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Baryon asymmetry from dark matter decay in the vicinity of a phase transition

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Based on Phys.Rev.D 108 (2023) 9, L091701 arXiv: 2306.05459

Outline:

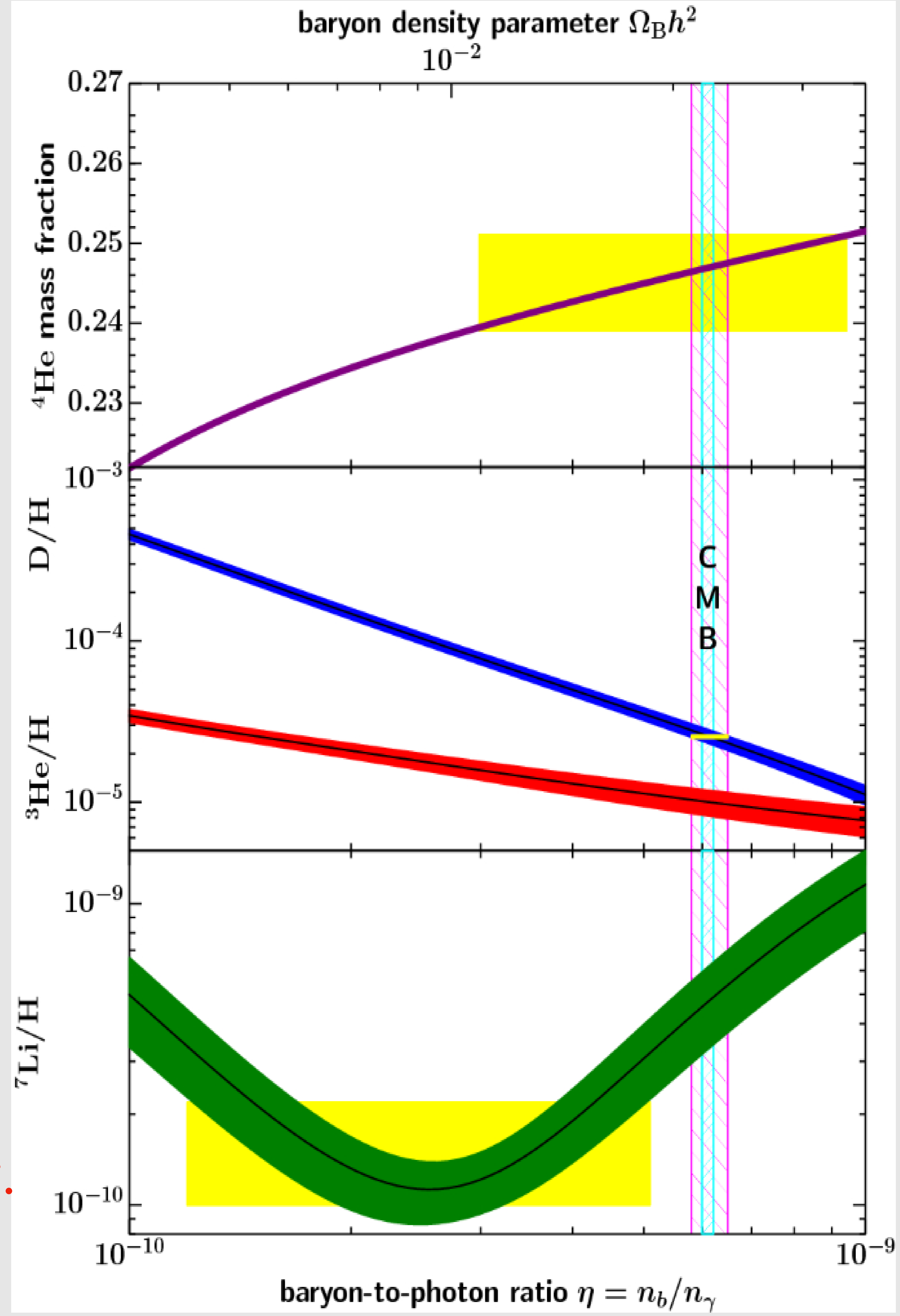
- Motivation
- Leptogenesis
- Dark matter
- First order Phase Transition (FOPT)
- Scotogenic model
- Stochastic Gravitational Waves (GW)
- Conclusion

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



Particle Data Group

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.

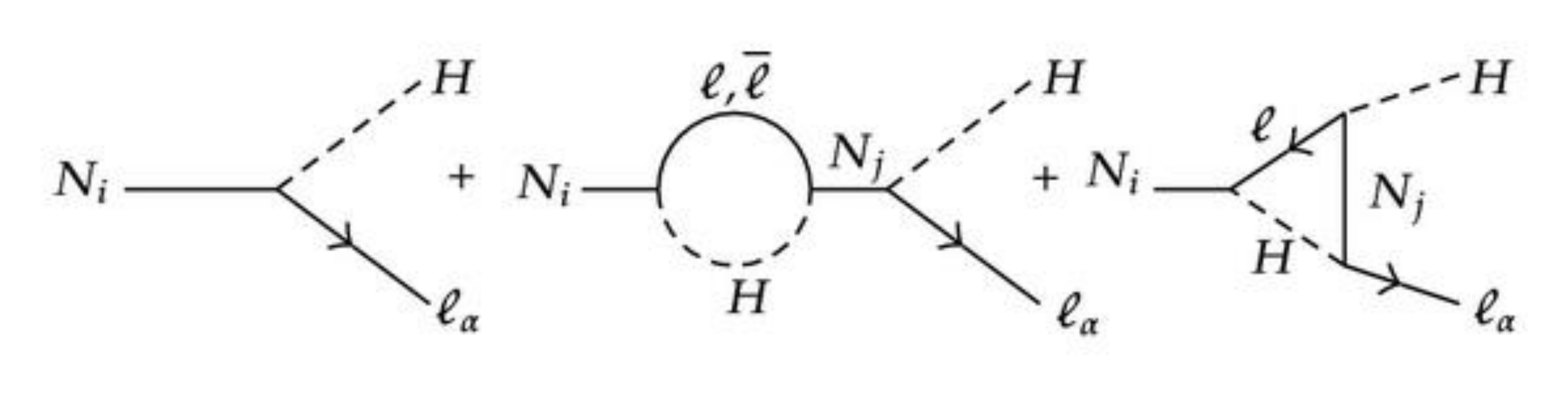
Baryogenesis via Leptogenesis

❖ 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

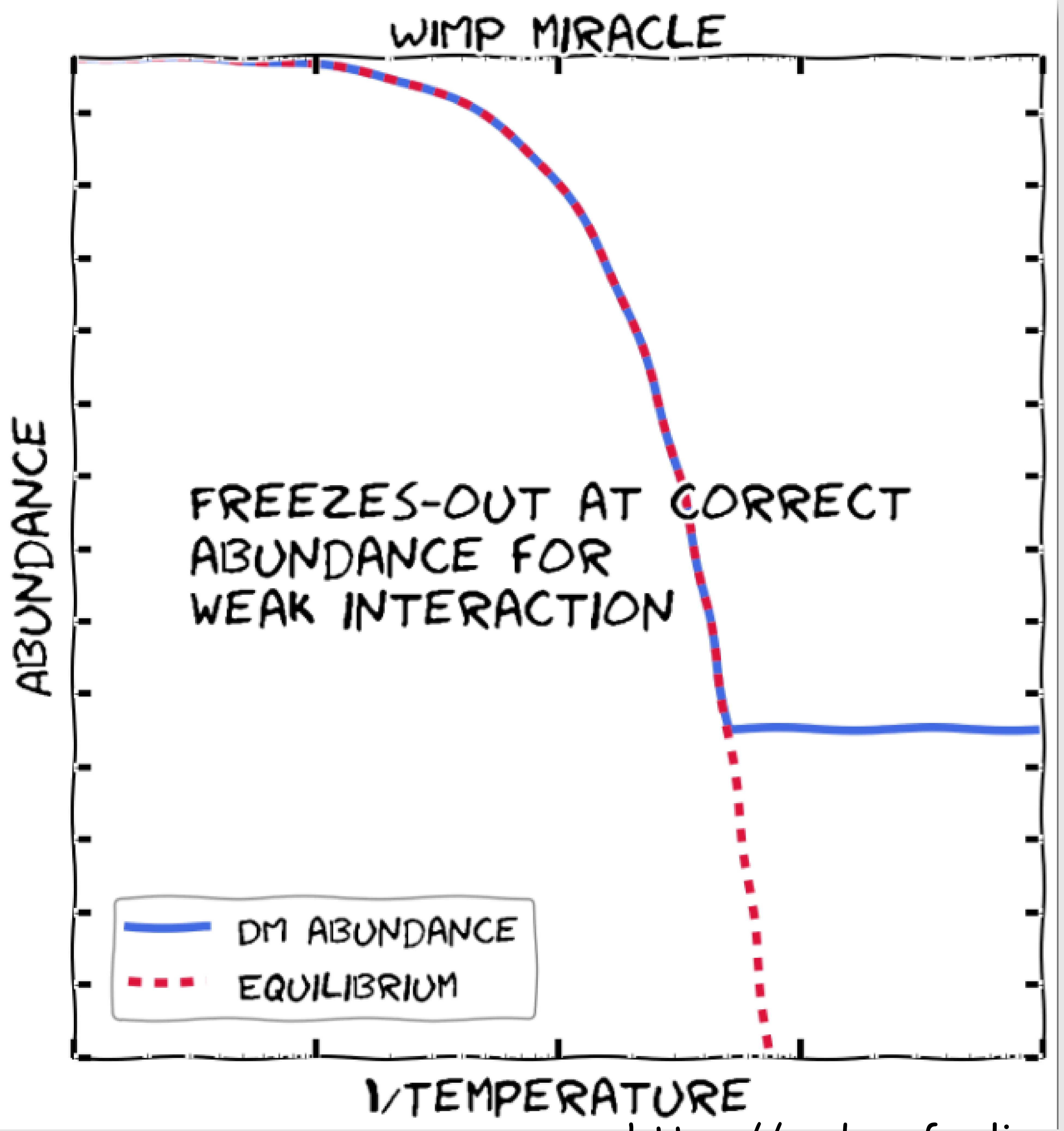
$$\epsilon_{\alpha\alpha} \equiv \frac{\Gamma(N_1 \to \phi\ell_\alpha) - \Gamma(N_1 \to \bar{\phi}\bar{\ell}_\alpha)}{\Gamma(N_1 \to \phi\ell) + \Gamma(N_1 \to \bar{\phi}\bar{\ell})}$$



