南京理工大学
NANJING UNIVERSITY OF SCIENCE & TECHNOLOGY

Testing Leptogenesis from Observable Gravitational Waves

Wei Liu (刘威)
Nanjing University of Science and Technology
in collaboration with Yongcheng Wu
Arxiv:2504.07819

Baryon Asymmetry of the Universe

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

from Planck satellite

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

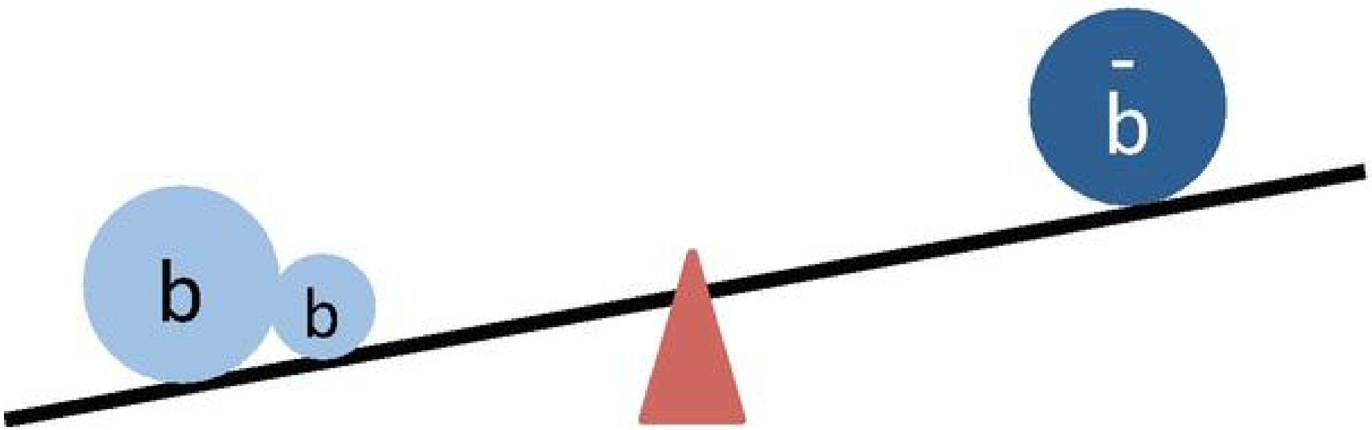
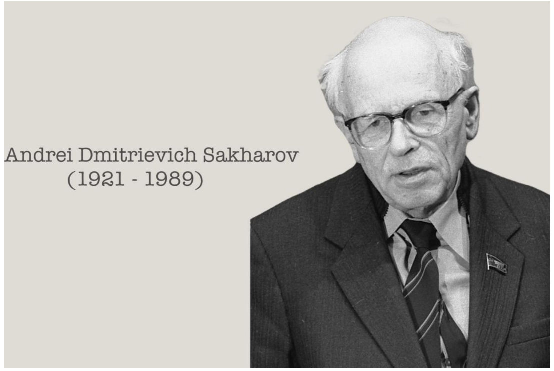


Figure from Kaori Fuyuto

Baryon Asymmetry of the Universe



- Sakhorov's criteria

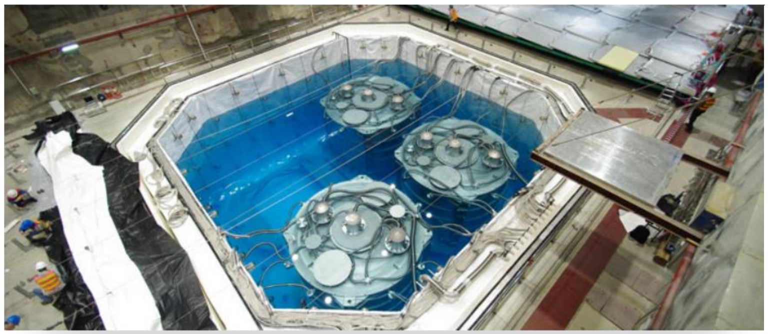
1. Baryon number violating process,
   Generate $n_{\Delta B}$.
   Triangle Anomoly
2. C and CP violations,
   $\Gamma(X \rightarrow Y + b) \neq \Gamma(\overline{X} \rightarrow \overline{Y} + \overline{b})$, L *and* R.
   CKM
3. Out of equilibrium.
   $\Gamma(X \rightarrow Y + b) \neq \Gamma(Y + b \rightarrow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

