# Chiral EFT for dark matter detection experiments

Martin Hoferichter

Albert Einstein Center for Fundamental Physics,
Institute for Theoretical Physics, University of Bern

UNIVERSITÄT BERN

AEC
ALBERT EINSTEIN CENTER
FOR FUNDAMENTAL PHYSICS

August 2, 2022

INT program 22-2b on

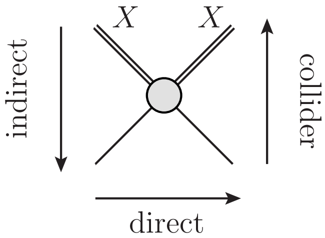
Dark Matter in Compact Objects, Stars, and Low-Energy Experiments

# Direct detection of dark matter: scales

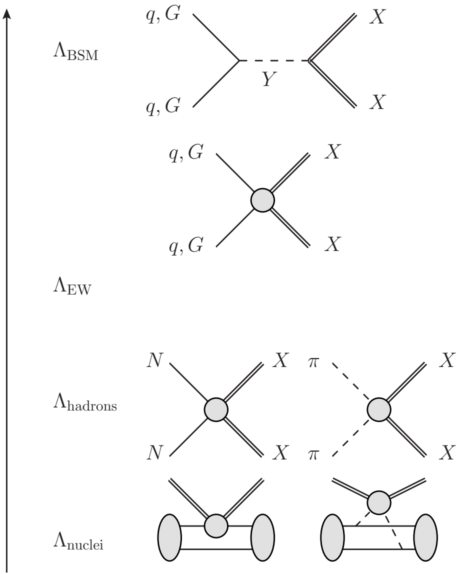
## Rate for WIMP–nucleus scattering

$$\frac{dR}{dE_r} = \underbrace{\frac{\sigma^{SI}_{\chi N}}{m_\chi \mu_N^2}}_{\text{particle + hadronic physics}} \times \underbrace{\left|\mathcal{F}_+^M(q^2)\right|^2}_{\text{nuclear physics}} \times \underbrace{\rho_0 \int_{v_{min}}^{v_{esc}} \frac{f(\mathbf{v}, t)}{v} d^3 v}_{\text{astrophysics}}$$

- Decomposition follows from EFT
- $\sigma^{SI}_{\chi N}$ subsumes physics from QCD to BSM scale
  $\hookrightarrow$ use EFT to keep track
- Can also use EFT for comparison with indirect detection or collider constraints (as long as EFT applies)
- **Chiral EFT for hadronic/nuclear part**

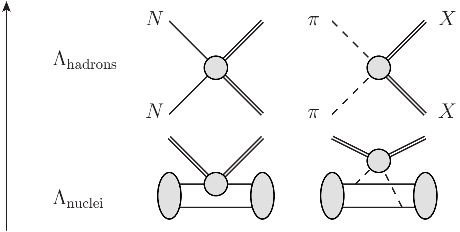


# Direct detection of dark matter: scales




1. **BSM scale** $\Lambda_{\rm BSM}$: $\mathcal{L}_{\rm BSM}$
2. **Effective Operators**: $\mathcal{L}_{\rm SM} + \sum_{i,k} \frac{1}{\Lambda^i_{\rm BSM}} \mathcal{O}_{i,k}$
   SMEFT
3. Integrate out **EW physics**
4. **Hadronic scale**: nucleons and pions
   $\hookrightarrow$ effective interaction Hamiltonian $H_I$
   Chiral EFT
5. **Nuclear scale**: $\langle \mathcal{N} | H_I | \mathcal{N} \rangle$
   $\hookrightarrow$ nuclear wave function Chiral EFT, NREFT

# Direct detection of dark matter: scales




4. **Hadronic scale**: nucleons and pions

   ↪ effective interaction Hamiltonian $H_I$

   Chiral EFT

5. **Nuclear scale**: $\langle\mathcal{N}|H_I|\mathcal{N}\rangle$

   ↪ nuclear wave function Chiral EFT, NREFT

- Typical WIMP–nucleon **momentum transfer**

$$|\mathbf{q}_{\text{max}}| = 2\mu_{\mathcal{N}\chi}|\mathbf{v}_{\text{rel}}| \sim 200\,\text{MeV} \qquad |\mathbf{v}_{\text{rel}}| \sim 10^{-3} \qquad \mu_{\mathcal{N}\chi} \sim 100\,\text{GeV}$$

- **Chiral EFT**: pions, nucleons, and WIMPs as degrees of freedom

  Prézeau et al. 2003, Cirigliano et al. 2012, 2013, Menéndez et al. 2012, Klos et al. 2013, MH et al. 2015, Bishara et al. 2017

