Quantum Monte Carlo calculations of dark matter scattering off light nuclei

ECT*, Trento, Italy

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April 16, 2019

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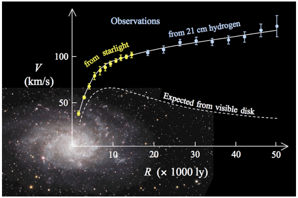
Outline

- Dark Matter and its direct detection
- Interaction: from DM-quarks to DM-nucleons
- Nuclear wave functions
- Results

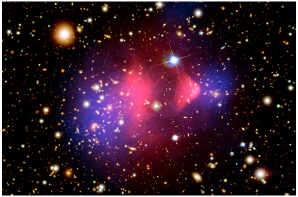
Dark Matter

Dark Matter

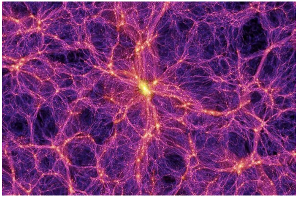
It's out there:



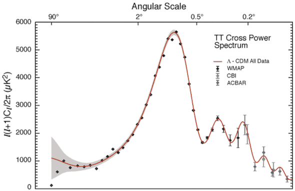
Rotation curves



Gravitational lensing



Structure formation

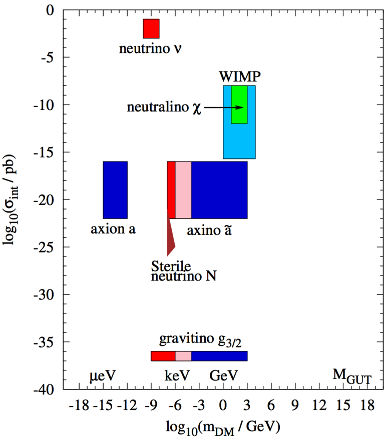


CMB anisotropy

Particle candidates

Requirements:

- Stable on cosmological time scales
- Very weakly interacting with EM radiation
- Correct density



Roszkowski et al., arXiv:1707.06277

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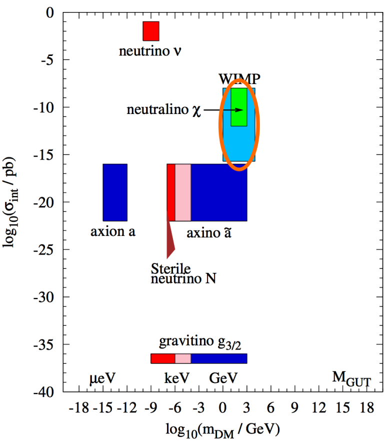

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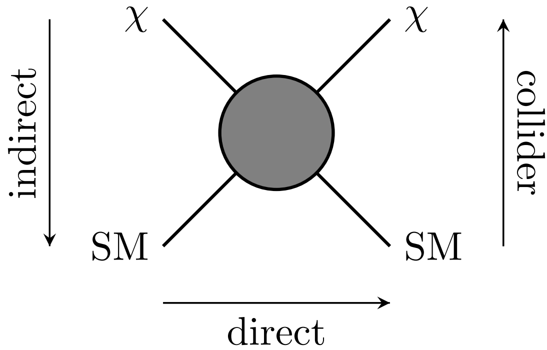
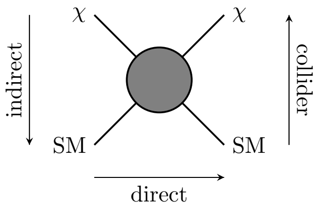
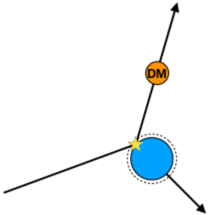
Detection

Mainly three possible methods to detect WIMPs:



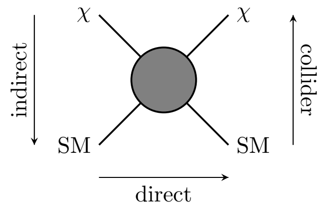
Detection

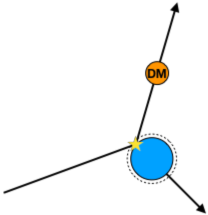




$$N(\boldsymbol{p}_i) + \chi(\boldsymbol{k}) \to N(\boldsymbol{p}_i') + \chi(\boldsymbol{k}')$$

$$\boldsymbol{q} = \boldsymbol{k}' - \boldsymbol{k}$$





$$N(\boldsymbol{p}_i) + \chi(\boldsymbol{k}) \to N(\boldsymbol{p}_i') + \chi(\boldsymbol{k}')$$

