# Scaling in a network of $\mathrm{Z}_2$ strings

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### What was known

- Spontaneous breaking of a non-abelian symmetry can produce 'beads' consisting of 't Hooft-Polyakov monopoles, on cosmic strings.
- It is not known how the monopoles influence the dynamics of the resulting string network.

### What this work adds

- We have carried out simulations of this scenario for the first time.
- Monopoles are carried along by the strings; the network behaves similarly to an abelian string network.

### Next steps

- Study larger ratios between the monopole and string scales, to check whether monopoles eventually slow strings down.
- Observational predictions for strings in grand unified models, e.g. $\mathrm{SO}(10)$.

## Introduction

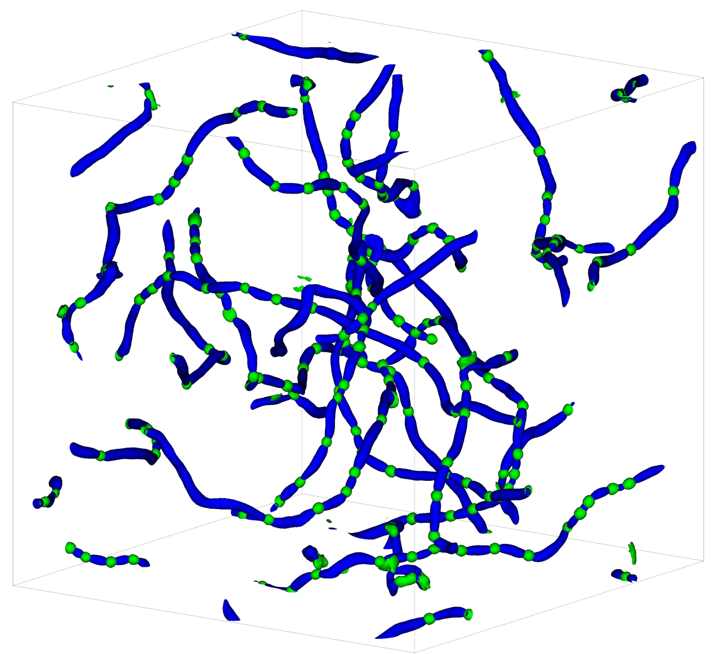
- We study the formation of cosmic string networks in the model with Lagrangian [1,2]

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{\mu\nu a} + \sum_n \mathrm{Tr}[D_\mu, \Phi_n][D^\mu, \Phi_n] - V(\Phi_1, \Phi_2); \qquad V(\Phi_1,\Phi_2) = -m_1^2\,\mathrm{Tr}\,\Phi_1^2 - m_2^2\,\mathrm{Tr}\,\Phi_2^2 + \lambda\left[\left(\mathrm{Tr}\,\Phi_1^2\right)^2 + \left(\mathrm{Tr}\,\Phi_2^2\right)^2\right] + \kappa\left(\mathrm{Tr}\,\Phi_1\Phi_2\right)^2$$

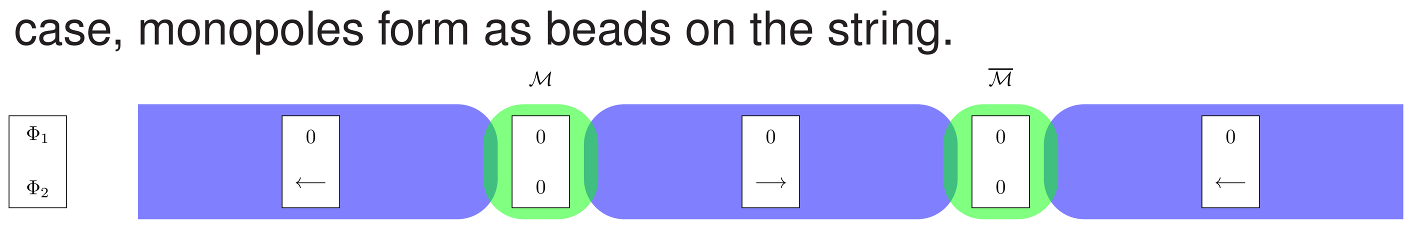
  where $D_\mu = \partial_\mu + igA_\mu$, $F_{\mu\nu} = F^a_{\mu\nu}\tau^a$ and $A_\mu = A^a_\mu\tau^a$, $\tau^a = \sigma^a/2$. Here, $\Phi_1$ and $\Phi_2$ are adjoint Higgs fields ($\Phi = \phi^a\sigma^a$).
- The system undergoes two symmetry breaking phase transitions, $\mathrm{SU}(2) \to \mathrm{U}(1) \to \mathrm{Z}_2$.
  The first, $\mathrm{SU}(2) \to \mathrm{U}(1)$, creates 't Hooft-Polyakov monopoles with mass $M$, the second, $\mathrm{U}(1) \to \mathrm{Z}_2$, confines the flux to cosmic strings with tension $\mu$, like beads on a wire.
- Simulations are performed in a comoving $V = 720^3$ box with lattice spacing $a = 1$, with Hubble damping corresponding to an expanding radiation-dominated universe.
- We determine the location of strings and monopoles within the box, yielding $L$, the total (Manhattan) length of string and $N$, the number of monopoles. These yield the average monopole and string separations $\xi_\mathrm{m} = (V/N)^{1/3}$ and $\xi_\mathrm{s} = (V/L)^{1/2}$. The monopole locations are also used to measure $\overline{v}_m$, root mean square monopole velocity.
- We compute monopole separation along the string $d = L/N$ and hence the ratio $r = M/\mu d$ measuring the importance of the monopoles for the string dynamics [3,4,5].