- **NREFT**: all degrees of freedom integrated out but nucleons and WIMPs

  Fan et al. 2010, Fitzpatrick et al. 2012, Anand et al. 2013

# Chiral Perturbation Theory

- Effective theory of QCD based on **chiral symmetry**

$$\mathcal{L}_{\text{QCD}} = \bar{q}_L i\not{D} q_L + \bar{q}_R i\not{D} q_R - \bar{q}_L \mathcal{M} q_R - \bar{q}_R \mathcal{M} q_L - \frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu}$$

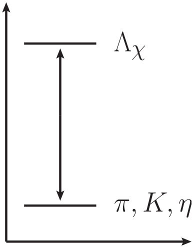
- Expansion in momenta $p/\Lambda_\chi$ and quark masses $m_q \sim p^2$

  $\hookrightarrow$ **scale separation**

- Breakdown scale: $\Lambda_\chi = M_\rho \ldots 4\pi F_\pi \sim 1\,\text{GeV}$
- Two variants
  - ***SU*(2)**: *u*- and *d*-quark **dynamical**, $m_s$ fixed at **physical value**

    $\hookrightarrow$ expansion in $M_\pi/\Lambda_\chi$, usually nice convergence
  - ***SU*(3)**: *u*-, *d*-, and *s*-quark dynamical

    $\hookrightarrow$ expansion in $M_K/\Lambda_\chi$, sometimes tricky



- Traditionally: meson-exchange potentials
- Chiral effective field theory
  - Based on **chiral symmetry** of QCD
  - **Power counting**
  - **Low-energy constants**
  - Hierarchy of multi-nucleon forces
  - Consistency of *NN* and 3*N*

$\hookrightarrow$ modern theory of nuclear forces

- Long-range part related to **pion–nucleon scattering**

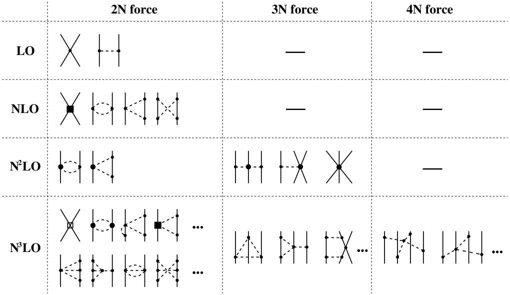
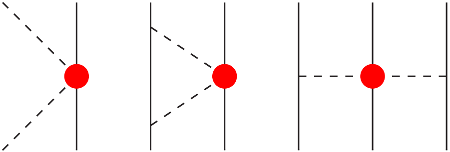


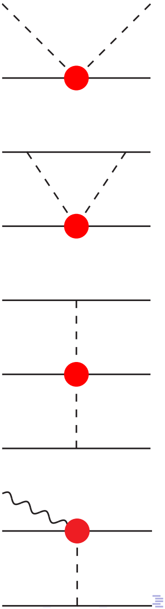

Figure taken from 1011.1343



# Chiral EFT: currents

- Coupling to **external sources** $\mathcal{L}(v_\mu, a_\mu, s, p)$
- Same LECs appear in **axial current**

  $\hookrightarrow$ $\beta$ decay, neutrino interactions, dark matter
- Vast literature for $v_\mu$ and $a_\mu$, up to one-loop level
  - With unitary transformations: Kölling et al. 2009, 2011, Krebs et al. 2016, 2019
  - Without unitary transformations: Park et al. 2003, Pastore et al. 2008, Baroni et al. 2015
- For **dark matter** further currents: $s$, $p$, tensor, spin-2, $\theta^\mu_\mu$



# Chiral counting

- **Effective WIMP Lagrangian** for spin-$1/2$ SM singlet $\chi$ Goodman et al. 2010

