Time evolution in non-supersymmetric strings

Based on work with E. Dudas, J. Mourad and A. Sagnotti

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Summary

- *Time-dependent* vacua as backreaction of susy breaking:

$$ds^2 = -e^{2B(t)}dt^2 + e^{2A(t)}d\Sigma^2_{p+1} + e^{2C(t)}d\Sigma^2_{D-p-2} \,.$$

- Only control of *asymptotics* $\Rightarrow$ universal singular behavior.

- Susy-breaking term only relevant in *one* type of asymptotic.

Plan

- ☐ Strings without spacetime supersymmetry
  - Tadpole potentials
- ☐ Time dependence
  - Codimension-one
  - Compactifications
- ☐ Discussion

Strings without spacetime supersymmetry

Arena: string-scale susy breaking.

Prototype: the three ten-dimensional

① Heterotic: $SO(16) \times SO(16)$ [Alvarez-Gaume, Ginsparg, Moore, Vafa 1986; Dixon, Harvey 1986].

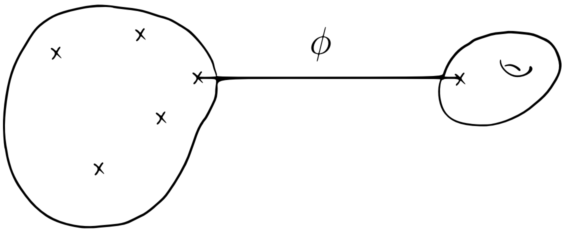
② Orientifold of bosonic 0B: 0'B [Sagnotti 1995].

③ Type IIB with $O9^+$ and 32 $\overline{D9}$: $USp(32)$ [Sugimoto 1999].

Focus on these and lower-dimensional models with 1 massless scalar.
recent ones [Fraiman, Graña, Parra De Freitas, Sethi 2023; Baykara, Tarazi, Vafa 2024]

Main issue: *backreaction*

From the worldsheet: IR divergences (tadpoles), sign of being *off-shell*



➠ Subtract tadpole contribution through background shift [Fischler, Susskind 1986; Callan, Lovelace, Nappi, Yost 1986–8; Tseytlin 1988–90].

Tadpole potentials

Tadpole subtraction $\sim$ string-loop *corrections*

$$S \sim \int (e^{-2\phi} + c_R)R + (e^{-2\phi} + c_\phi)4(\partial\phi)^2 - (e^{-2\phi} + c_H)\frac{1}{2}\frac{H^2}{3!} - \Lambda + \dots$$

tadpole scalar potential $\boxed{\Lambda = T\, e^{\gamma_s \phi}\,,}$ $\qquad \gamma_s = \{0, -1\}\,, \gamma_s > -2\,.$

- ➠ Replaces the cosmological constant problem.
- ➠ Perturbative expansion becomes consistency requirement.

Focus on the lowest-order terms (Einstein frame)

$$S \sim \int R - \frac{1}{2}(\partial\phi)^2 - \sum_k \frac{1}{2} e^{\beta_k \phi} \frac{F_k^2}{k!} - T e^{\gamma\phi} \, .$$

Today: no form fields, no fluxes. They make the story richer but less clear.

Question:

what does an empty universe look like?

- No Minkowski.
- No maximally symmetric.
- Static solutions haunted by singularities. dynamical cobordism [Angius, Basile, Blumenhagen, Buratti, Calderón-Infante, Cribiori, Delgado, Huertas, Kneissl, Makridou, Mininno, Uranga, Wang, ... 2020-4]

Time dependence

This talk: use $V(\phi)$ to *seed time evolution*.

- ➠ This must include the expected $\phi \to$ weak coupling ($T > 0$).
- ➠ We leave the worldsheet, embrace spacetime effective action.

In general:

$$\boxed{\begin{aligned} ds^2 &= g_{\mu\nu}(x)dx^\mu dx^\nu + h_{ij}(x)dy^i dy^j \ , \\ e^\phi &= e^{\phi(x)} \ . \end{aligned}}$$

In practice (lack of tools):

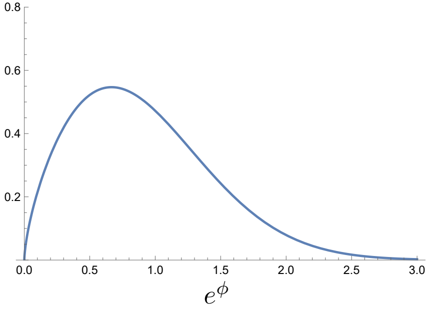
- Time dependence only.
- Einstein manifolds.

Codimension-one

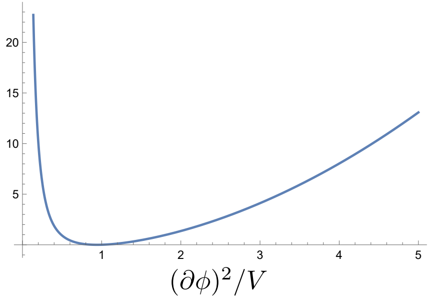
$$ds^2 = -dt^2 + e^{2A(t)} d\Sigma^2_{D-1} \,, \qquad \phi = \phi(t) \,.$$

flat Σ [Dudas, Mourad 2000; Dudas, Kitazawa, Sagnotti 2010; Basile, Thomée, SR 2022]

- Bounded e^{ϕ}.



