BARYOGENESIS AND GRAVITATIONAL WAVE PRODUCTION IN SIMPLE LEFT-RIGHT MODEL

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OUTLINE

1. Motivation
2. LR Symmetric Model
3. Baryogenesis Overview
4. Preliminary Results
5. Further work

MOTIVATION

- Standard model cannot explain:
  - Neutrino masses
    - See-saw mechanism
    - Sterile neutrinos
  - Observe baryon asymmetry
    - $\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6.2 * 10^{-10}$

MOTIVATION

- Asymmetry production during phase transitions
  - SM, MSSM, 2HDM, SM+singlet
- Propose this for a simple Left/Right model
- Fermion mass
  - Universal see-saw mechanism
- Use new quantum transport equations

MODEL

- Scalar sector: Add Higgs doublet and scalar singlet
- Introduce a $H_L \leftrightarrow H_R$ and $\sigma \leftrightarrow -\sigma$ symmetry

$$V = -\mu_1^2\sigma^2 - \mu_2^2(H_L^\dagger H_L + H_R^\dagger H_R) + \mu_3\sigma\left(H_L^\dagger H_L - H_R^\dagger H_R\right)$$
$$+ \lambda_1\sigma^4 + \lambda_2\left[(H_L^\dagger H_L)^2 + (H_R^\dagger H_R)^2\right]$$
$$+ \lambda_3 H_L^\dagger H_L H_R^\dagger H_R + \lambda_4\sigma^2\left(H_L^\dagger H_L + H_R^\dagger H_R\right)$$

MODEL

- Particle content

	n_f	$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_Y$
$q_L = \begin{pmatrix} u \\ d \end{pmatrix}$	3	(3,2,1,1/6)
$q_R = \begin{pmatrix} \overline{u} \\ \overline{d} \end{pmatrix}$	3	($\bar{3}$,1,2,-1/6)
$\ell_L = \begin{pmatrix} \nu \\ e \end{pmatrix}$	3	(1,2,1,-1/2)
$\ell_R = \begin{pmatrix} \overline{\nu} \\ \overline{e} \end{pmatrix}$	3	(1,1,2,1/2)

U_L	3	(3,1,1,2/3)
U_R	3	($\bar{3}$,1,1,-2/3)
D_L	3	(3,1,1,-1/3)
D_R	3	($\bar{3}$,1,1,1/3)
E_L	3	(1,1,1,-1)
E_R	3	(1,1,1,1)
N_L	3	(1,1,1,0)
N_R	3	(1,1,1,0)
H_L	1	(1,2,1,1/2)
H_R	1	(1,1,2,-1/2)
σ	1	(1,1,1,0)

BARYOGENESIS

- Sakaharov Conditions

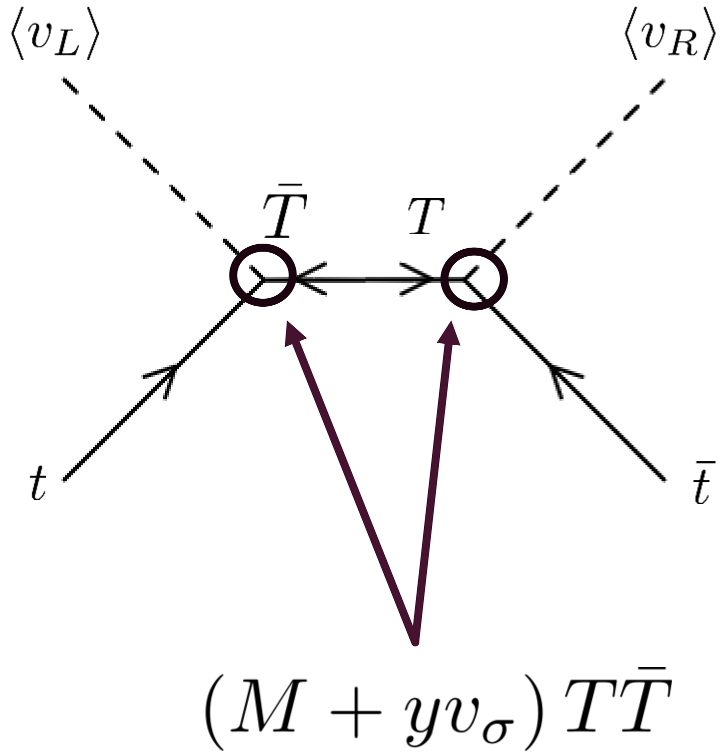
1. Baryon number violation
   - If $B_0 = 0$, need to somehow produce nonzero B
2. C and CP violation
   - Both need to be violated otherwise baryons and antibaryons are produced at the same rate
3. Non-equilibrium conditions
   - Decay and antiparticle decays happen at same rate

