

Testing fundamental symmetries with Nuclei

XL Reunión Biennial de la Real Sociedad Española de Física

Beatriz Romeo | July 21- 2026



THE UNIVERSITY
of NORTH CAROLINA
at CHAPEL HILL



OUTLINE

► Introduction

► P- and T-violation

PV extension VS-IMSRG

Benchmarks & Schiff moment ^{129}Xe

► L-violation: $0\nu\beta\beta$ decay

Correlation $\gamma\gamma$ - $0\nu\beta\beta$ NMEs

Potential of measuring $\gamma\gamma$

► Summary and outlook



Introduction

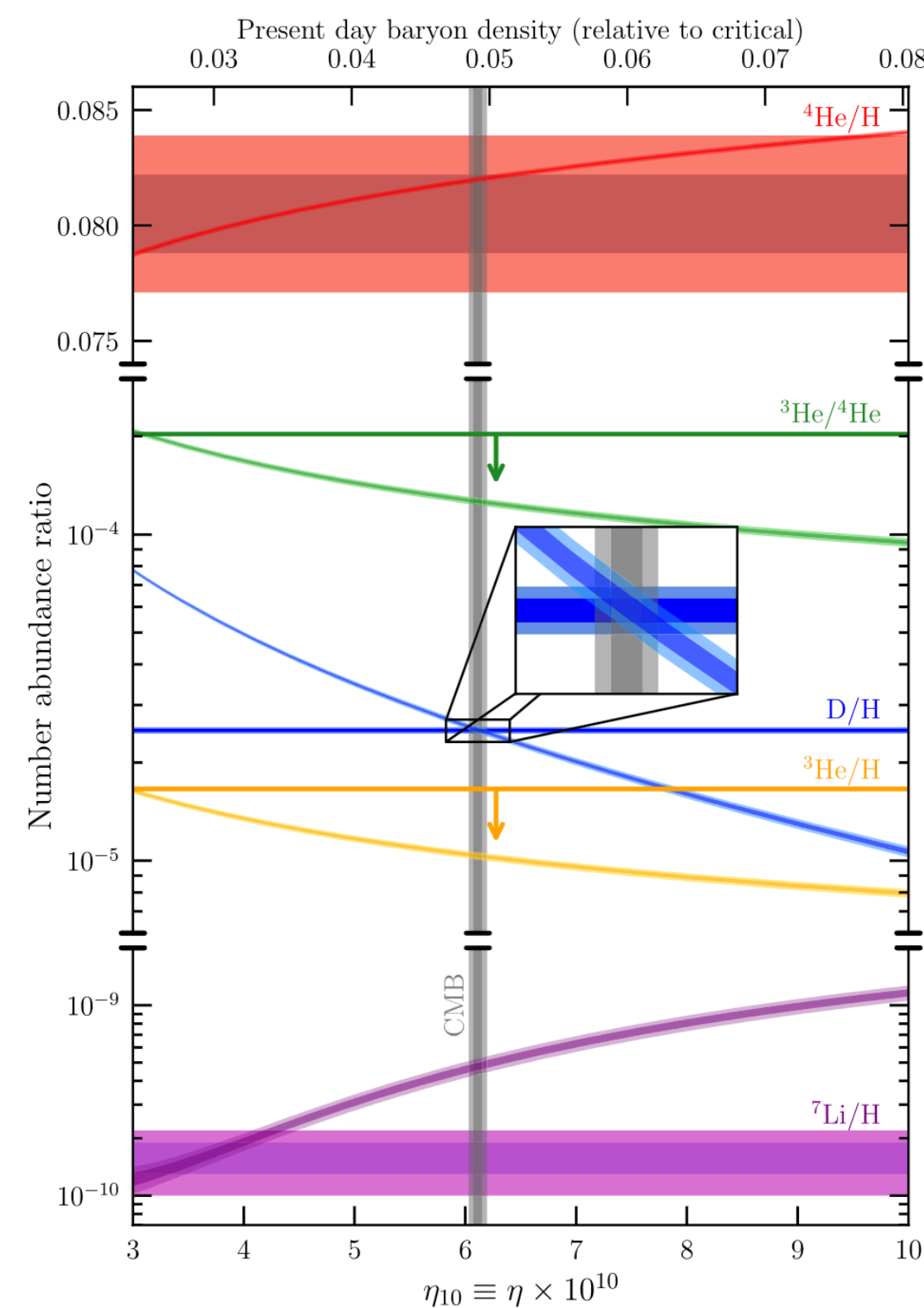
Standard Model open questions

The Standard Model (SM) describes many experimental observations with impressive accuracy, but there are still **unsolved puzzles**

Most pressing shortcomings

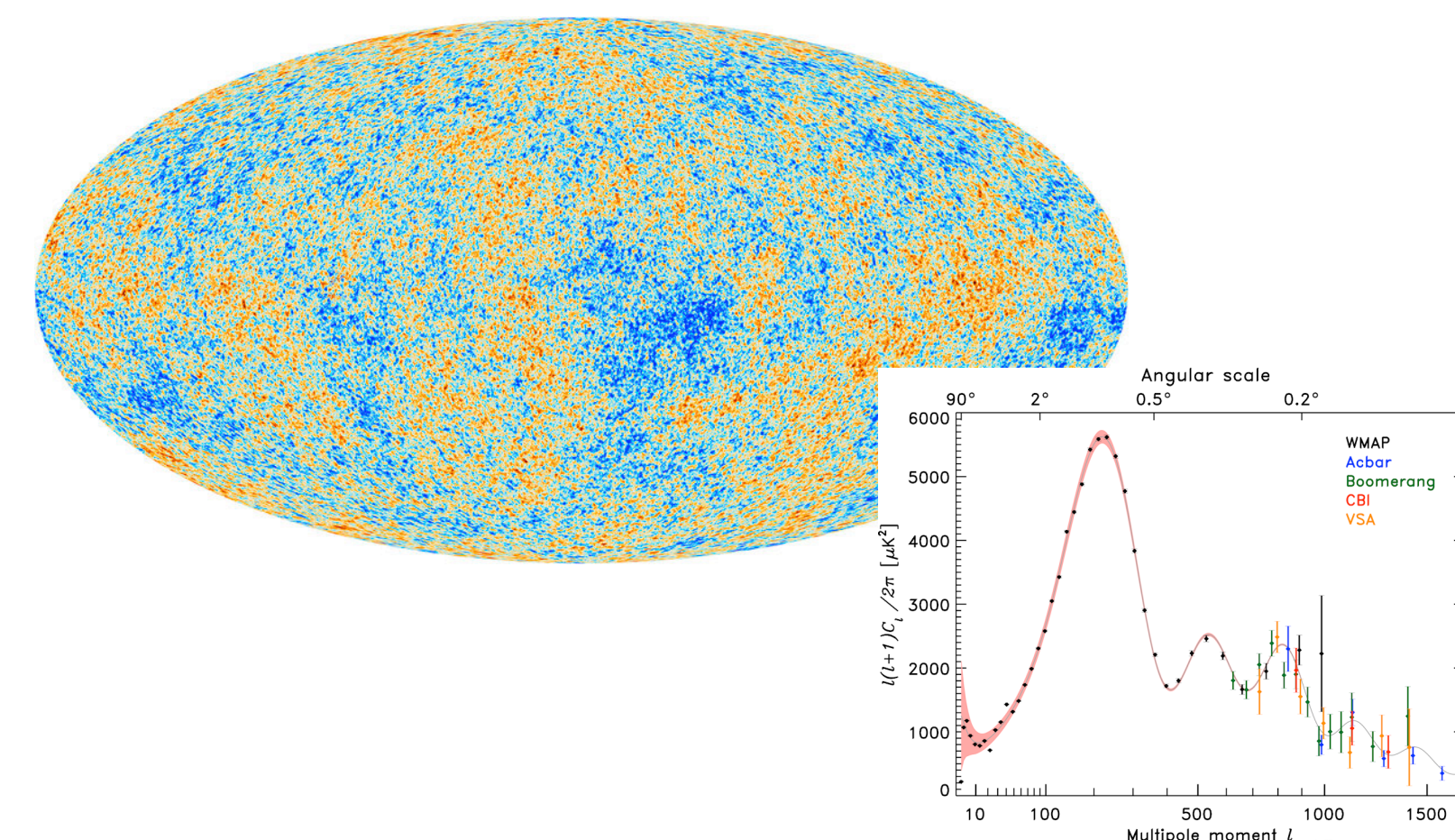
- ▶ Missing dark-matter candidate
- ▶ **Neutrino masses**
- ▶ **Baryon asymmetry**

A key ingredient to produce such asymmetry is the violation of charge conjugation and parity (CP)



Light element abundances (horizontal bands)+
expectations from CMB Ω_b

Cosmic microwave background (CMB)-Planck European Space Agency and the Planck Collaboration



CMB & BBN observations

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 6 \cdot 10^{-10}$$



Introduction

Violation of fundamental symmetries (P & T)

$$\eta^{\text{SM}} \ll \eta^{\text{obs}}$$

SM prediction many orders of magnitude smaller!

Complete theory requires **additional CPV**
Experimental programs searching for its **signatures**

Electric dipole moments (EDM) of elementary and composite systems **promising probe**

They violate both P- and time-reversal (T) symmetries, assuming CPT symmetry, T-violation implies CPV



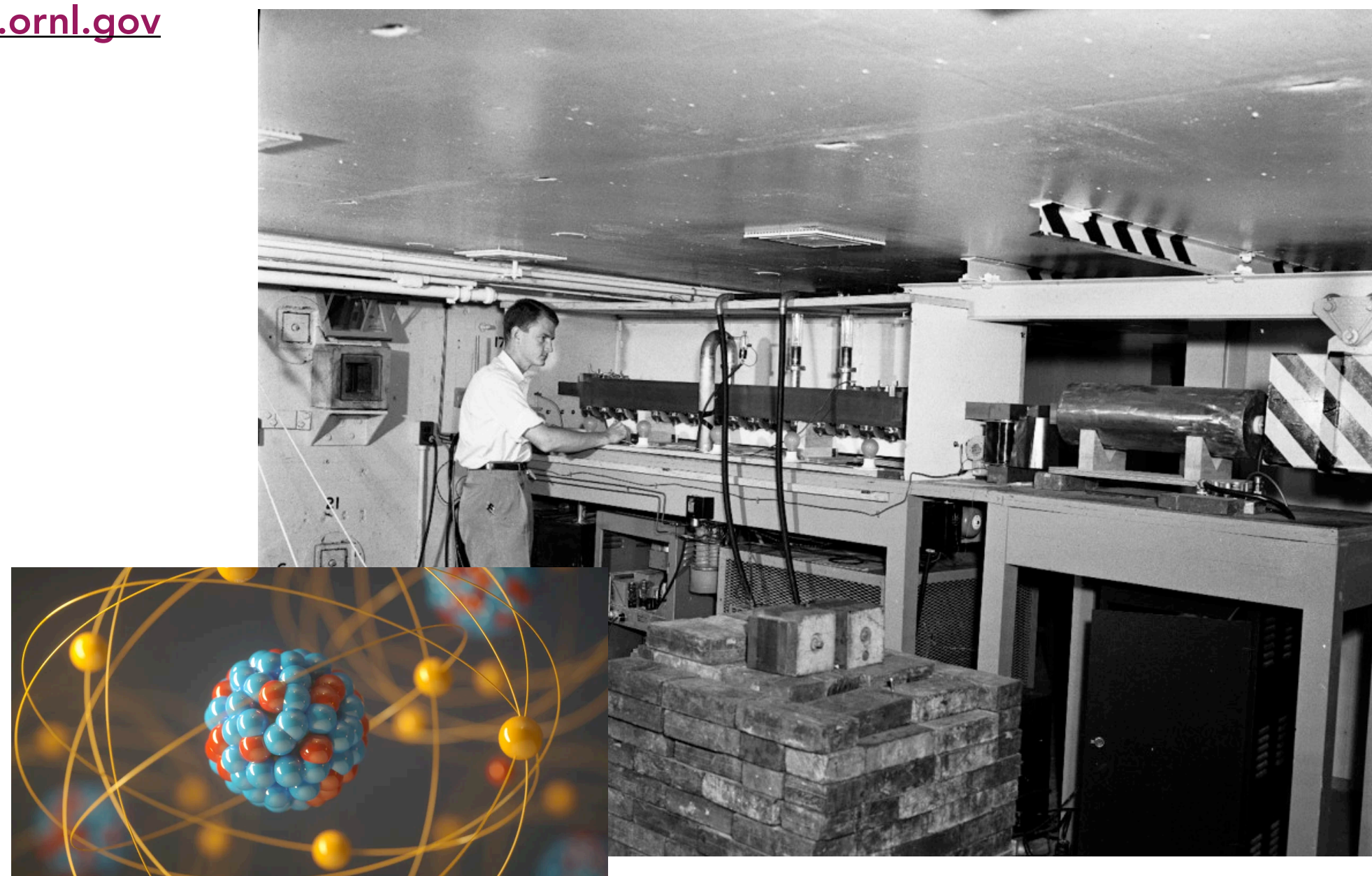
Introduction

Searches of CPV: low energy & high precision frontier

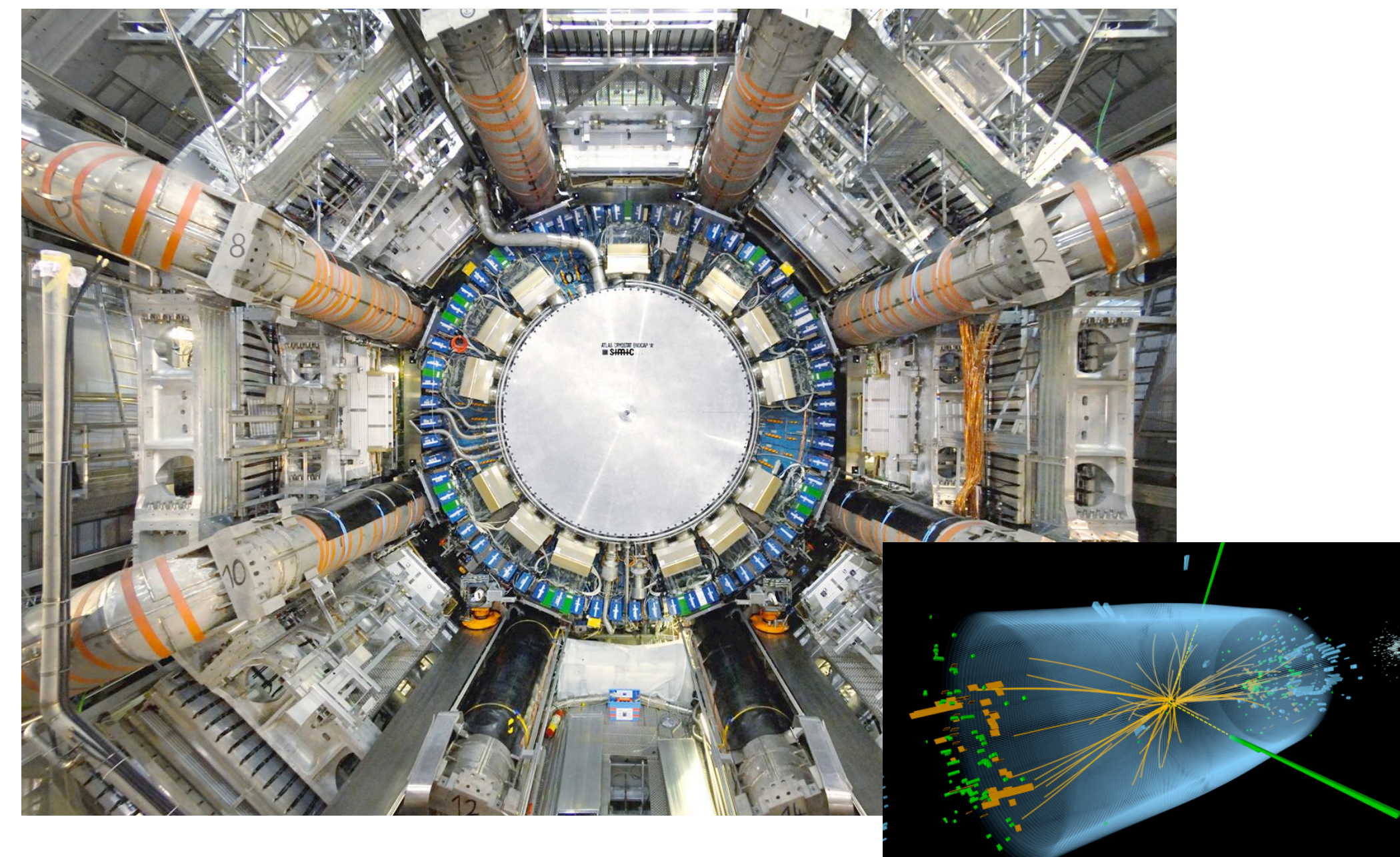
EDMs of fundamental particles, atoms and molecules are at the intersection of **low-energy** and **high-precision** frontier

Complementary pathway to **high-energy colliders** to uncover new physics beyond the Standard Model

James Smith with the neutron EDM apparatus 1950-ORNL
ned.ornl.gov



ATLAS detector at CERN





Introduction

Searches of CPV at low energy scales: Electric Dipole moments

Standard Model contributions are extremely suppressed

EDM searches require

- ▶ Highly precise experiments
- ▶ Reliable theoretical calculations

This interplay between **low-energy** and **high-precision** makes **challenging** interpreting measurements

