Leptogenesis Triggered by a First-Order Phase Transition

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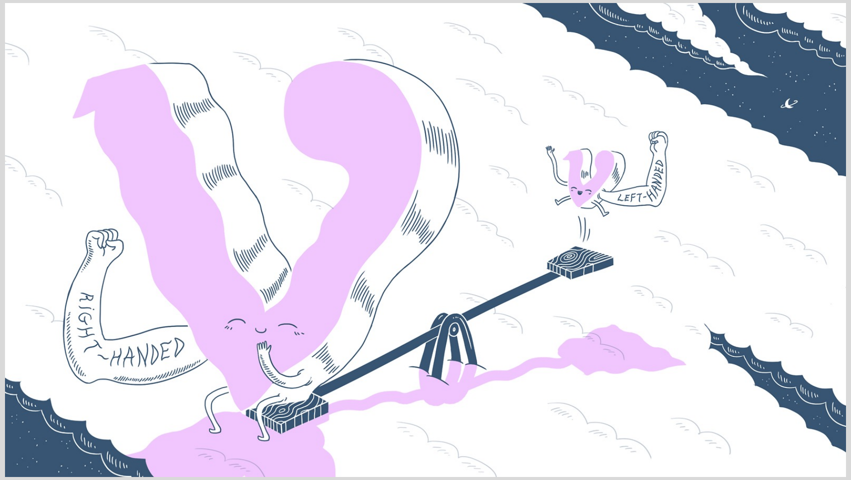
Leptogenesis, Two Birds with One Stone

- Type-I seesaw introduce right-handed neutrinos (mass *M*)

$$\mathcal{L} \supset \sum_i \bar{\nu}^i_R i\gamma^\mu \partial_\mu \nu^i_R - \frac{1}{2}\sum_{i,j}\left(M^{ij}\bar{\nu}^{i,c}_R \nu^j_R + \text{ h.c. }\right) - \sum_{i,j}\left(\lambda^{ij}_D \bar{\ell}^i_L \tilde{H}\nu^j_R + \text{ h.c. }\right)$$

$$\mathcal{M} = \begin{pmatrix} 0 & \frac{\lambda_D v}{\sqrt{2}} \\ \frac{\lambda_D v}{\sqrt{2}} & M \end{pmatrix}$$

$$m_\nu \simeq \frac{|\lambda_D|^2 v^2_{EW}}{2M} \simeq 0.08 \text{ eV } \left(\frac{\lambda_D}{0.5}\right)^2 \left(\frac{10^{14} \text{ GeV}}{M}\right)$$



Minkowski, 1977

Leptogenesis

$$\mathcal{L} \supset \sum_i \bar{\nu}_R^i i\gamma^\mu \partial_\mu \nu_R^i - \frac{1}{2}\sum_{i,j}\left(M^{ij}\bar{\nu}_R^{i,c}\nu_R^j + \text{h.c.}\right) \qquad \cancel{L}$$

$$- \sum_{i,j}\left(\lambda_D^{ij}\bar{\ell}^i_L \tilde{H}\nu_R^j + \text{h.c.}\right) \qquad \cancel{CP}$$

~~Thermal Equilibrium~~

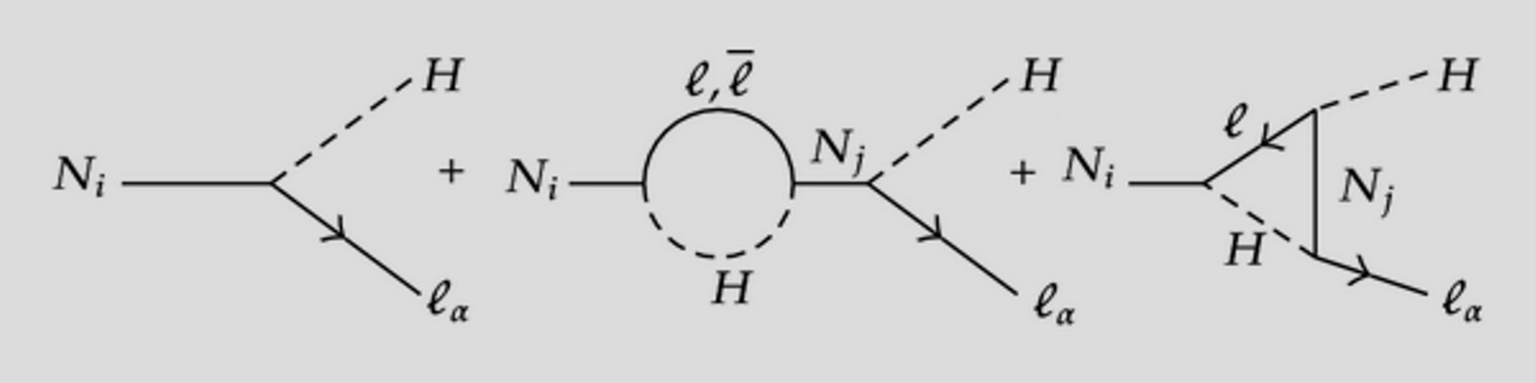
RHN decays

All three Sakharov conditions are satisfied

M. Fukugita, T. Yanagida, 1986
Luty 1992

Leptogenesis

Generate the Baryon asymmetry through the lepton asymmetry



$$\mathcal{L} \supset -\sum_{i,j} \left(\lambda_D^{ij} \bar{\ell}_L^i \tilde{H} \nu_R^j + \text{h.c.} \right)$$

