Nuclear structure calculations for dark matter searches

Daniel Gazda
Chalmers University of Technology

Partikeldagarna

Stockholm, 6–7 November 2017

Together with:
C. Forssén, R. Catena (Chalmers)

Funded by the Knut and Alice Wallenberg foundation

Outline

- Dark matter
- DM direct detection and nuclear physics
- Nuclear structure inputs for DM searches
- Conclusions & Outlook

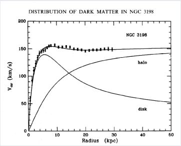
Dark matter

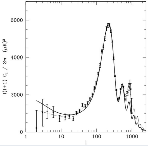
Dark matter makes up about 5/6 of the total matter in the Universe.

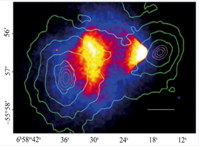
Evidence for dark matter

- rotational curves of galaxies
- cosmic microwave background, large structure formation
- gravitational lensing, the Bullet Cluster
- ...

New type of particle provides simple explanation. WIMP is a well motivated candidate.





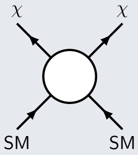


Dark matter

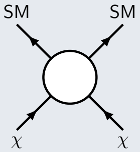
WIMP

- particle with $m_\chi \sim 100$ GeV
- interacts with Standard Model fields at $\sim$ electroweak scale

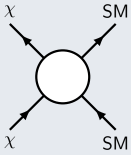
WIMP dark matter searches



production
collider searches

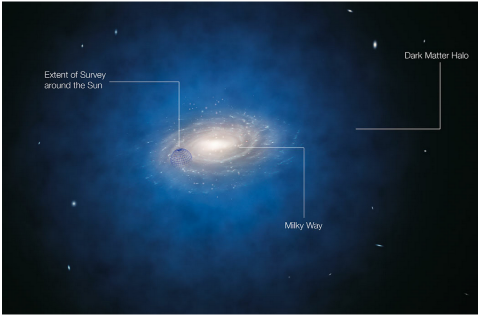


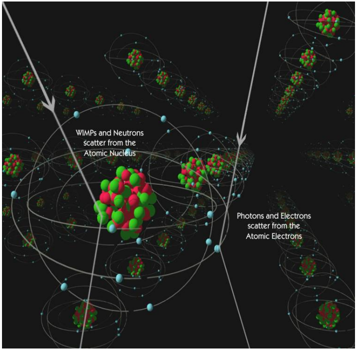
annihilation
indirect searches
γ, ν, CR telescopes



scattering
direct detection
deep underground detectors

Dark matter direct detection & nuclear physics





taken from: CDMS collaboration

Typical (expected) nuclear recoil momentum can reach

$$q \approx 200\ \mathrm{MeV} \longleftrightarrow r \sim \frac{1}{q} \approx 1\ \mathrm{fm}$$

Nuclear structure is resolved!

Aims

- Quantify the impact of **nuclear structure uncertainties** on the interpretation of data from dark matter searches.

- Apply *ab initio* methods in calculations of WIMP scattering off:

    - ^{3}**He,** ^{4}**He** (detectors in R&D phase)
      Jacobi-coordinate-NCSM [Phys. Rev. D 95, 103011 (2017)]

    ↓

    - ^{16}**O** (CRESST-II), ^{19}**F** (PICO experiment)
      Slater-Derminant-NCSM

    ↓

    - **Ge** (SuperCDMS), **Xe** (XENON)
      IM-SRG valence-space interactions + SM

Nonrelativistic EFT for DM–nucleus interaction

- Interaction of DM particles with SM fields is **not known** $\rightarrow$ EFT
- Construct the **most general** form of dark matter–nucleon interaction
  [Fitzpatrick *et al.*, JCAP 1302, 4 (2013)]
  - momentum conservation together with the requirement of Galilean invariance identifies 4 basic operators:

$$\mathrm{i}\hat{\mathbf{q}}, \quad \hat{\mathbf{v}}^{\perp} = \hat{\mathbf{v}} + \frac{\hat{\mathbf{q}}}{2\mu_{\chi N}}, \quad \hat{\mathbf{s}}_{\chi}, \quad \hat{\mathbf{s}}_N$$

