Bound-state dark matter and neutrino masses

Óscar Zapata

Universidad de Antioquia, Medellín, Colombia.

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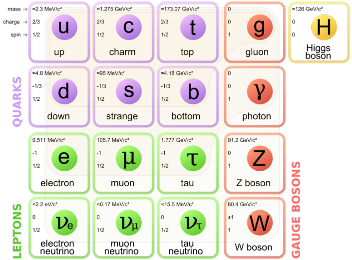
In coll. with: M. Reig, D. Restrepo, J. Valle

Outline

* Motivation
* Bound-state DM
* The neutrino connection
* Conclusions

Motivation

$$\mathcal{G}_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y .$$



The astonishing discovery of the Higgs boson at the LHC has closed a stage of the SM.

Evidence for physics beyond SM

- Dark matter.
- Neutrino masses.
- Matter-antimatter asymmetry.
- Inflation, Strong CP problem, Higgs hierarchy, vacuum unstability, CC, QG, ...

Normally, these problems are treated as separate problems, with many models trying to explain one or the other.
It may be, though, that they are related to each other and that, in addition, both originate from new physics at the TeV scale.

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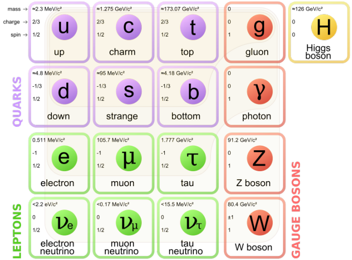

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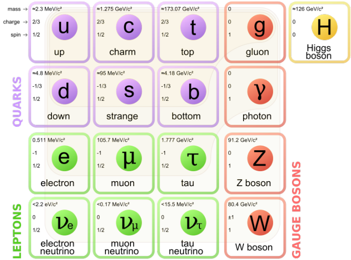

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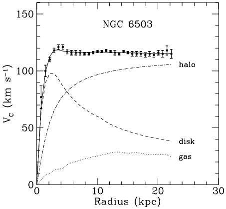
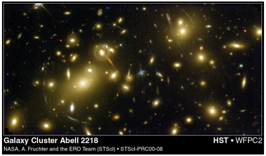
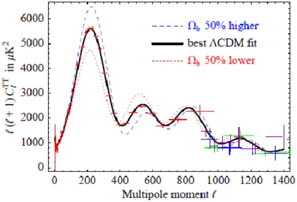
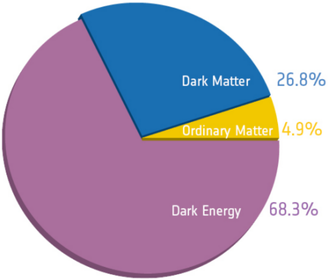






- Galactic rotation curves
- Big bang nucleosynthesis
- Cluster and supernova data
- Bullet cluster
- Weak lensing
- CMB anisotropies



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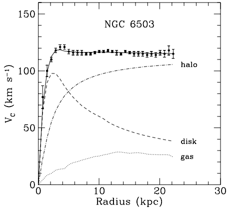

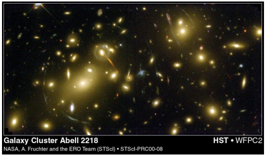

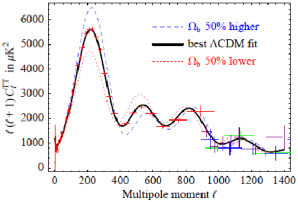

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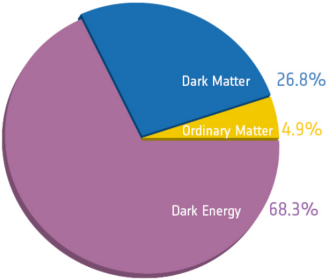

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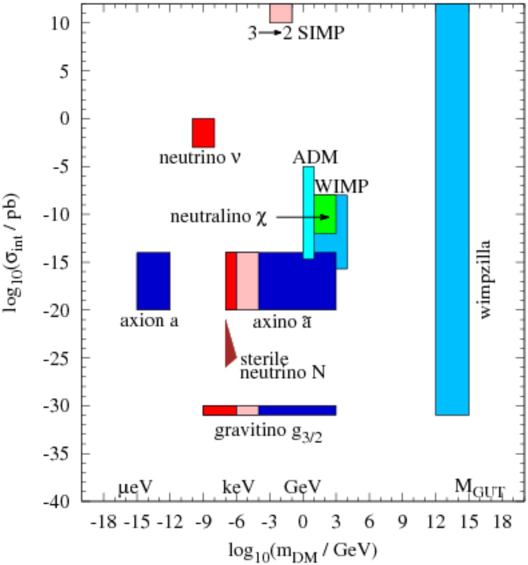
DM candidates



Colored DM

Proposed by De Luca, Mitridate, Redi, Smirnov, Strumia (PRD2018).

