Spotting (String) Axions in the Cosmos

OR

Seeing the Forest for the Axions

Jacob M. Leedom

COSMIC WISPers 2nd General Meeting

based on: 2312.13431

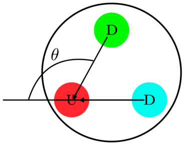
E.Dimastrogiovanni, M.Fasiello,
M.Putti, A.Westphal

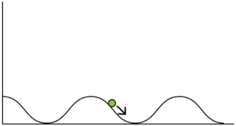
Overview

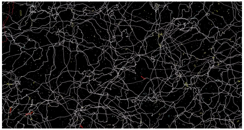
- Mechanism to look for string axions that do not couple directly to the Standard Model
- Illustrate the limitations of this mechanism in theories of quantum gravity
- How signals will tell us about the underlying structure of our universe

Axions

- Well-motivated from particle physics & cosmology:







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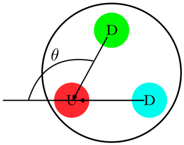
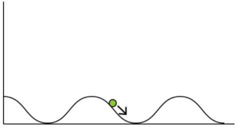
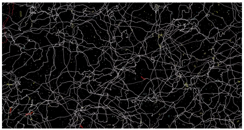




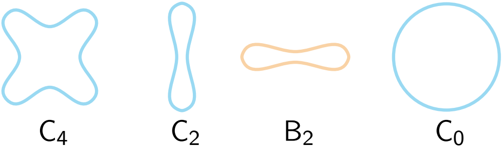


- From the stringy perspective:

Why should we care about these states?

- Unified quantum gravity theories have *p*-form gauge potentials:

Type IIB:



The String Axiverse

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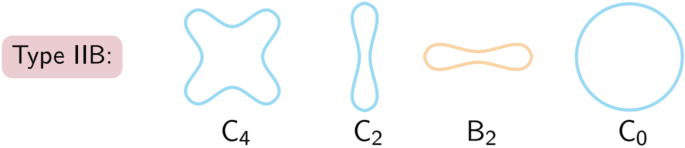

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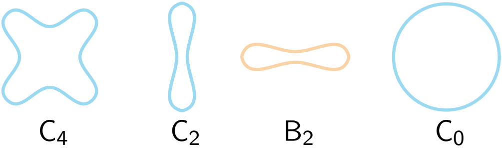

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$$C_4 = \rho_\alpha \tilde{\omega}^\alpha + \cdots$$

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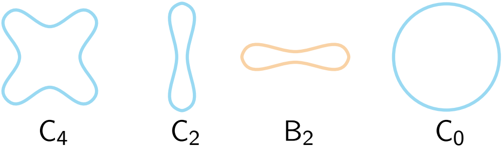

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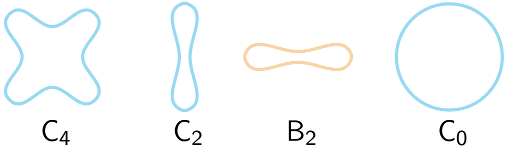

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[Arvanitaki,Dimopolous, Dubovsky,Kaloper,March-Russell]
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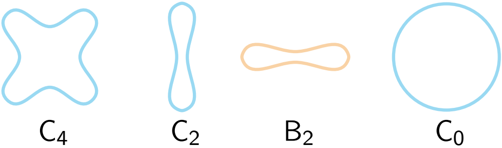

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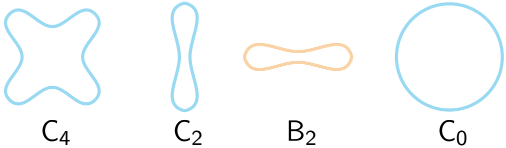

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Axions are one of the best prospects to tie string theory to experiment

Detecting the Axiverse

- If axions couple to Standard Model:

