Cosmological Unification of String Theories

Simeon Hellerman

based on :
hep-th/0611317, S.H. and Ian Swanson
hep-th/0612051, S.H. and Ian Swanson
hep-th/0612116, S.H. and Ian Swanson
arXiv:0705.0980, S.H. and Ian Swanson
arXiv:0709.2166, S.H. and Ian Swanson
arXiv:0710.1628, S.H. and Ian Swanson
and work in progress

Strings 2008, CERN, Geneva, August 22, 2008

Outline

Bosonic string solutions with nonzero tachyon

Dimension-changing solutions in the bosonic string

Transitions from type 0 to type II string theory

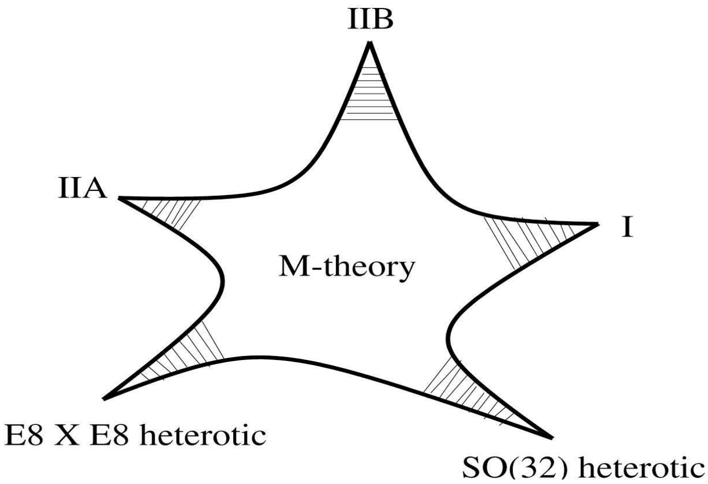
Lightlike tachyon condensation in Type 0

Other examples

Conclusions

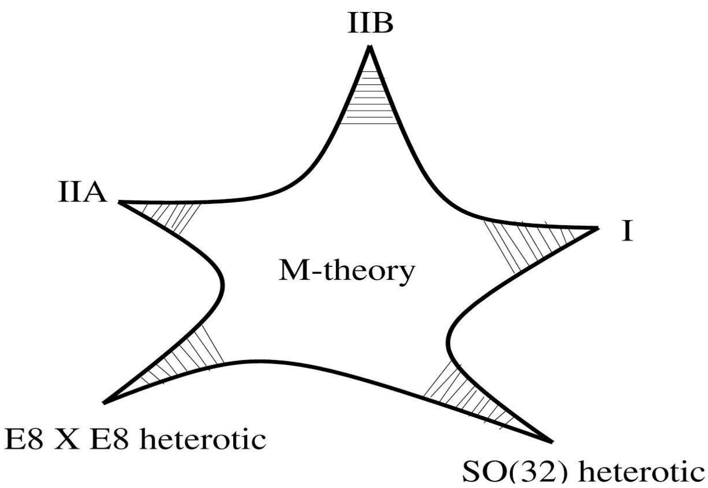
Introduction

We understand THIS very well:



Introduction

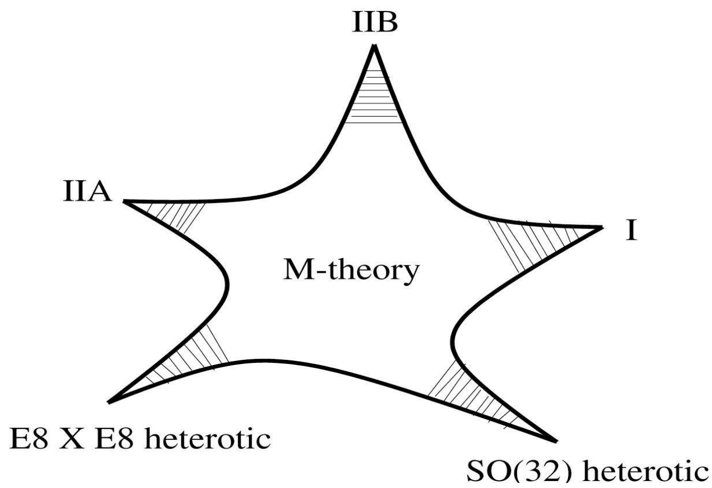
We understand THIS very well:



We also understand perturbations by weak SUSY breaking –

Introduction

We understand THIS very well:

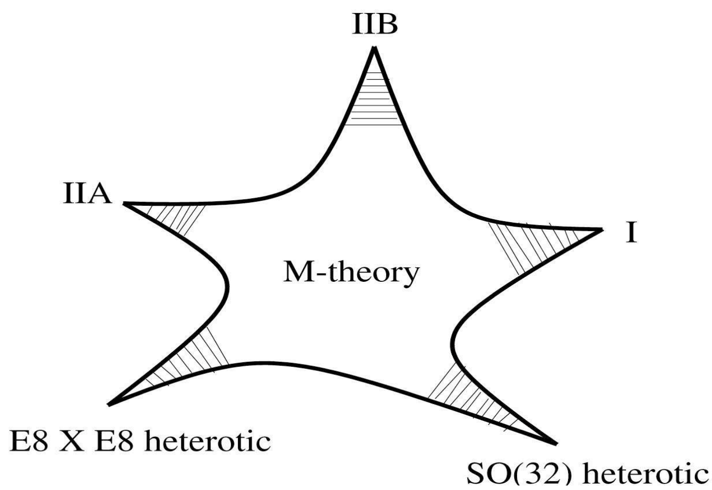


We also understand perturbations by weak SUSY breaking –

- Anti-D-branes

Introduction

We understand THIS very well:

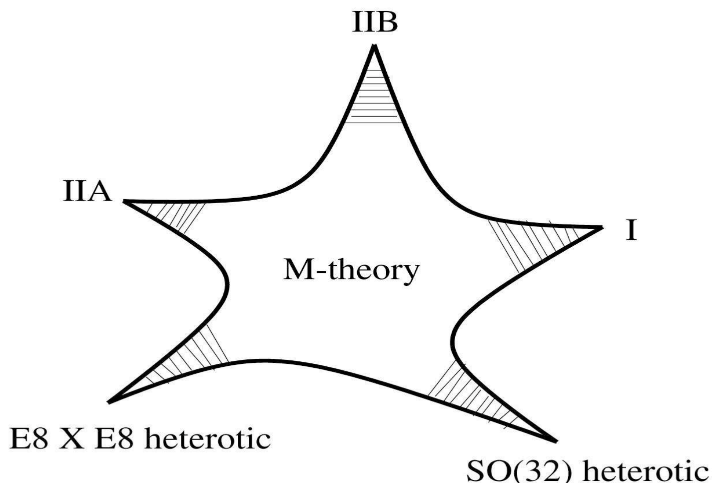


We also understand perturbations by weak SUSY breaking –

- Anti-D-branes
- Fluxes

Introduction

We understand THIS very well:



We also understand perturbations by weak SUSY breaking –

- Anti-D-branes
- Fluxes

We don't yet understand strong SUSY breaking very well!

Introduction

GOALS:

- Understand cosmology and strong time dependence

Introduction

GOALS:

- Understand cosmology and strong time dependence
- Understand strong SUSY breaking

Introduction

GOALS:

- Understand cosmology and strong time dependence
- Understand strong SUSY breaking
- Understand connections between string theories – each of the possible 10^{500} universes should contain all the others!

Introduction

GOALS:

- Understand cosmology and strong time dependence
- Understand strong SUSY breaking
- Understand connections between string theories – each of the possible 10^{500} universes should contain all the others!

Each of these questions is related to the others – if we understand one, we will understand all of them.

Introduction

GOALS:

- Understand cosmology and strong time dependence
- Understand strong SUSY breaking
- Understand connections between string theories – each of the possible 10^{500} universes should contain all the others!

Each of these questions is related to the others – if we understand one, we will understand all of them.

What are the simplest concrete models of connections and transitions?

What I will describe today

What I will describe today

- A class of α'-exact classical solutions of string theory

What I will describe today

- A class of α'-exact classical solutions of string theory
- With D not necessarily equal to 10 or 26

What I will describe today

- A class of α'-exact classical solutions of string theory
- With D not necessarily equal to 10 or 26
- D changes dynamically

What I will describe today

- A class of α'-exact classical solutions of string theory
- With D not necessarily equal to 10 or 26
- D changes dynamically
- Spacetime SUSY changes dynamically

What I will describe today

- A class of α'-exact classical solutions of string theory
- With D not necessarily equal to 10 or 26
- D changes dynamically
- Spacetime SUSY changes dynamically
- Worldsheet SUSY changes dynamically

What I will describe today

- A class of α'-exact classical solutions of string theory
- With D not necessarily equal to 10 or 26
- D changes dynamically
- Spacetime SUSY changes dynamically
- Worldsheet SUSY changes dynamically
- All involve closed string tachyon condensation, treated exactly in α' and in the tachyon strength.

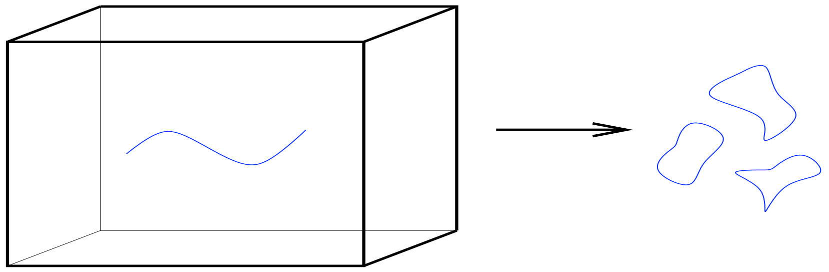
What I will describe today

- A class of α'-exact classical solutions of string theory
- With D not necessarily equal to 10 or 26
- D changes dynamically
- Spacetime SUSY changes dynamically
- Worldsheet SUSY changes dynamically
- All involve closed string tachyon condensation, treated exactly in α' and in the tachyon strength.

THIS TALK IS A CONJECTURE-FREE ZONE!