- Tadpole-free singularities separated by infinite time.



and negatively-curved Σ [SR 2022]:

$$
\begin{aligned}
ds^2 &\sim -d\tau^2 + \tau^2 d\Sigma_{D-1}^2 \,, \\
e^{\phi} &\sim \tau^{-\frac{2}{\gamma}} \,.
\end{aligned}
$$

- e^{ϕ} not bounded.
- Balance of tadpole and kinetic term.
- No free parameter: problem with α' corrections.

Comment:
for codimension-two, [Dudas, Mourad, Timirgaziu 2002] $\rightarrow$ *Lorentzian orbifolds*, although in one specific case.

Compactifications

The general ansatz with only time dependence becomes *brane-like*:

$$\begin{aligned} ds^2 &= -e^{2B(t)}dt^2 + e^{2A(t)}d\Sigma^2_{p+1} + e^{2C(t)}d\Sigma^2_{D-p-2} \,, \\ e^{\phi} &= e^{\phi(t)} \,. \end{aligned}$$

$\Rightarrow$ analysis of [Mourad, SR, Sagnotti 2024]: branes with tadpole potentials.

No analytic results, but *complete understanding of asymptotics*.

Here, the two spaces can have curvatures $(k = \pm 1, 0)$

$$\Sigma_{p+1} \to k_{ext} \,, \qquad \Sigma_{D-p-2} \to k_{int} \,.$$

Our strategy: harmonic gauge $B = (p+1)A + (D-p-2)C$:

$$\begin{pmatrix} X \\ Y \\ W \end{pmatrix}'' = \begin{pmatrix} -k_{int} & -k_{ext} & + \\ -k_{int} & -k_{ext} & + \\ -k_{int} & -k_{ext} & \pm, 0 \end{pmatrix} \begin{pmatrix} e^X \\ e^Y \\ e^W \end{pmatrix} ,$$

$$\boxed{X \sim k_{int} \, , \quad Y \sim k_{ext} \, , \quad W \sim \text{tadpole} \, .}$$

- A few analytic solutions.
- This gauge allows for a complete and clear understanding of asymptotics. 3 families of non-tadpole-free asymptotics (and analytic solutions):

$\mathfrak{a}$. Tadpole and two negative curvatures $k_{int} = k_{ext} = -1$ ($p < D - 3$)

$$ds^2 \sim -d\tau^2 + \tau^2 d\Sigma_{p+1}^2 + \tau^2 d\Sigma_{D-p-2}^2 \,,$$
$$e^{\phi} \sim \tau^{-\frac{2}{\gamma}} \,.$$

- For $p = D - 2$ it becomes the codimension-one solution of [SR 2022].
- For $p = D - 3$ similar but with a different exponent

$$ds^2 \sim -d\tau^2 + \tau^2 d\Sigma_{D-2}^2 + \tau^{\frac{1}{2\gamma^2}} dz^2$$

$\mathfrak{b}$. Tadpole and one negative curvature $k_{int} = -1$ (asymptotic as $\tau \to 0$)

$$ds^2 \sim -d\tau^2 + \tau^{\frac{32}{(D-2)^2\gamma^2}} d\Sigma_{p+1}^2 + \tau^2 d\Sigma_{D-p-2}^2 \,,$$
$$e^{\phi} \sim \tau^{-\frac{2}{\gamma}} \,.$$

see [Andriot, Tsimpis, Wrase 2023]

$\mathfrak{c}$. Tadpole only (asymptotic as $\tau \to 0$)

$$ds^2 \sim -d\tau^2 + \tau^{\frac{32}{(D-2)^2\gamma^2}} d\Sigma_{D-1}^2 \,,$$
$$e^{\phi} \sim \tau^{-\frac{2}{\gamma}} \,.$$

This requires $\gamma < \gamma_c = \frac{4\sqrt{D-1}}{D-2}$, only leaving *open string* tadpole in $D < 10$.

- All thes asymptotics have *no free parameters*.
- *Partial match* may be possible as in [Mourad, SR, Sagnotti 2024]: wip.
- Only $\mathfrak{a}$. can be trusted! $e^{\phi} \to 0$ region.

Emerging picture: reliable time-dependent vacua can end on

tadpole-free solutions; $\mathfrak{a}$.

Discussion

- Some sort of universality emerges, much like for static vacua.
  (dynamical cobordism)

- Ubiquitous presence of spacetime *singularities*. Some are weakly coupled, but which ones are stringy?

- No free parameters in the asymptotic solutions, but free parameters generically appear in the bulk description.

- If vacua for non-supersymmetric strings, then can they host the stringy spectrum of branes? [Mourad, Sagnotti 2023; Mourad, SR, Sagnotti 2024]

- Is there a way to access the asymptotics from the worldsheet?

Thank you!