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Cosmic string cusps produce powerful bursts of gravitational waves (GWs). These bursts provide the most promising observational signature of cosmic strings. In this letter we report stringent limits on cosmic string models obtained from the analysis of 625 days of observation with the LIGO and Virgo GW detectors. A significant fraction of the cosmic string parameter space is ruled out. This result complements and improves existing limits from searches for a stochastic background of GWs using cosmic microwave background and pulsar timing data. In particular, if the size of loops is given by gravitational back-reaction, we place upper limits on the string tension $G\mu$ below 10^{-8} in some regions of the cosmic string parameter space.

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Introduction. A cosmic network of strings may form as a result of phase transitions in the early universe [1]. When a U(1) symmetry is broken in multiple causally disconnected spacetime regions, one-dimensional topological defects, i.e. strings, are expected to form [2]. For a long time, cosmic strings were considered candidate sources for structure formation in the early universe [3]. Cosmic microwave background (CMB) experiments, however, have shown that cosmic strings can only contribute up to a few percent of the overall anisotropies observed [4–8]. More recently it was realized that strings can also be produced within the framework of string theory inspired cosmological models and grow to cosmic scales [9–13]. Cosmic strings produced in string theory motivated models (dubbed "cosmic superstrings") have received much attention since they could provide observational signatures of string theory [14, 15].

Observational constraints on cosmic string models are often given as bounds on the string tension, $G\mu$ ($c = 1$), where G is Newton's constant and μ the mass per unit length. Such constraints have been derived from direct searches for line discontinuities in the CMB temperature maps [16–18] and from simulations of string-sourced CMB anisotropies [4–7, 19, 20]. These analyses, based on various assumptions about the string network, set upper limits on $G\mu$ in the range of $10^{-7} - 10^{-6}$. The recent results from the Planck mission [8] constrain $G\mu$ to be lower than 1.5×10^{-7} and 3.2×10^{-7} for Nambu-Goto and abelian-Higgs strings respectively.

One of the most promising ways of detecting the presence of cosmic strings and superstrings is via gravitational wave (GW) emission from loops [21, 22]. GW radiation is the primary mechanism of energy loss for a string network. When two string segments meet, they exchange partners or intercommute with a probability p. For superstrings, the reconnection probability can be less than unity ($10^{-4} < p < 1$ [23]) while field theory simulations show that topological strings will essentially always reconnect. This is partly due to the fact that fundamental strings interact probabilistically. Furthermore, superstring models have extra spatial dimensions so that even though two strings may meet in 3 dimensions, they miss each other in the extra dimensions. After an intercommutation, each string presents a sharp edge called a kink which is progressively straightened by the GW emission. When a string intercommutes with itself, a closed loop breaks off. The loop oscillates, radiates gravitationally and decays. Cosmic string loops can form cusps, points along the string with a large Lorentz boosts, that produce powerful bursts of gravitational radiation [24]. The analysis described in this letter reports our efforts to detect these GW bursts.

The GW emission by cusps depends on the loop size, which is often written as a fraction of the horizon at the time of formation $l = \alpha t$, where t is the cosmic time. Neither abelian-Higgs nor Nambu-Goto simulations can provide a reliable estimate for α. One possibility is that the size of loops is given by the large scale dynamics of the network, in which case $\alpha \lesssim 1$. In this case loops are large and long-lived because they decay gravitationally in many Hubble times. A second possibility is that the size of loops is given by gravitational back-reaction and $\alpha \leq \Gamma G\mu$, where $\Gamma \sim 50$ [2]. In this case loops are small, and they decay within a Hubble time. The search reported in this paper only considers the small loop regime since the large-loop scenario is already well constrained [7, 25]. We parameterize α as $\alpha = \varepsilon \Gamma G\mu$ with $\varepsilon < 1$ following the convention of [21].

