Nanohertz gravitational waves from melting domain walls

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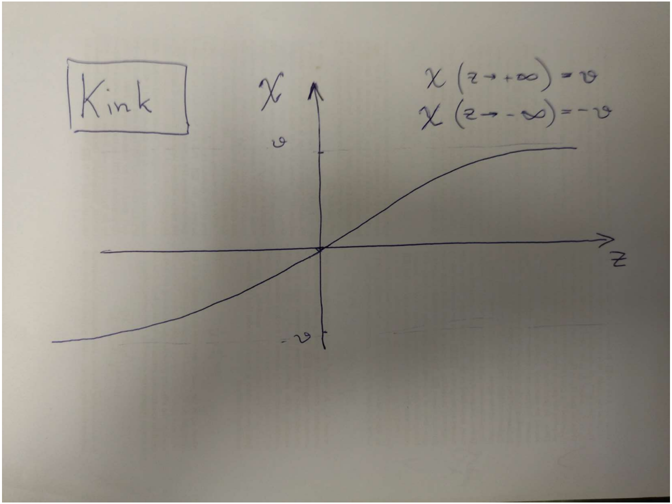
Domain walls arise in models with spontaneous breaking of discrete symmetries, e.g., Z_2

Zeldovich, Kobzarev, and Okun'74

$$\mathcal{L} = \frac{(\partial_\mu \chi)^2}{2} - \frac{\lambda \cdot (\chi^2 - v^2)^2}{4}$$

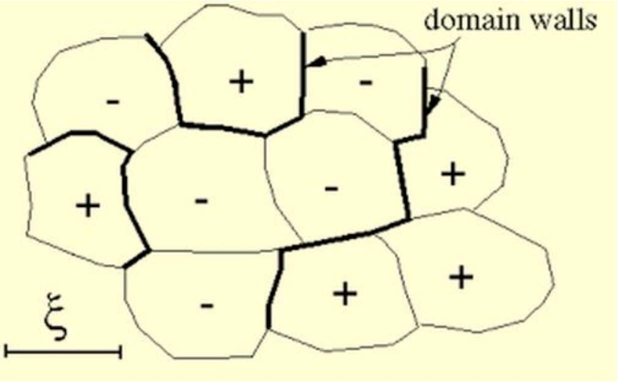
Static localized solution in $1+1$D

Kink $\quad \chi(z) = v \cdot \tanh\left(\sqrt{\frac{\lambda}{2}} \cdot v \cdot z\right)$


Kink
χ
χ (z → +∞) = v
χ (z → −∞) = −v
v
−v
z

Domain walls are embeddings of kinks into 4D

Domain walls separate regions, where $\chi = \pm v$



The picture is taken from http://www.ctc.cam.ac.uk/

$$\boxed{v = \text{const}} \quad \text{vs} \quad \boxed{v(t) \propto T(t) \propto \frac{1}{a(t)}}$$

Conventional vs Melting
domain walls vs domain walls

Domain wall problem

In the scaling regime: one or a few domain walls in the horizon volume $\sim H^{-3}$.

Ryden, Press, Spergel'89

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$$\rho_{wall} \sim M_{wall} H^3 \sim \sigma_{wall} H$$

Domain wall tension: $\sigma_{wall} = \frac{M_{wall}}{S} = \frac{2\sqrt{2\lambda} v^3}{3}$

Constant tension domain walls: $\rho_{wall} \sim \sigma_{wall} H \propto T^2$

$\frac{\rho_{wall}}{\rho_{rad}} \propto \frac{1}{T^2(t)} \propto a^2(t) \Longrightarrow$ domain walls overclose the Universe!

Domain walls are very energetic

and threat standard cosmological evolution.