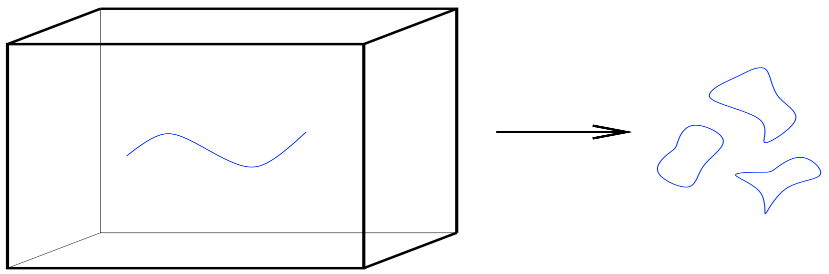
Analogy with open string tachyon dynamics

D-brane decay

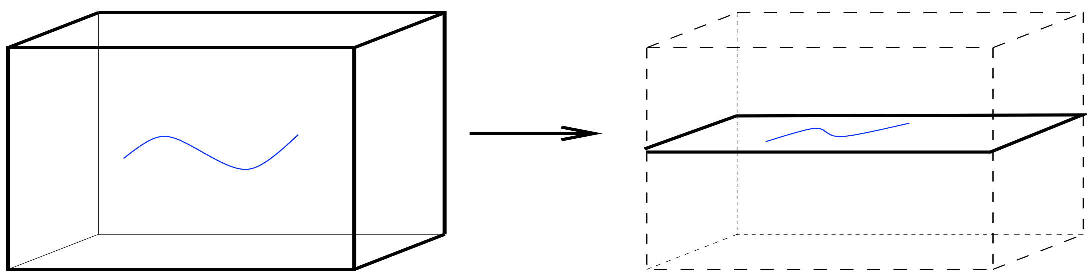


Analogy with open string tachyon dynamics

D-brane decay

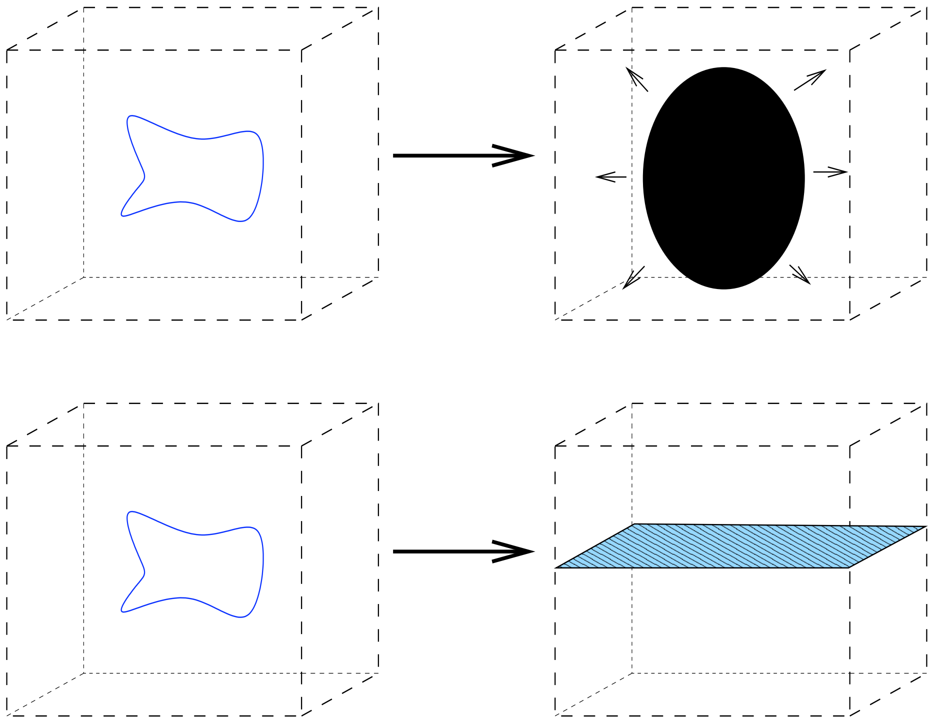


Solitons



Parallel with Open String Tachyon Dynamics

An analogy arises for the (bosonic) closed string tachyon, representing an instability of spacetime itself.



Outline

- Bosonic string solutions with nonzero tachyon
- Dimension-changing solutions in the bosonic string
- Transitions from type 0 to type II string theory
- Lightlike tachyon condensation in Type 0
- Other examples
- Conclusions

Tachyonic perturbations

We are interested in tachyonic perturbations of unstable string theories. In the bosonic string, for instance, the tachyon $\mathcal{T}(X)$ couples to the worldsheet as a normal-ordered potential $:\mathcal{T}(X):$.

Tachyonic perturbations

We are interested in tachyonic perturbations of unstable string theories. In the bosonic string, for instance, the tachyon $\mathcal{T}(X)$ couples to the worldsheet as a normal-ordered potential $:\mathcal{T}(X):$.

We will now discuss a large class of solvable and exactly marginal perturbations of this form.

Bubble of nothing

Consider a theory with stress tensor

$$T_{++} = -\frac{1}{\alpha'} : \partial_{\sigma^+} X^\mu \partial_{\sigma^+} X_\mu : + \partial^2_{\sigma^+} (V_\mu X^\mu)$$

$$T_{--} = -\frac{1}{\alpha'} : \partial_{\sigma^-} X^\mu \partial_{\sigma^-} X_\mu : + \partial^2_{\sigma^-} (V_\mu X^\mu)$$

where colons represent normal ordering of the $2D$ theory. Here, $\sigma^\pm$ are particular light-cone combinations of the worldsheet coordinates $\sigma^{0,1}$:

$$\sigma^\pm = -\sigma^0 \pm \sigma^1$$

Bubble of nothing

Consider a theory with stress tensor

$$T_{++} = -\frac{1}{\alpha'} : \partial_{\sigma^+} X^\mu \partial_{\sigma^+} X_\mu : + \partial^2_{\sigma^+} (V_\mu X^\mu)$$

$$T_{--} = -\frac{1}{\alpha'} : \partial_{\sigma^-} X^\mu \partial_{\sigma^-} X_\mu : + \partial^2_{\sigma^-} (V_\mu X^\mu)$$

where colons represent normal ordering of the $2D$ theory. Here, $\sigma^\pm$ are particular light-cone combinations of the worldsheet coordinates $\sigma^{0,1}$:

$$\sigma^\pm = -\sigma^0 \pm \sigma^1$$

Physical states of the string correspond to local operators $\mathcal{U}$ that are Virasoro primaries of weight one. That is, their operator product expansion (OPE) with the stress tensor satisfies:

$$T_{++}(\sigma)\mathcal{U}(\tau) \simeq \frac{\mathcal{U}(\tau)}{(\sigma^+ - \tau^+)^2} + \frac{\partial_+ \mathcal{U}(\tau)}{\sigma^+ - \tau^+}$$

and similarly for T_{--},

Bubble of nothing

A profile $\mathcal{T}(X)$ for the tachyon corresponds to the vertex operator

$$\mathcal{U}_M \equiv : \mathcal{T}(X) :$$

and admits the following on-shell condition:

$$\partial_\mu \partial^\mu \mathcal{T}(X) - 2V^\mu \partial_\mu \mathcal{T}(X) + \frac{4}{\alpha'} \mathcal{T}(X) = 0$$

Bubble of nothing

A profile $\mathcal{T}(X)$ for the tachyon corresponds to the vertex operator

$$\mathcal{U}_M \equiv : \mathcal{T}(X) :$$

and admits the following on-shell condition:

$$\partial_\mu \partial^\mu \mathcal{T}(X) - 2V^\mu \partial_\mu \mathcal{T}(X) + \frac{4}{\alpha'} \mathcal{T}(X) = 0$$

For tachyon profiles of the form

$$\mathcal{T}(X) = \mu^2 \exp\left(B_\mu X^\mu\right)$$

this condition is

$$B^2 - 2V \cdot B = -4/\alpha'$$

Bubble of nothing

A profile $\mathcal{T}(X)$ for the tachyon corresponds to the vertex operator

$$\mathcal{U}_M \equiv : \mathcal{T}(X) :$$

and admits the following on-shell condition:

$$\partial_\mu \partial^\mu \mathcal{T}(X) - 2V^\mu \partial_\mu \mathcal{T}(X) + \frac{4}{\alpha'}\mathcal{T}(X) = 0$$

For tachyon profiles of the form

$$\mathcal{T}(X) = \mu^2 \exp\left(B_\mu X^\mu\right)$$

this condition is

$$B^2 - 2V \cdot B = -4/\alpha'$$

A general value of B_μ will lead to a nontrivial interacting theory when the strength μ^2 of the perturbation is treated as non-infinitesimal.

Bubble of nothing

There is a special set of choices for B_μ that renders the $2D$ theory well-defined and conformal to all orders in perturbation theory.

Bubble of nothing

There is a special set of choices for B_μ that renders the $2D$ theory well-defined and conformal to all orders in perturbation theory.

We choose the first term in the linearized tachyon equation of motion to vanish separately.

Bubble of nothing

There is a special set of choices for B_μ that renders the $2D$ theory well-defined and conformal to all orders in perturbation theory.

We choose the first term in the linearized tachyon equation of motion to vanish separately.

This is tantamount to choosing the vector B_μ to be null. This renders the vertex operator $:\exp\left(B_\mu X^\mu\right):$ non-singular in the vicinity of itself.

Bubble of nothing

There is a special set of choices for B_μ that renders the $2D$ theory well-defined and conformal to all orders in perturbation theory.

We choose the first term in the linearized tachyon equation of motion to vanish separately.

This is tantamount to choosing the vector B_μ to be null. This renders the vertex operator $:\exp(B_\mu X^\mu):$ non-singular in the vicinity of itself.

We therefore put B_μ in the form

$$\begin{aligned} B_0 &= B_1 \equiv \beta/\sqrt{2} \\ B_i &= 0, \qquad i \geq 2 \end{aligned}$$

Bubble of nothing

The initial singularity of the cosmology lies in the strong-coupling region, and the tachyon increases into the future.

Bubble of nothing

The initial singularity of the cosmology lies in the strong-coupling region, and the tachyon increases into the future.

This gives rise to a particularly simple quantum theory. The kinetic term for $X^{\pm}$ appears as

$$\mathcal{L} \sim -\frac{1}{2\pi\alpha'}\Big[\,(\partial_{\sigma^0}X^+)(\partial_{\sigma^0}X^-) - (\partial_{\sigma^1}X^+)(\partial_{\sigma^1}X^-)\,\Big]$$

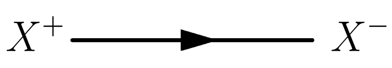
Bubble of nothing

The initial singularity of the cosmology lies in the strong-coupling region, and the tachyon increases into the future.

This gives rise to a particularly simple quantum theory. The kinetic term for $X^{\pm}$ appears as

$$\mathcal{L} \sim -\frac{1}{2\pi\alpha'}\Big[\,(\partial_{\sigma^0}X^+)(\partial_{\sigma^0}X^-) - (\partial_{\sigma^1}X^+)(\partial_{\sigma^1}X^-)\,\Big]$$

The propagator for the $X^{\pm}$ fields is therefore oriented.



