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Precise neutron densities of nuclei and what this means for neutron skins

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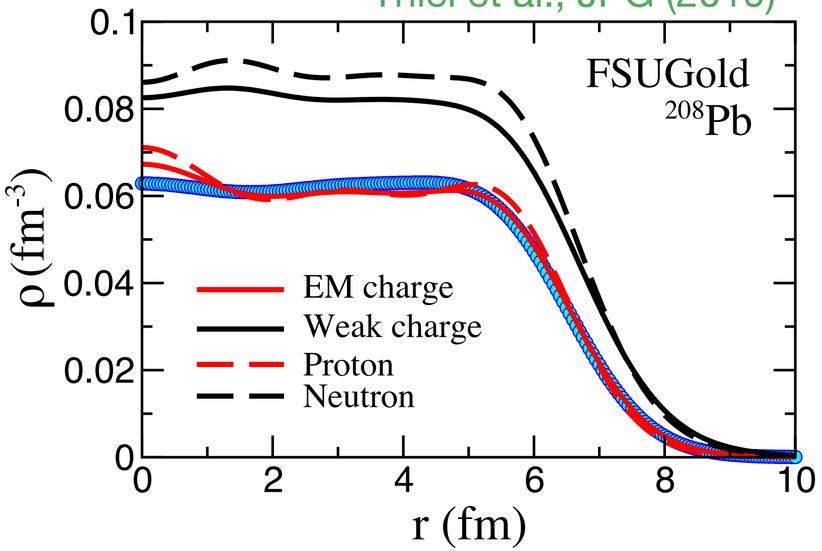
Neutron skins and densities

Thiel et al., JPG (2019)

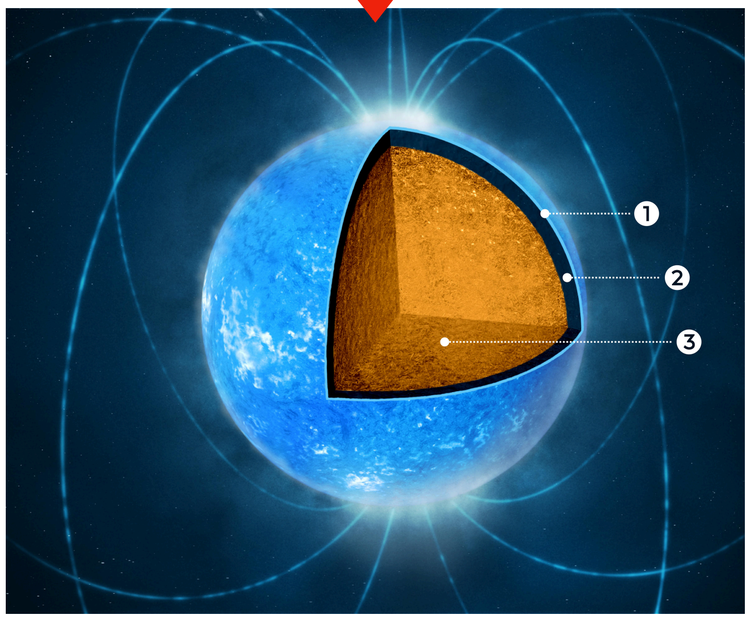


Neutron skins

- Connection to nuclear matter properties
- **Many proposed experimental probes**
  - Parity-violating electron scattering
  - High-precision electron scattering
  - Proton/pion scattering, etc.

Neutron densities

- Critical component in some new physics searches
- Difficult to measure, **theory predictions required**

