Falsifying Pati-Salam models with LIGO

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[P. Athron, C. Balázs, T.G,, M. Pearce, arXiv:2307.02544 [hep-ph]]

Outline

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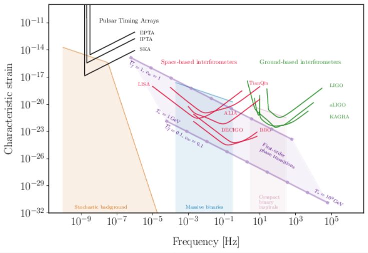
Motivation

- Gravitational waves have opened a new window to astrophysical and cosmological phenomena
- Can we use GWs to explore the mechanism of neutrino mass generation?
  - → Cosmological phase transition ⇒ produce GWs
  - → Relationship between m_ν and phase transition scale
- Strong PT at scale visible by today or near future detectors
  - → $f \sim \mathcal{O}(10)$ Hz, $v_{\rm PT} \sim 10^{6-8}$ GeV
  - → $\Omega_{\rm GW} \sim 10^{-9} \to m_\phi / v_{\rm PT} \gg 1$
- Neutrino mass generation
  - → Type I / II seesaw mechanism
  - → Connect $v_{\rm PT}$ and $\mu_{\rm SS}$ via RG flow



[P. Athron el al, arXiv:2305.02357]

⇒ **Pati-Salam model**

Outline

Pati-Salam model

- Generalised colour group and right-handed interactions

$$SU(4)_c \times SU(2)_L \times SU(2)_R$$

- Unified quarks and leptons into a single representation

$$\Psi_L = \{\mathbf{4}, \mathbf{2}, \mathbf{1}\} = \begin{Bmatrix} u_a & \nu \\ d_a & l \end{Bmatrix}, \qquad \Psi_R = \{\bar{\mathbf{4}}, \mathbf{1}, \mathbf{2}^*\} = \begin{Bmatrix} d_a^c & l^c \\ -u_a^c & -\nu^c \end{Bmatrix},$$

- Gauge bosons $G = \{\mathbf{15}, \mathbf{1}, \mathbf{1}\}$, $W_L = \{\mathbf{1}, \mathbf{3}, \mathbf{1}\}$, $W_R = \{\mathbf{1}, \mathbf{1}, \mathbf{3}\}$
- EW symmetry breaking at M_Z triggered by Higgs in bi-doublet

$$\Phi = \{\mathbf{1}, \mathbf{2}, \mathbf{2}\} = \begin{Bmatrix} \phi_1^+ & \phi_2^0 \\ \phi_1^0 & \phi_2^- \end{Bmatrix}$$

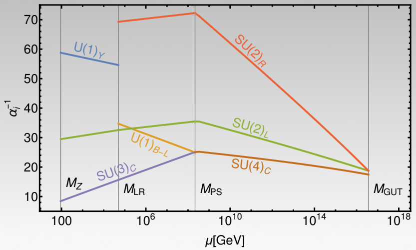
- Some other scalar field Ξ responsible for PS breaking

Pati-Salam model

- Breaking path with intermediate left-right scale

$$SU(4)_c \times SU(2)_L \times SU(2)_R \to SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \to SM$$

- Pati-Salam breaking to left-right at M_{PS} with $\Xi = \{\mathbf{15}, \mathbf{1}, \mathbf{1}\}$
- Left-right breaking to SM at M_{LR} with $\Delta_R = \{\overline{\mathbf{10}}, \mathbf{1}, \mathbf{3}\}$
- Type-II seesaw $\Delta_L = \{\mathbf{10}, \mathbf{3}, \mathbf{1}\}$
- GUT-scale unification requires manifest D-parity breaking $\Omega_R = \{\mathbf{15}, \mathbf{1}, \mathbf{3}\}$
- 2-loop RGEs with $\mathcal{O}(1)$ couplings and threshold corrections fix M_{LR}, M_{PS} and M_{GUT}



- Agnostic about GUT scale completion

Pati-Salam model

- Pati-Salam model naturally provides a mechanism for neutrino mass generation
  - → Type-I seesaw with right-handed neutrino in $(\Psi_R)_{\text{sing}} = \nu^c$
  - → Type-II with $\delta_L = \{\mathbf{1}, \mathbf{3}, \mathbf{1}, -2\} \in \Delta_L$
- The neutrino mass matrix

$$M_\nu = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix} = \begin{pmatrix} \lambda_L v_L & y_\nu v_{\text{SM}} \\ y_\nu v_{\text{SM}} & \lambda_R v_R \end{pmatrix} \simeq \begin{pmatrix} \zeta M_{LR} & y_\nu M_Z \\ y_\nu M_Z & M_{LR} \end{pmatrix}$$

- Active and sterile neutrino masses are generated $(M_{LR} \gg y_\nu M_Z)$

$$m_{\nu_L} \simeq \zeta M_{LR} - y_\nu^2 \frac{M_Z^2}{M_{LR}}, \qquad m_{\nu_R} \simeq M_{LR}$$

$$\Theta \simeq y_\nu \frac{M_Z}{M_{LR}}$$

- Neutrino masses are fully determined by M_{LR} (or M_{PS})

