Cosmic String Interpretation of NANOGrav Pulsar Timing Data

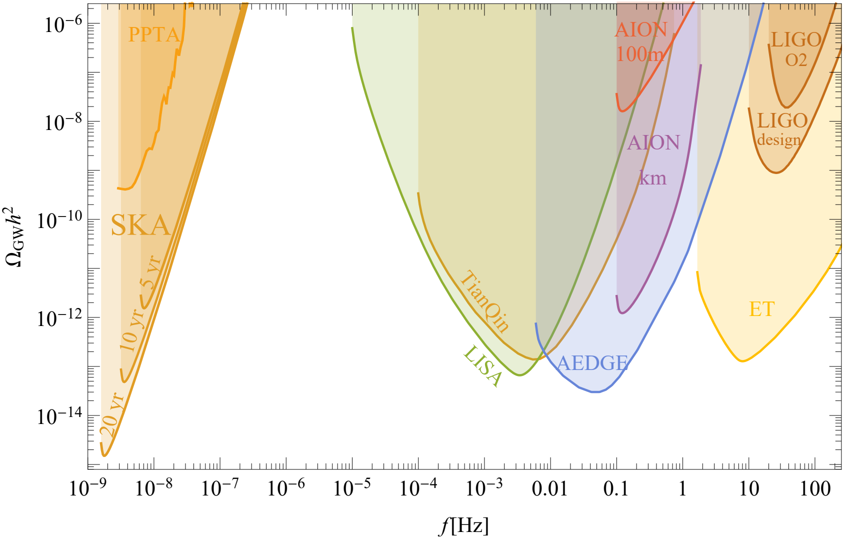
Marek Lewicki

Kings College London & University of Warsaw

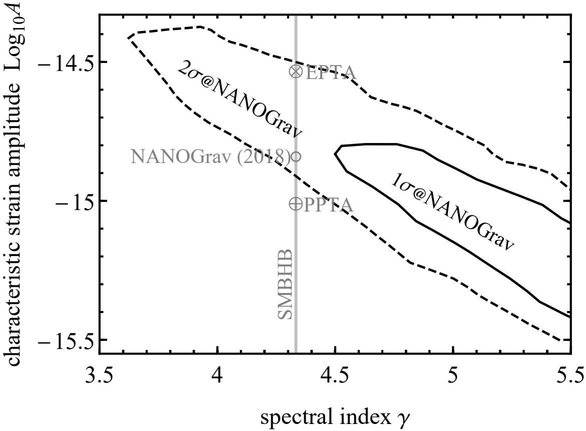
POTOR, 25 IX 2020

Based on:

J. Ellis, ML 2009.06555


PPTA
SKA
5 yr
10 yr
20 yr
LISA
TianQin
AEDGE
AION 100m
AION km
LIGO O2
LIGO design
ET
$\Omega_{\rm GW}h^2$
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
f[Hz]
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
0.01
0.1
1
10
100

NANOGrav 12.5 yr data



- power-law fit to the data

$$\Omega(f) = \frac{2\pi^2}{3H_0^2} A^2 f_{yr}^2 \left(\frac{f}{f_{\mathrm{yr}}}\right)^{5-\gamma}$$

The NANOGrav Collaboration 2009.04496

Cosmic String

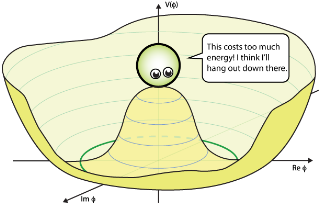
- **What are cosmic strings?**
  → Stable one-dimensional topological defects
- **The origins of cosmic strings:**
  → Prediction from Superstring theory:
  (F-) string, D-string
  → Vortex-like solutions in field theory
  e.g. from spontaneously broken U(1) symmetry

Cosmic String

- **What are cosmic strings?**
  → Stable one-dimensional topological defects
- **The origins of cosmic strings:**
  → Prediction from Superstring theory:
  (F-) string, D-string
  → Vortex-like solutions in field theory
  e.g. from spontaneously broken U(1) symmetry

