UNIVERSIDAD DE ANTIOQUIA
1803

Secluded-Scotogenic (SS) models

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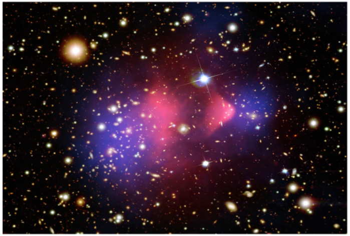
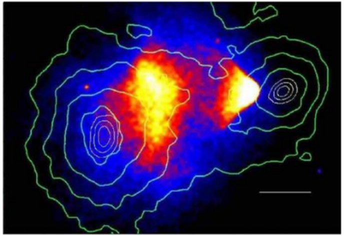
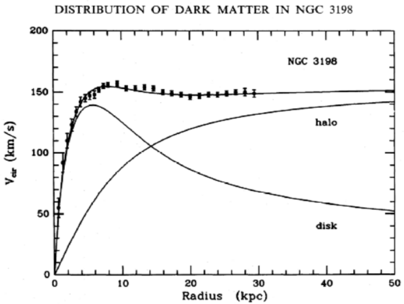
Evidences for Dark Matter

Several observations indicate the existence of non-luminous Dark Matter (*missing gravitational force*) at very different scales!

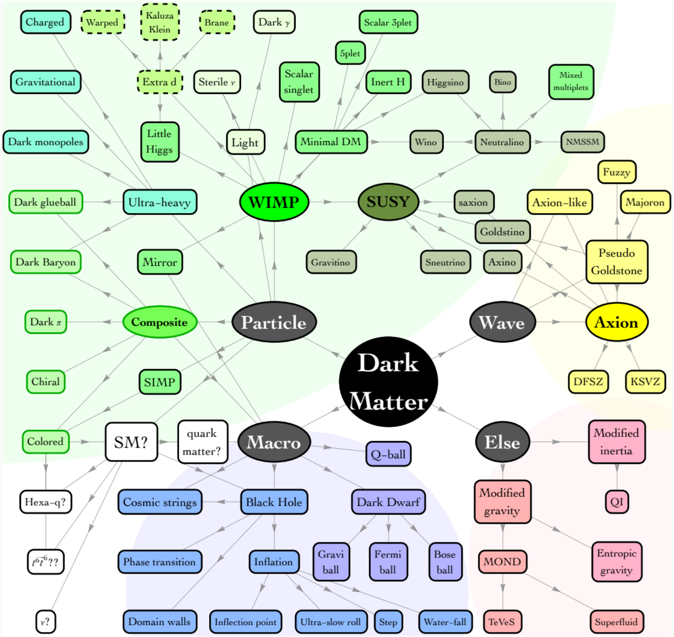
* Galactic rotation curves
* RC in Clusters of galaxies
* Clusters of galaxies



From Nicolas Bernal at NEMO-C (Medellín 2024)

DM Zoo



Charged
Warped
Kaluza Klein
Brane
Dark γ
Scalar 3plet
5plet
Gravitational
Extra d
Sterile ν
Scalar singlet
Inert H
Higgsino
Bino
Mixed multiplets
Dark monopoles
Little Higgs
Light
Minimal DM
Wino
Neutralino
NMSSM
Fuzzy
Dark glueball
Ultra–heavy
WIMP
SUSY
saxion
Axion–like
Majoron
Goldstino
Dark Baryon
Mirror
Gravitino
Sneutrino
Axino
Pseudo Goldstone
Dark π
Composite
Particle
Wave
Axion
Dark Matter
Chiral
SIMP
DFSZ
KSVZ
Colored
SM?
quark matter?
Macro
Q–ball
Else
Modified inertia
Hexa–q?
Cosmic strings
Black Hole
Dark Dwarf
Modified gravity
QI
Phase transition
Inflation
Gravi ball
Fermi ball
Bose ball
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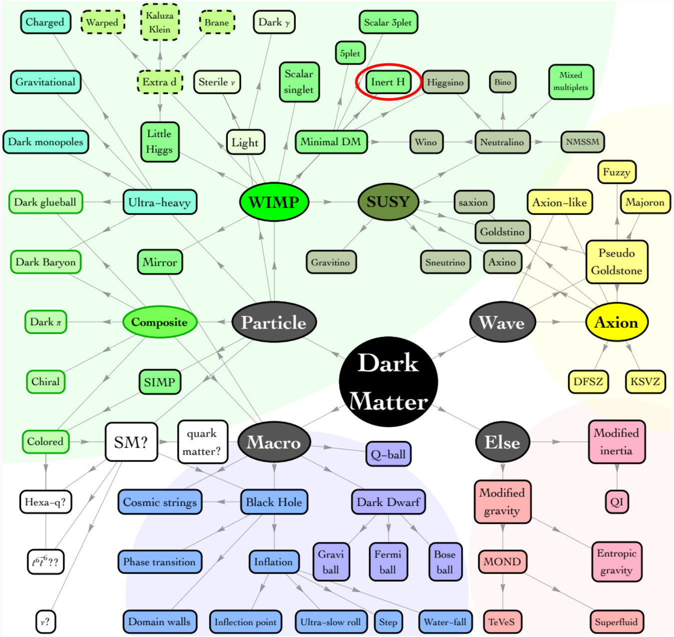
Entropic gravity
ν?
Domain walls
Inflection point
Ultra–slow roll
Step
Water–fall
TeVeS
Superfluid