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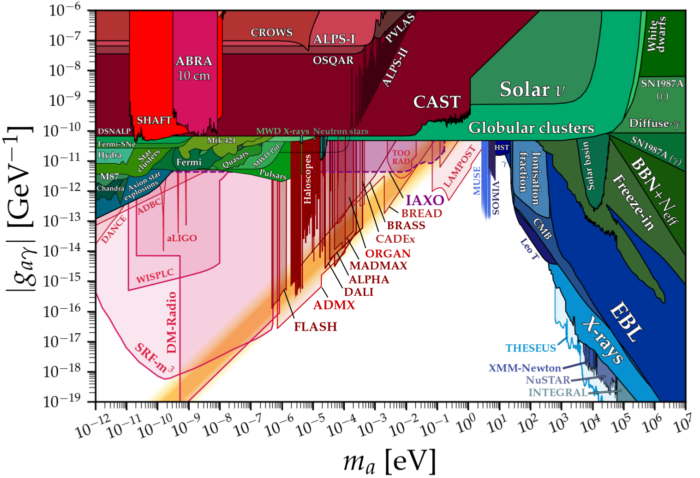

[O'hare's GitHub]

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What about the rest of the Axiverse?

The Spectator Mechanism

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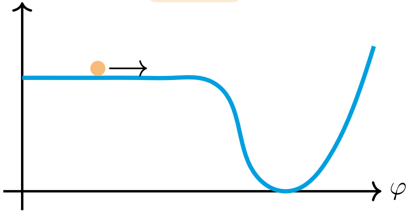

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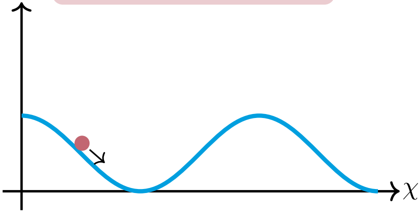

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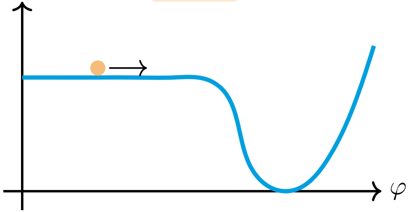

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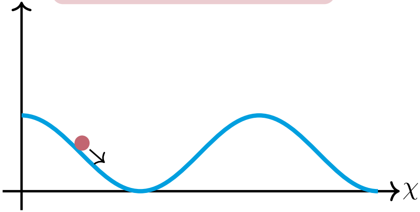

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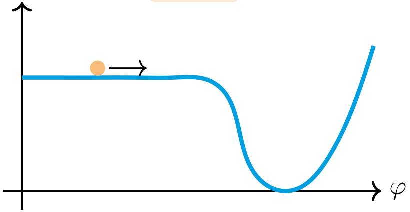

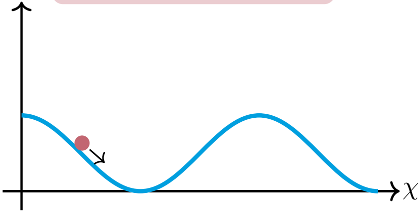

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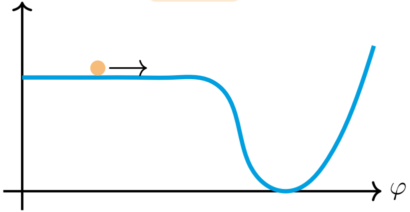

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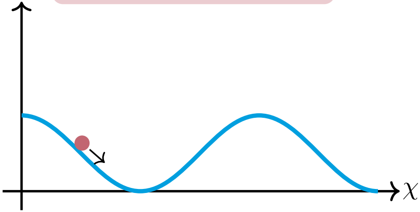

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For non-Abelian spectators, GW spectrum is flat. For Abelian spectators....

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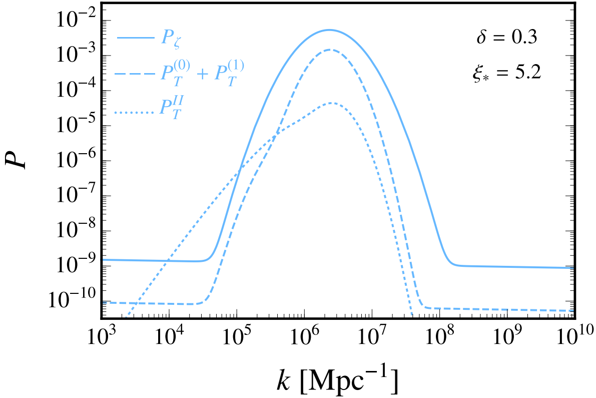

