FIRST-PRINCIPLES NUCLEAR STRUCTURE COMPUTATIONS FOR SEARCHES OF PHYSICS BEYOND THE STANDARD MODEL

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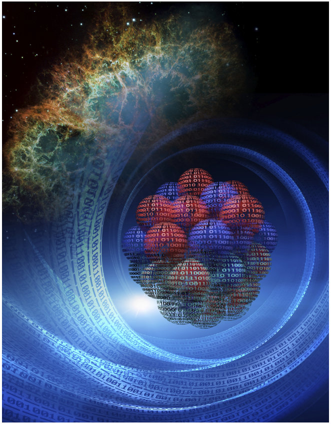
OUTLINE

- **MOTIVATION**
  - BSM searches and nuclear physics
- **NUCLEAR MANY-BODY METHODS**
  - Microscopic, phenomenological
  - Ab initio no-core shell model
  - Chiral EFT
- **NUCLEAR STRUCTURE INPUTS FOR DARK MATTER SEARCHES**
  - Nuclear response functions (structure factors)
  - Theoretical uncertainties
- **SUMMARY & OUTLOOK**



MOTIVATION

MOTIVATION

High-precision measurements of low-energy nuclear processes use atomic nuclei as laboratories to explore fundamental symmetries of nature and to search for signals of new physics beyond the Standard Model.

Beta decays

- precision searches for violations of SM predictions
- unitarity of CKM matrix

Neutrino scattering

- ν oscillations
- fluxes of atmospheric, supernova ν

$0\nu\beta\beta$ decays

- ν masses, hierarchy
- Dirac/Mayorana ν
- violation of lepton number conservation
- matter–antimatter asymmetry in the Universe

Dark matter

- searching for DM-induced nuclear recoil events in deep-underground experiments

Observables

nuclear half-life of $0\nu\beta\beta$:
$T_{1/2}^{-1} = G_{0\nu}|f|^2|M^{0\nu}|^2$
depends on nuclear matrix element $M^{0\nu}$

- However, we are still lacking a systematic first-principles description of nuclear many-body systems.

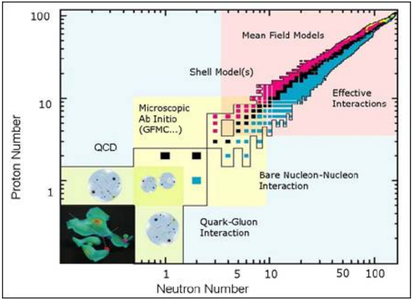
NUCLEAR MANY-BODY METHODS

Nuclear many-body problem

Starting point: Non-relativistic Schrödinger equation with point nucleons as our degrees of freedom

$$\hat{H}\,\Psi(\mathbf{r}_1,\ldots,\mathbf{r}_A) = E\,\Psi(\mathbf{r}_1,\ldots,\mathbf{r}_A)$$

- difficult to solve
- we don't really know $\hat{H}$
- strongly interacting highly correlated system
- many computational methods on the market



NUCLEAR MANY-BODY METHODS

Microscopic

- NCSM, GFMC, CC, etc.
- Use realistic V_{NN}
- Direct (brute-force) solution
- Operators treated consistently
- Basis dimension grows rapidly (exponentially)
- Light nuclei

Phenomenological

- SM, RPA, DFT, etc.
- Use effective $\langle V_{NN}^{eff} \rangle$ adjusted to nuclear observables
- How to treat operators? (quenching factors!)
- More gentle scaling with A

Nonperturbative renormalization

- Okubo-Lee-Suzuki, many-body perturbation theory, similarity renormalization group
- systematic way for $V_{NN} \rightarrow \langle V_{NN}^{eff} \rangle$
- consistent transformation of other operators

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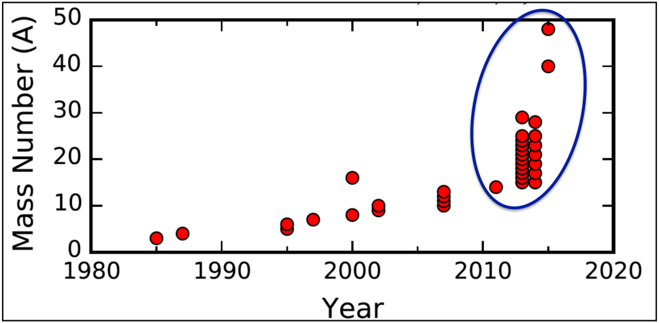
REACH OF AB INITIO METHODS

