Ab initio calculations of nuclear structure factors for spin-dependent WIMP-nucleus scattering

– with full leading two-body current

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PandaX-xT 2nd Open Meeting
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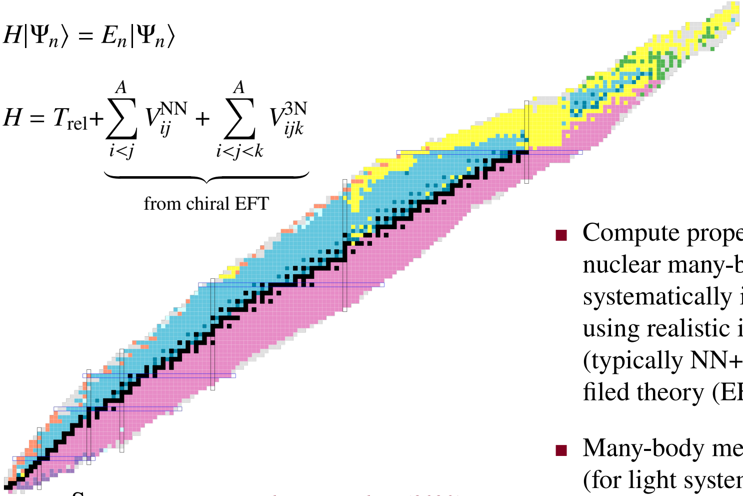
- A. Schwenk (TU Darmstadt)

for collaborations and discussions!

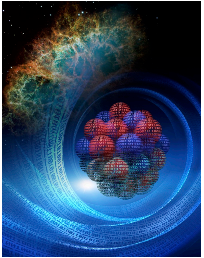
Ab initio calculation for atomic nuclei

$$H|\Psi_n\rangle = E_n|\Psi_n\rangle$$

$$H = T_{\rm rel} + \underbrace{\sum_{i<j}^{A} V_{ij}^{\rm NN} + \sum_{i<j<k}^{A} V_{ijk}^{\rm 3N}}_{\text{from chiral EFT}}$$



See *e.g.*, *Hergert et al., Front. Phys. (2020)*
Hebeler, Phys. Rept. (2021)
and ref therein



- Compute properties of nuclei by solving the nuclear many-body Schrödinger equation with systematically improvable many-body methods, using realistic inter-nucleon interactions (typically NN+3N) derived from chiral effective filed theory (EFT)

- Many-body methods: NCSM, QMC, HH, $\cdots$ (for light system $A \lesssim 16$), and MBPT, CC, SCGF, IMSRG, $\cdots$ (for heavier systems)

Chiral EFT for nuclear forces

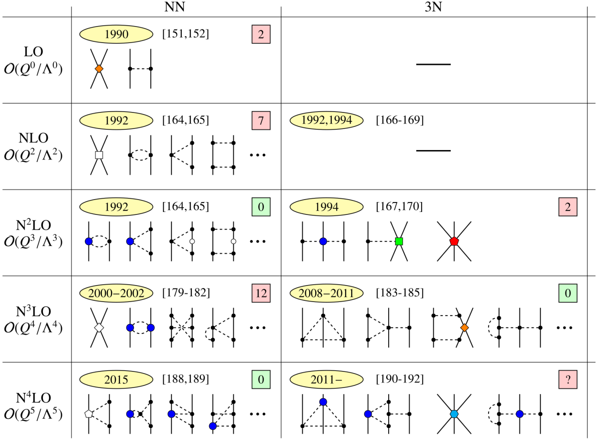


Fig. from Hebeler, Phys. Rept. (2021)

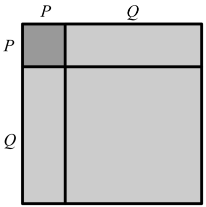
See e.g., Epelbaum et al., Rev. Mod. Phys. (2009)

Machleidt et al., Phys. Rep. (2011)

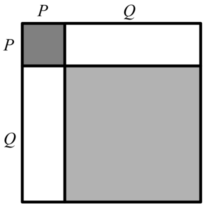
Krebs, Eur. Phys. J. A (2020)

- A low-energy effective theory of QCD with pions/nucleons (and optionally the Δ) as degrees of freedom, constrained by chiral symmetry and its breaking
- Expansion parameter $Q/\Lambda_b \simeq 1/3$
- Short-distance (high-energy) physics encoded in low-energy constants (LECs), fitted to NN scattering & few-body observables ^{2}H, ^{3}H, $\cdots$
- Systematically improvable and allows for uncertainty quantification
- Nuclear currents coupling to external probes (photons, electrons, neutrinos, etc.) can be derived consistently

Valence-space in-medium similarity renormalization group (VS-IMSRG)



Unitary transformations $U(s)$ $\longrightarrow$ Decouple P space from Q space



Hergert et al., Phys. Rep. (2016)
Stroberg et al., Ann. Rev. Nucl. Part. Sci. (2019)

$$H|\Psi_n\rangle = E_n|\Psi_n\rangle$$

$$H_{\text{eff}}|\Psi_n^P\rangle = E_n|\Psi_n^P\rangle$$

$$H = T_{\text{rel}} + \sum_{i<j}^{A} V_{ij}^{\text{NN}} + \sum_{i<j<k}^{A} V_{ijk}^{\text{3N}}$$

$$H_{\text{eff}} = [U(s) H U^\dagger(s)]_{s\to\infty}$$
$$O_{\text{eff}} = [U(s) O U^\dagger(s)]_{s\to\infty}$$

- The large model-space eigenvalue problem mapped to a tractable valence-space (P space) problem
- Particle-hole excitations from P to Q encoded in the *effective* Hamiltonian & operators
- Diagonalizing $H_{\text{eff}} \rightarrow$ energies and wavefunctions $\rightarrow$ other observables

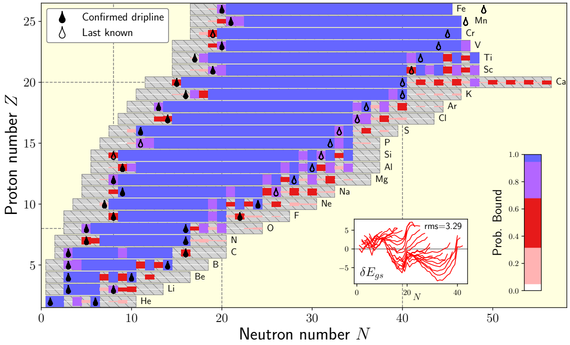
Highlights of *ab initio* calculations with VS-IMSRG

PHYSICAL REVIEW LETTERS 126, 022501 (2021)

Editors' Suggestion　Featured in Physics

Ab Initio Limits of Atomic Nuclei

S. R. Stroberg,[1,2,*] J. D. Holt,[2,3,†] A. Schwenk,[4,5,6,‡] and J. Simonis[7,4,5,§]



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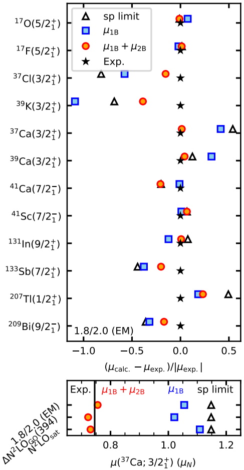
PHYSICAL REVIEW LETTERS 132, 232503 (2024)