A stochastic background is expected to arise from the incoherent superposition of GW signals produced by cusps and kinks [22]. $G\mu$ can therefore be constrained by estimating the spectral density of the GW background. Under the assumption of large-loop production, pulsar timing experiments provide the best constraints [7, 22, 25] with $G\mu \lesssim 10^{-9}$ for $p = 1$ and $G\mu \lesssim 10^{-12}$ for $p < 10^{-2}$ taking $\alpha \sim 0.1$. Constraints from pulsar timing experiments were also derived for small loops [22] and are represented in Fig. 2. This result is complemented by the LIGO stochastic analysis in the very small loop region [26]: $G\mu \lesssim 3 \times 10^{-8}$ for $p < 10^{-3}$ and for $\varepsilon \sim 10^{-11}$. Some additional bounds on the GW background can be indirectly derived from CMB [27] data and big-bang nucleosynthesis (BBN) constraints [28]. At the epochs of last scattering and BBN, the energy density of the GW background must be sufficiently small so as not to distort the CMB fluctuations or affect the abundances of primordial elements. The CMB bound is shown in Fig. 2 and, until the present publication, offered the best limit on $G\mu$ for intermediate values ε. However this limit, in addition to being indirect, only applies to GW backgrounds generated prior to decoupling, while LIGO and pulsar timing data also constrain GWs produced later.

GW bursts from cosmic string cusps. Damour and Vilenkin have shown that the stochastic GW background generated by oscillating loops is strongly non-Gaussian [24]. Occasional sharp bursts of GW produced by cusps are expected to stand out above the stochastic background [21, 24, 29]. Damour and Vilenkin predict that the GW burst signal produced by cusps is linearly polarized and the expected waveform in the frequency domain is $h_{cusp}(f) = Af^{-4/3}$ with an exponential decay that sets on at frequency f_h. The signal amplitude A is determined by the string tension, the loop size and the propagation distance. The high frequency cutoff, f_h, is determined by the size of the loop and the angle between the line of sight and the direction of the moving cusp. It can be arbitrarily large, therefore we take f_h to be a free parameter. Following [29], the signal amplitude is written as:

$$A(z; G\mu, \varepsilon) = \frac{g_1 H_0^{1/3} (G\mu)^{5/3} (\varepsilon \Gamma \varphi_t(z))^{2/3}}{(1+z)^{1/3} \varphi_r(z)}, \qquad (1)$$

where g_1 is an ignorance constant that absorbs the unknown fraction of the loop length, which contributes to the cusp, and factors of $\mathcal{O}(1)$. $H_0 = 70.1$ km s^{-1} Mpc^{-1} [30] is the Hubble constant. Two dimensionless cosmology-dependent functions of the redshift z enter the amplitude expression: φ_t and φ_r relate the redshift and the cosmic time $t = H_0^{-1}\varphi_t(z)$ and the proper distance $r = H_0^{-1}\varphi_r(z)$ respectively. We use the φ_r and φ_t functions derived in Appendix A of [31] for a universe which contains matter and radiation and includes a late-time acceleration. Those functions are computed using the energy densities relative to the critical density: $\Omega_m = 0.279$, $\Omega_r = 8.5 \times 10^{-5}$ and $\Omega_\Lambda = 0.721$ for matter, radiation and cosmological constant respectively [30]. In addition, we use the generic loop density distribution taken by Damour and Vilenkin in [21]:

$$n(l, t) = (p\Gamma G\mu)^{-1} t^{-3} \delta(l - \varepsilon \Gamma G\mu t). \qquad (2)$$

This means that at a given cosmic time, the loop size is given by the gravitational back-reaction (the δ function) and is identical for all loops.

Our aim is to search for cusp burst signals in ground-based interferometer data and constrain the string parameter space $(G\mu, \varepsilon, p)$. Our search not only offers the most direct way to detect GWs from cosmic string cusps but also explores an unconstrained region of the string parameter space. Such a search has already been conducted on early LIGO data [32], but constraints were not competitive due to a low sensitivity and limited observation time. The results presented in this paper cover a much longer observation period, they include data from both LIGO and Virgo detectors operating near or at design sensitivity and they benefit from a much improved search pipeline.

The search. The LIGO-Virgo detector network [33, 34] is composed of four kilometer-scale Michelson interferometers: H1 (4 km) and H2 (2 km) share the same location at Hanford, Washington, USA, L1 (4 km) is in Livingston Parish, Louisiana, USA, and V1 (3 km) is located near Pisa, Italy. We analyze data collected between November 2005 and October 2010, at times when at least two detectors were operating simultaneously in stable conditions. This corresponds to a total of 625 days of observation time.

