Connecting **Leptogenesis** with Observable **Gravitational Waves**

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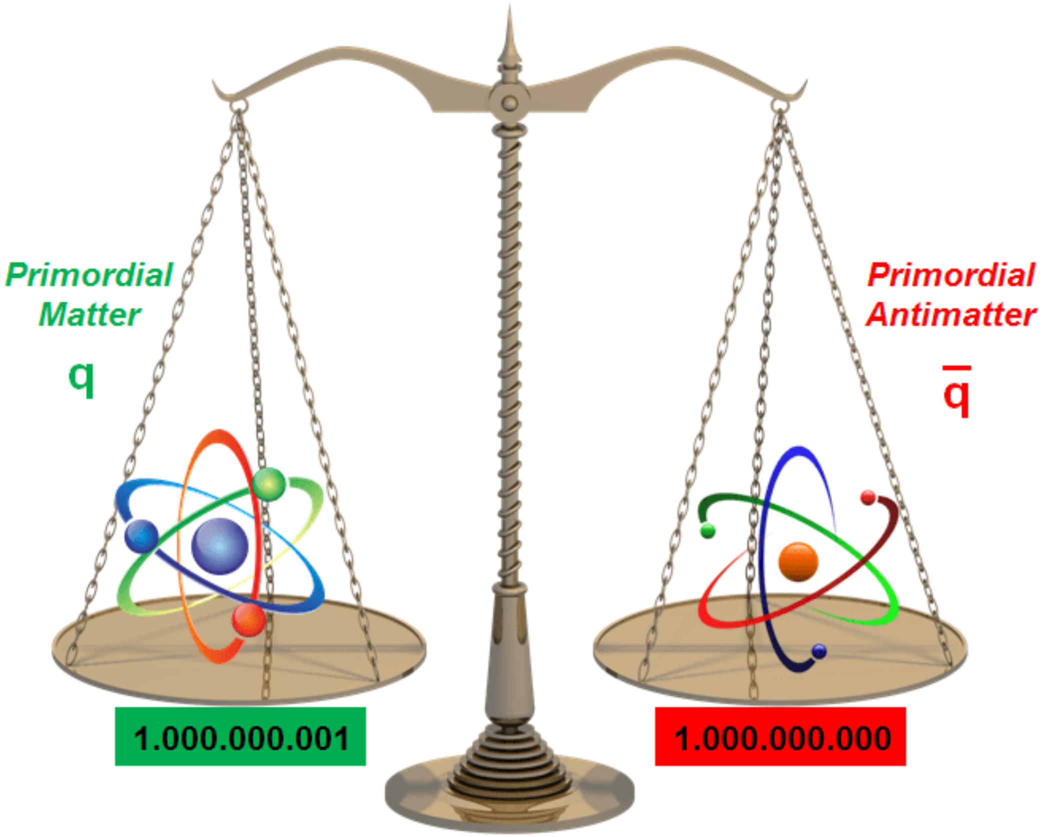
Wei Liu, YW; arXiv: 2504.07819

Baryon Asymmetry of the Universe

- The observed Universe



$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6.12\times 10^{-10}$$

$$Y_B \equiv \frac{n_B - n_{\bar{B}}}{s} \approx 8.69\times 10^{-11}$$

Initial Condition **vs.** Dynamical Procedure

Baryon Asymmetry of the Universe

- Sakharov Criteria – Dynamical Generation
  - Baryon Number Violation
    - Sphaleron Process in SM
  - CP and C Violation
    - CP phase in CKM matrix
      - Not sufficient for the observed BAU
    - New CPV sources vs. EDM constraints
      - **CPV in Vacuum, CPV in Yukawa (PMNS matrix)**, etc.
  - Departure from Thermal Equilibrium
    - **1st order PT, bubble nucleation/expansion** (not the case in SM)
    - **Out-of-Equilibrium Decay of Heavy Particles (RHN)**

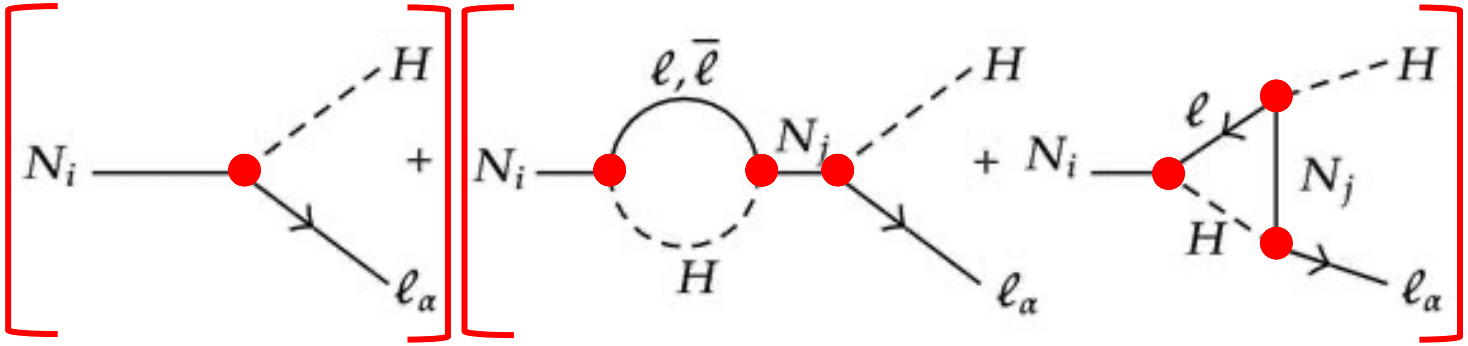
New CPV Sources & Departure from thermal equilibrium

Leptogenesis

- Connecting Neutrino Physics with BAU
  - Right-hand neutrino (RHN) – Type-I seesaw for neutrino mass