Possible solution: explicitly break Z_2-symmetry

$$V_{bias}(\chi) = \epsilon v \chi (\chi^2 - v^2)$$

Domain walls emit gravitational waves

For more details see the talk by Ivan Dankovsky

Most energetic gravitational waves are emitted, when the domain wall network is being destroyed.

$$\rho_{gw} \sim (P \cdot t) \cdot H^3 \sim \frac{\sigma_{wall}^2}{M_{Pl}^2} \Longrightarrow \frac{\rho_{gw}}{\rho_{rad}} \propto a^4$$

Numerical simulations: Hiramatsu, Kawasaki, Saikawa'13

$$\boxed{f_{peak} \simeq H(t_{dec}) \cdot \frac{a(t_{dec})}{a_0}}$$

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$$\Omega_{gw}(f) \simeq \Omega_{gw,peak} \begin{cases} \left(\frac{f}{f_{peak}} \right)^3 & f \lesssim f_{peak} \\ \frac{f_{peak}}{f} & f \gtrsim f_{\rm peak} \end{cases} .$$

Caprini et al'09 Cai, Pi, Sasaki'19

inspirehep.net

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The NANOGrav 15 yr Data Set: Search for Signals from New Physics

NANOGrav Collaboration • Adeela Afzal (Munster U. and Quaid-i-Azam U.) Show All(123)

Jun 28, 2023

56 pages
Published in: *Astrophys.J.Lett.* 951 (2023) 1, L11
Published: Jun 29, 2023
e-Print: 2306.16219 [astro-ph.HE]
DOI: 10.3847/2041-8213/acdc91
Experiments: NANOGRAV
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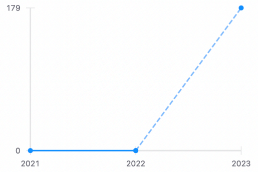


Abstract: (IOP)
The 15 yr pulsar timing data set collected by the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) shows positive evidence for the presence of a low-frequency gravitational-wave (GW) background. In this paper, we investigate potential cosmological interpretations of this signal, specifically cosmic inflation, scalar-induced GWs, first-order phase transitions, cosmic strings, and domain walls. We find that, with the exception of stable cosmic strings of field theory origin, all these models can reproduce the observed signal. When compared to the standard interpretation in terms of inspiraling supermassive black hole binaries (SMBHBs), many cosmological models seem to provide a better fit resulting in Bayes factors in the range from 10 to 100. However, these results strongly depend on modeling assumptions about the cosmic SMBHB population and, at this stage, should not be regarded as evidence for new physics. Furthermore, we identify excluded parameter regions where the predicted GW signal from cosmological sources significantly exceeds the NANOGrav signal. These parameter constraints are independent of the origin of the NANOGrav signal and illustrate how pulsar timing data provide a new way to constrain the parameter space of these models. Finally, we search for deterministic signals produced by models of ultralight dark matter (ULDM) and dark matter substructures in the Milky Way. We find no evidence for either of these signals and thus report updated constraints on these models. In the case of ULDM, these constraints outperform torsion balance and atomic clock constraints for ULDM coupled to electrons, muons, or gluons.

Note: 74 pages, 31 figures, 4 tables; published in Astrophysical Journal Letters as part of Focus on NANOGrav's 15-year Data Set and the Gravitational Wave Background. For questions or comments, please email comments@nanograv.org

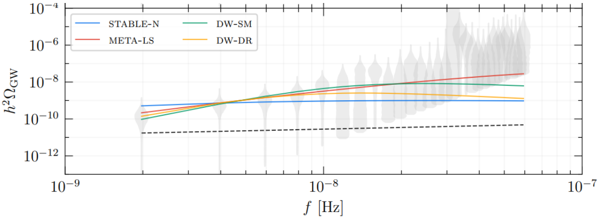
black hole: binary | cosmic string: stability | NANOGrav | new physics | dark matter: mass | gravitational radiation | pulsar | galaxy | observatory | critical phenomena | Show all (19)

References (322) | Figures (44)

$$\Omega_{gw}(f) = \Omega_{yr} \cdot \left(\frac{f}{f_{yr}} \right)^{\alpha}$$

$\alpha = 1.8 \pm 0.6$ 68% CL NANOGrav 15 yr

That's different from $\alpha = 3$ for domain walls!



Melting domain walls.

$$\mathcal{L} = \frac{(\partial_\mu \chi)^2}{2} - \frac{\lambda(\chi^2 - v^2(T))^2}{4}$$

$$v(T) \propto T \propto \frac{1}{a(t)}$$

Something, what one could expect from scale-invariant physics.

