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Model Independent Bounds in Direct DM Searches

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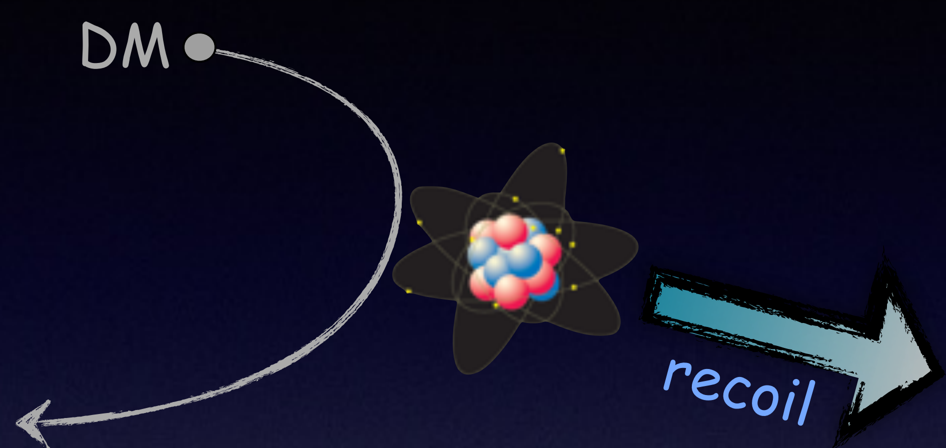
based on:
P.Panci,
Review in Adv.High Energy.Phys. [arXiv: 1402.1507]

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

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:

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

DM signals are very rare events (less then 1 cpd/kg/keV)

Experimental priorities for DM Direct Detection:

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

Direct Detection: Overview

DM local velocity $v_0 \sim 10^{-3}c$ $\Rightarrow$ the collision between $\chi\,\&\,\mathcal{N}$ occurs in deeply non relativistic regime

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

- $\frac{1}{2} m_\chi v^2$: DM kinetic energy
- $\frac{4 m_\chi m_{\mathcal{N}}}{(m_\chi + m_{\mathcal{N}})^2}$: Kinematics factor
- θ: scatter angle
- $v_{\rm t}$: threshold velocity

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DM kinetic energy — Kinematics factor — scatter angle — threshold velocity

Theoretical differential rate of nuclear recoil in a given detector

$$\frac{dR_\mathcal{N}}{dE_{\rm R}} = N_\mathcal{N} \frac{\rho_\odot}{m_\chi} \int_{v_{\rm min}(E_{\rm R})}^{v_{\rm esc}} d^3 v \, |\vec{v}| \, f(\vec{v}) \frac{d\sigma}{dE_{\rm R}}$$

- ✔ $N_\mathcal{N} = N_a / A_\mathcal{N}$: Number of target
- ✔ $v_{\rm min}(E_{\rm R}) = \sqrt{\frac{m_\mathcal{N} E_{\rm R}}{2\,\mu_{\chi\mathcal{N}}^2}} \left(1 + \frac{\mu_{\chi\mathcal{N}}\,\delta}{m_\mathcal{N} E_{\rm R}}\right)$: Minimal velocity
- ✔ $\rho_\odot / m_\chi$: DM number density
- ✔ $v_{\rm esc}$: DM escape velocity (450 - 650 km/s)

Differential Cross Section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{R}}}(v, E_{\mathrm{R}}) = \frac{1}{32\pi}\frac{1}{m_\chi^2 m_{\mathcal{N}}}\frac{1}{v^2}|\mathcal{M}_{\mathcal{N}}|^2 \longrightarrow$$ Matrix Element (ME) for the DM-nucleus scattering

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

Differential Cross Section

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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

The DM-nucleon ME can be constructed from Galileian invariant combination of d.o.f.

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

functions of the parameters of your favorite theory (e.g. couplings, mixing angles, mediator masses), expressed in terms of NR operators

Differential Cross Section

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functions of the parameters of your favorite theory (e.g. couplings, mixing angles, mediator masses), expressed in terms of NR operators

Contact interaction (q << Λ)

$$\mathcal{O}_1^{NR} = \mathbb{1}\,,$$
$$\mathcal{O}_3^{NR} = i\,\vec{s}_N\cdot(\vec{q}\times\vec{v}^\perp)\,, \qquad \mathcal{O}_4^{NR} = \vec{s}_\chi\cdot\vec{s}_N\,,$$
$$\mathcal{O}_5^{NR} = i\,\vec{s}_\chi\cdot(\vec{q}\times\vec{v}^\perp)\,, \qquad \mathcal{O}_6^{NR} = (\vec{s}_\chi\cdot\vec{q})(\vec{s}_N\cdot\vec{q})\,,$$
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$$\mathcal{O}_{11}^{NR} = i\,\vec{s}_\chi\cdot\vec{q}\,, \qquad \mathcal{O}_{12}^{NR} = \vec{v}^\perp\cdot(\vec{s}_\chi\times\vec{s}_N)\,.$$

