SUSY 2022, University of Ioannina,
June 27-July 2, 2022

Gauge Group Topology and Higher-Form Structures in Consistent Quantum Gravity

Mirjam Cvetič

Penn
University of Pennsylvania

CAMTP
University of Maribor

CERN

Univerza v Ljubljani
Fakulteta za matematiko in fiziko

Motivation

Motivation

- Quantum field theories coupled to consistent quantum gravity should be subject to additional constraints beyond standard QFT consistency ones → Swampland Program [Vafa '06]

Motivation

- Quantum field theories coupled to consistent quantum gravity should be subject to additional constraints beyond standard QFT consistency ones → Swampland Program [Vafa '06]

- Globally consistent compactifications of String Theory → automatically include quantum gravity & constraints emerge due to geometry of compactified space → Does String Theory realize all consistent theories of quantum gravity [String Universality]?

Motivation

- Quantum field theories coupled to consistent quantum gravity should be subject to additional constraints beyond standard QFT consistency ones → Swampland Program [Vafa '06]

- Globally consistent compactifications of String Theory → automatically include quantum gravity & constraints emerge due to geometry of compactified space → Does String Theory realize all consistent theories of quantum gravity [String Universality]?

- Focus on finding physical conditions, reflecting geometric constraints of consistent quantum gravity (without reference to String Theory)

Motivation

- Quantum field theories coupled to consistent quantum gravity should be subject to additional constraints beyond standard QFT consistency ones → Swampland Program [Vafa '06]

- Globally consistent compactifications of String Theory → automatically include quantum gravity & constraints emerge due to geometry of compactified space → Does String Theory realize all consistent theories of quantum gravity [String Universality]?

- Focus on finding physical conditions, reflecting geometric constraints of consistent quantum gravity (without reference to String Theory)

Long history: [...Kumar, Taylor '09; Adams, DeWolfe, Taylor '10;... García-Etxebarria, Hayashi, Ohmori, Tachikawa, Yonekura '17; Kim, Tarazi, Vafa '19; M.C., Dierigl, Lin, Zhang '20; Montero, Vafa '20; Hamada, Vafa '21; Tarazi, Vafa '21;...]

Highlight

- Gauge symmetry topology for
  N =1 Supergravity in 8D →
  gauging of one-form symmetries

Highlight

- Gauge symmetry topology for N =1 Supergravity in 8D → gauging of one-form symmetries

- Top-down classification via string junctions → all 8D (& 9D) N=1 string vacua

Highlight

- Gauge symmetry topology for
  N =1 Supergravity in 8D →
  gauging of one-form symmetries

- Top-down classification via string junctions →
  all 8D (& 9D) N=1 string vacua

Guiding principles

- Geometry: primarily F-theory compactification
- Physics: global symmetries, including higher-form ones,
  gauged or broken in consistent quantum gravity
  [No Global Symmetry Hypothesis]

…[Harlow, Ooguri '18]

Based on

- Gauge symmetry topology constraints in 8D

- M.C., M.Dierigl, L.Lin and H.Y.Zhang,
  ``String Universality and Non-Simply-Connected Gauge Groups in 8d,''
  PRL, arXiv:2008.10605 [hep-th];

- ``Higher-form Symmetries and Their Anomalies in M-/F-theory Duality,''
  PRD, arXiv:2106.07654 [hep-th] - 8D/7D & 6D/5D

- ``Gauge group topology of 8D Chaudhuri-Hockney-Lykken vacua,''
  PRD, arXiv:2107.04031 [hep-th];

- ``One Loop to Rule Them All: Eight and Nine Dimensional String Vacua from Junctions,'' arXiv:2203.03644 [hep-th]– String junctions

Based on

- Gauge symmetry topology constraints in 8D

- M.C., M.Dierigl, L.Lin and H.Y.Zhang,
  ``String Universality and Non-Simply-Connected Gauge Groups in 8d,"
  PRL, arXiv:2008.10605 [hep-th];

- ``Higher-form Symmetries and Their Anomalies in M-/F-theory Duality,"
  PRD, arXiv:2106.07654 [hep-th] - 8D/7D & 6D/5D

- ``Gauge group topology of 8D Chaudhuri-Hockney-Lykken vacua,"
  PRD, arXiv:2107.04031 [hep-th];

- ``One Loop to Rule Them All: Eight and Nine Dimensional String Vacua
  from Junctions," arXiv:2203.03644 [hep-th]– String junctions

Based on

- Gauge symmetry topology constraints in 8D

- M.C., M.Dierigl, L.Lin and H.Y.Zhang,
  ``String Universality and Non-Simply-Connected Gauge Groups in 8d,''
  PRL, arXiv:2008.10605 [hep-th];

- ``Higher-form Symmetries and Their Anomalies in M-/F-theory Duality,''
  PRD, arXiv:2106.07654 [hep-th] - 8D/7D & 6D/5D

- ``Gauge group topology of 8D Chaudhuri-Hockney-Lykken vacua,''
  PRD, arXiv:2107.04031 [hep-th];

- ``One Loop to Rule Them All: Eight and Nine Dimensional String Vacua from Junctions,'' arXiv:2203.03644 [hep-th]– String junctions

Digression: [Vafa'96;Morrison,Vafa'96],...review [Weigand'18]

Key features of F-theory compactification

Digression: [Vafa'96;Morrison,Vafa'96],...review [Weigand'18]

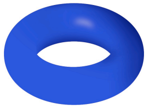
Key features of F-theory compactification

- F-theory, a powerful framework that geometrizes τ =axio-dilaton as a modular parameter of T^2 (SL(2,Z) duality of Type IIB string)

Digression: [Vafa'96;Morrison,Vafa'96],...review [Weigand'18]

Key features of F-theory compactification

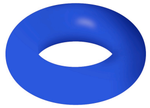
- F-theory, a powerful framework that geometrizes τ =axio-dilaton as a modular parameter of T^2 (SL(2,Z) duality of Type IIB string)



Digression: [Vafa'96;Morrison,Vafa'96],...review [Weigand'18]

Key features of F-theory compactification

- F-theory, a powerful framework that geometrizes τ =axio-dilaton as a modular parameter of T^2 (SL(2,Z) duality of Type IIB string)

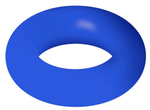


- Compactification on singular, elliptically fibered Calabi-Yau fewfolds

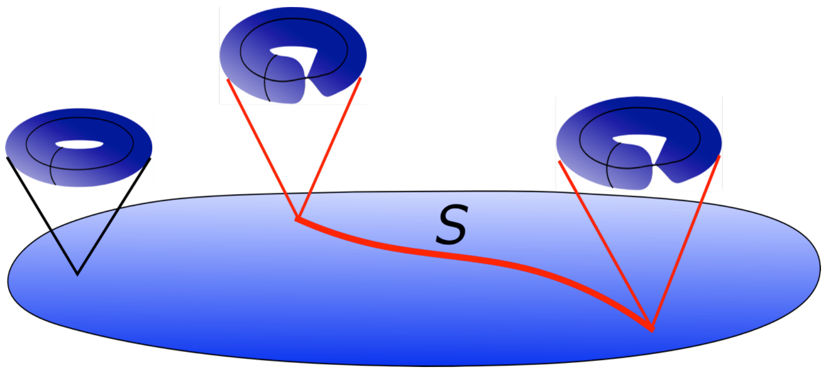
Digression: [Vafa'96;Morrison,Vafa'96],...review [Weigand'18]

Key features of F-theory compactification

- F-theory, a powerful framework that geometrizes τ =axio-dilaton as a modular parameter of T^2 (SL(2,Z) duality of Type IIB string)



- Compactification on singular, elliptically fibered Calabi-Yau fewfolds

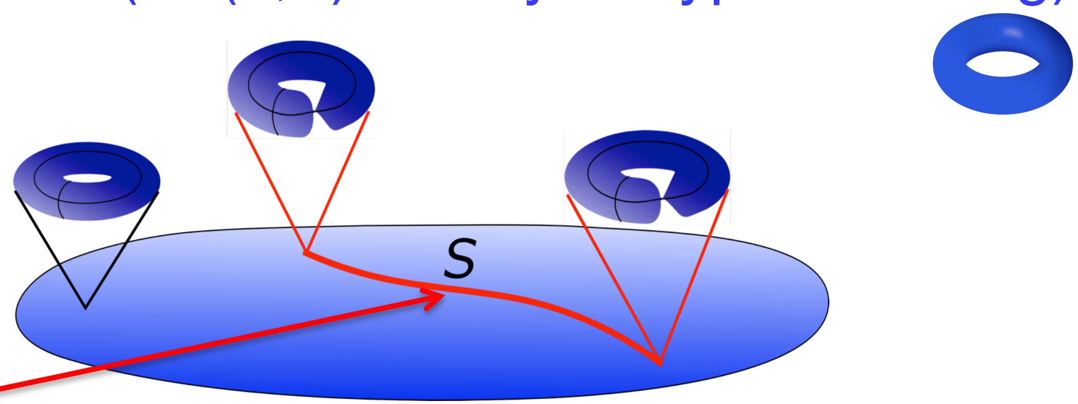


Digression: [Vafa'96;Morrison,Vafa'96],...review [Weigand'18]

