Z'-mediated Majorana dark matter: complementarity of direct-detection and LHC searches

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arXiv:2202.02292 [hep-ph]

(JHEP __ (2022) ___)

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Motivations

The null results relative to the detection of Dark Matter (DM) scattering events in Direct Detection (DD) experiments such as **LUX** and **XENON**, impose severe constraints on the size of DM-SM interaction.

It is possible to retain sizeable couplings while <u>suppressing the event rate by tuning the interactions to up and down quarks:</u>

- In the case of coherent spin-independent (SI) cross sections, the cancellation in a particular isotope can be effected by tuning the non-relativistic coefficients of the proton and neutron operator, i.e. by breaking isospin symmetry.

J. Kopp, V. Niro, T. Schwetz, J. Zupan
PoS IDM2010 (2011) 118

- **In the following we focus on the case with axial interactions to the DM (Majorana DM)**

  - Spin-dependent (SD) contributions are suppressed by either the absence of coherent enhancement or via its dependence on the velocity of the DM in the halo or on the momentum exchange between the DM and the nucleus.

  - Suppression of the SD event rate by isospin-breaking interactions is more complicated since axial and vectorial quark currents contribute equally to the scattering cross section.

C. Blanco, M. Escudero, D. Hooper, S.J. Witte
JCAP 11 (2019) 024

Topics of this talk

- **EFT for direct detection of Majorana DM:**
  - ➢ Parametrisation of Wilson coefficients
  - ➢ Suppression of the scattering rate
- **UV completion constraints and their effect on:**
  - ➢ Direct detection
  - ➢ LHC contrains
- **Conclusions**

EFT for Majorana DM

- **EFT for direct detection of Majorana DM:**
  - Parametrisation of Wilson coefficients
  - Suppression of the scattering rate
- **UV completion constraints and their effect on:**
  - Direct detection
  - LHC contrains
- **Conclusions**

Effective Lagrangian and operators

Minimal BSM extension of the SM containing a Majorana singlet χ as DM candidate interacting with the SM through a heavy *Z'*:

The effective Lagrangian contains an axial-vector DM current coupled to the SM:

$$\mathcal{L}_{\mathrm{DMEFT}} = \sum_{i,d} C_i^{(d)} Q_i^{(d)} \equiv \frac{\hat{c}_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)}$$

where the dimension-6 operators are:

$$Q_{6,i}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{Q}_L^i\gamma^\mu Q_L^i)\,, \quad Q_{7,i}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{u}_R^i\gamma^\mu u_R^i)\,, \quad Q_{8,i}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{d}_R^i\gamma^\mu d_R^i)$$

After Electroweak Symmetry Breaking the operators match onto:

$$\mathcal{L}_{\mathrm{DMEFT}} \xrightarrow{\mathrm{EWSB}} \sum_{i,d} \mathscr{C}_i^{(d)} \mathcal{Q}_i^{(d)}$$

$$\mathcal{Q}_{2,q}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu q)\,, \qquad \mathcal{Q}_{4,q}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)$$

Effective Lagrangian and operators

Interactions between DM and 1st gen quarks written in terms of Wilson coefficients:

$$(A \otimes V)_u: \quad \mathscr{C}^{(6)}_{2,u} = C^{(6)}_{7,1} + C^{(6)}_{6,1}\,, \qquad (A \otimes V)_d: \quad \mathscr{C}^{(6)}_{2,d} = C^{(6)}_{8,1} + C^{(6)}_{6,1}\,,$$

$$(A \otimes A)_u: \quad \mathscr{C}^{(6)}_{4,u} = C^{(6)}_{7,1} - C^{(6)}_{6,1}\,, \qquad (A \otimes A)_d: \quad \mathscr{C}^{(6)}_{4,d} = C^{(6)}_{8,1} - C^{(6)}_{6,1}\,,$$

- We can eliminate either the vectorial **V** or axial **A** currents on the SM side chosing:

  $$C^{(6)}_{6,1} = \mp C^{(6)}_{7,1} = \mp C^{(6)}_{8,1}$$

  which automatically enforces isospin-symmetric EFT coefficients.

- If we allow isospin breaking **A ⊗ V** and **A ⊗ A** currents contribute equally to the SD cross section for heavy nuclei (A ~ 100).

- Unlike in the SI case, the suppression of DD rates is more complicated as only special regions in the parameter space allow for the <u>simultaneous suppression</u> of the contributions from both operators.

DD and LHC observables

Direct Detection rate:

We calculate the event rate for experiments:

$$\frac{d\mathcal{R}}{dE_{\rm R}} = \frac{\rho_\chi}{m_A m_\chi} \int_{v_{\rm min}} \frac{d\sigma}{dE_{\rm R}} v f_\oplus(\vec{v}) d^3\vec{v},$$

XENON1T (exposure: *1300 kg x 278.8 days*)

XENONnT (exposure: *20 ton x year*)

E_R = recoil energy → integrated over *[3, 40] keV*
m_A = nucleus mass
ρ_χ = local DM density
f(v) = Boltzmann velocity distribution

Coefficients of the effective theory computed with **`DirectDM`**

F. Bishara, J. Brod, G. Grinstein, J. Zupan
arXiv:1708.02678

Nuclear responses and direct-detection rates computed with **`DMFormFactor`**

N. Anand, A.L. Fitzpatrick, W. Haxton
Phys. Rev. C 89, 065501 (2014)

LHC limits:

Monojet analysis reproduced (with some effort) from:
ATLAS Collaboration
Phys. Rev. D 103, 112006 (2021)

eploying the chain of tools:
`MadGraph5_aMC@NLO + PYTHIA8 + DELPHES`

Dijet limits obtained from:

- Low mass region: [0.7, 2] TeV
29.3 fb^{-1} dataset
ATLAS Collaboration
Phys. Rev. Lett. 121 081801 (2018)

- High mass region: > 2 TeV
139 fb^{-1} dataset
ATLAS Collaboration
JHEP 03 145 (2020)

Ditaus limits recasted from:
ATLAS Collaboration
JHEP 07 157 (2015)

Mass region: [0.5, 2.5] TeV
19.5 – 20.3 fb^{-1} dataset

(combination of hadronic and leptonic channels)

XENON sensitivity

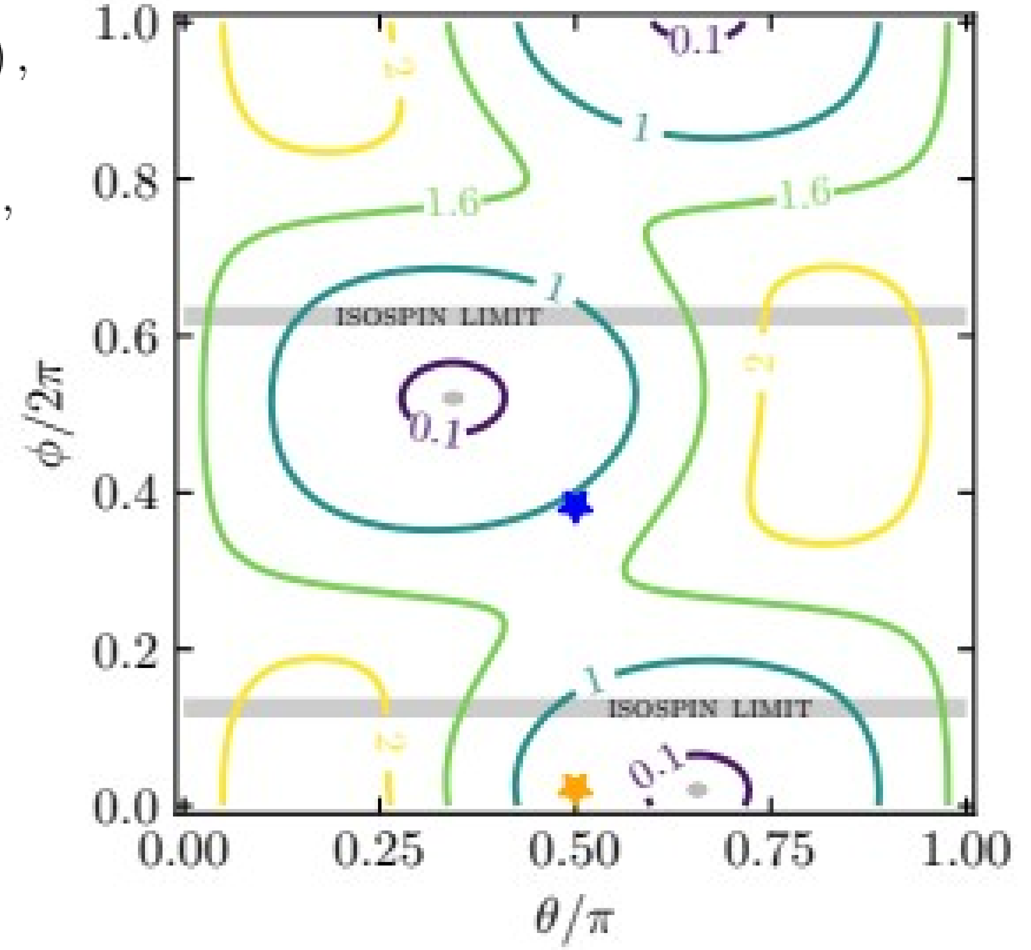
Parametrisation of Wilson coefficients:

$$C_{6,1}^{(6)} \to \frac{g'^2}{\Lambda^2}\cos\theta\,, \qquad Q_{6,i}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{Q}_L^i\gamma^\mu Q_L^i)\,,$$

$$C_{7,1}^{(6)} \to \frac{g'^2}{\Lambda^2}\sin\theta\cos\phi\,, \quad Q_{7,i}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{u}_R^i\gamma^\mu u_R^i)\,,$$

$$C_{8,1}^{(6)} \to \frac{g'^2}{\Lambda^2}\sin\theta\sin\phi \quad Q_{8,i}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{d}_R^i\gamma^\mu d_R^i)$$

Relative DD event rate [m_χ = *100 GeV*]



Combinations of θ and Φ represent different *U(1)'* charge assignments to SM fermions and the Majorana DM.

We can achieve suppression of events up to a factor 10^{-2} for certain choices of the couplings.