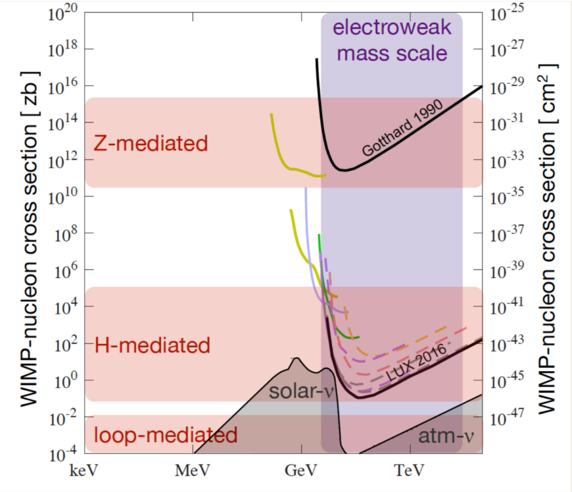
$$\boldsymbol{q} = \boldsymbol{k}' - \boldsymbol{k}$$

$$|\boldsymbol{q}| \lesssim 2\mu v_\chi^{(\mathrm{esc})} \lesssim A \times 2.5\ \mathrm{MeV}$$

$$E_R < \frac{|\boldsymbol{q}|^2}{2m_A}$$

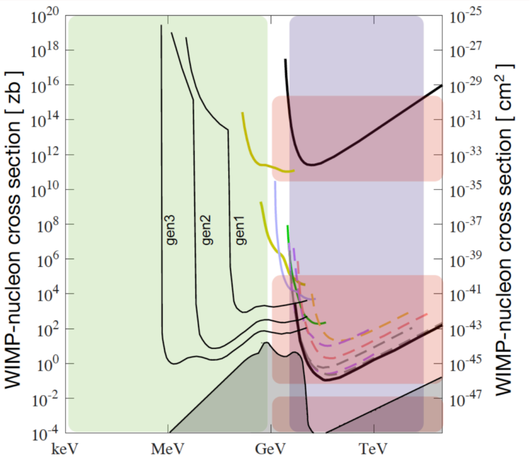
Sensitivity

Great expertimental progress



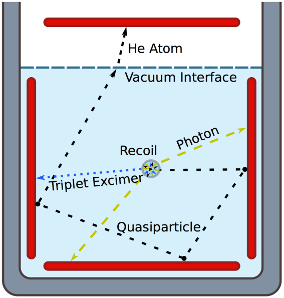
S. Hertel

From nucelar recoil on ^4He



S. A. Hertel, A. Biekert, J. Lin, V. Velan, and D. N. McKinsey, arXiv:1810.06283

Nuclear recoil in liquid He



Superfluid He:

- better kinematich matching with light DM
- high impedance to external vibration noise
- mechanism for observing phonon-like modes via liberation atoms into a vacuum

S. A. Hertel, A. Biekert, J. Lin, V. Velan, and D. N. McKinsey, arXiv:1810.06283

Light nuclei

- Benchmark: accurate nuclear calculations
- Potential experimental targets: He
- More sensitive to relatively light dark matter

^{2}H

^{3}H

^{3}He

^{4}He

^{6}Li

Interaction

A solid theoretical control of nuclear effects is necessary to interpret direct detection experiments

[1] J. Fan, M. Reece, and L.-T. Wang, JCAP 1011, 042 (2010), arXiv:1008.1591

[2] A. L. Fitzpatrick, W. Haxton, E. Katz, N. Lubbers, and Y. Xu, JCAP 1302, 004 (2013), arXiv:1203.3542

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[4] E. Chang et al., Phys. Rev. Lett. 120, 152002 (2018)

EFT

A solid theoretical control of nuclear effects is necessary to interpret direct detection experiments

A variety of approaches based on effective field theory have been proposed:

- non-relativistic DM-nucleus interactions[1]
- non-relativistic DM-nucleon interactions[2]
- DM-nucleon interactions derived from DM-quark and DM-gluon interactions[3]
- First principle, lattice-QCD calculations[4]

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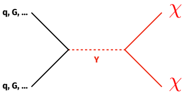
EFT

