

The phenomenology of Isospin Violating Dark Matter

Based on 2508.05787 with Shankar Pramanik, Soumya Sadhukhan and Adrián Terrones
and work in progress with Adrián Terrones

Víctor Martín Lozano

victor.lozano@ific.uv.es



Composition of the Universe.

Our Universe's composition is:

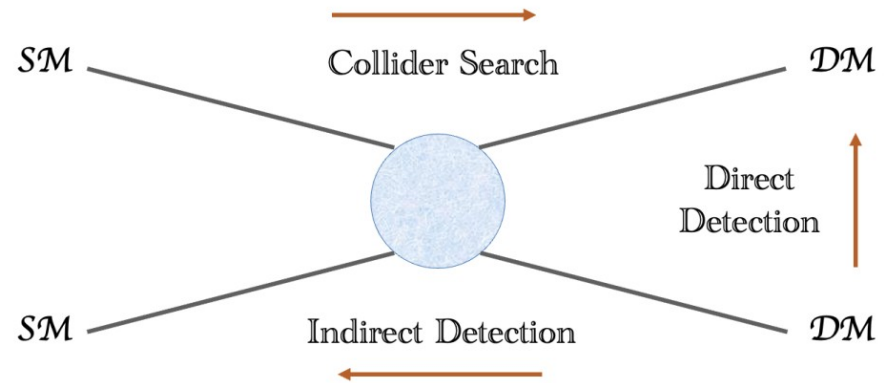
- Dark Energy (68%)
- Dark Matter (27%)
- Baryonic Matter (5%)



Dark Matter searches.

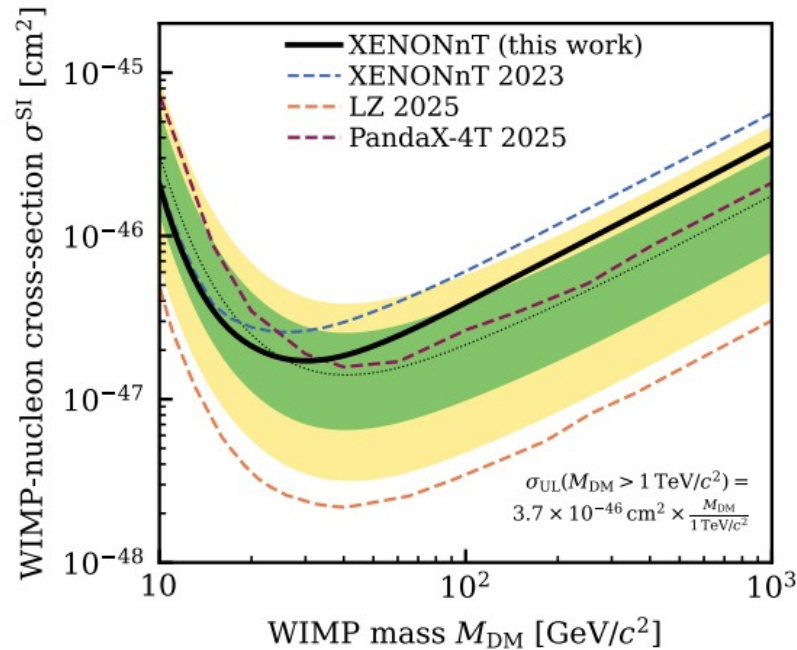
:

- Colliders (missing energy signatures)
- Direct Detection (scattering off nuclei/
electron scattering)
- Indirect Detection (cosmic rays)



Dark Matter Direct Detection.

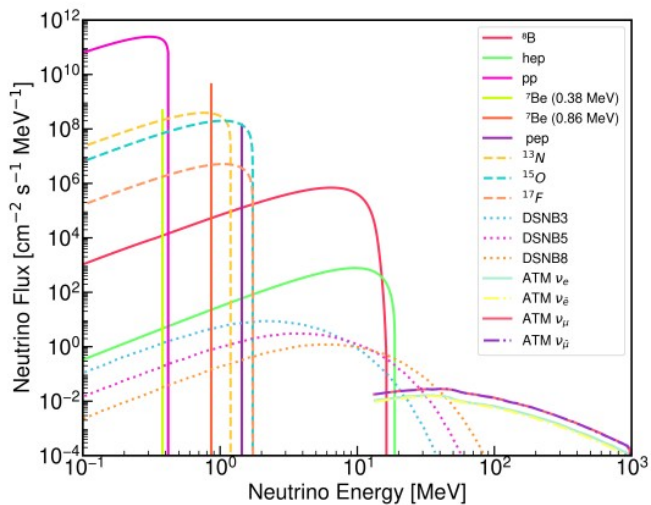
- Experimental bounds direct detection: XENONnT, LZ and PandaX-4T are pushing down the parameter space of the dark matter.



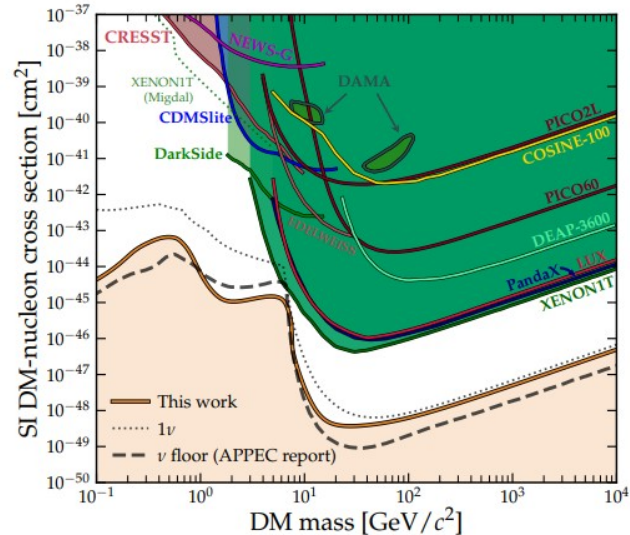
[XENONnT, 2502.18005]

Neutrino Floor/Fog.

- Neutrinos hitting direct detection detectors can mimic DM signals. Once the limit is crossed (neutrino floor) the search for DM is no longer background free.



[Duque, Lamprea, Miranda, 2512.19784]



[O'Hare, 2109.03116]

Direct Detection Exclusion Bounds.

Let us assume a general U(1) Lagrangian,

$$\mathcal{L} \supset Z'_\mu \sum_f \bar{f} \gamma^\mu (g_V^f + g_A^f \gamma_5) f + Z'_\mu \bar{\chi} \gamma^\mu (g_V^\chi + g_A^\chi \gamma_5) \chi + \frac{1}{2} m_{Z'}^2 Z'_\mu Z'^\mu + m_\chi \bar{\chi} \chi$$

We can obtain the effective interaction with the nucleons,

$$\begin{bmatrix} 1011.3300 \\ 1503.01780 \end{bmatrix}$$

$$f_{p,n} = g_V^\chi \frac{(2g_V^{u,d} + g_V^{d,u})}{2m_{Z'}^2}$$

So the ration between proton and neutron interactions is

$$\frac{f_n}{f_p} = \frac{2g_V^d + g_V^u}{2g_V^u + g_V^d}$$

Direct Detection Exclusion Bounds.

So in order to compute the exclusion bounds we have to study the event rate of a dark matter particle interacting with a given detector (Z,A),

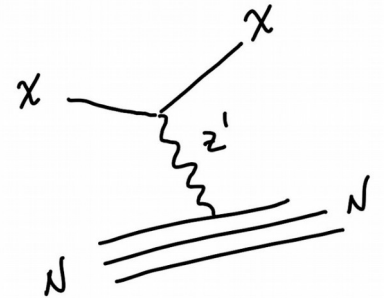
$$R = \sum_i \eta_i \sigma_{A_i}^0 \times I_{A_i}$$

where η_i are the natural abundance of the isotope A_i .

The spin independent cross section at zero momentum (A_i) can be written as,

$$\sigma_{A_i}^0 = \frac{4\mu_{A_i}^2}{\pi} [f_p Z + f_n (A_i - Z)]^2 \quad \mu_{A_i} = m_{A_i} m_\chi / (m_{A_i} + m_\chi)$$

The experimental limits are presented in terms of the DM-nucleon cross section σ_N^Z assuming $f_p = f_n$ making $\sigma_N^Z = \sigma_p$.



