Laboratoire Charles Coulomb (L2C) & LUPM
28/03/2019

Dark Matter Direct Detection: a brief Status

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Laboratori Nazionali del Gran Sasso

CERN

Based on M. Cirelli, E. Del Nobile, PP, JCAP 1310 (2013) **019**
and F. D'Earmo, B.J. Kavanagh, PP, JHEP 1608 (2016) **111**

Plan of the Talk

Formalism of non-relativistic (NR) EFT

Match high-energy operators to NR EFT

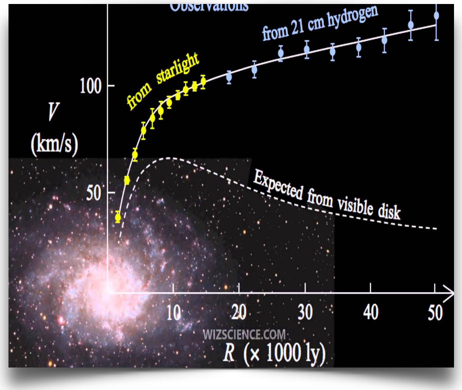
Connect DM model to the nuclear energy scale

Complementarity between DD & colliders

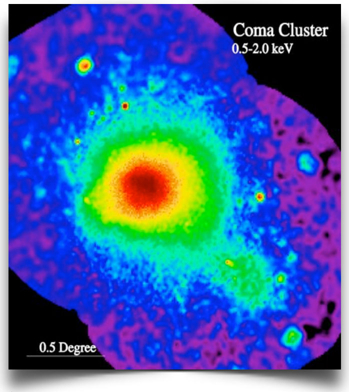
Outlook & Discussions

Dark Matter in the Universe

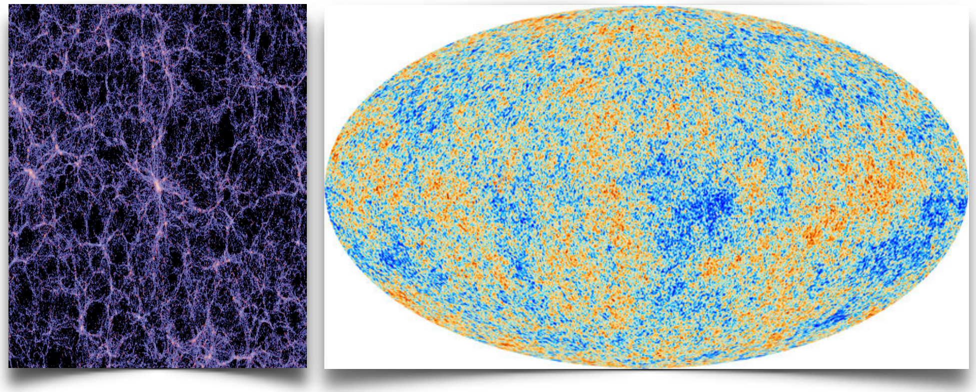
Compelling **macroscopic** evidence of Dark Matter



Galaxy scale



Cluster scale



Cosmological scale

DM Exists !

80% of the matter
in the Universe is **DARK**

- **Stable**
- **Non-relativistic**
- **Weakly interacting**

Dark Matter in the Universe

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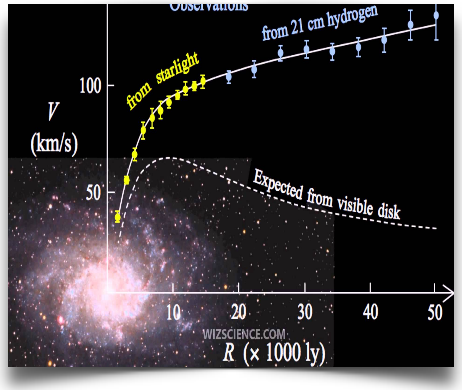

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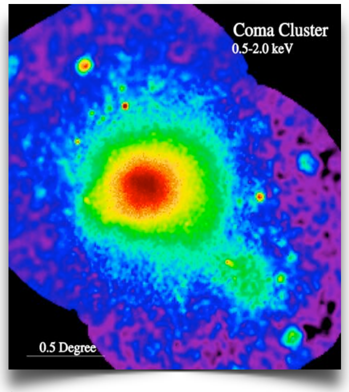
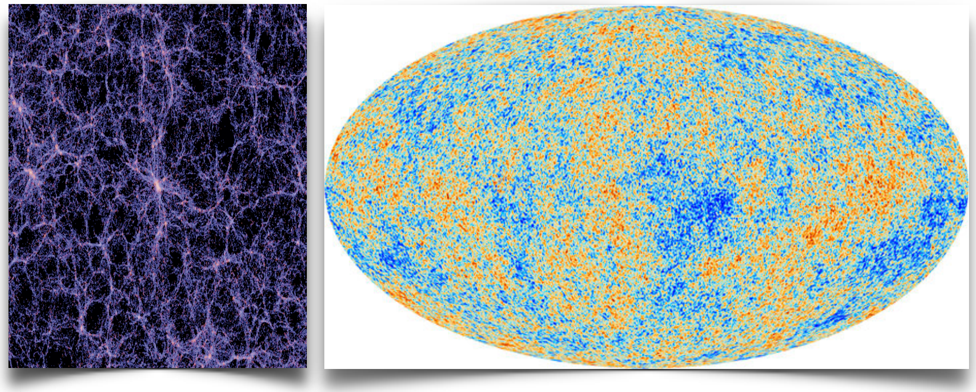


Cluster scale



Cosmological scale

BUT ⇨ The DM **microphysics** is unknown

THEORY: Hidden sector theories, Supersymmetry, Technicolor, etc…

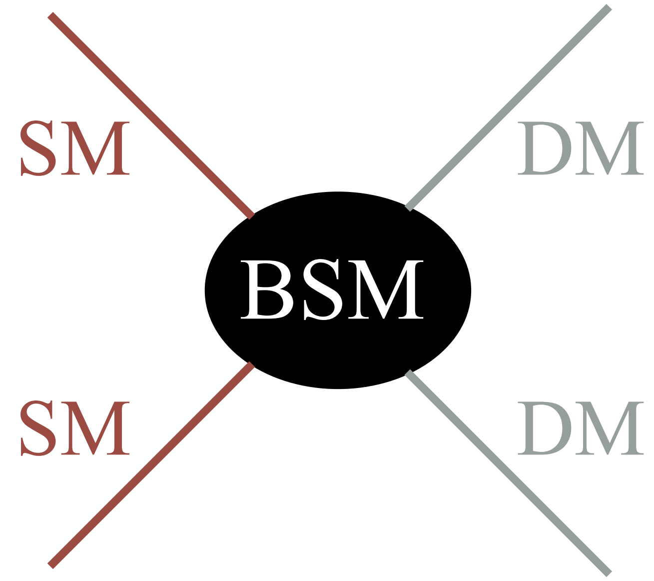
DM CANDIDATE: **axions, asymmetric DM, WIMP, primordial Black Holes**, etc…

DM DENSITY: cuspy DM density profiles **(e.g. NFW)** or cored profiles **(e.g. IsoT)**

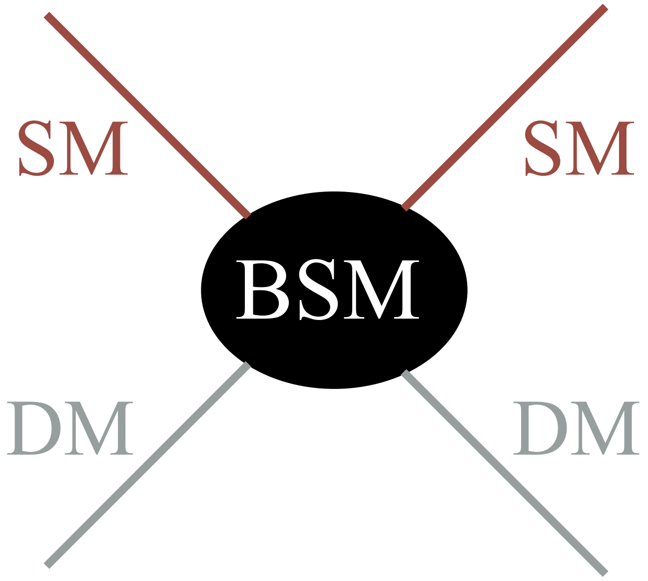
Dark Matter Detection

Experimental strategies to identify the **DM microphysics**

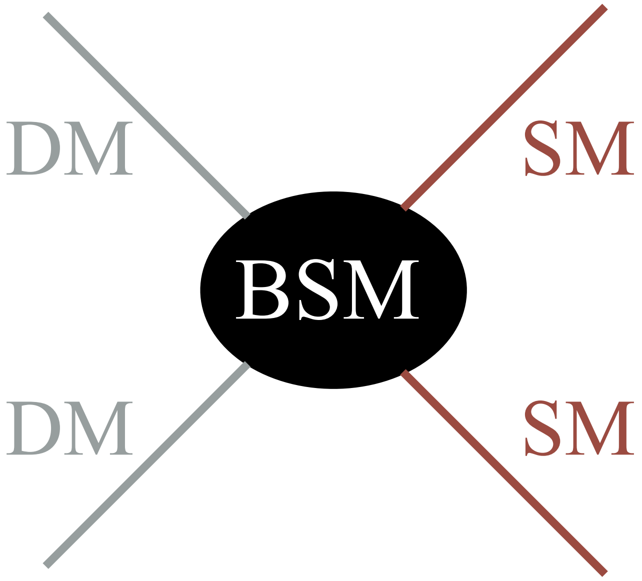
Colliders



Direct Detection



Indirect Detection

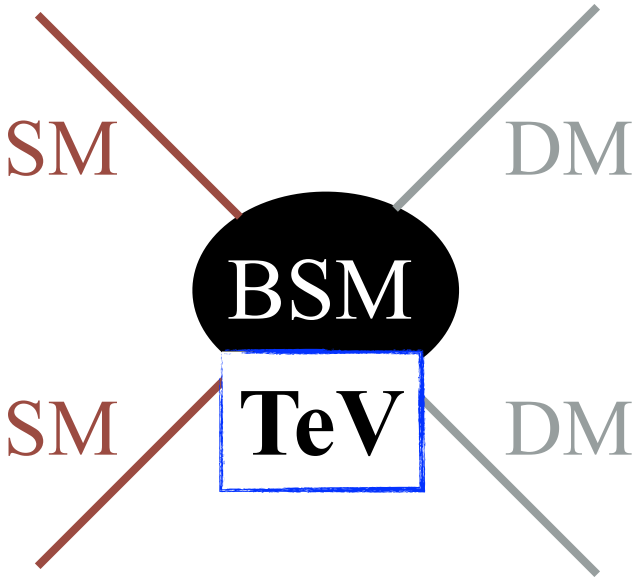


Constrain the parameter space
Find several anomalies

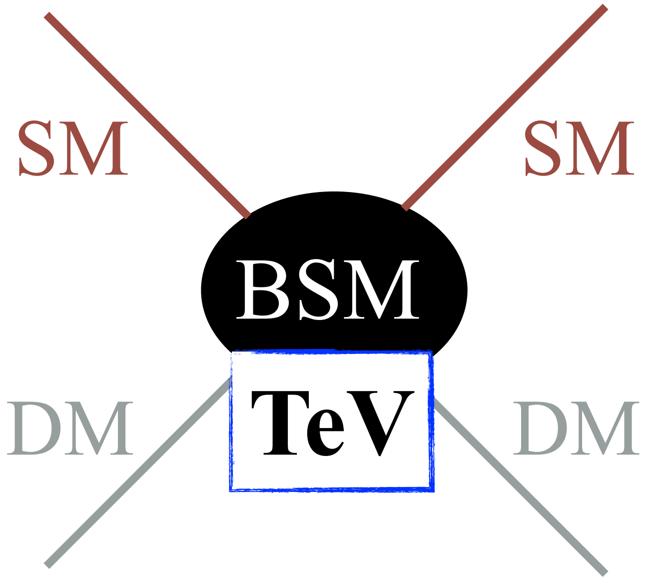
Dark Matter Detection

Experimental strategies to identify the **DM microphysics**

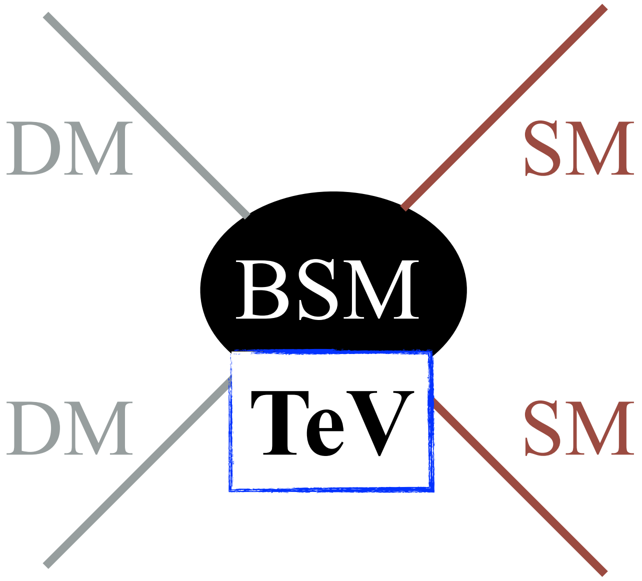
Colliders



Direct Detection



Indirect Detection



2018
LHC Run 2
XENON1T
AMS-02

2019

2020
LHC Run 3
Next generation direct detection exps.

2021

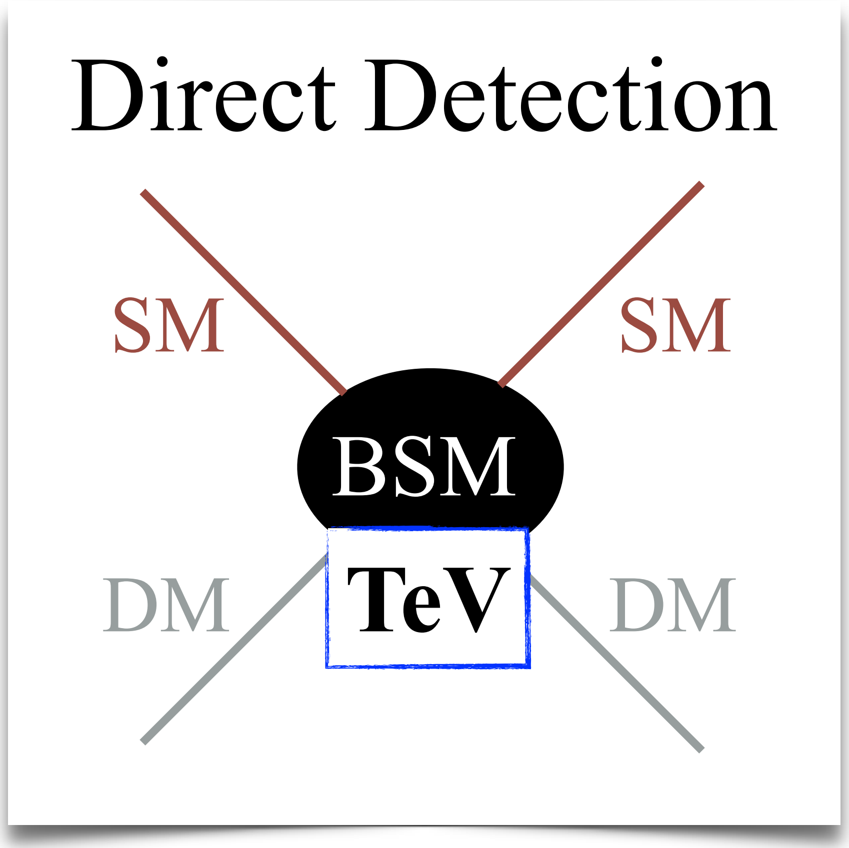
2022
CTA
XENONnT

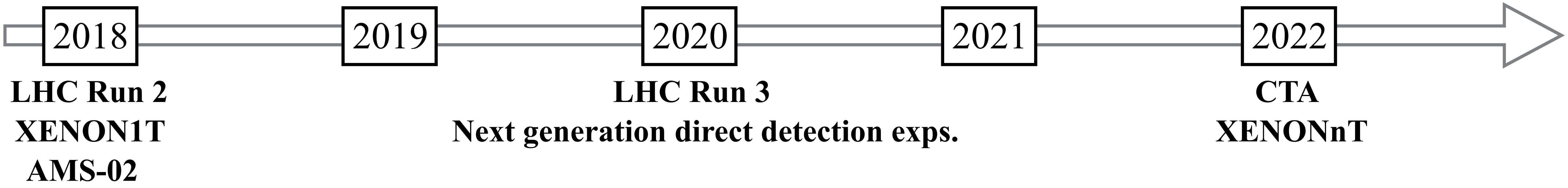
Approaching ***now*** the **TeV scale**

A new era has begun

Dark Matter Detection

Experimental strategies to identify the **DM microphysics**





Approaching ***now*** the **TeV scale**

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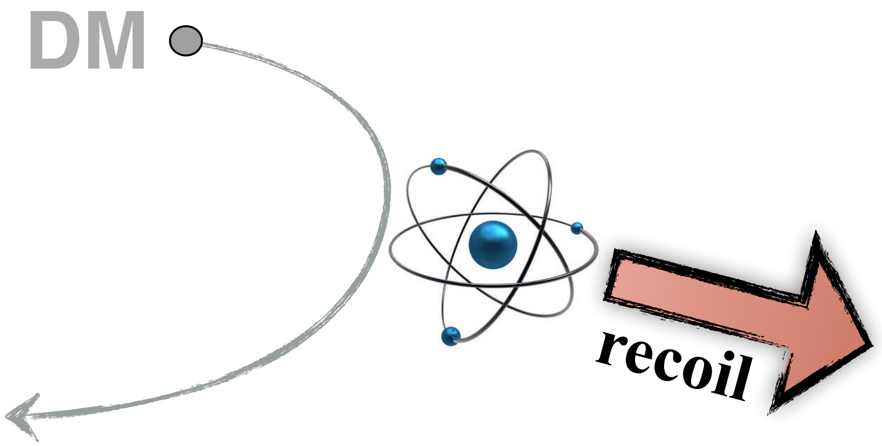
Direct Detection: overview



Elastic Scattering:

$$\mathrm{DM} + \mathcal{T}(A, Z)_{\mathrm{rest}} \longrightarrow \mathrm{DM} + \mathcal{T}(A, Z)_{\mathrm{recoil}}$$

Inelastic Scattering:

$$\mathrm{DM} + \mathcal{T}(A, Z)_{\mathrm{rest}} \longrightarrow \mathrm{DM}' + \mathcal{T}(A, Z)_{\mathrm{recoil}}$$

DM collisions are **very rare**
(less then 0.01 cpd/kg/keV)

- ☑ the detectors must **work deeply underground**
- ☑ they must **use active shields and very clean materials**
- ☑ they must **discriminate multiple scattering**

Direct Detection: overview

Tiny velocity ⇒ Collisions: **Non Relativistic regime**

$v_\odot \sim 10^{-3} c$

$$E_{\rm R} = \frac{1}{2} m_{\rm DM} v^2 \frac{4 m_{\rm DM} m_{\mathcal{T}}}{(m_{\rm DM} + m_{\mathcal{T}})^2} \frac{1}{2} \left(1 - \frac{v_t^2}{2v^2} - \sqrt{1 - \frac{v_t^2}{v^2}} \cos\theta\right)$$

DM kinetic energy

kinematic factor

threshold velocity kinematics

scattering angle

Direct Detection: overview

Tiny velocity ⇒ Collisions: **Non Relativistic regime**

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DM kinetic energy

kinematic factor

threshold velocity kinematics

scattering angle

RATE OF NUCLEAR RECOIL

$$\frac{\mathrm{d}R_{\mathcal{T}}}{\mathrm{d}E_{\rm R}} = N_{\mathcal{T}} \frac{\rho_\odot}{m_{\rm DM}} \int_{v_{\rm min}(E_{\rm R})}^{v_{\rm esc}} \mathrm{d}^3|\vec{v}| \; |\vec{v}| f_{\rm DM}(|\vec{v}|) \frac{\mathrm{d}\sigma}{\mathrm{d}E_{\rm R}}$$

total number of targets

Local DM number density

DM velocity distribution

Differential cross section

Direct detection: Uncertainties

$$\frac{\mathrm{d}R_{\mathcal{T}}}{\mathrm{d}E_{\mathrm{R}}} = N_{\mathcal{T}} \underbrace{\frac{\rho_\odot}{m_{\mathrm{DM}}}}_{\text{Local DM number density}} \int_{v_{\min}(E_{\mathrm{R}})}^{v_{\mathrm{esc}}} \mathrm{d}^3|\vec{v}| \; |\vec{v}| \underbrace{f_{\mathrm{DM}}(|\vec{v}|)}_{\text{DM velocity distribution}} \underbrace{\frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{R}}}}_{\text{Differential cross section}}$$