Key features of F-theory compactification

- F-theory, a powerful framework that geometrizes τ =axio-dilaton as a modular parameter of T^2 (SL(2,Z) duality of Type IIB string)

- Compactification on singular, elliptically fibered Calabi-Yau fewfolds



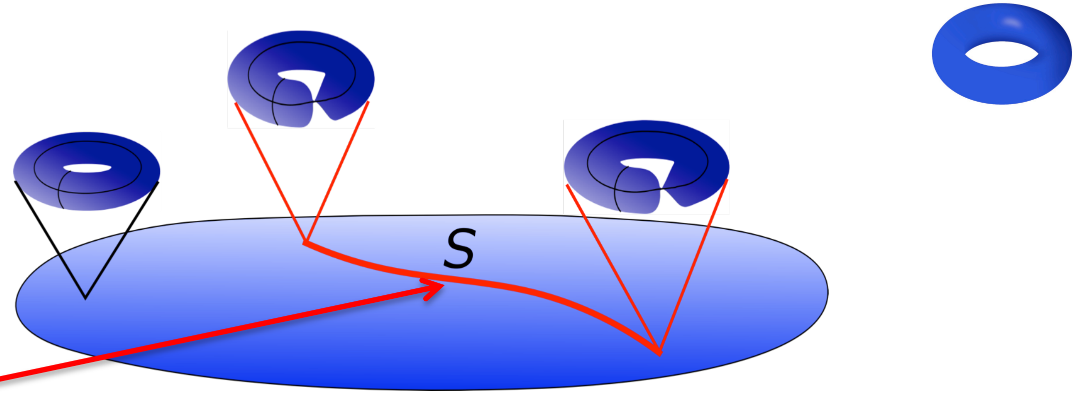
- 7-brane non-Abelian gauge symmetries *G*, encoded in types of singular T^2 fibration (ADE singularities)

Digression: [Vafa'96;Morrison,Vafa'96],...review [Weigand'18]

Key features of F-theory compactification

- F-theory, a powerful framework that geometrizes τ =axio-dilaton as a modular parameter of T^2 (SL(2,Z) duality of Type IIB string)

- Compactification on singular, elliptically fibered Calabi-Yau fewfolds



- 7-brane non-Abelian gauge symmetries *G*, encoded in types of singular T^2 fibration (ADE singularities)

- T^2 (elliptic curve) carries arithmetic structure: Mordell-Weil group of rational points → U(1)'s [Morrison,Park'12; M.C.,Klevers,Piragua'13; Borchmann, Mayrhofer,Palti,Weigand'13;...]
  torsional points → gauge group topology *Z* → *G/Z*

[Aspinwall,Morrison'98; Mayrhofer,Morrison,Till,Weigand'14; M.C.,Lin'17]

F-theory compactification on elliptically fibered Calabi-Yau fourfolds led, for specific elliptic fibration to D=4 N=1effective theory with

[M.C., Klevers, Peña, Oehlmann, Reuter '15]

Standard Model gauge group SU(3) x SU(2) x U(1)

F-theory compactification on elliptically fibered Calabi-Yau fourfolds led, for specific elliptic fibration to D=4 N=1effective theory with

[M.C., Klevers, Peña, Oehlmann, Reuter '15]

Standard Model gauge group

with gauge group topology

(geometric - encoded in Shioda Map of MW)

$$\frac{SU(3) \times SU(2) \times U(1)}{\mathbb{Z}_6}$$

[M.C.,Lin '17]

F-theory compactification on elliptically fibered Calabi-Yau fourfolds led, for specific elliptic fibration to D=4 N=1effective theory with

[M.C., Klevers, Peña, Oehlmann, Reuter '15]

Standard Model gauge group $\frac{SU(3) \times SU(2) \times U(1)}{\mathbb{Z}_6}$

with gauge group topology

(geometric - encoded in Shioda Map of MW) [M.C.,Lin '17]

toric geometry techniques

(toric bases B_3)

F-theory compactification on elliptically fibered Calabi-Yau fourfolds led, for specific elliptic fibration to D=4 N=1effective theory with

[M.C., Klevers, Peña, Oehlmann, Reuter '15]

Standard Model gauge group

with gauge group topology

(geometric - encoded in Shioda Map of MW)

$$\frac{SU(3) \times SU(2) \times U(1)}{\mathbb{Z}_6}$$

[M.C.,Lin '17]

toric geometry techniques

(toric bases B_3)

[M.C., Halverson, Lin, Liu, Tian '19, PRL]

Quadrillion Standard Models (QSMs)

with 3-chiral families & gauge coupling unification

[gauge divisors – in class of *anti-canonical divisor K*]

F-theory compactification on elliptically fibered Calabi-Yau fourfolds led, for specific elliptic fibration to D=4 N=1effective theory with

[M.C., Klevers, Peña, Oehlmann, Reuter '15]

Standard Model gauge group $\frac{SU(3) \times SU(2) \times U(1)}{\mathbb{Z}_6}$

with gauge group topology

(geometric - encoded in Shioda Map of MW) [M.C.,Lin '17]

⬇ toric geometry techniques (toric bases B_3)

[M.C., Halverson, Lin, Liu, Tian '19, PRL]

Quadrillion Standard Models (QSMs) with 3-chiral families & gauge coupling unification

[gauge divisors – in class of *anti-canonical divisor K]*

Current efforts: determination the exact matter spectra (including # of Higgs pairs) [Bies, M.C., Donagi,(Liu), Ong '21,'22]

Bies, M.C., Donagi, Ong 2205.00008

Matter spectra specified by root bundles ($K^{\{\text{frac no}\}}|_{\text{curve}}$)
on matter curves:

Bies, M.C., Donagi, Ong 2205.00008

Matter spectra specified by root bundles $(K^{\{\text{frac no}\}}|_{\text{curve}})$ on matter curves:

Identified $O(10^{11})$ F-theory QSM geometries without vector-like matter exotics in the representations of Q_L , q_R , e_R

Bies, M.C., Donagi, Ong 2205.00008

Matter spectra specified by root bundles ($K^{\{\text{frac no}\}}|_{\text{curve}}$) on matter curves:

Identified O(10^{11}) F-theory QSM geometries without vector-like matter exotics in the representations of Q_L , q_R , e_R by studying [Caporaso,Casagrande, Cornalba '04]

limit root bundles on nodal matter curves (deformed matter curves)

Bies, M.C., Donagi, Ong 2205.00008

Matter spectra specified by root bundles ($K^{\{\text{frac no}\}}|_{\text{curve}}$) on matter curves:

Identified $O(10^{11})$ F-theory QSM geometries without vector-like matter exotics in the representations of Q_L, q_R, e_R by studying [Caporaso,Casagrande, Cornalba '04] limit root bundles on nodal matter curves (deformed matter curves)

- Develop algorithm to determine h^0 for all limit root bundles (w/ chirality: $\chi = h^0 - h^1 = 3$)

Bies, M.C., Donagi, Ong 2205.00008

Matter spectra specified by root bundles ($K^{\{\text{frac no}\}}|_{\text{curve}}$) on matter curves:

Identified $O(10^{11})$ F-theory QSM geometries without vector-like matter exotics in the representations of Q_L, q_R, e_R by studying [Caporaso,Casagrande, Cornalba '04] limit root bundles on nodal matter curves (deformed matter curves)

- Develop algorithm to determine h^0 for all limit root bundles (w/ chirality: $\chi = h^0 - h^1 = 3$)

- For **Δ_4** polytope (10^{11} triangulations) 99.995% of root-bundles exactly $h^0 = 3$ → -no vector-like exotics
- Statistical analysis for other polytopes → w/ $h^0 = 3$ by far most prevalent

Bies, M.C., Donagi, Ong 2205.00008

Matter spectra specified by root bundles ($K^{\{\text{frac no}\}}|_{\text{curve}}$) on matter curves:

Identified $O(10^{11})$ F-theory QSM geometries without vector-like matter exotics in the representations of Q_L, q_R, e_R by studying [Caporaso,Casagrande, Cornalba '04]
limit root bundles on nodal matter curves (deformed matter curves)

- Develop algorithm to determine h^0 for all limit root bundles (w/ chirality: $\chi = h^0 - h^1 = 3$)

- For Δ_4 polytope (10^{11} triangulations) 99.995% of root-bundles exactly $h^0 = 3$ → no vector-like exotics
- Statistical analysis for other polytopes → w/ $h^0 = 3$ by far most prevalent

→ Study of Higgs nodal curves [Bies, M.C., Liu, work in progress]

Back to the main topic:

I. Gauge group topology in 8D N=1 SG

a) Geometry - String compactification

Back to the main topic:

I. Gauge group topology in 8D N=1 SG

a) Geometry - String compactification

- G versus G/Z $\quad$ $w/\ Z \subset Z(G)$-center
- For simplicity: $G = SU(n_1) \times SU(n_2) \times \ldots$
  $w/\ Z(G) = \mathbb{Z}_{n1} \times \mathbb{Z}_{n2} \times \ldots$
- Subgroup Z w/ generators represented as
  $(k_1, k_2, \ldots) \in \Pi_i \mathbb{Z}_{ni}$

Back to the main topic:

