Ab Initio Nuclear Structure Calculations for Dark Matter Direct Detection

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Outline

- Dark matter direct detection and nuclear physics
- Nuclear structure inputs for DM searches
    - nuclear response functions (structure factors)
    - light and medium-mass nuclear targets
    - nuclear structure uncertainties
- Conclusions & Outlook

Introduction

Introduction

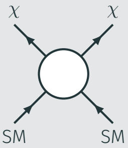
Dark matter

- makes up about 5/6 of the total matter in the Universe
- evidence from astrophysics, from galaxies to the largest structures

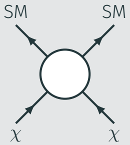
WIMP

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

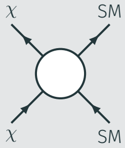
WIMP searches



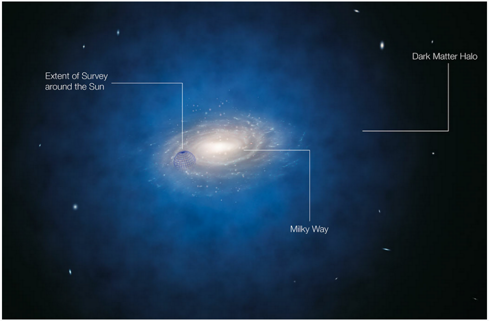
production
collider searches

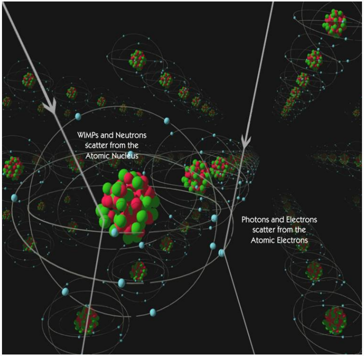


annihilation
indirect searches
γ, ν, CR telescopes



scattering
direct detection
deep-underground detectors





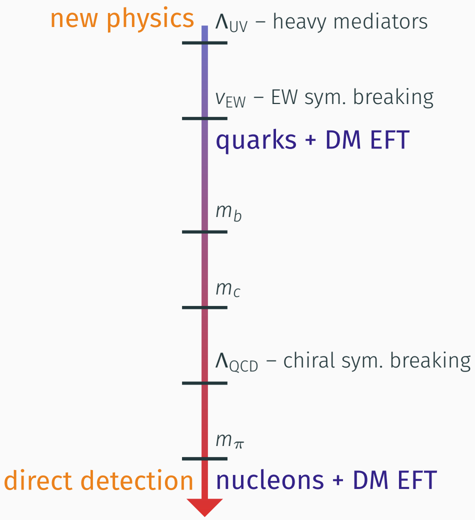
[Taken from CDMS collaboration]

Typical (expected) nuclear recoil momentum can reach

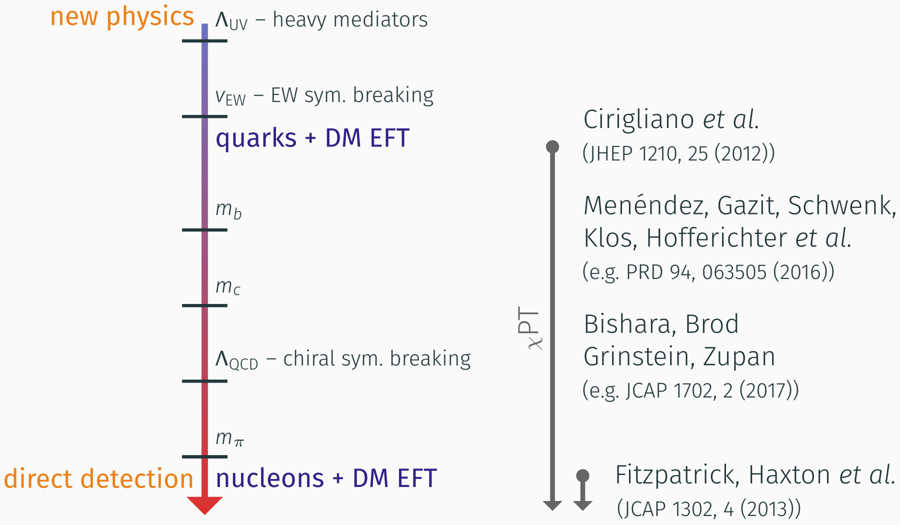
$$q \approx 200 \text{ MeV} \sim m_\pi \longleftrightarrow \text{length scale } r \sim \frac{1}{q} \approx 1 \text{ fm}$$

Nuclear structure is resolved!

