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

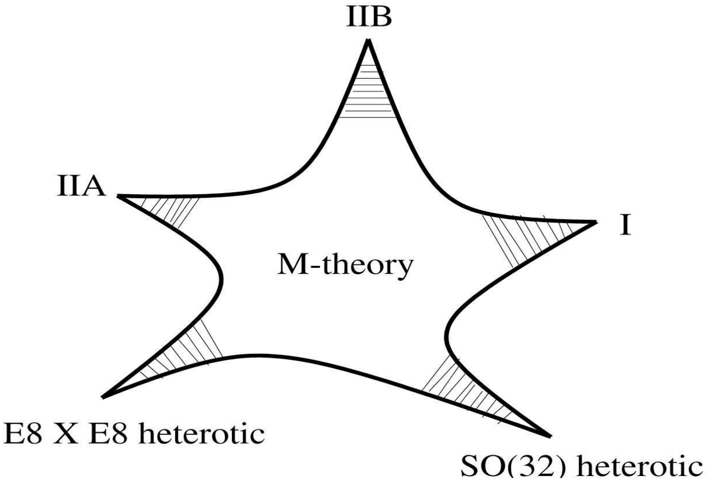
Lightlike tachyon condensation in Type 0

Other examples

Conclusions

Introduction

We understand THIS very well:



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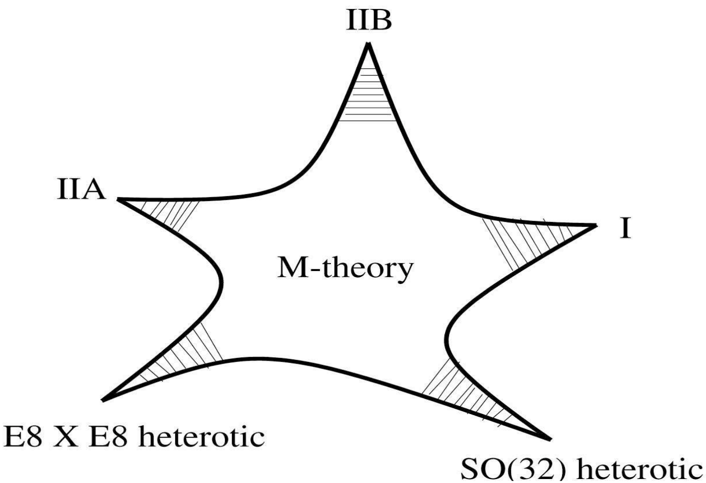

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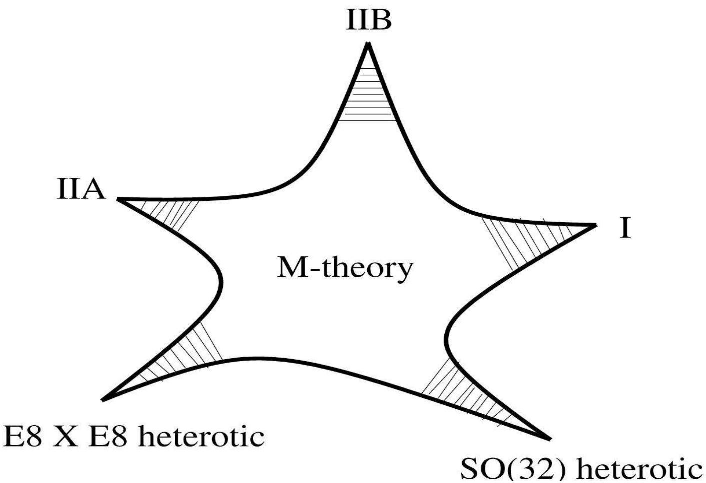

