PQ Quality

$$\Lambda^4_{\mathrm{PQ}} < \Lambda^4_{\text{lightest axion}} \leq \Lambda^4_{\text{fuzzy}} \quad \Rightarrow \quad \frac{\Lambda^4_{\mathrm{PQ}}}{\Lambda^4_{\mathrm{QCD}}} \lesssim 10^{-10} \Leftrightarrow \frac{m_{\text{lightest axion}}}{m_{\mathrm{QCD}}} \lesssim 10^{-5}$$



Backup: How to Approach the Landscape

[Kreuzer, Skarke '00]



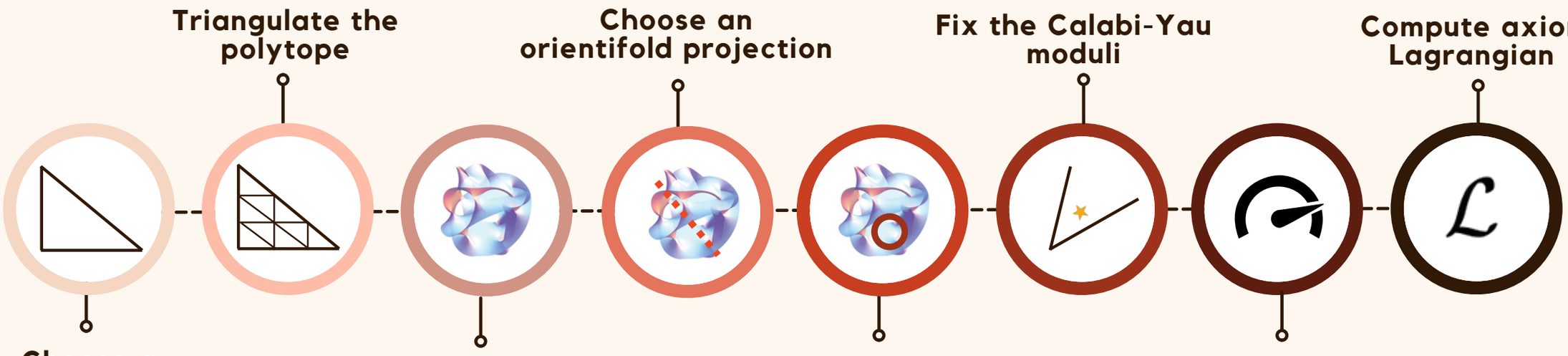
[Demirtas, Rios-Tascon, McAllister '22]

Choose a Fine, Regular, and Star triangulation of the polytope

Break the supersymmetry to N=1 by involuting the Calabi-Yau manifold and the string spectrum

Choose a point in the Kähler moduli space at which the Standard Model gauge couplings match IR expectations

Use the now fully-specified data of the Kähler potential and superpotential to compute axion masses and decay constants



A 4d reflexive polytope from the Kreuzer-Skarke database

Take the anti-canonical hypersurface in the toric variety defined by the triangulation

Pick a four-cycle to host a toy version of QCD via a stack of D7-branes

- Fix the scale of supersymmetry breaking
- Assume Euclidean D3-branes on every holomorphic divisor contribute