Cosmic Strings and Superstrings

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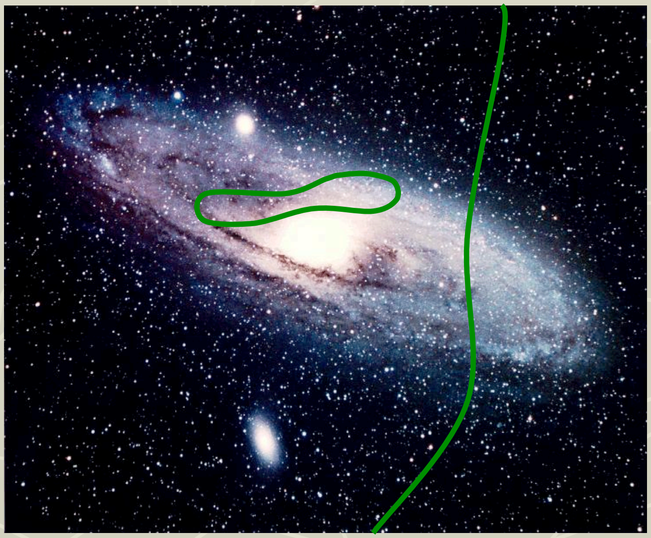
Congratulations to GGI from KITP

String compactifications give rise to many kinds of one-dimensional object:

- The fundamental strings themselves
- Dirichlet strings
- Solitonic strings
- Confining strings

Some of these arise in the effective low energy field theory; some arise from higher dimensional branes that are partly wrapped so that only one dimension is visible. All are potential cosmic strings:



Necessary conditions:

1. The strings must be produced at the appropriate time in the early universe.
2. They must be stable on cosmological time scales.
3. They must be observable, but not already excluded.

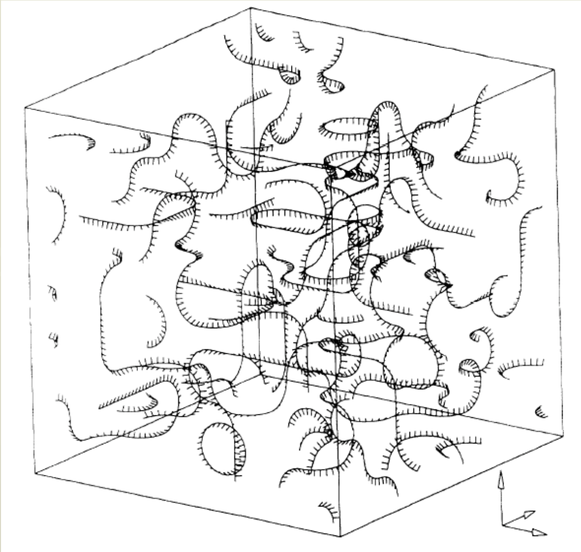
Also:

4. It would be good if there were ways to distinguish strings with different microscopic structures.

References: JP, hep-th/0412244

Production

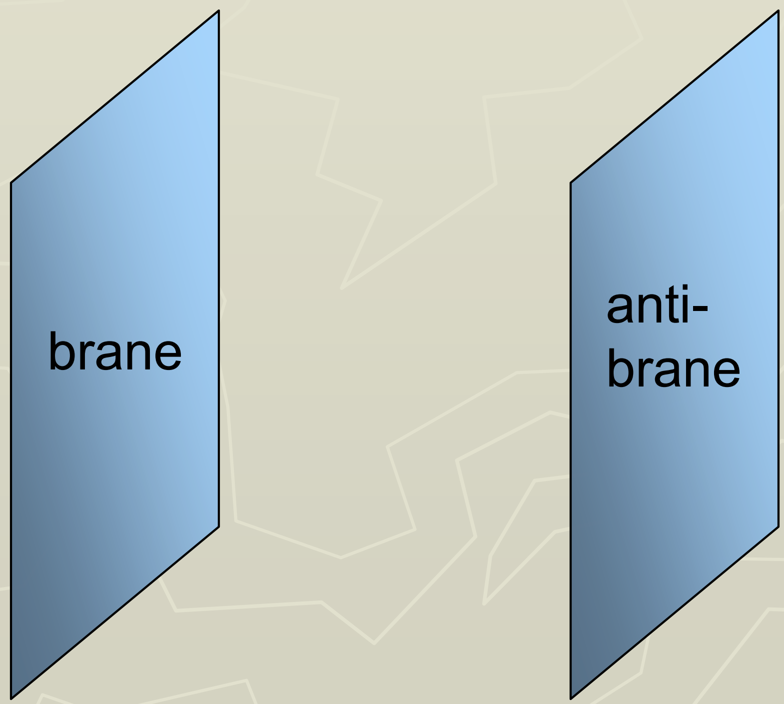
In field theory: string solitons (Nielsen-Oleson vortices) exist whenever a $U(1)$ is spontaneously broken. Whenever a $U(1)$ *becomes* broken, a network of strings must form, because the phase of the Higgs field is uncorrelated over long scales.



Bennett & Bouchet

This must happen after inflation, but ideally right at the end of inflation to give a high scale for the string tension. *Hybrid inflation* ends in just such a transition.

