Connecting Leptogenesis from Observable Gravitational Waves

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Baryon Asymmetry of the Universe

$$\frac{n_{\Delta B}}{s} \approx (8.59 \pm 0.11) \times 10^{-11}$$

from Planck satellite

$10^{10} + 1$ $\qquad\qquad\qquad$ 10^{10}

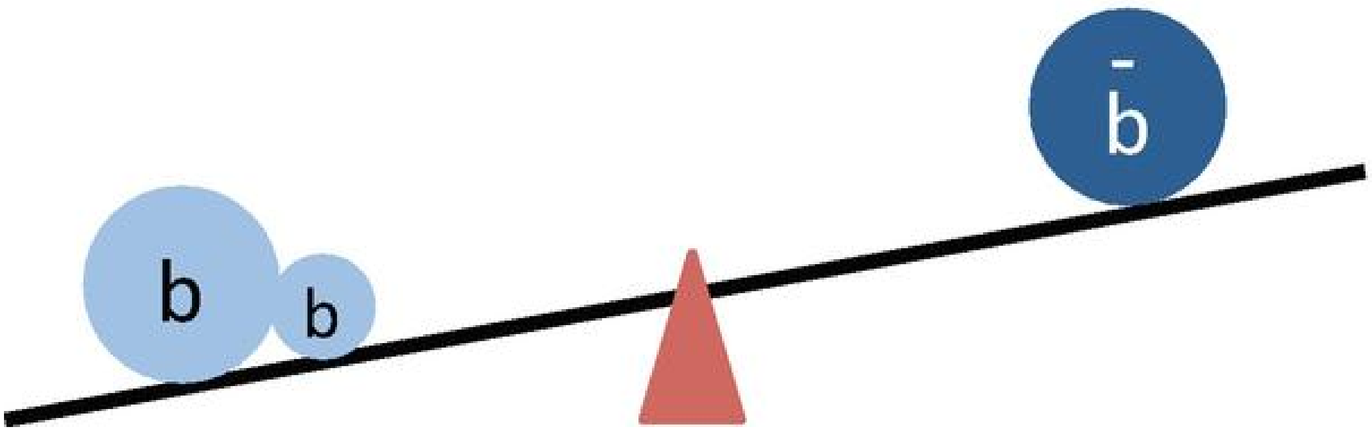
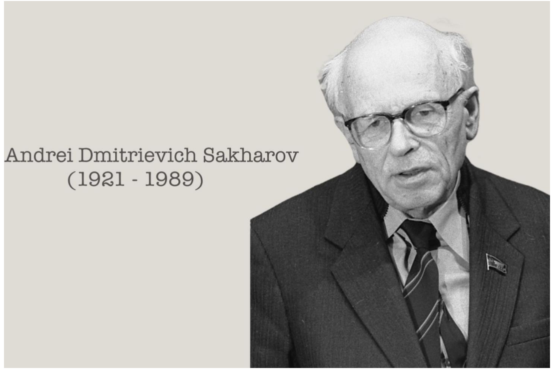


Figure from Kaori Fuyuto

Baryon Asymmetry of the Universe

- Sakhorov's criteria

1. Baryon number violating process,
   Generate $n_{\Delta B}$.
   Triangle Anomoly
2. C and CP violations,
   $\Gamma(X \to Y + b) \neq \Gamma(\overline{X} \to \overline{Y} + \overline{b})$, L *and* R.
   CKM
3. Out of equilibrium.
   $\Gamma(X \to Y + b) \neq \Gamma(Y + b \to X)$.
   Electroweak phase transition



Way too small to explain the observed BAU within the SM. **We need new physics!**

Baryon Asymmetry of the Universe

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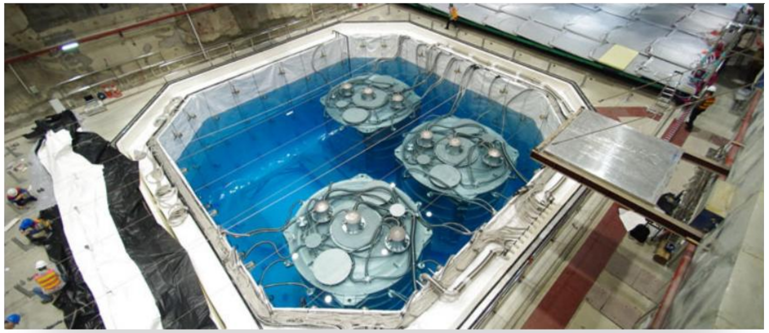
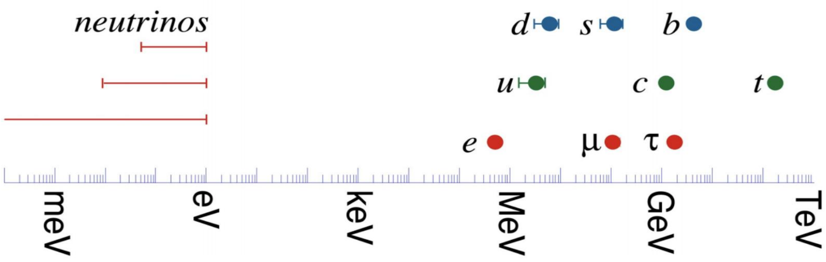
$$\sum m_\nu \lesssim 0.12\ eV$$

from Planck satellite





Seesaw mechanism

$$L \supset -y_D \overline{l_L} \widetilde{H} \nu_R - M_R \overline{\nu_R{}^c} \nu_R$$

$$M = \begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix}$$

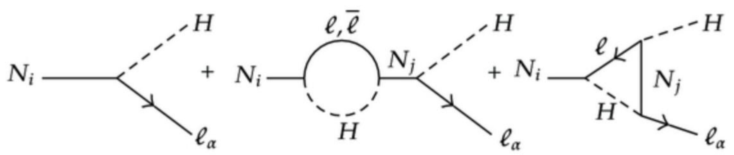
$$m_1 \approx \frac{-M_D^2}{M_R}, m_2 \approx M_R.$$

The lightness of the observed neutrinos is explained by heavy right-handed neutrinos,

Additional CP violations can exists in the **neutrino mass matrix.**

Leptogenesis

- ϵ_{aa} is the CP asymmetry in N_1 decay,
  comes from the interference between the tree-level and one loop amplitude.



