— PAINT2026 —
Workshop on Progress in Ab Initio Nuclear Theory
25th February 2026

TWO-BODY CURRENTS AT FINITE MOMENTUM TRANSFER AND APPLICATIONS TO DARK MATTER SCATTERING OFF NUCLEI

work in progress

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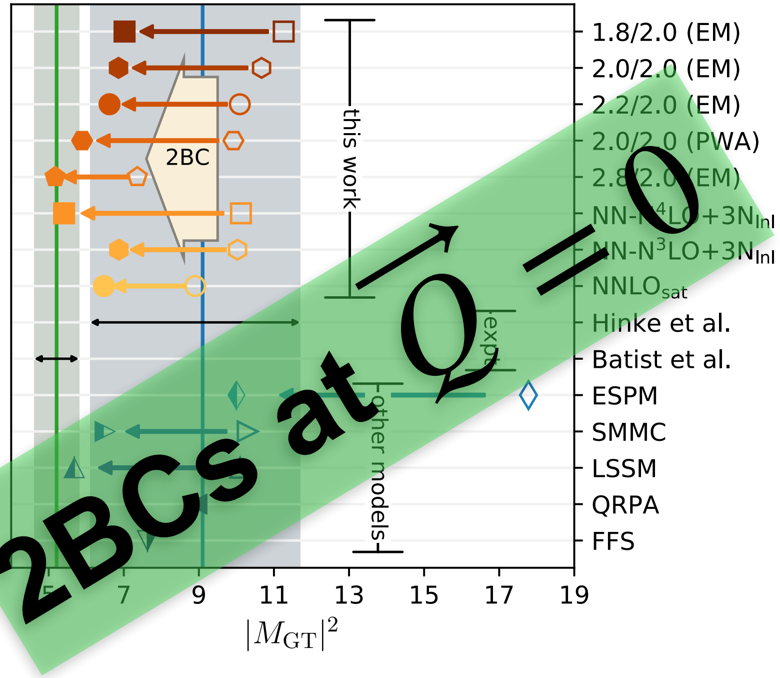
2BCs — FINITE MOMENTUM TRANSFER

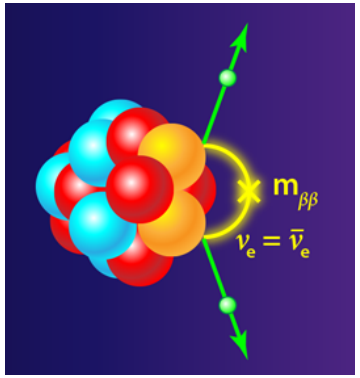
Gysbers et al., Nat. Phys. 15, 428 (2019)



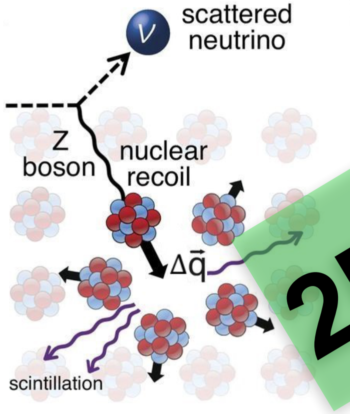
2BCs at $\vec{Q} = 0$

Nuclear theory crucial for extraction of BSM physics

$\longrightarrow$ we need to include 2BCs at $\vec{Q} \neq 0$



Engel and Vogel. Physics 11, 30 (2018)



Del Castello, arXiv:2302.02843 (2023)

2BCs at $\vec{Q} \neq 0$

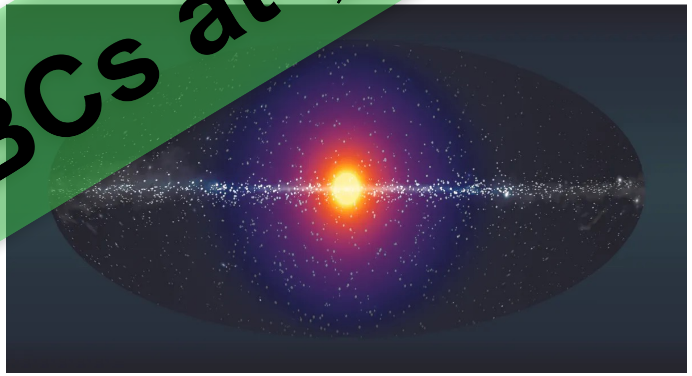


Image credit: Artistic rendering by Christopher Dessert, Nicholas L. Rodd, Benjamin R. Safdi, Zosia Rostomian (Berkeley Lab), based on data from the Fermi Large Area Telescope.
https://www.space.com/dark-matter-haloes-ancient-galaxy-1st-weight-measurements

For calculation **without approximating 2BCs** in **medium-mass or heavy nuclei**:
Multipole decomposition of 2BCs helpful

$$\vec{j}(\vec{Q}) = 4\pi \sum_{\lambda\mu} (-i)^{\lambda} \left(L_{\lambda\mu}(Q)\,\vec{Y}^{*}_{\lambda\mu}(\hat{Q}) + T^{\mathrm{el}}_{\lambda\mu}(Q)\,\vec{\Psi}^{*}_{\lambda\mu}(\hat{Q}) + T^{\mathrm{mag}}_{\lambda\mu}(Q)\,\vec{\Phi}^{*}_{\lambda\mu}(\hat{Q}) \right)$$

Takayuki Miyagi derived and implemented multipole decomposed 2BCs for inclusion at finite momentum transfer → first application to M1 transitions

Miyagi et al., Phys. Rev. Lett. 132, 232503 (2024)

DARK MATTER SCATTERING OFF NUCLEI

Dark matter candidate: weakly interacting massive particle (WIMP)

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WIMP-nucleus interaction at low energies

Spin-independent (SI)

Coherent contribution
of all nucleons in nucleus

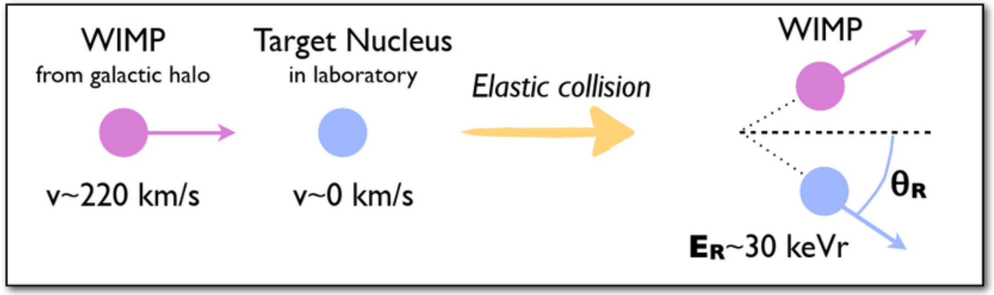
Response proportional to A^2

Spin-dependent (SD)

Response scaled by spin
expectation of unpaired
nucleon

Relevant detector nuclei:
$^{\mathbf{19}}$**F**, ^{23}Na, ^{27}Al, $^{\mathbf{29}}$**Si**, ^{73}Ge, ^{127}I and $^{\mathbf{129},131}$**Xe**

- Apply 2BCs at finite momentum transfer
- multipole decomposition for 2BCs: ground-state spin determines up to which rank the multipole decomposed 2BCs need to be generated
- **Bold nuclei**: $1/2^+ \rightarrow$ **only rank 1 needed**



Cooley, SciPost Phys. Lect. Notes 55 (2022)

EXPERIMENTS

& SD WIMP-nucleus interaction

Nuclear physics in structure factor

Many experimental efforts for direct detection using different detector nuclei, e.g.

