Sigma models on gerbes

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A survey of a few highlights of:

2d models: hep-th/0502053, 0502027, 0502044, 0606034, arXiv:0709.3855, 1806.01283

4d models: arXiv: 1012.5999, 1404.3986, 1606.07078, 1609.00011, 1707.05322, & to appear

Today I will give a survey of work over the last ~ 15 years concerning QFT of strings on stacks, and strings on particular stacks known as gerbes.

One popular application of gerbes is as a mechanism to globally define two-form potentials, just as bundles can be thought of as mechanisms to define gauge fields on compact spaces.

That's **not** what I will have in mind today today.

Both stacks and (for the purposes of today's talk) gerbes can be thought of as generalized spaces — pseudo-geometric constructions that are locally, though not necessarily globally, spaces.

(see e.g. Urs's talk Mon)

Today's talk outlines work done to answer the question, to what extent can strings propagate on these generalized geometries?

Can one make sense of strings propagating on stacks and gerbes?
What is the quantum field theory of a sigma model on a stack or a gerbe?
How is it defined, and what are its properties?

Can one get new SCFT's, new string compactifications, from a string on a stack or a gerbe?

Furthermore, in sugrav theories, when should stacks enter low-energy effective nonlinear sigma models (NLSMs) on moduli spaces/stacks ?

Outline of today's talk

- QFT of 2d worldsheet sigma model with target stack or gerbe

- Properties — esp. decomposition:

  string on gerbe = string on disjoint union of spaces

- 4d low-energy effective sigma models with target stacks

- Examples of sugrav moduli stacks

  Prototype: moduli stack of elliptic curves: $[\mathfrak{h}/PSL(2,\mathbb{Z})]$, $[\mathfrak{h}/SL(2,\mathbb{Z})]$, vs $[\mathfrak{h}/Mp(2,\mathbb{Z})]$

- Implications for string dualities $SL(2,\mathbb{Z}) \mapsto Mp(2,\mathbb{Z})$

- Questions for the future

Briefly, what is a stack?

There are several ways to define analogues of geometry that don't involve point/set topology.
For ex, in noncommutative geometry, one defines a space via ring of functions.

Briefly, we define a stack via all the maps from other spaces to the stack.

This is nicely set up for sigma models,
in which the path integral sums over maps into the target.
For a stack, in principle the stack defines the maps into itself.

Examples of stacks include:
- ordinary spaces
- orbifolds
- gerbes

Brief example: Orbifold $[X/G]$, G finite.

A map $Y \to [X/G]$ is a pair

(principal G-bundle $E \to Y$, G-equivariant map Tot$(E) \to X$)

In physics, the bundle defines twisted sector,
and map is a map within that twisted sector.

Naturally have a *category* of such maps, as opposed to a *set* of maps,
with gauge transformations defining equivalent maps — as Urs described Monday.

How to define the QFT for a nonlinear sigma model with target a stack?

- Stacks can be locally presented as spaces — couldn't we glue NLSM's on spaces?

Unfortunately, it is not known how to perform such a glueing.
(Witten '05 proposed something like this for perturbative part,
but glueing nonperturbative physics currently unknown.)

- Stacks can be presented as groupoids — couldn't we just implement groupoid relations?

Unfortunately, this would appear to require a significant generalization of
current gauging, Faddeev-Popov, Batalin-Vilkovisky techniques.

- Is this even possible? What reason do we have to believe such a QFT exists?

Since before this work began, the Gromov-Witten community had been working on
(& now posseses) a notion of GW invariants of stacks.
Such a notion is no guarantee of existence of a full QFT,
but it is suggestive.

So, how to define the QFT of a NLSM for a stack target?

How to define the QFT for a nonlinear sigma model with target a stack?

Every* (smooth, Deligne-Mumford) stack can be presented as
a (stacky) global quotient [X/G],
for X a space and G a group.

(G need not be finite, & need not act effectively.)

To such a presentation,
associate a G-gauged sigma model on X.

Different presentations of the same stack can yield very different QFTs;
associate stacks to RG universality classes of such gauged sigma models.