I. Gauge group topology in 8D N=1 SG

a) Geometry - String compactification

- G versus G/Z w/ $Z \subset Z(G)$-center
- For simplicity: $G = SU(n_1) \times SU(n_2) \times \ldots$
  w/ $Z(G) = \mathbb{Z}_{n1} \times \mathbb{Z}_{n2} \times \ldots$
- Subgroup Z w/ generators represented as
  $(k_1, k_2, \ldots) \in \Pi_i \mathbb{Z}_{ni}$

- In F-theory compactification Z encoded in the geometry
  (Mordell-Weil torsion)
  F-theory on elliptically fibered $K3 \rightarrow$ 8D N=1 SG

Back to the main topic:

I. Gauge group topology in 8D N=1 SG

a) Geometry - String compactification

- G versus G/Z w/ $Z \subset Z(G)$-center
- For simplicity: $G = SU(n_1) \times SU(n_2) \times \ldots$
  w/ $Z(G) = \mathbb{Z}_{n1} \times \mathbb{Z}_{n2} \times \ldots$
- Subgroup Z w/ generators represented as
  $(k_1, k_2, \ldots) \in \prod_i \mathbb{Z}_{ni}$

- In F-theory compactification Z encoded in the geometry (Mordell-Weil torsion)
  F-theory on elliptically fibered $K3$ → 8D N=1 SG
  → Arithmetic constraint [Miranda, Persson'89]:

$$\Sigma_i\, k^2_{\mathrm{i}}\, (n_i - 1)/(2n_i) \in \mathbb{Z}$$

Back to the main topic:

I. Gauge group topology in 8D N=1 SG

a) Geometry - String compactification

- G versus G/Z $w/\ Z \subset Z(G)$-center
- For simplicity: $G = SU(n_1) \times SU(n_2) \times \ldots$
  $w/\ Z(G) = \mathbb{Z}_{n1} \times \mathbb{Z}_{n2} \times \ldots$
- Subgroup Z w/ generators represented as
  $(k_1, k_2, \ldots) \in \Pi_i \mathbb{Z}_{ni}$

- In F-theory compactification Z encoded in the geometry (Mordell-Weil torsion)
  F-theory on elliptically fibered $K3$ → 8D N=1 SG
  → Arithmetic constraint [Miranda, Persson'89]:

$$\boxed{\Sigma_i\, k^2_{\mathrm{i}}\, (n_i - 1)/(2n_i) \in \mathbb{Z}}$$

b) Physics - constraints on higher-form symmetries

b) Physics - constraints on higher-form symmetries

- *G/Z* has gauged 1-form symmetry [Gaiotto,Kapustin,Seiberg,Willet'14]
  G/Z requires no obstruction to gauging the global 1-form!

b) Physics - constraints on higher-form symmetries

- G/Z has gauged 1-form symmetry [Gaiotto,Kapustin,Seiberg,Willet'14]
  G/Z requires no obstruction to gauging the global 1-form!
- For G, instanton density fractional ['t Hooft '81]
  w/ 1-form symmetry background C_2 ($F/2\pi \to F/2\pi + C_2$):

  $\mathrm{Tr}(F^2)/8\pi^2 \equiv \alpha_G \mathcal{P}(C_2)$ *mod* $\mathbb{Z}$ (``$\mathcal{P}(C_2)$-Pontryagin square")

  w/ α_G fractional, e.g., $\alpha_{SU(n)} = (n-1)/(2n)$

b) Physics - constraints on higher-form symmetries

- G/Z has gauged 1-form symmetry [Gaiotto,Kapustin,Seiberg,Willet'14]
  G/Z requires no obstruction to gauging the global 1-form!

- For G, instanton density fractional ['t Hooft '81]
  w/ 1-form symmetry background C_2 ($F/2\pi \to F/2\pi + C_2$):

  $\mathrm{Tr}(F^2)/8\pi^2 \equiv \alpha_G \mathcal{P}(C_2)$ *mod* $\mathbb{Z}$ (``$\mathcal{P}(C_2)$-Pontryagin square'')

  w/ α_G fractional, e.g., $\alpha_{SU(n)} = (n-1)/(2n)$

- In 8D N=1 SG, instanton density couples to a tensor in the gravity multiplet, B_4, w/ $B_4 \to B_4 + b_4$ - U(1) large gauge symmetry:

  $\mathcal{L} \supset B_4 \wedge \mathrm{Tr}(F^2)/8\pi^2$ [Awada,Townsend '85]

b) Physics - constraints on higher-form symmetries

- *G/Z* has gauged 1-form symmetry [Gaiotto,Kapustin,Seiberg,Willet'14]
  G/Z requires no obstruction to gauging the global 1-form!
- For *G*, instanton density fractional ['t Hooft '81]
  w/ 1-form symmetry background C_2 ($F/2\pi \to F/2\pi + C_2$):

  $\mathrm{Tr}(F^2)/8\pi^2 \equiv \alpha_G \mathcal{P}(C_2)$ *mod* $\mathbb{Z}$ (``$\mathcal{P}(C_2)$-Pontryagin square'')

  w/ α_G fractional, e.g., $\alpha_{SU(n)} = (n-1)/(2n)$
- In 8D N=1 SG, instanton density couples to a tensor in the gravity multiplet, B_4, w/ $B_4 \to B_4 + b_4$ - U(1) large gauge symmetry:

  $\mathcal{L} \supset B_4 \wedge \mathrm{Tr}(F^2)/8\pi^2$ [Awada,Townsend '85]
- Shown [M.C., Dierigl, Lin, Zhang '20]: fractional instantons lead to mixed anomaly between global 1-form Z and gauge U(1):

$$\mathcal{A} = \Sigma_i k^2_i\, \alpha_{Gi} \qquad = \qquad \Sigma_i k^2_i\, (n_i - 1)/(2n_i) \qquad \text{mod } \mathbb{Z}$$

b) Physics - constraints on higher-form symmetries

- *G/Z* has gauged 1-form symmetry [Gaiotto,Kapustin,Seiberg,Willet'14]
  G/Z requires no obstruction to gauging the global 1-form!
- For *G*, instanton density fractional ['t Hooft '81]
  w/ 1-form symmetry background C_2 ($F/2\pi \to F/2\pi + C_2$):

  $\mathrm{Tr}(F^2)/8\pi^2 \equiv \alpha_G \mathcal{P}(C_2)$ *mod* $\mathbb{Z}$ (``$\mathcal{P}(C_2)$-Pontryagin square'')
  w/ α_G fractional, e.g., $\alpha_{SU(n)} = (n-1)/(2n)$
- In 8D N=1 SG, instanton density couples to a tensor in the gravity multiplet, B_4, w/ $B_4 \to B_4 + b_4$ - U(1) large gauge symmetry:

  $\mathcal{L} \supset B_4 \wedge \mathrm{Tr}(F^2)/8\pi^2$ [Awada,Townsend '85]
- Shown [M.C., Dierigl, Lin, Zhang '20]: fractional instantons lead to mixed anomaly between global 1-form Z and gauge U(1):

$$\mathcal{A} = \Sigma_i k^2_i\, \alpha_{Gi} \quad = \quad \Sigma_i k^2_i\, (n_i - 1)/(2n_i) \in \mathbb{Z} \qquad mod\ \mathbb{Z}$$

Physics: No anomaly Geometry: Miranda-Persson constraint!

b) Physics - constraints on higher-form symmetries

- *G/Z* has gauged 1-form symmetry [Gaiotto,Kapustin,Seiberg,Willet'14]
  G/Z requires no obstruction to gauging the global 1-form!
- For *G*, instanton density fractional ['t Hooft '81]
  w/ 1-form symmetry background C_2 ($F/2\pi \to F/2\pi + C_2$):

  $\mathrm{Tr}(F^2)/8\pi^2 \equiv \alpha_G \mathcal{P}(C_2)$ *mod* $\mathbb{Z}$ (``$\mathcal{P}(C_2)$-Pontryagin square'')
  w/ α_G fractional, e.g., $\alpha_{SU(n)} = (n-1)/(2n)$
- In 8D N=1 SG, instanton density couples to a tensor in the gravity multiplet, B_4, w/ $B_4 \to B_4 + b_4$ - U(1) large gauge symmetry:

  $\mathcal{L} \supset B_4 \wedge \mathrm{Tr}(F^2)/8\pi^2$ [Awada,Townsend '85]
- Shown [M.C., Dierigl, Lin, Zhang '20]: fractional instantons lead to mixed anomaly between global 1-form Z and gauge U(1):

$\mathcal{A} = \Sigma_i k^2_i\, \alpha_{Gi}$ = $\Sigma_i k^2_i\, (n_i - 1)/(2n_i) \in \mathbb{Z}$ *mod* $\mathbb{Z}$

Physics: No anomaly ⟺ Geometry: Miranda-Persson constraint!

b) Physics - constraints on higher-form symmetries

- *G/Z* has gauged 1-form symmetry [Gaiotto,Kapustin,Seiberg,Willet'14]
  G/Z requires no obstruction to gauging the global 1-form!
- For *G*, instanton density fractional ['t Hooft '81]
  w/ 1-form symmetry background C_2 ($F/2\pi \to F/2\pi + C_2$):

  $\mathrm{Tr}(F^2)/8\pi^2 \equiv \alpha_G \mathcal{P}(C_2)$ *mod* $\mathbb{Z}$ (``$\mathcal{P}(C_2)$-Pontryagin square'')

  w/ α_G fractional, e.g., $\alpha_{SU(n)} = (n-1)/(2n)$
- In 8D N=1 SG, instanton density couples to a tensor in the gravity multiplet, B_4, w/ $B_4 \to B_4 + b_4$ - U(1) large gauge symmetry:

  $\mathcal{L} \supset B_4 \wedge \mathrm{Tr}(F^2)/8\pi^2$ [Awada,Townsend '85]
- Shown [M.C., Dierigl, Lin, Zhang '20]: fractional instantons lead to mixed anomaly between global 1-form Z and gauge U(1):

$\mathcal{A} = \Sigma_i k^2_i \alpha_{Gi}$ = $\Sigma_i k^2_i (n_i - 1)/(2n_i) \in \mathbb{Z}$ *mod* $\mathbb{Z}$

Physics: No anomaly ⟺ Geometry: Miranda-Persson constraint!

