Cosmic Strings + Superstrings

String compactifications give rise to many one-dimensional objects:

- F-strings
- D-strings
- wrapped D/NS/M branes (w/ one noncompact dimension)
- classical solitons (magnetic flux tubes) in low energy EFT
- electric flux tubes in EFT.

- Under what conditions do these grow to cosmic size?
- What are the limits and signatures?

~50% overlap with Cargese lectures hep-th/0412244

To first approx all are described by Nambu action (in curved space) with ~~the~~ tension μ.

Dimensionless combination $G\mu$ = string tension in Planck units = typical metric perturbation produced by string

Current: $G\mu \lesssim 3 \times 10^{-7}$

Lecture 1: Production + Stability

Lecture 2: Models

Lectures 3, 4: String networks + phenomenology.

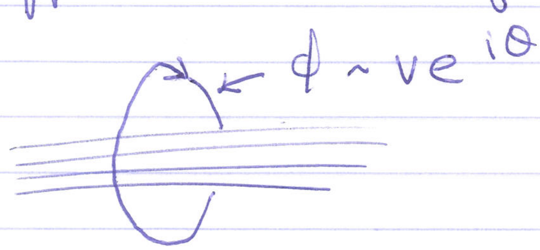
Landscape ideas $\Rightarrow$ compactification of complicated topology $\Rightarrow$ $\gtrsim O(10^3)$ cosmic string candidates.

Must be produced; loops smaller than Hubble scale decay, don't grow: must form at larger scales. Acausal? No! (Kibble).

Consider complex scalar with

$$V(\phi) = \lambda(\phi^*\phi - v^2)^2$$

For $v^2 > 0$, manifold of vacua is a circle, supports excitations of codimension 2 (strings):

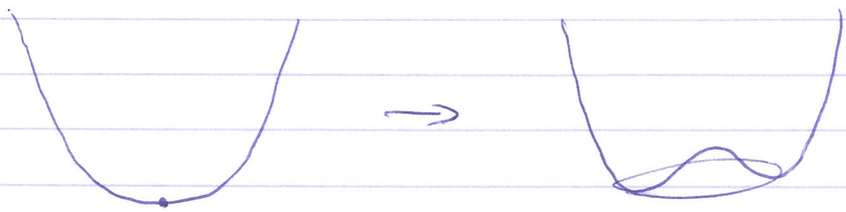


Production

(A.)

Cosmologically v^2 can depend on temperature, fields (e.g. inflaton*), might have

$V(\phi)$:



$v^2 < 0$ $\qquad\qquad$ $v^2 > 0$

ϕ starts at zero, rolls in some direction. Phase is uncorrelated over some correlation length ($\leq$ horizon size) $\rightarrow$ defects ~~form~~ (strings) form.

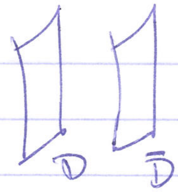
~ random walks over long distance. In 3 space dimensions a random walk has a finite ~~prop~~ probability not to return to its starting point $\Rightarrow \infty$ strings. (Simulations:

~ 50 % in loops of correlation length,

~ 50 % in ∞ rand. walks) $\equiv$ "percolation"

(Note: we will see in lect. 3 that the details of the initial network do not matter, the final state is independent of them.

* Hybrid inflation: very good for cosmic strings.

(B) $D\bar{D}$ inflation 

→ radiation ⊕ strings

(Jones, Stoica, Tye ; Sarangi + Tye).

Each brane has a U(1), which is absent in final state → two kinds of string, D and F.
(but no 0-branes or 2-branes: good! [see lect. 3])
For D-string this is just Kibble mechanism
($D\bar{D}$ tachyon is complex scalar).

For F-string, dual argument should apply (not quantitatively valid, but all that matters is causality).

(C) Actually, F-string production should be describable in CFT. Similar problem: Lambert, Liu, and Maldacena: production of closed strings by decaying D-brane. Production of finite loops nonzero. Production of winding strings does not go to zero as box size goes to ∞ (actually, it diverges in their approx)
⟹ percolation! (Effect of linear dilaton??)

