

# Multistep Single-Field Strong Phase Transitions from New TeV Scale Fermions

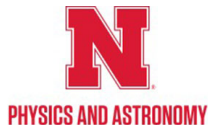
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Based on arXiv:18xx.xxxxx,  
in collaboration with P. Huang

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# Introduction and Motivation

- Baryon Asymmetry in the Universe (BAU)?  
→ Sakharov conditions:
  - $B$ -number violation;
  - $C$  and  $CP$  violation;
  - interactions out of thermal equilibrium;
- Interactions out of thermal equilibrium?  
→ Strongly First Order (SFO) Electroweak Phase Transition (EWPT)!
- Solution within the Standard Model (SM)?  
→ No strong EWPT! (plus not enough  $CP$ )  $\Rightarrow$  add new particles!
- Usually, new bosons  $\rightarrow \mathcal{O}(100)$  papers ...

## WHAT ABOUT NEW FERMIONS AND PHASE TRANSITIONS?

Extra Dimensions, Composite Higgs, ...  $\Rightarrow$  new fermions!

Rather uncharted territory (but: Carena et al. '04, Fok et al. '08, Davoudiasl et al. '12, Fairbairn et al. '13, Egana-Ugrinovic '17).

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# A Minimal Vector-Like Lepton (VLL) Model

- Dirac fermion model for strong PTs in the Early Universe?  
→ need strong couplings to the Higgs!
- However: strong Yukawas  $\Rightarrow$  large custodial symmetry breaking!
- Solution  $\rightarrow$  a minimal model which can possess (approximate) custodial symmetry:

$$L_{L,R} = \begin{pmatrix} N \\ E \end{pmatrix}_{L,R} \sim (1, 2, -1/2), \quad N'_{L,R} \sim (1, 1, 0), \quad E'_{L,R} \sim (1, 1, -1).$$

- VLL masses + Yukawa couplings (assume negligible mixing with the SM):

$$\begin{aligned} -\mathcal{L}_{VLL} = & y_{N_R} \bar{L}_L \tilde{H} N'_R + y_{N_L} \bar{N}'_L \tilde{H}^\dagger L_R + y_{E_R} \bar{L}_L H E'_R + y_{E_L} \bar{E}'_L H^\dagger L_R \\ & + m_L \bar{L}_L L_R + m_N \bar{N}'_L N'_R + m_E \bar{E}'_L E'_R + \text{h.c.} \end{aligned}$$

- EW symmetry breaking  $\Rightarrow$  mass matrices ( $v = 246$  GeV,  $v_h = v/\sqrt{2} \simeq 174$  GeV):

$$\mathcal{M}_N = \begin{pmatrix} m_L & v_h y_{N_L} \\ v_h y_{N_R} & m_N \end{pmatrix}, \quad \mathcal{M}_E = \begin{pmatrix} m_L & v_h y_{E_L} \\ v_h y_{E_R} & m_E \end{pmatrix}.$$

- Diagonalization  $\Rightarrow$  eigenmasses  $m_{N_1} < m_{N_2}$ ,  $m_{E_1} < m_{E_2}$  and interaction basis couplings.

# Approach

- Calculate the 1-loop finite  $T$  effective potential (on-shell renormalization scheme,  $V(0, T) \equiv 0$ ):

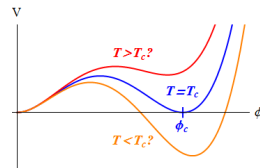
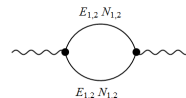
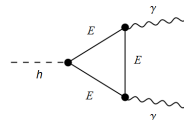
$$V(\phi, T) = V_{\text{tree}}^{\text{SM}}(\phi) + V_{1\text{-loop}}^{\text{SM}}(\phi, T) \\ + V_{1\text{-loop}}^{\text{VLL}}(\phi, T) + V_{\text{Daisy}}(\phi, T);$$

- Many parameters  $\Rightarrow$  scan approach:

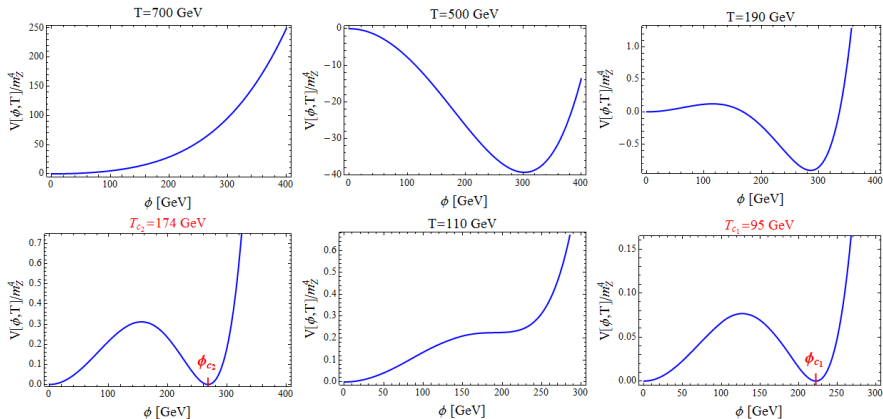
$$m_L, m_N, m_E \in [500, 1500] \text{ GeV},$$

$$y_{N_{L,R}}, y_{E_{L,R}} \in [2, \sqrt{4\pi}];$$

- Impose  $0.71 \leq \mu_{\gamma\gamma} < 1.29$  (1802.04146),  $\Delta\chi^2(S, T) \leq 6.18$ ;
- Calculate PT strength for each point  $\rightarrow \xi \equiv \phi_c / T_c$ .



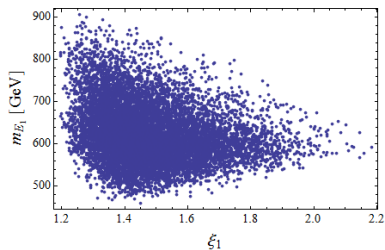
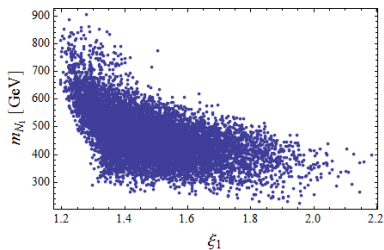
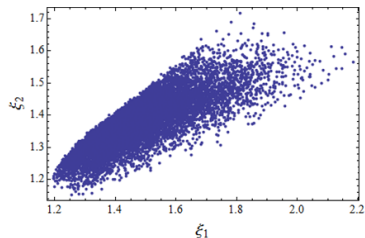
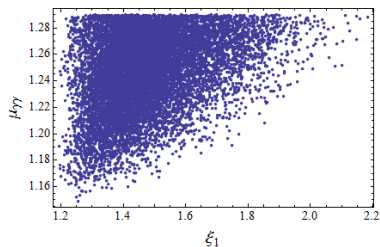
# Thermal Evolution of the Effective Potential: Multistep Phase Transition



**Figure:** Typical temperature dependence of the 1-loop effective potential in the VLL model under study.

N.B.: Only the **last SFOPT** is responsible for generating the **BAU**!  $\Rightarrow \xi_1 \geq 1.3$ .

# Correlations Between Observables





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  - **Benchmark**
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# Benchmark

- Chosen benchmark point  $\Rightarrow$  **strongest PT**:

$$y_{N_L} \simeq 3.4, y_{N_R} \simeq 3.49, y_{E_L} \simeq 3.34, y_{E_R} \simeq 3.46,$$

$$m_L \simeq 1.06 \text{ TeV}, m_N \simeq 0.94 \text{ TeV}, m_E \simeq 1.34 \text{ TeV}.$$

- Predictions:

$\xi_1$	2.34
$\xi_2$	1.54
$\mu_{\gamma\gamma}$	1.28
$\Delta\chi^2(S, T)$	1.33
$m_{N_1}$	400 GeV
$m_{E_1}$	592 GeV

# Gravitational Wave Signature

- **Strong PTs** in the Early Universe  $\Rightarrow$  **Gravitational Wave (GW)** stochastic background!  
 $\rightarrow$  **Detectable** by future GW experiments, such as **eLISA**?
- **GW amplitude and spectrum** controlled (mostly) by two parameters:

$$\alpha = \frac{\text{latent heat}}{\text{radiation energy}}, \quad \frac{\beta}{H_{\text{PT}}} = \frac{\text{"inverse PT duration"}}{\text{Hubble rate}}$$

