

Ab initio nuclear structure for dark matter searches

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Nuclear Structure and Reactions: Building Together for the Future
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*Knut och Alice
Wallenbergs
Stiftelse*



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Outline

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

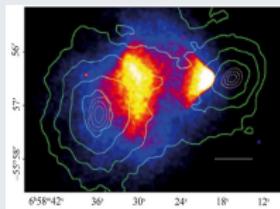
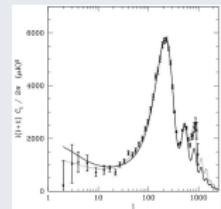
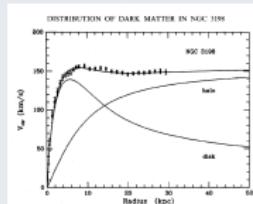
Dark matter

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.

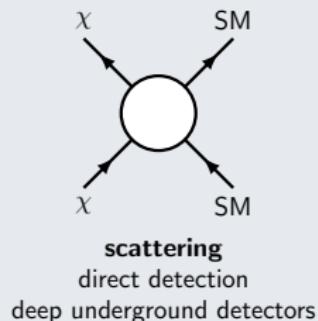
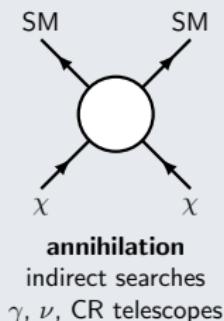
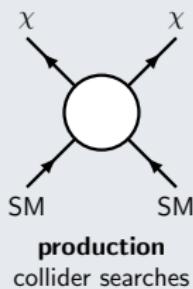


Dark matter

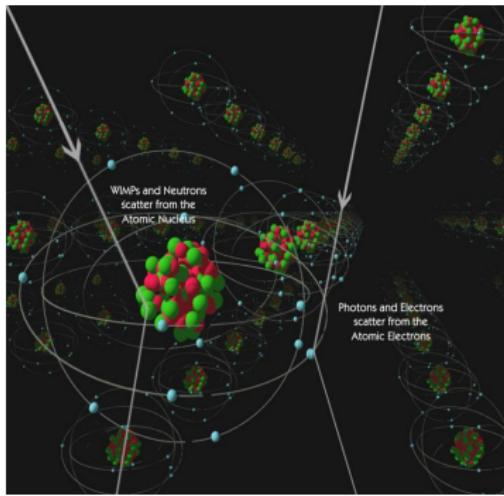
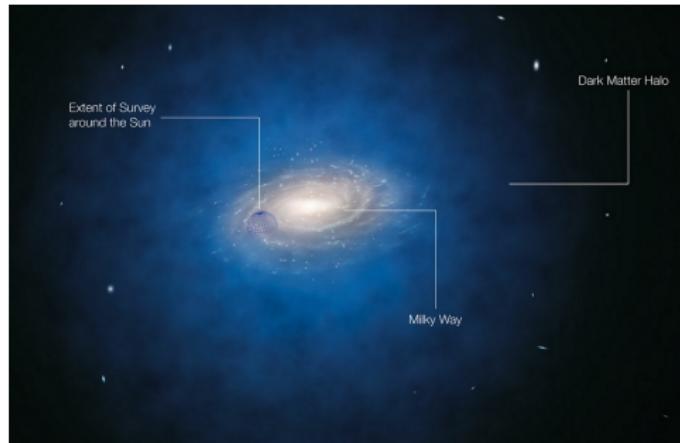
WIMP