Local DM number density

DM velocity distribution

Differential cross section

Uncertainties from Astrophysics → i.e. local DM energy density & geometry of the halo

Uncertainties from Particle Physics → i.e. nature of the DM interaction & nuclear response functions

Uncertainties from Experimental side → i.e. background & detection efficiency close to lower threshold

Direct detection: Uncertainties

$$\frac{\mathrm{d}R_{\mathcal{T}}}{\mathrm{d}E_{\mathrm{R}}} = N_{\mathcal{T}}\frac{\rho_{\odot}}{m_{\mathrm{DM}}}\int_{v_{\mathrm{min}}(E_{\mathrm{R}})}^{v_{\mathrm{esc}}} \mathrm{d}^3|\vec{v}|\;|\vec{v}|\,f_{\mathrm{DM}}(|\vec{v}|)\,\frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{R}}}$$

Local DM number density

DM velocity distribution

Differential cross section

Uncertainties from Particle Physics

i.e. nature of the DM interaction & nuclear response functions

Non-relativistic (NR) EFT

Deeply NR DM-nucleus scattering

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{R}}} = \frac{1}{32\pi}\frac{1}{m_{\mathrm{DM}}^2 m_{\mathcal{T}}}\frac{1}{v^2}\left|\mathcal{M}_{\mathcal{T}}\right|^2$$

Non-relativistic (NR) EFT

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$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{R}}} = \frac{1}{32\pi}\frac{1}{m_{\mathrm{DM}}^2 m_{\mathcal{T}}}\frac{1}{v^2}\left|\mathcal{M}_{\mathcal{T}}\right|^2$$

DM-nucleon ME:
Galileian combination of NR d.o.f. $(\vec{q}, \vec{v}_{\perp}, \vec{s}_N, \vec{s}_{\mathrm{DM}})$

$$\mathcal{M}_N \equiv \sum_i \underbrace{\mathfrak{c}_i^N(\lambda, m_{\mathrm{DM}})}_{\substack{\textbf{NR coefficients}\\ \textbf{(details of the UV)}}} \underbrace{\mathcal{O}_i^{\mathrm{NR}}}_{\substack{\textbf{NR}\\ \textbf{operators}}}$$

Non-relativistic (NR) EFT

Deeply NR DM-nucleus scattering

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{R}}} = \frac{1}{32\pi}\frac{1}{m_{\mathrm{DM}}^2 m_{\mathcal{T}}}\frac{1}{v^2}\left|\mathcal{M}_{\mathcal{T}}\right|^2$$

$$\Downarrow$$

DM-nucleon ME:
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$$\mathcal{M}_N \equiv \sum_i \underbrace{\mathfrak{c}_i^N(\lambda, m_{\mathrm{DM}})}_{\textbf{NR coefficients (details of the UV)}} \underbrace{\mathcal{O}_i^{\mathrm{NR}}}_{\textbf{NR operators}}$$

$$\mathcal{O}_1^{\mathrm{NR}} \equiv \mathcal{I}_\chi \mathcal{I}_N \ ,$$

$$\mathcal{O}_3^{\mathrm{NR}} \equiv i\,\mathcal{I}_\chi \boldsymbol{s}_N \cdot (\boldsymbol{q} \times \boldsymbol{v}^\perp) \ , \qquad \mathcal{O}_4^{\mathrm{NR}} \equiv \boldsymbol{s}_\chi \cdot \boldsymbol{s}_N \ ,$$

$$\mathcal{O}_5^{\mathrm{NR}} \equiv i\,\mathcal{I}_N \boldsymbol{s}_\chi \cdot (\boldsymbol{q} \times \boldsymbol{v}^\perp) \ , \qquad \mathcal{O}_6^{\mathrm{NR}} \equiv (\boldsymbol{s}_\chi \cdot \boldsymbol{q})(\boldsymbol{s}_N \cdot \boldsymbol{q}) \ ,$$

$$\mathcal{O}_7^{\mathrm{NR}} \equiv \mathcal{I}_\chi \boldsymbol{s}_N \cdot \boldsymbol{v}^\perp \ , \qquad \mathcal{O}_8^{\mathrm{NR}} \equiv \mathcal{I}_N \boldsymbol{s}_\chi \cdot \boldsymbol{v}^\perp \ ,$$

$$\mathcal{O}_9^{\mathrm{NR}} \equiv i\,\boldsymbol{s}_\chi \cdot (\boldsymbol{s}_N \times \boldsymbol{q}) \ , \qquad \mathcal{O}_{10}^{\mathrm{NR}} \equiv i\,\mathcal{I}_\chi \boldsymbol{s}_N \cdot \boldsymbol{q} \ ,$$

$$\mathcal{O}_{11}^{\mathrm{NR}} \equiv i\,\mathcal{I}_N \boldsymbol{s}_\chi \cdot \boldsymbol{q} \ , \qquad \mathcal{O}_{12}^{\mathrm{NR}} \equiv \boldsymbol{v}^\perp \cdot (\boldsymbol{s}_\chi \times \boldsymbol{s}_N) \ ,$$

$$\mathcal{O}_{13}^{\mathrm{NR}} \equiv i(\boldsymbol{s}_\chi \cdot \boldsymbol{v}^\perp)(\boldsymbol{s}_N \cdot \boldsymbol{q}) \ , \qquad \mathcal{O}_{14}^{\mathrm{NR}} \equiv i(\boldsymbol{s}_\chi \cdot \boldsymbol{q})(\boldsymbol{s}_N \cdot \boldsymbol{v}^\perp) \ ,$$

$$\mathcal{O}_{15}^{\mathrm{NR}} \equiv [\boldsymbol{s}_\chi \cdot (\boldsymbol{q} \times \boldsymbol{v}^\perp)](\boldsymbol{s}_N \cdot \boldsymbol{q}) \ , \qquad \mathcal{O}_{16}^{\mathrm{NR}} \equiv (\boldsymbol{s}_\chi \cdot \boldsymbol{v}^\perp)(\boldsymbol{s}_N \cdot \boldsymbol{v}^\perp) \ ,$$

$$\mathcal{O}_{17}^{\mathrm{NR}} \equiv i[\boldsymbol{s}_\chi \cdot (\boldsymbol{q} \times \boldsymbol{v}^\perp)](\boldsymbol{s}_N \cdot \boldsymbol{v}^\perp) \ .$$

Non-relativistic (NR) EFT

Deeply NR DM-nucleus scattering

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{R}}} = \frac{1}{32\pi}\frac{1}{m_{\mathrm{DM}}^2 m_{\mathcal{T}}}\frac{1}{v^2}\left|\mathcal{M}_{\mathcal{T}}\right|^2$$

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$$\mathcal{M}_N \equiv \sum_i \underbrace{\mathfrak{c}_i^N(\lambda, m_{\mathrm{DM}})}_{\substack{\textbf{NR coefficients}\\ \textbf{(details of the UV)}}} \underbrace{\mathcal{O}_i^{\mathrm{NR}}}_{\substack{\textbf{NR}\\ \textbf{operators}}}$$

Experiments consider:

Spin independent

$$\mathcal{O}_1^{\mathrm{NR}} \equiv \mathcal{I}_{\mathrm{DM}}\mathcal{I}_N$$

Spin dependent

$$\mathcal{O}_4^{\mathrm{NR}} \equiv \vec{s}_{\mathrm{DM}} \cdot \vec{s}_N$$

Non-relativistic (NR) EFT

The nucleus is not point-like:

$$|\mathcal{M}_\mathcal{T}|^2 = \frac{m_\mathcal{T}^2}{m_N^2} \sum_{i,j} \sum_{N,N'=p,n} \mathfrak{c}_i^N \mathfrak{c}_j^{N'} \underbrace{F_{i,j}^{(N,N')}(\vec{q}, \vec{v}_\perp, \vec{s}_N, \vec{s}_{\rm DM})}_{\textbf{NUCLEAR RESPONSES}}$$

Non-relativistic (NR) EFT

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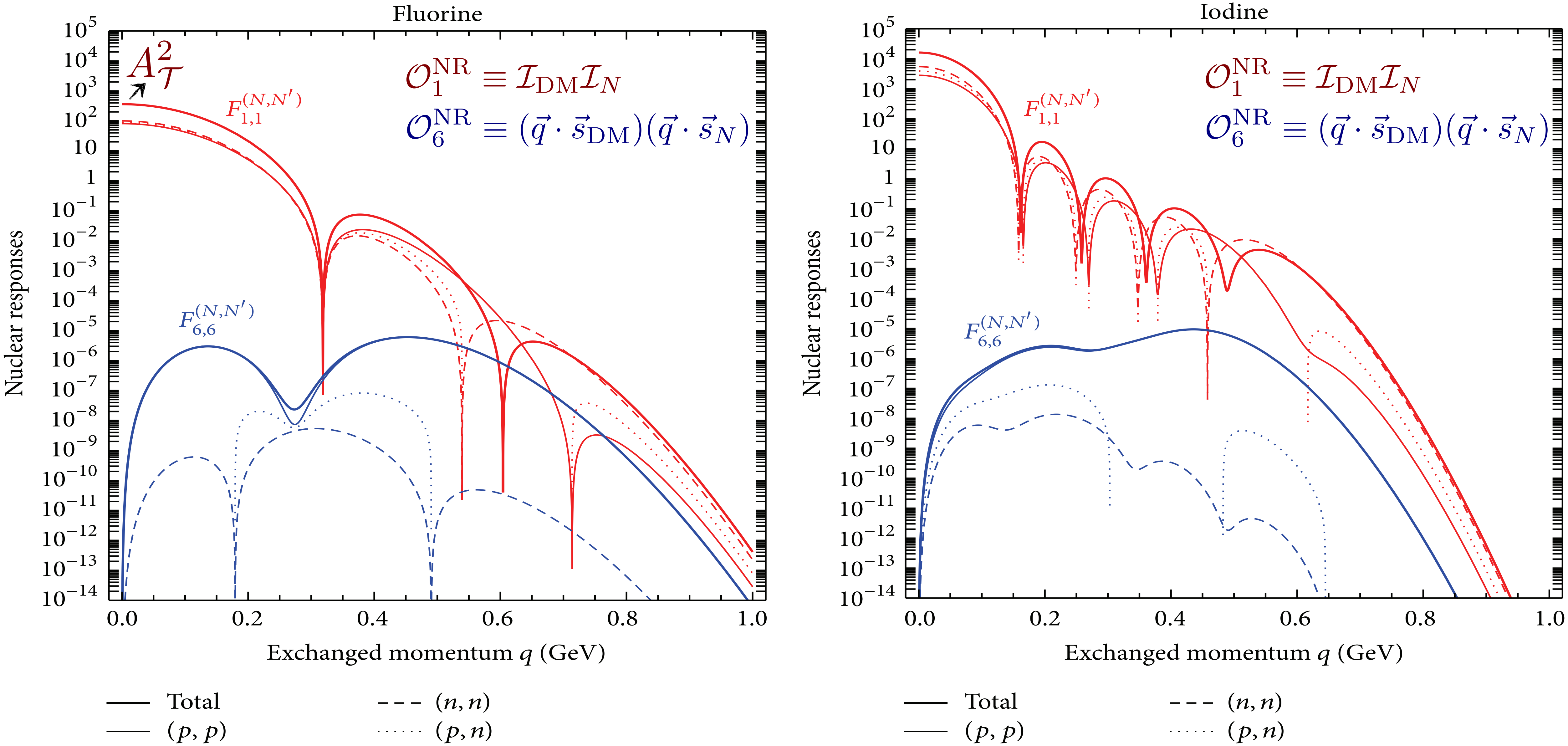
see e.g. JCAP 1302 (2013) **004**



The rate of nuclear recoils

# of Events: in terms of **model independent form factor**

$$\mathcal{N}(\lambda, m_{\rm DM}) \propto \sum_{i,j} \sum_{N,N'=p,n} \underbrace{\mathfrak{c}_i^N(\lambda, m_{\rm DM})\mathfrak{c}_j^{N'}(\lambda, m_{\rm DM})}_{\text{PARTICLE PHYSICS}} \underbrace{\mathcal{F}^{ij}_{N,N'}(m_{\rm DM})}_{\text{MODEL INDEPENDENT}}$$

ME sensitives to Galileian combinations of NR d.o.f.

Going beyond the usual pictures (i.e. SI & SD interactions)

The standard interactions

SPIN INDEPENDENT

SPIN DEPENDENT

The standard interactions

SPIN INDEPENDENT

SPIN DEPENDENT

Dimension-6 four fermion interactions

$$\lambda^N_{\rm SI}\,\bar\chi\gamma_\mu\chi\,\bar N\gamma^\mu N$$

$$\lambda^N_{\rm SD}\,\bar\chi\gamma_\mu\gamma_5\chi\,\bar N\gamma^\mu\gamma_5 N$$

The standard interactions

SPIN INDEPENDENT

SPIN DEPENDENT

Dimension-6 four fermion interactions

$$\lambda_{\mathrm{SI}}^{N}\,\bar{\chi}\gamma_{\mu}\chi\,\bar{N}\gamma^{\mu}N$$

$$\lambda_{\mathrm{SD}}^{N}\,\bar{\chi}\gamma_{\mu}\gamma_5\chi\,\bar{N}\gamma^{\mu}\gamma_5 N$$

DM-nucleon ME $\mathcal{M}_{q^2\to 0}\equiv\langle\chi N\,|\mathcal{L}|\,\chi' N'\rangle_{q^2\to 0}$

$$\underbrace{4\lambda_{\mathrm{SI}}^{N}m_{\mathrm{DM}}m_N}_{\mathfrak{c}_1^N}\,\underbrace{\mathcal{I}_{\mathrm{DM}}\mathcal{I}_N}_{\mathcal{O}_1^{\mathrm{NR}}}$$

$$\underbrace{-16\lambda_{\mathrm{SD}}^{N}m_{\mathrm{DM}}m_N}_{\mathfrak{c}_4^N}\,\underbrace{\vec{s}_{\mathrm{DM}}\cdot\vec{s}_N}_{\mathcal{O}_4^{\mathrm{NR}}}$$

The standard interactions

SPIN INDEPENDENT

SPIN DEPENDENT

Dimension-6 four fermion interactions

$$\lambda_{\rm SI}^N \, \bar{\chi}\gamma_\mu\chi \, \bar{N}\gamma^\mu N \qquad\qquad \lambda_{\rm SD}^N \, \bar{\chi}\gamma_\mu\gamma_5\chi \, \bar{N}\gamma^\mu\gamma_5 N$$

DM-nucleon ME $\mathcal{M}_{q^2\to 0} \equiv \langle \chi N \, |\mathcal{L}| \, \chi' N' \rangle_{q^2\to 0}$

$$\underbrace{4\lambda_{\rm SI}^N m_{\rm DM} m_N}_{\mathfrak{c}_1^N} \underbrace{\mathcal{I}_{\rm DM}\mathcal{I}_N}_{\mathcal{O}_1^{\rm NR}} \qquad\qquad \underbrace{-16\lambda_{\rm SD}^N m_{\rm DM} m_N}_{\mathfrak{c}_4^N} \underbrace{\vec{s}_{\rm DM}\cdot\vec{s}_N}_{\mathcal{O}_4^{\rm NR}}$$

THE RATE

coherent factor ↗ **SI form factor** ↗ **Halo function** ↗

$$N_\mathcal{T} \frac{\rho_\odot}{m_\chi} \frac{m_\mathcal{T}}{2\mu_{\chi\mathcal{T}}^2} \begin{cases} A_\mathcal{T}^2 \sigma_{\rm SI}^N F_{\rm SI}^2(E_{\rm R}) \mathcal{H}(E_{\rm R}) & \text{with } \sigma_{\rm SI}^N = \dfrac{(\lambda_{\rm SI}^N \mu_{\chi N})^2}{\pi} \\ \langle J_\mathcal{T}^2 \rangle \sigma_{\rm SD}^N F_{\rm SD}^2(E_{\rm R}) \mathcal{H}(E_{\rm R}) & \text{with } \sigma_{\rm SD}^N = \dfrac{3(\lambda_{\rm SD}^N \mu_{\chi N})^2}{\pi} \end{cases}$$

