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Constraining the energy scale of cosmic strings with PTAs

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Outline

- A brief introduction to cosmic strings

- Modelling of the cosmic string SGWB

  Sanidas, Battye, Stappers, 2012, Phys. Rev. D, 85, 122003
  Sanidas, Battye, Stappers, 2013, Ap.J., 764, 108

- Updated constraints from the EPTA + NANOGrav

  Lentati et al., 2015, MNRAS, 453, 2576
  Arzoumanian et al., 2015, arXiv:1508.03024

Cosmic strings

Cosmic strings: 1-dimensional topological defects

- "Field Theory objects", created during phase transitions in the early Universe (Kibble mechanism - Spontaneous Symmetry Breaking)

  $\rightarrow$ Generic in all supersymmetric hybrid inflation scenarios

- String theory counterparts as well - cosmic (D- and F-) superstrings

  $\rightarrow$ Generic in brane inflation scenarios

For GUT scale cosmic strings

i. formation: $\sim 10^{-35}\,\mathrm{sec}$
ii. linear energy density: $\sim 10^{22}\,\mathrm{gr/cm}$
iii. width: $\sim 10^{-30}\,\mathrm{m}$
iv. velocity: relativistic
v. Length: any

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Why do we look for them?

- The most characteristic quantity is their linear energy density μ (or tension)

$$G\mu/c^2$$

- They provide a *unique* “laboratory” for High Energy Physics in the Early Universe

Cosmic Strings

1) Energy scale of the phase transition

Cosmic superstrings

1) Fundamental string coupling
2) Compactification/Warping scales

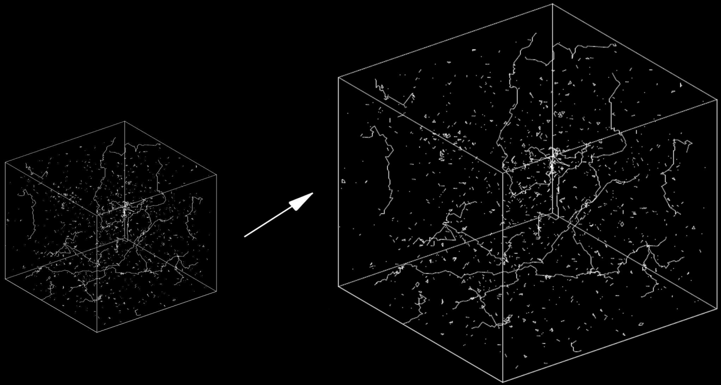
All these quantities are *directly* related to $G\mu/c^2$

Cosmic strings a relics of the Early Universe that might still exist and evolve *today*

→ *Key cosmological source for PTAs and eLISA*

Cosmic String Network Evolution

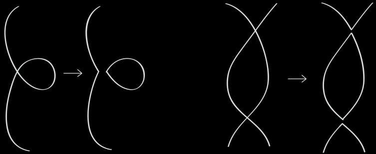
A cosmic string network consists of:
1) Infinite cosmic strings
2) Cosmic string loops



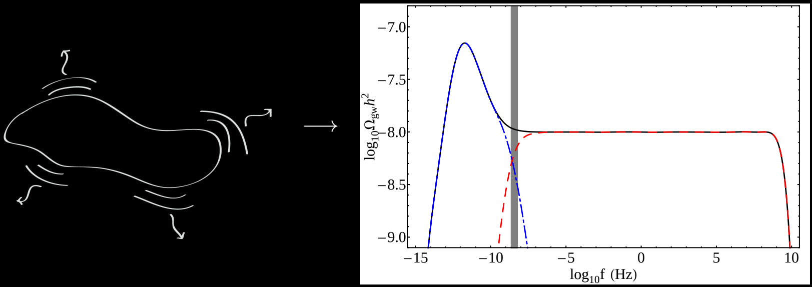
The cosmic string network evolution is *scale-invariant* in the radiation and matter eras.

