Has NANOGrav found first evidence for cosmic strings?

based on arXiv:2009.06607 in collaboration with S. Blasi and K. Schmitz

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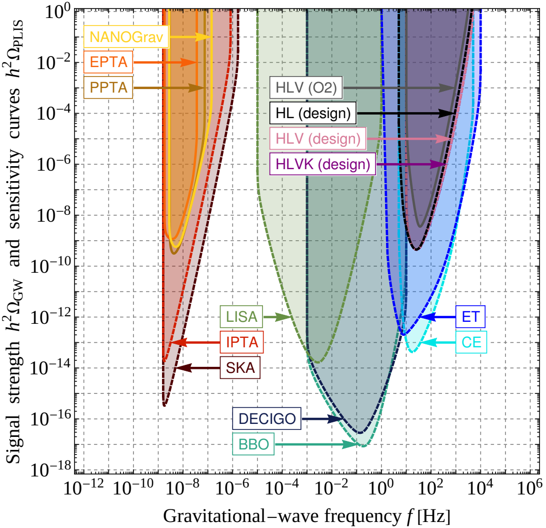
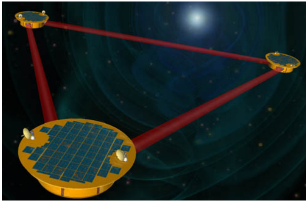
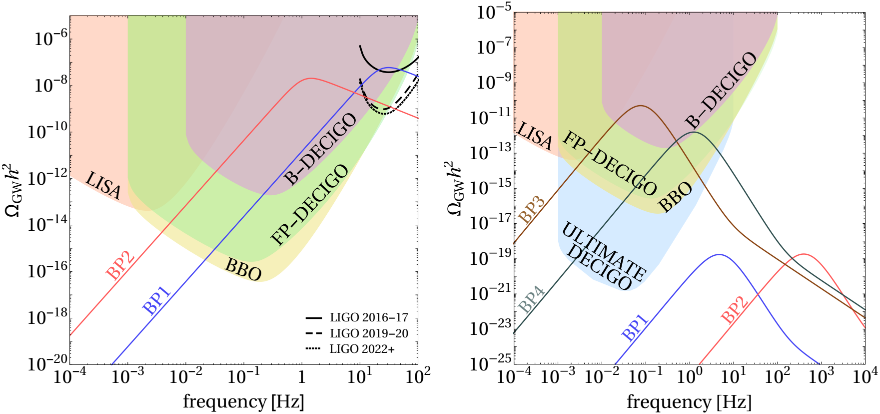
Gravitational waves – A Window to New Physics





From April and November 2019 (pre-COVID-19)



June-September 2020 (COVID-19)

Excess electronic recoil events in XENON1T #1

XENON Collaboration • E. Aprile (Columbia U.) et al. (Jun 17, 2020)

Published in: *Phys.Rev.D* 102 (2020) 7, 072004 • e-Print: 2006.09721 [hep-ex]

pdf links DOI cite 146 citations

The NANOGrav 12.5-year Data Set: Search For An Isotropic Stochastic Gravitational-Wave Background #1

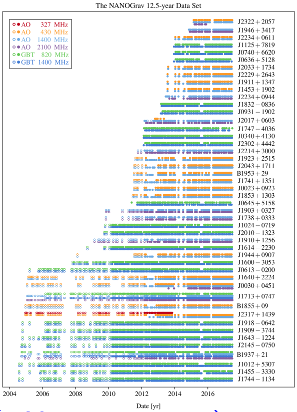
NANOGrav Collaboration • Zaven Arzoumanian (CRESST, Greenbelt and NASA, Goddard) et al. (Sep 9, 2020)

e-Print: 2009.04496 [astro-ph.HE]

pdf links cite 35 citations

Pulsar Timing Arrays (PTA)

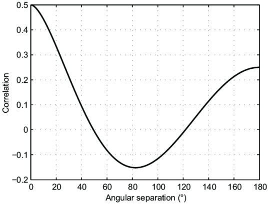
- pulsars are magnetized and rapidly rotating neutron stars; sources of radio waves
- the core of the sensitivity to gravitational waves using pulsars is in the change of the time of arrival of the signal
- PTA include analysis of large number of pulsars:
  - Parkes Pulsar Timing Arrays (25)
  - EPTA (42)
  - NANOGrav (47)
- So far, PTA measurement were able to report limits on the stochastic gravitational wave background at the level of $\Omega h^2 \sim 10^{-8}$
- In contrast, recently NANOGrav reported a strong preference for a stochastic common spectrum process in 12.5-year data set analysis (arXiv:2009.04496)



