Quantum gravity constraints from EFT strings

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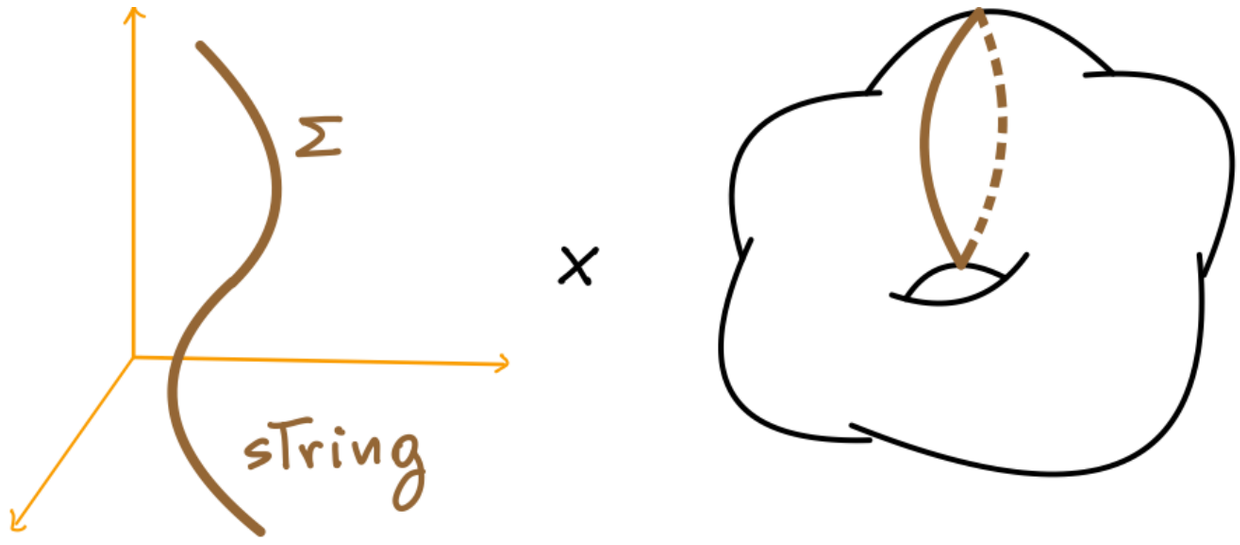
2104.05726, 2006.15154, 2205.04532

"Back to the Swamp" 2022 - Madrid

- In QG models, EFTs are populated by strings (and other extended objects)



$$e^{i\int_\Sigma B_{2,i}}$$

↓

existence by completeness hypothesis

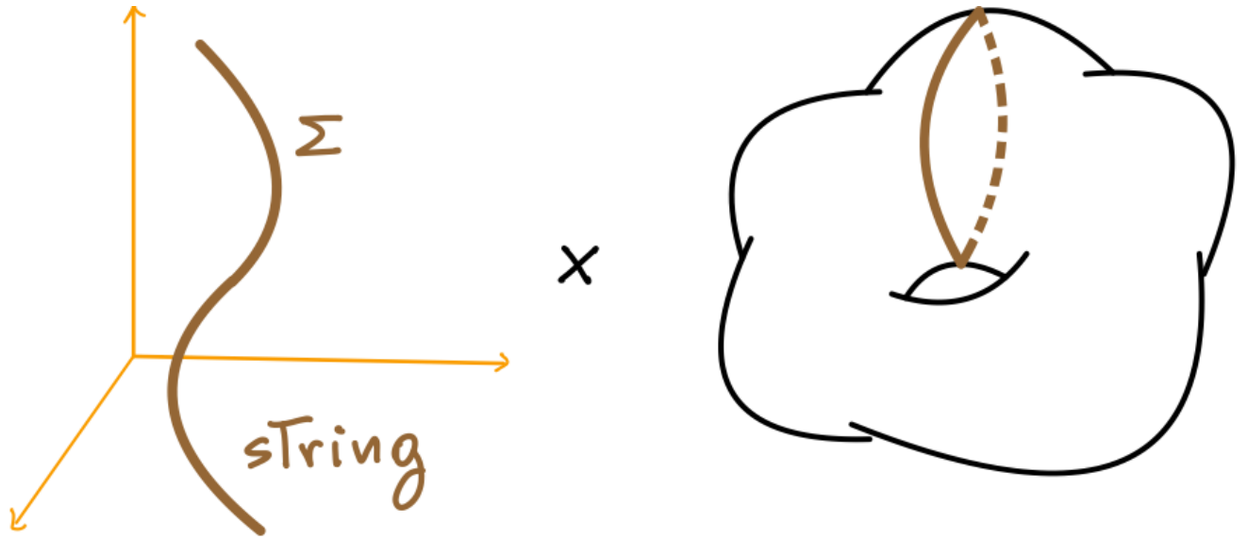
[Polchinski '03, Banks & Seiberg '11, Halow-Ooguri '18,...]

- I'll focus on 'fundamental' BPS strings in d=4 $\mathcal{N}=1$ EFT

see also [Reece '18]

⇝ natural probes of quantum gravity UV completion

- In QG models, EFTs are populated by strings (and other extended objects)



$$e^i \int_\Sigma B_{2,i}$$

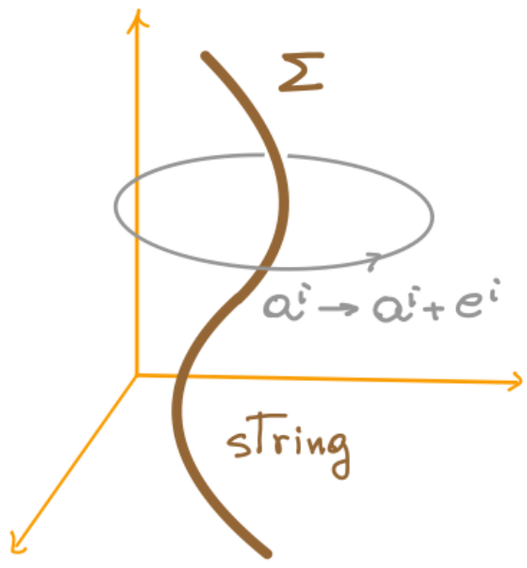
$\downarrow$

existence by completeness hypothesis

[Polchinski '03, Banks & Seiberg '11, Halow-Ooguri '18,...]