- Hierarchical RH neutrinos,
  $M_{N_1} \geq 10^9$GeV.
  Davidson-Ibarra Bound, no possible signatures.
  Higgs mass unstable, Hierarchy problem

- **Resonant leptogenesis**
  if **at least two of the RH neutrinos masses are degenerate,**
  Fine-tuned
  $\epsilon \lesssim \frac{1}{2}$, only needs $M_{N_1} \geq T_{sph} \approx 130$ GeV.

- **ARS leptogenesis**
  Degenerate RH neutrinos Oscillate,
  Fine-tuned

  $M_{N_1} \geq 1$GeV.

Test Leptogenesis

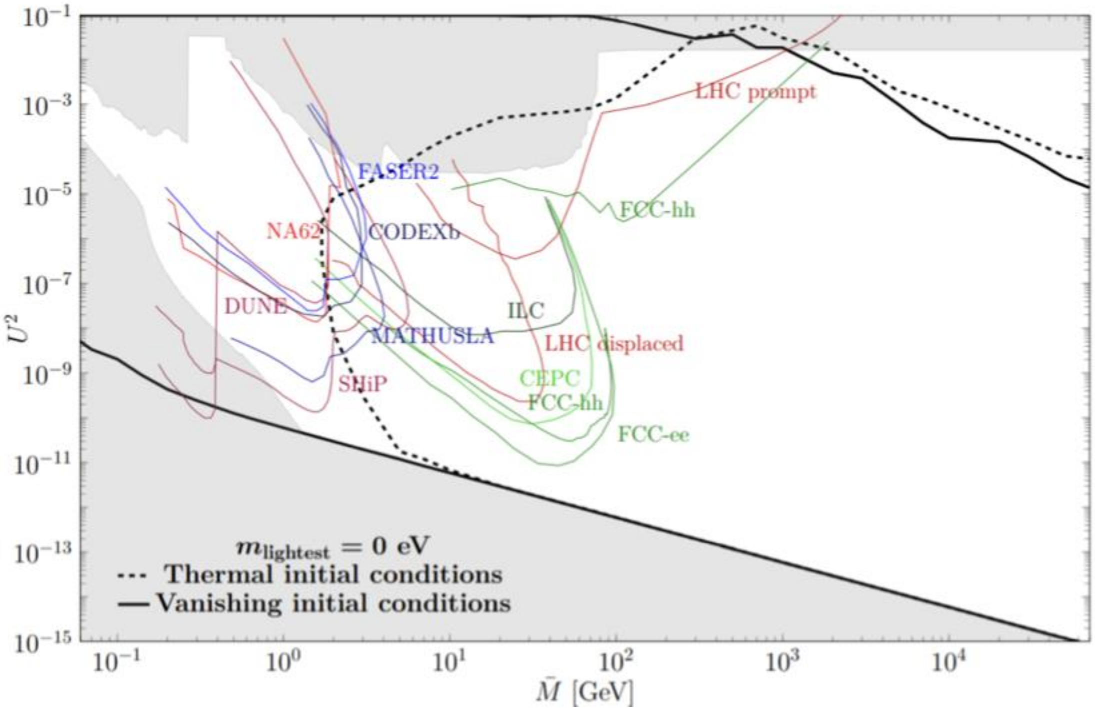
6

- **How to test leptogenesis?**

High scale: Collider can not reach

Low scale: Can not measure mass degeneracy

Only allowed region, **No test**

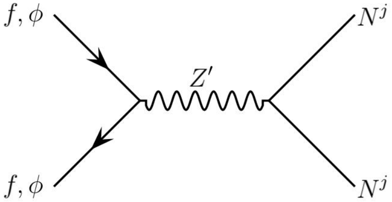


Marco Drewes, Yannis Georis et al, Phys.Rev.Lett. 128 (2022) 5, 051801

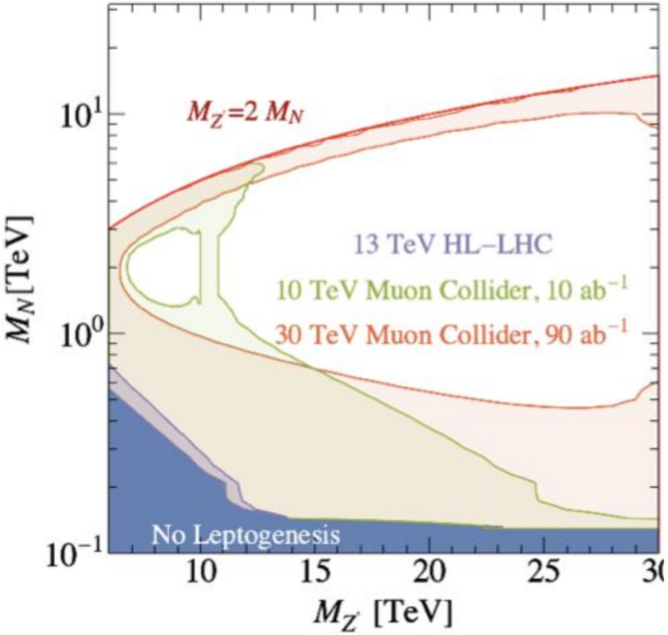
Test Leptogenesis in Extended Model

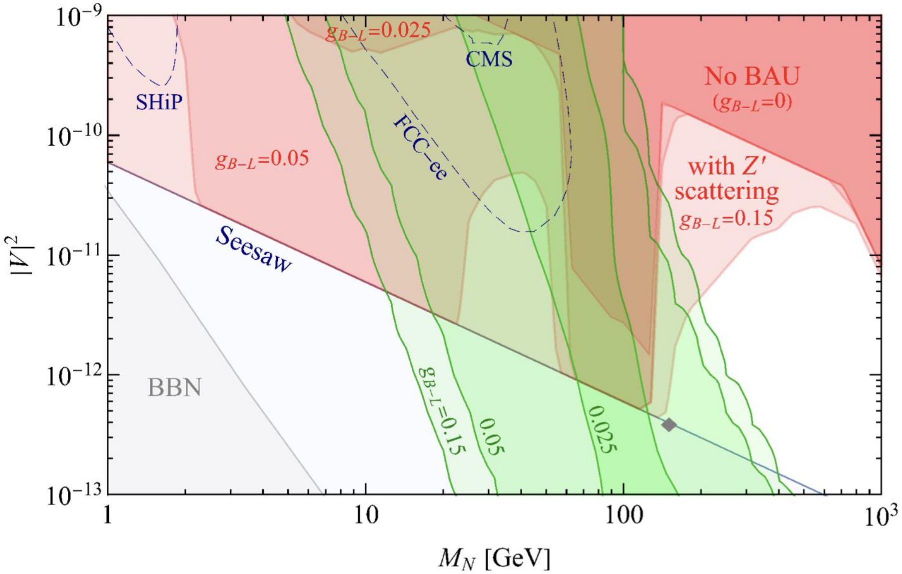
- **Testing U(1) extended Leptogenesis?**

$$f\overline{f} \to Z' \to N N$$



- Additional washout from scattering in Leptogenesis