Xe: **XENON**, LZ, PandaX, … xenonexperiment.org lz.lbl.gov pandax.sjtu.edu.cn

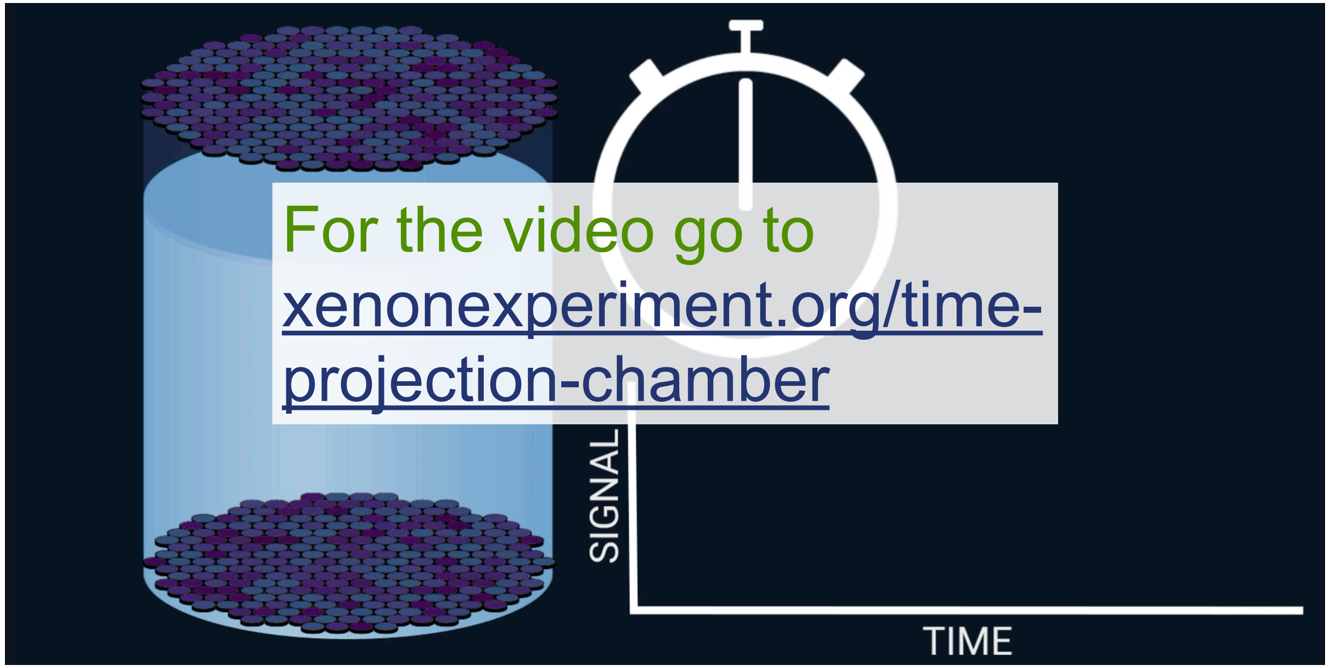
Si: SuperCDMS, … supercdms.slac.stanford.edu

F: PICO, … picoexperiment.com

Experimentalists model rate for events to search for excess events (candidates for WIMP events)

Nuclear response needs to be known to model the rate for WIMP-nucleus scattering events

$$\frac{d\sigma}{dQ^2} = \frac{8G_F^2}{(2J+1)v^2}\boxed{S_A(Q^2)}$$



For the video go to xenonexperiment.org/time-projection-chamber

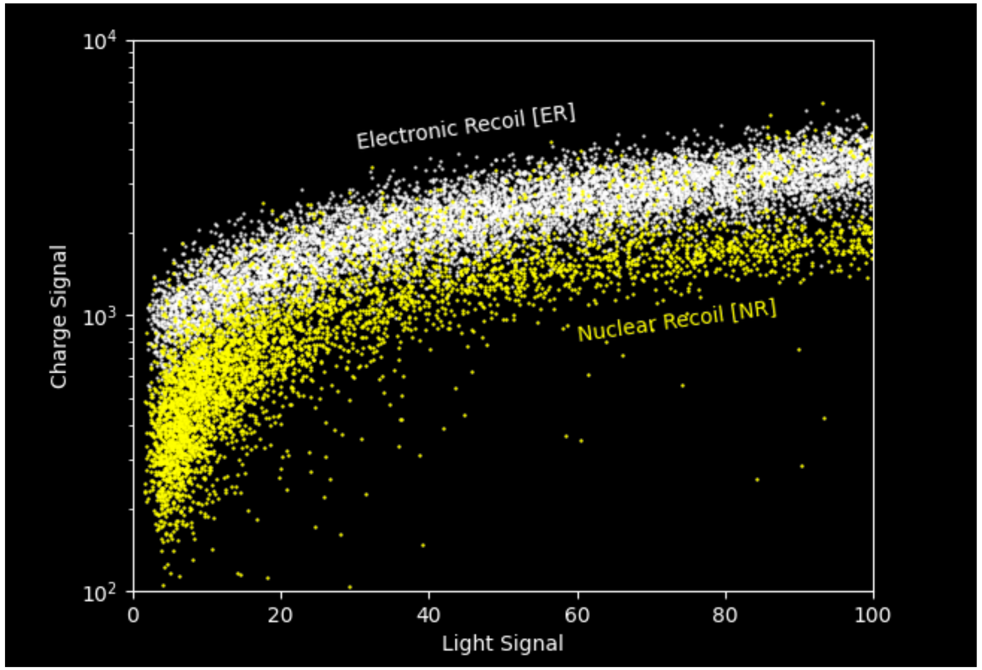


Figure taken from xenonexperiment.org/time-projection-chamber

STRUCTURE FACTORS (SF)

$$\frac{d\sigma}{dQ^2} = \frac{8G_F^2}{(2J+1)v^2} S_A(Q)$$

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Decomposed into different contributions:

- Isoscalar (IS) and isovector (IV) contributions

with $a_0 = \pm a_1 = 1$

$$S_A(Q) = a_{00}^2 S_{00}(Q) + a_0 a_1 S_{01}(Q) + a_1^2 S_{11}(Q)$$

$S_{00} = \mathrm{IS}^2$

$S_{01} = \mathrm{IS} \cdot \mathrm{IV}$

$S_{11} = \mathrm{IV}^2$

Standard used in experiment

$S_{\mathrm{n}}(Q) = S_{00}(Q) - S_{01}(Q) + S_{11}(Q)$, neutron SF

$S_{\mathrm{p}}(Q) = S_{00}(Q) + S_{01}(Q) + S_{11}(Q)$, proton SF

- Multipole decomposed contributions ($L =$ rank of operator)

$$S_A(Q) = \sum_{L\geq 0} \left| \langle J_f || \mathscr{L}_L^5 || J_i \rangle \right|^2 + \sum_{L\geq 1} \left| \langle J_f || \mathscr{T}_L^{\mathrm{el}5} || J_i \rangle \right|^2$$

