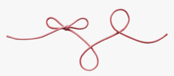
Summery of constraints on cosmic strings using data from the third Advanced LIGO-Virgo observing run

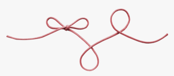
Mitchell Gerrard

University Of Southampton



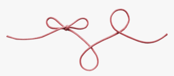
Why Look at gravitational waves for cosmic strings?

- Cosmic strings exist before recombination and the CMB. This means that there is a wall of electromagnetic waves that we cannot examine before the CMB.
- This means we need to look at gravitational waves to view items in this time period. Because there is no such wall for gravitational waves.



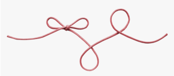
What are cosmic strings?

Cosmic strings are line-like 1D topological defects. These stable configurations of matter are formed by spontaneous symmetry-breaking phase transition. These early universe phase transitions correspond to an energy scale of around $10^{16} GeV$ and lower. This allows us to probe beyond the standard model with our ground-based detectors, such as LIGO and Virgo.



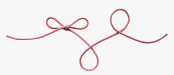
Nambo-Gato

Cosmic strings are well-defined by the Nambo-Goto string action. It is the starting point of the analysis of zero-thickness (infinitely thin) string behaviour using the principles of Lagrangian mechanics. Just as the action for a free point particle is proportional to its proper time — i.e., the "length" of its world-line — a relativistic string's action is proportional to the area of the sheet which the string traces as it travels through spacetime.



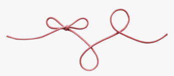
String tension

The dimensionless quantity of the string tension $G\mu$ parameterises these strings, with μ being the string linear mass density and G is Newton's gravitational constant. This is the value that constants were obtained for. The string tension is also related to the energy scale η by $G\mu \sim (\frac{\eta}{M_{Plank}})^2$.

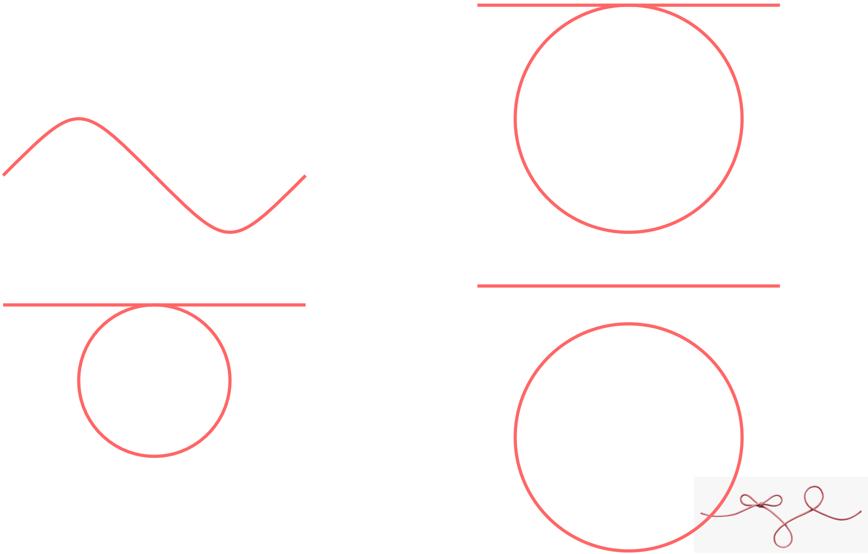


How are the Gravitational waves produced?

In cosmology, a cosmic string network relaxes towards a scaling solution. These solutions are self-similar attractor solutions in which typical loop lengths are proportional to cosmic time, meaning they scale with the Hubble radius. Infinitive strings reach these solutions by forming loops that cascade into smaller loops by emitting gravitational waves. This paper analyses the string networks and their distribution because it changes the loop production and the cascade, affecting the gravitational waves.

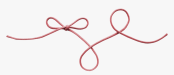


Loop Cascade

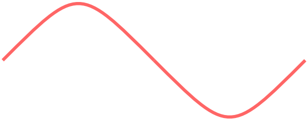


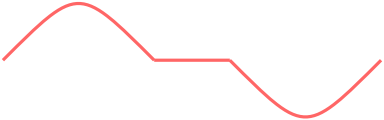
How are the Gravitational waves produced?