- A new Dirac fermion octect (*quorn*) $\mathcal{Q} \sim (8,1)_0$.

$$\mathcal{L} = \bar{\mathcal{Q}}(i\not{D} - M_{\mathcal{Q}})\mathcal{Q}.$$

- $\mathcal{Q}$ is automatically stable.
- After confinement $\mathcal{Q}$ forms bound states.
  - The $\mathcal{Q}\bar{\mathcal{Q}}$ bound states are unstable: $\mathcal{Q}$ and $\bar{\mathcal{Q}}$ annihilate into gluons and quarks.
  - No such annihilation arises in $\mathcal{Q}\mathcal{Q}$ bound states due to an unbroken U(1) dark baryon number that enforces that $\mathcal{Q}\mathcal{Q}$ is stable.

DM candidate: quorn-onlyum $\mathcal{Q}\mathcal{Q}$

The lightest hadron made of two $\mathcal{Q}$ fermions.
It is neutral, color-less and with spin-0.

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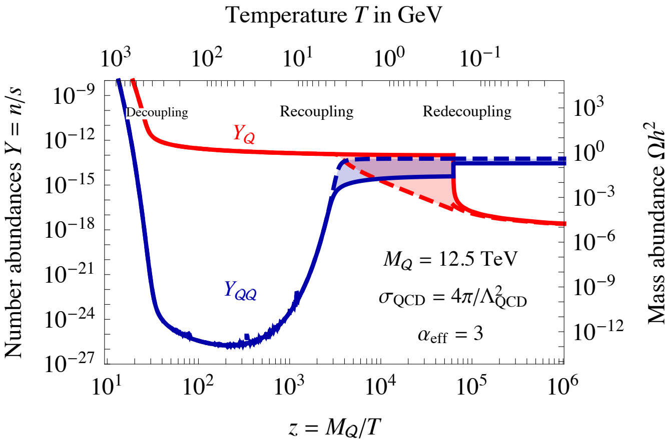
Colored DM

- Perturbative interactions between $\mathcal{Q}$ and $\bar{\mathcal{Q}}$ lead to $\Omega_{\mathcal{Q}} h^2 = 0{,}1\,\frac{M_{\mathcal{Q}}}{7\,\text{TeV}}$.
- After QCD PT colored particles bind in *quorn-onlyum* hadron $\mathcal{Q}\mathcal{Q}$.
- Subsequent annihilations lead to $\Omega_{\mathcal{Q}\mathcal{Q}} h^2 \sim 0{,}1\,\frac{M_{\mathcal{Q}}}{10\,\text{TeV}}$.



Hybrid hadrons: $\mathcal{Q}g$, $\mathcal{Q}q\bar{q}'$. $\Omega_{\text{hybrid}} \sim 10^{-4}\Omega_{\text{DM}} \rightarrow$ viable scenario.

DM signals

Indirect detection

- Dominated by the recombination process $\mathcal{Q}\mathcal{Q} + \bar{\mathcal{Q}}\bar{\mathcal{Q}} \to \mathcal{Q}\bar{\mathcal{Q}} + \mathcal{Q}\bar{\mathcal{Q}} \to SM$.
- Future CTA bound is above $< \sigma v >$ value for $M_{\mathcal{Q}\mathcal{Q}} = 25$ TeV.

