Latest observational signatures of cosmic strings : gravitational waves and particle emission

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Outline

Introduction to cosmic strings

Spontaneous symmetry breaking

The Abelian-Higgs model

$$\mathcal{L} = -\frac{1}{4}\mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu} + (\mathcal{D}_\mu \phi)^* \mathcal{D}^\mu \phi - \frac{\lambda}{4}\left(|\phi|^2 - \eta^2\right)$$

- ϕ is a complex scalar field
- The action is $U(1)$-invariant
- At high temperature, i.e. in the early Universe, the symmetry is preserved
- As the temperature decreases, the symmetry is spontaneously broken

Cosmic strings [Kibble, 1976]

1D topological defects

- After the phase transition the field *falls* into the new vacuum manifold $\mathcal{M}$
- Strings arise if $\mathcal{M}$ is not simply connected, i.e. $\mathcal{M}$ contains holes around which loops can be trapped
- We expect strings to be formed in most models of spontaneous symmetry breaking

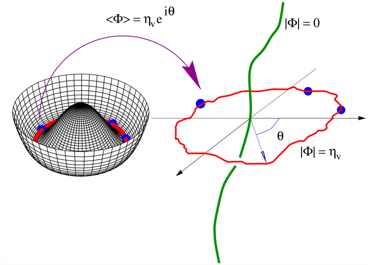

Figure: [Ringeval, 2010]

The one-dimensional limit

Nambu-Goto action

Energy scale	Width	Linear density
GUT : 10^{16} GeV	5×10^{-31} m	$G\mu = 10^{-9}$
EW : 100 GeV	5×10^{-18} m	$G\mu = 10^{-35}$

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$$\mathcal{S} = -\mu \int \sqrt{-\det(\gamma)} \mathrm{d}^2\zeta$$

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In Minkowski space-time, under appropriate gauge choices

$$\ddot{\vec{X}} - \vec{X}'' = 0$$

Typical properties of cosmic strings

Loop formation and decay

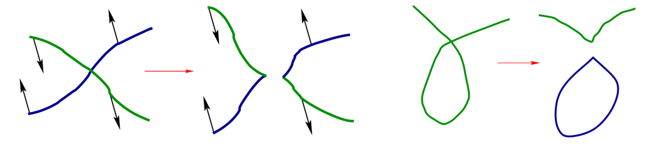

Figure: "As the strings move they will sometimes cross. When they do, they may be apt to change partners" [Kibble, 1976]

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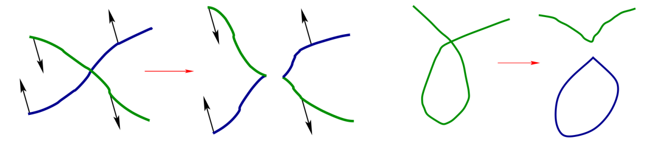

Figure: "As the strings move they will sometimes cross. When they do, they may be apt to change partners" [Kibble, 1976]

Closed loop oscillates with a period $T = \frac{\ell}{2}$. These oscillations lead to gravitational radiation.

$$\dot{E} \propto G \left(\frac{\mathrm{d}^3 D}{\mathrm{d}t^3} \right)^2 = \Gamma G \mu^2$$

Probing the gravitational wave background from cosmic strings with LISA

P. A. , J. J. Blanco-Pillado , D. G. Figueroa, A. C. Jenkins, M. Lewicki, M. Sakellariadou, S. Sanidas, L. Sousa, D. A. Steer, J. M. Wachter, S. Kuroyanagi

arxiv:1909.XXXXXX

The stochastic background of gravitational waves

Method 1 [Blanco-Pillado and Olum, 2017]

- All the energy radiated by loops is converted to gravitational waves
- An effective average power P_m emitted in mode m determined by simulations and/or analytical arguments
- Can include effects of gravitational back-reaction