Specially in the nuclear domain, where systematically improvable nuclear calculations remain limited for many nuclei of experimental interest

We propose a ***first-principles*** framework capable of describing symmetry breaking observables in nuclei of experimental interest



Introduction

EDMs: upper limits and SM prediction

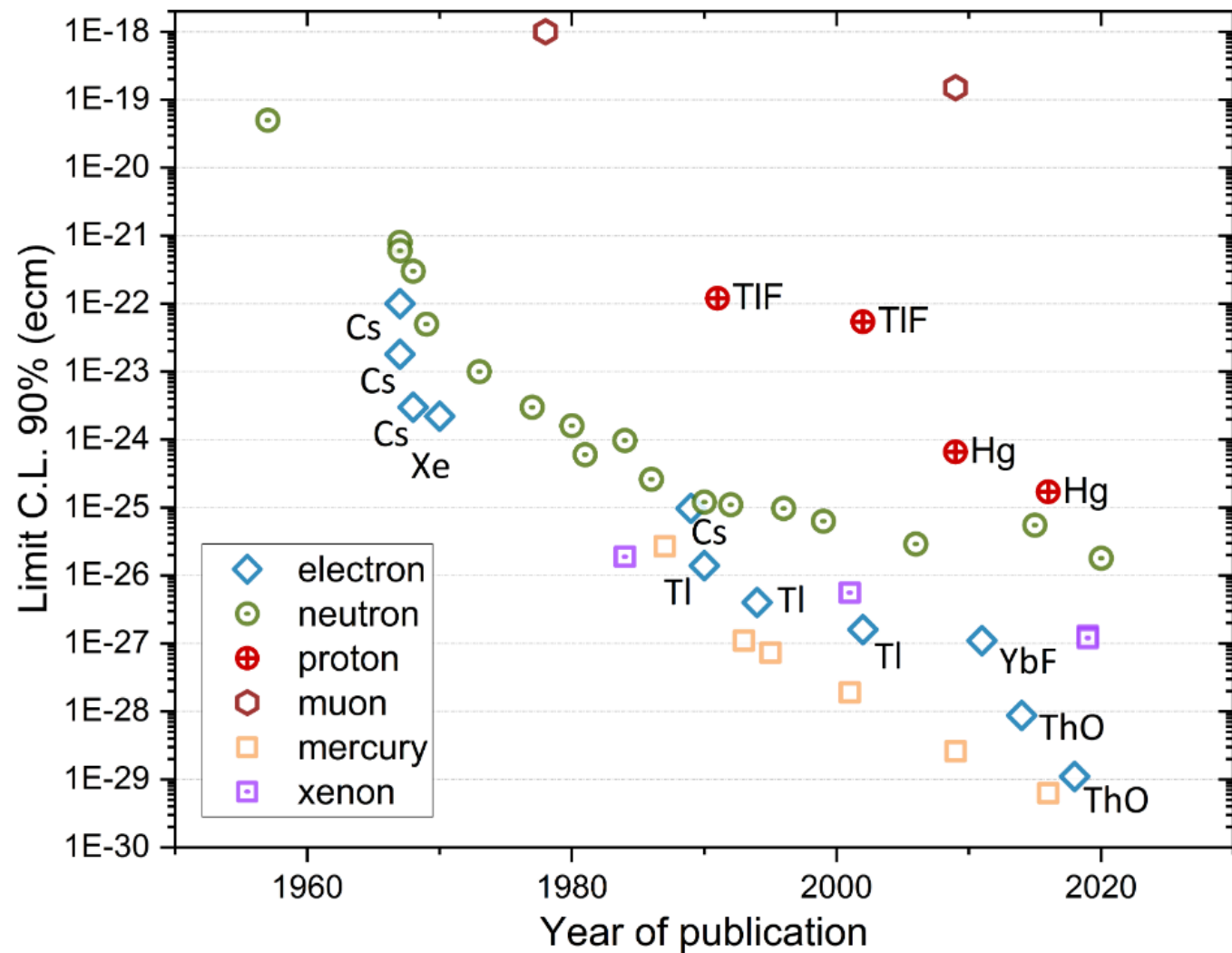
Upper limits for EDMs of various systems of interest and their SM predictions

	Standard Model	Experiment
neutron	$\sim 10^{-31} \text{ e cm}$	$3.6 \times 10^{-26} \text{ e cm}$
electron	$\sim 10^{-38} \text{ e cm}$	$1.1 \times 10^{-29} \text{ e cm}$
^{199}Hg	$\sim 10^{-34} \text{ e cm}$	$7.4 \times 10^{-30} \text{ e cm}$
^{129}Xe	$\sim 10^{-34} \text{ e cm}$	$6.6 \times 10^{-27} \text{ e cm}$

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

Almost **background-free** window to new CP-violating physics

EDM experimental searches



Klaus Kirch and Philipp Schmidt-Wellenburg, *EPJ Web Conf.* 233, 2020

Open-shell ("paramagnetic")
atoms and molecules
(ThO, YbF, HfF⁺, Cs, Tl)

d_e, semileptonic CPV

Closed-shell ("diamagnetic")
atoms and molecules (Hg, Xe, Ra, TlF)
eEDM suppressed

Hadronic CPV → **Nuclear Schiff moment**

Nucleons , and light nuclei



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P- and T-violation

The nuclear shell model

Microscopic treatment of the nucleus requires to solve

$$H|\Psi_i\rangle = E_i|\Psi_i\rangle$$

$$H|\Psi_i\rangle = E_i|\Psi_i\rangle$$



$$H_{eff}|\Psi_i^{eff}\rangle = E_i|\Psi_i^{eff}\rangle$$

full-space
(typically intractable)

model-space
(tractable)

$|\Psi_i^{eff}\rangle$ configuration (valence) space wave function

$|\Psi_i^{eff}\rangle = \sum_{k=1}^d a_{ik} |\Phi_k\rangle$ a_{ik} obtained from diagonalising H_{eff}  step that **limit** the nuclei accessible
basis dimension $N_{SD} \sim 10^{10}$

$|\Phi_\alpha\rangle = \prod_{\alpha_i=(n_i, l_i, j_i, m_i, m_{t_i})}^A c_{\alpha_i}^\dagger |0\rangle$ Slater determinant

This is only one part of the story....



P- and T-violation

Symmetry breaking interaction V_{PTV}

P- and T- violating nuclear observables arise from tiny **symmetry-breaking** interaction V_{PTV}

$$H = H_{PTC} + \lambda V_{PTV}$$

$|\Psi_0 J^\pi\rangle$ ground state H, V_{PTV} mixes opposite parities $|\Psi_0 J\rangle \approx |\Psi_0 J^\pi\rangle + \sum_{k \neq 0} |\Psi_k J^{-\pi}\rangle \frac{\langle \Psi_k J^{-\pi} | V_{PTV} | \Psi_0 J^\pi \rangle}{E_0 - E_k}$

$$\langle O_{PTV} \rangle = 2 \sum_{k \neq 0} \frac{\langle \Psi_0 J^\pi | O_{PTV} | \Psi_k J^{-\pi} \rangle \langle \Psi_k J^{-\pi} | V_{PTV} | \Psi_0 J^\pi \rangle}{E_0 - E_k}$$



Violation of fundamental symmetries (P & T)

Nuclear Schiff moment

$$S = \langle S_z \rangle = 2 \sum_{k \neq 0} \frac{\langle \Psi_0 J^\pi | S_z | \Psi_k J^{-\pi} \rangle \langle \Psi_k J^{-\pi} | V_{PTV} | \Psi_0 J^\pi \rangle}{E_0 - E_k}$$

Challenges

- ▶ opposite parity states needed within the model space
- ▶ S induces high-energy excitations
- ▶ Approximations must be done to make the problem numerically tractable with the difficulty of quantifying the errors

Idea

- ▶ Use a method that incorporate physics at high energies into valence space
- ▶ In-medium similarity renormalization group (IMSRG) and generalise to include PTV op's
- ▶ Systematically improvable many-body framework quantitatively describing nuclei



P- and T-violation

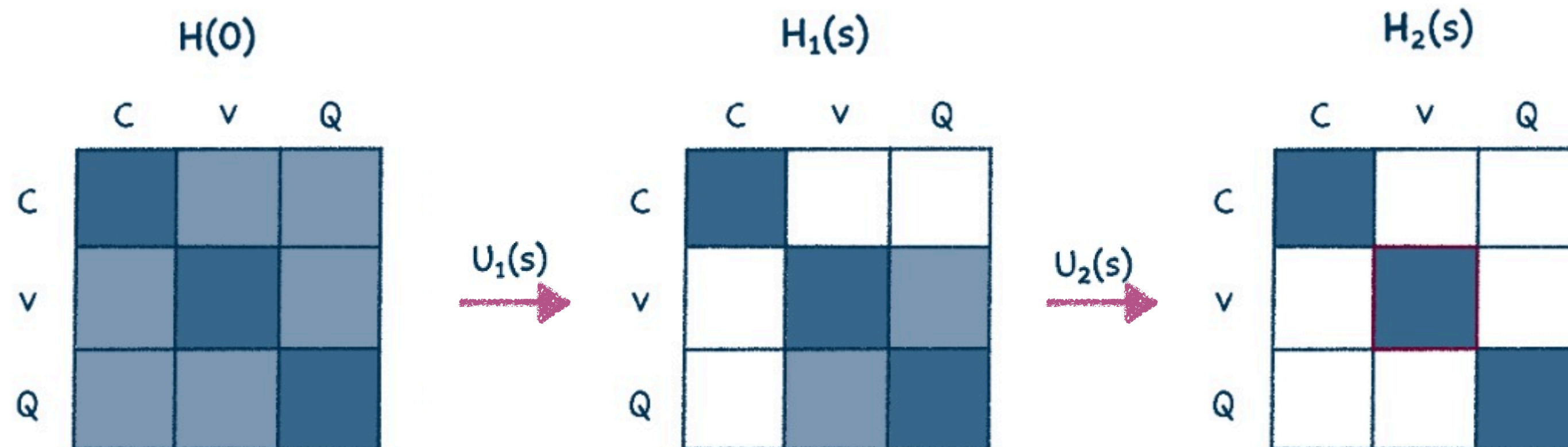
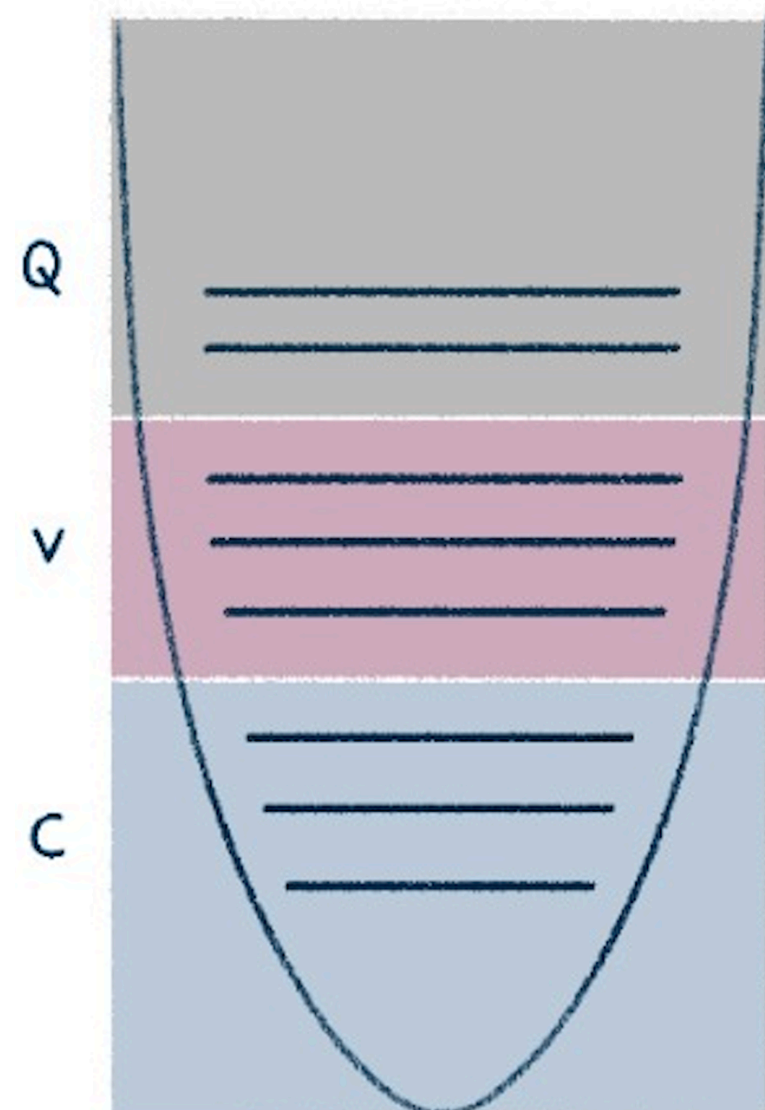
Valence space-in medium similarity renormalization group (VS-IMSRG)

Basic idea **similarity renormalization group**: perform continuous unitary transformation so H is more easy to diagonalize

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

$$\begin{aligned} H(s) &= U(s) H U^\dagger(s) \\ H(s) &= H^d(s) + H^{od}(s) \end{aligned} \quad \left| \quad \begin{aligned} U(s) \mid s \rightarrow \infty \quad H^{od}(s) &\longrightarrow 0 \end{aligned} \right.$$

VS-IMSRG





P- and T-violation

Break parity in IMSRG flow equations

Unitary transformation into flow eq's

η generator

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

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

with

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

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

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

$$\begin{aligned} \frac{dH_{PC}}{ds} &= [\eta_{PC}, H_{PC}] + \mathcal{O}(\lambda^2) \\ \frac{dV_{PV}}{ds} &= [\eta_{PV}, H_{PC}] + [\eta_{PC}, V_{PV}] \end{aligned}$$

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

With

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

$$\langle S \rangle = \langle S_{PC} \rangle + \langle S_{PV} \rangle = \langle \psi_{gs} J^\pi | S_{PC} | \psi_{gs} J^\pi \rangle + 2\lambda \sum_n \frac{\langle \psi_{gs} J^\pi | S_{PV} | \psi_n J^{-\pi} \rangle \langle \psi_n J^{-\pi} | V_{PV} | \psi_{gs} J^\pi \rangle}{E_{gs} - E_n}$$

$s \longrightarrow \infty$

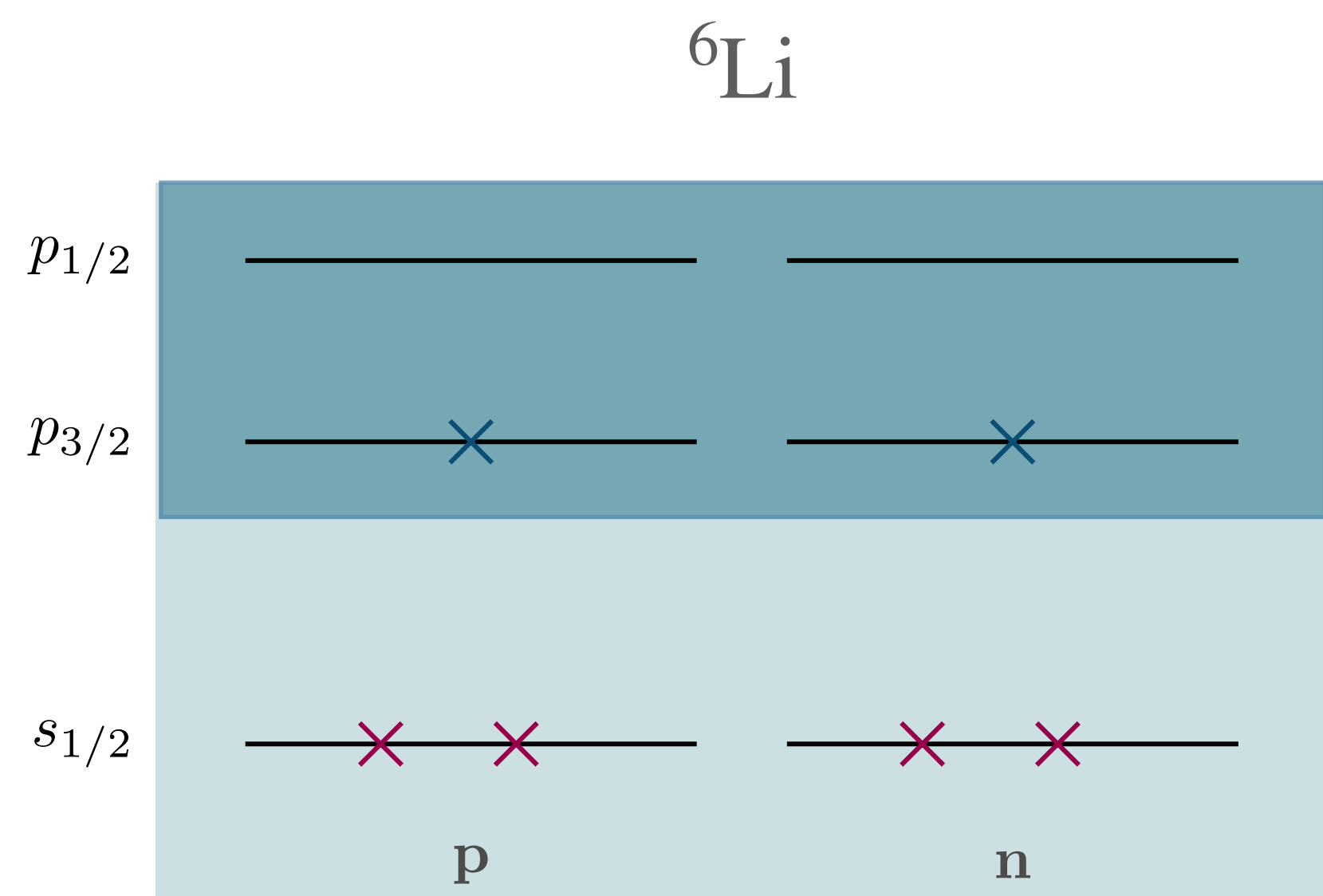
0



P- and T-violation

Proof of concept

IMSRG(2) approximation: operators normal-ordered with respect the reference and truncated at 2 body level



