Cosmic F- and D-strings

w/ Ed Copeland
Sandip Trivedi

1. Before and after the 2nd S.S. revolution.
2. Stability of cosmic strings.
3. The KKLMMT model.
4. Observational consequences.

1. $t < 1995$: There was a clear distinction between fundamental and cosmic strings.

Fundamental strings had tension μ close to the Planck scale: e.g. heterotic:

$$G\mu = \frac{\alpha_{GUT}}{16\pi} \gtrsim 10^{-3}$$

Cosmic strings must have

$$G\mu \lesssim 10^{-5}$$

from $\delta T/T$. (deficit angle $\Delta = 4\pi G\mu$)

Thus cosmic strings had to be magnetic or electric flux tubes in the low energy theory.

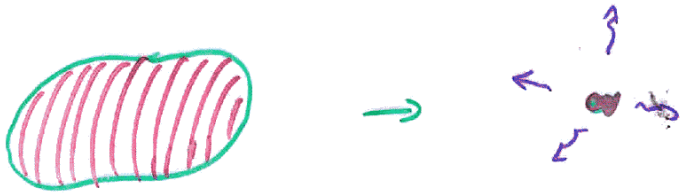
Why don't fundamental strings of cosmic length exist?

a. inflation $(V^{1/4} < \mu^{1/2})$

b. decay (Witten 1985)

- A long type I string breaks into pieces on a stringy time scale:

- A long heterotic string always bounds an axion domain wall, which makes it contract + disappear



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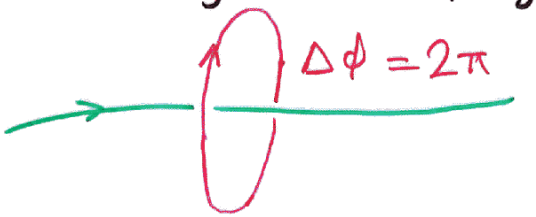
Axion domain walls: Fundamental heterotic string couples $\int B_{\mu\nu}\, dx^\mu dx^\nu$

$B_{\mu\nu} \approx$ axion ϕ in effective 4-d theory:

$$\partial_{[\mu} B_{\nu\lambda]} = \varepsilon_{\mu\nu\lambda}{}^{\rho} \partial_\rho \phi + \text{Chern-Simons}$$

Direct (electric) coupling to $B_{\mu\nu}$ = topological (magnetic) coupling to ϕ:



Chern-Simons coupling of $B_{\mu\nu}$ → axion coupling $\phi F \wedge F$

Gauge instantons produce $V(\phi) \propto \cos\phi$

⇒ domain wall

Type II? Wrapped NS5-instantons

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After the revolution:

A. More kinds of string:

F-strings, D-strings, partly wrapped NS-, D-, M-branes.

B. Possible lower string scale due to large compact dimensions, warping.

C. Dualities relate various objects, including gauge theory flux tubes.

$\Rightarrow$ must revisit question of cosmic strings.

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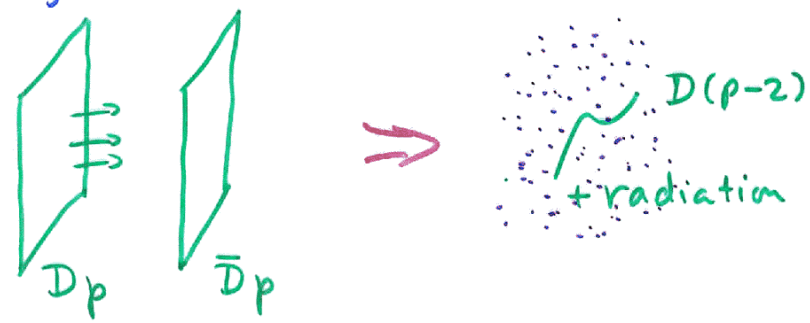
Cosmic strings from brane inflation –

Jones, Stoica + Tye ×2; Sarangi + Tye; Pogosian, Tye, Wasserman, + Wyman.