Impact of Two-Body Currents on Magnetic Dipole Moments of Nuclei

T. Miyagi,[1,2,3,*,‡‡] X. Cao,[4,†] R. Seutin,[3,1,2,‡] S. Bacca,[5,6,§] R. F. Garcia Ruiz,[7,∥] K. Hebeler,[1,2,3,¶] J. D. Holt,[8,9,**] and A. Schwenk[1,2,3,††]



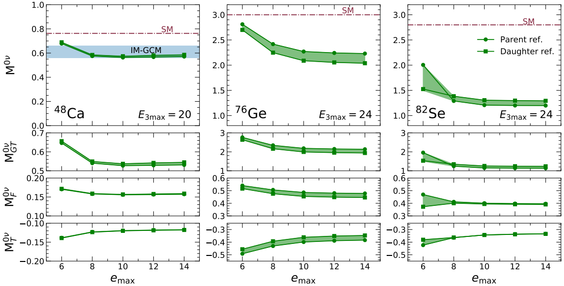
Magnetic dipole moments

Highlights of *ab initio* calculations with VS-IMSRG

PHYSICAL REVIEW LETTERS **126,** 042502 (2021)

Ab Initio Neutrinoless Double-Beta Decay Matrix Elements for ^{48}Ca, ^{76}Ge, and ^{82}Se

A. Belley,[1,2,3] C. G. Payne,[1,3,†] S. R. Stroberg,[4] T. Miyagi,[1] and J. D. Holt[1,2,*]

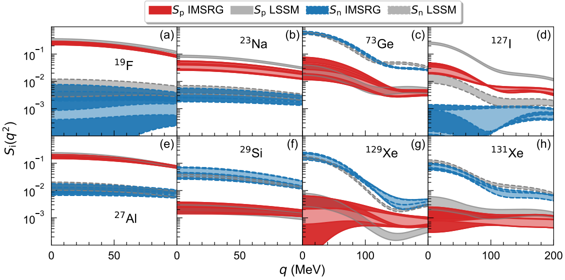


$0\nu\beta\beta$

PHYSICAL REVIEW LETTERS **128,** 072502 (2022)

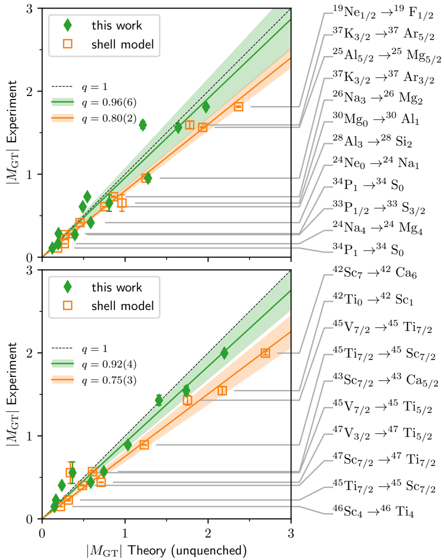
Ab Initio Structure Factors for Spin-Dependent Dark Matter Direct Detection

B. S. Hu,[1,*] J. Padua-Argüelles,[1,2,†] S. Leutheusser,[1,3,‡] T. Miyagi,[1,§] S. R. Stroberg,[4,∥,¶] and J. D. Holt[1,5,**]



WIMP-nucleus scattering

Highlights of *ab initio* calculations with VS-IMSRG



LETTERS
https://doi.org/10.1038/s41567-019-0450-7
nature physics

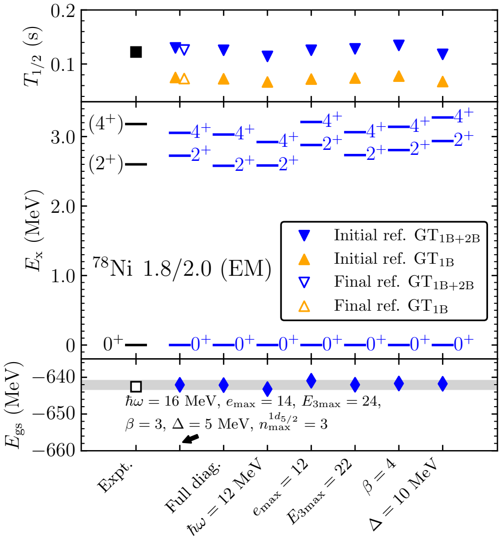
Discrepancy between experimental and theoretical β-decay rates resolved from first principles

P. Gysbers[1,2], G. Hagen[3,4*], J. D. Holt[1], G. R. Jansen[3,5], T. D. Morris[3,4,6], P. Navrátil[1], T. Papenbrock[3,4], S. Quaglioni[7], A. Schwenk[8,9,10], S. R. Stroberg[1,11,12] and K. A. Wendt[7]

GT quenching puzzle explained in *ab initio* calculations by taking into account the **many-body correlations** and **two-body currents**

VS-IMSRG calc. of β-decay half-lives

ZL, Miyagi and Schwenk, arXiv:2509.06812



Expt.: Taniuchi et al., Nature (2019); Xu et al., PRL (2014)

- ^{78}Ni ground-state energy and low-lying spectra are well described using VS-IMSRG with the 1.8/2.0 (EM) interaction *Hebeler et al., PRC (2011)*
- The leading 2BC appears at N^{2}LO, sharing same LECs as the leading 3NF

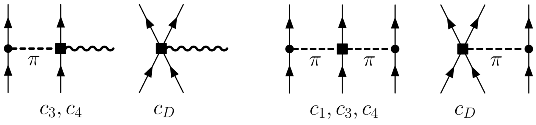
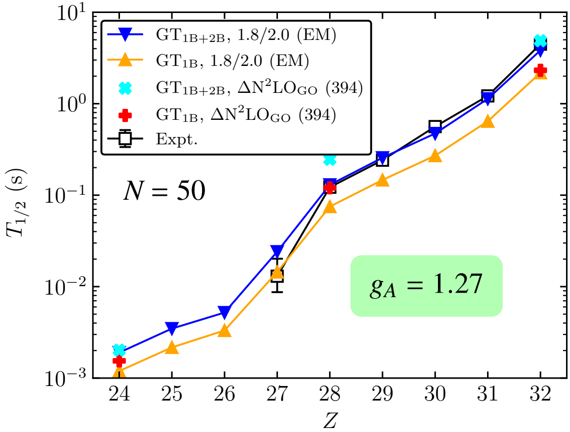


Fig. from Menéndez et al., PRL (2011)

- GT operators are evolved by VS-IMSRG to include the correlations coupled to the space outside
- 2BC increases the total half-life by reducing the GT transition strength

VS-IMSRG calc. of β-decay half-lives

ZL, Miyagi and Schwenk, arXiv:2509.06812



Total Gamow-Teller (dominant) half-lives of $N = 50$ isotones with VS-IMSRG

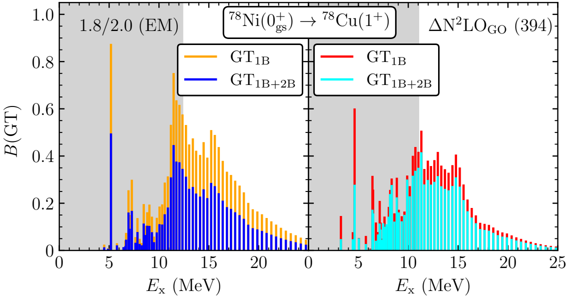
- Half-lives of waiting point nuclei ($N = 50, 82, 126, \ldots$ neutron-rich nuclei) are critical inputs for *r* process simulations, but less known experimentally
- 2BC increases the total half-life
- Expt. half-lives are well described with the 1.8/2.0 (EM) interaction
- No need to quench g_A in *ab initio* calculations