Pati-Salam model

- Low-scale constraints at M_{LR}
  - $\rightarrow$ Collider searches for Z' and W'

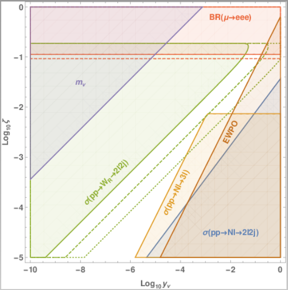
$$M_{Z'} \sim M_{W'} \sim g_R M_{LR} \gtrsim 5 \text{ TeV}$$

  - $\rightarrow$ Neutrino masses

$$m_\nu \sim \zeta M_{LR} - y_\nu^2 \frac{M_Z^2}{M_{LR}} \lesssim 0.23 \text{ eV}$$

$$\Theta \sim y_\nu M_Z / M_{LR} \lesssim 10^{-3}$$

  - $\rightarrow$ Lepton flavour violation $\text{BR}(\mu \to 3e) \sim \zeta^4$



[JHEP 1902 (2019) 083]

- High scale constraints at M_{PS} and M_{GUT}
  - $\rightarrow$ Proton decay, none at M_{PS}

$$M_{GUT} \gtrsim 10^{16} \text{ GeV}$$

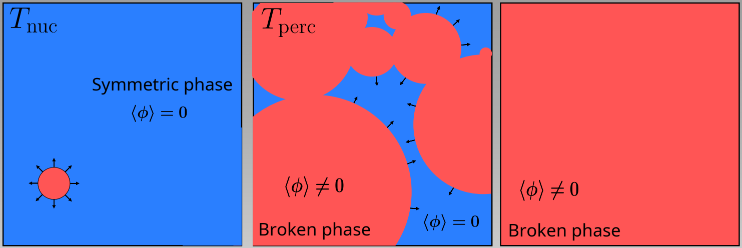
  - $\rightarrow$ Gravitational waves

$$f_{\text{peak}} \sim M_{PS} \sim 25\text{Hz}$$

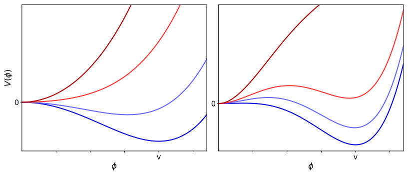
$$\Omega_{\text{peak}} \lesssim 5.7 \times 10^{-9}$$

Outline

- First-order phase transitions may produce gravitational waves



- Requirements for strong GW signal
  - → First order PT $v_{PS}(T_c) > 0$
  - → Strong PT $\alpha > 1$
  - → Slow (supercooled) PT $T_p/T_c \ll 1$
  - → Fast bubble walls $v_w \lesssim 1$



Gravitational waves

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- Properties of the PT are computed from $V_{\rm eff}$ $(\phi \equiv \Xi_{15})$

$$V_{\rm eff}(\phi, T) = V_{\rm tree}(\phi) + V_{\rm CW}(\phi) + V_T(\phi, T) + V_{\rm daisy}(\phi, T)$$

- Nucleation rate of bubbles determines temperature of nucleation T_Γ

$$\Gamma(T) \simeq T^4 \left(\frac{S_3(T)}{2\pi T}\right)^{\frac{3}{2}} e^{-S_3(T)/T} \Rightarrow \Gamma(T_\Gamma) > H$$

- Energy released in the PT $\alpha = \frac{1}{\rho_R}\left(\Delta V - \frac{1}{4} T \frac{\partial \Delta V}{\partial T}\right)\Big|_{T_\Gamma}$
- Mean bubble separation (gaussian nucleation, i.e. $\beta \to 0$)

$$R_* = \left(\frac{\beta_V}{\sqrt{2\pi}\Gamma(T_\Gamma)}\right)^{1/3}, \quad \beta_V = \sqrt{\frac{d^2}{dt^2}\left(\frac{S_3(T)}{T}\right)}$$

- PT must complete $v_w > -\left(\frac{3\log(f_f)}{4\pi N}\right)^{1/3}\left[\sqrt{\frac{T_\Gamma^4}{T_{\rm eq}^4} + 1} + {}_2F_1\left(\frac{1}{4}; \frac{1}{2}; \frac{5}{4} - \frac{T_\Gamma^4}{T_{\rm eq}^4}\right)\right]^{-1}$

Gravitational waves

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- GWs are produced primarly by the collision of sound waves

$$h^2\Omega_{\rm sw}(f) = 2.59\times 10^{-6}\left(\frac{g_*}{100}\right)^{-1/3}\left(\frac{\beta}{H_*}\right)^{-1}\left(\frac{\kappa_{\rm sw}\alpha}{1+\alpha}\right)^2 v_w \Upsilon(\tau_{\rm sw}) S_{\rm sw}(f)$$

$$S_{\rm sw}(f) = \left(\frac{f}{f_{\rm peak}}\right)^3\left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2}$$

$$f_{\rm sw} = 8.9\ \text{Hz}\left(\frac{g_*}{100}\right)^{1/6}\left(\frac{T_\Gamma}{10^8\ \text{GeV}}\right)\left(\frac{z_p}{10}\right)v_w^{-1}\left(\frac{\beta}{H_*}\right)$$