  - all possible DM–nucleon interaction terms (up to q^2):

$$\begin{aligned}
\hat{\mathcal{O}}_1 &= 1_{\chi N} & \hat{\mathcal{O}}_9 &= \mathrm{i}\hat{\mathbf{s}}_{\chi} \cdot \left(\hat{\mathbf{s}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right) \\
\hat{\mathcal{O}}_3 &= \mathrm{i}\hat{\mathbf{s}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^{\perp}\right) & \hat{\mathcal{O}}_{10} &= \mathrm{i}\hat{\mathbf{s}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N} \\
\hat{\mathcal{O}}_4 &= \hat{\mathbf{s}}_{\chi} \cdot \hat{\mathbf{s}}_N & \hat{\mathcal{O}}_{11} &= \mathrm{i}\hat{\mathbf{s}}_{\chi} \cdot \frac{\hat{\mathbf{q}}}{m_N} \\
\hat{\mathcal{O}}_5 &= \mathrm{i}\hat{\mathbf{s}}_{\chi} \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^{\perp}\right) & \hat{\mathcal{O}}_{12} &= \hat{\mathbf{s}}_{\chi} \cdot \left(\hat{\mathbf{s}}_N \times \hat{\mathbf{v}}^{\perp}\right) \\
\hat{\mathcal{O}}_6 &= \left(\hat{\mathbf{s}}_{\chi} \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{s}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right) & \hat{\mathcal{O}}_{13} &= \mathrm{i}\left(\hat{\mathbf{s}}_{\chi} \cdot \hat{\mathbf{v}}^{\perp}\right)\left(\hat{\mathbf{s}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right) \\
\hat{\mathcal{O}}_7 &= \hat{\mathbf{s}}_N \cdot \hat{\mathbf{v}}^{\perp} & \hat{\mathcal{O}}_{14} &= \mathrm{i}\left(\hat{\mathbf{s}}_{\chi} \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{s}}_N \cdot \hat{\mathbf{v}}^{\perp}\right) \\
\hat{\mathcal{O}}_8 &= \hat{\mathbf{s}}_{\chi} \cdot \hat{\mathbf{v}}^{\perp} & \hat{\mathcal{O}}_{15} &= -\left(\hat{\mathbf{s}}_{\chi} \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{s}}_N \times \hat{\mathbf{v}}^{\perp}\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]
\end{aligned}$$

  No evidence to justify a simple form!

  - DM–nucleus Hamiltonian density: $\hat{\mathcal{H}}_{\chi A} = \sum_{i=1}^{A} \sum_{\tau=0,1} \sum_{j=1}^{15} c_j^{\tau} \hat{\mathcal{O}}_j^{(i)} \, t_{(i)}^{\tau}$

Nonrelativistic EFT for DM–nucleus interaction

Rate of nuclear scattering events in direct detection experiments:

$$\frac{\mathrm{d}\mathcal{R}}{\mathrm{d}q^2} = \frac{\rho_\chi}{m_A m_\chi} \int \mathrm{d}^3\vec{v}\, f(\vec{v}+\vec{v}_e)\, v \frac{\mathrm{d}\sigma}{\mathrm{d}q^2}$$

- astrophysics $\longrightarrow$ m_χ, ρ_χ, f - dark matter mass, density, velocity distributions
- particle and nuclear physics $\longrightarrow$ $\frac{\mathrm{d}\sigma}{\mathrm{d}q^2}$

Scattering cross section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q^2} = \frac{1}{(2J+1)v^2} \sum_{\tau,\tau'} \left[\sum_{\ell=M,\Sigma',\Sigma''} R_\ell^{\tau\tau'} W_\ell^{\tau\tau'} + \frac{q^2}{m_N^2} \sum_{\substack{\ell=\Phi'',\Phi''M,\\ \tilde{\Phi}',\Delta,\Delta\Sigma'}} R_\ell^{\tau\tau'} W_\ell^{\tau\tau'} \right]$$

- dark matter response functions $R_m^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}, c_i^\tau c_j^{\tau'}\right)$
- nuclear response functions $W_\ell^{\tau\tau'}(q^2)$

Uncertainties?