In string theory, a natural model of inflation is *brane inflation,* where inflation is driven by the potential energy of a brane-antibrane pair, which slowly attract and eventually annihilate:



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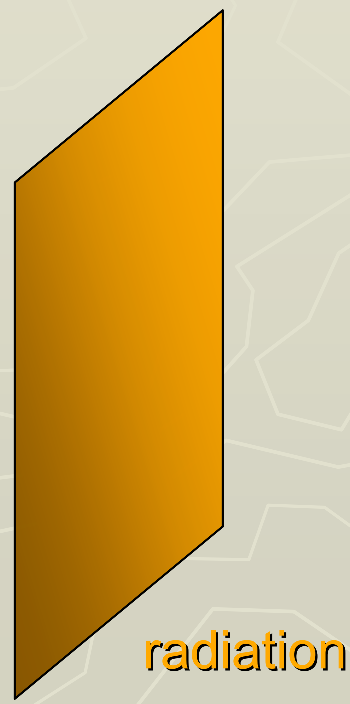
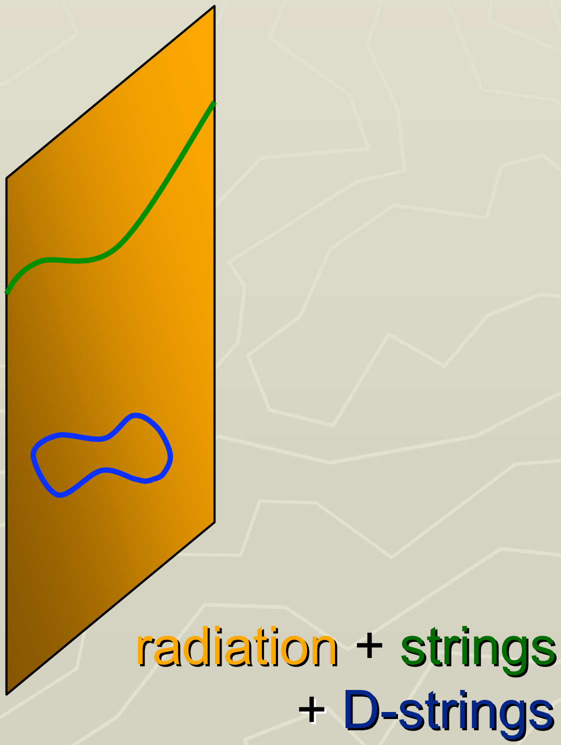


Each D-brane carries a $U(1)$ gauge field, which disappears in the annhilation. The Kibble mechanism then produces *two* kinds of string, fundamental and Dirichlet .



Thus, considerations from cosmology and from string theory both lead to string production at the end of inflation.

Open question: how generic is this? E.g. in heterotic atring vacua, is there a natural mechanism for inflation (such as M-branes in the strongly coupled theory), and does it produce strings? Candidate cosmic strings include open membranes, the heterotic string itself, M5-branes wrapped on 4-cycles, and gauge strings in the low energy gauge theory. Jeannerot, Rocher, Sakellariadou ’03 consider general GUTS and (with assumption of monopole suppression and hybrid inflation) argue that cosmic strings are generic.

Stability

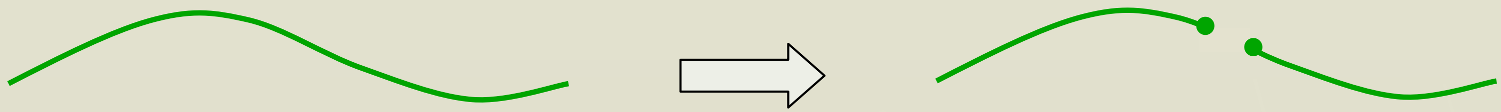
There are three kinds of string:

Local strings have no topological charge that can be measured from outside the string.

Global strings have a long-range periodic scalar field (axion) that winds as one goes around the string.

Aharonov-Bohm strings have a charge that can be seen through Bohm-Aharonov interference, but not in an local measurement.

Local strings can decay by breakage:

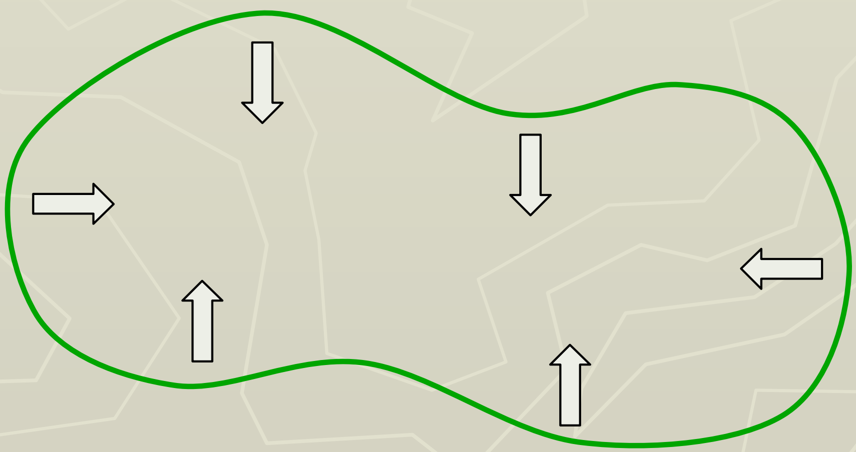


E.g. if we embed the $U(1)$ Higgs model into the $SO(3)$ Georgi-Glashow model, then the strings can end on magnetic monopoles.

In string theory it appears that every local string has such a decay. Unless it is very slow, a would-be cosmic string will immediately decay to ordinary quanta (short open strings)

The rate of monopole production is $exp(-2\pi M_m{}^2/\mu)$. This is slow enough provided that the monopole mass M_m is an order of magnitude heavier than the string tension.