Each multipole can have IS and IV contributions

Leading 2BCs are purely IV

Multipole decomposed

Fermi-Gas approximation

FERMI GAS (FG) APPROXIMATION

Hoferichter et al. Phys. Rev. D 94, 063505 (2016)

One-body current (1BC), IV part:

$$\mathbf{J}^3_{i,1b} = \frac{1}{2}\tau^3_i \left(G^3_A(Q^2)\,\boldsymbol{\sigma}_i - \frac{G^3_P(Q^2)}{4m_N^2}(\mathbf{Q}\cdot\boldsymbol{\sigma}_i)\,\mathbf{Q} \right)$$

δa dependence:

- LECs: $c_1,\ c_3,\ c_4,\ c_D,\ c_6$
- Density: $\rho = 2k_F^3/(3\pi^2)$ = $0.09\ \ldots\ 0.011\ \mathrm{fm}^{-3}$
- Momentum transfer Q

Normal-ordered one-body part of 2BCs:

$$\mathbf{J}^{\mathrm{eff}}_{i,2b} = \sum_j (1 - P_{ij}) J^3_{ij}$$

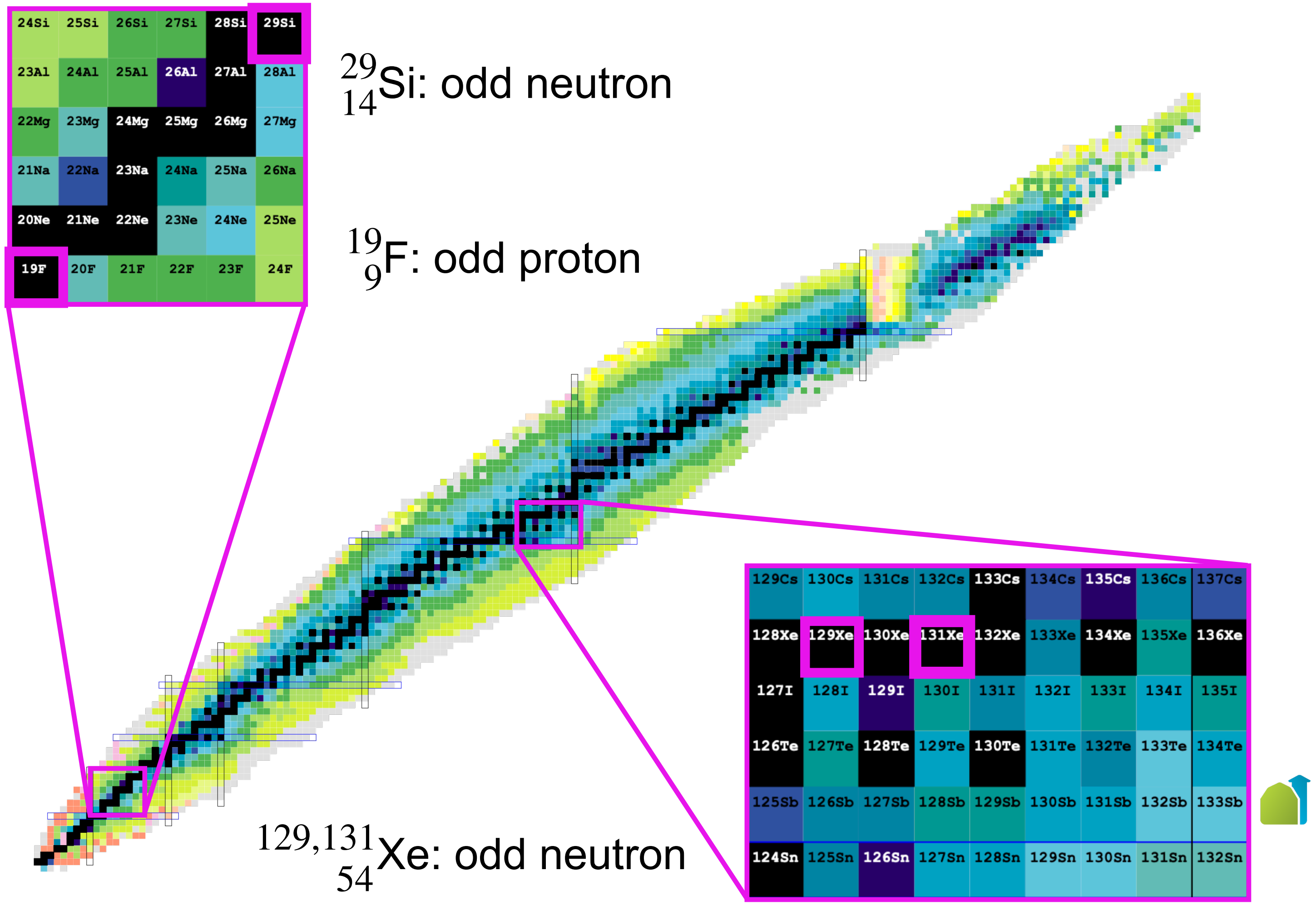
$$\mathbf{J}^{\mathrm{eff}}_{i,2b}(\boldsymbol{\rho},\mathbf{Q}) = g_A \frac{\tau^3_i}{2}\left[\boxed{\delta a(Q^2)}\,\boldsymbol{\sigma}_i + \frac{\boxed{\delta a^P(Q^2)}}{Q^2}(\mathbf{Q}\cdot\boldsymbol{\sigma}_i)\,\mathbf{Q} \right]$$

Analytical, can be easily added to 1BC

$$\boxed{\delta a(Q^2)} = -\frac{\rho}{F_\pi^2}\left[\frac{c_4}{3}\Big(3I_2^\sigma(\rho,|\mathbf{Q}|) - I_1^\sigma(\rho,|\mathbf{Q}|)\Big) - \frac{1}{3}\left(c_3 - \frac{1}{4m_N}\right)I_1^\sigma(\rho,|\mathbf{Q}|) - \frac{c_6}{12}I_{c6}(\rho,|\mathbf{Q}|) - \frac{c_D}{4g_A\Lambda_\chi}\right]$$

$$\boxed{\delta a^P(Q^2)} = \frac{\rho}{F_\pi^2}\left[-2(c_3-2c_1)\frac{M_\pi^2 Q^2}{(M_\pi^2+Q^2)^2} + \frac{1}{3}\left(c_3 + c_4 - \frac{1}{4m_N}\right)I^P(\rho,|\mathbf{Q}|) - \left(\frac{c_6}{12} - \frac{2}{3}\frac{c_1 M_\pi^2}{M_\pi^2+Q^2}\right)I_{c6}(\rho,|\mathbf{Q}|) - \frac{Q^2}{M_\pi^2+Q^2}\left[\frac{c_3}{3}\Big(I_1^\sigma(\rho,|\mathbf{Q}|) + I_1^P(\rho,|\mathbf{Q}|)\Big) + \frac{c_4}{3}\Big(I_1^\sigma(\rho,|\mathbf{Q}|) + I^P(\rho,|\mathbf{Q}|)\Big) - 3I_2^\sigma(\rho,|\mathbf{Q}|)\right] - \frac{c_D}{4g_A\Lambda_\chi}\frac{Q^2}{M_\pi^2+Q^2}\right]$$

