Dark matter direct detection at one loop

Michael A. Schmidt

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based on
C. Hagedorn, J. Herrero-García, E. Molinaro, MS [1804.04117]
J. Herrero-García, E. Molinaro, MS [1803.05660]

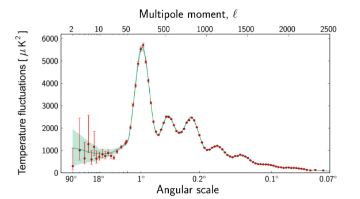
THE UNIVERSITY OF SYDNEY

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

Gravitational evidence for dark matter

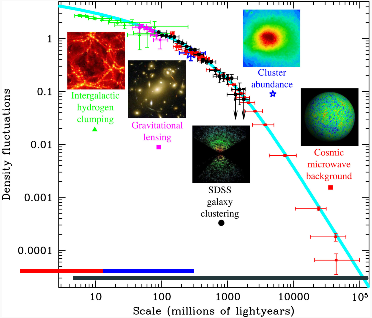
Evidences across all astrophysical scales

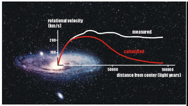
- Galaxy rotational curve
- Bullet cluster with grav. lensing
- Cosmic microwave background

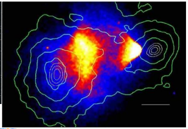


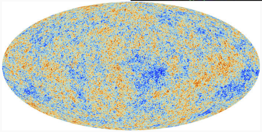
  - fit with ΛCDM
  - dark matter abundance:

$$\Omega_{\mathrm{CDM}} h^2 = 0.12$$









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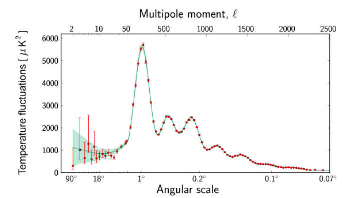

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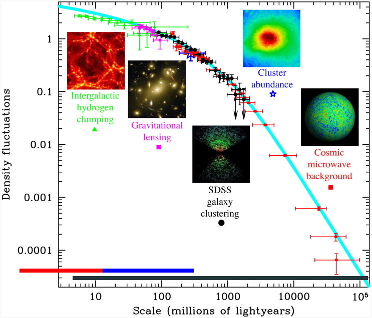
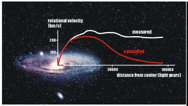
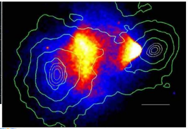
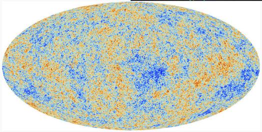
Popular candidate:

Weakly Interacting Massive Particles







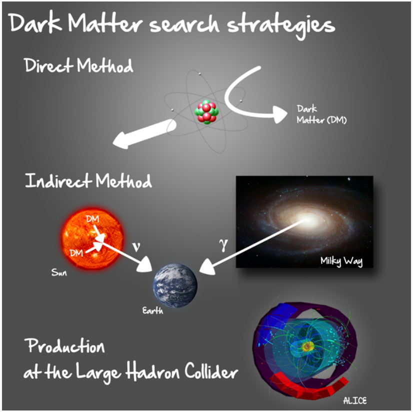


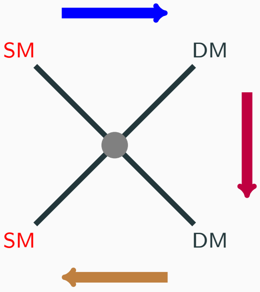
No other clear signal in dark matter searches

? dark matter mass

? spin and other quan. numbers

? interactions and strength



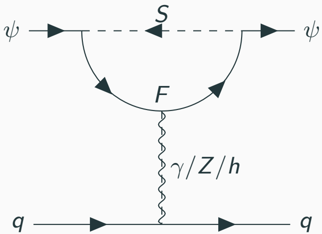


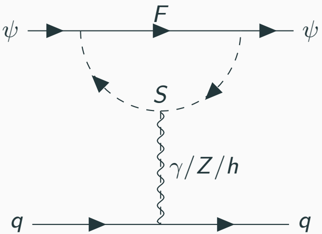
- Direct detection: nuclear recoil
- Indirect detection: cosmic rays
- Collider search: missing transverse energy

So far no clear evidence for DM in direct/indirect detection or at LHC

Motivation for direct detection at loop level

- no clear evidence for DM in direct/indirect detection or at lhc
- only hints from DAM.*
- option: DM is not directly coupled to quarks
- examples: fermionic singlet DM ψ such as bino, fermionic DM in scotogenic model, or models explaining the DAMPE result
- direct detection occurs at one loop
- next generation (liquid noble gas) experiments could probe it



