Ab initio nuclear response functions for dark matter searches

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Progress in Ab Initio Techniques in Nuclear Physics
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Outline:

- Introduction
  - Motivation
  - Direct detection and dark matter–nucleon/nucleus interaction

- Methodology
  - Nonrelativistic EFT for dark matter–nucleus interaction
  - *Ab initio* no-core shell model

- Results
  - Nuclear response functions
  - Physical observables

- Conclusions & outlook

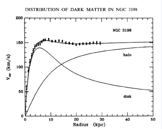
Motivation

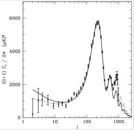
Dark matter makes up about 5/6 of the total matter in the Universe.

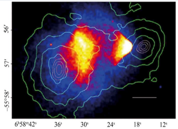
Evidence for dark matter

- 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.

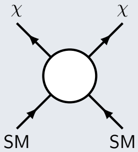




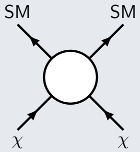


Motivation

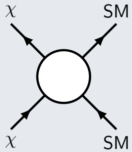
WIMP dark matter searches



production
collider searches

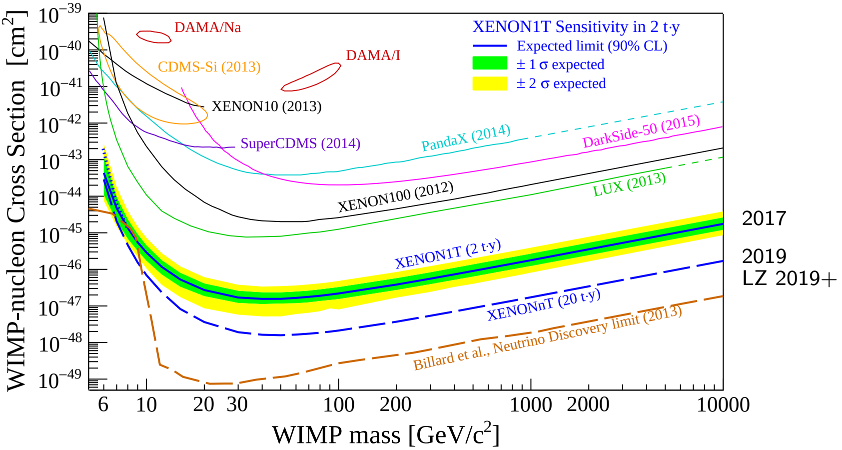


annihilation
indirect searches
γ, ν, CR telescopes



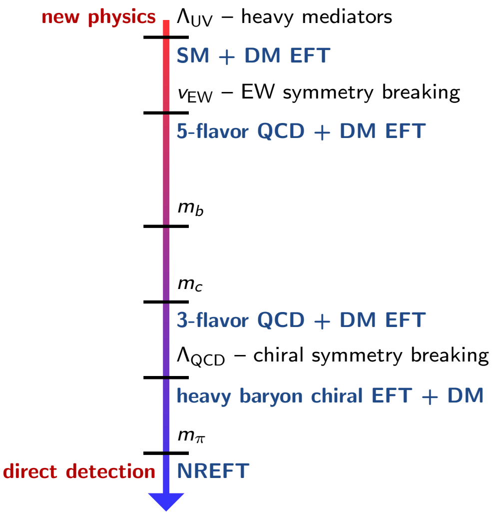
scattering
direct detection
deep underground detectors

Current status



taken from: XENON collaboration, JCAP 1604, 027 (2016)

Dark matter direct detection & nuclear physics



Dark matter direct detection & nuclear physics

new physics Λ_{UV} – heavy mediators

SM + DM EFT

v_{EW} – EW symmetry breaking

5-flavor QCD + DM EFT

m_b

m_c

3-flavor QCD + DM EFT

Λ_{QCD} – chiral symmetry breaking

heavy baryon chiral EFT + DM

m_π

direct detection **NREFT**

Cirigliano *et al.*
(JHEP 1210, 25 (2012))

Darmstadt group:
Menéndez, Gazit,
Schwenk, Klos *et al.*
(e.g. PRD 94, 063505 (2016))

Fitzpatrick, Haxton *et al.*
(JCAP 1302, 4 (2013))

Nonrelativistic EFT for $\chi - N$/nucleus interaction

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:

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

- all possible $\chi - N$ interaction terms (up to q^2):

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

- $\rightarrow$ χ–nucleus Hamiltonian:

$$\hat{\mathcal{H}}_{\chi A} = \sum_{i=1}^{A} \sum_{\tau=0,1} \sum_{j} c_j^{\tau}\, \hat{\mathcal{O}}_j^{(i)}\, t_{(i)}^{\tau}$$

Nonrelativistic EFT for $\chi - N$/nucleus interaction

Rate of nuclear scattering events in direct detection experiments:

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

m_χ, ρ_χ, f: dark matter mass, density, velocity distributions ← astrophysics
$\frac{\mathrm{d}\sigma}{\mathrm{d}q^2}$: scattering cross section ← particle and nuclear physics

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

- 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 $W_\ell^{\tau\tau'}(q^2)$

