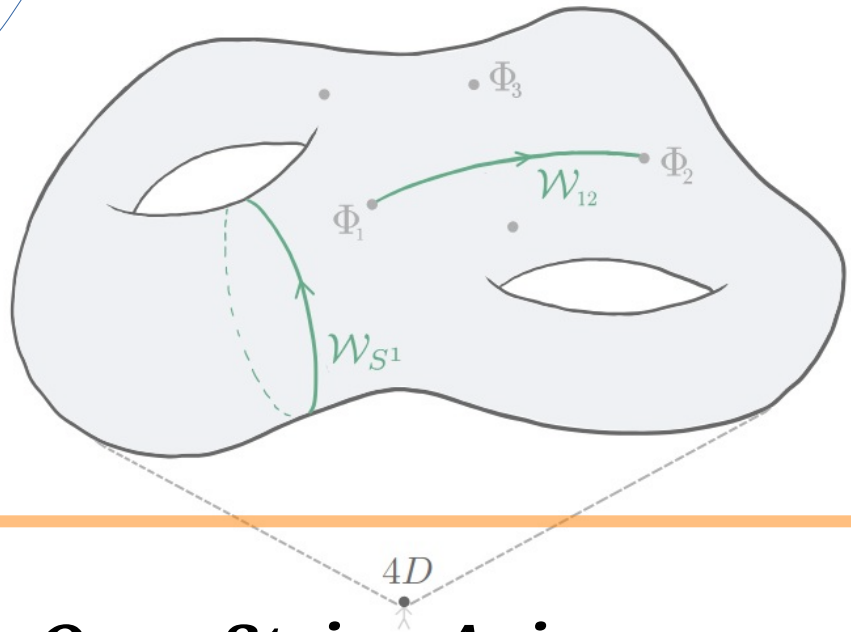


Open String Axiverse

Rudin Petrossian-Byrne

(University of Oxford & ICTP, Trieste)

based on 2503.16387 with Giovanni Villadoro

In 2014….

Gian taught me BSM

In 2025...

Beyond the Standard Model

What should I work on?

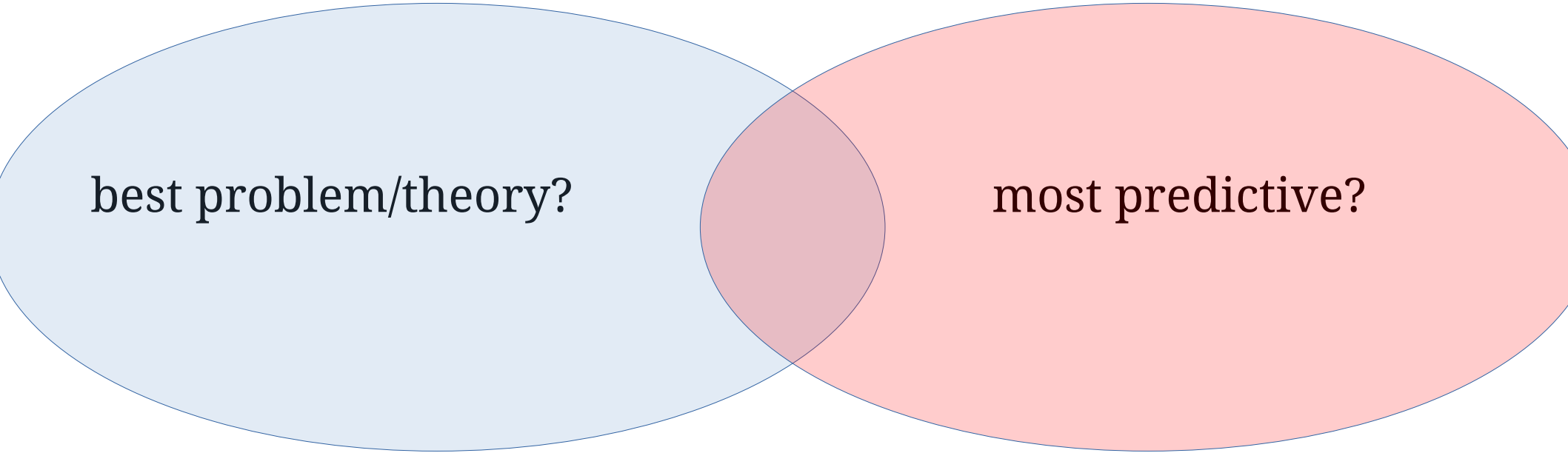
In 2025...

Beyond the Standard Model

What is the best problem/theory?

In 2025...

Beyond the Standard Model



In 2025...

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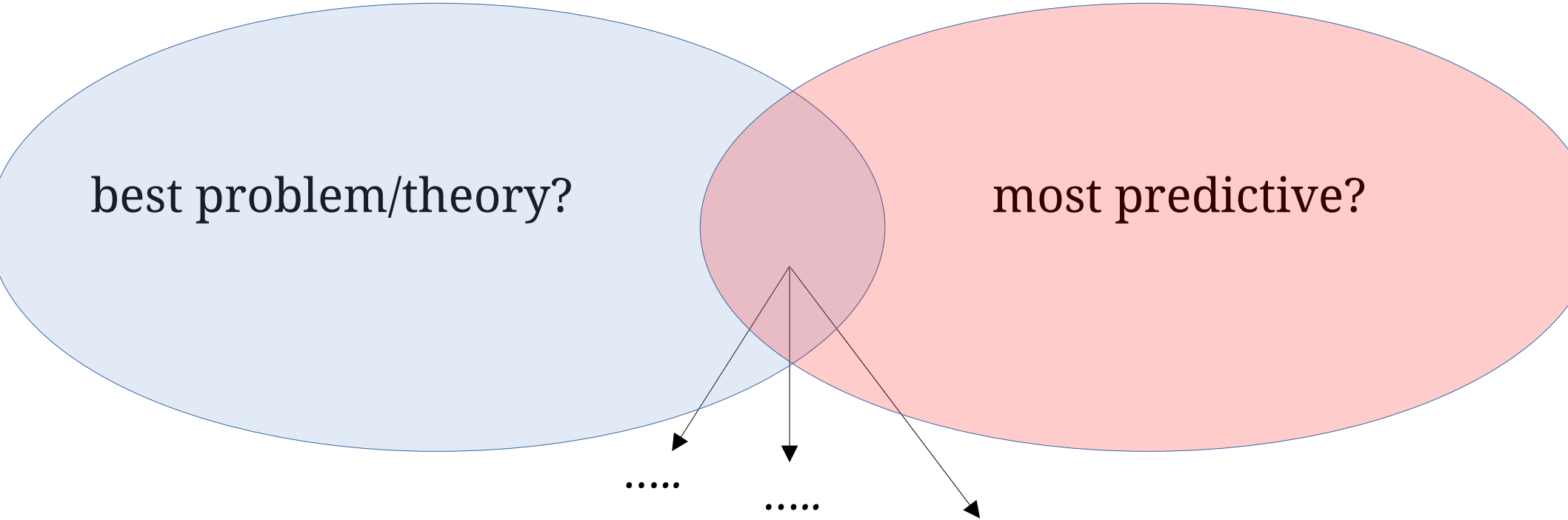

The QCD axion

$$\mathcal{L}_{\rm IR} \supset \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G\tilde{G}$$

Cosmology

“Pre-inflationary” scenario **(~~UV~~)** $H_I \ll f_a$ and $T_{\rm max} \lesssim f_a$

“Post-inflationary” scenario **(UV!)** H_I or $T_{\rm max} \gtrsim f_a$

Cosmology

“Pre-inflationary” scenario **~~(UV)~~** $H_I \ll f_a$ and $T_{\rm max} \lesssim f_a$

near-homogeneous initial condition $\langle a \rangle = \theta_i f_a \quad \Longrightarrow \quad \Omega_{mis}\left(\theta_i, f_a\right) \approx \theta_i^2 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{1.2} \Omega_{\rm DM}$

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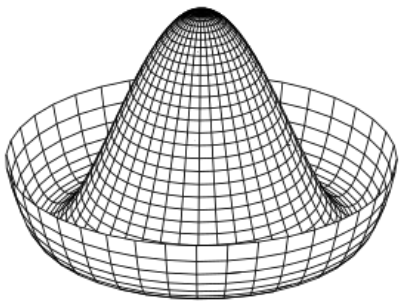
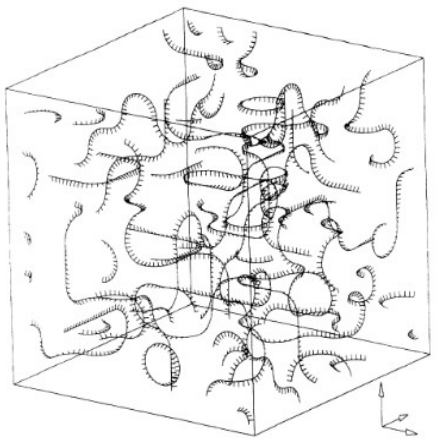


Cosmic string network



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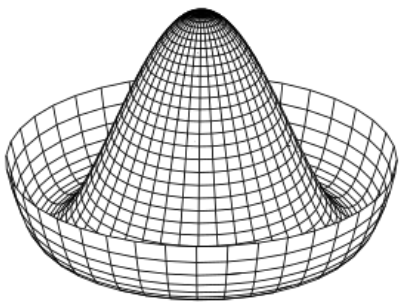

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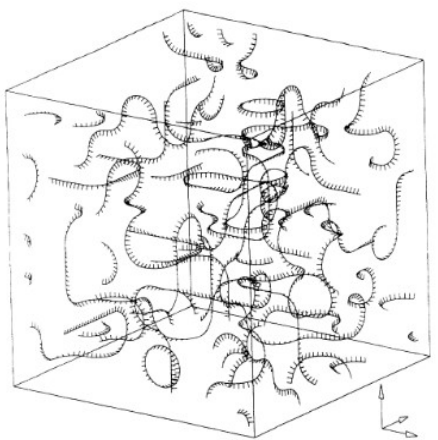

Attractor 'scaling' solution

$\implies \Omega_a = \Omega_a(f_a)$

→ *Gorghetto, Hardy, Villadoro (2021)*
→ *Kim, Park, Son (2024)*
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→ *Benabou, Buschmann, Foster, Safdi*

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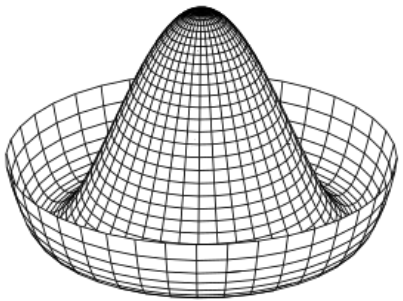

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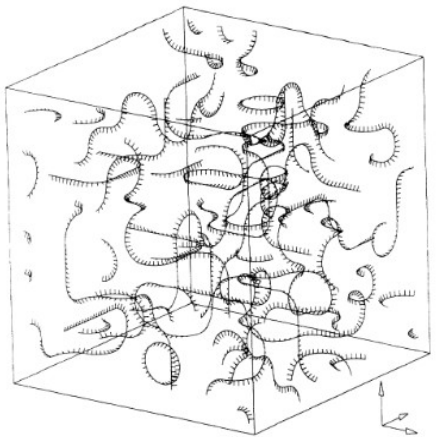

Attractor 'scaling' solution

$\implies \Omega_a \stackrel{!}{=} \Omega_{\rm DM}$

for $f_a \sim 10^{10}\,\mathrm{GeV}$

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Quality of PQ Symmetry

Operationally simplest model: KSVZ *Kim (1979) Shifman, Vainshtein, Zakharov (1980)*

$$\mathcal{L}_{\rm UV} \supset |\partial_\mu \Phi|^2 - V(|\Phi|) + y\,\Phi\,\bar{\psi}_L \psi_R$$

anomaly

$$V(a) = V_{QCD}(a)$$

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anomaly

Abel et al. (2020)

$\theta_{\rm eff} \lesssim 10^{-10}$

$$V(a) = V_{QCD}(a) + \cancel{V_{PQ}}(a)$$

Very dangerous

Not necessarily a concern in field theory.
But standard lore suggests quantum **gravity breaks all global symmetries.**

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But irreducible breaking suggested (e.g. black holes...) is **non-perturbative**

Can expect exponential suppression $b_n \sim e^{-M_{BH}^2/M_{\rm pl}^2}$

Axions from string theory

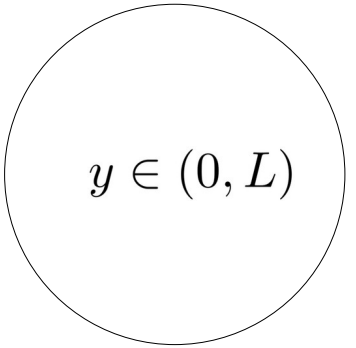
A UV-complete, calculable theory of QG where we can explicitly check.

