Axiverse wormholes

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Outline

1. Motivation

2. Euclidean wormholes
   - Extremal and non-extremal solutions
   - Physical implications

3. Conclusion

1. Motivation

Axion:

spin-0 field with approximate shift symmetry

$$a \to a + \text{const}$$

↓

Pheno applications: Inflation, dark matter, Strong CP problem

<u>To what extent is this symmetry exact?</u>

String Theory: natural framework to investigate this question

Compactification to 4d $\longrightarrow N \gg 1$ fields with approximate shift symmetries

"String Axiverse"

Shift symmetries broken only **non-perturbatively**

UV

Worldsheet &
Brane instantons

4d EFT

Gauge &
Gravitational instantons

?

Euclidean wormholes

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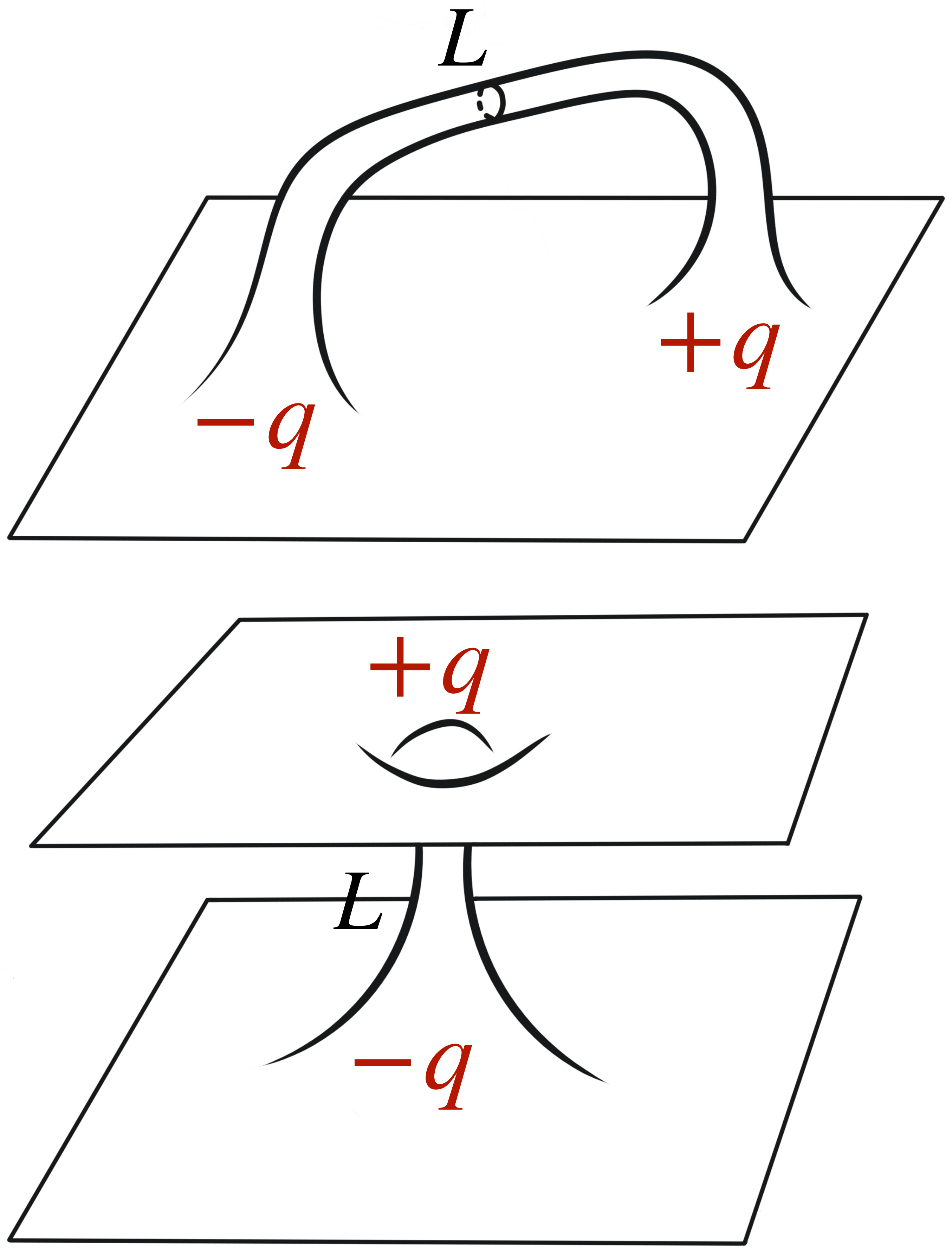
Euclidean wormholes

Non-perturbative axion+gravity solutions to Euclidean EoM



$$ds^2 = e^{2A(r)}dr^2 + r^2 d\Omega_3^2$$

$$e^{2A(r)} = \frac{1}{1 - \frac{L^4}{r^4}} \qquad \frac{M_P^2}{2\pi^2}\int_{S^3} \star\, d\, a(r) = q \in Z$$

