

Outline and references, with M. Hoferichter, J. Menéndez, P. Klos

Chiral effective field theory for nuclear forces and nuclei ✓

Spin-dependent WIMP-nucleus scattering ✓ **Structure factor fits:**

Klos et al., PRD 88, 083516 (2013), update Hoferichter et al., PRD 102, 074018 (2020)

Signatures of WIMP **inelastic scattering** off nuclei

Baudis et al., PRD 88, 115014 (2013)

General coherent (spin-independent+) **WIMP-nucleus scattering**

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First limits for **WIMP-pion interactions**

XENON1T + Hoferichter, Klos, Menéndez, AS, PRL 122, 071301 (2019)

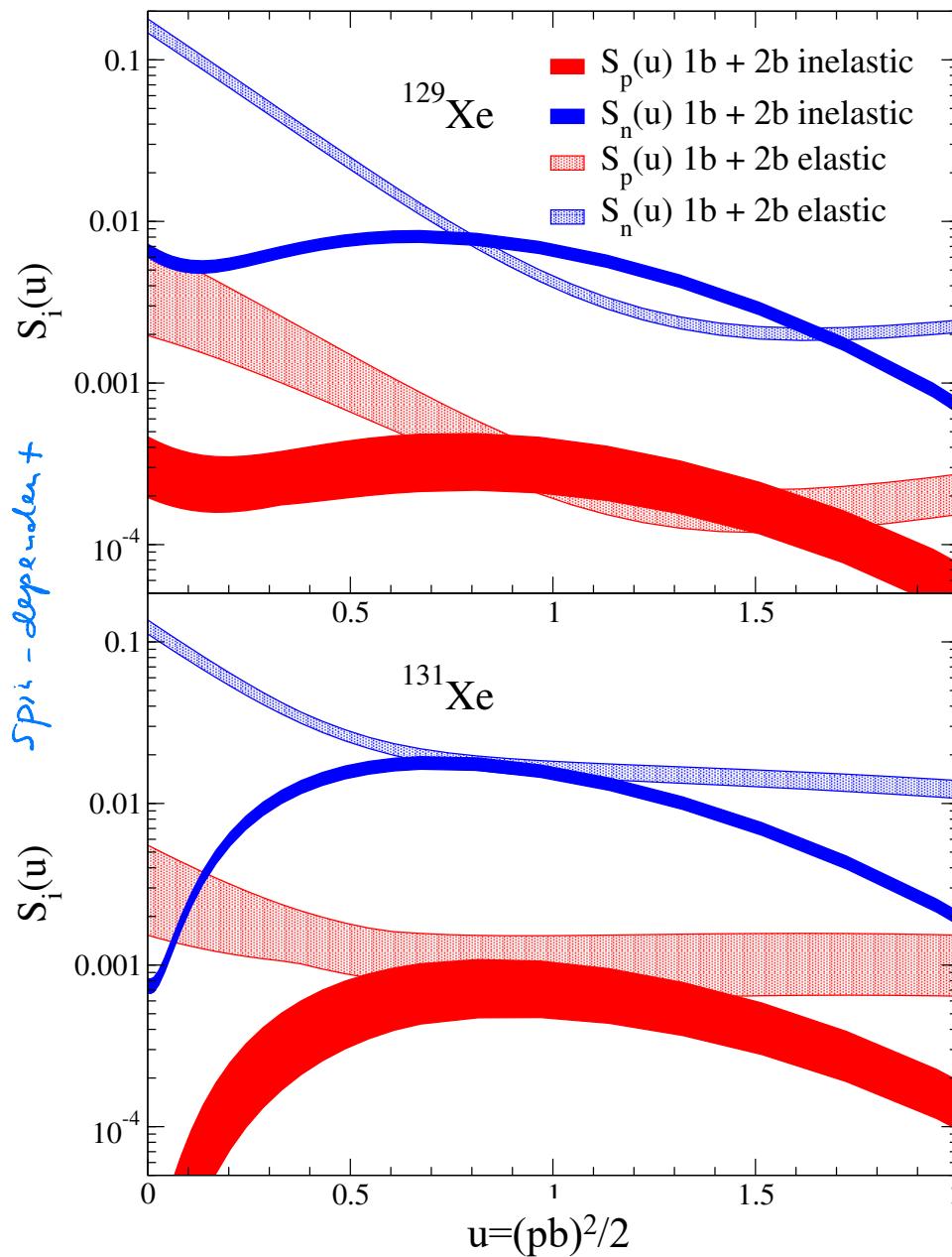
CEvNS: EFT analysis and nuclear responses Hoferichter et al., PRD (2020)

ChiraleFT4DM Jupyter notebook: www.strongint.eu

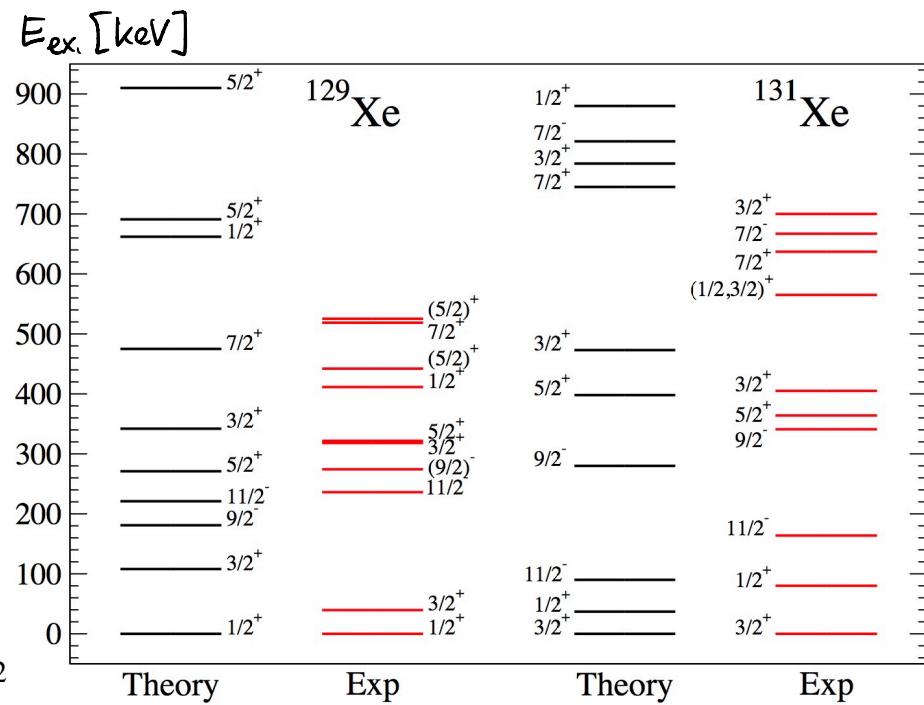
Contact/Questions: schwenk@physik.tu-darmstadt.de