Long-range interaction (q >> Λ)

$$\mathcal{O}_1^{lr} = \frac{1}{q^2}\mathcal{O}_1^{NR}\,, \qquad \mathcal{O}_5^{lr} = \frac{1}{q^2}\mathcal{O}_5^{NR}\,,$$
$$\mathcal{O}_6^{lr} = \frac{1}{q^2}\mathcal{O}_6^{NR}\,, \qquad \mathcal{O}_{11}^{lr} = \frac{1}{q^2}\mathcal{O}_{11}^{NR}\,.$$

Differential Cross Section

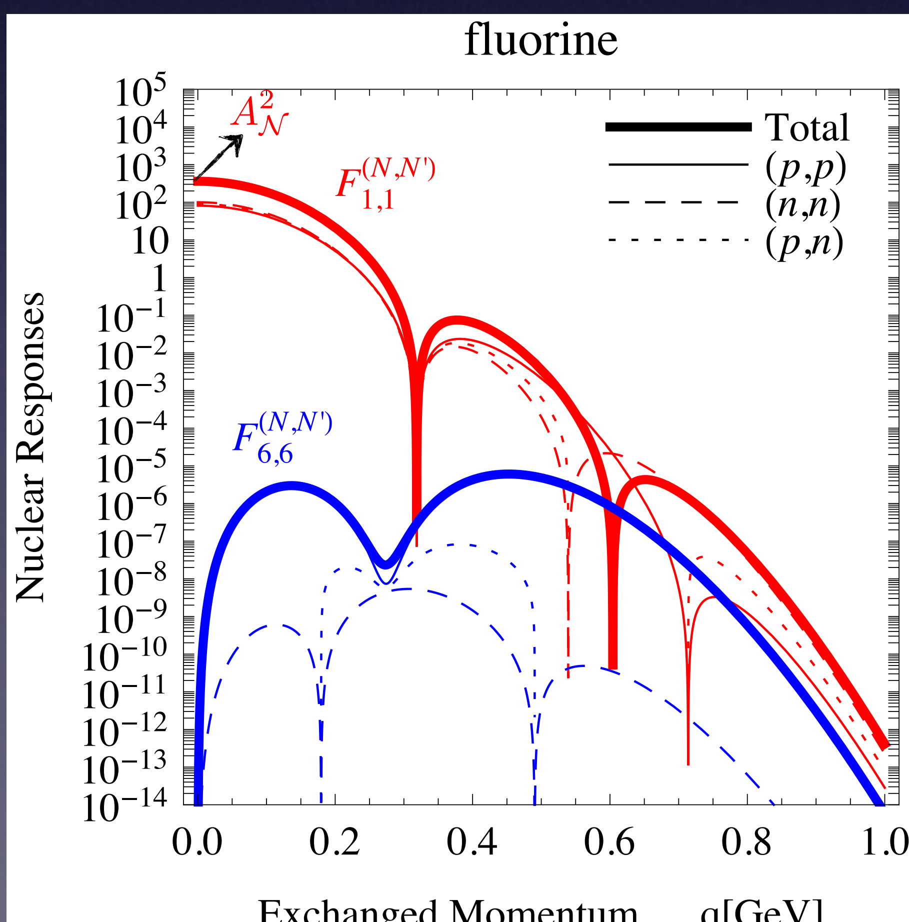
Nucleus is not point-like

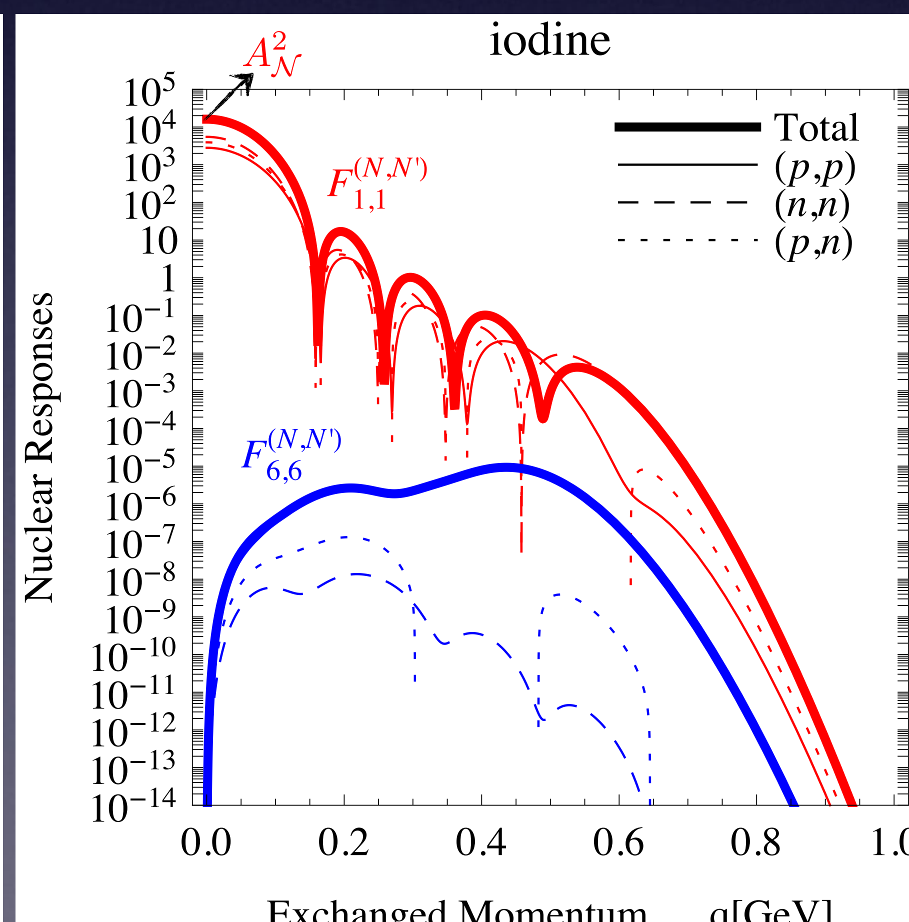
There are different Nuclear Responses for any pairs of nucleons & any pairs of NR Operators

$$|\mathcal{M}_N|^2 = \frac{m_N^2}{m_N^2} \sum_{i,j=1}^{12} \sum_{N,N'=p,n} c_i^N c_j^{N'} F_{i,j}^{(N,N')}(v, q^2)$$

pairs of NR operators — pairs of nucleons — Nuclear response of the target nuclei

Nuclear responses for some common target nuclei in Direct Searches





Contact interaction ($q \ll \Lambda$)

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

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

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Long-range interaction ($q \gg \Lambda$)

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

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

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

Rate of Nuclear Recoil

$$\frac{\mathrm{d}R_{\mathcal{N}}}{\mathrm{d}E_{\mathrm{R}}} = N_{\mathcal{N}} \frac{\rho_{\odot}}{m_\chi} \frac{1}{32\pi} \frac{m_{\mathcal{N}}}{m_\chi^2 m_N^2} \sum_{i,j=1}^{12} \sum_{N,N'=p,n} \mathfrak{c}_i^N \mathfrak{c}_j^{N'} \int_{v_{\min}(E_{\mathrm{R}})}^{v_{\mathrm{esc}}} \mathrm{d}^3 v \frac{1}{v} f_{\oplus}(v)\, F_{i,j}^{(N,N')}(v, q^2)$$

