Kinetic mixing between visible & hidden $U(1)$'s from String Theory

Arthur Hebecker (Heidelberg)

[Based on work with Jörg Jäckel & Ruben Küspert]

Outline

- KM : Introduction ; small kinetic mixing
- KM : Swampland constraints ; stringy origin
- KM between sequestered sectors (D3 , localized D7)
- Small, calculable KM from sequestering and (broken) $SL(2,\mathbb{Z})$ invariance

Introduction

$$\mathcal{L}_{SM} \sim \sum_i \mathrm{tr}\, F_i^2 + \bar{\psi} \not{D} \psi + |\partial\phi|^2 + V(\phi) + y\bar{\psi}\phi\psi$$

- With this field content, no further dim-4 operators can be added

  $\Rightarrow$ The SM is surprisingly "complete", "self-contained".

- Even extending the field content (≡ hidden sectors), the options for coupling them to $\mathcal{L}_{SM}$ are very limited

- Technical term for this: Portals

Portals

- Higgs: $|\phi|^2 \varphi^2$; $\varphi \equiv$ extra scalar
- Neutrino: $\bar{\Psi} \phi \Psi_n$; $\Psi_n \equiv$ extra fermion
- Gauge: $\underbrace{F_A^{\mu\nu}}_{U(1)_Y \,\equiv\, U(1)_A} F_{B\,\mu\nu}$; $F_{B\,\mu\nu} \equiv$ hidden $U(1)$

$\Rightarrow$ When studying "KM", we are not doing something exotic – we are studying "1/3" of the options for low-energy discovery of new physics.

Observability of KM

[Okun '82, Holdom '86, ...

... Abel/Goodsell/Jäckel/Khoze/Redondo/Ringwald '08/'09]

- Think of $F_A^{\mu\nu}$, $F_B^{\mu\nu}$ as vectors in 2d vector space V:

$$\mathcal{L} \supset F^i_{\mu\nu}\, g_{ij}\, F^{j\mu\nu} \quad ; \quad i,j \in \{1,2\}$$

metric on space V

- SM matter $\Rightarrow j_{SM} \Rightarrow$ distinguished $\bar{v}_{SM} \in V$
- Choose $U(1)_A \parallel \bar{v}_{SM}$ & $U(1)_B \perp \bar{v}_{SM}$

$\Rightarrow$ $U(1)_B$ decouples perfectly, no effect!

Observability – option (1)

There exist hidden-sector particles charged under "the other" U(1)

$$\Rightarrow \quad j_{SM} \Rightarrow \bar{v}_{SM} \in V$$

$$j_h \Rightarrow \bar{v}_h \in V$$

If $\bar{v}_{SM} \not\parallel \bar{v}_h$, then observability through "millicharged particles" arises.

Observability – option (2)

The other $U(1)$ is massive (by Higgsing or Stückelberg)

$\Rightarrow$ Call the massive propagating field $U(1)_B$ and the corresponding direction $\bar{v}_m \in V$

If $\bar{v}_m \not\perp \bar{v}_{SM}$, then observability arises since since massive $U(1)_B$ mediates interactions between j_{SM} & j_{SM}.

Parameterization: $-\frac{1}{4}F_A^2 - \frac{1}{4}F_B^2 - \chi F_A F_B \left(-\tilde{\chi} F_A \tilde{F}_B\right)$

