

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

Zhao-Huan Yu (余钊煥)

School of Physics, Sun Yat-Sen University

<https://yzhxxzxy.github.io>

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



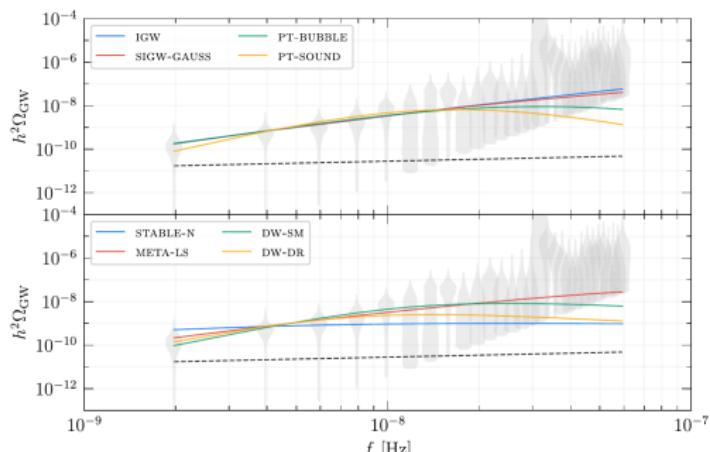
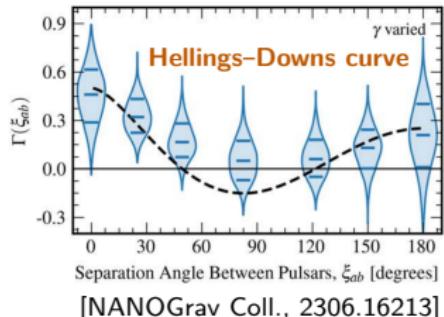
The 4th Workshop on Frontiers of Particle Physics
August 9, 2023, Taiyuan



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**

- 穰 Potential **gravitational wave (GW) sources** include
- 穰 Supermassive black hole binaries
- 穰 Inflation
- 穰 Scalar-induced GWs
- 穰 First-order phase transitions
- 穰 Cosmic strings
- 穰 Collapsing domain walls



[NANOGrav Coll., 2306.16219]

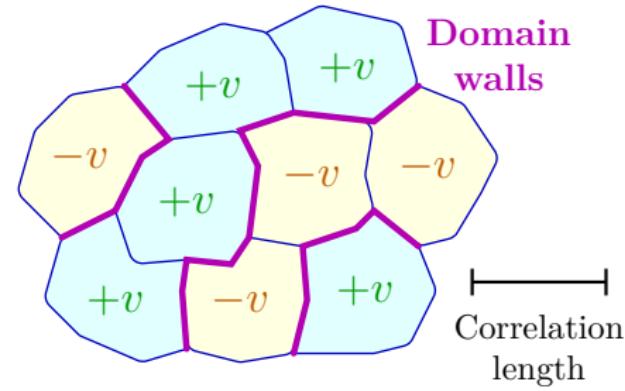
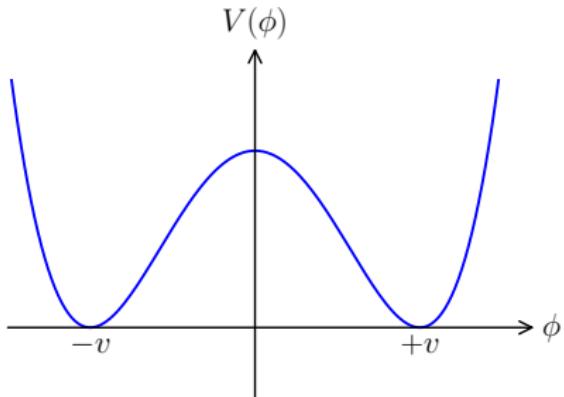
Domain Walls

⌚ 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]

-II 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]

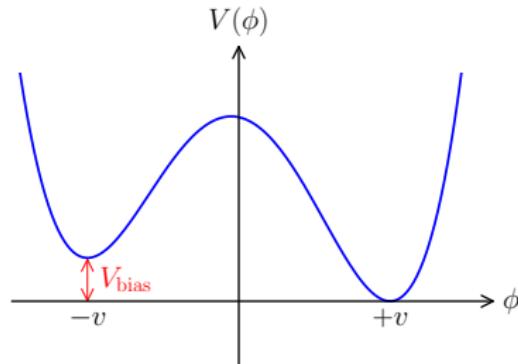
Such **unstable DWs** can be realized if the **discrete symmetry is explicitly broken** by a **small potential term** that gives an **energy bias** among the minima of the potential

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** $S \rightarrow -S$, 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