↘ **Nuclear spin factor** ↘ **SD form factor** ↘ **Halo function**

Worldwide DM searches

~50% use Noble Liquids

SNOLab
DEAPCLEAN
PICO
DAMIC

Boulby
DRIFT

YangYang
KIMS,COSINE

Homestake
LUX-LZ

Modane
EDELWEISS
MIMAC

Kamioka
XMASS
Newage

Soudan
SuperCDMS
CoGeNT

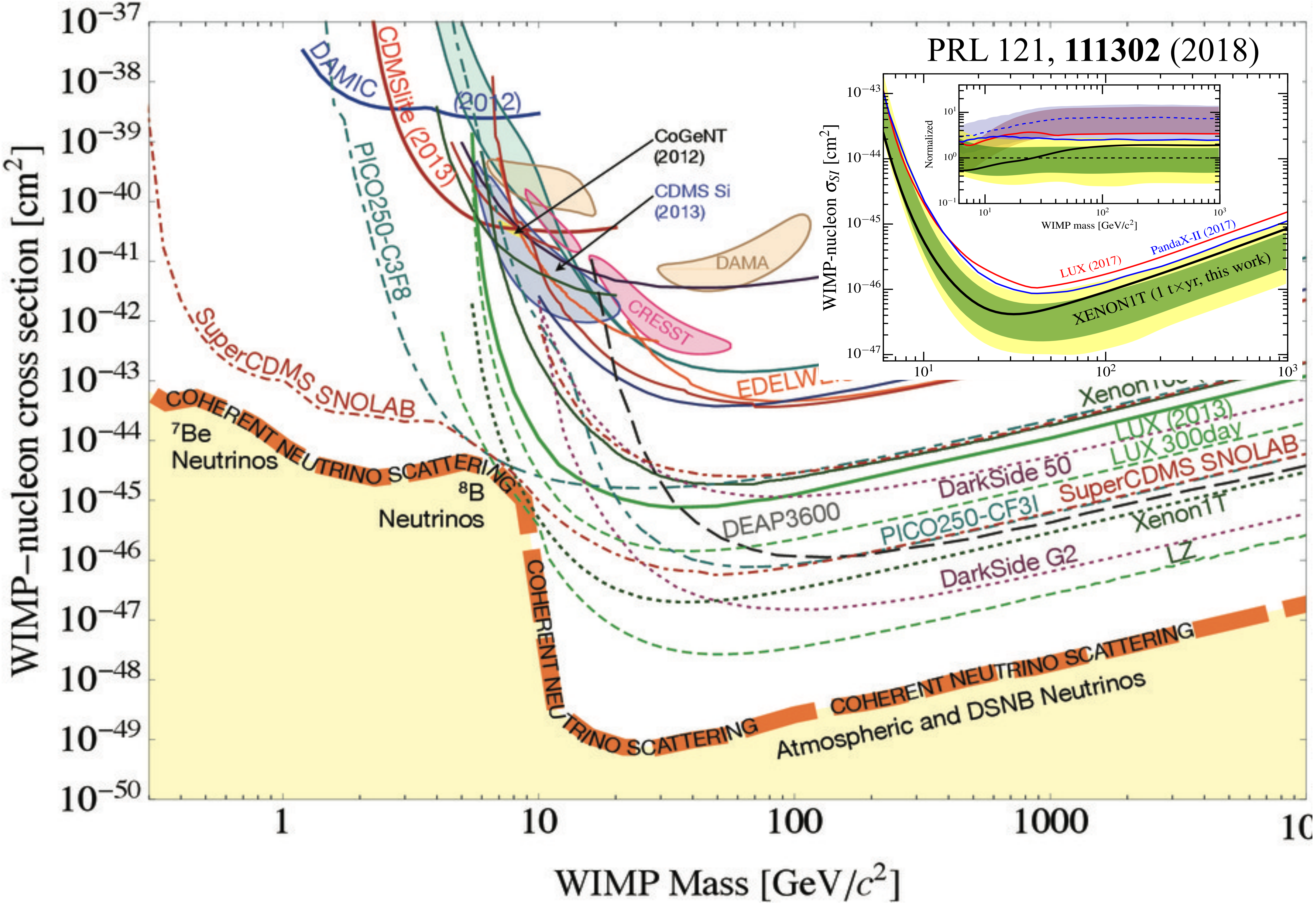
Canfranc
ArDM
Rosebud
ANAIS

Gran Sasso
XENON
CRESST
DAMA/LIBRA
DarkSide

Jinping
Panda-X
CDEX

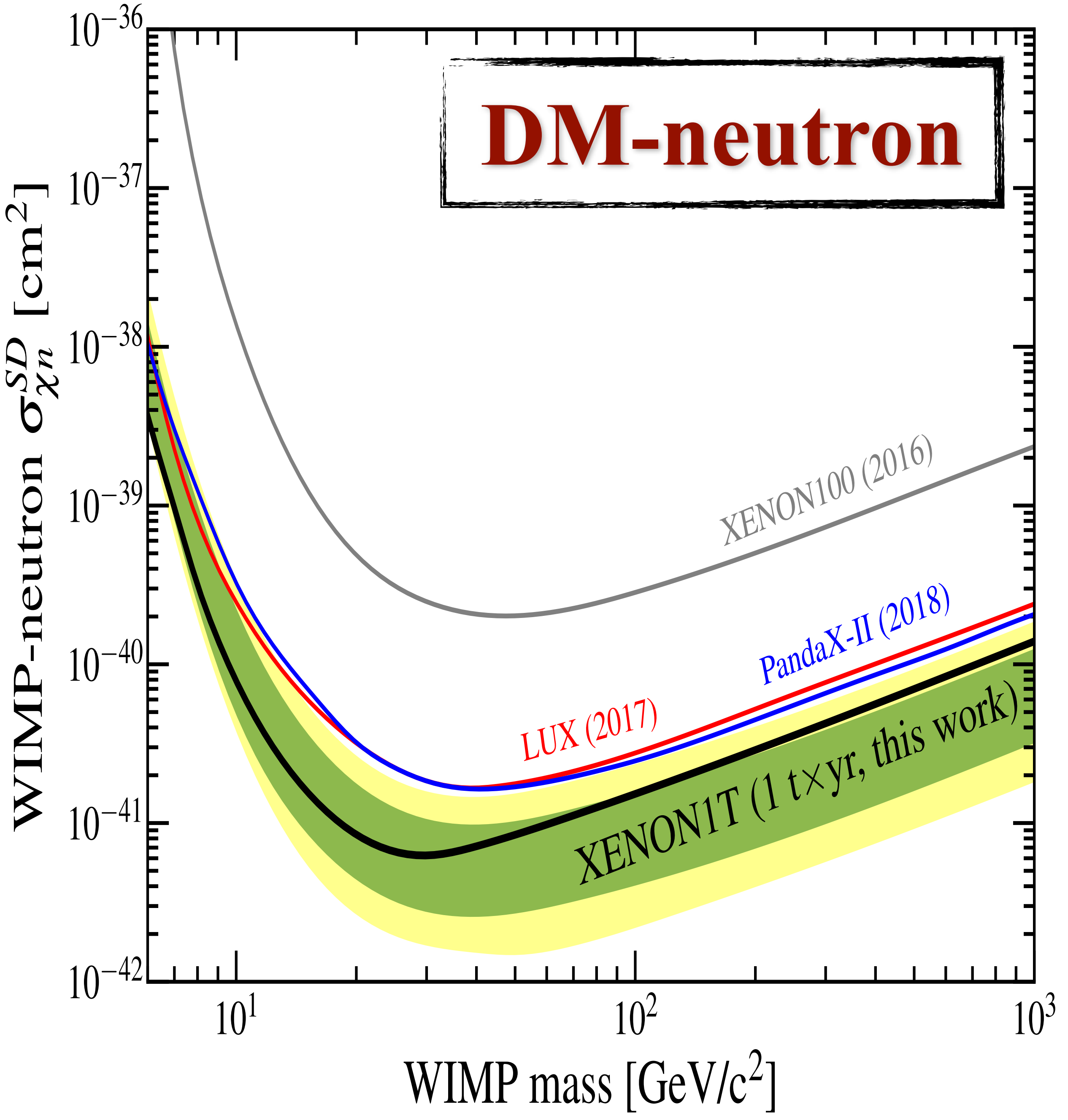
South Pole
DM Ice

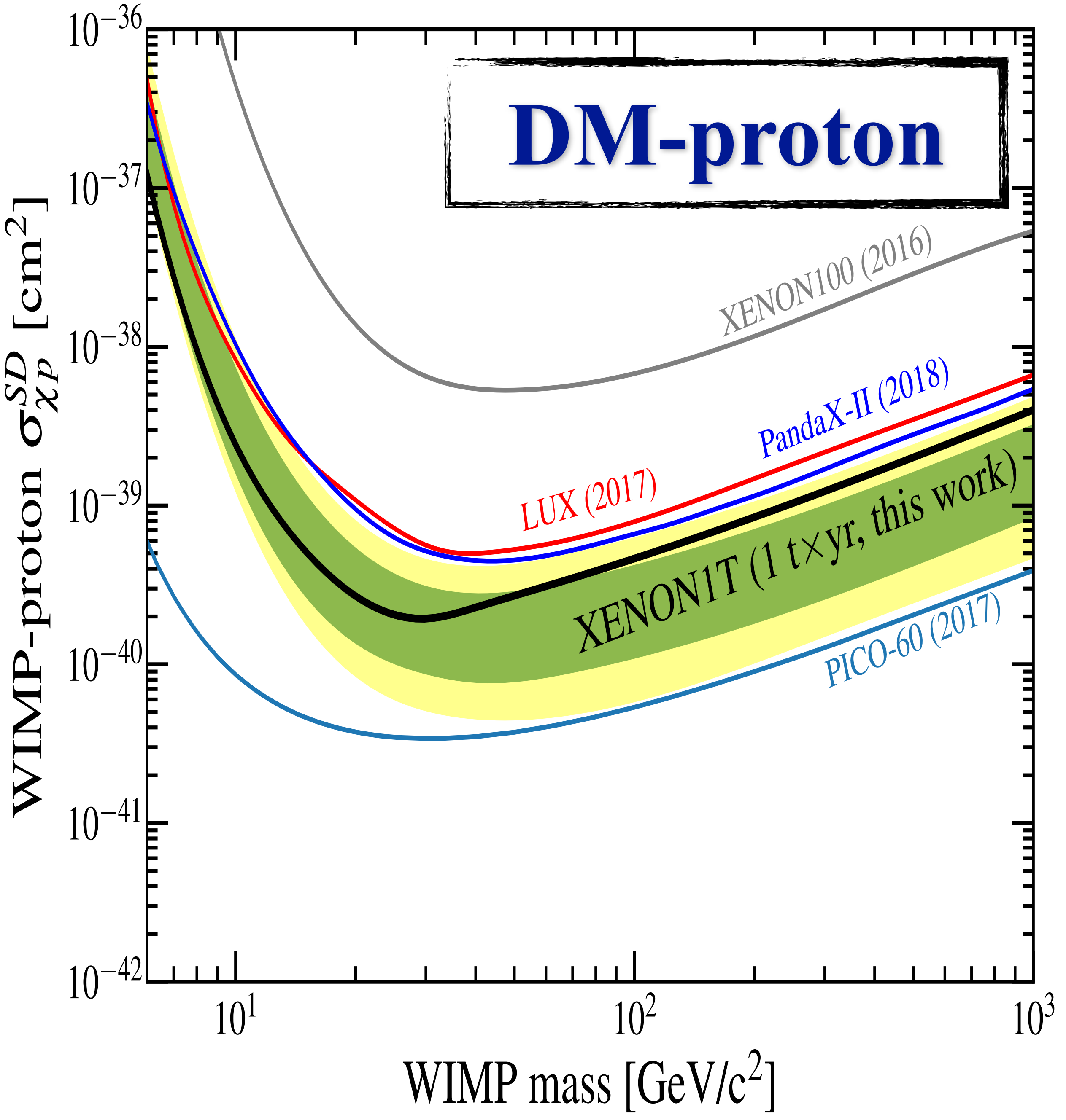
Spin independent: Status



PRL 121, **111302** (2018)

Spin dependent: Status





XENON1T, arXiv: 1902.03234

SENSITIVITIES:

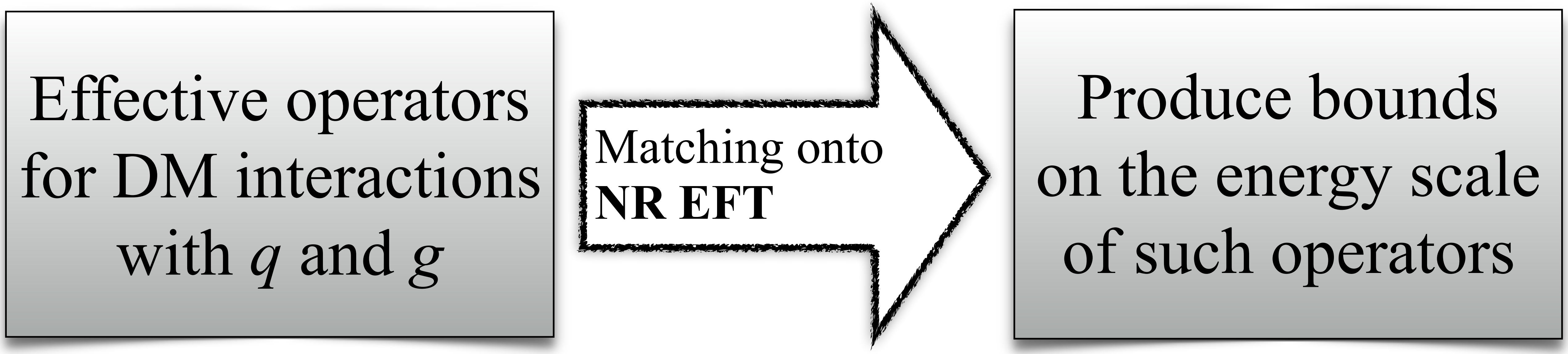
unpaired neutrons in the outer nuclear shell (e.g. xenon): large **DM-*n* SD**

unpaired protons in the outer nuclear shell (e.g. fluorine): large **DM-*p* SD**

II PART

Match high-energy operators to NR EFT

High-energy Operators



Effective operators for DM interactions with q and g

Matching onto **NR EFT**

Produce bounds on the energy scale of such operators

J. Goodman, M. Ibe, A. Rajaraman, W. Shepherd, T. M. P. Tait and H. -B. Yu, PRD 82 (2010) 116010, arXiv:1008.1783

P. J. Fox, R. Harnik, J. Kopp and Y. Tsai, PRD 84 (2011) 014028, arXiv:1103.0240

K. Cheung, P. -Y. Tseng, Y. -L. S. Tsai and T. -C. Yuan, JCAP 1205 (2012) 001, arXiv:1201.3402

J.-M. Zheng, Z.-H. Yu, J.-W. Shao, X.-J. Bi, Z. Li and H.-H. Zhang, NPB 854 (2012) 350, arXiv:1012.2022

Z.-H. Yu, J.-M. Zheng, X.-J. Bi, Z. Li, D.-X. Yao and H.-H. Zhang, NPB 860 (2012) 115, arXiv:1112.6052

and …

High-energy Operators

DIRAC DM

DIM-6 operators:
Constructed with neutral DM & SM quarks

$$\mathcal{O}_1^q = \bar{\chi}\chi\ \bar{q}q\,,\qquad \mathcal{O}_2^q = \bar{\chi}\,i\gamma^5\chi\ \bar{q}q\,,$$

$$\mathcal{O}_3^q = \bar{\chi}\chi\ \bar{q}\,i\gamma^5 q\,,\qquad \mathcal{O}_4^q = \bar{\chi}\,i\gamma^5\chi\ \bar{q}\,i\gamma^5 q\,,$$

$$\mathcal{O}_5^q = \bar{\chi}\gamma^\mu\chi\ \bar{q}\gamma_\mu q\,,\qquad \mathcal{O}_6^q = \bar{\chi}\gamma^\mu\gamma^5\chi\ \bar{q}\gamma_\mu q\,,$$

$$\mathcal{O}_7^q = \bar{\chi}\gamma^\mu\chi\ \bar{q}\gamma_\mu\gamma^5 q\,,\qquad \mathcal{O}_8^q = \bar{\chi}\gamma^\mu\gamma^5\chi\ \bar{q}\gamma_\mu\gamma^5 q\,,$$

$$\mathcal{O}_9^q = \bar{\chi}\,\sigma^{\mu\nu}\chi\ \bar{q}\,\sigma_{\mu\nu}q\,,\qquad \mathcal{O}_{10}^q = \bar{\chi}\,i\,\sigma^{\mu\nu}\gamma^5\chi\ \bar{q}\,\sigma_{\mu\nu}q\,,$$

High-energy Operators

DIRAC DM

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DIM-7 operators:
SM gauge invariant couple DM with gluons

$$\mathcal{O}_1^g = \frac{\alpha_\mathrm{s}}{12\pi}\;\bar\chi\chi\, G^a_{\mu\nu}G^a_{\mu\nu}\,, \qquad \mathcal{O}_2^g = \frac{\alpha_\mathrm{s}}{12\pi}\;\bar\chi\, i\gamma^5\chi\, G^a_{\mu\nu}G^a_{\mu\nu}\,,$$

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High-energy Operators

MAJORANA DM

DIM-6 operators:
Constructed with neutral
DM & SM quarks

$$\mathcal{O}_1^q = \bar\chi\chi\,\bar q q\,, \qquad \mathcal{O}_2^q = \bar\chi\, i\gamma^5\chi\,\bar q q\,,$$

$$\mathcal{O}_3^q = \bar\chi\chi\,\bar q\, i\gamma^5 q\,, \qquad \mathcal{O}_4^q = \bar\chi\, i\gamma^5\chi\,\bar q\, i\gamma^5 q\,,$$

$$\mathcal{O}_5^q = \xcancel{\bar\chi\gamma^\mu\chi\,\bar q\gamma_\mu q}\,, \qquad \mathcal{O}_6^q = \bar\chi\gamma^\mu\gamma^5\chi\,\bar q\gamma_\mu q\,,$$

$$\mathcal{O}_7^q = \xcancel{\bar\chi\gamma^\mu\chi\,\bar q\gamma_\mu\gamma^5 q}\,, \qquad \mathcal{O}_8^q = \bar\chi\gamma^\mu\gamma^5\chi\,\bar q\gamma_\mu\gamma^5 q\,,$$

$$\mathcal{O}_9^q = \xcancel{\bar\chi\,\sigma^{\mu\nu}\chi\,\bar q\,\sigma_{\mu\nu} q}\,, \qquad \mathcal{O}_{10}^q = \xcancel{\bar\chi\, i\,\sigma^{\mu\nu}\gamma^5\chi\,\bar q\,\sigma_{\mu\nu} q}\,,$$

DIM-7 operators:
SM gauge invariant
couple DM with gluons

$$\mathcal{O}_1^g = \frac{\alpha_s}{12\pi}\,\bar\chi\chi\,G^a_{\mu\nu}G^a_{\mu\nu}\,, \qquad \mathcal{O}_2^g = \frac{\alpha_s}{12\pi}\,\bar\chi\, i\gamma^5\chi\,G^a_{\mu\nu}G^a_{\mu\nu}\,,$$

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LAGRANGIAN at the *q* & *g* level

$$\mathscr{L}_{\rm eff} = \sum_{k=1}^{10}\sum_q c_k^q\,\mathcal{O}_k^q + \sum_{k=1}^{4} c_k^g\,\mathcal{O}_k^g\,,$$

c_k^q dim. of $[\mathrm{mass}]^{-2}$
c_k^g dim. of $[\mathrm{mass}]^{-3}$

Main steps to NR cross section

DM-nucleus collisions: **deeply NR regime**

Main steps to NR cross section

DM-nucleus collisions: **deeply NR regime**

STEP I:

dress the q and g operators to the nucleon level

$$\langle N(p')|\mathcal{O}_k^{(q,g)}|N(p)\rangle$$

DM-*nucleon* $\mathcal{L}$

$$\mathcal{L}_{\rm eff}^N = \sum_k c_k^N \mathcal{O}_k^N$$

Main steps to NR cross section

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$$\mathcal{L}_{\text{eff}}^N = \sum_k c_k^N \mathcal{O}_k^N$$

STEP II:

compute DM-*nucleon* ME & reduce it to NR operators

$$\langle \chi N \left| \mathcal{L}_{\text{eff}}^N \right| \chi' N' \rangle_{q^2 \to 0}$$

NR DM-*nucleon* ME

$$\sum_i \mathfrak{c}_i^N(\{c_{(q,g)}\}, m_\chi)\mathcal{O}_i^{\text{NR}}$$

Main steps to NR cross section

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NR DM-*nucleon* ME

$$\sum_i \mathfrak{c}_i^N(\{c_{(q,g)}\}, m_\chi)\mathcal{O}_i^{\text{NR}}$$

STEP III:

correct the DM-nucleon ME with the nuclear response

$$|\mathcal{M}_N|^2 \Rightarrow |\mathcal{M}_\mathcal{T}|^2$$

DM-Nucleus XS

$$\frac{d\sigma}{dE_{\text{R}}} \propto \sum_{i,j} \sum_{N,N'=p,n} \mathfrak{c}_i^N \mathfrak{c}_j^{N'} F_{i,j}^{(N,N')}$$

Main steps to NR cross section

DM-nucleus collisions: **deeply NR regime**

STEP I:

dress the *q* and *g* operators to the nucleon level

see e.g. J.R. Ellis, K. A. Olive, C. Savage,
PRD 77 (2008) **065026**, [arXiv: 0801.3656]

H.-Y. Cheng, C.-W. Chiang.
JHEP 07 (2012) **009**, [arXiv: 1202.1292]

F. Bishara, J. Brod, B. Grinstein, J. Zupan
JHEP 1711 (2017) **059**, [arXiv: 1707.06998]

☑

STEP II:

compute DM-*nucleon* ME & reduce it to NR operators

see e.g. M. Cirelli, E. Del Nobile, P. Panci,
JCAP 1310 (2013) **019**, [arXiv: 1307.5955]

F. Bishara, J. Brod, B. Grinstein, J. Zupan
[arXiv: 1708.02678]

☑

STEP III:

correct the DM-nucleon ME with the nuclear response

A. L. Fitzpatrick, W. Haxton, E. Katz, N. Lubbers, Y. Xu,
JCAP 1302 (2013) **004**, [arXiv: 1203.3542]

☑

NR structure

NR structure

$\mathcal{S}$-$\mathcal{S}$	$c_1^q \, \bar{\chi}\chi \, \bar{q}q$
$\mathcal{V}$-$\mathcal{V}$	$c_5^q \, \bar{\chi}\gamma^\mu\chi \, \bar{q}\gamma_\mu q$
$\mathcal{S}$-GG	$\frac{\alpha_s}{12\pi} c_1^g \, \bar{\chi}\chi \, G^a_{\mu\nu} G^{\mu\nu}_a$

$$\mathcal{M}_N \propto \mathcal{I}_\chi \mathcal{I}_N$$

Contact SI
different coefficients
due to quark/gluon currents
dressing into *nucleons*

NR structure

$\mathcal{S}$-$\mathcal{S}$	$c_1^q \, \bar\chi\chi \, \bar q q$
$\mathcal{V}$-$\mathcal{V}$	$c_5^q \, \bar\chi\gamma^\mu\chi \, \bar q\gamma_\mu q$
$\mathcal{S}$-GG	$\frac{\alpha_s}{12\pi} c_1^g \, \bar\chi\chi \, G^a_{\mu\nu}G_a^{\mu\nu}$

$$\mathcal{M}_N \propto \mathcal{I}_\chi \mathcal{I}_N$$

Contact SI
different coefficients
due to quark/gluon currents
dressing into *nucleons*