- Charged complex scalar field

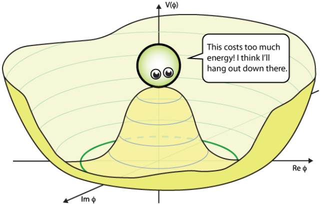
$$V = \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^2$$



Cosmic String formation (Kibble mechanism)

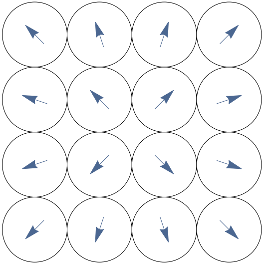
- Charged complex scalar field

$$V = \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^2$$



- Horizon size at early time (high temperature) $d_H \propto M_p / T^2$
- we need a solution:

$$\Phi \xrightarrow{r \to \infty} \frac{v}{\sqrt{2}} e^{i\theta}$$



Cosmic String solution

- In the Abelian Higgs model

$$\mathcal{L} = D_\mu \Phi D^\mu \Phi^\dagger - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^2$$

  - approximate solution

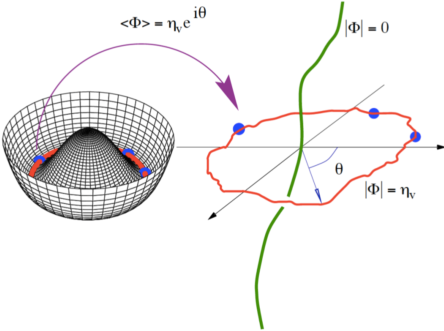
$$\Phi = \frac{v}{\sqrt{2}} \left(1 - \exp(-r/r_1)\right) \exp(-i\theta)$$

$$A_\theta = \frac{1}{er} \left(1 - \exp(-r/r_2)\right)^2$$

$$\langle \Phi \rangle = 0 \text{ at the origin}$$

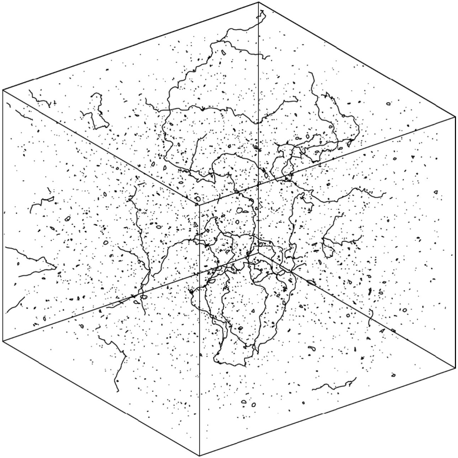
$$r_1, r_2 \propto v^{-1}$$

  - tension of the string
    (energy per unit length)
    $\mu \propto v^2$



Christophe Ringeval (Adv.Astron. 2010)

Cosmic Strings



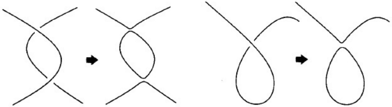
Vilenkin and Shellard 94’

