General $SU(N)$ Scotogenic (non-)Supersymmetric and CFT Models

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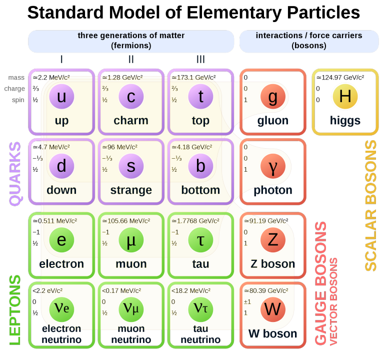
Overview

Introduction/Motivation

- (Naturally) small neutrino masses
- Connection with dark sector, self-interacting dark matter
- General $SU(N)$ gauge symmetry
- non-SUSY, SUSY, CFT
- Unification

Standard Model



Gauge symmetry group $\mathbb{G}_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$

$$\mathcal{L}^Y = \bar{u} Y_u Q H + \bar{Q} Y_d d H + \text{h.c.}$$

$$\langle h^0 \rangle = v \rightarrow \quad m_f = Y_f v$$

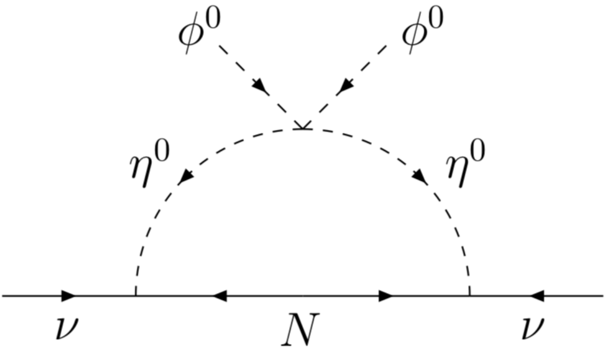
Requirements for neutrino mass

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

Categorizing neutrino mass models

1. Framework: non-SUSY, SUSY, CFT, *etc.*
2. Order: tree level or radiative?
3. Gauge sector extension: new gauge sectors? ($U(1), SU(2), SU(N)$)
4. New particles? (scalar, fermionic, vector)
5. Connection with other problems: DM, GUT, flavor anomalies, hierarchy problem, X-dim, *etc.*

Scotogenic radiative neutrino mass

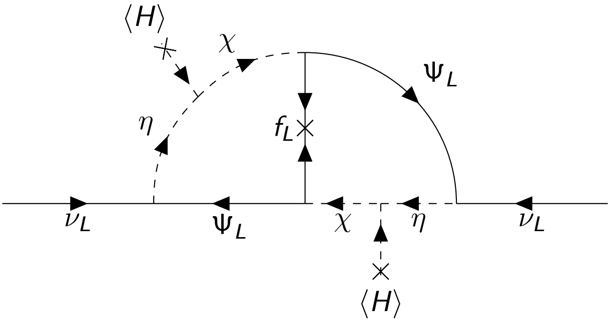


Add $\mathbb{Z}_2$ symmetry under which $\eta \sim (1, 2, 1/2)$ and N_R are odd

non-SUSY case

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(N)_D$	Flavor
Q_L	**3**	**2**	$\frac{1}{6}$	**1**	3
u_L^c	$\bar{\mathbf{3}}$	**1**	$-\frac{2}{3}$	**1**	3
d_L^c	$\bar{\mathbf{3}}$	**1**	$\frac{1}{3}$	**1**	3
L_L	**1**	**2**	$-\frac{1}{2}$	**1**	3
e_L^c	**1**	**1**	1	**1**	3
H	**1**	**2**	$\frac{1}{2}$	**1**	1
$\Psi_{L,R}$	**1**	**1**	0	$\square$	3
f_L	**1**	**1**	0	**Adj**	3
η	**1**	**2**	$-\frac{1}{2}$	$\square$	1
χ	**1**	**1**	0	$\square$	1