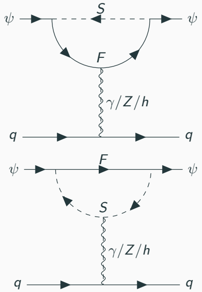


Simplified fermionic DM model

dark sector	field	$\mathrm{SU(3)_c}$	$\mathrm{SU(2)_L}$	$\mathrm{U(1)_Y}$	$\mathrm{U(1)}_{DM}$
dark matter	ψ	1	1	0	1
dark scalar	S	1	d_F	Y_F	q_S
dark fermion	F	1	d_F	Y_F	$q_S + 1$

$$\mathcal{L}_\psi = i\,\overline{\psi}\,\partial\!\!\!/\,\psi - m_\psi\,\overline{\psi}\,\psi + i\,\overline{F}\,D\!\!\!\!/\,F - m_F\,\overline{F}\,F + (D_\mu S)^\dagger D^\mu S$$
$$- \left(y_1\,\overline{F_\mathrm{R}}\,S\,\psi_\mathrm{L} + y_2\,\overline{F_\mathrm{L}}\,S\,\psi_\mathrm{R} + \mathrm{h.c.}\right) - \lambda_{HS}\,v\,h\,S^\dagger S + \ldots$$

- Higgs portal coupling may arise in different ways
- easy to generalise to larger dark symmetry groups



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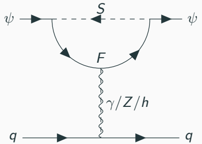
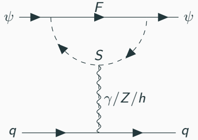


SM fields in loop

1. $F \to L_L/e_R$: ψ or S have $L = 1$ LFV, EDM/AMMs, LNV
2. $F \to \nu_r$: ν_r and ψ or S have $L = 1$ Gonzalez-Macias, Escudero, ...
3. $S \to H$: mixing $\psi - F_0$, thus tree-level h/Z exchange



(Relevant) effective interactions for direct detection

Dirac DM

- Electric and magnetic dipoles: $\mathcal{L} = \mu_\psi \mathcal{O}_{\rm mag} + d_\psi \mathcal{O}_{\rm edm}$ [long-range]

$$\mathcal{O}_{\rm mag} = \frac{e}{8\pi^2}(\overline{\psi}\sigma^{\mu\nu}\psi)F_{\mu\nu}, \qquad \mathcal{O}_{\rm edm} = \frac{e}{8\pi^2}(\overline{\psi}\sigma^{\mu\nu}i\gamma_5\psi)F_{\mu\nu}\,,$$

- Vector interactions from Z/γ penguins [anapole $(\overline{\psi}\gamma^\mu\psi)(\partial^\nu F_{\mu\nu}) \equiv \mathcal{O}^q_{VV}$ by eom]

$$\mathcal{O}^q_{VV} = (\overline{\psi}\gamma^\mu\psi)(\overline{q}\gamma_\mu q) \qquad \mathcal{O}^q_{AA} = (\overline{\psi}\gamma^\mu\gamma_5\psi)(\overline{q}\gamma_\mu\gamma_5 q),$$

- Scalar interactions [and gluon interaction induced by heavy quarks]

$$\mathcal{O}^q_{SS} = m_q(\overline{\psi}\psi)(\overline{q}q) \qquad \mathcal{O}_g = \frac{\alpha_s}{8\pi}(\overline{\psi}\psi)G^{a\mu\nu}G^a_{\mu\nu}$$

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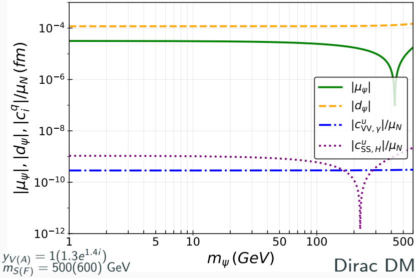
Majorana DM

- no dipole and vector interactions
- P-violating vector interaction [momentum suppressed]

$$\mathcal{O}^q_{AV} = (\overline{\psi}\gamma^\mu\gamma_5\psi)\,(\overline{q}\gamma_\mu q)$$