Classification of allowed gauge groups in 8D N=1 SG

Classification of allowed gauge groups in 8D N=1 SG

- Anomalies of non-*SU* groups is integer sums of *SU* subgroups

  [Cordova, Freed, Lam, Seiberg '19]

Classification of allowed gauge groups in 8D N=1 SG

- Anomalies of non-*SU* groups is integer sums of *SU* subgroups

  [Cordova, Freed, Lam, Seiberg '19]

- Solutions to $\Sigma_i k^2{}_i (n_i - 1)/(2n_i) \in \mathbb{Z}$, subject to $\Sigma_i (n_i - 1) = 18$

  [Montero, Vafa '20]

  limited. E.g., $G/\mathbb{Z}_\ell$ w/ $\ell > 8$ no anomaly-free solution;
  unique solutions $\ell = 7$: $SU(7)^3/\mathbb{Z}_7$; $\ell = 8$: $[SU(8)^2 \times SU(4) \times SU(2)]/\mathbb{Z}_8$

Classification of allowed gauge groups in 8D N=1 SG

- Anomalies of non-*SU* groups is integer sums of *SU* subgroups

  [Cordova, Freed, Lam, Seiberg '19]

- Solutions to $\Sigma_i\, k^2{}_i\,(n_i - 1)/(2n_i) \in \mathbb{Z}$, subject to $\Sigma_i\,(n_i - 1) = 18$

  [Montero, Vafa '20]

  limited. E.g., $G/\mathbb{Z}_\ell$ w/ $\ell > 8$ no anomaly-free solution;
  unique solutions $\ell = 7$: $SU(7)^3/\mathbb{Z}_7$; $\ell = 8$: $[SU(8)^2{\times}SU(4){\times}SU(2)]/\mathbb{Z}_8$

- Also predictions for rank 10 and 2 theories.
  Confirmed in compactifications of CHL string (rank 10)

  [M.C., Dierigl, Lin, Zhang '21]

Classification of allowed gauge groups in 8D N=1 SG

- Anomalies of non-*SU* groups is integer sums of *SU* subgroups
  [Cordova, Freed, Lam, Seiberg '19]

- Solutions to $\Sigma_i k^2_i (n_i - 1)/(2n_i) \in \mathbb{Z}$, subject to $\Sigma_i (n_i - 1) = 18$
  [Montero, Vafa '20]
  limited. E.g., $G/\mathbb{Z}_\ell$ w/ $\ell > 8$ no anomaly-free solution;
  unique solutions $\ell = 7$: $SU(7)^3/\mathbb{Z}_7$; $\ell = 8$: $[SU(8)^2 \times SU(4) \times SU(2)]/\mathbb{Z}_8$

- Also predictions for rank 10 and 2 theories.
  Confirmed in compactifications of CHL string (rank 10)
  [M.C., Dierigl, Lin, Zhang '21]

- Independently quantified by advancing string junction techniques
  including rank 2 [M.C., Dierigl, Lin, Zhang '21 & '22]

Classification of allowed gauge groups in 8D N=1 SG

- Anomalies of non-*SU* groups is integer sums of *SU* subgroups
  [Cordova, Freed, Lam, Seiberg '19]
- Solutions to $\Sigma_i k^2_i (n_i - 1)/(2n_i) \in \mathbb{Z}$, subject to $\Sigma_i (n_i - 1) = 18$
  [Montero, Vafa '20]
  limited. E.g., $G/\mathbb{Z}_\ell$ w/ $\ell > 8$ no anomaly-free solution;
  unique solutions $\ell = 7$: $SU(7)^3/\mathbb{Z}_7$; $\ell = 8$: $[SU(8)^2 \times SU(4) \times SU(2)]/\mathbb{Z}_8$
- Also predictions for rank 10 and 2 theories.
  Confirmed in compactifications of CHL string (rank 10)
  [M.C., Dierigl, Lin, Zhang '21]
- Independently quantified by advancing string junction techniques including rank 2 [M.C., Dierigl, Lin, Zhang '21 & '22]

→ Long digression:

[M.C., Dierigl, Lin, Zhang 2203.03644]

String Junctions & All Gauge Groups in 8D String Theory

[M.C., Dierigl, Lin, Zhang 2203.03644]

String Junctions & All Gauge Groups in 8D String Theory

String junctions between (p,q) 7-branes ⇔ geometry of 2-cycles

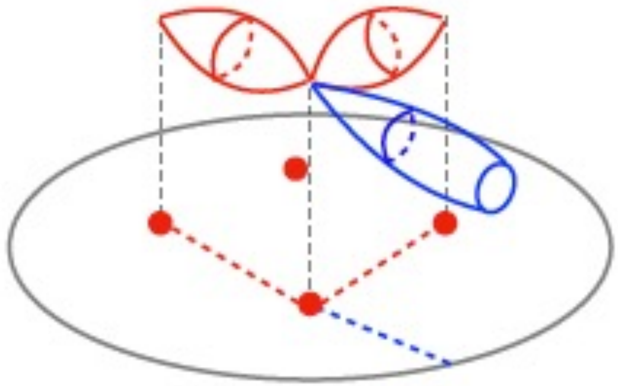
[Gaberdiel,Zwiebach '97, DeWolfe,Zwiebach '98]

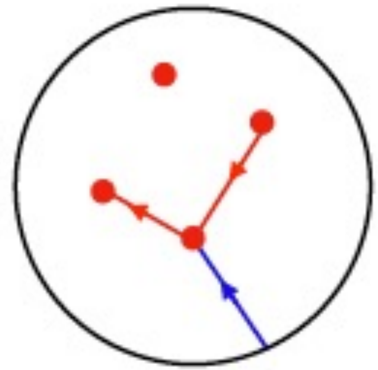
[M.C., Dierigl, Lin, Zhang 2203.03644]

String Junctions & All Gauge Groups in 8D String Theory

String junctions between (p,q) 7-branes ⬌ geometry of 2-cycles

[Gaberdiel,Zwiebach '97, DeWolfe,Zwiebach '98]





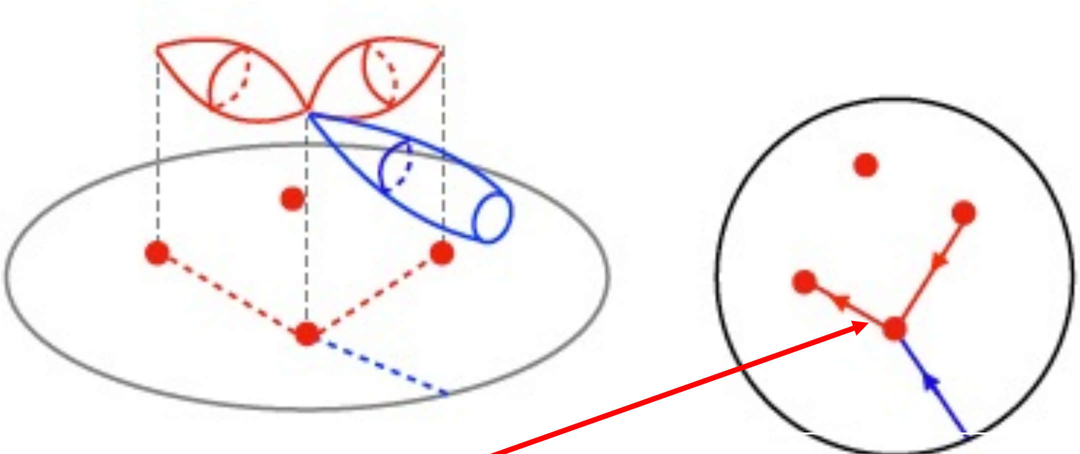
in perpendicular
2d space

[M.C., Dierigl, Lin, Zhang 2203.03644]

