15 January 2018

Max-Planck-Institut für Kernphysik (Heidelberg)

Direct Dark Matter Searches: Brief review

PANCI Paolo

- Brief Introduction
- Formalism of NR Interactions
- Match high-energy operators to NR Interactions
- Effects of the Running of the SM couplings

Plan of the Talk

Review of the formalism of NR interactions

Most general formalism to study low-energy signals in direct detection

A. L. Fitzpatrick, W. Haxton, E. Katz, N. Lubbers, Y. Xu
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Match high-energy operators down to NR interactions

We do not specify the nature of the mediator: ***model independent bounds*** on the energy scale

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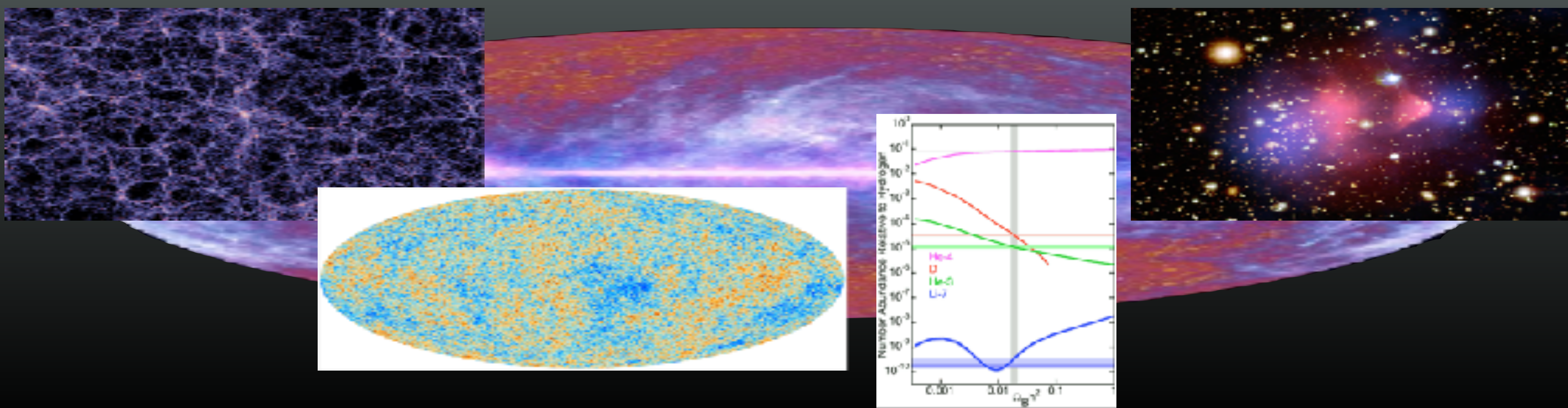
Connect simplified model of DM down to the nuclear scale

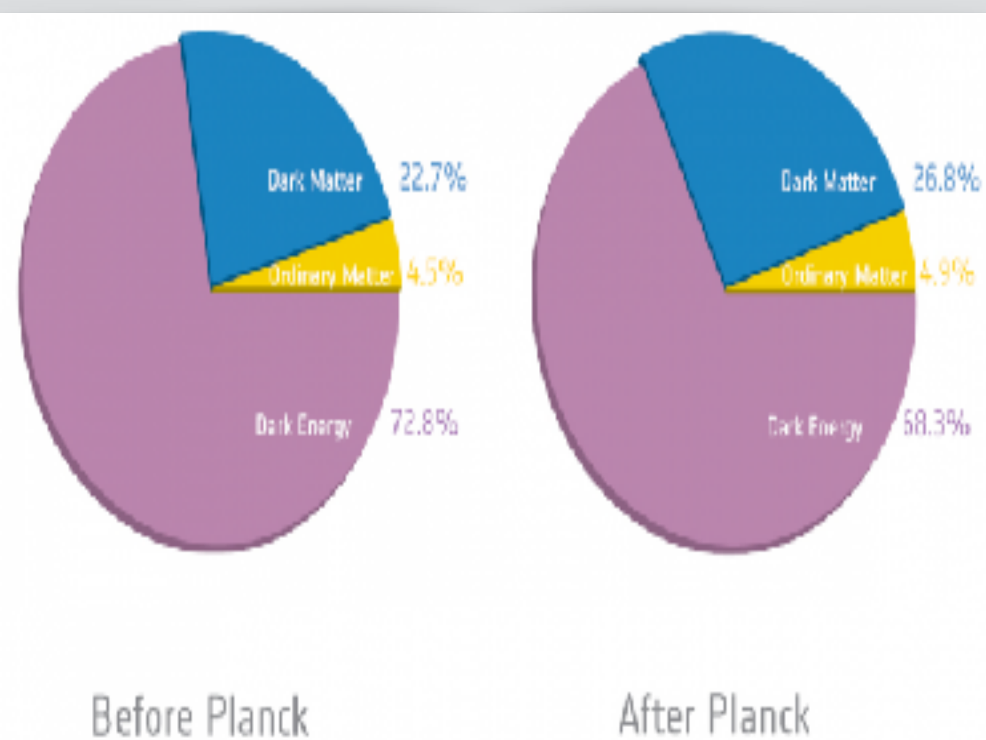
We specify the nature of the mediator: the ***evolution of the SM couplings*** between different energy scales ***generates new interactions at low energy***

F. D'Eramo, B. J. Kavanagh, P. Panci,
"*You can hide but you have to run: direct detection with vector mediator*"
Published in JHEP 1608 (2016) **111**, [arXiv: 1605.04917]

Dark Side: Overview

Precise measurements on CMB, BBN, LSS, etc...





Planck reveals an almost perfect Universe

$$\Omega_{\rm tot} = \Omega_\Lambda + \Omega_{\rm M} + \Omega_\gamma \simeq 1 \qquad \Omega_{\rm M} = \Omega_{\rm b} + \Omega_{\rm DM}$$

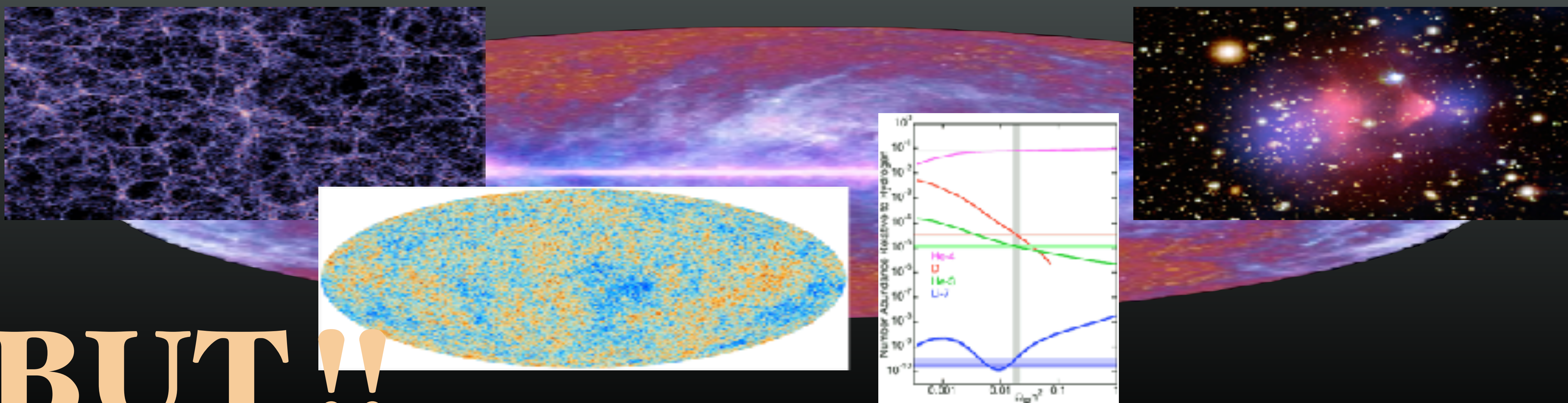
$$\Omega_\gamma \simeq 10^{-5} \qquad \Omega_\Lambda \simeq 0.68$$

$$\Omega_{\rm b} \simeq 0.05 \qquad \Omega_{\rm DM} \simeq 0.27$$

DARK Sector: $\Omega_{\rm b} + \Omega_{\rm DM} \simeq 0.95$

DM Open Questions

There are compelling and strong evidence of ***non-baryonic*** Matter in the Universe: from Galactic to Cosmo scale



BUT!!

The DM microphysics is still unknown

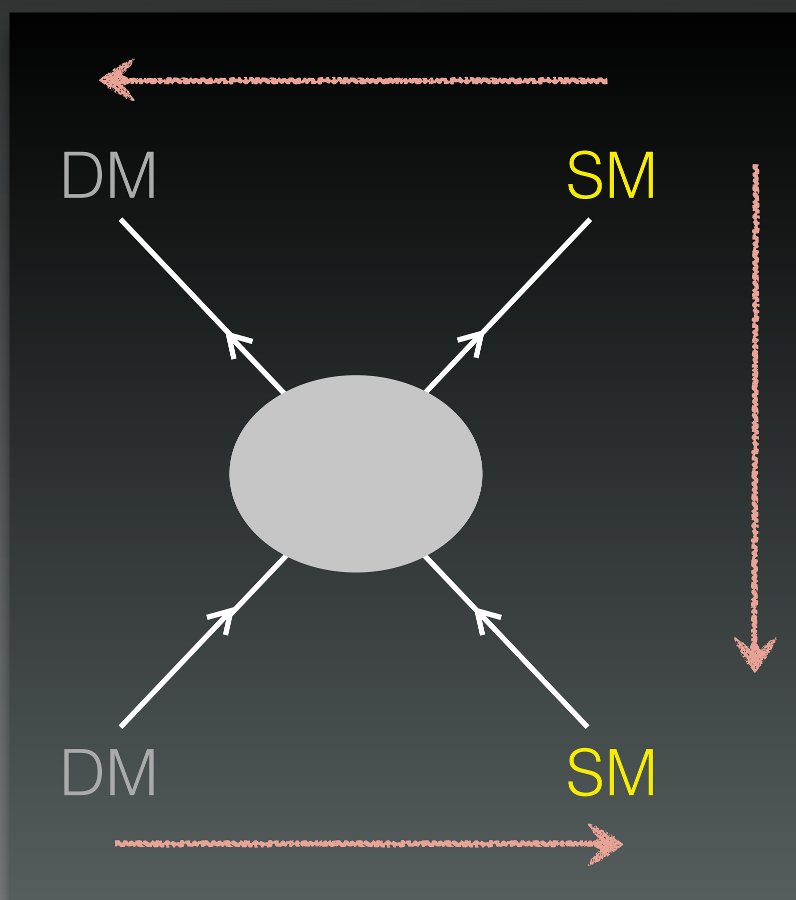
- ☑ ***DM candidate***: axions, WIMP, wimpzillas, primordial BH, etc…
- ☑ ***Underlying theory***: supersymmetry, technicolor, mirror DM, etc...
- ☑ ***DM density profile***: cuspy profile (NFW, Einasto), cored profile (isothermal)

Dark Matter Detection

Common strategies to identify the DM microphysics nature

production at collider

LHC



direct detection

DAMA/Libra, CoGeNT, CRESST.... (Edelweiss, LUX, XENON1T, SuperCDMS....)

indirect detection

γ from DM in the Galaxy
Fermi, radio telescopes....

e^+ from DM in the Galaxy
PAMELA, Fermi, HESS, AMS-02, balloons....

$\bar{p}$ from DM in the Galaxy
PAMELA, AMS-02

$\bar{d}$ from DM in the Galaxy
AMS-02, GAPS....

$\bar{\nu}, \nu$ from DM in the Galaxy
SuperK, Icecube....

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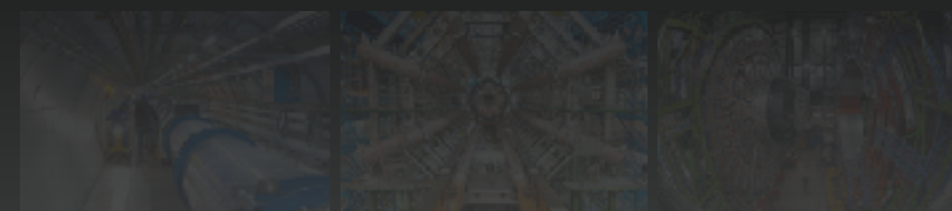

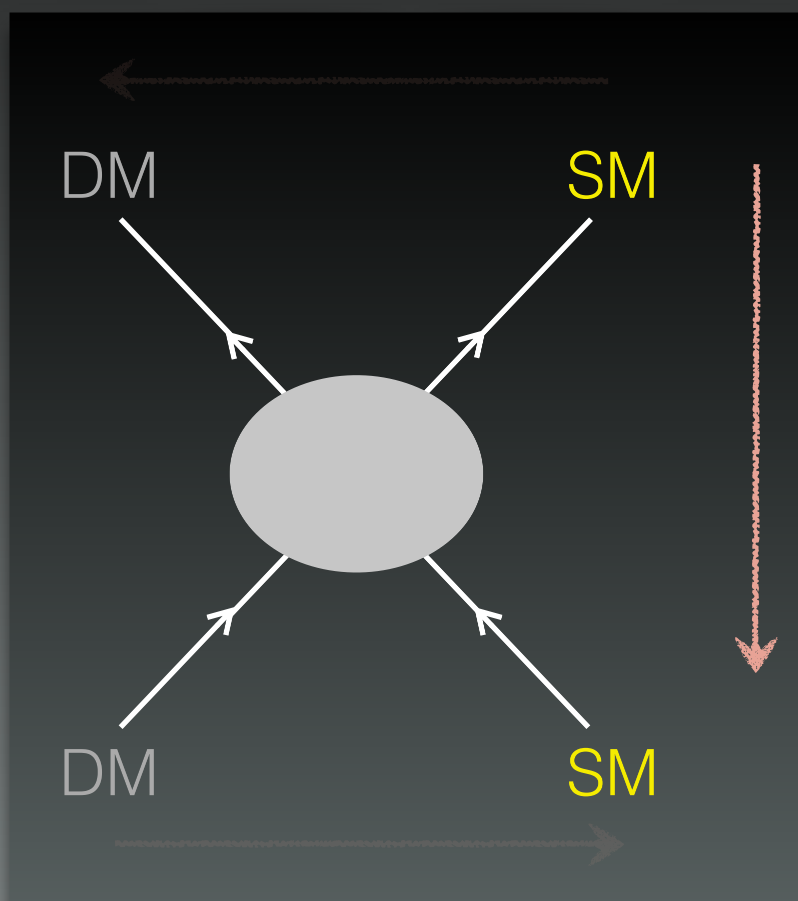

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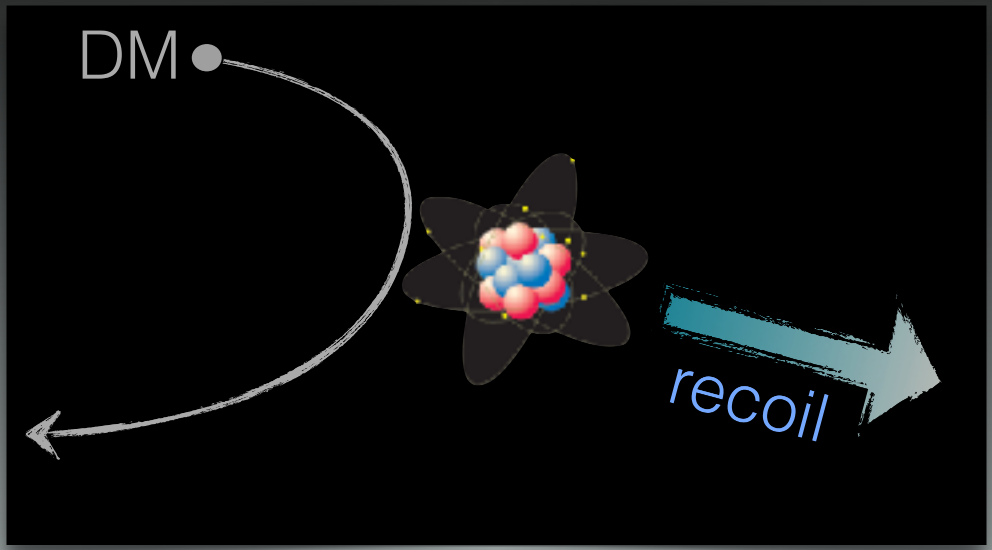
Direct detection: Overview

Direct searches aim at detecting the nuclear recoil possibly induced by:



- elastic scattering:

$$\chi + \mathcal{N}(A,Z)_{\rm rest} \to \chi + \mathcal{N}(A,Z)_{\rm recoil}$$

- inelastic scattering:

$$\chi + \mathcal{N}(A,Z)_{\rm rest} \to \chi' + \mathcal{N}(A,Z)_{\rm recoil}$$

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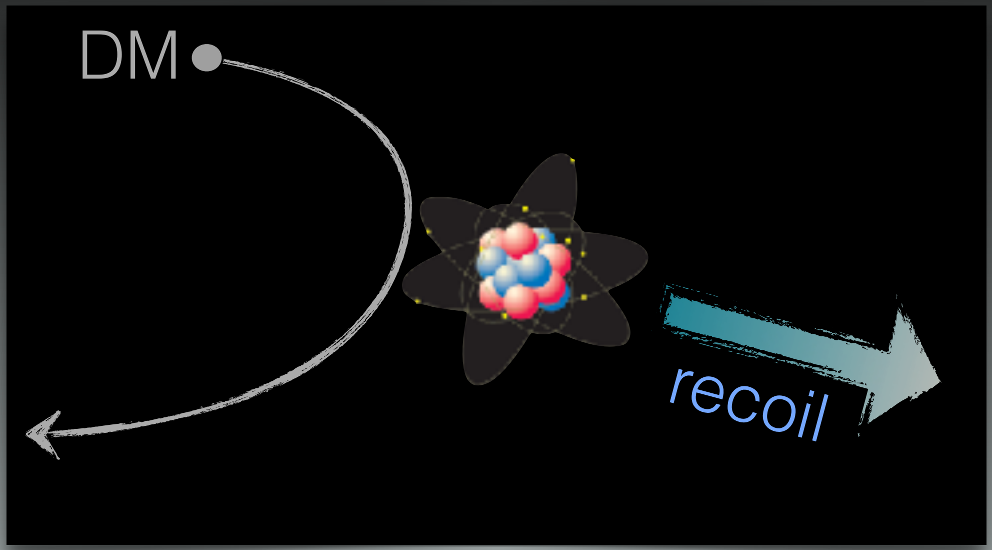

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DM signals are **very rare events** (less then one cpd/kg/keV)

Experimental priorities

- ☑ the detectors must *work deeply underground* in order to reduce the background of cosmic rays
- ☑ the detectors must *use active shields and very clean materials* against the residual radioactivity in the tunnel (γ, α and neutrons)
- ☑ the detectors must *discriminate multiple scattering* (DM particles do not scatter twice in the detector)

Direct detection: Overview

DM local velocity
$v_0 \simeq 10^{-3}c$

the DM-nucleus collision
occurs in **non relativistic (NR) regime**

$$E_{\mathrm{R}} = \underbrace{\frac{1}{2} m_\chi v^2}_{\text{DM kinetic energy}} \underbrace{\frac{4 m_\chi m_{\mathcal{N}}}{(m_\chi + m_{\mathcal{N}})^2}}_{\text{Kinematics factor}} \left(\frac{1 - \frac{v_{\mathrm{t}}^2}{2v^2} - \sqrt{1 - \frac{v_{\mathrm{t}}^2}{v^2}} \cos\theta}{2} \right), \qquad \begin{cases} v_{\mathrm{t}} = 0 & \text{elastic} \\ v_{\mathrm{t}} = \sqrt{\frac{2\delta}{\mu_{\chi\mathcal{N}}}} \neq 0 & \text{inelastic} \end{cases}$$

scatter angle

threshold velocity

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Main observable in Direct Detection

Theoretical differential rate of nuclear recoil

$$\frac{\mathrm{d}R_{\mathcal{N}}}{\mathrm{d}E_{\rm R}} = \underbrace{N_{\mathcal{N}}}_{\text{total number of targets}} \underbrace{\frac{\rho_\odot}{m_\chi}}_{\text{local DM density}} \int_{v_{\rm min}(E_{\rm R})}^{v_{\rm esc}} \mathrm{d}^3 v \, |\vec{v}| \underbrace{f(\vec{v})}_{\text{DM velocity distribution}} \underbrace{\frac{\mathrm{d}\sigma}{\mathrm{d}E_{\rm R}}}_{\text{differential cross section}}$$

Direct detection: Uncertainties

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total number of targets

local DM density

DM velocity distribution

differential cross section

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Uncertainties from Astrophysics ⇨ i.e. local DM energy density and from the geometry of the halo

Direct detection: Uncertainties

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local DM density

DM velocity distribution

differential cross section

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

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

Direct detection: Uncertainties

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Theoretical differential rate of nuclear recoil

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$N_{\mathcal{N}}$: total number of targets

$\rho_{\odot}$: local DM density

$f(\vec{v})$: DM velocity distribution

$\frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{R}}}$: differential cross section

Uncertainties from Astrophysics	⇨	i.e. local DM energy density and from the geometry of the halo
Uncertainties from Particle Physics	⇨	i.e. nature of the DM interactions & nuclear response functions
Uncertainties from Exp. side	⇨	i.e. background & detection efficiency close to lower threshold

Direct detection: Uncertainties

Main observable in Direct Detection

Theoretical differential rate of nuclear recoil

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DM Velocity Distribution

"Violent relaxation" lead to fast mixing of the DM phase-space elements
DM particles are frozen in high entropy configuration: ~ Maxwell-Boltzmann-like

"Statistical Mechanics of Violent Relaxation in Stellar System", Mon.Not.Roy.Astrom.Soc. (1966) **136**, 101

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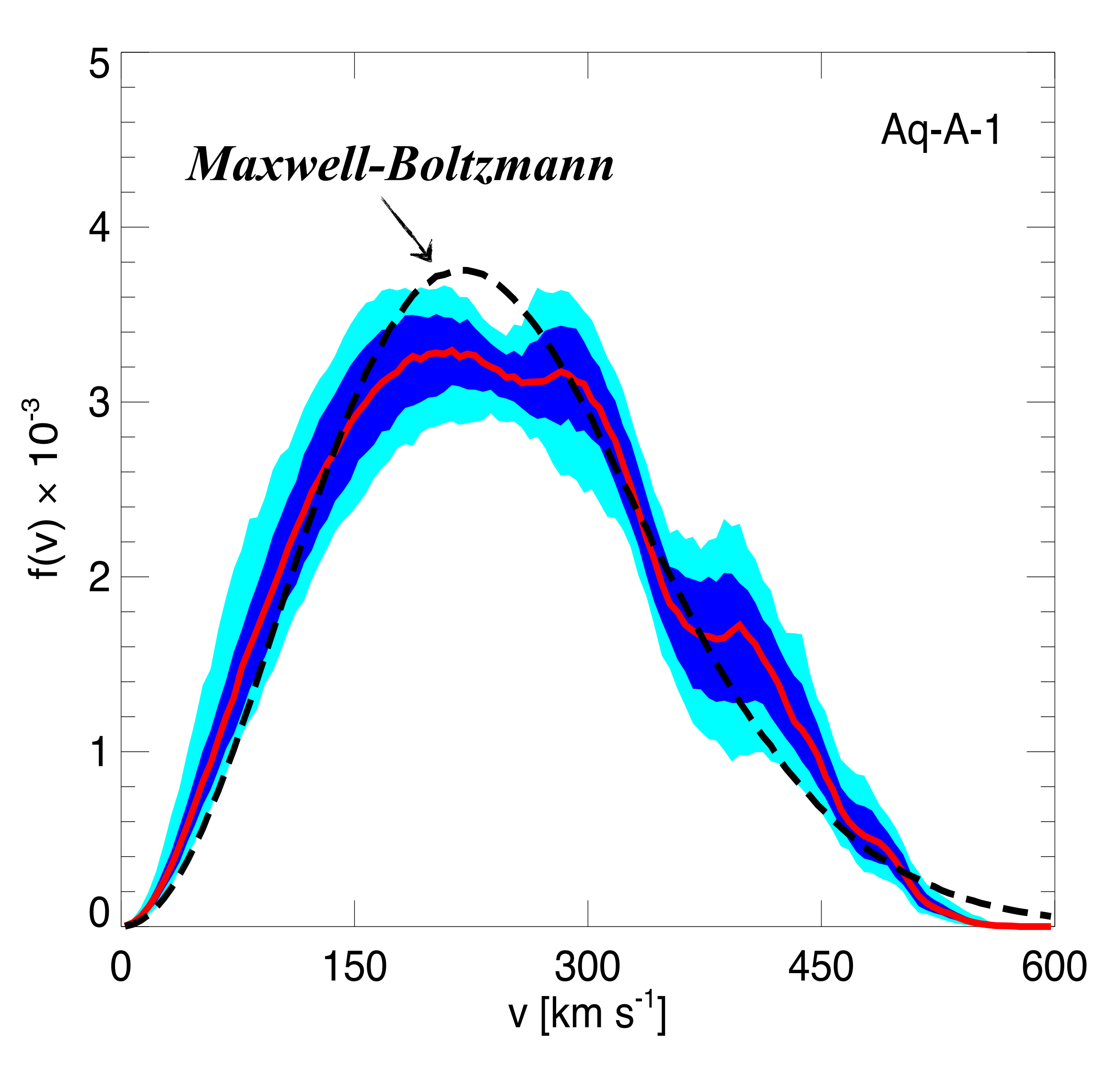
Numerical Simulations

