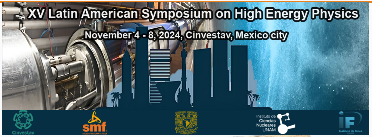
UNIVERSIDAD DE ANTIOQUIA
1803

Neutrino masses and dark matter

Scotogenic models



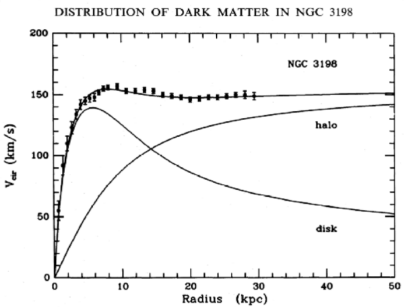
Diego Restrepo

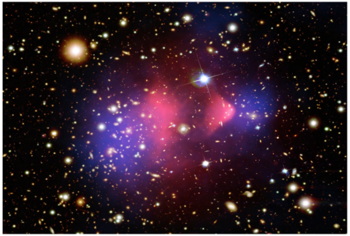
Instituto de Física
Universidad de Antioquia
Phenomenology Group
http://gfif.udea.edu.co

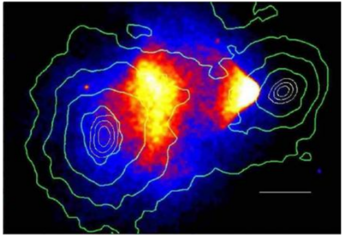
Evidences for Dark Matter

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

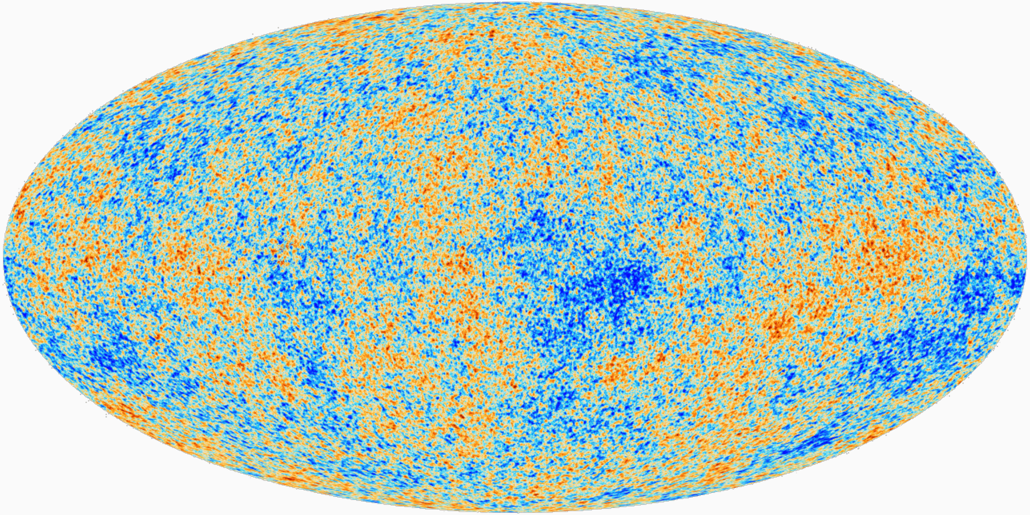




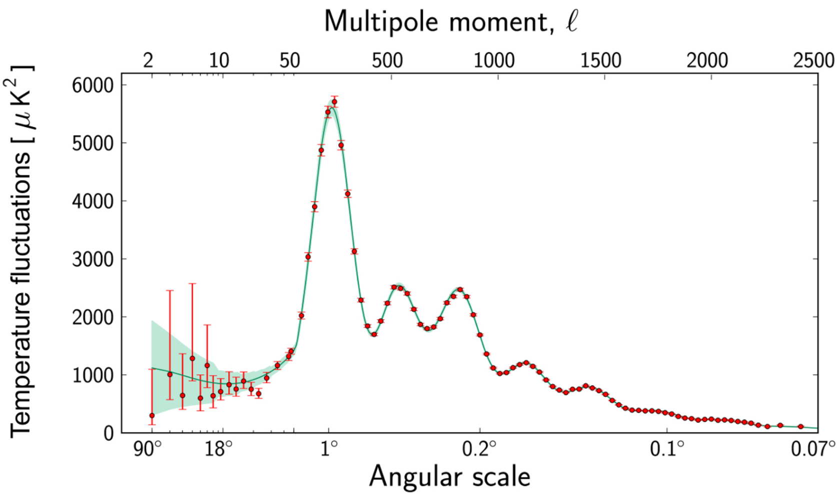


From Nicolas Bernal at NEMO-C (Medellín 2024)

