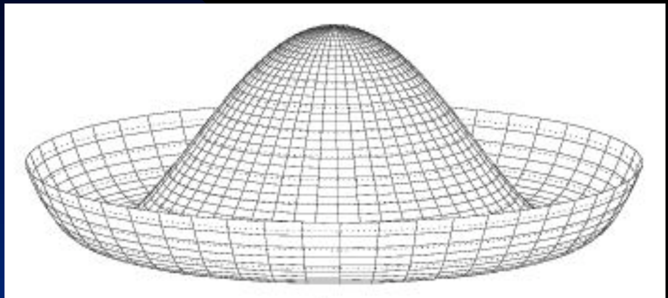
Cosmic superstrings

Ed Copeland University of Nottingham

1. Brief review of cosmic strings
2. Why cosmic superstrings
3. Modelling strings with junctions.
4. Potential observational properties -- scaling solutions, grav lensing, grav wave production...

New Views of the Universe: Chicago - Dec 10 2005

Original cosmic strings, in gauge theory :

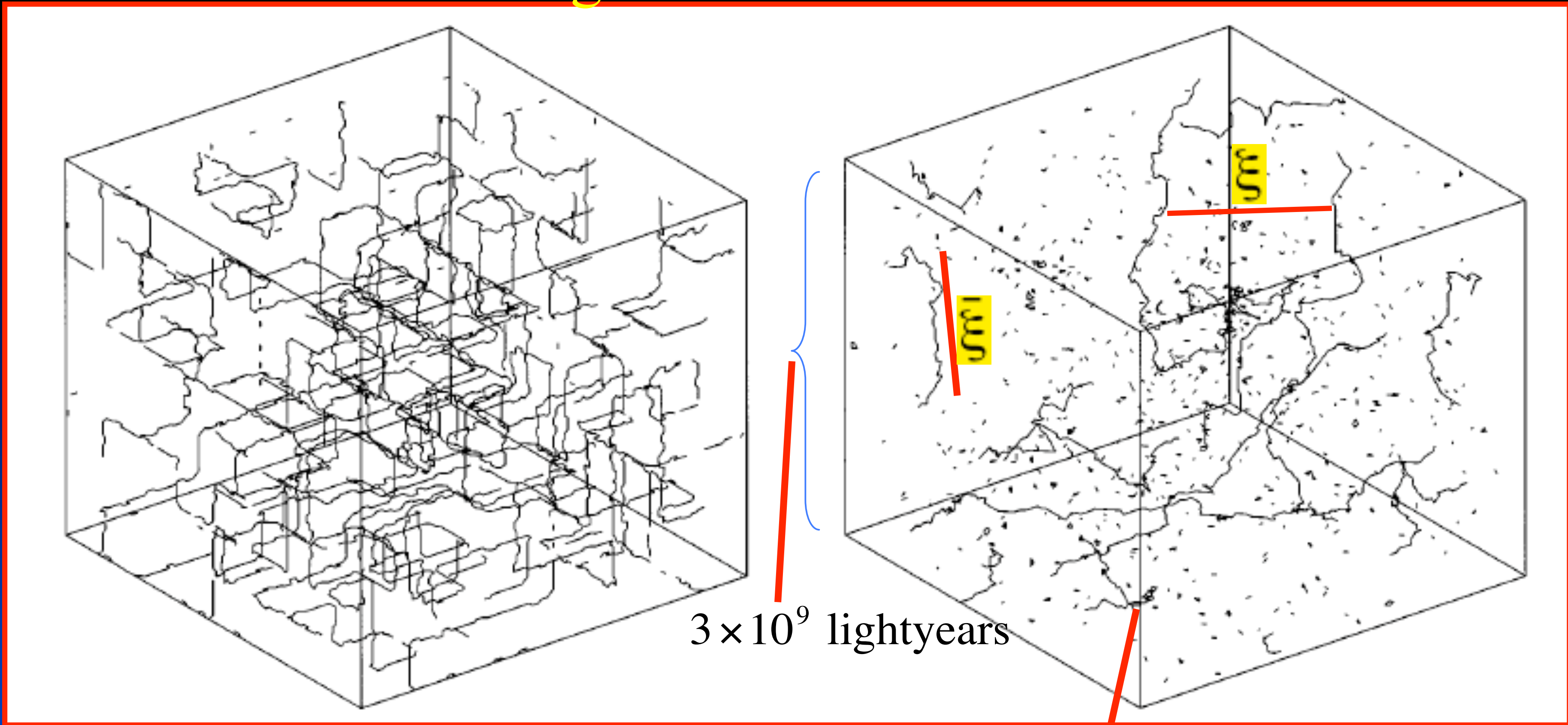


Spontaneously broken $U(1)$ symmetry, has magnetic flux tube solutions (Nielsen-Oleson vortices).

Network would form in early universe phase transitions where $U(1)$ symmetry *becomes* broken. Higgs field roles down the potential in different directions in different regions (Kibble 76).

String tension : μ Dimensionless coupling to gravity : G μ
GUT scale strings : G $\mu \sim 10^{-6}$ -- size of string induced metric perturbations.

Length scales on networks [Vincent et al]



Initial

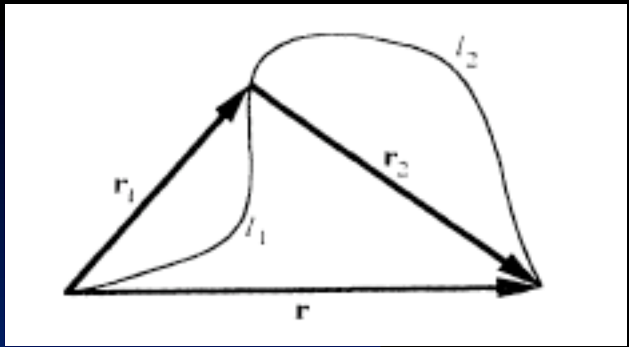
$\bar{\xi}$ - persistence length of string

ξ - interstring distance

Scaling

ζ - small scale structure on network

Analytic modelling of networks [Kibble + many authors]



Approach: take random segment of string of length l and extension r. Write down evolution equations for the probability distribution p[r(l)] due to physical processes.

Probability:

$$\frac{\partial p}{\partial t} = \left(\frac{\partial p}{\partial t}\right)_{\mathrm{str}} + \left(\frac{\partial p}{\partial t}\right)_{\mathrm{GR}} + \left(\frac{\partial p}{\partial t}\right)_{\mathrm{LSI}} + \left(\frac{\partial p}{\partial t}\right)_{\mathrm{loops}},$$

Total length:

$$\frac{\partial L}{\partial t} = \left(\frac{\partial L}{\partial t}\right)_{\mathrm{str}} + \left(\frac{\partial L}{\partial t}\right)_{\mathrm{GR}} + \left(\frac{\partial L}{\partial t}\right)_{\mathrm{loops}}.$$

Gaussian ansatz:

$$p[\mathbf{r}(l)] = \left(\frac{3}{2\pi K(l)}\right)^{3/2} \exp\left(-\frac{3}{2}\frac{\mathbf{r}^2}{K(l)}\right).$$

