Cosmic Strings and Pulsar Timing

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work in collaboration with V. Brdar and K. Schmitz

Based on PRL 126 (2021) [2009.06607]

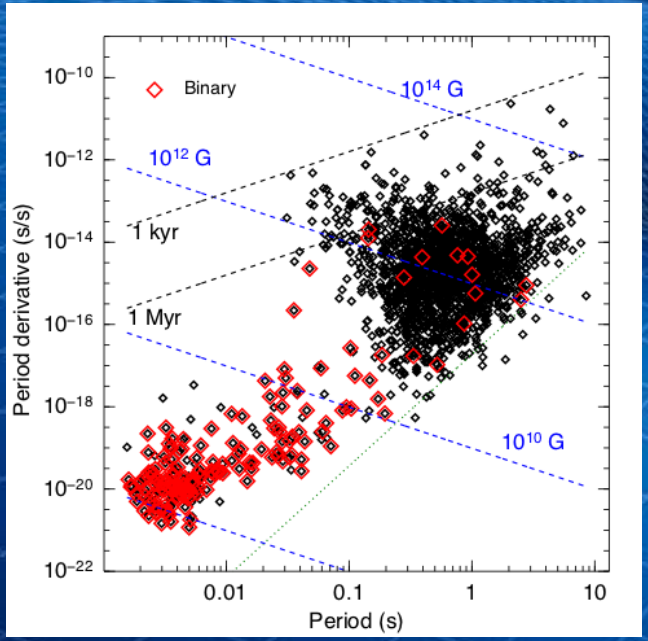
16th Marcel Grossmann meeting 07.07.21

Pulsar Timing Arrays

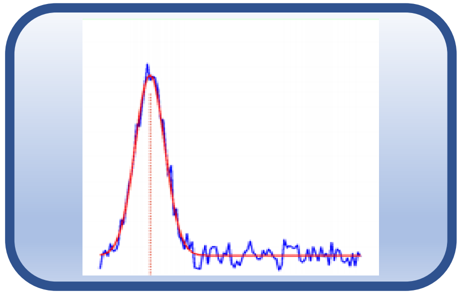
Neutron stars, $\mathrm{R} \sim 10\ \mathrm{km},\ \ \mathrm{B} \sim 10^{8} - 10^{15}\ G$

Great clocks: rapid rotation + large inertia = very stable

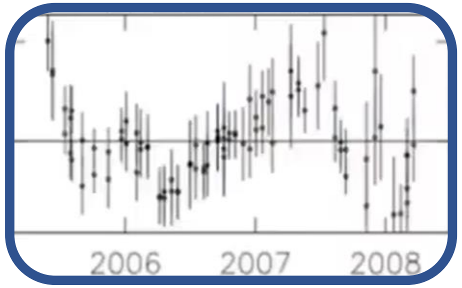
Lighthouse effect: very precise ticks when beam crosses line of sight



Pulsar Timing Arrays

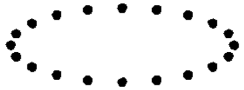


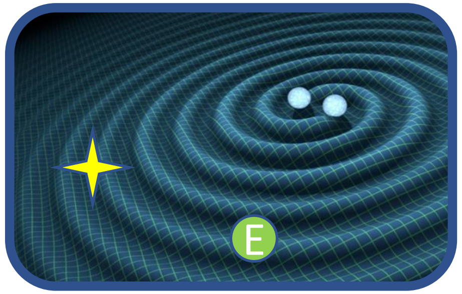
Observe the pulsar and measure the **Time of Arrival** (with respect to the solar system barycenter)



Find the theoretical model that fits the ToAs in terms of $\nu, \dot{\nu}$.. and construct the **time residuals**

$$R = \mathrm{ToA}_{\mathrm{th}} - \mathrm{ToA}_{\mathrm{m}}$$





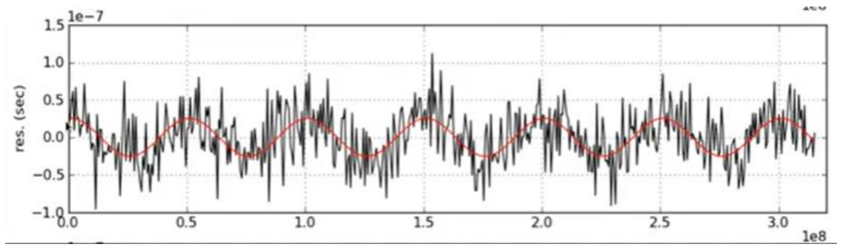
Look for **unaccounted-for physics** in the time residuals, e.g. GWs from resolved supermassive black hole binary during inspiral

$$R \sim \frac{h}{2\pi f} \sim 25.7\ \mathrm{ns} \left(\frac{\mathrm{M}}{10^9\ \mathrm{M}_\odot}\right)^{5/3} \left(\frac{D}{100\ \mathrm{Mpc}}\right)^{-1} \left(\frac{f}{50\ \mathrm{nHz}}\right)^{-1/3}$$