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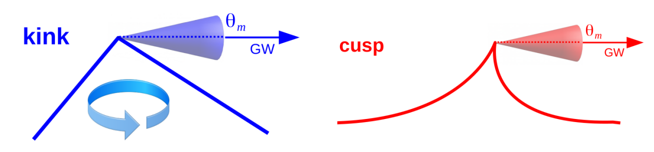
$$\rho_{\mathrm{GW}}(f) = G\mu^2 \sum_{m=1}^{\infty} \mathrm{P}_m C_m(f)$$

$$\Omega_{\mathrm{GW}} = \frac{8\pi G}{3\mathrm{H}_0^2} f \rho_{\mathrm{GW}}$$

$$C_m(f) = \frac{2m}{f^2} \int_0^{z_*} \frac{\mathrm{d}z}{\mathrm{H}(z)(1+z)^6} \frac{\mathrm{d}n}{\mathrm{d}\ell} \left(\frac{2m}{(1+z)f}, t(z) \right)$$

The stochastic background of gravitational waves

Method 2 [Damour and Vilenkin, 2001]



For a given loop distribution, the idea is to calculate the *GW burst rate*

$$\frac{\mathrm{d}^2 R}{\mathrm{d}z \mathrm{d}h}(h, z, f)$$

The stochastic background is the sum of all the unresolvable bursts of GW from the cosmic strings.

Loop number density

Analytical modeling – Nambu-Goto strings

Usually the cosmic strings are divided into two populations

- *Infinite strings* closed loops larger than the horizon. They are mainly stretched by the expansion of the Universe and lose of energy through formation of loops.

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The two are linked through the loop production function $\mathcal{P}(\ell, t)$.

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Scaling of the infinite strings

Prediction of analytical model and observed in numerical simulations

$$\rho_\infty \propto t^{-2} \text{ and typical length scales are proportional to } t$$

if we assume either radiation or matter-domination. This is not true during the case the transition from radiation to matter.

Analytical modeling

Loops

Boltzmann equation for the evolution of the population of loops

$$\frac{\mathrm{d}}{\mathrm{d}t}\left[a^3\frac{\mathrm{d}n}{\mathrm{d}\ell}(\ell,t)\right]=a^3\mathcal{P}(\ell,t)$$

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Loops decay by radiating gravitational waves $\frac{\mathrm{d}\ell}{\mathrm{d}t} = -\Gamma G\mu$

$$\frac{\partial}{\partial t}\left(a^3\frac{\mathrm{d}n}{\mathrm{d}\ell}\right) - \Gamma G\mu\frac{\partial}{\partial \ell}\left(a^3\frac{\mathrm{d}n}{\mathrm{d}\ell}\right) = a^3\mathcal{P}(\ell,t)$$

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One need to either assume or measure the loop production function to compute the loop number density.

Loop distributions

Model I: Velocity dependent one-scale model [Kibble, 1985, Martins and Shellard, 1996]

The basic idea is to suppose that

- The properties of the network can be described by two parameters, typical separation lengthscale and velocity

$$L \equiv \sqrt{\frac{\mu}{\rho_\infty}}, \bar{v}$$

- These parameters obey some non-linear equations, and rapidly fall into the attractor solution
- The loop production function can be normalized by energy conservation arguments
- All the loops are produced with the same size

$$t^5 \mathcal{P}(\ell, t) = C\delta(\ell - L(t))$$

Loop distributions

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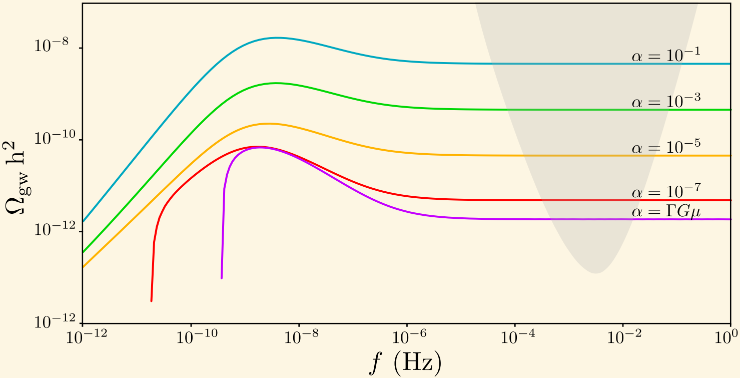

