Colored Scotogenic

with Dirac neutrino masses

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Focus on
arXiv:1803.08528
In collaboration with
Mario Reig, Jose Valle (IFIC Valencia), Oscar Zapata (UdeA)

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2. (Dirac) Neutrino masses

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Exotic $B - L$

SM-like $B-L$ model

Field	$\mathrm{U}(1)_{B-L}$
L	-1
H	0
$(\nu_R)_i^\dagger$	ν_i

If $\nu_i \neq 0$

- No neutrino masses.
- No DM,

SM+ν_R with exotic $B-L$ charges is equivalent to SM

six massless neutrinos instead of three

(Dirac) Neutrino masses

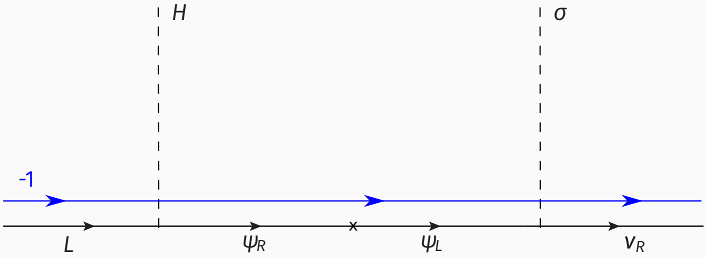
For Dirac neutrino masses: we require to introduce at least one SM-singlet heavy Dirac fermión (Weyl fermion notation)

$$\mathcal{L} = i\,(\psi_L)^\dagger\,\overline{\sigma}^\mu \partial_\mu \psi_L - m\,(\psi_R)^\dagger\,\psi_L + \text{h.c}\,. \tag{1}$$

The required **U(1)** symmetry is identified with $B - L$

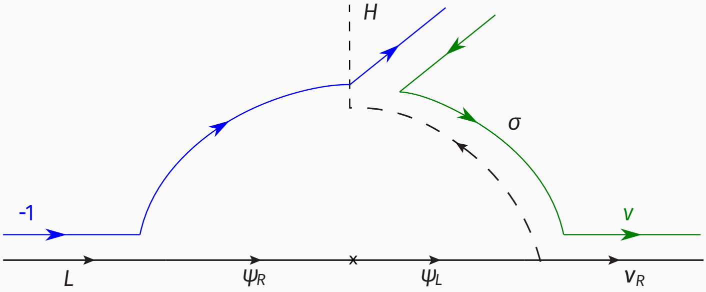
Field	$\mathrm{U}(1)_{B-L}$
L	-1
H	0
$(\nu_R)_i^\dagger$	ν_i
$(\psi_R)^\dagger$	r
ψ_L	$-r$

~~tree-level~~

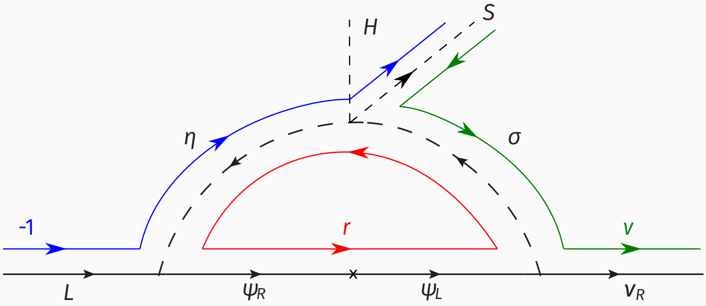


$$(\psi_L)^\dagger \nu_R \sigma \to \nu_R \nu_R \sigma$$

$\nu \neq -1$



Radiative Dirac seesaw

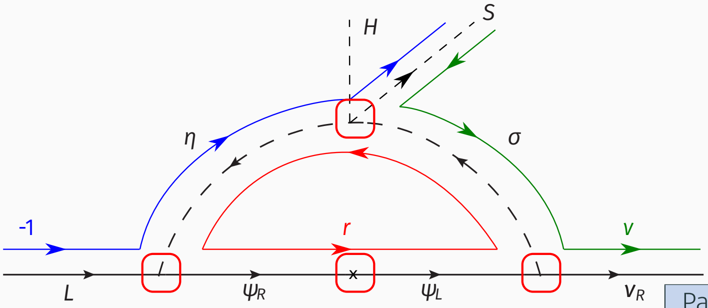


Soft breaking term induced:

$$\mathcal{L} \supset \kappa \sigma \eta^\dagger H \,,$$

where $\kappa = \lambda \langle S \rangle$.

