Orientifolds,

RG Flows, and

Closed String Tachyons

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Introduction

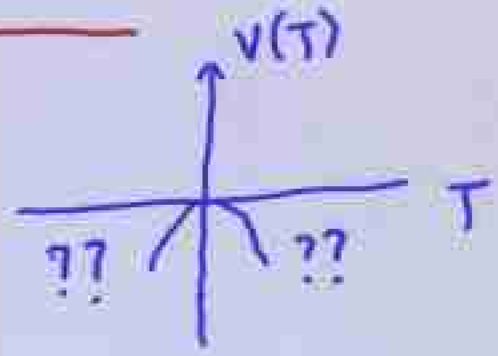
There are several motivations for studying non-supersymmetric strings:

- It is possible that in nature, SUSY is broken at $M_s \gg M_{EW}$
- It is possible that in nature $M_s \approx M_{EW}$ $\Rightarrow$ SUSY broken at M_s
- In cosmology (finite T) or generic processes, in any vacuum, no SUSY
- If $\exists$ "stringy" mechanisms for addressing hierarchy problems ($\Lambda \approx 0$) which SUSY doesn't solve in nature, they may be most easily identified in non-SUSY strings.

It is encouraging that e.g. AdS/CFT does provide a new way of viewing some of the problems of non-SUSY strings in terms of large N QFT. We will not discuss these qualitative issues today. S.K. + Silverstein

Common Concrete Problems:

Tree-level: Tachyon(s)

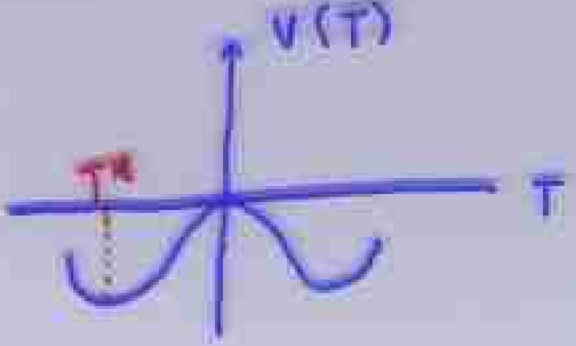


$\geq$ 1 loop: Cosmological constant, tadpole(s) for dilaton Φ and other moduli, ...

Today I discuss some ideas about the fate of tachyonic 'vacua'.

Suppose, in some case, $V(T)$ looks like:

i.e. $\exists$ minima at finite $\langle T \rangle$



Here we are artificially imagining that we "fix"

$$\Phi = \text{const}, \quad G_{\mu\nu} = \eta_{\mu\nu}$$

Problem: At $\langle T \rangle = T^*$, $V(T) < 0$. For closed string backgrounds, tadpole freedom $\Rightarrow$ $\Lambda_{tree} = 0$. How to describe theory at T^* in string language?

An Illustrative Open String Model

} also appeared in papers of Antoniadis et al '98

1st Step: IIB on $T^d / I_d \Omega$ $(d=4)$

(I_d reflects d coords, Ω = orientation reversal)

- Fixed pts. of $I_4 \Omega \Rightarrow$ 16 O5 planes
- RR charge considerations $\Rightarrow$ add 16 D5 s

This yields a 6d (1,1) SUSY model.

Note that:

$$\text{Tension}\ (O5) = -\ \text{Tension}\ (D5)$$

This is clear since $\Lambda_{tree} = 0$, from cancellation of Φ tadpole, ...

<u>2nd Step</u>: Consider orientifold generated by

$$g_1 = I_4 \Omega, \quad g_2 = I_4 \Omega (-1)^F \delta$$

$\delta: \ X_1 \to X_1 + \pi R$ } one of the T^4 coords.

g_2 preserves <u>opposite</u> half of SUSYs from g_1; it $\Rightarrow$ anti-orientifolds $\overline{O5}$ shifted from O5s by πR in X_1. g_2 alone $\to$ 16 $\overline{D5}$s needed.

⑤

Given <u>both</u> g_1 & g_2, several options:

A) Add 16 ($D5 + \overline{D5}$s) and then project

$\Rightarrow$ theory with:

$$G = SO(16) \times SO(16), \quad \Lambda_{tree} = 0$$

or rank (16) subgroups as you move D5s around

Tachyon in (16, 16) ← for small radii or brane separation

B) Add $k < 16 \times (D5 + \overline{D5})$ & project.