Cosmic Microwave Background temperature: $T = 2.726\,\mathbf{K}$ with $\Delta T/T \sim 10^{-6}$



The Cosmic Microwave Background - as seen by Planck. Credit: ESA and the Planck Collaboration

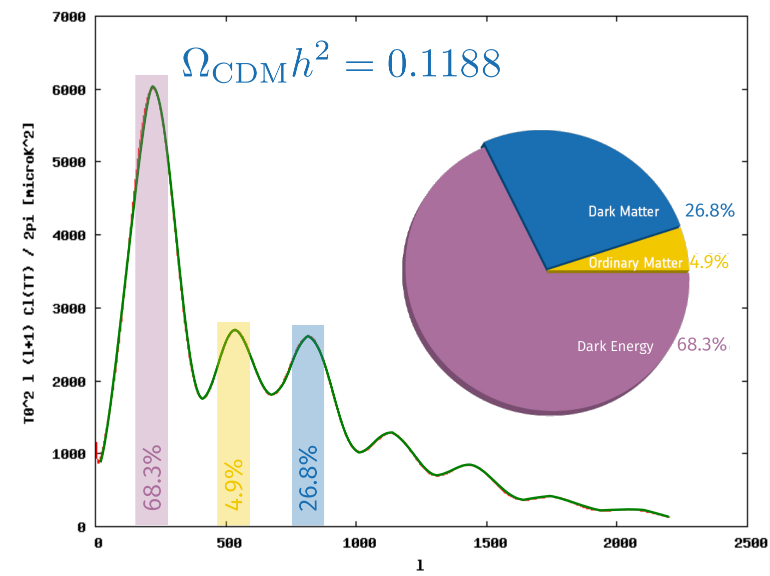


Planck's power spectrum of temperature fluctuations, ΔT, in the Cosmic Microwave Background. Credit: ESA and the Planck Collaboration

ΛCDM: $\Omega = 1$, $w = -1^{\dagger}$

Symbol	Value
$\Omega_b h^2$	0.022 30(14)
$\Omega_{CDM} h^2$	0.1188(10)
t_0	$13.799(21) \times 10^9$ year
n_s	0.9667(40)
Δ_R^2	2.441×10^{-9}
τ	0.066(12)