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

WIMP dark matter searches



Dark matter direct detection & nuclear physics



taken from: CDMS collaboration

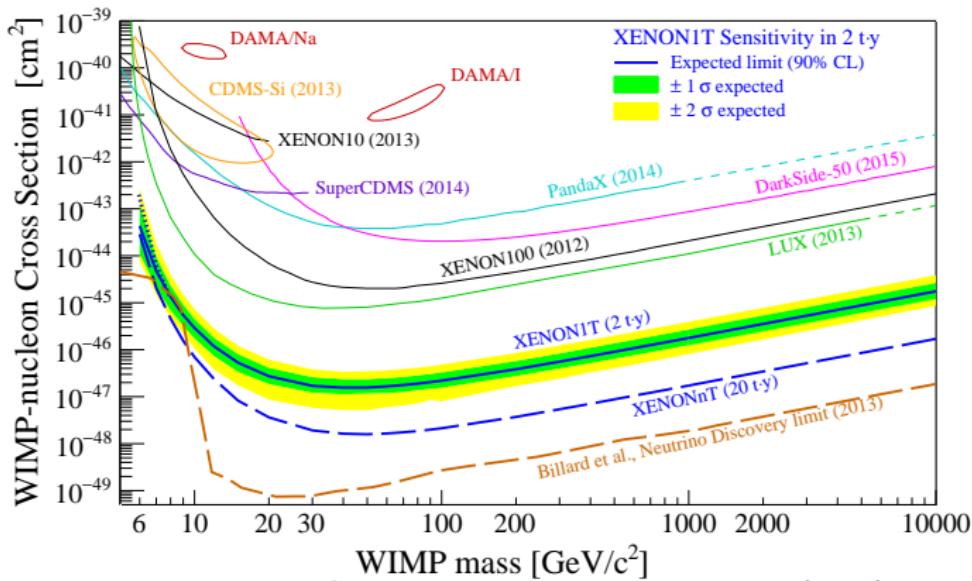
Typical (expected) nuclear recoil momentum can reach

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

Nuclear structure is resolved!

Current status

- no signal → upper bounds on *spin-independent* cross section



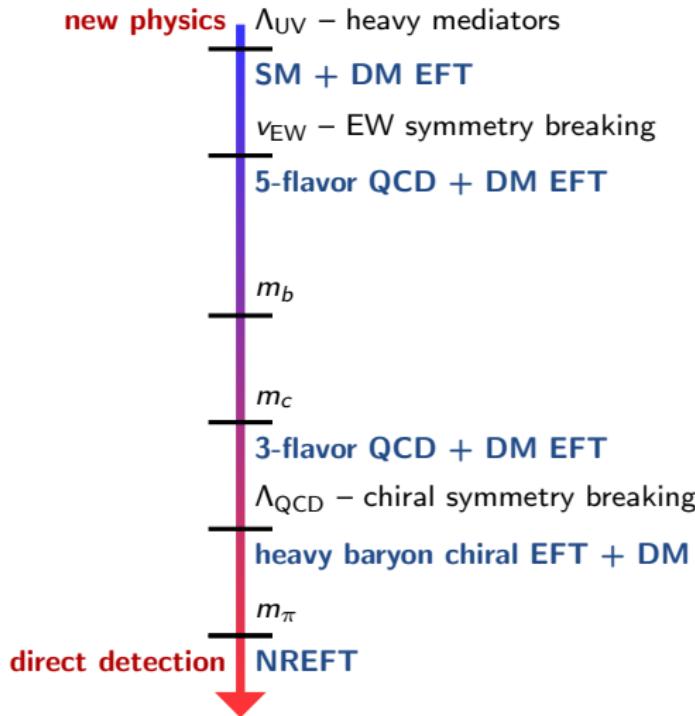
taken from: XENON collaboration, JCAP 1604, 027 (2016)

- 2017: XENON1T (run 0: [arXiv:1705.06655](https://arxiv.org/abs/1705.06655) [astro-ph.CO], still collecting data),
PandaX-II ([arXiv:1708.06917](https://arxiv.org/abs/1708.06917) [astro-ph.CO])
- 2019: XENONnT, 2019+ LZ
- 2020+: DARWIN (will reach the neutrino floor)