Global strings decay via `confinement.' In string theory there are no exact global symmetries, so the axion field costs *potential* energy as well as gradient energy, leading to a confining force (much like 2+1 PQED):



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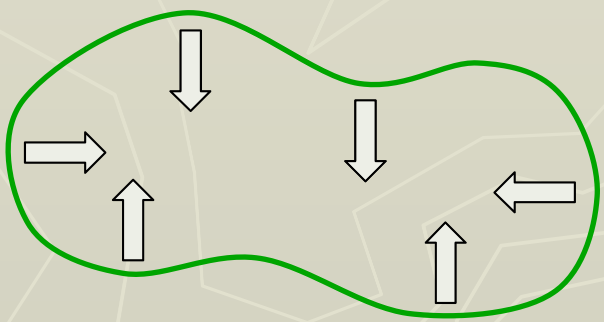

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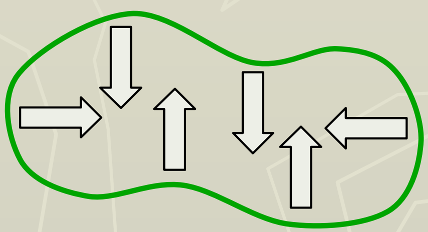
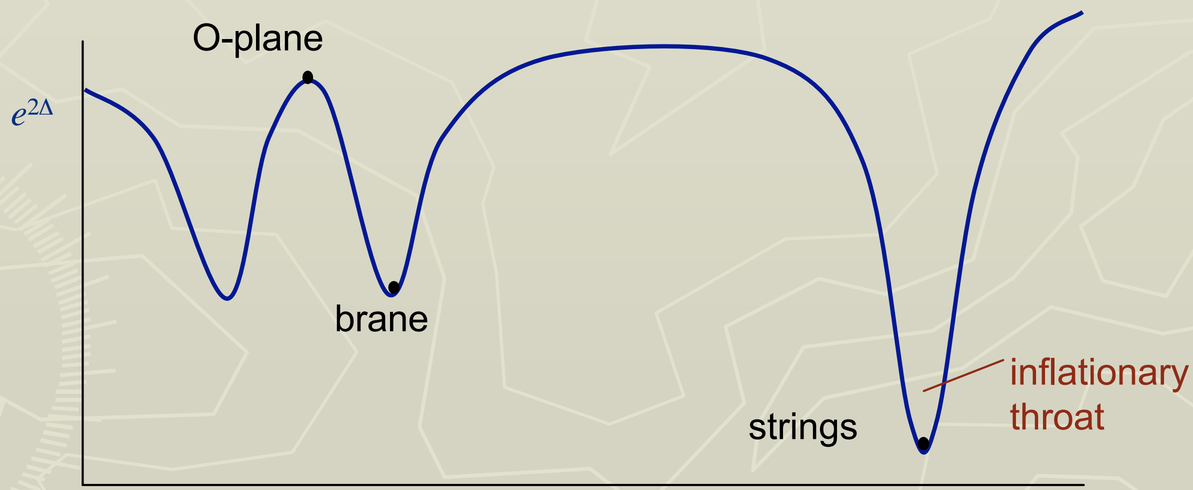


Again this is fatal unless the symmetry-breaking effects are extremely small, which seems difficult to arrange.

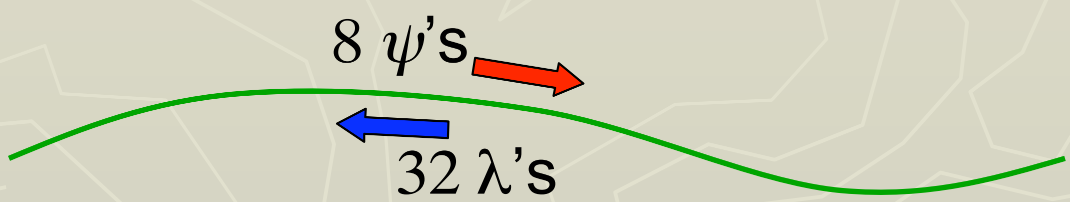
Only Aharonov-Bohm strings are exactly stable (unless spacetime itself decays!).

Thus stability is very model-dependent. In model of Kachru, Kallosh, Linde, Maldacena, McAllister, Trivedi, the strings are *local* and so can break (no 4-d axion). They sit in the bottom of a redshift well, and have to fluctuate to a brane or image string to break. This can be slow …



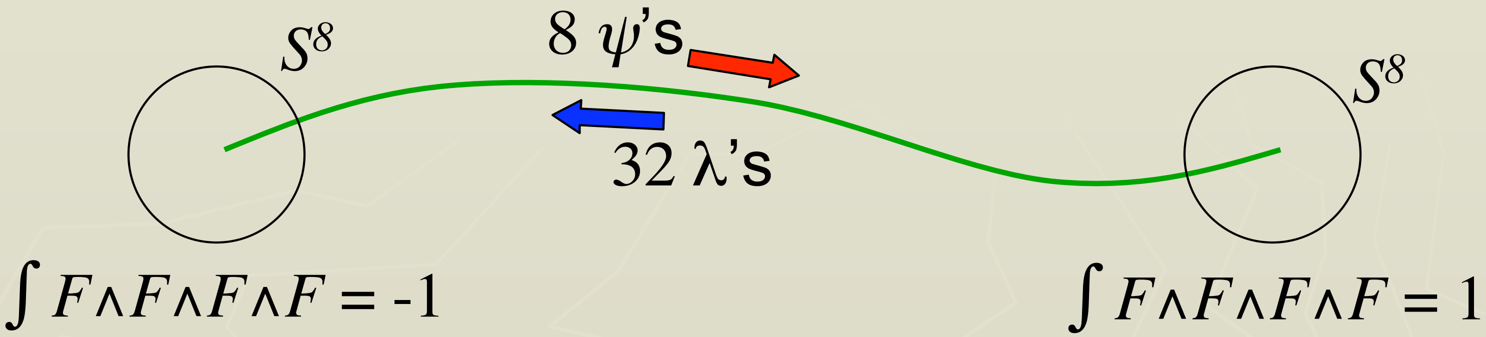
An aside (something new):

Witten (1985) argued that the heterotic string is a global string, through it coupling to the two-form gauge field $B_{\mu\nu}$, which is dual to an axion. However, in some compactifications this Higgses with a pseudoanomalous $U(1)$. The heterotic string is then Aharonov-Bohm or local (depending on the model). In the latter case it should decay via breakage…



However, there are no open heterotic strings! There is no way to match up the right- and left-movers at the endpoints.