Cosmic string loops oscillate in time; these oscillations emit gravitational waves. Cusps and kinks dominate the high-frequency oscillations; kinks are discontinuities in the tangent vector of the string that propagate at the speed of light. They appear in pairs due to collisions between two cosmic strings and are chopped off when a loop forms. These kinks propagate around the string (like a fan) while the cusps, which are short-lived, produce beamed gravitational waves in the forward direction. And when two kinks collide, it's expected to radiate gravitational waves isotropically.



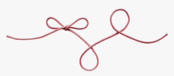
Kinks





How do these gravitational waves look?

The power of these gravitational waves that the loops produce is $P_{gw} = \Gamma_d G\mu^2$ and a decay lifetime $\frac{\ell}{\gamma_d}$ where γ is a numerical factor, ℓ is the invariant loop length and $\gamma_d = \Gamma_d G\mu^2$ is the gravitational-wave length scale measured in time.



How do these gravitational waves look?

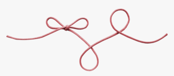
The wave-forms have been calculated in [**?**, **?**, **?**] at a redshift z, we get our h being

$$h_i(\ell, z, f) = A_i(\ell, z) f^{q_i} \tag{1}$$

where $i = c, k, kk$ which identifies the different cases. The indices q are $q_c = \frac{4}{3}, q_k \frac{5}{3}, q_{kk} = 2$ and then the amplitude will be

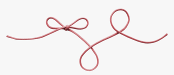
$$A_i(\ell, z) = g_{1,i} \frac{G\mu\ell^{2-q_i}}{(1+z)^{q_i-1} r(z)} \tag{2}$$

where r(z) is the comoving distance to the loop and the prefactor $g_{1,i}$ taking 3 diffrent numerical values for each case
$g_{1,c} \approx 0.85, g_{1,k} \approx 0.29, g_{1,kk} \approx 0.10$



What are they looking for?

These are discussed in the context of numerical simulations of [**?**, **?**] and they develop an interpolation between the two. From these, they developed the burst rate of the gravitational waves and the energy density spectra using the O3 data from LIGO and Virgo. They also use a stochastic search combining the sensitivities of the searches to constrain the string tension.



Burst Search

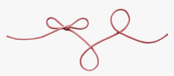
The burst search uses three main steps, a matched filter search using the waveform in Eq 1. Then the candidates are filtered through for the ones in more than one detector within a time window accounting for the difference in the gravitational-wave arrival time between detectors. Finally, double and triple-coincident events are ranked using a likelihood function $\Lambda(x)$, where x is a set of parameters used to discriminate true cosmic string signals from noise. The burst search is performed separately for cusps, kinks and kink-kink collision waveforms.

Burst Search

The incoherent superposition of bursts from loops with all possible sizes through the history of the Universe produces a stochastic gravitational wave background [**?**]. The normalized energy density of which is defined as

$$\Omega_{GW}(f) = \frac{f}{\rho_c}\frac{d\rho_{GW}}{df} \tag{3}$$

where $\rho_c = \frac{3H_0^2c^2}{8\pi G}$



Burst Search

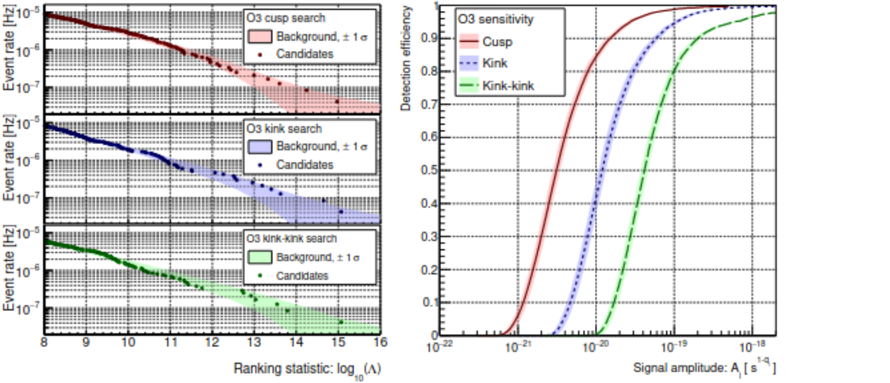
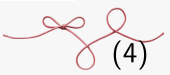


FIG. 2. Left panel: cumulative distribution of cosmic string burst candidate events produced by cusps (top), kinks (middle) and kink-kink collisions (bottom). The expected distributions from background noise are represented by $\pm 1\sigma$ shaded areas. Right panel: the detection efficiency is measured using simulated signals, as a function of the signal amplitude for cusps, kinks and kink-kink collisions. Note that the horizontal axis measures different amplitude quantities, A_i, for the three types of signals, parameterized by the waveform frequency power law q_i.