- Many-body methods with polynomial scaling (CC, SCGF, IMSRG) reach Ca, Ni region and even beyond
- Precision of computational methods exceeds accuracy of available nuclear interactions



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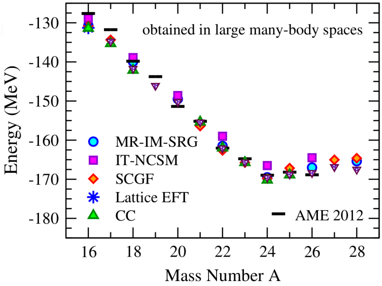
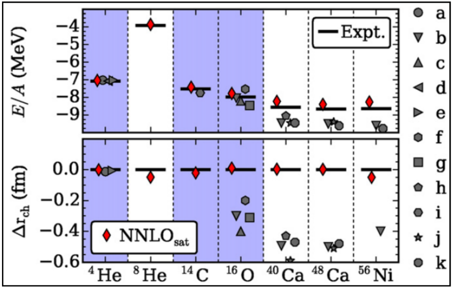




AB INITIO NO-CORE SHELL MODEL

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

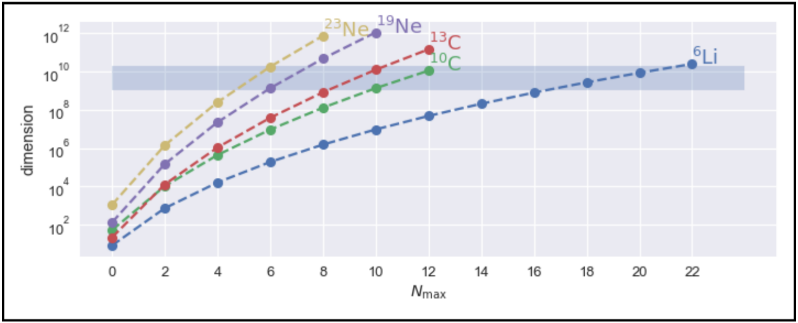
$$\Psi(\mathbf{r}_1,\ldots,\mathbf{r}_A)=\sum_{n\leq N_{tot}}\phi_n^{HO}(\mathbf{r}_1,\ldots,\mathbf{r}_A)$$

  (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, $N_{tot}\to\infty$

  [P. Navrátil et al., PPNP 69, 131 (2013)]

AB INITIO NO-CORE SHELL MODEL

- Basis dimensions for p- and sd-shell nuclei:



Taken from: C. Forssén, `pAntoine` code.

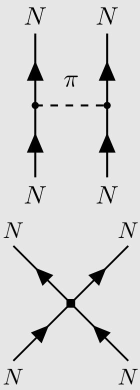
- Symmetry-Adapted-NCSM (T. Dytrych et al. @ LSU)
  - Exploits dynamical symmetries to select relevant basis states.
  - Calculations up to pf-shell nuclei possible!

CHIRAL EFT BASED NUCLEON–NUCLEON INTERACTIONS

Chiral EFT

- incorporates symmetries of QCD at low energies
- scale separation in nuclear physics
- pions (π) and nucleons (N) as relevant degrees of freedom
- long-range physics = one-pion exchange
- short-range physics = contact interactions (fitted to experimental data)
- systematic expansion of V_{NN} in powers of $\frac{Q}{\Lambda}$, with typical momentum Q and $\Lambda \approx 1$ GeV breakdown scale