Exotic $(\nu_R)^\dagger$ with $\nu \neq -1$, and vector-like Dirac fermion with $r \neq 1$



$$-1 + \eta = -r$$

$$-r = -r$$

$$-r = -\nu + \sigma$$

$$\sigma = \eta + S$$

$$N_C = 1\,.$$

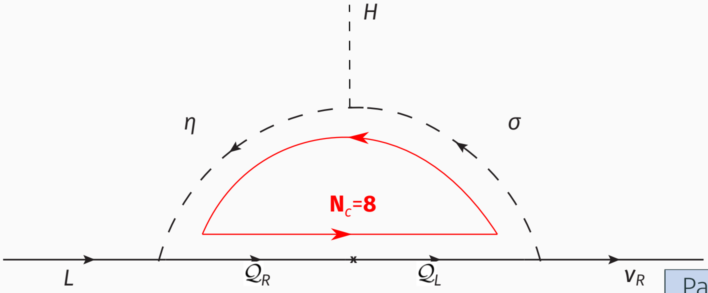
Soft breaking term induced:

$$\mathcal{L} \supset \kappa \sigma \eta^\dagger H\,,$$

where $\kappa = \lambda \langle S \rangle$.

Particles	$U(1)_{B-L}$	$(SU(3)_c, SU(2)_L)_Y$
L_i	-1	$(1,2)_{-1/2}$
H	0	$(1,2)_{1/2}$
$(\nu_{Ri})^\dagger$	ν	$(1,1)_0$
ψ_L	$-r$	$(N_c,1)_0$
$(\psi_R)^\dagger$	r	$(N_c,1)_0$
σ_a	$\nu - r$	$(N_c,1)_0$
η_a	$1-r$	$(N_c,2)_{1/2}$
S	$\nu - 1$	$(N_c,2)_{1/2}$

The model: *colored scotogenic*



$$-1+\eta = -\,r$$

$$-r = -\,r$$

$$-r = -\,\nu+\sigma$$

$$\sigma = \eta + s$$

$$N_c = 8\,.$$

Soft breaking term induced:

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L_i	-1	$(1,2)_{-1/2}$
H	0	$(1,2)_{1/2}$
$(\nu_{Ri})^\dagger$	ν	$(1,1)_0$
$\mathcal{Q}_L$	$-r$	$(\mathbf{N}_c,1)_0$
$(\mathcal{Q}_R)^\dagger$	r	$(\mathbf{N}_c,1)_0$
σ_a	$\nu-r$	$(\mathbf{N}_c,1)_0$
η_a	$1-r$	$(\mathbf{N}_c,2)_{1/2}$

- ν_i are free parameter and could be fixed if we impose $\mathrm{U}(1)_{B-L}$ to be local

$$r \neq 1\,, \qquad \sum_i \nu_i = 3\,, \qquad \sum_i \nu_i^3 = 3$$

	$(\nu_R)_1^\dagger$	$(\nu_R)_2^\dagger$	$(\nu_R)_3^\dagger$
$\mathrm{U}(1)_{B-L}$	$+4$	$+4$	-5
$\mathrm{U}(1)_{B-L}$	-6	$+\frac{10}{3}$	$+\frac{17}{3}$

Neutrino masses and mixings

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- To have at least a rank 2 neutrino mass matrix we need either:
    - At least two heavy Dirac fermions $\mathcal{Q}_a$, $a = 1, 2, \ldots$
    - At least two sets of scalars η_a, σ_a

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$$\mathcal{L} \supset \left[M_{\mathcal{Q}} \, (\mathcal{Q}_R)^\dagger \, \mathcal{Q}_L + h_i^a \, (\mathcal{Q}_R)^\dagger \, \widetilde{\eta}_a^\dagger L_i + y_i^a \overline{\nu_{Ri}} \, \sigma_a^* \mathcal{Q}_L + \mathrm{h.c} \right] + \kappa^{ab} \, \sigma_a \eta_b^\dagger H + \ldots$$