(T Pantev, ES, ’05)

This is part of a more general story…
Yoga: homotopy ~ RG

(* with minor caveats)

Aside: Yoga: Homotopy as RG

Math	Physics
Stacks:	
presentation of a stack	gauged sigma model
equivalences of presentations	RG
Derived categories:	
complex of sheaves	branes/antibranes/tachyons
quasi-isomorphism	RG
(-1)-shft'd-symp'-Derived schemes:	
presentation of a derived scheme	Landau-Ginzburg model
equivalences	RG

(ES, Pantev, '05)

(ES, '99)

(Joyce '13; Ben-Bassat et al '13; `derived Darboux'; Pantev '13)

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(T Pantev, ES, '05)

In this language, what is a gerbe?

(* with minor caveats)

How to define the QFT for a nonlinear sigma model with target a stack?

Every* (smooth, Deligne-Mumford) stack can be presented as
a (stacky) global quotient [X/G],
for X a space and G a group.

To such a presentation,
associate a G-gauged sigma model on target space X.

(G need not be finite, & need not act effectively.)

In this language, what is a gerbe?

A sigma model on a gerbe can be described in several equivalent ways on 2d worldsheets:

- a gauge theory in which a subgroup of G acts trivially on X
- a gauge theory with a restriction on nonperturbative sectors
- a gauge theory `coupled to a TFT'

For the moment, we'll focus on the first description,
as a gauge theory in which a subgroup acts trivially,
and later will return to the description in terms of restricted nonperturbative sectors.

How to define the QFT for a nonlinear sigma model with target a stack?

A sigma model on a gerbe is

- a gauge theory in which a subgroup of G acts trivially on X

Potential issue:

Mathematics/stacks remember even trivial group actions,
but why should physics?

Why is such a gauge theory any different at all
from a gauge theory in which one gauges the effectively-acting coset?

For example, if I have a U(1) gauge theory,
and declare that all the electrons have charge 2 instead of charge 1,
what possible difference can it make?

Answer: nonperturbative effects **(T Pantev, ES, '05)**

How to define the QFT for a nonlinear sigma model with target a stack?

A sigma model on a gerbe is

- a gauge theory in which a subgroup of G acts trivially on X

Why is such a gauge theory any different at all
from a gauge theory in which one gauges the effectively-acting coset?

Answer: nonperturbative effects **(T Pantev, ES, '05)**

- *Compact worldsheet:*

To specify Higgs field, must specify bundle.
If gauge field ~L, then charge Q means section of $L^{\otimes Q}$

Different bundle => different zero modes => different anomalies => different physics

- *Noncompact worldsheet:* 2d case: theta angle periodicity

Distinguish gerbe from non-gerbe by adding massive charge ± 1 fields.

2d theta angle acts like electric field. As field increases, eventually pair produces any massive states, which determines theta angle periodicity.

- *Defects:* add Wilson lines of charges that only well-defined in certain theories.

Example: Analogue of the 2d susy $\mathbb{CP}^{N-1}$ model.

Ordinary 2d $\mathbb{CP}^{N-1}$ model: U(1) gauge theory, N chiral superfields of charge 1

Gerby analogue: U(1) gauge theory, N chiral superfields of charge k

Differences:

Anomalous global U(1)s:

$\mathbb{CP}^{N-1}: \quad U(1)_A \mapsto \mathbb{Z}_{2N}$ Gerby: $U(1)_A \mapsto \mathbb{Z}_{2kN}$

A model correlation functions:

$\mathbb{CP}^{N-1}: \quad \langle x^{N(d+1)-1} \rangle = q^d$ Gerby: $\langle x^{N(kd+1)-1} \rangle = q^d$

(Note ~ restriction on nonpert' sectors)

Quantum cohomology:

$\mathbb{CP}^{N-1}: \quad \mathbb{C}[x]/(x^N - q)$ Gerby: $\mathbb{C}[x]/(x^{kN} - q)$

Different physics

Another issue: **Cluster decomposition**

As we briefly saw in the $\mathbb{CP}^{N-1}$ model example,
these theories are equivalent to restricting allowed nonperturbative sectors,
which violates cluster decomposition,
a fundamental axiom of QFT.

Similarly, if one computes chiral rings & spectra in such 2d theories,
one finds multiple dimension zero operators,
again signalling violation of cluster decomposition.

Resolution (in 2d theories): **Decomposition**

strings on gerbes = strings on disjoint unions of spaces

(which also violate cluster decomposition,
but in a manner we understand & control.)

