Exploring Leptogenesis in the Era of First-Order Electroweak Phase Transition

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with

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- Our observable Universe is mostly made of matter

asymmetry is defined as :

$$\eta_B = \frac{n_B - n_{\bar{B}}}{s} \quad \text{or} \quad \eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

- Can it be just an initial value for η (accepting the fine tuning) ?

- Inflation erases any pre-existing asymmetry, if any. Hence, asymmetry must be created only after inflation.

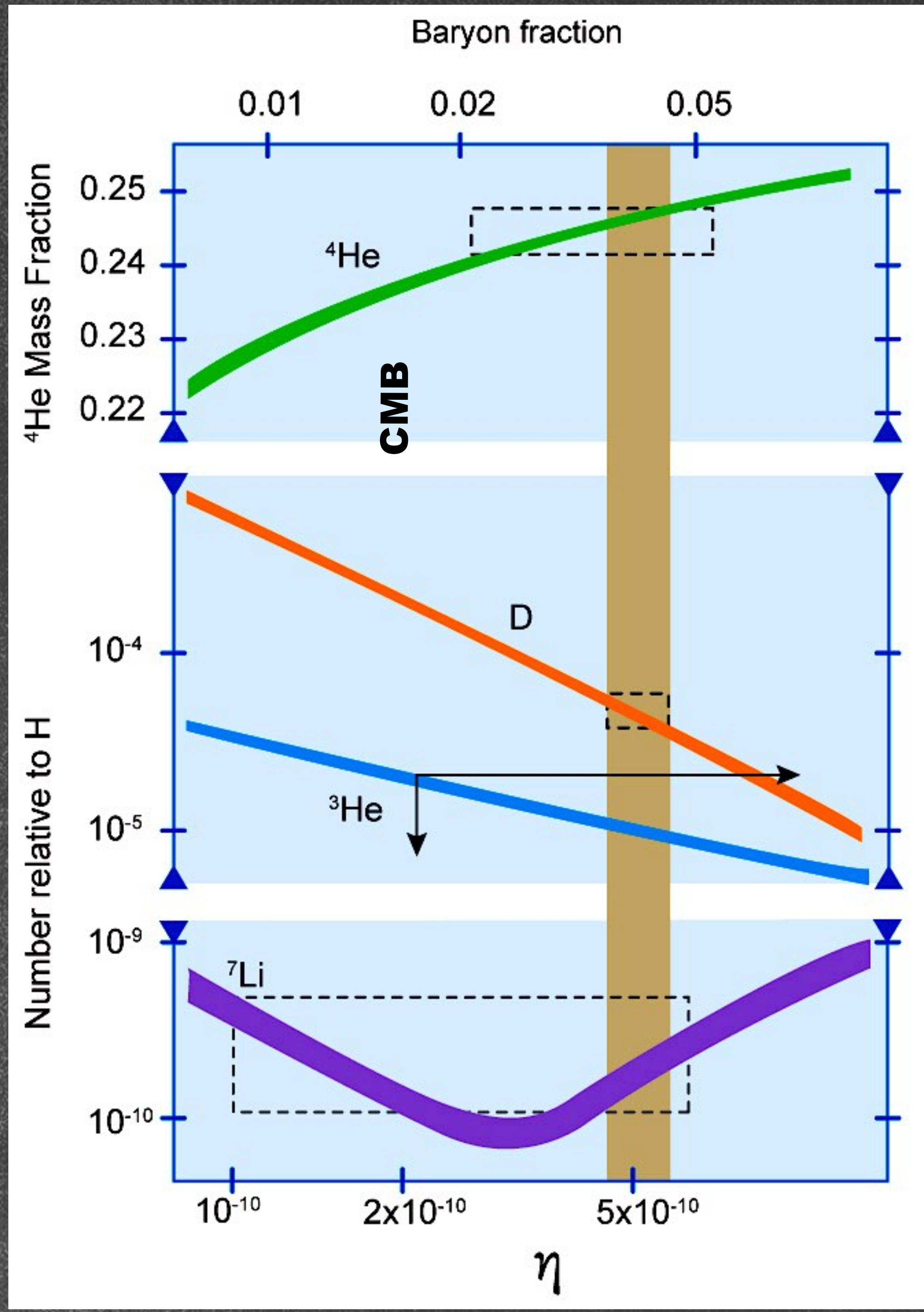


Photo credits: Libretexts Physics

- From WMAP data :

$$\eta = (6.14 \pm 0.25) \times 10^{-10}$$

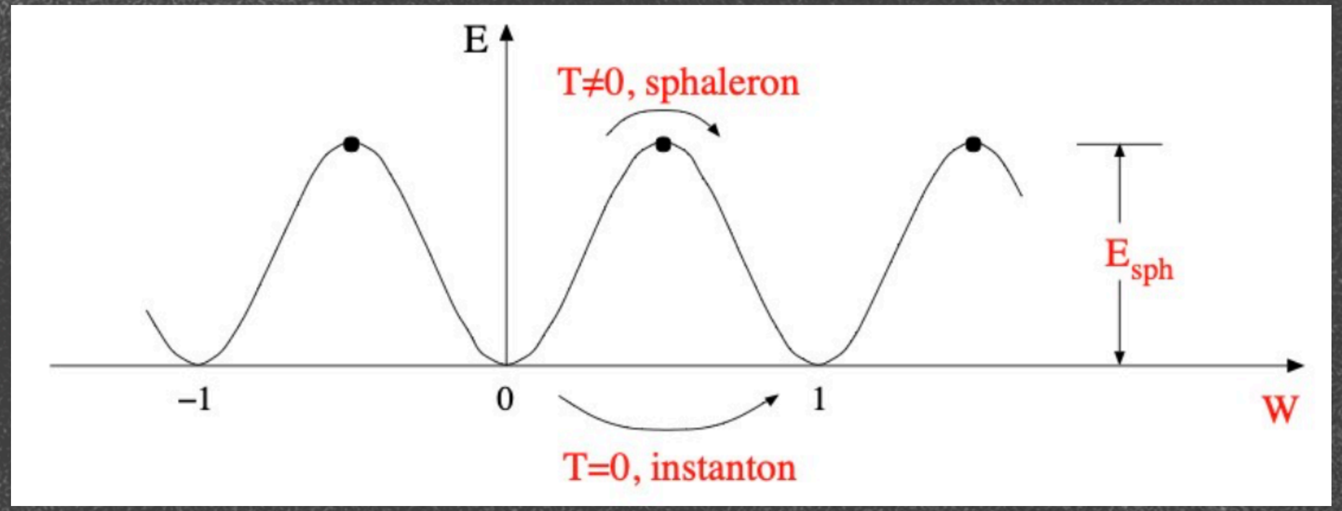
- Measurement of η from deuterium abundance (D/H) :

$$\eta = (6.28 \pm 0.35) \times 10^{-10}$$

dynamical origin of asymmetry

Sakharov's Conditions:

- B violation → Sphaleron process
- C & CP violation → CKM matrix element
- Out-of-equilibrium



B+L violating
&
B-L conserving

$\cancel{CP}$ amount is not sufficient

Need BSM sector

One promising mechanism is Thermal Leptogenesis (Hierarchical RHNs)

