Cosmic Strings from String Theory

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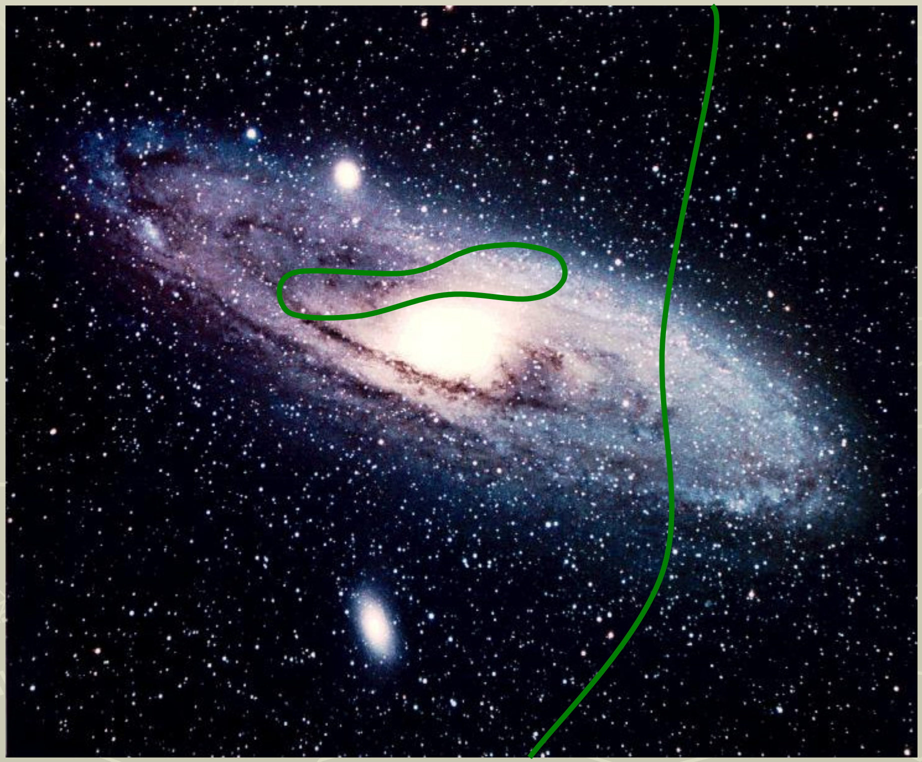


Pheno-06, 5/16/06

Many potential cosmic strings from string compactifications:

- The fundamental string themselves
- D-strings
- Higher-dimensional D-branes, with all but one direction wrapped.
- Solitonic strings and branes in ten dimensions
- Magnetic flux tubes (classical solitons) in the effective 4-d theory: the classic cosmic strings.
- Electric flux tubes in the 4-d theory.

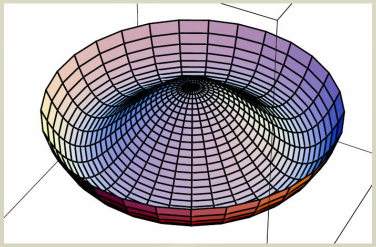
To first approximation the phenomenology depends little on the internal structure.

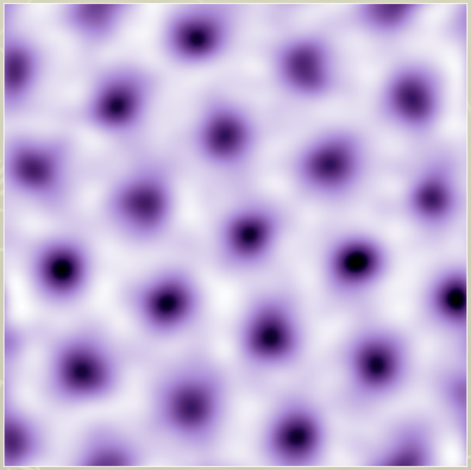
Landscape ideas suggest a compactification of high topological complexity, so there might be $O(10^3)$ distinct cosmic string candidates – and the bound states of these.

However, the only strings that matter are those that are produced in an appropriate phase transition in the early universe. It is necessary to start with strings that are very long compared to the horizon scale.

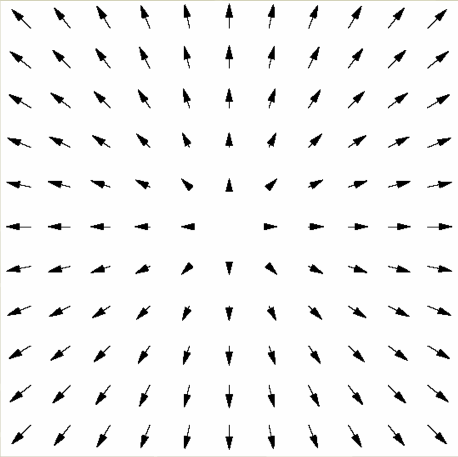
Production of cosmic strings:

Example: gauge theory solitons. These solutions exist as topological defects in the Higgs field whenever a $U(1)$ symmetry is broken:



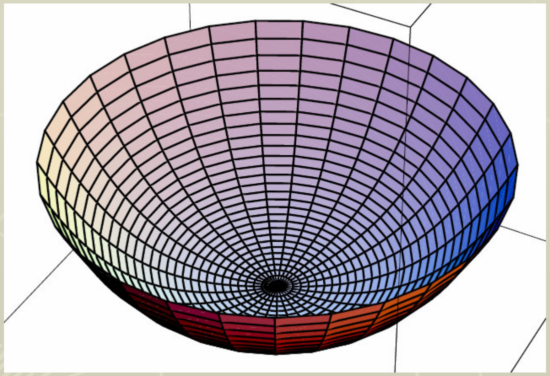


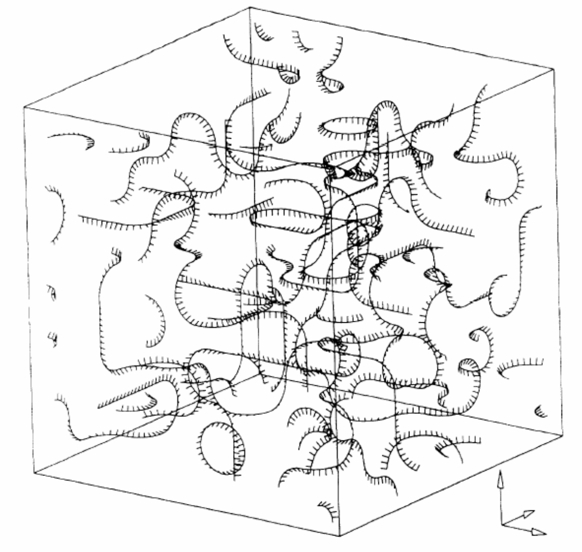
Flux tubes in superconductor (end view).



Defect in Higgs field.

