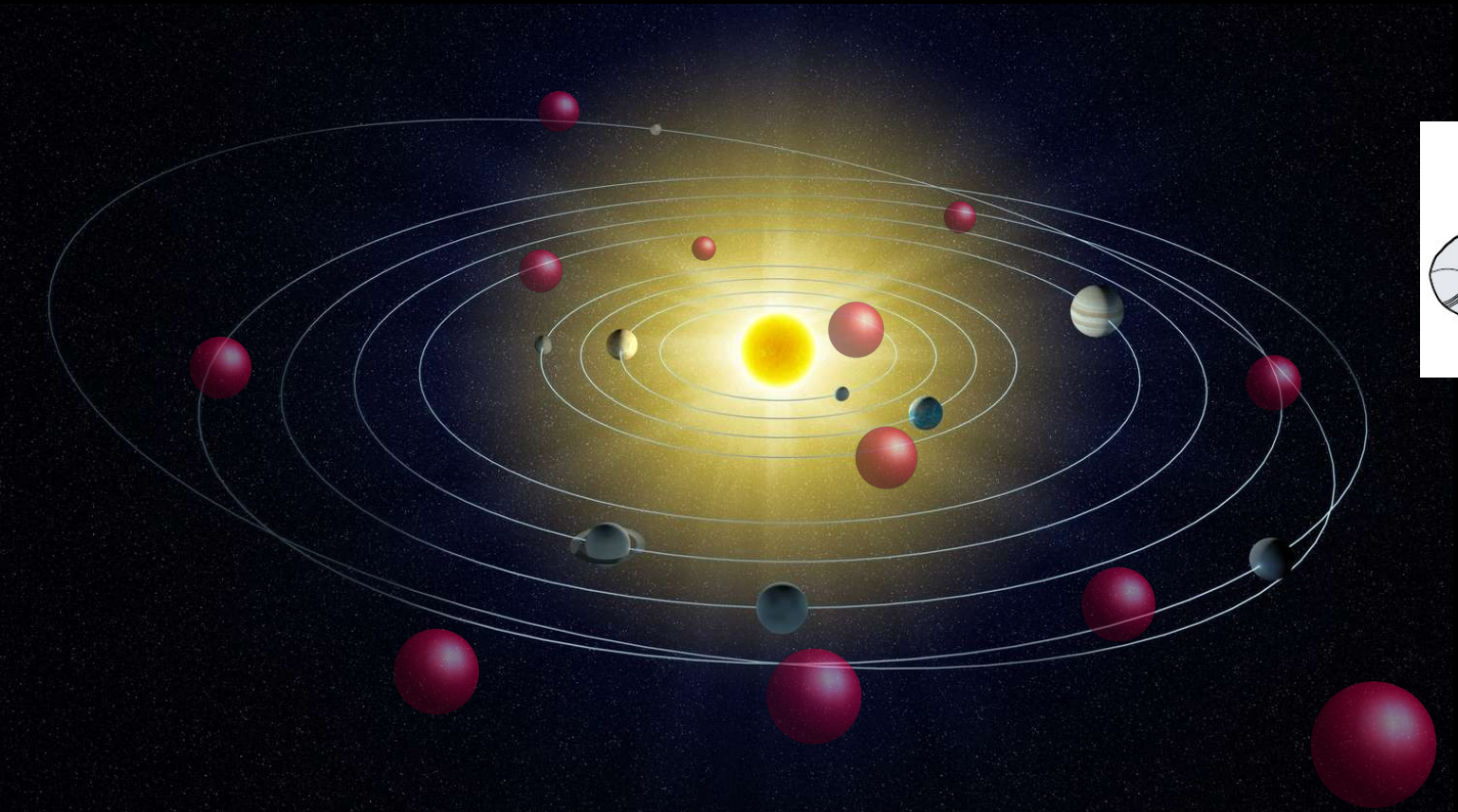
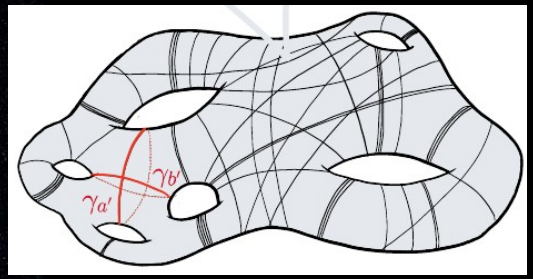
Open String Axiverse

Giovanni Villadoro
ICTP



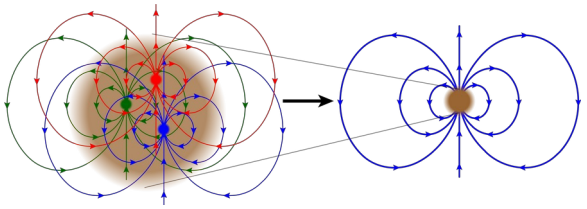


with
Rudin Petrossian-Byrne
2503.16387

The Strong CP problem

The Strong CP ~~problem~~ puzzle

No nEDM

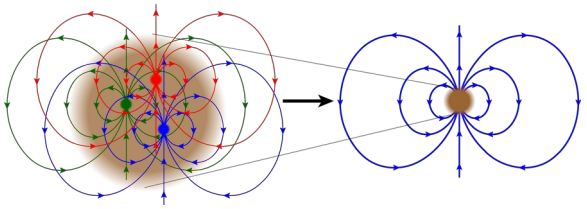


$$\theta \equiv \arg\left\{\det\left(Y_u Y_d\right) e^{i\theta_0}\right\} \lesssim 10^{-10}$$

$$\frac{\theta_0}{32\pi^2} G\tilde{G} \in \mathcal{L}_{\rm SM}$$

The Strong CP ~~problem~~ puzzle

No nEDM



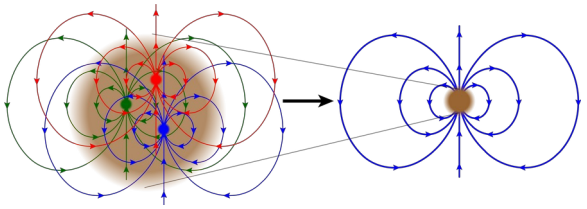
$$\theta \equiv \arg\left\{\det\left(Y_u Y_d\right) e^{i\theta_0}\right\} \lesssim 10^{-10}$$

$$\frac{\theta_0}{32\pi^2} G\tilde{G} \in \mathcal{L}_{\rm SM}$$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial a)^2 + \frac{a}{f_a}\frac{\alpha_s}{8\pi} G\tilde{G} + \ldots \qquad \Rightarrow \qquad m = \frac{\chi_{\rm top}^{1/2}}{f_a} \simeq 0.57\,{\rm meV}\left(\frac{10^{10}\ {\rm GeV}}{f_a}\right)$$

The Strong CP ~~problem~~ puzzle

No nEDM

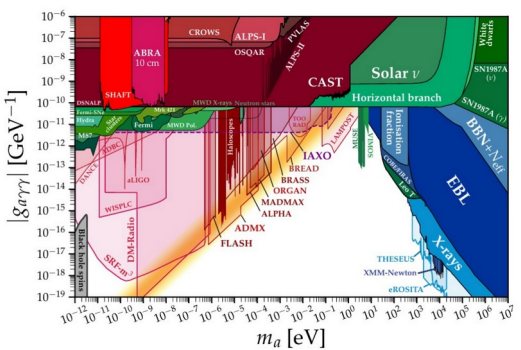


$$\theta \equiv \arg\left\{\det\left(Y_u Y_d\right) e^{i\theta_0}\right\} \lesssim 10^{-10}$$

$$\frac{\theta_0}{32\pi^2} G\tilde{G} \in \mathcal{L}_{\rm SM}$$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial a)^2 + \frac{a}{f_a}\frac{\alpha_s}{8\pi} G\tilde{G} + \ldots \qquad \Rightarrow \qquad m = \frac{\chi_{\rm top}^{1/2}}{f_a} \simeq 0.57\,{\rm meV}\left(\frac{10^{10}\ {\rm GeV}}{f_a}\right)$$

Testable:



2203.14923

Dark Matter:

Cosmological Scenarios:

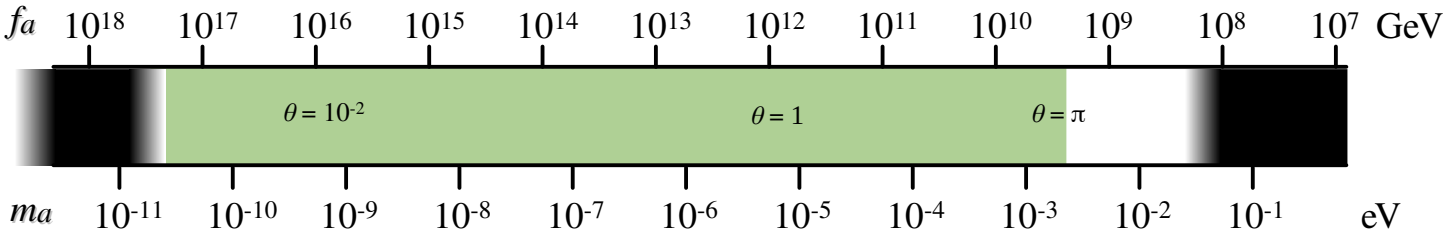
1. “pre-inflation”:
   (standard misalignment)

2. “post-inflation”:
   (topological defects)

Cosmological Scenarios:

1. “pre-inflation”:
   (standard misalignment)

$$\Omega_a \simeq \theta_0^2 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}} \right)^{1.2} \Omega_{\mathrm{DM}}$$

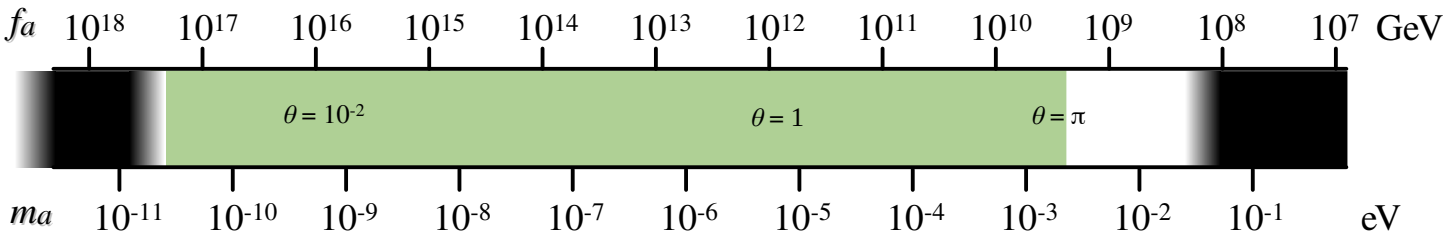


2. “post-inflation”:
   (topological defects)

Cosmological Scenarios:

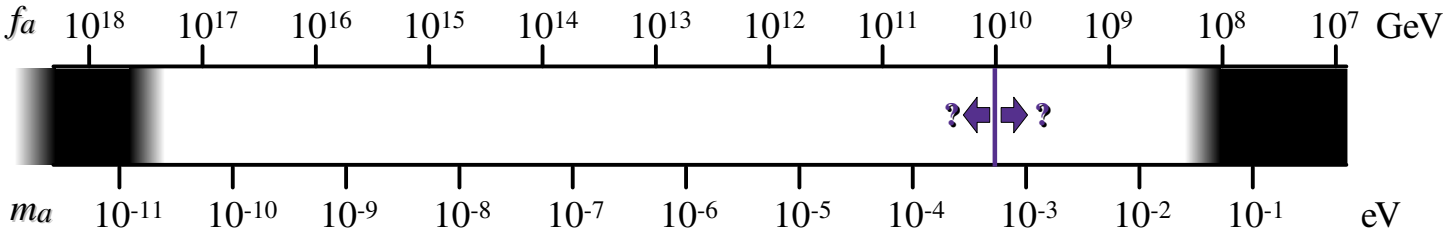
1. "pre-inflation":
   (standard misalignment)

$$\Omega_a \simeq \theta_0^2 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}} \right)^{1.2} \Omega_{\mathrm{DM}}$$



2. "post-inflation":
   (topological defects)

$$\Omega_a \simeq \left(\frac{f_a}{? \cdot 10^{10}\,\mathrm{GeV}} \right)^{1.2} \Omega_{\mathrm{DM}}$$



PQ Quality:

$$V(a) = V_{\rm QCD}(a) + V_{\not{\rm PQ}}$$

$$\theta \lesssim 10^{-10}$$

$$\Rightarrow$$

$$V_{\not{\rm PQ}} \lesssim 10^{-10} \chi_{\rm top} \sim (0.2 \text{ MeV})^4$$

PQ Quality:

$$V(a) = V_{\rm QCD}(a) + V_{\not{\rm PQ}}$$

$$\theta \lesssim 10^{-10}$$

$$\Rightarrow$$

$$V_{\not{\rm PQ}} \lesssim 10^{-10}\chi_{\rm top} \sim (0.2\ {\rm MeV})^4$$

Quantum Gravity → No Global Symmetries...

$$V_{\not{\rm PQ}} \sim M_P^4 \sim 10^{78}\chi_{\rm top}$$

PQ Quality:

$$V(a) = V_{\rm QCD}(a) + V_{\not{\rm PQ}}$$

$$\theta \lesssim 10^{-10}$$

$$\Rightarrow$$

$$V_{\not{\rm PQ}} \lesssim 10^{-10}\chi_{\rm top} \sim (0.2\ {\rm MeV})^4$$

Quantum Gravity → No Global Symmetries...

$$V_{\not{\rm PQ}} \sim M_P^4 \sim 10^{78}\chi_{\rm top}$$

Accidental PQ

→ forbids PQ operators up to dim. ~ 10 ÷ 40 (for $f_a \sim 10^{10}$ GeV ÷ GUT)

Irreducible QG symm. breaking is non-perturbative (BH, wormholes, ...)

Irreducible QG symm. breaking is non-perturbative (BH, wormholes, ...)

NOTE: QCD-breaking $\rightarrow$ $\chi_{\rm top} \propto e^{-\frac{\#}{g_s^2}}$

Irreducible QG symm. breaking is non-perturbative (BH, wormholes, ...)

NOTE: QCD-breaking $\rightarrow$ $\chi_{\rm top} \propto e^{-\frac{\#}{g_s^2}}$

High Quality PQ $\rightarrow$ QG is weakly coupled

i.e. worry about PQ quality only in explicit UV completion of QG:
e.g. string theory

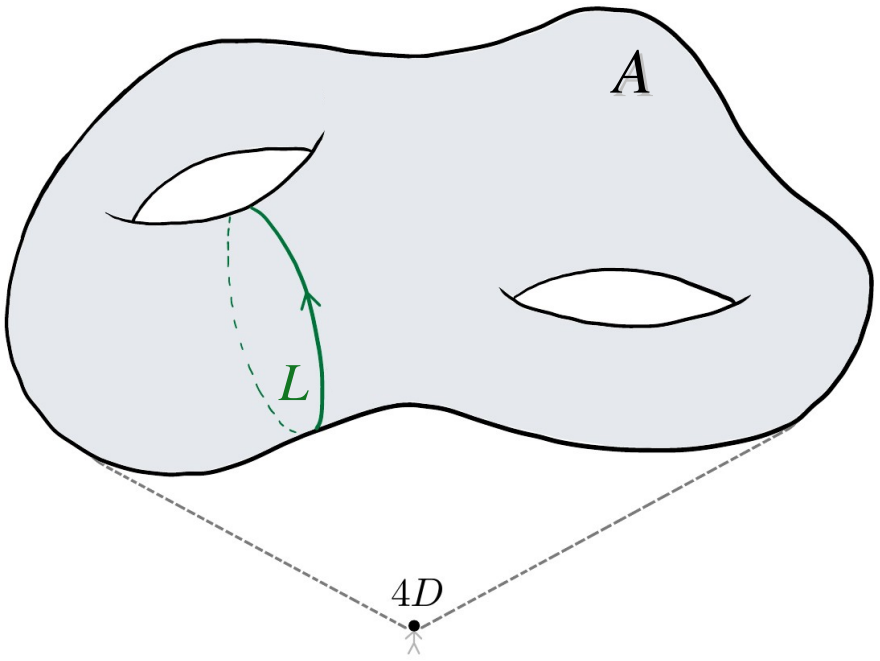
Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell ‘10

String Axiverse

Gauge Fields in Extra Dimensions

Choi ‘03

$$\frac{a}{v} = \arg\left(e^{i\oint A}\right)$$



Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell ‘10

String Axiverse

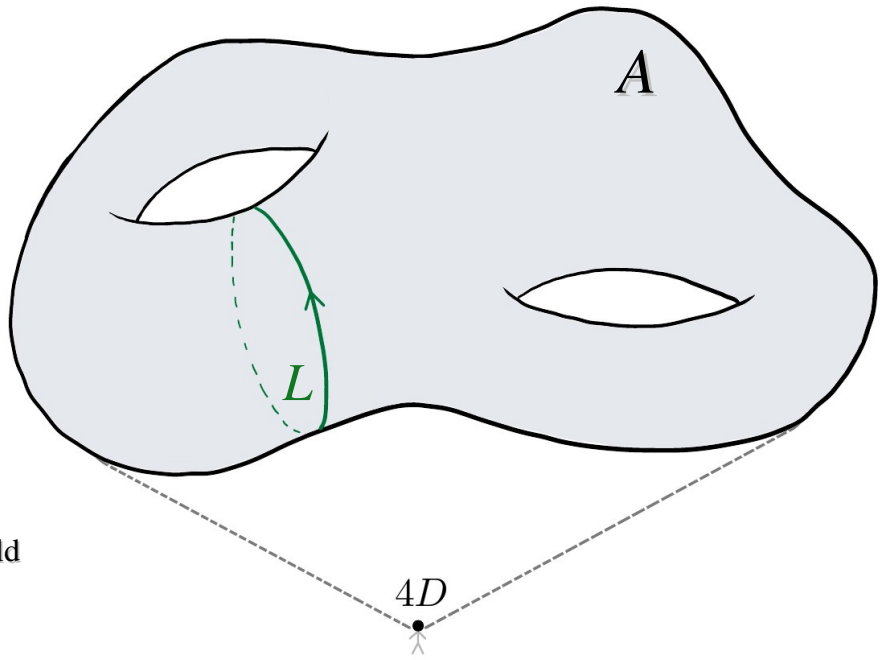
Gauge Fields in Extra Dimensions

Choi ‘03

$$\frac{a}{v} = \arg\left(e^{i\oint A}\right)$$

$$V_{\not{\mathrm{PQ}}} \propto e^{-ML}$$

lightest charged bulk field



String Axiverse

Gauge Fields in Extra Dimensions

Choi ‘03

$$\frac{a}{v} = \arg\left(e^{i\oint A}\right)$$

$$V_{\not{\mathrm{PQ}}} \propto e^{-ML}$$

In String Theory:

A = typically RR, NSNS p-forms
(Closed string gauge field)

String Axiverse

Gauge Fields in Extra Dimensions

Choi ‘03

$$\frac{a}{v} = \arg\left(e^{i\oint A}\right)$$

$$V_{\not{\mathrm{PQ}}} \propto e^{-ML}$$

In String Theory:

A = typically RR, NSNS p-forms
(Closed string gauge field)

Charged states (D-branes, NS5,…)
$\rightarrow M > M_s/g_s$

String Axiverse

Gauge Fields in Extra Dimensions

Choi ‘03

$$\frac{a}{v} = \arg\left(e^{i\oint A}\right)$$

$$V_{\not\text{PQ}} \propto e^{-ML}$$

In String Theory:

A = typically RR, NSNS p-forms
(Closed string gauge field)