- Main **GW sources**  $\rightarrow$  **bubble collisions** ( $\Omega_{\text{col}}$ ), **MHD turbulence** ( $\Omega_{\text{turb}}$ ), **sound waves** ( $\Omega_{\text{sw}}$ ):

$$h^2 \Omega_{\{\text{col}, \text{turb}, \text{sw}\}}(f) \propto \left( \frac{\beta}{H_{\text{PT}}} \right)^{-\{2, 1, 1\}} \left( \frac{\alpha}{1 + \alpha} \right)^{\{2, \frac{3}{2}, 2\}} S_{\{\text{col}, \text{turb}, \text{sw}\}}(f; \beta/H_{\text{PT}})$$

- Typically, for our **VLL** model:

$$\alpha = \mathcal{O}(10^{-1} - 10^{-2}), \quad \frac{\beta}{H_{\text{PT}}} = \mathcal{O}(10^3 - 10^4),$$

$\Rightarrow$  **SW contribution dominant for  $f \in [10^{-3}, 10^{-2}]$  Hz** (eLISA max sensitivity).

# GW Spectrum Calculation and Comparison with eLISA Sensitivity

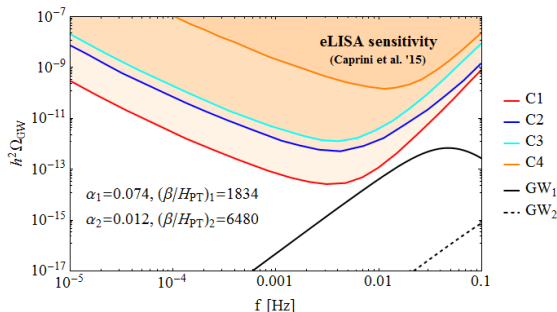
- Compute the bounce action  $S_3(T)$ , find the temperature at which the PT occurs:

$$\frac{S_3(T_{\text{PT}})}{T_{\text{PT}}} \simeq 142;$$

- Calculate  $\alpha$  and  $\beta$  for the two SFOPTs:

$$\alpha = \frac{|V(\phi_{\text{broken}}, T_{\text{PT}})| + T_{\text{PT}} \left| \frac{\partial V(\phi_{\text{broken}}, T)}{\partial T} \right|_{T_{\text{PT}}}}{\rho_{\text{rad}}(T_{\text{PT}})}, \quad \frac{\beta}{H_{\text{PT}}} = T_{\text{PT}} \frac{d}{dT} \left( \frac{S_3}{T} \right) \Big|_{T_{\text{PT}}}.$$

- Compute **GW spectrum**  $\rightarrow$  GW detection by eLISA improbable:



# Collider Predictions

- $N_1$  not a suitable Dark Matter candidate  $\Rightarrow$  SM-VLL mixing should be present!
- Measurements:  $W\tau\nu$  and  $Z\tau\tau$  couplings  $\Rightarrow$  take  $y_{\tau E} \simeq 0.05$ ;
- For simplicity,  $y_{\nu N} \simeq 0 \Rightarrow \text{BR}(N_1 \rightarrow W\tau) = 1$ ;
- Masses, widths, branching ratios, and production cross sections for lighter VLLs:

$m_{N_1}$	400 GeV	$\text{BR}(E_1 \rightarrow N_1 W)$	0.995	$\sigma(pp \rightarrow E_1 E_1)$	0.32 fb
$\Gamma_{N_1}$	1.32 MeV	$\text{BR}(E_1 \rightarrow \tau h)$	$3.5 \times 10^{-3}$	$\sigma(pp \rightarrow E_1 N_1)$	0.36 fb
$m_{E_1}$	592 GeV	$\text{BR}(E_1 \rightarrow \nu W)$	$7.6 \times 10^{-4}$	$\sigma(pp \rightarrow N_1 N_1)$	0.31 fb
$\Gamma_{E_1}$	7.46 GeV	$\text{BR}(E_1 \rightarrow \tau Z)$	$4.6 \times 10^{-4}$	$\sigma(pp \rightarrow \psi_{\text{NP}} \psi_{\text{SM}})$	$\mathcal{O}(10^{-4})$ fb

DIRECT PRODUCTION OF VLLS SUPPRESSED ...