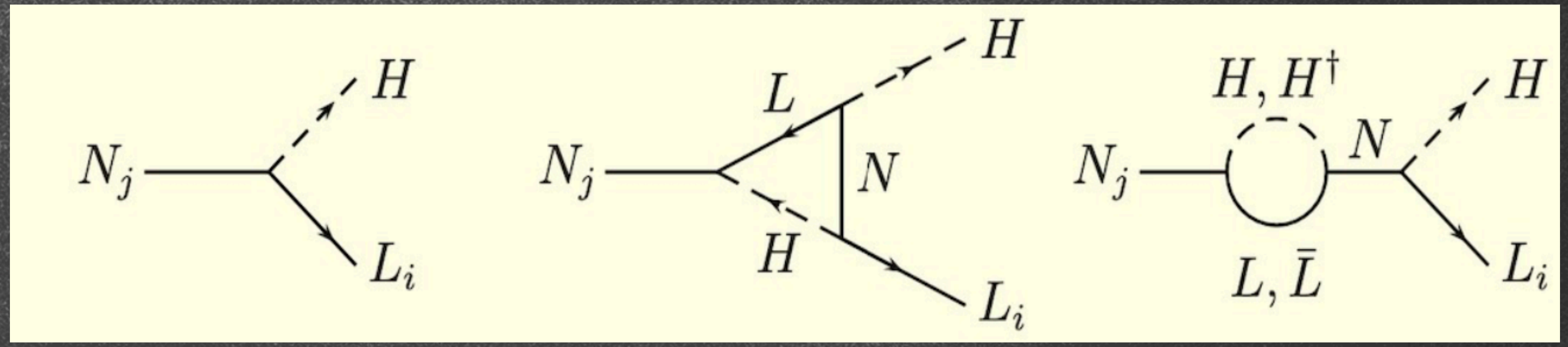
Type-I seesaw Lagrangian: $-\mathscr{L}_{\mathrm{I}} = (Y_\nu)_{\alpha i}\, \bar{\ell}_{L_\alpha} \tilde{H} N_i + \frac{1}{2} \overline{N_i^c} M_i N_i + h.c.$

Out-of-equilibrium, $\cancel{CP}$ & $\cancel{L}$ decay: $N_i \to \bar{\ell}_{L_\alpha} + H$

Solves smallness of neutrino mass problem

$\boxed{\mathrm{B-L}\ \text{asymmetry}} \longrightarrow \boxed{\text{Sphaleron transitions}} \longrightarrow \boxed{\text{Baryon asymmetry}}$

RHNs decay out of equilibrium



To satisfy the observed baryon asymmetry $\mathcal{O}(10^{-10}) \longrightarrow M_1 > 10^9$ GeV (Davidson-Ibarra bound)

[Phys. Lett. B 535, 25 (2002)]

From detection perspective, lowering the RHN mass scale is interesting!

A possible way:
Resonant Leptogenesis

For (quasi-degenerate) RHN mass $\longrightarrow$

Works for $M_1 > T_{\mathrm{EW}}$ (~ 160 GeV)

$$\varepsilon_\ell^i = \sum_{j\neq i} \frac{\mathrm{Im}(Y_\nu^\dagger Y_\nu)_{ij}^2}{(Y_\nu^\dagger Y_\nu)_{ii}(Y_\nu^\dagger Y_\nu)_{jj}} \frac{[M_i^2 - M_j^2] M_i \Gamma_{N_j}}{[M_i^2 - M_j^2]^2 + M_i^2 \Gamma_{N_j}^2}$$

The CP asymmetry can be enhanced $\mathcal{O}(1)$

Will it be possible to work with RHN mass below T_{EW}

$$\Gamma_{\rm Sp}^{\rm broken} \sim T^4 e^{-E_{\rm sp}(T)/T}$$

$\propto v(T)$

- Below $T_{\rm EW}$ ($\sim$ 160 GeV)
$N_i \to \overline{\ell}_{L_\alpha} + H$ is kinematically forbidden as Higgs and lepton, thermally corrected, become massive.

Leptogenesis can proceed via Higgs decay in a small temperature window: $T_{\rm sp}^{\rm SM} < T < T_{\rm EW}$

Phys. Rev. Lett. 117, 091801 (2016)

- Below $T_{\rm EW}$, the sphaleron rate becomes exponentially suppressed and gets decoupled at $T_{sp}^{SM} \sim 131.7$ GeV
as a result, NO lepton-to-baryon asymmetry

Bottom line: leptogenesis requires the temperature of the Universe to exceed $T_{sp}^{SM} \sim 131.7$ GeV

- The problem is further compounded provided the reheating temperature of the universe $T_{\rm RH} < T_{\rm sp}^{SM}$

The universe never reaches the temperature above $T_{\rm EW}$

No other existing mechanism of Baryogenesis via Leptogenesis can occur.

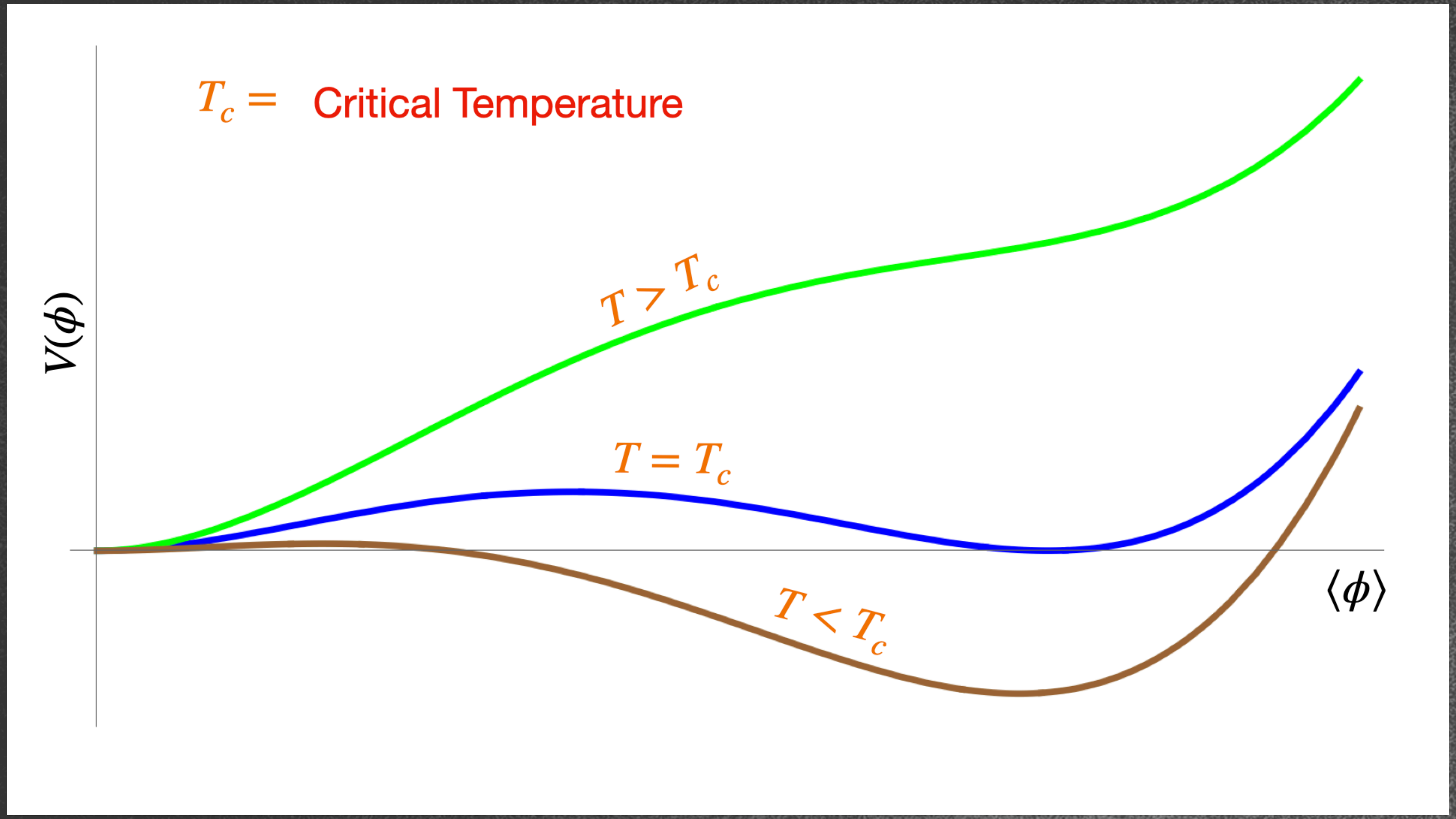
Leptogenesis below $T_{\rm sp}^{\rm SM}$ (~ 131.7 GeV) is not apparently possible

A relevant question emerges: is it feasible to realize leptogenesis when the reheating temperature lies below the $T_{\mathrm{sp}}^{\mathrm{SM}}$, i.e., 131.7 GeV?