$$\mathcal{L} \supset h_{ij}\bar{N}_i \ell_j H$$

- CP Asymmetry from out-of-equilibrium decay of N



$$\epsilon \sim \Im\left(\left(hh^\dagger\right)^2\right)\frac{M_1}{M_i}$$

Leptogenesis

- Davidson-Ibarra Bound
  - Hierarchical, Neutrino mass

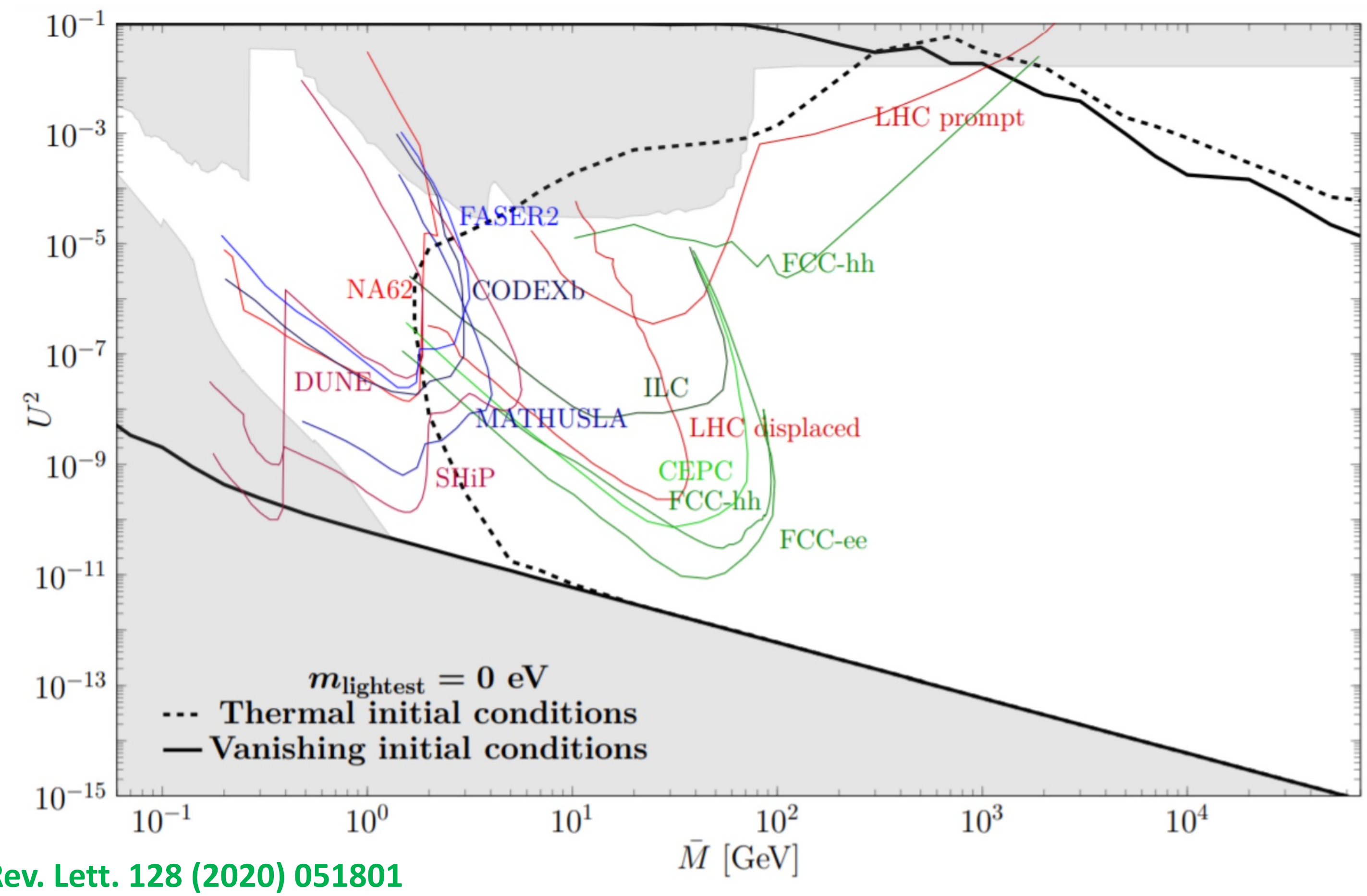
$$|\epsilon| \lesssim \frac{M_1}{v^2}\sqrt{\Delta m^2_{atm}} \quad \Rightarrow \quad M_1 \gtrsim 10^9\ \mathrm{GeV}$$

For Thermal Leptogenesis

- Other options:
  - Flavored Leptogenesis
    - Flavor Effects – only lower the scale by 1-2 orders
  - Resonant Leptogenesis
    - Two degenerate RHNs - as low as TeV scale
    - Fine-tune
  - Non-thermal Leptogenesis
    - RHNs not from thermal bath

Probing Leptogenesis

- Probing Viable Leptogenesis Parameter Space



Phys. Rev. Lett. 128 (2020) 051801

- Other Probes
  - $0\nu\beta\beta$ – Majorana RHN
  - δ_{CP} in PMNS matrix

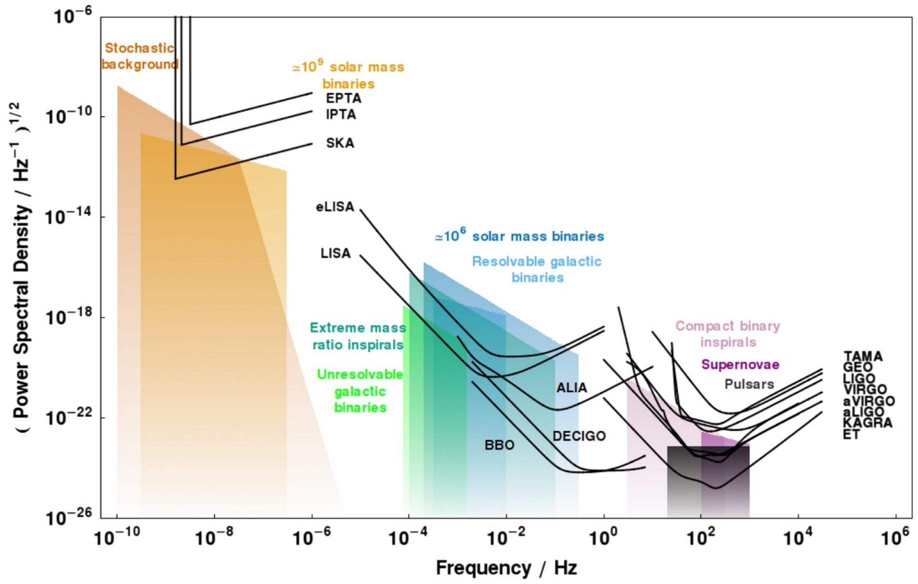
Probing Leptogenesis

- Any other probes?
  - Gravitational Waves
- GW probes of Leptogenesis
  - RHN mass related
    - Symmetry breaking providing RHN mass
      - $U(1)_{B-L}$ – Cosmic string - GW
    - Scalar - RHN coupling
      - Determining both RHN mass and Scalar decay
      - Changing Thermal History – special characteristics in GW spectrum

arXiv: 1908.03227, 2004.02889, 2205.03422, 2406.01231, 2208.09949, 2405.00641, 2503.09884, 2504.20135

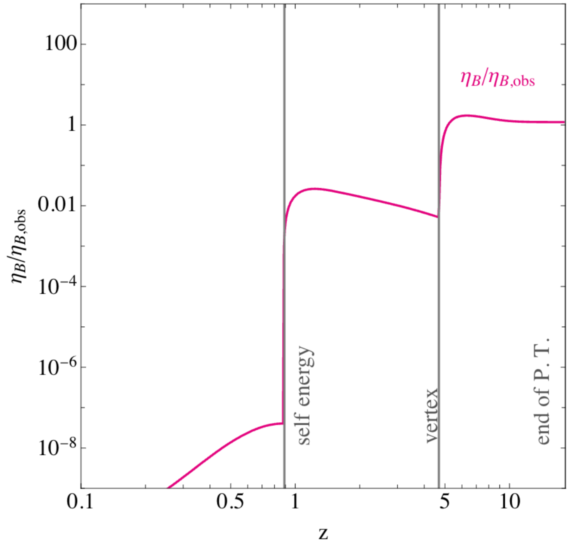
  - Strong Phase Transition **out-of-equilibrium, suppress washout**
    - Sudden change of RHN mass
    - Bubble wall production of RHN

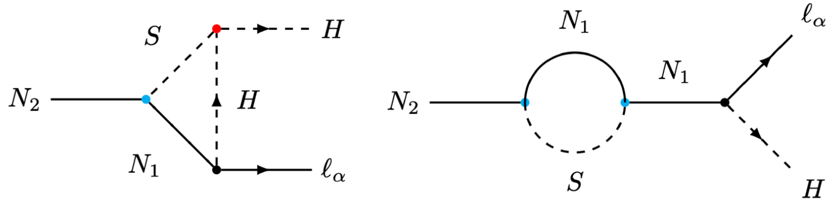
arXiv: 2106.15602, 2206.04691, 2207.14226, 2305.10759