Charged states (D-branes, NS5,…)
$\rightarrow M > M_s/g_s$

$$V_{\not\text{PQ}} \propto e^{-\text{Vol}/g_s} \sim e^{-8\pi^2/g_4^2}$$

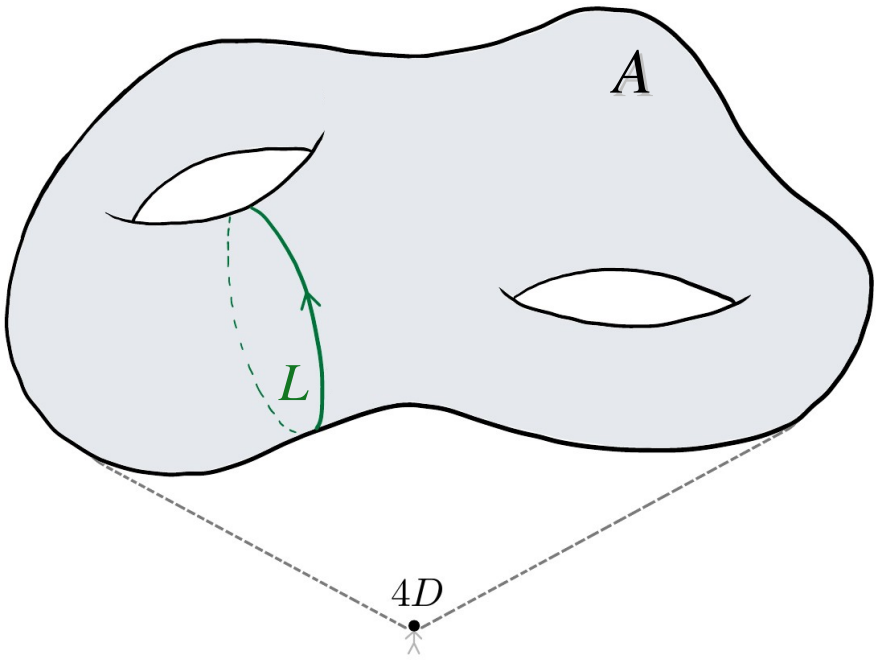
String Axiverse

Gauge Fields in Extra Dimensions

Choi ‘03

$$\frac{a}{v} = \arg\left(e^{i\oint A}\right)$$

$$v > \frac{1}{L}$$



Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell ‘10

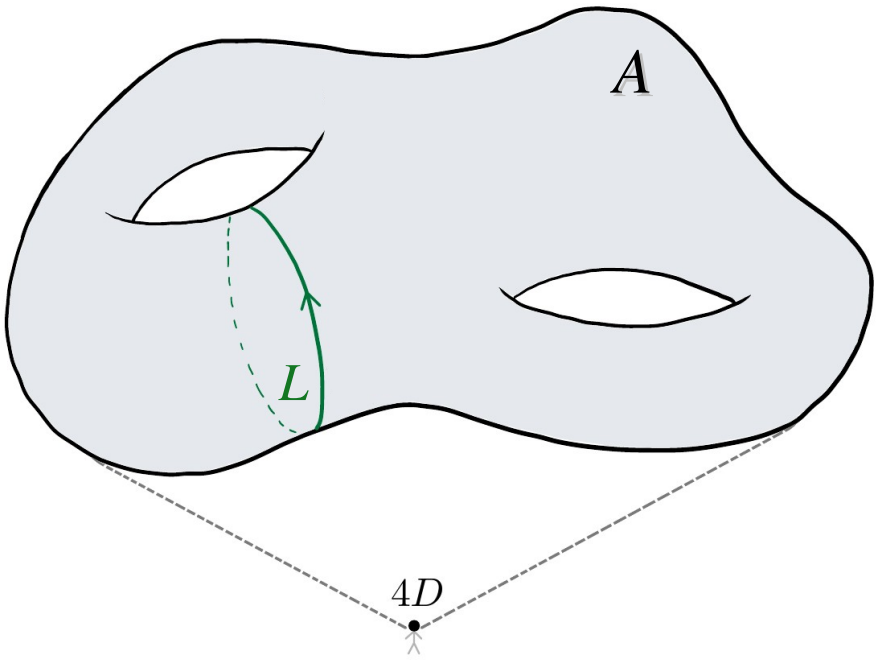
String Axiverse

Gauge Fields in Extra Dimensions

Choi ‘03

$$\frac{a}{v} = \arg\left(e^{i\oint A}\right)$$

$$v > \frac{1}{L}$$



✓ pre-inflationary and large f_a axions

Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell ‘10

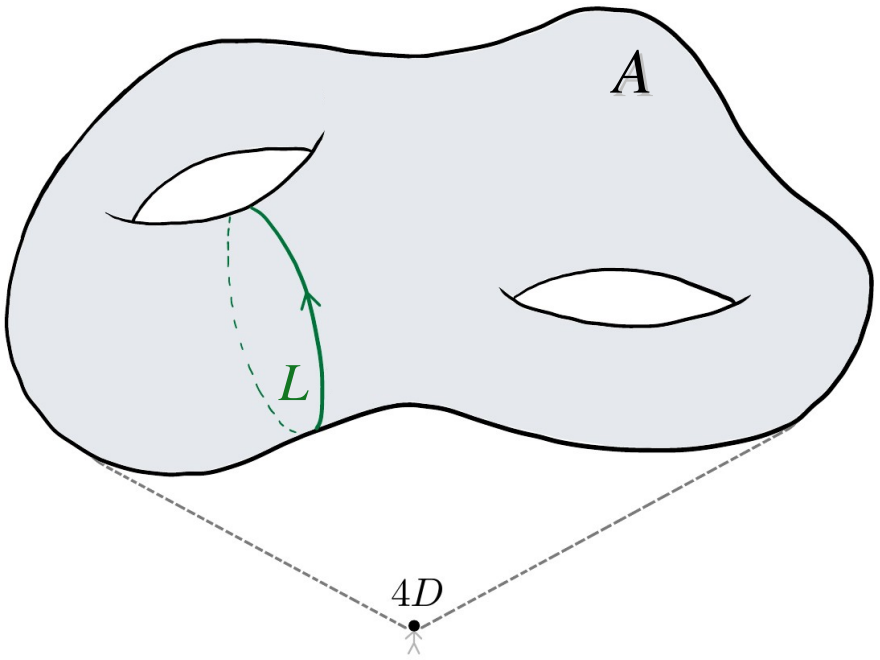
String Axiverse

Gauge Fields in Extra Dimensions

Choi ‘03

$$\frac{a}{v} = \arg\left(e^{i\oint A}\right)$$

$$v > \frac{1}{L}$$



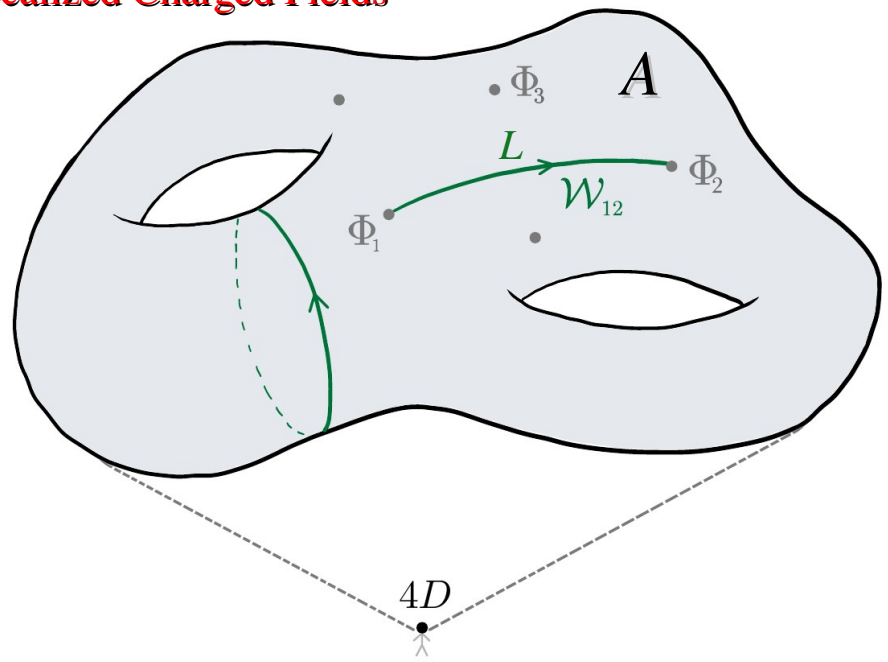
✓ pre-inflationary and large f_a axions

✗ post-inflationary axions

(PQ-phase restoration → D-branes after inflation...)

Open String Axiverse:

Gauge Fields in Extra Dimensions + Localized Charged Fields

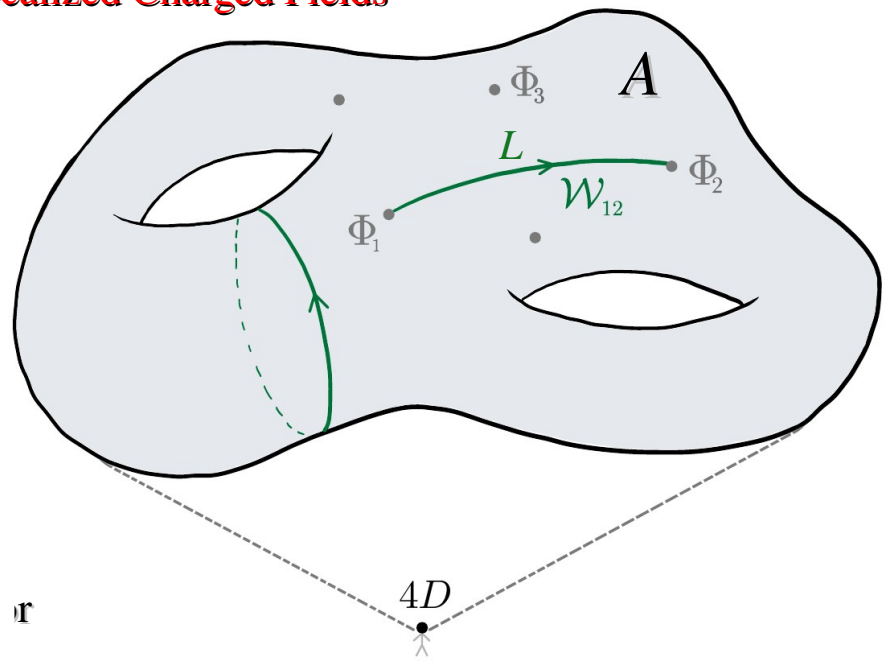


Open String Axiverse:

Gauge Fields in Extra Dimensions + Localized Charged Fields

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

gauge invariant: $\begin{cases} A \to A + \partial\Lambda \\ \Phi_\pm \to e^{\pm i\Lambda}\Phi_\pm \end{cases}$



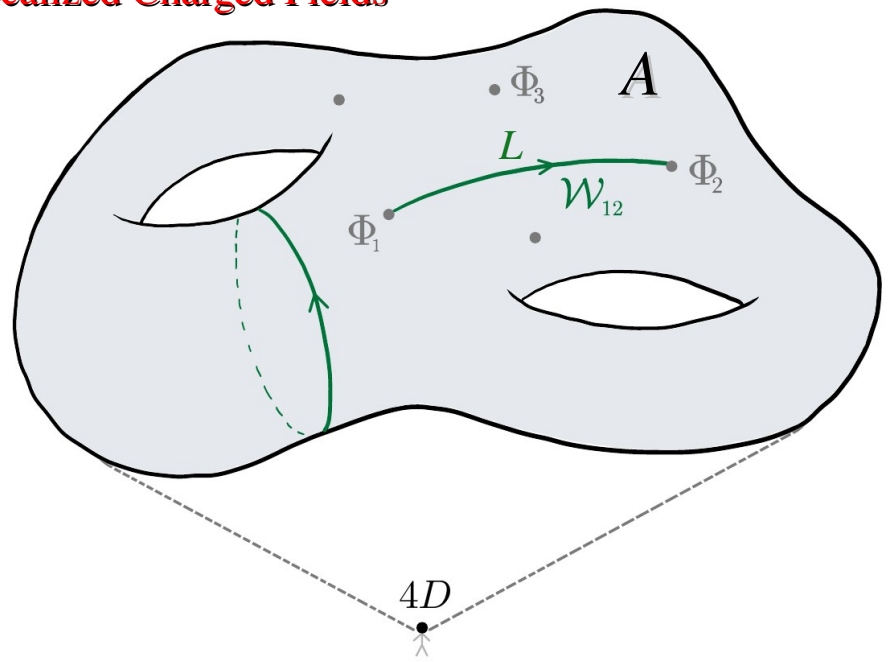
Open String Axiverse:

Gauge Fields in Extra Dimensions + Localized Charged Fields

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

gauge invariant: $\begin{cases} A \to A + \partial\Lambda \\ \Phi_\pm \to e^{\pm i\Lambda}\Phi_\pm \end{cases}$

PQ charged: $\Phi_\pm \to e^{i\alpha}\Phi_\pm$



Open String Axiverse:

Gauge Fields in Extra Dimensions + Localized Charged Fields

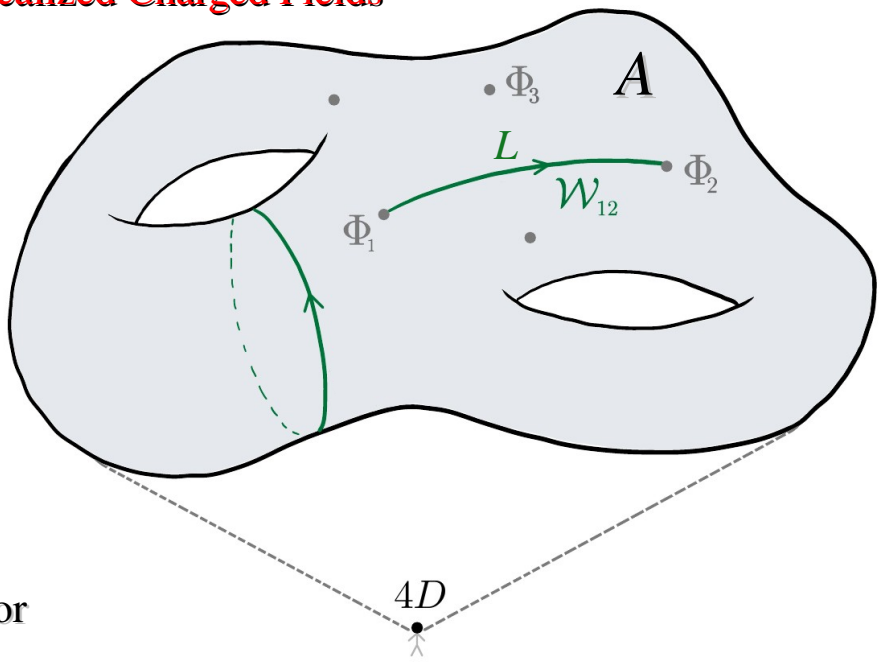
$$\mathcal{W} = \Phi_+ e^{i\int_{y_+}^{y_-} A}\, \Phi_-$$

gauge invariant: $\begin{cases} A \to A + \partial\Lambda \\ \Phi_\pm \to e^{\pm i\Lambda}\Phi_\pm \end{cases}$

PQ charged: $\Phi_\pm \to e^{i\alpha}\Phi_\pm$

Locally PQ = gauge transf.