Witten (1984)	Type I string theory
Choi, Kim, Barr, Dine, Seiberg, Wen, Banks (1985 - 96)	Type I and heterotic
Kallosh, Linde, Linde, Susskind (1995)	Re quality problem
Douglas, Vafa, Green, Harvey, Moore (1997 – 99)	Type II
Conlon (2006) *Svrcek, Witten (2006)*	Bridging to phenomenology
Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell (2010)	String Axiverse
....	....
....	....

Gauge theory in extra dimensions

$$S_{\rm UV} \supset -\frac{1}{4}\int d^4x \int_0^L dy\; F_{MN}F^{MN}$$

$$A_{M=\mu,5}$$



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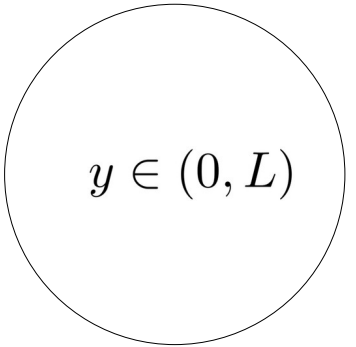

$$A_M = \frac{a_M^0(x^\mu)}{\sqrt{L}} + \sum_{n=1}^{\infty}\left[\frac{a_M^n(x^\mu)}{\sqrt{L/2}}\cos\left(\frac{2\pi n y}{L}\right) + \frac{\bar{a}_M^n(x^\mu)}{\sqrt{L/2}}\sin\left(\frac{2\pi n y}{L}\right)\right]$$

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$y \in (0, L)$

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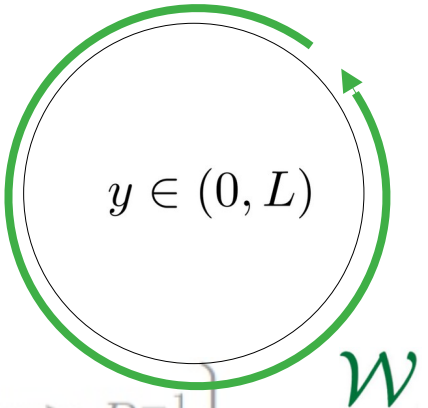

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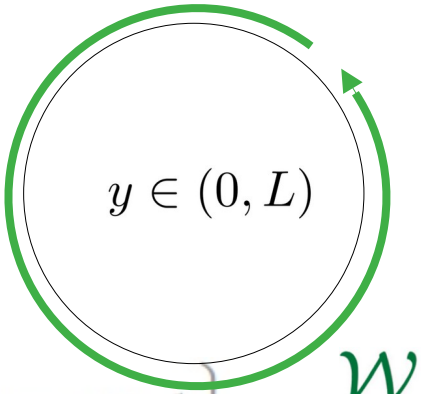

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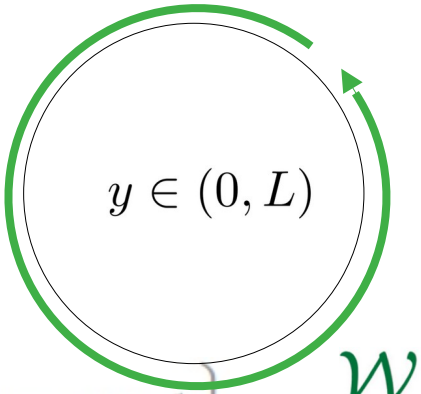

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Broken by any bulk charged field. If $M \gg L^{-1}$

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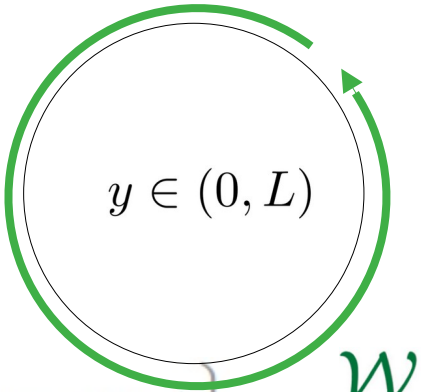

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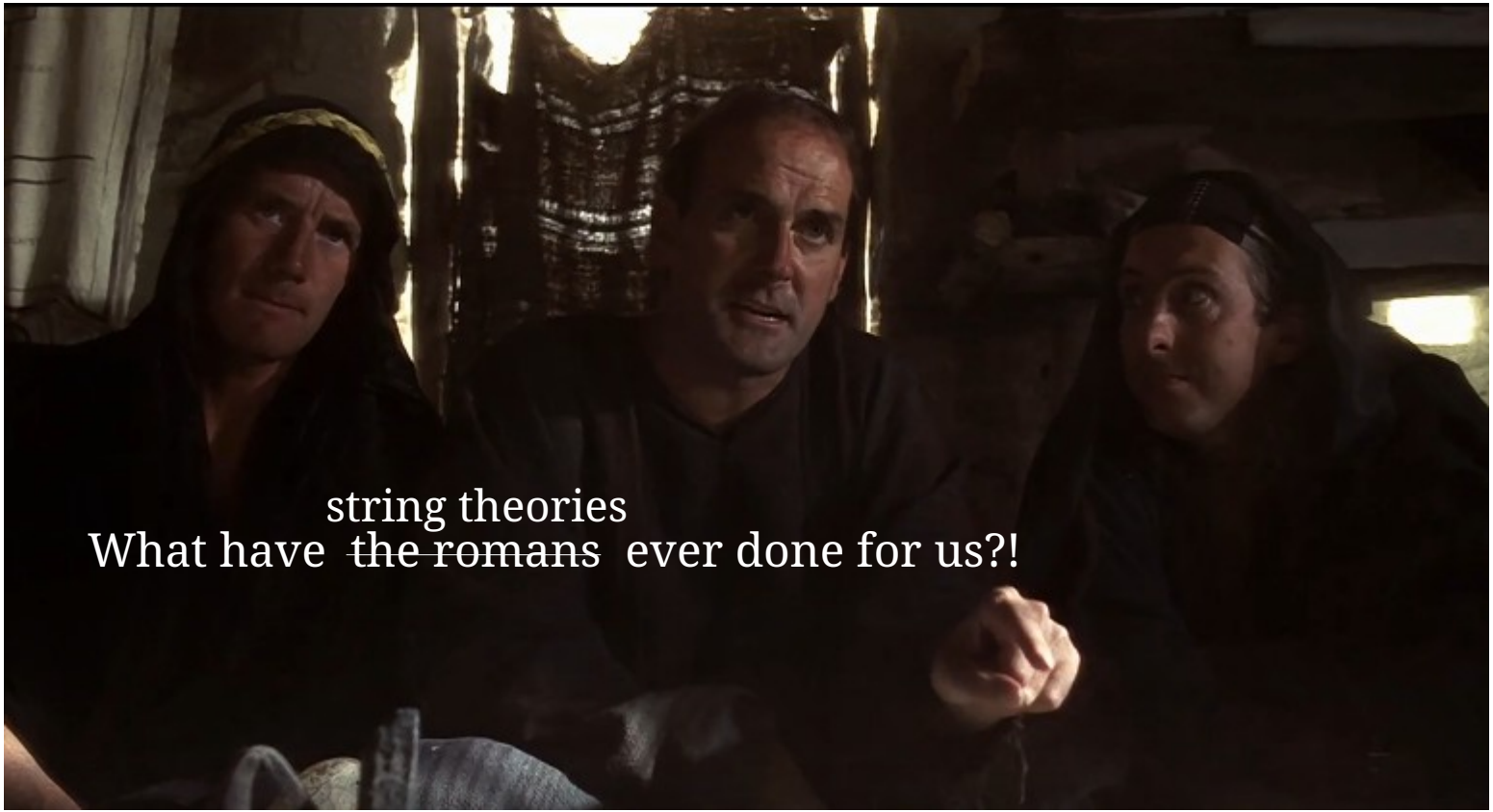
back to... *Axions from* ***string theory***



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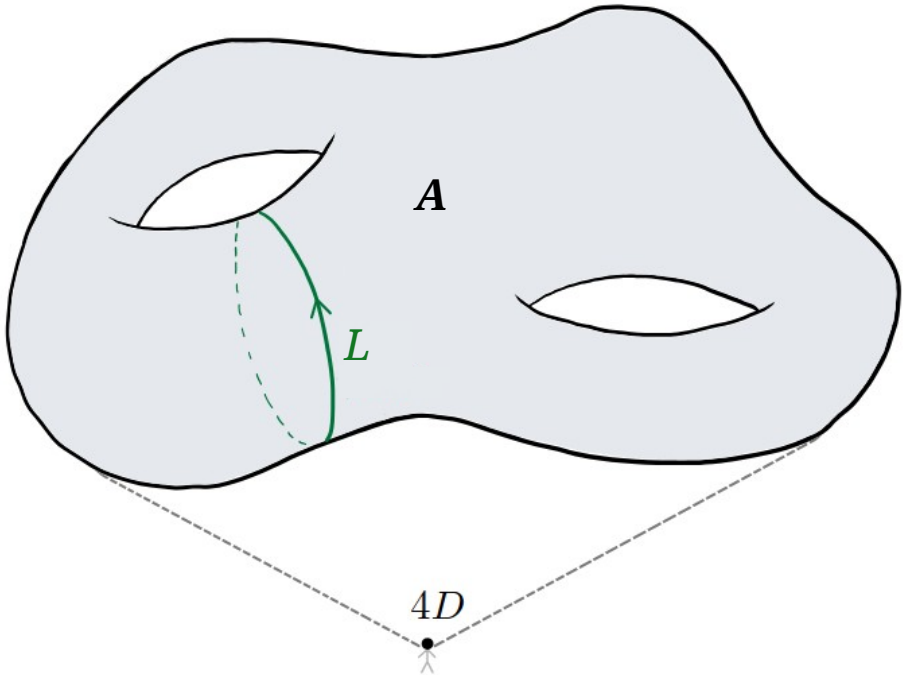