Maxwell-Boltzmann-like configuration confirmed:

BUT

- There are deviations due to the DM assembly history of the Milky Way
- The geometry of the halo is not exactly spherical; tends to a triaxial configuration



"Phase Space Structure in the Local DM Distribution", Mon.Not.Roy.Astrom.Soc. (2009) **395**, 797

DM Velocity Distribution

The velocity distribution (VD) in the Earth frame $f_\oplus$ is related to the VD in the Galactic frame $f_{\rm gal}$ through a Galileian transformation

$$f_\oplus(\vec{v},t) = f_{\rm gal}\left(\vec{v} + \vec{v}_\odot + \vec{v}_\oplus(t)\right)$$

velocity distribution in the Earth's frame

$$f_{\rm gal}(\vec{v}) = \begin{cases} k \exp\left(-\frac{v^2}{v_0^2}\right) & v < v_{\rm esc} \\ 0 & v > v_{\rm esc} \end{cases}$$

e.g: Maxwell-Boltzmann distribution

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The Earth is moving around the Sun and the Sun around the GC

$$\vec{v}_{\rm obs}(t) = \underbrace{\vec{v}_\odot}_{\text{drift velocity of the Sun}} + \underbrace{v_\oplus\left[\vec{\varepsilon}_1\cos w(t-t_1) + \vec{\varepsilon}_2\sin w(t-t_1)\right]}_{\text{time dependent Earth's velocity projected in the GP}}$$

$\vec{v}_\odot \simeq (0,220,0) + (10,13,7)$ km/s

$v_\oplus \simeq 29.8$ km/s

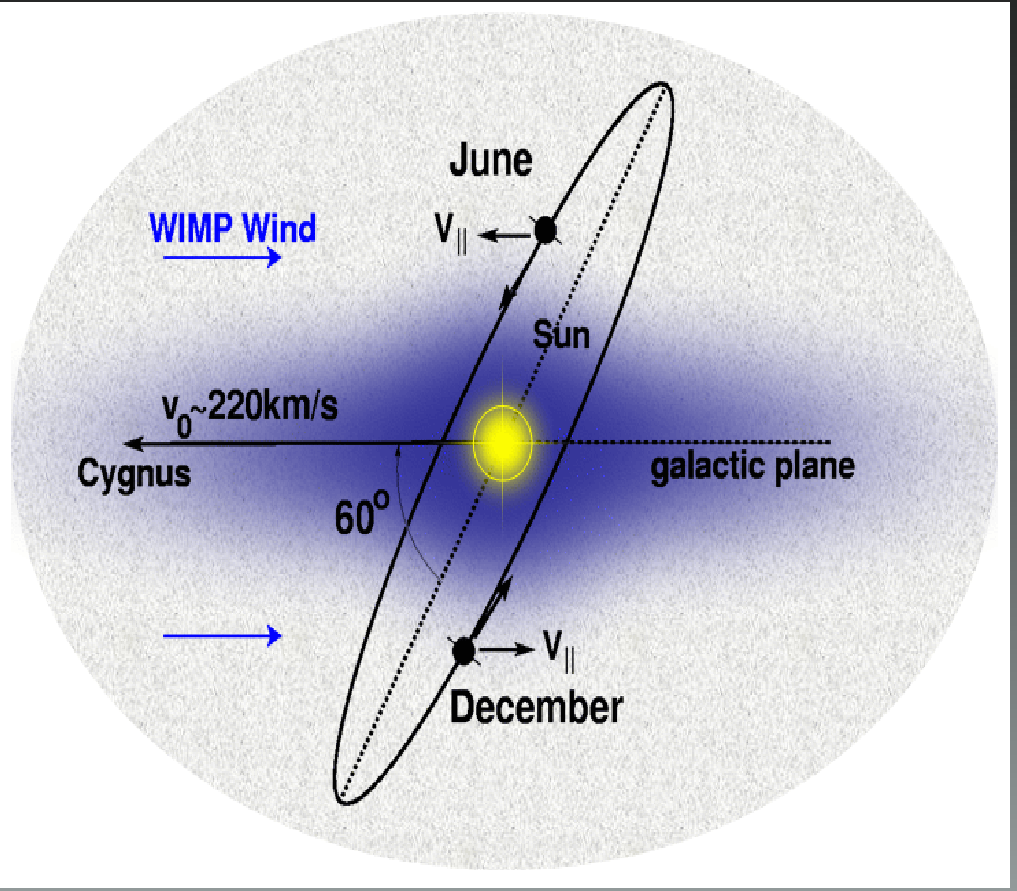
$|\vec{v}_\oplus| / |\vec{v}_\odot| \simeq 0.05$

$\vec{\varepsilon}_1 \simeq (0.9931, 0.1170, -0.0103)$

$\vec{\varepsilon}_2 \simeq (-0.0670, 0.4927, -0.8676)$

$t_1 \simeq 21^{\rm st}$ March

$w = 2\pi/{\rm year}$



Looking for annual modulation is very challenge from the exp. point of view

Differential Cross Section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{R}}}(v, E_{\mathrm{R}}) = \frac{1}{32\pi}\frac{1}{m_\chi^2 m_{\mathcal{N}}}\frac{1}{v^2}\boxed{|\mathcal{M}_{\mathcal{N}}|^2} \longrightarrow$$

Matrix Element (ME) for the DM-nucleus scattering

$v \ll c \quad \Rightarrow$ the framework of relativistic quantum field theory is not appropriate

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Non relativistic (NR) operators framework

NR d.o.f. for elastic scattering

- $\vec{v}$: DM-nucleon relative velocity
- $\vec{q}$: exchanged momentum
- $\vec{s}_N$: nucleon spin ($N = (p, n)$)
- $\vec{s}_\chi$: DM spin

DM-nucleon Matrix Element

The ME must be Galileian invariant:

$$|\mathcal{M}_N| = \sum_{i=1}^{12} \mathfrak{c}_i^N(\lambda, m_\chi)\boxed{\mathcal{O}_i^{\mathrm{NR}}}$$

NR coefficients: depend on the details of the underlying relativistic theory

Differential Cross Section

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NR coefficients: depend on the details of the underlying relativistic theory

Galileian Invariant combination of d.o.f.

$$\mathcal{O}_1^{NR} = \mathbb{1} ,$$

$$\mathcal{O}_3^{NR} = i\,\vec{s}_N \cdot (\vec{q} \times \vec{v}^\perp) , \quad \mathcal{O}_4^{NR} = \vec{s}_\chi \cdot \vec{s}_N ,$$

$$\mathcal{O}_5^{NR} = i\,\vec{s}_\chi \cdot (\vec{q} \times \vec{v}^\perp) , \quad \mathcal{O}_6^{NR} = (\vec{s}_\chi \cdot \vec{q})(\vec{s}_N \cdot \vec{q}) ,$$

$$\mathcal{O}_7^{NR} = \vec{s}_N \cdot \vec{v}^\perp , \quad \mathcal{O}_8^{NR} = \vec{s}_\chi \cdot \vec{v}^\perp ,$$

$$\mathcal{O}_9^{NR} = i\,\vec{s}_\chi \cdot (\vec{s}_N \times \vec{q}) , \quad \mathcal{O}_{10}^{NR} = i\,\vec{s}_N \cdot \vec{q} ,$$

$$\mathcal{O}_{11}^{NR} = i\,\vec{s}_\chi \cdot \vec{q} , \quad \mathcal{O}_{12}^{NR} = \vec{v}^\perp \cdot (\vec{s}_\chi \times \vec{s}_N) .$$

Exp. collaborations consider only 2 of them

$\mathcal{O}_1^{NR} = \mathbb{1}$: "Spin-independent"

$\mathcal{O}_4^{NR} = \vec{s}_\chi \cdot \vec{s}_N$: "Spin-dependent"

NR Nuclear Resposes

Nucleus is not point-like

There are different Nuclear Responses for any pairs of nucleons & any pairs of NR Operators

$$|\mathcal{M}_{\mathcal{N}}|^2 = \frac{m_{\mathcal{N}}^2}{m_N^2} \sum_{i,j=1}^{12} \sum_{N,N'=p,n} \mathfrak{c}_i^N \mathfrak{c}_j^{N'} \boxed{F_{i,j}^{(N,N')}(v,q^2)}$$

pairs of NR operators

pairs of nucleons

Nuclear responses of the target nuclei

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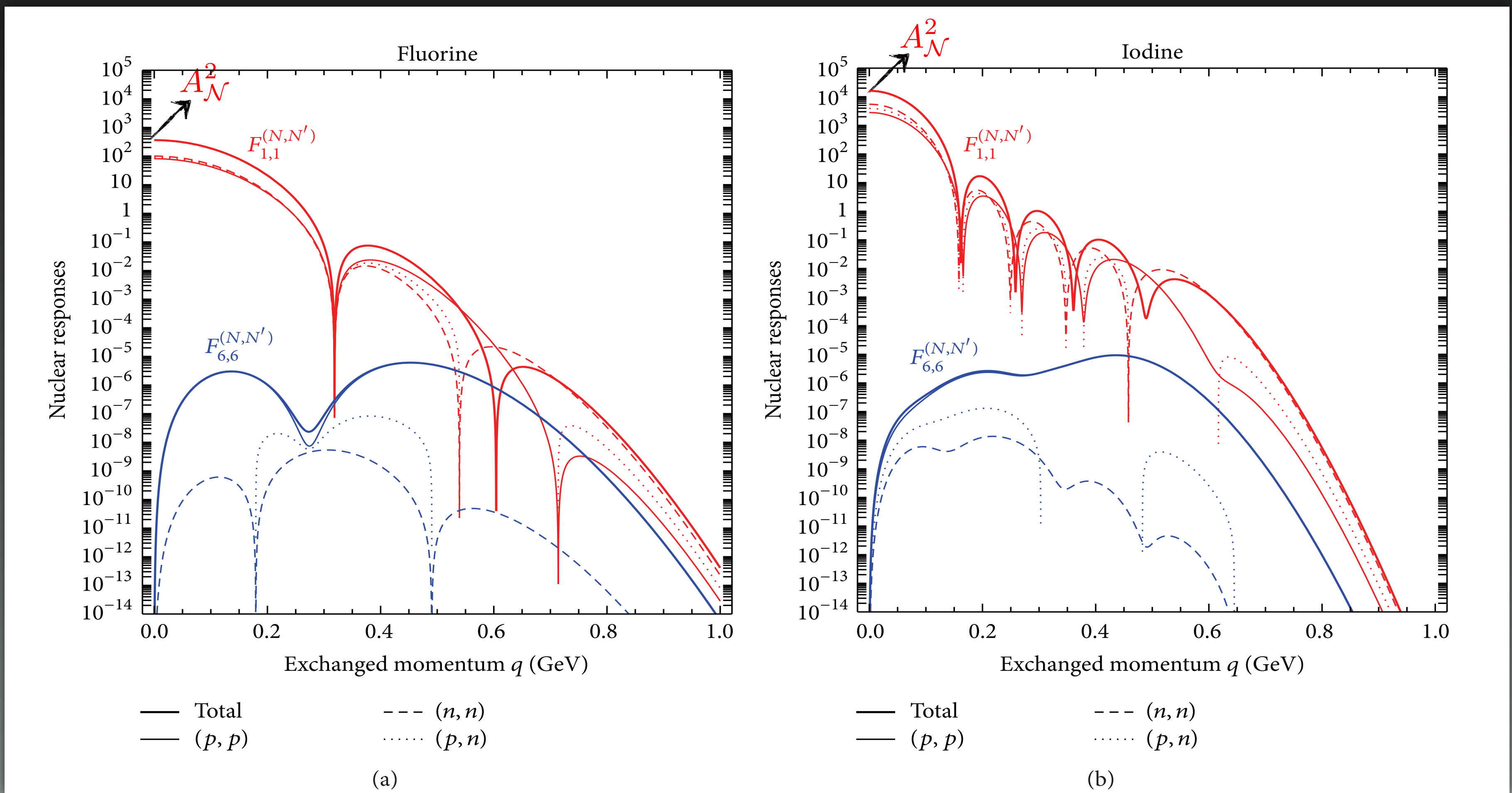
Nuclear responses of the target nuclei

Nuclear responses for some common target nuclei in Direct Searches



Contact interaction (q << Λ)

$\mathcal{O}_1^{\rm NR} = \mathbb{1}$,

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$\mathcal{O}_{11}^{\rm NR} = i\,\vec{s}_\chi \cdot \vec{q}$, $\quad \mathcal{O}_{12}^{\rm NR} = \vec{v}^\perp \cdot (\vec{s}_\chi \times \vec{s}_N)$.

Long-Range interaction (q >> Λ)

$$\mathcal{O}_1^{\rm lr} = \frac{1}{q^2}\mathcal{O}_1^{\rm NR}, \qquad \mathcal{O}_5^{\rm lr} = \frac{1}{q^2}\mathcal{O}_5^{\rm NR},$$

$$\mathcal{O}_6^{\rm lr} = \frac{1}{q^2}\mathcal{O}_6^{\rm NR}, \qquad \mathcal{O}_{11}^{\rm lr} = \frac{1}{q^2}\mathcal{O}_{11}^{\rm NR}.$$

“The Effective Field Theory of Dark Matter Direct Detection”, JCAP 1302 (2013) **004**

Formalism of NR Operators

Number of events

Particle physics part

Model independent part

$$N_k^{\rm th}(\lambda, m_\chi) = X \sum_{i,j=1}^{12} \sum_{N,N'=p,n} \mathfrak{c}_i^N(\lambda, m_\chi)\mathfrak{c}_j^{N'}(\lambda, m_\chi) \tilde{\mathcal{F}}_{i,j}^{(N,N')}(m_\chi, k)$$

“Tools for model-independent bounds in direct DM searches”, JCAP 1310 (2013) **019**

P. Panci, “New Directions in Direct DM Searches”, Adv.High Energy Phys. 2014 (2014) **681312**

Bottom line: the DM-nucleon Matrix Element is sensitive to few **Galileian invariant** combinations of NR d.o.f.

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Bottom line: the DM-nucleon Matrix Element is sensitive to few **Galileian invariant** combinations of NR d.o.f.

Towards a model independent analysis in Direct Detection

- ☑ Number of events expressed in terms of **model independent nuclear responses**
- ☑ **Going beyond** the usual SI and SD pictures and study non-conventional models

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SI DM-nucleus collision

SD DM-nucleus collision

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SI DM-nucleus collision

Dim. 6 DM-n effective Lagrangian

$$\mathcal{L}_{\text{SI}}^N \equiv \lambda_{\text{SI}}^N \, \bar{\chi}\gamma^\mu\chi \, \bar{N}\gamma_\mu N$$

SD DM-nucleus collision

Dim. 6 DM-n effective Lagrangian

$$\mathcal{L}_{\text{SD}}^N \equiv \lambda_{\text{SD}}^N \, \bar{\chi}\gamma^\mu\gamma^5\chi \, \bar{N}\gamma_\mu\gamma^5 N$$

Formalism of NR Operators

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Dim. 6 DM-n effective Lagrangian

$$\mathcal{L}_{\mathrm{SI}}^N \equiv \lambda_{\mathrm{SI}}^N \, \bar{\chi}\gamma^\mu\chi \, \bar{N}\gamma_\mu N$$

NR DM-n Matrix element

$$|\mathcal{M}_{\mathrm{SI}}^N| \simeq \underbrace{4\lambda_{\mathrm{SI}}^N m_N m_\chi}_{\mathfrak{c}_1^N} \underbrace{\mathbf{1}}_{\mathcal{O}_1^{\mathrm{NR}}}$$

SD DM-nucleus collision

Dim. 6 DM-n effective Lagrangian

$$\mathcal{L}_{\mathrm{SD}}^N \equiv \lambda_{\mathrm{SD}}^N \, \bar{\chi}\gamma^\mu\gamma^5\chi \, \bar{N}\gamma_\mu\gamma^5 N$$

NR DM-n Matrix element

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

Formalism of NR Operators

Number of events

Particle physics part

Model independent part

$$N_k^{\mathrm{th}}(\lambda, m_\chi) = X \sum_{i,j=1}^{12} \sum_{N,N'=p,n} \mathfrak{c}_i^N(\lambda, m_\chi)\mathfrak{c}_j^{N'}(\lambda, m_\chi) \tilde{\mathcal{F}}_{i,j}^{(N,N')}(m_\chi, k)$$

SI DM-nucleus collision

Dim. 6 DM-n effective Lagrangian

$$\mathcal{L}_{\mathrm{SI}}^N \equiv \lambda_{\mathrm{SI}}^N\, \bar{\chi}\gamma^\mu\chi\, \bar{N}\gamma_\mu N$$

NR DM-n Matrix element

$$|\mathcal{M}_{\mathrm{SI}}^N| \simeq \underbrace{4\lambda_{\mathrm{SI}}^N m_N m_\chi}_{\mathfrak{c}_1^N} \underbrace{1}_{\mathcal{O}_1^{\mathrm{NR}}}$$

SI Rate of nuclear recoils

$$\frac{\mathrm{d}R_{\mathcal{N}}}{\mathrm{d}E_{\mathrm{R}}} = N_{\mathcal{N}} \frac{\rho_\odot}{m_\chi} \frac{m_{\mathcal{N}}}{2\mu_{\chi\mathcal{N}}^2} \mathcal{I}(E_{\mathrm{R}}) \underbrace{A^2\sigma_{\mathrm{SI}}^N F_{\mathrm{SI}}^2(q^2)}_{\text{Total DM-n SI XS}}$$

Total DM-n **SI** XS

SD DM-nucleus collision

Dim. 6 DM-n effective Lagrangian

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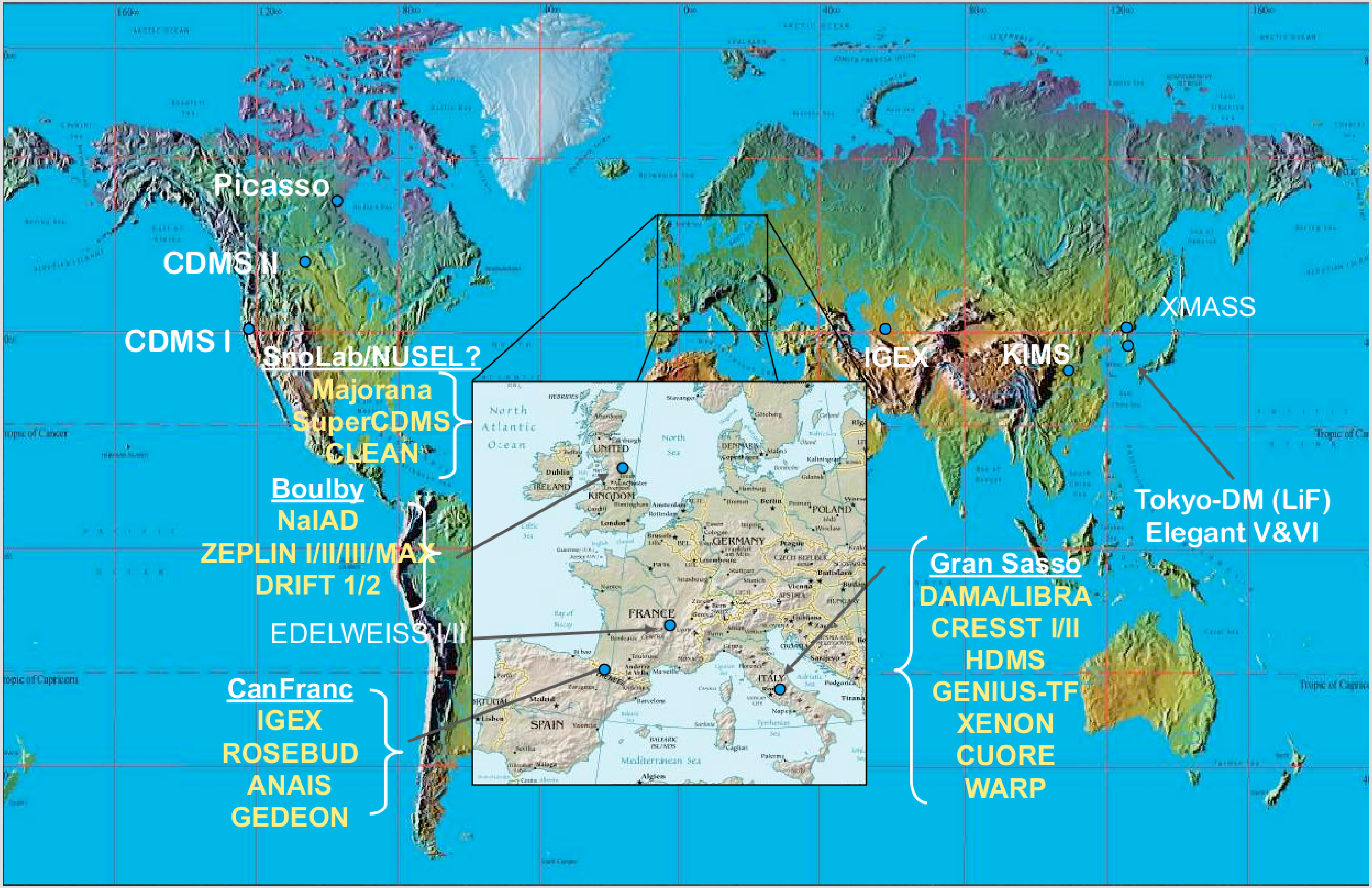
Total DM-n **SD** XS

