Neutrino masses and Gravitational Waves

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In collaboration with Graham White

Overview

Introduction/Motivation

- Neutrino masses (Dirac)
- Non-Abelian Dark Sector(self-interacting dark matter)
- Gravitational waves from early universe
- Neutrinogenesis
- Connect all of the above

Requirements for neutrino mass

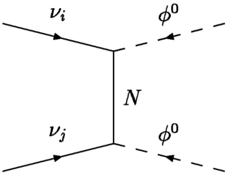
- Majorana or Dirac type?
- Tree level or radiative?
- New particles? (scalar, fermionic, vector)
- New gauge sectors? $(U(1), SU(2), SU(N))$

Tree level, Majorana

Weinberg Operator 1979: $\frac{LHLH}{\Lambda} = \frac{(l^- H^+ - \nu H^0)(l^- H^+ - \nu H^0)}{\Lambda}$

Add $N_R \sim (1,1,0)$ under $\mathbb{G}_{SM}$

$$\mathcal{L}_{new} = \bar{N} Y_D L H + m_N N_R N_R + \text{h.c.}$$



$$\begin{pmatrix} 0 & m_D \\ m_D & m_N \end{pmatrix} \Rightarrow m_\nu \simeq \frac{-m_D^2}{m_N}$$

$v \ll m_N \sim 10^{11}\text{GeV} \rightarrow m_\nu \ll v$ with $Y_D \sim 1$

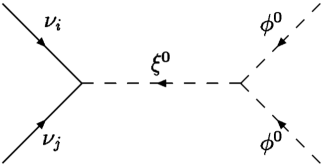
or $Y_D \ll 1 \rightarrow m_\nu \ll v$ with $m_N \sim O(10^{2-3} GeV)$

Seesaw$-$I

Seesaw-II

Add[1980] $\xi = (\xi^{++}, \xi^{+}, \xi^{0}) \sim (1,3,1)$ under $\mathbb{G}_{SM}$

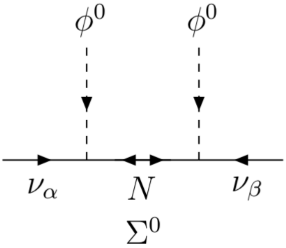
$$\mathcal{L}_{new} = YL\xi L - \mu H\xi H + \text{h.c.} \rightarrow m_\nu = Y\left\langle \xi^0 \right\rangle = -2\frac{Y\mu v^2}{M_\xi}$$



Seesaw-III

Add $\Sigma \sim (1,3,0)$ under $\mathbb{G}_{SM}$

$$\mathcal{L} = \Sigma Y_D L H + m_N \Sigma\Sigma + \text{h.c.}$$



$$\begin{pmatrix} 0 & m_D \\ m_D & m_N \end{pmatrix} \Rightarrow m_\nu \simeq \frac{-m_D^2}{m_N}$$

$v \ll m_\Sigma \sim 10^{11}\text{GeV} \rightarrow m_\nu \ll v$ with $Y_D \sim 1$
or $Y_D \ll 1 \rightarrow m_\nu \ll v$ with $m_\Sigma \sim O(10^{2-3}GeV)$

Seesaw variations

$$\mathscr{M}_{\nu N} = \begin{pmatrix} 0 & m_D \\ m_D & m_N \end{pmatrix},$$

Seesaw[1979] $m_\nu = -m_D^2/m_N$

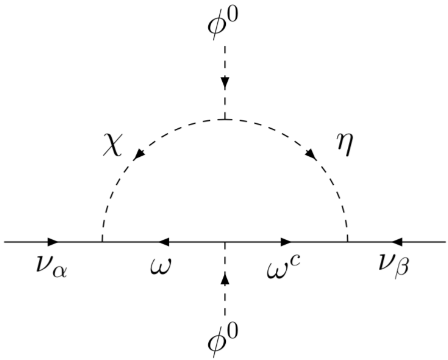
$$\mathscr{M}_{\nu n} = \begin{pmatrix} 0 & m_D & 0 \\ m_D & m_1 & m_N \\ 0 & m_N & m_2 \end{pmatrix}$$