No domain wall problem

$$v \propto T \Longrightarrow \sigma_{wall} \sim \sqrt{\lambda} v^3 \propto T^3$$

$$\rho_{wall} \simeq \sigma_{wall} H \propto T^5 \qquad \frac{\rho_{wall}}{\rho_{rad}} \propto T(t) \propto \frac{1}{a(t)}$$

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Energy density of domain walls redshifts faster than radiation

Domain walls completely vanish at inverse phase transition

Vilenkin'81

Do melting domain walls leave any trace?

Melting domain walls also emit gravitational waves

Most energetic gravitational waves are emitted right after domain wall formation

$$\rho_{gw} \sim (P \cdot t) \cdot H^3 \sim \frac{\sigma_{wall}^2}{M_{Pl}^2} \Longrightarrow \rho_{gw}(t) \propto T^6(t) \propto \frac{1}{a^6(t)}$$

GW emission at domain wall formation $\Longrightarrow$ peak frequencies.

Late time GW emission $\Longrightarrow$ low frequencies.

$\alpha = 2$ from melting domain walls

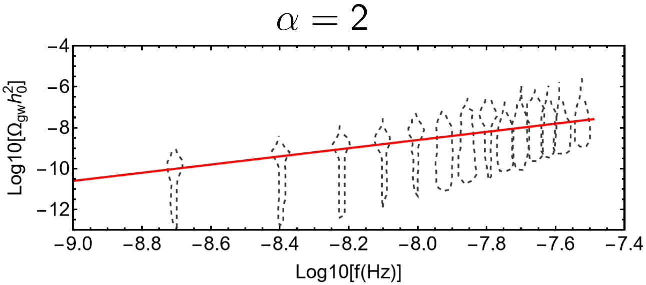
Gravitational waves produced around the time t:

$$\rho_{gw,0} = \rho_{gw}(t) \cdot \left(\frac{a(t)}{a_0} \right)^4 \propto T^2(t)$$

Characteristic present-day frequency:

$$f \simeq H(t) \cdot \frac{a(t)}{a_0} \propto T(t)$$

$$\frac{d\rho_{gw,0}}{d \ln f} \propto f^2 \Longrightarrow \alpha = 2$$



- Where does $v(T) \propto T$ come from?
- What is the amplitude of GWs?

$$\mathcal{L} = \frac{(\partial_\mu \chi)^2}{2} - \frac{\lambda \cdot \chi^4}{4} + \frac{g^2 \chi^2 \phi^\dagger \phi}{2} \; .$$

χ is cold

ϕ is in thermal equilbrium with plasma

$$\boxed{0 < g^2 \ll 1}$$

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$$\langle \phi^\dagger \phi \rangle_T = \frac{NT^2}{12} \Longrightarrow V_{eff} = \frac{\lambda \cdot \chi^4}{4} - \frac{Ng^2 T^2 \chi^2}{24}$$

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$T \propto \frac{1}{a(t)} \Longrightarrow Z_2$-symmetry breaking at early times

$$v^2 = \frac{Ng^2 T^2}{12\lambda}$$

Numerical simulations: Hiramatsu, Kawasaki, Saikawa'13

$$f_{peak} \simeq H(t_i) \cdot \frac{a(t_i)}{a_0}$$

$$\Omega_{gw,peak} h_0^2 = \frac{\epsilon_{gw} \mathcal{A}^2}{\rho_{tot,0}} \cdot \frac{\sigma^2_{wall}(t_i)}{M^2_{Pl}} \cdot \left(\frac{a(t_i)}{a_0} \right)^4$$

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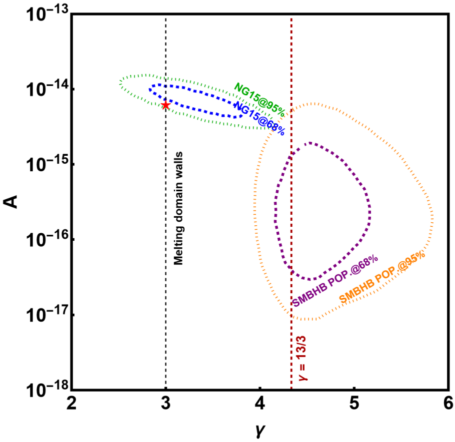
$$f_{peak} \simeq 6 \text{ nHz} \cdot \sqrt{\frac{N}{B}} \cdot \left(\frac{g}{10^{-18}}\right)$$

$$\Omega_{gw,peak} \cdot h_0^2 \approx \frac{4 \cdot 10^{-14} \cdot N^4}{B \cdot \beta^2}$$

