SO(10) Model of pseudo-Goldstone Dark Matter, Gravitational Waves from Walls Bounded by Strings and PTA data

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Outline

1. *Introduction*

Standard Model ($SU(2)_L \otimes U(1)_Y \otimes SU(3)_C$)

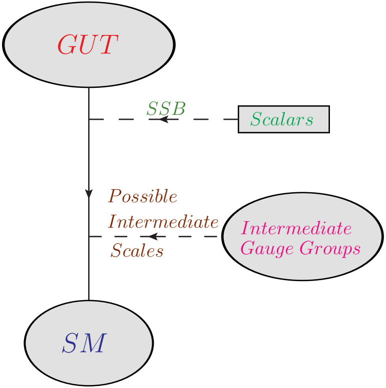
		Fields	Quantum numbers
Spin-$\frac{1}{2}$	Quarks	$Q_g^{i\alpha} = \{ \begin{pmatrix} u^\alpha \\ d^\alpha \end{pmatrix}_L , \begin{pmatrix} c^\alpha \\ s^\alpha \end{pmatrix}_L , \begin{pmatrix} t^\alpha \\ b^\alpha \end{pmatrix}_L \}$	$(2, \frac{1}{6}, 3)$
		$u^C_{\alpha\, L},\ c^C_{\alpha\, L},\ t^C_{\alpha\, L}$	$(1, -\frac{2}{3}, \overline{3})$
		$d^C_{\alpha L},\ s^C_{\alpha L},\ b^C_{\alpha L}$	$(1, \frac{1}{3}, \overline{3})$
	Leptons	$\ell_g^i = \{ \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \}$	$(2, -\frac{1}{2}, 1)$
		$e^C_L,\ \mu^C_L,\ \tau^C_L$	$(1, 1, 1)$
Spin-1	$SU(2)_L$	W^a_μ	$(3, 0, 1)$
	$U(1)_Y$	B_μ	$(1, 0, 1)$
	$SU(3)_C$	G^a_μ	$(1, 0, 8)$
Spin-0	Higgs	$\Phi^i = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	$(2, \frac{1}{2}, 1)$

Table: *Fields in the Standard Model.*

Grand Unification beyond the SM

- The basic idea in a Grand Unified Theory (GUT) is that the SM, $SU(2)_L \otimes U(1)_Y \otimes SU(3)_C$, is embedded in a larger simple group, $\mathcal{G}$.

Schematic view



GUT Examples

- $SU(5)$ (rank $= 4$): $\bar{5} + 10 \Rightarrow$ SM fermions.

  Georgi, Glashow, PRL **32**, 438 (1974)

- $SO(10)$ (rank $= 5$): $16 \Rightarrow$ SM fermions $\oplus\ \nu_L^C$.

  Fritzsch, Minkowski, Ann. Phys. **93**, 93-266 (1975)

- $E(6)$ (rank $= 6$): $27 \Rightarrow$ SM fermions $\oplus\ \nu_L^C \oplus$

$$\underbrace{(2, \pm\frac{1}{2}, 1) + (1, -\frac{1}{3}, 3) + (1, \frac{1}{3}, \bar{3}) + (1, 0, 1)}_{\text{Exotic fermions}}.$$

  Gursey, Ramond, Sikivie, PLB **60** (1976) 177

  Shafi, PLB **79** (1978) 301

2 *Model of Pseudo-Goldstone Dark Matter (pGDM)*

Model of Pseudo-Goldstone Dark Matter (pGDM)

- Introduce a complex singlet scalar S and a softly broken global $U(1)$ symmetry $S \to e^{i\alpha} S$.
- $V = -\mu_h^2 |H|^2 - \mu_s^2 |S|^2 + \lambda_h |H|^4 + \lambda_{hs} |H|^2 |S|^2 + \lambda_s |S|^4 - {\mu'_s}^2 (S^2 + \text{h.c.})$
- The last term explicitly breaks $\boxed{U(1) \to \mathbb{Z}_2}$.
- As the radial component of S gets a VEV, its angular component will be a pseudo Nambu-Goldstone boson (pNGB) due the spontaneous and explicit breaking of the $U(1)$ symmetry.
- Becomes a viable dark matter candidate stabilized by the symmetry $S \to S^*$.

