Listening for Right-Handed Neutrinos in Gravitational-Wave Backgrounds

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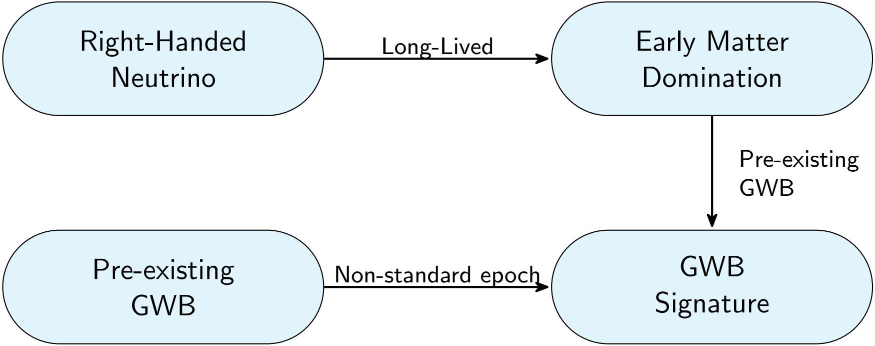
Based on 2511.01779 and 2604.20792

Setting and Overview



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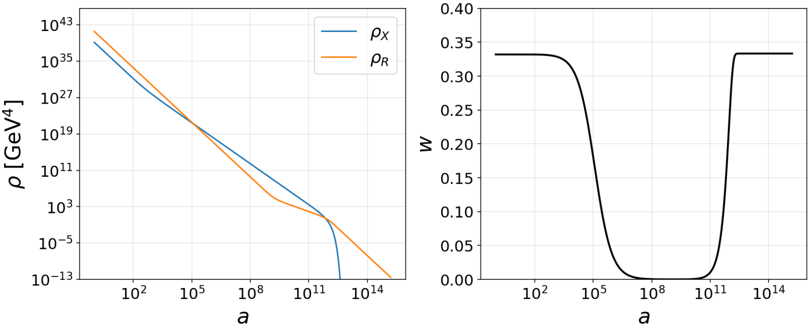
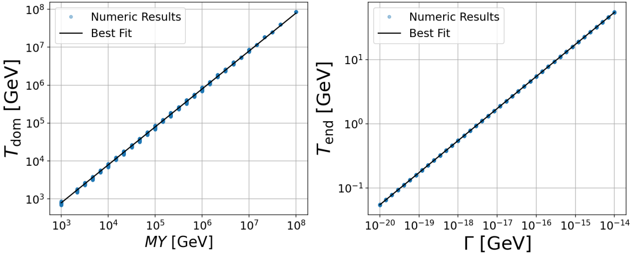
Tracking Particles in the Early Universe

- BSM particles can come to dominate the universe if the decaying heavy species X is long-lived:

$$\dot{\rho}_X + 3(1+w)H\rho_X = -\Gamma_X \rho_X, \quad \dot{\rho}_R + 4H\rho_R = \Gamma_X \rho_X \qquad (1)$$



Onset and End of Early Matter Domination



The best–fit relations extracted from the numerical scan are

$$T_{\rm dom} = 0.793\,(Y_i M), \quad T_{\rm end} = 0.16\,\sqrt{\Gamma M_{\rm Pl}} \tag{2}$$

The condition for matter domination is then,

$$\boxed{\frac{\Gamma M_{pl}}{Y_i^2 M^2} < \; 24.6} \tag{3}$$

Right-Handed Neutrinos

- For RHN decays,

$$\Gamma_N = \frac{\tilde{m} M^2}{8\pi v^2}, \quad \frac{\Gamma_N M_{\rm Pl}}{Y_i^2 M^2} < 24.6. \tag{4}$$

so the explicit dependence on the RH neutrino mass cancels in the condition

$$\frac{\tilde{m}\, M_{\rm Pl}}{8\pi v^2\, Y_i^2} < 24.6. \tag{5}$$

- Using $v = 174\,{\rm GeV}$ and expressing $\tilde{m}$ in eV,

$$\tilde{m}({\rm eV}) < 7.7 \times 10^{-3}\, Y_i^2. \tag{6}$$

- In the minimal Type-I seesaw with vanishing initial abundance, this condition cannot be satisfied.
- Non-thermal production mechanisms can evade this relation, allowing Y_i to be treated as a free parameter.