Claim: there *are* open heterotic strings.



First point: gauge field must emanate from endpoint, so that gauge transformation of world-sheet action $\int B$ is offset by transformation of $\int B \wedge F \wedge F \wedge F \wedge F$ in spacetime action (same as for string ending on D-brane, with $\int *F$).

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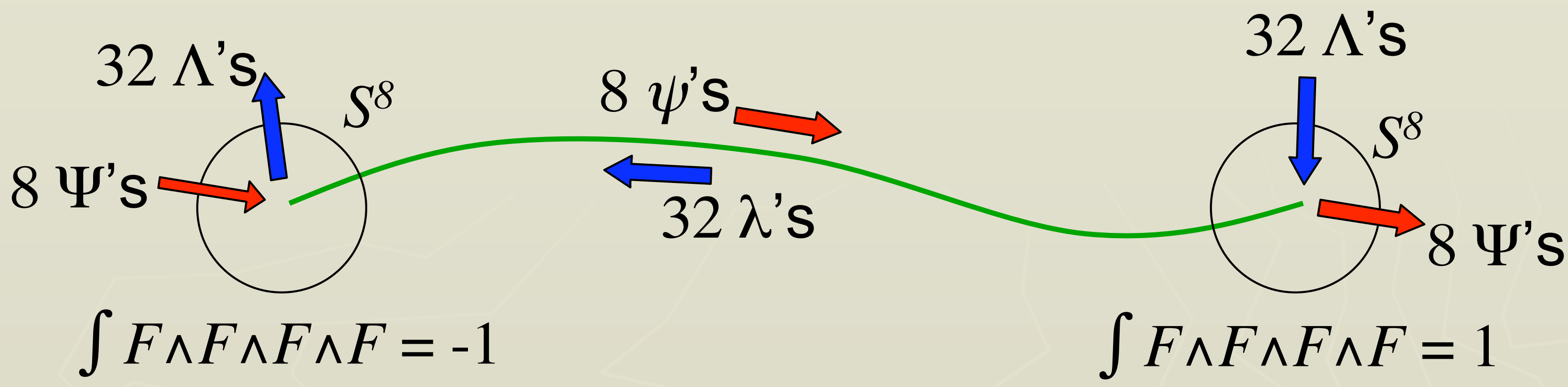


Second point: in the presence of this gauge field, there is a mismatch in the *spacetime* spectrum of out-movers and in-movers. (cf. Rubakov-Callan effect.) Thus there are perfectly good boundary conditions where the chiral world-sheet fields do not reflect off the endpoints but pour out into spacetime!
(Can also justify with dual D-brane picture).

Not a new perturbative string theory (coupling of world-sheet fields to spacetime fields can’t be described in world-sheet CFT, it is nonperturbative.

Supports general stability classification of strings.

May be relevant to nonperturbative description of heterotic string.

Seeing strings

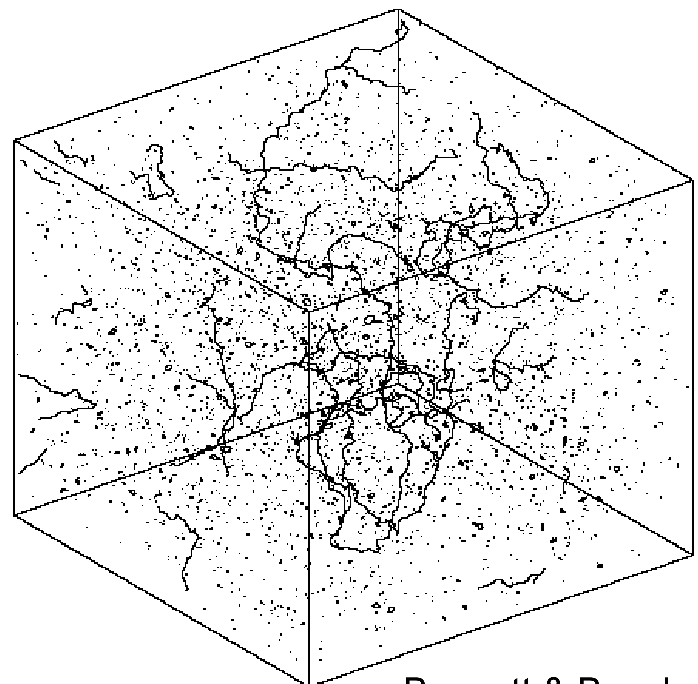
A brief history of the cosmic string network:

1. Percolating strings form.
2. Strings expand with universe.
3. Long strings collide and reconnect, building up short scale kink structure.
4. Loops break off.
5. Loops decay by gravitational radiation.

Result:

Scales with horizon size.

Total string length in Hubble volume ~ 100 Hubble lengths



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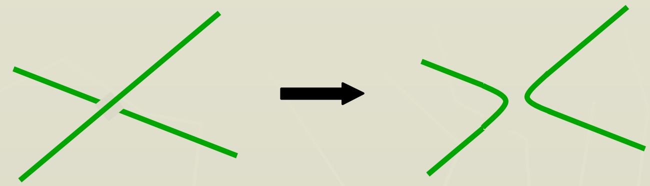
For now assume simplest networks --- one kind of string, gravitational interactions only, and strings always reconnect when they collide:



Gravitational signatures controlled by dimensionless parameter $G\mu$ (Newton's constant x string tension).

$G\mu$ = string tension in Planck units

= typical metric perturbation produced by string

(e.g. string bends light by $8\pi\, G\mu$).

Current bounds roughly $G\mu < 10^{-6.5}$ CMB power spectrum (strings do not produce acoustic peaks), CMB pattern search, pulsar timing (limits stochastic gravitational waves from string decay).