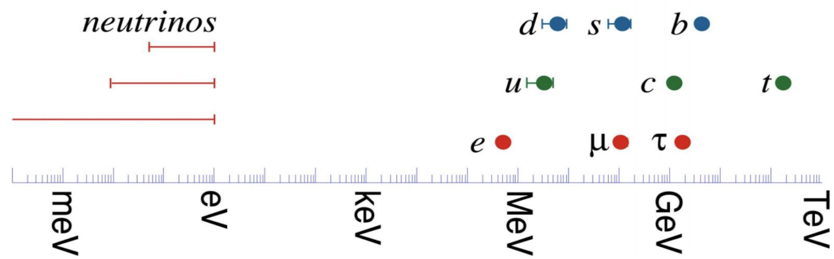
Way too small to explain the observed BAU within the SM. **We need new physics!**

Baryon Asymmetry of the Universe

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

from Planck satellite





Seesaw mechanism

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

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

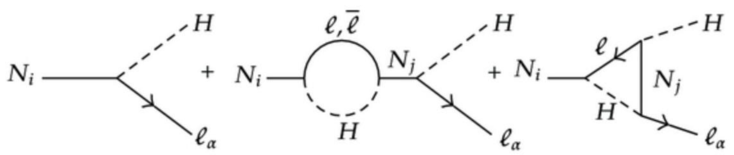
$$m_1 \approx \frac{-M_D^2}{M_R}, m_2 \approx M_R.$$

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.

