Testing fundamental symmetries with nuclei

HADNUCMAT workshop

Universitat de Barcelona | Hadron and Nuclear Physics group

Beatriz Romeo | January 27th 2026

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

In collaboration with Jon Engel, Antoine Belley and Wouter Dekens, Jordy de Vries, Lemonia Gialidi, Heleen Mulder and Javier Menéndez

OUTLINE

- **Introduction**
- **P- and T-violation**
  - NMEs for EDMs
  - PV extension VS-IMSRG
  - Benchmarks
- **Summary and outlook**

Introduction

Standard Model open questions

The Standard Model (SM) is structurally complete, but it **fails to explain** key observations

The **most pressing** shortcomings

- Neutrino masses
- Missing dark-matter candidate
- **Baryon asymmetry**

CMB & BBN observations

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

key ingredient **C and CP violation (CPV)**

SM provides CPV via a complex phase in the CKM matrix and through the θ term in strong interactions

SM prediction many orders of magnitude smaller!

Complete theory **additional CPV** and **experimental** programs searching for its **signatures**

Introduction

Searches of CPV at low energy scales: Electric Dipole moments

Precision measurements of parity P and time reversal T invariance in atoms and molecules are a powerful tool to probe physics at high energies

Concept of a electric dipole moment

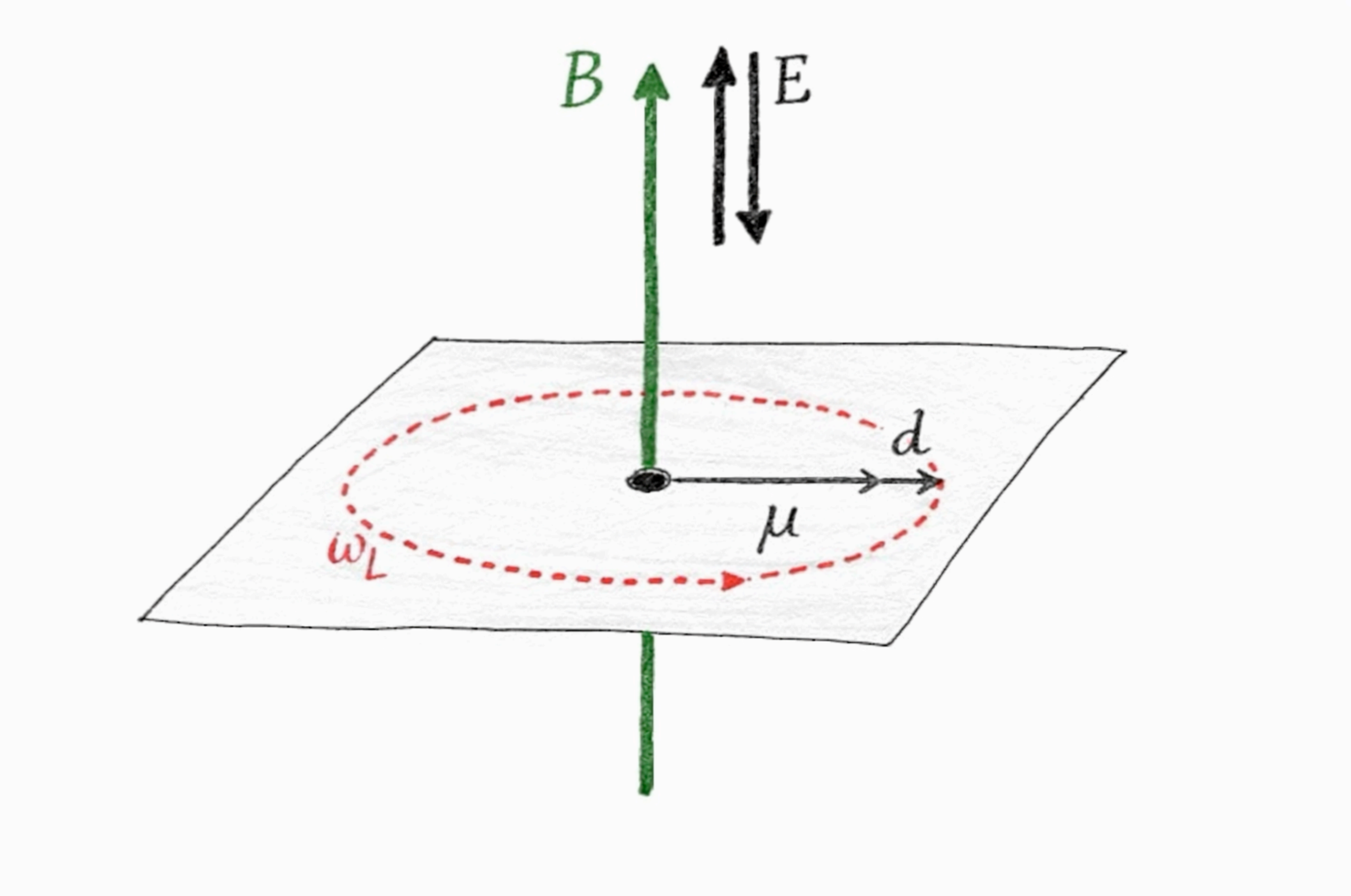
Particle at rest, follow spin degrees of freedom as they interact with background electric and magnetic fields magnetic moment interaction (B,S) P(T) even, EDM interaction (E,S) odd und

General technique to search for an EDM, spin polarised species in an magnetic (B) and electric (E) fields