Direct Detection Exclusion Bounds.

If we assume different DM couplings to protons and neutrons (isospin violation) then the DM-nucleon cross section is written as

$$\sigma_N^Z = \sigma_p \frac{\sum_i \eta_i \mu_{A_i}^2 [Z + (A_i - Z) f_n / f_p]^2}{\sum_i \eta_i \mu_{A_i}^2 A_i^2}$$

Now the bounds from the experimental results change depending on the amount of isospin violation. We can quantify the shift in the experimental bounds with the ratio,

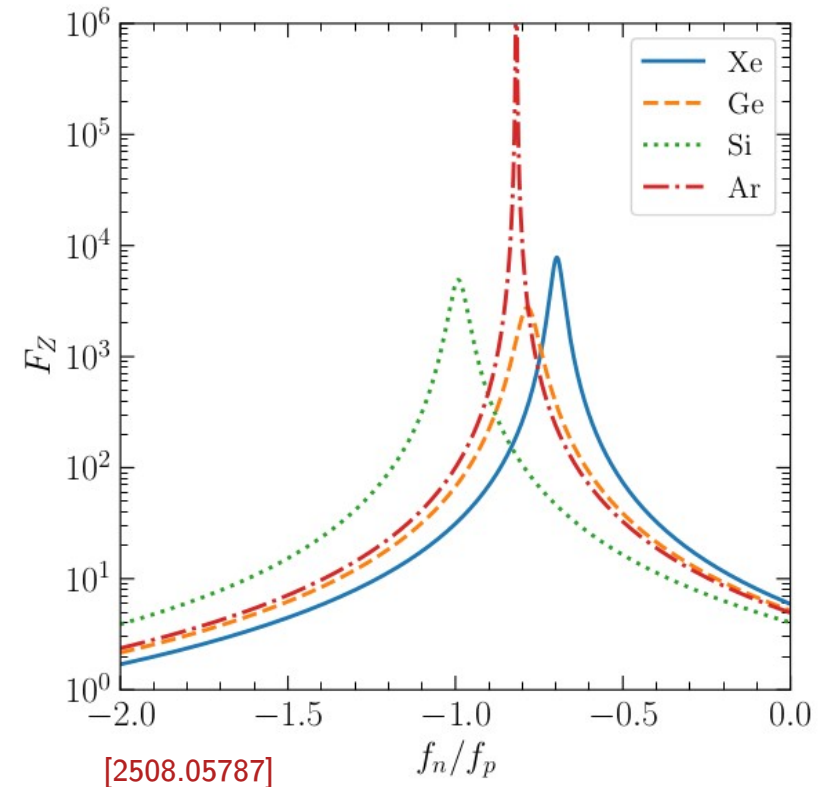
$$F_Z \equiv \frac{\sigma_p}{\sigma_N^Z} = \frac{\sum_i \eta_i \mu_{A_i}^2 A_i^2}{\sum_i \eta_i \mu_{A_i}^2 [Z + (A_i - Z) f_n / f_p]^2}$$

Direct Detection Exclusion Bounds.

$$F_Z \equiv \frac{\sigma_p}{\sigma_N^Z} = \frac{\sum_i \eta_i \mu_{A_i}^2 A_i^2}{\sum_i \eta_i \mu_{A_i}^2 [Z + (A_i - Z) f_n / f_p]^2}$$

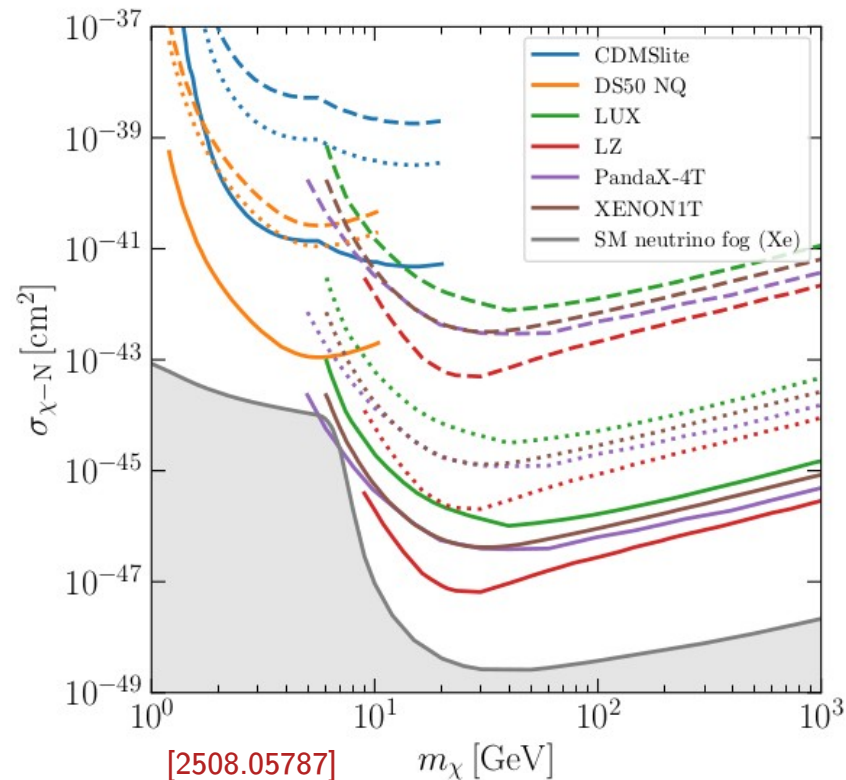
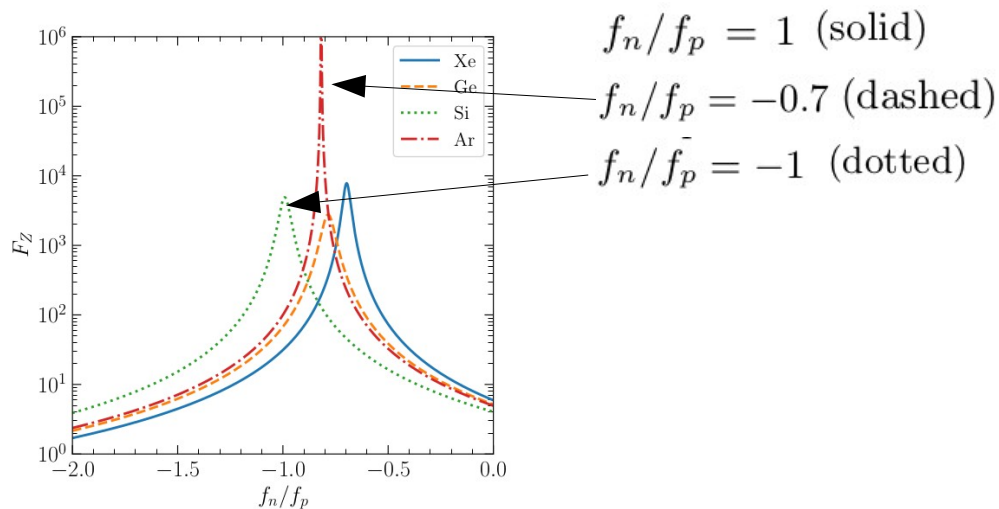
^{54}Xe	A_i	128	129	130	131	132	134	136
	η_i (%)	1.9	26	4.1	21	27	10	8.9
^{32}Ge	A_i	70	72	73	74	76		
	η_i (%)	21	28	7.7	36	7.4		
^{28}Si	A_i	28	29	30				
	η_i (%)	92	4.7	3.1				
^{18}Ar	A_i	40						
	η_i (%)	96						

[1102.4331]



Direct Detection Exclusion Bounds.

We can observe how the bounds change depending on the amount of isospin violation and also the material of the detector.



Neutrino Fog.

If the dark sector is also connected to the leptonic sector of the SM, the neutrino interactions can also change respect to the standard picture.