non-SUSY case



non-SUSY case

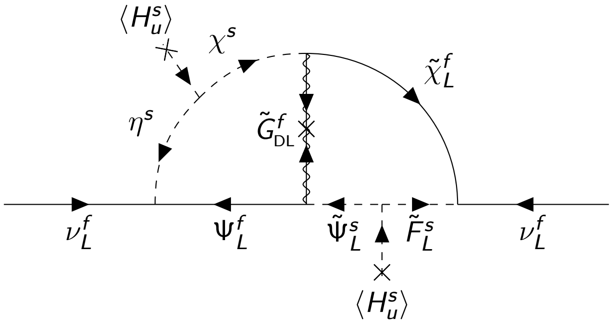
$$
\begin{aligned}
-\mathcal{L}^{Yuk}_{New} &= L^a_i Y_{L,ab} \Psi^b_{L,\alpha} \eta^{i\alpha\dagger} + \Psi^a_{L,\alpha} Y_{Lf,ab} f^{b,\alpha}_{L,\beta} \chi^{\dagger\beta} \\
&\quad + \bar{\Psi}^{a,\alpha}_R Y_{Rf,ab} f^{b,\beta}_{L,\alpha} \chi_\beta + \text{h.c.} \\
-\mathcal{L}^{M}_{New} &= f^{a,\beta}_{L,\alpha} m_{f,ab} f^{b,\alpha}_{L,\beta} + \left(\bar{\Psi}^{a,\alpha}_L m_{\Psi,ab} \Psi^b_{R,\alpha} + \text{h.c.} \right) \\
V_{3,4} &= \mu_3 \eta_{i,\alpha} H_j \chi^{\alpha *} \epsilon^{ij} + \text{h.c.}
\end{aligned}
$$

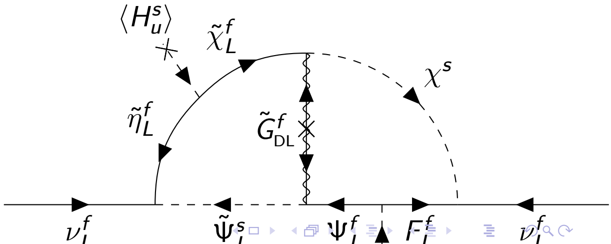
SUSY case

Neutrino Theory with SU(N)

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(N)_D$	B-L	P_M	Flavor
$\hat{Q}$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	$\mathbf{1}$	1/3	-	3
$\hat{\bar{u}}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	$\mathbf{1}$	-1/3	-	3
$\hat{\bar{d}}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	$\mathbf{1}$	-1/3	-	3
$\hat{L}$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	$\mathbf{1}$	-1	-	3
$\hat{\bar{e}}$	$\mathbf{1}$	$\mathbf{1}$	1	$\mathbf{1}$	1	-	3
$\hat{H}_u$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	$\mathbf{1}$	0	+	1
$\hat{H}_d$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	$\mathbf{1}$	0	+	1
$\hat{\Psi}$	$\mathbf{1}$	$\mathbf{1}$	0	$\square$	-1	-	3
$\hat{\chi}$	$\mathbf{1}$	$\mathbf{1}$	0	$\square$	0	+	1
$\hat{F}$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	$\bar{\square}$	1	-	3
$\hat{\eta}$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	$\bar{\square}$	2	+	1

SUSY case


$\langle H_u^s \rangle$
χ^s
$\tilde{\chi}_L^f$
η^s
$\tilde{G}_{\rm DL}^f$
ν_L^f
Ψ_L^f
$\tilde{\Psi}_L^s$
$\tilde{F}_L^s$
ν_L^f
$\langle H_u^s \rangle$


$\langle H_u^s \rangle$
$\tilde{\chi}_L^f$
χ^s
$\tilde{\eta}_L^f$
$\tilde{G}_{\rm DL}^f$