$$H = -\mu \mathbf{B} \cdot \mathbf{S} - d \mathbf{E} \cdot \mathbf{S}$$

μ magnetic dipole moment

d electric dipole moment



$$d = \frac{\hbar(w^{\parallel} - w^{\nparallel})}{4E}$$

Introduction

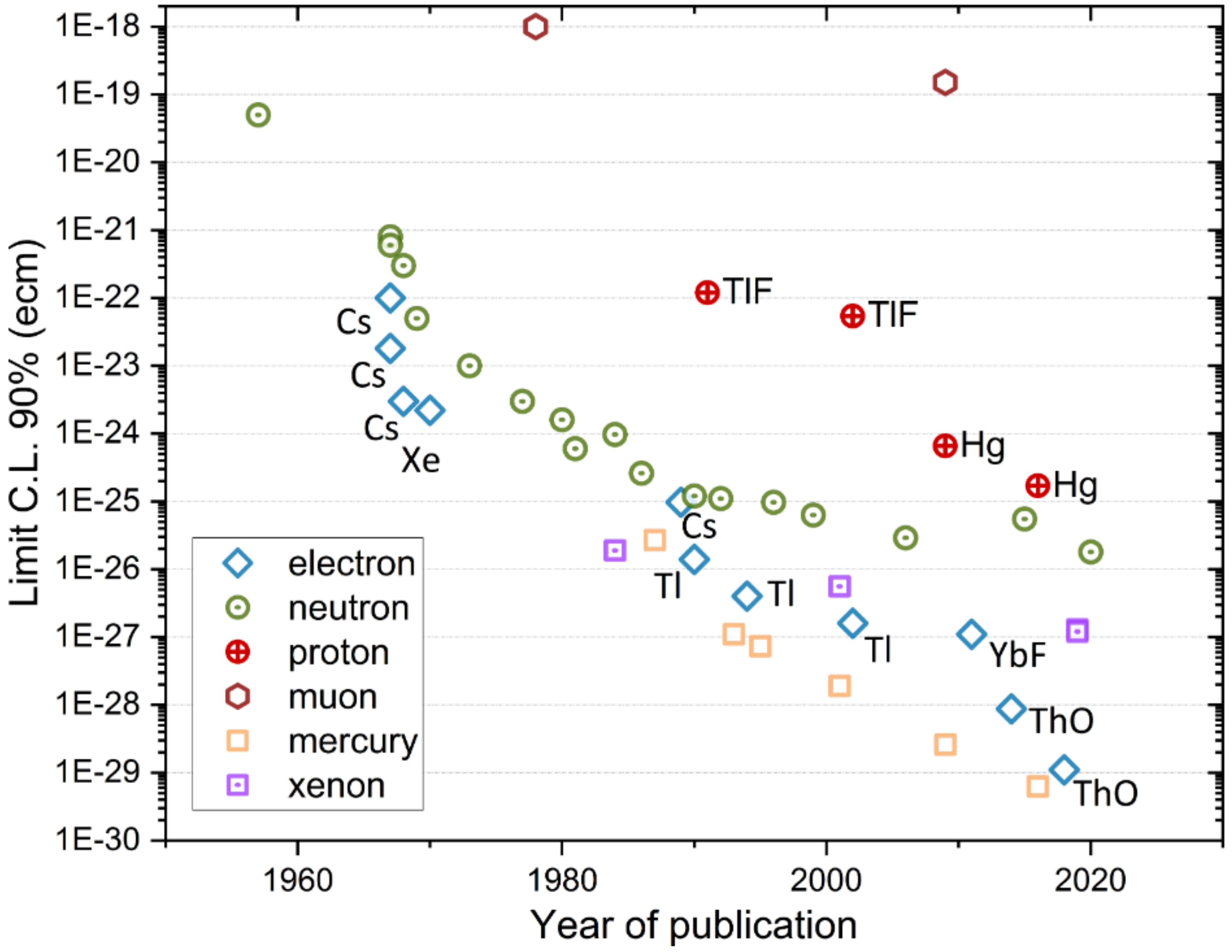
Searches of CPV at low energy scales: Electric Dipole moments

Upper limits for EDMs of various systems of interest and their SM predictions

	Standard Model	Experiment
neutron	$\sim 10^{-31}$ e cm	3.6×10^{-26} e cm
electron	$\sim 10^{-38}$ e cm	1.1×10^{-29} e cm
^{199}Hg	$\sim 10^{-34}$ e cm	7.4×10^{-30} e cm
^{129}Xe	$\sim 10^{-34}$ e cm	6.6×10^{-27} e cm
^{225}Ra	–	1.4×10^{-24} e cm

Kuchler, F.; on behalf of the TUCAN and HeXeEDM Collaborations, *Universe*, *5*, 56, 2019

EDM experimental searches history



Klaus Kirch and Philipp Schmidt-Wellenburg, EPJ Web Conf. 234, 2020

Different contributions to atomic/molecular EDMs are tested with different systems, three main categories

- Paramagnetic (uncompensated electron spin) atoms and molecules (ThO,YbF, HfF^{+},Cs,…)

Electron EDM, semileptonic CPV

- Diamagnetic atoms-closed electron shell (^{199}Hg, ^{129}Xe, ^{225}Ra)

- nEDM

Hadronic CPV

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Nucleon EDMs in Paramagnetic Molecules

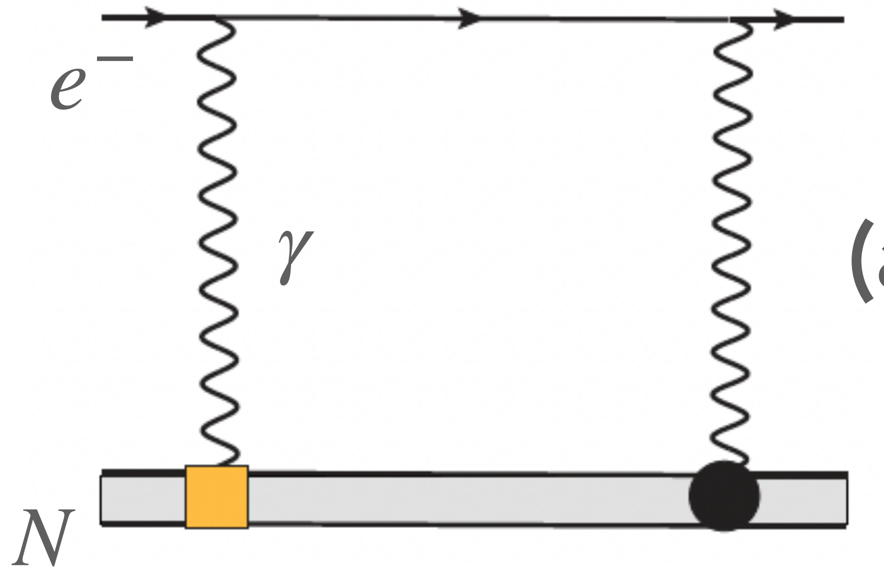
Nuclear Matrix Elements

The upper bounds on paramagnetic EDMs can be translated to limits on the electron EDM, but also to another CP-violating contribution: **CPV electron-nuclear forces**

Wouter Dekens, Jordy de Vries, Lemonia Gialidi, Javier Menéndez, Heleen Mulder, Beatriz Romeo (2510.14933)

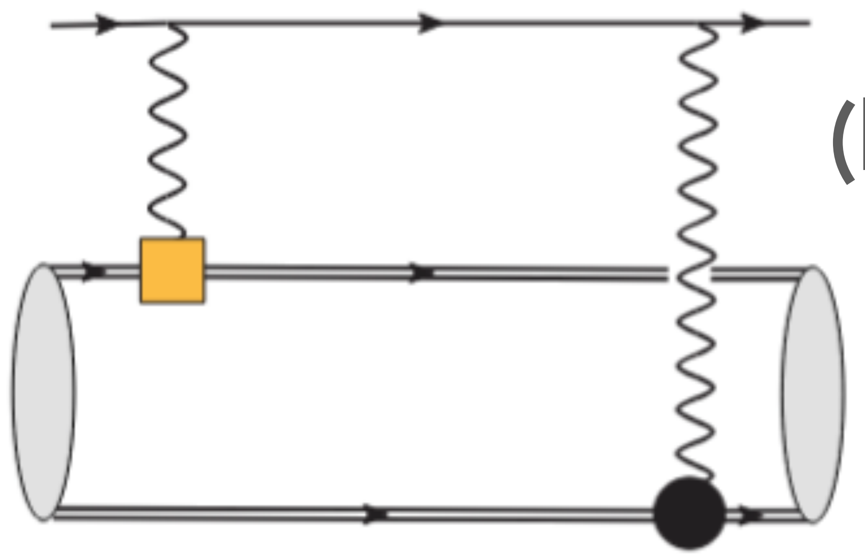
$$d_{\text{para}} \sim \alpha d_e + \beta C_{\text{SP}}$$