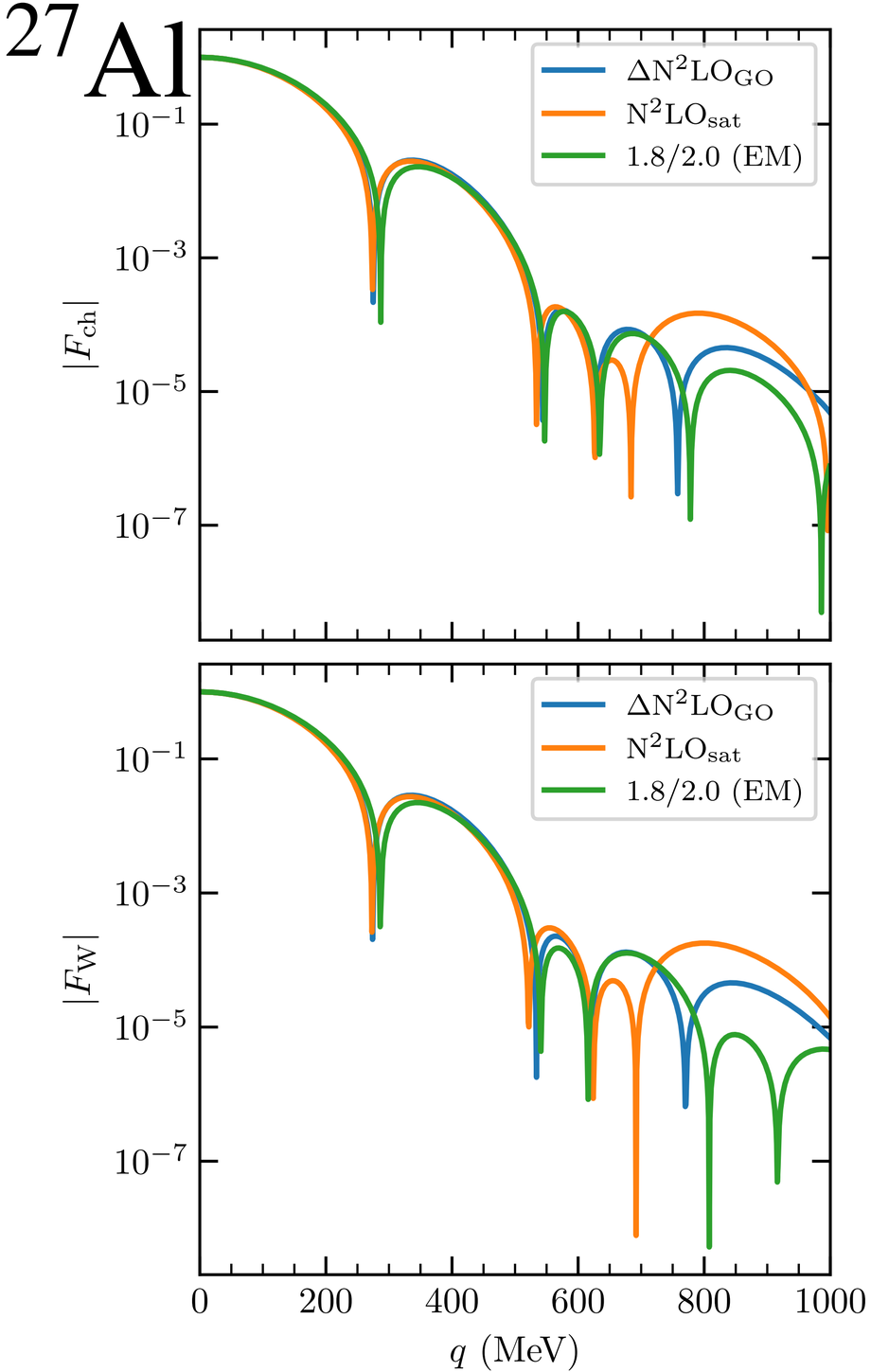


Watts et al., RMP (2016)

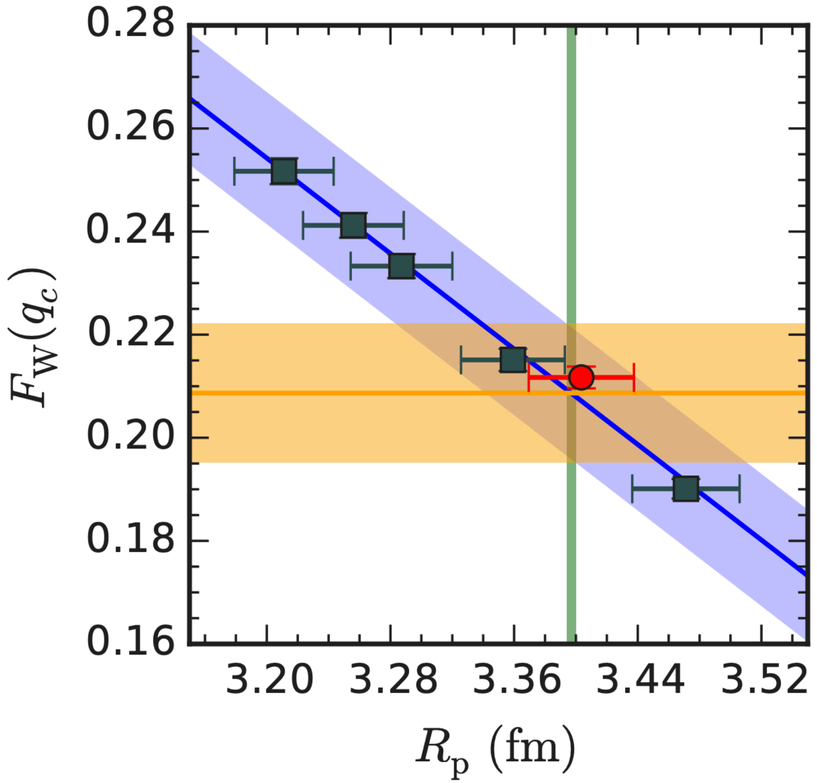
See, e.g., Fitzpatrick et al., JCAP (2013)

Nuclear responses

- Nuclear response to external probe with momentum transfer q
- Expansion in **general operator basis**
  - **Spin-independent (coherent) responses**
  - **Semi-coherent responses**
  - Spin-dependent (incoherent) responses
- Powerful formalism to describe
  - **Electroweak interactions**
  - **BSM physics** in connection with SMEFT



A few things to keep in mind



Hagen et al., Nat. Phys. (2016)

Nuclear Hamiltonians

- Are uncertain
- Variation in regulator, LECs, chiral order probes this uncertainty

Scalable many-body methods

- Approximate, systematically improvable
- Model-space and many-body uncertainties **MH** et al., PRC (2021, 2025)

