Thermal leptogenesis, dark matter and gravitational waves from an extended canonical seesaw

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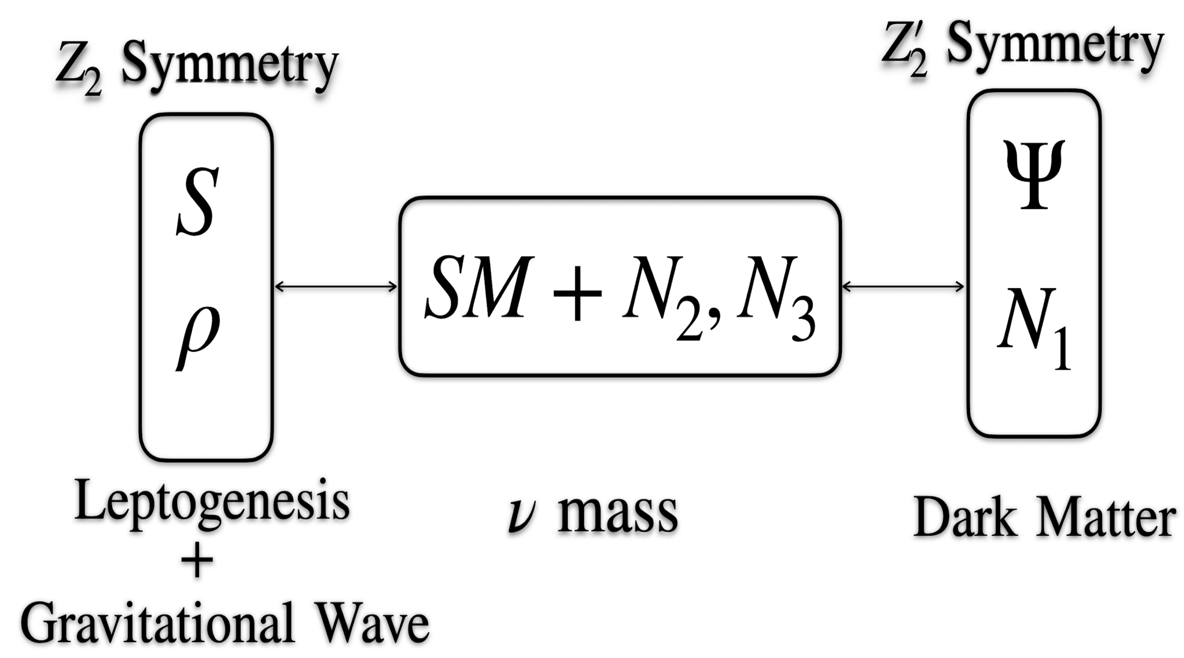
Motivation

- SM is extremely successful in describing the masses of elementary particles and their interactions, but it can not explain non-zero neutrino mass, dark matter ($\Omega_{DM}h^2 \sim 0.12$), matter anti-matter asymmetry of the Universe ($\eta_B \sim 6\times 10^{-10}$) etc..
- NANOGrav, EPTA, PPTA etc have reported positive evidence for stochastic gravitational wave (GW) background which could originate from various sources like domain walls (DWs), cosmic string, phase transition etc.
- DWs emerge when a discrete symmetry is spontaneously broken in the early universe and can quickly surpass the total energy density of the Universe. It's possible that DWs are inherently unstable and collapse before they can dominate the total energy density of the Universe.
- Pure singlet dark matter models struggles with overproduction of dark matter and suppressed detection signals. In addition, the pure doublet case is excluded from relic density and direct search bound up to several TeVs of DM mass, rendering the model unprobable.