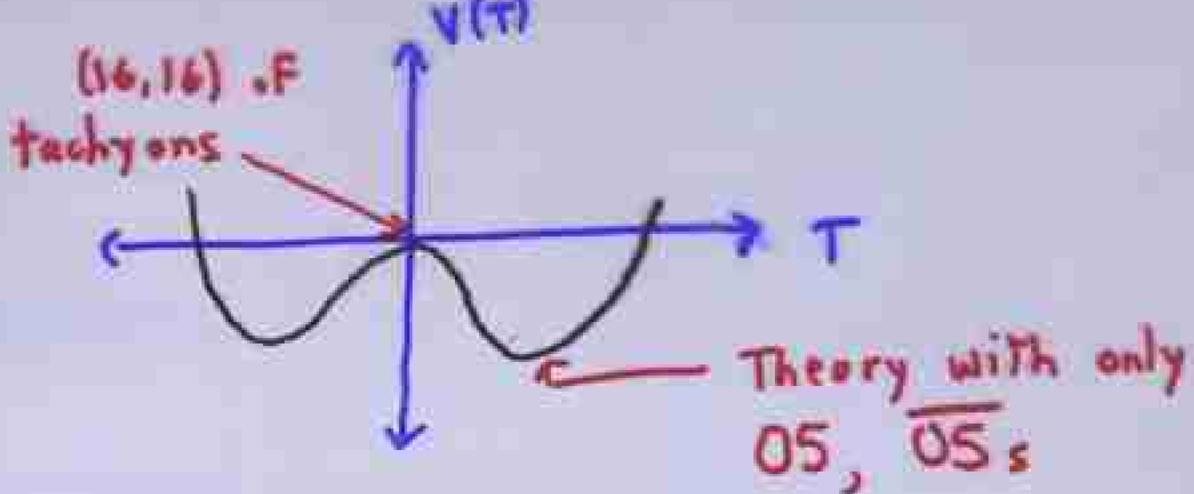
RR charge still ok, now $\Lambda_{tree} < 0$

(too few branes to cancel $O5 + \overline{O5}$s).

$$G = O(k) \times O(k)\ ; \quad (k,k) \text{ tachyon}$$

Pretty clear that A) → B) by annihilating (16-k) Ds & $\overline{D}$s, condensing (part of) (16,16) tachyon

So in the open string models, the orientifolds provide the (finite) $V < 0$ configuration that results from tachyon condensation:



What are analogous candidate $V < 0$ configurations in closed string theory?

Simplest e.g. : S-dual orientifold — Kutasov, Sen

IIB on $\mathbb{R}^4/I_4\Omega \Rightarrow D5 + O5$

S-dual of this : IIB on $\mathbb{R}^4/I_4(-1)^{F_L}$

"Twisted moduli" → collective coords. of NS 5 brane sitting at the fixed point.

From $\Lambda_{tree} = 0 \Rightarrow \exists$ also negative tension S-dual of O5 sitting at $\mathbb{Z}_2$ fixed point.

As in the previous open string case, we can find closed string models with tachyons which very plausibly "roll" to $V < 0$ configurations composed of these objects.

EXAMPLE: IIB on T^4, orbifold by

$$g_1 = I_4 (-1)^{F_L} \qquad g_2 = I_4 (-1)^{F_R} \delta_1$$

$$\delta_1 : X_1 \to X_1 + \pi R$$

$\exists$ 8 fixed pts each for g_1 & g_2

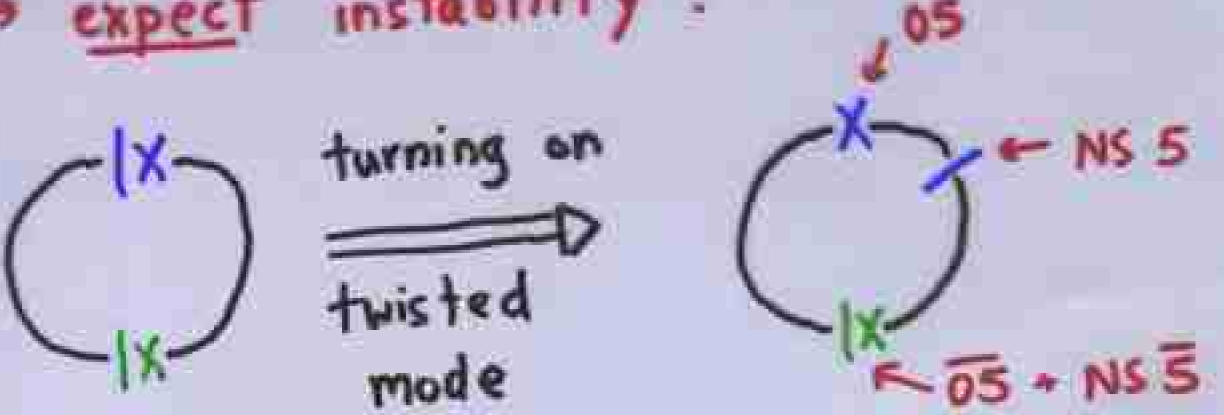
$g_1 \Rightarrow$ NS 5 branes

$g_2 \Rightarrow$ NS $\overline{5}$ branes

What is the fate of this model?

· $\Lambda_{tree} = 0$; large enough radii ⇒ no tachyon in perturbative spectrum.