Effect on Gravitational Waves

- The two key quantities ρ_{total} and ρ_{GW}.The fluid equations for each of the species is,

$$\dot{\rho}_{GW} - 4H\rho_{GW} = 0, \quad \dot{\rho}_{tot} - 3H(w(a)+1)\rho_{tot} = 0 \tag{7}$$

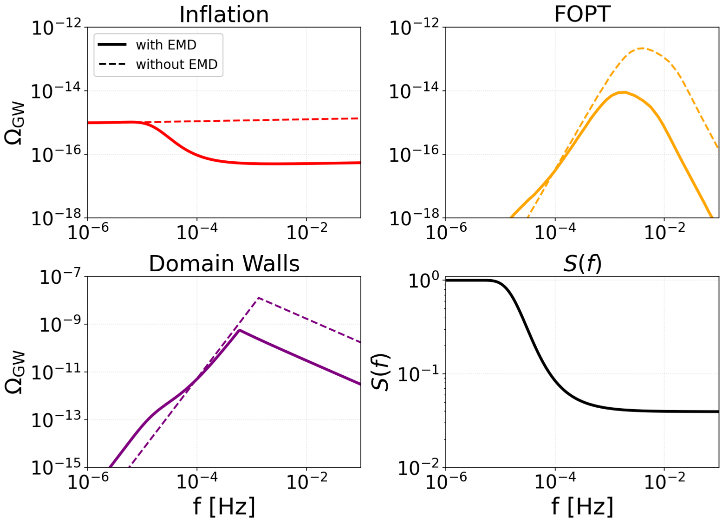
- The gravitational-wave energy density evolves according to

$$\Omega_{\rm GW}(a,f) = \Omega^{i}_{\rm GW}(f')C\exp\left[\int_{a_{ent}(f)}^{a_f}(3w(a)-1)\,d\ln a\right] \tag{8}$$

- During radiation domination ($w = 1/3$) the spectrum remains unchanged.
- During matter domination ($w = 0$) the spectrum is suppressed.
- We look to find the change which we

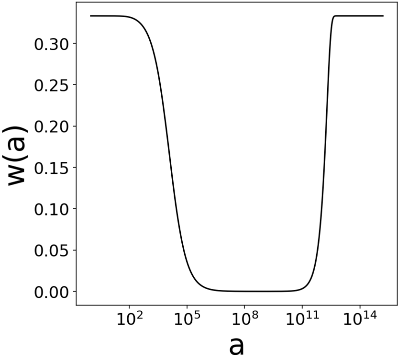
$$S(f) = \exp\left[\int_{a_{ent}(f)}^{a_f}(3w(a)-1)\,d\ln a\right] \tag{9}$$

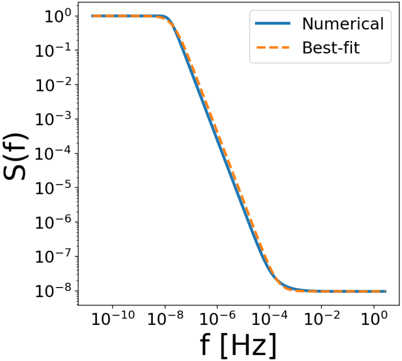
Benchmark



Inflation
with EMD
without EMD
FOPT
Domain Walls
$S(f)$
Ω_{GW}
$S(f)$
f [Hz]
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{0}
10^{-1}
10^{-2}
10^{-6}
10^{-4}

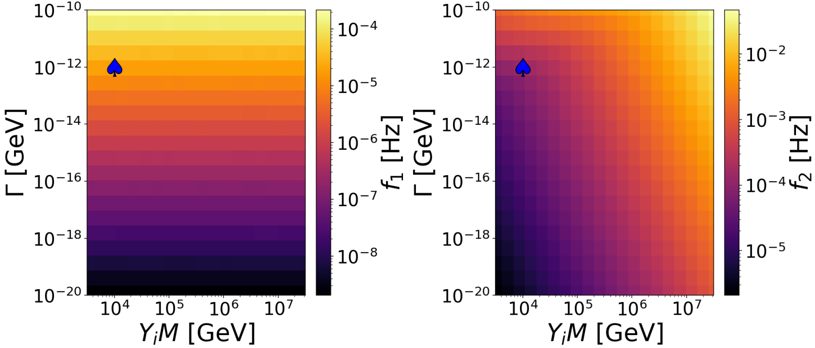
Benchmark





Best fit described by,

$$S(f, f_1, f_2) = \frac{1 + (f/f_1)^2}{1 + (f/f_2)^2}, \tag{10}$$



these results have best fits,

$$f_1 = 20.6 \left(\frac{\Gamma}{\mathrm{GeV}}\right)^{1/2} \mathrm{Hz} \tag{11}$$

$$f_2 = 2.10 \times 10^{-5} \left(\frac{Y_i M}{\mathrm{GeV}}\right)^{2/3} \left(\frac{\Gamma}{\mathrm{GeV}}\right)^{1/6} \mathrm{Hz}, \tag{12}$$