$$\mathcal{L}_\chi = \frac{1}{\Lambda^3}\sum_q \Big[C_q^{SS}\bar\chi\chi\, m_q\bar q q + C_q^{PS}\bar\chi i\gamma_5\chi\, m_q\bar q q + C_q^{SP}\bar\chi\chi\, m_q\bar q i\gamma_5 q + C_q^{PP}\bar\chi i\gamma_5\chi\, m_q\bar q i\gamma_5 q\Big]$$
$$+\frac{1}{\Lambda^2}\sum_q \Big[C_q^{VV}\bar\chi\gamma^\mu\chi\,\bar q\gamma_\mu q + C_q^{AV}\bar\chi\gamma^\mu\gamma_5\chi\,\bar q\gamma_\mu q + C_q^{VA}\bar\chi\gamma^\mu\chi\,\bar q\gamma_\mu\gamma_5 q + C_q^{AA}\bar\chi\gamma^\mu\gamma_5\chi\,\bar q\gamma_\mu\gamma_5 q\Big]$$
$$+\frac{1}{\Lambda^2}\sum_q \Big[C_q^{TT}\bar\chi\sigma^{\mu\nu}\chi\,\bar q\sigma_{\mu\nu}q + \tilde C_q^{TT}\bar\chi\sigma^{\mu\nu}\gamma_5\chi\,\bar q\sigma_{\mu\nu}q\Big] + \frac{1}{\Lambda^3}\Big[C_g^S\bar\chi\chi\,\alpha_s G^a_{\mu\nu}G_a^{\mu\nu} + \cdots\Big]$$

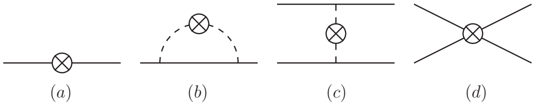
- **Chiral power counting**

$$\partial = \mathcal{O}(p), \qquad m_q = \mathcal{O}(p^2) = \mathcal{O}(M_\pi^2), \qquad a_\mu, v_\mu = \mathcal{O}(p), \qquad \frac{\partial}{m_N} = \mathcal{O}(p^2)$$

$\hookrightarrow$ construction of effective Lagrangian for nucleon and pion fields

$\hookrightarrow$ organize in terms of **chiral order $\nu$**, $\mathcal{M} = \mathcal{O}(p^\nu)$

# Classes of contributions




- Three classes of corrections:
  - **Subleading one-body responses** (*a*)
  - **Radius corrections** (*b*)
  - **Two-body currents** (*c*), (*d*)
- (*a*)+(*b*) just **ChPT for nucleon matrix elements**, but (*c*)+(*d*) genuinely new effects
- Hierarchy predicted from chiral EFT

# Example: scalar currents

- For a Majorana WIMP $\chi$: **scalar quark current**

$$\mathcal{L} = \sum_q C_q^{SS} \bar{\chi}\chi\, m_q \bar{q} q$$

leading contribution to responses with coherent enhancement

$\hookrightarrow$ **spin-independent scattering**

- Need nucleon matrix elements

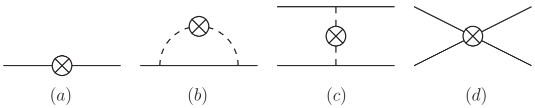
$$\langle N | m_q \bar{q} q | N \rangle = f_q^N m_N \qquad m_N \big( f_u^N + f_d^N \big) = \sigma_{\pi N}$$

to extract BSM information from cross section

$$\sigma_{\text{SI}} = \frac{4\mu_N^2}{\pi} \bigg| m_N \sum_q C_q^{SS} f_q^N + \cdots \bigg|^2 \qquad \mu_N = \frac{m_N m_\chi}{m_N + m_\chi}$$

- $\sigma_{\pi N}$ critical for interpretation of direct-detection searches, especially in SUSY models Bottino et al. 2000, Ellis et al. 2008

- $\sigma_{\pi N} = \mathcal{O}(p^2)$ suppressed due to absence of scalar current at leading order



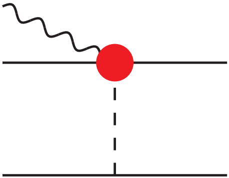

- Diagram $(a)$ scales like $\mathcal{O}(p^2)$ in the chiral counting
- In contrast to the nucleon, the pion has a **leading-order scalar coupling**

$$\mathcal{M}_{(b)} \simeq \underbrace{p \times \frac{1}{p} \times p}_{\text{nucleon line}} \times \underbrace{\frac{1}{p^2} \times p^2 \times \frac{1}{p^2}}_{\text{pion line}} \times \underbrace{p^4}_{\text{loop}} = \mathcal{O}(p^3)$$

$$\mathcal{M}_{(c)} \simeq \underbrace{p \times \frac{1}{p^2} \times p^2 \times \frac{1}{p^2} \times p}_{\text{pion line}} \times \underbrace{p^3}_{\delta\text{-function for spectator nucleon}} = \mathcal{O}(p^3)$$

$\hookrightarrow$ two-body effects as important as loop corrections

- Chiral corrections only **suppressed by a single chiral order**



- Axial-vector current can couple via pion pole

  $\hookrightarrow$ two-body effects proportional to $c_i$, including $\Delta(1232)$ enhancement