→ no local PQ charged gauge inv. operator



Open String Axiverse:

Gauge Fields in Extra Dimensions + Localized Charged Fields

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

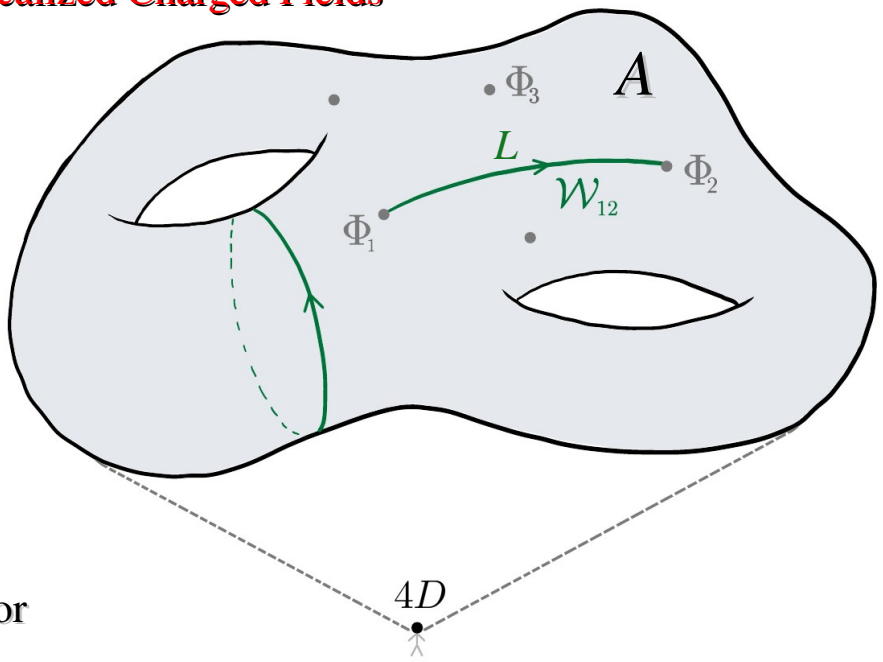
gauge invariant: $\begin{cases} A \to A + \partial\Lambda \\ \Phi_\pm \to e^{\pm i\Lambda}\Phi_\pm \end{cases}$

PQ charged: $\Phi_\pm \to e^{i\alpha}\Phi_\pm$

Locally PQ = gauge transf.

→ no local PQ charged gauge inv. operator

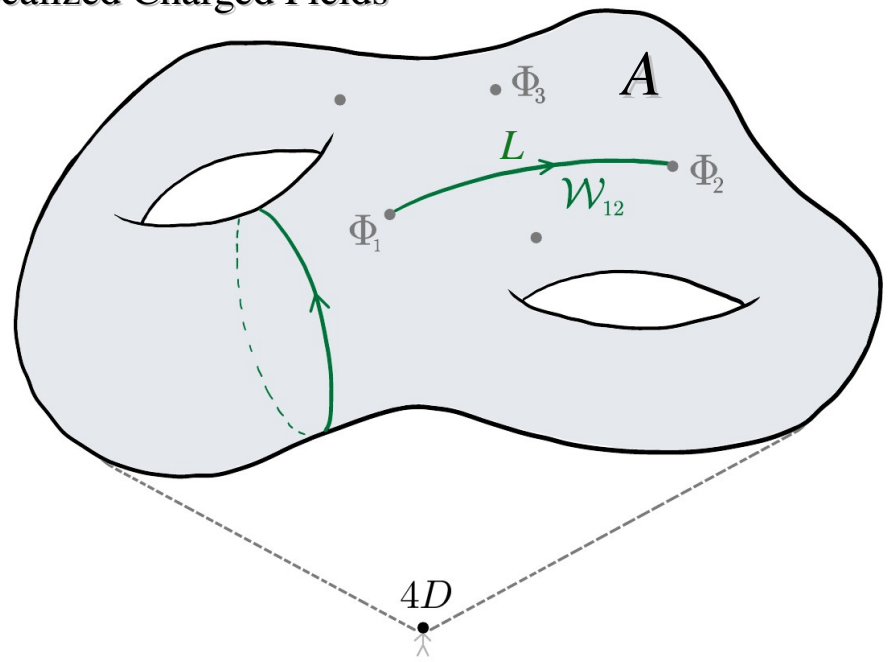
$$V_{\rm PQ} \propto e^{-ML}$$



Open String Axiverse:

Gauge Fields in Extra Dimensions + Localized Charged Fields

– With N localized fields → N - 1 global U(1)s



Open String Axiverse:

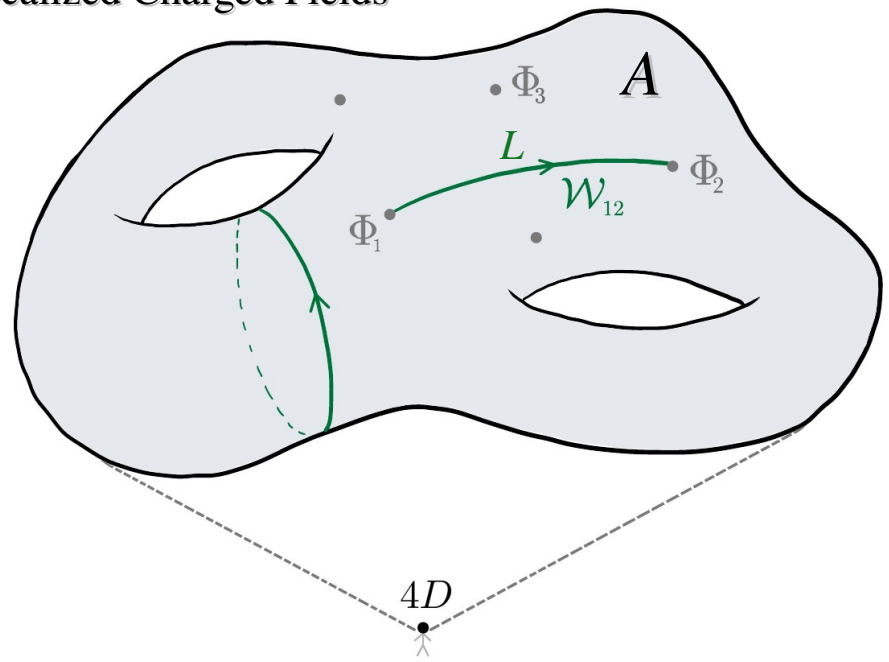
Gauge Fields in Extra Dimensions + Localized Charged Fields

– With N localized fields → N - 1 global U(1)s

– PQ is linearly realized in 4D:

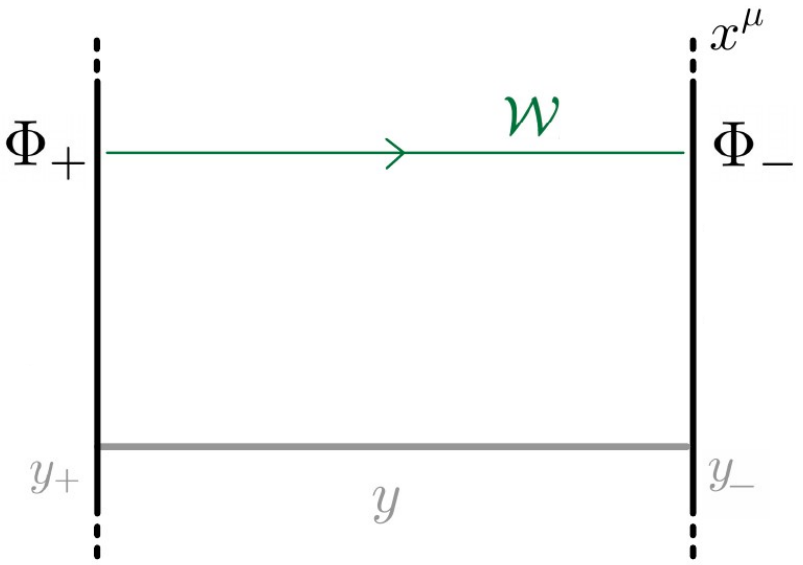
$$\frac{a}{v} = \arg\left(\Phi_+ e^{i\int_{y_+}^{y_-} A}\, \Phi_-\right)$$

$$v \ll \frac{1}{L} \quad \text{if} \quad \min\langle\Phi_\pm\rangle \ll \frac{1}{L}$$



