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Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

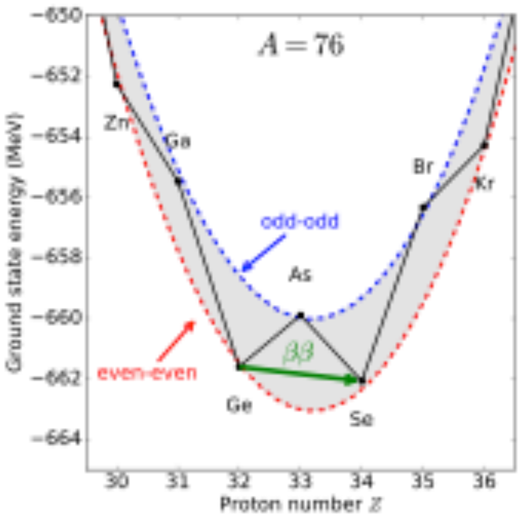
Ab initio calculations of double-beta decay and WIMP-nucleus scattering

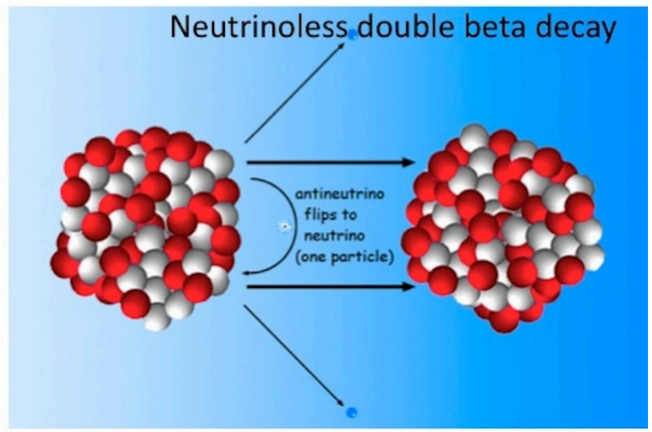
Jason D. Holt

INT, 6 March 2018

The Next Big Discovery: $0\nu\beta\beta$-decay?

Neutrino own antiparticle $\Longleftrightarrow$ $0\nu\beta\beta$ decay



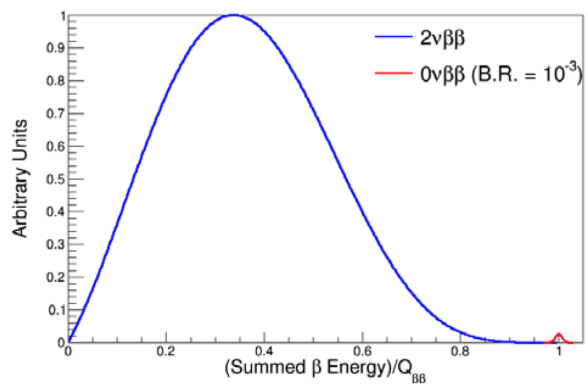


Tremendous impact on BSM physics:

Lepton-number violating process

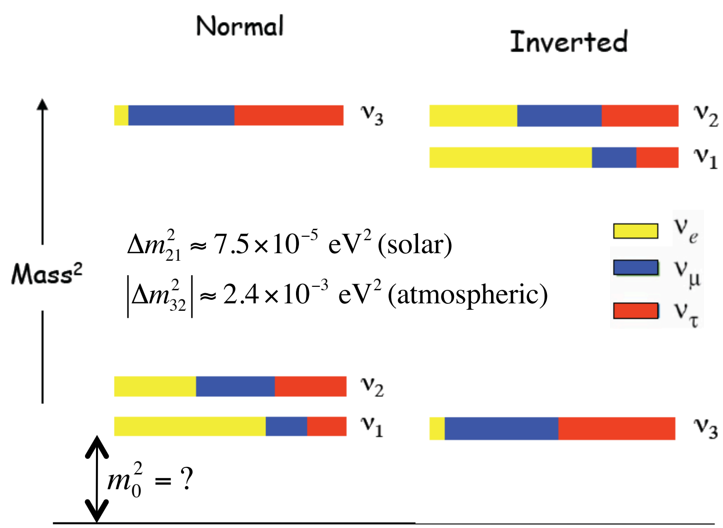
Majorana character of neutrino

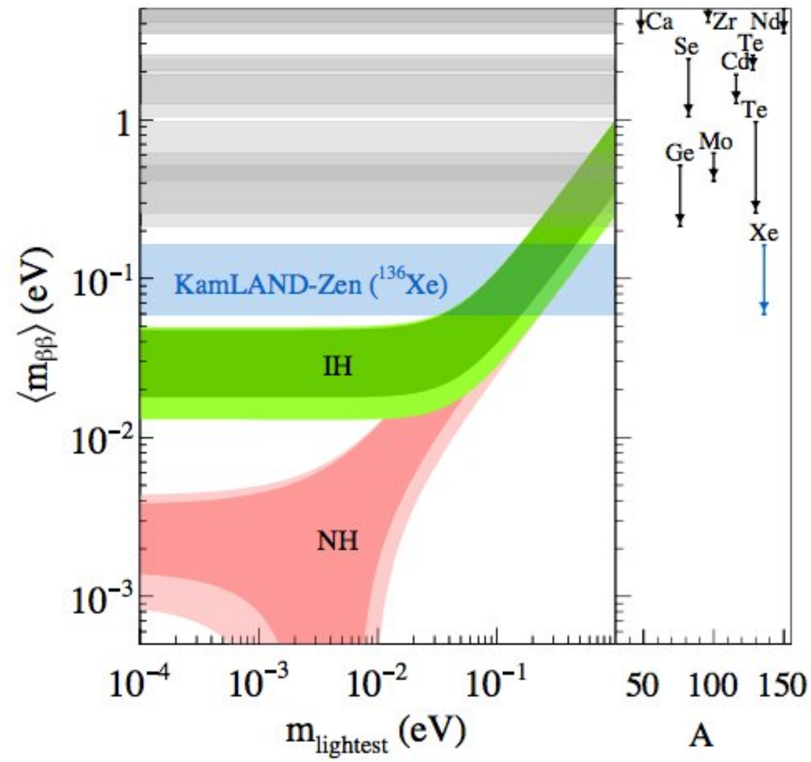
Absolute neutrino mass scale



The Next Big Discovery: 0νββ-decay?

Progress in large-scale searches pushing towards **IH**





$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2 \quad \langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei} m_i\right|$$

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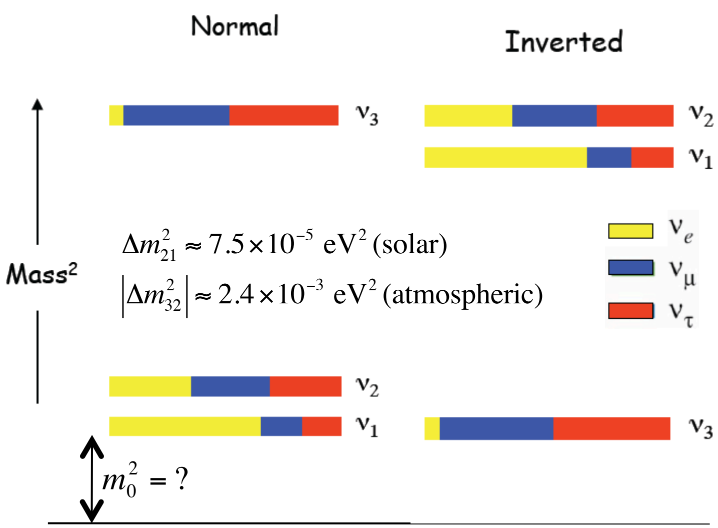

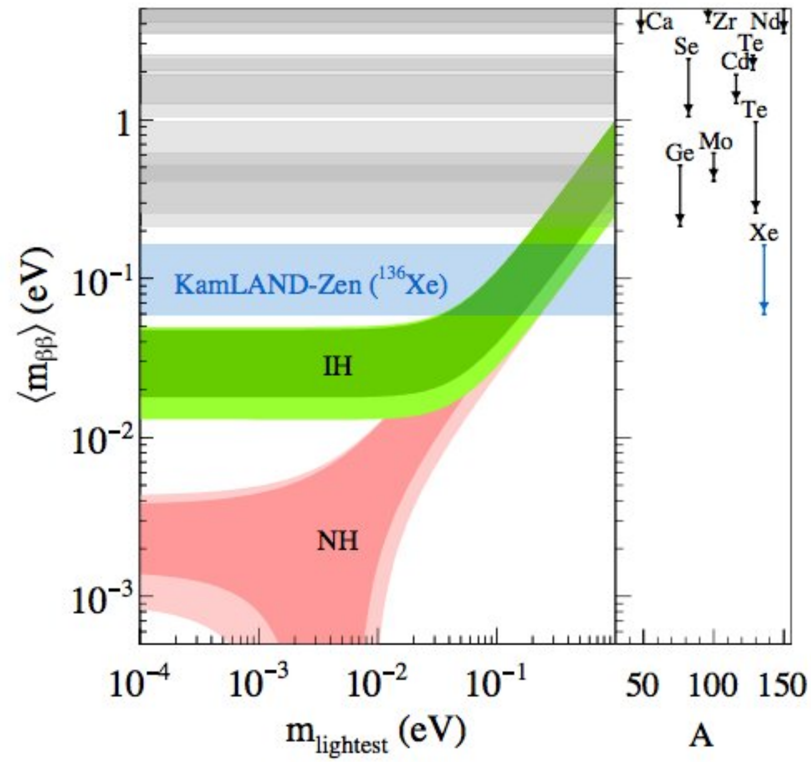

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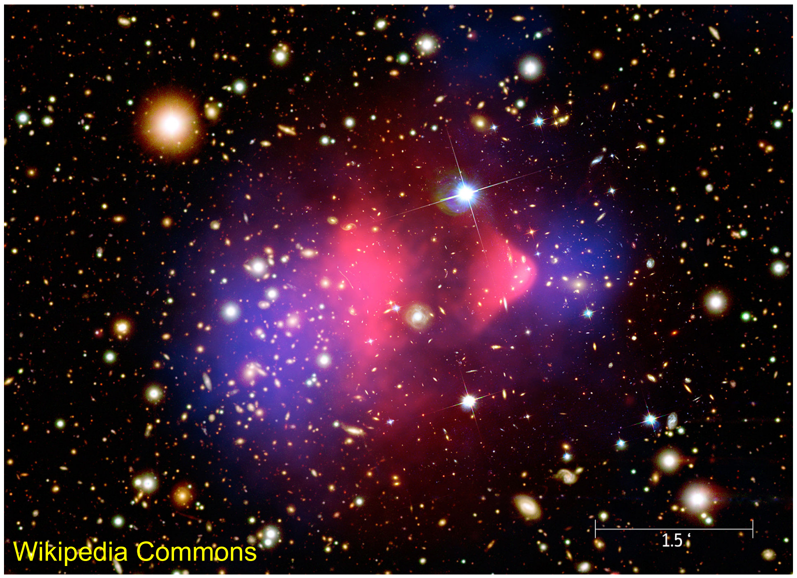
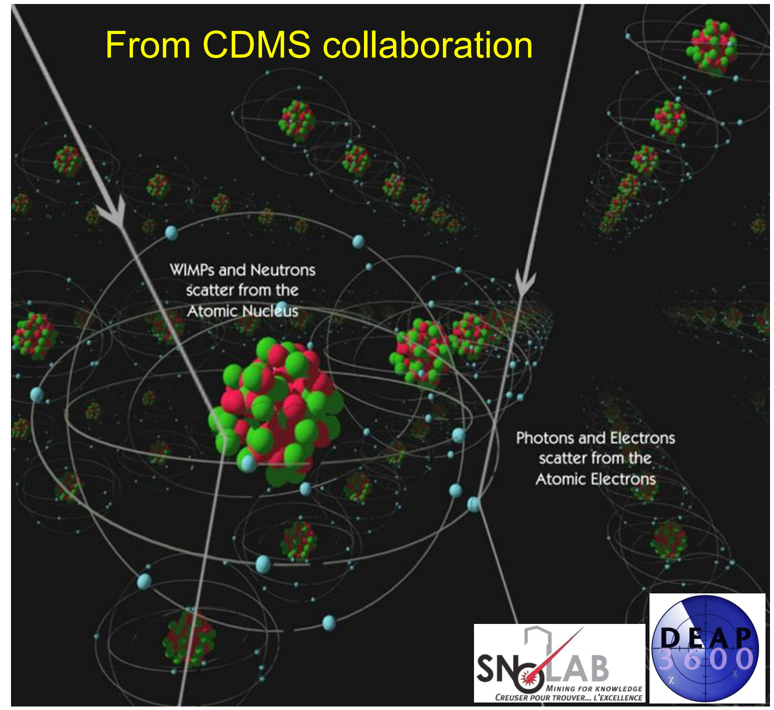
Uncertainty from **Nuclear Matrix Element**; bands do not represent rigorous uncertainties

Next Big Discovery: Nature of Dark Matter?

Many direct-detection searches underway worldwide





Observation of nuclear recoil

Direct detection: $X\,\mathrm{SM} \to X\,\mathrm{SM}$

Leading candidates: neutralinos

Couples primarily to scalar and axial-vector currents in atomic nuclei

Next Big Discovery: Nature of Dark Matter?