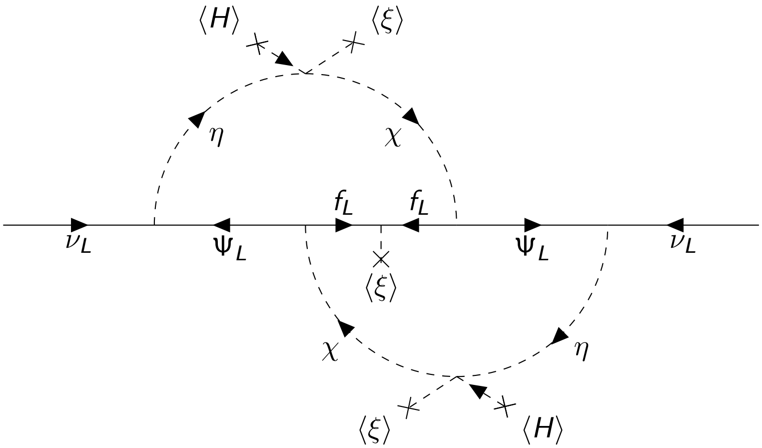
SUSY case

$$W = \hat{\bar{u}} \boldsymbol{y_u} \hat{Q} \hat{H}_u - \hat{\bar{d}} \boldsymbol{y_d} \hat{Q} \hat{H}_d - \hat{\bar{e}} \boldsymbol{y_e} \hat{L} \hat{H}_d + \mu \hat{H}_u \hat{H}_d$$
$$+ \hat{L} \boldsymbol{y_{L\eta\Psi}} \hat{\Psi} \hat{\eta} + \hat{L} \boldsymbol{y_{LF\chi}} \hat{F} \hat{\chi} + \underbrace{\hat{H}_d \boldsymbol{y_{H_d \eta\chi}} \hat{\chi} \hat{\eta}}_{\Delta L = -2} + \hat{H}_d \boldsymbol{y_{H_d F\Psi}} \hat{F} \hat{\Psi}$$

CFT case

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(N)_D$	Flavor
Q_L	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	$\mathbf{1}$	3
u_L^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	$\mathbf{1}$	3
d_L^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	$\mathbf{1}$	3
L_L	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	$\mathbf{1}$	3
e_L^c	$\mathbf{1}$	$\mathbf{1}$	1	$\mathbf{1}$	3
H	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	$\mathbf{1}$	1
$\Psi_{L,R}$	$\mathbf{1}$	$\mathbf{1}$	0	$\square$	3
f_L	$\mathbf{1}$	$\mathbf{1}$	0	**Adj**	3
η	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	$\square$	1
χ	$\mathbf{1}$	$\mathbf{1}$	0	$\square$	1
ξ	$\mathbf{1}$	$\mathbf{1}$	0	**Adj**	1

CFT case



CFT case

$$
\begin{aligned}
-\mathcal{L}^{Yuk}_{New} &= L^a_i Y_{L,ab} \Psi^b_{L,\alpha} \eta^{i\alpha\dagger} + \Psi^a_{L,\alpha} Y_{Lf,ab} f^{b,\alpha}_{L,\beta} \chi^{\dagger\beta} \\
&+ \bar{\Psi}^{a,\alpha}_R Y_{Rf,ab} f^{b,\beta}_{L,\alpha} \chi_\beta \\
&+ f^{a,\beta}_{L,\alpha} Y_{f,ab} \xi^\gamma_\beta f^{b,\alpha}_{L,\gamma} + \bar{\Psi}^{a,\alpha}_L Y_{\Psi,ab} \xi^\beta_\alpha \Psi^b_{R,\beta} + \text{h.c.} \\
V &= \lambda \eta_{i,\alpha} H_j \xi^\alpha_\beta \chi^{\dagger\beta} \epsilon^{ij} + \lambda_{4\xi} \xi^4 + \lambda_{\eta\xi 2} \eta^{\dagger i} \xi^j_i \xi^k_j \eta_k \\
&+ \lambda_{\chi\xi 2} \chi^{\dagger i} \xi^j_i \xi^k_j \chi_k + \text{h.c.} + \text{canonical terms.}
\end{aligned}
$$