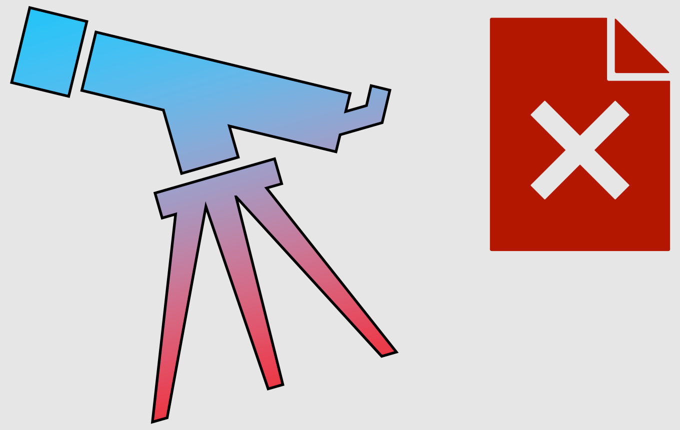
❖ The frozen out lepton asymmetry at is converted into baryon asymmetry by electroweak sphalerons

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

We know it exist → Dark Matter



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



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

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

They can have a common origin !

First order Phase transition:

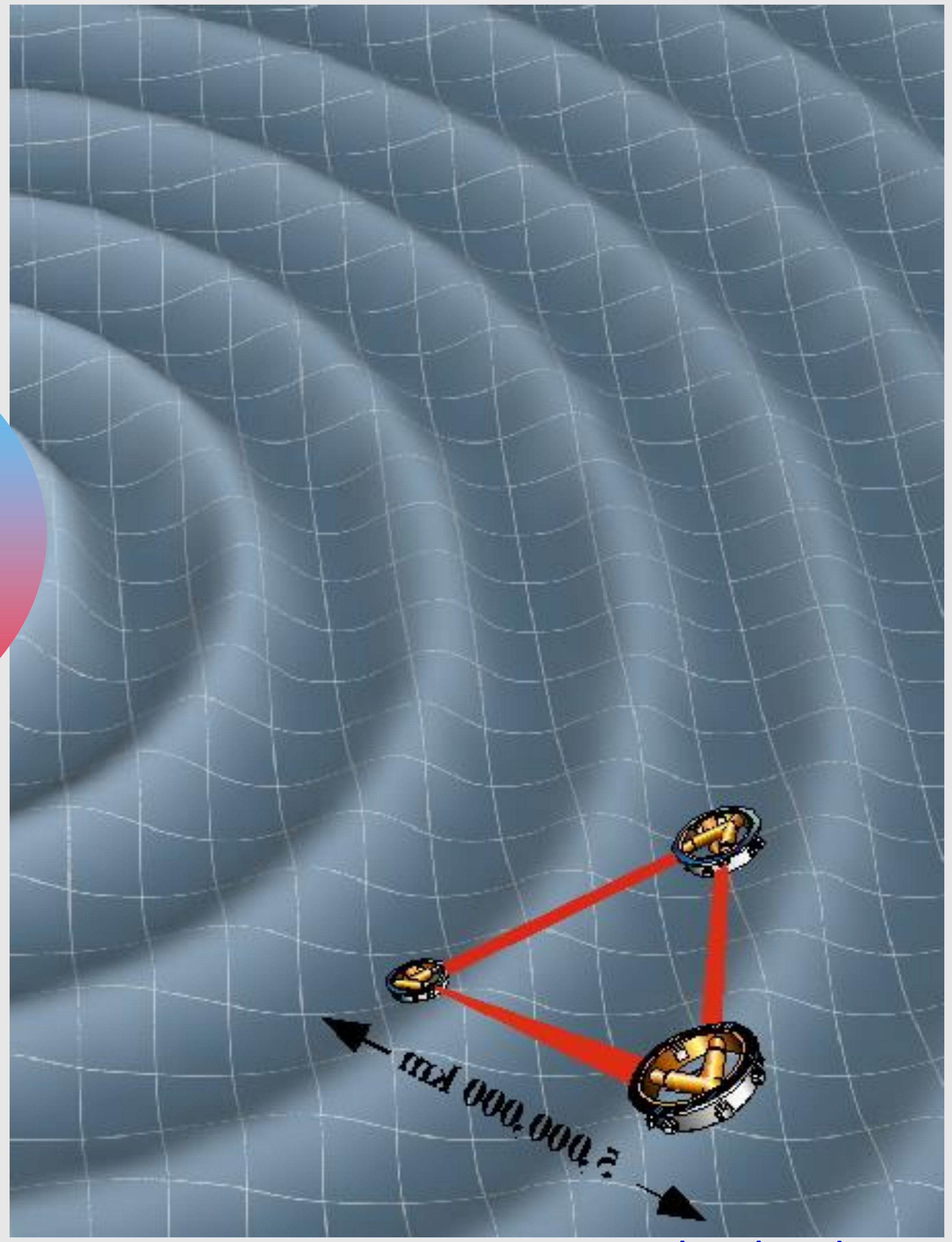
Leptogenesis

Dark Matter

Common origin