[Sesana et al. 0809.3412]

Pulsar Timing Arrays

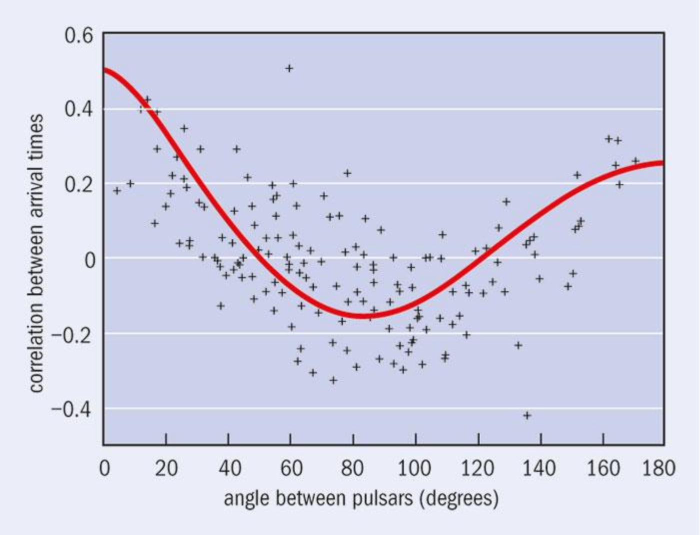
Is this is a gravitational wave?

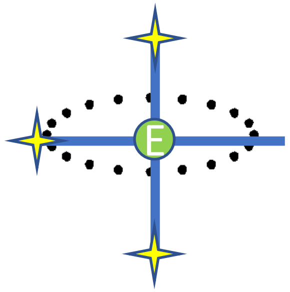


Not so fast… **red noise** can be

- offset of the clock (monopolar)
- misplaced SSB (dipolar)
- intrinsic to the source

Look at correlation of ToAs for pairs of pulsars:



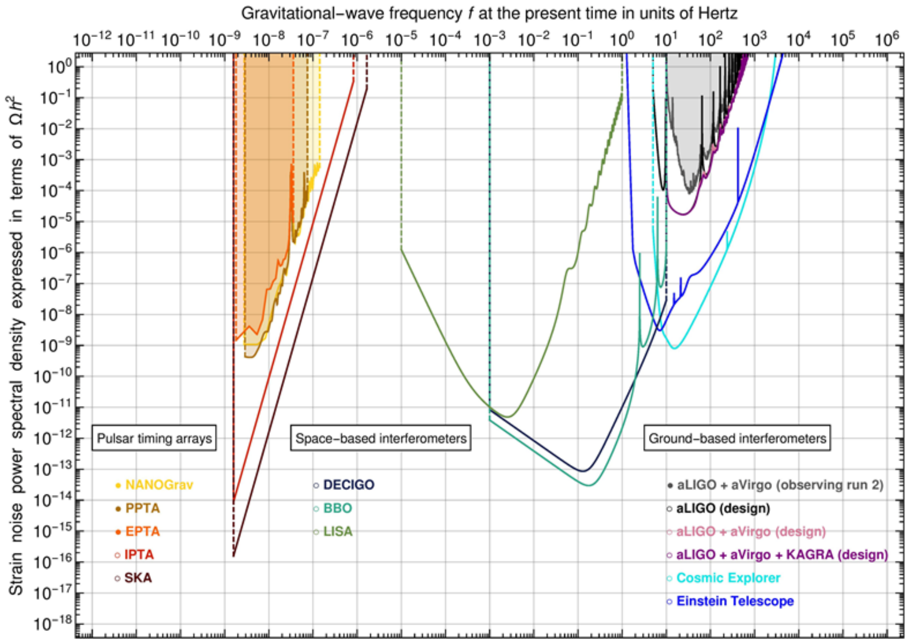


- Hellings-Downs curve (quadrupolar), only dependence on the angle

Pulsar Timing Arrays

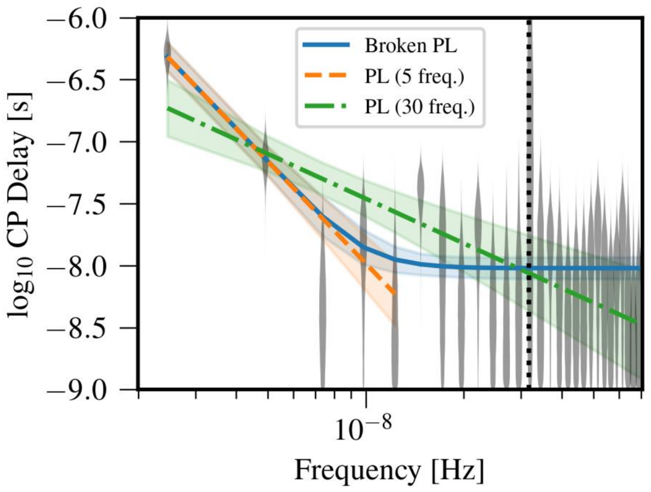
NANOGrav + PPTA + EPTA = IPTA

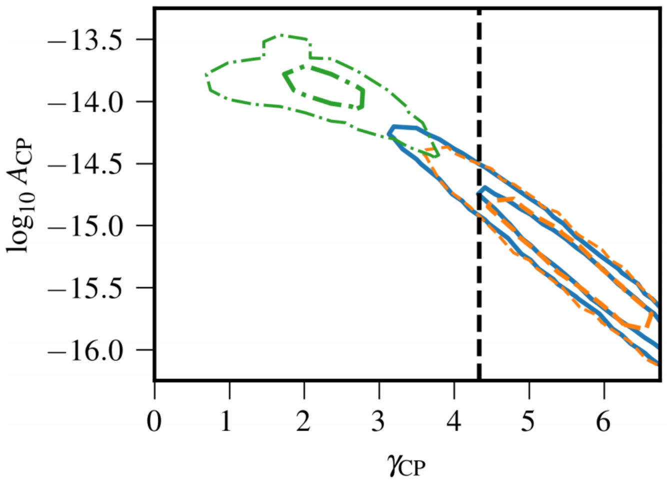
Pulsars are excellent probes at very low frequencies: $3\ \mathrm{nHz} \approx \dfrac{1}{10\ \mathrm{years}} < f < \dfrac{1}{1\ \mathrm{month}} \approx 400\ \mathrm{nHz}$

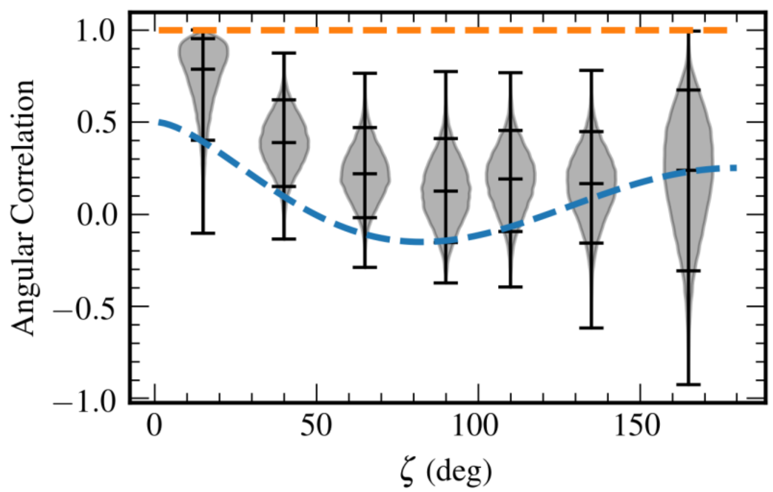


[Schmitz 2002.04615]

NANOGrav 12.5-year data set [40+ ms pulsars, 2009.04496]







- Clear detection of a common red process fitted by a power law

$$S_{ab} = \Gamma_{ab}\, h_c^2(f) \left(\frac{f}{f_{\rm yr}}\right)^{-3} \qquad h_c(f) = A_{\rm GWB} \left(\frac{f}{f_{\rm yr}}\right)^{\alpha} \qquad \gamma = 3 - 2\alpha \qquad (\alpha = -2/3 \text{ for BHs})$$

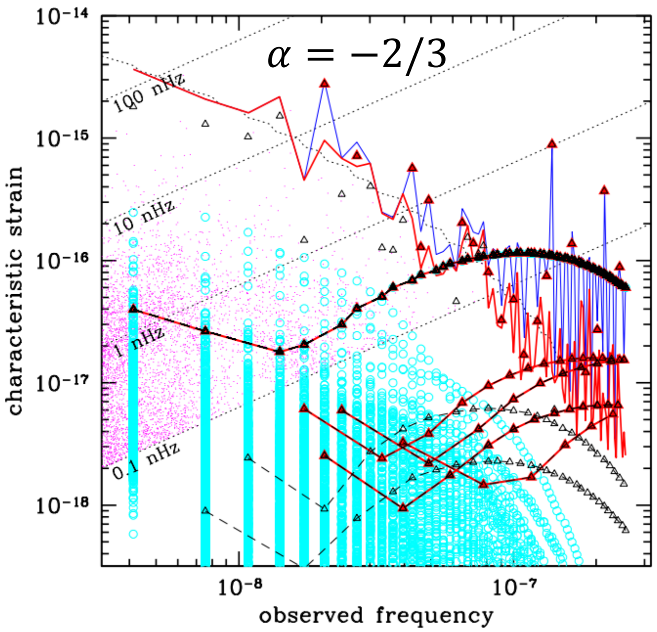
- Either monopolar or dipolar correlation is disfavored with respect to no correlation
- Quadrupolar correlation vs no correlation gives inconclusive evidence

Possible interpretations

See [2009. 13893] for Bayesian comparison of different cosmo sources (cosmic strings are favored)