(Hellerman, Henriques, Pantev, ES, Ando,
hep-th/0606034)

Decomposition of sigma models on gerbes

- Version for NLSMs on spaces/orbifolds:

Consider $[X/G]$ where $1 \longrightarrow K \longrightarrow G \longrightarrow H \longrightarrow 1$

and K acts trivially on X. For simplicity, also assume gerbe is `banded.'

Decomposition: For $Y = [X/H]$ (effectively-acting quotient)

$$\mathrm{QFT}([X/G]) = \mathrm{QFT}\left(\coprod_{\hat{G}} (Y, B) \right)$$

$\hat{G}$ = irreps of G

where B field is determined by the image of

$$H^2(Y, Z(G)) \stackrel{Z(G) \to U(1)}{\longrightarrow} H^2(Y, U(1))$$

(Hellerman, Henriques, Pantev, ES, Ando, hep-th/0606034)

- Version for nonabelian 2d gauge theories:

If matter is invariant under a subgroup of the center of gauge group, then decompose with factors differing by discrete theta angles.

Example, schematic: pure SU(2) = pure $SO(3)_+$ + pure $SO(3)_-$

(ES, 1404.3986)

Idea behind decomposition: (version for spaces)

Summing over NLSMs on Y with different B fields
projects out many nonperturbative sectors,
realizing the gerbe theory.

Schematically,

path integral with restriction on nonpert' sectors

$$= \int [d\phi] \exp(-S) \underbrace{\sum_B \exp\left(\int \phi^* B \right)}$$

projection operator

$$= \sum_B \int [d\phi] \exp\left(-S + \int \phi^* B \right)$$

= path integral for disjoint union of spaces with variable B fields

Example: Partition function of a Z_2 gerbe over [X/ Z_2xZ_2]

Consider $[X/D_4]$ where the center acts trivially.

$$1 \longrightarrow \mathbb{Z}_2 \longrightarrow D_4 \longrightarrow \mathbb{Z}_2 \times \mathbb{Z}_2 \longrightarrow 1$$

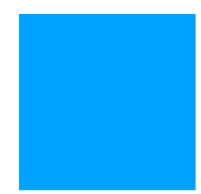
Decomposition predicts $$\mathrm{CFT}\left([X/D_4]\right) = \mathrm{CFT}\left([X/\mathbb{Z}_2 \times \mathbb{Z}_2] \coprod [X/\mathbb{Z}_2 \times \mathbb{Z}_2]\right)$$

where one of the $\mathbb{Z}_2 \times \mathbb{Z}_2$ orbifolds has discrete torsion & the other does not.

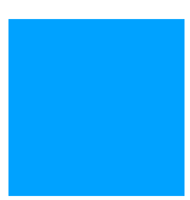
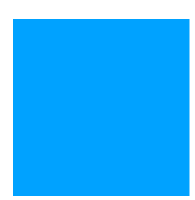
Compute genus one partition function:

$$D_4 = \{1, z, a, b, az, bz, ab, ba = abz\} \qquad \mathbb{Z}_2 \times \mathbb{Z}_2 = D_4/\mathbb{Z}_2 = \{1, \overline{a}, \overline{b}, \overline{ab} = \overline{ab}\}$$

$$Z([X/D_4]) = \frac{1}{|D_4|} \sum_{gh=hg} Z_{g,h}$$

$Z_{g,h}$ = g  h

Each D_4 twisted sector is the same as a $\mathbb{Z}_2 \times \mathbb{Z}_2$ twisted sector, appearing with multiplicity $|\mathbb{Z}_2|^2 = 4$, except for the

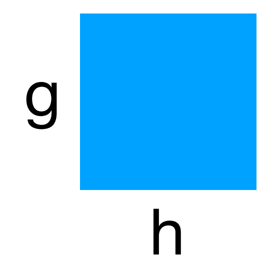
$\overline{a}$  $\overline{b}$ $\quad$ $\overline{a}$  $\overline{ab}$ $\quad$ $\overline{b}$  $\overline{ab}$ $\quad$ sectors.

(Lifts to D_4 don't commute.)