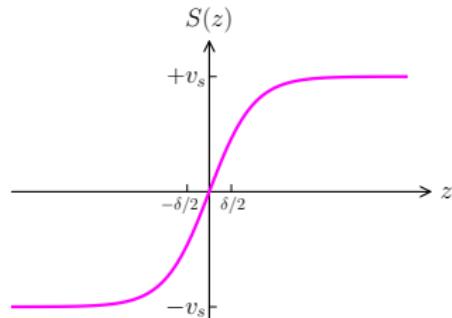
Kink Solution

🛡 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 $z \rightarrow \pm\infty$

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



cil 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

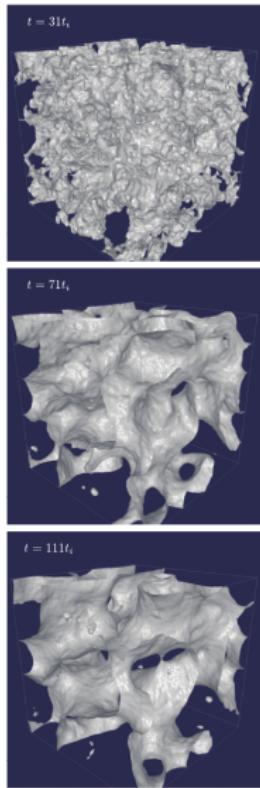
Once DWs are created, their **tension σ** acts to **stretch** them up to the **horizon size**, and they would enter the **scaling regime**

with an energy density evolves as $\rho_{\text{DW}} = \frac{\mathcal{A}\sigma}{t}$

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

 $\rho_{\text{DW}} \propto t^{-1}$ 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]

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 $\rho_{\text{DW}} = \frac{\mathcal{A}\sigma}{t}$

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

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

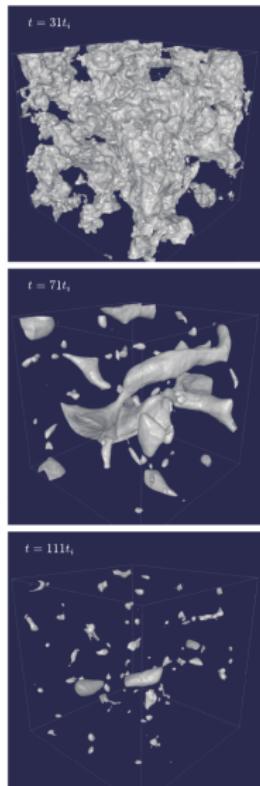
If DWs are **stable**, they would soon **dominate** the evolution of the universe, **conflicting** with cosmological observations

This can be evaded by an **explicit Z_2 -violating potential**

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

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_{vio} , the **two minima** are shifted to

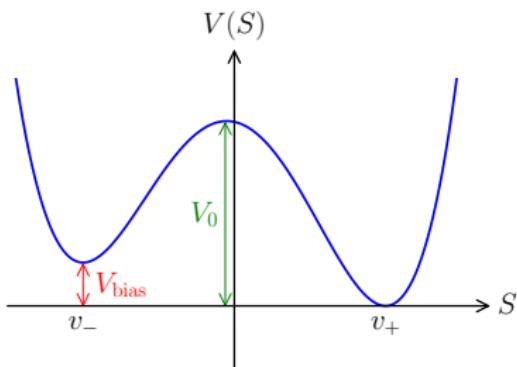
$$v_{\pm} \approx \pm v_s - \delta, \text{ with } \delta \approx \frac{2\kappa_1 + \kappa_3 v_s^2}{4\lambda_S v_s^2}$$

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

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

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

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



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

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

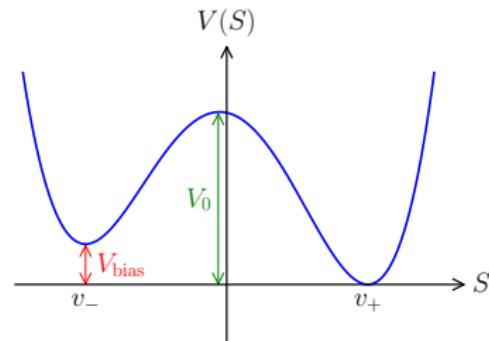
$$= 76.3 \text{ MeV } \mathcal{A}^{-1/2} \left[\frac{g_*(T_{\text{ann}})}{10} \right]^{-1/4} \left(\frac{0.2}{\lambda_S} \frac{m_s}{10^5 \text{ GeV}} \frac{\epsilon}{10^{-26}} \right)^{1/2}$$

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 $V_{\text{bias}} < 0.795V_0$

