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EPTA constraints on the SGWB of cosmic strings

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Outline

- A (very) brief introduction on cosmic strings and the difficulties involved in the GW spectrum computation.
- Modelling of the cosmic string SGWB and our approach in setting the tension upper limits.
- Updated constraints on the cosmic string SGWB by the EPTA
  (New EPTA limit on an isotropic SGWB submitted yesterday).
- Projected tension constraints for GW detection experiments.

Introduction

- Main SGWB sources for PTAs (probed frequencies: $10^{-9} - 10^{-8}$ Hz)

1. Supermassive Black Hole Binaries
2. Cosmic (super)strings

Potentially, any other broadband SGWB source
$\rightarrow$ *Inflation*
$\rightarrow$ *1st Order phase transitions* (Caprini, Durrer, Siemens 2010)
$\rightarrow$ *Global Phase Transitions* (Jones-Smith, Krauss, Mathur 2008)
$\rightarrow$ *Self-ordering of scalar fields* (Fenu, Figueroa, Durrer, Garcia-Bellido 2009)
$\rightarrow$ *ANY scaling source in the radiation era* (Figueroa, Hindmarsh, Urrestilla 2013)

- Cosmic (super)strings provide a *unique* “laboratory” for High Energy Physics in the Early Universe

Cosmic Strings

1)Energy scale of the phase transition

Cosmic superstrings

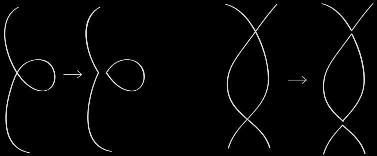
1)Fundamental string coupling
2)Compactification/Warping scales

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

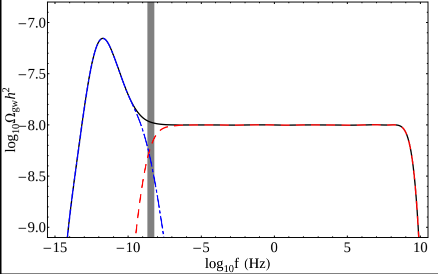
Introduction

Cosmic string network: “Infinite” strings and loops

- Scaling evolution in the radiation and matter eras.
- Energy loss mechanism required
  $\rightarrow$ loop creation through (self)intercommutation



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



Loop birth scale / number density

Basic ingredient: The size of the loops born. . .

Loop size at birth: $\ell(t) = \alpha t$

- Numerical simulations

1. $\alpha \sim 0.1$: Vanchurin et al. 2005/6, Olum & Vanchurin 2007
2. $\alpha \sim 10^{-2} - 10^{-3}$: Martins & Shellard 2006, Ringeval et al. 2007, Blanco-Pillado et al. 2011/14
3. $\alpha \sim (\Gamma G\mu/c^2)^k$: Bennett & Bouchet 1989, Allen & Shellard 1990, Siemens & Olum 2001, Siemens et al. 2002
4. $\alpha \sim \delta$: Vincent, Antunes & Hindmarsh 1998, Hindmarsh et al. 2008

- Analytic results
  Polchinski-Rocha 2007, Lorenz et al. 2010, and approximate estimations (i.e., Damour & Vilenkin 2001/2005)

Qualitative and quantitative disagreement due to:

- Differences in the underlying physics (e.g. Nambu-Goto vs. Abelian-Higgs)
- Simulation specific differences and approximations.

Dominant GW emission mechanism from loops

GW emission from:

- Cusps (Damour & Vilenkin 2001/5)
- Kinks (Damour & Vilenkin 2001, O'Callaghan & Gregory 2010)

It's not just cusps!!!