- Additional Production of RHNs at Colliders, connected to Leptogenesis





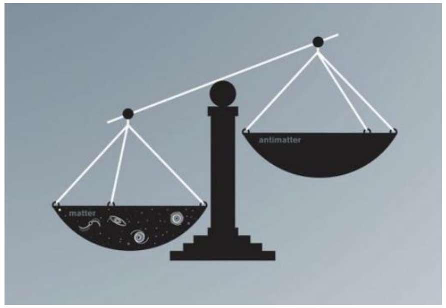
WL, F.Deppisch, Z. Chen, Phys.Rev.D 110 (2024) 3, 035017

WL, K. Xie, Z. Yi, Phys.Rev.D 105 (2022) 9, 095034

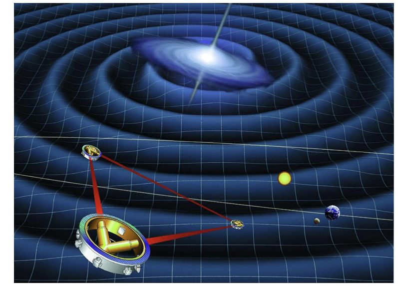
- Prompt: Search for same-sign dilepton, can probe $CP\ \epsilon$
- Displaced: Search for LLPs, depend on active-sterile mixing V^2

Test Leptogenesis from GWs

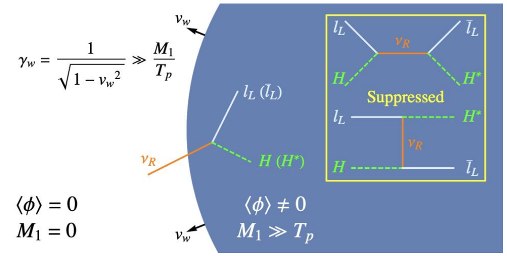
- **Can we test leptogenesis from GWs?**



Leptogenesis



GWs



- **Relativistic bubble wall dynamics**

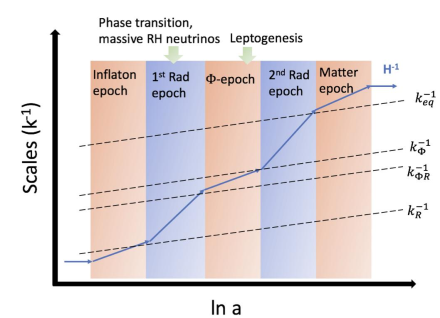
  EWPT, RHN mass, wall speed

  I. Baldes, S. Blasi et al, Phys.Rev.D 104 (2021) 11, 115029
  P. Huang, K. Xie, JHEP 09 (2022), 052
  D. Borah, A. Dasgupta et al, JHEP 11 (2022), 136
  E. J. Chun, T. P. Dutka et al, JHEP 09 (2023), 164

- **Early Matter Dominance from RHNs or scalar**

  Inflation or EWPT GWs

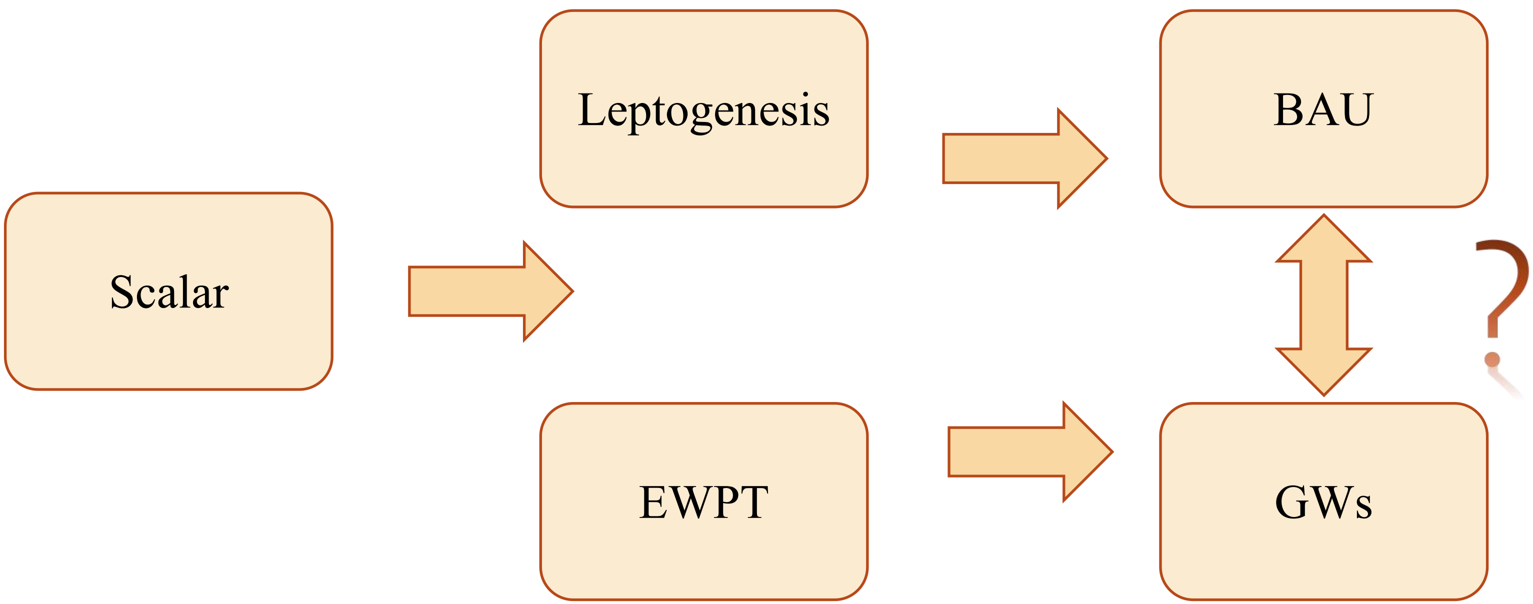
  S. Datta, R. Samanta et al, JHEP 11 (2022), 159,
  JCAP 11 (2024) 051, JCAP 08 (2025), 095