1. The Right Handed Neutrinos, decay (CP violating) asymmetrically

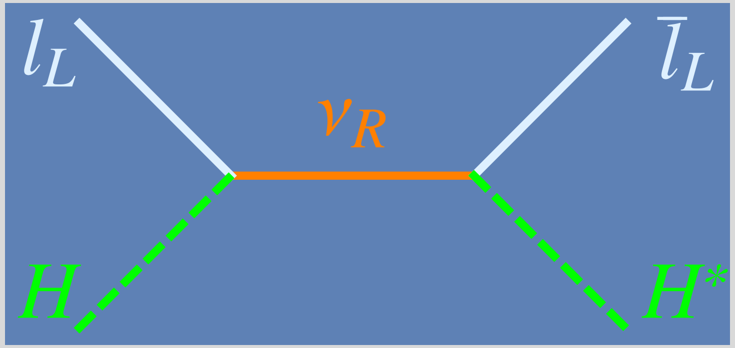
$$\epsilon_i = \frac{\sum_j \Gamma\left(\nu_R^i \to \ell_L^j H\right) - \Gamma\left(\nu_R^i \to \bar{\ell}_L^j H^*\right)}{\sum_j \Gamma\left(\nu_R^i \to \ell_L^j H\right) + \Gamma\left(\nu_R^i \to \bar{\ell}_L^j H^*\right)} \propto \text{Im}\left[\left(\lambda_D \lambda_D^\dagger\right)^2\right]$$

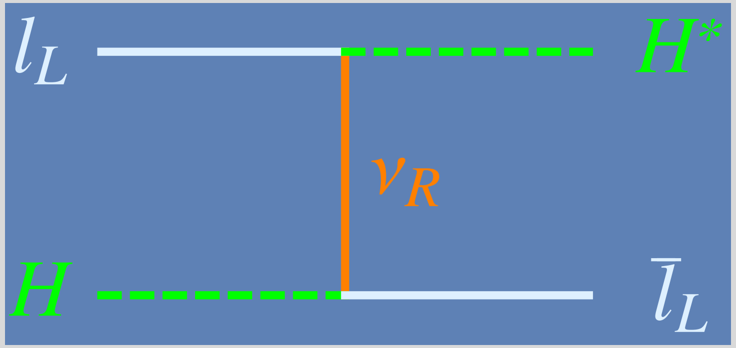
M. Fukugita, T. Yanagida, 1986
Luty 1992

2. Part of the generated asymmetry will be converted to a baryon asymmetry (about order one, detailed calculation gives 28/79)

Difficulties in Leptogenesis

3. Inverse decays and scattering wash out the generated asymmetry





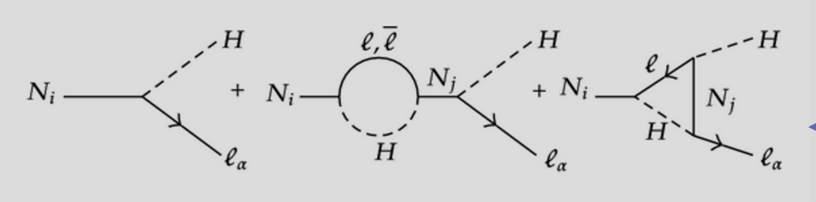
Only 1% of the generated asymmetry will survive

How to fix this? – This talk

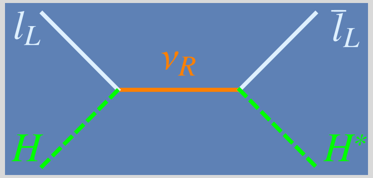
Difficulties in Leptogenesis

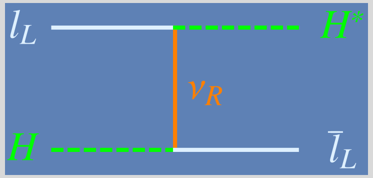
- Naively, the strong washout effect is unavoidable

See for example, Flanz et al, 1996, Pilaftsis, 1997, Dev et al, 2017 ….



Competition





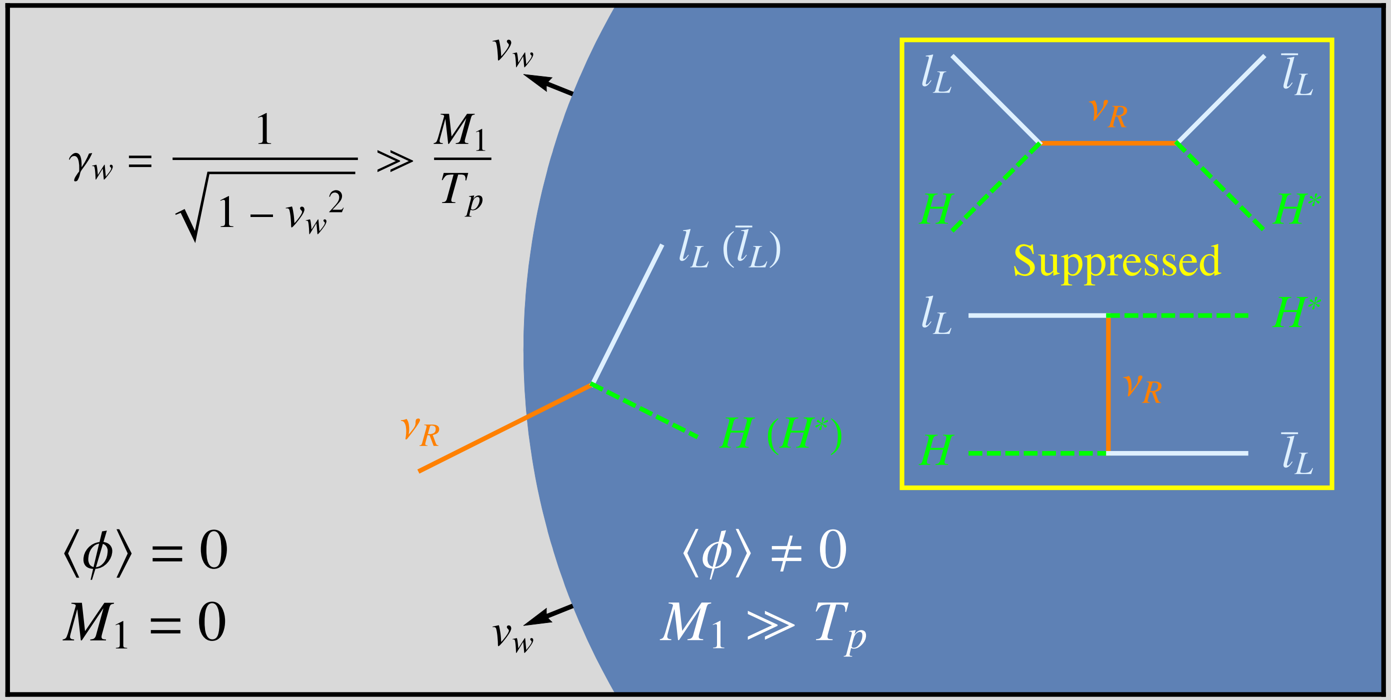
T~M

- The RHN decouples from the thermal bath at T~M
- Only if the cosmic temperature changes discontinuously, the RHN decays, generates the lepton asymmetry. Then the temperature falls T<<M, the washout effects are Boltzmann suppressed

