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Shaping the Universe:
Framework and Footprints of Cosmological Phase Transitions
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Gravitational wave signatures of dark sector portal leptogenesis

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Based on : 2504.14671
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भारतीय प्रौद्योगिकी संस्थान गुवाहाटी • Indian Institute of Technology Guwahati •

Outline:

- Motivation
- Scotogenic model (Extended)
- First order Phase Transition (FOPT)
- Leptogenesis
- Stochastic Gravitational Waves (GW)
- Dark matter
- Conclusion

Motivation

- The Observed baryon asymmetry of the Universe as baryon to photo ratio is

$$\eta_B = \frac{n_B - n_{\overline{B}}}{n_\gamma} \simeq 6.2 \times 10^{-10}$$

Planck 2018 data, arXiv:1807.06209

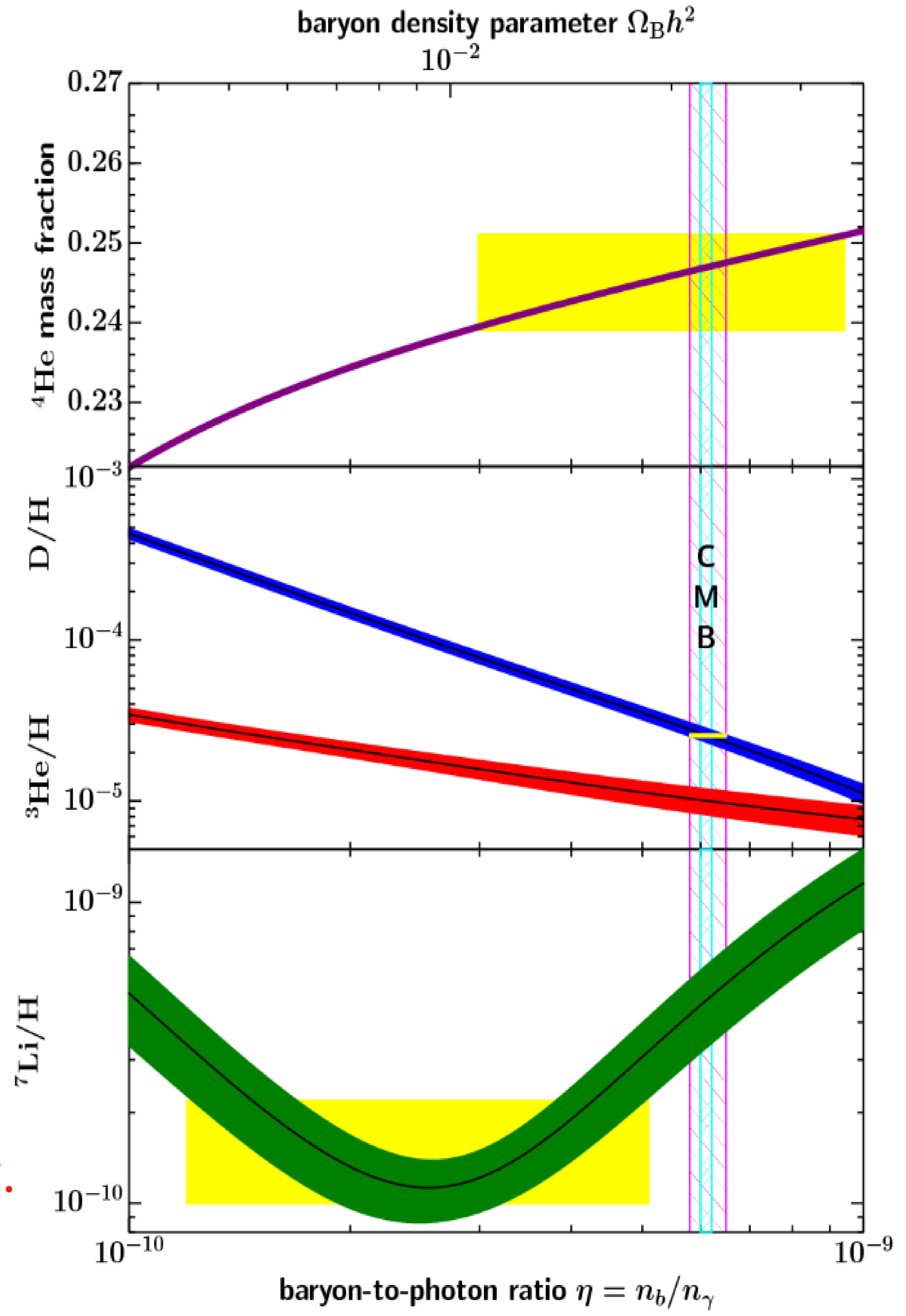
Baryogenesis

Sakharov's Conditions

Sakharov 1967

- Baryon number violation
- C & CP violation
- Departure from thermal equilibrium

Standard Model unable to satisfy above conditions in required amount.



Particle Data Group

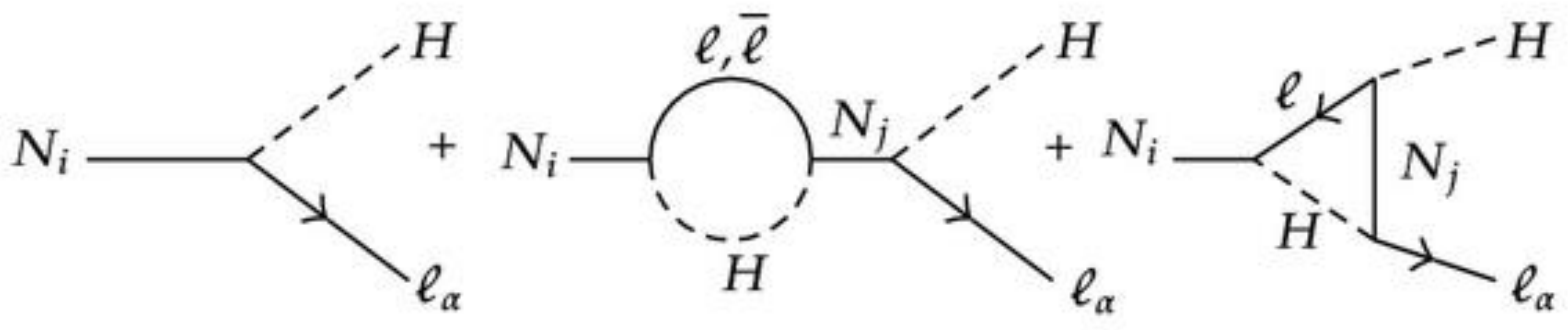
Baryogenesis via Leptogenesis

❖ Right-handed neutrino decays out of equilibrium (Fukugita & Yanagida 1986)

$$Y_{ij}\bar{L}_i\tilde{H}N_j + \frac{1}{2}M_{ij}N_iN_j$$

❖ CP violation due to phases in Yukawa couplings Y, leads to a lepton asymmetry

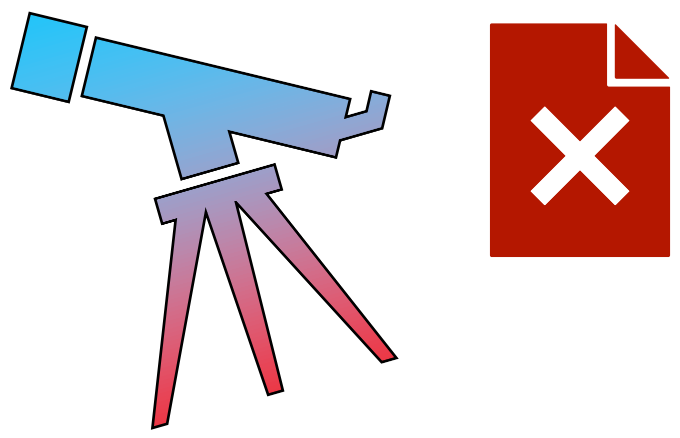
$$\epsilon_{\alpha\alpha} \equiv \frac{\Gamma(N_1 \to \phi\ell_\alpha) - \Gamma(N_1 \to \bar{\phi}\bar{\ell}_\alpha)}{\Gamma(N_1 \to \phi\ell) + \Gamma(N_1 \to \bar{\phi}\bar{\ell})}$$

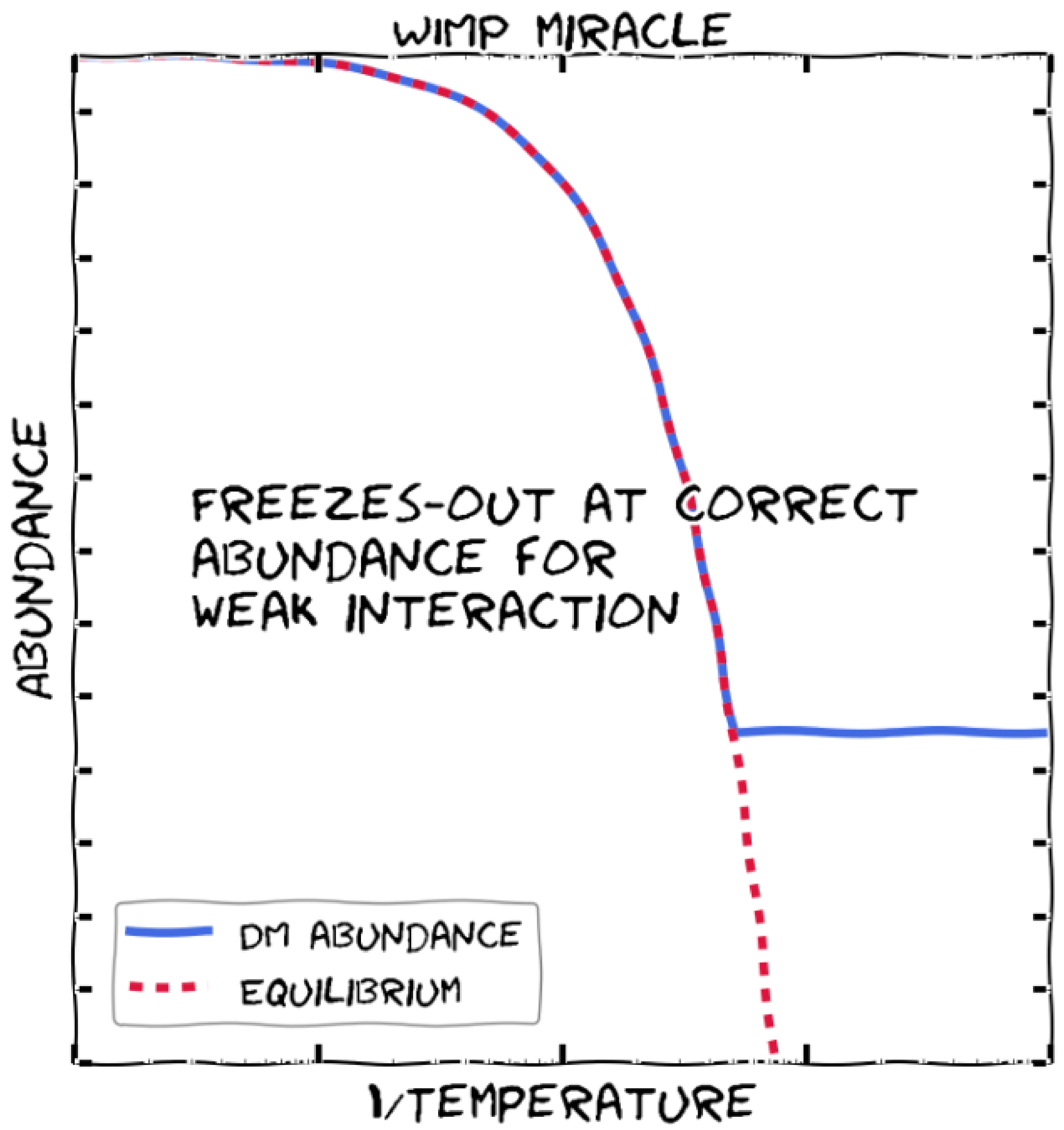


❖ The frozen-out lepton asymmetry at is converted into baryon asymmetry by electroweak sphalerons

$$\eta_B = \frac{a_{\rm sph}}{f}\epsilon_1\kappa$$

We know it exist





$$\frac{dn_X}{dt} = -3Hn_X - \langle \sigma_{\rm ann} v \rangle (n_X^2 - n_{\rm eq}^2)$$