Hawking (1987)
Giddings, Strominger (1988)
Coleman (1988)
Coleman, Lee (1989)
Banks, Klebanov, Susskind (1989)
Preskill (1989)
Kallosh, Linde, Linde, Susskind (1994)
Arkan-Hamed, Orgera, Polchinski (2007)

Hebecker, Mikhail, Soler (2018)
Maldacena et al (2019)
Marolf, Maxfiled (2020)
McNamara, Vafa (2020)
Loges, Shiu, Sudhir (2022)
Andriolo, Shiu, Soler, Van Riet (2022)
Jonas, Lavrelashvili, Lehners (2023)
Van Riet et al (2024)

Euclidean wormholes

$$O_I(x) \sim e^{-S_{\rm hw}+iqa(x)}$$

$$Z_E = \int D\phi \, e^{-S_E - C_{IJ}\int d^4x\sqrt{g}\, O_I(x)\int d^4y\sqrt{g}\,\bar{O}_J(y)}$$

Coleman "α-parameters"

$$= \int D\phi \prod_I d\alpha_I \, d\bar{\alpha}_I \, e^{-S_E - C^{-1}_{IJ}\bar{\alpha}_I\,\alpha_J + \boxed{\int d^4x\sqrt{g}\,\alpha_I\,O_I(x)+\text{h.c}}}$$

Shift symmetry breaking

How α_I vev arises?
Undetermined couplings vs string theory?
Cluster decomposition principle? Loss of locality?
Euclidean path integral and QG?

} Many open questions… not (all) for today

Axiverse wormholes: setup

4d $\mathcal{N}=1$ EFT $\qquad t^i = a^i + is^i \qquad N \gg 1$

Dual: $H_{3,i} = -M_P^2 \mathcal{G}_{ij} \star da^j \qquad 2\ell_i = -\partial K/\partial s^i$

$\mathcal{G}_{ij} = \frac{1}{2}\frac{\partial^2 K}{\partial s^i \partial s^j}$

$\mathcal{F}(\ell) = K + 2\ell_i s^i = \log P(\ell) \qquad P(\lambda\ell) = \lambda^n P(\ell)$

Homogeneous with n=1…7

Lanza, Marchesano, Martucci, Valenzuela (2020-2022)

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UV BPS instantons:

$$e^{2\pi i q_i t^i} = e^{2\pi i q_i a^i} e^{-2\pi q_i s^i} \ll 1 \longrightarrow s^i \gg (2\pi)^{-1}$$ **EFT validity regime**

(QFT instantons $\sim e^{-\frac{2\pi}{\alpha}} \rightarrow s \sim 1/\alpha$)

I) Extremal wormholes: $L = 0$

Flat space, not technically wormholes

BPS: $H_{3,i} = - M_P^2 \star d\ell_i$

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BPS: $H_{3,i} = -M_P^2 \star d\ell_i$

$$\ell_i(r) = \ell_{i,\infty} + \frac{q_i}{2\pi M_P^2 r^2}$$

$$dH_{3,i} = 2\pi\delta^{(4)}(0)$$

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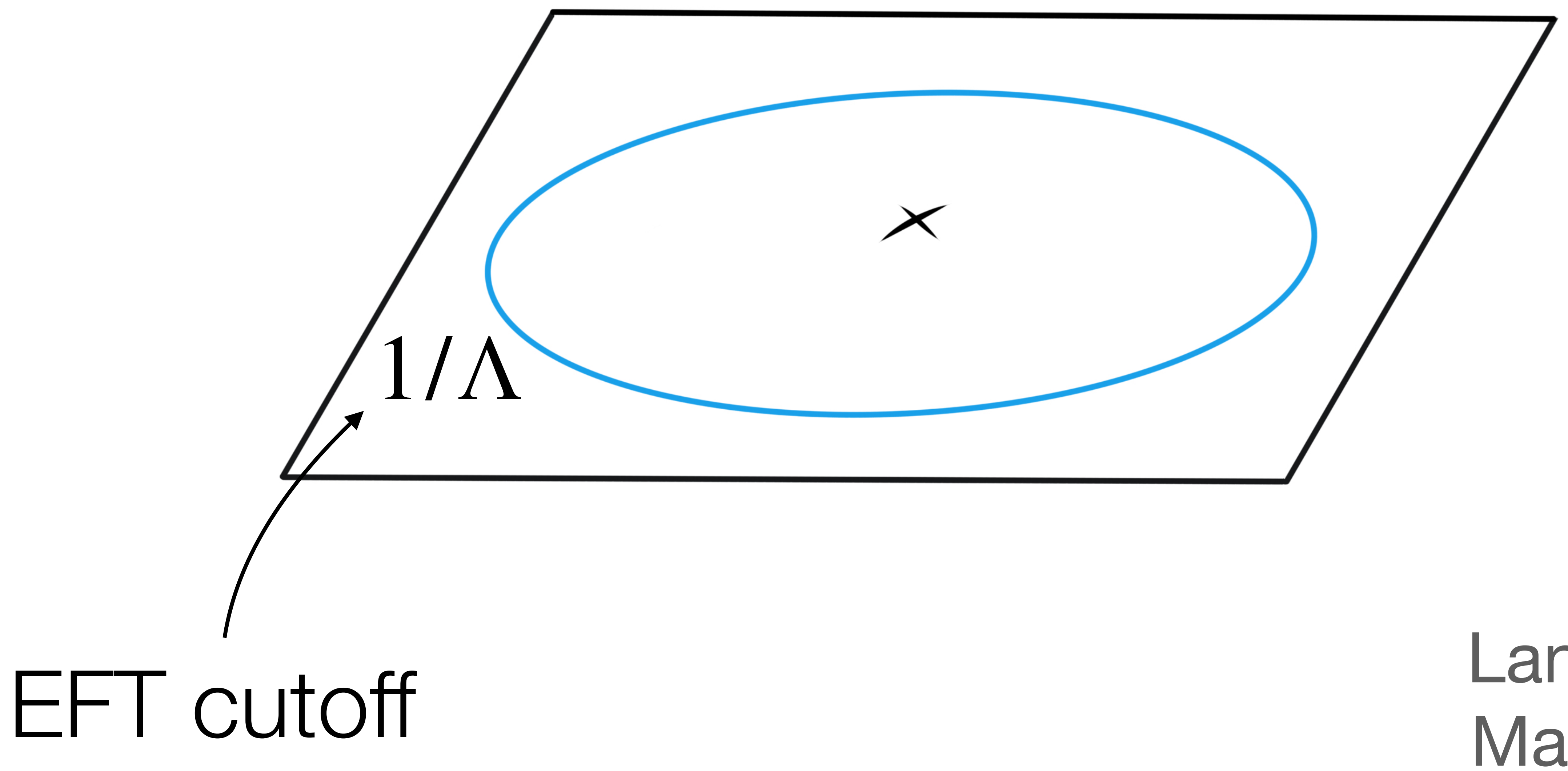