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$M \gg L^{-1}$ just a plausible accident in field theory

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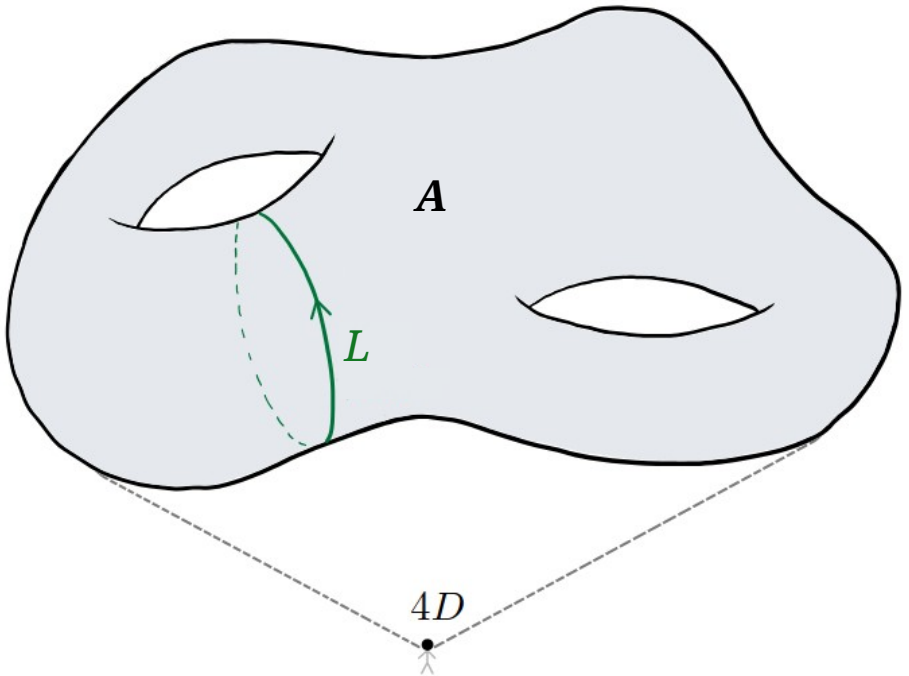

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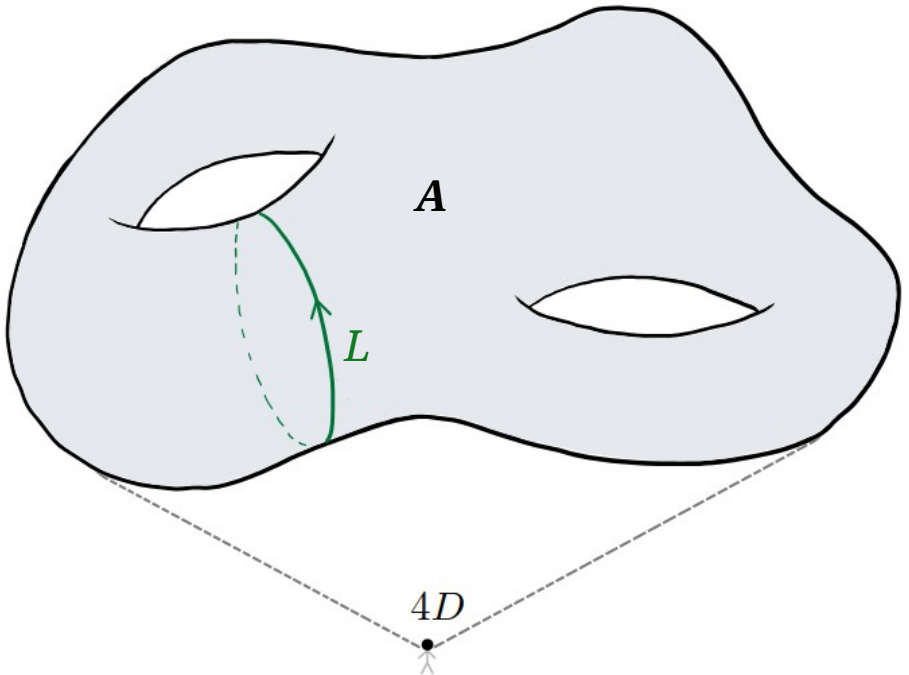
the spectrum is fixed and known.
Breaking effects are unambiguously calculable.

A = RR, NSNS p-forms (closed string sector)

Charged states (*D* branes...) have $M > M_s/g_s \gg L^{-1}$

High quality QCD axion + many ALPs **Axiverse** ✓

back to... *Axions from* ***string theory***



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✗ Post-inflationary cosmology

Axion cosmic strings are (magnetic) *D* branes

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e.g. *March-Russell, Tillim, (2021)*
Benabou, Bonnefoy, Buschmann, Kumar, Safdi (2024)
Reece (2024)

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RPB, Villadoro (2025)

PART I

Theory

Phenomenology

(Reconciling exponential quality & 4D post-inflationary cosmology)

RPB, Villadoro (2025)

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Theory

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See also Loladze, Platschorre, Reig (2025)

Symmetries from separated charges

Localized charged fields living at separate points

$U(1)$ bulk gauge field

$$S_{\rm UV} \supset \int d^4x \int dy \left[-\frac{1}{4} F_{MN} F^{MN} + |\mathcal{D}_\mu \Phi_\pm|^2 \delta(y - y_\pm) \right]$$

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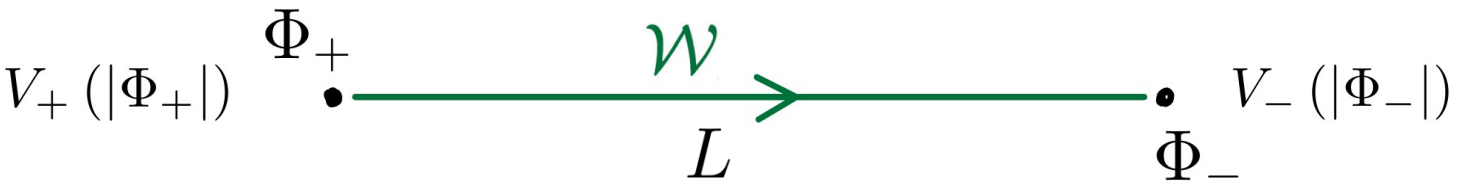
Only gauge-invariant PQ-charged operators are non-local !

$$\mathcal{W} = \Phi_+ \, e^{i g_5 \int_{y_+}^{y_-} dy \, A_5} \, \Phi_-$$

$\Longrightarrow$ Breaking effects from heavy bulk charged fields $V_{\not{PQ}} \propto e^{-ML}$

Symmetries from separated charges

Localized charged fields living at separate points



Gauge transformations $U(1)$ bulk gauge field

$$\Phi_\pm \to \Phi_\pm e^{\pm i g_5 \Lambda(y_\pm)} \qquad A_M \to A_M + \partial_M \Lambda$$

Global (PQ) symmetry

$$\Phi_\pm \to \Phi_\pm e^{i\alpha}$$

An order parameter for PQ breaking / resoration $\langle |\Phi_\pm| \rangle = v_\pm$

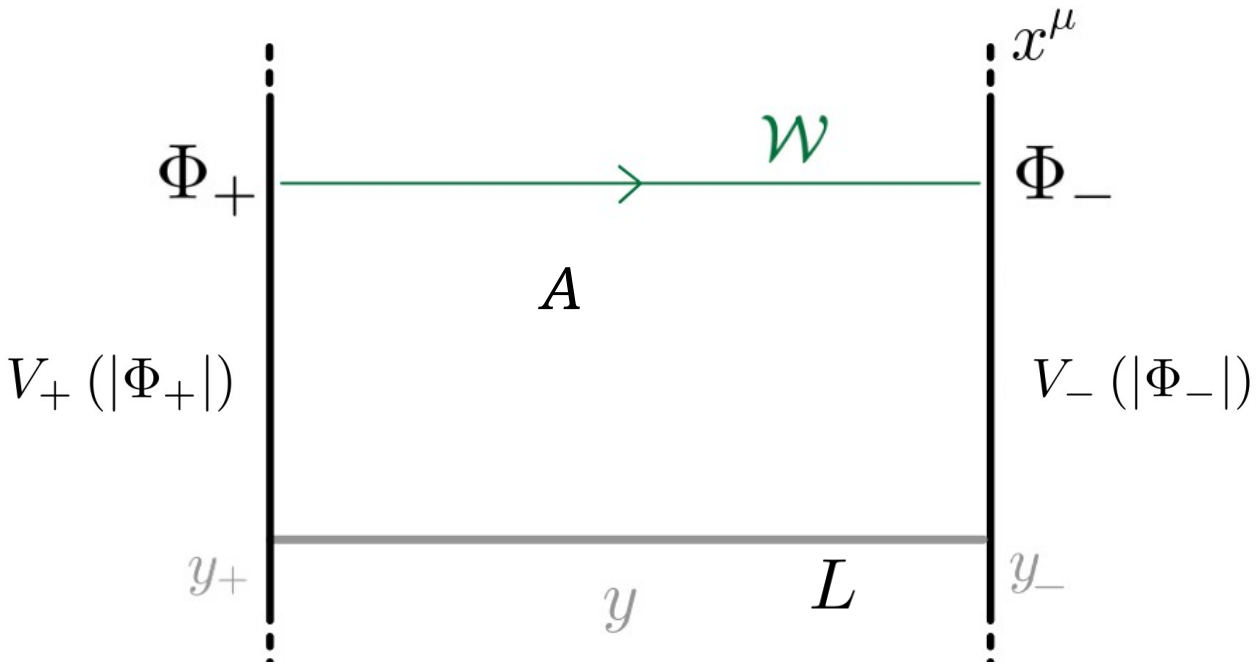
$$\langle \mathcal{W} \rangle = \langle \Phi_+ \, e^{i g_5 \int_{y_+}^{y_-} dy \, A_5} \, \Phi_- \rangle = v_+ v_- e^{ia/v}$$

PQ phase transition at $T_{\rm PQ} \approx \mathrm{Min}\{v_+, v_-\} \approx v$

A 5D toy model

$S^1/\mathbb{Z}_2$ orbifold

$y_\pm$ boundaries of an interval, where impose Neumann A_μ and Dirichlet A_5



$\langle |\Phi_\pm| \rangle = v_\pm$

In 4D $\quad a/v = \theta_- + \theta_+ - 2\sqrt{2}\, g_4 \sum_{n \text{ odd}} \frac{L}{n\pi} a_5^n \,, \qquad v^2 = \left(g_4^2 L^2 + \frac{1}{v_-^2} + \frac{1}{v_+^2} \right)^{-1}$