Inelastic WIMP scattering to 40 and 80 keV excited states

Baudis, Kessler, Klos, Lang, Menéndez, Reichard, AS, PRD (2013)



inelastic channel
comparable/dominates elastic
channel for
 $p \sim 150$ MeV

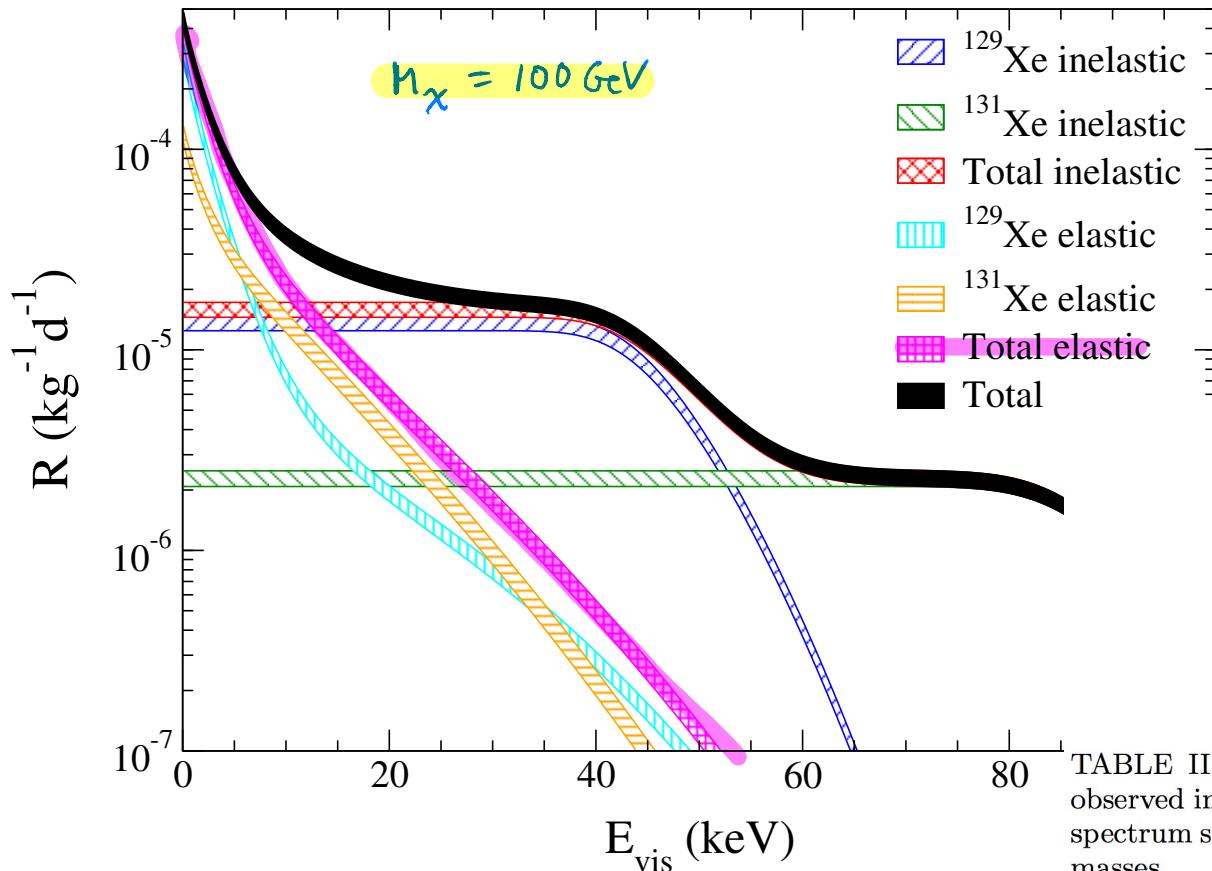


Signatures for inelastic WIMP scattering

elastic recoil + prompt γ from de-excitation

combined information from elastic and inelastic channel will allow to
determine dominant interaction channel in one experiment

inelastic excitation sensitive to WIMP mass



Mass [GeV]	^{129}Xe	^{131}Xe	Total
10	—	—	—
25	5	—	5
50	7	17	9
100	7	24	12
250	9	32	19
500	11	35	24

TABLE II. Minimum energy E_{vis} in keV above which the observed inelastic spectrum for ^{129}Xe , ^{131}Xe and for the total spectrum starts to dominate the elastic one for various WIMP masses.

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Chiral EFT for general WIMP-nucleon interactions

chiral symmetry implies a hierarchy for general responses with Q^v

Hoferichter, Klos, AS, PLB (2015)

Nucleon		V		A		Nucleon		S	P
WIMP		t	x	t	x	WIMP	m_{π}^2		
V	1b	0	$1 + 2$	2	$0 + 2$	1b	Q^2	2	1
	2b	4	$2 + 2$	2	$4 + 2$	2b	Q^2	3	5
	2b NLO	-	-	5	$3 + 2$	2b NLO	-	-	4
A	1b	$0 + 2$	1	$2 + 2$	0	1b		$2 + 2$	$1 + 2$
	2b	$4 + 2$	2	$2 + 2$	4	2b		$3 + 2$	$5 + 2$
	2b NLO	-	-	$5 + 2$	3	2b NLO	-	-	$4 + 2$