BARYOGENESIS

1. Baryon Number Violation
   - B_L+B_R is conserved
   - Asymmetry in right → asymmetry in left

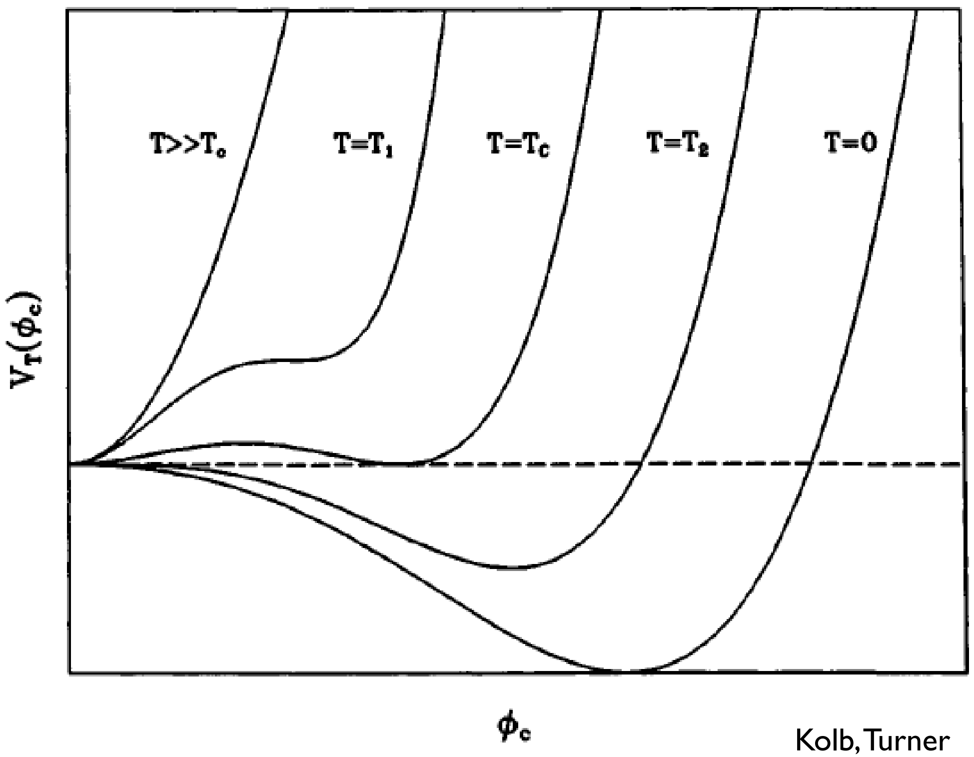
BARYOGENESIS

2. C/CP violation
   - h_L, h_R phase difference
   - Complex Yukawa



BARYOGENESIS

3. Non-equilibrium conditions
   - First order phase transition



Kolb, Turner

MODEL: PHASE TRANSITIONS

- 1st Transition: $(0,0,0) \rightarrow (0,0,v_\sigma)$
  - Second order phase transition

$$T_c^\sigma = \frac{\mu_1^2 - \lambda_1 v_\sigma^2}{c_\sigma}$$

- 2nd Transition: $(0,0,v_\sigma) \rightarrow (0,v_R,v_\sigma)$
  - Strongly first order phase transition
  - W_R becomes massive
  - Produces lepton asymmetry
  - Produces gravitational waves

$$T_c^R = \frac{2\mu_2^2 - \lambda_2 v_R^2 + 2v_\sigma\left(\mu_3 - \lambda_4 v_\sigma\right)}{2c_R}$$