MORE PROMISING SEARCH AVENUE?  $\longrightarrow \mu_{\gamma\gamma}$ !

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# Summary and Conclusions

- Studied the impact of **new VLLs** on the **phase structure** of the Universe;  
→ Indeed, **TeV-scale VLLs** with **strong Yukawas** can induce **SFOEWPTs**!
- Interestingly, such a **simple model** predicts a **complex PT structure**:  
→ First example of **single-field multistep SFOPT**!
- **GW signature** → multiple peaks, but likely **undetectable by eLISA**;
- **Collider** searches → **direct production** and detection of VLLs **not promising**;
- **$\mu\gamma\gamma$**  = **most promising collider** signature → **5% precision** @ HL-LHC! (CMS 1307.7135, ATLAS 1307.7292)  
⇒ **HL-LHC** can **fully test** our model for **VLL-induced SFOEWPTs**!

THANK YOU FOR YOUR ATTENTION!

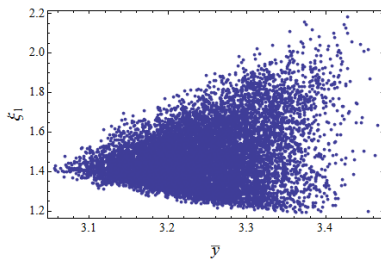
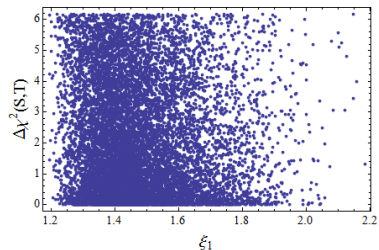
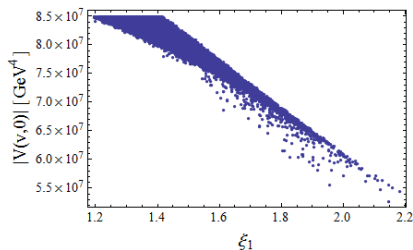
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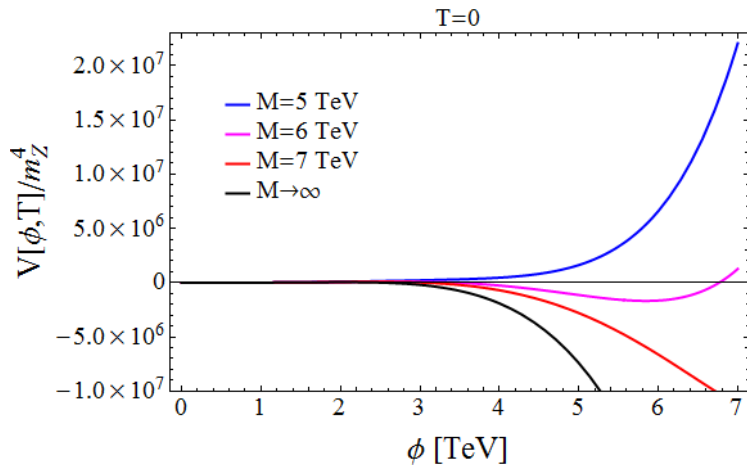


# Other Correlations

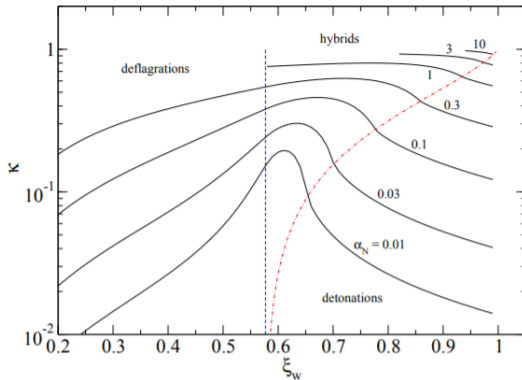


# Vacuum Stability

$$V(\phi, T) \rightarrow V(\phi, T) + \frac{\phi^6}{M^2}$$



# Choice of Bubble Wall Velocity



**Figure:** Ratio of bulk kinetic energy over to vacuum energy  $\kappa$  (efficiency factor) as a function of the bubble wall velocity,  $\xi_w$ , for various values of  $\alpha_N \equiv \alpha$  (result from 1004.4187).