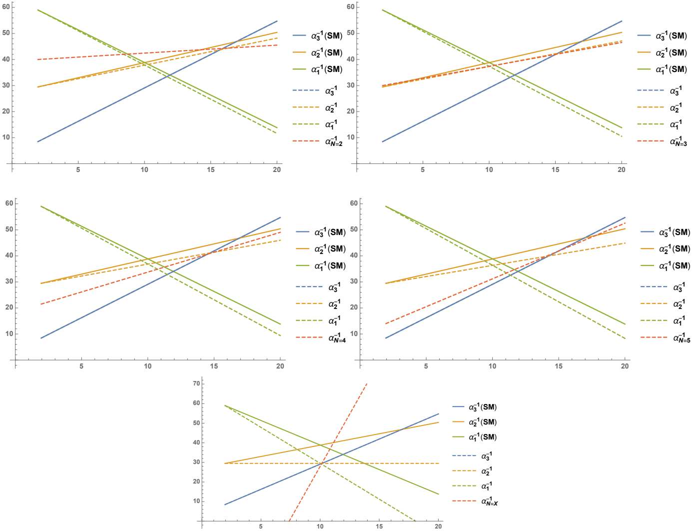
To breaking or not to break

- Non to break: strongly interacting dark sector
- To break: $SU(N) \to \mathbb{G}$ where $\mathbb{G}$ is a subgroup of $SU(N)$ and fields in the loop must transform as non-singlets under $\mathbb{G}$
- $N = 2$: $\mathbb{G} = U(1), \mathbb{Z}_2$; $N = 3$: $\mathbb{G} = SU(2) \times U(1), U(1), \mathbb{Z}_2$, *etc.*

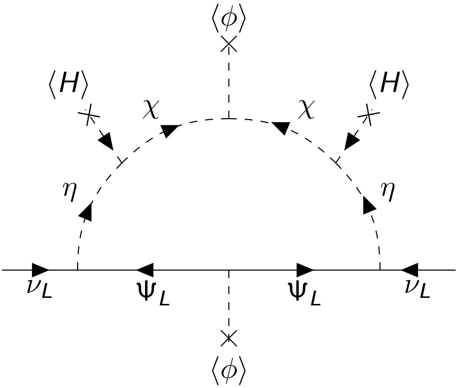
Connection to GW signals

- $SU(N) \rightarrow G$ phase transition can be strong first order phase transition ($\frac{v}{m} > 1$) that can give GW
- $N^2 - 1$ gauge gosons couple to scalar(s) that break(s) $SU(N)$ to G
- GW signal is enhanced with large g, number of strongly couple fermions, rank of the group
- GW constrain scalar sector parameters which influence neutrino sector

Unification



$SU(2)$ case



Summary

- Scotogenic neutrino mass via $SU(N)$
- Framework: non-SUSY, SUSY, CFT
- $SU(N)$ can be broken or unbroken
- Natural (self-interacting) DM
- Constraints via GW

Thank you!

Lagrangian for SUSY case

Then new Lagrangian terms generated are given by

$$\mathcal{L}^{Yuk}_{New} = -\frac{1}{2} Y_{\mathrm{L}\eta\Psi} \eta^s L \Psi^f_L - \frac{1}{2} Y_{\mathrm{LF}\chi} \tilde{F}^s_L L \tilde{\chi}^f_L + \mathrm{h.c.}$$

$$\mathcal{L}^{Yuk,Gauge}_{New} = -\sqrt{2} g_D \left(\tilde{\Psi}^{s*}_L T^a \Psi^f_L \right) \tilde{G}^{fa}_{\mathrm{DL}} - \sqrt{2} g_D \left(\chi^{s*} T^a \tilde{\chi}^f_L \right) \tilde{G}^{fa}_{\mathrm{DL}} + \mathrm{h}$$