Absolute uncertainties may be large, but correlated

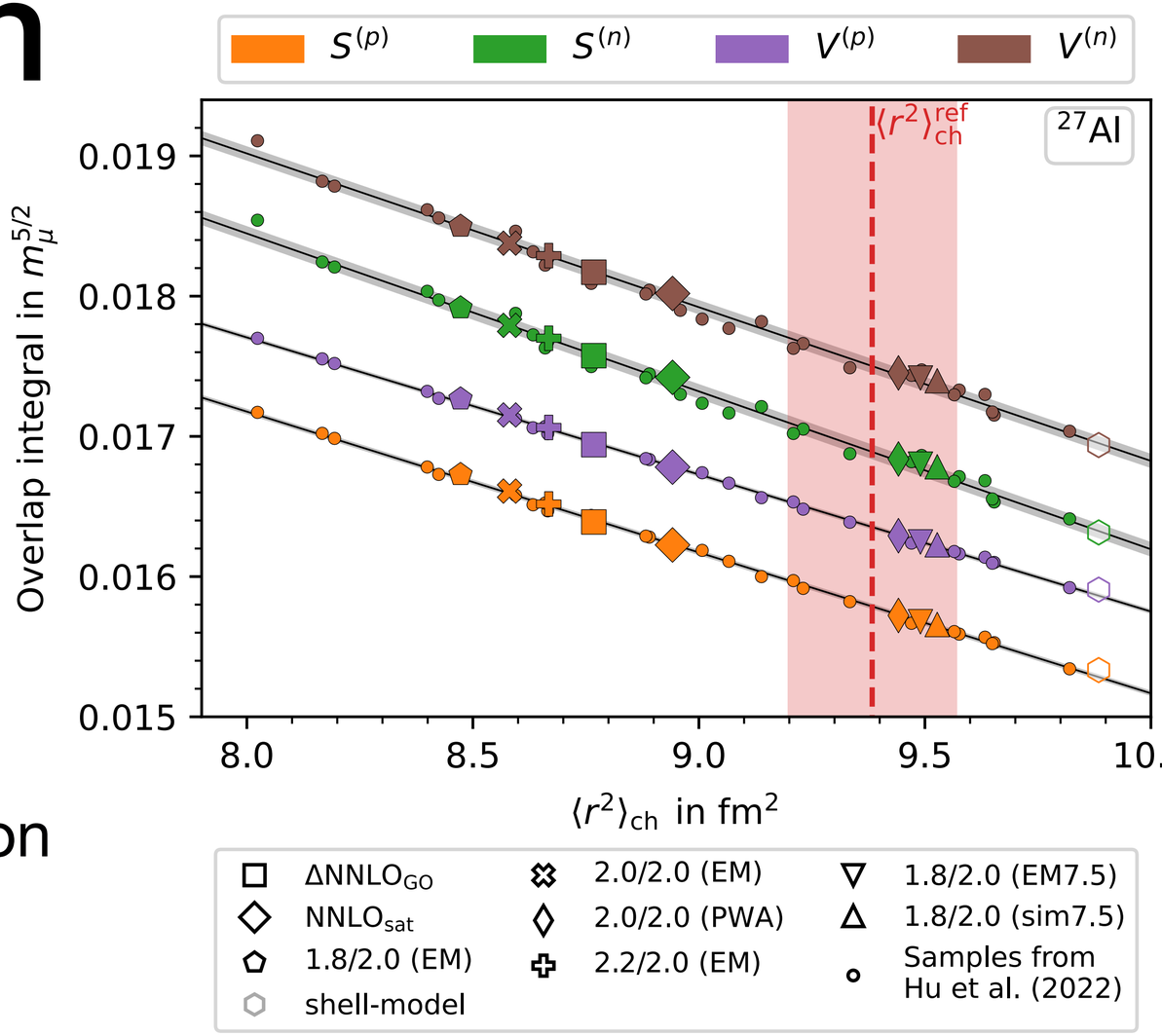
→ **constrain correlations with exp. data**

$\mu \rightarrow e$ conversion

- Proposed BSM lepton flavor violating process, also in muonic atoms
- Nuclear structure contribution in overlap integrals

$$S^{(n)} \sim \int dr\, r^2\, \rho_n(r)\, s(r)$$

- Sensitivity to neutron density
- Correlation with charge radius, prediction for neutron overlap integrals
- **Systematic study of all uncertainties**
- **Center-of-mass factorization demonstrated**
  Hagen, Papenbrock, Dean, PRL (2009)

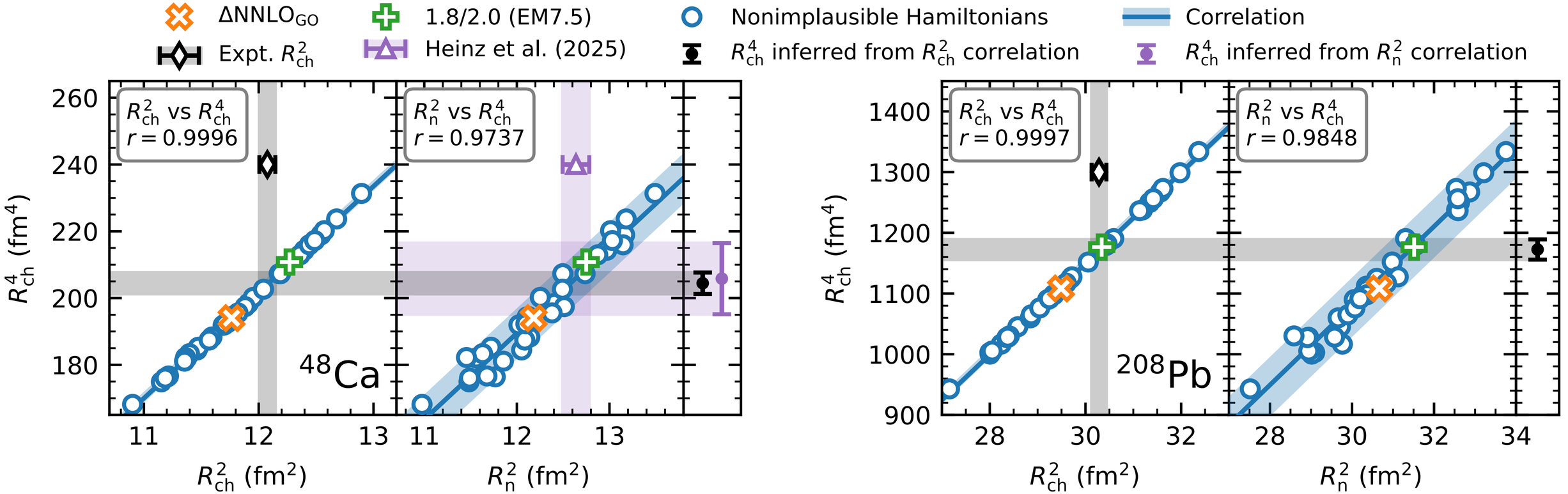


MH et al., PLB (2025)

Miyagi, **MH**, Schwenk, PLB (2026)