Dominant interactions: electric/magnetic dipole moments



for Dirac DM ψ $[m_\psi \ll m_F < m_S]$

$$\mu_\psi \approx -\frac{Q_F}{4\,m_S}\left(|y_V|^2 - |y_A|^2\right) x_F \,\frac{1 - x_F^2 + 2\ln x_F}{(1-x_F^2)^2}$$

$$d_\psi \approx -\frac{Q_F}{2\,m_S}\,\mathrm{Im}[y_V^*\,y_A]\,x_F\,\frac{1 - x_F^2 + 2\ln x_F}{(1-x_F^2)^2}$$

where

$$x_F \equiv \frac{m_F}{m_S} \quad \text{and} \quad y_{V,A} = \frac{y_2 \pm y_1}{2}\,.$$

Dominant contribution:

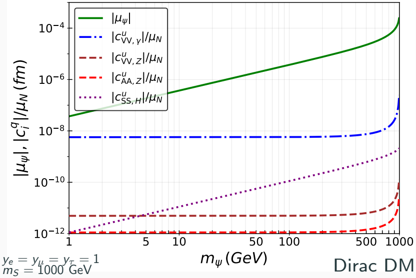
Dirac DM: electromagnetic dipole moment

Majorana DM Higgs and photon penguin

analytical expressions provided in paper
and compared to existing results

Berlin, Chang, Agrawal, Kumar, Schmidt, Kopp, Ibarra...

m_ψ dependence of μ_ψ and $c^u_{SS,H}$ due to helicity



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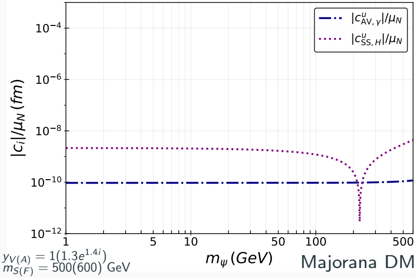

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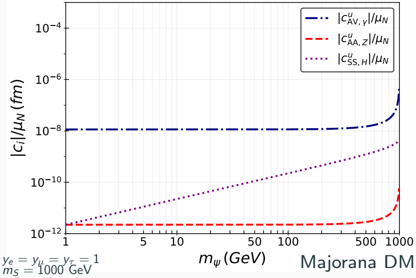
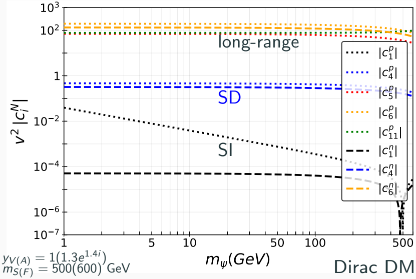


Nucleon level (non-relativistic): vector-like fermions



$$\mathcal{O}_1^N = I_\psi I_N$$

$$\mathcal{O}_4^N = \vec{S}_\psi \cdot \vec{S}_n$$

$$\mathcal{O}_5^N = \vec{S}_\psi \cdot \left(\vec{v}_\perp \times \frac{i\vec{q}}{m_N}\right) I_N$$

$$\mathcal{O}_6^N = \left(\vec{S}_\psi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_n \cdot \frac{\vec{q}}{m_N}\right)$$

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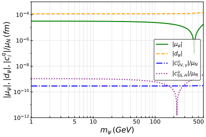

DirectDM[1708.02678] to match to NR Wilson coefficients

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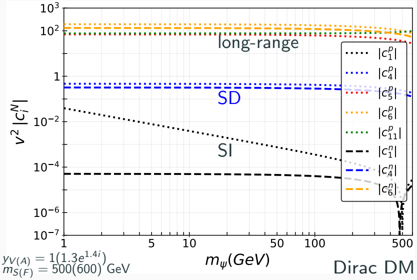

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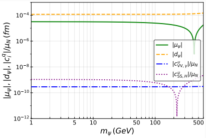

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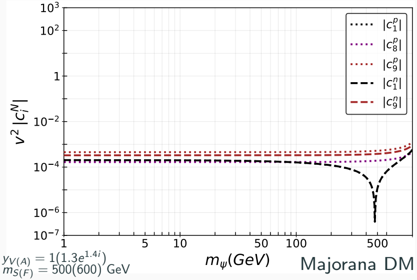
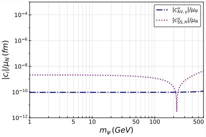


$$\mathcal{O}_1^N = I_\psi I_N$$

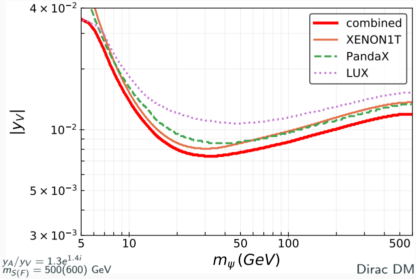
$$\mathcal{O}_8^N = \left(\vec{S}_\psi \cdot \vec{v}_\perp\right) I_N$$