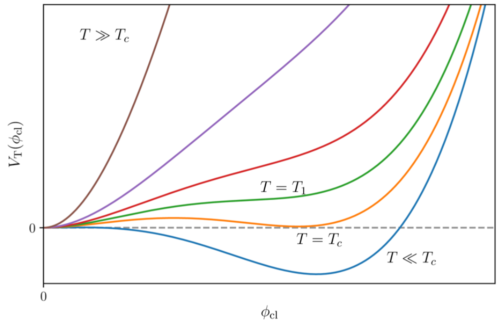
Phase Transition and Leptogenesis

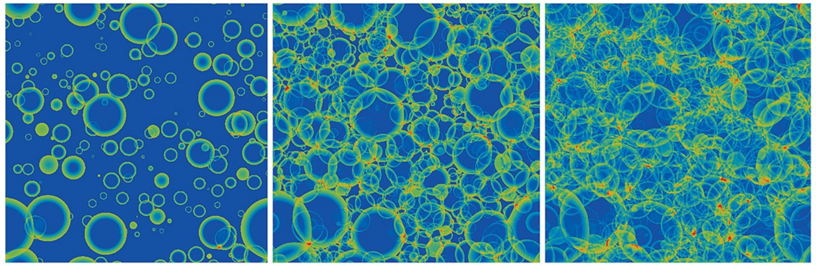
- The PT can be more involved in Leptogenesis
  - Significantly enhance CP asymmetry $Y_{B-L} \sim \epsilon\ \kappa$
  - Link GW and Leptogenesis

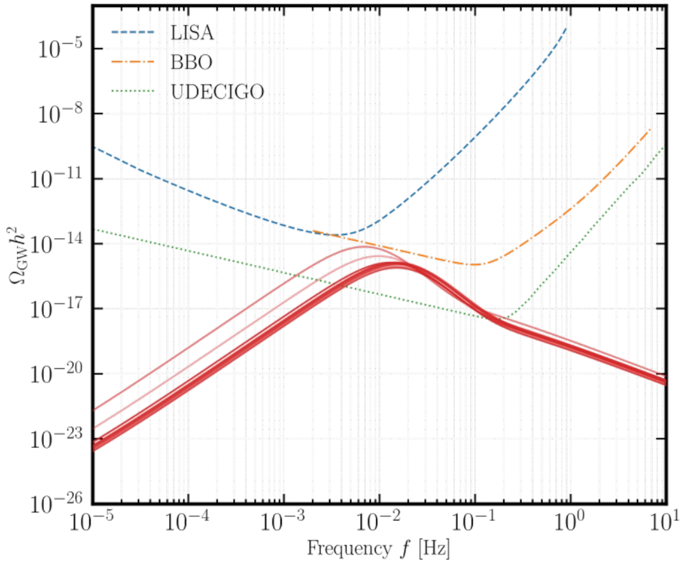




Scalar







Benchmark Scenario

- Real Singlet Extended SM (xSM) + Type-I Seesaw
  - Scalar Sector:

$$V_0(H,\mathcal{S}) = \mu_H^2|H|^2 + \lambda_H|H|^4 + \frac{1}{2}\mu_S^2\mathcal{S}^2 + \frac{1}{4}\lambda_S\mathcal{S}^4 + \lambda_{SH}\mathcal{S}^2|H|^2$$

$$H = \begin{pmatrix} \phi^+ \\ \frac{\omega_h + h + i\phi_0}{\sqrt{2}} \end{pmatrix} \qquad \mathcal{S} = \omega_s + S$$

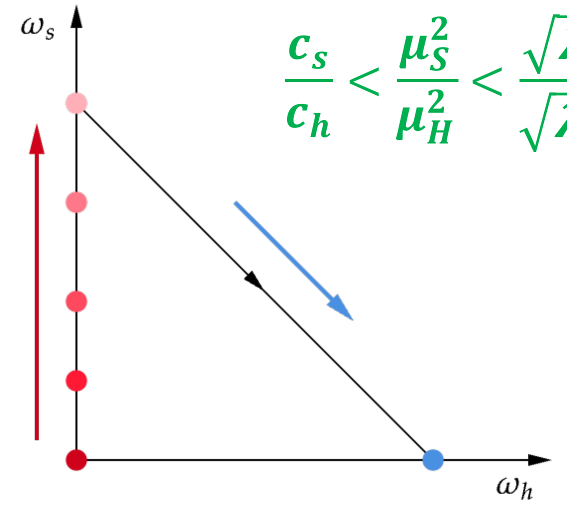
  - Neutrino Sector:

$$-\mathcal{L} \supset h_{\alpha i}\bar{\ell}_\alpha N_i H + \frac{1}{2}\left(M_{ij} + a_{ij}\mathcal{S}\right)N_i N_j + h.c.$$

Cosmological Phase Transition

- PT in xSM with High Temperature Expansion **for illustration only**

$$V_{\rm eff}(\omega_h,\omega_s,T) = V_0 + \frac{1}{2}c_h T^2\omega_h^2 + \frac{1}{2}c_s T^2 \omega_s^2 \qquad c_h = \frac{3g^2+g'^2+4y_t^2}{16} + \frac{\lambda_H}{2} + \frac{\lambda_{SH}}{12}, \qquad c_s = \frac{\lambda_S}{4} + \frac{\lambda_{SH}}{3}$$

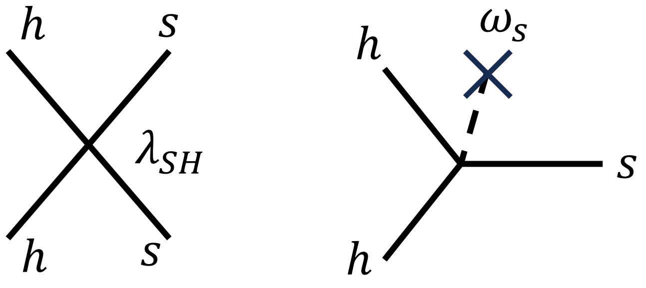


$$\frac{c_s}{c_h} < \frac{\mu_S^2}{\mu_H^2} < \frac{\sqrt{\lambda_S}}{\sqrt{\lambda_H}} < \frac{\lambda_{SH}}{\lambda_H}$$

High T → **Low T**

$$T_h = \sqrt{-\frac{\mu_S^2}{c_s}} \qquad T_c^2 = \frac{\mu_H^2\sqrt{\lambda_S} - \mu_S^2\sqrt{\lambda_H}}{c_s\sqrt{\lambda_H} - c_h\sqrt{\lambda_S}} \qquad T_l = T_n$$

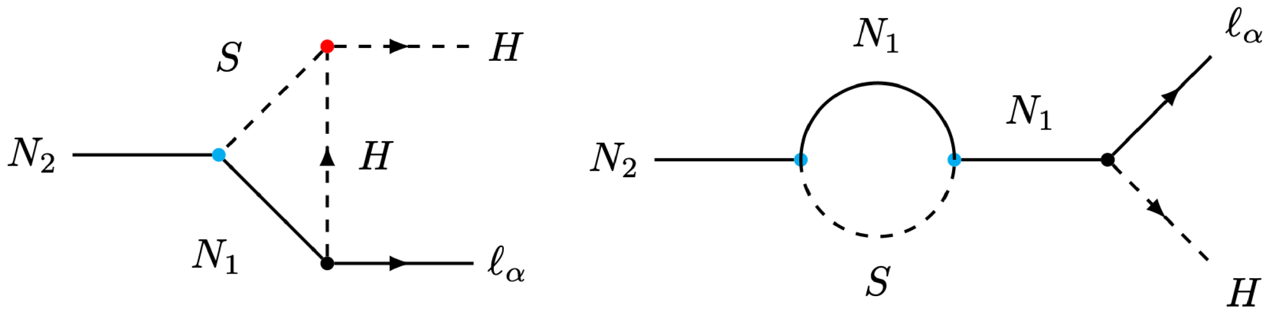
(ω_h,ω_s)	$(0,0)$	$(0,\bar\omega_s)$	$(\bar\omega_h,0) \to (v,0)$
m_h^2	$\mu_H^2 + c_h T^2$	$\frac{\lambda_S(\mu_H^2 + c_h T^2) - \lambda_{SH}(\mu_S^2 + c_s T^2)}{\lambda_S}$	$-2(\mu_H^2 + c_h T^2)$
m_s^2	$\mu_S^2 + c_s T^2$	$-2(\mu_S^2 + c_s T^2)$	$\frac{\lambda_H(\mu_S^2 + c_s T^2) - \lambda_{SH}(\mu_H^2 + c_h T^2)}{\lambda_H}$
μ_{hhs}	0	$2\lambda_{SH}\sqrt{-\frac{\mu_S^2 + c_s T^2}{\lambda_S}}$	0