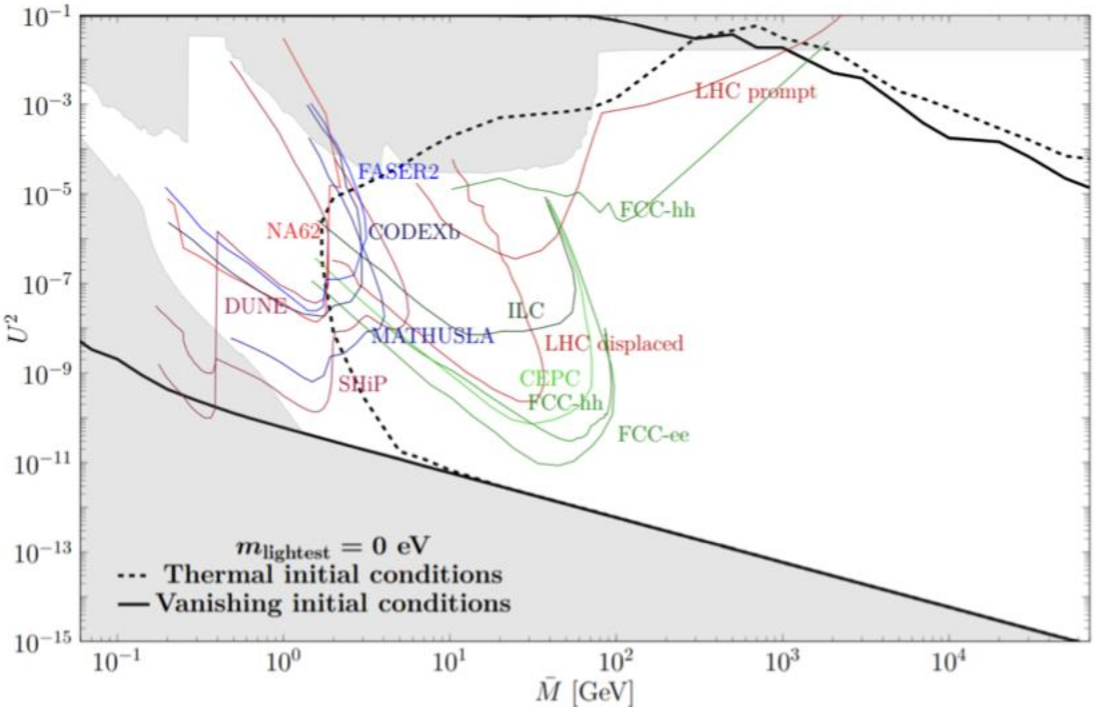
Test Leptogenesis

- **How to test leptogenesis?**

High scale: Collider can not reach

Low scale: Can not measure mass degeneracy

Only allowed region, **No test**

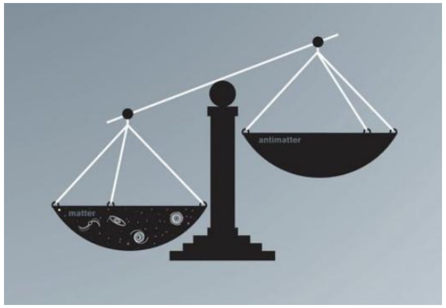


Marco Drewes, Yannis Georis et al, Phys.Rev.Lett. 128 (2022) 5, 051801

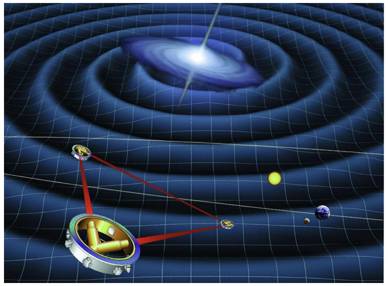
Test Leptogenesis from GWs

7

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



Leptogenesis

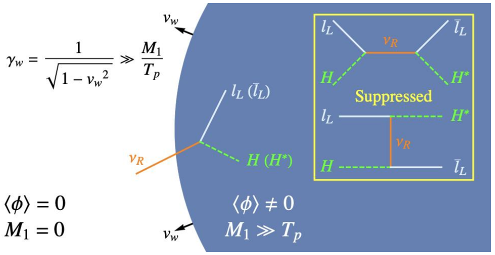


GWs

- **Relativistic bubble wall dynamics**

EWPT, RHN mass, wall speed

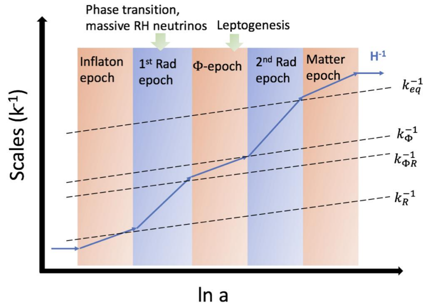
I. Baldes, S. Blasi et al, Phys.Rev.D 104 (2021) 11, 115029
P. Huang, K. Xie, JHEP 09 (2022), 052
D. Borah, A. Dasgupta et al, JHEP 11 (2022), 136
E. J. Chun, T. P. Dutka et al, JHEP 09 (2023), 164



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

Inflation or EWPT GWs

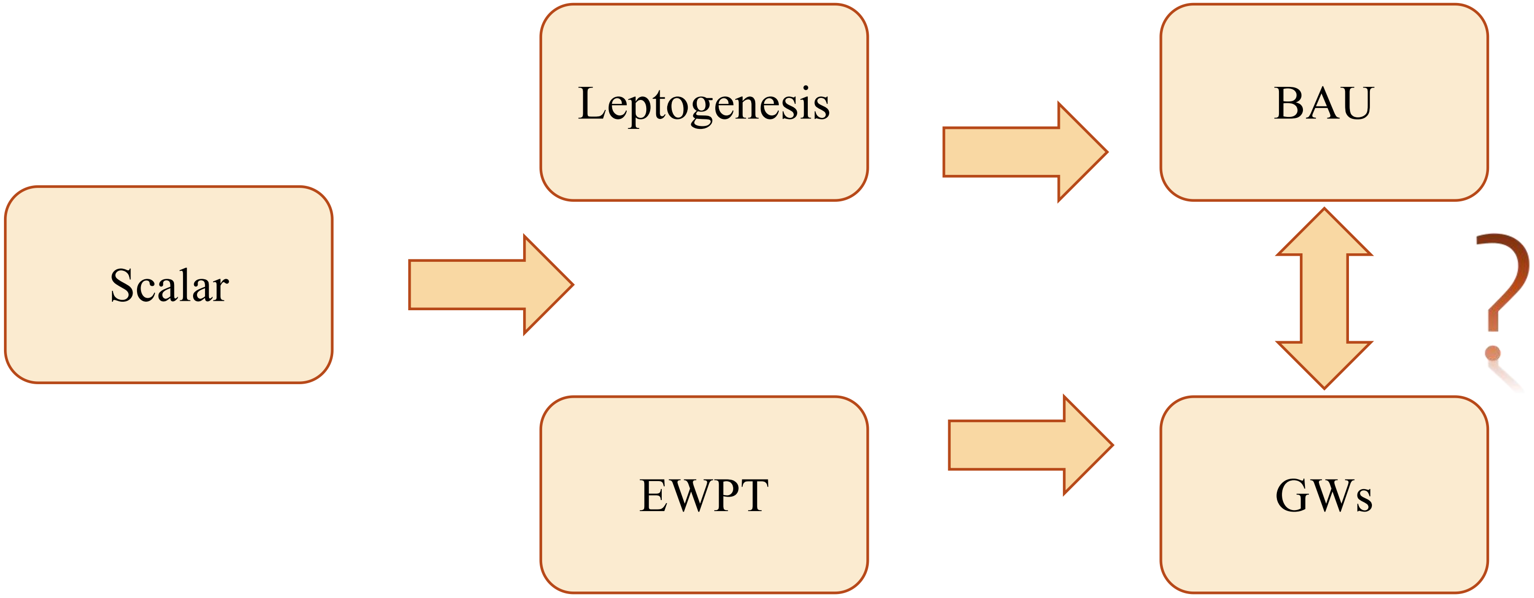
S. Datta, R. Samanta et al, JHEP 11 (2022), 159,
JCAP 11 (2024) 051, JCAP 08 (2025), 095
More from A. Ghoshal et al



- **Graviton...**

Test Leptogenesis from GWs

- Can we modify mechansim of Leptogenesis to connect GWs?