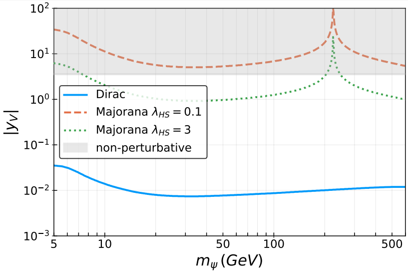
$$\mathcal{O}_9^N = \vec{S}_\psi \cdot \left(\frac{i\vec{q}}{m_N} \times \vec{S}_N\right)$$



Direct detection limits

vector-like fermions   we use LikeDM 1708.04630 to calculate event rates and obtain limits





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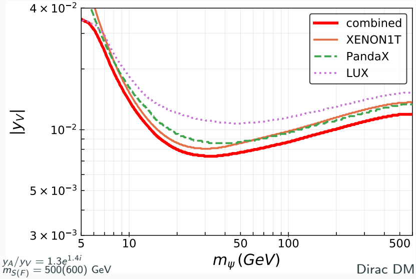
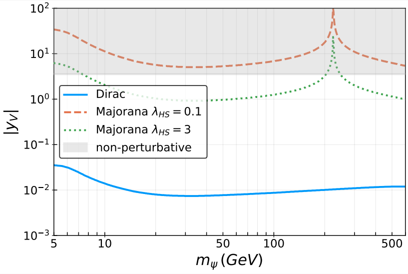
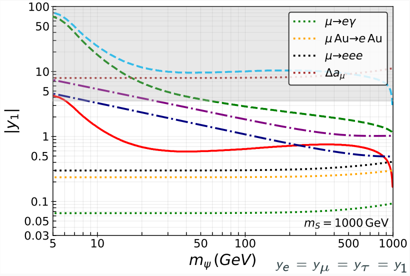
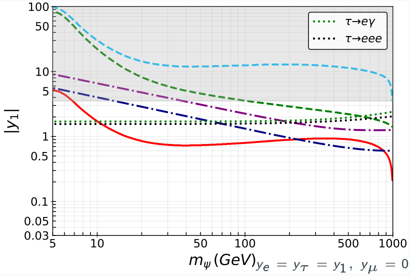




right-handed charged leptons





connection to neutrino masses: generalised scotogenic model

Generalised scotogenic model with Dirac fermion DM

simple example of DD at loop level with radiative ν masses:

Dirac DM ψ, $F \equiv L_L$, $S = \Phi, \Phi'$. dark global (anomaly-free) $\mathrm{U(1)_{DM}}$

field	$\mathrm{SU(3)_c}$	$\mathrm{SU(2)_L}$	$\mathrm{U(1)_Y}$	$\mathrm{U(1)_{DM}}$
Φ	1	2	1/2	1
Φ'	1	2	-1/2	1
ψ	1	1	0	1

just **one fermionic singlet** ψ needed. $\mathbf{y}_{\Phi^{(\prime)}}$ are 3-component vectors

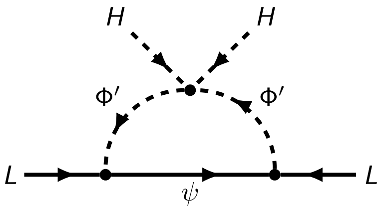
$$\mathcal{L}_\psi \supset i\,\overline{\psi}\,\partial\!\!\!/\,\psi - m_\psi\,\overline{\psi}\,\psi - \left(y^\alpha_\Phi\,\overline{\psi}\,\tilde{\Phi}^\dagger\,L^\alpha_L + (y^\alpha_{\Phi'})^*\,\overline{\psi}\,\tilde{\Phi}'^\dagger\tilde{L}^\alpha_L + \text{h.c.}\right).$$

two neutral complex scalars $\eta_0^{(\prime)}$ (mixing angle θ),
two charged scalars $\eta^{(\prime)\pm}$ (no mixing)

$$V \supset \lambda_{H\Phi\Phi'}\left[(H^\dagger\tilde{\Phi}')(H^\dagger\Phi) + \mathrm{h.c.}\right] \quad \longrightarrow \quad \sin 2\theta \propto \lambda_{H\Phi\Phi'}\,.$$

scalar DM heavily constrained by DD (mediated by Z-exchange).