$B = \ln^2 \frac{2\langle\chi\rangle}{\delta\chi} \simeq 1 - 100$ contains info about domain wall formation

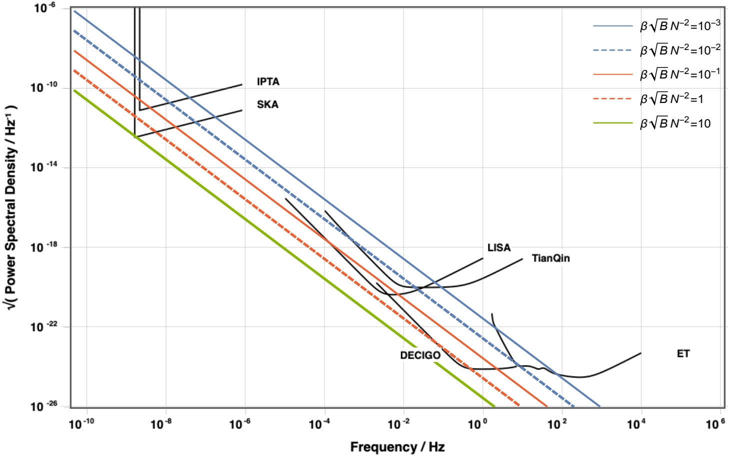
Vanilla region: $\beta \equiv \frac{\lambda}{g^4} \simeq 1$ $\qquad$ $N \gg 1$

$$g^2 = 10^{-36} \quad \lambda = 10^{-72} \quad \boxed{N = 24} \quad B = 1$$



$$A = \sqrt{\frac{3\Omega_{gw,peak} H_0^2}{2\pi^2 f_{peak}^2}}$$

Gravitational waves vs sensitivity curves



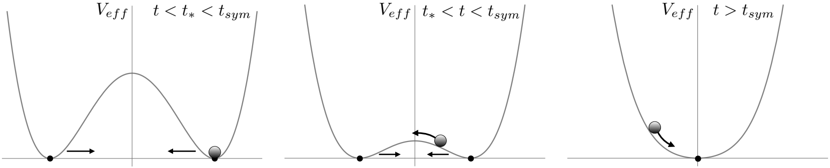
Strain $\sqrt{S_h}$ $\quad$ $\Omega_{gw} H_0^2 = \frac{2\pi^2 f^3}{3} S_h$

gwplotter.com Moore, Cole, and Berry'14

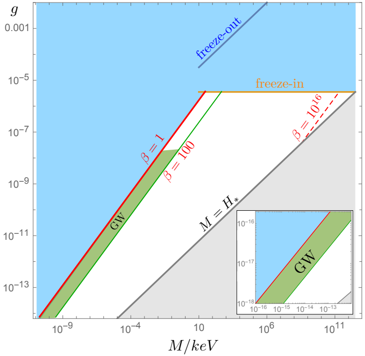
A bit of dark matter

Slightly break conformal invariance $\Longrightarrow$ dark matter

$$\mathcal{L} = \frac{(\partial_\mu \chi)^2}{2} - \frac{M^2 \cdot \chi^2}{2} - \frac{\lambda \cdot \chi^4}{4} + \frac{g^2 \chi^2 \phi^\dagger \phi}{2} \, .$$



Abundance constraint: $M \simeq 3\times 10^{-13}\text{eV}\cdot\frac{\beta^{3/5}}{\sqrt{N}}\cdot\left(\frac{g}{10^{-18}}\right)^{7/5}$



$M \simeq 10^{-12} - 10^{-13}$ eV $\Longrightarrow$ superradiance Zeldovich

- Melting domain walls serves as a source of gravitational waves, and at the same time avoid the problem of overclosing the Universe.
- The spectral index of gravitational waves from melting domain walls is in a very good agreement with PTA measurements.
- Melting domain walls may be closely linked to dark matter.

Thanks for your attention!!!