$\mathcal{AV}$-$\mathcal{AV}$	$c_8^q \, \bar\chi\gamma^\mu\gamma^5\chi \, \bar q\gamma_\mu\gamma^5 q$
$\mathcal{T}$-$\mathcal{T}$	$c_9^q \, \bar\chi\sigma^{\mu\nu}\chi \, \bar q\sigma_{\mu\nu} q$

$$\mathcal{M}_N \propto \vec{s}_\chi \cdot \vec{s}_N$$

Contact SD
different coefficients
due to quark/gluon currents
dressing into *nucleons*

NR structure

$\mathcal{S}$-$\mathcal{S}$ $\mathcal{V}$-$\mathcal{V}$ $\mathcal{S}$-$\mathcal{G}\mathcal{G}$	$c_1^q\,\bar\chi\chi\,\bar q q$ $c_5^q\,\bar\chi\gamma^\mu\chi\,\bar q\gamma_\mu q$ $\frac{\alpha_s}{12\pi}c_1^g\,\bar\chi\chi\,G^a_{\mu\nu}G_a^{\mu\nu}$	$\mathcal{M}_N \propto \mathcal{I}_\chi \mathcal{I}_N$	**Contact SI** different coefficients due to quark/gluon currents dressing into *nucleons*
$\mathcal{AV}$-$\mathcal{AV}$ $\mathcal{T}$-$\mathcal{T}$	$c_8^q\,\bar\chi\gamma^\mu\gamma^5\chi\,\bar q\gamma_\mu\gamma^5 q$ $c_9^q\,\bar\chi\sigma^{\mu\nu}\chi\,\bar q\sigma_{\mu\nu} q$	$\mathcal{M}_N \propto \vec{s}_\chi \cdot \vec{s}_N$	**Contact SD** different coefficients due to quark/gluon currents dressing into *nucleons*
$\mathcal{PS}$-$\mathcal{PS}$ $\mathcal{PS}$-$\mathcal{G}\tilde{\mathcal{G}}$	$c_4^q\,\bar\chi\gamma^5\chi\,\bar q\gamma^5 q$ $\frac{\alpha_s}{12\pi}c_4^g\,\bar\chi\gamma^5\chi G^a_{\mu\nu}\tilde G_a^{\mu\nu}$	$\mathcal{M}_N \propto (\vec{q}\cdot\vec{s}_\chi)(\vec{q}\cdot\vec{s}_N)$	**Longitudinal SD** highly suppressed $q^4/(m_N^2 m_\chi^2)$

NR structure

$\mathcal{S}$-$\mathcal{S}$ $\quad c_1^q\,\bar\chi\chi\,\bar q q$

$\mathcal{V}$-$\mathcal{V}$ $\quad c_5^q\,\bar\chi\gamma^\mu\chi\,\bar q\gamma_\mu q$

$\mathcal{S}$-GG $\quad \frac{\alpha_s}{12\pi}c_1^g\,\bar\chi\chi\,G^a_{\mu\nu}G_a^{\mu\nu}$

$$\mathcal{M}_N \propto \mathcal{I}_\chi\mathcal{I}_N$$

Contact SI
different coefficients
due to quark/gluon currents
dressing into *nucleons*

$\mathcal{AV}$-$\mathcal{AV}$ $\quad c_8^q\,\bar\chi\gamma^\mu\gamma^5\chi\,\bar q\gamma_\mu\gamma^5 q$

$\mathcal{T}$-$\mathcal{T}$ $\quad c_9^q\,\bar\chi\sigma^{\mu\nu}\chi\,\bar q\sigma_{\mu\nu}q$

$$\mathcal{M}_N \propto \vec{s}_\chi\cdot\vec{s}_N$$

Contact SD
different coefficients
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dressing into *nucleons*

$\mathcal{PS}$-$\mathcal{PS}$ $\quad c_4^q\,\bar\chi\gamma^5\chi\,\bar q\gamma^5 q$

$\mathcal{PS}$-$G\tilde G$ $\quad \frac{\alpha_s}{12\pi}c_4^g\,\bar\chi\gamma^5\chi G^a_{\mu\nu}\tilde G_a^{\mu\nu}$

$$\mathcal{M}_N \propto (\vec{q}\cdot\vec{s}_\chi)(\vec{q}\cdot\vec{s}_N)$$

Longitudinal SD
highly suppressed
$q^4/(m_N^2 m_\chi^2)$

The other 7 parity violating Operators

Matching onto
NR EFT

SI & SD interaction
suppressed by
$(q^2/(m^2_{N,\chi}), v^2)$

How do we put limits?

➡The simplest method:

assume the idealized case in which **only one operator** is active at a time

Scalar operators

$$\mathcal{O}_1^q = \bar{\chi}\chi\,\bar{q}q\,, \qquad \mathcal{O}_2^q = \bar{\chi}\,i\gamma^5\chi\,\bar{q}q\,,$$

$$\mathcal{O}_3^q = \bar{\chi}\chi\,\bar{q}\,i\gamma^5 q\,, \qquad \mathcal{O}_4^q = \bar{\chi}\,i\gamma^5\chi\,\bar{q}\,i\gamma^5 q\,,$$

Higgs-like couplings

$$c_i^q = \frac{m_q}{\Lambda^3}$$

Vector operators

$$\mathcal{O}_5^q = \bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu q\,, \qquad \mathcal{O}_6^q = \bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu q\,,$$

$$\mathcal{O}_7^q = \bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu\gamma^5 q\,, \qquad \mathcal{O}_8^q = \bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu\gamma^5 q\,,$$

Flavour-uni. couplings

$$c_i^q = \frac{1}{\Lambda^2}$$

Draw Bounds (V & AV)

Flavour-uni. couplings

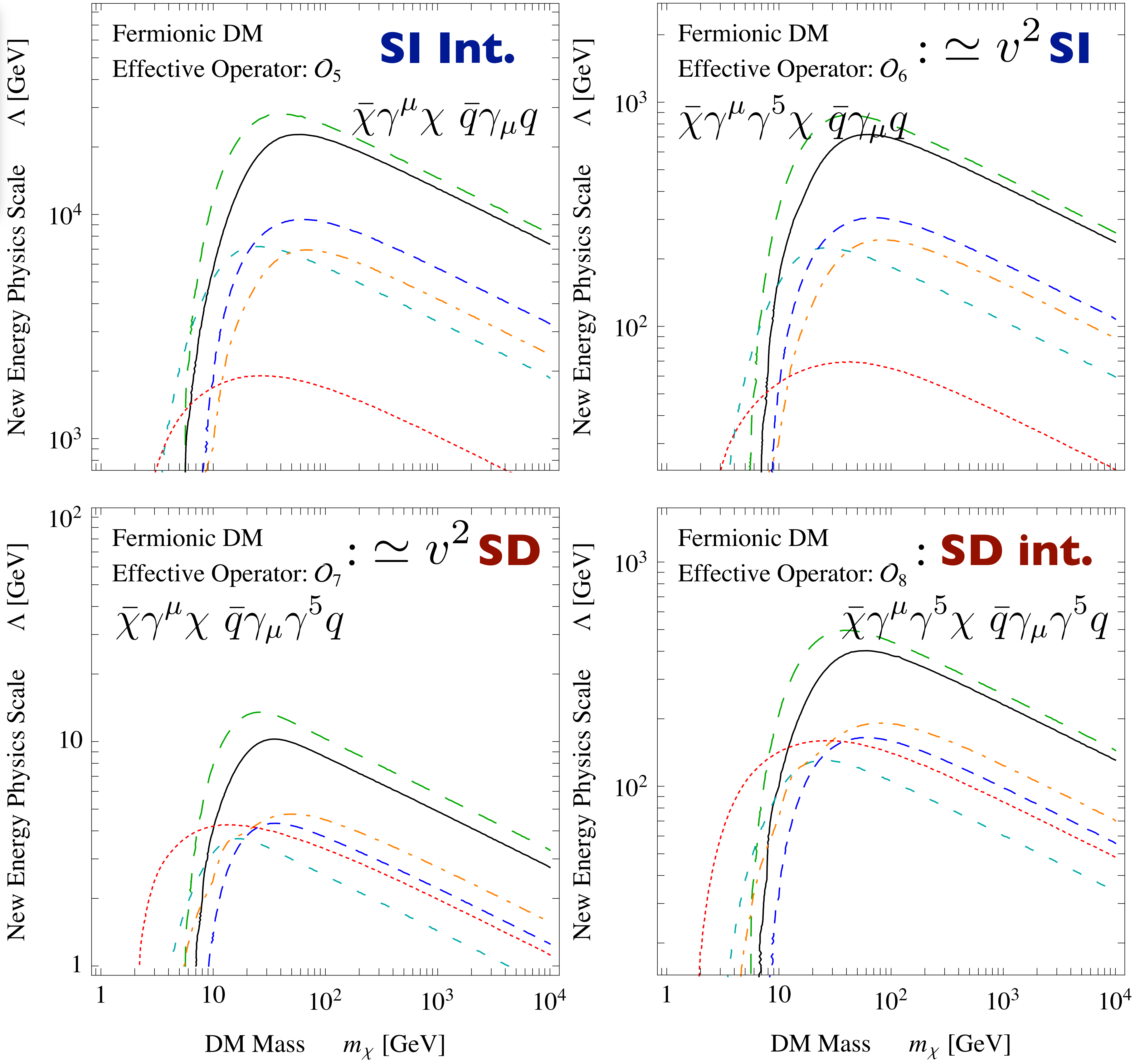
$$c_i^q = \frac{1}{\Lambda^2}$$

$\mathcal{O}_5^q$ **: SI Int.**

$\mathcal{O}_6^q$ **:** $\simeq v^2$ **SI Int.**

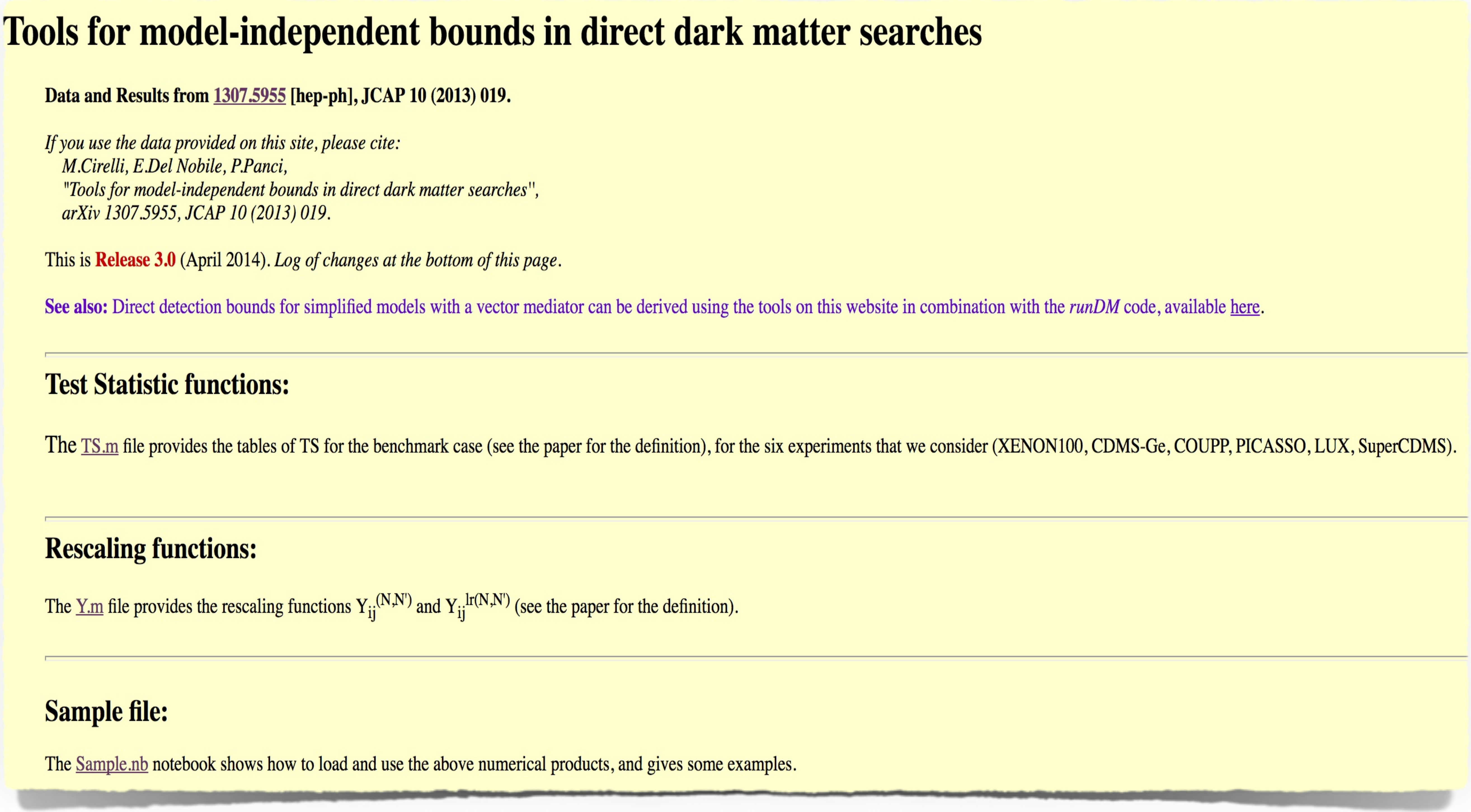
$\mathcal{O}_7^q$ **:** $\simeq v^2$ **SD Int.**

$\mathcal{O}_8^q$ **: SD Int.**



Direct detection tools

Interested in the limits from **all possible** non-relativistic DM-nucleus elastic collisions?



Tools for model-independent bounds in direct dark matter searches

Data and Results from 1307.5955 [hep-ph], JCAP 10 (2013) 019.

If you use the data provided on this site, please cite:
M.Cirelli, E.Del Nobile, P.Panci,
"Tools for model-independent bounds in direct dark matter searches",
arXiv 1307.5955, JCAP 10 (2013) 019.

This is **Release 3.0** (April 2014). *Log of changes at the bottom of this page*.

See also: Direct detection bounds for simplified models with a vector mediator can be derived using the tools on this website in combination with the *runDM* code, available here.

Test Statistic functions:

The TS.m file provides the tables of TS for the benchmark case (see the paper for the definition), for the six experiments that we consider (XENON100, CDMS-Ge, COUPP, PICASSO, LUX, SuperCDMS).

Rescaling functions:

The Y.m file provides the rescaling functions $Y_{ij}^{(N,N')}$ and $Y_{ij}^{lr(N,N')}$ (see the paper for the definition).

Sample file:

The Sample.nb notebook shows how to load and use the above numerical products, and gives some examples.

Limitations of the naive matching

Limitations of the naive matching

➡ In **UV Models several HE operators are generated**
with Wilson coefficients related in a non-trivial way

Limitations of the naive matching

➡ In **UV Models several HE operators are generated**
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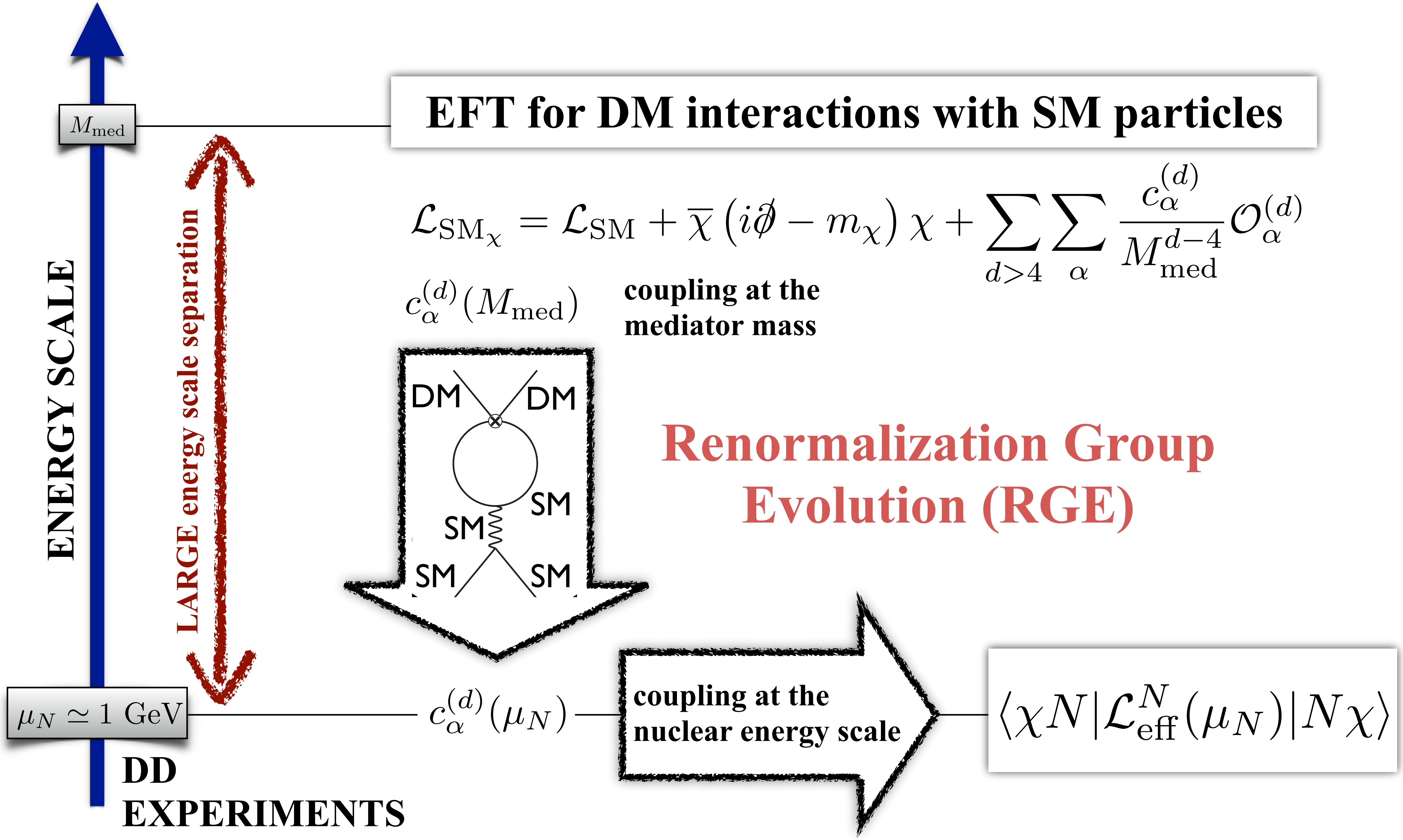


EFT for DM interactions with SM particles

$$\mathcal{L}_{\text{SM}_\chi} = \mathcal{L}_{\text{SM}} + \overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \sum_{d>4}\sum_{\alpha}\frac{c_\alpha^{(d)}}{M_{\text{med}}^{d-4}}\mathcal{O}_\alpha^{(d)}$$

$c_\alpha^{(d)}(M_{\text{med}})$ **coupling at the mediator mass**

Renormalization Group Evolution (RGE)

$c_\alpha^{(d)}(\mu_N)$ **coupling at the nuclear energy scale**

$$\langle \chi N | \mathcal{L}_{\text{eff}}^N(\mu_N) | N \chi \rangle$$

III PART

Connect DM model to the nuclear energy scale

"You can hide but you have to run: Direct detection with vector mediator"

F. D'Eramo, B. J. Kavanagh, PP, JHEP 1608 (2016) **111**, [arXiv:1605.04917]

Why is RGE Relevant?

Should we worry about **loop corrections** in a pre-discovery era?