p-shell

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

sp-shell

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

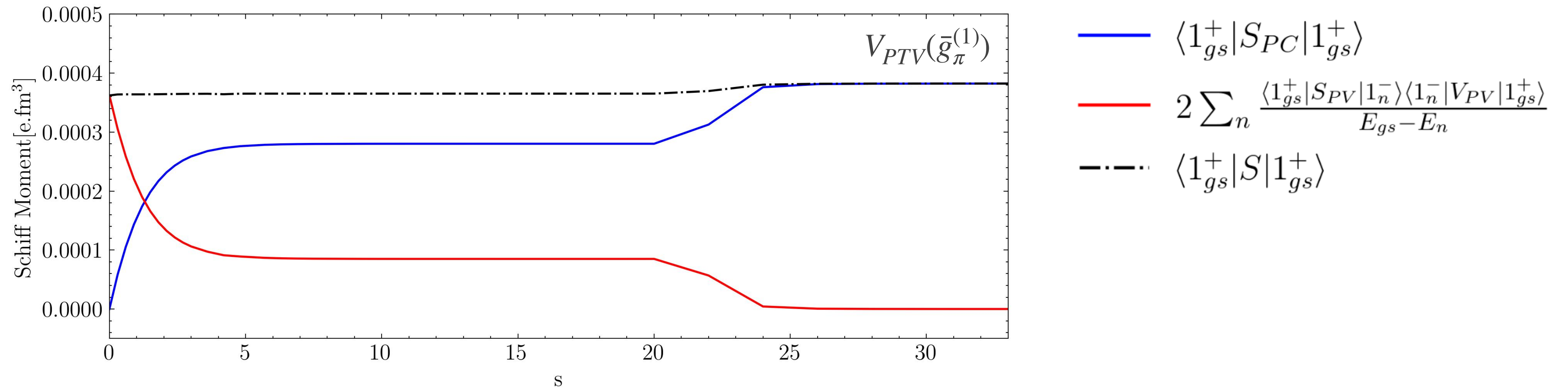
$$\{ 1_n^- \}_{98}$$

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



P- and T-violation

Proof of concept



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

- We decouple p-shell
- $\langle S \rangle_{sp} \approx \langle S^+ \rangle_p$ at the end of the flow

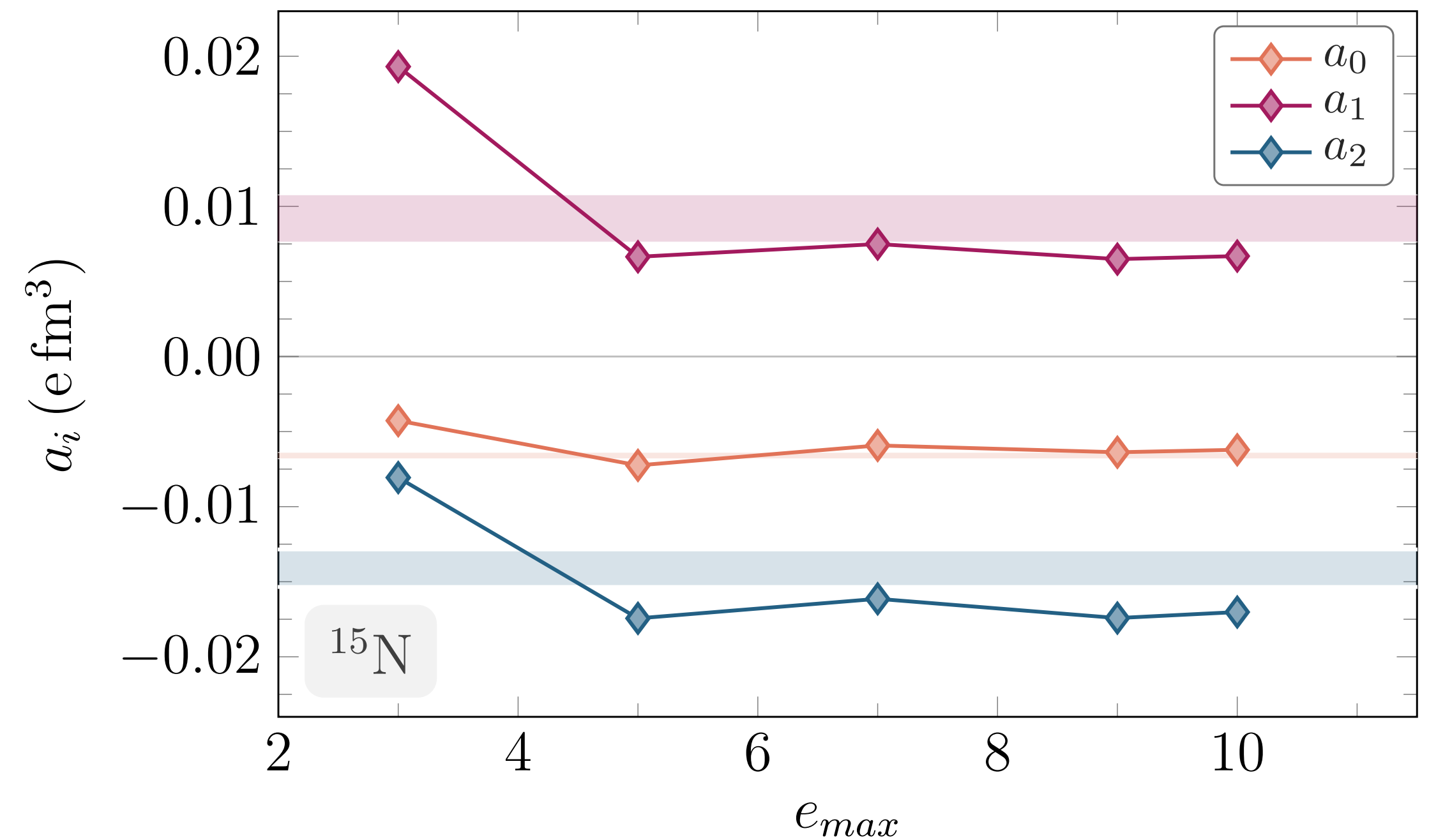
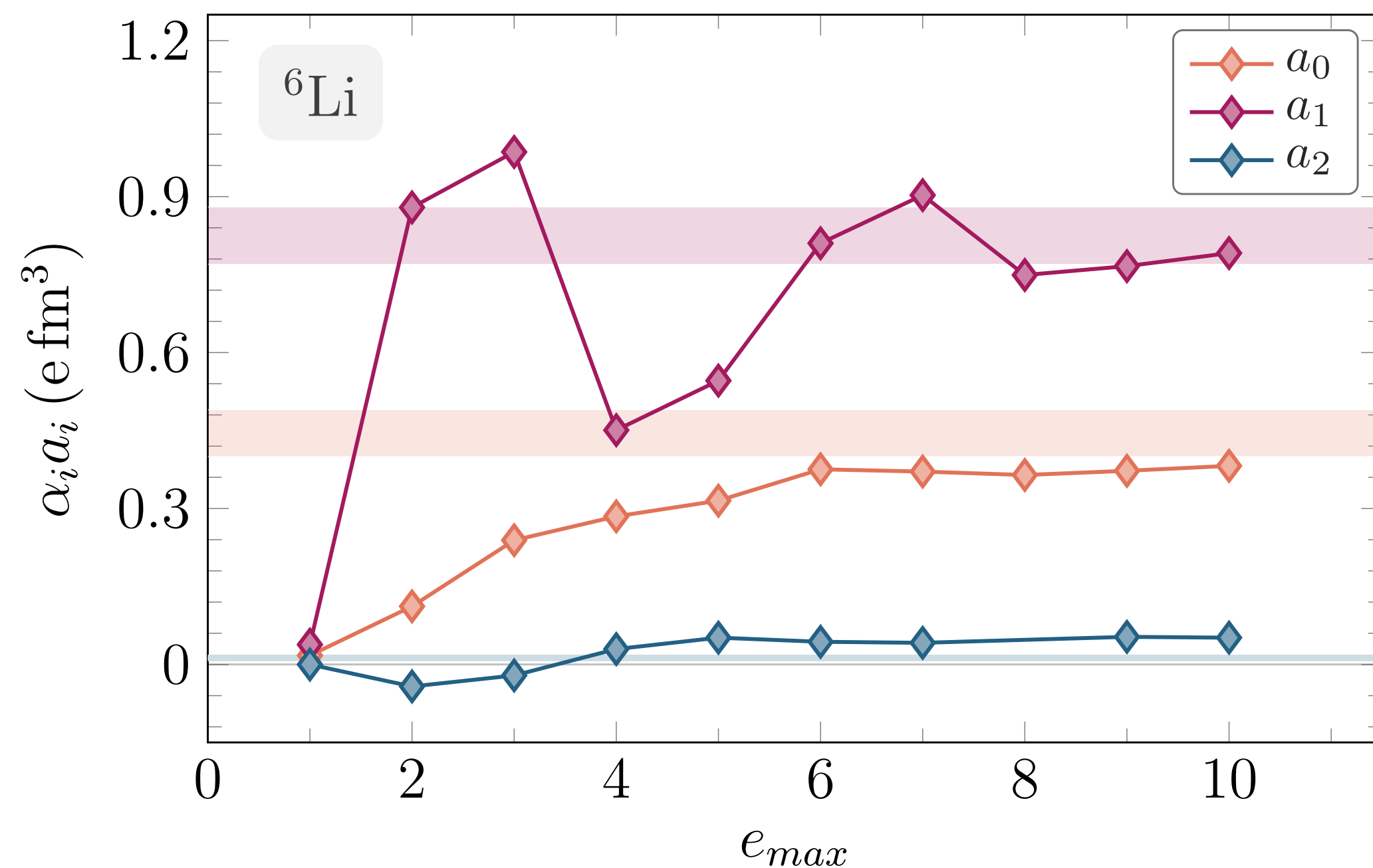


P- and T-violation

Benchmark PV-IMSRG(2)

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

A. Belley et. al. ,2605.11353 [nucl-th]



Compare with no core shell-model (NCSM), horizontal bands

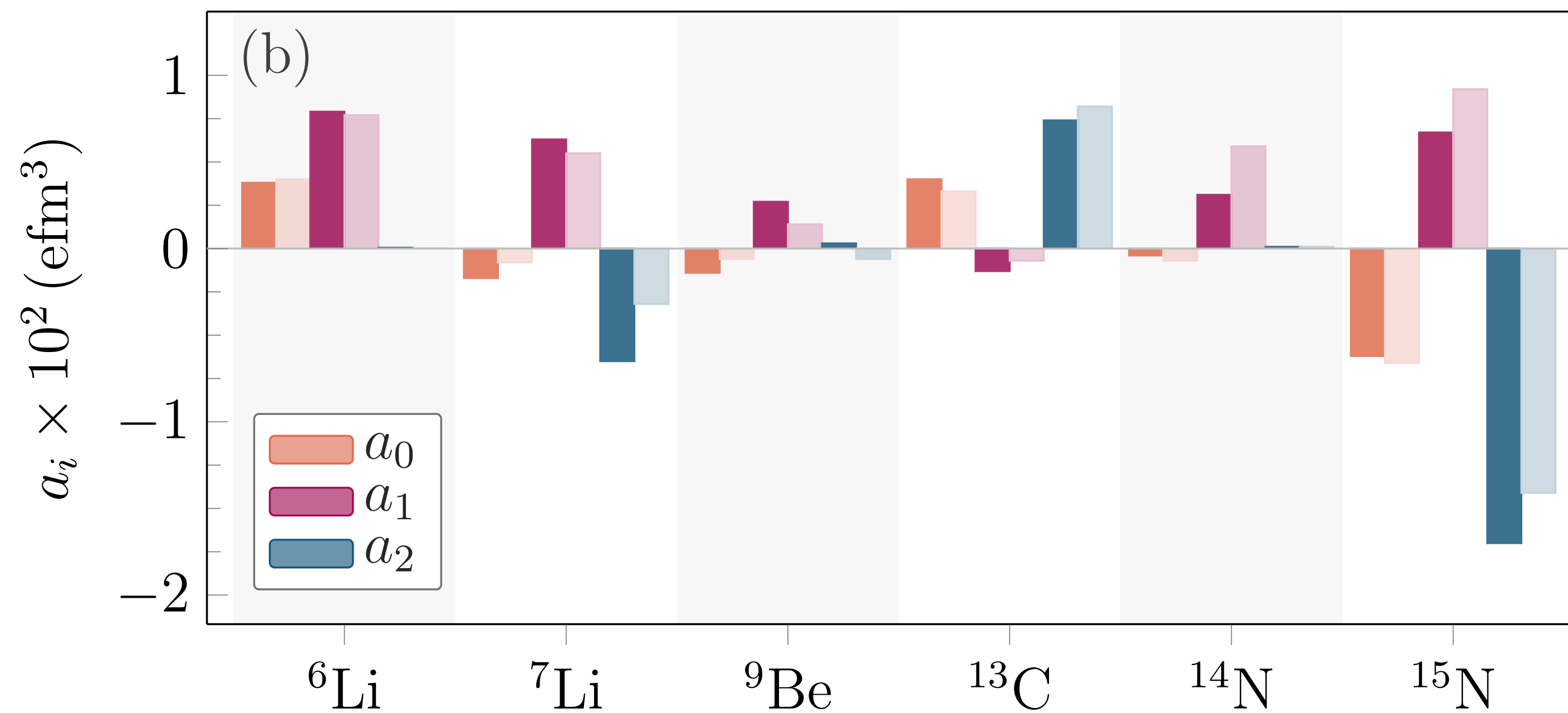
We **truncate** the harmonic oscillator single-particle basis $2n + l \leq e_{max}$



P- and T-violation Benchmark PV-IMSRG(2)

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

A. Belley et. al. ,2605.11353 [nucl-th]





P- and T-violation

The nuclear shell model

^{129}Xe is a diamagnetic atom of interest in ongoing and future searches

$$S(^{129}\text{Xe}) = -0.021g\bar{g}_{\pi}^{(0)} - 0.010g\bar{g}_{\pi}^{(1)} - 0.044g\bar{g}_{\pi}^{(2)}$$

Reasonable close to large scale nuclear shell model results

$$S(^{129}\text{Xe}) = -0.038g\bar{g}_{\pi}^{(0)} - 0.041g\bar{g}_{\pi}^{(1)} - 0.081g\bar{g}_{\pi}^{(2)}$$

K. Yanase and N. Shimizu, *Physical Review C* 102 (2020)

These are **preliminary results**, only one interaction, without a systematic exploration of the model-space, and many-body truncation

It provides a **path to systematically improved predictions of nuclear observables** relevant for precision tests of fundamental symmetries