†Cosmological constant



ΛCDM: $\Omega = 1$, $w = -1$†

Symbol	Value
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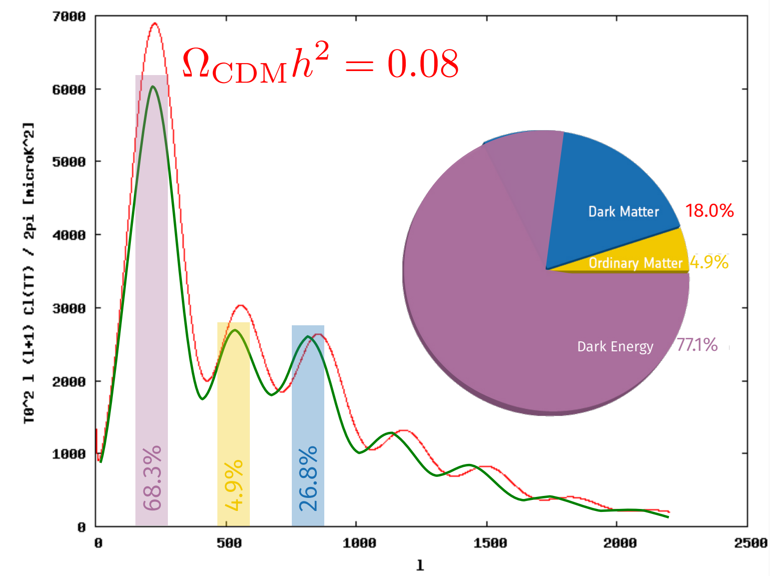
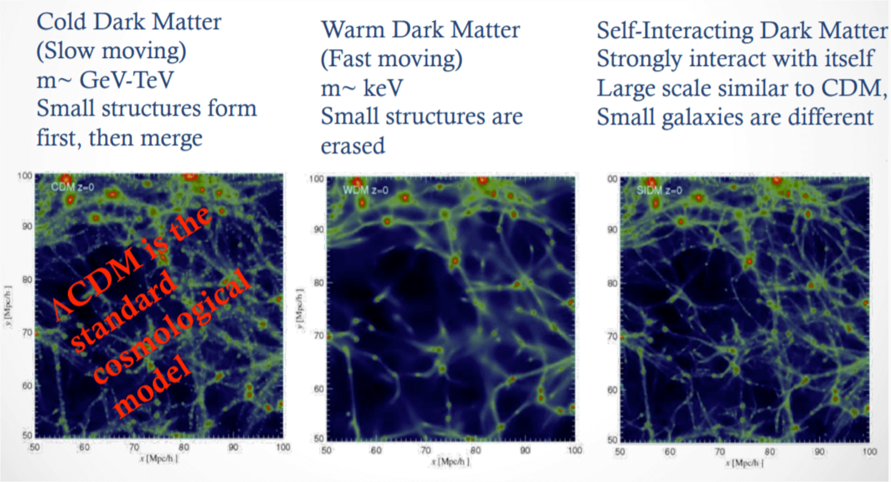


Large scale structure simulations: Gas of not hot and almost collisionless dark matter particles

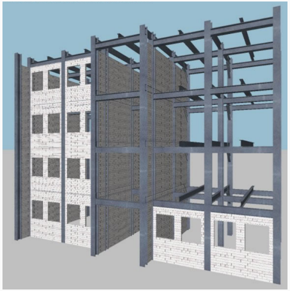


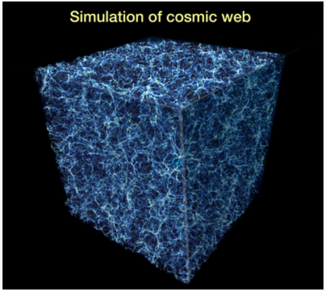
Credit: Arianna Di Cintio (Conference on Shedding Light on the Dark Universe with Extremely Large Telescopes, ICTP - 2018)

Particle: from elementary sub-eV to Primordial Black Hole of several solar masses

Cosmic web

Dark matter connects clusters of galaxies with massive tendrils, forming a cosmic web that serves as an unseen skeleton for the universe.
https://phys.org/news/2018-06-years-scientists-account-universe.html





Cosmic web

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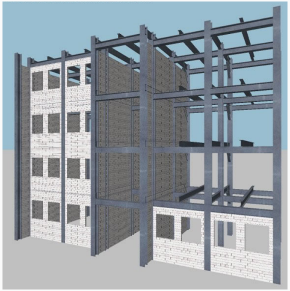
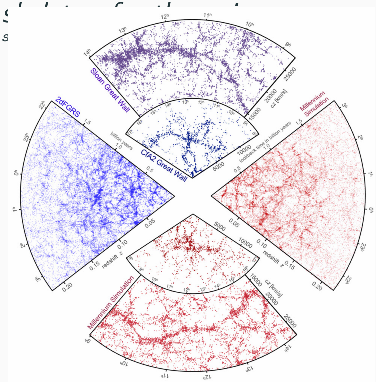
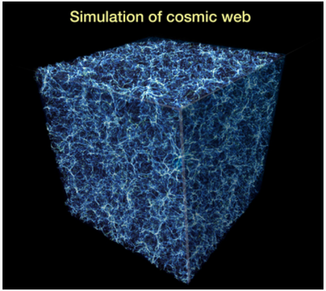