- Gravitational backreaction might play an important role. (Goldstone boson radiation simulations suggest damping of high emission modes, Battye & Shellard 1994)
- Reduced cusp formation probability in superstrings? (O'Callaghan et al. 2010)

Generic SGWB investigations (Caldwell & Allen 1992, Caldwell et al. 1996, DePies & Hogan 2007)

Impact on PTA tension constraints:
1)PPTA:$G\mu/c^2 < 1.5 \times 10^{-8}$ Jenet et al. 2006
2)EPTA:$G\mu/c^2 < 1.2 \times 10^{-8}$ Van Haasteren et al 2011 (2012 erratum)
3)NANOGrav:$G\mu/c^2 < 10^{-9}$ Demorest et al. 2013

Our philosophy $\rightarrow$ minimize the assumptions made and being conservative

Loop number density

Assumptions:
1)The one-scale model accurately describes the cosmic string network evolution.
2)The network is always at the scaling regime.
(see, Avelino-Sousa 2013 for alternative)

Main parameters:

- String tension, $G\mu/c^2$
- birthscale of loops relative to the horizon, α
- intercommutation probability p ($p = [10^{-3} - 1]$, $k = -0.6 \text{ or } -1$)

Loop produced since the creation of the network

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

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

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 effects: $\rho_{\infty,\, p\neq 1} \propto p^k \rho_{\infty,\, p=1}$

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GW emission mechanism

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

- number of emission modes (harmonics), n
  n_* high frequency cut-off ($n_* = 1 \to \infty$)
- spectral index q (cusps:$q = 4/3$, kinks:$q = 2$)

SGWB computation

- GW emission harmonics (modes):$f_n = \frac{2nc}{\ell}\,, n = 1, \ldots, n_*$
- GW power emission: $\frac{dE_{\rm gw,loop}}{dt} = P_n G\mu^2 c\,, \quad P_n = \Gamma n^{-q} / \sum_{m=1}^{n_*} m^{-q}$

$$\frac{d\rho_{\rm gw}}{df}(t) = 2\pi \int_{t_{\rm f}}^{t} dt' \left(\frac{a(t')}{a(t)}\right)^3 \int_0^{f_r \alpha d_{\rm H}(t')} \ell d\ell n(\ell, t') g\left(\frac{a(t_0)}{a(t')}\frac{2\pi}{c} f\ell\right)$$

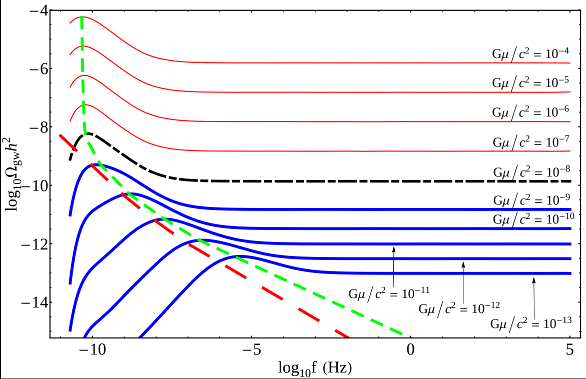
- GW radiation spectrum (unknown; assuming discrete):
  $g(z) = G\mu^2 c \sum_{j=1}^{n_*} P_j \delta(z - 4\pi j)$, normalisation: $\int_0^\infty g(z)dz = \Gamma G\mu^2 c$

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

Varying $G\mu/c^2$

Two qualitatively different regimes, signified by the gravitational backreaction scale

$$\alpha \approx \Gamma G\mu/c^2$$



For $\alpha \gg \Gamma G\mu c^2$, $\Omega \propto (\Gamma G\mu/c^2)^{1/2}$

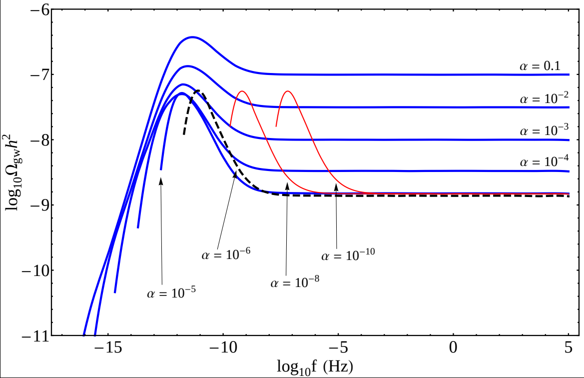
For $\alpha \ll \Gamma G\mu/c^2$, $\Omega \propto \Gamma G\mu/c^2$

$$f_{\text{peak}} = \frac{2}{3 f_r \alpha t_0}\left(2 + \frac{3 f_r \alpha c^2}{\Gamma G\mu}\right)^{10/9}$$