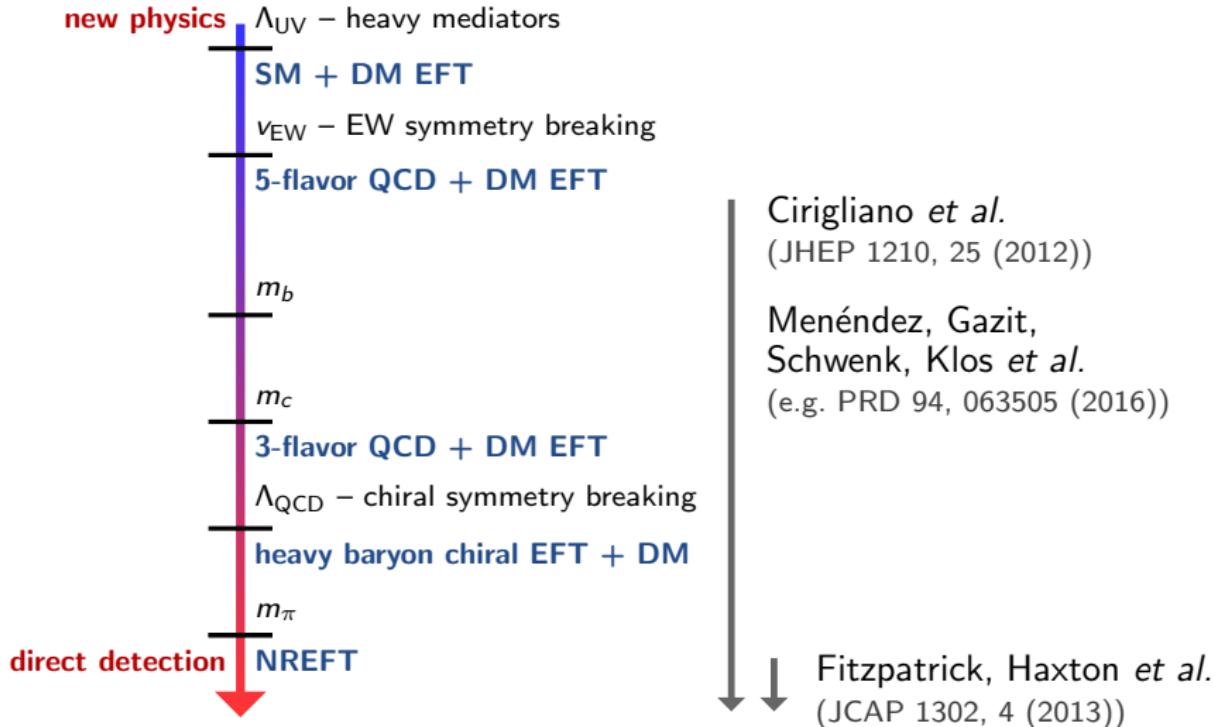
Aims

- Quantify the impact of **nuclear structure uncertainties** on the interpretation of data from dark matter searches.
- Apply *ab initio* methods in calculations WIMP scattering off:
 - ^3He , ^4He (detectors in R&D phase)
Jacobi-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

Dark matter – nucleus interaction



Dark matter – nucleus interaction



Nonrelativistic EFT for DM–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:

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

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

$$\hat{\mathcal{O}}_1 = 1_{\chi N}$$

$$\hat{\mathcal{O}}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N} \right)$$

$$\hat{\mathcal{O}}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp \right)$$

$$\hat{\mathcal{O}}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}$$

$$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$$

$$\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}$$

$$\hat{\mathcal{O}}_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp \right)$$

$$\hat{\mathcal{O}}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp \right)$$

$$\hat{\mathcal{O}}_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N} \right) \left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N} \right)$$

$$\hat{\mathcal{O}}_{13} = i \left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp \right) \left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N} \right)$$

$$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp$$

$$\hat{\mathcal{O}}_{14} = i \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N} \right) \left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp \right)$$

$$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp$$

$$\hat{\mathcal{O}}_{15} = - \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N} \right) \left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp \right) \cdot \frac{\hat{\mathbf{q}}}{m_N} \right]$$

No evidence to justify simple $\hat{\mathcal{O}}_1 + \hat{\mathcal{O}}_4$ form!

- → DM–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:

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

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

Scattering cross section:

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

- 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?