SD-WIMP SCATTERING OFF NUCLEI



24Si	25Si	26Si	27Si	28Si	29Si
23Al	24Al	25Al	26Al	27Al	28Al
22Mg	23Mg	24Mg	25Mg	26Mg	27Mg
21Na	22Na	23Na	24Na	25Na	26Na
20Ne	21Ne	22Ne	23Ne	24Ne	25Ne
19F	20F	21F	22F	23F	24F

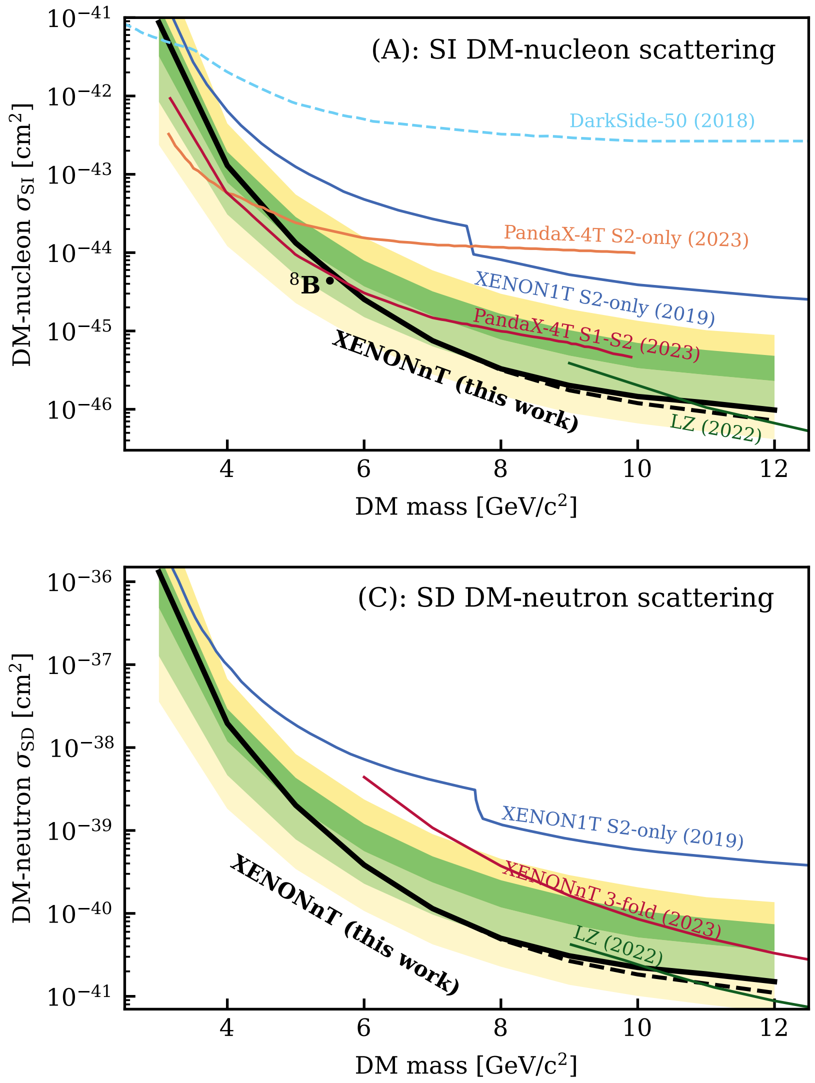
$^{29}_{14}$Si: odd neutron

$^{19}_{9}$F: odd proton

129Cs	130Cs	131Cs	132Cs	133Cs	134Cs	135Cs	136Cs	137Cs
128Xe	129Xe	130Xe	131Xe	132Xe	133Xe	134Xe	135Xe	136Xe
127I	128I	129I	130I	131I	132I	133I	134I	135I
126Te	127Te	128Te	129Te	130Te	131Te	132Te	133Te	134Te
125Sb	126Sb	127Sb	128Sb	129Sb	130Sb	131Sb	132Sb	133Sb
124Sn	125Sn	126Sn	127Sn	128Sn	129Sn	130Sn	131Sn	132Sn

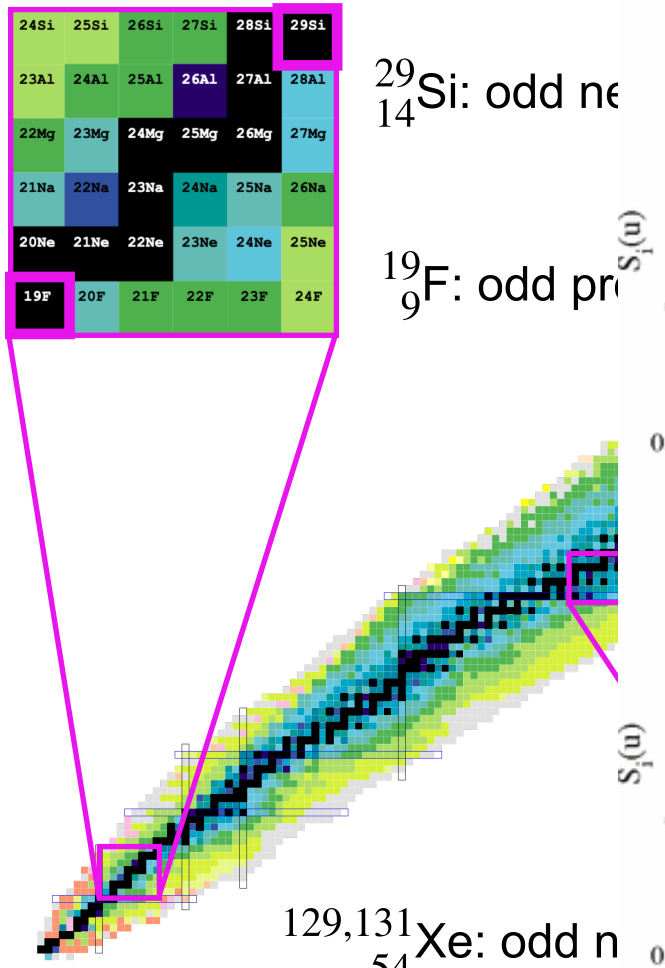
$^{129,131}_{54}$Xe: odd neutron

Figure modified from www.nndc.bnl.gov/nudat3



Aprile et al., Phys. Rev. Lett. 134, 111802 (2025)

SD-WIMP SCATTERING OFF NUCLEI



24Si	25Si	26Si	27Si	28Si	29Si
23Al	24Al	25Al	26Al	27Al	28Al
22Mg	23Mg	24Mg	25Mg	26Mg	27Mg
21Na	22Na	23Na	24Na	25Na	26Na
20Ne	21Ne	22Ne	23Ne	24Ne	25Ne
19F	20F	21F	22F	23F	24F

