ANTON PANNEKOEK INSTITUTE

Updated constraints on the cosmic string tension from the EPTA

Sotiris Sanidas

Anton Pannekoek Institute for Astronomy, University of Amsterdam

July 2, 2015

ANTON PANNEKOEK INSTITUTE

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 European Pulsar Timing Array

ANTON PANNEKOEK INSTITUTE

Cosmic strings

- Cosmic strings: 1-dimensional topological defects (other defects:domain walls, magnetic monopoles, textures...).

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

$$G \to ? \to SU(3)\times SU(2)\times U(1) \to SU(3)\times U(1)$$

- $\to$ Generic in all supersymmetric hybrid inflation scenarios (Jeannerot, Rocher, Sakellariadou 2003)

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

- Their formation is generic in any robust brane inflation scenario (Sarangi, Henry Tye 2002)

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

Why do we look for them?

ANTON PANNEKOEK INSTITUTE

- 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 $G\mu/c^2$

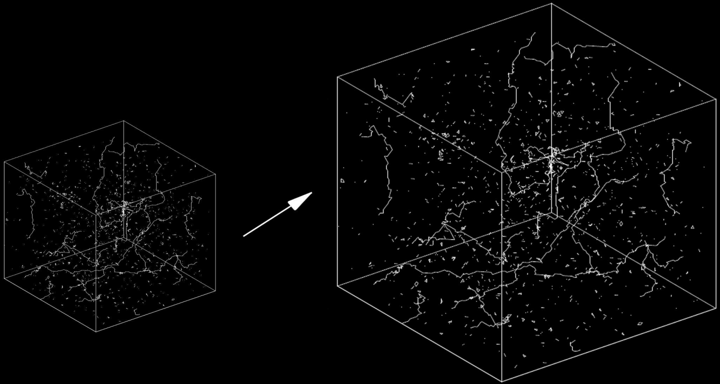
Physics at $\sim 10^{16}\,\mathrm{GeV}$ energy scale. LHC$\sim$TeV energy scale

$\rightarrow$*Key cosmological source for PTAs and eLISA*

ANTON PANNEKOEK INSTITUTE

Cosmic String Network

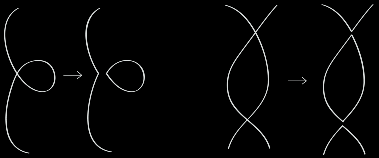
A cosmic string network consists of:
1)Infinite cosmic strings
2)Cosmic string loops



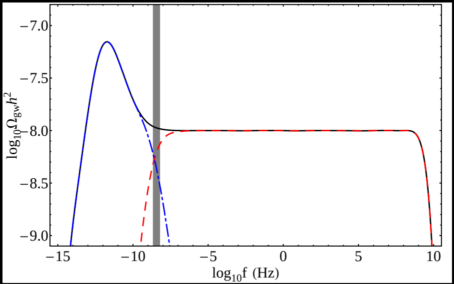
The cosmic string network evolution is *scale-invariant* in the radiation and matter eras.

Cosmic String Network

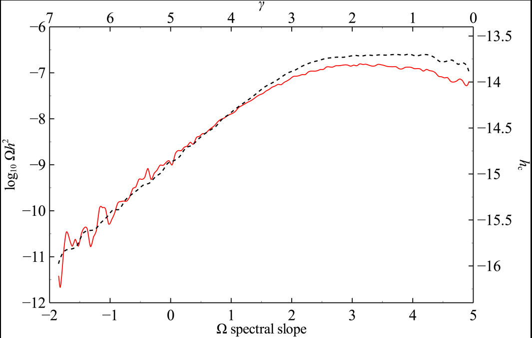
- Scaling of the network can be achieved only if it loses specific amount of energy per Hubble time.
- Such a mechanism exists: loop creation through (self)intercommutation