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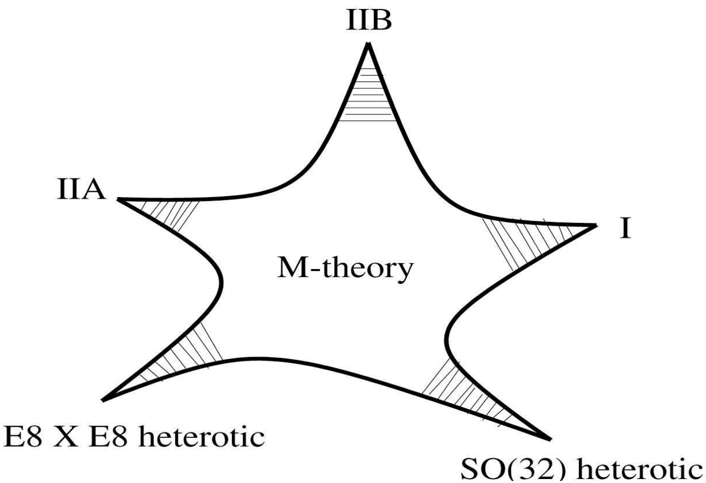

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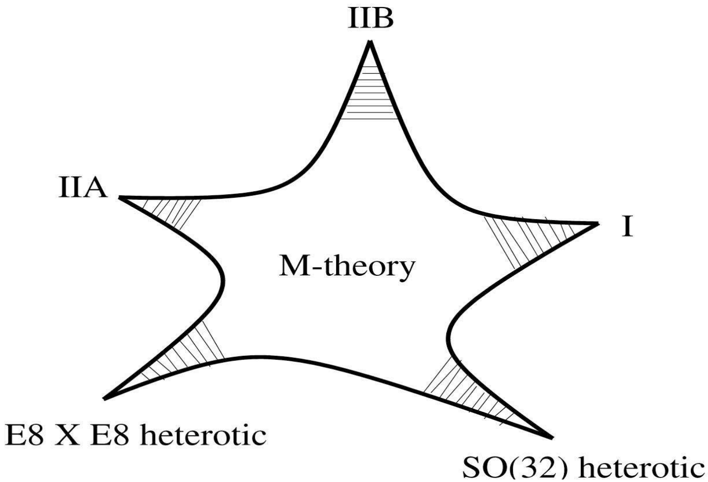

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We don't yet understand strong SUSY breaking very well!

Introduction

GOALS:

- Understand cosmology and strong time dependence

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What are the simplest concrete models of connections and transitions?

What I will describe today

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

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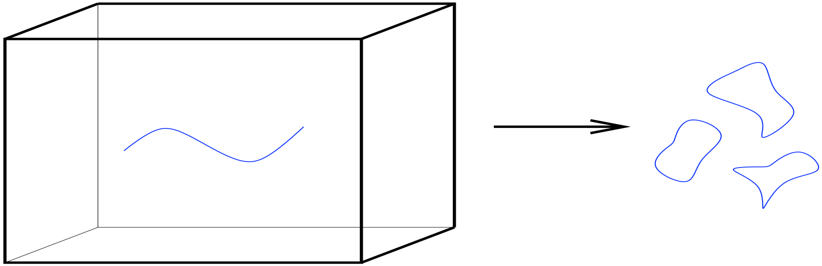
THIS TALK IS A CONJECTURE-FREE ZONE!

