Non-supersymmetric string theory

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Quantum Gravity and Modularity

Dublin May 3rd, 2021

Based on work with Niccolò Cribiori, Susha Parameswaran and Flavio Tonioni 2012.04677 + forthcoming
Outline

• Introduction and motivation

• Non-linear supergravity

• Misaligned supersymmetry

• Conclusion
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• Non-linear supergravity

• Misaligned supersymmetry

• Conclusion
Our universe

- The LHC has done a spectacular job at confirming the SM of particle physics
No SUSY discovery

- The LHC has done a spectacular job at confirming the SM of particle physics
- Unfortunately no discovery of supersymmetry

“The status of supersymmetry: Once the most popular framework for physics beyond the Standard Model, supersymmetry is facing a reckoning—but many researchers are not giving up on it yet”
https://www.symmetrymagazine.org/
No SUSY discovery

• The LHC has done a spectacular job at confirming the SM of particle physics

• Unfortunately no discovery of supersymmetry

• We are now faced with two problems:
  1. The cosmological constant problem
  2. The hierarchy problem

  SUSY cannot really explain either
The problems:

1. The cosmological constant problem:

   Fermion

   Supersymmetry leads to perfect cancellations

   Boson

2. The hierarchy problem:

   Supersymmetry leads to perfect cancellations
The problems:

1. The cosmological constant problem:

   Broken supersymmetry leads to:

   \[ \frac{1}{\Lambda^4} \sim E_{\text{SUSY}} > E_{\text{cut-off}} \sim 10 \text{ TeV} \]

2. The hierarchy problem:

   Broken supersymmetry leads to:

   \[ \delta m_H \sim E_{\text{SUSY}} > E_{\text{cut-off}} \sim 10 \text{ TeV} \]
Non-SUSY string theory

• Without SUSY things are substantially more complicated

• However, it seems incredibly important to understand non-supersymmetric string theories better
Non-SUSY string theory

SUSY breaking in string theory:
1. It seems clearly possible to get low energy 4d $N = 1$ supergravities in string theory
   ⇒ break SUSY via F-terms and D-terms

   • Heterotic string theory on orbifolds or $CY_3$
   • intersecting D-branes
   • D-branes at singularities
   • F-theory on $CY_4$
   • ...

This mimics SUSY model building (BSM physics via string theory).
Non-SUSY string theory

SUSY breaking in string theory:

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   $\Rightarrow$ break SUSY via F-terms and D-terms

2. Do something more stringy:
   a) Break SUSY at compactification scale
      
      Bonnefoy, Dudas, S. Lüst  1811.11199
      Acharya  1906.06886
      Acharya, Aldazabal, Andrés, Font, Narain, Zadeh  2010.02933

   b) Break SUSY at the string scale using non-mutually supersymmetric ingredients

   c) Start with non-SUSY string theories

   d) ....
Non-SUSY string theory

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Very hard problems but we are asking basic questions like:
Can the cosmological constant be finite in theories without SUSY?
Non-SUSY string theory

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Can the cosmological constant be finite in theories without SUSY?
String theories is UV complete and finite, so the answer is: YES!
But how exactly does this work?
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See part 3 below and also Niccolò Cribiori tomorrow!
Non-SUSY string theory

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      supersymmetric ingredients
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   d) ....
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Non-linear supergravity

• The most debated string compactifications involve an anti-D3-branes that are not mutually supersymmetric with respect to other ingredients

• This makes them worthwhile to study and the last few years have seen lots of progress
Non-linear supergravity

• dS vacua in type IIB (KKLT and LVS) need an anti-D3-brane to uplift AdS vacua

Kachru, Kallosh, Linde, Trivedi  hep-th/0301240
Balasubramanian, Berglund, Conlon, Quevedo  hep-th/0502058
Non-linear supergravity

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  Kachru, Kallosh, Linde, Trivedi hep-th/0301240
  Balasubramanian, Berglund, Conlon, Quevedo hep-th/0502058

- Similar in type IIA dS vacua are unstable without anti-D6-branes

  Kallosh, Wrase 1808.09427
  Blåbäck, Danielsson, Dibitetto 1810.11365
  Andriot 2101.06251
Non-linear supergravity

- **Anti-branes** are an interesting toy for studying SUSY breaking in string theory.
- We can study them for example in flat space and have a lot of control (full string theory).
Non-linear supergravity