Cosmic String network

- Static string network would red-shift as

$$\rho_\infty \propto a^{-2}$$

- strings intercommute on collision



- overall energy density of the network scales with total energy density

$$\frac{\rho_\infty}{\rho_{\mathrm{tot}}} \propto G\mu$$

Stochastic GW background from Cosmic String loops

- After its creation each loop radiates energy at a constant rate

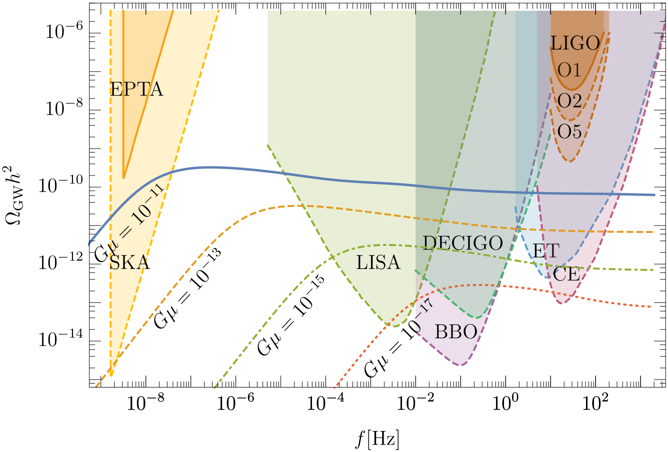
$$l(t) = \alpha t_i - \Gamma G\mu (t - t_i), \quad \alpha \approx 0.1\,,\ \Gamma \approx 50$$

Blanco-Pillado '13 '17 Lorenz '10

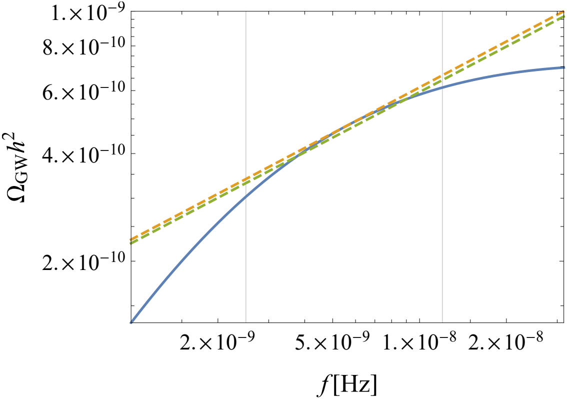
- The final estimate for GW density today, reads

$$\Omega_{\rm GW}(f)h^2 = h^2 \frac{16\pi}{3f}\frac{\Gamma (G\mu)^2}{H_0^2 \alpha\left(\alpha + \Gamma G\mu\right)}\int_{t_F}^{t_0} d\tilde{t}\frac{C_{\rm eff}(t_i)}{t_i^4}\left(\frac{a(\tilde{t})}{a(t_0)}\right)^5\left(\frac{a(t_i)}{a(\tilde{t})}\right)^3 \Theta\left(t_i - t_F\right)$$

Stochastic GW background from Cosmic Strings



power-law fit to Cosmic String spectrum

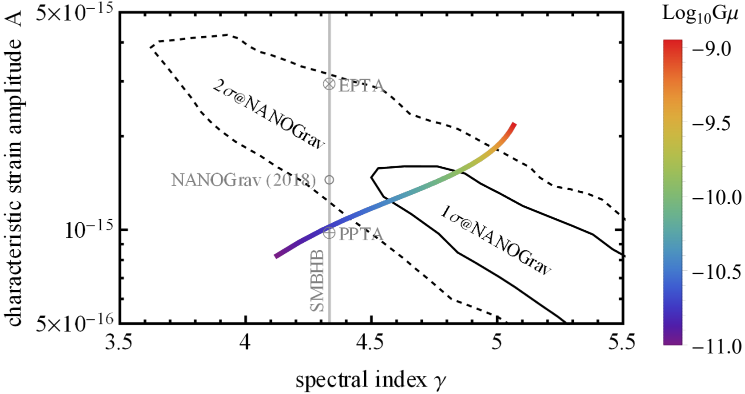


- power-law fit to string spectra

$$\gamma = 5 - \left.\frac{d\log\Omega_{GW}^{CS}(f)}{d\log f}\right|_{f=f_*}, \quad A = \sqrt{\frac{3H_0^2}{2\pi^2}\ \frac{\Omega_{GW}^{CS}(f_*)(f_{\rm yr}/f_*)^{5-\gamma}}{f_{\rm yr}^2}}$$

at the reference frequency $f_* \approx 5.6\times10^{-9}$ Hz.