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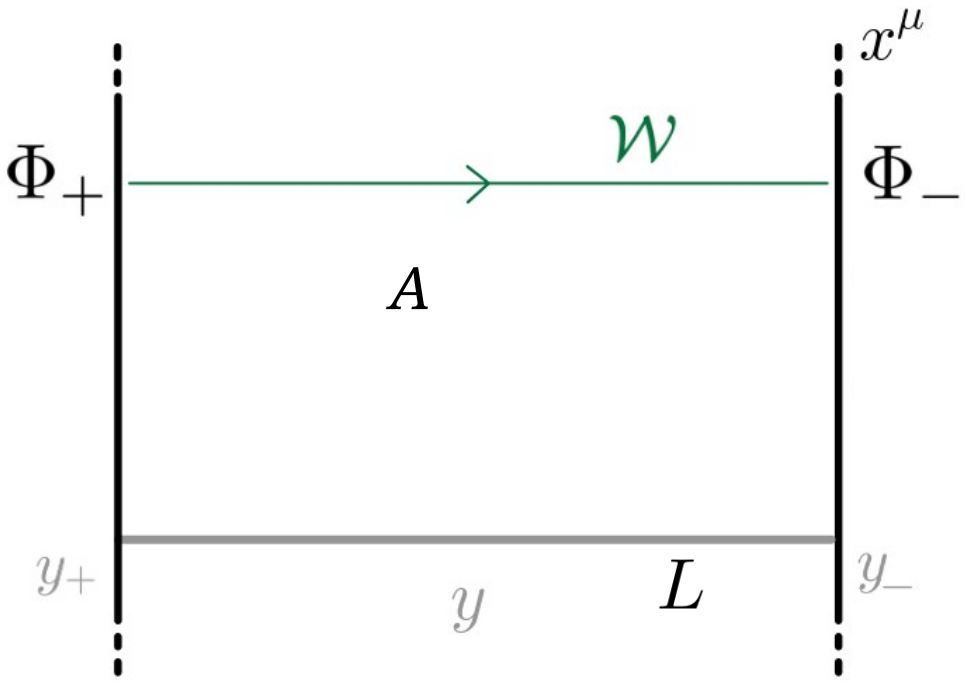
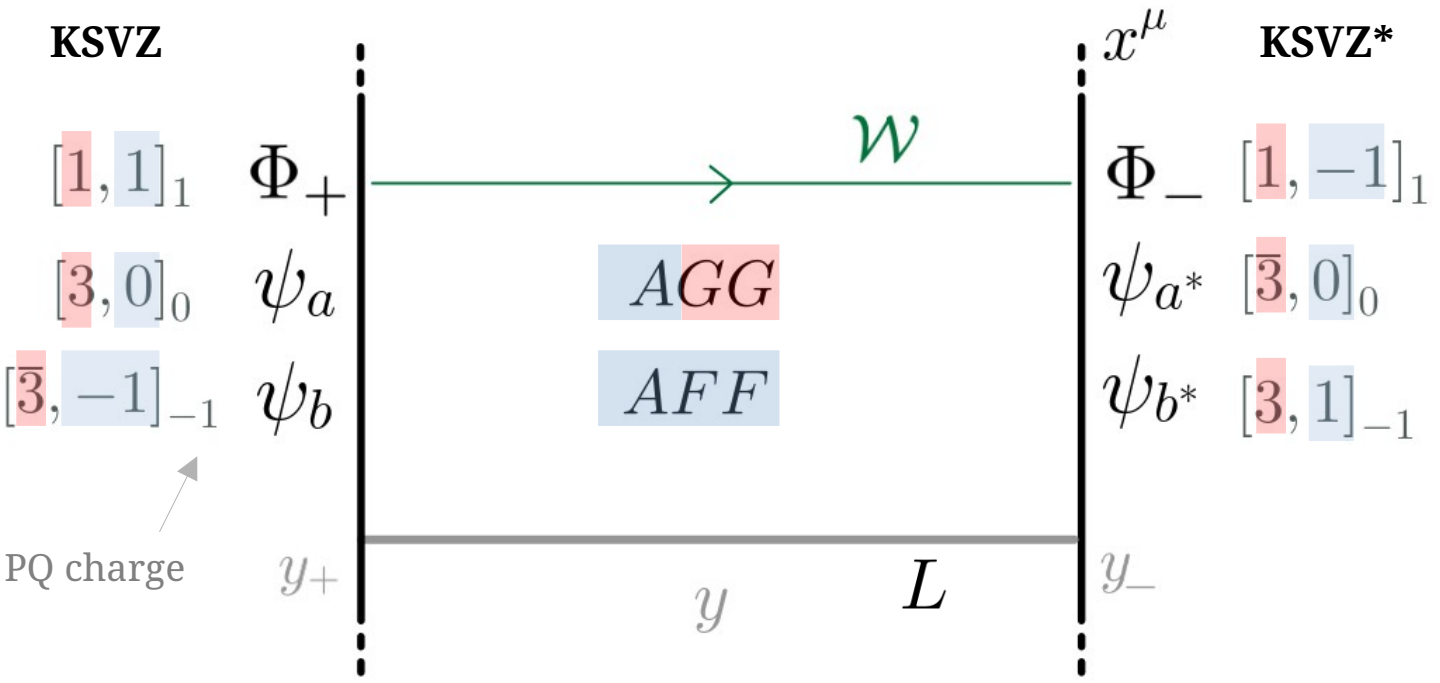


In 4D the PQ-breaking term $\Phi_-\Phi_+$ is perfectly allowed, but easily suppressed e^{-ML}

*A 5D **QCD axion** toy model* $S^1/\mathbb{Z}_2$ orbifold

$y_\pm$ boundaries of an interval, where impose Neumann A_μ and Dirichlet A_5



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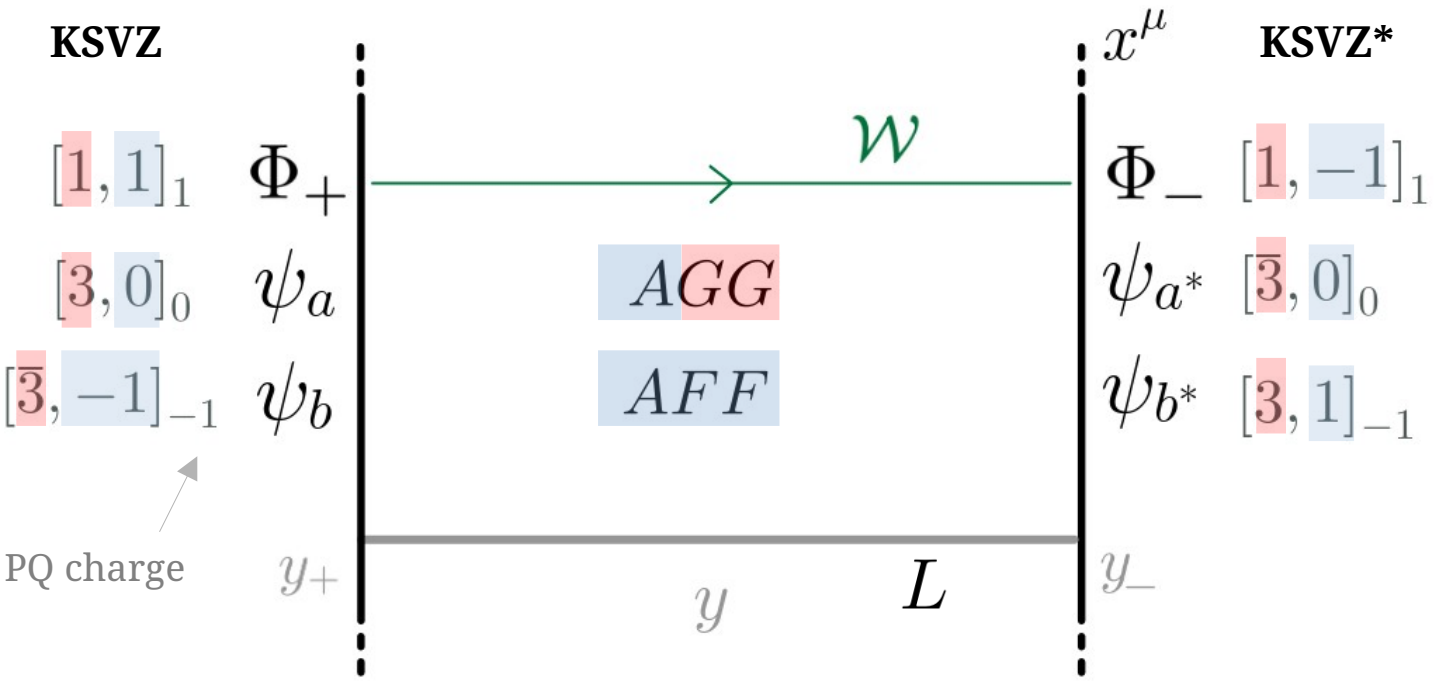

for $v_+ \ll v_-, L^{-1}$ **one recovers the minimal 4D KSVZ scenario**

$$\mathcal{L} \supset |\partial_\mu \Phi|^2 - V(|\Phi|) + y\,\Phi\,\bar{\psi}_L \psi_R$$

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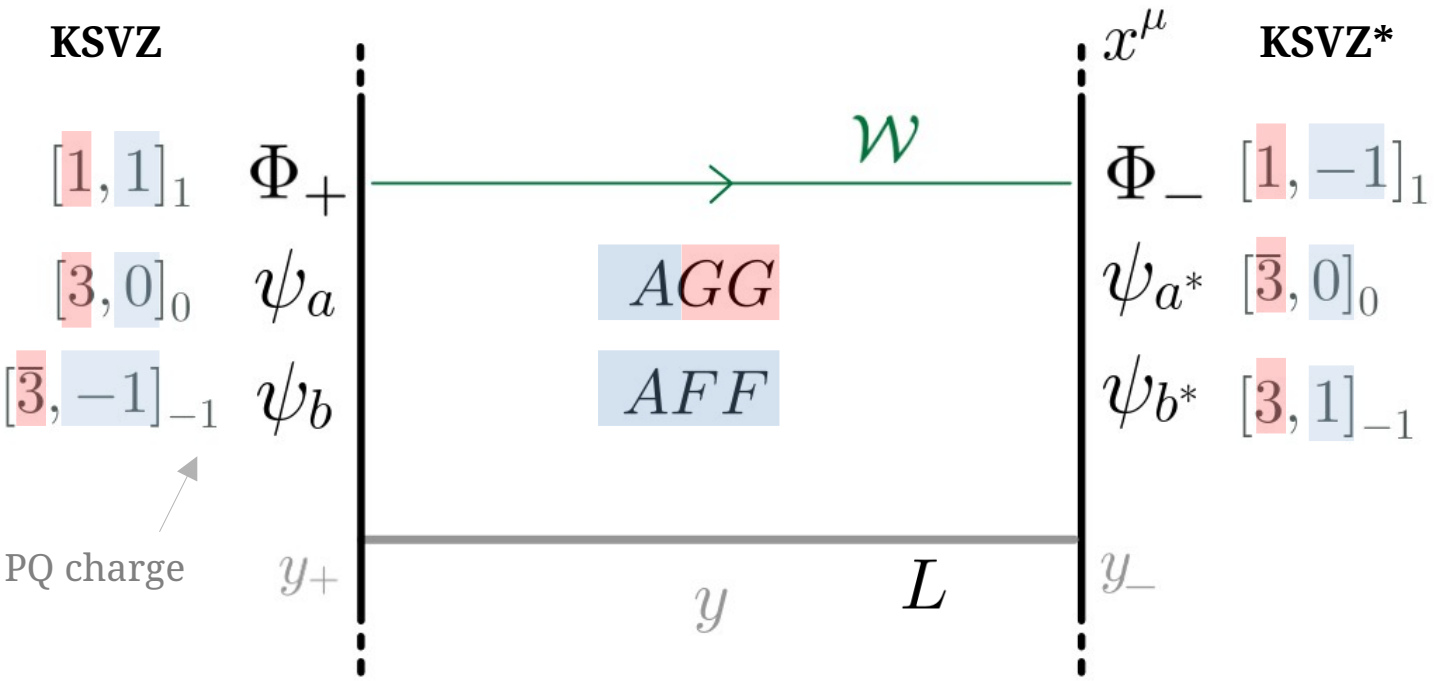