- 3rd Transition: $(0,v_R,v_\sigma) \rightarrow (v_L,v_R,v_\sigma)$
  - Second order phase transition
  - Electroweak phase transition occurs

$$T_c^L = \frac{2\mu_2^2 - \lambda_2 v_L^2 - \lambda_3 v_R^2 - 2v_\sigma\left(\mu_3 + \lambda_4 v_\sigma\right)}{2c_L}$$

BARYOGENESIS: TRANSPORT EQUATION

- Evolution of particle chemical potentials across bubble wall
- How do we use this to calculate baryon asymmetry?
  - Integrate chemical potential over all space

Cline, Kainulainen
arXiv:2001.00568

$$\boxed{A_i w_i' + m_i^{2\prime} B_i w_i = S_i + \delta C_i}$$

$$w_i \equiv (\mu_i, u_i)^T \qquad \delta C \equiv (\delta C_1, \delta C_2)$$

$$\delta C_1 \equiv K_0 \sum_i \frac{\Gamma_i}{T} \sum_j s_{ij}\mu_j \qquad \delta C_2 = -\Gamma_{tot} u - v_w \delta C_1$$

TRANSPORT EQUATIONS

$$A_i w_i' + m_i^{2\prime} B_i w_i = S_i + \delta C_i \qquad \delta C_2^i = -\Gamma_{tot}^i u_i - v_w \delta C_1^i$$

$$\delta C_1^t = \Gamma_{m_t}(\mu_t - \mu_{\bar{t}}) + \Gamma_{W_L}(\mu_t - \mu_b) + \tilde{\Gamma}_{SS}[\mu_i] + \tilde{\Gamma}_{W_L}[\mu_i]$$

$$\delta C_1^{\bar{t}} = \Gamma_{m_t}(\mu_{\bar{t}} - \mu_t) + \Gamma_{W_R}(\mu_{\bar{t}} - \mu_{\bar{b}}) - \tilde{\Gamma}_{SS}[\mu_i] + \tilde{\Gamma}_{W_R}[\mu_i]$$

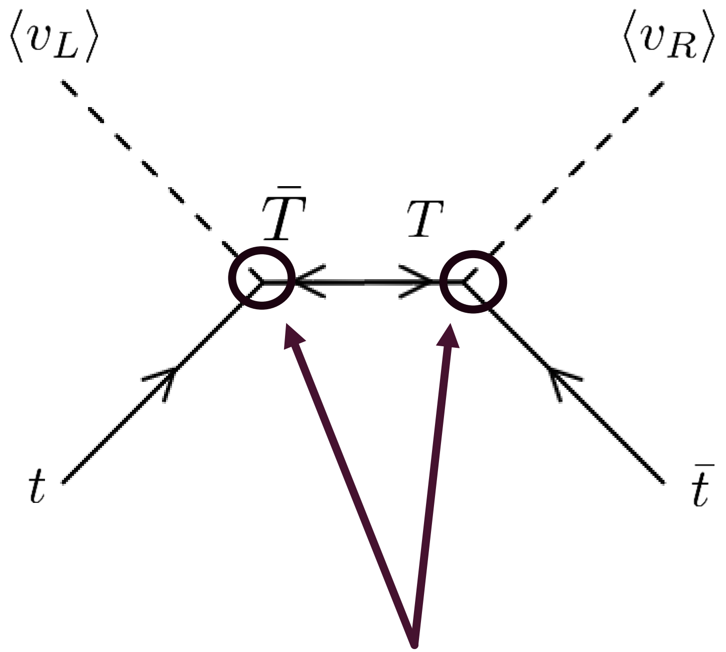
$$\delta C_1^b = \Gamma_{m_b}(\mu_b - \mu_{\bar{b}}) + \Gamma_{W_L}(\mu_b - \mu_t) + \tilde{\Gamma}_{SS}[\mu_i] + \tilde{\Gamma}_{W_L}[\mu_i]$$

$$\delta C_1^{\bar{b}} = \Gamma_{m_b}(\mu_{\bar{b}} - \mu_b) + \Gamma_{W_R}(\mu_{\bar{b}} - \mu_{\bar{t}}) - \tilde{\Gamma}_{SS}[\mu_i] + \tilde{\Gamma}_{W_R}[\mu_i]$$

$$\delta C_1^{h_L} = \Gamma_{h_L}\mu_{h_L} \qquad \delta C_1^{h_R} = \Gamma_{h_R}\mu_{h_R}$$