Rate of Nuclear Recoil

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Comparison with the Experimental data

exposure

$$N_k^{\rm th} = w_k \int_{\Delta E_k} dE_{\rm det}\, \epsilon(E_{\rm det}) \int_0^\infty dE_R \sum \mathcal{K}_{\mathcal{N}}(q_{\mathcal{N}} E_R, E_{\rm det}) \frac{dR_{\mathcal{N}}}{dE_R}(E_R)$$

$\mathcal{N}$=Nucleus

takes into account the response and energy resolution of the detector

runs over the different species in the detector (e.g. DAMA and CRESST are multiple-target)

quenching factor: accounts for the partial recollection of the released energy

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exposure (w_k)

$\mathcal{N}$=Nucleus

takes into account the response and energy resolution of the detector

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Uncertainties in Direct DM Searches

- ✓ Local DM energy Density & Geometry of the Halo (e.g: spherically symmetric halos with isotropic or not velocity dispersion, triaxial models, co-rotating dark disk and so on......)
- ✓ Nature of the interaction & Nuclear Responses (e.g: SI & SD scattering, long-range or point like character of the interaction and so on......)
- ✓ Experimental uncertainties (e.g: detection efficiency close to the lower threshold, energy dependence of the quenching factors, channeling in crystals and so on......)

Rate of Nuclear Recoil

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- Experimental uncertainties (e.g: detection efficiency close to the lower threshold, energy dependence of the quenching factors, channeling in crystals and so on......)

