Outline
Cosmic Strings
Current $G\mu$ constraints
Projected constraints
Other results
Conclusions

CONSTRAINTS ON THE COSMIC STRING TENSION BY FUTURE PTA EXPERIMENTS

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- Current constraints on the cosmic string tension by the EPTA SGWB limit.
  (difficulties and method)
- Projected constraints by future PTA experiments.
  (complications and details)
- Comparison with the projected constraints of present/future GW experiments + CMB studies.

Why do we look for them?

Outline
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- Cosmic strings are 1-dimensional topological defects (other defects:domain walls, magnetic monopoles...). Extremely thin ($\sim 10^{-30}$m for GUT strings), string-like concentrations of energy of cosmological sizes.
- Generic in many cosmological models:
  1)Spontaneous Symmetry Breaking in Phase Transitions in the Early Universe (GUT, Electroweak) (field theory strings)
  2)Brane-inflation scenarios (D- and F- cosmic superstrings)
- They provide a *unique* laboratory for High Energy Physics in the Early Universe

Cosmic Strings	*Cosmic superstrings*
1)Exact energy scale of the phase transition	1)Fundamental string coupling 2)Compactification/Warping scales

Directly related to the linear energy density of cosmic strings $G\mu/c^2$

Physics at $\sim 10^{16}\mathrm{GeV}$ energy scale!!! LHC$\sim$TeV energy scale

Cosmic String Network

Outline
Cosmic Strings
Current $G\mu$ constraints
Projected constraints
Other results
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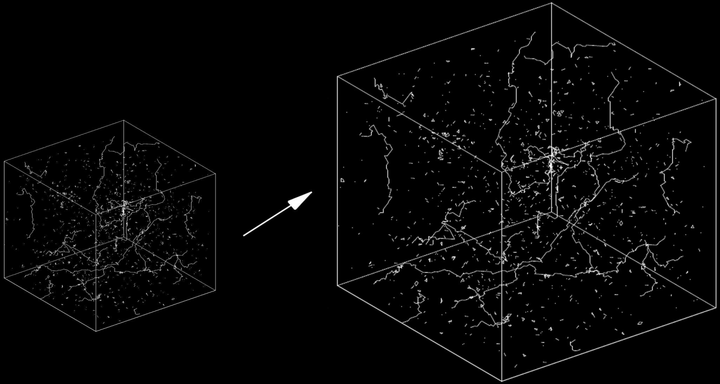
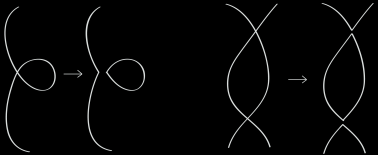
A cosmic string network consists of:
1)Infinite cosmic strings
2)Cosmic string loops



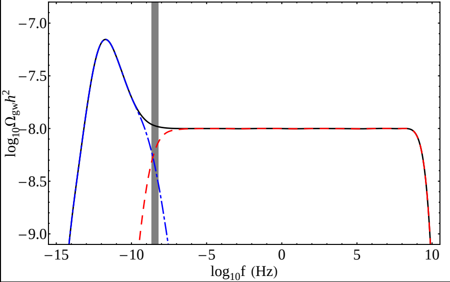
The cosmic string network evolution is *scale-invariant* in the radiation and matter eras.

Cosmic String Network

- Scaling of the network can be achieved only if it loses specific amount of energy per Hubble time.
- Such a mechanism exists: loop creation through (self)intercommutation



Loops once formed, decay through GW emission and create a SGWB



Outline
Cosmic Strings
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Projected constraints
Other results
Conclusions

The model parameters

Outline
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Projected constraints
Other results
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The SGWB of a cosmic string network depends on:

- The cosmic string tension, $G\mu$; *unknown*: $G\mu = 10^{-6} - 10^{-16}$(?)
- The birth scale of loops, α relative to the horizon radius; *unknown*: loop size $0.1\,\mathrm{d_H(t_0)}$–string width

  Often this is seen as ϵ, where $\epsilon = \alpha/\Gamma G\mu$, with $\Gamma \approx 50$
- The intercommutation probability, p; *unknown*:

  $p = 1$ (cosmic strings), $p = 1 - 10^{-3}$ (F- supestrings), $p = 1 - 0.1$ (D-superstrings)
  Also unknown is how it affects the infinite string/loop population: $\rho_\infty = p^{-1}$ or $p^{-0.6}$
- The dominant GW emission mechanism; *unknown*: cusps or kinks?