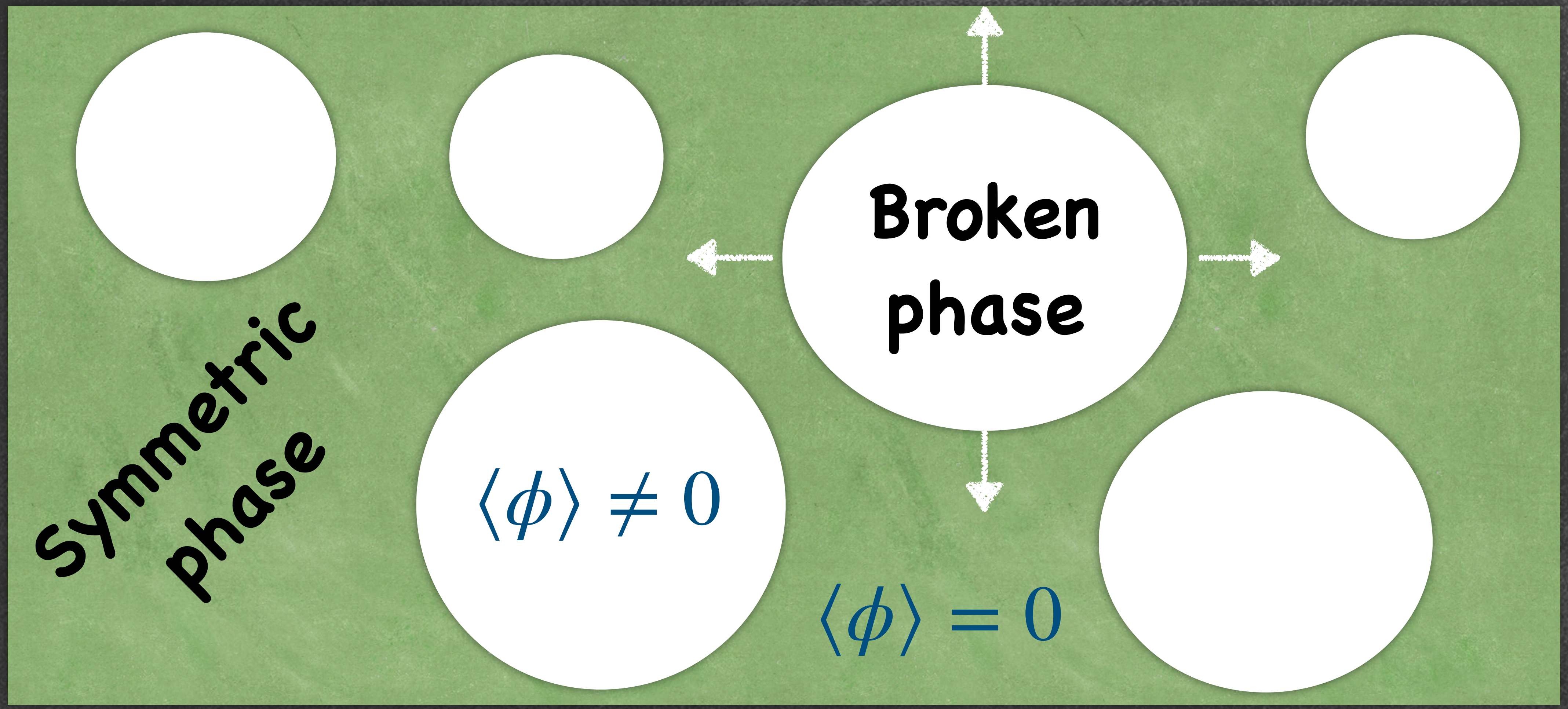
Proposal:

Leptogenesis indeed remains a possibility at such a low scale, provided the electroweak phase transition (EWPT) is of strongly first order

First Order Phase Transition



Proceeds through bubble nucleation



At T_n ($< T_c$) One true vacuum bubble, inside which $\langle \phi \rangle \neq 0$, is nucleated per horizon volume [in the background of false vacuum ($\langle \phi \rangle = 0$)]

↓

The **symmetric phase** is prevalent in the entire Universe until T_n

↓

If T_n associated to EWSB can be kept below $T_{\rm sp}^{\rm SM} \sim 131.7$ GeV, then

Till such a lower temperature:

(I) SM fields remain massless [$N_i \to \overline{\ell}_{L_\alpha} + H$ allowed]

(II) Sphaleron rate remains unsupressed

(inside the bubble, $\Gamma_{\rm sph}^{\rm (in)} \sim T^4 \exp\left[-8\pi v(T)/g_{\rm w} T\right]$)

Lepgogenesis via RHN decay (of mass even closer to T_n) seems to work till Universe attains a temperature $T_n < T_{\rm sp}^{\rm SM}$

Can we realise $T_n < T_{\rm sp}^{\rm SM}$ in a First Order Electroweak Phase Transition (FOEWPT) ?

To investigate, let us have a specific construction for the FOEWPT by extending the Tree-level Higgs potential extended by dimension-6 operator $(H^\dagger H)^3/\Lambda^2$

First Order Electroweak Phase Transition

Tree-level Higgs potential extended by dimension-6 operator $(H^\dagger H)^3/\Lambda^2$ can be written in terms of the background (classical) field ϕ as:

$$V^{\text{tree}}_{(\phi)} = -\frac{\mu_h^2}{2}\phi^2 + \frac{\lambda_h}{4}\phi^4 + \boxed{\frac{1}{8}\frac{\phi^6}{\Lambda^2}}$$

Here, $H^T = \left[G_1 + iG_2,\, \phi + h + iG_3\right]/\sqrt{2}$ with G_i as the Goldstone bosons and h the physical Higgs field, and Λ is the cut-off scale.

The Coleman-Weinberg (CW) potential:

$$V_{CW}(\phi, T) = \frac{1}{64\pi^2}\sum_{i=\phi,G,W,Z,\gamma_L,t} n_i m_i^4(\phi, T)\left[\log\left(\frac{m_i^2(\phi, T)}{\mu^2}\right) - c_i\right]$$

Finite temperature one-loop potential :

$$V_T(\phi, T) = \frac{T^4}{2\pi^2}\left[\sum_{i=\phi,G,W,Z} n_i J_B\left(\frac{m_i^2(\phi, T)}{T^2}\right) - \sum_{i=t} n_i J_F\left(\frac{m_i^2(\phi, T)}{T^2}\right)\right]$$

Full effective potential: $V_{\text{eff}}(\phi, T) = V^{\text{tree}}_{(\phi)} + V_{\text{CW}}(\phi, T) + V_{\text{T}}(\phi, T) + V_{\text{ct}}(\phi)$

The daisy correction has been implemented through Parwani resummation method: $m_i^2(\phi, T) \to m_i^2(\phi) + \Pi_i(T)$