DM-nucleus collisions

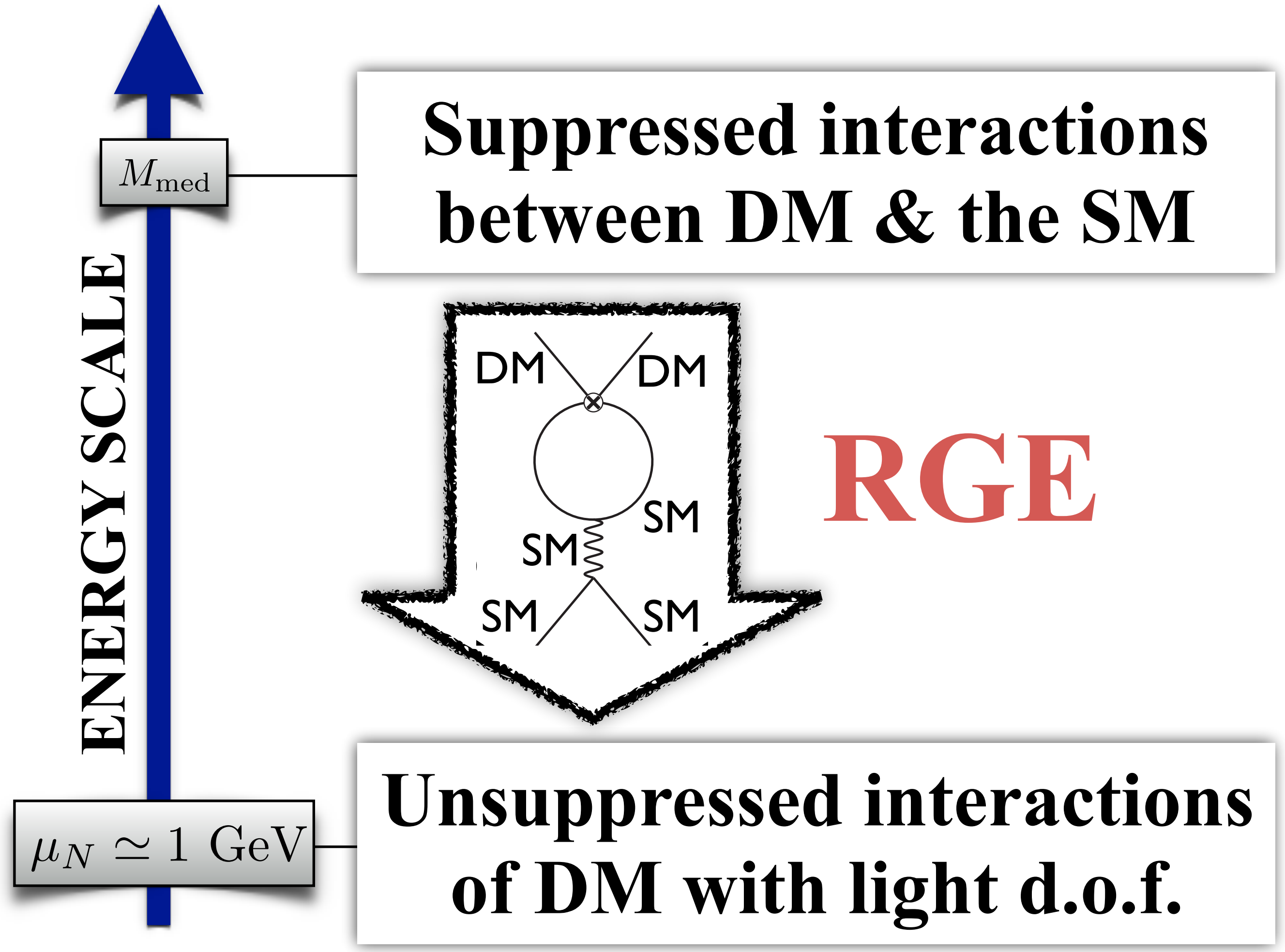
- only sensitive to **light degrees of freedom** (light *quarks* & *gluons*)
- particularly sensitive to the **Lorentz structure** of the HE operators

RGE Effects

- **change the size** of the Wilson coefficient of the HE operators
- **generate operator mixing** at low energy

Why is RGE Relevant?

Should we worry about **loop corrections** in a pre-discovery era?



Suppressed interactions between DM & the SM

RGE

Unsuppressed interactions of DM with light d.o.f.

RGE Effects

- **change the size** of the Wilson coefficient of the HE operators
- **generate operator mixing** at low energy

Vector mediator

SIMPLIFIED MODEL

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \mathcal{L}_V + J^\mu_{\rm DM} V_\mu + J^\mu_{\rm SM} V_\mu$$

Powerful tool
to study LHC
phenomenology and
complementary
among DM searches

Frandsen, Kahlhoefer, Preston, Sarkar, K. Schmidt-Hoberg, JHEP07 (2012), arXiv:1204.3839

Buchmueller, Dolan, McCabe, JHEP01 (2014), arXiv:1308.6799

Alves, Profumo, Queiroz, JHEP04 (2014), arXiv:1312.5281

Arcadi, Mambrini,Tytgat, Zaldivar, JHEP03 (2014), arXiv:1401.0221

Lebedev, Mambrini, PLB734 (2014), arXiv:1403.4837

Buchmueller, Dolan, Malik, McCabe, JHEP01 (2015), arXiv:1407.8257

Harris, Khoze, Spannowsky,Williams, PRD91 (2015), arXiv:1411.0535

Alves, Berlin, Profumo, Queiroz, PRD92 (2015), arXiv:1501.03490

Jacques, Nordström, JHEP06 (2015), arXiv:1502.05721

Chala, Kahlhoefer, McCullough, Nardini, Schmidt-Hoberg, JHEP07 (2015), arXiv:1503.05916

Vector mediator

SIMPLIFIED MODEL

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \mathcal{L}_V + J^\mu_{\rm DM}\, V_\mu + J^\mu_{\rm SM}\, V_\mu$$

Kinetic term for both scalar (complex) and fermion DM (Dirac & Majorana)

$$\mathcal{L}_{\rm DM} = \begin{cases} |\partial_\mu \phi|^2 - m_\phi^2\, |\phi|^2 & \text{scalar DM} \\ \mathcal{K}_\chi\, \overline{\chi}\, (i\partial\!\!\!/ - m_\chi)\, \chi & \text{fermion DM} \end{cases}$$

$$\mathcal{K}_\chi = \begin{cases} 1 & \text{Dirac} \\ 1/2 & \text{Majorana} \end{cases}$$

Vector mediator

SIMPLIFIED MODEL

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \mathcal{L}_V + J^\mu_{\rm DM} V_\mu + J^\mu_{\rm SM} V_\mu$$

Kinetic term for the spin 1 massive mediator

$$\mathcal{L}_V = -\frac{1}{4} V^{\mu\nu} V_{\mu\nu} + \frac{1}{2} m_V^2 V^\mu V_\mu$$

We do not consider **mass and kinetic mixing** with the *Z* boson since they depend on the **details of the UV theory**

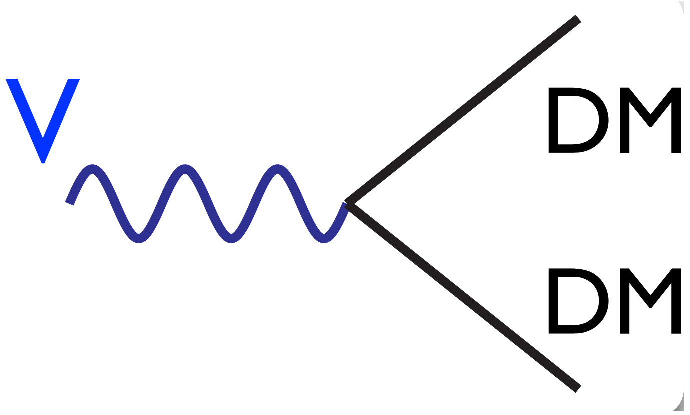
Vector mediator

SIMPLIFIED MODEL

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \mathcal{L}_{V} + J^{\mu}_{\rm DM} V_\mu + J^{\mu}_{\rm SM} V_\mu$$

Mediator coupled with spin 1 DM currents

$$J^{\mu}_{\rm DM} = \begin{cases} c_\phi \, \phi^\dagger \overleftrightarrow{\partial}_\mu \phi & \text{scalar DM} \\ \mathcal{K}_\chi \left(c_{\chi V} \, \overline{\chi} \gamma^\mu \chi + c_{\chi A} \, \overline{\chi} \gamma^\mu \gamma^5 \chi \right) & \text{fermion DM} \end{cases}$$



Vector mediator

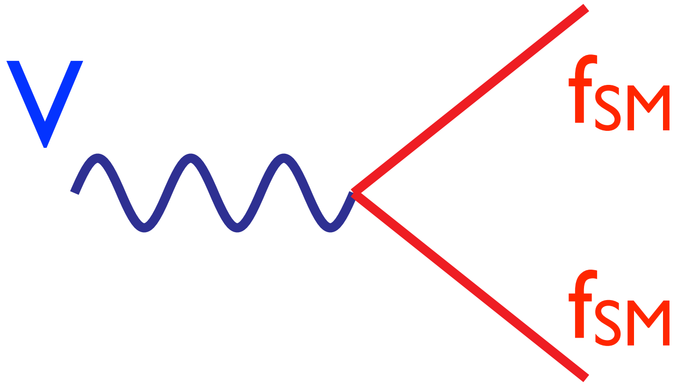
SIMPLIFIED MODEL

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DM}} + \mathcal{L}_V + J^\mu_{\text{DM}} V_\mu + J^\mu_{\text{SM}} V_\mu$$

Mediator coupled with spin 1 currents of SM fermions

$$J^\mu_{\text{SM}} = \sum_{i=1}^{3} \left[c_q^{(i)} \, \overline{q_L^i} \gamma^\mu q_L^i + c_u^{(i)} \, \overline{u_R^i} \gamma^\mu u_R^i + c_d^{(i)} \, \overline{d_R^i} \gamma^\mu d_R^i + c_l^{(i)} \, \overline{l_L^i} \gamma^\mu l_L^i + c_e^{(i)} \, \overline{e_R^i} \gamma^\mu e_R^i \right]$$

15 independent SU(2) x U(1) gauge invariant couplings to SM fermions



Main steps to NR cross section

DM-nucleus collisions: **deeply NR regime**

3 STEPS to get the

EFT for DM interactions with quarks and gluons

Matching onto NR EFT

DM-Nucleus XS

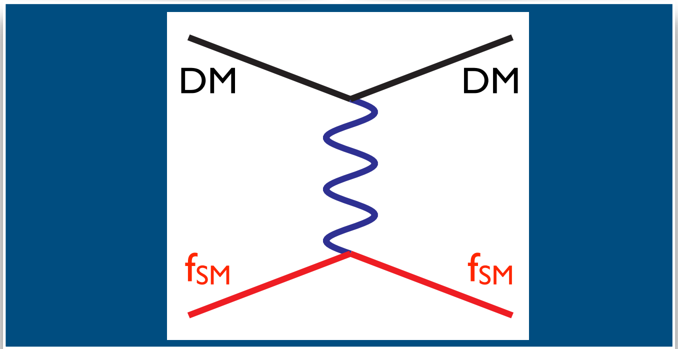
$$\frac{d\sigma}{dE_{\mathrm{R}}} \propto \sum_{i,j} \sum_{N,N'=p,n} \mathfrak{c}_i^{N} \mathfrak{c}_j^{N'} F_{i,j}^{(N,N')}$$

Main steps to NR cross section

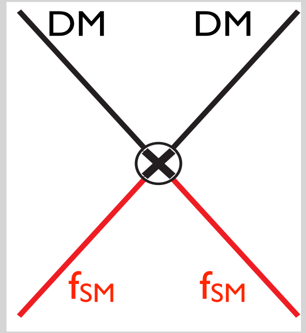
DM-nucleus collisions: **deeply NR regime**

STEP I:

integrate-out the mediator



$$\frac{1}{q^2 - m_V^2} \simeq -\frac{1}{m_V^2}$$



EFT
DM contact interactions

3 STEPS to get the

EFT for DM interactions with quarks and gluons

Matching onto NR EFT

DM-Nucleus XS

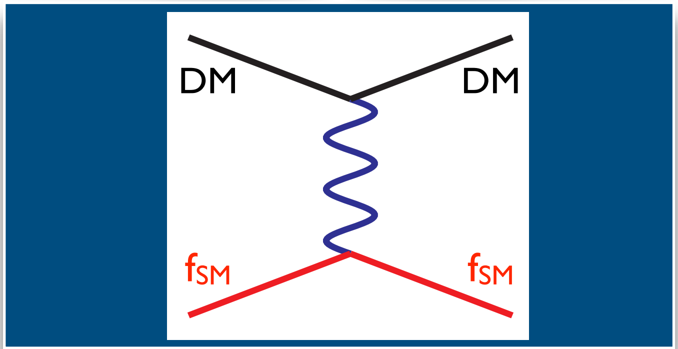
$$\frac{d\sigma}{dE_{\rm R}} \propto \sum_{i,j} \sum_{N,N'=p,n} \mathfrak{c}_i^N \mathfrak{c}_j^{N'} F_{i,j}^{(N,N')}$$

Main steps to NR cross section

DM-nucleus collisions: **deeply NR regime**

STEP I:

integrate-out the mediator



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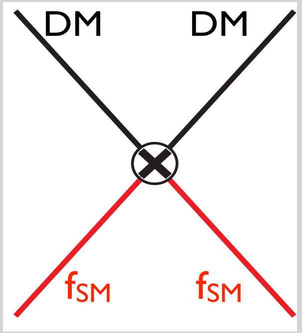
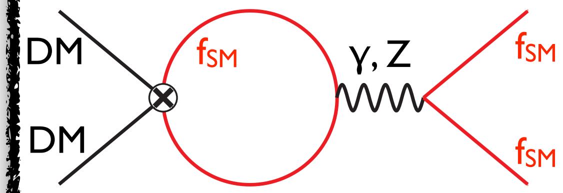


EFT
DM contact interactions

STEP II:

connecting energy scale

EFT
coupling at the mediator mass



NUCLEAR SCALE
- ➡ size couplings changed
- ➡ **New interactions** are generated (mixing)

3 STEPS to get the

EFT for DM interactions with quarks and gluons

Matching onto NR EFT

DM-Nucleus XS

$$\frac{d\sigma}{dE_R} \propto \sum_{i,j} \sum_{N,N'=p,n} c_i^N c_j^{N'} F_{i,j}^{(N,N')}$$

Main steps to NR cross section

DM-nucleus collisions: **deeply NR regime**

STEP I:

integrate-out the mediator

straightforward for vector mediator ☑

STEP II:

connecting energy scale

complete **one loop RGE analysis** for Spin 1 mediator can be found in ☑

F. D’Eramo, M. Procura, JHEP 1504 (2015), [arXiv:1411.3342]
F. Bishara, J. Brod, B. Grinstein, J. Zupan, [arXiv:1809.03506]

3 STEPS to get the

EFT for DM interactions with quarks and gluons

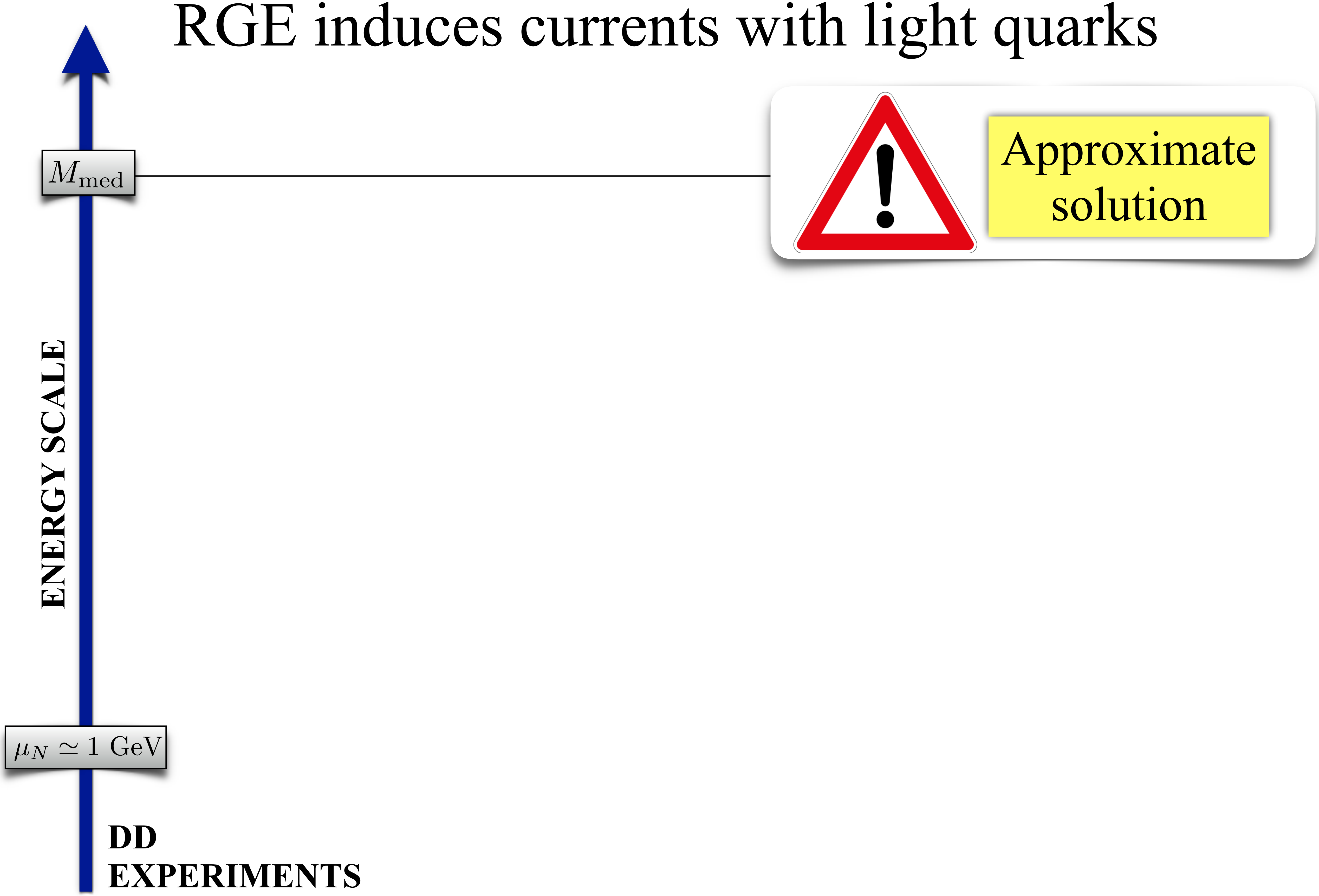
Matching onto NR EFT

DM-Nucleus XS

$$\frac{d\sigma}{dE_{\rm R}} \propto \sum_{i,j} \sum_{N,N'=p,n} \mathfrak{c}_i^N \mathfrak{c}_j^{N'} F_{i,j}^{(N,N')}$$