- Anti-branes are an interesting toy for studying SUSY breaking in string theory
- We can study them for example in flat space and have a lot of control (full string theory)
- They exhibit a couple of interesting features (see below)
- Supersymmetry is spontaneously broken and non-linear realized

Aalsma, Antoniadis, Bandos, Bansal, Bergshoeff, Carrasco, Cribiori, Dall'Agata, Dasgupta, Dudas, Farakos, Ferrara, Freedman, Garcia del Moral, Garcia-Etxebarria, Hasegawa, Heller, Kallosh, Kehagias, Kuzenko, Linde, Martucci, McDonough, McGuirk, Nagy, Padilla, Parameswaran, Quevedo, Quiroz, Roupec, Sagnotti, Scalisi, Schillo, Shiu, Sorokin, Thaler, Tournoy, Tyler, Uranga, Valandro, Van Der Schaar, van der Woerd, Van Proeyen, Vercnocke, Wrase, Yamada, Zavala, Zwirner, ...

Cribiori, Roupec, Tournoy, Van Proeyen, Wrase 2004.13110
Non-linear supergravity

Op-plane

Dp-brane
Non-linear supergravity

\[ M_{\text{SUSY}}^2 \sim \sin(\theta) M_s^2 \]
Non-linear supergravity

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Op-plane \hspace{1cm} Dp-brane
Non-linear supergravity

\[ M_{\text{SUSY}}^2 \sim \sin(\theta) M_s^2 \]

\[ \theta = \pi \]

Op-plane \quad \text{anti-Dp-brane}
Non-linear supergravity

\[ \theta = \pi \]

There is a maximal SUSY breaking scale (it is not \( \infty \)):

\[ M_{\text{SUSY}}^2 \sim \sin(\theta) M_s^2 \]

\[ M_{\text{SUSY}}^2 = M_s^2 \]
Non-linear supergravity

There is a maximal SUSY breaking scale (it is not $\infty$): 

$$M_{SUSY}^2 \sim \sin(\theta) M_s^2$$

$\theta = \pi$

The setup has 16 spontaneously broken and non-linearly realized supercharges. Is something similar true for other non-SUSY string theories?

$$M_{SUSY}^2 = M_s^2$$

Op-plane

anti-Dp-brane
Non-linear supergravity

The spectrum of the anti-Dp-brane is essentially the same as that of a Dp-brane. Expect substantial cancellations in loops (but unstable).

\[ \theta = \pi \]

\[ M_{\text{SU}}^2 \sim \sin(\theta) M_s^2 \]

There is a maximal SUSY breaking scale (it is not \( \infty \)):

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Non-linear supergravity

Op-plane

anti-Dp-brane
Non-linear supergravity

Op-plane

anti-Dp-brane
Non-linear supergravity

Op-plane anti-Dp-brane
Non-linear supergravity
Non-linear supergravity

- Perturbatively stable
- No massless bosonic degrees of freedom
- Can arise for example at the bottom the KS-throat for $p=3$

Kallosh, Quevedo, Uranga 1507.07556
Garcia-Etxebarria, Quevedo, Valandro 1512.06926
Cribiori, Roupec, Wrase, Yamada 1906.07727
Non-linear supergravity

Boson-fermion degeneracy broken: 8 fermionic DOF at the massless level but no bosons

E.g. O3-anti-D3: $A_\mu$, $\phi^I, I = 1,2,3$, $\lambda^0$, $\lambda^I$

• Perturbatively stable
• no massless bosonic degrees of freedom

Projected out by O3

anti-Dp-brane Op-plane
How can we get the finite results expected from string theory without supersymmetry?

- We will answer this in this model
- It is special: $M_{\text{susy}} = M_S$
- It exhibits the same features as generic non-SUSY string theories but is simpler
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Non-SUSY string theory

There are a variety of non-supersymmetric string theories:

1. The bosonic string in D=26, ...

String theories with tachyons ⇔ no good
Non-SUSY string theory

There are a variety of non-supersymmetric string theories:

1. The bosonic string in D=26, ...

   String theories with tachyons $\Leftrightarrow$ no good

2. The heterotic $SO(16) \times SO(16)$ string (= an orbifold of the heterotic $E_8 \times E_8$), Dp-brane on an Op-plane, ...
Non-SUSY string theory

30 years ago people thought about these theories:

• It was proposed that bosons and fermions cancel asymptotically among the massive tower of string states

Asymptotic SUSY

Kutasov, Seiberg 1991
Kutasov  hep-th/9110041
Non-SUSY string theory

30 years ago people thought about these theories:

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  \textbf{Asymptotic SUSY}

  Kutasov, Seiberg 1991
  Kutasov hep-th/9110041

- It was then noticed that there is never ever an exact cancellation between bosons and fermions at any level.
  