Analogy with open string tachyon dynamics

D-brane decay



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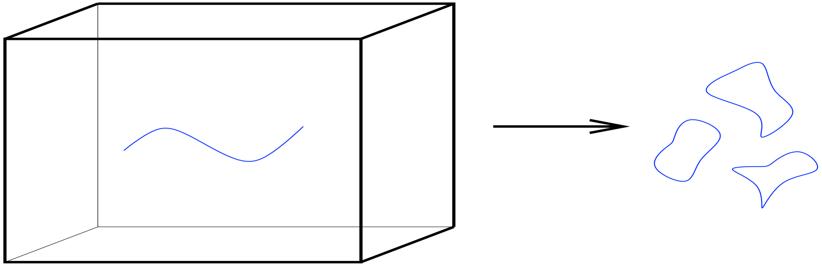
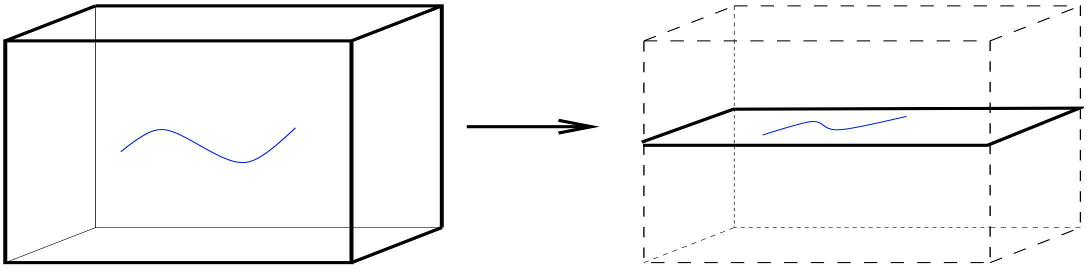
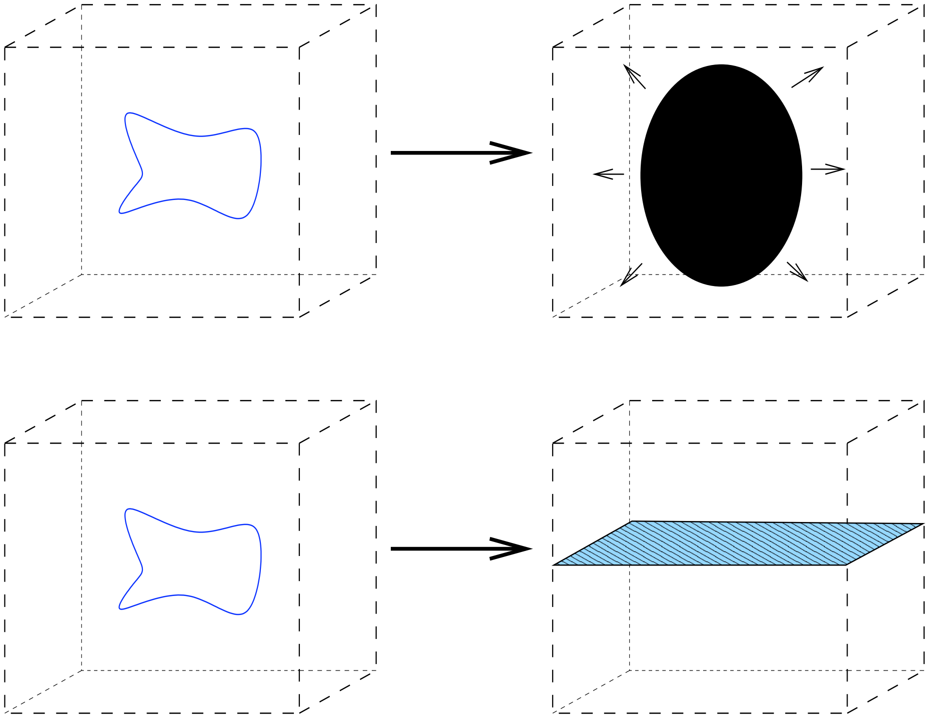


Solitons



Parallel with Open String Tachyon Dynamics

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



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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 $\sigma^{0,1}$:

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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:

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

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For tachyon profiles of the form

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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.

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We therefore put B_μ in the form

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

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

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

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

$$X^+ \longrightarrow X^-$$

Bubble of nothing

- The X field has oriented propagators.
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- This constitutes an interacting quantum theory, without quantum corrections.

