PTA observations of nHz gravitational waves, collapsing domain walls, and freeze-in dark matter

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Based on Zhao Zhang, Chengfeng Cai, Yu-Hang Su, Shiyu Wang, Zhao-Huan Yu, Hong-Hao Zhang, arXiv:2307.11495

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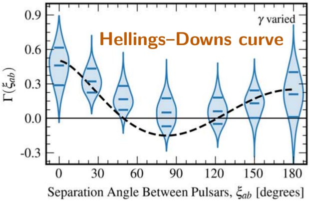
Strong Evidence for a nHz SGWB from PTAs

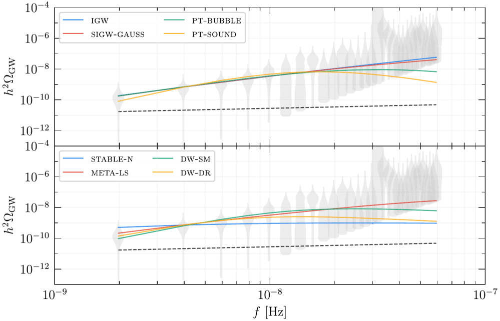
On June 29, four **pulsar timing array (PTA)** collaborations **NANOGrav** [2306.16213, 2306.16219, ApJL], **CPTA** [2306.16216, RAA], **PPTA** [2306.16215, ApJL], and **EPTA** [2306.16214, 2306.16227] reported **strong evidence** for a nHz **stochastic gravitational wave background (SGWB)** with expected **Hellings–Downs correlations**



[NANOGrav Coll., 2306.16213]

Potential **gravitational wave (GW) sources** include

- **Supermassive black hole binaries**
- **Inflation**
- **Scalar-induced GWs**
- **First-order phase transitions**
- **Cosmic strings**
- **Collapsing domain walls**



[NANOGrav Coll., 2306.16219]

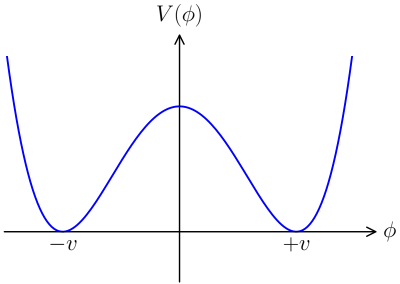
Domain Walls

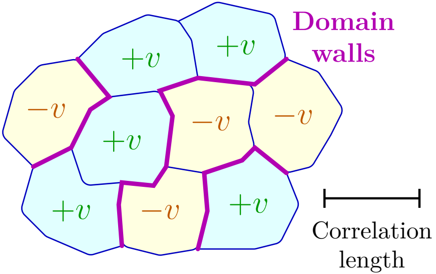
☯ **Domain walls (DWs)** are **two-dimensional topological defects** which could be formed when a **discrete symmetry** of the **scalar potential** is **spontaneously broken** in the early universe [Kibble, J.Phys.A **9** (1976) 1387]

♊ They are **boundaries** separating spatial regions with different **degenerate vacua**

🚫 **Stable DWs** are thought to be a **cosmological problem** [Zeldovich, Kobzarev, Okun, Zh.Eksp.Teor.Fiz. **67** (1974) 3]

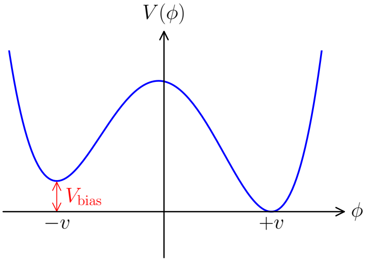
⚠ As the universe expands, the **DW energy density** decreases **slower** than radiation and matter, and would soon **dominate** the total energy density