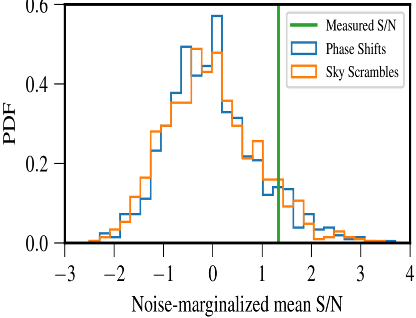
NANOGrav Findings

- despite a very strong hint, these results are still inconclusive with respect to GW discovery
- missing piece : quadrupolar spatial correlation (Hellings & Downs, 1983)

- for the signal from i-th pulsar :
  $\alpha_i \, h(t) + \, n_i(t)$
- cross-correlation from two pulsars :
  $\alpha_i \alpha_j < h^2 > + \, \alpha_i < h \, n_j > + \, \alpha_j < n_i \, h >$
  $+ < n_i \, n_j >$
- $< h^2 >= \frac{1}{T} \int_{-T-\tau}^{T+\tau} h(t) h(t+\tau) dt$
  $\alpha_{ij} = \frac{1}{4\pi} \int d\Omega \, \alpha_i \alpha_j$ arXiv:2002.01954

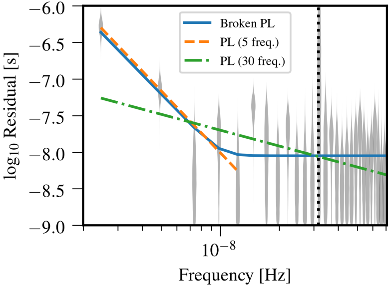


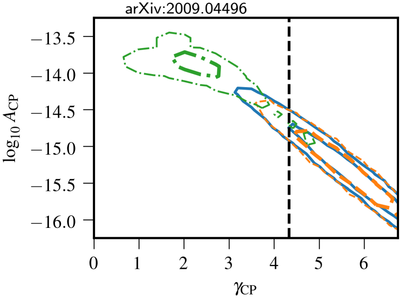
arXiv:2009.04496



- for no correlation hypothesis, large p-value at the level of 5%

NANOGrav Findings





- median value of A_{CP} higher than the 95% CL upper limit from 11 year data set!
- change in the data processing procedure led to the reduction in the amount of white noise which increases the sensitivity to low-frequency red noise processes
  $\Longrightarrow$ stochastic gravitational waves
- free spectrum, 5-frequency power law and broken power law cases capture correctly lowest frequencies where GWs are detectable
- one of prime candidates for stochastic GW signal at $f \sim nHz$ are supermassive black hole binaries (distribution as a function of mass and redshift uncertain)

Viable explanations

- assuming the discovery of quadrupolar spatial correlations will occur, a number of scenarios could be responsible for such stochastic GW signal:

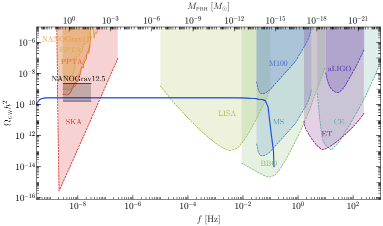
- Cosmic strings (2009.06607, 2009.06555, 2009.10649, 2009.13452)

- First-order phase transition (2009.09754, 2009.10327, 2009.11875)

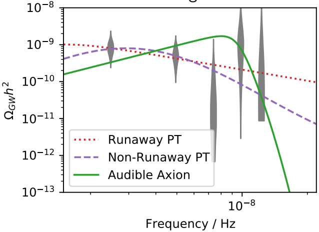
- Inflation (2009.13432)

- Primordial Black Holes (2009.07832, 2009.08268, 2009.11853)

De Luca et al. 2009.08268

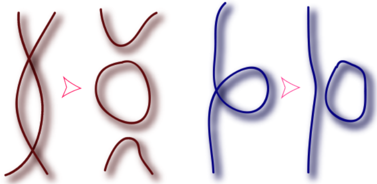


Schwaller and Ratzinger 2009.11875



Cosmic Strings

- cosmic strings are topological defects $\Longrightarrow$ physical objects produced in the phase transitions (postulated by Kibble 1976)
- characterized by their tension μ
- long strings intersect and form loops which oscillate and radiate energy



- dominant radiation in form of gravitational waves (string dynamics described in terms of Nambu-Goto action)
- GW emission from long strings can be neglected compared to the GW emission from loops