- $dB_2 \sim *da$

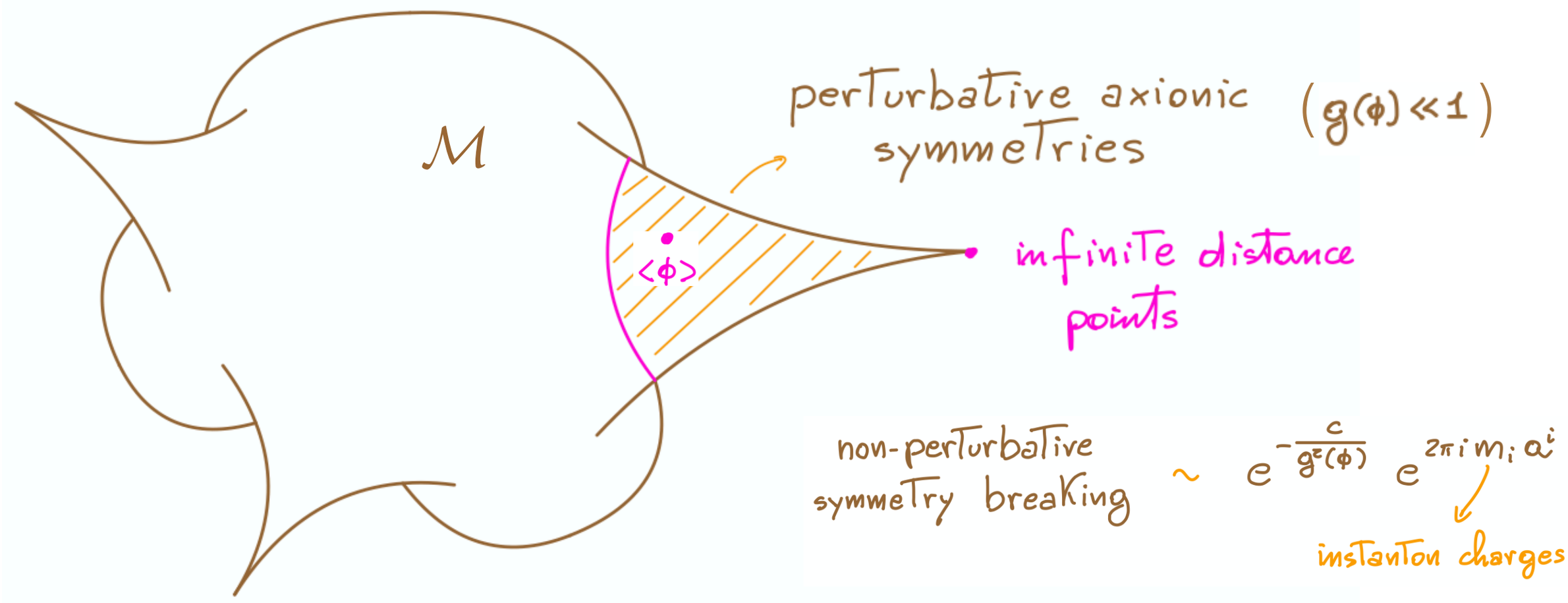
$\longrightarrow$ axionic strings!



Strings in 4d?

- Perturbative axionic shift symmetries

[Misner-Wheeler '56,...,
Kallosh-Linde-Linde-Susskind '95, ...,
Banks & Seiberg '06,...,
Harlow-Ooguri '19]



- Fundamental BPS strings as natural probes of asymptotic field space regions

Strings in 4d?

- Warning: strong back-reaction:
  - bulk vacuum destroyed
  - fields possibly driven to strongly coupled regions
  - IR effects out of control

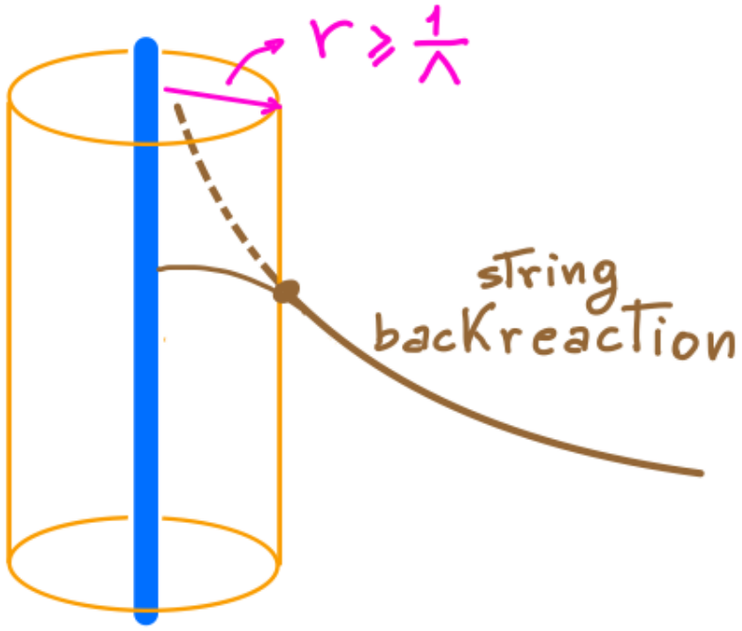
See [Marchesano-Wiesner '22]