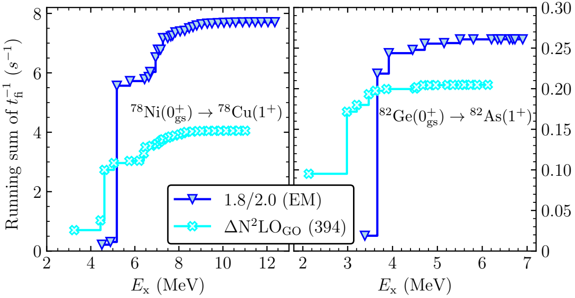
1.8/2.0 (EM): Hebeler et al., PRC (2011)

ΔN^2LO_{GO} (394): Jiang et al., PRC (2020)

VS-IMSRG calc. of β-decay half-lives

ZL, Miyagi and Schwenk, arXiv:2509.06812





- 2BC reduces B(GT) strength systematically → increase the total half-life
- Quite different running sums of t_{fi}^{-1} between 1.8/2.0 (EM) and ΔN^{2}LO$_{GO}$ (394) due to different B(GT) (related to wavefunctions) and phase space factors (related to energies)

1.8/2.0 (EM): Hebeler et al., PRC (2011)

ΔN^{2}LO$_{GO}$ (394): Jiang et al., PRC (2020)

Direct detection of WIMP via elastic SD WIMP-nucleus scattering

- Low-momentum-transfer Lagrangian density with axial-vector-axial-vector coupling

$$\mathcal{L}_\chi^{\text{SD}} = -\frac{G_F}{\sqrt{2}}\bar{\chi}\gamma\gamma_5\chi \cdot \sum_q A_q \bar{q}\gamma\gamma_5 q$$

Engel et al., Int. J. Mod. Phys. E (1992) *Jungman et al., RP (1996)*

- At one-nucleon level $\sum_q A_q \bar{q}\gamma\gamma_5 q \to \sum_{i=1}^{A}(\mathbf{J}_{i,1\text{b}}^0 + \mathbf{J}_{i,1\text{b}}^3)$ *Menéndez et al., PRD (2012)* *Klos et al., PRD (2013)*

$$\mathbf{J}_{i,1\text{b}}^0 = \frac{1}{2}a_0\boldsymbol{\sigma}_i, \quad \mathbf{J}_{i,1\text{b}}^3 = \frac{1}{2}a_1\tau_i^3\left\{\left(1-\frac{2}{\Lambda_A^2}\mathbf{Q}^2\right)\boldsymbol{\sigma}_i - \left[\frac{g_{\pi NN}F_\pi}{(\mathbf{Q}^2+M_\pi^2)m_N^2 g_A} - \frac{2}{\Lambda_A^2}\right](\mathbf{Q}\cdot\boldsymbol{\sigma}_i)\mathbf{Q}\right\}$$

- Differential cross section of elastic spin-dependent (SD) WIMP-nucleus scattering

$$\frac{\mathrm{d}\sigma^{\text{SD}}}{\mathrm{d}Q^2} = \frac{8G_F^2}{(2J+1)v^2}S_A(Q), \quad S_A(Q) = \sum_{\lambda=1,3,5,\ldots}\left\{|\langle J||L_\lambda^5||J\rangle|^2 + |\langle J||T_\lambda^{\text{el}5}||J\rangle|^2\right\}$$

- Longitudinal $L_{\lambda\mu}^5$, transverse electric $T_{\lambda\mu}^{\text{el}5}$ and transverse magnetic $T_{\lambda\mu}^{\text{mag}5}$ (does not contribute to S_A) operators from multipole decomposition of nuclear current $\mathbf{J}$ *Brase et al., PRC (2026)*

$$\mathbf{J}(\mathbf{Q}) = 4\pi\sum_{\lambda\mu} i^{\lambda+1}\left\{L_{\lambda\mu}^5(Q)\mathbf{Y}_{\lambda\mu}^*(\hat{\mathbf{Q}}) + T_{\lambda\mu}^{\text{el}5}(Q)\mathbf{\Psi}_{\lambda\mu}^*(\hat{\mathbf{Q}}) + T_{\lambda\mu}^{\text{mag}5}(Q)[i\mathbf{\Phi}_{\lambda\mu}(\hat{\mathbf{Q}})]^*\right\}$$

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

Direct detection of WIMP via elastic SD WIMP-nucleus scattering

- Low-momentum-transfer Lagrangian density with axial-vector-axial-vector coupling

$$\mathcal{L}_\chi^{\rm SD} = -\frac{G_F}{\sqrt{2}}\bar{\chi}\boldsymbol{\gamma}\gamma_5\chi \cdot \sum_q A_q\bar{q}\boldsymbol{\gamma}\gamma_5 q$$

Engel et al., Int. J. Mod. Phys. E (1992)   *Jungman et al., RP (1996)*

- At one-nucleon level $\sum_q A_q\bar{q}\boldsymbol{\gamma}\gamma_5 q \to \sum_{i=1}^{A}(\mathbf{J}_{i,1\mathrm{b}}^0 + \mathbf{J}_{i,1\mathrm{b}}^3)$ *Menéndez et al., PRD (2012)* *Klos et al., PRD (2013)*

$$\mathbf{J}_{i,1\mathrm{b}}^0 = \frac{1}{2}a_0\boldsymbol{\sigma}_i, \quad \mathbf{J}_{i,1\mathrm{b}}^3 = \frac{1}{2}a_1\tau_i^3\left\{\left(1-\frac{2}{\Lambda_A^2}\mathbf{Q}^2\right)\boldsymbol{\sigma}_i - \left[\frac{g_{\pi NN}F_\pi}{(\mathbf{Q}^2+M_\pi^2)m_N^2 g_A} - \frac{2}{\Lambda_A^2}\right](\mathbf{Q}\cdot\boldsymbol{\sigma}_i)\mathbf{Q}\right\}$$

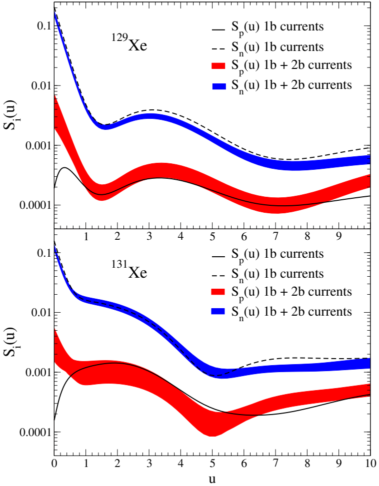
- The isovector $\mathbf{J}_{i,1\mathrm{b}}^3$ is identical to the axial-vector weak neutral current by replacing a_1 by g_A