SD interactions are axial-vector (A) – A interactions, SI is scalar (S) – S

2-body currents as large as 1-body currents in V-A channel

Chiral EFT for general WIMP-nucleon interactions

chiral symmetry implies a hierarchy for general responses with Q^v

Hoferichter, Klos, AS, PLB (2015)

		Nucleon		V		A				Nucleon		S	P
		t	x	t	x			t	x	t	x		
V	WIMP	1b	0	1 + 2	2			0 + 2					
	2b	4		2 + 2	2			4 + 2				1b	2
	2b NLO	–		–	5			3 + 2				2b	3
A	1b	0 + 2		1	2 + 2			0				1b	2 + 2
	2b	4 + 2		2	2 + 2			4				2b	3 + 2
	2b NLO	–		–	5 + 2			3				2b NLO	5 + 2

matching to non-relativistic EFT

Fitzpatrick et al., JCAP (2013)

without chiral physics

$$\begin{aligned}
 O_1 &= \mathbb{1}, & O_2 &= (\mathbf{v}^\perp)^2, & O_3 &= i\mathbf{S}_N \cdot (\mathbf{q} \times \mathbf{v}^\perp), \\
 O_4 &= \mathbf{S}_\chi \cdot \mathbf{S}_N, & O_5 &= i\mathbf{S}_\chi \cdot (\mathbf{q} \times \mathbf{v}^\perp), & O_6 &= \mathbf{S}_\chi \cdot \mathbf{q} \mathbf{S}_N \cdot \mathbf{q}, \\
 O_7 &= \mathbf{S}_N \cdot \mathbf{v}^\perp, & O_8 &= \mathbf{S}_\chi \cdot \mathbf{v}^\perp, & O_9 &= i\mathbf{S}_\chi \cdot (\mathbf{S}_N \times \mathbf{q}), \\
 O_{10} &= i\mathbf{S}_N \cdot \mathbf{q}, & O_{11} &= i\mathbf{S}_\chi \cdot \mathbf{q},
 \end{aligned}$$

shows that NREFT operators are not linearly indep. (e.g., 4+6 are SD)

and not all are present up to $v=3$ (only 8 of 11 operators)

General coherent (SI+) WIMP-nucleus scattering

Hoferichter, Klos, Menéndez, AS, PRD (2016), PRD (2019)

Standard SI, $I=+$

include all QCD effects + new operators that are coherent ($\sim A$)

$$\frac{d\sigma}{dq^2} = \frac{1}{4\pi v^2} \left| \sum_{I=\pm} \left(c_I^M - \frac{q^2}{m_N^2} \hat{c}_I^M \right) \mathcal{F}_I^M(q^2) + c_\pi \mathcal{F}_\pi(q^2) + c_b \mathcal{F}_b(q^2) + \frac{q^2}{2m_N^2} \sum_{I=\pm} c_I^{\Phi''} \mathcal{F}_I^{\Phi''}(q^2) \right|^2$$

chiral EFT *nucleon radius corr.*

$$+ \frac{1}{4\pi v^2} \sum_{i=5,8,11} \left| \sum_{I=\pm} \xi_i(q, v_T^\perp) c_I^{M,i} \mathcal{F}_I^M(q^2) \right|^2$$

isoscalar/isovector
 $\rightarrow O_{S_1, 8, 11}$

$v = |\vec{q}|$
mom. transfer

\checkmark relative velocity of WIMP

$$(v_T^\perp)^2 = v^2 - \frac{q^2}{4\mu_N} \quad \text{velocity of WIMP w.r.t. nucleus}$$

$$\mu_W = \frac{m_N m_X}{m_N + m_X}$$

$$\xi_{11} = -\frac{q}{2m_X}$$

Couplings $C \sim$ Wilson coefficients in BSM Lagrangian \times hadronic matrix elements

$$C_I \rightarrow \text{Nucleon} \quad C_\pi \rightarrow \text{pion}$$

nuclear responses \mathcal{F}_I , $\tilde{\mathcal{F}}_I^M \rightarrow$ SI response \rightarrow Helm ff. $\sim A$