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

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:

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

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

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

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

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

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

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

Ab initio

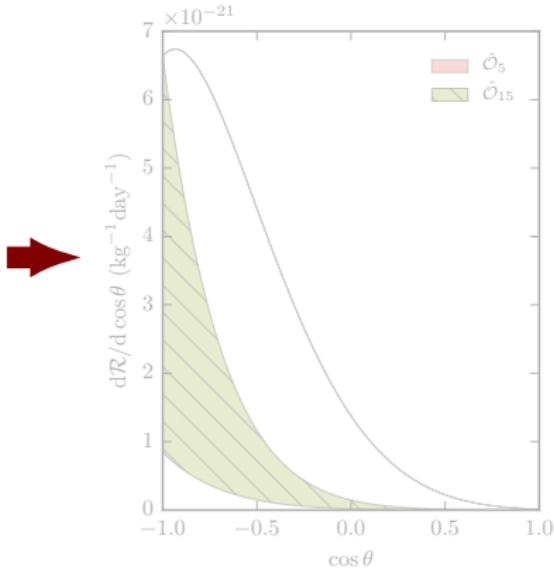
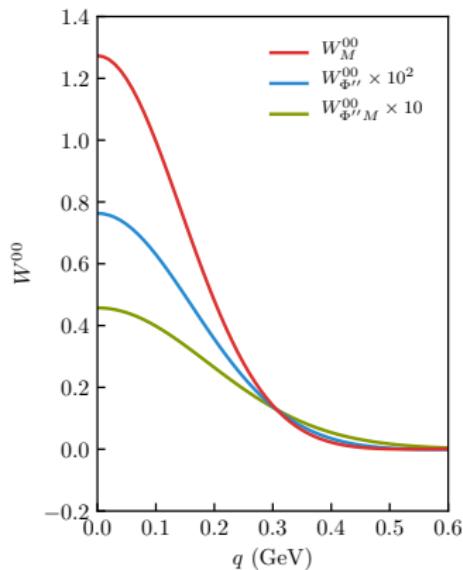
- all particles are active (no rigid core)
 - exact Pauli principle
 - realistic internucleon interactions
 - controllable approximations
-
- Hamiltonian is diagonalized in a *finite A*-particle harmonic oscillator basis
 - NCSM results converge to exact results

Input Hamiltonians

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

- **NNLO_{sim}** Hamiltonian family (Carlsson *et al.*, PRX 6, 011019 (2016))
 - parameters fitted to reproduce *simultaneously* πN , NN , and NNN low-energy observables
$$\left. \begin{array}{ll} T_{NN}^{\text{lab,max}} & \leq 125, \dots, 290 \text{ MeV} \\ \Lambda_{\text{EFT}} & \leq 450, \dots, 600 \text{ MeV} \end{array} \right\} \rightarrow 42 \text{ Hamiltonians}$$
 - all Hamiltonians give equally good description on the fit data
- **NNLO_{opt}** (A. Ekström *et al.*, PRL 110, 192502 (2013))
optimized 2-nucleon V_{NN} ; found to minimize the effect of V_{NNN}
- **NNLO_{sat}** (A. Ekström *et al.*, PRC 91, 051301 (2015))
optimized to reproduce πN , NN , NNN + *binding energies and radii of selected isotopes of carbon and oxygen*

^4He nuclear response functions and recoil rates



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

^4He nuclear response functions and recoil rates

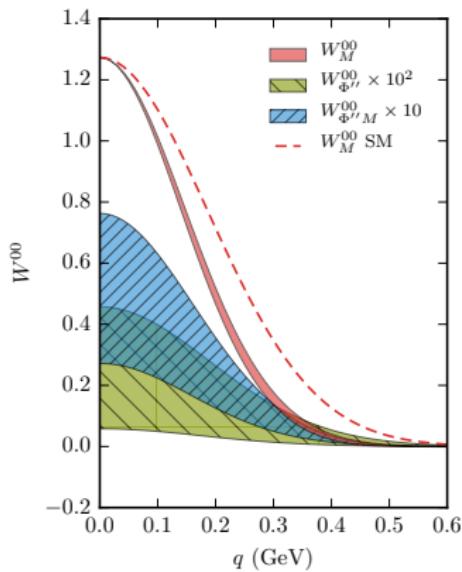


Figure: Isoscalar nuclear response functions of ^4He as functions of the recoil momentum q calculated within *ab initio* NCSM and NI-SM.