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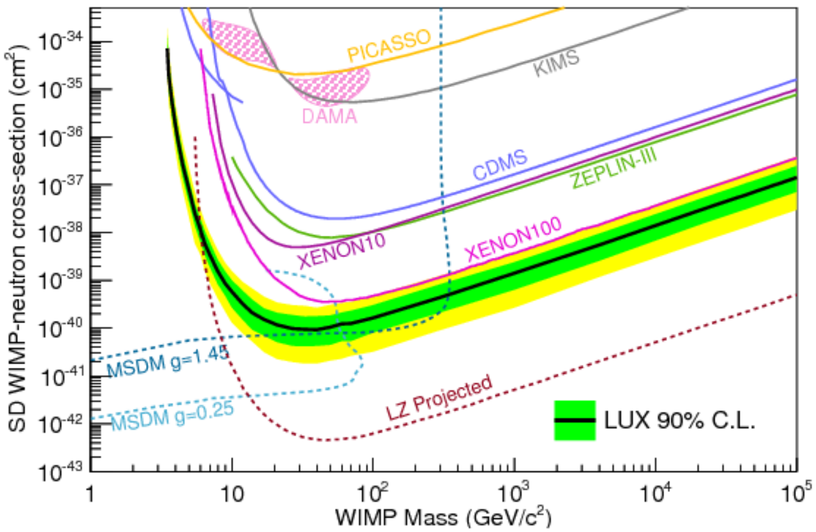
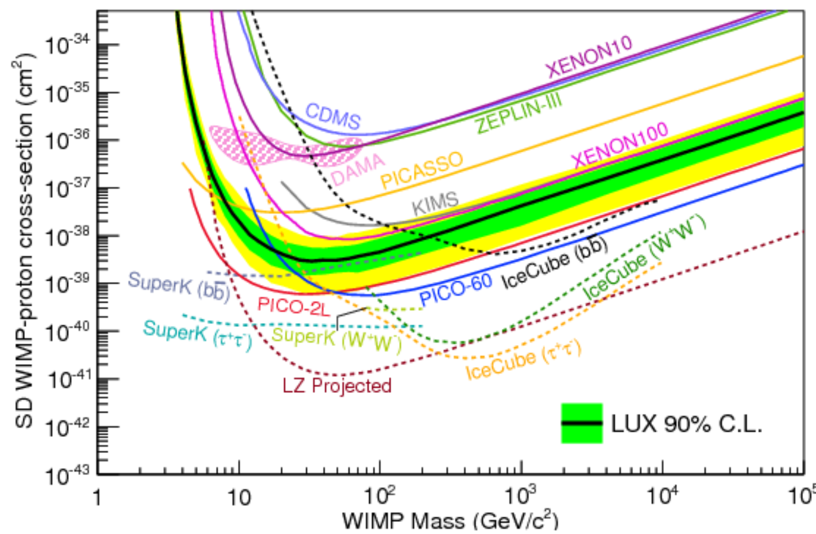
Exclusion plots for WIMP-nucleon total cross section (spin-dependent)





Differential cross section: compare results from different targets

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p^2} = \frac{8G_F^2}{(2J_i+1)v^2} S_A(p)$$

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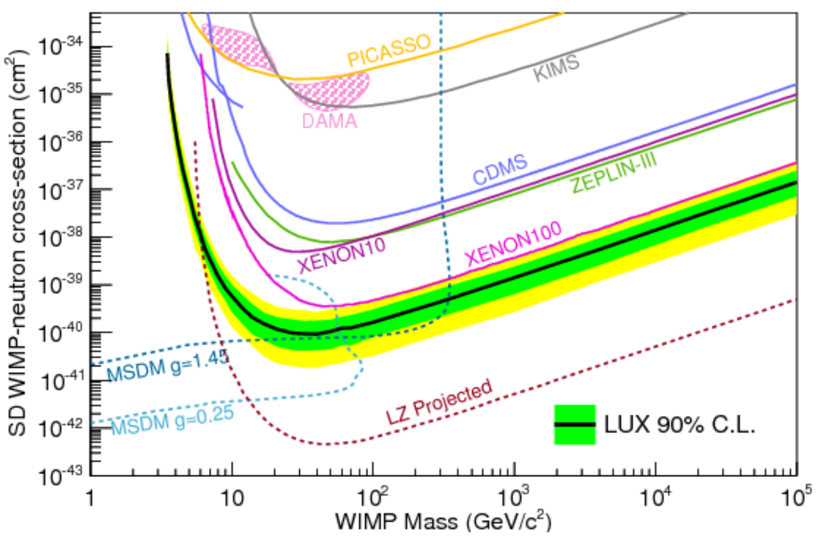

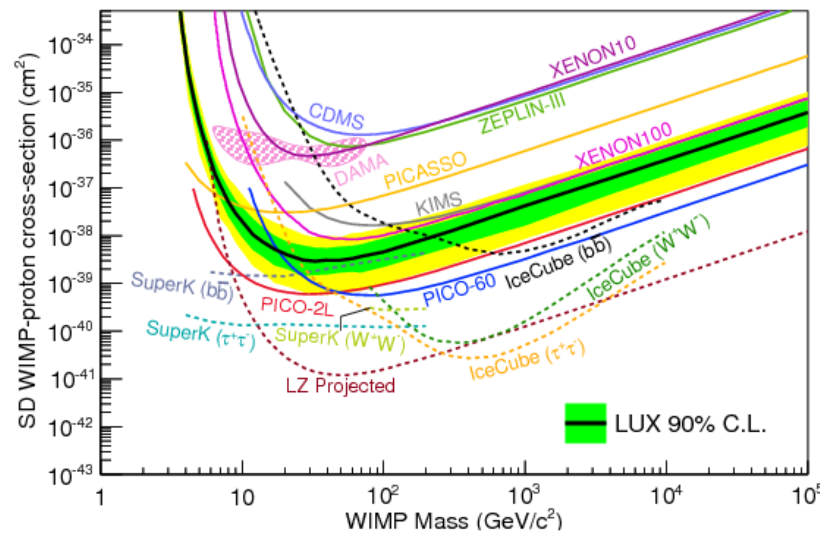

Differential cross section: compare results from different targets

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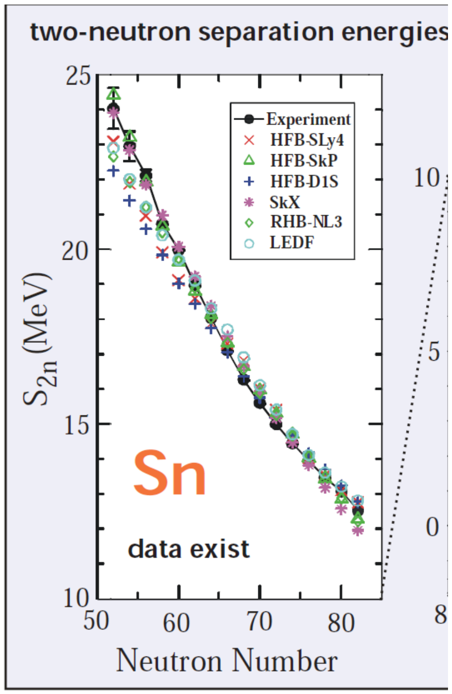
Structure functions required from nuclear theory

Predictions with Models

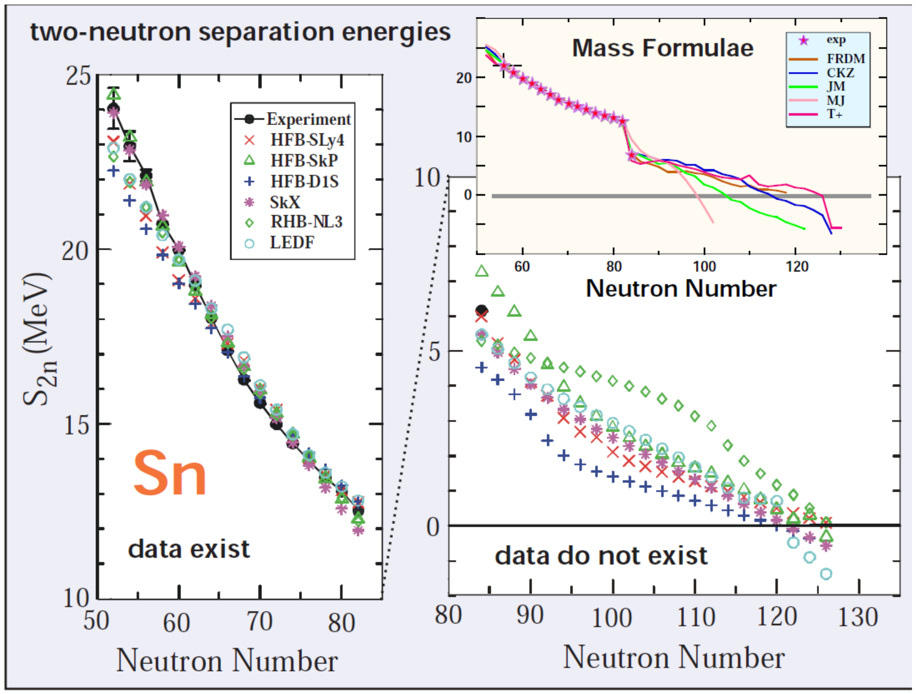
How well can nuclear models motivate experiments, predict beyond data?



Work well in regions where informed by data

Predictions with Models

How well can nuclear models motivate experiments, predict beyond data?



Often extrapolate unreliably

Spread in results = meaningful uncertainty?

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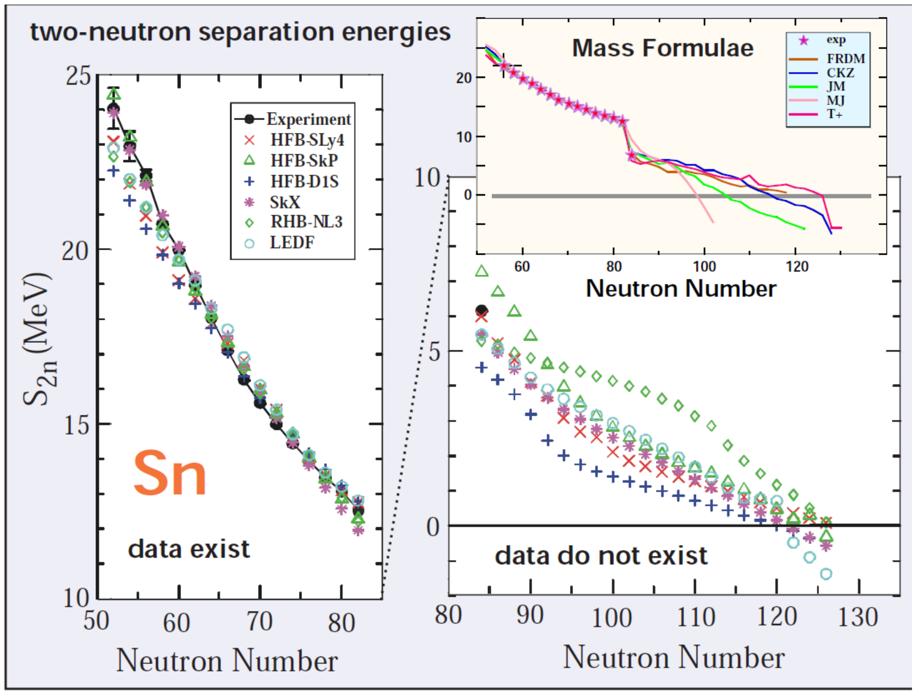

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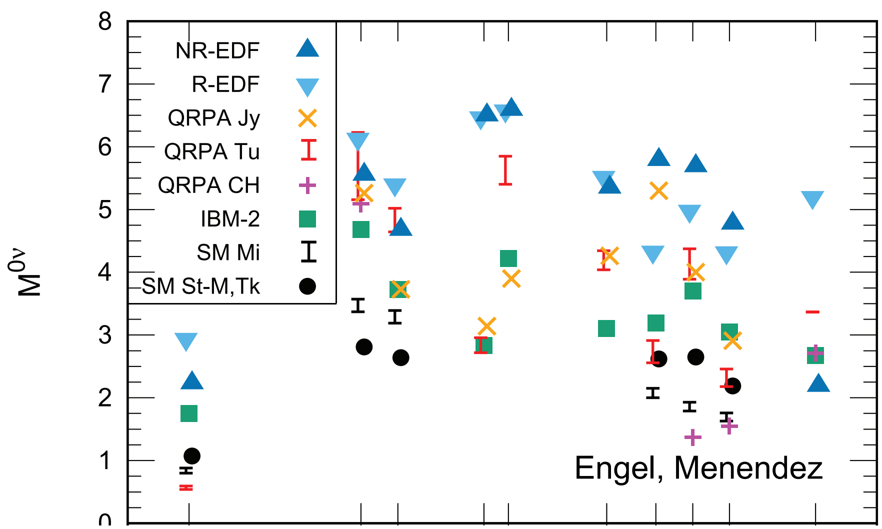
Spread in results = meaningful uncertainty?

