Leptogenesis and Dark Matter Through Relativistic Bubble Walls with Observable Gravitational Waves

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Based on
JHEP 11 (2022) 136 (2207.14226) and 2304.08888

Collaborator: Debasish Borah, Arnab Dasgupta

Outline:

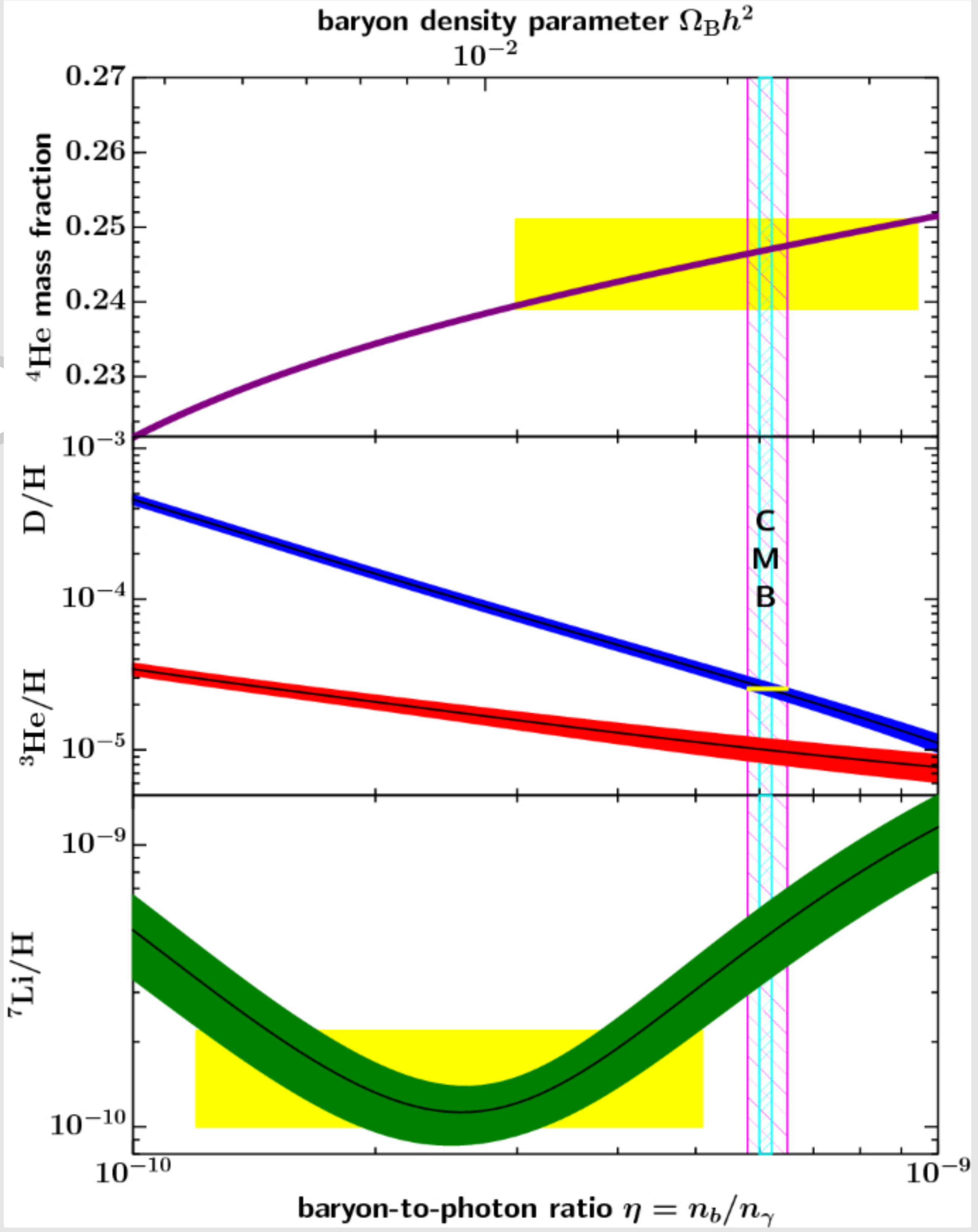
- Motivation
- First order Phase Transition (FOPT)
- Conformal Scotogenic model
- Stochastic Gravitational Waves (GW)
- Leptogenesis
- Dark Matter
- Conclusion

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



Particle Data Group

Baryogenesis

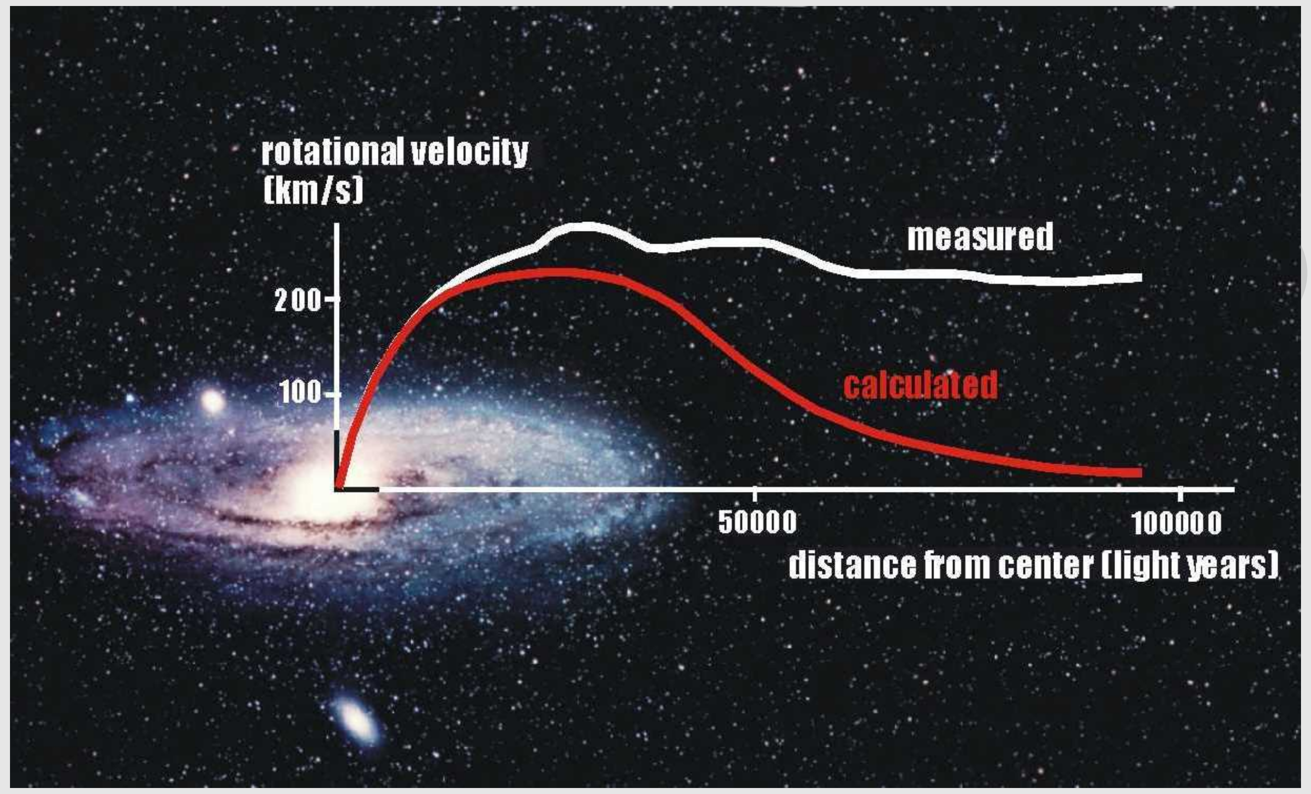
Sakharov's Conditions

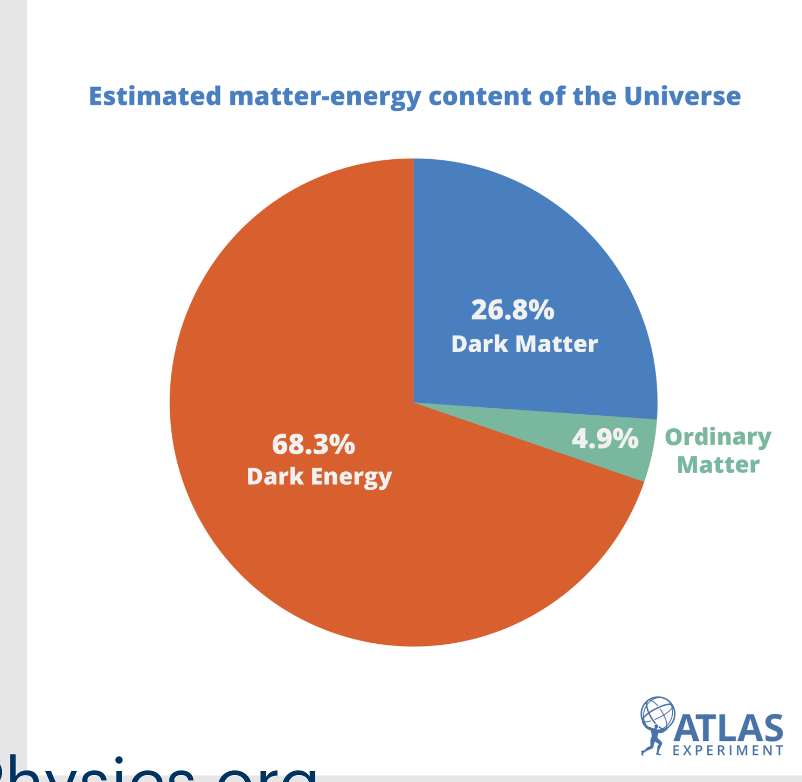
Sakharov 1967

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

Standard Model unable to satisfy above conditions in required amount.

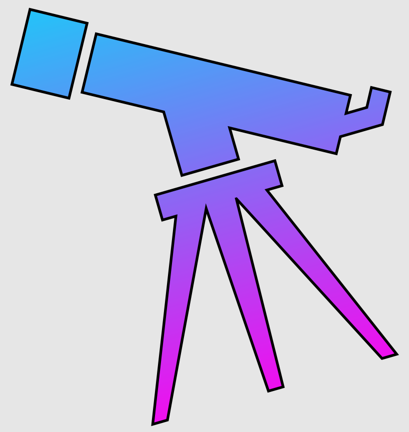
Leptogenesis





Physics.org

Dark Matter



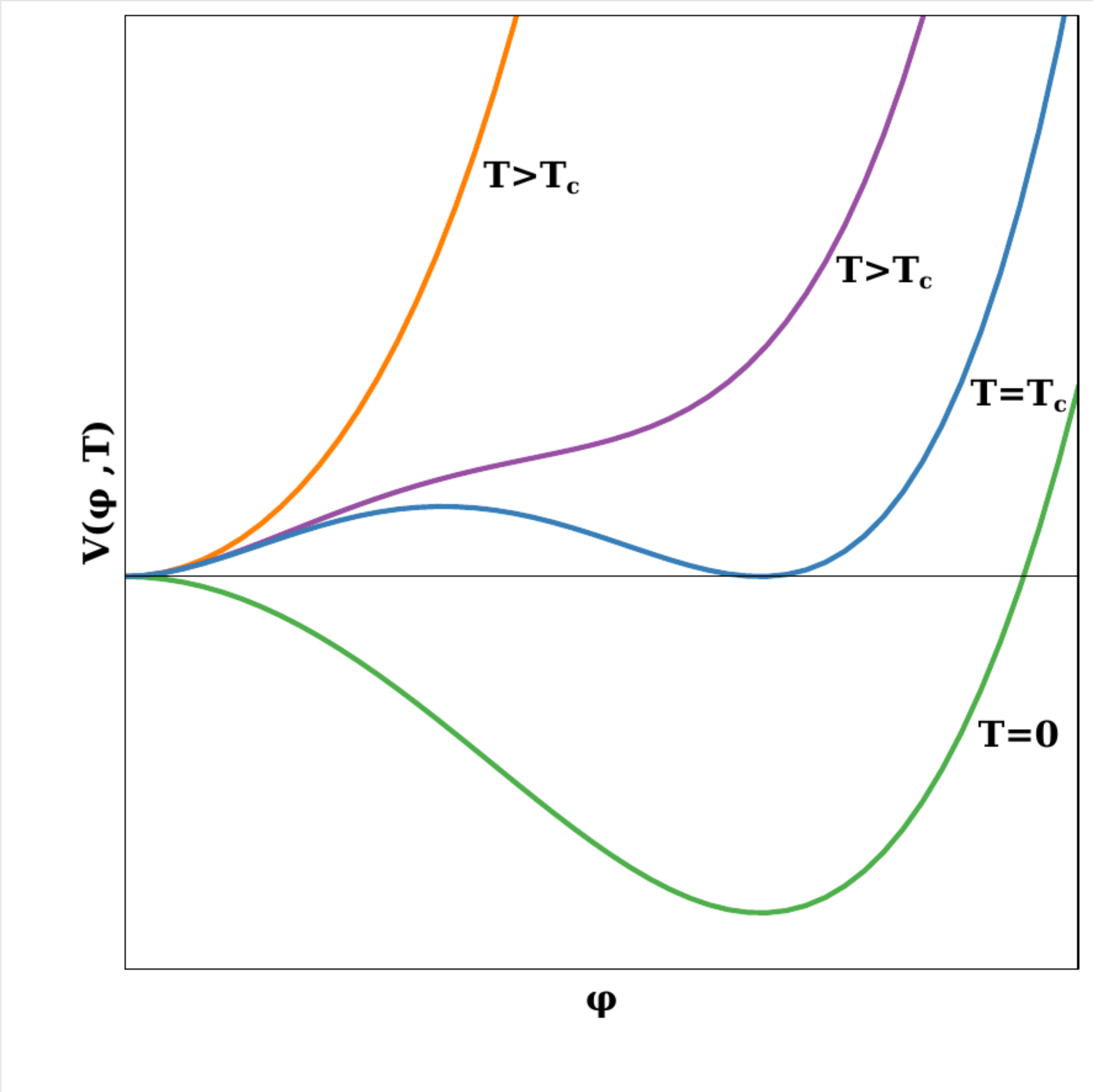
First order Phase transition:

Leptogenesis

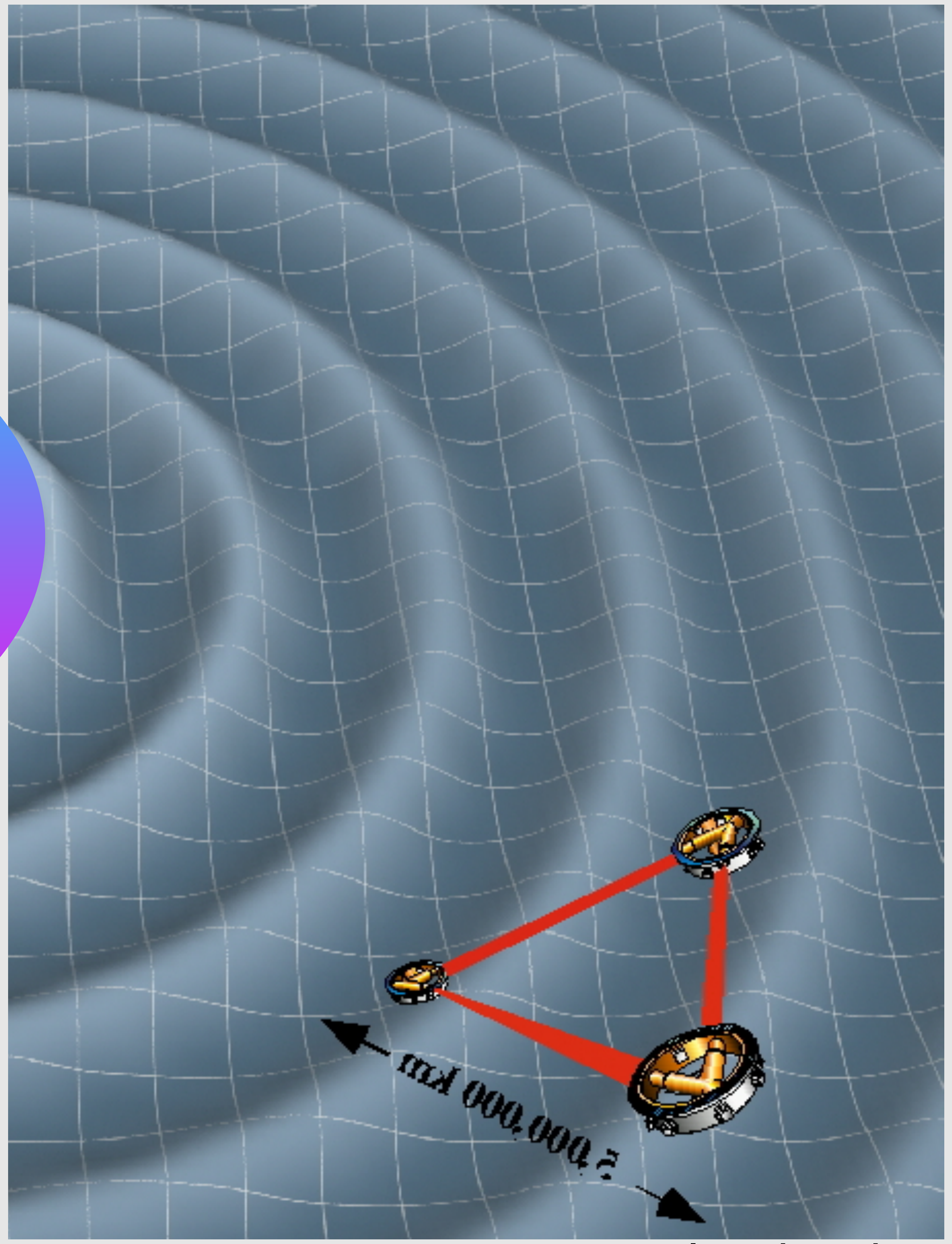
Dark Matter

Common origin

First order Phase transition

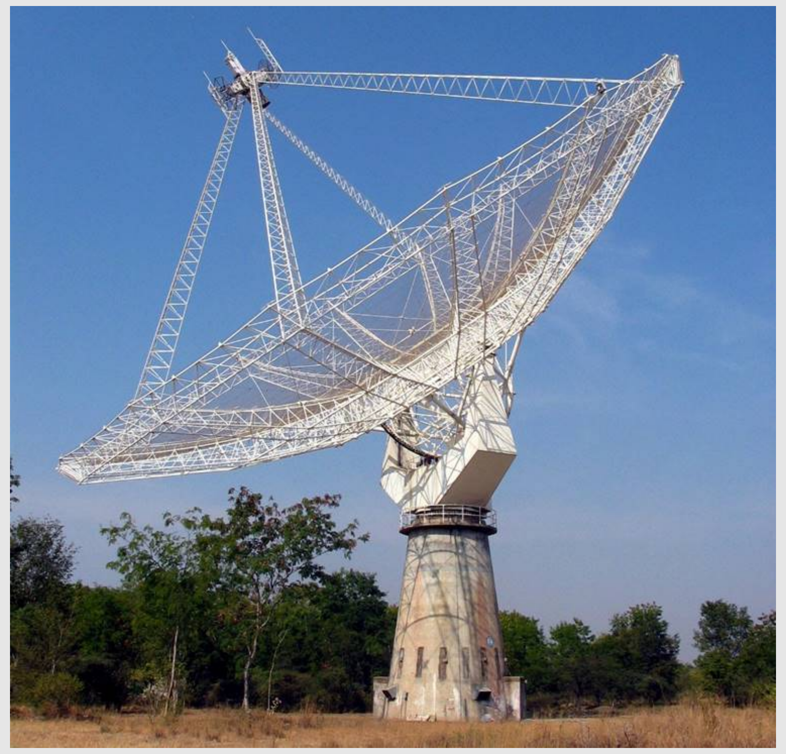


Gravitational waves



caltech.edu

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.

Conformal Scotogenic Model

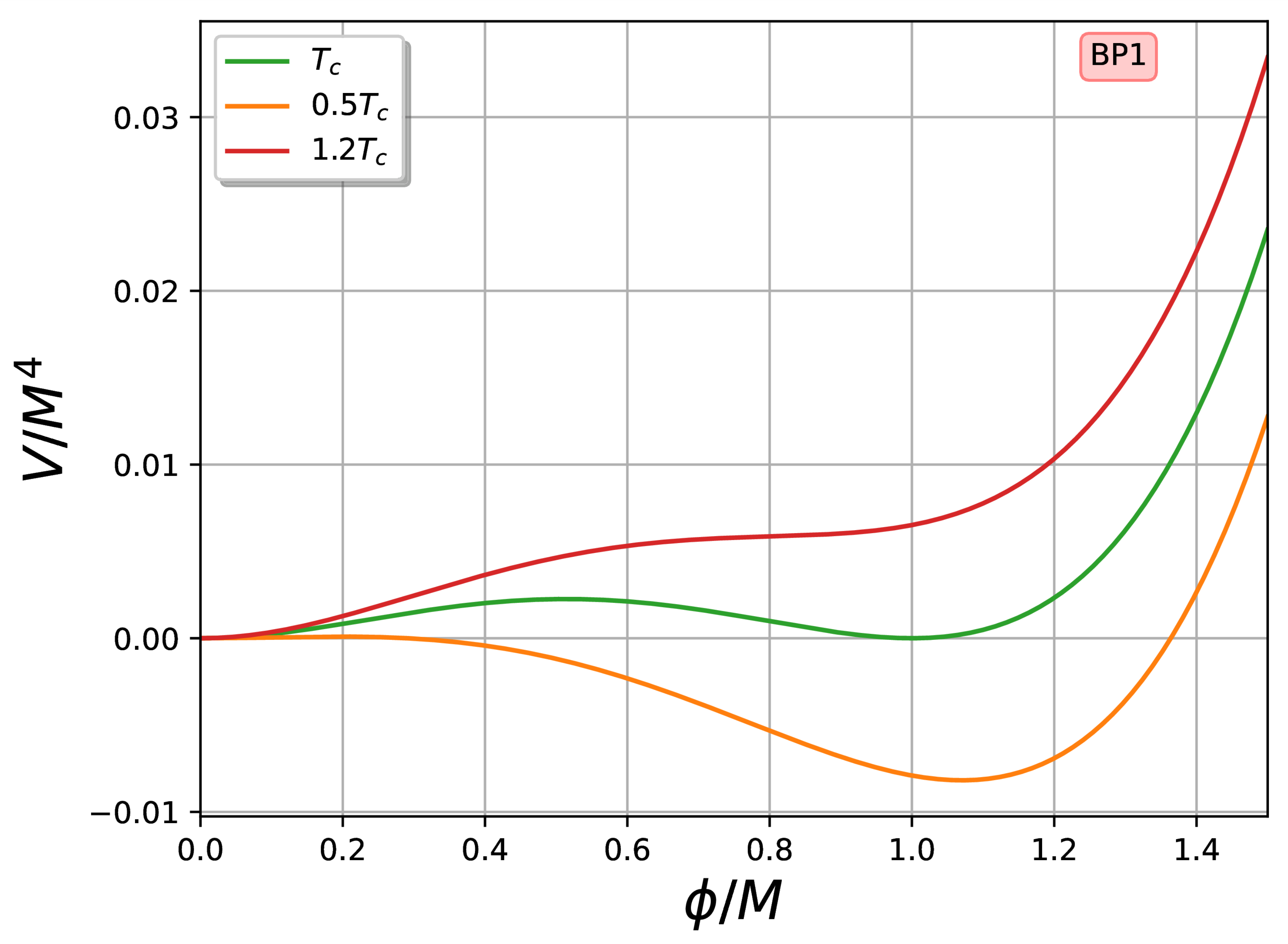
Leptonic Yukawa interaction:

$$\mathcal{L} \supset \frac{1}{2} Y'_{ij} S N_i N_j + \left(Y_{ij} \bar{L}_i \tilde{\eta} N_j + \text{h.c.} \right)$$

Scalar Potential:

$$V(\Phi_1, \eta, S) = \frac{\lambda_1}{4}|\Phi_1|^4 + \frac{\lambda_2}{4}|\eta|^4 + \lambda_3|\Phi_1|^2|\eta|^2 + \frac{1}{4}\lambda_S S^4 + \lambda_4|\Phi_1^\dagger\eta|^2 + \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\eta)^2 + \text{h.c.}\right] + \lambda_6|\Phi_1|^2 S^2 + \lambda_7|\eta|^2 S^2 \,.$$

Full One-loop Potential:



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

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

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

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

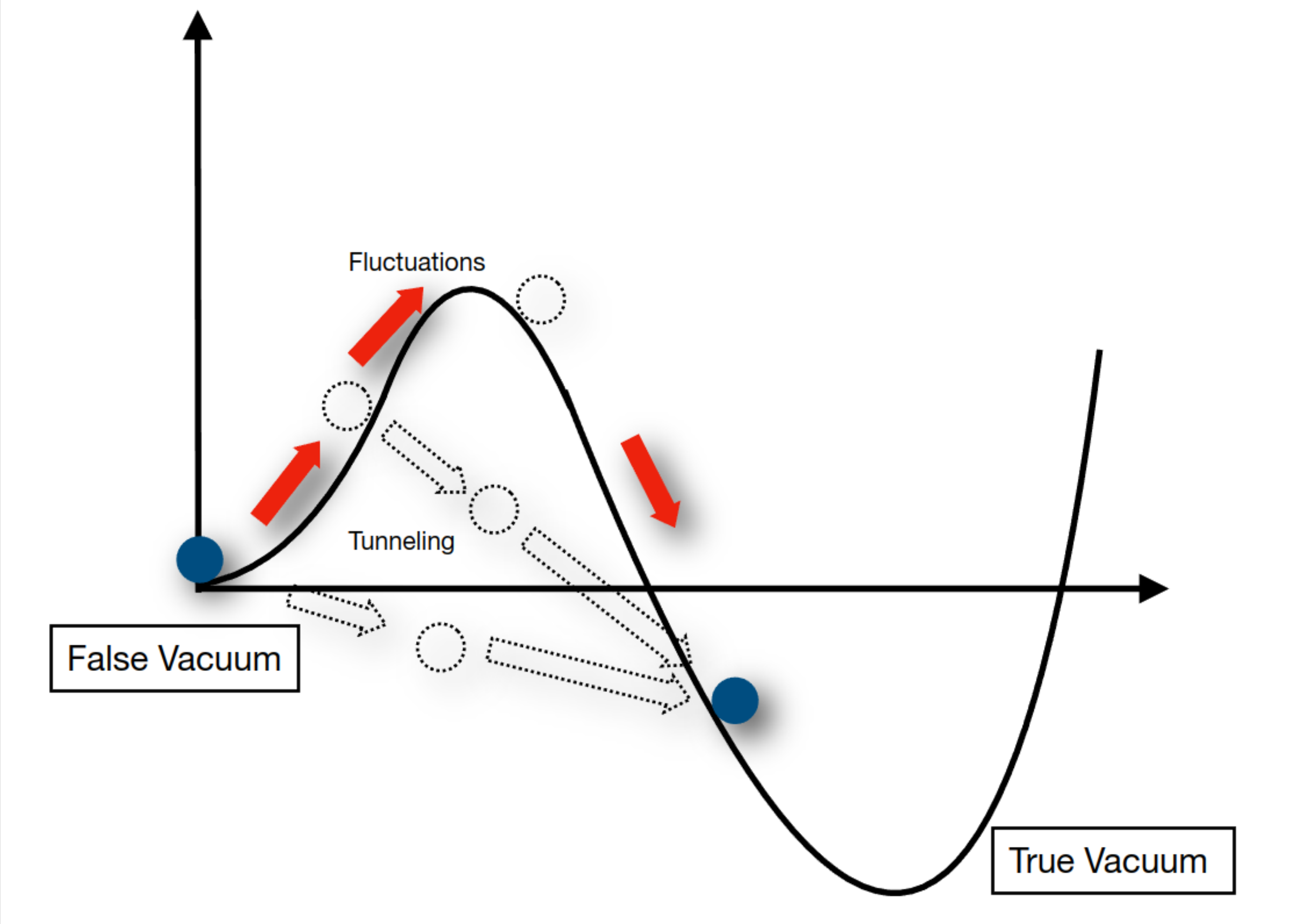
The rate of tunneling per unit volume:

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

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

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

Linde, Phys.Lett.B 100 (1981)