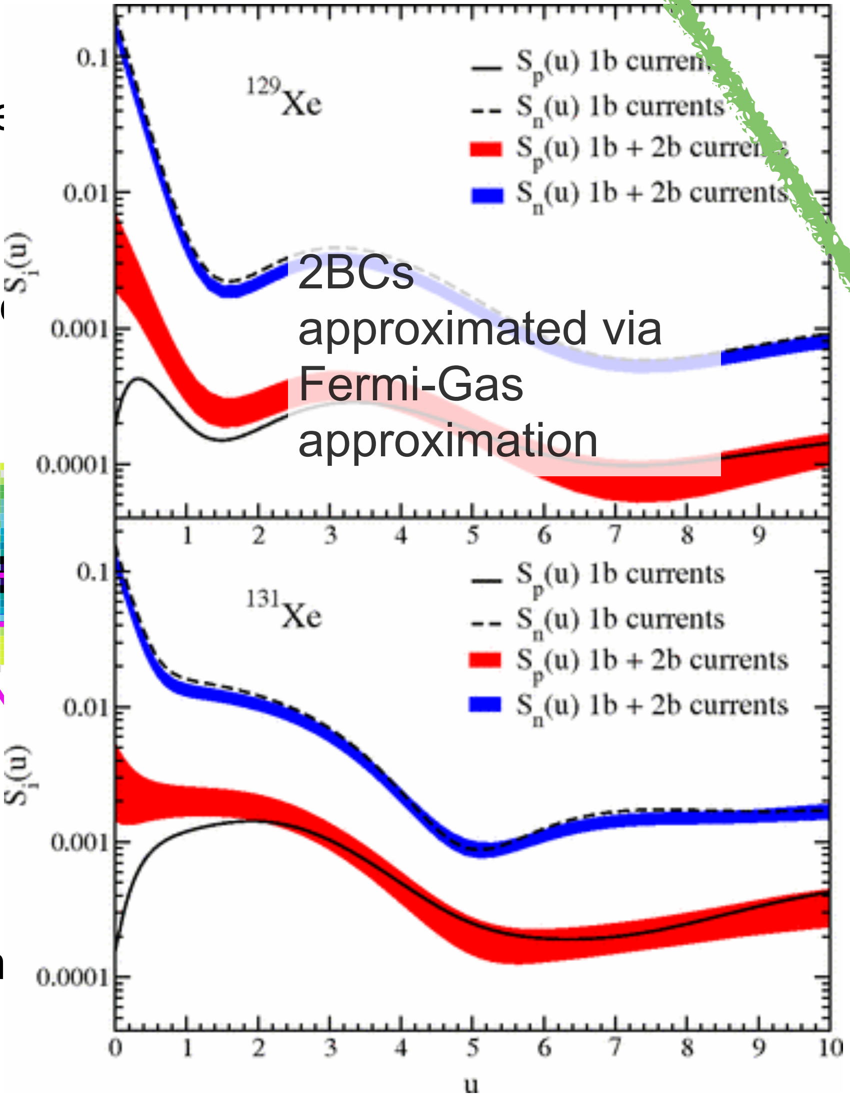
$^{29}_{14}$Si: odd ne

$^{19}_{9}$F: odd pr

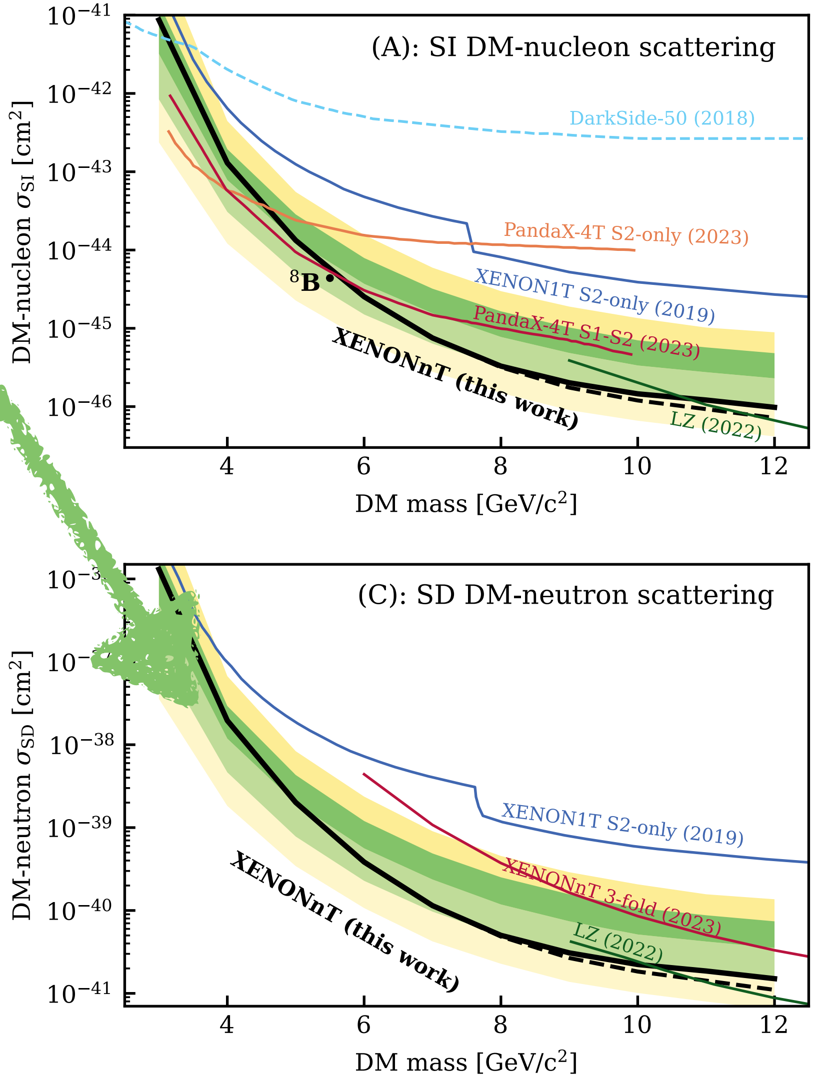
$^{129,131}_{54}$Xe: odd n

Figure modified from www.nndc.bnl.gov/nudat3

Klos et al., Phys. Rev. D 89, 029901 (2014)



2BCs approximated via Fermi-Gas approximation



Aprile et al., Phys. Rev. Lett. 134, 111802 (2025)

OUR WORK — INPUT AND METHOD

Interaction:
magic and ΔNNLO$_{\mathrm{GO}}$ (394)

Operators: With 2BCs
(at finite momentum transfer)