V_{NN} at LO in $\frac{Q}{\Lambda}$



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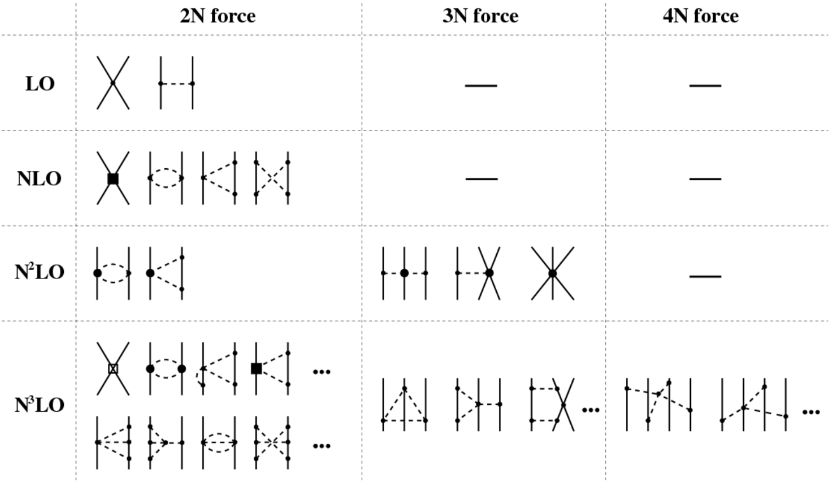
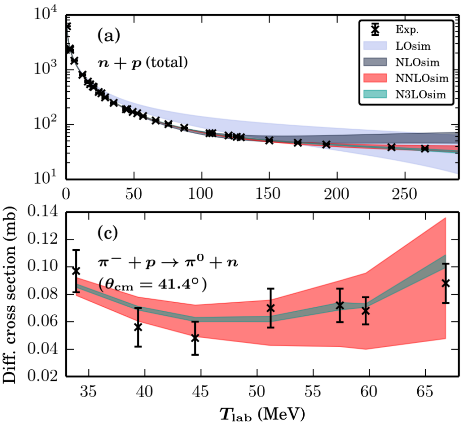


[E. Epelbaum, H. Hammer, U. Meissner, Rev. Mod. Phys. 81, 1773 (2009).
R. Machleidt, D. Entem, Phys. Rep. 503, 1 (2011).]

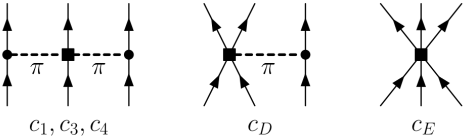
Order by order convergence of scattering observables



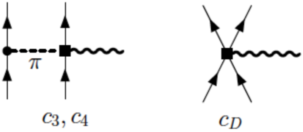
[B. Carlsson et al., PRX 6, 011019 (2016)]

CONSISTENCY OF CHIRAL FORCES AND NUCLEAR CURRENTS

- The same low-energy constants (LECs) appearing in nuclear forces determine coupling to external electroweak probes
- Weak axial-vector currents couple to spin, similar to pions (g_A)
- Chiral EFT 3-body nuclear forces



- Chiral EFT 2-body nuclear currents



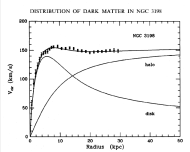
NUCLEAR PHYSICS FOR DARK MATTER SEARCHES

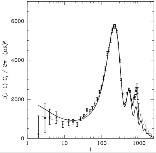
Evidence for dark matter

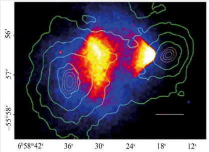
Dark matter makes up about 85% of the total matter in the Universe.

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

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





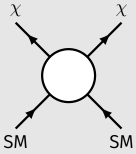


DARK MATTER SEARCHES

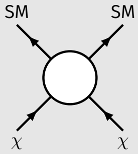
WIMP

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

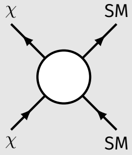
WIMP searches



production
collider searches

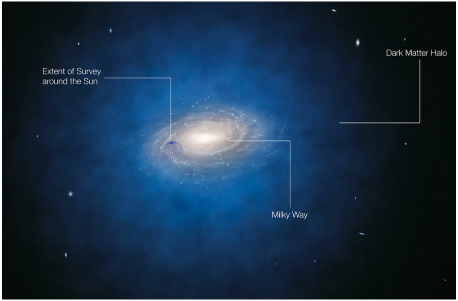


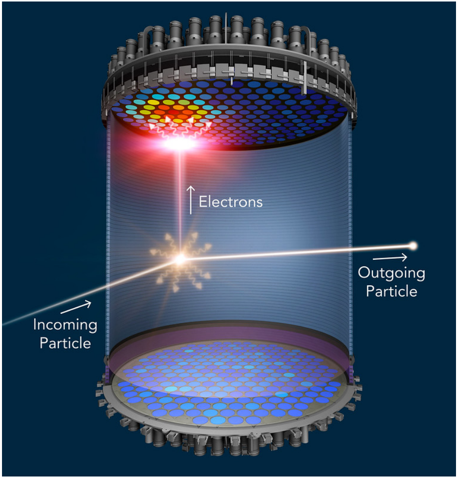
annihilation
indirect searches
γ, ν, CR telescopes