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



EPTA 2015 limit on an Isotropic SGWB



arXiv:1504.03692

Upper Limit

$$h_c < 3.0 \times 10^{-15} \ @ \ f = 1 \mathrm{yr}^{-1}$$

for a SMBH SGWB

- 6 pulsars
- 18 years data span
- Bayesian analysis (intrinsic psr noise parameters + common correlated signals)
- Spectral index free

Computation of the cosmic string SGWB

ANTON PANNEKOEK INSTITUTE

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)

- Results are (usually) in quantitative and qualitative disagreement (assumptions,physics)

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

ANTON PANNEKOEK INSTITUTE

Loop number density

We use the one-scale model (Kibble, 1974)
Fundamental prerequisite: The network follows a scaling evolution.
(see, Avelino-Sousa 2013 for alternative)

Main parameters:

- String tension, $G\mu/c^2$
- birthscale of loops relative to the horizon α ($\ell_{\rm b} \propto \alpha t$)
- intercommutation probability p

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

Loop produced since the creation of the network

$$\frac{dN_{\rm loop}}{dt} = -\frac{V(t)}{f_{\rm r}\mu\alpha d_{\rm H}(t)c^2} \times \left[\dot{\rho}_\infty(t) + 2\frac{\dot{a}(t)}{a(t)}\rho_\infty(t)\left(1 + \langle v^2\rangle/c^2\right)\right]$$

Number density: $n(\ell_{\rm i}, t_{\rm j}) = \frac{1}{V(t_{\rm j})\left[f_{\rm r}\alpha\dot{d}_{\rm H}(t_{\rm b,j}) + \Gamma G\mu/c\right]} \left.\frac{dN_{\rm loop}}{dt}\right|_{t=t_{\rm b,j}}$

Intercommutation probability works as a scaling factor in ρ_∞

GW emission mechanism

ANTON PANNEKOEK INSTITUTE

The main GW emission structures on cosmic strings are kinks and cusps.

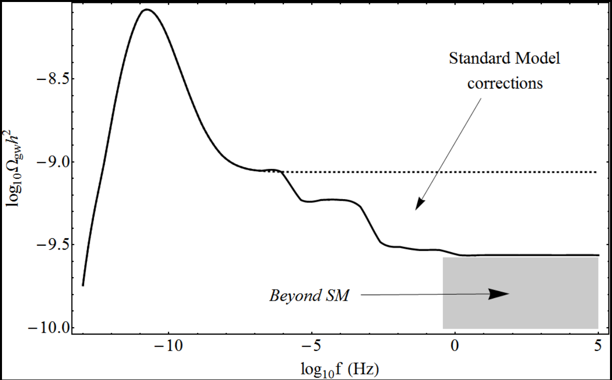
Not focussing on cusps: gravitational backreaction might play a significant role (see, Battye & Shellard 1994 on global strings)

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

- GW emission harmonics (modes): $f_n = \frac{2nc}{\ell}\, , n = 1, \ldots, \infty$
  $\rightarrow$ High emission modes cut-off imposed, n_* (gravitational backreaction)
- GW power emission: $\frac{dE_{\mathrm{gw,loop}}}{dt} = P_n G\mu^2 c\, , \quad P_n = \Gamma n^{-q} / \sum_{m=1}^{\infty} m^{-q}$
  $\rightarrow$ spectral index q depending on the emission mechanism

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

Corrections due to massive particle annihilation



- PTAs are affected for a small region of the parameter space. Interferometric detectors are affected significantly.

ANTON PANNEKOEK INSTITUTE

The model parameters

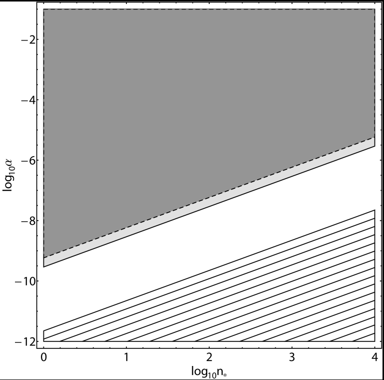
The SGWB of a cosmic string network depends on:

- The cosmic string tension, $G\mu$: $G\mu = 10^{-6} - 10^{-16}$(?)
- 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_* : $n_* = 1 \to 10^4$

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

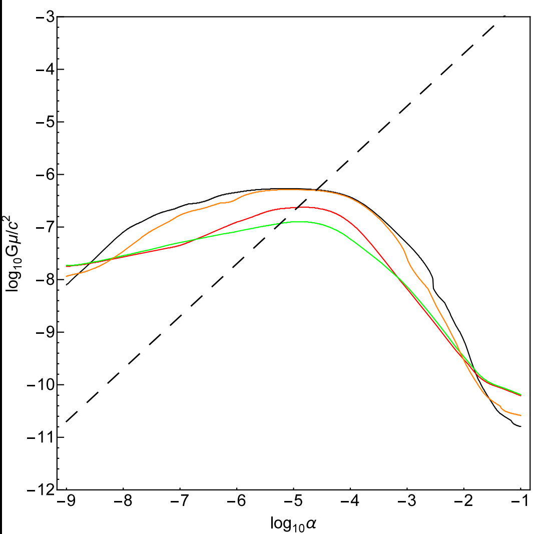
$$f \approx \frac{2n}{\alpha d_{\rm H}(t_0)}\,, \quad \alpha_{\rm min.} \approx \frac{2}{f d_{\rm H}(t_0)}$$



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

Exclusion curves

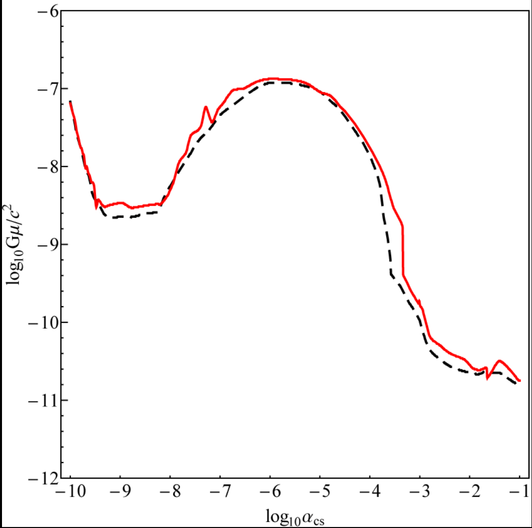
ANTON PANNEKOEK INSTITUTE



- Exclusion curves: Networks which comply with the SGWB limit
- Constraints utilising amplitude+slope information
- Only $n_* = 1$ and $n_* = 10^4$, $q = 4/3$ needed for the upper limits on $G\mu/c^2$

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

ANTON PANNEKOEK INSTITUTE



Upper limit
arXiv:1504.03692

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

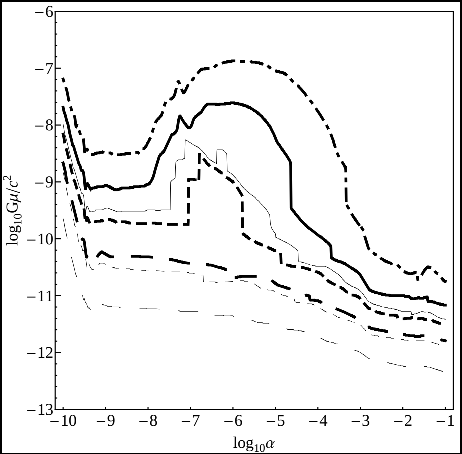
for $p = 1$

Planck+ACT+SPT

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

depends only on $G\mu/c^2$ and p

EPTA 2015 limit 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}

ANTON PANNEKOEK INSTITUTE

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
  - minimal philosophy to assumptions
- New tension upper limit from the EPTA
  - tension upper limits independent of the major model parameters $\rightarrow$ robustness closer to CMB
  - both SGWB amplitude and local spectral slope information used
- This is the *first* time that such a conservative constraint matches the CMB constraints.
- The future looks promising for PTAs!