- ρ_χ: $\pm 30\%$, $f(\vec{v})$: $\pm$? (important only for light DM), $W_l^{\tau\tau'}$: $\pm$?

Nonrelativistic EFT for DM–nucleus interaction

- nuclear response functions:

$$W_{AB}^{\tau\tau'}(q^2) = \sum_{L\leq 2J} \langle J, T, M_T \| \hat{A}_{L;\tau}(q) \| J, T, M_T \rangle \langle J, T, M_T \| \hat{B}_{L;\tau'}(q) \| J, T, M_T \rangle$$

  - $\hat{A}_{L;\tau}$, $\hat{B}_{L;\tau}$ – nuclear response operators:

$$M_{LM;\tau}(q) = \sum_{i=1}^{A} M_{LM}(q\boldsymbol{\rho}_i)\, t_{(i)}^{\tau}, \quad \Sigma'_{LM;\tau}(q) = -\mathrm{i} \sum_{i=1}^{A} \left[\frac{1}{q} \overrightarrow{\nabla}_{\rho_i} \times \mathbf{M}_{LL}^{M}(q\boldsymbol{\rho}_i) \right] \cdot \vec{\sigma}_{(i)} t_{(i)}^{\tau},$$

$$\Sigma''_{LM;\tau}(q) = \sum_{i=1}^{A} \left[\frac{1}{q} \overrightarrow{\nabla}_{\rho_i} M_{LM}(q\boldsymbol{\rho}_i) \right] \cdot \vec{\sigma}_{(i)} t_{(i)}^{\tau}, \quad \Delta_{LM;\tau}(q) = \sum_{i=1}^{A} \mathbf{M}_{LL}^{M}(q\boldsymbol{\rho}_i) \cdot \frac{1}{q} \overrightarrow{\nabla}_{\rho_i} t_{(i)}^{\tau},$$

$$\tilde{\Phi}'_{LM;\tau}(q) = \sum_{i=1}^{A} \left[\left(\frac{1}{q} \overrightarrow{\nabla}_{\rho_i} \times \mathbf{M}_{LL}^{M}(q\boldsymbol{\rho}_i) \right) \cdot \left(\vec{\sigma}_{(i)} \times \frac{1}{q} \overrightarrow{\nabla}_{\rho_i} \right) + \frac{1}{2} \mathbf{M}_{LL}^{M}(q\boldsymbol{\rho}_i) \cdot \vec{\sigma}_{(i)} \right] t_{(i)}^{\tau},$$

$$\Phi''_{LM;\tau}(q) = \mathrm{i} \sum_{i=1}^{A} \left(\frac{1}{q} \overrightarrow{\nabla}_{\rho_i} M_{LM}(q\boldsymbol{\rho}_i) \right) \cdot \left(\vec{\sigma}_{(i)} \times \frac{1}{q} \overrightarrow{\nabla}_{\rho_i} \right) t_{(i)}^{\tau}$$

  - nuclear ground-state wave functions $|J, T, M_T\rangle$ calculated within no-core shell model

Ab initio no-core shell model

Given a Hamiltonian operator solve the eigenvalue problem of A nucleons

$$\left[\sum_{i\leq A}\frac{\hat{\mathbf{p}}_i^2}{2m}+\sum_{i<j\leq A}\hat{V}_{NN}(\mathbf{r}_i,\mathbf{r}_j)+\sum_{i<j<k\leq A}\hat{V}_{NNN}(\mathbf{r}_i,\mathbf{r}_j,\mathbf{r}_k)\right]\psi=E\psi$$

Ab initio

- all particles are active (no rigid core)
- exact Pauli principle
- realistic internucleon interactions
- controllable approximations

- Hamiltonian is diagonalized in a *finite* A-particle harmonic oscillator basis

$$\psi(\mathbf{r}_1,\ldots,\mathbf{r}_A)=\sum_{n\leq N_{\text{tot}}}\phi_n^{\text{HO}}(\mathbf{r}_1,\ldots,\mathbf{r}_A)$$

