How to Mimic a Cosmic Superstring

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+ work in progress

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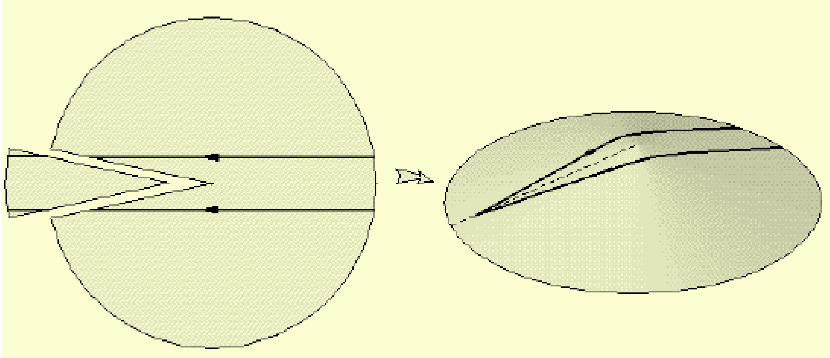
Motivations

- Cosmic Strings stretch across the Heavens
  - both across the horizon
  - and in loops measured in astronomical units (lightdays +)
- They have the width of elementary particles, but are very dense and very long

$$G\mu \leq 10^{-7}$$

- They have not been observed. They are not predicted by any established law of physics…
  - But they are a robust prediction of many theories beyond the standard model. They would provide a window onto new microscopic physics that is not accessible in terrestrial experiments.

Observation by Lensing

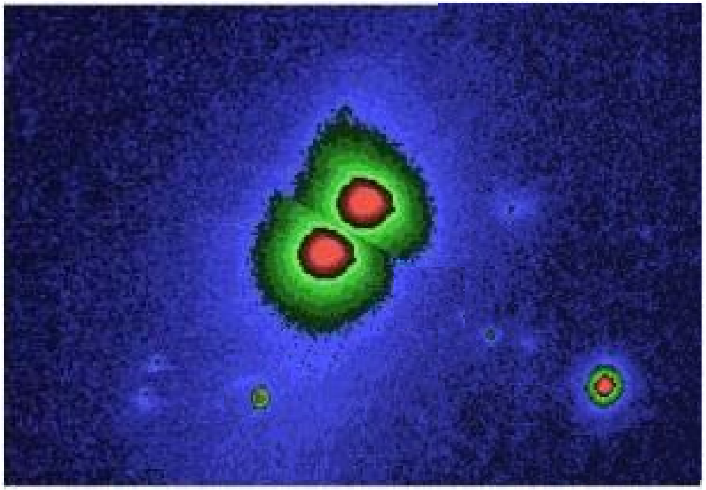


Cosmic strings leave a conical deficit angle in space

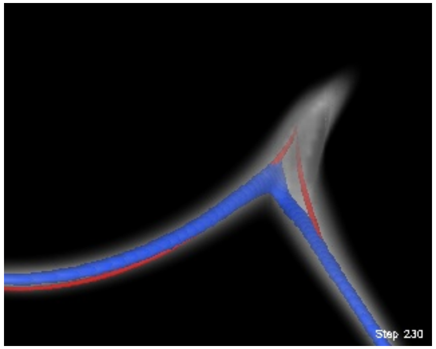
$$\delta = 8\pi G\mu$$

This gives rise to a distinctive lensing signature in the sky.

(Vilenkin ’81)



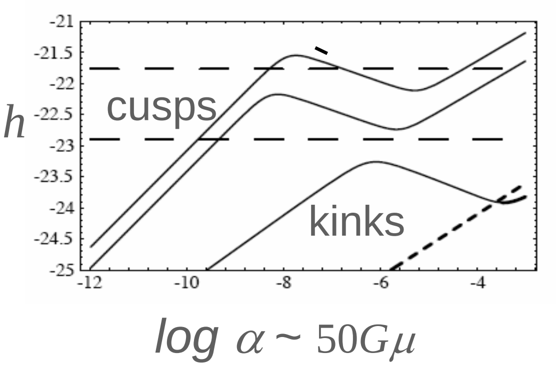
Observation by Gravitational Waves

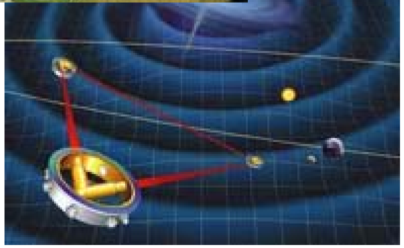


Cusps in string loops emit an intense burst of gravitational radiation in the direction of the string motion. (Damour and Vilenkin ’01)