E

$\mathcal{L}_{BSM}$

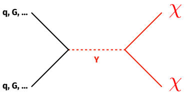


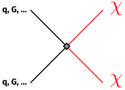
EFT

E

$$\mathcal{L}_{BSM}$$

$$\mathcal{L}_{SM} + \sum_{k,i} \frac{c_i^{(k)}}{\tilde{\Lambda}^k} \mathcal{O}_i^{(k)}[\chi^\dagger, \chi; q, G, \ldots]$$





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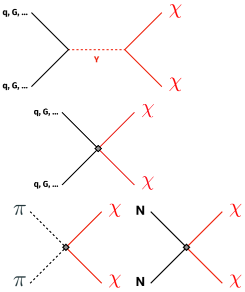
$$\mathcal{L}_{ChPT}[\chi; N, \pi, \ldots]$$



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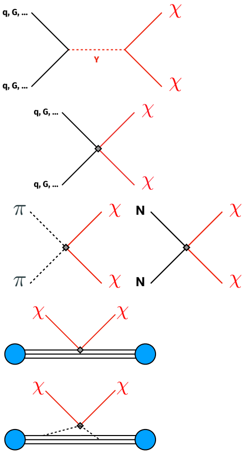
$$\mathcal{L}_{ChPT}[\chi; N, \pi, \ldots]$$

$$H_I = V_{\chi N} + V_{\chi NN} + \ldots$$

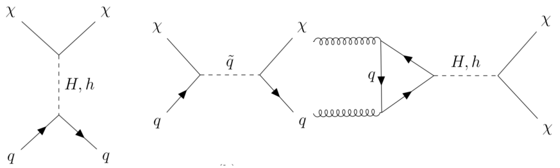
$$\langle \psi'_{(A,Z)}, X' | H_I | \psi_{(A,Z)}, X \rangle$$



Effective Lagrangian

Scalar case:

- Well motivated, e.g. Higgs and squark exchange mediate scalar interactions



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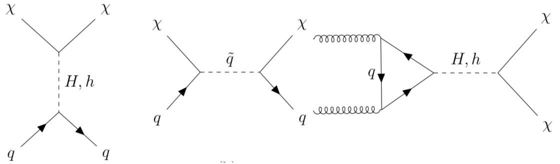

- interesting two body currents at NLO

Effective Lagrangian

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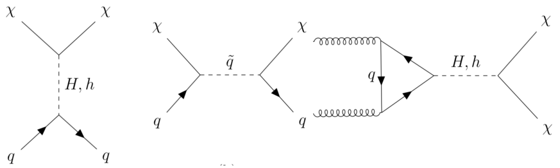
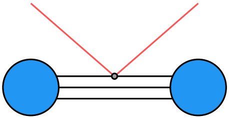
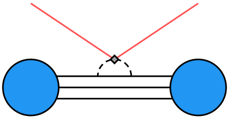


- interesting two body currents at NLO

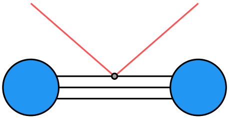
$$\mathcal{L}_{\text{eff}} = \frac{1}{\tilde{\Lambda}^3}\left(\sum_{q=u,d,s} c_q \bar{\chi}\chi m_q \bar{q}q + c_G \bar{\chi}\chi \alpha_s G^a_{\mu\nu} G^{\mu\nu}_a\right)$$

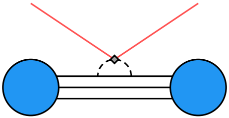
Effective Lagrangian





$$J^{(1)}(\boldsymbol{q}_i) = \frac{c_{\text{is}}}{\tilde{\Lambda}^3}\left[\sigma_{\pi N} - \frac{9 g_A^2 \pi m_\pi^3}{4(4\pi f_\pi)^2} F\left(\frac{|\boldsymbol{q}_i|}{2m_\pi}\right)\right] - \frac{c_{\text{iv}}}{\tilde{\Lambda}^3}\frac{\delta m_N}{4}\tau_i^z$$
$$+ \frac{c_s}{\tilde{\Lambda}^3}\left(\sigma_s - \dot{\sigma}_s \boldsymbol{q}^2\right) - \frac{c_G}{\tilde{\Lambda}^3}\frac{8\pi m_N^G}{9}$$


LO


NLO

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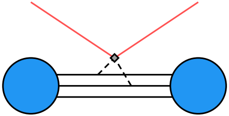
$$F(x) = \frac{-x + (1+2x^2)\arctan x}{3x}$$

$$c_{\text{is}} = \frac{c_u m_u + c_d m_d}{m_u + m_d}, \qquad c_{\text{iv}} = 2\frac{c_d m_d - c_u m_u}{m_d - m_u}$$