Avoiding the Washout Effects With a Mass Jump

- The cosmic temperature can not change discontinuously, but the mass of the RHNs can -- first-order PT!

$$\mathcal{L} \supset -\sum_{i,j} \frac{1}{2}\left(\lambda_R^{ij}\bar{\nu}_R^{i,c}\nu_R^j\frac{\phi}{\sqrt{2}} + \text{h.c.}\right),$$



- The RHNs are massless in the old vacuum
- During the PT, the RHN gains mass M_1
- If $M_1 \gg Tp$, the washout effects are Boltzmann suppressed

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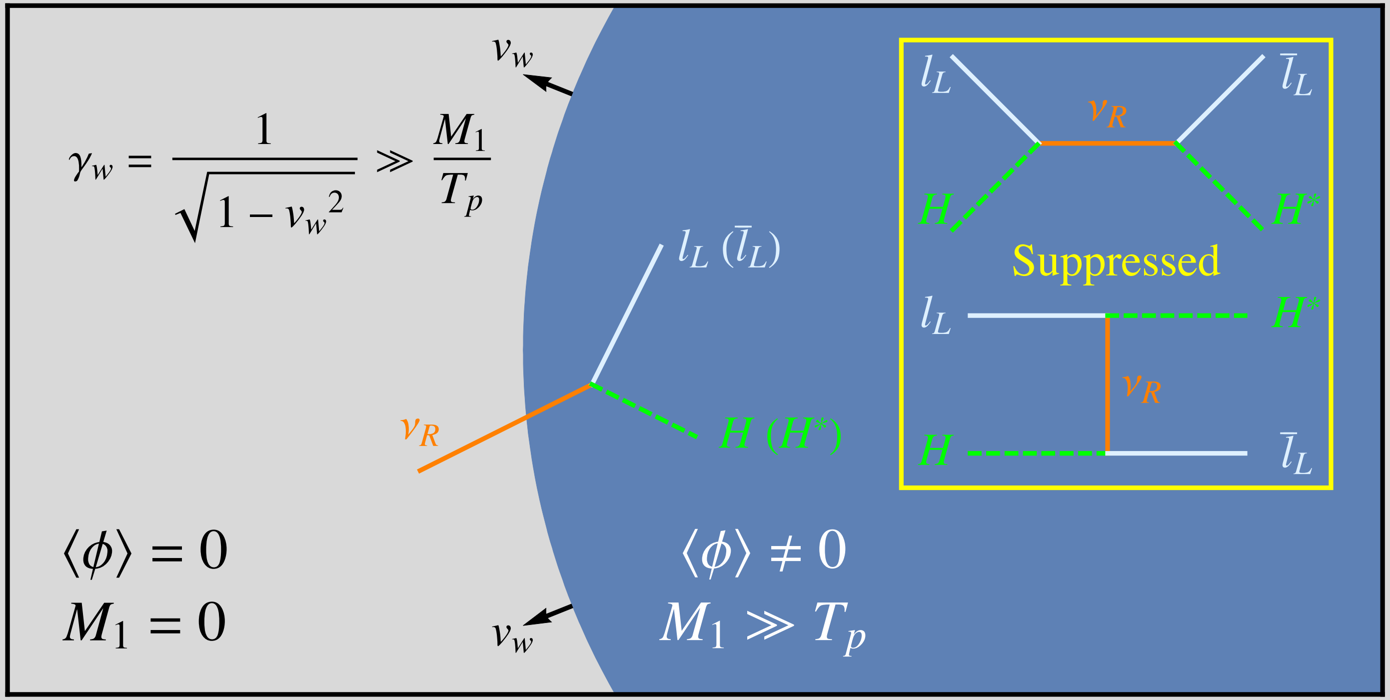
Wait – $M_1 >> T_p$, How Can That Happen?

$M_1 >> T_p$, how?



- If the phase transition is very strong, the bubble wall can be relativistic
- Although in the plasma frame, RHNs are in thermal equilibrium, they have very high energy in the wall frame
- They can penetrate into the true vacuum, and decay immediately

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Leptogenesis with a first-order PT