$$dH_{3,i} = 2\pi\delta^{(4)}(0)$$

Interpretation:

insertion of UV BPS instanton

Lanza, Marchesano, Martucci, Valenzuela (2021)

$$S_{\mathrm{tot}} = S_{\mathrm{hw,extr}} + S_{\mathrm{ct}} = 2\pi i q_i t^i_\infty$$

I) Extremal wormholes: $L = 0$

Physical implications

Wilsonian flow: EFT at $\Lambda' < \Lambda$ = integrate them out

Result: $W_{\mathrm{q}} = A_{\mathrm{q}} M_P^3 \, e^{2\pi i q_i t^i}$

Extremal wormholes can induce shift-symmetry breaking superpotential

II) Non-extremal wormholes: $L \neq 0$

Universal "Homogeneous" solution

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Universal "Homogeneous" solution

Regular for $n > 3$

$$\ell_i(r) = q_i \ell_0 \cos\left[\sqrt{\frac{3}{n}}\left(\frac{\pi}{2} - \arcsin\frac{L^2}{r^2}\right)\right]$$

$$S_{\mathrm{hw,non-extr}} = 3\pi^3 M_P^2 L^2 = 2\pi \sin\left(\frac{\pi}{2}\sqrt{\frac{3}{n}}\right) q_i s_\infty^i + \text{axions}$$

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Universal "Homogeneous" solution

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- $n = 3$ + IR regularization→ identical to extremal up to $O(\Lambda_{\text{IR}}^4 L^4)$ McNamara, Vafa (2020)

  $\Rightarrow$ **UV instanton in disguise? α-parameters solution within String Theory!**

- $|S_{\text{hw,non-extr}}| \leq |S_{\text{hw,extr}}|$: BPS bound violation → **bound state of UV instantons?**

II) Non-extremal wormholes: $L \neq 0$

Physical implications

EFT matching at $\Lambda' < \Lambda$

Result: $$K_{\rm q} \simeq A'_{\rm q} M_P^2 \left(e^{2\pi i q_i a^i} + \mathrm{h.c.} \right) e^{-S_{\rm hw}}$$

Non-extremal wormholes can induce shift-symmetry breaking Kähler potential

However…

II) Non-extremal wormholes: $L \neq 0$

Physical implications

EFT validity: $\begin{cases} s > 1/\alpha \\ L > 1/\Lambda_{\text{UV}} \end{cases} \Longrightarrow S_{\text{hw,non-extr}} \gtrsim \dfrac{2\pi}{\alpha} N$

$$\Lambda_{\text{UV}} \lesssim \frac{2\pi M_P}{\sqrt{N}}$$

"species scale"

Symmetry breaking by non-extremal wormholes very suppresed

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- String axiverse natural laboratory to study QG shift symmetry breaking
- Euclidean wormholes: EFT probes of breaking

Extremal

- Low-energy manifestation of UV BPS instantons
- Symmetry breaking superpotential $W_q \sim e^{2\pi i q_i t^i}$

Always relevant:

$$S_{\rm hw} \sim 2\pi i q_i t^i$$

Non-extremal

- New universal "homogeneous" solutions
- Symmetry breaking Kähler potential $K \sim e^{-S_{\rm hw}}$

Suppressed in EFT regime:

$$S_{\rm hw} \sim 2\pi N/\alpha$$

- Details and much more in 2404.14489
  (numerical explorations, connection with species scale…)

Thank you for your attention!