K-theory: $D\bar{D}$ annihilation can produce lower dimensional D-branes (defects in tachyon field)

Kibble theory: " " must " " ...

Here strings, not monopoles or domain walls.

Models: $10^{-11} \lesssim G\mu \lesssim 10^{-6}$ $\left(\frac{\delta T}{T} \to H \to \mu_{\text{infl.}}\right)$
(tori)

Current bound: $G\mu \lesssim 10^{-6}$
(power spectrum)

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Necessary conditions for strings to be cosmologically interesting:

$G\mu$ not too large ✓

produced after inflation ✓

stable ?

Naive extrapolation of Witten (1985):

BPS strings confined by domain walls

non-BPS strings unstable.

The actual story is more interesting, and model-dependent.

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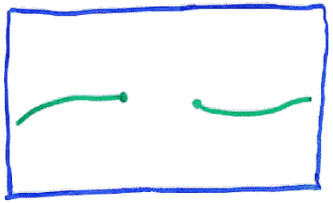
2. Stability.

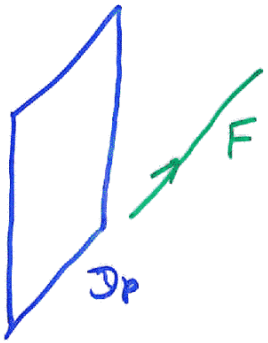
a. Breakage: prototype is type I string

Modern interpretation: endpoints attach to spacetime-filling D9-brane



A type II F-string can decay on any Dp-brane that fills the non-compact directions ($p \geq 3$).

Possible source of stability: transverse separation — need $\alpha' H^2$



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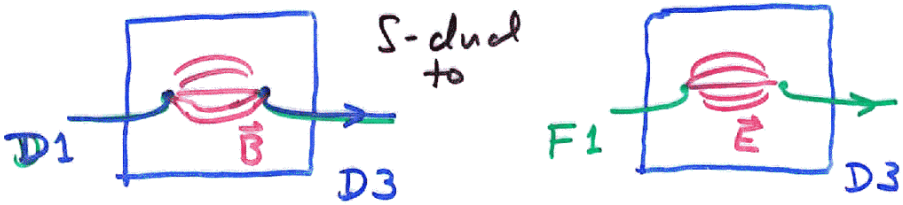
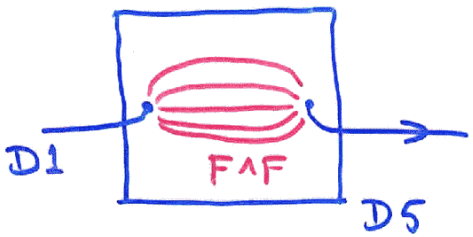
D-strings



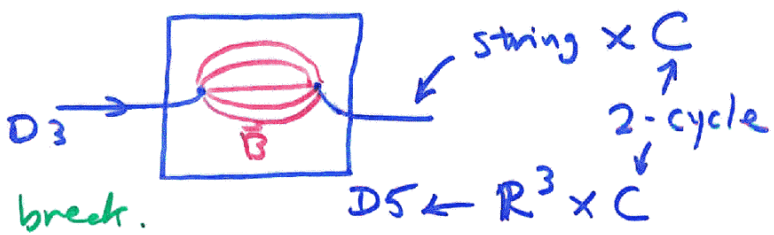
D1, F1 can break, $\vec{E}$ or $\vec{B}$ spreads and energy $\to 0$.

But



cannot lower energy by spreading (instanton string). So D1 breaks on D3, not D5 or D7.