Bubble of nothing

- The X field has oriented propagators.
- All the interaction vertices in the theory depend only on X^+.
- There are no non-trivial Feynman diagrams in the theory.
- This constitutes an interacting quantum theory, without quantum corrections.

Bubble of nothing

- The X field has oriented propagators.
- All the interaction vertices in the theory depend only on X^+.
- There are no non-trivial Feynman diagrams in the theory.
- This constitutes an interacting quantum theory, without quantum corrections.

(In conformal gauge, prior to enforcing gauge constraints, the theory is not unitary.)

Bubble of nothing

- The X field has oriented propagators.
- All the interaction vertices in the theory depend only on X^+.
- There are no non-trivial Feynman diagrams in the theory.
- This constitutes an interacting quantum theory, without quantum corrections.

(In conformal gauge, prior to enforcing gauge constraints, the theory is not unitary.)

The tachyon couples to the worldsheet in the term

$$\mathcal{L} \sim -\frac{1}{2\pi}\mu^2 \exp\left(\beta X^+\right)$$

Bubble of nothing

- The X field has oriented propagators.
- All the interaction vertices in the theory depend only on X^+.
- There are no non-trivial Feynman diagrams in the theory.
- This constitutes an interacting quantum theory, without quantum corrections.

(In conformal gauge, prior to enforcing gauge constraints, the theory is not unitary.)

The tachyon couples to the worldsheet in the term

$$\mathcal{L} \sim -\frac{1}{2\pi}\mu^2 \exp\left(\beta X^+\right)$$

Classically, X^+ is harmonic, and acts as a source for X^-.

Bubble of nothing

By writing the solution to the Laplace equation for X^+ as

$$X^+ = f_+(\sigma^+) + f_-(\sigma^-)$$

the general solution for X^- can be expressed as follows:

$$X^- = g_+(\sigma^+) + g_-(\sigma^-) + \frac{\alpha' \beta \mu^2}{4} \left[\int_{\sigma^+}^{\infty} dy^+ \exp\left(\beta f_+(y^+)\right) \right] \left[\int_{\sigma^-}^{\infty} dy^- \exp\left(\beta f_-(y^-)\right) \right]$$

Bubble of nothing

By writing the solution to the Laplace equation for X^+ as

$$X^+ = f_+(\sigma^+) + f_-(\sigma^-)$$

the general solution for X^- can be expressed as follows:

$$X^- = g_+(\sigma^+) + g_-(\sigma^-) + \frac{\alpha' \beta \mu^2}{4} \left[\int_{\sigma^+}^{\infty} dy^+ \exp\left(\beta f_+(y^+)\right) \right] \left[\int_{\sigma^-}^{\infty} dy^- \exp\left(\beta f_-(y^-)\right) \right]$$

We thus see that the theory is exactly solvable.

Bubble of nothing

By writing the solution to the Laplace equation for X^+ as

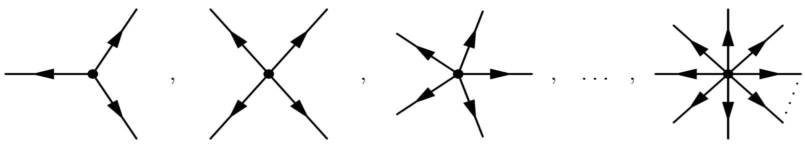
$$X^+ = f_+(\sigma^+) + f_-(\sigma^-)$$

the general solution for X^- can be expressed as follows:

$$X^- = g_+(\sigma^+) + g_-(\sigma^-) + \frac{\alpha' \beta \mu^2}{4} \left[\int_{\sigma^+}^{\infty} dy^+ \exp\left(\beta f_+(y^+)\right) \right] \left[\int_{\sigma^-}^{\infty} dy^- \exp\left(\beta f_-(y^-)\right) \right]$$

We thus see that the theory is exactly solvable.

All interaction vertices in the theory depend only on X^+, and therefore correspond to diagrams composed strictly from outgoing lines:



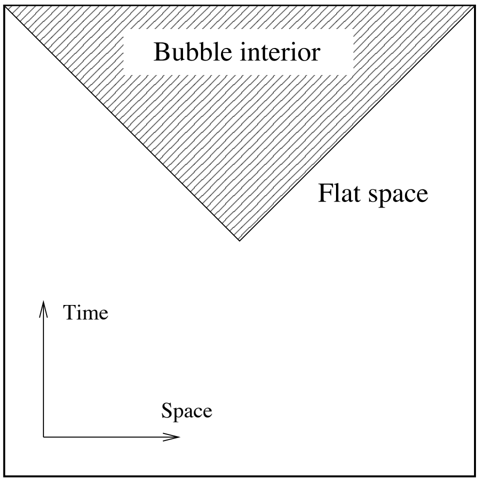
Physical interpretation

The solution can be thought of as a phase boundary in spacetime between the $\mathcal{T} = 0$ phase and the $\mathcal{T} > 0$ phase.

Physical interpretation

The solution can be thought of as a phase boundary in spacetime between the $\mathcal{T} = 0$ phase and the $\mathcal{T} > 0$ phase.

The spacetime picture is therefore a phase bubble expanding out from a nucleation point:

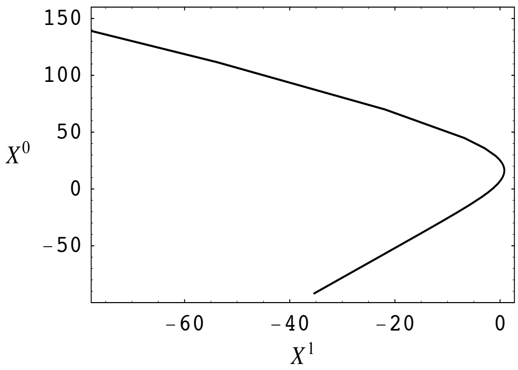


Physical interpretation

To see what happens to states in the neighborhood of the bubble we can place a string state near the phase boundary.

Physical interpretation

To see what happens to states in the neighborhood of the bubble we can place a string state near the phase boundary.



The state collides with the bubble wall and is forced out of the region with nonzero tachyon. (The solution has $\mu^2 = 1,\ \beta = .1$, and the trajectory corresponds to $p^+ = 3,\ H_\perp \equiv \frac{\alpha' p_i^2}{2} = 4$.)

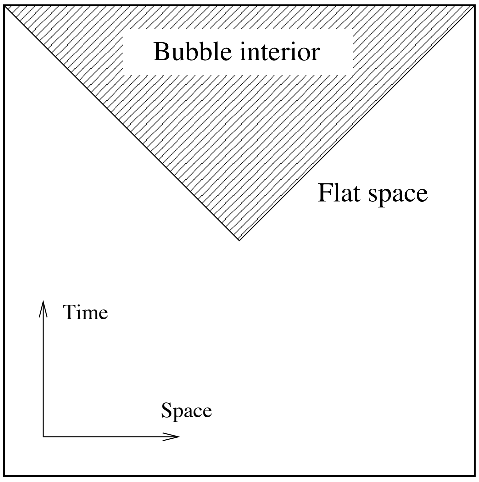
Physical interpretation

Absolutely no matter (including gravitons) can enter the region of nonzero tachyon.

Physical interpretation

Absolutely no matter (including gravitons) can enter the region of nonzero tachyon.

The solution can be thought of as a bubble of nothing.



Outline

Bosonic string solutions with nonzero tachyon

Dimension-changing solutions in the bosonic string

Transitions from type 0 to type II string theory

Lightlike tachyon condensation in Type 0

Other examples

Conclusions

Dimension-changing solutions in the bosonic string

Let's now inroduce some dependence on a third direction:

$$\mathcal{T}(X^+, X_2) = +\frac{\mu^2}{2\,\alpha'}\,\exp\left(\beta X^+\right)\;:X_2^2:+\mathcal{T}_0(X^+)$$

$$\mathcal{T}_0(X^+) = \frac{\mu^2\,X^+}{\alpha'\,q\,\sqrt{2}}\exp\left(\beta X^+\right) + \mu'^2\exp\left(\beta X^+\right)$$

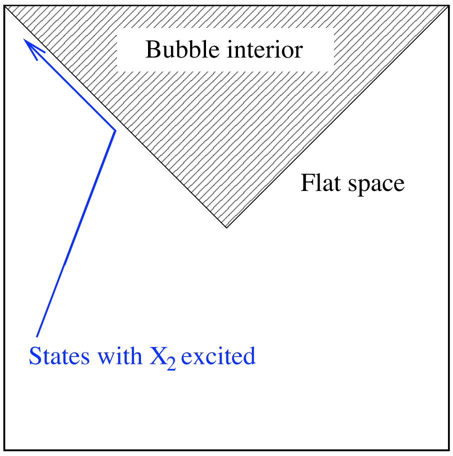
Dimension-changing solutions in the bosonic string

States with modes of X_2 excited are pushed out along the bubble wall: the physics is essentially the same as the bubble of nothing.

Dimension-changing solutions in the bosonic string

States with modes of X_2 excited are pushed out along the bubble wall: the physics is essentially the same as the bubble of nothing.

So these string states are pushed out to infinity and disappear from the theory in the late-time limit:

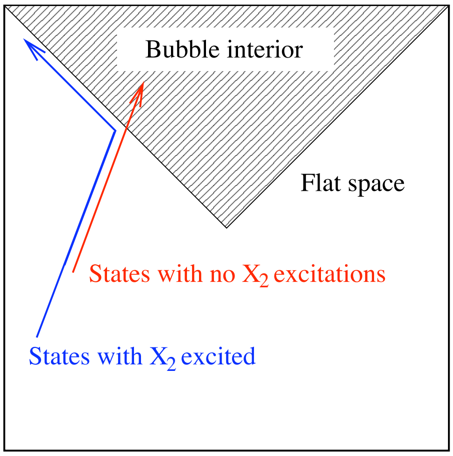


Dimension-changing solutions in the bosonic string

There is a less generic class of states with no energy in the X_2 direction.