Defns of length scales:

$$K(l,t) \sim 2\bar{\xi}(t)l, \qquad l \gg t,$$

Brownian

$$\xi^2 = \frac{V}{L}.$$

$$K \approx l^2 - \frac{l^3}{3\zeta}.$$

l << t

Evolution equations -- simplified ignoring expansion

$$\frac{\dot{\xi}}{\xi} = \frac{c}{2\bar{\xi}},$$

$$\frac{\dot{\bar{\xi}}}{\bar{\xi}} = \frac{-\chi\bar{\xi}}{\omega\xi^2} + \frac{I}{2\bar{\xi}},$$

$$\frac{\dot{\zeta}}{\zeta} = \frac{-\chi\zeta}{\xi^2} + \frac{kc}{\bar{\xi}}.$$

c,I -- related to loop production

χ-- related to intercommuting prob

k - related to removing small scales

Scaling solutions: lengths scale with H^{-1}

$$x = \xi/\eta, \quad \bar{x} = \bar{\xi}/\eta, \quad \text{and} \quad z = \zeta/\eta$$

$$\bar{x}_* = \frac{c}{2},$$

$$x_* = \sqrt{\frac{\chi c^2}{2\omega(I-c)}},$$

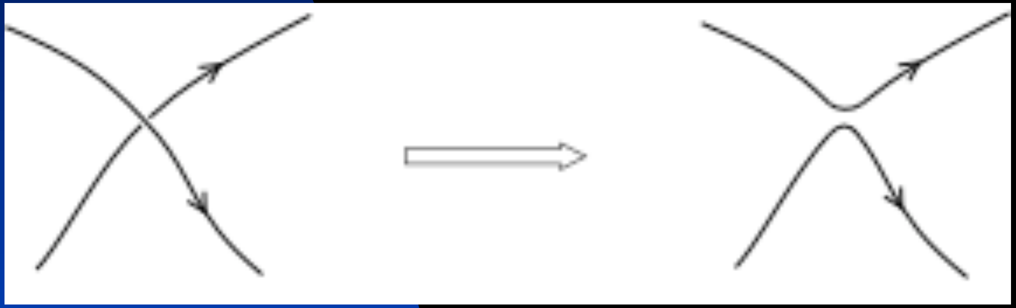
$$z_* = \begin{cases} (2k-1)x_*^2/\chi & \text{if } 2k-1 > 0, \\ 0 & \text{if } 2k-1 \leq 0. \end{cases}$$

Note $\xi \propto \sqrt{\chi}\eta$

Decreases as intercommuting probability decreases

Observational consequences : 1980's and 90's

Single string networks evolve with Nambu-Goto action, decaying primarily by forming loops through intercommutaion and emitting gravitational radiation



For gauge strings, reconnection probability P~1

Scaling solutions are reached where energy density in strings reaches constant fraction of background energy density:

$\rho_{string}/\rho_{rad} \sim 400G\mu$

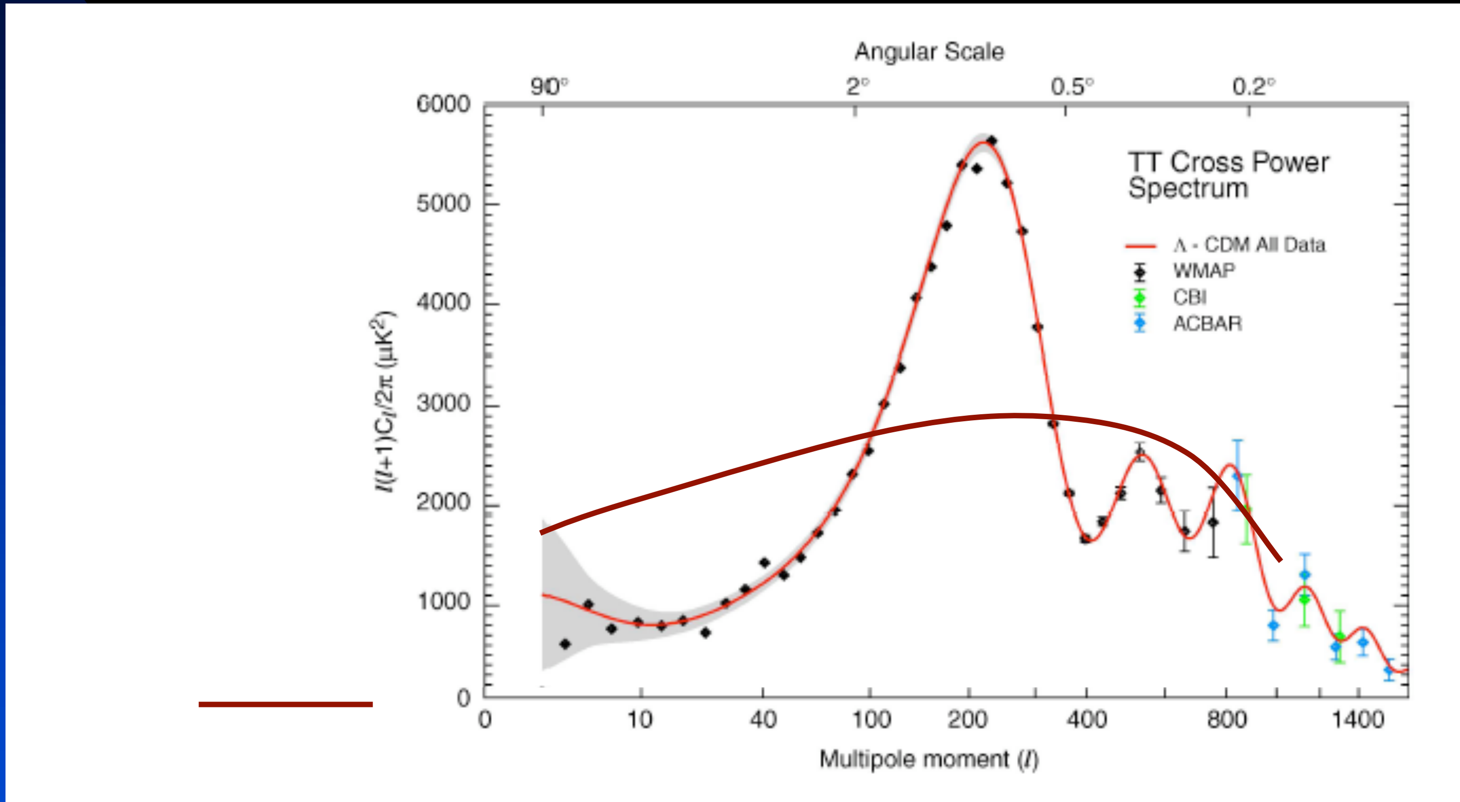
$\rho_{string}/\rho_{mat} \sim 60G\mu$

[Albrecht &Turok, Bennett & Bouchet, Allen & Shellard]

Density increases as P decreases because takes longer for network to lose energy to loops.

Unfortunately for those of us who spent over 12 years working on them -- they didn't do the job!

CMB power spectrum



Acoustic peaks come from temporal coherence. Inflation has it, strings don't. String contribution < 13% implies $G\mu < 10^{-6}$.

E.g. Pogosian et al 2004, Bevis et al 2004.