scattering
direct detection
deep-underground detectors

DARK MATTER DIRECT DETECTION

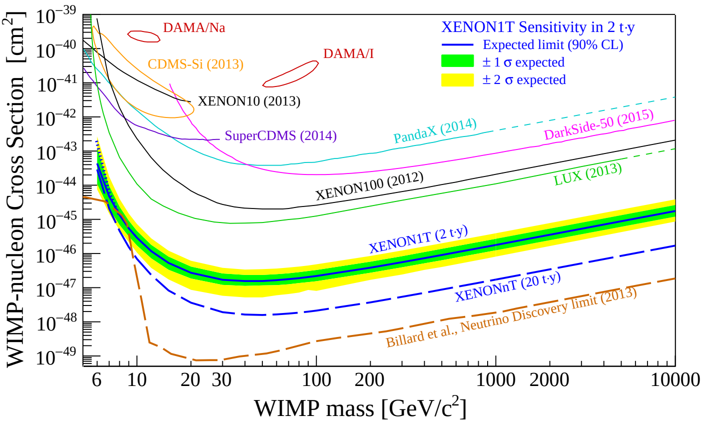




[Taken from: LZ collaboration.]

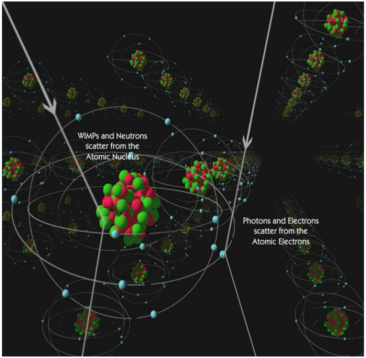
- Galaxies submerged in halos of DM particles
- Deep-underground low-background sensitive experiments searching for WIMP-induced nuclear/electronic recoils

CURRENT STATUS OF DARK MATTER DIRECT DETECTION



- **2017**: PandaX-II (arXiv:1708.06917 [astro-ph.CO])
- **2018**: XENON1T Phys. Rev. Lett. 121, 111302 (2018)
- **2019**: XENONnT, **2019+** LZ
- **2020+**: DARWIN (will reach the neutrino floor)

- Null results: upper bounds on dark matter–nucleon cross section



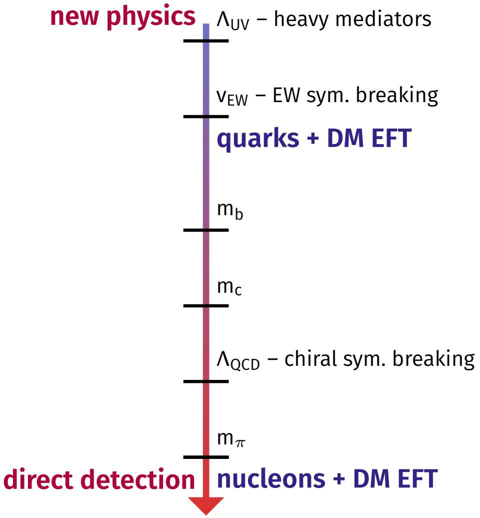
[Taken from: CDMS collaboration]

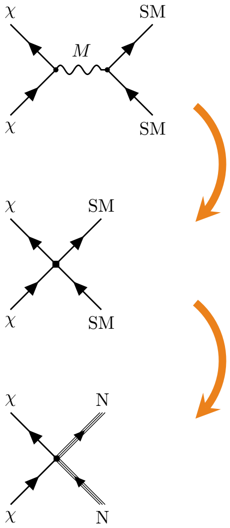
Typical (expected) nuclear recoil momentum can reach

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

Nuclear structure is resolved!