First Order Electroweak Phase Transition continued

Taking high-temperature approximation, expand the thermal functions $J_{B,F}(m^2/T^2)$ in terms of m^2/T^2 and restricting terms upto order T^2, the effective potential takes the form as :

$$\boxed{V_{\text{eff}}(\phi, T) = \left(-\frac{\mu_h^2}{2} + \frac{1}{2}c_h T^2\right)\phi^2 + \left(\frac{\lambda_h}{4} + \frac{\lambda_1}{4}T^2\right)\phi^4 + \frac{1}{8}\frac{\phi^6}{\Lambda^2},}$$

where,

$$c_h = \frac{1}{16}\left(\frac{4m_h^2}{v_0^2} + 3g_w^2 + g_Y^2 + 4y_t^2 - 12\frac{v_0^2}{\Lambda^2}\right)$$

and

$$\lambda_1 = \frac{1}{\Lambda^2}$$

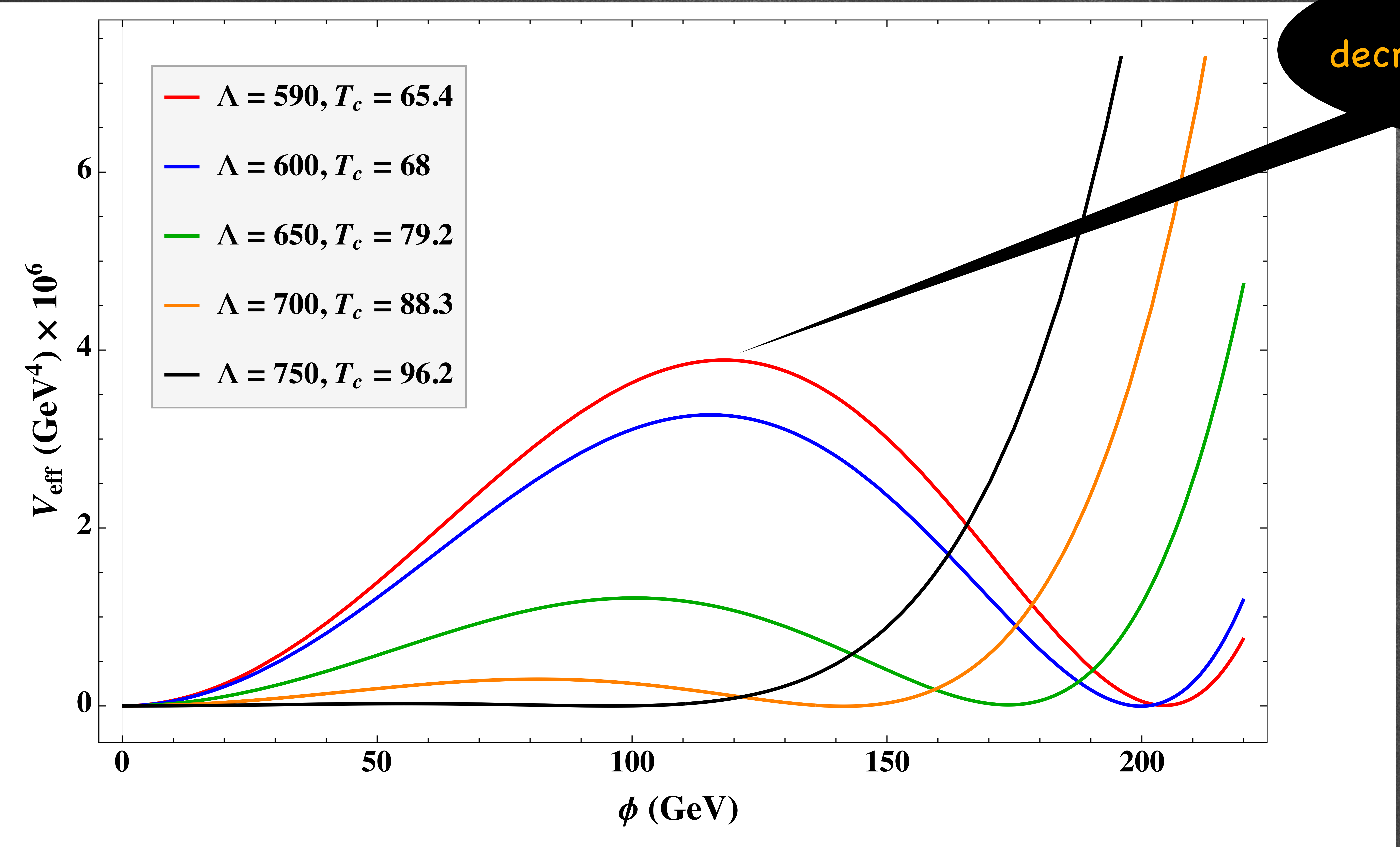
The parameters μ_h and λ_h can be determined using the conditions:

$$\left.\frac{dV_{\text{eff}}(\phi, T=0)}{d\phi}\right|_{\phi=v_0} = 0 \quad , \quad \left.\frac{d^2V_{\text{eff}}(\phi, T=0)}{d\phi^2}\right|_{\phi=v_0} = m_h^2$$

Upper bound on the cut-off scale Λ

At T_c , the critical temperature, the false (local) and true (global) minima become degenerate and a potential barrier arises in between.

$\phi = 0$ $\phi \neq 0$



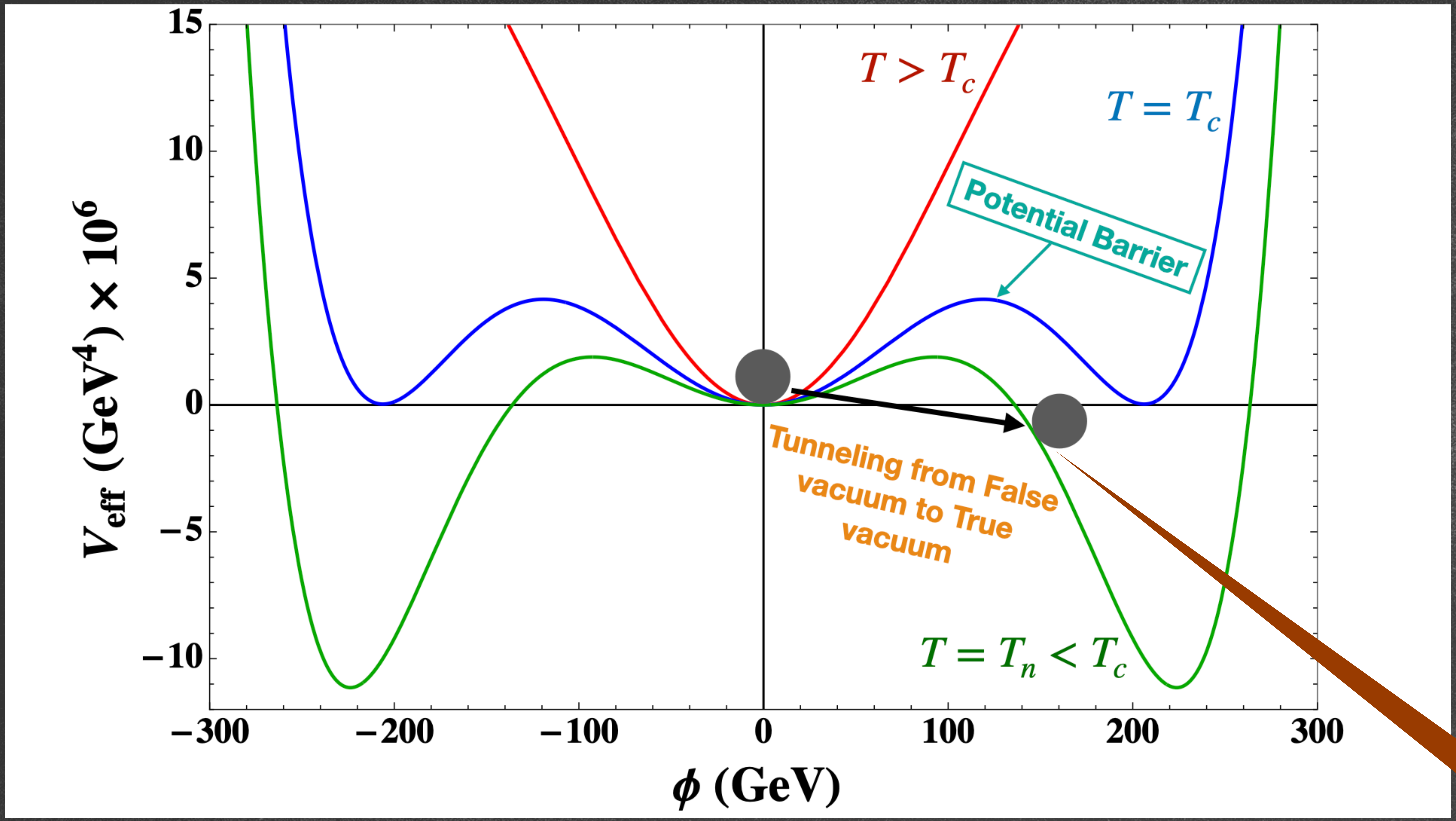
Barrier height decreases with increasing Λ