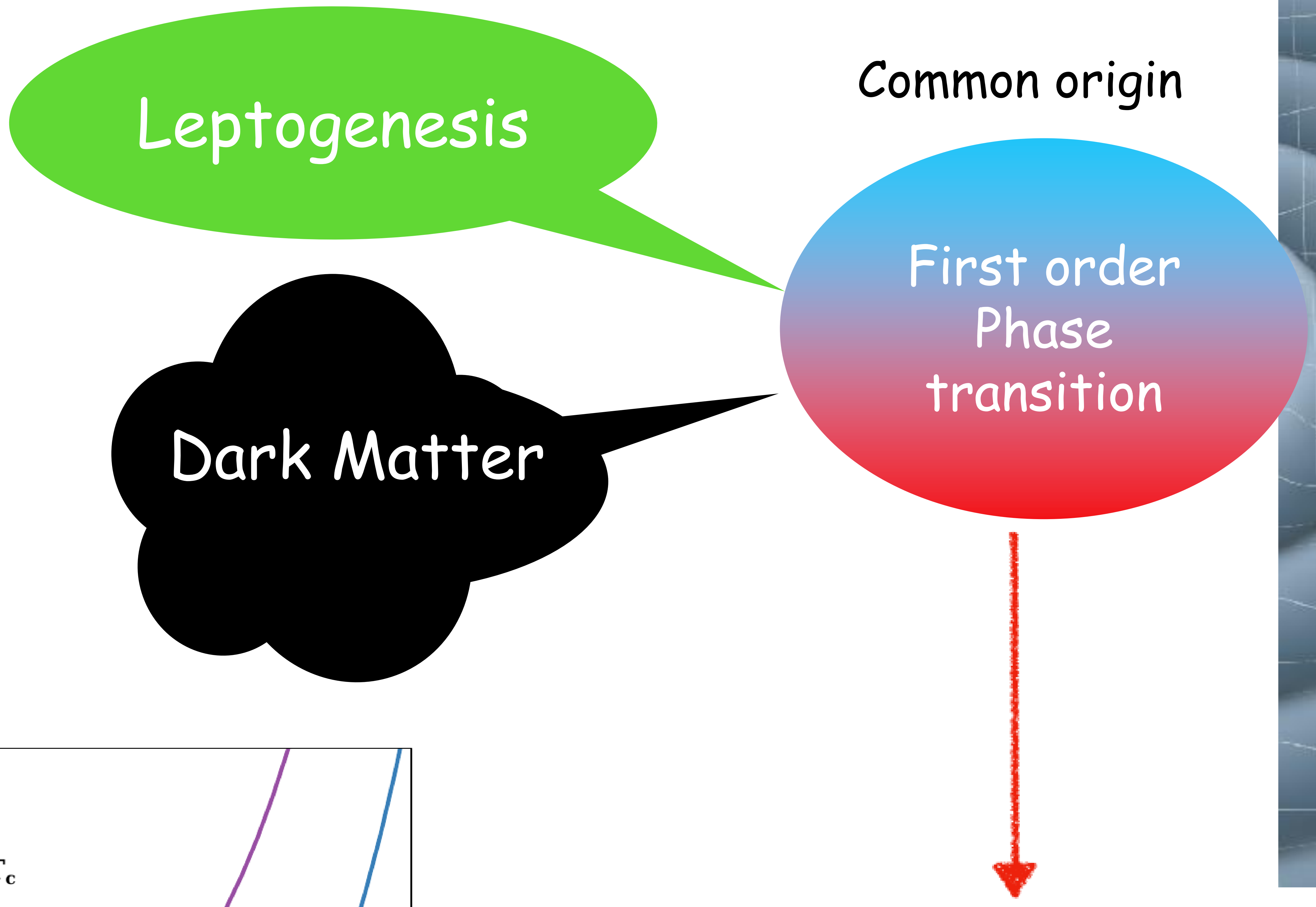
Baryon-DM coincidence: $\Omega_{DM} \approx 5\Omega_{B}$

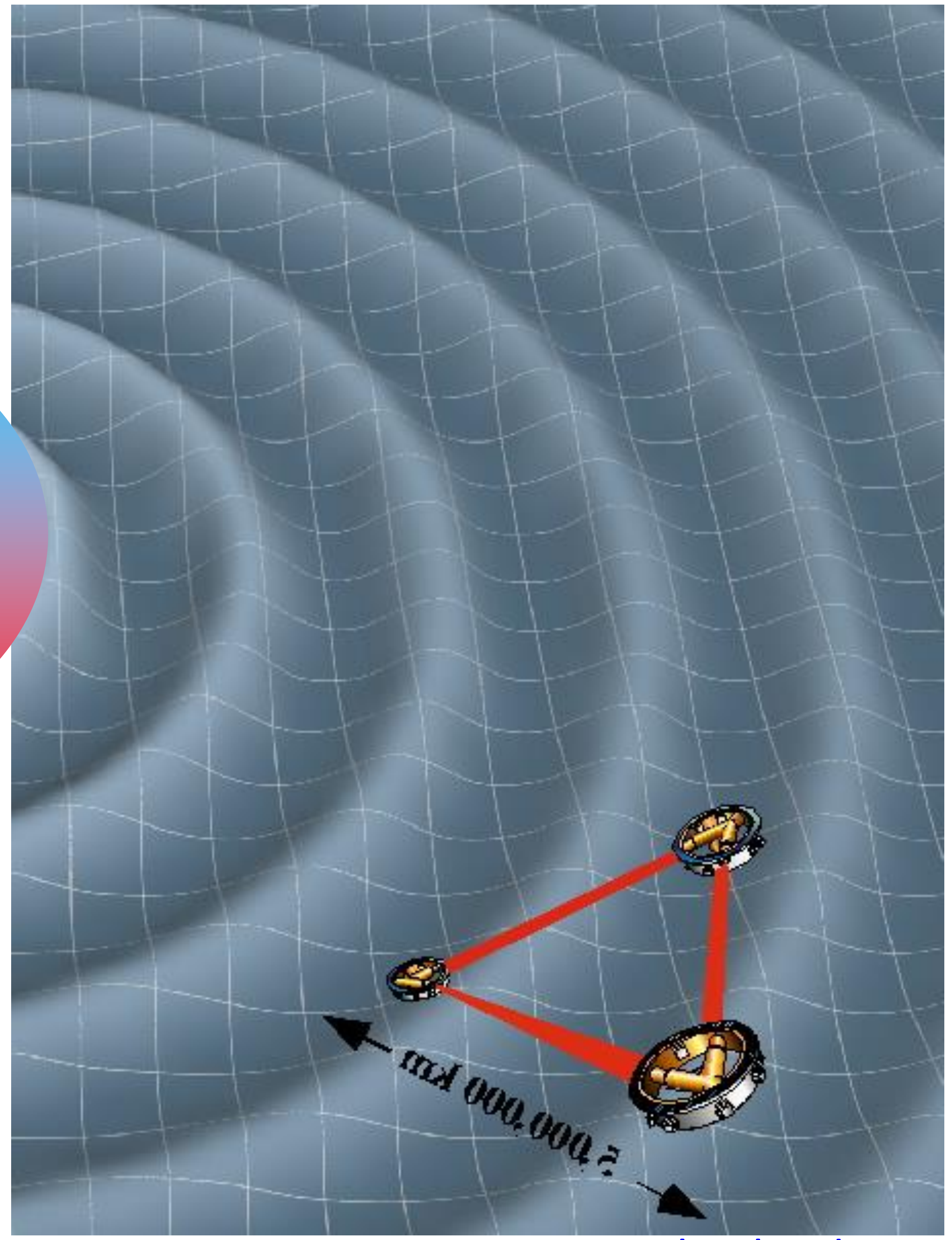
They can have a common origin !

https://andrewfowlie.github.io/talks/melbourne_dm.pdf

First order Phase transition:

Gravitational waves





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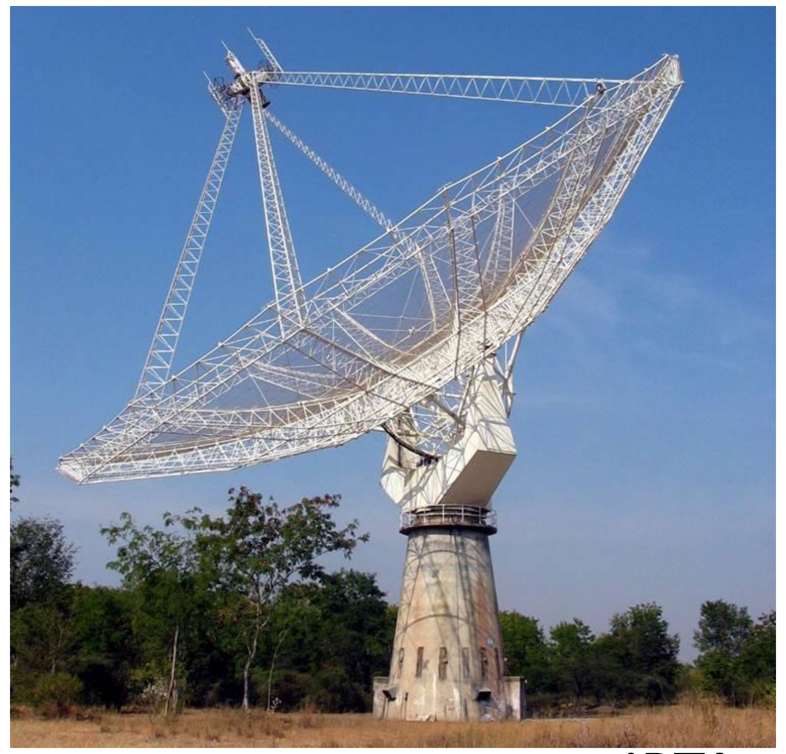
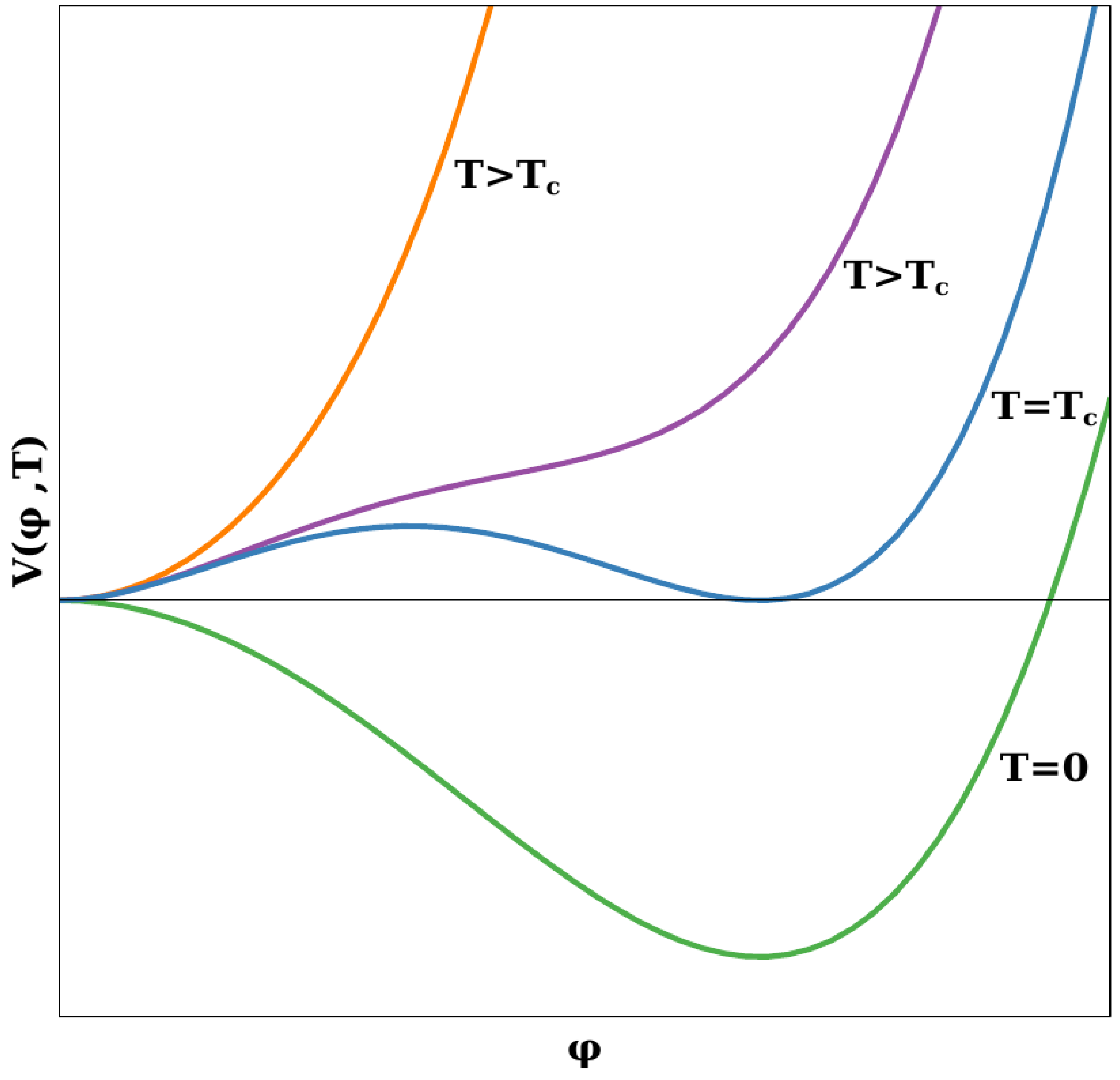
LIGO



IPTA



- As the Universe cools down, the scalar field went from symmetric phase to broken phase.
- The vacuum expectation value (vev) of the scalar field is the order parameter.
- In first order phase transition (FOPT), the vev of the scalar field changes discontinuously.
- The minima become degenerate at critical temperature.

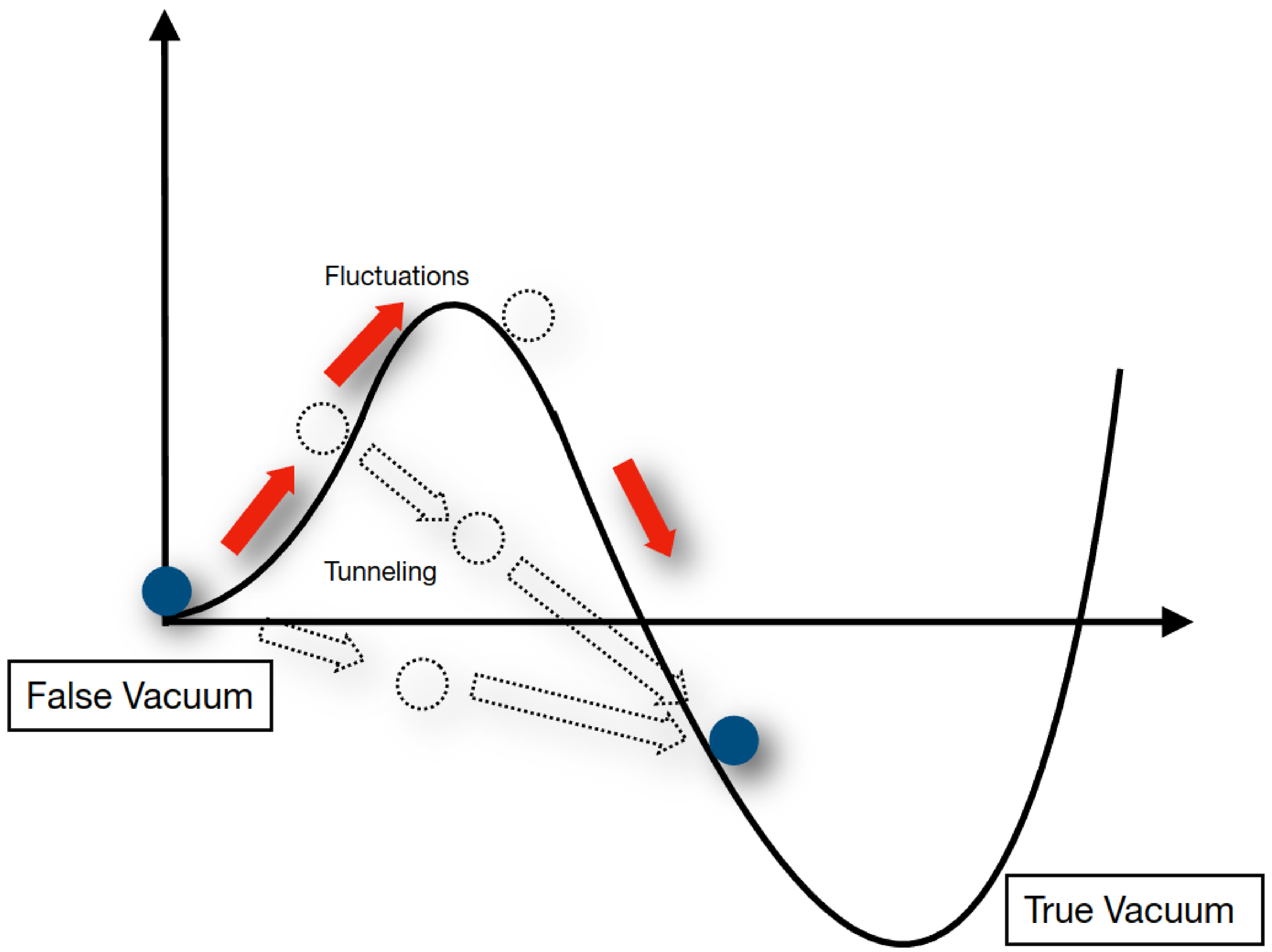
The rate of tunneling per unit volume:

$$\Gamma(T) = \mathcal{A}(T) e^{-S_3(T)/T},$$

$$S_3 = \int_0^\infty dr 4\pi r^2 \left[\frac{1}{2} \left(\frac{d\phi}{dr} \right)^2 + V_{\rm tot}(\phi, T) \right].$$

$$\Gamma(T_n) = \mathbf{H}^4(T_n).$$

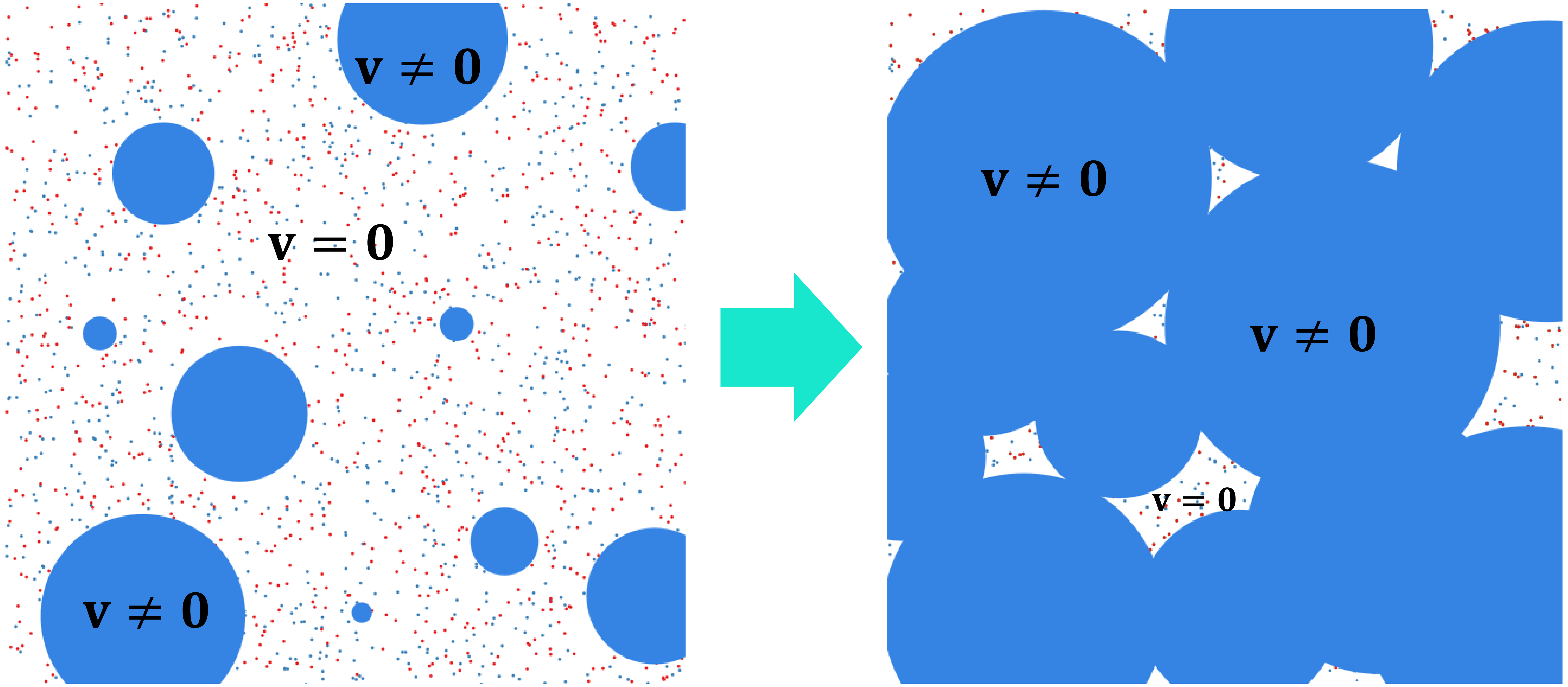
Linde, Phys.Lett.B 100 (1981)