Brane inflation models predict $10^{-11} < G\mu < 10^{-6}$ from

$$\delta T/T \Longrightarrow H_{\mathrm{inflation}} \Longrightarrow G\mu$$

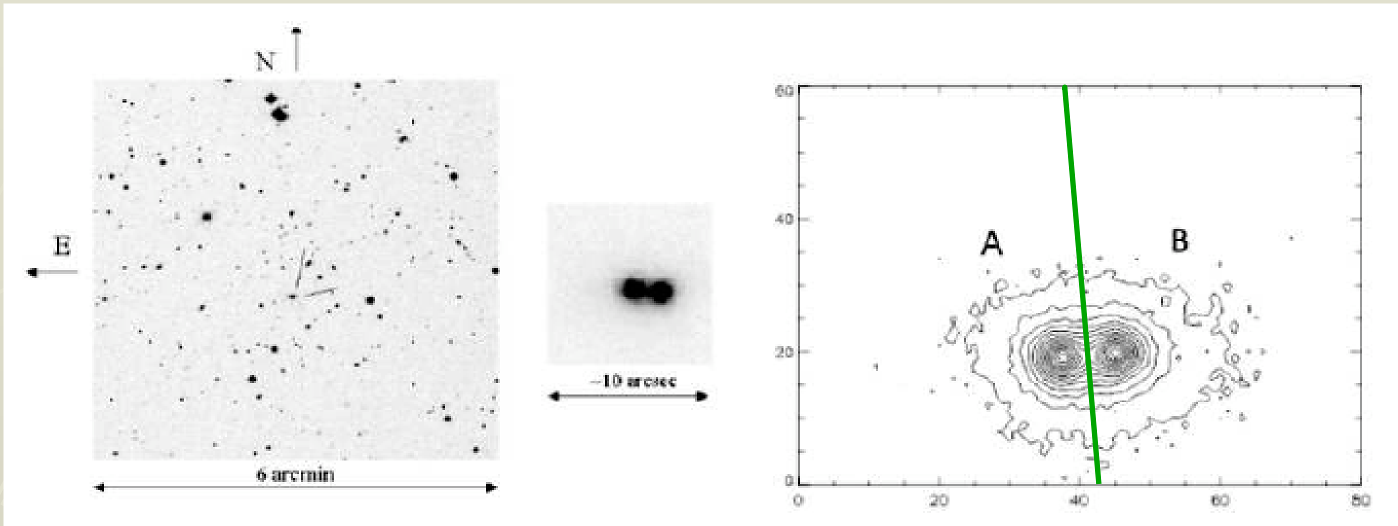
(Assumes perturbations are from quantum fluctuations of inflaton).

Possible gravitational signatures:

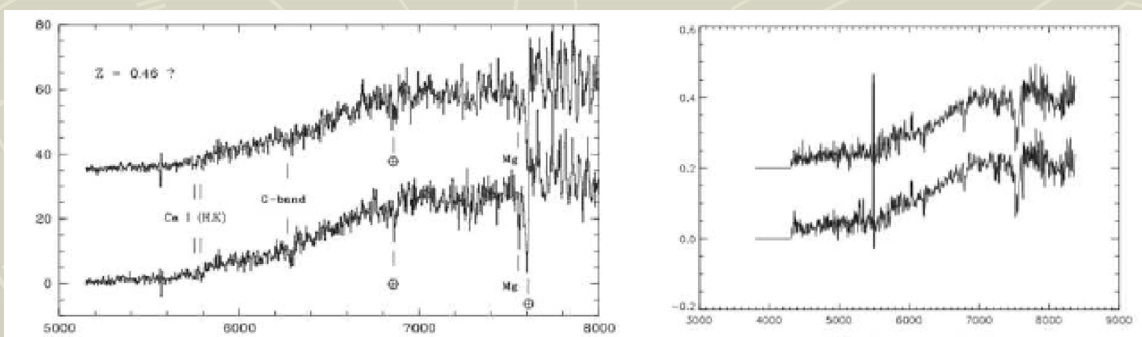
- Lensing
- Effect on CMB
- Gravitional waves
- *Not* dark matter, $\rho_{\mathrm{string}}/\rho_{\mathrm{matter}} \sim 60G\mu$

Lensing

Possible cosmic string lens:

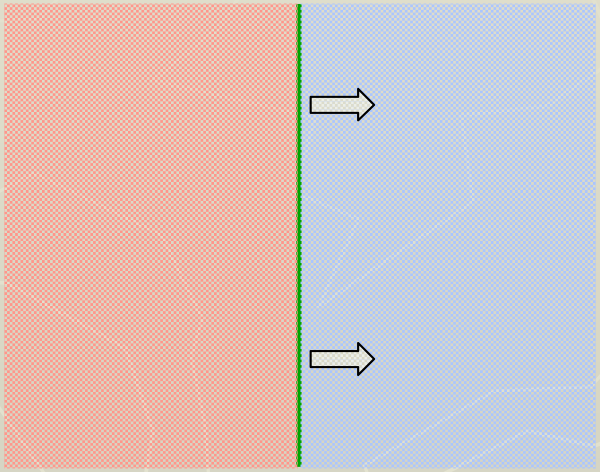


Sazhin, et al. 2003. $\delta\phi \sim 2''$. Matching spectra:



• Eleven other candidate lenses in nearby field - consistent with string, vs. two expected from normal lenses.

• Lo and Wright report 2-sigma feature in CMB.