α, β are coefficients that depend on the electric field, molecular properties



Energy of the photons: **ultrasoft** region **(a)** $q_\gamma^0 \sim |\mathbf{q}_\gamma| \sim m_\pi^2/m_N$

potential region **(b)** $m_\pi \sim \mathbf{q}_\gamma \gg q_\gamma^0$



Total contribution to C_{SP} at the low energy scale (ultrasoft)

$$\bar{C}_{SP}^{\text{usoft}} = -\frac{\sqrt{2}\alpha^2 m_e}{3 m_N G_F} M_{SP}^{\text{usoft}} \qquad M_{SP}^{\text{usoft}} = \sum_n \frac{\langle 0_{gs}^+ | D^{(i)} \boldsymbol{\sigma} | 1_n^+ \rangle \cdot \langle 1_n^+ | \mu^{(i)} \boldsymbol{\sigma} | 0_{gs}^+ \rangle}{\Delta_n} \left(1 + 3 \ln \frac{4\Delta_n^2}{m_e^2} \right)$$

$$\Delta_n = E(1_n^+) - E(0_{gs}^+)$$

nucleon-electric moment

nucleon-magnetic moment

$$\mu^{(i)} = (\mu_0 + \mu_1 \tau_3^{(i)})$$

$$D^{(i)} = (\bar{d}_0 + \bar{d}_1 \tau_3^{(i)})$$

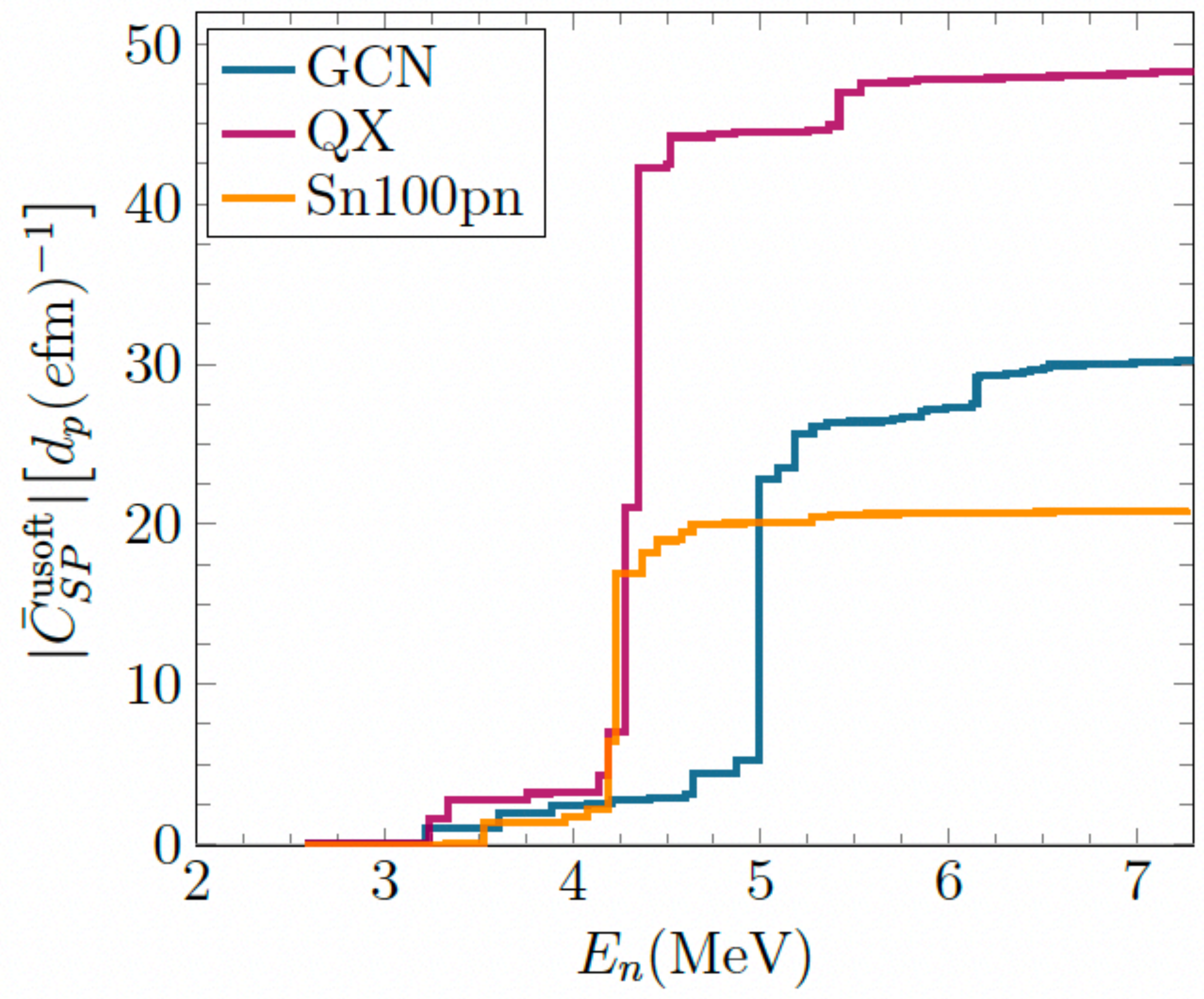
Nucleon EDMs in Paramagnetic Molecules
Nuclear Matrix Elements

Interest of polar molecule BaF targeted by NL-eEDM experiment, ^{138}**Ba** using nuclear shell model

configuration space $[^{100}\mathrm{Sn\ CORE}]$ $0g_{7/2}1d_{5/2}1d_{3/2}1s_{1/2}0h_{11/2}$

GCN5082 E. Caurier et. al., Phys. Rev. Lett 100, 052 503 (2008)
QX C. Qi and Z.X. Xu, Phys. Rev. C 86, 044323 (2012)
Sn100pn B. A. Brown, et.al., Phys. Rev. C 71, 044317 (2005)

82 neutrons completely fill the configuration space, sensitivity only to **proton EDM**



For ^{138}**Ba**

$$\bar{C}_{SP}^{\rm usoft} = (67 \pm 28) d_p (efm)^{-1}$$

Wouter Dekens, Jordy de Vries, Lemonia Gialidi, Javier Menéndez, Heleen Mulder, Beatriz Romeo (2510.14933)

Few states between 4-5MeV dominate

Sensitive to nuclear structure

Nucleon EDMs in Paramagnetic Molecules

Nuclear Matrix Elements

Potential region

$$\bar{C}_{SP}^{\mathrm{pot}} = -\frac{\sqrt{2}}{G_F}\langle 0^+_{gs}|V|0^+_{gs}\rangle$$

$$V(\vec{r}) = -\frac{e^4 m_e}{18\pi m_N}\sum_{i\neq j}\mu^{(i)}D^{(j)}|\vec{r}|\left[\sigma^{(i)}\cdot\sigma^{(j)} + \frac{1}{16}S^{(ij)}(r)\right]$$