XENON sensitivity

Parametrisation of Wilson coefficients:

$$C_{6,1}^{(6)} \to \frac{g'^2}{\Lambda^2}\cos\theta\,, \qquad Q_{6,i}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar Q_L^i\gamma^\mu Q_L^i)\,,$$

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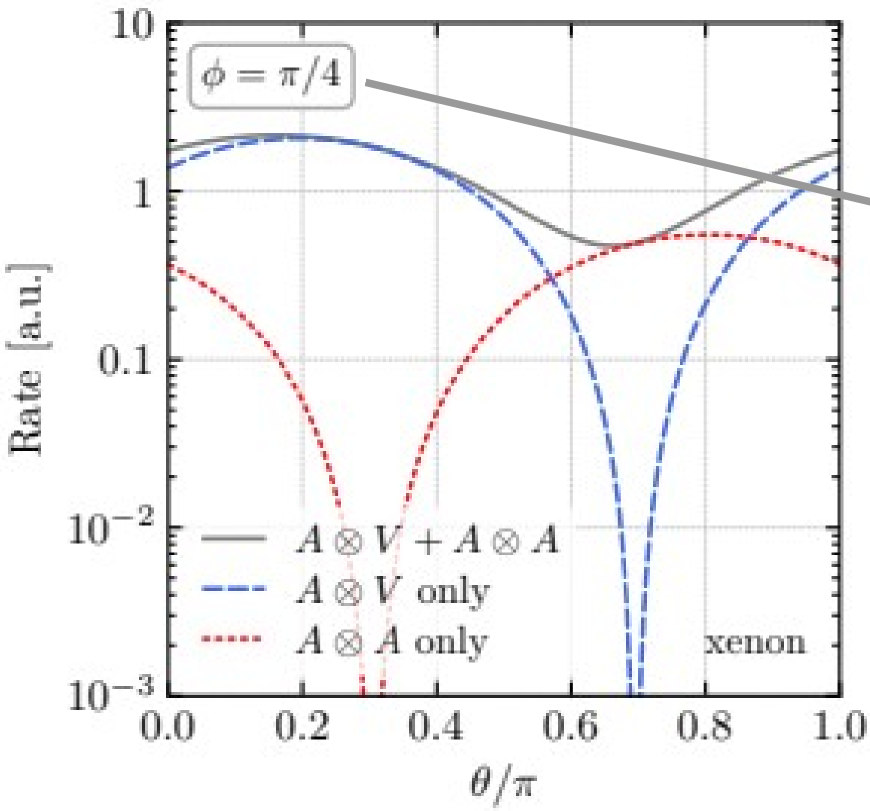
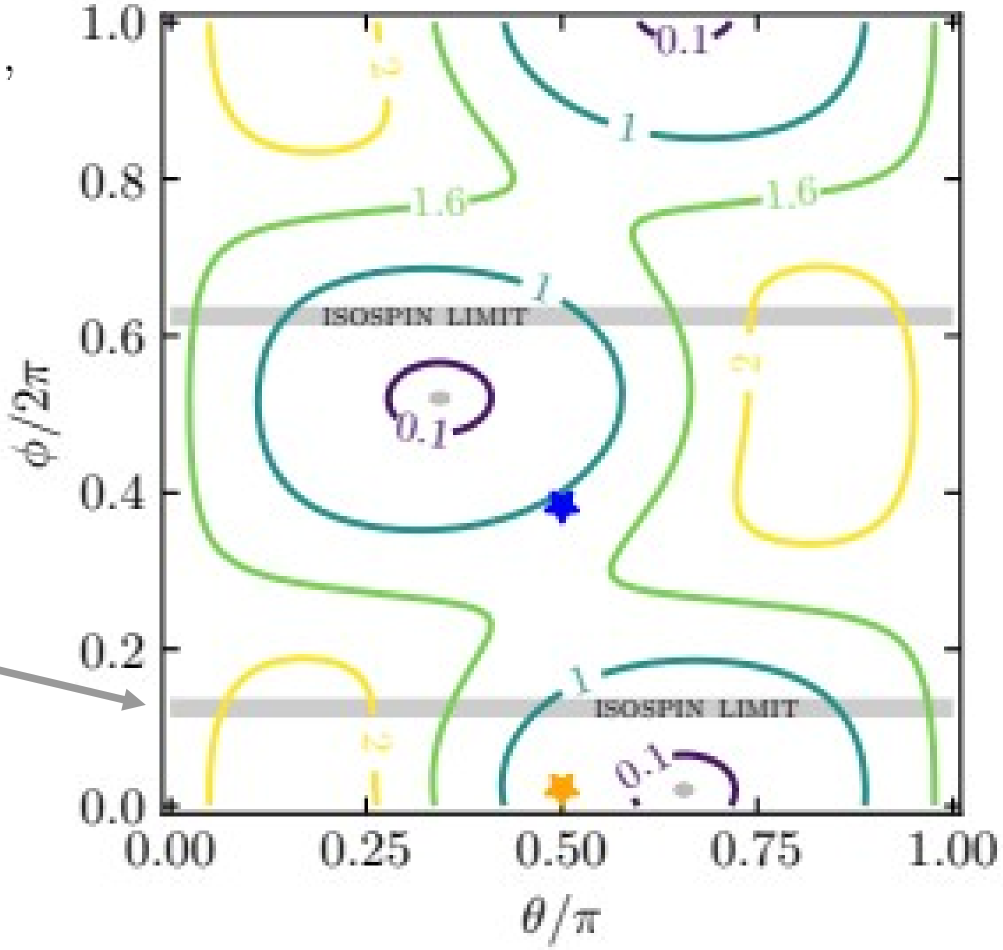


Relative DD event rate [m_χ = 100 GeV]



In the isospin limit vector **V** and axial **A** currents to SM matter cannot be suppressed simultaneously.

XENON sensitivity

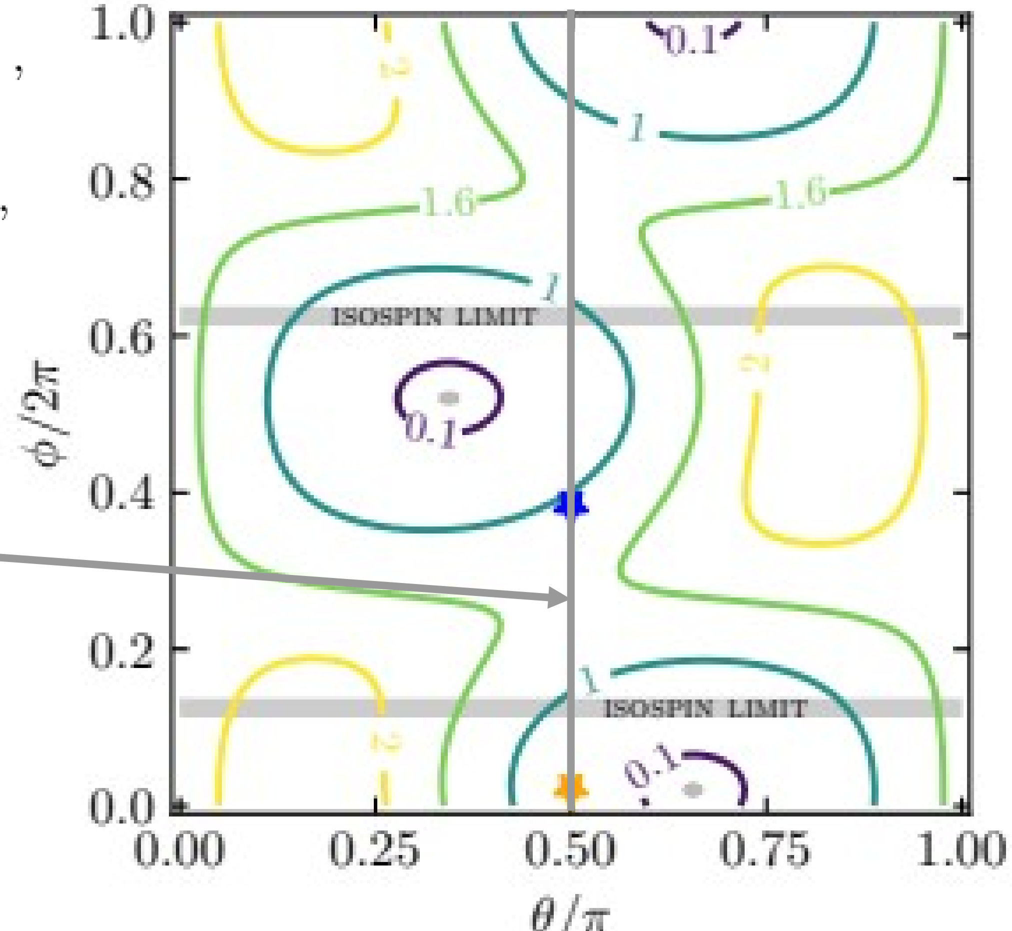
Parametrisation of Wilson coefficients:

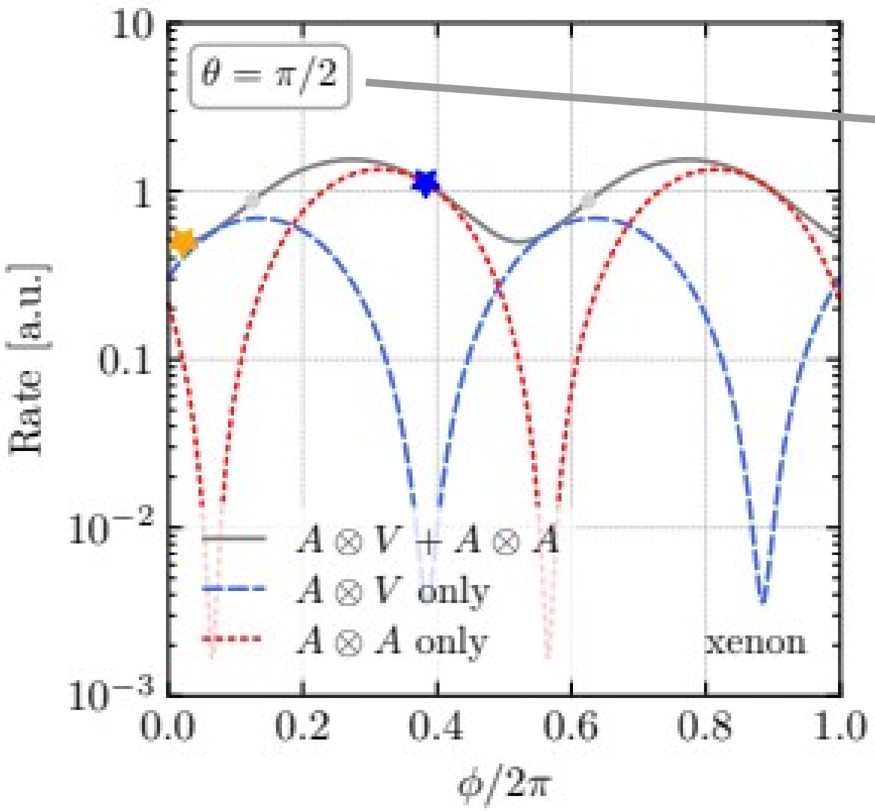
$$C^{(6)}_{6,1} \to \frac{g'^2}{\Lambda^2}\cos\theta\,, \qquad Q^{(6)}_{6,i} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar Q^i_L\gamma^\mu Q^i_L)\,,$$

$$C^{(6)}_{7,1} \to \frac{g'^2}{\Lambda^2}\sin\theta\cos\phi\,, \quad Q^{(6)}_{7,i} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar u^i_R\gamma^\mu u^i_R)\,,$$

$$C^{(6)}_{8,1} \to \frac{g'^2}{\Lambda^2}\sin\theta\sin\phi \quad Q^{(6)}_{8,i} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar d^i_R\gamma^\mu d^i_R)$$

Relative DD event rate [$m_\chi = 100\ GeV$]





Only couplings to right-handed quarks:

Blue star: BM1

(**A⊗V** contribution is suppressed)

Orange star : BM2

(Minimal DD rate in this construction)

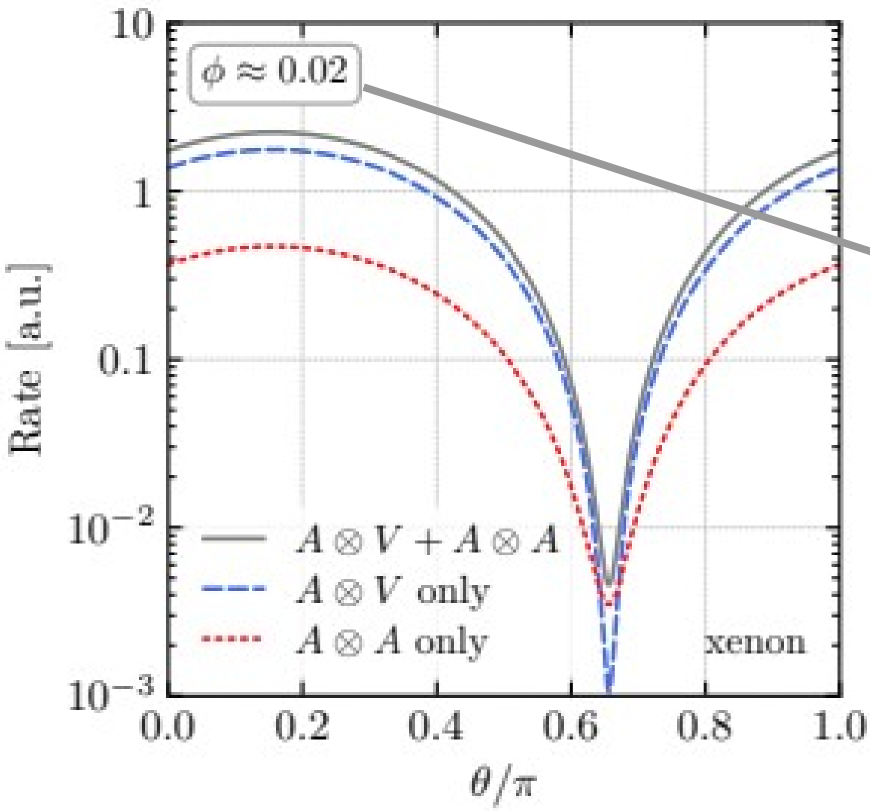
XENON sensitivity

Parametrisation of Wilson coefficients:

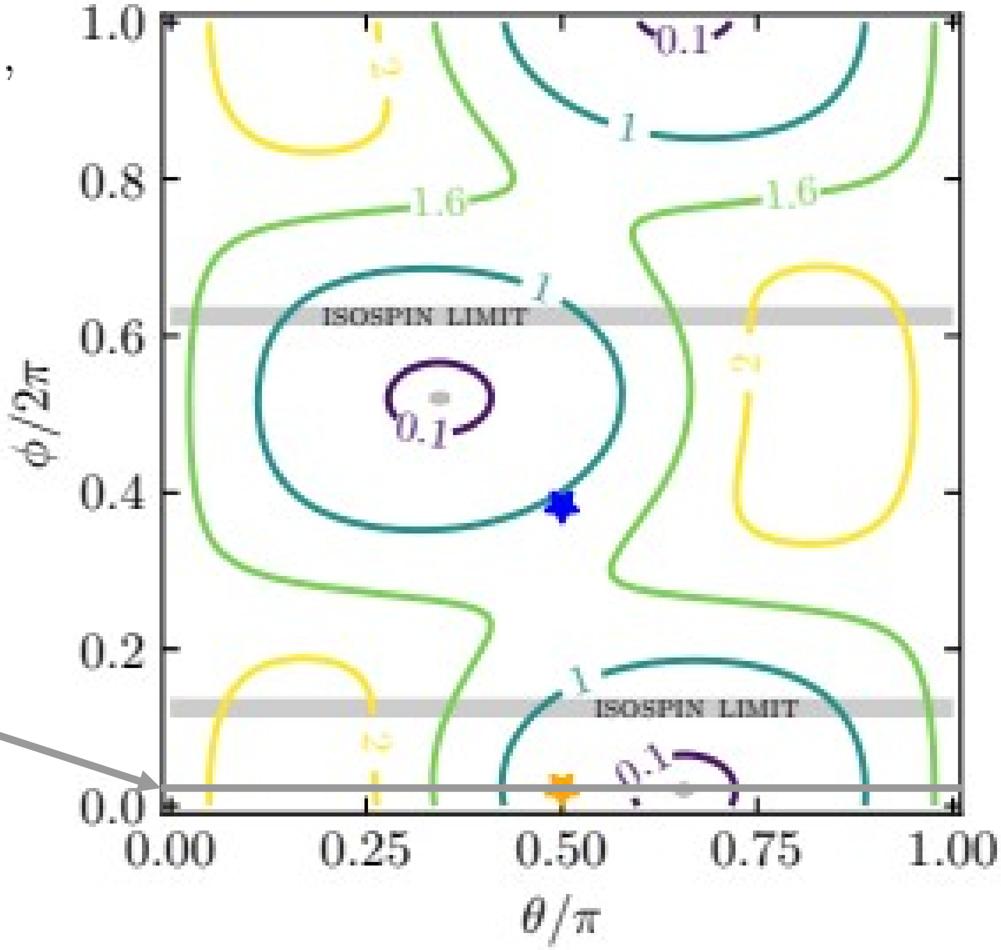
$$C^{(6)}_{6,1} \to \frac{g'^2}{\Lambda^2}\cos\theta\,, \qquad Q^{(6)}_{6,i} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar Q^i_L\gamma^\mu Q^i_L)\,,$$

$$C^{(6)}_{7,1} \to \frac{g'^2}{\Lambda^2}\sin\theta\cos\phi\,, \quad Q^{(6)}_{7,i} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar u^i_R\gamma^\mu u^i_R)\,,$$

$$C^{(6)}_{8,1} \to \frac{g'^2}{\Lambda^2}\sin\theta\sin\phi \quad Q^{(6)}_{8,i} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar d^i_R\gamma^\mu d^i_R)$$



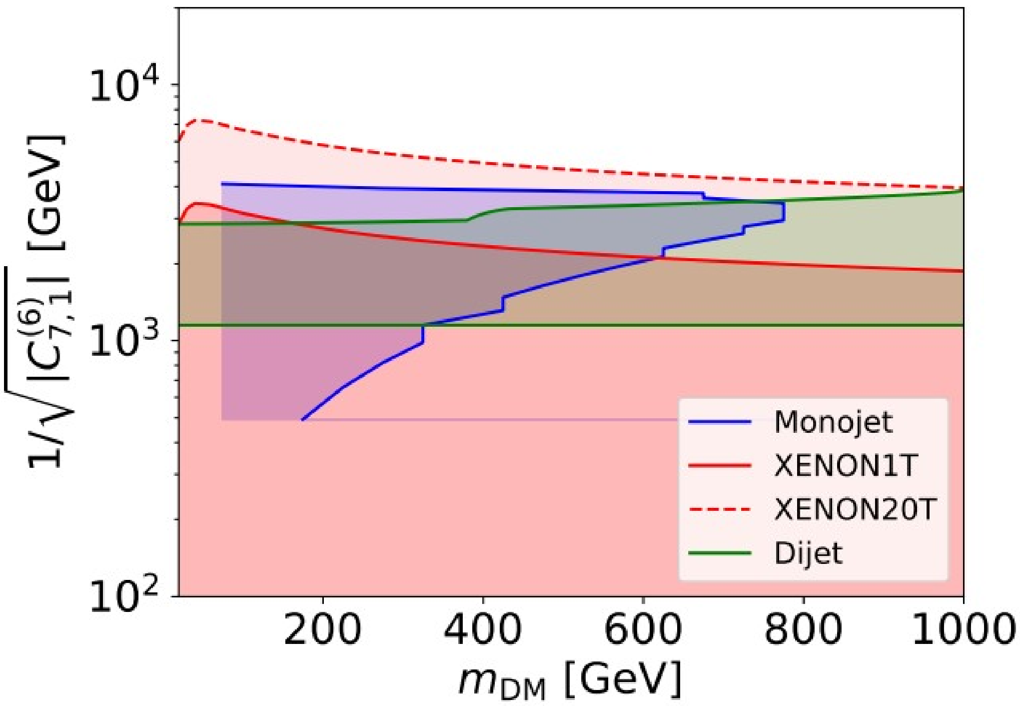
Relative DD event rate [m_χ = 100 GeV]



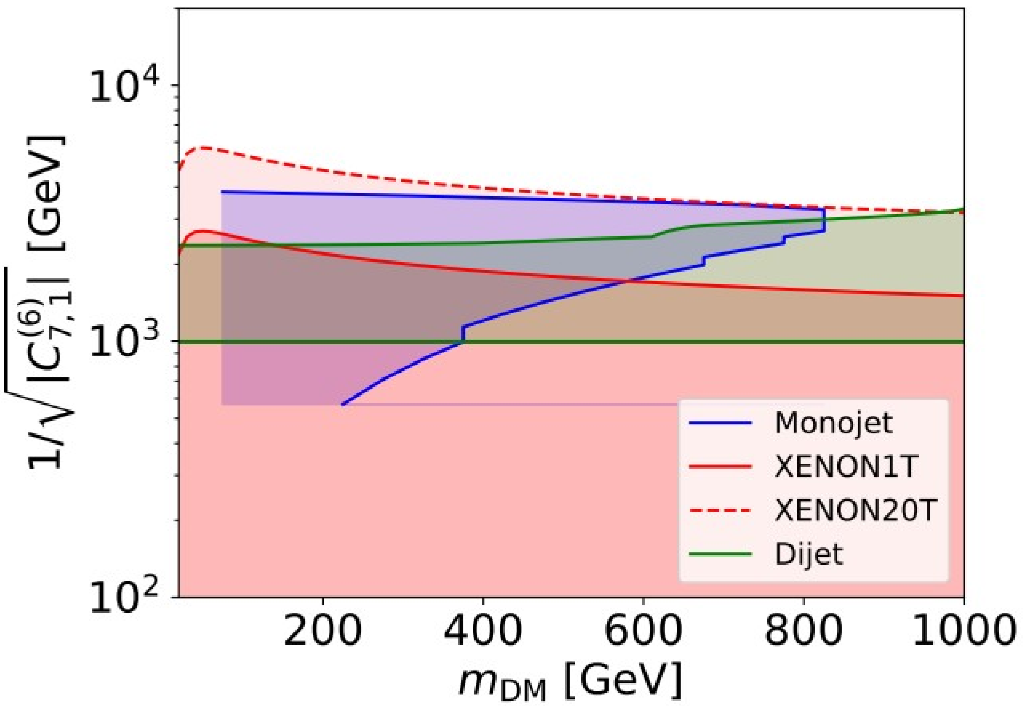
Global minimum where both **A** and **V** contributions are suppressed.
Event rate suppression ~10^{-2} can be achieved.

Experimental exclusions

BM 1



BM 2



- Benchmark models feature $\left|C^{(6)}_{6,1}\right| = 0$
- Results presented as function of $1/\sqrt{\left|C^{(6)}_{7,1}\right|} = m_{Z'}/\sqrt{g_q g_\chi}$
  - Representation in terms of Wilson coefficients → Easy reinterpretation in other models
  - Direct connection with BSM Z' mass → Easy reinterpretation of experimental analysis
  - Magnitude of the interaction fixed to match the Snowmass benchmark models of the experimental analysis g_q and g_χ (while chiral couplings vary with θ and Φ)
- **LHC** and **XENON1T** constraints are comparable in this scenario.

Constraints from the UV

- **EFT for direct detection of Majorana DM:**
  - Parametrisation of Wilson coefficients
  - Suppression of the scattering rate
- **UV completion constraints and their effect on:**
  - Direct detection
  - LHC contrains
- **Conclusions**

Constraints from UV

Several considerations from the UV completion are in order:

1. For the *Z'* to couple axial-vectorially to the DM, the latter has to be chiral under the *U(1)'*. DM and SM charges have to be chosen such that pure and mixed gauge anomaly cancel.

2. Mixed anomaly equations feature charges of the SM fermions which are, in general, a linear combination of their hypercharge *Y* and *B-L* numbers. Consequently, the coupling between *Z'* and SM leptons is unavoidable. Observables including leptons must be included in the analysis.

3. Some standard Yukawa couplings are now forbidden by the *U(1)'* invariance. However alternative mechanisms (i.e. involving vector-like quark) can be employed to recover Yukawa-like interactions.

4. The breaking of the *U(1)'* gauge group requires a dark-Higgs acquiring a vev. However, in our context, its contribution to the phenomenology of DM can be safely ignored.

Constraints from UV

Several considerations from the UV completion are in order:

5. SI contributions can arise at loop level, depending on the specific UV completion.

   Adopting a naive dimensional analysis we estimate their contribution in comparison with the tree-level SD interaction:

$$\frac{\sigma_{\rm SI}}{\sigma_{\rm SD}} \sim A^2 \frac{g'^4}{(4\pi)^4} \frac{m_N^2 m\chi^2}{m_{Z'}^4} \sim \mathcal{O}(10^{-11})$$

   for $g' = 0.1$, $m_{Z'} = 1$ *TeV*, $m_X = m_{Z'} / 2$, $m_N = 1$ *GeV* and $A \sim 100$ (i.e. for Xenon atoms)

   We can thus safely ignore this contribution.