DARK MATTER–NUCLEUS INTERACTION





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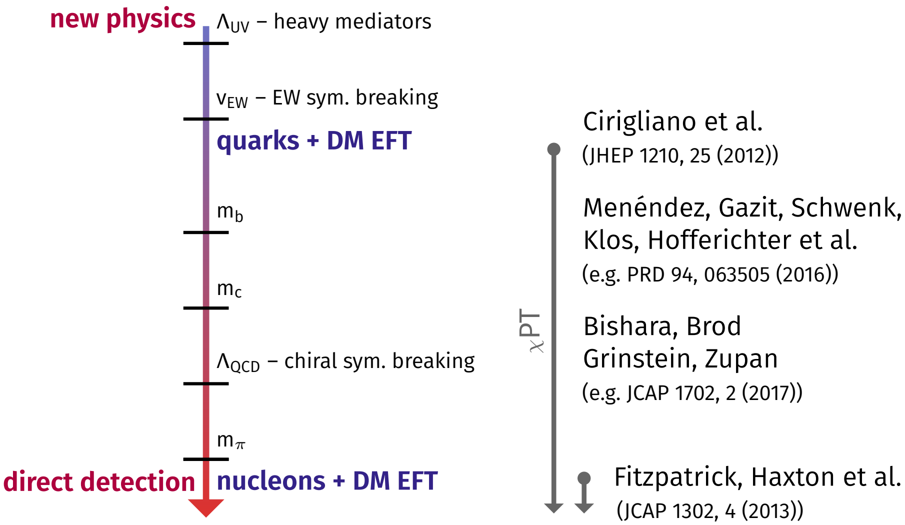

AIMS

- 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)
      IMSRG valence-space interactions + SM

NONRELATIVISTIC EFT FOR DM–NUCLEUS INTERACTION

- Interaction of DM particles with SM fields is not known $\rightarrow$ effective theories
- 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 $\mathbf{q}^2$):

$$\hat{O}_1 = 1_{\chi N} \qquad \hat{O}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right)$$

$$\hat{O}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right) \qquad \hat{O}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}$$

$$\hat{O}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N \qquad \hat{O}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}$$

$$\hat{O}_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right) \qquad \hat{O}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right)$$

$$\hat{O}_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right) \qquad \hat{O}_{13} = i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$$

$$\hat{O}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp \qquad \hat{O}_{14} = i\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right)$$

$$\hat{O}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp \qquad \hat{O}_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$$

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

Scattering cross section:

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

- 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:

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

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

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

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

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

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

  - many-body nuclear wave function $|\Psi\rangle$

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

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

^{4}He TARGET: NUCLEAR RESPONSE FUNCTIONS AND RECOIL RATES

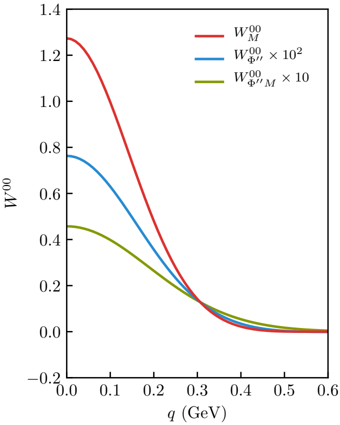

Figure 1: Isoscalar nuclear response functions of ^{4}He as functions of the recoil momentum q calculated within ab initio NCSM using $\mathrm{NNLO_{sim}}$.

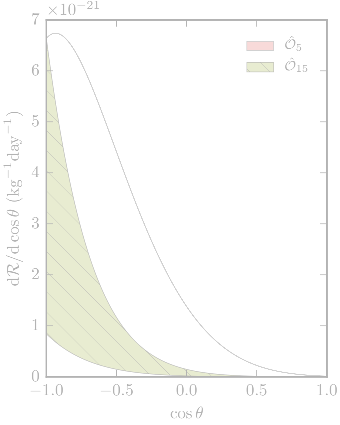

Figure 2: Differential rate of nuclear recoil events as a function of the recoil direction.

- 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 $W^{00}_{\Phi''} \propto \langle \sum_i^A \mathbf{l}_{(i)} \cdot \boldsymbol{\sigma}_{(i)} \rangle^2$

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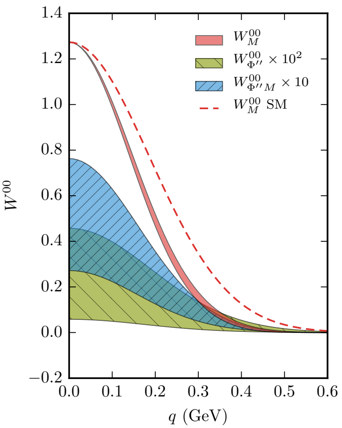
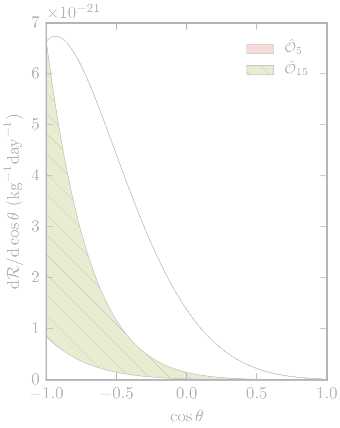


Figure 1: Isoscalar nuclear response functions of ^{4}He as functions of the recoil momentum q calculated within ab initio NCSM using NNLO$_{\text{sim}}$ and NI-SM.