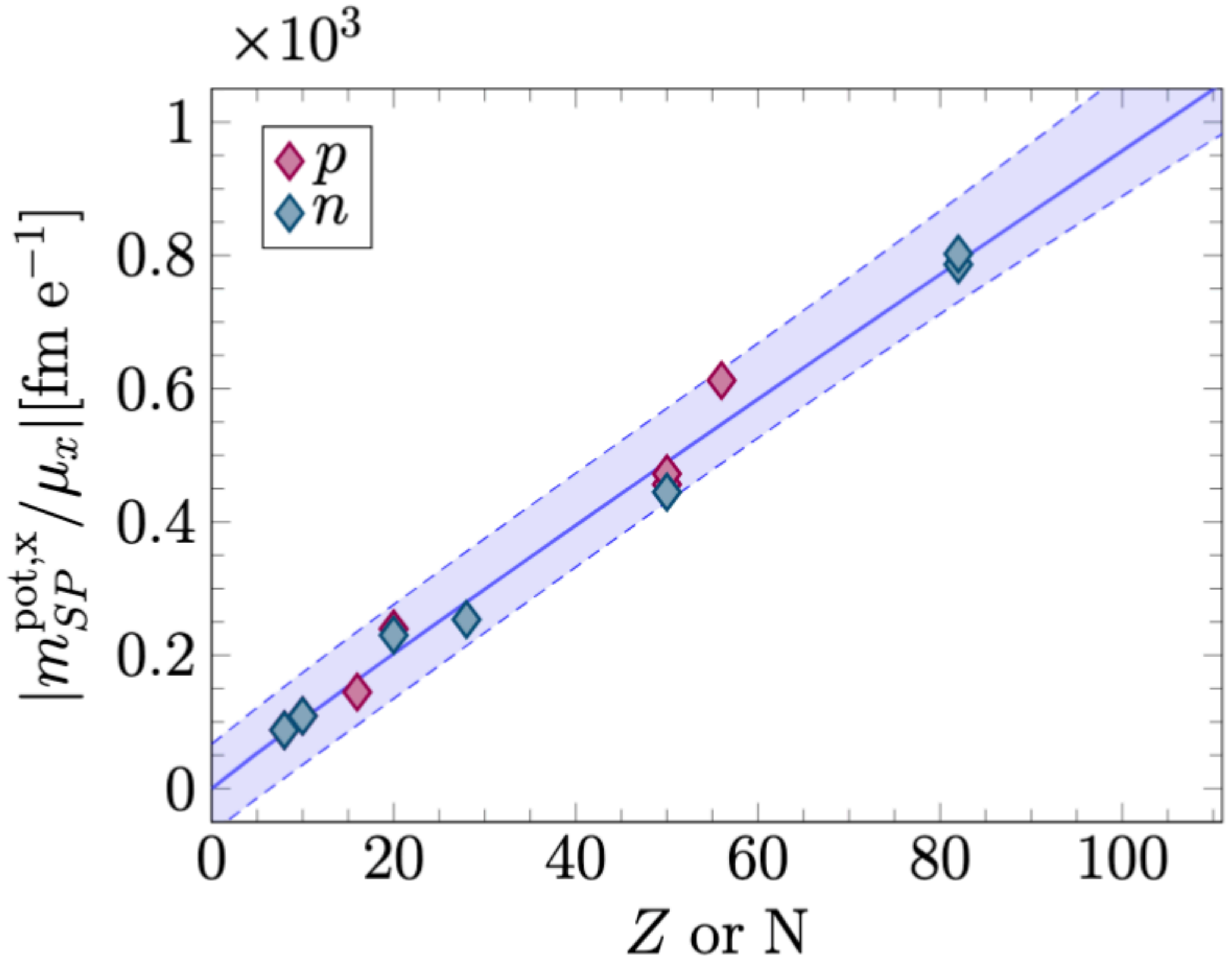
$$S^{(ij)} = 3\hat{\mathbf{r}}\cdot\boldsymbol{\sigma}_i\hat{\mathbf{r}}\cdot\boldsymbol{\sigma}_j - \boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j$$

Both core and valence nucleons contribute to the nuclear matrix elements $\sum\sigma^{(i)}\cdot\sigma^{(j)}$ + isospin structure of $\mu^{(i)}D^{(j)}$ would count number of proton an neutron pairs coupled to S=0 and the NMEs would be $-3Z\mu_p d_p - 3N\mu_n d_n$

$$\bar{C}_{SP}^{\mathrm{pot}} = \frac{\sqrt{2}e^4 m_e}{18\pi G_F m_N}M_{SP}^{\mathrm{pot}} \qquad M_{SP}^{\mathrm{pot}} = m_{SP}^{\mathrm{pot,p}}d_p + m_{SP}^{\mathrm{pot,n}}d_n$$

For ^{138}Ba

$$\bar{C}_{SP}^{\mathrm{pot}} = [(-433\pm 5)d_p + (387\pm 0.4)d_n](efm)^{-1}$$



The potential contribution is dominant due to coherent nature of the potential NME, which scales linearly with the total number of protons (Z) and neutrons (N)

Nucleon EDMs in Paramagnetic Molecules

Nuclear Matrix Elements

We can estimate the sensitivity of the paramagnetic EDMs experiments to proton and neutron EDMs

Convenient to interpret single source constraints

$$d_e^{equiv} \equiv r_{\text{mol}} \bar{C}_{SP} \longrightarrow \quad |d_p|_{\text{BaF}} < 8.4 \cdot 10^{-24}\, e\,\text{cm} \quad \text{and} \quad |d_n|_{\text{BaF}} < 8.0 \cdot 10^{-24}\, e\,\text{cm}$$

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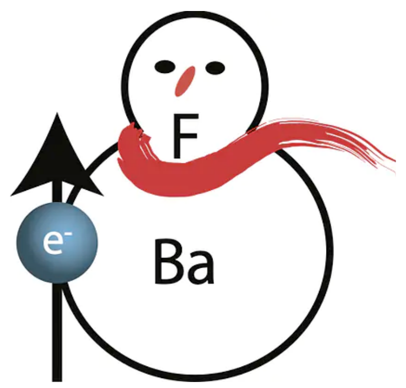

NL-eEDM collaboration $d_e \leq 10^{-30}$e cm

P. Aggarwal et al. (NL-eEDM), Eur. Phys. J. D 72, 197 (2018)

They are two and three orders of magnitude away from current direct the limits set through (respectively) ^{199}Hg atom and direct neutron EDM searches

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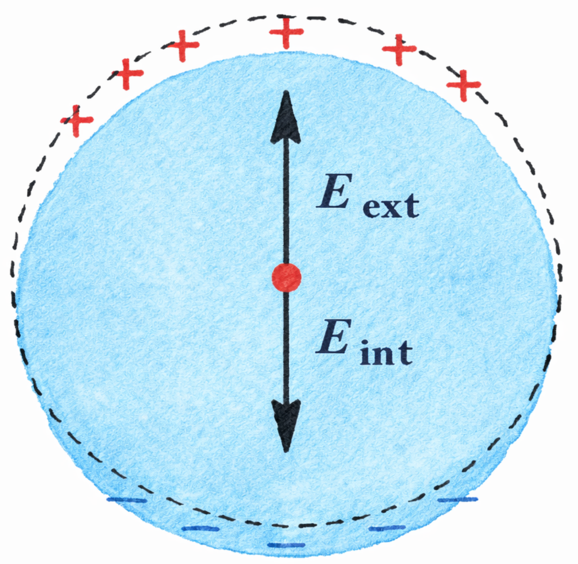
Violation of fundamental symmetries (P & T)

Nuclear Schiff moment

Neutral atom placed in a uniform electric field, the electrons rearrange themselves so that there is no net electric field in the nucleus.