- 2BC present at N^{2}LO in chiral EFT   *Krebs, Eur. Phys. J. A (2020)*   *Hoferichter et al., PRD (2020)*

$$\mathbf{J}_{2\mathrm{b},12}^{3,1\pi} = -\frac{a_1}{2F_\pi^2}[\boldsymbol{\tau}_1\times\boldsymbol{\tau}_2]^3\left[c_4\left(1-\frac{\mathbf{Q}\mathbf{Q}\cdot}{\mathbf{Q}^2+M_\pi^2}\right)(\boldsymbol{\sigma}_1\times\mathbf{k}_2) + \frac{c_6}{4}(\boldsymbol{\sigma}_1\times\mathbf{Q})\right]\frac{\boldsymbol{\sigma}_2\cdot\mathbf{k}_2}{M_\pi^2+k_2^2}$$
$$-\frac{a_1}{F_\pi^2}\tau_2^3\left[c_3\left(1-\frac{\mathbf{Q}\mathbf{Q}\cdot}{\mathbf{Q}^2+M_\pi^2}\right)\mathbf{k}_2 + 2c_1M_\pi^2\frac{\mathbf{Q}}{\mathbf{Q}^2+M_\pi^2}\right]\frac{\boldsymbol{\sigma}_2\cdot\mathbf{k}_2}{M_\pi^2+k_2^2} + (1\leftrightarrow 2),$$

$$\mathbf{J}_{2\mathrm{b},12}^{3,\mathrm{ct}} = \frac{a_1}{g_A}\left[-d_1\tau_1^3\left(1-\frac{\mathbf{Q}\mathbf{Q}\cdot}{\mathbf{Q}^2+M_\pi^2}\right)\boldsymbol{\sigma}_1 + (1\leftrightarrow 2) - d_2(\boldsymbol{\tau}_1\times\boldsymbol{\tau}_2)^3(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\left(1-\frac{\cdot\mathbf{Q}\mathbf{Q}}{\mathbf{Q}^2+M_\pi^2}\right)\right]$$

Existing calculations of SD structure factors



$u \equiv Q^2 b^2/2$

Fig. from *Klos et al., PRD (2013)*

ρ, c_3, c_4 $\longrightarrow$ uncertainty band

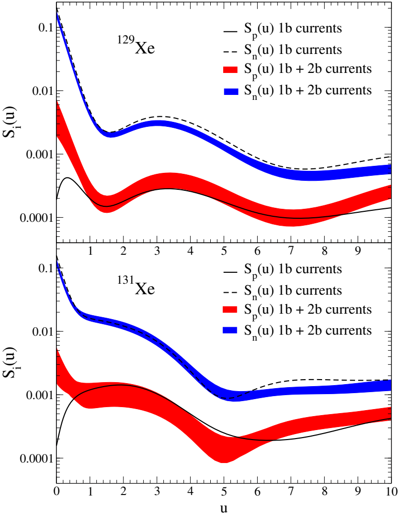
- **Approximate** 2BC: NO1B approx. w/ spin- and isospin-symmetric Fermi gas as the reference state with density $\rho = 2k_F^3/(3\pi^2)$
  $\longrightarrow$ ρ-dependent eff. 1BC: $\mathbf{J}^{\text{eff}}_{i,2\text{b}}(\rho) = \sum_{\text{occupied } j} (1 - \mathcal{P}_{ij})\mathbf{J}^3_{ij}$
  - Phenomenological calc.: *Menéndez et al., PRD (2012)* *Klos et al., PRD (2013)* *Pirinen et al., NPA (2019)* *Hoferichter et al., PRD (2020)* *Kasurinen et al., PRC (2025)* …
  - *Ab initio* VS-IMSRG calc.: *Hu et al., PRL (2022)*
- $S_A(Q=0) = \frac{(J+1)(2J+1)}{4\pi J}\left[(a_0+a_1)\langle\hat{\mathbf{S}}_p\rangle + (a_0-a_1)\langle\hat{\mathbf{S}}_n\rangle\right]^2$

  $\langle\hat{\mathbf{S}}_{p(n)}\rangle \equiv \langle JM=J|\sum_{i_{p(n)}=1}^{Z(N)} \frac{1}{2}\boldsymbol{\sigma}_{i_{p(n)}}|JM=J\rangle$

  ^{129,131}Xe: odd $N \longrightarrow \langle\hat{\mathbf{S}}_n\rangle > \langle\hat{\mathbf{S}}_p\rangle$
- Define S_p with $a_0 = a_1 = 1$ and S_n with $a_0 = -a_1 = 1$:

$$S_p(Q) = S_{00}(Q) + S_{01}(Q) + S_{11}(Q)$$
$$S_n(Q) = S_{00}(Q) - S_{01}(Q) + S_{11}(Q)$$

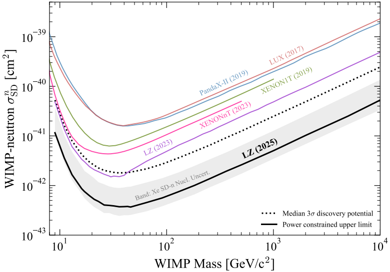
Existing calculations of SD structure factors

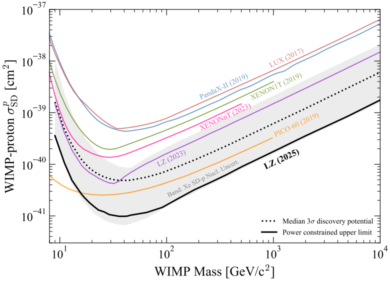


$u \equiv Q^2 b^2/2$

Fig. from *Klos et al., PRD (2013)*

$\rho, c_3, c_4 \rightarrow$ uncertainty band





Aalbers et al., PRL (2025)

- Large uncertainty from ρ in $\mathbf{J}^{\text{eff}}_{i,2b}(\rho)$
- Propagate into the WIMP-nucleon cross section calculation

Uncertainty band of *Aalbers et al., PRL (2025)*:

- *Pirinen et al., NPA (2019)*
- *Hoferichter et al., PRD (2020)*
- *Hu et al., PRL (2022)*

all with NO1B 2BC

Computational setup for ^{19}F, ^{29}Si, ^{129,131}Xe with full leading 2BC

- Multipole decomposition of 2BC using `NuHamil` by T. Miyagi *Miyagi, EPJA (2023)*
- VS-IMSRG evolution $\rightarrow H_{\text{eff}}$, $L^{5,\,\text{eff}}_{\lambda\mu}$, and $T^{\text{el5},\,\text{eff}}_{\lambda\mu}$ in valence space
- Diagonalize H_{eff} in the valence space to get the ground-state wavefunction $|J\rangle$
- Calculate the nuclear matrix elements $\langle J||L^{5,\,\text{eff}}_{\lambda\mu}||J\rangle$ and $\langle J||T^{\text{el5},\,\text{eff}}_{\lambda\mu}||J\rangle$ and therefore the structure factor $S_{ij}(Q)$ and then $S_{p,n}(Q)$

Computational setup for ^{19}F, ^{29}Si, ^{129,131}Xe with full leading 2BC

- NN+3N interactions 1.8/2.0 (EM) and ΔN^{2}LO$_{\text{GO}}$ (394) and consistent 2BCs
  Hebeler et al., PRC (2011) Jiang et al., PRC (2020) Krebs et al., Ann. Phys. (2017) Hoferichter et al., PRD (2020)