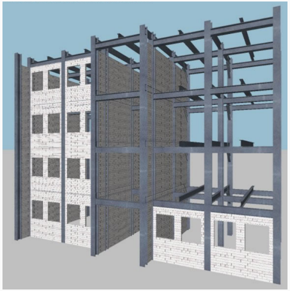


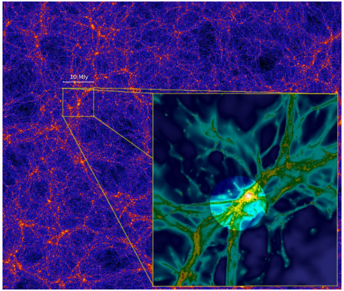


Galaxy redshift surveys vs large scale structure formation simulations: V. Springel, *et al* `astro-ph/0604561` [Nature]

Cosmic web

Dark matter connects clusters of galaxies with massive tendrils, forming a cosmic web that serves as an unseen skeleton for the universe.
https://phys.org/news/2018-06-years-scientists-account-universe.html





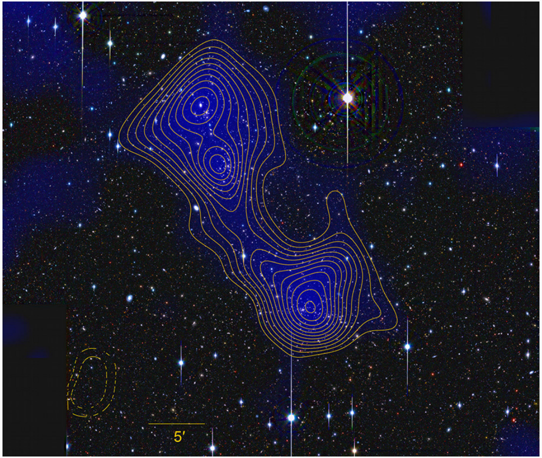
These great filaments are made largely of dark matter located in the space between galaxies and filled with 60% of the primordial gas!

An excess of a gas (20σ) is observed between Milky Way and Andromeda (M31): arXiv:1403.7528 [MNRAS] [1]

Clouds of HI likeky embeded in a filament between M31 and M33: arXiv:1305.1631 [nature]

[1] See also: arXiv:1603.05400 [A&A]

A filament of dark matter between two clusters of galaxies



Supercluster system of three galaxy clusters

- Abell 222 (south) detected at $\sim 8\sigma$
- Abell 223 (north) double galaxy cluster seen at $\sim 7\sigma$

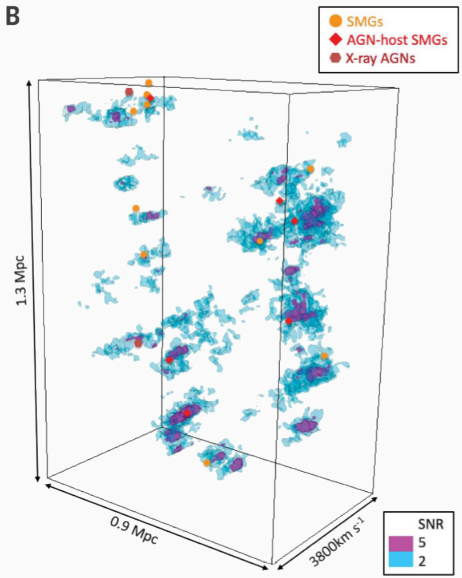
reconstructed surface mass density (blue)

significance contours from 0.5σ to 2.5σ

J.P. Dietrich *et al*, arXiv:1207.0809 [Nature]