Scalar assisted Leptogenesis

- Can we enhance CP, without finetuned mass splitting?
And without distablize the Higgs mass?

- Can we probe leptogenesis with GWs?

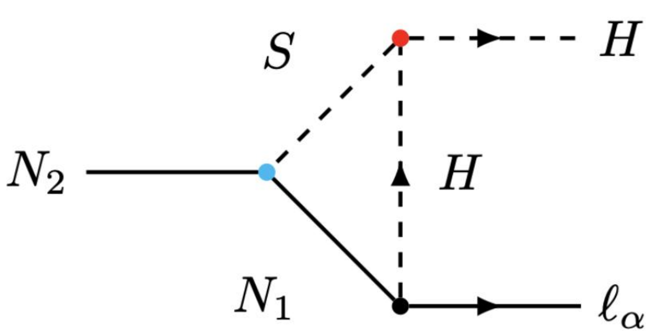
- **Toy model:**
Scalar assisted Leptogenesis, scalar Z_2 symmetric Model

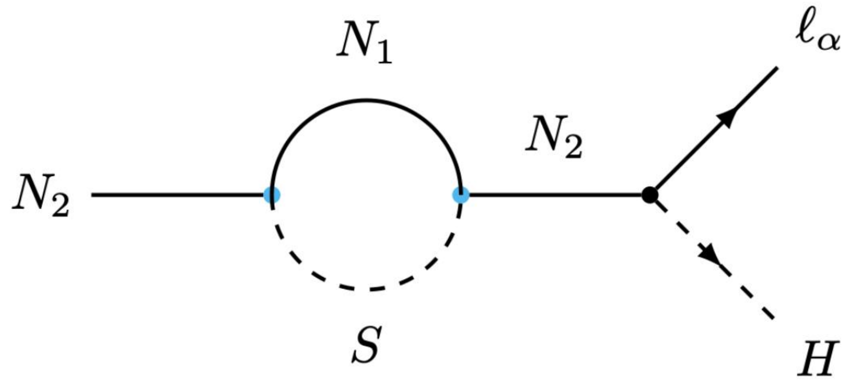
$$-\mathcal{L} \supset \left[h_{\alpha i}\, \bar{\ell}_\alpha N_i H + \frac{1}{2} \left(M_{ij} + a_{ij} \mathcal{S} \right) N_i N_j + \text{H.c.} \right],$$

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

Scalar assisted Leptogenesis

10





- **CP Asymmetry**

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

CP Asymmetry from **vertex correction,** $\propto$ ***SHH*, $\propto$ *N*$_2$*N*$_1$*S***

CP Asymmetry from **self energy,** $\propto$ $(N_2N_1S)^2$

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

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

- **Advantage:**

Do not need degenerate RHNs, or too heavy RHNs

No fine-tuning, Higgs mass stable

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

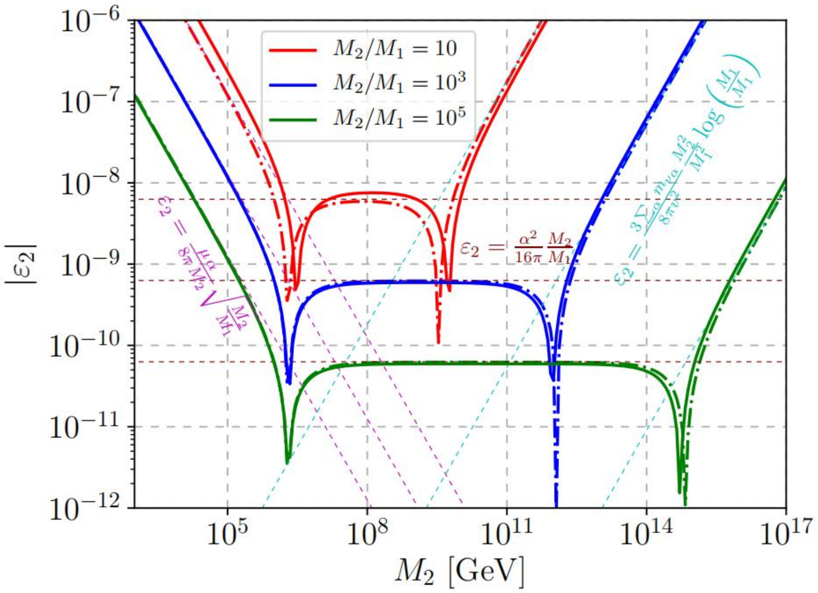
Leptogenesis is highly connected to 1st order EWPT, **in magnitude**