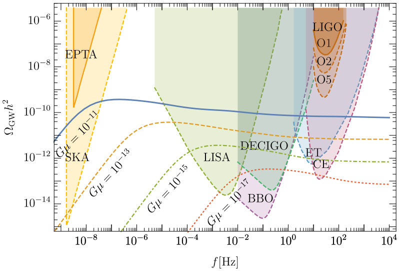
Gravitational Wave Signature

1711.03104, 1808.08968, 1909.00819

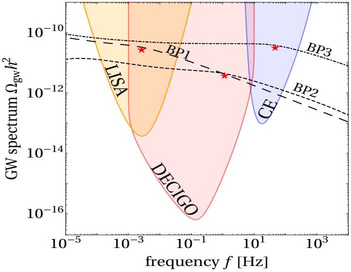
$$\Omega_{\rm gw}(f) = \sum_{k=1}^{\infty} \Omega_{\rm gw}^{(k)}(f) = \frac{8\pi}{3H_0^2}(G\mu)^2 f \sum_{k=1}^{\infty} C_k P_k$$

- $P_k = \frac{\Gamma}{k^q \zeta(q)}$; $q = 4/3$ for cusp-dominated loops and $\Gamma \approx 50$
- $C_k(f) = \frac{2k}{f^2} \int_{t_{\rm scl}}^{t_0} dt\, \Theta(t) \left(\frac{a(t)}{a(t_0)}\right)^5 n(\ell_k, t)$
- number of loops per unit volume $n(\ell_k, t)$ and length depends on $G\mu$ and parameter describing loop length at formation α

1808.08968



2004.02889

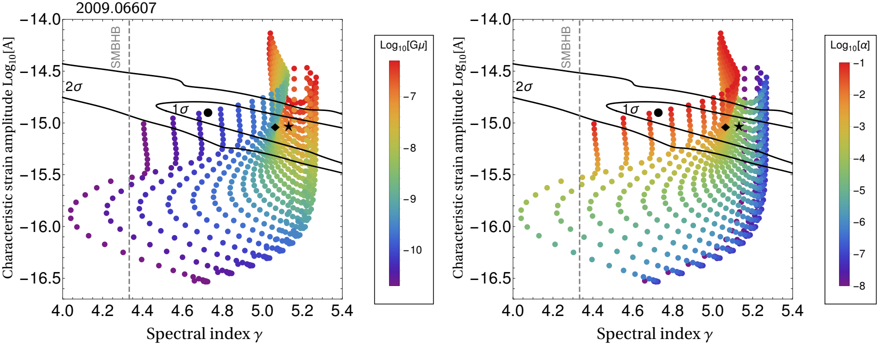


Cosmic String Explanation of NANOGrav Result

- NANOGrav models the cross power spectrum around a reference frequency by a single power law $S \propto (f/f_{ref})^{-\gamma}$
- can be expressed in terms of characteristic strain $h_c(f) = A\left(\frac{f}{f_{ref}}\right)^{(3-\gamma)/2}$
- spectral GW energy density $\Omega_{\rm gw}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c^2(f) = \frac{2\pi^2}{3H_0^2} f_{ref}^2 A^2 \left(\frac{f}{f_{ref}}\right)^{5-\gamma}$
- by having $\Omega_{\rm gw}$ as a function of both $(G\mu, \alpha)$ and (A, γ) we can determine the latter from the chosen $(G\mu, \alpha)$ combination
- for all points in the scan, we check that a simple power-law fit provides a good approximation of the actual GW spectrum in the frequency range $f \sim [3 \times 10^{-9}, 3 \times 10^{-8}]\,\mathrm{Hz}$ where NANOGrav observes the signal

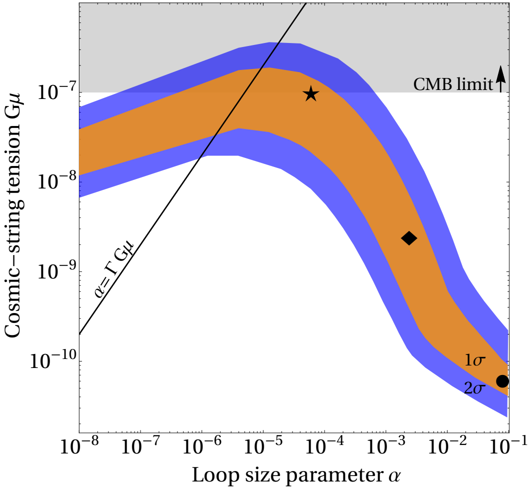
	α	$G\mu$	γ	A
★	6.0×10^{-5}	1.0×10^{-7}	5.13	9.25×10^{-16}
◆	2.4×10^{-3}	2.4×10^{-9}	5.06	9.20×10^{-16}
●	1.0×10^{-1}	6.0×10^{-11}	4.73	1.28×10^{-15}