Dimension-changing solutions in the bosonic string

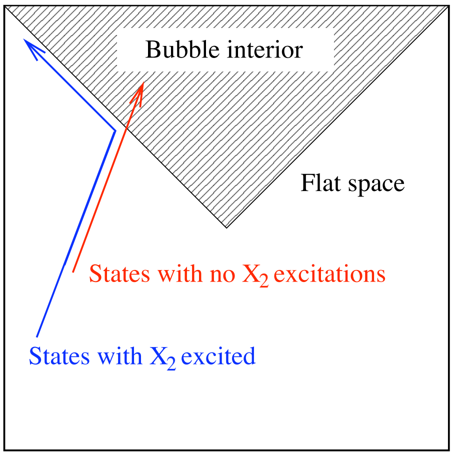
There is a less generic class of states with no energy in the X_2 direction.



These propagate *through the domain wall and into the bubble region*.

Dimension-changing solutions in the bosonic string

There is a less generic class of states with no energy in the X_2 direction.



These propagate *through the domain wall and into the bubble region*.

The result is that the amount of matter on the worldsheet decreases dynamically as a function of time.

Dimension-changing solutions in the bosonic string

In other words, the number of dimensions in the target space decreases as a function of time.

Dimension-changing solutions in the bosonic string

In other words, the number of dimensions in the target space decreases as a function of time.

Question: What happens to the central charge if the spacetime dimension shifts? How can the perturbation be marginal?

Dimension-changing solutions in the bosonic string

In other words, the number of dimensions in the target space decreases as a function of time.

Question: What happens to the central charge if the spacetime dimension shifts? How can the perturbation be marginal?

The theory is solvable, so we should be able to answer this question exactly.

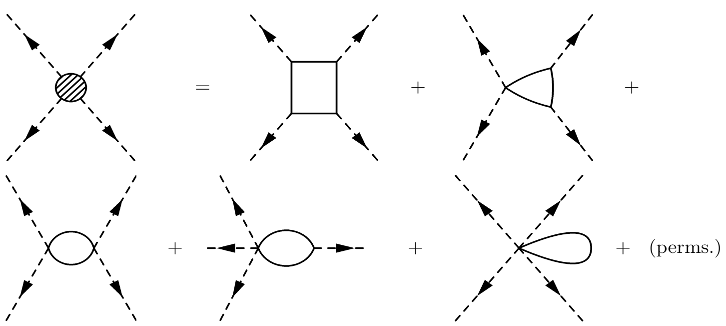
Dimension-changing solutions in the bosonic string

In other words, the number of dimensions in the target space decreases as a function of time.

Question: What happens to the central charge if the spacetime dimension shifts? How can the perturbation be marginal?

The theory is solvable, so we should be able to answer this question exactly.

In fact, quantum corrections in this theory truncate at one-loop order:



Dimension-changing solutions in the bosonic string

The one-loop diagrams can be thought of as a set of effective vertices for X^+, associated with integrating out the massive field X_2.

Dimension-changing solutions in the bosonic string

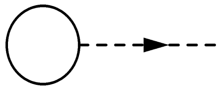
The one-loop diagrams can be thought of as a set of effective vertices for X^+, associated with integrating out the massive field X_2.

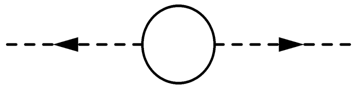
In fact: in the far future, all corrections coming from integrating out X_2 decay away, except for three contributions:

- the effective tachyon,
- the dilaton,
- the string-frame metric.

Dimension-changing solutions in the bosonic string

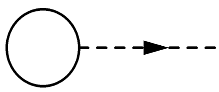
The remaining contributions are always nonzero, coming from the following diagrams:

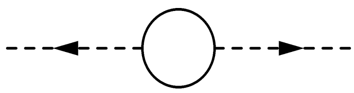
$\Delta(\partial_+\Phi) \;=$ 

$\Delta G_{++} \;=$ 

Dimension-changing solutions in the bosonic string

The remaining contributions are always nonzero, coming from the following diagrams:

$\Delta(\partial_+\Phi) \;=$ 

$\Delta G_{++} \;=$ 

Write the renormalized dilaton gradient and string-frame metric as:

$$\hat{V}_\mu \equiv V_\mu + \Delta V_\mu$$
$$\hat{G}^{\mu\nu} \equiv G_{\mu\nu} + \Delta G_{\mu\nu}$$

Dimension-changing solutions in the bosonic string

In the $X^+ \to \infty$ limit, we therefore get

$$c^{\rm dilaton} = 6\alpha' \hat{G}^{\mu\nu} \hat{V}_\mu \hat{V}_\nu = -(D-26)+1$$

Dimension-changing solutions in the bosonic string

In the $X^+ \to \infty$ limit, we therefore get

$$c^{\rm dilaton} = 6\alpha' \hat{G}^{\mu\nu} \hat{V}_\mu \hat{V}_\nu = -(D-26)+1$$

The result is that the shift in cenral charge contribution from the dilaton precisely cancels the central charge shift due to the reduction in spacetime dimension.

Dimension-changing solutions in the bosonic string

This mechanism of central charge transfer works equally well when the tachyon has a quadratic minimum in several transverse directions:

$$c^{\text{dilaton}} = 6\alpha' \hat{G}^{\mu\nu} \hat{V}_\mu \hat{V}_\nu = -6\alpha' q^2 + \frac{nq\beta\alpha'}{\sqrt{2}} - \frac{n\alpha'^2 q^2 \beta^2}{8} = -(D-26) + n$$

Dimension-changing solutions in the bosonic string

This mechanism of central charge transfer works equally well when the tachyon has a quadratic minimum in several transverse directions:

$$c^{\text{dilaton}} = 6\alpha' \hat{G}^{\mu\nu} \hat{V}_\mu \hat{V}_\nu = -6\alpha' q^2 + \frac{nq\beta\alpha'}{\sqrt{2}} - \frac{n\alpha'^2 q^2 \beta^2}{8} = -(D-26) + n$$

We can get rid of as many dimensions as we want.

Dimension-changing solutions in the bosonic string

This mechanism of central charge transfer works equally well when the tachyon has a quadratic minimum in several transverse directions:

$$c^{\text{dilaton}} = 6\alpha' \hat{G}^{\mu\nu} \hat{V}_\mu \hat{V}_\nu = -6\alpha' q^2 + \frac{nq\beta\alpha'}{\sqrt{2}} - \frac{n\alpha'^2 q^2 \beta^2}{8} = -(D-26) + n$$

We can get rid of as many dimensions as we want.

We can even get down to D=2!

Outline

Bosonic string solutions with nonzero tachyon

Dimension-changing solutions in the bosonic string

Transitions from type 0 to type II string theory

Lightlike tachyon condensation in Type 0

Other examples

Conclusions

Transitions from type 0 to type II string theory

The type 0 theory also has a rich structure of transitions – including dimension-reducing transitions of the type we have just discussed for the bosonic string. (We will not review these here.)

Transitions from type 0 to type II string theory

The type 0 theory also has a rich structure of transitions – including dimension-reducing transitions of the type we have just discussed for the bosonic string. (We will not review these here.)

Let us consider some other types of transitions that the type 0 string can undergo, in a linear dilaton background.

Transitions from type 0 to type II string theory

The type 0 theory also has a rich structure of transitions – including dimension-reducing transitions of the type we have just discussed for the bosonic string. (We will not review these here.)

Let us consider some other types of transitions that the type 0 string can undergo, in a linear dilaton background.

Instead of starting with type 0 on a smooth space, we can consider starting on a $\mathbb{Z}_2$ orbifold of flat space.

Transitions from type 0 to type II string theory

The type 0 theory also has a rich structure of transitions – including dimension-reducing transitions of the type we have just discussed for the bosonic string. (We will not review these here.)

Let us consider some other types of transitions that the type 0 string can undergo, in a linear dilaton background.

Instead of starting with type 0 on a smooth space, we can consider starting on a $\mathbb{Z}_2$ orbifold of flat space.

As an example, start with type 0 string theory in 12 dimensions, with one dimension orbifolded by a reflection:

$$X^{11} \to -X^{11} \,.$$

Transitions from type 0 to type II string theory

(For modular invariance, we can stipulate that this acts simultaneously as a chiral R parity, $(-1)^{F_{L_W}}$.)

Transitions from type 0 to type II string theory

(For modular invariance, we can stipulate that this acts simultaneously as a chiral R parity, $(-1)^{F_{L_W}}$.)

That is, the orbifold symmetry acts on the worldsheet fields as:

Transitions from type 0 to type II string theory

(For modular invariance, we can stipulate that this acts simultaneously as a chiral R parity, $(-1)^{F_{L_W}}$.)

That is, the orbifold symmetry acts on the worldsheet fields as:

$$\begin{aligned} X^{0-10} &: \quad + \\ X^{11} &: \quad - \\ \tilde{G} &: \quad - \\ G &: \quad + \end{aligned}$$

where G and $\tilde{G}$ are the right- and left-moving worldsheet supercurrents.

Transitions from type 0 to type II string theory

The orbifold singularity has real codimension 1, with massless spacetime fermions propagating on the $10+1$ dimensional fixed locus $\{X^M = X^{0,\cdots,10}\}$.

Transitions from type 0 to type II string theory

The orbifold singularity has real codimension 1, with massless spacetime fermions propagating on the $10+1$ dimensional fixed locus $\{X^M = X^{0,\cdots,10}\}$.

The boundary conditions at the orbifold force the tachyon $\mathcal{T}$ to vanish at $X_{11} = 0$:

Transitions from type 0 to type II string theory

The orbifold singularity has real codimension 1, with massless spacetime fermions propagating on the $10+1$ dimensional fixed locus $\{X^M = X^{0,\cdots,10}\}$.