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 $N_2 \to N_1 S$:**

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

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

Scalar induced EWPT

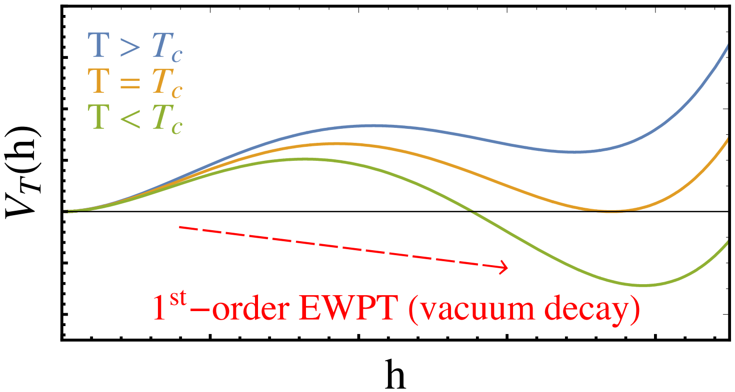
- At finite temperature:

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

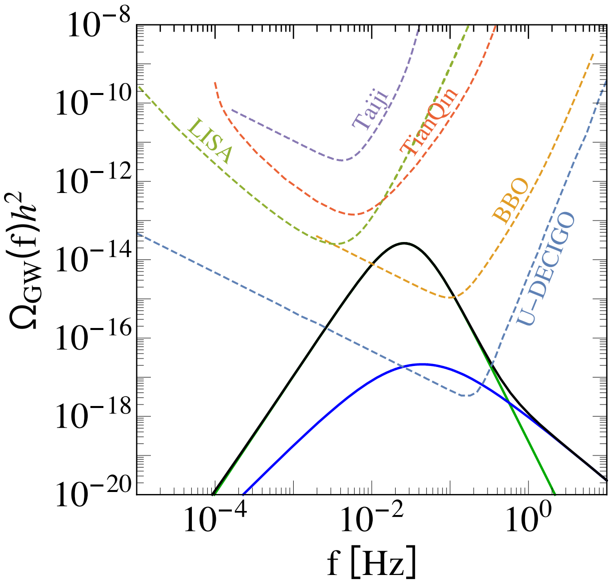
$$V(\omega_h,\omega_s,T) = V_0 + \frac{1}{2}c_h T^2\omega_h^2 + \frac{1}{2}c_s T^2\omega_s^2$$

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

- An Illustration –



Gravitational wave spectrum



Magnitude controlled by λ_{SH}, λ_S, ω_s

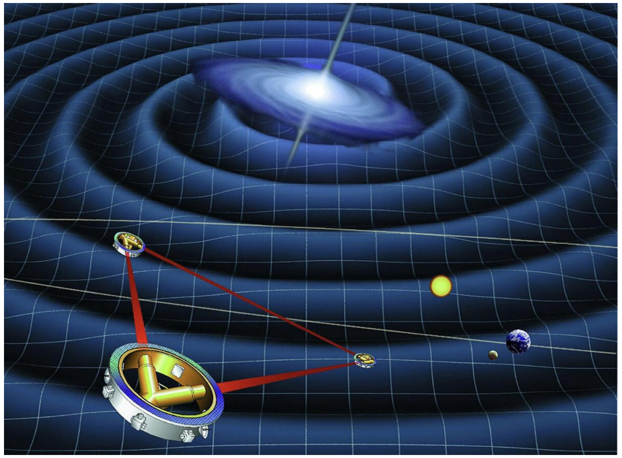
Observable GWs

- 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):

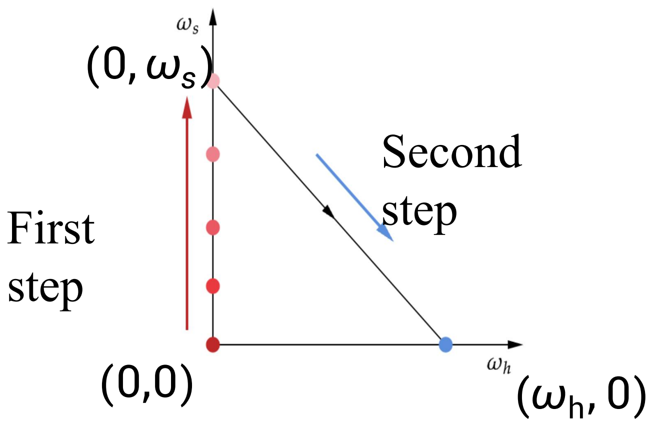
$$\mathrm{SNR} = \sqrt{\mathcal{T}\int_{f_{\min}}^{f_{\max}} df \left(\frac{\Omega_{\mathrm{GW}}(f)}{\Omega_{\mathrm{LISA}}(f)}\right)^2}$$