DM Zoo



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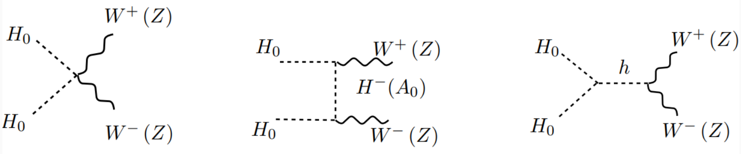
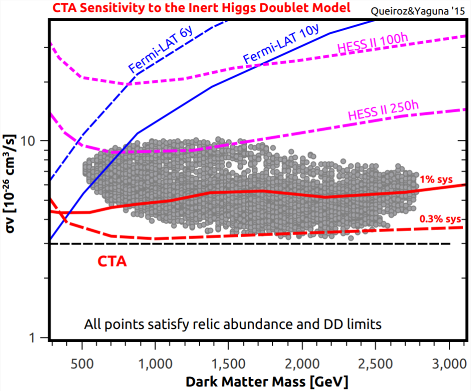
Simple WIMP dark matter model: Inert doublet model: Deshpande&Ma'77

SM + Inert Higgs doublet

Lopez Honorez&*et al*'06

$$\eta = \begin{pmatrix} \eta^+ \\ H_0 + iA_0 \end{pmatrix}$$





Effective neutrino masses

Majorana

Baryon and Lepton Nonconserving Processes #1

Steven Weinberg (Harvard U.) (1979)

Published in: *Phys.Rev.Lett.* 43 (1979) 1566-1570

Dirac

Naturally Light Dirac Neutrinos in Gauge Theories #1

M. Roncadelli (Munich, Max Planck Inst.), D. Wyler (CERN) (Aug, 1983)

Published in: *Phys.Lett.B* 133 (1983) 325-329

Name	$SU(2)_L$	$U(1)_Y$	$U(1)_L$	Z_2
L	**2**	$-1/2$	-1	$+$
H	**2**	$1/2$	0	$+$

$$\mathcal{L}_M = \frac{y_M}{\Lambda} L \cdot H L \cdot H + \text{h.c} \to \Delta L = 2$$

Dark matter (radiative) realization $\to Z_2$

Effective neutrino masses

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Name	$SU(2)_L$	$U(1)_Y$	$U(1)_L$	Z_2'
L	**2**	$-1/2$	-1	$+$
H	**2**	$1/2$	0	$+$
ν_R	**1**	0	-1	$-$

$$\mathcal{L}_M = \frac{y_M}{\Lambda} L \cdot H L \cdot H + \text{h.c} \to \Delta L = 2$$

$$\mathcal{L}_D = \cancel{y_D (\nu_R)^\dagger L \cdot H} + \text{h.c}$$

Avoids Higgs mechanism for $\nu_R \to Z_2'$

$$\cancel{M_N \nu_R \nu_R} \to U(1)$$

Scotogenic one-loop realizations

Majorana

Systematic study of the d=5 Weinberg operator at one-loop order #1

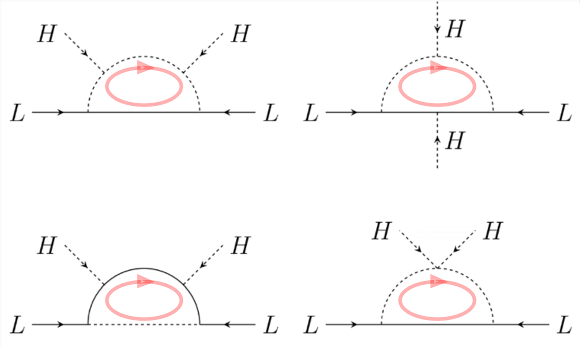
Florian Bonnet (Wurzburg U.), Martin Hirsch (Valencia U., IFIC), Toshihiko Ota (Munich, Max Planck Inst.), Walter Winter (Wurzburg U.) (Apr, 2012)