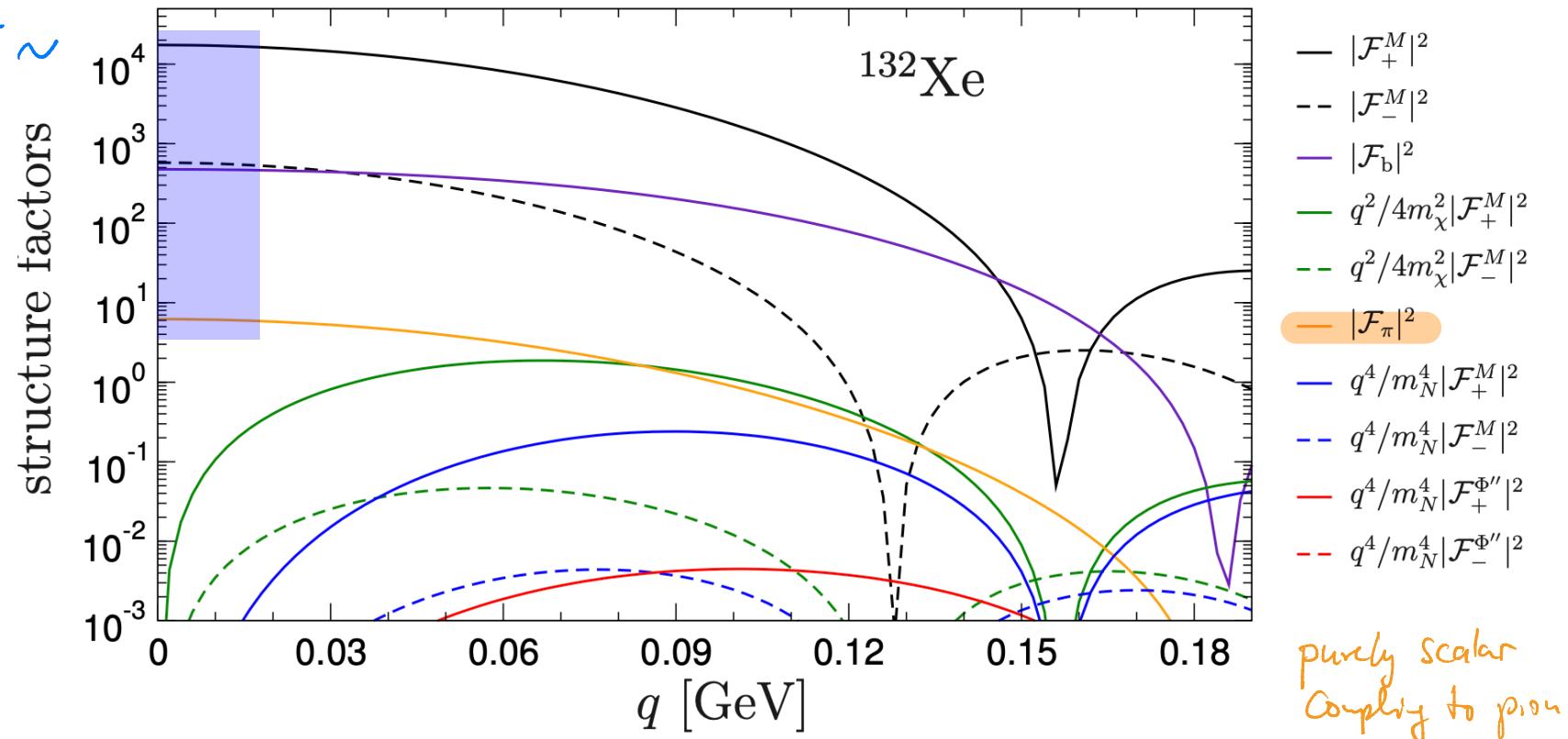
Structure factor	QCD operators	Chiral scaling	NR operators	Overall scaling	Interference with \mathcal{O}_1
\mathcal{F}^M	$\bar{\chi}\chi m_q \bar{q}q$	$\mathcal{O}(M_\pi^2) = \mathcal{O}(p^2)$	\mathcal{O}_1	$\mathcal{O}\left(\frac{M_\pi^2}{\Lambda_\chi^2} A\right)$	yes
	$\bar{\chi}\chi \theta_\mu^\mu$	$\mathcal{O}(1)$	\mathcal{O}_1	$\mathcal{O}(A)$	yes
	$\bar{\chi}\gamma_\mu i\partial_\nu \chi \bar{\theta}^{\mu\nu}$	$\mathcal{O}(1)$	\mathcal{O}_1	$\mathcal{O}(A)$	yes
	$\bar{\chi}\gamma^\mu \chi \bar{q}\gamma_\mu q$	$\mathcal{O}(1)$	\mathcal{O}_1	$\mathcal{O}(A)$	yes
		$\mathcal{O}\left(\frac{qv^\perp}{m_\chi + m_N}\right) = \mathcal{O}(p^4)$	\mathcal{O}_5	$\mathcal{O}\left(\frac{qv_T^\perp}{m_\chi + m_N} A\right)$	no
	$\bar{\chi}\sigma^{\mu\nu} \chi \bar{q}\sigma_{\mu\nu} q$	$\mathcal{O}\left(\frac{q^2}{m_N m_\chi}\right) = \mathcal{O}(p^4)$	\mathcal{O}_1	$\mathcal{O}\left(\frac{q^2}{m_N m_\chi} A\right)$	yes
		$\mathcal{O}\left(\frac{qv^\perp}{m_N}\right) = \mathcal{O}(p^4)$	\mathcal{O}_5	$\mathcal{O}\left(\frac{qv_T^\perp}{m_N} A\right)$	no
	$\bar{\chi}\gamma^\mu \gamma_5 \chi \bar{q}\gamma_\mu q$	$\mathcal{O}(v^\perp) = \mathcal{O}(p^2)$	\mathcal{O}_8	$\mathcal{O}(v_T^\perp A)$	no
	$\bar{\chi}\sigma^{\mu\nu} i\gamma_5 \chi \bar{q}\sigma_{\mu\nu} q$	$\mathcal{O}\left(\frac{q}{m_N}\right) = \mathcal{O}(p^2)$	\mathcal{O}_{11}	$\mathcal{O}\left(\frac{q}{m_N} A\right)$	no
	$\bar{\chi}i\gamma_5 \chi m_q \bar{q}q$	$\mathcal{O}\left(\frac{qM_\pi^2}{m_\chi}\right) = \mathcal{O}(p^4)$	\mathcal{O}_{11}	$\mathcal{O}\left(\frac{qM_\pi^2}{m_\chi \Lambda_\chi^2} A\right)$	no
\mathcal{F}_π	$\bar{\chi}\chi m_q \bar{q}q$	$\mathcal{O}(M_\pi^3) = \mathcal{O}(p^3)$	—	$\mathcal{O}\left(\frac{M_\pi^3}{\Lambda_\chi^3} A\right)$	yes
	$\bar{\chi}\chi \theta_\mu^\mu$	$\mathcal{O}(M_\pi^3) = \mathcal{O}(p^3)$	—	$\mathcal{O}\left(\frac{M_\pi^3}{\Lambda_\chi^3} A\right)$	yes
	$\bar{\chi}\gamma_\mu i\partial_\nu \chi \bar{\theta}^{\mu\nu}$	$\mathcal{O}(M_\pi^3) = \mathcal{O}(p^3)$	—	$\mathcal{O}\left(\frac{M_\pi^3}{\Lambda_\chi^3} A\right)$	yes
\mathcal{F}_b	$\bar{\chi}\chi \theta_\mu^\mu$	$\mathcal{O}(M_\pi^3) = \mathcal{O}(p^3)$	—	$\mathcal{O}\left(\frac{M_\pi^3}{\Lambda_\chi^3} A\right)$	yes
	$\bar{\chi}\gamma_\mu i\partial_\nu \chi \bar{\theta}^{\mu\nu}$	$\mathcal{O}(M_\pi^3) = \mathcal{O}(p^3)$	—	$\mathcal{O}\left(\frac{M_\pi^3}{\Lambda_\chi^3} A\right)$	yes
$\mathcal{F}^{\Phi''}$	$\bar{\chi}\gamma^\mu \chi \bar{q}\gamma_\mu q$	$\mathcal{O}(qv^\perp) = \mathcal{O}(p^3)$	\mathcal{O}_3	$\mathcal{O}\left(\frac{q^2}{m_N \Lambda_\chi} \xi A\right)$	yes
	$\bar{\chi}\sigma^{\mu\nu} \chi \bar{q}\sigma_{\mu\nu} q$	$\mathcal{O}\left(\frac{qv^\perp}{m_\chi}\right) = \mathcal{O}(p^4)$	\mathcal{O}_3	$\mathcal{O}\left(\frac{q^2}{m_N m_\chi} \xi A\right)$	yes
S_{ij}	$\bar{\chi}\gamma^\mu \gamma_5 \chi \bar{q}\gamma_\mu \gamma_5 q$	$\mathcal{O}(1)$	$\mathcal{O}_4, \mathcal{O}_6$	$\mathcal{O}(1)$	no
	$\bar{\chi}\sigma^{\mu\nu} \chi \bar{q}\sigma_{\mu\nu} q$	$\mathcal{O}(1)$	\mathcal{O}_4	$\mathcal{O}(1)$	no
	$\bar{\chi}\gamma_5 \chi \bar{q}\gamma_5 q$	$\mathcal{O}(1)$	\mathcal{O}_6	$\mathcal{O}(1)$	no