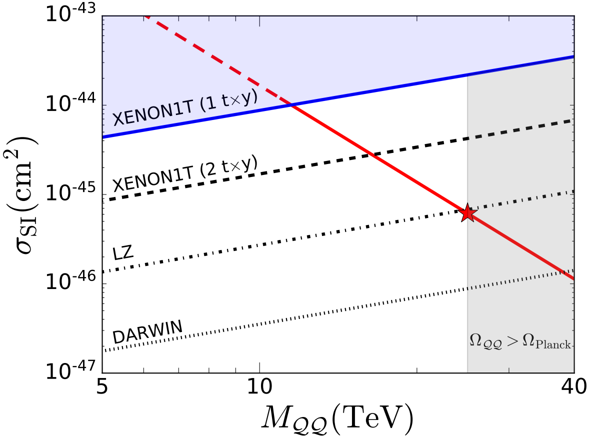
Collider searches

- $\mathcal{Q}$ is pair produced at colliders via QCD interactions.
- After hadronization they form hybrids: $\mathcal{Q}g$ and $\mathcal{Q}q\bar{q}'$ are long-lived on collider time-scales, giving rise to tracks.
- LHC at $\sqrt{s} = 13$ TeV set the bound $M_{\mathcal{Q}} \gtrsim 2$ TeV.
- A pp collider with $\sqrt{s} = 100$ TeV would be sensitive up to $M_{\mathcal{Q}} \lesssim 15$ TeV.

DM direct detection

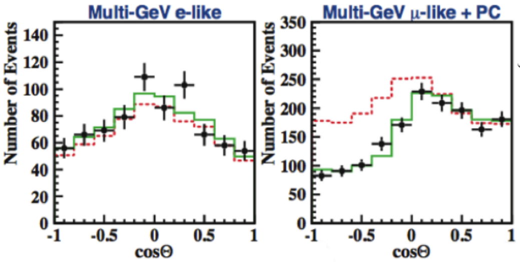
$\mathcal{QQ}$ interacts with gluons through chromo-electric and chromo-magnetic dipole moments.

$$\sigma_{\rm SI} \approx 5{,}2 \times 10^{-46}\ {\rm cm}^2 \left(\frac{25\ {\rm TeV}}{M_{\mathcal{QQ}}}\right)^6 \frac{\Omega_{\mathcal{QQ}}}{\Omega_{\rm Planck}}\,,$$

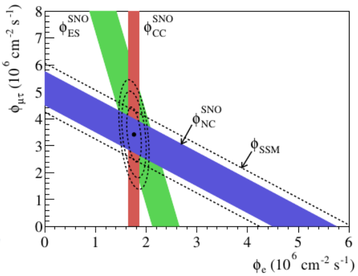


M.R., J.V., D.R., O.Z. (2018).

SuperKamiokande(1998)



SNO (2003)



From solar, atmospheric, accelerator and reactor neutrino experiments:

- At least two massive neutrinos: $\Delta m^2_{12} = 8 \times 10^{-5}\text{eV}^2$, $\Delta m^2_{23} \sim 10^{-3}\text{eV}^2$.
- Three non-zero mixing angles: $\theta_{12} \sim 35°$, $\theta_{23} \sim 49°$, $\theta_{13} \sim 9°$.

Neutrino masses in the SM

Dirac mass term: $m_D(\bar{\nu}_R \nu_L + h.c.)$
Majorana mass term: $m_L(\bar{\nu}^c_L \nu_L + h.c.)$

$\Rightarrow$ neutrino oscillations lead to physics beyond SM.

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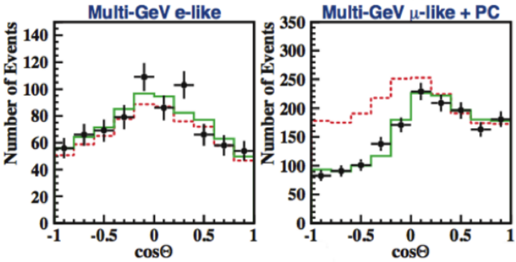

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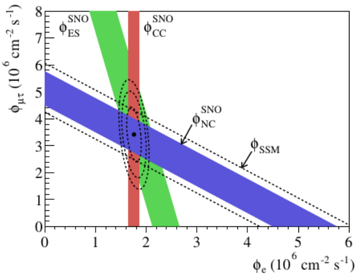

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Neutrino masses and mixing

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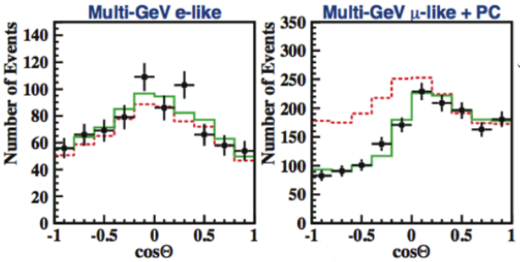