Vacuum energy released

$$\alpha_* = \frac{\epsilon_*}{\rho_{\rm rad}},$$

$$\epsilon_* = \left[\Delta V_{\rm tot} - \frac{T}{4} \frac{\partial \Delta V_{\rm tot}}{\partial T} \right]_{T=T_*},$$



Duration of the FOPT

$$\frac{\beta}{\mathbf{H}(T)} \simeq T \frac{d}{dT} \left(\frac{S_3}{T} \right)$$

Scotogenic Model (Extended):

	L	Φ	N_1	ψ	η	χ
$SU(2)$	2	2	1	1	2	1
$U(1)_Y$	$-\frac{1}{2}$	$\frac{1}{2}$	0	0	$\frac{1}{2}$	0
Z_2	1	1	1	-1	-1	-1

Leptonic Yukawa interaction:

$$-\mathcal{L}_Y \supset y_N \bar{\ell}\tilde{\Phi} N_1 + y_\psi \bar{\ell}\tilde{\eta}\psi + y_1 \overline{N_1^c}\psi\chi + \frac{1}{2} M_{N_1}\overline{N_1^c}N_1 + \frac{1}{2} M_\psi \overline{\psi^c}\psi + \text{h.c.}$$

Scalar Potential:

$$V_{\text{tree}} = \mu_\Phi^2|\Phi|^2 + \mu_\eta^2|\eta|^2 + \lambda_1|\Phi|^4 + \lambda_2|\eta|^4 + \lambda_3|\Phi|^2|\eta|^2 + \lambda_4|\eta^\dagger\Phi|^2 + \lambda_5[(\eta^\dagger\Phi)^2 + \text{h.c.}]$$
$$+ \frac{\mu_\chi^2}{2}\chi^2 + \lambda_7\chi^4 + \lambda_8\chi^2|\Phi|^2 + \lambda_9\chi^2|\eta|^2 + (\mu_1\chi\Phi^\dagger\eta + \mu_1^*\chi\eta^\dagger\Phi).$$

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \phi + v \end{pmatrix}, \eta = \begin{pmatrix} \eta^\pm \\ \frac{(H+iA)}{\sqrt{2}} \end{pmatrix}$$

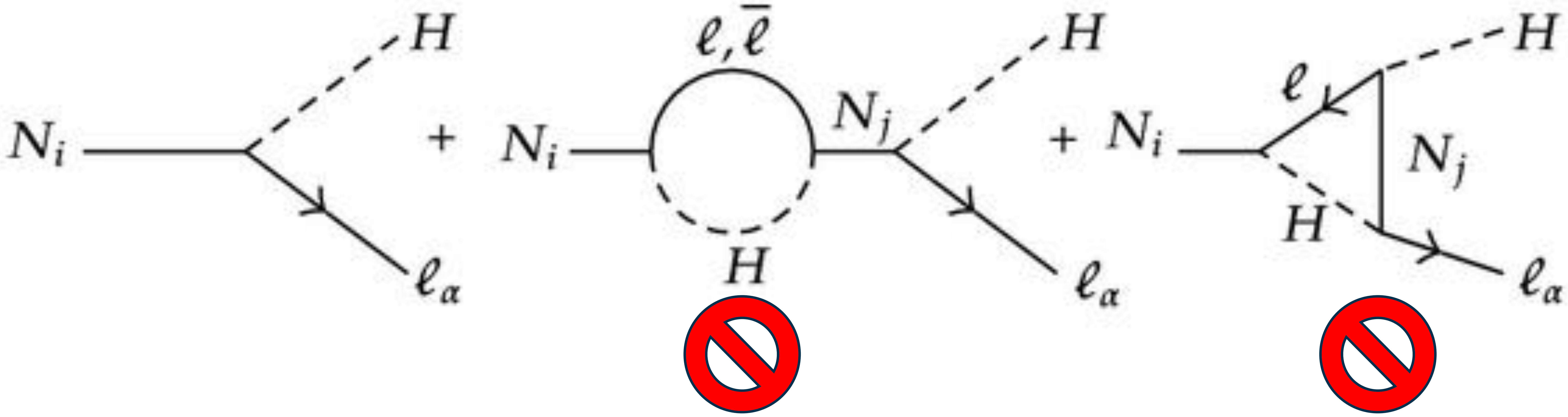
Scoto-Seesaw:

$$\mathcal{Y} = \sqrt{X_M^{-1}} R \sqrt{m_\nu^{\text{diag}}} U^\dagger$$

→ Neutrino mass

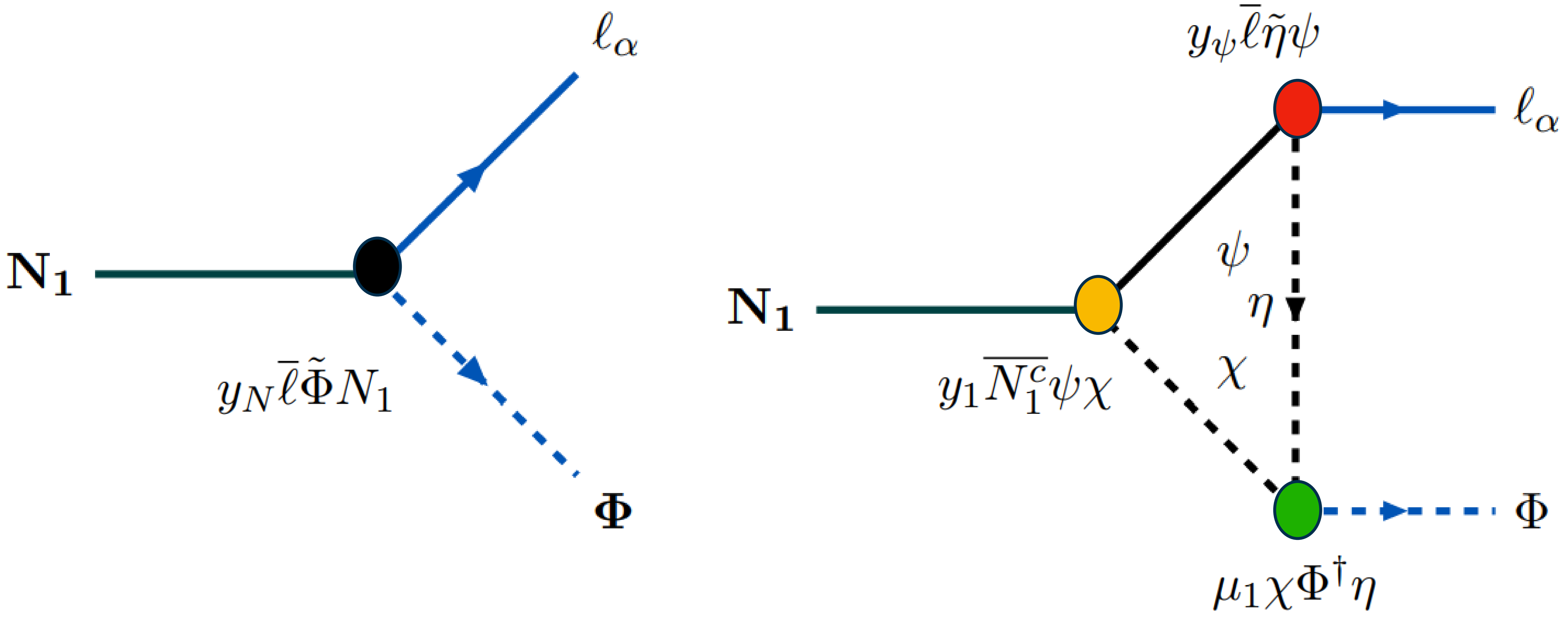
$$X_M = \begin{pmatrix} -X_1 & 0 \\ 0 & X_0 \end{pmatrix}, \quad X_1 = \frac{M_\psi}{32\pi^2}\left(\cos^2\theta F_1(\eta_1) + \sin^2\theta F_1(\eta_2) - F_1(A)\right), \quad X_0 = \frac{v^2}{2M_{N_1}}$$

Leptogenesis



No asymmetry

Scalar portal Leptogenesis



Non-Zero asymmetry

H or Φ, Higgs
N_j or ψ, RHN

First Order Phase Transition:

$$V_{\rm tot} = V_{\rm tree} + V_{\rm CW} + V_{\rm th},$$

$$V_{\rm CW} = \sum_i (-)^{n_f} \frac{n_i}{64\pi^2} m_i^4(\phi) \left(\log \left(\frac{m_i^2(\phi)}{\mu^2} \right) - \frac{3}{2} \right),$$

$$V_{\rm th} = \sum_i \left(\frac{n_{\rm B_i}}{2\pi^2} T^4 J_B \left[\frac{m_{\rm B_i}}{T} \right] - \frac{n_{\rm F_i}}{2\pi^2} T^4 J_F \left[\frac{m_{\rm F_i}}{T} \right] \right),$$

Coleman & Weinberg, PRD 7 (1973), Dolan & Jackiw, PRD 9 (1974)

Field dependent masses:

$$m_{\eta^\pm}^2(\phi) = \mu_\eta^2 + \frac{\lambda_3}{2}\phi^2 \ (n_{\eta^\pm} = 2, C_{\eta^\pm} = \frac{3}{2}), \ m_A^2(\phi) = \mu_\eta^2 + \frac{\lambda_3 + \lambda_4 - 2\lambda_5}{2}\phi^2 \ (n_A = 1, C_A = \frac{3}{2}),$$

$$m_W^2(\phi) = \frac{g_2^2}{4}\phi^2 \ (n_W = 6, C_W = \frac{5}{6}), \ m_Z^2(\phi) = \frac{g_1^2 + g_2^2}{4}\phi^2 \ (n_Z = 3, C_Z = \frac{5}{6}),$$

$$m_t^2(\phi) = \frac{y_t^2}{2}\phi^2 \ (n_t = 12, C_t = \frac{3}{2}), \ m_b^2(\phi) = \frac{y_b^2}{2}\phi^2 \ (n_b = 12, C_b = \frac{3}{2}),$$

$$m_{\eta_1}^2(\phi) = \frac{1}{2}(\mu_\chi^2 + \mu_\eta^2 + (\lambda_8 + \lambda_{\rm H}/2)\phi^2 - \sqrt{\{\mu_\chi^2 - \mu_\eta^2 + (\lambda_8 - \lambda_{\rm H}/2)\phi^2\}^2 + |\mu_1|^2\phi^2}) \ (n_{\eta_1} = 1, C_{\eta_1} = \frac{3}{2}),$$

$$m_{\eta_2}^2(\phi) = \frac{1}{2}(\mu_\chi^2 + \mu_\eta^2 + (\lambda_8 + \lambda_{\rm H}/2)\phi^2 + \sqrt{\{\mu_\chi^2 - \mu_\eta^2 + (\lambda_8 - \lambda_{\rm H}/2)\phi^2\}^2 + |\mu_1|^2\phi^2}) \ (n_{\eta_2} = 1, C_{\eta_2} = \frac{3}{2}).$$

$$m_i^2(\phi, T) = m_i^2(\phi) + \Pi_S(T), \ m_{\eta_2}^2(\phi, T) = m_{\eta_2}^2(\phi) + \Pi_\chi(T)$$