6. If lepton doublets couple with non-universal charges the *Z'* mediates flavour changing neutral currents.

   Strong bounds on the breaking of the first- and second-generation *U(2)* flavour symmetry constrain $m_{Z'} > 50$ *TeV*.
   Retaining the *U(2)* symmetry can lower this bound significantly.

XENON sensitivity

Parametrisation of Wilson coefficients:

$$C_{6,1}^{(6)} \to \frac{g'^2}{\Lambda^2}\cos\theta\,, \qquad Q_{6,i}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{Q}_L^i\gamma^\mu Q_L^i)\,,$$

$$C_{7,1}^{(6)} \to \frac{g'^2}{\Lambda^2}\sin\theta\cos\phi\,, \quad Q_{7,i}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{u}_R^i\gamma^\mu u_R^i)\,,$$

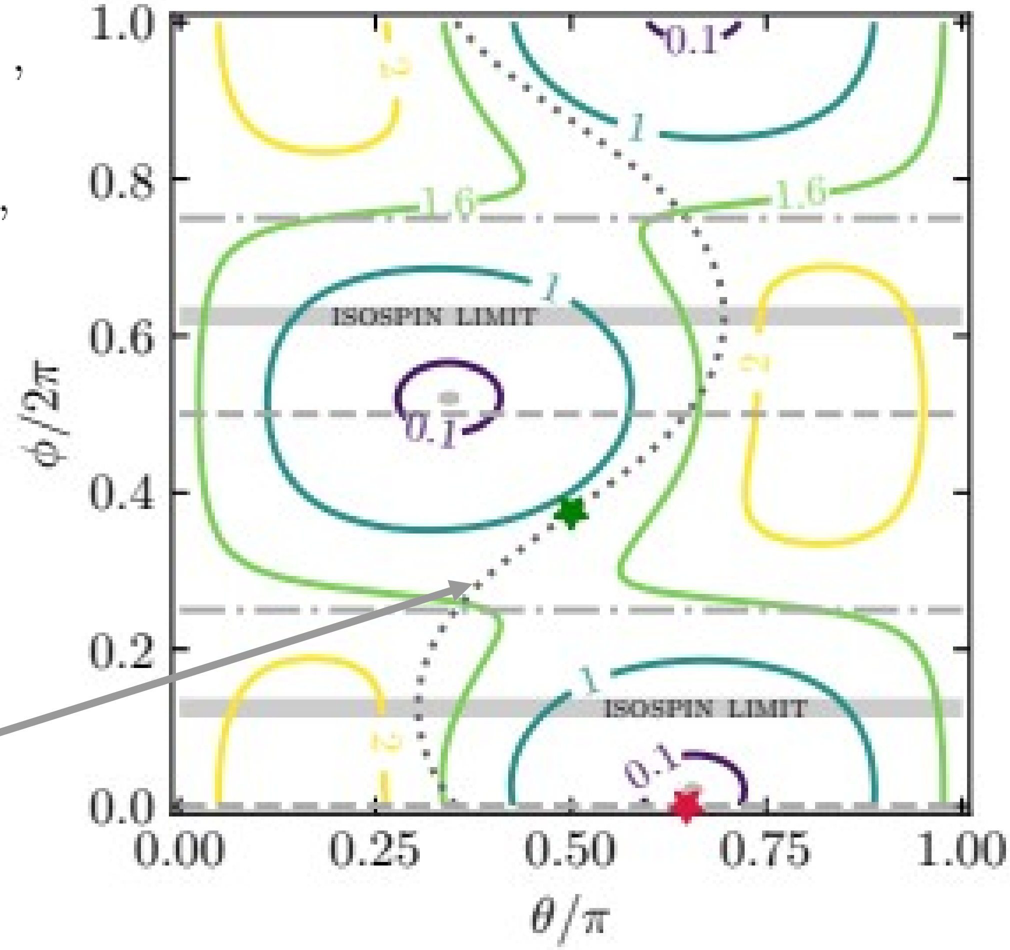
$$C_{8,1}^{(6)} \to \frac{g'^2}{\Lambda^2}\sin\theta\sin\phi \quad Q_{8,i}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{d}_R^i\gamma^\mu d_R^i)$$

If we charge only <u>first generation quarks</u>, **anomaly cancellation** requires:

$$\tan\theta = 2/\left(\sin\phi + \cos\phi\right)$$

represented by the dotted line

Relative DD event rate [*m_χ = 100 GeV*]



XENON sensitivity

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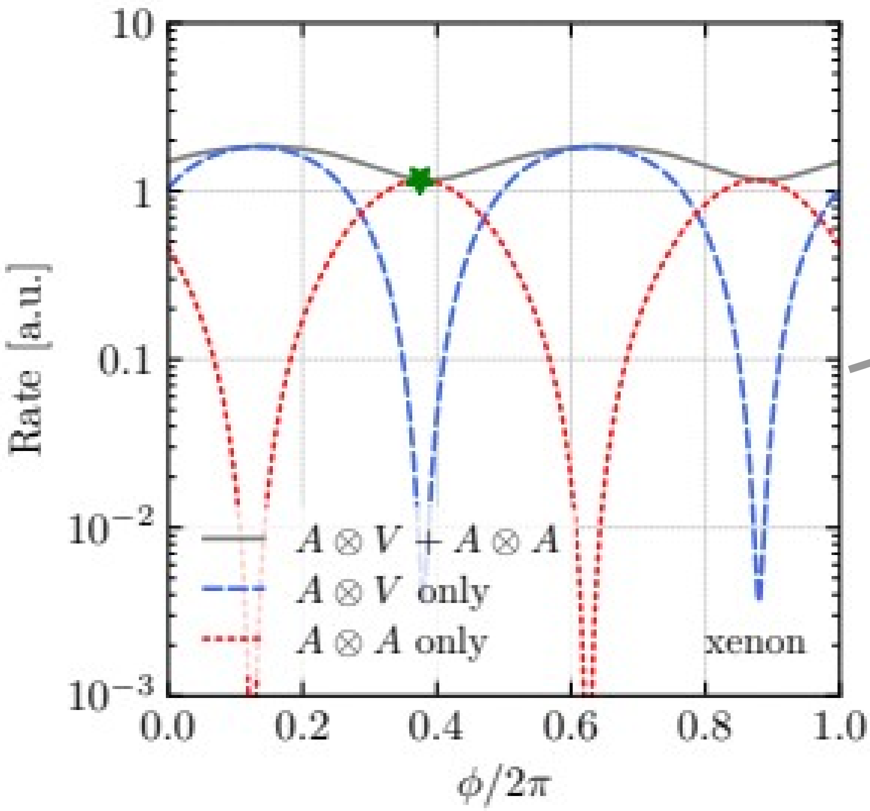
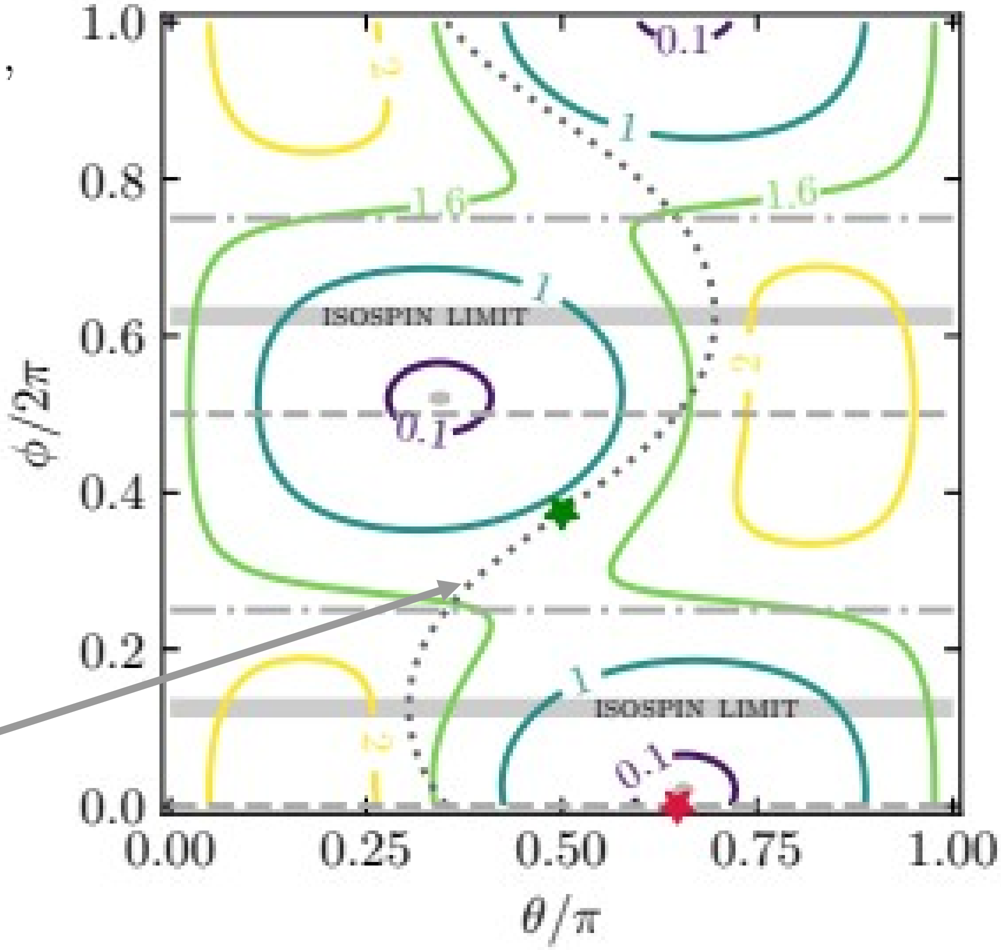


Relative DD event rate [m_χ = *100 GeV*]



No suppression is achievable in this scenario (**Green star** = minimum)

XENON sensitivity

Parametrisation of Wilson coefficients:

$$C_{6,1}^{(6)} \rightarrow \frac{g'^2}{\Lambda^2}\cos\theta\,, \qquad Q_{6,i}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{Q}_L^i\gamma^\mu Q_L^i)\,,$$

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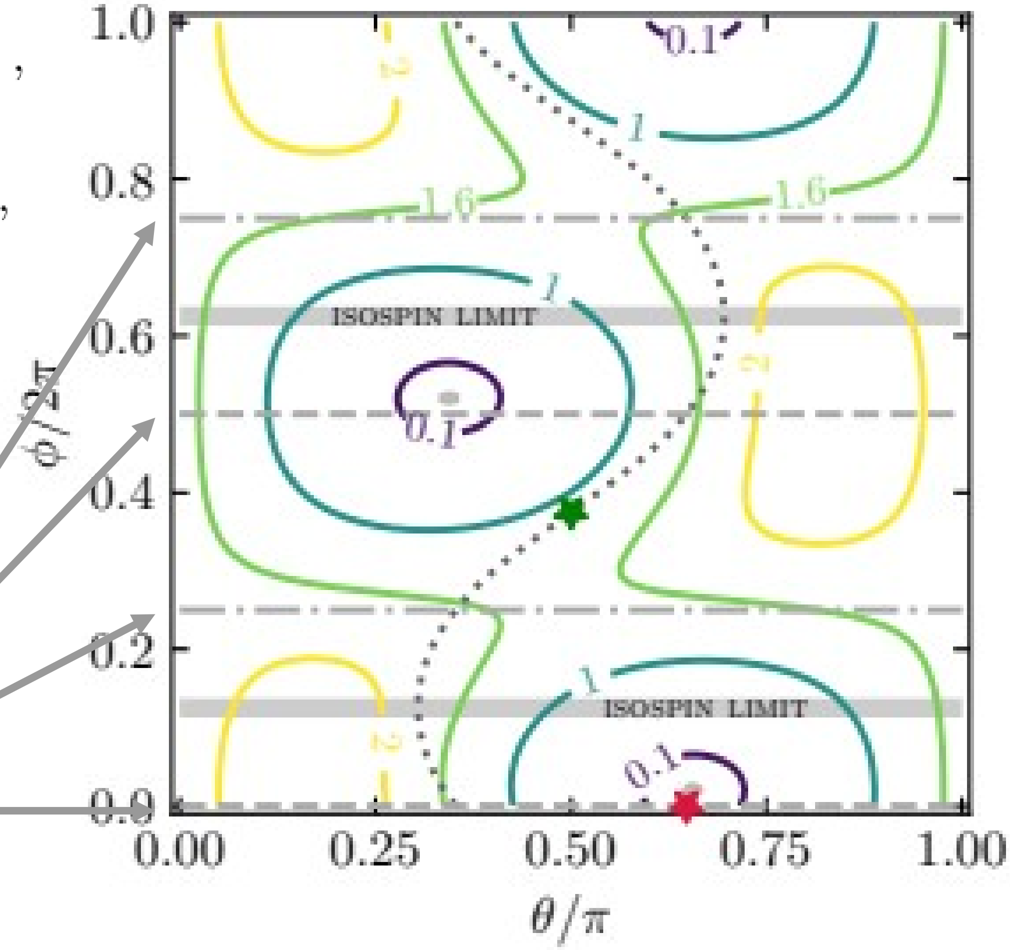
If we give <u>independent charges to second generation quarks</u>, **anomaly cancellation** conditions allow the solutions represented by the dashed and dot-dashed lines.