- **One-body current**

$$\mathbf{J}^3_{i,1\mathrm{b}} = \frac{1}{2}\,\tau_i^3\left(G_A^3(\mathbf{q}^2)\,\boldsymbol{\sigma}_i - \frac{G_P^3(\mathbf{q}^2)}{4m_N^2}\,(\mathbf{q}\cdot\boldsymbol{\sigma}_i)\,\mathbf{q}\right)$$

- **Two-body current**

$$\mathbf{J}^3_{12,2\mathrm{b}} = -\frac{g_A}{2F_\pi^2}\,[\tau_1\times\tau_2]^3\left[c_4\left(1-\frac{\mathbf{q}}{\mathbf{q}^2+M_\pi^2}\mathbf{q}\cdot\right)(\boldsymbol{\sigma}_1\times\mathbf{k}_2)+\frac{c_6}{4}(\boldsymbol{\sigma}_1\times\mathbf{q})+i\,\frac{\mathbf{p}_1+\mathbf{p}_1'}{4m_N}\right]\frac{\boldsymbol{\sigma}_2\cdot\mathbf{k}_2}{M_\pi^2+k_2^2}$$
$$-\frac{g_A}{F_\pi^2}\,\tau_2^3\left[c_3\left(1-\frac{\mathbf{q}}{\mathbf{q}^2+M_\pi^2}\mathbf{q}\cdot\right)\mathbf{k}_2+2c_1M_\pi^2\,\frac{\mathbf{q}}{\mathbf{q}^2+M_\pi^2}\right]\frac{\boldsymbol{\sigma}_2\cdot\mathbf{k}_2}{M_\pi^2+k_2^2}+\text{contact terms}$$

# Integrating out the pions: NREFT

- **Non-relativistic EFT for dark matter** Fan et al. 2010, Fitzpatrick et al. 2012, Anand et al. 2013

  $\hookrightarrow$ integrate out the pions

- Similar to **pionless EFT** for nuclear physics

  $\hookrightarrow$ only remaining degrees of freedom nucleons and WIMPs

- Calculation organized in terms of

$$\mathbf{q} \qquad \mathbf{v}^{\perp} = \mathbf{v} + \frac{\mathbf{q}}{2\mu_N} \qquad \mathbf{S}_{\chi} \qquad \mathbf{S}_N$$

$\hookrightarrow$ expand in $\mathbf{q}$, $\mathbf{v}^{\perp}$ (using $\mathbf{v}^{\perp} \cdot \mathbf{q} = 0$)

# Matching to NREFT

- Operator basis for **WIMP and nucleon fields** Fan et al. 2010, Fitzpatrick et al. 2012

$$\mathcal{O}_1 = \mathbb{1} \qquad \mathcal{O}_2 = (\mathbf{v}^\perp)^2 \qquad \mathcal{O}_3 = i\mathbf{S}_N \cdot (\mathbf{q} \times \mathbf{v}^\perp) \qquad \mathcal{O}_4 = \mathbf{S}_\chi \cdot \mathbf{S}_N$$

$$\mathcal{O}_5 = i\mathbf{S}_\chi \cdot (\mathbf{q} \times \mathbf{v}^\perp) \qquad \mathcal{O}_6 = \mathbf{S}_\chi \cdot \mathbf{q}\, \mathbf{S}_N \cdot \mathbf{q} \qquad \mathcal{O}_7 = \mathbf{S}_N \cdot \mathbf{v}^\perp \qquad \mathcal{O}_8 = \mathbf{S}_\chi \cdot \mathbf{v}^\perp$$

$$\mathcal{O}_9 = i\mathbf{S}_\chi \cdot (\mathbf{S}_N \times \mathbf{q}) \qquad \mathcal{O}_{10} = i\mathbf{S}_N \cdot \mathbf{q} \qquad \mathcal{O}_{11} = i\mathbf{S}_\chi \cdot \mathbf{q} \qquad \ldots$$

- Matching to relativistic amplitudes

$$\mathcal{M}^{SS}_{1,\text{NR}} = \mathcal{O}_1 f_N(t) \qquad \mathcal{M}^{SP}_{1,\text{NR}} = \mathcal{O}_{10} g_5^N(t) \qquad \mathcal{M}^{PP}_{1,\text{NR}} = \frac{1}{m_\chi}\mathcal{O}_6 h_5^N(t)$$

$$\mathcal{M}^{VV}_{1,\text{NR}} = \mathcal{O}_1 \Big(f_1^{V,N}(t) + \frac{t}{4m_N^2} f_2^{V,N}(t)\Big) + \frac{1}{m_N}\mathcal{O}_3 f_2^{V,N}(t) + \frac{1}{m_N m_\chi}\Big(t\mathcal{O}_4 + \mathcal{O}_6\Big) f_2^{V,N}(t)$$