Example: **Partition function of a Z_2 gerbe over [X/ Z_2xZ_2]**

$$D_4 = \{1, z, a, b, az, bz, ab, ba = abz\} \qquad \mathbb{Z}_2 \times \mathbb{Z}_2 = D_4/\mathbb{Z}_2 = \{1, \overline{a}, \overline{b}, \overline{ab} = \overline{ab}\}$$

$$Z([X/D_4]) = \frac{1}{|D_4|} \sum_{gh=hg} Z_{g,h} \qquad Z_{g,h} =$$



Each D_4 twisted sector is the same as a $\mathbb{Z}_2 \times \mathbb{Z}_2$ twisted sector,
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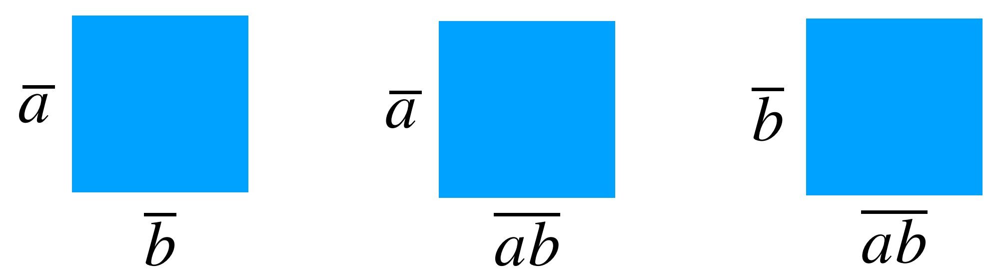


sectors.

(Lifts to D_4 don't commute.)

$$Z([X/D_4]) = \frac{|\mathbb{Z}_2 \times \mathbb{Z}_2|}{|D_4|} |\mathbb{Z}_2|^2 \left(Z([X/\mathbb{Z}_2 \times \mathbb{Z}_2]) - \left(\text{some twisted sectors}\right) \right)$$

$$= 2 \left(Z([X/\mathbb{Z}_2 \times \mathbb{Z}_2]) - \left(\text{some twisted sectors}\right) \right)$$

Discrete torsion acts as a sign on the omitted twisted sectors above of the $\mathbb{Z}_2 \times \mathbb{Z}_2$ orbifold, hence

$$Z([X/D_4]) = Z\left([X/\mathbb{Z}_2 \times \mathbb{Z}_2] \coprod [X/\mathbb{Z}_2 \times \mathbb{Z}_2] \right)$$

with discrete torsion in one component, consistent with prediction of decomposition.

Applications of decomposition of sigma models on gerbes:

- Gromov-Witten theory:

GW invariants of gerbe = GW invariants of disjoint union of spaces

Proven in work of H-H Tseng, Y Jiang, & others

(e.g. 0812.4477, 0905.2258, 0907.2085, 0912.3580, 1001.0435, 1004.1376)

- Phases of GLSMs

Prototype: LG point of GLSM for intersection of quadrics

= branched double cover, realized via nonpert' effects

Physical realization of Kuznetsov's homological projective duality

(e.g. Caldararu, Distler, Hellerman, Pantev, ES 0709.3855;
Hori 1104.2853; Halverson, Jockers, Lapan, Morrison '13;
Chen, Pantev, ES 1806.01283)

Question: Is there a 3d analogue of decomposition?

I don't expect the theory to decompose as a disjoint union,
but there may be some sort of analogous statement for just defects, for example.

Summary so far

- QFT of 2d worldsheet sigma model with target stack or gerbe

- Properties — esp. decomposition:

  string on gerbe = string on disjoint union of spaces

Remaining:

- 4d low-energy effective sigma models with target stacks

- Examples of sugrav moduli stacks

  Prototype: moduli stack of elliptic curves: $[\mathfrak{h}/PSL(2,\mathbb{Z})]$, $[\mathfrak{h}/SL(2,\mathbb{Z})]$, vs $[\mathfrak{h}/Mp(2,\mathbb{Z})]$

- Implications for string dualities $SL(2,\mathbb{Z}) \mapsto Mp(2,\mathbb{Z})$

- Questions for the future

Four-dimensional nonlinear sigma models

So far we have focused on 2d NLSMs,
that is, QFTs on 2d spaces with targets of unspecified dimension.

In principle, we can also consider 4d low-energy effective NLSMs,
that is, QFTs on 4d spaces with targets of unspecified dimension.

These arise in e.g. four-dimensional supergravity theories,
describing the space of scalar field vevs.

Analogous considerations apply there.

A 4d NLSM on a gerbe is distinguished by:

- *Compact 4d spaces:* to specify Higgs fields, specify line bundles, as before.

- *Noncompact 4d spaces*:

  Distinguish gerbe from non-gerbe by adding massive charge ± 1 fields.