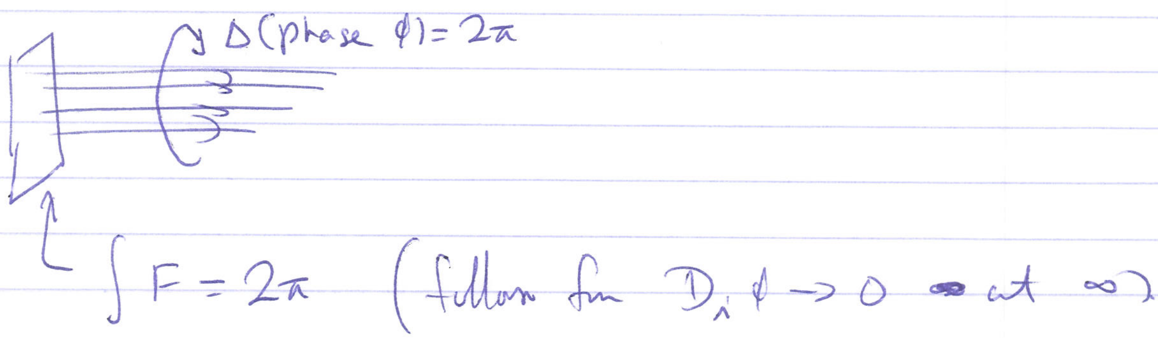
(D) If we cool a confining theory below its deconfinement transition (or, dual, cool a black hole in a warped throat below its Hawking-Page transition) a ~~periodic~~ percolating network should form (cf. Englert, Orloff, Piran).

A/B/C/D are dual versions of Kibble (E). A different mechanism (Greene) if $v^2 > 0$ but rapidly oscillating, can get resonant production of percolating strings.

Stability:

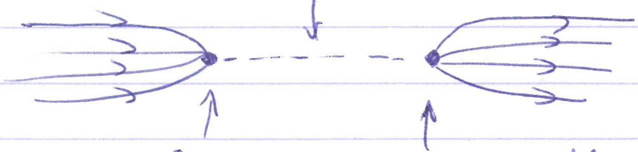
Abelian Higgs: $\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - D_\mu \phi^* D^\mu \phi - V(\phi)$

Vacua $\pi_1(S_1) = Z \rightarrow$ topo stable strings



But in any unified theory expect monopoles; min charge here would be $\int F = 2\pi$

ϕ-winding offset by Dirac sea



$\Rightarrow$ string can break.

Rate (Schwinger) $\quad e^{-\pi M^2/\mu}$

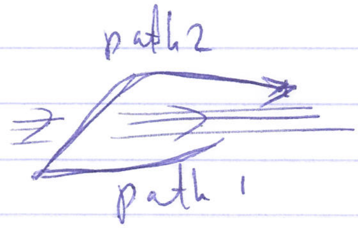
Want rate $< H^2 \sim 10^{-120} M_p^2 \Rightarrow$ for $M \sim 10\sqrt{\mu}$ get e^{-300}; OK.

So just need a small hierarchy of scales.

Criterion for absolute stability? This string has no topo charge that can be measured ~~by~~ outside core.

By contrast: suppose minimum mon. charge is $q \in \mathbb{Z}$, > 1.
($\int F = 2\pi q$ for monopole).

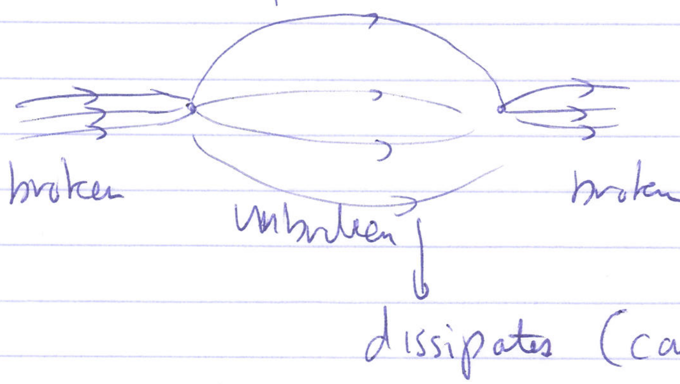
String stable. Saturate Dirac $\Rightarrow$ fields of charge $1/q$



AB phase $\frac{2\pi}{q}$, observable.

(Cannot decay, by causality).

Note: if there are unbroken gauge sym., AB phase must be measurable by neutral (possibly composite), particle*. Else there is a decay



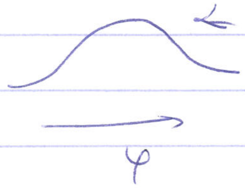
* otherwise ≡ quasi - AB.

Finally, anti gauge field:

$$\vec{\partial}\phi \sim \frac{\theta}{r} \qquad |\vec{\partial}\phi|^2 \sim \frac{1}{r^2} \qquad \int \frac{d^2r}{r^2}$$

has log div at ∞. Global string: topo. charge directly measurable by gradient of scalar. ∞ energy not a problem: log cut off by string spacing, these still form by Kibble process.