C. Gross, O. Lebedev and T. Toma, Phys. Rev. Lett.**119** (2017) 191801

Domain Wall Problem

- The VEV of S spontaneously breaks $\mathbb{Z}_2$.
- Breaking of exact $\mathbb{Z}_2$ produces topologically stable domain walls.
- The domain walls gradually dominate the energy density of the universe ($t \sim m_{\rm Pl}^2 / \langle S \rangle^3$) and the scale factor $a(t) \propto t^2$.
- Contradict the standard cosmology.

Zeldovich, Kobzarev, Okun, Zh. Eksp. Teor. Fiz. **67**, 3-11 (1974)

Gauge $U(1)_{B-L}$ Model of pGDM

- A $U(1)_{B-L}$ gauge symmetry and two complex scalars S and Φ carrying one and two units of $B-L$ charges respectively.

- Trilinear interaction Lagrangian: $\boxed{\beta(\Phi^\dagger S^2 + \text{h.c.})}$.

- The spontaneous breaking of $U(1)_{B-L}$ gauge symmetry by the Φ VEV leaves a remnant gauge $\mathbb{Z}_2$ symmetry and generates the soft breaking term from the trilinear term.

Abe, Toma, Tsumura JHEP **05** (2020) 057

Okada, Raut, Shafi, PRD **103** (2021) 055024

$SO(10)$ model of pGDM

- A unified approach is based on $SO(10)$ with $S \in 16_H$ and $\Phi \in \overline{126}_H$.
- Trilinear term arising from the coupling $\boxed{\overline{126}_H (16_H)^2 + \text{h.c.}}$ in the scalar potential.
- The dark matter candidate is the pseudo-Goldstone mode coming from a linear combination of the CP-odd components of the SM singlets.

Abe, Toma, Tsumura, Yamatsu, PRD **104** (2021) 035011

Okada, Raut, Shafi, Thapa, PRD **104** (2021) 095002

Phenomenological Implications of $SO(10)$ pGDM

- The dark matter can decay via gauge interactions.
- The VEV along the SM singlet direction in 126_H should be above 10^{11} GeV in order to satisfy the lifetime bound, $\tau_{\rm DM} \gtrsim 10^{27}$ sec, for decaying dark matter.
- $\langle 126_H \rangle \gtrsim 10^{11}$ GeV coincides with the requirement from the fitting of neutrino oscillation data in the minimal $SO(10)$ GUT.
- A VEV $\sim 10^2$ GeV of 16_H gives a viable pNGB thermal dark matter.

Baring, Ghosh, Queiroz, Sinha, PRD **93** (2016) 103009

Abe, Toma, Tsumura, Yamatsu, PRD **104** (2021) 035011

Okada, Raut, Shafi, Thapa, PRD **104** (2021) 095002

3 *Formation of Domain Walls Bounded by Strings*

Formation of Domain Walls Bounded by Strings

$$\underbrace{SO(10) \to ... \to \mathcal{G}_I}_{\text{rank}=5} \xrightarrow[M_R(\nu_L^C)]{\langle\Phi\in\overline{126}\rangle \gtrsim 10^{11}\ \text{GeV}} \underbrace{\text{SM} \times \mathbb{Z}_2 \xrightarrow[\simeq 10^2 - 10^5\ \text{GeV}]{\langle S\in 16\rangle} \text{SM}}_{\text{rank}=4}$$

- $\langle 126_H \rangle \gtrsim 10^{11}$ GeV leaves an unbroken $\mathbb{Z}_2$ and therefore generates topologically stable cosmic strings.

  Kibble, Lazarides, Shafi, Phys. Lett. B **113** (1982)

- The VEV $\langle 16_H \rangle \simeq [10^2, 10^5]$ GeV, breaks this $\mathbb{Z}_2$ symmetry, which leads to the formation of domain walls bounded by strings.

  RM, Park, Shafi, Phys.Lett.B **845** (2023) 138127

  Kibble, Lazarides, Shafi, Phys. Rev. D **26** (1982), 435

- String has a tension $\mu \sim \langle 126_H \rangle^2$ and wall has a tension $\sigma \sim \langle 16_H \rangle^3$.

4 *Gravitational Wave Background from WBS*

Timescale for String Network

- Strings formed at time t_F form a network and domain walls are formed at a later time $t_{\rm dw}$ with the strings as their boundary.

- For a wall bounded by a string of radius of curvature R, the force per unit length on the string boundary $\sim \mu/R$ dominates over the wall tension σ for $R < \boxed{R_c = \mu/\sigma}$.

- String dynamics dominates till R_c if $R_c > t_{\rm dw}$.

- For $t_{\rm dw} > R_c$, the domain wall dynamics starts dominating right after their formation.