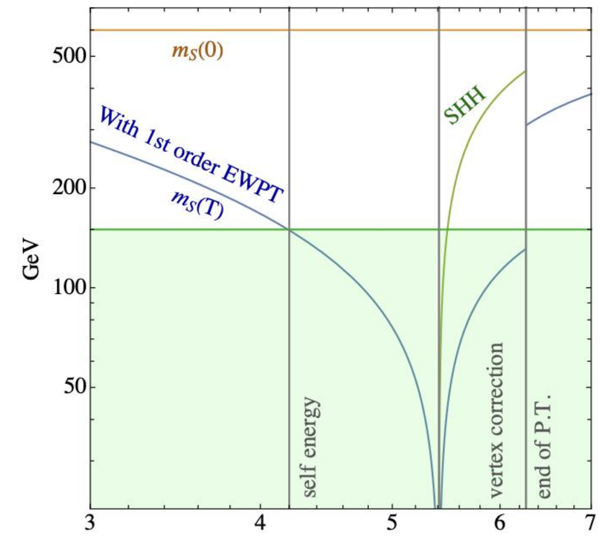


SNR > 10, can be regarded as criteria of signal

Connection between Leptogenesis and EWPT

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

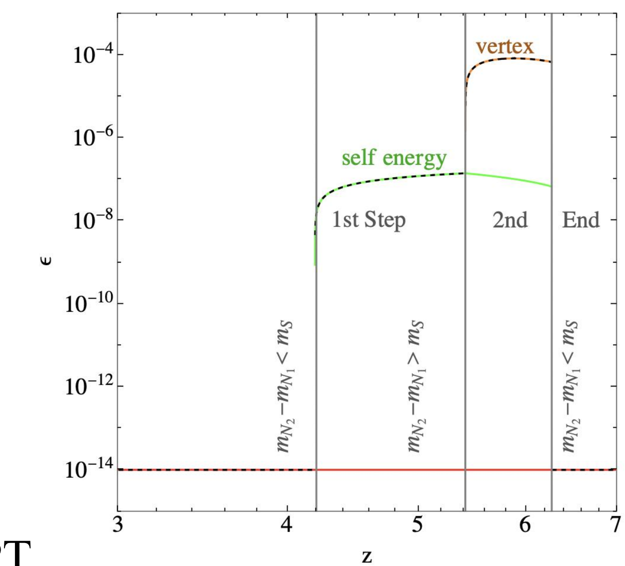




$$\begin{cases} m_h^2 = \mu_H^2 + c_h T^2 \\ m_s^2 = \mu_S^2 + c_s T^2 \\ \mu_{hhs} = 0 \end{cases} \qquad T > -\frac{\mu_S^2}{c_s}$$

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

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



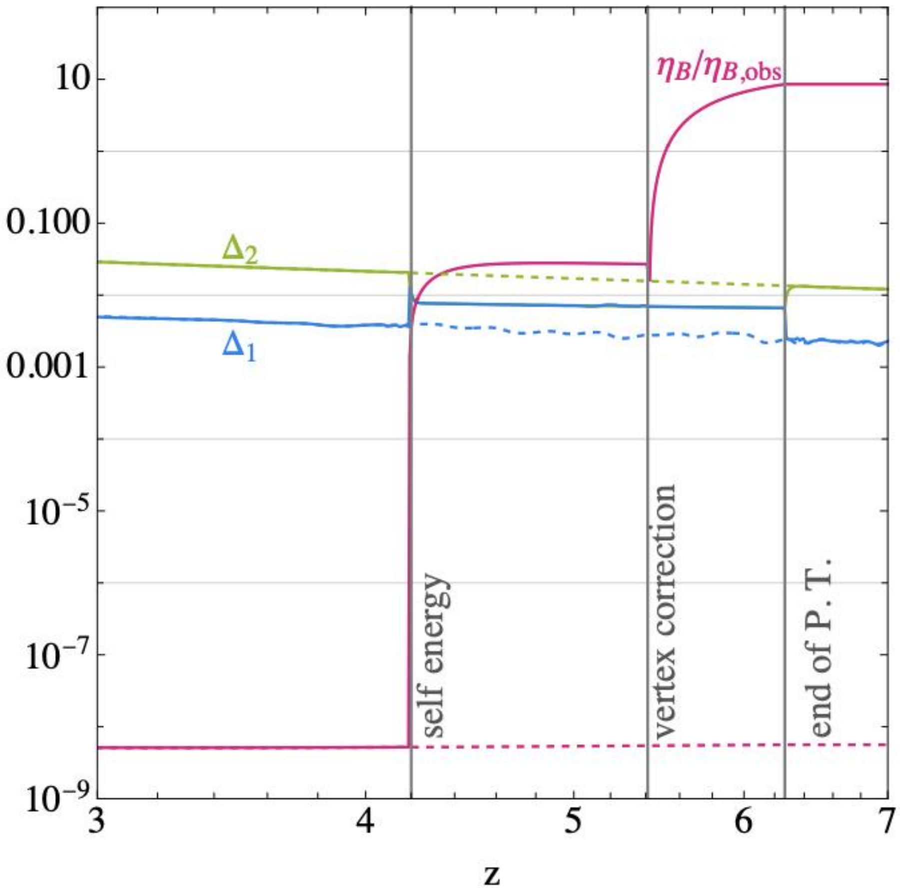
- CP Asymmetry is highed related to the EWPT