🍞 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**

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

SGWB Spectrum from Collapsing DWs

The **SGWB spectrum** is commonly characterized by $\Omega_{\text{GW}}(f) = \frac{f}{\rho_c} \frac{d\rho_{\text{GW}}}{df}$

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

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

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

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

$\tilde{\epsilon}_{\text{GW}} = 0.7 \pm 0.4$ 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 $\sigma \sim \mathcal{O}(10^{17})$ GeV³ and $V_{\text{bias}} \sim \mathcal{O}(10^{-3})$ GeV⁴ can explain the **PTA observations**

The **brown region** is excluded by the requirement that **DWs** should **annihilate before** they **dominate** the universe

$$\sigma = 10^{17} \text{ GeV}^3$$

$$V_{\text{bias}} = 3.3 \times 10^{-3} \text{ GeV}^4$$

$$\lambda_S = 0.2$$

$$v_s = 6.2 \times 10^5 \text{ GeV}$$

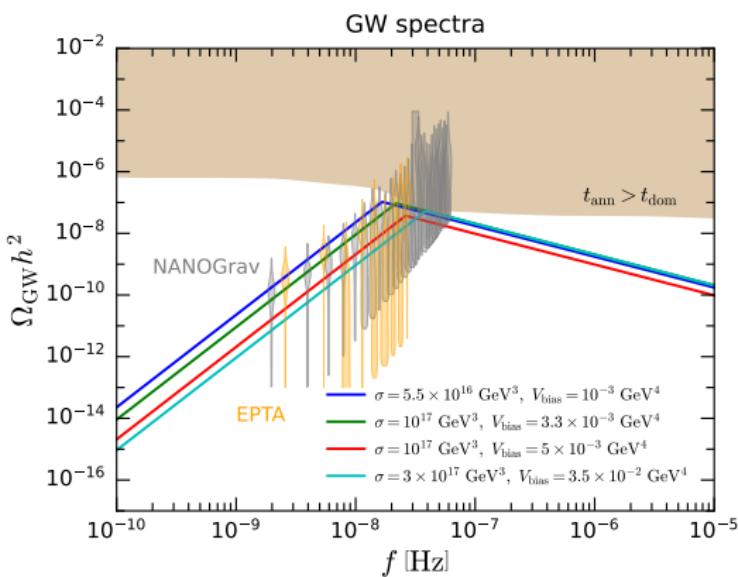
$$m_s = 3.9 \times 10^5 \text{ GeV}$$

$$\epsilon = 3.6 \times 10^{-26}$$

$$T_{\text{ann}} = 163 \text{ MeV}$$

$$\Omega_{\text{GW}}^{\text{peak}} h^2 = 9.4 \times 10^{-8}$$

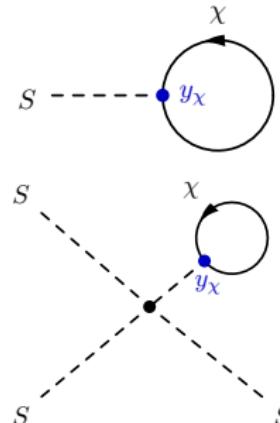
$$f_{\text{peak}} = 2.2 \times 10^{-8} \text{ Hz}$$



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 $\epsilon \sim \mathcal{O}(10^{-26})$
- hog We consider V_{bias} to be generated by **loops** of **fermionic dark matter** through a **feeble Yukawa interaction** with the **scalar field S**
- squirrel Assume a Lagrangian with a **Dirac fermion field χ** : $\mathcal{L}_\chi = \bar{\chi}(i\cancel{\partial} - m_\chi)\chi - y_\chi S \bar{\chi}\chi$
- hog y_χ is the **Yukawa coupling constant**
- bear When S acquires the VEV $\langle S \rangle \approx \pm v_s$, the χ mass becomes $m_\chi^{(\pm)} \approx m_\chi \pm y_\chi v_s$
- hog We assume that $m_\chi \gg y_\chi v_s$, so $m_\chi^{(\pm)} \approx m_\chi$ holds
- skunk The **$S \bar{\chi}\chi$ coupling explicitly breaks the Z_2 symmetry** even if the tree-level Z_2 -violating potential is **absent**
- octopus The **ϵ value** at the m_s scale induced by **χ loops** is