Expected Number of Events

Particle physics part

Model independent part

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

linear combination of integrated form factors

$$X = \frac{\rho_\odot}{m_\chi}\frac{1}{32\pi}\frac{1}{m_\chi^2 m_N^2}$$

$$\tilde{\mathcal{F}}_{i,j}^{(N,N')}(m_\chi, k) = w_k \sum_{\mathcal{N}=\text{Nucleus}} N_\mathcal{N} m_\mathcal{N} \int_{\Delta E_k} \mathrm{d}E_{\rm det}\, \epsilon(E_{\rm det}) \int \mathrm{d}E'\, \mathcal{K}(E_{\rm det}, E') \int_{v_{\rm min}\left(\frac{E'}{q_\mathcal{N}}\right)}^{v_{\rm esc}} \mathrm{d}^3 v \frac{1}{v} f_\oplus(v) F_{i,j}^{(N,N')}(v, q^2)$$

once computed the integrated form factors, one can easily derive the expected number of events for any kinds of interactions, whose particle physics in completely encapsulated in the coefficient $\mathfrak{c}_i^N$

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Model independent Bounds in direct DM searches

- ✔ I'm going to present a new framework for "scaling" a bound given on a certain benchmark interaction to any other kinds of interactions
- ✔ For example the model dependent bounds presented by the experimental collaborations can also be applied to other class of models

Benchmark interaction

Contact interaction

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

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

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

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LR interaction

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

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

Among all the NR interactions we choose the simplest:
(a model where DM interact with only protons with a constant cross section)

$\mathfrak{c}_1^p = \lambda_B$, while $\mathfrak{c}_1^N = 0$

Benchmark DM-nucleon ME

$$|\mathcal{M}_{p,B}| = \lambda_B \mathcal{O}_1^{NR}$$

Events for the benchmark model

$$N_{k,B}^{th} = X\,\lambda_B^2\,\tilde{\mathcal{F}}_{1,1}^{(p,p)}(m_\chi, k)$$

↙ benchmark DM constant

Benchmark interaction

Contact interaction

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

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$$N_{k,{\rm B}}^{\rm th} = X\,\lambda_{\rm B}^2\,\tilde{\mathcal{F}}_{1,1}^{(p,p)}(m_\chi, k)$$

benchmark DM constant

Determination of the maximal value of $\lambda_{\rm B}$ allowed by the experimental data-set

Likelihood Ratio Test Statistic (TS)

$$\mathrm{TS}(\lambda_{\rm B}, m_\chi) = -2\ln\left(\mathcal{L}(\vec{N}^{\rm obs}\,|\,\lambda_{\rm B})/\mathcal{L}_{\rm bkg}\right)$$

likelihood of obtaining the set of observed data

bkg. likelihood

for any given value of m_χ, a 90% CL lower bound on the free parameter can be obtained by solving

$$\mathrm{TS}(\lambda_{\rm B}, m_\chi) = \chi^2_{90\%\,\rm CL} \simeq 2.71$$

Benchmark interaction

Contact interaction

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Events for the benchmark model

$$N_{k,B}^{th} = X\,\lambda_B^2\,\tilde{\mathcal{F}}_{1,1}^{(p,p)}(m_\chi, k)$$

benchmark DM constant

Determination of the maximal value of λ_B allowed by the experimental data-set

Likelihood Ratio Test Statistic (TS)

$$\mathrm{TS}(\lambda_B, m_\chi) = -2\ln\left(\mathcal{L}(\vec{N}^{obs}\,|\,\lambda_B)/\mathcal{L}_{bkg}\right)$$