Finite temperature effect on masses:

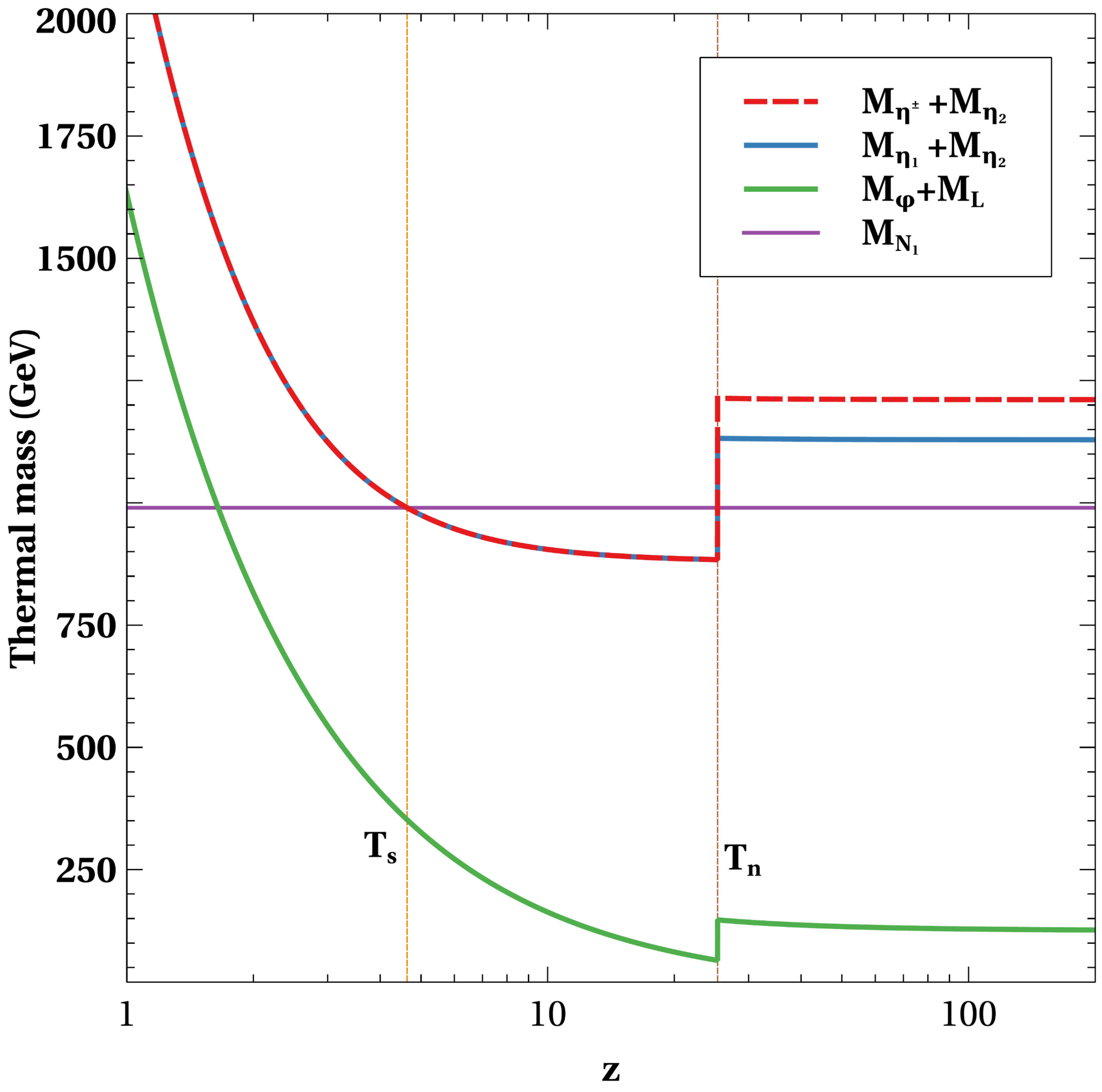
N_1 can decay if

$$M_\Phi(T) + M_L(T) < M_{N_1}$$

But, N_1 decay can generate asymmetry if η and χ are on-shell

$$M_\eta(T) + M_\chi(T) < M_{N_1}$$

Mass of ψ is higher than mass of N_1



Boltzmann equation:

$$\frac{dY_{\mathrm{N}_1}}{dz} = - D_{\mathrm{N}}\left(Y_{\mathrm{N}_1} - Y_{\mathrm{N}_1}^{\mathrm{eq}}\right) - \frac{s}{H(z)z}\left(Y_{\mathrm{N}_1}^2 - \left(Y_{\mathrm{N}_1}^{\mathrm{eq}}\right)^2\right)\Big[\langle\sigma v\rangle_{N_1N_1\longrightarrow\chi\chi} + \langle\sigma v\rangle_{N_1N_1\longrightarrow\Phi\Phi^\dagger}$$
$$+ \langle\sigma v\rangle_{N_1N_1\longrightarrow\ell_\alpha\bar{\ell}_\beta}\Big] - \frac{s}{H(z)z}\left(Y_{\mathrm{N}_1} - Y_{\mathrm{N}_1}^{\mathrm{eq}}\right)\Big[2Y_l^{\mathrm{eq}}\langle\sigma v\rangle_{\bar{l}N_1\longrightarrow\bar{q}t} + 4Y_t^{\mathrm{eq}}\langle\sigma v\rangle_{N_1t\longrightarrow\bar{l}q}$$
$$+ 2Y_\chi^{\mathrm{eq}}\langle\sigma v\rangle_{N_1\chi\longrightarrow\bar{\ell}\eta^\dagger} + 2Y_\Phi^{\mathrm{eq}}\langle\sigma v\rangle_{N_1\Phi\longrightarrow l_\alpha V_\mu} + 2y_\psi^{\mathrm{eq}}\langle\sigma v\rangle_{N_1\psi\longrightarrow\Phi\eta^\dagger}\Big], \tag{3.3}$$

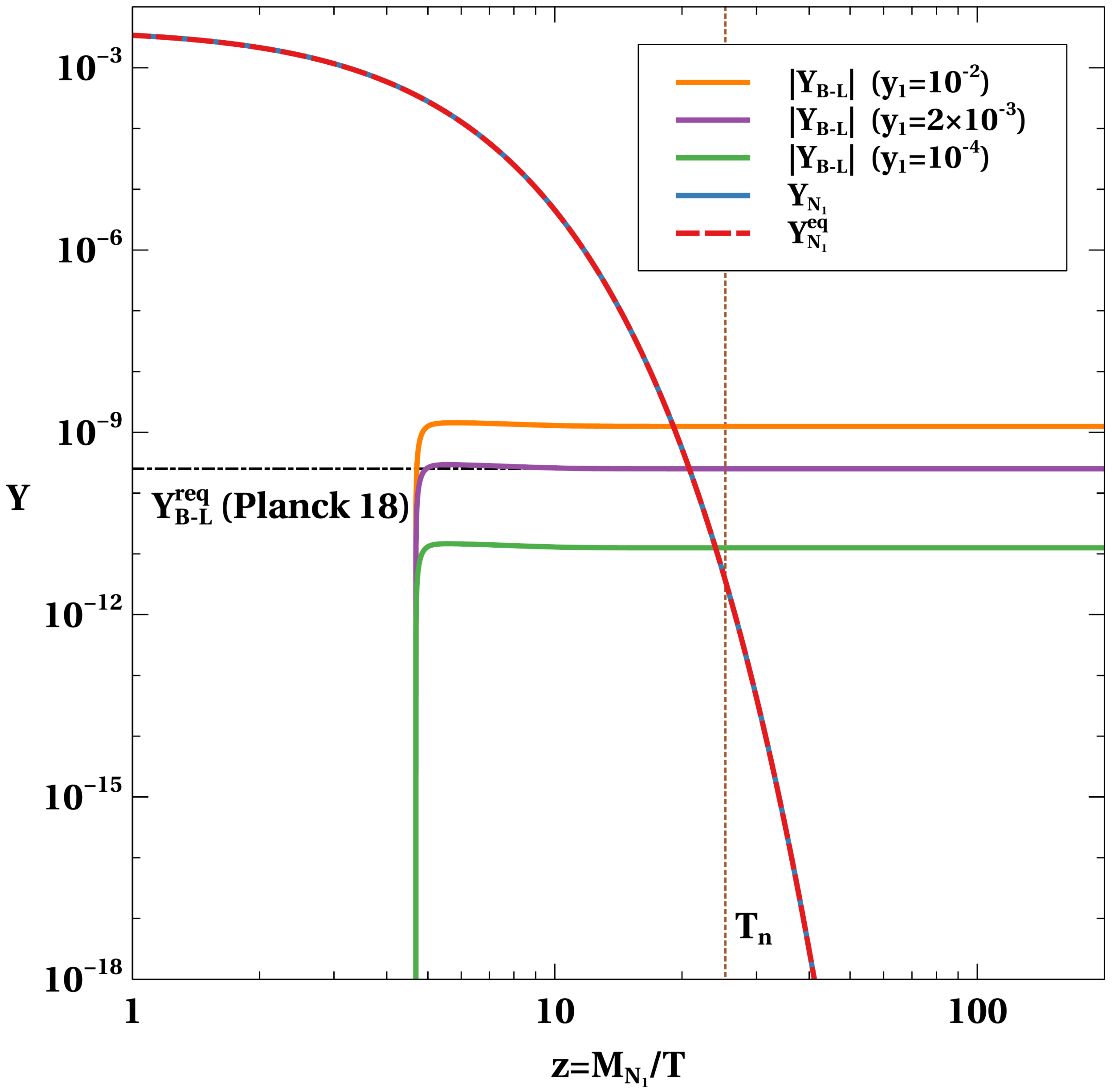
$$\frac{dY_{\mathrm{B-L}}}{dz} = - \epsilon_1 D_{\mathrm{N}}\left(Y_{\mathrm{N}_1} - Y_{\mathrm{N}_1}^{\mathrm{eq}}\right) - W_{\mathrm{ID}}Y_{\mathrm{B-L}} - \frac{\mathrm{s}}{H(z)z}Y_{\mathrm{B-L}}\Big[2Y_\Phi^{\mathrm{eq}}\langle\sigma v\rangle_{l\Phi^\dagger\longrightarrow\bar{\ell}\Phi} + Y_{\mathrm{N}_1}\langle\sigma v\rangle_{\bar{\ell}N_1\longrightarrow\bar{q}t}$$
$$+ 2Y_q^{\mathrm{eq}}\langle\sigma v\rangle_{\bar{\ell}q\longrightarrow N_1t} + 2Y_l^{\mathrm{eq}}\langle\sigma v\rangle_{\ell\ell\longrightarrow\Phi^\dagger\Phi^\dagger} + Y_\eta^{\mathrm{eq}}\langle\sigma v\rangle_{\bar{\ell}\eta^\dagger\longrightarrow N_1\chi} + Y_V^{\mathrm{eq}}\langle\sigma v\rangle_{\bar{\ell}V_\mu\longrightarrow\Phi N_1}\Big].$$