Model



The relevant Lagrangian is

$$\mathcal{L} = \bar{N} i\gamma_\mu \partial^\mu N + \bar{S} i\gamma_\mu\partial^\mu S - y_{N_1}\bar{L}\tilde{H}N - y_{NS}\bar{N}\rho S - \frac{1}{2}M_S\bar{S}^c S - \frac{1}{2}M_N\bar{N}^c N + h.c + \mu_H^2 H^\dagger H - \lambda_H(H^\dagger H)^2 + \mu_\rho^2\rho^2 - \lambda_\rho\rho^4 - \lambda_{H\rho}(H^\dagger H)\rho^2, \text{ Here } N = N_1, N_2$$

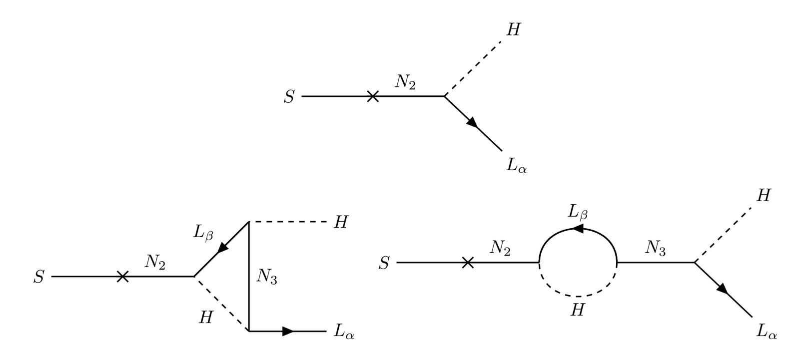
- At a scale larger than electroweak scale, ρ obtains spontaneous vev and breaks the Z_2 symmetry which leads to the mixing between $S - N_{2,3}$ and formation of DWs.
- Assume a strong mass hierarchy $M_S \ll M_2 \ll M_3$, any lepton asymmetry produced by the decay of N_2 and N_3 will be erased by the lepton number violating interaction of S.

The neutrino mass is given as

$$(m_\nu)_{ij} \simeq -\sum_k (m_D)_{ik}\left(M_k + \frac{d^2}{M_k - M_S}\right)^{-1}(m_D)_{kj}$$

where $d = y_{NS}v_\rho/\sqrt{2}$, $m_D = y_{N_1}v_h/\sqrt{2}$.