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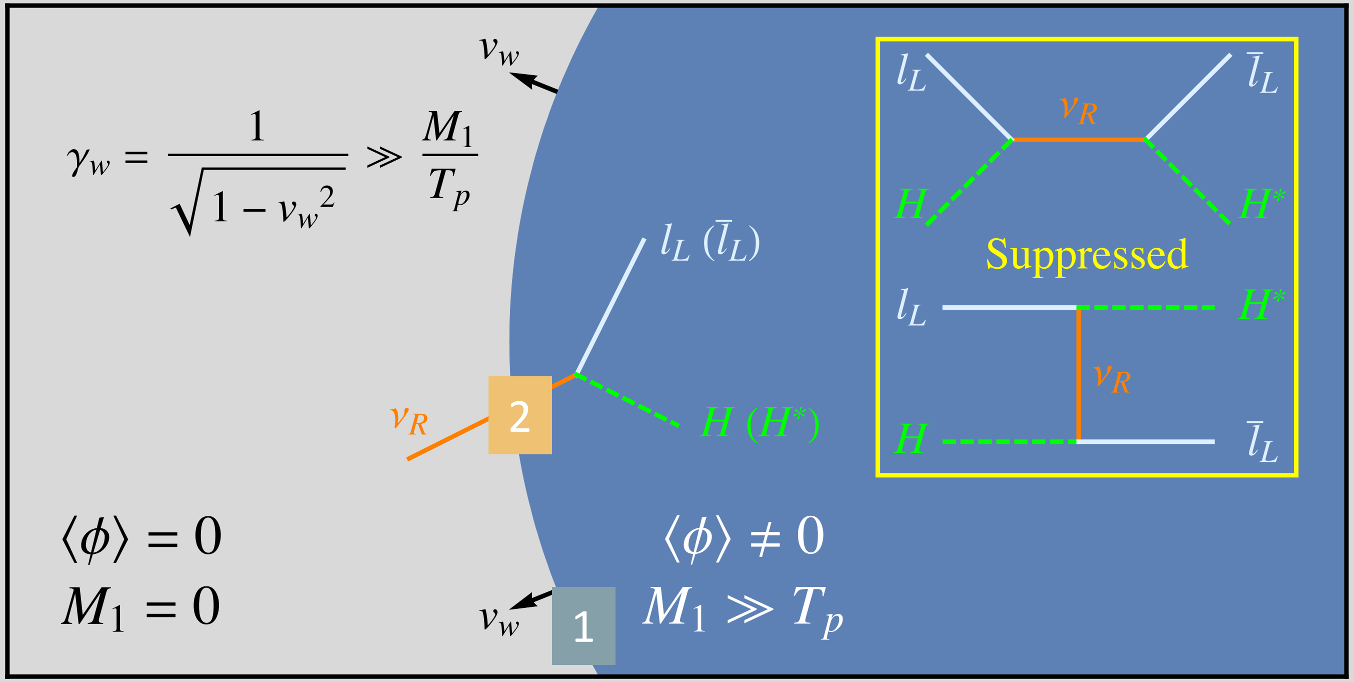


To suppress the wash-out

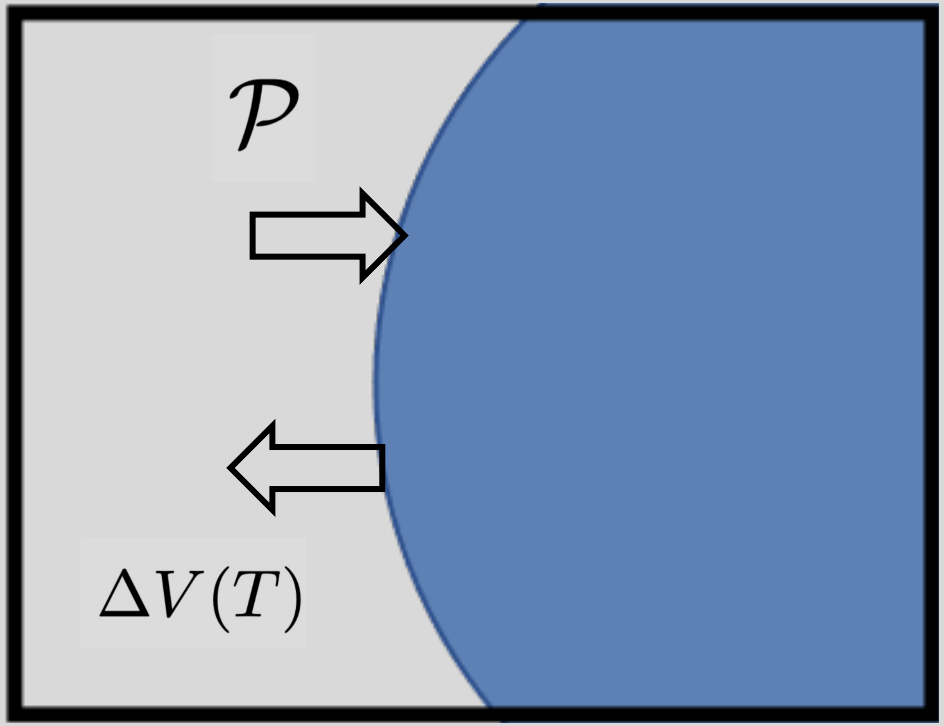
1. $M_1 >> T_p$, easy

$$\mathcal{L} \supset -\sum_{i,j}\frac{1}{2}\left(\lambda_R^{ij}\bar{\nu}_R^{i,c}\nu_R^j\frac{\phi}{\sqrt{2}} + \text{h.c.}\right),$$

2. RHN can penetrate into the new vacuum -> relativistic walls

Model building task: write down the scalar potential for ϕ, that undergoes a strong first-order PT, and the bubble walls are relativistic.

Relativistic Walls



The wall velocity is determined by

$$\Delta V(T) - \mathcal{P}$$

At LO,

$$\mathcal{P}_{1->1} = \sum c_i \frac{\Delta m_i^2 T^2}{24}$$

Bodeker and Moore, 2009

All order resummation,

$$\mathcal{P}_{1\to N} \sim \gamma_w$$

$$\mathcal{P}_{1\to N} \sim \gamma_w^2$$

Gouttenoire, Jinno and Sala, 2021 Hoeche et al, 2021

Terminal wall velocity,

$$\gamma_{\rm eq} = \sqrt{\frac{\Delta V_p - \mathcal{P}_{1\to 1}}{\mathcal{P}_{1\to N}/\gamma_w^2}}; \quad \gamma_{\rm eq} = \frac{\Delta V_p - \mathcal{P}_{1\to 1}}{\mathcal{P}_{1\to N}/\gamma_w}$$

Relativistic Walls

- Relativistic walls can be achieved if

$$\Delta V(T) \gg \mathcal{P}_{1->1} = \sum c_i \frac{\Delta m_i^2 T^2}{24}$$

- This can be easily done in a classical conformal theory,

$$\mathcal{L}_{B-L} = \sum_i \bar{\nu}_R^i i\gamma^\mu D_\mu \nu_R^i - \frac{1}{2}\sum_{i,j}\left(\lambda_R^{ij}\bar{\nu}_R^{i,c}\Phi\nu_R^j + \text{ h.c. }\right) - \sum_{i,j}\left(\lambda_D^{ij}\bar{\ell}_L\tilde{H}\nu_R^j + \text{ h.c. }\right)$$
$$+ D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu}$$