Relative DD event rate [*m_χ = 100 GeV*]



We can reach a near-to-maximal suppression condition!

XENON sensitivity

Parametrisation of Wilson coefficients:

$$C_{6,1}^{(6)} \to \frac{g'^2}{\Lambda^2}\cos\theta\,, \qquad Q_{6,i}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{Q}_L^i\gamma^\mu Q_L^i)\,,$$

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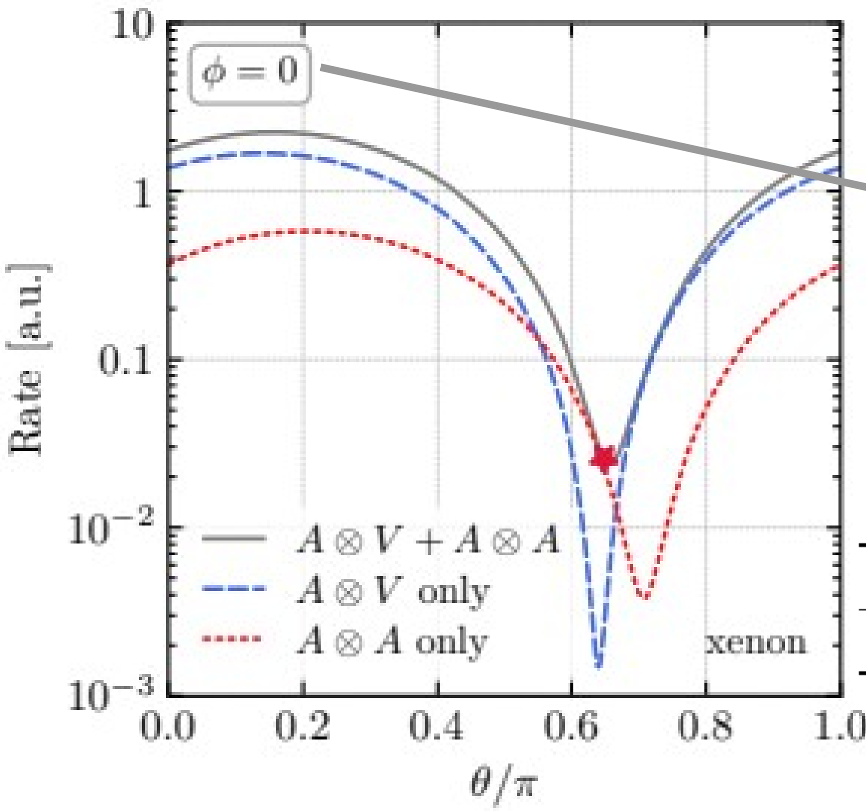
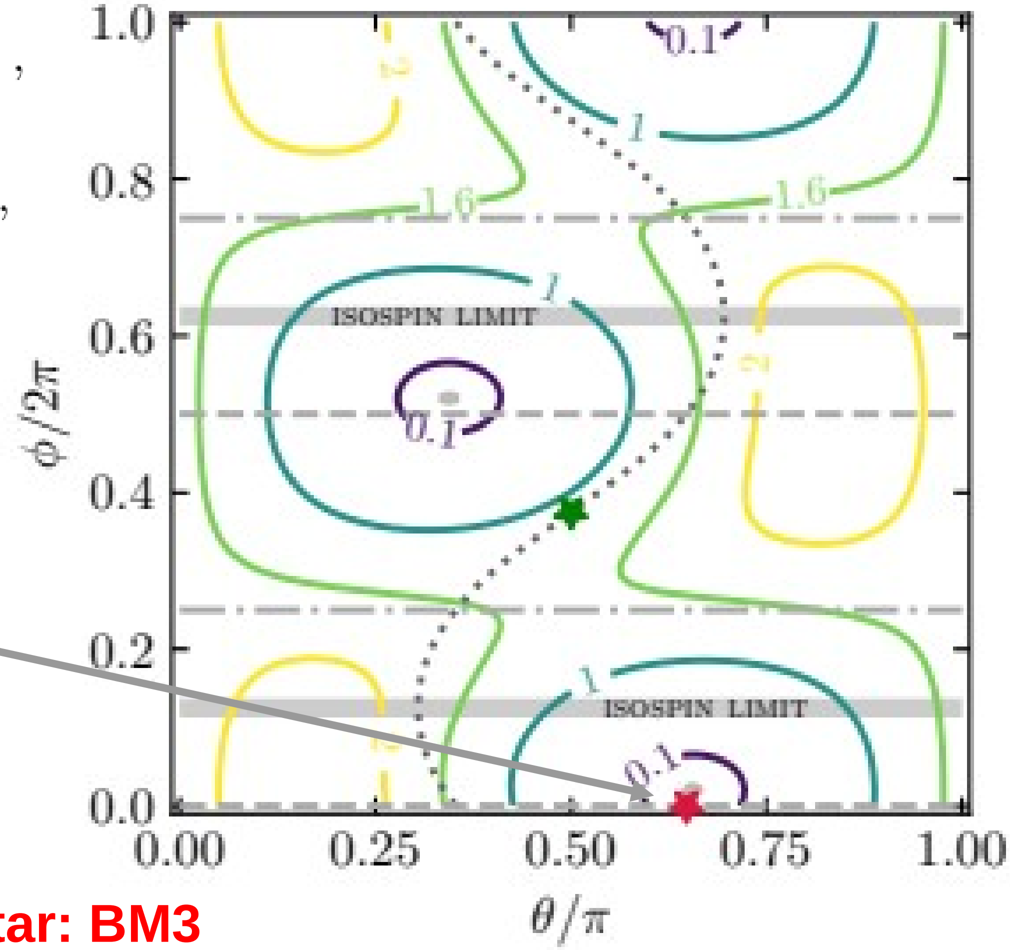


Relative DD event rate [m_χ = 100 GeV]

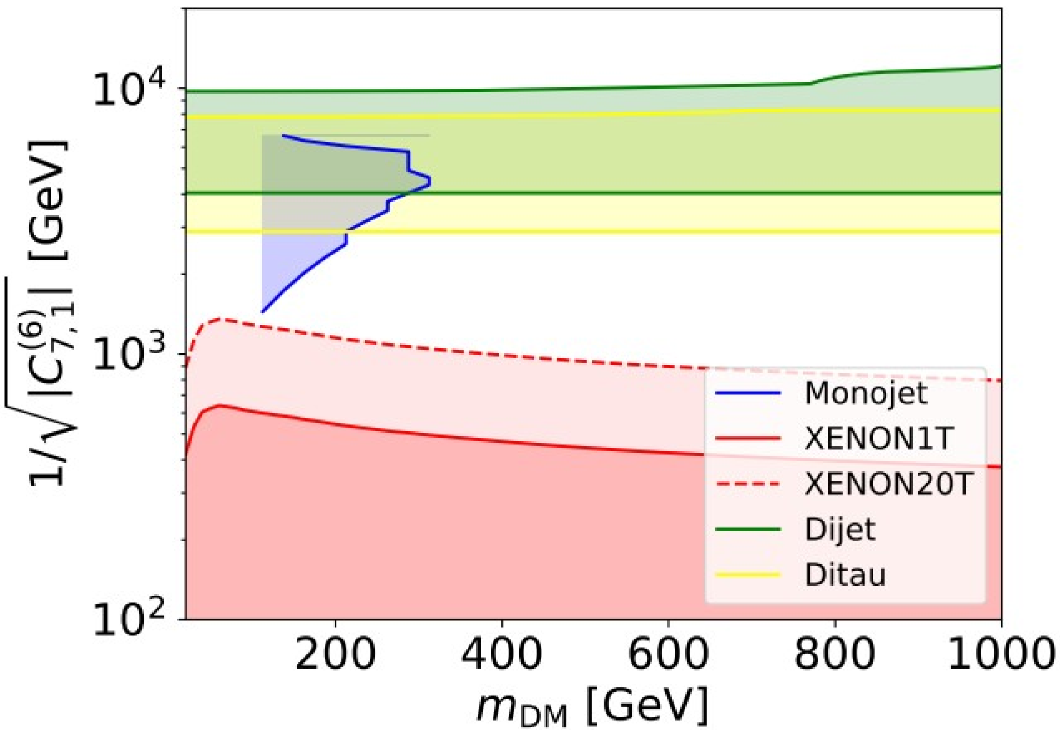


Red star: BM3

	$Q^c_{L,1}$	$u_{R,1}$	$d_{R,1}$	$u_{R,2}$	$d_{R,2}$	$L^c_{L,3}$	$e_{R,3}$	χ_R
BM3	$+\frac{1}{2}$	+1	0	0	-2	$-\frac{3}{2}$	0	3

Experimental exclusions

BM 3



- Drop of the DD rate events strongly reduces the sensitivity of **XENON**
  - Retain sensitivity on light *Z'* mediators
- **Monojet limits** are somewhat depleted:
  - Probe up to $m_{Z'}$ ~ *1.2 TeV* (scale with the interaction strength)
  - Probe up to m_X ~ *300 GeV* (extra decay channels of *Z'* mediator)
- **Dijet** and **ditaus** searches mostly independent on DM mass
  - Resonant searches dominant for heavy *Z'*

Couplings from charges multiplied by $g_{q,X}$ *= 0.1*

	$Q^c_{L,1}$	$u_{R,1}$	$d_{R,1}$	$u_{R,2}$	$d_{R,2}$	$L^c_{L,3}$	$e_{R,3}$	χ_R
BM3	$+\frac{1}{2}$	$+1$	0	0	-2	$-\frac{3}{2}$	0	3

Conclusions

- **EFT for direct detection of Majorana DM:**
  - Parametrisation of Wilson coefficients
  - Suppression of the scattering rate
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Conclusions

- General BSM constructions extension of the SM with an extra *U(1)'* gauge group and a singlet Majorana fermion acting as DM.
  - Breaking of the *U(1)'* → massive vector boson *Z'* mediator of DM-SM interaction.

- Sensitivity on this class of models from SI cross section measurements at the DD experiment **XENON** compared against **LHC** constraints from monojet, dijet and dilepton analyses.

