Domain wall constraints on the doublet left-right symmetric model using PTA data

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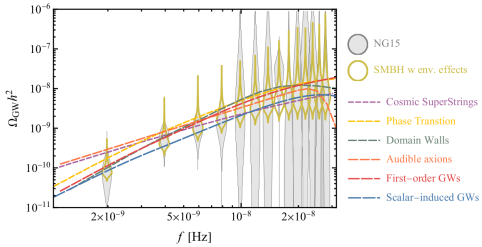
Introduction

Motivation

- Compelling evidence of a nHz GW background by recent PTA results (NANOGrav, EPTA, InPTA, PPTA ..).
- Some models of cosmological origin provide a better fit compared to the standard SMBHB interpretation.
- For DWs, the Bayes factor is $\mathcal{O}(10)$, with $\sigma \sim \mathcal{O}(10^5\,\text{GeV})^3$, and $T_{\text{ann}} \sim \mathcal{O}(100)\,\text{MeV}$. Cannot come from EW scale physics.
- LRSMs with parity symmetry can produce DWs with such large tension.
- We constrain the parameter space of DLRSM using PTA data.



[Ellis et.al. 2023]

Doublet left-right symmetric model

- LRSM gauge group: [Senjanovic, Mohapatra, Pati, Salam ..]

$$\mathcal{G}_{\rm LRSM} = SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times \mathcal{P}$$

- Breaking pattern: $\mathcal{G}_{\rm LRSM} \xrightarrow{v_R} \mathcal{G}_{\rm SM} \xrightarrow{v_L, \kappa_1, \kappa_2} U(1)_{\rm em}$
- Scalars for SSB: a bidoublet (Φ), and 2 triplets ($\Delta_{L,R}$) (TLRSM), or a bidoublet (Φ) and 2 doublets ($\chi_{L,R}$) (DLRSM).
- Hierarchy of scales: $v_R \gg v_{\rm EW}$, $v_L^2 + \kappa_1^2 + \kappa_2^2 = v_{\rm EW}^2$, $v_{\rm EW} = 246.02\,{\rm GeV}$.
- Higgs and EWPO data: EWSB in DLRSM can be much different from that in TLRSM. [Bernard et. al. 2020; Uma et.al. 2022]
- $r \equiv \frac{\kappa_2}{\kappa_1}$, $w \equiv \frac{v_L}{\kappa_1}$ are ~ 0 in TLRSM, can be larger in DLRSM.
- GW signature from FOPT was calculated for $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$ in DLRSM. [S. Karmakar, DR, 2024]

DLRSM potential

- Assuming $\mathcal{P}: L \leftrightarrow R, \Phi \leftrightarrow \Phi^\dagger$,

$$
\begin{aligned}
V &= V_\chi + V_{\chi\Phi} + V_\Phi, \\
V_\chi &= -\mu_3^2\ [\chi_L^\dagger \chi_L + \chi_R^\dagger \chi_R] + \rho_1\ [(\chi_L^\dagger \chi_L)^2 + (\chi_R^\dagger \chi_R)^2] + \rho_2\ \chi_L^\dagger \chi_L \chi_R^\dagger \chi_R, \\
V_{\chi\Phi} &= \mu_4\ [\chi_L^\dagger \Phi \chi_R + \chi_R^\dagger \Phi^\dagger \chi_L] + \mu_5\ [\chi_L^\dagger \tilde{\Phi} \chi_R + \chi_R^\dagger \tilde{\Phi}^\dagger \chi_L] \\
&\quad + \alpha_1 \mathrm{Tr}(\Phi^\dagger \Phi)[\chi_L^\dagger \chi_L + \chi_R^\dagger \chi_R] + \left\{ \frac{\alpha_2}{2}\ [\chi_L^\dagger \chi_L \mathrm{Tr}(\tilde{\Phi} \Phi^\dagger) + \chi_R^\dagger \chi_R \mathrm{Tr}(\tilde{\Phi}^\dagger \Phi)] + \mathrm{h.c.} \right\} \\
&\quad + \alpha_3\ [\chi_L^\dagger\ \Phi \Phi^\dagger \chi_L + \chi_R^\dagger \Phi^\dagger \Phi \chi_R] + \alpha_4\ [\chi_L^\dagger\ \tilde{\Phi} \tilde{\Phi}^\dagger \chi_L + \chi_R^\dagger \tilde{\Phi}^\dagger \tilde{\Phi} \chi_R], \\
V_\Phi &= -\mu_1^2 \mathrm{Tr}(\Phi^\dagger \Phi) - \mu_2^2\ [\mathrm{Tr}(\tilde{\Phi} \Phi^\dagger) + \mathrm{Tr}(\tilde{\Phi}^\dagger \Phi)] + \lambda_1 [\mathrm{Tr}(\Phi^\dagger \Phi)]^2 \\
&\quad + \lambda_2\ [[\mathrm{Tr}(\tilde{\Phi} \Phi^\dagger)]^2 + [\mathrm{Tr}(\tilde{\Phi}^\dagger \Phi)]^2] + \lambda_3 \mathrm{Tr}(\tilde{\Phi} \Phi^\dagger)\, \mathrm{Tr}(\tilde{\Phi}^\dagger \Phi) \\
&\quad + \lambda_4 \mathrm{Tr}(\Phi^\dagger \Phi)\, [\mathrm{Tr}(\tilde{\Phi} \Phi^\dagger) + \mathrm{Tr}(\tilde{\Phi}^\dagger \Phi)],
\end{aligned}
$$