RG Effects

RGE induces currents with light quarks



M_{med}

Approximate solution

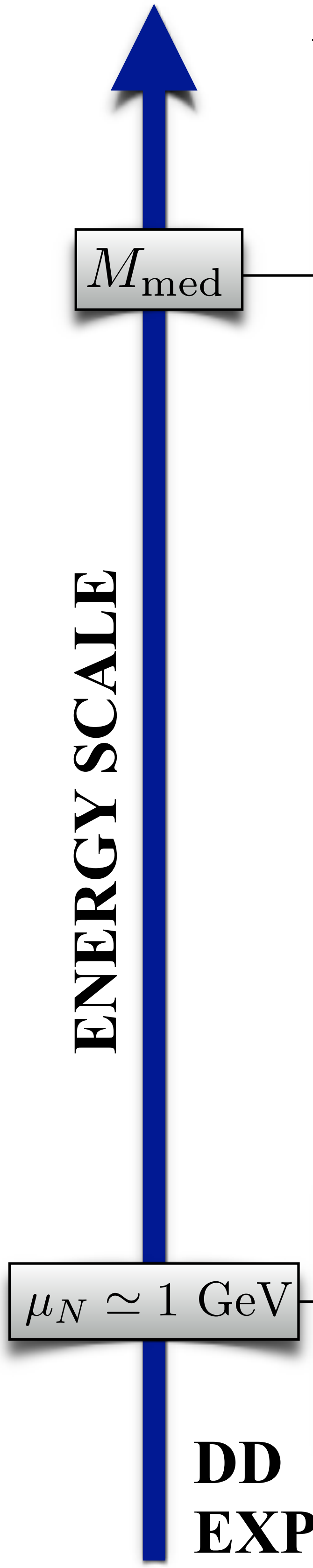
ENERGY SCALE

$\mu_N \simeq 1$ GeV

DD EXPERIMENTS

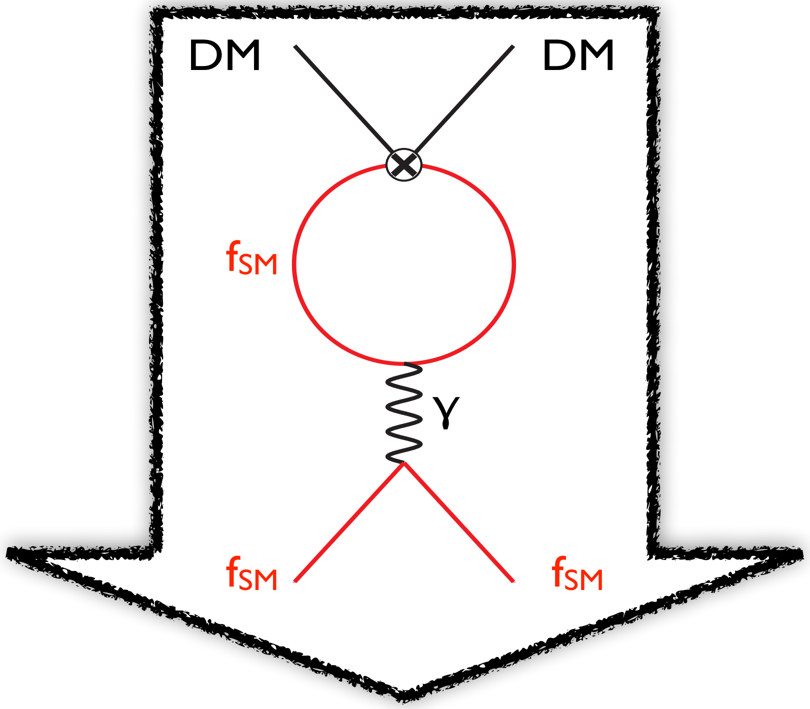
RG Effects

RGE induces currents with light quarks



V coupled to ***vector currents*** of SM fermions

Approximate solution



Important if V is not coupled to light quarks
(e.g. leptons or heavy quarks)

Otherwise 1% corrections

RGE only induces ***vector current*** of light quarks

$$\Delta c_V \simeq \frac{e^2}{16\pi^2} \ln(m_V/\mu_N)$$

DD EXPERIMENTS

RG Effects

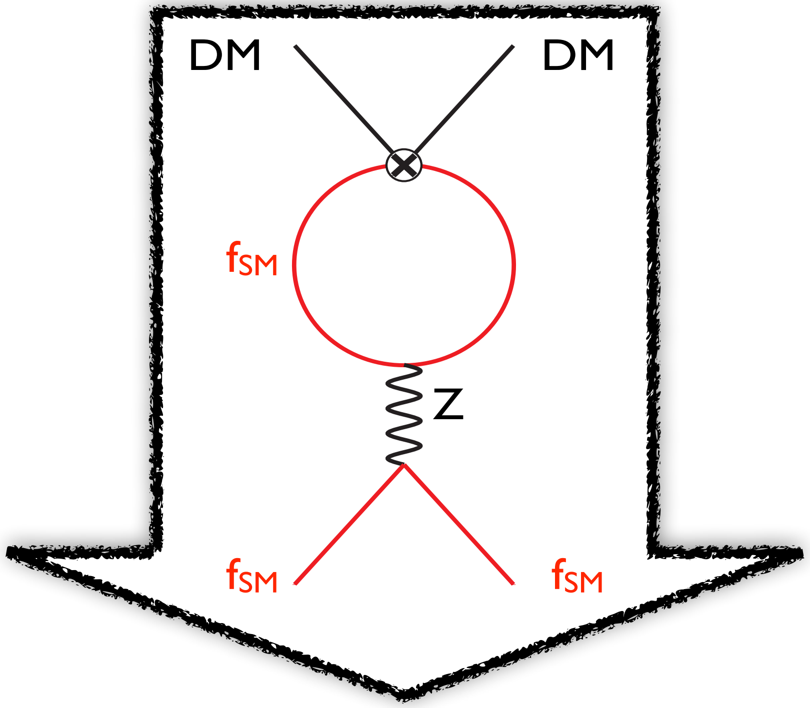
RGE induces currents with light quarks

ENERGY SCALE

M_{med}

V coupled to ***axial-vector currents*** of SM fermions

Approximate solution



Phenomenologically very important
(operator mixing)

Dominated by heavy SM fermions (prop to Yukawa)

$\mu_N \simeq 1 \text{ GeV}$

RGE induces ***vector & axial current*** of light quarks

$$\Delta c_{V,A} \simeq \frac{\lambda_f^2}{16\pi^2} \ln(m_V/\mu_N)$$

DD EXPERIMENTS

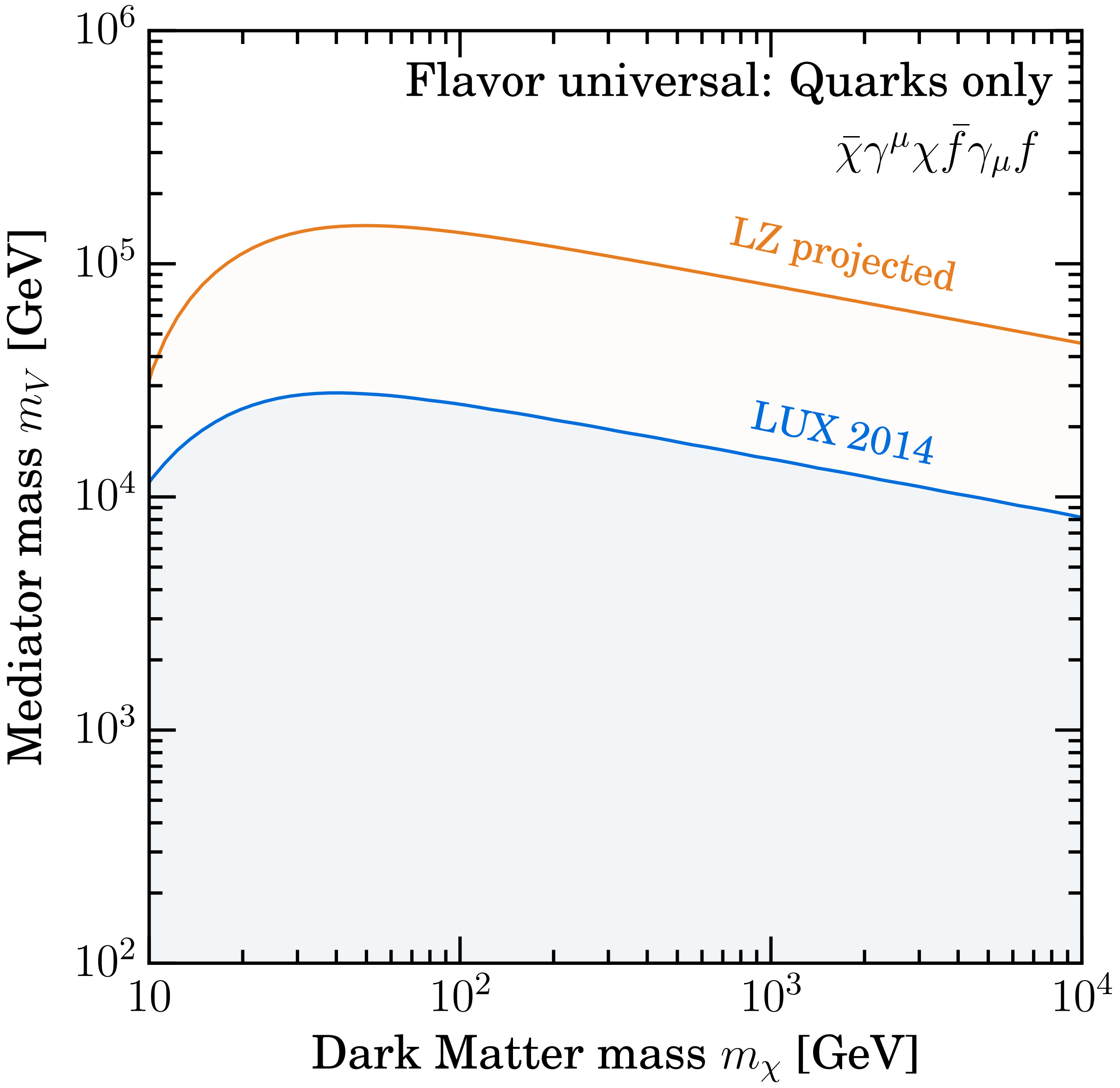
Some Results: Quark Vector

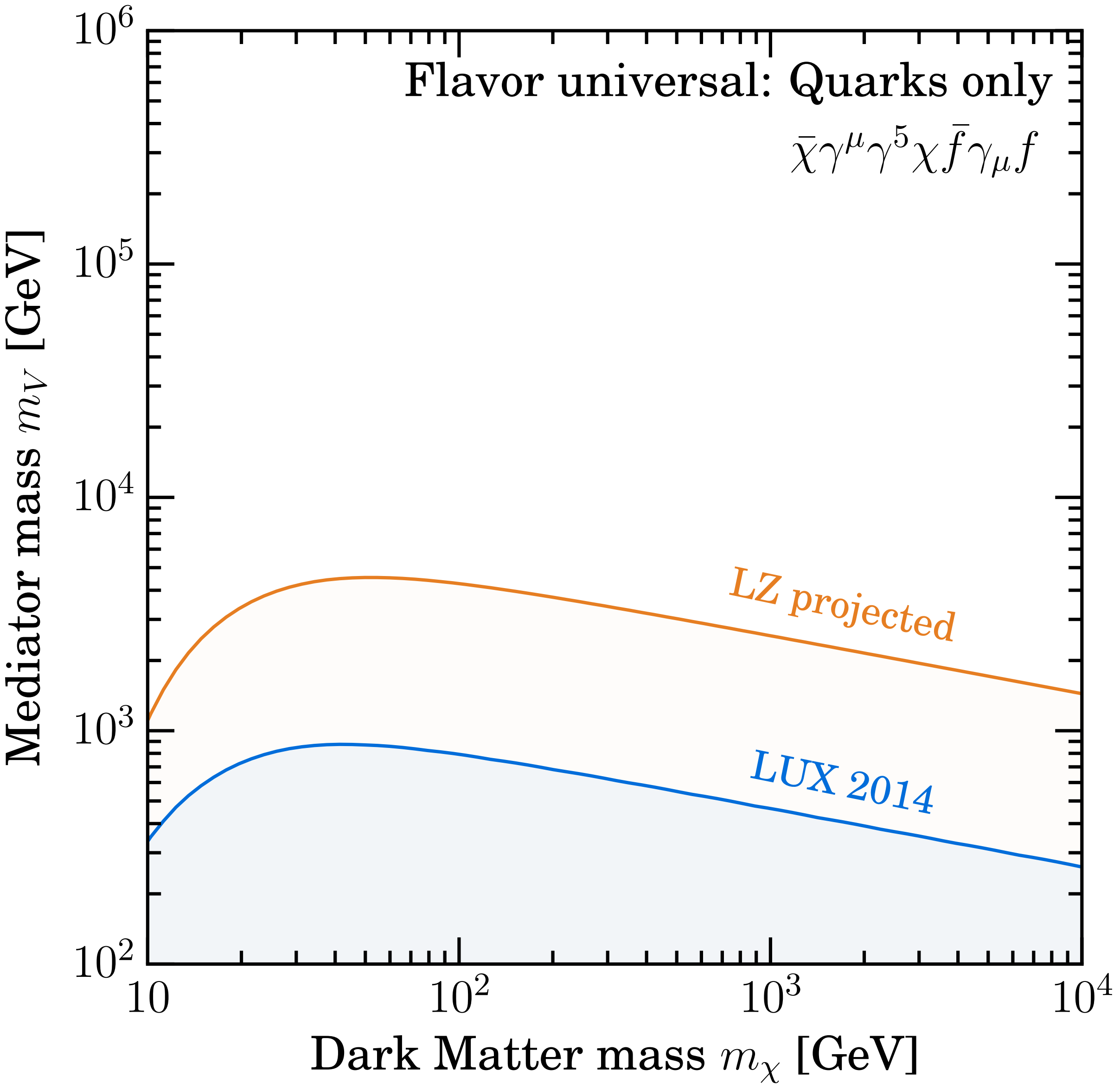
Some Results: Quark Vector

Mediator coupled FU with ***vector currents*** *of quarks*

$$= -\frac{1}{m_V^2} J_{\mathrm{DM}\,\mu} \sum_{i=1}^{3} \left[\overline{u^i} \gamma^\mu u^i + \overline{d^i} \gamma^\mu d^i \right]$$

RGE driven by loops of **electromagnetic currents** (**no mixing**)



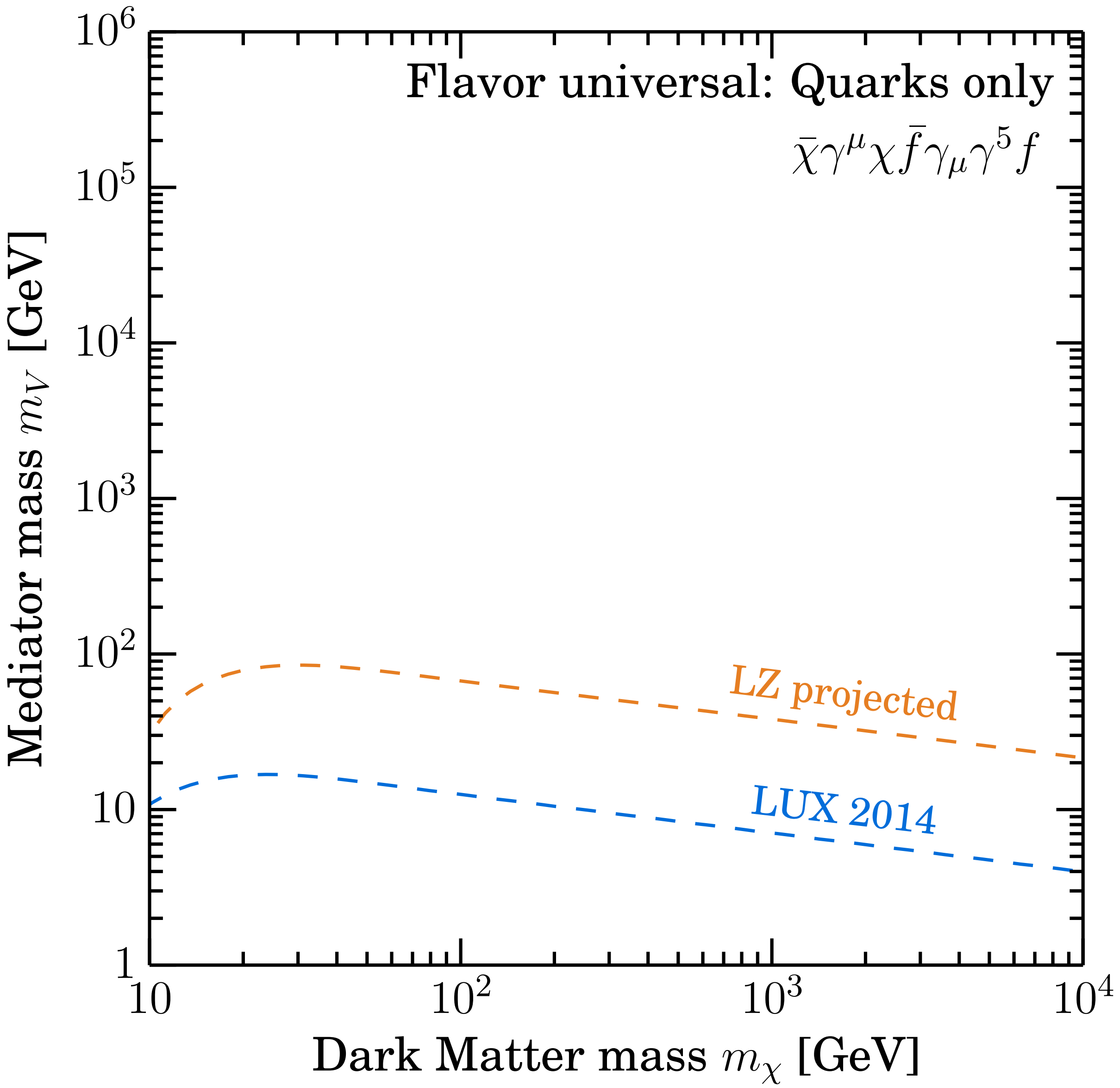


Some Results: Quark Axial

Mediator coupled FU with
***axial currents** of quarks*

$$= -\frac{1}{m_V^2} J_{\mathrm{DM}\,\mu} \sum_{i=1}^{3} \left[\overline{u^i}\gamma^\mu\gamma^5 u^i + \overline{d^i}\gamma^\mu\gamma^5 d^i\right]$$

RGE driven by **Yukawa couplings** alter the rate **(<u>mixing</u>)**



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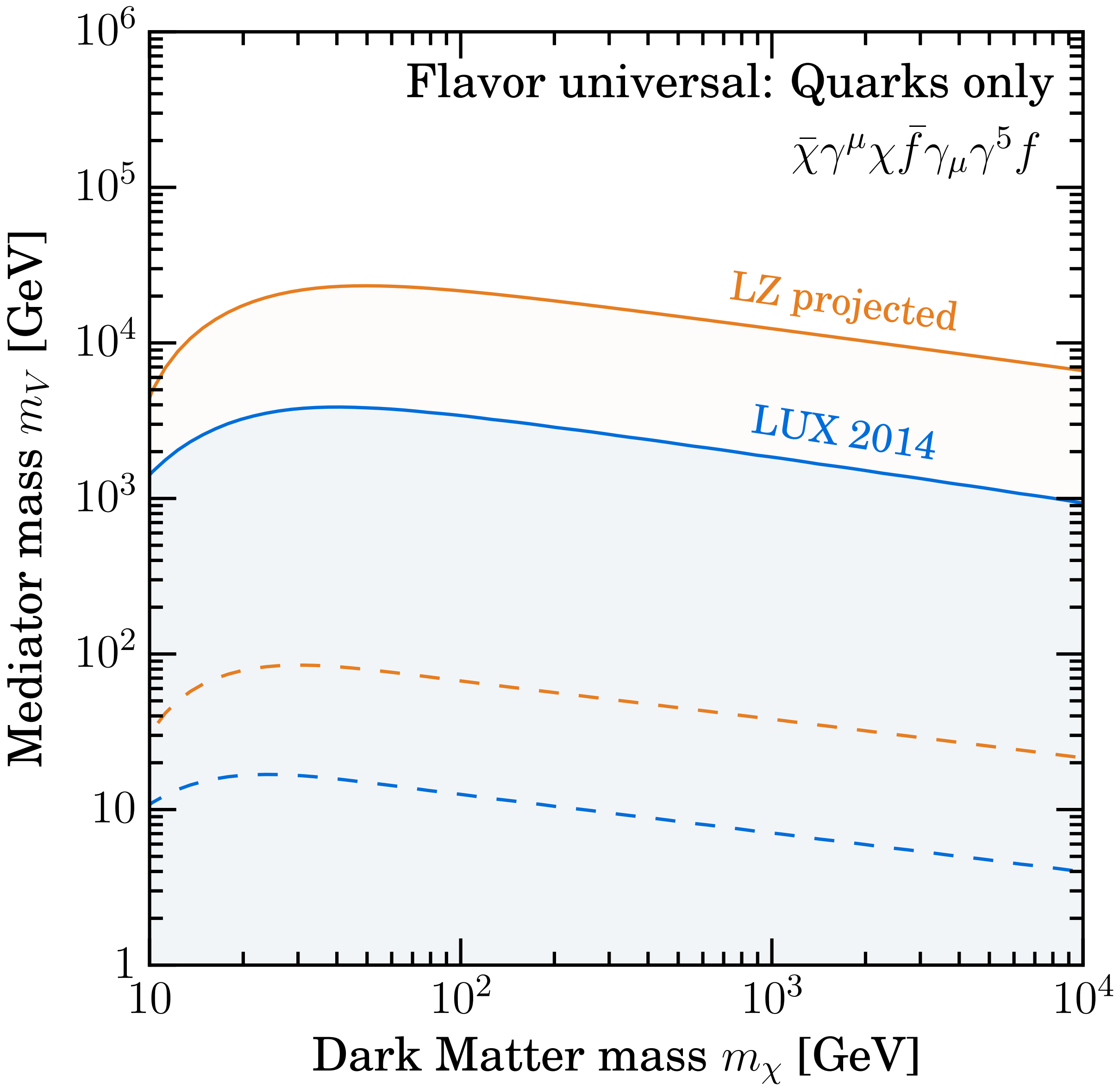