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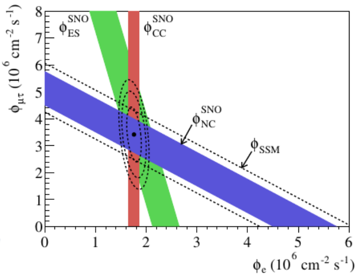

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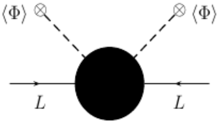
Neutrino mass models

Majorana neutrino masses can be generated in the SM after EWSB from the unique $d = 5$ Weinberg operator

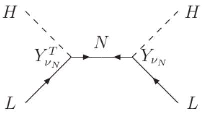
$$\mathcal{O}_5 \sim \frac{Y_\nu^2}{\Lambda} L^T \widetilde{H}^* \widetilde{H}^\dagger L \quad \Rightarrow \quad m_\nu \sim \frac{Y_\nu^2 \langle H \rangle^2}{\Lambda}$$

$$L = (\nu_L, \ell_L), \qquad H = (0, H^0)$$

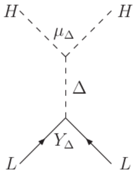


At tree level there are only 3 realizations of $\mathcal{O}_5$

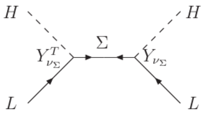
Ma(98); Bonnet, et. al.(12)



Type-I



Type-II



Type-III

The scale of new physics is too high

For $Y_\nu \sim 1 \Rightarrow \Lambda \sim 10^{14}$ GeV
Models with a new physics at the LHC scale need to have additional suppression for m_ν (loops, $d \geq 7$, small LNV).

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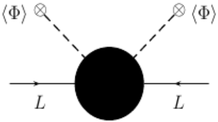

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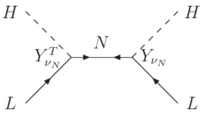

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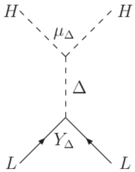

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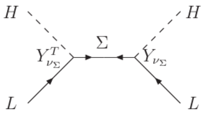

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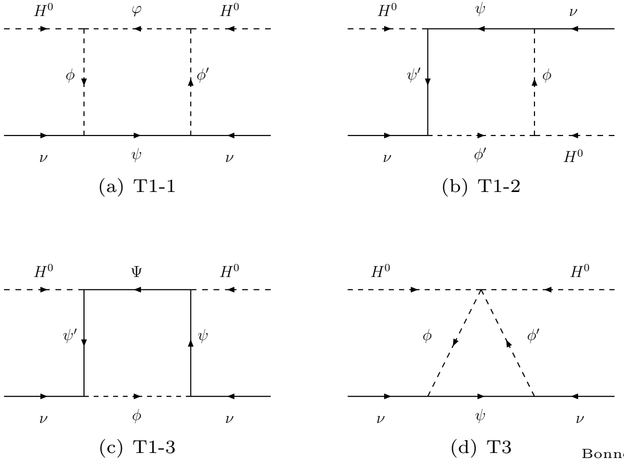
At one-loop level there are only 4 topologies of Weinberg operator $\mathcal{O}_5$.



Bonnet(2012)

The neutrino connection: Dirac case

We argue that neutrino mass and cosmological dark matter may have a common origin, with the underlying DM physics acting as messenger of neutrino mass generation.

- $\mathcal{Q}\mathcal{Q}$ stabilized by the same conserved $B-L$ symmetry associated to the Dirac nature of neutrinos.
- The Z_2 forbids $\overline{\nu_{Ri}}\widetilde{H}^\dagger L_j$.