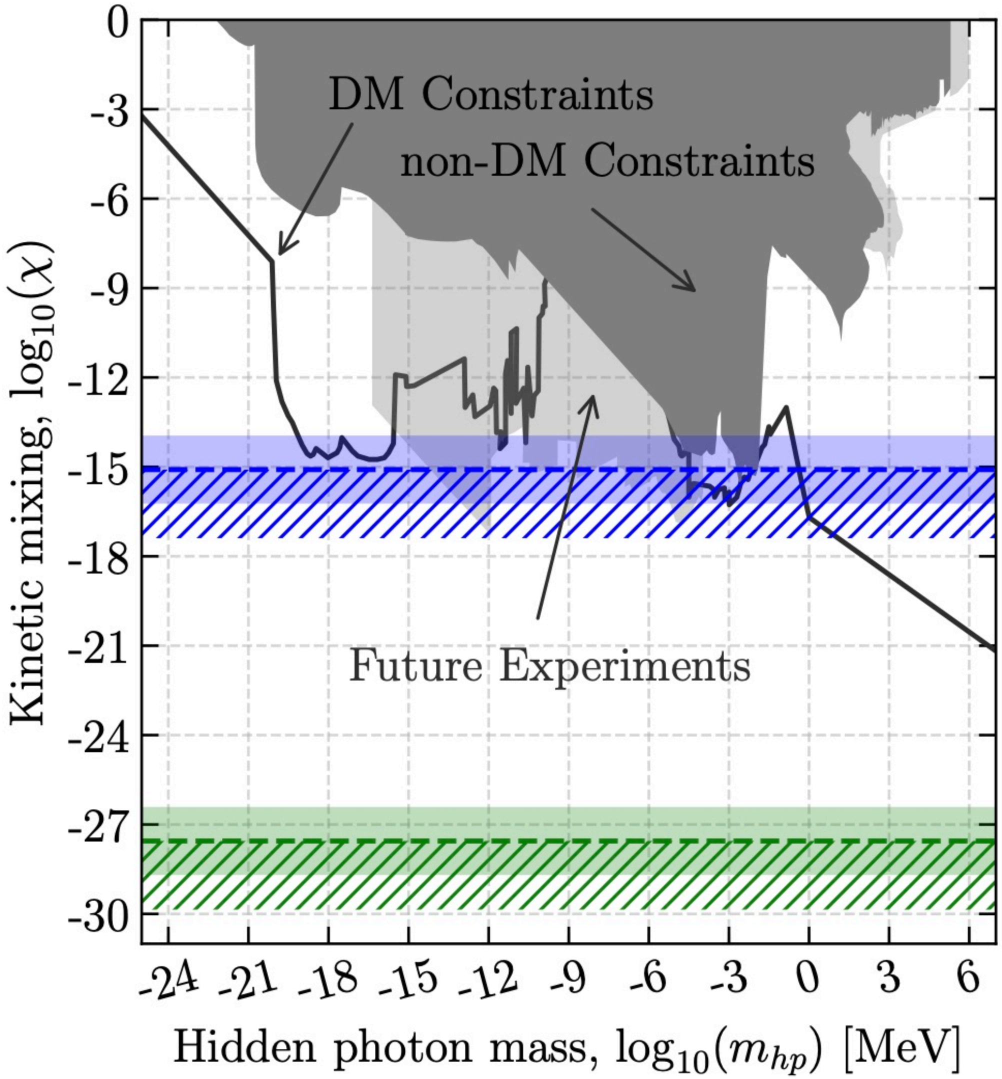
magnetic *

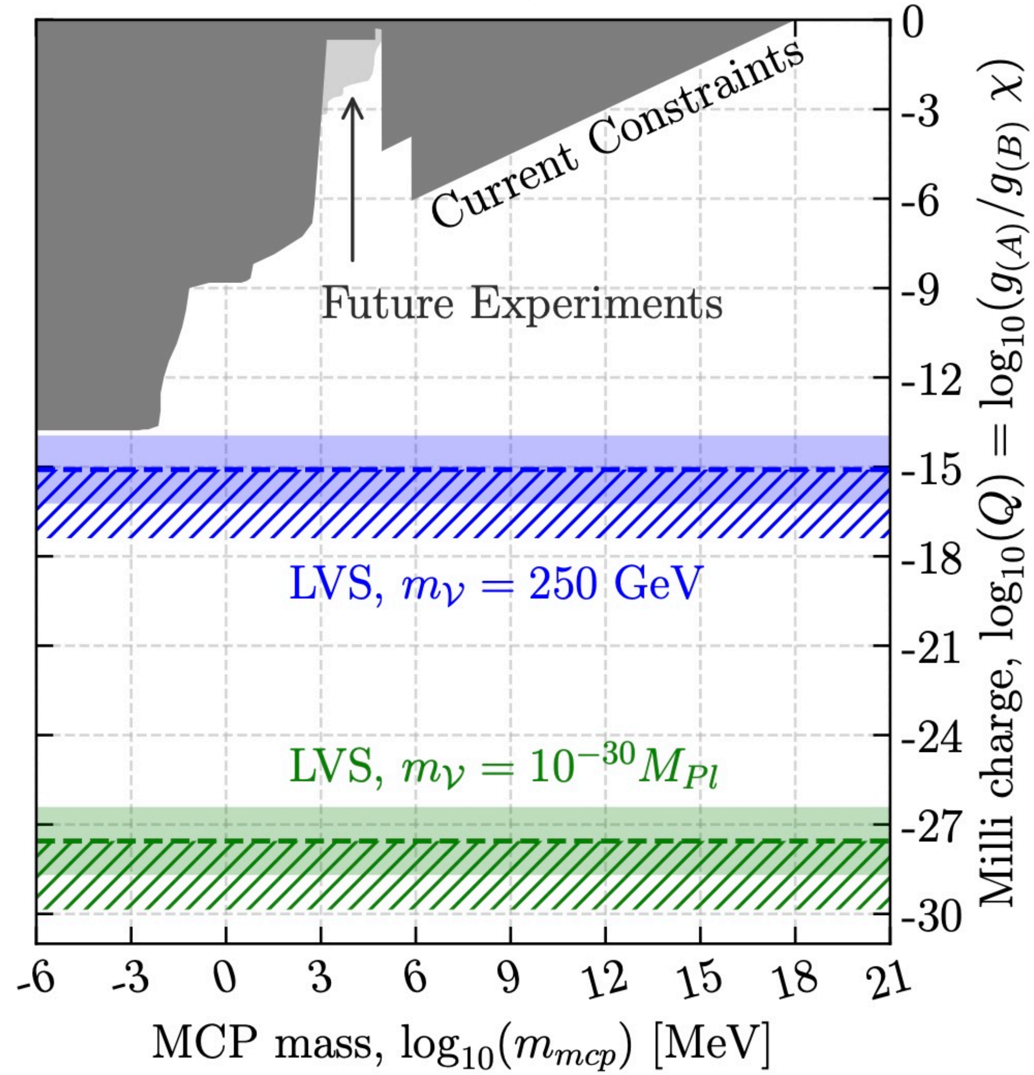
* [Brümmer / Jäckel / Khoze]

... most interesting is the regime of small kinetic mixing

massive photon

millicharged (MCP)



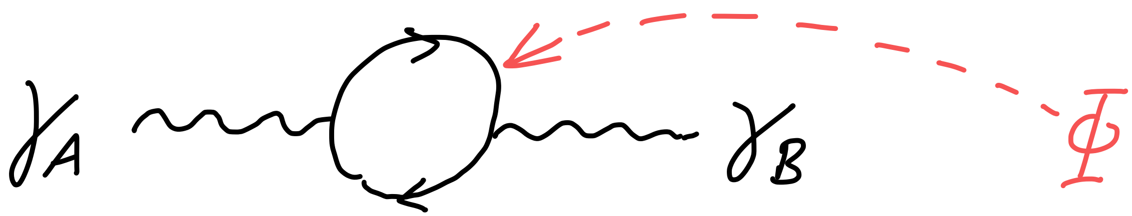


Field Theoretic Expectations

- As we have seen, experimental bounds are severe (especially in the small-mass domain)

$\Rightarrow$ Models with very small χ are most interesting

- However, KM is generated at the 1-loop level:



$$\Rightarrow \quad \chi \sim c_{loop}\, g_A\, g_B \ln\left(\Lambda / m_\phi\right)$$

$\Rightarrow$ Unless gauge couplings tiny, expect $\chi \sim O(1)$!

Swampland Constraints

[Benakli/Branchina/Lafforgue-Marmet '20 ; Obied/Parikh '21]

- The above problem/tension can be made sharper using Swampland logic:

(1) Completeness: doubly-charged Φ-particles must exist

(2) Weak Gravity Conjecture:

- These Φ particles can not be too heavy

$$(m \leq g M_p)$$

- Even worse: If $g \to 0$, then $\Lambda \to 0$

$$(\Lambda \sim g M_p)$$

Ways out do certainly exist:

[Goldberg/Hall '86 ; Dienes/Kolda/March-Russell '96 ;
Arkani-Hamed/Weiner '08 ; Brümmer/Jäckel/Khoze '09 ;
Garny/Palessandro/Sandora/Sloth '18 ;
Gherghetta/Kersten/Olive/Pospelov '19 ; ....]

