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

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October 10, 2019, GdR OG

Outline

Introduction to cosmic strings

Gravitational wave emission from cosmic strings

Adding particle emission to Nambu-Goto strings

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References

Introduction to cosmic strings

Following :
(Kibble, 1976)
(Vilenkin & Shellard, 2001)
(Vachaspati, Pogosian, & Steer, 2015)

Cosmic strings (Kibble, 1976)

1D topological defects

- Cosmic strings are 1D topological defects that may appear after a symmetry breaking phase transition
- 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

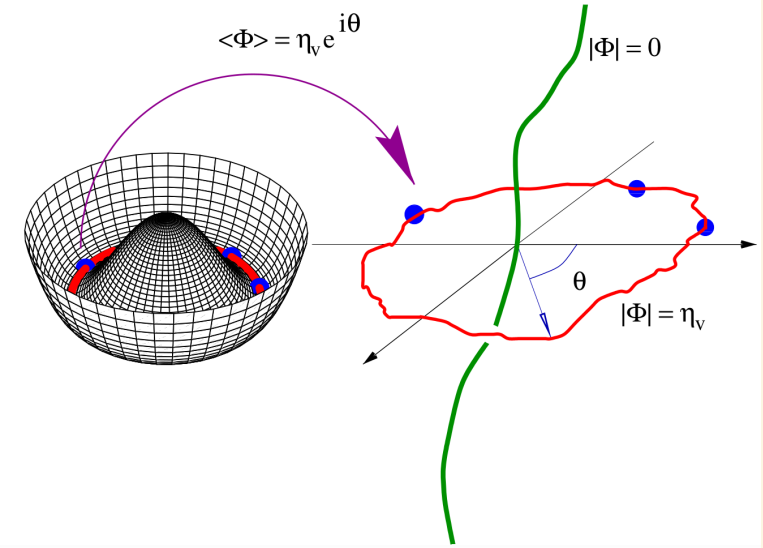


Figure: (Ringeval, 2010)

The one-dimensional limit

Nambu-Goto action

$$\text{Energy scale} \approx \sqrt{\frac{G\mu}{10^{-10}}} 10^{14}\text{GeV}$$

Energy scale	Width	Linear density
GUT : 10^{16} GeV	2×10^{-32} m	$G\mu \approx 10^{-6}$
3×10^{10} GeV	5×10^{-27} m	$G\mu \approx 10^{-17}$
10^{8} GeV	2×10^{-24} m	$G\mu \approx 10^{-22}$
EW : 100 GeV	2×10^{-18} m	$G\mu \approx 10^{-34}$

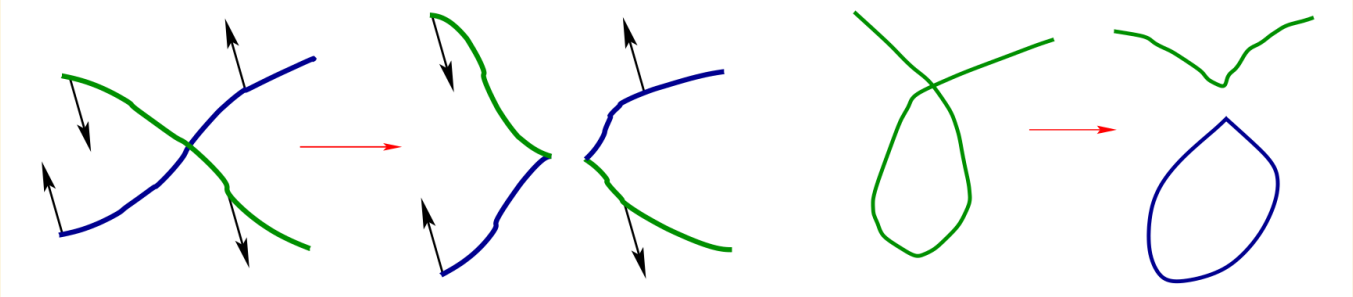
The Nambu-Goto action describes an infinitely thin object

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

$\zeta^{\mathrm{a}} = (t, \zeta)$ and γ_{ab} the induced metric on the string

Typical properties of cosmic strings

Loop formation and scaling



Scaling of the infinite strings

Attractor solution independent of initial conditions.
All length-scales proportional to t cosmic time.