String Junctions & All Gauge Groups in 8D String Theory

String junctions between (p,q) 7-branes ⟺ geometry of 2-cycles

[Gaberdiel,Zwiebach '97, DeWolfe,Zwiebach '98]



in perpendicular
2d space

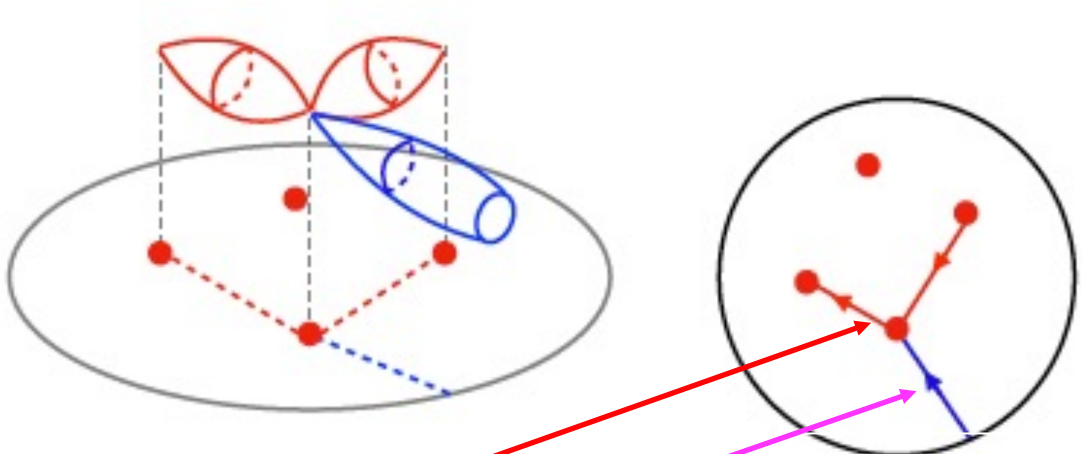
String junctions w/ prongs on stack ⇔ roots of gauge algebra lattice

[M.C., Dierigl, Lin, Zhang 2203.03644]

String Junctions & All Gauge Groups in 8D String Theory

String junctions between (p,q) 7-branes ⬌ geometry of 2-cycles

[Gaberdiel,Zwiebach '97, DeWolfe,Zwiebach '98]



in perpendicular 2d space

String junctions w/ prongs on stack ⇔ roots of gauge algebra lattice

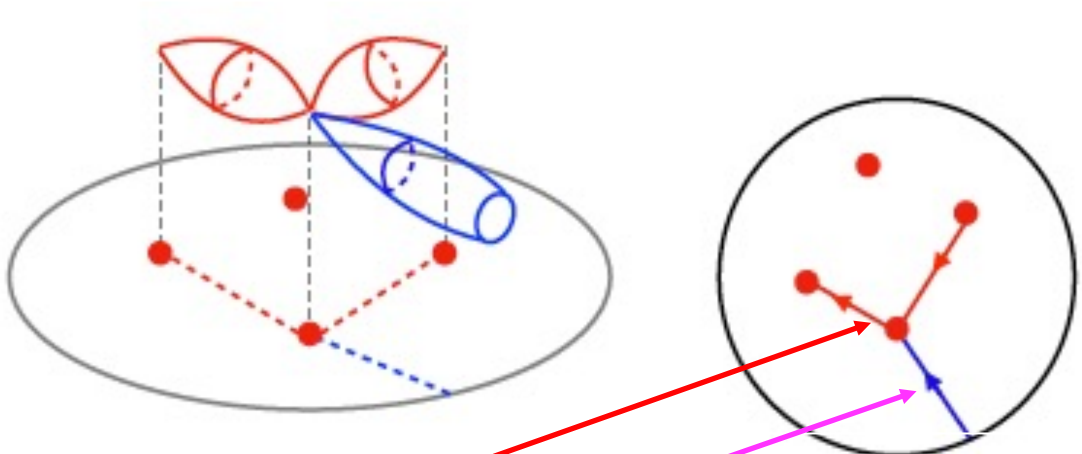
String junctions w/ external (asymptotic) prongs ⇔ weights

[M.C., Dierigl, Lin, Zhang 2203.03644]

String Junctions & All Gauge Groups in 8D String Theory

String junctions between (p,q) 7-branes ⬌ geometry of 2-cycles

[Gaberdiel,Zwiebach '97, DeWolfe,Zwiebach '98]



in perpendicular
2d space

String junctions w/ prongs on stack ⇔ roots of gauge algebra lattice

String junctions w/ external (asymptotic) prongs ⇔ weights

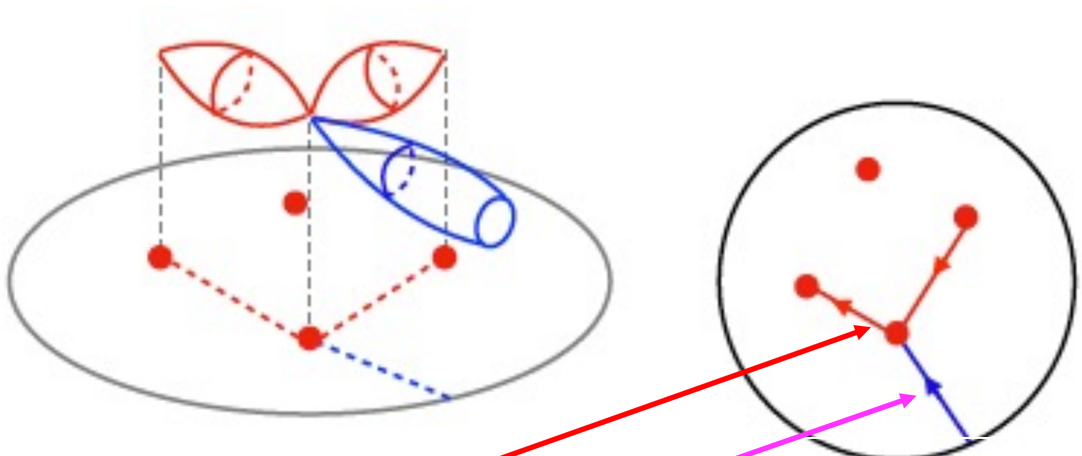
[Magnetic ``junctions" → 5-branes wrapping the same 2-cycles;
realizes ADE gauge algebras w/ weights = co-weights]

[M.C., Dierigl, Lin, Zhang 2203.03644]

String Junctions & All Gauge Groups in 8D String Theory

String junctions between (p,q) 7-branes ↔ geometry of 2-cycles

[Gaberdiel,Zwiebach ’97, DeWolfe,Zwiebach ’98]



in perpendicular 2d space

String junctions w/ prongs on stack ⇔ roots of gauge algebra lattice

String junctions w/ external (asymptotic) prongs ⇔ weights

[Magnetic ``junctions” → 5-branes wrapping the same 2-cycles; realizes ADE gauge algebras w/ weights = co-weights]

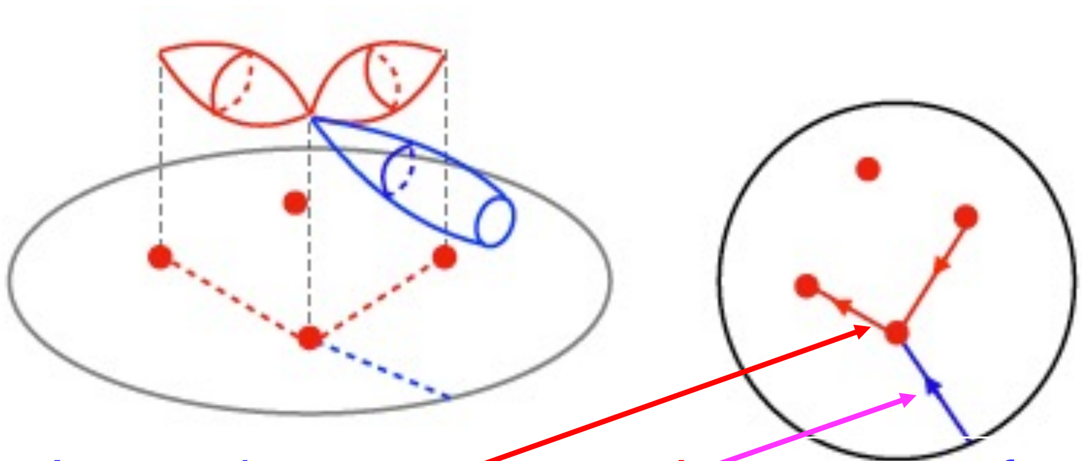
$$\frac{\text{(co-)weights}}{\text{(co-)roots}}$$

[M.C., Dierigl, Lin, Zhang 2203.03644]

String Junctions & All Gauge Groups in 8D String Theory

String junctions between (p,q) 7-branes ⟷ geometry of 2-cycles

[Gaberdiel,Zwiebach '97, DeWolfe,Zwiebach '98]



in perpendicular
2d space

String junctions w/ prongs on stack ⇔ roots of gauge algebra lattice

String junctions w/ external (asymptotic) prongs ⇔ weights

[Magnetic ``junctions'' → 5-branes wrapping the same 2-cycles; realizes ADE gauge algebras w/ weights = co-weights]