Published in: *JHEP* 07 (2012) 153 • e-Print: 1204.5862 [hep-ph]

Models with radiative neutrino masses and viable dark matter candidates #1

Diego Restrepo (Antioquia U.), Oscar Zapata (Antioquia U.), Carlos E. Yaguna (Munster U., ITP) (Aug 16, 2013)

Published in: *JHEP* 11 (2013) 011 • e-Print: 1308.3655 [hep-ph]

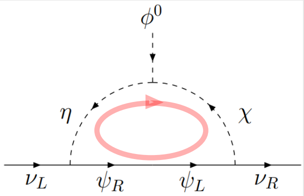


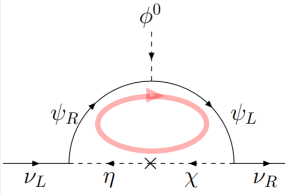
Dirac

Pathways to Naturally Small Dirac Neutrino Masses #1

Ernest Ma (UC, Riverside), Oleg Popov (UC, Riverside) (Sep 8, 2016)

Published in: *Phys.Lett.B* 764 (2017) 142-144 • e-Print: 1609.02538 [hep-ph]





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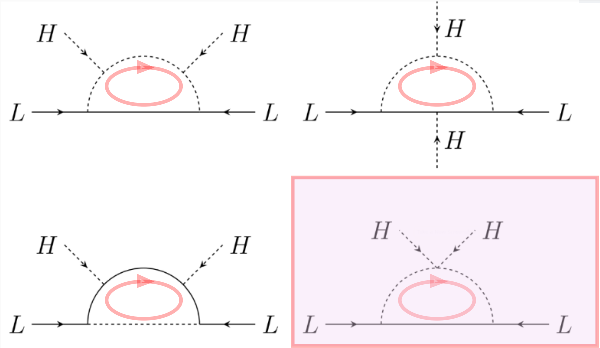

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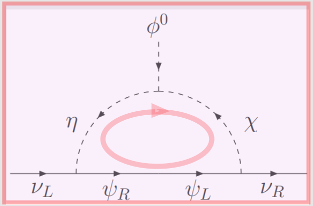

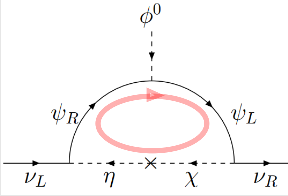

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Dirac

#1

Radiative seesaw mechanism at weak scale

Zhi-jian Tao (Beijing, Inst. High Energy Phys.) (Mar, 1996)

Published in: *Phys.Rev.D* 54 (1996) 5693-5697 • e-Print: hep-ph/9603309 [hep-ph]

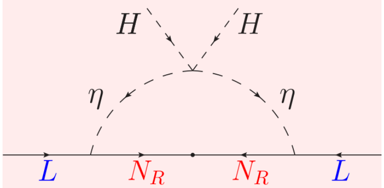
#2

Verifiable radiative seesaw mechanism of neutrino mass and dark matter

Ernest Ma (UC, Riverside) (Jan, 2006)

Published in: *Phys.Rev.D* 73 (2006) 077301 • e-Print: hep-ph/0601225 [hep-ph]

Name	$SU(2)_L$	$U(1)_Y$	Z_2
N_R	**1**	0	$-$
η	**2**	1/2	$-$



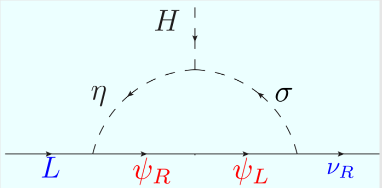
#1

Radiative Neutrino Mass, Dark Matter and Leptogenesis

Pei-Hong Gu (ICTP, Trieste), Utpal Sarkar (Ahmedabad, Phys. Res. Lab) (Dec, 2007)