## Case 1: $m_1^2 > m_2^2$

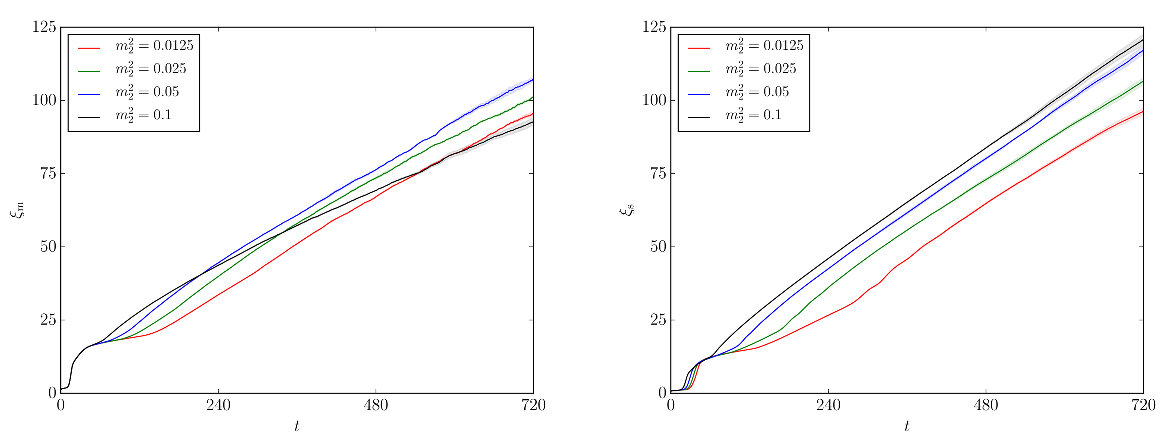
$240^3$ *simulation with* $m_1^2 = 0.25$, $m_2^2 = 0.1$, *isosurfaces* $\mathrm{Tr}\Phi_1^2 = 0.2$, $\mathrm{Tr}\Phi_2^2 = 0.04$, *time* $t = 240$.



- In this case, monopoles form as beads on the string.

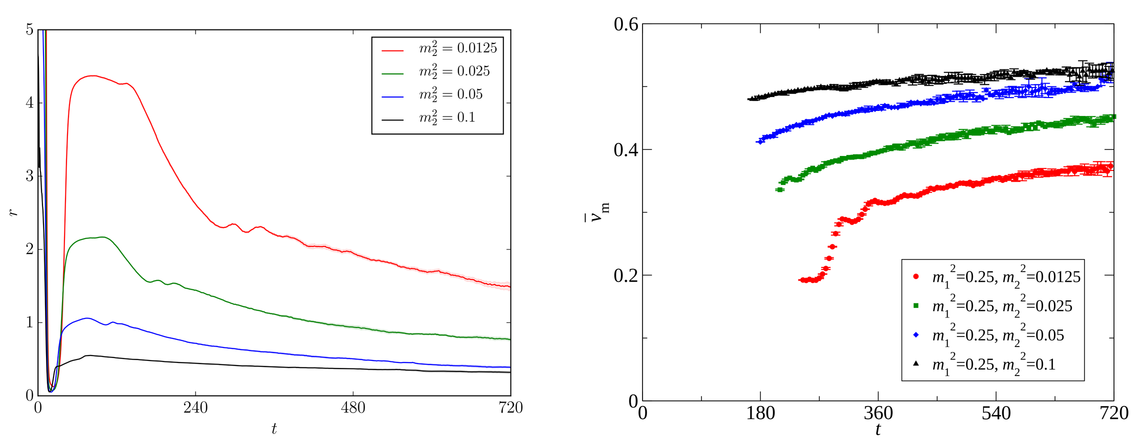



- We measured $\xi_\mathrm{s}$ and $\xi_\mathrm{m}$ and they grow linearly: a scaling network forms.



There is little apparent difference between the scaling for different $\mu$.

