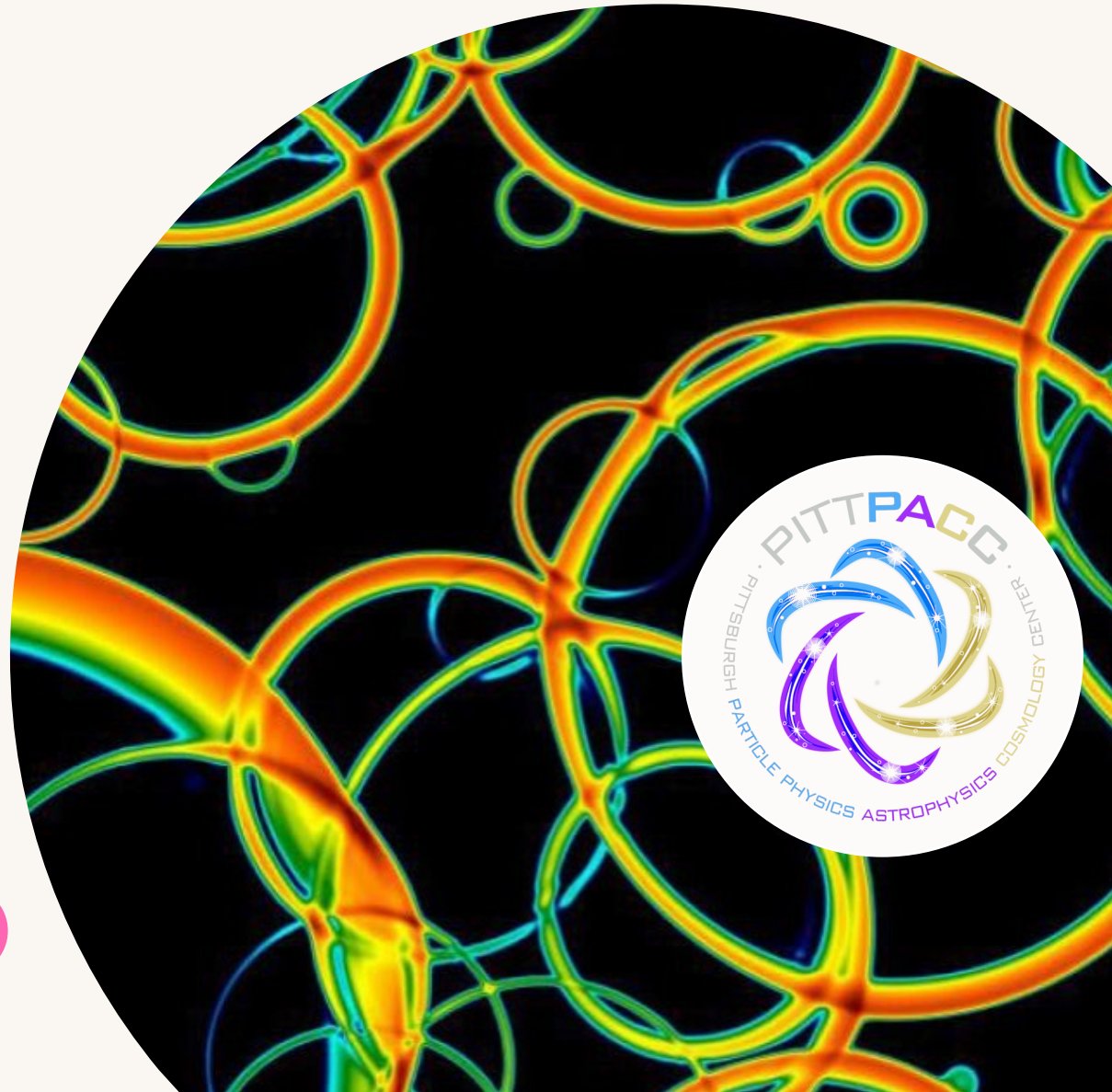
Matter-Antimatter Asymmetry from Dirac-Majorana Flip-Flop



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Leptogenesis

- Observed matter anti-matter asymmetry

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

- Generate dynamically & satisfy Sakharov Conditions
    i. ***B-Violation***
    ii. ***CP-Violation***
    iii. ***Departure from Thermal Eq***
- Transform asymmetry of one to another: $B - L$ symmetric interactions of EW Sphalerons