Stochastic GW background from Cosmic Strings



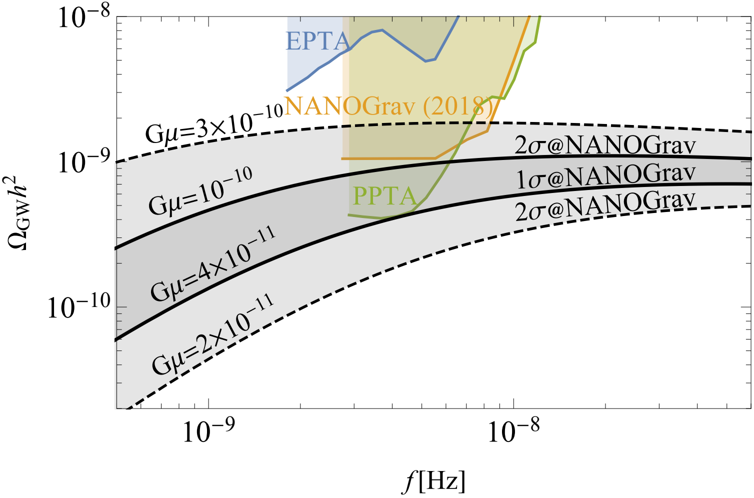
- results within the 68% CL

$$G\mu \in (4 \times 10^{-11}, 10^{-10})$$

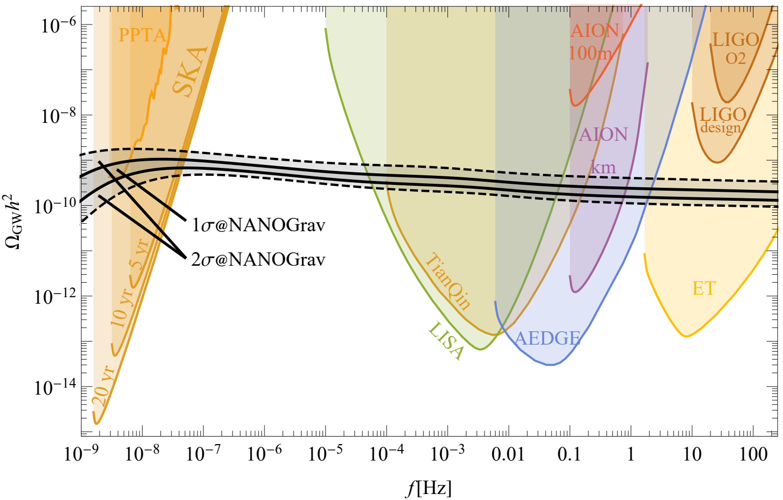
- results within the 95% CL

$$G\mu \in (2 \times 10^{-11}, 3 \times 10^{-10})$$

Stochastic GW background from Cosmic Strings



Stochastic GW background from Cosmic Strings

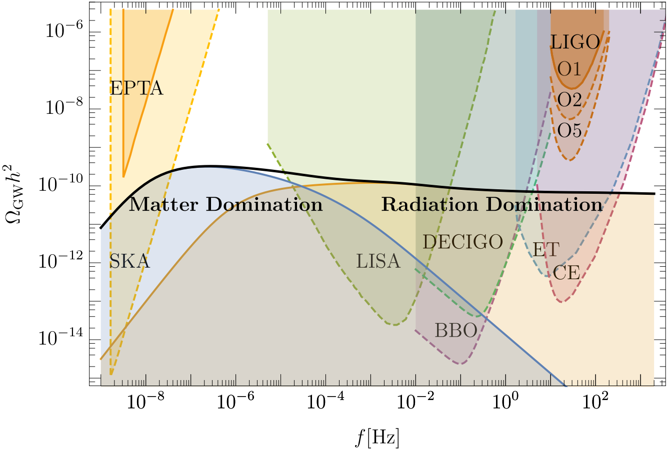


Conclusions

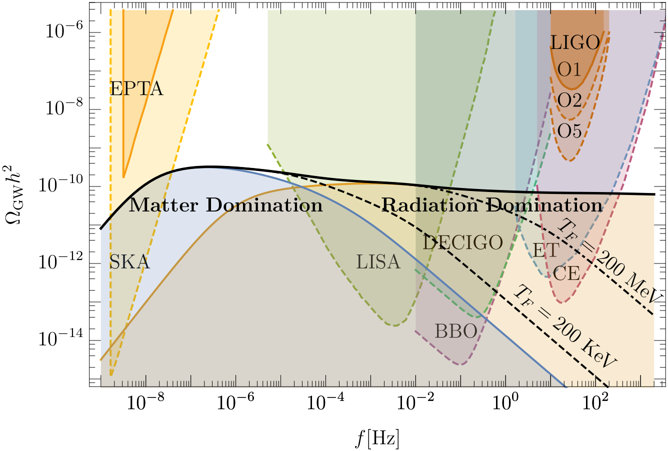
- Cosmic Strings are a very good candidate to fit the new NANOGrav data