At $\Lambda = 810\,\text{GeV}$, barrier height diminishes significantly.

For $\Lambda > 810\,\text{GeV}$, no first order transition happens.

$\Lambda = 810\,\text{GeV}$serves the upper limit.

False-vacuum decay and Bubble Nucleation



False-vacuum decay rate:

$$\Gamma(T) \simeq T^4 \left(\frac{S_3(T)}{2\pi T}\right)^{3/2} \exp\left(-S_3(T)/T\right)$$

[A. D. Linde, Nucl. Phys. B 216, 421 (1983)]

The action S_3 has the form as:

$$S_3(T) = 4\pi \int dr\, r^2 \left(\frac{1}{2}\left(\frac{d\phi}{dr}\right)^2 + V_{\rm eff}(\phi, T)\right)$$

$$\Gamma(T) \geq \mathscr{H}^4(T)$$

where, $\mathscr{H}(T)$ is the Hubble parameter

Tunneling from false vacuum to true one proceeds efficiently.

Nucleation temperature and Lower limit of Λ

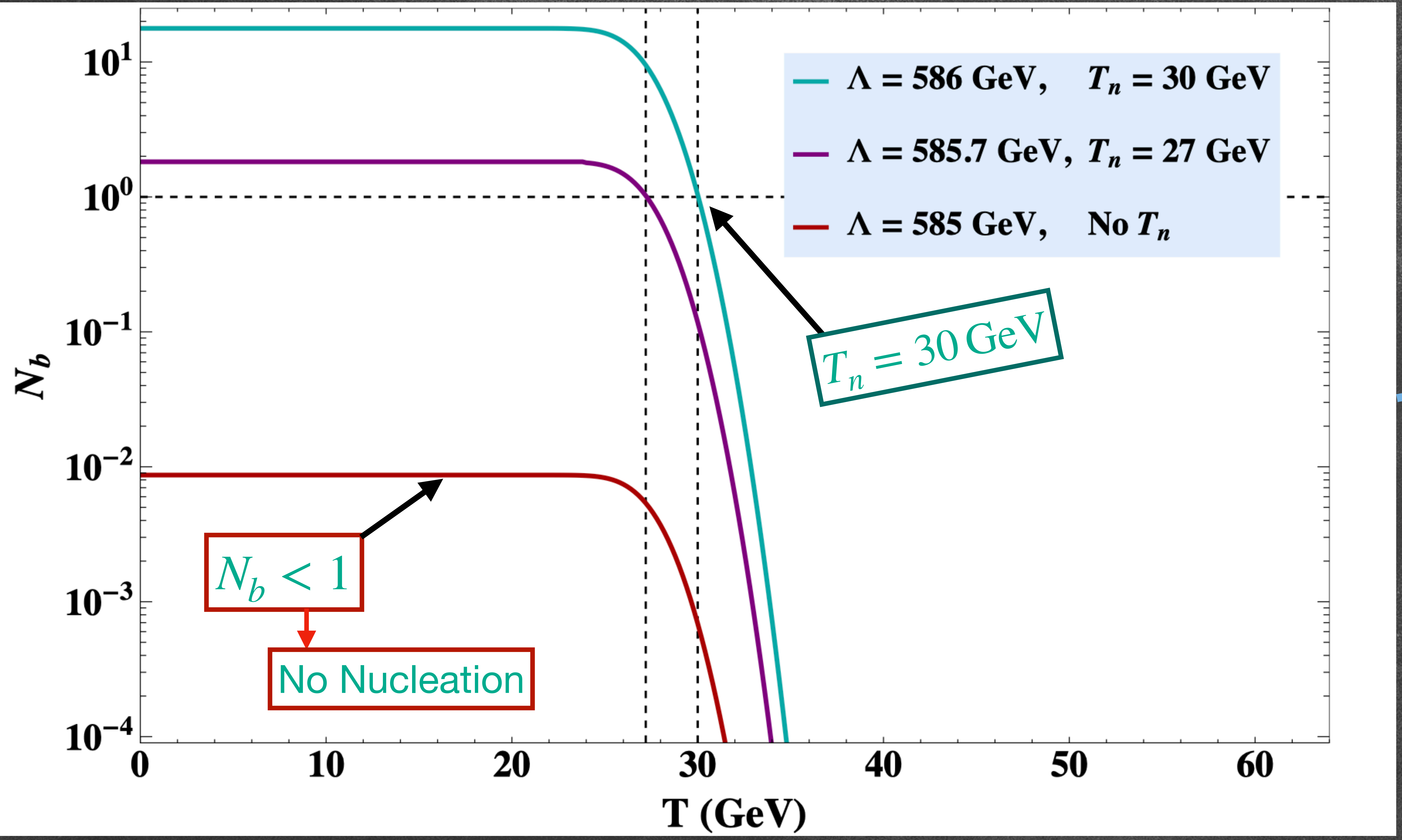
Number of bubbles per horizon volume

$$N_b(T_n) = \int_{T_n}^{T_c} \frac{dT}{T} \frac{\Gamma(T)}{\mathcal{H}(T)^4} = 1$$

The temperature at which the probability of forming at least one bubble per horizon volume reaches order one is known as Nucleation Temperature: T_n