Particles	$\mathrm{U}(1)_{B-L}$	$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_Y$	Z_2
$Q_i = \begin{pmatrix} u_L & d_L \end{pmatrix}_i^{\mathrm{T}}$	$+1/3$	$(\mathbf{3},\mathbf{2})_{1/6}$	$+$
$\overline{u_{Ri}}$	$-1/3$	$(\overline{\mathbf{3}},\mathbf{1})_{-2/3}$	$+$
$\overline{d_{Ri}}$	$-1/3$	$(\overline{\mathbf{3}},\mathbf{1})_{1/3}$	$+$
$L_i = \begin{pmatrix} \nu_L & e_L \end{pmatrix}_i^{\mathrm{T}}$	-1	$(\mathbf{1},\mathbf{2})_{-1/2}$	$+$
$\overline{e_{Ri}}$	$+1$	$(\mathbf{1},\mathbf{1})_{1}$	$+$
$\overline{\nu_{Ri}}$	$+1$	$(\mathbf{1},\mathbf{1})_{0}$	$-$
$\mathcal{Q}_L$	$-r$	$(\mathbf{8},\mathbf{1})_{0}$	$+$
$\overline{\mathcal{Q}_R}$	r	$(\mathbf{8},\mathbf{1})_{0}$	$+$
H	0	$(\mathbf{1},\mathbf{2})_{1/2}$	$+$
σ_a	$1-r$	$(\mathbf{8},\mathbf{1})_{0}$	$-$
η_a	$1-r$	$(\mathbf{8},\mathbf{2})_{1/2}$	$+$

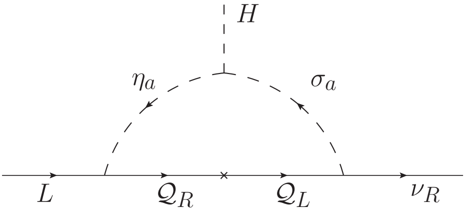
Neutrino masses

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

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

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

$$\sim 0{,}03 \, \mathrm{eV} \left(\frac{M_{\mathcal{Q}}}{9{,}5 \, \mathrm{TeV}} \right) \left(\frac{\kappa^{aa}}{1 \, \mathrm{GeV}} \right) \left(\frac{50 \, \mathrm{TeV}}{\mu_\eta^{aa}} \right)^2 \left(\frac{h_i^a y_j^a}{10^{-6}} \right).$$

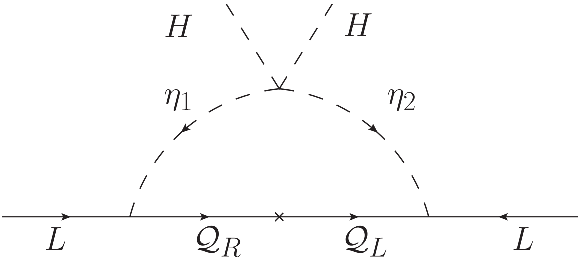


The neutrino connection: Majorana case

- $B-L$ symmetry is violated and neutrinos are Majorana fermions.
- DM is stabilized by $\mathrm{U}(1)_D$, under which SM particles are assumed to be neutral.

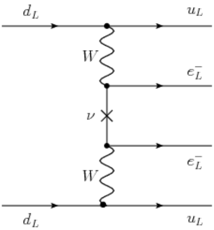
Particles	$\mathrm{U}(1)_D$	$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_Y$
$Q_i = \begin{pmatrix} u_L & d_L \end{pmatrix}_i^{\mathrm{T}}$	0	$(\mathbf{3}, \mathbf{2})_{1/6}$
$\overline{u_{Ri}}$	0	$(\overline{\mathbf{3}}, \mathbf{1})_{-2/3}$
$\overline{d_{Ri}}$	0	$(\overline{\mathbf{3}}, \mathbf{1})_{1/3}$
$L_i = \begin{pmatrix} \nu_L & e_L \end{pmatrix}_i^{\mathrm{T}}$	0	$(\mathbf{1}, \mathbf{2})_{-1/2}$
$\overline{e_{Ri}}$	0	$(\mathbf{1}, \mathbf{1})_1$
$\mathcal{Q}_L$	-1	$(\mathbf{8}, \mathbf{1})_0$
$\overline{\mathcal{Q}_R}$	1	$(\mathbf{8}, \mathbf{1})_0$
H	0	$(\mathbf{1}, \mathbf{2})_{1/2}$
η_a	$(-1)^a$	$(\mathbf{8}, \mathbf{2})_{1/2}$