Neutrino masses and mixings

$$(\mathcal{M}_\nu)_{ij} = N_c \frac{M_{\mathcal{Q}}}{64\pi^2} \sum_{a=1}^{2} h_i^a y_j^a \frac{\sqrt{2}\kappa_{aa} v}{m^2_{S^a_{2R}} - m^2_{S^a_{1R}}} \left[F\left(\frac{m^2_{S^a_{2R}}}{M^2_{\mathcal{Q}}}\right) - F\left(\frac{m^2_{S^a_{1R}}}{M^2_{\mathcal{Q}}}\right)\right] + (R \to I) \tag{2}$$

where $F(m^2_{S_\beta}/M^2_Q) = m^2_{S_\beta} \log(m^2_{S_\beta}/M^2_Q)/(m^2_{S_\beta} - M^2_Q)$. The four CP-even mass eigenstates are denoted as $S^1_{1R}, S^1_{2R}, S^2_{1R}, S^2_{2R}$, with a similar notation for the CP-odd ones.

If $(\mu^{aa}_\eta)^2 \gg M^2_{\mathcal{Q}}$ one has

$$(\mathcal{M}_\nu)_{ij} = N_c \frac{M_{\mathcal{Q}}}{32\pi^2} \sqrt{2} v \sum_{a=1}^{2} \kappa^{aa} \frac{h_i^a y_j^a}{(\mu^{aa}_\eta)^2} \tag{3}$$

$$\sim 0.03\,\text{eV} \left(\frac{M_{\mathcal{Q}}}{9.5\,\text{TeV}}\right) \left(\frac{\kappa^{aa}}{1\,\text{GeV}}\right) \left(\frac{50\,\text{TeV}}{\mu^{aa}_\eta}\right)^2 \left(\frac{h_i^a y_j^a}{10^{-6}}\right).$$

Dark matter

$U(1)_{B\text{-}L} \rightarrow$

SM

$+\ \nu_R$

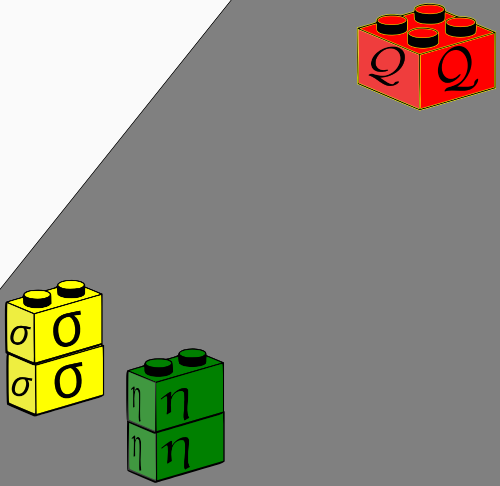
$$\mathbb{Z}_N$$

if $r \neq 0$ (even with $\mathbf{N_c=8}$)

SM

+

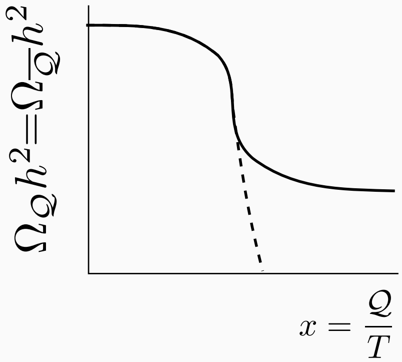
$(\nu_R)_i^\dagger$



(Switch to Dirac fermions)

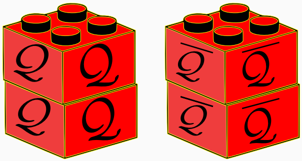
Because $\mathcal{Q}$ is a Dirac fermion, $\mathcal{Q}\mathcal{Q}$ is also stable

$$\mathcal{Q}\mathcal{Q} \not\to g\,, \qquad \overline{\mathcal{Q}\mathcal{Q}} \not\to g\,.$$