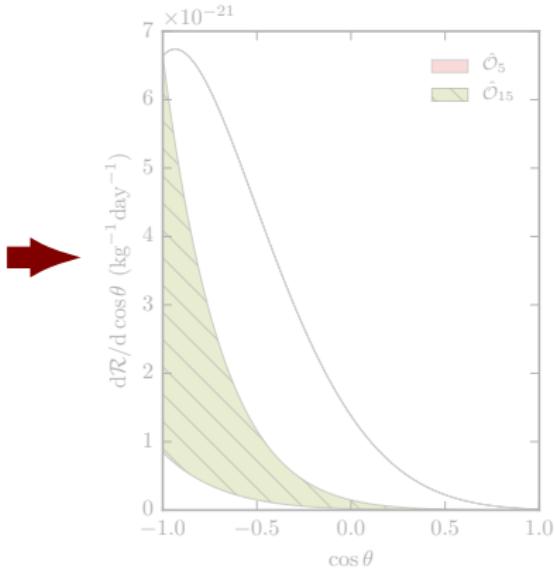


Figure: Differential rate of nuclear recoil events as a function of the recoil direction.

- only W_M^{00} , $W_{\Phi''}^{00}$, and $W_{\Phi''M}^{00}$ due to $J = T = 0$
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^4He nuclear response functions and recoil rates

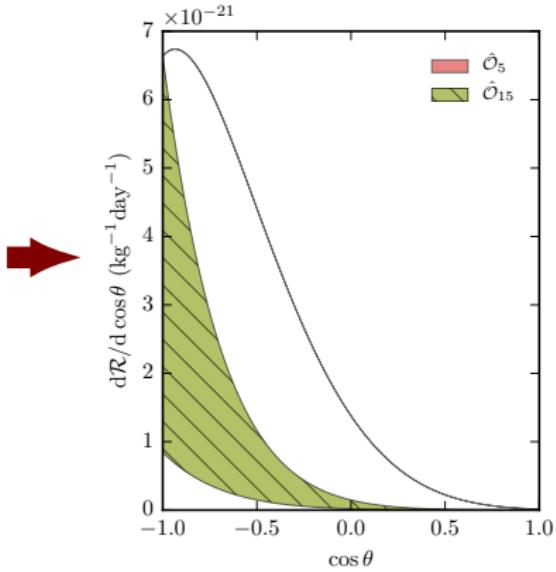
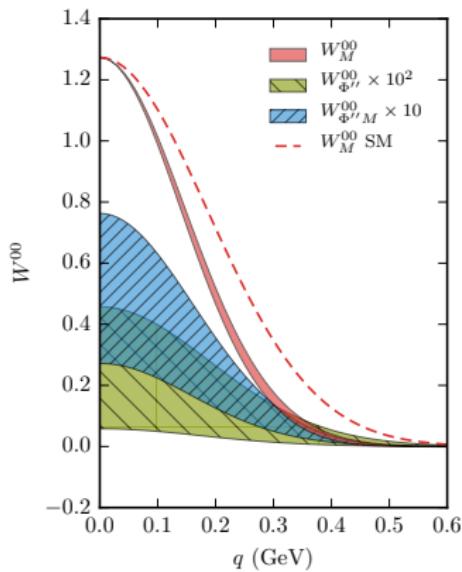


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^3He nuclear response functions and recoil rates