  Can `see' beyond cutoff scale using Hawking radiation of charged Riessner-Nordstrom black holes; if start at charge k but massive charge 1 exists, will radiate down to charge 1.

- *Defects:* add e.g. Wilson lines of charges that only well-defined in certain theories

Next, we'll consider examples of gerby moduli spaces that can arise as targets of 4d low-energy effective NLSMs in e.g. supergravity theories.

In a perturbative string compactification,
the low energy 4d sugrav contains a low energy effective NLSM
with target a moduli space of Calabi-Yau's,
= moduli space of 2d SCFTs.

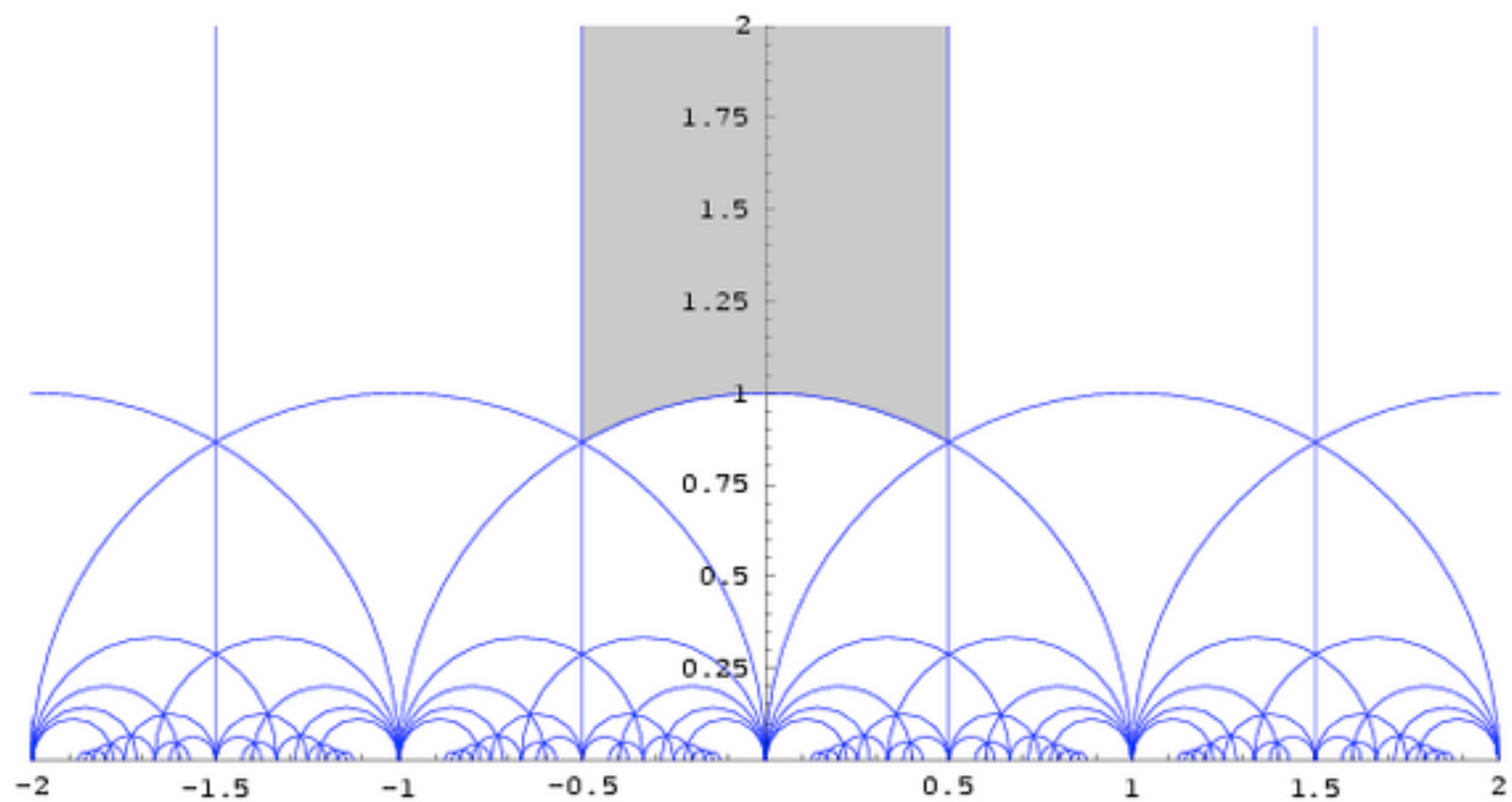
So, let's look at moduli spaces of 2d SCFTs,
corresponding to moduli spaces of (NLSMs on) Calabi-Yau's.