TRANSPORT EQUATIONS

$$A_i w_i' + m_i^{2\prime} B_i w_i = S_i + \delta C_i$$



$$(M + y v_\sigma)\, T\bar{T}$$

MODEL: CONSTRAINTS

- Particles:
  - SM Higgs (125 GeV)
  - W_R mass
    - Using strongest bound (715 GeV)
    - Provides constraint: $v_R > 8.8 v_L$
- Scalar Sector:
  - Boundedness from below
  - Oblique parameters – Not major constraint

PRELIMINARY DATA POINTS

	λ_1	λ_2	λ_3	λ_4	m_H (TeV)	m_S	M_T	v_R	v_S
BP1	0.12038	1.4	-2.373	0.1832	2	2.5	1.18	2.5	1.1
BP2	0.111	2.869	-5.298	0.183	3	4	1.24	4.2	1

FURTHER WORK

- Parameter scan
- Calculate asymmetry
  - New transport equations
- Calculate gravitational wave signal

THANK YOU!

EXTRA SLIDES

TRANSPORT EQUATIONS

$$A_t w_t' + m_{t\bar{t}}^{2\prime} B_t w_t = S_t + \delta C_t$$
$$A_{\bar{t}} w_{\bar{t}}' + m_{t\bar{t}}^{2\prime} B_{\bar{t}} w_{\bar{t}} = S_{\bar{t}} + \delta C_{\bar{t}}$$
$$A_b w_b' + m_{b\bar{b}}^{2\prime} B_b w_b = S_b + \delta C_b$$
$$A_{\bar{b}} w_{\bar{b}}' + m_{b\bar{b}}^{2\prime} B_{\bar{b}} w_{\bar{b}} = S_{\bar{b}} + \delta C_{\bar{b}}$$
$$A_{h_L} w_{h_L}' + m_{h_L}^{2\prime} B_{h_L} w_{h_L} = S_{h_L} + \delta C_{h_L}$$
$$A_{h_R} w_{h_R}' + m_{h_R}^{2\prime} B_{h_R} w_{h_R} = S_{h_R} + \delta C_{h_R}$$

$$\delta C_1^t = \Gamma_{m_t}\left(\mu_t - \mu_{\bar{t}}\right) + \Gamma_{W_L}\left(\mu_t - \mu_b\right) + \tilde{\Gamma}_{SS}\left[\mu_i\right] + \tilde{\Gamma}_{W_L}\left[\mu_i\right]$$
$$\delta C_1^{\bar{t}} = \Gamma_{m_t}\left(\mu_{\bar{t}} - \mu_t\right) + \Gamma_{W_R}\left(\mu_{\bar{t}} - \mu_{\bar{b}}\right) - \tilde{\Gamma}_{SS}\left[\mu_i\right] + \tilde{\Gamma}_{W_R}\left[\mu_i\right]$$
$$\delta C_1^b = \Gamma_{m_b}\left(\mu_b - \mu_{\bar{b}}\right) + \Gamma_{W_L}\left(\mu_b - \mu_t\right) + \tilde{\Gamma}_{SS}\left[\mu_i\right] + \tilde{\Gamma}_{W_L}\left[\mu_i\right]$$
$$\delta C_1^{\bar{b}} = \Gamma_{m_b}\left(\mu_{\bar{b}} - \mu_b\right) + \Gamma_{W_R}\left(\mu_{\bar{b}} - \mu_{\bar{t}}\right) - \tilde{\Gamma}_{SS}\left[\mu_i\right] + \tilde{\Gamma}_{W_R}\left[\mu_i\right]$$

$$\delta C_1^{h_L} = \Gamma_{h_L}\mu_{h_L}$$
$$\delta C_1^{h_R} = \Gamma_{h_R}\mu_{h_R}$$