Pulsar bounds on gravitational wave emission also problematic for GUT scale strings:

Strings produce stochastic GW, $\Omega_{\mathrm{GW}} \sim 10^{-1.5}\, G\mu$.
(Allen '95, Battye, Caldwell, Shellard '97)

Kaspi, Taylor, Ryba '94: $\Omega_{\mathrm{GW}} < 1.2 \times 10^{-7}$, $G\mu < 10^{-5.5}$

Lommen, Backer '01: $\Omega_{\mathrm{GW}} < 4 \times 10^{-9}$, $G\mu < 10^{-7}$

In relevant frequency range ~ 0.1 inverse year

Might need to reduce string tension

In 1980's Fundamental (F) strings excluded as being cosmic strings [Witten 85]:

1. F string tension close to Planck scale (e.g. Heterotic)

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

Cosmic strings deflect light, hence constrained by CMB:

$$G\mu \propto \frac{\delta T}{T} \leq 10^{-6}$$

Consequently, cosmic strings had to be magnetic or electric flux tubes arising in low energy theory

2. Why no F strings of cosmic length?

a. Diluted by any period of inflation as with all defects.

b. They decay ! (Witten 85)

1990’s: along came branes --> new one dimensional objects:

1. Still have F strings
2. D-strings
3. Higher dimensional D-, NS-, M- branes partly wrapped on compact cycles with only one non-compact dimension left.
4. Large compact dimensions and large warp factors allow for much lower string tensions.
5. Dualities relate strings and flux tubes, so can consider them as same object in different regions of parameter space.

What do they imply for cosmic strings?

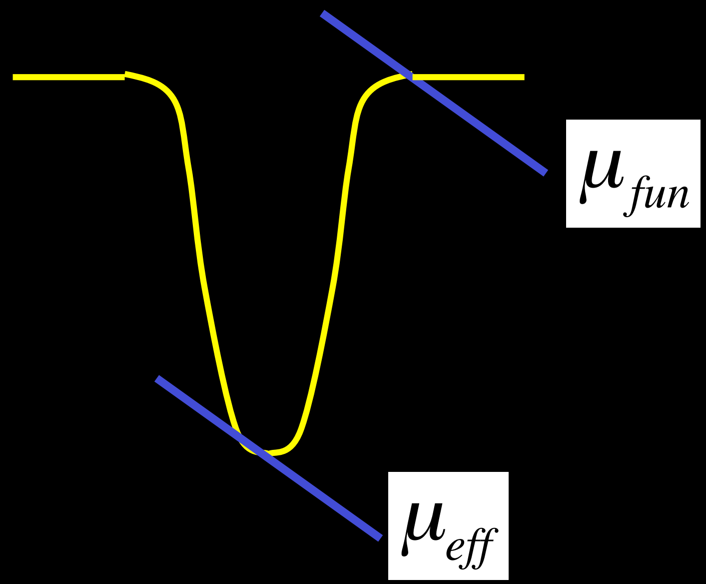
Ex: String tension reduced in “exotic” compactifications:

warped compactifications: tension is redshifted by internal warp factors

$$ds^2 = e^{2A(y)}\left(\eta_{\mu\nu}dx^\mu dx^\nu\right) + ds_\perp^2(y)$$

$$UV: \quad e^{2A} \approx 1$$

$$IR: \quad e^{2A} << 1$$



$$\mu_{eff} = \frac{e^{2A(IR)}}{e^{2A(UV)}}\mu_{fun} << \mu_{fun}$$

Strings surviving inflation:

D-brane-antibrane inflation leads to formation of D1 branes in non-compact space [**Burgess et al; Jones, Sarangi &Tye; Stoica & Tye**]

Form strings, not domain walls or monopoles.

$$10^{-11} \leq G\mu \leq 10^{-6}$$

In general for cosmic strings to be cosmologically interesting today we require that they are not too massive (from CMB constraints), are produced after inflation (or survive inflation) and are stable enough to survive until today [**EJC,Myers and Polchinski (2003)**].

What sort of strings? Expect strings in non-compact dimensions where reheating will occur: F1-brane (fundamental IIB string) and D1 brane localised in throat.
[Jones,Stoica & Tye, Dvali & Vilenkin]

D1 branes - defects in tachyon field describing D3-anti D3 annihilation, so produced by Kibble mechanism.

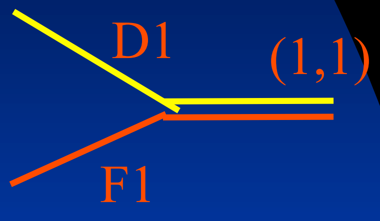
Strings created at end of inflation at bottom of inflationary throat. Remain there because of deep pot well. Eff 4d tensions can be reduced because they depend on warping and 10d tension $\bar{\mu}$

$$\mu = e^{2A(x_\perp)}\bar{\mu}$$

Depending on the model considered these strings can be metastable, with an age comparable to age of the universe

F1-branes and D1-branes --> also (p,q) strings for relatively prime integers p and q. [Harvey & Strominger; Schwarz]

Interpreted as bound states of p F1-branes and q D1-branes [Polchinski;Witten]



Tension in 10d theory:

$$\bar{\mu}_{p,q} = \frac{1}{2\pi\alpha'}\sqrt{(p - Cq)^2 + e^{-2\Phi}q^2}$$

C- RR scalar, Φ - Dilaton -- evaluated at string. Fixed in terms of 3 form fluxes in model.

Tension in KLMT

$$\frac{G^2 e^{4A_0}}{(2\pi\alpha')^2 g_s} = \frac{\delta_H^3}{32\pi C_1^3 N_e^{5/2}}$$

Using: $\delta_H = 1.9 \times 10^{-5}, C_1 = 0.39, N_e = 60$

$$\frac{G^2 e^{4A_0}}{(2\pi\alpha')^2 g_s} = \frac{\delta_H^3}{32\pi C_1^3 N_e^{5/2}}$$

LHS: product of $G\mu$ for F and D string.

$$\delta_H = 1.9\times 10^{-5}\,, C_1 = 0.39\,, N_e = 60$$

Find:

$$\sqrt{G\mu_F\, G\mu_D} \sim 2\times 10^{-10}\,, \qquad \frac{\mu_D}{\mu_F} = \frac{1}{g_s}$$

For $0.1 < g_s < 1$ have $G\mu \sim 10^{-9} - 10^{-10}$

Note: assumes all perturbations from inflation here.

Distinguishing superstrings

1. Intercommuting probability for gauged strings P~1 always ! In other words when two pieces of string cross each other, they reconnect. Not the case for superstrings -- model dependent probability.

2. Existence of new `defects' D-strings allows for existence of new hybrid networks of F and D strings which could have different scaling properties, and distinct observational effects.

What are the probabilities for reconnection in this case?