The boundary conditions at the orbifold force the tachyon $\mathcal{T}$ to vanish at $X_{11} = 0$:

$$\mathcal{T}(X^M, X^{11}) = -\mathcal{T}(X^M, -X^{11})$$

Transitions from type 0 to type II string theory

Starting with type 0 in this 12-dimensional geometry, we can consider a local tachyon profile which describes the behavior of a generic tachyon vev near the orbifold fixed locus:

$$\mathcal{T} = \mu \exp\left(\beta X^{+}\right) \ X_{10} X_{11}, \qquad \beta q = \frac{\sqrt{2}}{\alpha'}$$

Transitions from type 0 to type II string theory

Starting with type 0 in this 12-dimensional geometry, we can consider a local tachyon profile which describes the behavior of a generic tachyon vev near the orbifold fixed locus:

$$\mathcal{T} = \mu \exp\left(\beta X^{+}\right) \ X_{10} X_{11}, \qquad \beta q = \frac{\sqrt{2}}{\alpha'}$$

The tachyon couples to the worldsheet as a $(1,1)$ superpotential:

$$\mathcal{L}_{\rm int} = \frac{i}{2\pi} \int d\theta_{+} d\theta_{-} \, \mathcal{T}(X)$$

Transitions from type 0 to type II string theory

Starting with type 0 in this 12-dimensional geometry, we can consider a local tachyon profile which describes the behavior of a generic tachyon vev near the orbifold fixed locus:

$$\mathcal{T} = \mu \exp\left(\beta X^+\right) \; X_{10} X_{11}, \qquad \beta q = \frac{\sqrt{2}}{\alpha'}$$

The tachyon couples to the worldsheet as a $(1,1)$ superpotential:

$$\mathcal{L}_{\rm int} = \frac{i}{2\pi} \int d\theta_+ d\theta_- \, \mathcal{T}(X)$$

This gives rise to a potential and Yukawa term:

$$\mathcal{L}_{\rm int} = -\frac{\alpha' \mu^2}{8\pi} \exp\left(+2\beta X^+\right) \cdot$$

$$\left[\left(X_{10}^2 + X_{11}^2 \right) + \frac{i\alpha'\mu}{4\pi} \left(\tilde{\psi}^{10}\psi^{11} + \tilde{\psi}^{11}\psi^{10} \right) \right]$$

Transitions from type 0 to type II string theory

To discern the effective physics of the ten-dimensional final state, note that the GSO projection of the $X^+ \to \infty$ theory is now generated by two elements.

Transitions from type 0 to type II string theory

To discern the effective physics of the ten-dimensional final state, note that the GSO projection of the $X^+ \to \infty$ theory is now generated by two elements.

The orbifold symmetry $(-1)^{F_{Lw}}$ acts on the remaining worldsheet fields as:

Transitions from type 0 to type II string theory

To discern the effective physics of the ten-dimensional final state, note that the GSO projection of the $X^+ \to \infty$ theory is now generated by two elements.

The orbifold symmetry $(-1)^{F_{Lw}}$ acts on the remaining worldsheet fields as:

$$\begin{aligned} X^{0-10}: &\quad + \\ \tilde{G}: &\quad - \\ G: &\quad + \end{aligned}$$

We also have the generator $(-1)^{F_w}$ of the type 0 GSO projection. The product $(-1)^{F_{Rw}} \equiv (-1)^{F_w} \cdot (-1)^{F_{Lw}}$ acts as:

$$\begin{aligned} X^{0-9}: &\quad + \\ \tilde{G}: &\quad + \\ G: &\quad - \end{aligned}$$

Transitions from type 0 to type II string theory

We thus have the usual GSO projection of critical type II string theory. The worldsheet theory $X^+ \to \infty$ is therefore identical to the worldsheet theory of the type II superstring.

Transitions from type 0 to type II string theory

We thus have the usual GSO projection of critical type II string theory. The worldsheet theory $X^+ \to \infty$ is therefore identical to the worldsheet theory of the type II superstring.

The background values of all fields are trivial, save for the dilaton, which has a lightlike gradient, rolling to weak coupling in the future.

Transitions from type 0 to type II string theory

We thus have the usual GSO projection of critical type II string theory. The worldsheet theory $X^+ \to \infty$ is therefore identical to the worldsheet theory of the type II superstring.

The background values of all fields are trivial, save for the dilaton, which has a lightlike gradient, rolling to weak coupling in the future.

A type II background with flat string-frame metric and lightlike linear dilaton actually preserves sixteen Killing spinors.

Transitions from type 0 to type II string theory

We thus have the usual GSO projection of critical type II string theory. The worldsheet theory $X^+ \to \infty$ is therefore identical to the worldsheet theory of the type II superstring.

The background values of all fields are trivial, save for the dilaton, which has a lightlike gradient, rolling to weak coupling in the future.

A type II background with flat string-frame metric and lightlike linear dilaton actually preserves sixteen Killing spinors.

Our final state is therefore a half-BPS vacuum of type II string theory.

Transitions from type 0 to type II string theory

We thus have the usual GSO projection of critical type II string theory. The worldsheet theory $X^+ \to \infty$ is therefore identical to the worldsheet theory of the type II superstring.

The background values of all fields are trivial, save for the dilaton, which has a lightlike gradient, rolling to weak coupling in the future.

A type II background with flat string-frame metric and lightlike linear dilaton actually preserves sixteen Killing spinors.

Our final state is therefore a half-BPS vacuum of type II string theory.

This exact solution establishes conclusively that the type 0 theory in supercritical dimensions can relax by tachyon condensation to a supersymmetric ground state in D=10!

Outline

Bosonic string solutions with nonzero tachyon

Dimension-changing solutions in the bosonic string

Transitions from type 0 to type II string theory

Lightlike tachyon condensation in Type 0

Other examples

Conclusions

Lightlike tachyon condensation in type 0

In all examples so far, the basic *kind* of string theory is unchanged between the initial and final configurations.

Lightlike tachyon condensation in type 0

In all examples so far, the basic *kind* of string theory is unchanged between the initial and final configurations.

We now turn to a related model of lightlike tachyon condensation in type 0 string theory, where the tachyon depends only on X^+, and is independent of the $D-2$ dimensions transverse to $X^\pm$.

Lightlike tachyon condensation in type 0

In all examples so far, the basic *kind* of string theory is unchanged between the initial and final configurations.

We now turn to a related model of lightlike tachyon condensation in type 0 string theory, where the tachyon depends only on X^+, and is independent of the $D-2$ dimensions transverse to $X^\pm$.

We start with the Lagrangian for a timelike linear dilaton theory on a flat worldsheet, describing D free, massless fields and their superpartners:

$$\mathcal{L}_{\rm kin} = \frac{1}{2\pi} G_{MN} \left[\frac{2}{\alpha'}(\partial_+ X^M)(\partial_- X^N) - i\psi^M(\partial_-\psi^N) - i\tilde{\psi}^M(\partial_+\tilde{\psi}^N) \right]$$

Lightlike tachyon condensation in type 0

We would like to consider solutions for which the type 0 tachyon condenses, growing exponentially in the lightlike direction X^+.

Lightlike tachyon condensation in type 0

We would like to consider solutions for which the type 0 tachyon condenses, growing exponentially in the lightlike direction X^+.

We again take the simple form

$$\mathcal{T} \equiv \tilde{\mu} \exp\left(\beta X^+\right)$$

Lightlike tachyon condensation in type 0

Remember that the tachyon couples to the worldsheet as a $(1,1)$ superpotential, giving rise to a worldsheet potential and Yukawa term:

$$\mathcal{L}_{\rm int} = -\frac{\alpha'}{8\pi} G^{MN}\, \partial_M \mathcal{T} \partial_N \mathcal{T} + \frac{i\alpha'}{4\pi} \partial_M \partial_N \mathcal{T}\, \tilde{\psi}^M \psi^N$$

Lightlike tachyon condensation in type 0

Remember that the tachyon couples to the worldsheet as a $(1,1)$ superpotential, giving rise to a worldsheet potential and Yukawa term:

$$\mathcal{L}_{\rm int} = -\frac{\alpha'}{8\pi} G^{MN}\,\partial_M \mathcal{T} \partial_N \mathcal{T} + \frac{i\alpha'}{4\pi} \partial_M \partial_N \mathcal{T}\,\tilde{\psi}^M \psi^N$$

We also get a modified supersymmetry transformation for the fermions:

$$\begin{aligned} \{Q_-, \psi^M\} &= -\{Q_+, \tilde{\psi}^M\} = F^M \\ F^M &\equiv -\sqrt{\frac{\alpha'}{8}}\, G^{MN} \partial_N \mathcal{T} \end{aligned}$$

Lightlike tachyon condensation in type 0

Since the gradient of the tachyon is null, the worldsheet potential

$$\frac{\alpha'}{16\pi} G^{MN}\,\partial_M \mathcal{T} \partial_N \mathcal{T}$$

is ZERO.

Lightlike tachyon condensation in type 0

Since the gradient of the tachyon is null, the worldsheet potential

$$\frac{\alpha'}{16\pi} G^{MN} \partial_M \mathcal{T} \partial_N \mathcal{T}$$

is ZERO.

But there is a nonvanishing F-term and Yukawa coupling between the lightlike fermions:

$$\begin{aligned} F^- &= +\frac{q\sqrt{\alpha'}\mu}{2} \exp\left(\beta X^+\right) \\ \mathcal{L}_{\text{Yukawa}} &= \frac{i\,\mu}{4\pi} \exp\left(\beta X^+\right) \tilde{\psi}^+ \psi^+ \end{aligned}$$

where $\mu \equiv \beta^2 \alpha' \, \tilde{\mu}$.

Lightlike tachyon condensation in type 0

Since the gradient of the tachyon is null, the worldsheet potential

$$\frac{\alpha'}{16\pi} G^{MN} \partial_M \mathcal{T} \partial_N \mathcal{T}$$

is ZERO.

But there is a nonvanishing F-term and Yukawa coupling between the lightlike fermions:

$$\begin{aligned} F^- &= +\frac{q\sqrt{\alpha'}\mu}{2} \exp\left(\beta X^+\right) \\ \mathcal{L}_{\text{Yukawa}} &= \frac{i\,\mu}{4\pi} \exp\left(\beta X^+\right) \tilde{\psi}^+ \psi^+ \end{aligned}$$

where $\mu \equiv \beta^2 \alpha' \, \tilde{\mu}$.

The 2D interaction terms become large as $X^+ \to +\infty$:

Lightlike tachyon condensation in type 0

Since the gradient of the tachyon is null, the worldsheet potential

$$\frac{\alpha'}{16\pi} G^{MN} \partial_M \mathcal{T} \partial_N \mathcal{T}$$

is ZERO.

But there is a nonvanishing F-term and Yukawa coupling between the lightlike fermions:

$$\begin{aligned} F^- &= +\frac{q\sqrt{\alpha'}\mu}{2} \exp\left(\beta X^+\right) \\ \mathcal{L}_{\rm Yukawa} &= \frac{i\,\mu}{4\pi} \exp\left(\beta X^+\right) \tilde{\psi}^+ \psi^+ \end{aligned}$$

where $\mu \equiv \beta^2 \alpha' \, \tilde{\mu}$.

The 2D interaction terms become large as $X^+ \to +\infty$:

We'll have to deal with that!

Lightlike tachyon condensation in type 0

There is no worldsheet potential, so all string states pass through the domain wall of the tachyon condensate.

Lightlike tachyon condensation in type 0

There is no worldsheet potential, so all string states pass through the domain wall of the tachyon condensate.

Perform a canonical change of variables so that the new variables have weak interactions in the limit $X^+ \to \infty$:

Lightlike tachyon condensation in type 0

There is no worldsheet potential, so all string states pass through the domain wall of the tachyon condensate.