- *vev* structure:

$$
\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} \kappa_1 & 0 \\ 0 & \kappa_2 \end{pmatrix},\ \langle \chi_L \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_L \end{pmatrix},\ \langle \chi_R \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_R \end{pmatrix}.
$$

- $\mathcal{P}$ also imposes $g_L = g_R$.

Domain walls in DLRSM

Effective potential

- We could have an alternative hierarchy, $v_L \gg v_R, \kappa_1, \kappa_2 \sim v_{\rm EW}$.
- Call the $\mathcal{P}$-breaking scale v_0.
- In terms of background fields,

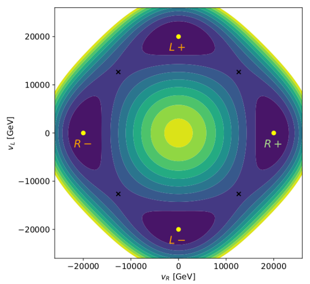
$$V_0 \equiv V_\chi(\langle\chi_L\rangle,\langle\chi_R\rangle) + V_{\chi\Phi}(\langle\chi_L\rangle,\langle\chi_R\rangle,\langle\Phi\rangle) + V_\Phi(\langle\Phi\rangle)\,,$$

$$V_{\rm eff} = V_0 + V_1 + V_{1T} + \cdots$$

- DWs exist for $T_{\rm ann} \lesssim T \lesssim v_0$, where

$$V_{\rm eff}(v_L, v_R) \approx V_\chi = -\frac{\mu_3^2}{2}(v_L^2 + v_R^2) + \frac{\rho_1}{4}(v_L^4 + v_R^4) + \frac{\rho_2}{4} v_L^2 v_R^2\,.$$

- For $\rho_2 > 2\rho_1,\ \mu_3^2 > 0$, there are four degenerate minima
- V_χ has a $Z_4 \simeq \mathcal{P} \times Z_2$ symmetry.
- Parameter set: $\{\rho_1,\ \rho_2.\ v_0\}$.



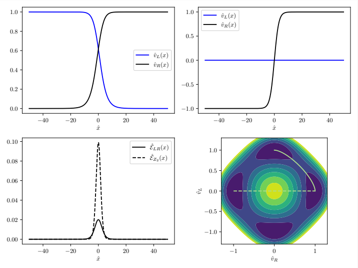
$v_0 = 20\ \text{TeV},\ \rho_1 = 0.2,\ \rho_2 = 0.6$

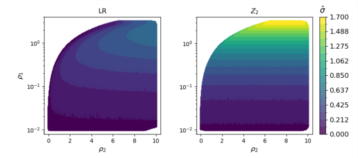
Domain walls in DLRSM

- There are two types of DWs: Z_2 and LR.
- For a DW located at $x = 0$,

$$\mathcal{E} = \frac{1}{2}\left(\frac{dv_L}{dx}\right)^2 + \frac{1}{2}\left(\frac{dv_R}{dx}\right)^2 + V(v_L, v_R),$$
$$\sigma = \int_{-\infty}^{\infty} \mathcal{E} dx$$

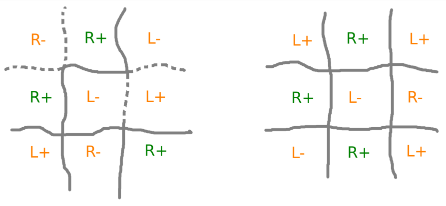
- Rescale, $\hat{v}_L = \frac{v_L}{v_0}$, $\hat{v}_R = \frac{v_R}{v_0}$, $\hat{\mu}_3^2 = \frac{\mu_3^2}{v_0^2} = \rho_1$, $\hat{x} = x\, v_0$, $\hat{\sigma} = \frac{\sigma}{v_0^3}$.
- Kink solutions are obtained using relaxation method, for the $\rho_1 - \rho_2$ plane.
- This yields the parametric dependence: $\sigma(v_0, \rho_1, \rho_2) = \hat{\sigma}(\rho_1, \rho_2) v_0^3$.