  In the framework of a relativistic oscillating source we still have two unknown parameters:

  1) Spectral index, q: $q = 4/3$ (cusps) or $q = 2$ (kinks)

  2) Number of emission modes, n_*: $n_* = 1 \to \infty$

  GW frequency: $f = 2n/\ell$, Power emitted: $P_n = \Gamma n^{-q} / \sum_{m=1}^{n_*} m^{-q}$

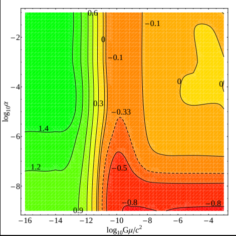
Current tension constraints

- All these uncertainties, combined with different computation methods for the loop population, have led to a variety of constraints in the literature (e.g. Ölmez et al. 2010, DePies et al. 2007, Siemens et al. 2007), based on different assumptions.

Damour-Vilenkin equation

$$h \approx 9.8 \times 10^{-15} c^{1/2} p^{-1/2} \left(\frac{\alpha}{\Gamma G\mu}\right)^{-1/6} \left(\frac{G\mu}{10^{-6}}\right)^{1/3} \left(\frac{f}{\mathrm{yr}^{-1}}\right)^{-7/6} \left(\frac{h}{0.65}\right)^{7/6}$$

- Cusps are the main GW production mechanism
- No high emission mode damping due to gravitational backreaction, $n_* = \infty$
- It has a specific spectral slope
- Oversimplified number density for loops; good approximation only for small loops (violates scaling for large)
- One *has* to select some fiducial values for parameters which are *unknown*...
- Good for order of magnitude estimations (see discussion in Schlaer, Vilenkin, Loeb 2012)



Sanidas et al. 2012

One crucial advantage: Ease of use for PTA investigations

Current tension constraints

Outline
Cosmic Strings
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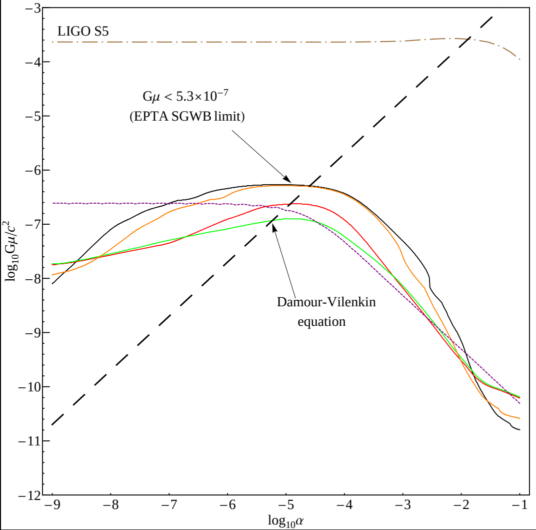
Conclusions



Constraints utilising amplitude+slope information

Can we use this method for estimating future constraints though?

Evolution of constraints

Outline
Cosmic Strings
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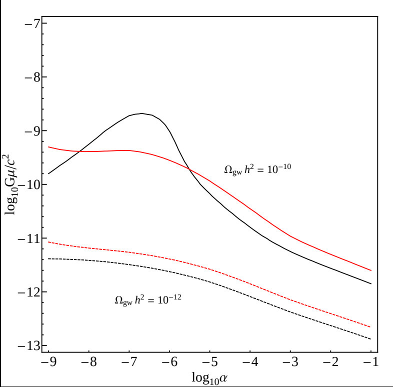
Ideally, we would be able to perform exactly the same analysis for a range of $\Omega_{\rm gw}h^2$ values and get the result.