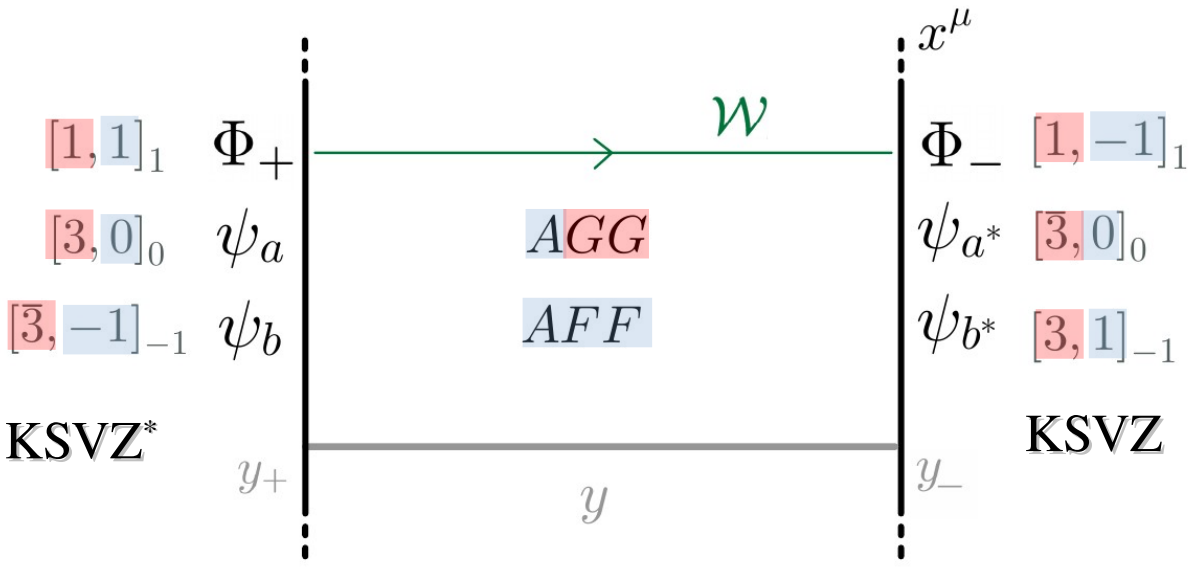
see also Cheng, Kaplan ‘01

A 5D toy model:



see also Cheng, Kaplan ‘01

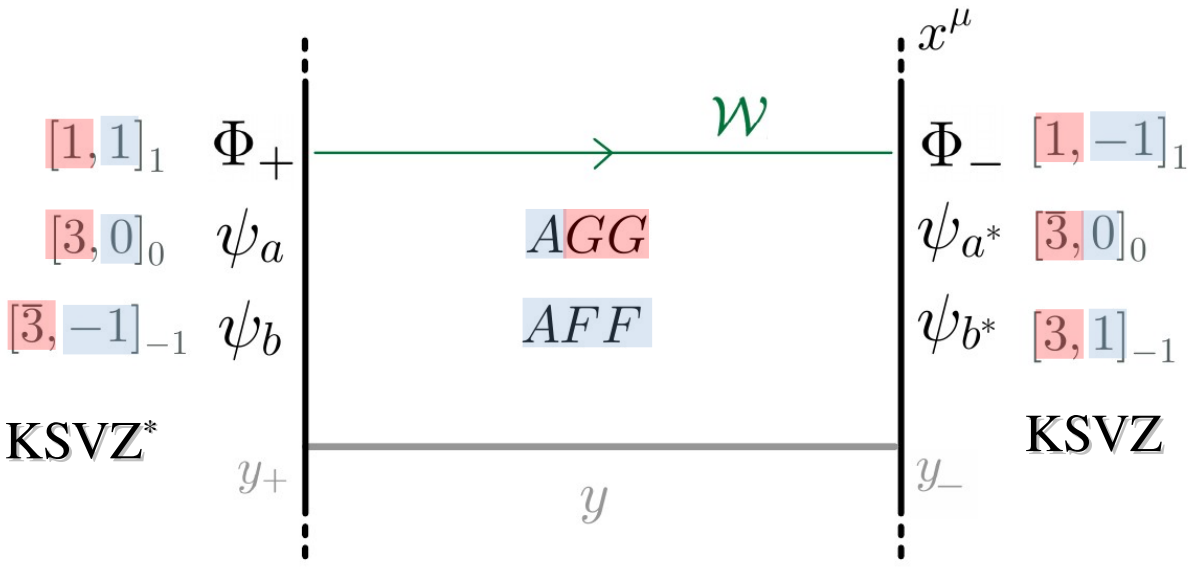
A 5D toy model:



Kim ‘79,
Shifman, Vainshtein, Zakharov ‘80

see also Cheng, Kaplan ‘01

A 5D toy model:



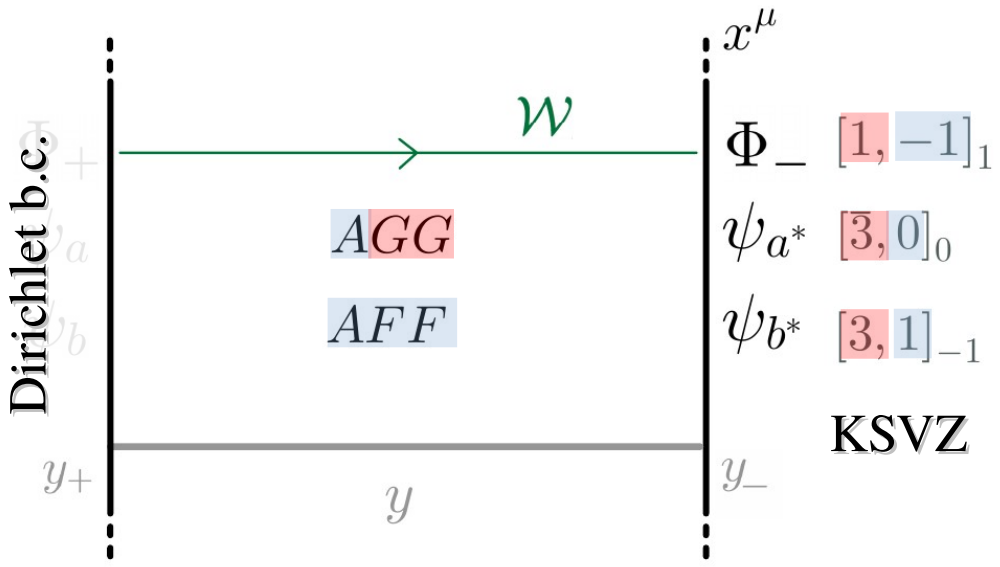
Kim ‘79,
Shifman, Vainshtein, Zakharov ‘80

– In the limit $v_- \ll (v_+, 1/L)$ minimal ($N_{\rm DW} = 1$) KSVZ model recovered:

– L can be small so that all 4D KSVZ extensions work as usual: SUSY, GUT, exotics, ...

A 5D toy model:

NOTE: in the limit $v_+ \to \infty$

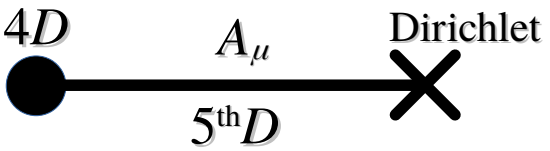


KK lifting of symmetries

U(1) global

$$\mathcal{O}(x) \to e^{iq\alpha}\mathcal{O}(x)$$

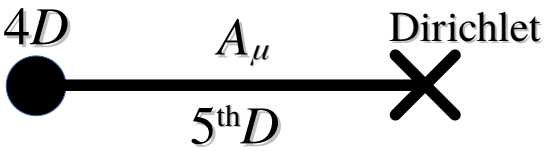
KK lifting of symmetries



U(1) global

$$\mathcal{O}(x) \to e^{iq\alpha}\mathcal{O}(x)$$

KK lifting of symmetries



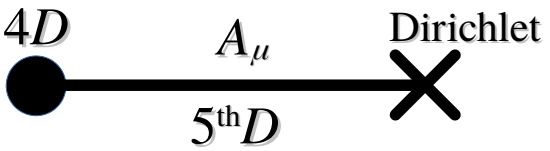
U(1) global

$$\mathcal{O}(x) \to e^{iq\alpha}\mathcal{O}(x)$$

$$\mathcal{O}(x)\, e^{iq\int A}$$

gauge invariant charged operator
→ non-local

KK lifting of symmetries



U(1) global

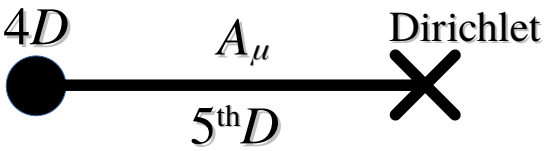
$$\mathcal{O}(x) \to e^{iq\alpha}\mathcal{O}(x)$$

$$\mathcal{O}(x)\, e^{iq\int A}$$

gauge invariant charged operator
→ non-local

Breaking → e^{-ML}

KK lifting of symmetries



U(1) global

$$\mathcal{O}(x) \to e^{iq\alpha}\mathcal{O}(x)$$

$$\mathcal{O}(x)\, e^{iq\int A}$$

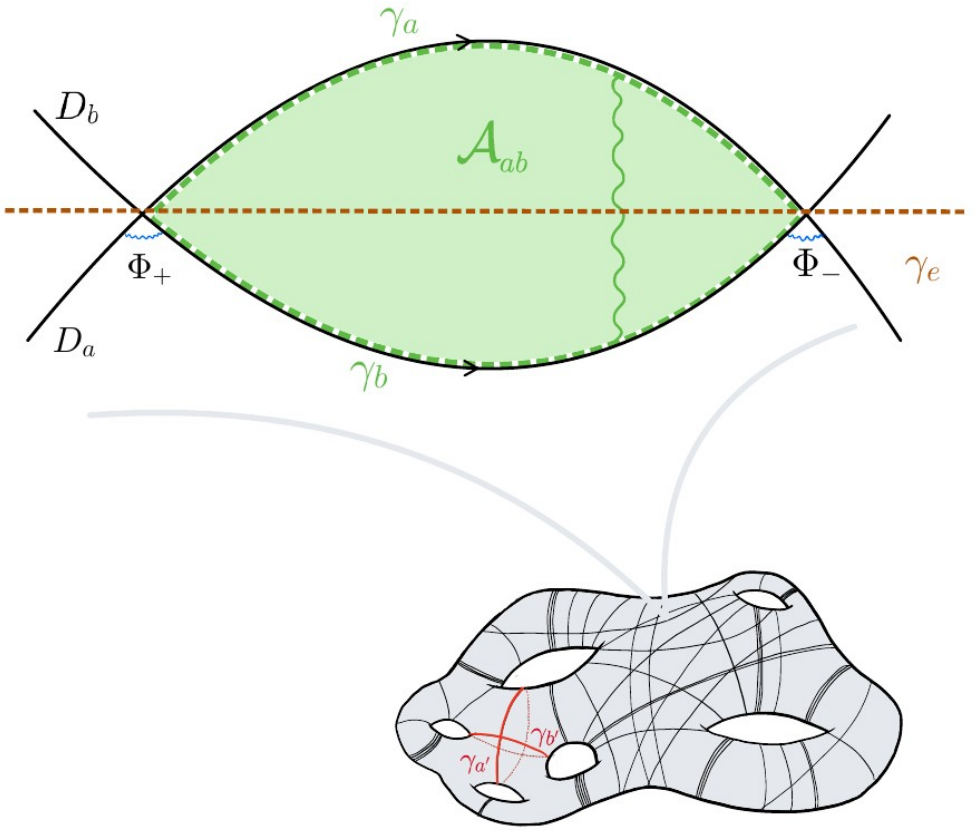
gauge invariant charged operator
→ non-local