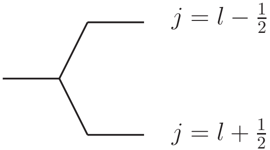
$$\mathcal{M}^{AV}_{1,\text{NR}} = 2\mathcal{O}_8 f_1^{V,N}(t) + \frac{2}{m_N}\mathcal{O}_9\Big(f_1^{V,N}(t) + f_2^{V,N}(t)\Big)$$

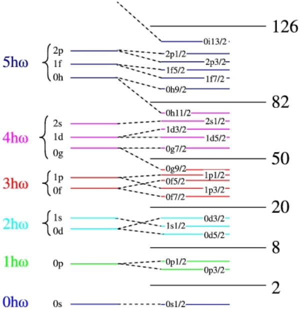
$$\mathcal{M}^{AA}_{1,\text{NR}} = -4\mathcal{O}_4 g_A^N(t) + \frac{1}{m_N^2}\mathcal{O}_6 g_P^N(t) \qquad \mathcal{M}^{VA}_{1,\text{NR}} = \Big\{-2\mathcal{O}_7 + \frac{2}{m_\chi}\mathcal{O}_9\Big\} h_A^N(t)$$

- Observations
  - SI: $\mathcal{O}_1$, SD: combination of $\mathcal{O}_4$ and $\mathcal{O}_6$
  - Not all the $\mathcal{O}_i$ equally important, QCD implies relations among them

# Coherence effects

- NREFT especially useful to analyze **coherence effects**
- Six distinct nuclear responses
  Fitzpatrick et al. 2012, Anand et al. 2013
  - $M \leftrightarrow \mathcal{O}_1 \leftrightarrow$ SI
  - $\Sigma', \Sigma'' \leftrightarrow \mathcal{O}_4, \mathcal{O}_6 \leftrightarrow$ SD
  - $\Phi'' \leftrightarrow \mathcal{O}_3 \leftrightarrow$ quasi-coherent, spin-orbit operator
  - $\Delta, \tilde{\Phi}'$: not coherent
- **Quasi-coherence** of $\Phi''$
  - Spin-orbit splitting
  - Coherence until mid-shell
  - About 20 coherent nucleons in Xe
  - Interference $M$–$\Phi'' \leftrightarrow \mathcal{O}_1$–$\mathcal{O}_3$
- Further coherent $M$-responses from $\mathcal{O}_5$, $\mathcal{O}_8$, $\mathcal{O}_{11}$, but no interference with $\mathcal{O}_1$ due to sum over $\mathbf{S}_\chi$



# EFT decomposition of direct detection rate

## Rate for WIMP–nucleus scattering

$$\frac{dR}{dE_r} = \underbrace{\frac{\sigma^{SI}_{\chi N}}{m_\chi \mu_N^2}}_{\text{particle + hadronic physics}} \times \underbrace{|\mathcal{F}^M_+(q^2)|^2}_{\text{nuclear physics}} \times \underbrace{\rho_0 \int_{v_{min}}^{v_{esc}} \frac{f(\mathbf{v}, t)}{v} d^3 v}_{\text{astrophysics}}$$

- **EFT constraints** on particle + hadronic part
- **Convolution with nuclear wave function** replaces traditional Helm form factor

  ↪ nuclear shell model, ab-initio techniques
- Different options for EFT parameterizations, in terms of
  1. **Wilson coefficients at high scale**

     ↪ need to specify quantum numbers of WIMP
  2. **effective couplings at QCD scale**, e.g., $\sigma^{SI}_{\chi N}$, $\sigma^{SD}_{\chi N}$

     ↪ combination of Wilson coefficients and hadronic matrix elements
  3. **NREFT coefficients**

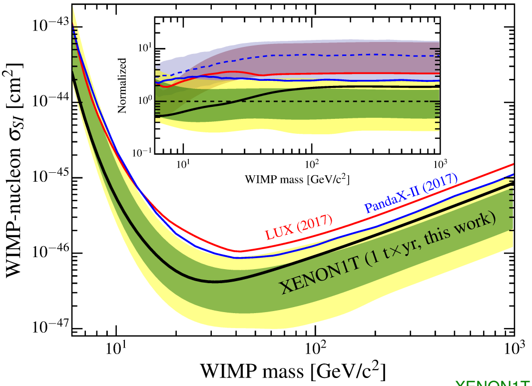
     ↪ BSM constraints obtained after matching to QCD