Timescale for String Network

- $t_* = \max[R_c, t_{\rm dw}]$ to be the maximum timescale for domination by the string dynamics.

- The cosmic strings inter-commute, form loops before t_* with $R < t_*$ and can produce gravitational waves.

$$f = \frac{2n}{l(t)} \frac{a(t)}{a_0}$$

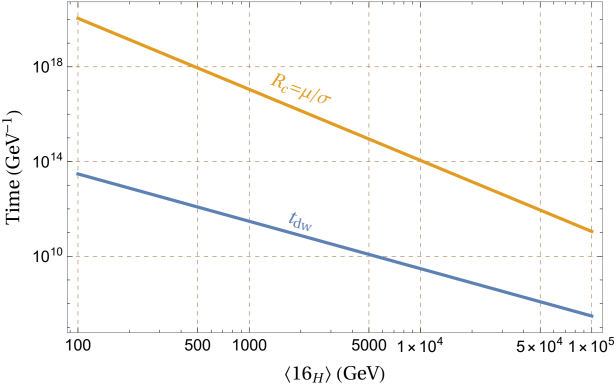
- The domain wall dynamics become dominant for $t > t_*$, and the string-wall networks collapse as the walls pull the strings.

Vilenkin, Everett, PRL **48** (1982) 1867

Martin, Vilenkin, PRL **77** (1996) 2879

Dunsky et. al., PRD **106** (2022) 075030

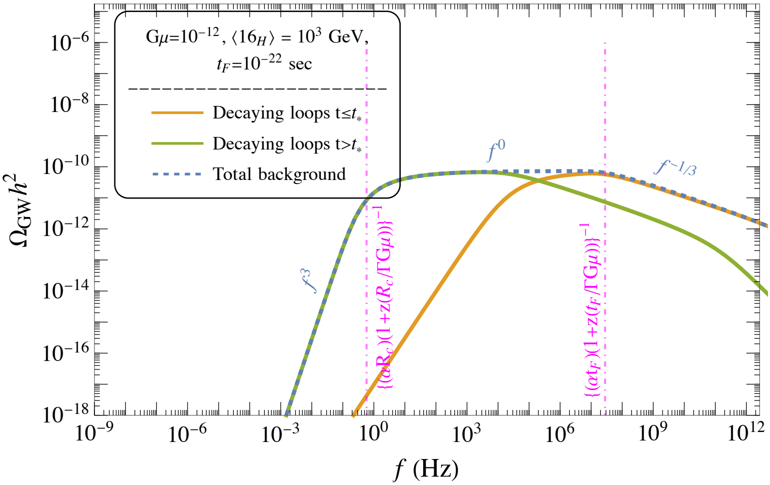
Timescale for String Network



- $R_c \gg t_{\rm dw}$ for pGDM implies $t_* = R_c$, and the gravitational wave background is dominated by string loops.

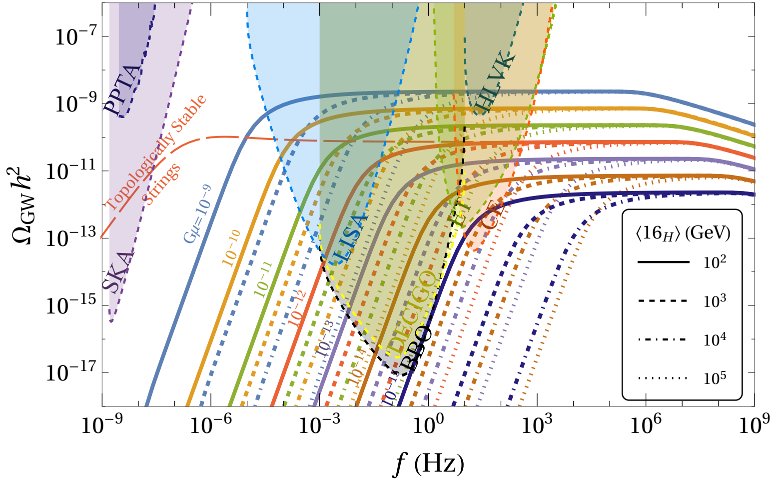
RM, Park, Shafi, Phys.Lett.B **845** (2023) 138127

Gravitational Waves from WBS



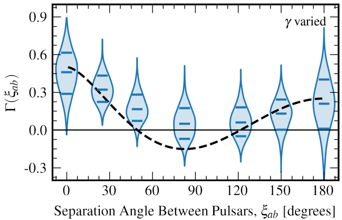
RM, Park, Shafi, Phys.Lett.B **845** (2023) 138127