Dark matter – nucleus interaction



Dark matter – nucleus interaction



Aims

- Establish a new framework for nuclear structure calculations in the context of dark matter searches
- Quantify the impact of **nuclear structure uncertainties** on the interpretation of data from dark matter searches.
- Apply *ab initio* nuclear many-body 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),
      Slater-Derminant-NCSM
    - ^{23}**Na** (DAMA/LIBRA, COSINE-100, COSINUS), ^{40}**Ca** (CRESST-II), **Ge** (SuperCDMS), ... **Xe** (XENON)
      IM-SRG valence-space interactions + SM

Methodology

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

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

No evidence to justify a simple form!

Nonrelativistic EFT for DM–nucleus interaction

Rate of nuclear scattering events in direct detection experiments:

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

- astrophysics $\to m_\chi, \rho_\chi, f$ - dark matter mass, density, velocity distributions
- particle and nuclear physics $\to \frac{d\sigma}{dq^2}$

Scattering cross section:

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

- 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), $W_l^{\tau\tau'}$: $\pm$?

- nuclear response functions:

$$W_{AB}^{\tau\tau'}(q^2) = \sum_{L\leq 2J} \langle \Psi \| \hat{A}_{L;\tau}(q) \| \Psi \rangle \langle \Psi \| \hat{B}_{L;\tau'}(q) \| \Psi \rangle$$

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

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

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

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

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

  - nuclear ground-state $|\Psi\rangle$

Ab initio nuclear structure calculations

Given a Hamiltonian solve the eigenvalue problem of A nucleons

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

- realistic internucleon interactions
- controllable approximations

Ab initio no-core shell model

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

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

  (dimensions up to $\sim 10^{10}$ with $\sim 10^{14}$ nonzero matrix elements)
- all particles are active (no core)
- NCSM results converge to exact results, $N_{\mathrm{tot}}\to\infty$

- 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$_{\text{sim}}$ [Carlsson *et al.*, PRX 6, 011019 (2016)]
    - parameters fitted to reproduce *simultaneously* πN, NN, and NNN low-energy observables
    - family of 42 Hamiltonians where the experimental uncertainties propagate into LECs
    - 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}

Results

^{4}He target: nuclear response functions and recoil rates

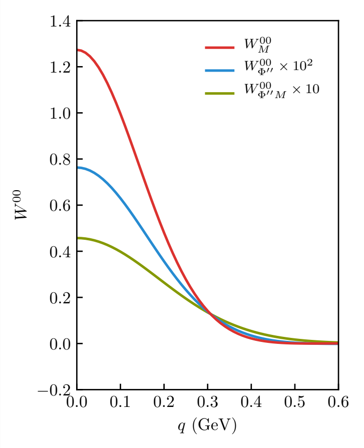


Figure 1: Isoscalar nuclear response functions of ^{4}He as functions of the recoil momentum q calculated within *ab initio* NCSM using $\mathrm{NNLO_{sim}}$.

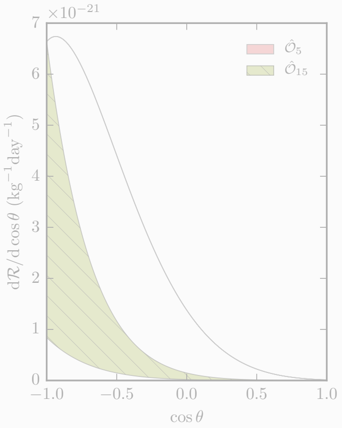


Figure 2: Differential rate of nuclear recoil events as a function of the recoil direction.

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

^{4}He target: nuclear response functions and recoil rates

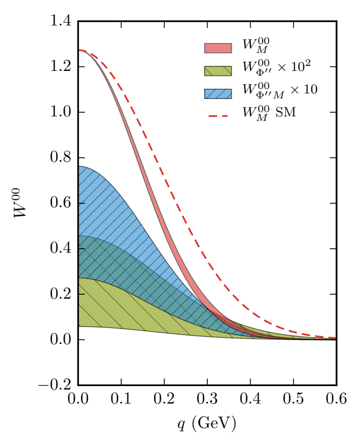


Figure 1: Isoscalar nuclear response functions of ^{4}He as functions of the recoil momentum q calculated within *ab initio* NCSM using $\mathrm{NNLO_{sim}}$ and NI-SM.