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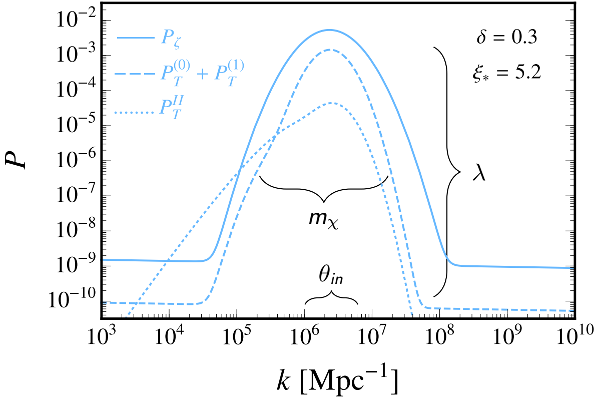

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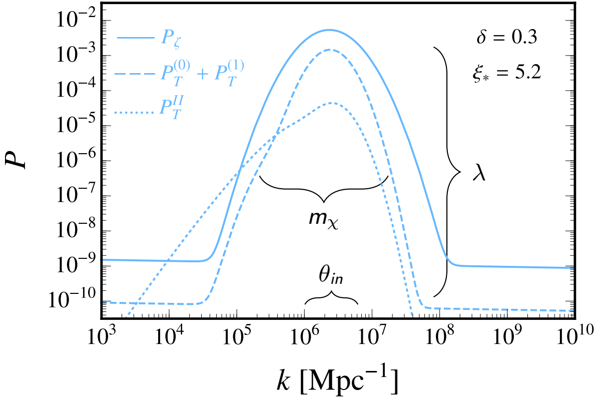

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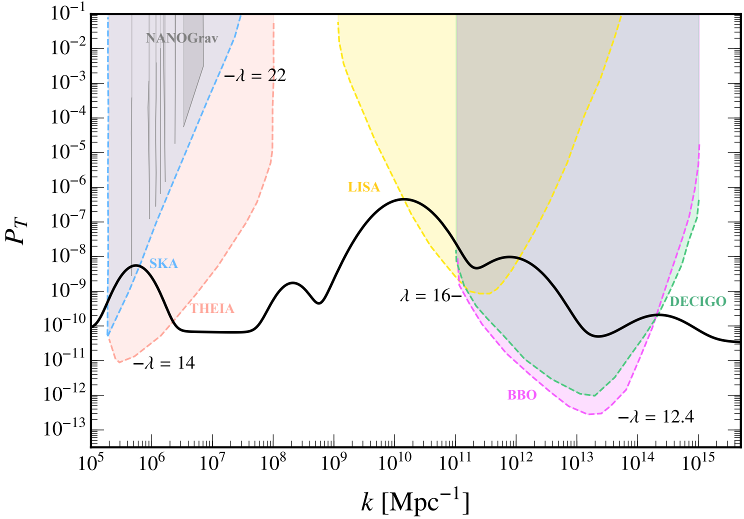
Axion properties determine signal features: "Gravitational Spectroscopy"



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For fixed mass, signal is independent of f_χ

Strength is determined by λ - what can we expect?

Chern-Simons Coupling in QFT

- Chern-Simons coupling:

$$\frac{\mathcal{L}_{\mathsf{EFT}}}{\sqrt{-g}} \supset \frac{\lambda}{4f_\chi}\chi F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

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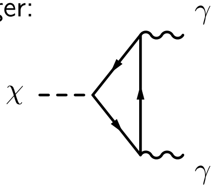

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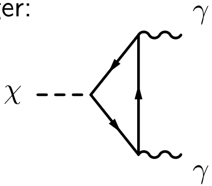

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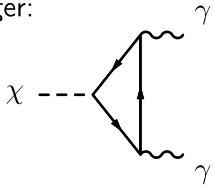

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- But these are usually restricted: [Agrawal,Fan,Reece] [Bagherian,Reece,Xu] [Ibanez,Montero] [Dror,JML]

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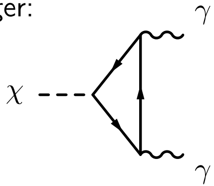

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- But these are usually restricted: [Agrawal,Fan,Reece] [Bagherian,Reece,Xu] [Ibanez,Montero] [Dror,JML]

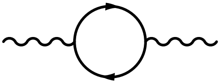
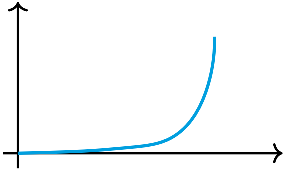
Chern-Simons Coupling in QFT