SD

General coherent (SI+) WIMP-nucleus scattering

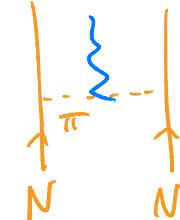
Hoferichter, Klos, Menéndez, AS, PRD (2016), PRD (2019)

include all QCD effects + new operators that are coherent ($\sim A$)



dominant corrections are QCD effects: coupling to pion, isovector correction, radius correction to formfactor

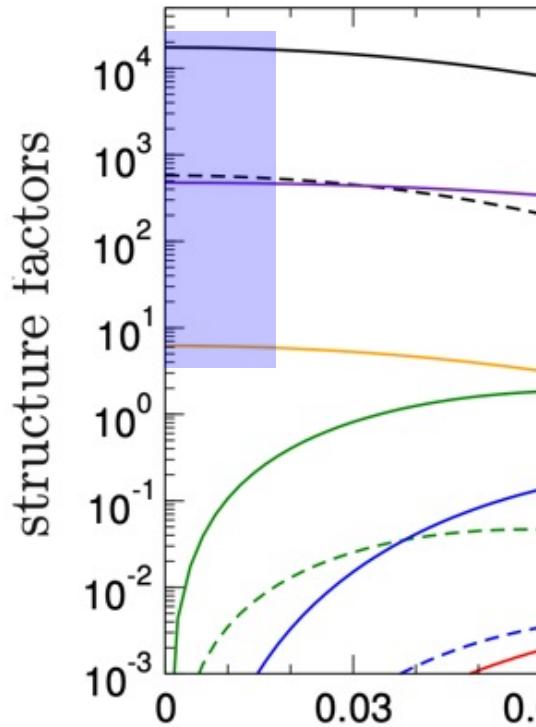
first new operator $O_{3,11}$ contributions are 4 orders smaller



General coherent (SI+) WIMP-nucleus scattering

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include all QCD effects + new operators that are coherent ($\sim A$)