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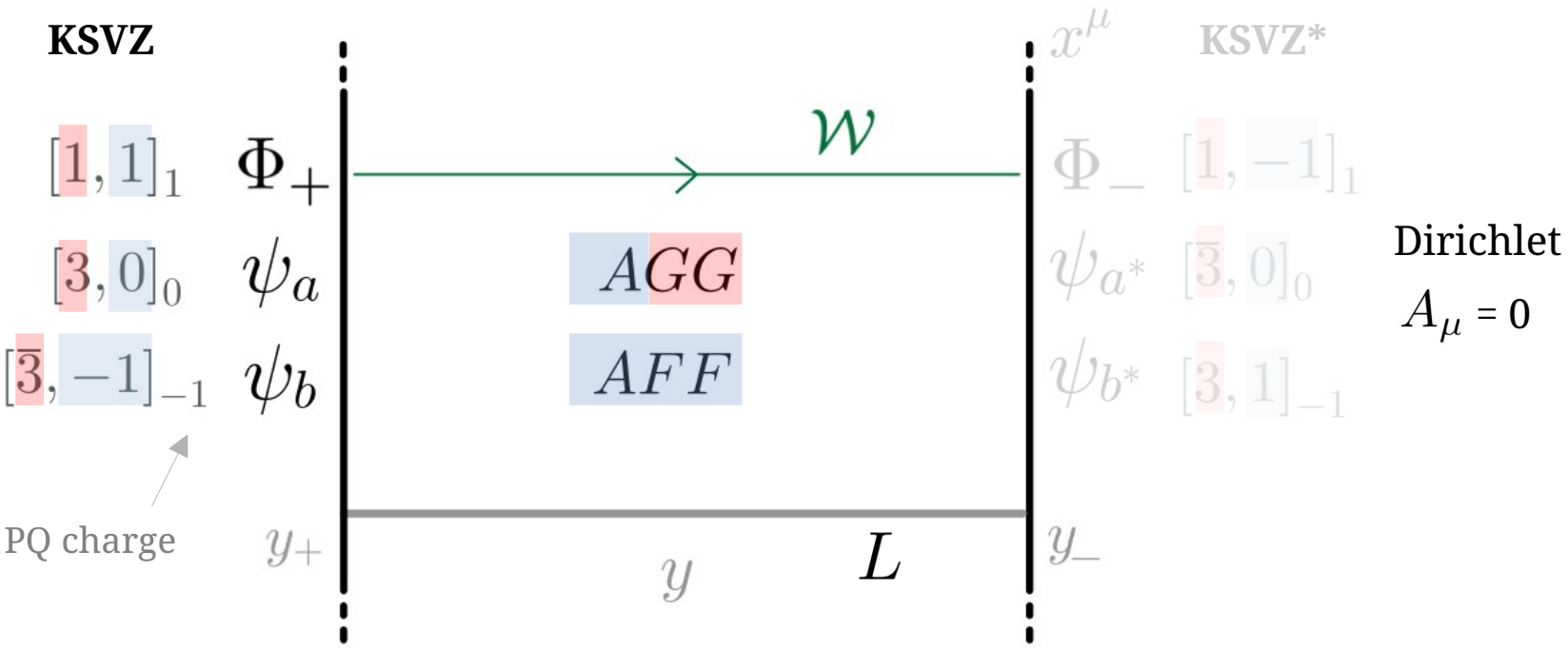
$$\mathcal{L} \supset |\partial_\mu \Phi|^2 - V(|\Phi|) + y\,\Phi\,\bar{\psi}_L \psi_R \overset{?}{+} b_n \Phi^n$$

*A 5D **QCD axion** toy model*

$S^1/(\mathbb{Z}_2 \times \mathbb{Z}_2)$ orbifold

$y_\pm$ boundaries of an interval, where impose Neumann A_μ and Dirichlet A_5



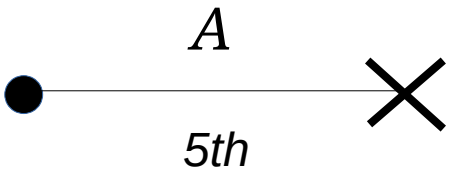
Dirichlet

$A_\mu = 0$

Note the formal decoupling limit $v_- \to \infty$ is equivalent to opposite b.c.

KK-lifting of global symmetries

$U(1)$ global in 4D



1) Gauge the global $U(1)$

2) Extend gauge into bulk of a 5th dimension

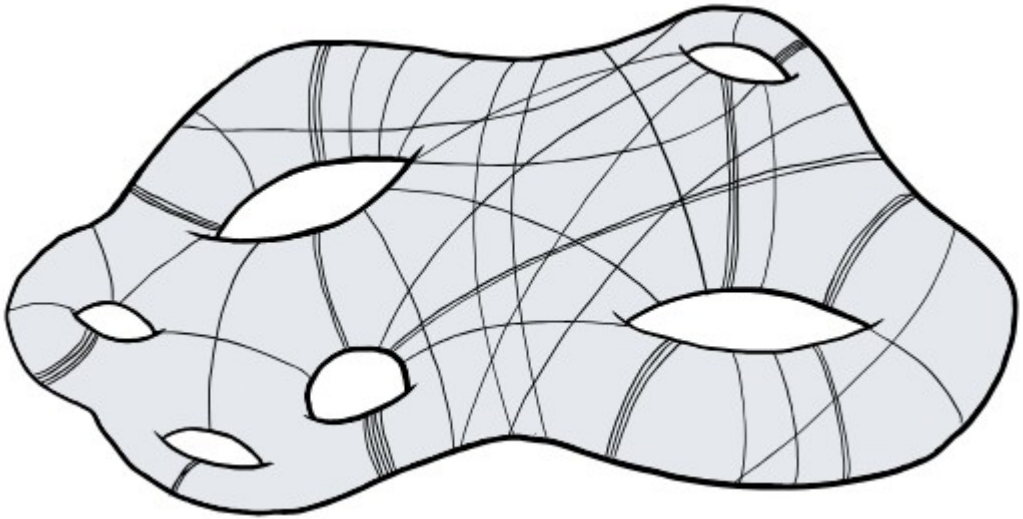
3) Impose Dirichlet b.c. on A_μ

Charged operators $\mathcal{O}_q(x^\mu)$ $\longrightarrow$ $e^{iqg\int_0^L dx^5 A_5}\mathcal{O}_q(x^\mu)$

Generalisation to non-Abelian symmetries left as an exercise.

String theory cartoon

Sketch of a Type IIA string theory compactification



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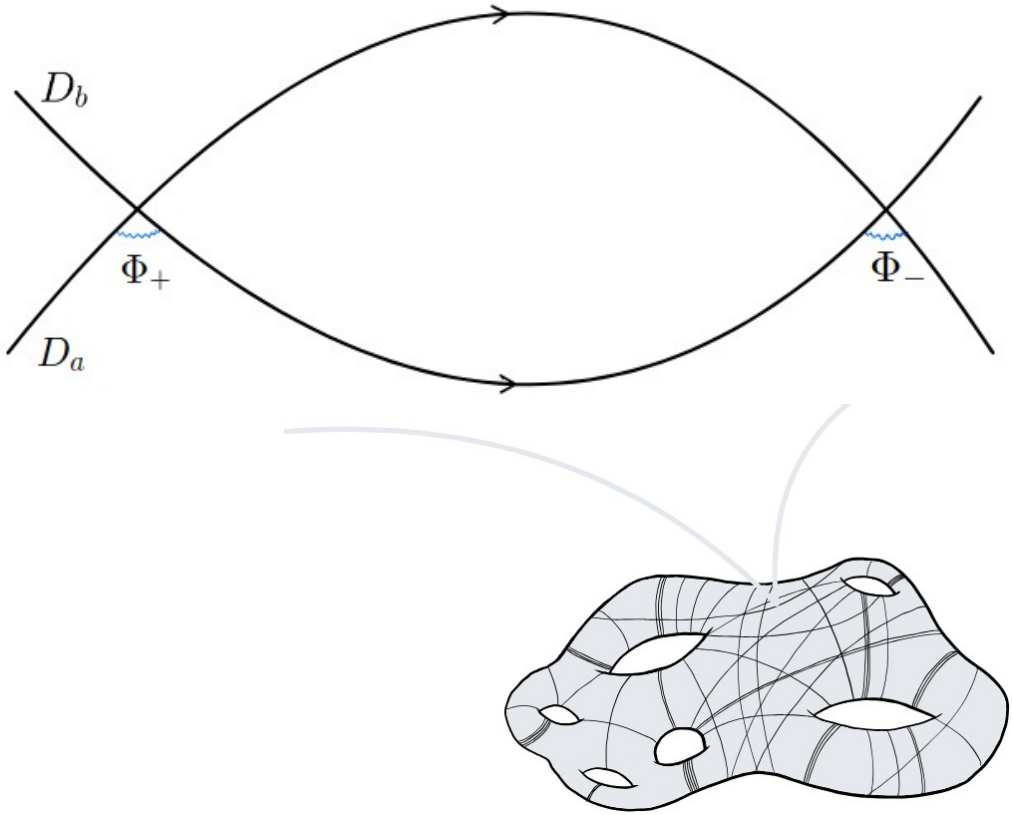