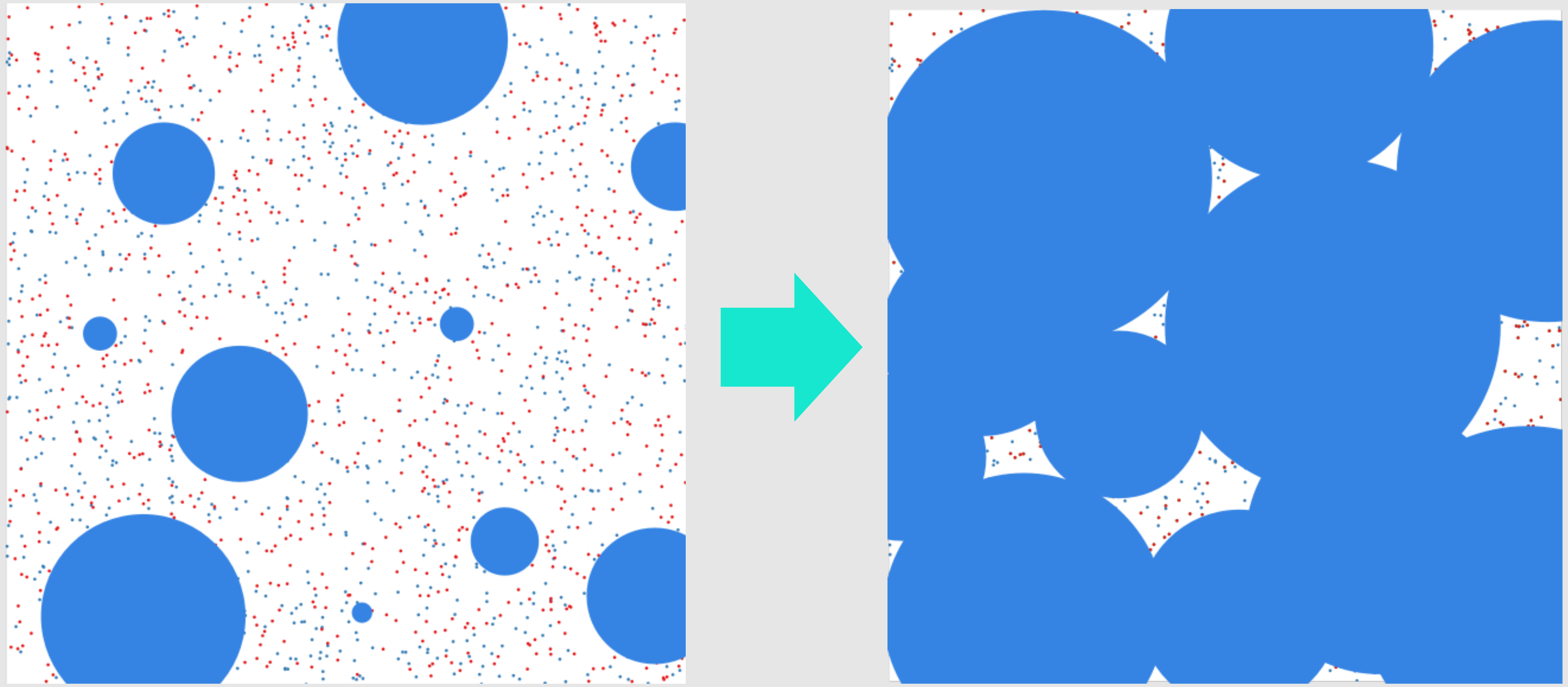
Vacuum energy released

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

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

Duration of the FOPT

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

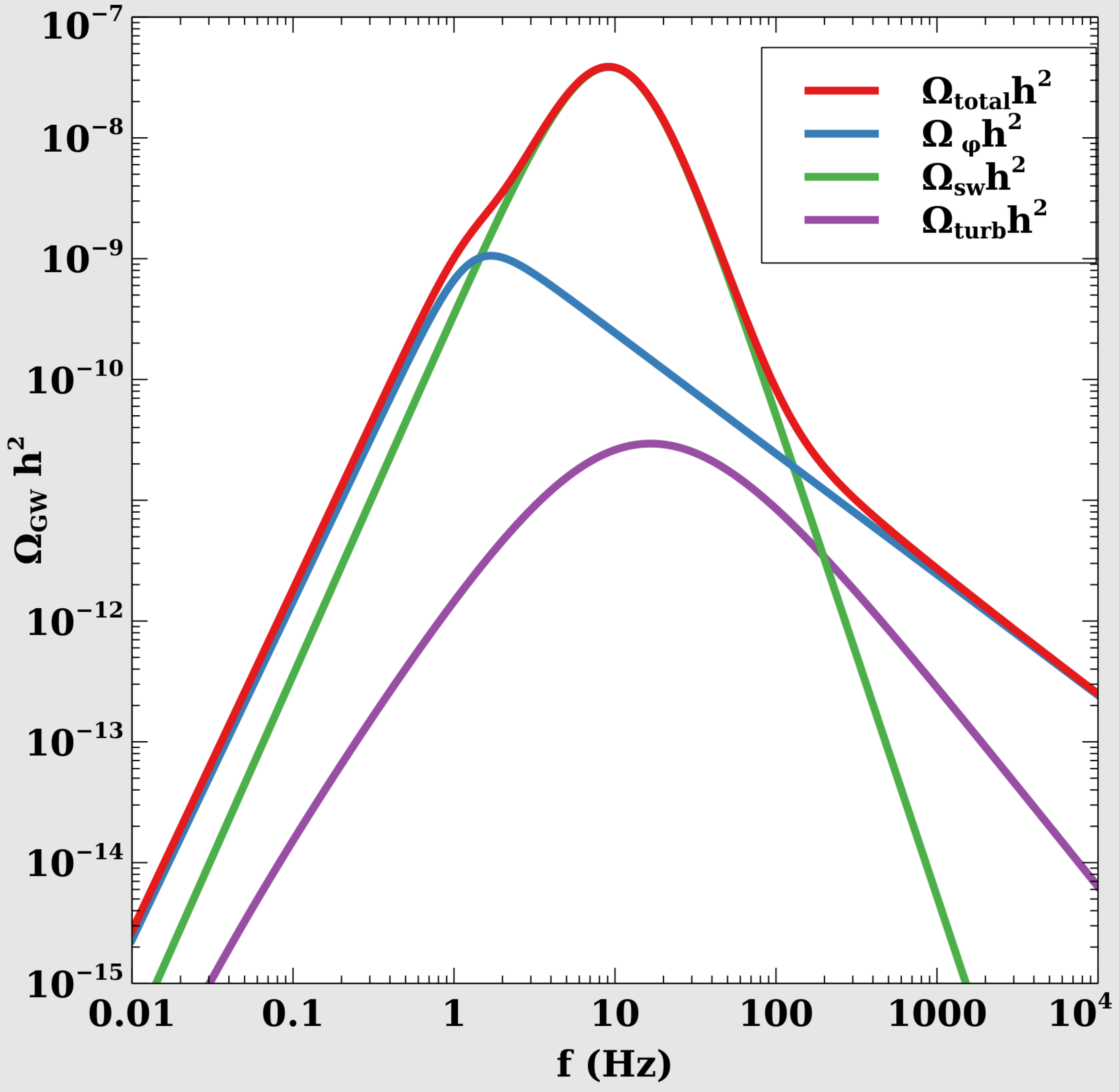


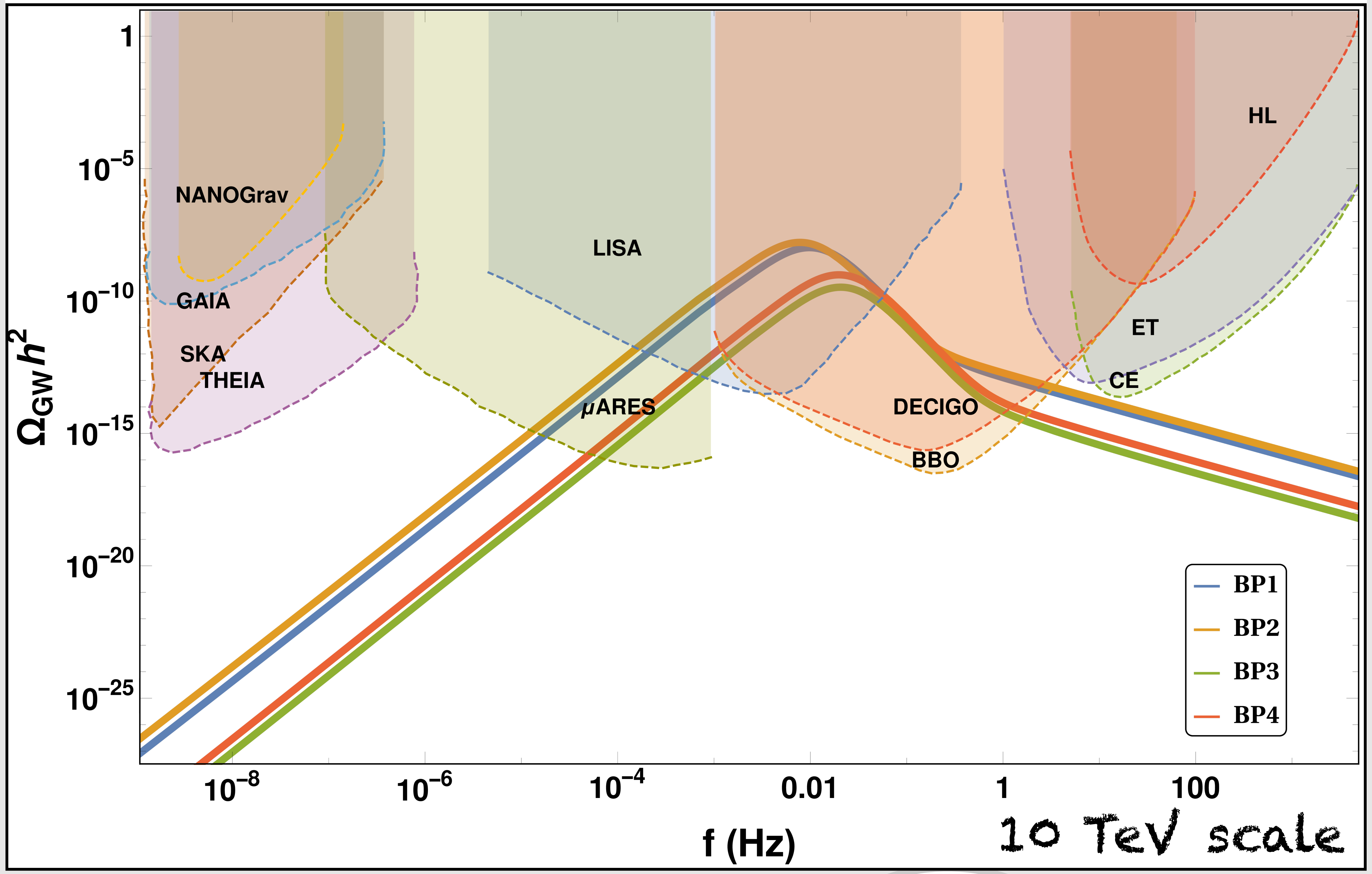
Stochastic Gravitational Waves:

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

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

Caprini et al. JCAP 04 (2016)





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

Sound wave in the plasma has dominating contribution

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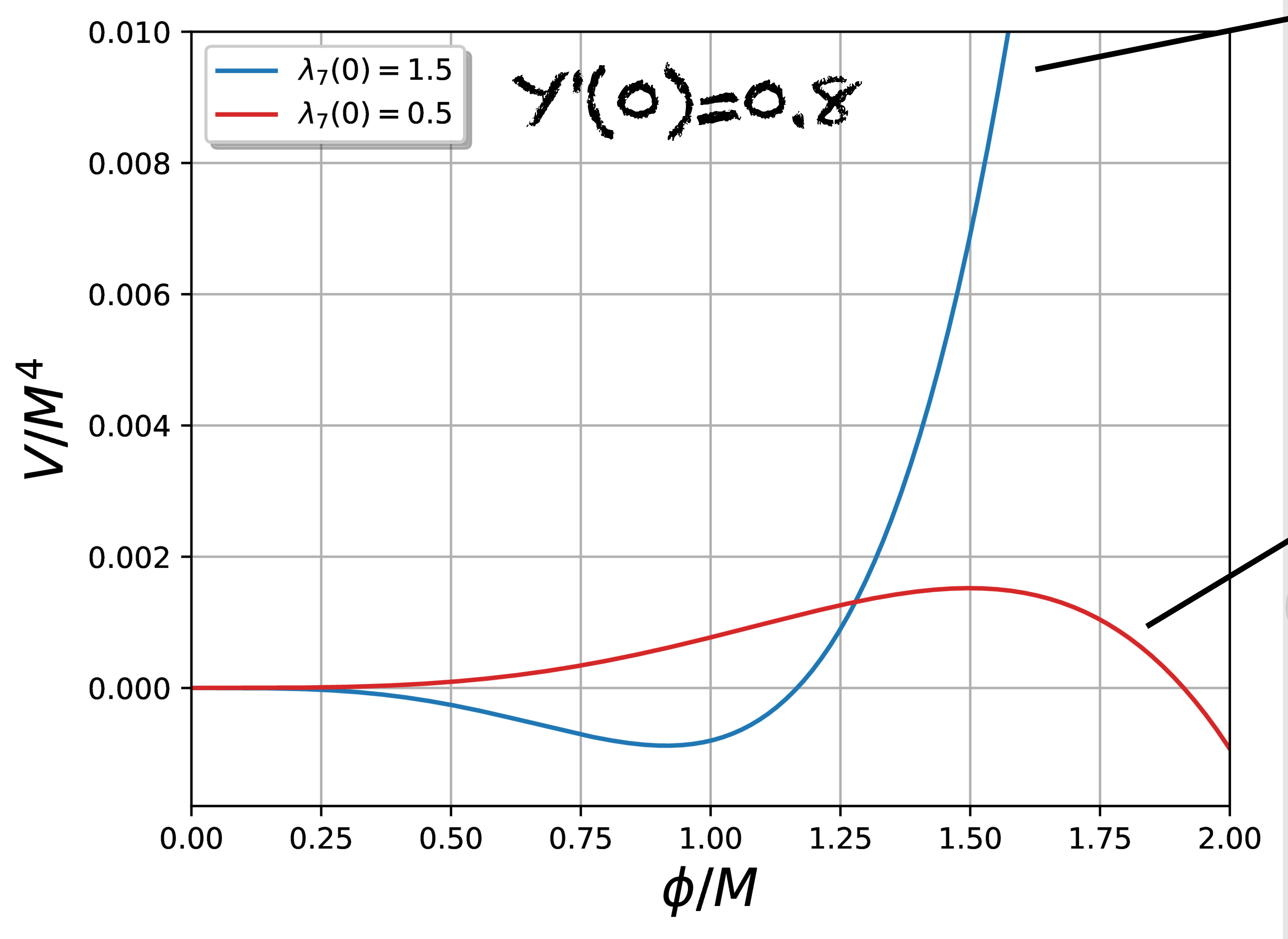
Leptogenesis:

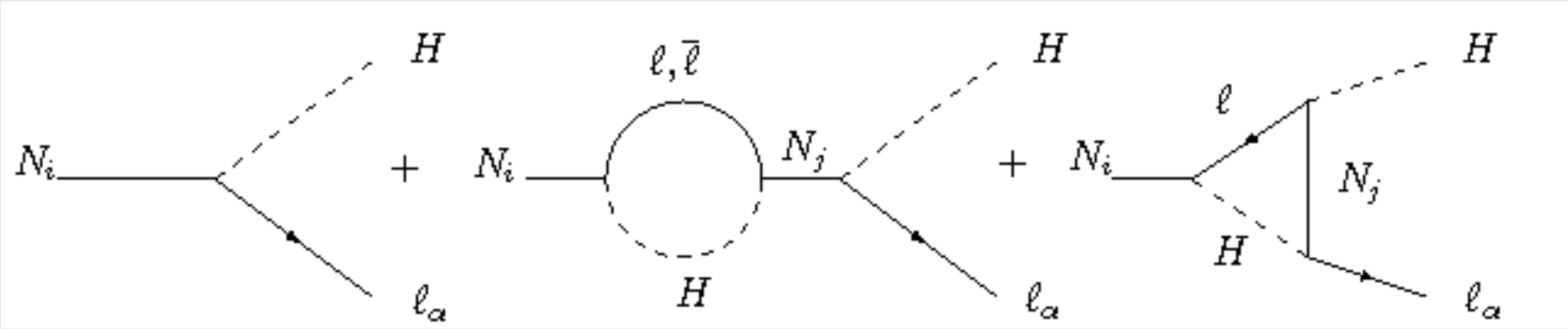


Zero temperature potential

$M_N < M_\eta$

$M_N > M_\eta$

How leptogeneis will occur !