Collapsing Domain Walls

- It is **allowed** if **DWs collapse** at a very early epoch [Vilenkin, PRD **23** (1981) 852; Gelmini, Gleiser, Kolb, PRD **39** (1989) 1558; Larsson, Sarkar, White, hep-ph/9608319, PRD]
- Such **unstable DWs** can be realized if the **discrete symmetry** is **explicitly broken** by a **small potential term** that gives an **energy bias** among the minima of the potential
- The bias induces a **volume pressure force** acting on the DWs that leads to their collapse



- **Collapsing DWs** significantly produce **GWs** [Preskill *et al.*, NPB 363 (1991) 207; Gleiser, Roberts, astro-ph/9807260, PRL; Hiramatsu, Kawasaki, Saikawa, 1002.1555, JCAP]
- A **SGWB** would be formed and remain to the present time
- It could be the one probed by **recent PTA experiments**

Spontaneously Broken Z_2 Symmetry

🌈 We consider a **real scalar field** S with a **spontaneously broken** Z_2**-symmetric potential** to be the **origin** of **DWs**

⛱ The **Lagrangian** is $\mathcal{L} = \frac{1}{2}(\partial_\mu S)\partial^\mu S + (D_\mu H)^\dagger D^\mu H - V_{Z_2}$ with a Z_2**-conserving potential** $V_{Z_2} = -\frac{1}{2}\mu_S^2 S^2 - \mu_0^2|H|^2 + \frac{1}{4}\lambda_S S^4 + \lambda_H|H|^4 + \frac{1}{2}\lambda_{HS}|H|^2 S^2$

💧 H is the **standard model (SM) Higgs field** and S is a **SM gauge singlet**

🌀 $\mathcal{L}$ respects a Z_2 **symmetry** $S \to -S$, which would be **spontaneously broken** for $\mu_S^2 > 0$ at low temperatures

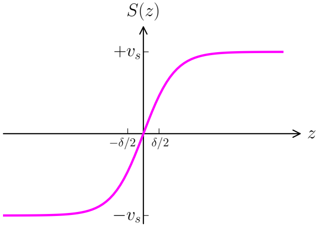
❄️ At the **zero temperature**, H and S develop nonvanishing **vacuum expectation values (VEVs)** $\langle H\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$ and $\langle S\rangle = \pm v_s$

🔥 The Z_2 and **electroweak symmetries** would be **restored** at **high temperatures** due to **thermal corrections** to the scalar potential

Kink Solution

A **DW** corresponds to a **kink solution** of the equation of motion for S given by

$$S(z) = v_s \tanh\frac{z}{\delta}, \quad \delta \equiv \left(\sqrt{\frac{\lambda_S}{2}} v_s\right)^{-1}$$



$S(z)$ approaches the **VEVs** $\pm v_s$ for $z \to \pm\infty$

The **DW** locates at $z = 0$ with a **thickness** δ, separating **two domains** with $S(z) > 0$ and $S(z) < 0$

The **DW tension** (**surface energy density**) is $\sigma = \frac{4}{3}\sqrt{\frac{\lambda_S}{2}} v_s^3$

Inside each domain with $S \sim S(\pm\infty) \approx \pm v_s$, we can parametrize H and S as

$$H(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}, \quad S(x) = \pm v_s + s(x)$$

We assume a **hierarchy** of $v_s \gg v$, and the masses squared of the **scalar bosons** h and s are given by $m_h^2 \approx 2\lambda_H v^2$ and $m_s^2 \approx 2\lambda_S v_s^2$

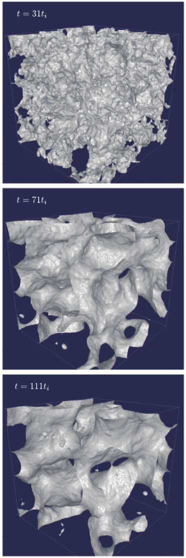
Evolution of Domain Walls

Once DWs are created, their **tension σ** acts to **stretch** them up to the **horizon size**, and they would enter the **scaling regime** with an energy density evolves as $\rho_{\mathrm{DW}} = \dfrac{\mathcal{A}\sigma}{t}$