World Wide DM Searches



World Wide DM Searches

No discrimination between EM and nuclear recoil signals

DAMA

CoGeNT

Discrimination between EM and nuclear recoil signals

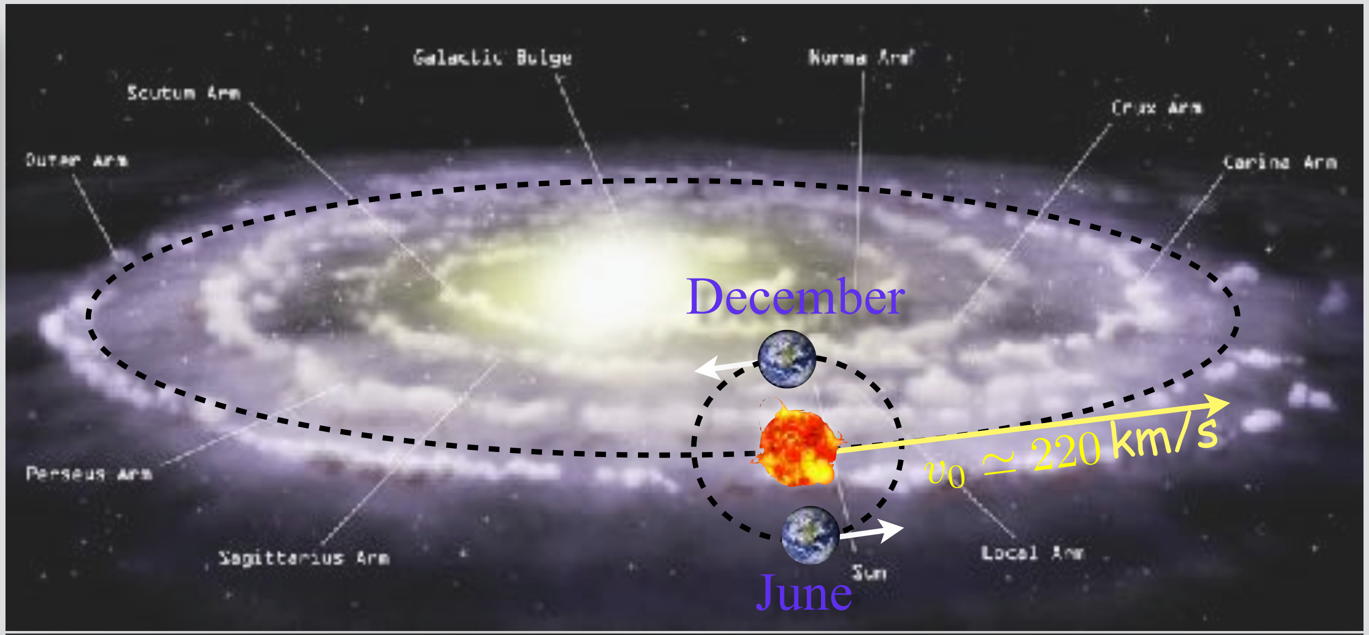
XENON

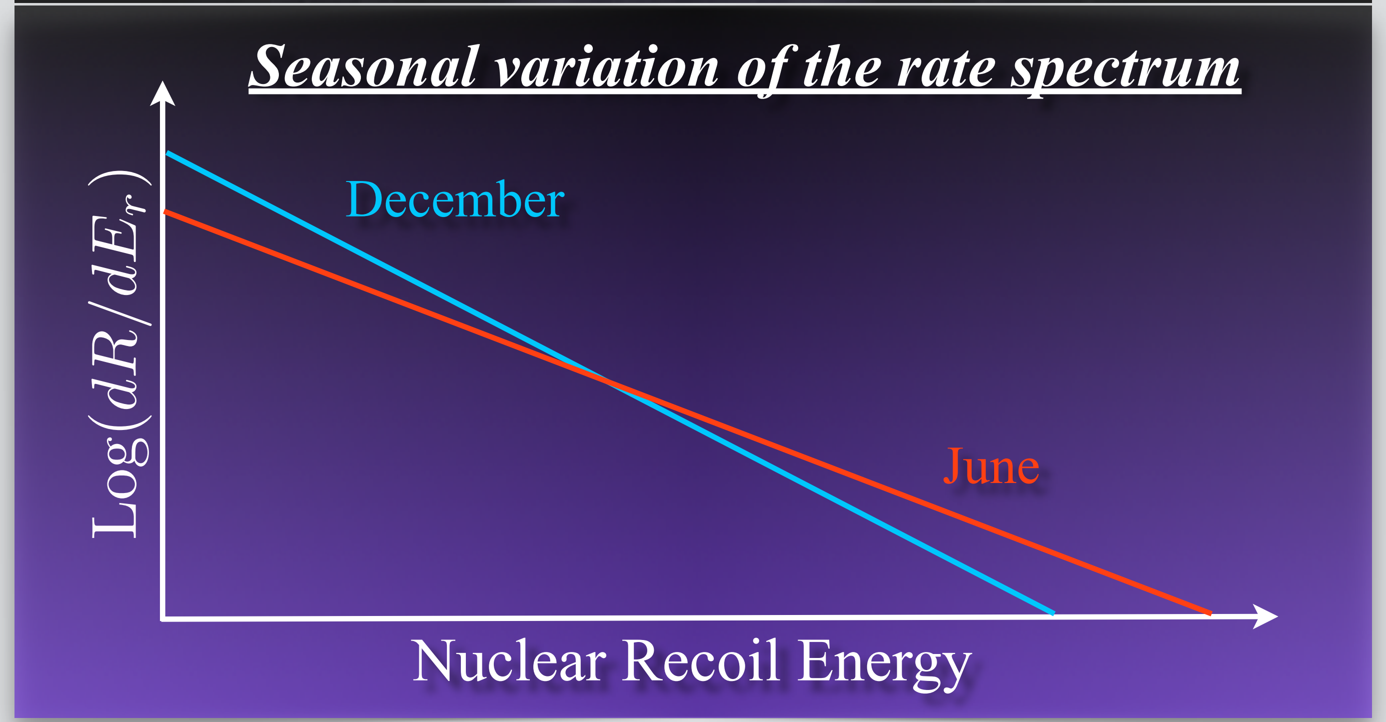
CDMS

CRESST

Model independent signal

- DM exists: ***annual modulation*** is expected
- DAMA & CoGeNT infer DM from the ***annual modulation*** effect

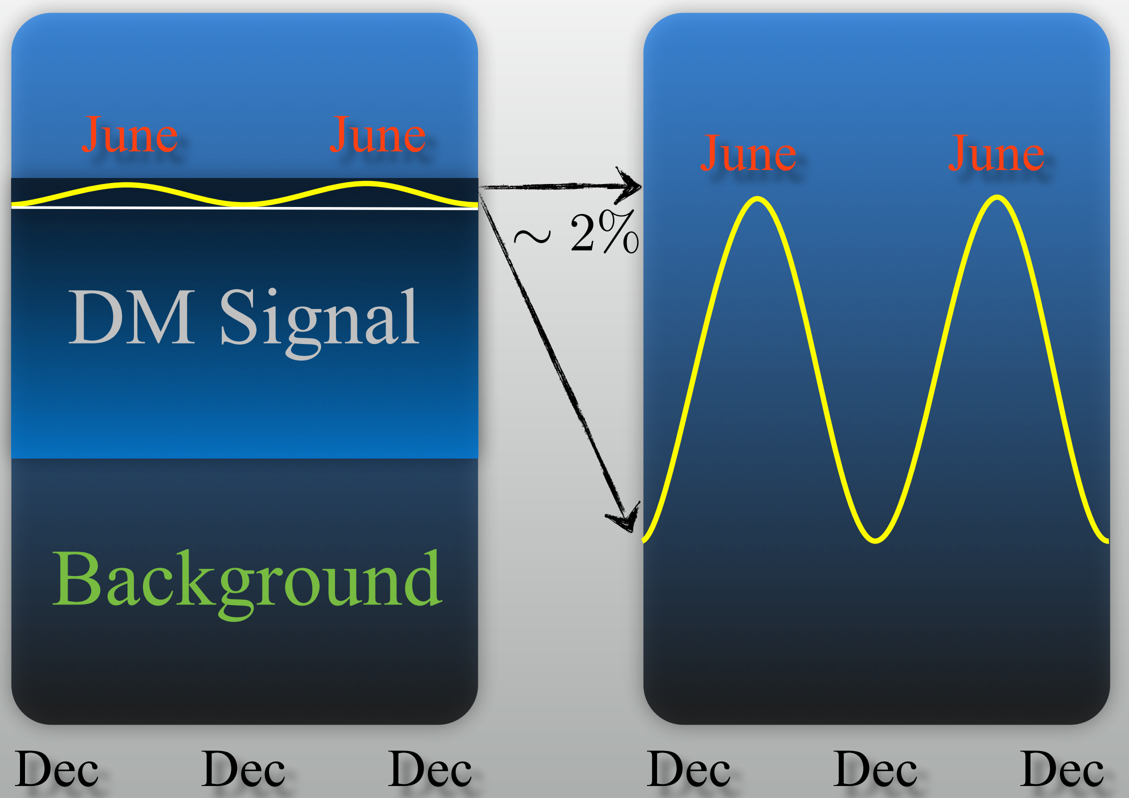


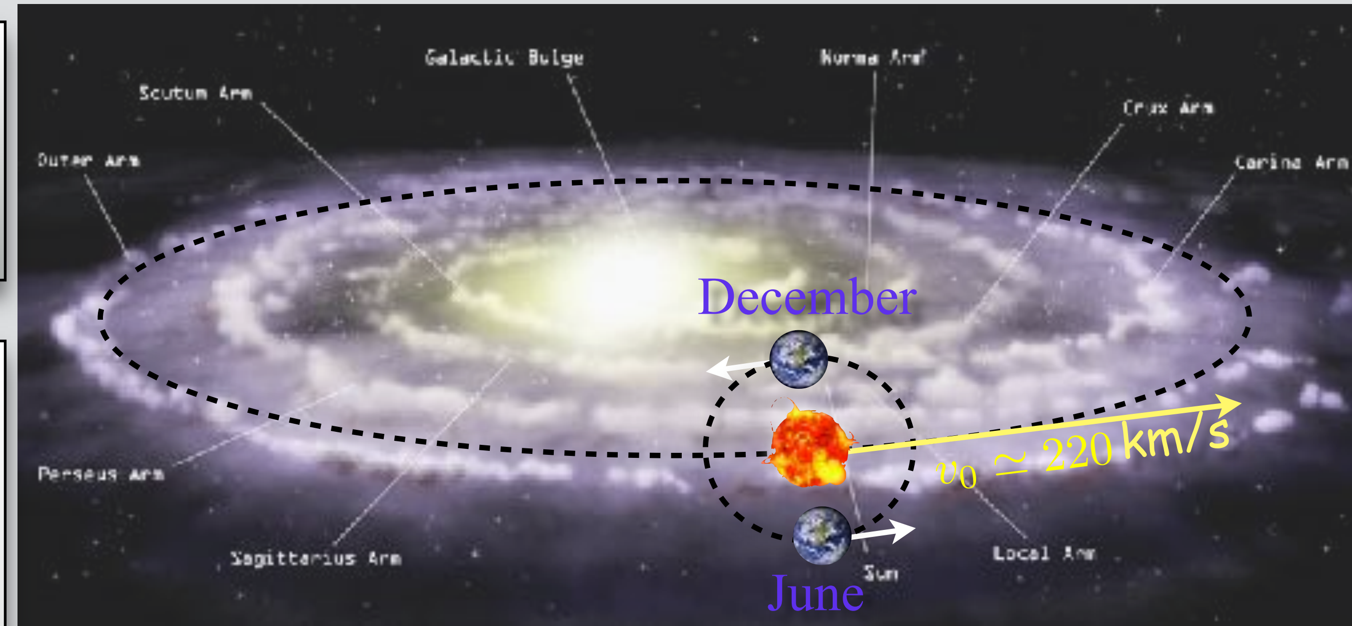


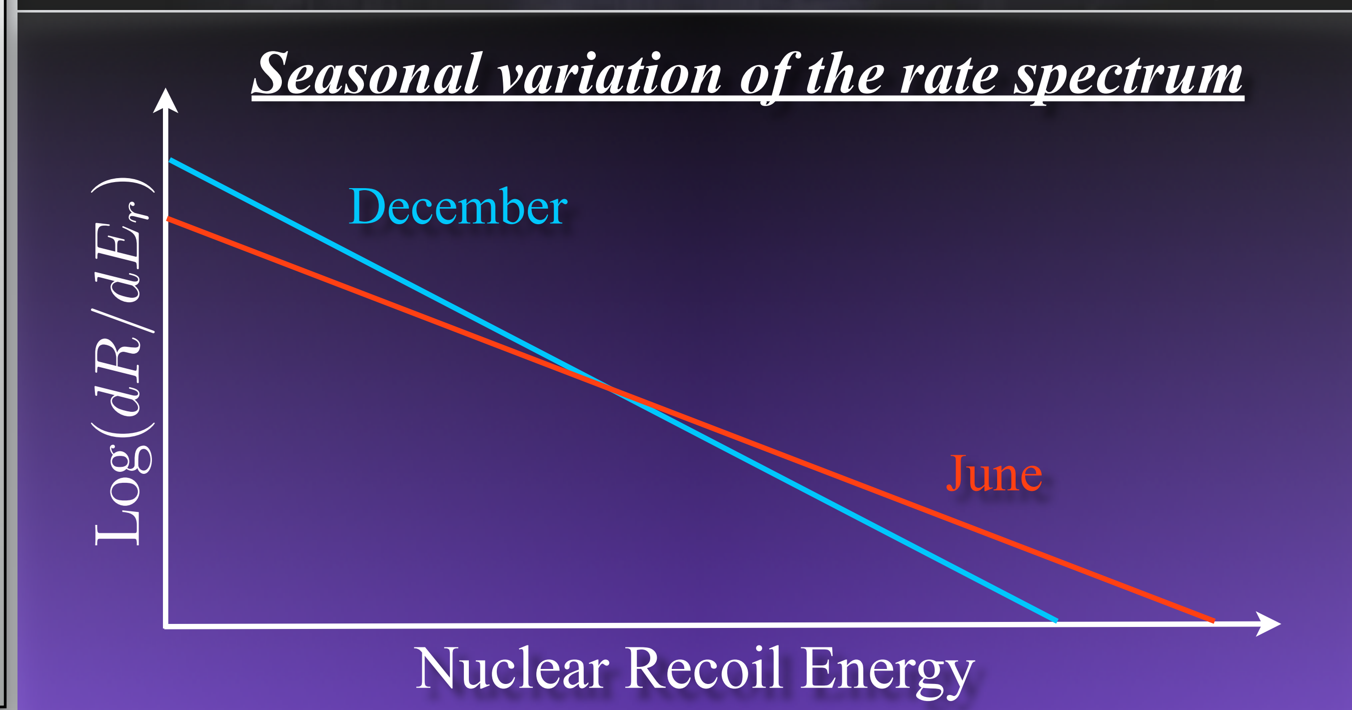
Model independent signal

- DM exists: ***annual modulation*** is expected
- DAMA & CoGeNT infer DM from the ***annual modulation*** effect

MODULATION:



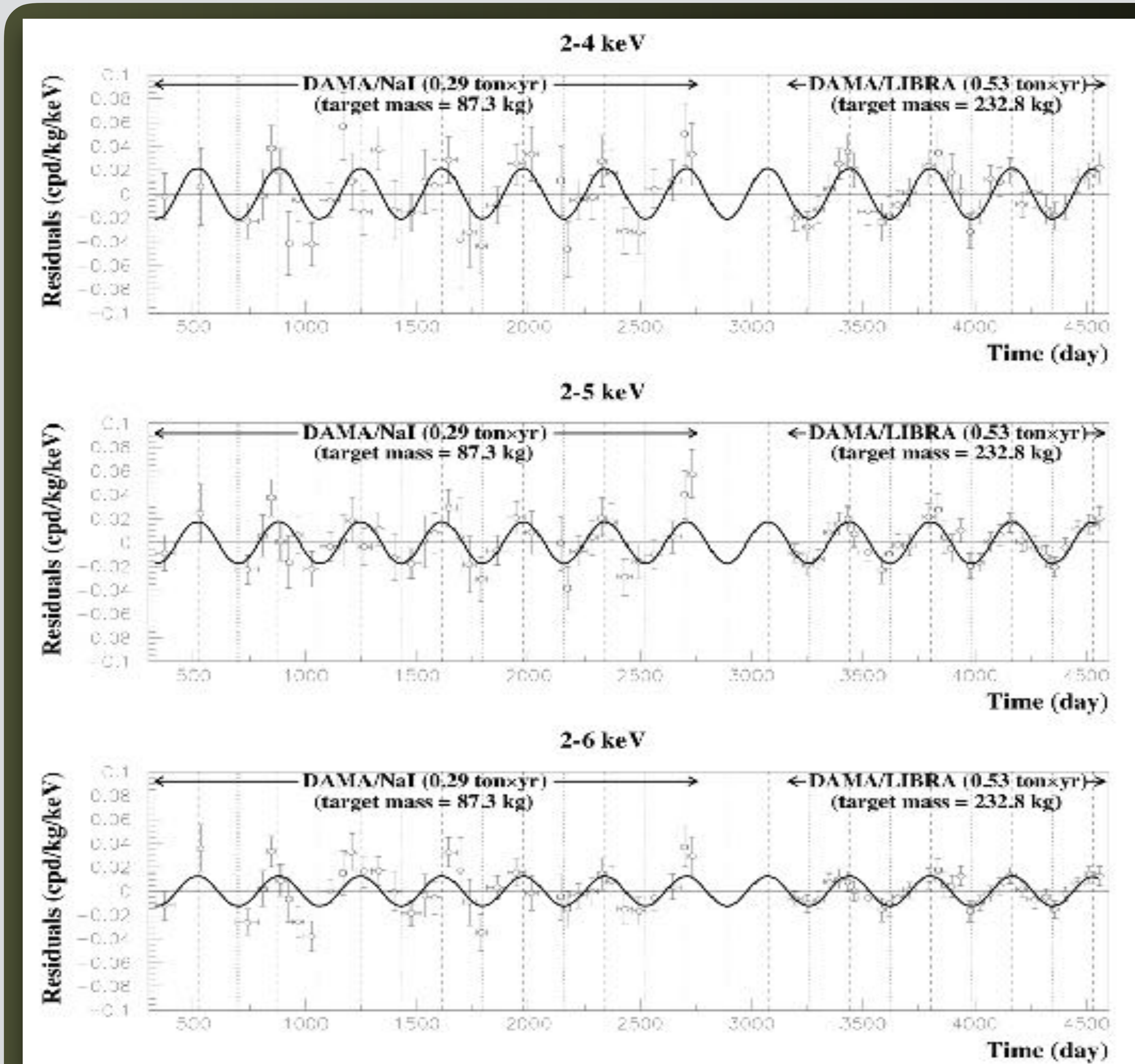




DAMA & CoGeNT are looking at the small ***annual modulation*** of the sum of the DM signal and the background