Jackson, Jones and Polchinski [hep-th/0405229]

The results depend on the type of string, the string coupling, the details of the compactification

For example for F-F reconnection in KKLMMT depending on type of compactification obtain:

Summarise as $P_{FF} = 10^{-3} - 1$; $P_{DD} = 10^{-1} - 1$

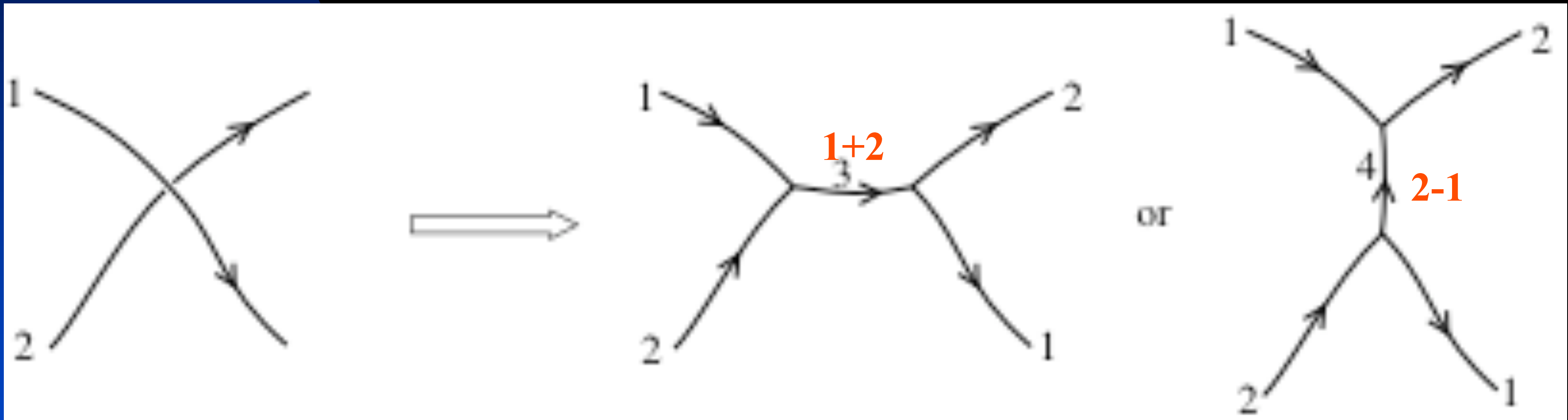
Need to see how they feed into simulations:

Sakellariadou]hep-th/0410234]; Martins [hep-ph/0410326];

Avgoustidis & Shellard - [hep-ph/0410349]

(p,q) string networks -- exciting prospect.

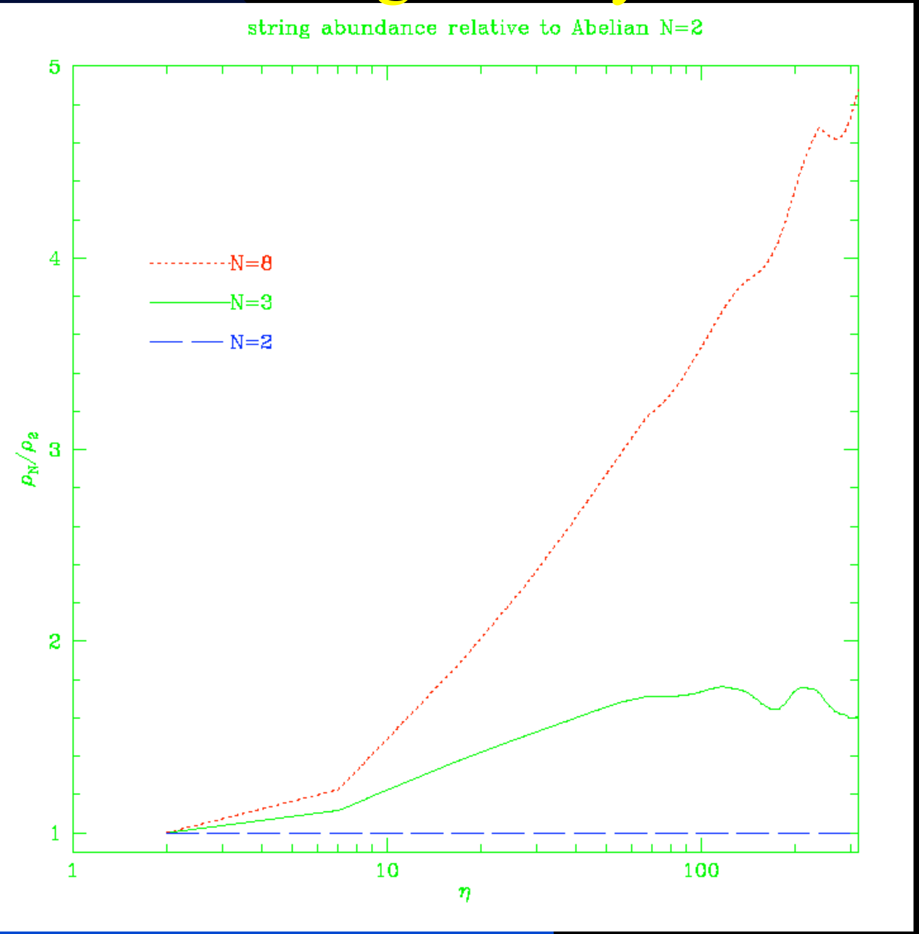
Two strings of different type cross, can not intercommute in general -- produce pair of trilinear vertices connected by segment of string.



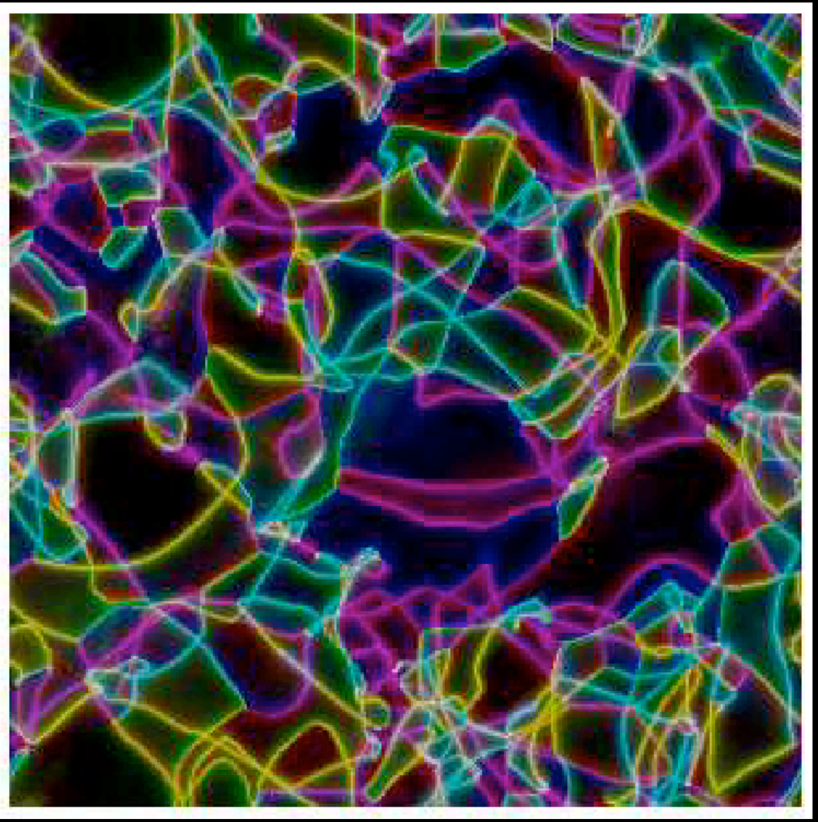
What happens to such a network in an expanding background? Does it scale or freeze out in a local minimum of its PE [Sen]?Then it could lead to a frustrated network scaling as w=-1/3 (p,q) string networks -- mimic with field theory. Under sym breaking G -->K (non-Abelian) find defects that do not intercommute.