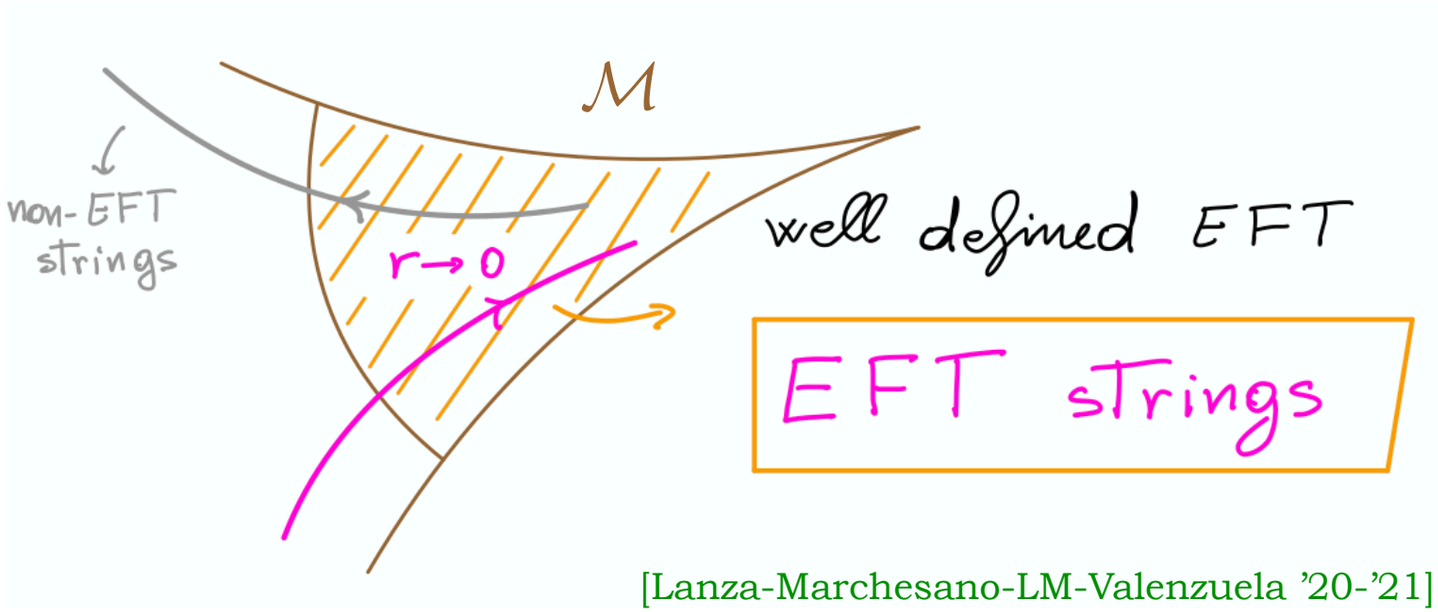
Strings in 4d?

- Warning: strong back-reaction:
  - bulk vacuum destroyed
  - fields possibly driven to strongly coupled regions — See [Marchesano-Wiesner '22]
  - IR effects out of control

- However, strings can still have a well defined EFT description

[..., Goldberger&Wise '01,
Michel-Mintun-Polchiski-Puhm-Saad '14, Polchinski '15...,]





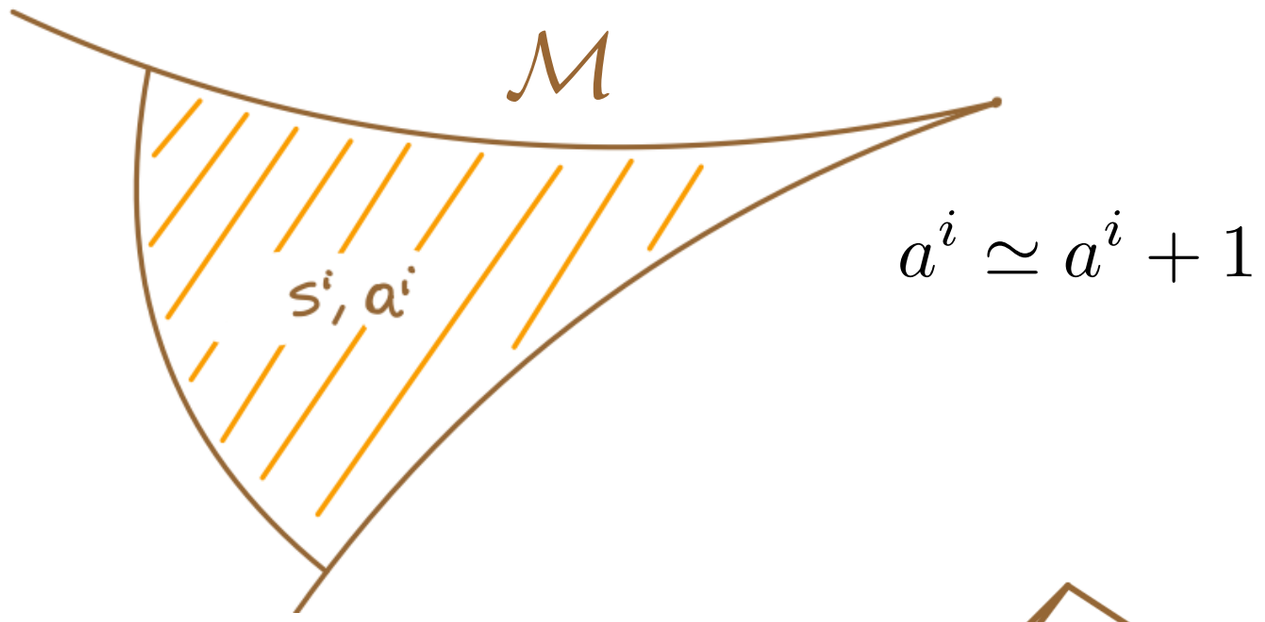
[Lanza-Marchesano-LM-Valenzuela '20-'21]