Neutrinos coming from the Sun can interact with the nuclei of the direct detection experiments via Coherent Elastic Neutrino-Nucleus Scattering (CE ν NS). The typical cross section for this process can be written as

$$\frac{d\sigma_{\text{SM}}^{\nu}}{dE_R} = \frac{G_F^2 m_N}{4\pi} \mathcal{F}(E_R)^2 (Q_V^{\text{SM}})^2 \left(1 - \frac{E_R m_N}{2E_\nu^2}\right) \quad \begin{array}{l} m_N E_R \ll m_Z^2 \\ E_\nu \ll m_N \end{array}$$

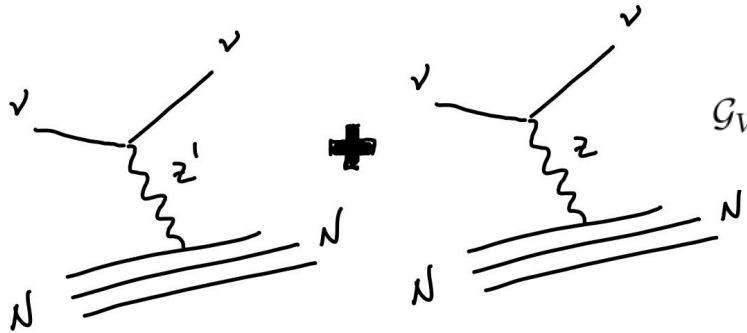
where $Q_V^{\text{SM}} = N - Z(1 - 4\sin^2 \theta_w)$ and the Helm nucleus form factor is

$$\mathcal{F}(E_R) = 3 \frac{j_1(q(E_R)r_n)}{q(E_R)r_n} e^{-\frac{1}{2}s^2 q(E_R)^2} \quad \begin{array}{l} q(E_R) = \sqrt{2m_N E_R} \quad r_n = a_n A^{1/3} + b_n \\ s \simeq 0.9 \text{ fm} \quad a_n = 1.14 \text{ fm} \quad b_n = 0 \end{array}$$

Neutrino Fog.

If the new physics modifies the neutral currents, then the differential cross section can be written as

$$\frac{d\sigma_V^\nu}{dE_R} = \mathcal{G}_V \frac{d\sigma_{SM}^\nu}{dE_R} \quad [1604.01025, 1701.07443]$$



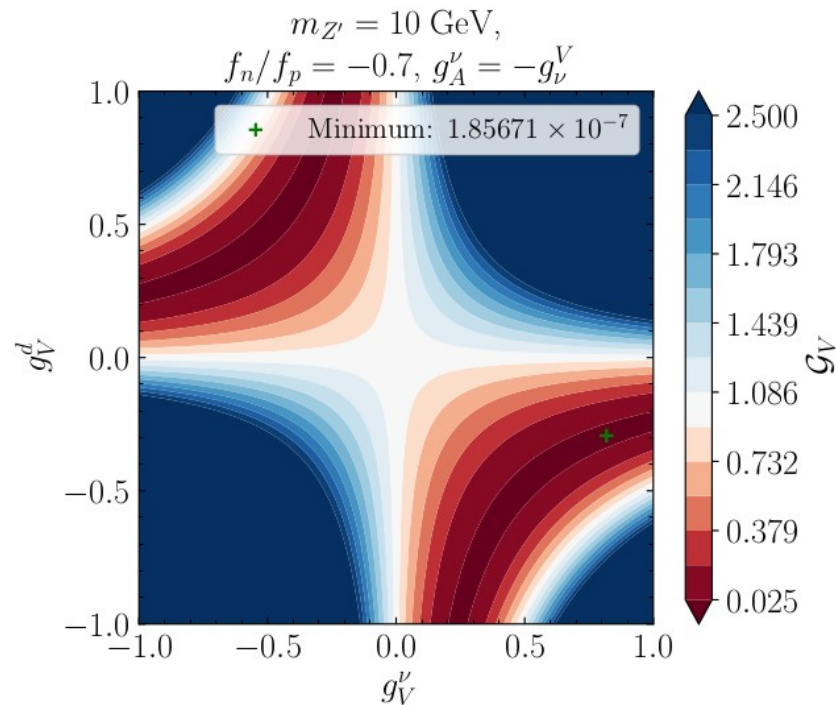
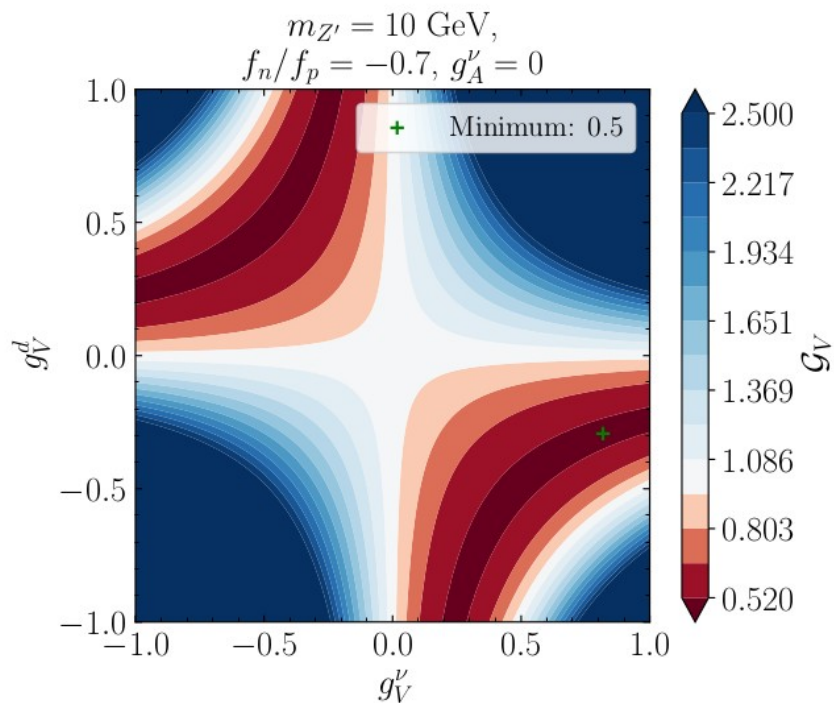
$$\mathcal{G}_V = 1 - \frac{2\sqrt{2}}{G_F} \frac{Q_V}{Q_V^{SM}} \frac{g_V^\nu - g_A^\nu}{2m_N E_R + m_{Z'}^2} + \left(\frac{2}{G_F}\right)^2 \left(\frac{Q_V}{Q_V^{SM}}\right)^2 \frac{(g_V^\nu)^2 + (g_A^\nu)^2}{(2m_N E_R + m_{Z'}^2)^2}$$

$$Q_V = Z(2g_V^u + g_V^d) + (A - Z)(2g_V^d + g_V^u)$$

we can see that if we have $\mathcal{G}_V < 1$ there is a reduction in the neutrino event rate and similarly if $\mathcal{G}_V > 1$ the event rate of neutrinos will be higher than that of the SM.

Neutrino Fog.

$$g_V = 1 - \frac{2\sqrt{2}}{G_F} \frac{Q_V}{Q_V^{SM}} \frac{g_V^\nu - g_A^\nu}{2m_N E_R + m_{Z'}^2} + \left(\frac{2}{G_F}\right)^2 \left(\frac{Q_V}{Q_V^{SM}}\right)^2 \frac{(g_V^\nu)^2 + (g_A^\nu)^2}{(2m_N E_R + m_{Z'}^2)^2}$$



Neutrino Fog.