Majorana neutrino mass



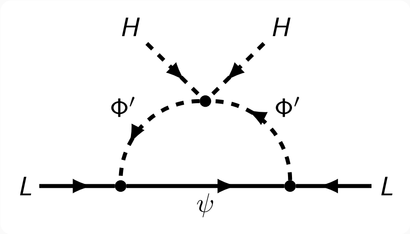
$$\mathcal{M}_\nu^{\alpha\beta} = \frac{\sin 2\theta \, m_\psi}{32\,\pi^2} \left(y_\Phi^\alpha \, y_{\Phi'}^\beta + y_{\Phi'}^\alpha y_\Phi^\beta \right) \left[\frac{m_{\eta_0}^2}{m_{\eta_0}^2 - m_\psi^2} \log \frac{m_{\eta_0}^2}{m_\psi^2} - (\eta_0 \leftrightarrow \eta_0') \right]$$

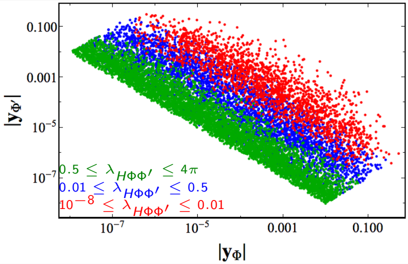
lepton number L violated by combination of $\mathbf{y}_\Phi$, $\mathbf{y}'_\Phi$, $\lambda_{H\Phi\Phi'}(\sin 2\theta)$, m_ψ

m_ν is rank 2 $\Rightarrow$ one massless neutrino

Yukawa vectors $\mathbf{y}_\Phi^{(\prime)}$ determined by low-energy data up to one parameter ζ which determines relative size of Yukawa vectors

Majorana neutrino mass





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Lepton flavour violation: $\mu \to e$ transition

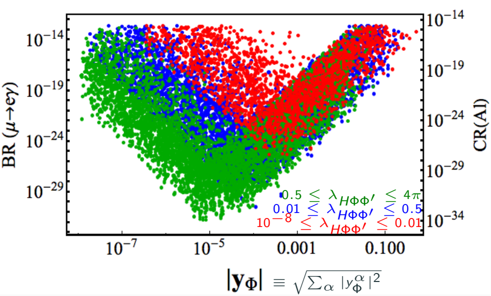
$$\mathrm{BR}(\mu \to e\,\gamma) = \frac{3\,\alpha_{\rm em}}{64\pi G_F^2}\left| \frac{y_\Phi^{e*}\, y_\Phi^{\mu}}{m_{\eta^\pm}^2} f\left(\frac{m_\psi^2}{m_{\eta^\pm}^2}\right) + \frac{y_{\Phi'}^{e*}\, y_{\Phi'}^{\mu}}{m_{\eta'^\pm}^2} f\left(\frac{m_\psi^2}{m_{\eta'^\pm}^2}\right)\right|^2$$

$$\mathrm{CR(Al)} \simeq [0.0077, 0.011] \times \mathrm{BR}(\mu \to e\gamma)$$ dipole dominance

only free parameters: masses m_ψ, $m_{\eta^\pm}$, and ζ

$$\mathrm{NO}: \mathbf{y}_{\Phi'} = \sqrt{\frac{32\pi^2}{\sin 2\theta\, m_\psi F}}\,\frac{\zeta}{\sqrt{2}}\left(\sqrt{m_{sol}}\,u_2^* \pm i\sqrt{m_{atm}}\,u_3^*\right)$$

$$\mathbf{y}_{\Phi'} = \sqrt{\frac{32\pi^2}{\sin 2\theta\, m_\psi F}}\,\frac{1}{\zeta\sqrt{2}}\left(\sqrt{m_{sol}}\,u_2^* \mp i\sqrt{m_{atm}}\,u_3^*\right)$$



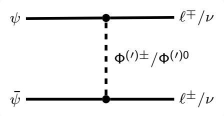
with u_i being the columns of the PMNS matrix

using $f\left(m_{\eta^\pm}^2/m_\psi^2\right) \xrightarrow{m_{\eta^\pm}\to m_\psi} \frac{1}{12}$

$$0.0003\,\frac{100\,\mathrm{GeV}}{m_{\eta'^\pm}} \lesssim |\zeta| \lesssim 4000\,\frac{m_{\eta^\pm}}{100\,\mathrm{GeV}}$$