- We do not have spectral information $\rightarrow$ Assumption of locally flat spectrum.



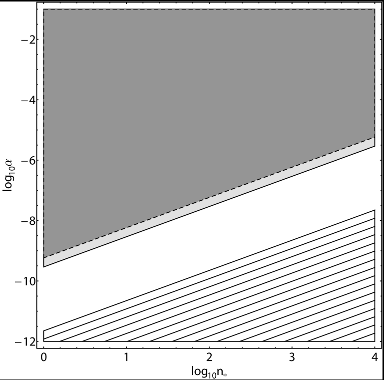
Different behaviour of exclusion curves at low $\Omega_{\rm gw}h^2$. Upper limit tension constraints:

- High $\Omega_{\rm gw}h^2$
  i. Low n_*
  ii. Characteristic peak
- Low $\Omega_{\rm gw}h^2$
  i. High n_*
  ii. Minimum α detectable

The low frequency cut-off

Possible observed networks are limited by a low-frequency cut-off.
The minimum frequency at which a network can emit is defined by the largest loops present
$\rightarrow$It depends on the duration of the PTA experiment

$$f = \frac{2n}{f_{\mathrm{r}} \alpha d_{\mathrm{H}}(t_0)}, \quad \alpha_{\mathrm{min.}} = \frac{2}{f_{\mathrm{r}} f d_{\mathrm{H}}(t_0)}, \ \mathrm{with} f_r \approx 0.7$$



Depending on the duration of the PTA experiment we have:

- 5-year:$\alpha_{\mathrm{min.}} = 10^{-9.53}$
- 10-year:$\alpha_{\mathrm{min.}} = 10^{-9.23}$
- 20-year:$\alpha_{\mathrm{min.}} = 10^{-8.93}$

Just a couple more values for α needed!
However. . .

Constraints for various Ω_{gw}

Outline
Cosmic Strings
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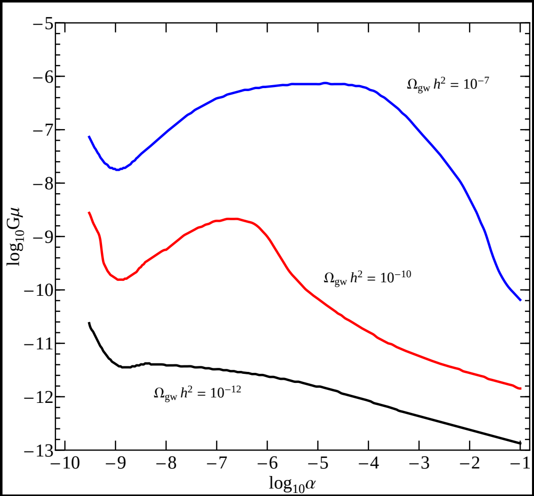
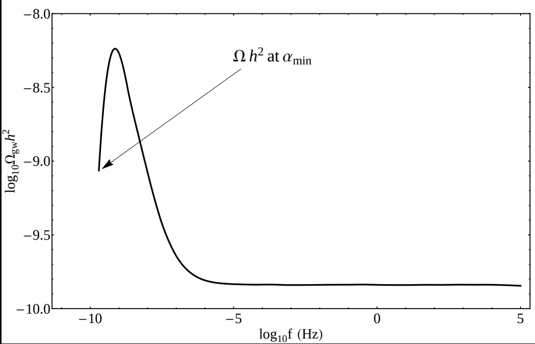
For $\Omega_{\mathrm{gw}} h^2 \lesssim 10^{-10}$ the upper limit is provided by the $\alpha_{\mathrm{min.}}$ networks



Constraints for various $\Omega_{\rm gw}$

Outline
Cosmic Strings
Current $G\mu$ constraints
Projected constraints
Other results
Conclusions



Requirements:

- High sampling of $G\mu - \alpha$ space
- Careful treatment of loop number densities in Λ-dominated era