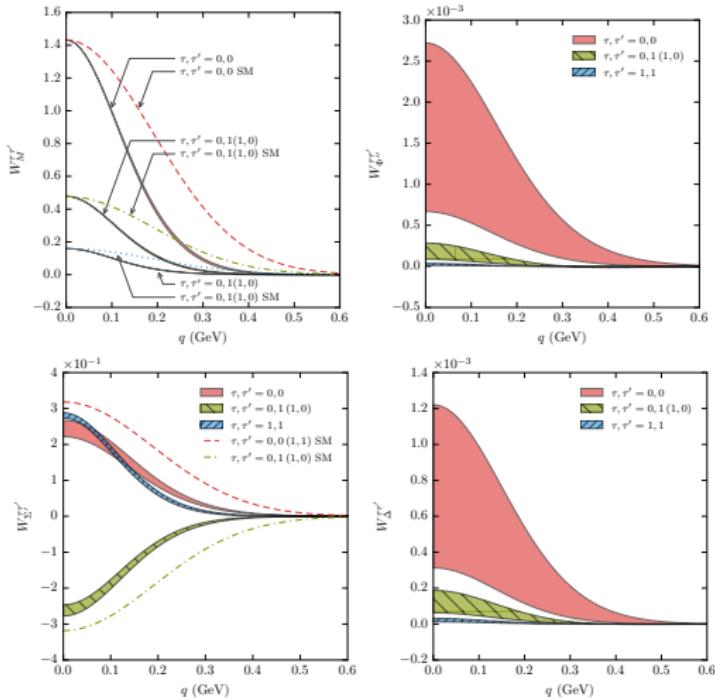


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- for $q \rightarrow 0$: $W_M^{00} \propto A^2$, $W_{\Phi''}^{00} \propto \langle \sum_i^A \mathbf{l}(i) \cdot \boldsymbol{\sigma}(i) \rangle^2$, $W_{\Sigma''}^{00} \propto \langle \sum_i^A \boldsymbol{\sigma}(i) \rangle^2$, $W_{\Delta}^{00} \propto \langle \sum_i^A \mathbf{l}(i) \rangle^2$

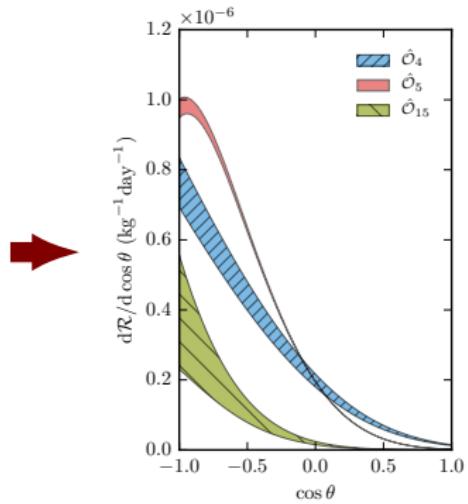


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^{16}O nuclear response functions

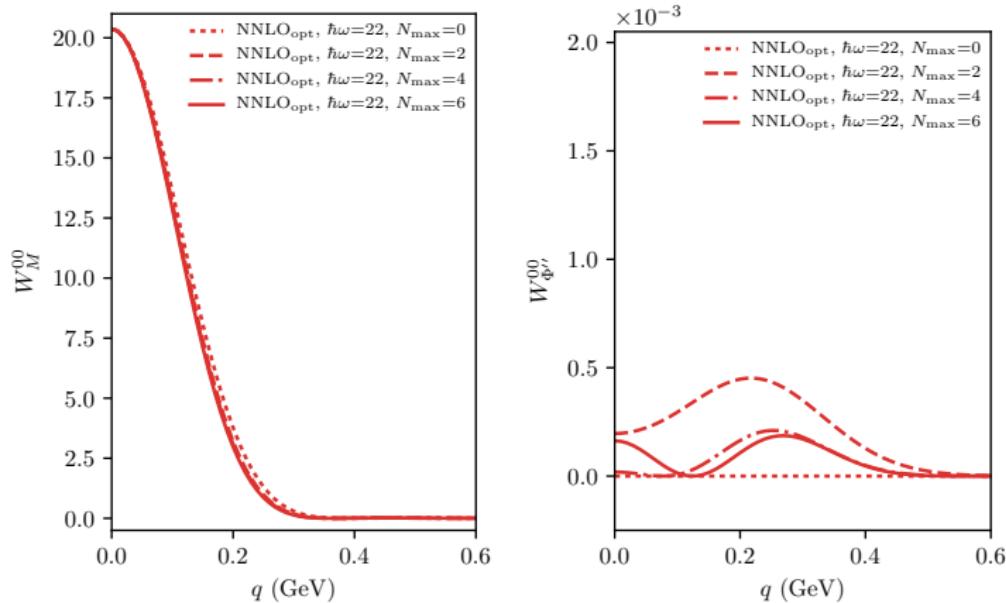


Figure: Isoscalar nuclear response functions W_M^{00} and $W_{\Phi''}^{00}$ of ^{16}O as functions of the recoil momentum q calculated within *ab initio* NCSM.