Perform a canonical change of variables so that the new variables have weak interactions in the limit $X^+ \to \infty$:

$$\{\psi^+, \psi^-, \tilde{\psi}^+, \tilde{\psi}^-, X^\mu\} \Rightarrow \{b_1, c_1, \tilde{b}_1, \tilde{c}_1, X'^\mu\}$$

Lightlike tachyon condensation in type 0

There is no worldsheet potential, so all string states pass through the domain wall of the tachyon condensate.

Perform a canonical change of variables so that the new variables have weak interactions in the limit $X^+ \to \infty$:

$$\{\psi^+, \psi^-, \tilde{\psi}^+, \tilde{\psi}^-, X^\mu\} \Rightarrow \{b_1, c_1, \tilde{b}_1, \tilde{c}_1, X'^\mu\}$$

where b_1 and c_1 are a new set of ghost variables, with weights $3/2$ and $-1/2$, and $c = -11$.

Lightlike tachyon condensation in type 0

There is no worldsheet potential, so all string states pass through the domain wall of the tachyon condensate.

Perform a canonical change of variables so that the new variables have weak interactions in the limit $X^+ \to \infty$:

$$\{\psi^+, \psi^-, \tilde{\psi}^+, \tilde{\psi}^-, X^\mu\} \Rightarrow \{b_1, c_1, \tilde{b}_1, \tilde{c}_1, X'^\mu\}$$

where b_1 and c_1 are a new set of ghost variables, with weights $3/2$ and $-1/2$, and $c = -11$.

These have nothing to do with the Fadeev-Popov ghosts.

Lightlike tachyon condensation in type 0

There is no worldsheet potential, so all string states pass through the domain wall of the tachyon condensate.

Perform a canonical change of variables so that the new variables have weak interactions in the limit $X^+ \to \infty$:

$$\{\psi^+, \psi^-, \tilde{\psi}^+, \tilde{\psi}^-, X^\mu\} \Rightarrow \{b_1, c_1, \tilde{b}_1, \tilde{c}_1, X'^\mu\}$$

where b_1 and c_1 are a new set of ghost variables, with weights 3/2 and $-1/2$, and $c = -11$.

These have nothing to do with the Fadeev-Popov ghosts.

Also, twelve units of central charge are transferred from the light cone fermions $\psi^\pm$ to the dilaton gradient.

Deep inside the tachyon condensate

Deep inside the tachyon condensate

The new Lagrangian is free, except for the interaction term

Deep inside the tachyon condensate

The new Lagrangian is free, except for the interaction term

$$\mathcal{L}_{int} = \mu^{-1} \exp\left(-\beta X^{+}\right) \tilde{b}_1 b_1$$

and becomes free in the limit $X^{+} \to \infty$
What is this new theory?

Deep inside the tachyon condensate

The new Lagrangian is free, except for the interaction term

$$\mathcal{L}_{int} = \mu^{-1} \exp\left(-\beta X^{+}\right) \tilde{b}_1 b_1$$

and becomes free in the limit $X^{+} \to \infty$
What is this new theory?

In the late time limit, the theory deep inside the tachyon condensate is formally type 0 string theory, but in actuality, it is precisely equal to bosonic string theory.

Deep inside the tachyon condensate

The new Lagrangian is free, except for the interaction term

$$\mathcal{L}_{int} = \mu^{-1} \exp\left(-\beta X^{+}\right) \tilde{b}_1 b_1$$

and becomes free in the limit $X^{+} \to \infty$
What is this new theory?

In the late time limit, the theory deep inside the tachyon condensate is formally type 0 string theory, but in actuality, it is precisely equal to bosonic string theory.

In the natural variables of the late-time limit, the theory precisely realizes a well-known mechanism, originally found by Berkovits and Vafa.

The IR limit

The total final supercurrent $G \equiv G^{\rm LC} + G^{\perp}$ in IR variables is

$$
\begin{aligned}
G &= b_1 + i c_1' b_1 c_1 - c_1 T^{\rm mat} + c_1'' \left(-\frac{1}{6} c^{\perp} - \frac{1}{2} + \alpha' q^2 \right) \\
&\quad + c_1 c_1' c_1'' \left(-\frac{i}{4} \alpha' q^2 - \frac{i}{2} + \frac{i}{24} c^{\perp} \right)
\end{aligned}
$$

The IR limit

The total final supercurrent $G \equiv G^{\rm LC} + G^{\perp}$ in IR variables is

$$
\begin{aligned}
G &= b_1 + i c_1' b_1 c_1 - c_1 T^{\rm mat} + c_1'' \left(-\frac{1}{6} c^{\perp} - \frac{1}{2} + \alpha' q^2 \right) \\
&\quad + c_1 c_1' c_1'' \left(-\frac{i}{4} \alpha' q^2 - \frac{i}{2} + \frac{i}{24} c^{\perp} \right)
\end{aligned}
$$

The IR limit

The total transformed stress tensor is

$$T = T^{\mathrm{mat}} + T^{b_1 c_1}$$

with

$$T^{b_1 c_1} = -\frac{3i}{2}\partial_+ c_1 b_1 - \frac{i}{2} c_1 \partial_+ b_1 + \frac{i}{2}\partial_+(c_1 \partial_+^2 c_1)$$

The IR limit

The total transformed stress tensor is

$$T = T^{\mathrm{mat}} + T^{b_1 c_1}$$

with

$$T^{b_1 c_1} = -\frac{3i}{2}\partial_+ c_1 b_1 - \frac{i}{2} c_1 \partial_+ b_1 + \frac{i}{2}\partial_+(c_1 \partial_+^2 c_1)$$

Plugging in $q = \sqrt{\frac{D-10}{4\alpha'}}$ and $c^\perp = \frac{3}{2}(D-2)$:

$$G = b_1 + i c_1' b_1 c_1 - c_1 T^{\mathrm{mat}} - \frac{5}{2} c_1''$$

The IR limit

The $X^+ \to \infty$ limit of our solution is described by a free worldsheet theory, D free scalars X'^M and $D-2$ free fermions ψ'^i.

The IR limit

The $X^+ \to \infty$ limit of our solution is described by a free worldsheet theory, D free scalars X'^M and $D-2$ free fermions ψ'^i.

The total central charge of the X^M, ψ^i system is 26, and the contribution of -11 from the $b_1 c_1$ system brings the total central charge to 15.

The IR limit

The $X^+ \to \infty$ limit of our solution is described by a free worldsheet theory, D free scalars X'^M and $D-2$ free fermions ψ'^i.

The total central charge of the X^M, ψ^i system is 26, and the contribution of -11 from the $b_1 c_1$ system brings the total central charge to 15.

The theory has critical central charge for a SCFT interpreted as the worldsheet theory of a RNS superstring in conformal gauge.

Berkovits-Vafa construction

This type of superconformal field theory is an embedding of the bosonic string in the solution space of the superstring. [hep-th/9310170]

Berkovits-Vafa construction

This type of superconformal field theory is an embedding of the bosonic string in the solution space of the superstring. [hep-th/9310170]

For a conformal field theory T^{mat} with a central charge of 26, it is possible to construct a corresponding superconformal field theory defined by $G,\ T$ with central charge 15.

Berkovits-Vafa construction

This type of superconformal field theory is an embedding of the bosonic string in the solution space of the superstring. [hep-th/9310170]

For a conformal field theory T^{mat} with a central charge of 26, it is possible to construct a corresponding superconformal field theory defined by $G,\ T$ with central charge 15.

Upon treating the superconformal theory as a superstring theory, the resulting physical states and scattering amplitudes are identical to those of the theory defined by T^{mat} when treated as a bosonic string theory.

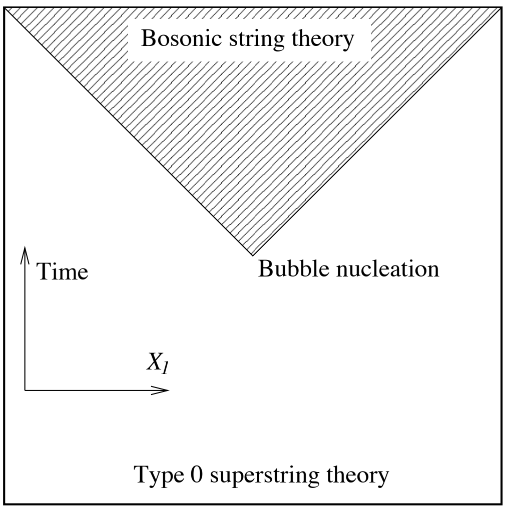
Transition to bosonic string theory

To summarize, the transition follows an instability in an initial D-dimensional type 0 theory.

Transition to bosonic string theory

To summarize, the transition follows an instability in an initial D-dimensional type 0 theory.

The dynamics then spontaneously break worldsheet supersymmetry, giving rise to a bosonic string theory in the same number of dimensions deep inside the tachyonic phase.



Outline

- Bosonic string solutions with nonzero tachyon
- Dimension-changing solutions in the bosonic string
- Transitions from type 0 to type II string theory
- Lightlike tachyon condensation in Type 0
- Other examples
- Conclusions

E_8 heterotic string theory

These techniques can be used to determine the fate of many other famous instabilities of closed string theories.

E_8 heterotic string theory

These techniques can be used to determine the fate of many other famous instabilities of closed string theories.

Consider unstable 10D heterotic string theory with a single E_8 gauge group, realized as a current algebra at level two.

E_8 heterotic string theory

These techniques can be used to determine the fate of many other famous instabilities of closed string theories.

Consider unstable 10D heterotic string theory with a single E_8 gauge group, realized as a current algebra at level two.

This theory has a single real tachyon $\mathcal{T}$.

E_8 heterotic string theory

These techniques can be used to determine the fate of many other famous instabilities of closed string theories.

Consider unstable 10D heterotic string theory with a single E_8 gauge group, realized as a current algebra at level two.

This theory has a single real tachyon $\mathcal{T}$.

The endpoint of tachyon condensation in this theory has been a subject of much speculation.

[Hořava + Fabinger, 2000]

E_8 heterotic string theory

We consider the theory in the background of a lightlike linear dilaton

$$\Phi = -\frac{q}{\sqrt{2}} X^-$$

E_8 heterotic string theory

We consider the theory in the background of a lightlike linear dilaton

$$\Phi = -\frac{q}{\sqrt{2}} X^-$$

This theory admits several exact solutions describing dynamical tachyon condensation to different types of endpoints.