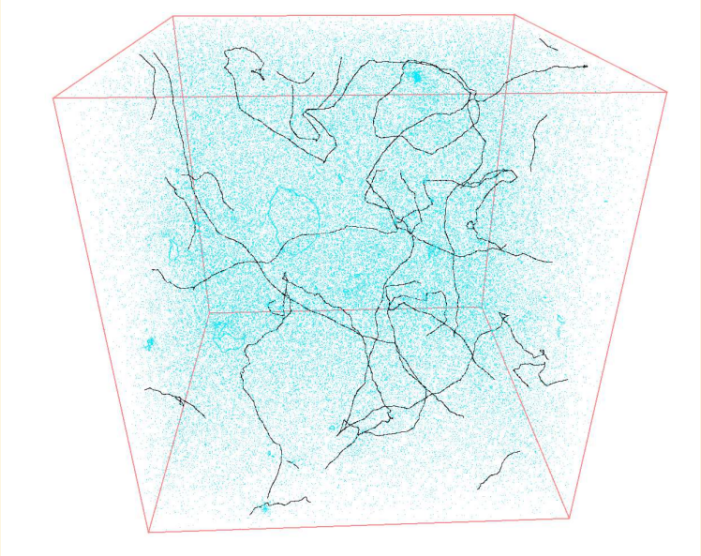


Figure: (Ringeval et al., 2007)

Observational signatures of cosmic strings

Selection of observational signatures

- CMB : line discontinuities in the temperature or polarization patterns, and statistical methods based on calculations of various correlation functions. $G\mu <$ few $\times 10^{-7}$
- 21-cm : brightness fluctuations or spatial correlations between the 21 cm and CMB anisotropies. Future experiments can in principle constrain $G\mu \approx 10^{-10} - 10^{-12}$

- The metric around a cosmic string can result in characteristic lensing patterns of distant light sources.

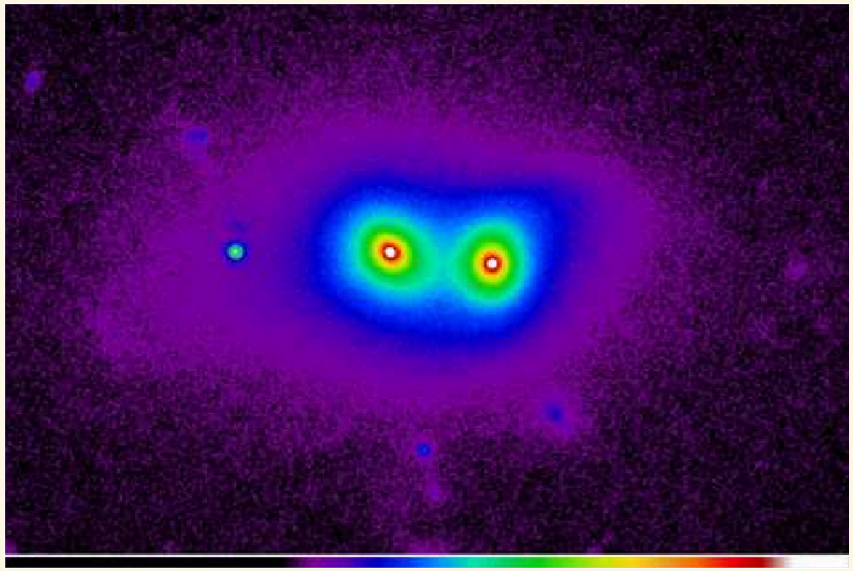


Figure: CLS-1, discovered in 2003, was once considered as a good candidate

Gravitational wave emission from cosmic strings

Following :
(Vachaspati & Vilenkin, 1985)
(Abbott et al., 2018)
(Collaboration & the Virgo Collaboration, 2019)
(Auclair et al., 2019)

Closed loops of cosmic strings

Oscillation and gravitational wave emissions

In Minkowski space-time, under appropriate gauge choices

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

For a closed loop one can show that the loop oscillates with a period $T = \frac{\ell}{2}$.
These oscillations lead to gravitational radiation. The *quadrupole formula* can give a rough estimate of the power emitted