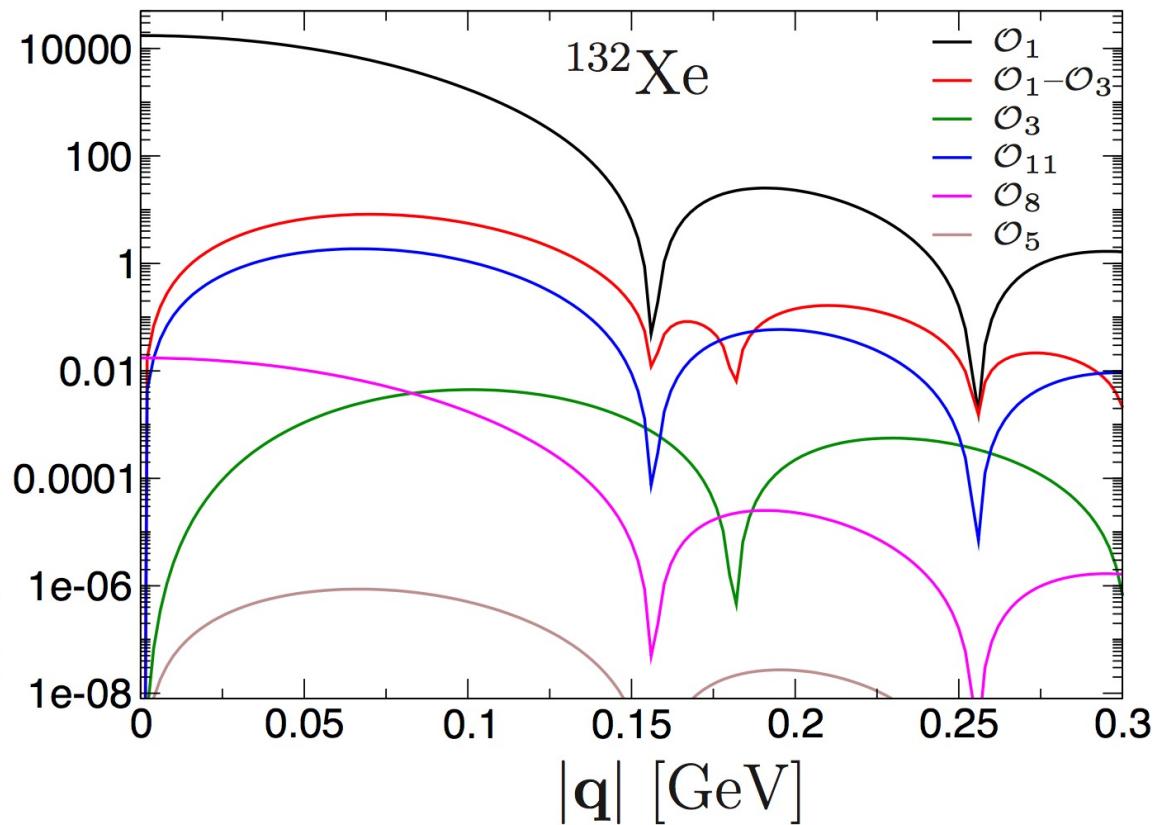


dominant corrections are
isovector correction, radii

$$|\xi_{\mathcal{O}_i} \mathcal{F}_+|^2 + \text{interference terms}$$

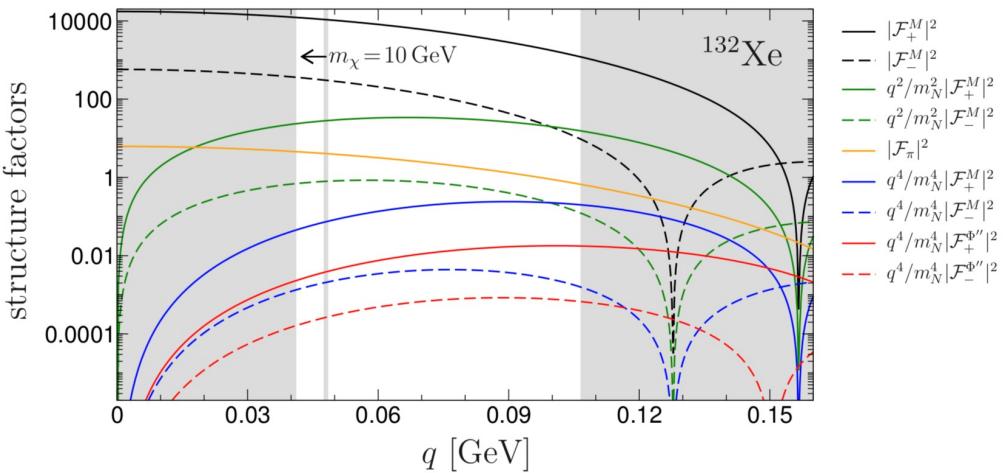
first new operator $\mathcal{O}_{3,11}$ c

$$\begin{aligned} \mathcal{O}_1 &= 1, & \mathcal{O}_2 &= (\mathbf{v}^\perp)^2, & \mathcal{O}_3 &= i\mathbf{S}_N \cdot (\mathbf{q} \times \mathbf{v}^\perp), \\ \mathcal{O}_4 &= \mathbf{S}_\chi \cdot \mathbf{S}_N, & \mathcal{O}_5 &= i\mathbf{S}_\chi \cdot (\mathbf{q} \times \mathbf{v}^\perp), & \mathcal{O}_6 &= \mathbf{S}_\chi \cdot \mathbf{q} \mathbf{S}_N \cdot \mathbf{q}, \\ \mathcal{O}_7 &= \mathbf{S}_N \cdot \mathbf{v}^\perp, & \mathcal{O}_8 &= \mathbf{S}_\chi \cdot \mathbf{v}^\perp, & \mathcal{O}_9 &= i\mathbf{S}_\chi \cdot (\mathbf{S}_N \times \mathbf{q}), \\ \mathcal{O}_{10} &= i\mathbf{S}_N \cdot \mathbf{q}, & \mathcal{O}_{11} &= i\mathbf{S}_\chi \cdot \mathbf{q}, \end{aligned}$$



Discriminating different WIMP-nucleus response functions

Fieghuth et al., PRD (2018) white region accessible to XENON-type experiment

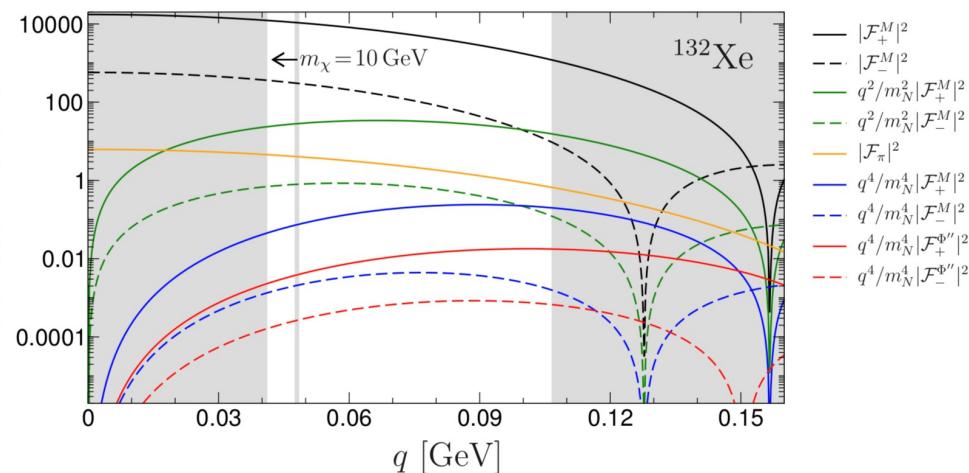


$$\begin{aligned} \frac{d\sigma}{dq^2} = & \frac{1}{4\pi v^2} \left| \sum_{I=\pm} \left(c_I^M - \frac{q^2}{m_N^2} \dot{c}_I^M \right) \mathcal{F}_I^M(q^2) \right. \\ & + c_\pi \mathcal{F}_\pi(q^2) + \frac{q^2}{2m_N^2} \sum_{I=\pm} c_I^{\Phi''} \mathcal{F}_I^{\Phi''}(q^2) \Big|^2 \\ & + \frac{1}{4\pi v^2} \left| \sum_{I=\pm} \frac{q}{2m_\chi} \tilde{c}_I^M \mathcal{F}_I^M(q^2) \right|^2. \end{aligned}$$

Can one discriminate responses in XENON1T, nT or DARWIN?