For a recent review see: arXiv:1905.08991

Three-dimensional pictures of Lyα filaments



The 3D distribution of Lyα filaments shown with

signal-to-noise ratio (SNR) > 5

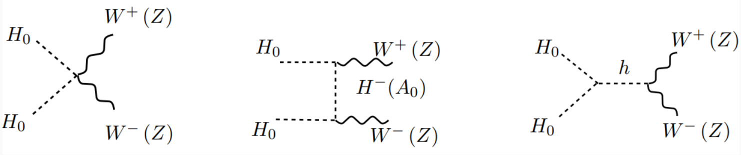
signal-to-noise ratio (SNR) > 2

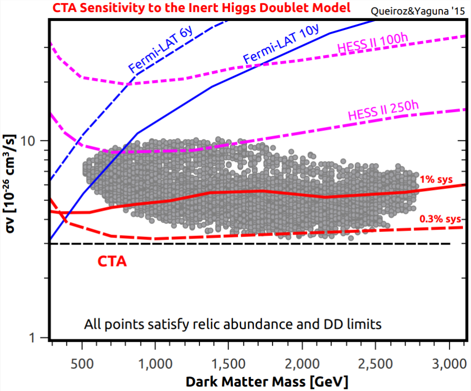
H. Umehata *et al*, Science **366**, 97, 4 Oct 2019

Example: 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

Dirac

Baryon and Lepton Nonconserving Processes #1

Steven Weinberg (Harvard U.) (1979)

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

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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Steven Weinberg (Harvard U.) (1979)

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

pdf DOI cite claim reference search 2,488 citations

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

DOI cite claim reference search 116 citations

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

Dirac

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

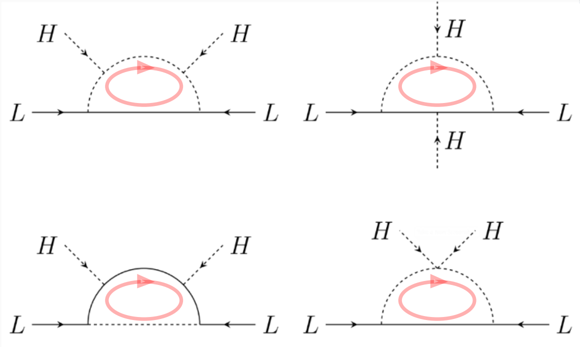
Florian Bonnet (Wurzburg U.), Martin Hirsch (Valencia U., IFIC), Toshihiko Ota (Munich, Max Planck Inst.), Walter Winter (Wurzburg U.) (Apr, 2012)

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)

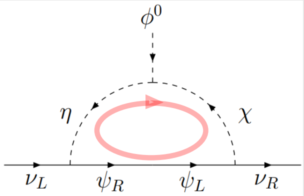
Published in: *JHEP* 11 (2013) 011 • e-Print: 1308.3655 [hep-ph]

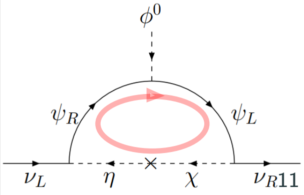


Pathways to Naturally Small Dirac Neutrino Masses #1

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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pdf DOI cite claim reference search 197 citations

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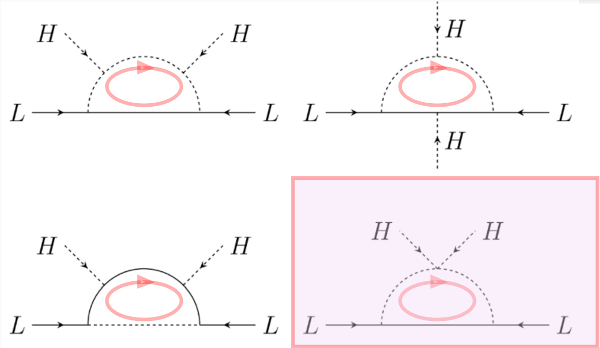
pdf DOI cite claim reference search 123 citations