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

Bursts of gravitational waves

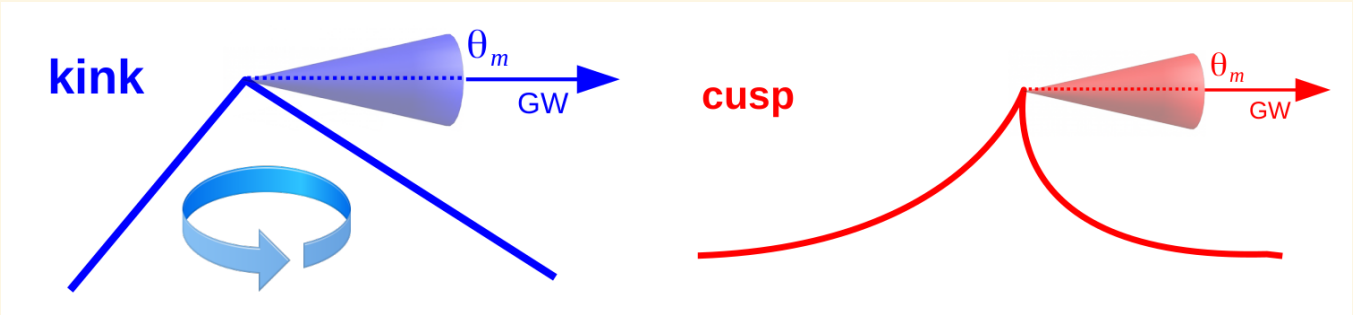


Figure: F. Robinet

For a given loop distribution, you can estimate the *GW burst rate*

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

These gravitational wave bursts are looked for in the LIGO/Virgo data

The stochastic background of gravitational waves

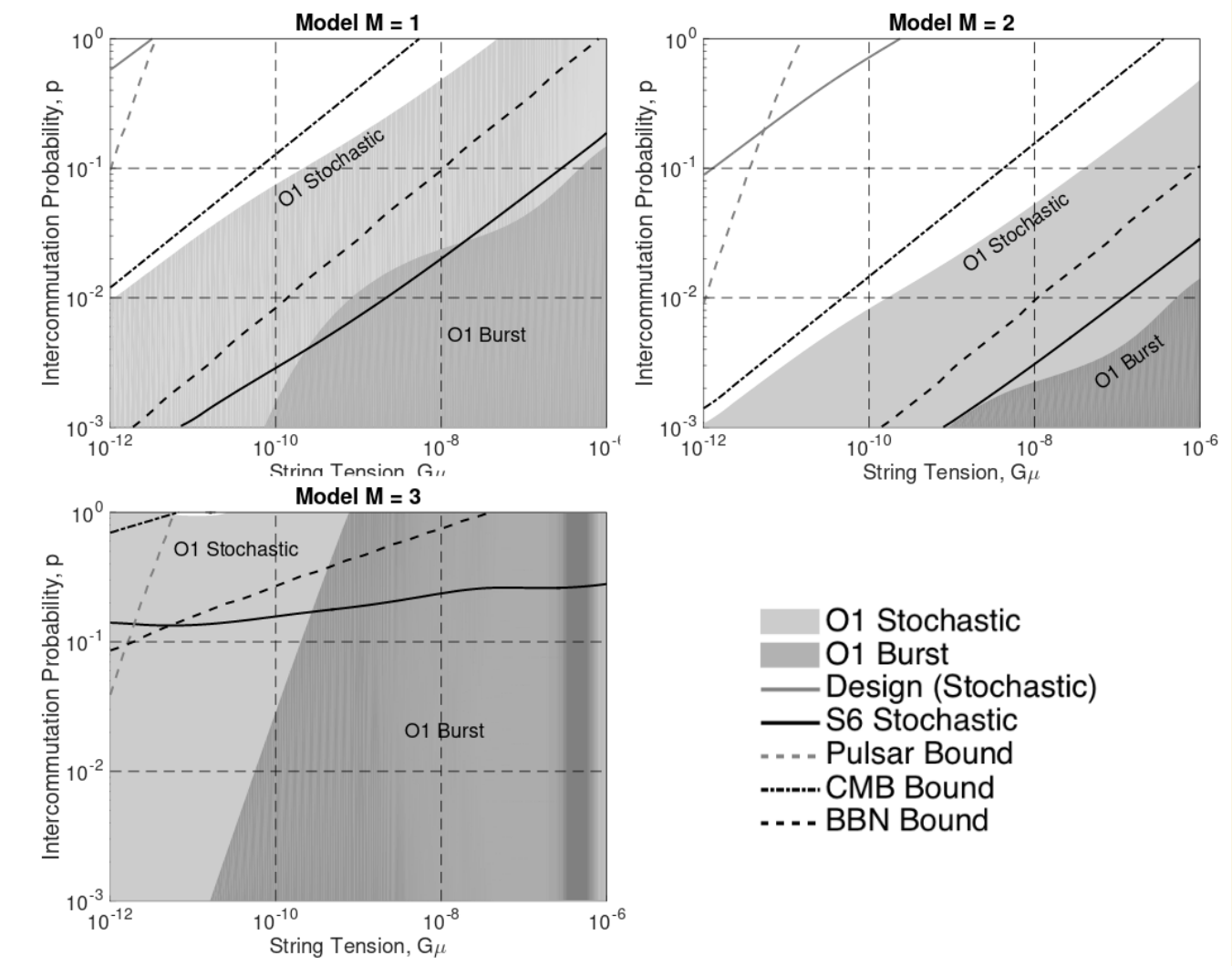
- All the energy radiated by loops is converted to gravitational waves
- An effective average power P_m emitted in mode m determined by simulations and/or analytical arguments
- Can include effects of gravitational back-reaction