Setting up a Toy Model

- 2 scalar singlets (σ, ϕ), 2 RHN (ν_{R_i}), 1 dark Majorana (χ), neutrinophilic Higgs doublet (η)

$$-\mathcal{L}_y = y_{\alpha i}\bar{L}_\alpha \tilde{\eta} \nu_{R_i} + Y_{ij}\phi\overline{\nu^c}_{R_i}\nu_{R_j} + Y\overline{\chi^c}\chi + \text{h.c.}$$

- Tree level potential of scalars

$$V_0(\sigma,\phi) = -\frac{\mu_\phi^2}{2}\phi^2 - \frac{\mu_\sigma^2}{2}\sigma^2 + \frac{\lambda_\phi}{4}\phi^4 + \frac{\lambda_\sigma}{4}\sigma^4 + \frac{\lambda_{\sigma\phi}}{4}\sigma^2\phi^2$$

- Dirac **AND** Majorana mass terms from scalar VEVs
- 2 step P.T. $(0,0) \to (0, v_\phi) \to (v_\sigma, 0)$

Effective Potential

- VEVS arise from effective potential
  - *i.* **1-loop Correction**: SSB and barrier height

$$V_{CW} = \sum_i (-1)^{f_i} \frac{n_i m_i^4(\sigma,\phi)}{64\pi^2}\left[\ln\left(\frac{m_i^2(\sigma,\phi)}{\mu^2}\right) - \frac{3}{2}\right]$$

  - *ii.* **Thermal Correction**: Finite Temp QFT

$$V_{T,i} = \pm T^4 \int_0^\infty \frac{dy\, y^2}{2\pi^2} \ln\left(1 \mp \exp\left(-\sqrt{y^2 + {x_i}^2}\right)\right) = \pm \frac{T^4}{2\pi^2} J_{B/F}({x_i}^2)$$

  - *iii.* **Daisy Correction**: Resum IR divergence

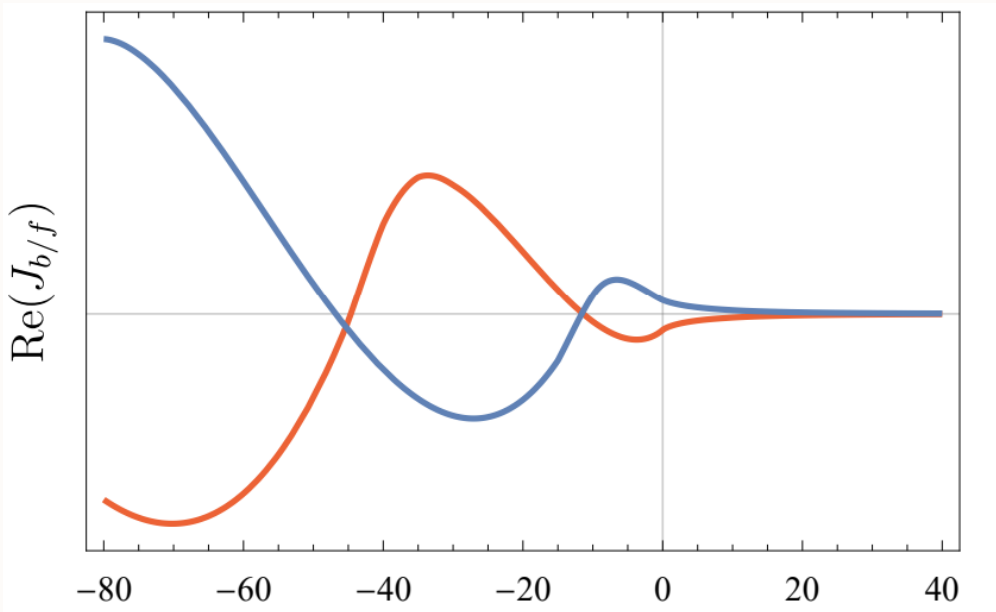
$$V_{\text{daisy}} = -\frac{T}{12\,\pi} \sum_b n_b \left[\left(m_b^2 - \Pi_b(T)\right)^{3/2} - \left(m_b^2\right)^{3/2}\right]$$

- Debye masses

$$\Pi_\phi^2(T) = \frac{T^2}{24}\left(\lambda_{\sigma\phi} + 6\lambda_\phi + 2\sum |Y_{ij}|^2\right)$$

$$\Pi_\sigma^2(T) = \frac{T^2}{24}\left(\lambda_{\sigma\phi} + 6\lambda_\sigma + 2|Y_\chi|^2\right)$$