$$1.7 \times 10^{6} (G\mu/10^{-10})^{-\frac{3}{2}} \text{light years at redshift } 100 \qquad (4)$$

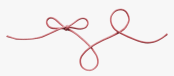


Stochastic Search

The authors used data from this run and the first two for this search. The results reported in [**?**] assume the normalized energy density of the stochastic background, Eq 3, to be a power-law α of the frequency:

$$\Omega_{GW}(f) = \Omega_{ref}(\frac{f}{f_{ref}})^{\alpha} \tag{5}$$

where f_{ref} denotes a reference frequency, fixed to 25Hz. LIGO and Virgo did not detect a stochastic back- ground, and so set upper limits depending on the value of α. The upper bound of this background is $G_{GW} \leq 5.8 \times 10^{-9}$ for a flat background $\alpha = 0$.



Stochastic Search

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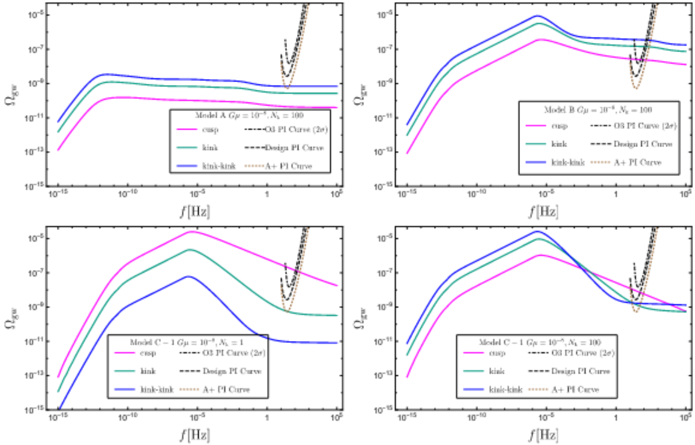
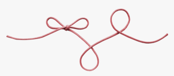
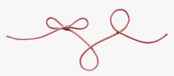


FIG. 1. Predictions of the gravitational-wave energy density spectra using different models for the loop distribution function $n(\gamma, z)$ and varying the number of kinks per loop oscillation N_k. The string tension $G\mu$ is fixed to 10^{-8}. Top-left: model **A**, $N_k = 100$. Top-right: model **B**, $N_k = 100$. Bottom-left: model **C-1**, $N_k = 1$. Bottom-right: model **C-1**, $N_k = 100$. For model **C-1**, we use the following model parameters (see Supplemental Material): $\chi_{\rm rad} = 0.45$, $\chi_{\rm mat} = 0.295$, $c_{\rm rad} = 0.15$, $c_{\rm mat} = 0.019$; the subscripts refer to the radiation and matter eras, respectively. We also show the energy density spectra of the three different components and 2-σ power-law integrated (PI) curves [40] for the O3 isotropic stochastic search [27], and projections for the HLV network at design sensitivity, and the A+ detectors [41].

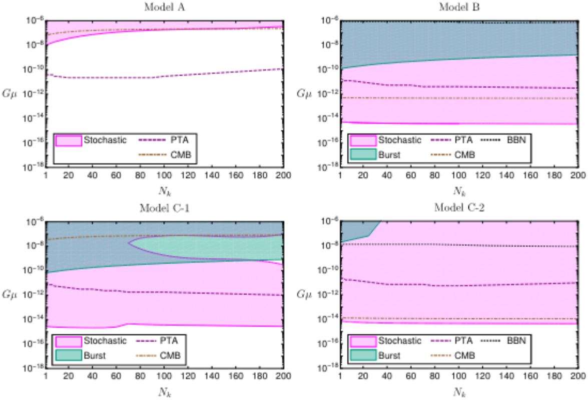


Stochastic Search

The upper bound is $G\mu \leq 10^{-6}$ coming from the cosmic microwave background measurements [?, ?, ?, ?].



Stochastic Search



constraints on $G\mu$. model A, $G\mu \leq (9.6 \times 10^{-9} - \times 10^{-6})$.
model B: $G\mu \leq (4.0 - 6.3) \times 10^{-15}$.
model C-1 $G\mu \leq (4.0 - 6.3) \times 10^{-15}$.
model C-2: $G\mu \leq (4.2 - 7.0) \times 10^{-15}$.

$$G\mu \lesssim 4 \times 10^{-15} \tag{6}$$