In order to compute the neutrino floor we have to compute the number of neutrino events hitting the detector. The differential cross section is

$$\frac{dN_{\nu-N}}{dE_R} = \frac{\varepsilon}{m_N} \int_{E_\nu^{\min}} dE_\nu \mathcal{A}(E_R) \frac{d\Phi}{dE_\nu} \frac{d\sigma^\nu}{dE_R}$$

and $E_\nu^{\min} = \sqrt{m_N E_R / 2}$ is the minimum energy of the incoming neutrinos to produce a nuclear recoil. The total number of events is then written as

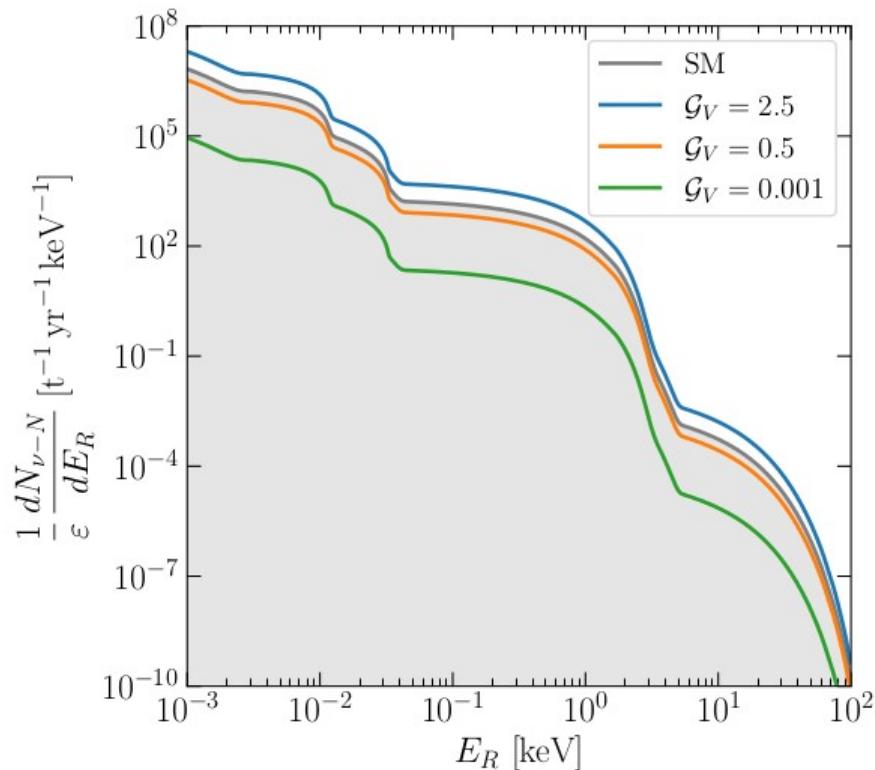
$$N_{\nu-N} = \int_{E_{\text{th}}} dE_R \frac{dN_{\nu-N}}{dE_R}$$

and E_{th} is the recoil energy threshold.

Neutrino Fog.

We can see how the differential event rate changes for different values of \mathcal{G}_V .

As we predicted the differential event rate is greater for values greater than one and smaller for values smaller than one.



Neutrino Fog.

[1307.5458, 1701.07443, 1809.06385, 2006.05981]

Our approach to compute the neutrino floor is the following. We will compute the exposure required to have 1 neutrino event produced by CE ν NS in the detector of a given nucleus and a given energy threshold.

$$\varepsilon(E_{\text{th}}) = \frac{1}{\int_{E_{\text{th}}} dE_R \frac{dN^\nu}{dE_R}}$$

This exposure has to be calculated for every E_{th} in order to obtain the background-free exclusion limit, which at 90% C.L. corresponds to 2.3 DM events.

Now we have to compute the number of DM events to match the 2.3 events.

Neutrino Fog.

The differential number of DM events per recoil energy can be written as

$$\frac{dN_{\chi-N}}{dE_R} = \varepsilon \frac{\rho_{\text{DM}} \sigma_0^A}{2m_\chi \mu_n^2} \mathcal{F}^2(E_R) \int_{v_{\text{min}}} d^3v \frac{f(v)}{v}$$

with $\sigma_{A_i}^0 = \frac{4\mu_{A_i}^2}{\pi} [f_p Z + f_n (A_i - Z)]^2$. So the number of DM events is

$$N_{\chi-N} = \int_{E_{\text{th}}} dE_R \frac{dN_{\chi-N}}{dE_R}$$

In order to compute the neutrino floor we solve the equation of number of events for different values of E_{th} from 0.001 keV to 100 keV.

$$\int_{E_{\text{th}}} dE_R \frac{dR^\chi}{dE_R} = \frac{2.3}{1} \int_{E_{\text{th}}} dE_R \frac{dN^\nu}{dE_R}$$

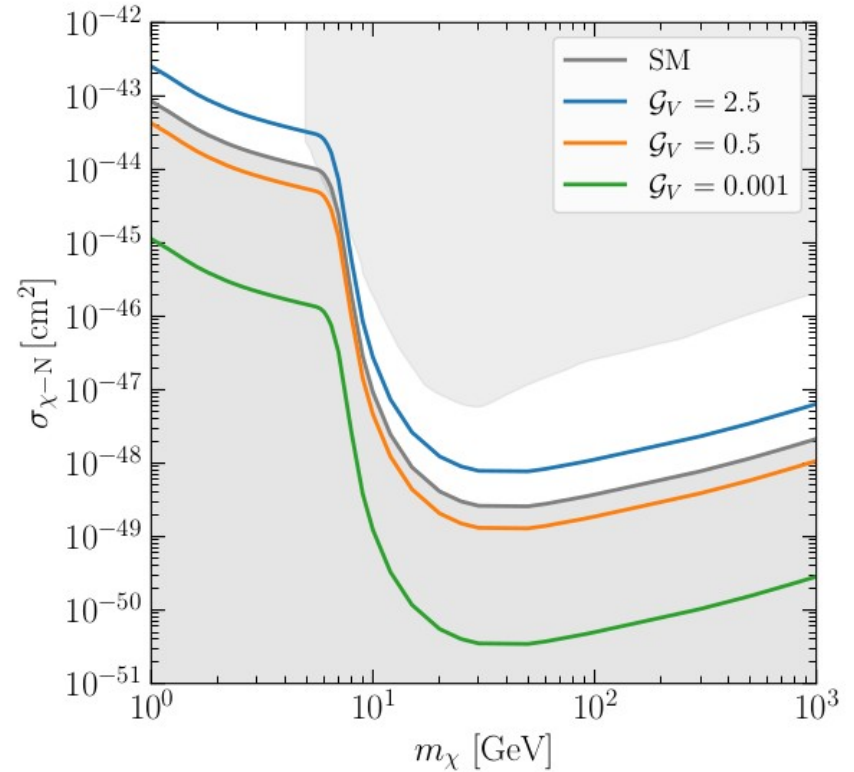
Each E_{th} will generate a curves in the mass-cross section space. To obtain the neutrino floor we take the lowest cross section for each mass to obtain the limit at the 90% C.L.

Neutrino Fog.

In order to compute the neutrino floor we solve the equation of number of events for different values of E_{th} from 0.001 keV to 100 keV.

$$\int_{E_{\text{th}}} dE_R \frac{dR^X}{dE_R} = \frac{2.3}{1} \int_{E_{\text{th}}} dE_R \frac{dN^\nu}{dE_R}$$

Each E_{th} will generate a curves in the mass-cross section space. To obtain the neutrino floor we take the lowest cross section for each mass to obtain the limit at the 90%C.L.



Results.

We will define the qualitative parameter Δ that represents the difference in the allowed parameter space with respect to the standard case (isospin conserving).

- **Type I** ($\Delta < 0$):
The parameter space gets reduced.
- **Type II** ($\Delta = 0$):
The parameter space remains the same
- **Type III** ($\Delta > 0$):
The parameter space gets larger

		Neutrino floor		
		Down	Unchanged	Up
Dark matter bound	Down	IIa ($\Delta = 0$) IIIa ($\Delta > 0$)		Disfavoured by exp. results
	Unchanged	IIIc	SM	I
	Up	IIIc		IIb ($\Delta = 0$) IIIb ($\Delta > 0$)

Results.