$\mathcal{A} \approx 0.8 \pm 0.1$ is a numerical factor given by lattice simulation

$\rho_{\mathrm{DW}} \propto t^{-1}$ implies that DWs are **diluted more slowly** than **radiation** and **matter**

If DWs are **stable**, they would soon **dominate** the evolution of the universe, **conflicting** with cosmological observations



[Hiramatsu *et al.*, 1002.1555]

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- If DWs are **stable**, they would soon **dominate** the evolution of the universe, **conflicting** with cosmological observations
- This can be evaded by an **explicit Z_2-violating potential**

$$V_{\mathrm{vio}} = \kappa_1 S + \frac{\kappa_3}{6} S^3$$

- V_{vio} generates a **small energy bias** between the two minima
- It leads to a **volume pressure force** acting on the DWs, making the **DWs collapse** and the **false vacuum domains shrink**

[Hiramatsu *et al.*, 1002.1555]

Energy Bias and Annihilation Temperature

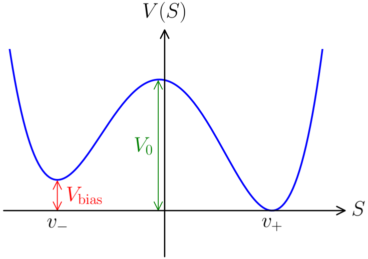
With the Z_2**-violating potential** $V_{\rm vio}$, the **two minima** are shifted to

$$v_\pm \approx \pm v_s - \delta, \text{ with } \delta \approx \frac{2\kappa_1 + \kappa_3 v_s^2}{4\lambda_S v_s^2}$$

The **energy bias** between **the minima** is

$$V_{\rm bias} = V(v_-) - V(v_+) = \frac{4}{3}\epsilon v_s^4$$

$$\epsilon = -\frac{6\kappa_1 + \kappa_3 v_s^2}{4v_s^3}$$



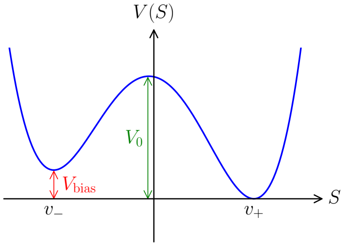
DWs collapse when the **pressure force** becomes **larger** than the **tension force**

Consequently, the **annihilation temperature** of DWs can be estimated as

$$T_{\rm ann} = 34.1 \text{ MeV } \mathcal{A}^{-1/2} \left[\frac{g_*(T_{\rm ann})}{10}\right]^{-1/4} \left(\frac{\sigma}{\rm TeV^3}\right)^{-1/2} \left(\frac{V_{\rm bias}}{\rm MeV^4}\right)^{1/2}$$

$$= 76.3 \text{ MeV } \mathcal{A}^{-1/2} \left[\frac{g_*(T_{\rm ann})}{10}\right]^{-1/4} \left(\frac{0.2}{\lambda_S} \frac{m_s}{10^5 \text{ GeV}} \frac{\epsilon}{10^{-26}}\right)^{1/2}$$

Upper and Lower Bounds on V_{bias}



🧀 If V_{bias} is **too large**, DWs **cannot** be created from the beginning

🌭 According to **percolation theory**, **large-scale DWs** can be **formed** only if $V_{\text{bias}} < 0.795 V_0$

🍞 Requiring DWs should **collapse before** they **dominate** the universe leads to

$$V_{\text{bias}}^{1/4} > 0.0218 \text{ MeV } C_{\text{ann}}^{1/4} \mathcal{A}^{1/2} \left(\frac{\sigma}{\text{TeV}^3} \right)^{1/2}$$

🍔 Moreover, the **energetic particles** produced from **DW collapse** could **destroy** the **light elements** generated in the **Big Bang Nucleosynthesis (BBN)**