- Perfect shielding: **point-like** nucleus, **non-relativistic** electrons (Coulomb force)

- **Finite charge distribution** of the nucleus makes the nuclear electric dipole moment to be tested through the **nuclear Schiff moment**

$$\mathbf{S} = \frac{e}{10}\sum_{i=1}^{Z}\left(r_i^2 - \frac{5}{3}R_{ch}^2\right)\mathbf{r}_i$$

Can be induced by P- and T-violating nucleon-nucleon interaction, leading order in χEFT given by one pion-exchange

$$V_{PTV}^{\pi NN} \sim g[\bar{g}_0 \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 + \bar{g}_2(3\tau_{1_z}\tau_{2_z} - \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2) - \bar{g}_1(\boldsymbol{\sigma}_1\tau_{1_z} - \boldsymbol{\sigma}_2\tau_{2_z})] \cdot \nabla(e^{-m_\pi r}/4\pi r)$$

$\bar{g}_i$ unknown PT violating versions of strong pion-nucleon coupling g

V_{PT} mixes opposite parities, decomposed in **isoscalar** ($\bar{g}_0$), **isovector** ($\bar{g}_1$), and **isotensor** ($\bar{g}_2$) components

Violation of fundamental symmetries (P & T)

Nuclear Schiff moment

V_{PT} small perturbation to the strong Hamiltonian, leading first order expression

$$H = H_{PC} + \lambda V_{PTV} \longrightarrow S \equiv \langle S_z \rangle_{gs} = \sum_n \frac{\langle \psi_{gs}^{(0)} J^{\pi} | S_z | \psi_n^{(0)} J^{-\pi} \rangle \langle \psi_n^{(0)} J^{-\pi} | V_{PTV} | \psi_{gs}^{(0)} J^{\pi} \rangle}{E_{gs}^{(0)} - E_n^{(0)}} + \text{c.c.}$$

$$S \equiv g_{\pi NN} \bar{g}_{\pi NN}^{(0)} a_0 + g_{\pi NN} \bar{g}_{\pi NN}^{(1)} a_1 + g_{\pi NN} \bar{g}_{\pi NN}^{(2)} a_2$$

Challenges

- opposite parity states needed within the model space
- r^3 term S induces high-energy excitations ($\Delta n \leq 2$)

Idea

- IMSRG can incorporate physics at high energies into valence space
- Generalize the flow eq's to include a PV part of the Hamiltonian
- Induces an effective PC Schiff operator captures effects of intermediate states outside the model space

Violation of fundamental symmetries (P & T)

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

Basic idea **similarity renormalization group**: perform continuous unitary transformation U to the H so is more amenable to diagonalise

Partition of H, "diagonal" and "off-diagonal" parts, and transform it by a sequence of unitary transformation

$$H(s) = U(s)H(0)U^\dagger(s) \qquad U(s)\,|\, s \to \infty \qquad H^{od}(s) \longrightarrow 0$$

$$H(s) = H^d(s) + H^{od}(s)$$

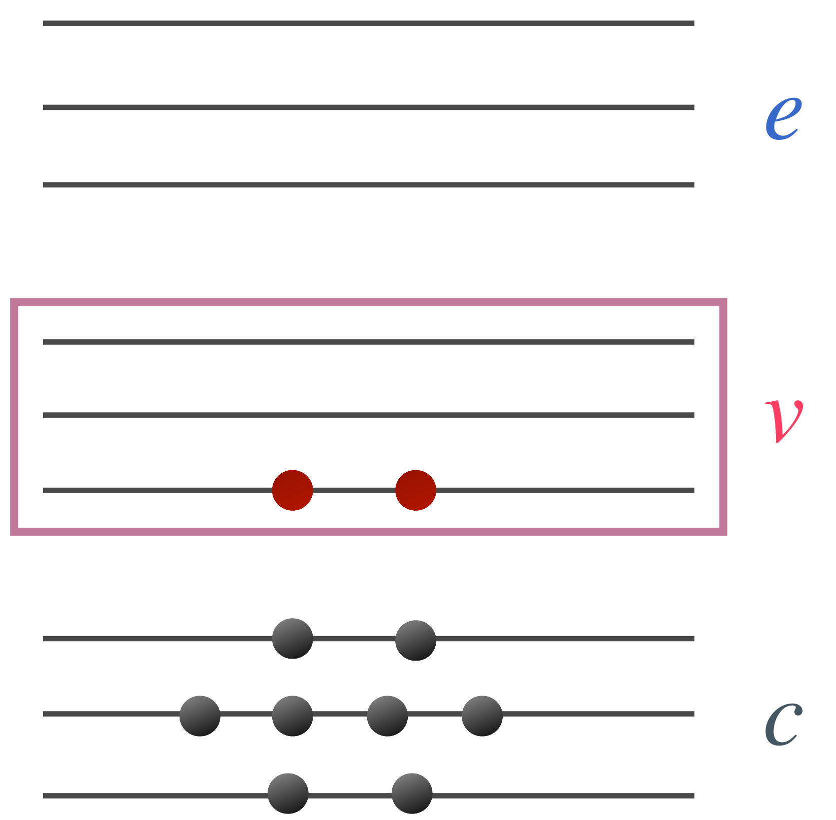
In the VS formulation $H^{\mathrm{od}} \equiv H^{\mathrm{exc}}$, all terms connecting valence configurations to non-valence configurations

0

$$\begin{aligned} H^{od} \equiv & \langle v|H|c\rangle + \langle e|H|c\rangle + \langle e|H|v\rangle + \\ & + \langle vv|H|cc\rangle + \langle ev|H|cc\rangle + \langle ee|H|cc\rangle + \langle vv|H|vc\rangle \\ & + \langle ev|H|vc\rangle + \langle ee|H|vc\rangle + \langle ev|H|vv\rangle + \langle ee|H|vv\rangle \end{aligned}$$

VS effective interaction

$$\langle v|H|v\rangle + \langle vv|H|vv\rangle$$



Violation of fundamental symmetries (P & T)

Break parity in IMSRG flow equations

Unitary transformation into flow eq's

Generator η, encodes the degrees of freedom one want to decouple

$$\frac{dH}{ds} = [\eta, H]$$

$$\frac{dS}{ds} = [\eta, S]$$

with

$$H(s) = H_{PC}(s) + \lambda V_{PV}(s)$$

$$\eta(s) = \eta_{PC}(s) + \lambda \eta_{PV}(s)$$

$$S(s) = S_{PC}(s) + S_{PV}(s)$$

These lead to

$$\frac{dH_{PC}}{ds} = [\eta_{PC}, H_{PC}] + \mathcal{O}(\lambda^2)$$

$$\frac{dV_{PV}}{ds} = [\eta_{PV}, H_{PC}] + [\eta_{PC}, V_{PV}]$$

$$\frac{dS_{PC}}{ds} = [\eta_{PC}, S_{PC}] + \lambda[\eta_{PV}, S_{PV}]$$

$$\frac{S_{PV}}{ds} = [\eta_{PC}, S_{PV}] + \lambda[\eta_{PV}, S_{PC}]$$

Unitarity of the flow

$$\langle S \rangle = \langle S_{PC} \rangle + \langle S_{PV} \rangle = \langle \psi_{gs} J^{\pi} | S_{PC} | \psi_{gs} J^{\pi} \rangle + \lambda \sum_n \cancelto{0}{\frac{\langle \psi_{gs} J^{\pi} | S_{PV} | \psi_n J^{-\pi} \rangle \langle \psi_n J^{-\pi} | V_{PV} | \psi_{gs} J^{\pi} \rangle}{E_{gs} - E_n}} + cc$$