EFT strings

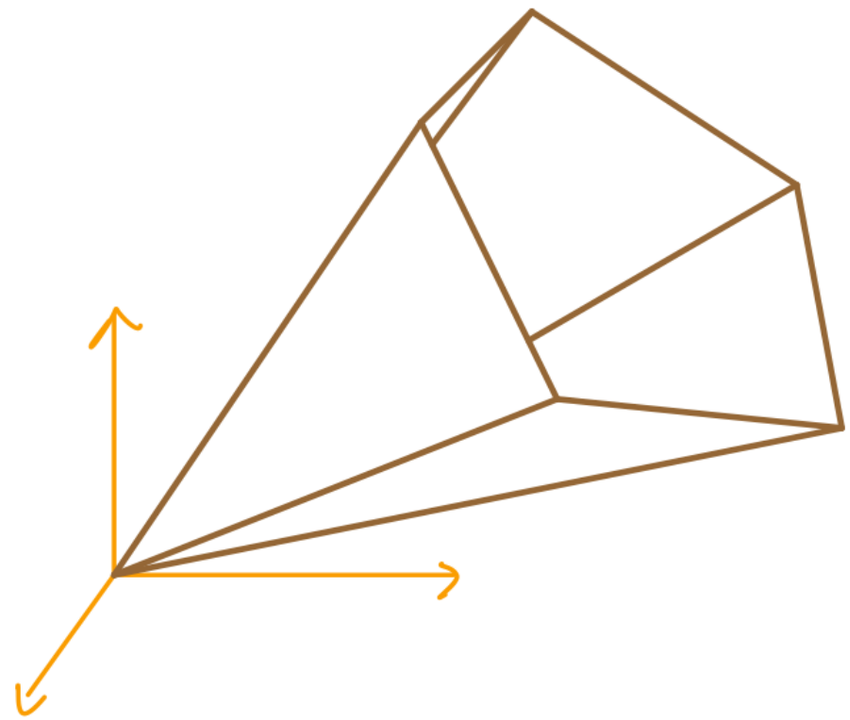
- Perturbative region:

$$t^i \equiv a^i + \mathrm{i}\, s^i$$

axions (chiral mult.) saxions



- $\{s^i\} \in \{\text{saxionic cone}\}$



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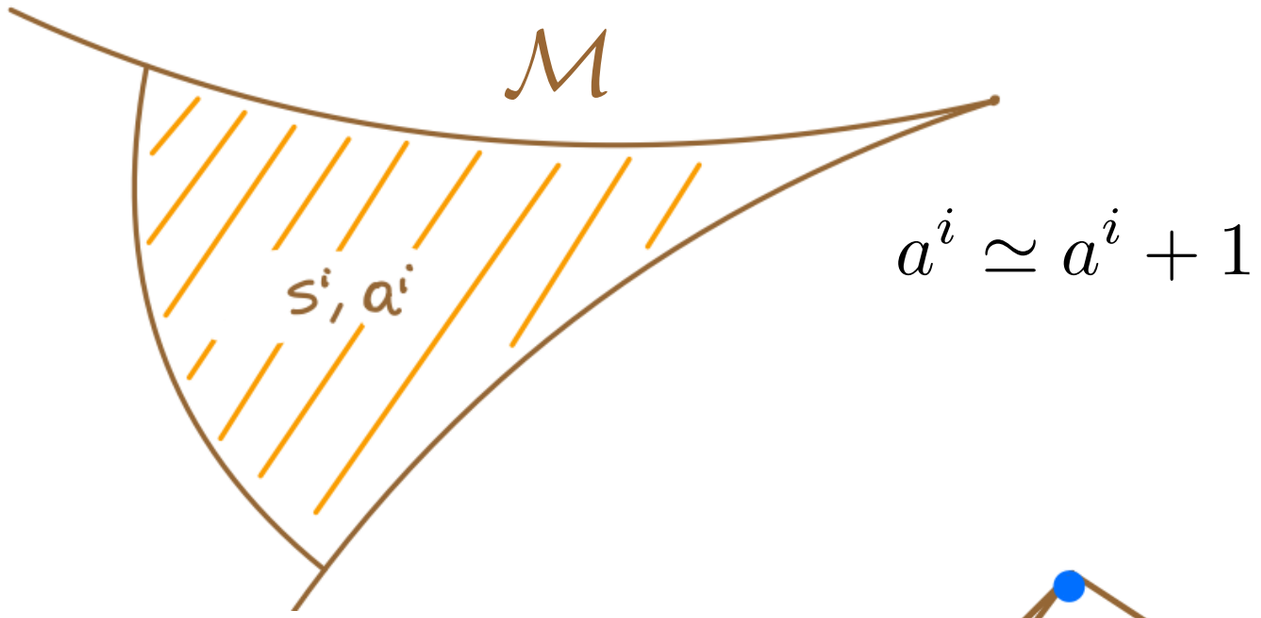


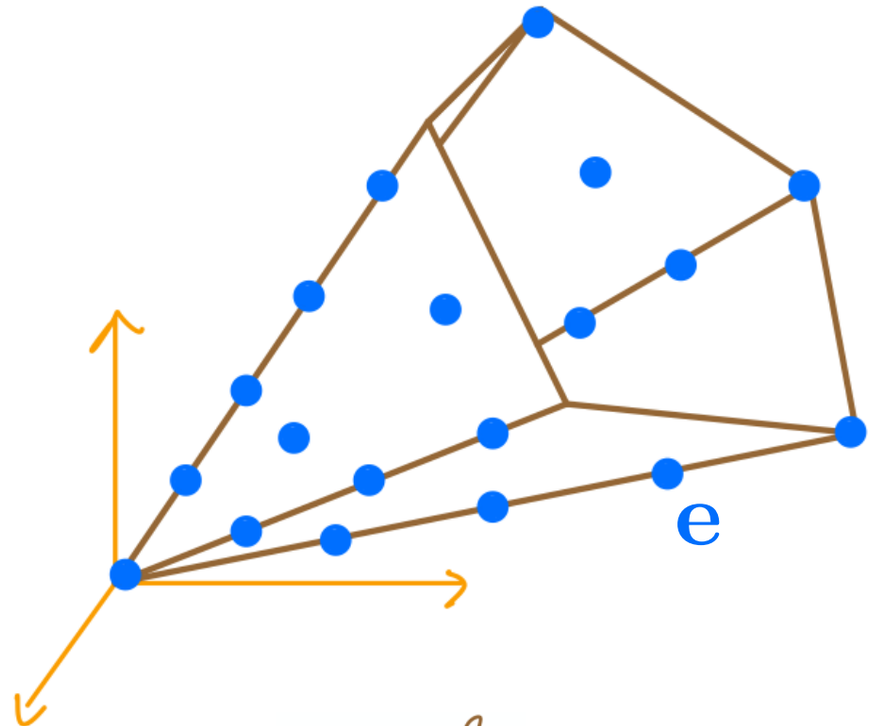
- $\{s^i\} \in \{\text{saxionic cone}\}$

- EFT string charges:

$$\mathbf{e} \equiv \{e^i\} \in \mathcal{C}_{\rm S}^{\rm EFT} \equiv \{\text{saxionic cone}\}_{\mathbb{Z}}$$

EFT strings strongly characterize asymptotic field space regions!