- **Graviton...**

Test Leptogenesis from GWs

- **Can we modify mechansim of Leptogenesis to connect GWs?**
- **Scalar assisted Leptogenesis**
- **Scalar induced EWPT GWs**



Scalar assisted Leptogenesis

- Can we enhance CP, without finetuned mass splitting?

And without distablize the Higgs mass?

- Can we probe leptogenesis with GWs?

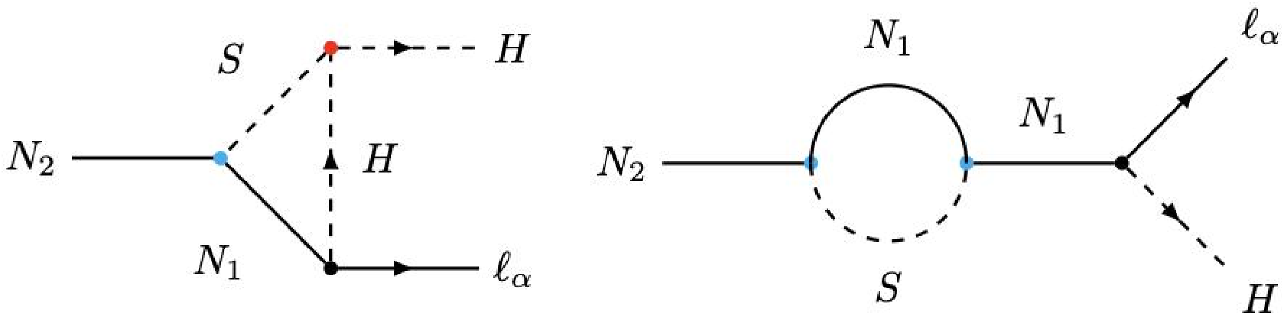
- **Toy model:**

Scalar assisted Leptogenesis, scalar Z_2 symmetric Model

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

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

Scalar assisted Leptogenesis



- **CP Asymmetry**

Require $m_{N_2} - \ m_{N_1} > m_S(T)$

CP Asymmetry from **vertex correction,** $\propto$ ***SHH***, $\propto$ $\boldsymbol{N_2 N_1 S}$

CP Asymmetry from **self energy,** $\propto$ $(\boldsymbol{N_2 N_1 S})^2$

$$\varepsilon_2^{\rm v} \sim \frac{|a_{21}|}{8\pi} \frac{\mu_{hhs}}{m_{N_2}} \sqrt{\frac{m_{N_1}}{m_{N_2}}} \left(\mathcal{F}^{\rm v}_{jLL} + \mathcal{F}^{\rm v}_{jRL} \right) , \tag{11}$$

$$\varepsilon_2^{\rm s} \sim \frac{|a_{11} a_{21}|}{8\pi} \sqrt{\frac{m_{N_1}}{m_{N_2}}} \left(\mathcal{F}^{\rm s}_{jlLL} + \mathcal{F}^{\rm s}_{jlRL} + \mathcal{F}^{\rm s}_{jlLR} + \mathcal{F}^{\rm s}_{jlRR} \right) ,$$

- **Advantage:**

Do not need degenerate RHNs, or too heavy RHNs

Need SHH couplings = $2\lambda_{SH}\omega_s$, ω_s is the vev of S

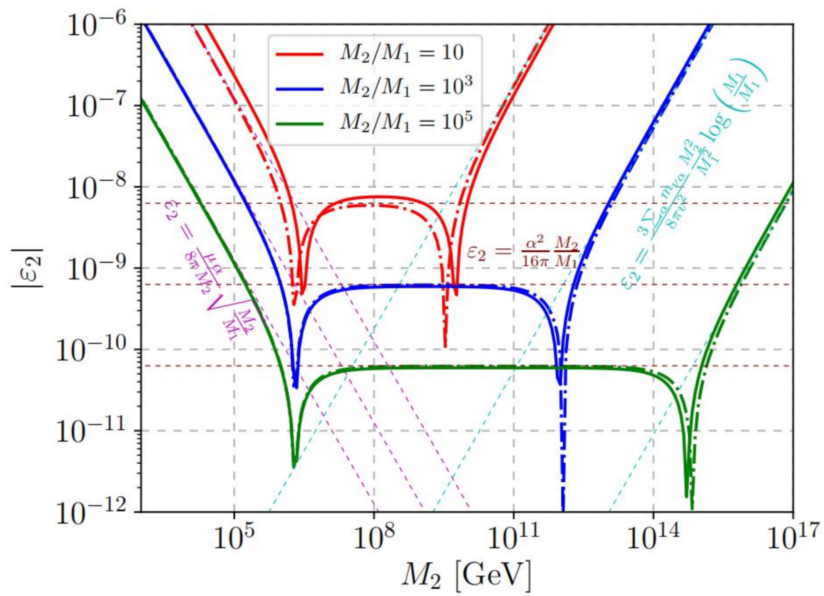
Leptogenesis is highly connected to 1st order EWPT, **in magnitude**