Cosmic String Network Evolution

- Scaling evolution: Requires an energy loss mechanism to attain.
  → loop creation through (self)intercommutation with probability p

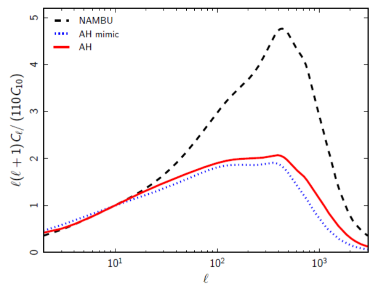


Loops once formed, decay (mainly) through GW emission and create a SGWB



Signatures of cosmic strings

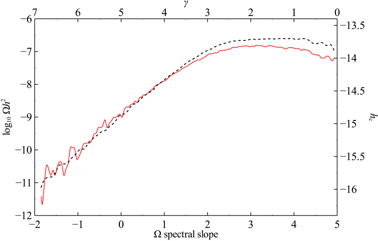
- *CMB*



Planck 2013 XXV

- Depends on long strings
- Less uncertainties

- *Gravitational Waves*



EPTA 2015 SGWB limit

- Depends on loops
- More uncertainties

CMB-based results inherently more robust than GW-based ones

Can GW-based results compete CMB ones?

Computation of the cosmic string SGWB

Two main difficulties

- Loop number density
  1) Analytic approaches (Damour-Vilenkin, Polchinski-Rocha 2007, Lorenz et al. 2010)
  2) Evolution simulations (Vilenkin et al. 2006, Ringeval et al 2007, Blanco-Pillado et al 2011,2014, Hindmarsh et al 2009)
- Dominant GW emission mechanism
  1) Kinks (O'Callaghan-Gregory 2010)
  2) Cusps (Damour-Vilenkin 2001, Siemens et al. 2007)
  3) Generic investigations (Caldwell-Allen 1992, DePies-Hogan 2007)

- ► Common the results to disagree quantitatively and qualitatively.

In SGWB investigations particularly:
1) many approximations used in the computation of the loop number density.
2) GW emission is mainly credited to cusps.

With total lack of any observational facts, our approach is to be

conservative and generic

Loop number density

Our approach is based on the one-scale model (Kibble, 1974)

- Loops are born at a characteristic length scale

$$\ell_{\rm b} = \alpha d_{\rm H}(t_{\rm b})$$

→*Fundamental prerequisite*: The network follows a scaling evolution.

- Energy lost to attain scaling → Loop creation rate:

$$\frac{dN_{\rm loop,css}}{dt}$$

→ For cosmic superstrings $\frac{dN_{\rm loop,css}}{dt} = \frac{1}{p^k}\frac{dN_{\rm loop,css}}{dt}$

- Loops decay through GW emission only

$$\ell(t,t_{\rm b}) = f_{\rm r}\alpha d_{\rm H}(t_{\rm b}) - \frac{\Gamma G\mu}{c}(t-t_{\rm b})$$

From these we can compute the *loop number density* $n(\ell,t)$

GW emission mechanism

Generic GW emission modelling:
a loop that oscillates relativistically and emits GWs

- GW emission harmonics (modes): $f_n = \frac{2nc}{\ell}, n = 1, \ldots, \infty$

  → High emission modes cut-off imposed, n_* (gravitational backreaction)

- GW power emission: $\frac{dE_{\text{gw,loop}}}{dt} = P_n G\mu^2 c, \quad P_n = \Gamma n^{-q} / \sum_{m=1}^{\infty} m^{-q}$

  → spectral index q depending on the emission mechanism (cusps or kinks)

$$\Omega_{\text{gw}}(f) = \frac{2G\mu^2 c^3}{\rho_{\text{crit}} a^5(t_0) f} \sum_{j=1}^{n_*} j P_j \int_{t_{\text{f}}}^{t_0} a^5(t') n_j(f, t') dt'$$

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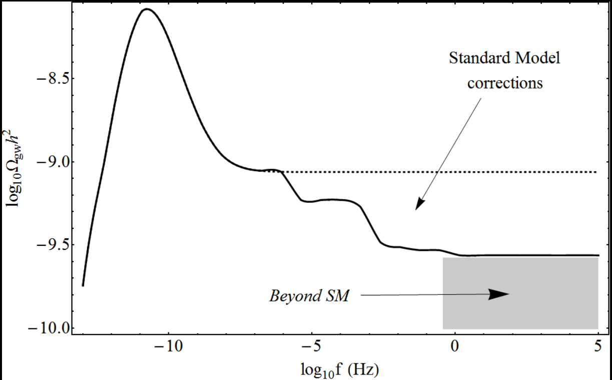
Corrections due to massive particle annihilation