Published in: *Phys.Rev.D* 77 (2008) 105031 • e-Print: 0712.2933 [hep-ph]

Name	$SU(2)_L$	$U(1)_Y$	Z_2	$U(1)_L$
ν_R	**1**	0	$-$	-1
ψ_R	**1**	0	$+$	$r-1$
ψ_L	**1**	0	$+$	$r-1$
η	**2**	1/2	$+$	r
σ	**1**	0	$-$	r



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Radiative seesaw mechanism at weak scale

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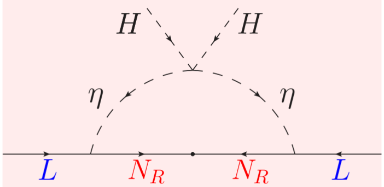

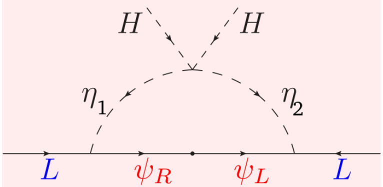

New Scotogenic Model of Neutrino Mass with $U(1)_D$ Gauge Interaction

#1

Ernest Ma (UC, Riverside), Ivica Picek (Zagreb U., Phys. Dept.), Branimir Radovčić (Zagreb U., Phys. Dept.) (Aug 24, 2013)

Published in: *Phys.Lett.B* 726 (2013) 744-746 • e-Print: 1308.5313 [hep-ph]

Dirac

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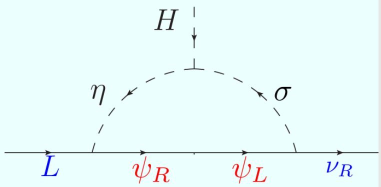
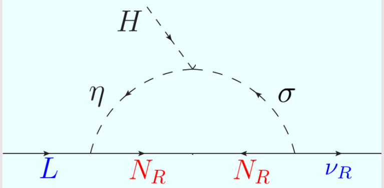
Pei-Hong Gu (ICTP, Trieste), Utpal Sarkar (Ahmedabad, Phys. Res. Lab) (Dec, 2007)

Published in: *Phys.Rev.D* 77 (2008) 105031 • e-Print: 0712.2933 [hep-ph]





Dirac neutrino mass generation from a Majorana messenger

#1

Julian Calle (Antioquia U.), Diego Restrepo (Antioquia U. and IIP, Brazil), Óscar Zapata (Antioquia U.) (Sep 20, 2019)

Published in: *Phys.Rev.D* 101 (2020) 3, 035004 • e-Print: 1909.09574 [hep-ph]

Majorana

From $Z_2 \times U(1)$ to local $U(1)_{B-L}$: Dirac

Dark matter stability and Dirac neutrinos using only Standard Model symmetries #1

Cesar Bonilla (Munich, Tech. U.), Salvador Centelles-Chuliá (Valencia U., IFIC), Ricardo Cepedello (Valencia U., IFIC), Eduardo Peinado (Mexico U.), Rahul Srivastava (Valencia U., IFIC) (Dec 4, 2018)

Published in: *Phys.Rev.D* 101 (2020) 3, 033011 • e-Print: 1812.01599 [hep-ph]

Minimal radiative Dirac neutrino mass models #1

Julian Calle (Antioquia U.), Diego Restrepo (Antioquia U.), Carlos E. Yaguna (UPTC, Tunja), Óscar Zapata (Antioquia U.) (Dec 13, 2018)

Published in: *Phys.Rev.D* 99 (2019) 7, 075008 • e-Print: 1812.05523 [hep-ph]

$$\mathcal{L}_5 = \frac{h}{\Lambda}(\nu_R)^\dagger L \cdot H S^* + \text{H.c.},$$

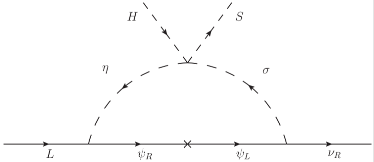


FIG. 6. T3-1-A-I ($\alpha = 0$): $B - L$ flux in the Dirac radiative seesaw.