Scalar assisted Leptogenesis

- CP Asymmetry from **vertex correction**
Dominates for light RHNs

- CP Asymmetry from **self energy**
Dominates for not that heavy RHNs

- CP Asymmetry from **vannila seesaw**
Dominates for heavy RHNs



We consider light RHNs to avoid **Hierarchy problem**
Dominant vertex correction

Scalar assisted Leptogenesis

- Boltzmann Equations

$$\frac{\mathrm{d}N_{N_2}}{\mathrm{d}z} = -\,(D_2 + D_{21})\Delta_2 + D_{21}\Delta_1$$
$$- \Delta_{12} S_{N_1 N_2 \to HH} - \Delta_{22} S_{N_2 N_2 \to HH}$$
$$\frac{\mathrm{d}N_{N_1}}{\mathrm{d}z} = -\,(D_1 + D_{21})\Delta_1 + D_{21}\Delta_2$$
$$- \Delta_{12} S_{N_1 N_2 \to HH} - \Delta_{11} S_{N_1 N_2 \to HH}$$
$$\frac{\mathrm{d}N_{B-L}}{\mathrm{d}z} = -\sum_{i=1}^{2} \varepsilon_i D_i \Delta_i - W N_{B-L}$$

- **Additional terms from $N_2 \to N_1 S$:**

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

$$\Gamma(N_2 \to N_1 S) = \frac{|\alpha_{12}|^2 M_2}{16\pi} \left[(1 + r_{12})^2 - \sigma_2\right] \sqrt{\delta_{12}},$$

Z_2 symmetric Scalar induced EWPT

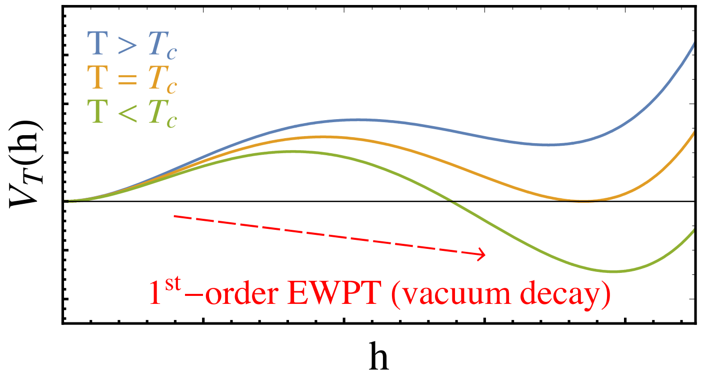
- At finite temperature up to T^2 (higher-order in numerical):

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

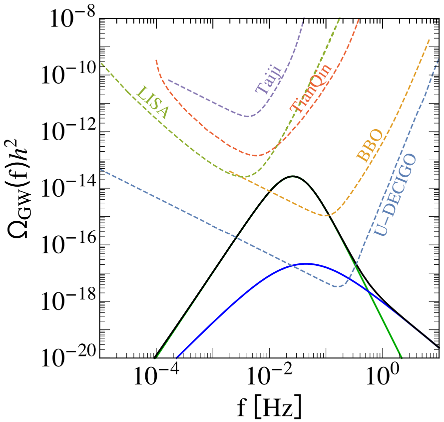
$$V(\omega_h,\omega_s,T) = V_0 + \frac{1}{2}c_h T^2\omega_h^2 + \frac{1}{2}c_s T^2\omega_s^2$$

$$c_h = \frac{3g^2+g'^2+4y_t^2}{16} + \frac{\lambda_H}{2} + \frac{\lambda_{SH}}{12},\ c_s = \frac{\lambda_S}{4} + \frac{\lambda_{SH}}{3}$$

- An Illustration –



Gravitational wave spectrum



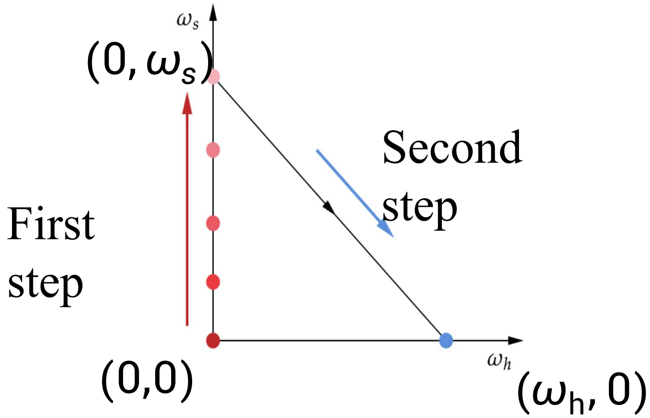
- For non− Z_2 xSM and Collider test see

WL, A.Yang, H. Sun, Phys.Rev.D 105 (2022) 11, 115040

WL, K. Xie, JHEP 04 (2021) 015

Connection between Leptogenesis and EWPT

- Two Step Phase Transition: for $\boldsymbol{Z_2}$ symmetric Model



$$\begin{cases} m_h^2 = \mu_H^2 + c_h T^2 \\ m_s^2 = \mu_S^2 + c_s T^2 \\ \mu_{hhs} = 0 \end{cases} \qquad T > -\frac{\mu_S^2}{c_s}$$

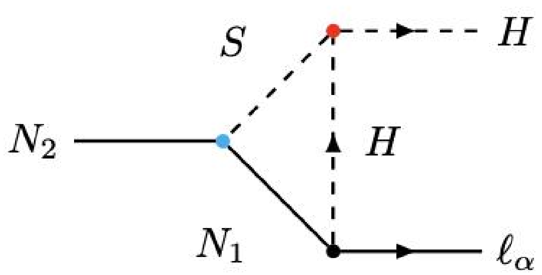
$$\begin{cases} m_h^2 = \frac{\lambda_S(\mu_H^2 + c_h T^2) - \lambda_{SH}(\mu_S^2 + c_s T^2)}{\lambda_S} \\ m_s^2 = -2(\mu_S^2 + c_s T^2) \\ \mu_{hhs} = 2\lambda_{SH}\sqrt{-\frac{\mu_S^2 + c_s T^2}{\lambda_S}} \end{cases} \qquad T_n < T < -\frac{\mu_S^2}{c_s}$$