Analogous picture in 0νββ decay

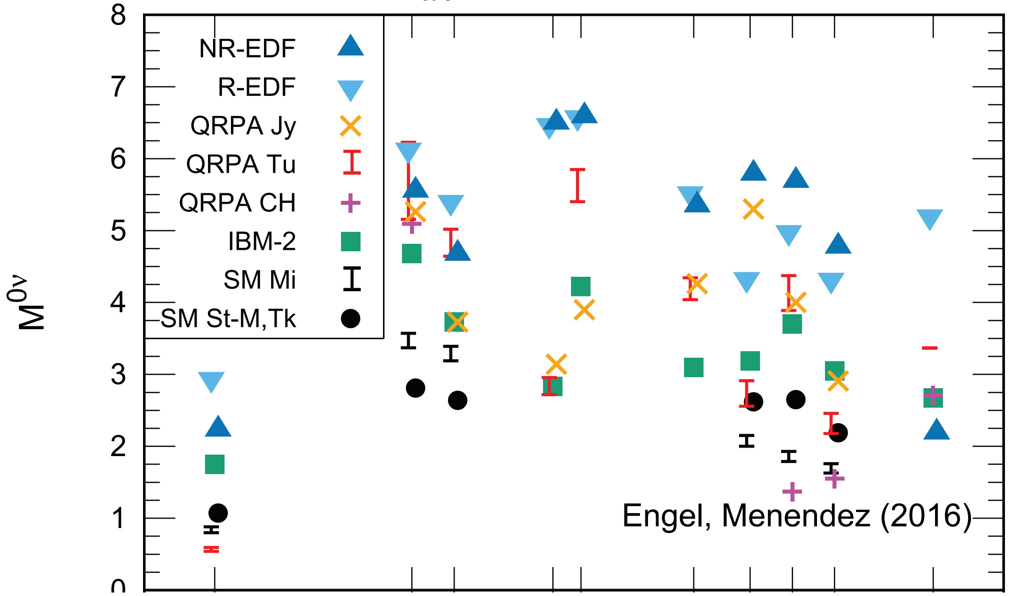
$$M^{0\nu}_{GT} = \langle f | \sum_{ab} H(r_{ab}) \sigma_a \cdot \sigma_b \; \tau^+_a \tau^+_b | i \rangle$$



0νββ-Decay Nuclear Matrix Element Status

All calculations to date from **extrapolated** phenomenological models; large spread in results

$$M^{0\nu}_{GT} = \langle f | \sum_{ab} H(r_{ab}) \sigma_a \cdot \sigma_b \, \tau_a^+ \tau_b^+ | i \rangle$$



All models missing essential physics

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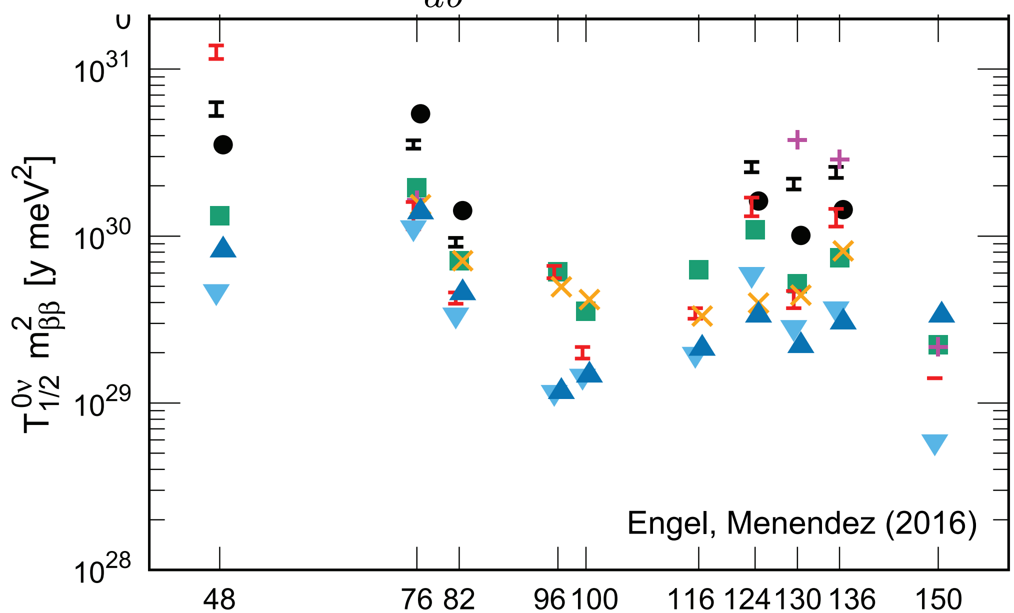
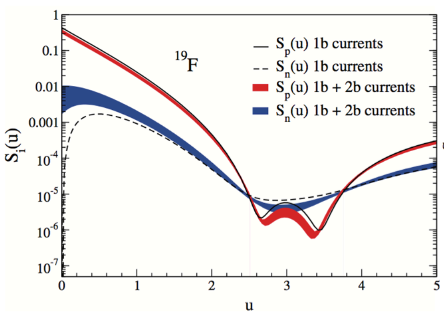


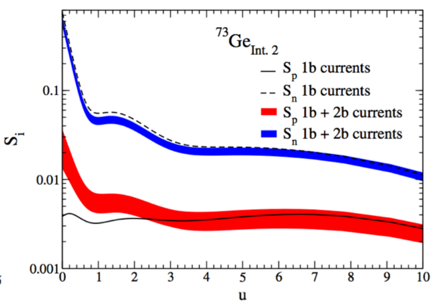
All models missing essential physics

Phenomenological wfs + inconsistent bare operator (**with two-body currents**)

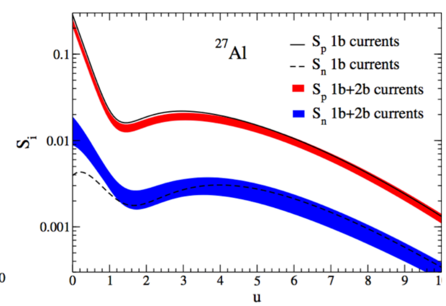
$$S_A(p) = \sum_{L\geqslant 0} |\langle J_f \| \mathcal{L}_L \| J_i \rangle|^2 + \sum_{L\geqslant 0} \left(|\langle J_f \| \mathcal{T}_L^{\mathrm{el}} \| J_i \rangle|^2 + |\langle J_f \| \mathcal{T}_L^{\mathrm{mag}} \| J_i \rangle|^2 \right)$$



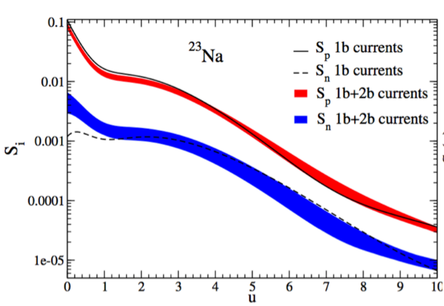
PICASSO, COUPP, SIMPLE



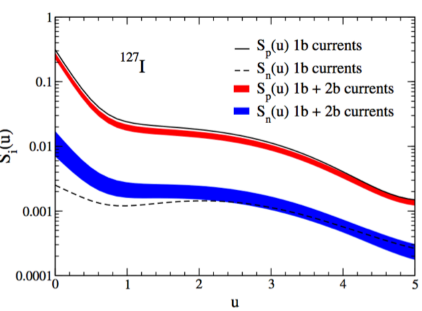
CDMS, EDELWEISS, EURECA



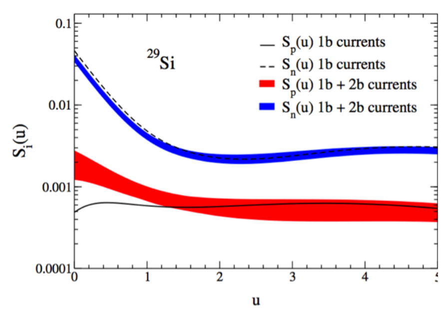
CRESST



DAMA, ANAIS, DM-Ice



DAMA, ANAIS, DM-Ice, KIMS



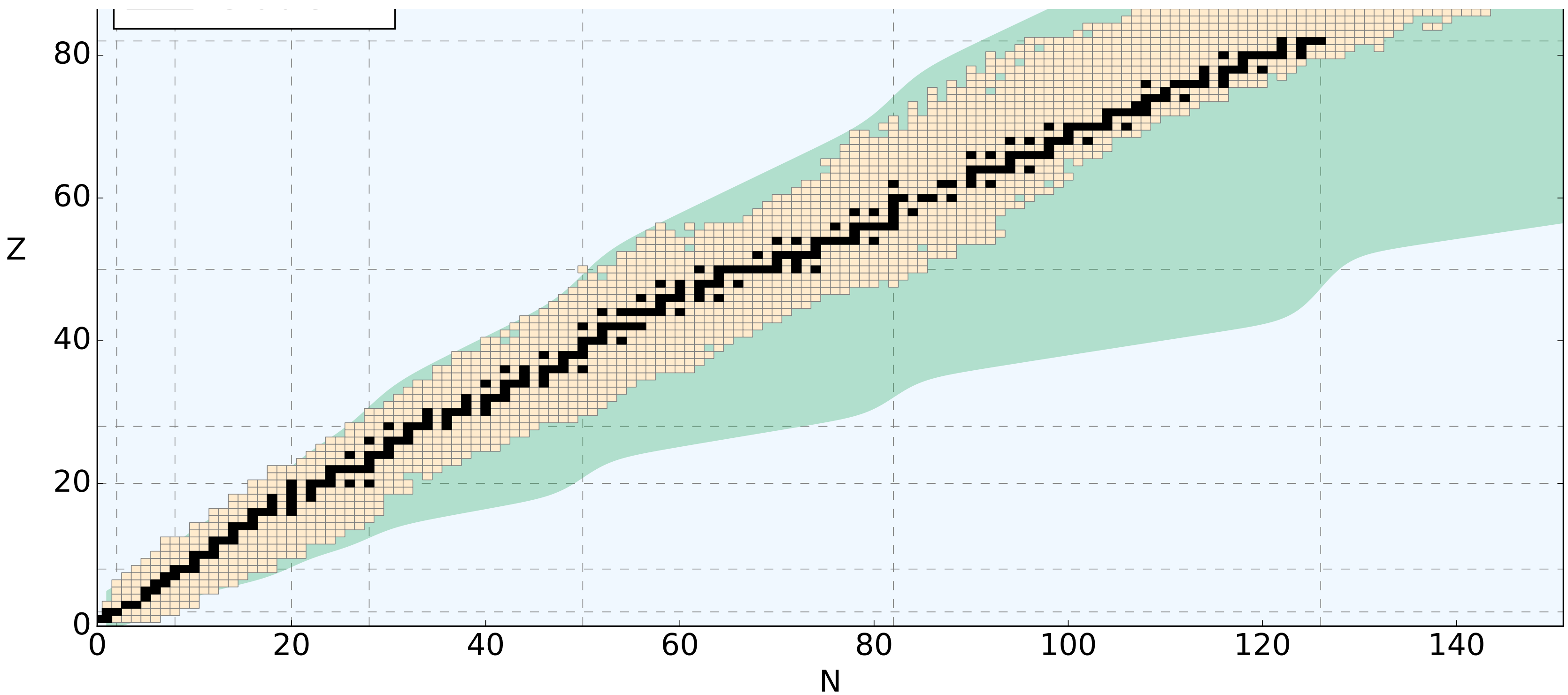
CDMS-II

Klos et al, PRD (2013)

Ab Initio Approach

Aim of modern nuclear theory: Develop unified *first-principles* picture of structure and reactions

$$H\psi_n = E_n\psi_n$$



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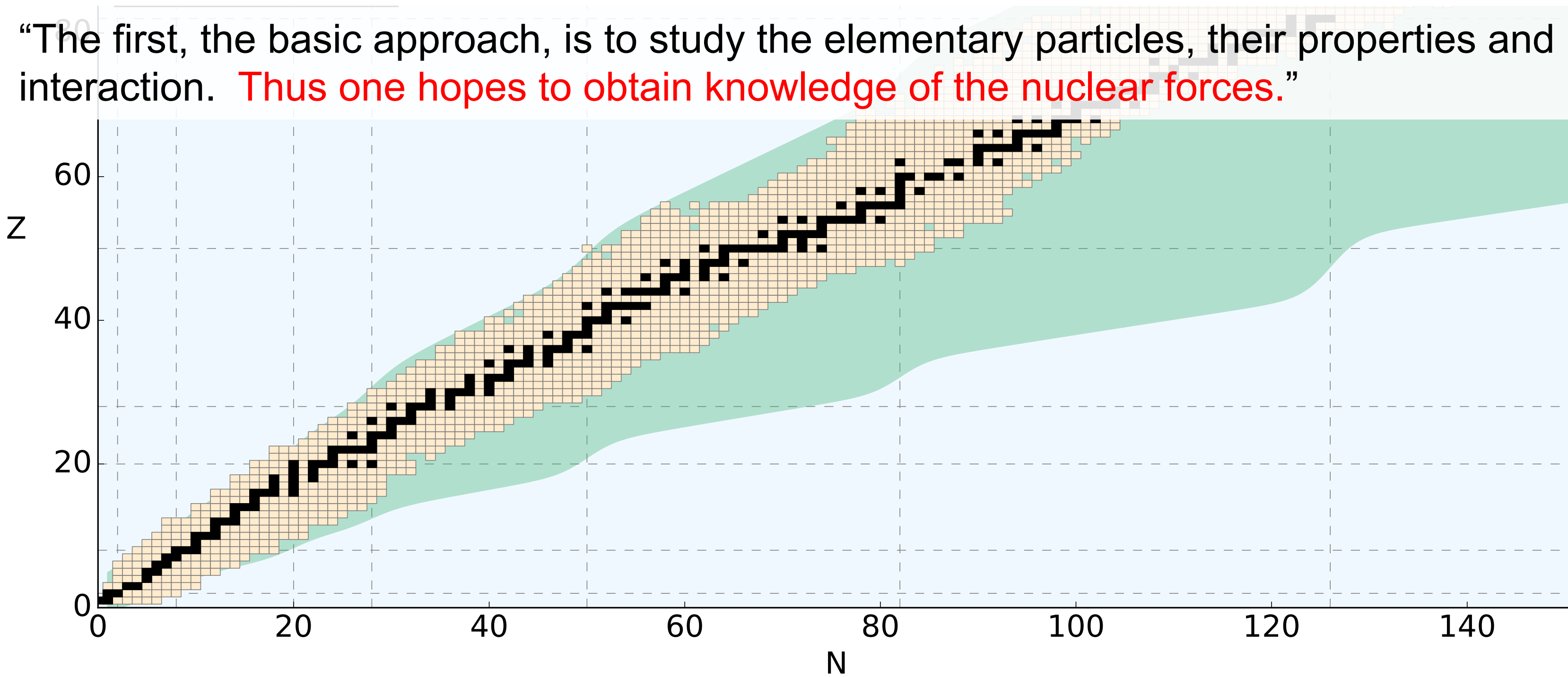
Ab Initio Approach: Interactions