Also:

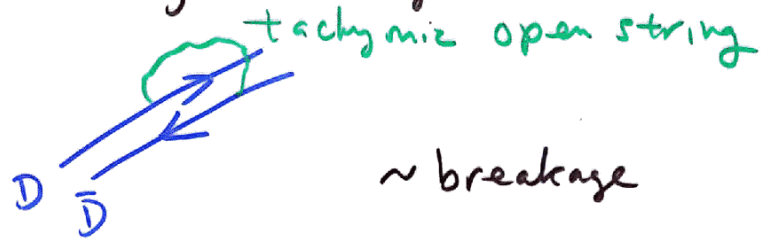


can break.

b. Domain walls

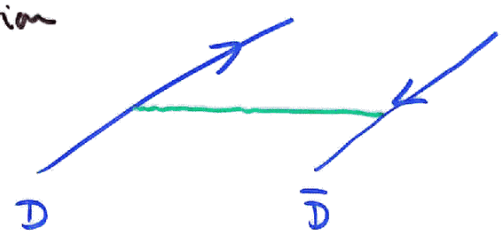
Every BPS string couples to form field = 4d axion, every axion gets a potential from some instanton; difficult to see how domain wall tension can be suppressed $\Rightarrow$ need non-BPS strings.

c. Tachyonic decays:

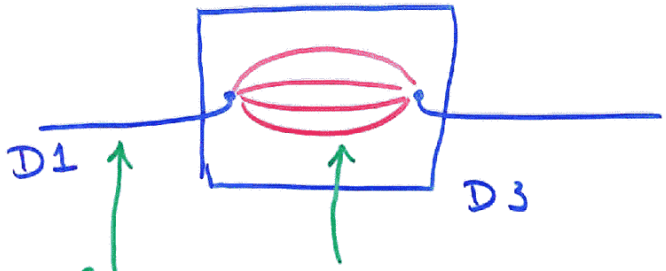


~ breakage

Can be suppressed by transverse separation



Puzzle: what if a string appears to have both instabilities : it can't, because the boundary of a boundary is zero! What happens?



$$\int_{D1} C + \int_{D3} C \wedge F \qquad C \equiv C_{\mu\nu}$$

topological coupling of $C_{\mu\nu}$ = electric coupling of axion ϕ:

$$(\partial_\mu \phi + A_\mu)^2$$

A_μ eats ϕ ⇒ no domain wall.

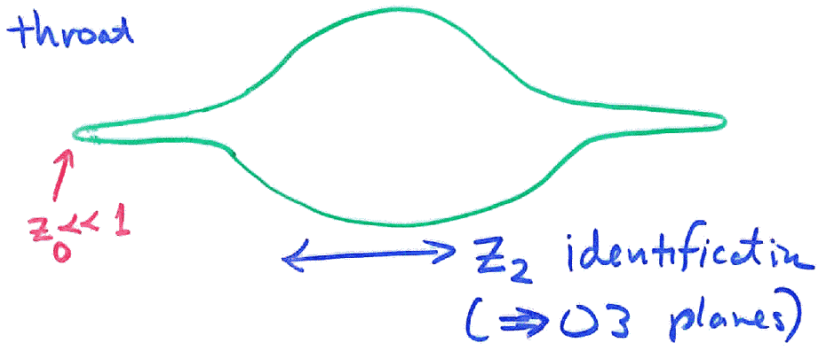
But U(1) is Higgsed so flux can't spread: string can't break, it's stable!

(non-perturbative decays ???)

3. Example: KKLMMT model

Kachru, Kallosh, Linde, Maldacena, McAllister, Trivedi

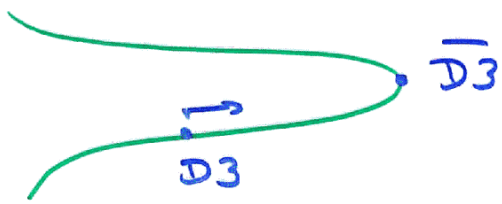
Orientifold of Calabi-Yau with RS-like throat



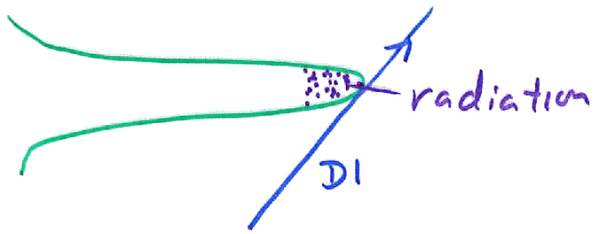
$$ds^2 = z^2(x^4 \ldots x^9)\, dx^\mu dx^\nu \eta_{\mu\nu} + \ldots$$