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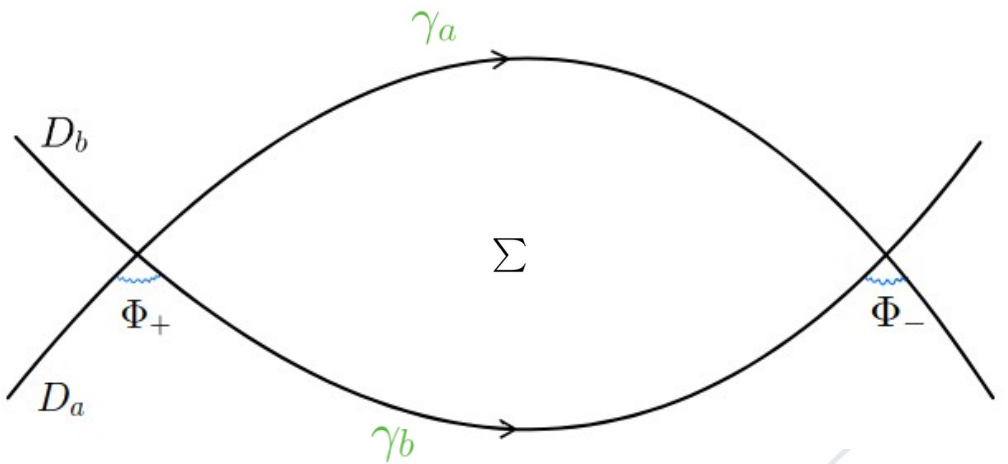
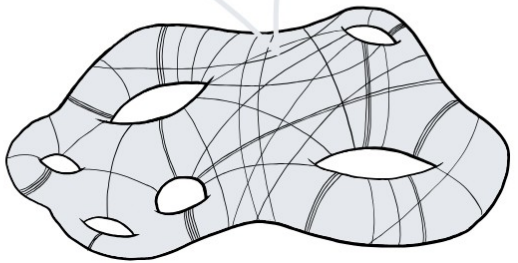
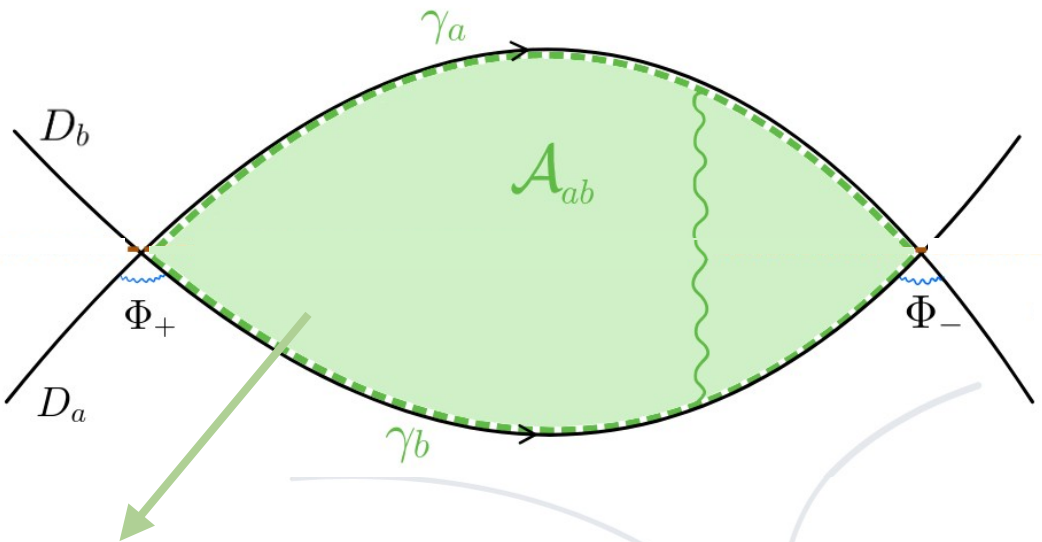


$$\mathcal{W}_{+-} = \Phi_+ \; e^{ig_a \int_{\gamma_a} A_a - ig_b \int_{\gamma_b} A_b - i \int_\Sigma B} \; \Phi_-$$



String theory cartoon

breaking effects are 'calculable'



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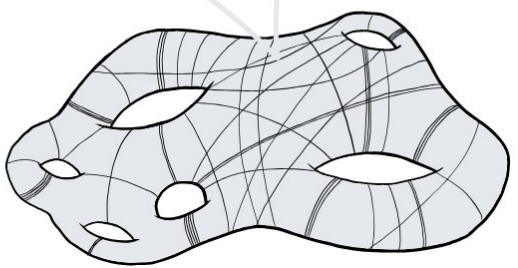
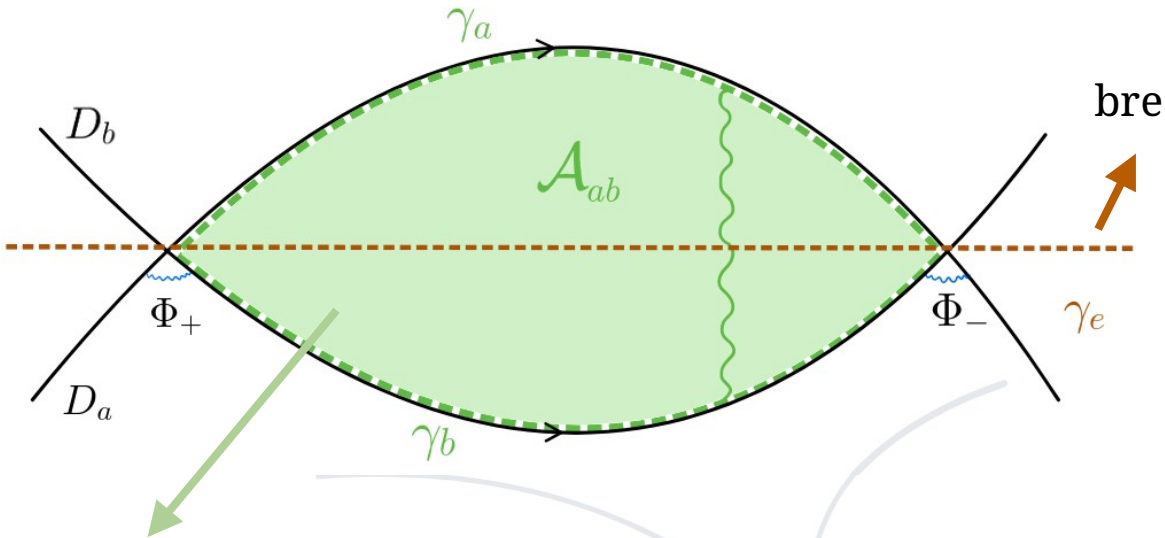
breaking ~ $e^{-\mathcal{A}_{ab}}$ (worldsheet instanton)



String theory cartoon

breaking effects are 'calculable'

$$\mathcal{W}'_{+-} = \Phi_+ \; e^{i\int_{\gamma_e} C} \; \Phi_-$$



breaking ~ $e^{-V_e/g_{str}}$

(euclidean D-brane instanton)

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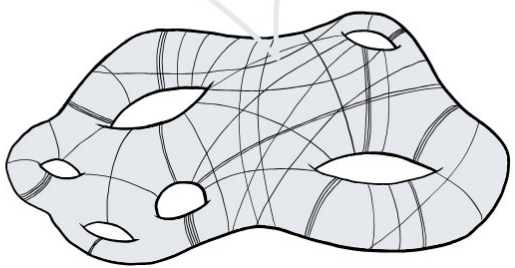

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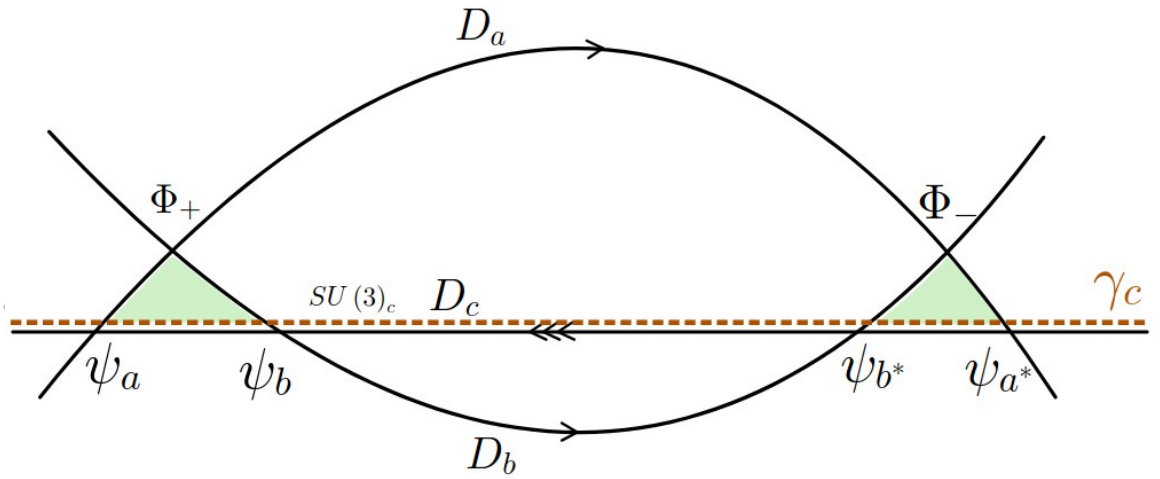

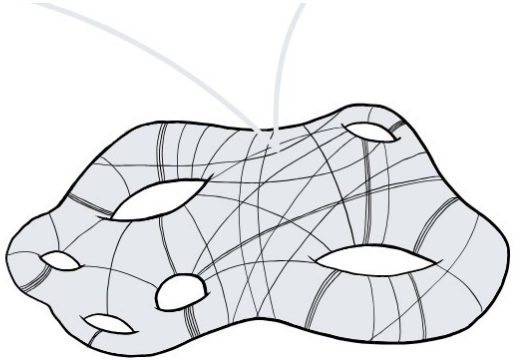

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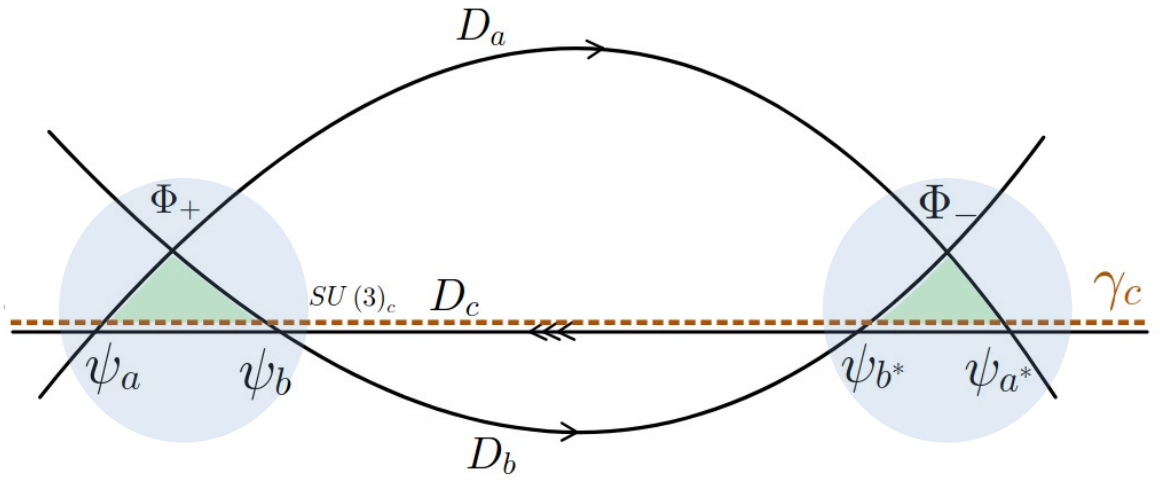

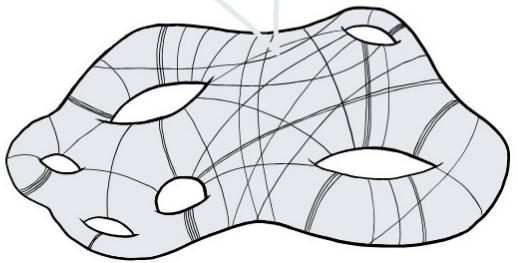

Concluding Theory Remarks

PQ quality is not really a 'problem'

- Explicit constructions can give exponentially good **linearly realised, non-accidental global symmetries** in **4D**

- If spontaneously broken they give **(open string) axions** compatible with post-inflationary evolution

Aspects of this story appear in string literature.