First order Phase transition

Gravitational waves



caltech.edu

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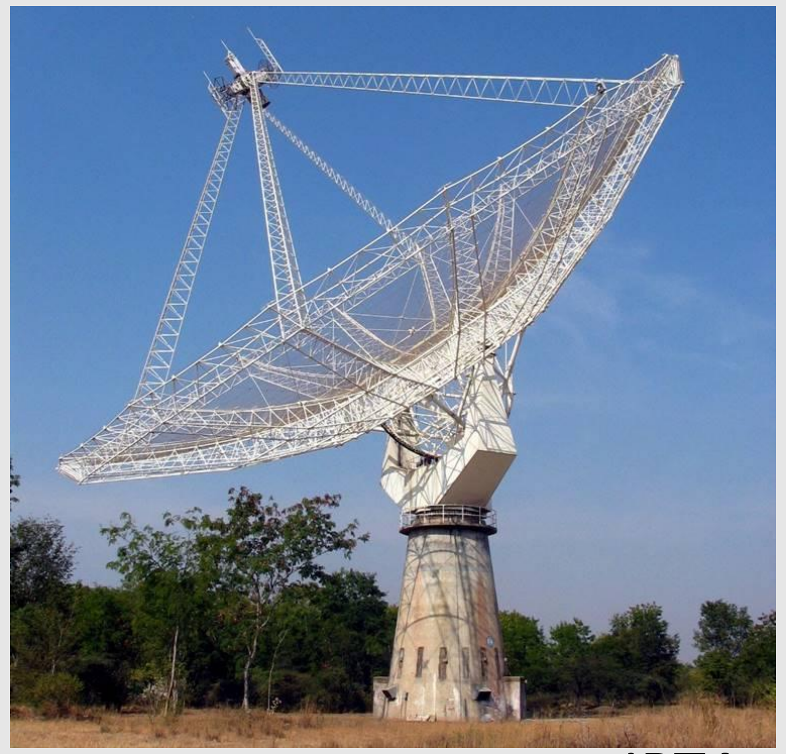
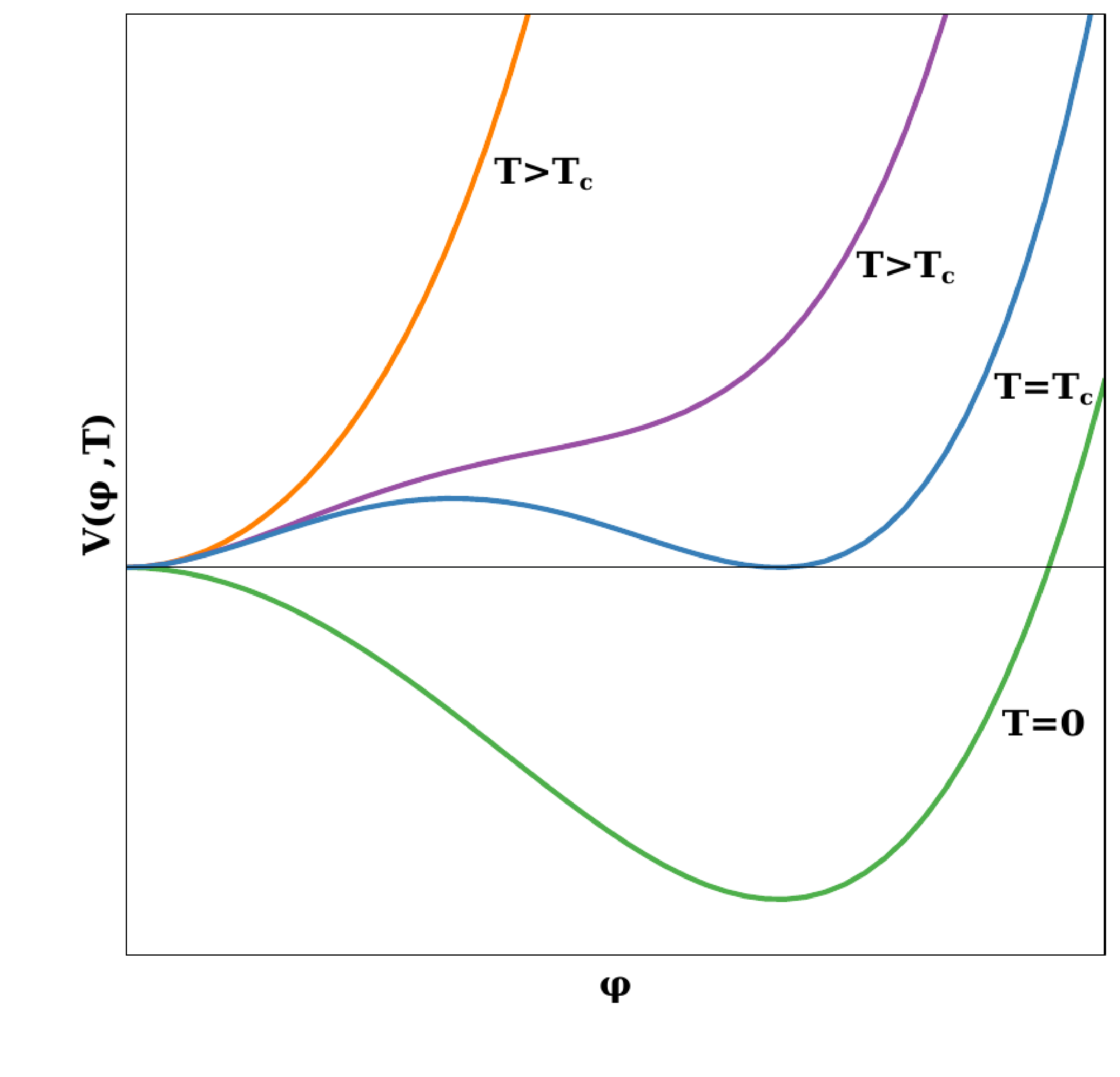


IPTA



- 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.

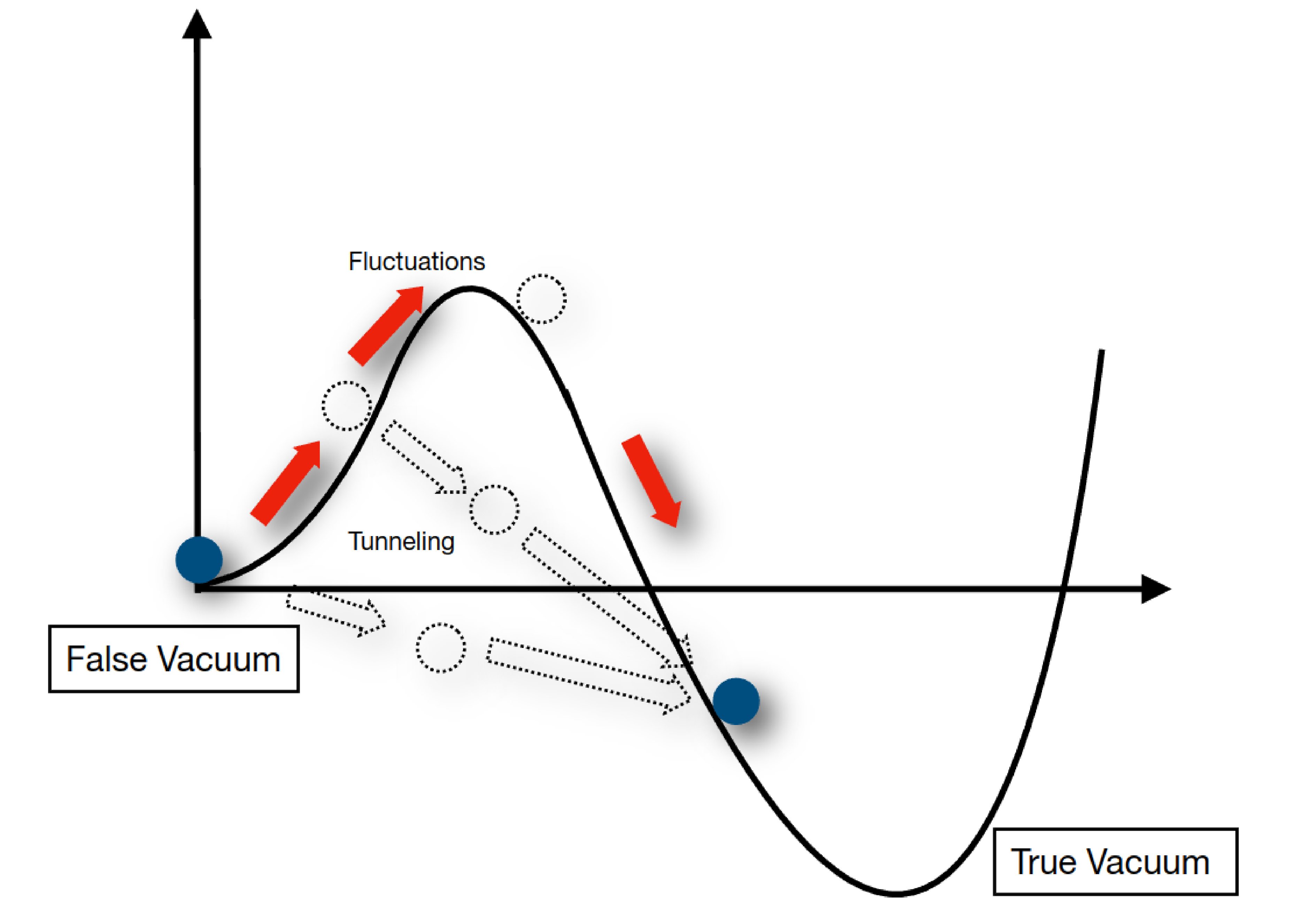
The rate of tunneling per unit volume:

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

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

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

Linde, Phys.Lett.B 100 (1981)