These solutions exist whenever a $U(1)$ is broken, and they are actually produced whenever a $U(1)$ *becomes* broken during the evolution of the universe (Kibble):



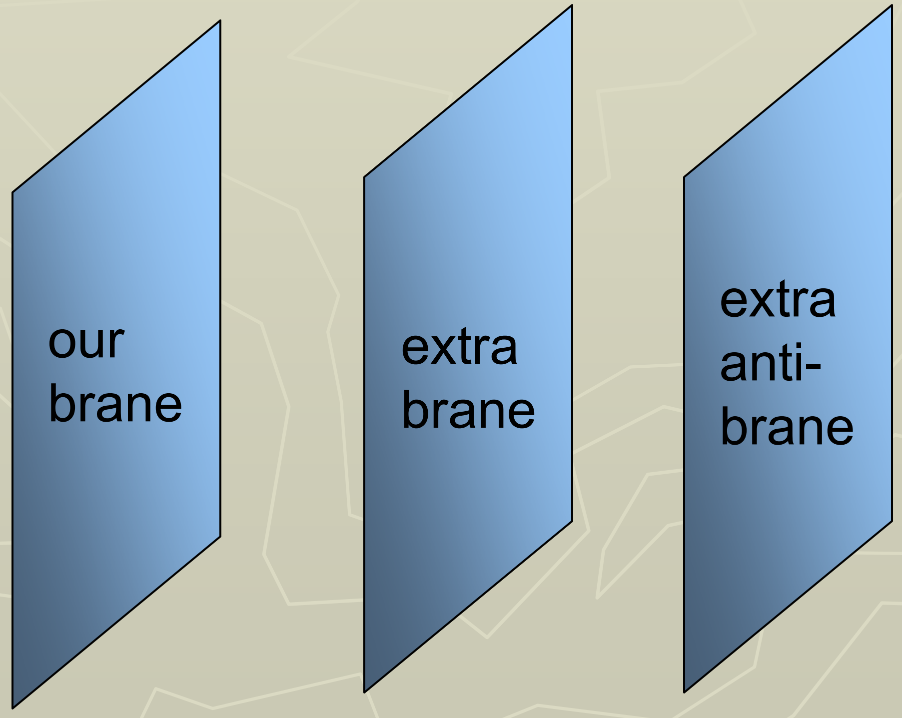


From Allen and Shellard (1990).

Phase uncorrelated over distances greater than the horizon. $O(50\%)$ of string is in infinite random walks (percolation).

Brane inflation:

An attractive model of inflation is that there were additional brane-antibrane pairs in the early universe. Their energy density induced inflation; subsequently they annihilated:



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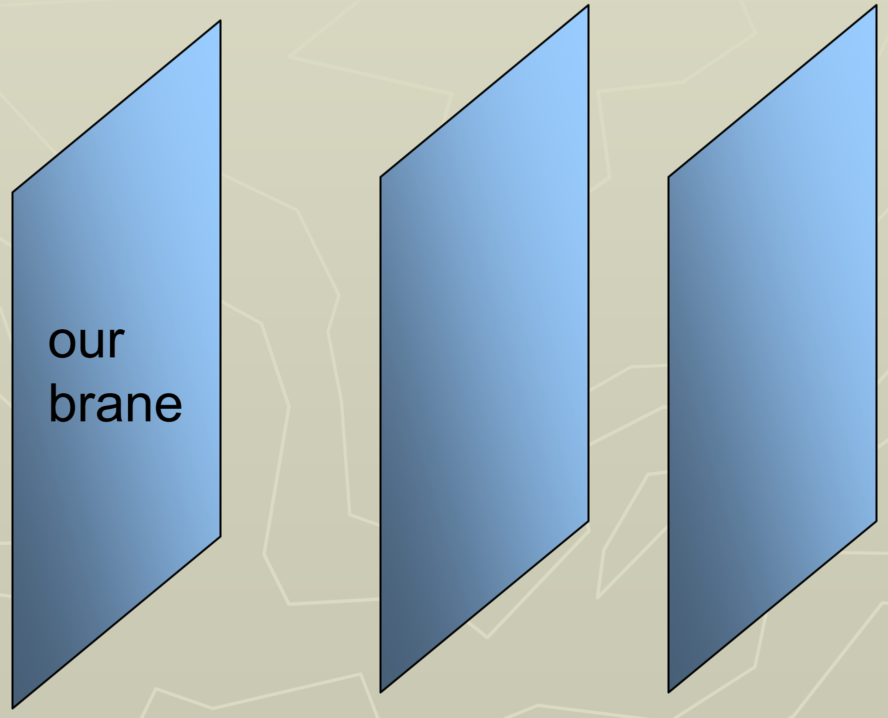

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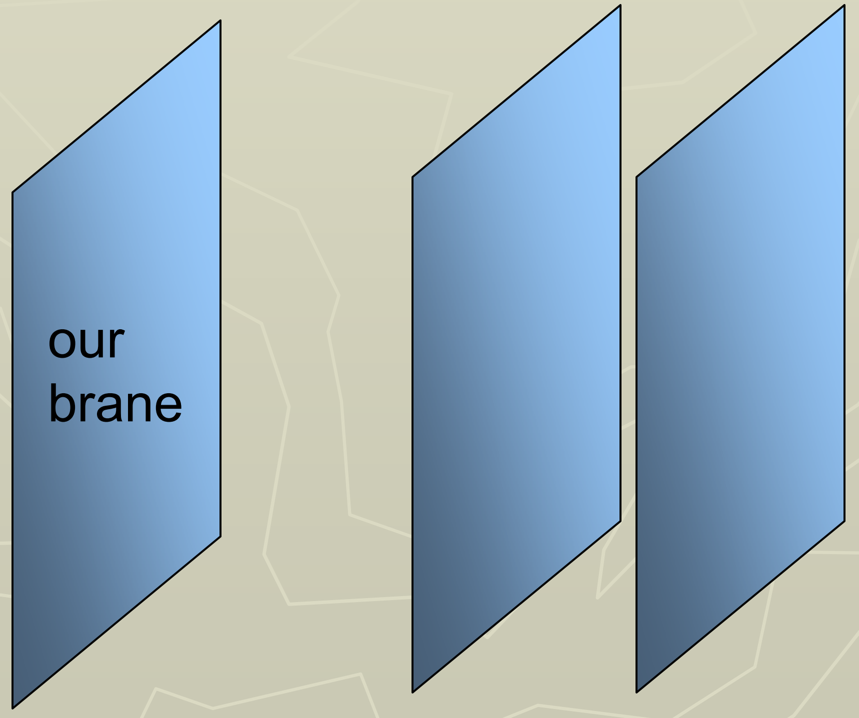

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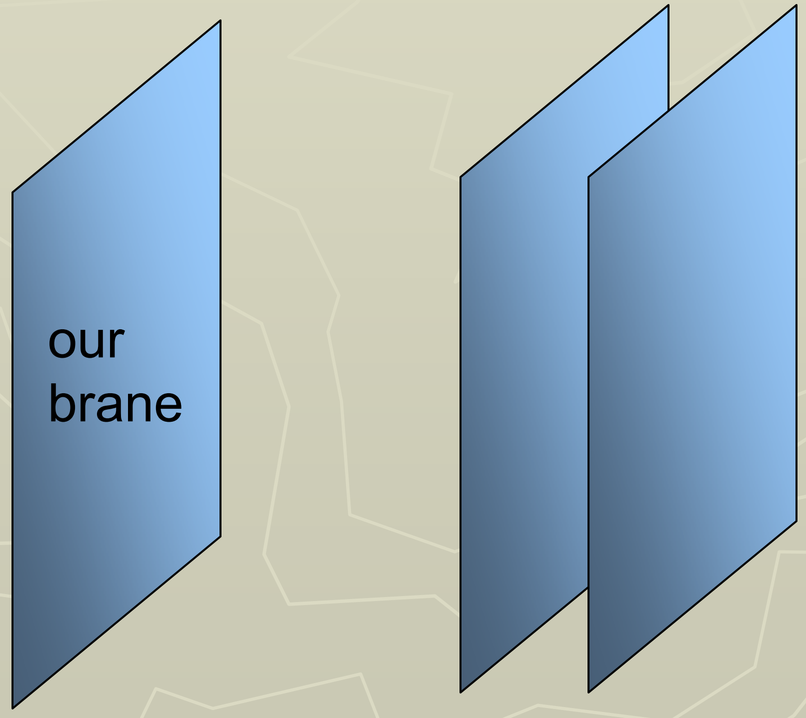