Gravitational wave bursts from cosmic string cusp events are first searched at a single-detector level. A matched-filter search is performed over each detector strain data [31]. It consists of projecting the whitened data onto an over-populated [35] template bank defined by a set of cusp waveforms with a high-frequency cutoff spanning from 75 Hz up to 8192 Hz. This procedure results in a time series for the signal-to-noise ratio (SNR) for each template. An event is identified when SNR > 3.6 and only the template with the largest SNR is retained when several templates are triggered at the same time. A set of five variables is used to characterize an event. The event time t_e and the SNR ρ are determined by the point where the SNR time series is maximum. The triggered template provides the high-frequency cutoff f_h and the amplitude A. In addition, a χ^2 parameter can be computed to characterize the match between the event and the signal waveform in the time domain [36].

Many transient noise events can mimic the properties of a GW burst from a cusp. They constitute the background of our search and limit our chances to detect weak signals. It is possible to exclude a fraction of these noise events by using a set of data quality vetoes resulting from noise studies performed for each detector [37, 38]. Another way to reduce the false alarm rate is to demand that an event is detected simultaneously by at least two interferometers. The central time of the single-detector events must therefore lie within a time window sufficiently large to take into account the maximum light travel time between detectors, the signal duration and the timing uncertainty. For each pair of detectors, a coincident event is characterized by a set of three variables: $(\delta t_e, rA, rf_h)$ where δ is used for the difference and r for the ratio between the two detectors of the pair.

To discriminate true signals from background events we apply the multi-variate technique described in [39] instead of using a standard per-parameter selection. This method proposes using two separate and realistic samples of GW and noise events and applying statistical inference techniques to estimate the probability for a given event to belong to one sample or the other. Given a set of parameters $\vec{x}$ describing an event E, a likelihood ratio can be computed and used to rank the events:

$$\Lambda(\vec{x}) = \frac{P(\vec{x}|E \in S)}{P(\vec{x}|E \in B)}, \tag{3}$$

where S and B refer to the signal and background training sample respectively. The background sample is obtained by artificially time-shifting the single-detector triggers and by performing the coincident search described above. The signal sample is generated by injecting fake cosmic string signals in the detectors' data. The simulated sources are uniformly distributed in volume and the distribution of frequency cutoffs f_h is $dN \propto f_h^{-5/3} df_h$ [31]. Moreover, simulated signals are injected on a time-shifted data set in order not to bias the event ranking performed on the non-shifted data.

For our analysis, we choose to parameterize an event by the coincidence variables δt_e, rA and rf_h given for each of the six possible pairs of detectors. These variables allow us to favor signals which are coherent in the network. We also include the single-detector SNR and χ^2 parameters to discriminate genuine signals from noise. Finally, one last parameter is introduced to describe the combination of interferometers which actually detect the event (from 2 to 4). This parameter takes a discrete value among the 11 possible combinations of detectors. The sensitivity of a given combination of detectors is different and this should be taken into account: an event detected by three detectors should be enhanced in comparison to an event coincident in only two detectors. An event is therefore represented by a total of 27 variables. Working in a 27-dimensional parameter space is computationally challenging and would require very large signal and background samples to obtain statistically reliable results. Instead we choose to assume the parameters to be uncorrelated so the likelihood ratio of equation 3 can be factorized:

$$\Lambda(\vec{x}) \approx \prod_{i=0}^{27} \Lambda(x_i) = \prod_{i=0}^{27} \frac{P(x_i|E \in S)}{P(x_i|E \in B)}. \tag{4}$$

This simplification allows us to compute the likelihood ratio one variable at a time. Since this estimator of Λ neglects possible correlations between parameters, it might result in the search being less sensitive, compared to the idealized case where the full 27-dimensional likelihood ratio is known. In fact, we do not perform such a factorization for the SNR and χ^2 parameters because of the strong correlation between these two variables.