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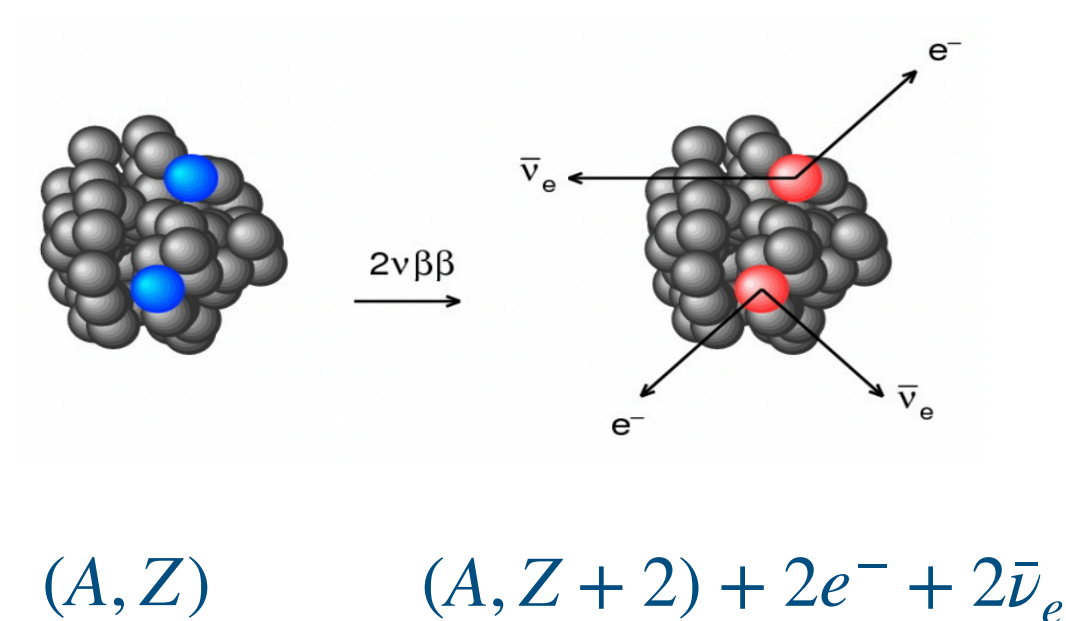
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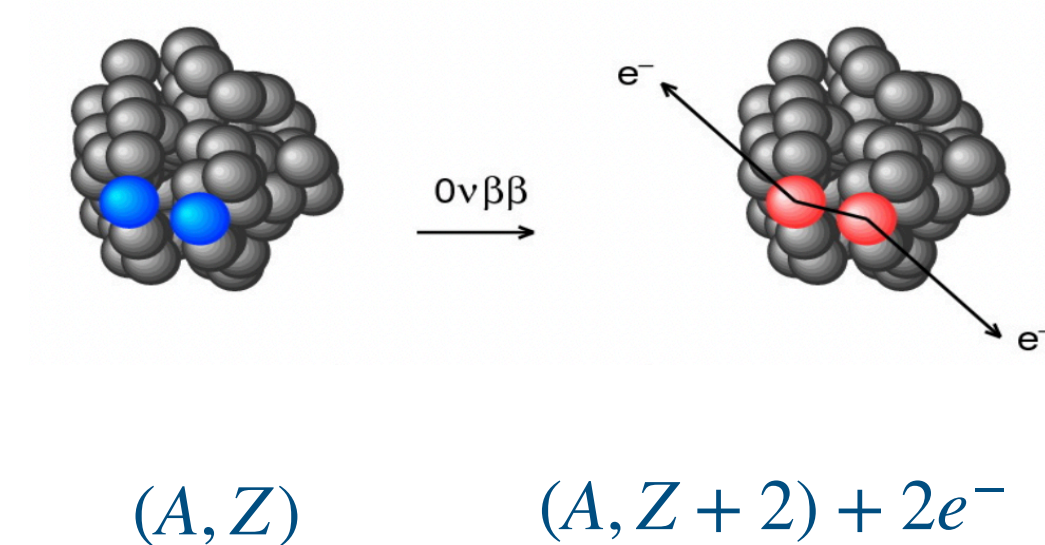
L-violation: $0\nu\beta\beta$ decay $2\nu\beta\beta$ & $0\nu\beta\beta$ decay modes

Standard $2\nu\beta\beta$ -decay



- ▶ Allowed by Standard Model - Lepton number conserved
- ▶ Observed in 11 isotopes
- ▶ Half-lives $10^{18} - 10^{21}y$
- ▶ Improved precision: test **nuclear structure** & **search new physics**

Beyond Standard Model $0\nu\beta\beta$



- ▶ Not allowed within Standard Model-**Lepton number violated**
- ▶ Immediately demonstrate **Majorana** nature of ν
- ▶ Current limits $> 10^{26}y \sim 10^{15}$ age of the universe!



L-violation: $0\nu\beta\beta$ decay

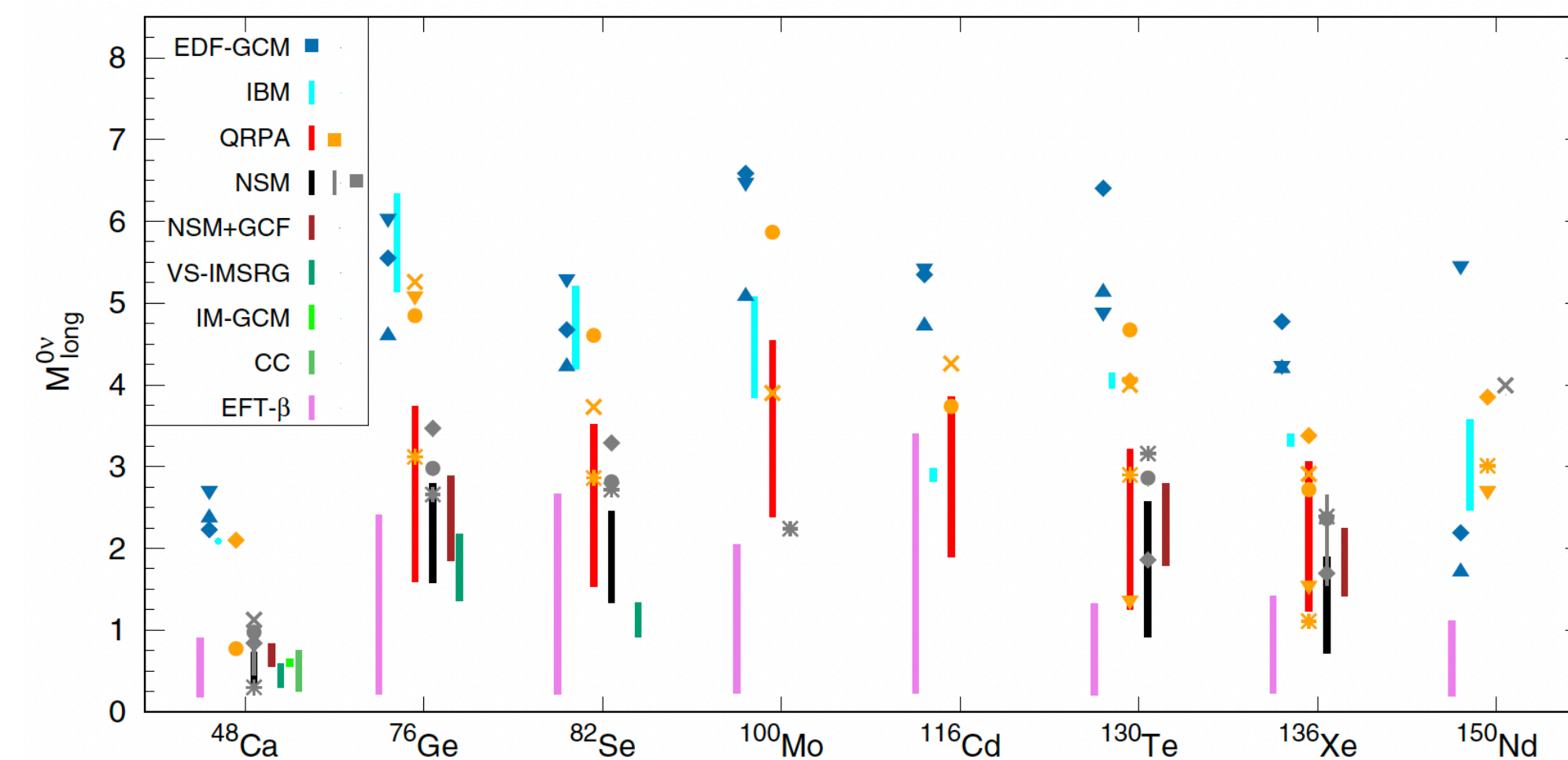
$0\nu\beta\beta$ Half life: Nuclear Matrix Element

$$[T_{1/2}^{0\nu}]^{-1} = G_{0\nu}(Q, Z) g_A^4 (M^{0\nu})^2 \phi^2$$

↙ ↘

Phase Space Factor **New Physics parameter**

$g_A^2 M^{0\nu}$ **Nuclear Matrix Element (NME)** a theoretical input, interpret **experimental results** demands the most **accurate evaluation NME**, essential to obtain predictions if a positive signal is observed and plan future experiments



JJ Gómez-Cadenas *et. al.*, *Nuovo Cim.* 45, 619–692 (2023)



L-violation: $0\nu\beta\beta$ decay

Approach to address uncertainty quantification of $0\nu\beta\beta$ NMEs

Search of **observables** that are **linked** to $0\nu\beta\beta$ even not mediated by same interaction

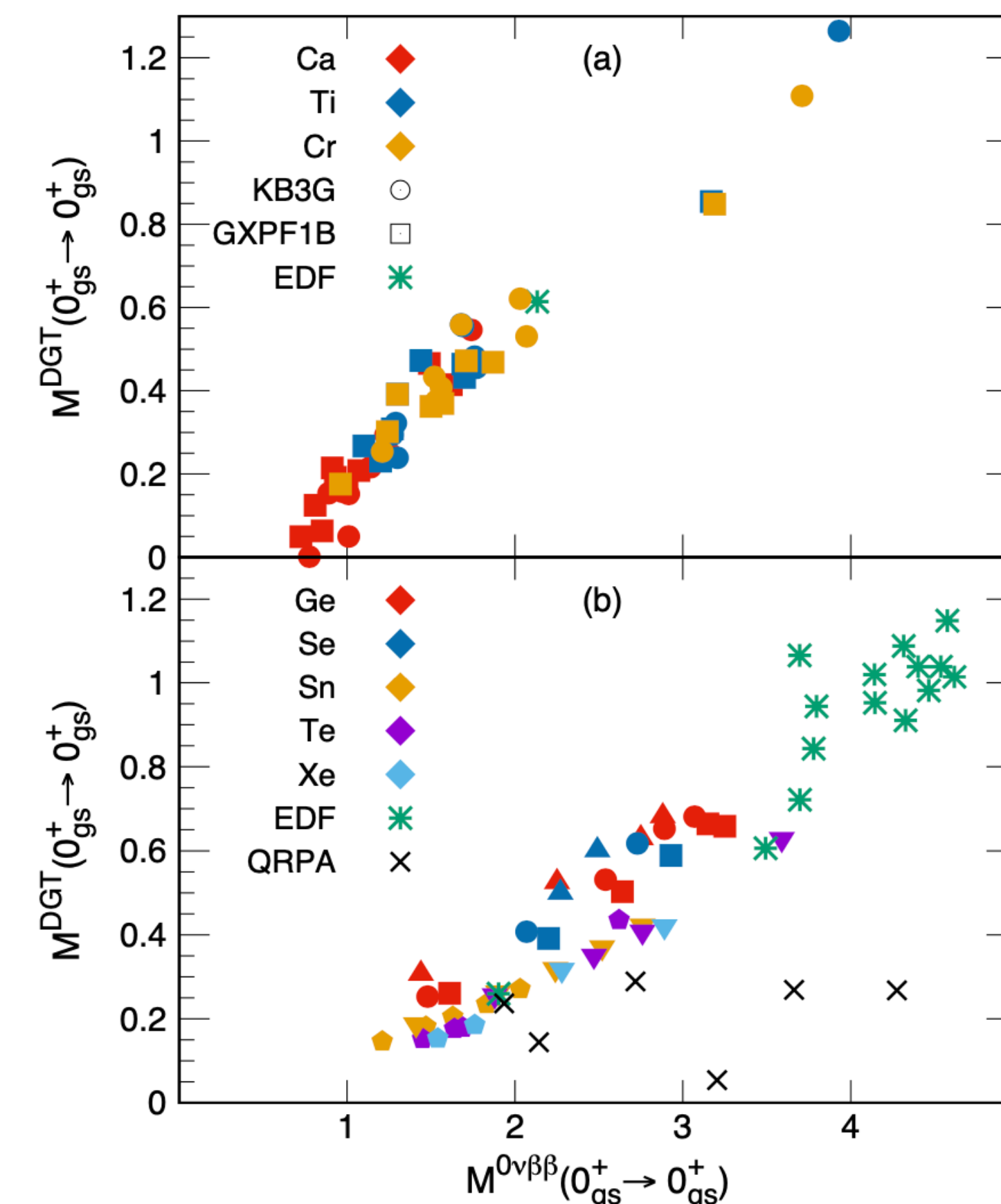
Good linear correlation **Double Gamow-Teller(DGT)** and the $0\nu\beta\beta$ NMEs

$$M^{DGT} = \langle 0_{gs,f}^+ | | \sum_{j,k} [\sigma_j \tau_j^- \times \sigma_k \tau_k^-]^0 | | 0_{gs,i}^+ \rangle$$

Measure M^{DGT} is challenging

Key: look for more accessible experiments and try to measure giving valuable information for $0\nu\beta\beta$ NME

Electromagnetic transitions powerful nuclear spectroscopic tool



N. Shimizu et. al., Phys. Rev. Lett 120, 143302 (2018)-**NSM**

JM. Yao et. al., Phys. Rev. C 106, 014315 (2022)-**IMSRG**

L. Jokiniemi et. al., Phys. Rev. C 107, 044316 (2023)-**QRPA**



L-violation: $0\nu\beta\beta$ decay

Correlation $\gamma\gamma$ - $0\nu\beta\beta$ NMEs

Second order electromagnetic transitions, expect experimental measurement **more accessible** than $0\nu\beta\beta$

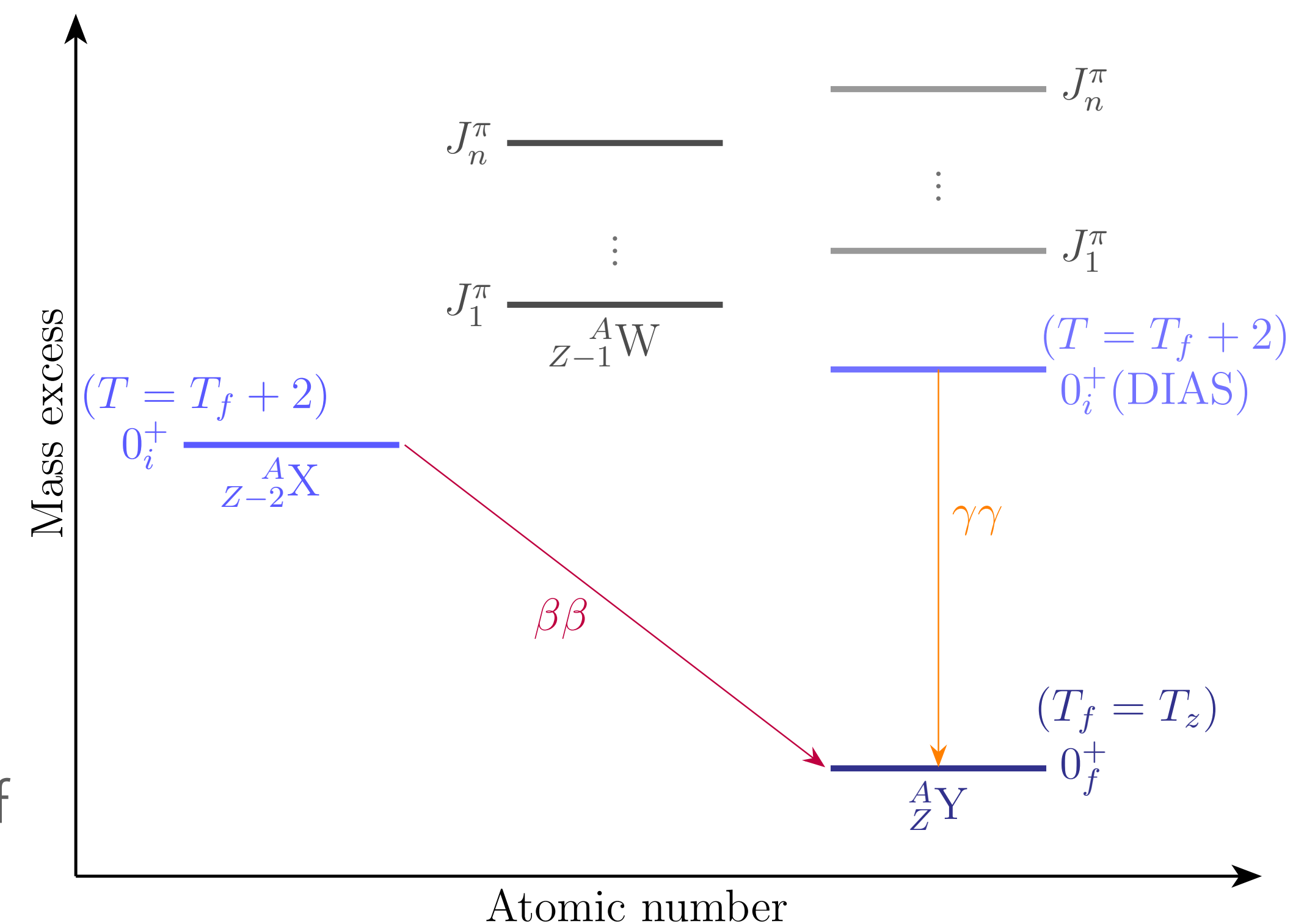
$\gamma\gamma$ and $\beta\beta$ nuclear states relation

$$|0_i^+\rangle_{\gamma\gamma} \equiv |0_i^+\rangle_{\beta\beta}(\text{DIAS}) = \frac{T_- T_-}{N_f} |0_i^+\rangle_{\beta\beta}$$