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

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



Testing Leptogenesis from Observable GWs

- Leptogenesis is strongly correlated to GWs!

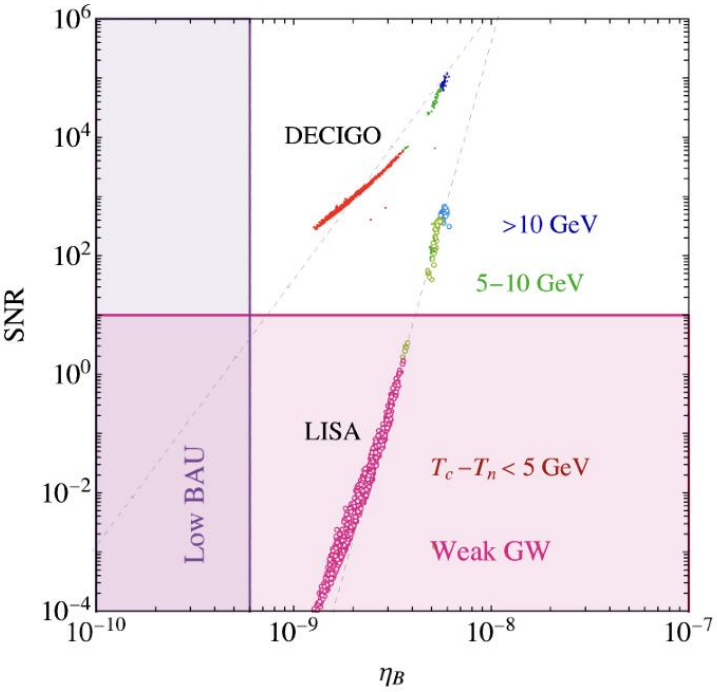
T_n: Nucleation temperature,
T_c: Critical temperature, degenerate vacuum
$T_c - T_n > 10$ GeV: Strong EWPT,

- 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, Higgs mass stable
- **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.

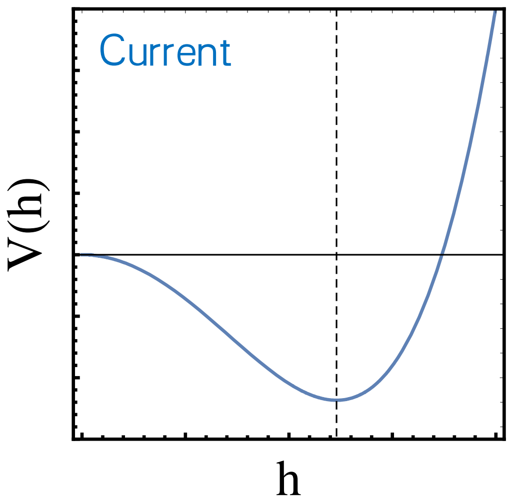
And EW sphaleron to transfer $n_{\Delta L}$ into $n_{\Delta B}$ before EW phase transition,

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

Scalar induced EWPT

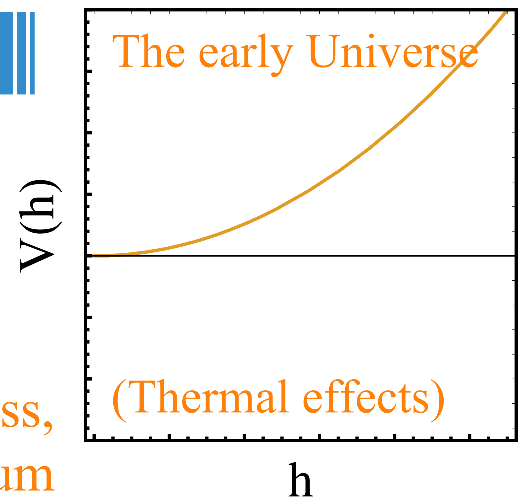
What is EWPT?