# EFT decomposition of direct detection rate

- Different EFT approaches basically differ by **choice of scale** at which EFT coefficients are determined
- All can be used to **generalize the standard SI/SD picture**
- Example for approach 2 (most natural from **chiral-EFT perspective**):

$$\frac{d\sigma_{\chi\mathcal{N}}}{dq^2} = \frac{1}{4\pi v^2}\bigg|\sum_{I=\pm}\Big(c_I^M - \frac{q^2}{m_N^2}\,\dot{c}_I^M\Big)\mathcal{F}_I^M(q^2) + c_\pi\mathcal{F}_\pi(q^2) + c_b\mathcal{F}_b(q^2) + \frac{q^2}{2m_N^2}\sum_{I=\pm}c_I^{\Phi''}\mathcal{F}_I^{\Phi''}(q^2)\bigg|^2$$
$$+ \frac{1}{4\pi v^2}\sum_{i=5,8,11}\bigg|\sum_{I=\pm}\xi_i(q, v_T^\perp)c_I^{M,i}\mathcal{F}_I^M(q^2)\bigg|^2$$
$$+ \frac{1}{v^2(2J+1)}\Big(|a_+|^2 S_{00}(q^2) + \text{Re}\,(a_+a_-^*)S_{01}(q^2) + |a_-|^2 S_{11}(q^2)\Big)$$

green: Wilson coefficients + hadronic matrix elements, red: nuclear structure factors

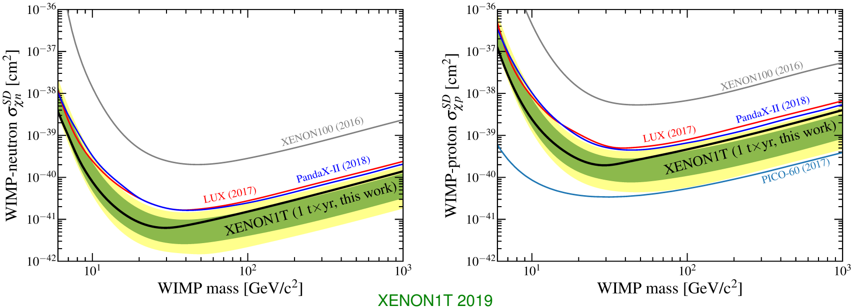



XENON1T 2018

- All $c = 0$, $a = 0$ except for $c_+^M$: **spin-independent scattering**

$$\frac{d\sigma_{\chi\mathcal{N}}}{dq^2} = \frac{\sigma_{\chi N}^{SI}}{4\mu_N^2 v^2}\left|\mathcal{F}_+^M(q^2)\right|^2 \qquad \sigma_{\chi N}^{SI} = \frac{\mu_N^2}{\pi}\left|c_+^M\right|^2 \qquad \mu_N = \frac{m_N m_\chi}{m_N + m_\chi}$$

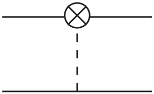
# Case 2: spin-dependent scattering




XENON1T 2019

- All $c = 0$, $a_+ = \pm a_-$: **spin-dependent scattering**

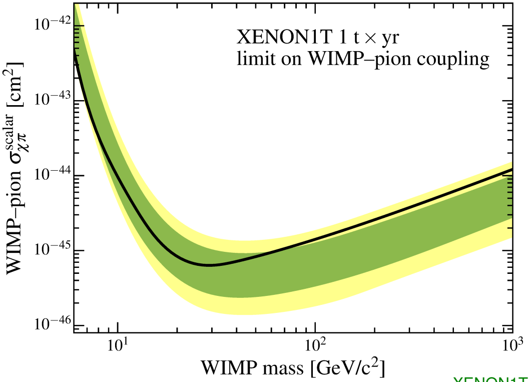
$$\frac{d\sigma_{\chi\mathcal{N}}}{dq^2} = \frac{\sigma^{\text{SD}}_{\chi N}}{3\mu_N^2 v^2}\frac{\pi}{2J+1}S_N(q^2) \qquad \sigma^{\text{SD}}_{\chi N} = \frac{3\mu_N^2}{\pi}|a_+|^2$$