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

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

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

Existing constraints on the string tension by LIGO/Virgo first run



Projected constraints by LISA

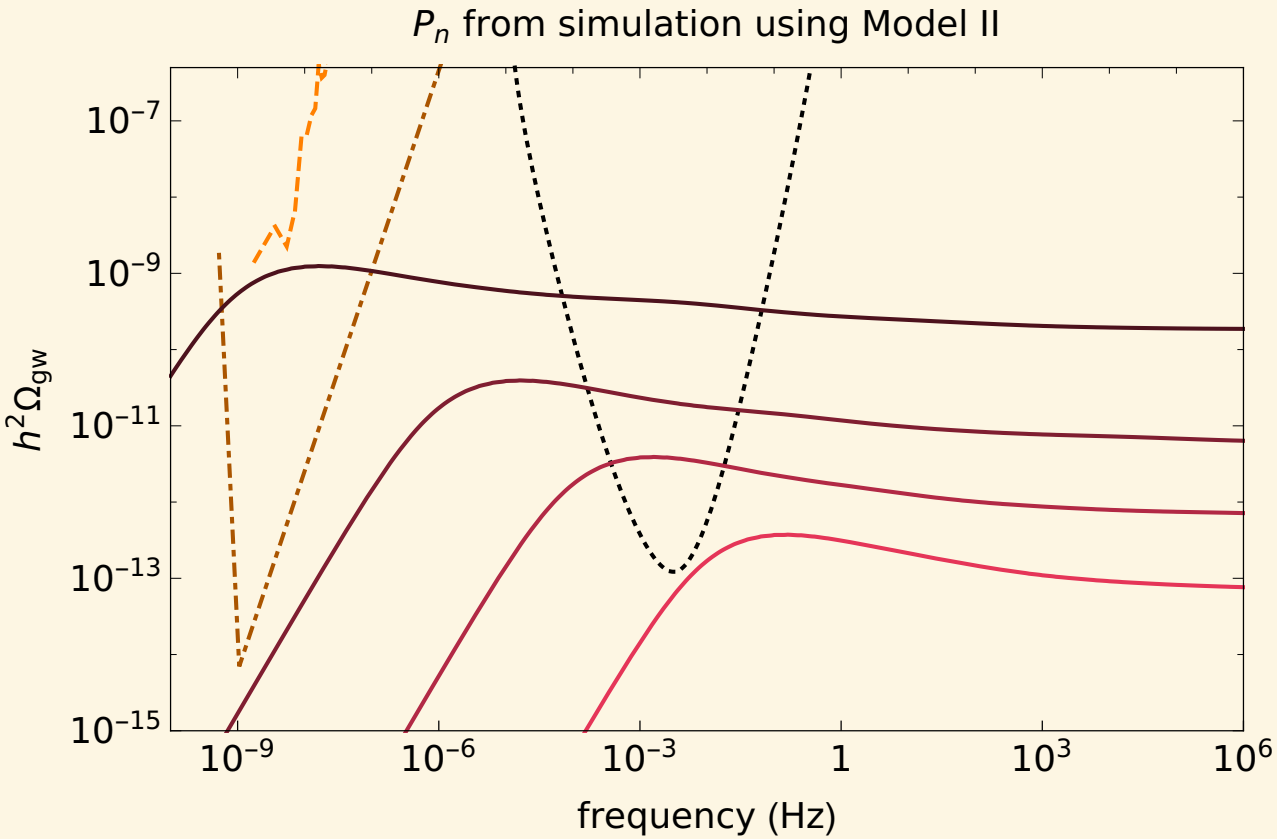


Figure: A comparison of the LISA sensitivity curve to the SBGW predicted. LISA could only constain string tensions higher than $G\mu = 10^{-17}$