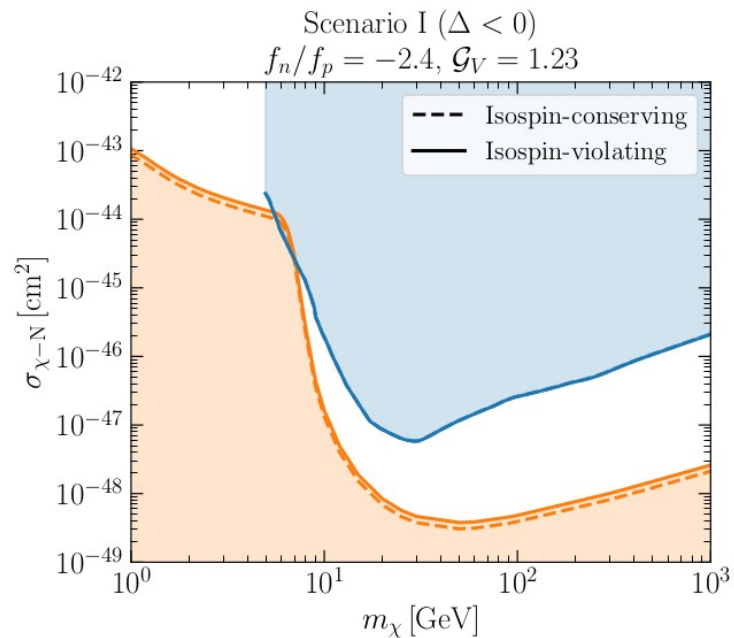
We will define the qualitative parameter Δ that represents the difference in the allowed parameter space with respect to the standard case (isospin conserving).

	f_n/f_p	F_Z^{Xe}	\mathcal{G}_V	g_V^ν	g_A^ν	g_V^d	$m_{Z'} [\text{GeV}]$
Scenario I	-2.4	0.99	1.23	0.55	-0.55	-0.5	750
Scenario IIA	1.7	0.5	0.52	0.6	-0.6	0.6	1000
Scenario IIB	0.4	2.4	2.38	0.5	0.0	0.04	300
Scenario IIIA	2.0	0.4	0.007	0.6	-0.6	0.67	550
Scenario IIIB	-0.7	7640.0	1.23	0.5	0.0	0.1	10
Scenario IIIC	0.95	1.06	0.12	0.25	-0.25	0.3	400
Scenario IIID	-1.0	31.27	0.15	0.45	-0.45	0.4	150

		Neutrino floor		
		Down	Unchanged	Up
Dark matter bound	Down	IIa ($\Delta = 0$) IIIa ($\Delta > 0$)		Disfavoured by exp. results
	Unchanged	IIIc	SM	I
	Up	IIId		IIb ($\Delta = 0$) IIIb ($\Delta > 0$)

Results.

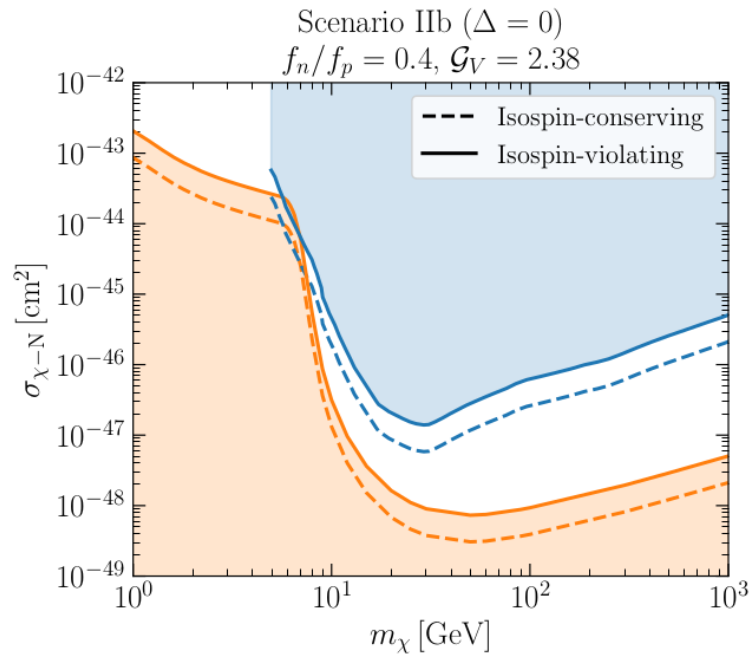
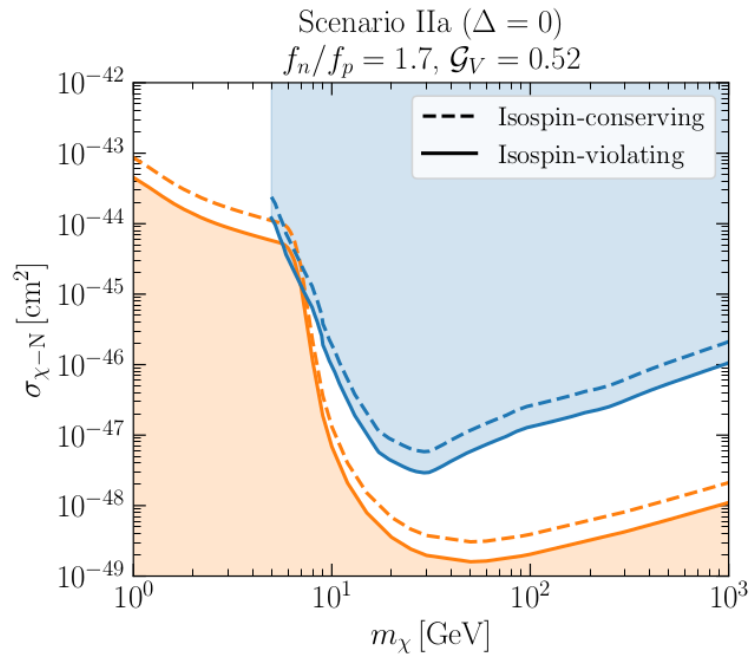
- Type I ($\Delta < 0$):



	f_n/f_p	F_Z^{Xe}	\mathcal{G}_V	g_V^ν	g_A^ν	g_V^d	$m_{Z'}$ [GeV]
Scenario I	-2.4	0.99	1.23	0.55	-0.55	-0.5	750

Results.

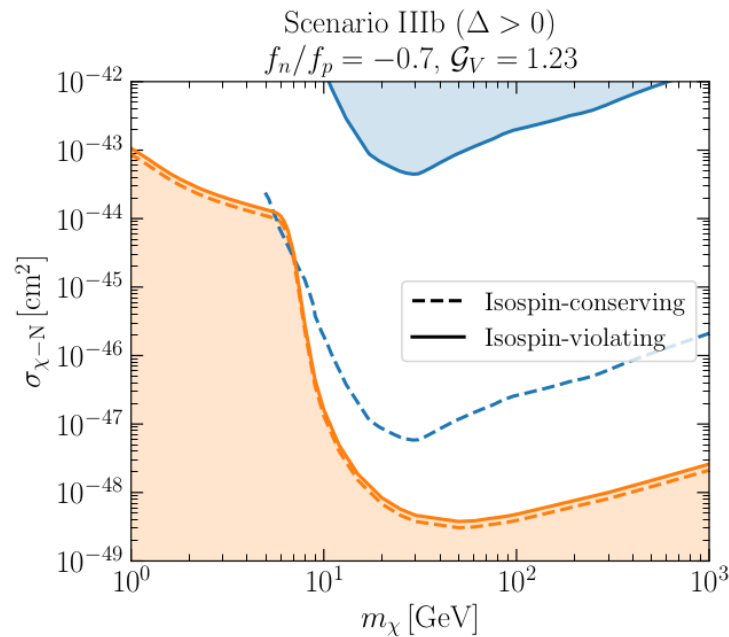
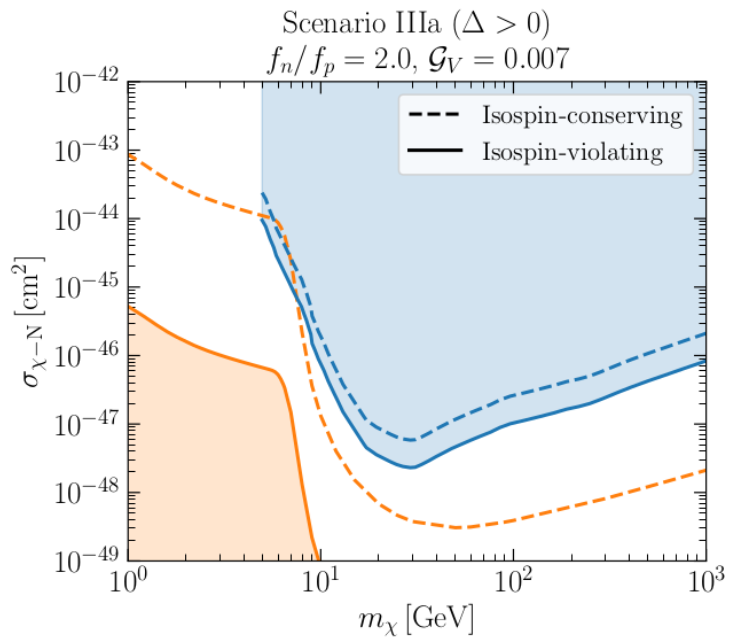
- Type II ($\Delta = 0$):



	f_n/f_p	F_Z^{Xe}	\mathcal{G}_V	g_V^ν	g_A^ν	g_V^d	$m_{Z'}$ [GeV]
Scenario IIA	1.7	0.5	0.52	0.6	-0.6	0.6	1000
Scenario IIB	0.4	2.4	2.38	0.5	0.0	0.04	300

Results.