(1) A special charge conjugation: $(A_A^\mu, A_B^\mu) \to (A_A^\mu, -A_B^\mu)$

(2) Non-abelian embedding: $\mathcal{L} \supset \frac{1}{\Lambda} F_A^{\mu\nu}\, \mathrm{tr}(\langle\phi\rangle F_B^{\mu\nu})$

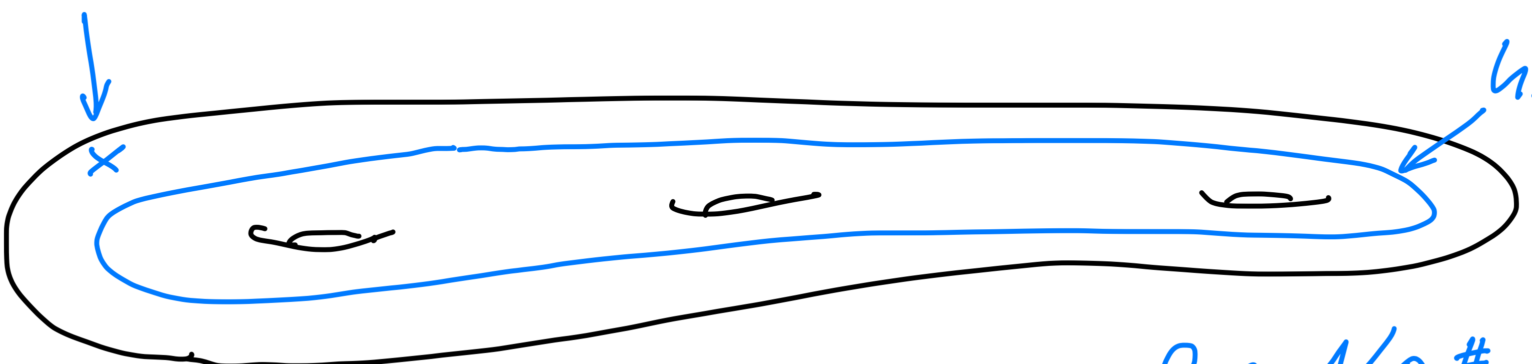
needed for non-zero result

$$\boxed{\chi \sim \frac{\langle\phi\rangle}{\Lambda}} \Leftarrow$$

While $\chi \ll 1$ can be achieved in this way, it's not satisfactory.

Explicitly stringy expectations

- "Special" C-symmetry — unknown
- non-abelian embedding — certainly possible, but not better than in field theory
- tiny gauge coupling ($\chi \sim g_A g_B$) — constraints even worse than expected by swampland arguments:



$\Rightarrow$ Key difficulty:

- In the (most promising) landscape-setting of type IIB string theory, gauge theories live on D-branes
- The gauge coupling is set by $\frac{1}{g^2} \sim \mathrm{Vol}(D\text{-brane})$
- Hence, $g \sim \frac{1}{R^{\#}} \longrightarrow 0$ with $R \to \infty$.
- But at $R \to \infty$ the "volume modulus" usually becomes very light $\Rightarrow$ severe cosmological constraints