- And a small contribution from turbulence of the plasma

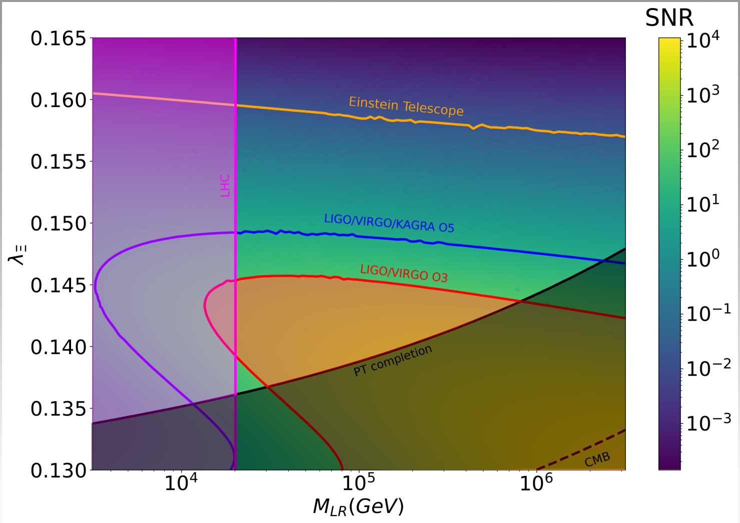
$$h^2\Omega_{\rm turb}(f) = 3.35\times 10^{-4}\left(\frac{g_*}{100}\right)^{-1/3}\left(\frac{\beta}{H_*}\right)^{-1}\left(\frac{\kappa_{\rm turb}\alpha}{1+\alpha}\right)^{3/2} v_w S_{\rm turb}(f)$$

$$S_{\rm turb}(f) = \frac{(f/f_{\rm turb})^3}{(1+f/f_{\rm turb})^{11/3}(1+8\pi f/H_*)}$$

$$f_{\rm turb} = 27\ \text{Hz}\left(\frac{g_*}{100}\right)^{1/6}\left(\frac{T_\Gamma}{10^8\ \text{GeV}}\right)\left(\frac{\beta}{H_*}\right)v_w^{-1}$$

Outline

Results



SNR
Einstein Telescope
LHC
LIGO/VIRGO/KAGRA O5
LIGO/VIRGO O3
PT completion
CMB
λ_{Ξ}
$M_{LR}(GeV)$
0.165
0.160
0.155
0.150
0.145
0.140
0.135
0.130
10^4
10^5
10^6
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}

Outline

Conclusions and outlook

- Models inspired by grand unification can be probed at high scales using gravitational waves
  - → Complementarity with searches at low energy (colliders, etc)
- GWs can probe the mechanism for neutrino masses in Pati-Salam
  - → Types I and II are generated by the intermediate LR
  - → Constraints on M_{PS} scale affect M_{LR}, and therefore m_ν
- Current results from LIGO/VIRGO already constrain model
  - → GW prediction very sensitive to values of λ_Ξ
  - → Importance of checking for the completion of the PT
- Model is discoverable by upcoming results from the LIGO/VIRGO/KAGRA network
  - → First evidence of GW stochastic background from LIGO
- Future missions, e.g. Einstein Telescope, will probe a large portion of model parameter space

Backup

Effective potential

- One-loop CW potential, in the Landau gauge and $\overline{\text{MS}}$ renormalisation scheme

$$V_{\text{CW}}(\phi) = \sum_i \pm g_i \frac{m_i^4(\phi)}{64\pi^2}\left(\log\frac{m_i^2(\phi)}{\mu^2} - c_i\right), \qquad \begin{aligned} c_s &= 3/2 \\ c_f &= 5/6 \end{aligned}$$

- Finite temperature potential

$$V_T(\phi, T) = \frac{T^4}{2\pi^2}\sum_i \pm g_i J_b/f\left(\frac{m_i^2(\phi)}{T^2}\right)$$

- Daisy corrections

$$V_{\text{daisy}}(\phi, T) = -\frac{T}{12\pi}\sum_i g_i\left[\left(m_i^2(\phi) + \Pi_i(T)\right)^{3/2} - \left(m_i^2(\phi)\right)^{3/2}\right]$$

Signal-to-noise ratio

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- In a given detector network the SNR, ρ is

$$\rho = \sqrt{2\tau}\left(\int_{f_{min}}^{f_{max}} df \sum_{I=1}^{M}\sum_{J>I}^{M} \frac{\Gamma_{IJ}(f) S_h^2(f)}{P_{nI}(f) P_{nJ}(f)}\right)^{1/2}$$

  → $S_h(f)$ is the GW power spectral density

$$S_h(f) = \frac{3H_0^2 \Omega_{\rm GW}(f)}{2\pi^2 f^2}$$

  → Γ_{IJ} overlap reduction function of detectors I and J
  → P_{nI} the power spectral density in detector I due to noise
  → τ duration of simultaneous observation

- The detectability threshold $\rho > 10$