Gravitational waves from phase transitions and cosmic strings in neutrino mass models with multiple Majorons

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Neutrino mass

- Neutrino oscillations prove that they must be massive, but the nature of their mass remains unknown
- Massless in the Standard Model, introduce right-handed partners to make them massive
- Dirac mass vs. Majorana mass: is lepton number symmetry violated?
- Type-I seesaw mechanism: very massive Majorana right-handed neutrinos, naturally generates tiny masses for SM neutrinos, also useful for explaining baryogenesis via leptogenesis ...
- Lepton number violation at high energy scale, three possibilities: (a) explicit breaking, (b) spontaneous breaking of local $U(1)_L$, (c) spontaneous breaking of global $U(1)_L$

Majoron Model

- Introduce right-handed neutrinos and a complex scalar charged under a global $U(1)_L$, [Chikashige, Mohapatra, Peccei 1981]

$$-\mathcal{L}_{N_I+\sigma} = \overline{L_\alpha}\, h_{\alpha I}\, N_I\, \widetilde{\Phi} + \frac{\lambda_I}{2}\, \sigma\, \overline{N_I^c}\, N_I + V_0(\sigma) + \text{h.c.}$$

- Majorana mass term for the RHNs arise when $\langle\sigma\rangle \neq 0$
- $\sigma = \frac{1}{\sqrt{2}}(\langle\sigma\rangle + \rho + i\chi)$, ρ becomes massive and χ is the Nambu-Goldstone boson called Majoron
- Single Majoron model: breaking of lepton number symmetry sets the scale of the heaviest RHN, nondegenerate masses arise from $\lambda_I \neq \lambda_J$
- SM neutrino masses are generated via Type-I seesaw mechanism

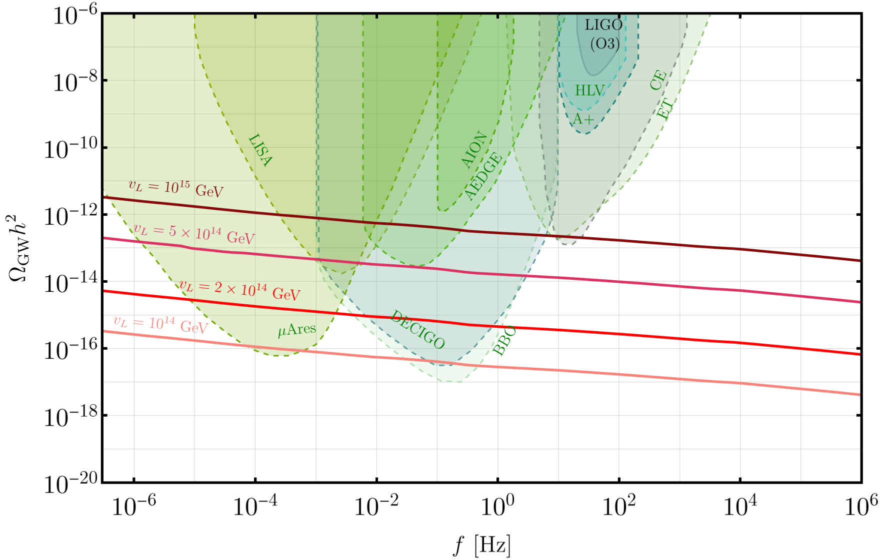
Testing Lepton Number Violation

- Smoking gun for SM Majorana neutrinos: neutrinoless double beta decay, so far unobserved, RHN Majorana masses are generated at very high scale, laboratory tests not viable
- Cosmological probes: gravitational wave (GW) from first order phase transition (FOPT) of the complex scalar spontaneously breaking global lepton number
- GW amplitude is very suppressed as FOPT is weak, can be enhanced by explicit violation and/or non-renormalizable terms [Addazi et al. 2020], introducing an auxiliary real scalar [Di Bari, Marfatia, Zhou 2020] etc.
- **New perspective:** spontaneous breaking of global lepton number symmetry generates cosmic strings which emit gravitational waves
- Strong phase transition in multiple Majoron models, characteristic GW signal with peak(s) soaring above the slanted plateau from global cosmic string