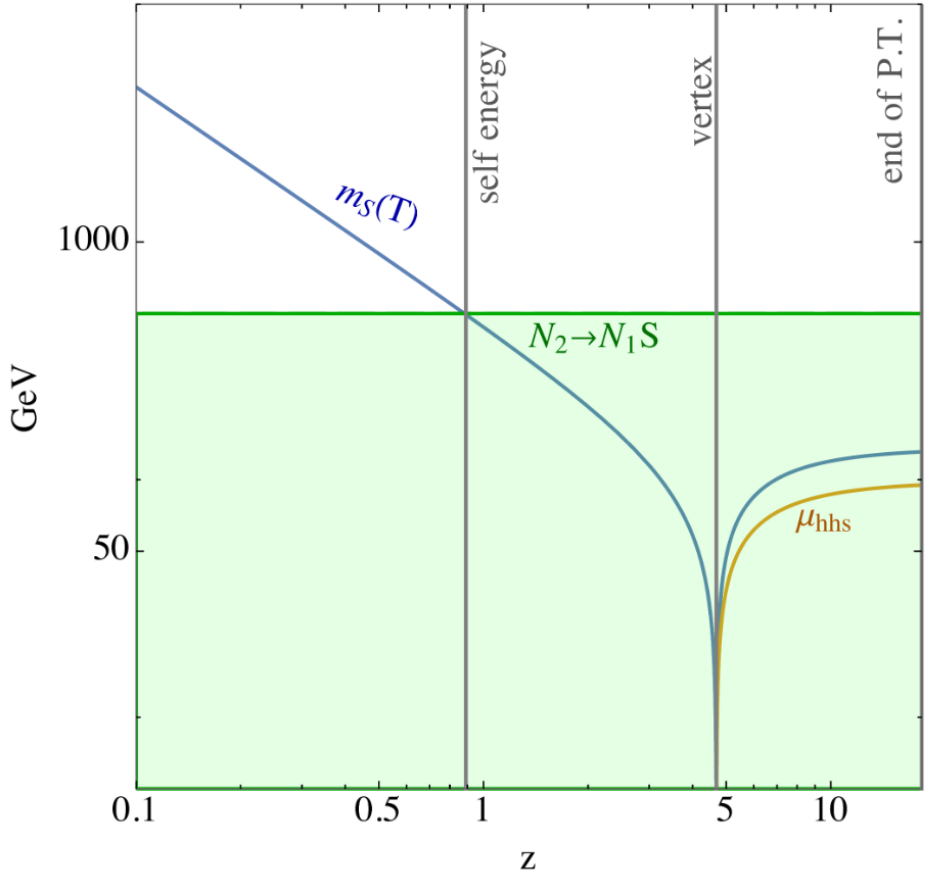
$\mu_{hhs} \sim \omega_s \lambda_{SH}$

Scalar assisted Leptogenesis

- The extra CP asymmetry contributions



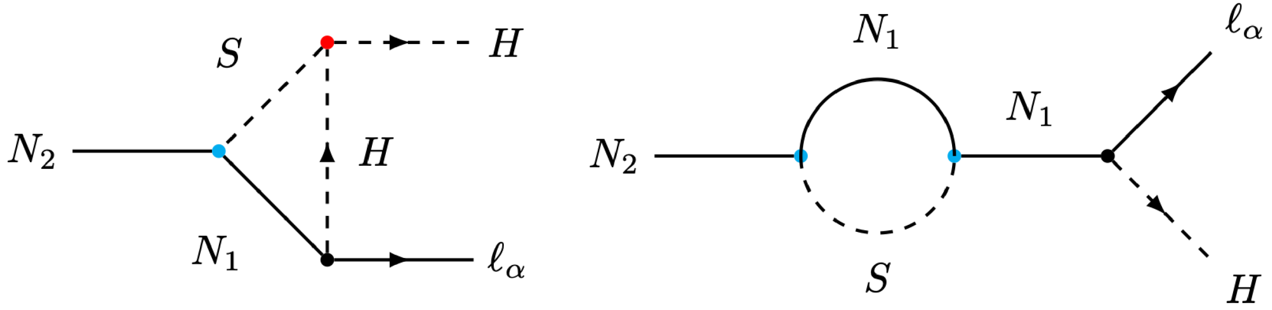
- Vertex & Self-energy
  - Non-zero when $m_{N_2} > m_{N_1} + m_S$
  - For vertex contribution, also $\mu_{hhs} \neq 0$



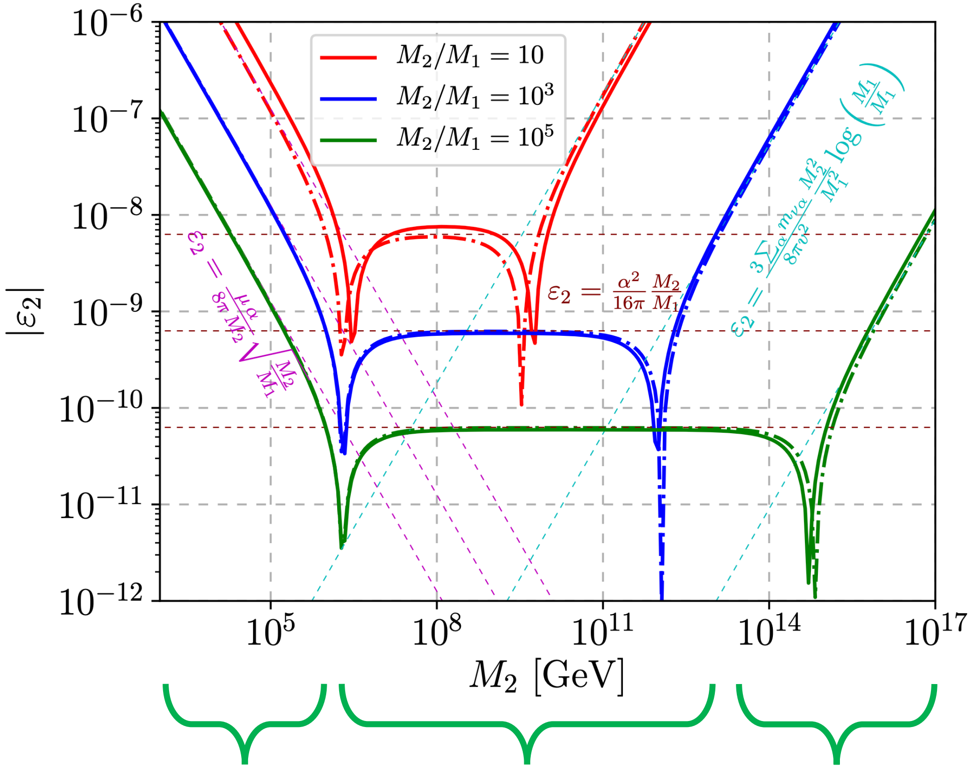
Determined by PT history

Scalar assisted Leptogenesis

- The extra CP asymmetry contributions



arXiv: 1812.04421



$$\epsilon_2^V \sim \frac{|a_{21}|}{8\pi}\frac{\boldsymbol{\mu_{hhs}}}{m_{N_2}}\sqrt{\frac{m_{N_1}}{m_{N_2}}}\left(\mathcal{F}_{jLL}^V + \mathcal{F}_{jRL}^V\right)$$

$$\epsilon_2^S \sim \frac{|a_{11}a_{21}|}{8\pi}\sqrt{\frac{m_{N_1}}{m_{N_2}}}\left(\mathcal{F}_{jlLL}^S + \mathcal{F}_{jlRL}^S + \mathcal{F}_{jlLR}^S + \mathcal{F}_{jlRR}^S\right)$$