T3-1-A-I	$(\nu_{Ri})^\dagger$	$(\nu_{Rj})^\dagger$	$(\nu_{Rk})^\dagger$	$(\psi_R)^\dagger$	ψ_L	η_a	σ_a	—	S
L	$+4$	$+4$	-5	r	$-r$	$1-r$	$4-r$	—	3

From $Z_2 \times U(1)$ to a (secluded) U(1) gauge symmetry with chiral fermions

In a fundamental theory the elementary fermions are expected to be chiral, i.e, the their charges should not allow a mass term larger than the scale of spontaneous symmetry breaking. For any set of chargues associted to a U(1) gauge symmetry

$$\boldsymbol{Z} = [Z_1, Z_2, \cdots, Z_N] \,,$$

The triangle anomaly with three U(1) gauge bosons on the external lines, i.e., the $[U(1)]^3$ anomaly, and with one U(1) gauge boson and two gravitons on the external lines should also be cancelled

$$\sum_{\alpha=1}^{N} Z_\alpha = 0\,, \qquad \sum_{\alpha=1}^{N} Z_\alpha^3 = 0\,, \tag{1}$$

$U(1)_Y$: no vector-like, i.e., pairs of fields with ‘equal-but-opposite’ charges

The hypercharge for one generation in the standard model can be seen as gauge Abelian symmetry $U(1)_Y$ with 15 left-handed Weyl massless fermions with integer charges

$$Y = [1, 1, 1, 1, 1, 1, -4, -4, -4, 2, 2, 2, -3, -3, 6]$$

which satisfy

$$\sum_i Y_i = 0\,, \qquad \sum_i Y_i^3 = 0\,.$$

If we introduce an scalar, H, of charge 3 we can form Yukawa couplings through the Dirac pairs

$$u_\alpha = (1, -4), (1, -4), (1, -4), \qquad d_\alpha = (1, 2), (1, 2), (1, 2), \qquad e = (-3, 6)$$

and the *chiral fermions* acquire Dirac masses after the EWSB. They are degenerate because the additional color symmetry. One remains massless, $\nu_L = (-3)$. The renmant Z_3 symmetry guarantees the stability of the lightest quark

$$Q'(3,2) = \begin{pmatrix} \sqrt{3}a\lambda^8_{11} + b\lambda^3_{11} + 2c\sigma^3_{11} \\ \sqrt{3}a\lambda^8_{11} + b\lambda^3_{11} - 2c\sigma^3_{11} \end{pmatrix}, \quad \begin{pmatrix} \sqrt{3}a\lambda^8_{22} + b\lambda^3_{22} + 2c\sigma^3_{22} \\ \sqrt{3}a\lambda^8_{22} + b\lambda^3_{22} - 2c\sigma^3_{22}, \end{pmatrix}, \quad \begin{pmatrix} \sqrt{3}a\lambda^8_{33} + b\lambda^3_{33} + 2c\sigma^3_{33} \\ \sqrt{3}a\lambda^8_{33} + b\lambda^3_{33} - 2c\sigma^3_{33}, \end{pmatrix}$$

$$\bar{u}(3^*,1) = -\sqrt{3}a\lambda^8_{11} - b\lambda^3_{11}, \quad -\sqrt{3}a\lambda^8_{22} - b\lambda^3_{22}, \quad -\sqrt{3}a\lambda^8_{33} - b\lambda^3_{33}$$

$$\bar{d}(3^*,1) = -\sqrt{3}a\lambda^8_{11} - b\lambda^3_{11}, \quad -\sqrt{3}a\lambda^8_{22} - b\lambda^3_{22}, \quad -\sqrt{3}a\lambda^8_{33} - b\lambda^3_{33}$$

$$S = [a+b+c, a+b-c, a-b+c, a-b-c, -2a+c, -2a-c, -a-b, -a-b, -a+b, -a+b, -2a, 2a]$$

Secluded gauge $U(1)_D$ without vector-like fermions:

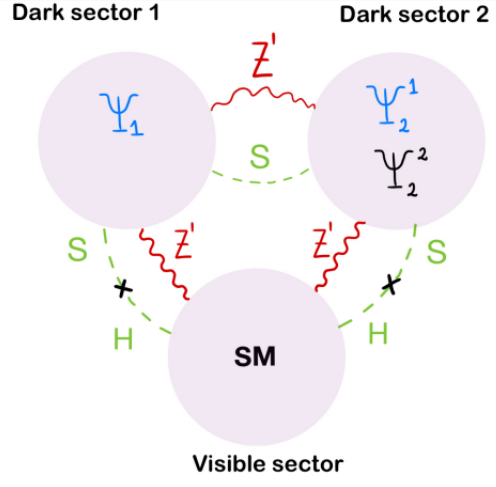
$$\boldsymbol{S} = [\chi_1, \chi_2, \cdots, \psi_1, \psi_2, \cdots, \psi_{N'}]$$