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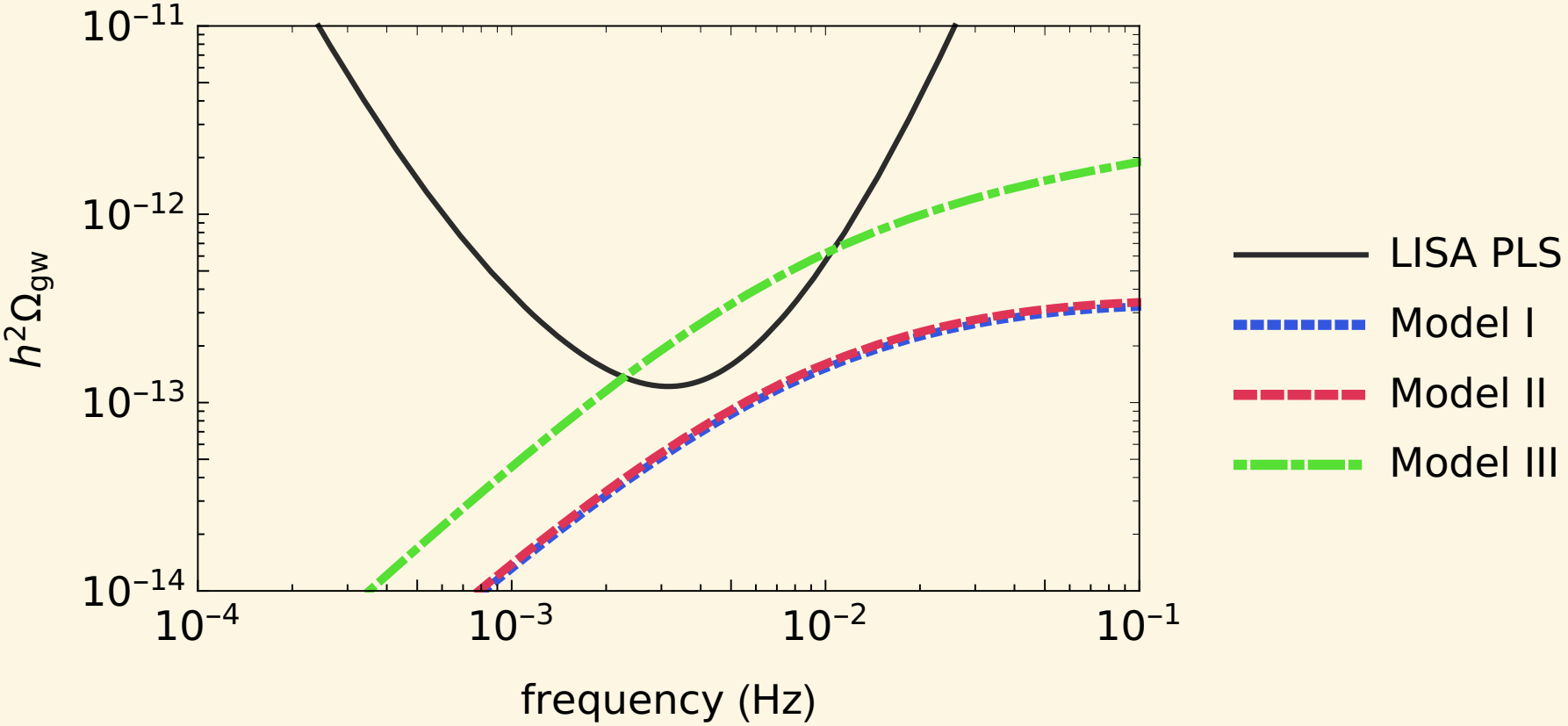

Figure: A comparison of the LISA sensitivity curve to the SBGW predicted. LISA could only constain string tensions higher than $G\mu = 10^{-17}$

Adding particle emission to Nambu-Goto strings

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

In preparation

Field-Theory (FT) simulations of individual loops

Formation, evolution and decay

- So far we studied Nambu-Goto strings, ie. infinitely thin strings
- FT simulations find that CS decay rapidly into particles (Hindmarsh, Stuckey, & Bevis, 2009)
- We propose a first step to bridge the gap between Nambu-Goto and FT

$$\frac{\mathrm{d}\ell}{\mathrm{d}t} = -\Gamma G\mu\mathcal{J}(\ell)$$

$$\mathcal{J}(\ell) \approx \begin{cases} 1 & \text{GW only} \\ 1 + \dfrac{\ell_0}{\ell} & \text{GW + kinks} \\ 1 + \sqrt{\dfrac{\ell_0}{\ell}} & \text{GW + cusps} \end{cases}$$

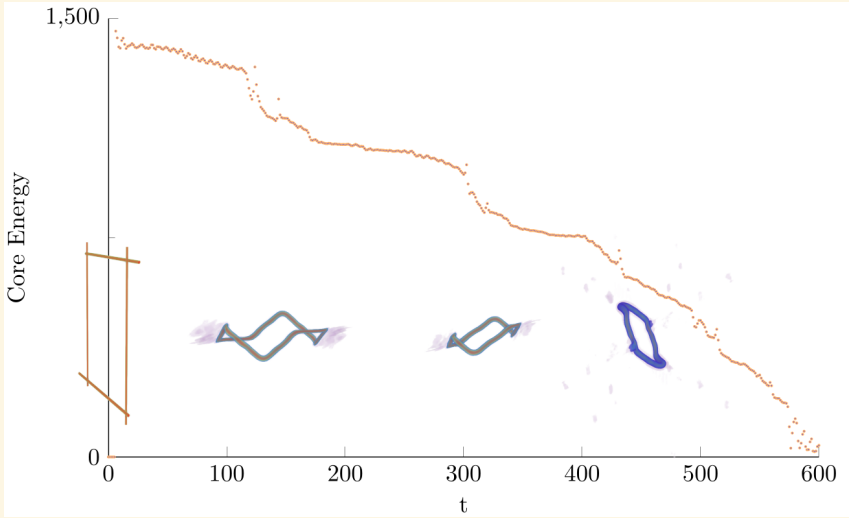

Figure: Energy of a loop with the initial size of 390 lattice spacings plotted vs time. (Matsunami et al., 2019)

