Colored Scotogenic

with dirac neutrino masses

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Exotic $B - L$

SM-like $B - L$ model

Field	$U(1)_{B-L}$
L	-1
H	0
$(\nu_R)^\dagger_i$	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

Seesaw mechanism

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	U(1)$_{B-L}$
L	-1
H	0
$(\nu_R)_i^\dagger$	ν_i
$(\psi_R)^\dagger$	r
ψ_L	$-r$
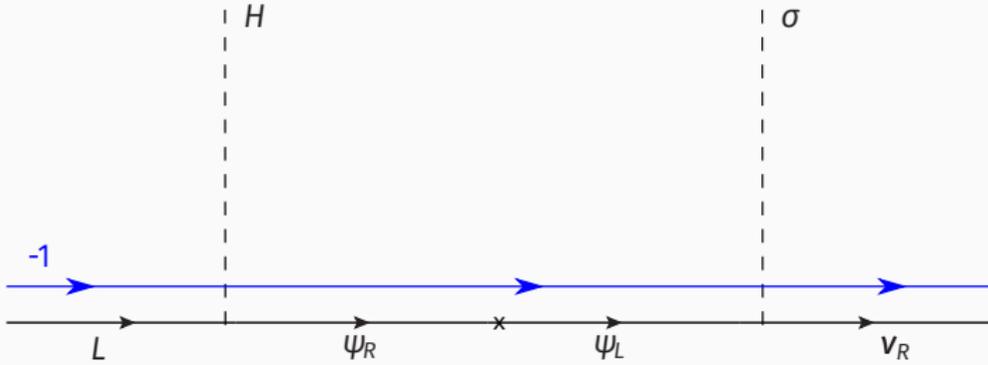
$$(\psi_L)^\dagger \, \nu_R \sigma \rightarrow \nu_R \nu_R \sigma$$
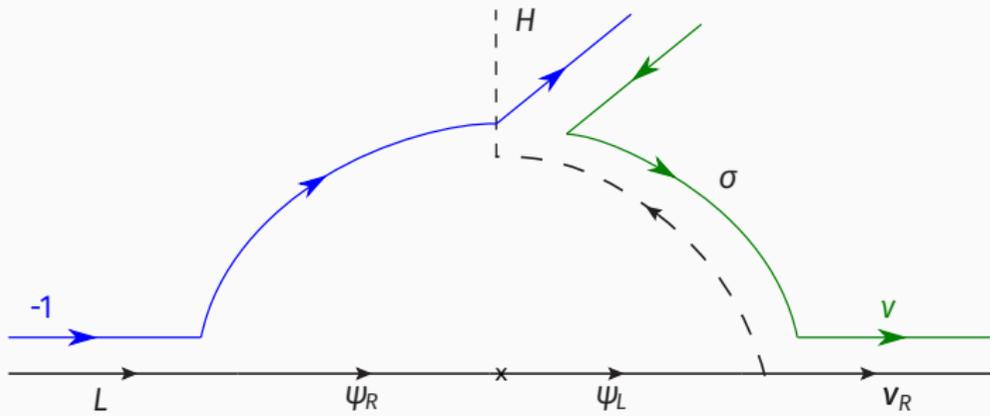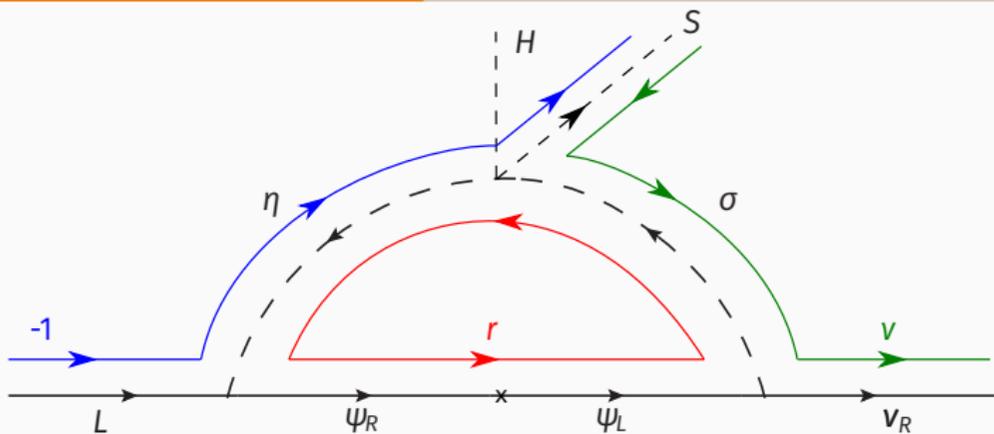
Soft breaking term induced:

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

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

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

$$-r = -r$$

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

$$\sigma = \eta + s$$

$$N_c = 1.$$

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	$\nu - 1$	$(N_c, 2)_{1/2}$

Soft breaking term induced:

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

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$$\sigma = \eta + s$$

$$N_c = 8.$$

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	$(1, 1)_0$
$\mathcal{Q}_L$	$-r$	$(N_c, 1)_0$
$(\mathcal{Q}_R)^\dagger$	r	$(N_c, 1)_0$
σ_a	$\nu - r$	$(N_c, 1)_0$
η_a	$1 - r$	$(N_c, 2)_{1/2}$
S	$\nu - 1$	$(N_c, 2)_{1/2}$