EW symmetry restoration in the early Universe



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

Phase transition

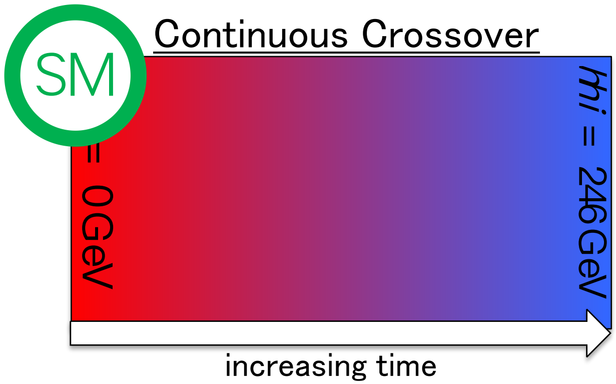


$SU(2)_L$ & $U(1)_Y$ bosons are massless,
True vacuum

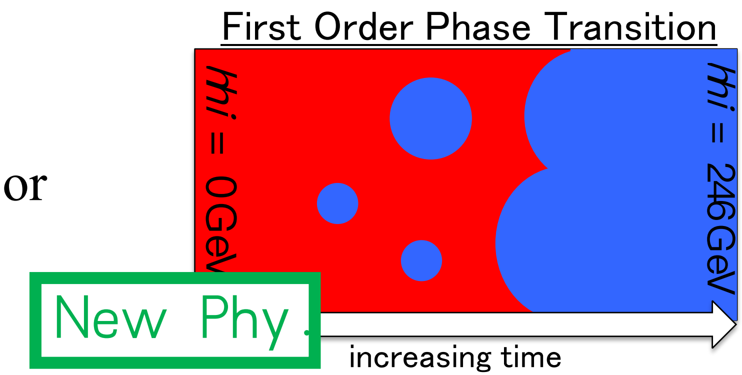
Scalar induced EWPT

It could be –

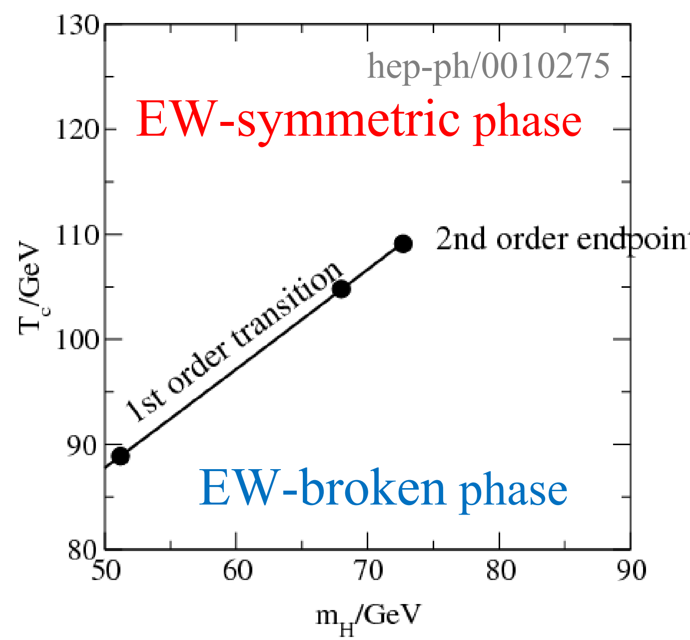
Figure from L.-T. Wang's talk in IHEP workshop



or



Lattice calculation shows the phase diagram ==>



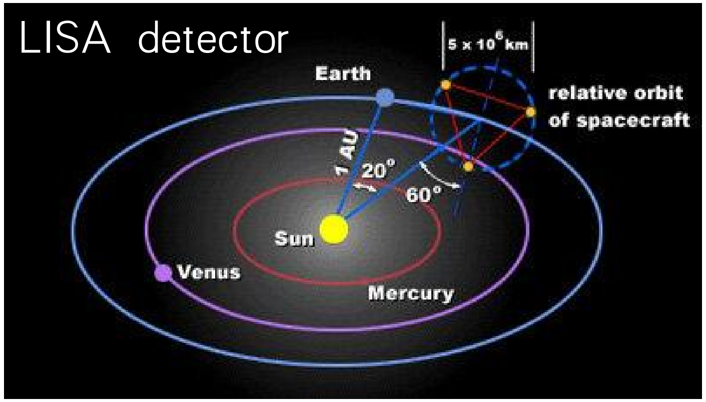
Thus in the SM it is a crossover, since M_h = 125 GeV > 75 GeV;

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.