Searching for cosmic superstrings in Gravitational Waves and the CMB

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1. Brief review of of cosmic strings
2. Cosmic superstrings
3. GW and strings
4. CMB and strings
5. New approaches to cosmic strings from string theory

Particle Physics in the Early Universe

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Fifty years since this amazing paper by Tom Kibble:

J. Phys. A: Math. Gen., Vol. 9, No. 8, 1976. Printed in Great Britain.

Topology of cosmic domains and strings

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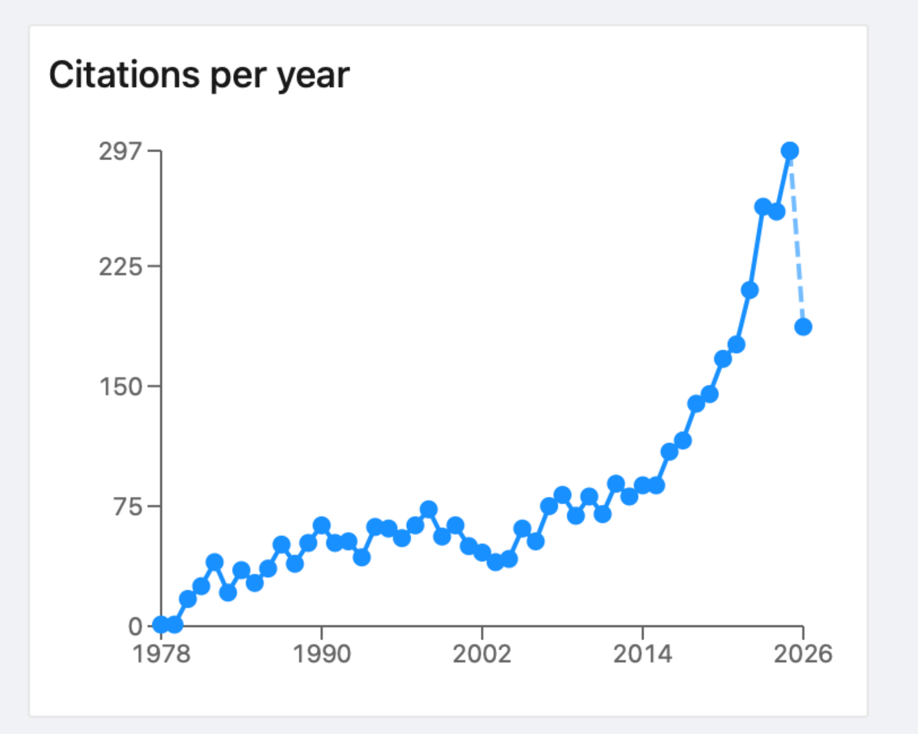
Received 11 March 1976

Abstract. The possible domain structures which can arise in the universe in a spontaneously broken gauge theory are studied. It is shown that the formation of domain walls, strings or monopoles depends on the homotopy groups of the manifold of degenerate vacua. The subsequent evolution of these structures is investigated. It is argued that while theories generating domain walls can probably be eliminated (because of their unacceptable gravitational effects), a cosmic network of strings may well have been formed and may have had important cosmological effects.

Dramatic increase in citations since LIGO discovery of GWs - over 4000 citations.



Topological defects are predicted by many field theory models and may have formed at symmetry breaking transitions in the early universe.

Cosmic strings stretch across cosmological distances, are extremely thin yet so massive as to have noticeable gravitational effects.

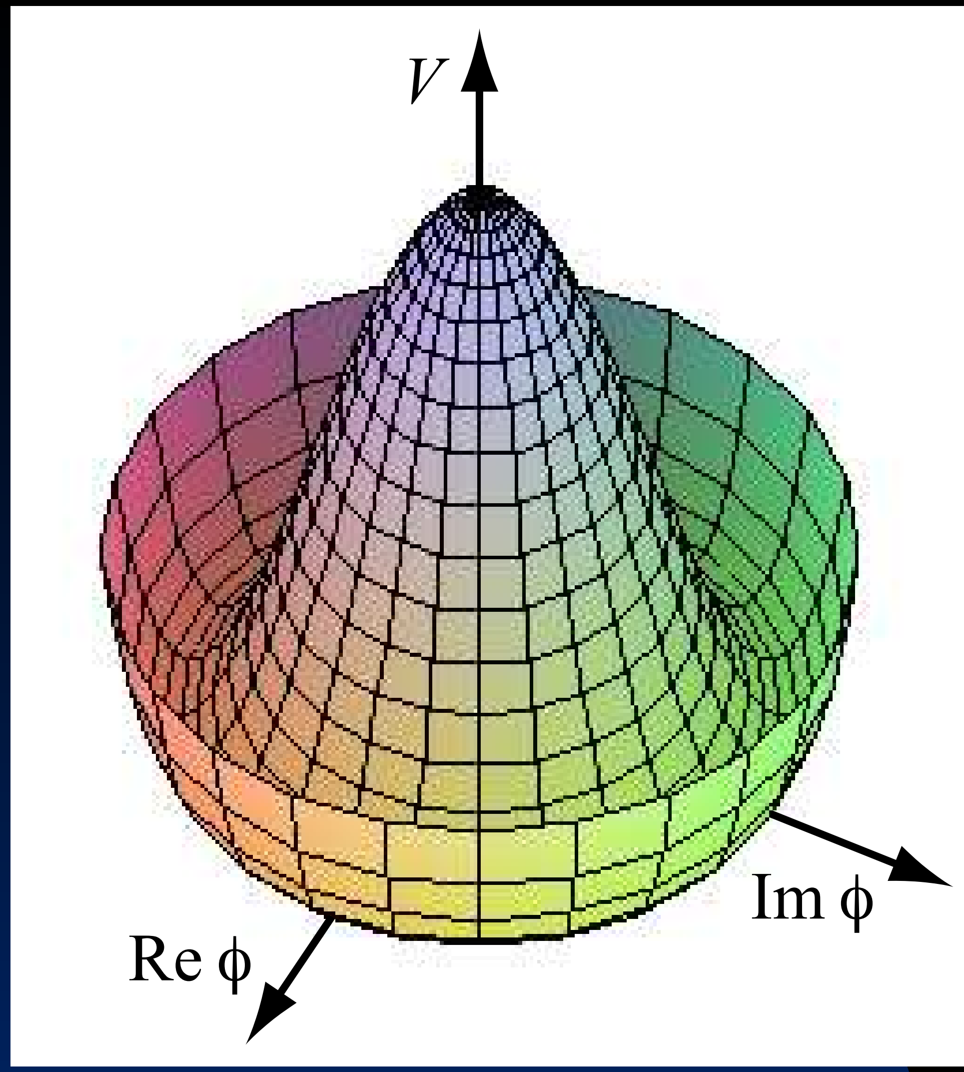
Being field theory objects they are also likely to leave signals through the interaction of the fields with matter.

As we go up in energy, there appears to be a unification of the interactions of nature, and many believe that at the GUT scale we can unify the strong and ewk interactions.

At such a scale a large symmetry group G is spontaneously broken down to the symmetry group of the standard model SU(3)xSU(2)xU(1).

Such spontaneously broken gauge theories often exhibit stable topological defects - domain walls, cosmic strings or monopoles [ex: Kibble, Lazarides & Shafi 1982, Jeannerot et al 2003].