likelihood of obtaining the set of observed data — bkg. likelihood

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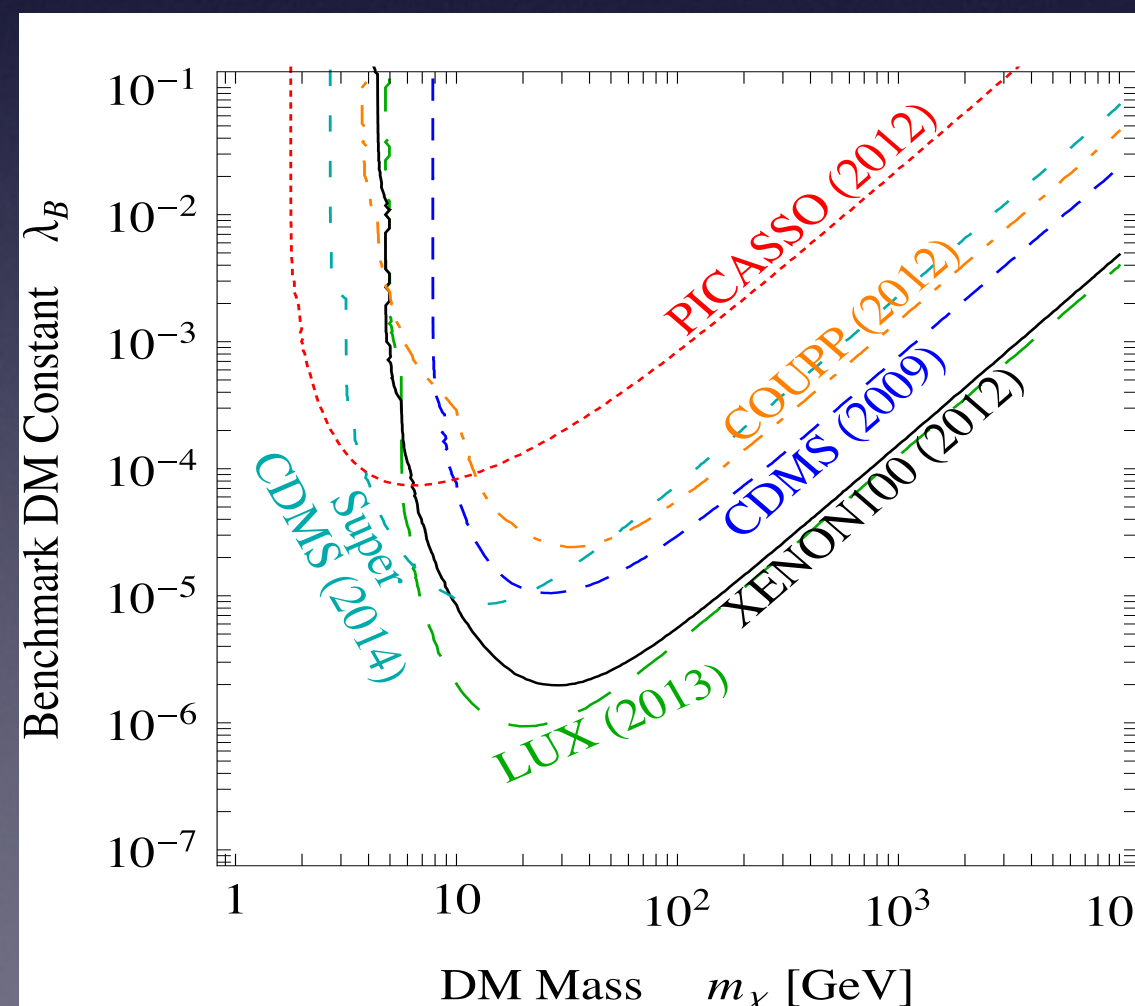
The functions TS that allow the users to compute the bound λ_B^{CL} at the desired CL are provided here:

http://www.marcocirelli.net/NROpsDD.html



Rescaling Functions

For any model the bound must be drawn at the same CL:

$$\mathrm{TS}(\lambda, m_\chi) = \mathrm{TS}(\lambda_\mathrm{B}, m_\chi)$$

For null-results Exps. a solution is:

$$\sum_k N_k^{\mathrm{th}}(\lambda, m_\chi) = \sum_k N_{k,\mathrm{B}}^{\mathrm{th}}(\lambda_\mathrm{B}, m_\chi)$$

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Particle physics part | Model independent

$$\tilde{\mathcal{Y}}_{i,j}^{(N,N')}(m_\chi) = \frac{\sum_k \tilde{\mathcal{F}}_{i,j}^{(N,N')}(m_\chi, k)}{\sum_k \tilde{\mathcal{F}}_{1,1}^{(p,p)}(m_\chi, k)}$$