Initiating bubble nucleation

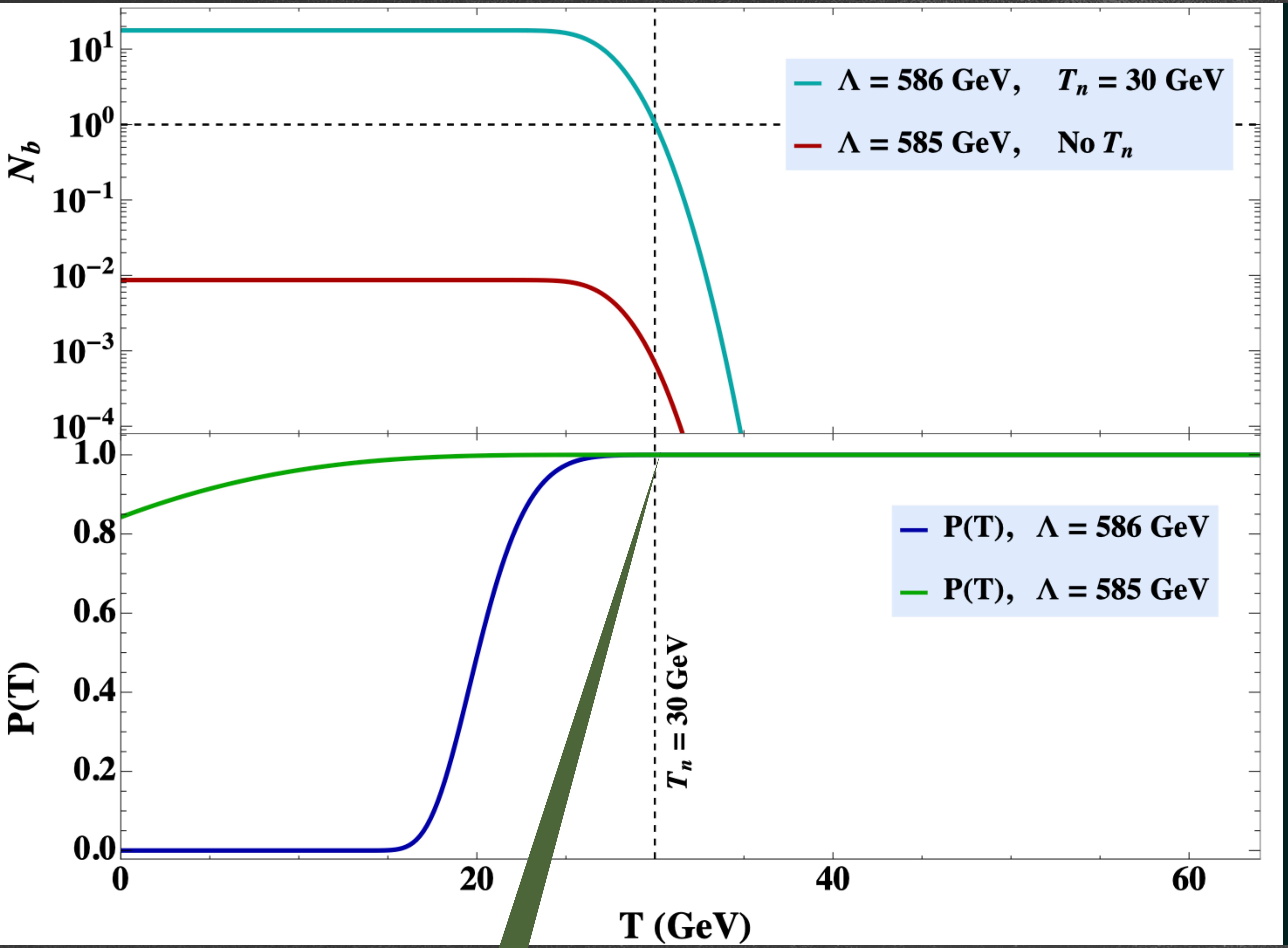
Allowing bubbles to exceed the critical size and continue expanding.



$\Lambda \simeq 586\,\text{GeV}$ serves the lower bound on Λ .

The corresponding lowest nucleation temperature $T_n^{\min} = 30\,\text{GeV}$.

Lowering the Sphaleron decoupling temperature



The probability, $P(T)$, of a spatial point remaining in the false vacuum state at a temperature T is defined as:

$$P(T) = e^{-I(T)},$$

$$I(T) = \frac{4\pi}{3}\int_T^{T_c} dT' \frac{\Gamma(T')}{T'^4\,\mathscr{H}(T')}\left(\int_T^{T'} d\tilde{T}\,\frac{v_w}{\mathscr{H}(\tilde{T})}\right)^3$$

[Phys. Rev. D 23, 876 (1981)]
[Phys. Rev. Lett. 44, 631 (1980)]

But in the Standard Model, the sphaleron decoupling temperature is $131.7\,\mathrm{GeV}$.

$P(T_n = 30\,\mathrm{GeV}) \simeq 1$ implies that the symmetric phase (false vacuum) still exists till T_n.

The Sphaleron is active and in thermal equilibrium till $T_n = 30\,\mathrm{GeV}$, as the sphaleron rate, $\Gamma_{\rm sph} \sim T^4 \exp\left(-8\pi v(T)/g_w T\right)$, is unsuppressed due to the $\mathrm{Higgs\ vev},\, v(T) = 0$.

Low Scale Leptogenesis

Electroweak phase transition is of strong first order

Till $T_n^{\rm min} = 30\,\rm GeV$, the universe is trapped in the false vacuum $\left(\text{Higgs vev} = 0\right)$ where SM fields are massless.

RHNs of mass $T_n^{\rm min} < M_N < m_{W,Z}$ can decay out of equilibrium to SM Higgs and lepton doublets and produce lepton asymmetry.

The sphaleron decoupling temperature can be lowered as low as $T_n^{\rm min} = 30\,\rm GeV$.

Lepton-to-baryon asymmetry conversion remains possible down to temperatures as low as $30\,\rm GeV$.

low scale leptogenesis remains viable even with RHN masses below the SM gauge boson's masses, $m_{W,Z}$.

Reheating (instantaneous) temperature below the SM sphaleron decoupling temperature $131.7\,\rm GeV$

No existing low scale leptogenesis mechanism successfully generates baryon asymmetry.

In strongly first order electroweak phase transition scenario, baryon asymmetry can be generated even through direct decay of RHNs to SM lepton and Higgs

Resonant Leptogenesis

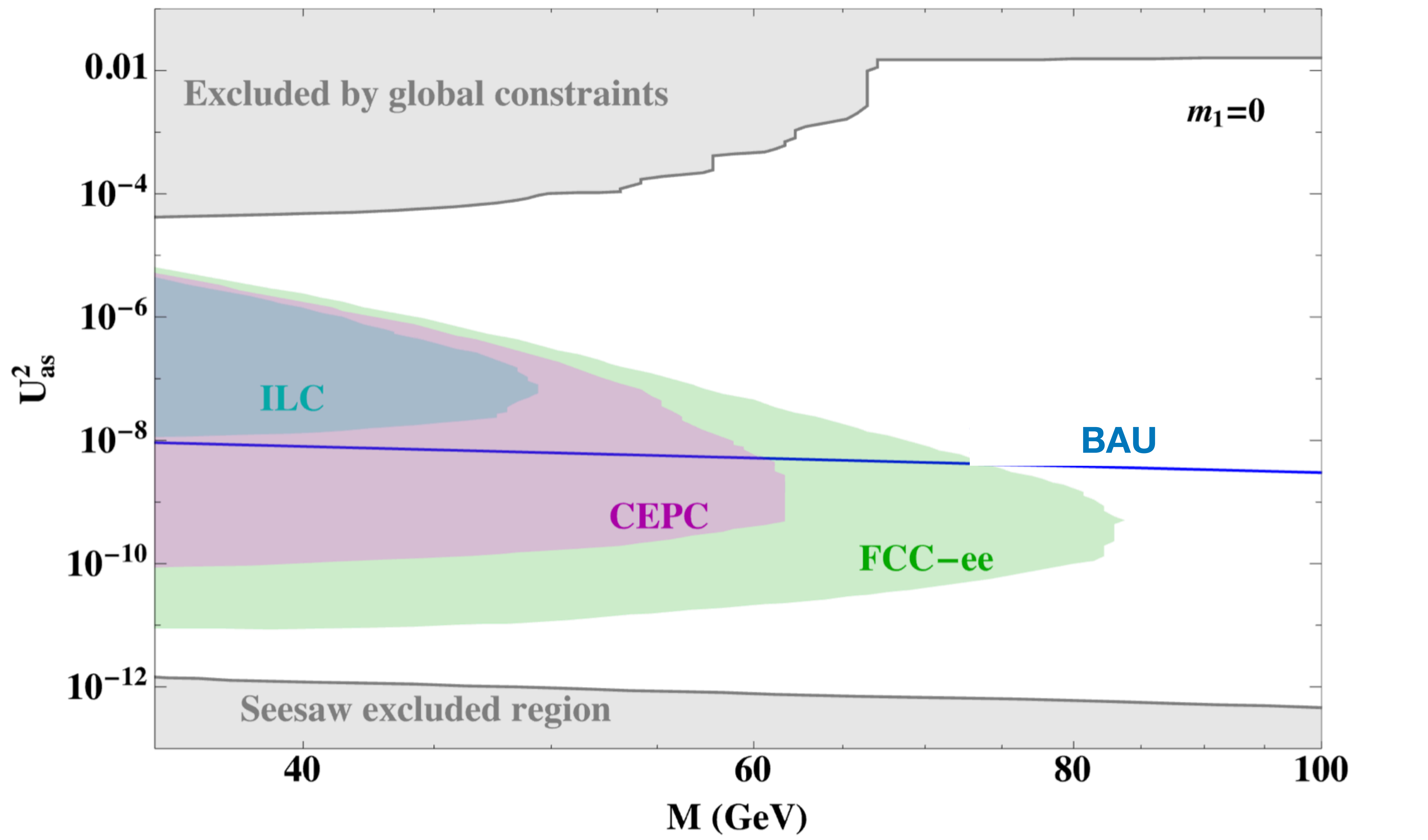
Consider the minimal Type-I Seesaw model with two quasi-degenerate RHNs (N_1, N_2).