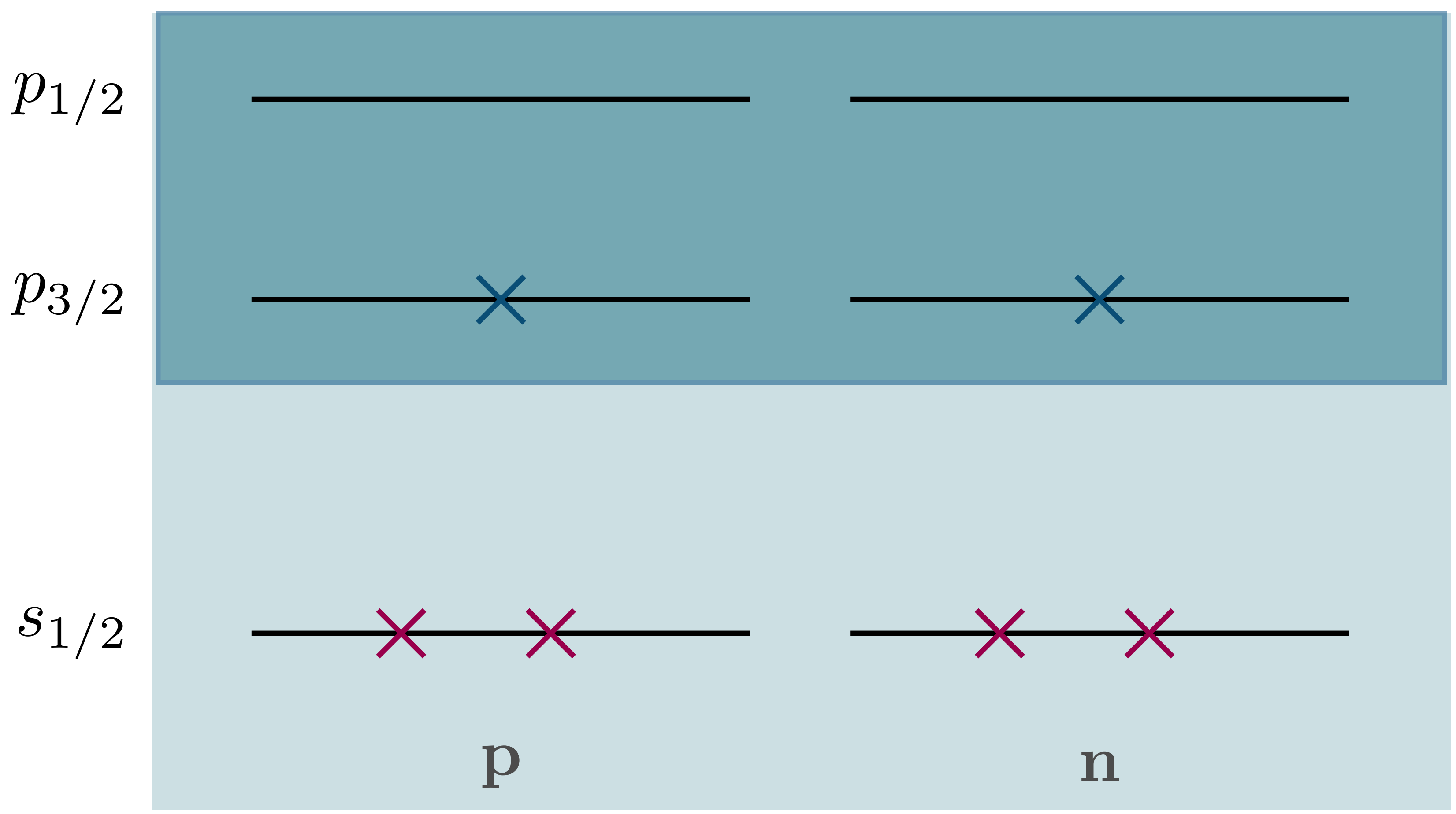
$$\langle S_{PC} \rangle \Big|_{s=0} = 0 \qquad s \longrightarrow \infty$$

Violation of fundamental symmetries (P & T)

Unitarity test small model space

A first test

- Exact diagonalization can be done in the sp-shell
- Decouple p-shell
- Normal ordered two-body approximation



$^{6}\mathrm{Li}$

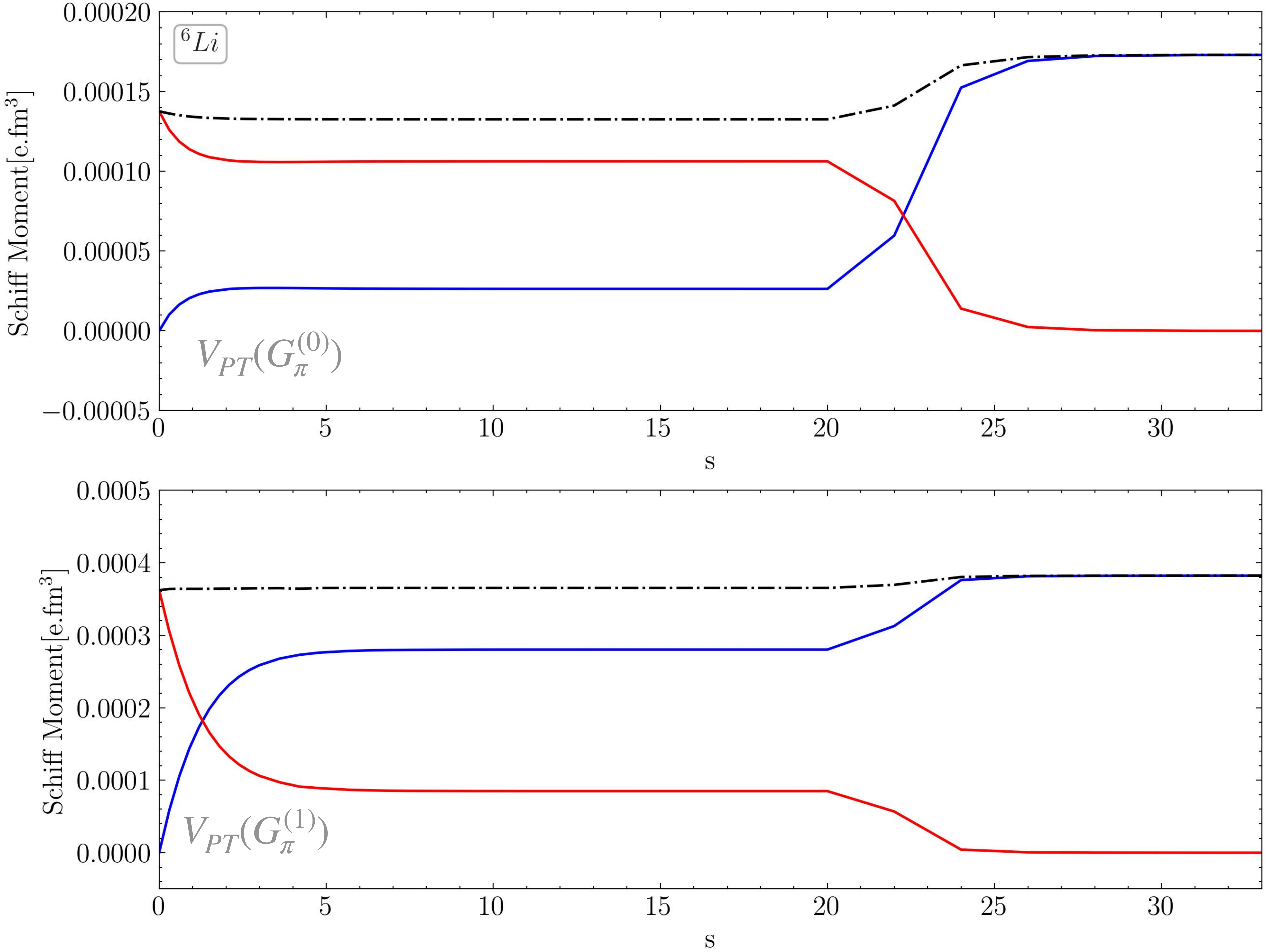
p-shell $\langle 1^+_{gs} | S_{PC} | 1^+_{gs} \rangle$