[Lanza-Marchesano-LM-Valenzuela '20-'21]



see also

[Buratti, Calderón-Infante, Delgado, Uranga `21]

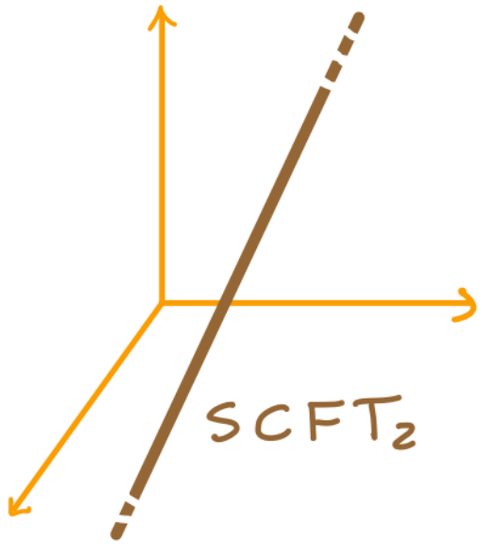
[Angius, Calderón-Infante, Delgado, Huertas, Uranga `22]

[Grimm, Lanza, Li `22]

[Fierro Cota, Mininno, Weigand, Wiesner`22]

Quantum consistency?

- BPS strings as quantum probes of $d \geq 5$ supergravities!



Quantum consistency of IR SCFT$_2$

$\Downarrow$

constraints on bulk EFT

[Kim-Shiu-Vafa `19]

[Lee-Weigand `19]

[Kim-Tarazi-Vafa '20]

[Katz-Kim-Tarazi-Vafa '20]

[Angelantonj-Bonnefoy-Condeescu-Dudas'20]

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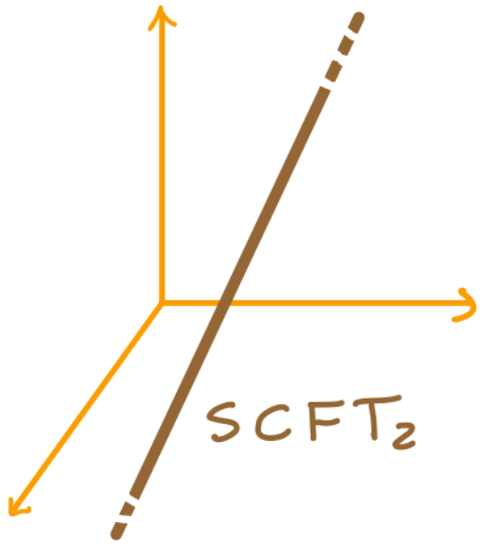

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- In $d = 4$ we cannot assume IR SCFT, however...

- ... EFT strings support weakly-coupled (0,2) NLSM!

- EFT string completeness $\Longrightarrow$ EFT quantum gravity constraints!

[Lanza-Marchesano-LM-Valenzuela '20-'21]

EFT strings probing gauge and (curvature)^2 terms

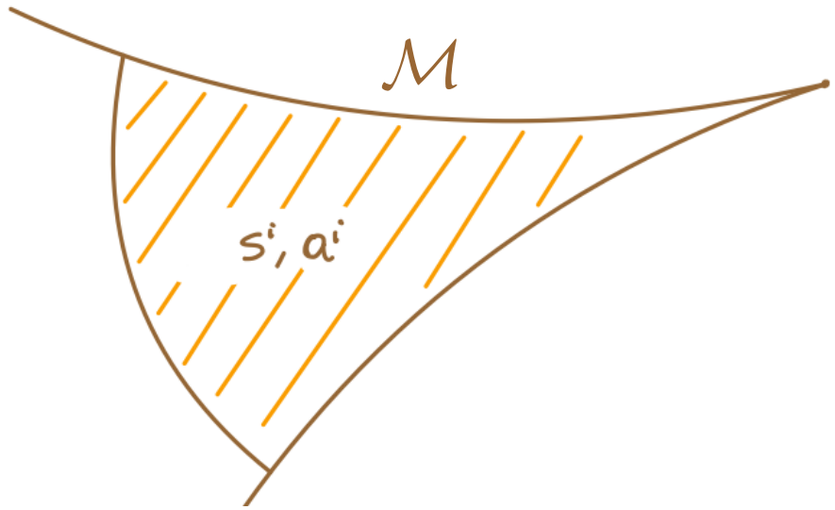
[LM-Risso-Weigand ’22]

- Bulk perturbative gauge group:

$$-\frac{1}{2}\int (C_i s^i + \ldots)\ \mathrm{Tr}(F\wedge *F) - \frac{1}{2}\int (C_i a^i + \ldots)\ \mathrm{Tr}(F\wedge F)$$

$\frac{1}{g^2} \gg 1$ in

$$\Longrightarrow \quad \boxed{C_i s^i > 0}$$



- Gauss-Bonnet and Pontryagin terms

$$-\frac{1}{48}\int (\tilde{C}_i s^i + \ldots)\ [\mathrm{Tr}(R\wedge *R) + \ldots] - \frac{1}{48}\int (\tilde{C}_i a^i + \ldots)\ \mathrm{Tr}(R\wedge R)$$

sign ?

positivity suggested by

[..., Kallosh-Linde-Linde-Susskind '95, Cheung-Remmen '16,
GarcíaEtxebarria-Montero-Sousa-Valenzuela '20, Aalsma-Shiu '22, Chin Ong '22, ...]