K= S_3 and S_8 - [Spergel & Pen 96]

String density



N=3



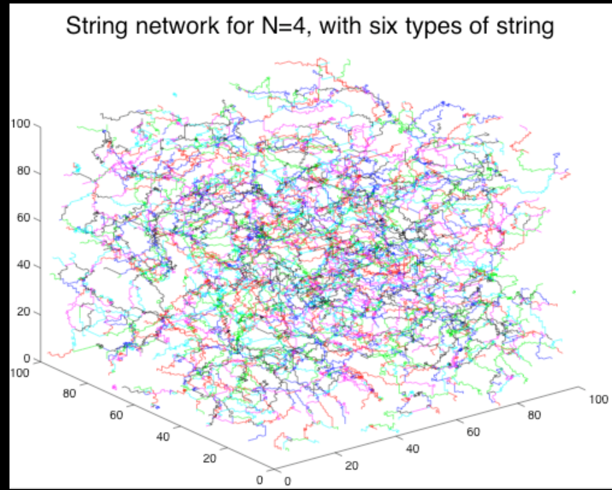
Enters scaling regime for N=3, no evidence for scaling for N=8. Not evolved for long enough?

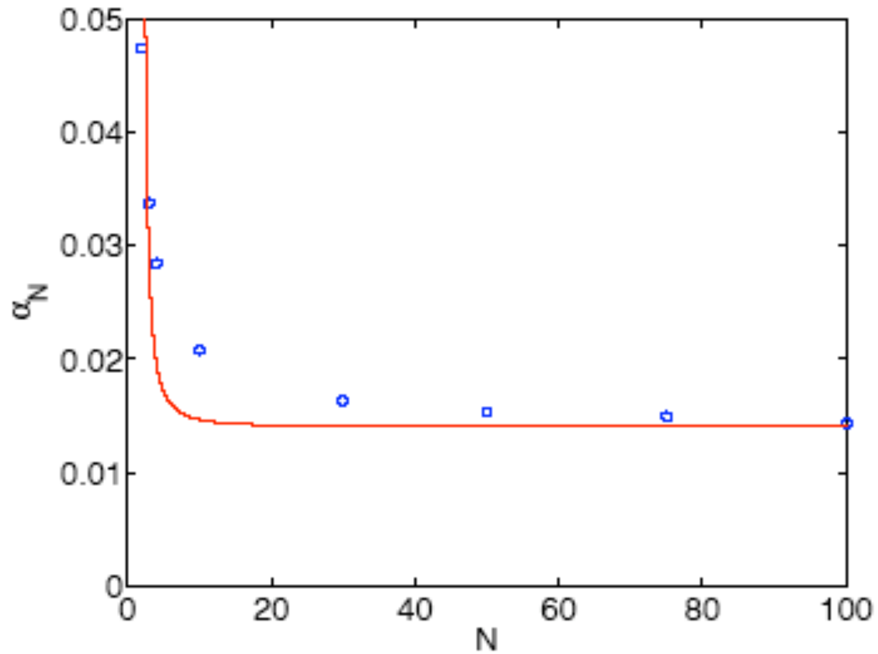
Modelling the case K= S_N

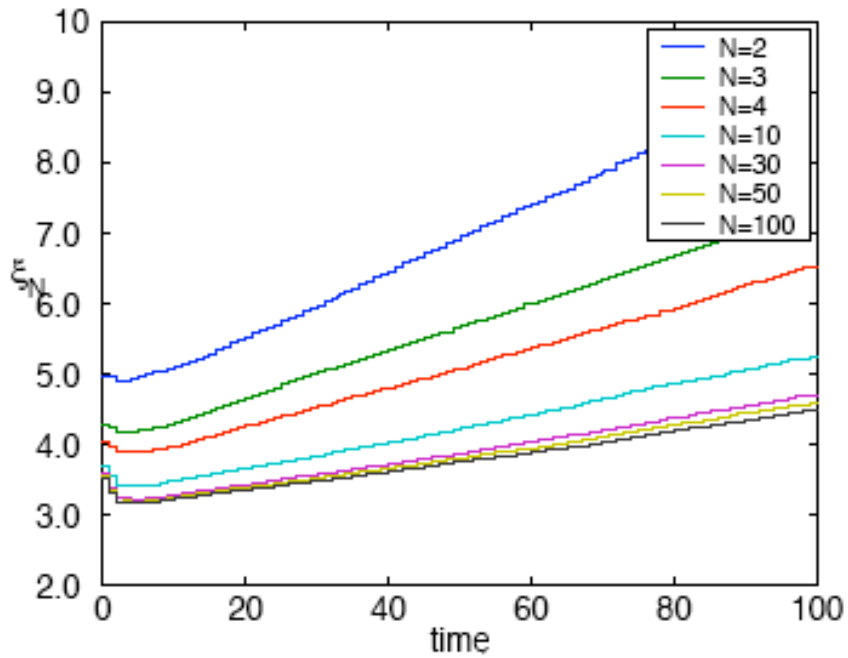
Numerically: Scaling solutions seem to exist for all N :