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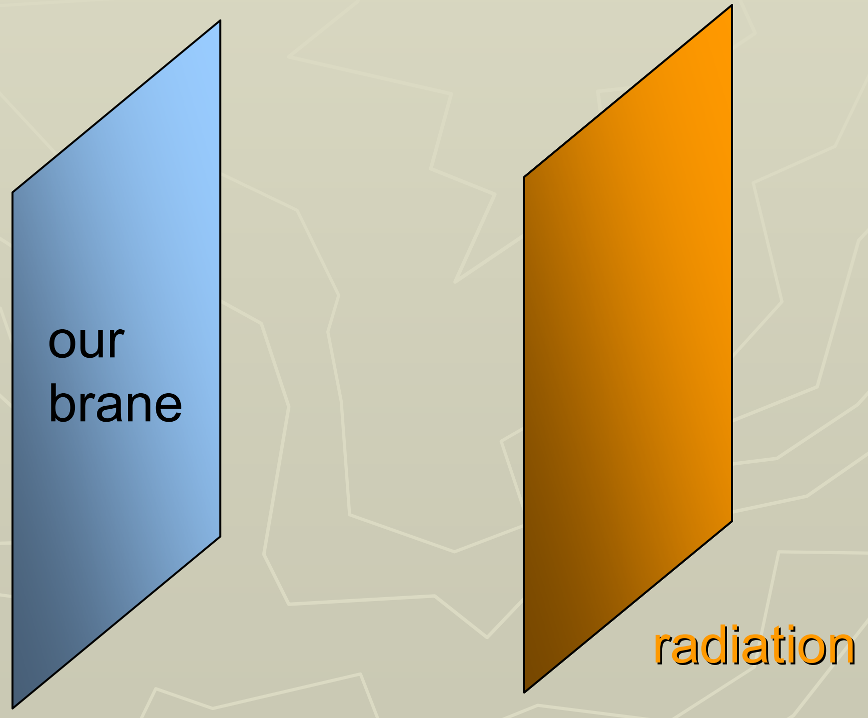
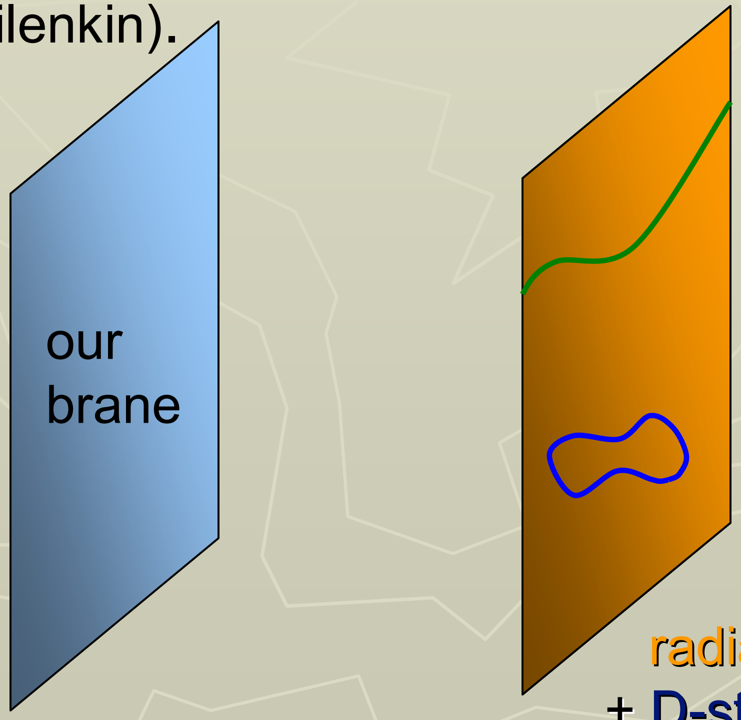


Brane inflation produces strings:

Two $U(1)$ symmetries are broken at the end of brane inflation (one from the brane and one from the antibrane), so superstrings and Dirichlet strings are produced (Jones, Stoica, Tye; Sarangi & Tye; Copeland, Myers, JP; Dvali & Vilenkin).



radiation + strings
+ D-strings (but not magnetic monopoles or domain walls).

Other production mechanisms

- Cooling below a Hagedorn/deconfinement transition (Englert, Orloff, Piran). Long string soup above the transition. ~ Magnetic dual to Kibble mechanism.

- Parametric resonance --- scalar field oscillating near point of zero string tension (Gubser).

Hybrid inflation

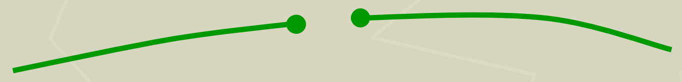
Generic cosmic strings interact only gravitationally, so one wants the highest possible tension, but not higher than the inflation scale. *Hybrid inflation* is ideal: inflation ends with a symmetry-breaking transition; brane inflation is a special case of hybrid inflation.

Caveat: WMAP 3 year data give $n_s = 0.951 \pm 0.015$, while hybrid inflation models give $n_s > 0.975$.

Instabilities of strings I

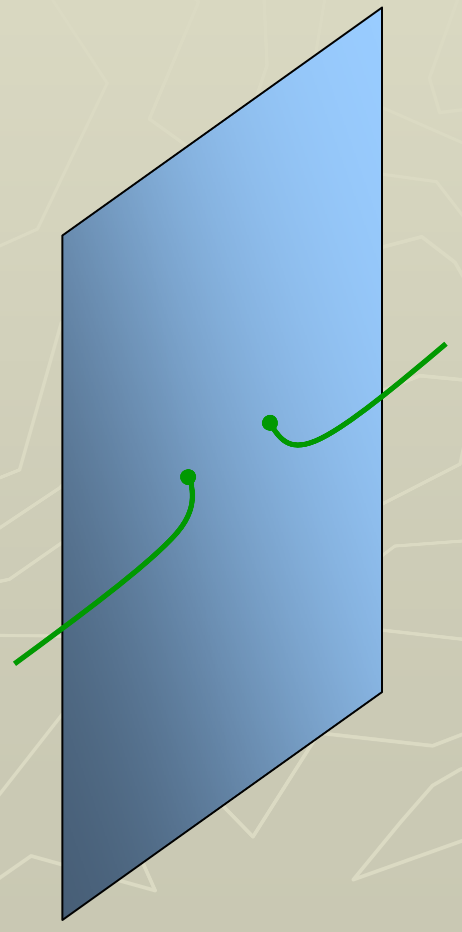
Witten (1985) discusses two instabilities that would prevent strings from reaching cosmic sizes.