(matrix dimensions up to $\sim 10^{10}$ with $\sim 10^{14}$ nonzero elements)

- NCSM results converge to exact results, $N_{\text{tot}}\to\infty$

Input Hamiltonians

V_{NN} and V_{NNN} potentials derived from chiral EFT

- long-range part of the interaction, π-exchange, predicted by chiral perturbation theory
- short-range part parametrized by contact interactions, LECs fitted to experimental data

- **NNLO$_{\text{sim}}$** Hamiltonian family [Carlsson *et al.*, PRX 6, 011019 (2016)]
  - parameters fitted to reproduce *simultaneously* πN, NN, and NNN low-energy observables

$$\left.\begin{array}{ll} T_{NN}^{\text{lab,max}} & \leq 125, \ldots, 290 \text{ MeV} \\ \Lambda_{\text{EFT}} & \leq 450, \ldots, 600 \text{ MeV} \end{array}\right\} \rightarrow \text{42 Hamiltonians}$$

  - all Hamiltonians give equally good description on the fit data

- **NNLO$_{\text{opt}}$** [A. Ekström *et al.*, PRL 110, 192502 (2013)]
  optimized 2-nucleon V_{NN}; found to minimize the effect of V_{NNN}

^{4}He nuclear response functions and recoil rates

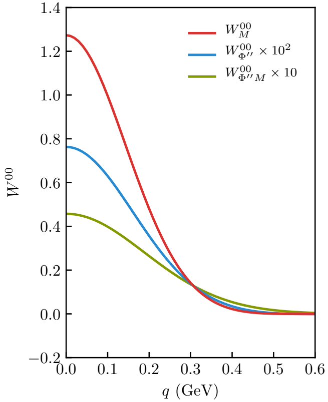


Figure: Isoscalar nuclear response functions of ^{4}He as functions of the recoil momentum q calculated within *ab initio* NCSM using NNLO_{sim}.

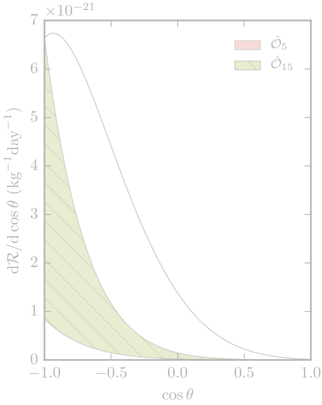


Figure: Differential rate of nuclear recoil events as a function of the recoil direction.

- only W_M^{00}, $W_{\Phi''}^{00}$, and $W_{\Phi'' M}^{00}$ due to $J = T = 0$
- for $q \to 0$: $W_M^{00} \propto A^2$, $W_{\Phi''}^{00} \propto \langle \sum_i^A \mathbf{l}(i) \cdot \boldsymbol{\sigma}(i) \rangle^2$

^{4}He nuclear response functions and recoil rates

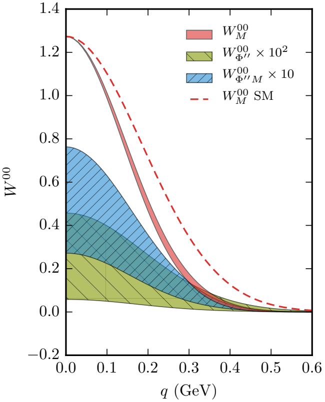


Figure: Isoscalar nuclear response functions of ^{4}He as functions of the recoil momentum q calculated within *ab initio* NCSM using NNLO$_{\text{sim}}$ and NI-SM.

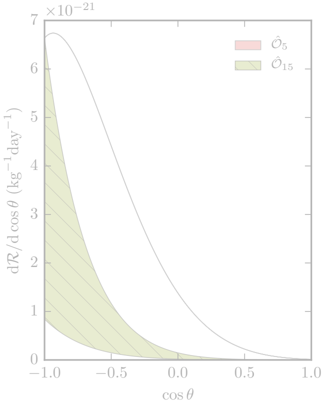


Figure: Differential rate of nuclear recoil events as a function of the recoil direction.