$\tau \to \ell\gamma$ correlated with $\mu \to e\gamma$

DM s-wave annihilations into leptons and LFV



$$\xrightarrow{ch.lep.} \langle v\sigma_{\ell\ell}\rangle = \frac{1}{32\pi m_\psi^2}\left| y_\Phi^\alpha y_\Phi^{\beta *}\frac{m_\psi^2}{m_{\eta^\pm}^2 + m_\psi^2} - y_{\Phi'}^\alpha y_{\Phi'}^{\beta *}\frac{m_\psi^2}{m_{\eta'^\pm}^2 + m_\psi^2}\right|^2$$

only depends on masses and ζ and thus strongly constrained by LFV

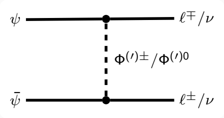
a conservative estimate

$$\frac{\sum_{\alpha,\beta}\langle v\sigma(\psi\bar{\psi}\to \ell_\alpha^- \ell_\beta^+, \nu_\alpha\nu_\beta)\rangle}{\langle v\sigma\rangle_{\rm th}} \lesssim 2\times 10^{-4}\left(\frac{2.2\times 10^{-26}{\rm cm}^3/{\rm s}}{\langle v\sigma\rangle_{\rm th}}\right)\left(\frac{m}{100\,{\rm GeV}}\right)^2$$

for $m_{\eta_0'} \simeq m_{\eta^\pm} \simeq m_\psi \equiv m$. larger scalar masses lead to a further suppression. this is confirmed by numerical scan with micrOMEGAs.

caveat: MeV DM $m_\psi \simeq m_{\eta_0'} \ll m_{\eta^\pm}$ Boehm,Farzan,Hambye,Palomares-Ruiz,Pascoli [hep-ph/0612228]

DM s-wave annihilations into leptons and LFV



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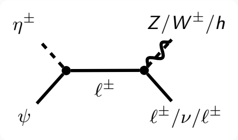
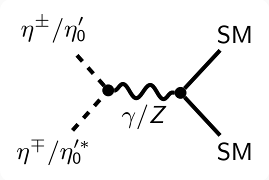
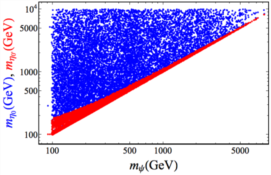
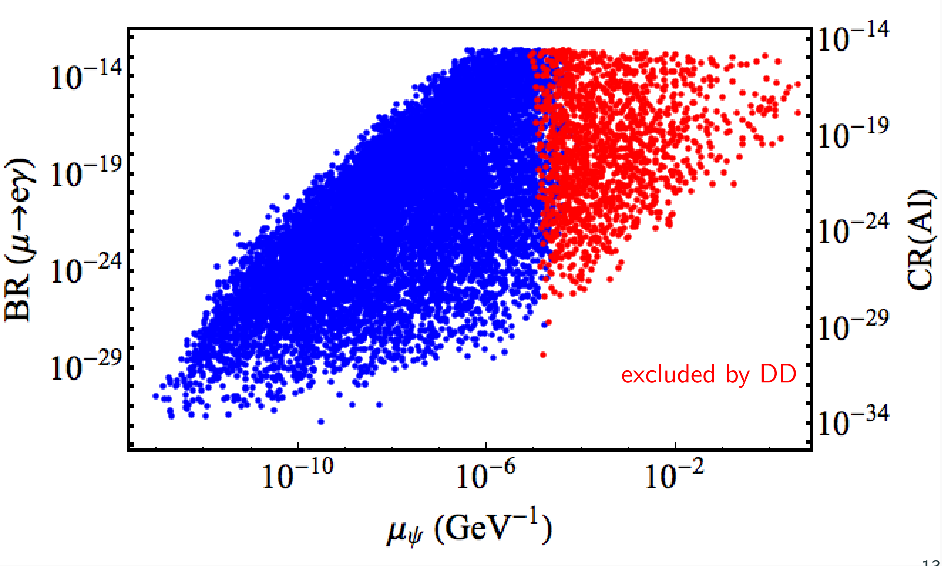
annihilations into leptons too small: need coannihilation with scalars $\eta^{(\prime)}$







Complementarity of LFV and DM direct detection



Conclusions

Conclusions

DM may not couple directly to quarks

DM - nucleus scattering only at 1-loop order (or higher)

discussion of simplifed fermionic DM model

magnetic and electric dipole moment dominate
Higgs penguins are important for Majorana DM