I. Some strings can break:

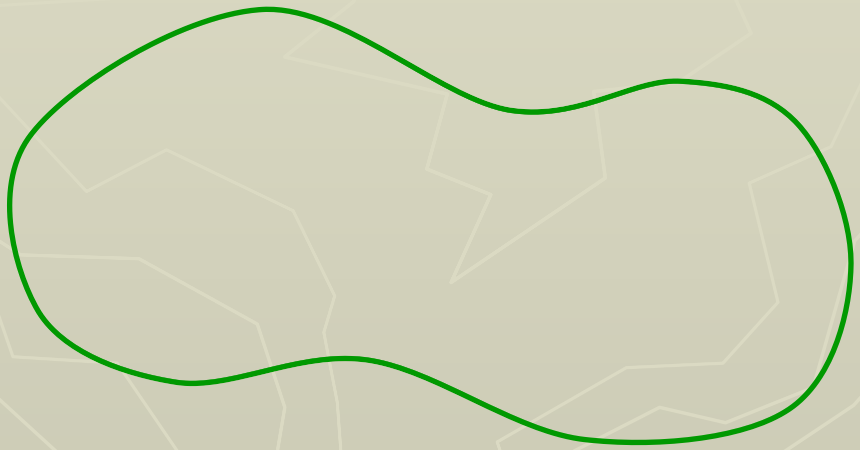


4-d picture: breakage of flux tube due to monopole-antimonopole pair production.

10-d picture: breakage on a brane:



The would-be cosmic string then breaks up into short strings (diffuse particles):



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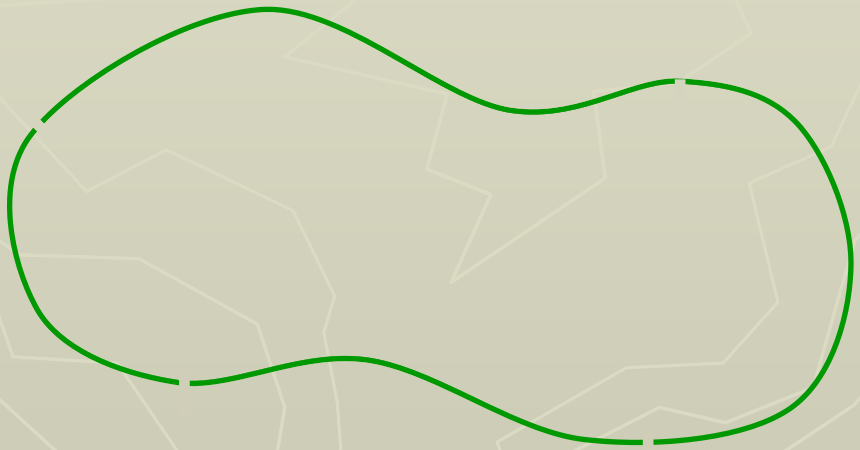

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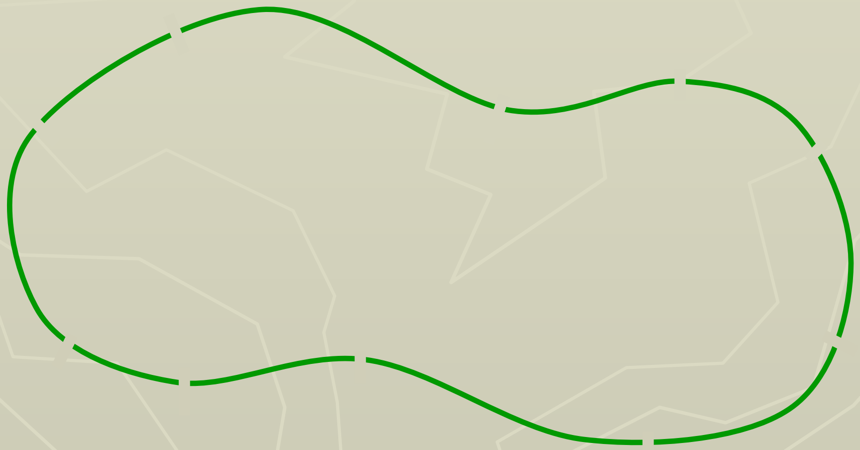

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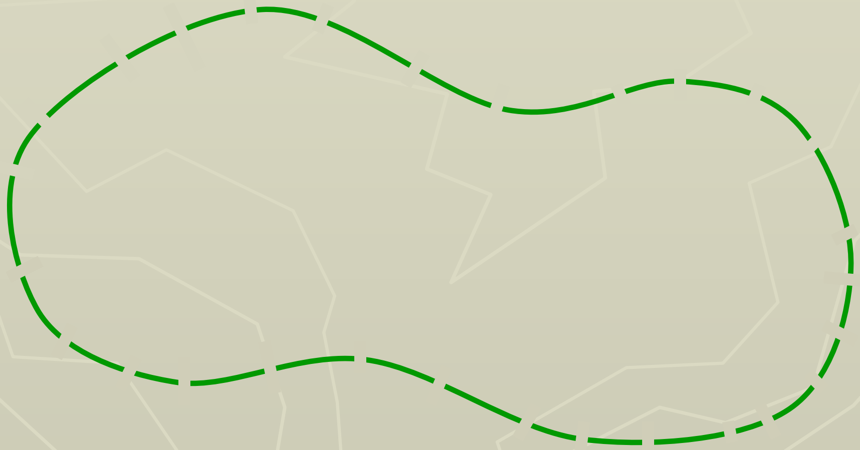
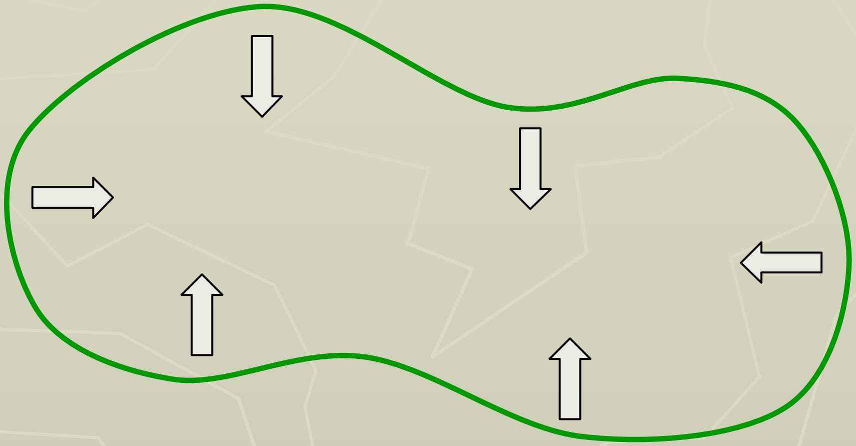