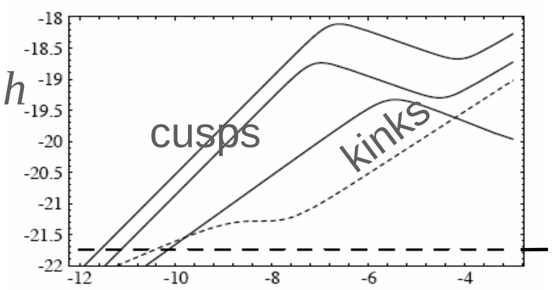
(Olum)

LIGO 1 (online) and Advanced LIGO (2009)





LISA (2015?)



Cosmic Superstrings

- Could cosmic strings be fundamental strings stretched across the sky?
  - First proposed by Witten in 1985 in heterotic string theory.
  - The strings are too heavy and unstable.

- Revisited in type IIB flux compactifications.

  (Tye et al, Copeland, Myers and Polchinski)
  - Strings live down a warped throat, ensuring they have a lowered tension.
  - Strings can be stable.
  - Strings naturally produced during reheating after brane inflation.

Smoking Superstring Guns

- Suppose we discover a cosmic string network in the sky. Do we have evidence for string theory? Or merely for the abelian Higgs model?

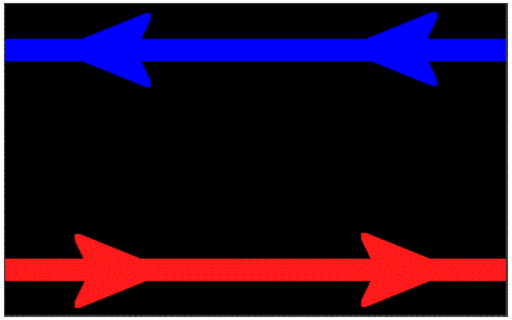
- There are two features which may distinguish superstrings from simple semi-classical solitons

  - Reconnection probability
  - (p,q) string webs

- Let’s look at each of these in turn….

Reconnection

- When two strings intersect, reconnection swaps partners, leaving behind kinks.
- When a single string self-intersects, reconnection cuts off a loop.



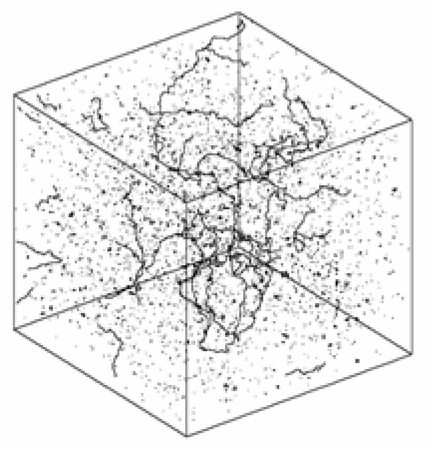
- Abelian vortices reconnect with probability P = 1
- Superstrings intersect with probability P ~ g_s^2

The full angle and velocity dependence was computed by Jackson, Jones and Polchinski ‘04.

The probability P is potentially observable

Effects of Reduced Reconnection

The evolution of a string network leads to a “scaling solution”, with a few strings stretched across the horizon, together with loops of many sizes. The properties of this solution depend only on $G\mu$ and P.



Allen and Shellard (1990)

As the universe expands:

- more of the stretched strings are revealed,
- the loops decay through gravitational radiation.

Reduced probability of reconnection means:

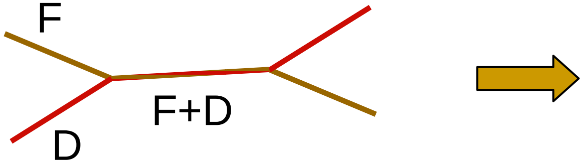
- Fewer kinks
- Fewer loops, and hence more string: N ~ 1/P
- Better chance to see strings.