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

^{16}O nuclear response functions

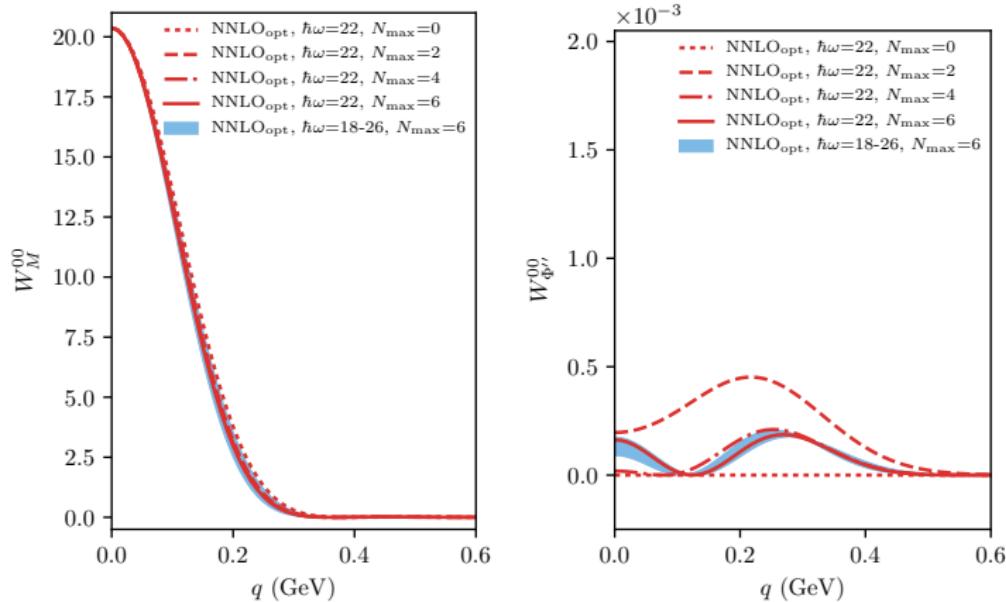


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^{16}O nuclear response functions

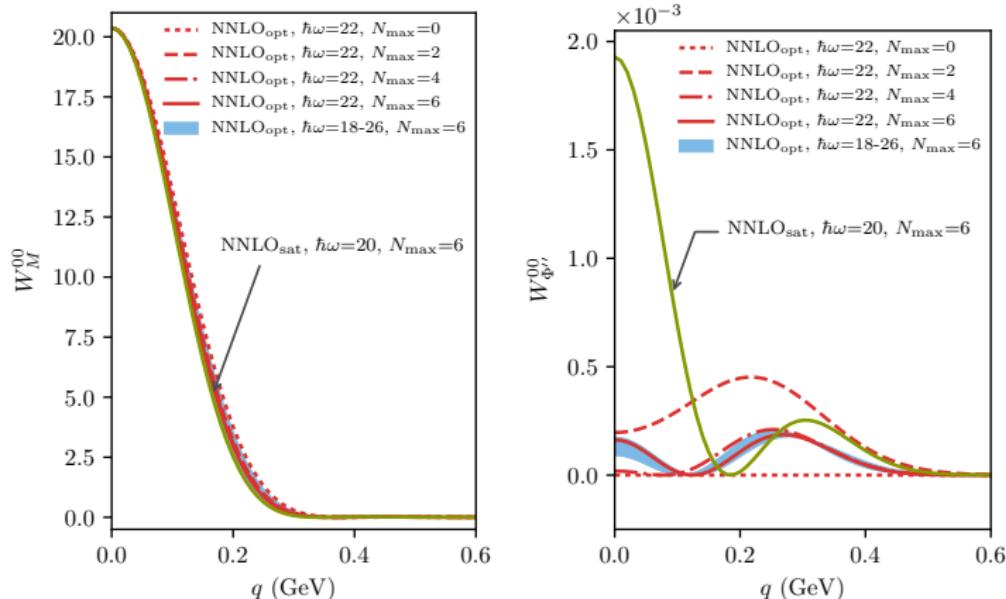


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^{19}F nuclear response functions