(+fluxes + $\overline{D3}$ + D-instantons)

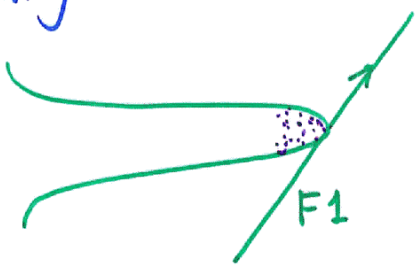
Inflation from $D3 + \overline{D3}$ in throat



K theory + Kibble ⟹

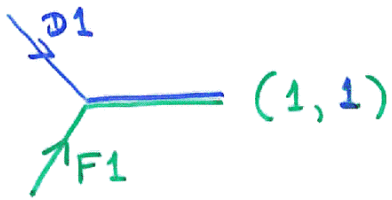


S-duality ⟹



(Kibble? $g_s = O(1)$)

+ also (Schwarz, Witten)



(p, q): $\mu \propto \sqrt{p^2 + q^2/g_s^2}$

relatively prime

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Tension?

$$z_0^4 \sim \frac{V}{M_{Pl}^4} \overset{*}{\sim} \frac{\delta_H^{3/2}}{N_c^{5/2}} \sim 10^{-17}$$

$$G\mu \sim z_0^2 \sim 10^{-8 \text{ or } 9}$$

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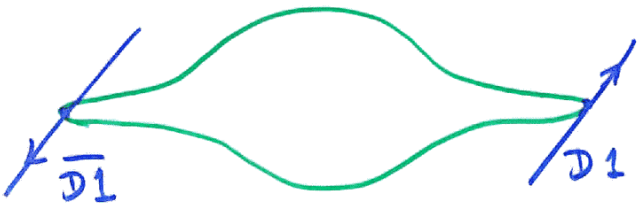
Stability? First, neglect all branes after inflation...

These 1-branes are non-BPS...
(~ T-dual to type I D7-branes)
Orientifold removes $B_{\mu\nu}$, $C_{\mu\nu}$ from spectrum. (cf. T^6/Z_2)



$D1 + \overline{D1}$ can annilate, but to do so they must tunnel out of warped throat... action $\sim z_0^{-2} \sim 10^8$

amplitude $\sim e^{-10^8}$

$\Rightarrow$ essentially stable

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A complete model also requires

- A $\overline{D3}$ in a throat for stabilization.
- Standard Model branes - e.g.
  D3's at orbifold singularity
  $\overline{D3}$'s at orbifold singularity
  intersecting D7's.

- If these are all outside the inflationary throat, the (p,q) strings are stable due to tunnelling suppression.
- If only the stabilizing $\overline{D3}$ is in the inflationary throat, there are <u>no</u> stable strings. But this scenario has a problem with reheating: all the energy goes into the gauge field on the $\overline{D3}$.

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- If the Standard Model $D3/\overline{D3}$ + orbifold sing. is in the inflationary throat, D1 and F1 are unstable. However, fractional D-strings (D3's wrapped on collapsed S^2's) exist. These can break on the $\overset{(-)}{D3}$ and couple to a twisted sector axion, so they are stable. ($\mathbb{Z}_3 \to 3$ kinds, not necessarily degenerate)
- If only a D7 intersects the inflationary throat, the F-strings can break but the D-strings are stable.

Wide range of possibilities:

- No strings
- 1 kind of string
- several kinds of string $\left\{ \begin{array}{l} \text{fractional D-strings} \\ (p,q) \text{ strings} \end{array} \right.$

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4. Signatures

Strings decay through intercommutation

and gravitational radiation. If this is maximally efficient, the distribution of strings per horizon volume will be constant (scaling behavior). This is what the simulations show.