$$\delta C_f = \left(\delta C_1^f, \delta C_2^f\right)^T$$

$$\delta C_2^i = -\Gamma_{tot}^i u_i - v_w \delta C_1^i$$

$$\tilde{\Gamma}_{W_{R,L}}\left[\mu_i\right] = \Gamma_{\tilde{W}_{R,L}}\left(\left(1 + 9D_0^{\bar{t},t}\right)\mu_{\bar{t},t} + \left(1 + 9D_0^{\bar{b},b}\right)\mu_{\bar{b},b}\right)$$

$$\tilde{\Gamma}_{SS}\left[\mu_i\right] = \Gamma_{SS}\left(\left(1 + 9D_0^t\right)\mu_t + \left(1 + 9D_0^b\right)\mu_b - \left(1 - 9D_0^{\bar{t}}\right)\mu_{\bar{t}}\right)$$

	n_f	$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_Y$
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$\ell_L = \begin{pmatrix} \nu \\ e \end{pmatrix}$	3	(1,2,1,-1/2)
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E_R	3	(1,1,1,1)
N_L	3	(1,1,1,0)
N_R	3	(1,1,1,0)
H_L	1	(1,2,1,1/2)
H_R	1	(1,1,2,-1/2)
σ	1	(1,1,1,0)

$$\lambda_1 \geq 0$$

$$\lambda_2 \geq 0$$

$$\lambda_2 + \frac{1}{2}\lambda_3 \geq 0$$

$$2\sqrt{\lambda_1\lambda_2} + \lambda_4 \geq 0$$

$$(\lambda_2 + \frac{1}{2}\lambda_3)\sqrt{2\lambda_1} + \lambda_4\sqrt{2\lambda_2} + (2\sqrt{\lambda_1\lambda_2} + \lambda_4)\sqrt{(\lambda_2 + \frac{1}{2}\lambda_3)} \geq 0$$

$$m_u = y_U \frac{v_L v_R}{M_U} y_U^\dagger$$
$$m_d = y_D \frac{v_L v_R}{M_D} y_D^\dagger$$
$$m_l = y_E \frac{v_L v_R}{M_E} y_E^\dagger$$
$$m_\nu = y_N \frac{v_L v_R}{M_N} y_N^\dagger$$

$$m_h^2 = 2 \begin{pmatrix} 2\lambda_2 v_L^2 & \lambda_3 v_L v_R & 2\lambda_4 v_L v_\sigma + \lambda_v v_L \\ \lambda_3 v_L v_R & 2\lambda_2 v_R^2 & 2\lambda_4 v_R v_\sigma - \lambda_v v_R \\ 2\lambda_4 v_L v_\sigma + \lambda_v v_L & 2\lambda_4 v_R v_\sigma - \lambda_v v_R & 8\lambda_1 v_\sigma^2 - \lambda_v \frac{(v_L^2 - v_R^2)}{2v_\sigma} \end{pmatrix}$$

$$= \mathcal{O}.m_D.\mathcal{O}^T$$

$$m_D = \begin{pmatrix} m_{Higgs}^2 & 0 & 0 \\ 0 & m_{H_R}^2 & 0 \\ 0 & 0 & m_\sigma^2 \end{pmatrix}; \quad \mathcal{O} = \begin{pmatrix} c_{12}c_{13} & -c_{13}s_{12} & s_{13} \\ c_{23}s_{12} - c_{12}s_{13}s_{23} & c_{12}c_{23} + s_{12}s_{13}s_{23} & c_{13}s_{23} \\ -c_{12}c_{23}s_{13} - s_{12}s_{23} & c_{23}s_{12}s_{13} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix}$$

$$\mathcal{L}_Y = -y_D(\bar{q}_L H_L D_R + \bar{q}_R H_R D_L) - M_D \bar{D}_L D_R$$

$$- y_U(\bar{q}_L \tilde{H}_L U_R + \bar{q}_R \tilde{H}_R U_L) - M_U \bar{U}_L U_R$$

$$- y_E(\bar{\ell}_L H_L E_R + \bar{\ell}_R H_R E_L) - M_E \bar{E}_L E_R$$

$$- y_N(\bar{\ell}_L \tilde{H}_L E_R + \bar{\ell}_R \tilde{H}_R E_L) - M_N \bar{N}_L N_R$$