Leptogenesis from Z_2 symmetry breaking

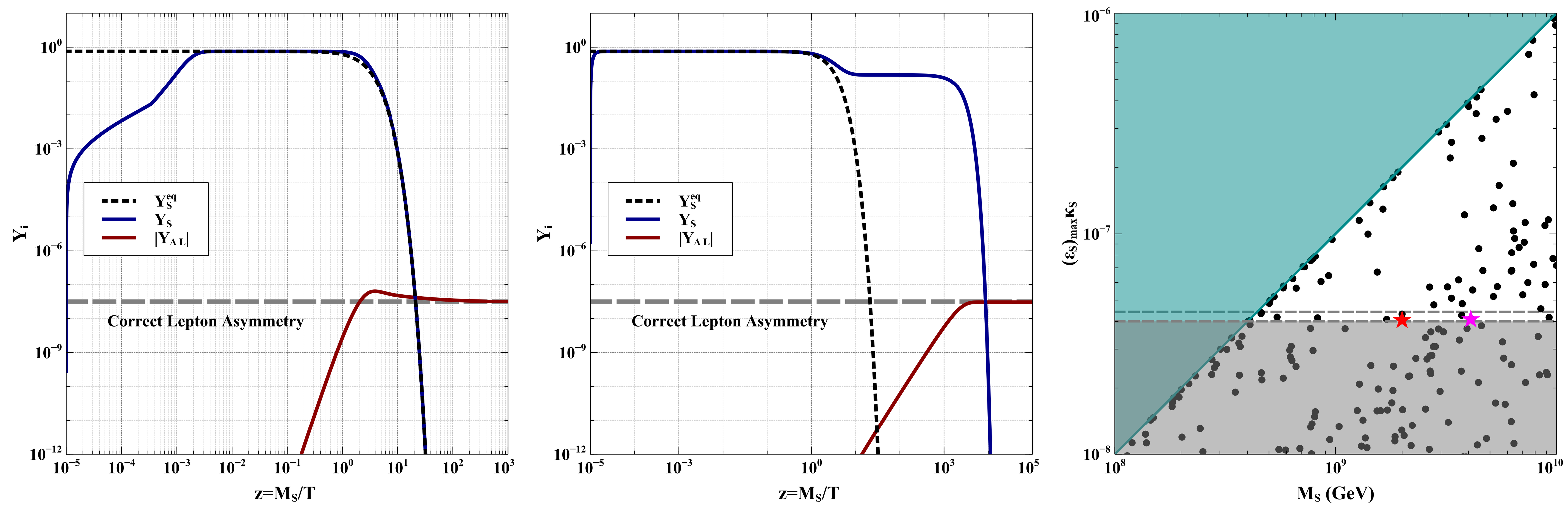


$$\Gamma_S = \theta_s^2\frac{(y_{N_1}^\dagger y_{N_1})_{22}}{8\pi}M_S, \quad |\epsilon_S| \le \frac{3}{8\pi v_h^2}M_S m_3$$

$$\eta_B = \frac{C_{L\to B}}{f}Y_{\Delta L} = \frac{C_{L\to B}}{f}\epsilon_S\kappa_S Y_S^{eq} = -0.0144719\epsilon_S\kappa_S$$