"Scaling" Functions
- nuclear physics
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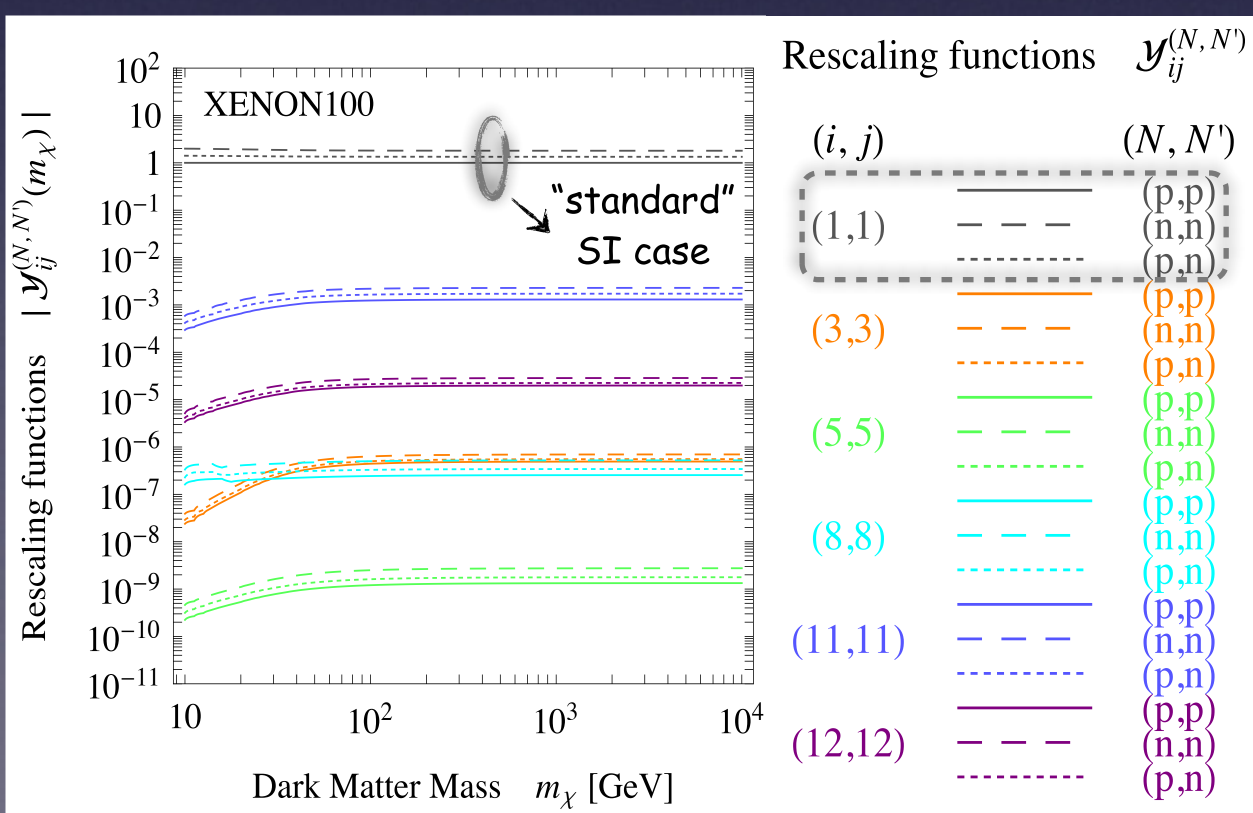