  \textbf{Misaligned SUSY}

  Dienes hep-th/9402006
  Dienes, Moshe, Myers, hep-th/9503055
  ...
  Niarchos hep-th/0010154

- A very nice overview is provided in for example
  
  Dienes hep-ph/0104274
Misaligned supersymmetry

An anti-Dp-brane on top of an Op-plane is a simple example of misaligned SUSY

Cribiori, Parameswaran, Tonioni, TW 2012.04677

The 1-loop partition function counts the states at each mass level \( n = 1, 2, \ldots \) (\( q^n \leftrightarrow m^2 = n/\alpha' \)):

\[
Z \sim \sum_n a_n \ q^n = -8 + 128 \ q - 1152 \ q^2 + 7680 \ q^3 - \cdots
\]

Our massless 8 fermions: \( |0\rangle_R \)

128 bosons with \( m^2 = 1/\alpha' \):

- 56 \( b_{-1/2}^i b_{1/2}^j b_{-1/2}^k |0\rangle_{NS} \)
- 64 \( \alpha_{-1/2}^i b_{1/2}^j |0\rangle_{NS} \)
- 8 \( b_{-3/2}^i |0\rangle_{NS} \)
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Bosons and fermions never cancel at any fixed mass level
Misaligned supersymmetry

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$$Z \sim \sum_n a_n \ q^n = -8 + 128 \ q - 1152 \ q^2 + 7680 \ q^3 - \ldots$$

$$= -\frac{1}{2} \frac{\theta_2(-q)^4}{\eta(-q)^{12}} = -\frac{8}{\theta_3(q)^8} = -8 \frac{\eta(q^2)^8}{\eta(-q)^{16}}$$

This is a modular function under a subgroup of $SL(2, \mathbb{Z})$
Misaligned supersymmetry

An anti-Dp-brane on top of an Op-plane is a simple example of misaligned SUSY.
Misaligned supersymmetry

The spectrum oscillates between net bosonic and net fermionic degeneracies in a highly symmetric way.
Misaligned supersymmetry

Insight: While bosons and fermions do not cancel at any mass level, they can average out because of the oscillation!

• Incredibly subtle to get such cancellations (not at all natural from a low energy effective point of view)

• There is no supersymmetry whatsoever!
Misaligned supersymmetry

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• Averaged boson and fermion cancellation led to the name asymptotic or misaligned SUSY

• Bosons and fermions are misaligned in some sense but also grow: $-8 + 128 \ q - 1152 \ q^2 + 7680 \ q^3 - \cdots$
Misaligned supersymmetry

• Can we make the above insight precise?
• The number of states $a_n$ grows exponentially (Cardy):

$$a_n \sim e^{4\pi \sqrt{n} \sqrt{\frac{c}{24}}} \sim e^{2\pi \sqrt{2} \sqrt{n}}, \quad c = 8 + 8 \cdot \frac{1}{2} = 12$$
Misaligned supersymmetry

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• For the open string example one can split them into $n$ even integer with $a_n^f < 0$ and $n$ odd with $a_n^b > 0$

• For large $n$ one then has $-a_n^f \approx a_n^b \approx e^{2\pi\sqrt{2}\sqrt{n}}$
Misaligned supersymmetry

• For large $n$ one can use that $-a_n^f \approx a_n^b \approx e^{2\pi \sqrt{2} \sqrt{n}}$ and replace the sum by an integral and find that

$$\lim_{q \to 1} Z \sim \sum_{n \in 2\mathbb{Z}} a_n^f + \sum_{n \in 2\mathbb{Z}+1} a_n^b$$

$$\approx -e^{2\pi \sqrt{2} \sqrt{n}} + e^{2\pi \sqrt{2} \sqrt{n}} < \Theta \left( e^{2\pi \sqrt{2} \sqrt{n}} \right)$$

The leading order exponential divergence cancels
Misaligned supersymmetry

The leading order exponential divergence cancels:

$$\pm \log_{10}|N_{\text{bos}} - N_{\text{fer}}|$$

$$+e^{2\pi\sqrt{2}\sqrt{n}}$$

$$-e^{2\pi\sqrt{2}\sqrt{n}}$$
Misaligned supersymmetry

• Using *conformal symmetry* one can proof that the leading order exponential divergence always cancels in non-supersymmetric string theories