Effective Lagrangian



NLO

$$J_{\pi\pi}^{(2)}(\boldsymbol{q}_i, \boldsymbol{q}_j) = -\frac{c_{\text{is}}}{\tilde{\Lambda}^3}\left(\frac{g_A}{2F_\pi}\right)^2 m_\pi^2 \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j \frac{\boldsymbol{\sigma}_i \cdot \boldsymbol{q}_i \boldsymbol{\sigma}_j \cdot \boldsymbol{q}_j}{(\boldsymbol{q}_i^2 + m_\pi^2)(\boldsymbol{q}_j^2 + m_\pi^2)}$$

Nuclear Wave Functions

Cross section

End goal: calculate matrix elements for elastic scattering

$$J(\boldsymbol{q}) = \sum_i e^{i\boldsymbol{q}\cdot\boldsymbol{r}_i} J^{(1)}(\boldsymbol{q}) + \sum_{i<j} J^{(2)}_{\pi\pi}(\boldsymbol{q}; \boldsymbol{r}_i, \boldsymbol{r}_j)$$

$J(\boldsymbol{q})$ is the Fourier transform of the regularized one- and two-body currents

$$\frac{d\sigma}{d\boldsymbol{q}^2} = \frac{1}{4\pi v_\chi^2} \frac{1}{2j+1} \sum_{m_j, m_j' = -j}^{j} \left| \langle \psi_{jm_j'} | J(\boldsymbol{q}) | \psi_{jm_j} \rangle \right|^2$$

Nuclear Wave Functions

Nuclear Hamiltonian: Argonne v_{18}[5] + Urbana IX[6]

$$H = \sum_i T_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} v_{ijk}$$

[5] R. B. Wiringa, V. G. J. Stoks, and R. Schiavilla, Phys. Rev. C 51, 38 (1995)
[6] B. S. Pudliner, V. R. Pandharipande, J. Carlson, S. C. Pieper, and R. B. Wiringa, Phys. Rev. C 56, 1720 (1997)

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Use nuclear wave functions that minimize the expectation value of E

$$E_V = \frac{\langle\psi|H|\psi\rangle}{\langle\psi|\psi\rangle} \geq E_0$$

The evaluation is performed using Metropolis sampling

[5] R. B. Wiringa, V. G. J. Stoks, and R. Schiavilla, Phys. Rev. C 51, 38 (1995)
[6] B. S. Pudliner, V. R. Pandharipande, J. Carlson, S. C. Pieper, and R. B. Wiringa, Phys. Rev. C 56, 1720 (1997)

Nuclear Wave Functions

Variational wave function for nucleus in J state:

$$|\psi\rangle = \mathcal{S} \prod_{i<j}^{A} \left[1 + U_{ij} + \sum_{k \neq i,j}^{A} U_{ijk} \right] \left[\prod_{i<j} f_c(r_{ij}) \right] |\Phi(JMTT_3)\rangle \, .$$

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Two-body spin- and isospin-dependent correlations

$$U_{ij} = \sum_p f^p(r_{ij}) O_{ij}^p$$

$$O_{ij}^p = [1, \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j, S_{ij}] \otimes [1, \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j]\,.$$

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$$U_{ijk} = \epsilon v_{ijk}\left(\overline{r}_{ij}, \overline{r}_{jk}, \overline{r}_{ki}\right).$$

Results

Event rate

Event rate:

$$\frac{dN}{dE_R} \propto \Phi \otimes \frac{d\sigma}{dE_R}$$

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Flux factor: DM local density and velocity distribution

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Wimp-nucleus cross section: particle physics $\times$ hadronic & nuclear physics

$$d\sigma \sim \sigma_p \otimes R_{nuclear}$$

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Focus on the cross section

Nuclear response function

It is convenient to expand the total cross section in terms of nuclear response functions:

$$\frac{d\sigma}{d\boldsymbol{q}^2} = \frac{c_{\text{is}}^2}{\tilde{\Lambda}^6} \frac{\sigma_{\pi N}^2 A^2}{4\pi v_\chi^2} \times$$

$$\left|\mathcal{F}_{\text{is}}^{(0)}(\boldsymbol{q}^2) + \mathcal{F}_{\text{is,r}}^{(1)}(\boldsymbol{q}^2) + \mathcal{F}_{\text{is,2b}}^{(1)}(\boldsymbol{q}^2) - \frac{c_{\text{iv}}}{c_{\text{is}}} \frac{\delta m_N}{4\sigma_{\pi N}} \mathcal{F}_{\text{iv}}^{(0)}(\boldsymbol{q}^2)\right|^2$$