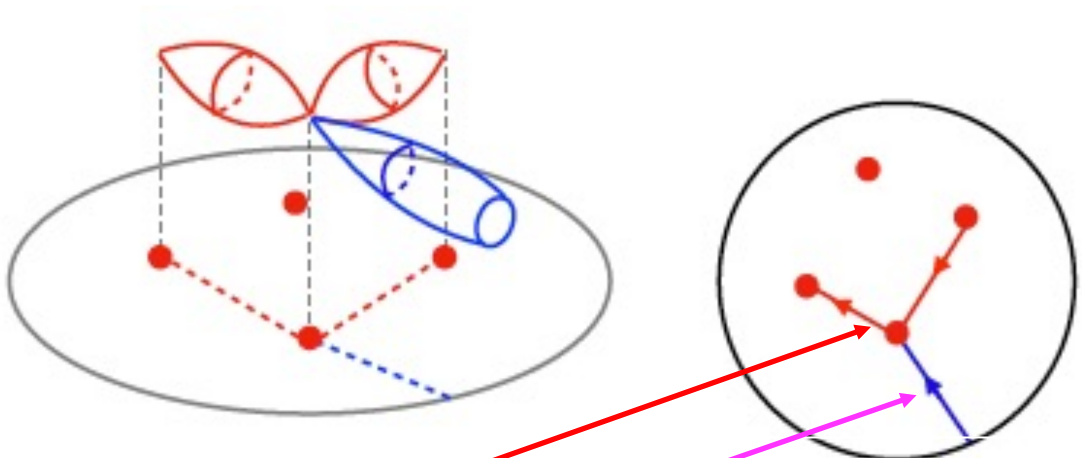
$$\frac{\text{(co-)weights}}{\text{(co-)roots}} \longleftrightarrow \frac{\text{non-compact}}{\text{compact 2-cycles}}$$

[M.C., Dierigl, Lin, Zhang 2203.03644]

String Junctions & All Gauge Groups in 8D String Theory

String junctions between (p,q) 7-branes ⟺ geometry of 2-cycles

[Gaberdiel,Zwiebach ’97, DeWolfe,Zwiebach ’98]



in perpendicular
2d space

String junctions w/ prongs on stack ⇔ roots of gauge algebra lattice

String junctions w/ external (asymptotic) prongs ⇔ weights

[Magnetic ``junctions” → 5-branes wrapping the same 2-cycles;
realizes ADE gauge algebras w/ weights = co-weights]

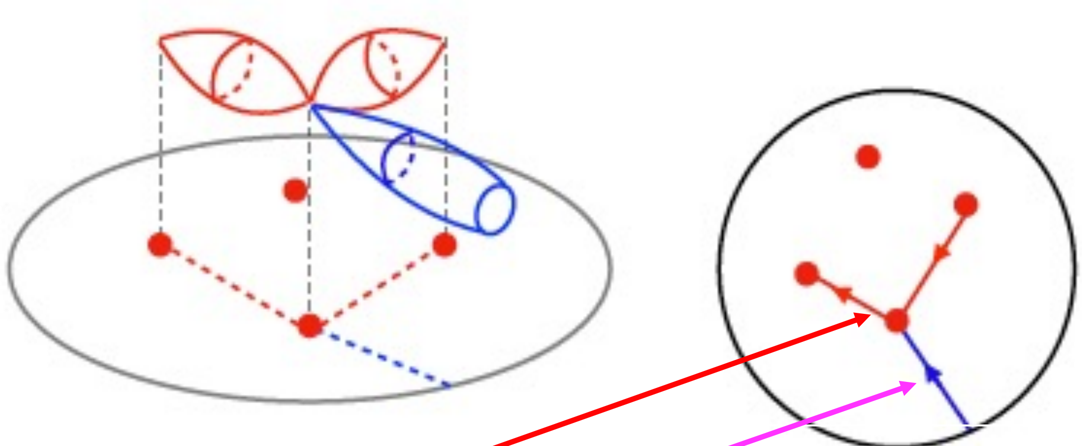
$$\frac{\text{(co-)weights}}{\text{(co-)roots}} \Longleftrightarrow \frac{\text{non-compact}}{\text{compact 2-cycles}} = Z(G) \ !$$

[M.C., Dierigl, Lin, Zhang 2203.03644]

String Junctions & All Gauge Groups in 8D String Theory

String junctions between (p,q) 7-branes ⟷ geometry of 2-cycles

[Gaberdiel,Zwiebach ’97, DeWolfe,Zwiebach ’98]



in perpendicular
2d space

String junctions w/ prongs on stack ⇔ roots of gauge algebra lattice

String junctions w/ external (asymptotic) prongs ⇔ weights

[Magnetic ``junctions” → 5-branes wrapping the same 2-cycles; realizes ADE gauge algebras w/ weights = co-weights]

$$\frac{\text{(co-)weights}}{\text{(co-)roots}} \longleftrightarrow \frac{\text{non-compact}}{\text{compact 2-cycles}} = Z(G) \;\; !$$

(magnetic) electric higher-form symmetries

[Morrison,Schäfer-NamekiWillett ’20, Albertini,Del Zotto,García-Etxebarria,Hosseini ’20]

From local (non-compact) gauge group topology

From local (non-compact) gauge group topology

Non-root junctions carry non-zero asymptotic (p,q)-charge

$$\mathbf{j} = \lambda_i \boldsymbol{\alpha}_i + \boldsymbol{\omega}_{(p,q)} \; (\lambda_i \in \mathbb{Q})$$

From local (non-compact) gauge group topology

Non-root junctions carry non-zero asymptotic (p,q)-charge

$$\mathbf{j} = \lambda_i \boldsymbol{\alpha}_i + \boldsymbol{\omega}_{(p,q)} \ (\lambda_i \in \mathbb{Q})$$

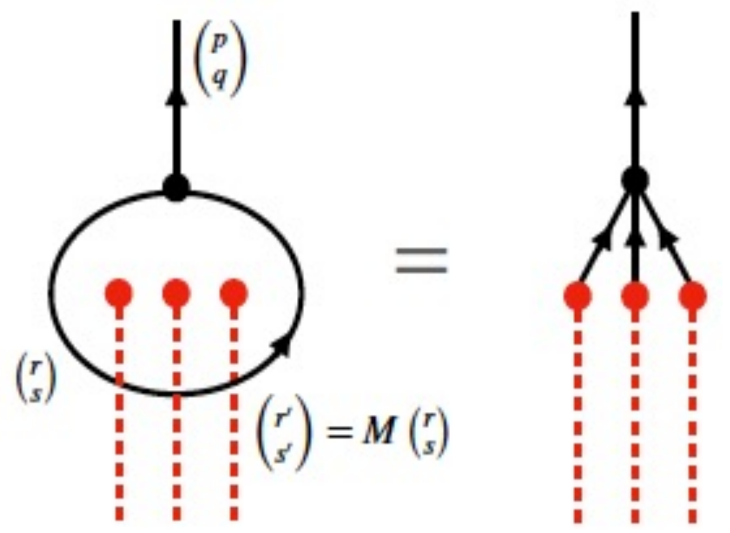
"Fractionality" of $\lambda_i \boldsymbol{\alpha}_i \equiv \mathbf{w}$ encodes charge under *Z(G)* → equivalently captured by *extended weights* $\boldsymbol{\omega}_{(p,q)}$ which *are fractional loop junctions*.

From local (non-compact) gauge group topology

Non-root junctions carry non-zero asymptotic (p,q)-charge

$$\mathbf{j} = \lambda_i \boldsymbol{\alpha}_i + \boldsymbol{\omega}_{(p,q)} \quad (\lambda_i \in \mathbb{Q})$$

"Fractionality" of $\lambda_i \boldsymbol{\alpha}_i \equiv \mathbf{w}$ encodes charge under *Z(G)* → equivalently captured by *extended weights* $\boldsymbol{\omega}_{(p,q)}$ which *are fractional loop junctions*.



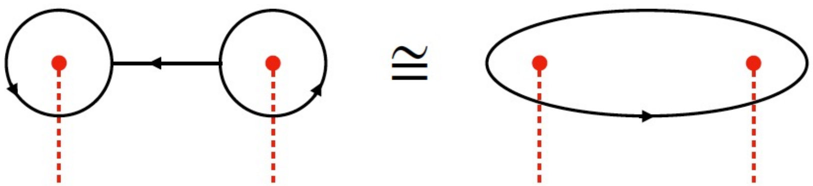
…to global compactification & gauge group topology there

→ no net asymptotic (p,q) charge

…to global compactification & gauge group topology there

→ no net asymptotic (p,q) charge

→ restricts allowed junctions in "gluing" local patches
encoded in fractional null junctions of 5-branes (encode *Z*)



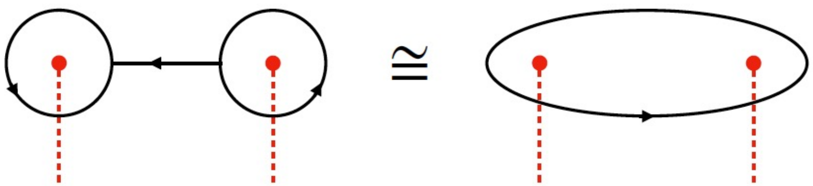
[Fukae,Yamada,Yang '99, Guralnik '01]