• It seems we are clearly on the right track and discovered something fascinating
Misaligned supersymmetry

• Using \textit{conformal symmetry} one can proof that the leading order exponential divergence always cancels in non-supersymmetric string theories

• It seems we are clearly on the right track and discovered something fascinating

• There are power law suppressed terms and an infinite number of subleading exponentials (see below)

• All subleading exponentials need to cancel as well. How?
All order cancellation

• We have seen above that leading order cancellation of exponentials is achieved but not enough
• Extension beyond leading order was unclear

Dienes hep-th/9402006
All order cancellation

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Dienes hep-th/9402006

• The Hardy-Ramanujan-Rademacher sum:

See for example: Sussman 1710.03415

Let $Z(q) \sim \sum_n a_n q^n$ be a modular function for a subgroup of $SL(2, \mathbb{Z})$, then

$$a_n = \sum_{k=1}^{\infty} A_k(n) \ I_m \left( \frac{4\pi \sqrt{n}}{k} \sqrt{c} \right)$$
All order cancellation

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$I$-Bessel function, for large $x$:

$$I_m(x) = \frac{e^x}{\sqrt{2\pi x}} \left( \frac{2}{x} \right)^m \left( 1 - \frac{4m^2-1}{8x} + O \left( \frac{1}{x^2} \right) \right)$$
All order cancellation

\[ a_n^{B/F} = \sum_{k=1}^{\infty} A_k^{B/F}(n) I_m \left( \frac{4\pi \sqrt{n}}{k} \sqrt{\frac{c}{24}} \right) \]
All order cancellation

\[ a_n^{B/F} = \sum_{k=1}^{\infty} A_k^{B/F} (n) \ I_m\left(\frac{4\pi \sqrt{n}}{k} \sqrt{\frac{c}{24}}\right) \]

At leading order, i.e. for \( k=1 \) bosons and fermion cancel the leading exponential term, including polynomial dependence:

\[ a_n^B \sim A_1^B (n) \ I_m\left(4\pi \sqrt{n} \sqrt{\frac{c}{24}}\right) \]

\[ a_n^F \sim - A_1^F (n) \ I_m\left(4\pi \sqrt{n} \sqrt{\frac{c}{24}}\right) \]
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This works because \( A_1^B(n) = A_1^F(n) \) are real functions of \(n \)
All order cancellation

\[ a_n^{B/F} = \sum_{k=1}^{\infty} A_k^{B/F}(n) I_m \left( \frac{4\pi \sqrt{n}}{k} \sqrt{\frac{c}{24}} \right) \]

For \( k > 1 \), the \( A_k^{B/F}(n) \) are complex functions:

\[ a_n^B \sim A_1^B(n) I_m \left( 4\pi \sqrt{n} \sqrt{\frac{c}{24}} \right) + A_2^B(n) I_m \left( \frac{4\pi \sqrt{n}}{2} \sqrt{\frac{c}{24}} \right) \]

\[ a_n^F \sim - A_1^F(n) I_m \left( 4\pi \sqrt{n} \sqrt{\frac{c}{24}} \right) - A_2^F(n) I_m \left( \frac{4\pi \sqrt{n}}{2} \sqrt{\frac{c}{24}} \right) \]

Cannot compare \( A_2^B(n = odd) \) and \( A_2^F(n = even) \) because they are real only for odd/even values of \( n \).
All order cancellation

Solution: All subleading corrections are cancelling for bosons and fermions separately:

Leading order contribution from bosons and fermions cancel out
All order cancellation

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All order cancellation

Solution: All subleading corrections are cancelling for bosons and fermions separately:

Positive and negative subleading corrections average out

All subleading contributions cancel within each sector
All order cancellation

Solution: All subleading corrections are cancelling for bosons and fermions separately:

• Subleading cancellations within each sector result from particular properties of the Kloosterman sum \( \sim A_k(n) \)

\[
a_n = \sum_{k=1}^{\infty} A_k(n) \ I_m \left( \frac{4\pi\sqrt{n}}{k} \sqrt{\frac{c}{24}} \right)
\]

for any fixed \( k \): \(
0 = \sum_{n=1}^{k} A_k(n) \)

\[A_3(n) \sim \{1,1,-2,1,1,-2,1, \ldots \} \text{ for } n = 1,2,3,4, \ldots\]
All order cancellation

Solution: All subleading corrections are cancelling for bosons and fermions separately:

• This should work in the same way for all non-supersymmetric string theories without tachyons