sp-shell $\sum_n \frac{\langle 1^+_{gs} | S_{PV} | 1^- \rangle \langle 1^- | V_{PT} | 1^+_{gs} \rangle}{E_{1^+} - E_{1^-_n}}$

$\{1^-_n\}_{98}$

Violation of fundamental symmetries (P & T)

Unitarity test small model space: Schiff Moment



$\langle 1^+_{gs}|S_{PC}|1^+_{gs}\rangle$

$2\sum_n \frac{\langle 1^+_{gs}|S_{PV}|1^-_n\rangle\langle 1^-_n|V_{PV}|1^+_{gs}\rangle}{E_{gs}-E_n}$

$\langle 1^+_{gs}|S|1^+_{gs}\rangle$

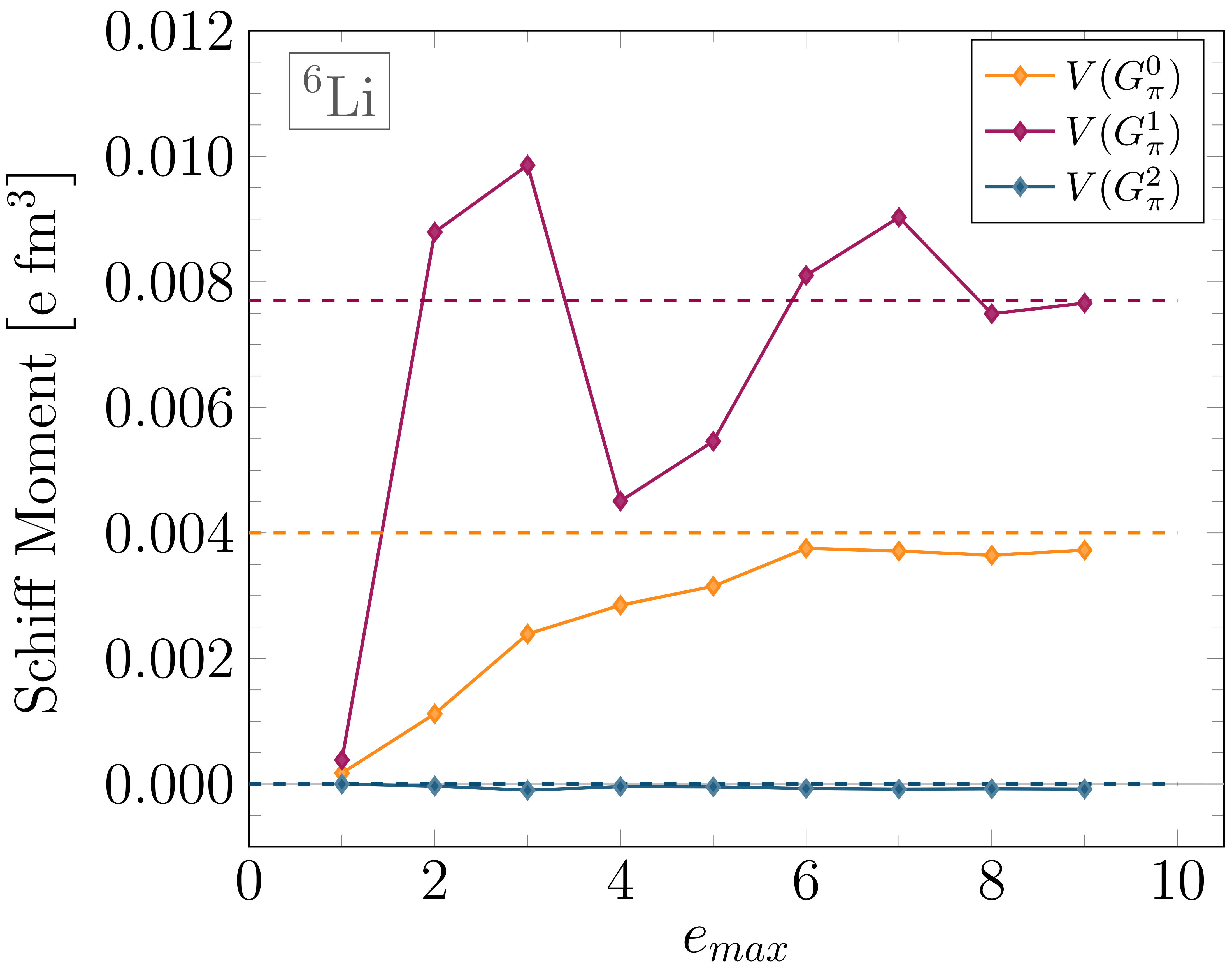
- Exact diagonalization can be done in the sp-shell
- Use PV VS-IMSRG(2) to decouple p-shell
- $\langle S\rangle_{sp} \approx \langle S^+\rangle_p$
- Unitarity preserved
- Isotensor usually small

Violation of fundamental symmetries (P & T)

Benchmark PV-IMSRG(2)

No Core Shell-Model (all nucleons active)
Paul Froese and Petr Navrátil, Phys. Rev. C 104, 025502 (2021)

- EDM, Schiff moment and anapole moment
- PV-VS IMSRG(2)
- NN-N^{3}LO+ 3N(lnl), hw=16
- NCSM results for hw=20, except ^{6}Li, which use the same interaction



Petr Navrátil and Stephan Foster (private communication)

Violation of fundamental symmetries (P & T)

Benchmark PV-IMSRG(2)