$$f = 28.4527, C_{L\to B} = -0.54902$$

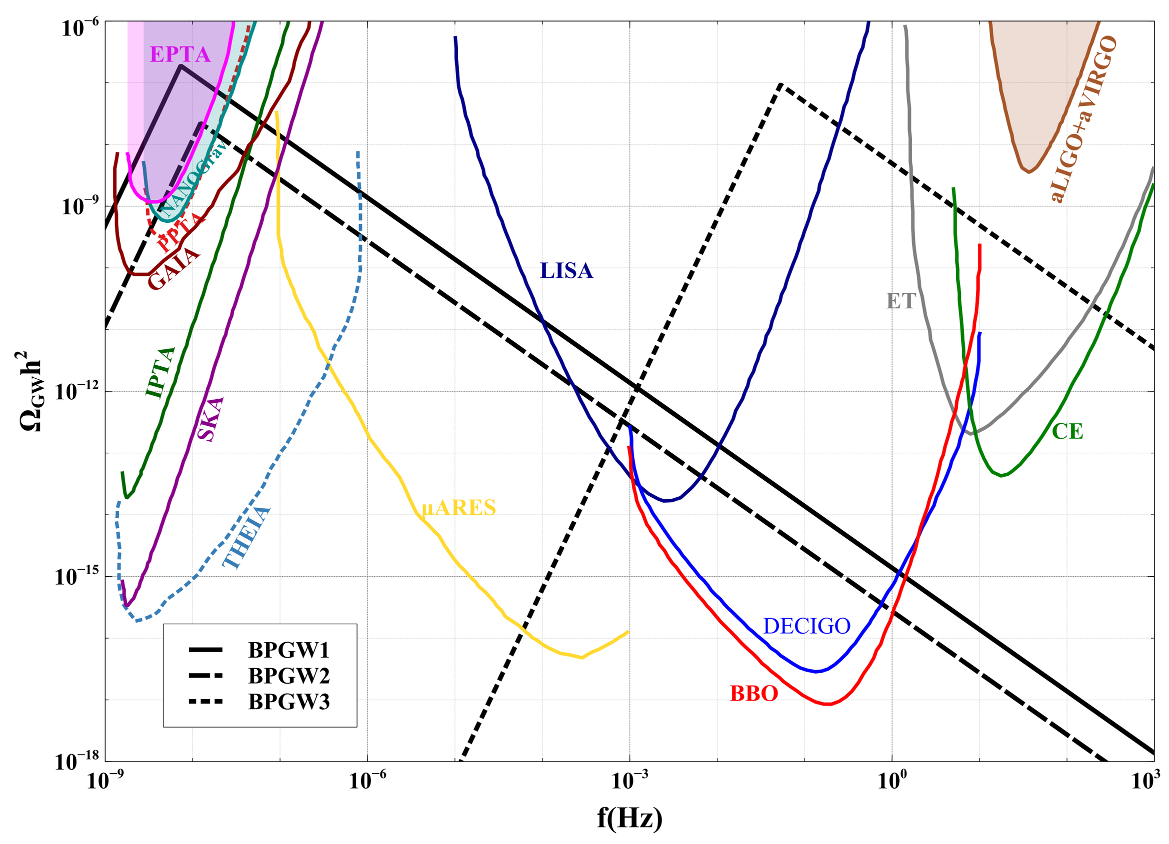
- BP1: $M_2 = 1.3\times 10^{12}$ GeV, $M_S = 2\times 10^9$ GeV, $v_\rho = 2.57\times 10^{11}$ GeV, $\theta_s = 7\times 10^{-3}$, $y_{NS} = 0.05$
- BP2: $M_2 = 10^{12}$ GeV, $M_S = 2\times 10^9$ GeV, $v_\rho = 3.36\times 10^7$ GeV, $\theta_s = 10^{-5}$, $y_{NS} = 0.42$