CP asymmetry can be resonantly enhanced $\mathcal{O}(1)$ if $\Delta M \simeq \dfrac{\Gamma_{N_1}}{2}$ is satisfied.

The Boltzmann equations for the abundance of RHNs and yield of B-L asymmetry:

$$s\,\mathscr{H}\,T\frac{dY_{N_i}}{dT} = \left(\frac{Y_{N_i}}{Y^{eq}_{N_i}} - 1\right)\gamma^i_D \; ; \qquad s\,\mathscr{H}\,T\frac{dY_{B-L}}{dT} = \sum_{i=1}^{2}\left[\varepsilon^i_\ell\left(\frac{Y_{N_i}}{Y^{eq}_{N_i}} - 1\right) + \frac{Y_{B-L}}{2Y^{eq}_l}\right]\gamma^i_D;$$

considering $T_n(\Lambda) \lesssim M_i < \Lambda$



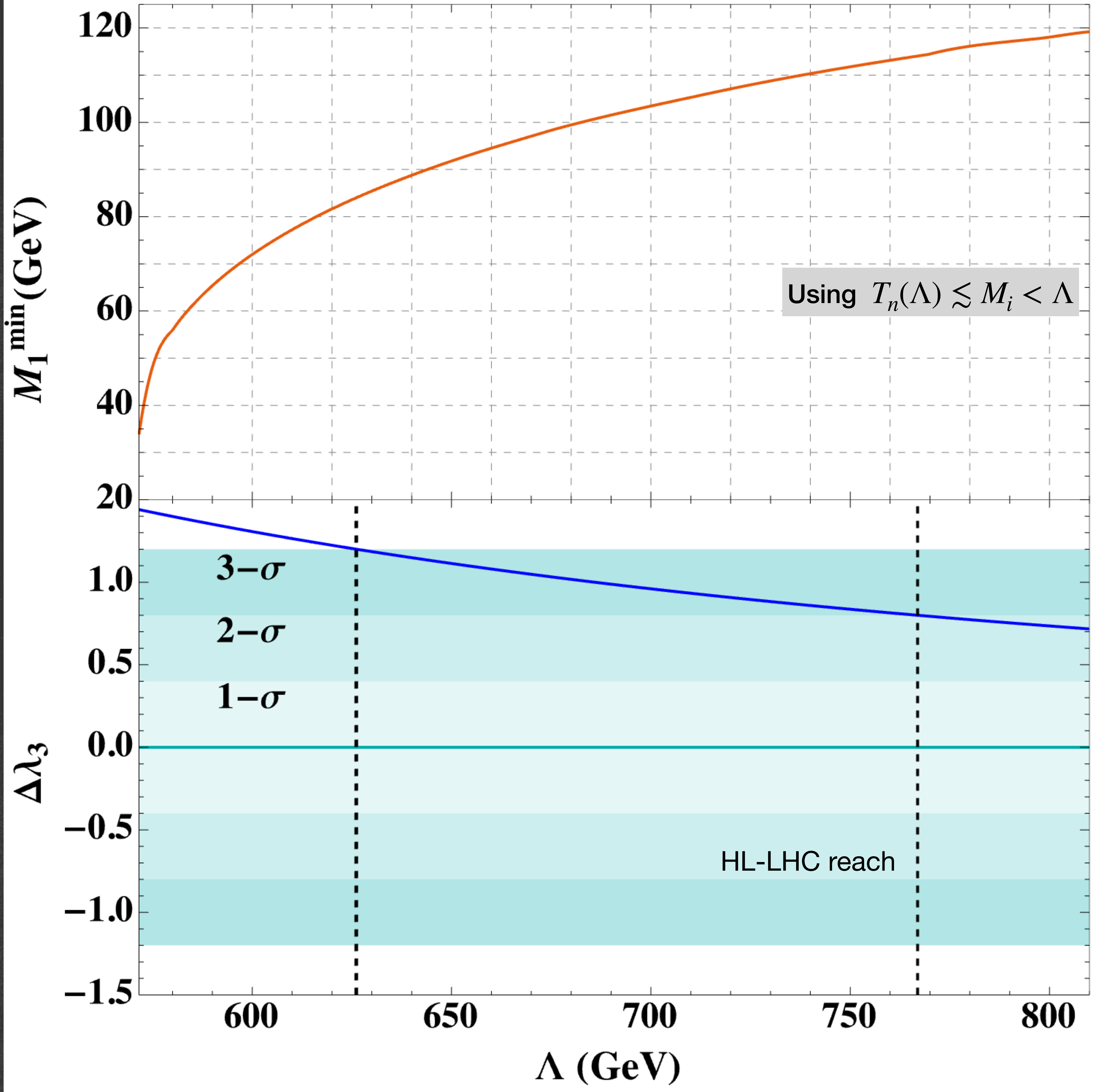
$$U^2_{as} = \Sigma_{i,\alpha}|\Theta_{\alpha i}|^2 = \Sigma_{i,\alpha}|(Y_\nu)_{\alpha i}|^2\frac{v_0^2}{M_i^2}$$

Construction using CI parametrization

$\Theta_{\alpha i}$ is the active-sterile mixing angle

$\Delta M \in \left[10^{-12}, 10^{-6}\right]$,
$\mathrm{Im}\,(\theta_R) \in \left[-5, -0.2\right]$ with $\mathrm{Re}\,(\theta_R) = 0.8$

Correlation of Λ with low scale Leptogenesis and triple Higgs coupling



Inclusion of $(H^\dagger H)^3/\Lambda^2$ in the SM Higgs potential modifies the triple Higgs coupling as:

$$\lambda_3 = \frac{1}{6}\frac{d^3V_{\rm eff}(\phi, T=0)}{d\phi^3}\bigg|_{\phi=v_0} = \lambda_3^{\rm SM} + \frac{v_0^3}{\Lambda^2},$$

where, $\lambda_3^{\rm SM} = m_h^2/(2v_0)$ is the value in the Standard Model.

We show the variation of $\Delta\lambda_3 = (\lambda_3 - \lambda_3^{\rm SM})/\lambda_3^{\rm SM}$ with the cut-off scale Λ in the lower panel of the figure.

We show correlation of the minimum RHN mass, required for leptogenesis, with Λ in the upper panel.