- *Dark Higgs mechanism*: Singlet dark Higgs ϕ acquires a vev and give mass to the dark photon

$$\mathcal{L} = i\psi_a^\dagger \overline{\sigma^\mu} \left(\partial_\mu - i g_D Z'_\mu\right) \psi_a - \frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \sum_{a<b} h_{ab} \psi_a \psi_b \phi^{(*)} + \text{h.c} - V(\phi)\,. \qquad (2)$$

- S_α are the charges of SM-singlet right-handed chiral fermions with $N \geq 5$
  - χ_i *massless fermions* with $i = 1, \cdots, N'$ with $N' \leq N$
  - ψ_a *multi-component dark matter*: massive after the spontaneous symmetry breaking of $U(1)_D$ with $a = N' + 1, \cdots, N$
- *Larger parameter space*: Dark photon, Z', exclusions instead of $B - L$-like Z'
- Two mediators with Z' and ϕ masses are related by (arXiv:1610.03063)

$$h/g_D = \sqrt{2} m_\psi / m_{Z'}\,.$$


Dark sector 1
Dark sector 2
Z'
S
S
S
Z'
Z'
H
H
SM
Visible sector

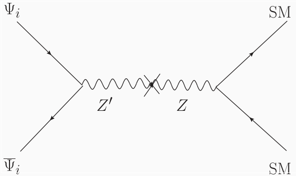
Two-mediator: Dark photon and dark Higgs

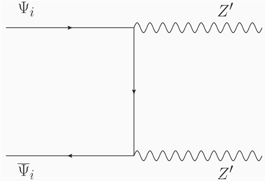
$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \mathrm{Re}(H^0) \\ \mathrm{Re}(S) \end{pmatrix}$$

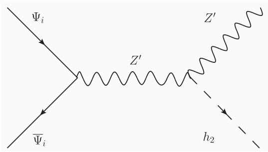
$$\mathcal{L}_{B'} \supset -\frac{\epsilon}{2} B'_{\mu\nu} B^{\mu\nu}$$

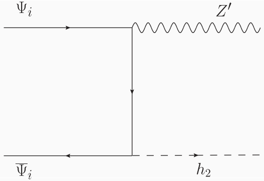
After the diagonalization of the kinetic terms

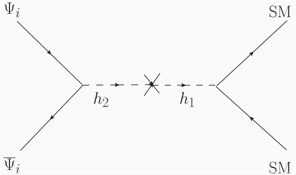
$$\mathcal{L}_{\text{mix}} \supset Z'_\mu (\epsilon e J^\mu_{EM} + g_D J^\mu_D)$$

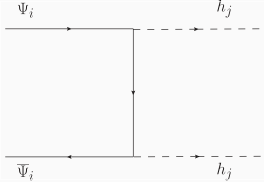


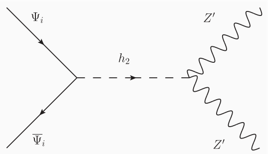




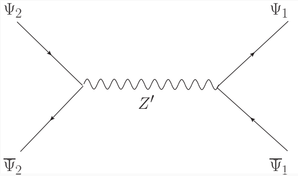


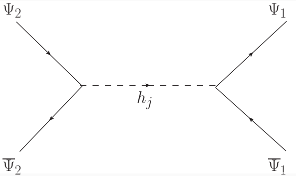






DM conversion channels





Decrease the number of charges to be assigned to dark matter particles, ψ_i below

$$[\chi_1, \chi_2, \cdots, \psi_1, \psi_2, \cdots, \psi_{N'}]$$

Secluded case:

$$[\nu, \nu, (\nu), \psi_1, \psi_2, \cdots, \psi_{N'}]$$

$$\chi_1 \to \nu_{R1}, \cdots, \chi_{N_\nu} \to \nu_{R\,N_\nu}, \qquad 2 \leq N_\nu \leq 3\,,$$

$$\mathcal{L}_{\text{eff}} = h_\nu^{ij} \, (\nu_{Ri})^\dagger \, \epsilon_{ab} \, L_j^a \, H^b \left(\frac{\phi^*}{\Lambda} \right)^\delta + \text{H.c.}, \qquad \text{with } i,j = 1,2,3\,,$$