$$\rho \sim \mu \xi^{-2}$$

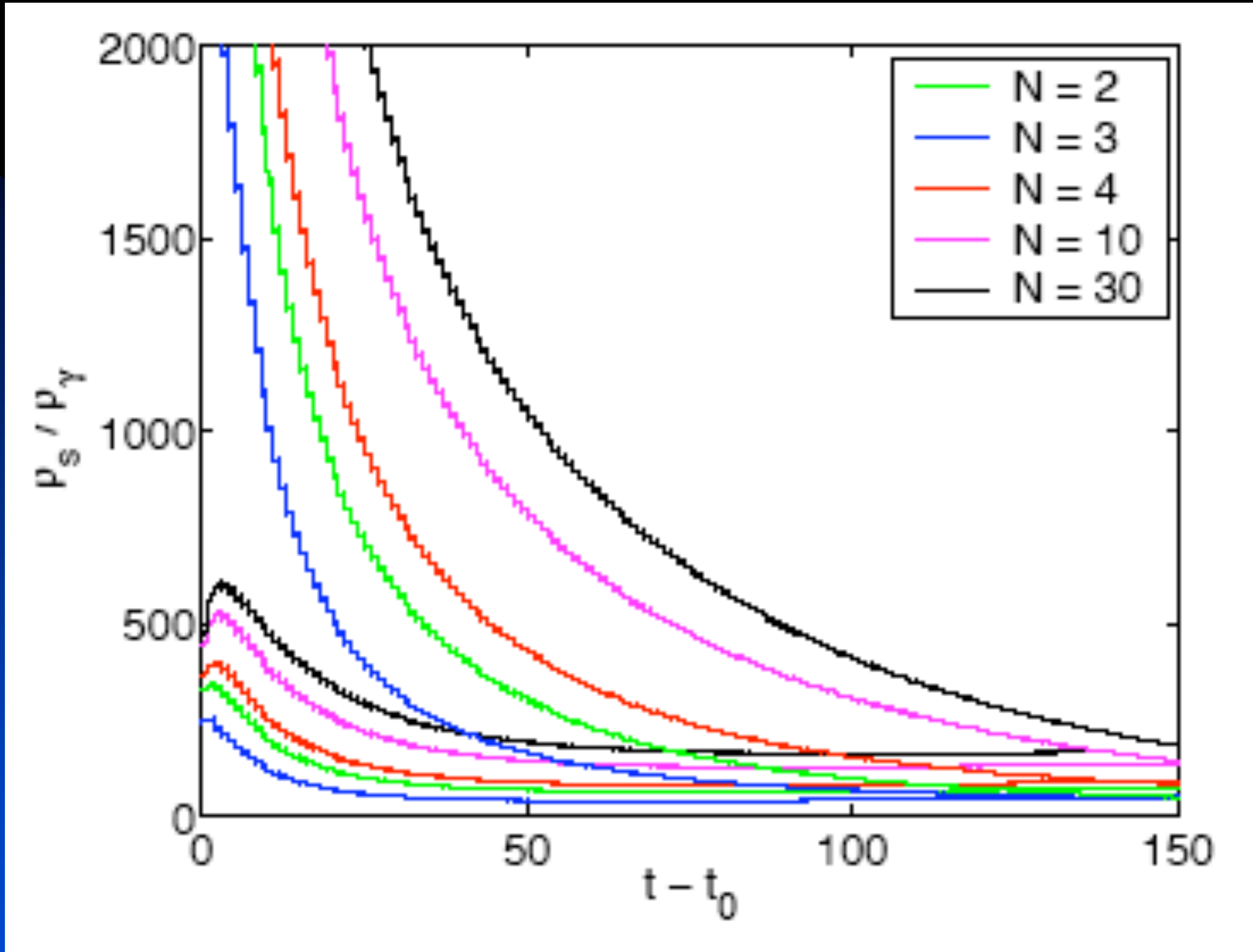
$$\xi_N(t) = \xi_0(N) + \alpha_N\, t$$







[EC and Saffin 05]



Scaling solutions in radiation as a function of N

Other approaches to dynamics of cosmic superstrings.

1. Including multi-tension cosmic superstrings [Tye, Wasserman and Wyman 05].

$$v = HL\left(\frac{1+3\omega}{2c}\right)$$

$$\frac{dn}{dt} + 2Hn = -\frac{cnv}{L} - Pn^2vL$$

Based on velocity dependent 1-scale model [Martins and Shellard 96].

Characteristic Length L, ave velocity v. Loop parameter c, string number density n,

For (p,q) strings they write an equation of the form

$$\dot{n}_\alpha + 2Hn_\alpha = -\frac{c_2 n_\alpha v}{L} - Pn_\alpha^2 vL + FvL\left[\frac{1}{2}\sum_{\beta,\gamma} P_{\alpha\beta\gamma} n_\beta n_\gamma (1+\delta_{\beta\gamma}) - \sum_{\beta,\gamma} P_{\beta\gamma\alpha} n_\gamma n_\alpha (1+\delta_{\gamma\alpha})\right],$$

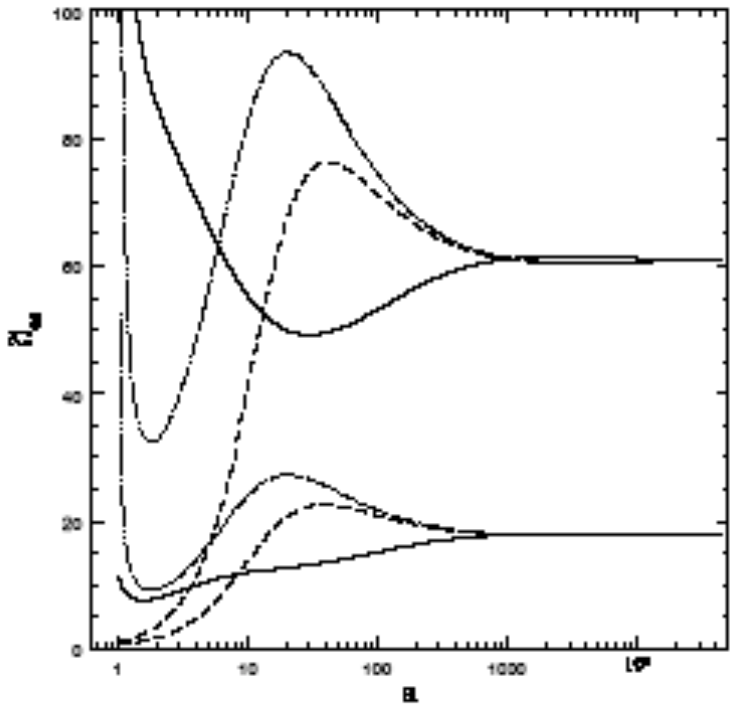
Loops from one type of string

String binding

$$\dot{v} = (1-v^2)\left(-2Hv + \frac{c_2}{L}\right);$$

$$\dot{L} = HL + c_1 v$$

Scaling of cosmic superstrings.



Density of (p,q) cosmic strings.

Density of D1 strings.

Scaling achieved indep of initial conditions, and indep of details of interactions.

Interesting feature: If turn off loop production, still reach scaling. Claim energy is lost through string binding and binding mediated annihilation.

2. Dealing with compact dimensions [Avgoustidis and Shellard 04].

$$ds^2 = N(t)\,dt^2 - a(t)\,d\mathbf{x}^2 - b(t)\,d\mathbf{l}^2$$

Isotropic case: a(t)=b(t) -- no scaling, the strings can't find each other to form loops in D-1 dimensions.

Anisotropic case: b=const, extra dim periodic. If small compared to correlation length, have effective 3D description and vel in compact dim can be taken into account. Act to slow down strings in infinite dim, reduce number of intercommutations and change effective string tension. Network will generally scale in that case but with density reduced compared to usual prediction.

Observational bounds

If network freezes into w=-1/3 state will come to dominate unless initial energy density much lower than considered here. So if (p,q) string networks freeze, exclude those models with the parameters considered here.

Assume they reach scaling: CMB constrains allowed tension

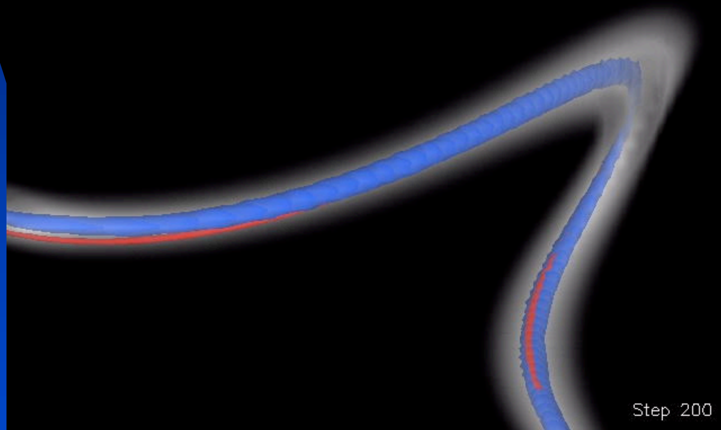
$G\mu \leq 0.7 \times 10^{-6}$ [Landriau & Shellard; Pogosian et al]

CMB power spectrum, gravitational lensing, pulsar timing are all sensitive to this range of values.

If superconducting, loops could act as vortons. [Davis & Shellard]
Speculated to be dark matter candidates - would require inflation in throat occurring near electroweak scale

Any smoking guns?