Astrophysical

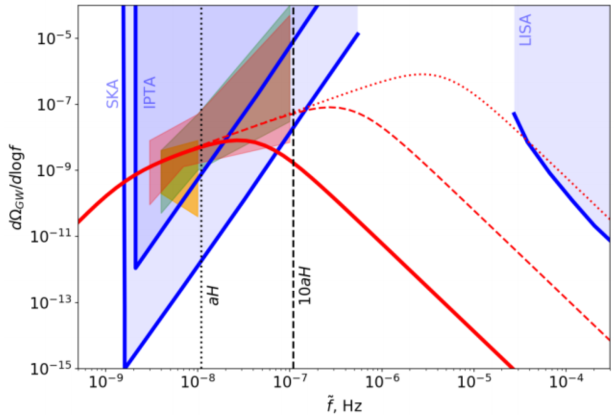
- Supermassive black hole binaries

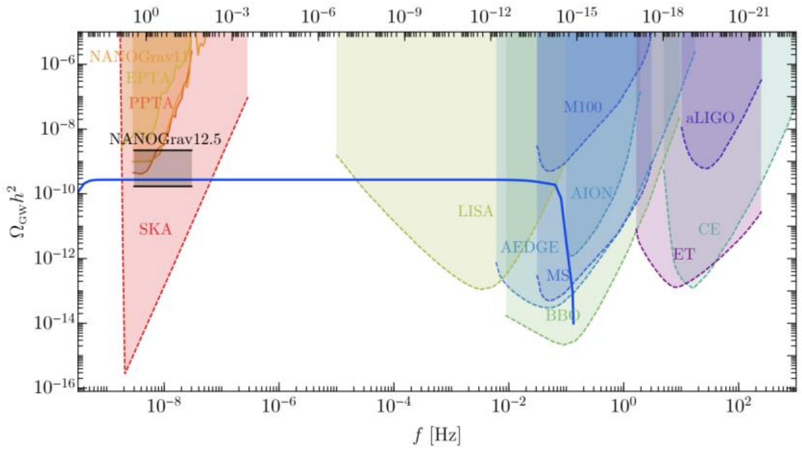


[Amaro-Seoane et al. 0910.1587]

Cosmological + BSM

- Phase transitions [2009.09754, 2009.10327, 2009.14174, 2009.14663]
- Primordial black holes [2009.07832, 2009.08268, 2009.11853, 2010.03976]
- Audible axions [2009.11875]
- Inflation [2009.13432, 2010.05071]
- Cosmic strings [2009.06555, **2009.06607**, 2009.10649, 2009.13452]
- Domain walls [2104.08750]



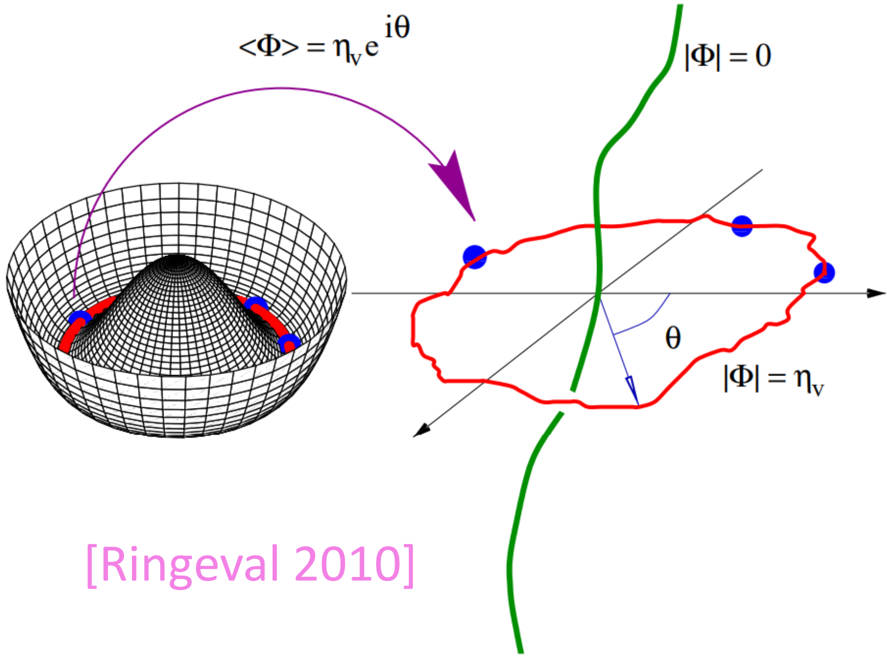


Cosmic strings

Defects as relics of phase transitions depending on topology of vacuum manifold
[Zel'dovich et al. 74, Kibble 76] (or as fundamental strings in string theory)

Defect	Dimension	Homotopy group
Domain walls	2	$\pi_0(M)$
Strings	1	$\pi_1(M)$
Monopoles	Point-like	$\pi_2(M)$
Textures	-	$\pi_3(M)$

[Vilenkin,Shellard '94]