Figure: Dependence on the size of the loops

Loop distributions

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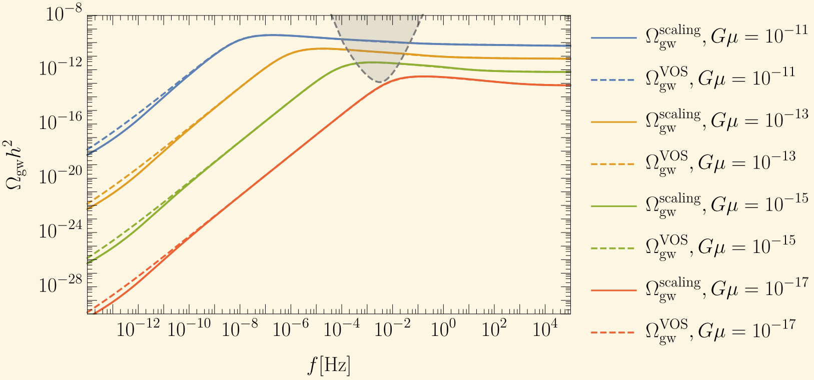

Figure: Dependence on the dynamics of the radiation to matter transition

Loop distributions

Model II: simulation-inferred model of [Blanco-Pillado et al., 2014]

- Authors performed NG simulations of cosmic string networks in the radiation and matter eras
- They obtained the loop production functions for non-self-intersecting loops directly from these simulations
- As NG simulations probe large scales, they supposed the loop production function is cutoff below the gravitational radiation scale.

$$\frac{\mathrm{d}n}{\mathrm{d}\ell}_{\mathrm{rad}} = \frac{0.18}{t^{3/2}(\ell + \Gamma G\mu t)^{5/2}}$$

$$\frac{\mathrm{d}n}{\mathrm{d}\ell}_{\mathrm{rad,mat}} = \frac{0.18}{(\ell + \Gamma G\mu t)^{5/2}}(2\sqrt{\Omega_{\mathrm{rad}}})(1+z)^3$$

$$\frac{\mathrm{d}n}{\mathrm{d}\ell}_{\mathrm{mat}} = \frac{0.27 - 0.45(\ell/t)^{0.31}}{t^2(\ell + \Gamma G\mu t)^2}$$

Loop distributions

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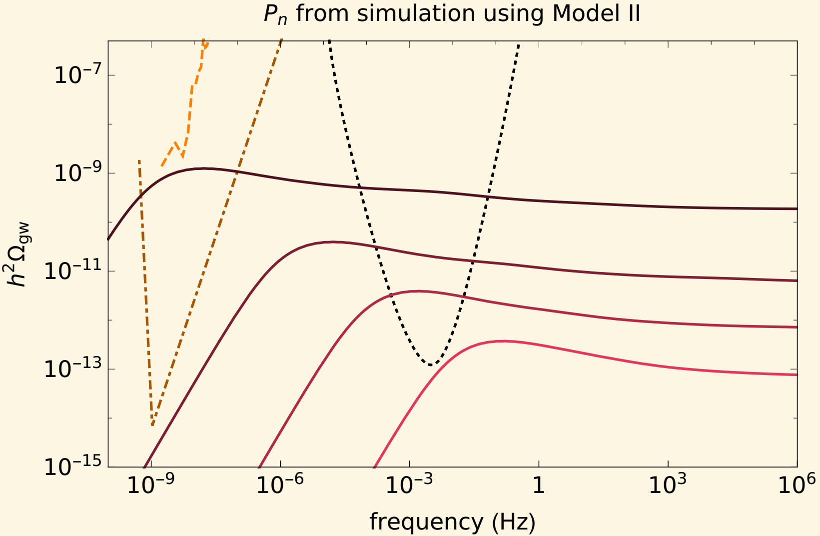

Figure: Cosmic string SBGW for various values of $G\mu$

Loop distributions

Model III: simulation-inferred model of [Ringeval et al., 2007, Lorenz et al., 2010]

Based on analytical work by [Polchinski and Rocha, 2006]

$$t^5\mathcal{P}(\ell,t) = c\left(\frac{\ell}{t}\right)^{2\chi-3}, \ \chi_{\rm rad} = 0.2, \chi_{\rm mat} = 0.295$$

The Boltzmann equation can be solved analytically and NG simulations used to fit the loop number density.