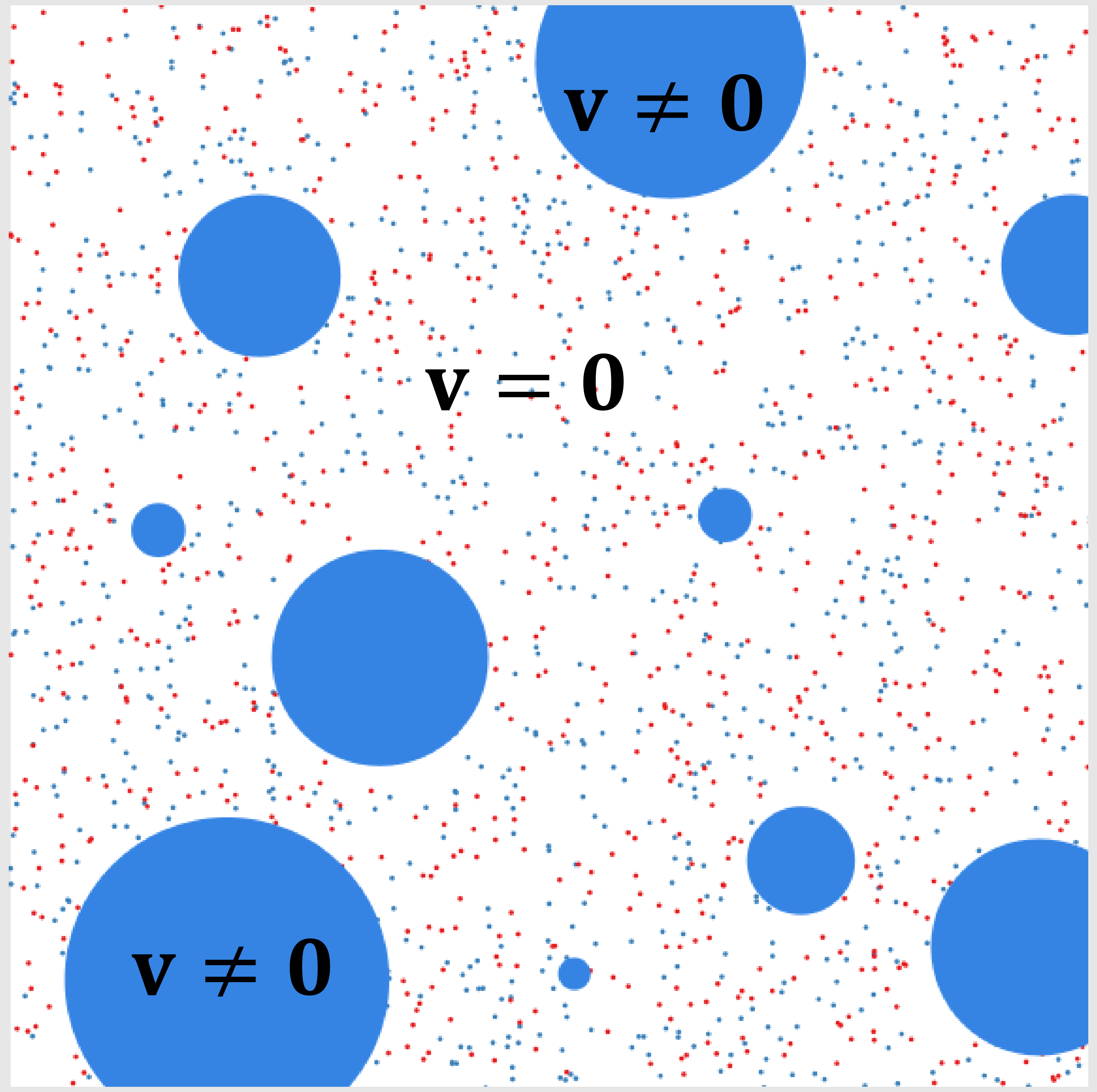
Vacuum energy released

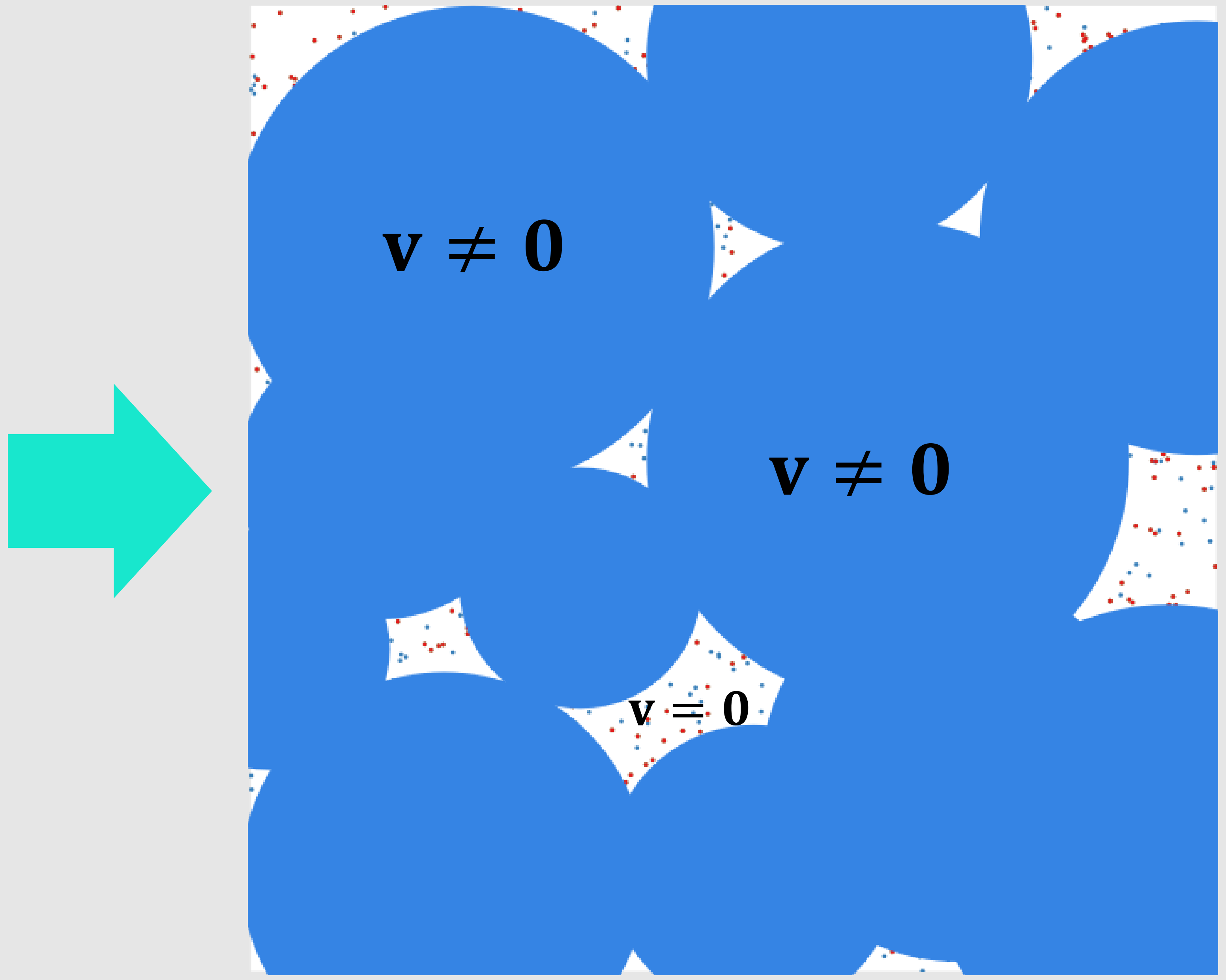
$$\alpha_* = \frac{\epsilon_*}{\rho_{\rm rad}},$$

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

Duration of the FOPT

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





Scotogenic Model

Leptonic Yukawa interaction:

$$-\mathcal{L} \supset \frac{1}{2} M_{ij} \overline{N_i^c} N_j + Y_{\alpha i} \overline{L_\alpha} \tilde{\eta} N_i + \text{h.c.}$$

Scalar Potential:

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

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

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

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

$$V_{\text{th}} = \sum_i \left(\frac{n_{\text{B}_i}}{2\pi^2} T^4 J_B \left[\frac{m_{\text{B}_i}}{T} \right] - \frac{n_{\text{F}_i}}{2\pi^2} T^4 J_F \left[\frac{m_{\text{F}_i}}{T} \right] \right),$$

BSM fields: 3 singlet right handed neutrinos, one extra scalar doublet

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

Finite temperature effect on masses:

Scalar masses

$$m_i^2(\phi, T) = m_i^2(\phi) + \Pi_S(T)$$

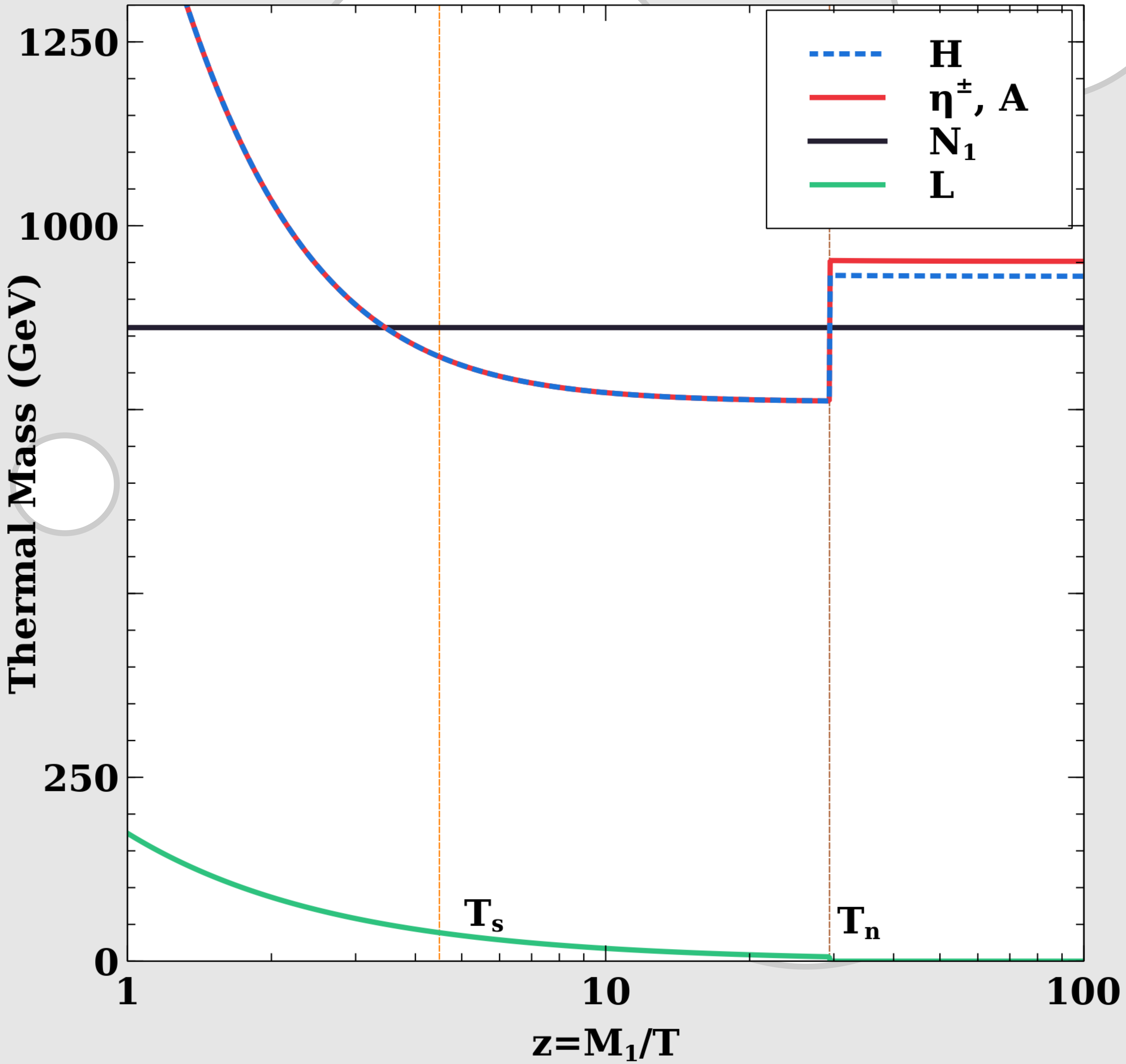
Lepton masses

$$M_L(T) = \sqrt{m_L^2 + \frac{1}{2}\Pi^2_{\rm gauge}(T)},$$

$$\Pi^2_{\rm gauge}(T) = \left(\frac{1}{16}g'^2 + \frac{3}{16}g^2\right)T^2.$$

DM decay if

$$M_N > M_L + \eta$$



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Boltzmann equation:

$$\frac{dY_N}{dz} = \frac{g_\eta \langle \Gamma_\eta \rangle}{z\tilde{\mathcal{H}}} \left[Y_\eta - \frac{Y_\eta^{eq} Y_N}{Y_N^{\rm eq}} \right] - \frac{g_\eta \langle \Gamma_{N_1} \rangle}{z\tilde{\mathcal{H}}} \left[Y_N - \frac{Y_N^{\rm eq} Y_\eta}{Y_\eta^{\rm eq}} \right],$$

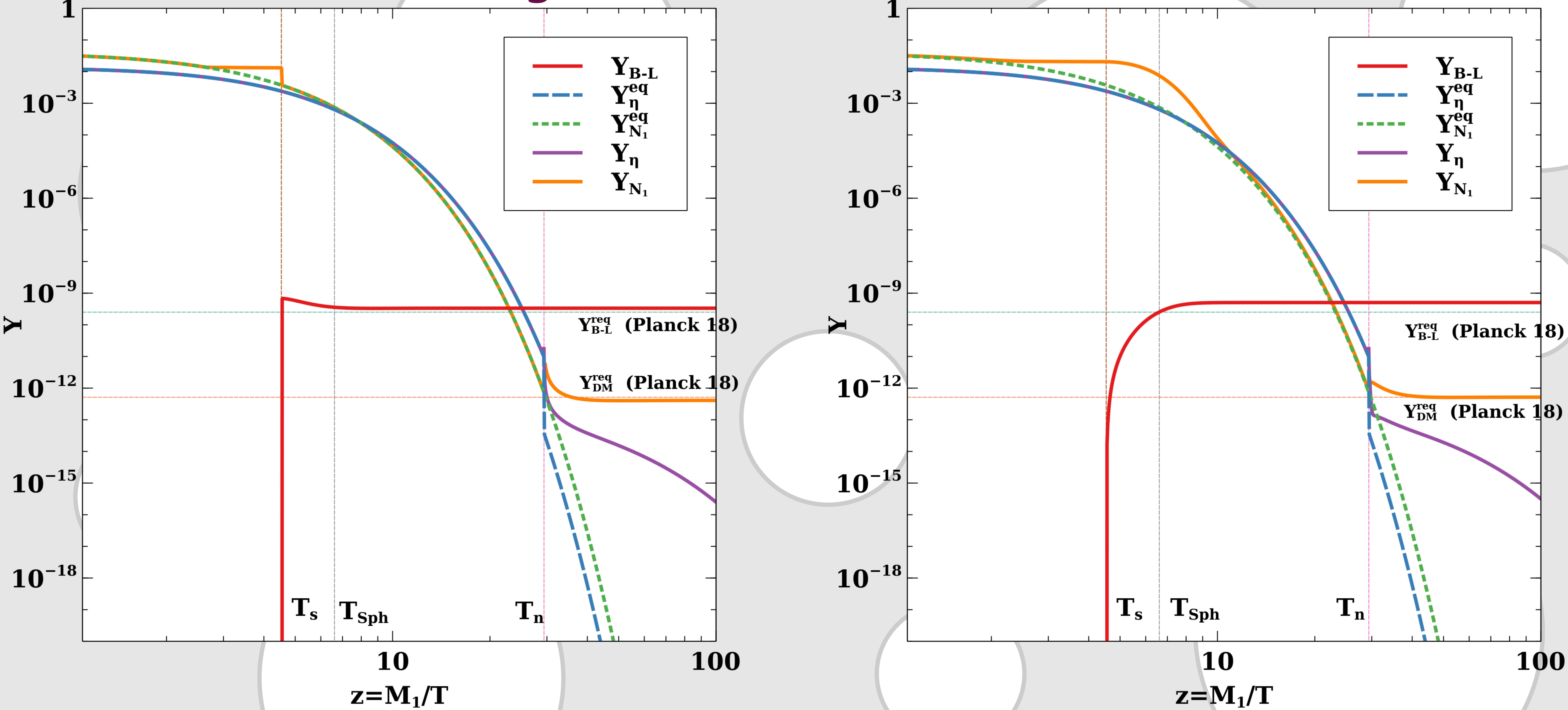
$$\frac{dY_\eta}{dz} = -\frac{g_\eta \langle \sigma_{\eta\eta} v_{\rm rel} \rangle s}{z\tilde{\mathcal{H}}} \left[Y_\eta^2 - Y_\eta^{\rm eq\,2} \right] - \frac{g_\eta \langle \Gamma_\eta \rangle}{z\tilde{\mathcal{H}}} \left[Y_\eta - \frac{Y_\eta^{\rm eq} Y_N}{Y_N^{\rm eq}} \right] + \frac{g_\eta \langle \Gamma_{N_1} \rangle}{z\tilde{\mathcal{H}}} \left[Y_N - \frac{Y_N^{\rm eq} Y_\eta}{Y_\eta^{\rm eq}} \right],$$

$$\frac{dY_{B-L}}{dz} = -\epsilon_1 \frac{g_\eta \langle \Gamma_{N_1} \rangle}{z\tilde{\mathcal{H}}} \left[Y_N - \frac{Y_N^{\rm eq} Y_\eta}{Y_\eta^{\rm eq}} \right] - \epsilon_\eta \frac{g_\eta \langle \Gamma_\eta \rangle}{z\tilde{\mathcal{H}}} \left[Y_\eta - \frac{Y_\eta^{\rm eq} Y_N}{Y_N^{\rm eq}} \right] - (W_1 + \Delta W)\, Y_{B-L}.$$

Lepton asymmetry:

$$\epsilon_i = \left[\left(M_i^2 + M_L^2 - m_\eta^2 \right) \lambda^{1/2} \left(M_i^2, M_L^2, m_\eta^2 \right) \Theta \left(M_i^2 - (m_\eta + M_L)^2 \right) \right] \frac{1}{(Y^\dagger Y)_{ii}} \sum_{j \neq i} \frac{{\rm Im}[((Y^\dagger Y)_{ij})^2]}{16\pi M_i^3} \frac{M_j \Delta_{ij}}{\Delta_{ij}^2 + \left(M_j \Gamma_{N_j} \right)^2}$$