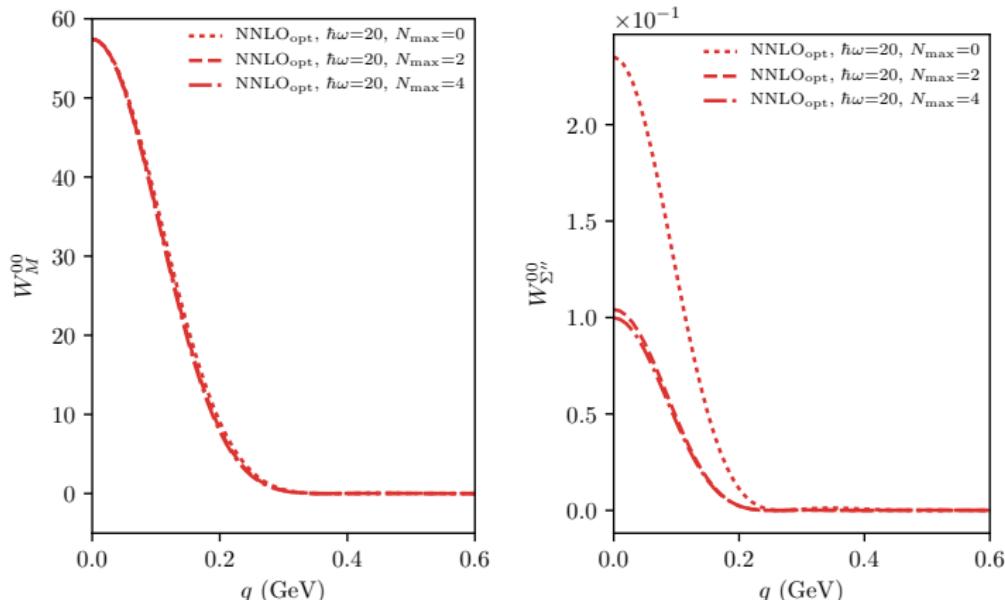


Figure: Isoscalar nuclear response functions W_M^{00} and $W_{\Sigma''}^{00}$ of ^{19}F as functions of the recoil momentum q calculated within *ab initio* NCSM.

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

^{19}F nuclear response functions

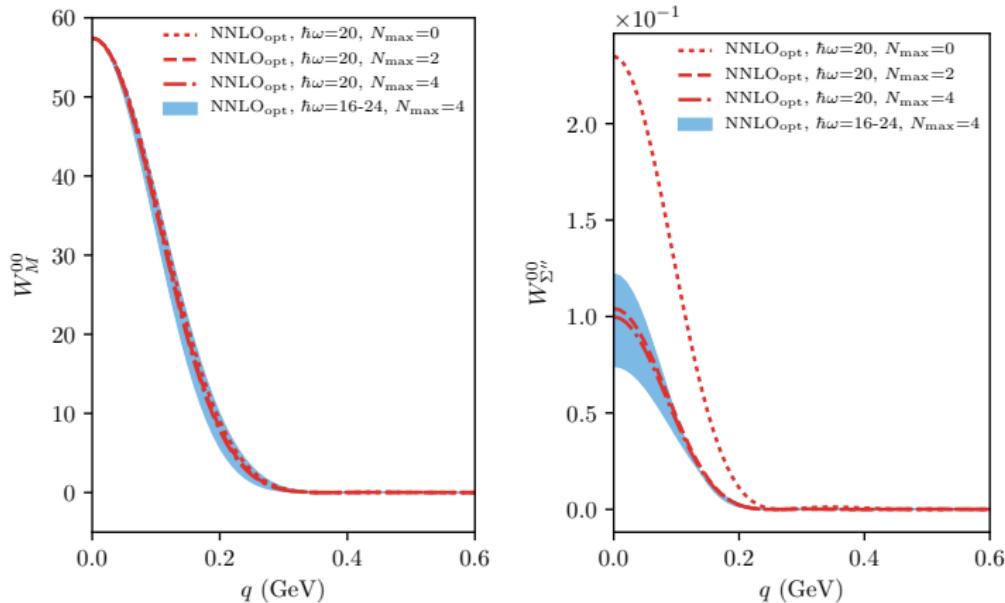


Figure: Isoscalar nuclear response functions W_M^{00} and $W_{\Sigma''}^{00}$ of ^{19}F as functions of the recoil momentum q calculated within *ab initio* NCSM.

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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.

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Outlook:

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