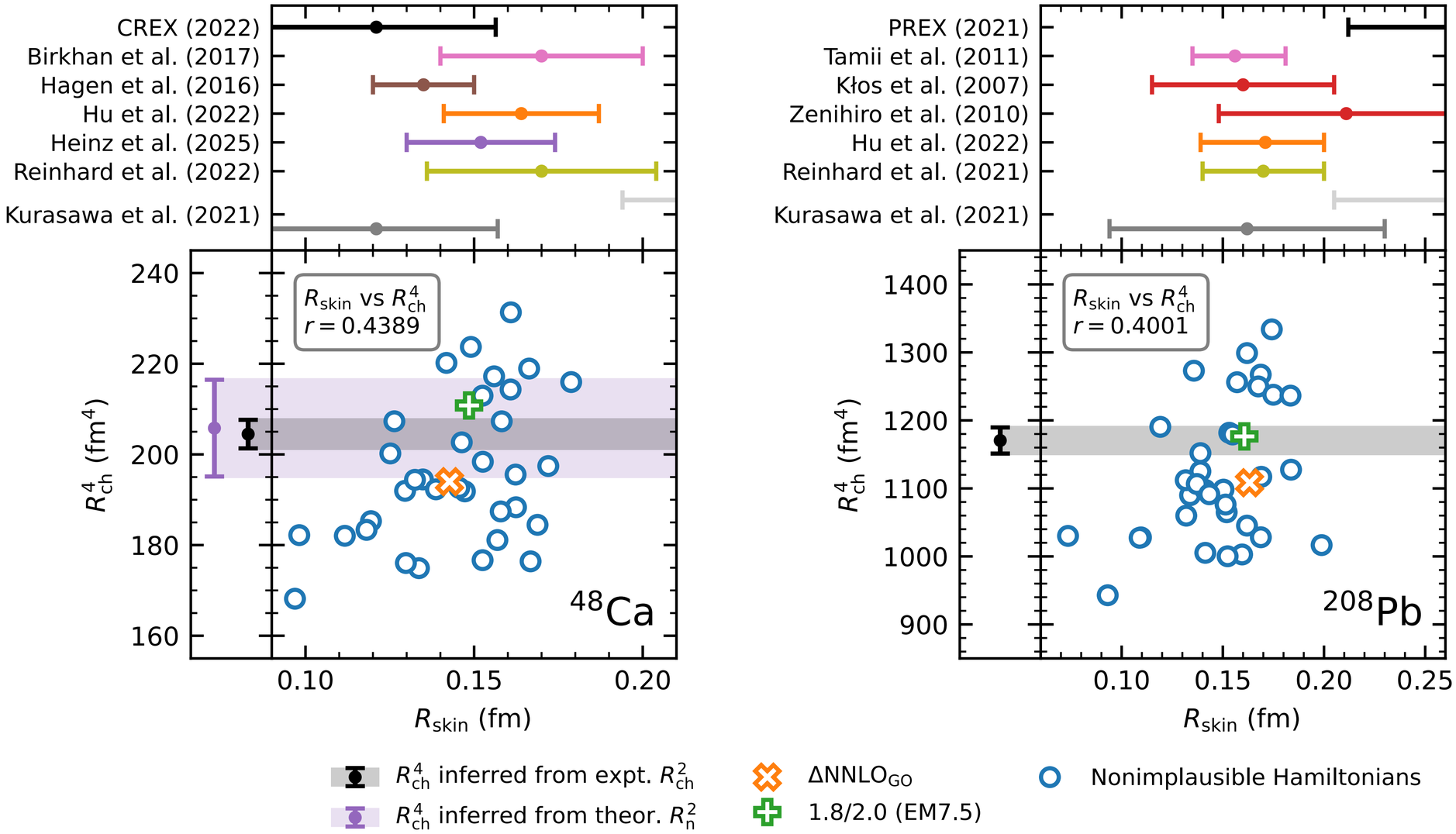
$R^4_{\rm ch}$ to probe nuclear structure

- $R^4_{\rm ch}$ can be measured directly in high-precision electron scattering
- Proposed to be sensitive to neutron radius, skin Kurasawa et al., PTEP (2021)



Miyagi, **MH**, Schwenk, PLB (2026)

Weak connection with $R_{\rm skin}$



Weak correlation **prevents model-independent inference** of $R_{\rm skin}$ from $R^4_{\rm ch}$