Prototype: moduli space of elliptic curves.

Prototype: moduli spaces of elliptic curves

Let's now consider a moduli space of elliptic curves.

To review, this is often presented as a $PSL(2,\mathbb{Z})$ quotient of the upper half plane.



Action on the upper half plane: $\tau \mapsto \dfrac{a\tau + b}{c\tau + d}$ $\quad \begin{bmatrix} a & b \\ c & d \end{bmatrix} \in SL(2,\mathbb{Z})$

The center $\begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}$ acts trivially, hence we describe as $PSL(2,\mathbb{Z}) = SL(2,\mathbb{Z})/\mathbb{Z}_2$.

There's more to this story….

Prototype: moduli spaces of elliptic curves

To review, this is often presented as a $PSL(2,\mathbb{Z})$ quotient of the upper half plane.

However, the line bundle of holomorphic top forms (1-forms) is not well-defined over the $PSL(2,\mathbb{Z})$ quotient.

Let z be an affine coordinate on the complex plane cover, then under $SL(2,\mathbb{Z})$,

$$(\tau, z) \mapsto \left(\frac{a\tau + b}{c\tau + d}, \frac{z}{c\tau + d} \right)$$

(Hain, 0812.1803)

hence

$$dz \mapsto \frac{dz}{c\tau + d}$$

The center $\left[\begin{array}{cc} -1 & 0 \\ 0 & -1 \end{array} \right]$ acts trivially on τ but $z \mapsto -z$

Thus, holomorphic top-form not well-defined in $PSL(2,\mathbb{Z})$ quotient.

Fix: define moduli space to be $[\mathfrak{h}/SL(2,\mathbb{Z})]$ for $\mathfrak{h}$ = upper half plane.

(= $\mathbb{Z}_2$ gerbe)

Line bundle of hol' top forms (= Hodge line bundle) is naturally defined over $SL(2,\mathbb{Z})$ quotient.

Physics: dz ~ spectral flow operator, so for moduli space of SCFTs, want $SL(2,\mathbb{Z})$ quotient.

Prototype: moduli spaces of elliptic curves

So far: mathematically `nice' moduli space is $[\mathfrak{h}/SL(2,\mathbb{Z})]$ (for $\mathfrak{h}$ = upper half plane).

— this is standard.

— also, since hol' top form ~ spectral flow operator, is part of what we need for a good moduli space of SCFTs.

However, to get a good moduli space of SCFTs, we need more.

Issue: chiral Ramond vacuum **not** well-defined under either PSL or SL quotient.

Under $SL(2,\mathbb{Z})$, $$(\tau, z, |0\rangle) \mapsto \left(\frac{a\tau + b}{c\tau + d}, \frac{z}{c\tau + d}, \pm \frac{|0\rangle}{\sqrt{c\tau + d}} \right)$$

— sign ambiguity in action on Fock vacuum

To fix, replace $SL(2,\mathbb{Z})$ by a $\mathbb{Z}_2$ extension.

Result: $|0\rangle$ well-defined in families on $[\mathfrak{h}/Mp(2,\mathbb{Z})]$

(Gu, ES, 1606.07078)

$Mp(2,\mathbb{Z})$ = unique nontrivial central $\mathbb{Z}_2$ ext of $SL(2,\mathbb{Z})$ = metaplectic group

Conjecture: Moduli space of (cpx structures of) SCFTs for elliptic curves = $[\mathfrak{h}/Mp(2,\mathbb{Z})]$

Prototype: moduli spaces of elliptic curves

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Proposal for string dualities:

Due to sign ambiguities in duality actions on fermions, other $SL(2,\mathbb{Z})$'s are replaced by $Mp(2,\mathbb{Z})$'s.

(Pantev, ES, 1609.00011)

T-duality of T²: For ~ same reasons, replace $SL(2,\mathbb{Z})$ factors in $SO(2,2;\mathbb{Z})$ by $Mp(2,\mathbb{Z})$.