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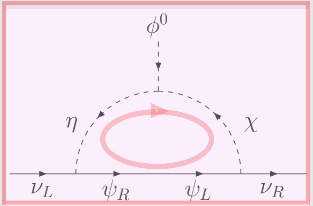
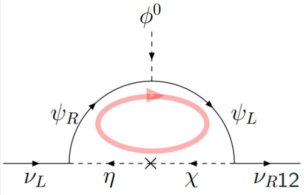




Majorana

Radiative seesaw mechanism at weak scale #1

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]

pdf DOI cite claim reference search

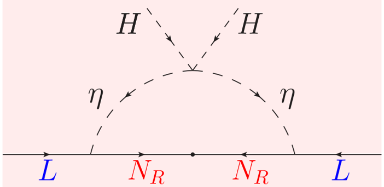
Verifiable radiative seesaw mechanism of neutrino mass and dark matter #2

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

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

pdf DOI cite claim reference search

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



Dirac

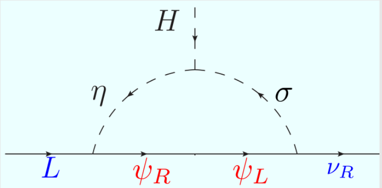
Radiative Neutrino Mass, Dark Matter and Leptogenesis #1

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]

pdf DOI cite claim reference search

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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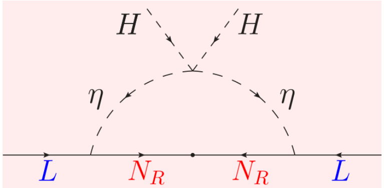

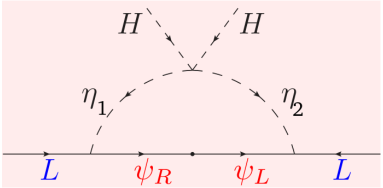

New Scotogenic Model of Neutrino Mass with $U(1)_D$ Gauge Interaction

#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

Radiative Neutrino Mass, Dark Matter and Leptogenesis

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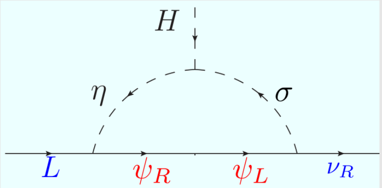
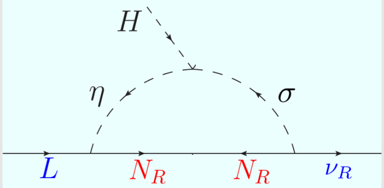
Pei-Hong Gu (ICTP, Trieste), Utpal Sarkar (Ahmedabad, Phys. Res. Lab) (Dec, 2007)

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]

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

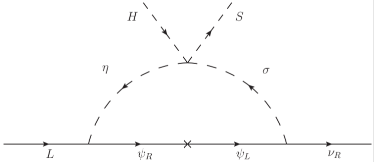


FIG. 6. T3-1-A-I ($\alpha = 0$): $B - L$ flux in the Dirac radiative seesaw.

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

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

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

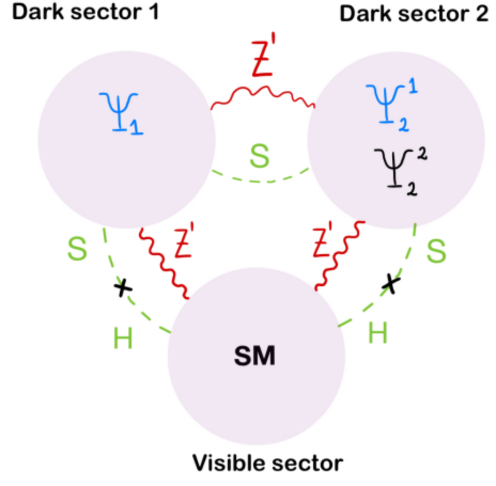
- *Dark Higgs mechanism*: Singlet dark Higgs ϕ acquires a vev and give mass to the dark photon