J_B & J_F



$$x_i(\sigma,\phi) = {m_i(\sigma,\phi)}/{T}, \qquad y = {k}/{T}$$

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Phase History

I. T_1: $(0, v_\phi)$ global minima

⟶ RHN Majorana mass

$$M_{\nu_R}^2 = |Y|^2 \phi^2$$

⟶ Asymmetry: $\nu_R \to L\eta$ vs $\nu_R \to \bar{L}\bar{\eta}$

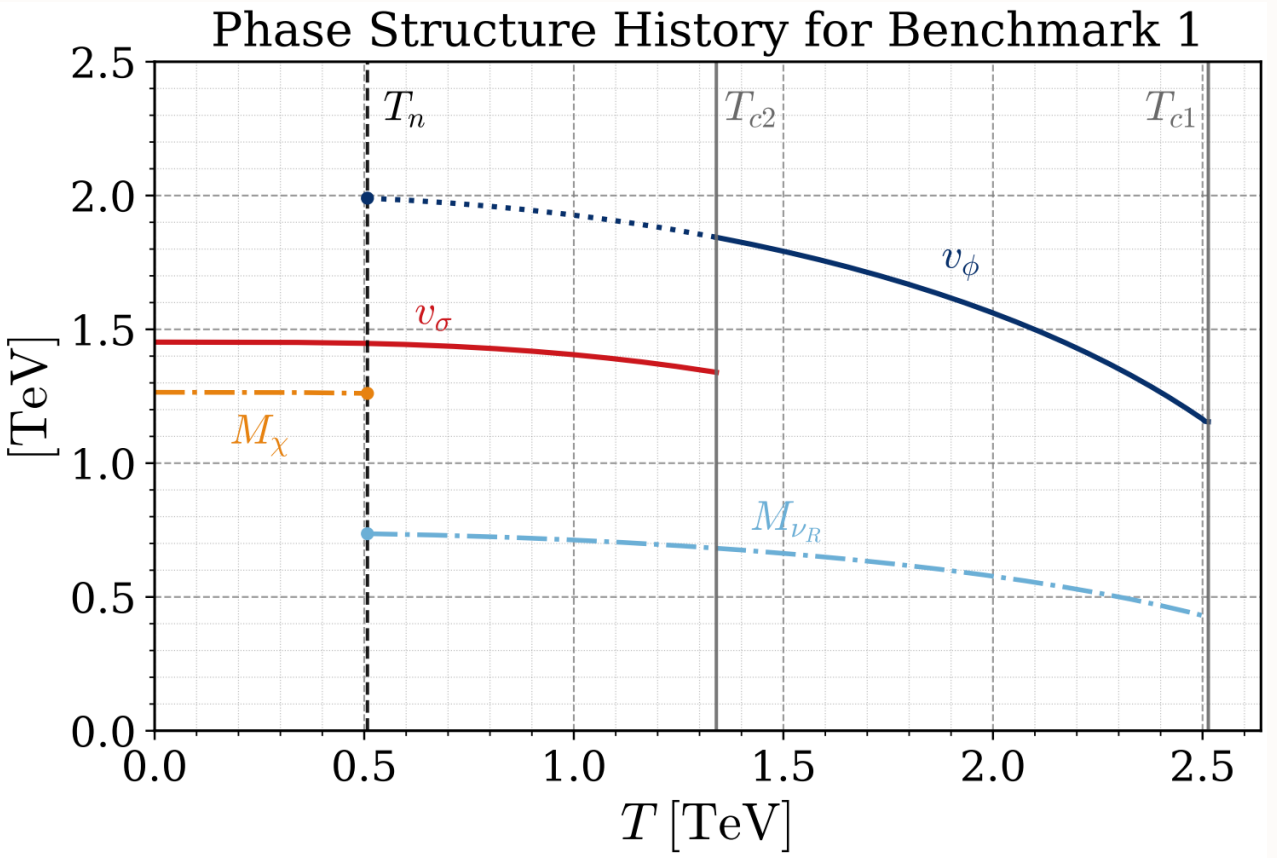
II. T_2: $(0, v_\phi)$ metastable & $(v_\sigma, 0)$ global minima