Aim of modern nuclear theory: Develop unified *first-principles* picture of structure and reactions

- Nuclear forces (low-energy QCD)
- Electroweak physics

$$H\psi_n = E_n\psi_n$$

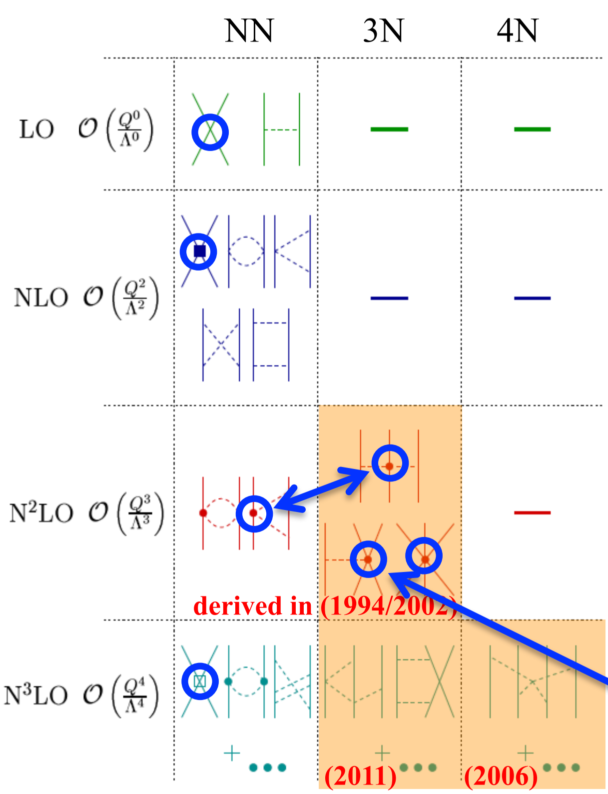
"The first, the basic approach, is to study the elementary particles, their properties and mutual interaction. Thus one hopes to obtain knowledge of the nuclear forces."



Effective Theory of Nuclear Forces

Chiral effective field theory: systematic expansion of nuclear interactions

$$H\psi_n = E_n\psi_n$$

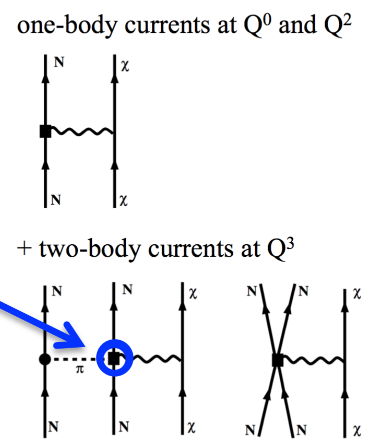


Nucleons interact via contact and pion exchanges

Undetermined low-energy constants fit to 2,3,4-body data

Consistent treatment of NN, 3N, 4N… forces

Quantitative estimation of neglected orders possible



Consistent EW interactions

Quantifiable uncertainties possible

Best fitting strategy for ~30 undetermined couplings debated

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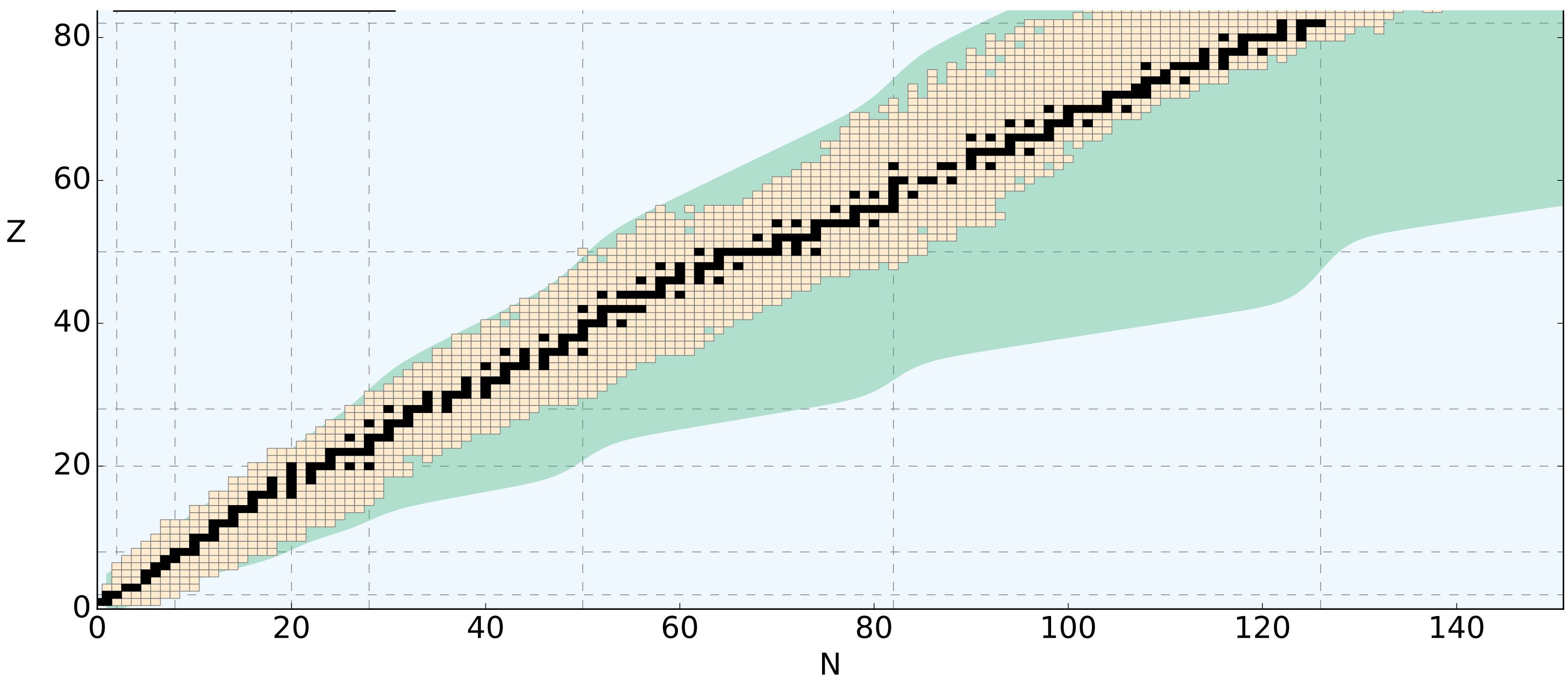


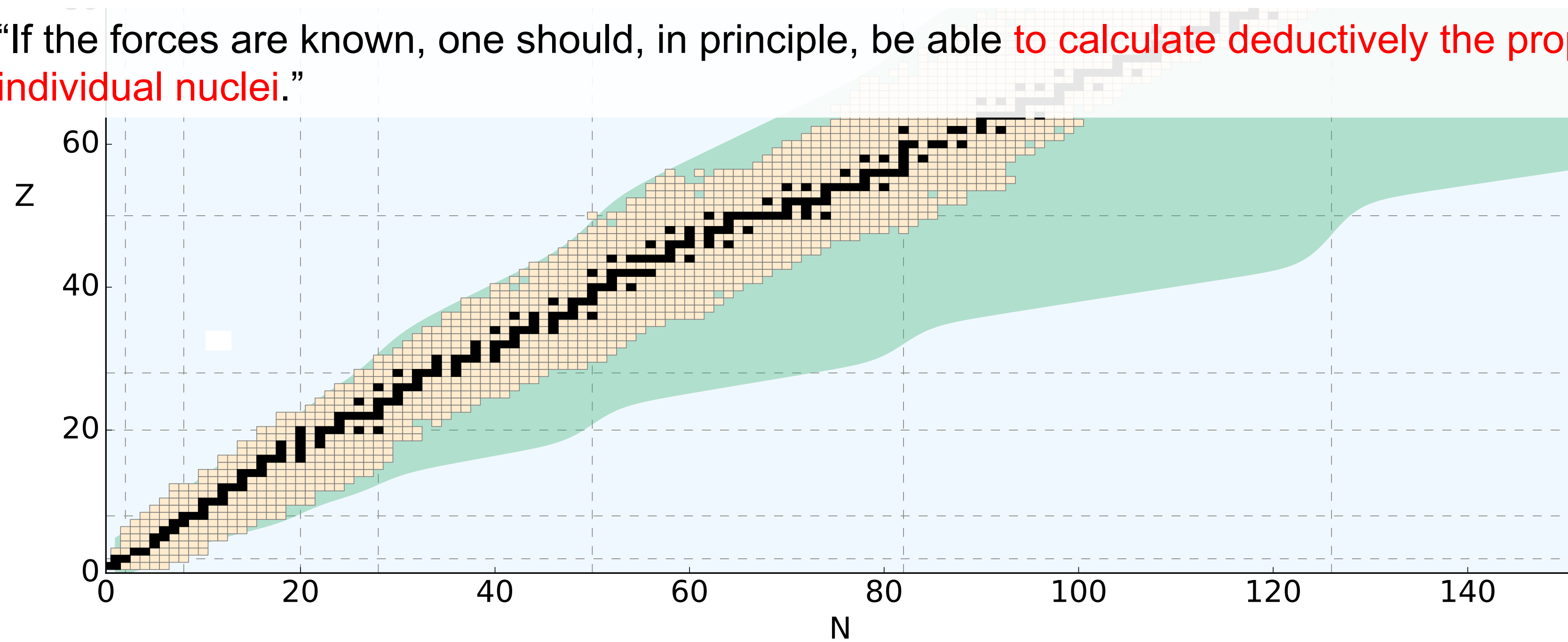
Ab Initio Approach: Many-Body Methods

Aim of modern nuclear theory: Develop unified *first-principles* picture of structure and reactions

- Nuclear forces (low-energy QCD)
- Electroweak physics
- **Nuclear many-body problem**

$$H\psi_n = E_n\psi_n$$

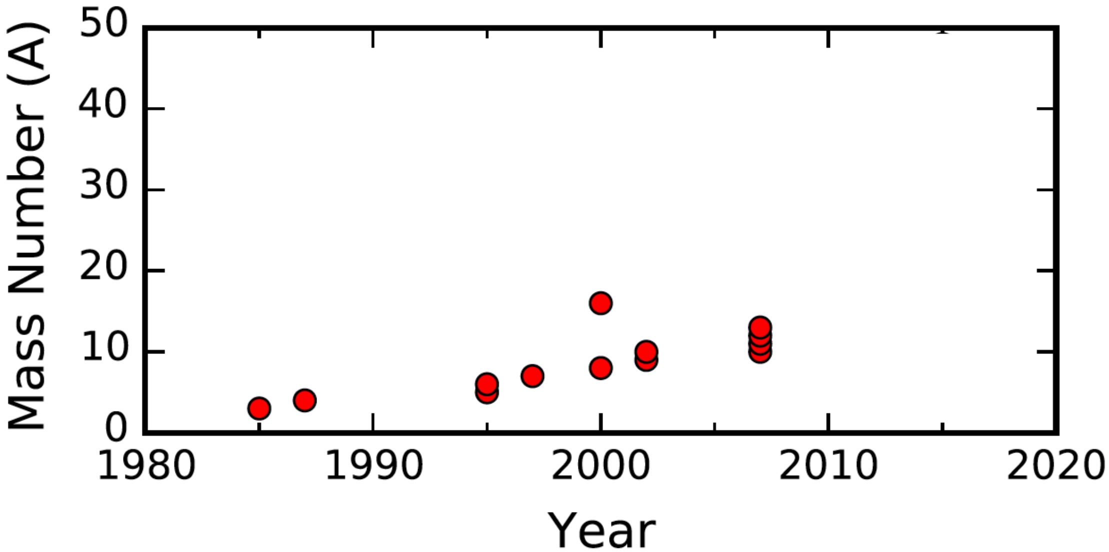
"If the forces are known, one should, in principle, be able to calculate deductively the properties of individual nuclei."