Iso, Okada, and Orikasa, 2009

$$V_{tree}(\Phi) = \lambda_\phi|\Phi|^4$$

C-W potential, $V(\phi) = V_0 + \frac{B}{4}\phi^4\left(\ln\frac{\phi}{v_\phi} - \frac{1}{4}\right)$

$$M_{Z'} = 2g_{B-L}v_\phi, \quad M_i = \lambda_{R,i}\frac{v_\phi}{\sqrt{2}}, \quad M_\phi = \sqrt{B}v_\phi$$

Relativistic Walls, CC B-L

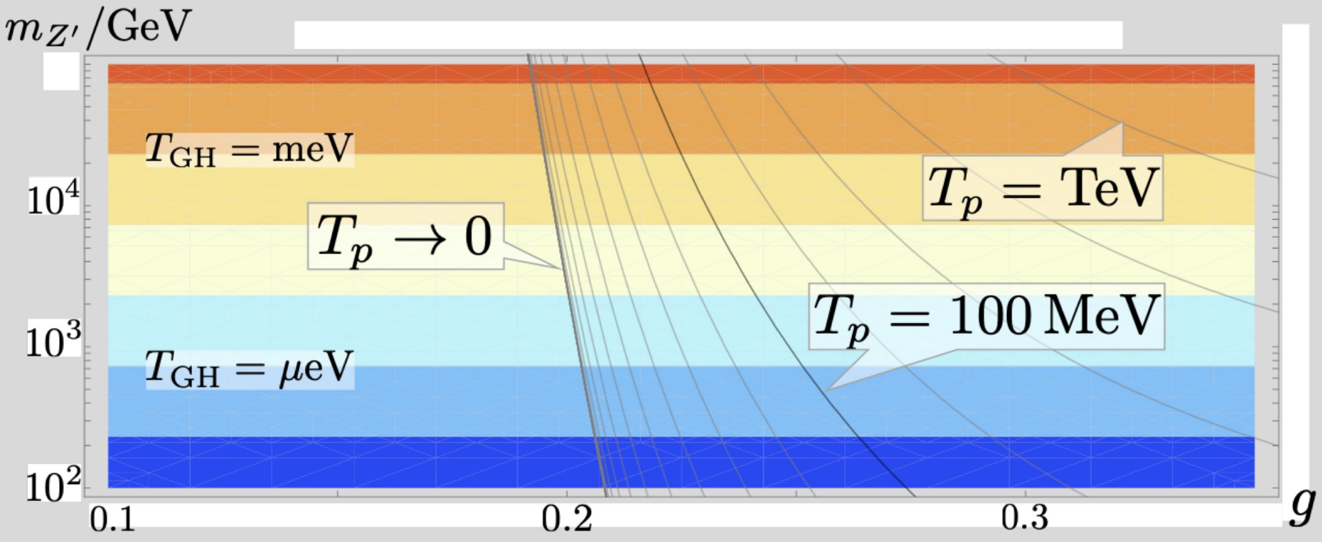


Figure 1: Contour plot of the percolation temperature T_p (black lines) as a function of g and $m_{Z'}$. The horizontal color bands show the temperature $T_{\mathrm{GH}} \equiv \mathcal{H}/2\pi$.

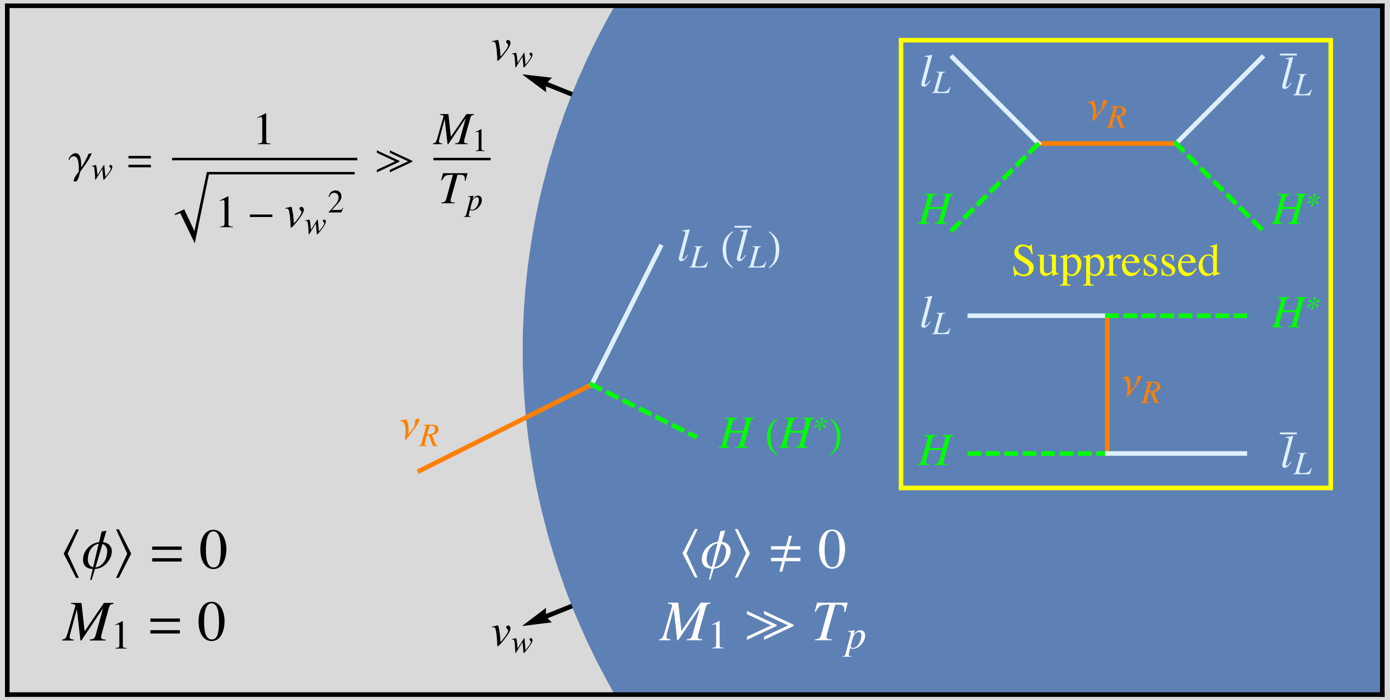
$$V(\phi) \sim \frac{g_{B-L}^2 T^2}{2} + \frac{3 g_{B-L}^4 \phi^4}{4\pi^2}\left[\ln\left(\frac{\phi^2}{v_\phi}\right) - \frac{1}{2}\right]$$

Iso, Serpico, and Shimada, 2017

$$\Delta V(T) \gg \mathcal{P}_{1->1} = \sum c_i \frac{\Delta m_i^2 T^2}{24}$$

Relativistic walls can be achieved

Towards an Actual Model



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Similar ideas in Baldes et al, 2021
Dasgupta, Dev, Ghoshal, Mazumdar 2022

- RHN in thermal equilibrium

✓ ϕ undergoes a 1st order PT, with relativistic bubble walls.