Varying α

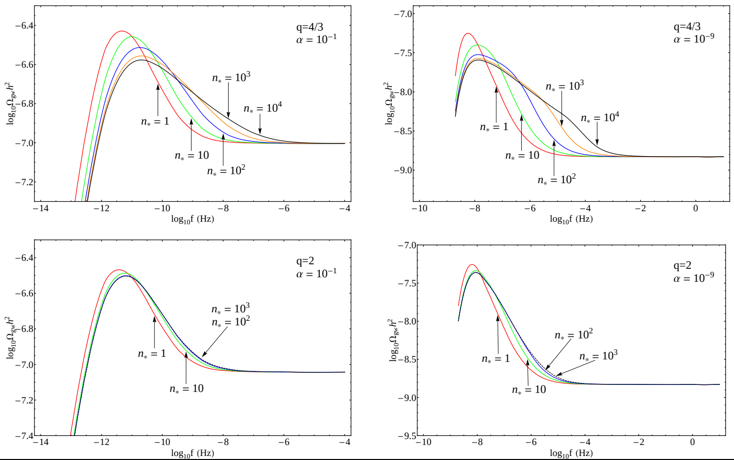
Two qualitatively different regimes, signified by the gravitational backreaction scale

$$\alpha \approx \Gamma G\mu/c^2$$



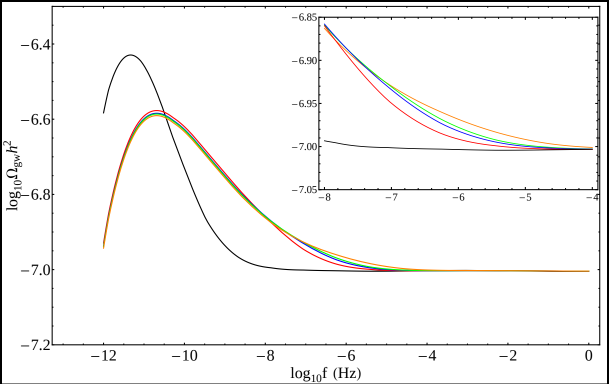
For $\alpha \gg \Gamma G\mu c^2$, $\Omega \propto \alpha^{1/2} \to \alpha^{1/4}$
For $\alpha \ll \Gamma G\mu/c^2$, $f_{\rm peak} \propto \alpha^{-1}$

Varying n_*



Less prominent differences between the two regimes for varying q and n_* (for kink dominated emission almost insignificant)

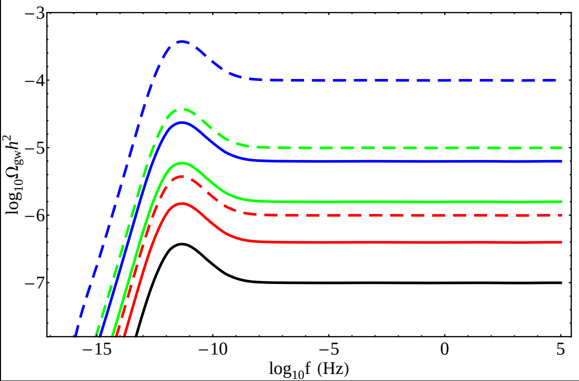
Varying n_*



Minimal differences for $n_* > 10^4$ (cusps)
$n_* > 10^2$ (kinks)