DAMA: Results

*A clear **annual modulation** over the course of many years is present !!*



Fitted with: $S_{\mathrm{m}} \cos(t/\tau + \phi)$

2-4 keV energy bin

$S_{\mathrm{m}} = 0.0223 \pm 0.0027$ cpd/kg/keV

$\tau = 0.996 \pm 0.002$ year

$\phi = 138 \pm 7$ days $\simeq 2^{\mathrm{nd}}$ June

with significance 8.3 σ CL

2-5 keV energy bin

$S_{\mathrm{m}} = 0.0178 \pm 0.0020$ cpd/kg/keV

$\tau = 0.998 \pm 0.002$ year

$\phi = 145 \pm 7$ days $\simeq 2^{\mathrm{nd}}$ June

with significance 8.9 σ CL

2-6 keV energy bin

$S_{\mathrm{m}} = 0.0131 \pm 0.0016$ cpd/kg/keV

$\tau = 0.998 \pm 0.003$ year

$\phi = 144 \pm 8$ days $\simeq 2^{\mathrm{nd}}$ June

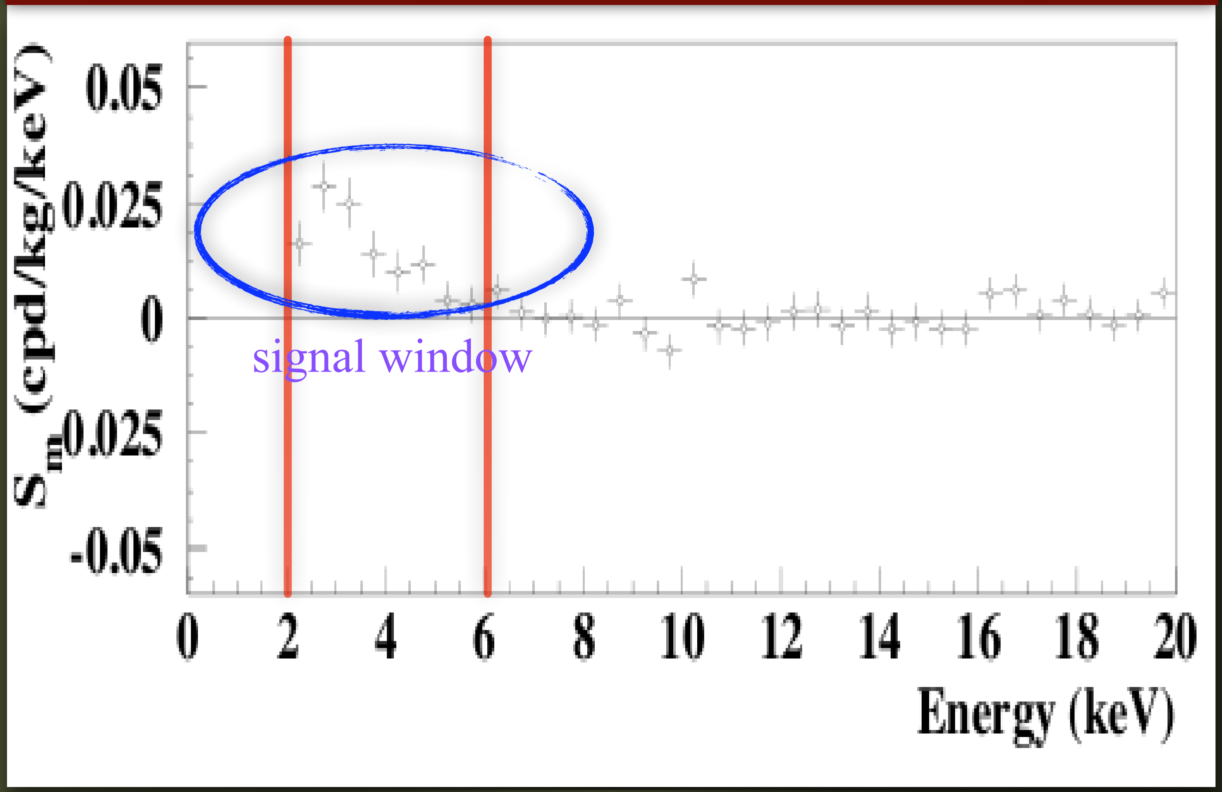
with significance 8.2 σ CL

"First results from the DAMA/LIBRA experiments", Eur.Phys.J. C56 (2008) **333**

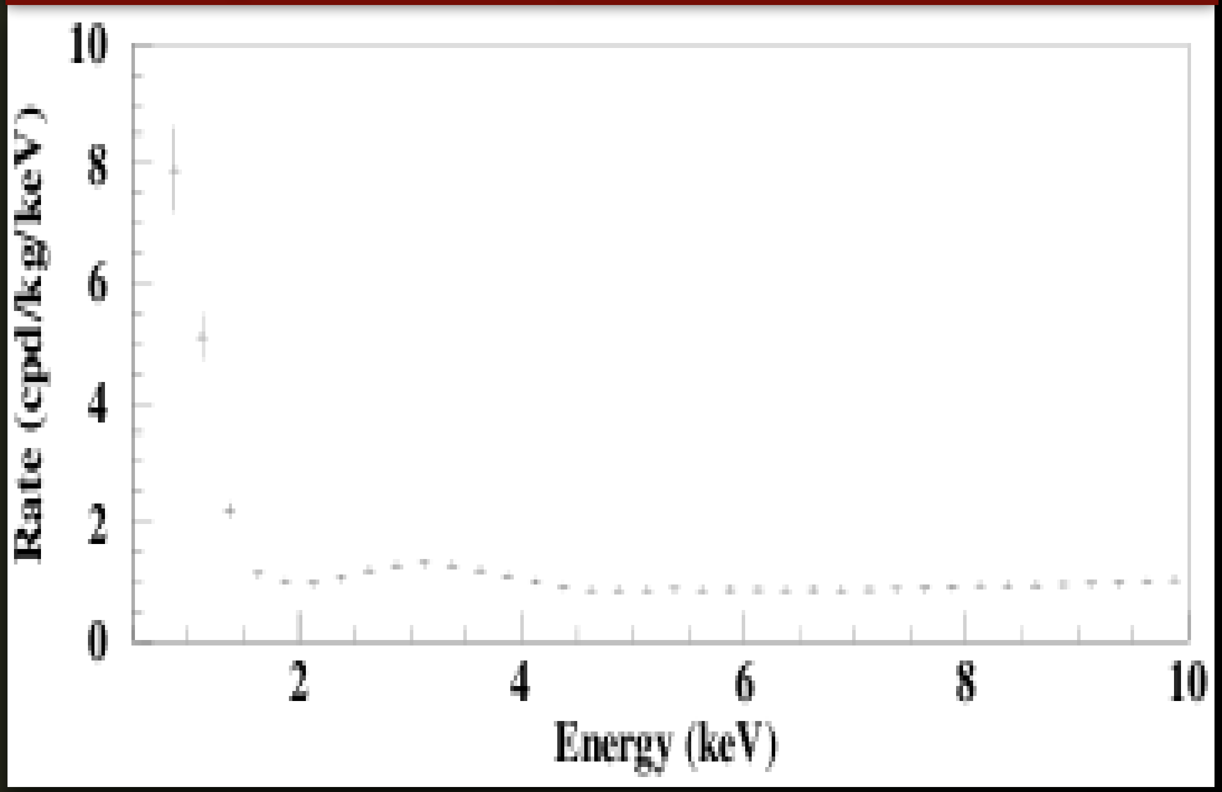
DAMA: Results

<u>Spectral features</u> *<u>of the DAMA signal in the low-energy bin</u>*

Spectrum of the modulated signal



Spectrum of the total rate



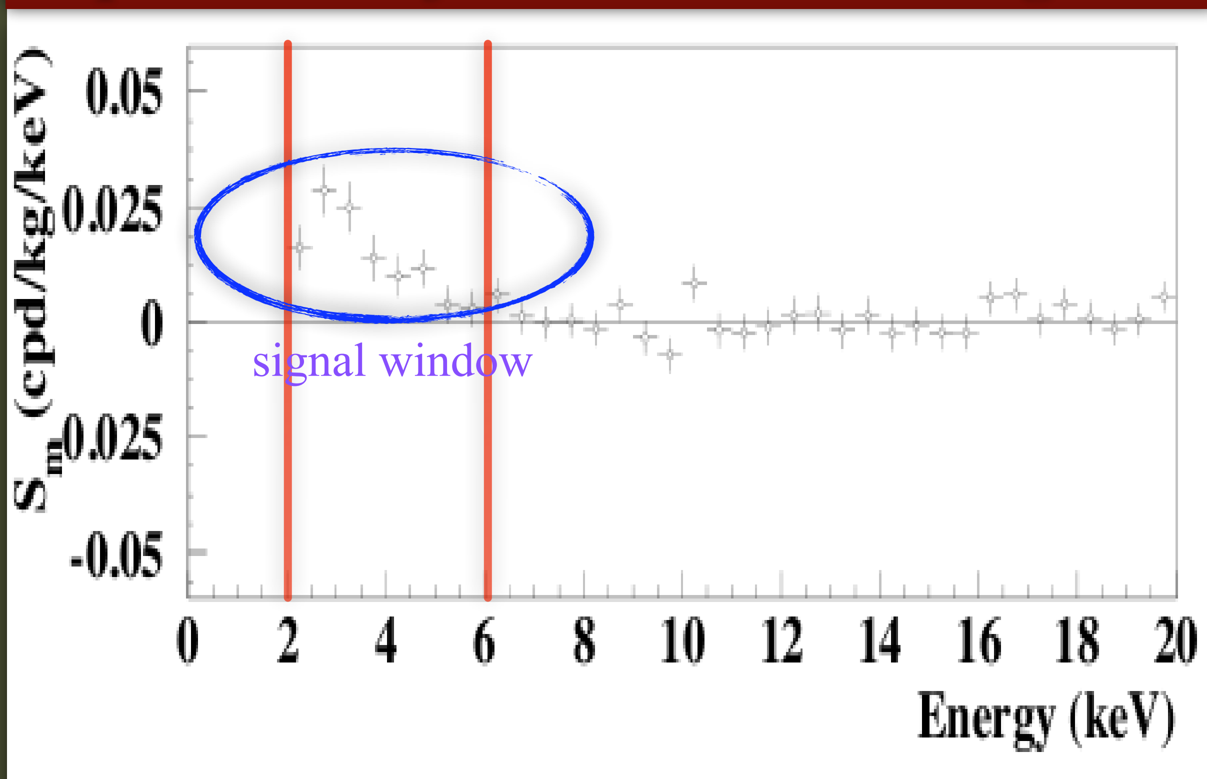
"First results from the DAMA/LIBRA experiments", Eur.Phys.J. C56 (2008) **333**

Bottom line: <u>the modulation is only visible at low energy (from 2 to 6 keVee)</u>

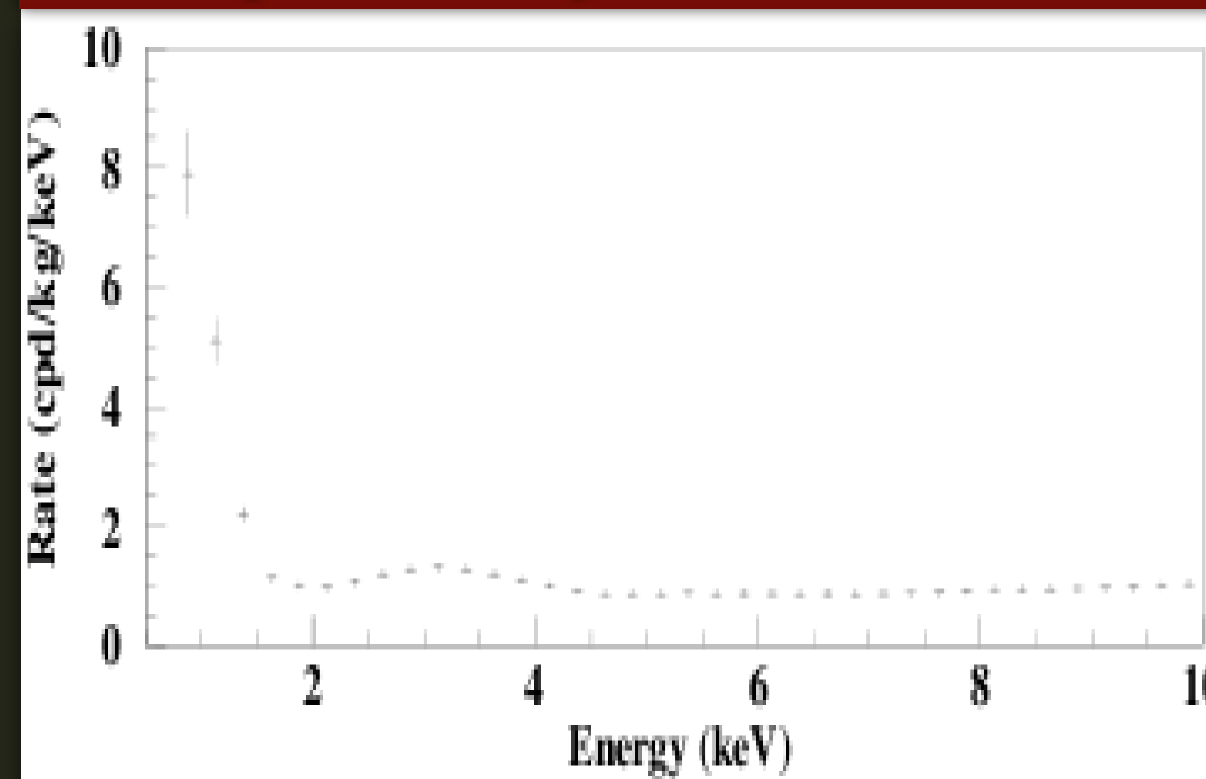
DAMA: Results

***Spectral features** of the DAMA signal in the low-energy bin*

Spectrum of the modulated signal



Spectrum of the total rate



"First results from the DAMA/LIBRA experiments", Eur.Phys.J. C56 (2008) **333**

Bottom line: the modulation is only visible at low energy (from 2 to 6 keVee)

Comparison with the DAMA datasets

one has to compare the *theoretical modulated signal* with the experimental one in the energy bins of interest, *without exceed the total rate*

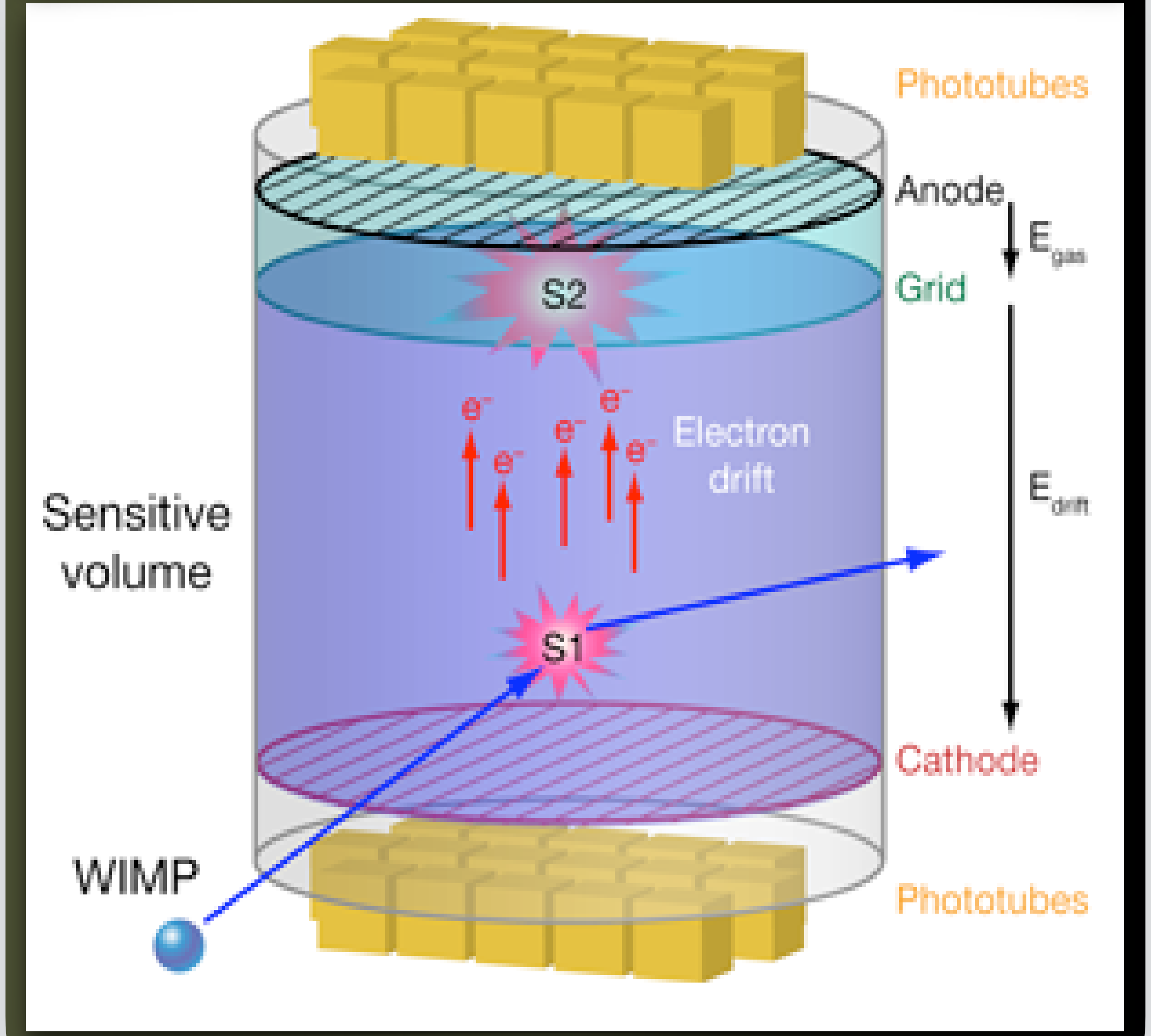
Xenon-based DM experiments

- **Nuclear Recoil:** $S_{\rm liq} \gg S_{\rm gas}$

  the density of ionization is very high, mostly of the ionized electrons promptly recombine, without drift in the gas phase, producing in the liquid the majority of the signal

- **Electron Recoil:** $S_{\rm liq} \ll S_{\rm gas}$

  the density of ionization is very poor, the ionized electrons can drift in the gas phase producing there a scintillation signal



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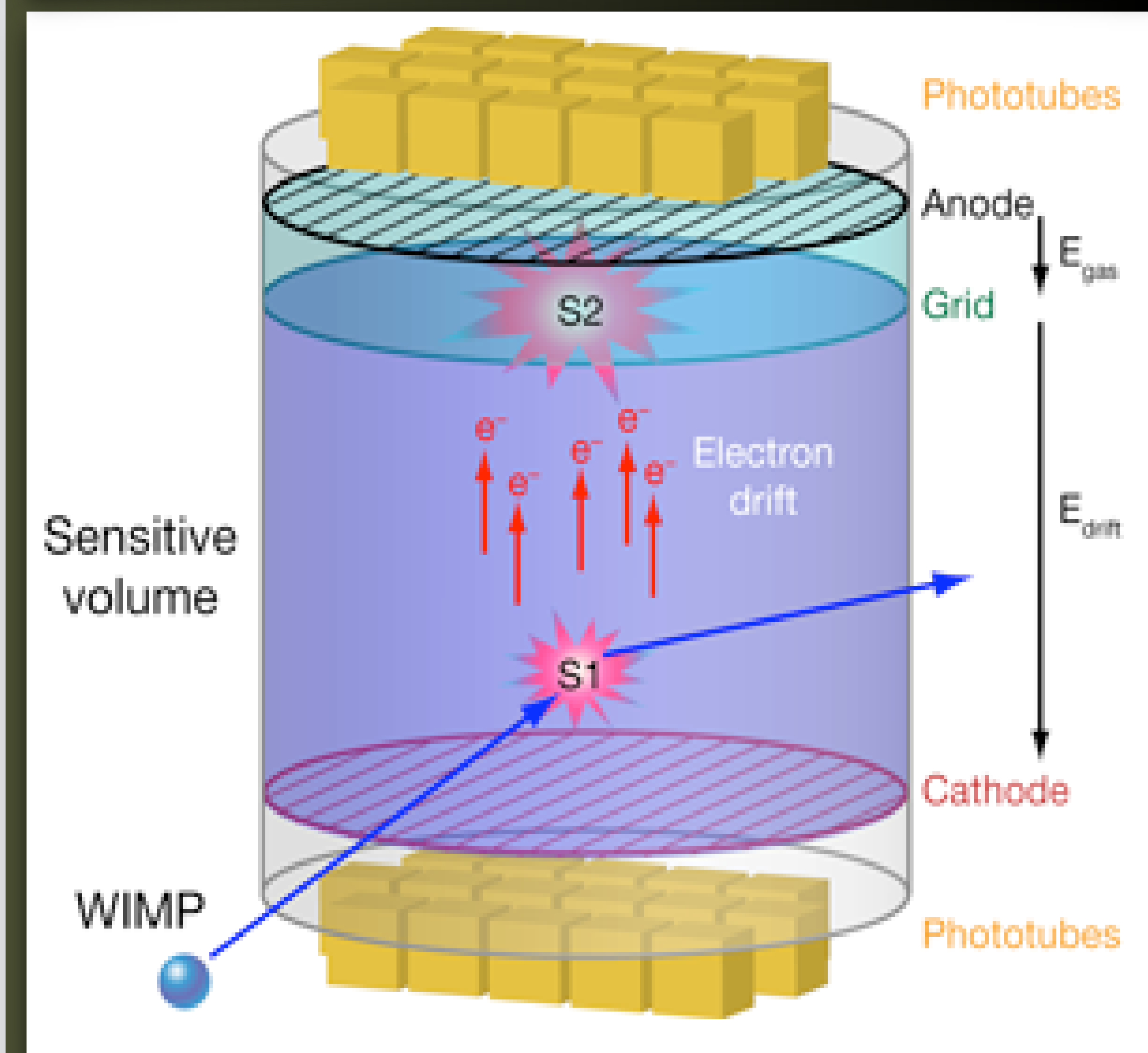
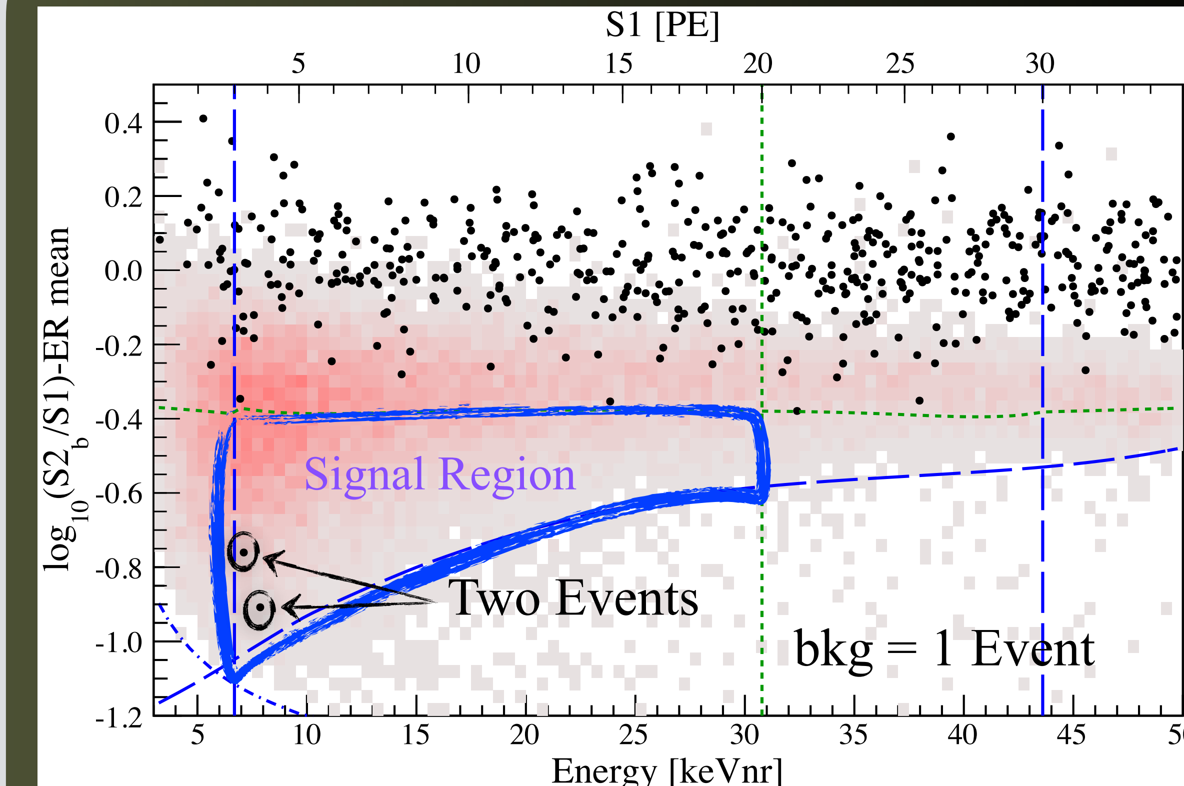
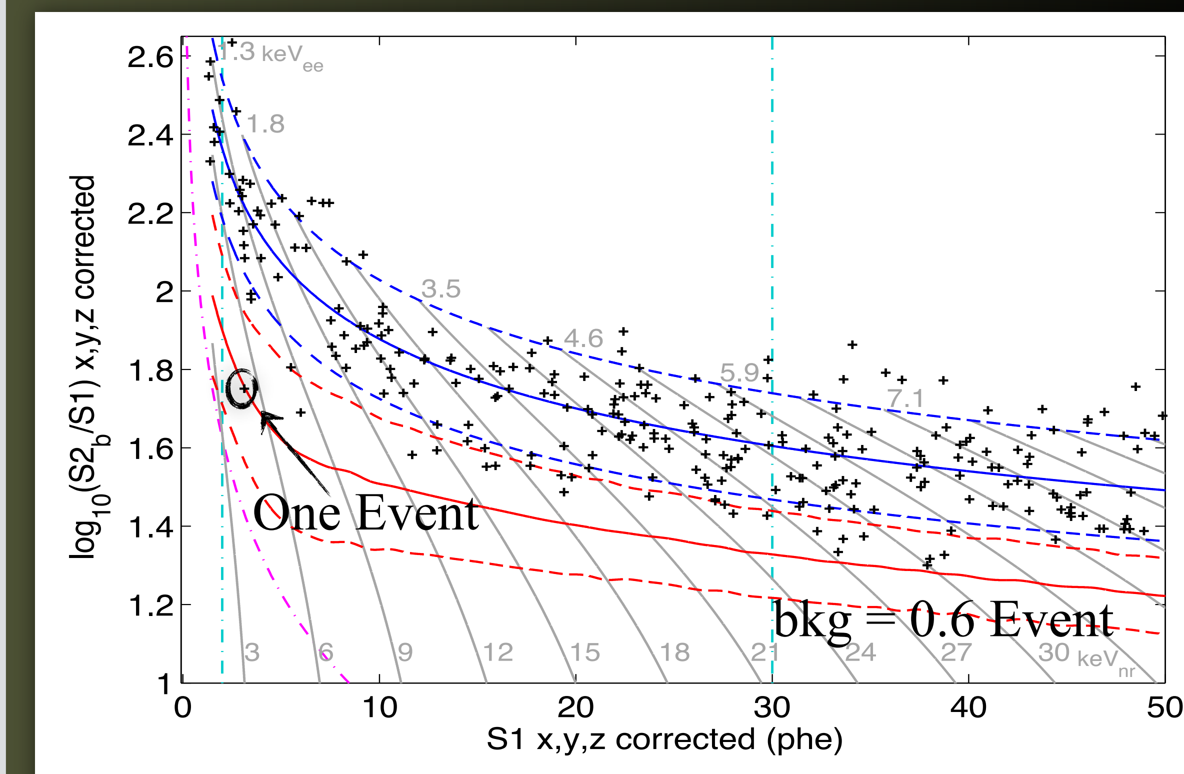