Results. The LIGO-Virgo data set is divided into 24 time chunks which are analyzed independently. In particular, the training sets S and B are generated for each chunk to account for the noise non-stationarities and the evolution of the detector sensitivities. The upper plot in Fig. 1 shows the combined cumulative event rate as a function of the ranking statistic $\Lambda(\vec{x})$. We also plot the distribution obtained with time-shifted data to measure the event compatibility with the expected background. The highest-ranked event of the search occurred on May 10th, 2007 at 16:27:15 UTC and is detected simultaneously by the three LIGO interferometers. The ranking value of this event is less than one sigma away from the expected background distribution. Therefore, we cannot

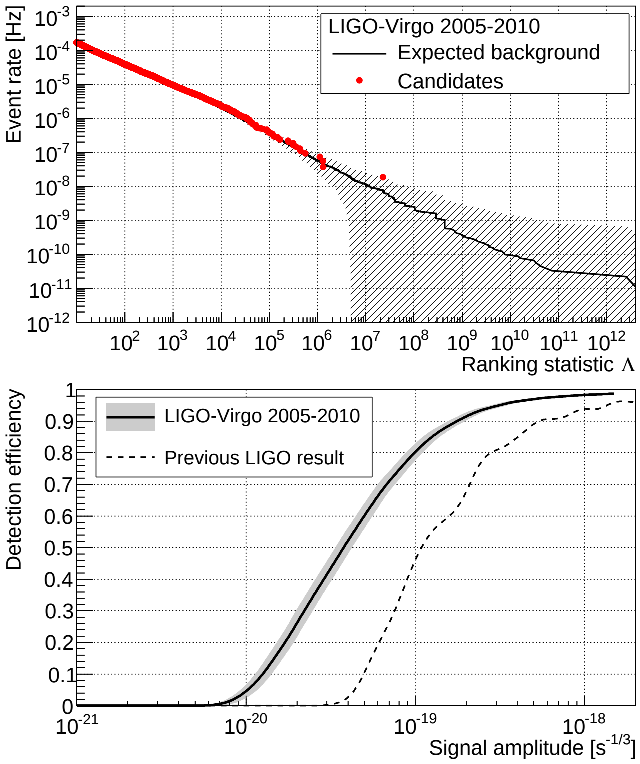

FIG. 1. In the upper plot, the red plain circles show the cumulative event rate as a function of the ranking statistic Λ. The black line shows the expected background of the search with the 1-σ statistical error represented by the hatched area. The highest-ranked event ($\Lambda_h \simeq 2.3 \times 10^7$) is well compatible with the background. The lower plot shows the sensitivity of the search as a function of the signal amplitude. This is measured by the fraction of simulated cusp events recovered with $\Lambda > \Lambda_h$. This is to be compared to the sensitivity of the previous LIGO search [32] represented by the dashed line.

claim this event to result from a GW signal produced by cosmic strings.

To determine the search sensitivity and derive an upper limit, about 7 million simulated cusp signals are injected into a time-shifted data set as described previously. To avoid self-selection issues, we use a set of injections which is independent from the S sample used to train the likelihood ranking. We run the search using the same likelihood functions as for the non-shifted analysis and count how many simulated signals are detected with Λ larger than the highest-ranked event [40]. The lower plot in Fig. 1 shows the detection efficiency e as a function of the injected signal amplitude A. The uncertainties associated with the efficiency curve include binomial counting fluctuations, calibration uncertainties and an amplitude binning uncertainty. This result shows that the search sensitivity has improved by a factor 3 with respect to previous LIGO results [32]. Half of this gain is explained by the increased sensitivity of the detectors, the rest of the gain is due to the improved search method.

To derive an upper limit on the cosmic string parameters, we use the method described in [31] and already used in [32]. Given the search efficiency $e(A)$, we should expect to observe an effective rate of GW bursts given by the integral over the reshift z:

$$\gamma(G\mu, \varepsilon, p) = \int_0^\infty e(z; G\mu, \varepsilon) \frac{dR(z; G\mu, \varepsilon, p)}{dz} dz, \qquad (5)$$