- only W^{00}_M, $W^{00}_{\Phi''}$, and $W^{00}_{\Phi'' M}$ due to $J = T = 0$
- for $q \to 0$: $W^{00}_M \propto A^2$, $W^{00}_{\Phi''} \propto \langle \sum_i^A \mathbf{l}(i) \cdot \boldsymbol{\sigma}(i) \rangle^2$

^{4}He nuclear response functions and recoil rates

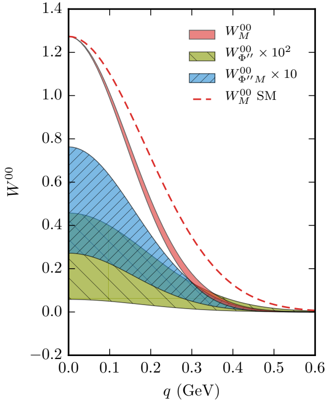


Figure: Isoscalar nuclear response functions of ^{4}He as functions of the recoil momentum q calculated within *ab initio* NCSM using $\mathrm{NNLO_{sim}}$ and NI-SM.

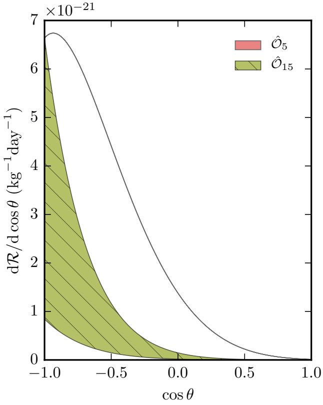


Figure: Differential rate of nuclear recoil events as a function of the recoil direction.

- only W_M^{00}, $W_{\Phi''}^{00}$, and $W_{\Phi'' M}^{00}$ due to $J = T = 0$
- for $q \to 0$: $W_M^{00} \propto A^2$, $W_{\Phi''}^{00} \propto \langle \sum_i^A \mathbf{l}(i) \cdot \boldsymbol{\sigma}(i) \rangle^2$

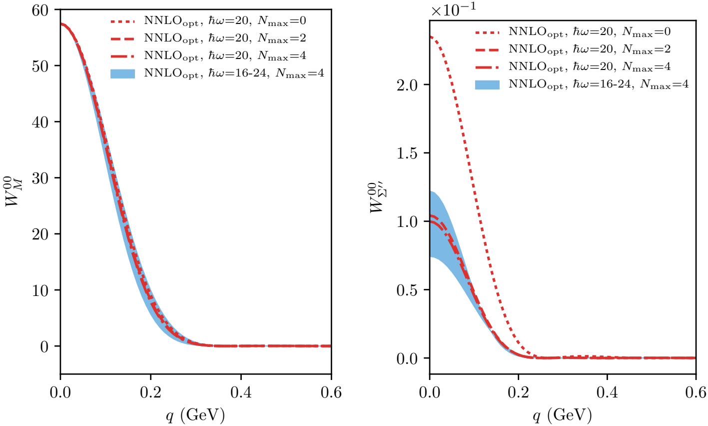


Figure: Isoscalar nuclear response functions W_M^{00} and $W_{\Sigma''}^{00}$ of ^{19}F as functions of the recoil momentum q calculated within *ab initio* NCSM using NNLO$_{\rm opt}$.

- for $q \to 0$: $W_M^{00} \propto A^2$, $W_{\Sigma''}^{00} \propto \langle \sum_i^A \boldsymbol{\sigma}(i) \rangle^2$

Conclusions

- *Ab initio* framework for computation of nuclear response functions for dark matter scattering off nuclei have been developed.
- Certain nuclear response functions suffer from **large uncertainties** which propagate into physical observables.
- *Ab initio* nuclear structure calculations result in **additional** response functions not appearing in SM calculations.

Phys. Rev. D 95, 103011 (2017)

Outlook:

- Heavier nuclei (IM-SRG + SM), ...
- Inelastic scattering, two-body meson-exchange currents, ...