- Our simulations show that $r$ always decreases while $\overline{v}_m$ increases, appearing to asymptote to a relativistic value.

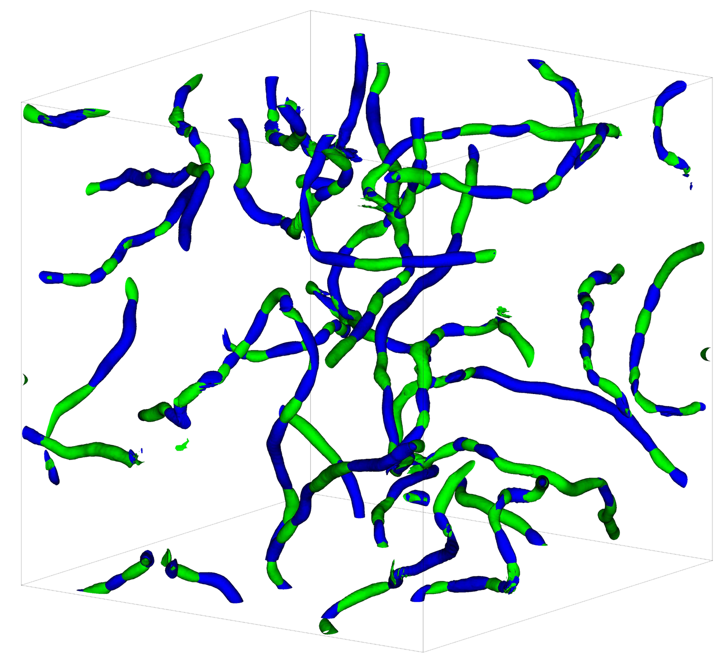


The monopole velocities are also in line with expected string velocities.

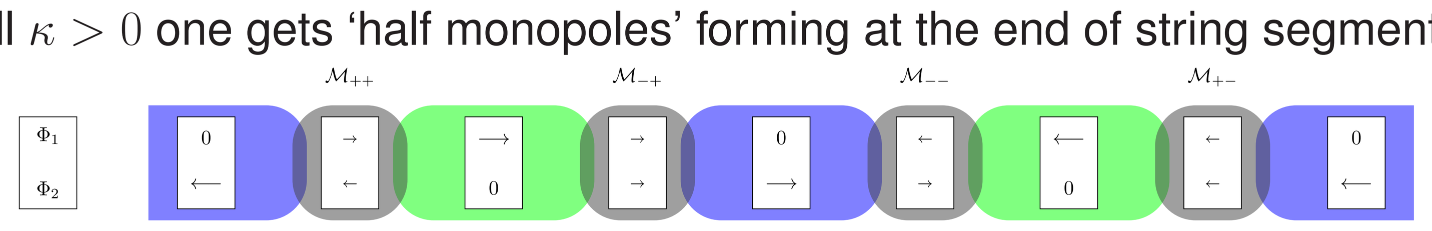
**Key results**: Scaling network forms; monopoles are unimportant; average monopole velocity does not decrease.

## Case 2: $m_1^2 = m_2^2$

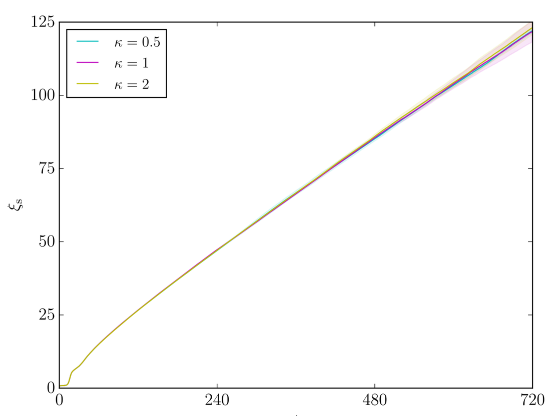
$240^3$ *simulation with* $m_1^2 = m_2^2 = 0.25$, $\kappa = 1$, *isosurfaces* $\mathrm{Tr}\Phi_1^2 = \mathrm{Tr}\Phi_2^2 = 0.2$, *time* $t = 240$.



- For all $\kappa > 0$ one gets 'half monopoles' forming at the end of string segments:



- There is a global symmetry between the two scalar fields, and the larger $\kappa$ is, the less the two fields overlap.
- However, for all values of $\kappa$, the result is a scaling network of strings:



- We find that $\xi_\mathrm{s}$ scales with coefficient $0.16 \pm 0.01$, which corresponds to string densities approximately 40% higher than in the abelian Higgs model. CMB constraints are therefore stronger for this model [6].
- Because of the global symmetry, we cannot count the number of half monopoles.

**Key results**: When $m_1^2 = m_2^2$, we get novel strings with 'half monopole' structures. These still produce a scaling network.

## References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