$$\epsilon_2 = \epsilon_2^0 + \epsilon_2^V + \epsilon_2^S$$

Scalar assisted Leptogenesis

- Different CP asymmetry contributions

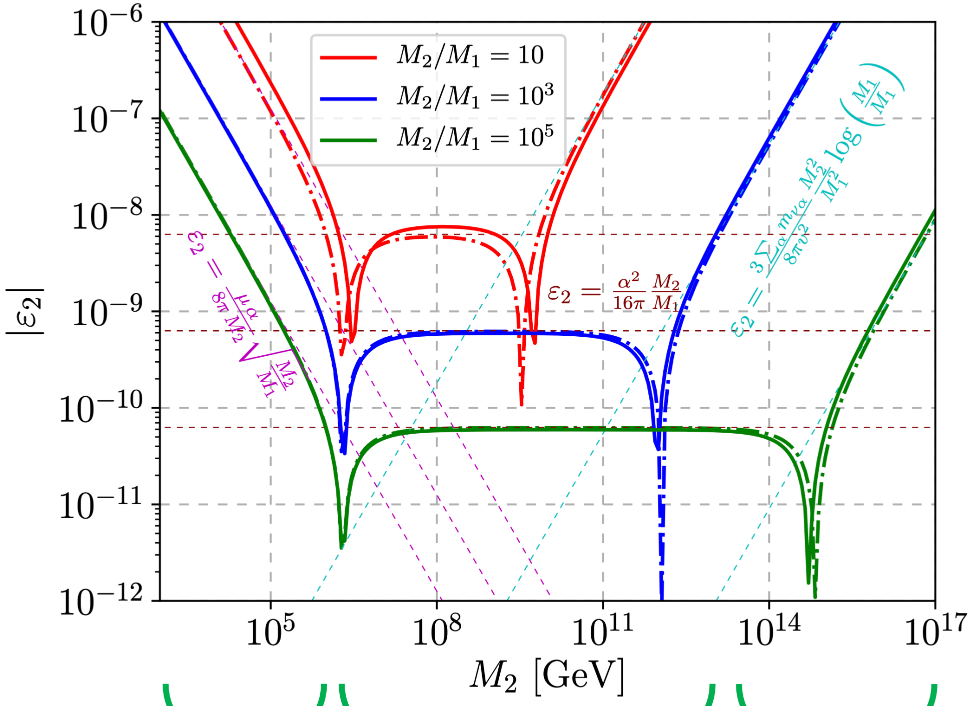
$$\epsilon_2 = \epsilon_2^0 + \epsilon_2^V + \epsilon_2^S$$

$$\epsilon_2^0 \sim \frac{M_2}{v^2}\sqrt{\Delta m^2}$$ **Type-I Seesaw contribution**

$$\epsilon_2^V \sim \frac{|a_{21}|}{8\pi}\frac{\mu_{hhs}}{m_{N_2}}\sqrt{\frac{m_{N_1}}{m_{N_2}}}$$ **Vertex with Scalar**

$$\epsilon_2^S \sim \frac{|a_{11}a_{21}|}{8\pi}\sqrt{\frac{m_{N_1}}{m_{N_2}}}$$ **Self-energy with Scalar**