…to global compactification & gauge group topology there

→ no net asymptotic (p,q) charge

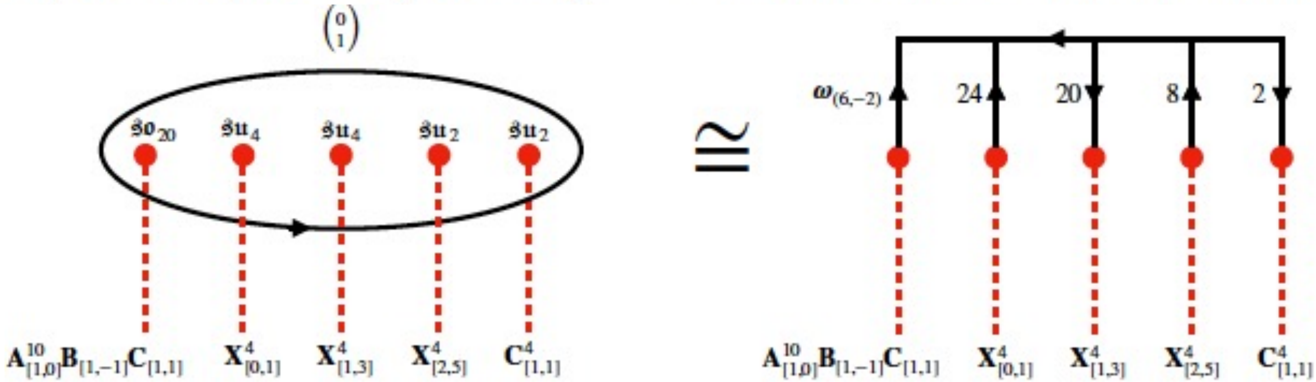
→ restricts allowed junctions in "gluing" local patches
encoded in fractional null junctions of 5-branes (encode *Z*)

[Fukae,Yamada,Yang '99, Guralnik '01]



All rank 18 vacua → Example:

$$\mathfrak{g} = \mathfrak{so}_{20} \oplus \mathfrak{su}_4 \oplus \mathfrak{su}_4 \oplus \mathfrak{su}_2 \oplus \mathfrak{su}_2 \implies [Spin(20) \times SU(4)^2 \times SU(2)^2]/(\mathbb{Z}_2 \times \mathbb{Z}_2)$$

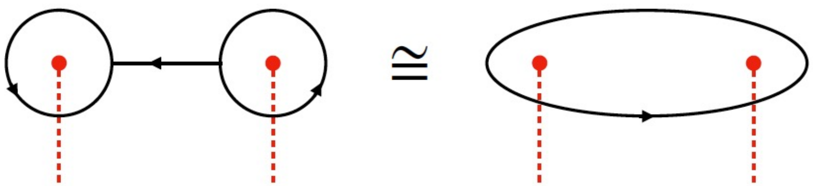


…to global compactification & gauge group topology there

→ no net asymptotic (p,q) charge

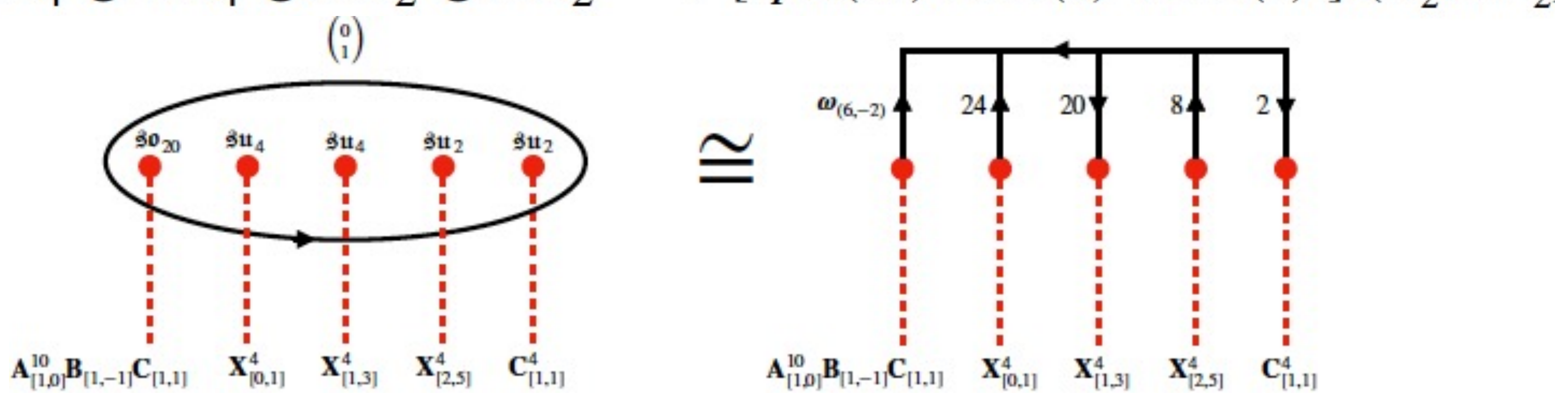
→ restricts allowed junctions in "gluing" local patches
encoded in fractional null junctions of 5-branes (encode Z)

[Fukae,Yamada,Yang '99, Guralnik '01]



All rank 18 vacua → Example:

$$\mathfrak{g} = \mathfrak{so}_{20} \oplus \mathfrak{su}_4 \oplus \mathfrak{su}_4 \oplus \mathfrak{su}_2 \oplus \mathfrak{su}_2 \implies [Spin(20) \times SU(4)^2 \times SU(2)^2]/(\mathbb{Z}_2 \times \mathbb{Z}_2)$$



Also for all examples with U(1)'s

Junctions on $O7^{+}$

Junctions on $O7^+$

- $O7^+$ does not split into (p,q) 7-branes at finite g_s (unlike $O7^-$)

Junctions on $O7^+$

- $O7^+$ does not split into (p,q) 7-branes at finite g_s (unlike $O7^-$)
- Same monodromy as $\mathfrak{so}_{16}$ - stack, but w/ "non-trivial flux" that "freezes" singularity in M-/F-theory

[Witten '97, de Boer et al '01, Tachikawa '15]

Junctions on $O7^+$

- $O7^+$ does not split into (p,q) 7-branes at finite g_s (unlike $O7^-$)
- Same monodromy as $\mathfrak{so}_{16}$ - stack, but w/ "non-trivial flux" that "freezes" singularity in M-/F-theory

[Witten '97, de Boer et al '01, Tachikawa '15]

- Freezing - local: "replacing" one stack [two stacks] with $O7^+$ yields theories of rank 10 [rank 2]

[Hamada,Vafa '21]

Junctions on $O7^+$

- $O7^+$ does not split into (p,q) 7-branes at finite g_s (unlike $O7^-$)
- Same monodromy as $\mathfrak{so}_{16}$ - stack, but w/ "non-trivial flux" that "freezes" singularity in M-/F-theory

[Witten '97, de Boer et al '01, Tachikawa '15]

- Freezing - local: "replacing" one stack [two stacks] with $O7^+$ yields theories of rank 10 [rank 2]

[Hamada,Vafa '21]

- Strings ending on $O7^+$ must have even p and q charges

[Imamura '99, Bergman,Gimon,Sugimoto '01]

[5-brane prongs of any integer (p,q)]

Derived, if configs. with one $O7^+$ are dual to CHL vacua

Junctions on $O7^+$

- $O7^+$ does not split into (p,q) 7-branes at finite g_s (unlike $O7^-$)
- Same monodromy as $\mathfrak{so}_{16}$ - stack, but w/ "non-trivial flux" that "freezes" singularity in M-/F-theory

[Witten '97, de Boer et al '01, Tachikawa '15]

- Freezing - local: "replacing" one stack [two stacks] with $O7^+$ yields theories of rank 10 [rank 2]

[Hamada,Vafa '21]

- Strings ending on $O7^+$ must have even p and q charges

[Imamura '99, Bergman,Gimon,Sugimoto '01]

[5-brane prongs of any integer (p,q)]
Derived, if configs. with one $O7^+$ are dual to CHL vacua

→ Analogous constructions w/global topology
w/ one $O7^+$ → all rank 10 vacua
w/ two $O7^+$ → all rank 2 vacua - first construction

Junctions in 9D uplifts:
sharpens swampland distance conjecture

Junctions in 9D uplifts: sharpens swampland distance conjecture

- Suitable infinite distance limits of F-theory in *K3* moduli space describe 9D N=1 theories of rank 17

[Lee, Lerche,Weigand '21]

Junctions in 9D uplifts: sharpens swampland distance conjecture

- Suitable infinite distance limits of F-theory in *K3* moduli space describe 9D N=1 theories of rank 17

[Lee, Lerche,Weigand '21]

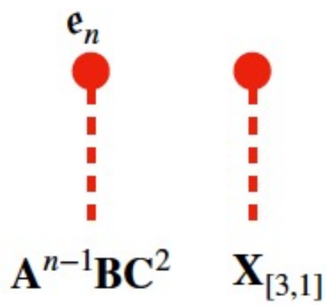
- Junctions characterized by appearance of singularities associated with affine algebras $\hat{e}_n$:

Junctions in 9D uplifts: sharpens swampland distance conjecture

- Suitable infinite distance limits of F-theory in *K3* moduli space describe 9D N=1 theories of rank 17

[Lee, Lerche,Weigand '21]

- Junctions characterized by appearance of singularities associated with affine algebras $\hat{e}_n$:

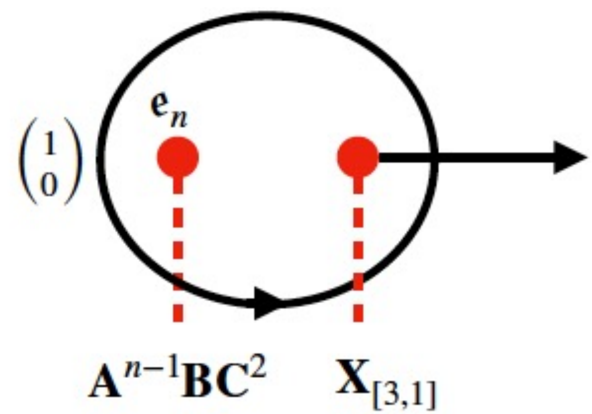


Junctions in 9D uplifts: sharpens swampland distance conjecture

- Suitable infinite distance limits of F-theory in *K3* moduli space describe 9D N=1 theories of rank 17