Discriminating different WIMP-nucleus response functions

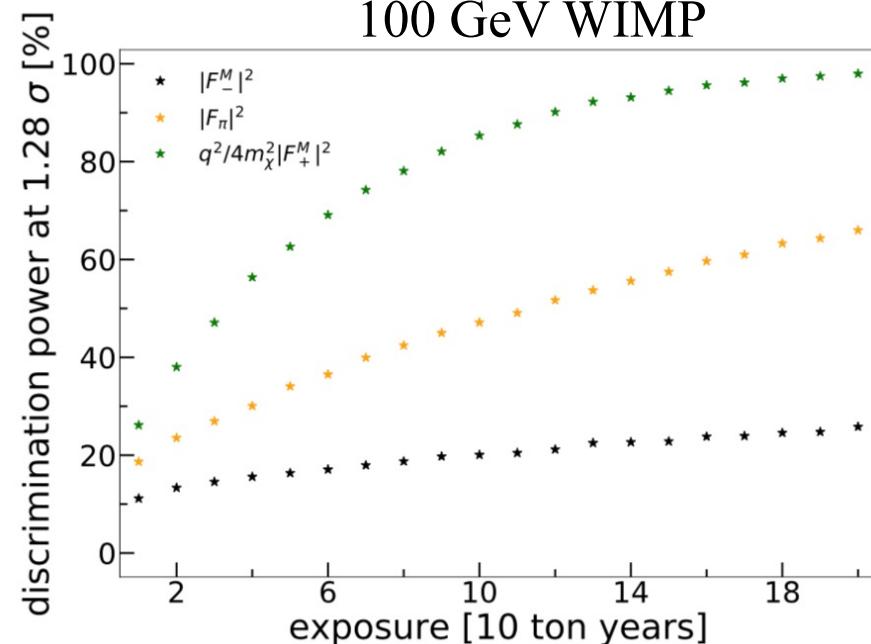
Fieghuth et al., PRD (2018) white region accessible to XENON-type experiment



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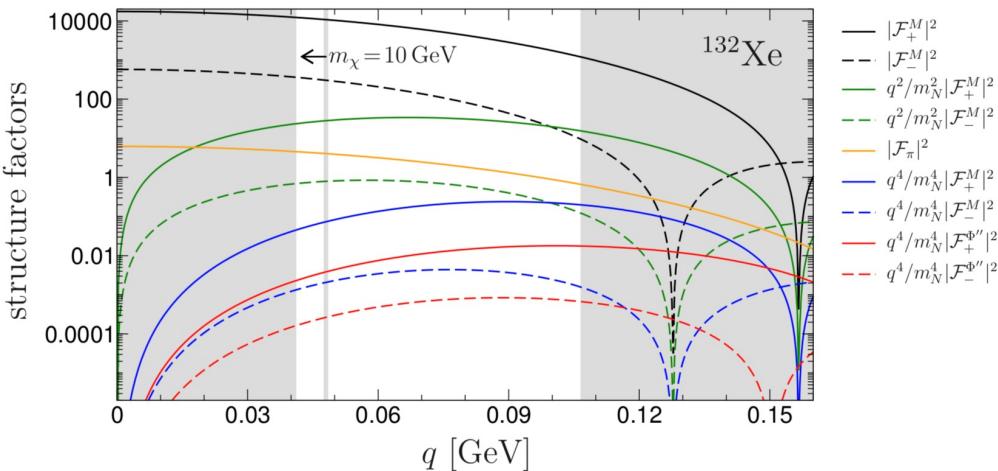
Can one discriminate responses in XENON1T, nT or **DARWIN**?
 compared to standard SI response
 (Helm form factor)

q -dependent responses more easily
 distinguishable



Discriminating different WIMP-nucleus response functions

Fiegle et al., PRD (2018) white region accessible to XENON-type experiment



$$\begin{aligned} \frac{d\sigma}{dq^2} = & \frac{1}{4\pi v^2} \left| \sum_{I=\pm} \left(c_I^M - \frac{q^2}{m_N^2} \dot{c}_I^M \right) \mathcal{F}_I^M(q^2) \right. \\ & + c_\pi \mathcal{F}_\pi(q^2) + \frac{q^2}{2m_N^2} \sum_{I=\pm} c_I^{\Phi''} \mathcal{F}_I^{\Phi''}(q^2) \Big|^2 \\ & + \frac{1}{4\pi v^2} \left| \sum_{I=\pm} \frac{q}{2m_\chi} \tilde{c}_I^M \mathcal{F}_I^M(q^2) \right|^2. \end{aligned}$$

Can one discriminate responses in XENON1T, nT or **DARWIN**?
compared to standard SI response
(Helm form factor)

DARWIN could discriminate most responses, unless WIMP-nucleon cross section very small

TABLE III: Discrimination power (in %) of a DARWIN-like experiment after 200 ton years of exposure.