generalised scotogenic model with Dirac fermion

fermionic DM requires coannihilation
interplay between LFV and direct detection

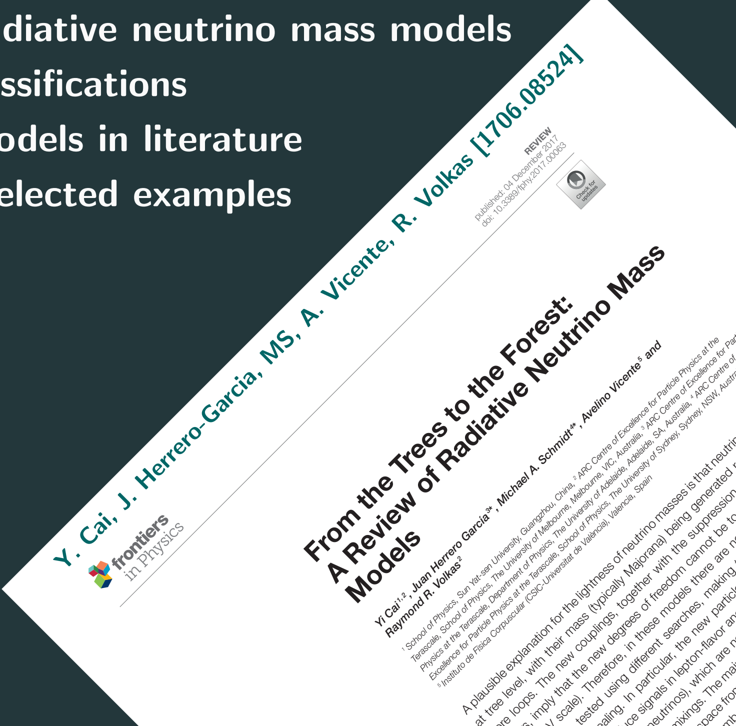
Review of radiative neutrino mass models

Different classifications

Survey of models in literature

Details for selected examples

Y. Cai, J. Herrero-Garcia, MS, A. Vicente, R. Volkas [1706.08524]



frontiers in Physics

REVIEW
published: 04 December 2017
doi: 10.3389/fphy.2017.00063

From the Trees to the Forest: A Review of Radiative Neutrino Mass Models

Yi Cai[1,2], Juan Herrero García[3]*, Michael A. Schmidt[4]*, Avelino Vicente[5] and Raymond R. Volkas[2]

[1] School of Physics, Sun Yat-sen University, Guangzhou, China, [2] ARC Centre of Excellence for Particle Physics at the Terascale, School of Physics, The University of Melbourne, Melbourne, VIC, Australia, [3] ARC Centre of Excellence for Part Physics at the Terascale, Department of Physics, The University of Adelaide, Adelaide, SA, Australia, [4] ARC Centre of Excellence for Particle Physics at the Terascale, School of Physics, The University of Sydney, Sydney, NSW, Austra
[5] Instituto de Física Corpuscular (CSIC-Universitat de València), Valencia, Spain

A plausible explanation for the lightness of neutrino masses is that neutri at tree level, with their mass (typically Majorana) being generated r ... loops. The new couplings, together with the suppression ... imply that the new degrees of freedom cannot be to ... scale). Therefore, in these models there are n ... tested using different searches, making ... In particular, the new partic ... signals in lepton-flavor an ... neutrinos), which are n ... mixings. The ma ... space fro

Review of radiative neutrino mass models

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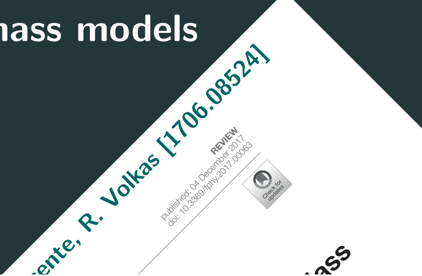
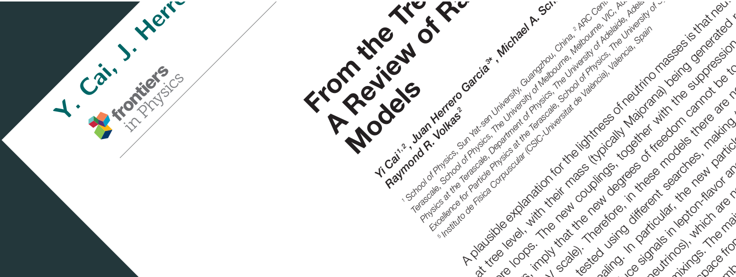
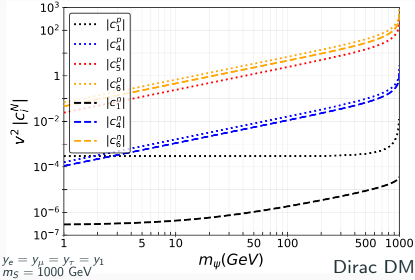


Thank you!