GW from Global Cosmic String Network in Single Majoron Model

- Spontaneous breaking of global $U(1)_L$ creates horizon sized long stings, which randomly intersect and form sub-horizon sized loops
  [Martins, Shellard 1996, 2000 . . . , Chang, Cui 2019, 2021]
- Loops lose energy predominantly (90%) by decaying into Goldstone bosons (unlike Nambu-Goto strings from local $U(1)$ symmetry breaking), and sub-dominantly (10%) by emitting GW
- GW spectrum falls off approximately as $\log^3(1/f)$ and depends crucially on the symmetry breaking scale v_L^4
- Detectable signals in planned interferometers for $v_L \gtrsim 10^{14}$ GeV

GW from Global Cosmic String Network



GW from First Order Phase Transition

- Tree level potential $V_0(\rho) = -\frac{1}{2}\mu^2\rho^2 + \frac{\lambda}{4}\rho^4$
- Minimum of the potential at $\rho = 0$ at high temperatures, as the universe cools down a second minimum appears, and is separated by a barrier
- Two minima becomes degenerate at 'critical' temperature, below which the bubbles of the 'false' vacuum has a higher probability to nucleate to the 'true' vacuum
- Phase transition happens around a 'percolation' temperature $T_\star$, when only $1/e$ fraction of the space is still in the 'false' vacuum
- Rapid expansion of the bubbles create GW, whose spectrum depends on two parameters: (a) $\beta/H_\star$ (inverse of the duration of the phase transition), and (b) α (strength of the phase transition)

GW from First Order Phase Transition

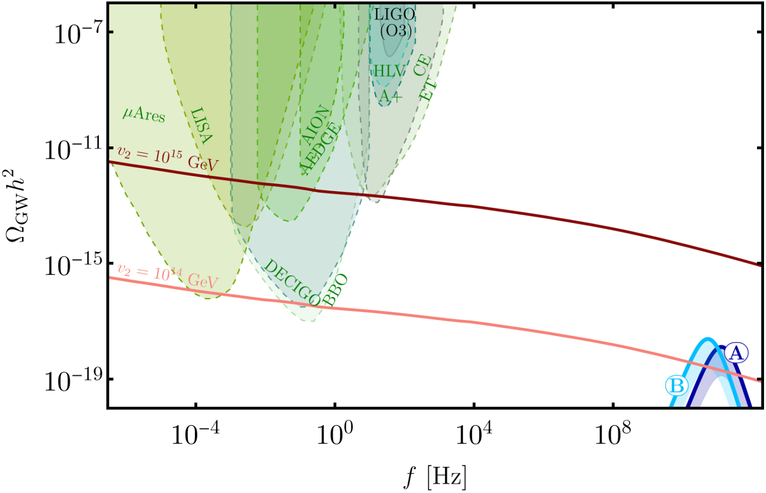


Figure: A: $v_2 = M = 10^{15}$ GeV, B: $v_2 = M = 10^{14}$ GeV

Two Majoron Model

- Thermal effective potential for single Majoron model has a temperature dependent cubic term, creating a small barrier between the 'false' and 'true' vacua, FOPT does not happen at all, or is very weak
- Presence of a zero temperature cubic term in the thermal effective potential enhances the barrier and strengthens the phase transition
- Consider two complex scalars with their own global lepton number symmetry, one gets a VEV at high scales $(10^{14} - 10^{15}$ GeV) undergoing a phase transition, and the other gets a VEV at lower scales
- Presence of the first scalar induces a cubic term in the 1-loop Coleman-Weinberg potential of the second scalar, strong phase transition and GW spectrum follows