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

- 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)

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

Multi-component and two-mediator DM with kinetic mixing



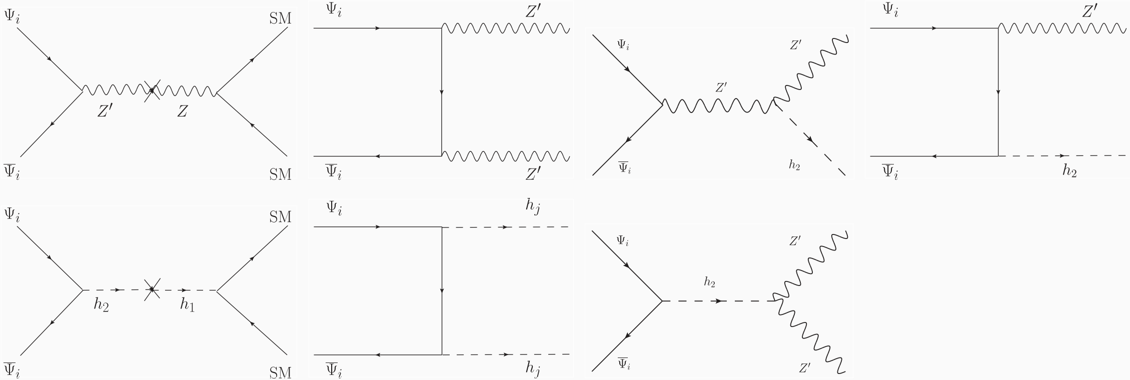
Two-mediator: Dark photon and dark Higgs

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

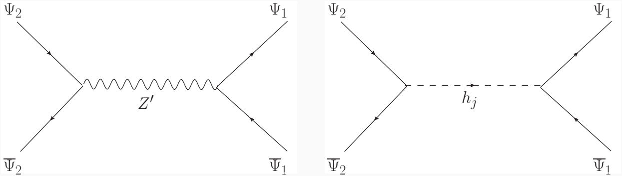
$$\mathcal{L}_{B'} \supset -\frac{\epsilon}{2} B'_{\mu\nu} B^{\mu\nu}$$

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:

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

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

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

Effective Dirac neutrino mass operator

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

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

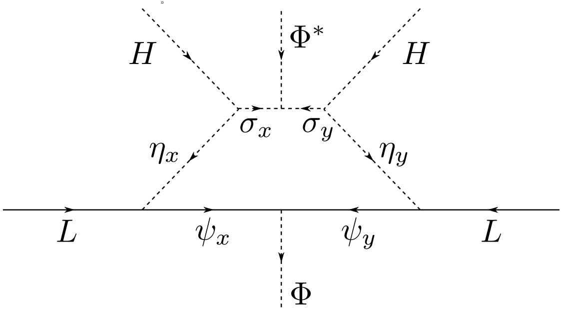
$$\mathcal{L}_{\text{eff}} = h_\nu^{aj} \, (\nu_{Ra})^\dagger \, \epsilon_{bc} \, L_j^b \, H^c \left(\frac{\phi^*}{\Lambda}\right) + \text{H.c.}, \qquad \text{with } j = 1, 2, 3\,,$$

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

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

Majorana

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



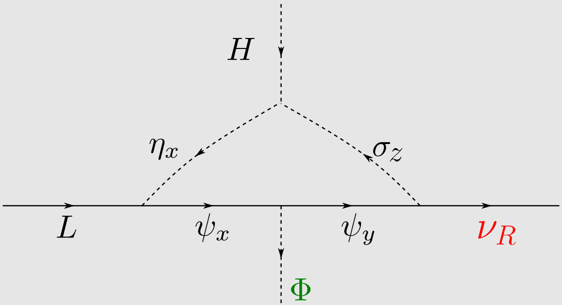
$$\frac{y}{\Lambda} LLHH \to \frac{y}{\Lambda} LLHH \frac{\phi}{\Lambda}\frac{\phi^*}{\Lambda}$$