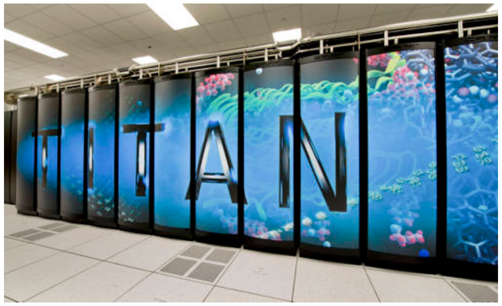


Chronological Reach of Ab Initio Many-Body Methods

Moore's law: exponential growth in computing power

Methods for light nuclei (QMC, NCSM) scale exponentially with mass





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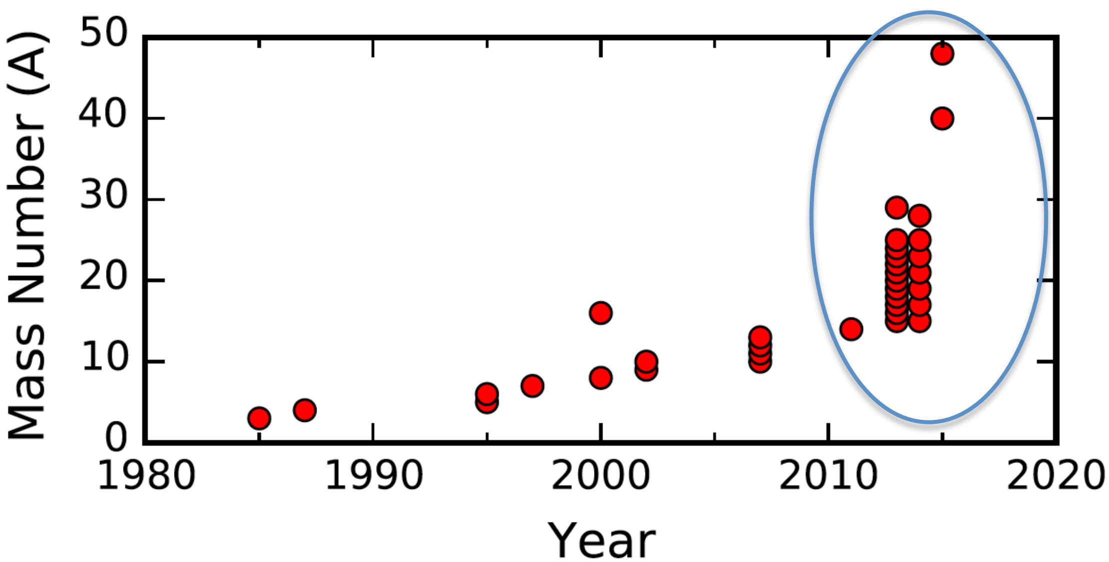
Mid 2000's **polynomial scaling methods developed** (coupled cluster, in-medium SRG,…)
Explosion in limits of ab initio theory



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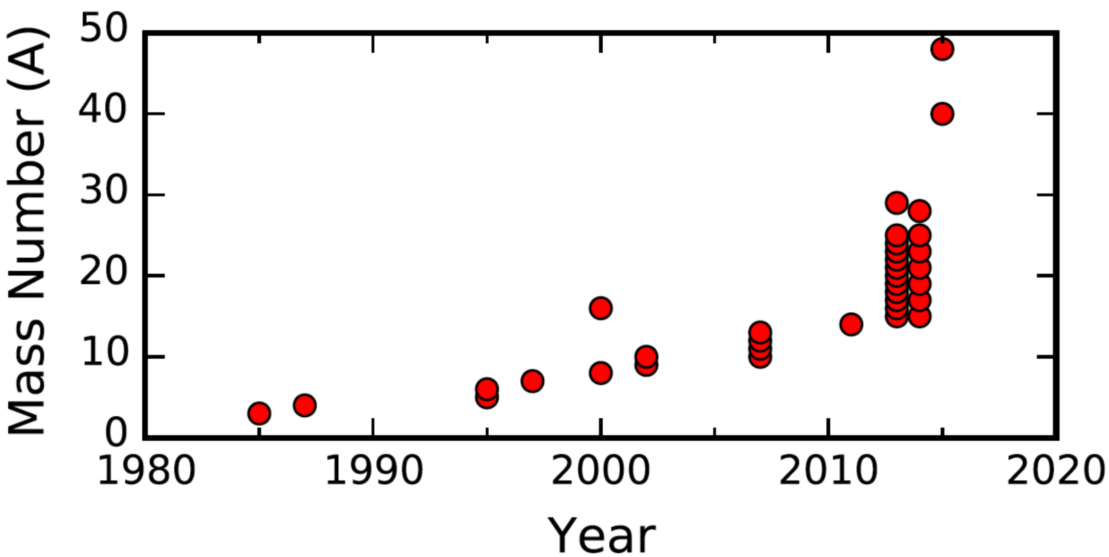
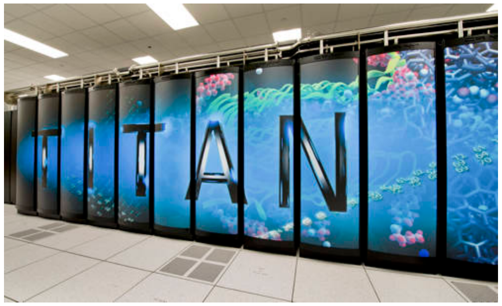


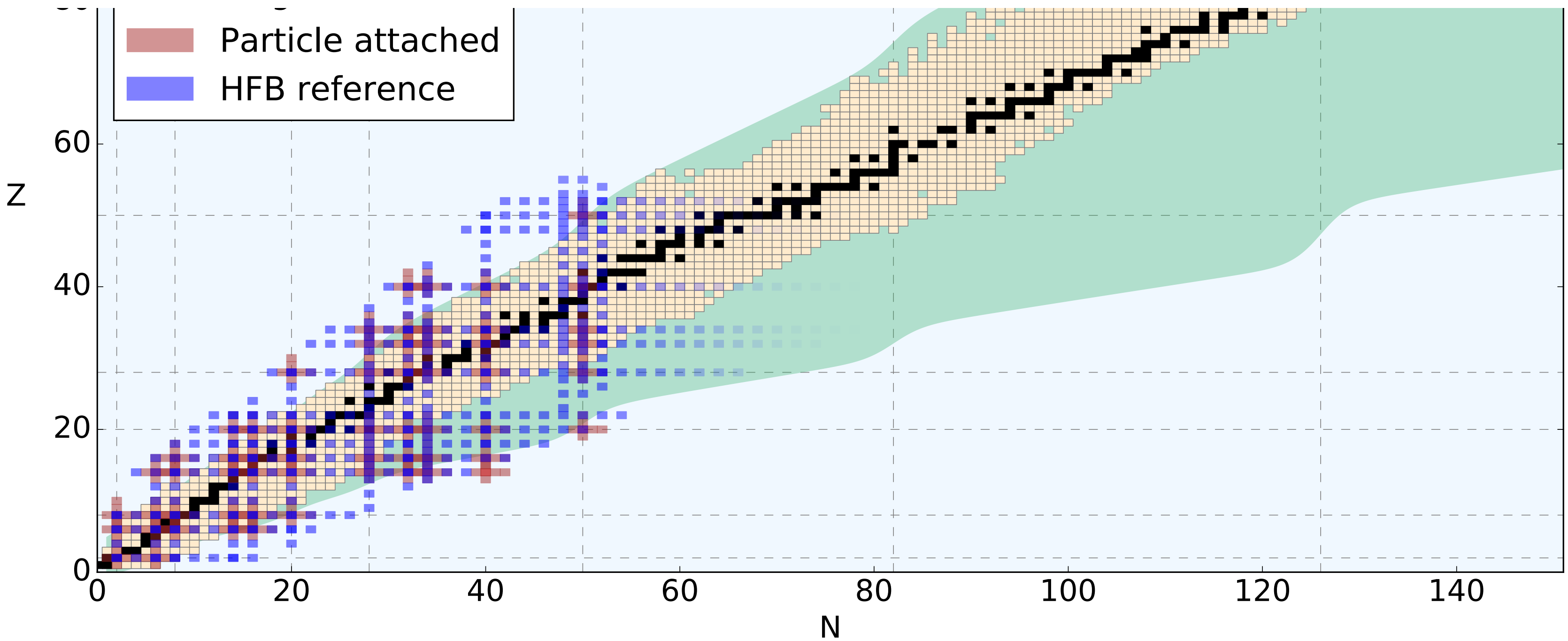


Breadth of Ab Initio Many-Body Methods

Aim of modern nuclear theory: Develop unified *first-principles* picture of structure and reactions

- Nuclear forces (low-energy QCD)
- Electroweak physics
- **Nuclear many-body problem**

$$H\psi_n = E_n\psi_n$$



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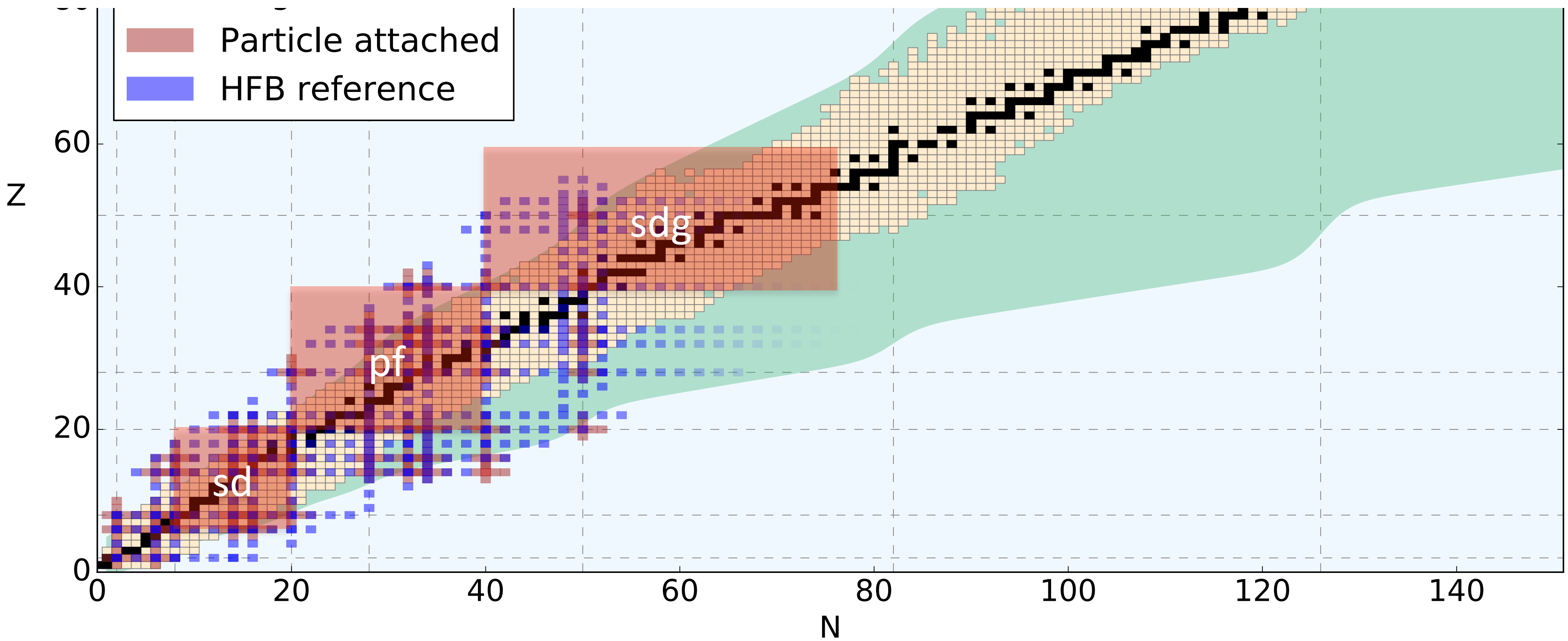