Evolution of comoving number densities:



Strong washout $m_1 = 10^{-1}$ eV (NO)

Weak washout $m_1 = 10^{-5}$ eV (NO)

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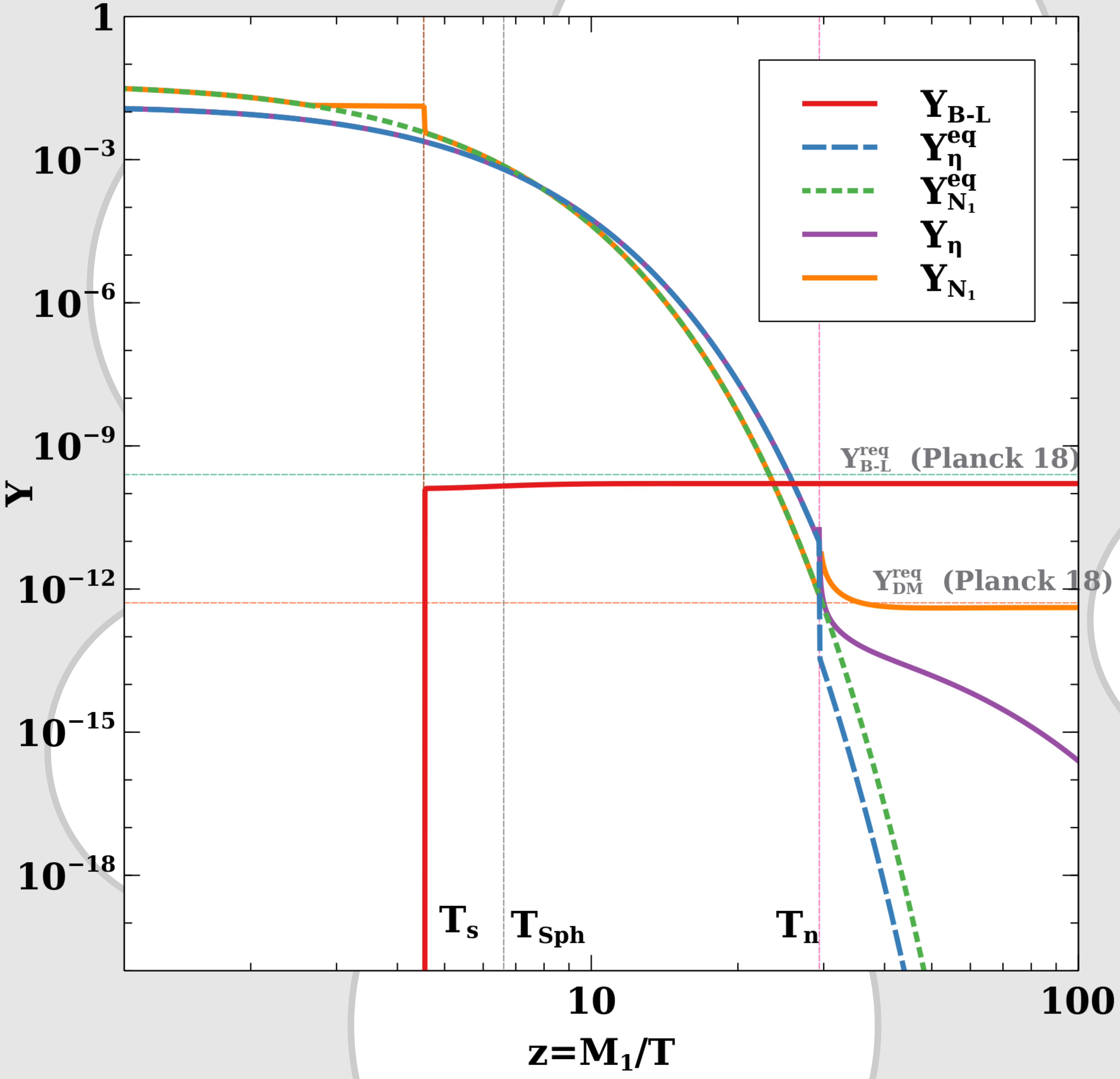
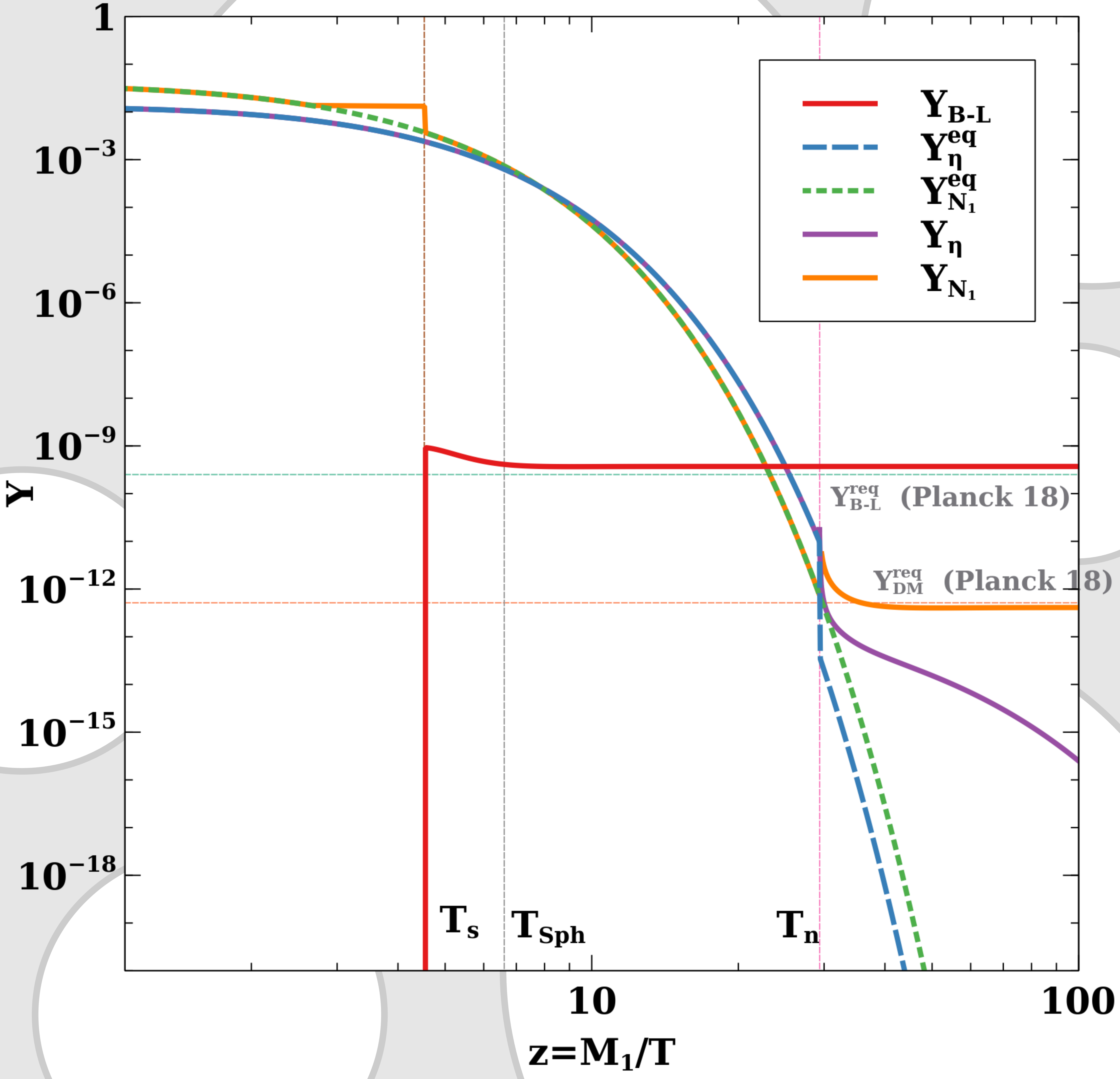
Evolution of comoving number densities:



Weak washout $m_3 = 10^{-1}$ eV (IO)



Strong washout $m_3 = 10^{-5}$ eV (IO)