The model parameters

The main parameters that govern the GW spectrum are:

- The cosmic string tension, $G\mu$: $G\mu = 10^{-6} - 10^{-20}$(?)
- The birth scale of loops, α: loop size $0.1\,\mathrm{d_H(t_0)}$–string width
- The intercommutation probability, p: $p = 1 - 10^{-3}$
  $p = 1$ (cosmic strings), $p = 1 - 10^{-3}$ (cosmic superstrings)
  Also unknown is how it affects the infinite string/loop population: $\rho_\infty \propto p^{-1\,\mathrm{or}\,-0.6}$
- The dominant GW emission mechanism: cusps or kinks?

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

  2) Emission modes cut-off, n_*: $n_* = 1 \to \infty$

Reducing the parameter space

→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

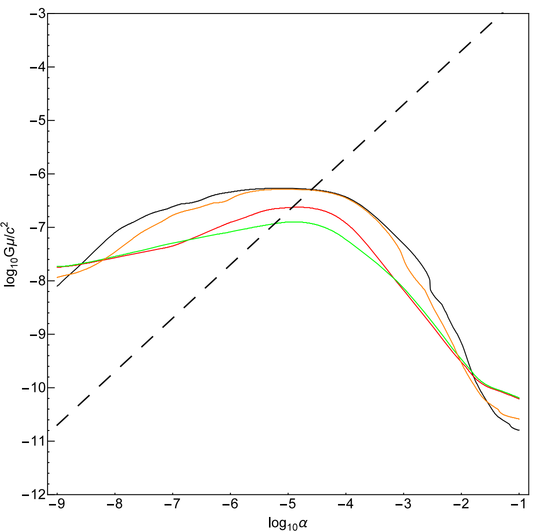
$$f \approx \frac{2n}{\alpha d_{\mathrm{H}}(t_0)}\,, \quad \alpha_{\mathrm{min.}} \approx \frac{2}{f d_{\mathrm{H}}(t_0)}$$

- PTAs: $\alpha_{\mathrm{min.}} \approx 10^{-9}$
- eLISA: $\alpha_{\mathrm{min.}} \approx 10^{-16}$
- LIGO: $\alpha_{\mathrm{min.}} \approx 10^{-20}$

→The high-emission mode cut-off saturates much below infinity.
Insignificant changes in the GW spectrum for:

- $n_* > 10^4$ in the cusp dominated emission
- $n_* > 10^2$ in the kink dominated emission

Exclusion curves



- Exclusion curves: Networks which comply with the SGWB limit
- Constraints utilising amplitude+slope information

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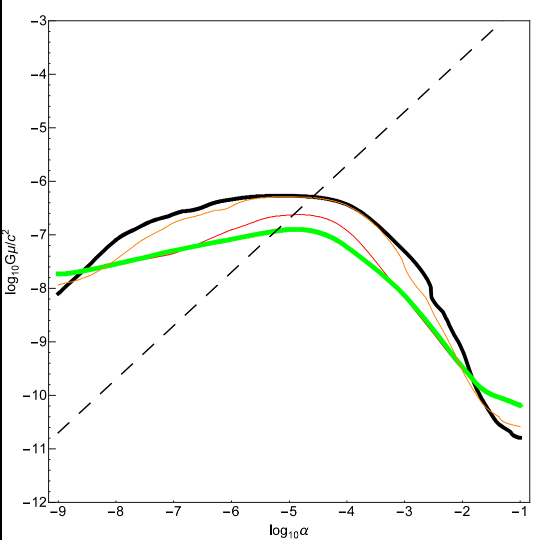
Exclusion curves



Only $n_* = 1$ and $n_* = 10^4$, $q = 4/3$ needed for the upper limits on $G\mu/c^2$

EPTA 2015 limit on $G\mu/c^2$ ($p = 1$)