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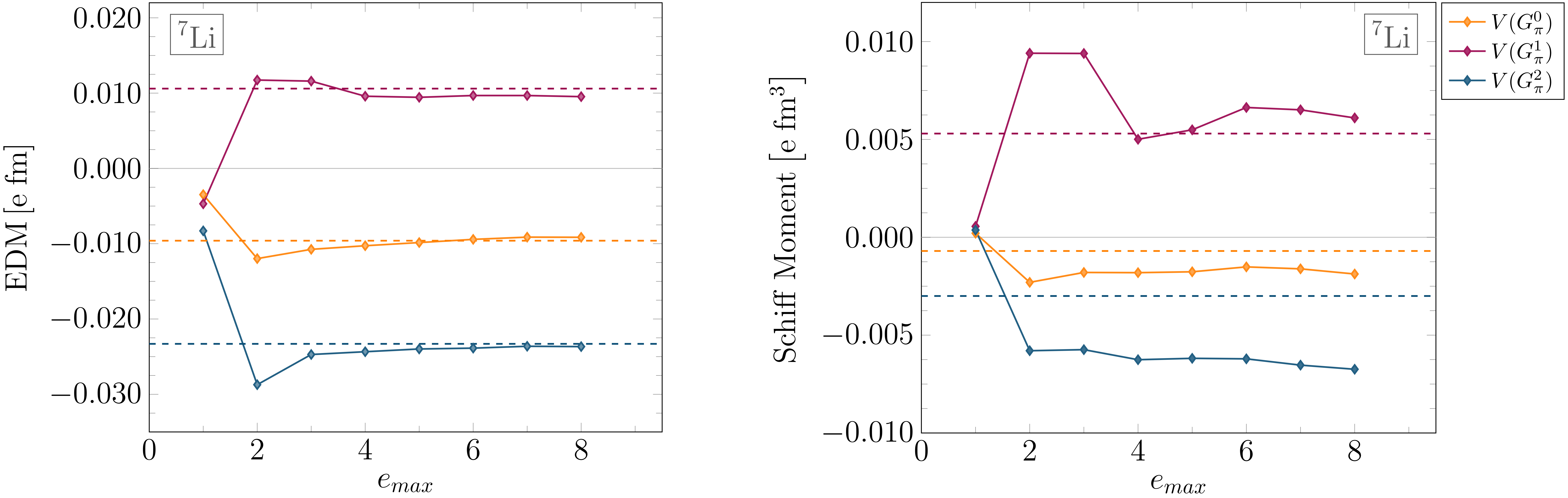
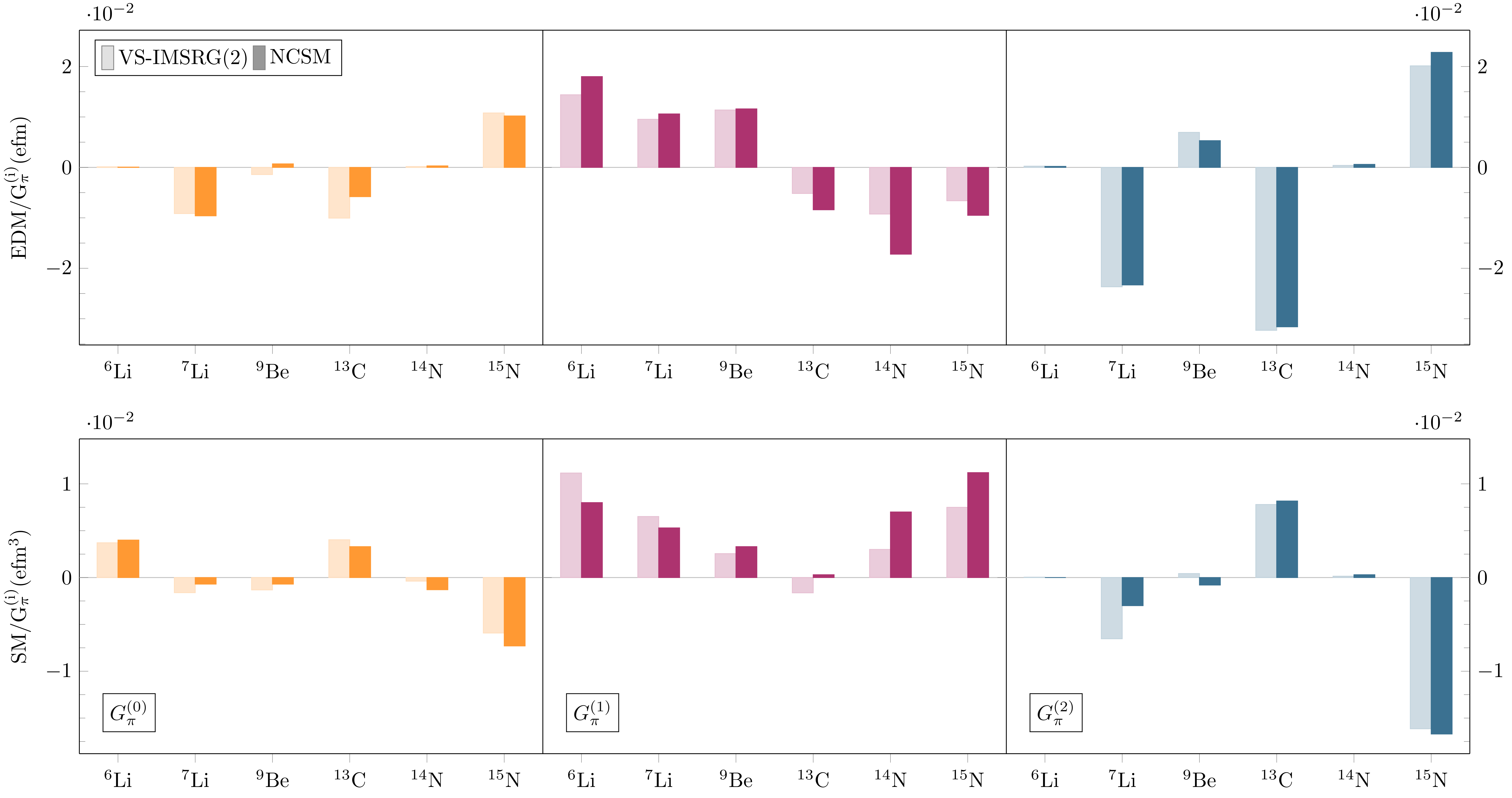


Violation of fundamental symmetries (P & T)

Benchmark PV-IMSRG(2)



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Summary and outlook

Next steps

- **EFT** framework to systematically calculate the **proton and neutron EDM's contributions to paramagnetic EDMs**
- Key NMEs have been identified, need to **compute** them in **heavy nuclei** ^{174}Yb (YbF), ^{180}Hf(HfF^{+}), ^{232}Th(ThO)
- Check dominance of the NME in the potential contribution
- Extension of the IMSRG formalism designed to target symmetry-breaking observables
- Apply to heavy nuclei, calculate nuclear Schiff moments (^{129}Xe, ^{199}Hg)
- Gain insight in the **relative importance** of the different **terms** in the **V_{PT} across nuclei**
- **Uncertainty quantification** introduce by the many-body and model space truncation

Thank you!

PV-IMSRG

Benchmark PV-IMSRG(2) with NCSM

Schiff moment may not be fully converged