Inverse Seesaw[1986] $m_\nu = m_D^2 m_2/(m_N^2 - m_1 m_2)$

$$\mathscr{M}_{\nu N} = \begin{pmatrix} 0 & m_D & m'_D \\ m_D & 0 & m_N \\ m'_D & m_N & 0 \end{pmatrix}$$

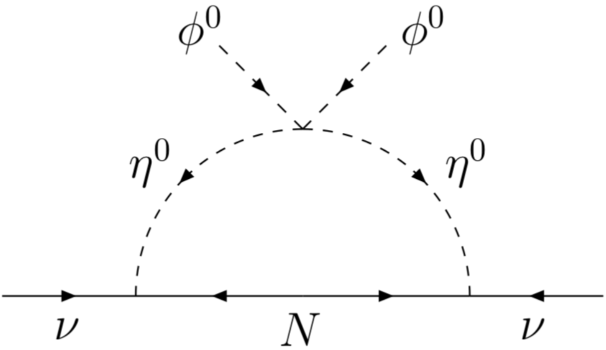
Linear Seesaw $m_\nu = -2 m_D m_{D'}/m_N$

Radiative neutrino mass, Majorana



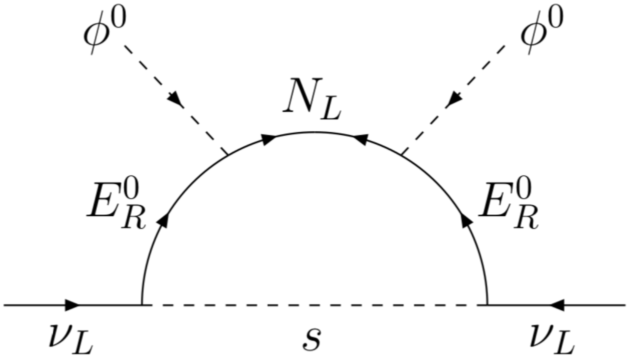
Zee[1986]

Scotogenic radiative neutrino mass



Add $\mathbb{Z}_2$ symmetry under which $\eta \sim (1, 2, 1/2)$ and N_R are odd

Radiative inverse seesaw neutrino mass, Majorana



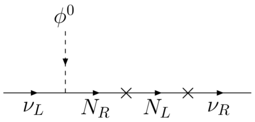
Add $\mathbb{Z}_2$ symmetry under which real singlet scalar and $E_{L,R} \sim (1,2,1/2)$ and $N_L \sim (1,1,0)$ are odd

Dirac neutrinos

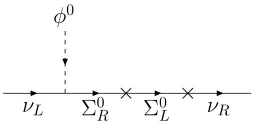
- Add $N_R \sim (1, 1, 0)$ under G_{SM}
- N_R MUST transfor under some other symmetry non-trivially
- New symmetry S is discrete, global, gauged, dark?

Tree Dirac case

- Insert a Dirac fermion singlet N which does not transform under $\mathcal{S}$, then break $\mathcal{S}$ softly by the dimension-three $\bar{\nu}_R N_L$ term.

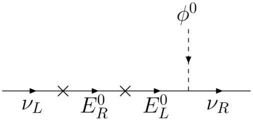


- Insert a Dirac fermion triplet $(\Sigma^+, \Sigma^0, \Sigma^-)$ which does not transform under $\mathcal{S}$, then break $\mathcal{S}$ and $SU(2)_L \times U(1)$ together spontaneously to obtain the dimension-three $\bar{\nu}_R \Sigma^0_L$ term.