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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:

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

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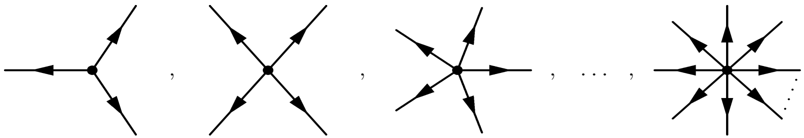
All interaction vertices in the theory depend only on X^+, and therefore correspond to diagrams composed strictly from outgoing lines:



Physical interpretation

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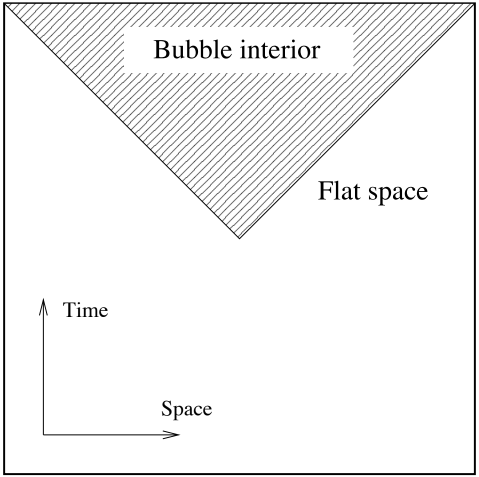
The spacetime picture is therefore a phase bubble expanding out from a nucleation point:



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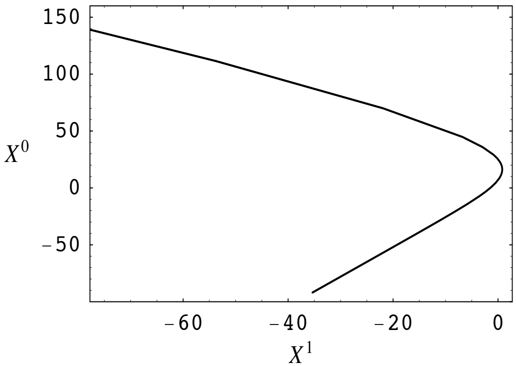

The state collides with the bubble wall and is forced out of the region with nonzero tachyon. (The solution has $\mu^2 = 1,\ \beta = .1$, and the trajectory corresponds to $p^+ = 3,\ H_\perp \equiv \frac{\alpha' p_i^2}{2} = 4$.)

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

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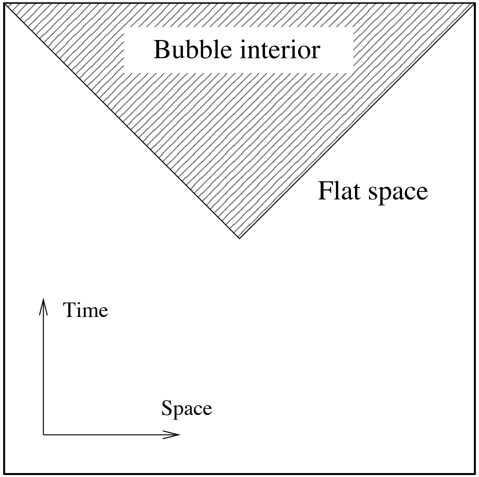

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Dimension-changing solutions in the bosonic string

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

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

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

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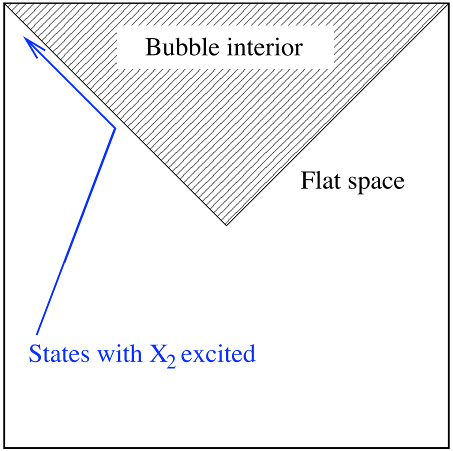
So these string states are pushed out to infinity and disappear from the theory in the late-time limit:



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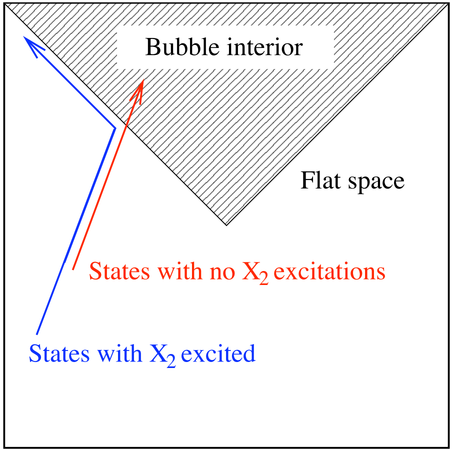

These propagate *through the domain wall and into the bubble region*.

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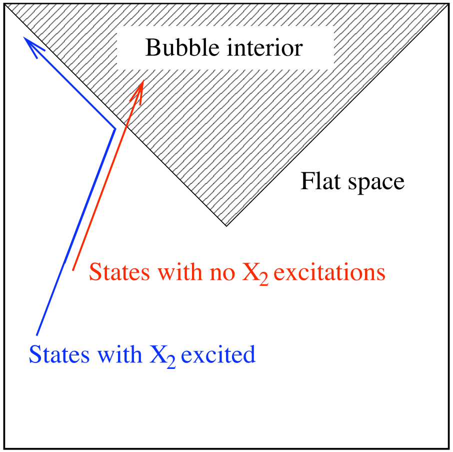

These propagate *through the domain wall and into the bubble region*.

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

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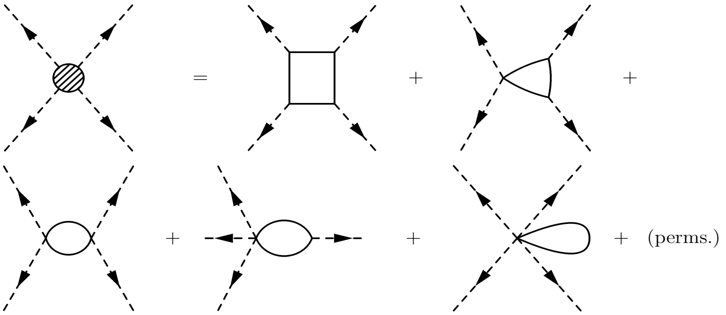
In fact, quantum corrections in this theory truncate at one-loop order:



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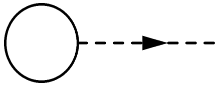
In fact: in the far future, all corrections coming from integrating out X_2 decay away, except for three contributions:

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

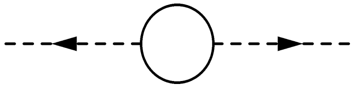
Dimension-changing solutions in the bosonic string

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

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



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



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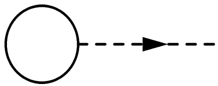
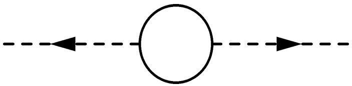
$\Delta(\partial_+\Phi) \quad =$ 

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

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

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

Dimension-changing solutions in the bosonic string

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

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

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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:

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

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

We can even get down to D=2!

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

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

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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:

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

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

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

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

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:

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This gives rise to a potential and Yukawa term:

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

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

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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:

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

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:

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

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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.

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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!

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

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

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We again take the simple form

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

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

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

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We also get a modified supersymmetry transformation for the fermions:

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

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

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We'll have to deal with that!

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

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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 $G \equiv G^{\mathrm{LC}} + G^{\perp}$ in IR variables is

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

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with

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

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

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

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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.

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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

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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.