- χ is a parameter set by the numerical simulations
- A cutoff has to be taken on small scales γ_c. For instance $\gamma_{\rm c} \sim (G\mu)^{1+2\chi}$
- For similar large-scale behavior, an extra population of small-loops can be present

Loop distributions

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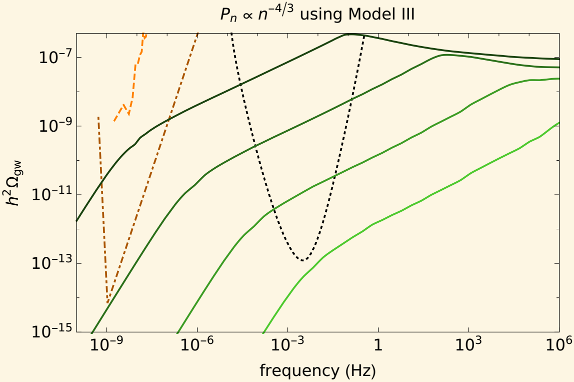

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Projected constraints on the string tension

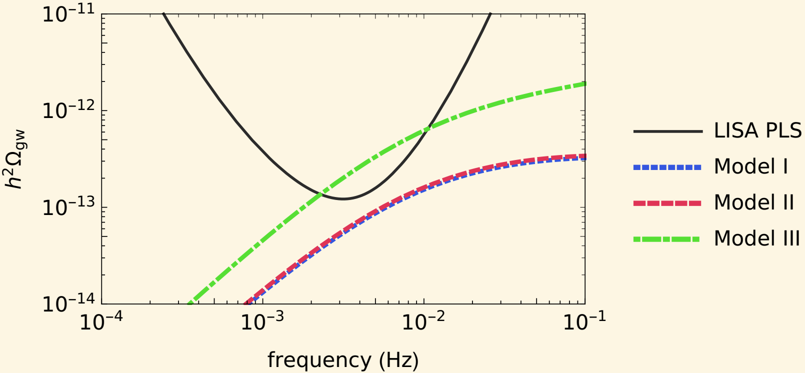

Figure: A comparison of the LISA sensitivity curve to the SBGW predicted by all three models using $G\mu = 10^{-17}$, $\mathrm{P}_m \propto n^{-4/3}$. LISA could only constain string tensions higher than $G\mu = 10^{-17}$

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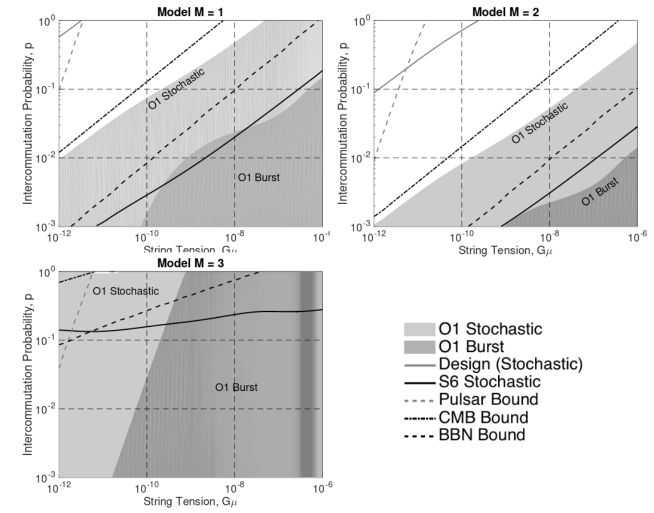


Figure: [Abbott et al., 2018]

New results on modeling the loop number density and its SBGW

P.A., C. Ringeval, M. Sakellariadou, D.A. Steer
arXiv: 1903.06685 [Auclair et al., 2019]
Under preparation