GWs from WBS and Observational Prospects



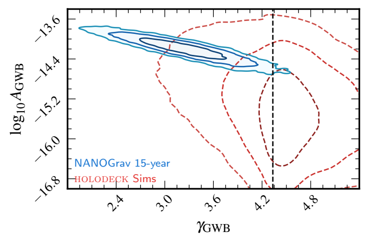
RM, Park, Shafi, Phys.Lett.B **845** (2023) 138127

Evidence of GWB in PTA

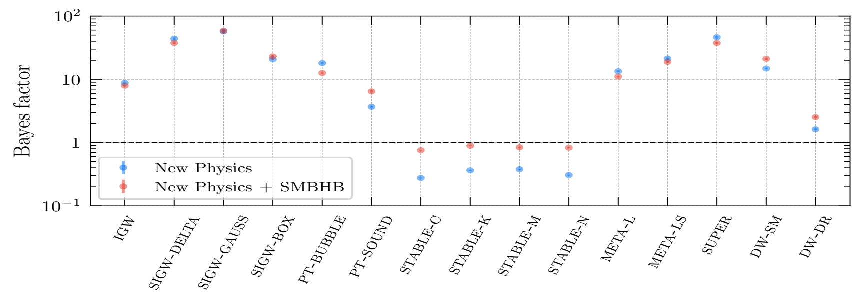


NG15:2306.16219,...

Mergers of SMBHBs?

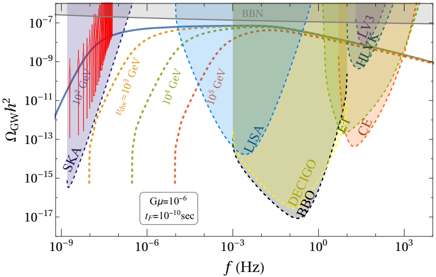


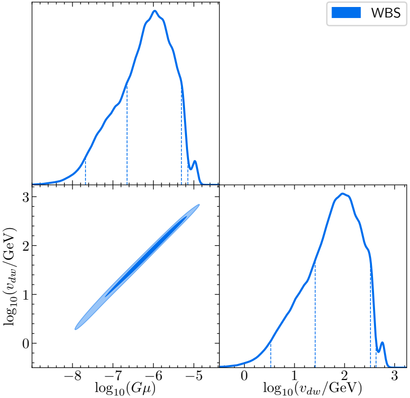
Cosmological Origin? New Physics?



WBS and NANOGrav data

Parameters	Bayesian Credible Intervals	
	68%	95%
$\log_{10}(G\mu)$	$[-6.65, -5.31]$	$[-7.68, -5.15]$
$\log_{10}(v_{\rm dw}/{\rm GeV})$	$[1.41, 2.52]$	$[0.53, 2.63]$





Lazarides, **RM**, Shafi, Phys. Rev. D **108** (2023) 095041

5 *Summary*

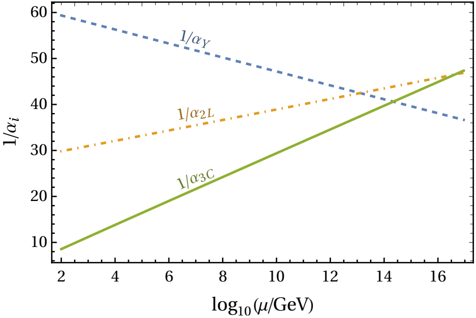
Summary

- PGDM models based on realistic grand unified gauge symmetries such as $SO(10)$ predict the existence of composite topological structures known as 'walls bounded by strings'.
- Gravitational wave spectrum produced by this string-wall system will be accessible in the foreseeable future at a number of proposed experiments.
- We note that the PTA data has a strong evidence of GWs background from the string-wall composite structures with $G\mu \sim 10^{-6}$ and $v_{\rm dw} \sim 10^2$ GeV.

Thank You

Back up slides

Motivation towards the Grand Unification



- Renormalization Group Evolution of Standard Model gauge couplings gives the hint of the possibility of the Grand Unified Theories.

- Imposition of higher symmetry may constraint some free parameters.
- All fermions including $(\nu^c)_L$ can be put in one representation in GUT.
- One way to understand the charge quantization.