Simplest model of cosmic strings arise in a U(1) gauge theory with a complex scalar field interacting with the emg field



$$V = \tfrac{1}{2}\lambda(\phi^*\phi - \tfrac{1}{2}\eta^2)^2,$$

$$L = D_\mu\phi^* D^\mu\phi - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} - V(\phi).$$

where

$$D_\mu\phi = \partial_\mu\phi + ieA_\mu\phi$$
$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu,$$

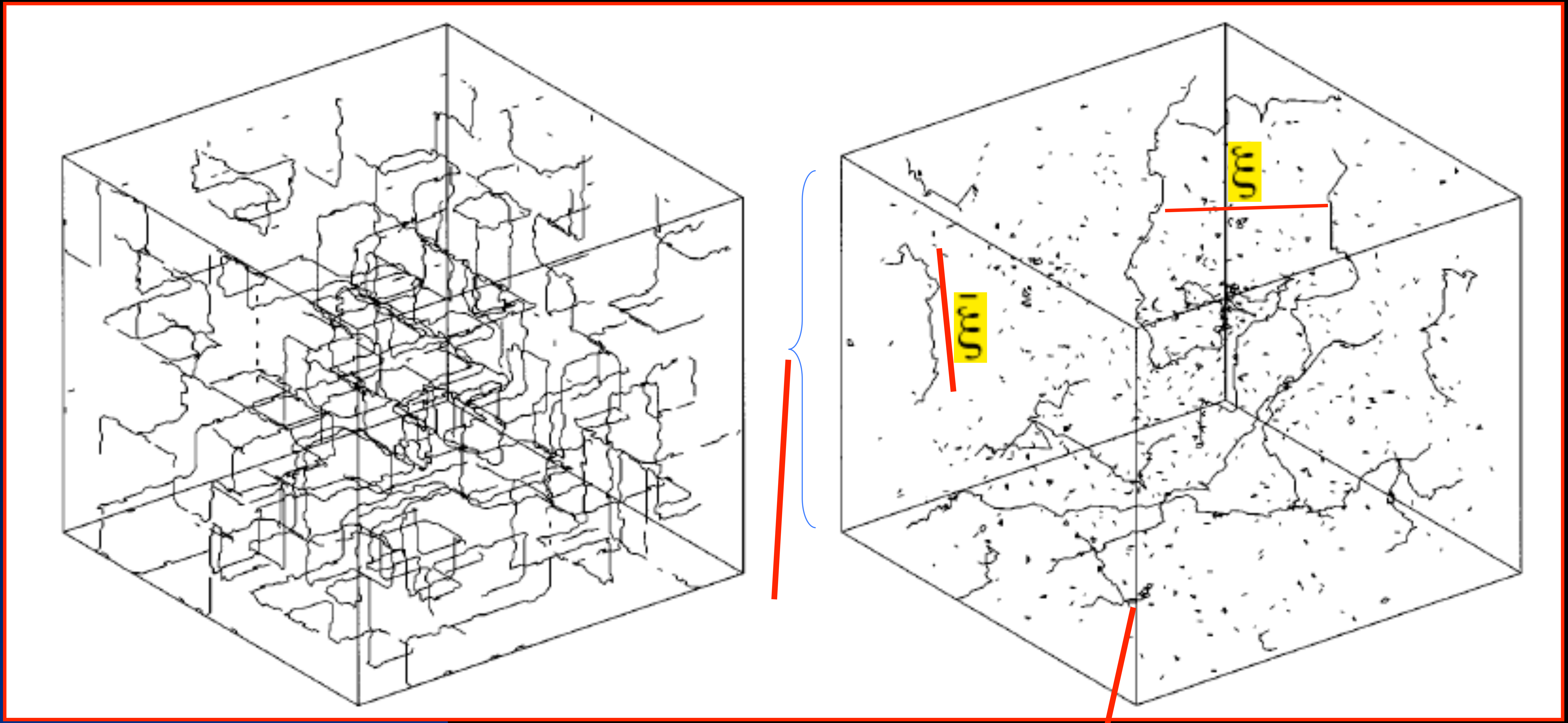
Model is inv under local U(1) gauge transformations

$$\phi(x) \rightarrow \phi(x)e^{i\alpha(x)},$$
$$A_\mu(x) \rightarrow A_\mu(x) - \frac{1}{e}\partial_\mu\alpha(x).$$

High T - large fluctuations of ϕ around zero average. As T decreases below $T_C \sim O(\eta)$, ϕ begins to settle into valley of its potential. At T=0, expect $\langle \phi \rangle = \eta e^{i\alpha}$ with arbitrary phase angle α. Hence the theory exhibits SSB below T_C, with ϕ randomly choosing a phase angle. This has to occur in widely separated regions so ϕ may be frustrated from reaching the minimum everywhere. In particular if α varies by 2π then somewhere within that loop ϕ must vanish, the locus of such points is a cosmic string.

Length scales on networks

[Vincent et al]