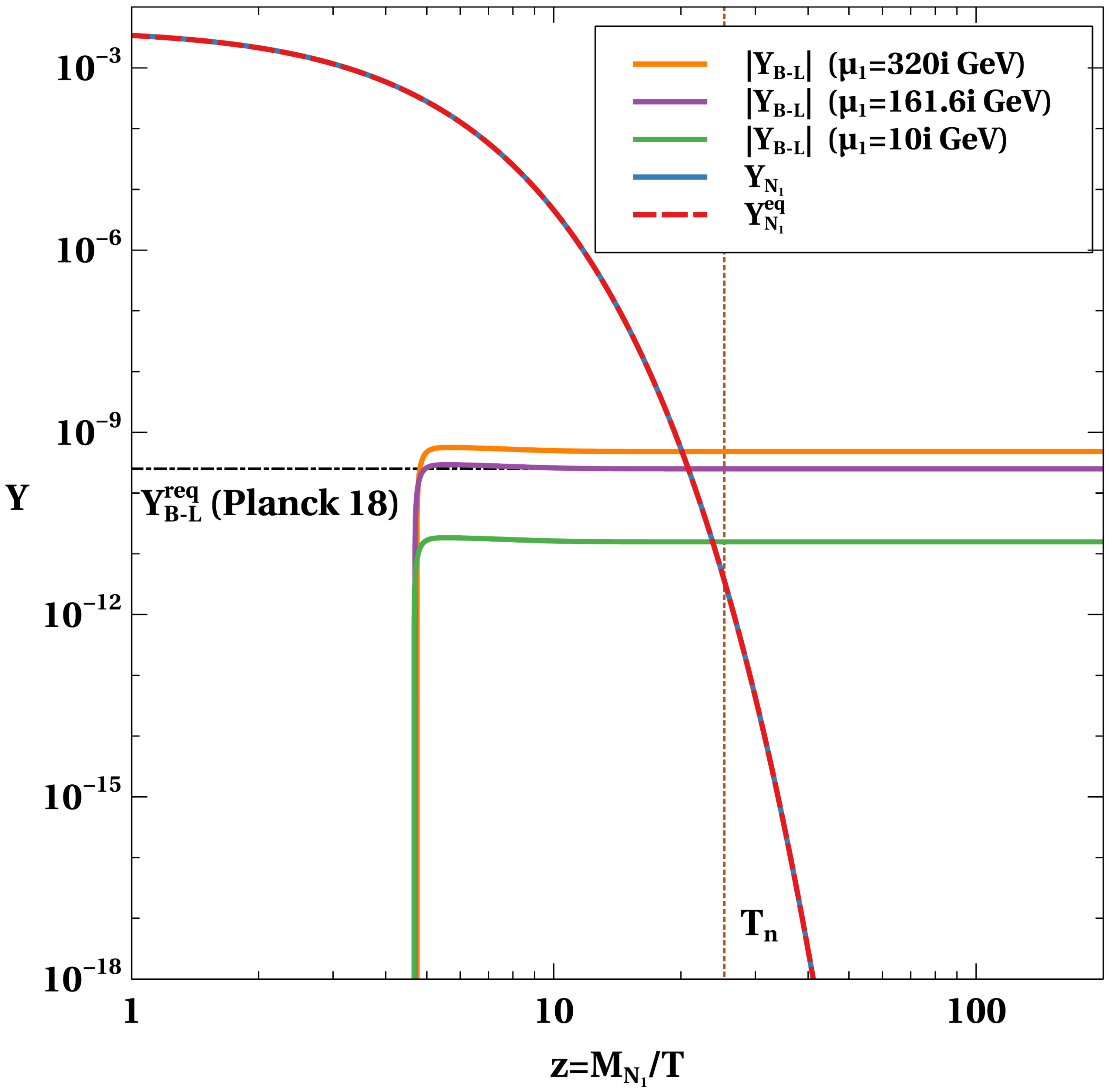
CP asymmetry parameter:

$$\epsilon_1 = \frac{1}{8\pi}\frac{\mathrm{Im}(y_N^\dagger y_\psi y_1\mu_1)}{(y_N^\dagger y_N)M_{N_1}}\left(1 - 2\sqrt{\sigma} + (\delta - \sqrt{\delta} - \zeta)\ln\left[\frac{\delta - (1-\sqrt{\sigma})^2}{\delta - \sigma}\right]\right)$$

$\delta = \frac{M_\psi^2}{M_{N_1}^2}$, $\zeta = \frac{m_\eta^2}{M_{N_1}^2}$, $\xi = \frac{m_h^2}{M_{N_1}^2}$, $\omega = \frac{m_l^2}{M_{N_1}^2}$ and $\sigma = \frac{m_\chi^2}{M_{N_1}^2}$

Evolution of comoving number densities:



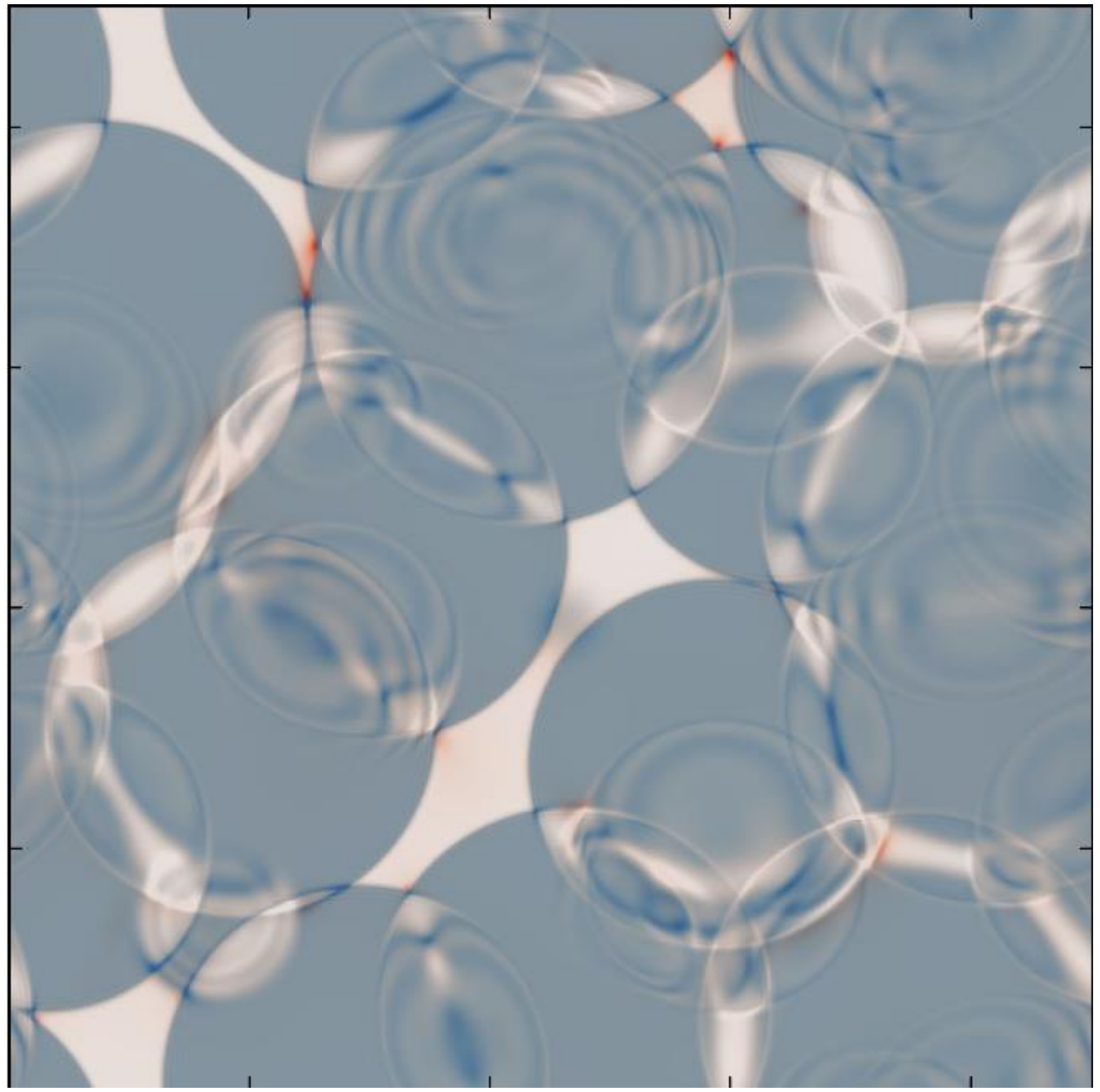


Stochastic Gravitational Waves:

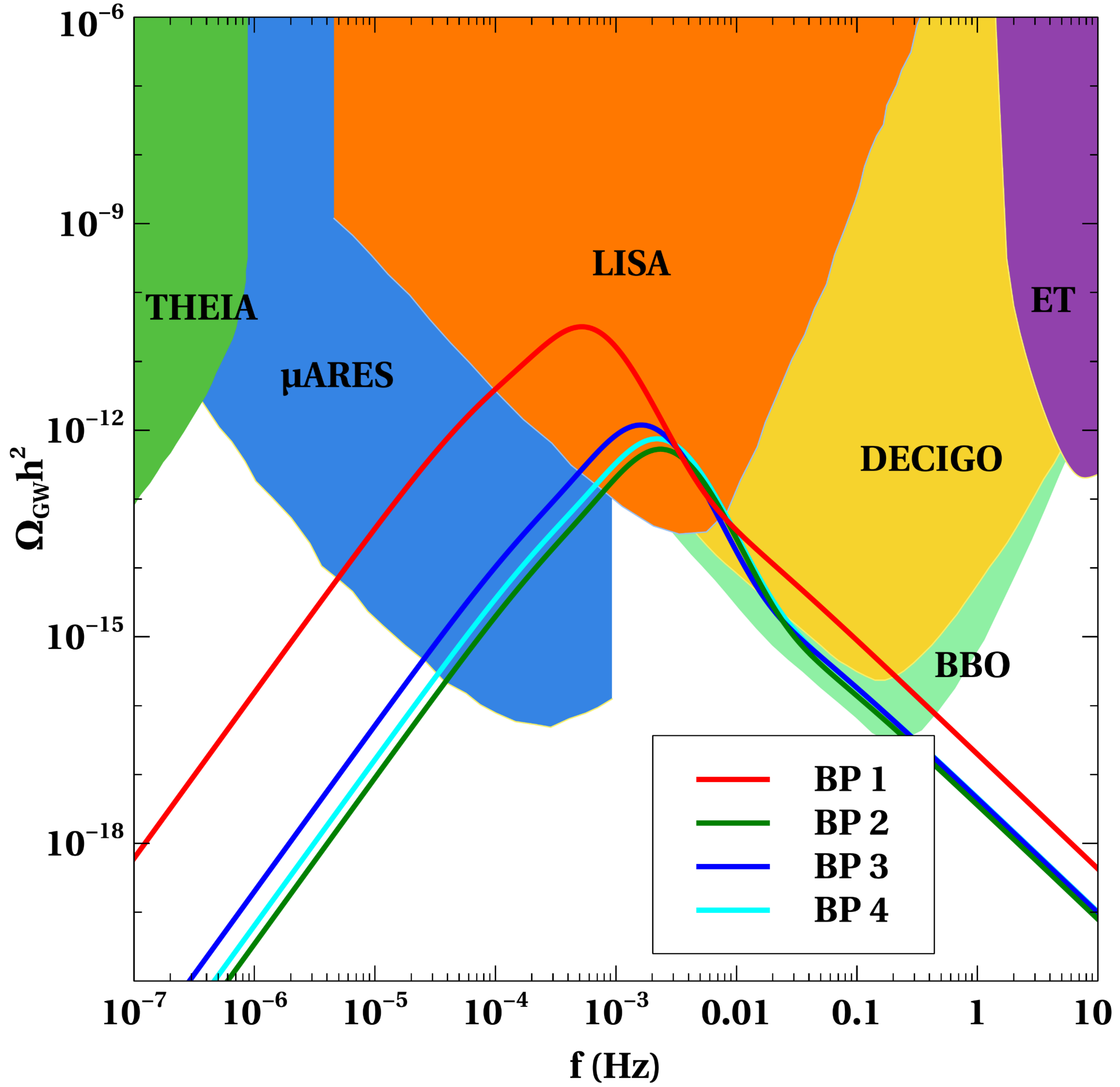
$$\Omega_{\rm GW}^{\rm PT}(f) = \Omega_\phi(f) + \Omega_{\rm sw}(f) + \Omega_{\rm turb}(f),$$

$$h^2\Omega(f) = \mathcal{R}\Delta(v_w)\left(\frac{\kappa\alpha_*}{1+\alpha_*}\right)^p\left(\frac{\mathbf{H}_*}{\beta}\right)^q \mathcal{S}(f/f_{\rm peak})$$