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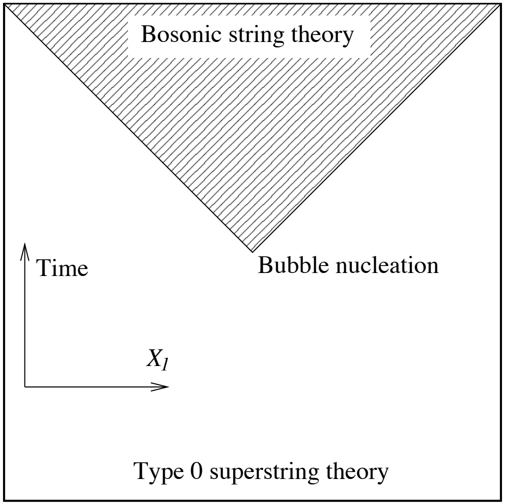
The dynamics then spontaneously break worldsheet supersymmetry, giving rise to a bosonic string theory in the same number of dimensions deep inside the tachyonic phase.



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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]

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

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

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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.

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- E_8 gauge symmetry left unbroken

The tachyonic E_8 string

The spectrum of the final theory is

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\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
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There is tachyon-free, with no supersymmetry.

$\mathcal{N} = 2$ string theory

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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

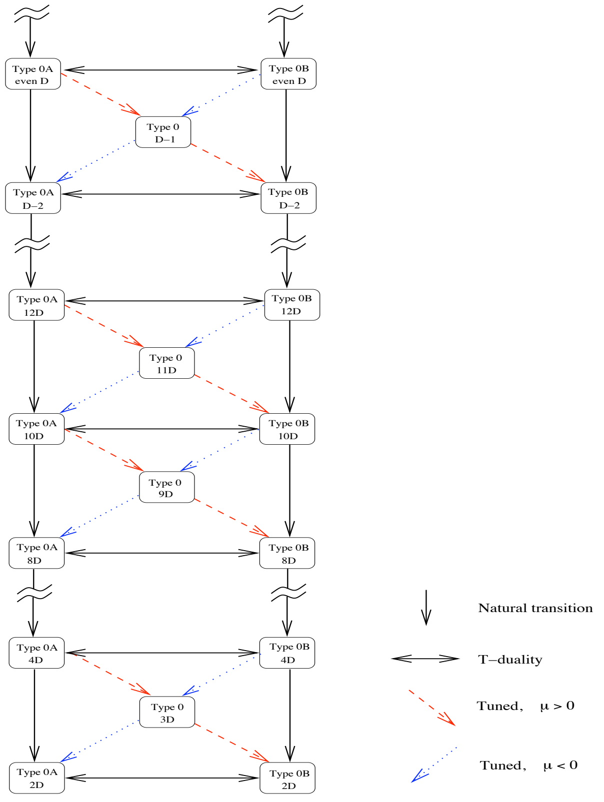