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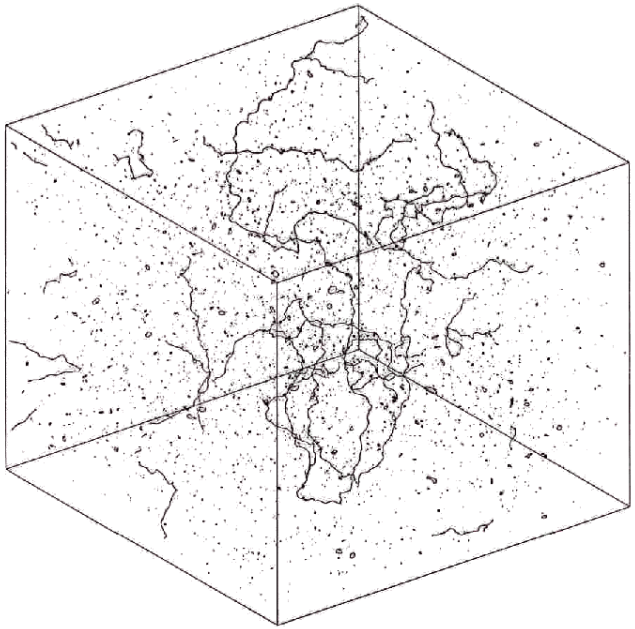

arXiv:hep-ph/9411342 v1 19 Nov 94

From Allen + Caldwell (1991)

19.

Sensitivity / bounds –

CMB power spectrum: $G\mu \lesssim 10^{-6}$

CMB nongaussianity: ?

lensing: 1 arc-sec $\equiv$ $G\mu = 4 \times 10^{-7}$

(1.9" lens reported by Sazhin, et al. astro-ph/0302547)

Gravitational waves:

Pulsar timing: $G\mu \lesssim$ several $\times 10^{-6}$

BBN: $G\mu \lesssim$ several $\times 10^{-6}$

radiation from cusps:

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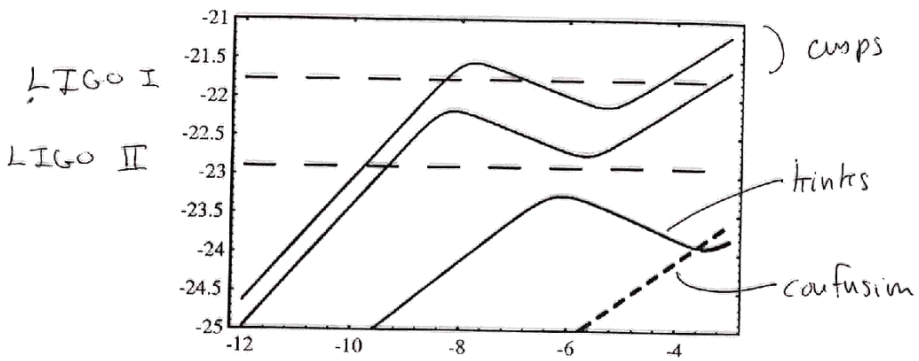
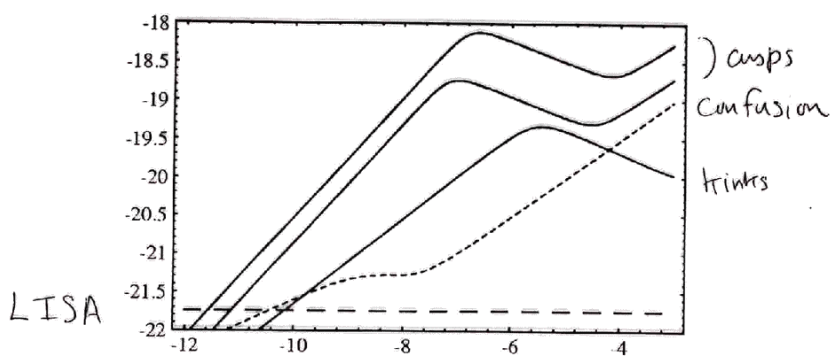
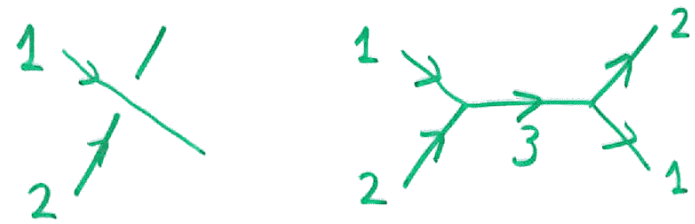
From Damour + Vilenkin (2001)