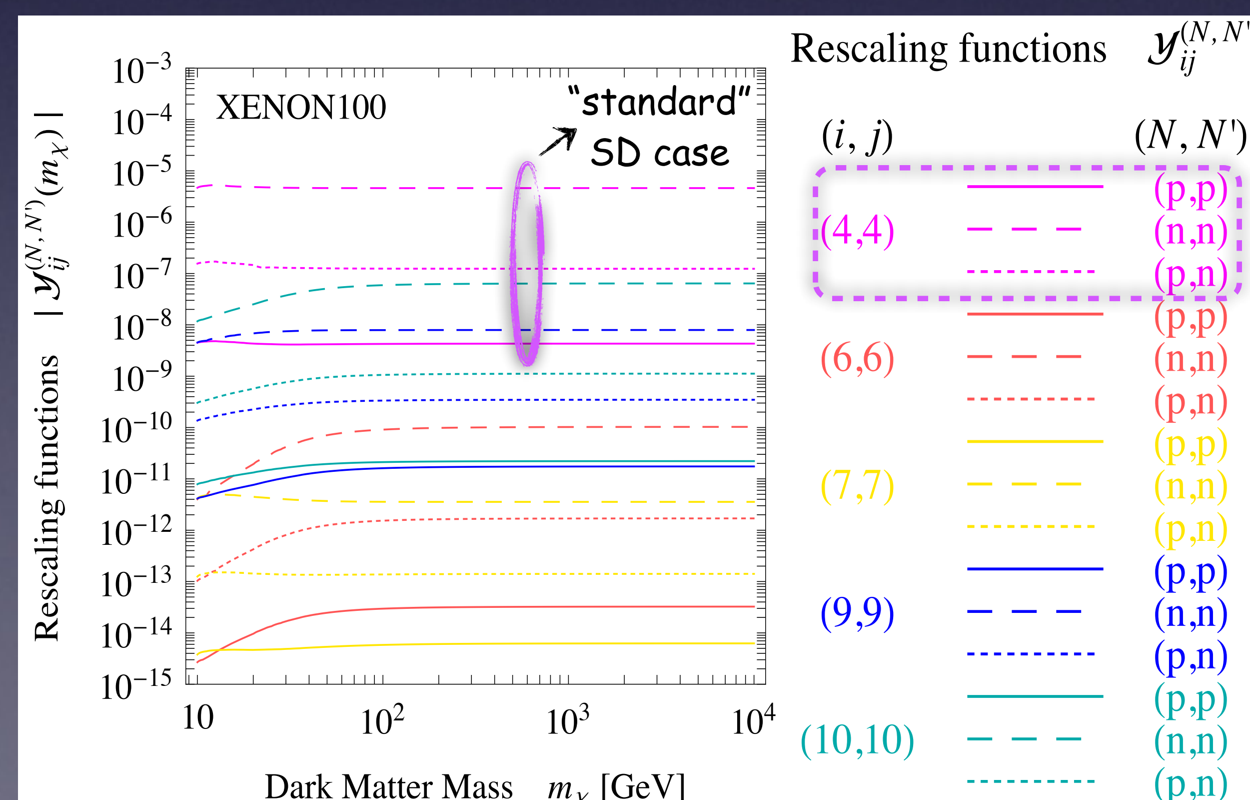

Example: SI & SD Interactions

SI DM-nucleon effective Lagrangian

$$\mathcal{L}^N_{\rm SI} = \lambda_{\rm SI} \cdot \bar{\chi}\chi \, \bar{N} N$$

$$\sigma^p_{\rm SI} = \frac{\lambda^2_{\rm SI}}{\pi} \mu^2_{\chi p}$$

Total SI DM-nucleon Cross section

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Non-relativistic SI DM-nucleon ME

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$$|\mathcal{M}^N_{\rm SD}| = \underbrace{16\,\lambda_{\rm SD} m_\chi m_N}_{\mathfrak{c}^N_4}\, \vec{s}_\chi \vec{s}_N \rightarrow \mathcal{O}^{\rm NR}_4$$

Example: SI & SD Interactions

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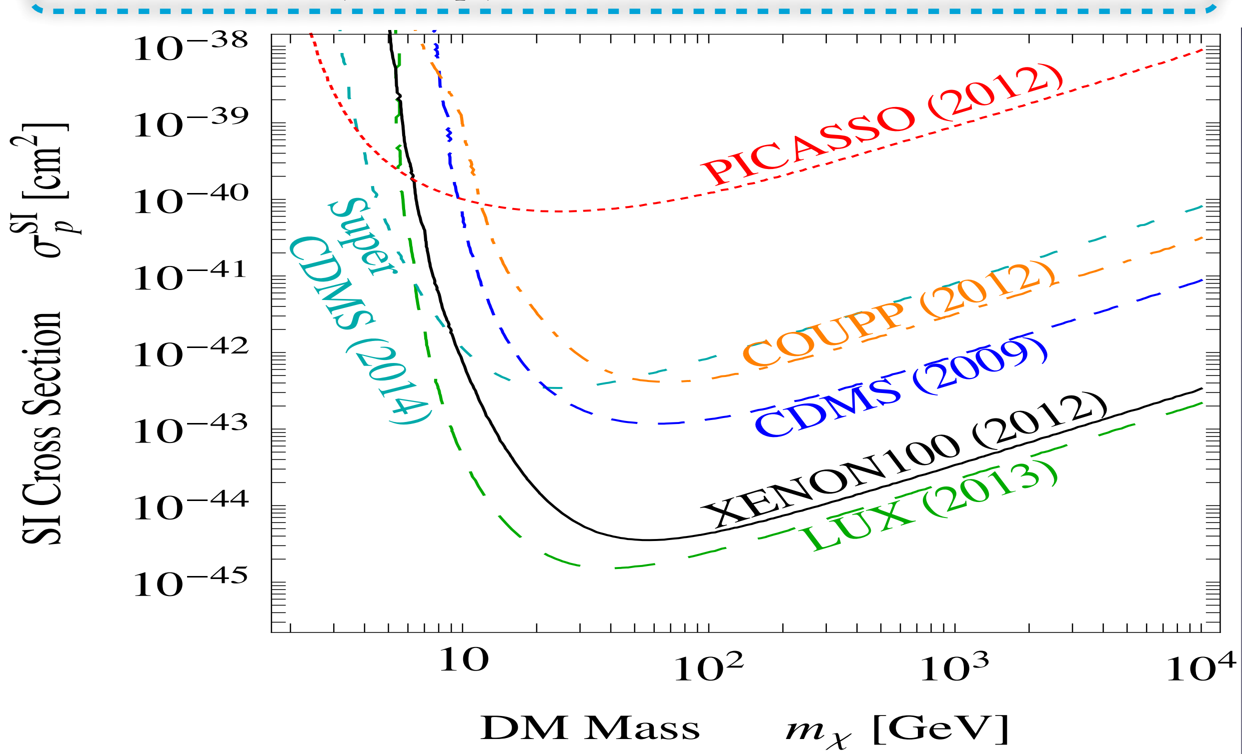
Non-relativistic SI DM-nucleon ME

$$\left|\mathcal{M}_{\rm SI}^{N}\right| = \underbrace{4\,\lambda_{\rm SI} m_\chi m_N}_{\mathfrak{c}_1^N}\,\underset{\to\,\mathcal{O}_1^{\rm NR}}{1}$$

$$\lambda_{\rm B}^2 = \sigma_{\rm SI}^{p} \sum_{N,N'=p,n} 16\pi\, m_\chi^2 \frac{m_N^2}{\mu_{\chi p}^2}\,\tilde{\mathcal{Y}}_{1,1}^{(N,N')}(m_\chi)$$