🌮 Thus, we should require that **DWs annihilate before the BBN epoch**

🌯 This leads to $V_{\text{bias}}^{1/4} > 0.507 \text{ MeV } C_{\text{ann}}^{1/4} \mathcal{A}^{1/4} \left(\frac{\sigma}{\text{TeV}^3} \right)^{1/4}$

SGWB Spectrum from Collapsing DWs

- The **SGWB spectrum** is commonly characterized by $\Omega_{\mathrm{GW}}(f) = \dfrac{f}{\rho_c}\dfrac{d\rho_{\mathrm{GW}}}{df}$
- ρ_{GW} is the **GW energy density**, and ρ_c is the critical energy density
- The SGWB from **collapsing DWs** can be estimated by **numerical simulations**

[Hiramatsu, Kawasaki, Saikawa, 1002.1555, 1309.5001, JCAP]

- The **present SGWB spectrum** induced by collapsing DWs can be evaluated by

$$\Omega_{\mathrm{GW}}(f)h^2 = \Omega_{\mathrm{GW}}^{\mathrm{peak}}h^2 \times \begin{cases} \left(\dfrac{f}{f_{\mathrm{peak}}}\right)^3, & f < f_{\mathrm{peak}} \\ \dfrac{f_{\mathrm{peak}}}{f}, & f > f_{\mathrm{peak}} \end{cases}$$

$$\Omega_{\mathrm{GW}}^{\mathrm{peak}}h^2 = 7.2\times 10^{-18}\ \tilde{\epsilon}_{\mathrm{GW}}\mathcal{A}^2 \left[\frac{g_{*s}(T_{\mathrm{ann}})}{10}\right]^{-4/3} \left(\frac{\sigma}{1\ \mathrm{TeV}^3}\right)^2 \left(\frac{T_{\mathrm{ann}}}{10\ \mathrm{MeV}}\right)^{-4}$$

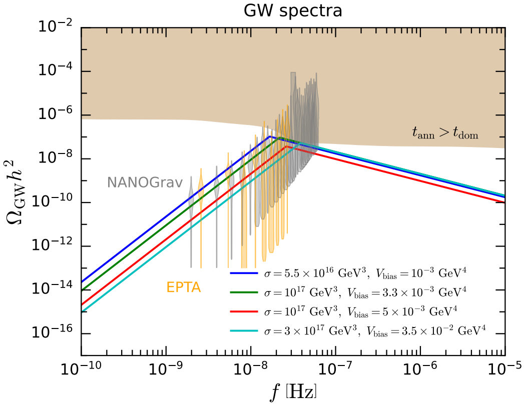
$$f_{\mathrm{peak}} = 1.1\times 10^{-9}\ \mathrm{Hz}\ \left[\frac{g_*(T_{\mathrm{ann}})}{10}\right]^{1/2} \left[\frac{g_{*s}(T_{\mathrm{ann}})}{10}\right]^{-1/3} \frac{T_{\mathrm{ann}}}{10\ \mathrm{MeV}}$$

- $\tilde{\epsilon}_{\mathrm{GW}} = 0.7 \pm 0.4$ is derived from numerical simulation

Comparison with the PTA data

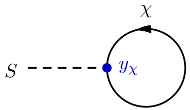
- Comparing with the **reconstructed posterior distributions** for the **NANOGrav** and **EPTA** nHz GW signals, we find that the **GW spectra** from **collapsing DWs** with $\sigma \sim \mathcal{O}(10^{17})$ GeV^3 and $V_{\text{bias}} \sim \mathcal{O}(10^{-3})$ GeV^4 can explain the **PTA observations**
- The **brown region** is **excluded** by the requirement that **DWs** should **annihilate before** they **dominate** the universe

$$\sigma = 10^{17}\ \text{GeV}^3$$
$$V_{\text{bias}} = 3.3 \times 10^{-3}\ \text{GeV}^4$$
$$\lambda_S = 0.2$$
$$v_s = 6.2 \times 10^5\ \text{GeV}$$
$$m_s = 3.9 \times 10^5\ \text{GeV}$$
$$\epsilon = 3.6 \times 10^{-26}$$
$$T_{\text{ann}} = 163\ \text{MeV}$$
$$\Omega_{\text{GW}}^{\text{peak}} h^2 = 9.4 \times 10^{-8}$$
$$f_{\text{peak}} = 2.2 \times 10^{-8}\ \text{Hz}$$