Step one

$\mathcal{Q}$-onlyum

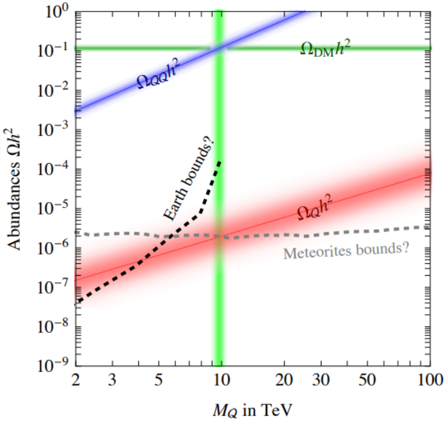


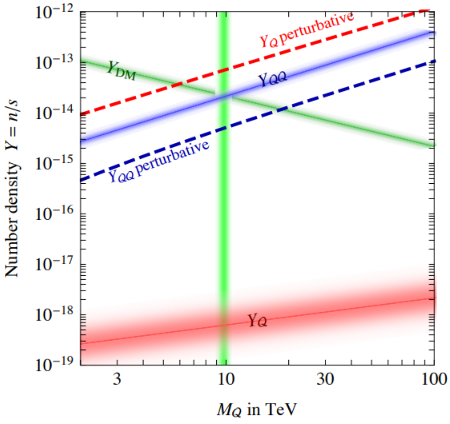
Step two

Relic abundance. From: `http://bit.ly/Mitridate_53d_53rd_Rencontres_de_Moriond`

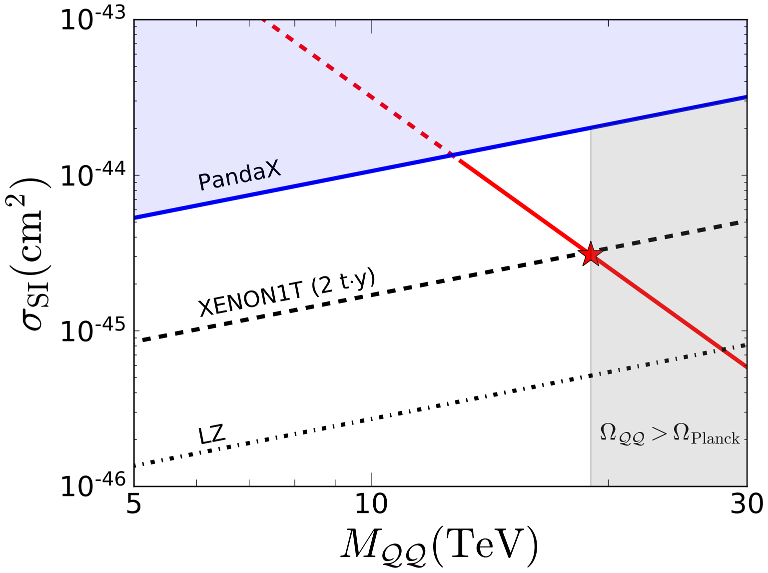
$$M_Q \simeq 9.5\,\mathrm{TeV}$$

$$\Omega_{\rm hyb} \sim 10^{-5}\Omega_{\rm DM}$$





Direct detection



One year later· · ·

The Daily W

Sunday, June 30, 2018

Dark matter discovered by X

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The New Y

Sunday June 24, 2029

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Long lived hadrons

$$p + p \longrightarrow \mathcal{Q} + \overline{\mathcal{Q}}$$

$$\Downarrow$$

$$\mathcal{Q} \to \mathcal{Q}g \qquad \mathcal{Q} \to \mathcal{Q}q\bar{q}$$

$\sqrt{s} = 65$ TeV needed to discover $M_{\mathcal{Q}} = 9.5$ TeV .

Conclusions

Standard Model with right-handed neutrinos of exotic $B-L$ charges

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Standard Model with right-handed neutrinos of exotic $B-L$ charges

Dirac neutrino masses and DM

- Spontaneously broken $U(1)_{B-L}$ generates a radiative Dirac Type-I seesaw.
- A remnant symmetry makes the lightest field circulating the loop stable and good dark matter candidate.
- If color is also circulating the loop, the colored dark matter scenario can be realized

DM is made of two color octets with mass around 9.5 TeV

- For standard cosmology:
  - A single point to be discovered in Direct Detection.
  - Crosscheck at future colliders possible.