Towards distinguishing Dirac from Majorana neutrino mass with gravitational waves

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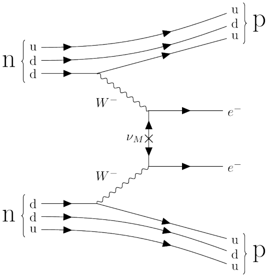
with S.F. King, and D. Marfatia

Neutrino mass

- Massless in the Standard Model, Dirac/Majorana nature indistinguishable in weak interactions
- Neutrino oscillations prove that they must be massive, go beyond the SM by adding right-handed partners
- Dirac mass vs. Majorana mass: is lepton number symmetry violated?
- Neutrinoless double beta decay: if neutrinos have Majorana mass [Schechter, Valle 1982]



Dirac vs Majorana signatures

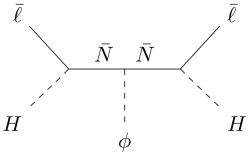
- Current constraint from KamLAND-Zen $|m_{\beta\beta}| \sim \mathcal{O}(10 - 100)$ meV
- Projected sensitivity of upcoming experiments

Experiment	$\lvert m_{\beta\beta}\rvert$ (meV)	Experiment	$\lvert m_{\beta\beta}\rvert$ (meV)
LEGEND	11 - 28	SNO+-II	20 - 70
nEXO	8 - 22	AMoRE-II	15 - 30
CUPID	6 - 17	PandaX-III	20 - 55

- Nonobservation of $0\nu\beta\beta$ does not guarantee Dirac nature
- Complementary tests from cosmology? CMB [Abazajian, Heeck 2019], primordial black holes [Lunardini, Perez-Gonzalez 2019], $\Delta N_{\rm eff}$ [Adshead, Cui, Long, Shamma 2020], CνB [Hernandez-Milinero, Jiminez, Pena-Garay 2022]
- This work: gravitational wave signatures

Majorana mass model

- Type-I seesaw, SM extended with three heavy right-handed neutrinos $\bar{N}_i$ and a scalar ϕ, both singlet under SM gauge groups, but charged under a gauged $U(1)_{B-L}$ symmetry



- ϕ gets a nonzero VEV, spontaneously breaks $U(1)_{B-L}$, generates mass of the RHNs

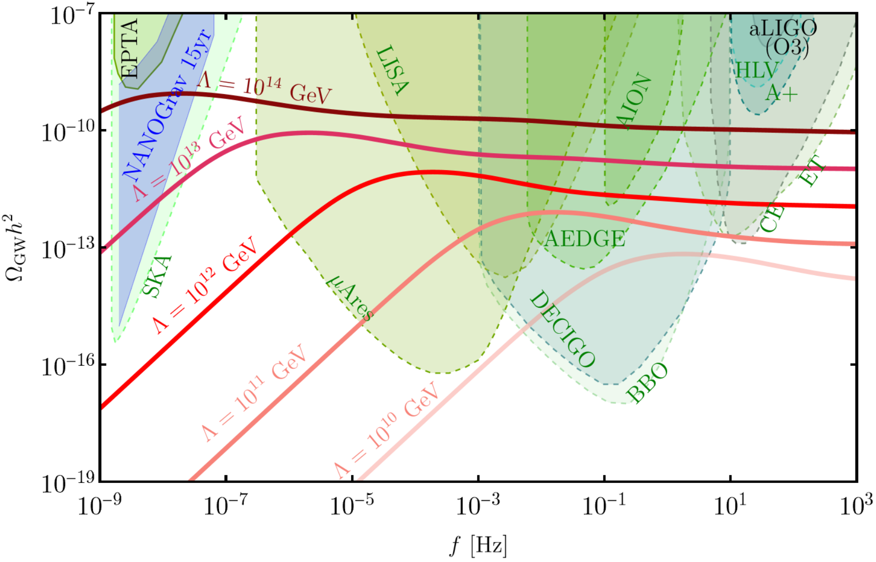
- Light neutrino masses are generated after integrating out the heavy RHNs

$$\mathcal{M}_M \sim v^2 \mathcal{Y}\, \mathcal{M}_N^{-1}\, \mathcal{Y}^T$$

Cosmic string from $U(1)_{B-L}$ breaking

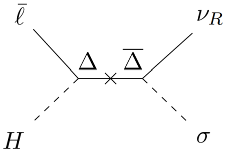
- Spontaneous breaking of $U(1)_{B-L}$ generates horizon-length string network
- Long strings intersect and produce closed loops, 90% are small loops that simply redshift away, 10% are large loops that primarily emit gravitational waves
- Loop size decreases as they lose energy, gravitational waves are created until all loops disappear
- $\Omega_{\rm GW}h^2$ has a rising slope at low frequencies, then flat over a large frequency range in the observable window
- Signal amplitude depends on the string tension, which is roughly determined by the symmetry breaking scale

GW from cosmic string network



Dirac mass model

- To be comparable to the Type-I seesaw model, consider no tree-level Dirac mass
- Can be generated from a dimension-5 operator (Δ is a heavy Dirac fermion, ν_R are RHNs, σ is a complex scalar)



- (i) Lepton number symmetry is protected, (ii) no tree-level Dirac mass term for neutrinos — minimal symmetry is Z_2 under which σ and ν_R are odd
- Z_2 symmetry is spontaneously broken by σ, generates Dirac neutrino mass

Domain wall from Z_2 breaking

- Z_2 symmetric potential for σ

$$V(\sigma) = \frac{\lambda}{4}(\sigma^2 - u^2)^2$$

Two degenerate vacua at $\sigma = \pm u$, two domains

- Domain walls are problematic for cosmology, may dominate the energy budget, generate density perturbations etc.