Initial

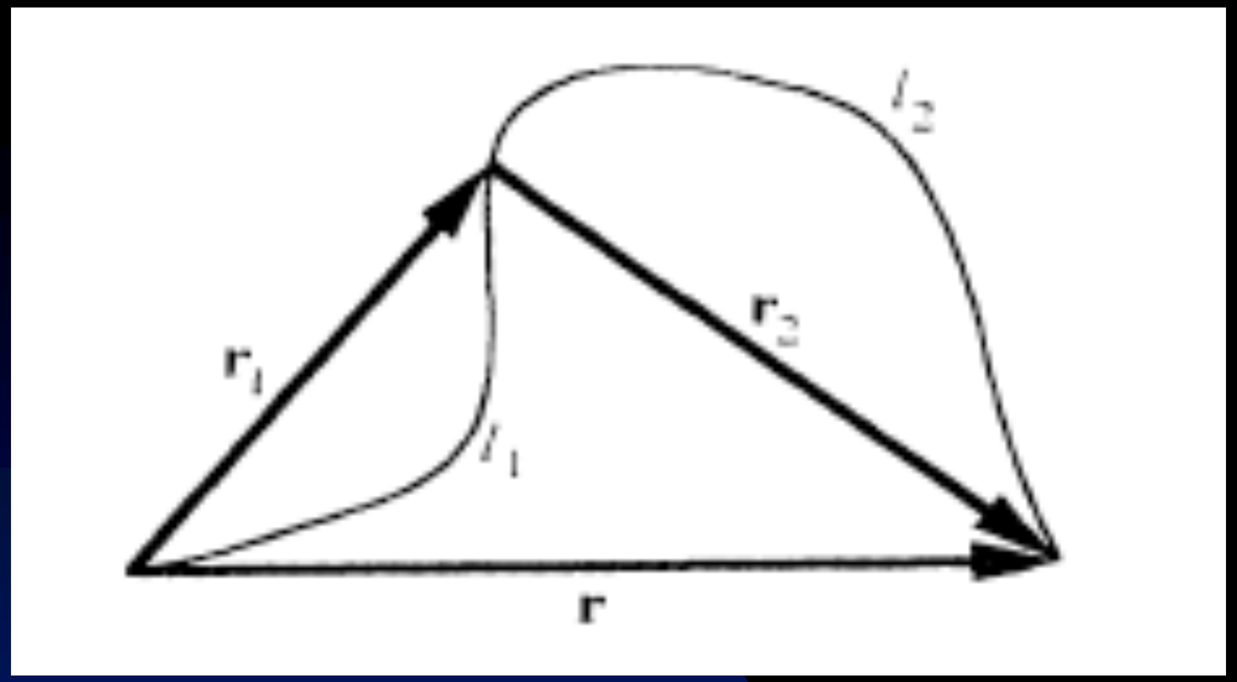
Scaling

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

ξ - interstring distance

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}

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

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

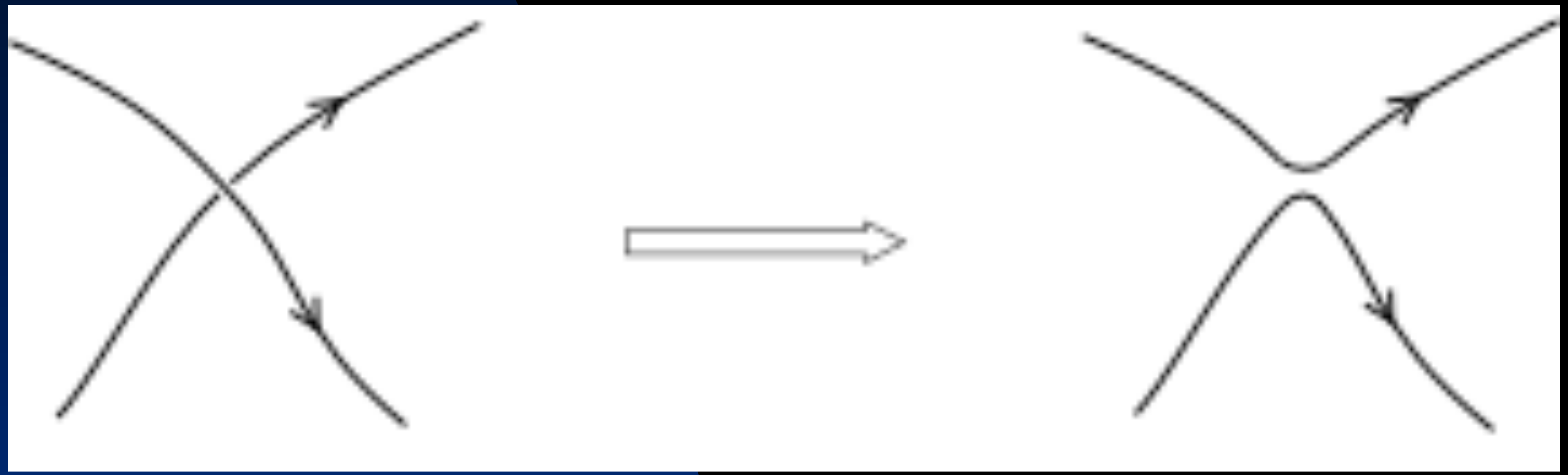
$$x_* = \sqrt{\frac{\chi c^2}{2\,\omega(I-c)}},$$

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

Three scales !

Observational consequences : 1980's and 90's

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



For gauge strings, reconnection probability P~1

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

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

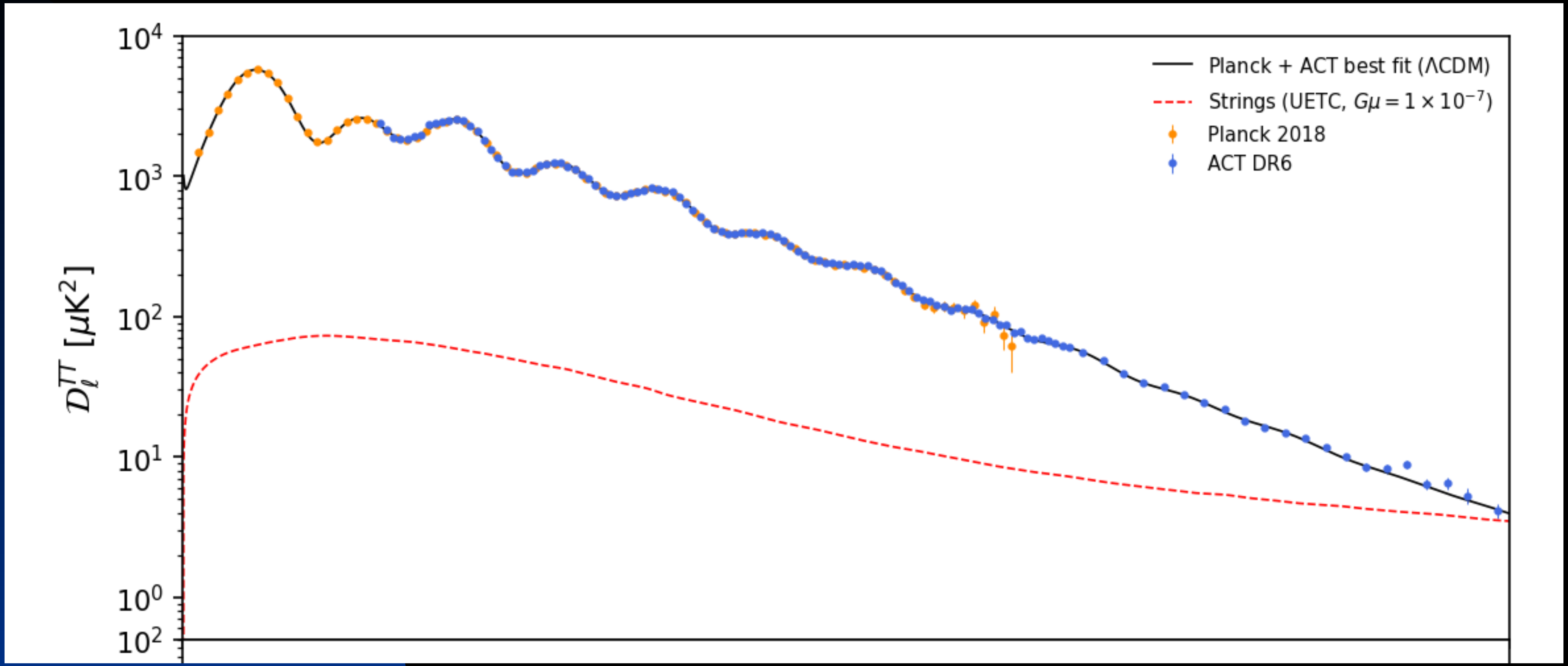
$$\rho_{string}/\rho_{mat} \sim 60G\mu$$

[Albrecht &Turok; Bennett & Bouchet; Allen & Shellard …]

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

Unfortunately cosmic strings didn't do the full job! [Albrecht et al 1997]

CMB power spectrum



Avgoustidis et al 2026

Acoustic peaks come from temporal coherence. Inflation has it, strings don't. E.g. Pogosian et al 2004, Bevis et al (2004, 2007, 2010), Lizarrago et al 2017, Avgoustidis et al 2026 - find Gμ ~3.66 x 10^{-8} for NG strings

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.