After penetration…

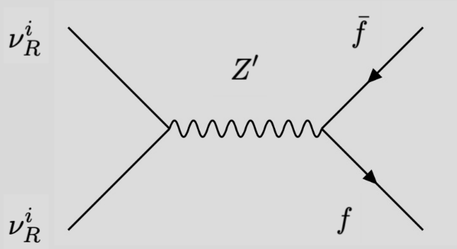
? Completing processes?

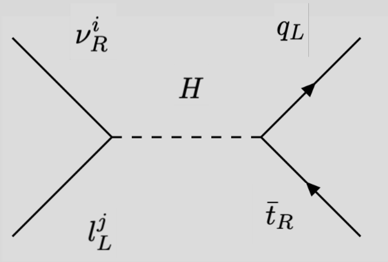
? Additional washouts from the decay products?

? Strong reheating?

After penetration

Competing processes

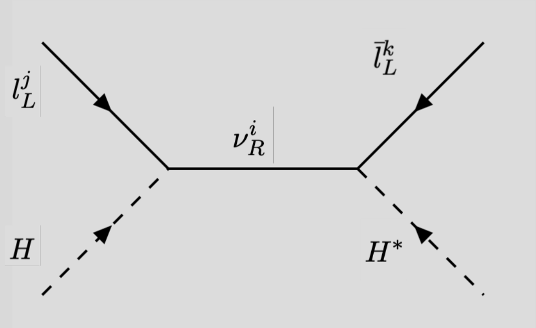




$$\Gamma_D > \Gamma_{\rm ann}, \quad \Gamma_D > \Gamma_{\rm sca}.$$

No additional washouts

$$E_1 = \gamma_1 M_1 = M_1^2/T_p.$$



$\Gamma_{\rm on}$

$$\Gamma_{\rm th} > \Gamma_{\rm on}\,, \quad \Gamma_{\rm th} > H_p$$

Ensures thermalization is fast enough

Considerations

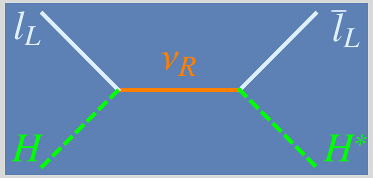
Strong reheating?

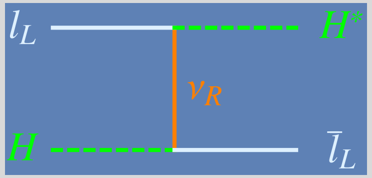
The latent heat released from the PT will reheat the universe to

$$T_{\rm rh} = (1+\alpha)^{1/4} T_p,$$

For the PT to provide ultra-relativistic bubble walls, typically α>>1

With a high reheating temperature,





will become active

The generated asymmetry will be diluted by ~ $(T_p/T_{\rm rh})^3$

Difficulties in the Minimal Model

- The minimal gauged $\mathrm{U(1)_{B\text{-}L}}$ model

$$\mathcal{L}_{B-L} = \sum_i \bar{\nu}_R^i i\gamma^\mu D_\mu \nu_R^i - \frac{1}{2}\sum_{i,j}\left(\lambda_R^{ij}\bar{\nu}_R^{i,c}\Phi\nu_R^j + \text{ h.c. }\right) - \sum_{i,j}\left(\lambda_D^{ij}\bar{\ell}_L\tilde{H}\nu_R^j + \text{ h.c. }\right)$$
$$+ D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu}$$

- The scalar potential $V(\phi) = V_0 + \frac{B}{4}\phi^4\left(\ln\frac{\phi}{v_\phi} - \frac{1}{4}\right)$

- In the minimal gauged $\mathrm{U(1)_{B\text{-}L}}$ $B = \frac{6}{\pi^2}\left(g_{B-L}^4 - \sum_i \frac{\lambda_{R,i}^4}{96}\right) = \frac{3}{8\pi^2 v_\phi^4}\left(M_{Z'}^4 - \sum_i \frac{2M_i^4}{3}\right)$

>0, for stability

$$T_{\mathrm{rh}} = \left(1 + \frac{Bv_\phi^4/16}{\pi^2 g_* T_p^4/30}\right)^{1/4} \sim g_{B-L}v_\phi \sim M_{Z'} \gtrsim M_1$$

Wash-out unavoidable!!

Extend the Minimal Model

- Wash-out unavoidable

$$T_{\rm rh} = \left(1 + \frac{Bv_\phi^4/16}{\pi^2 g_* T_p^4/30}\right)^{1/4} \cancel{\sim} M_{Z'}$$