⟶ *Stuck* with Majorana term

III. T_n: Transition to true VEV

⟶ Nucleation of bubbles and production of GW

⟶ Return to Dirac



Transition Parameters

I. ***Nucleation Temp***: When false vacuum decays

$$\frac{\Gamma(T_N)}{H^4(T_N)} = 1$$

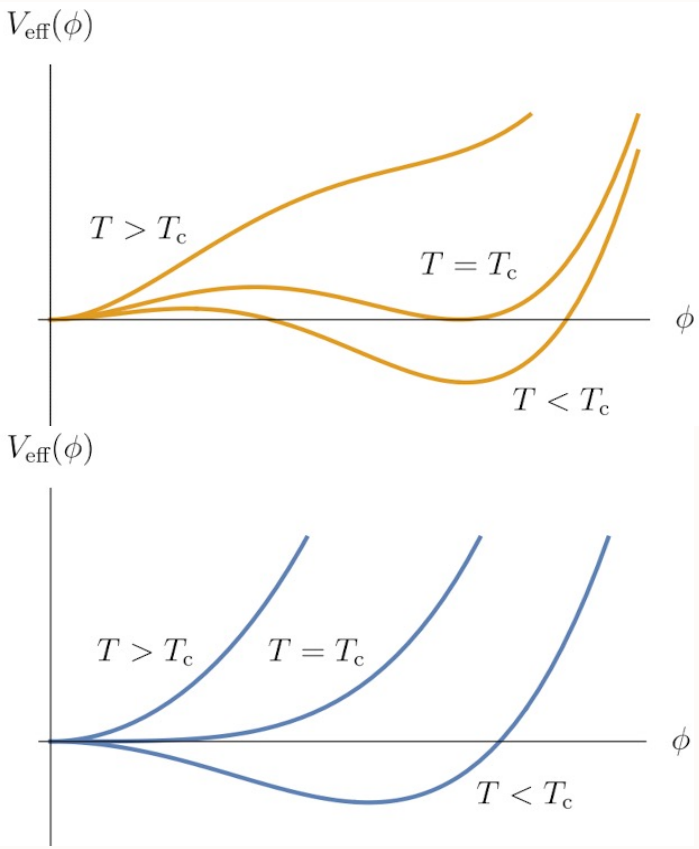
II. ***Latent Heat***: Energy released in transition

$$\alpha = \frac{\left(\Delta V_{eff} - \frac{T}{4}\frac{\partial V_{eff}}{\partial T}\right)\Big|_{T_n}}{\rho_{rad}(T_n)}$$

III. ***Duration***: Inverse time scale of transition

$$\frac{\beta}{H} = T\frac{d}{dT}\left(\frac{S_3(T)}{T}\right)\Big|_{T_n}$$

IV. ***Wall Velocity***: Bubble wall velocity. Simplicity $v_w \sim 1$



Boltzmann Equation

- Asymmetry from decay

$$\epsilon_i = \frac{\Gamma\left(\nu_{R_i} \to \sum_\alpha L_\alpha \eta\right) - \Gamma\left(\nu_{R_i} \to \sum_\alpha \bar{L}_\alpha \bar{\eta}\right)}{\Gamma\left(\nu_{R_i} \to \sum_\alpha L_\alpha \eta\right) + \Gamma\left(\nu_{R_i} \to \sum_\alpha \bar{L}_\alpha \bar{\eta}\right)}$$