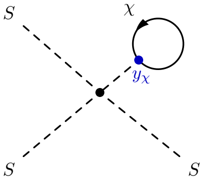
Loop-induced Z_2-violating Potential

- The **PTA GW signals** require a **very small** $V_{\text{bias}} = \frac{4}{3}\epsilon v_s^4$ with $\epsilon \sim \mathcal{O}(10^{-26})$
- We consider V_{bias} to be generated by **loops** of **fermionic dark matter** through a **feeble Yukawa interaction** with the **scalar field** S
- Assume a Lagrangian with a **Dirac fermion field** χ: $\mathcal{L}_\chi = \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + y_\chi S\bar{\chi}\chi$
- y_χ is the **Yukawa coupling constant**
- When S acquires the VEV $\langle S \rangle \approx \pm v_s$, the χ mass becomes $m_\chi^{(\pm)} \approx m_\chi \mp y_\chi v_s$
- We assume that $m_\chi \gg y_\chi v_s$, so $m_\chi^{(\pm)} \approx m_\chi$ holds
- The $S\bar{\chi}\chi$ **coupling explicitly breaks** the Z_2 **symmetry** even if the **tree-level** Z_2**-violating potential** is **absent**



- The ϵ **value** at the m_s scale induced by χ **loops** is

$$\epsilon(m_s) \approx \frac{3\lambda_S^{3/2} y_\chi}{\sqrt{2}\pi^2} \left(\frac{m_\chi}{m_s}\right)^3 \ln \frac{M_{\text{Pl}}}{m_s}$$



- Here, $\epsilon = 0$ at the **Planck scale** M_{Pl} is assumed

Freeze-in Dark Matter

- After reheating, s **bosons** are in **thermal equilibrium** with the SM particles, while χ **fermions** would be **out of equilibrium** with $n_\chi \approx 0$ for a **feeble coupling** y_χ

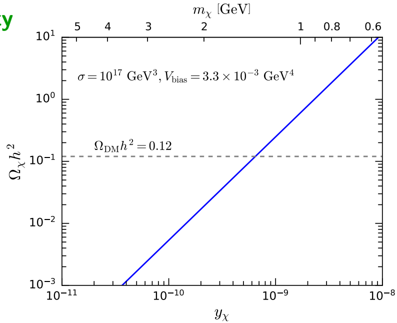
- In this case, χ **fermions** could be **produced** via the s **decay** $s \to \chi\bar{\chi}$, but **never reach thermal equilibrium** if y_χ is **extremely small**, say, $y_\chi \sim \mathcal{O}(10^{-10})$

- This is the **freeze-in mechanism** of DM production [Hall *et al.*, 0911.1120, JHEP]

- χ acts as a **DM candidate** with a **relic density**

$$\Omega_\chi h^2 \approx 8.13 \times 10^{22} \, \frac{y_\chi^2 m_\chi}{m_s}$$

- Both the **extremely tiny** $\epsilon \sim \mathcal{O}(10^{-26})$ and the **observed DM relic density** $\Omega_{\rm DM} h^2 = 0.1200 \pm 0.0012$ can be **naturally explained** by the **feeble Yukawa coupling** $y_\chi \sim \mathcal{O}(10^{-10})$