$$|0_f^+\rangle_{\gamma\gamma} \equiv |0_f^+\rangle_{\beta\beta}$$

Isospin lowering operator $T^- = \sum_i \tau_i^-$ N_f normalization factor

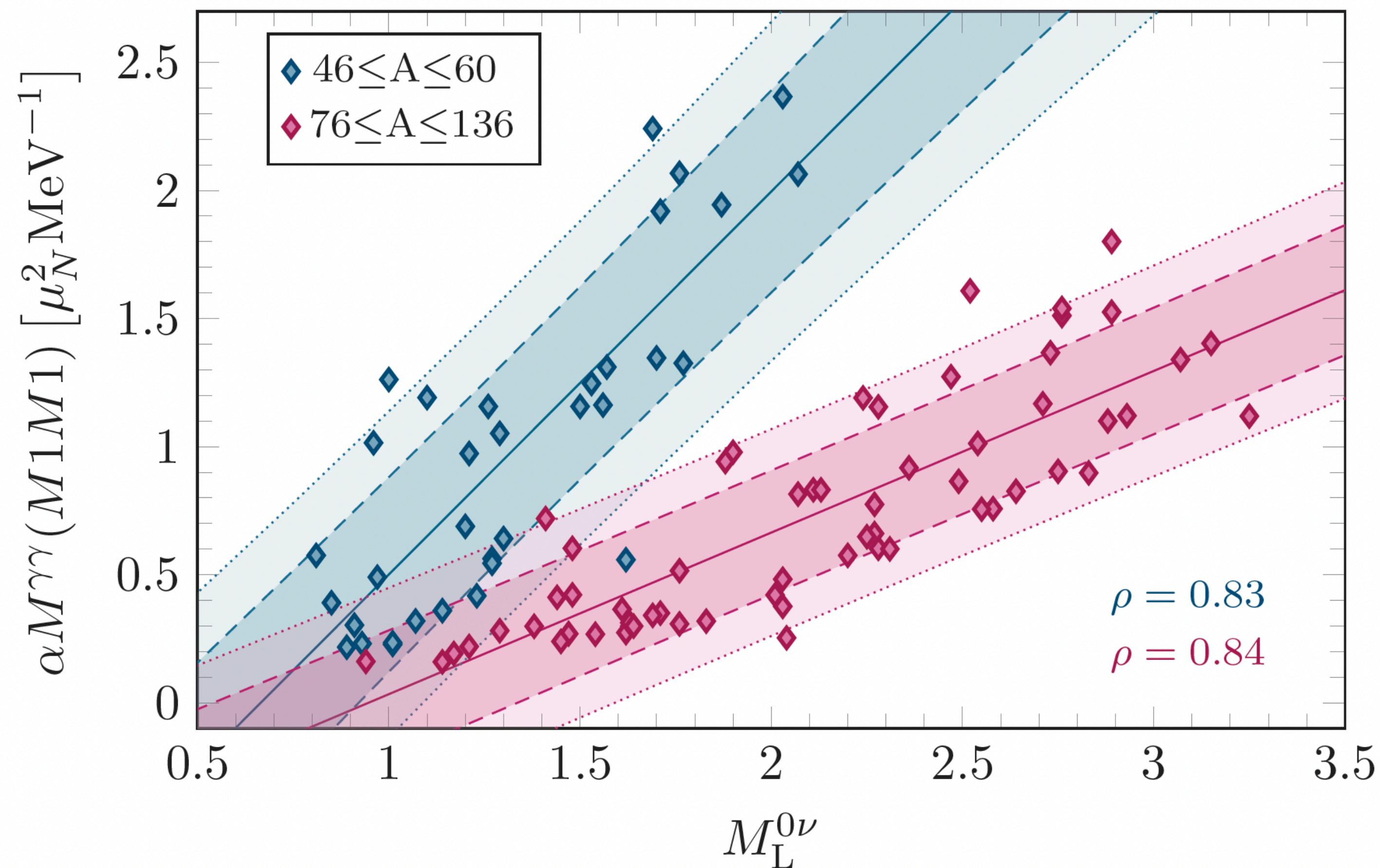
Isospin symmetry holds very well in nuclei: nuclear structure of **double isobaric analog state (DIAS)** in $\gamma\gamma$ is similar to the initial state of $0\nu\beta\beta$





L-violation: $0\nu\beta\beta$ decay

Correlation $\gamma\gamma$ - $0\nu\beta\beta$ NMEs



Phys. Lett. B 827, 136965 (2022)

19 nuclei **Ti, Cr, Fe** in region $46 \leq A \leq 60$

GXPF1, KB3G

33 nuclei **Zn, Se, Kr, Te, Xe, Ba** in $72 \leq A \leq 136$

(JJ44B, JUN45, GCN2850, QX, GCN5082)

Very good correlation coefficients

$$\rho_{\text{pf}} = 0.80 \quad \rho_{\text{pfg+gds}} = 0.84$$

α from Wigner-Eckart Th. to isospin space

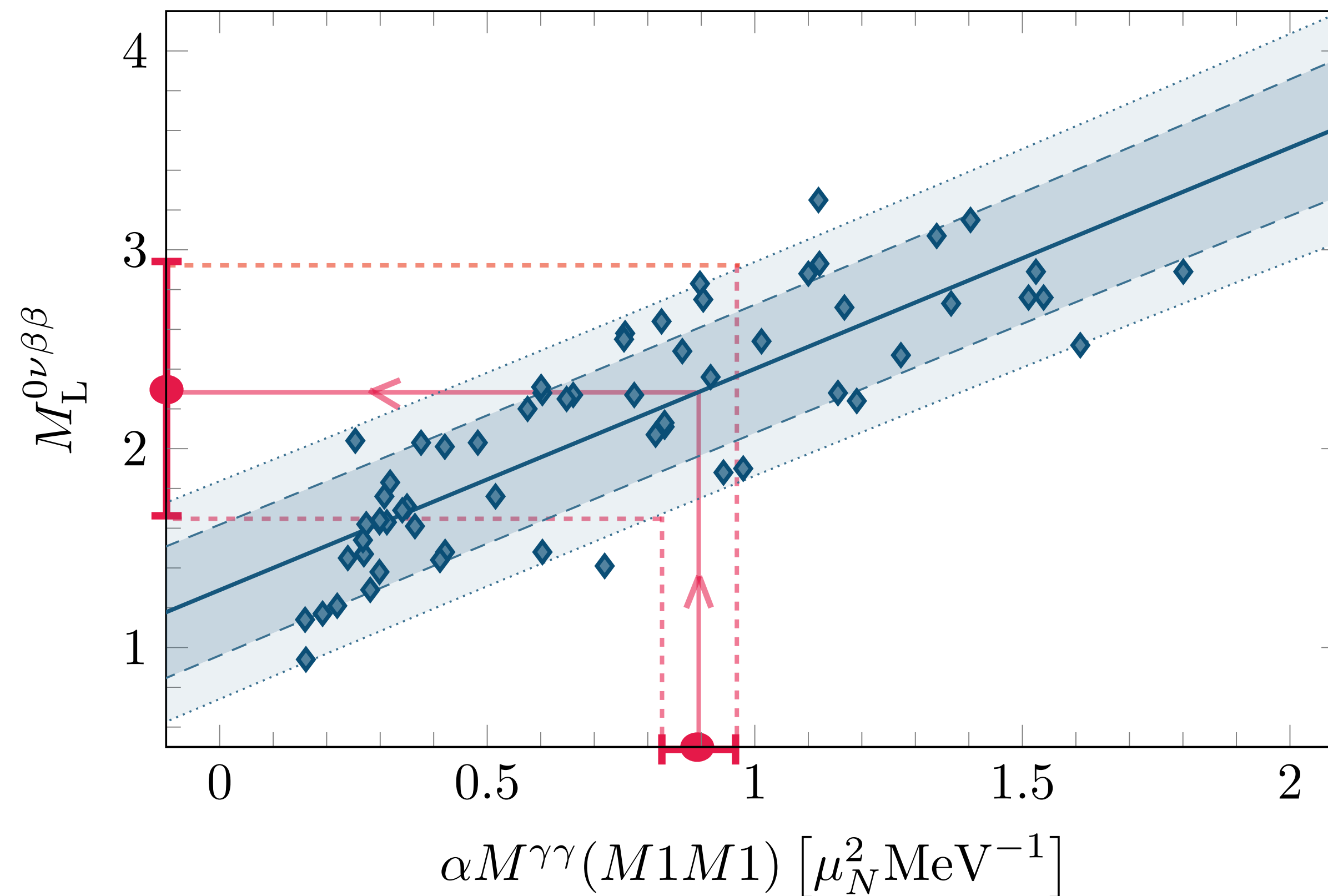


L-violation: $0\nu\beta\beta$ decay

$0\nu\beta\beta$ -decay NMEs from $\gamma\gamma$ -M1M1 data

Using $M^{0\nu} = a + bM^{\gamma\gamma}$ and prediction bands: predict $0\nu\beta\beta$ NMEs from a measurement of $\gamma\gamma(M1M1)$

Constrains on single estimated NMEs, estimate what we would expect from single measure of $0\nu\beta\beta$



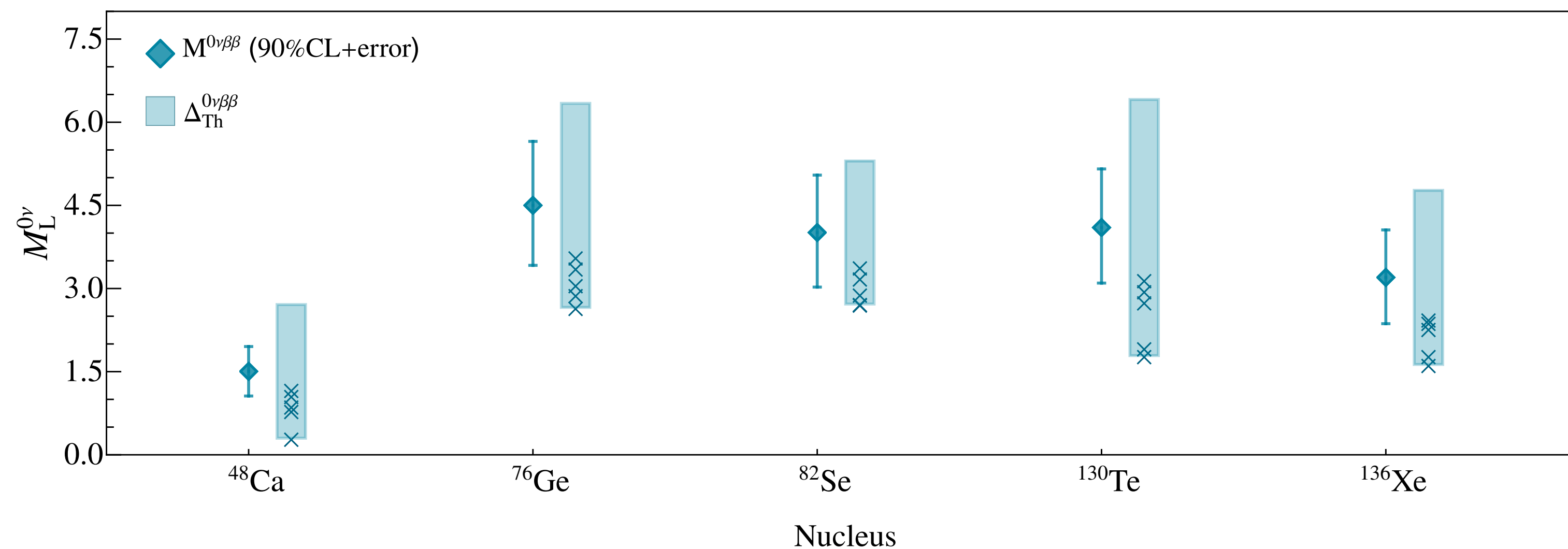


L-violation: $0\nu\beta\beta$ decay

$0\nu\beta\beta$ -decay NMEs from $\gamma\gamma$ -M1M1 data

Using $M^{0\nu} = a + bM^{\gamma\gamma}$ and prediction bands we want to predict $0\nu\beta\beta$ NMEs from a hypothetical measurement of $\gamma\gamma(M1M1)$ from DIAS to GS

Give the uncertainty in each of these single estimated NMEs



"x" ShM NMEs literature [Rev. Mod. Phys. 95, 033002 \(2023\)](#)

Shaded bands combined calculated NME (SM,EDF,IBM)



L-violation: $0\nu\beta\beta$ decay

Previous experimental measurements $\gamma\gamma$

New avenue to quantify $0\nu\beta\beta$ NMEs uncertainties if $\gamma\gamma(M1M1)$ from DIAS to ground state can be measured

Measurements of second order em decays are difficult but they have been done using NaI(Tl) detectors, for $0_2^+ \rightarrow 0_1^+$ in double magic nuclei ^{16}O , ^{40}Ca , ^{90}Zr

$$\Gamma_{\gamma\gamma}/\Gamma \simeq 10^{-4}$$

Phys. Rev. C 41, 1727 (1990)

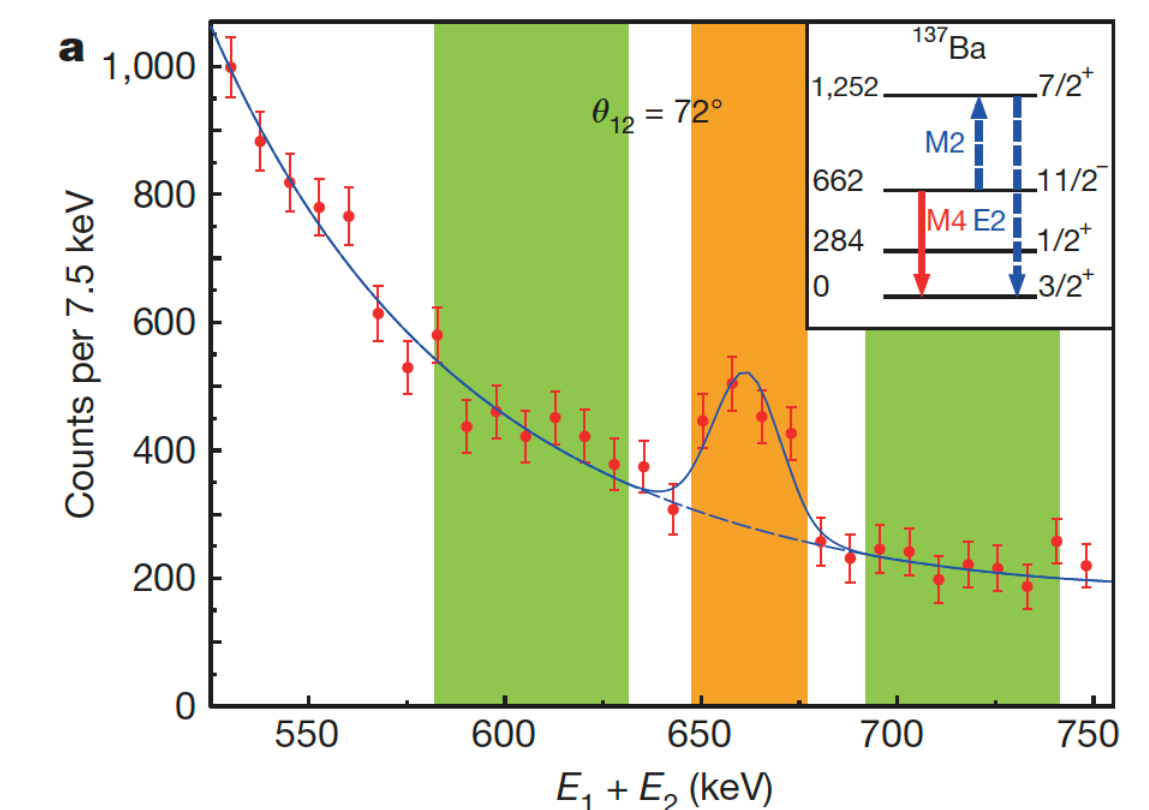
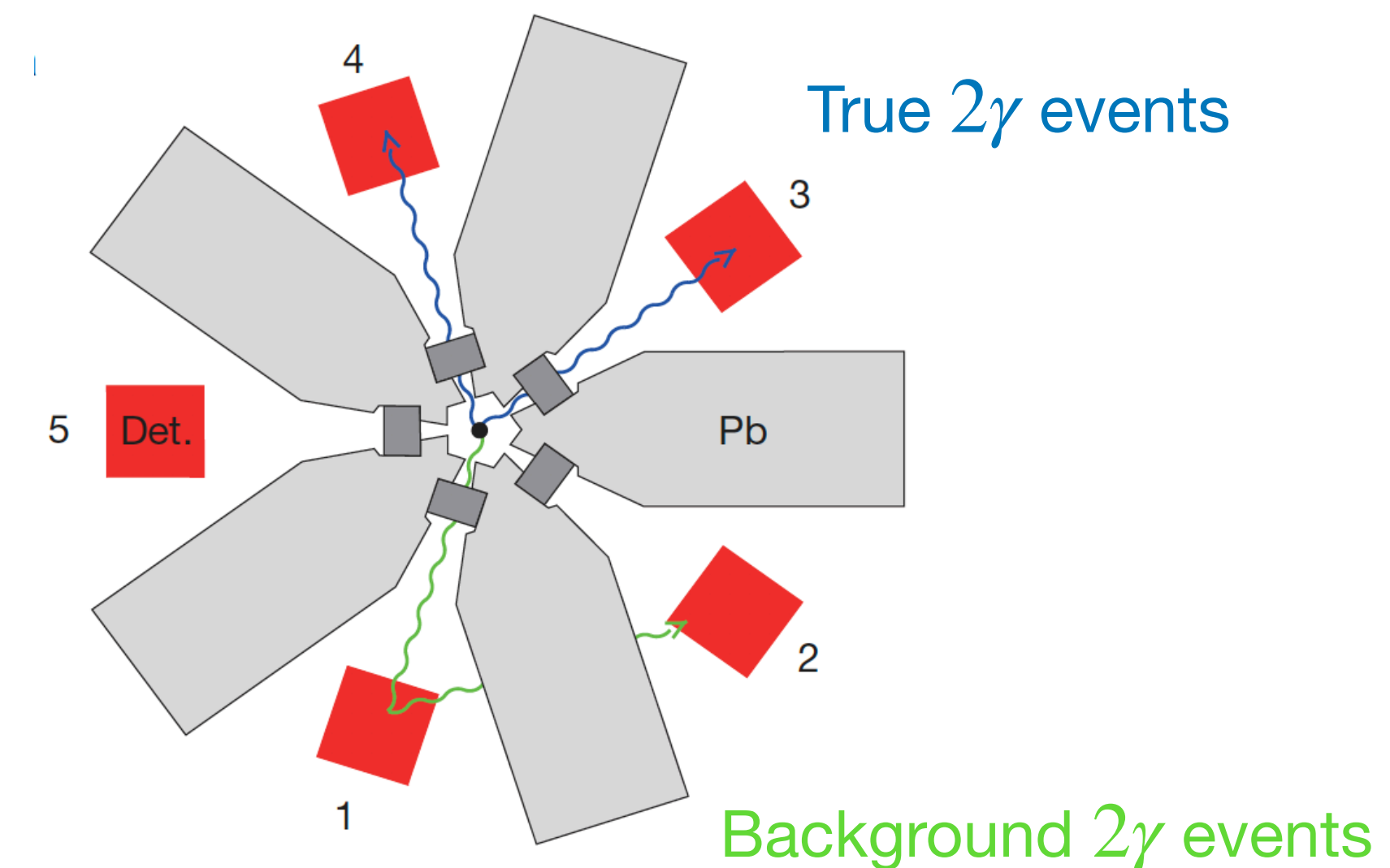
Phys. Rev. Lett. 53, 1897 (1984)