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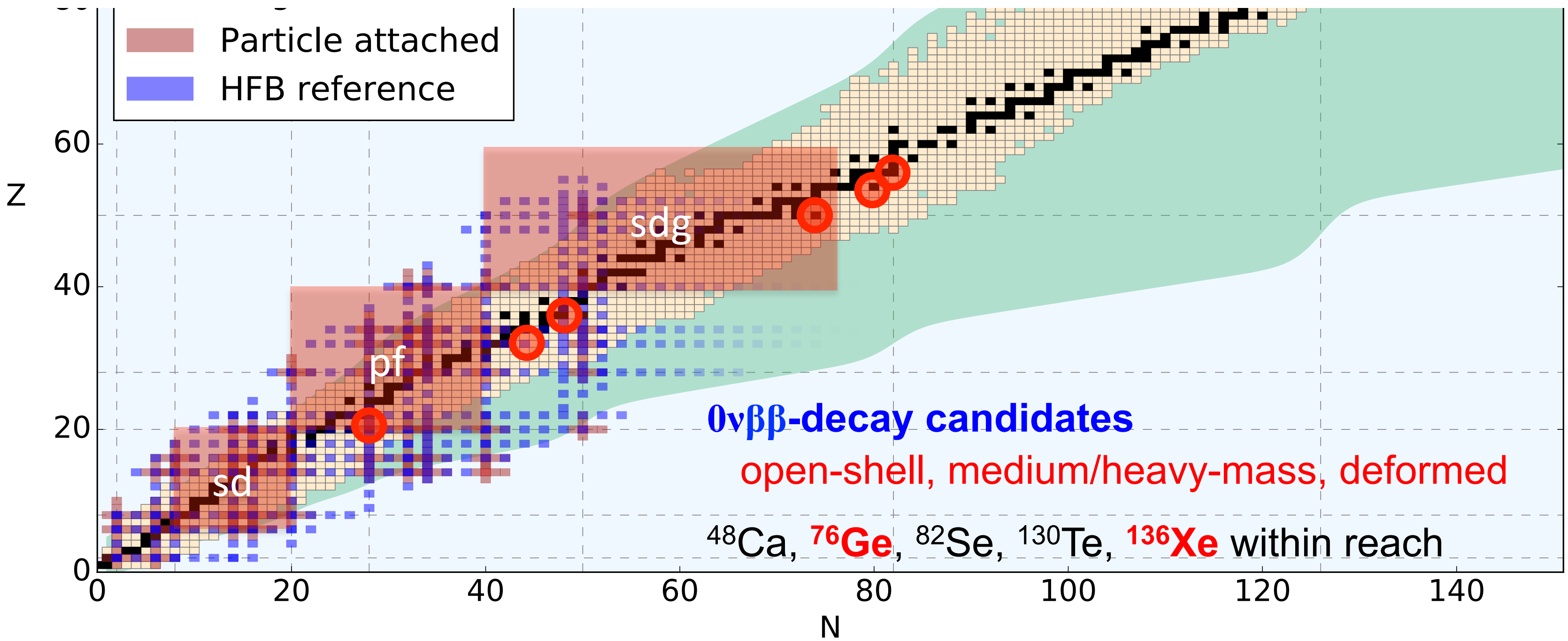

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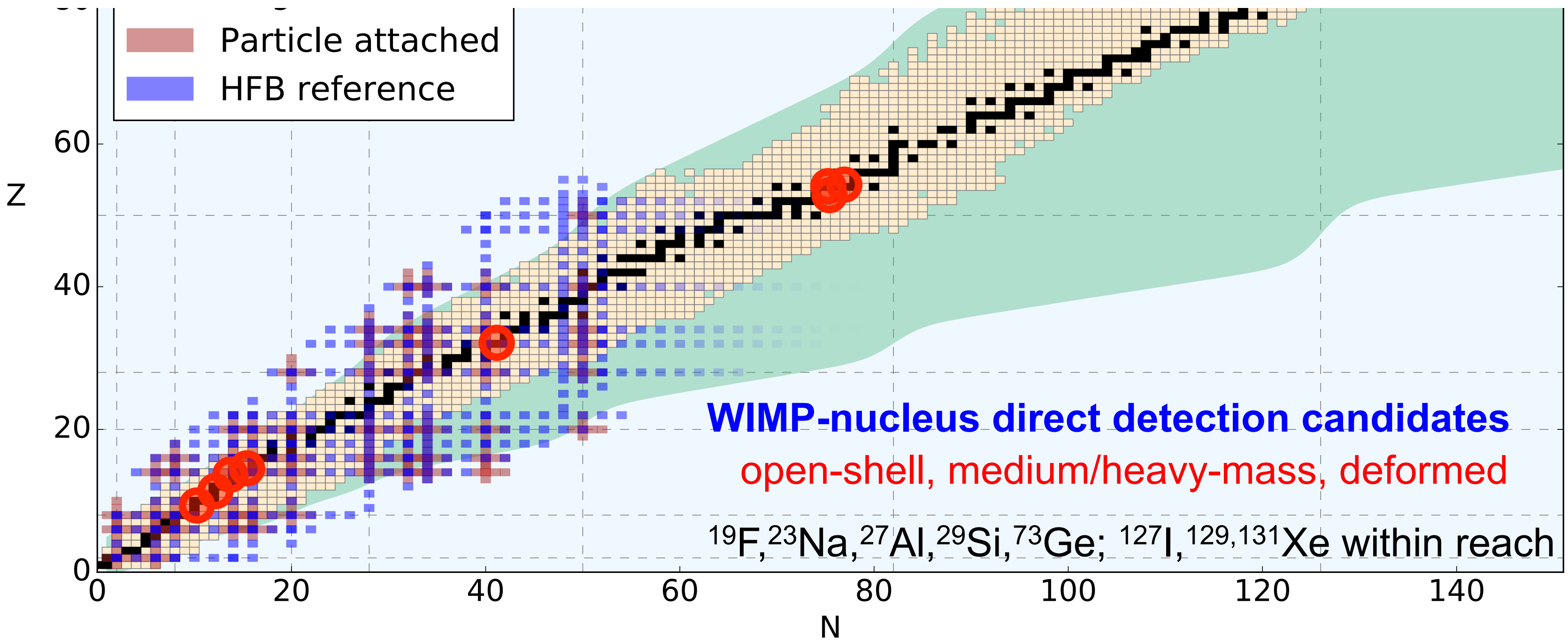

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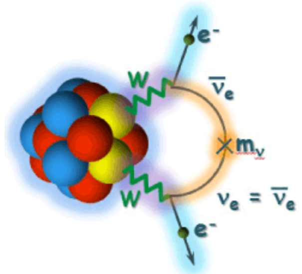
Ab Initio 0νββ-Decay Predictions in the Shell Model

Conventional Shell Model: phenomenological wavefunctions

Ab initio valence-space: **wavefunctions based on NN+3N forces from chiral EFT**

$$M^{0\nu} = M^{0\nu}_{GT} - \frac{M^{0\nu}_{F}}{g_A^2} + M^{0\nu}_{T}$$

$$M^{0\nu}_{GT} = \langle f | \sum_{ab} H(r_{ab}) \sigma_a \cdot \sigma_b \, \tau_a^+ \tau_b^+ | i \rangle$$



Neutrinoless double beta decay

1) Ab initio energies in medium/heavy-mass region

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Valence-Space In-Medium SRG

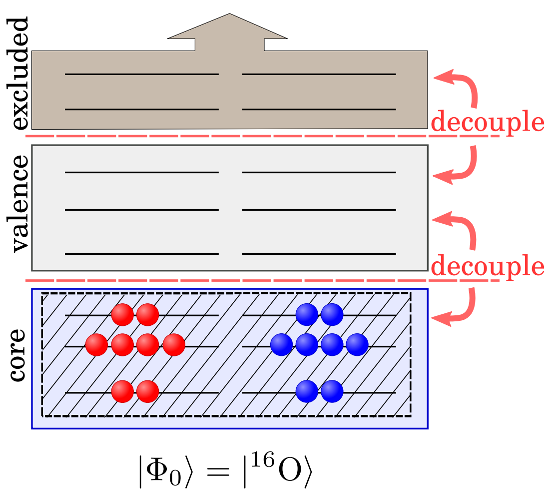
Explicitly construct unitary transformation from sequence of rotations

$$U = e^{\Omega} = e^{\eta_n} \dots e^{\eta_1} \qquad \eta = \frac{1}{2} \arctan\left(\frac{2H_{\mathrm{od}}}{\Delta}\right) - \mathrm{h.c.}$$

$$\tilde{H} = e^{\Omega} H e^{-\Omega} = H + [\Omega, H] + \frac{1}{2}[\Omega, [\Omega, H]] + \cdots$$

All operators truncated at two-body level

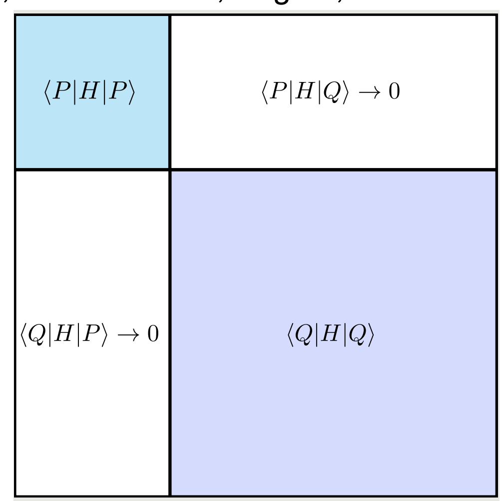
Tsukiyama, Bogner, Schwenk, PRC 2012
Morris, Parzuchowski, Bogner, PRC 2015



Step 1: Decouple core
Step 2: Decouple valence space

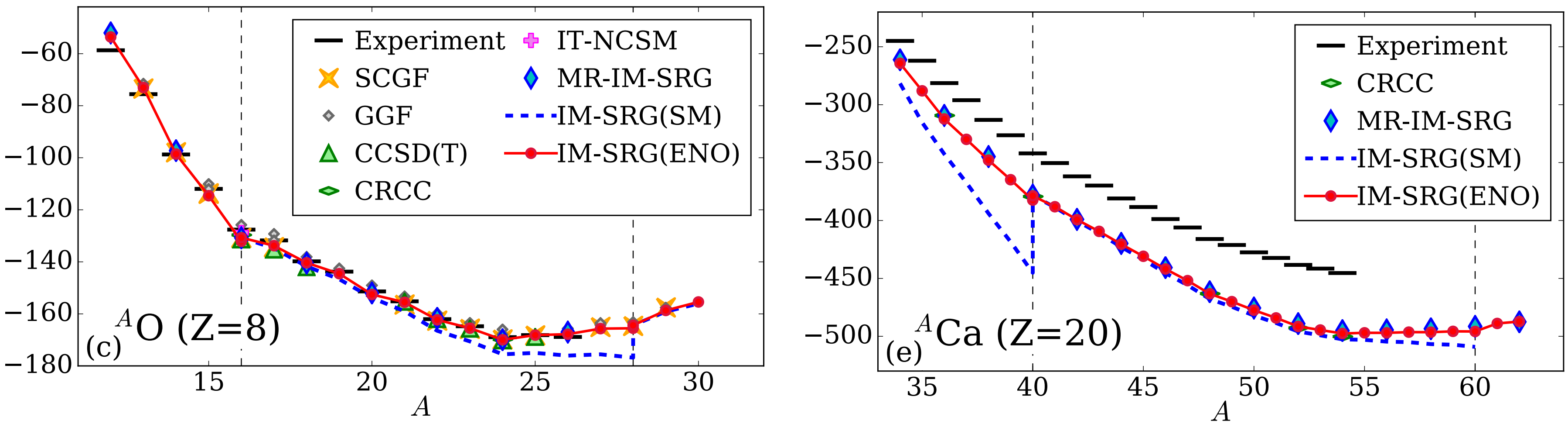
Can we achieve accuracy of large-space methods?

$$\langle \tilde{\Psi}_n | P\tilde{H}P \mid \tilde{\Psi}_n \rangle \approx \langle \Psi_i | H | \Psi_i \rangle$$



Ground States: From Oxygen to Nickel

ENO agrees to 1% with large-space methods (where calculations exist)



Stroberg et al., PRL (2017)

Extend beyond standard *sd*/*pf* shells

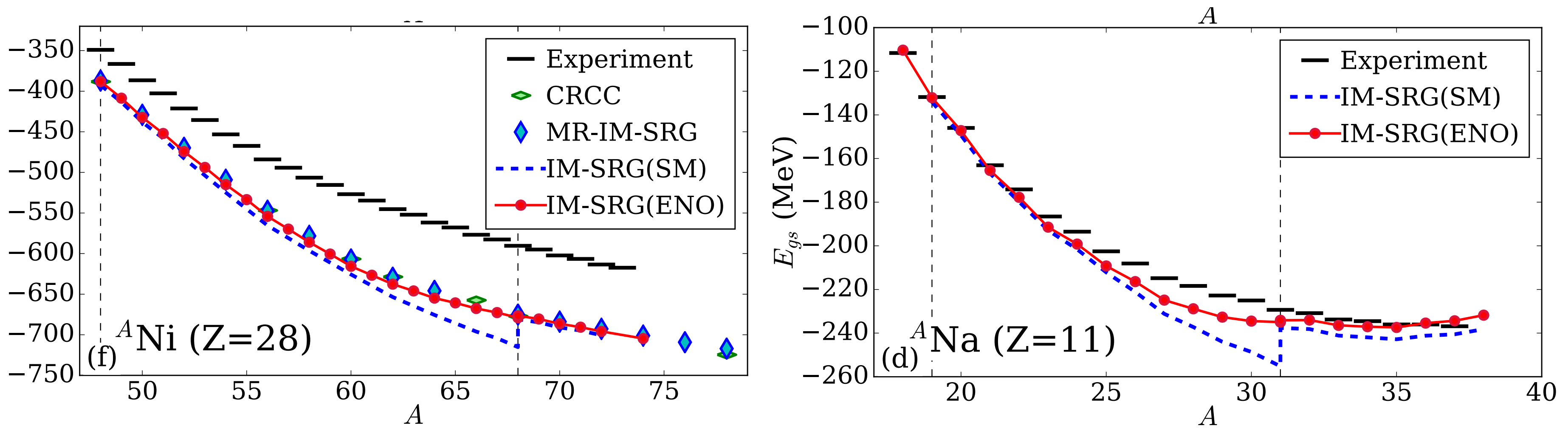
Agreement with experiment deteriorates for heavy chains (due to input Hamiltonian)

Significant gain in applicability with little/no sacrifice in accuracy

Low computational cost: ~1 node-day/nucleus

Ground States: From Oxygen to Nickel

Targeted valence space agrees to 1% with all large-space methods (where calculations exist)