Instabilities of strings II

II. Some strings are ‘confined’ by a strong self-attraction:



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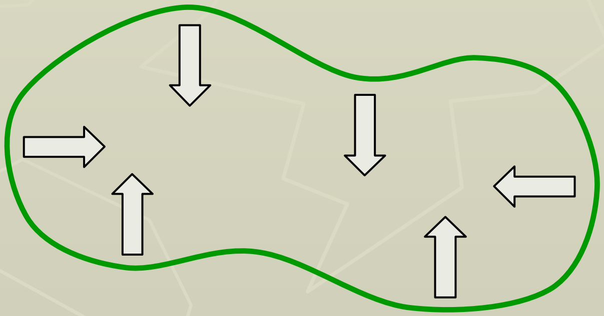

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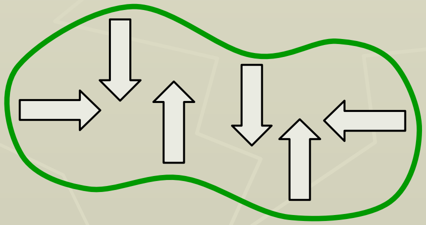

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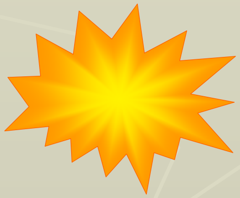


Again, the strings convert to ordinary quanta before reaching cosmic size.

Summary

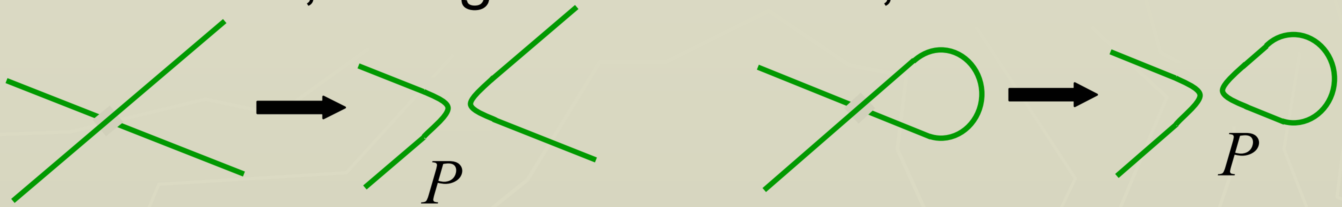
- Strings that have no long-range topology can break, but the decay rate is of order $\exp(-2\pi m^2/\mu)$ (where m = endpoint mass, μ = string tension) and so slow on cosmological time scales if $m > 10\,\mu^{1/2}$. Depends on details of compactification.

- Strings with axion charge are confined.

- Strings with Aharonov-Bohm charges are absolutely stable.

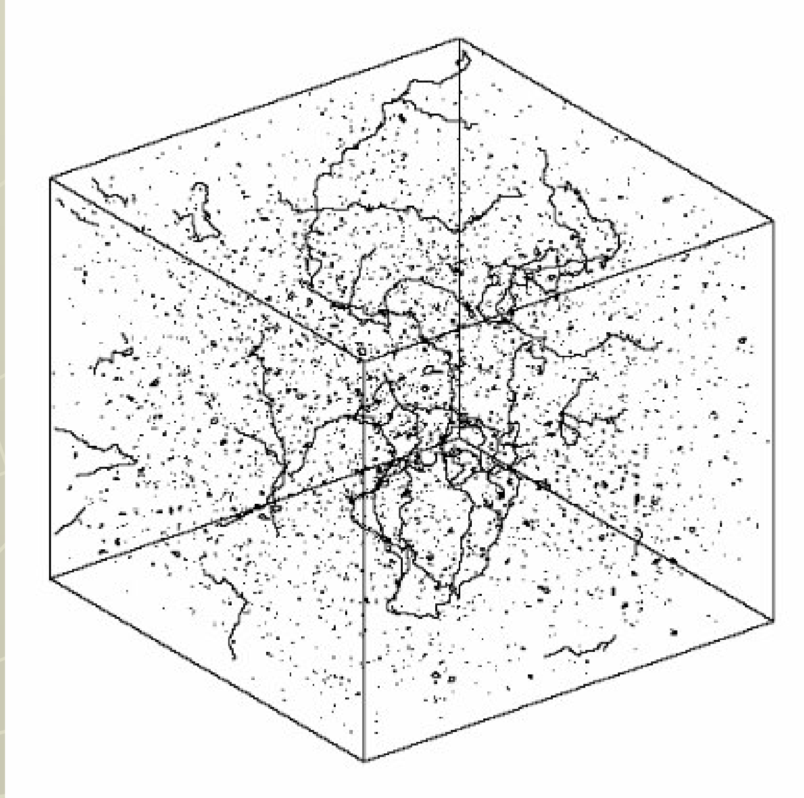
String evolution

After formation, dominant processes are expansion of the universe, string reconnection,



and decay of loops by gravitational radiation. Attractor solution, scales with horizon size:

String density, signatures scale as $P^{-1(?)}$, where P is the probability of reconnection.

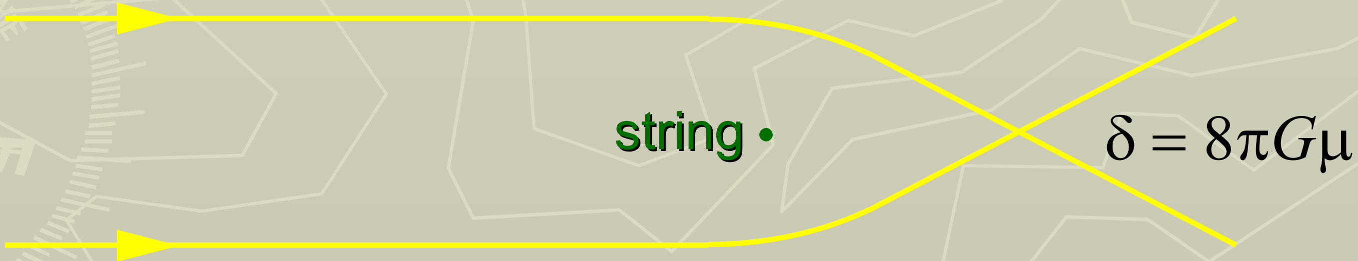


Seeing strings

Generic strings have only gravitational interactions, and this is the case we will focus on. Their signatures are therefore controlled by the dimensionless parameter $G\mu$,

$=$ string tension in Planck units

$=$ typical metric perturbation produce by string, as seen e.g. in bending of light:



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

In brane inflation, $G\mu \sim (G^2 V_{\text{inf}})^{1/2} \sim G^{1/2} H_{\text{inf}}$, up to model-dependent geometric factors. H_{inf} is normalized from observed $\delta T/T$. Typical range in brane inflation models $10^{-12} < G\mu < 10^{-6}$.

E.g. KKLMMT model (D3/anti-D3 in Randall-Sundrum-Klebanov-Strassler throat), $G\mu \sim 10^{-9}$.