- Add a new scalar

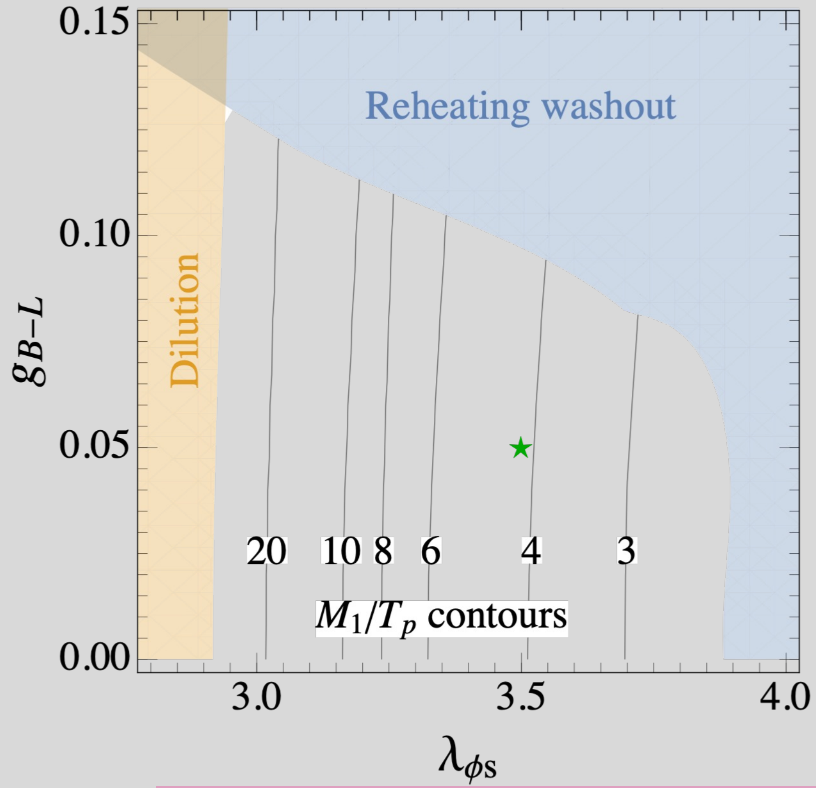
$$\mathcal{L}_{B-L} = \sum_i \bar{\nu}_R^i i\not{D}\nu_R^i - \frac{1}{2}\sum_{i,j}\left(\lambda_R^{ij}\bar{\nu}_R^{i,c}\Phi\nu_R^j + \text{h.c.}\right) - \sum_{i,j}\left(\lambda_D^{ij}\bar{\ell}_L^i\tilde{H}\nu_R^j + \text{h.c.}\right)$$
$$+ D_\mu\Phi^\dagger D^\mu\Phi + \boxed{D_\mu S^\dagger D^\mu S} - V(\Phi, S) - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu},$$

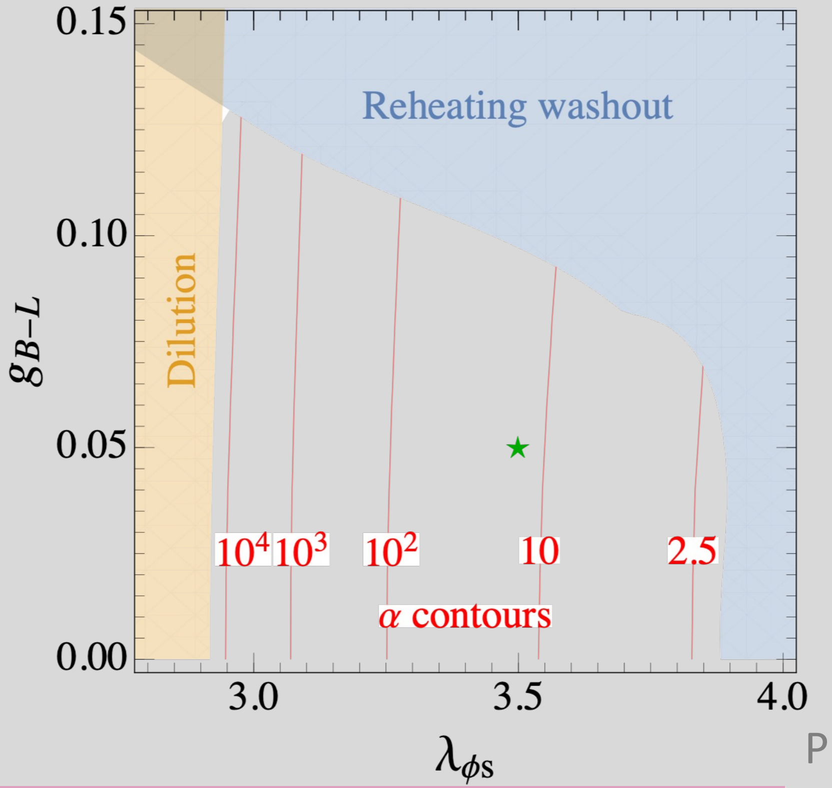
$$V_{\rm tree}(\Phi, S) = \lambda_\phi|\Phi|^4 + \lambda_s|S|^4 + \boxed{\lambda_{\phi s}|\Phi|^2|S|^2,} \qquad B = \frac{6}{\pi^2}\left(\boxed{\frac{\lambda_{\phi s}^2}{96}} + g_{B-L}^4 - \sum_i \frac{\lambda_{R,i}^4}{96}\right),$$

T_{rh} no longer correlated with $M_{Z'}$, wash-out avoidable

Parameter Space

$$M_1 = 2.5 \times 10^{11}\ \mathrm{GeV}, \quad \lambda_{R,1} = 0.3, \quad \lambda_{R,2} = \lambda_{R,3} = 4\lambda_{R,1},$$