Faster crystal detectors allowed measurement of competitive $\gamma\gamma/\gamma$ decay in ^{137}Ba for $11^+/2 \rightarrow 3^+/2$

$$\Gamma_{\gamma\gamma}/\Gamma_{\gamma} \simeq 10^{-6}$$

Nat. 526, 406–409 (2015)

Nat. Commun. 11, 3242 (2020)



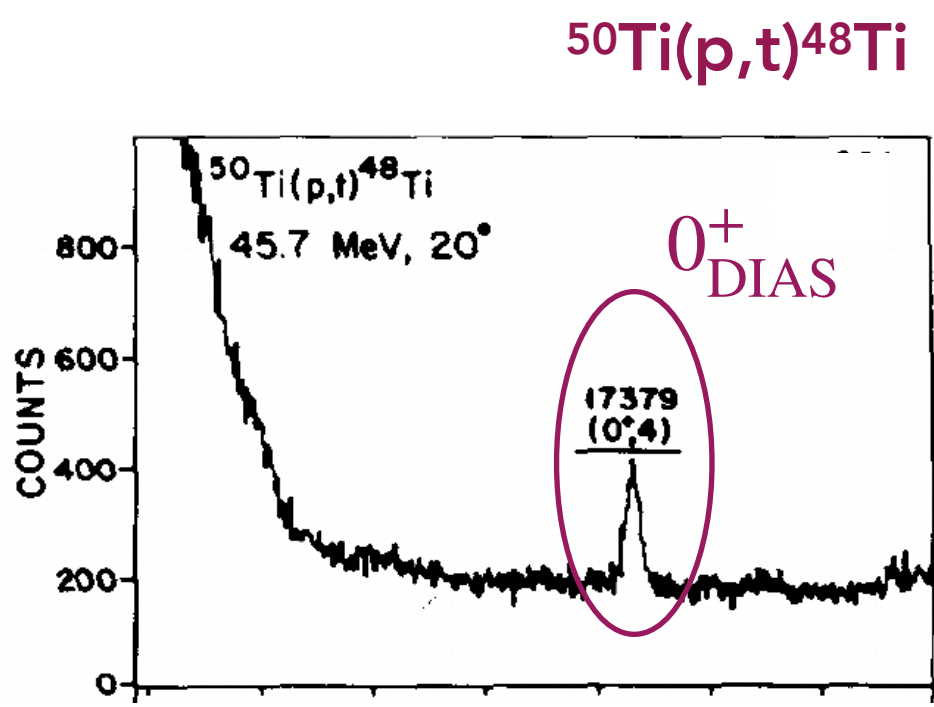
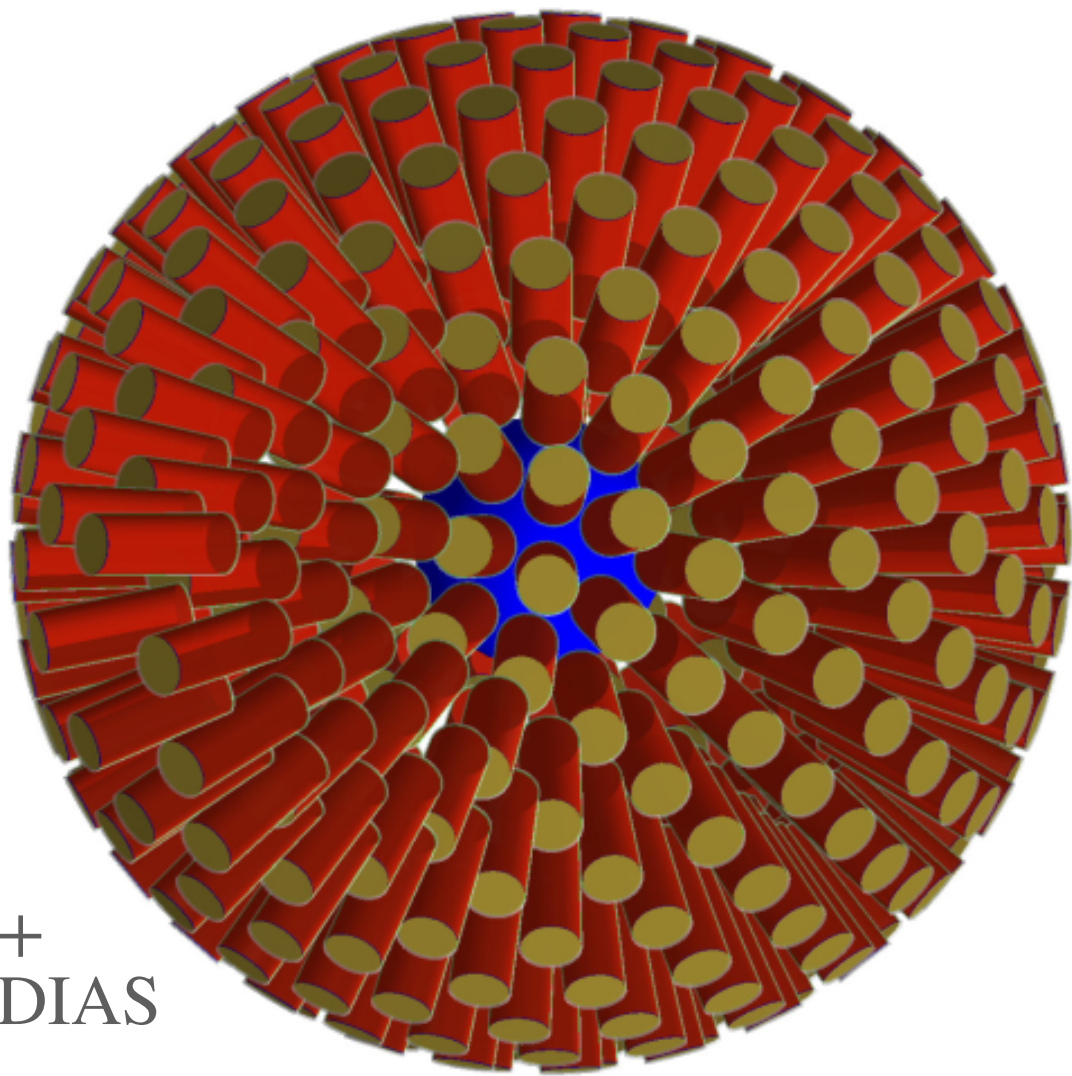


L-violation: $0\nu\beta\beta$ decay

The experimental challenge

New avenue to quantify $0\nu\beta\beta$ NMEs uncertainties if $\gamma\gamma(M1M1)$ from DIAS to ground state can be measured

Nucleus	$\Gamma_{\gamma\gamma}/\Gamma_{\gamma}$	$\Gamma_{\gamma\gamma}/\Gamma_p$	$\Gamma_{\gamma\gamma}/\Gamma_{IC}$	$\Gamma_{\gamma\gamma}/\Gamma_{IPC}$
^{48}Ti	2×10^{-8}	7×10^{-10}	3×10^{-5}	0.5
^{76}Se	5×10^{-7}	$< 2 \times 10^{-8}$	7×10^{-6}	0.07
^{82}Kr	5×10^{-7}	$< 4 \times 10^{-8}$	2×10^{-6}	0.03
^{130}Xe	8×10^{-8}	$< 4 \times 10^{-9}$	10^{-7}	2×10^{-4}
^{136}Ba	1×10^{-7}	$< 1 \times 10^{-8}$	6×10^{-7}	0.001



R.Kouzes et. al., *Nuc. Phys. A*, 309, 329–343 (1978)

Challenge: extremely small decay width, difficult to populate 0^+_{DIAS}

Collaboration Damiano Stramaccioni, Jose Javier Valiente Dobón and Javier Menéndez

B. Romeo, D. Stramaccioni, J. Menéndez, and J. J. Valiente-Dobón *Physics Letters B* 860 (2023) 139186

Key setup requirements:

- ▶ Good efficiency (small BRs, little statistics)
- ▶ Good time resolution (distinguishing $\gamma\gamma$)



- ▶ $\gamma\gamma$ -decay in ^{48}Ti , 10^7 events each process
- ▶ **302**, 3.5''x8'' cylindrical **LaBr₃** detectors
- ▶ $\Delta t = 800\text{ps}$
- ▶ Reaction chamber (Al, 17cm, 2mm thick)



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Summary and outlook

What's next?

- ▶ Extension of the IMSRG formalism: **PV-IMSRG**
- ▶ Consistent and systematically improvable framework to **quantify the effects of nuclear structure** in searches for new **sources of CP violation**
- ▶ Gain insight in the **relative importance** of the different **terms** in the **V_{PT} across nuclei**
- ▶ Target heavier nuclei ^{129}Xe , ^{199}Hg
- ▶ **Uncertainty quantification** introduced by the many-body and model space truncation

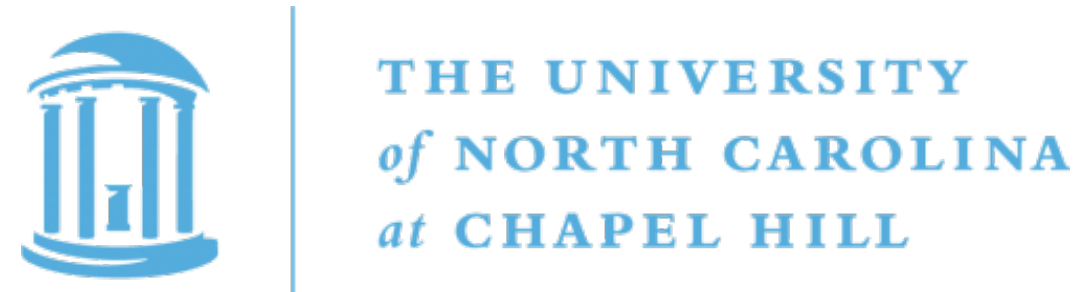


Summary and outlook

What's next?

- ▶ The connection between $\gamma\gamma(M1M1)$ and $0\nu\beta\beta$ suggests a new avenue to **constrain $0\nu\beta\beta$ -decay NMEs** from a **measurement** of $\gamma\gamma(M1M1)$ decay from $0^+(DIAS)$, also provides an **uncertainty** based on many systematic calculations
- ▶ $\gamma\gamma(M1M1)$ decay in VS-IMSRG, and study the effect of **two-body currents** in M1M1
- ▶ The experimental feasibility of measuring $\gamma\gamma(M1M1)$ in the final nuclei of **$\beta\beta$** measured decays has been addressed
- ▶ **Started!** initial experiment aiming to measure γ -decay from $^{48}\text{Ti}(T=4,0^+)$ and cross section using **proton beam** from **Cyclotron Centre Bronowice** in Krakow (D. Stramaccioni, M. Balogh, J.J. Valiente-Dobón)

Jon Engel



Antoine Belley



S. Ragnar Stroberg



Takayuki Miyagi



Javier Menéndez



Wouter Dekens



Jordy de Vries, Lemonia Gialdi, Heleen Mulder



Thank you!



Backup

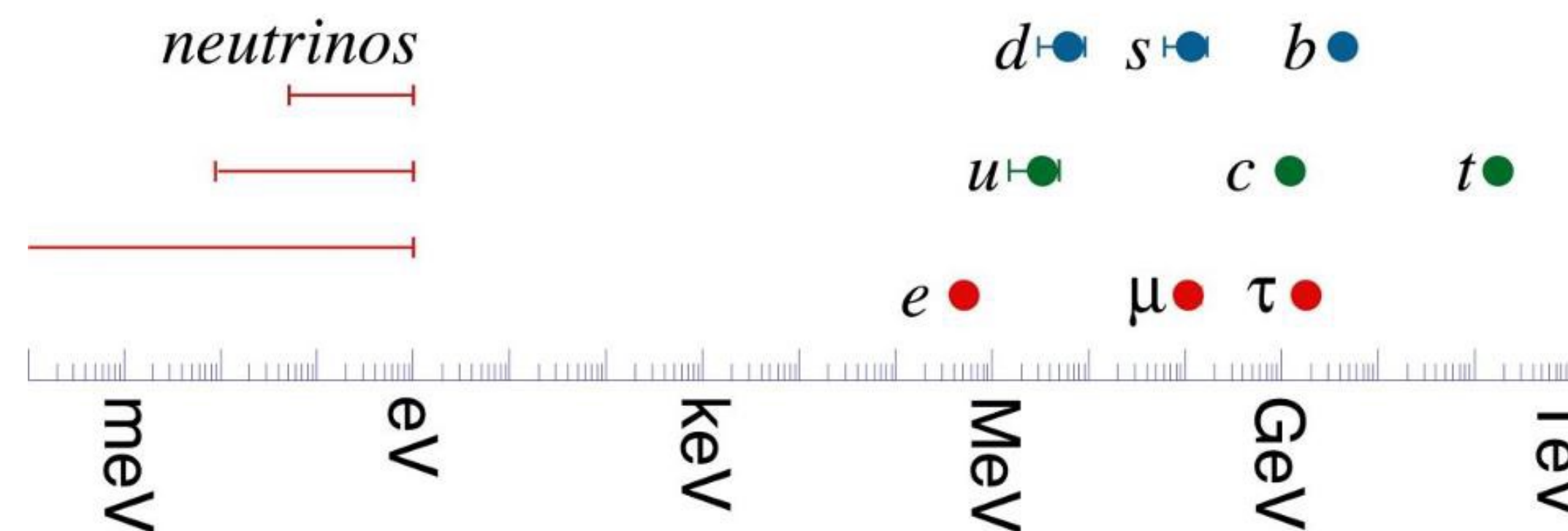
Standard Model open questions

The Standard Model (SM) describes many experimental observations with impressive accuracy, but there are still **unsolved puzzles**

Why they are so small?

Most pressing shortcomings

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



Intrinsically related with the **nature of neutrinos** (Dirac or Majorana)

The most feasible process to observe LNV and test Majorana nature of ν 's is $0\nu\beta\beta$



Backup

Baryon asymmetry: CP violation

Difficult to attribute simply to initial conditions

Sakharov showed that for dynamically generate baryon asymmetry

- ▶ Baryon number violation
- ▶ Departure from thermal equilibrium
- ▶ Charge conjugation (C) and charge **conjugation and parity violation (CPV)**

A key ingredient to produce such asymmetry is the violation of CP

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov

Submitted 23 September 1966

ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from anti-matter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of C asymmetry in the hot model of the expanding Universe (see [1]) by making use of effects of CP invariance violation (see [2]). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.