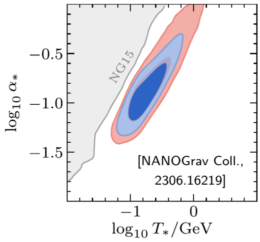


Favored Parameter Regions

The **NANOGrav collaboration** has reconstructed the posterior distributions of $(T_{\rm ann}, \alpha_*)$ accounting for the **observed nHz GW signal**, where

$$\alpha_* \equiv \left.\frac{\rho_{\rm DW}}{\rho_{\rm rad}}\right|_{T=T_{\rm ann}}$$

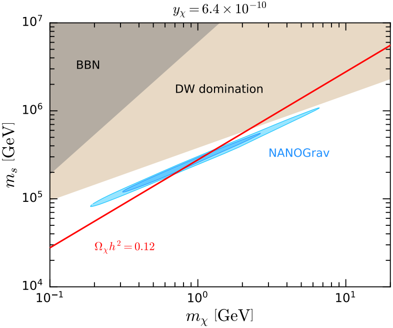
$$= 0.035 \left[\frac{10}{g_*(T_{\rm ann})}\right]^{1/2} \frac{\mathcal{A}}{0.8} \frac{0.2}{\lambda_S} \left(\frac{m_s}{10^5\ \rm GeV}\right)^3 \left(\frac{100\ \rm MeV}{T_{\rm ann}}\right)^2$$



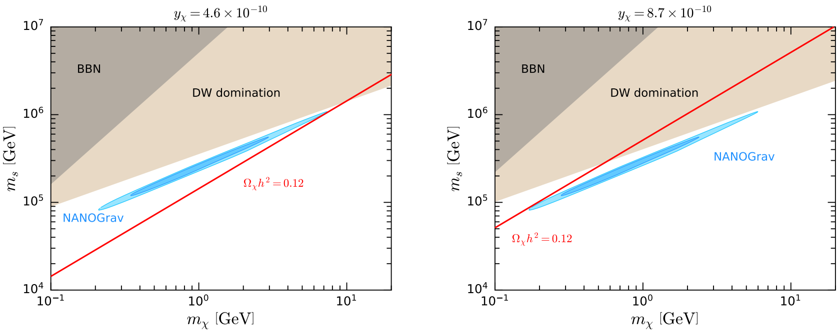
We apply this result to our model and find the **favored parameter regions**

Deep and **light** **blue regions** corresponds to the **68%** and **95%** **Bayesian credible regions** favored by the **NANOGrav data**, respectively

Brown and **gray** regions are excluded because DWs would **dominate the universe** and would inject energetic particles to **affect the Big Bang Nucleosynthesis**, respectively



Viable Parameter Ranges



🍜 The **intersection** of the $\Omega_\chi h^2 = 0.12$ **line** and the **NANOGrav favored regions sensitively depends** on the y_χ **value**

🍱 For $\lambda_S = 0.2$, the parameter ranges where our model can **simultaneously explain** the **NANOGrav GW signal** and the **DM relic density** are

$$4.6 \times 10^{-10} \lesssim y_\chi \lesssim 8.7 \times 10^{-10}$$

$$0.17\ \text{GeV} \lesssim m_\chi \lesssim 7.5\ \text{GeV}, \quad 8.1 \times 10^4\ \text{GeV} \lesssim m_s \lesssim 10^6\ \text{GeV}$$

Summary

- The observations of a **nHz SGWB** by **PTA collaborations NANOGrav, EPTA, CPTA, and PPTA** can be interpreted by **GWs** from **collapsing DWs**
- We assume such DWs arising from the **spontaneous breaking** of a Z_2 **symmetry** in a scalar field theory, where a **tiny** Z_2**-violating potential** is required to **make DWs unstable**
- We propose that this Z_2-violating potential is **radiatively induced** by a **feeble Yukawa coupling** between the scalar field S and a fermion field χ, which is also responsible for **DM production** via the **freeze-in mechanism**
- Combining the **PTA data** and the **observed DM relic density**, we find that the model parameters can be **narrowed down** to **small ranges**

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Thanks for your attention!

GW Spectra with a Correct DM Relic Density