where $dR(z; G\mu, \varepsilon, p)$ is the cosmological rate of events with a redshift between z and $z + dz$ and is derived in [31]. In addition, knowing how the GW amplitude A scales with redshift (Eq. 1), the efficiency curve in Fig. 1 can be constructed as a function of the redshift and parameterized with $G\mu$ and ε. As a result, the parameter space $(G\mu, \varepsilon, p)$ can be scanned and the effective rate γ computed. The parameter space is ruled out at a 90% level when the effective rate exceeds $2.303/T$ which is the expected rate from a Poisson process over an observation time T. In addition to the ignorance constant g_1 in equation 1, the $dR(z; G\mu, \varepsilon, p)$ expression given in [31] includes two other ignorance constants: g_2, and the average number of cusps per loop oscillation n_c. These three constants are expected to be of $\mathcal{O}(1)$ provided the loops are smooth. Instead of fixing these factors to 1 as it is usually done, we choose to absorb these unknown factors in modified cosmic string parameters: $G\tilde{\mu} = g_1 g_2^{-2/3} G\mu$, $\tilde{\varepsilon} = g_1^{-1} g_2^{5/3} \varepsilon$ and $\tilde{p} = (n_c g_1)^{-1} g_2^{-1/3} p$.

Fig. 2 displays the region of the cosmic string parameter space which is excluded by our analysis (grey-shaded areas). For comparison, we also show limits, fixing $\tilde{p}$ at 10^{-3}, derived from constraints on the GW stochastic background spectrum. These limits were computed adopting the same cosmic string model and using the same parameters $(G\tilde{\mu}, \tilde{\varepsilon}, \tilde{p})$. Our result improves the indirect CMB bound [26, 27] by a factor 3 for intermediate $\tilde{\varepsilon}$ values. It nicely complements existing limits provided by pulsar timing experiments for large $\tilde{\varepsilon}$ [7, 25] and by the LIGO stochastic search in the very small loop regime [26].

Conclusion. In summary, no evidence for GW bursts produced by cosmic (super)string cusps is found in recent LIGO-Virgo data. However, it is possible to significantly constrain parameters of cosmic string models and to surpass existing limits from CMB data. Future LIGO-Virgo results will probe even further the cosmic string parameter space. Firstly, in addition to cusp signals, GW produced by kinks might be worth searching for in the case of superstring loops with junctions [41]. Secondly, the sensitivity to cosmic string signals is expected to improve with the future Advanced LIGO [38] and Advanced Virgo [42] detectors. The improved sensitivity of Advanced detectors will allow us to search for cosmic strings with an order of magnitude lower tension.

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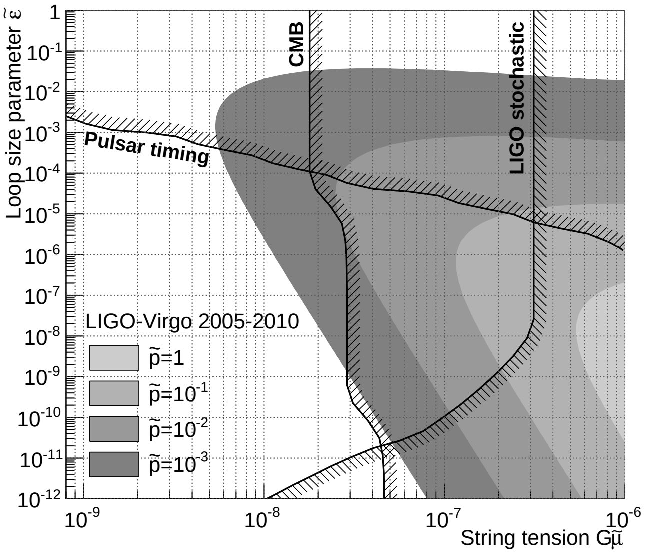

FIG. 2. Constraints on the modified cosmic string parameters $G\tilde{\mu} = g_1 g_2^{-2/3} G\mu$, $\tilde{\varepsilon} = g_1^{-1} g_2^{5/3} \varepsilon$ and $\tilde{p} = (n_c g_1)^{-1} g_2^{-1/3} p$ where g_1, g_2 and n_c are numerical factors of $\mathcal{O}(1)$. The grey regions, corresponding to 4 reconnection probability values, are rejected by our analysis at a 90% level. The black lines show the bounds derived from the constraints on the GW stochastic background spectrum for $\tilde{p} = 10^{-3}$ and for a small-loop scenario (CMB, pulsar and LIGO data). The rejected region is always on the right-hand side of these lines.

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