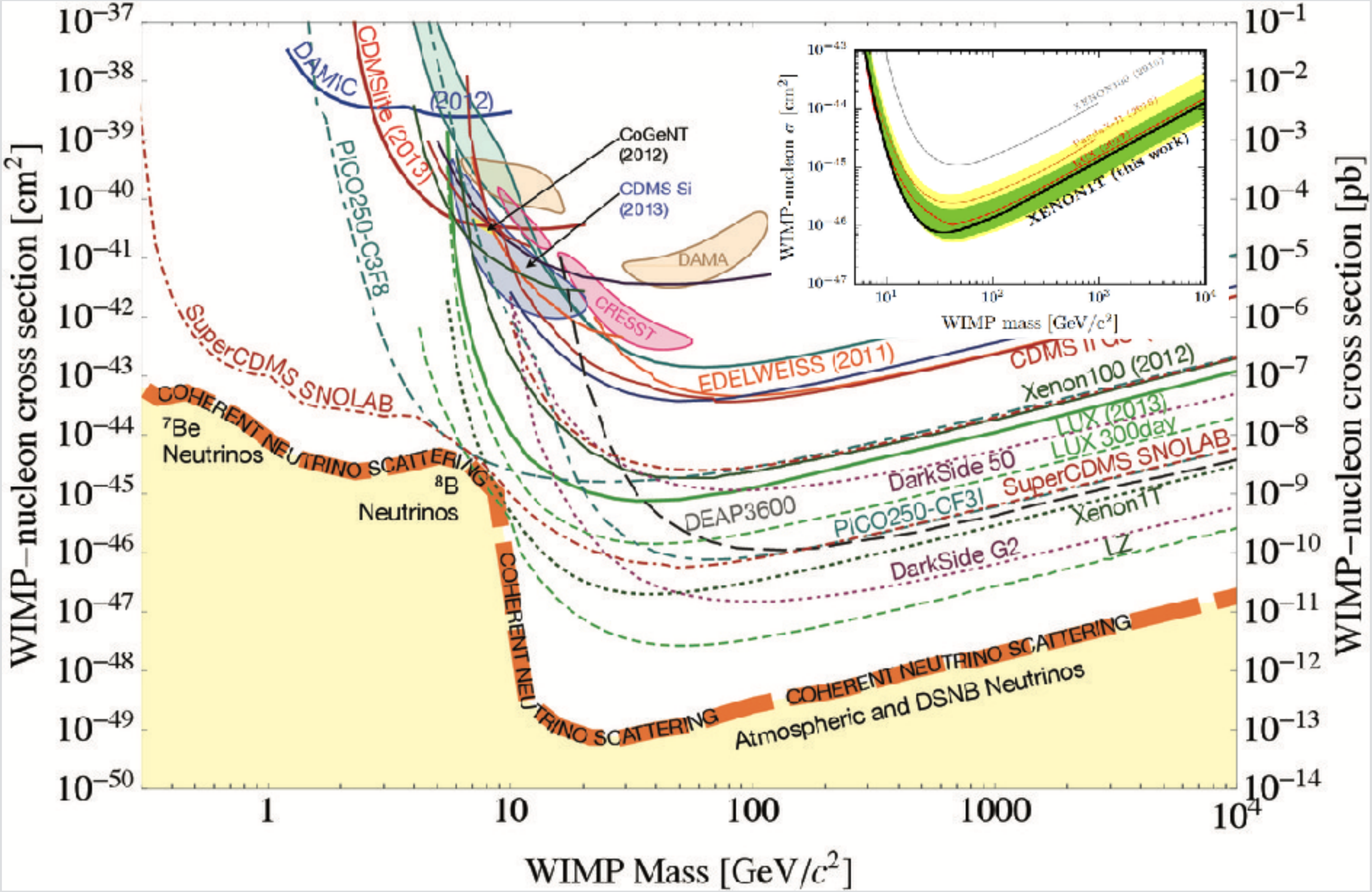


Phys.Rev.Lett. **109** (2012) 18130

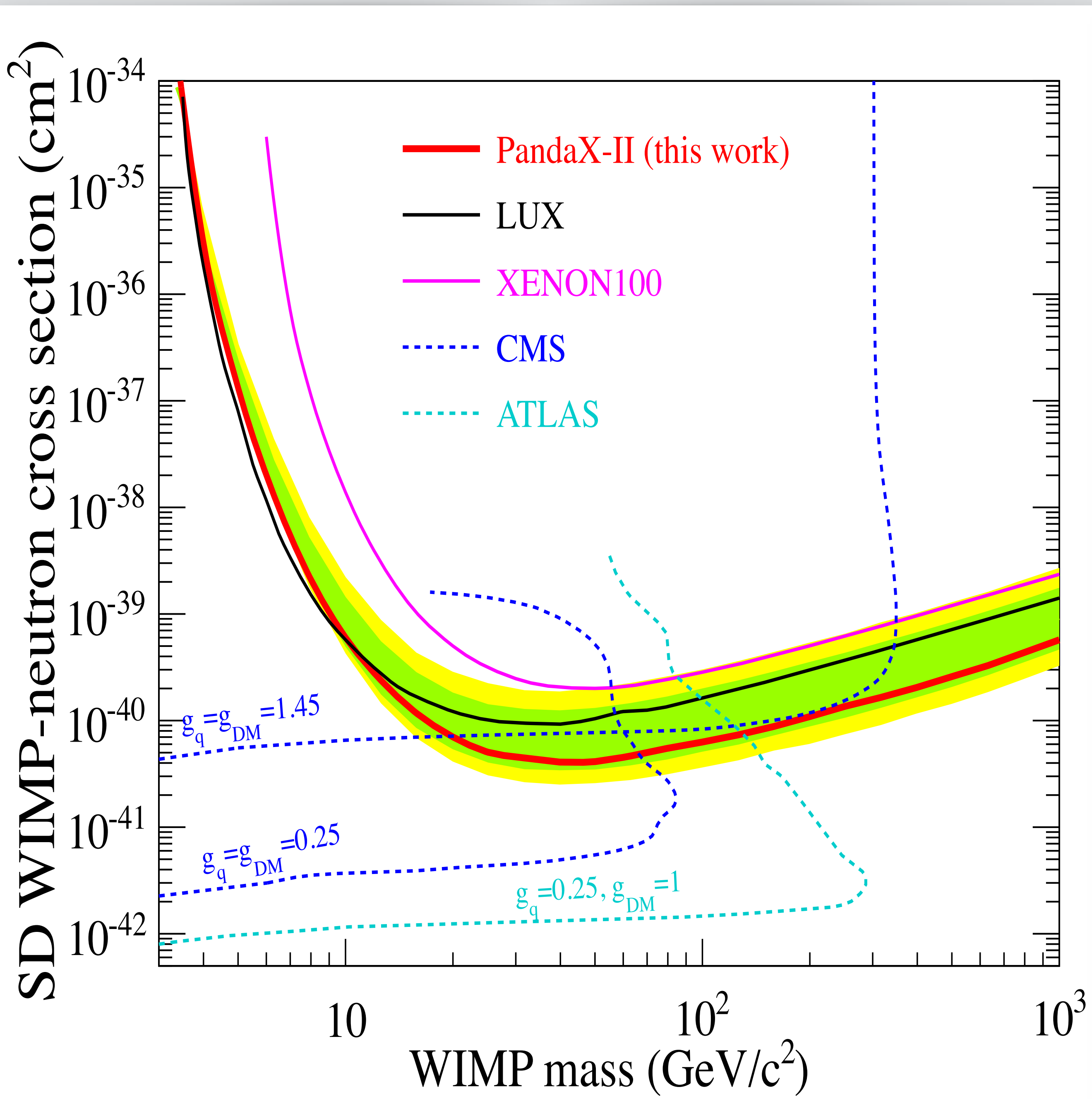


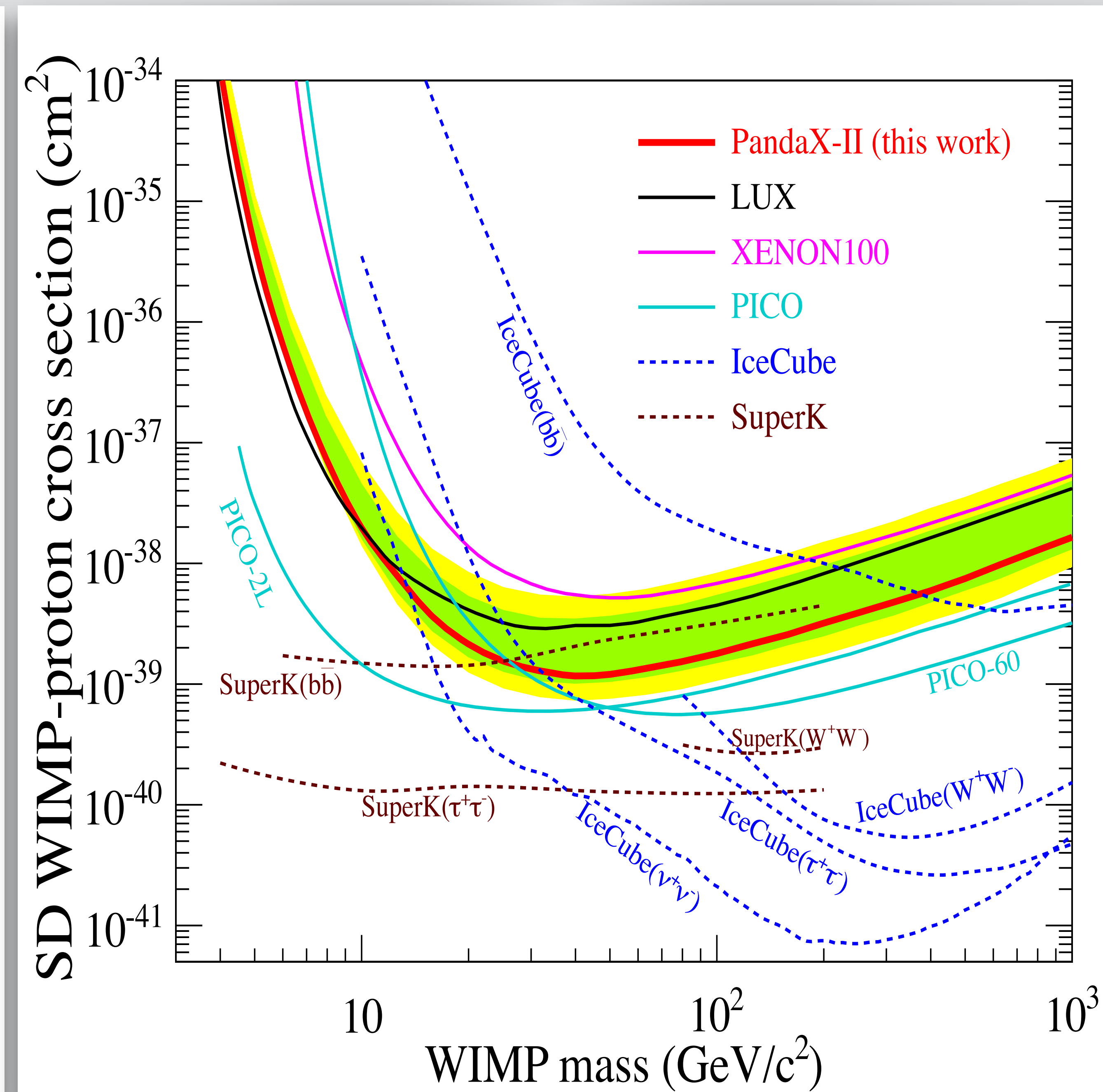
LUX results; arXiv: 1310.8214

SI Interaction: Current Status



SD Interaction: Current Status





Bottom line: *sensitivities are different* given the fact that not all the nuclei used in direct detections have the *same unpaired nucleons in the outer nuclear shell*

Relativistic Effective Operators

A standard approach used to address this issue is:

Effective operators for DM interactions with quarks and gluons

Matching onto NR Interactions

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 …

Relativistic Effective Operators

Effective operators for DM interactions with quarks and gluons

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Produce bounds on the energy scale of such operators

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

Dimension 6 operators one can construct with neutral DM & SM quarks

Dirac DM

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

Dimension 6 operators one can construct with neutral DM & SM quarks

Dirac DM

$$\mathcal{O}_1^g = \frac{\alpha_s}{12\pi}\,\bar{\chi}\chi\,G^a_{\mu\nu}G^a_{\mu\nu}\,, \qquad \mathcal{O}_2^g = \frac{\alpha_s}{12\pi}\,\bar{\chi}\,i\gamma^5\chi\,G^a_{\mu\nu}G^a_{\mu\nu}\,,$$
$$\mathcal{O}_3^g = \frac{\alpha_s}{8\pi}\,\bar{\chi}\chi\,G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}\,, \qquad \mathcal{O}_4^g = \frac{\alpha_s}{8\pi}\,\bar{\chi}\,i\gamma^5\chi\,G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}\,,$$

Gauge Invariant **Dimension 7** operators that couple chi with gluons

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Produce bounds on the energy scale of such operators

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

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<u>Dimension 6</u> operators one can construct with neutral DM & SM quarks

Majorana DM

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

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Gauge Invariant **Dimension 7** operators that couple chi with gluons

Lagrangian at the quark/gluon level

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

c_k^q and c_k^g are real *dimensionful* coefficients

c_k^q dim. of $[\text{mass}]^{-2}$

c_k^g dim. of $[\text{mass}]^{-3}$

Main Steps to NR XS

DM particles interact with the nucleus in deeply NR regime

Main Steps to NR XS

DM particles interact with the nucleus in deeply NR regime

STEP I:

dress the quark and gluon currents to the nucleon level

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

L at the nucleon-level

$N = (p, n)$

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

Main Steps to NR XS

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$N=(p,n)$

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

STEP II:

compute the DM-nucleon ME & reduce it to NR Op.

$\langle\chi N|\mathcal{L}_{\rm eff}^N|N\chi\rangle\big|_{q\ll m_\chi}$

DM-nucleon ME

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

Main Steps to NR XS

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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

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

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 XS

DM particles interact with the nucleus in deeply NR regime

STEP I:

dress the quark and gluon currents to the nucleon level

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

J.R. Ellis, A. Ferstl, K.A. Olive, PLB 481 (2000) **304**, [hep-ph/0001005]

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

STEP II:

compute the DM-nucleon ME & reduce it to NR Op.

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

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]

Non-Relativistic Structure

Non-Relativistic Structure

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

Matching onto
NR Interactions

$|\mathcal{M}_N| \propto \mathbb{1}$

Trigger SI contact interaction with different coefficient due quark/gluon currents dressing into N

Non-Relativistic Structure

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

Matching onto NR Interactions $|\mathcal{M}_N| \propto \mathbb{1}$

Trigger SI contact interaction with different coefficient due quark/gluon currents dressing into N

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

Matching onto NR Interactions $|\mathcal{M}_N| \propto \vec{s}_\chi \cdot \vec{s}_N$

Trigger SD contact interaction with different coefficient due quark/gluon currents dressing into N

Non-Relativistic Structure

S-S $c_1^q\, \bar\chi\chi\, \bar q q$ **V-V** $c_5^q\, \bar\chi\gamma^\mu\chi\, \bar q\gamma_\mu q$ **S-GG** $\frac{\alpha_s}{12\pi} c_1^g\, \bar\chi\chi\, G^a_{\mu\nu}G_a^{\mu\nu}$	Matching onto NR Interactions	$\lvert\mathcal{M}_N\rvert \propto \mathbb{1}$	Trigger SI contact interaction with different coefficient due quark/gluon currents dressing into N
AV-AV $c_8^q\, \bar\chi\gamma^\mu\gamma^5\chi\, \bar q\gamma_\mu\gamma^5 q$ **T-T** $c_9^q\, \bar\chi\sigma^{\mu\nu}\chi\, \bar q\sigma_{\mu\nu} q$	Matching onto NR Interactions	$\lvert\mathcal{M}_N\rvert \propto \vec{s}_\chi \cdot \vec{s}_N$	Trigger SD contact interaction with different coefficient due quark/gluon currents dressing into N
PS-PS $c_4^q\, \bar\chi\gamma^5\chi\, \bar q\gamma^5 q$ **PS-GG** $\frac{\alpha_s}{12\pi} c_4^g\, \bar\chi\gamma^5\chi G^a_{\mu\nu}\tilde{G}_a^{\mu\nu}$	Matching onto NR Interactions	$\lvert\mathcal{M}_N\rvert \propto (\vec{s}_\chi \cdot \vec{q})(\vec{s}_N \cdot \vec{q})$	Trigger longitudinal SD interaction suppressed by $q^4/(m_N^2 m_\chi^2)$

Non-Relativistic Structure

S-S $c_1^q\,\bar\chi\chi\,\bar q q$

V-V $c_5^q\,\bar\chi\gamma^\mu\chi\,\bar q\gamma_\mu q$

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

Matching onto NR Interactions $|\mathcal{M}_N| \propto \mathbb{1}$

Trigger SI contact interaction with different coefficient due quark/gluon currents dressing into N

AV-AV $c_8^q\,\bar\chi\gamma^\mu\gamma^5\chi\,\bar q\gamma_\mu\gamma^5 q$

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

Matching onto NR Interactions $|\mathcal{M}_N| \propto \vec{s}_\chi\cdot\vec{s}_N$

Trigger SD contact interaction with different coefficient due quark/gluon currents dressing into N

PS-PS $c_4^q\,\bar\chi\gamma^5\chi\,\bar q\gamma^5 q$

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

Matching onto NR Interactions $|\mathcal{M}_N| \propto (\vec{s}_\chi\cdot\vec{q})(\vec{s}_N\cdot\vec{q})$

Trigger longitudinal SD interaction suppressed by $q^4/(m_N^2 m_\chi^2)$

The other 7 parity violating Operators

Matching onto NR Interactions

Trigger SD or SI interactions suppressed by $(q^2/(m_{N,\chi}^2), v^2)$

Non-Relativistic Structure

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

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

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

DD Experiments are:
maximally sensitive to SI interactions

Trigger SI contact interaction with different coefficient due quark/gluon currents dressing into N

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

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

DD Experiments are:
sensitive to SD interactions if the target nucleus has unpaired N

Trigger SD contact interaction with different coefficient due quark/gluon currents dressing into N

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

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

DD Experiments are:
poorly sensitive since the XS is very suppressed

Trigger longitudinal SD interaction suppressed by $q^4/(m_N^2 m_\chi^2)$

The other 7 parity violating Operators

DD Experiments are:
not very sensitive since the XS is suppressed

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

Draw Bounds (simple method)

A **simple method** to derive bounds on the energy scale of the operators is to assume the idealized case in which **only one operator** is generated 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

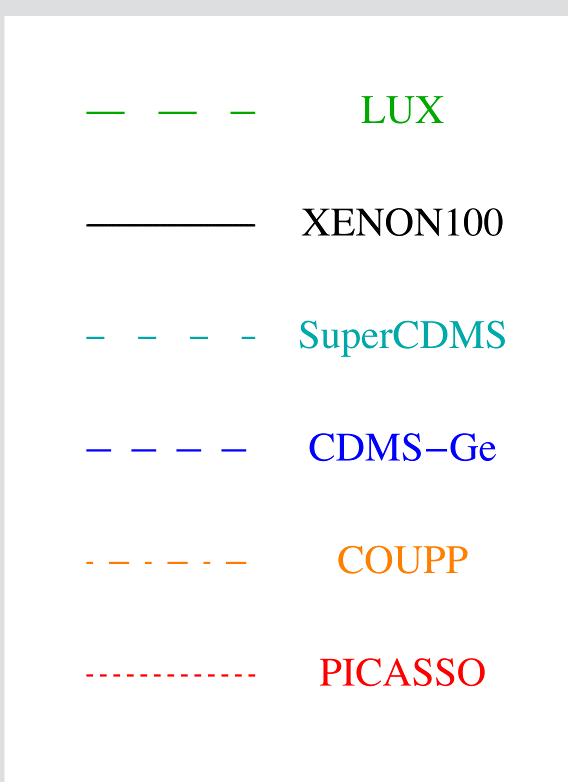
$$c_i^q = \frac{1}{\Lambda^2}$$

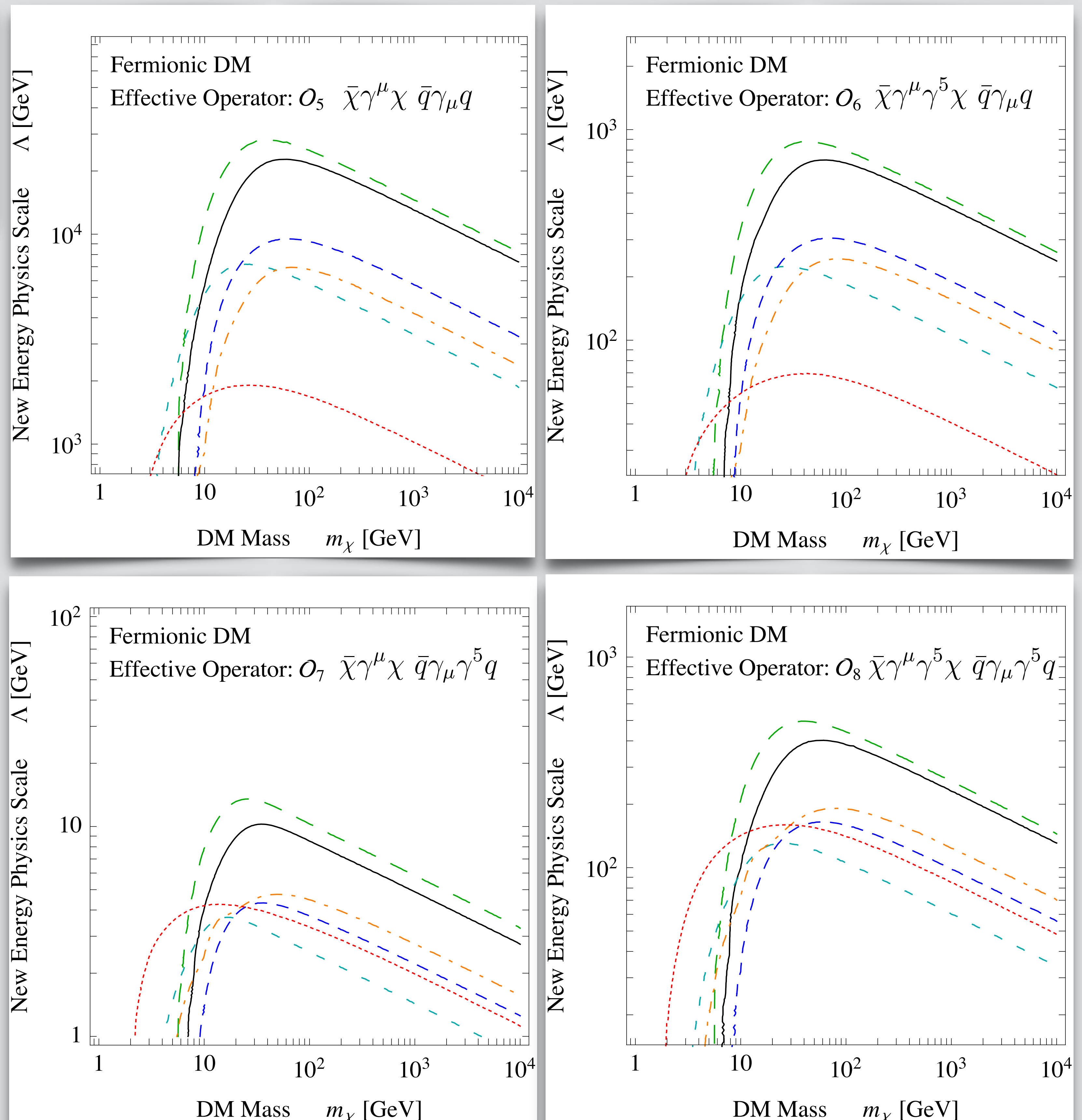
$\mathcal{O}_5^q$ **: SI Int.**

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

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

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





Direct Detection Tools

Direct detection of DM particles:

We provide tools for deriving bounds for DM-nucleus elastic collisions in a model independent way

"Tools for model independent bounds in Direct DM Searches", JCAP 1103 (2011) **051**

The tools are provided in numerical form in this webpage:

more than 100 papers used our tools !!

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 $Y_{ij}^{\mathrm{lr}(N,N')}$ (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 rel. EFT

Limitations of rel. EFT

☑ **UV Complete Models:** predict different high-energy operators enter together with the Wilson coefficients that are related in a non-trivial way

Limitations of rel. EFT

☑ **UV Complete Models:** predict different high-energy operators enter together with the Wilson coefficients that are related in a non-trivial way

☑

Energy scale

$M_{\rm med}$

Many orders of magnitude

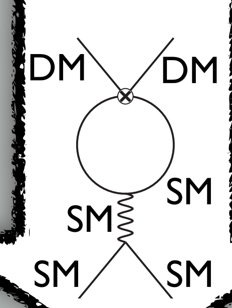
μ_N

DD Experiments

EFT for DM interactions with SM particles

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

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



Renormalization Group Evolution (RGE)

$c_\alpha^{(d)}(\mu_N)$

coupling at the nuclear energy scale $\mu_N \simeq 1$ GeV

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

Running in Direct Detection

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]

Energy scale

$M_{\rm med}$

Many orders of magnitude

μ_N

DD Experiments

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

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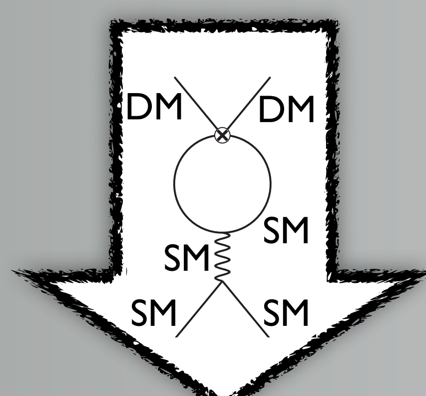

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Why is RGE Relevant?

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]

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

Why is RGE Relevant?

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

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

RGE Effects:

- change the size of the effective couplings

- can generate operator mixing at low energy

DM-nucleus collisions:

- only sensitive to light degrees of freedom (light quarks and gluons)

- scattering cross sections particularly sensitive to the Lorentz structure of the high-energy effective operators

Why is RGE Relevant?