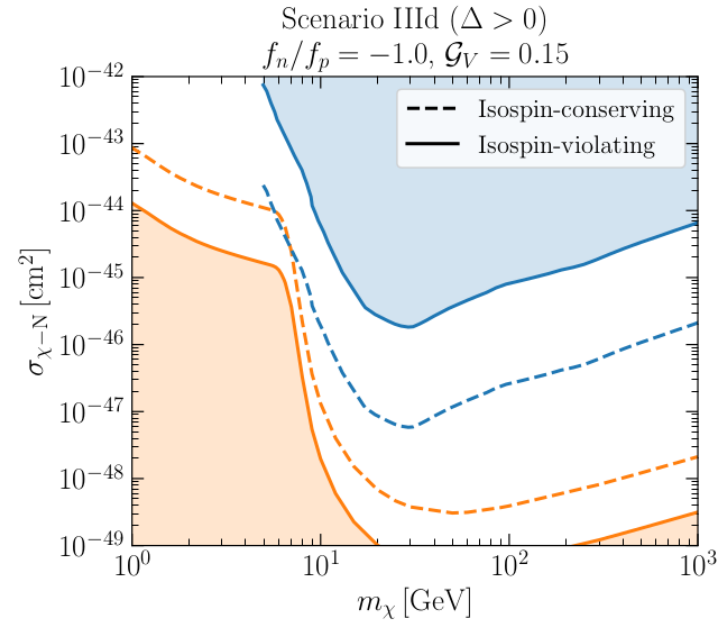
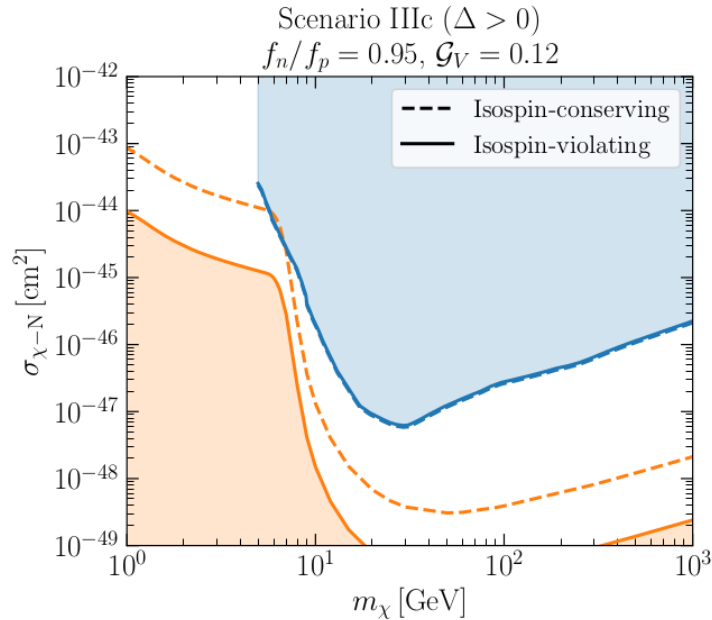
- Type III ($\Delta > 0$):



	f_n/f_p	F_Z^{Xe}	\mathcal{G}_V	g_V^ν	g_A^ν	g_V^d	$m_{Z'}$ [GeV]
Scenario IIIA	2.0	0.4	0.007	0.6	-0.6	0.67	550
Scenario IIIB	-0.7	7640.0	1.23	0.5	0.0	0.1	10

Results.

• Type III ($\Delta > 0$):



	f_n/f_p	F_Z^{Xe}	\mathcal{G}_V	g_V^ν	g_A^ν	g_V^d	$m_{Z'}$ [GeV]
Scenario IIIc	0.95	1.06	0.12	0.25	-0.25	0.3	400
Scenario IIId	-1.0	31.27	0.15	0.45	-0.45	0.4	150

UV origin of IVDM.

The isospin violating dark matter presents a richer phenomenology that could explain why there is no hint of DM in the direct detection experiments.

One can argue that IVDM is not “natural”, however the SM is already isospin violating, for example the Z boson interaction to neutrons and protons,

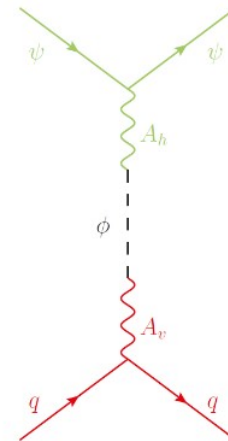
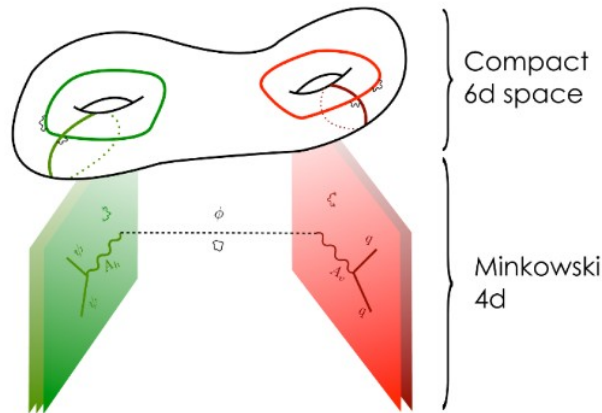
$$\frac{f_n}{f_p} = \frac{2V_d + V_u}{V_d + 2V_u} = -\frac{1}{1 - 4\sin^2\theta_W} \approx -22.18$$

It is fair to ask if there is any UV completion that can manifest IVDM at low energies.

UV origin of IVDM.

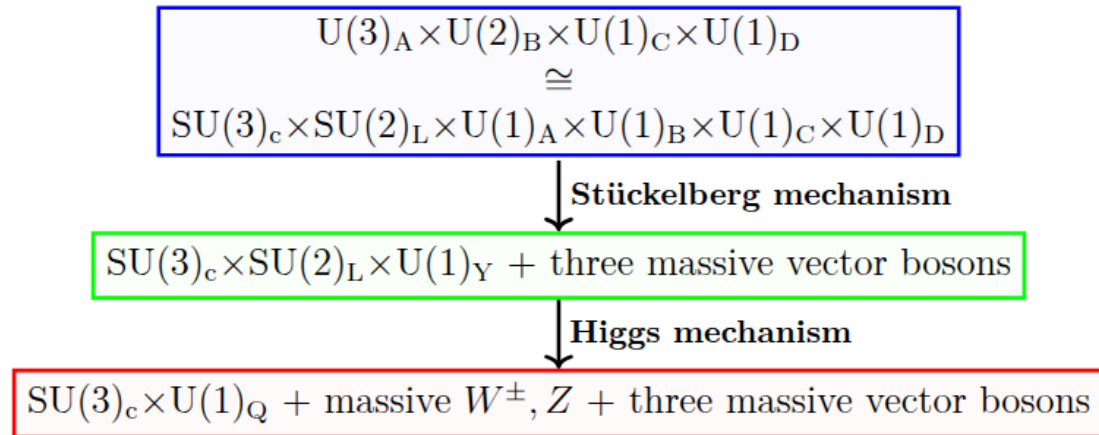
[[hep-th/0105155](#), [1401.5890](#), [1503.0178](#), ...]

In type IIA string theory one can construct sets of interacting D6-branes wrapped on an orientifolded six-torus. A stack of N overlapping D-branes gives rise to a $U(N)$ gauge factor. With the correct amount of stacking branes one can get the SM or the dark sector. Closed strings such as the graviton and RR axion fields couple to the gauge bosons, allowing the mixing between them.



UV origin of IVDM.

In type IIA string theory one can construct sets of interacting D6-branes wrapped on an orientifolded six-torus. A stack of N overlapping D-branes gives rise to a $U(N)$ gauge factor. With the correct amount of stacking branes one can get the SM or the dark sector. Closed strings such as the graviton and RR axion fields couple to the gauge bosons, allowing the mixing between them.