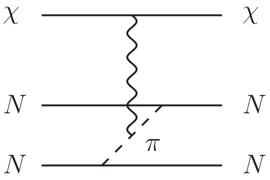


- Xe sensitive to proton spin due to **two-body currents**

Klos, Menéndez, Gazit, Schwenk 2013

# Case 3: WIMP–pion scattering



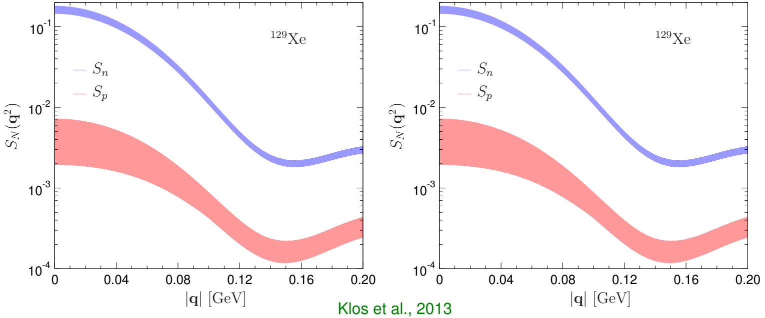

XENON1T + MH, Klos, Menéndez, Schwenk 2019

- Only $c_\pi$ nonzero: **WIMP–pion scattering**

$$\frac{d\sigma_{\chi\mathcal{N}}}{dq^2} = \frac{\sigma^{\text{scalar}}_{\chi\pi}}{\mu_\pi^2 v^2}\big|\mathcal{F}_\pi(q^2)\big|^2 \qquad \sigma^{\text{scalar}}_{\chi\pi} = \frac{\mu_\pi^2}{4\pi}\big|c_\pi\big|^2 \qquad \mu_\pi = \frac{m_\chi M_\pi}{m_\chi + M_\pi}$$

- Expression in terms of cross section depends on underlying operator, here for a scalar $\bar\chi\chi\bar q q$

# Calculation of spin-dependent responses

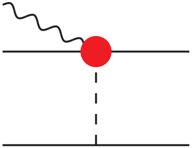



Klos et al., 2013

- Main challenge: **two-body currents**

  $\hookrightarrow$ dominant contribution for even-numbered species

- Developments since 2013:
  - New information on **low-energy constants** $c_i$
  - **Nuclear axial-vector current** at 1-loop
    Baroni et al. 2016, Krebs et al. 2016
  - Improved understanding of $g_A$ **quenching** in $\beta$ decays



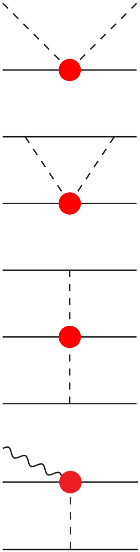
# Low-energy constants

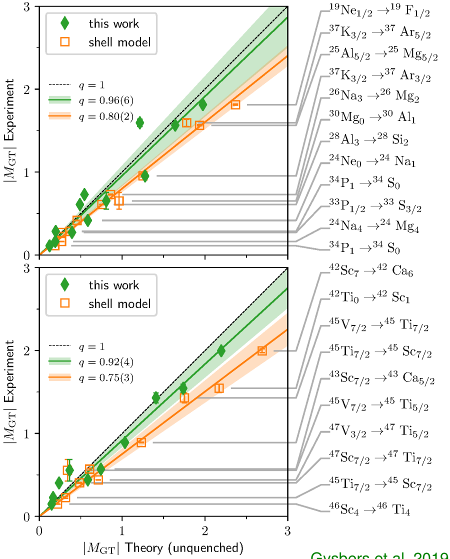
- $c_i$ first contribute to $\pi N$ scattering
- At given scheme and order, uncertainties negligible when matching in the **subthreshold region** MH et al. 2015, Siemens et al. 2016
- Large shifts when including **loop effects** Bernard et al. 2008
  $\hookrightarrow$ can be partially captured by

$$\delta c_1 = -\frac{g_A^2 M_\pi}{64\pi F_\pi^2} \qquad \delta c_3 = -\delta c_4 = \frac{g_A^4 M_\pi}{16\pi F_\pi^2} \qquad \delta c_6 = -\frac{g_A^2 M_\pi}{4\pi F_\pi^2}$$

- Absorbing relativistic corrections, we use

| $c_1$ [GeV$^{-1}$] | $c_3$ [GeV$^{-1}$] | $c_4$ [GeV$^{-1}$] | $c_6$ [GeV$^{-1}$] |
|---|---|---|---|
| $-1.20(17)$ | $-4.45(86)$ | $2.96(70)$ | $5.01(1.06)$ |