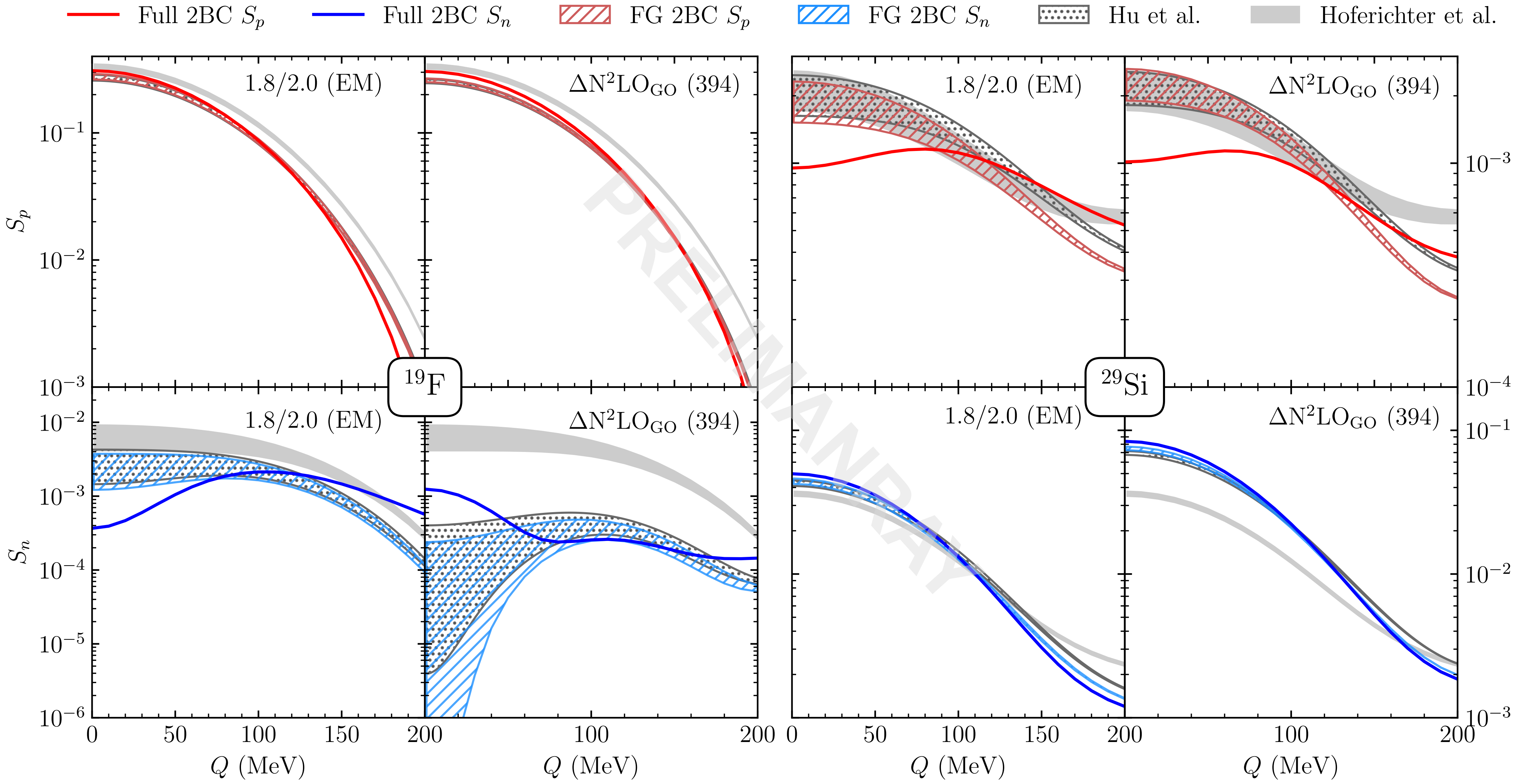
+

Many body method:
VS-IMSRG +
Hartree Fock & natural orbitals basis

=

Structure factors for
SD dark mattering scattering off nuclei
^{19}F, ^{29}Si, ^{129}Xe and ^{131}Xe

RESULTS — ^{19}F AND ^{29}Si



WHAT IS INCLUDED IN EACH?

— Full 2BC S_p

- VS-IMSRG
- LECs as in Hamiltonian
- Two interactions

— Full 2BC S_n

- Uncertainty (for Xe isotopes):
  - ✳Interactions
  - ✳e_{max} variation
  - ✳$\hbar\omega$ variation
  - ✳Basis variation (HF and NAT)

▨ FG 2BC S_p

- VS-IMSRG
- LECs as in Hamiltonian
- Two interactions
- NO2BC FG approx.

▨ FG 2BC S_n

- Uncertainty:
  - ✳Interactions
  - ✳e_{max} variation
  - ✳$\hbar\omega$ variation
  - ✳Density range ρ

▬ Hoferichter et al.

- Large scale shell model
- NO2BC FG approx.
- Uncertainty:
  - ✳LECs from χEFT
  - ✳Density range ρ

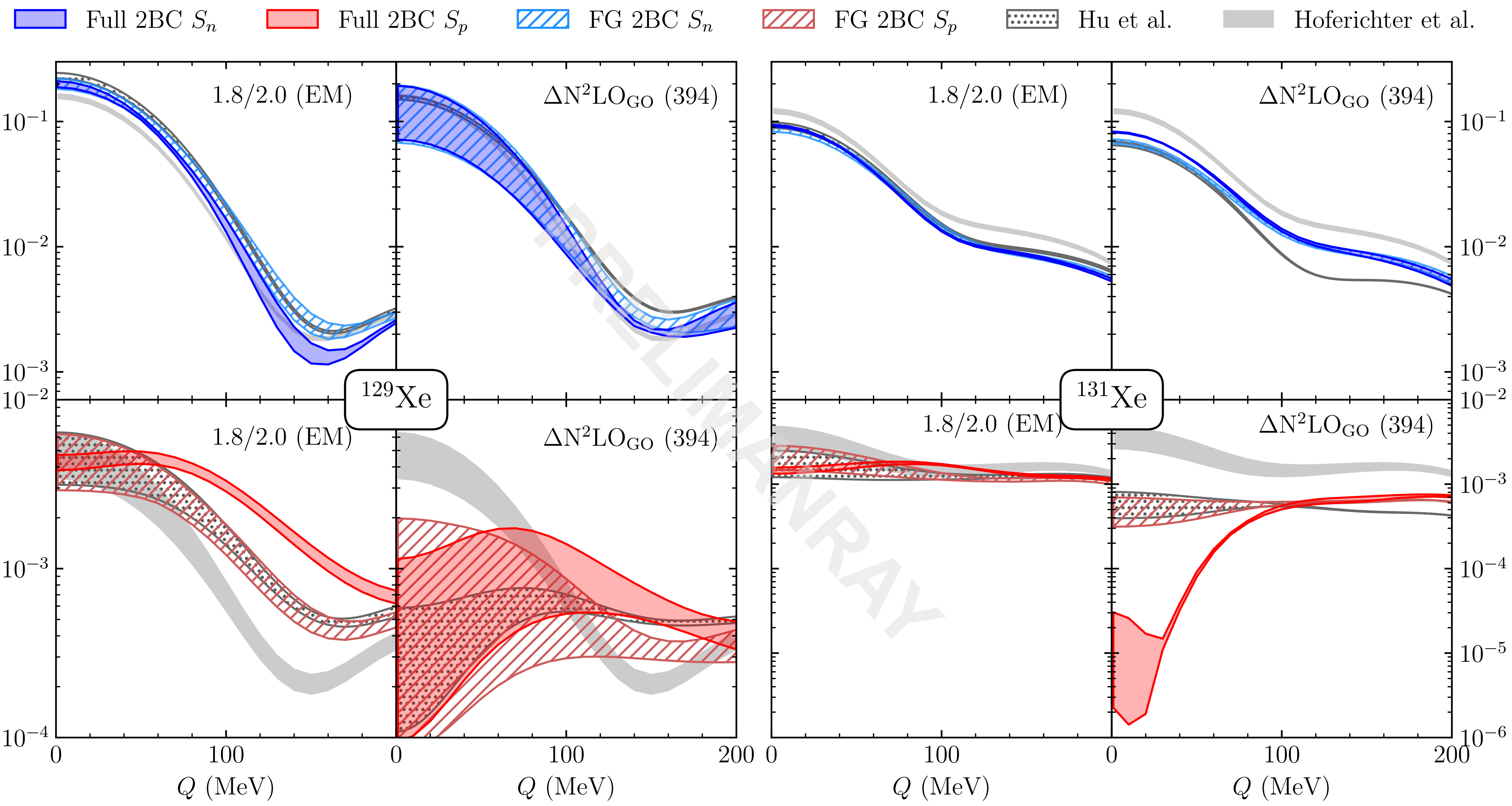
Hoferichter et al. Phys. Rev. D 94, 063505 (2016)