Varying p

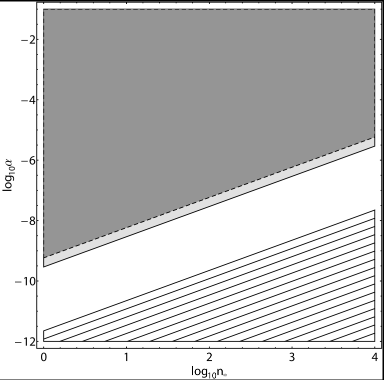
Effects of $p \neq 1$, just a rescaling



The low frequency cut-off

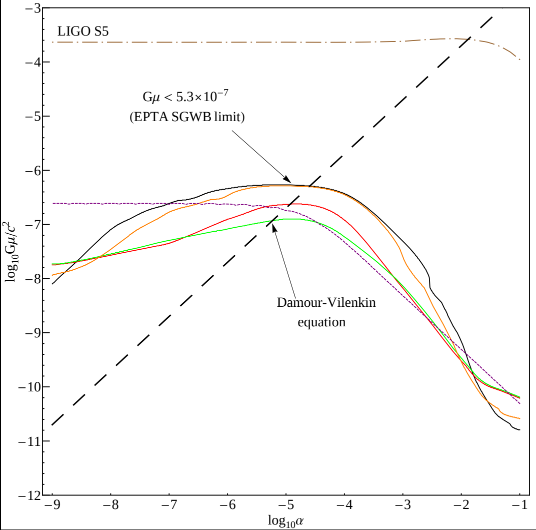
The minimum frequency at which a network can emit is defined by the largest loops present.
$\rightarrow$ GW detection experiments can probe networks with $\alpha \geq \alpha_{\rm min}$

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

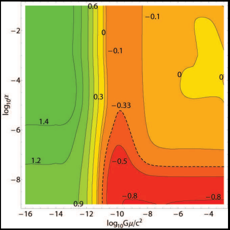


- PTAs:$\alpha_{\rm min.} \approx 10^{-9}$
- eLISA:$\alpha_{\rm min.} \approx 10^{-16}$
- LIGO:$\alpha_{\rm min.} \approx 10^{-20}$

Tension constraints



Constraints (*the only*) utilising amplitude+slope information.



For upper limits:
$n_* = 1$ and
$n_* = 10^4$, $q = 4/3$
networks necessary.

Massive Particle Annihilation

- Corrections due to the massive particle annihilation correction apply!
  $\rightarrow$Remember that the network forms at the end of inflation

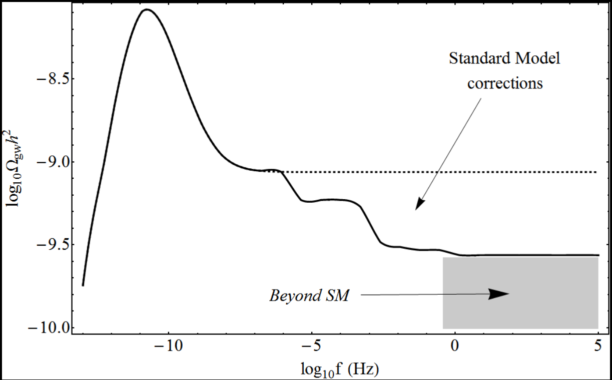
- Every time $T_{\rm Univ.} <$particle mass threshold, the respective family becomes non-relativistic
- Change in the relativistic degrees of freedom, g_*
  $\rightarrow$change in the expansion rate of the Universe, and therefore, $\Omega_{\rm gw}$