Possible signatures (gravitational!):

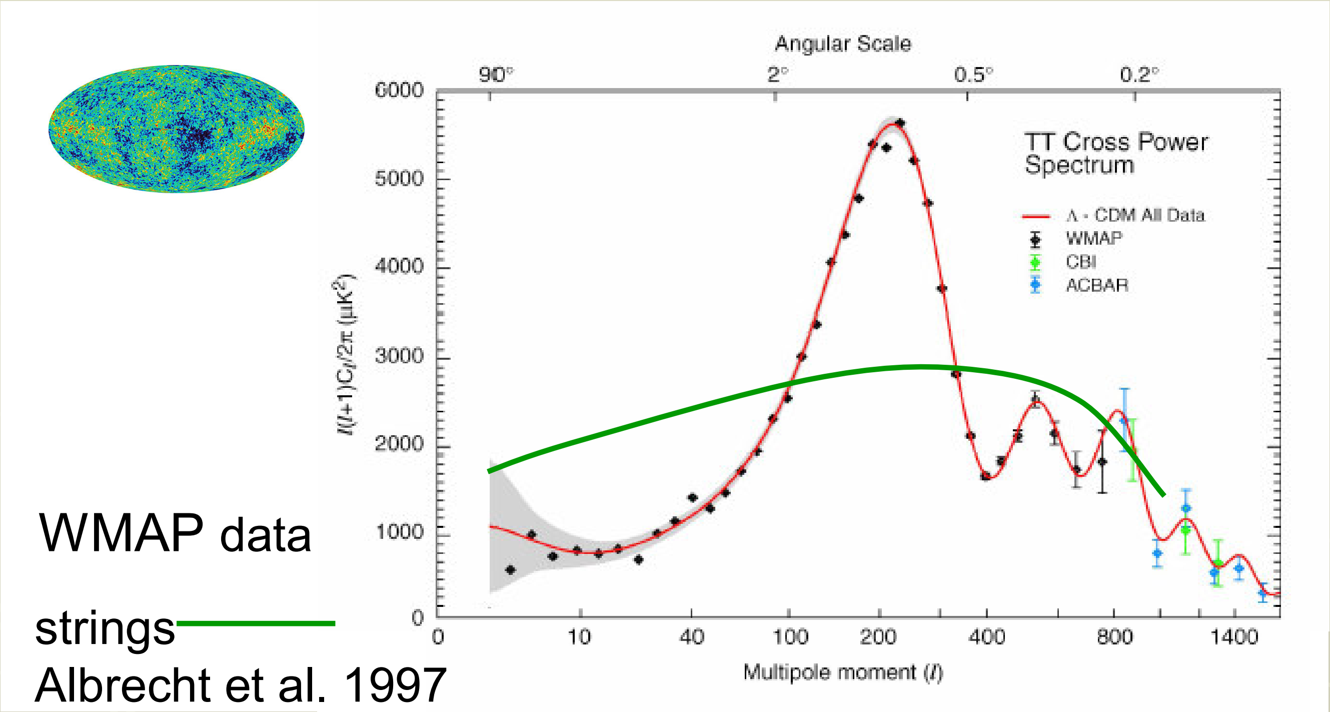
- Effect on CMB
- Lensing
- Gravitional waves
- *Not* dark matter, $\rho_{\text{string}}/\rho_{\text{matter}} \sim 60G\mu$

Cosmic microwave background and galaxy formation

Strings with $G\mu \sim 10^{-5.5}$ produce observed $\delta T/T$ and $\delta\rho/\rho$ (Zeldovich 1980, Vilenkin 1981).

However, they produce the wrong CMB power spectrum:

CMB power spectrum



WMAP data

strings

Albrecht et al. 1997

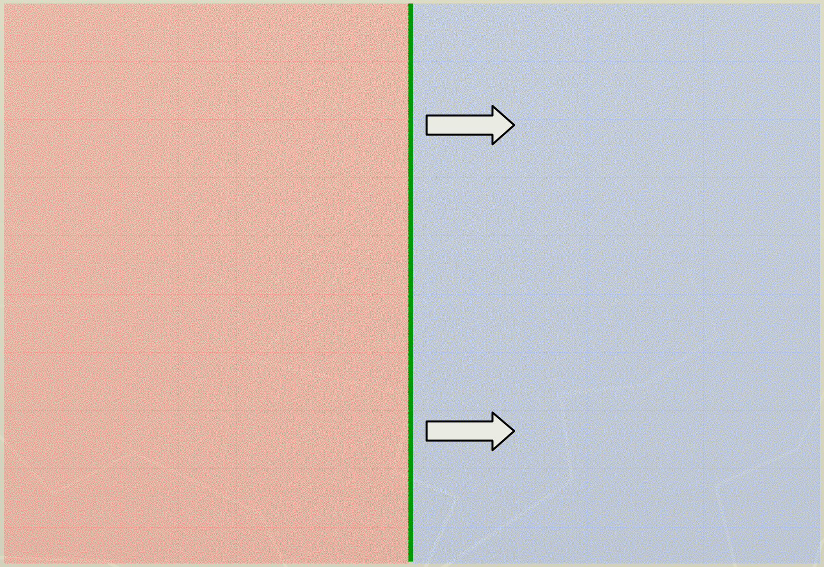
Bound from first year WMAP: $G\mu < 2.7 \times 10^{-7}$

(Wyman, Pogosian, Wasserman 2006).

Bound from three-year WMAP: $G\mu < 2.3 \times 10^{-7}$

--- cosmic variance limit (McDonald, Seljak, Slosar).

CMB Nongaussianity



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

$G\mu < 3.3 \times 10^{-7}$ from width of temperature distribution
$G\mu < 6 \times 10^{-7}$ from pattern search (Jeong & Smoot 2004).

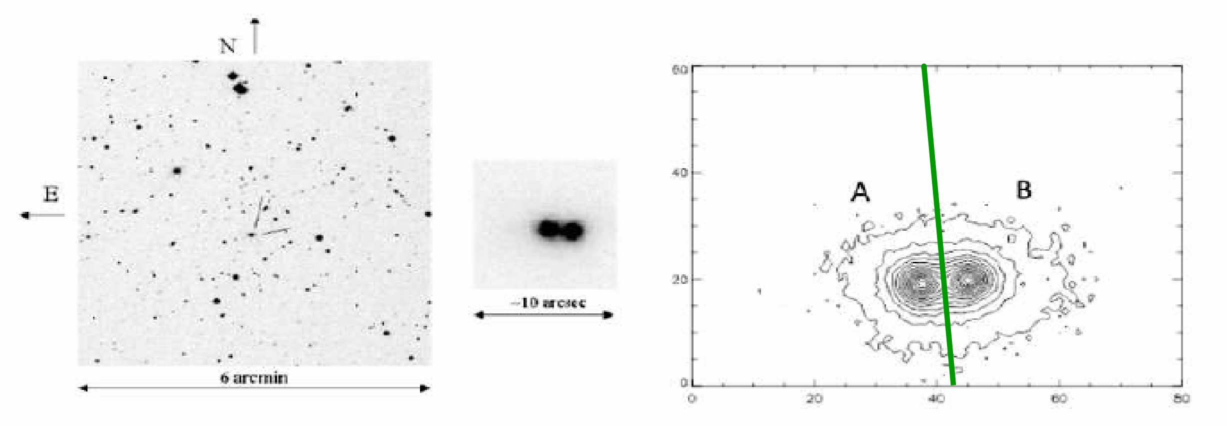
CMB Polarization

Brane inflation models tend to have lower H_{inf}, low levels of tensor modes (e.g. $r \sim 10^{-9}$ for KKLMMT).

