COST EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

COSMIC WISPERS CA21106

UNIVERSITY OF CAMBRIDGE

Aspects of Cosmic Superstrings in Large Volume Compactifications

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2408.13803 [hep-th], 2411.04186 [hep-ph], 2504.20994 [astro-ph.co]

With Frey, Mahanta, Maharana, Quevedo, Revello (x2), Ghoshal

22/10/2025, Dark Universe Cosmology workshop, Bologna, Italy

Why cosmic strings?

Cosmic (super)strings are receiving a lot of attention.

Three main points:

- Gravitational waves

- Production of dark matter

- Varying tension phenomena

Varying tension

Moduli dynamics in the early Universe alters the dynamics of these objects via varying tension.

This may lead to *growth* which can:

- Lead to percolation and network formation. Conlon et al ‘24

Cicoli et al’25

- Occur for F-strings and wrapped branes, not only in kination.

Sánchez-González et al’25
Cicoli et al’25 (2)

- Lead to strings dominating the energy density of the Universe.

This talk: two main points

Review worldsheet dynamics when the tension varies.

Ask you, as a community, questions:

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- What can we learn from the cosmic string community?
  - Can we simulate varying tension?
- Is there anything we can teach them?
  - Worldsheet computations
  - Synergies GWs-axions

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Today: my thoughts on this

Cosmic Strings & Superstrings: Worldsheet dynamics

Cosmic strings & superstrings

- Field theory: topological defects from symmetry breaking in the early Universe.

Kibble'76

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- String theory: highly excited strings/D1 branes/wrapped higher dimensional branes. Formed after brane-antibrane inflation?

Sarangi-Tye'02

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Moduli-dependent!

Worldsheet dynamics

At low energies, described by the Nambu-Goto action:

$$S = -\int d^2\zeta\, \mu\sqrt{-\gamma}.$$

$$\gamma_{ab} = \frac{\partial X^\mu(\zeta)}{\partial \zeta^a}\frac{\partial X^\nu(\zeta)}{\partial \zeta^b} a(\tau)^2 \eta_{\mu\nu}$$

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(One of the) equations of motion reads:

$$\dot{\varepsilon} + \left(2\frac{\dot{a}}{a} + \frac{\dot{\mu}}{\mu}\right)\varepsilon\dot{x}^2 = 0, \qquad \varepsilon \equiv \sqrt{\frac{x'^2}{1-\dot{x}^2}}\,.$$

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Proper length

A novel effect: the strings can grow

For a cosmology of the form $$H = \frac{2}{nt}\,, \qquad \mu = \mu_0 \left(\frac{t_0}{t}\right)^p$$

$$\dot{\varepsilon} + \left(\frac{4}{n} - p\right)\frac{\dot{x}^2}{t}\varepsilon = 0$$

The strings grow for $p > 4/n$

Conlon et al ‘24

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Examples:

n	p	4/n-p	
6	1	-1/3	Volume modulus kination
4	2/3	1/3	LVS radiation tracker
4	1	0	Temperature-dependent tension

Emond et al’22

Concrete example: the circular loop

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With the circular loop as the paramount example:

$$\mathbf{x} = R(\tau)L(\cos(\zeta^1/L), \sin(\zeta^1/L), 0)$$

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$$\mathbf{x} = R(\tau)L(\cos(\zeta^1/L), \sin(\zeta^1/L), 0)$$

A semi-explicit solution can be worked out:

$$R(\tau) = e^{-q\int \frac{d\tau}{\tau}\sin(f(\tau/L))^2}\cos(f(\tau/L))$$

Concrete example: the circular loop

$f(x)$ satisfies a nasty nonlinear equation which can be solved analitically in some limits.

Cosmic Strings & Superstrings: network dynamics

Cosmic strings & scaling

Cosmic strings track the energy density of the background. Kibble'85

- Slower dillution $\sim 1/a(t)^2$

- Energy loss via intercommutation:

The VOS model

Martins-Shellard'96

A simple, analytic approach averages the worldsheet equations of motion and describes the network in terms of two variables.

$$\rho = \frac{\mu}{L^2} \qquad\qquad v^2 = \frac{\int d\zeta^1\, \varepsilon \dot{x}^2}{\int d\zeta^1\, \varepsilon}.$$

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Revello-GV'24

$$\begin{cases} 2\frac{\mathrm{d}L}{\mathrm{d}t} = 2HL(1+v^2) + \tilde{c}v + \frac{L}{\mu}\frac{\mathrm{d}\mu}{\mathrm{d}t}v^2. \\ \frac{\mathrm{d}v}{\mathrm{d}t} = (1-v^2)\left[\frac{k(v)}{L} - \left(2H + \frac{1}{\mu}\frac{\mathrm{d}\mu}{\mathrm{d}t}\right)v\right]. \end{cases}$$

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Small scale structure

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Scaling solutions are attractors

$$L = \xi t \,, \qquad v = \text{const.}$$

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$$L = \xi t\,, \qquad v = \text{const.}$$

$$\Omega_s = \frac{\rho_s}{3H^2M_p^2} = G\mu \times \text{const.}$$

The momentum parameter

- A key feature of the scaling solutions is that they require a negative momentum parameter:

$$k(v) \sim \langle \dot{x} \cdot x'' \rangle$$

We worked out the momentum parameter for small perturbations of a long string and showed that it changes sign if p n > 4

Challenges & opportunities

- The next step is obvious: simulate the dynamics!