Possibly through strong non-gaussian nature of stochastic gravitational wave emission from loops which contain kinks and cusps. [Damour & Vilenkin 01 and 04]



[Blanco-Pillado]

Cusp: x’=0 for instant in an oscillation

Kink: x’ discontinuous, occurs every intercommuting -- common

Both produce beams of GW, cusps much more powerful

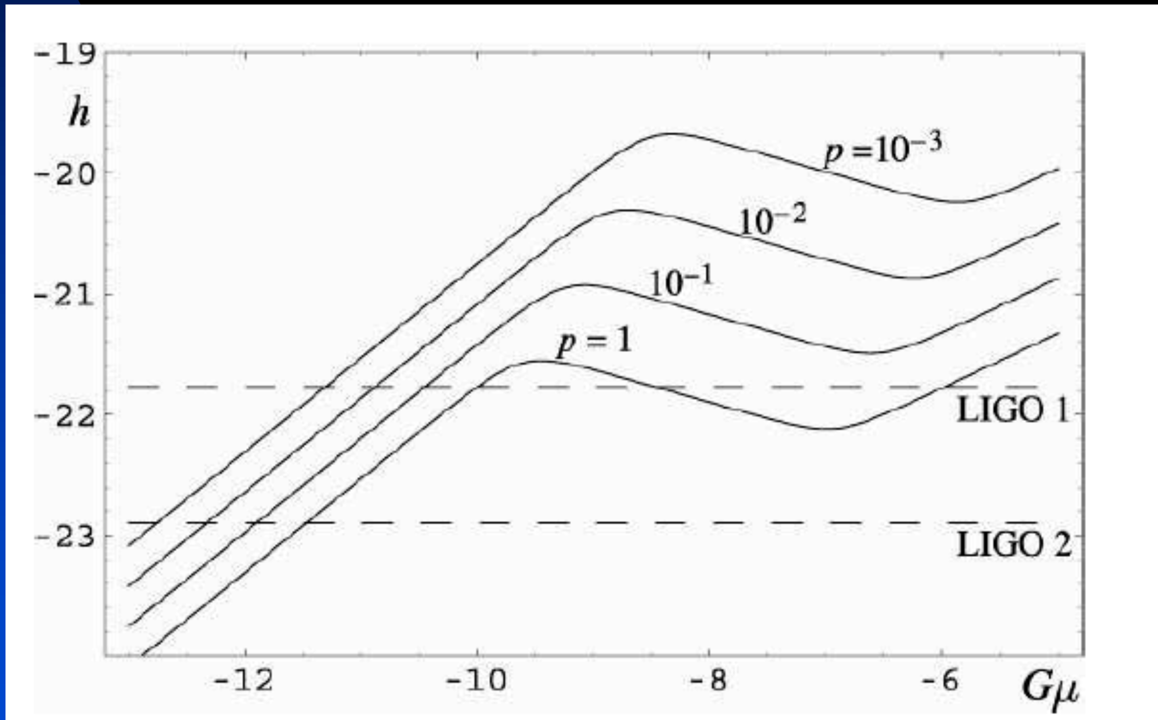
In loop network, if only 10% of loops have cusps, bursts of GW above `confusion' GW noise could be detected by LIGO and LISA for $G\mu \sim 10^{-12}$!

$\log_{10} h$

strain

LIGO I

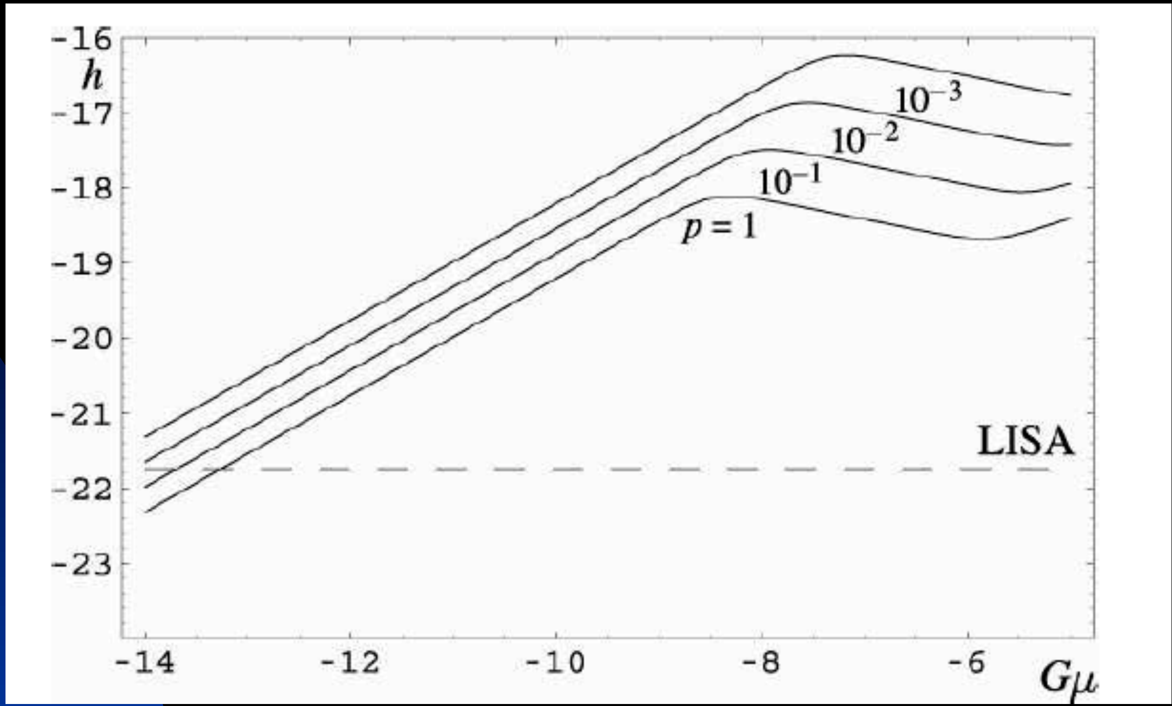
LIGO II



[Damour & Vilenkin 04]