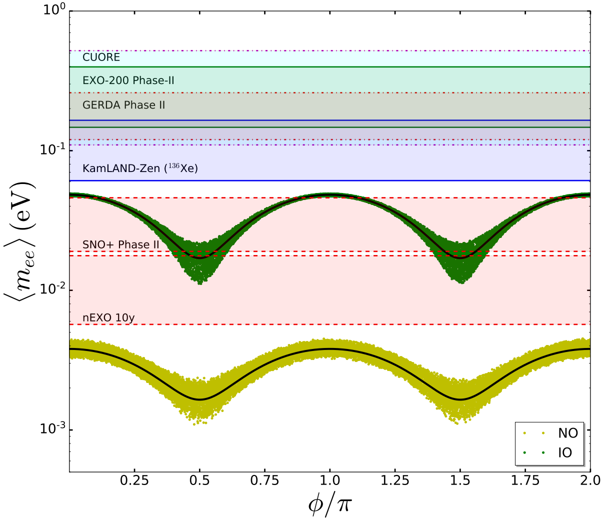
$$-\mathcal{L} \supset h_i \overline{\mathcal{Q}_R} \widetilde{\eta}_1^\dagger L_i + y_i \overline{\mathcal{Q}_L^c} \widetilde{\eta}_2^\dagger L_i + M_{\mathcal{Q}} \, \overline{\mathcal{Q}_R} \mathcal{Q}_L + \mathrm{Tr}\left[\lambda_{\eta_1 \eta_2 H} \left(H^\dagger \eta_1\right) \left(H^\dagger \eta_2\right)\right] + \text{h.c.}$$



For $\mu_{\eta_1}^2 \gg M_{\mathcal{Q}}^2$, $\mu_{\eta_1}^2 = \mu_{\eta_2}^2 \gg \lambda_{\eta_1 \eta_2 H} v^2$ and $\lambda_{3\eta H}, \lambda_{4\eta H} \ll 1$:

$$\left(\mathcal{M}_\nu\right)_{ij} \sim 0{,}04\,\text{eV} \left(\frac{M_{\mathcal{Q}}}{12{,}5\,\text{TeV}}\right) \left(\frac{\lambda_{\eta_1 \eta_2 H} v^2}{0{,}1\,\text{GeV}^2}\right) \left(\frac{15\,\text{TeV}}{\mu_{\eta_1}}\right)^2 \left(\frac{h_i y_j}{10^{-6}}\right).$$


d_L
u_L
W
e_L^-
ν
e_L^-
W
d_L
u_L

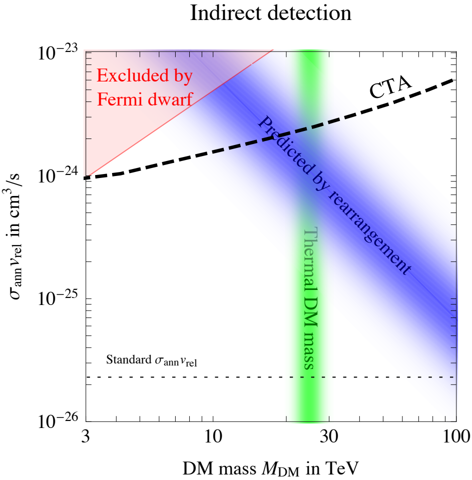

10^0
10^{-1}
10^{-2}
10^{-3}
CUORE
EXO-200 Phase-II
GERDA Phase II
KamLAND-Zen (^{136}Xe)
SNO+ Phase II
nEXO 10y
NO
IO
$\langle m_{ee} \rangle$ (eV)
0.25
0.5
0.75
1.0
1.25
1.5
1.75
2.0
ϕ/π

Summary

- We have proposed a simple and viable theory in which dark matter emerges as a stable neutral hadronic thermal relics, whose stability results from an exact $\mathrm{U}(1)_{B-L}$ ($\mathrm{U}(1)_D$) symmetry.
- Neutrinos pick up radiatively induced Dirac (Majorana) masses from the exchange of colored dark matter constituents, giving a common origin for both dark matter and neutrino mass.
- Can be tested at direct DM experiments (and with a lower bound for neutrinoless double beta decay).

DM indirect detection

Dominated by the recombination process $QQ + \bar{Q}\bar{Q} \to Q\bar{Q} + Q\bar{Q} \to SM$.



$$\left|\sum_a h_\mu^a h_e^{a*}\left(\frac{50\,\mathrm{TeV}}{M_{\eta_a^+}}\right)^2\right| \lesssim 1{,}5.$$