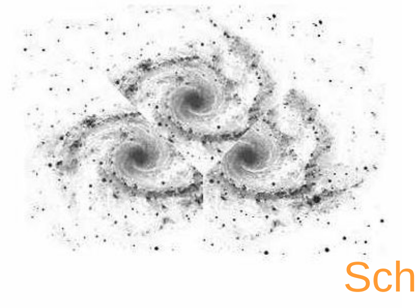
(p,q) String Webs

- The spectrum of IIB string theory includes
  - Fundamental strings, with tension $\mu_F \sim 1/\alpha'$
  - D-Strings, with tension $\mu_D \sim \mu_F/g_s$
  - Bound states of (p,q) strings with tension

$$\mu_{(p,q)} = \sqrt{p^2\mu_F^2 + q^2\mu_D^2}$$

Bound states means 3-string junctions, with angles determined by tensions





Schlaer and Wyman '06

Smoking Superstring Guns?

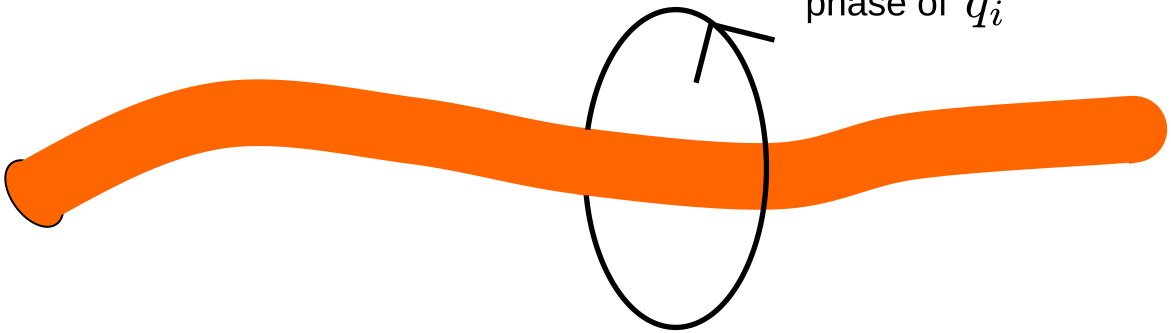
Can we cook up a simple field theory model which mimics the cosmic superstring?

For example: flux tubes in SU(N) Yang-Mills have probability of reconnection $P \sim 1/N^2$

The Abelian Higgs Model

$$L = \frac{1}{4e^2} F_{\mu\nu}F^{\mu\nu} + |\mathcal{D}q|^2 - \frac{\lambda e^2}{2}(|q|^2 - v^2)^2$$

Broken U(1) gauge symmetry ⇒ vortices

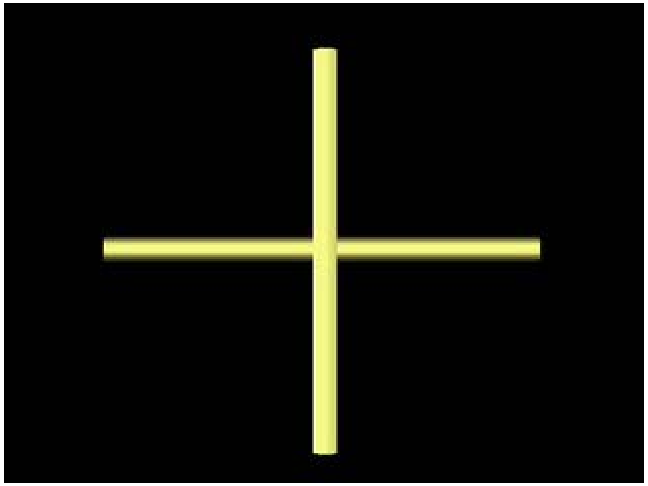


$$\mu = 2\pi v^2\, f(\lambda)$$

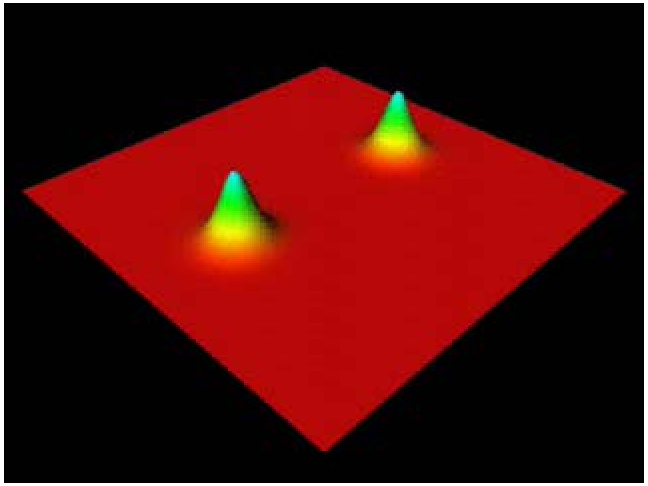
Nielsen and Olesen, ‘73

Reconnection

The reconnection of cosmic strings follows from classical field equations. In general this requires numerical work. Matzner



Battye and Shellard



Moore and Shellard

The key to reconnection is the right angle scattering of vortices.