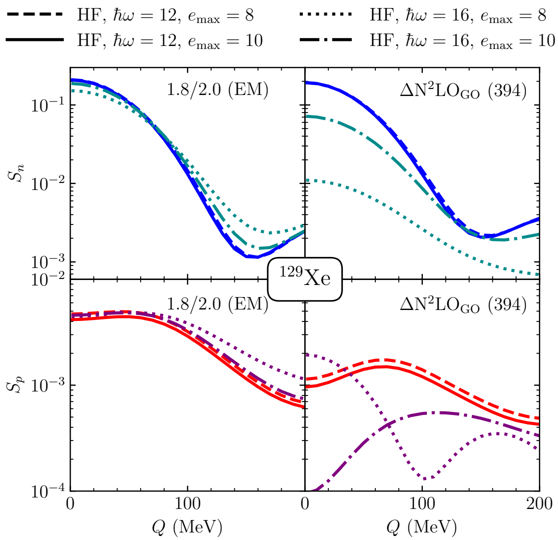
- Basis (build on top of harmonic oscillator basis with $\hbar\omega$ = 12 or 16 MeV):
  - Hartree-Fock (HF): solve HF equation truncated by $e_{\max}^{\text{HF}} = (2n+l)_{\max}$ *Stroberg et al., PRL (2017)*
    $e_{\max}^{\text{HF}} = 12$ for ^{19}F, ^{29}Si and $e_{\max}^{\text{HF}} = 10$ for ^{129,131}Xe $\rightarrow e_{\max} = e_{\max}^{\text{HF}}$ in VS-IMSRG evolution
  - Natural orbitals (NAT): diagonalize 1B density matrix w/ perturbative corr. *Hoppe et al., PRC (2021)*
    truncated by $e_{\max}^{\text{NAT}} = 14 \rightarrow e_{\max} = 10$ in VS-IMSRG evolution

- $V_{ijk}^{3\text{N}}$ matrix elements are restricted by $E_{3\max} = (e_i + e_j + e_k)_{\max} = 24$ *Miyagi et al., PRC (2022)*

- Valence space:
  - ^{19}F and ^{29}Si: *sd*-shell
  - ^{129,131}Xe: $\{2s_{1/2}, 1d_{3/2,5/2}, 0g_{7/2}, 0h_{11/2}\}$ (orbitals between the magic numbers 50 and 82)

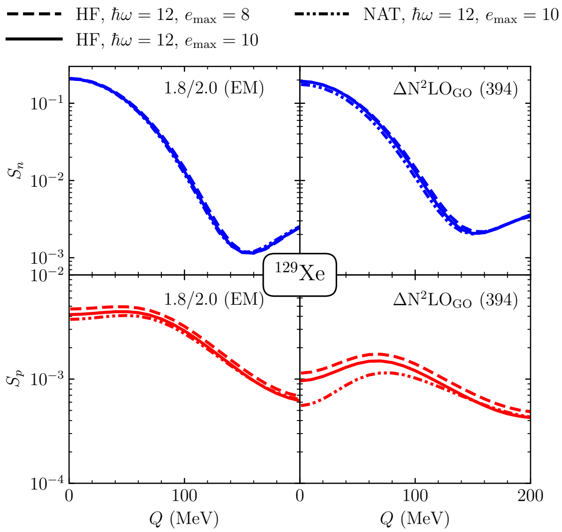
- Effective Hamiltonian and operators are truncated up to NO2B level *Stroberg et al., PRL (2017)*

Convergence w.r.t. model-space parameters $\hbar\omega$ and $e_{\max}$ for ^{129,131}Xe



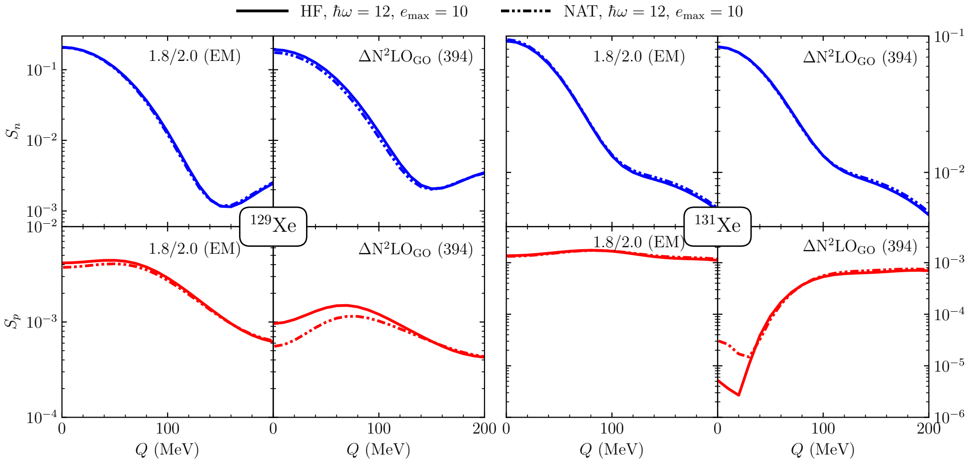
- **HF basis**: $e_{\max}^{\text{HF}} = e_{\max}$ in VS-IMSRG evolution
- Faster convergence with $\hbar\omega$ = 12 MeV, especially for ΔN^2LO_{GO} (394)
  → **take $\hbar\omega$ = 12 MeV**
- Prohibitively expensive for VS-IMSRG evolution with $e_{\max}$ = 12 in such calculations, since we have to do VS-IMSRG evolution for each momentum
  → **take $e_{\max}$ = 10 in VS-IMSRG evolution**
- **NAT basis** capture correlations from a larger model space (here $e_{\max}^{\text{NAT}}$ = 14) by concentrating their effects into the most important low-lying orbitals, so that a truncated space (here $e_{\max}$ = 10) retains more of the relevant physics

Convergence w.r.t. model-space parameters $\hbar\omega$ and $e_{\max}$ for ^{129,131}Xe



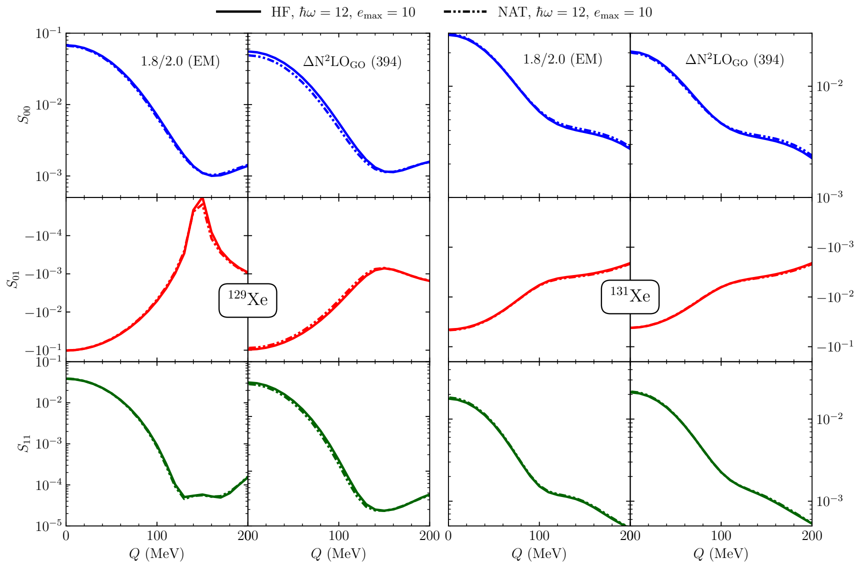
- NAT basis: $e_{\max}^{\mathrm{NAT}} = 14$
  $\rightarrow e_{\max} = 10$ in VS-IMSRG evolution
  $\rightarrow$ captures correlations in the larger model space
- Nice convergence pattern with $\hbar\omega = 12$ MeV
  - HF basis: $e_{\max} = 8 \rightarrow e_{\max} = 10$
  - $e_{\max} = 10$: HF basis $\rightarrow$ NAT basis
- Slower convergence for S_p with ΔN^2LO_{GO} (394)
- Take the spread between HF and NAT basis with $e_{\max} = 10$ as the uncertainty band