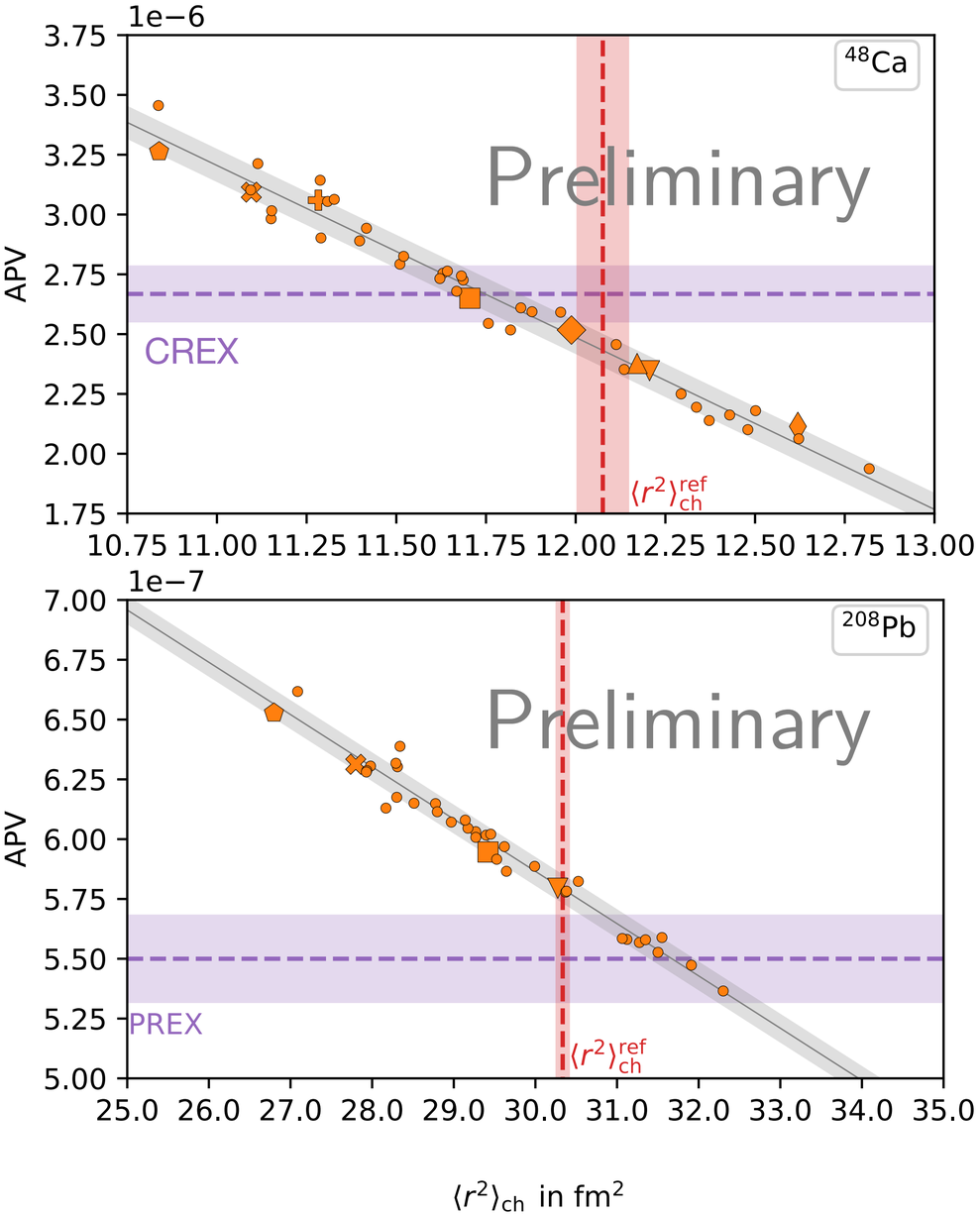
Noël, **MH**, et al., in prep.

Ab initio parity-violating electron scattering

- Computations based on DFT, RMF are routine
- R_{skin} inference from R^4_{ch} **from mean-field theory is model-dependent**
- **But now we can compute this using ab initio methods!**
- Ingredients:
  - Charge and weak densities
  - $d\sigma/d\Omega$ with Coulomb corrections https://pypi.org/project/phasr/ (Frederic Noël)
- Full prediction: $A_{\mathrm{PV}} \sim \frac{d\sigma}{d\Omega}\left(V_{\mathrm{ch}} + V_{\mathrm{W}}\right) - \frac{d\sigma}{d\Omega}\left(V_{\mathrm{ch}} - V_{\mathrm{W}}\right)$

Noël, **MH**, et al., in prep.

Weak tension with CREX & PREX

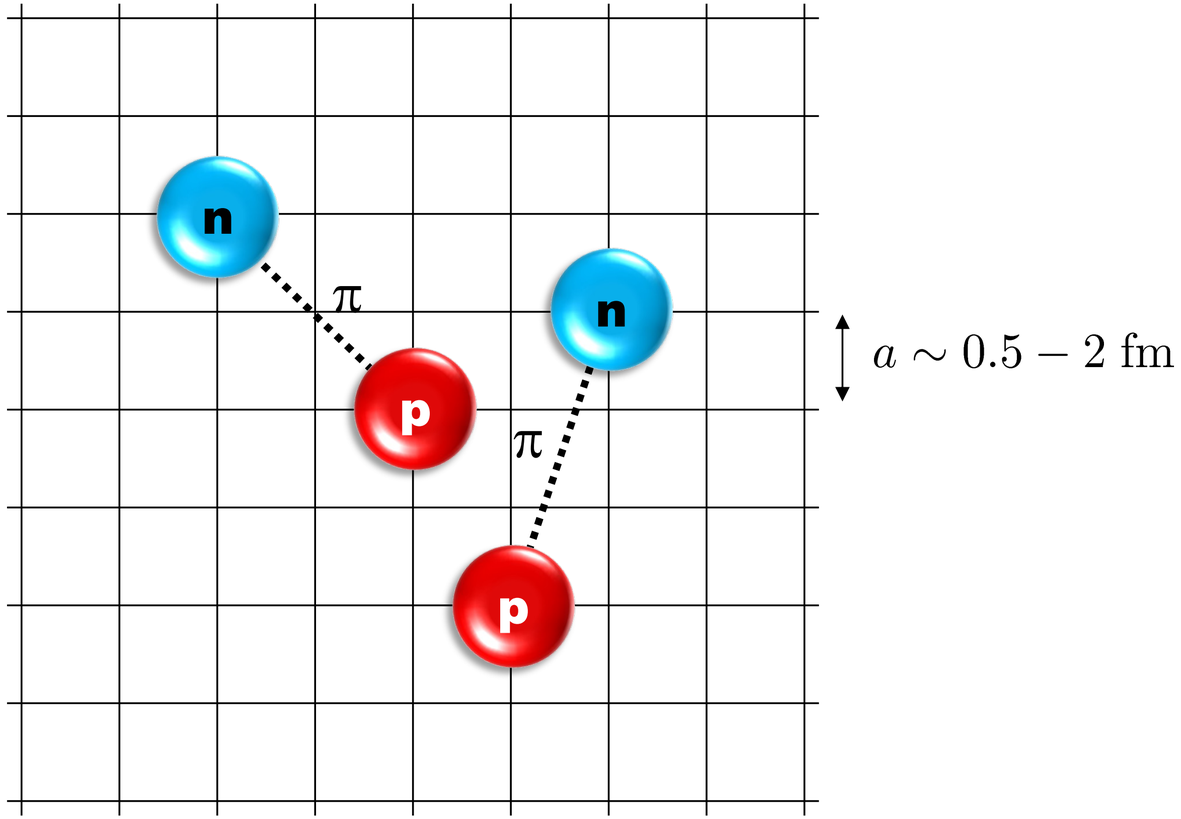


- **Sample by sample calculation of A_{PV}**
- Weak tension found with both expts.
- Open questions:
  - Dispersive corrections?
  - Impact of 2BCs?
  - Expt. charge radius of ^{208}Pb?
    Sun, Beyer, Mandrykina, Valuev, Keitel, Oreshkina, PRL (2025)
  - Model dependences in analyses of PREX and CREX?