- The axionic couplings detect the presence of EFT strings:

  * $$S_{\text{bulk}} \supset \int a^i I_{4,i} = -\int \mathrm{d}a^i \wedge I_{3,i}$$

    with $$I_{4,i} = \mathrm{d}I_{3,i} = -\frac{1}{2} C_i \,\mathrm{Tr}(F \wedge F) - \frac{1}{48} \tilde{C}_i \,\mathrm{Tr}(R \wedge R)$$

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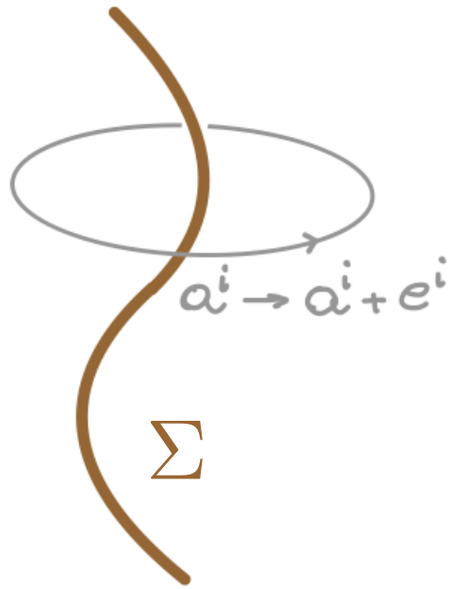
  * $\mathrm{d}^2 a^i = e^i \delta_2(\Sigma)$



$$\boxed{\delta\, S_{\text{bulk}} = -e^i \int_\Sigma \delta I_{2,i} \quad \neq 0} \qquad \left(\mathrm{d}\delta I_{2,i} = \delta I_{3,i} \right)$$

anomaly inflow [Callan-Harvey '85]

- Anomaly inflow must be cancelled by world-sheet `t Hooft anomaly

[Callan-Harvey '85]

$$I_4^{\rm ws} = e^i I_{4,i} = -\frac{1}{2}(e^i C_i)\,{\rm Tr}(F\wedge F) - \frac{1}{2}(e^i \tilde{C}_i)\,{\rm Tr}(R_{\rm T}\wedge R_{\rm T}) - \frac{1}{2}(e^i \tilde{C}_i)\,{\rm Tr}(R_{\rm N}\wedge R_{\rm N})$$

$$G = \prod_A U(1)_A \times \prod_I G_I \qquad SO(1,1)_{\rm T} \qquad U(1)_{\rm N}$$

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- Weakly-coupled (0,2) NLSM on EFT string:

Fermion	#	$U(1)_{\rm N}$ charge	$U(1)_A$ charge	G_I repr.	(0,2) multiplet
ρ_+	1	$\frac{1}{2}$	0	$\mathbf{1}$	chiral U
χ_+	$n_{\rm C}$	$-\frac{1}{2}$	$*$	$*$	chiral Φ
ψ_-	$n_{\rm F}$	0	q_A	$\mathbf{r}_I$	Fermi Ψ_-
λ_-	$n_{\rm N}$	$\frac{1}{2}$	0	$\mathbf{1}$	Fermi Λ_-

- Anomaly matching + $n_{\rm F}, n_{\rm C} \geq 0$ $\Longrightarrow$ EFT constraints! [LM-Risso-Weigand '22]

$$-\frac{1}{2}\int (C_i s^i + \ldots)\ \mathrm{Tr}(F \wedge *F) - \frac{1}{48}\int (\tilde{C}_i s^i + \ldots)\,[\mathrm{Tr}(R \wedge *R) + \ldots]$$

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(1) $\quad \tilde{C}_i e^i \in 3\mathbb{Z}_{\geq 0}\,, \qquad \forall \mathbf{e} \in \mathcal{C}_{\rm S}^{\rm EFT}$ $\longrightarrow$ $\tilde{C}_i s^i > 0$

positive GB coupling!

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(2) $r(\mathbf{e}) \leq r(\mathbf{e})_{\rm max} \equiv 2\tilde{C}_i e^i - 2\,, \qquad \forall \mathbf{e} \in \mathcal{C}_{\rm S}^{\rm EFT}$

bounds on ranks determined by GB!

total rank of gauge group 'coupled' to the string $(C_i e^i \neq 0)$

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bounds on ranks determined by GB!

↑ total rank of gauge group 'coupled' to the string $(C_i e^i \neq 0)$

- actually: $r(\mathbf{e})_{\rm max} = r_{\rm F}(\mathbf{e})_{\rm max} + r_{\rm C}(\mathbf{e})_{\rm max}$ [Blaszczyk-Groot Nibbelink-Ruehle, Quigley-Sethi '11]

't Hooft anomaly: $\frac{4}{3}\tilde{C}_i e^i$ ↙ GS contribution: $\frac{2}{3}\tilde{C}_i e^i - 2$ ↘

Simplest example

- Single-field model

$$-\frac{1}{2}\int (Cs+\ldots)\ \mathrm{Tr}(F\wedge *F) - \frac{1}{48}\int (\tilde{C}s+\ldots)\ \mathrm{Tr}(R\wedge *R+\ldots)+\ldots$$

- $\{\text{saxionic cone}\} = \mathbb{R}_{>0}\ ,\quad \mathcal{C}_{\mathrm{S}}^{\mathrm{EFT}} = \mathbb{Z}_{\geq 0}$