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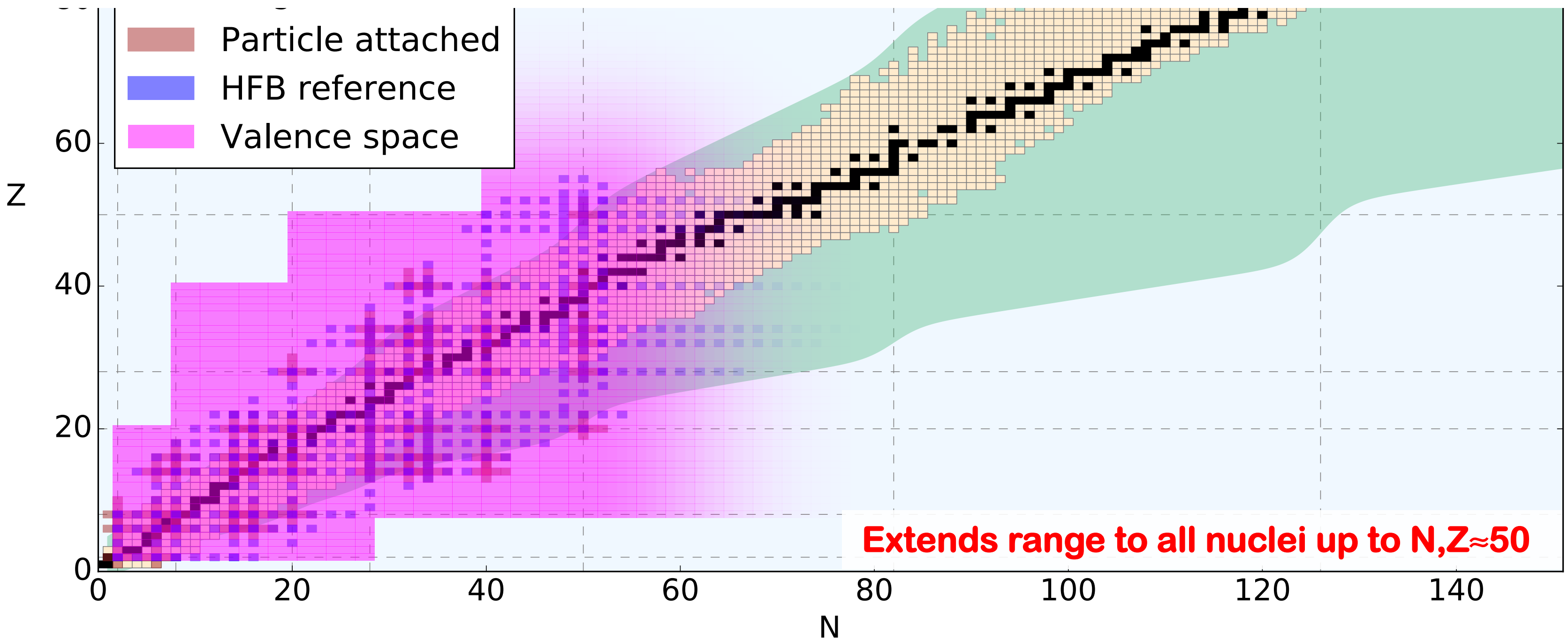
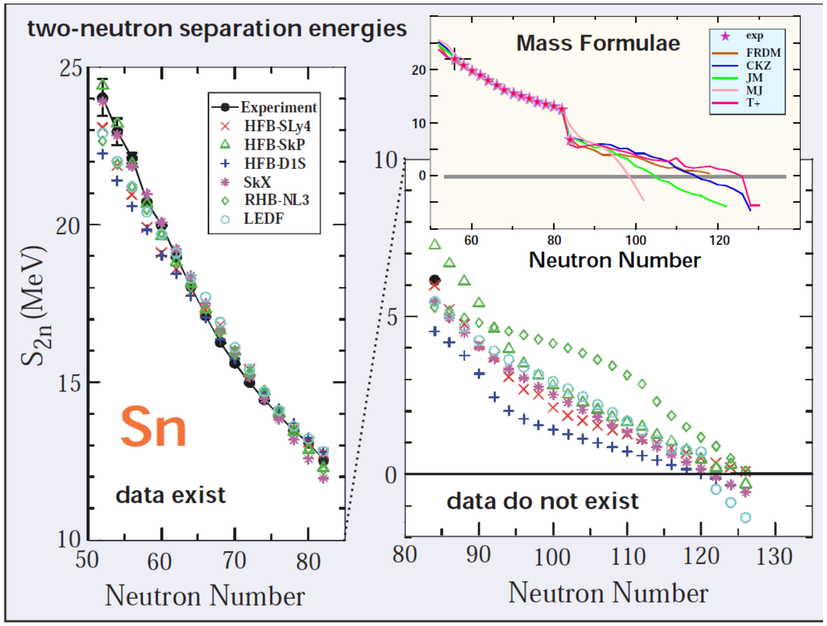
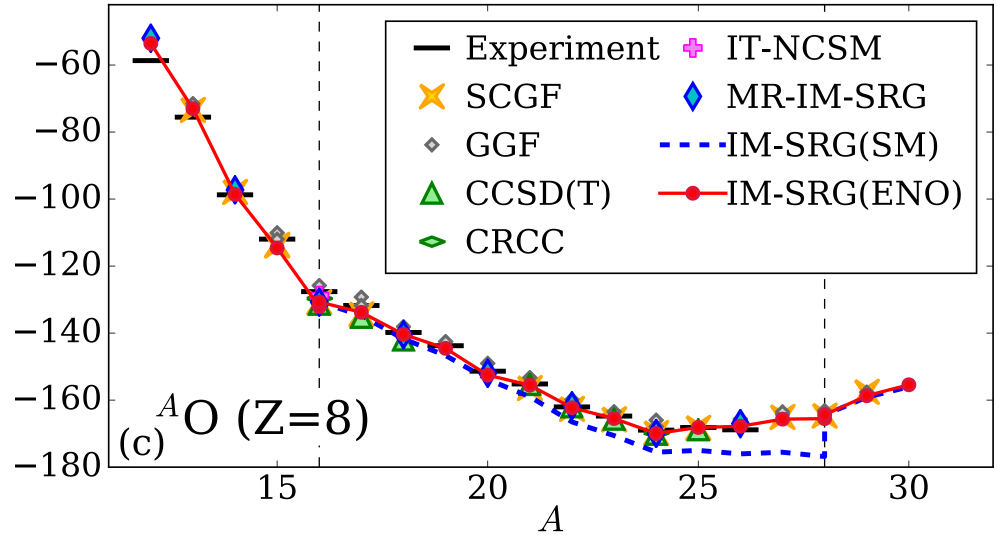


Extrapolating Beyond Data

Stark contrast in extrapolations between model extrapolations and ab initio



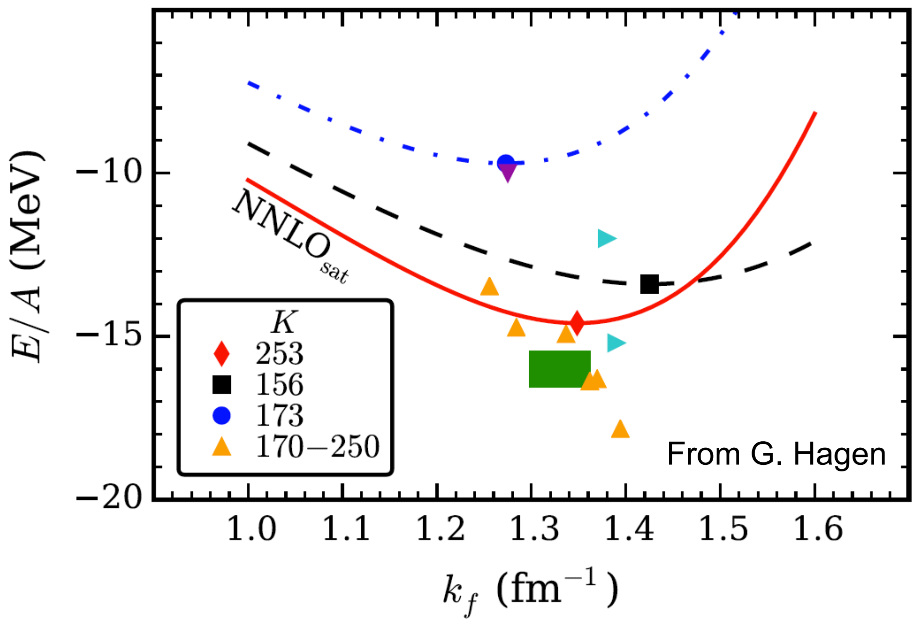


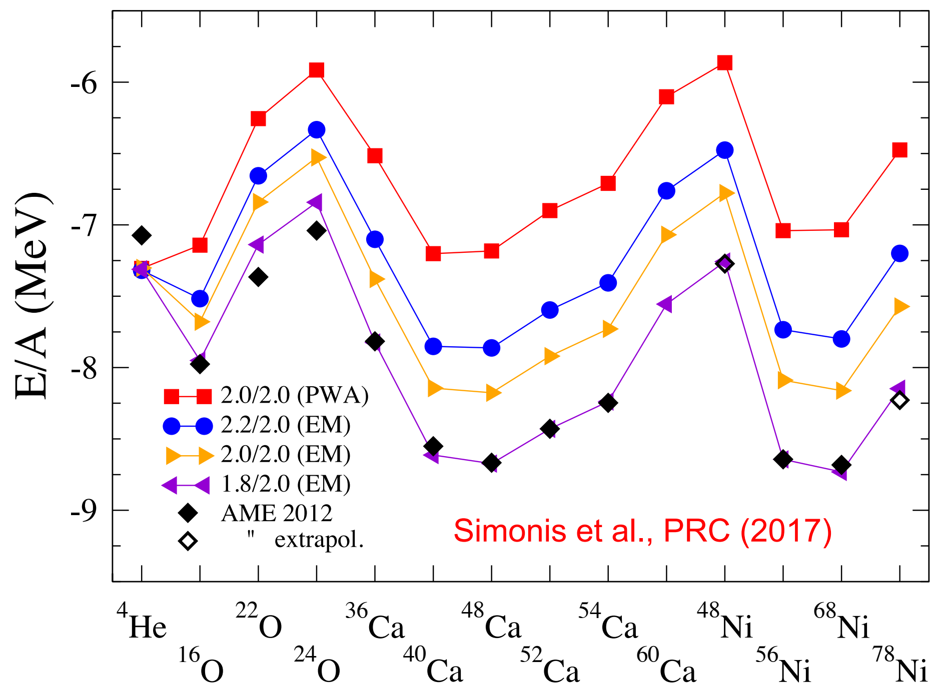
All ab initio methods in good agreement when starting from same input NN+3N forces

Only informed by 2,3-body data

Connection to Infinite Matter: Saturation as a Guide for Nuclei

Hebeler/Simonis NN+3N forces with reasonable saturation properties



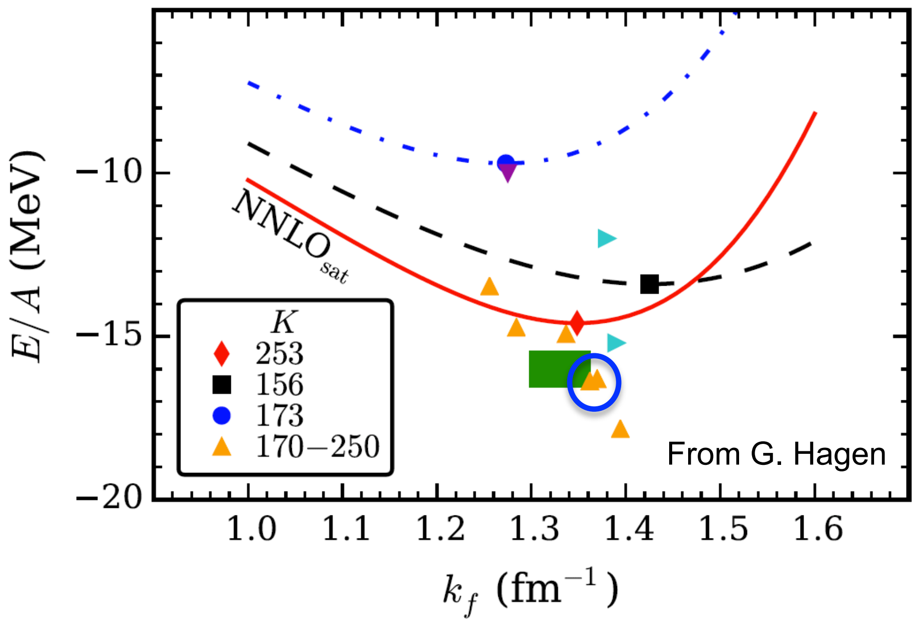


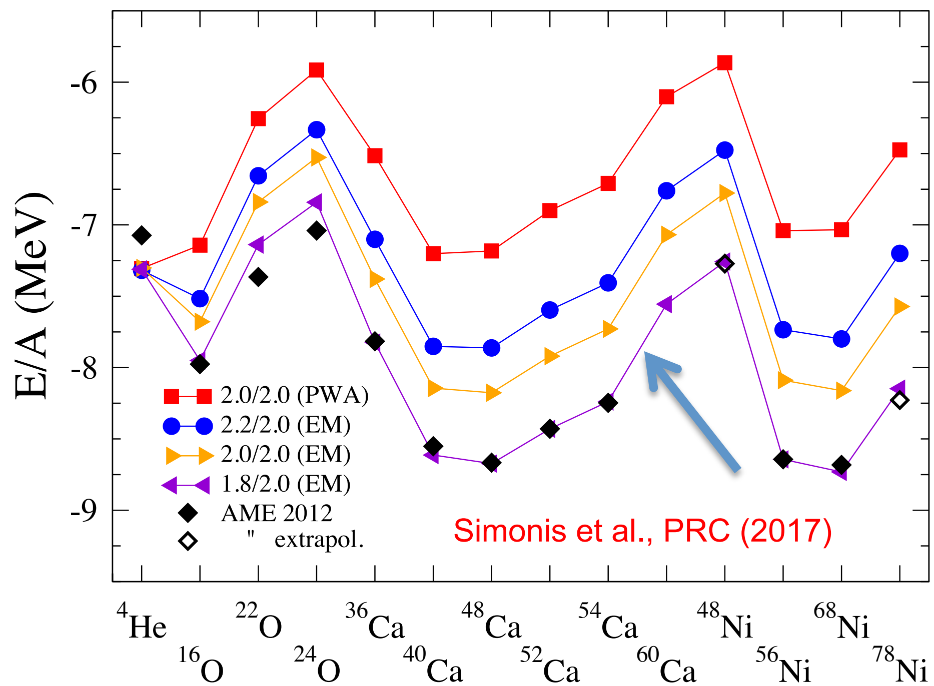
1.8/2.0 (EM) reproduces closed shells through ^{78}Ni