Noise levels

Bursts emitted by cusps in LIGO frequency range f_{ligo}=150 Hz

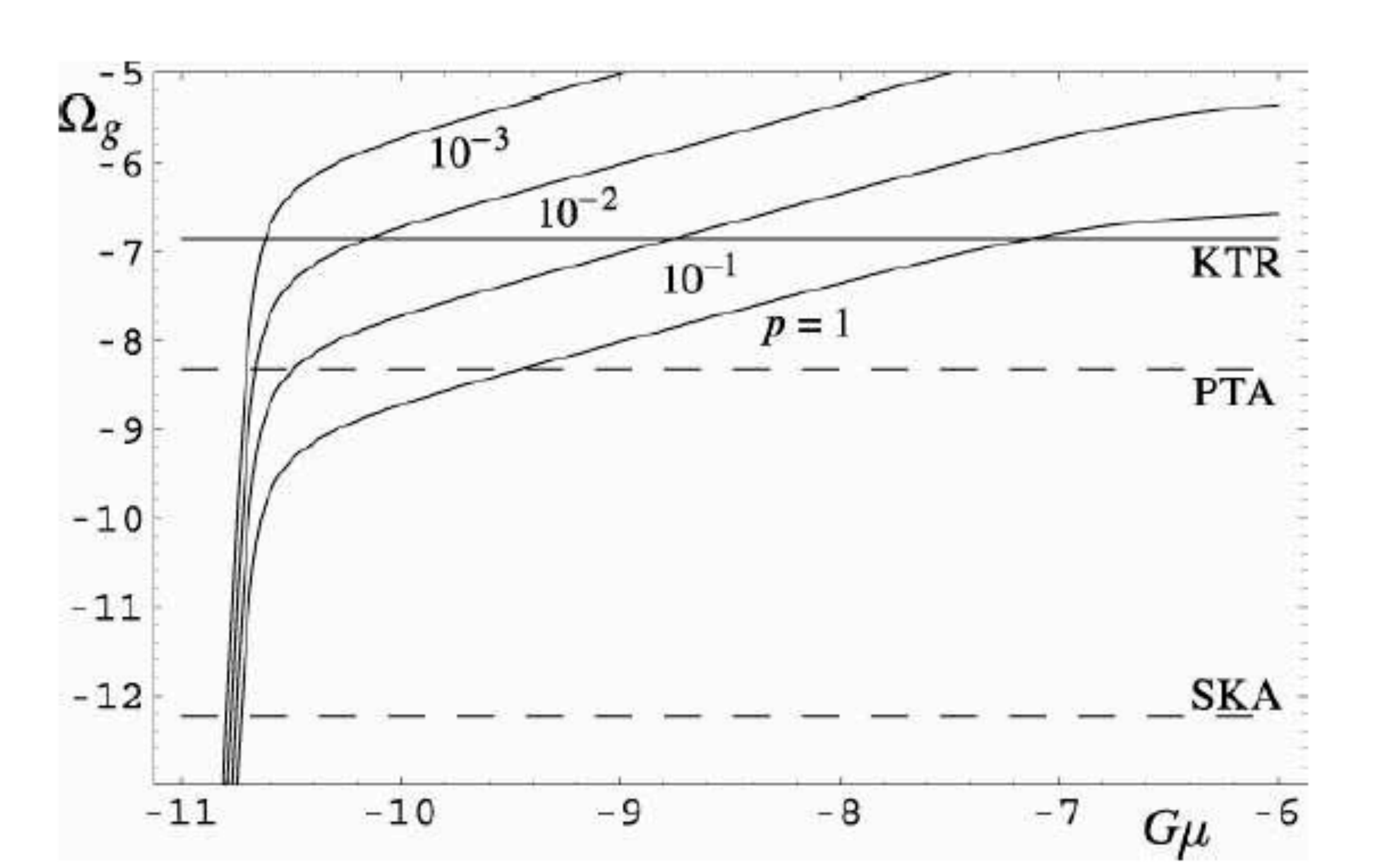


Noise

Bursts emitted by cusps in LISA frequency range f_{lisa}=3.88 mHz

For those cosmic stringers -- the old questions are back including how to estimate the fraction of loops that have cusps on them.

Stochastic GW background from oscillating loops forms nearly Gaussian `confusion noise' made of overlapping loops



8 yr - timing of 2 msec pulsars

17 yr from 3 surveys- pulsar timing array

Square km array

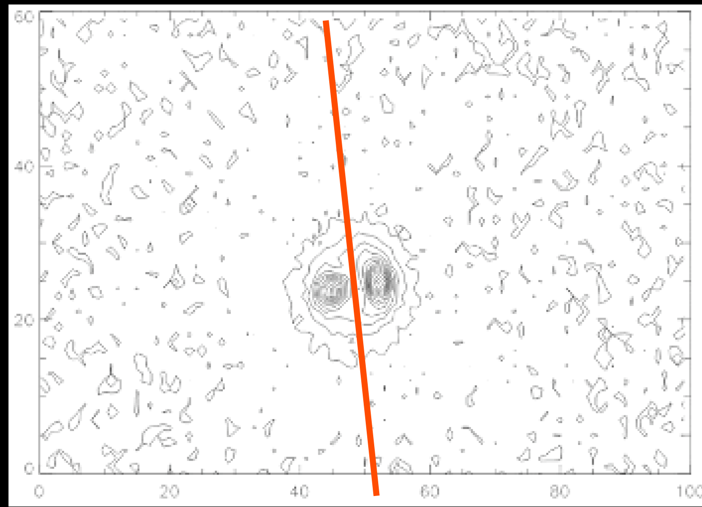
Pulsar timimg freq: f_{par}~0.1/yr: 10 year observation window

Damour & Vilenkin [hep-th/0410222]

And finally: have we already seen some string out there?

a). Grav lens : 2 images of giant elliptical galaxy with large number of lens candidates in vicinity.

$G\mu \geq 4 \times 10^{-7}$



Sazhin et al 03;04

b.) Possible observation of loop, through brightness fluctuations in grav lens system Q0957+561. Two quasars separated by 6”.

$R \sim 0.02$ pc, $D_{loop} \sim 3$kpc

$G\mu \geq 6 \times 10^{-7}$

Large uncertainties of course

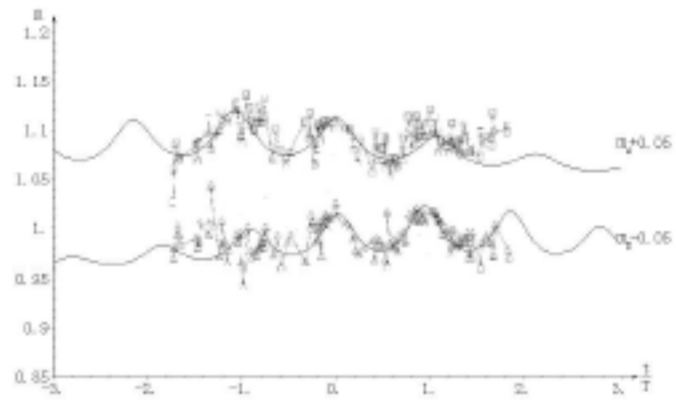


Fig. 5. Oscillations of quasar image magnification predicted by the cosmic string model. Upper and lower curves are shifted up and down by 0.05 and fitted to image A and B brightness records, respectively.

Schild et al 04

Searching for strings in WMAP - Lo &Wright: astro-ph/0503120

Claim no evidence for individual strings at $G\mu \geq 1.07 \times 10^{-5}$ with $v=c/2^{0.5}$

However when searching in region of the reported string sighting, they see evidence of an `edge' at 2σ significance.

Claim would require $v \geq 0.96$!

Planck would be twice as sensitive to strings as WMAP.

Probability of large velocities [with T.Vachaspati]

String soln:

$$x = (a(s+t) + b(s-t))/2$$

$$v = (a' - b')/2$$

$$v^2 = (1 - a' \cdot b')/2 \equiv (1 - \cos\theta)/2$$

Assume vectors a' and b' uniformly distributed on Kibble-Turok sphere

$$v^2 = (1 - \cos\theta)/2$$

$$< v^{2n} > = \frac{1}{2}\int_0^\pi d\theta \sin\theta \frac{(1-\cos\theta)^n}{2^n}$$

$$< v^{2n} > = \frac{1}{n+1}$$

Implies prob for velocity is uniform distribution:

$$P[v^2] = 1 \ , \quad v^2 \in [0,1]$$

and zero otherwise

Therefore the probability for $v^2 > 0.9$ (i.e. $v > 0.95$) is 0.1.

This is in com frame of loops. Need to account for fact loop is moving relative to us really.

Conclusions

If we are lucky with inflation in string models, they may form metastable F and D strings which will survive long enough to be of interest.

If they do, then we should be working out how they would evolve and how we might see them as they might just show up.

This will have to be a combination of analytic and theoretical approaches, and should involve both field theory representations and phenomenolgical model building.

It leaves open the possibility that there is a window on string theory through cosmology!