Convergence w.r.t. model-space parameters $\hbar\omega$ and $e_{\max}$ for ^{129,131}Xe



S_p calculated from ΔN^2LO_{GO} (394) converges slower

Convergence w.r.t. model-space parameters $\hbar\omega$ and $e_{\max}$ for ^{129,131}Xe



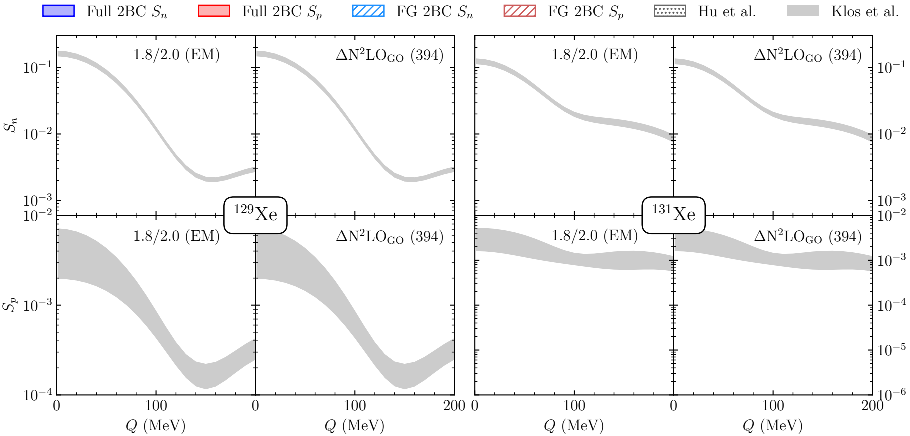
- S_{00}, S_{01}, and S_{11} are well converged → small uncertainty from model space
- The larger uncertainty band for S_p with ΔN^{2}LO$_{\text{GO}}$ (394) is due to the delicate cancellation between positive $S_{00}(q)+S_{11}(q)$ and negative $S_{01}(q)$:

$$S_p(Q) = S_{00}(Q)+S_{11}(Q)+S_{01}(Q)$$

- S_n is well converged with ΔN^{2}LO$_{\text{GO}}$ (394) since

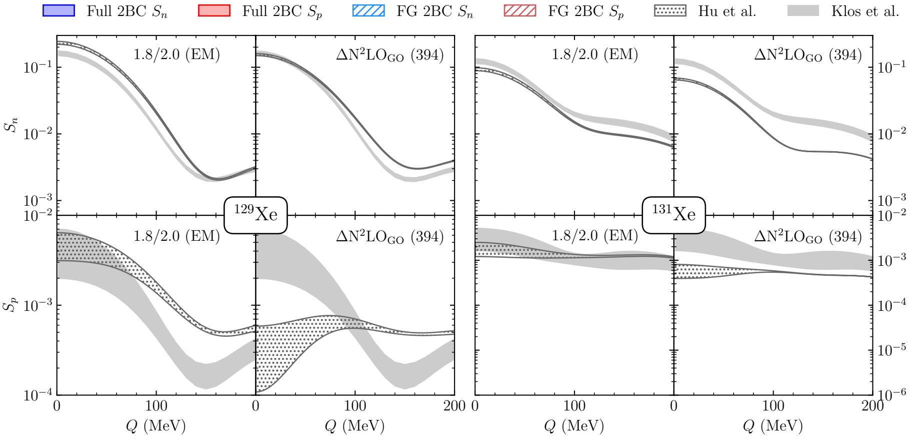
$$S_n(Q) = S_{00}(Q)+S_{11}(Q)-S_{01}(Q)$$

Structure factors of ^{129}Xe and ^{131}Xe from Klos et al.



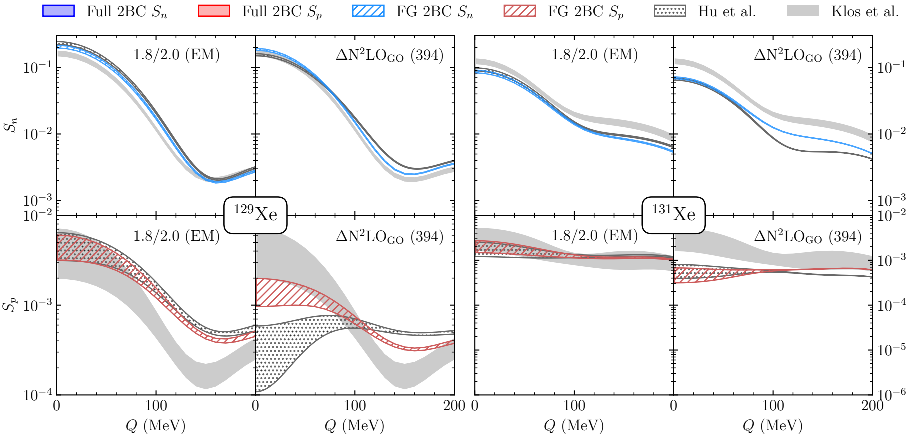
- *Klos et al., PRD (2013)*: phenomenological shell model calculation with NO1B 2BC in FG model

Structure factors of ^{129}Xe and ^{131}Xe from Klos et al. and Hu et al.



- *Klos et al., PRD (2013)*: phenomenological shell model calculation with NO1B 2BC in FG model
- *Hu et al., PRL (2022)*: *ab initio* calculation using VS-IMSRG with NO1B 2BC in FG model

Structure factors of ^{129}Xe and ^{131}Xe from NO1B 2BC



- *Klos et al., PRD (2013)*: phenomenological shell model calculation with NO1B 2BC in FG model
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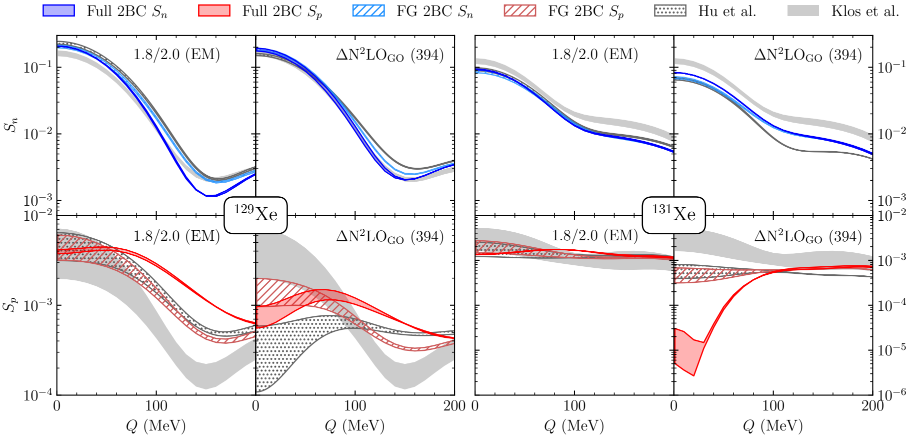
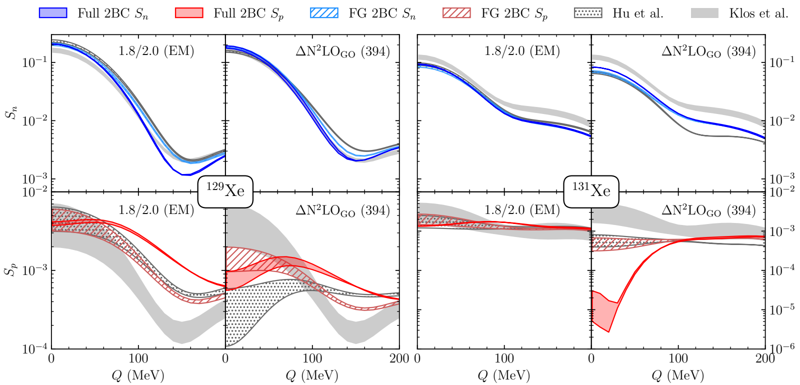
- FG 2BC $S_{p,n}$: Our *ab initio* calculation similar to *Hu et al., PRL (2022)* but with larger model space