(1) $\quad \tilde{C} = 3k \quad , \quad k\in\mathbb{Z}_{\geq 0}$

(2) $\quad \mathrm{rk}(\mathfrak{g}) \leq 2\tilde{C} - 2 = 6k-2$

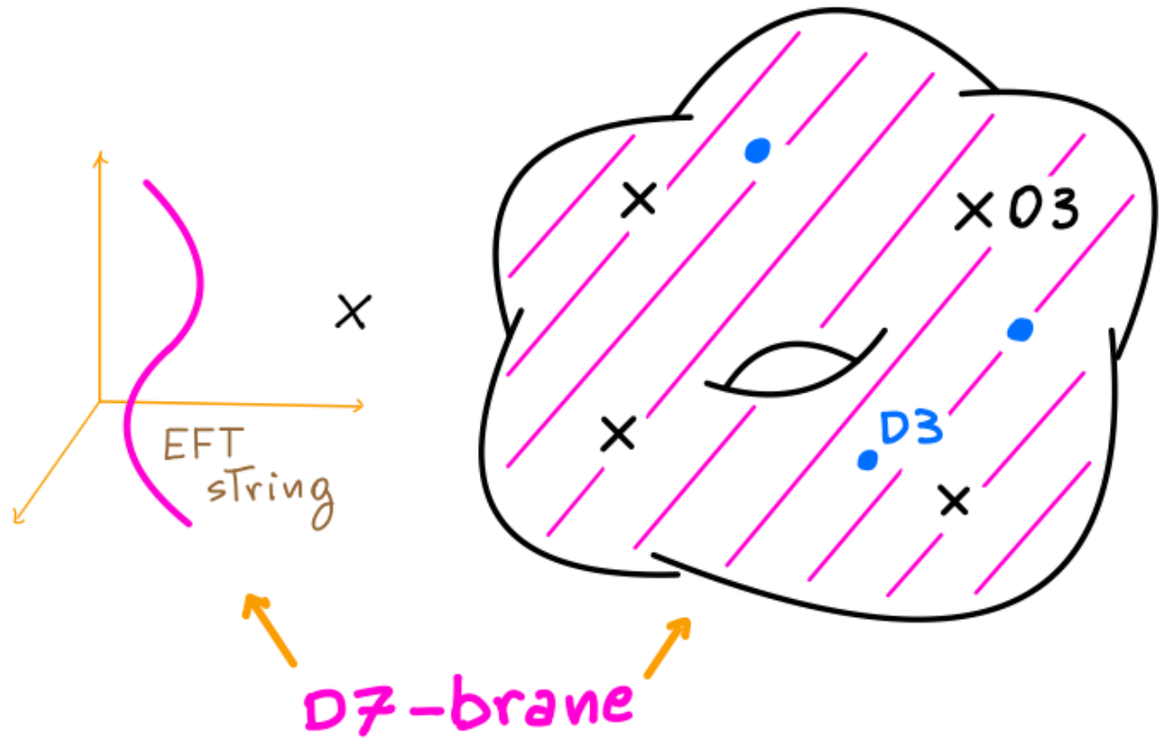
UV test: O3/D3 models

* (s)axion: $a + \mathrm{i}s \equiv C_0 + \mathrm{i}e^{-\phi}$

(1) $\tilde{C} = \frac{3}{16} n_{\mathrm{O3}} \in 3\mathbb{Z}$

$\Downarrow$

$n_{\mathrm{O3}} \in 16\mathbb{N}$ ✓ [Favale '17]



(2) $r(\mathbf{e}) = n_{\mathrm{D3}} \leq r_{\mathrm{F}}(\mathbf{e})_{\max} \leq r(\mathbf{e})_{\max}$

$\| $

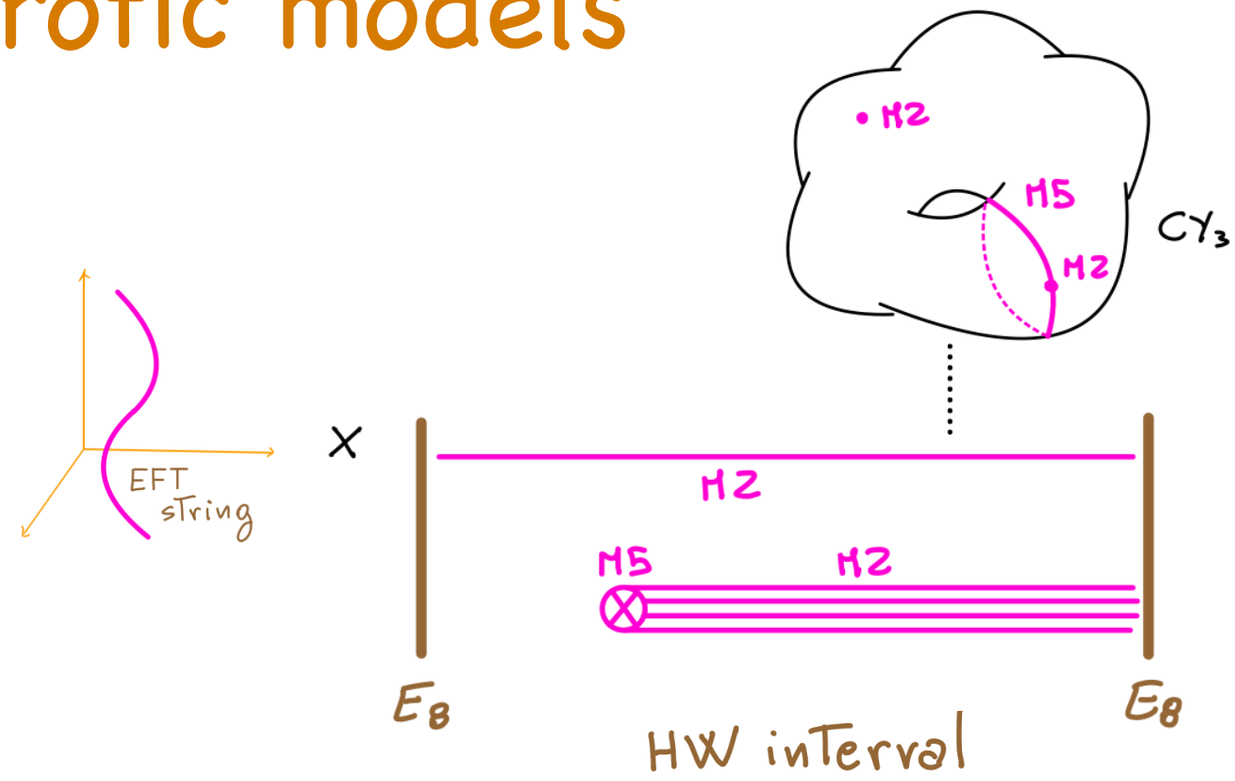
$\frac{4}{3}\tilde{C}_i e^i = \frac{1}{4} n_{\mathrm{O3}}$

$\longleftrightarrow$ $4n_{\mathrm{D3}} \leq n_{\mathrm{O3}}$ ✓

D3 Tadpole bound!