Caprini et al. JCAP 04 (2016)



Cutting et al. 97, 123513 (2018)

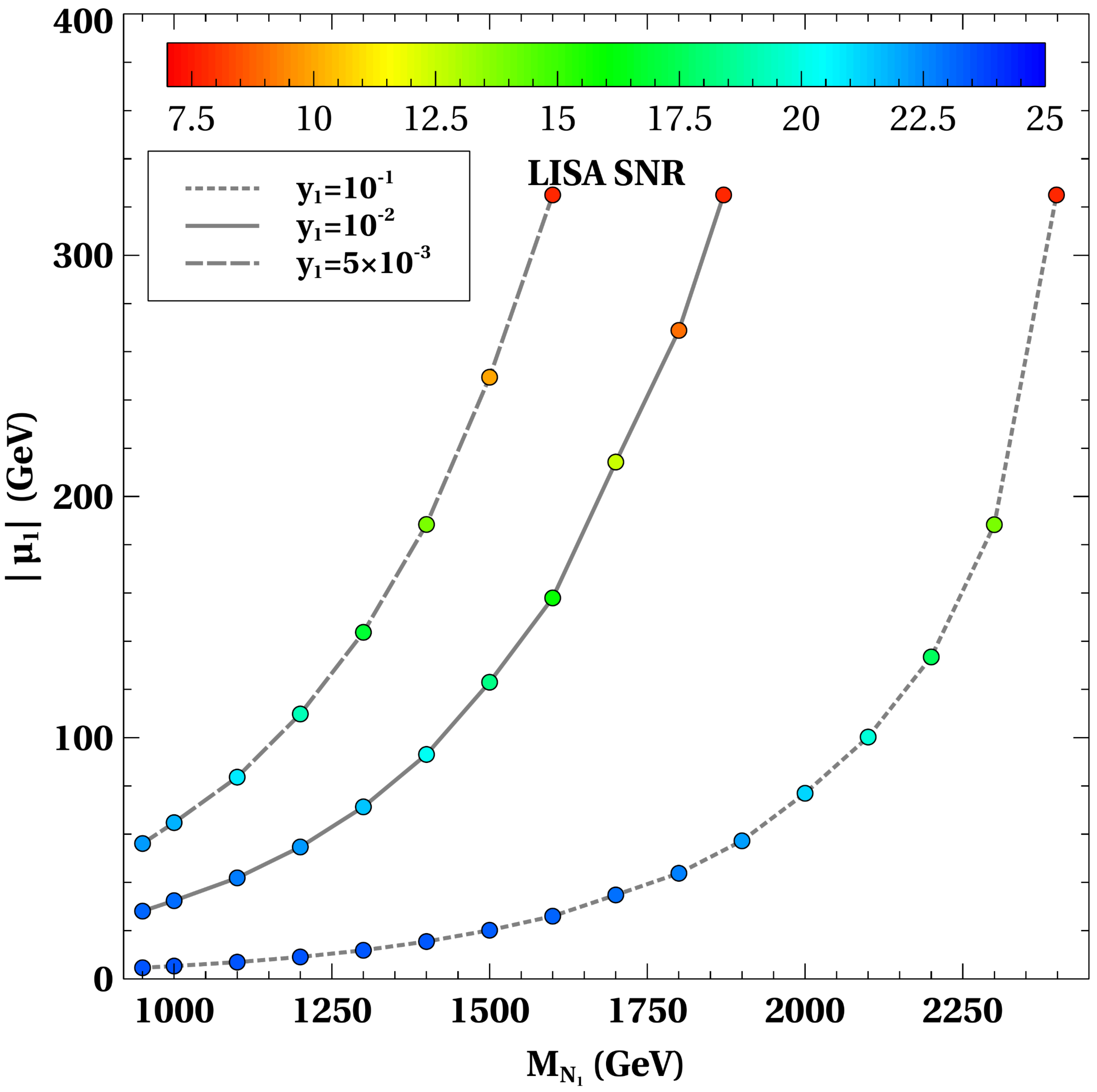


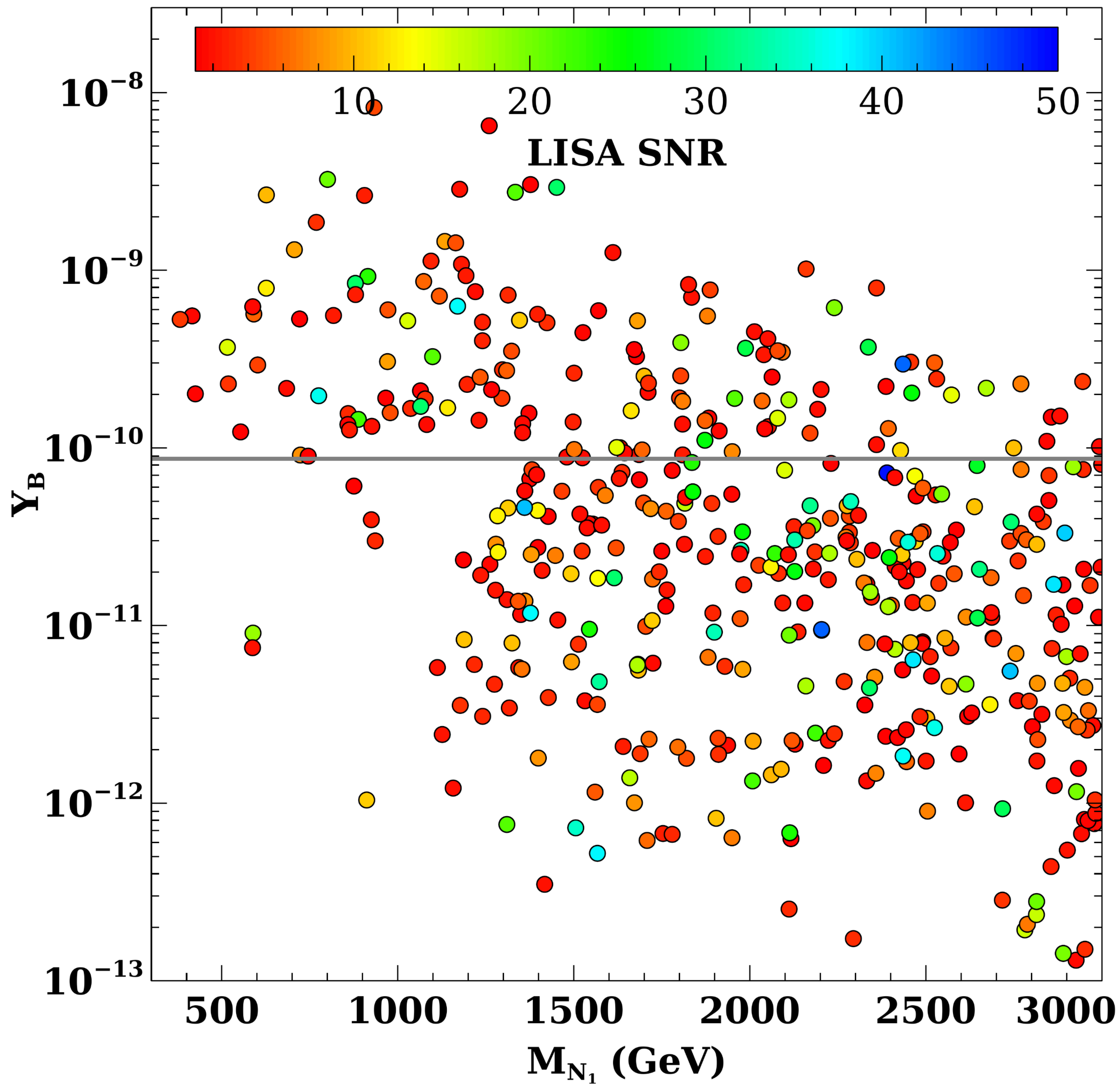
Total contributions from bubble collision,
sound wave and turbulence in plasma medium

Sound wave in the plasma has dominating contribution

2306.05459

Correlation between Gravitational Waves and Leptogenesis:





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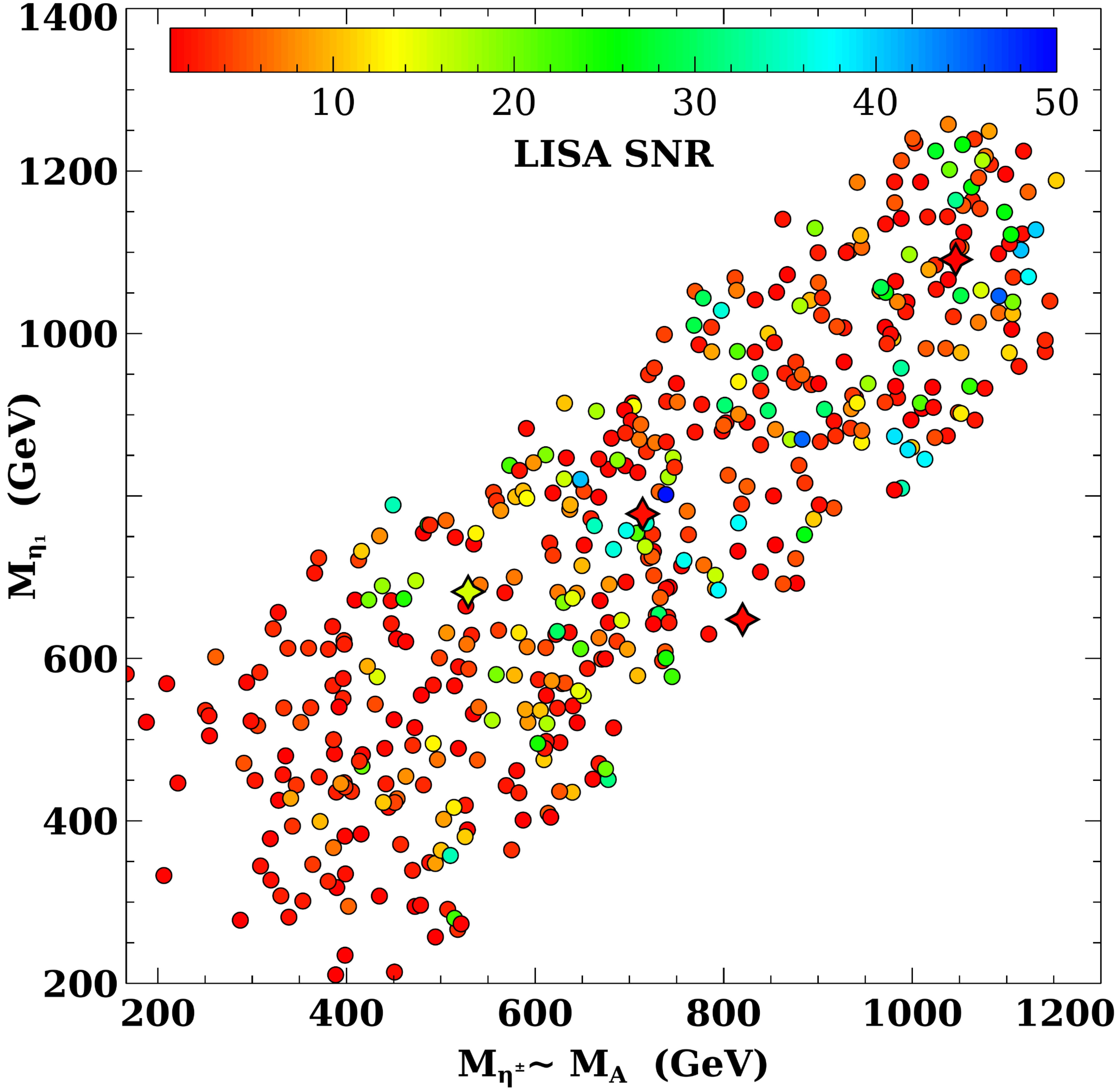
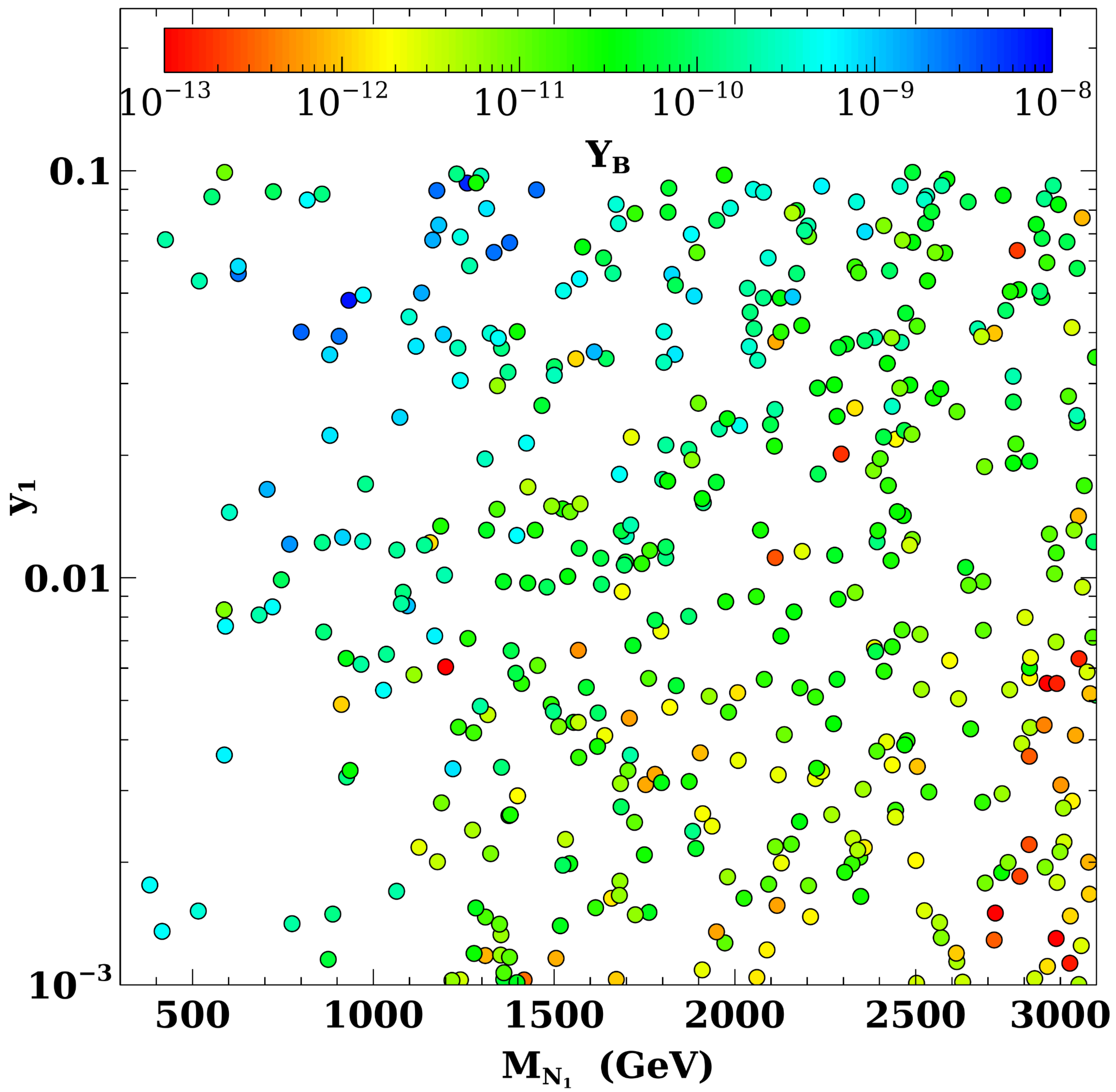
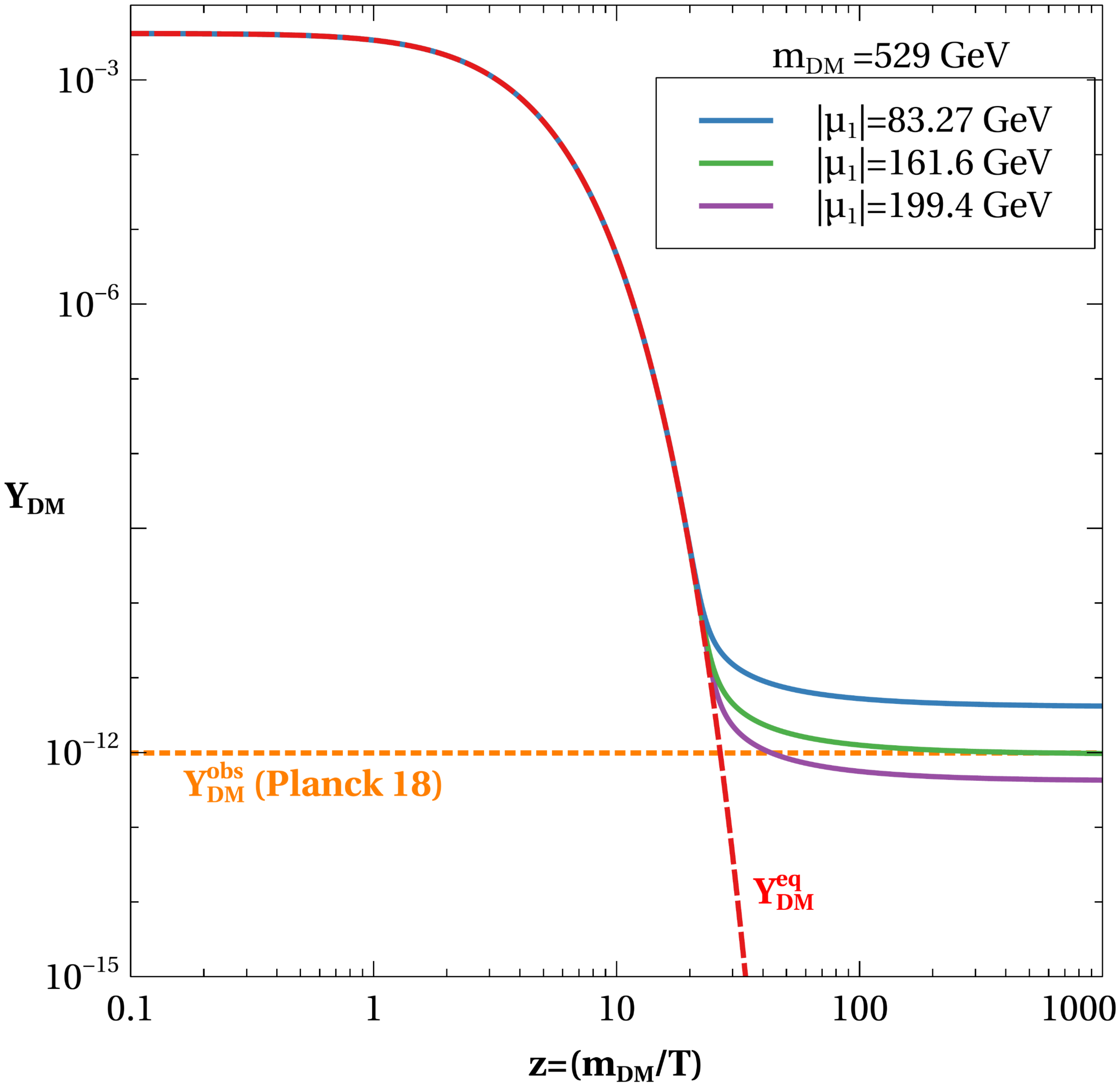




Dark Matter:

Dark matter candidates: η_1, η_2 , A

$$\frac{dY_{\rm DM}}{dx} = -\frac{s}{H(x)x}(Y_{\rm DM}^2 - (Y_{\rm DM}^{\rm eq})^2)\langle\sigma v\rangle_{\rm DM\,DM\to SM\,SM}$$



Conclusion:

- We have addressed baryon-DM coincidence $\Omega_{DM} \approx 5\Omega_{\boldsymbol{B}}$.
- We have realized first order Electroweak phase transition with GW within LISA sensitivity.
- The scalar portal is responsible for generation of asymmetry..
- There is a correlation between leptogenesis and signal to noise ratio..

Thank You

	μ_η (GeV)	μ_χ (GeV)	M_{η_1} (GeV)	$M_\eta(M_A)$ (GeV)	M_{η_2} (GeV)	$\|\mu_1\|$ (GeV)	y_1 (10^{-3})	T_c (GeV)	T_n (GeV)	β/H_*	α_*	M_{N_1} (GeV)
BP1	450	430	529	682	600	161.6	2.00	65.6	39.1	136.0	0.52	989
BP2	938	592	1046	1091	815	733.5	1.10	66.5	48.9	443.6	0.20	1700
BP3	660	220	714	778	598	301.2	1.33	71.6	48.8	308.2	0.21	995
BP4	524	57	820	648	336	461.1	1.62	67.2	47.9	429.4	0.23	935

Table 2. Benchmark points satisfying the requirements of observed baryon asymmetry and dark matter. The mass of Z_2-odd heavy fermion is kept at $M_\psi \sim 10 M_{N_1}$.