Combined GW Signatures

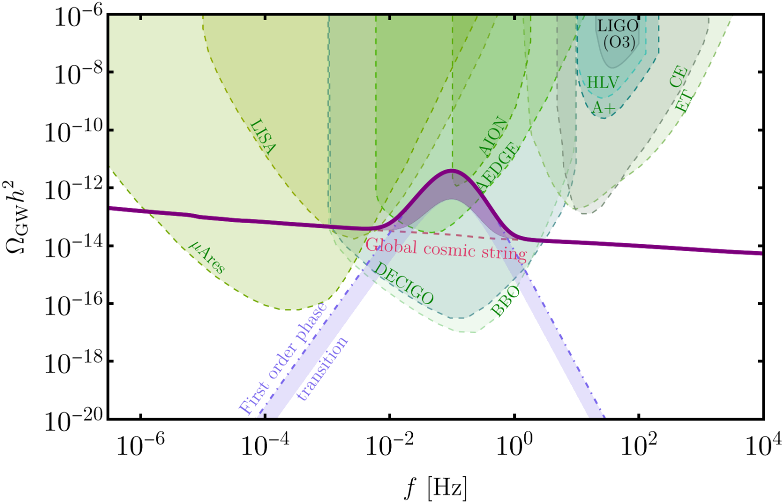


Figure: Global CS $v_{L2} = 5 \times 10^{14}$ GeV, FOPT $v_{L1} = 1.2$ TeV

Three Majoron Model

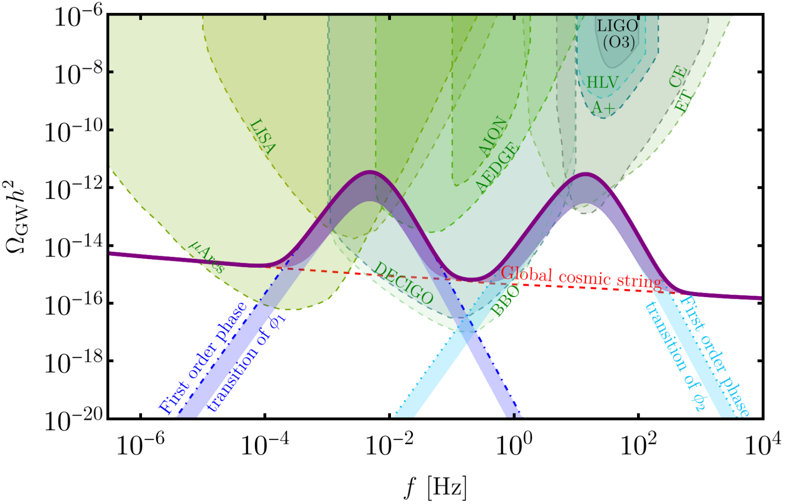


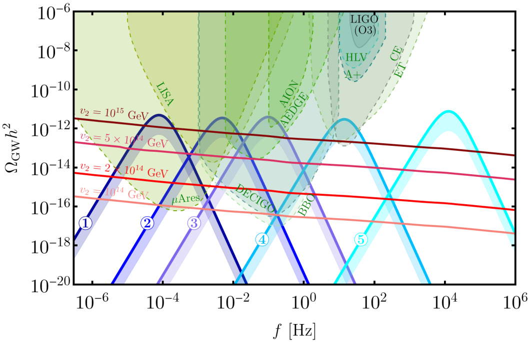
Figure: GCS $v_{L3} = 2 \times 10^{14}$ GeV, FOPT $v_{L1} = 52.3$ TeV, $v_{L2} = 2.3 \times 10^{5}$ GeV

Summary

- Single Majoron model can be probed via gravitational waves from cosmic strings if global lepton number symmetry is spontaneously broken above 10^{14} GeV
- Multiple Majoron model with hierarchical breaking of global lepton number symmetries may also have strong first order phase transition induced peaked GW spectrum, auxiliary scalar needed to enhance the strength of FOPT is not ad-hoc
- Single or double peaked over a slanted plateau GW spectrum would be a smoking gun of multiple Majoron models of neutrino mass genesis

Backup Slides

Benchmark Points



B.P.	λ_1	v_1 [GeV]	M [GeV]	C [GeV]	α	$\beta/H_\star$	$T_\star$ [GeV]	$\langle\phi_1\rangle_{T_\star}^{\rm true}$ [GeV]
1	0.00023	1.45	0.32	0.0013	0.13	556.4	0.62	24.5
2	0.00031	52.3	8.2	0.10	0.098	337.9	58.4	1135.3
3	0.00032	1188.2	186.5	2.39	0.099	310.2	1278.1	25345.6
4	0.00032	231555	36349.3	323.0	0.091	317.072	177895.7	3.37×10^6
5	0.00031	8.87×10^6	1.08×10^6	6.4×10^5	0.098	148.9	3.47×10^8	6.77×10^9

Table 3. Benchmark points for gravitational wave signals from first order phase transition of ϕ_1.

Scatter Plot of α and $\beta/H_\star$