arXiv: 1812.04421

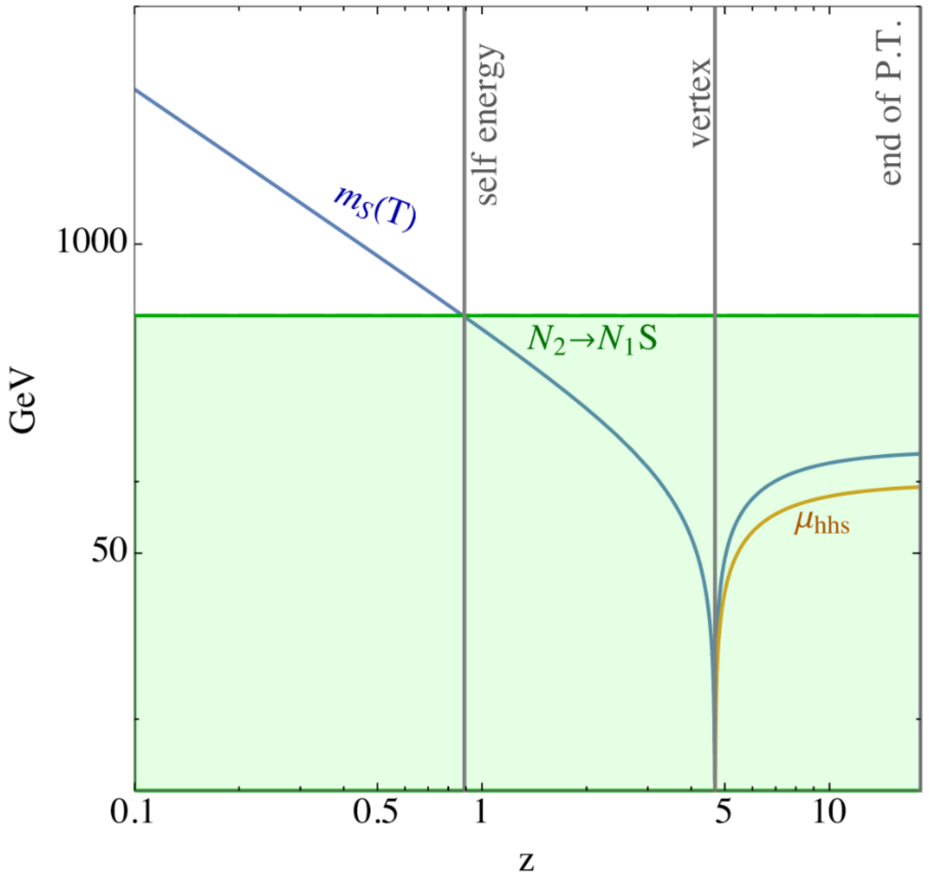


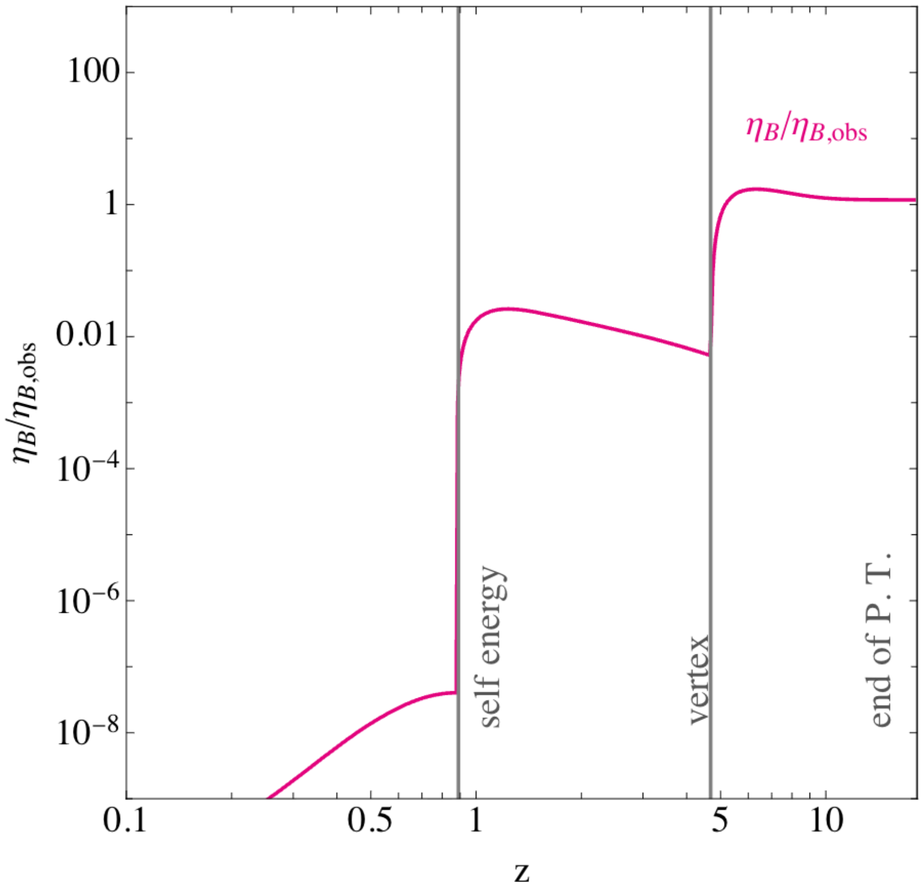
S-Vertex S-Self-energy Type-I Seesaw

Focus on the low mass region, with vertex with scalar correction dominates

Scalar assisted Leptogenesis

- Solving Boltzmann Equation involving $N_{N_1}, N_{N_2}, N_{B-L}$



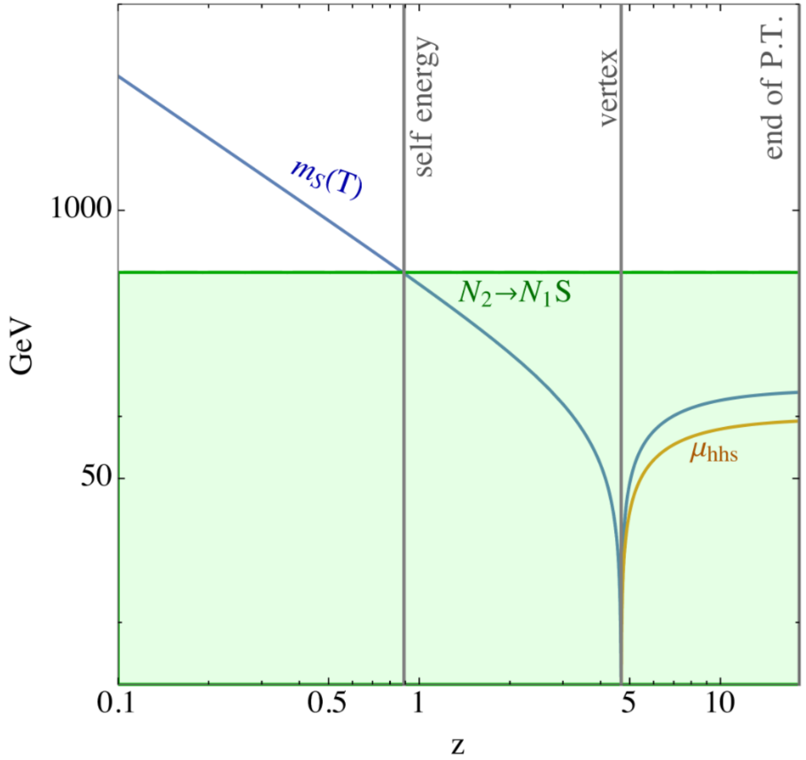


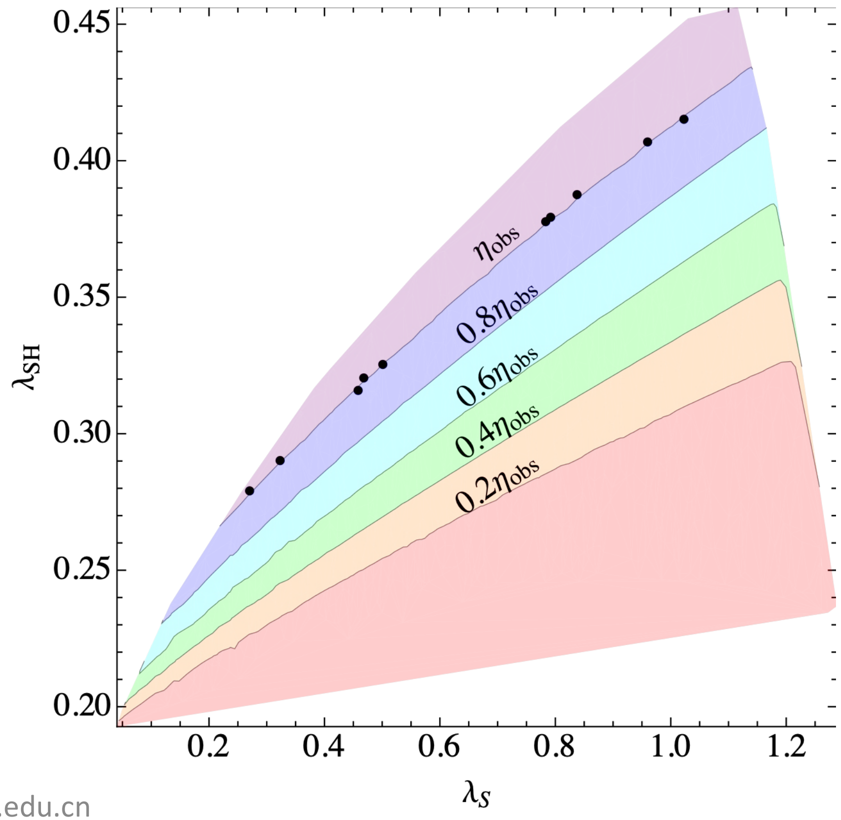
Connecting Leptogenesis with PT

- For Leptogenesis

$$V_0(H,\mathcal{S}) = \mu_H^2|H|^2 + \lambda_H|H|^4 + \frac{1}{2}\mu_S^2\mathcal{S}^2 + \frac{1}{4}\lambda_S\mathcal{S}^4 + \lambda_{SH}\mathcal{S}^2|H|^2$$

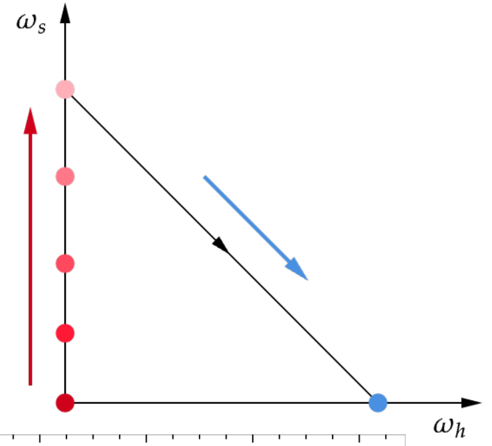
  - λ_S, λ_{SH}: Determine the $T_{h,c,l}$, $m_S^2(T)$, $\mu_{hhs} \sim \lambda_{SH}\omega_S \sim \frac{\lambda_{SH}}{\sqrt{\lambda_S}} m_S(T)$