· Globally, charges of NS $(5 + \bar{5})_s$ same as vacuum → <u>expect</u> instability :



Latter configuration can be expected to have "tachyonic" $(\text{mass})^2$ for NS $\bar{5}_s$ attracting them to NS 5_s, i.e.

$$\langle Q_5 \, Q_5 \, \bar{Q}_{\bar{5}} \, \bar{Q}_{\bar{5}} \rangle$$

} 1^{st} possibility consistent w/ orbifold symmetry

can ⇒ tachyonic mass for $\bar{Q}_{\bar{5}}$ when we turn on Q_5. Natural guess: NS 5 & $\bar{5}_s$ annihilate, leaving S-dual $O5_s$ as $V<0$ "vacuum".

There are actually a zoo of such $V<0$ closed string configs (see paper for discussion).

Tachyons & RG Flow

de Alwis et al; Antoniadis et al; Myers

Backgrounds with $\Lambda_{tree} < 0$ also can be described as follows. Consider bosonic strings in $D < D_{crit} = 26$. The Weyl anomaly cancellation conditions, including:

$$\beta^{\Phi} = \frac{D - D_{crit}}{6} - \frac{\alpha'}{2} \nabla^2 \Phi + \alpha' \nabla_\mu \Phi \nabla^\mu \Phi - \frac{\alpha'}{24} H_{\mu\nu\rho} H^{\mu\nu\rho} + \cdots = 0$$

can still be solved, by allowing Φ to vary.

(Famous e.g.: linear dilaton background)

The β-function eqns follow as EOM from

$$S \sim \int d^D x \sqrt{-G}\, e^{-2\Phi} \left\{ -\frac{2(D-D_{crit})}{3\alpha'} + R - \frac{1}{12} H^2 + 4\,\partial_\mu \Phi\, \partial^\mu \Phi + \cdots \right\}$$

1st term ⟹ cosmological constant $\propto D - D_{crit}$.

<u>Natural Idea</u>: Tachyon condensation → subcritical theory (tachyon vertex op ~ relevant operator in internal CFT).

de Alwis et al; Antoniadis & Kounnas

<u>Specific Case</u>: Bosonic string on SO(32) lattice.

$SO(32)^2$ current algebra comes from

$$32 \times (\lambda^I \quad \tilde{\lambda}^I) \qquad I = 1 \cdots 32$$

left moving (λ^I), right moving ($\tilde{\lambda}^I$)

Also $\exists\, X^\mu \quad \mu = 1 \cdots 10$

$$V = \lambda^I \tilde{\lambda}^J e^{ik\cdot x}$$

Tachyons? Singlet + (32, 32)

To describe tachyon condensation, add what to action?

$k = 0 \Rightarrow \int d^2\sigma \sqrt{g}\, \lambda \tilde{\lambda}$

In conformal gauge $g = \eta e^{2\omega}$, this has nontrivial ω dependence. Heuristically, would give mass to $\lambda, \tilde{\lambda} \Rightarrow D < D_{crit}$ theory.

How to do without breaking Weyl symmetry?

$k_0^2 = m^2 < 0 \Rightarrow$ add

$$\int d^2\sigma \sqrt{g}\, \lambda \tilde{\lambda}\, e^{+\kappa X_0} \Big\} \text{ vanishes at } t = -\infty$$

$$k_0 = -i\kappa \quad \kappa > 0$$

This describes initial time-dep. of tachyon as it rolls down hill. Expect $\lambda, \tilde{\lambda}$ mass up, need to solve $\beta^{\Phi} = 0$ w/ $D < D_{crit} \rightarrow \Phi$ varies over space.

Some relation between this bosonic model and $IIB/\mathbb{Z}_2\times\mathbb{Z}_2$ ← gen by Ω, $(-1)^F$ has been conjectured by Bergman & Gaberdiel.

$$IIB/\{\Omega, (-1)^F\} \rightarrow \begin{matrix} O9 & \overline{O9} \\ 16\,D9 & 16\,\overline{D9} \end{matrix}$$

Bianchi
Sagnotti

Has a D1 whose worldvolume fields <u>are</u> those of the previous bosonic string:

1-1 strings → X^μ
1-9 → λ^I
1-$\bar{9}$ → $\tilde{\lambda}^I$

This model also has the (32, 32) tachyon. Condensation (9-$\bar{9}$ annihilation) ⇒ 1-9, 1-$\bar{9}$ strings gone → λ, $\tilde{\lambda}$s lifted in D1 theory.

Can similarly analyze charged tachyons in some other theories.

e.g. (T-dual) Scherk-Schwarz models

$$\text{Type II} / (-1)^F \delta \quad \Big\} \text{ choose so tachyons are } \vec{p} \text{ modes}$$

<u>Upshot</u>: If shift is in X^9 direction, the $\hat{c}=1$ X^9, ψ^9 theory $\rightarrow$ massive theory or (for fine tuning) $\hat{c}<1$ minimal CFT.

So again solving $\beta^{\Phi} = 0$ with $D < D_{crit}$ will be required.

Other directions:

- Hagedorn?
- Transitions