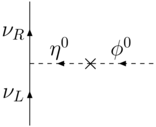


Dirac case

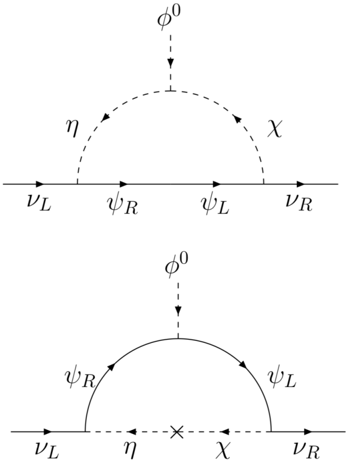
- Insert a Dirac fermion doublet (E^0, E^-) which transforms as ν_R under $\mathcal{S}$, then break $\mathcal{S}$ softly by the dimension-three $(\bar{E}^0\nu_L + E^+e^-)$ term.



- Insert a scalar doublet (η^+, η^0) which transforms as ν_R under $\mathcal{S}$, then break $\mathcal{S}$ softly by the dimension-two $(\eta^-\phi^+ + \bar{\eta}^0\phi^0)$ term.



Dirac case

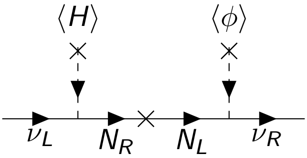


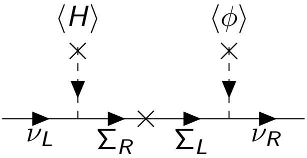
Models

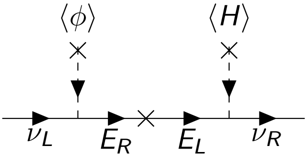
Model*	Field	$SU(2)_L$	$U(1)_Y$	$SU(N)$	Flavor
1,2	ν_R	1	0	$\square$	N_f
1a	$N_{R,L}$	1	0	1	N_f
	ϕ	1	0	$\square$	1
1b	$\Sigma_{R,L}$	3	0	1	N_f
1b	ϕ	3	0	$\square$	1
1c	$E_{R,L}$	2	$-\frac{1}{2}$	$\square$	N_f
1c	ϕ	1	0	$\square$	1
2	η	2	$\frac{1}{2}$	$\square$	1
2	ϕ	1	0	$\square$	1

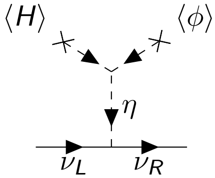
*10.1016/j.physletb.2016.11.027

Models









$$m_\nu \cong -\boldsymbol{Y_R M_N^{-1} Y_L} \frac{v v_\phi}{2} \qquad m_\nu \cong -Y_\nu \frac{v_\eta}{\sqrt{2}} \cong \frac{Y_\nu \mu v v_\phi}{\sqrt{2} 4 m_\eta^2}$$

Thermal potential

$$V_0 = -\mu_H^2 H^\dagger H + \frac{\lambda_H}{2}(H^\dagger H)^2 - m_\phi^2 \phi^\dagger \phi + \frac{\lambda_\phi}{2}(\phi^\dagger\phi)^2$$
$$+ \lambda_{H\phi}(H^\dagger H)(\phi^\dagger \phi) + \delta_{\mathrm{SU}(2)}\lambda'_{H\phi} H^\dagger \phi \phi^\dagger H$$
$$V_{CW} = n_{GB}\frac{m_{GB}^4}{64\pi^2}\left(\log\left[\frac{m_{GB}^2}{\mu^2}\right] - \frac{5}{6}\right) + \sum_{i\neq GB} n_i \frac{m_i^4}{64\pi^2}\left(\log\left[\frac{m_i^2}{\mu^2}\right] - \frac{3}{2}\right)$$
$$V_{T\neq 0} = \sum_i \frac{T^4}{2\pi^2} J_B\left(\frac{m_i^2 + \Pi_i}{T^2}\right)$$
$$V(\phi, T) = V_0(\phi) + V_{CW}(\phi, \mu) + V_{T\neq 0}(\phi, T)$$

Thermal parameters

$$\frac{\partial^2\phi}{\partial r^2} + \frac{2}{r}\frac{\partial\phi}{\partial r} = \frac{\partial V(\phi, T)}{\partial\phi} \quad \phi'(0) = 0 \quad \phi(\infty) = 0$$