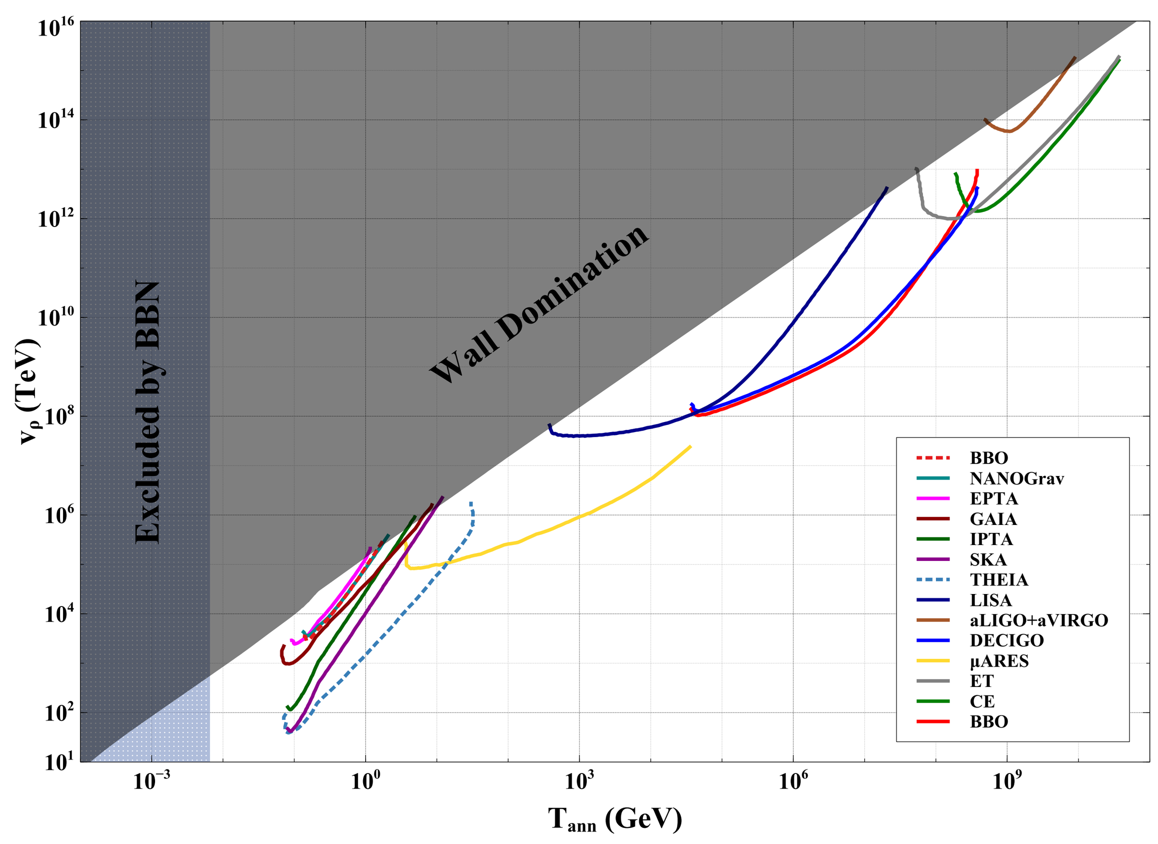


"We obtain the minimum value of M_S which can give rise to observed baryon asymmetry as $M_S \simeq 4\times 10^8$ GeV as for $M_S < 4\times 10^8$ GeV, ϵ_S will not give rise to correct lepton asymmetry"

Domain Walls and signatures of Gravitational Waves from Z_2 symmetry breaking

- The potential of the scalar ρ has two degenerate minima at $< \rho >= \pm v_\rho$ and the field can occupy any one of the two minima after the symmetry breaking resulting in two different domains, separated by a wall.
- The equation of motion for the DW is : $\frac{d^2\rho}{dx^2} - \frac{dV}{d\rho} = 0$ with the boundary condition : $\lim_{x\to\pm\infty}\rho(x) = \pm v_\rho$
- The surface energy density : $\sigma = \frac{4}{3}\sqrt{\frac{\lambda_\rho}{2}v_\rho^3} \simeq \frac{2}{3}M_\rho v_\rho^2$
- We introduce an energy bias in the potential as $\mu_b^3\rho$, which breaks the Z_2 symmetry explicitly and the degeneracy of the minima is lifted by $V_{bias} = \sqrt{2}\mu_b^3 v_\rho$
- This creates a pressure difference across the wall and they can then annihilate and emit their energy in the form of stochastic gravitational wave.
- $\Omega_{GW}h^2|_{peak} \propto \sigma^2\, T_{ann}^{-4}$ and $f_{peak} \propto T_{ann}$
- BPGW1 : $\sigma = 7.53\times 10^8\ TeV^3, T_{ann} = 0.3$ GeV
- BPGW2 : $\sigma = 7.53\times 10^8\ TeV^3, T_{ann} = 0.5$ GeV
- BPGW3 : $\sigma = 3.29\times 10^{22}\ TeV^3, T_{ann} = 2\times 10^6$ GeV.