Breaking → e^{-ML}

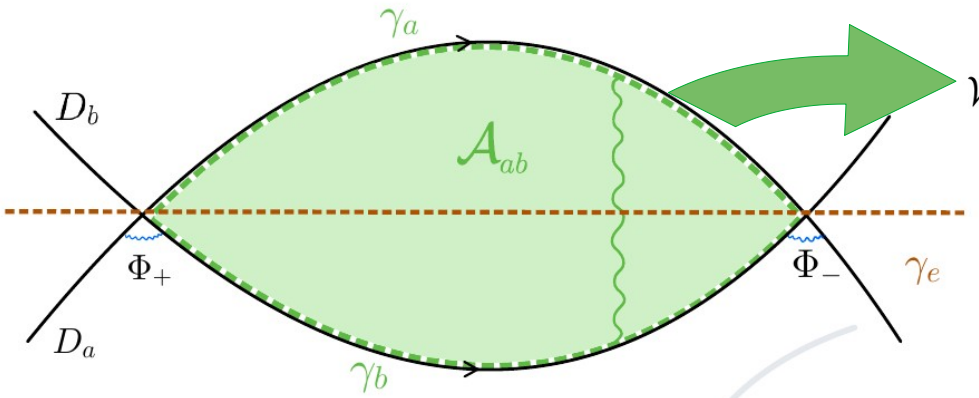
NOTE:

in 4D the global symmetry is not *accidental* but exponentially good

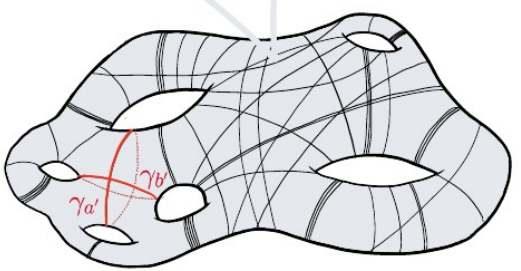
A simple string theory embedding



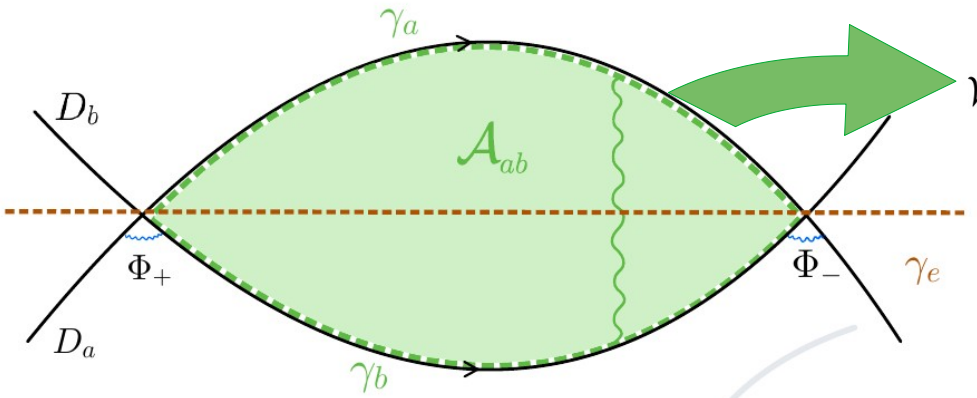
A simple string theory embedding



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

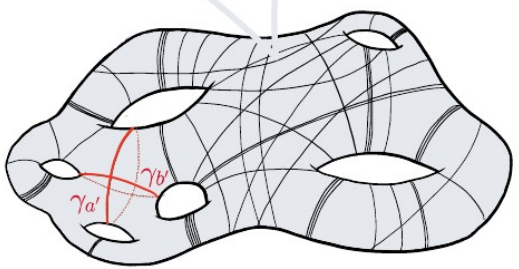


A simple string theory embedding

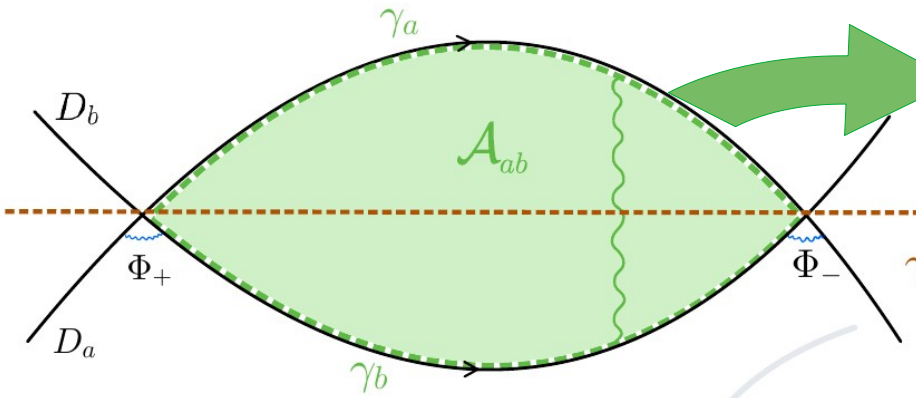


$$\mathcal{W}_{+-} = \Phi_+ \, e^{ig_a\int_{\gamma_a}A_a - ig_b\int_{\gamma_b}A_b - i\int_\Sigma B} \, \Phi_-$$

breaking $\rightarrow$ $\mathcal{W}_{+-}e^{-\mathcal{A}_{ab}}$



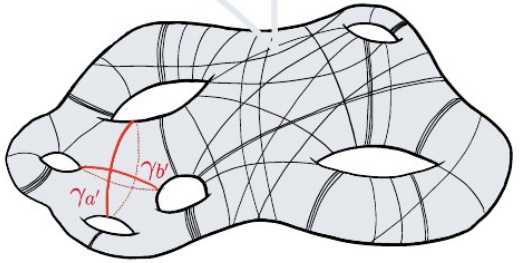
A simple string theory embedding



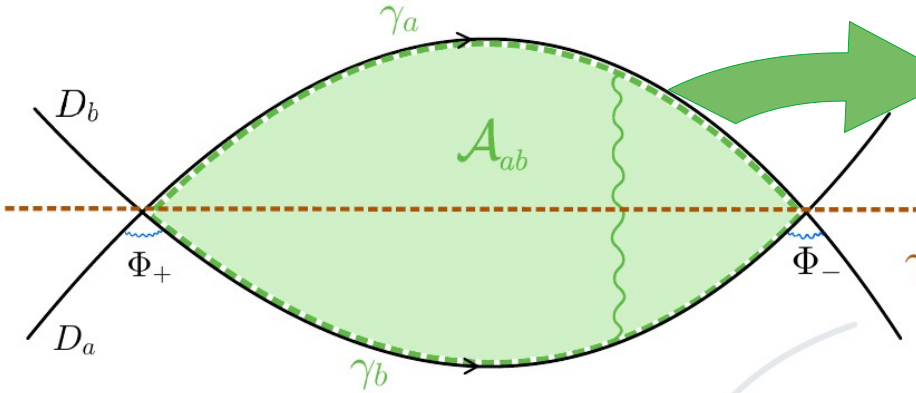
$$\mathcal{W}_{+-} = \Phi_+ \; e^{ig_a\int_{\gamma_a}A_a - ig_b\int_{\gamma_b}A_b - i\int_\Sigma B} \; \Phi_-$$

breaking $\rightarrow$ $\mathcal{W}_{+-}e^{-\mathcal{A}_{ab}}$

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



A simple string theory embedding

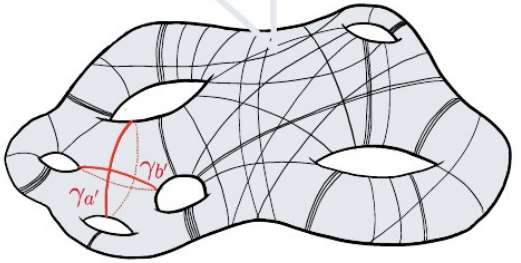


$$\mathcal{W}_{+-} = \Phi_+ \; e^{ig_a\int_{\gamma_a}A_a - ig_b\int_{\gamma_b}A_b - i\int_\Sigma B} \; \Phi_-$$

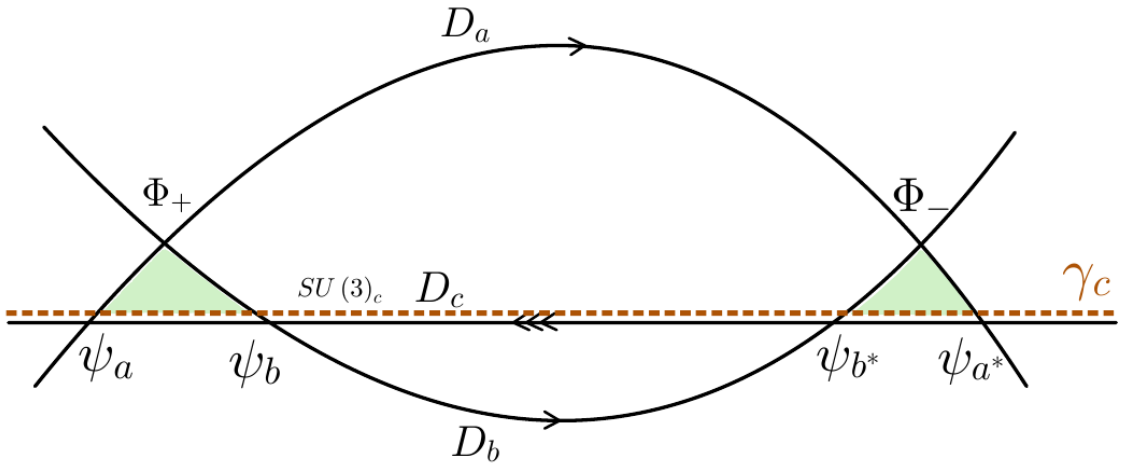
breaking $\rightarrow$ $\mathcal{W}_{+-}e^{-\mathcal{A}_{ab}}$

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

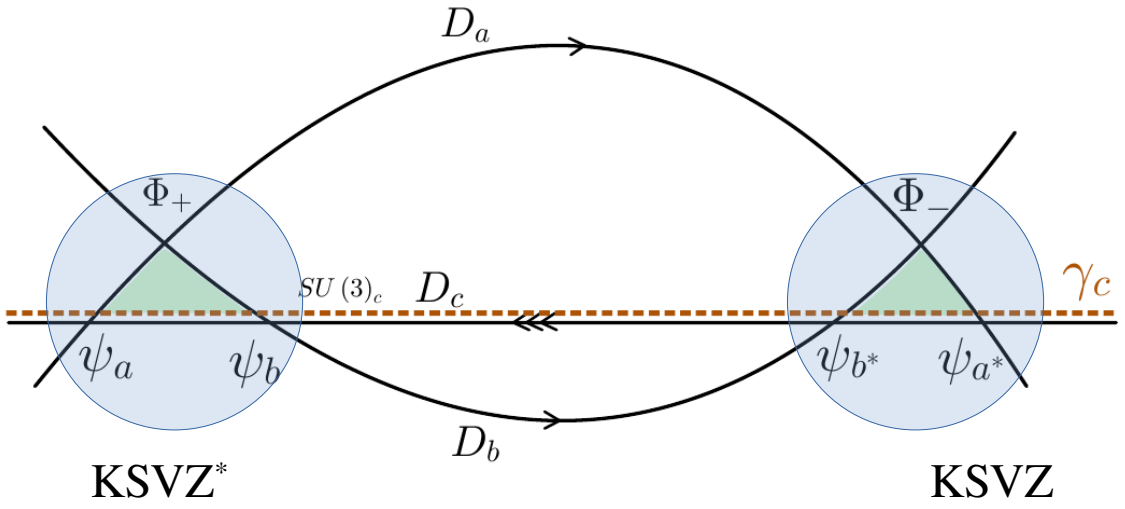
breaking $\rightarrow$ $\mathcal{W}'_{+-}e^{-V_e/g_s}$ $\left(\sim e^{-8\pi^2/g^2_{a,b}}\right)$