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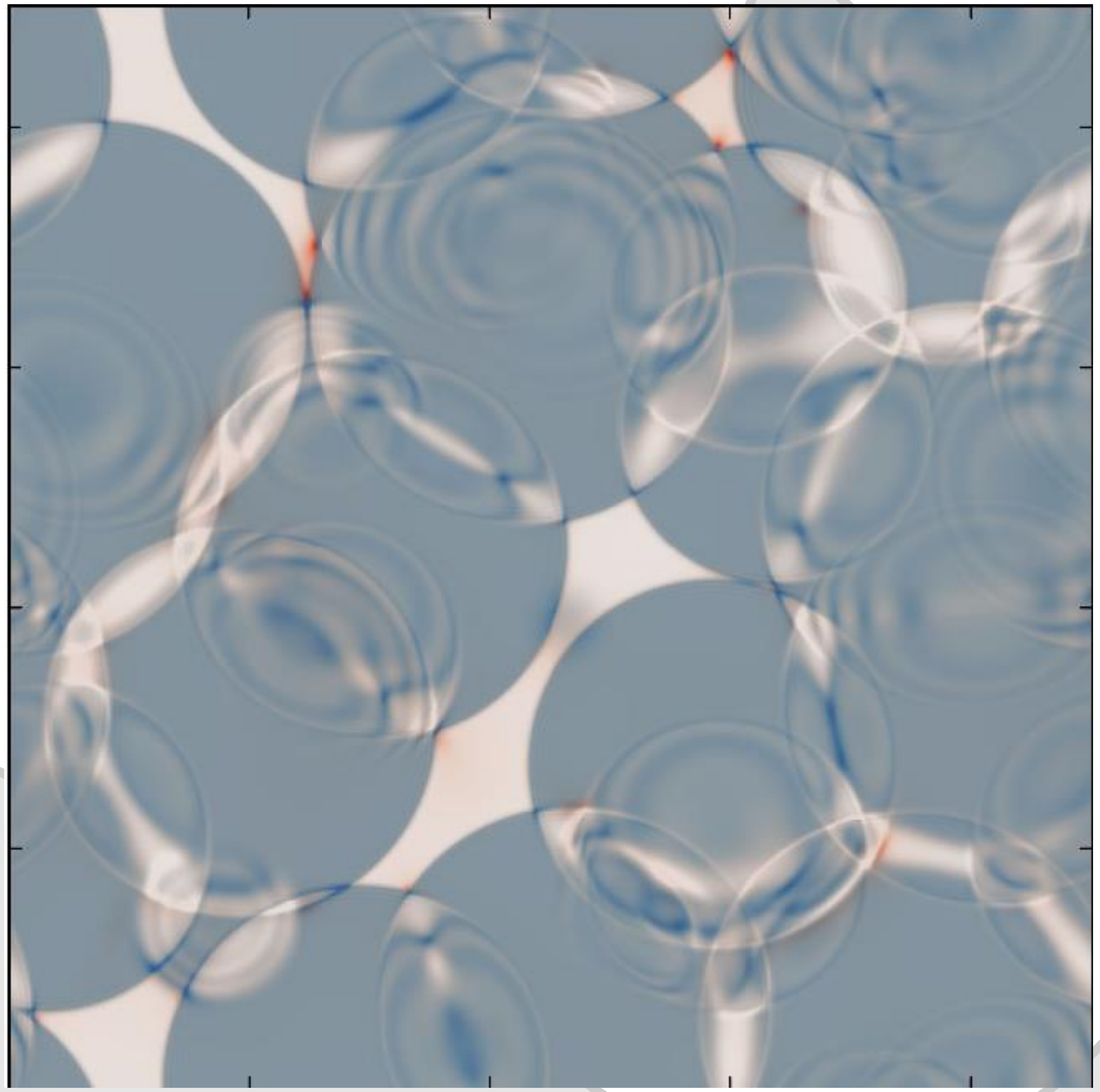
Stochastic Gravitational Waves:

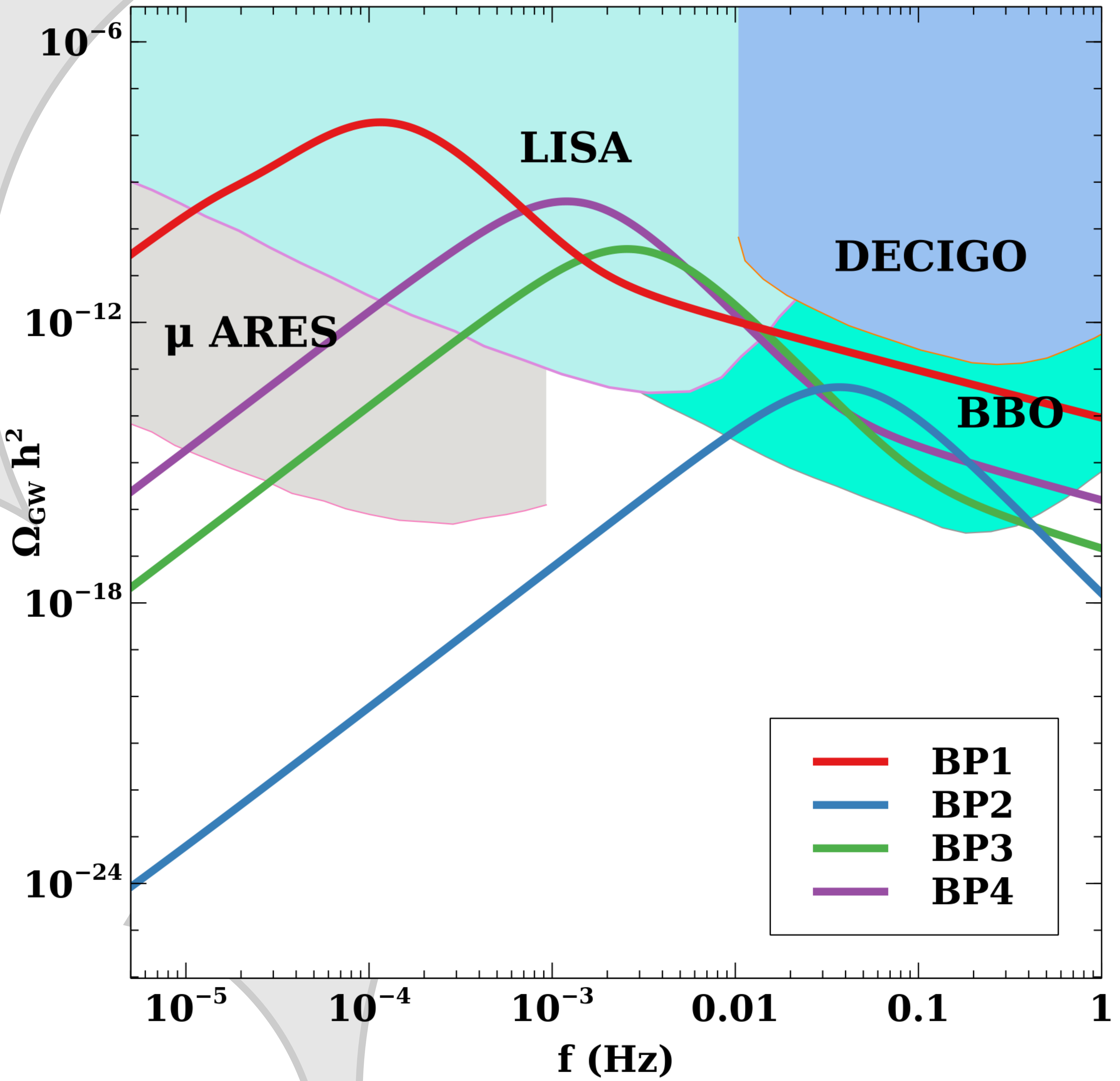
$$\Omega_{GW}^{PT}(f) = \Omega_{\phi}(f) + \Omega_{sw}(f) + \Omega_{turb}(f),$$