Right-Handed Neutrinos

- Using the frequency relations we already have in generality,

$$f_1 = 20.6 \left(\frac{\Gamma}{\mathrm{GeV}}\right)^{1/2} \mathrm{Hz} \tag{13}$$

$$f_2 = 2.10 \times 10^{-5} \left(\frac{Y_i M}{\mathrm{GeV}}\right)^{2/3} \left(\frac{\Gamma}{\mathrm{GeV}}\right)^{1/6} \mathrm{Hz}, \tag{14}$$

- We apply the initial abundance, Mass and effective neutrino mass

$$f_1 = 2.36 \times 10^{-6} \left(\frac{\tilde{m}}{\mathrm{eV}}\right)^{1/2} \left(\frac{M}{\mathrm{GeV}}\right) \mathrm{Hz} \tag{15}$$

$$f_2 = 1.01 \times 10^{-7}\, Y_i^{2/3} \left(\frac{\tilde{m}}{\mathrm{eV}}\right)^{1/6} \left(\frac{M}{\mathrm{GeV}}\right) \mathrm{Hz} \tag{16}$$

- So if a production mechanism is imposed, say thermal initial conditions from freeze-out. The Mass and effective neutrino mass of the dominating RHN can be determined.

$U(1)_{B-L}$ Model

- One nice mechanism is the $U(1)_{B-L}$ model that enforces RHNs and occurs in many GUT models.
- The RHNs can be produced thermally and then frozen out. Studied in 2511.01779

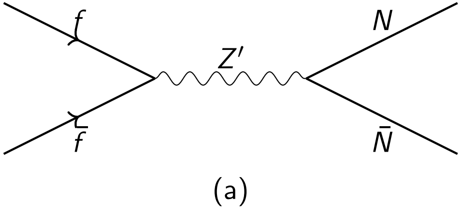


Figure: *Thermal Production of right-handed neutrinos via a Z' mediator.*

- Naturally get the early-matter domination from right-handed neutrinos and the GWB from Cosmic Strings.

$U(1)_{B-L}$ Model

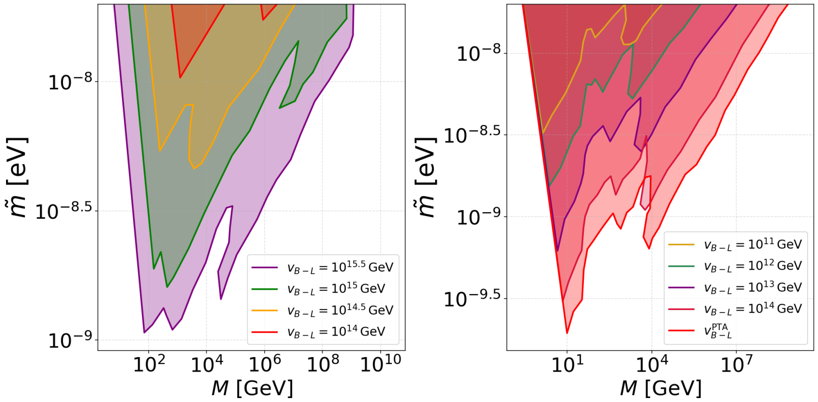


Figure: The panels show the detectable parameter space for global (left) and local (right) strings cases shown in the massm effective neutrino mass plane.

Conclusions

- Long-lived RHNs generically induce a period of early matter domination.
- This non-standard expansion history leaves a universal imprint on primordial gravitational-wave backgrounds.
- The resulting spectral distortion is well described by two characteristic frequencies, f_1 and f_2, corresponding to the onset and termination of the matter-dominated era.
- These frequencies are directly determined by microscopic parameters, with $f_1 \propto \Gamma^{1/2}$ and $f_2 \propto (YM)^{2/3}\Gamma^{1/6}$, establishing a direct map between observables and particle physics.
- Gravitational-wave measurements therefore provide a model-independent probe of long-lived RHNs.