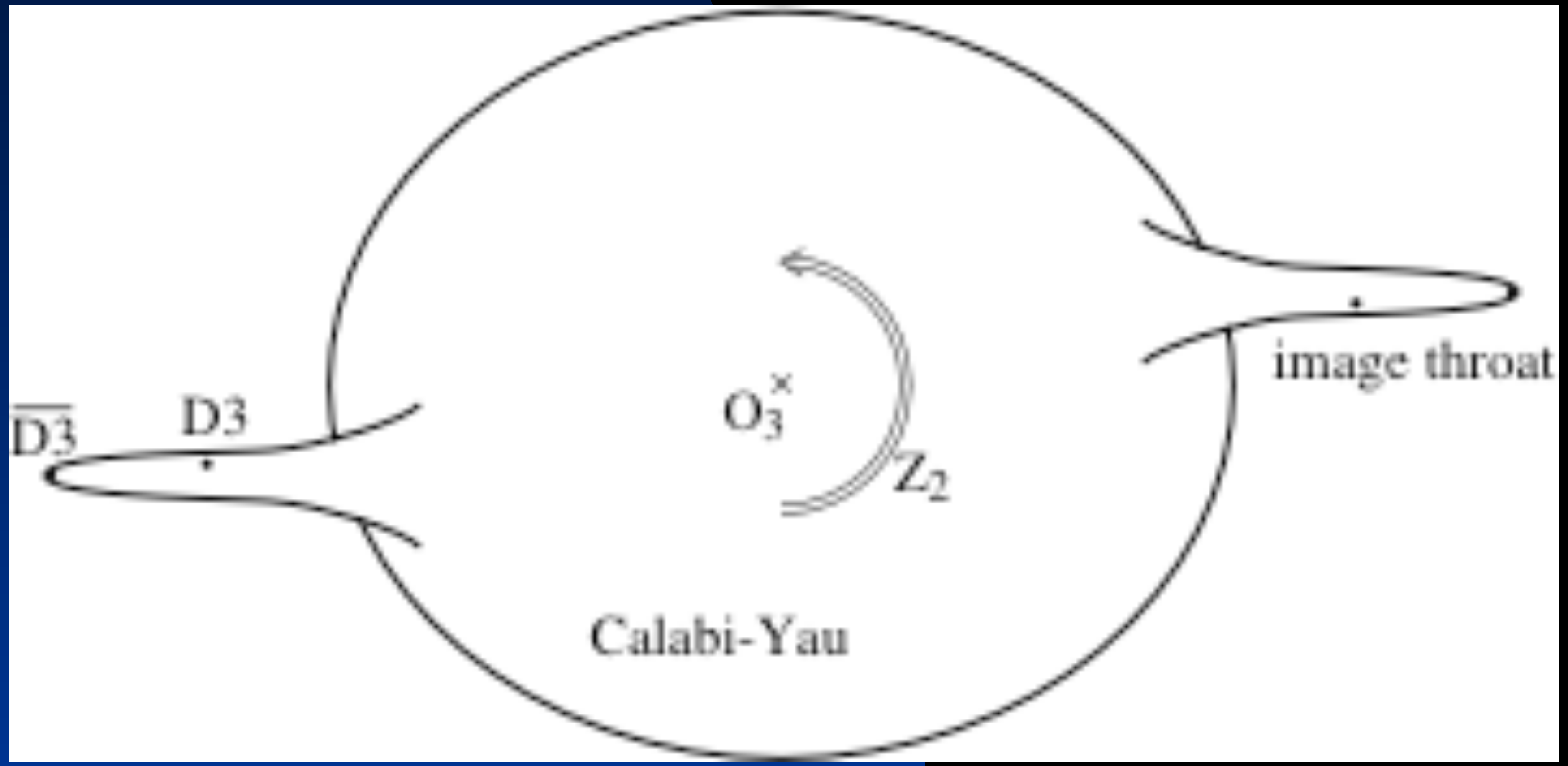
What do they imply for cosmic strings?

Strings in KLMT © model -- an example.

[Kachru, Kallosh, Linde, Maldacena, McAllister & Trivedi 03]

IIB string theory on CY manifold, orientifolded by Z_2 sym with isolated fixed points, become O3 planes. Warped metric:

$$ds^2 = e^{2A(x_\perp)}\eta_{\mu\nu}dx^\mu dx^\nu + ds_\perp^2 \; .$$



Inflaton: sep of D3 and anti D3 in throat.

Annihilation in region of large grav redshift,

$$min\{e^{A(x_\perp)}\} = e^{A_0} \ll 1$$

Redshift in throat important. Inflation scale and string tension, as measured by a 10 dim inertial observer, are set by string physics -- close to the four-dimensional Planck scale. Corresponding energy scales as measured by a 4 dim obs are suppressed by a factor of e^{A_0}

Strings surviving inflation:

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

Can lead to very small tensions $G\mu < 10^{-10}$

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. Depending on the model, if the CY space has sufficiently warped throat regions there can be fundamental F strings, D1 branes or combinations of (p,q) strings. [**Dvali and Vilenkin (2004); EJC,Myers and Polchinski (2004)**].

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.

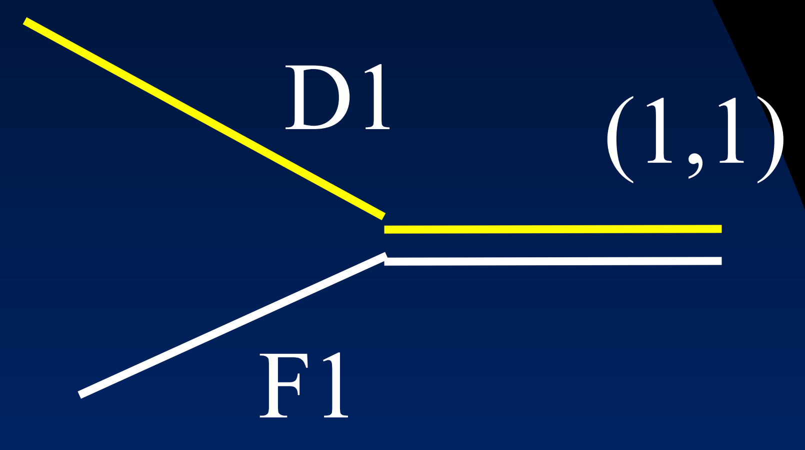
Strings created at end of inflation at bottom of inflationary throat. Remain there because of deep pot well. Eff 4d tensions depend on warping and 10d tension $\bar{\mu}$

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

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:

$$\mu_i \equiv \mu_{(p_i,q_i)} = \frac{\mu_F}{g_s}\sqrt{p_i^2 g_s^2 + q_i^2}$$

Modelling strings with junctions -- solve the modified Nambu-Goto equations

EJC, Kibble and Steer: hep-th/0601153, hep-th/0611243

EJC, Firouzjahi, Kibble and Steer: arXiv: 0712.0808

Distinguishing cosmic 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 [Jackson et al 04].

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

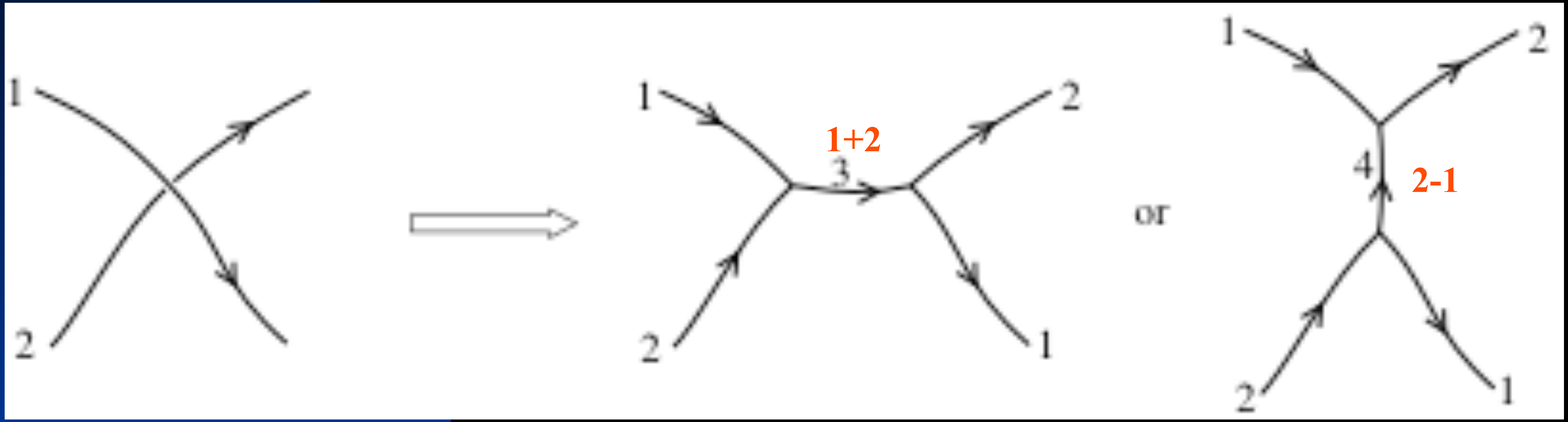
$$P_{\rm FF}({\rm A}) \sim \frac{100 g_s^{1/2}}{M^{3/2} \ln^{3/2}(1+g_s M)},$$

$$P_{\rm FF}({\rm B}) \sim \frac{1.5 g_s^2}{\ln^{3/2}(1+g_s M)},$$

$$P_{\rm FF}({\rm C}) \sim 0.5 g_s^2 \left[\frac{\pi n}{\ln(g_s/16\pi G\mu_{\rm D}\delta)}\right]^{n/2}$$