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

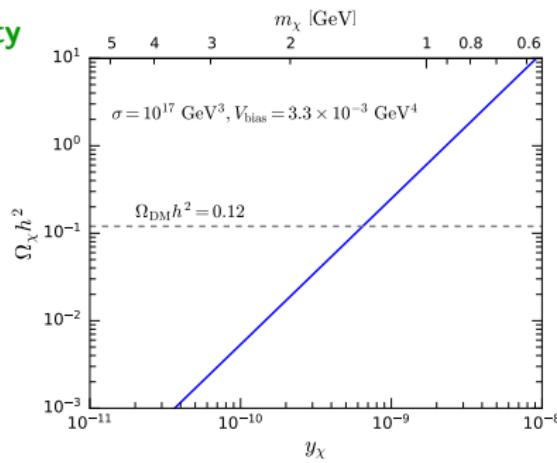
In this case, χ fermions could be **produced** via the s decay $s \rightarrow \chi\bar{\chi}$, but never reach thermal equilibrium if y_χ is **extremely small**, say, $y_\chi \sim \mathcal{O}(10^{-10})$

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**

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

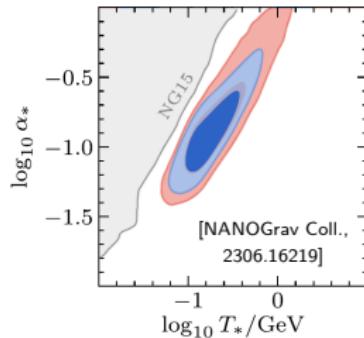
Both the **extremely tiny** $\epsilon \sim \mathcal{O}(10^{-26})$ and the **observed DM relic density** $\Omega_{\text{DM}} h^2 = 0.1200 \pm 0.0012$ can be **naturally explained** by the **feeble Yukawa coupling** $y_\chi \sim \mathcal{O}(10^{-10})$



Favored Parameter Regions

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

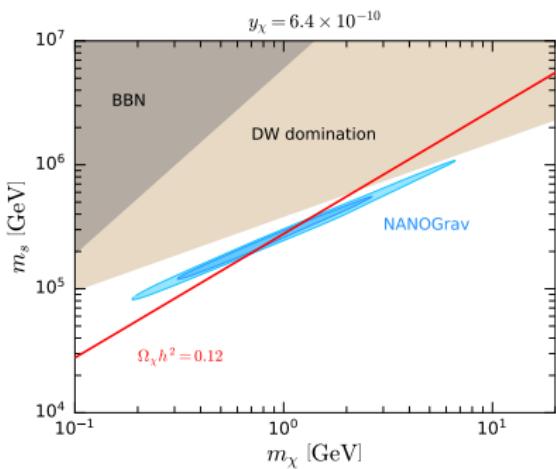
$$\alpha_* \equiv \left. \frac{\rho_{\text{DW}}}{\rho_{\text{rad}}} \right|_{T=T_{\text{ann}}} = 0.035 \left[\frac{10}{g_*(T_{\text{ann}})} \right]^{1/2} \frac{\mathcal{A}}{0.8} \frac{0.2}{\lambda_S} \left(\frac{m_s}{10^5 \text{ GeV}} \right)^3 \left(\frac{100 \text{ MeV}}{T_{\text{ann}}} \right)^2$$



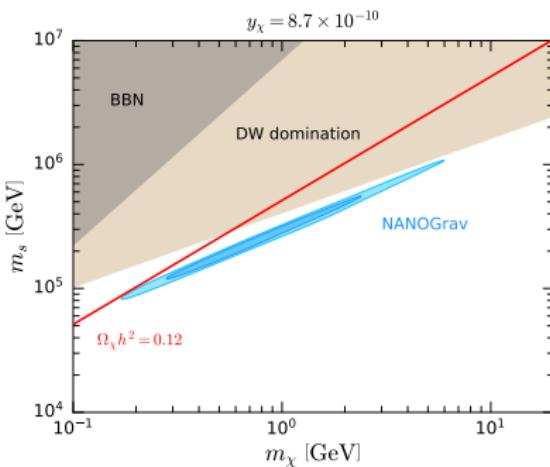
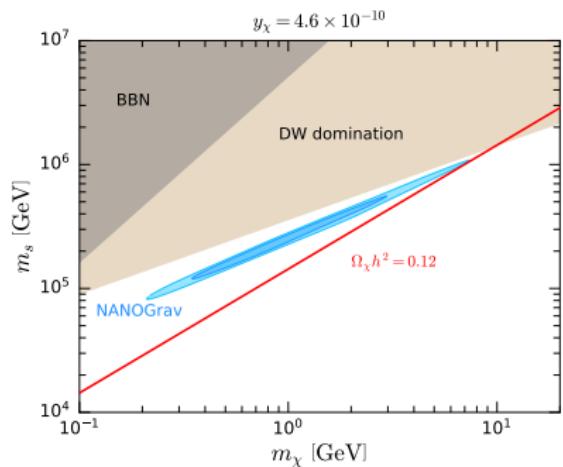
We apply this result to our model and find the **favored parameter regions**

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**

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**

Thanks for your attention!

GW Spectra with a Correct DM Relic Density