Backup

Searches of CPV at low energy scales: Electric Dipole moments

Particle at rest, spin degrees of freedom as they interact with background electric and magnetic fields

$\mathbf{d} = d\hat{\mathbf{S}}$ d electric dipole moment

$\mu = \mu\hat{\mathbf{S}}$ μ magnetic dipole moment

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

conserves
both **P** and **T**

violates both
P and **T**

	P	T
S	+	-
E	-	+
B	+	-

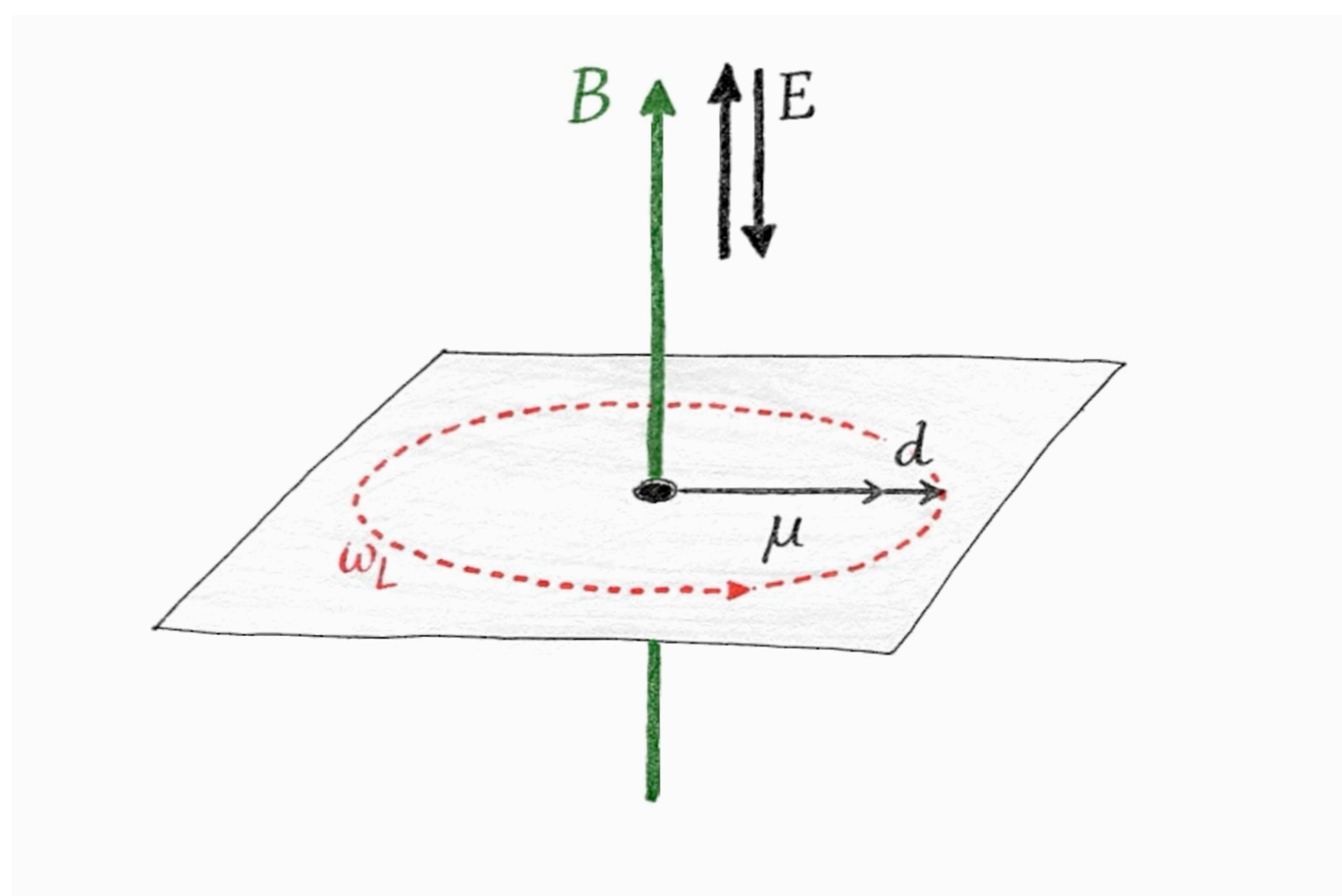
A permanent EDM can only arise from interactions that violate both P and T



Backup

General method to detect Electric Dipole moments

Basic idea to search for an EDM, spin polarised system in an magnetic (B) and electric (E) fields



$$\hbar w_{\uparrow\downarrow} = 2(\mu B \pm dE)$$

$$d = \frac{\hbar \Delta w}{4E}$$

Basis of the original method used by Smith, Purcell and Ramsey (1950) - first upper limit neutron EDM

EDM-induced **energy shifts are extraordinarily small**

Enhancing experimental sensitivity is a central challenge in EDM searches

Different physical systems exploit different enhancement mechanisms

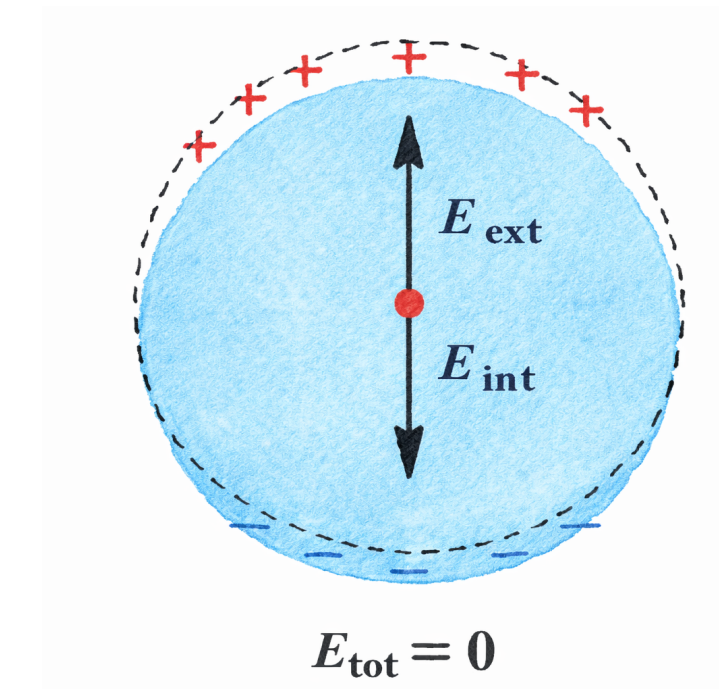


Backup

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 mitigates this cancellation
- ▶ CPV nuclear effects still induce observable atomic EDMs through higher order moments of the charge distribution, leading contribution arise from the nuclear **Schiff moment**



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

Schiff moment $S \equiv \langle gs; J, M = J | S_z | J, M = J; gs \rangle$

$$H_{Schiff} \sim S \cdot \nabla \rho_e(r)$$



Backup

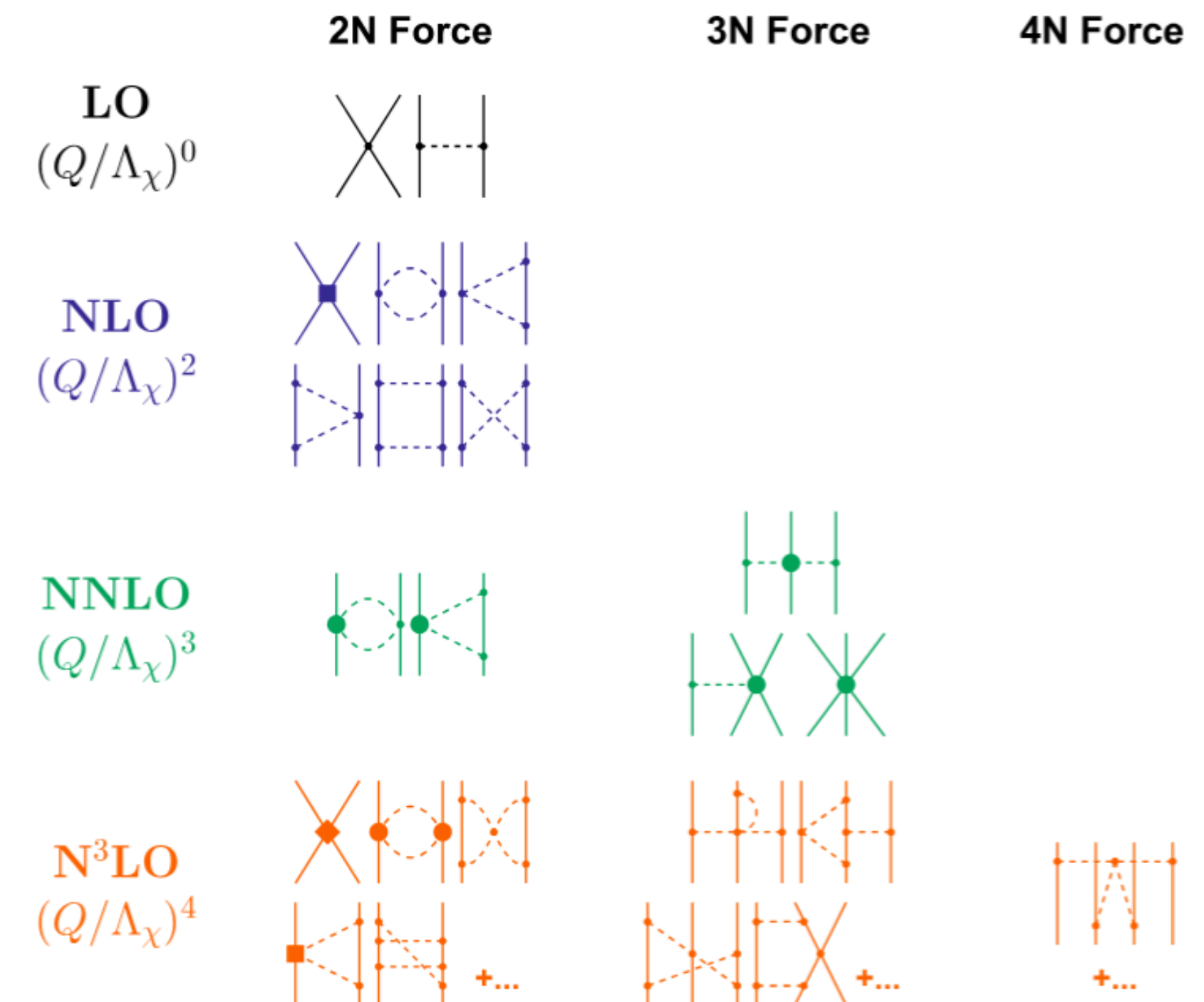
Nuclear interactions

Traditionally shell model uses empirical interactions

- ▶ parameters adjusted to reproduce low energy spectra
- ▶ highly successful
- ▶ predictive power is limited

Major advance was the development of **Chiral effective field theory**

- ▶ Rooted in low energy QCD
- ▶ Systematic low energy expansion (Q/Λ) , allows uncertainty of predictions
- ▶ Consistent approach to Hamiltonians and currents



input for modern
nuclear theory



Backup

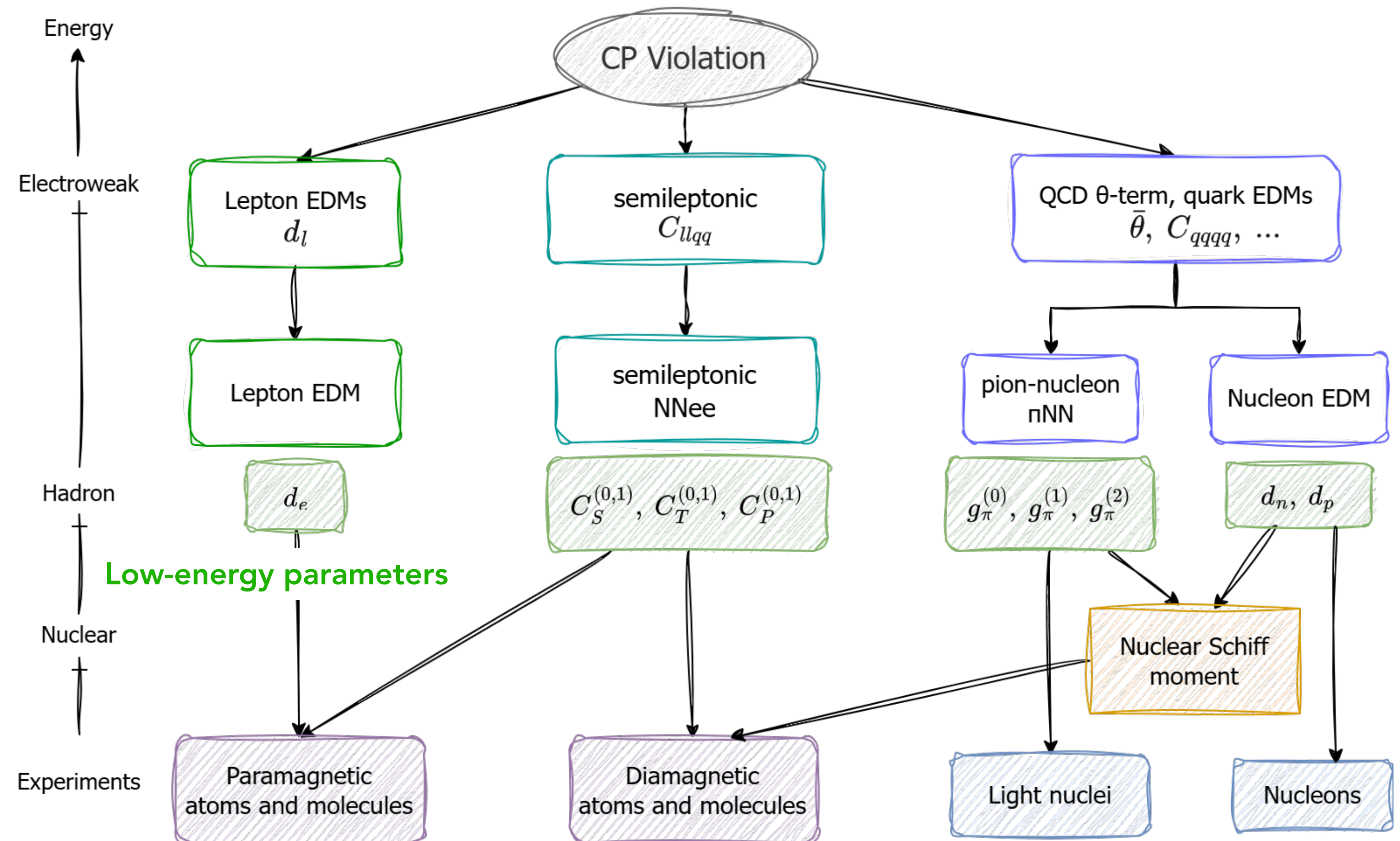
EDMs: from theory to experiment

Connecting EDM measurements to fundamental CP-violating physics requires a multi-scale framework

$$\mathcal{L}_{\text{CPV}} = \mathcal{L}_{\text{CKM}} + \mathcal{L}_{\bar{\theta}} + \mathcal{L}_{\text{BSM}}$$

$$\mathcal{L}_{\text{BSM}} \longrightarrow \mathcal{L}_{\text{CPV}}^{\text{eff}} \sim \sum_i \frac{C_i}{\Lambda^2} O_i$$

Challenge: EDMs are measured far below the electroweak scale, where degrees of freedom are leptons, non-relativistic nucleons, and pions



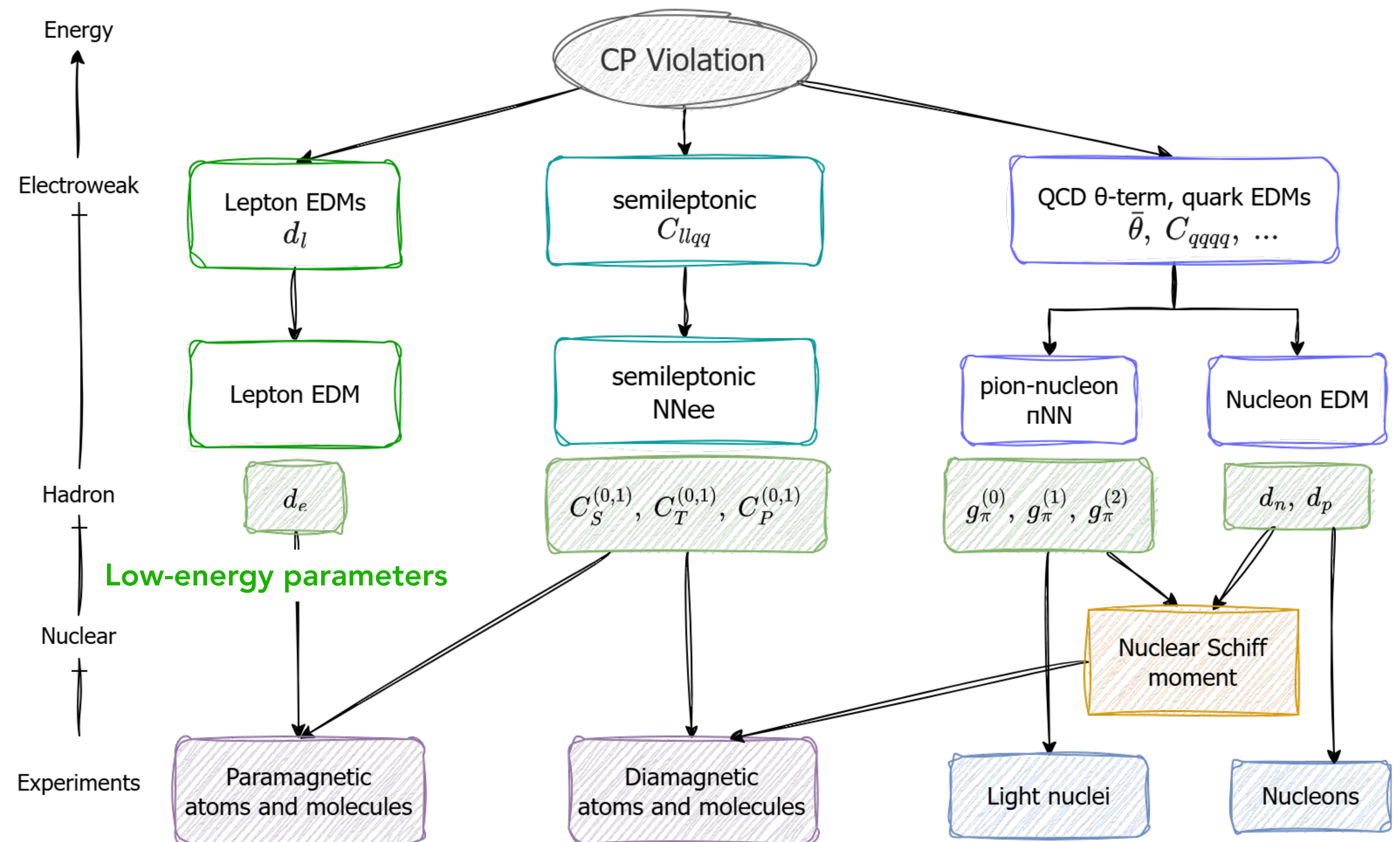


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EDMs: from theory to experiment