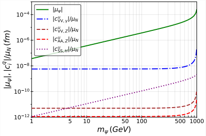


Backup slides

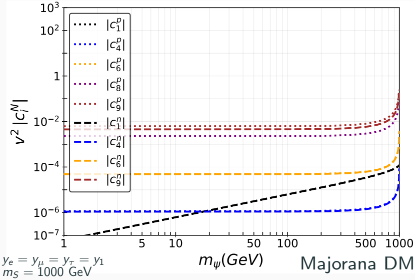
Nucleon level (non-relativistic): leptons



$$\mathcal{O}_1^N = I_\psi I_N$$
$$\mathcal{O}_4^N = \vec{S}_\psi \cdot \vec{S}_N$$
$$\mathcal{O}_5^N = \vec{S}_\psi \cdot \left(\vec{v}_\perp \times \frac{i\vec{q}}{m_N}\right) I_N$$
$$\mathcal{O}_6^N = \left(\vec{S}_\psi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$
$$\mathcal{O}_{11}^N = -\left(\vec{S}_\psi \cdot \frac{\vec{q}}{m_N}\right) I_N$$



DirectDM[1708.02678] to match to NR Wilson coefficients



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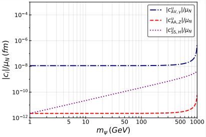
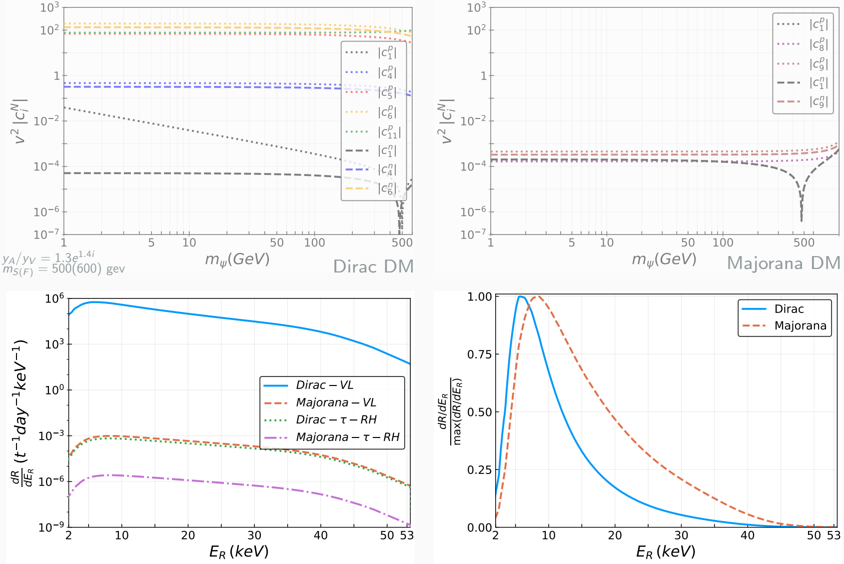
$$\mathcal{O}_4^N = \vec{S}_\psi \cdot \vec{S}_N$$
$$\mathcal{O}_6^N = \left(\vec{S}_\psi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$
$$\mathcal{O}_8^N = \left(\vec{S}_\psi \cdot \vec{v}_\perp\right) I_N$$
$$\mathcal{O}_9^N = \vec{S}_\psi \cdot \left(\frac{i\vec{q}}{m_N} \times \vec{S}_N\right)$$



Differential event rates

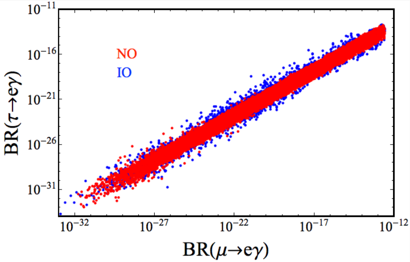


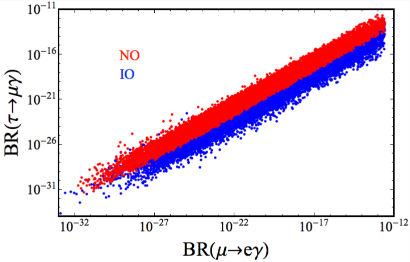
LikeDM [1708.04630] to calculate event rates and obtain limits

Correlation between different LFV rates

$$\mathrm{NO}: \frac{\mathrm{BR}(\tau \to e\,\gamma)}{\mathrm{BR}(\mu \to e\,\gamma)} \approx 0.2 \quad \text{and} \quad \frac{\mathrm{BR}(\tau \to \mu\,\gamma)}{\mathrm{BR}(\mu \to e\,\gamma)} \approx 5$$

$$\mathrm{IO}: \frac{\mathrm{BR}(\tau \to e\,\gamma)}{\mathrm{BR}(\mu \to e\,\gamma)} \approx \frac{\mathrm{BR}(\tau \to \mu\,\gamma)}{\mathrm{BR}(\mu \to e\,\gamma)} \approx 0.2\,,$$





Papers on radiative neutrino mass generation