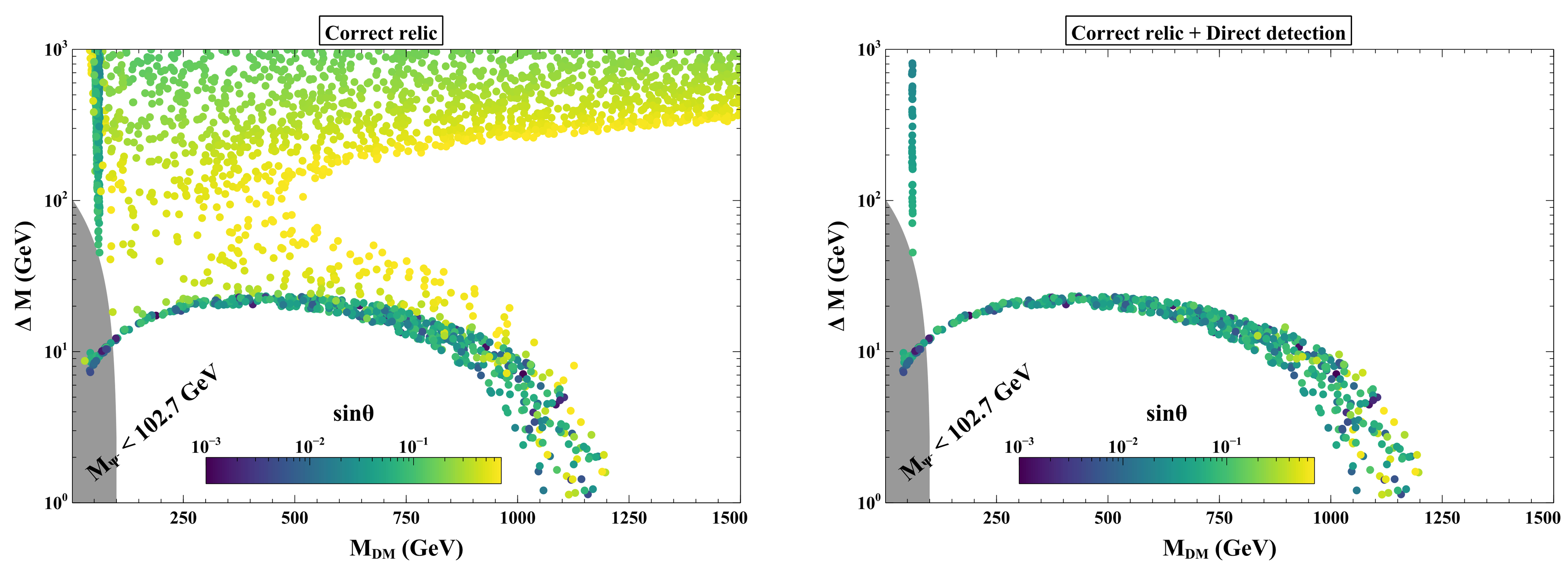
Singlet-doublet dark matter

- Due to the unbroken Z_2' symmetry combination of N_1 and $\Psi = (\psi^0\ \ \psi^-)^T \equiv (\psi_L^0 + \psi_R^0\ \ \psi^-)^T$ can give rise to a singlet-doublet Majorana DM
- The DM Langrangian is

$$\mathcal{L}_{\rm DM} = \overline{\Psi}i\gamma^\mu\mathcal{D}_\mu\Psi - M\overline{\Psi}\Psi + \overline{N_1}i\gamma^\mu\partial_\mu N_1 - \frac{1}{2}M_1\overline{N_1^c}N_1 - \frac{y_1}{\sqrt{2}}\overline{\Psi}\tilde{H}(N_1 + N_1^c) + h.c.$$

- The DM relic is decided by the freeze-out of various annihilation and co-annihilation processes in the early Universe.
- The Yukawa coupling is $y_1 = \frac{\Delta M\sin 2\theta}{\sqrt{2}v_h}$
- The direct detection is possible via the Higgs portal and the spin-independent DM-nucleon cross-section is

$$\sigma_{DM-N}^{SI} \propto y_1^2\sin^2 2\theta \propto \Delta M^2\sin^4 2\theta$$



Conclusion

- We explored the potential for generating successful thermal leptogenesis at a scale lower than the Davidson Ibarra bound in an extended type-I seesaw framework along with non-zero neutrino mass, dark matter and gravitational wave.
- At high scale, typically above the EWPT ρ acquires a vev and breaks the Z_2 symmetry spontaneously. As a result we got S mixed up with N_2 such that late decay of S could give rise to a relatively low scale thermal leptogenesis.
- The successful thermal leptogenesis requires $M_S \gtrsim 4\times 10^8$ GeV which is one order magnitude smaller than the usual Davidson Ibarra bound (2.4×10^9 GeV).
- The spontaneous breaking of the Z_2 symmetry also gave rise DWs in the early Universe. We discussed the evolution of the DWs which disappear by emitting stochastic GWs.
- In appropriate parameter space they can give rise signatures at various GW experiments like NANOGrav, EPTA, PPTA, LISA etc.
- In our setup the lightest RHN N_1 mixes with the neutral component of a vector like fermion doublet Ψ which are odd under an unbroken Z_2' symmetry. As a result we get singlet-doublet Majorana DM in a wide range of parameter space.

Reference

1. Partha Kumar Paul, Narendra Sahu, Prashant Shukla, *"Thermal leptogenesis, dark matter and gravitational waves from an extended canonical seesaw"*, [arXiv:2409.08828[hep-ph]]

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