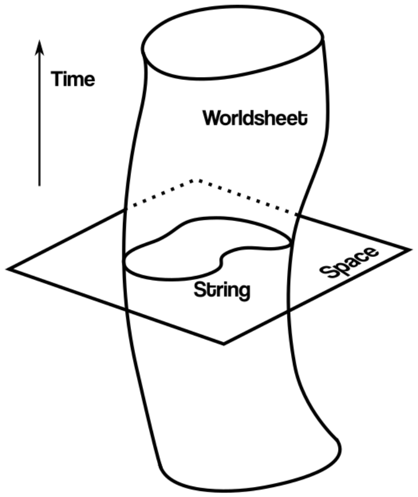


[Ringeval 2010]

$Theorem$: $\pi_1(G/H) \cong \pi_0(H)$

GUT strings : $\mu \sim 1\, M_{\oplus}/\mathrm{km}$

Cosmic strings in field theory



Vortex solutions of classical EoM [Nielsen-Olesen 1973]

- **Gauge U(1)**: energy density finite

$$\mu \approx \eta^2$$

- **Global U(1)**: energy density log divergent (Nambu-Goldstone mode)

$$\mu \approx \eta^2 \log\left(\frac{m_\phi}{H}\right)$$

See [Gorghetto et al. 1806.04677] for Peccei-Quinn strings

- At **low energies** effectively **Nambu-Goto** action (+ corrections)

$$S = -\mu \int \sqrt{-\gamma}\, d^2\zeta + \alpha \int \kappa \sqrt{-\gamma}\, d^2\zeta + \cdots$$

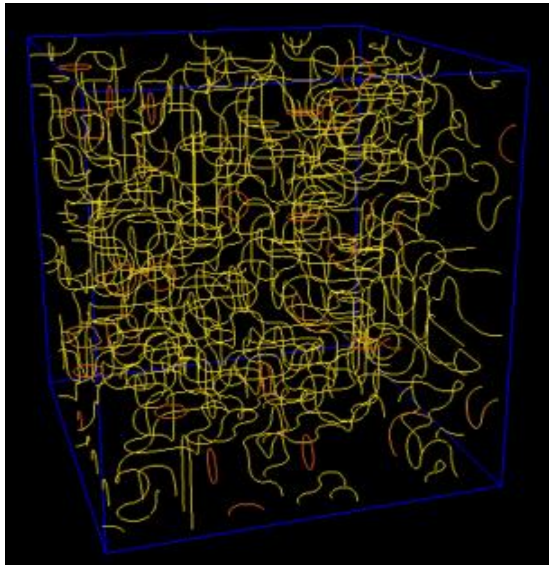
extrinsic curvature may be neglected: exception cusps and kinks, particle production?

[Gouttenoire et al. 1912.02569]

Cosmic string network

Formation:

- $\rho_\infty \sim$ 80% in long strings
- $\rho_L \sim$ 20% small loops



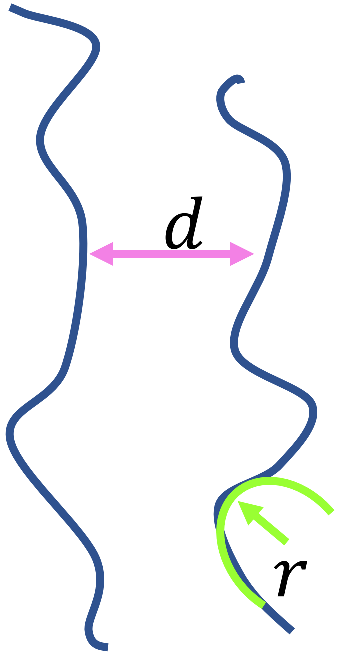
Evolution:

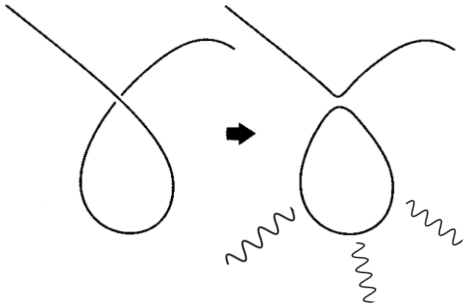
- Naively $\rho_\infty \sim \mu\, a/a^3$ leads to string domination
- Expansion of the universe + large prob intercommutation gives **scaling solution**

$$d \sim r \sim t \quad \Rightarrow \quad \rho_\infty \sim \mu/t^2$$

- Small loops produced at large rate to maintain scaling, which **decay to GW**

$$\frac{\rho_\infty}{\rho_c} \sim G\mu \ll \frac{\rho_L}{\rho_c} \sim \sqrt{G\mu}$$