Structure factors of ^{129}Xe and ^{131}Xe from full 2BC



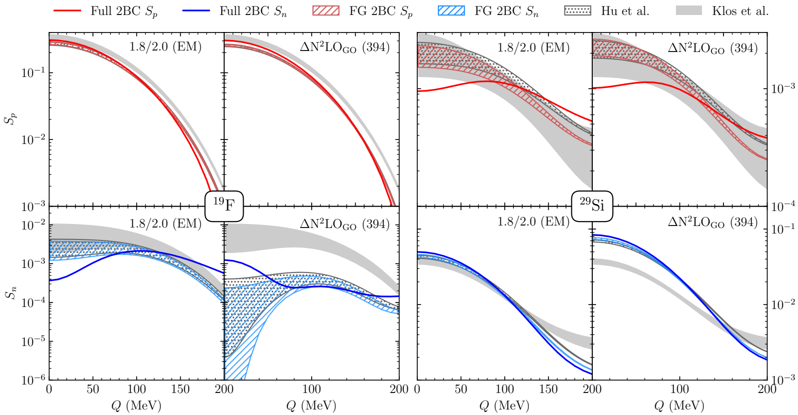
- *Klos et al., PRD (2013)*: phenomenological shell model calculation with NO1B 2BC in FG model
- *Hu et al., PRL (2022)*: *ab initio* calculation using VS-IMSRG with NO1B 2BC in FG model
- FG 2BC $S_{p,n}$: Our *ab initio* calculation similar to *Hu et al., PRL (2022)* but with larger model space
- Full 2BC $S_{p,n}$: Our *ab initio* calculation using VS-IMSRG with full leading 2BC

Structure factors of ^{129}Xe and ^{131}Xe from full 2BC



- Xe: even Z and odd N
  → spin mainly carried by neutrons
  → $S_n > S_p$
- Full leading 2BC
  → no ρ dependence
  → uncertainty reduction
- The difference between 1.8/2.0 (EM) and ΔN^2LO_{GO} (394) is much larger than the uncertainty band from the model space
  → UQ for interaction

Structure factors of ^{19}F and ^{29}Si



- Much lighter nuclei, HF basis with $\hbar\omega = 16$ and $e_{\max} = 12$ is enough to get converged results
- ^{19}F: odd $Z \rightarrow S_p > S_n$
- ^{29}Si: odd $N \rightarrow S_n > S_p$
- Results from 1.8/2.0 (EM) and ΔN^{2}LO$_{GO}$ (394) are quite different $\rightarrow$ UQ for interaction

Summary and outlook

Summary

- First *ab initio* calculation of SD nuclear structure factors with full leading 2BC without approximation
- Eliminates the uncertainty associated with ρ in previous NO1B approximations
- Reduction of uncertainty will propagate into the elastic SD WIMP-nucleon scattering analysis

Outlook

- Study the impact of the uncertainty reduction of nuclear structure to the limits of elastic SD WIMP-nucleon cross section
- Quantify the uncertainty arising from nuclear interaction and higher-order 2BCs

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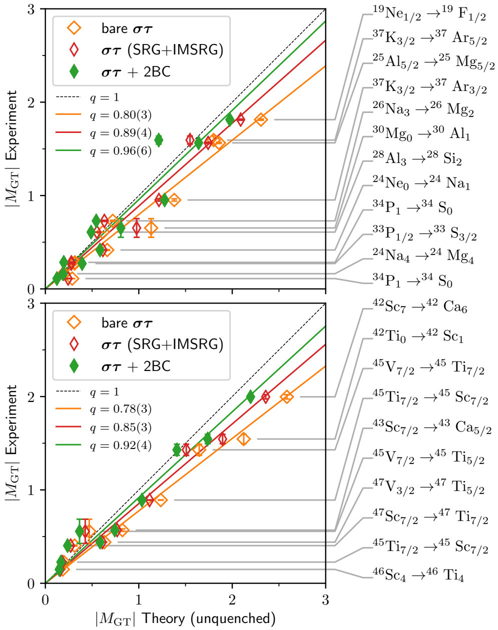
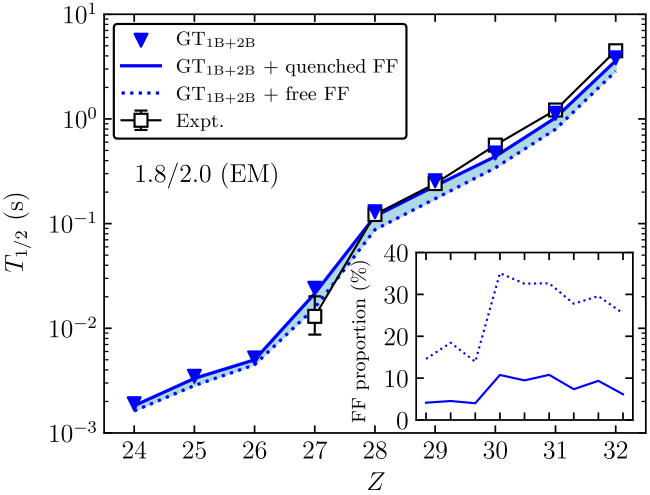
Thank you for your attention!

Backup Slides



bare στ
στ (SRG+IMSRG)
στ + 2BC
q = 1
q = 0.80(3)
q = 0.89(4)
q = 0.96(6)
|M_GT| Experiment
$^{19}Ne_{1/2} \to ^{19}F_{1/2}$
$^{37}K_{3/2} \to ^{37}Ar_{5/2}$
$^{25}Al_{5/2} \to ^{25}Mg_{5/2}$
$^{37}K_{3/2} \to ^{37}Ar_{3/2}$
$^{26}Na_3 \to ^{26}Mg_2$
$^{30}Mg_0 \to ^{30}Al_1$
$^{28}Al_3 \to ^{28}Si_2$
$^{24}Ne_0 \to ^{24}Na_1$
$^{34}P_1 \to ^{34}S_0$
$^{33}P_{1/2} \to ^{33}S_{3/2}$
$^{24}Na_4 \to ^{24}Mg_4$
$^{34}P_1 \to ^{34}S_0$
bare στ
στ (SRG+IMSRG)
στ + 2BC
q = 1
q = 0.78(3)
q = 0.85(3)
q = 0.92(4)
|M_GT| Experiment
|M_GT| Theory (unquenched)
$^{42}Sc_7 \to ^{42}Ca_6$
$^{42}Ti_0 \to ^{42}Sc_1$
$^{45}V_{7/2} \to ^{45}Ti_{7/2}$
$^{45}Ti_{7/2} \to ^{45}Sc_{7/2}$
$^{43}Sc_{7/2} \to ^{43}Ca_{5/2}$
$^{45}V_{7/2} \to ^{45}Ti_{5/2}$
$^{47}V_{3/2} \to ^{47}Ti_{5/2}$
$^{47}Sc_{7/2} \to ^{47}Ti_{7/2}$
$^{45}Ti_{7/2} \to ^{45}Sc_{7/2}$
$^{46}Sc_4 \to ^{46}Ti_4$