DW evolution

- Z_2 DWs are unstable, decay into two LR DWs.



- In the scaling regime, $\rho_{\rm DW} \approx \sigma H$.
- DWs annihilate when $\rho_{\rm DW}(T_{\rm ann}) \approx V_{\rm bias}$.

$$T_{\rm ann} \propto \left(V_{\rm bias}^{1/4}\right)^2 / \left(\sigma^{1/3}\right)^{\frac{3}{2}} .$$

- $V_{\rm bias}$ is introduced as a free parameter.
- $T_{\rm ann} > T_{\rm BBN}$ gives lower bound on $V_{\rm bias}$.
- Upper bound from percolation: $\frac{V_{\rm bias}}{V_0} > \ln\left(\frac{1-p_c}{p_c}\right)$

Constraints from the PTA signal

GW background from DLRSM DWs

- GWs are produced due to DW dynamics [Vilenkin, 1981],

$$
\begin{aligned}
h^2\Omega_{\rm GW}^{\rm DW}(f) &\simeq 10^{-10}\,\tilde{\epsilon}_{\rm GW}\left(\frac{10.75}{g_*(T_{\rm ann})}\right)^{\frac{1}{3}}\left(\frac{\alpha_*}{0.01}\right)^2 S\left(\frac{f}{f_p^0}\right), \\
\alpha_* &= \frac{\rho_{\rm DW}(T_{\rm ann})}{\rho_{\rm rad}(T_{\rm ann})}
\end{aligned}
$$

- We perform MCMC using `PTArcade` over the NG15 data
  $\mathcal{H}_1: \quad h^2\Omega_{\rm GW}^{\rm DW}(f; v_0, \rho_1, \rho_2, V_{\rm bias})$.
- DLRSM DW model is considered with and without SMBHB contibution.

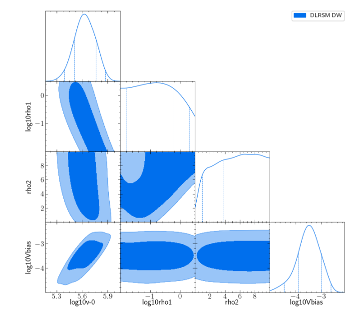
$$
h^2\Omega_{\rm GW}^{\rm BHB}(f) = \frac{2\pi^2 h^2 A_{\rm BHB}^2}{3H_0^2}\left(\frac{f}{f_{\rm yr}}\right)^{5-\gamma_{\rm BHB}} f_{\rm yr}^2,
$$

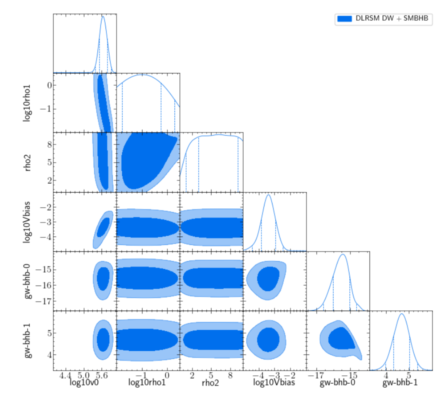
$\mathcal{H}_2: \quad h^2\Omega_{\rm GW}^{\rm DW}(f; v_0, \rho_1, \rho_2, V_{\rm bias}) + h^2\Omega_{\rm GW}^{\rm BHB}(f; A_{\rm BHB}, \gamma_{\rm bhb})$.

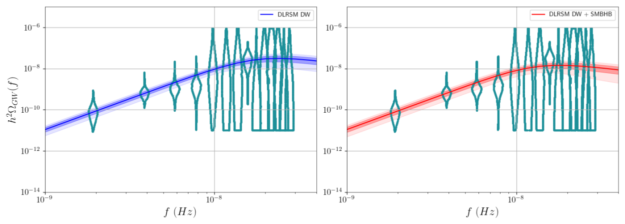
- If energy loss is purely due to GWs, $\gamma_{\rm BHB} = 13/3$.