Requires exact global sym. We do not expect this in string theory. Let ψ = phase of ϕ. Instantons give $V \sim f_\pi^2 m_\psi^2 \cos\psi \qquad \mathcal{L} \sim \frac{1}{2} f_\pi^2 \partial\psi\partial\psi - V$



↳ domain wall where $\Delta\varphi = 2\pi$, thickness ~ m_φ^{-1}

(pulls sideways on string, makes it annihilate oppositely ~~oriented~~ oriented string)

Stability: a (acceleration) $< H$

$$\uparrow$$

$$\frac{T_{DW}}{\mu} \sim \frac{m_\varphi f_a^2}{\mu} < H$$

$$H^2 \sim 10^{-120} M_p^2 \rightarrow m_\varphi^2 \lesssim \underbrace{10^{-120}}_{e^{-280}} M_p^2$$

e^{-280}: ← instanton action.

Same as recent Sweeper paper.

(Also, hard to form?).

So: local/QAB break } conjecture: holds ~~in string theory~~.

AB stable

global confined } for stringy strings also.

Example: compactified heterotic string : hep-th/0510033

CY comp of $E_8 \times E_8$ string: $B_{\mu\nu} \to$ massless 4-d field, couples electrically to string $\to$ couples topologically to dual scalar.

$\Rightarrow$ global string.

But in some compactifications a U(1) anomaly requires a 1-loop term $\int B \wedge F$, so Chern-Simons variation $\delta B \sim tr(\lambda F)$ cancels the anomaly.

E.g. SO(32) on CY of Euler number χ

$SO(26) \times U(1))$

Chiral spectrum

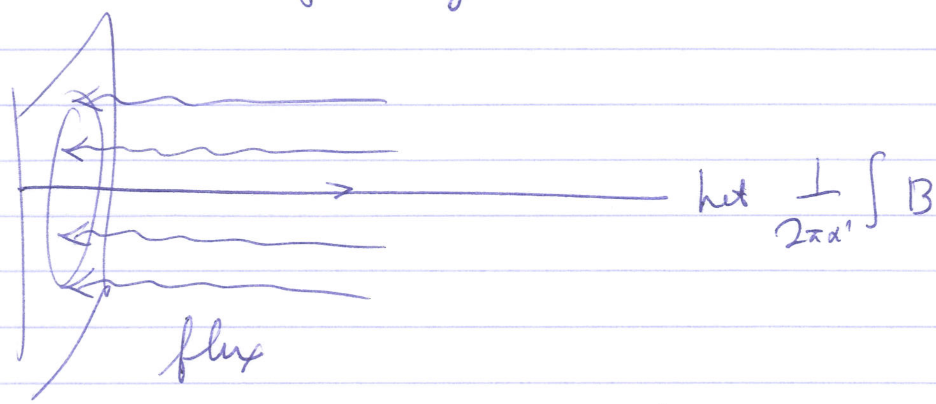
$$\frac{\chi}{2} \times \quad (26, +1) + (1, -2)$$

$$Tr\, Q = 24 \times \frac{\chi}{2}$$

$$\to \frac{\chi}{(2\pi)^2 \alpha'} \int B \wedge F$$ gives mass to $B_{\mu\nu}$: no axion, anomalous U(1) broken)

(in general, U(1) anomalous also broken by other axions, and by light charged fields, but we consider the case where this does not happen).

What kind of string do we have?



$$\int F = \frac{2\pi}{x}$$

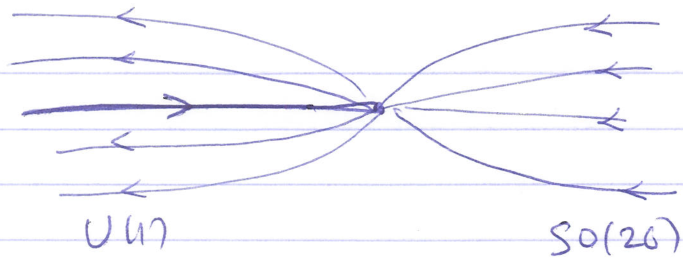
- No net coupling to B: B falls at ∞.
- width of flux $= \frac{\sqrt{\alpha'}}{g_s^2} >> \sqrt{\alpha'}$
- x is even. For $|x| = 4, 6, \ldots$ this is AB string (visible to $(1,-2)$)

  For $|x| = 2$ it is QAB (visible to $(26,+1)$) but not to $(1,-2)$.

How can a heterotic string break?