VS-IMSRG calc. of β-decay half-lives



Total half-life $T_{1/2}$ of β-decay

- Total β^--decay half-life from initial ground state:

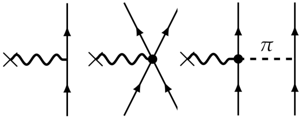
$$T_{1/2}^{-1} = \sum_f t_{fi}^{-1}$$

$$t_{fi}^{-1} = \frac{1}{\kappa}\int_1^{W_0} C(W)F(Z,W)\sqrt{W^2-1}\,W(W_0-W)^2\mathrm{d}W$$

- Gamow-Teller (GT) transition (dominates)

$$C_{\mathrm{GT}}(W) = B(\mathrm{GT}) = \frac{1}{(2J_i+1)}|\langle\Psi_f(J_f)||\mathrm{GT}||\Psi_i(J_i)\rangle|^2$$

$$t_{fi}^{-1} = \frac{1}{\kappa}B(\mathrm{GT})f_0$$



$$f_0 = \int_1^{W_0} F(Z,W)\sqrt{W^2-1}\,W(W_0-W)^2\mathrm{d}W$$

$$\mathrm{GT}_{1\mathrm{B}} = \sum_{k=1}^{A} g_A\vec{\sigma}_k\tau_k^-, \quad \mathrm{GT}_{2\mathrm{B}} = \sum_{i<j}^{A}\boldsymbol{A}_{ij}^-$$

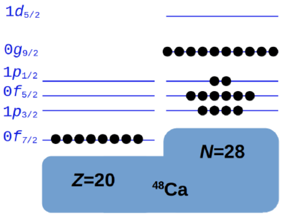
Park et al., PRC 67 (2003) 055206

Menéndez, Gazit and Schwenk, PRL 107 (2011) 062501

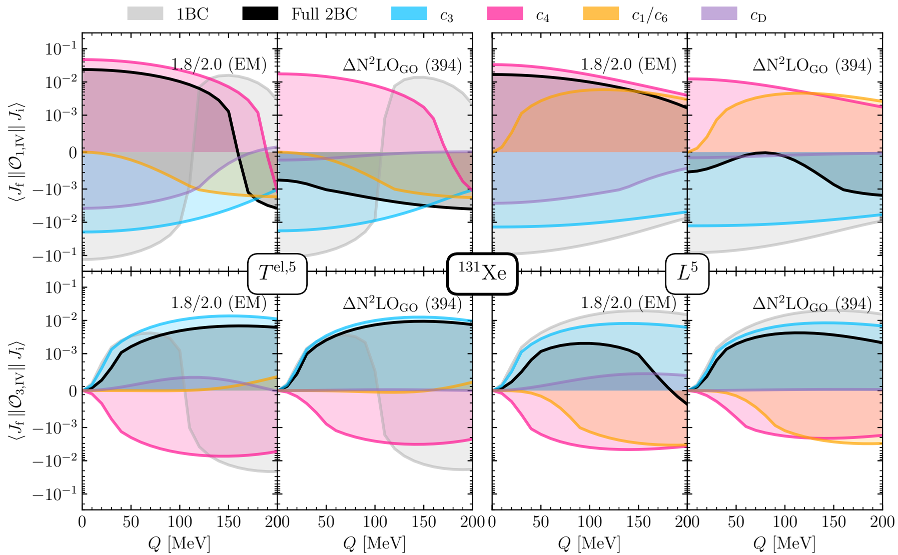
Krebs, EPJA 56 (2020) 234

Calculational setup for $N = 50$ isotones

- "Magic" 1.8/2.0 (EM) with NN + 3N interactions, consistent 2B currents
- Hartree-Fock basis $\hbar\omega = 16$ MeV, $e_{\max} \equiv (2n + l)_{\max} = 14$, $E_{3\max} \equiv (e_1 + e_2 + e_3)_{\max} = 24$
- VS-IMSRG(2), NO2B approximation with ensemble reference
- $\mathbb{P}$: core ^{48}Ca + valence space $\{0f^p_{7/2,5/2}, 1p^p_{3/2,1/2}, 0f^n_{5/2}, 1p^n_{3/2,1/2}, 0g^n_{9/2}, 1d^n_{5/2}\}$
- Arctangent (White) generator with $\Delta = 5$ MeV
- $H' = H + \beta H_{\text{cm}}$, $\beta = 3$
- Effective Hamiltonian $H_{\text{eff}} = [U(s)H'U^\dagger(s)]_{s\to\infty}$
- Reference state from initial nucleus to evolve GT operator $\text{GT}_{\text{eff}} = [U(s)\text{GT}U^\dagger(s)]_{s\to\infty}$
- Lanczos strength function method in the calculation of total GT transition probability

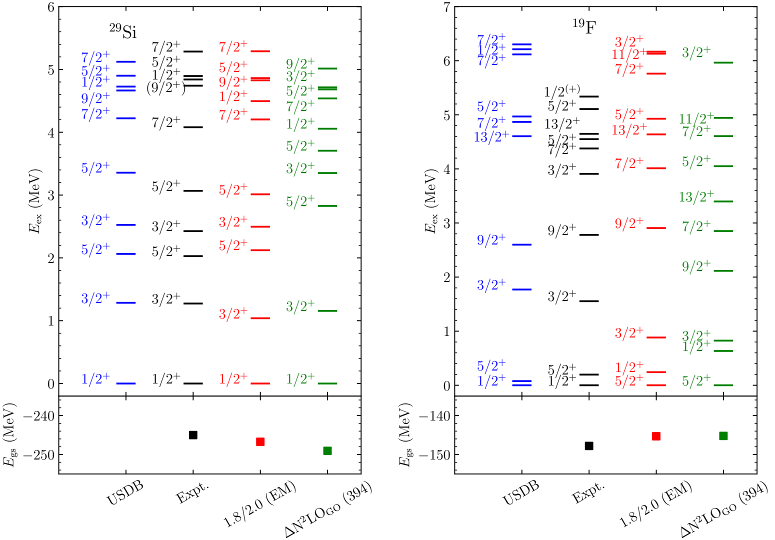


1.8/2.0 (EM): Hebeler et al., PRC 83 (2011) 031301
VS-IMSRG(2): Stroberg et al., PRL 118 (2017) 032502
Multi-shell valence space: Miyagi et al., PRC 102 (2020) 034320
Lanczos strength function: Haxton et al., PRC 72 (2005) 065501



c_3 and c_4 terms dominate

Ground-state energies and spectra for ^{19}F and ^{29}Si



Ground-state energies and spectra for ^{129}Xe and ^{131}Xe