- Chern-Simons coupling:

$$\frac{\mathcal{L}_{\mathsf{EFT}}}{\sqrt{-g}} \supset \frac{\lambda}{4 f_\chi} \chi F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

$$\lambda \simeq \mathfrak{q} \frac{\alpha}{2\pi}$$

• $\alpha = \frac{g^2}{4\pi}$

γ  $\gamma \propto \frac{N_f Q_f^2 \alpha_{EM}}{4\pi} \Rightarrow$ 

Large charges/number of fermions brings down Landau pole

- ... and typically $\mathcal{O}(1)$. Many strategies exist to (try to) evade this:
  - Large Charges
  - Clockworking
  - Discrete Symmetry
  - Kinetic Mixing
  - . . .
- But these are usually restricted: [Agrawal,Fan,Reece] [Bagherian,Reece,Xu] [Ibanez,Montero] [Dror,JML]

Spectator Summary

- Axions coupled to hidden gauge sectors produce GWs during inflation
- Non-Abelian spectators produce a flat spectrum
- Abelian spectators produce peaked spectrum
  - Signal strength depends on **Chern-Simons Coupling**
  - Peak frequency depends on **axion initial displacement**
  - Peak width depends on **axion mass**
- Multiple Abelian Spectator Axions (**MASA**) $\rightarrow$ **GW Forest**

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- **To relate this to the String Axiverse**:
  - What viable spectator candidates exist in string theory?
  - Can the Chern-Simons coupling be made large enough?

Spectators in String Theory: Axionic States

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p-form axions

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$$M_{10} \to M_4 \times \tilde{X}_3$$

- $\tilde{X}_3 = X_3/\Omega$
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- p-form Decomposition

$$C_4 = \rho_\alpha \tilde{\omega}^\alpha + \cdots \qquad C_2 = c^a \omega_a \qquad B_2 = b^a \omega_a$$

- $a \in \{1, 2, ..., h^-_{1,1}\}$
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- Result is a 4d theory with $\mathcal{N} = 1$ supersymmetry

- $a \in \{1, 2, ..., h^-_{1,1}\}$
- $\alpha \in \{1, 2, ..., h^+_{1,1}\}$

$$S = C_0 + ie^{-\phi}$$

$$G^a = c^a - Sb^a$$

$$T_\alpha = \tau_\alpha + i\rho_\alpha + \cdots$$

These are candidate spectator axions - need gauge fields

Spectators in String Theory: Gauge States

- D7-branes wrapping submanifold (divisor) $\widetilde{\mathcal{D}}$ of $\widetilde{X}_3$
- Gives $\mathcal{N} = 1$ SUSY gauge theory sector to the 4d EFT
- Gauge kinetic function determines coupling:

$$\mathcal{L}_{\mathsf{EFT}} \supset -\frac{1}{4}\mathrm{Re}\,[f_{\widetilde{\mathcal{D}}}]F^{A}_{\mu\nu}F^{A\mu\nu} - \frac{1}{4}\mathrm{Im}\,[f_{\widetilde{\mathcal{D}}}]F^{A}_{\mu\nu}\widetilde{F}^{A\mu\nu}$$

$$g_{\widetilde{\mathcal{D}}}^{-2} = \langle \mathrm{Re}\,[f_{\widetilde{\mathcal{D}}}] \rangle \quad \Longrightarrow \quad \alpha_{\widetilde{\mathcal{D}}} = \frac{g^2_{\widetilde{\mathcal{D}}}}{4\pi}$$

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- Without worldvolume flux:

$$\begin{aligned} f_{\widetilde{\mathcal{D}}} &= \frac{w^\alpha}{2\pi}T_\alpha \\ &= \frac{w^\alpha}{2\pi}\left(\tau_\alpha + i\rho_\alpha + \cdots\right) \end{aligned}$$

- w^α = wrapping number

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- With (odd) worldvolume flux: $\frac{1}{2\pi} F_2 = m^{\alpha}\omega_{\alpha} + m^{a}\omega_{a} + m^{r_\vee}\omega_{r_\vee}$

$$f_{\widetilde{\mathcal{D}}} = \frac{w^{\alpha}}{2\pi}\left\{ T_{\alpha} + i\kappa_{\alpha bc} G^{b} m^{c} + \cdots \right\}$$

$$= \frac{w^{\alpha}}{2\pi}\left\{ \tau_{\alpha} + \cdots \right\} + i\frac{w^{\alpha}}{2\pi}\left(\rho_{\alpha} + \kappa_{\alpha bc} c^{b}(m^{c} - b^{c}) + \cdots \right)$$