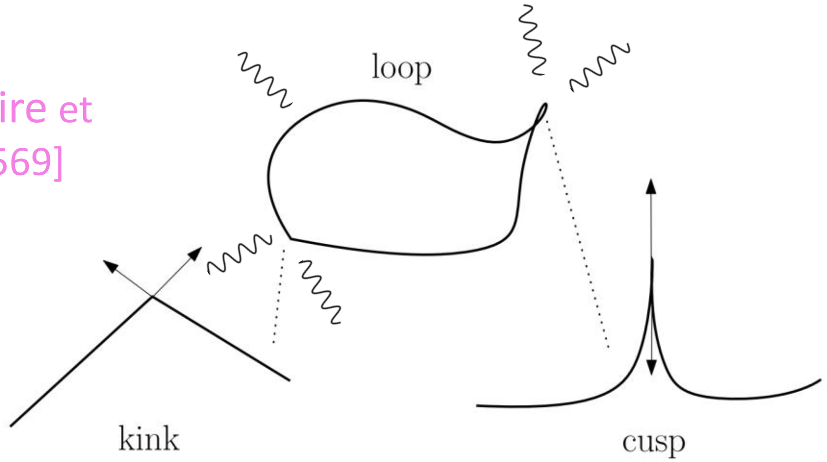


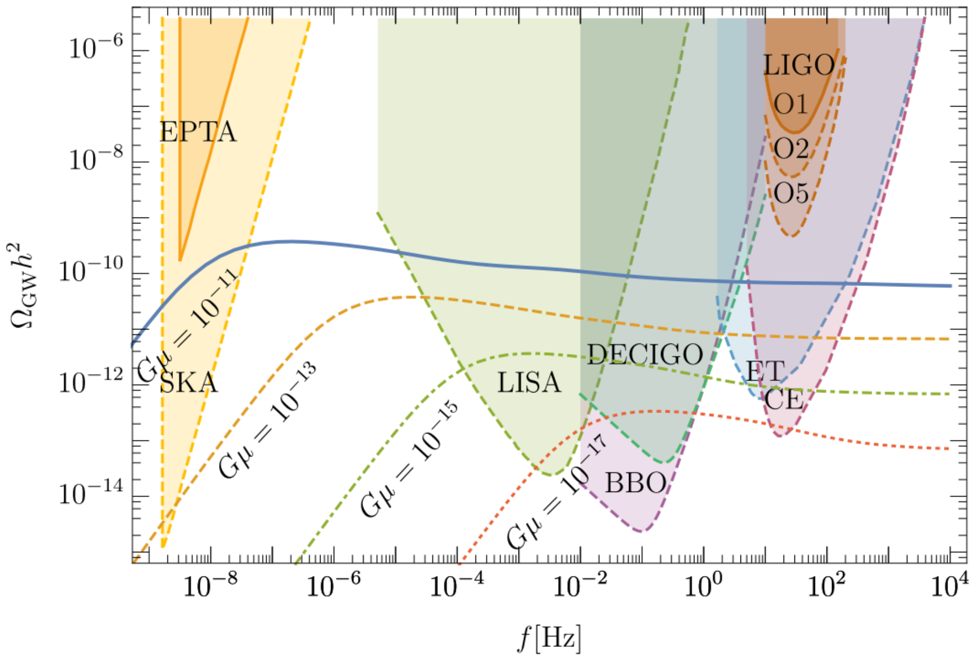


GWs from cosmic strings

[Cui et al. 1808.08968]

[Gouttenoire et al. 1912.02569]





Sub-horizon loops are free to oscillate: **long-lasting source of GWs**

Total emission **power** $\mathrm{P} = \Gamma G\mu^2$, loops shrink while their density redshifts

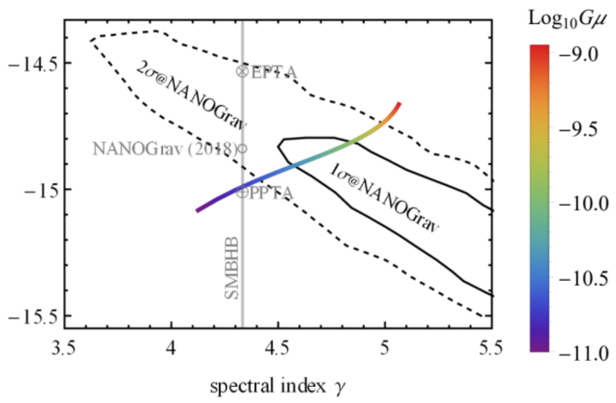
$$l(t) = l(t_i) - \Gamma G\mu\,(t - t_i), \quad l(t_i) = \alpha\, t_i$$

populating **harmonics** $f_k = 2k/l(t)$ with power P_k

Production	Emission	Ω_{GW} (k=1)
RD	RD	$\sim f^0$
RD	MD	$\sim f^{-1/2}$
MD	RD	$\sim f^{-1}$