Leptonic Yukawa interaction:

$$\mathcal{L} \supset \frac{1}{2} Y'_{ij} S N_i N_j + \left(Y_{\alpha 1}\, \bar{L}_\alpha \tilde{\eta} N_1 + \sum_{j=2,3} (y_D)_{\alpha j}\, \bar{L}_\alpha \tilde{\Phi}_1 N_j + \text{h.c.} \right)$$

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Leptogenesis:

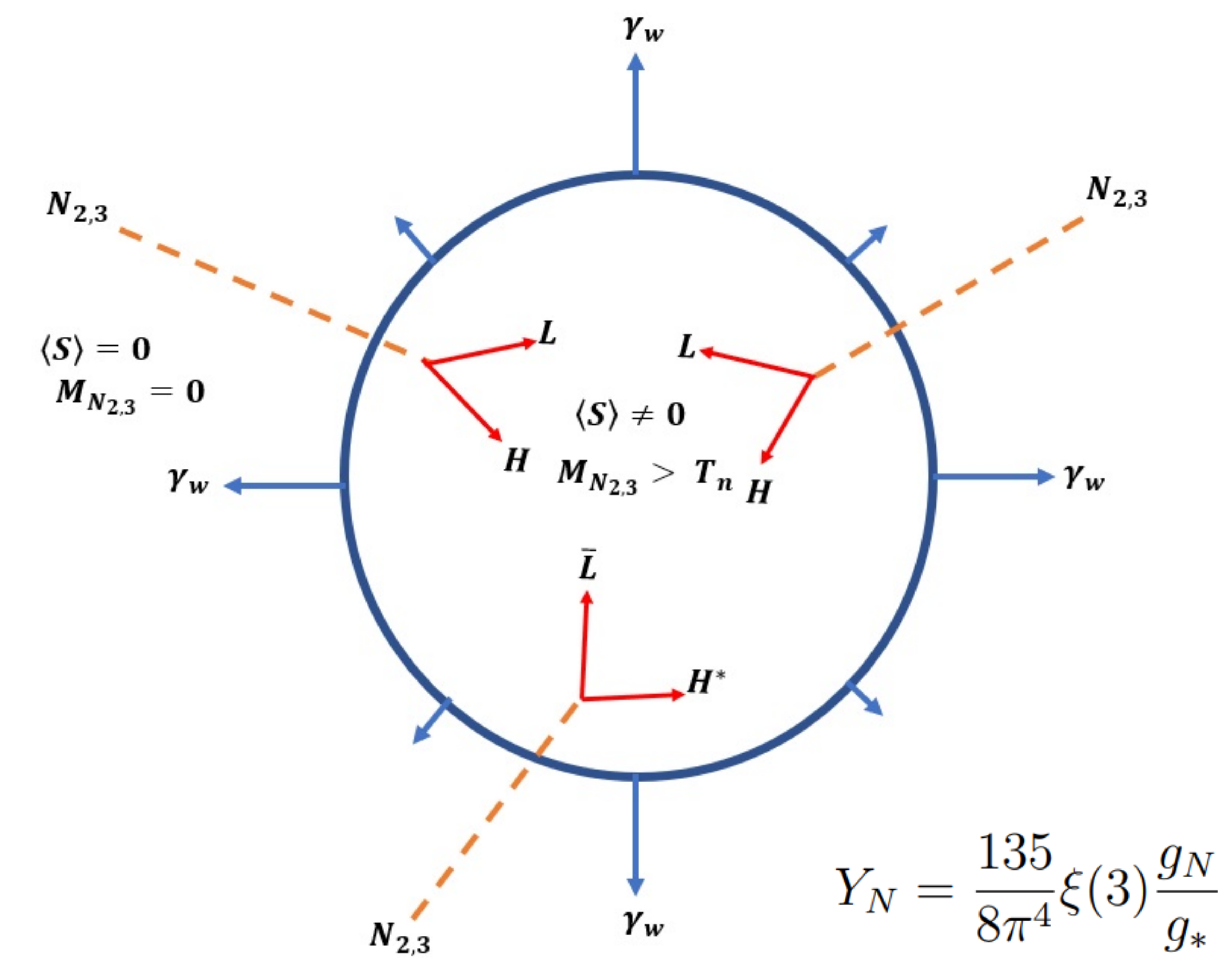
- For the leptogenesis we follow Iason Baldes et. al [Phys. Rev. D 104, 115029, 2021] and Arnab Dasgupta et. al [Phys. Rev. D 106, 075027, 2022] i.e., the mass-gain mechanism.
- The Lorentz boost of the bubble wall should be more than the Lorentz factor of the particle in the plasma frame.

$$\gamma_w > \gamma_N \sim \frac{M_N}{T_n}$$

final baryonic asymmetry:

$$Y_B = \epsilon_N \kappa_{\rm sph} Y_N \left(\frac{T_n}{T_{RH}}\right)^3$$

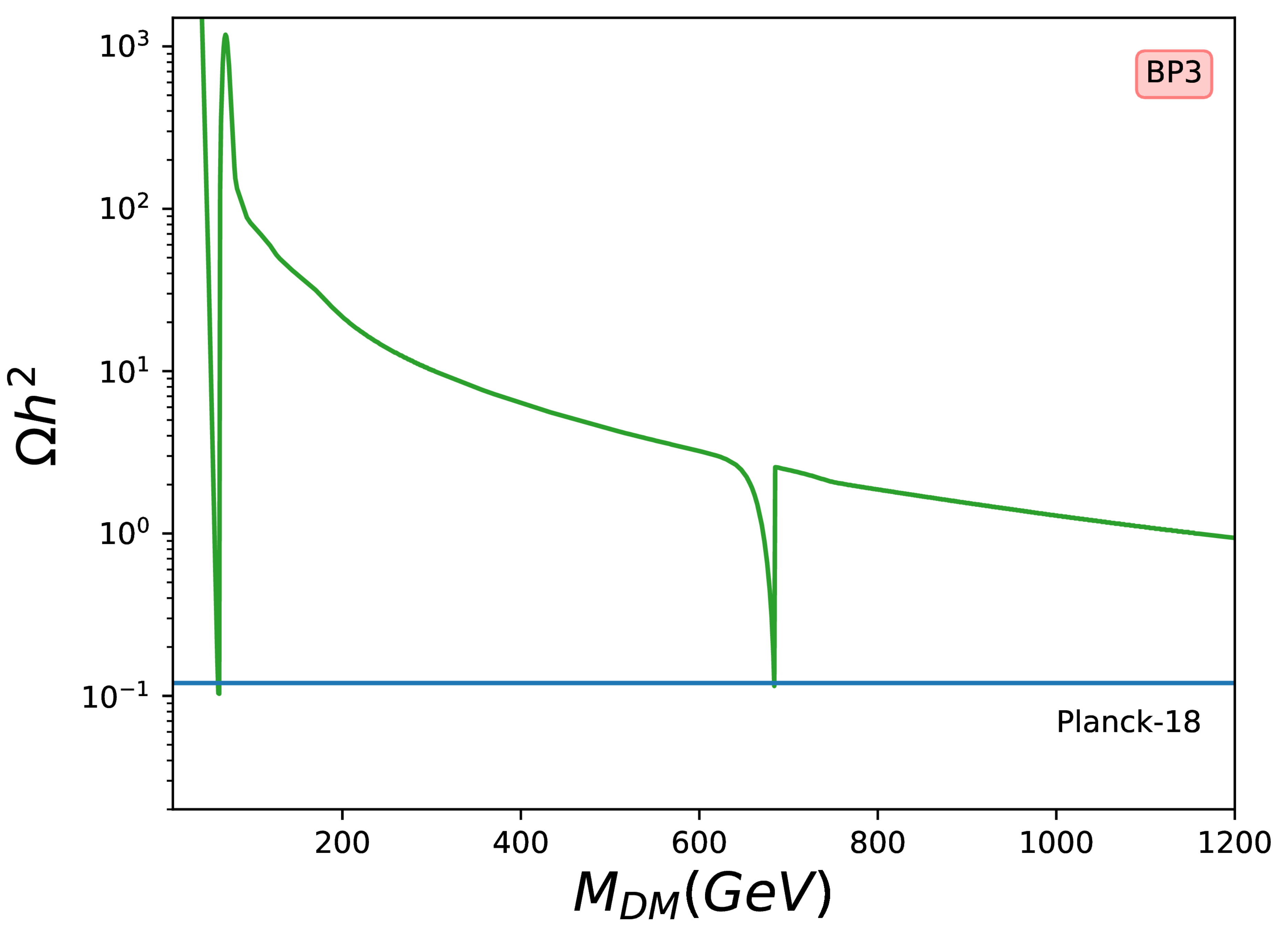
A large abundance of RHN in true vacuum inside the bubble sufficient for generating the required lepton asymmetry without washout or Boltzmann suppression.

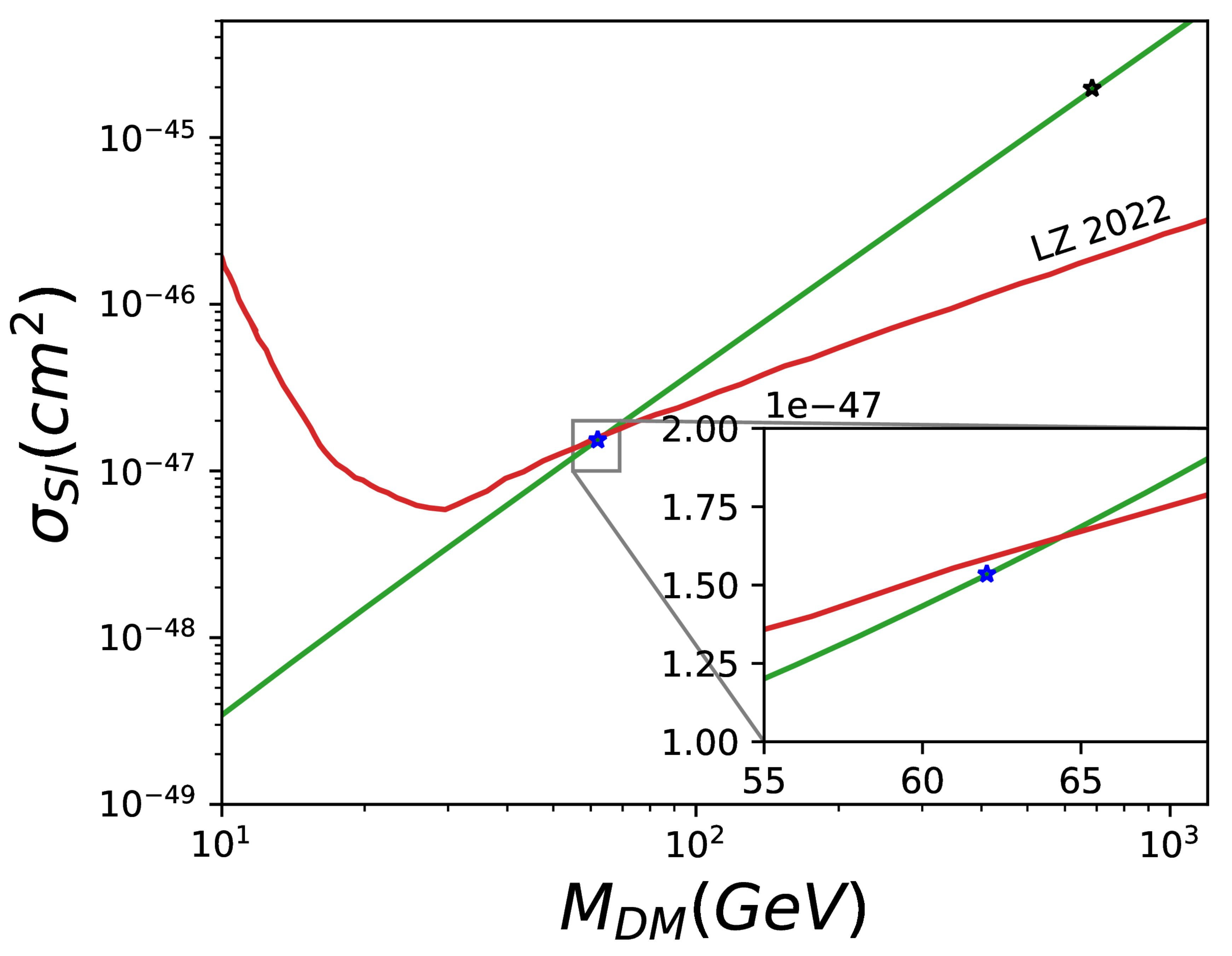


$$Y_N = \frac{135}{8\pi^4}\xi(3)\frac{g_N}{g_*}$$

Dark Matter:

WIMP scenario





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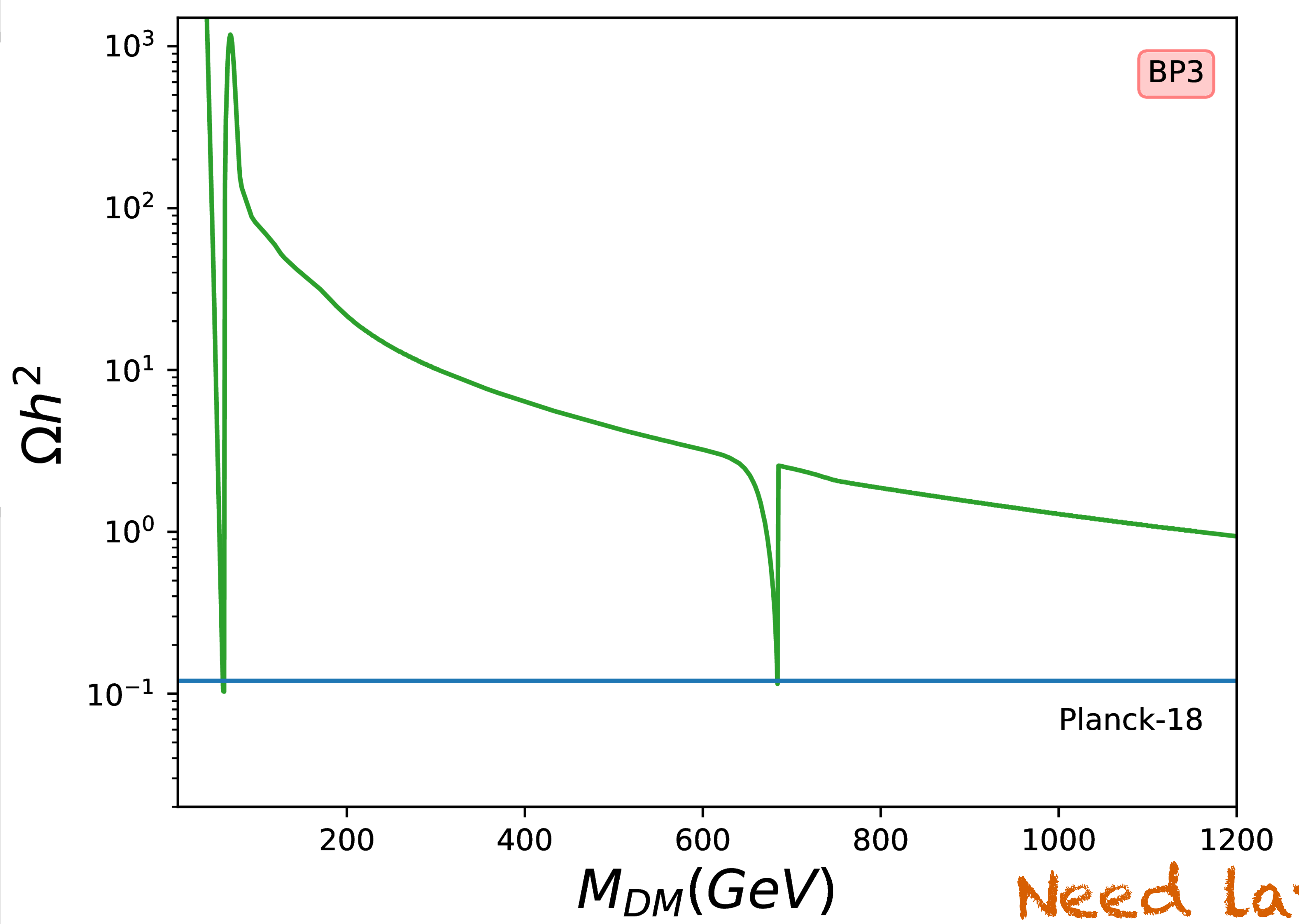
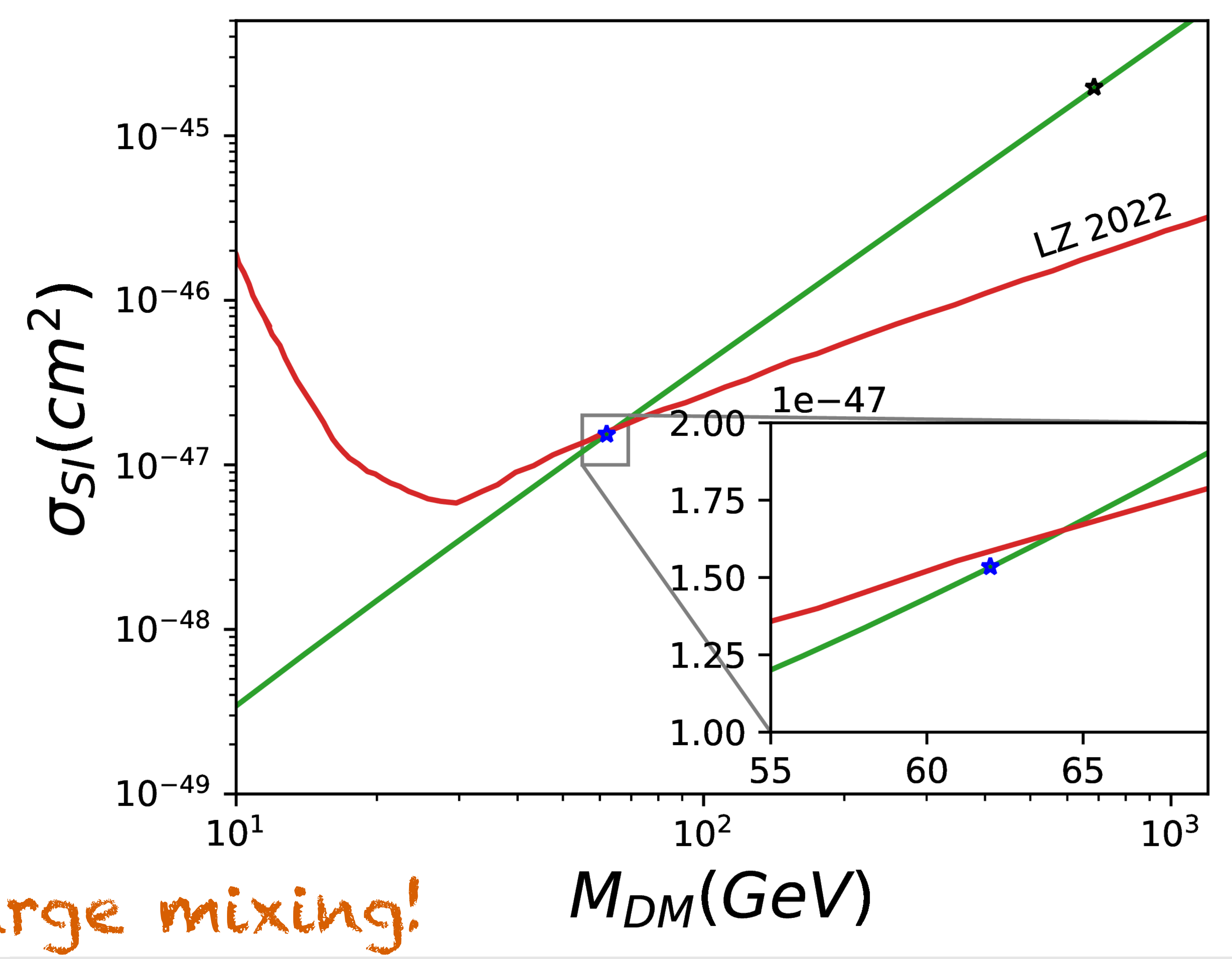
Dark Matter:

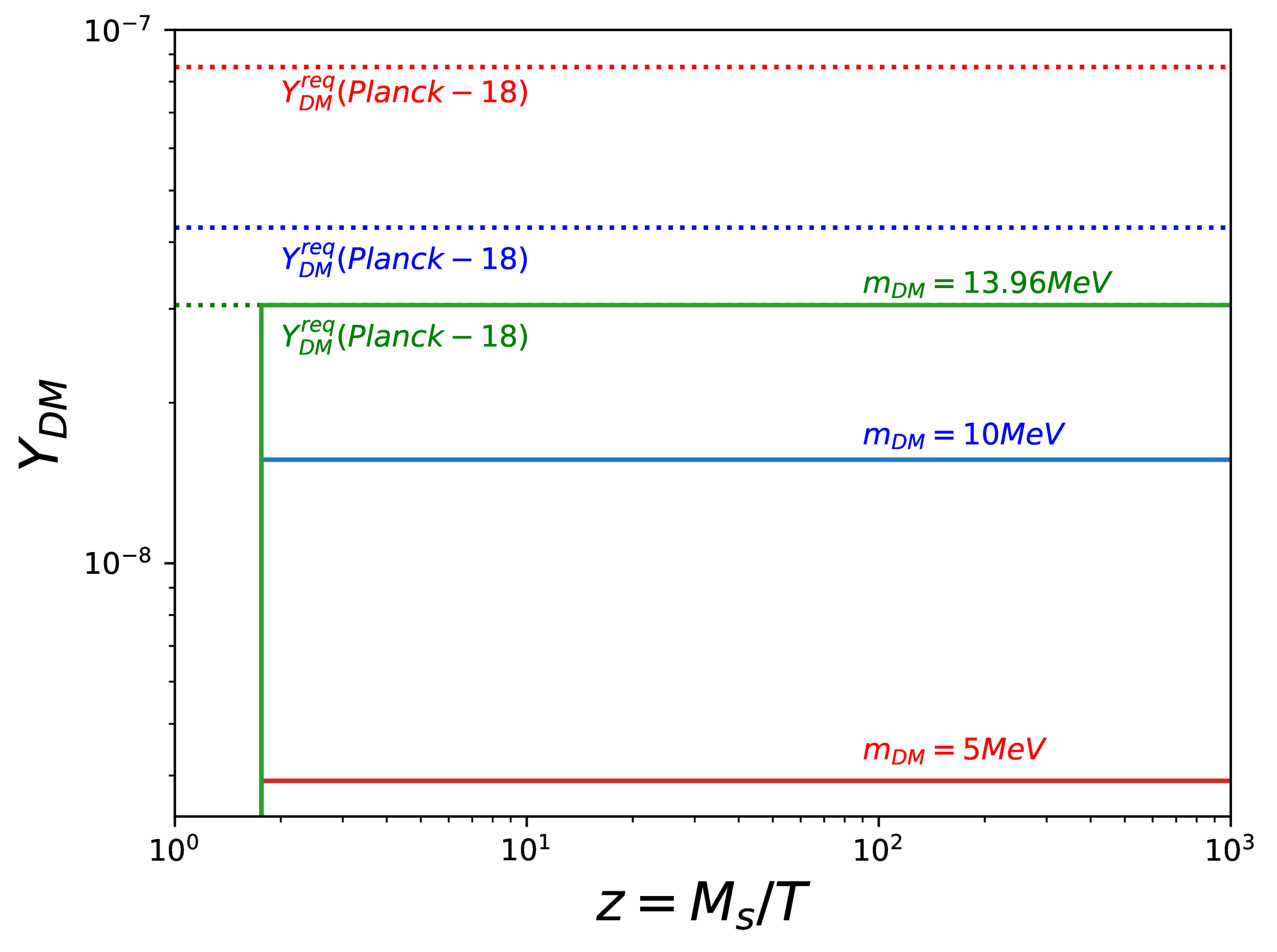
WIMP scenario





Need large mixing!

FIMP scenario



Boltzmann Equations:

$$\frac{dY_{\rm DM}}{dz} = \frac{2}{z\mathbf{H}}\Gamma_{sDM}Y_S,$$

$$\frac{dY_S}{dz} = -\frac{1}{z\mathbf{H}}(\Gamma_{sDM} + \Gamma_{sh} + \Gamma_{sN2} + \Gamma_{sN3})Y_S,$$

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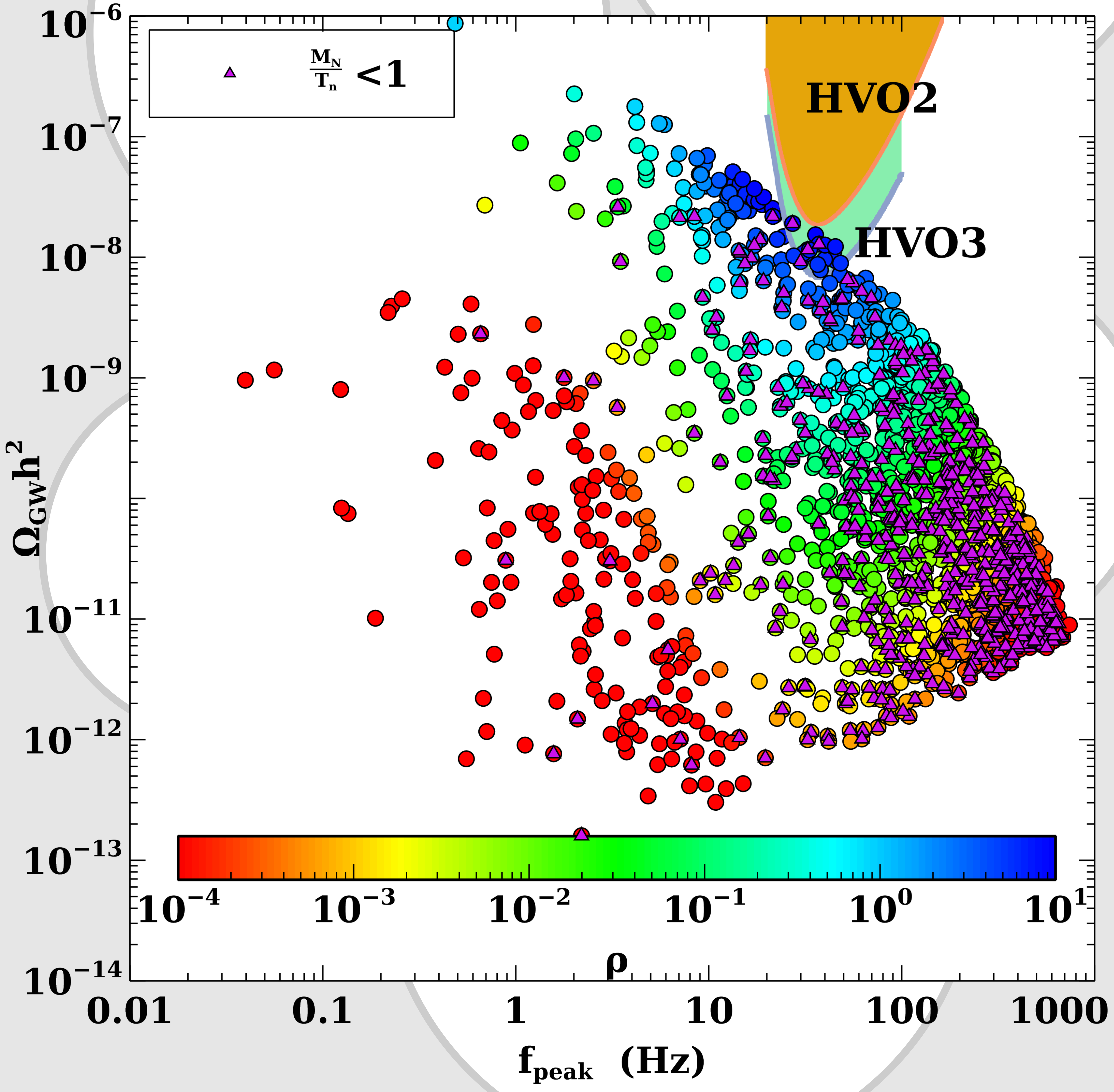
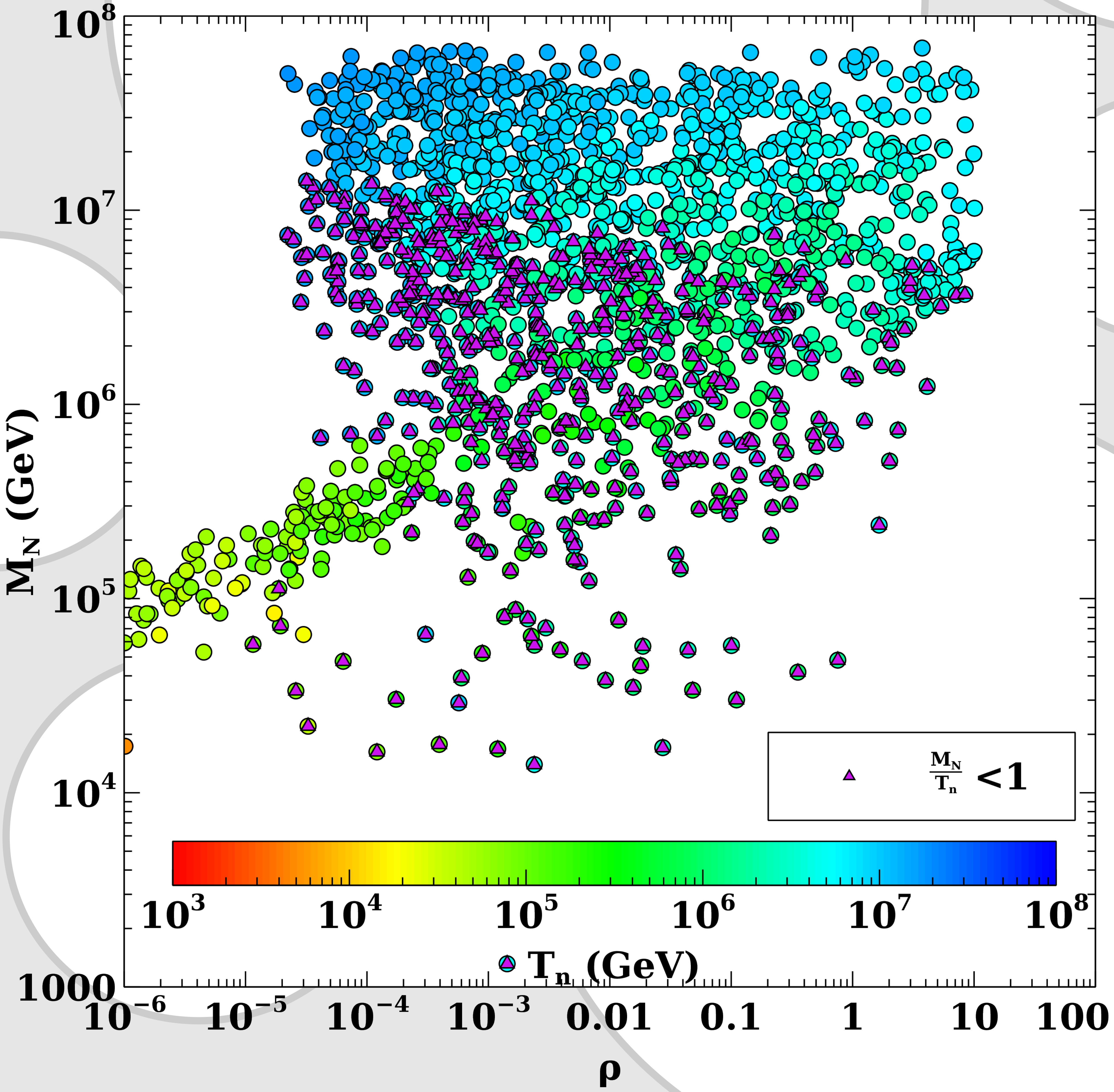
LIGO-VIRGO constraints at high scale (arxiv:2304.08888):

Signal to noise ratio (SNR):

$$\rho = \sqrt{\tau \int_{f_{\min}}^{f_{\max}} df \left[\frac{\Omega_{\rm GW}(f)\, h^2}{\Omega_{\rm expt}(f)\, h^2}\right]^2}$$