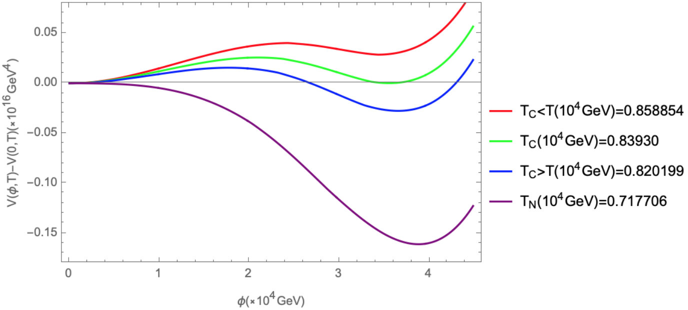
$$\mathcal{S}_E = 4\pi \int_0^\infty r^2 dr \left[\left(\frac{\partial\phi}{\partial r}\right)^2 + V(\phi, T)\right]$$

$$p(t_N)t_N^4 \approx 1 \quad p(T) \approx T^4 e^{-\mathcal{S}_E(\mathcal{S}_b;T)/T} \quad T^2 t = \sqrt{\frac{45}{16\pi^3}}\frac{M_p}{\sqrt{g_\star}}$$

$$\alpha = \left.\frac{\Delta\left(V - T\frac{\partial V}{\partial T}\right)}{\pi^2 g_\star T^4/30}\right|_{T_N}$$

$$\frac{\beta}{H} = T\left.\left(\frac{d(\mathcal{S}_E/T)}{dT}\right)\right|_{T_N}$$

Thermal parameters



$$\lambda_\phi = 0.0009,\ \lambda_{h\phi} = 0.05,\ g_D = 0.5,\ N = 5,\ \frac{\phi_C}{T_C} = 4.268,\ \alpha = 0.278,\ \beta/H = 1942$$

$$V(0, T_C) = V(\phi_C, T_C) \quad \frac{\phi_C}{T_C} > 1$$

Gravitational waves

$$h^2\Omega_{sw}(f) = 8.5\times 10^{-6}\left(\frac{100}{g_\star}\right)^{1/3}\Gamma^2\bar{U}_f^4\left(\frac{H_\star}{\beta}\right)v_w S_{sw}(f)^\dagger$$

$$\Gamma = 4/3,\quad \bar{U}_f^2 = \frac{3}{4}\kappa_f\alpha_{T_\star},\quad S_{sw}(f) = \left(\frac{f}{f_{sw}}\right)^3\left(\frac{7}{4+3(f/f_{sw})^2}\right)^{7/2}$$

$$f_{sw} = 8.9\mu Hz\frac{1}{v_w}\left(\frac{\beta}{H_\star}\right)\left(\frac{z_p}{10}\right)\left(\frac{T_\star}{100\mathrm{GeV}}\right)\left(\frac{g_\star}{100}\right)^{1/6}$$

$$h^2\Omega_{turb}(f) = 3.35\times 10^{-4}\left(\frac{H_\star}{\beta}\right)\left(\frac{\kappa_{turb}(\alpha_{T_\star})\alpha_{T_\star}}{1+\alpha_{T_\star}}\right)^{3/2}\left(\frac{100}{g_\star}\right)^{1/3}v_w S_{turb}(f)$$

$$S_{turb}(f) = \frac{(f/f_{turb})^3}{[1+(f/f_{turb})]^{11/3}(1+8\pi f/h_\star)}\quad h_\star = 16.5\mu Hz\left(\frac{T_\star}{100\mathrm{GeV}}\right)\left(\frac{g_\star}{100}\right)^{1/6}$$

$$f_{turb} = 27\mu Hz\frac{1}{v_w}\left(\frac{\beta}{H_\star}\right)\left(\frac{T_\star}{100\mathrm{GeV}}\right)\left(\frac{g_\star}{100}\right)^{1/6}$$