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Total SD DM-nucleon Cross section

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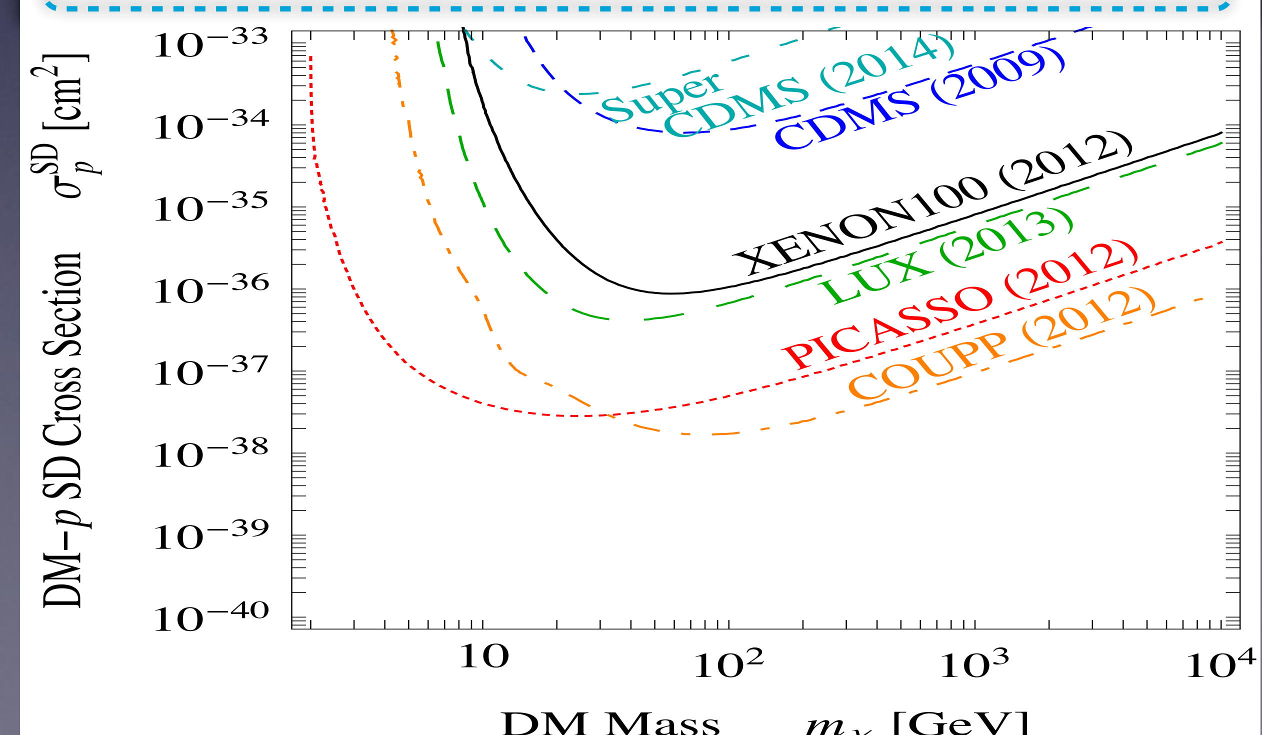
Non-relativistic SD DM-nucleon ME

$$\left|\mathcal{M}_{\rm SD}^{N}\right| = \underbrace{16\,\lambda_{\rm SD} m_\chi m_N}_{\mathfrak{c}_4^N}\,\underset{\to\,\mathcal{O}_4^{\rm NR}}{\vec{s}_\chi \vec{s}_N}$$

$$\lambda_{\rm B}^2 = \sigma_{\rm SD}^{p} \frac{256}{3}\pi\, m_\chi^2 \frac{m_N^2}{\mu_{\chi p}^2}\,\tilde{\mathcal{Y}}_{4,4}^{(p,p)}(m_\chi)$$



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I have described a method and a self-contained set of numerical tools to derive the bounds from some current experiments to virtually any arbitrary models of DM

- The method is based on the formalism of non-relativistic operators
- it incorporates into the nuclear responses all the necessary detector and astrophysical ingredients

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.*

Test Statistic functions:

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