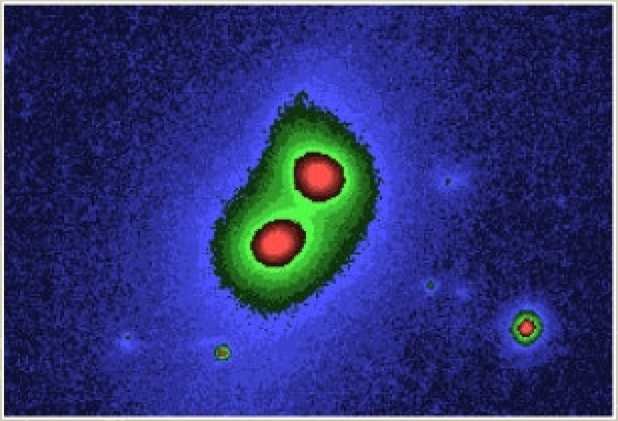
However, the strings themselves produce tensor modes, polarization might ultimately be sensitive down to $G\mu \sim$ few x 10^{-9} at CMBPOL (Seljak & Slosar).

(Polarization vs. power spectrum).

A cosmic string lens (CSL1)?



Unfortunately not (higher resolution Hubble pictures):



No quoted bounds from lensing. (Bounds from CMB imply $\delta < 1.2''$).

Gravitational waves from strings

Cosmic strings eventually decay into grav. waves.

Bound on GW energy density from BBN: $\Omega_{GW} < 1 \times 10^{-5}$
Implies $G\mu < 1 \times 10^{-5}$.

From effect of GW on pulsar timing:

$$fh^2 d\Omega_{GW}/df < 6 \times 10^{-8} \text{ at } f \sim (10 \text{ yr})^{-1}$$

(Kaspi, et. al 1994); gives $G\mu < 1 \times 10^{-6}$.

Bound should be stronger today, $\sim t^{-6}$, but data noisy (Lommen 2001). Potentially much stronger in future, down to $G\mu < 10^{-11}$ with a square kilometer array (Lommen 2001, Damour & Vilenkin 2005).

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

String cusps

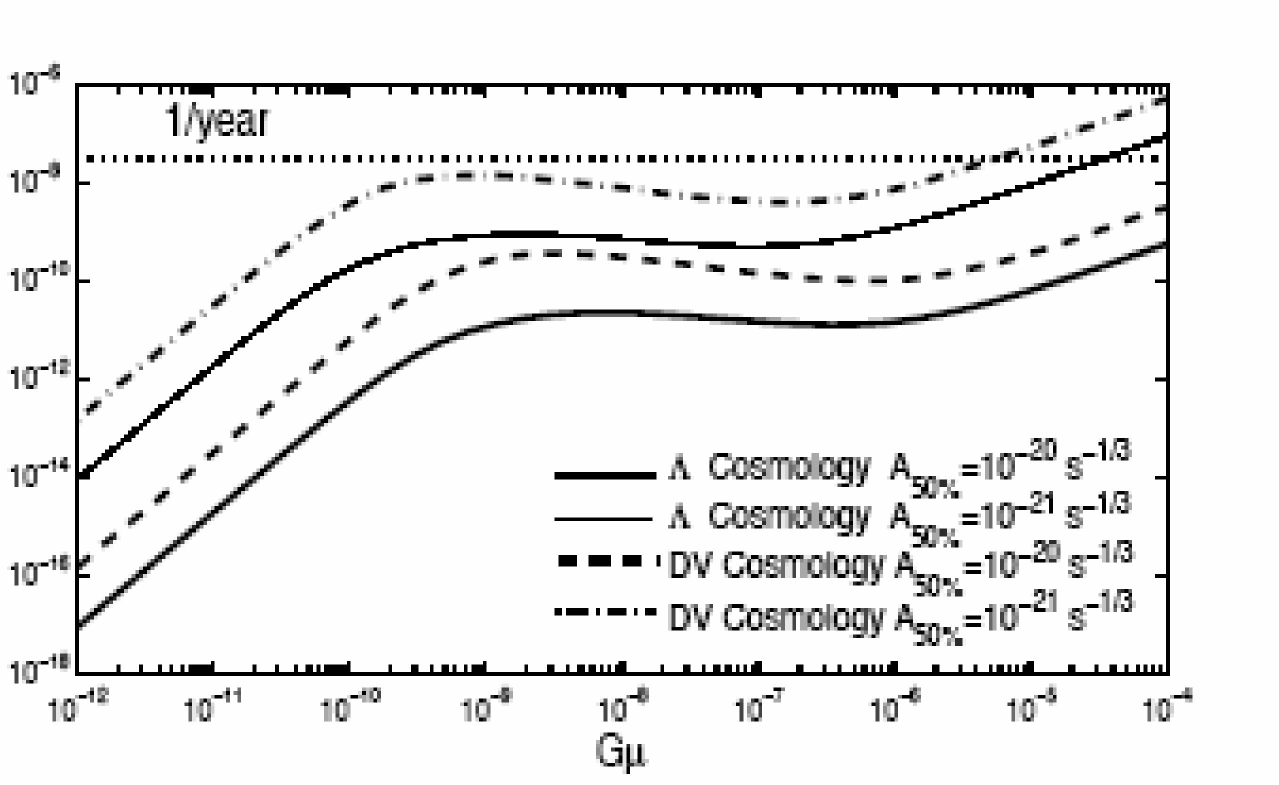
Typically, several times per oscillation a cusp will form somewhere on a cosmic string.

QuickTime™ and a
Animation decompressor
are needed to see this picture.

The instantaneous velocity of the tip approaches c.

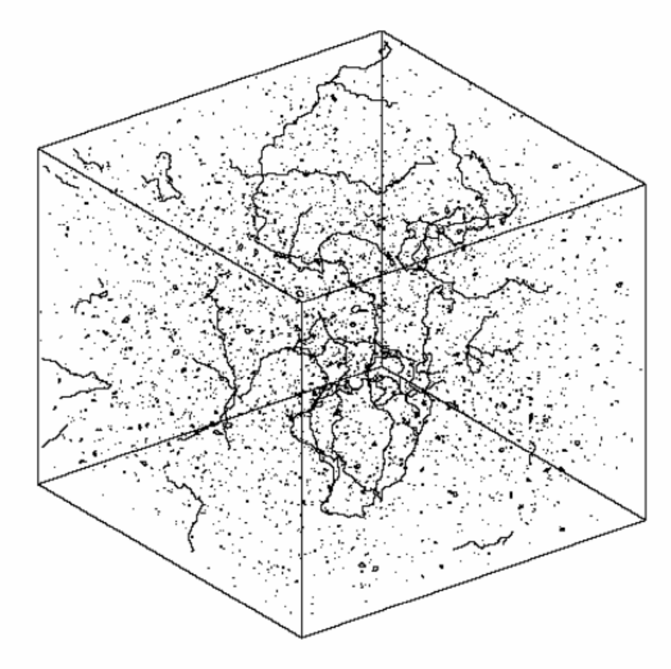
The cusp emits an intense beam of GW.