Reconnection at Small Velocity

For strings intersecting at small velocity, and with small angle of incidence, one can use the moduli space (or adiabatic) approx.

(Copeland and Turok)

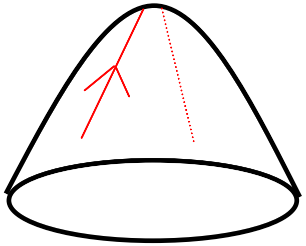
center of mass

relative separation

$$\mathcal{M}_{2-vortex} \cong \mathbf{C} \times \mathbf{C}/\mathbf{Z}_2$$

← identical particles

$$\cong \mathbf{C} \times$$



→ right angle scattering → reconnection

Non-Abelian Higgs Model

Consider U(N_c) gauge group with N_f fundamental scalars

$$L = \frac{1}{4e^2}\mathrm{Tr}F_{\mu\nu}F^{\mu\nu} + \sum_{i=1}^{N_f} |\mathcal{D}_\mu q_i|^2 - \frac{\lambda e^2}{2}\mathrm{Tr}(\sum_{i=1}^{N_f} q_i \otimes q_i^\dagger - v^2)^2$$

The simplest model has $N_c = N_f$. The vacuum is $q^a{}_i = v\delta^a{}_i$

(where $a = 1,\ldots N_c$ and $i = 1,\ldots N_f$)

$$q \to \underset{\overset{\nearrow}{\text{gauge}}}{U} q \underset{\overset{\nwarrow}{\text{flavor}}}{V^\dagger} \quad \Rightarrow \quad U(N_c)\times SU(N_f) \to SU(N)_{\mathrm{diag}}$$

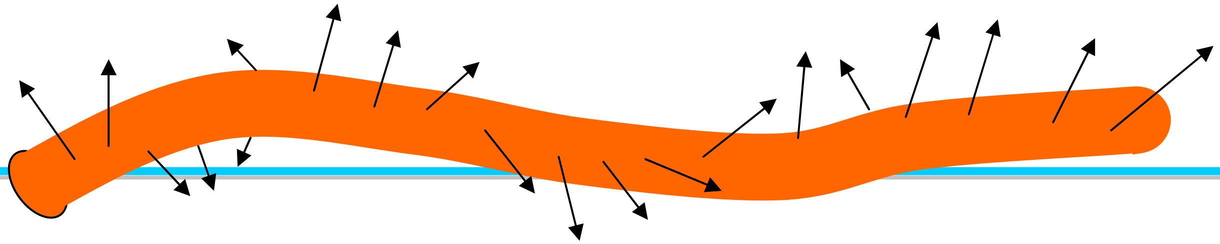
Non-Abelian Vortices

Suppose we have an abelian vortex solution $B_\star$,$q_\star$. We can trivially embed this in the non-abelian theory.

$$B = \begin{pmatrix} B_\star & & \\ & 0 & \\ & & \ddots \\ & & & 0 \end{pmatrix} \qquad q = \begin{pmatrix} q_\star & & & \\ & v & & \\ & & \ddots & \\ & & & v \end{pmatrix}$$

Different embeddings ⇒ internal degrees of freedom for single vortex

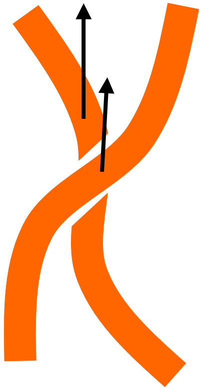
$$SU(N)_{\rm diag}/SU(N-1)\times U(1) \cong \mathbf{CP}^{N-1}$$



Simple Idea:

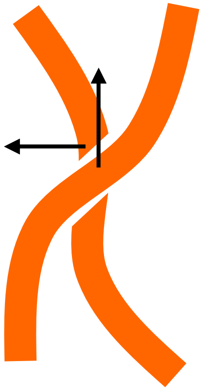
Hashimoto and Tong

The strings can miss each other in the internal space.