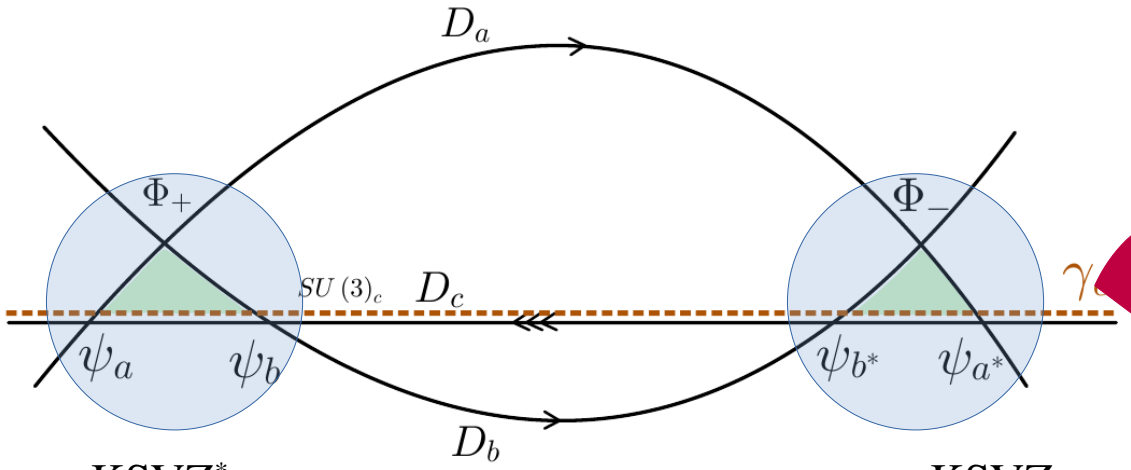
A simple string theory embedding of minimal KSVZ



A simple string theory embedding of minimal KSVZ



A simple string theory embedding of minimal KSVZ

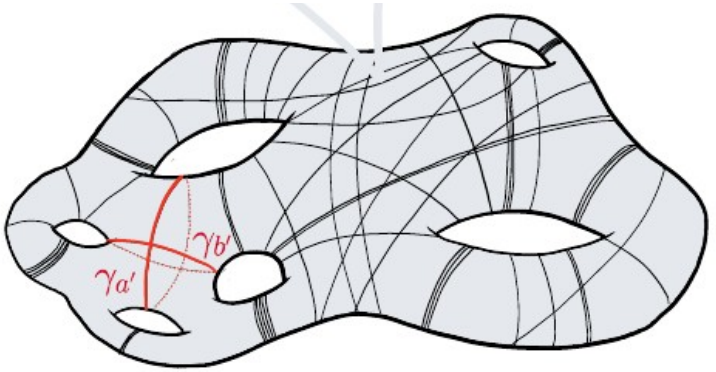


$e^{-8\pi^2/g_s^2}$

~ QCD Small Instanton contrib.

$\ll \chi_{\rm top}$

Open String Axiverse

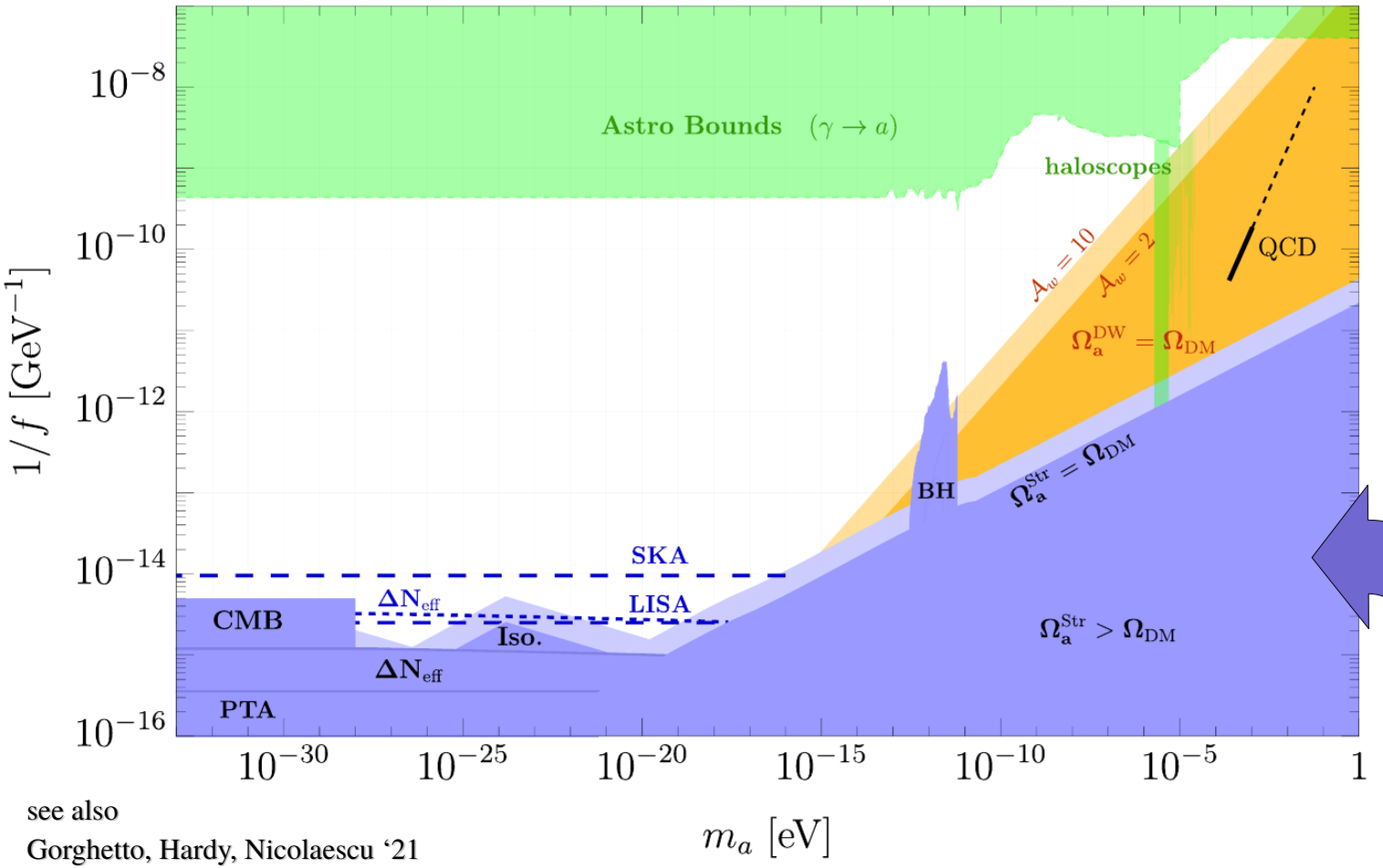


In realistic compactifications branes have multiple intersections

$\rightarrow$ potentially multiple post-inflationary ALPs

see e.g. works of:
Allahverdi, Berenstein, Cicoli, Diaz, Dutta, Guidetti, Honecker, Klevers, Krippendorf, Mayrhofer, Perkin, Quevedo, Rummel, Sinha, Staessens, Valandro ...