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

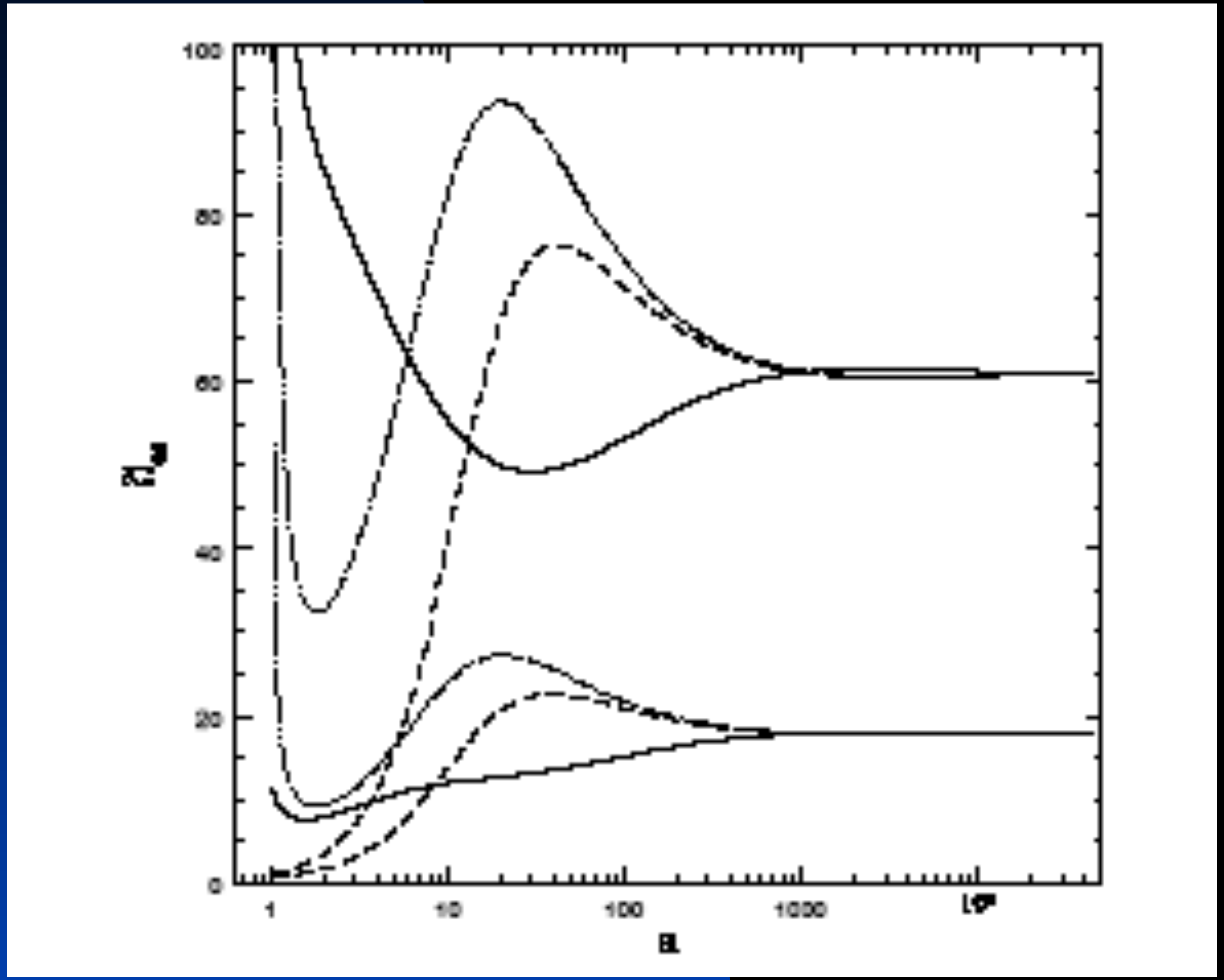
Two strings of different type cross, can not intercommute in general -- produce pair of trilinear vertices connected by segment of string.



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

Including multi-tension cosmic superstrings

[Tye et al 05, Avgoustidis and Shellard 07, Urrestilla and Vilenkin 07, Avgoustidis and EJC 10, Rybak et al 18].



Density of (p,q) cosmic strings.

Density of D1 strings.

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

Modelling a network —single one-scale model: (Kibble + many...)

Infinite string density $\rho = \frac{\mu}{L^2}$

$$\dot{\rho} = -2\frac{\dot{a}}{a}\rho - \frac{\rho}{L}$$

Expansion Loss to loops

Correlation length $L(t) = \xi(t)t, \quad a(t) \sim t^{\beta}$ Scale factor

$$\frac{\dot{\xi}}{\xi} = \frac{1}{2t}\left(2(\beta - 1) + \frac{1}{\xi}\right)$$

Scaling solution $\xi = [2(1-\beta)]^{-1}.$

Need this to understand the behaviour with the CMB.

Velocity dependent model: (Shellard and Martin)

$$\dot{\rho} = -2\frac{\dot{a}}{a}(1+v^2)\rho - \frac{\tilde{c}\,v\rho}{L},$$

RMS vel of segments

$$\dot{v} = (1-v^2)\left(\frac{k}{L} - 2\frac{\dot{a}}{a}v\right)$$

Curvature type term encoding small scale structure

$$k = \frac{2\sqrt{2}}{\pi}\left(\frac{1-8v^6}{1+8v^6}\right)$$

$$\xi^2 = \frac{k(k+\tilde{c})}{4\beta(1-\beta)}, \qquad v^2 = \frac{k(1-\beta)}{\beta(k+\tilde{c})}$$

Both correlation length and velocity scale

Multi tension string network:(Avgoustidis & Shellard 08, Avgoustidis & EJC 10, Rybak et al 18)

$$\dot{\rho}_i = -2\frac{\dot{a}}{a}(1+v_i^2)\rho_i - \frac{c_i v_i \rho_i}{L_i} - \sum_{a,k} \frac{d^k_{ia}\bar{v}_{ia}\mu_i \ell^k_{ia}(t)}{L_a^2 L_i^2} + \sum_{b,\, a\leq b} \frac{d^i_{ab}\bar{v}_{ab}\mu_i \ell^i_{ab}(t)}{L_a^2 L_b^2}$$

Expansion

Loop of `i' string

Segment of `i' collides with `a' to form segment `k' -- removes energy

Segment of `i' forms from collision of `a' and `b' -- adds energy

$$\dot{v}_i = (1-v_i^2)\left[\frac{k_i}{L_i} - 2\frac{\dot{a}}{a}v_i + \sum_{b,\, a\leq b} b^i_{ab}\frac{\bar{v}_{ab}}{v_i}\frac{(\mu_a+\mu_b-\mu_i)}{\mu_i}\frac{\ell^i_{ab}(t)L_i^2}{L_a^2 L_b^2}\right]$$

$$v_{ab} = \sqrt{v_a^2 + v_b^2}$$

$$\mu_i \equiv \mu_{(p_i,q_i)} = \frac{\mu_F}{g_s}\sqrt{p_i^2 g_s^2 + q_i^2}$$

$$\rho_i = \frac{\mu_i}{L_i^2}$$

`k' segment length

$$\ell^k_{ij} = \frac{L_i L_j}{L_i + L_j}$$

d^k_{ia} incorporate the probabilities of intercommuting and the kinetic constraints. They have a strong dependence on the string coupling g_s

Cosmic superstrings and GWs

[Avgoustidis, EJC, Moss and Raidal - 2503.10361]

For earlier work see: Afzal et al (NANOGrav) [2306.16219], Ellis et al [2306.17147], Figueroa et al [2307.02399]

The question we wanted to ask was are there any new signals that appear by keeping the full set of strings that could be there, F strings, D strings, FD strings etc…?