Question:*Is this SGWB?*

Projected constraints on $G\mu$

Outline
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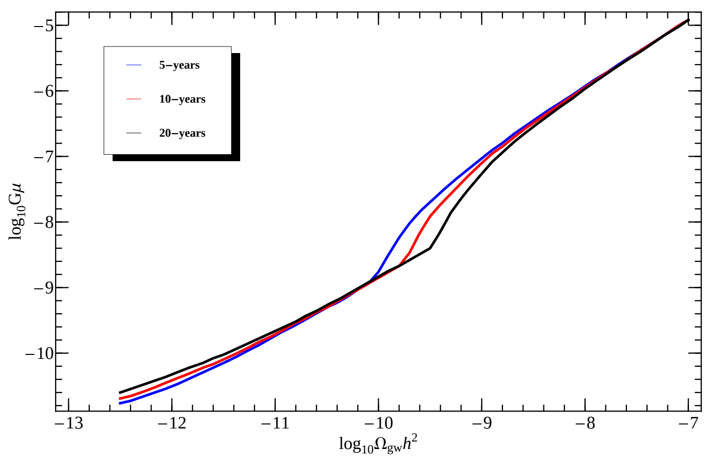
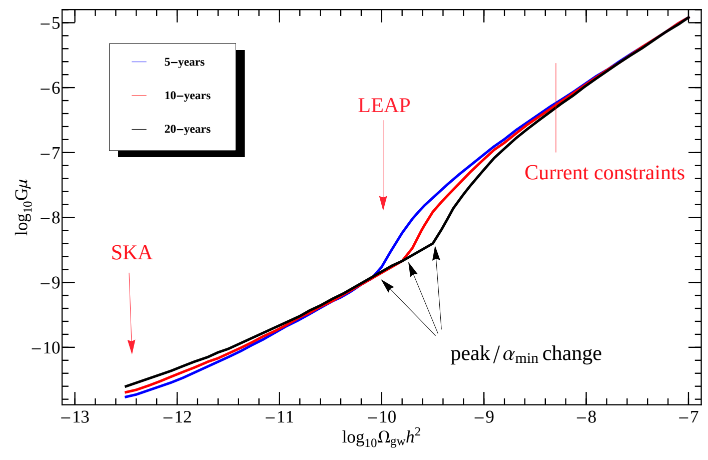


Projected constraints on $G\mu$

Outline
Cosmic Strings
Current $G\mu$ constraints
Projected constraints
Other results
Conclusions



Analytic expressions

Outline
Cosmic Strings
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Other results
Conclusions

Analytic expressions for all results through least squares fitting ($x = \Omega_{\rm gw} h^2$)

$$\log(G\mu_{5\rm yrs}) = \begin{cases} 0.09[\log x]^3 + 2.29[\log x]^2 + 19.2[\log x] + 50.3 & , -10 < \log x \leq -7 \\ 0.09[\log x]^2 + 2.85[\log x] + 10.5 & , -12.5 \leq \log x \leq -10 \end{cases}$$

Similar expressions evaluated for PTA experiments of different durations + LIGO/NGO bands

Implications of flat spectrum assumption?

i. negative slope: overestimation
$G\mu < 5.6 \times 10^{-7}$ for the EPTA, 5.6% higher
Remember, we are interested in conservative constraints!

ii. positive slope: underestimation
Similar % differences expected.

Massive Particle Annihilation

Outline
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- The same approach can be followed for LIGO/NGO, but we have to take into consideration massive particle annihilation;
  remember that the network forms at the end of inflation
  - Every time $T_{\rm Univ.}$ <particle mass threshold, the respective family becomes non-relativistic
  - Change in the relativistic degrees of freedom, g_*
    $\rightarrow$change in the expansion rate of the Universe, and therefore, $\Omega_{\rm gw}$

Correction: $\left(\frac{g_{*,t_0}}{g_{*,t_{\rm sp.}}}\right)^{1/3}$

applied at $t_{\rm sp.} = \left(\frac{32\pi G\rho}{3}\right)^{-1/2}$, $\rho = \frac{\pi^2}{30} g_* T_{\rm Univ.}$