Same orientation ⇒ Live in same U(1) subgroup

⇒ Reconnect

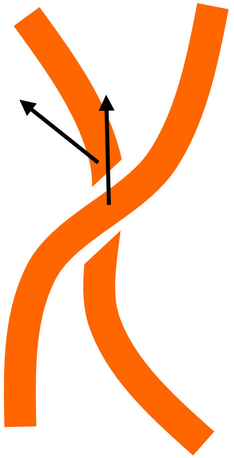


Opposite orientation ⇒ Don’t see each other

⇒ Don’t reconnect

Probability of Reconnection

What happens for intermediate angles?



Expectation: there exists a critical angle

$\theta < \theta_c$ ⇒ Reconnect

$\theta > \theta_c$ ⇒ Miss each other

Coarse graining over θ could then give probability P<1.

What really happens: $\theta_c = \frac{\pi}{2}$ ⇒ Always reconnect except for finely tuned initial conditions.

⇒ P=1 !!!!

But…

There are two subtleties

- Quantum Effects
  - In d=1+1, the groundstate wavefunction smears over the string.
  - Massless spin waves get a mass $\Lambda \sim ev\,\exp(-4\pi/e^2N)$
  - We can't even fine tune!

- Fermion Zero Modes
  - Charged fermions in four dimensions induce massless fermionic excitations on the string
  - These change the quantum physics considerably…

Effects of Fermions

- Consider adding the following fermion coupling in four dimensions.

$$L_{\text{Yuk}} = \sum_{i=1}^{N_f} \bar{\psi}_i \lambda q_i$$

fundamental adjoint

- This gives rise to fermion zero modes χ_i on the cosmic string
- The axial symmetry $\chi_i \to e^{i\beta\gamma_5}\chi_i$ is anomalous: $U(1) \to Z_{2N}$
- A condensate forms on the string $\langle\chi\chi\rangle \sim \Lambda$, breaking $Z_{2N} \to Z_2$
- This means that the cosmic string has N ground states.

The Punchline

- The presence of fermi zero modes cause the vortex to have N quantum ground states

- These are identified with the string sitting in the N different diagonal components of the gauge group

- The strings reconnect in the same state, and pass through each other in different states.
    - ❑ At energies $E \ll \Lambda$ we have N types of string, and P=1/N.
    - ❑ At energies $E \gg \Lambda$ we have P=1.

(p,q) Strings in Field Theory

Unpublished work with Matt Strassler and Mark Jackson.

- Making strings bind isn't hard…the difficult part is getting the right tension formula $\mu_{(p,q)} = \sqrt{p^2\mu_F^2 + q^2\mu_D^2}$ (e.g. Saffin)
- Two hopeful possibilities
  - Binding of Electric Fluxes and Magnetic Fluxes
  - Binding different magnetic flux tubes (F-term and D-term vortices)

Electric and Magnetic Fluxes

- Consider SU(N) theories with adjoint matter
  - Higgs phase has Z_N magnetic flux tubes; electric charge screened
  - Confining phase has Z_N electric flux tubes; magnetic charge screened

- Need more exotic phases. 't Hooft showed that phases of SU(N) are characterized by dimension N subgroup of the lattice $Z_N \times Z_N$

  - e.g. Take N=pq and a symmetry breaking such that $SU(N) \to SU(p)$ This has Z_q magnetic strings and Z_p electric strings.

  - Big Question: Do the strings bind?! What is their energy? (Can we use S-duality e.g in N=1* theory?)

Magnetic and Magnetic Fluxes

- Vortex flux tubes come in two different types
  - D-term: $D = |q|^2 - |\tilde{q}|^2 - \zeta$ is real. Vortices are BPS in both N=1 and N=2 susy theories
  - F-term: $F = \tilde{q}q - \xi$ is complex. Vortices are BPS in N=2 susy theories, but non-BPS in N=1 susy theories.
- Consider $U(1)^k$ theories. What is binding energy between F- and D-term vortices? Bogomolnyi bound gives

$$\mu_{(p,q)} \geq \sqrt{|p\mu_F|^2 + q^2\mu_D^2}$$

- But: There are no solutions saturating the bound!

Conclusions

- We’ve seen
  - Semi-classical strings that have an effective, velocity-dependent P<1.
  - Semi-classical strings that (almost) mimic the IIB string spectrum.
- If a cosmic string network is discovered, the task of distinguishing between these models may become an experimental question.