In particular allowing for their different probabilities of intercommution.

VOS equations for multiple strings [Avgoustidis & EJC (2010), Avgoustidis & Shellard (2008)]

$$\frac{\mathrm{d}L_i}{\mathrm{d}t} = H(t)L_i(1+v_i^2) + \frac{1}{2}\tilde{c}_i v_i + \frac{1}{2}\left(\sum_{a,k} \tilde{d}^k_{ia}\frac{v_{ia}\ell_{ia}}{L_i^2 L_a^2} - \sum_{b,a\le b}\tilde{d}^i_{ab}\frac{v_{ab}\ell_{ab}}{L_a^2 L_b^2}\right)L_i^3 \,,$$

$$\frac{\mathrm{d}v_i}{\mathrm{d}t} = (1-v_i^2)\left[\frac{k(v_i)}{L_i} - 2H(t)v_i + B\sum_{b,a\le b}\tilde{d}^i_{ab}\frac{v_{ab}}{v_i}\frac{\mu_a+\mu_b+\mu_i}{\mu_i}\frac{\ell_{ab}L_i^2}{L_a^2 L_b^2}\right] \,,$$

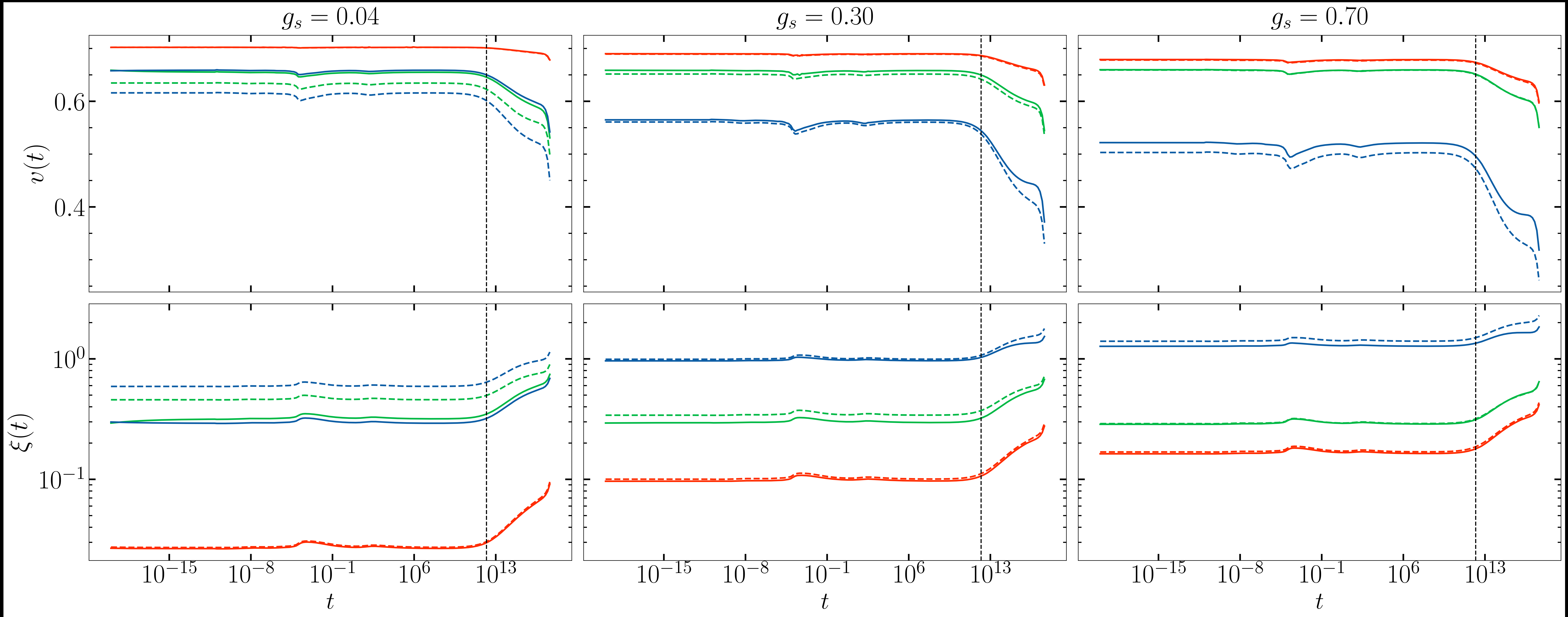
with

$$k(v_i) = \frac{2\sqrt{2}}{\pi}(1-v_i^2)(1+2\sqrt{2}v_i^3)\frac{1-8v_i^6}{1+8v_i^6}$$

and intercommuting prob

$$\tilde{c}_i = \tilde{c}\times\mathcal{P}_i^{1/3} \quad , \quad \tilde{d}_{ij} = \mathcal{P}_{ij}^{1/3}$$

Depend on 3 quantities, string coupling, fundamental string tension and size of compact dimension



Correlation lengths (L(t) = ξ(t) t) and velocities of F (Red), D (Green) and FD-junctions (Blue) for both 7 string (solid) and 3 string (dashed) models at different values of the string coupling. Vertical dashed line marks matter-radiation equality. Note no evidence of scaling in matter dominated era.

Long strings intercommute and form loops. A big question in cosmic strings involves the distribution of the loops. Because the fundamental string has the smallest correlation length, it dominates the overall string density ($\rho=\mu\, t^2/\xi^2$). This has led groups to model the overall network as a single species with a reduced probability of intercommuting.

Sousa and Avelino [1606.05585] showed that their are characteristic features in the GW emission from cosmic superstring networks that can not be captured by a single string species. In particular if the loops chopped from the network are small (of order the back reaction scale) a distinct multi-peaked signature in the spectrum is seen at low frequencies, just below the nano-Hz region. They considered 3 string species (F, D and FD). We considered 7 species to determine the influence of the higher mass strings.

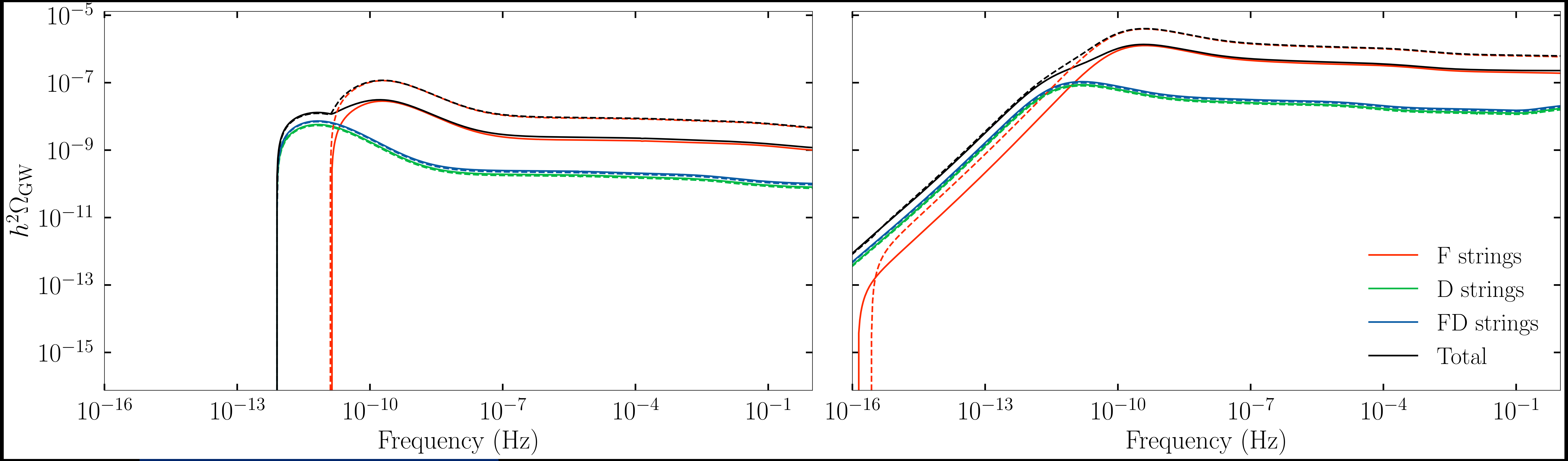
$$(p_i, q_i) = (1,0), (0,1), (1,1), (2,1), (1,2), (3,1), (1,3)$$

where $$\mu_i \equiv \mu_{(p_i,q_i)} = \frac{\mu_F}{g_s}\sqrt{p_i^2 g_s^2 + q_i^2}$$