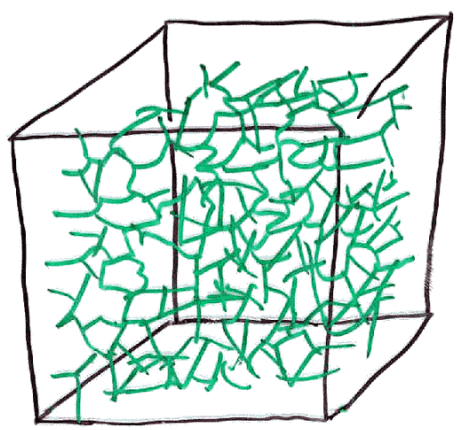


A complication:

Fractional and (p, q) cases have more than one kind of string, so can have



Can lead to frozen string networks:



Scaling: $\rho \propto 1/t^2$

($w = +\frac{1}{3}$ during radiation-dom. era

$w = 0$ during matter-dom.)

Frozen: $\rho \propto 1/a^2$

($w = -\frac{1}{3}$).

If frozen network forms, tension must be at electroweak scale.

Does it form?

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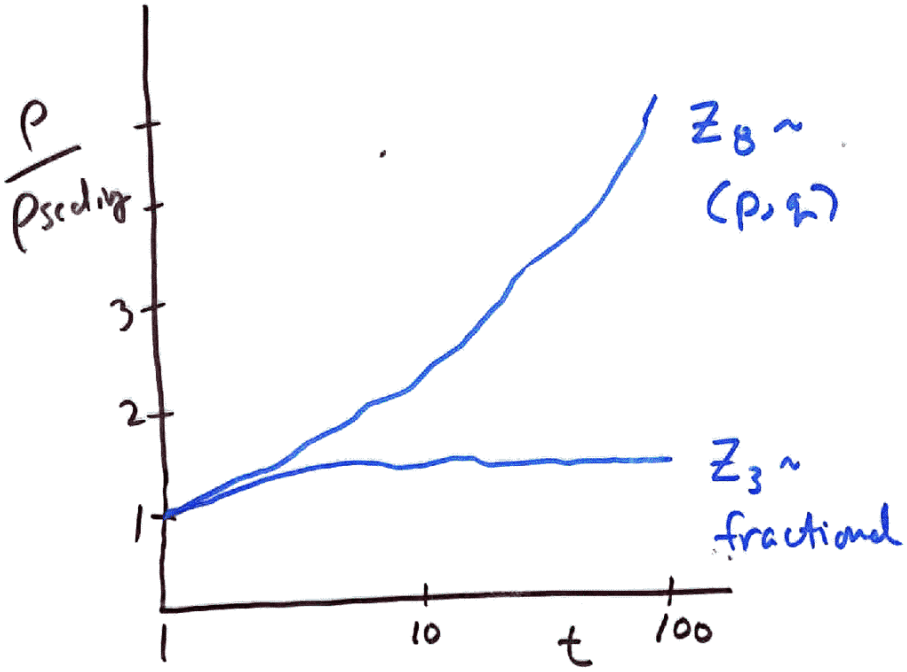

Spergel + Pen (1996)

Z_3 scales

Z_8 looks like it's freezing.

$g_s \ll 1$ might inhibit freezing.

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Conclusions –

- Cosmic F- and D-strings are a serious possibility.

  Tye et. al.
  Kachru et. al.
  Damour + Vilenkin

- The results are highly model dependent, and some cases (fractional D-strings, (p,q) strings) are particularly rich.

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