Gysbers et al. 2019

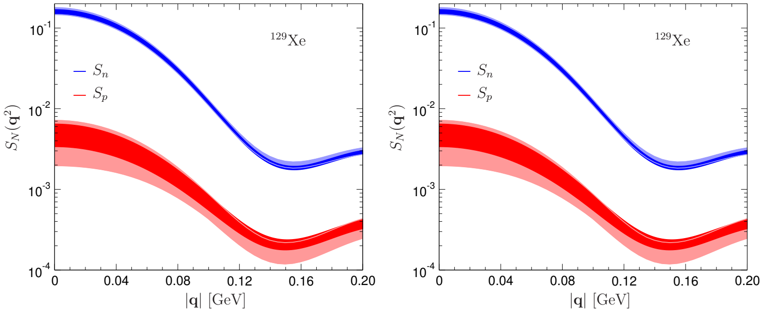
- **Ab initio calculation of $\beta$ decays** explains origin of quenching:
  - Two-body currents
  - Limitations of shell model
- We adjust the normalization accordingly, use chiral prediction for $\mathbf{q}^2$ dependence
- In practice done in terms of density of normal-ordering $\rho$ and value of $c_D$:

$$\{c_D, \rho\} = \{-6.08, 0.09\,\text{fm}^{-3}\}$$

$$\ldots\{0.30, 0.11\,\text{fm}^{-3}\}$$

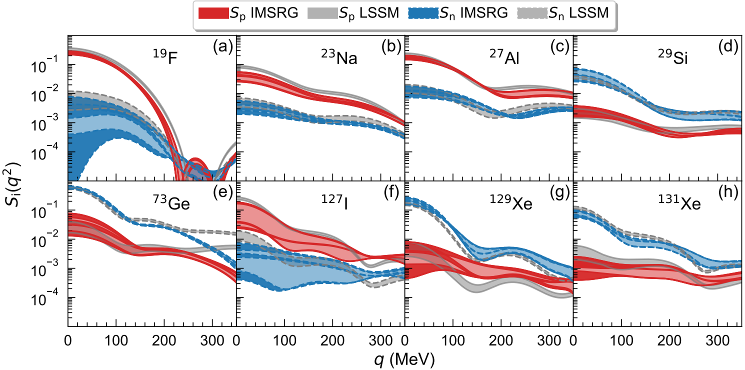
$$\to -30\% \ldots -20\%$$

# Improved spin-dependent responses for dark matter




- New results consistent with 2013 bands
- Uncertainties reduced especially of the suppressed (even-numbered) species

# Comparison to ab-initio methods

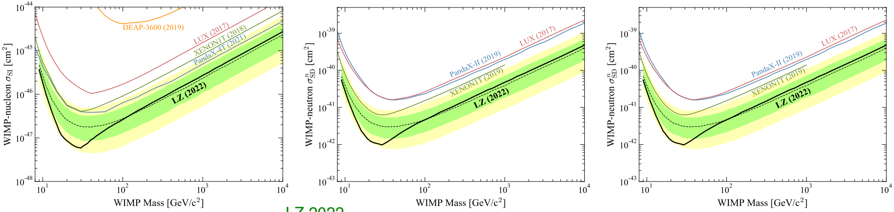



Hu et al. 2021

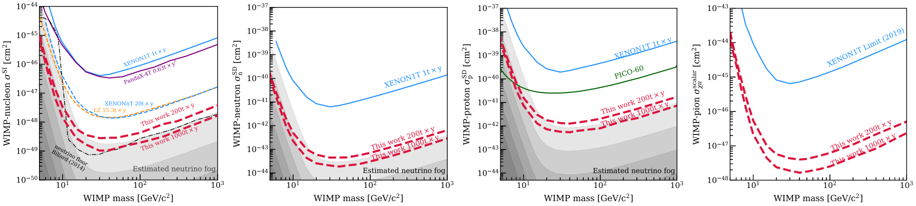
- Results shown so far use nuclear shell model for nuclear wave functions
- First results from **ab-initio methods** (in-medium SRG Hu et al. 2021)

  $\hookrightarrow$ *NN* and 3*N* interactions fully consistent with currents (eventually)

# New experimental results and prospects




LZ 2022




DARWIN Snowmass white paper 2022

- Impressive progress in experimental sensitivity

  ↪ should be analyzed with adequate theory

# Conclusions

- EFT allows one to move systematically **from BSM to nuclear scale**
- EFT-motivated decomposition of direct-detection rate depends on **choice of scale**

  $\hookrightarrow$ in principle equivalent, but more or less efficient depending on application
- **Chiral EFT**:
  - Directly generalizes standard SD/SI picture
  - Predicts hierarchy among NREFT coefficients
  - Allows one to include two-body corrections
  - Constrains Hamiltonian in ab-initio approaches