UV origin of IVDM.

The charge assignment under these gauge groups is

$$Y = \frac{1}{6} (Q_A - 3Q_C + 3Q_D)$$

Matter field	SU(3)×SU(2)	Charges				Y
		Q _A	Q _B	Q _C	Q _D	
q_L	2(3, 2)	1	1	0	0	1/6
Q_L	(3, 2)	1	-1	0	0	1/6
U_R	3(3̄, 1)	-1	0	1	0	-2/3
D_R	3(3̄, 1)	-1	0	-1	0	1/3
L	3(1, 2)	0	-1	0	-1	-1/2
E_R	3(1, 1)	0	0	-1	1	1
N_R	3(1, 1)	0	0	1	1	0

And we can obtain the couplings to the lightest Z'

$$g_\alpha^{Z'} = a(Q_A)_\alpha + b(Q_B)_\alpha + c(Q_C)_\alpha + d(Q_D)_\alpha + \sum_{i=1}^m h_i (Q_i^{(h)})_\alpha$$

$$\left\{ \begin{array}{ll} g_{\bar{u}_L}^{Z'} = a + b, & g_{\bar{u}_R}^{Z'} = -a + c \\ g_{\bar{d}_L}^{Z'} = a + b, & g_{\bar{d}_R}^{Z'} = -a - c \\ g_{t_L}^{Z'} = a - b, & g_{t_R}^{Z'} = -a + c \\ g_{b_L}^{Z'} = a - b, & g_{b_R}^{Z'} = -a - c \\ g_{l_L}^{Z'} = -b - d, & g_{l_R}^{Z'} = -c + d \\ g_{\nu_L}^{Z'} = -b - d, & g_{\nu_R}^{Z'} = c + d \end{array} \right. \Rightarrow \left\{ \begin{array}{ll} g_{\bar{u}}^V = b + c, & g_{\bar{u}}^A = -2a - b + c \\ g_{\bar{d}}^V = b - c, & g_{\bar{d}}^A = -2a - b - c \\ g_t^V = -b + c, & g_t^A = -2a + b + c \\ g_b^V = -b - c, & g_b^A = -2a + b - c \\ g_l^V = -b - c, & g_l^A = b - c + 2d \\ g_\nu^V = -b + c, & g_\nu^A = b + c + 2d, \end{array} \right.$$

UV origin of IVDM.

With the couplings of the Z' to the SM particles one can then compute the effective interactions to neutrons and protons

$$\frac{f_n}{f_p} = \frac{g_u^V + 2g_d^V}{2g_u^V + g_d^V} \longrightarrow \frac{f_n}{f_p} = \frac{3b/c - 1}{3b/c + 1}$$

Here in general we will have $f_n \neq f_p$ so IVDM appears naturally in intersection D6-branes.

UV origin of IVDM.

With the couplings of the Z' to the SM particles one can then compute the effective interactions to neutrons and protons

$$\frac{f_n}{f_p} = \frac{g_u^V + 2g_d^V}{2g_u^V + g_d^V} \longrightarrow \frac{f_n}{f_p} = \frac{3b/c - 1}{3b/c + 1}$$

Here in general we will have $f_n \neq f_p$ so IVDM appears naturally in intersection D6-branes.

However, if we have IVDM and affects to its detectability in direct detection experiments, how can we detect it?

UV origin of IVDM.

We can make use of the LHC in order to detect the Z' and the dark matter!!!

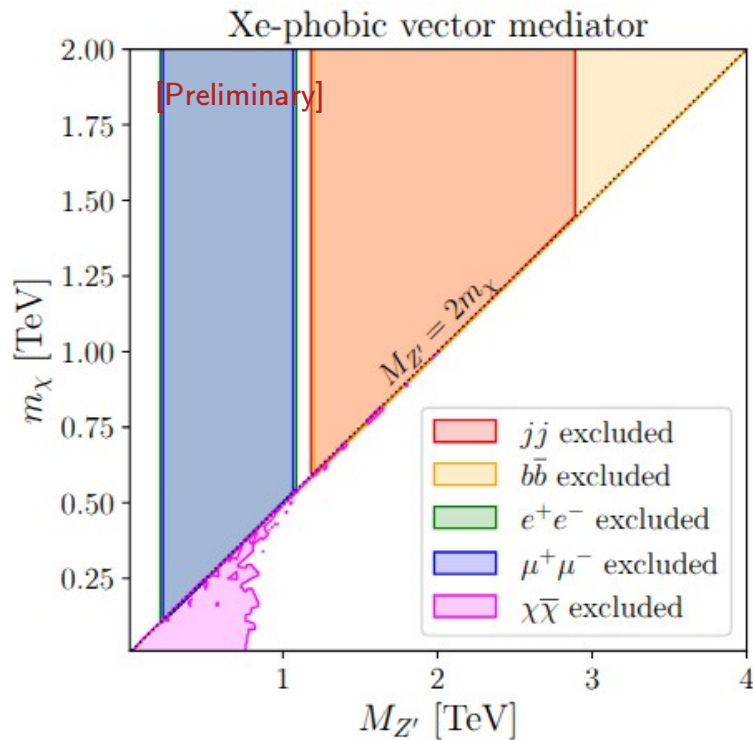
Let us assume the three scenarios: a) Xenon-phobic b) leptophilic and c) leptophobic

Mediator	a	b	c	d	$g_{\chi L}$	$g_{\chi R}$
Xe-phobic vector	0.07	0.00058	0.01	0.006	1	1
Xe-phobic axial-vector	0.07	0.00058	0.01	0.006	1	-1
Leptophilic vector	-0.05	-0.005	0.005	0.06	1	1
Leptophilic axial-vector	-0.05	-0.005	0.005	0.06	1	-1
Leptophobic vector	-0.25	-0.1	-0.1	0.1	1	1
Leptophobic axial-vector	-0.25	-0.1	-0.1	0.1	1	-1

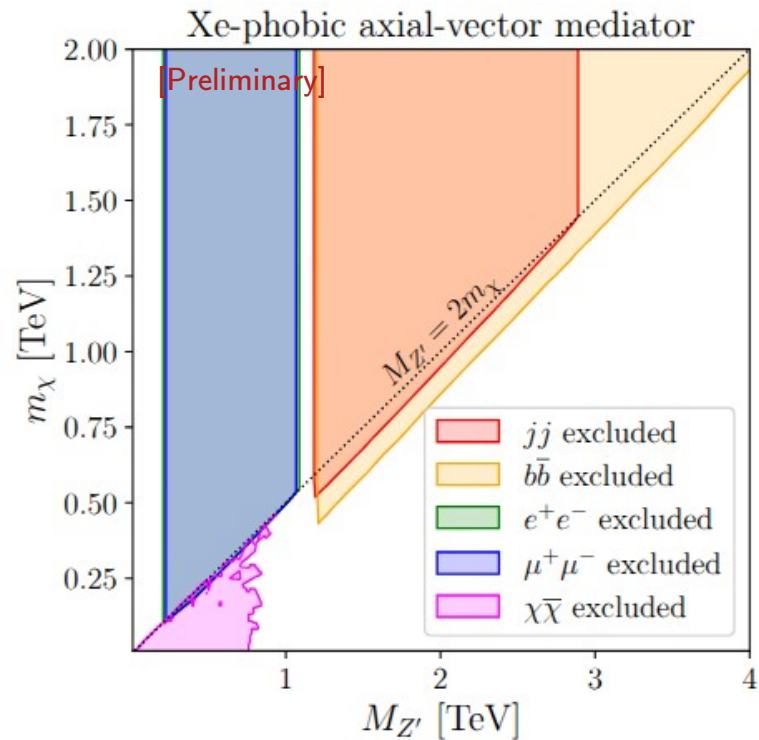
[2005.05194,2109.13194]

In order to test the IVDM Z' boson we make use of the public tool Z' -explorer that confronts Z' models against the latest searches in ATLAS and CMS in the dijet, bb , tt , ee , $\mu\mu$, $\tau\tau$, WW and Zh

UV origin of IVDM.