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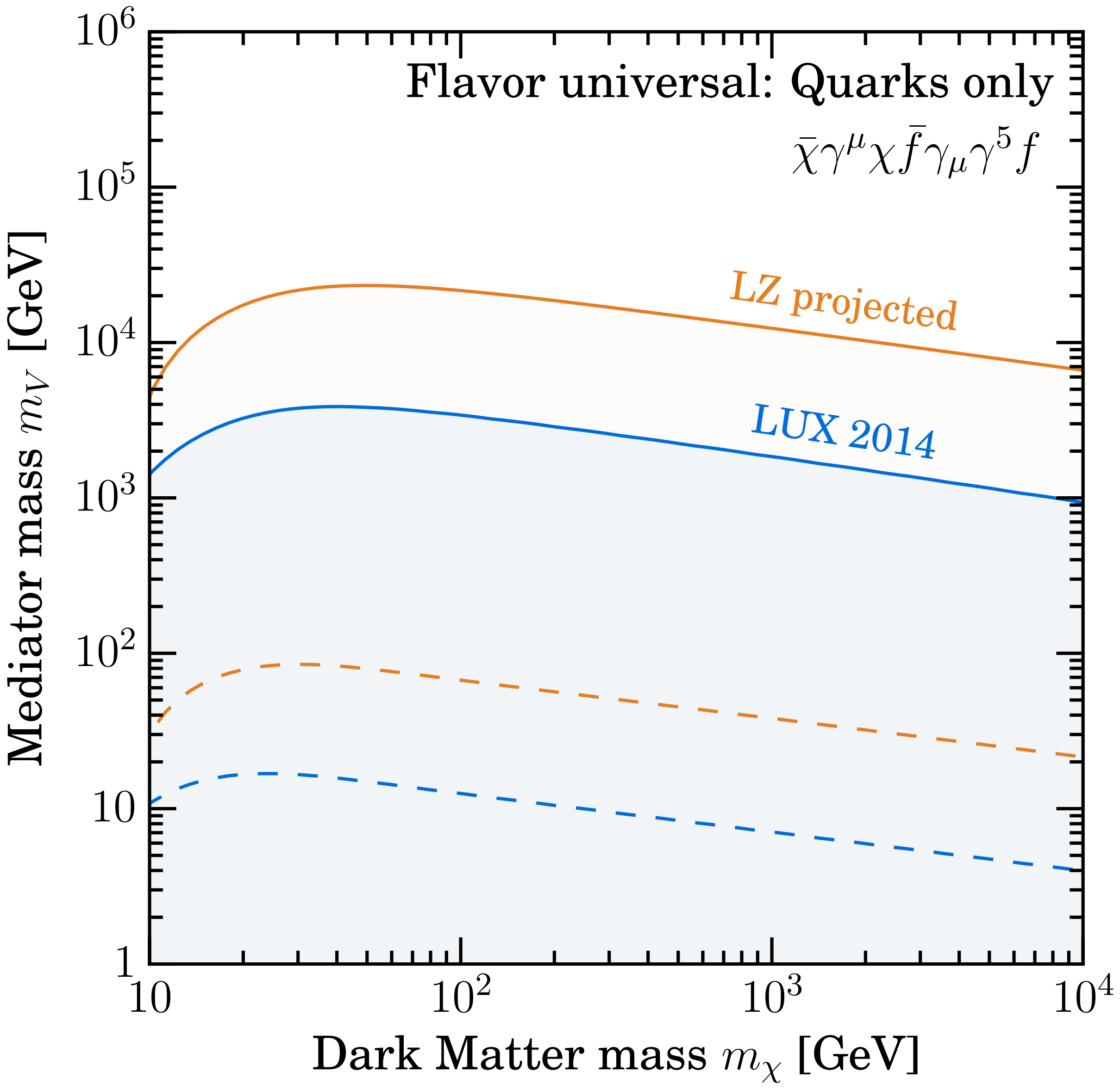

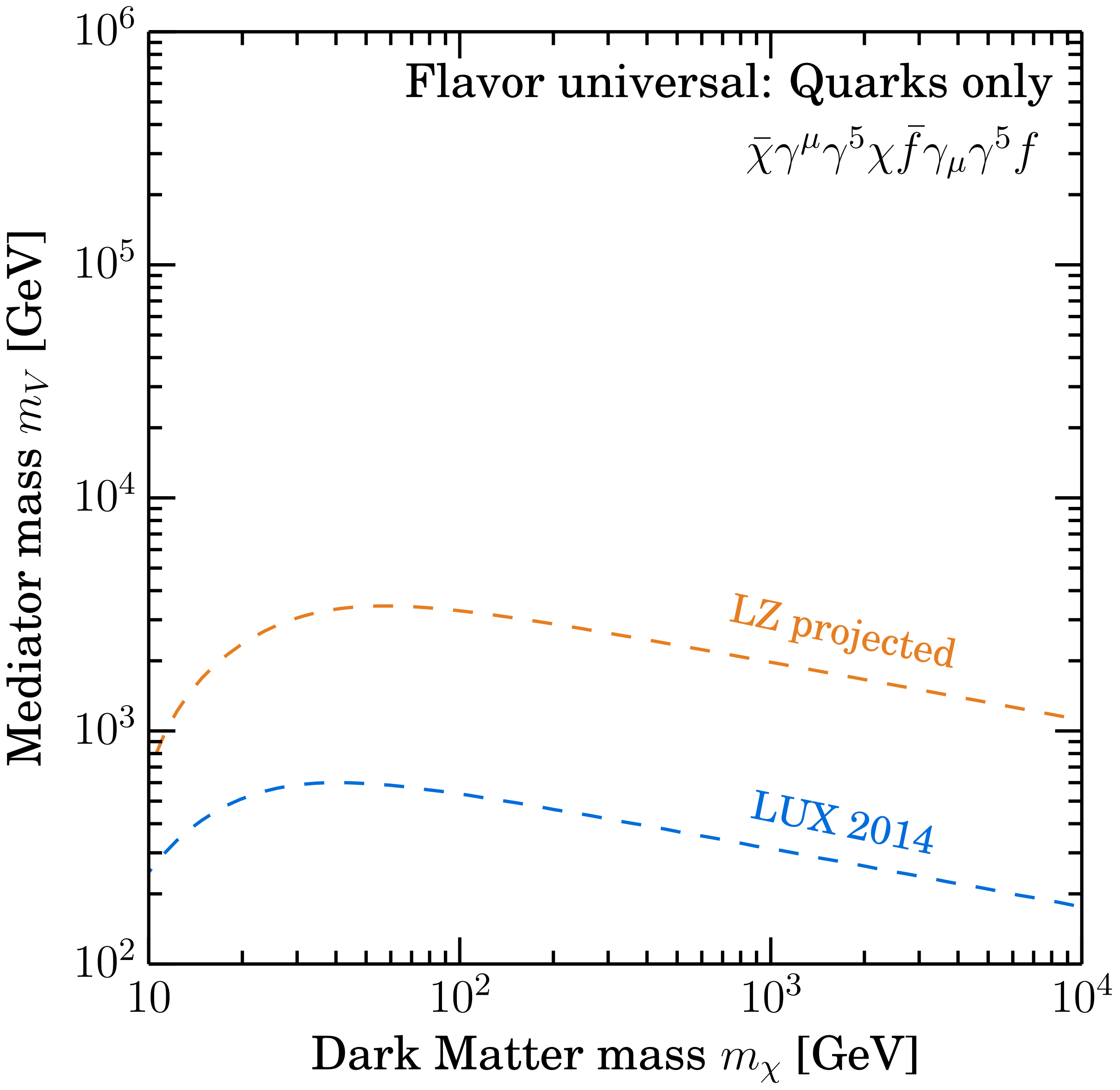

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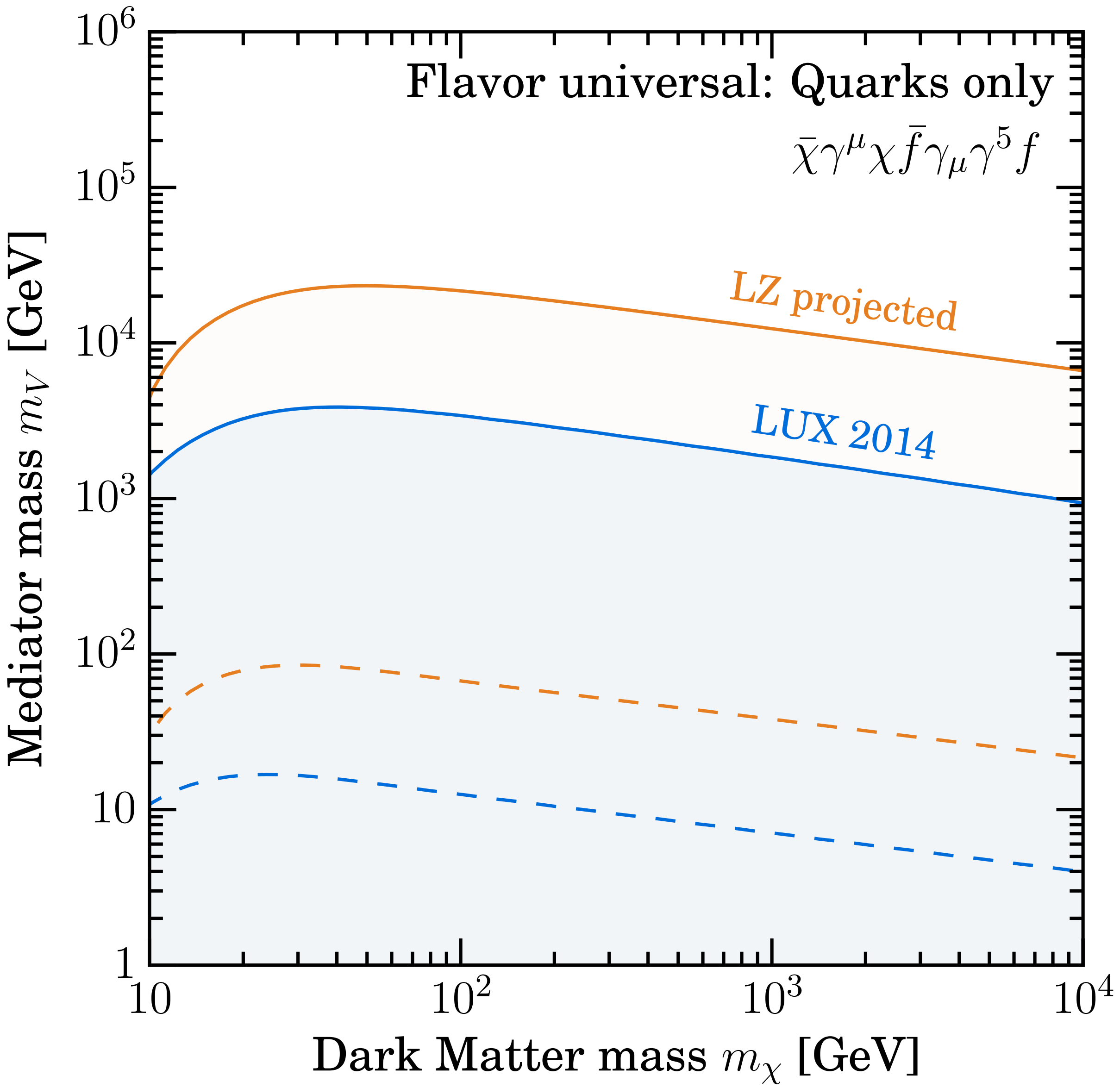
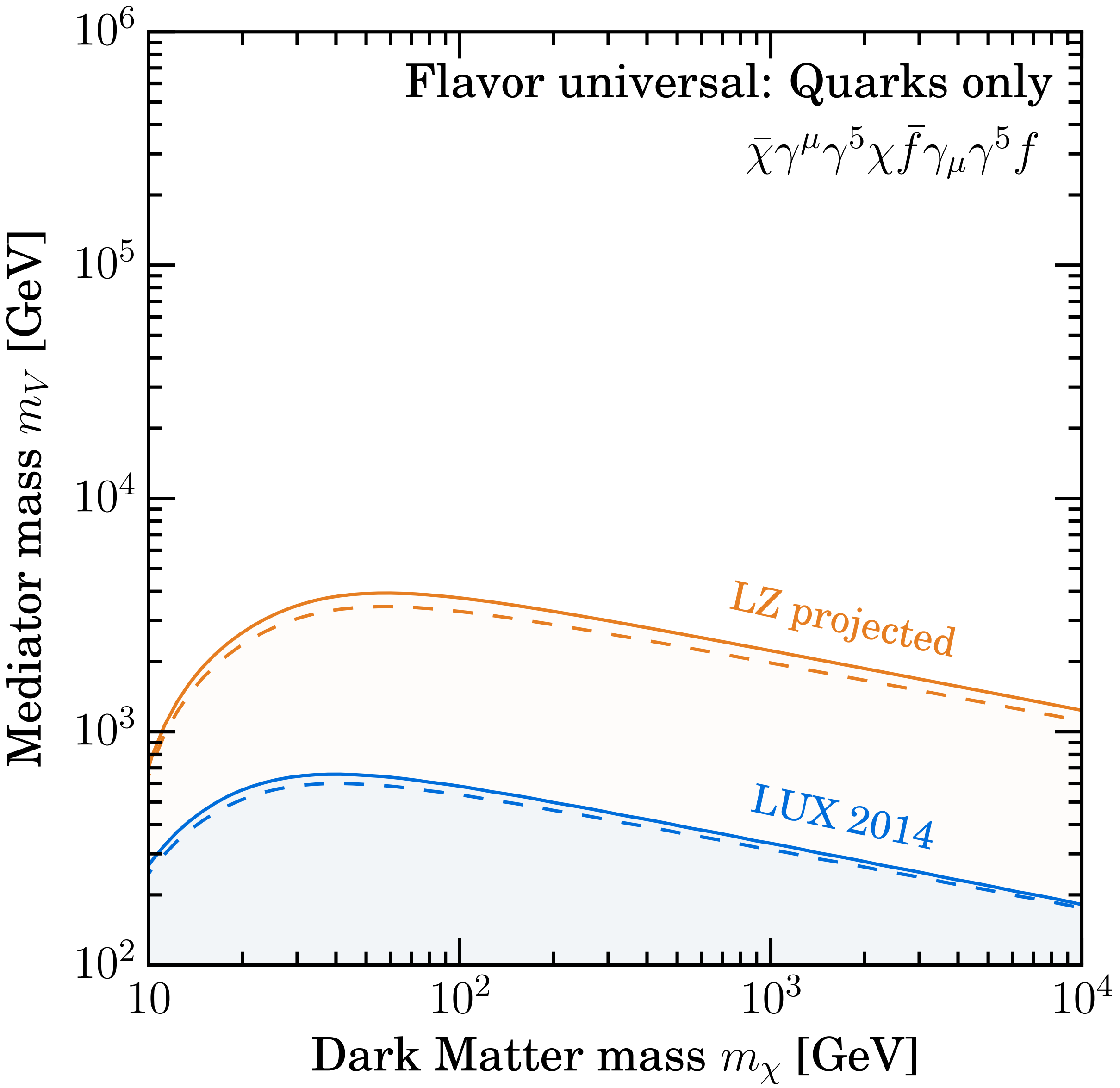
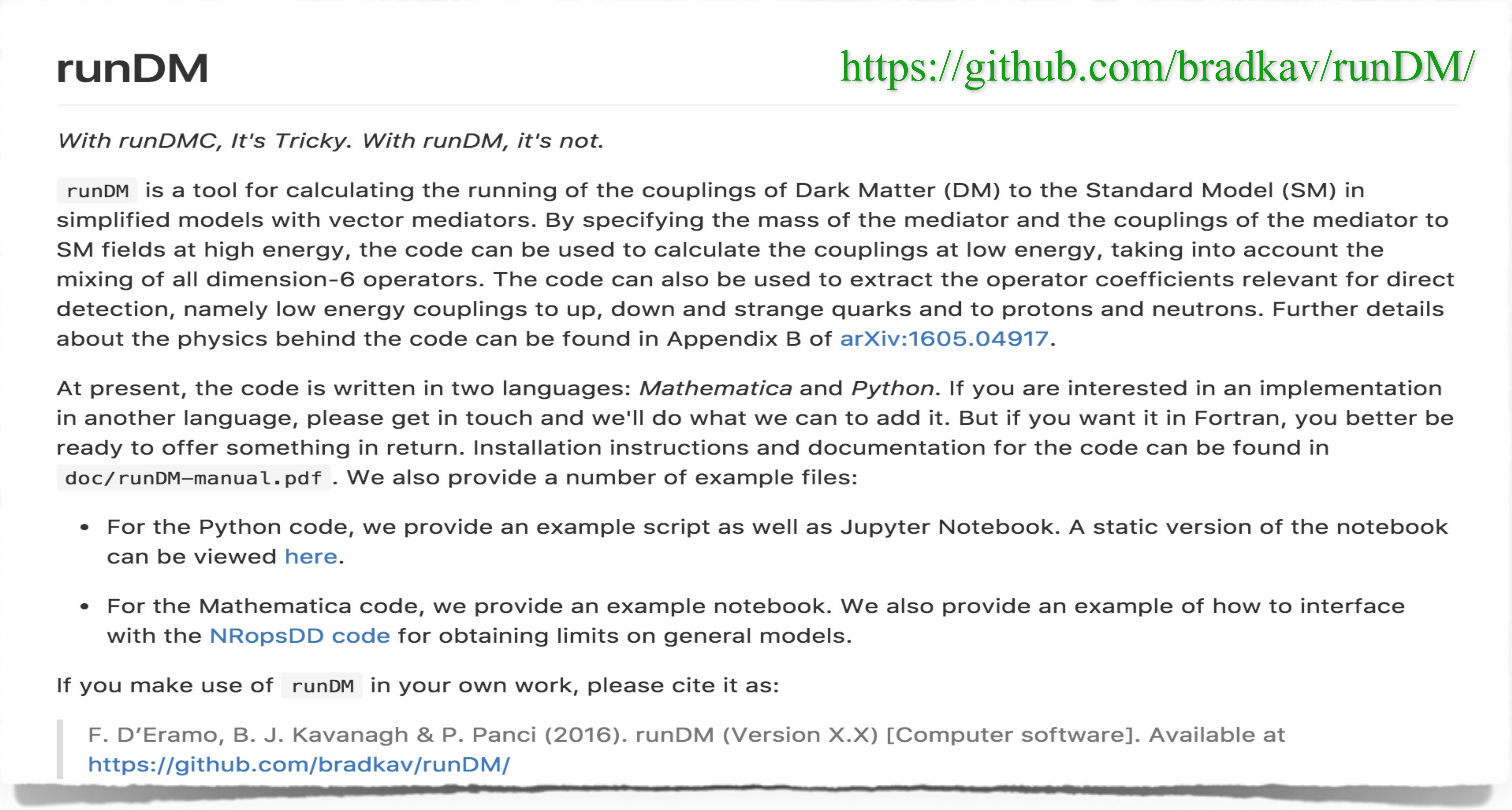




runDM: general RGE

Interested in the **RGE** of the 15 gauge invariant couplings from high energy to low energy ?

Exhaustive study for other cases in JHEP 1608 (2016) **111**, [arXiv: 1605.04917]



https://github.com/bradkav/runDM/

runDM

With runDMC, It's Tricky. With runDM, it's not.