⠿ Hu et al.

- VS-IMSRG
- NO2BC FG approx.
- LECs as in Hamiltonian
- Uncertainty:
  - ✳Interactions
  - ✳Density range ρ

Hu et al., Phys. Rev. Lett. 128, 072502 (2022)

RESULTS — ^{129}Xe AND ^{131}Xe



FULL 2BC — MODEL-SPACE UNC.

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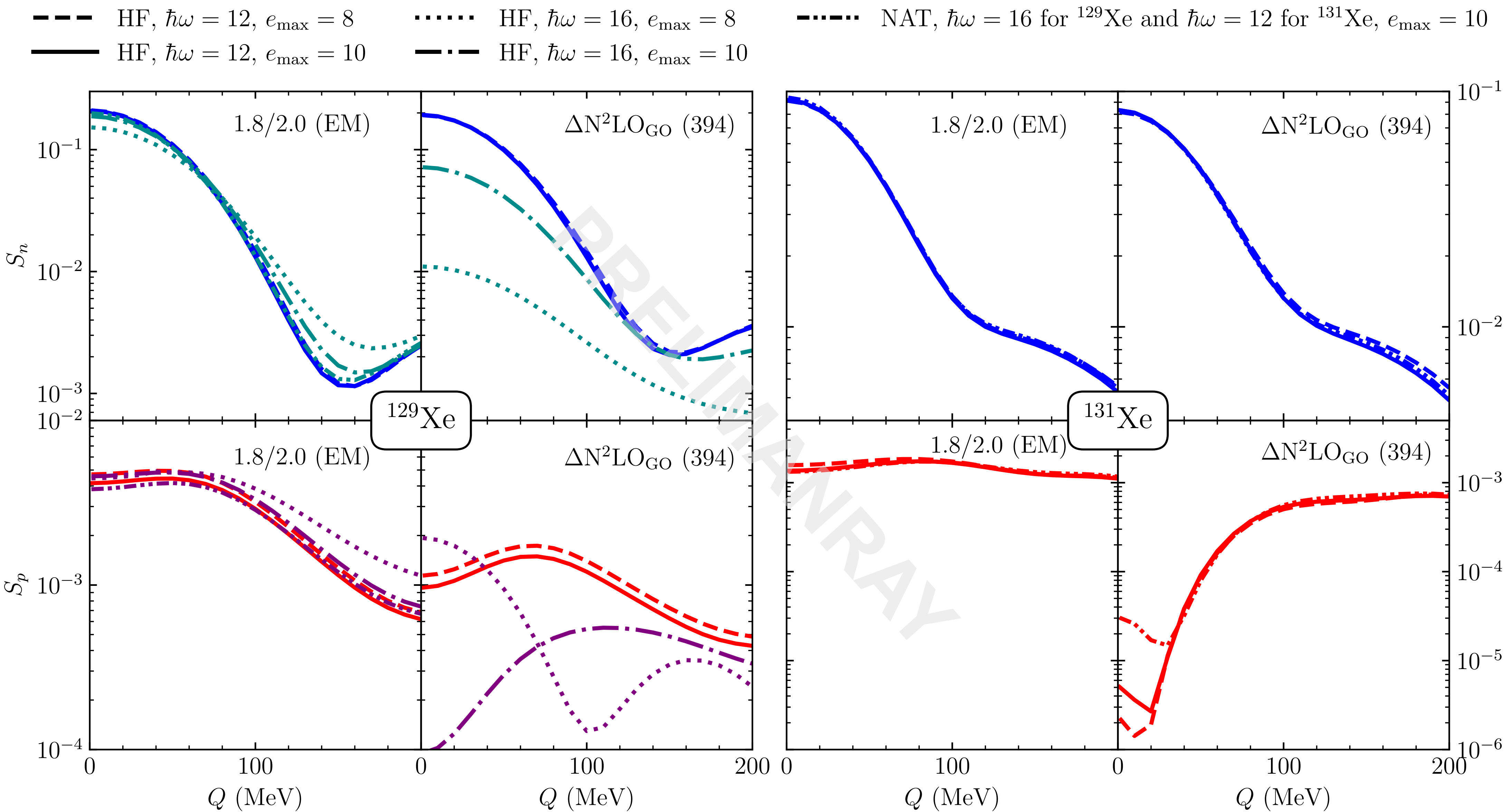
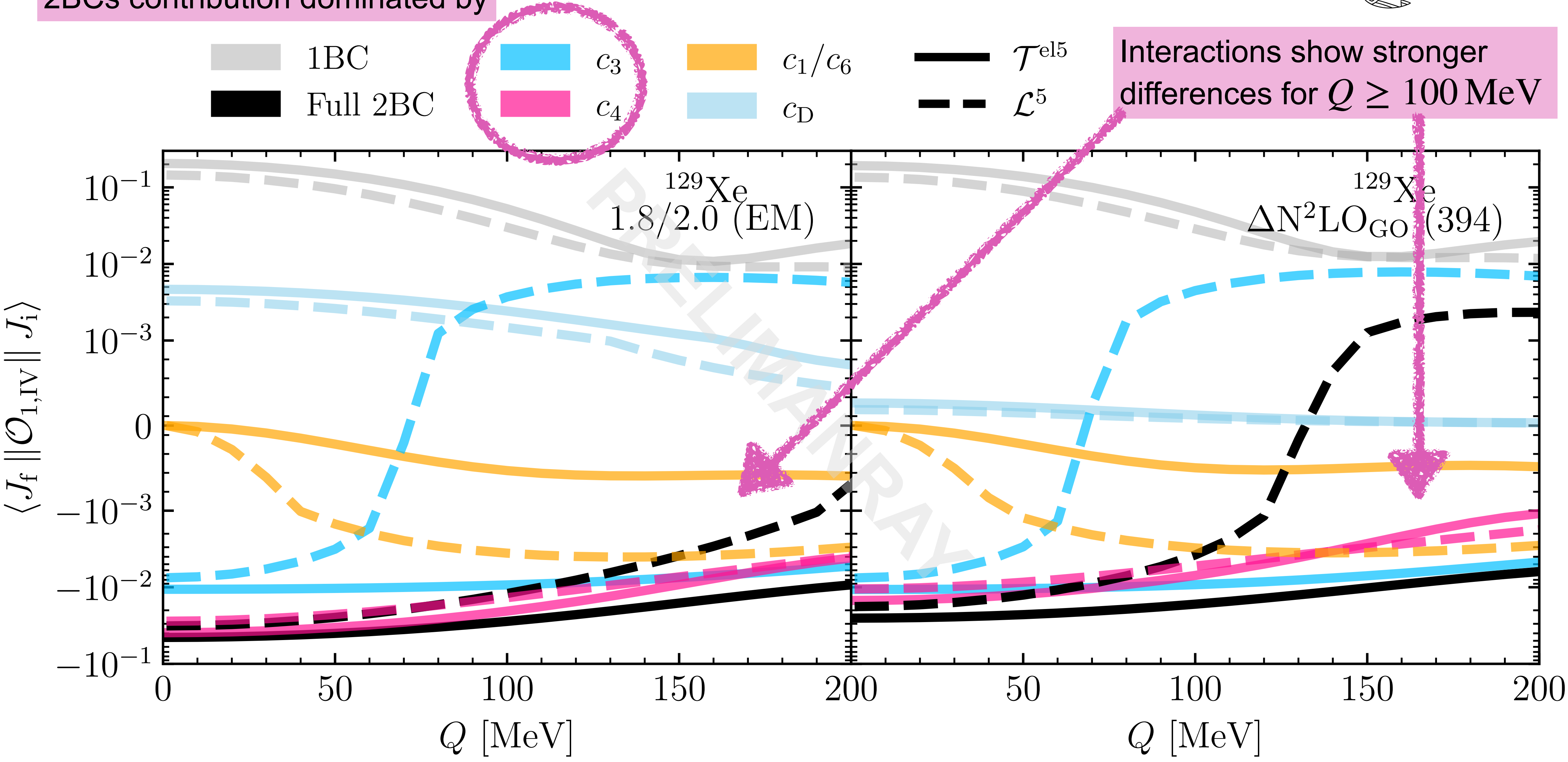