10d type IIB S-duality:

Because of sign ambiguity in S-duality action on 10d fermions, also replace $SL(2,\mathbb{Z})$ by $Mp(2,\mathbb{Z})$. (Also noticed by D. Morrison)

M theory / T²: Action of mapping class group on fermions is $Mp(2,\mathbb{Z})$.

U-duality in 9d: $Mp(2,\mathbb{Z})$ instead of $SL(2,\mathbb{Z})$,

& analogously in lower dimensions.

Which moduli stack is sensed by defects in 10D type IIB?

$[\mathfrak{h}/PSL(2,\mathbb{Z})]$ $[\mathfrak{h}/SL(2,\mathbb{Z})]$ or $[\mathfrak{h}/Mp(2,\mathbb{Z})]$?

In F theory compactifications, there is a defect which senses the center of $SL(2,\mathbb{Z})$,
corresponding to a Kodaira fiber I_0^*,
or a D7 brane on an $O7^-$ -plane.

So, at least $[\mathfrak{h}/SL(2,\mathbb{Z})]$ and maybe $[\mathfrak{h}/Mp(2,\mathbb{Z})]$

Question:

Is there a D7 brane configuration that senses the $\mathbb{Z}_2$ specific to $Mp(2,\mathbb{Z})$?

Examples of 4d sugrav moduli spaces from Calabi-Yau 3-fold compactification

Very few are completely known explicitly.

Several toroidal orbifolds are discussed in **(Donagi, ES 1707.05322)**

Three smooth cases, all freely-acting orbifolds of form $[T^6/(\mathbb{Z}_2)^r]$

Moduli spaces: $[\mathfrak{h}/\Gamma_1(2)]^3$ $\quad$ $[\mathfrak{h}/\Gamma(2)]^3$ $\quad$ $[\mathfrak{h}/\Gamma(2)]^2 \times [\mathfrak{h}/\Gamma_1(2)]$

(before taking into account spinor subtleties)

where $\Gamma(2), \Gamma_1(2) \subset SL(2,\mathbb{Z})$ and $\mathfrak{h} =$ upper half plane

In each case, Hodge line bundle is nontrivial & generates Picard group.

To take into account spinor subtleties, quotient $\mathfrak{h}^3$ by a $\mathbb{Z}_2$ extension of product of three Γ's.

(to appear)

Summary

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Remaining:

- Questions for the future

Questions for the future:

- Relevance of gerbe structures on moduli spaces of 6d (2,0) theories?

- Is there a D7 brane configuration that senses the $\mathbb{Z}_2$ specific to $Mp(2,\mathbb{Z})$ in 10d IIB?

- Is there a 3d analogue of decomposition?

I don't expect the theory to decompose as a disjoint union,
but there may be some sort of analogous statement for just defects, for example.

(1st pass: Aharony et al, 1710.00926)

- Conjecture: Hodge line bundles are nontrivial in UV complete theories

Very few explicit examples are known,
but in those examples — inc. free field theories —
the Hodge line bundle over the CY moduli space is nontrivial.

(variation on weak gravity conjecture)

Blue-sky questions

- *What about higher stack variations of the constructions presented here?*

The categorical equivalences of ordinary (1-)stacks are realized physically via RG flow.
We identify two physical presentations of the same stack,
two different gauged sigma models corresponding to the same stack,
if they lie in the same RG universality class.

To realize higher order structures, one would appear to need a refinement of RG flow.

Might higher-order structures be realized via irrelevant operator deformations ?

This would in fact seem to be a better model for what is meant physically by
`RG universality class', which roughly means related up to
irrelevant operator deformation;
sounds akin to saying operations close up to invertible higher morphism.

Blue-sky questions

- *More general constructions of fine moduli stacks of SCFTs*

Here I've presented a conjecture for moduli spaces of (cpx structures of) NLSMs with target elliptic curves.

More generally, one could imagine a construction in which over open sets on the moduli space, one has a sheaf of UV physical theories related by RG flow and irrelevant operators.

"sheaf of RG flows"

Gluing:

- On overlaps, match if two theories flow to same theory at some scale, up to field redef'ns & irrelevant operators
- On triple overlaps, match if three theories flow to same theory at some scale, up to field redef'ns & irrelevant operators
- On quadruple overlaps, ….

— some sort of infinity sheaf

— a `universal SCFT' would be a section

(Idea: W Gu, ES 1606.07078)

Thank you for your time!