`runDM` is a tool for calculating the running of the couplings of Dark Matter (DM) to the Standard Model (SM) in simplified models with vector mediators. By specifying the mass of the mediator and the couplings of the mediator to SM fields at high energy, the code can be used to calculate the couplings at low energy, taking into account the mixing of all dimension-6 operators. The code can also be used to extract the operator coefficients relevant for direct detection, namely low energy couplings to up, down and strange quarks and to protons and neutrons. Further details about the physics behind the code can be found in Appendix B of arXiv:1605.04917.

At present, the code is written in two languages: *Mathematica* and *Python*. If you are interested in an implementation in another language, please get in touch and we'll do what we can to add it. But if you want it in Fortran, you better be ready to offer something in return. Installation instructions and documentation for the code can be found in `doc/runDM–manual.pdf`. We also provide a number of example files:

- For the Python code, we provide an example script as well as Jupyter Notebook. A static version of the notebook can be viewed here.
- For the Mathematica code, we provide an example notebook. We also provide an example of how to interface with the NRopsDD code for obtaining limits on general models.

If you make use of `runDM` in your own work, please cite it as:

> F. D'Eramo, B. J. Kavanagh & P. Panci (2016). runDM (Version X.X) [Computer software]. Available at https://github.com/bradkav/runDM/

DD vs LHC (Axial-Axial)

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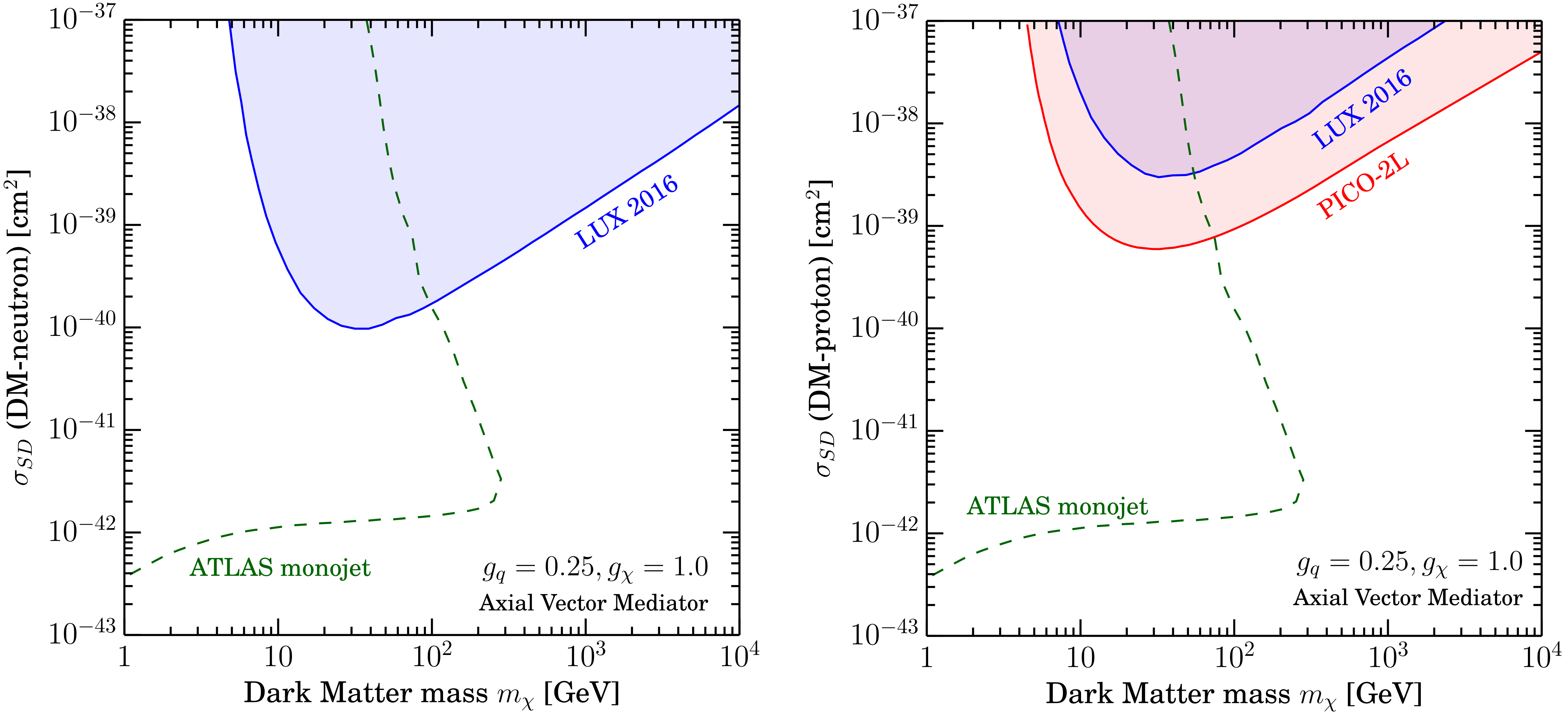
using **simplified DM model** is possible to **map** the **LHC constraints** on the V mass onto the **(m_χ, σ) plane**



See e.g. XENON1T [arXiv: 1902.03234]; LUX [arXiv: 1602.03489]; PICO-2L [arXiv: 1601.03729]; ATLAS [arXiv: 1604.01306], etc…..

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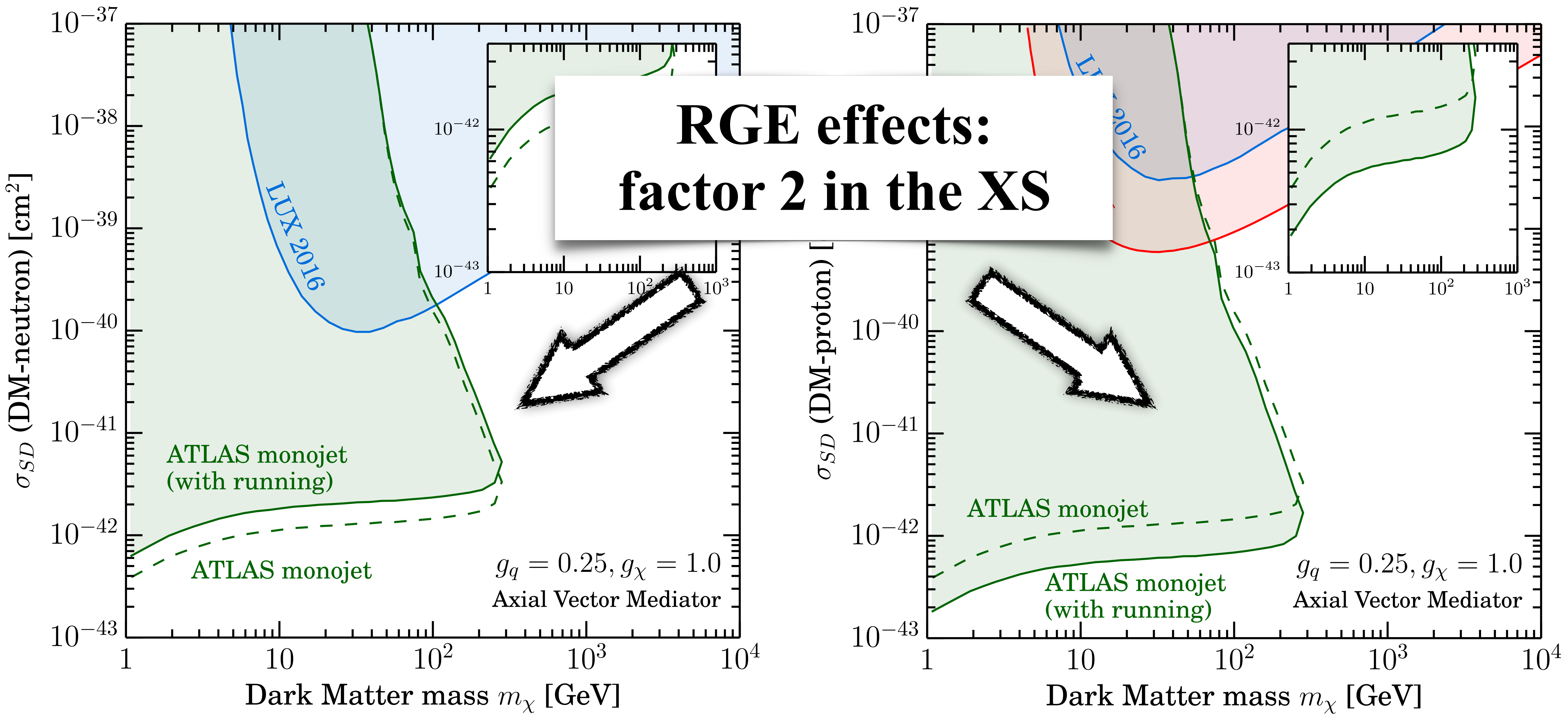

RGE effects:
factor 2 in the XS

See e.g. XENON1T [arXiv: 1902.03234]; LUX [arXiv: 1602.03489]; PICO-2L [arXiv: 1601.03729]; ATLAS [arXiv: 1604.01306], etc…..

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Match high-energy operators to NR EFT

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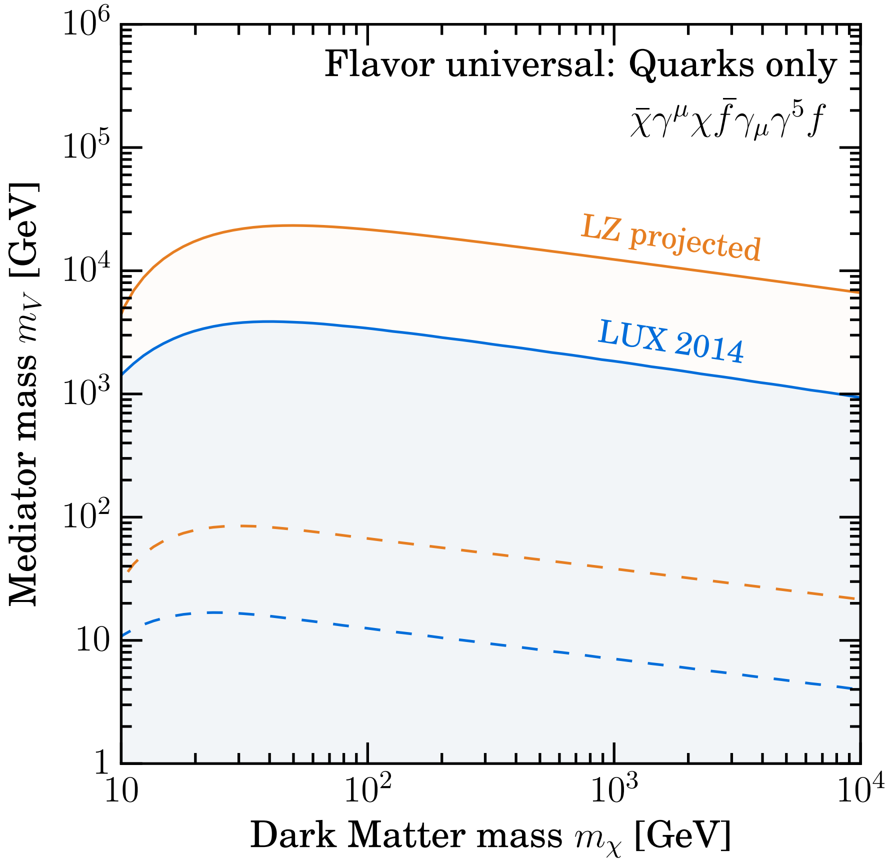
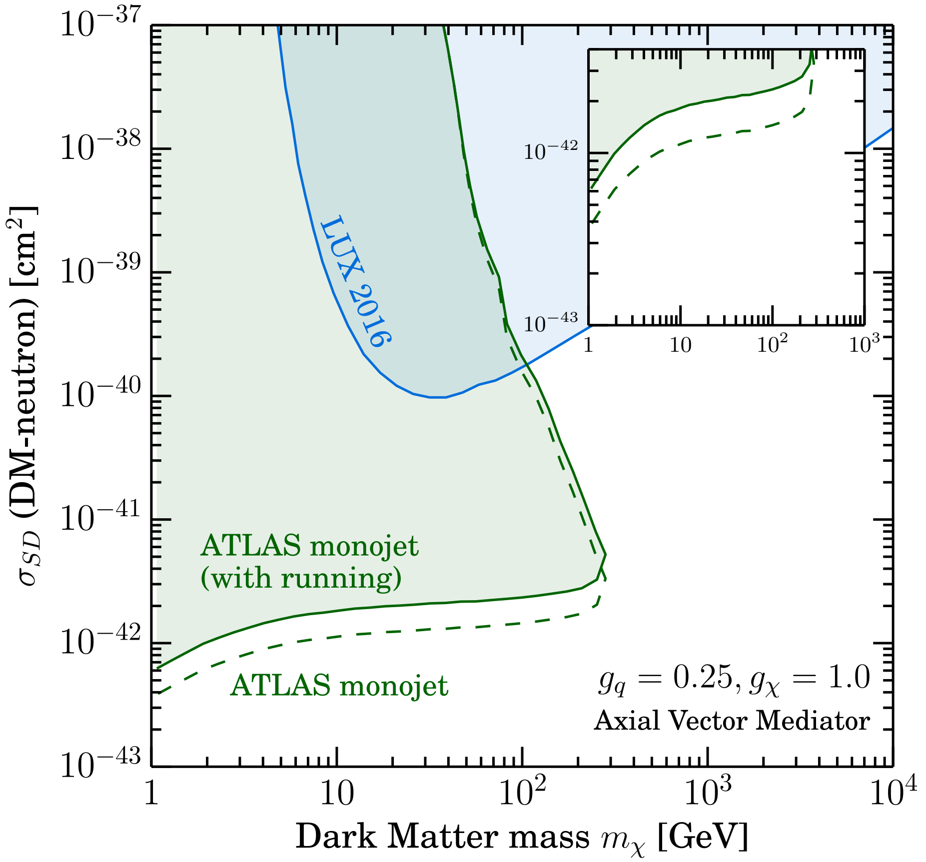
Connect DM model to the nuclear energy scale

You can hide but you have to run!!





Backup slides

Backup slide 1/2

NR Matching

Typical Dimension-6 Interactions

$$\begin{aligned} \mathcal{O}_1^N &= \bar{\chi}\chi\ \bar{N}N\,, & \mathcal{O}_2^N &= \bar{\chi}\,i\gamma^5\chi\ \bar{N}N\,, \\ \mathcal{O}_3^N &= \bar{\chi}\chi\ \bar{N}\,i\gamma^5 N\,, & \mathcal{O}_4^N &= \bar{\chi}\,i\gamma^5\chi\ \bar{N}\,i\gamma^5 N\,, \\ \mathcal{O}_5^N &= \bar{\chi}\gamma^\mu\chi\ \bar{N}\gamma_\mu N\,, & \mathcal{O}_6^N &= \bar{\chi}\gamma^\mu\gamma^5\chi\ \bar{N}\gamma_\mu N\,, \\ \mathcal{O}_7^N &= \bar{\chi}\gamma^\mu\chi\ \bar{N}\gamma_\mu\gamma^5 N\,, & \mathcal{O}_8^N &= \bar{\chi}\gamma^\mu\gamma^5\chi\ \bar{N}\gamma_\mu\gamma^5 N\,, \\ \mathcal{O}_9^N &= \bar{\chi}\,\sigma^{\mu\nu}\chi\ \bar{N}\,\sigma_{\mu\nu}N\,, & \mathcal{O}_{10}^N &= \bar{\chi}\,i\,\sigma^{\mu\nu}\gamma^5\chi\ \bar{N}\,\sigma_{\mu\nu}N\,, \end{aligned}$$

Galileian Invariant Operators

$$\begin{aligned} \mathcal{O}_1^{\rm NR} &= \mathbb{1}\ , \\ \mathcal{O}_3^{\rm NR} &= i\,\vec{s}_N\cdot(\vec{q}\times\vec{v}^\perp)\ , & \mathcal{O}_4^{\rm NR} &= \vec{s}_\chi\cdot\vec{s}_N\ , \\ \mathcal{O}_5^{\rm NR} &= i\,\vec{s}_\chi\cdot(\vec{q}\times\vec{v}^\perp)\ , & \mathcal{O}_6^{\rm NR} &= (\vec{s}_\chi\cdot\vec{q})(\vec{s}_N\cdot\vec{q})\ , \\ \mathcal{O}_7^{\rm NR} &= \vec{s}_N\cdot\vec{v}^\perp\ , & \mathcal{O}_8^{\rm NR} &= \vec{s}_\chi\cdot\vec{v}^\perp\ , \\ \mathcal{O}_9^{\rm NR} &= i\,\vec{s}_\chi\cdot(\vec{s}_N\times\vec{q})\ , & \mathcal{O}_{10}^{\rm NR} &= i\,\vec{s}_N\cdot\vec{q}\,, \\ \mathcal{O}_{11}^{\rm NR} &= i\,\vec{s}_\chi\cdot\vec{q}\ , & \mathcal{O}_{12}^{\rm NR} &= \vec{v}^\perp\cdot(\vec{s}_\chi\times\vec{s}_N)\ . \end{aligned}$$

NR structure of the fermion bilinear

$$\begin{aligned} \bar{u}(p')u(p) &\simeq 2m\,, \\ \bar{u}(p')i\,\gamma^5 u(p) &\simeq 2i\,\vec{q}\cdot\vec{s}\,, \\ \bar{u}(p')\gamma^\mu u(p) &\simeq \begin{pmatrix} 2m \\ \vec{P}+2i\,\vec{q}\times\vec{s} \end{pmatrix}\ , \\ \bar{u}(p')\gamma^\mu\gamma^5 u(p) &\simeq \begin{pmatrix} 2\vec{P}\cdot\vec{s} \\ 4m\,\vec{s} \end{pmatrix}\ , \\ \bar{u}(p')\sigma^{\mu\nu}u(p) &\simeq \begin{pmatrix} 0 & i\,\vec{q}-2\vec{P}\times\vec{s} \\ -i\,\vec{q}+2\vec{P}\times\vec{s} & 4m\,\varepsilon_{ijk}s^k \end{pmatrix}\ , \\ \bar{u}(p')i\,\sigma^{\mu\nu}\gamma^5 u(p) &\simeq \begin{pmatrix} 0 & -4m\vec{s} \\ 4m\vec{s} & i\,\varepsilon_{ijk}q_k - 2P_i s^j + 2P_j s^i \end{pmatrix}\ , \end{aligned}$$

Match to NR operators

$$\begin{aligned} \langle\mathcal{O}_1^N\rangle = \langle\mathcal{O}_5^N\rangle &= 4m_\chi m_N\mathcal{O}_1^{\rm NR}\,, \\ \langle\mathcal{O}_2^N\rangle &= -4m_N\mathcal{O}_{11}^{\rm NR}\,, \\ \langle\mathcal{O}_3^N\rangle &= 4m_\chi\mathcal{O}_{10}^{\rm NR}\,, \\ \langle\mathcal{O}_4^N\rangle &= 4\mathcal{O}_6^{\rm NR}\,, \\ \langle\mathcal{O}_6^N\rangle &= 8m_\chi\left(+m_N\mathcal{O}_8^{\rm NR}+\mathcal{O}_9^{\rm NR}\right)\ , \\ \langle\mathcal{O}_7^N\rangle &= 8m_N\left(-m_\chi\mathcal{O}_7^{\rm NR}+\mathcal{O}_9^{\rm NR}\right)\ , \\ \langle\mathcal{O}_8^N\rangle = -\frac{1}{2}\langle\mathcal{O}_9^N\rangle &= -16\,m_\chi m_N\mathcal{O}_4^{\rm NR}\,, \\ \langle\mathcal{O}_{10}^N\rangle &= 8\left(m_\chi\mathcal{O}_{11}^{\rm NR}-m_N\mathcal{O}_{10}^{\rm NR}-4m_\chi m_N\mathcal{O}_{12}^{\rm NR}\right) \end{aligned}$$

Backup slide 2/2

Draw Bounds (S & PS)

Higgs-like couplings

$$c_i^q = \frac{m_q}{\Lambda^3}$$

$\mathcal{O}_1^q$: **SI Int.**

$\mathcal{O}_2^q$: q^2/m_χ^2 **SI Int.**

$\mathcal{O}_3^q$: q^2/m_N^2 **SD Int.**

$\mathcal{O}_4^q$: $q^4/(m_N^2 m_\chi^2)$ **SD Int.**