Now for something completely different

Nuclei on a lattice

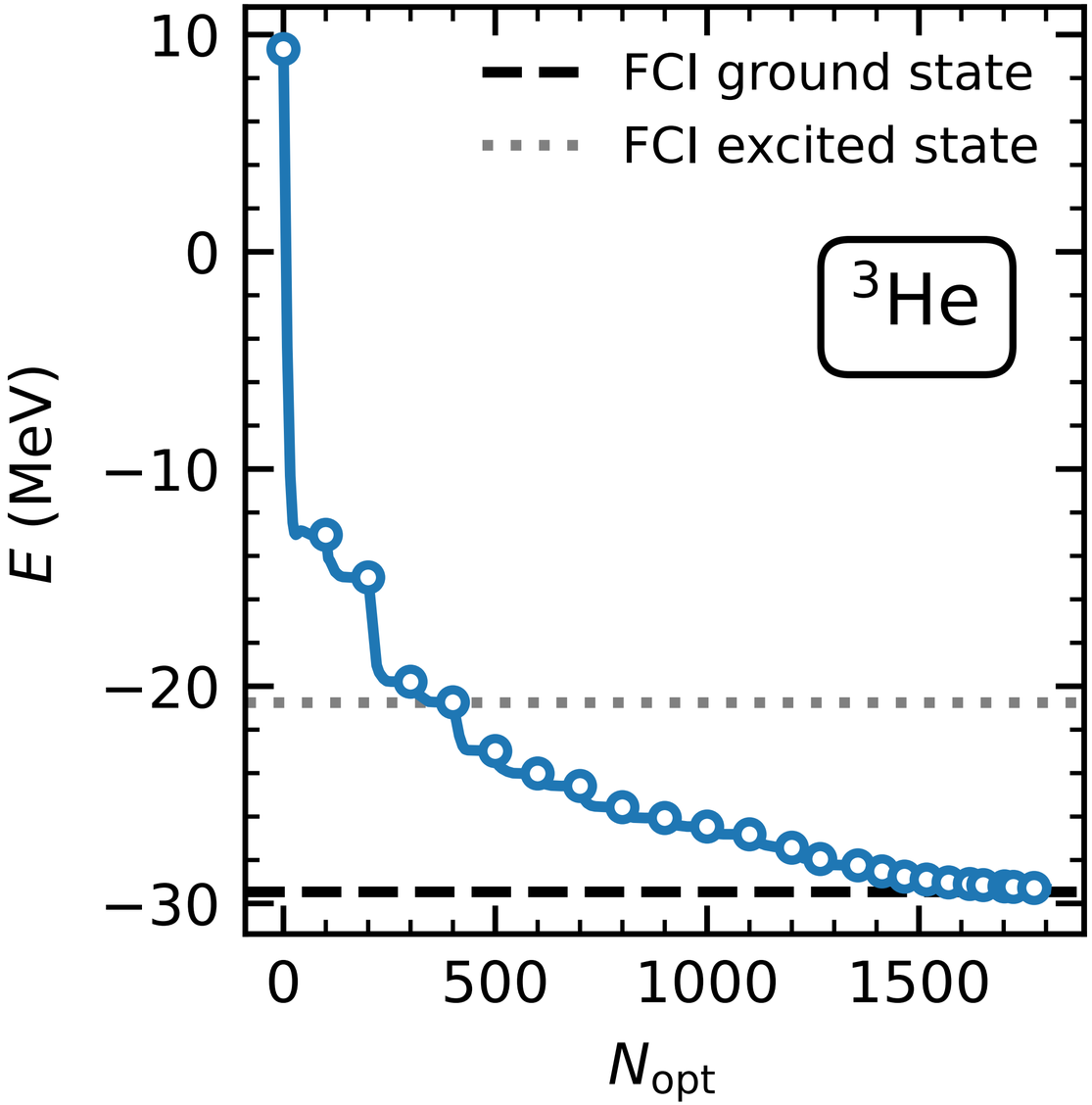
- Nuclear forces are finite-ranged
- We do not see this in a harmonic oscillator basis, but ...
- On a coordinate-space lattice, Hamiltonians are very sparse
- Interactions only in finite range r_{int}
- Volume of interactions small compared to total volume
- **This can drastically simplify computations!**



Lee, PPNP (2009)