Consequences on the number of loops

Modeling the loop number density with both GW and particle emission

A Boltzmann equation taking into account both GW and particle emission

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

can be solved analytically for simple loop production functions

$$\mathcal{P}(\ell,t)\propto t^{-5}\delta\left(\frac{\ell}{t}-\alpha\right)$$

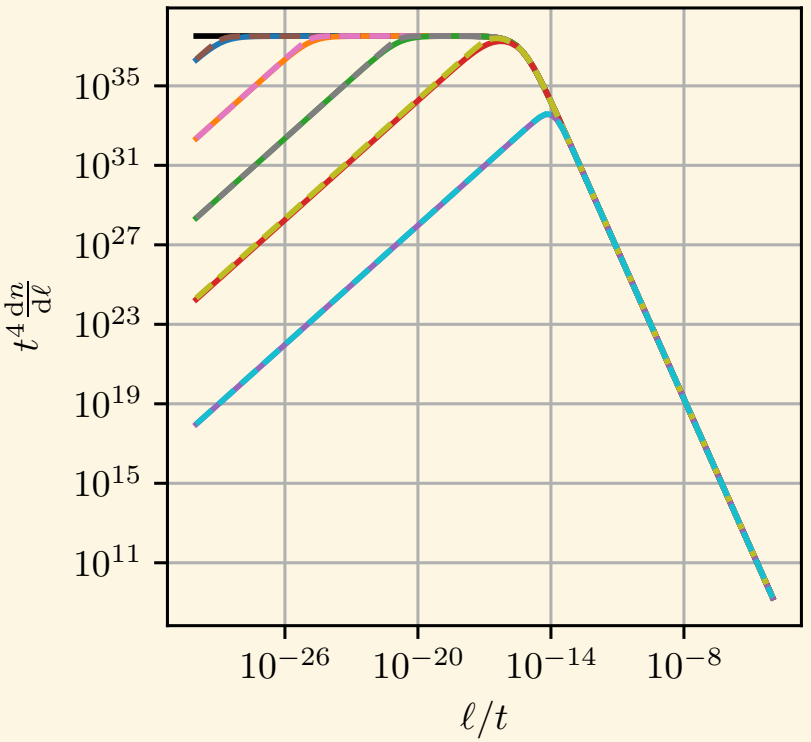

Figure: Influence of kinks, $G\mu = 10^{-17}$

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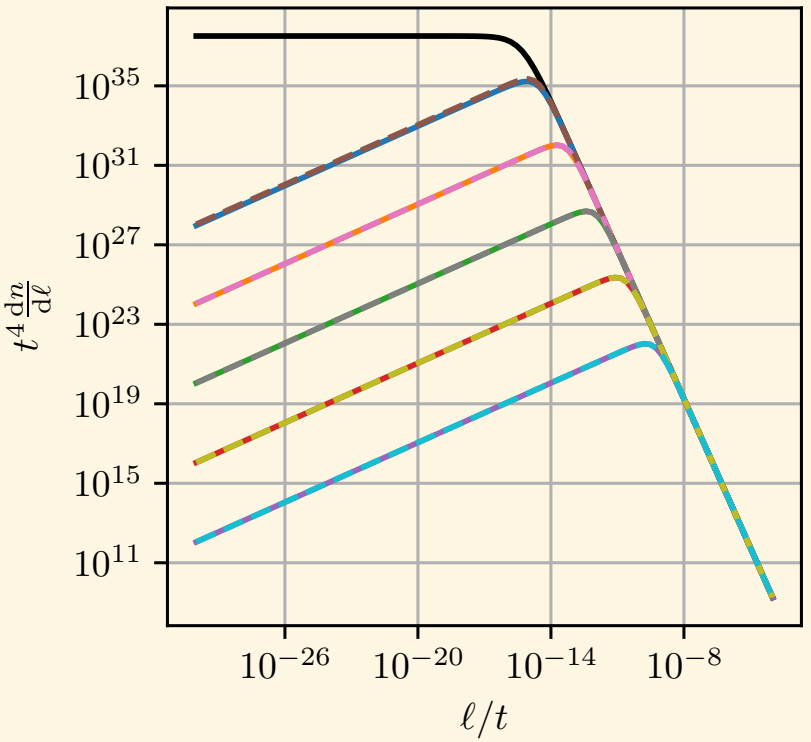