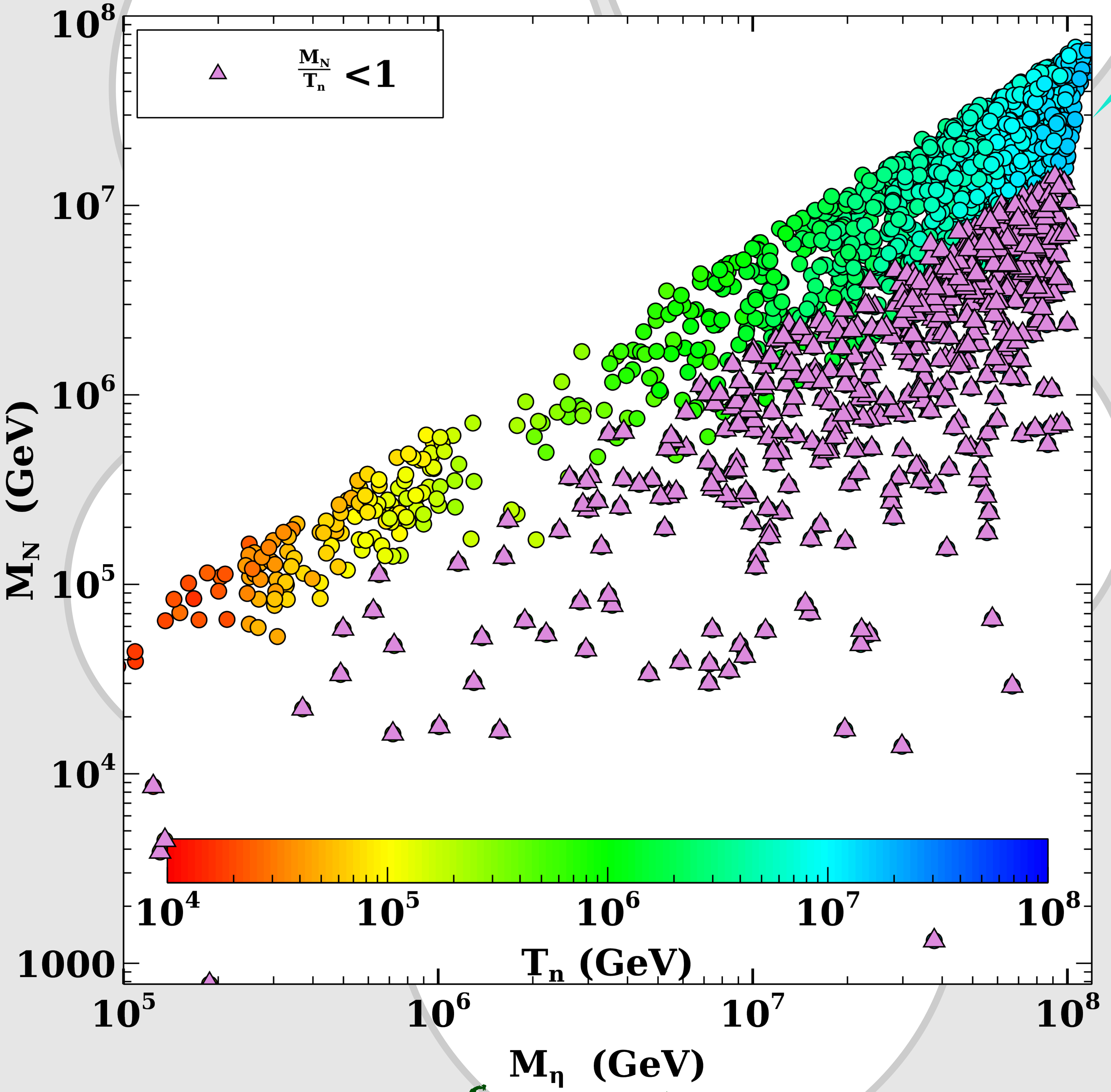




arxiv:2304.08888

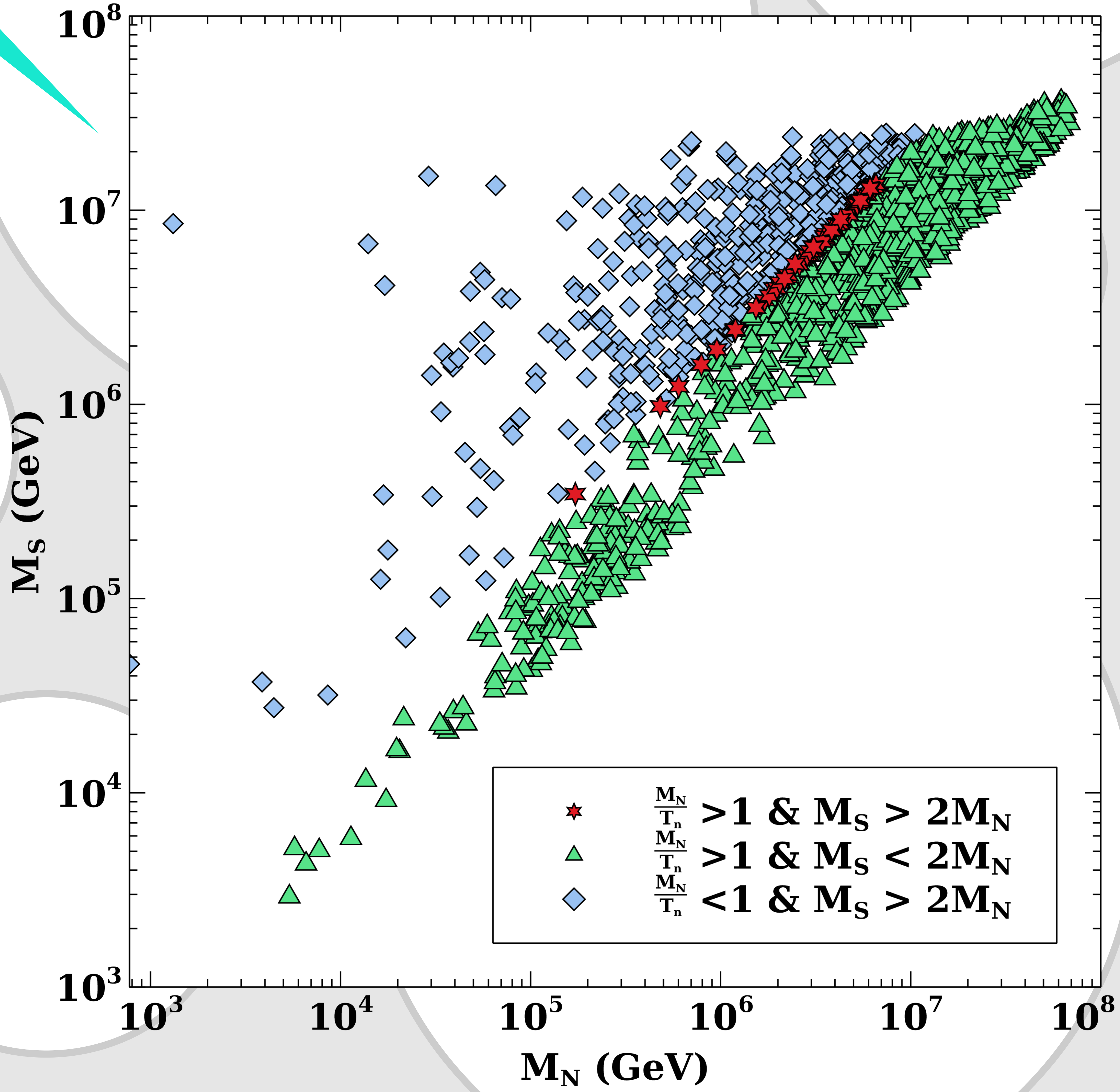
Dark Matter and Leptogenesis senarios:

Parameter space for $N_{2,3}$



successful leptogenesis

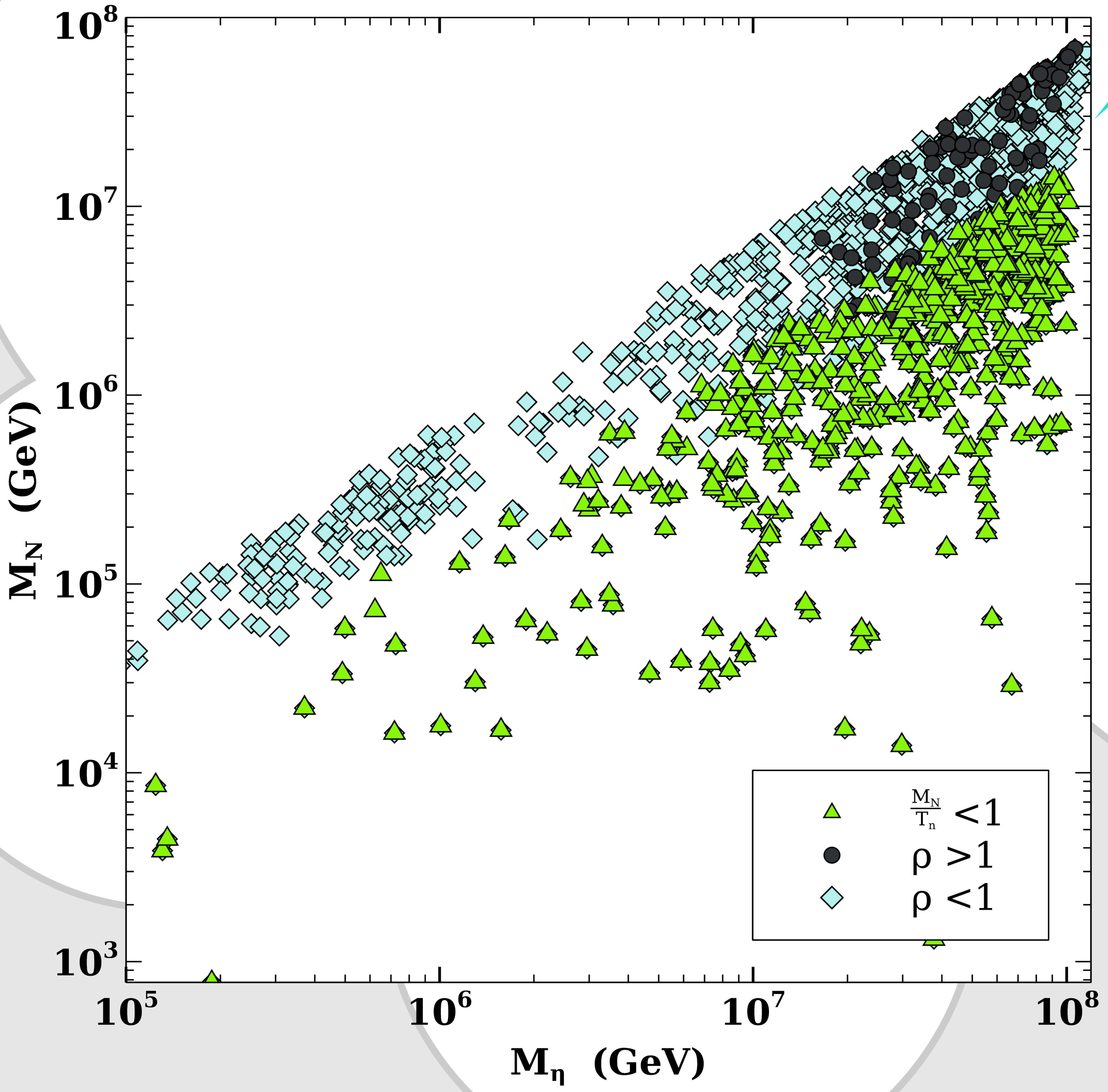
successful leptogenesis and DM



arxiv:2304.08888

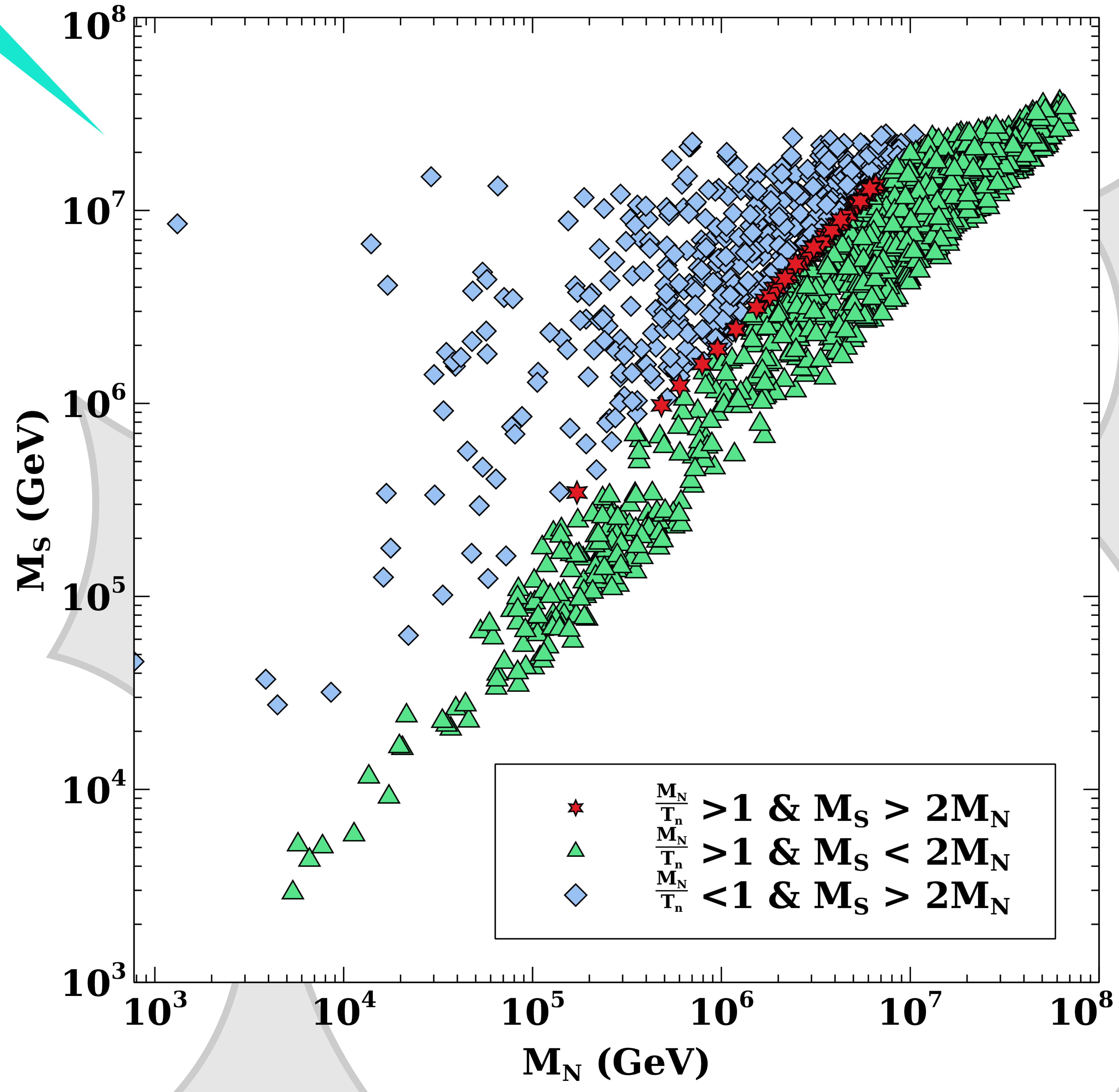
Dark Matter and Leptogenesis senarios:

Parameter space for $N_{2,3}$



Constrain from LIGO-VIRGO O3

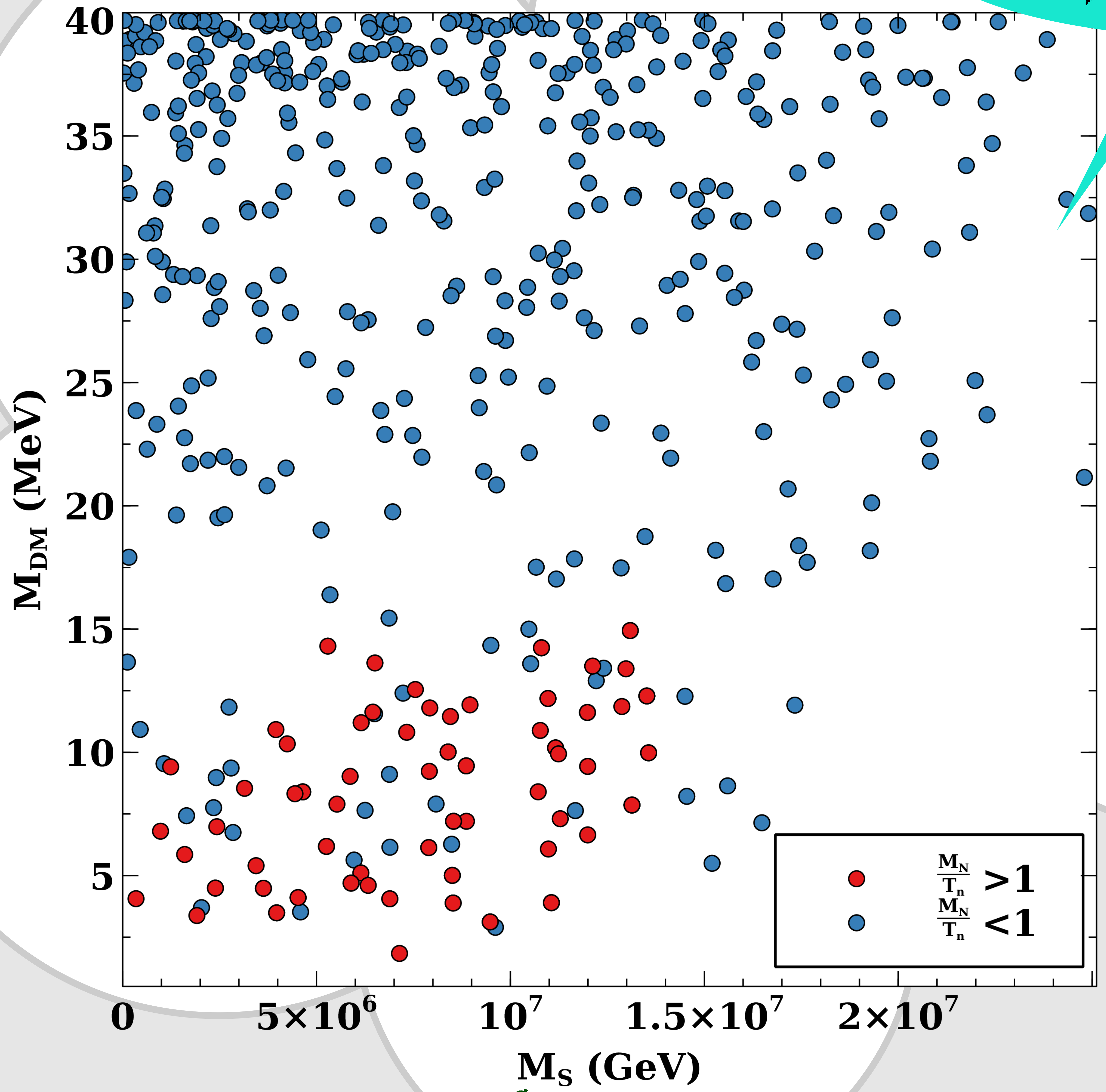
successful leptogenesis and DM



arxiv:2304.08888

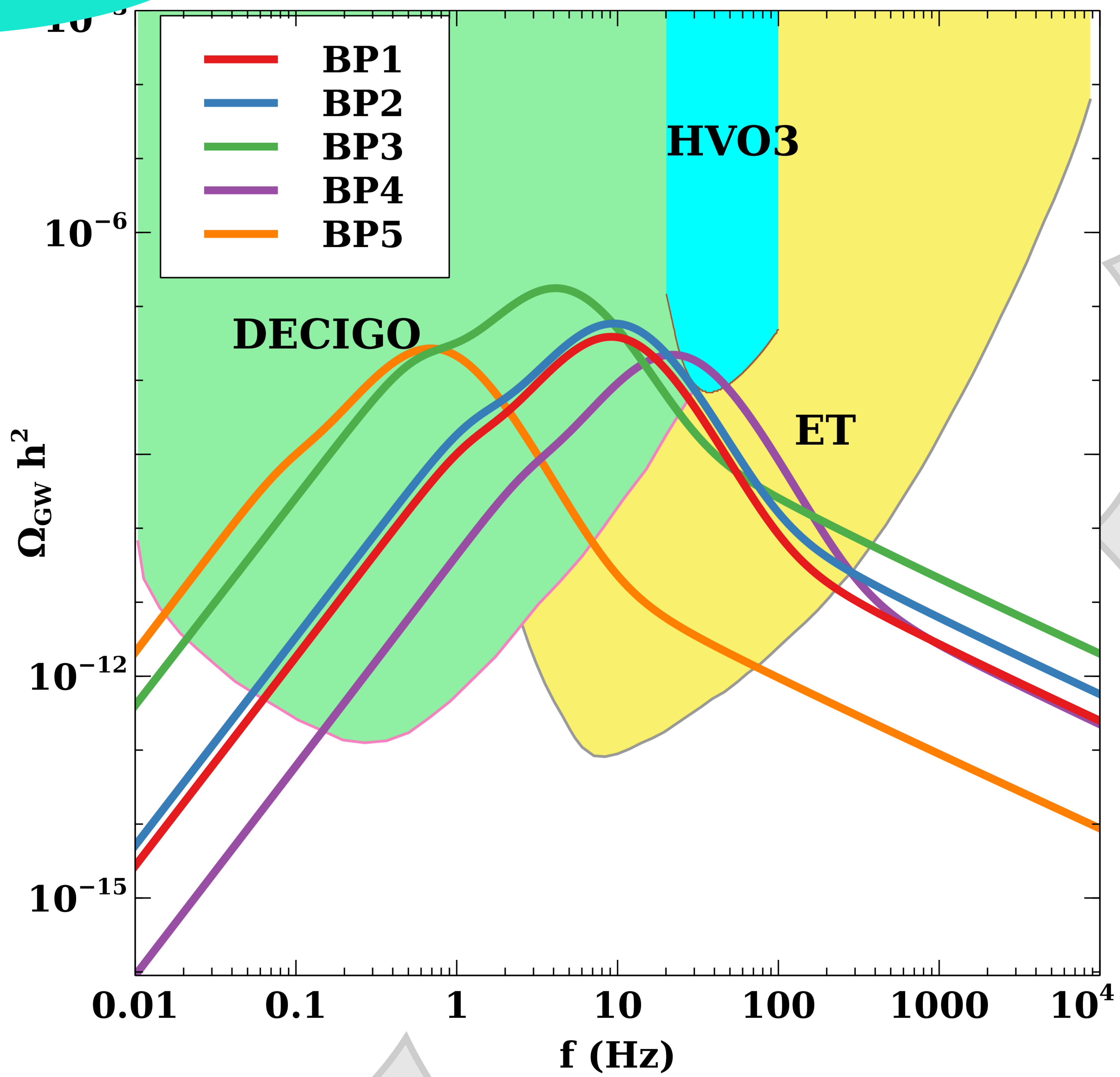
Dark Matter and Leptogenesis senarios:

Parameter space of Dark matter



successful leptogenesis

High scale PT GW spectrum



arxiv:2304.08888

Conclusion:

- We have studied the possibility of getting dark matter and low scale leptogenesis from a supercooled first order phase transition driven by a singlet scalar around TeV scale.
- The right handed neutrinos responsible for generating lepton asymmetry via decay and dark matter acquire masses by crossing the relativistic bubble walls which arise as a result of the FOPT.
- This also leads to a large abundance of RHN in true vacuum inside the bubble sufficient for generating the required lepton asymmetry without washout or Boltzmann suppression.
- Due to the high scale nature of the FOPT, the DM is favourably in the non-thermal or FIMP ballpark.
- The combined criteria of successful leptogenesis and DM relic constrain the model parameter space as well as the mass spectrum of BSM particles and also some points are disfavored from LIGO-VIRGO run 3.

Thank You

	v_c (GeV)	T_c (GeV)	v (GeV)	v_c/T_c	$\lambda_7(0)$	$Y'_2(0) \approx Y'_3(0)$	$\lambda_s(0)$	T_n (GeV)	T_p (GeV)	$(\beta/\mathbf{H}_*)$	v_J	α_*
BP1	9634.17	2521	9934.17	3.82	1.5	0.5	0.02	988.32	974.98	151.06	0.89	0.46
BP2	9553.88	2416	9757.60	3.95	1.6	0.7	0.02	896.89	887.67	110.66	0.91	0.66
BP3	9698.63	2370	9988.01	4.09	1.2	0.3	0.02	779.49	770.72	103.96	0.92	0.80
BP4	9692.84	2391	9978.08	4.05	1.3	0.4	0.02	1207.09	1190.58	204.51	0.84	0.24

	ϵ_N	$T_{\rm RH}$ (GeV)	T_n (GeV)	$M_{N_2} \approx M_{N_3}$ (GeV)	y_D	$\Delta V_{\rm tot}$ (GeV)^4
BP1	6.22×10^{-8}	988.32	988.32	4966.67	5.12×10^{-8}	1.75464×10^{13}
BP2	6.22×10^{-8}	896.89	896.89	6826.16	6×10^{-8}	1.69737×10^{13}
BP3	6.22×10^{-8}	779.49	779.49	2996.39	3.98×10^{-8}	1.15697×10^{13}
BP4	6.22×10^{-8}	1207.58	1207.58	3991.16	4.59×10^{-8}	2.15494×10^{13}

	M (GeV)	v_c (GeV)	T_c (GeV)	$\frac{v_c}{T_c}$	$\lambda_7(0)$	$Y'_{22}(0) \approx Y'_{33}(0)$	$\lambda_2(0)$	T_n (GeV)	T_p (GeV)	$\frac{\beta}{\mathbf{H}_*}$	v_J	α_*
BP1	5.54×10^7	5.01×10^7	1.37×10^7	3.65	1.17	0.091	0.02	3.55×10^6	1.99×10^6	13.97	0.95	1.69
BP2	7.85×10^7	6.97×10^7	1.93×10^7	3.61	1.18	0.090	0.02	5.00×10^6	2.76×10^6	9.71	0.95	1.76
BP3	9.47×10^7	8.38×10^7	2.34×10^7	3.56	1.19	0.096	0.02	5.95×10^6	3.25×10^6	3.56	0.95	1.89
BP4	7.95×10^7	2.37×10^7	1.96×10^7	1.20	1.19	0.097	0.02	5.29×10^6	3.10×10^6	21.24	0.95	1.51
BP5	2.80×10^6	1.54×10^6	6.57×10^5	2.36	1.06	0.086	0.02	1.700×10^5	9.78×10^4	20.81	0.95	1.75

	ϵ_N	$T_{\rm RH}$ (GeV)	T_n (GeV)	$M_{N_2} \approx M_{N_3}$ (GeV)	y_D	$\Delta V_{\rm tot}$ (GeV)^4	$M_{\rm DM}$ (MeV)
BP1	2.51×10^{-8}	4.05×10^6	3.55×10^6	3.58×10^6	4.35×10^{-5}	1.02×10^{28}	12.54
BP2	2.60×10^{-8}	5.77×10^6	5.00×10^6	5.04×10^6	5.16×10^{-5}	4.22×10^{28}	14.24
BP3	2.73×10^{-8}	6.98×10^6	5.95×10^6	6.43×10^6	5.83×10^{-5}	9.05×10^{28}	7.86
BP4	2.31×10^{-8}	5.87×10^6	5.29×10^6	5.50×10^6	5.39×10^{-5}	4.53×10^{28}	3.90
BP5	2.56×10^{-8}	1.95×10^5	1.70×10^5	1.71×10^5	9.51×10^{-6}	5.51×10^{22}	4.06

RGE

$$\frac{d\lambda_s}{dt} = \frac{1}{16\pi^2}(20\lambda_s^2 + 2\lambda_6^2 + 2\lambda_7^2 + 8\lambda_s \mathrm{Tr}[Y'^\dagger Y'] - \mathrm{Tr}[Y'^\dagger Y' Y'^\dagger Y'])$$

$$\frac{d\lambda_2}{dt} = \frac{1}{16\pi^2}(12\lambda_2^2 + 2\lambda_7^2 + 3g_1^2/4 + 9g_2^2/4 + 3g_1^2 g_2^2/2)$$

$$\frac{d\lambda_7}{dt} = \frac{1}{16\pi^2}(4\lambda_7^2 + 6\lambda_2\lambda_7 + 8\lambda_s\lambda_7 + 4\lambda_7 \mathrm{Tr}[Y'^\dagger Y'])$$

$$\frac{d\lambda_6}{dt} = \frac{1}{16\pi^2}(4\lambda_6^2 + 6\lambda_6 y_t^2 + 8\lambda_s\lambda_6 + 4\lambda_6 \mathrm{Tr}[Y'^\dagger Y'])$$