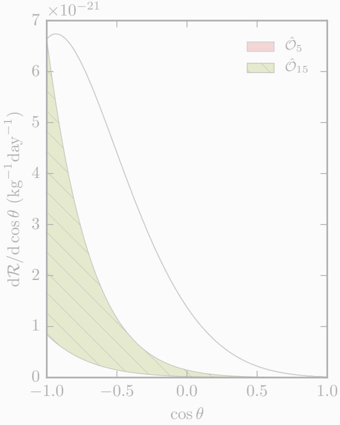
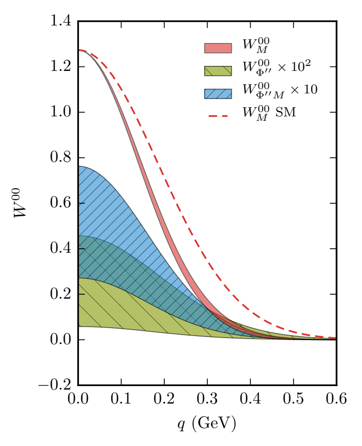


Figure 2: Differential rate of nuclear recoil events as a function of the recoil direction.

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

^{4}He target: nuclear response functions and recoil rates



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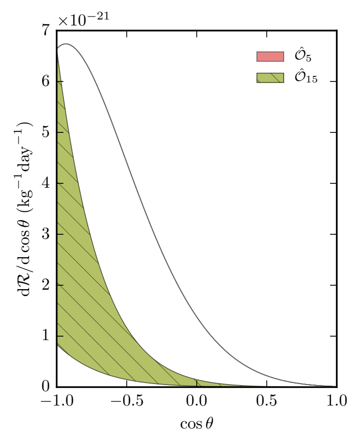

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^{16}O nuclear response functions

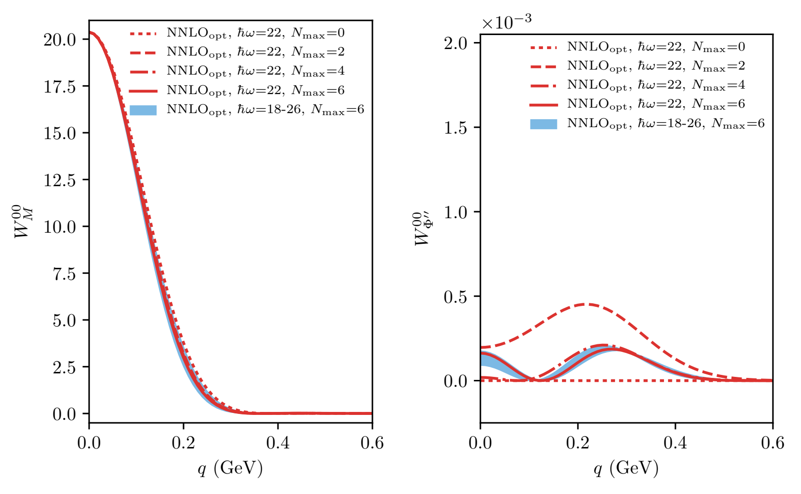


Figure 3: Isoscalar nuclear response functions W_M^{00} and $W_{\Phi''}^{00}$ of ^{16}O as functions of the recoil momentum q calculated within *ab initio* NCSM using NNLO$_{\rm opt}$.

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

^{19}F nuclear response functions

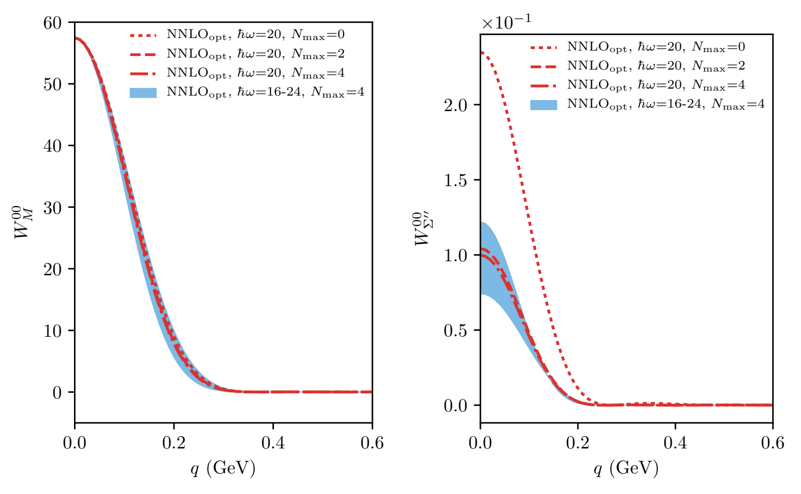
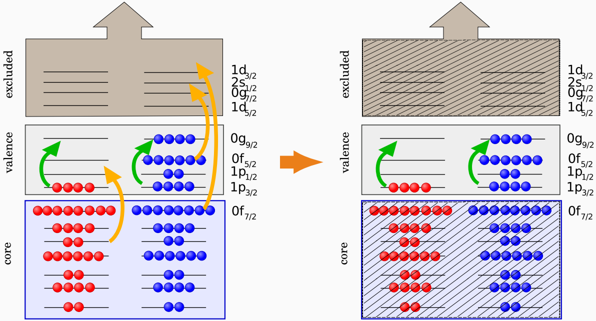


Figure 4: Isoscalar nuclear response functions W_M^{00} and $W_{\Sigma''}^{00}$ of ^{19}F as functions of the recoil momentum q calculated within *ab initio* NCSM using NNLO$_{\rm opt}$.