Other examples

Conclusions

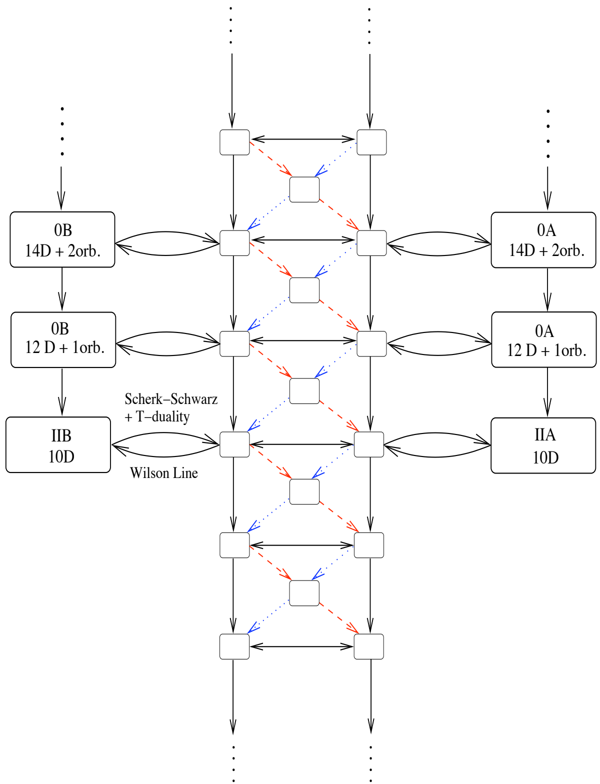
A partial catalog of exact transitions

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

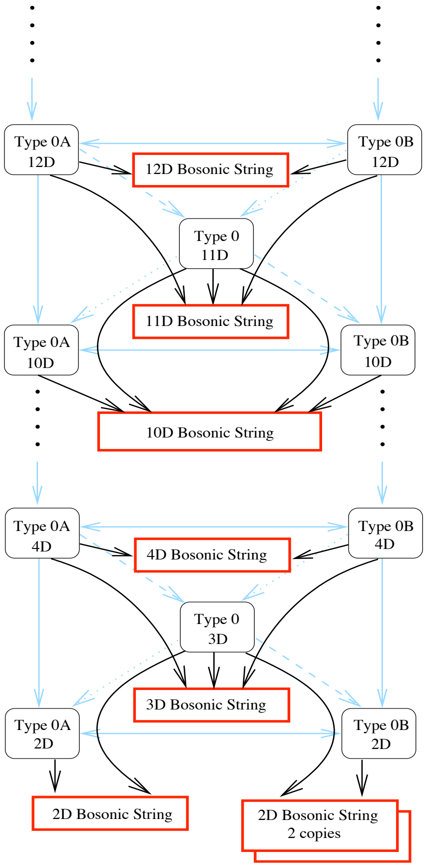
The Big Picture – Part I



The Big Picture – Part II



The Big Picture – Part III



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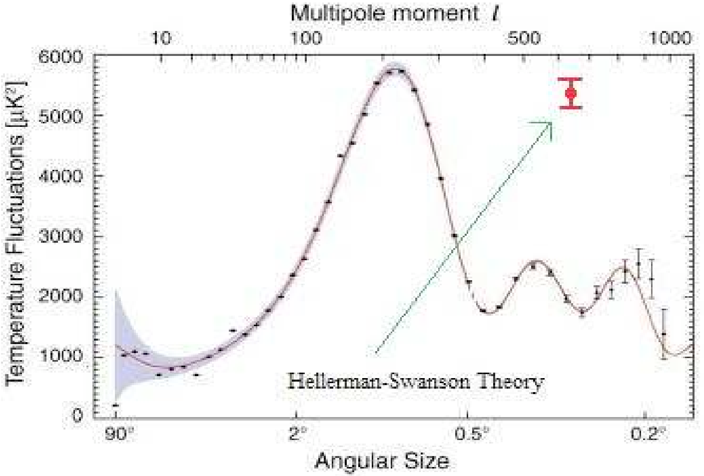

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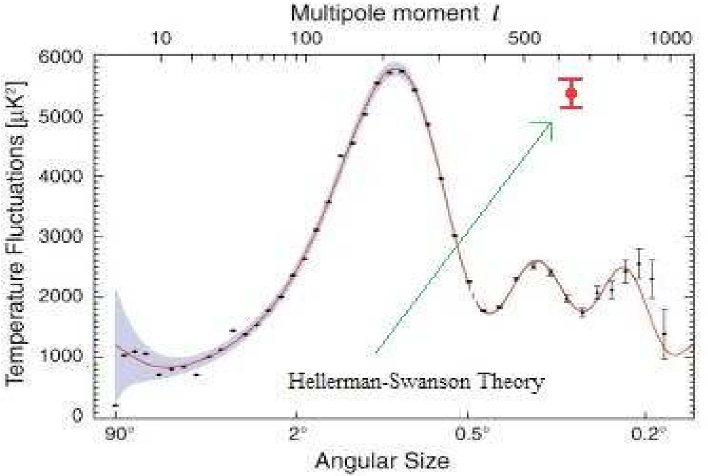

Details of the transformation

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:

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

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

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We therefore define new variables $b_2,\ c_2,\ Z^\mu$ by:

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

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

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

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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

$$U \equiv \exp\left(ig\right)$$