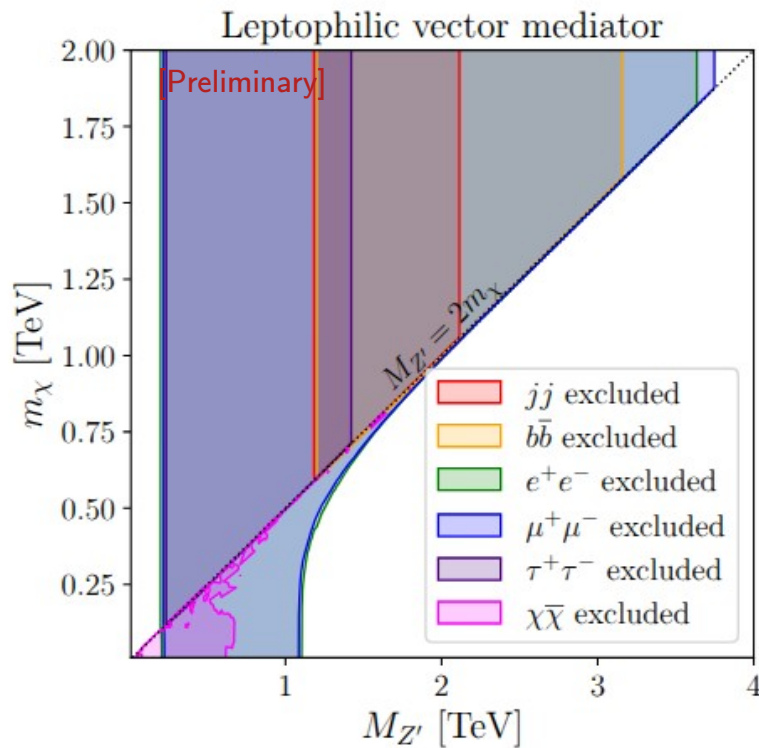


(a)

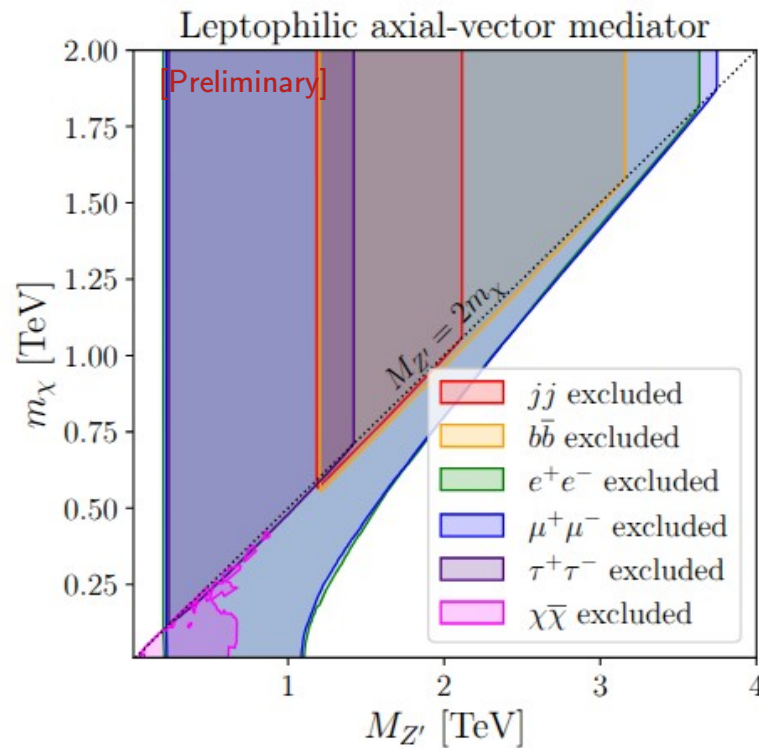


(b)

UV origin of IVDM.

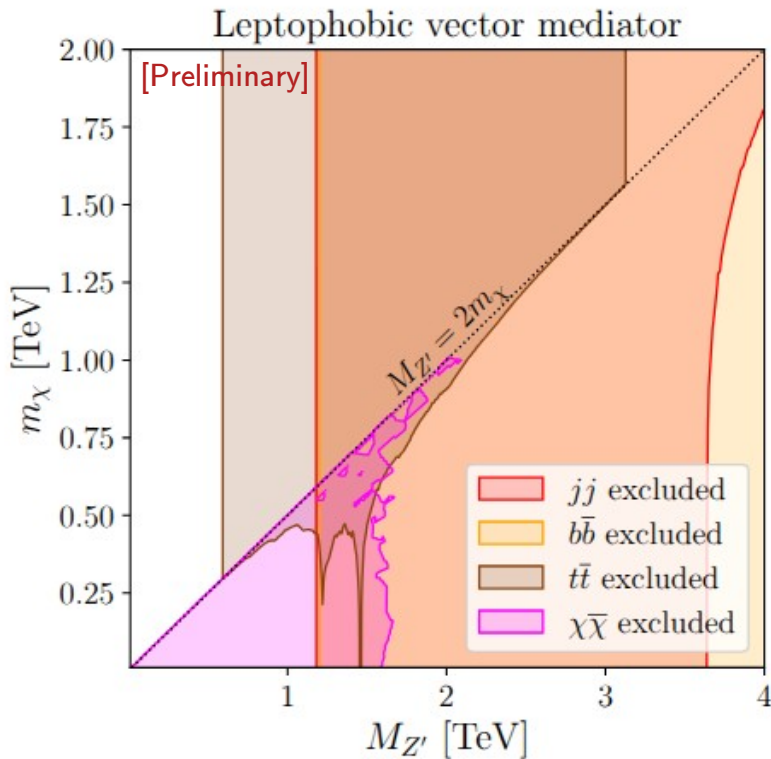


(a)

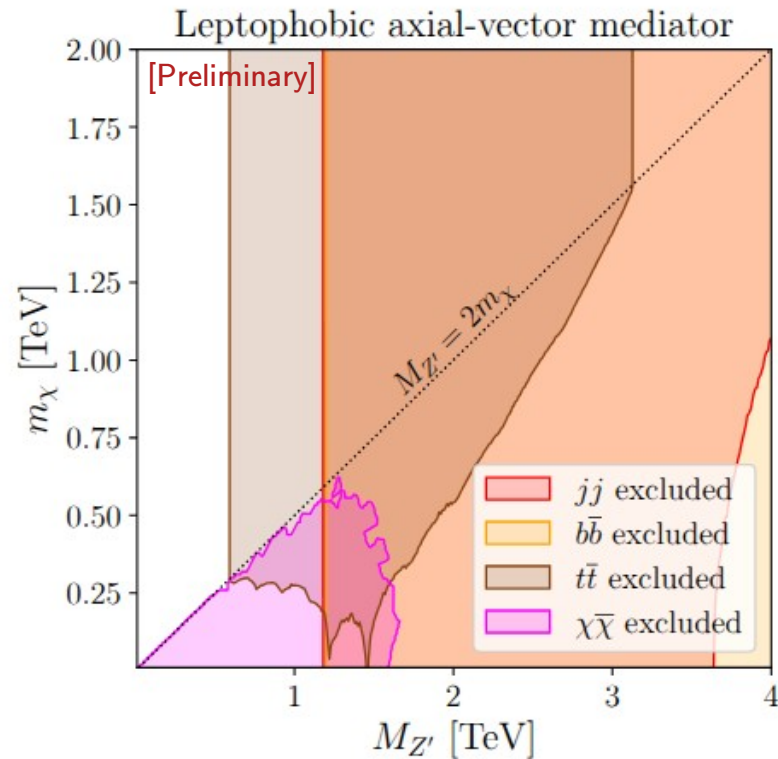


(b)

UV origin of IVDM.



(a)



(b)

Conclusions.

- Isospin Violating Dark Matter is a natural and general assumption when dealing with DM sectors, specially U(1).
- The difference between the interaction to neutrons and protons can change both the DM and neutrino interactions with nuclei.
- This allow the parameter space of the dark matter, in some cases, to expand with respect to the standard scenario. It also can explain the lack of DM events in direct detection experiments.
- IVDM can arise naturally. It could also be understood as a phenomenological aspect of type IIa string theory with D6-branes.
- In the construction of the SM with D6-branes several Z' appears with couplings to the SM that generally break isospin.
- LHC searches can help as a complementary approach to look for Dark Matter.

Back-up slides.