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]

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

RGE Effects:

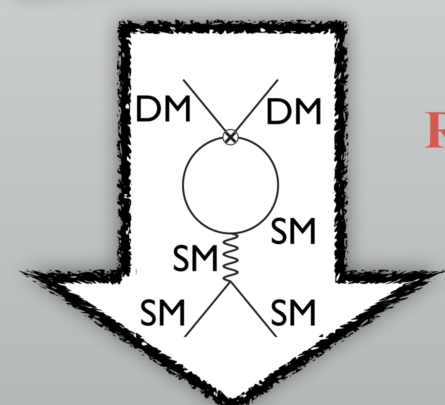
- change the size of the effective couplings

- can generate operator mixing at low energy

Energy scale

$M_{\rm med}$

Suppressed interactions between DM and SM



Renormalization Group Evolution (RGE)

μ_N

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

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

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

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

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

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

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 detail of the UV theory

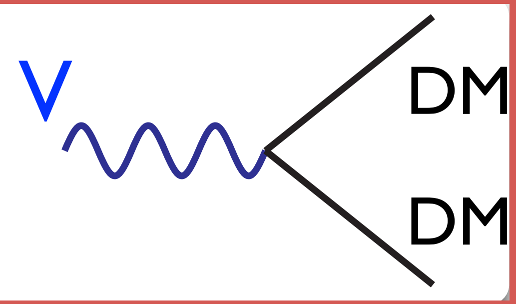
Vector mediator

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

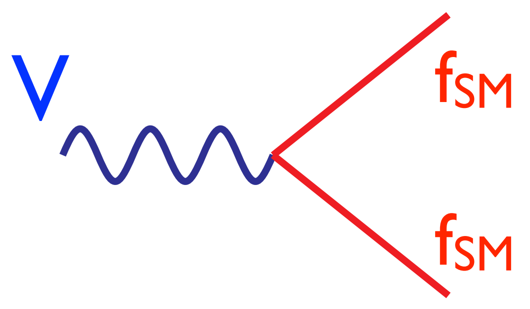
SIMPLIFIED MODEL

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

mediator coupled with spin 1 currents of SM fermions

$$J^\mu_{\rm SM} = \sum_{i=1}^{3} \left[c_q^{(i)}\, \overline{q^i_L} \gamma^\mu q^i_L + c_u^{(i)}\, \overline{u^i_R} \gamma^\mu u^i_R + c_d^{(i)}\, \overline{d^i_R} \gamma^\mu d^i_R + c_l^{(i)}\, \overline{l^i_L} \gamma^\mu l^i_L + c_e^{(i)}\, \overline{e^i_R} \gamma^\mu e^i_R \right]$$

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



Main Steps to NR XS

DM particles interact with the nucleus in deeply NR regime

STEP III:

DM-nucleus ME

EFT for DM interactions with quarks and gluons

Matching onto NR Interactions

DM-nucleus XS

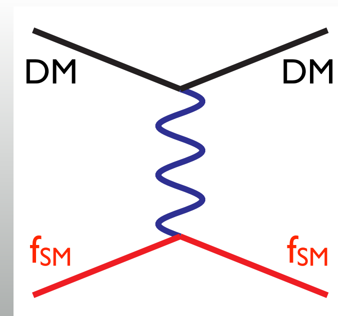
$$\frac{d\sigma}{dE_{\mathrm{R}}} \propto \sum_{i,j} \sum_{N,N'=p,n} \mathfrak{c}_i^N \mathfrak{c}_j^{N'} F_{i,j}^{(N,N')}$$

Main Steps to NR XS

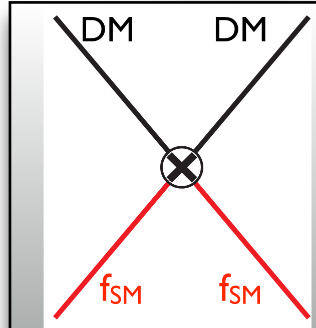
DM particles interact with the nucleus in deeply NR regime

STEP I:

integrate-out the mediator



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



EFT:
DM contact interactions

STEP III:

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EFT for DM interactions with quarks and gluons

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Main Steps to NR XS

DM particles interact with the nucleus in deeply NR regime

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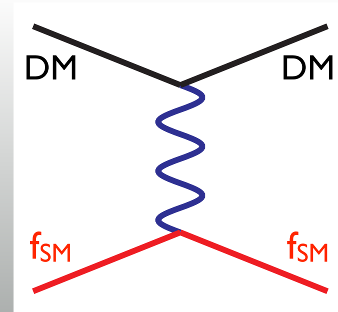

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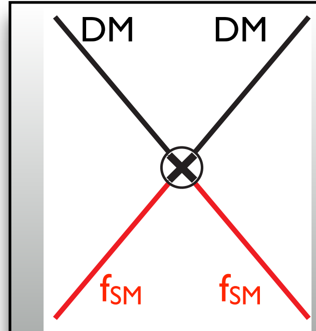
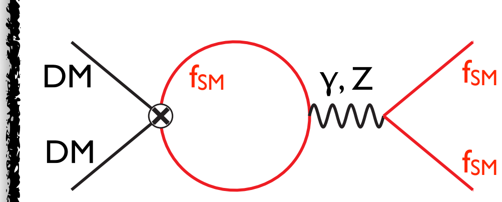


EFT:
DM contact interactions

STEP II:

connecting energy scale

EFT:
couplings at the mediator mass



Nuclear scale:

- size couplings changed
- new interactions are generated (mixing)

STEP III:

DM-nucleus ME

EFT for DM interactions with quarks and gluons

Matching onto NR Interactions

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 XS

DM particles interact with the nucleus in 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]

STEP III:

DM-nucleus ME

EFT for DM interactions with quarks and gluons

Matching onto NR Interactions

DM-nucleus XS

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

RG Effects

The RGE induces currents with light quarks

RG Effects

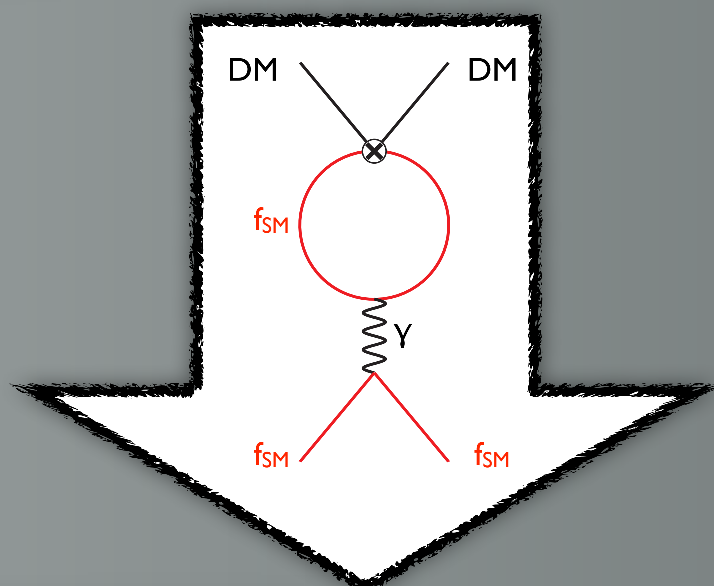
The RGE induces currents with light quarks

Energy scale

$M_{\rm med}$

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

approximate solution



important if V is not couple with light quarks (e.g. leptons or heavy quarks)

Otherwise O(1%) corrections

μ_N

RGE induces **vector current** of light quarks

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

RG Effects

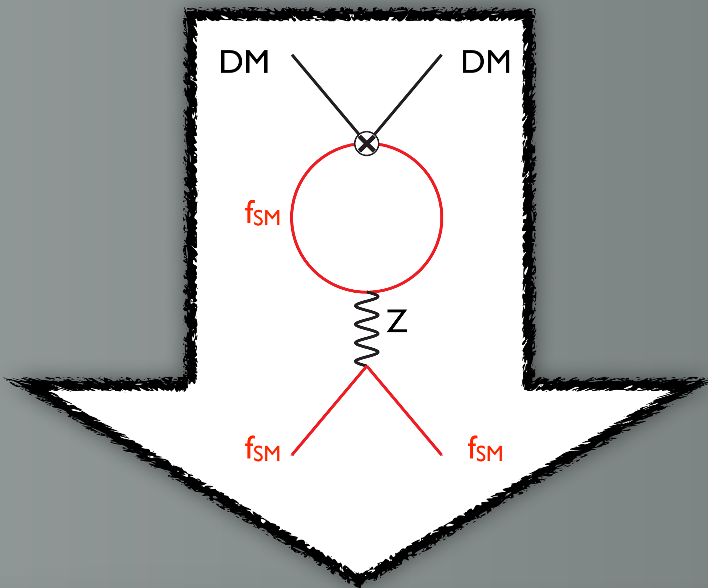
The RGE induces currents with light quarks

Energy scale

M_{med}

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

approximate solution



phenomenologically very important (operator mixing)

Dominated by heavy SM fermions (prop. to Yukawa)

μ_N

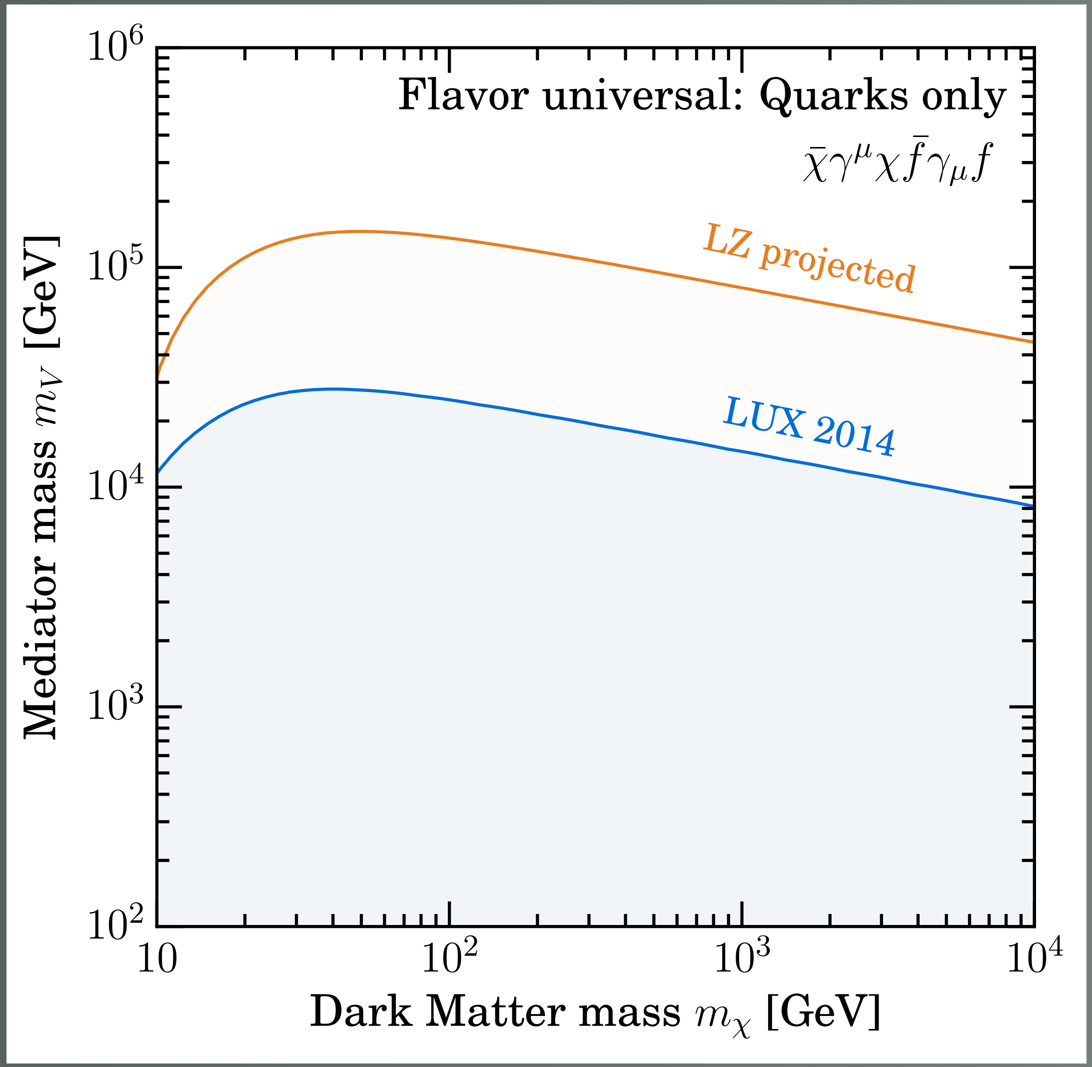
RGE induces **vector** & **axial currents** of light quarks

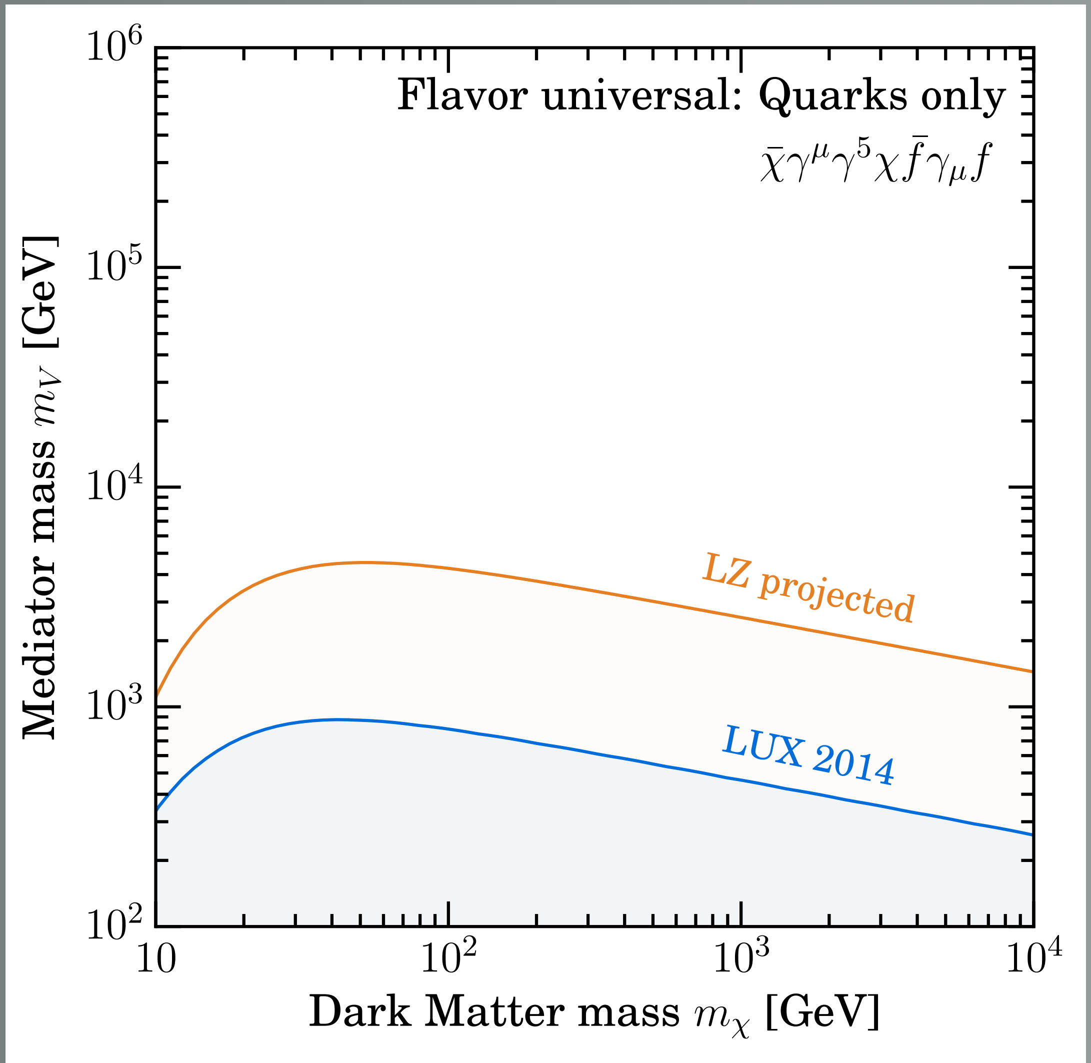
$$\Delta c_{V,A} \simeq \frac{\lambda_f^2}{16\pi^2} \ln(m_V/\mu_N)$$

Some Results: Quark Vector

mediator with FU couplings the V current of quarks

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



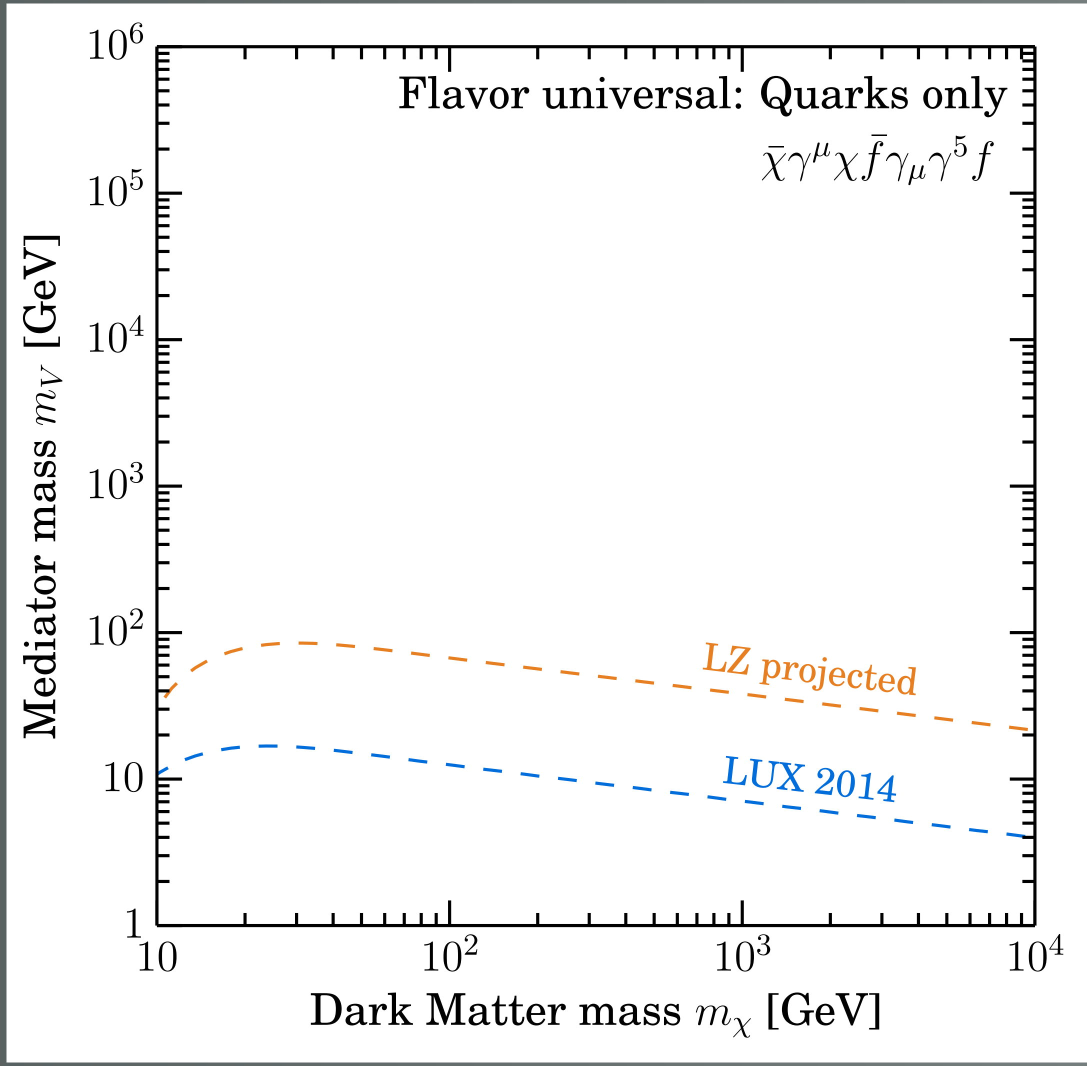


RGE driven by loops of electromagnetic currents (**no mixing**)

Some Results: Quark Axial

mediator with FU couplings the AV current of quarks

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



RGE effects drive by Yukawa couplings alter the rate (**mixing**)

Some Results: Quark Axial

mediator with FU couplings the AV current of quarks

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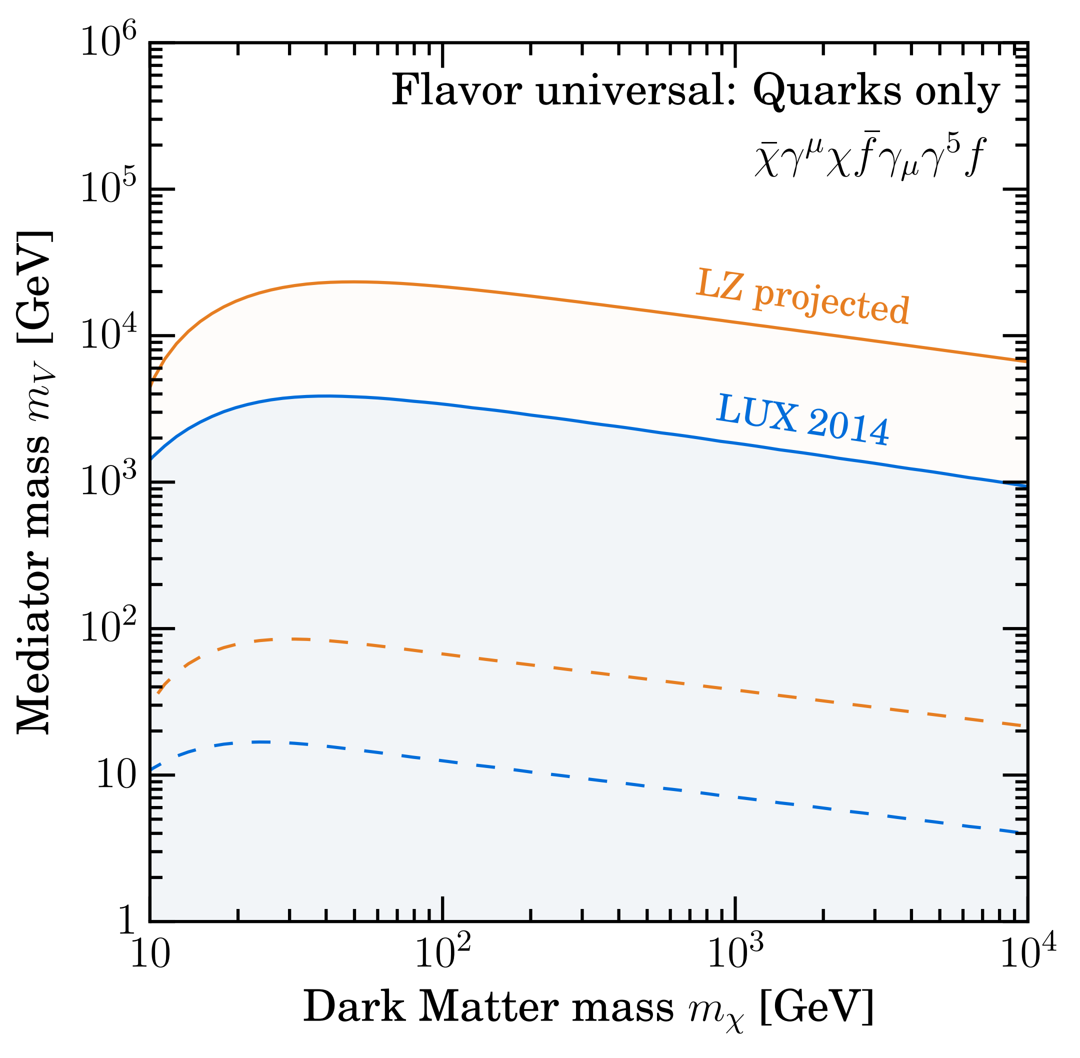

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mediator with FU couplings the AV current of quarks