ϕ is the complex singlet scalar responsible for the SSB of the anomaly-free gauge symmetry and **give mass to *all* ψ_a**

$$\phi = -\frac{\nu}{\delta}\,,$$

Effective Dirac neutrino mass operator

Decrease the number of charges to be assigned to dark matter particles, ψ_i below

$$[\chi_1, \chi_2, \cdots, \psi_1, \psi_2, \cdots, \psi_{N'}]$$

Secluded case:

$$[5, 5, -3, -2, 1, -6]$$

$$\chi_1 \to \nu_{R1}, \ \chi_2 \to \nu_{R2}, \qquad N_\nu = 2\,,$$

$$\mathcal{L}_{\text{eff}} = h_\nu^{aj}\,(\nu_{Ra})^\dagger\,\epsilon_{bc}\,L_j^b\,H^c\left(\frac{\phi^*}{\Lambda}\right) + \text{H.c.}, \qquad \text{with } j = 1, 2, 3\,,$$

Effective Dirac neutrino mass operator

Decrease the number of charges to be assigned to dark matter particles, ψ_i below

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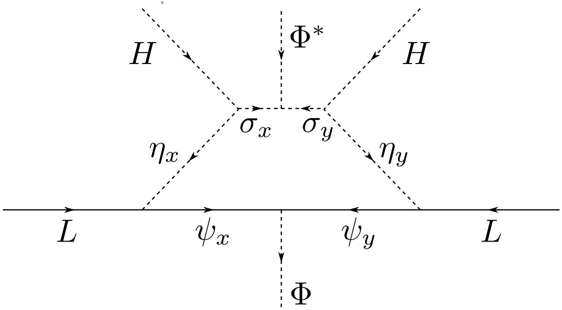
$$\mathcal{L}_{\text{eff}} = h_\nu^{aj} \, (\nu_{Ra})^\dagger \, \epsilon_{bc} \, L_j^b \, H^c \left(\frac{\phi^*}{\Lambda} \right) + \text{H.c.}, \qquad \text{with } j = 1, 2, 3\,,$$

$$\boldsymbol{z} = [5, 5, -3, -2, 1, -6] \to \phi = -5 \to [(5, 5), (-3, -2), (1, -6)]$$

$$\mathcal{L} \subset h_{(-3,-2)} \psi_{-3} \psi_{-2} \phi^* + h_{(1,-5)} \psi_1 \psi_{-6} \phi^* + \text{h.c.}$$

$$[\psi_1, \psi_2, \cdots, \psi_N]\,, \qquad N_{\text{min}} = 5$$

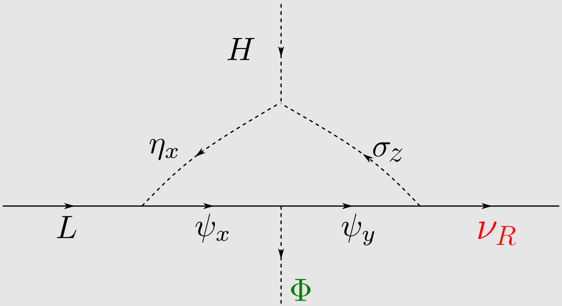


$$\frac{y}{\Lambda} LLHH \to \frac{y}{\Lambda} LLHH \frac{\phi}{\Lambda}\frac{\phi^*}{\Lambda}$$

ϕ **give mass to *all* ψ_a**

$\sim 1\,000$ solutions $[x, y, \cdots]$ with $N \geq 8$

$$[\nu, \nu, (\nu), \psi_1, \psi_2, \cdots, \psi_{N'}]\,, \qquad N = N_\nu + N'$$



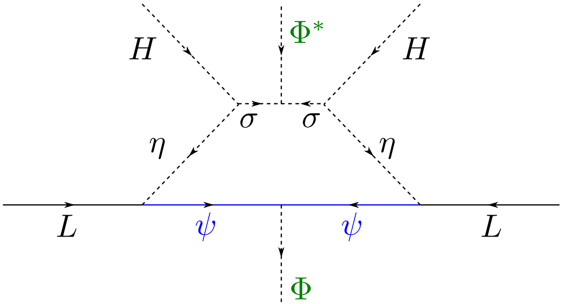
$$y\,(\nu_R)^\dagger\, LH \to y\,(\nu_R)^\dagger\, LH \frac{\phi^*}{\Lambda}$$