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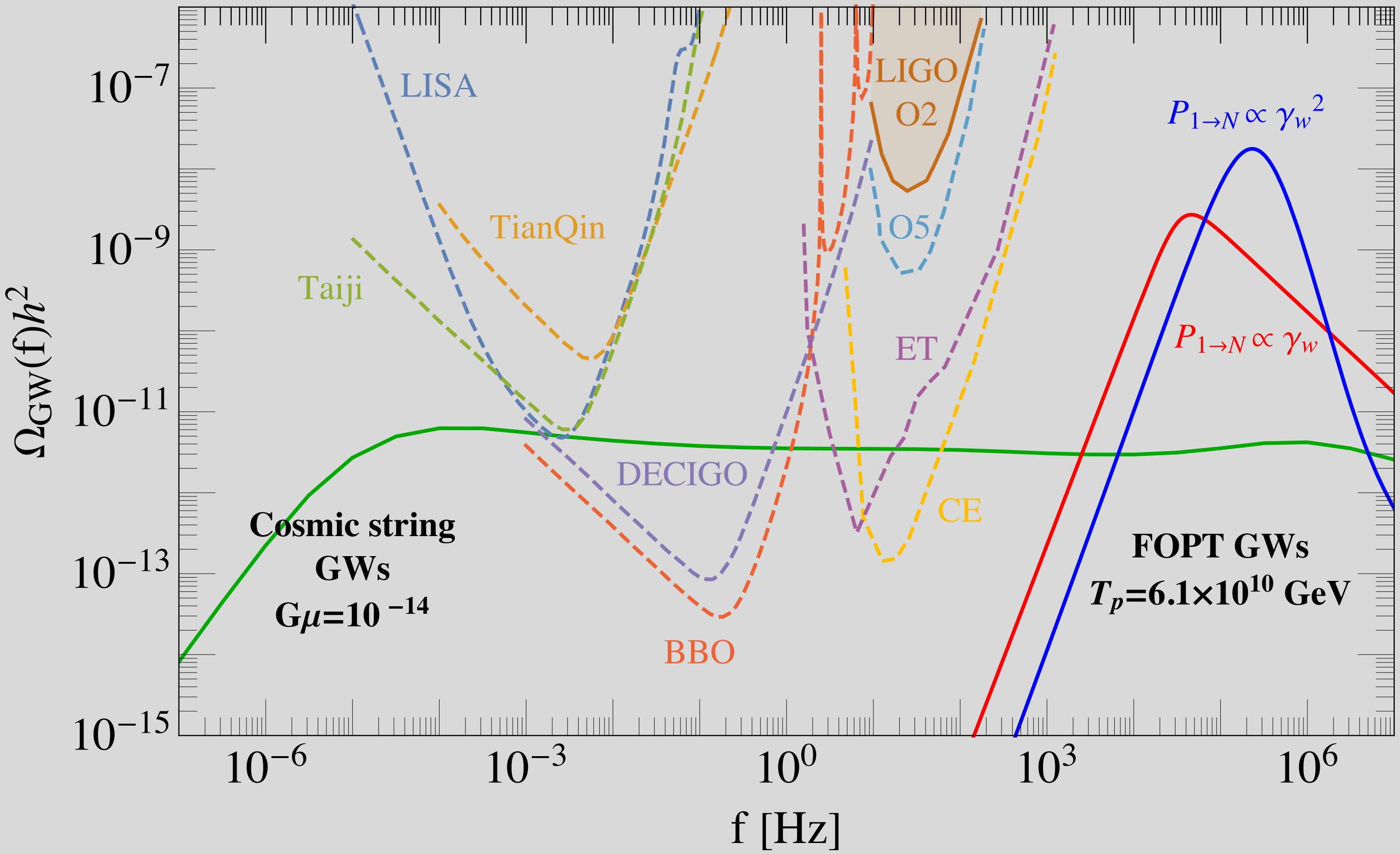
Conventional Leptogenesis needs CPV 30 times stronger

Gravitational Wave signal



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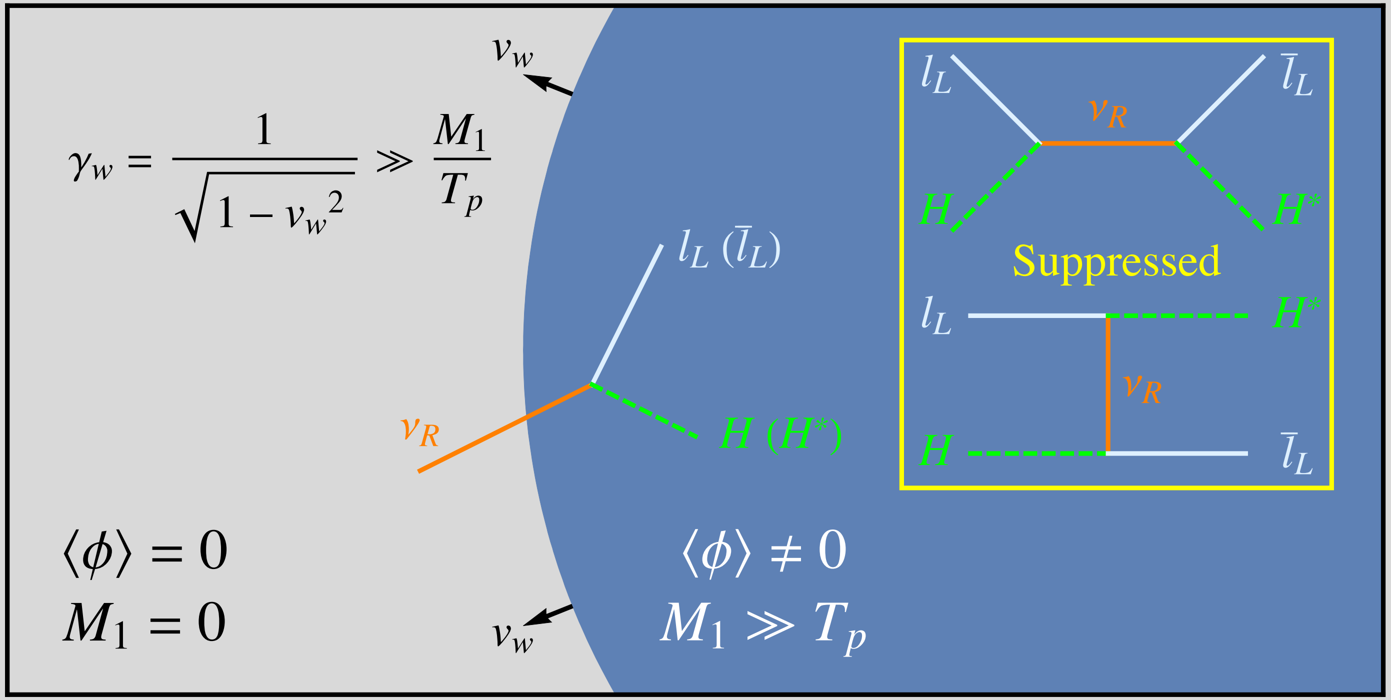
Conclusion



- Suppress the washout effects via a strong first-order PT
- Expand the parameter space for Leptogenesis
- Can be probed by GWs