Ibanez, Quevedo (1999)
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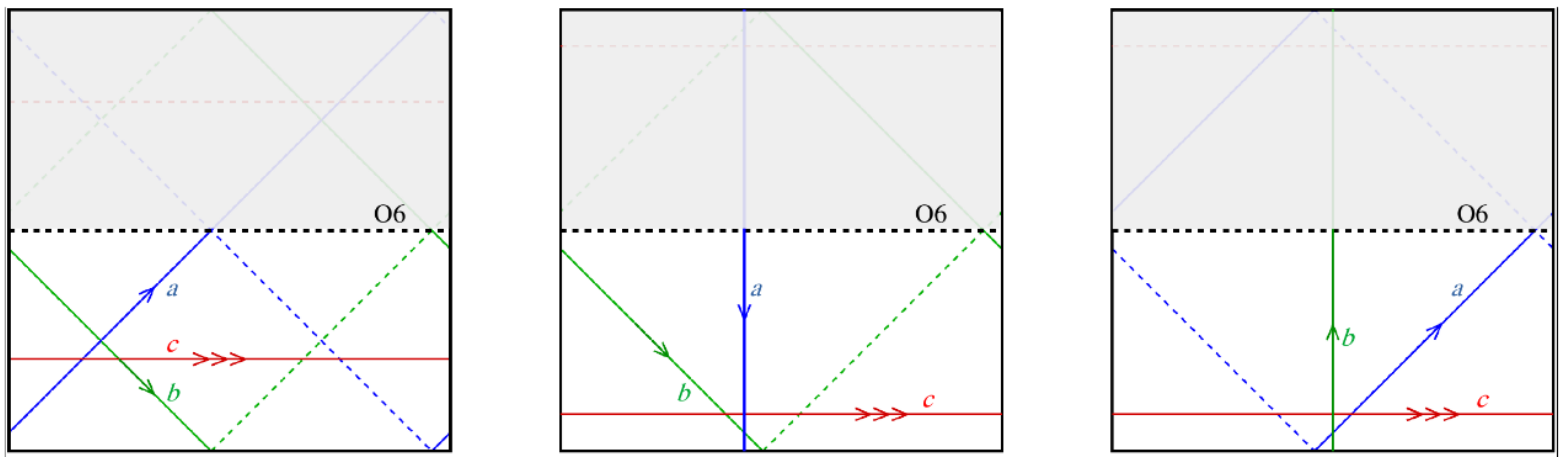

A simple supersting example
~ 8 open string ALPs

RPB, Villadoro (2025)

PART II

Theory

Phenomenology

Phenomenology

First, the minimal post-inflationary scenario is as robust as its pre-inflationary cousin

A Post-inflationary ALP $m = \text{const.}$

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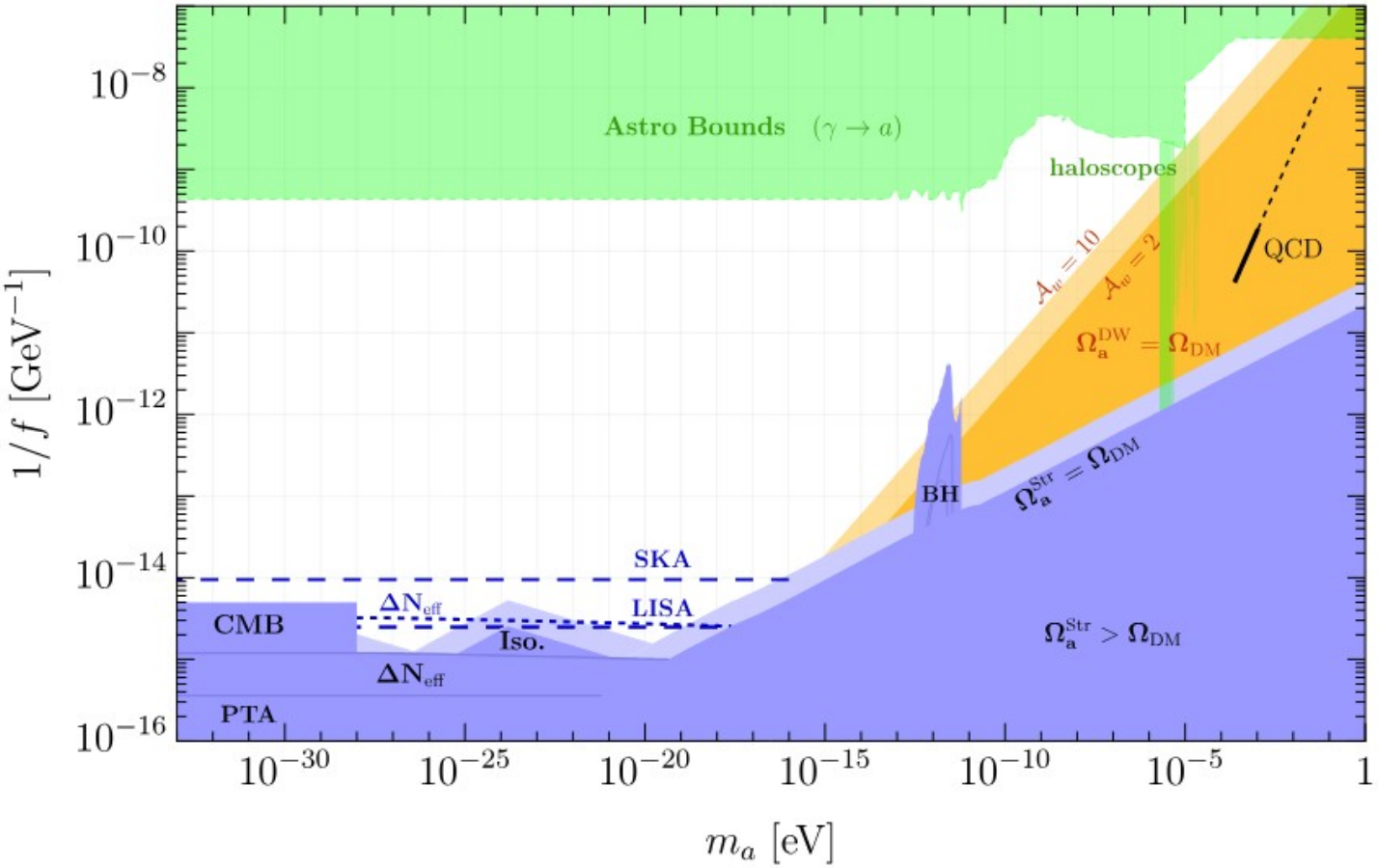
constraints also studied in Gorghetto, Hardy, Nicolaescu (2021) Gorghetto, Hardy (2023)



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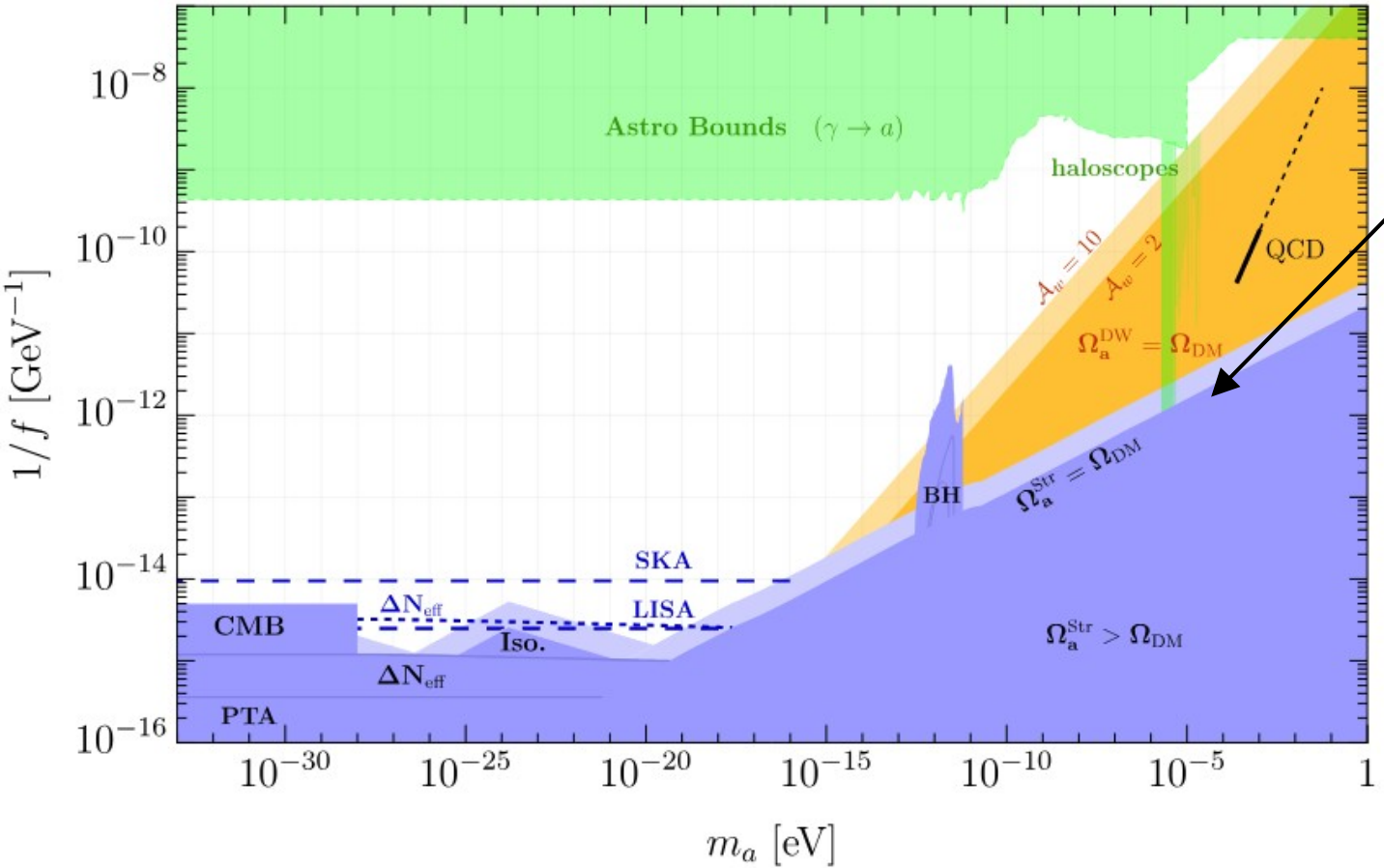
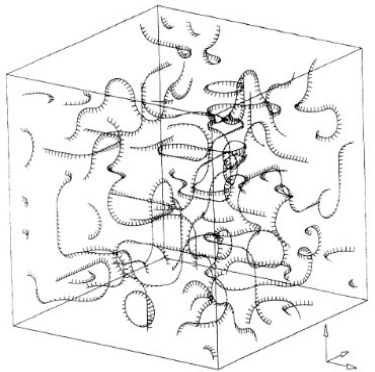


Greater predictivity!