- Network formation: do the strings percolate?

- More on percolation: can we do string thermodynamics to see what happens?

Further aspects: emission rates without quadrupole approximation

Non-relativistic emision rates

Consider the amplitude for photon-mediated transitions in eg Hydrogen:

$$\mathcal{M}_{A\to B,\gamma} \sim e\, e_\mu \left\langle B \left| e^{ik\cdot x(\sigma)} p^\mu \right| A \right\rangle .$$

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Which can be derived from

$$S = \int dt \left(L_{\mathrm{atom,p^\mu \to p^\mu - ieA^\mu}} - \frac{1}{4} \int d^3x\, F_{\mu\nu} F^{\mu\nu} \right)$$

Non-relativistic emision rates

For a 1+1-dimensional object coupled to gravity, have:

$$\mathcal{M}_{A\to B,g} = \frac{M_s^2}{2\pi M_p} e_{\mu\nu} \int d\sigma \left\langle B \left| e^{ik\cdot x(\sigma)} \sqrt{-\hat{\gamma}_{(0)}} x_a^\mu x_b^\nu \hat{\gamma}_0^{ab} \right| A \right\rangle .$$

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Which can be derived from

$$S = \int dt \left(\frac{M_{10}^8}{2} \int d^3x \, d^6y \sqrt{-g} \left[R_{10} + \cdots \right] + T_p \int d^p\sigma \sqrt{-\gamma} \right) ,$$

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Graviton vertex operator

Which can be derived from

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Typical emision rates

At fixed length, average over initial & sum over final states:

$$F(\omega) = \frac{1}{\mathcal{G}(N)} \sum_{i,j,\xi} |\langle \Phi_{N',i} | V_\xi(k)^* | \Phi_{N,j} \rangle|^2$$

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Amati-Russo'99

Which can be expressed as a trace using projectors:

$$F = \frac{1}{\mathcal{G}(N)} \sum_{\xi} \oint \frac{dz}{2\pi i z} z^{-N} \oint \frac{dz'}{2\pi i z'} z'^{-N'} \mathrm{Tr}[V_\xi^\dagger(k,1)\, z'^{\hat{N}} V_\xi(k,1) z^{\hat{N}}]$$

The computation

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The Minkowski part is computable:

$$\frac{1}{\mathcal{G}(N)}\oint\frac{dw}{2\pi i w}w^{-N'}f(w,N-N')Z(w)\simeq\frac{\mathcal{G}(N')}{\mathcal{G}(N)}f(e^{-M_s/(2\sqrt{N'}T_H)},N-N')$$

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After the dust settles:

$$\frac{d\Gamma_{o,g}}{d\omega}=\tilde{A}\left(\frac{M_s}{M_p}\right)^2 lM_s(\omega/T_H)^3\frac{e^{-\omega/T_H}}{\left(1-e^{-\omega/2T_H}\right)^2}$$

Observations

$$\frac{d\Gamma_{o,g}}{d\omega} = \tilde{A}\left(\frac{M_s}{M_p}\right)^2 l M_s(\omega/T_H)^3 \frac{e^{-\omega/T_H}}{\left(1-e^{-\omega/2T_H}\right)^2}$$

The result is generic: only uses exponential growth of states.

The result is tree level: should apply to any quantisable 1+1-dimensional object coupled to gravity.

The result is UV-complete: resolves the small scale structure.

Comparison with cosmic string literature

	Cosmic string	Worldsheet
Multipole expansion	Many orders	All orders
Shape	String with kinks/cusps	Typical strings
High frequency behaviour	Power-law decay	Exponential suppression
Other particle emission	???	Easy

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Observation: can give insights into decay of loops via massive radiation, & an (alternative?) computation of the GW spectrum.

Conclusions

Cosmic (super)strings are an extraordinary opportunity for testing UV Physics: we need to understand them & how they fit into string theory.

We can benefit from interactions with the cosmic string community:

- Simulations of varying tension
- Theoretical input into particle production
- Correlations with e.g. axions
- FURTHER OPPORTUNITIES??? Let me know if you have ideas!