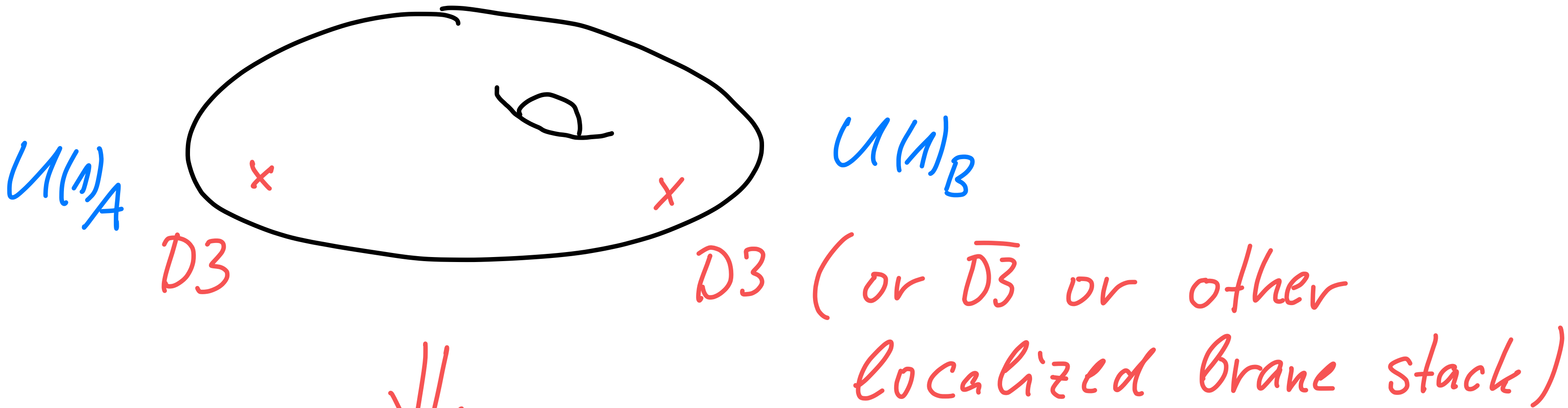
Small KM from Sequestering

- Our claim: Sequestering within compact Calabi-Yau provides a more general & natural reason for small KM than tiny gauge couplings

- Simplest setting: Type IIB with gauge theories on D3 or $\overline{\text{D3}}$ branes

points in CY, each with $U(1)$

Type IIB Calabi-Yau orientifold:



$\Downarrow$

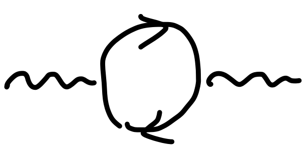
$\chi \ll 1$ with $g_{(A)}$ & $g_{(B)} \sim O(1)$ is possible due to sequestering

Our goal: Understand such "stringy small χ" at a quantitative level

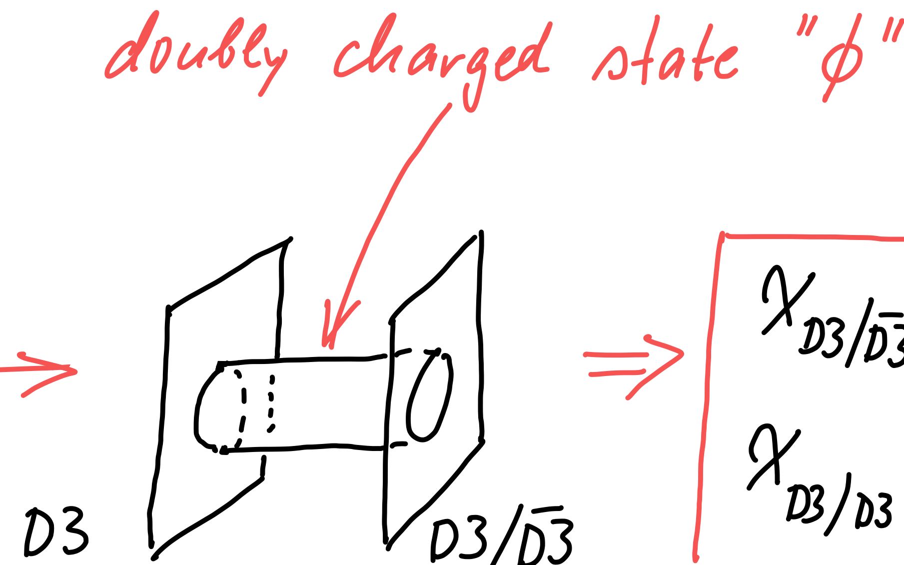
Old and new work on the subject include:

[Abel/Schofield '03 ; Goodsell/Jaeckel/Khoze/... Ringwald/Cicoli/Redondo '08 -- '11 ; Bullimore/Conlon/Witkowski '10 ; Heckman/Rey '11 ...]

Known fact:



$\xrightarrow{\text{string theory}}$

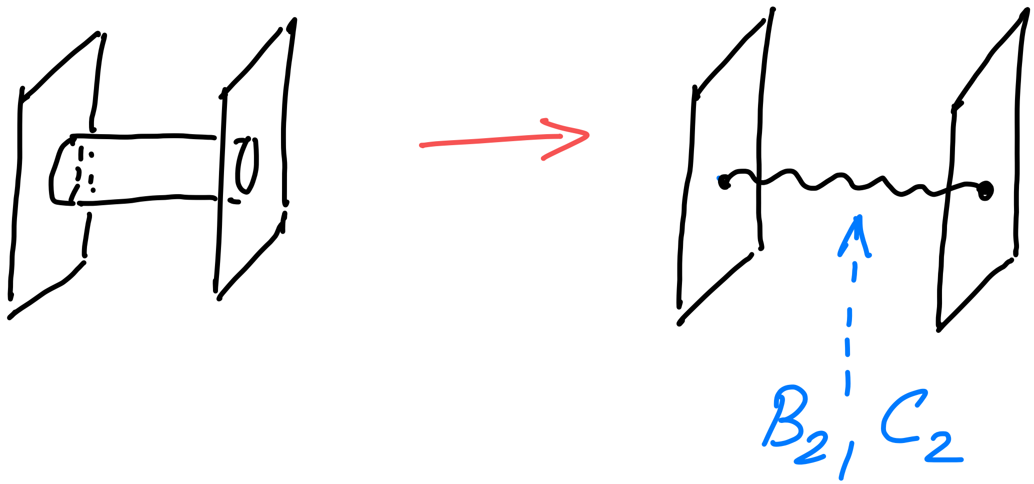


$\Longrightarrow$

$$\boxed{\begin{array}{l} \chi_{D3/\overline{D3}} \neq 0 \\ \chi_{D3/D3} = 0 \end{array}}$$

Underlying reason: SUSY (?)

SUGRA view:



$$\mathcal{L}_{D3} \supset F_2 \wedge {*B_2} + F_2 \wedge C_2$$

(with essentially same coefficients!)

$\Rightarrow$ Cancellation between B_2 & C_2 exchange (independently of ~~SUSY~~ in bulk)

More specific questions:

- Does the D3-D3 null result persist beyond LO?
- What is the reason for the cancellation?

Idea:

Maybe the famous $SL(2,\mathbb{R})$ symmetry of type-IIB string theory plays a role?

Facts:

- B_2/C_2 form an $SL(2,\mathbb{R})$ doublet
- $SL(2,\mathbb{Z})$ acts on the "axio-dilaton" $\tau = \frac{i}{g_s} + C_0$ by $g_s \to 1/g_s$ & $C_0 \to C_0 + 1$
- D-branes transform but $\boxed{\text{D3 is mapped to itself!}}$

Technical analysis (quadratic order)

$$S_{DBI} \sim \int (F_2 - B_2) \wedge * (F_2 - B_2)$$

$$S_{CS} \sim \int \Big(C_4 + \underbrace{\tfrac{1}{2} B_2 \wedge C_2}_{} + C_2 \wedge (F_2 - B_2) + \frac{C_0}{2} (B_2 - F_2)^2 \Big)$$

[e.g. Ortin's book]

$SL(2,\mathbb{Z})$
-invariant

often missing!
(but of key importance for us)

- At SUGRA level symm. enhanced to $SL(2,\mathbb{R})$
- Our strategy: Make $SL(2,\mathbb{R})$ as explicit as possible

Building on: [Bergshoeff, Ortin et al. '95 ; Morrison ; Tseytlin ; Gaillard/Zumino '81 ....]

SL(2,ℝ)-covariant objects:

$$F_3^{\,i} = dC_2^{\,i} = \begin{pmatrix} dC_2 \\ dB_2 \end{pmatrix} \quad ; \quad \hat{M}_{ij} = \frac{1}{\mathrm{Im}\,\tau} \begin{pmatrix} 1 & -\mathrm{Re}\,\tau \\ -\mathrm{Re}\,\tau & |\tau|^2 \end{pmatrix}$$

$$(\& \; \varepsilon_{ij} \, , \, \varepsilon^{ij} \;) \qquad \text{with } \tau = \frac{i}{g_s} + C_0$$

Only covariant w.r.t. Borel subgroup $\mathcal{B} \subset SL(2,\mathbb{R})$:

$$J_i = \begin{pmatrix} - * F_2 \\ g_s^{-1} F_2 + C_0 * F_2 \end{pmatrix} \quad ; \quad \hat{m}_{ij} = \begin{pmatrix} 0 & -\frac{1}{2} * \\ -\frac{1}{2} * & g^{-1} + C_0 * \end{pmatrix}$$

Note:

The Borel subgroup $\mathcal{B}$ of $SL(2,\mathbb{R})$ may be defined as the group being generated by

$$\delta\Lambda^{i}{}_{j} = \begin{pmatrix} \alpha & \beta \\ 0 & -\alpha \end{pmatrix}^{i}{}_{j}$$

not zero in $SL(2,\mathbb{R})$

Bulk action (SL(2,ℝ)-invariant)

$$S \supset \int_{10} \hat{M}_{ij}\, F_3^i \wedge * F_3^j$$

D3 action (not SL(2,ℝ)-inv. ; but EOMs are invariant)

$$S \supset \int_{D3,A} C_2^i \wedge * J_i^A + \int_{D3,B} C_2^i \wedge * J_i^B + \int_{\substack{\text{both}\\ D3}} -\frac{1}{2} C_2^i \wedge * m_{ij} C_2^j$$