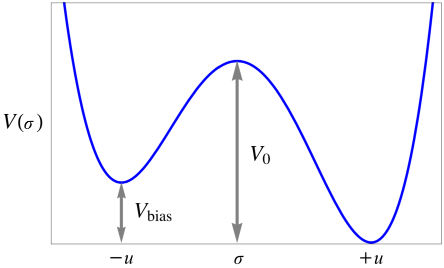
- Way out: softly break the Z_2 symmetry

$$\Delta V(\sigma) = \epsilon u \sigma \left(\frac{\sigma^2}{3} - u^2 \right)$$

Vacua still at $\sigma = \pm$, but non-degenerate, initiates the annihilation of the wall

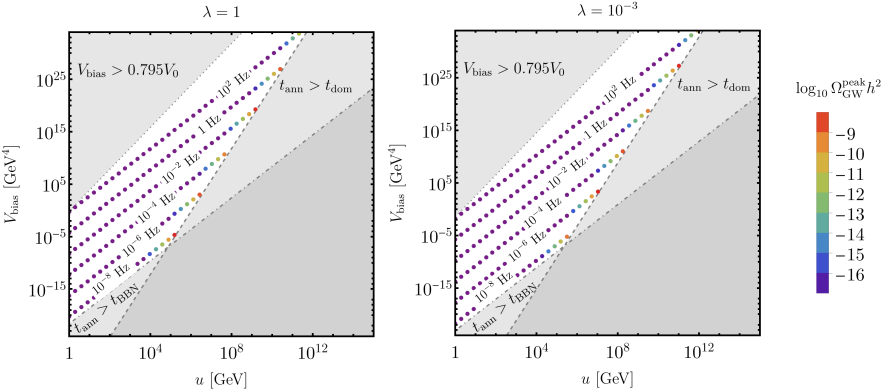
Domain wall dynamics

- Infinite cluster of 'false' vacuum ($\sigma = -u$) appears unless $V_{\text{bias}} < 0.795 V_0$
- Two competing pressures, surface energy density controlled by u, and volume pressure controlled by V_{bias}, wall collapses when they are equal



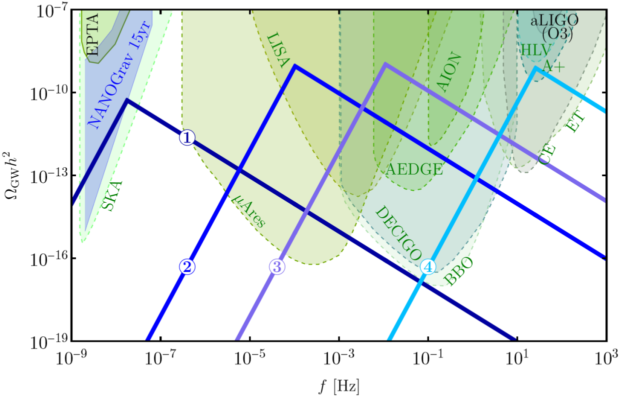
- Energy from domain wall annihilation is converted into gravitational waves, peaked signal with $\Omega_{\text{GW}} h^2 \propto f^3$ for $f < f_{\text{peak}}$ and $\Omega_{\text{GW}} h^2 \propto f^{-1}$ for $f > f_{\text{peak}}$
- Walls must annihilate before dominating the energy density of the Universe, and before BBN

Constraints on domain wall dynamics



(a) (b)

GW from domain wall annihilation



Benchmark Point	u [GeV]	$V_{\rm bias}$ [GeV^4]	$y_{\rm max}(M_\Delta < M_{\rm Pl})$
①	10^5	1.5×10^{-5}	4.93
②	5.2×10^7	7.14×10^{10}	0.216
③	1.2×10^9	10^{19}	0.045
④	2×10^{11}	2.5×10^{32}	0.0035

Summary

- Two models for Majorana and Dirac mass generation for neutrinos considered, without tiny Yukawa couplings
- Majorana mass generated from spontaneous breaking of gauged $B - L$ symmetry and type-I seesaw mechanism, produces cosmic string induced gravitational waves
- Dirac mass generated from spontaneous breaking of a Z_2 symmetry, necessary for preserving lepton number symmetry while prohibiting a tree-level Dirac mass term, produces domain wall induced gravitational waves
- Majorana mass model predicts a flat spectrum, potentially observable at multiple interferometers, Dirac mass model predicts a peaked spectrum, should be detected in a narrow band