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We concentrate on the case $c_{\text{is}} \neq 0$, setting $c_{\text{iv,s,G}}/c_{\text{is}} = 0$

Additional couplings do not introduce independent nuclear responses

$$\mathcal{F}_{\text{iv}}^{(0)}(\boldsymbol{q}^2) = \frac{2Z - A}{A} \times \mathcal{F}_{\text{is}}^{(0)}(\boldsymbol{q}^2)$$

Also, general case can be obtained rescaling $\mathcal{F}_{\text{is}}^{(0)}(\boldsymbol{q}^2)$ by the factor

$$1 + \left(\frac{c_s}{c_{\text{is}}}\right) \frac{\sigma_s - \dot{\sigma}_s \, \boldsymbol{q}^2}{\sigma_{\pi N}} - \left(\frac{c_G}{c_{\text{is}}}\right) \frac{8\pi m_N^G}{9\sigma_{\pi N}}$$

Radius correction

We define a "radius correction" as the percentual contributio of the NLO one-body current to the total cross section:

$$\Delta^{(r)} = \frac{\left|\mathcal{F}_{\mathrm{is}}^{(0+1)}(\boldsymbol{q}^2)\right|^2 - \left|\mathcal{F}_{\mathrm{is}}^{(0)}(\boldsymbol{q}^2) + \mathcal{F}_{\mathrm{is,2b}}^{(1)}(\boldsymbol{q}^2)\right|^2}{\left|\mathcal{F}_{\mathrm{is}}^{(0+1)}(\boldsymbol{q}^2)\right|^2}$$

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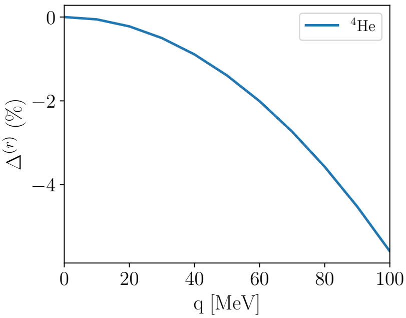
$$\Delta^{(r)} \sim \frac{2\mathcal{F}^{(1)}_{\mathsf{is,r}}(\boldsymbol{q}^2)}{\mathcal{F}^{(0+1)}_{\mathsf{is}}(\boldsymbol{q}^2)} \sim -\frac{2}{\sigma_{\pi N}} \frac{9 g_A^2 \pi m_\pi^3}{4(4\pi f_\pi)^2} F\left(\frac{|\boldsymbol{q}|}{2m_\pi}\right)$$



Two-body correction

Similarly, for the two-body current:

$$\Delta^{(2b)} = \frac{\left|\mathcal{F}_{\mathsf{is}}^{(0+1)}(\boldsymbol{q}^2)\right|^2 - \left|\mathcal{F}_{\mathsf{is}}^{(0)}(\boldsymbol{q}^2) + \mathcal{F}_{\mathsf{is,r}}^{(1)}(\boldsymbol{q}^2)\right|^2}{\left|\mathcal{F}_{\mathsf{is}}^{(0+1)}(\boldsymbol{q}^2)\right|^2}.$$

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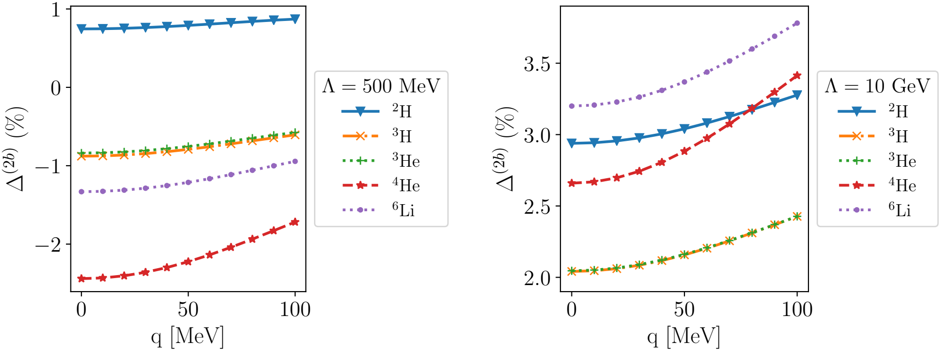