$\exists$ monopole in, $\int F = \pi$ in each fact of

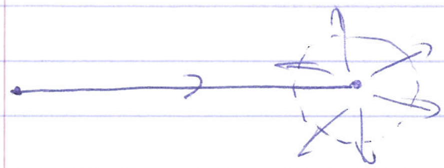
$$U(1) \times U(1)^{13}$$
$$\subset SO(26)$$



conserves all fluxes.

What are b.c. at end of string?

~~2~~ ~~8~~ ~~24~~ 32 r-moving λ } mismatch of 24
8 l-moving 4 }

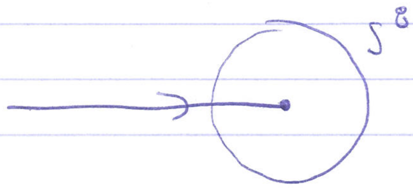


radial Dirac operator in spacetime has similar mismatch: 24 more outgoing modes (index thm on S_2).

CF Rubakov-Callan effect.

b.c. relates modes on string to spacetime modes: mixes levels of quantization

Now expand compactification: 10 d picture



$$\int_{S^8} F\wedge F\wedge F\wedge F = 24\cdot(2\pi)^4$$

all consistent — but does it happen?

No perturbative description.

[4-d endpoint mass ~ $R^5/g_s^2\alpha'^{5/2}$]

S-dual: Type I D1 ending on D9's of Type

Can construct as tachyon configuration on

$16+K$ D9 + K $\overline{D9}$.

$E_8 \times E_8$: · comp. string charges global

· $\int \mathrm{tr}\, F^4 = 0$ due to E_8 identity

· no open membrane in het. M

can't break!

significance ??

Models

Need a model for inflation. Most ~~natural~~ well-developed is KKLMMT: D3 $\overline{D3}$ in warped throat

KS throat (generic!)

$V_{inf} = 2T_3 \times e^{+4\Delta}$ (warp factor) ($\lesssim 10^{-12} M_p^4$ from absence of tensor modes)

$$ds^2 = e^{+2\Delta(y)} \eta_{\mu\nu} dx^\mu dx^\nu + g_{mn}(y) dy^m dy^n$$

Need $e^\Delta \sim 10^{-3}$.

These are reasonably generic: conifold sings. are codim 1 in moduli space, and if flux on 3-cycle in << flux on intersecting 3-cycle, manifold sits near singularity with warp factor exponential in ratio of fluxes ($e^{-2\pi K/3Mg_s}$).

(Hebecker + March-Russell).

$$\mu_D \mu_F = 2\pi T_3 \qquad \frac{\mu_D}{\mu_F} = \frac{1}{g_s}$$

$$V_{infl} = ~~2T~~ V_0 - \frac{V_0^2}{4\pi^2 \phi^4}$$

$\Rightarrow$ read off inflation parameters ~~from standy~~ from standard formulas.

obs. $\frac{\delta T}{T}$ at $N_e \sim 60$ e-folds $\Rightarrow$

$$V_0 = \left(\frac{\delta T}{T}\right)^3 \times M^4 \times \frac{1}{N_e^{5/2}} \times \text{numerical const}$$

$\sqrt{\mu_D \mu_F} \sim 2 \times 10^{-10}$ (current bds $\sim 2 \times 10^{-7}$)

$n_s \sim 0.98$

KLMT had to tune ϕ^2 term to zero to get slow-roll inflation. (Baumann, Dymarsky, Klebanov, Maldacena, McAllister, Murugan calculation)

Farazkhah + Tye : $+\frac{1}{2}\beta H_{inf}^2 \phi^2$

$0 < \beta < 0.15$ (not so badly tuned)

$4 \times 10^{-10} < \sqrt{\mu_D \mu_F} < 6 \times 10^{-7}$

$0.98 < n_s < 1.08$

WMAP3: 0.951 ± 0.015 ← inconsistent at 2σ?!

What kind of strings?

In $d=10$ F + D couple to $B_{\mu\nu}$, $C_{\mu\nu}$

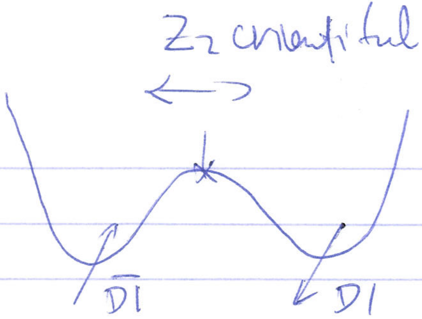
susy of flux comp $\subset$ susy of D3-brane

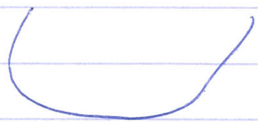
F1, D1 ∥ D3 has no common SUSY.