Original motivation: Quantum computing

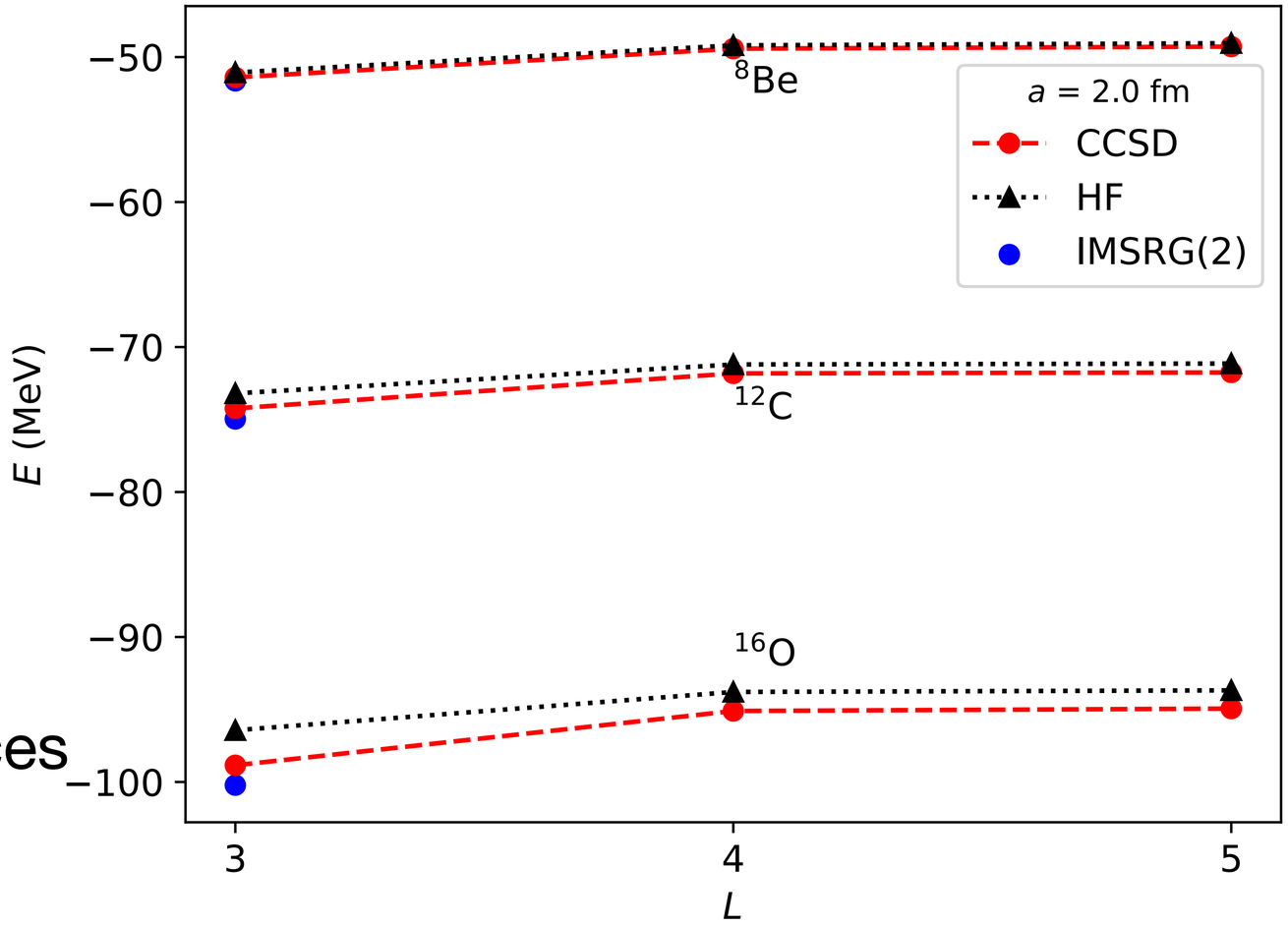
- Sparse Hamiltonian reduces number of 2-qubit gates
- Pionless EFT Hamiltonian (NN+3N)
- Simulations of 2- and 3-body systems
- Exact benchmarks met
- Scalability explored
- Next: Computations on quantum computers



Rothman et al., PRC (2025)
Rothman et al., EPJA (2026)