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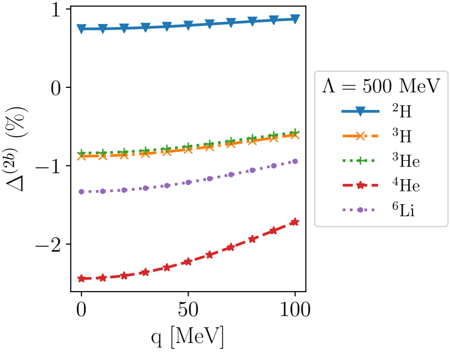
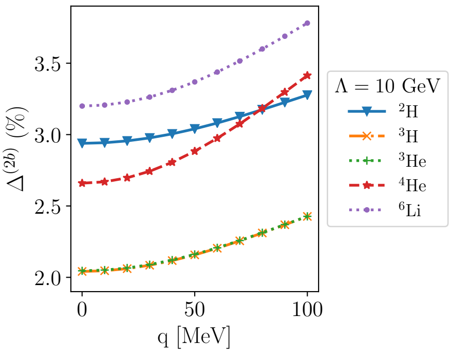
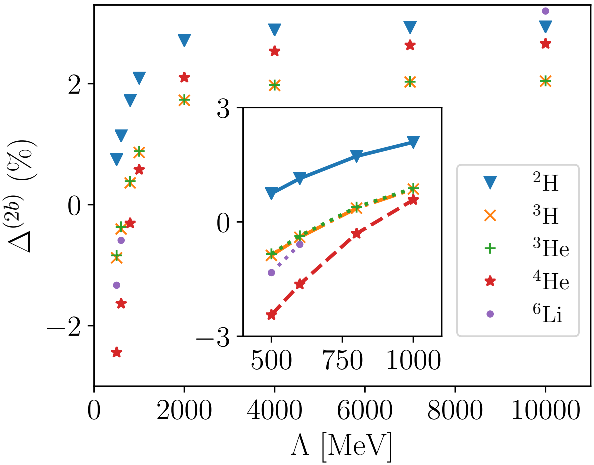


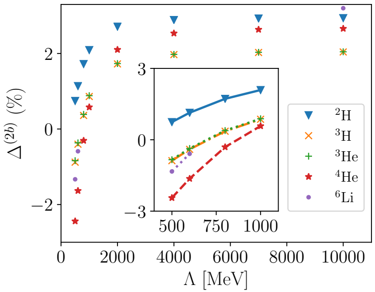


Two-body correction



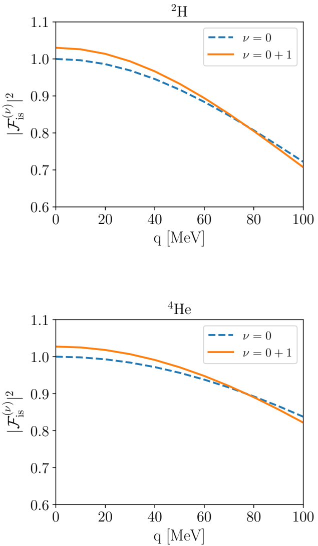
Two-body correction

Sources of uncertainty:



- Cutoff dependence
- Sigma term, tension between dispersion relation and lattice-QCD calculation

Total cross section



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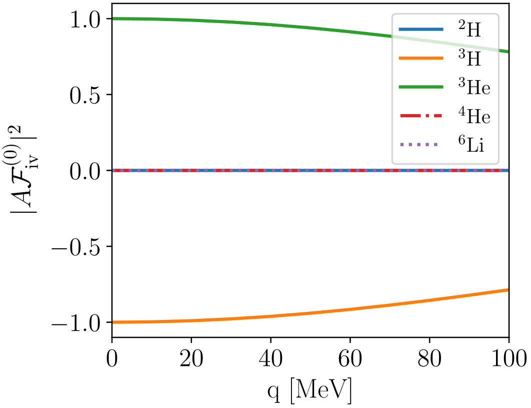

Conclusions

DM-nucleus scattering calculations for light nuclei, using QMC

- Light nuclei, first calculation for two-body currents in $A = 4, 6$
- Overall size of NLO correction of the order of few %, even assigning a conservative estimate on the two-body matrix elements
- Our results provide nuclear structure input needed to assess the sensitivity of future experimental searches of light dark matter using ^{3}He and ^{4}He targets.

Outlook

Future studies

- Other mediators - Vector and Axial-Vector
- Moving beyond the hybrid approach: chiral interactions + QMC
- Exploring consistency of Weinberg power counting

Thank you!