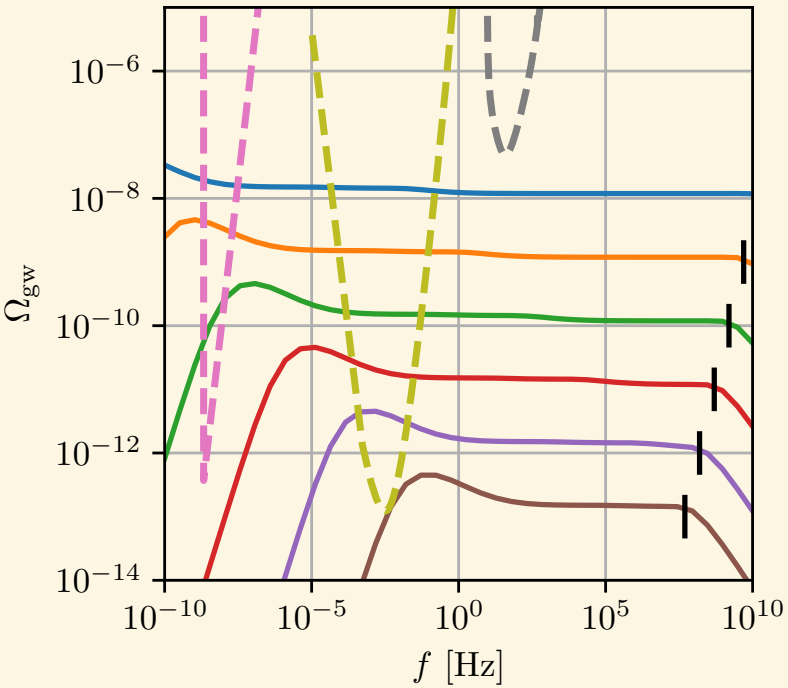
Figure: Influence of cusps, $G\mu = 10^{-17}$

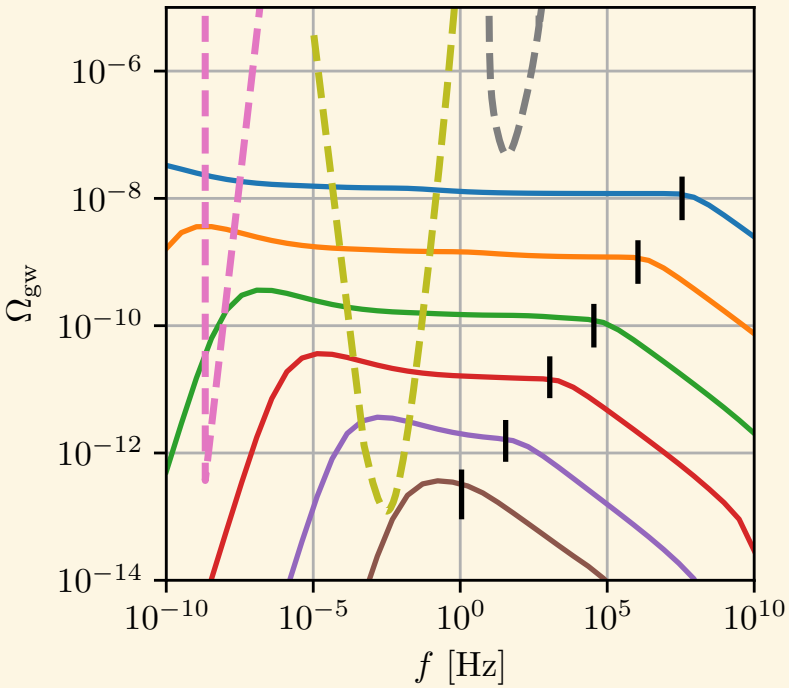
Impact on the SBGW

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

$$f = \sqrt{\frac{2\mathrm{H_r}c}{\ell_0 \Gamma G \mu}}$$





Particle emission bounds

Injected energy by cosmic strings and updated bounds on $G\mu$ (Mota & Hindmarsh, 2015; Vachaspati, 2010)

The energy density injected by cosmic strings per unit of time

$$\Phi_{\rm H}(t) = \int_0^{\alpha t} \left(-\frac{{\rm d}\ell}{{\rm d}t}(\ell')\mu \right)_{\rm particle} \frac{{\rm d}n}{{\rm d}\ell} {\rm d}\ell'$$