Results

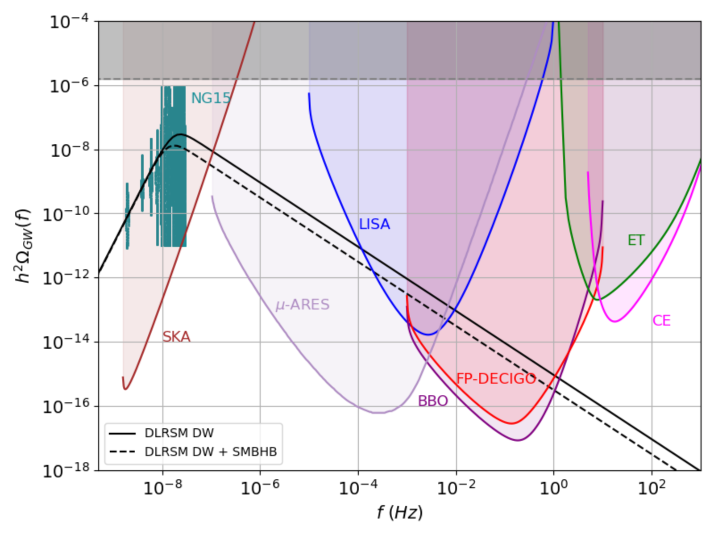
- For DLRSM DW, the central values are,
  $v_0 = 4.36 \times 10^5\,\text{GeV}, \;\; \text{V}_{\text{bias}} = 3.31 \times 10^{-4}\,\text{GeV}^4.$







Parameter	Uniform prior range	Maximum Posterior		68% credible interval	
		$\mathcal{H}_1$	$\mathcal{H}_2$	$\mathcal{H}_1$	$\mathcal{H}_2$
$\log_{10}\ v_0/\text{GeV}$	$[4, 8]$	5.63	5.66	$[5.52, 5.77]$	$[5.52, 5.79]$
$\log_{10}\ V_{\text{bias}}/\text{GeV}^4$	$[-5, -1]$	-3.47	-3.37	$[-3.90, -3.05]$	$[-3.82, -2.91]$
$\log_{10}\rho_1$	$[-2.5, 0.5]$	-0.77	-1.00	$[-1.90, -0.35]$	$[-1.76, -0.23]$
ρ_2	$[0, 10]$	6.55	6.50	$[2.88, 9.16]$	$[3.03, 9.23]$
$\log_{10} A_{\text{BHB}}$	-	-	-15.44	-	$[-15.97, -15.02]$
γ_{BHB}	-	-	4.69	-	$[4.35, 5.04]$



NG15 is fitted with DLRSM DWs, will be detected in SKA, μAres, LISA, BBO and DECIGO.

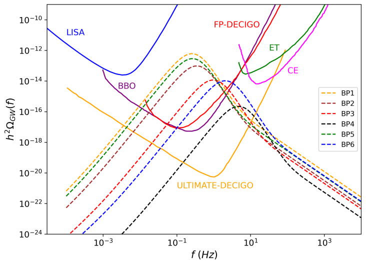
Conclusions

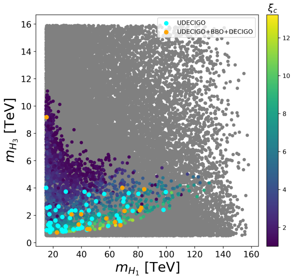
- GWs from DLRSM DWs can source the PTA signal.
- There are two kinds of DWs in the initial DW network.
- Z_2 DWs have higher σ, and quickly decay into LR DWs.
- We performed Bayesian analysis using the NG15 data, for parameter estimation.
- If true, the signal would also be detected by upcoming GW detectors.
- The techniques used can be similarly applied to TLRSM.

Thank You!

GW spectrum and collider probes

- Non-runaway scenario: $h^2\Omega_{\rm GW} \approx h^2\Omega_{\rm sw} + h^2\Omega_{\rm turb}$.





Left: GW spectra for 6 benchmark points. Right: Detectable points for $v_R = 20$ TeV.

- GW favours $\rho_1 \lesssim \mathcal{O}(10^{-1})$, i.e. light H_3.
- FCC-hh at $\sqrt{s} = 100\,\text{TeV}$ with $\sigma \sim \mathcal{O}(fb)$ can rule out m_{H_3} upto $2\,\text{TeV}$. [DeV, 2016]
- HE-LHC, CLIC$_{3000}$, and FCC-hh will improve sensitivity of κ_h to $\sim 20\%, 10\%$, and 5% respectively. Will rule out large number of points. [Dev, 2016]

Neutrino masses in DLRSM