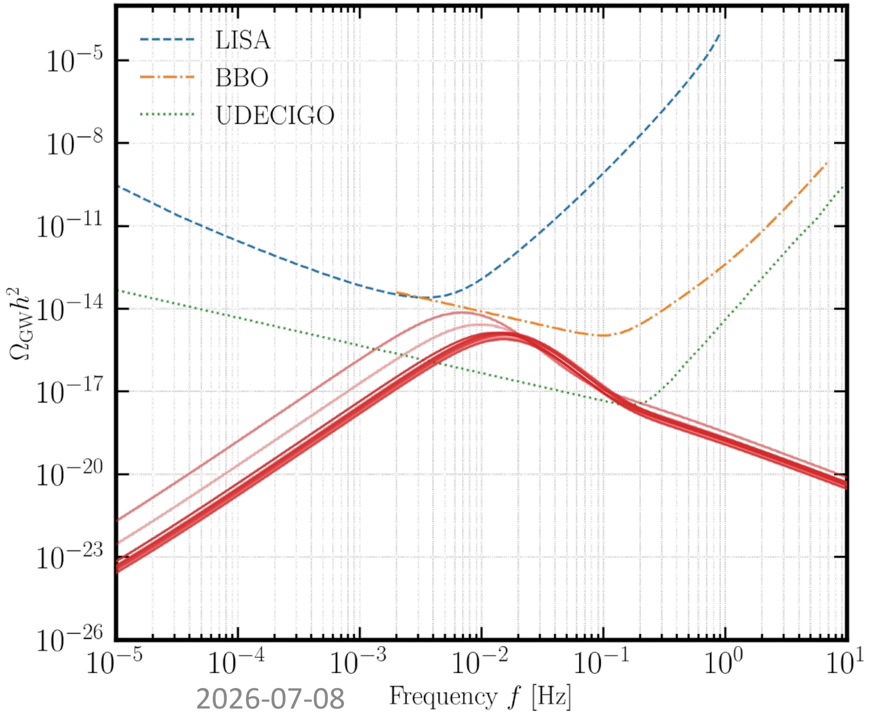




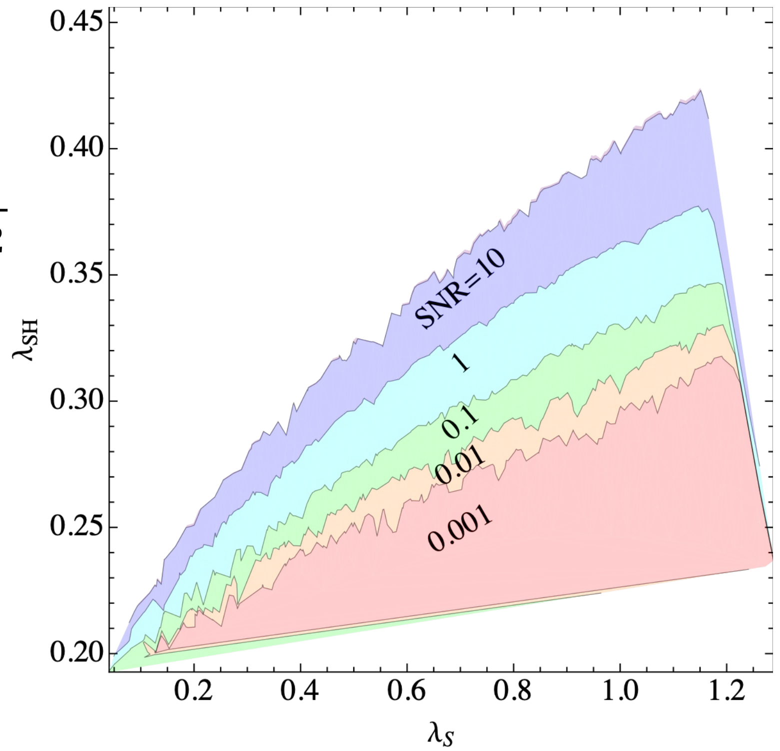
GW from PT

- True vacuum bubble nucleation from PT
  - GW signal mainly determined by $\alpha, \frac{\beta}{H}, T_n$
    - Depend on λ_S, λ_{SH}
  - Peak frequency ~ mHz
    - Covered by space-based detectors



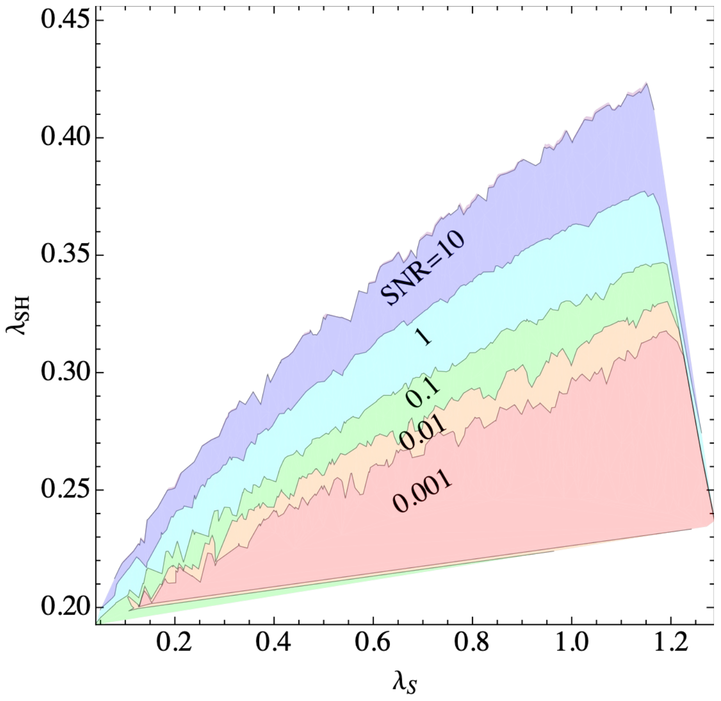


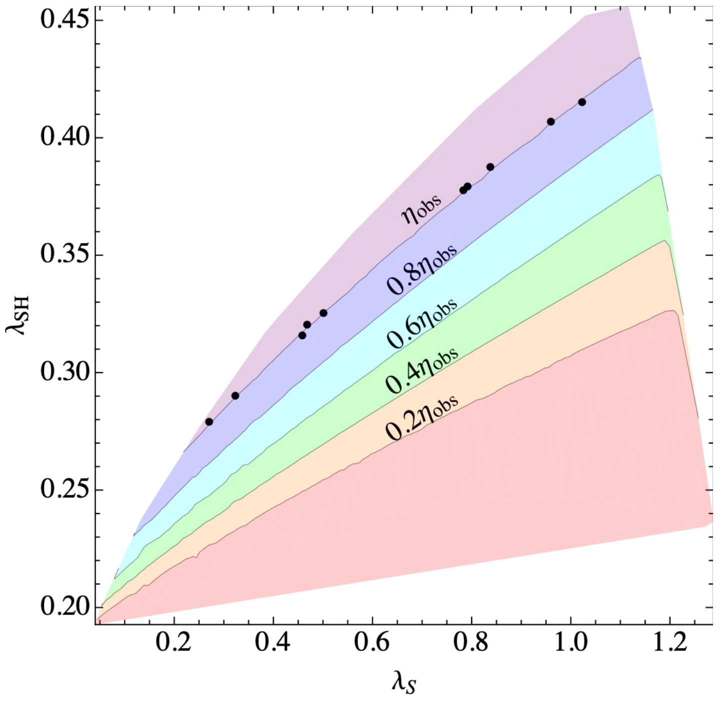
$$\mathrm{SNR} = \sqrt{\mathcal{T}\int df \left(\frac{\Omega_{\rm GW}h^2}{\Omega_{\rm sen}h^2}\right)^2}$$