E_8 heterotic string theory

One exact solution (studied by Hořava and Keeler) describes a bubble of nothing similar to the one we described in the bosonic string. The form of the solution is

$$\mathcal{T} = \mu \exp\left(\beta X^+\right)$$

with $q\beta = \frac{\sqrt{2}}{\alpha'}$.

[Hořava and Keeler, 2007]

E_8 heterotic string theory

One exact solution (studied by Hořava and Keeler) describes a bubble of nothing similar to the one we described in the bosonic string. The form of the solution is

$$\mathcal{T} = \mu \exp\left(\beta X^{+}\right)$$

with $q\beta = \frac{\sqrt{2}}{\alpha'}$.

[Hořava and Keeler, 2007]

We found another interesting exact solution, of the form

$$\mathcal{T} = \mu X_9 \exp\left(\beta X^{+}\right)$$

.

E_8 heterotic string theory

One exact solution (studied by Hořava and Keeler) describes a bubble of nothing similar to the one we described in the bosonic string. The form of the solution is

$$\mathcal{T} = \mu \exp\left(\beta X^{+}\right)$$

with $q\beta = \frac{\sqrt{2}}{\alpha'}$.

[Hořava and Keeler, 2007]

We found another interesting exact solution, of the form

$$\mathcal{T} = \mu X_9 \exp\left(\beta X^{+}\right)$$

.

The endpoint of this solution can be analyzed exactly . The solution does not destroy the universe, but it does reduce the dimension of the spacetime.

E_8 heterotic string theory

In this case, the endpoint is a previously unknown string theory that is interesting in its own right.

E_8 heterotic string theory

In this case, the endpoint is a previously unknown string theory that is interesting in its own right.

The final state lives in nine dimensions with the following properties:

E_8 heterotic string theory

In this case, the endpoint is a previously unknown string theory that is interesting in its own right.

The final state lives in nine dimensions with the following properties:

- stable (tachyon-free)

E_8 heterotic string theory

In this case, the endpoint is a previously unknown string theory that is interesting in its own right.

The final state lives in nine dimensions with the following properties:

- stable (tachyon-free)
- with spacelike linear dilaton

E_8 heterotic string theory

In this case, the endpoint is a previously unknown string theory that is interesting in its own right.

The final state lives in nine dimensions with the following properties:

- stable (tachyon-free)
- with spacelike linear dilaton
- with no moduli or other massless fields

E_8 heterotic string theory

In this case, the endpoint is a previously unknown string theory that is interesting in its own right.

The final state lives in nine dimensions with the following properties:

- stable (tachyon-free)
- with spacelike linear dilaton
- with no moduli or other massless fields
- E_8 gauge symmetry left unbroken

The tachyonic E_8 string

The spectrum of the final theory is

$$
\begin{aligned}
Z^{\mathrm{NS}}_{\mathrm{mass}}(\tau) &= (q\bar{q})^{+\frac{1}{16}} \left[1,785 + 108,500(q\bar{q})^{+\frac{1}{2}} + O\left(q\bar{q} \right) \right] \\
Z^{\mathrm{R}}_{\mathrm{mass}}(\tau) &= 1,984 + 4,058,880(q\bar{q})^{1} + O\left((q\bar{q})^{2} \right)
\end{aligned}
$$

theory	sector	mass	field content	mult.
UHE	NS	$m^2 = -2/\alpha'$	$\mathcal{T}$	1
	NS	$m^2 = 0$	$\Phi(1) + G(35) + B(28) + \mathbf{A}(1984)$	2048
	R	$m^2 = 0$	$\mathbf{\Lambda}_{+}(1984) + \mathbf{\Lambda}_{-}(1984)$	3968
HE9	NS	$m^2 = +1/(4\alpha')$	$\hat{\Phi}(1) + \hat{G}(27) + \hat{B}(21) + \hat{\mathbf{A}}(1736)$	1785
	R	$m^2 = 0$	$\hat{\mathbf{\Lambda}}(1984)$	1984

The tachyonic E_8 string

The spectrum of the final theory is

$$
\begin{aligned}
Z^{\mathrm{NS}}_{\mathrm{mass}}(\tau) &= (q\bar{q})^{+\frac{1}{16}} \left[1,785 + 108,500(q\bar{q})^{+\frac{1}{2}} + O\left(q\bar{q} \right) \right] \\
Z^{\mathrm{R}}_{\mathrm{mass}}(\tau) &= 1,984 + 4,058,880(q\bar{q})^{1} + O\left((q\bar{q})^{2} \right)
\end{aligned}
$$

theory	sector	mass	field content	mult.
UHE	NS	$m^2 = -2/\alpha'$	$\mathcal{T}$	1
	NS	$m^2 = 0$	$\Phi(1) + G(35) + B(28) + \mathbf{A}(1984)$	2048
	R	$m^2 = 0$	$\mathbf{\Lambda}_{+}(1984) + \mathbf{\Lambda}_{-}(1984)$	3968
HE9	NS	$m^2 = +1/(4\alpha')$	$\hat{\Phi}(1) + \hat{G}(27) + \hat{B}(21) + \hat{\mathbf{A}}(1736)$	1785
	R	$m^2 = 0$	$\hat{\mathbf{\Lambda}}(1984)$	1984

There is tachyon-free, with no supersymmetry.

$\mathcal{N} = 2$ string theory

Consider $\mathcal{N} = 2$ string theory.

$\mathcal{N} = 2$ string theory

Consider $\mathcal{N} = 2$ string theory.

In the critical dimension ($D = 4$), the signature of the theory is $(2, 2)$.

$\mathcal{N} = 2$ string theory

Consider $\mathcal{N} = 2$ string theory.

In the critical dimension ($D = 4$), the signature of the theory is $(2, 2)$.

The supercritical theory has a single timelike direction!

$\mathcal{N} = 2$ string theory

Consider $\mathcal{N} = 2$ string theory.

In the critical dimension ($D = 4$), the signature of the theory is $(2, 2)$.

The supercritical theory has a single timelike direction!

The theory has tachyonic modes that obey a holomorphic equation of motion.

$\mathcal{N} = 2$ string theory

Consider $\mathcal{N} = 2$ string theory.

In the critical dimension ($D = 4$), the signature of the theory is $(2, 2)$.

The supercritical theory has a single timelike direction!

The theory has tachyonic modes that obey a holomorphic equation of motion.

The simplest null holomorphic tachyon gives rise to a transition to bosonic string theory. At the endpoint, the theory is an analogue of the Berkovits-Vafa system discussed above.

Outline

Bosonic string solutions with nonzero tachyon

Dimension-changing solutions in the bosonic string

Transitions from type 0 to type II string theory

Lightlike tachyon condensation in Type 0

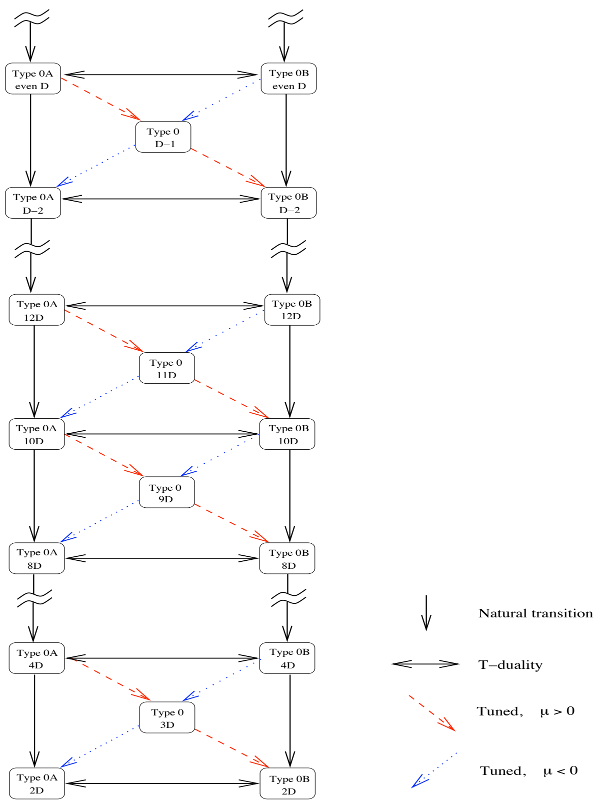
Other examples

Conclusions

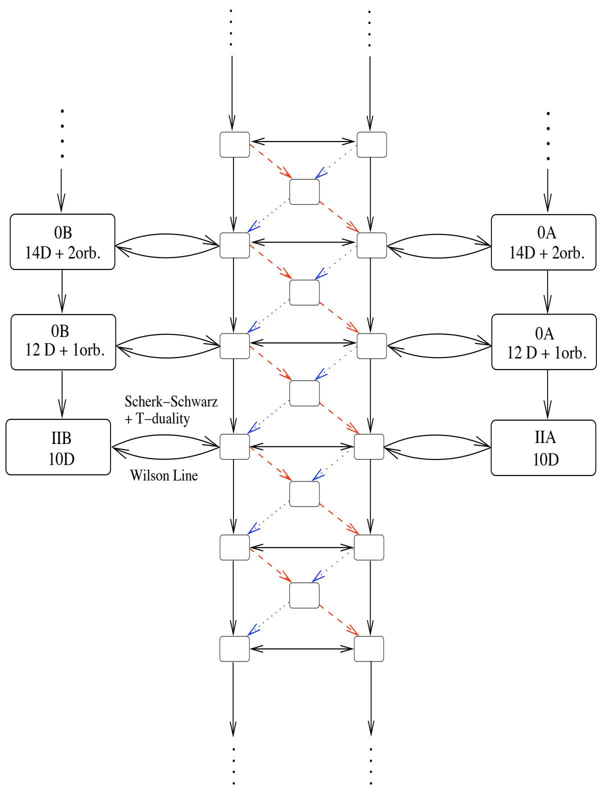
A partial catalog of exact transitions

start	D_{init}	$\exp\left(-\beta X^{+}\right) \mathcal{T}$	end	D_{fin}	comments
bos	D	$\mu^2\ X_2^2 + \mathcal{T}_0$	bos	D-1	tuned
0	D	$\mu X_2 X_3$	0	D-2	natural
0 (orb)	D	$\mu X_{i+1} Y_i$	II	10	stable
0	D	μ	bos	D $+\frac{1}{2}$ (D-2)	tuned
UHE	10	μX_2	HE9	9	stable
HO$^{(+1)}$	11	μX_2	HO	10	stable
HO$^{(+1)/}$	11	μX_2	HO$^{/}$	10	natural
HO$^{(+1)/}$ (orb)	11	μX_2	HO	10	stable
$\mathcal{N} = 2$	2 D_c - 1	$\mu \phi_2 \phi_3$	$\mathcal{N} = 2$	2 D_c - 5	natural
$\mathcal{N} = 2$	2 D_c - 1	μ	*bos*	3 D_c - 2	tuned