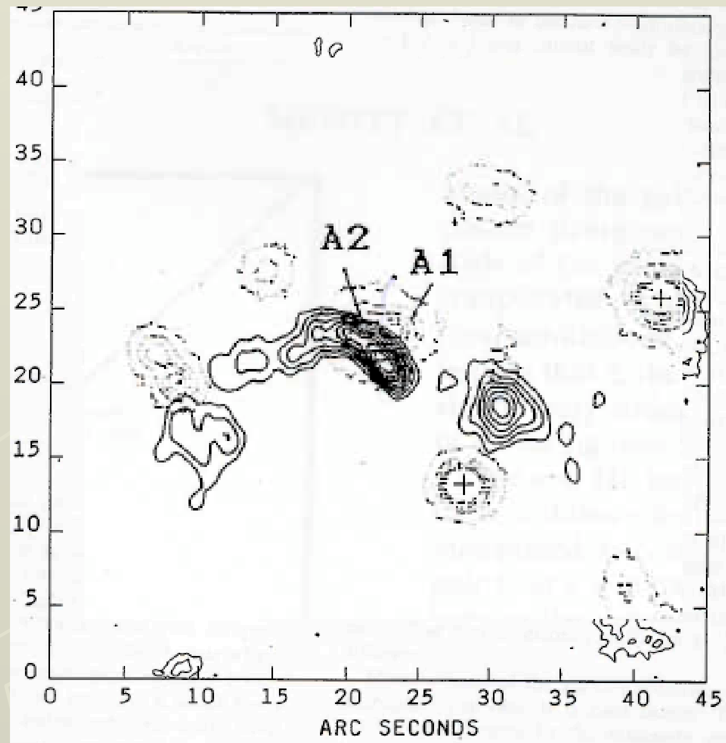
A moving string produces a differential redshift $\sim 8\pi G\mu \, v/(1-v^2)^{1/2}$.

Alternative explanations: binary galaxy, ordinary lens.

A cautionary tale: Field of four cosmic string lens candidates. Each pair at single redshift; each separation around 2”. Cowie & Hu ‘87

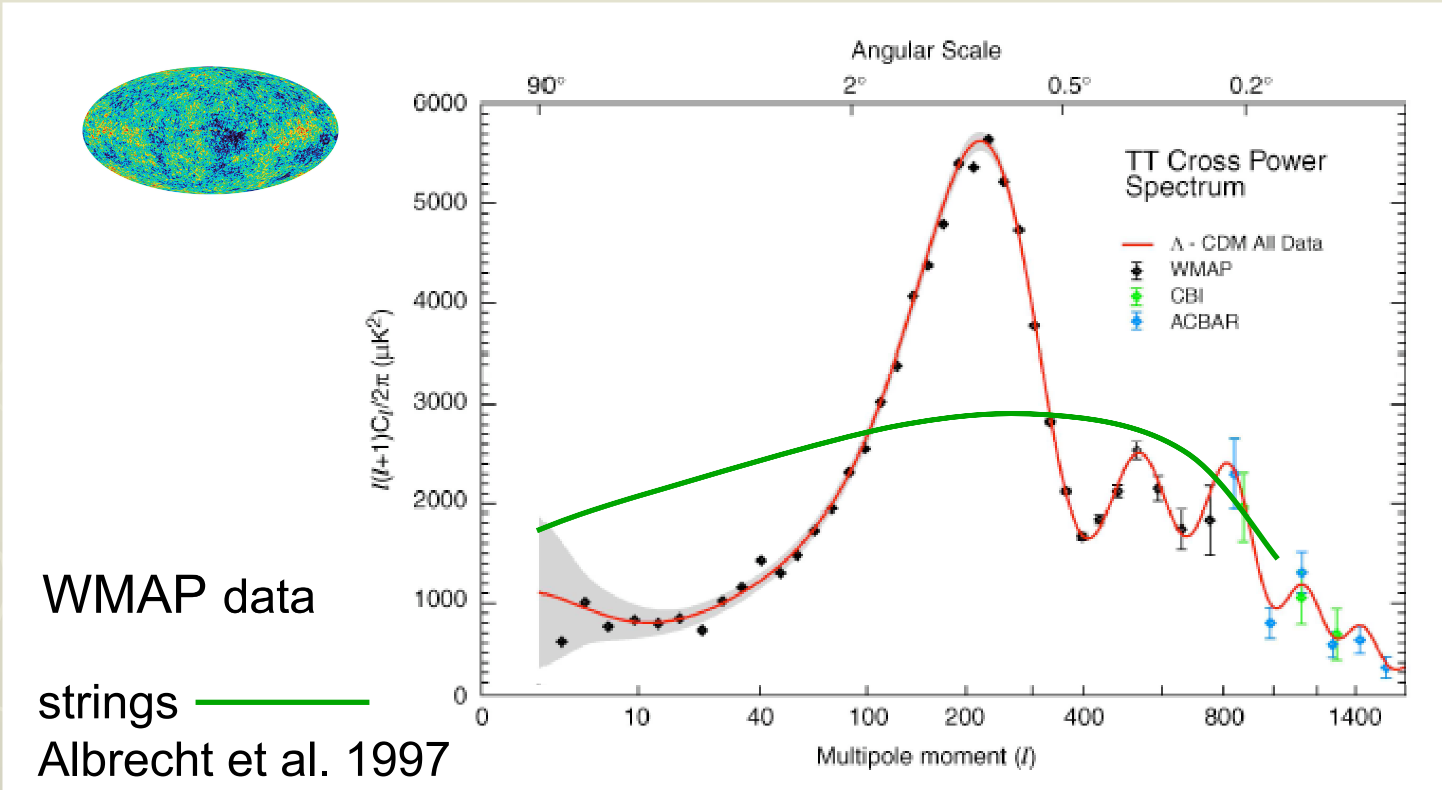
Observations in radio ‘90.

Apparent explanation: a random group of binary galaxies.



Nine Hubble orbits have been assigned to CSL-1 in Feb. 2006

CMB power spectrum



Acoustic peaks come from temporal coherence. Inflation has it, strings don't. String contribution < 10% implies $G\mu \lesssim 10^{-6.5}$.