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

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

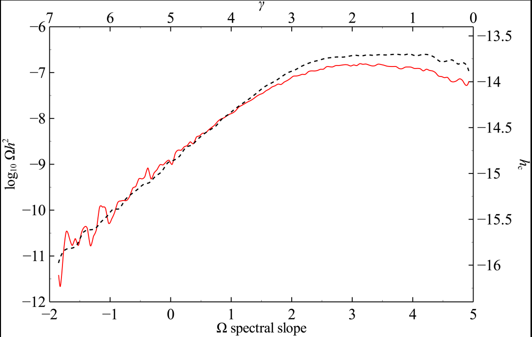
$\rightarrow$ frequency:$f = \frac{2}{f_{\rm r}\alpha d_{\rm H}(t_{\rm sp.})}\frac{a(t_{\rm sp.})}{a(t_0)}$, α-dependent

Corrected GW spectrum



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

New EPTA limit on an Isotropic SGWB



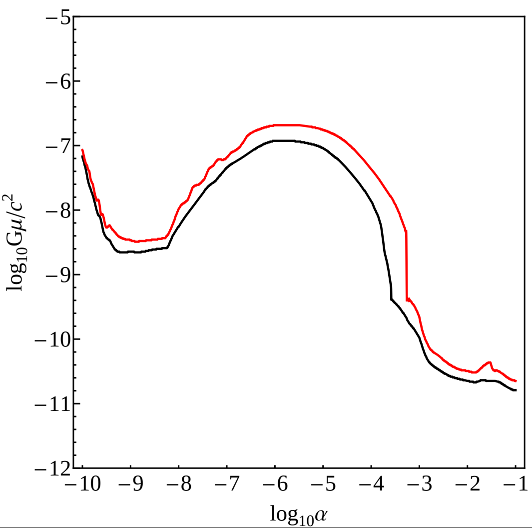
Upper Limit

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

for a SMBH SGWB

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

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



Upper limit

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

for $p = 1$

Planck+ACT+SPT

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

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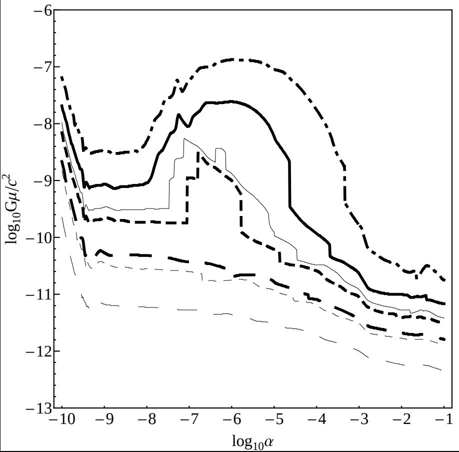
New EPTA limit on $G\mu/c^2$ $(p \neq 1)$

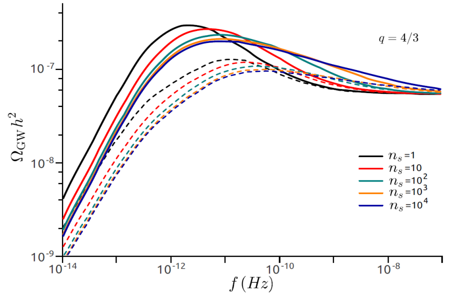


Model	Scenario ii (varying spectral index, varying noise)	
Scaling law	k=0.6	k=1
$p = 10^{-1}$	2.2×10^{-8}	1.1×10^{-8}
$p = 10^{-2}$	7.3×10^{-9}	1.6×10^{-9}
$p = 10^{-3}$	2.3×10^{-9}	2.8×10^{-10}