- Future pulsar timing data should allow a better reconstruction of the spectral shape pointing more clearly towards the correct source
- All next-generation GWdetectors including SKA, LISA, TianQin, AEDGE, AION and ET will be able to probe the cosmic string spectra that fit the current data, whereas LIGO seems unlikely be able to probe them in the absence of additional cosmological or model features.

Backup:Cosmic Archaeology

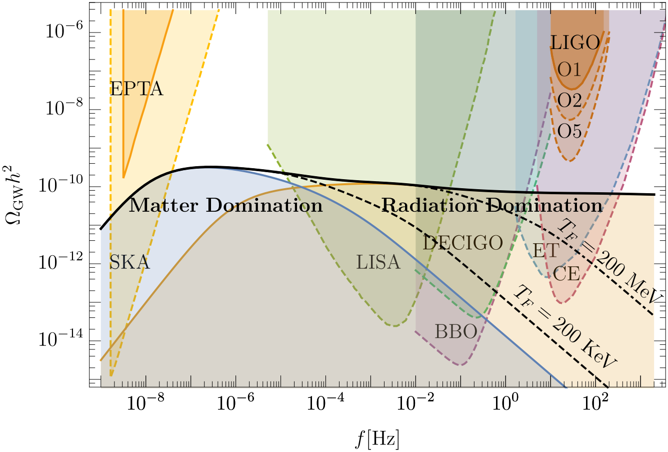
Stochastic GW background from Cosmic Strings



Stochastic GW background from Cosmic Strings



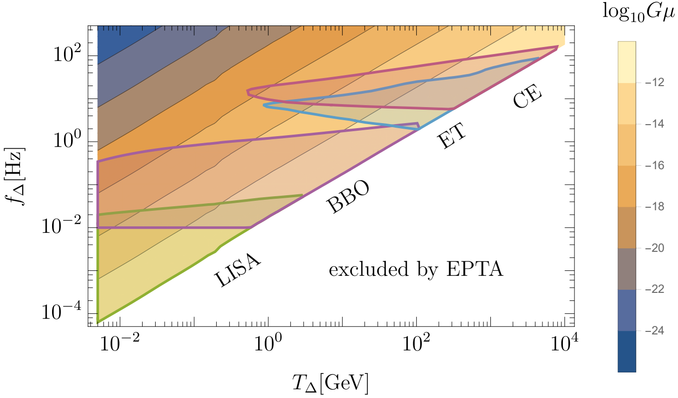
Stochastic GW background from Cosmic Strings