New results on modeling the loop number density

Promoting χ to a free parameter in model III [Auclair et al., 2019]

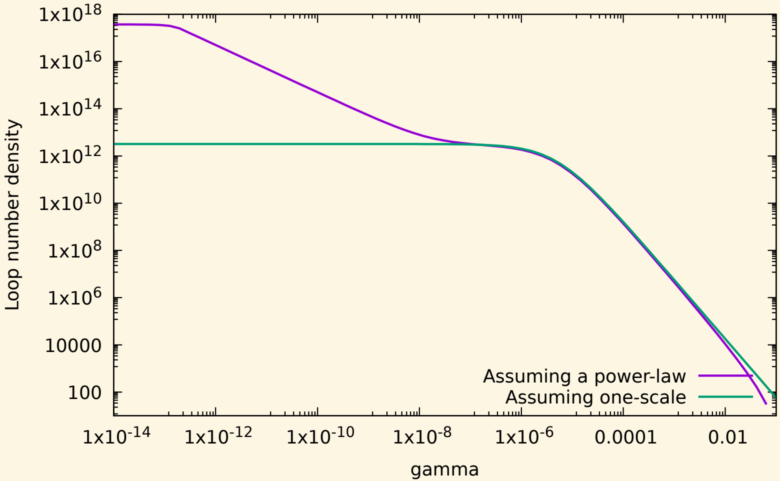
Model III solves the Boltzmann equation assuming the loop production function is a power-law with fixed values for $\chi_{\rm rad} < 1/4$ and $\chi_{\rm mat} < 1/2$

$$t^5 \mathcal{P}(\ell, t) = c \left(\frac{\ell}{t}\right)^{2\chi - 3}$$

- The model can be generalized for higher values of χ
- Model II is a point $\chi_{\rm rad}, \chi_{\rm mat}$
- One can explore this parameter space and obtain more understanding

Preliminary results

The extra population of small loops



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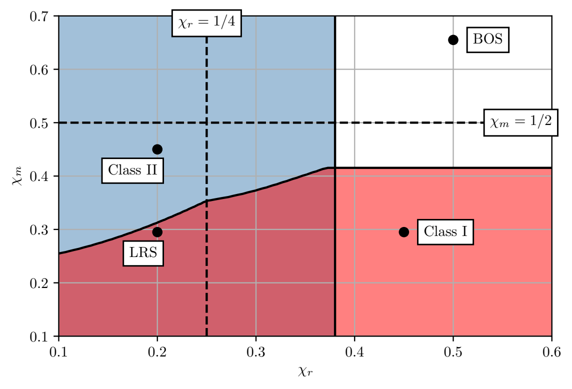
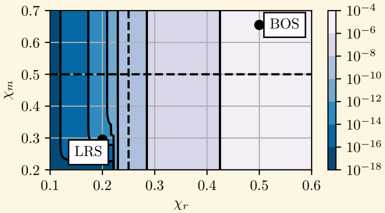


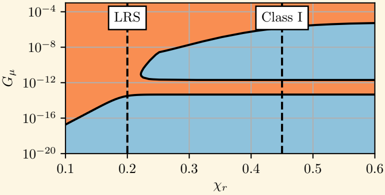
Preliminary results

Constraints on the string tension in the parameter space

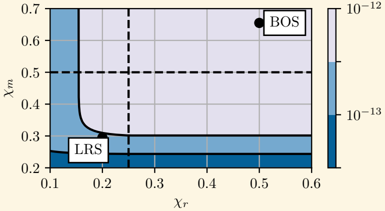
(a) LIGO/Virgo, $\Omega_{\mathrm{gw}} = 10^{-7}$, $f = 20$ Hz



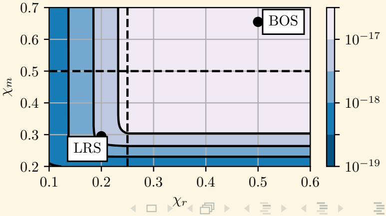
(b) LIGO/Virgo at $\chi_{\mathrm{m}} = 0.295$.