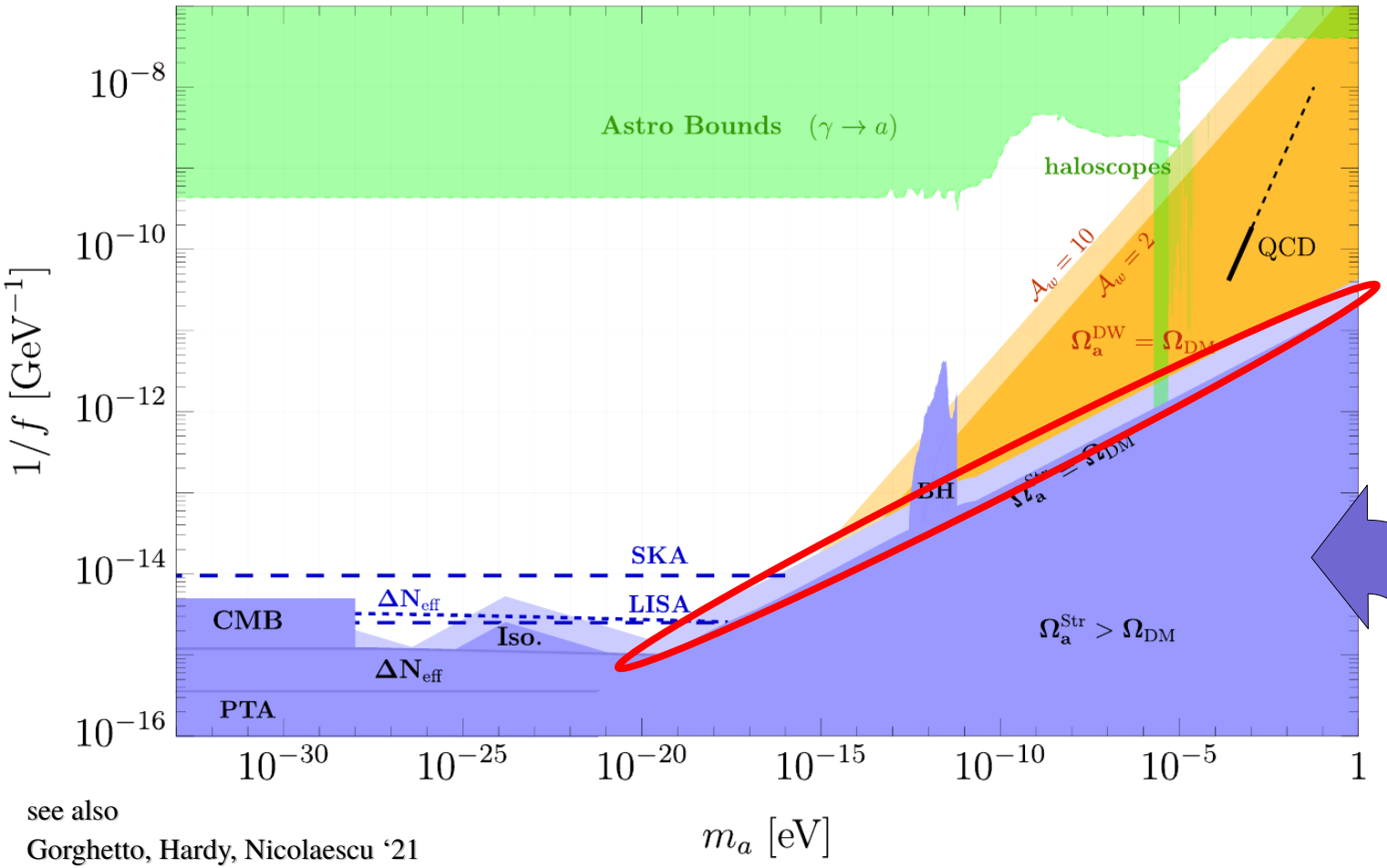
Open String Axiverse Phenomenology



post-inflationary ALPs

see also
Gorghetto, Hardy, Nicolaescu ‘21
Gorghetto, Hardy ‘22

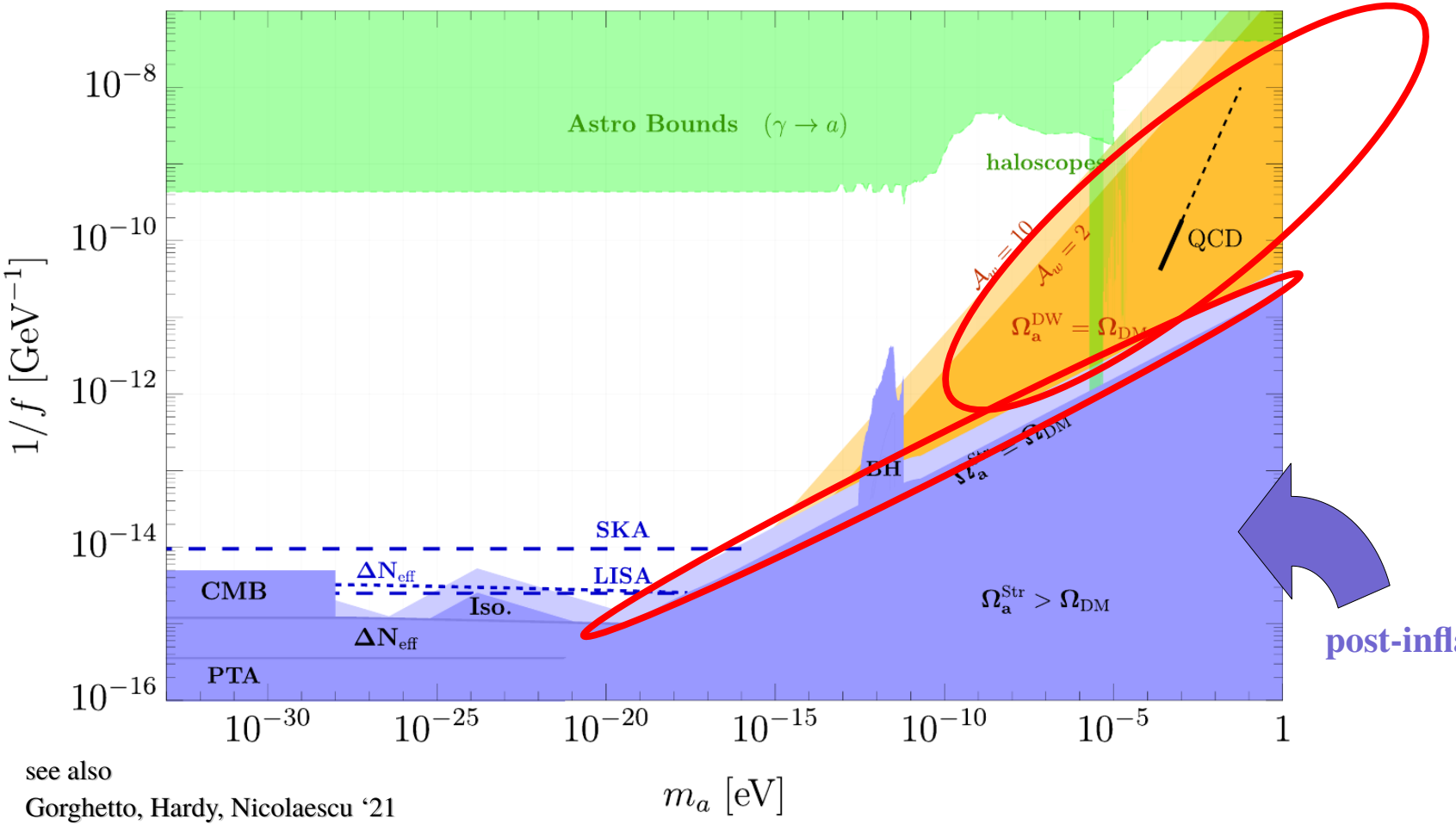
Open String Axiverse Phenomenology



post-inflationary ALPs

see also
Gorghetto, Hardy, Nicolaescu ‘21
Gorghetto, Hardy ‘22

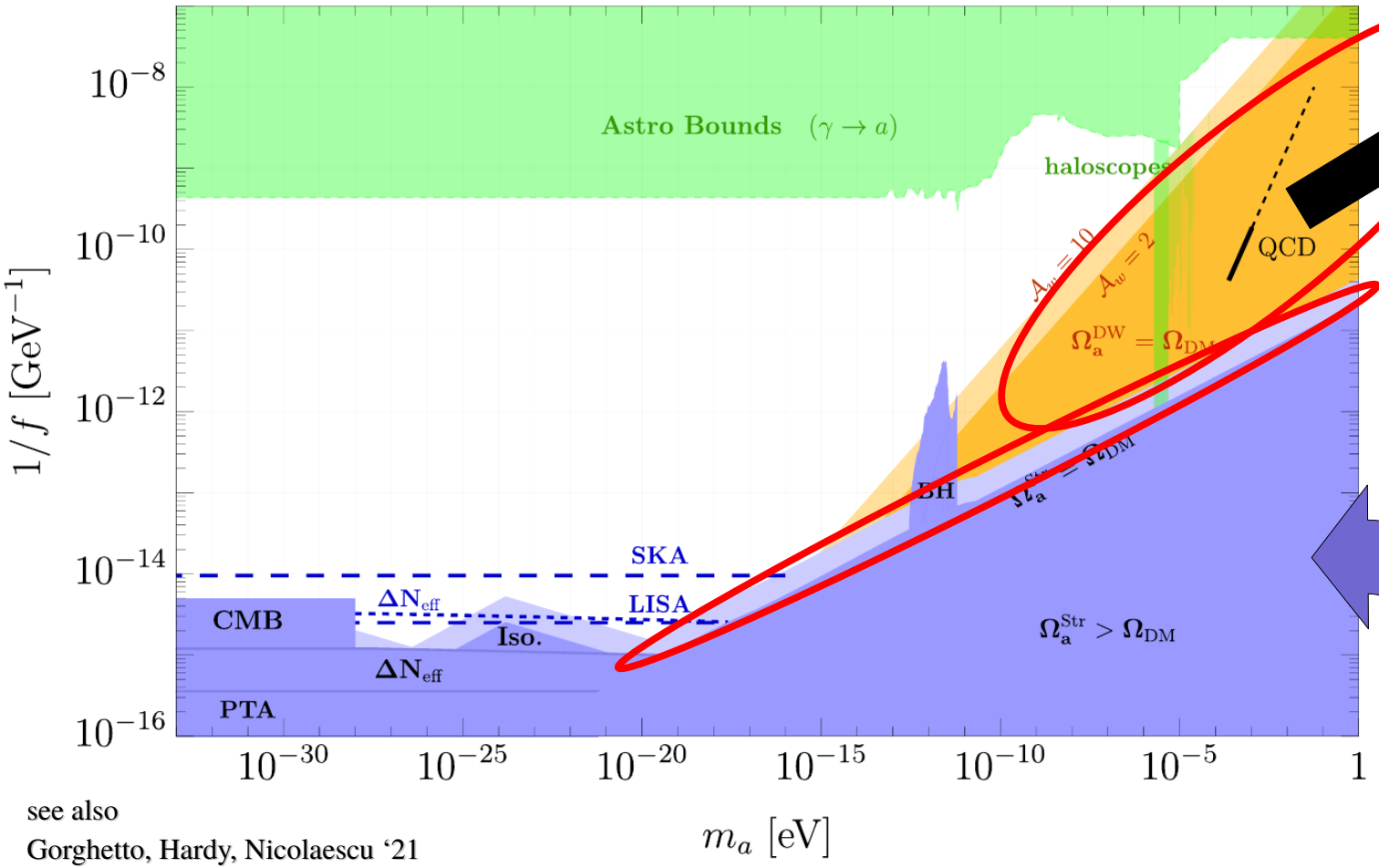
Open String Axiverse Phenomenology

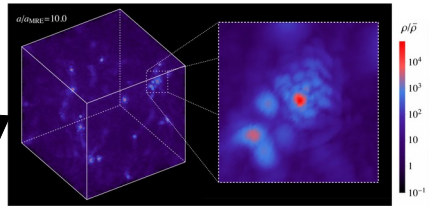


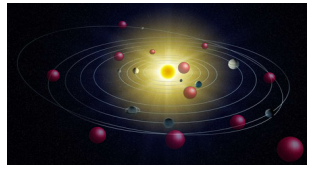
post-inflationary ALPs

see also
Gorghetto, Hardy, Nicolaescu ‘21
Gorghetto, Hardy ‘22

Open String Axiverse Phenomenology







see Gorghetto, Hardy, GV '24

post-inflationary ALPs

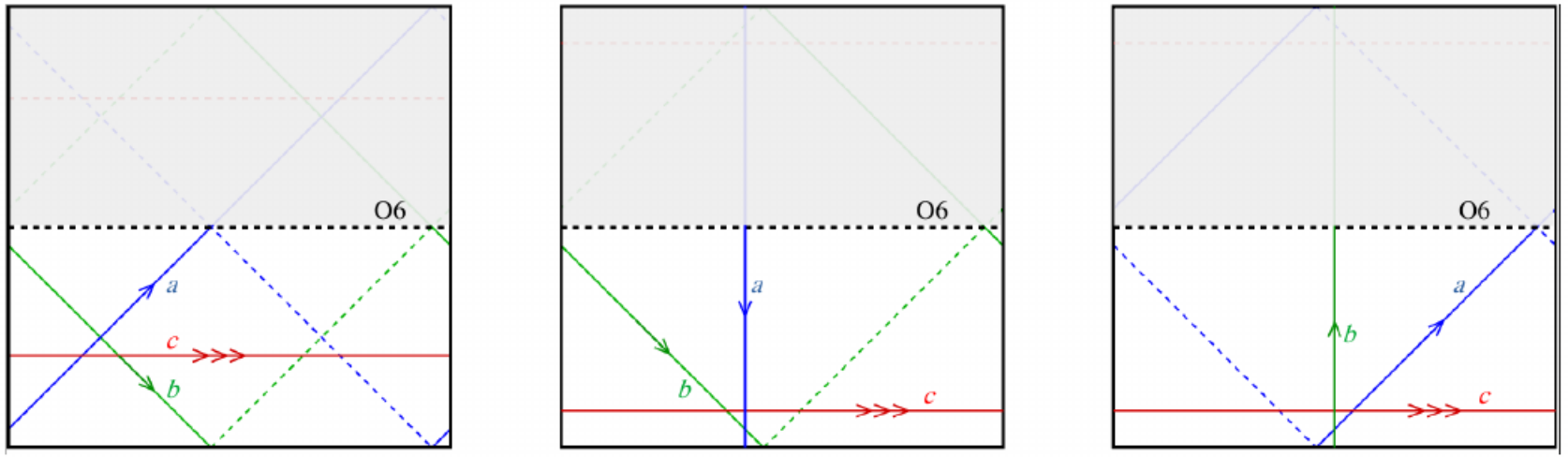
see also
Gorghetto, Hardy, Nicolaescu '21
Gorghetto, Hardy '22

Executive Conclusions

1. No problem between Quantum Gravity and HQ Symmetries
2. No fundamental obstruction to post-inflation QCD axions/ALPs
3. In fact it's generic → "open string axiverse"
4. New phenomenological opportunities

Thank You!

Back up



Example: SUSY cycles on T^6 compatible with (approx.) SUSY moduli stabilization