Connecting EDM measurements to fundamental CP-violating physics requires a multi-scale framework

- **Open-shell** ("paramagnetic") atoms and molecules (ThO, YbF, HfF⁺, Cs, Tl)
 d_e , semileptonic CPV
- **Closed-shell** ("diamagnetic") atoms and molecules (Hg, Xe, Ra, TlF) eEDM suppressed
Hadronic CPV
- Nucleons, and light nuclei





Backup

EDMs: from theory to experiment

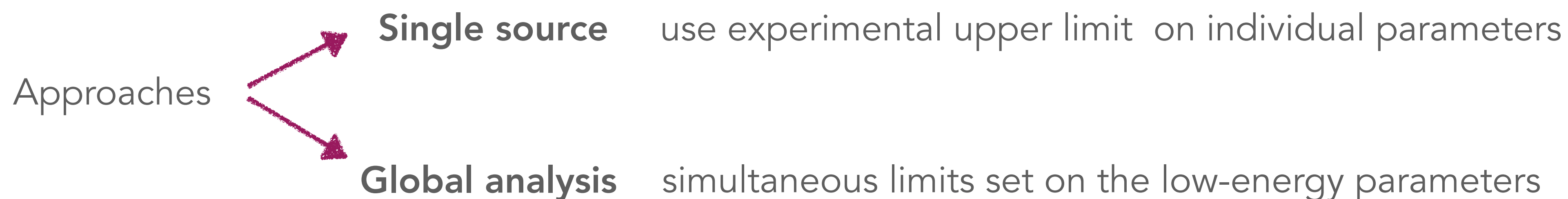
In terms of this low-energy parameters

$$d_i = \sum_j \alpha_{ij} C_j \quad \alpha_{ij} = \partial_{d_i} C_j$$

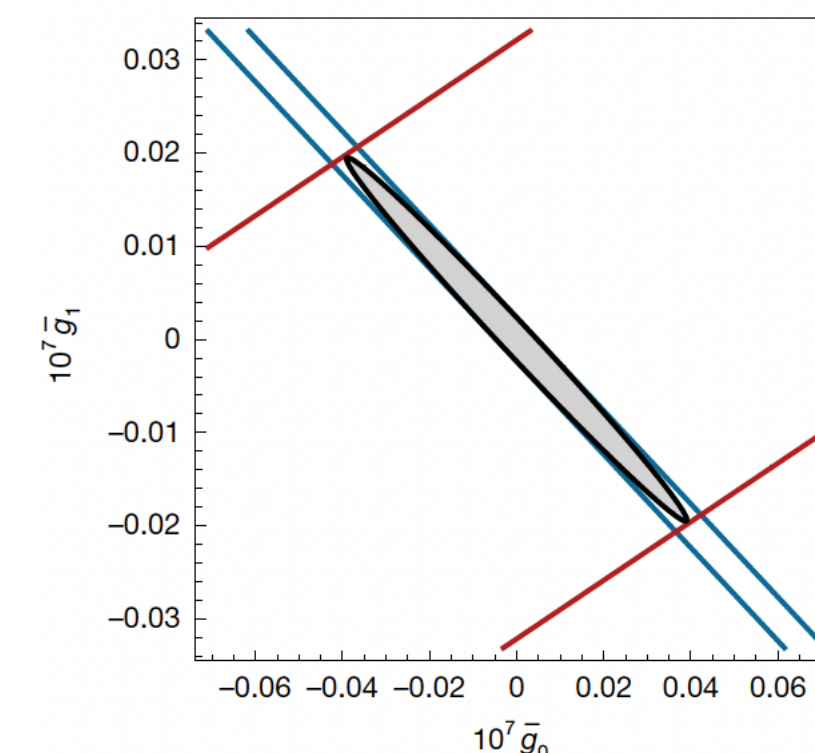
sensitivity of the EDM of the system-i to the CPV source C_j

Diamagnetic atom

$$d_A(\text{dia}) = \kappa_S S(g_\pi^{(i)}, d_N) + \kappa_{C_T} C_T + \dots$$



William B. Cairncross and Jun Ye, Nat. Rev. Phys., 1(8):510-521, 2019





Backup

EDMs: from theory to experiment

From the theory perspective

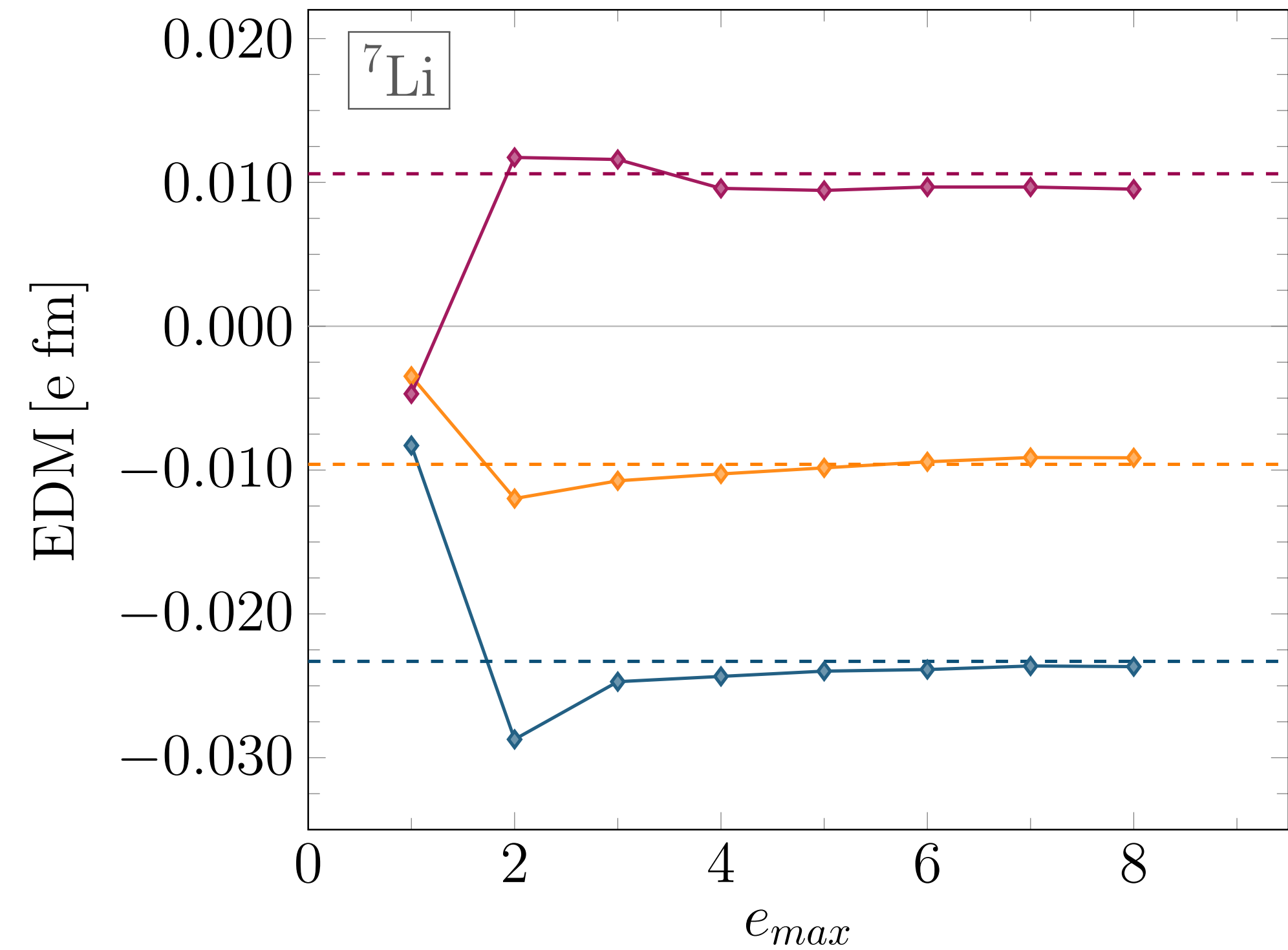
- ▶ Importance of **accurately** compute this factors
- ▶ **Plan experimental targets** based on **enhanced sensitivities**
- ▶ Atomic and molecular calculations are under control
- ▶ In diamagnetic systems this requires **accurate nuclear calculations** of the Schiff moment



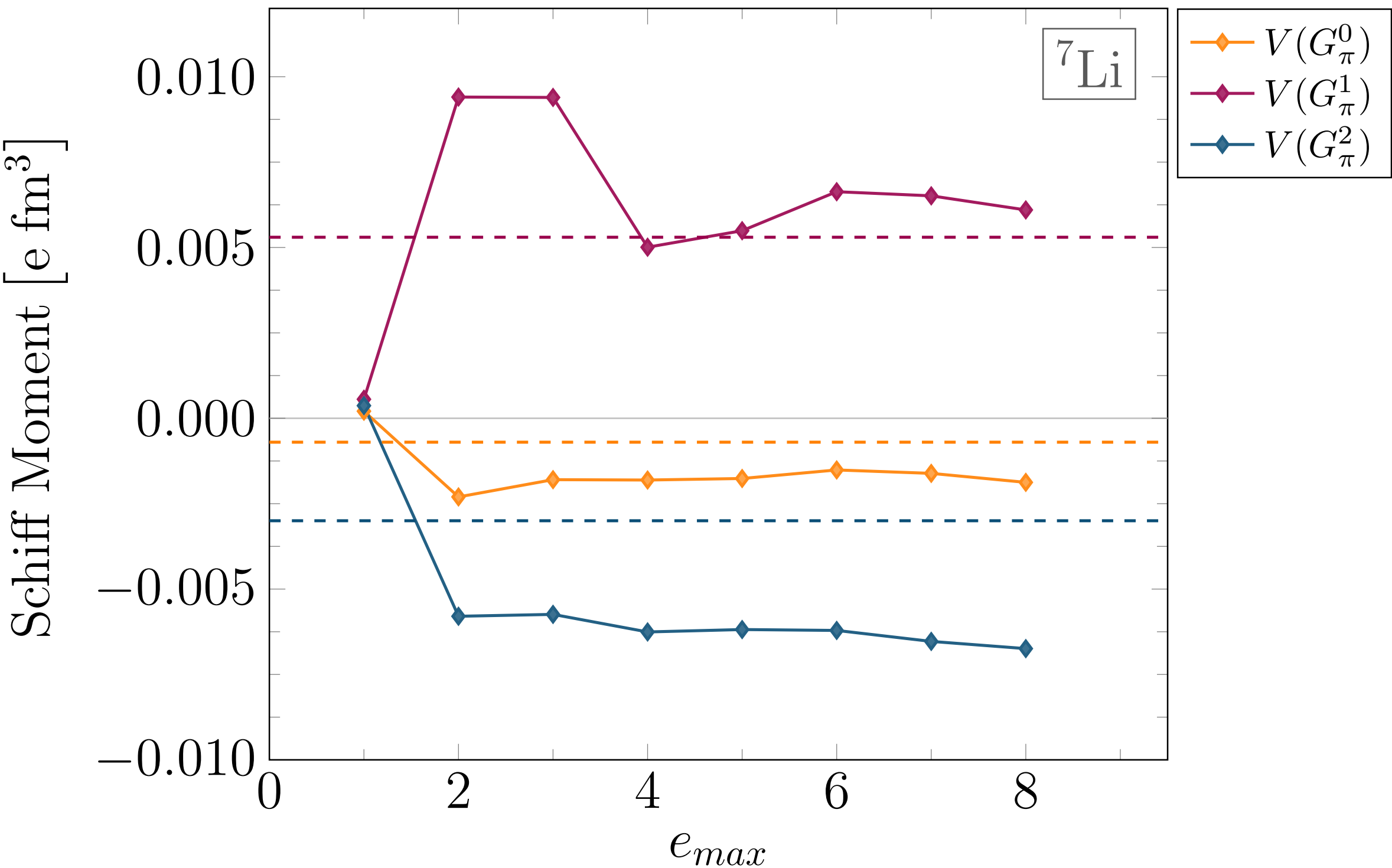
Backup

Benchmark PV-IMSRG(2)

Paul Froese and Petr Navrátil, Phys. Rev. C 104, 033502 (2021)



Petr Navrátil (in coll. with Stephan Foster) private communication





Backup

Double gamma spectroscopy in ^{48}Ti

First steps done!

- ▶ A **method to isolate** and measure 2γ -decay BR

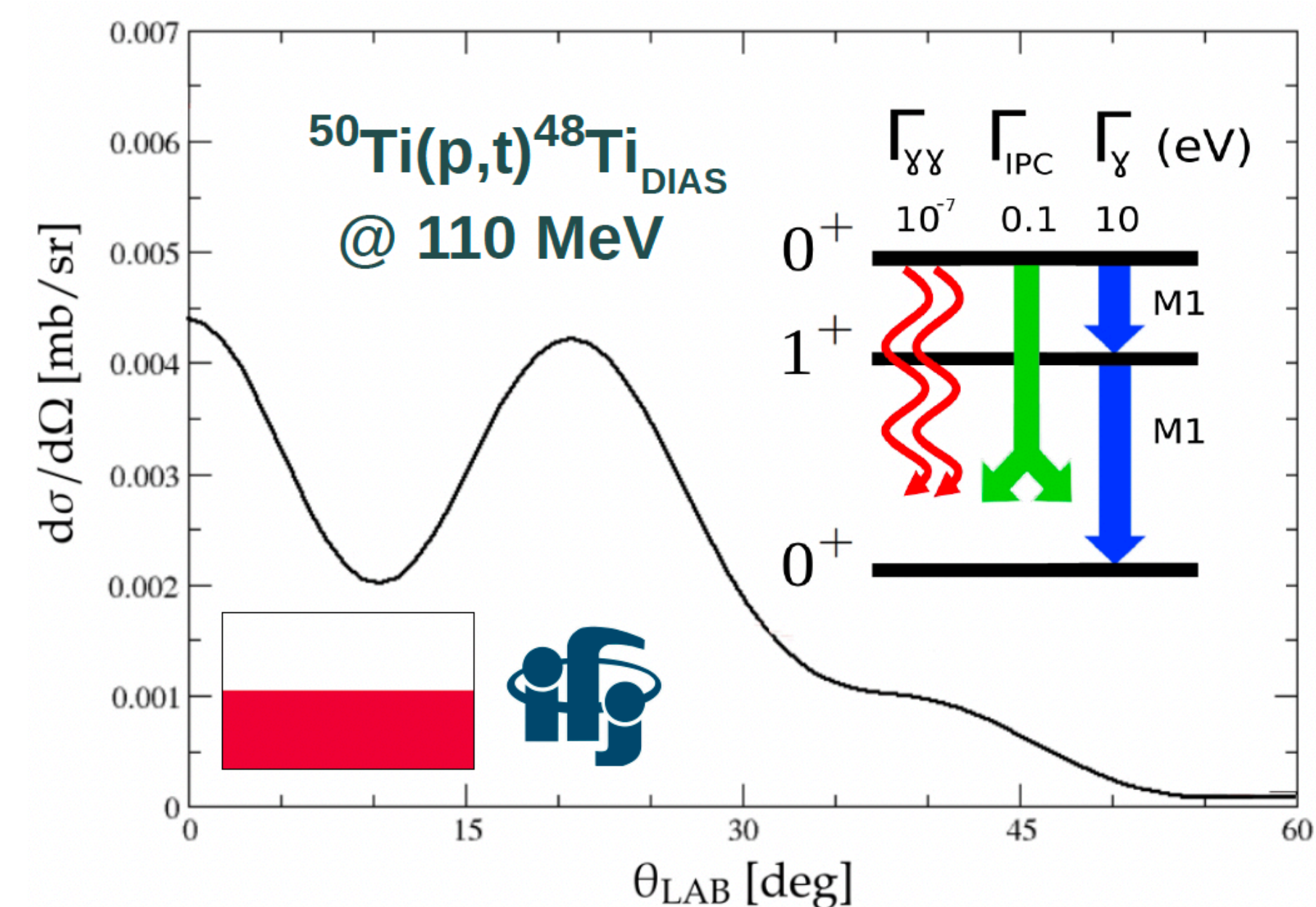
But there is still work to be done before real 2γ (M1M1)-decay measurement

- ▶ Perform the **preparatory experiment** to characterize ^{48}Ti (DIAS)
- ▶ Main goals: determine **cross section** to populate DIAS and measure **dominant** competing process: **γ -decay BR**
- ▶ Proposed at **Cyclotron Centre Bronowice** (CCB), part of the Institute of Nuclear Physics of the Polish Academy of Sciences (**IFJ PAN**) in Kraków

Gamma decay study of the Double Isobaric Analog State in ^{48}Ti .

Spokepersons: D. Stramaccioni, M. Balogh, J.J. Valiente-Dobón

G. Andreetta, F. Angelini, M. Balogh, D. Brugnara, G. de Angelis, A. Goasduff, B. Gongora, A. Gottardo, R. Nicolás del Álamo, S. Pigliapoco, E. Pilotto, D. Stramaccioni, J.J. Valiente-Dobón, L. Zago
INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy.



Courtesy of D. Stramaccioni