- $w^{\alpha} = \int_{\mathcal{D}^+} \widetilde{\omega}^{\alpha}$

Spectators in String Theory: Stückelberg Mechanism

- Above provides spectator axions & gauge fields
- This is not sufficient: must avoid the Stückelberg Mechanism

$$\mathcal{L}_{MP} = \frac{1}{2}(\partial_\mu \chi - qA_\mu)^2 - \frac{1}{4g^2}F_{\mu\nu}F^{\mu\nu} \quad \Longrightarrow \quad \text{Massive U(1)}$$

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- C_4 and C_2 axion shift symmetries can be gauged
  - Geometric Stückelberg

$$\nabla_\mu c^a = \partial_\mu c^a - q^a A_\mu \qquad \bullet\ q^a = \frac{N_{D7}}{2\pi} w^a$$

  - Flux Stückelberg

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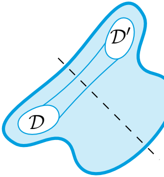
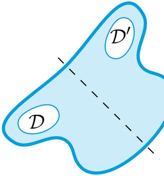
If geometric/flux Stückelberg mechanisms are active,
then U(1) gauge boson removed from massless spectrum

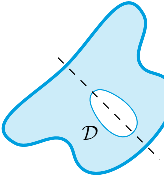
- Class I: $[\mathcal{D}] = [\mathcal{D}']$
  - Divisors in X_3 are homologous
  - Odd wrapping numbers vanish
  - Both Stückelbergs inactive
  - Massless U(1) & axions present in EFT



- Class II: $[\mathcal{D}] \neq [\mathcal{D}']$
  - U(N) = SU(N) $\times$ U(1) gauge theory
  - Geometric Stückelberg active
  - Must break gauge group to obtain U(1)



- Class III: $\mathcal{D} = \mathcal{D}'$ pointwise
  - Sp(N) or SO(N) gauge theory
  - Odd wrapping numbers vanish
  - Must break gauge group to obtain U(1)



Spectators in String Theory: Model Parameters

- Now that we have spectator states, need model parameters
- Axion Decay Constants: Kinetic Terms

$$\mathcal{S}_{\text{EFT}} \supset M_p^2 \int \left(K^{\alpha\beta}\, \partial_\mu \rho_\alpha \partial^\mu \rho_\beta + K_{ab}\, \partial_\mu c^a \partial^\mu c^b \right) \sqrt{-g}\, d^4x$$

$$f_\alpha = M_p \sqrt{2\lambda_\alpha} \qquad a_\alpha = f_\alpha \rho_\alpha$$

- Axion Masses
  - Euclidean D3-branes
  - Euclidean D1-branes
  - ED1s dissolved in an ED3
  - Gaugino Condensation

$$\Longrightarrow \quad V(a) = \Lambda^4 \cos(a/f_a)$$

- Gauge theory coupling: $g^{-2} = \frac{1}{2\pi} \langle w^\alpha \tau_\alpha \rangle$

Also need CS coupling - how large can we make it?

- How far can we push the CS Coupling in string theory?
- C_4**-axion spectators: difficult in controlled theories**

$$f_{\tilde{\mathcal{D}}} = \frac{w}{2\pi} T = \frac{w}{2\pi}(\tau + i\rho + \cdots)$$

Naively: increasing wrapping number boosts coupling of ρ to gauge sector

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However

$$\lambda_{C_4} \sim w\, g^2_{\tilde{\mathcal{D}}} \sim w \frac{1}{w\,\langle\tau\rangle} = \frac{1}{\langle\tau\rangle}$$

- Independent of w
- large CS possible only with large worldvolume gauge coupling
- May run into trouble with Distance/Emergent String Conjecture

Spectators in String Theory: C_2 CS Coupling

- How far can we push the CS Coupling in string theory?
- C_2**-axion spectators: better prospects**

$$\mathcal{L}_{\mathrm{EFT}} \supset \frac{\alpha_{\tilde{\mathcal{D}}}}{\pi} w^{\alpha} \kappa_{\alpha c d} m^{c} c^{d} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$\lambda_{C_2} \propto w^{\alpha} \kappa_{\alpha c d} m^{c}$$