The Diffuse Gamma Ray Background contribution from Fermi-LAT

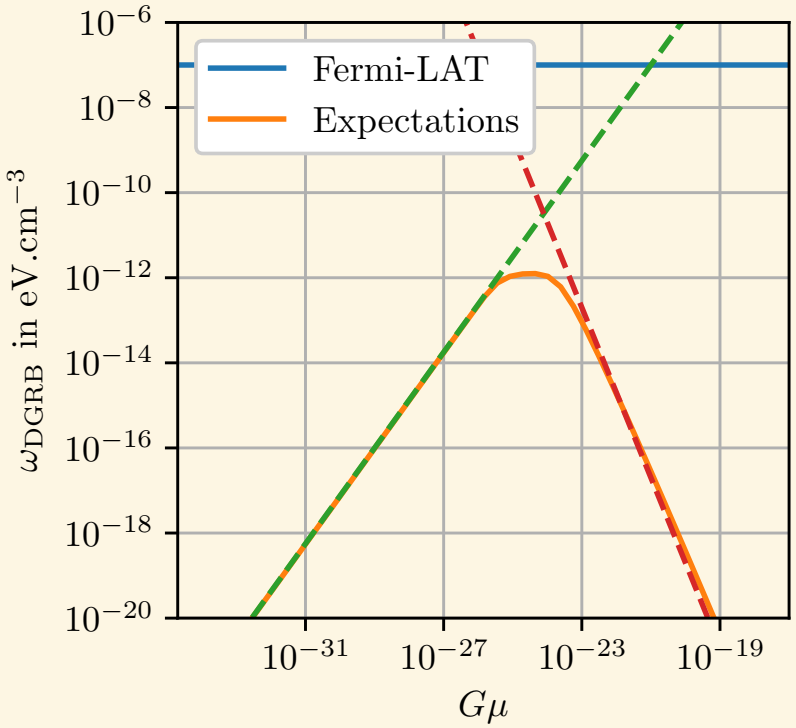
$$\omega_{\rm DGRB} = f_{\rm eff} \int_{t_c}^{t_0} \frac{\Phi_{\rm H}(t)}{(1+z)^4} {\rm d}t$$

in which $f_{\rm eff} = O(1)$

Preliminary results

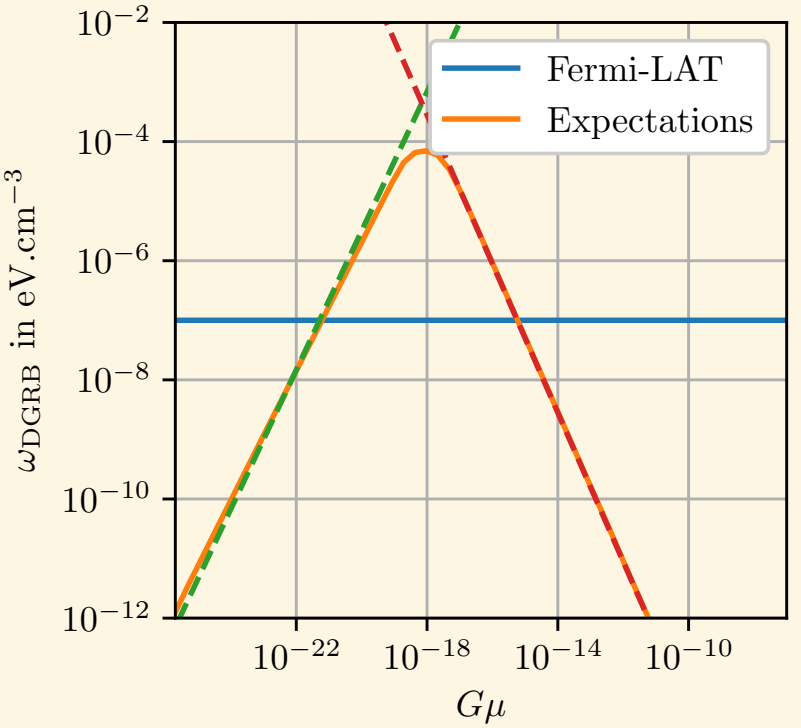
Diffuse Gamma Ray Background

$\ell_0 \propto (G\mu)^{-3/2}$



(a) Emission of particles from kinks. No observational signatures

$\ell_0 \propto (G\mu)^{-5/2}$



(b) Emission of particles from cusps. Can constrain $G\mu$ from 10^{-22} to 10^{-16}

Conclusion

- Cosmic strings have the potential to give us valuable information on fundamental physics at high energies
- A stochastic background of gravitational waves is a promising observational signature of cosmic strings
- LISA will be able to probe cosmic strings with $G\mu \geq 10^{-17}$, orders of magnitude lower than other experiments
- Introducing particle emission within the Nambu-Goto framework 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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