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}

Possible caveats

Delay on the onset of scaling

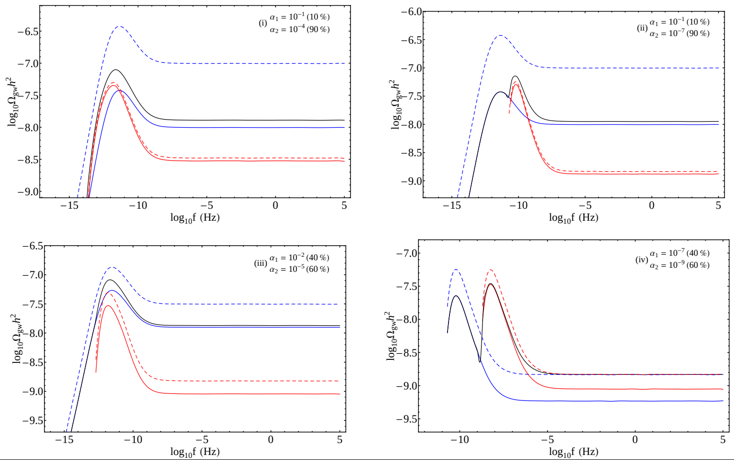


Avelino & Souza 2013

- Infinite string emission (Kawasaki et al. 2010)
- Emission from scaling evolution (Figueroa et al 2012)

Possible caveats

Multiple loop birth scales scales - 2 scales



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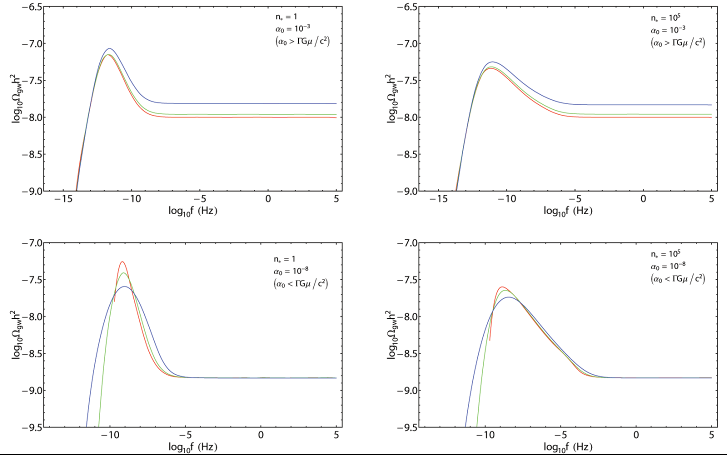
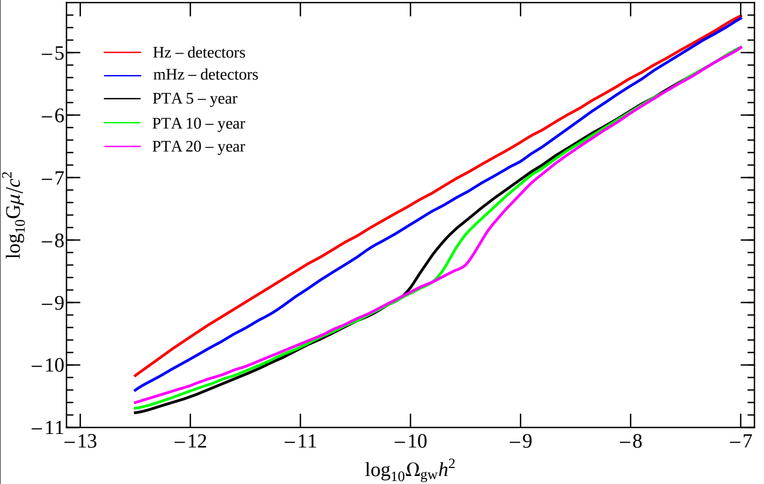
Possible caveats

Multiple loop birth scales scales - log normal α distribution



Projected constraints for GW detection experiments



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Conclusions

- We presented a generic model to describe the GW spectrum of cosmic strings minimising the involved assumptions.
  - Constraints independent of the main model parameters.
  - Robustness closer to that of CMB results.
  - Flexible to adapt and extend.
- EPTA tension constraints utilise amplitude and local spectral slope information from the SGWB limits.
  New EPTA limit $G\mu/c^2 < 1.3 \times 10^{-7}$ for $p = 1$, equal to the *Planck+SPT+ACT* limit.
- Cosmic string GW emission provide a unique opportunity for joint eLISA+PTA investigations.