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

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

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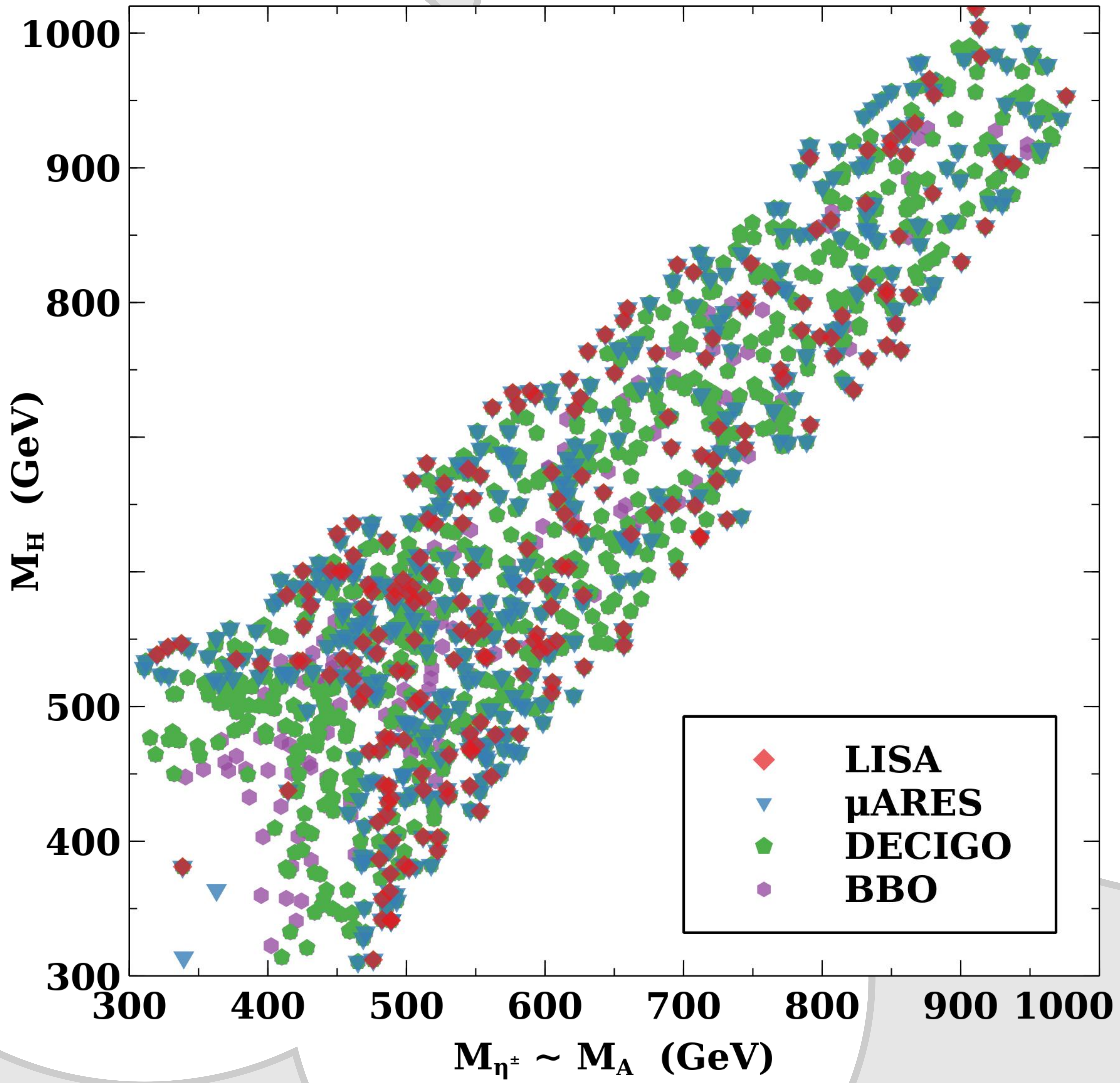
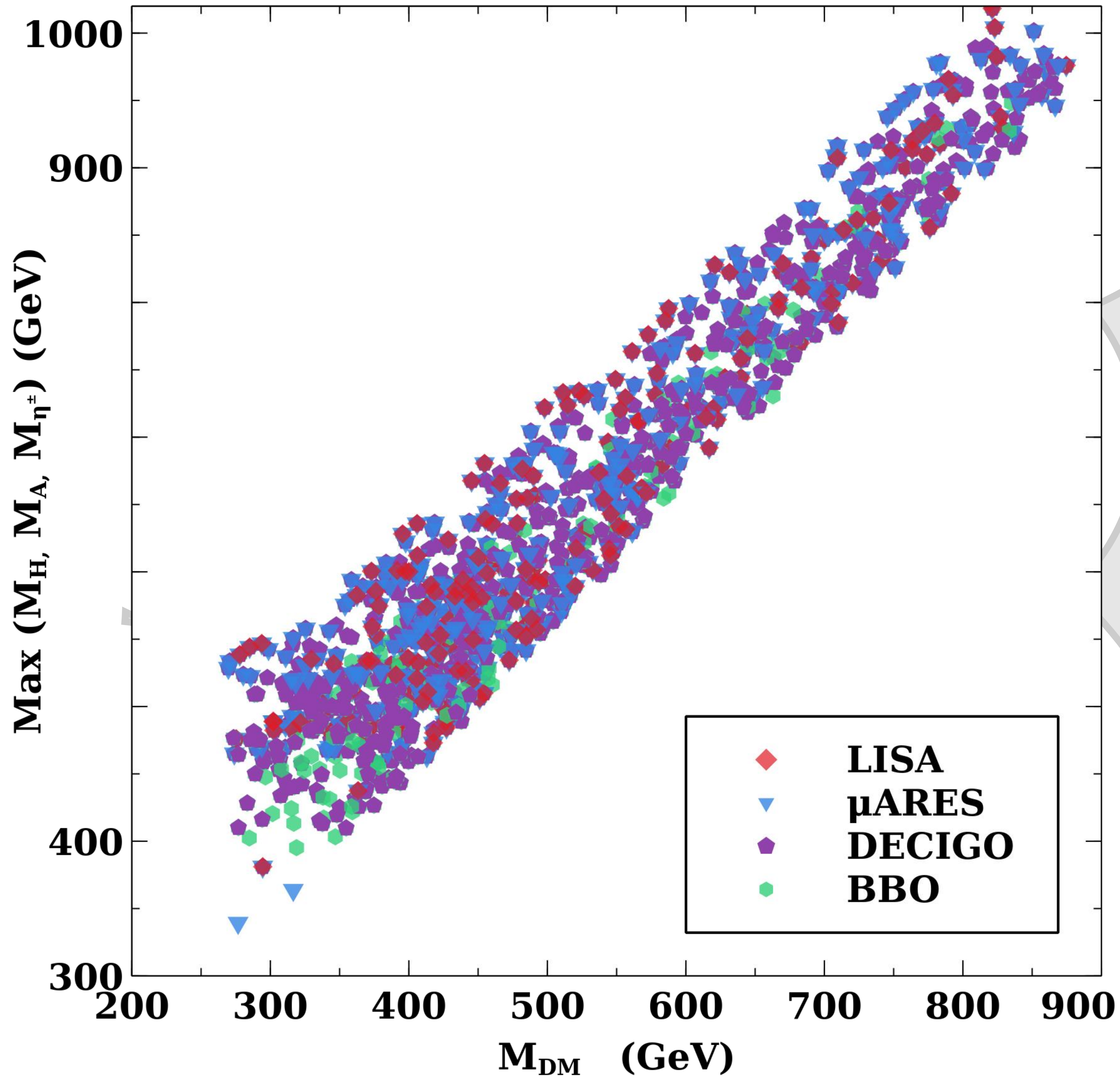
Detectional prospects of Gravitational Waves:





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Conclusion:

- We have addressed baryon-DM coincidence $\Omega_{DM} \approx 5\Omega_{B}$, from DM decay.
- We have realized first order Electroweak phase transition with GW within LISA sensitivity.
- The doublet scalar can have collider signature which can be probe.
- The two step first order phase transition can have other detection prospects.

Thank You

Backup:

	T_c (GeV)	v_c (GeV)	T_n(GeV)	M_1 (GeV)	μ_η (GeV)	$M_{\eta^\pm} \sim M_A$(GeV)	M_H (GeV)	α_*	$\beta/\mathcal{H}$	v_J	$T_{\rm RH}$ (GeV)
BP1	60.05	217.22	29.27	859.50	760.25	951.51	931.26	1.29	20.21	0.94	30.37
BP2	73.55	187.62	68.54	866.70	787.07	958.89	944.72	0.04	2862.35	0.71	68.54
BP3	71.30	199.28	64.33	676.64	579.36	774.96	743.73	0.06	1829.84	0.74	64.33
BP4	63.35	216.65	38.49	493.74	368.04	608.38	548.60	0.45	159.33	0.88	38.49

$$m_{\eta^\pm}^2(\phi) = \mu_\eta^2 + \frac{\lambda_3}{2}\phi^2 \;\; (n_{\eta^\pm} = 2, C_{\eta^\pm} = \frac{3}{2}), \;\; m_H^2(\phi) = \mu_\eta^2 + \frac{\lambda_3 + \lambda_4 + 2\lambda_5}{2}\phi^2 \;\; (n_H = 1, C_H = \frac{3}{2})$$

$$m_A^2(\phi) = \mu_\eta^2 + \frac{\lambda_3 + \lambda_4 - 2\lambda_5}{2}\phi^2 \, (n_A = 1, C_A = \frac{3}{2}), \, m_W^2(\phi) = \frac{g_2^2}{4}\phi^2 \, (n_W = 6, C_W = \frac{5}{6})$$

$$m_Z^2(\phi) = \frac{g_1^2 + g_2^2}{4}\phi^2 \;\; (n_Z = 3, C_Z = \frac{5}{6}), \;\; m_t^2(\phi) = \frac{y_t^2}{2}\phi^2 \;\; (n_t = 12, C_t = \frac{3}{2}), \;\; m_b^2(\phi) = \frac{y_b^2}{2}\phi^2 \;\; (n_b = 12, C_b = \frac{3}{2}).$$

$$Y_{\alpha i} \;=\; \left(U D_\nu^{1/2} R^\dagger \Lambda^{1/2}\right)_{\alpha i}$$