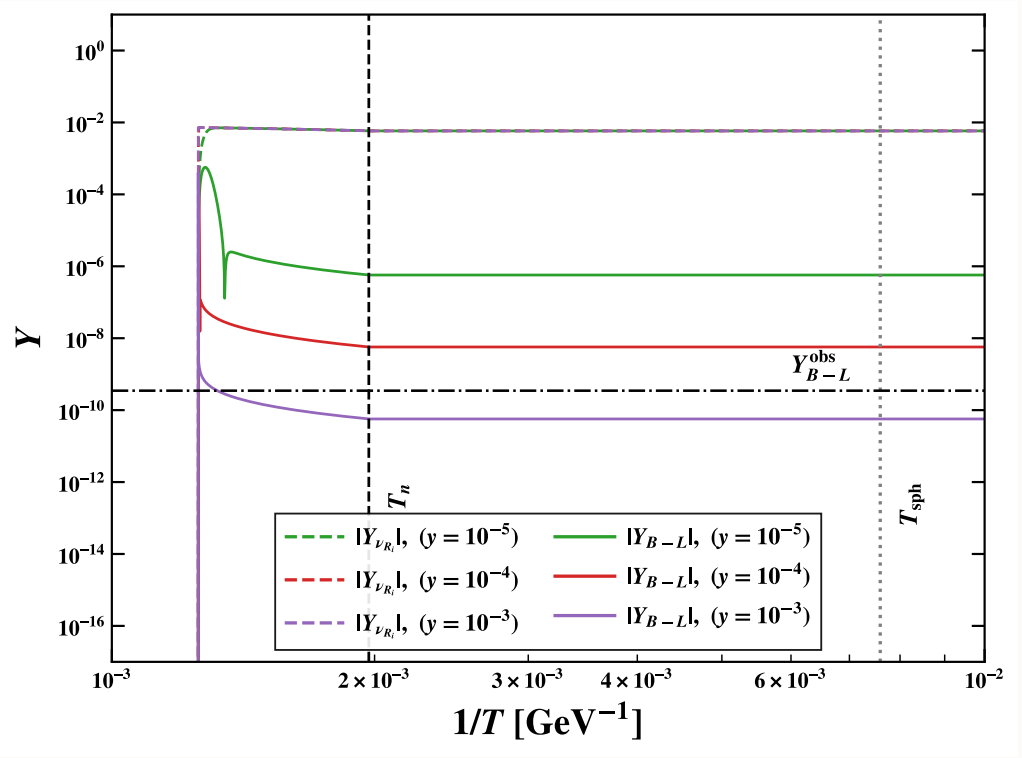
- Solve Boltzmann equation ($z = m_{\nu_R}/T$)

$$\frac{dY_{\nu_{R_i}}}{dz} = -D_i\left(Y_{\nu_{R_i}} - Y^{eq}_{\nu_{R_i}}\right)$$

$$\frac{dY_{B-L}}{dz} = -\sum_i \epsilon_i\, D_i\left(Y_{\nu_{R_i}} - Y^{eq}_{\nu_{R_i}}\right) - W_i Y_{B-L}$$