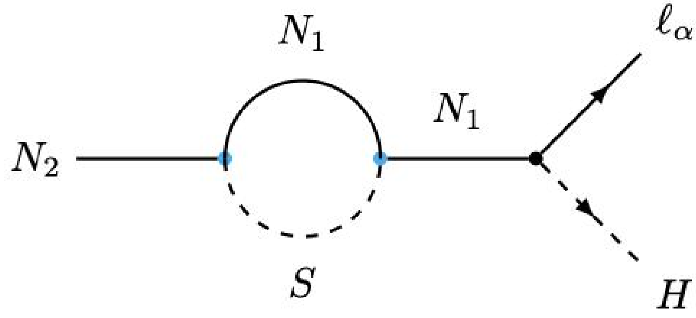
$$\begin{cases} m_h^2 = -2(\mu_H^2 + c_h T^2) \\ m_s^2 = \frac{\lambda_H(\mu_S^2 + c_s T^2) - \lambda_{SH}(\mu_H^2 + c_h T^2)}{\lambda_H} \\ \mu_{hhs} = 0 \end{cases} \qquad 0 < T < T_n$$

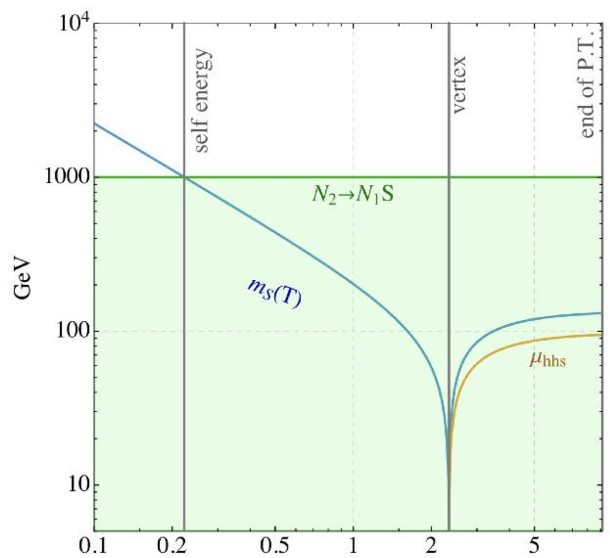
- $hhs \propto \lambda_{SH}\omega_s$ interaction **between** 1st and 2nd PT
- $m_S(T)$ decrease in time, to make $N_2 \to N_2 + S$ happen
- CP Asymmetry from **self energy** when this process happen
- from **vertex correction with** hhs interaction
- is highed related to the EWPT

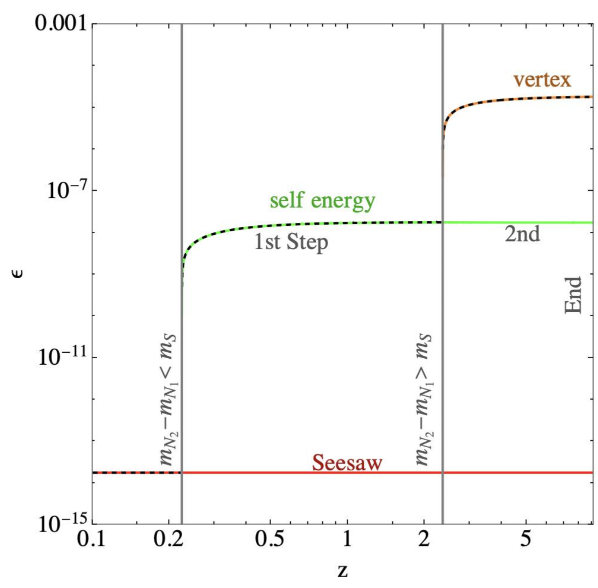
Connection between Leptogenesis and EWPT

- CP Asymmetry is highed related to the EWPT in time!