[Lee, Lerche, Weigand '21]

- Junctions characterized by appearance of singularities associated with affine algebras $\hat{e}_n$:

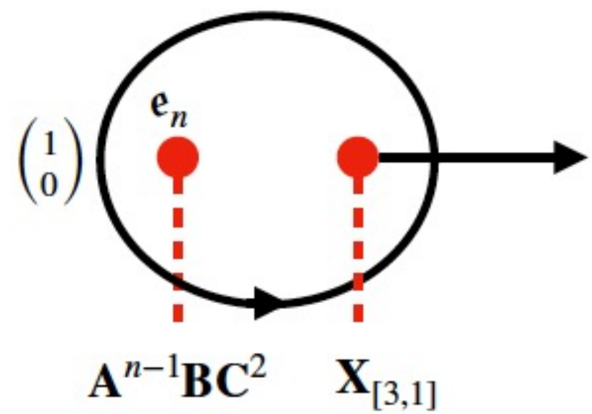


Junctions in 9D uplifts: sharpens swampland distance conjecture

- Suitable infinite distance limits of F-theory in *K3* moduli space describe 9D N=1 theories of rank 17

[Lee, Lerche, Weigand '21]

- Junctions characterized by appearance of singularities associated with affine algebras $\hat{e}_n$:

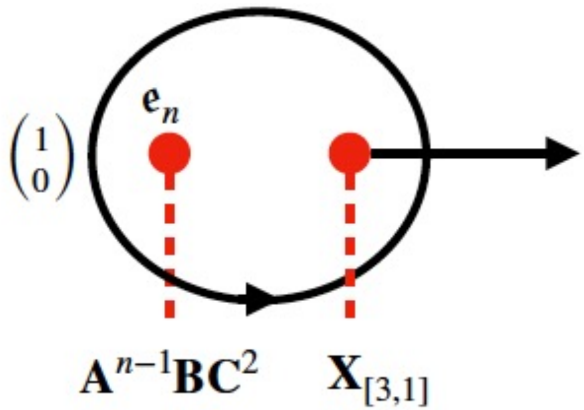


Junctions in 9D uplifts: sharpens swampland distance conjecture

- Suitable infinite distance limits of F-theory in *K3* moduli space describe 9D N=1 theories of rank 17

[Lee, Lerche, Weigand '21]

- Junctions characterized by appearance of singularities associated with affine algebras $\hat{e}_n$:



Two series:

$$\mathfrak{g}_{8d,\infty} = \mathfrak{su}_{18-m-n} \oplus \hat{\mathfrak{e}}_m \oplus \hat{\mathfrak{e}}_n \;\Rightarrow\; \mathfrak{g}_{9d} = \mathfrak{su}_{18-m-n} \oplus \mathfrak{e}_m \oplus \mathfrak{e}_n \,,$$

$$\mathfrak{g}_{8d,\infty} = \mathfrak{so}_{34-2k} \oplus \hat{\mathfrak{e}}_k \;\Rightarrow\; \mathfrak{g}_{9d} = \mathfrak{so}_{34-2k} \oplus \mathfrak{e}_k \,.$$

[Maximal non-Abelian enhancement in D=9 heterotic vacua

[Font, Fraiman, Grana, Parra de Freitas '20]]

9D uplifts with one $O7^+$ → rank 9

9D uplifts with one $O7^+$ → rank 9

- Characterized by ``freezing'' of one $\hat{e}_8$
- Maximal enhancements: $\mathfrak{su}_{10-n} \oplus \mathfrak{e}_n$ or $\mathfrak{so}_{18}$

[CHL: [Mikhailov '98; (Font), Fraiman, (Grana), Parra de Freitas '21]]

9D uplifts with one $O7^+$ → rank 9

- Characterized by ``freezing'' of one $\hat{e}_8$
- Maximal enhancements: $\mathfrak{su}_{10-n} \oplus \mathfrak{e}_n$ or $\mathfrak{so}_{18}$

[CHL: [Mikhailov '98; (Font), Fraiman, (Grana), Parra de Freitas '21]]

9D uplifts with two $O7^+$ → rank 1

9D uplifts with one $O7^+$ → rank 9

- Characterized by ``freezing'' of one $\hat{e}_8$
- Maximal enhancements: $\mathfrak{su}_{10-n} \oplus \mathfrak{e}_n$ or $\mathfrak{so}_{18}$

[CHL: [Mikhailov '98; (Font), Fraiman, (Grana), Parra de Freitas '21]]

9D uplifts with two $O7^+$ → rank 1

- Freezing of two $\hat{e}_8$: $\mathfrak{g}_{8d,\infty} = \mathfrak{su}_2 \oplus \hat{\mathfrak{e}}_8 \oplus \hat{\mathfrak{e}}_8 \quad \Rightarrow \quad G_{9d} = SU(2)$
- 9D, rank 1 has two disconnected moduli branches

[Aharony,Komargodski,Patir '07]

- Shown to be connected through D=8

9D uplifts with one $O7^+$ → rank 9

- Characterized by ``freezing'' of one $\hat{e}_8$
- Maximal enhancements: $\mathfrak{su}_{10-n} \oplus \mathfrak{e}_n$ or $\mathfrak{so}_{18}$

[CHL: [Mikhailov '98; (Font), Fraiman, (Grana), Parra de Freitas '21]]

9D uplifts with two $O7^+$ → rank 1

- Freezing of two $\hat{e}_8$: $\mathfrak{g}_{8d,\infty} = \mathfrak{su}_2 \oplus \hat{\mathfrak{e}}_8 \oplus \hat{\mathfrak{e}}_8 \;\Rightarrow\; G_{9d} = SU(2)$
- 9D, rank 1 has two disconnected moduli branches

[Aharony,Komargodski,Patir '07]

- Shown to be connected through D=8 ➡

All 9D string vacua are "emergent" from 8D ones!

Role of 1-form symmetry & Mixed 1-form - gauge anomalies in D≤8

- 8D [Font, Graña ,Fraiman, Freitas '21] – heterotic
  [M.C., Dierigl, Lin, Zhang '21, '22] – string junctions
- 7D [M.C., Dierigl, Lin, Zhang '21] – F/M-theory duality
  (torsional boundary G_4)
- 6D [Apruzzi, Dierigl, Lin '20] – excitations of BPS strings
- 5D [M.C., Dierigl, Lin, Zhang '21] – F/M-theory duality
  (torsional boundary G_4)
  [Apruzzi, Bonetti, García-Etxebarria, Hosseini, Schäfer-Nameki '22]...

Role of 1-form symmetry & Mixed 1-form - gauge anomalies in D≤8

- 8D [Font, Graña ,Fraiman, Freitas '21] – heterotic
  [M.C., Dierigl, Lin, Zhang '21, '22] – string junctions
- 7D [M.C., Dierigl, Lin, Zhang '21] – F/M-theory duality
  (torsional boundary G_4)
- 6D [Apruzzi, Dierigl, Lin '20] – excitations of BPS strings
- 5D [M.C., Dierigl, Lin, Zhang '21] – F/M-theory duality
  (torsional boundary G_4)
  [Apruzzi, Bonetti, García-Etxebarria, Hosseini, Schäfer-Nameki '22]...
- Mixed higher-form - gauge anomalies
  have important implications also for 6D and 5D SCFTs

Summary

- Physics:

  Employing higher-form symmetries to formulate anomaly condition for gauge group topology

  Gauged 1-form symmetry in 8D

Summary

- Physics:

  Employing higher-form symmetries to formulate anomaly condition for gauge group topology

  Gauged 1-form symmetry in 8D

- Geometry:

  F-theory/Heterotic string/CHL/string junctions

  Full 8D string theory landscape

Summary

- Physics:
  Employing higher-form symmetries to formulate anomaly condition for gauge group topology
  Gauged 1-form symmetry in 8D

perfect agreement

- Geometry:
  F-theory/Heterotic string/CHL/string junctions
  Full 8D string theory landscape

Future Directions

- Focused on 8D N=1 and role of 1-form gauge symmetry

$\Downarrow$

- Higher-group structures in D≤6

  0-form & 1-form symmetries → 2-group structures

Future Directions

- Focused on 8D N=1 and role of 1-form gauge symmetry

↓

- Higher-group structures in D≤6

  0-form & 1-form symmetries → 2-group structures

- Within SCFT's → geometric origin of higher group structures

[M. C., Heckman, Hübner , Torres '22]

[Del Zotto, Etxebarria, Schafer-Nameki '22]

Future Directions

- Focused on 8D N=1 and role of 1-form gauge symmetry

↓

- Higher-group structures in D≤6

  0-form & 1-form symmetries → 2-group structures

- Within SCFT's → geometric origin of higher group structures

[M. C., Heckman, Hübner , Torres '22]
[Del Zotto, Etxebarria, Schafer-Nameki '22]

- Their role in in quantum gravity -
  string theory on compact spaces

[M. C., Heckman,Hübner, E. Torres to appear]

Thank you!