(c) PTA, $\Omega_{\mathrm{gw}} = 10^{-12}$, $f = 2 \times 10^{-9}$ Hz



(d) LISA, $\Omega_{\mathrm{gw}} = 10^{-13}$, $f = 10^{-2}$ Hz



Consequences on the SBGW and particle production from new simulations of Abelian-Higgs strings

P.A, D.A. Steer, T. Vachaspati

In preparation

New FT simulations of individual loops

Formation, evolution and decay [Matsunami et al., 2019]

- Throwing 4 straight strings at each other, they were able to follow a loop from its formation to its decay
- The dominant channel for energy loss is the collision of kinks
- ℓ_0 is a new lengthscale for the energy loss

$$\ell_0 = \frac{\nu\sqrt{\mu}}{\Gamma G\mu}$$

$$\frac{\mathrm{d}\ell}{\mathrm{d}t} = -\Gamma G\mu \frac{\ell_0}{\ell}$$

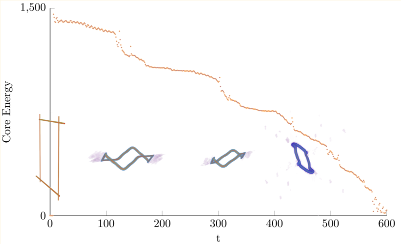


Figure: Energy of a loop with the initial size of 390 lattice spacings plotted vs time.
[Matsunami et al., 2019]

Consequences on the number of loops

Modeling the loop number density with both GW and particle emission

Considering both gravitational radiation and particle emission

$$\frac{\mathrm{d}\ell}{\mathrm{d}t} = -\Gamma G\mu \left(1 + \frac{\ell_0}{\ell}\right)$$

The Boltzmann equation can be rewriten to take both effects into account

$$\frac{\partial}{\partial t}\left(a^3 \frac{\mathrm{d}n}{\mathrm{d}\ell}\right) + \frac{\partial}{\partial t}\left(a^3 \frac{\mathrm{d}\ell}{\mathrm{d}t}\frac{\mathrm{d}n}{\mathrm{d}\ell}\right) = a^3 \mathcal{P}(\ell, t)$$

And can be solved analytically for simple loop production functions

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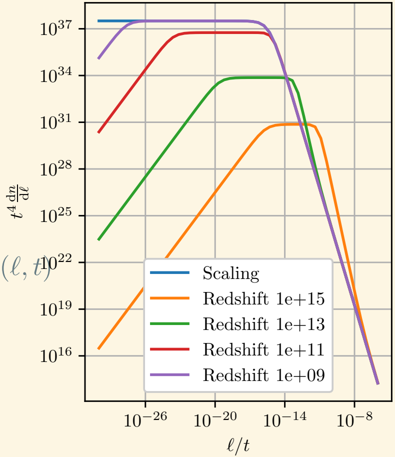

Figure: $G\mu = 10^{-17}$

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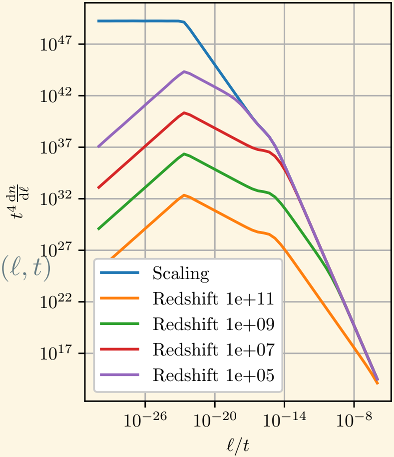