- GW frequency ↔ temperature

$$f_\Delta \propto \frac{T_\Delta}{\sqrt{G\mu\,\alpha}}$$

Detection capabilities



- slightly better numerical result

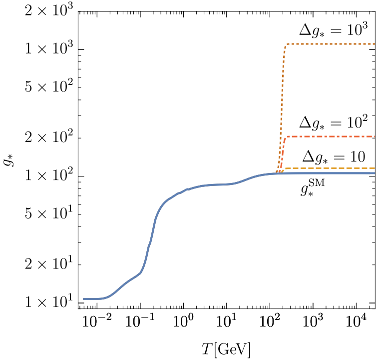
$$f_\Delta = (8.67 \times 10^{-9}\,\mathrm{Hz})\, \frac{T_\Delta/\mathrm{GeV}}{\sqrt{\alpha\, G\mu}} \left(\frac{g_*(T_\Delta)}{g_*(T_0)}\right)^{\frac{8}{6}} \left(\frac{g_S(T_0)}{g_S(T_\Delta)}\right)^{-\frac{7}{6}}$$

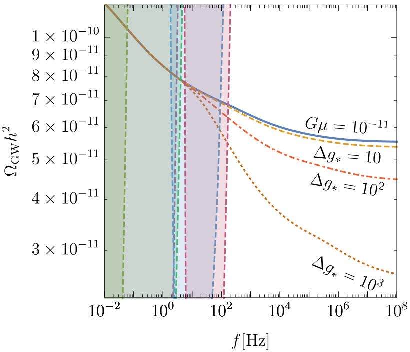
Extra DOF

- We add Δg_* new degrees of freedom at T_Δ

$$g_*(T) = \begin{cases} g_*^{\rm SM}(T) & \text{for} \quad T < T_\Delta \\ g_*^{\rm SM}(T) + \Delta g_* & \text{for} \quad T > T_\Delta \end{cases}$$

- An example with $T_\Delta = 200\,\text{GeV}$ and $G\mu = 10^{-11}$





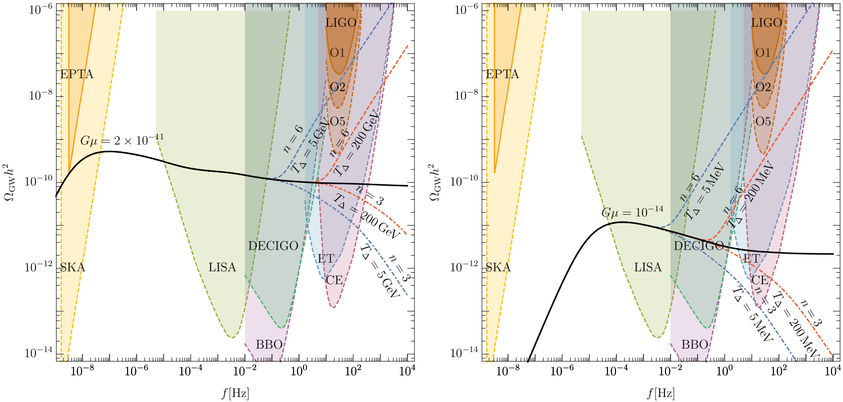
Non standard cosmologies

- We will model the energy budget of the universe as

$$\rho(t) = \begin{cases} \rho_{st}(t) & ;\ t \geq t_\Delta \\ \rho_{st}(t_\Delta)\ \left[\frac{a(t_\Delta)}{a(t)}\right]^n & ;\ t < t_\Delta \end{cases}$$

- examples:
  1. standard radiation domination ($n = 4$)
  2. early matter domination ($n = 3$)
  3. oscillating scalar field (for non-renormalisable potential $n \to 6$)
  4. ...
- experimental bounds: RD during BBN $\Rightarrow T_\Delta \gtrsim 5$ MeV

Non standard cosmologies



- at large frequencies

$$H^2 \propto a^{-n} \Longrightarrow \Omega_{GW}(f) \propto \begin{cases} f^{\frac{8-2n}{2-n}} & n > 10/3 \\ f^{-1} & n \leq 10/3 \end{cases}$$

Conclusions

1. Cosmic strings could provide a powerful tool for probing the early history of the universe.
2. Any departure from a flat spectrum predicted by standard cosmological evolution can be traced to the respective temperature of cosmological modification.
3. This method could probe the cosmological evolution to time well before the currently available BBN data.