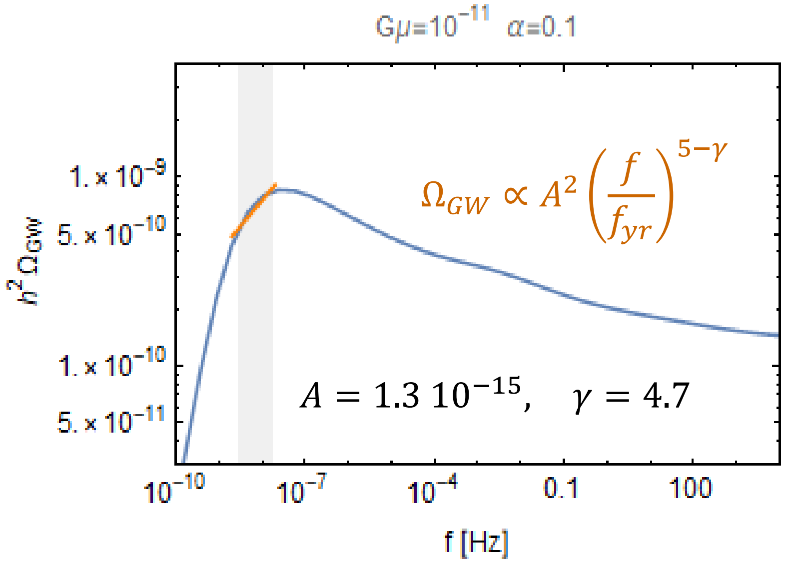
Cosmic strings & NANOGrav

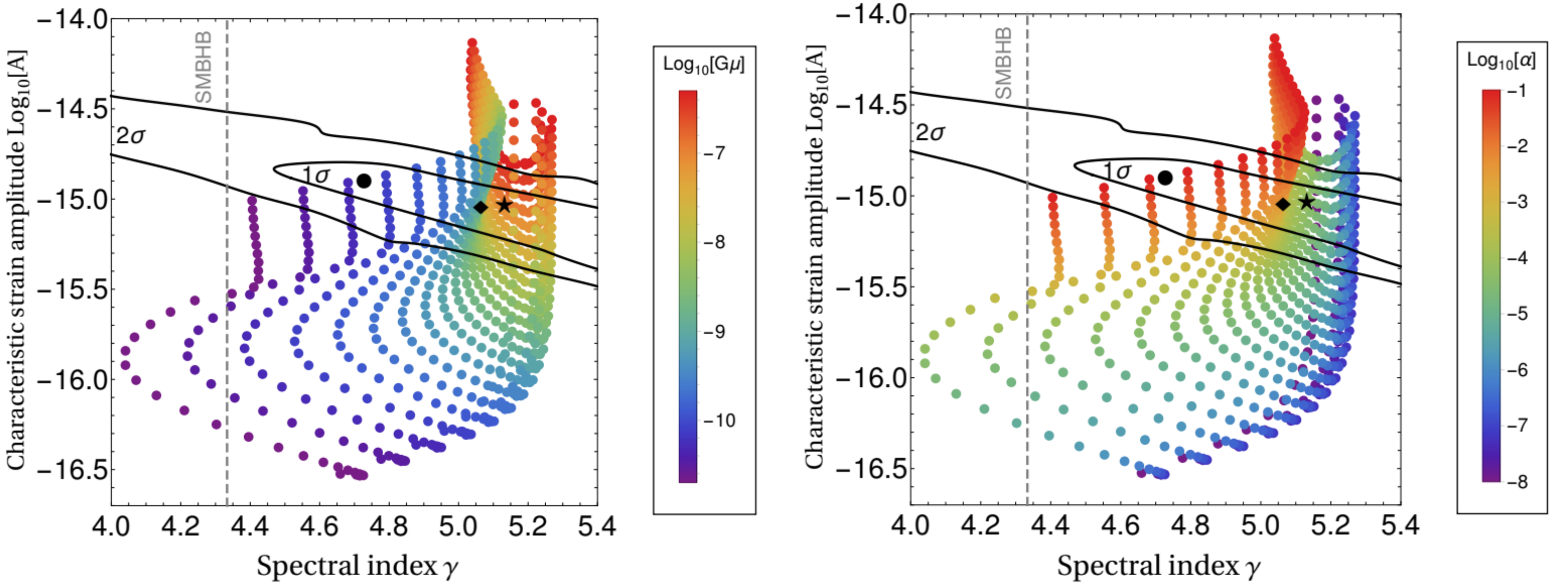
[Ellis,Lewicki 2009.06555]



Power-law fit of the GW signal (cusps) between $2\,10^{-9} \to 2\,10^{-8}$ Hz

[SB,Brdar,Schmitz 2009.06607]