Gravitational wave spectrum

$$\Omega_{\rm GW}h^2 \simeq \Omega_{\rm sw}h^2 + \Omega_{\rm turb}h^2$$

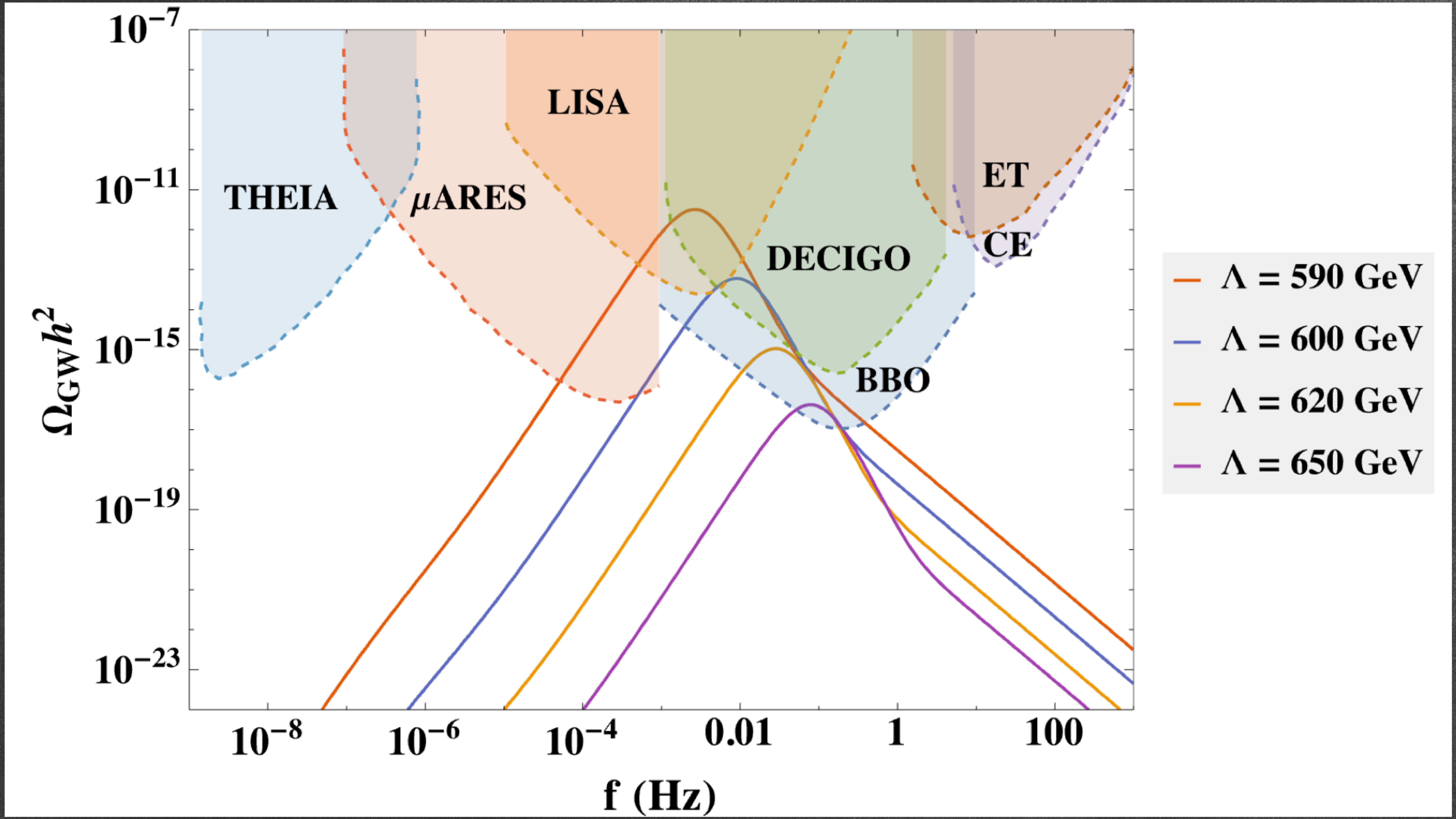
Sound waves

Magnetohydrodynamic turbulence.

Considering the non-runaway bubble wall scenario

The subsonic wall velocity $v_w < c_s$.

$c_s = 1/\sqrt{3}$, is the sound speed in the plasma.



The amplitude and frequency mainly depends on α_*, β, v_w and T_n

Conclusions

$$\boxed{\Lambda \longrightarrow \text{FOEWPT} \longrightarrow T_{\rm sph}\downarrow \longrightarrow M_N\downarrow \longrightarrow \text{testable low-scale leptogenesis}}$$

- FOEWPT lowers the effective sphaleron decoupling temperature: $T_{\rm Sp}$ < 131.7 GeV.
- Resonant leptogenesis below the EW scale: $M_N \gtrsim$ 35 GeV RHNs can generate BAU while sphalerons remain active.
- Low reheating temperature: viable even for $T_{\rm RH} <$ 131.7 GeV.
- Testable seesaw–leptogenesis connection:

$$\boxed{\text{Gravitational waves} + \text{collider probes} + \text{HNL searches}}$$

Thank You

Back up Slide

The dimension-6 Higgs operator modifies the triple Higgs coupling λ_3, given by:

$$\lambda_3 = \frac{m_h^2}{2v_0} + \frac{v_0^3}{\Lambda^2} = \lambda_3^{\mathrm{SM}} + \frac{v_0^3}{\Lambda^2}$$

Experimental determination of λ_3 can provide constraints on Λ. Current bounds from the ATLAS and CMS experiments at $95\ \%$ C.L., expressed in terms of $k_3 = \lambda_3/\lambda_3^{\mathrm{SM}}$ are given by:

$k_3 \in [-1.2, 7.2]$ ATLAS [Phys. Rev. Lett. 133, 101801 (2024)]

$k_3 \in [-1.2, 7.5]$ CMS [Phys. Lett. B 861, 139210 (2025)]

The lowest value of Λ used in our analysis is $572\,\mathrm{GeV}$ which corresponds to $k_3 = 2.43$, which lies well within the current experimental bounds of k_3 as reported by the ATLAS and CMS collaborations.

Back up Slide

$$\Omega_{\rm GW}h^2 \simeq \Omega_{\rm sw}h^2 + \Omega_{\rm turb}h^2$$

$$\Omega_{\rm sw}(f)h^2 = \frac{1.23\times 10^{-5}}{g_*^{1/3}}\frac{H_*}{\beta}\left(\frac{k_{\rm sw}\alpha_*}{1+\alpha_*}\right)^2 v_w\, S_{\rm sw}(f)\,\Upsilon$$

$$\Omega_{\rm turb}(f)h^2 = \frac{1.55\times 10^{-3}}{g_*^{1/3}}\frac{H_*}{\beta}\left(\frac{k_{\rm turb}\alpha_*}{1+\alpha_*}\right)^{\frac{3}{2}} v_w\, S_{\rm turb}(f)$$

$$\frac{\beta}{H_*} \simeq T_n \frac{d}{dT}\left(\frac{S_3}{T}\right)\bigg|_{T=T_n}$$

$$\alpha_* = \frac{1}{\rho_{\rm rad}^*}\left[\Delta V - \frac{T}{4}\frac{\partial \Delta V}{\partial T}\right]_{T=T_n}$$

where $\Delta V = V_{\rm eff}(\phi_{\rm false}, T) - V_{\rm eff}(\phi_{\rm true}, T)$ and $\rho_{\rm rad}^* = g_*\pi^2 T_n^4/30$ is the radiation energy density at T_n .

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

$$S_{\rm turb}(f) = \frac{(f/f_{\rm turb})^3}{(1+(f/f_{\rm trub}))^{\frac{11}{3}}(1+8\pi f/h_*)}$$

$$f_{\rm sw} = \frac{1.9\times 10^{-5}\ {\rm Hz}}{v_w}\frac{\beta}{H_*}\left(\frac{T_n}{100\ {\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{\frac{1}{6}}, \quad f_{\rm turb} = 1.42 f_{\rm sw}$$