At every point, the dark relic, etc are calculable



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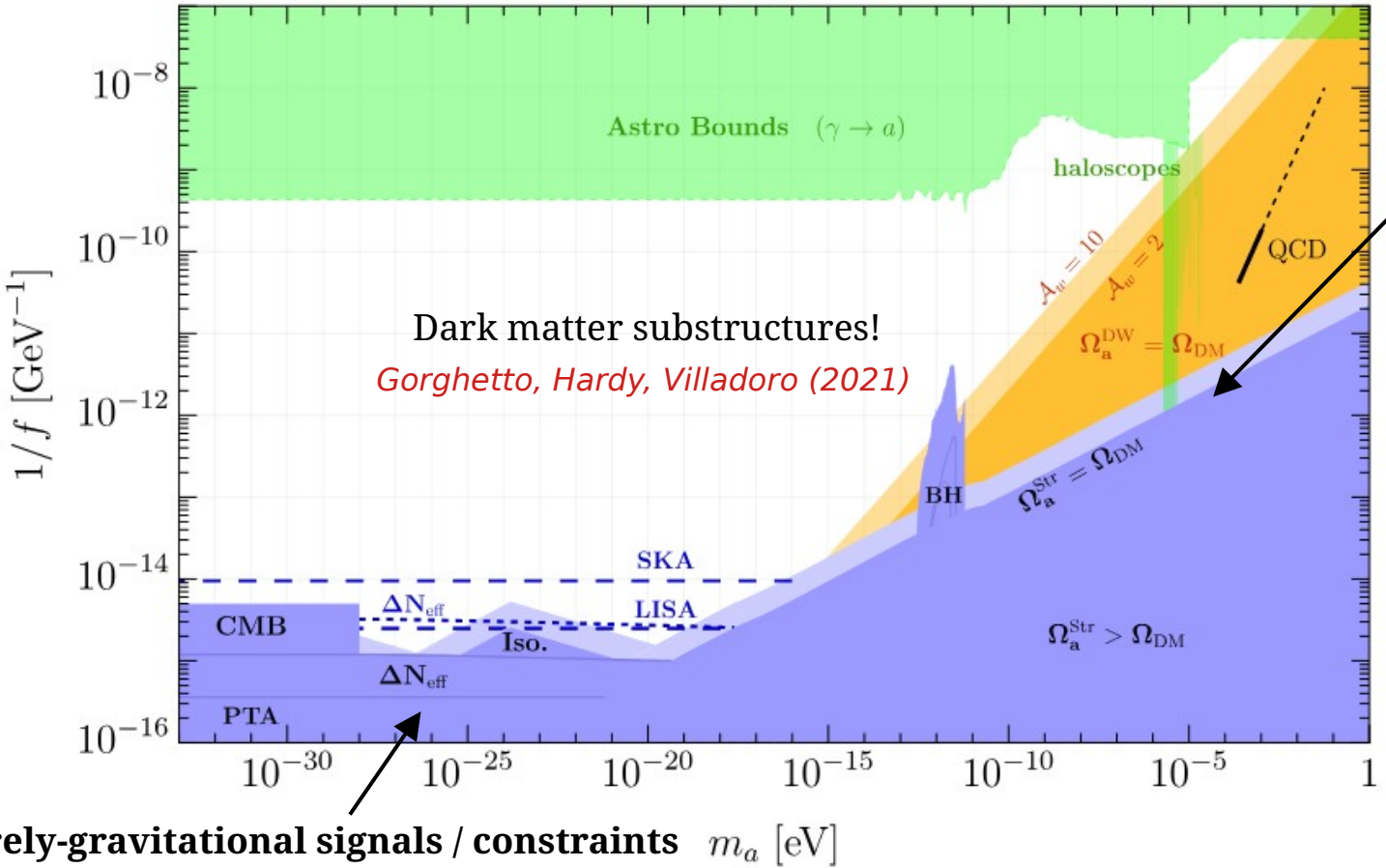

Dark matter substructures!

Gorghetto, Hardy, Villadoro (2021)

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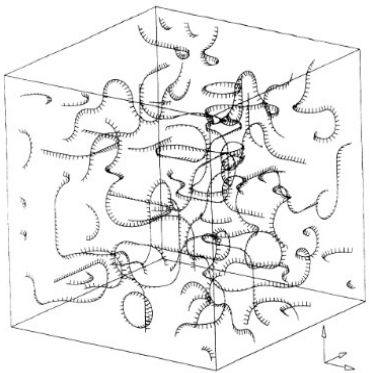

Far more purely-gravitational signals / constraints

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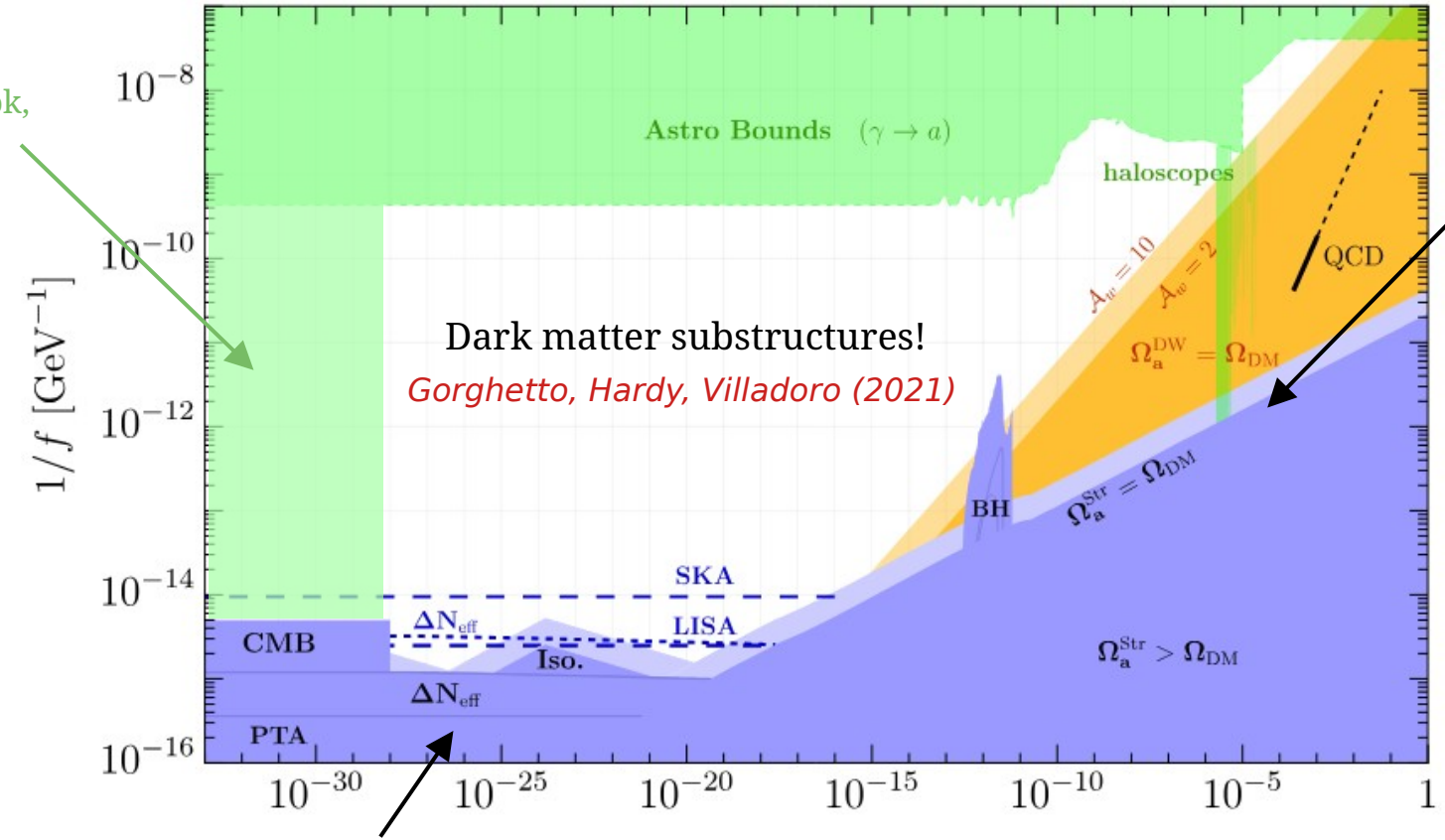

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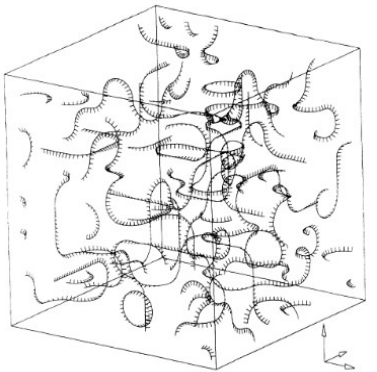
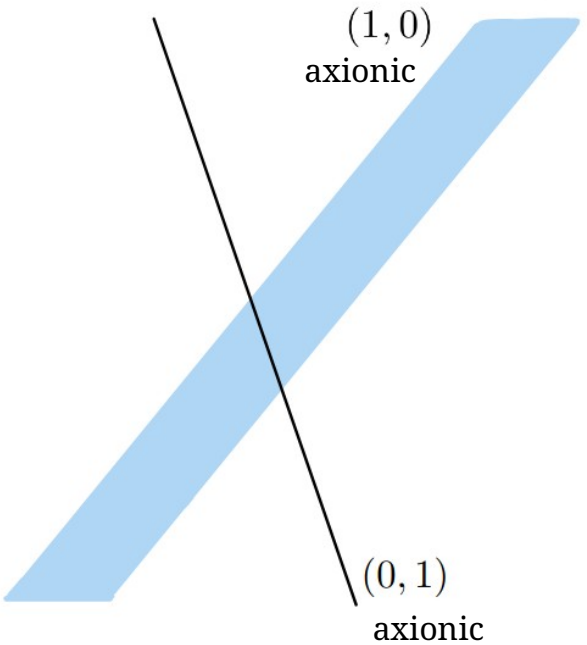


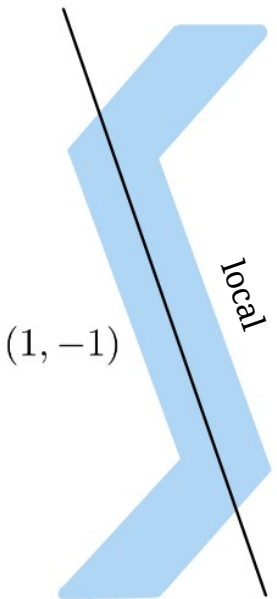
Far more purely-gravitational signals / constraints

Non-minimal: multi-string scenarios

In the case $T_{\max} \gtrsim v_{\pm} \ll L^{-1}$ two phase transitions with two different string types

In 4D $\mathcal{L} = -\frac{1}{4} F^0_{\mu\nu} F^{0,\mu\nu} + |\mathcal{D}_\mu \Phi_-|^2 + |\mathcal{D}_\mu \Phi_+|^2 - V_-(|\Phi_-|) - V_+(|\Phi_+|)$





axion-neutral string network survives to today

Concluding Pheno Remarks

Salesman's pitch: *open string axiverse*

High-quality axions compatible with post-inflationary cosmology

Equally plausible

more predictive

more purely-gravitational signals!

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In this post-inflationary world
manifold directions lay open for exploration...

Thank you!