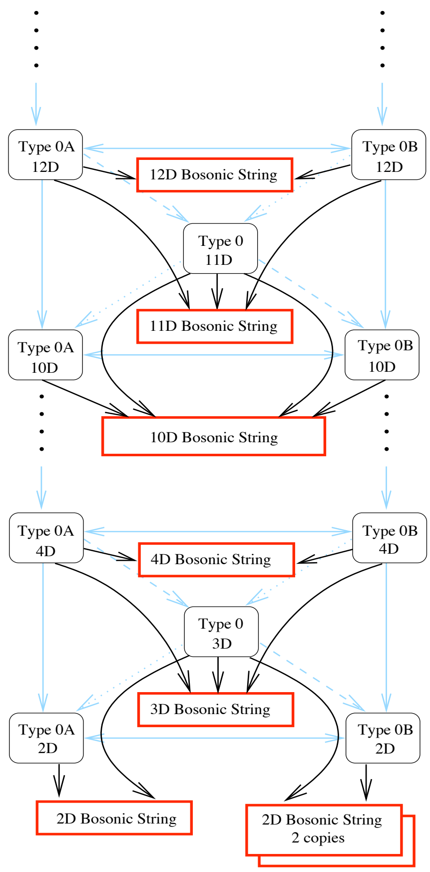
The Big Picture – Part I



The Big Picture – Part II



The Big Picture – Part III



Conclusions

- Supercritical string theory has some surprising and interesting properties.

Conclusions

- Supercritical string theory has some surprising and interesting properties.

- We see that the supercritical string can be connected to the duality web of critical string theory.

Conclusions

- Supercritical string theory has some surprising and interesting properties.
- We see that the supercritical string can be connected to the duality web of critical string theory.
- We have found solutions that interpolate between superstring theory and purely bosonic string theory.

Conclusions

- Supercritical string theory has some surprising and interesting properties.
- We see that the supercritical string can be connected to the duality web of critical string theory.
- We have found solutions that interpolate between superstring theory and purely bosonic string theory.
- The surprising feature of these connections is the crucial role of time dependence.

Conclusions

- Supercritical string theory has some surprising and interesting properties.
- We see that the supercritical string can be connected to the duality web of critical string theory.
- We have found solutions that interpolate between superstring theory and purely bosonic string theory.
- The surprising feature of these connections is the crucial role of time dependence.
- There may be other interesting links between theories that we have yet to discover.

Conclusions

- Supercritical string theory has some surprising and interesting properties.
- We see that the supercritical string can be connected to the duality web of critical string theory.
- We have found solutions that interpolate between superstring theory and purely bosonic string theory.
- The surprising feature of these connections is the crucial role of time dependence.
- There may be other interesting links between theories that we have yet to discover.

- Thank you!

Implications for Phenomenology

The phenomenological implications of our models remain to be worked out –

Implications for Phenomenology

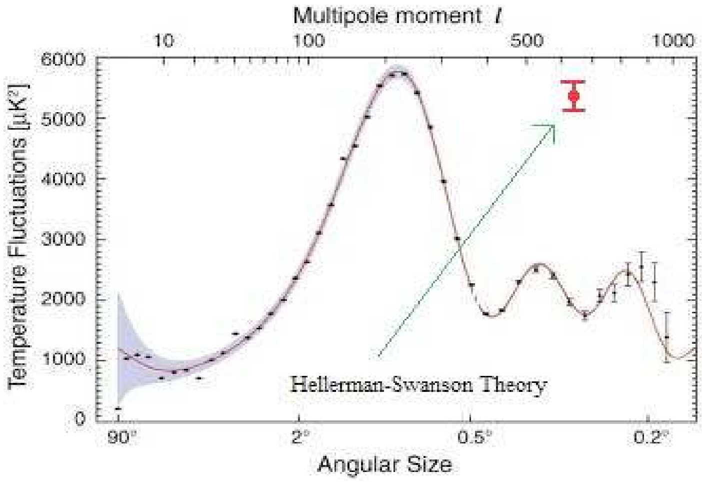
The phenomenological implications of our models remain to be worked out –

preliminary results are promising!

Implications for Phenomenology

The phenomenological implications of our models remain to be worked out –

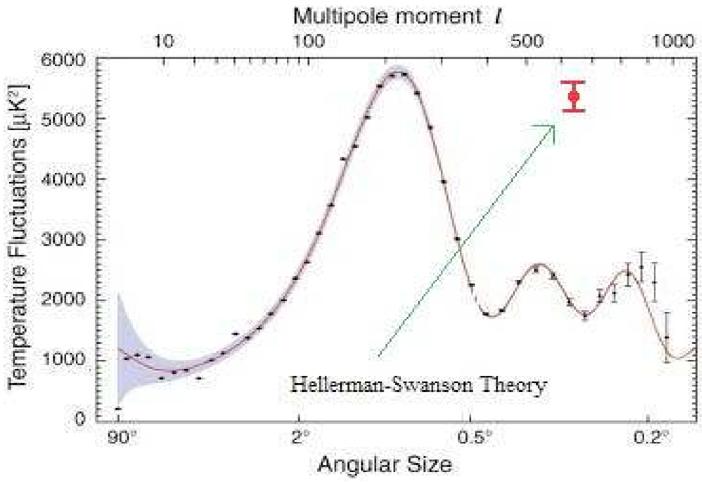
preliminary results are promising!



Implications for Phenomenology

The phenomenological implications of our models remain to be worked out –

preliminary results are promising!



Details of the transformation

Rescale the b_4 field so that the new b fermion appears in the supercurrent with unit normalization. To preserve all canonical commutators, however, we will rescale the c_4 field oppositely:

$$b_4 = \frac{2}{q\sqrt{\alpha'}} b_3 = \beta\sqrt{2\alpha'}\, b_3$$

$$c_4 = \frac{q\sqrt{\alpha'}}{2} c_3 = \frac{1}{\beta\sqrt{2\alpha'}} c_3$$

The IR limit

The invariance properties of the system under spatial reflection are still unclear.

The IR limit

The invariance properties of the system under spatial reflection are still unclear.

The stress tensor is invariant under the discrete symmetry reflecting the spacelike vector orthogonal to $\hat{V}_\mu$.

The IR limit

The invariance properties of the system under spatial reflection are still unclear.

The stress tensor is invariant under the discrete symmetry reflecting the spacelike vector orthogonal to $\hat{V}_\mu$.

The supercurrent is not, however, since V_μ and ΔV_μ appear independently in G^{LC}.

The IR limit

The invariance properties of the system under spatial reflection are still unclear.

The stress tensor is invariant under the discrete symmetry reflecting the spacelike vector orthogonal to $\hat{V}_\mu$.

The supercurrent is not, however, since V_μ and ΔV_μ appear independently in G^{LC}.

We would like to find field variables that render this discrete symmetry more manifest, such that only the vector $\hat{V}_\mu$ enters G^{LC}.

The IR limit

The invariance properties of the system under spatial reflection are still unclear.

The stress tensor is invariant under the discrete symmetry reflecting the spacelike vector orthogonal to $\hat{V}_\mu$.

The supercurrent is not, however, since V_μ and ΔV_μ appear independently in G^{LC}.

We would like to find field variables that render this discrete symmetry more manifest, such that only the vector $\hat{V}_\mu$ enters G^{LC}.
We therefore define new variables $b_2,\ c_2,\ Z^\mu$ by:

$$
\begin{aligned}
Y^\pm &= Z^\pm \pm \frac{i}{2\beta} c_2 \partial_+ c_2 \\
b_3 &= b_2 - \frac{2}{\beta\alpha'}(\partial_+ c_2)\left(\partial_+ Z^+ - \partial_+ Z^- \right) - \frac{1}{\beta\alpha'} c_2 \left(\partial_+^2 Z^+ - \partial_+^2 Z^- \right) \\
&\quad + \frac{i}{2\beta^2\alpha'} c_2 (\partial_+ c_2)(\partial_+^2 c_2) \\
c_3 &= c_2
\end{aligned}
$$

The IR limit

The worldsheet supersymmetry is now realized nonlinearly.

The IR limit

The worldsheet supersymmetry is now realized nonlinearly.

The bosons Z^μ transform into their own derivatives, times a goldstone fermion:

$$[Q, Z^\mu] = ic_2 \partial_+ Z^\mu \qquad \{Q, c_2\} = 1 + ic_2 \partial_+ c_2$$

where

$$Q \equiv \frac{1}{2\pi} \int d\sigma_1 \, G(\sigma)$$

The IR limit

The worldsheet supersymmetry is now realized nonlinearly.

The bosons Z^μ transform into their own derivatives, times a goldstone fermion:

$$[Q, Z^\mu] = ic_2 \partial_+ Z^\mu \qquad \{Q, c_2\} = 1 + ic_2 \partial_+ c_2$$

where

$$Q \equiv \frac{1}{2\pi} \int d\sigma_1 \, G(\sigma)$$

In the sector involving the transverse fields $X_i, \ \psi^i$, supersymmetry is realized in the usual linear fashion:

$$\begin{aligned} [Q, X_i] &= i\sqrt{\frac{\alpha'}{2}}\psi^i \\ \{Q, \psi^i\} &= \sqrt{\frac{2}{\alpha'}}\partial_+ X_i \end{aligned}$$

The IR limit

At first sight, our realization of supersymmetry in the full theory is unfamiliar, with worldsheet supersymmetry realized linearly in one sector and nonlinearly in another.

The IR limit

At first sight, our realization of supersymmetry in the full theory is unfamiliar, with worldsheet supersymmetry realized linearly in one sector and nonlinearly in another.

However, it turns out that this realization is equivalent to one for which worldsheet supersymmetry is realized completely nonlinearly in *all* sectors.

The IR limit

At first sight, our realization of supersymmetry in the full theory is unfamiliar, with worldsheet supersymmetry realized linearly in one sector and nonlinearly in another.

However, it turns out that this realization is equivalent to one for which worldsheet supersymmetry is realized completely nonlinearly in *all* sectors.

We now perform a final transformation on the system.
Defining the Hermitian infinitesimal generator

$$g \equiv -\frac{i}{2\pi} \int d\sigma_1 c_2(\sigma) G^{\perp}(\sigma)$$

we transform all operators in the theory according to

$$\mathcal{O} \to U \, \mathcal{O} \, U^{-1}$$

with

$$U \equiv \exp{(ig)}$$