- Interaction between DM and the atoms constituing the DD medium described in an appropriate EFT framework.
  - Identify the the regions where the XENON sensitivity is suppressed.
  - Compared XENON and monojet sensitivity in specific benchmarks (**BM1** & **BM2**).

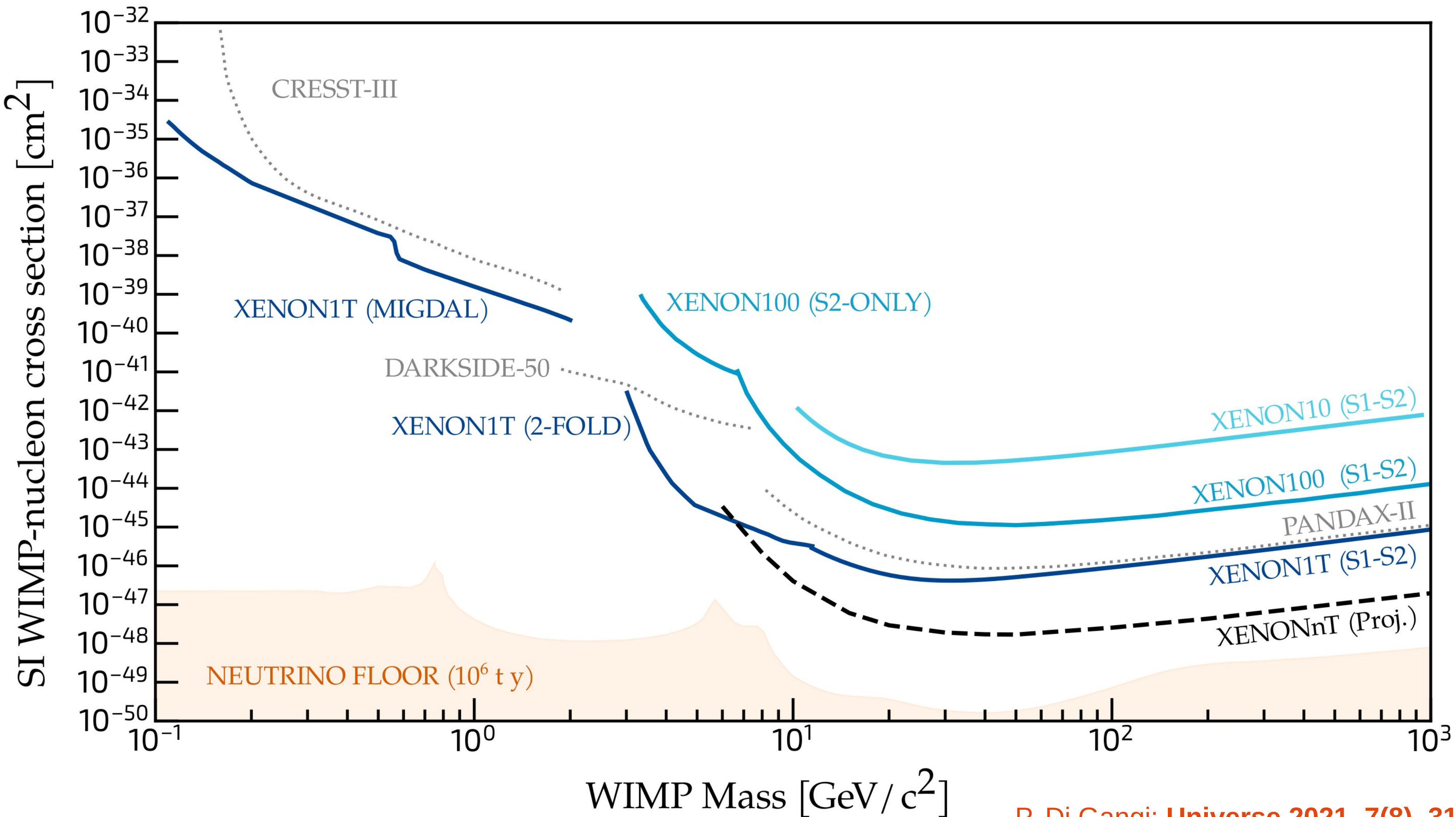
- Considerations from the UV completion of the models (in particular anomaly cancellation) only allow specific *U(1)'* charge assignments
  - In models with only first generation quark charged or model with family universal couplings no suppresson of scattering rate is possible.
  - Construct anomaly free model with near-to-maximal suppression of scattering rate, coupling right-handed strange quarks and left-handed τs (**BM3**).

- In such scenarios LHC constraints become dominant for heavy mediator masses, with resonant dijet and dilepton searches carring the strongest constraints.

Thank you!

Backup slides

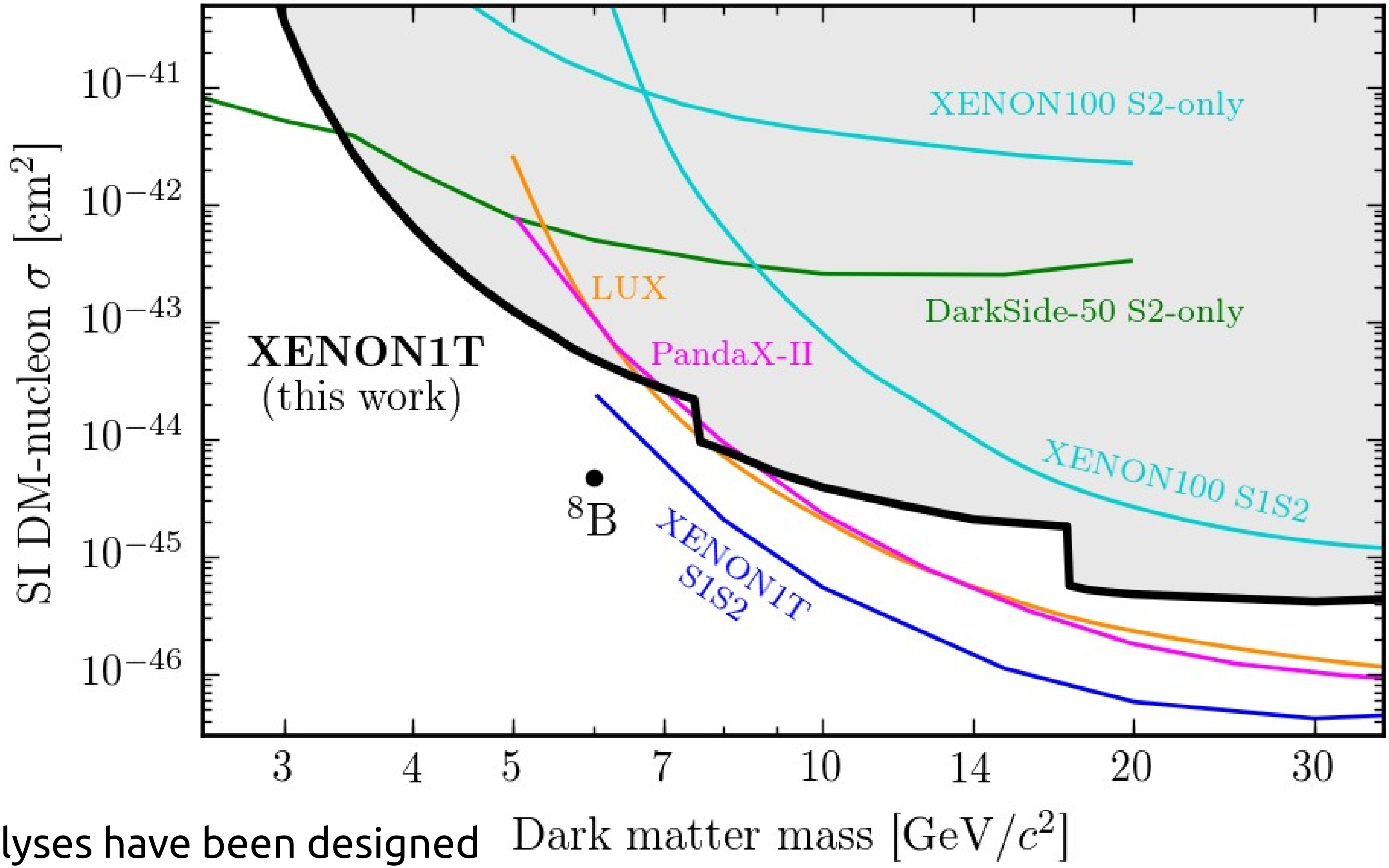
DM at XENON1T



P. Di Gangi: **Universe 2021, 7(8), 313**

Absence of signal (so far) translated into exclusion curves in the DM mass – SI/SD cross section plane.

DM at XENON1T

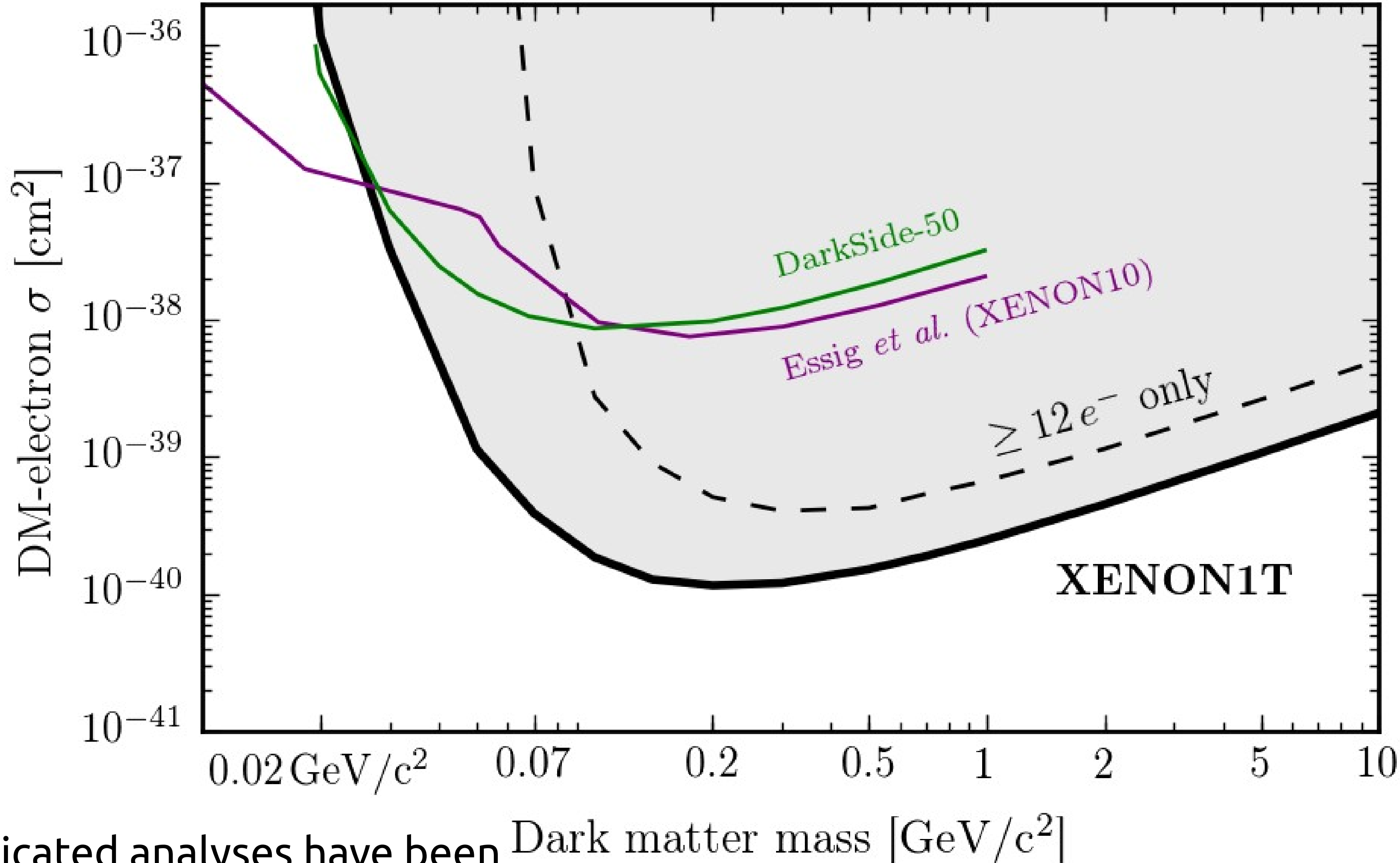


Specific analyses have been designed to improve the sensitivity to low-mass DM, such as S2-only signals and modelling of the Migdal effect.