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$$\lambda_{C_2} \propto w^{\alpha} \kappa_{\alpha cd} m^c$$

- Combined Boosting: $\begin{cases} \text{Wrapping} \quad w^{\alpha} \\ \text{Intersection Numbers} \quad \kappa_{\alpha cd} \\ \text{Magnetization} \quad m^c \end{cases}$
- This strategy was used for **non-Abelian** spectators [McDonough, Alexander] [Holland,Zavala,Tasinato]
- comes at a cost: **Induced D3-tadpole**

- Tadpole $\leftrightarrow$ total charge must vanish on a compact manifold

$$d \star F_2 \;=\; \star(Q\, j)$$

Spectators in String Theory: Tadpole Constraints

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- There must be positive and negative charges present for consistency
- Applies also to the extended Dp-branes of string theory
- D7-branes with flux contribute "effective" D3-brane charge

$$Q_{D3} \simeq w\kappa_{+--} m^2 N_{D7}$$

- This must be canceled by other charges, e.g. orientifold planes

Size of C_2 CS Coupling limited by tadpole

Spectators in String Theory: Tadpole Constraints

- If we consider lifting Type IIB to F-theory, the tadpole constraint is related to the topology of a CY 4-fold:

$$N_{D3} + \int_{Y_4} G_4 \wedge G_4 = \frac{\chi(Y_4)}{24}$$

- If there was a bound on the Euler characteristic χ, we could bound the allowed C_2 CS coupling.

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Non-Abelian spectators are borderline

Spectators in String Theory: General Constraints

- Problem with Non-Abelian Spectators: need small gauge coupling and $\lambda \simeq \mathcal{O}(10^2)$
- **Not** the case for Abelian models: only need $\lambda \simeq \mathcal{O}(10)$

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Constraints on Stringy Abelian Spectators

- Rough Tadpole Bound

$$w(\kappa_{+--})m^2 N_{D7} \lesssim (0.1) \times 10^5$$

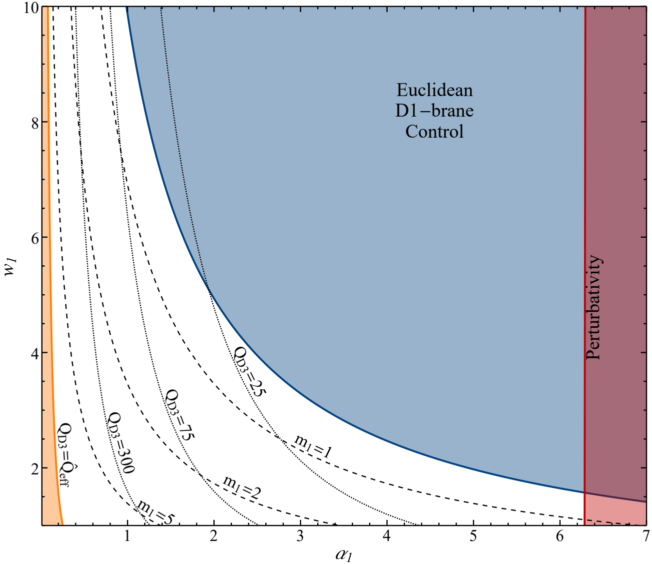
- Gauge Theory Perturbativity

$$\frac{\alpha}{2\pi} \lesssim 1 \qquad \bullet \alpha = \frac{1}{2w\langle\tau\rangle}$$

- Control of Non-Perturbative Corrections (ED1s)

$$2\pi v \gtrsim \mathcal{O}(1) \Rightarrow \frac{\pi^2}{\kappa_{+++} w \alpha} \gtrsim 1 \qquad \bullet \tau = \frac{1}{2}\kappa_{+++} v^2$$

Spectators in String Theory: Example Parameter Space



Conclusions

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- Spectator mechanism is an excellent complement to other searches
  - Observation of Abelian spectator peaks → gravitational spectroscopy
- Such models come with a cost - CS coupling constrained
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  - Multiple signals → topologically non-trivial corner of the landscape

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- Towards the future:
  - Heterotic Axiverse & Spectators

Acknowledgements

- Midjourney ai for introductory slide picture
- A. Hook for proton diagram
- Google images for cosmic string diagrams