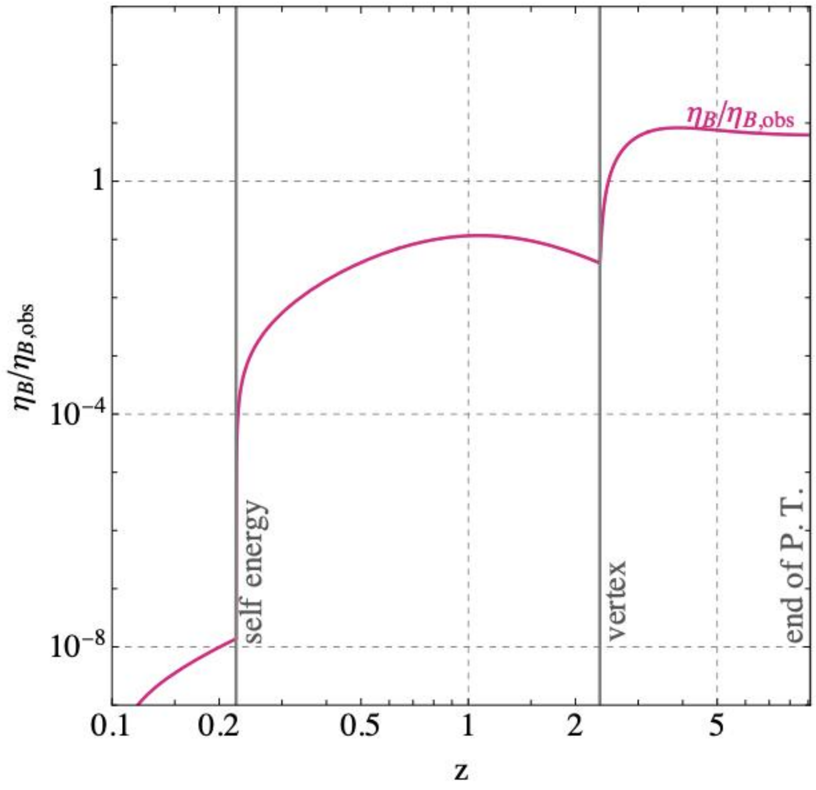


Connection between Leptogenesis and EWPT

- Leptogenesis is highly connected to 1st order EWPT, **in time**

Require $m_{N_2} - m_{N_1} > m_S(T)$, mass bound

$\lambda_{SHH} = 2\lambda_{SH}\omega_s$, ω_s is the vev of S

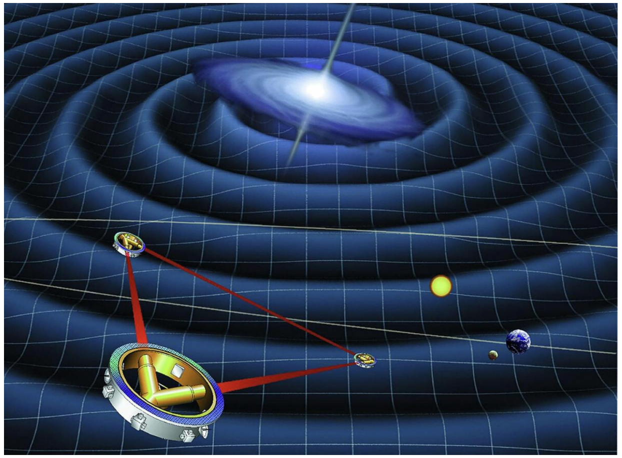


Observable GWs

- GW spectrum can be calculated from EWPT:

$$\alpha = \frac{\Delta(V - \frac{1}{4}T\partial_T V)|_{T_n}}{g_* \pi^2 T_n^4/30}, \quad \frac{\beta}{H_n} = T\frac{d(S_3/T)}{dT}\Big|_{T_n}.$$

- For the LISA detector, signal-to-noise ratio (SNR):



$$\mathrm{SNR} = \sqrt{\mathcal{T}\int_{f_{\min}}^{f_{\max}} df \left(\frac{\Omega_{\mathrm{GW}}(f)}{\Omega_{\mathrm{LISA}}(f)}\right)^2}$$

SNR > 10, can be regarded as criteria of signal

- **Large SNR** from $\boldsymbol{\lambda_{SHH} = 2\lambda_{SH}\omega_s}$

Test Leptogenesis from Observable GWs

- Leptogenesis is strongly correlated to GWs!

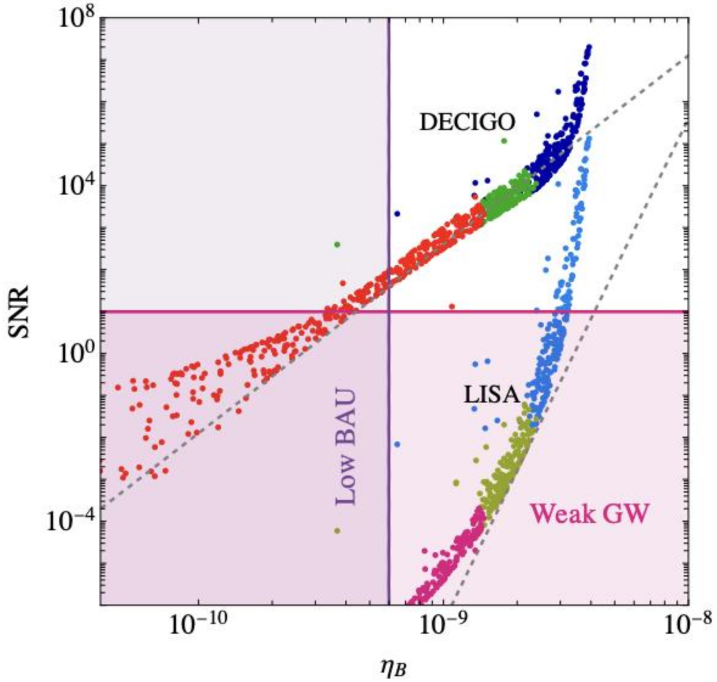
T_n: Nucleation temperature,
T_c: Critical temperature, degenerate vacuum
$T_c - T_n > 10$ GeV:
Strong EWPT,

- For one benchmark:

Linear dependence!

- **General correlation**

weaker dependence
when mass bound close before PT
$m_{N_2} - m_{N_1} > m_S(T)$



- **Successful Leptogenesis can lead to observable GWs in the near future**

Conclusion

Leptogenesis can be tested via Gravitational Waves

- CP Asymmetry can be enhanced by additional scalar
- No fine-tuning N mass splitting,
- **CP Asymmetry connected to 1st-order** EWPT

  in magnitude, $\propto \lambda_{SH}\omega_s$**, also control 1st-order EWPT**

  in time, near the EWPT period, EWPT control mass bound
- Leptogenesis is strongly correlated to GWs, **can be tested from Observable GWs**

Leptogenesis

BAU from neutrino!

1. Lepton number is violated within the neutrino masses terms.

2. **Additional CP violations** can exists in the **neutrino mass matrix.**

3. Right-handed neutrinos decay out of equilibrium potentially.

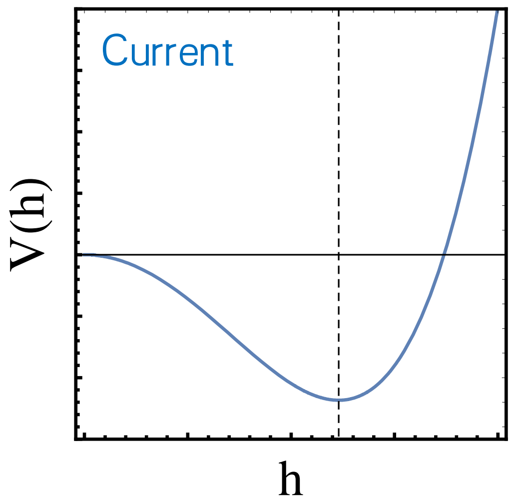
And EW sphaleron to transfer $n_{\Delta L}$ into $n_{\Delta B}$ before EW phase transition,