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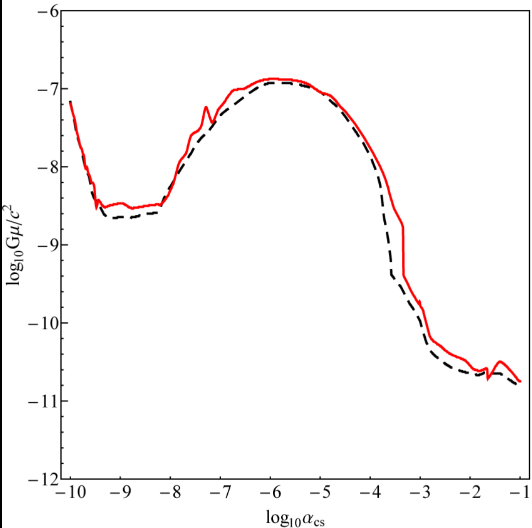


EPTA 2015 upper limit

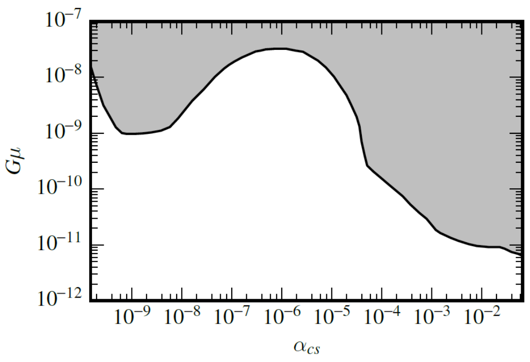
$G\mu/c^2 < 1.3 \times 10^{-7}$

for $p = 1$

Planck+ACT+SPT

$G\mu/c^2 < 1.3 \times 10^{-7}$

NANOGrav 2015 limit on $G\mu/c^2$ $(p = 1)$



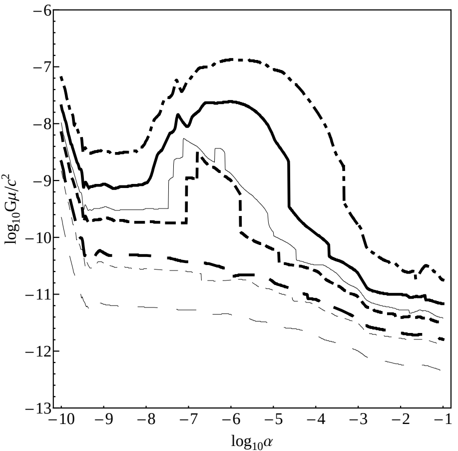
NANOGrav 2015 upper limit

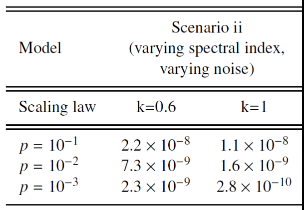
$G\mu/c^2 < 3.3 \times 10^{-8}$

Limit based on Blanco-Pillado 2014 $n(\ell, t)$

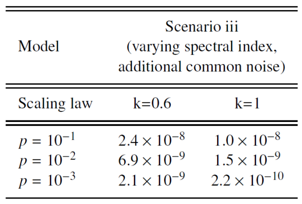
$G\mu/c^2 < 1.3 \times 10^{-10}$

EPTA 2015 limits on $G\mu/c^2$ ($p \neq 1$)





Model	Scenario ii (varying spectral index, varying noise)	
Scaling law	k=0.6	k=1
$p = 10^{-1}$	2.2×10^{-8}	1.1×10^{-8}
$p = 10^{-2}$	7.3×10^{-9}	1.6×10^{-9}
$p = 10^{-3}$	2.3×10^{-9}	2.8×10^{-10}



Model	Scenario iii (varying spectral index, additional common noise)	
Scaling law	k=0.6	k=1
$p = 10^{-1}$	2.4×10^{-8}	1.0×10^{-8}
$p = 10^{-2}$	6.9×10^{-9}	1.5×10^{-9}
$p = 10^{-3}$	2.1×10^{-9}	2.2×10^{-10}

Conclusions

- We provide a generic framework to describe the GW spectrum of cosmic strings based on the one-scale model.
  - easy to modify and expand
  - provides flexibility in marginalising its main uncertainties
- 2015 tension upper limits from the EPTA and NANOGrav
  - tension upper limits independent of the major model parameters $\rightarrow$ robustness closer to CMB
  - both SGWB amplitude and local spectral slope information used
- The EPTA limit was the *first* conservative limit to match the constraints from the CMB; NANOGrav limit already 4 times better
- Future looks promising for PTAs (and eLISA)!