Our choice:  $\xi_w = 0.6 \Rightarrow \kappa \simeq 0.4$  (for typical values of  $\alpha \simeq 10^{-1}$ ).

# GW Spectrum Formulae

$$\begin{aligned}
 h^2 \Omega_{\text{col}}(f) &= 1.67 \times 10^{-5} \left( \frac{0.11 \xi_w^3}{0.42 + \xi_w^2} \right) \left( \frac{\beta}{H_{\text{PT}}} \right)^{-2} \left( \frac{\kappa_{\text{col}} \alpha}{1 + \alpha} \right)^2 \left( \frac{g_{\text{eff}}}{100} \right)^{-1/3} \frac{3.8 (f/f_{\text{col}})^{2.8}}{1 + 2.8 (f/f_{\text{col}})^{3.8}}, \\
 h^2 \Omega_{\text{turb}}(f) &= 3.35 \times 10^{-4} \xi_w \left( \frac{\beta}{H_{\text{PT}}} \right)^{-1} \left( \frac{\kappa_{\text{turb}} \alpha}{1 + \alpha} \right)^{3/2} \left( \frac{g_{\text{eff}}}{100} \right)^{-1/3} \frac{(f/f_{\text{turb}})^3}{(1 + f/f_{\text{turb}})^{11/3} (1 + 8\pi f/h_*)}, \\
 h^2 \Omega_{\text{sw}}(f) &= 2.62 \times 10^{-6} \xi_w \left( \frac{\beta}{H_{\text{PT}}} \right)^{-1} \left( \frac{\kappa \alpha}{1 + \alpha} \right)^2 \left( \frac{g_{\text{eff}}}{100} \right)^{-1/3} \frac{7^{3.5} (f/f_{\text{sw}})^3}{(4 + 3 (f/f_{\text{sw}})^2)^{3.5}}.
 \end{aligned}$$

$$\kappa = 0.4, \epsilon = 0.05 \Rightarrow \kappa_{\text{turb}} = \epsilon \kappa = 0.02.$$

$$\begin{aligned}
 f_{\text{col}} &= (1.65 \times 10^{-5} \text{ Hz}) \left( \frac{0.62}{1.8 - 0.1 \xi_w + \xi_w^2} \right) \left( \frac{\beta}{H_{\text{PT}}} \right) \left( \frac{T_{\text{PT}}}{100 \text{ GeV}} \right) \left( \frac{g_{\text{eff}}}{100} \right)^{1/6}, \\
 f_{\text{turb}} &= (2.7 \times 10^{-5} \text{ Hz}) \left( \frac{1}{\xi_w} \right) \left( \frac{\beta}{H_{\text{PT}}} \right) \left( \frac{T_{\text{PT}}}{100 \text{ GeV}} \right) \left( \frac{g_{\text{eff}}}{100} \right)^{1/6}, \\
 h_* &= (1.65 \times 10^{-5} \text{ Hz}) \left( \frac{T_{\text{PT}}}{100 \text{ GeV}} \right) \left( \frac{g_{\text{eff}}}{100} \right)^{1/6}, \\
 f_{\text{sw}} &= (1.9 \times 10^{-5} \text{ Hz}) \left( \frac{1}{\xi_w} \right) \left( \frac{\beta}{H_{\text{PT}}} \right) \left( \frac{T_{\text{PT}}}{100 \text{ GeV}} \right) \left( \frac{g_{\text{eff}}}{100} \right)^{1/6}.
 \end{aligned}$$

# Contribution of Various GW Sources

Typical values for our case:

$$\alpha = 0.1, \quad \frac{\beta}{H_{\text{PT}}} = 2000, \quad T_{\text{PT}} = 100 \text{ GeV}, \quad g_{\text{eff}} = 100;$$