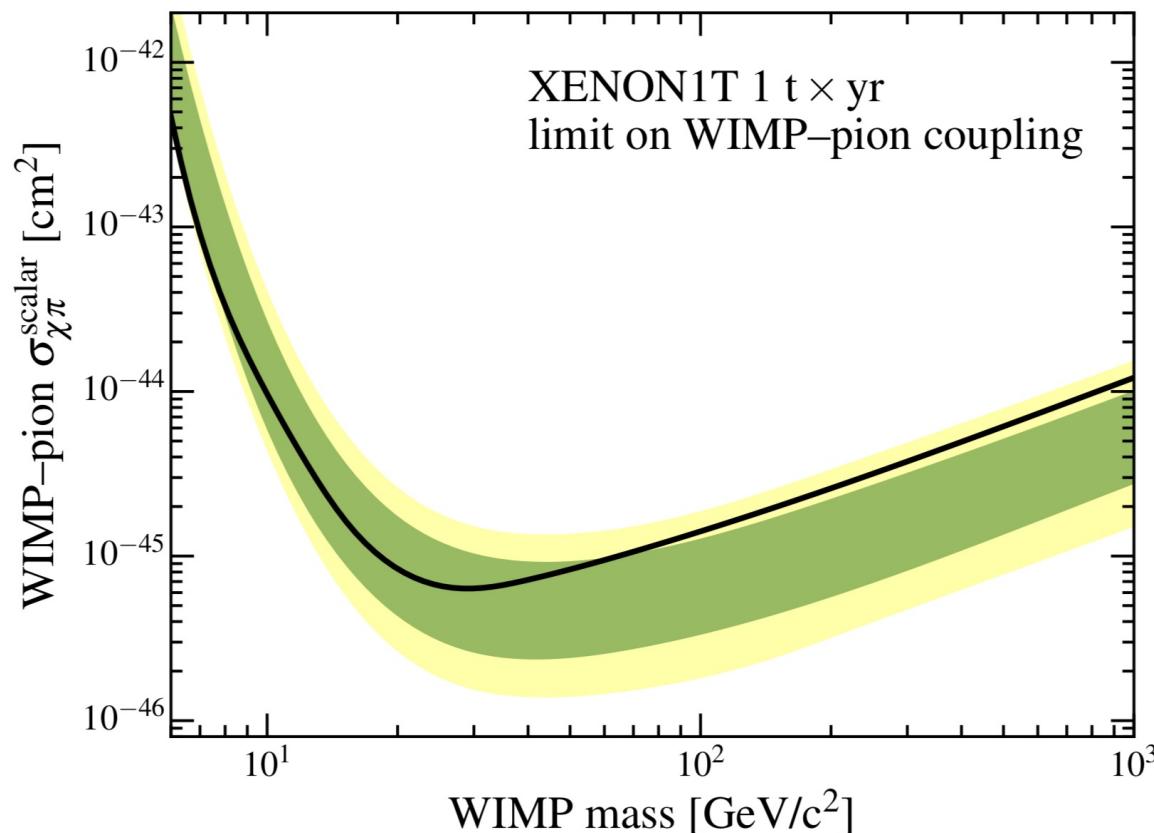
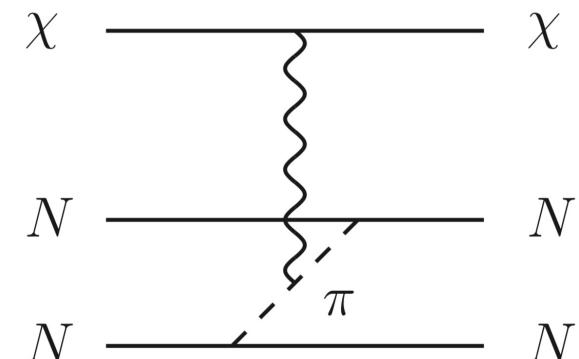
m_χ σ_0 [cm ²]	100 GeV			1 TeV		
	10^{-46}	10^{-47}	10^{-48}	10^{-45}	10^{-46}	10^{-47}
$ \mathcal{F}_-^M ^2$	94	26	12	100	35	13
$q^2/4m_\chi^2 \mathcal{F}_+^M ^2$	100	100	34	100	100	41
$q^2/4m_\chi^2 \mathcal{F}_-^M ^2$	100	98	25	100	100	32
$q^4/m_N^4 \mathcal{F}_+^M ^2$	100	100	55	100	100	63
$q^4/m_N^4 \mathcal{F}_-^M ^2$	100	100	47	100	100	53
$ \mathcal{F}_\pi ^2$	100	66	17	100	81	20
$q^4/4m_N^4 \mathcal{F}_+^{\Phi''} ^2$	100	100	58	100	100	69
$q^4/4m_N^4 \mathcal{F}_-^{\Phi''} ^2$	100	100	55	100	100	64

First limits for WIMP-pion interactions Aprile et al., PRL (2019)

based on chiral EFT for WIMP-pion interactions
are partially coherent (between SI and SD)

$$A^2 \gg 4 \left(\frac{M_\pi}{\Lambda_\chi} \right)^6 \left(\frac{m_N}{M_\pi} \right)^2 A^2 \gg \frac{4}{3} \frac{J+1}{J} \langle \mathbf{S}_{n/p} \rangle^2$$

$$1.7 \times 10^4 \gg 1.1 \times 10^3 \gg 0.34, 0.13 \text{ for } {}^{129,131}\text{Xe}$$



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Chiraleft4DM

Here we provide a Python package in form of a Jupyter notebook that calculates both structure factors and differential recoil spectra for the generalized spin-independent coupling of weakly interacting massive particles (WIMPs) to nuclei, as discussed in [1-4]. We give results for all possible coherently enhanced couplings of WIMPs to one and two nucleons up to third order in chiral effective field theory. The most relevant nuclear targets including fluorine, silicon, argon, germanium, and xenon are available. In addition, our package calculates the responses based on the fundamental couplings at the quark/gluon level, i.e., the Wilson coefficients.

The notebook aims to be self-explanatory and easy-to-use even for users new to Python. When downloaded from the website the files are stored in an archive. When unpacked to a common directory the notebook can be loaded. In the first part of the notebook users can specify a response and create data sets for both structure factors and differential recoil spectra. In the second part of the notebook, users can set specific values for the Wilson coefficient that describe the WIMP-quark/gluon couplings. The notebook generates the corresponding nucleon and pion matrix elements. Finally, the package yields the nuclear response including all channels that contribute to the choice of Wilson coefficients.

The notebook is based on:

- [1] M. Hoferichter, P. Klos, J. Menéndez, and A. Schwenk, [Phys. Rev. D 99, 055031 \(2019\)](#)
- [2] XENON Collaboration and M. Hoferichter, P. Klos, J. Menéndez, and A. Schwenk, [Phys. Rev. Lett. 122, 071301 \(2019\)](#)
- [3] M. Hoferichter, P. Klos, J. Menéndez, and A. Schwenk, [Phys. Rev. D 94, 063505 \(2016\)](#)
- [4] M. Hoferichter, P. Klos, and A. Schwenk, [Phys. Lett. B 746, 410 \(2015\)](#)

[Download Python notebook version 1.0](#)

Summary

Thanks to: **M. Hoferichter, P. Klos, J. Menéndez**

chiral effective field theory

nuclear forces and electroweak/WIMP/... interactions,
systematic for energies below ~ 300 MeV, so for direct detection

exciting era in nuclear physics, frontier of neutron-rich nuclei
with chiral EFT and powerful many-body calculations

structure factors for elastic/inelastic WIMP scattering (SD, SI+)
based on **large-scale nuclear structure calculations** and
systematic expansion of **WIMP-nucleon currents in chiral EFT**

incorporate what we know about QCD/nuclear physics
to go from future DM signal to nature of WIMP-q/g interactions

first limits for WIMP-pion interactions, next coherent after SI