• Verified for the SO(16)xSO(16) heterotic string
All order cancellation

Solution: All subleading corrections are cancelling for bosons and fermions separately:

• This should work in the same way for all non-supersymmetric string theories without tachyons

• Verified for the SO(16)xSO(16) heterotic string

• This proved the 25 year old conjecture that all exponential terms cancel, leaving only polynomial terms

• These tremendous cancellations lead to finite quantities
$\Lambda$ for anti-Dp-brane on Op-plane

For the case of an anti-Dp-brane on top of an Op-plane in flat space the tree-level cosmological constant is

$$\Lambda_{\text{tree-level}} = T_p \int d^{p+1}\xi \ e^{-\phi} \sqrt{-g} = T_p \ e^{-\phi} \ V_{p+1}$$
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One finds at 1-loop

$$\Lambda_{1-\text{loop}} = c_p \ T_p V_{p+1}$$

c$_p$ is an order unity coefficient that depends on $p$

$$\Lambda = \Lambda_{\text{tree-level}}(1 + e^\phi c_p + \Theta(e^{2\phi}))$$
**Λ for anti-Dp-brane on Op-plane**

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\[
\Lambda = \Lambda_{\text{tree-level}} \left(1 + e^\phi c_p + \Theta(e^{2\phi})\right)
\]

Not necessarily small but different from QFT expectation
Supertraces

The conjectured (and now better understood cancellations) lead to interesting properties:

\[ \text{Dienes, Moshe, Myers, hep-th/9503055} \]
\[ \text{Dienes hep-th/0104274} \]

In supersymmetric theories we can introduce supertraces

\[ \text{Str } M^{2\beta} \equiv \sum_{\text{states } i} (-1)^F (M_i)^{2\beta} \]
Supertraces

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Dienes, Moshe, Myers, hep-th/9503055
Dienes  hep-th/0104274

Misaligned SUSY leads (for generalized supertraces) to

\[ Str M^{2\beta} = 0 \text{ for } 2\beta < D - 2 \text{ and } \]
\[ Str M^{D-2} \propto \Lambda_{1-loop} \]
Supertraces

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In D=4 we have

\[ Str M^0 = 0 \]
\[ Str M^2 \propto \Lambda_{1-loop} \]
Supertraces

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\[ \text{Misaligned SUSY leads (for generalized supertraces) to} \]

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\[ Str M^{D-2} \propto \Lambda_{1-loop} \]

In D=10 we have

\[ StrM^0 = StrM^2 = StrM^4 = StrM^6 = 0 \]
\[ Str M^8 \propto \Lambda_{1-loop} \]
Misaligned SUSY

- (Some) supertraces vanish in all non-supersymmetric and tachyon free string theories!
- Further cancellations in $D=4$ such $Str\ M^2 \propto \Lambda_{1-loop}$ is very small or even zero could solve hierarchy problem
Misaligned SUSY

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• Further cancellations in D=4 such $Str \ M^2 \propto \Lambda_{1-loop}$ is very small or even zero could solve hierarchy problem

• There exist extensions to two loops
  
  Abel, Stewart 1701.06629

  and other recent related work on misaligned SUSY
  
  Abel, Dienes 21???.????
  Faraggi, Matyas, Percival 2010.06637
  Palti 2005.08538
...
Summary of Misaligned SUSY

• Non-supersymmetric string theories have fascinating cancellations between fermions and bosons

• No supersymmetry and no cancellation at any mass level between bosonic or fermionic states
Summary of Misaligned SUSY

• Non-supersymmetric string theories have fascinating cancellations between fermions and bosons

• No supersymmetry and no cancellation at any mass level between bosonic or fermionic states

• Averaging over states with different masses leads to vanishing supertraces and other cancellations
Summary of Misaligned SUSY

- Non-supersymmetric string theories have fascinating cancellations between fermions and bosons.
- No supersymmetry and no cancellation at any mass level between bosonic or fermionic states.
- Averaging over states with different masses leads to vanishing supertraces and other cancellations.
- This might provide insight into hierarchy problem and there might be connection to non-linear SUSY.
Summary of Misaligned SUSY

• Non-supersymmetric string theories have fascinating cancellations between fermions and bosons

• No supersymmetry and no cancellation at any mass level between bosonic or fermionic states

• Averaging over states with different masses leads to vanishing supertraces and other cancellations

• This might provide insight into hierarchy problem and there might be connection to non-linear SUSY

THANK YOU!