UV test: heterotic models

- EFT strings:
  - F1/M2
  - NS5/M5 on nef divisors



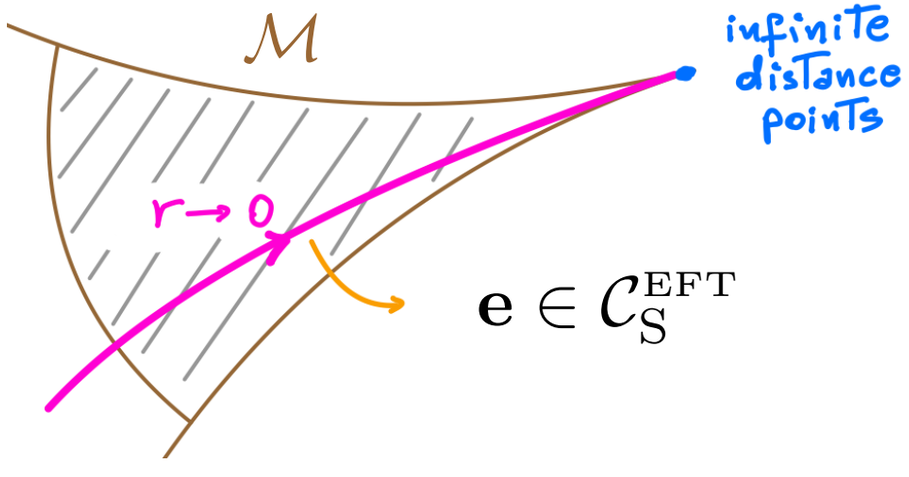
- $c_2(\mathrm{CY}_3)$ + internal bundle $\longrightarrow$ $\tilde{C}_i$
  - $r(\mathbf{e}_{\mathrm{F1/M2}}) \leq 22$ $\sim$ perturbative sector — as with 16 superchages [Kim-Tarazi-Vafa '20]
  - $r(\mathbf{e}_{\mathrm{NS5/M5}})_{\max}$ $\sim$ non perturbative sector — e.g. $r(G_{\text{non-pert}}) \leq 34$ in $T^2 \hookrightarrow \mathrm{CY}_3 \to \mathbb{P}^2$

Conclusions

- EFT strings are physical probes of asymptotic field space regions

- Constraints on gauge and (curvature)^2 sectors
  - Positivity of GB terms and upper bounds on gauge group ranks
  - All bounds microscopically satisfied (… so far)

- Richest testing class of models: F-theory! -> Timo's talk



Distant Axiomic String Conjecture

(see also [Grimm, Lanza, Li '22])

* $\mathcal{T}_{\mathbf{e}} \to 0$ along EFT string flows

EFT realization of Distance Conjecture

[Ooguri-Vafa '06]

* $$m^2_{\text{UV-tower}} \sim M_{\rm P}^2 \left(\frac{\mathcal{T}_{\rm e}}{M_{\rm P}^2} \right)^{w_{\mathbf{e}}} \longrightarrow 0$$

$w_{\mathbf{e}} = 1, 2, 3$
scaling weight

Integral Scaling Weight Conjecture

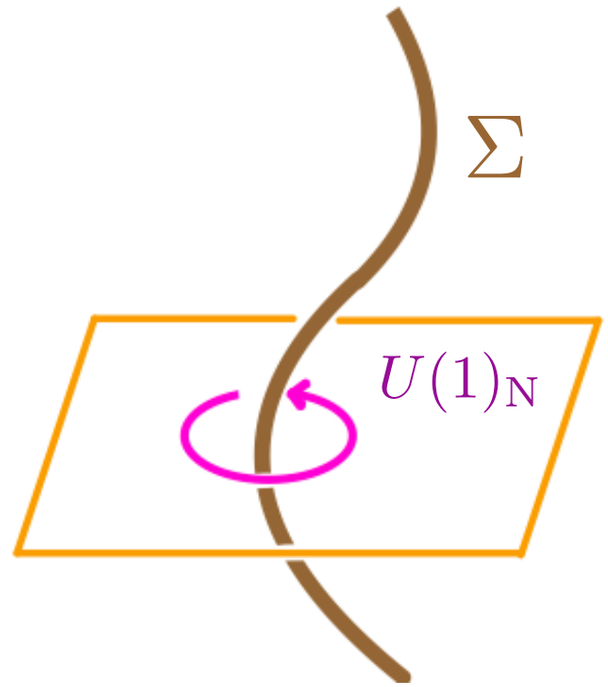
A subtle contribution

- Axionic strings in 4 dimensions can support additional term [Witten `96] [Becker-Becker `99]

$$-\frac{1}{24}\hat{C}_{ijk}e^j e^k \int_\Sigma \mathrm{d}a^i \wedge A_\mathrm{N}$$

it captures hidden 5d structure

$$\hat{C}_{ijk}\int_{5d} A^i \wedge F^j \wedge F^k$$



$\Downarrow$

contributes to anomaly inflow and anomaly matching

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(2) $$r(\mathbf{e}) \leq 2\tilde{C}_i e^i + \hat{C}_{ijk}e^i e^j e^k - 2\,, \quad \forall \mathbf{e} \in \mathcal{C}_\mathrm{S}^\mathrm{EFT}$$