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

Shell model with IM-SRG valence-space interactions

- **For large number of particles NCSM becomes intractable**
- Perform unitary transformation $\tilde{H} = UHU^{\dagger}$ which decouples valence-space orbits and provides effective interaction for shell-model calculations:



[Taken from Ragnar Stroberg]

- broad range of applicability $2 \lesssim A \lesssim 100$
- allows consistent evolution of all operators (no phenomenological g-factors!)

^{23}Na nuclear response functions

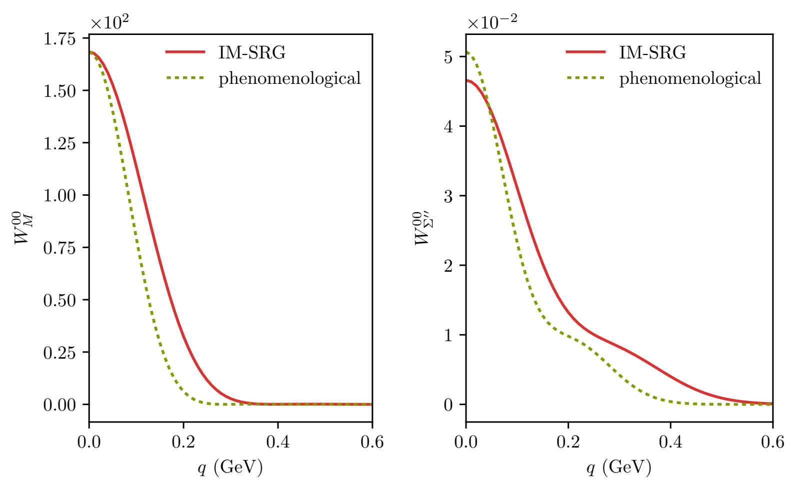


Figure 5: Isoscalar nuclear response functions W_M^{00} and $W_{\Sigma''}^{00}$ of ^{23}Na as functions of the recoil momentum q calculated within SM (^{16}O core + *sd*-shell) using IM-SRG (EM 1.8/2.0) and phenomenological (w) interactions.

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

^{40}Ca nuclear response functions

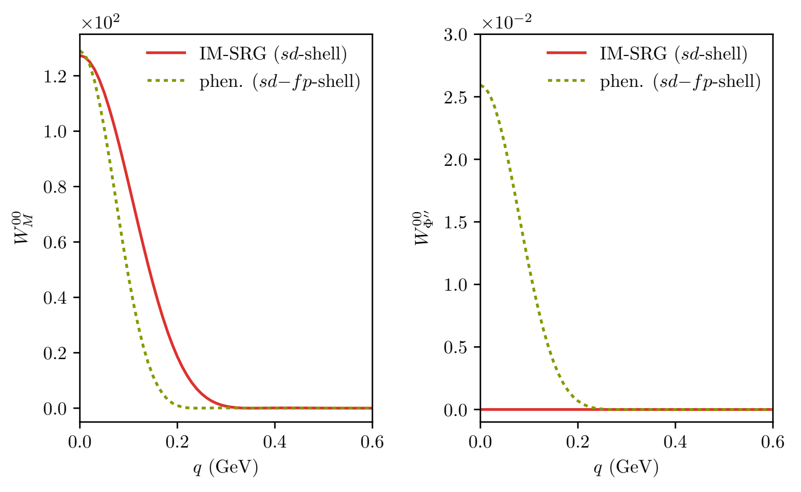


Figure 6: Isoscalar nuclear response functions W_M^{00} and $W_{\Sigma''}^{00}$ of ^{40}Ca as functions of the recoil momentum q calculated within SM using IM-SRG (EM 1.8/2.0) and phenomenological (sdpfnow) valence space interactions.

- for $q \to 0$: $W_M^{00} \propto A^2$, $W_{\Sigma''}^{00} \propto \langle \sum_i^A \boldsymbol{\sigma}_{(i)} \rangle^2$
- consistent evolution of all operators is necessary

Conclusions & outlook

Conclusions & Outlook

- *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 targets, consistent IM-SRG evolution of operators
- Two-body meson-exchange currents, inelastic scattering, …