Xenon Collaboration: **Phys. Rev. Lett. 123, 251801 (2019)**

Xenon Collaboration: **Phys. Rev. Lett. 123, 241803 (2019)**

DM at XENON1T



Further dedicated analyses have been designed to model the scattering of DM against electrons, with enhanced sensitivity on leptophilic low-mass DM.

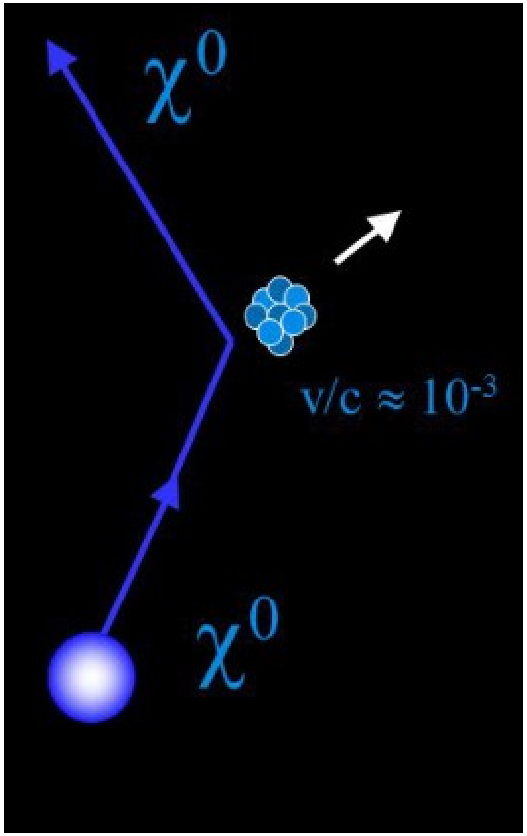
Xenon Collaboration: **Phys. Rev. Lett. 123, 251801 (2019)**

Xenon Collaboration: **Phys. Rev. Lett. 123, 241803 (2019)**

Describing DM interaction

We must find the appropriate description for the interaction of DM with atomic nuclei.

According to the **standard halo model**, the DM velocity distribution takes the form of an isotropic Maxwell-Boltzmann function in the halo rest rame, with typical velocities of the order 10^2 *km/s*, thus DM particles will move in the Earth rest frame with non-relativistic velocities.



The typical energy scale of the momentum transferred in the scattering between a DM particle and a nucleus depends on:

- the reduced mass of the DM-nucleus system
  - DM mass $m_X \sim TeV$, nucleons mass $m_N \sim 100\ GeV$
- the range of recoil energies that the experiment can measure
  - $E_R \sim 3$ -$50\ keV$

This givesa $q_{max} \leq 200\ MeV$

This is also the typical size of the momenta exchanged between nucleons in nuclei, thus as $q_{max} << m_N$ the nucleon will remain intact after the scattering and will continue to be non-relativistic.

This motivates the use a **Non-Relativistic Effective Field Theory (NREFT)**.

Describing DM interaction

Steps from UV theory to experimental observables:

- The interactions between DM and nucleons can be organised using **Chiral Effective Field Theory (ChEFT)** using an expansion in $q/\Lambda_{ChEFT} \sim m_\pi/\Lambda_{ChEFT} \sim 0.3$
  - This description catches the leading contributions coming from the interaction between DM and the lightest mesons (pion, η, etc.).

- **ChEFT** can be further generalised into a **Heavy Baryon Chiral Perturbation Theory (HBChPT)** which includes also DM interaction with protons and neutrons.

- Eventually we will also have to include nuclear physics effects from the interactions between nucleons, in order to obtain an effective theory describing the interaction between DM and nuclei.

From UV to experiment

$\Lambda > \mu_{EW}$

We start with an UV complete theory and write the **6-flavours EFT** above the EW scale

$$\mathcal{L}_{6f} = \sum_{a,b} C_a^{(d)} Q_a^{(d)}$$

(Examples of operators for axial mediator)

$$Q_{6,i}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{Q}_L^i\gamma^\mu Q_L^i)\,,$$
$$Q_{7,i}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{u}_R^i\gamma^\mu u_R^i)\,,$$
$$Q_{8,i}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{d}_R^i\gamma^\mu d_R^i)\,.$$

The d.o.f. are the right and left handed fields.

From UV to experiment

$\Lambda < \mu_{EW}$

Below EW scale we match the **6-flavours EFT** with the **5-flavours EFT**

$$\mathcal{L}_\chi = \sum_{a,d} \hat{\mathcal{C}}_a^{(d)} \mathcal{Q}_a^{(d)} .$$

$$\mathcal{Q}_{2,i}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu q) , \qquad \mathcal{Q}_{4,i}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q) .$$

The matching in this case is straightforward, with symmetries of the 6-flavours EFT setting constraints on the 5-flavour EFT coefficients:

$$\hat{\mathcal{C}}_{2,u}^{(6)} = \frac{C^{(6)} + C^{(7)}}{2}, \qquad \hat{\mathcal{C}}_{4,u}^{(6)} = \frac{-C^{(6)} + C^{(7)}}{2},$$

$$\hat{\mathcal{C}}_{2,d}^{(6)} = \frac{C^{(6)} + C^{(8)}}{2}, \qquad \hat{\mathcal{C}}_{4,d}^{(6)} = \frac{-C^{(6)} + C^{(8)}}{2},$$

<u>The d.o.f. are now the physical quarks fields.</u>

From UV to experiment

Non-relativistic limit

We take the non relativistic limit $$\mathcal{L}_{\rm NR} = \sum_{i,N} c_i^N(q^2)\mathcal{O}_i^N$$

The matching is done in two steps (**`DirectDM`** code):

F. Bishara, J. Brod, B. Grinstein, J. Zupan: **arXiv:1708.02678 [hep-ph]**

F. Bishara, J. Brod, B. Grinstein, J. Zupan: **JCAP 02 (2017) 009**

F. Bishara, J. Brod, B. Grinstein, J. Zupan: **JHEP 11 (2017) 059**

1) consider the matrix element of the quark currents between nucleon states:

$$\langle N'|\bar{q}\gamma^\mu q|N\rangle = \bar{u}'_N\left[F_1^{q/N}(q^2)\gamma^\mu + \frac{i}{2m_N}F_2^{q/N}(q^2)\sigma^{\mu\nu}q_\nu\right]u_N$$

$$\langle N'|\bar{q}\gamma^\mu\gamma_5 q|N\rangle = \bar{u}'_N\left[F_A^{q/N}(q^2)\gamma^\mu\gamma_5 + \frac{i}{2m_N}F_{P'}^{q/N}(q^2)\gamma_5 q^\mu\right]u_N,$$

R. J. Hill, M. P. Solon: **Phys. Rev. D 91, 043505 (2015)**

M. Hoferichter, P. Klos, A. Schwenk: **Phys. Lett. B 746 (2015) 410-416**

The nuclear form factors are extracted from experimental data of Deep Inelastic Scattering (DIS) with photons or pions.

From UV to experiment

Non-relativistic limit

We take the non relativistic limit
$$\mathcal{L}_{\rm NR} = \sum_{i,N} c_i^N(q^2)\mathcal{O}_i^N$$

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2) take non-relativistic limits of both DM currents and nucleon spinor structure:

The operators are build in terms of Galilean invariants:
$$\left\{\vec{q}, \vec{v}_\perp, \vec{S}_\chi, \vec{S}_N\right\}$$

A. L. Fitzpatrick, W. Haxton, E. Katz, N. Lubbers, Y. Xu: **JCAP 02 (2013) 004**

The simplest and most considered NR operators are the **Spin-independent (SI)** and **Spin-dependent (SD)** operators:

$$\mathcal{O}_1^N = \mathbb{1}_\chi \mathbb{1}_N, \qquad \mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N$$

From UV to experiment

Operative calculation:

The experimental measured quantity is the scattering rate, as function of the recoil energy

$$\frac{d\mathcal{R}}{dE_R} = \frac{\boxed{\rho_\chi}}{m_A m_\chi} \int_{\boxed{v_{\rm min}}} \frac{d\sigma}{dE_R} \boxed{v f_\oplus(\vec{v})} d^3\vec{v},$$

Input from Astrophysiscs

- Local DM density
- Integration over DM velocity distribution.
- Boltzmann distribution is generally assumed.

From UV to experiment

Operative calculation:

The experimental measured quantity is the scattering rate, as function of the recoil energy

$$\frac{d\mathcal{R}}{dE_R} = \frac{\rho_\chi}{\boxed{m_A}\boxed{m_\chi}} \int_{v_{\min}} \boxed{\frac{d\sigma}{dE_R}} v f_\oplus(\vec{v}) d^3\vec{v},$$

Input from particle physics

$$\frac{d\sigma}{dE_R} = \frac{m_A}{2\pi v^2} \frac{1}{2J_\chi+1} \frac{1}{2J_A+1} \sum_{\text{spins}} |\mathcal{M}|^2_{\text{NR}}$$

$$\frac{1}{2J_\chi+1} \frac{1}{2J_A+1} \sum_{\text{spins}} |\mathcal{M}|^2_{\text{NR}} = \frac{4\pi}{2J_A+1} \sum_{\tau,\tau'=0,1} \sum_i \boxed{R_i^{\tau\tau'}} \boxed{W_i^{\tau\tau'}(q)}$$

Input from nuclear physics

- DM response functions
- Nuclear response functions
- interface with **`DMFormFactor`** package

N. Anand, A. L. Fitzpatrick, W. C. Haxton: **Phys. Rev. C 89, 065501 (2014)**

From UV to experiment

The relevant nuclear response functions will be just 5:

- $\mathbf{W_M}$ encoding the SI scattering which in the long wavelength limit just counts the number of nucleons $W_M \sim O(A^2)$.
- $\mathbf{W_{\Sigma'}}$ and $\mathbf{W_{\Sigma''}}$ encoding the SD scattering which in the long wavelength limit parametrise the nucleon spin content of the nucleus.
- $\mathbf{W_\Delta}$ encoding the nuclear angular momentum (orbital) which in the long wavelength limit parametrises the nucleon angular momentum content of the nucleus.
- $\mathbf{W_{\Delta\Sigma}}$ representing the interference between the angular and spin momenta.

From UV to experiment

DM response functions can be obtained from non-relativistic Wilson coefficients:

$$R_M^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}\right) = \frac{j_\chi(j_\chi+1)}{3}\vec{v}_T^2 c_8^\tau c_8^{\tau'},$$

$$R_{\Sigma''}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}\right) = \frac{j_\chi(j_\chi+1)}{12}\left[c_4^\tau c_4^{\tau'} + \frac{\vec{q}^2}{m_N^2}\left(c_4^\tau c_6^{\tau'} + c_6^\tau c_4^{\tau'}\right) + \frac{\vec{q}^4}{m_N^4} c_6^\tau c_6^{\tau'}\right],$$

$$R_{\Sigma'}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}\right) = \frac{j_\chi(j_\chi+1)}{12}\left[c_4^\tau c_4^{\tau'} + \frac{\vec{q}^2}{m_N^2} c_9^\tau c_9^{\tau'}\right],$$

$$R_{\Delta}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}\right) = \frac{j_\chi(j_\chi+1)}{3} c_8^\tau c_8^{\tau'},$$

$$R_{\Delta\Sigma'}^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}\right) = \frac{j_\chi(j_\chi+1)}{3}\left[-c_8^\tau c_9^{\tau'}\right]$$

$$c_i^0 = \left(c_i^p + c_i^n\right)/2 \qquad c_i^1 = \left(c_i^p - c_i^n\right)/2$$

N. Anand, A. L. Fitzpatrick, W. C. Haxton: **Phys. Rev. C 89, 065501 (2014)**

Derivation of DD limits

Spin-dependent cross section calculation for **XENON1T** experiment:

- Developed independent C++ code interfaced with **DirectDM** and **DMFormFactor** programs.
- Numerical MC integrations over velocity distribution and recoil energy.
- Target mass defined averaging over Xenon nautral isotopes.
- Assumed exposure corresponding to 278.8 days x 1.3 tons.
- Exclusions at 90% CL calculated assuming Poisson statistic under the assumption of no background events.