$$h^2\Omega(f) = h^2\Omega_{sw}(f) + h^2\Omega_{turb}(f)$$

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† 10.1098/rsta.2017.0126

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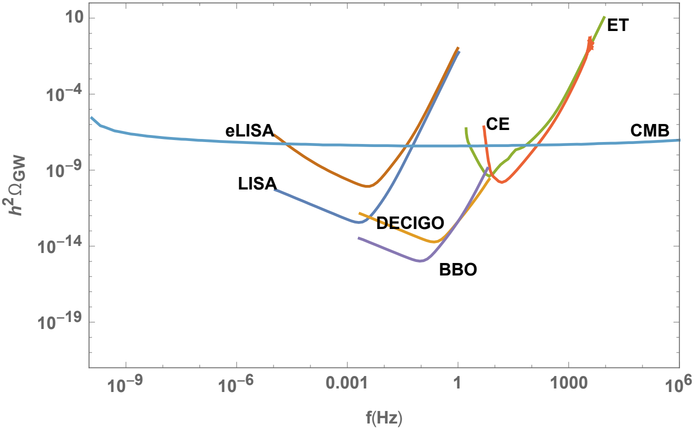
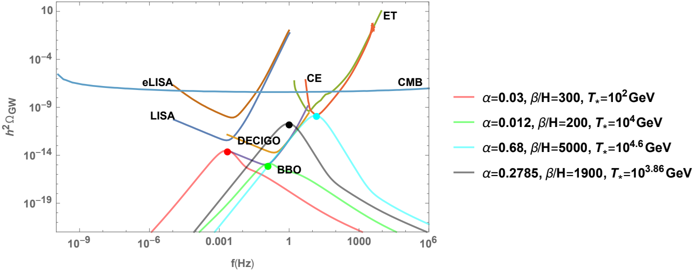
Gravitational waves



‡

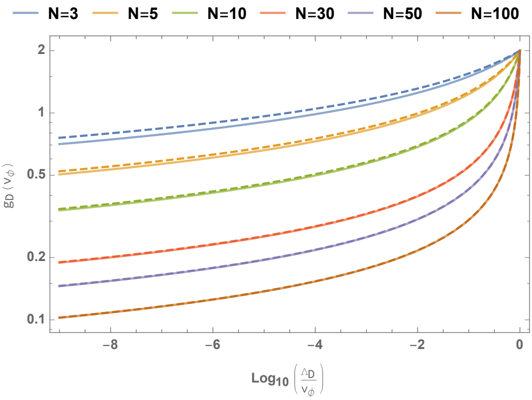
‡gwplotter

Gravitational waves



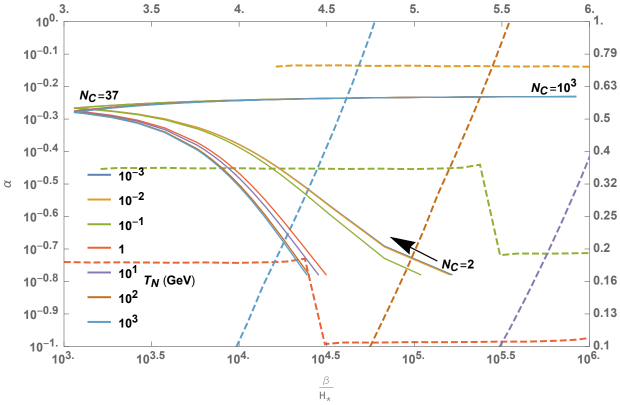
$\mu_\phi(10^4\ \mathrm{GeV})$	$\mu_H(10^4\ \mathrm{GeV})$	λ_ϕ	λ_H	$\lambda_{h\phi}$	g_D	N	$g_\star$
0.212168	1.58143	0.0009	3.04	0.05	0.5	5	184.25
$\frac{\phi_C}{T_C}$	$T_C(10^4\ \mathrm{GeV})$	$T_N(10^4\ \mathrm{GeV})$	α	$\frac{\beta}{H_\star}$			
4.268	0.8393	0.717706	0.278	1942			

Connection between SSB and confinement



Correlation between $g_d(v_\phi)$ and $\frac{\Lambda_D}{v_\phi}$ for different values of N where for solid(dashed) curves $N_f = 2(5)$. If $\Lambda_D > 0.2$ MeV (BBN) and $v_\phi \sim O(10^{4-6}\mathrm{GeV})$ than $\frac{\Lambda_D}{v_\phi}$ can be as low as $O(10^{-8} - 10^{-10})$.