$$V = W^*_i W^i + \frac{g_a^2}{2} \left(\phi^* T^a \phi \right) \left(\phi^* T_a \phi \right)$$

$$V \ni W^*_i W^i \Big|_{H_d} = |\mu|^2 |H^s_u|^2 + |Y_{\mathrm{H}_d\eta\chi}|^2 |\eta^s|^2 |\chi^s|^2 + |Y_{\mathrm{H}_d F\Psi}|^2 \left| \tilde{F}^s_L \right|^2$$

$$+ \mu^* H^{s\dagger}_u Y_{\mathrm{H}_d\eta\chi} \eta^s \chi^s + \mu^* H^{s\dagger}_u Y_{\mathrm{H}_d F\Psi} \tilde{F}^s_L \tilde{\Psi}^s_L + Y^*_{\mathrm{H}_d\eta\chi} Y_{\mathrm{H}_d F\Psi} \eta^{s\dagger} \chi^{s*} \tilde{F}^s_L \tilde{\Psi}$$

Scotogenic model in $SU(6)$ GUT*

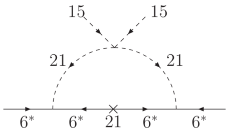
Simple case: Extend $SU(5)$ to $SU(6)$ to incude BSM particles needed

$\underline{5}^*_F \times \underline{10}_F \times \underline{5}^*_S$, $\underline{10}_F \times \underline{10}_F \times \underline{5}_S$ $SU(5)$ Yukawa terms are extended to

$\underline{6}^*_F \times \underline{15}_F \times \underline{6}^*_S$, $\underline{15}_F \times \underline{15}_F \times \underline{15}_S$ $SU(6)$ Yukawas

Anomaly free combinations: $\underline{5}^*_F + \underline{10}_F$ for $SU(5)$, $\underline{6}^*_F + \underline{6}^*_F + \underline{15}_F$ for $SU(6)$. New $SU(6)$ $\underline{21}_S$ scalar is added to obtain 2'nd Higgs doublet ($\mathbb{Z}_2 \sim -$) with new interactions

$\underline{6}^*_F \times \underline{6}^*_F \times \underline{21}_S$, $\underline{15}^*_S \times \underline{15}^*_S \times \underline{21}_S \times \underline{21}_S$



*10.1088/1742-6596/539/1/012001

Scotogenic model in $SU(7)$ GUT[†]

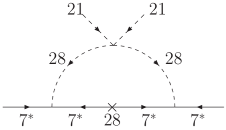
Less simple case: Extend $SU(5)$ to $SU(7)$ to incude BSM particles needed

$\underline{5}^*_F \times \underline{10}_F \times \underline{5}^*_S$, $\underline{10}_F \times \underline{10}_F \times \underline{5}_S$ $SU(5)$ Yukawa terms are extended to

$\underline{7}^*_F \times \underline{21}_F \times \underline{7}^*_S$, $\underline{21}_F \times \underline{21}_F \times \underline{35}_S$ $SU(7)$ Yukawas

Anomaly free combination for $SU(7)$: $\underline{7}^*_F + \underline{7}^*_F + \underline{7}^*_F + \underline{21}_F$.

New $\underline{28}_S$ scalar needed to accomodate $SU(2)_N$ doublet, with new interactions:$\underline{7}^*_F \times \underline{7}^*_F \times \underline{28}_S$, $\underline{21}^*_S \times \underline{21}^*_S \times \underline{28}_S \times \underline{28}_S$



[†]10.1088/1742-6596/539/1/012001

Possible effects/ Ways to test

- Collider (LHC,ILC, FCC), Constrains physics of particles involved
- Cosmological: Dark matter, Constraints from Galaxies and Galaxy clusters, Structure formation, Gravitational waves, CMB, Weak lensing constraints
- Grand unified theories
- Neutrino mixing
- Leptogenesis (CPV)
- Neutrinoless 2n−pole beta decay($0\nu 2n\beta$)