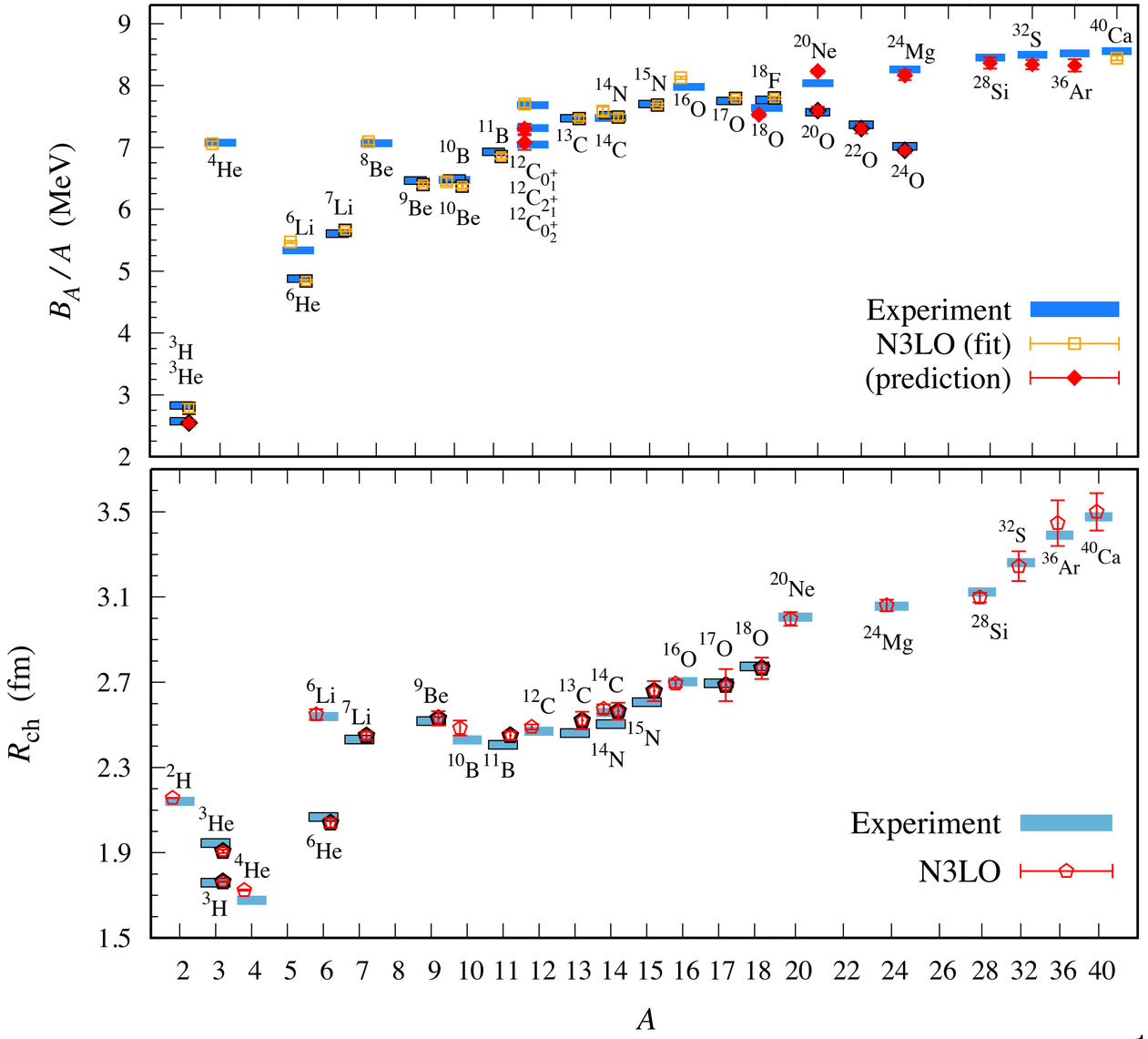
NuLattice

- Computations of nuclei on coordinate-space lattice
- https://github.com/NuLattice
- FCI, HF, IMSRG, CC implemented
- Educational tool
- Benchmark for methods
- New insights:
  - NO2B approximation for 3N forces
  - Hartree-Fock is pretty good for short-ranged forces



Many opportunities for progress

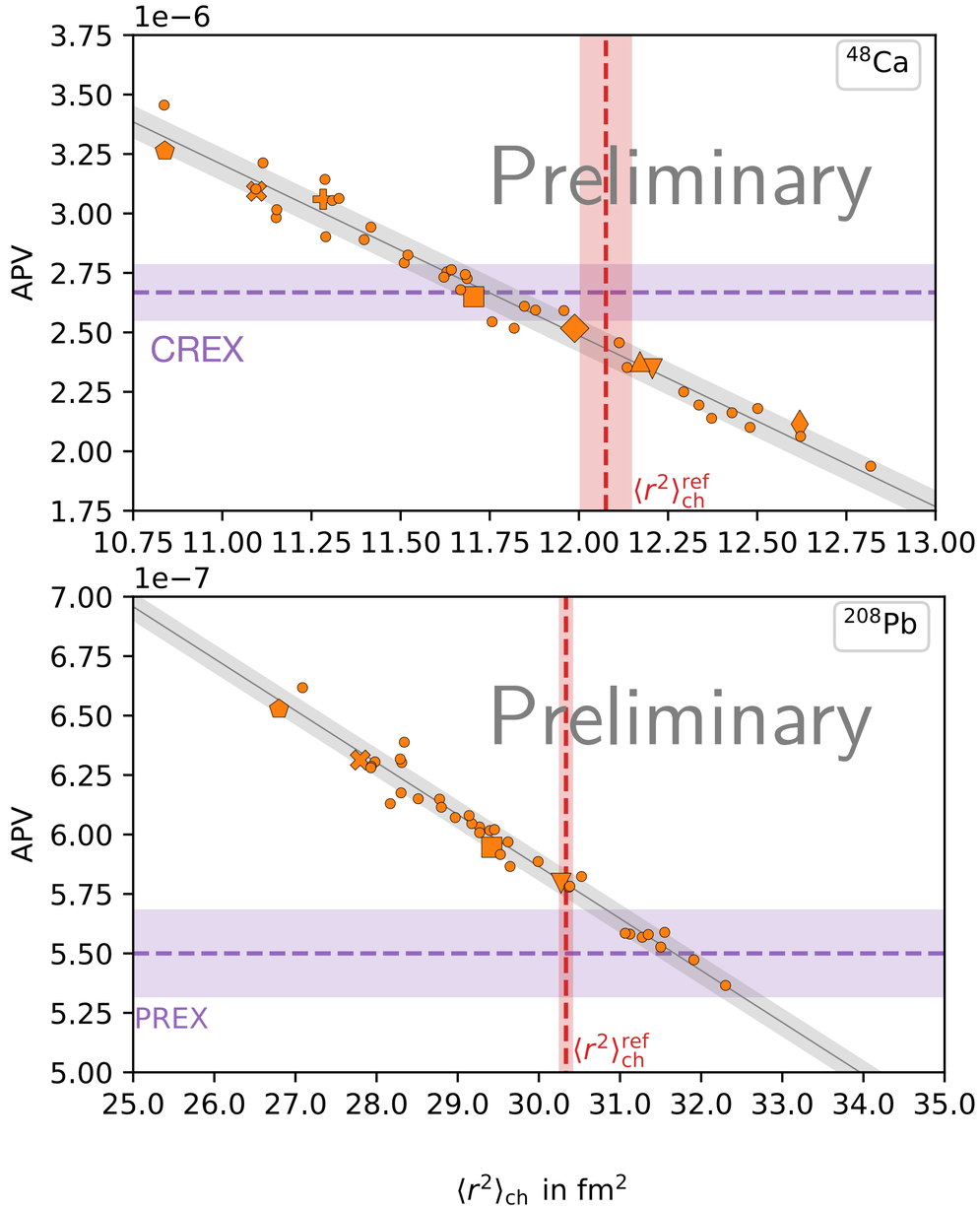
- Improved Hamiltonians on the way (thank you, Dean, Serdar!)
- Computations of exotic states
- Dynamics of nuclei
- **Other opportunities? Please contribute!**



Elhatisari et al., Nature (2024)

Conclusion

- Systematic improvement in understanding of nuclear densities
  - Implications for BSM physics
  - Ab initio analysis of neutron skin
- New lattice computations of nuclei
  - Amenable to quantum computing
  - New nuclear structure and dynamics insights



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