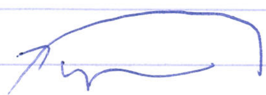
O3 projection or F theory monodromy remove

$B_{\mu\nu}$, $C_{\mu\nu}$ zero modes.

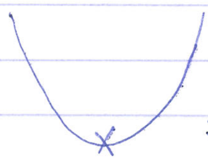
⇒ local strings.



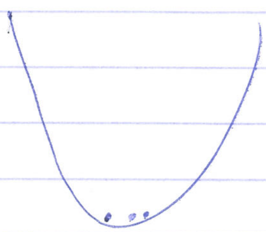




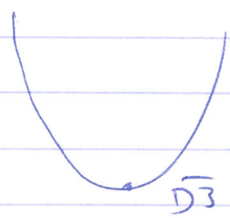
"monopole" : $\frac{M}{\sqrt{m}} \sim e^{-\Delta} \sim 10^3$



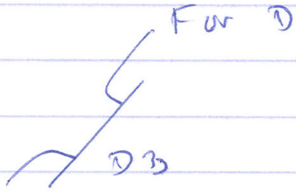
: F- and D- strings decay fast



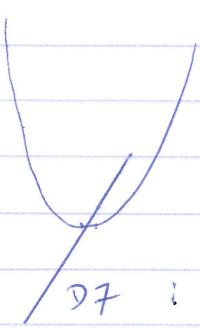
$D3 + 2\bar{D3} \rightarrow$



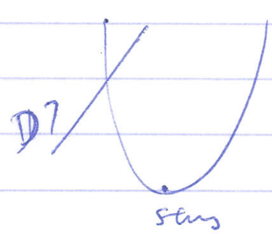
(break SUSY badly)



: not stable



: D1 stable
F1 unstable



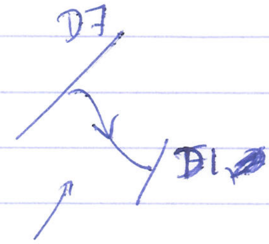
stable

Other properties?

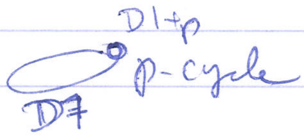
Only l.v. interaction grav.

(no axion)

(no charged modes on string)



carries D7 charge, but massive

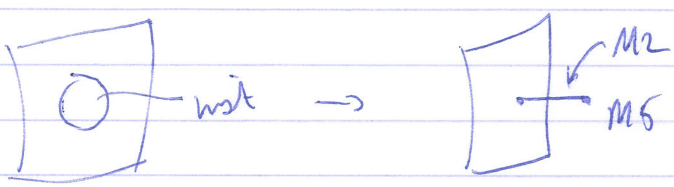


(this string might also be axionic).

Only collective coord $X^\mu(\sigma)$ $\mu = 0,1,2,3$

$\mu = 4 \ldots 9$ and fermions all massive

M-branes?

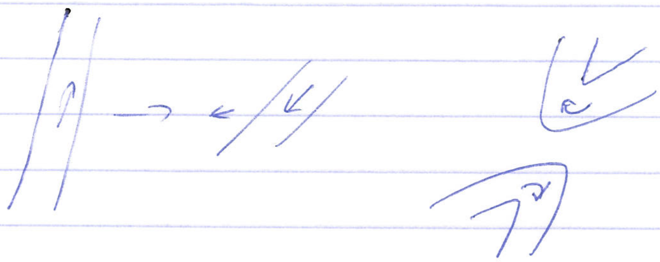


Distinguishing different microscopic strings:

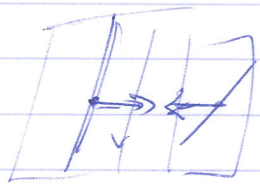
If we only had two kinds of string

- gauge theory solitons
- fundamental strings at weak coupling

we could.



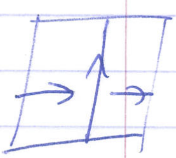
always reconnect, at least up to $v_{cm} \sim 0.95$ in standard models.



← reconnect w/ probability g_s^2

result: $g_s^2 f(v, \theta) \times \frac{1}{\text{effective trans vol.}}$ $\quad \frac{(2\pi)^3}{\pi\sqrt{\ln \alpha' m^2}}$

↑ Calc. in string pert thy.



$\langle x^2 \rangle \sim \frac{\alpha'}{2} \ln \alpha' m_y^2$