$\rightarrow$ frequency:$f = \frac{2}{f_{\rm r}\alpha d_{\rm H}(t_{\rm sp.})}\frac{a(t_{\rm sp.})}{a(t_0)}$, α-dependent

Corrected GW spectrum

Outline
Cosmic Strings
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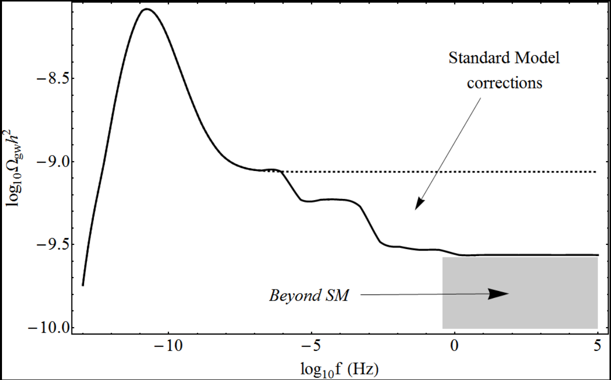

- For a very wide range of α LIGO/NGO are strongly affected!

Projected constraints LIGO/NGO

Outline
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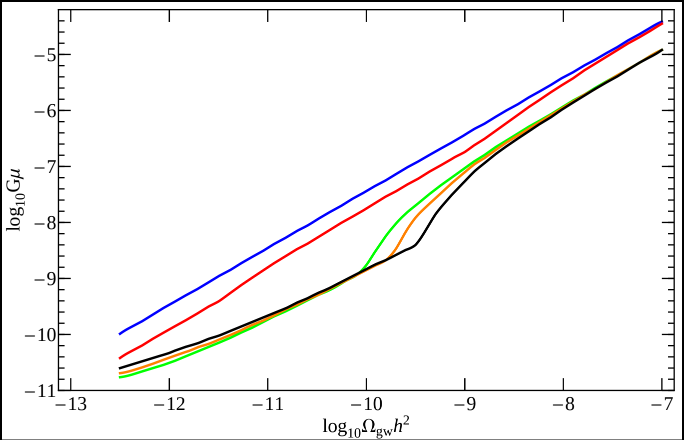
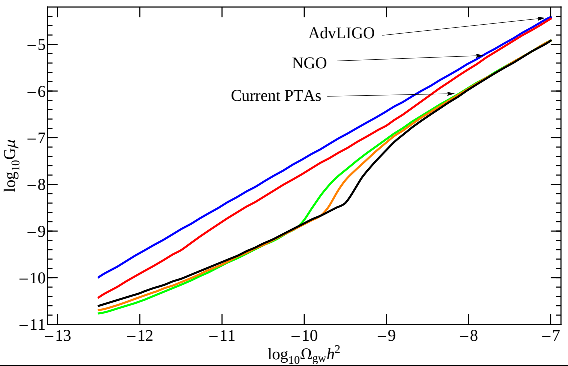


Projected constraints LIGO/NGO

Outline
Cosmic Strings
Current $G\mu$ constraints
Projected constraints
Other results
Conclusions



- CMB investigations???
  1. *PLANCK*: 6.5×10^{-8} Battye et al. 2008
  2. *Future CMB*: $\lesssim 7 \times 10^{-9}$ (lensing free, noiseless B-mode measurement) (Dvorkin et al. 2011, Foreman et al. 2011)

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- As far as the frequency we probe with maximum sensitivity in a PTA project is concerned, differences are minimal.
  For $10^{-10} \lesssim \Omega_{\mathrm{gw}} h^2 \lesssim 10^{-9}$ long duration experiments are preferred, whereas for $\Omega_{\mathrm{gw}} \lesssim 10^{-10}$ shorter duration experiments are slightly benefited.
- Tension constraints modeled with analytic functions of the form $G\mu(\Omega_{\mathrm{gw}} h^2)$ for PTA experiments of different durations. Similar expressions also available for LIGO/NGO frequency bands.
- PTAs, probing the nHz regime are strongly benefited in comparison to any other GW detection experiment in detecting a SGWB from cosmic strings. They also have much better potential than any future CMB experiment.