(at this level the analysis was never done

— previous results had $C_0 = 0$ and ignored

$(C_2^i)^2$-term on D3.

$$\boxed{\text{Plan: Integrate out } C_2^i \text{ to get term } \sim J_A \cdot J_B}$$

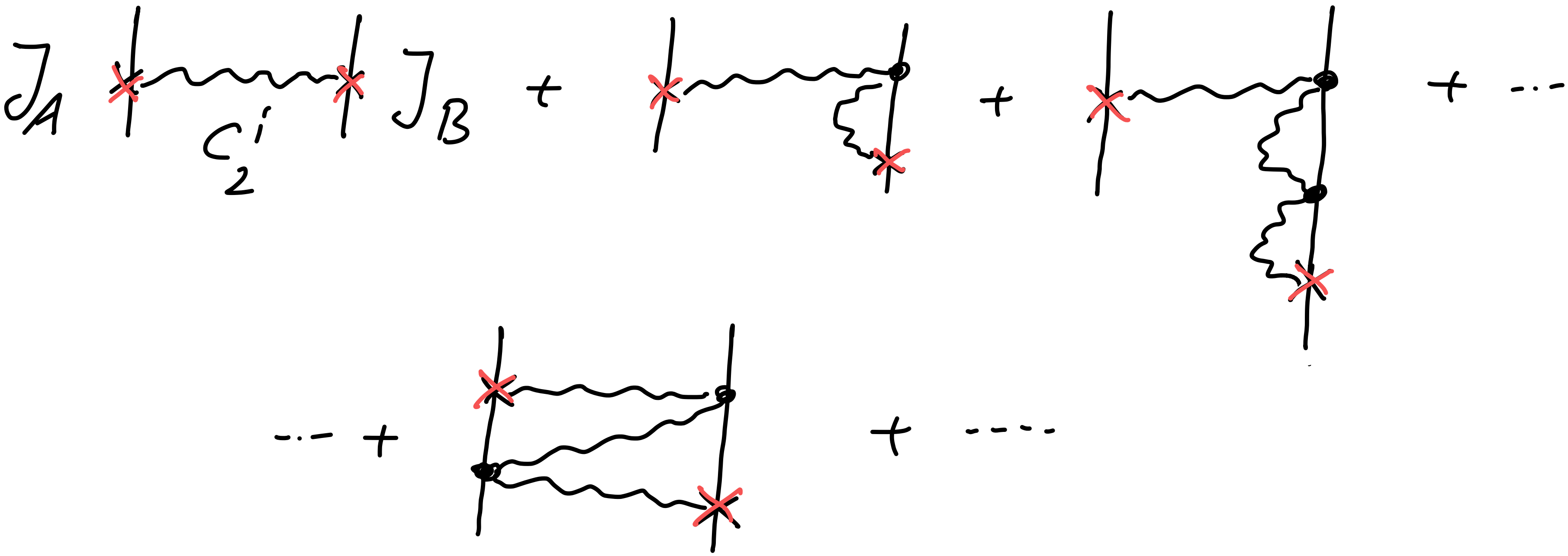
$\Rightarrow$ EOMs for C_2

$$\Big[\underbrace{\hat{M}_{ij}\, d^\dagger d}_{\text{bulk kinetic term}} + \underbrace{\hat{m}_{ij}\big(\delta^6(A) + \delta^6(B)\big)}_{\text{D3-localized mass term}}\Big] C_2^{\,j} = J_i^A \delta^6(A) + J_i^B \delta^6(B)$$

$$\Rightarrow \quad C_2 = \underbrace{[\;\cdots\;]^{-1}}_{\text{expand as power series in } \hat{m}} \big(J^A \delta^6(A) + J^B \delta^6(B)\big)$$

(but keep <u>all</u> orders)

Diagrammatic illustration



Key technical observations:

$$(\hat{m}^{-1})^{ij} J_j = - \ast J^i \quad ; \quad \hat{m}^{ij} J_j = \ast J^i$$