- Abundance: Decay vs Washout
- Convert to Baryon asymmetry

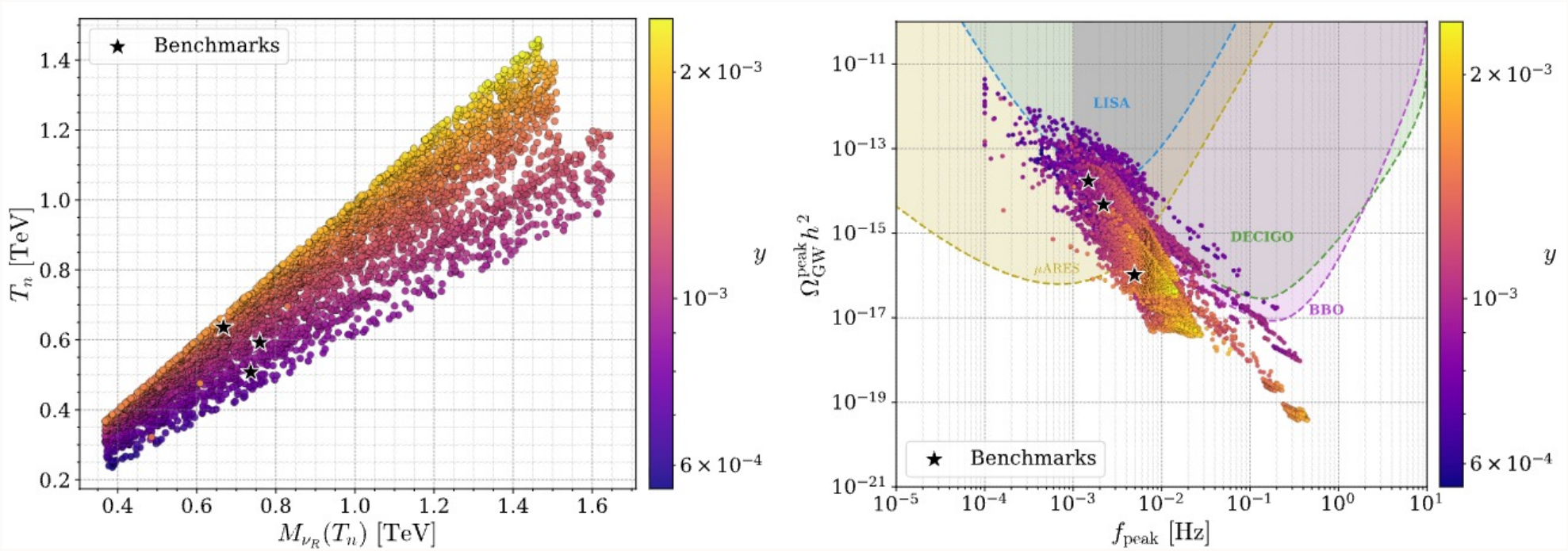
$$Y_B = a_{sph} Y_{B-L}$$



Set $\epsilon = 0.1$

Gravitational Waves

- Window for leptogenisis
- Bubble collisions and disturbance in plasma ⟹ gravitational waves
- Produce detectable gravitational waves



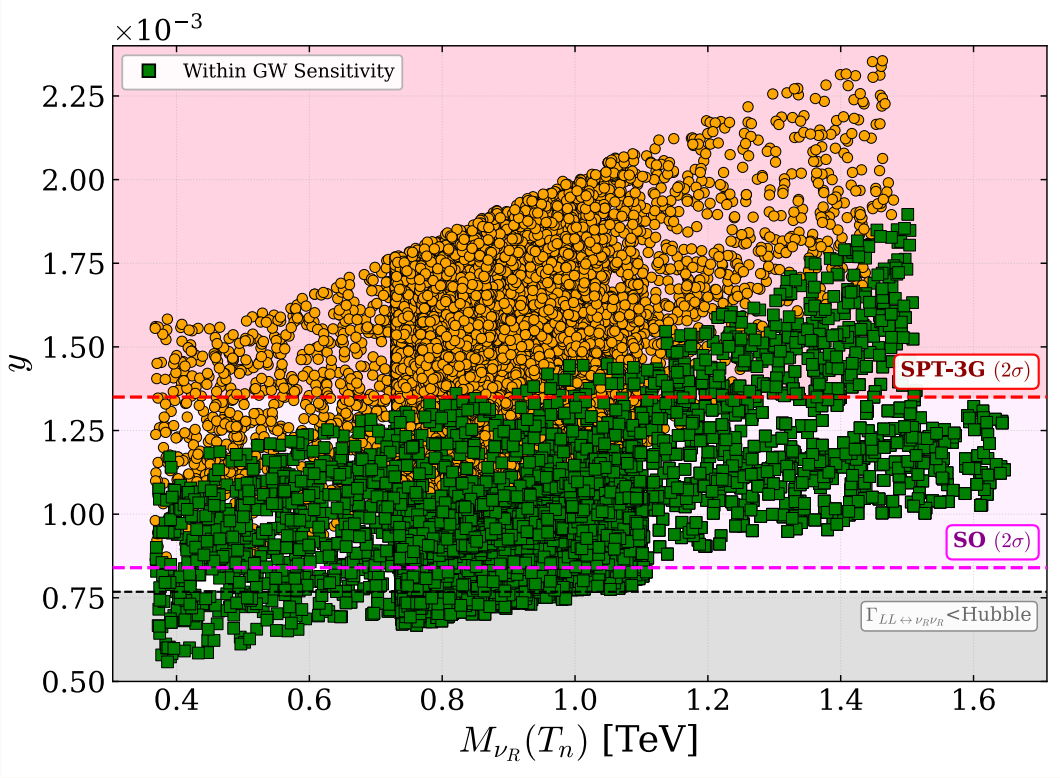
Dark Radiation

- Effective number of neutrinos $N_{eff}^{SM} = 3.044$
- Additional light DoF increase value

$$N_{eff} \sim \frac{\rho_R - \rho_\gamma}{\rho_\gamma}$$

- Need dark radiation in bath longer to maintain ρ at recombination for ΔN_{eff}
- Primary interaction: $\nu_R \nu_R \to LL$
- Decouple from bath

$$\frac{n_{\nu_R}^{eq} \langle \sigma v \rangle}{H} = 1$$



Key Takeaways

1) Dirac neutrinos could be shapeshifting having an earlier Majorana phase
2) Produce observable gravitational waves
3) Potentially observable effects in CMB

Thank you! Questions?