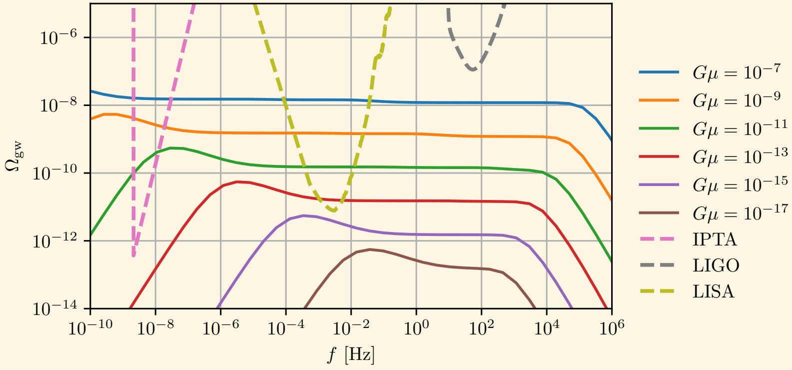
Figure: $G\mu = 10^{-17}$

Impact on the SBGW

Breaking of the high frequency plateau (preliminary results)

A consequence of the introduction of ℓ_0 is that the high frequency plateau is cutoff at

$$f = \sqrt{\frac{2\mathrm{H_r}c}{\ell_0 \Gamma G\mu}} \propto (G\mu)^{1/4}$$



Particle emission bounds

Injected energy by cosmic strings and updated bounds on $G\mu$
[Mota and Hindmarsh, 2015, Vachaspati, 2010]

The energy density injected by cosmic strings produced per unit of time

$$\begin{aligned}\Phi_{\mathrm{H}}(t) &= \int_0^{\alpha t} \left(-\frac{\mathrm{d}\ell}{\mathrm{d}t}(\ell')\mu\right)_{\text{particle}} \frac{\mathrm{d}n}{\mathrm{d}\ell}\mathrm{d}\ell' \\ &= \Gamma G\mu^2 \ell_0 \int_0^{\alpha t} \frac{\mathrm{d}n}{\mathrm{d}\ell}\frac{\mathrm{d}\ell'}{\ell'}\end{aligned}$$

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$$= \Gamma G\mu^2 \ell_0 \int_0^{\alpha t} \frac{\mathrm{d}n}{\mathrm{d}\ell}\frac{\mathrm{d}\ell'}{\ell'}$$

From this quantity you can calculate

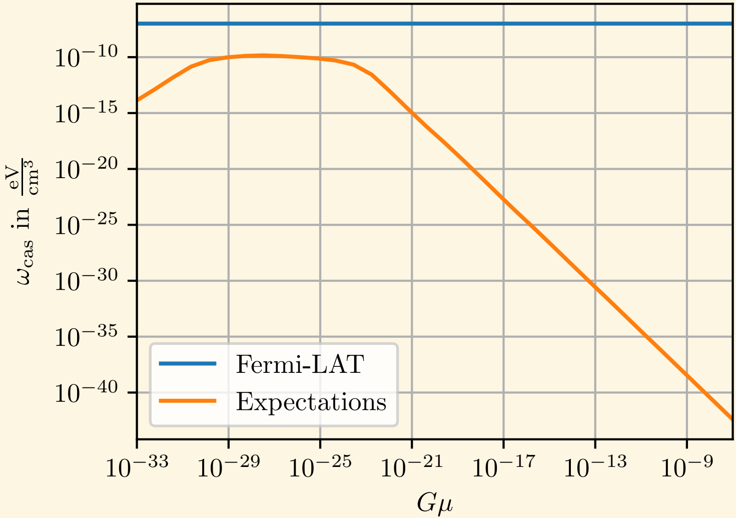
- the Diffuse Gamma Ray Background contribution from Fermi-LAT

$$\omega_{\rm DGRB} = f_{\rm eff} \int_{t_c}^{t_0} \frac{\Phi_{\rm H}(t)}{(1+z)^4}\mathrm{d}t$$

- energy injected into visible states during BBN

Preliminary result

Diffuse Gamma Ray Background



Conclusion

- LISA will be able to probe cosmic strings with $G\mu \geq 10^{-17}$. A result that does not depend on which model/method you use (if you believe in NG strings)
- One can study different models continuously in a given parameter space and test the robustness of the predictions of the different GW detectors
- Low-frequency detectors are the most robust and LISA will probe lower values of the string tension
- Introducing latest results from [Matsunami et al., 2019] does not modify theoretical expectations for the SBGW
- One can estimate jointly the bounds on $G\mu$ from particle and GW emission

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