N =odd case (dark glueball condensate)



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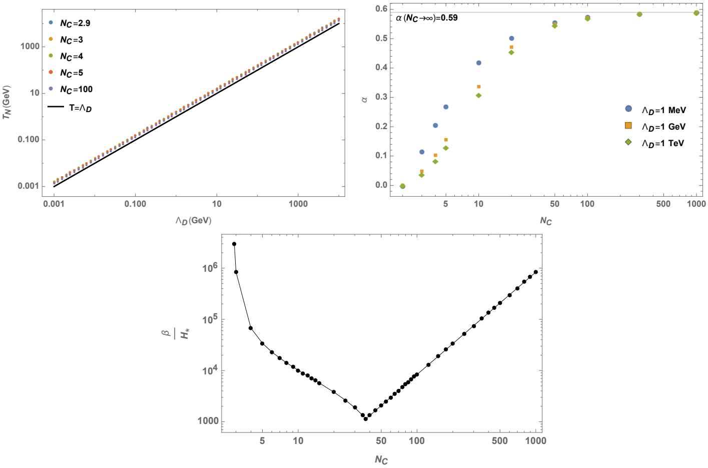
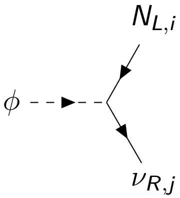


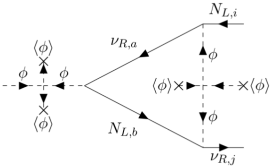
Neutrino mass models and gravitational waves

- $h^2\Omega \propto \frac{v_\phi}{m_\phi}$
- $h^2\Omega \propto g_D$
- $h^2\Omega \propto n_{f_i}$ where $m_{f_i} \propto v_\phi$
- $h^2\Omega \propto N$
- $h^2\Omega \propto g_\star^{-1}$
- Some models: Pati-Salam, LR, Dark Sector, GUT, confinement, CFT

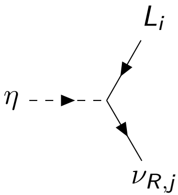
Neutrinogenesis



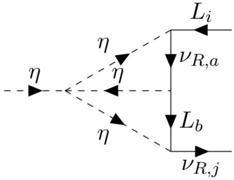
$\sim Y_R^{ij}$



$\sim \frac{1}{16\pi^2} Y_R^{ia} Y_R^{*ab} Y_R^{bj} \lambda_\phi^2 \langle\phi\rangle^4$



$\sim Y_\nu^{ij}$



$\sim \frac{1}{(16\pi^2)^2} Y_\nu^{ia} Y_\nu^{*ab} Y_\nu^{bj} \lambda_\eta^{\text{eff}}$

Parameters and Constraints

Parameter	Constrained by
N, N_F	GW, DM
g_D	DM, GW, DS
λ_H, v	SM
v_ϕ	GW, m$_\nu$, Direct searches
μ_H, μ_ϕ	V minimization
$\lambda_\phi, \lambda_{H\phi}$	GW, m$_\phi$
$Y_{R,L,\nu}$	m$_\nu$, Dirac leptogenesis, PMNS
M_{IM}	m$_\nu$, Dirac leptogenesis, DM

Future outlook

- Correlation between GW signals and DM dynamics
- GUT completions (multiple GW signals: cosmic strings, domain walls, phase transitions)
- Radiative neutrino models

Conclusion

- Minimal Dirac neutrino models
- Correlated GW signals
- Confined Dark Sector
- Baryon asymmetry via neutrinogenesis
- Probing neutrino models via GW

Thanks for your attention!