CONTRIBUTIONS FROM 2BCS — ^{129}Xe

2BCs contribution dominated by

Interactions show stronger differences for $Q \geq 100\,\text{MeV}$



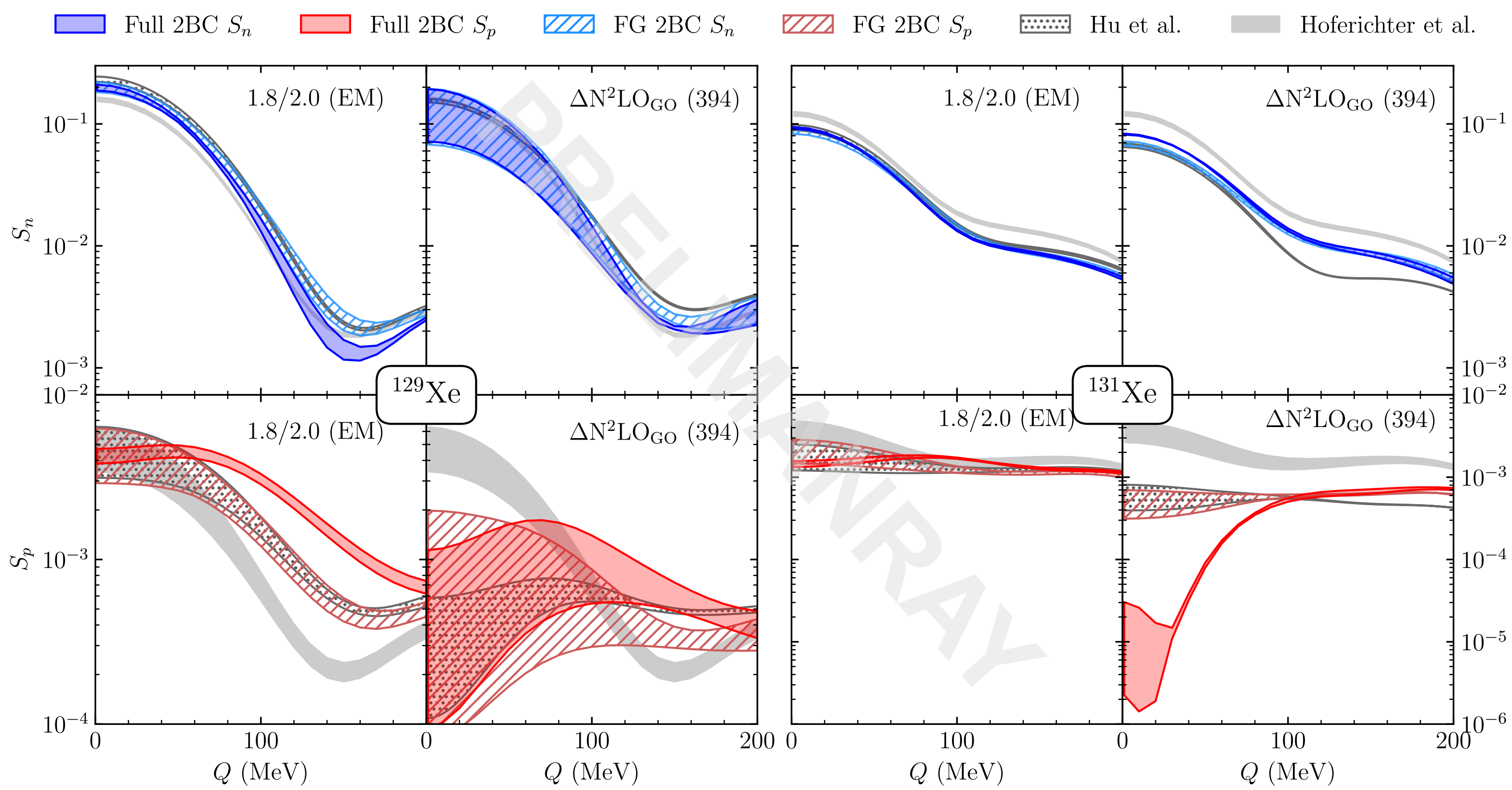
SUMMARY

Full 2BCs included in structure factors in $^{19}\mathrm{F}$, $^{29}\mathrm{Si}$, $^{129}\mathrm{Xe}$ and $^{131}\mathrm{Xe}$

$^{131}\mathrm{Xe}$: strong cancellation for $\triangle\mathrm{N2LO}_{\mathrm{GO}}(394)$ at low momenta

In lighter nuclei less differences between interactions

c_3 and c_4 dominate 2BCs at low momenta



OUTLOOK

Apply our structure factors to latest experimental results

Uncertainty quantification: χEFT truncation, Bayesian analysis

Other nuclei:
^{23}Na, ^{27}Al, ^{73}Ge, ^{127}I

Coherent elastic neutrino-nucleus scattering

Spin-independent nucleus - WIMP scattering

THANK YOU FOR YOUR ATTENTION!!