$$Y_B = \frac{28}{79} Y_{B-L}$$

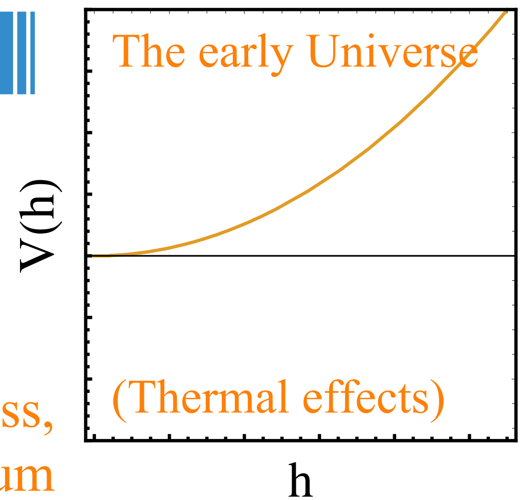
Scalar induced EWPT

What is EWPT?

EW symmetry restoration in the early Universe



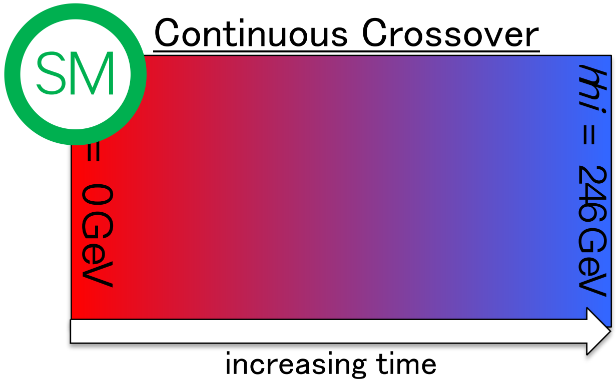
W & *Z* bosons are massive;
Photon is massless,
Mexican-hat like



$SU(2)_L$ & $U(1)_Y$ bosons are massless,
True vacuum

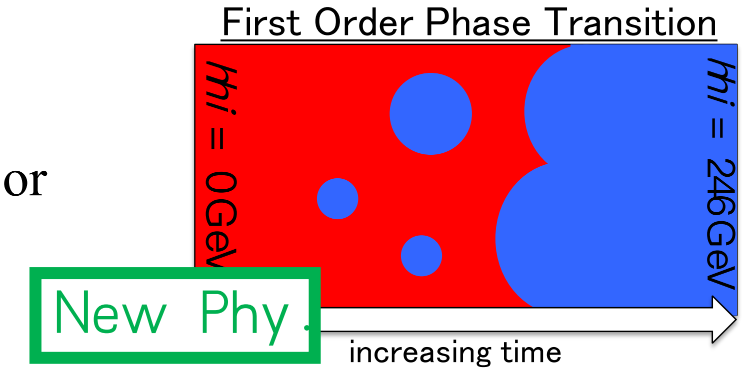
Scalar induced EWPT

It could be –

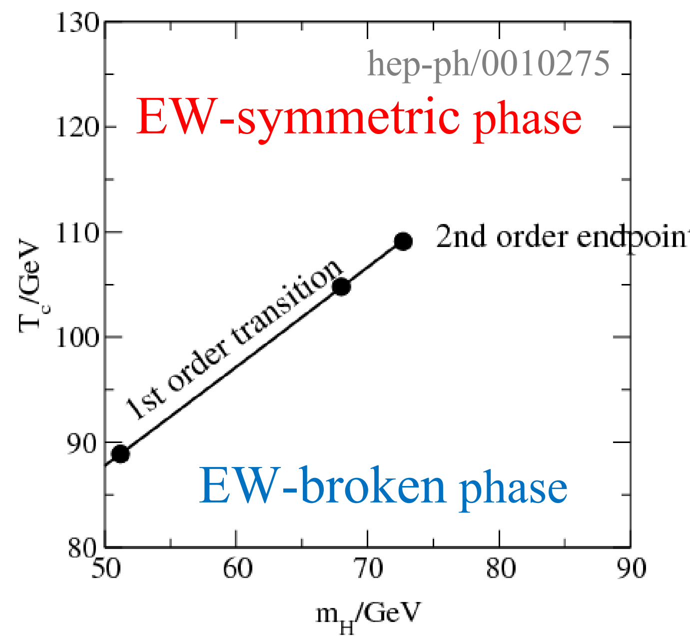


or

Figure from L.-T. Wang's talk in IHEP workshop



Lattice calculation shows the phase diagram ==>



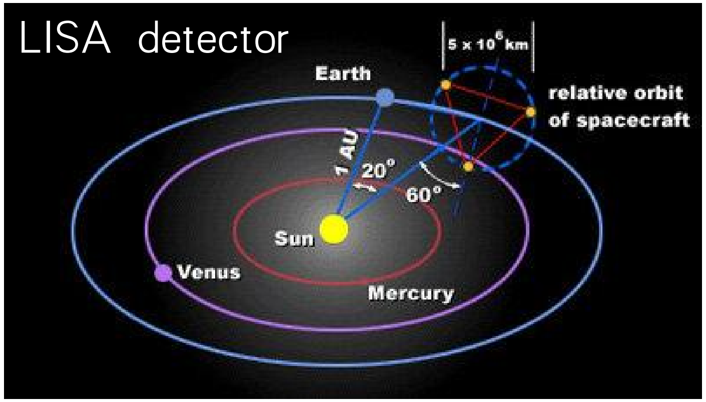
Thus in the SM it is a crossover, since M_h = 125 GeV > 75 GeV;

However, a 1st-order EWPT is more interesting.
(Needs new physics)

Scalar induced EWPT

Why we focus **1st-Order EWPT**?
Sources of the stochastic GWs:

- Collision of the bubbles
- Sound waves in plasma
- Turbulance in plasma



EWPT GWs typically peak in mHz.