The pion pole

Particular attention is necessaty in the treatment of the nuclear form factor $F_{P'}$

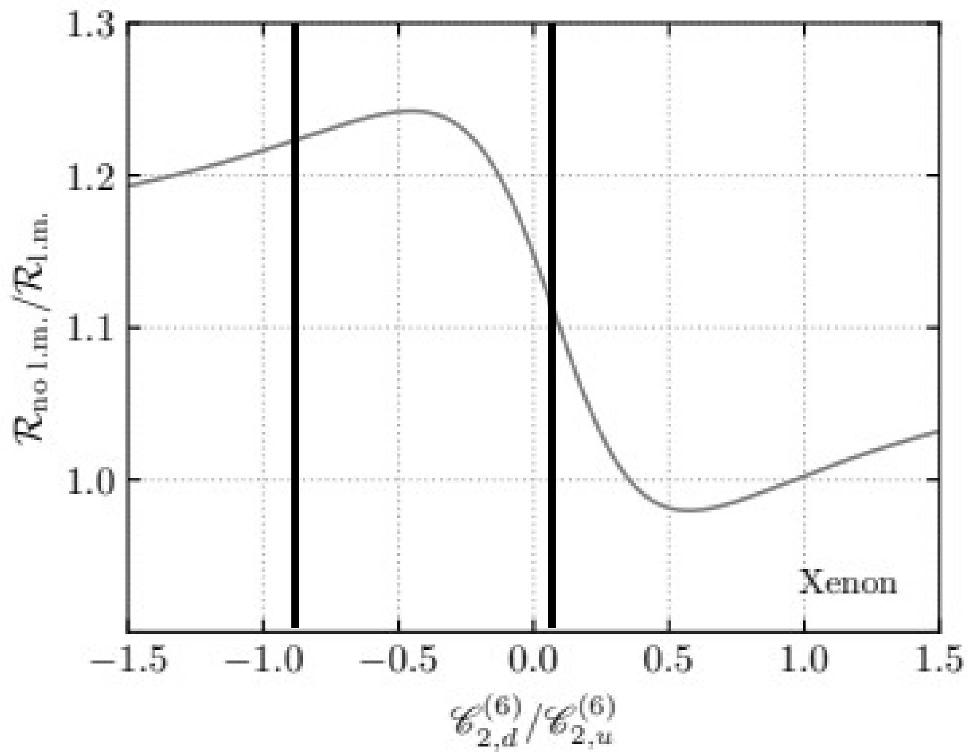
$$F_{P'}^{q/N}(q^2) = \frac{m_N^2}{m_\pi^2 - q^2} a_{P',\pi}^{q/N} + \frac{m_N^2}{m_\eta^2 - q^2} a_{P',\eta}^{q/N} + \dots .$$

In its expansion one needs to include the light-meson poles when DM couples to axial quark current or to the QCD anomaly term.

This captures the leading effects of the strong interactions.

All the other form factors do not have a light pseudoscalar pole and can be Taylor expanded around $q^2 = 0$.

Up to 25% correction to the scattering rate.



Larger correction when the contribution of Axial-Axial interaction to the total scattering rate is dominant.

Derivation of LHC limits

Derivation of **LHC** exclusion limits from **monojet analysis**:

- Large simulation scanning over the DM and *Z'* masses.
- Parton level events generated using **`MadGraph5_aMC@NLO`**.
- Events hadronized with **`PYTHIA8`**,
  detector efficiencies simulated with **`DELPHES`**.
- Imposed ATLAS analysis selection cuts.
- Expected number of signal events in each of the 13 missing E_T bins (exclusive signal regions) derived from the total cross section and the efficiency of the corresponding selection cuts, assuming an integrated luminosity of 139 fb^{-1}.
- Compared signal and backgound expectations in each signal region, taking into account the respective systematic and statistic uncertainties.
- Limits drawn as the signal hypothesis is excluded in every signal region.

Merging constraints

GOAL:
We want to compare the sensitivity of **LHC** and **XENON1T** to specific classes of models.

PRESENTATION OF RESULTS:
Exclusion limits presented as function of the EFT 6-flavour Wilson coefficients
- Easy re-interpretation of the results in different scenarios

THE BENCHMARK MODELS:
To facilitate the comparison, **BM1** & **BM2** the overall magnitude of the interaction is the same as in the experimental Snowmass benchmark models.

XENON1T sensitivity

The couplings to up/down quarks determine the contribution of each **Xe** atom to the scattering rate.

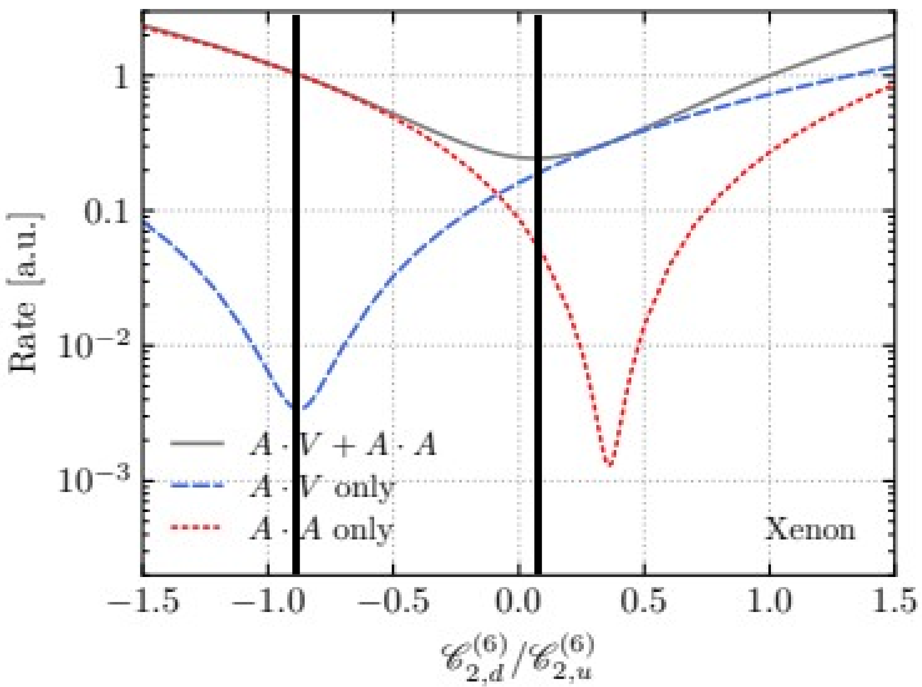
Considering the whole detector medium, we have different contributions from the various **Xe** isotopes, depending on their aboundance. Typical feature of SD processes.

⬇

Large cancellations occur for particular combinations of the couplings.

⬇

We encounter scenarios where the sensitivity of **XENON1T** is considerably reduced.



Define the ratio: $r = \frac{g_R^d}{g_R^u} = \frac{\mathscr{C}^{(6)}_{2,d}}{\mathscr{C}^{(6)}_{2,u}}$

For r = +0.05 the sensitivity of **XENON1T** is reduced by ~ factor 4.

We consider the scenarions with r = -0.9 (**BM1**) & r = +0.05 (**BM2**)

Constraints from the UV

This minimal model can be UV completed, albeit strict theoretical constraints:

- The interaction can also be mediated by an extra Higgs, which is necessary to break the extra *U(1)'* gauge group and give mass to the ***Z'*** boson.

- The DM must be chiral under the extra *U(1)'* gauge group.

- The cancellation of pure and mixed anomalies requires certain *U(1)'* charge assignment to the SM fermions:

u_R	d_R	e_R	χ_R
-1	+1	+1	-1

  - Generates *Z'* couplings to fermions → comply with LHC di-lepton exclusions.

- If only right-handed fermions are charged, the *U(1)'* gauge group forbids Yukawas dimension-4 couplings for the fermions:
  - To give mass to the fermions, non-renormalizable dimension-5 terms can be introduced (can be generated at higher scale by vector-like heavy fermions).
  - Alternatively an extra Higgs doublet charged under the *U(1)'* can be added.

- To give mass to the Majorana DM one needs an extra scalar with appropriate charges and VEV.
  - The interaction with extra scalar(s) affects the DM relic density.

Anomaly cancellation

(SM ⊗ U(1)’) + DM Majorana fermion

Generic U(1)’ charge assignment (with one 2nd generation right-handed quark)

$Q^c_{L,1}$	$u_{R,1}$	$d_{R,1}$	$L^c_{L,3}$	$e_{R,3}$	χ_R	$u_{R,2}$ or $d_{R,2}$
a	b	c	d	e	x	z

Anomaly cancellation conditions:

$$\begin{aligned}
\mathrm{SU}(3)\times\mathrm{SU}(3)\times\mathrm{U}(1)': &\qquad 2a+b+c+z=0\\
\mathrm{Grav}\times\mathrm{Grav}\times\mathrm{U}(1)': &\qquad 6a+3b+3c+2d+e+x+3z=0\\
\mathrm{SU}(2)\times\mathrm{SU}(2)\times\mathrm{U}(1)': &\qquad 3a+d=0\\
\mathrm{U}(1)_Y\times\mathrm{U}(1)_Y\times\mathrm{U}(1)': &\qquad 6a+48b+12c+18d+36e+108\,Q^2_{u(d)}\,z=0\\
\mathrm{U}(1)_Y\times\mathrm{U}(1)'\times\mathrm{U}(1)': &\qquad -6a^2+12b^2-6c^2+6d^2-6e^2+18\,Q_{u(d)}\,z^2=0\\
\mathrm{U}(1)'\times\mathrm{U}(1)'\times\mathrm{U}(1)': &\qquad 6a^3+3b^3+3c^3+2d^3+e^3+x^3+3z^3=0
\end{aligned}$$

Anomaly cancellation

	$Q^c_{L,1}$	$u_{R,1}$	$d_{R,1}$	$u_{R,2}$	$d_{R,2}$	L^c_L	e_R	χ_R
S1	$\frac{1}{6}(e+x)$	$\frac{1}{3}(x-2e)$	$\frac{1}{3}(e-2x)$	0	0	$-\frac{1}{2}(e+x)$	e	x
S2	$\frac{1}{4}(x-z)$	0	$-\frac{1}{2}(x+z)$	$z\neq 0$	0	$-\frac{3}{4}(x-z)$	$\frac{1}{2}(x-3z)$	x
S3	$\frac{1}{2}(x+z)$	$-x-2z$	0	0	$z\neq 0$	$-\frac{3}{2}(x+z)$	$2x+3z$	x

Only 3 solutions:

- 1 solution: S1 with *e = 1 ; x = -1 ; z = 0*

  minimal charge assignment:

u_R	d_R	e_R	χ_R
-1	$+1$	$+1$	-1

  requires alternatives constructions of Yukawa terms
  (i.e. inclusion of vector-like fermions).

- 2 solutions: independent charge *z* to either up or down 2nd generation quarks.

- S3 with *z = -2 ; x = 3* → **BM3**