$$\frac{dY'}{dt} = \frac{1}{16\pi^2}(4Y'^3 + 2Y' \mathrm{Tr}[Y'^\dagger Y'])$$

$$\frac{dg_1}{dt} = \frac{1}{16\pi^2}(7g_1^3)$$

$$\frac{dg_2}{dt} = \frac{1}{16\pi^2}(-3g_2^3)$$

$$\frac{dy_t}{dt} = \frac{1}{16\pi^2}(9y_t^3/2 - y_t(17g_1^2/12 + 9g_2^2/4))$$

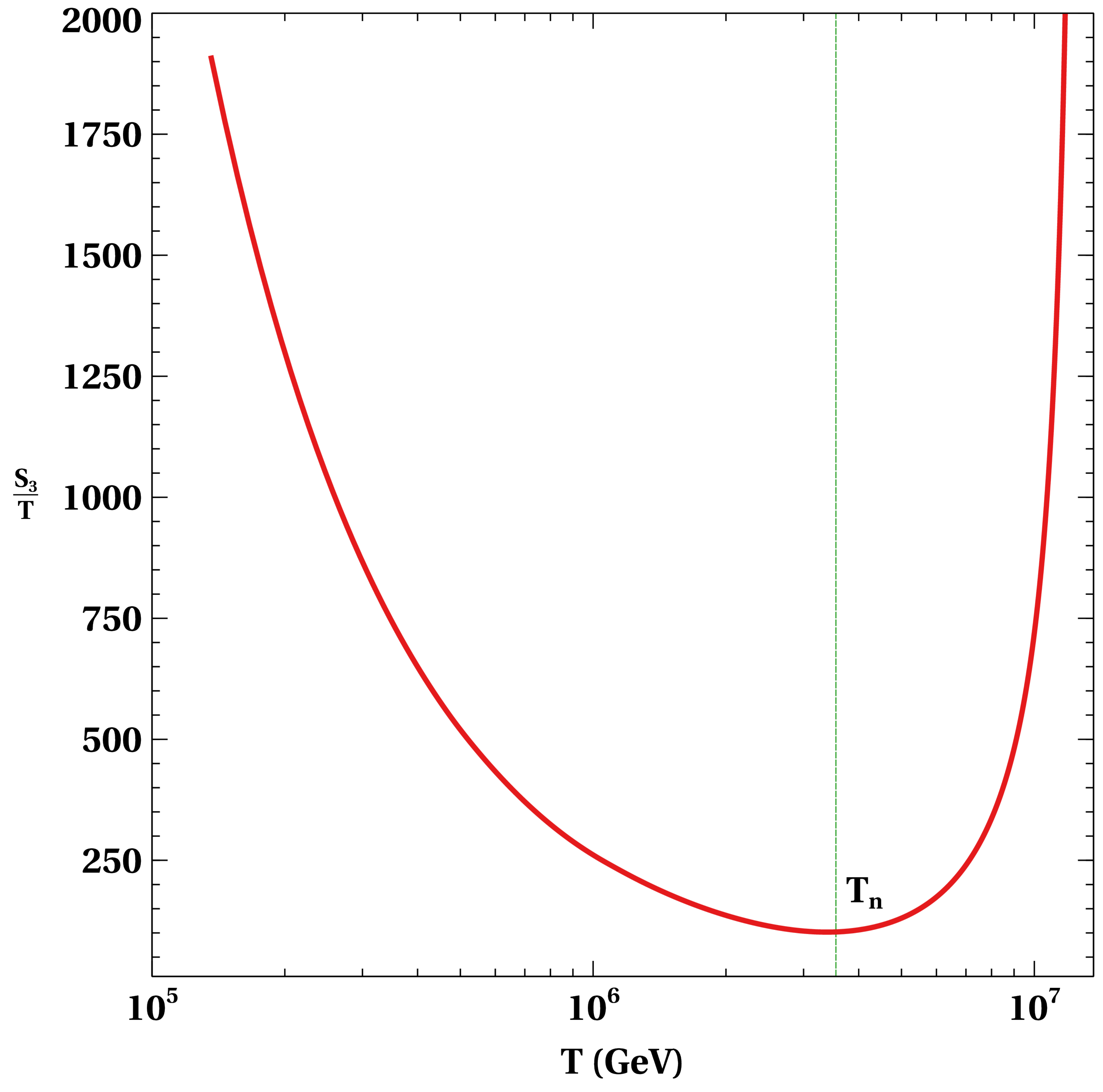
RGE

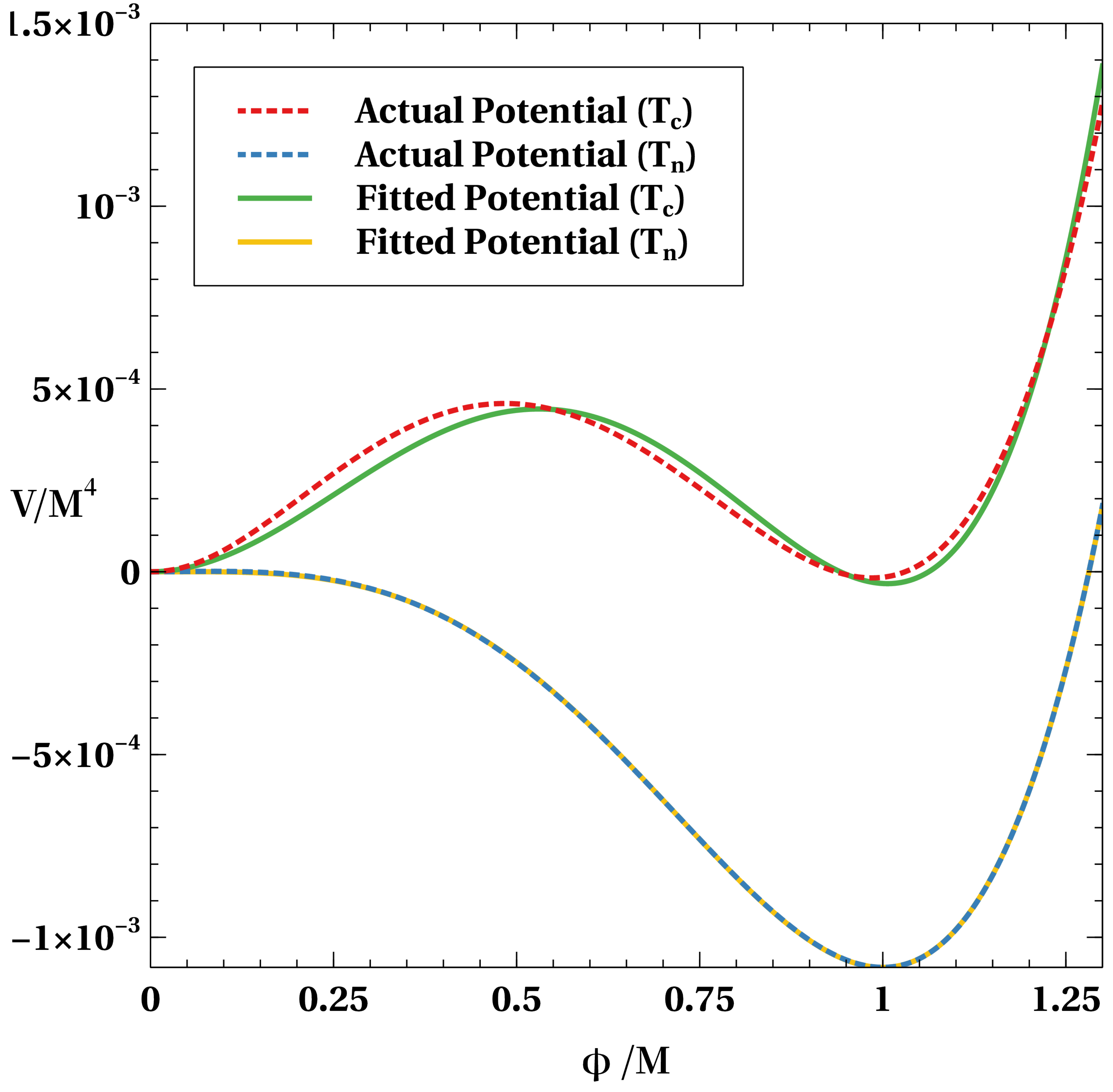
$$V_0 = V_{\text{tree}} + V_{\text{CW}},$$
$$= \frac{1}{4}\lambda_S(t) G^4(t)\phi^4$$

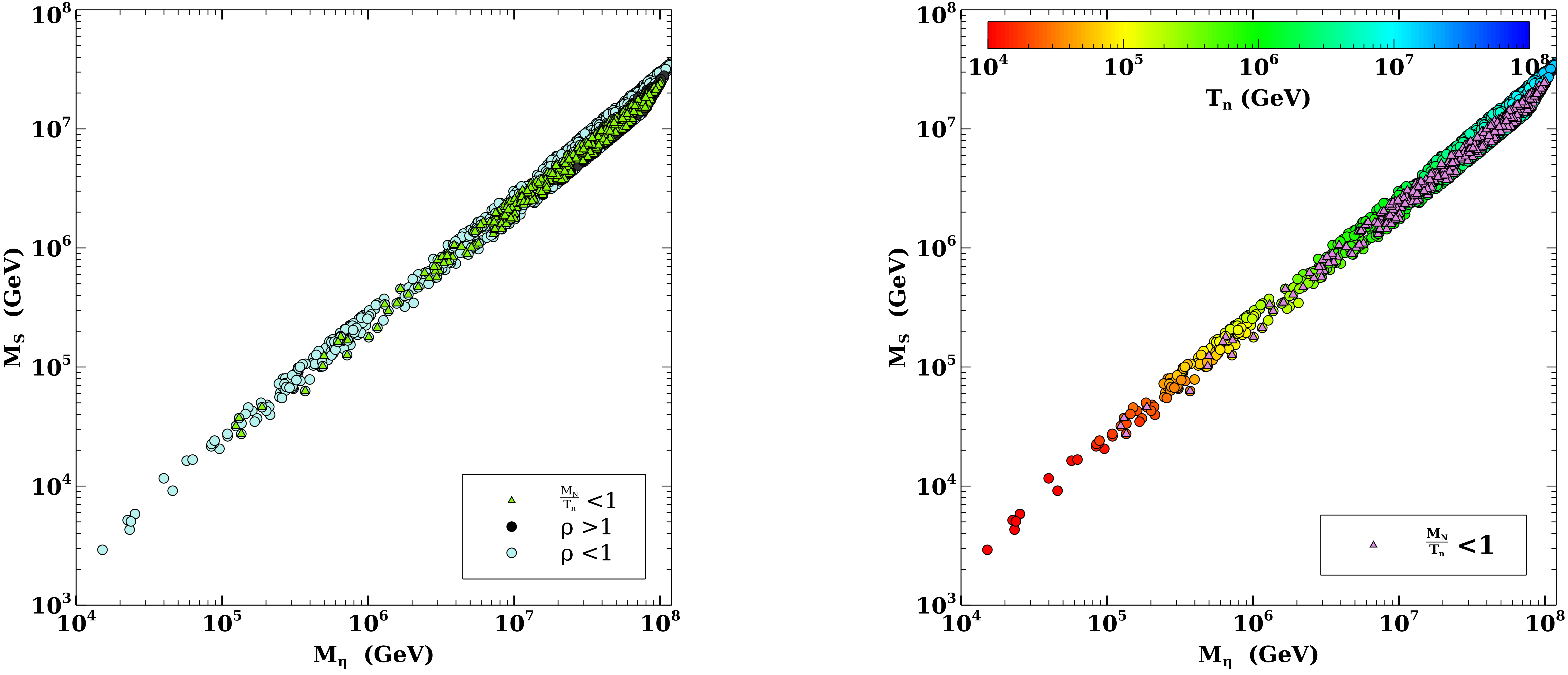
where $t = \log(\phi/\mu)$ with $\mu = M$ being the scale of renormalisation. $G(t)$ is given by

$$G(t) = e^{-\int_0^t dt' \gamma(t')}, \; \gamma(t) = \frac{1}{32\pi^2}\text{Tr}[Y'^{\dagger} Y'],$$

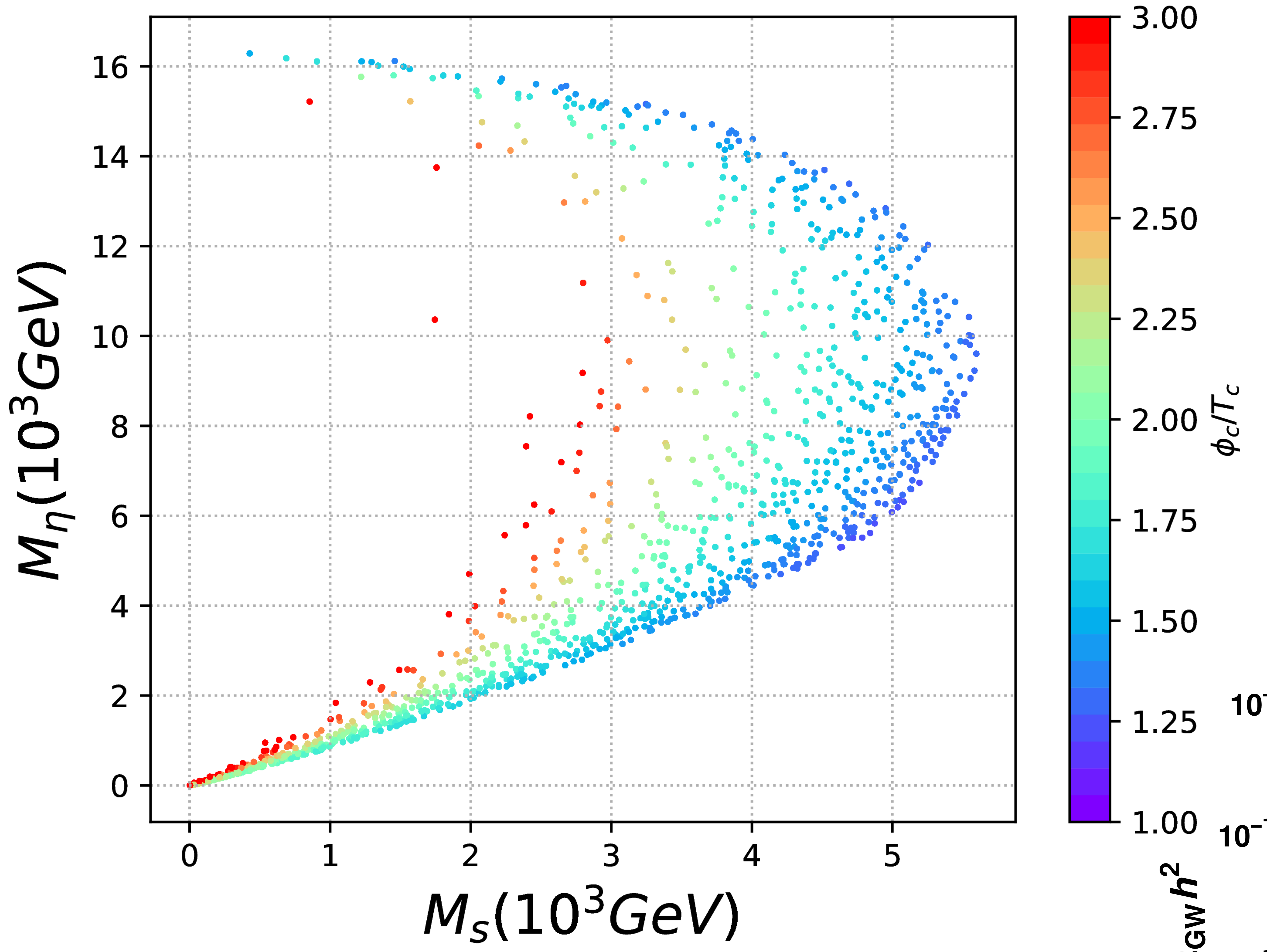
Action calculation



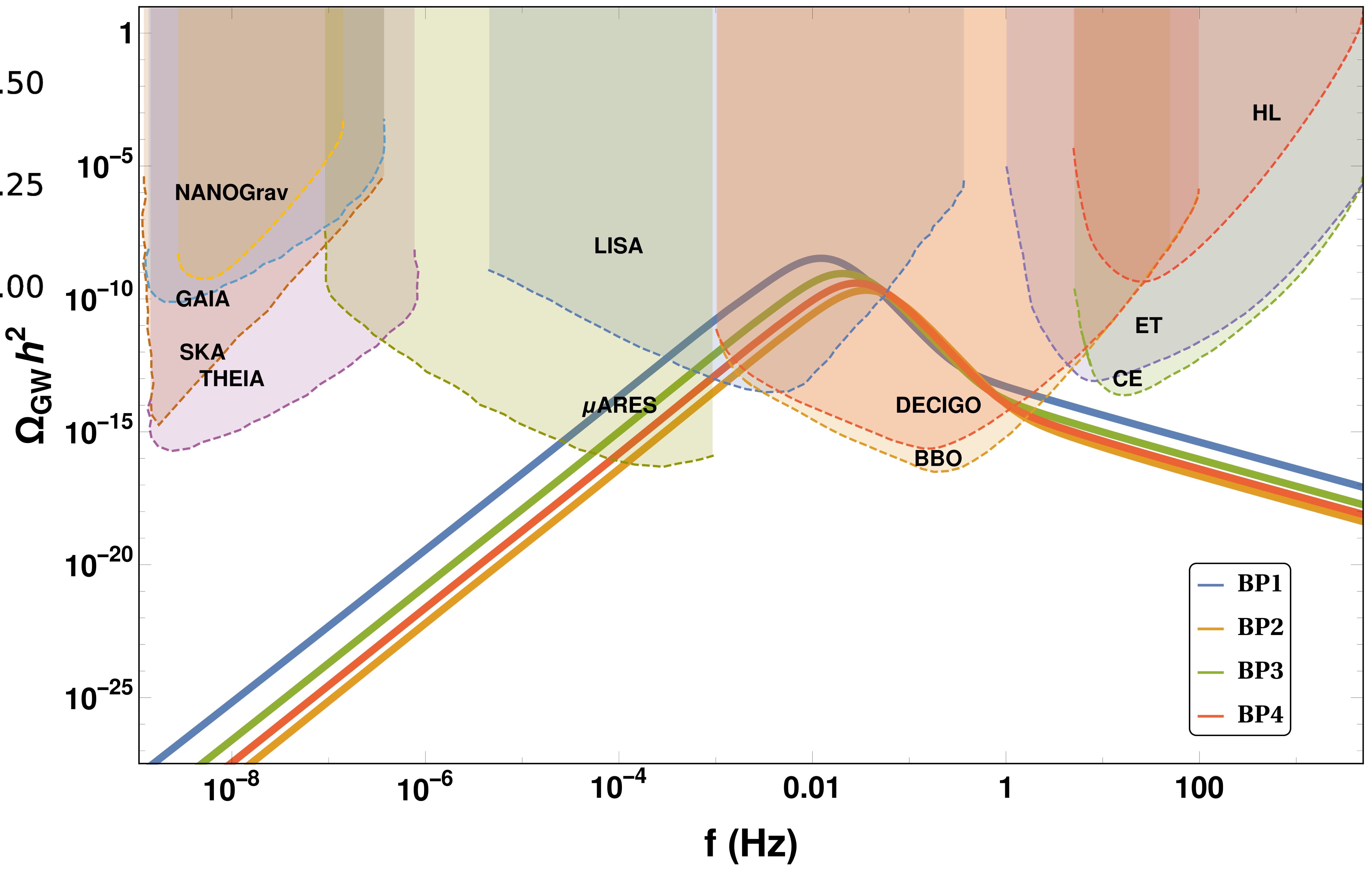




M_S (GeV)
M_η (GeV)
M_N/T_n <1
ρ >1
ρ <1
T_n (GeV)



$M_\eta(10^3 GeV)$
$M_s(10^3 GeV)$
ϕ_c/T_c



NANOGrav
GAIA
SKA
THEIA
LISA
μARES
DECIGO
BBO
HL
ET
CE
BP1
BP2
BP3
BP4
$\Omega_{GW}h^2$
f (Hz)