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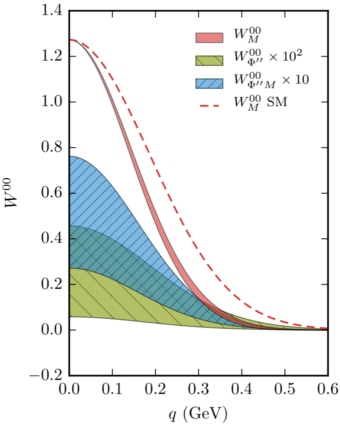

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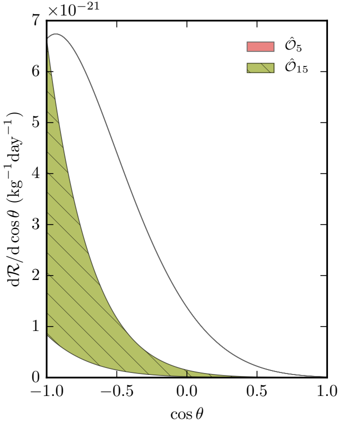

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^{16}O NUCLEAR RESPONSE FUNCTIONS

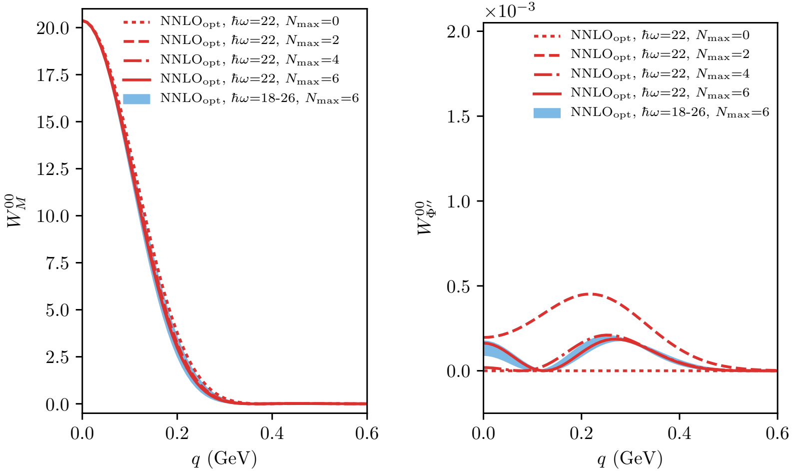


Figure 3: Isoscalar nuclear response functions W_M^{00} and $W_{\Phi''}^{00}$ of ^{16}O as functions of the recoil momentum q calculated within ab initio NCSM using NNLO$_{\mathrm{opt}}$.

- 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

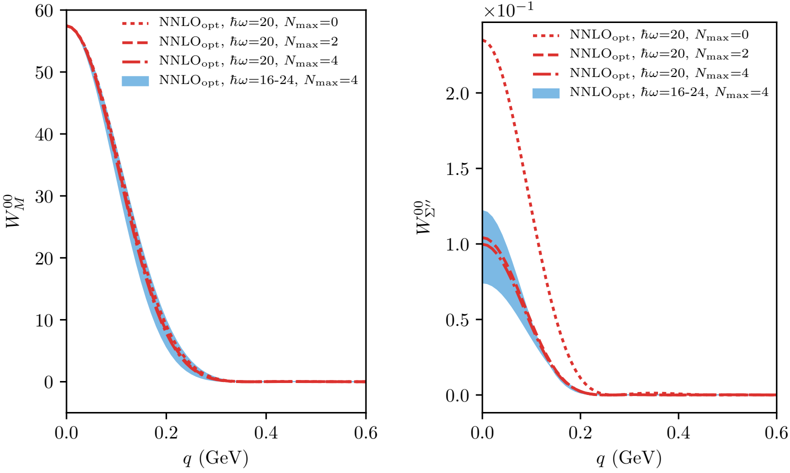
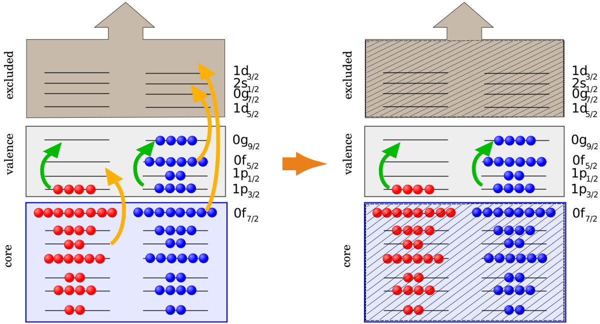