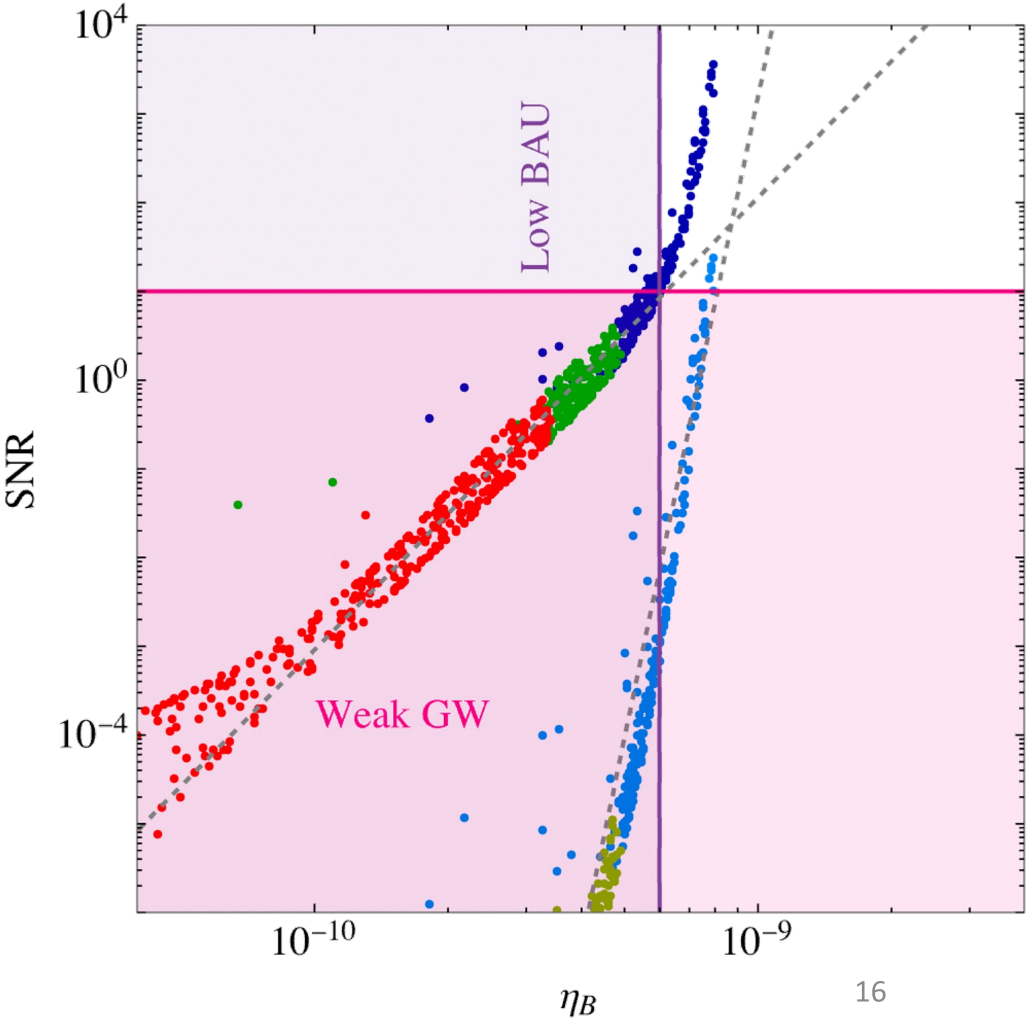


GW signal and BAU

- Same Scalar Dynamics Control Both PT and Leptogenesis
  - Strong correlation between GW SNR and BAU







Summary

- Scalar coupled with RHN can enhance the CP asymmetry
  - Lower the Leptogenesis scale – testable at current experiments
- Scalar extended model can induce strong 1st order PT
  - Strong GW signal
- Same Scalar Sector Dynamics Control PT and Leptogenesis
  - GW signal is strongly correlated with the BAU in this scenario
  - GW signal alone cannot be a test of Leptogenesis
    - Many different scalar sector can induce similar GW signals
  - GW signal can be treated as a new constraint/hint for Leptogenesis
    - Especially when we might have signals of RHN from other experiments

THANKS!

Backups

Scalar assisted Leptogenesis

- The Boltzmann Equations

$$\frac{dN_2}{dz} = -(D_2 + D_{21})\Delta_2 + D_{21}\Delta_1 - \Delta_{12} S_{N_1 N_2 \to HH} - \Delta_{22} S_{N_2 N_2 \to HH}$$

$$\frac{dN_1}{dz} = -(D_1 + D_{21})\Delta_1 + D_{21}\Delta_2 - \Delta_{12} S_{N_1 N_2 \to HH} - \Delta_{11} S_{N_1 N_1 \to HH}$$

$$\frac{dN_{B-L}}{dz} = -\sum_i \epsilon_i D_i \Delta_i - W N_{B-L}$$

$$D_i(z) = K_i z \frac{\mathcal{K}_1(z_i)}{\mathcal{K}_2(z_i)} N_{N_i}^{eq}(z)$$

The additional contribution from $N_2 \to N_1 S$

$$\Delta_i = \frac{N_i}{N_i^{eq}} - 1$$

$$D_{21}(z) = K_{21} z \frac{\mathcal{K}_1(z_2)}{\mathcal{K}_2(z_2)} N_{N_2}^{eq}(z) \qquad K_{21} \equiv \frac{\Gamma(N_2 \to N_1 S)}{H}$$

$$\Delta_{ij} = \frac{N_i N_j}{N_i^{eq} N_j^{eq}} - 1$$

$$W(z) = \sum_i \frac{1}{4} K_i z_i^3 \mathcal{K}_1(z_i) \qquad K_i \equiv \frac{\Gamma(N_i \to LH)}{H}$$

Gravitational Wave from PT

- Bubble Collision

$$\Omega_{coll}h^2 = 1.67\times10^{-5}\left(\frac{g_*}{100}\right)^{-\frac{1}{3}}\left(\frac{\kappa_{coll}\alpha}{1+\alpha}\right)^2\left(\frac{\beta}{H_*}\right)^{-2}\Delta(v_w)S_{coll}(f,v_w)$$

$$\Delta(v_w) = \frac{0.48\,v_w^3}{1+5.3v_w^2+5.0v_w^4}$$

$$S_{coll}(f) = \left[c_\ell\left(\frac{f}{f_{coll}}\right)^{-3} + (1-c_\ell-c_h)\left(\frac{f}{f_{coll}}\right)^{-1} + c_h\left(\frac{f}{f_{coll}}\right)\right]^{-1}$$

$$c_\ell \approx 0.064$$
$$c_h \approx 0.48$$

$$f_{coll} = 1.65\times10^{-5}Hz\left(\frac{g_*}{100}\right)^{\frac{1}{6}}\left(\frac{T_*}{100\ GeV}\right)\left(\frac{\beta}{H_*}\right)\left(\frac{f_*}{\beta}\right)$$

$$\frac{f_*}{\beta} = \frac{0.35}{1+0.069v_w+0.69v_w^4}$$

$$\kappa_{coll} = \frac{1}{1+0.715\alpha}\left(0.715\alpha+\frac{4}{27}\sqrt{\frac{3\alpha}{2}}\right)$$

Gravitational Wave from PT

- Sound Wave

$$\Omega_{sw}h^2 = 2.59\times10^{-6}\left(\frac{g_*}{100}\right)^{-\frac{1}{3}}\left(\frac{\kappa_{sw}\alpha}{1+\alpha}\right)^2\left(\frac{\beta}{H_*}\right)^{-1}\Delta(v_w)\Upsilon(\tau_{sw})S_{sw}(f)$$

$$\Delta(v_w) = \max(v_w, c_s)/c$$

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

$$\Upsilon(\tau_{sw}) = 1 - \frac{1}{\sqrt{1+2H_*\tau_{sw}}}$$

$$f_{sw} = 8.9\times10^{-6}Hz\left(\frac{g_*}{100}\right)^{\frac{1}{6}}\left(\frac{T_*}{100\ GeV}\right)\frac{1}{\Delta(v_w)}\left(\frac{\beta}{H_*}\right)$$

Gravitational Wave from PT

- MHD Turbulence

$$\Omega_{turb}h^2 = 3.35\times10^{-4}\left(\frac{g_*}{100}\right)^{-\frac{1}{3}}\left(\frac{\beta}{H_*}\right)^{-1}\left(\frac{\kappa_{turb}\alpha}{1+\alpha}\right)^{\frac{3}{2}}\Delta(v_w)S_{turb}(f)$$

$$\Delta(v_w) = \max(v_w, c_s)/c$$

$$S_{turb}(f) = \left(\frac{f}{f_{turb}}\right)^3\left(1+\frac{f}{f_{turb}}\right)^{-\frac{11}{3}}\left(1+\frac{8\pi f}{h_*}\right)^{-1}$$

$$f_{turb} = 2.7\times10^{-5}Hz\left(\frac{g_*}{100}\right)^{\frac{1}{6}}\left(\frac{T_*}{100\ GeV}\right)\frac{1}{\Delta(v_w)}\left(\frac{\beta}{H_*}\right)$$