$\Rightarrow$ Result: (symbolically)

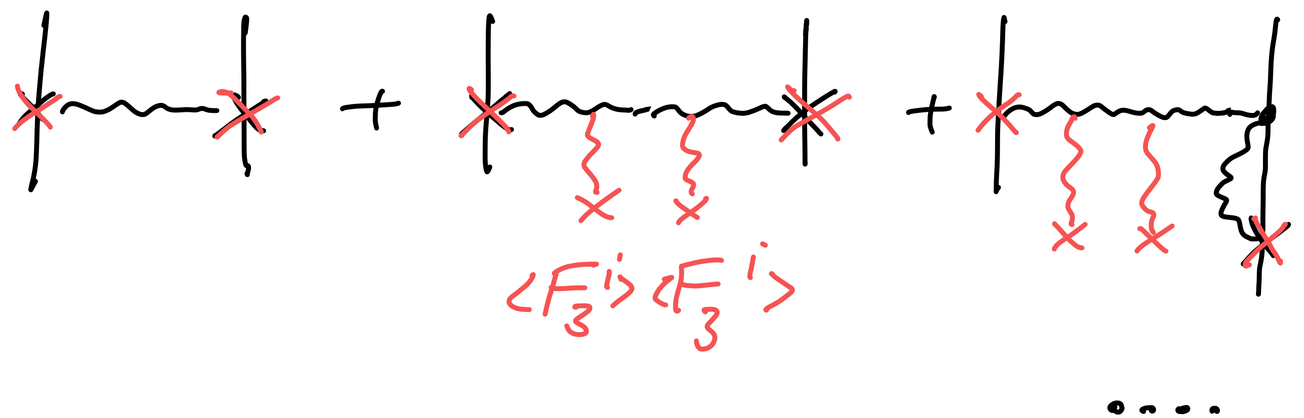
$$S_{eff}(J_A, J_B) \sim \Big(\underset{\uparrow\ \text{6d Green's fct.}}{\Delta_6^{-1}}(A,B) + \Delta_6^{-2}(A,B) + \cdots\Big)\,\varepsilon^{ij}\underbrace{\left(J_i^A \wedge J_j^B + J_i^B \wedge J_j^A\right)}_{=0}$$

- Need to build $\mathcal{B}$-invariant expression with J_A, J_B
- Symmetry in A, B guaranteed
- ε^{ij} remains the only rank-2 invariant tensor if $SL(2,\mathbb{R})$ is restricted to $\mathcal{B}$

$\Rightarrow$ The leading non-zero result arises when introducing 3-form fluxes

(since they break $SL(2,\mathbb{R})$)

Diagramatically:



(Our paper provides an explicit but unwieldy formula including $\langle F_3^i \rangle$ at LO. A result is that χ is more strongly volume suppressed than just by sequestering.)

Parametric result:

CP-odd flux

$$\chi \sim \frac{1}{g_s \mathcal{V}^{4/3}} \quad ; \quad \tilde{\chi} \sim \frac{f - C_0}{\mathcal{V}^{4/3}}$$

volume of CY (cosmology suggests $m_{\mathcal{V}} \gtrsim 2 m_H \Rightarrow \mathcal{V} \lesssim 10^{11}$)

Open theory challenge:

- $\mathcal{V}^{2/3} \sim (T + \bar{T})$, T – chiral superfield
- $T \to T + i\varepsilon$ is a perturbatively exact shift symmetry

$\Rightarrow$ By gauge coupling holomorphicity, our result should vanish if SUSY is unbroken, i.e. for ISD flux...

Challenges (continued)

- Is an even better understanding the B_2/C_2 cancellation and the role of $SL(2,\mathbb{Z})$ possible?

  (Maybe some cancellation survives if fluxes are ISD or SUSY?)

- For pheno, it is essential to extend to

$$D3 \nearrow \text{fractional D3} \qquad D3 \searrow \text{D7 wrapped on local 4-cycle w/ flux}$$

Summary

- Kinetic mixing is a key target in modern BSM physics, both phenomenologically & in string theory
- It appears that very explicit results for χ with phenomenologically interesting values are within reach.
- Some challenges still have to be overcome:
  - "holomorphicity / shift-symmetry / SUSY-breaking"
  - extension to fractional D3's / wrapped D7's.