Nonrelativistic EFT for $\chi - N$/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:

$$M_{LM;\tau}(q) = \sum_{i=1}^{A} M_{LM}(q\boldsymbol{\rho}_i) t_{(i)}^{\tau},$$

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

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

$$\Delta_{LM;\tau}(q) = \sum_{i=1}^{A} \mathbf{M}_{LL}^{M}(q\boldsymbol{\rho}_i) \cdot \frac{1}{q} \overleftrightarrow{\nabla}_{\boldsymbol{\rho}_i} t_{(i)}^{\tau},$$

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

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

- nuclear ground-state wave functions $|J,T,M_T\rangle$ calculated within no-core shell model (focus on ^{3}He and ^{4}He first)

No-core shell model

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
- NCSM results converge to exact results

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

- N2LO$_{\text{sim}}$ Hamiltonian family
  (Carlsson *et al.*, PRX 6, 011019 (2016))
  - parameters fitted to reproduce *simultaneously* πN, NN, and NNN low-energy observables

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

  - all Hamiltonians give equally good description on the fit data

Results

Aim

- quantify the impact of nuclear structure uncertainties on the interpretation of data from dark matter searches

- focus on ^{3}He and ^{4}He nuclei – converged (exact) NCSM calculations of ground-state wave functions possible
- calculate all relevant nuclear response functions using the complete N2LO$_{\text{sim}}$ Hamiltonian family
- study the impact of systematical uncertainties of nuclear response functions on the rate of nuclear recoil events in directional dark matter detection

^{4}He nuclear response functions and recoil rates

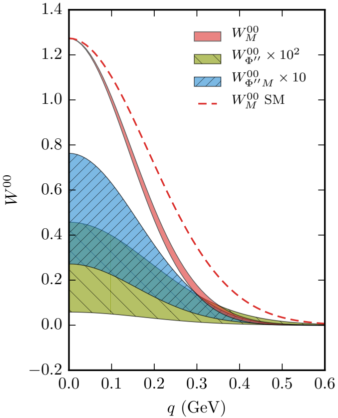


Figure: Isoscalar nuclear response functions of ^{4}He as functions of the recoil momentum q calculated within *ab initio* NCSM and SM.

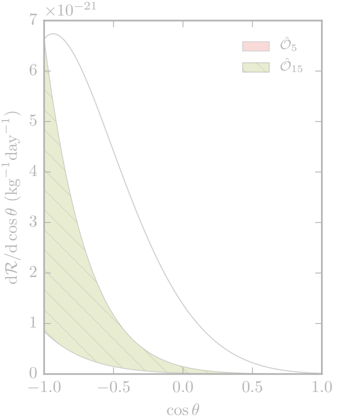
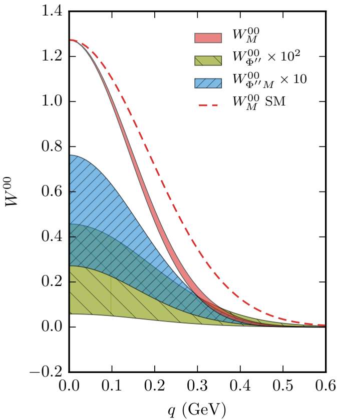


Figure: Differential rate of nuclear recoil events as a function of the recoil direction.

^{4}He nuclear response functions and recoil rates



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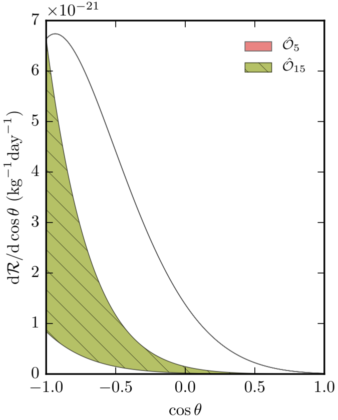
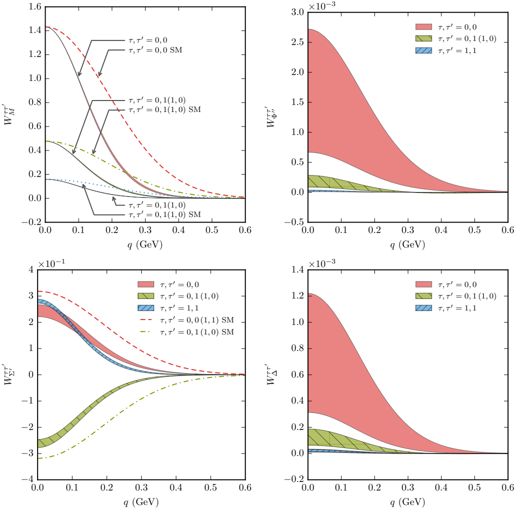


Figure: Differential rate of nuclear recoil events as a function of the recoil direction.

^{3}He nuclear response functions and recoil rates



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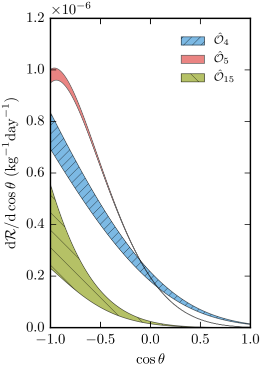

Figure: Differential rate of nuclear recoil events as a function of the recoil direction.

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.

arXiv:1612.09165 [hep-ph]

Outlook:

- response functions of ^{16}O (CRESST-II), ^{19}F (PICO), Xe, . . .
- inelastic scattering, two-body meson-exchange currents, . . .