Cosmic String Explanation of NANOGrav Result



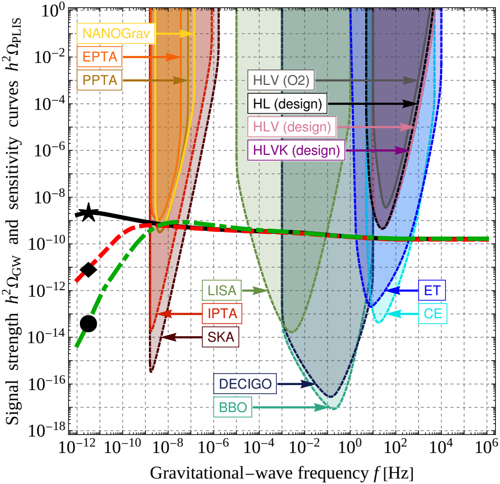
- we find that the cosmic-string-induced GW spectrum manages to reproduce the NANOGrav signal across large ranges of the parameters $G\mu$ and α; NANOGrav 1σ region populated!

Cosmic String Explanation of NANOGrav Result



- solutions in the range $10^{-11} \lesssim G\mu \lesssim 10^{-6}$
- agreement with Ellis and Lewicki (2009.06555) for $\alpha = 0.1$

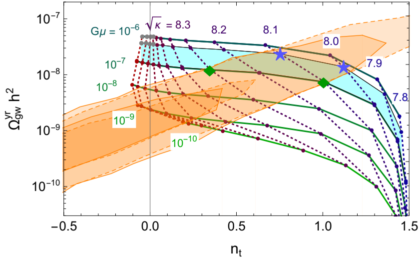
Cosmic String Explanation of NANOGrav Result

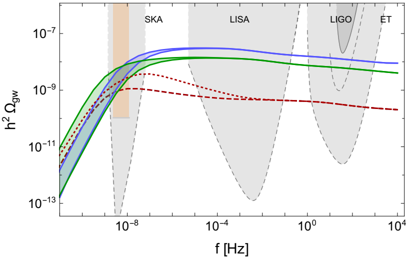


- The EPTA, PPTA, and NANOGrav curves at low frequencies represent the status of PTA constraints on the GW spectrum *prior to the new NANOGrav result*
- $h^2\Omega_{\rm gw}^{\rm plateau} \simeq 2\times10^{-4} \left(\frac{\max\{\alpha, 9/4\,\Gamma\,G\mu\}}{0.1}\right)^{1/2} \left(\frac{G\mu}{\Gamma}\right)^{1/2}$
- the expected spectrum is within the sensitivity reach of LISA, DECIGO, BBO, the *Einstein Telescope*, and *Cosmic Explorer*
- LIGO+Virgo+KAGRA will not be able to detect the signal at a sufficient signal-to-noise ratio but...

Metastable Cosmic Strings and NANOGrav

- embedding U(1) model into some GUT model, e.g., SO(10) makes the entire string nework unstable $\Longrightarrow$ existence of magnetic monopoles
- long strings and loops can decay to monopole-antimonopole pairs which can efficiently annihilate (arXiv:0808.1693)
- decay rate per unit length $\Gamma = \frac{\mu}{2\pi}\,\mathrm{Exp}[-\pi\kappa]$, with $\kappa = m^2/\mu$
- larger values than those in case of stable cosmic strings can fit NANOGrav (2009.10649) $\Longrightarrow$ possible signal at LIGO+Virgo+KAGRA





Summary

- The NANOGrav collaboration recently reported strong evidence for a stochastic common spectrum process across the pulsars in its 12.5-year data set

- we investigated the results of the NANOGrav analysis based on the assumption that this stochastic process corresponds to a primordial SGWB emitted by cosmic strings in the early Universe

- we identified the viable cosmic-string parameter space and argued that the entire viable parameter region will be probed in future GW experiments

- NANOGrav signal points to symmetry breaking scales in the range $v \sim 10^{16}\,\mathrm{GeV}\left(\frac{G\mu}{10^{-7}}\right)^{1/2} \sim 10^{14}\cdots 10^{16}\,\mathrm{GeV}$, (hep-ph/9411342)