Figure 4: Isoscalar nuclear response functions W^{00}_{M} and $W^{00}_{\Sigma''}$ of ^{19}F as functions of the recoil momentum q calculated within ab initio NCSM using NNLO$_{\rm opt}$.

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

SHELL MODEL WITH IMSRG VALENCE-SPACE INTERACTIONS

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



[Taken from: R. Stroberg]

- broad range of applicability $2 \lesssim A \lesssim 100$

^{23}Na NUCLEAR RESPONSE FUNCTIONS

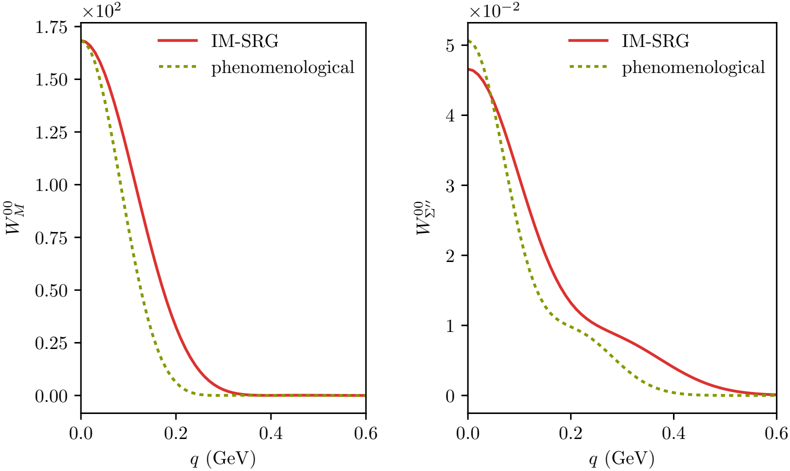


Figure 5: Isoscalar nuclear response functions W_M^{00} and $W_{\Sigma''}^{00}$ of ^{23}Na as functions of the recoil momentum q calculated within SM (^{16}O core + sd-shell) using IMSRG (EM 1.8/2.0) and phenomenological (w) interactions.

- 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

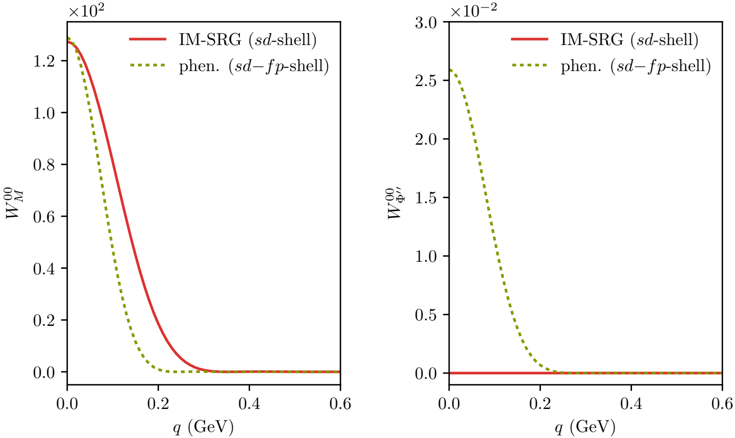


Figure 6: Isoscalar nuclear response functions W_M^{00} and $W_{\Sigma''}^{00}$ of ^{40}Ca as functions of the recoil momentum q calculated within SM using IMSRG (EM 1.8/2.0) and phenomenological (sdpfnow) valence space interactions.

- 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

SUMMARY & OUTLOOK

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Summary (DM scattering)

- 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 phenomenological calculations.

[Phys. Rev. D 95, 103011 (2017)]

Outlook

- Apply the framework in:
  - nuclear beta decays, $\beta - -\nu$ correlations
  - nuclear double-beta decays

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