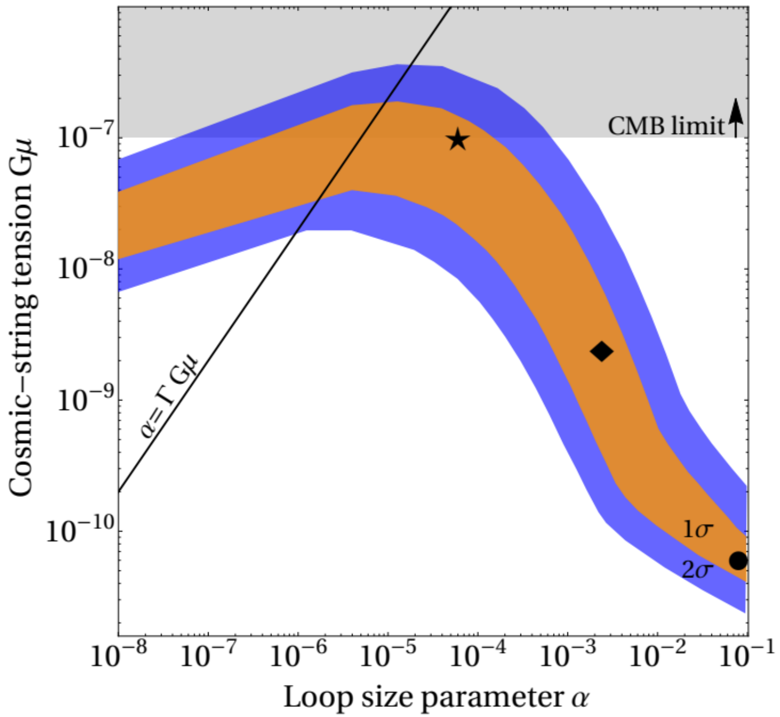


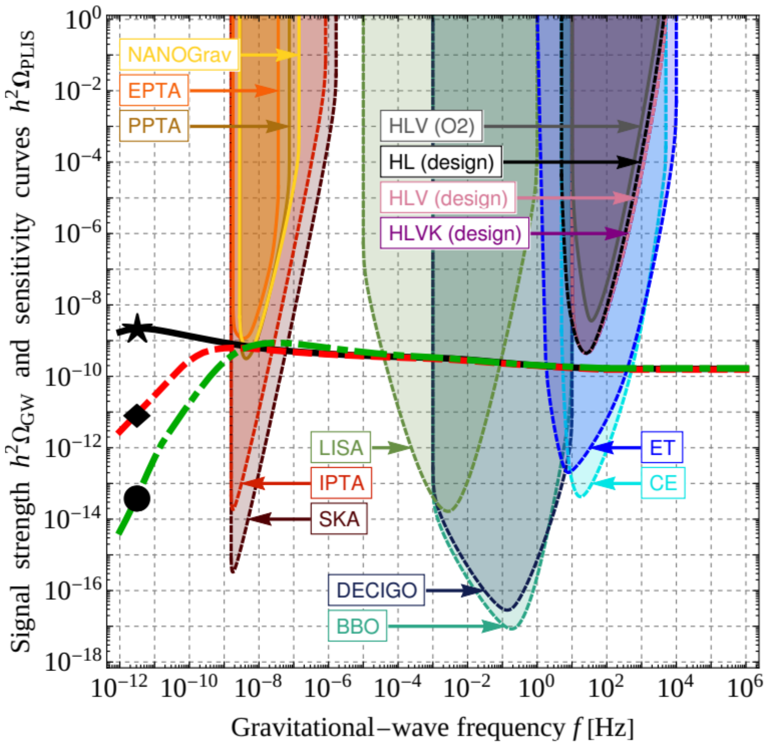


See [Blanco-Pillado et al. 2102.08194] for different assumptions on small-scale structure, still compatible with data

Cosmic strings & NANOGrav

[SB,Brdar,Schmitz 2009.06607]



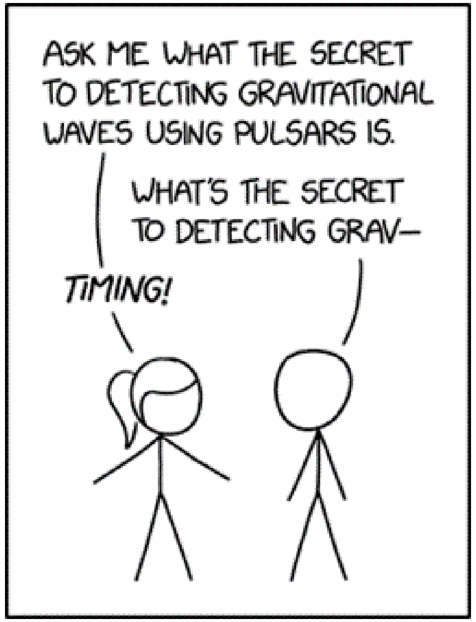


- Detection prospects of the plateau at future experiments
- Symmetry breaking scale can hint to BSM scenarios

$$h^2\Omega_{GW}^{\rm flat} = 2\;10^{-4}\left(\frac{\alpha}{0.1}\right)\left(\frac{G\mu}{\Gamma}\right)^{1/2}$$

$$\mathrm{SSB} = 10^{16}\ \mathrm{GeV}\left(\frac{G\mu}{10^{-7}}\right)^{1/2}$$

Conclusion



- Strong evidence for a stochastic red process in NANOGrav 12.5-year data set with 40+ pulsars

- Quadrupolar correlation still inconclusive

- Joint analysis within IPTA collaboration ongoing, see e.g talk by Jeffrey Hazboun (CERN Theory Colloquia, 27.01.21)

- Astrophysical and Cosmological (BSM) interpretations of signal have been proposed in terms of GWs

- Cosmic strings (topological defects) are interesting: formation independent of the strength of the phase transition, large signal in GWs, connection to fundamental physics

- NANOGrav may have just provided the first observation :)