ϕ **give mass to *all* ψ_a**

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

Dirac

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



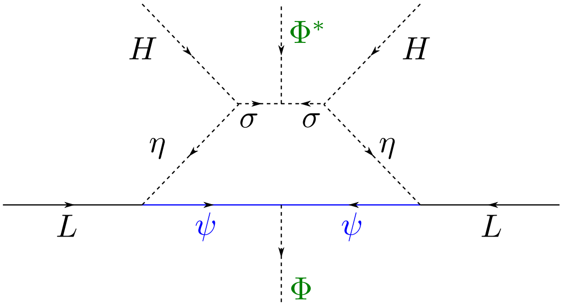
$$y\,(\nu_R)^\dagger\, LH \to y\,(\nu_R)^\dagger\, LH \frac{\phi^*}{\Lambda}$$

ϕ **give mass to *all* ψ_a**

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

Majorana

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



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

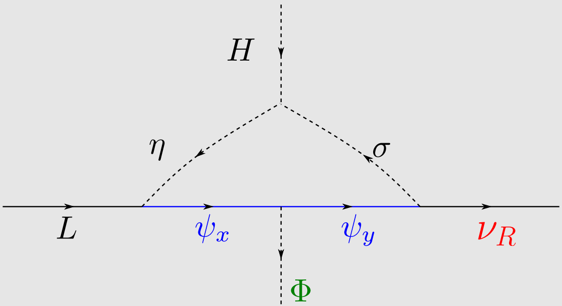
Anomaly-free chiral $U(1)_D$ and its scotogenic implication #1

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

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



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

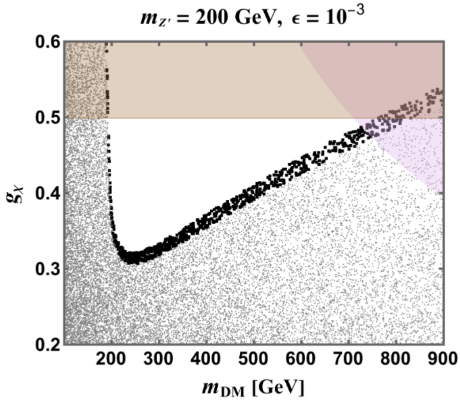
Anomaly-free Abelian gauge symmetries with Dirac scotogenic models #8

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]

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

Secluded DM with Majorana fermion candidate



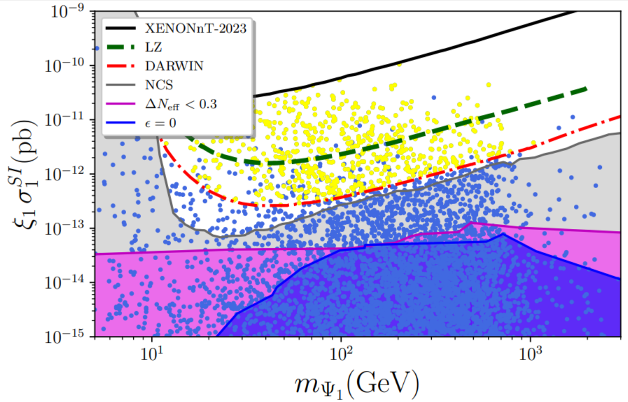
Chiral dark matter and radiative neutrino masses from gauged U(1) symmetry #1

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]

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

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



In progress...

Many other venues

$$m_\nu \propto \frac{\langle H^0 \rangle^2}{\Lambda} \times \left(\frac{1}{16\pi^2} \right)^n \times \epsilon \times \left(\frac{\langle H^0 \rangle}{\Lambda} \right)^{d-5},$$

Other representa-tions

Other Topologies

Two or three loops

Extra coupling suppression

Effective operators of higher dimension

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!