Gravitational waves from strings

Strings are asymmetric and moderately relativistic, so are good emitters of gravitational waves. Essentially all of the energy in the string network ends up as gravitational waves. Some limits:

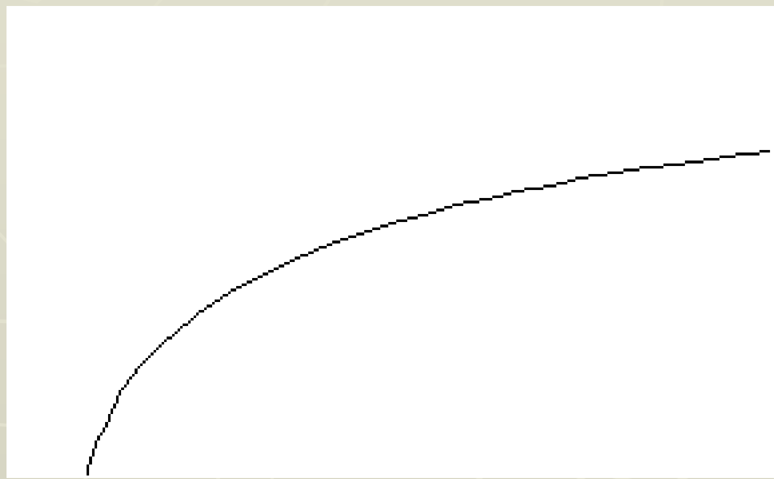
From effect of GW energy density on Big Bang Nucleosynthesis: $G\mu \lesssim 10^{-5}$.

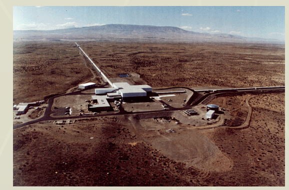
From effect of GW on pulsar timing: $G\mu \lesssim 10^{-6.5}$. (Kaspi, et. al 1994, Lommen 2001)***.

LIGO and LISA are sensitive to higher frequencies and are normally less sensitive to cosmological GW. However…

String cusps

Typically, several times per oscillation a cusp will form somewhere on a cosmic string.

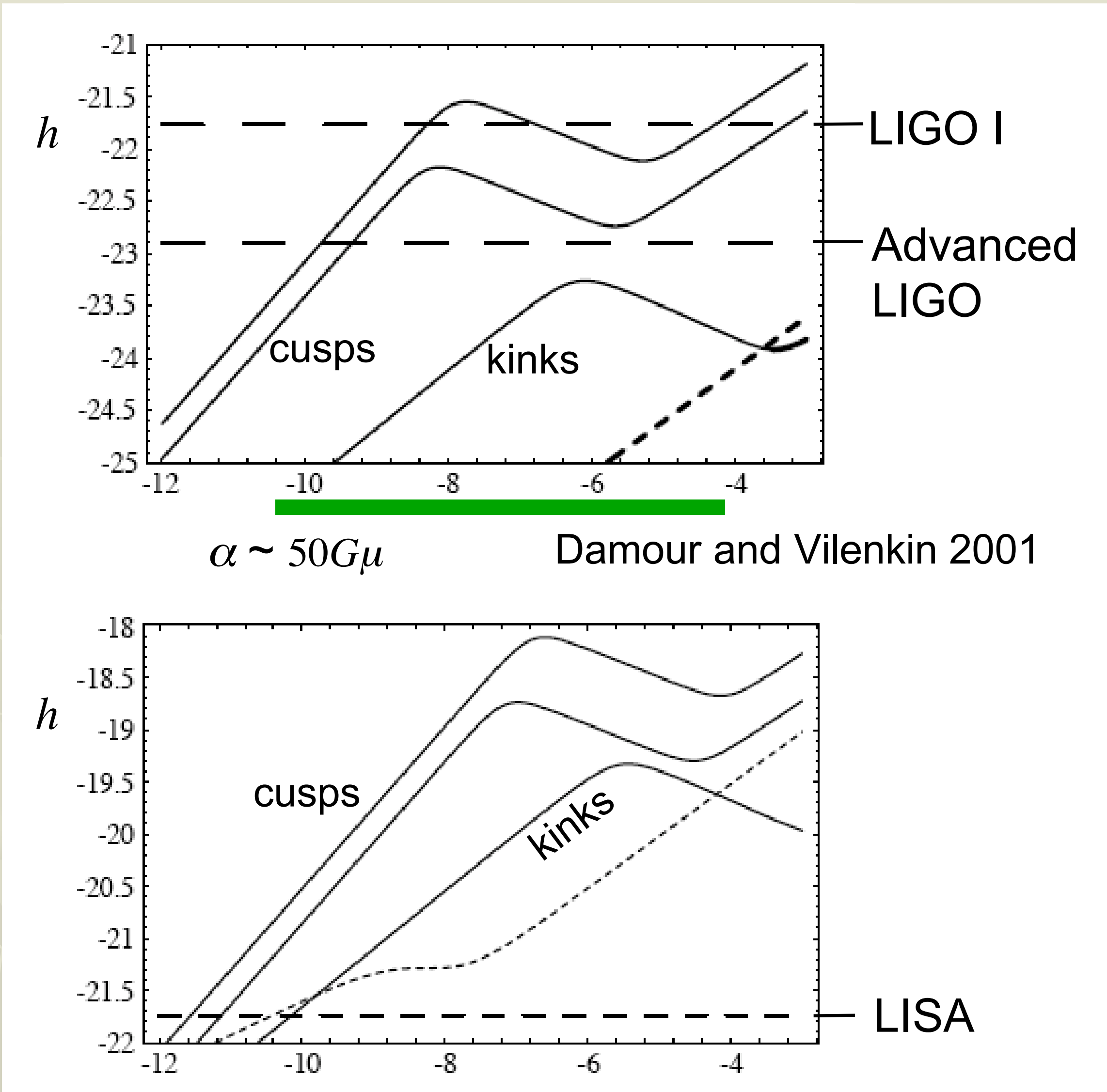




The instantaneous velocity of the tip approaches c.