ϕ **give mass to *all* ψ_a**

$\sim 1\,000$ solutions $[\nu, \nu, (\nu), x, y, \cdots]$ with $N \geq 6$

Majorana

$$[\psi_1, \psi_2, \cdots, \psi_N]$$



$$\phi = 2 \to [\underbrace{1, 1}_{\psi_a}, (2, -4), (4, -6), (3, -5)]$$

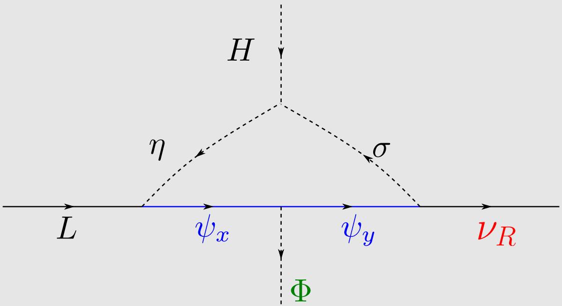
Anomaly-free chiral $U(1)_D$ and its scotogenic implication #1

Chi-Fong Wong (Macau U. Sci. Tech., SSI) (Aug 19, 2020)

Published in: *Phys.Dark Univ.* 32 (2021) 100818 • e-Print: 2008.08573 [hep-ph]

Dirac

$$[\nu, \nu, (\nu), \psi_1, \psi_2, \cdots, \psi_{N'}]$$



$$\phi = 9 \to [9, 9, 9, \underbrace{(1, -10), (1, -10)}_{\psi_a}, (-4, -5)],$$

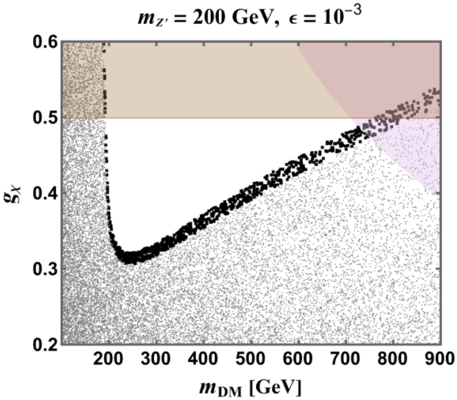
Anomaly-free Abelian gauge symmetries with Dirac scotogenic models #8

Nicolás Bernal (Antonio Narino U.), Julián Calle (Antioquia U.), Diego Restrepo (Antioquia U.) (Feb 11, 2021)

Published in: *Phys.Rev.D* 103 (2021) 9, 095032 • e-Print: 2102.06211 [hep-ph]

$\phi = 2 \to [1, 1, (2, -4), (4, -6), (3, -5)]$

Secluded DM with Majorana fermion candidate



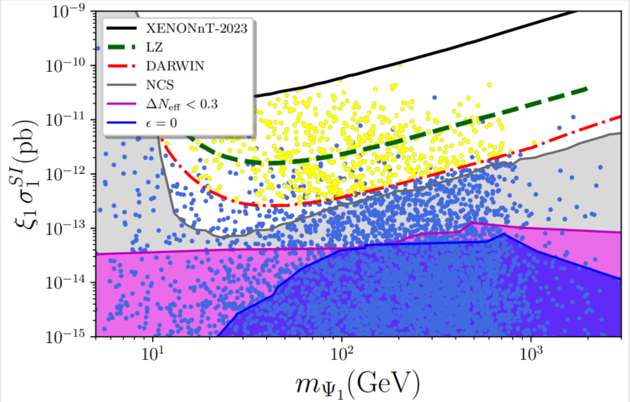
Chiral dark matter and radiative neutrino masses from gauged U(1) symmetry #1

K.S. Babu (Oklahoma State U.), Shreyashi Chakdar (Holy Cross Coll. and Munster U., ITP), Vishnu P. K (Sep 13, 2024)

e-Print: 2409.09008 [hep-ph]

$\phi = 9 \to [9, 9, 9, (1, -10), (1, -10), (-4, -5)]$,

New decay channel: $Z' \to \bar{\nu}\nu$



In progress...

Conclusions

Scotogenic models, which explain dark matter and neutrino masses and mixings, have diverse realizations with a wide range of predictions through various portals and messengers.

When applied to chiral dark matter models arising from Abelian gauge symmetries, the stability of dark matter is automatically ensured, giving rise to a rich secluded dark sector.

Thanks!