A Minimal Yukawa Sector in SO(10)

- The Lagrangian for the Yukawa interactions:

$$y_{10}\psi_{16}^{\mathrm{T}}\mathcal{C}\phi_{10}\psi_{16} + y_{126}\psi_{16}^{\mathrm{T}}\mathcal{C}\phi_{126}^{\dagger}\psi_{16} + \mathrm{H.c.},$$

- SM Higgs doublet (H) is a linear combination of bi-doublets from complex 10_H and $\overline{126}_H$.

  Lazarides, Shafi, Wetterich, NPB **181** (1981) 287

  Babu, Mohapatra, PRL **70** (1993) 2845

- A VEV (v_R) along the SM singlet direction of $\overline{126}_H$ breaks a diagonal generator orthogonal to the hypercharge (Y).

$$\underbrace{SO(10) \to ... \to \mathcal{G}_I}_{\text{rank=5}} \xrightarrow{\langle\overline{126}_H\rangle} \underbrace{\mathrm{SM} \times \mathbb{Z}_2}_{\text{rank=4}}.$$

- Example: $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \to SU(2)_L \times U(1)_Y$, where $T_{3R} - \frac{B-L}{2}$ is broken.

Right-handed Neutrino Mass in Minimal $SO(10)$

- The Majorana mass matrix of the RHNs: $\boxed{M_R = y_{126} v_R}$.

- Fit to the quark and lepton mass and mixing parameters requires $\boxed{v_R \gtrsim 10^{11}\ \text{GeV}}$.

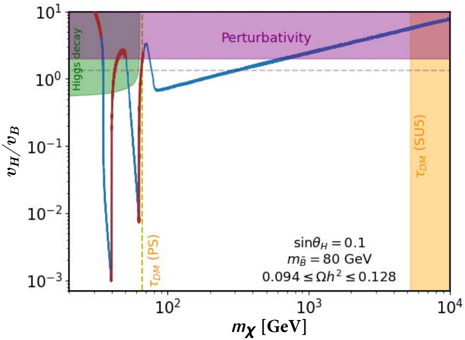
- For example, predicted physical masses of the RHNs from two recent fittings:
  $\{4.36 \times 10^9, 1.97 \times 10^{11}, 8.66 \times 10^{11}\}$ GeV Mummidi, Patel, JHEP **12** (2021)
  $\{1.87 \times 10^{10}, 4.46 \times 10^{11}, 2.36 \times 10^{12}\}$ GeV Ohlsson, Pernow, JHEP **06** (2019)

- Compatible with gauge coupling unification.

Chakrabortty, RM, King, Phys. Rev. D **99** (2019) 095008

Lazarides, RM, Roshan, Shafi, JCAP **12** (2022), 009

Phenomenological Implications of $SO(10)$ pGDM



Okada, Raut, Shafi, Thapa, PRD **104** (2021) 095002

- The VEV of 16_H is $\sim 10^2$ GeV for a viable pNGB thermal dark matter.
- It could be $\sim 10^5$ GeV or so near the resonance.
- Namely, $\langle 16_H \rangle / v_H \simeq [1, 10^3]$, with v_H being the VEV of the SM Higgs.

$$\underbrace{SO(10) \rightarrow \ldots \rightarrow \mathcal{G}_I}_{\text{rank}=5} \xrightarrow[M_R(\nu_L^C)]{\langle \Phi \in \overline{126} \rangle \gtrsim 10^{11}\ \text{GeV}} \underbrace{\text{SM} \times \mathbb{Z}_2 \xrightarrow[\simeq 10^2 - 10^5\ \text{GeV}]{\langle S \in 16 \rangle} \text{SM}}_{\text{rank}=4}$$

Predictions of GUTs: Topological Defects

- Topological defects may appear during the SSB of a group $\mathcal{G}$ down to its subgroup $\mathcal{H}$.
- Non-trivial homotopy group $\Pi_k(\mathcal{M})$ of the vacuum manifold $(\mathcal{M} = \mathcal{G}/\mathcal{H})$ implies formation of topological defects.
- Various types of topological defects which can be formed are : domain walls $(\mathrm{k} = 0)$, cosmic strings $(\mathrm{k} = 1)$, monopoles $(\mathrm{k} = 2)$ etc

Loop distribution

$$n_{rm}(l, t > t_{eq} > t_M) = \frac{0.18 t_{eq}^{1/2} \Theta(0.1 t_M - l - \Gamma G\mu(t - t_M))}{t^2 (l + \Gamma G\mu t)^{5/2}} \tag{1}$$