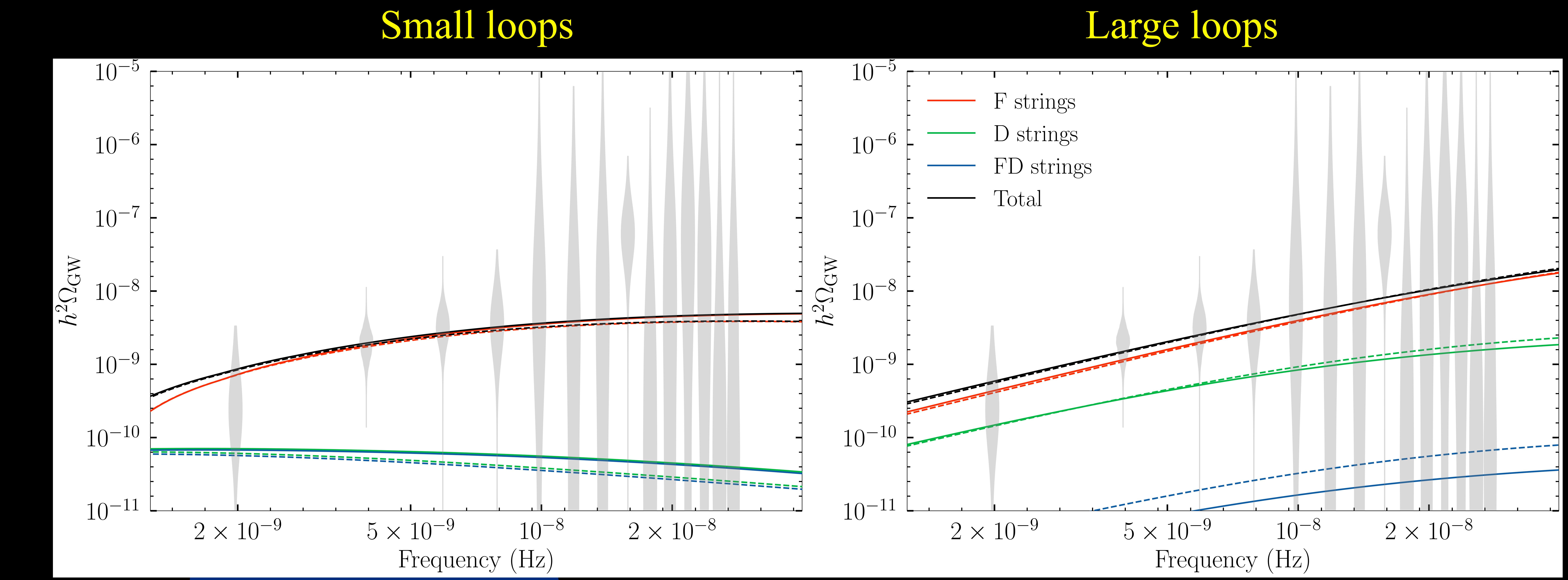
No evidence of scaling in matter regime. Changes in rad-mat regime impact low freq end of spectrum most, the NANOGrav end, hence the need for accurate modelling where possible.

Small loops

Large loops

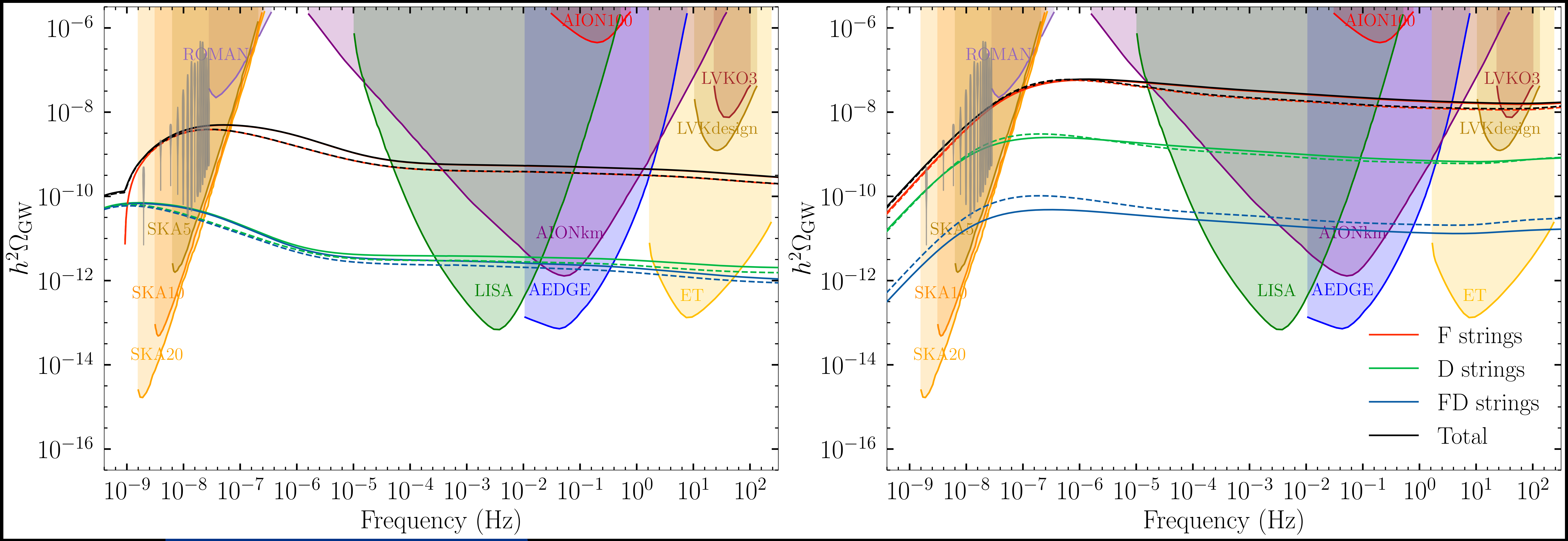


Gravitational wave bgd spectra generated at different sizes of the extra dimensions - w=0.1 (dashed lines) and w=1 (solid lines). The string tension $G\mu_1=10^{-9}$ and loop sizes are $\alpha_I=2\Gamma G\mu_I$ on the left and $\alpha_I=0.1$ on the right. Only the fundamental mode is shown.



Best fit spectra for the small (left) and large (right) loop cases. The solid (dashed) lines correspond to cuspy (kinky) loops. The NANOGrav 15-year data is shown as violins.