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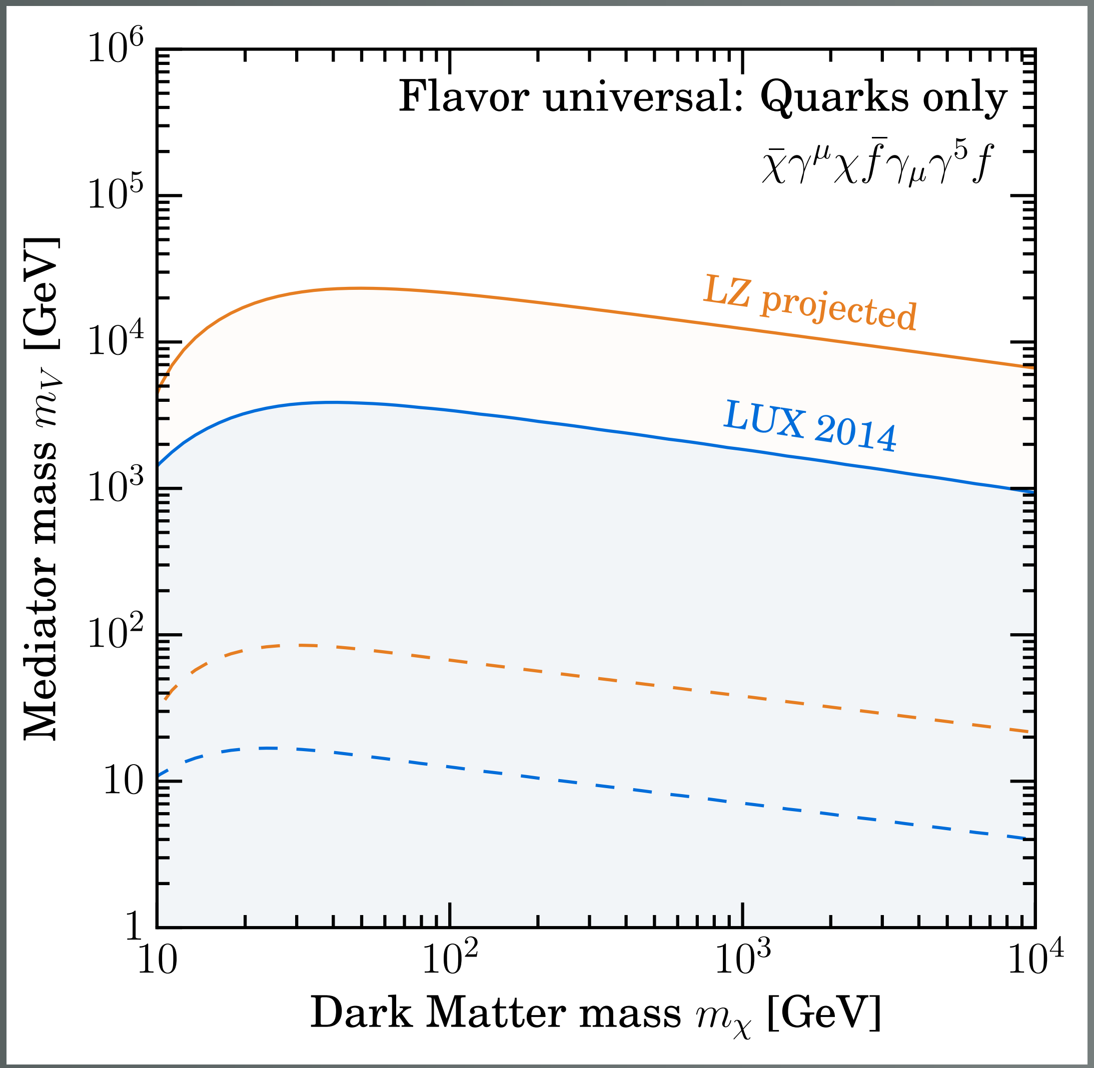

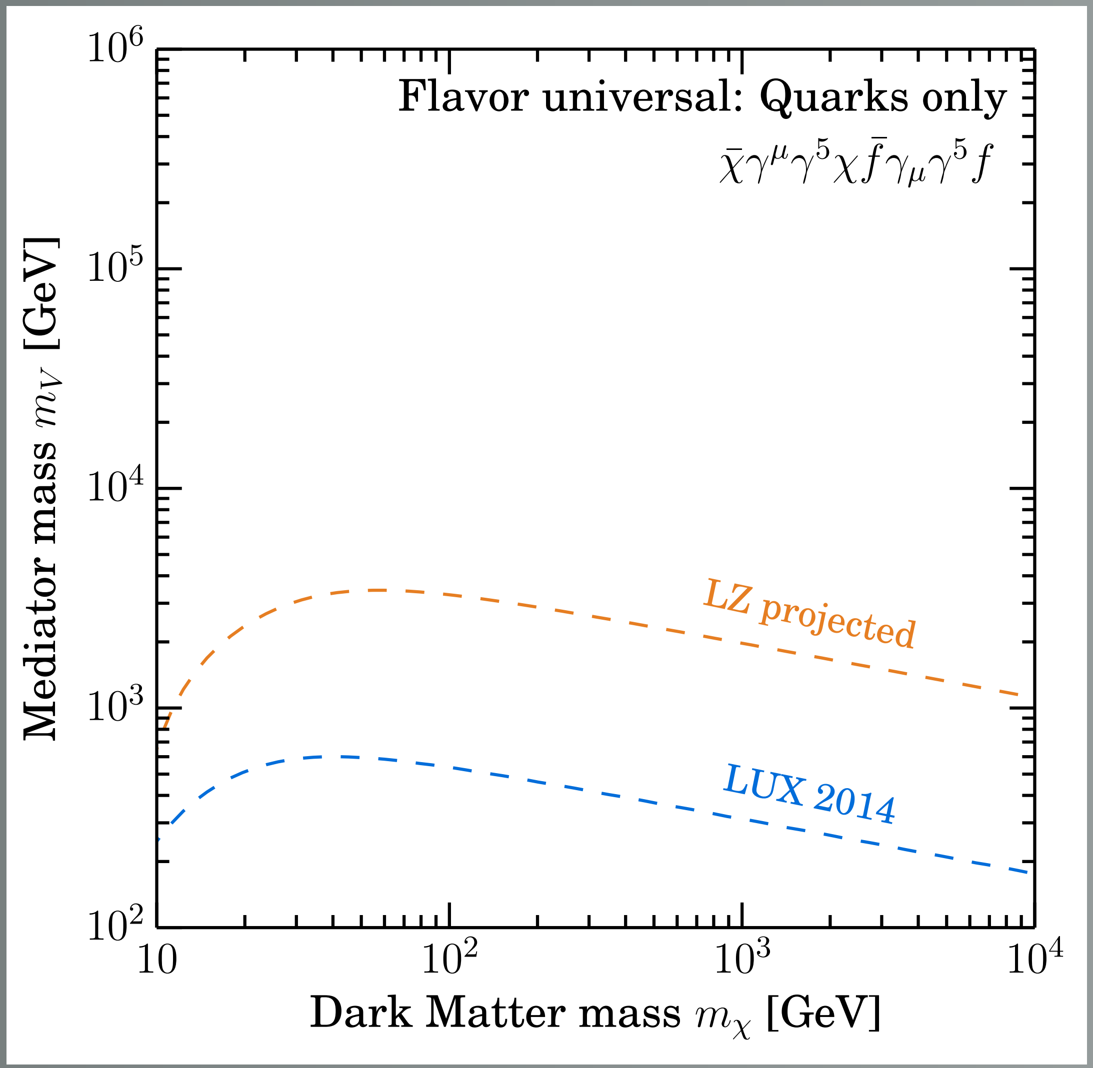

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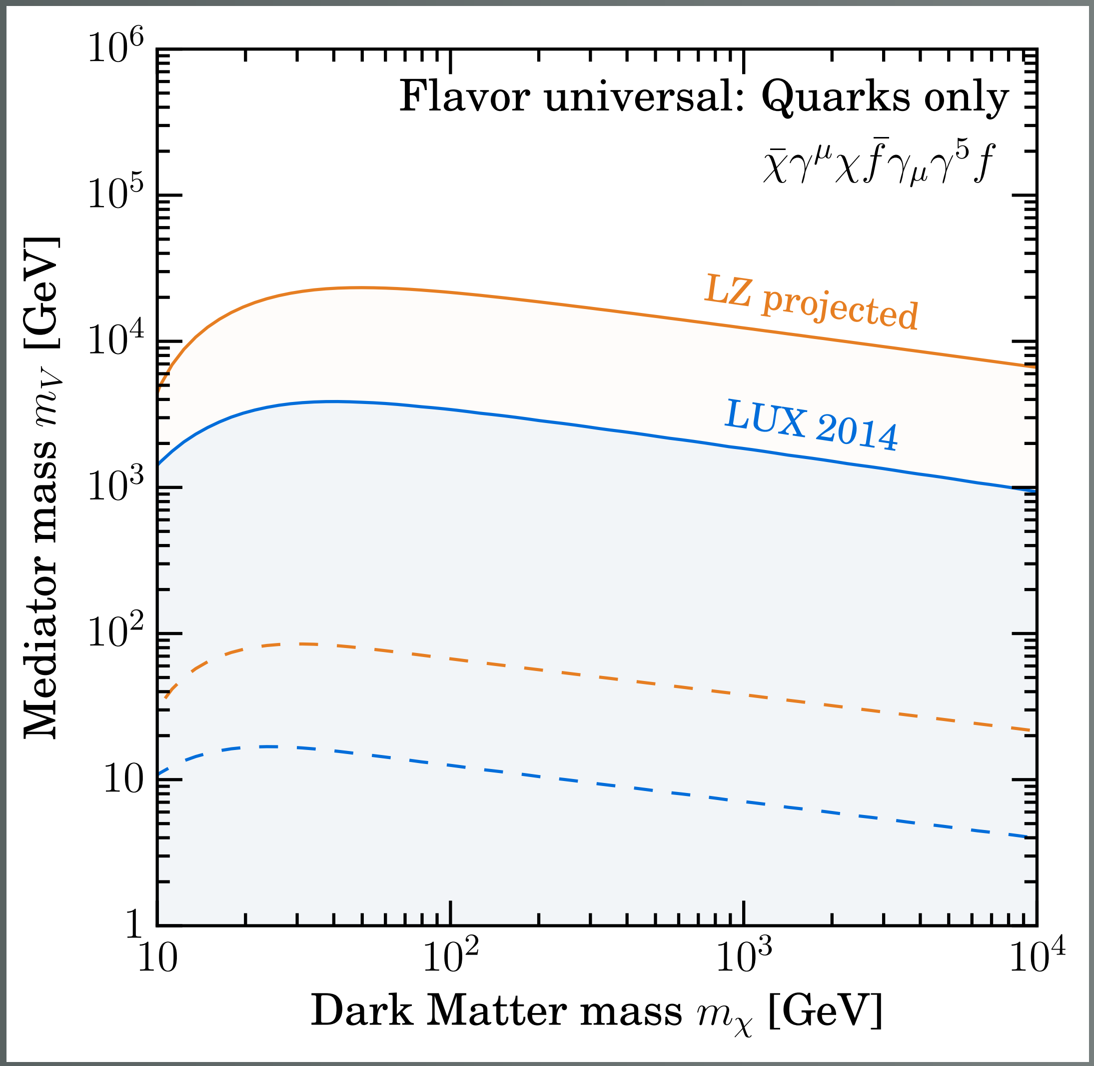
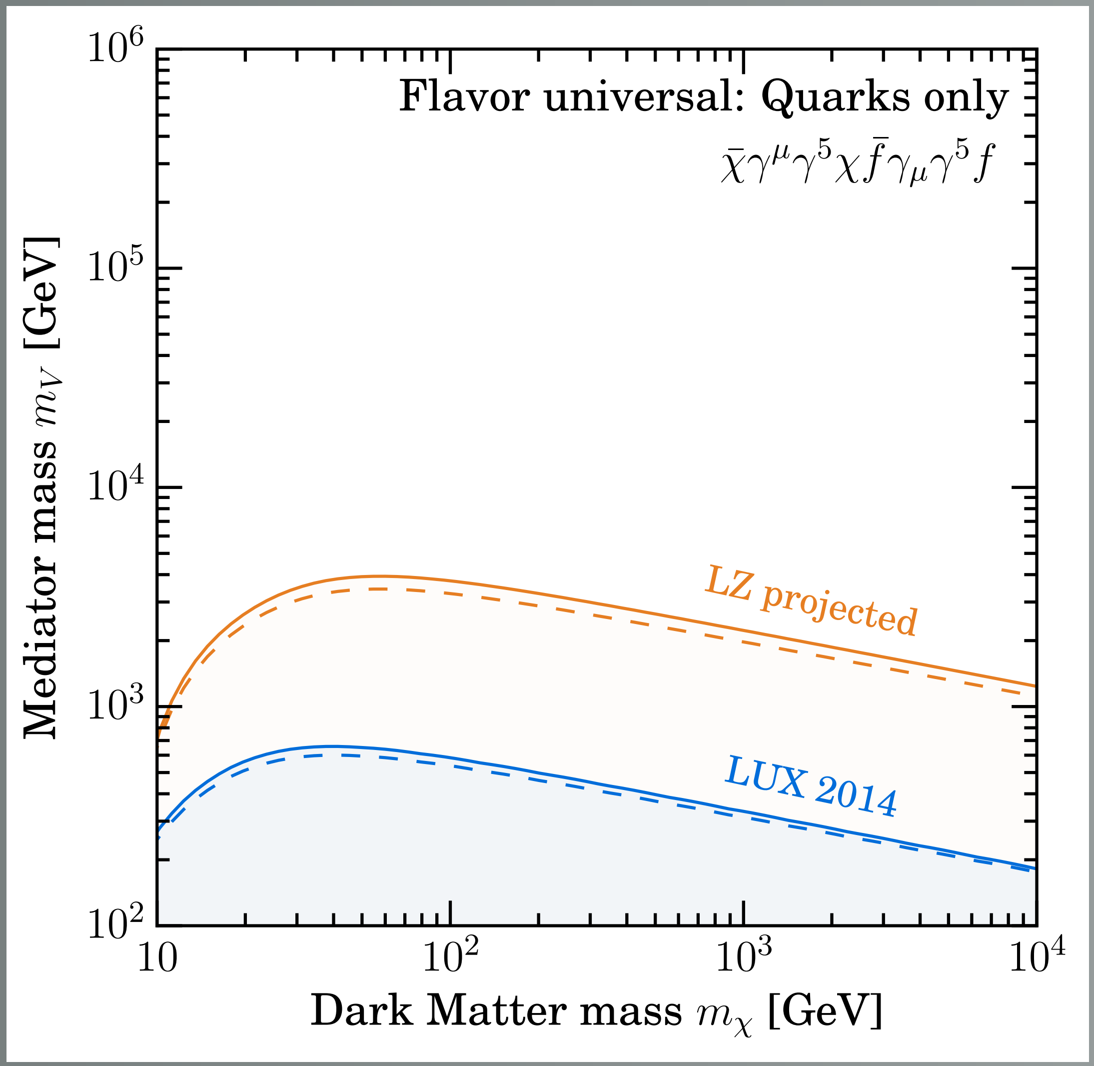




RGE effects drive by Yukawa couplings alter the rate (**mixing**)

runDM: general RGE

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

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.

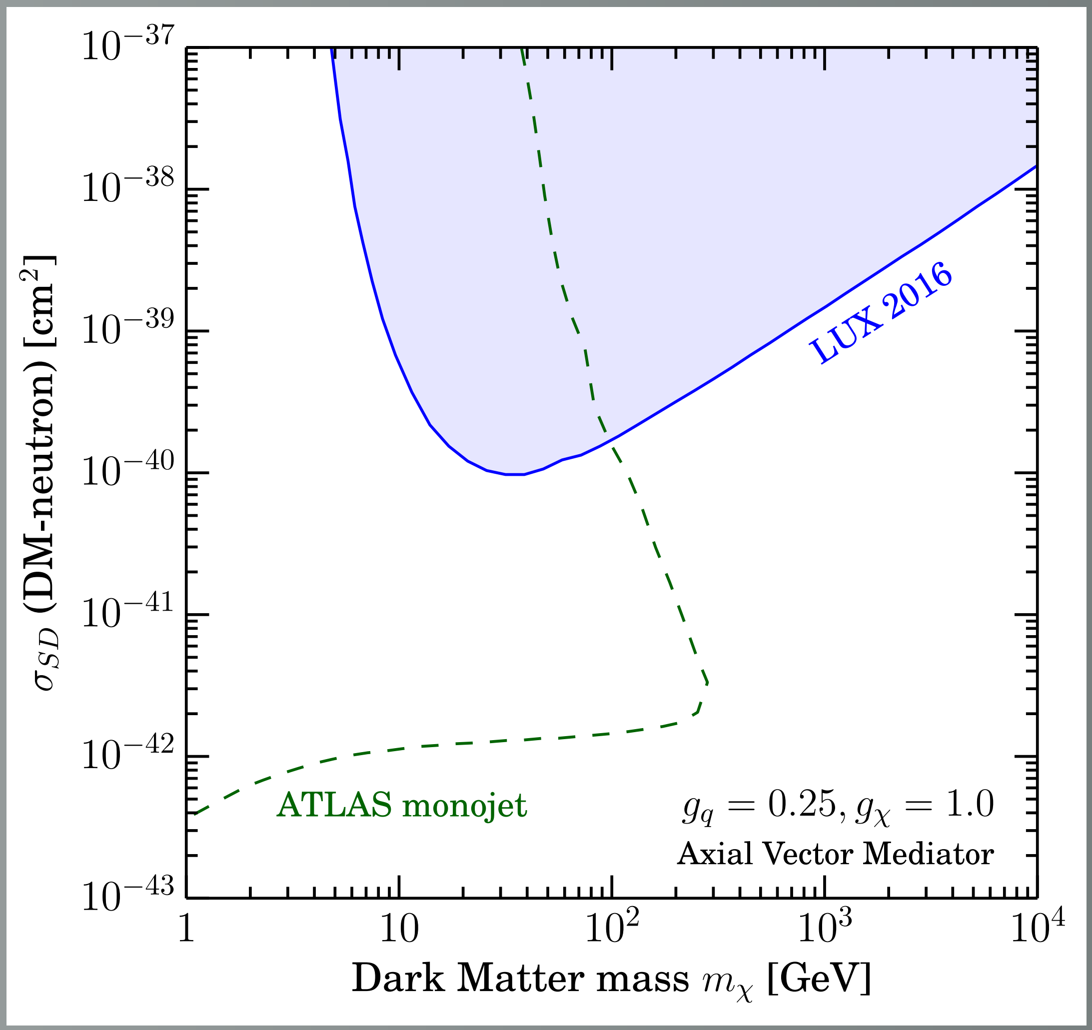
If you make use of `runDM` in your own work, please cite it as:

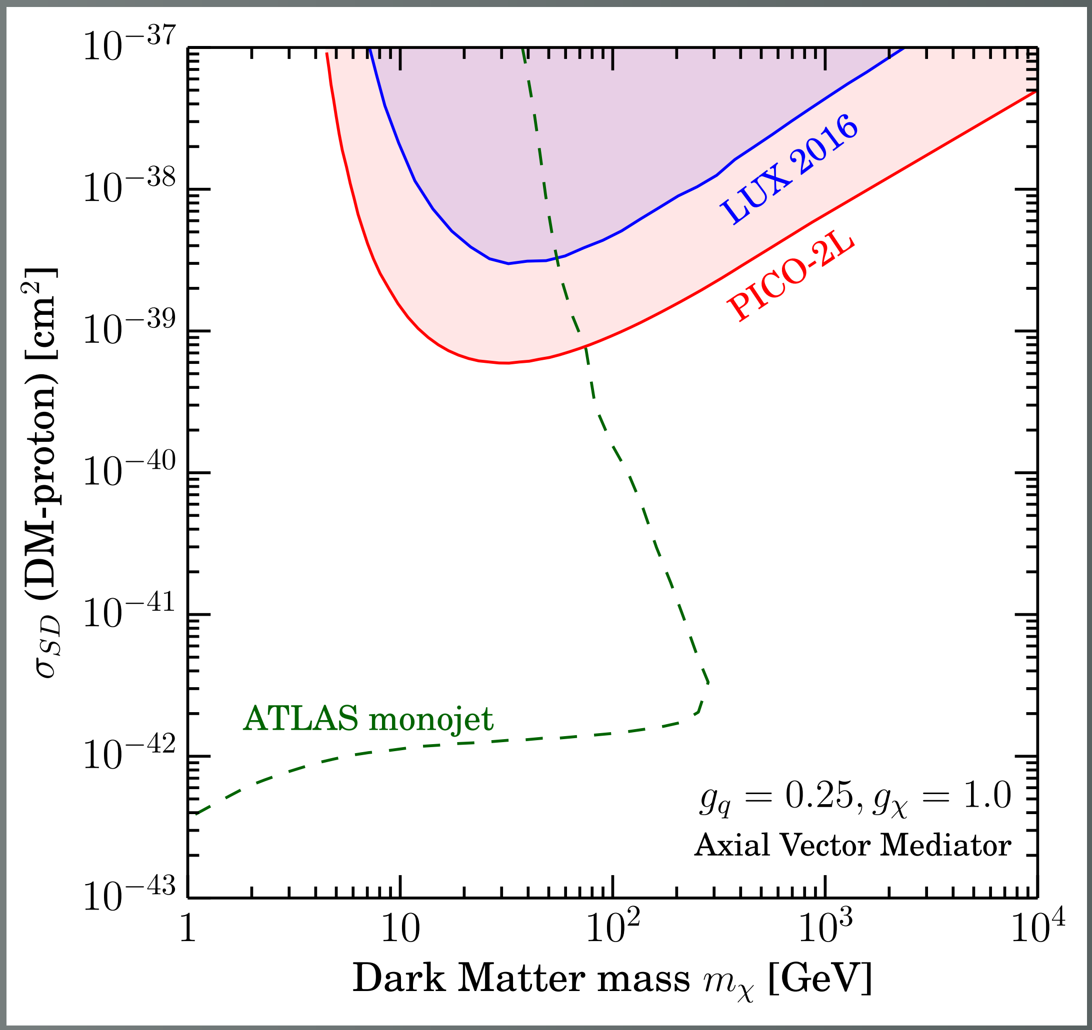
> F. D'Eramo, B. J. Kavanagh & P. Panci (2016). runDM (Version X.X) [Computer software]. Available at https://github.com/bradkav/runDM/

Exhaustive study for other cases in: F. D'Eramo, B. J. Kavanagh, P. Panci, JHEP 1608 (2016) **111**, [arXiv: 1605.04917]

DD vs LHC (Axial-Axial)

LHC phenomenology and complementary with Direct searches





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

LUX, [arXiv: 1602.03489]
PICO-2L, [arXiv: 1601.03729]
ATLAS, [arXiv: 1604.01306]

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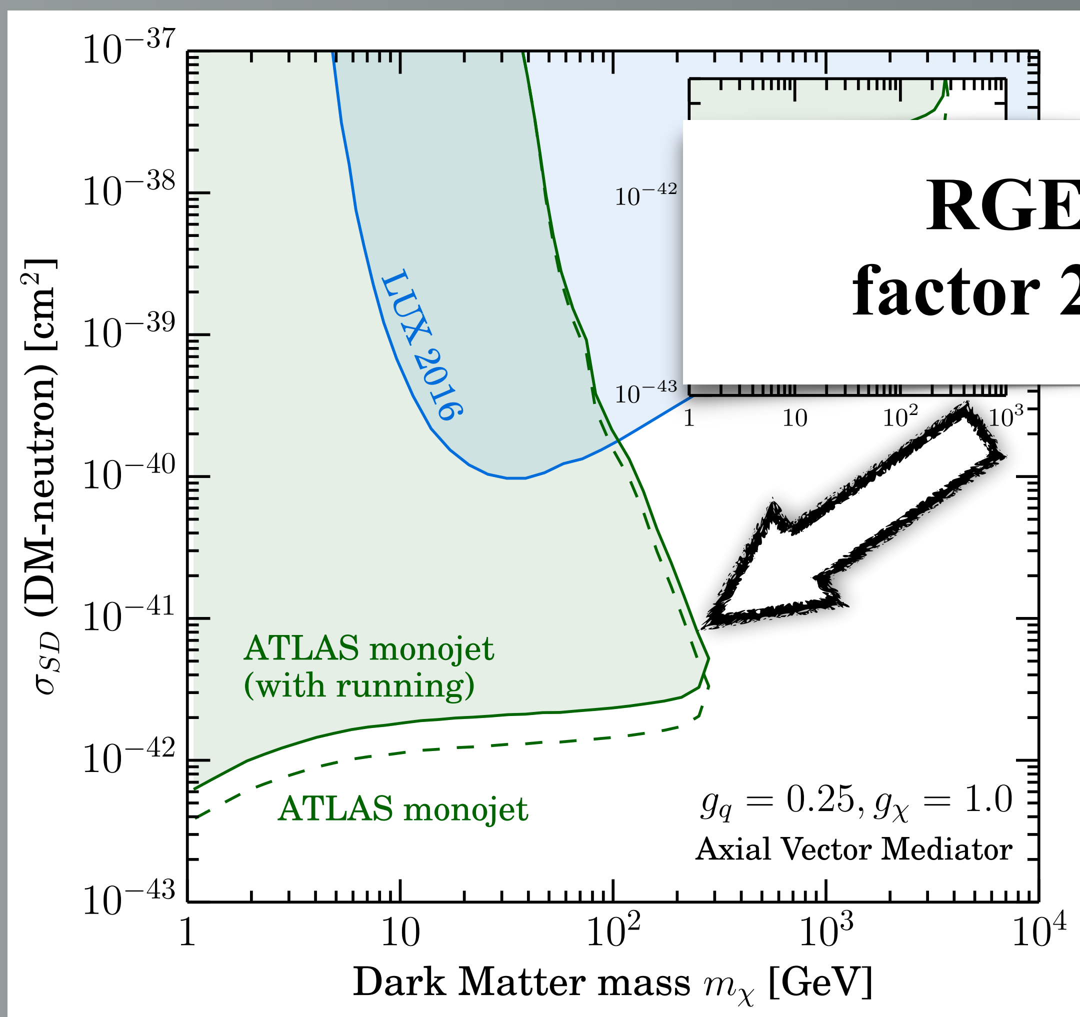