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

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

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

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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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-

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

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

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

If $(\mu_\eta^{aa})^2 \gg M_\mathcal{Q}^2$ one has

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

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

Dark matter

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

SM + ν_R

Z_N

if $r \neq 0$ (even with $N_c = 8$)
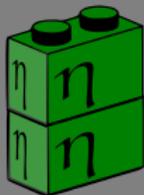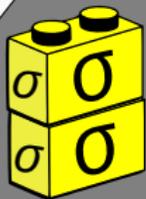
(Switch to Dirac fermions)

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

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

$$\Omega_{\mathcal{Q}} h^2 = \Omega_{\overline{\mathcal{Q}}} h^2$$

$$x = \frac{\mathcal{Q}}{T}$$
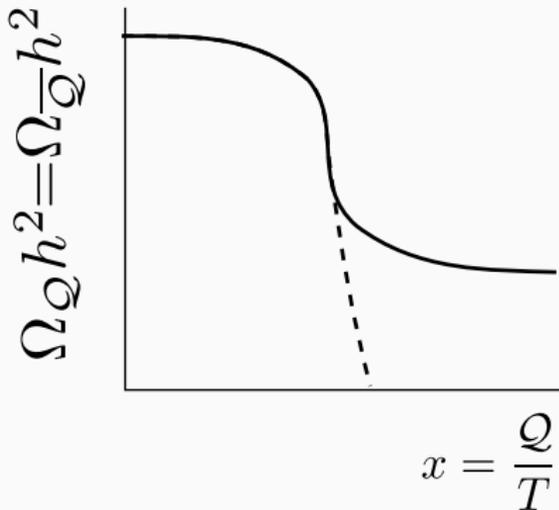
Step one

$\mathcal{Q}$-onlyum
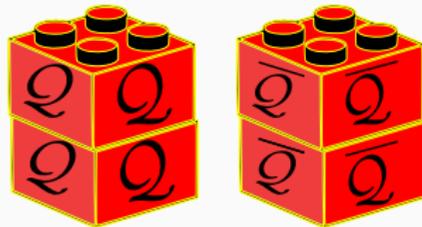
Step two

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

$\Omega_{\mathrm{hyb}} \sim 10^{-5}\Omega_{\mathrm{DM}}$
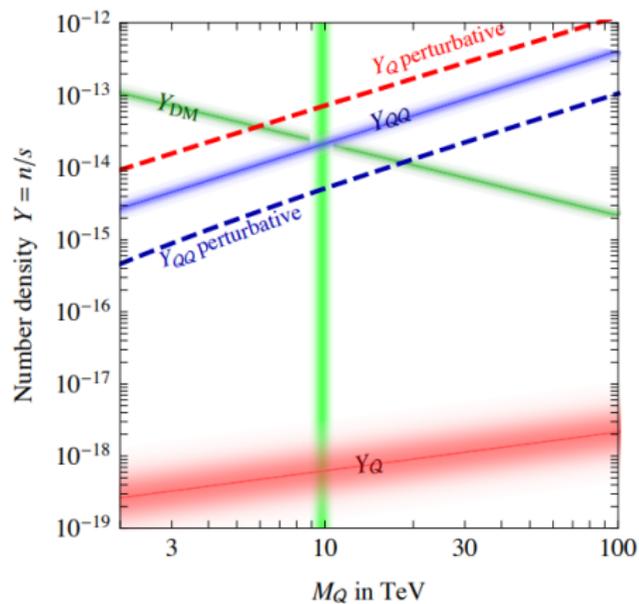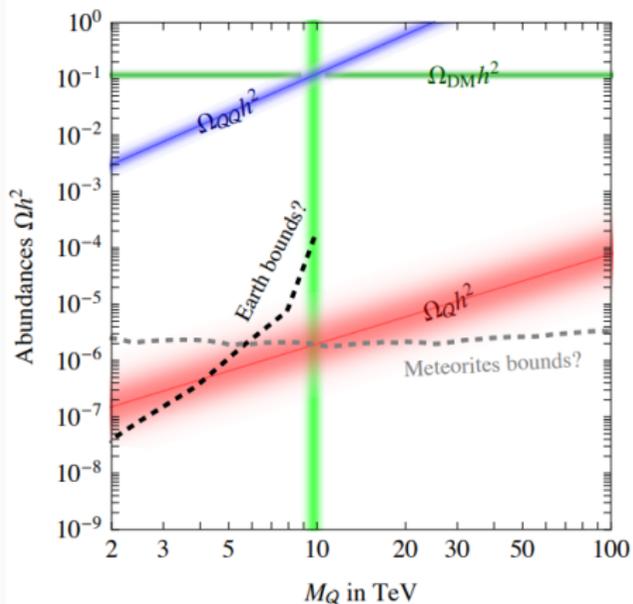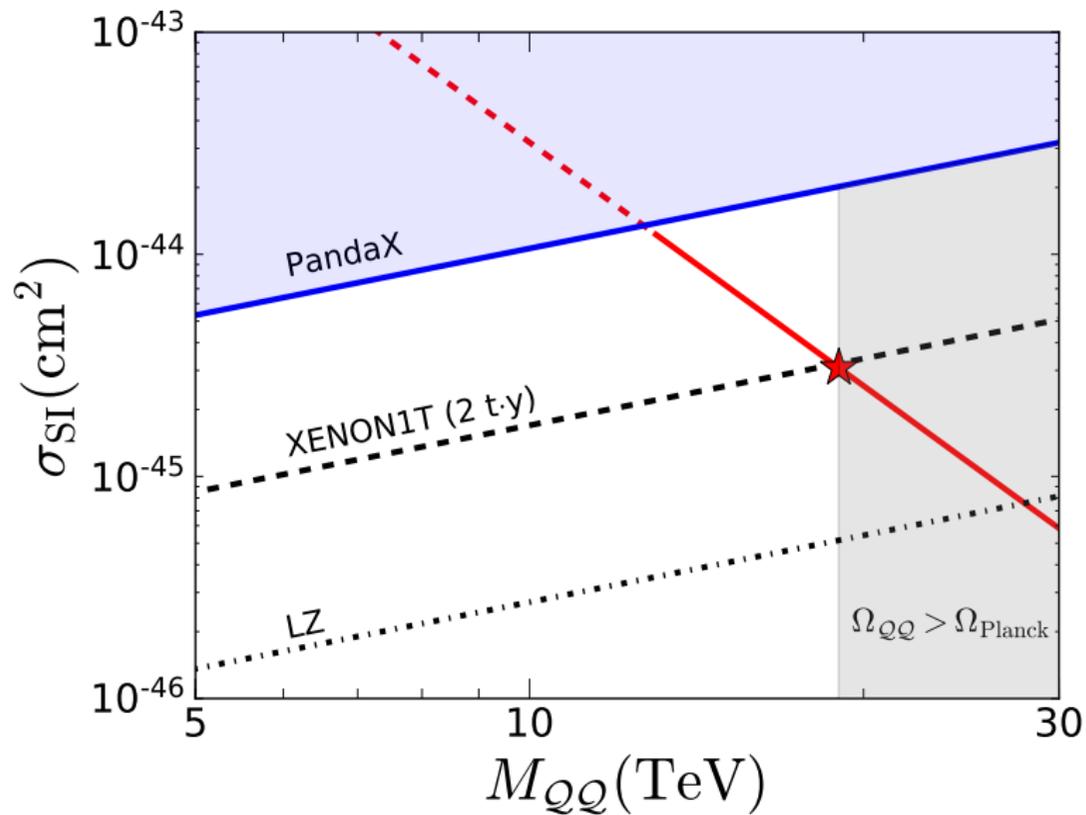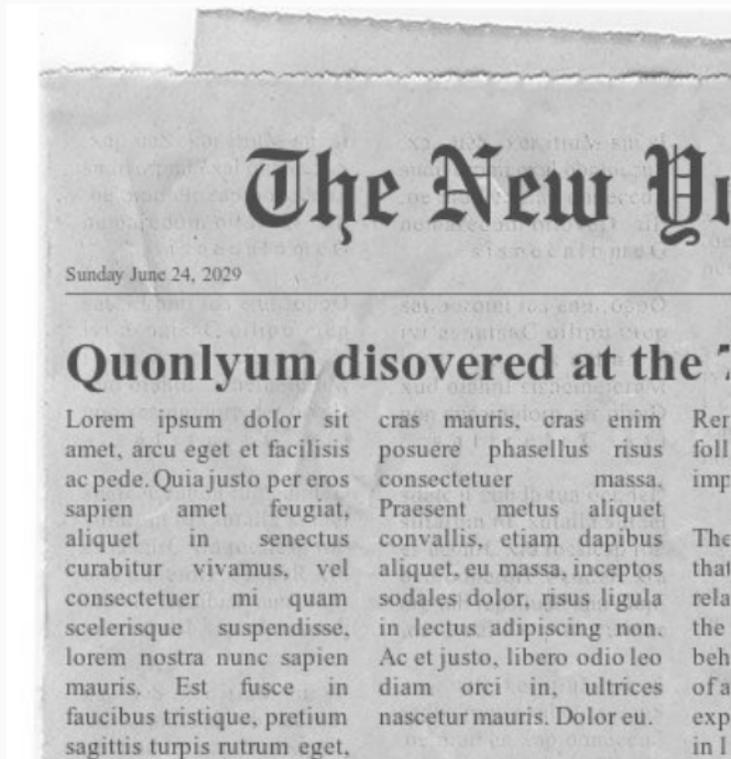
Long lived hadrons

$$p + p \longrightarrow \mathcal{Q} + \overline{\mathcal{Q}}$$
$$\Downarrow$$
$$\mathcal{Q} \to \mathcal{Q}g \qquad \mathcal{Q} \to \mathcal{Q}q\overline{q}$$

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

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

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 in Direct Detection.
    - Crosscheck at future colliders possible.