Early estimates (Damour and Vilenkin, 2001) indicated that these might be within reach of LIGO I or advanced LIGO; Siemens, et al, gr-qc/0603115 find lower signal, need LISA (or nonstandard enhanced network properties:

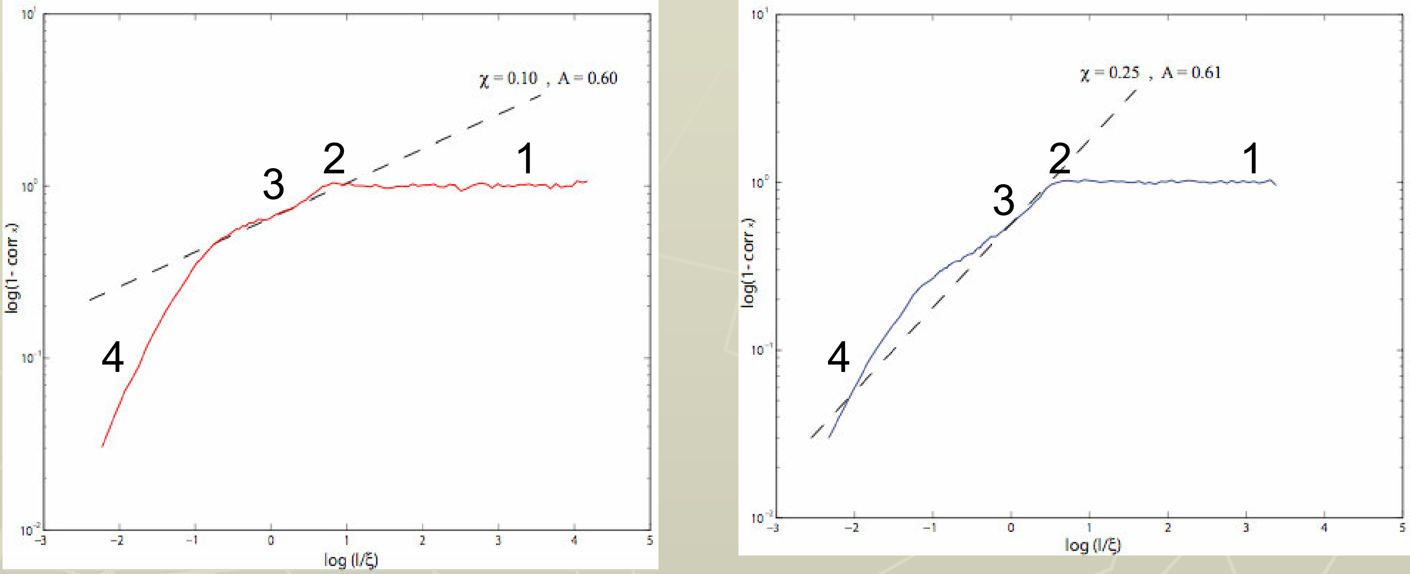


Network uncertainties --

What sets the size scale of loops? How non-smooth is the small scale structure, and does it cut off the cusps? Too nonlinear for analytic methods, too much dynamic range for numerical methods, must combine.



JP and Rocha: take results from simulations to fix horizon-scale features, use analytic methods to scale to shorter distances.

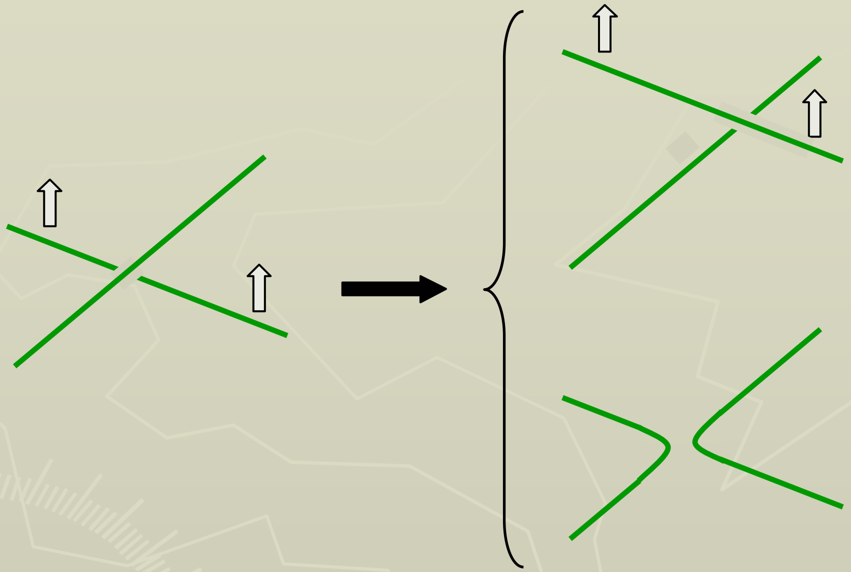


Correlation of direction of string, as a function of separation (radiation era; matter era).

Four regimes (R to L): 1. Random walk 2. Horizon scale 3. Sub-horizon scaling 4. Numerical artifact (insufficient simulation time). Note: Fractal dimension goes to 1 at short dist.

Distinguishing superstrings via interactions:

When two strings collide, two things can happen:



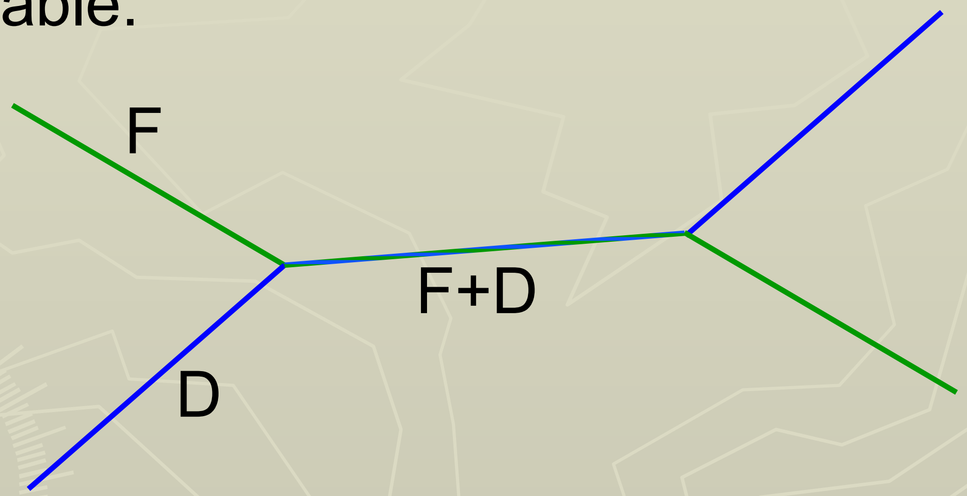
nothing:
probability $1{-}P$

reconnection:
probability P

Gauge theory solitons almost always reconnect (energetics: Matzner 1989). Superstrings reconnect with $P \sim g_s^{\,2}$ (Jackson, Jones , JP 2004). This affects the network behavior…

Distinguishing superstrings II

Superstring theories have a special kind of `defect’, the D-brane. One-dimensional D-brane = D-string. This gives richer networks, if both kinds of string are stable:



Distinctive spectrum of strings and bound states.

Conclusions

Not a guaranteed signal, but if seen it provides a direct window into GUT scale and string scale physics, and inflationary cosmology.

Observations can reach most or all of the parameter space of brane inflation models, although large gains depend on future instruments (LISA, CMBPOL, KPA).