The cusp emits an intense beam of GW.

LIGO/LISA signals from string cusps

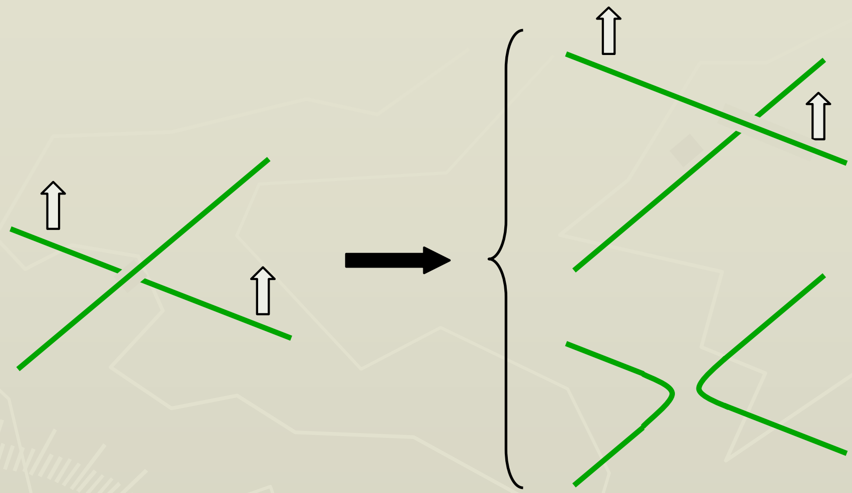


Cosmic strings could be the brightest GW sources, over a wide range of $G\mu$.

Summary: if $G\mu$ is near the current limit, lensing and CMB will allow us to map out the network in detail. Interferometers and pulsars ultimately reach the whole range for brane inflation models.

Studying string microphysics:

When two strings collide, two things can happen:



nothing:
probability $1-P$

reconnection:
probability P

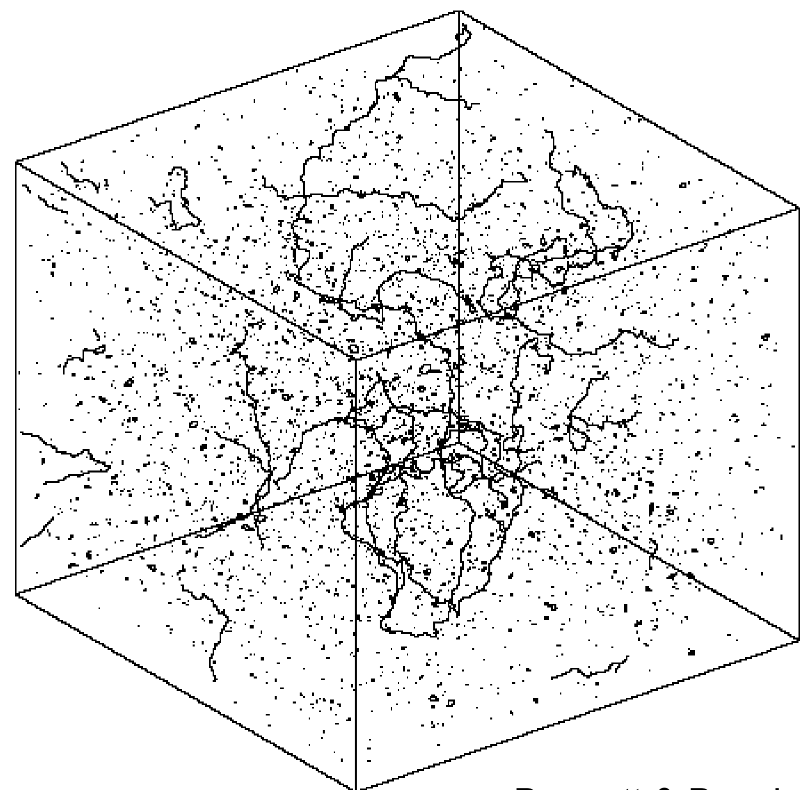
Gauge theory solitons in typical models reconnect if $v_{cm} < 0.9$; effective P around 0.98.

For F-strings $P \sim g_s^{\,2}$ (quantum process).

Hashimoto & Tong '05 find a field theory model with N kinds of string, such that $P_{\text{self}} = 1$ and $P_{\text{other}} = 0$. Thus for an average collision $P \sim 1/N$. However, this model can be distinguished:

At small P long string density grows as $1/P$, and short distance kinkiness also increases. HT strings have only the former.

Better analytic and numerical studies needed.



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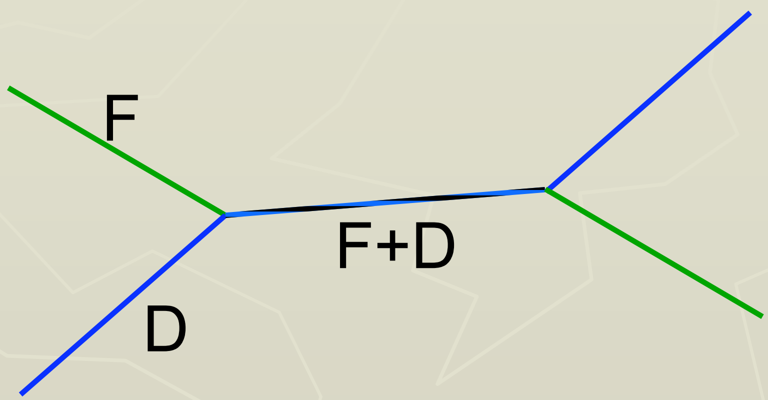
With multiple string can also have bound states and junctions:



Very interesting, especially for lensing.

Conclusions:

Cosmic strings are highly model-dependent, but exist in some of the best current models of string theory inflation.

Discovery of cosmic strings would give a new window onto near-Planck scales.

What do open heterotic strings teach us?