Small loops   Large loops



Best fit spectra for the small (left) and large (right) loop cases. The solid (dashed) lines correspond to cuspy (kinky) loops. The NANOGrav 15-year data is shown as violins and the sensitivity curves of current and (projected) future experiments are shown by shaded regions [Ellis et al. PRD 108, 103511 (2023)]

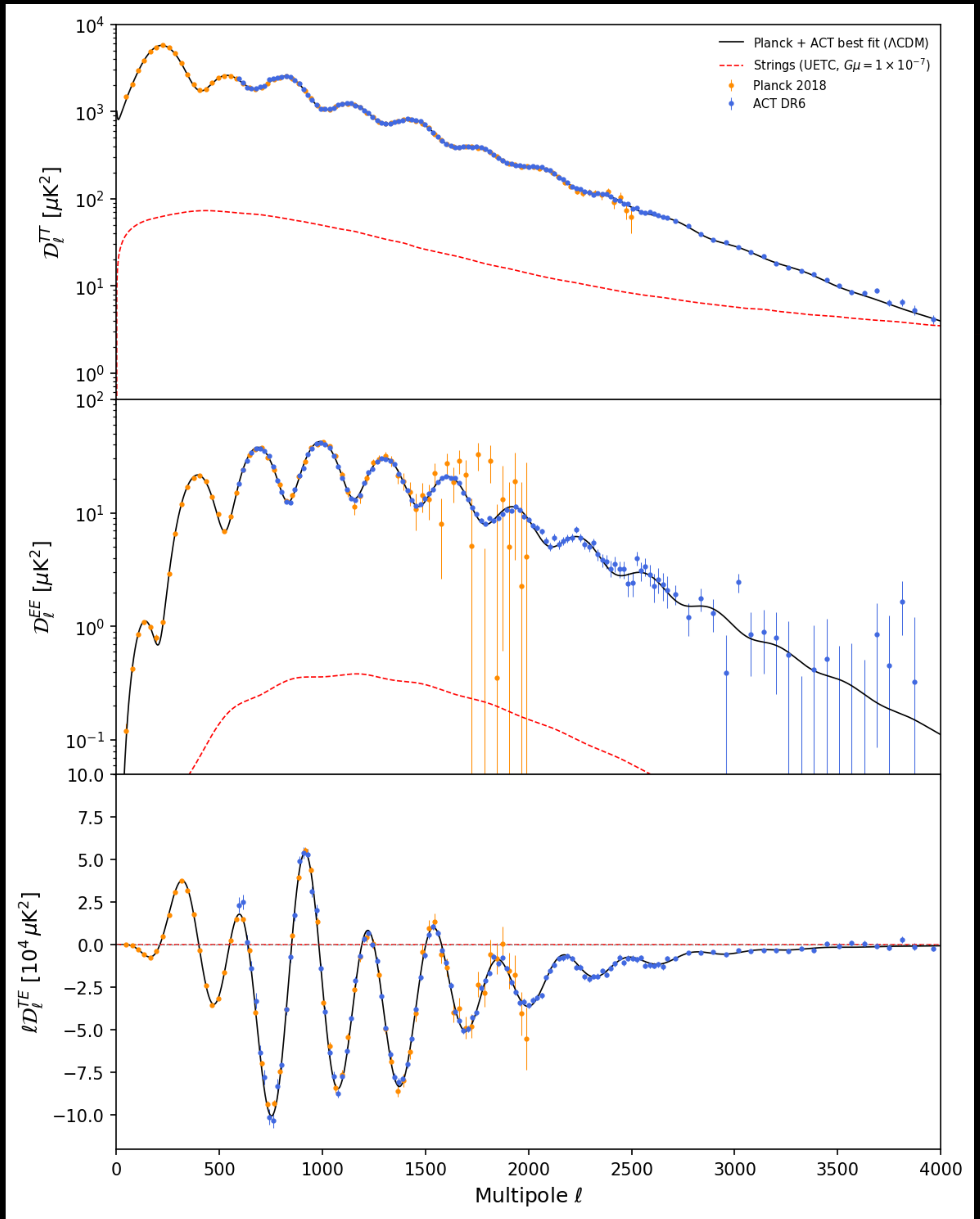
Bounds on Fundamental string tension, string coupling and size of extra dimensions.

[Avgoustidis, EJC, Moss and Raidal - 2503.10361]

Model	$-2\ln\mathcal{L}_{\max}$	$\log_{10}(G\mu_1)$	g_s	w
Cuspy big loops	47.9	$-11.4^{+0.3}_{-0.2}$	< 0.69	< 0.90
		-11.8	0.22	0.01
Kinky big loops	47.8	$-11.5^{+0.3}_{-0.2}$	< 0.70	< 0.91
		-11.9	0.26	0.01
Cuspy small loops	53.6	$-9.7^{+0.7}_{-0.7}$	< 0.63	< 0.88
		-10.8	0.04	0.01
Kinky small loops	53.5	$-9.9^{+1.0}_{-0.5}$	< 0.61	< 0.83
		-10.9	0.05	0.01

Juhan Raidal

CMB and Strings - based on modified CMBACT [Pogosian]



[Avgoustidis, EJC, Moss and Raidal (2026)]

Including ACT DR6 with Planck PR3

ACT DR6 and Planck PR3 combined TT (top), EE (middle) and TE (bottom) power spectra. The solid black curve shows the ACT and Planck best-fit ΛCDM model. The dashed red curve shows cosmic strings from the UETC with $G\mu=10^{-7}$ and loop sizes are $\alpha=1.9$ and $c_r=0.23$

You can see that in principle including ACT will allow us to pick up string contributions as they become comparable for large l

Bounds on Cosmic strings and cosmic superstrings

Model Type	**Parametrization**	**Priors on $\alpha, \tilde{c}$**	**Planck**	**Planck + ACT**
Cosmic Strings	$G\mu$	Flat	1.17×10^{-7}	1.16×10^{-7}
		Gaussian	6.85×10^{-8}	6.26×10^{-8}
	$\log_{10} G\mu$	Flat	3.53×10^{-8}	3.53×10^{-8}
		Gaussian	3.96×10^{-8}	3.66×10^{-8}
Cosmic Superstrings	$G\mu_F$	Flat	5.34×10^{-8}	6.55×10^{-8}
		Gaussian	3.28×10^{-8}	2.63×10^{-8}
	$\log_{10} G\mu_F$	Flat	1.54×10^{-8}	1.52×10^{-8}
		Gaussian	1.71×10^{-8}	1.38×10^{-8}

TABLE I: 95% C.L. upper limits on the cosmic string tension $G\mu$ and $G\mu_F$. The "Planck" column uses the CamSpec PR4 likelihood, while the "Planck + ACT" column uses the ACT DR6 likelihood combined with a cut version of the *Planck* 2018 PR3 likelihood. Results are shown across different models, parametrizations, and prior assumptions.

No significant improvement with ACT.

GWs from cosmic superstrings with time varying tensions

[Conlon, EJC, Hardy & Sanchez Gonzalez 2025, Rivello & Villa 2024]

Noelia Sanchez Gonzalez

In string theory, there are scenarios where between inflation and reheating, the moduli fields evolve during a period of kination. These moduli can be the core of the string, formed at the end of inflation, implying the string loops have time dependent tensions.

They can actually grow during this period, leading to loop tracker solutions with time dependent tensions. Do they have any observational consequences?

The solution exists as a tracker until the rolling modulus reaches its minimum, when the loops then ultimately decay through GW emission - recall this is before reheating has occurred.

Because this occurs at such early times, we find a spectrum of very high frequency GWs peaking in the GHz region today — very exciting, but very challenging from an observational standpoint.

See talk by Joe Conlon tomorrow

Summary

Cosmic strings have been with us for a remarkable fifty years since Tom Kibble's pioneering paper in 1976.

The fact that strings and cosmic superstrings can and do decay gravitationally, coupled with the amazing results of NANOGrav15 have opened up a new direction for us to probe these amazing objects through their GW emission.

The fact that cosmic superstrings can form y-junctions opens up the possibility that new configurations could be searched for in the cmb

The realisation that there could be an extended period of kination between the end of inflation and reheating, has opened up the possibility of forming strings with time dependent tensions, which could if we are lucky have a number of observational consequences. One of them is through their GW emission before BBN, but there are others:

evolving moduli imply time dependent gauge couplings, so the possibility of seeing new features in electromagnetism, QCD, possible consequences for the baryon asymmetry etc.. they are all there waiting to be explored.