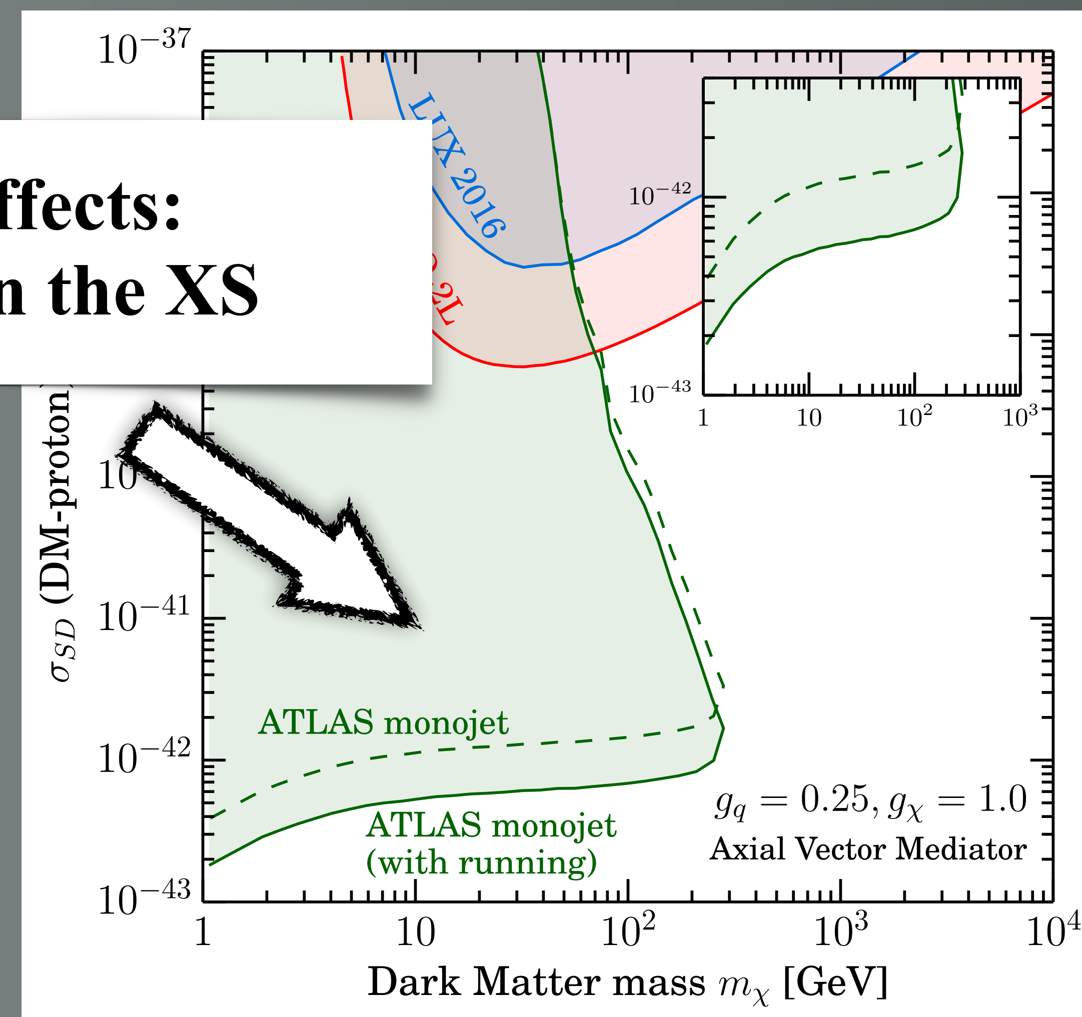

RGE effects:
factor 2 in the XS

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

LUX, [arXiv: 1602.03489]
PICO-2L, [arXiv: 1601.03729]
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Direct Detection: Conclusions

Review of the formalism of NR interactions

the rate can be parametrized in terms of **nuclear response functions**

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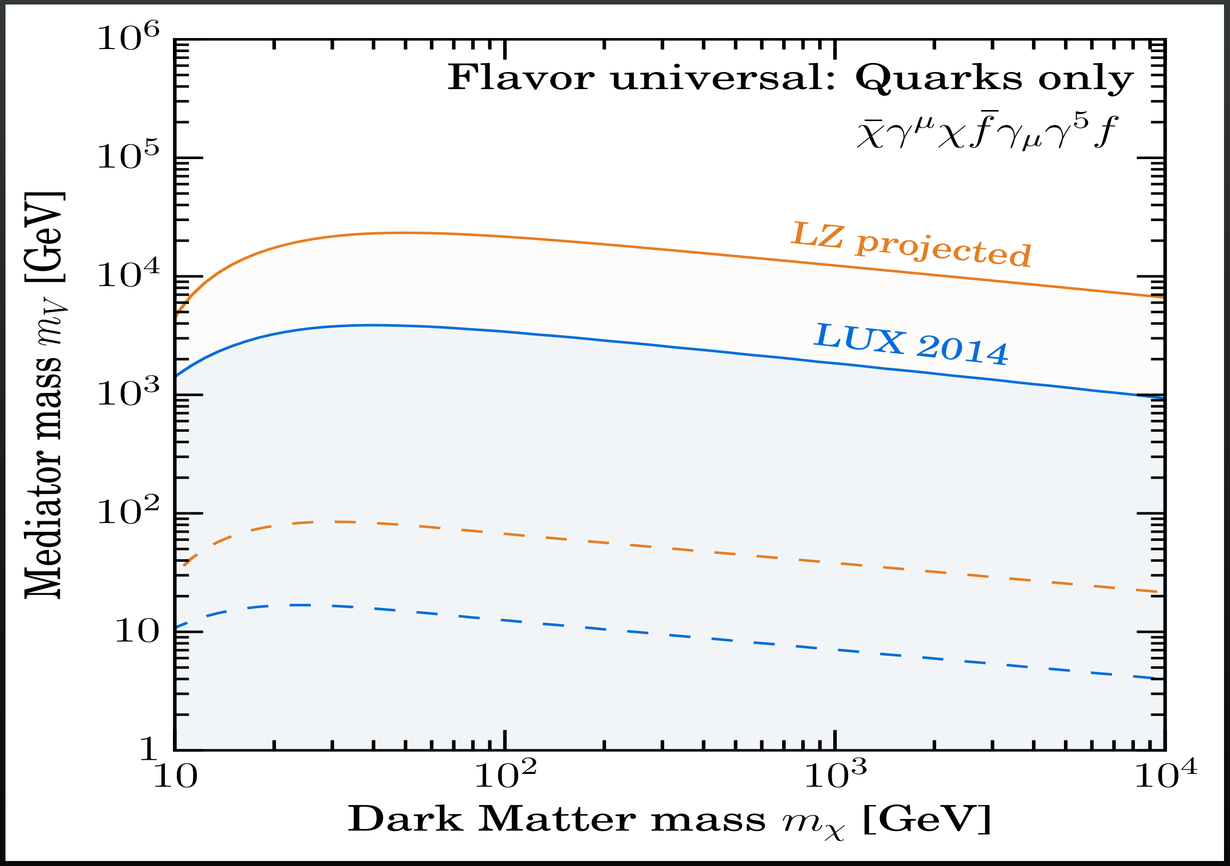
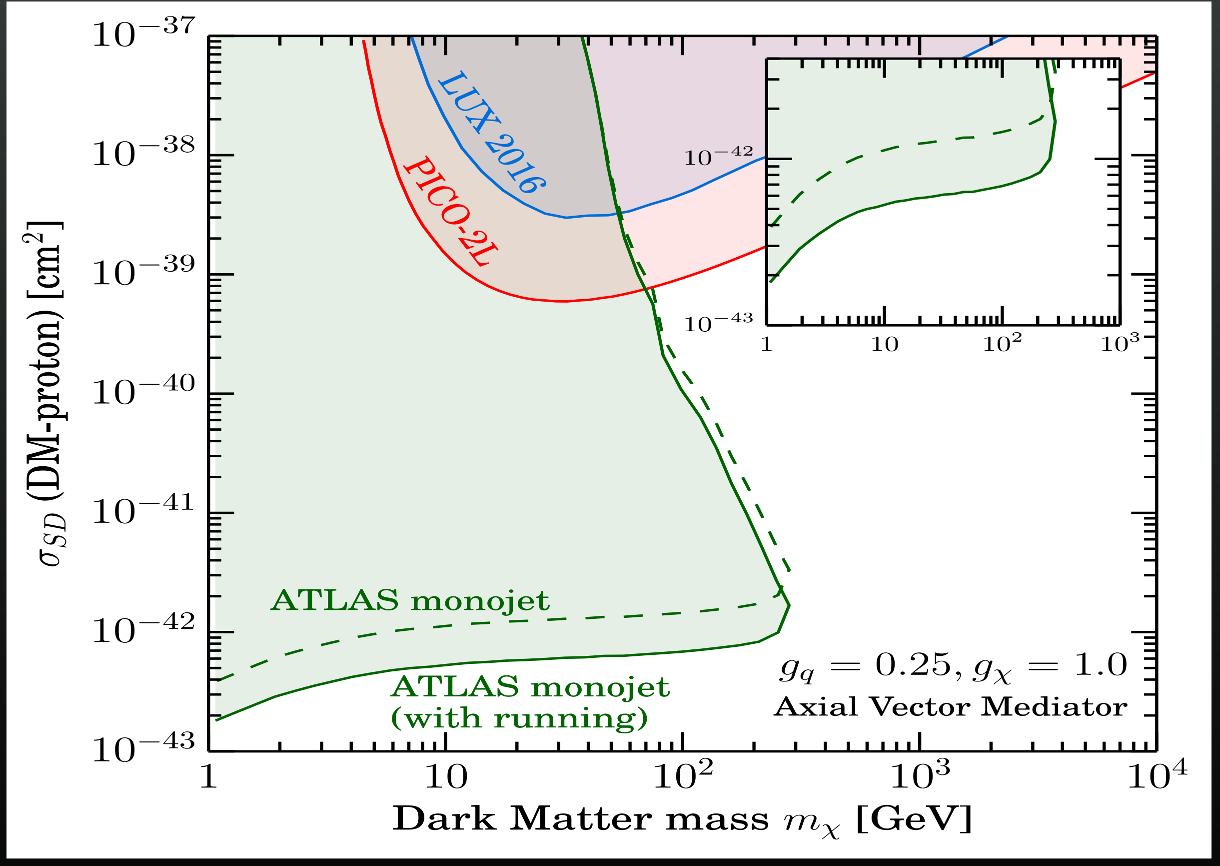
You can hide but you have to run !!





suppressed ops. give unsuppressed interactions

The RGE is important to explore complementarity

Back up slides

NR Matching

Typical Dimension-6 Interactions

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

Galileian Invariant Operators

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

NR dependences of the fermion bilinear

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

Match to NR operators

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

“Tools for model-independent bounds in direct DM searches”, JCAP 1310 (2013) **019**

Draw Bounds (S & PS)

Higgs-like couplings

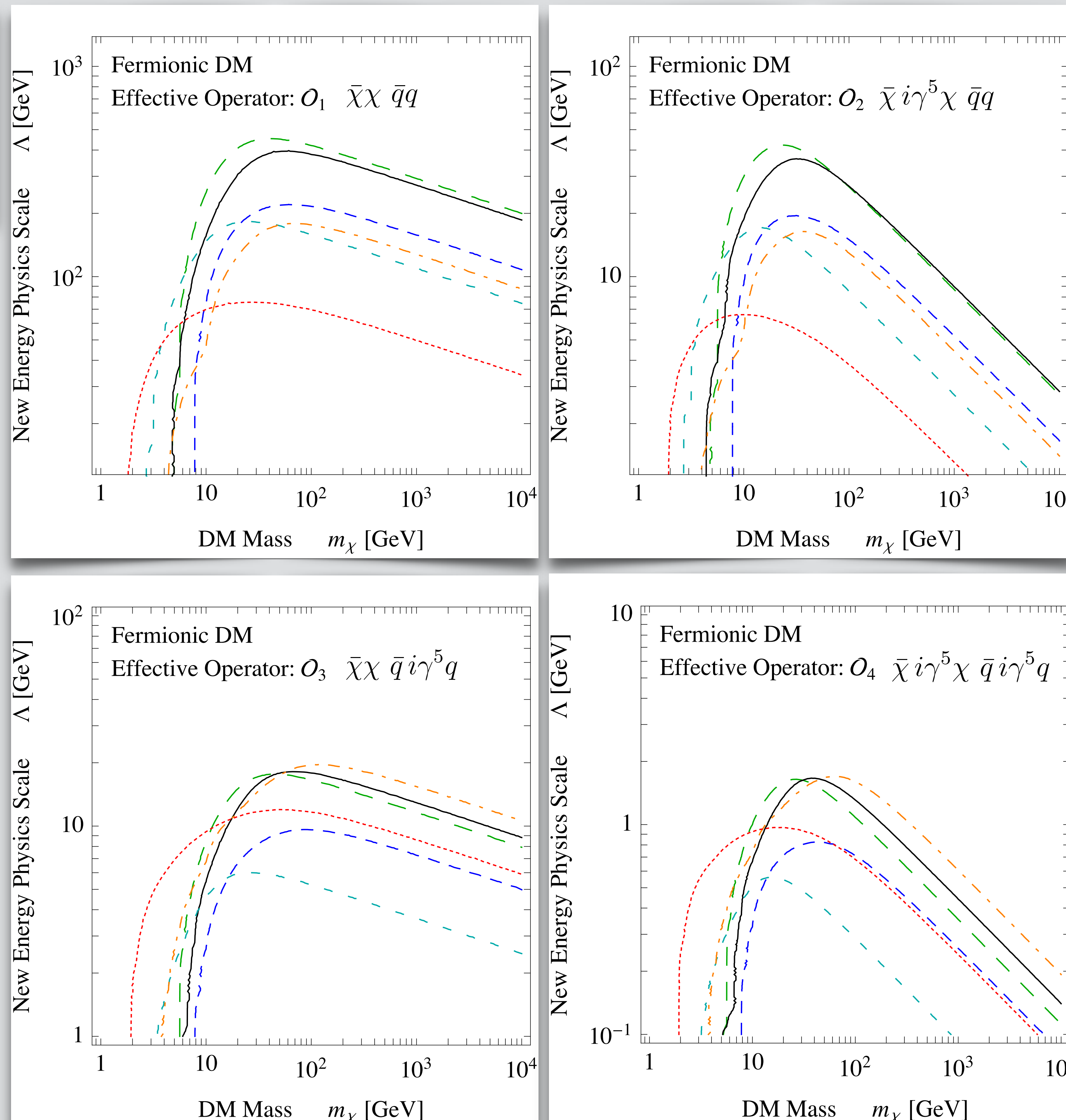
$$c_i^q = \frac{m_q}{\Lambda^3}$$

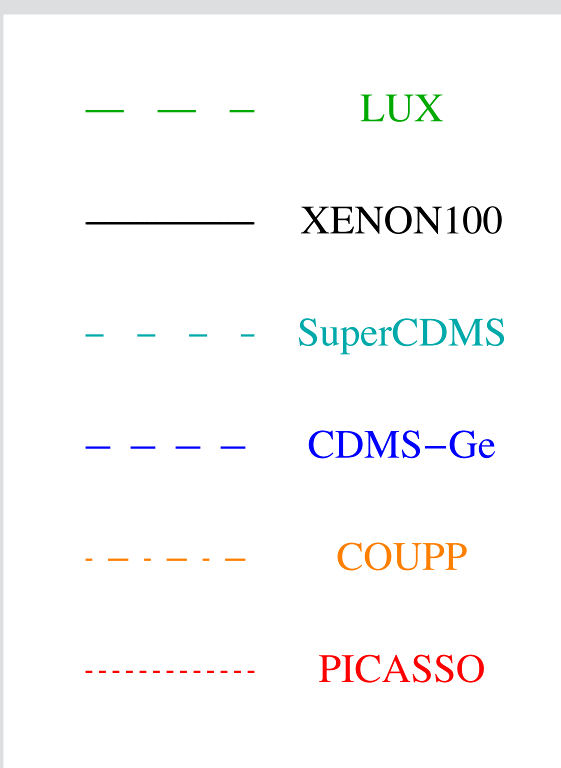
$\mathcal{O}_1^q$ **: SI Int.**

$\mathcal{O}_2^q$ **:** 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.**





DAMA?

Relativistic interaction

Relativistic Lagrangian at the quark level

$$\mathcal{L}_{\rm int} = -i\frac{g_{\rm DM}}{\sqrt{2}} a\,\bar{\chi}\gamma_5\chi - ig\sum_f \frac{g_f}{\sqrt{2}} a\,\bar{f}\gamma_5 f\,.$$

Particle Content:

χ : DM fermion with mass $m_{\rm DM}$

f : SM fermion with mass m_f

a : pseudo-scalar mediator with mass m_a

Couplings at the quark level

$g_{\rm DM}$: **DM coupling with the mediator**

$g\,g_f$: **SM fermion coupling with the mediator**

flavor-universal:
$g_f = 1$

independent on the fermion type

higgs-like:
$g_f = m_f/v_{\rm H}$

proportional to the fermion mass

"isoscalar" coupling:
$g_p = g_n$

see e.g. arXiv:1401.3739

BUT !!

for pseudo-scalar current this is
not a natural choice

Computing the XS

Relativistic Lagrangian at the quark level

$$\mathcal{L}_{\rm int} = -i\frac{g_{\rm DM}}{\sqrt{2}} a\,\bar{\chi}\gamma_5\chi - ig\sum_f \frac{g_f}{\sqrt{2}} a\,\bar{f}\gamma_5 f\,.$$

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Main Steps from the Relativistic Lagrangian to DD Rate

In DD, the DM particles interact with the entire nucleus in deeply NR regime:

- ☑ Dress up the quark-operators to the nucleon level
- ☑ Write down the DM-nucleon effective Lagrangian
- ☑ Reduce to NR limit in order to infer the NR operator and its coefficient
- ☑ Account for the composite structure of the nucleus with the nuclear responses

DM-nucleon Lagrangian

Effective Lagrangian for contact interaction

$$\mathcal{L}_{\rm eff} = \frac{1}{2\Lambda_a^2} \sum_{N=p,n} g_N \, \bar{\chi}\gamma^5\chi \, \bar{N}\gamma^5 N \,,$$

Energy Scale of the effective Lagrangian

$\Lambda_a = m_a/\sqrt{g\, g_{\rm DM}}$:

combination of the free parameters of the model (mediator mass and couplings)

DM-nucleon effective couplings

$$g_N = \sum_{q=u,d,s} \frac{m_N}{m_q}\left[g_q - \sum_{q'=u,\ldots,t} g_{q'}\frac{\bar{m}}{m_{q'}}\right]\Delta_q^{(N)}$$

Quark spin content of the nucleons

$$\Delta_u^{(p)} = \Delta_d^{(n)} = +0.84$$
$$\Delta_d^{(p)} = \Delta_u^{(n)} = -0.44$$
$$\Delta_s^{(p)} = \Delta_s^{(n)} = -0.03$$

H.-Y. Cheng and C.-W. Chiang, JHEP 1207 (2012) **009**

DM-nucleon Lagrangian

Effective Lagrangian for contact interaction

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"Natural" Isospin Violation

$g_p/g_n = -16.4$: flavor-universal couplings

$g_p/g_n = -4.1$: higgs-like couplings

large isospin violation going from the quark level to the nucleon one

Gross, Treiman, Wilczek, Phys. Rev. **D19** 2188, (1979)

Important consequences in DD

the pseudo-scalar interaction *measures a certain component of the spin* content of the nucleus *carried by the nucleons*.

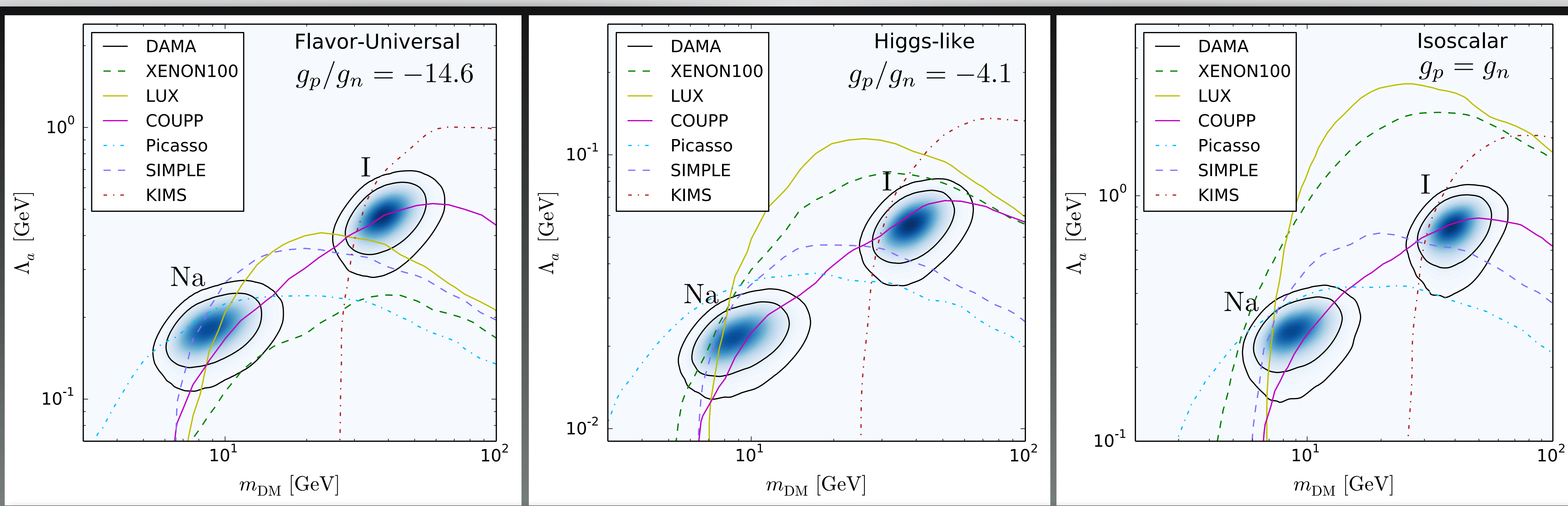
a large g_p/g_n will favor nuclides with a large spin due to their *unpaired proton*

(e.g. DAMA employs sodium & iodine)

nuclides with *unpaired neutron* will be largely disfavored

(e.g. XENON100 and LUX employ xenon)

Longitudinal SD interaction



"Not so Coy DM explains DAMA (and the GC excess)", Phys.Rev.Lett. 114 (2015) **011301**

Bottom line: the large enhancement of the ***DM-p coupling*** with respect to the ***DM-n coupling*** suppresses the LUX and XENON100 bounds

End