Only underbound for neutron-rich oxygen

Connection to Infinite Matter: Saturation as a Guide for Nuclei

Hebeler/Simonis NN+3N forces with reasonable saturation properties





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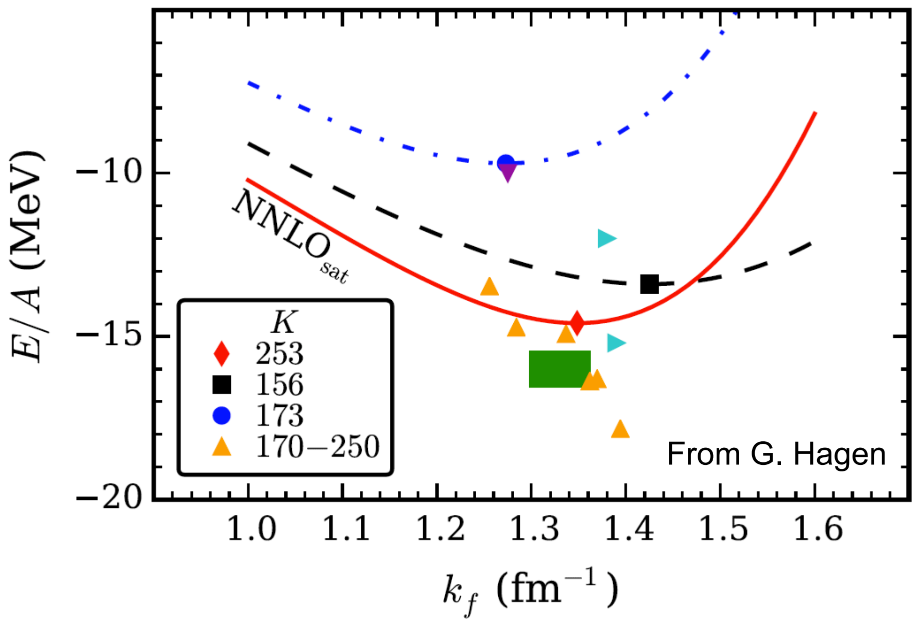
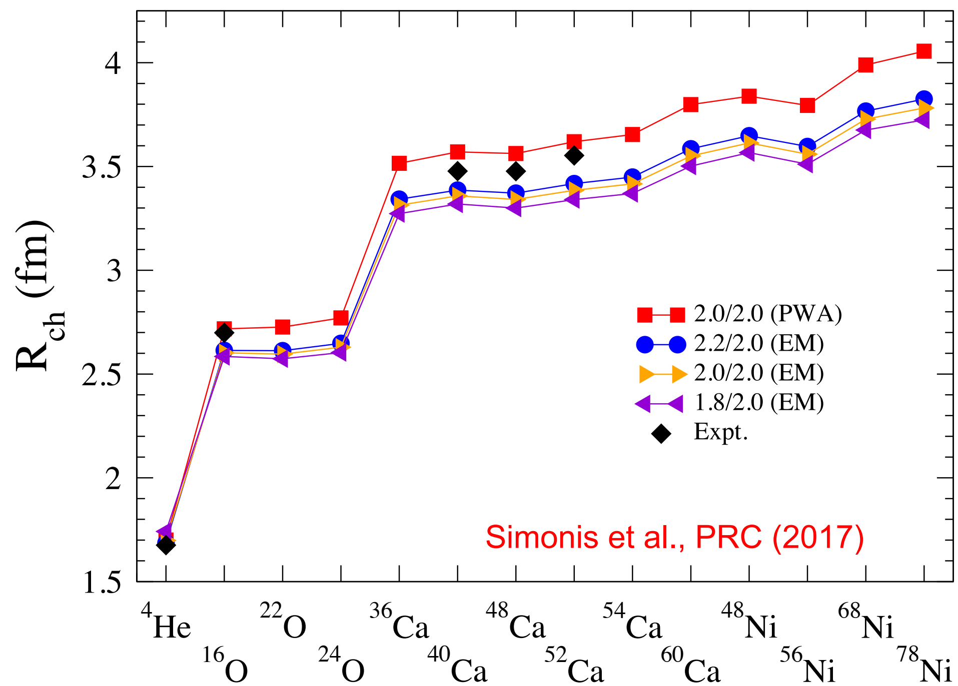


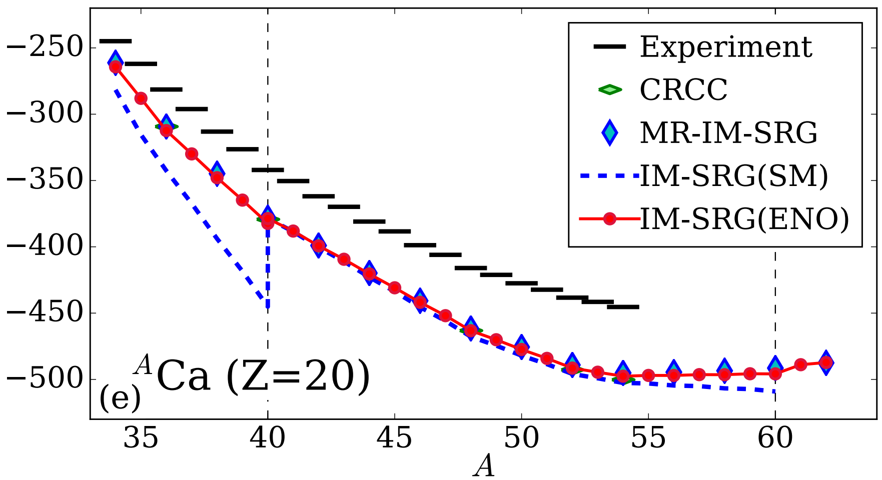


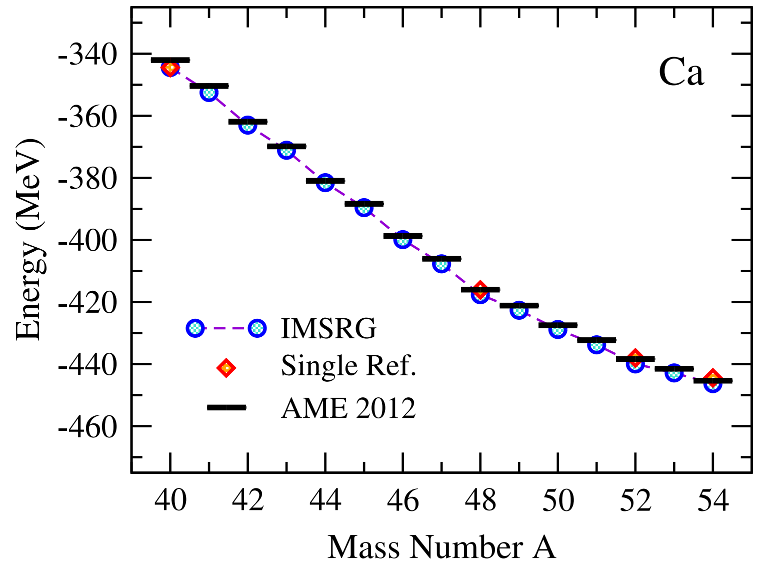
1.8/2.0 (EM) reproduces closed shells through ^{78}Ni

Only underbound for neutron-rich oxygen

Forces with good saturation

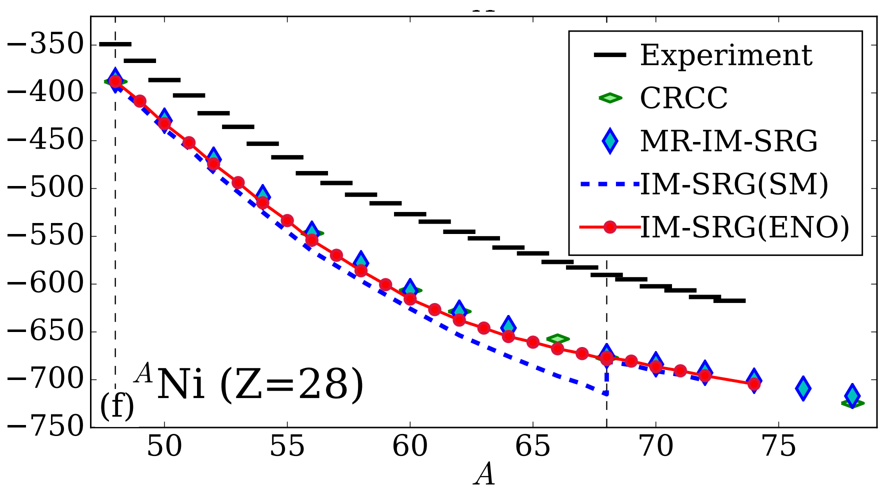
Isotopic chains: dramatic improvement with respect to experimental data

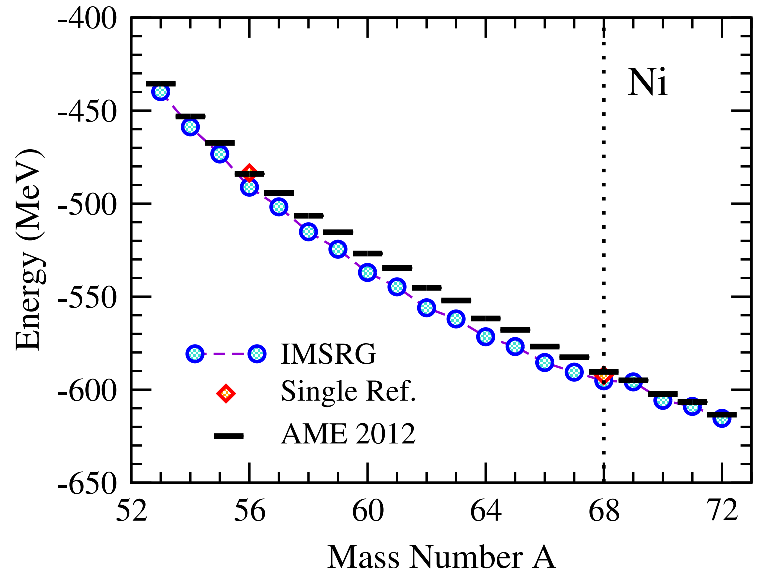




Forces with good saturation

Isotopic chains: dramatic improvement with respect to experimental data

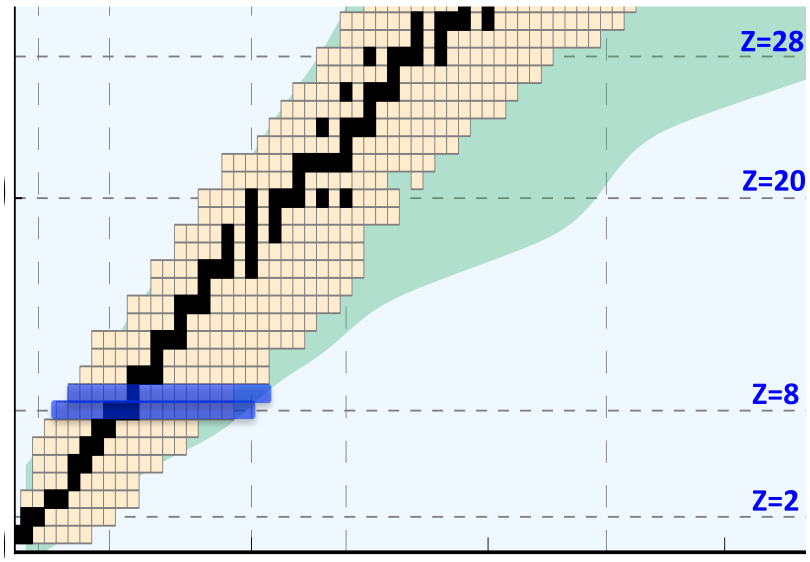


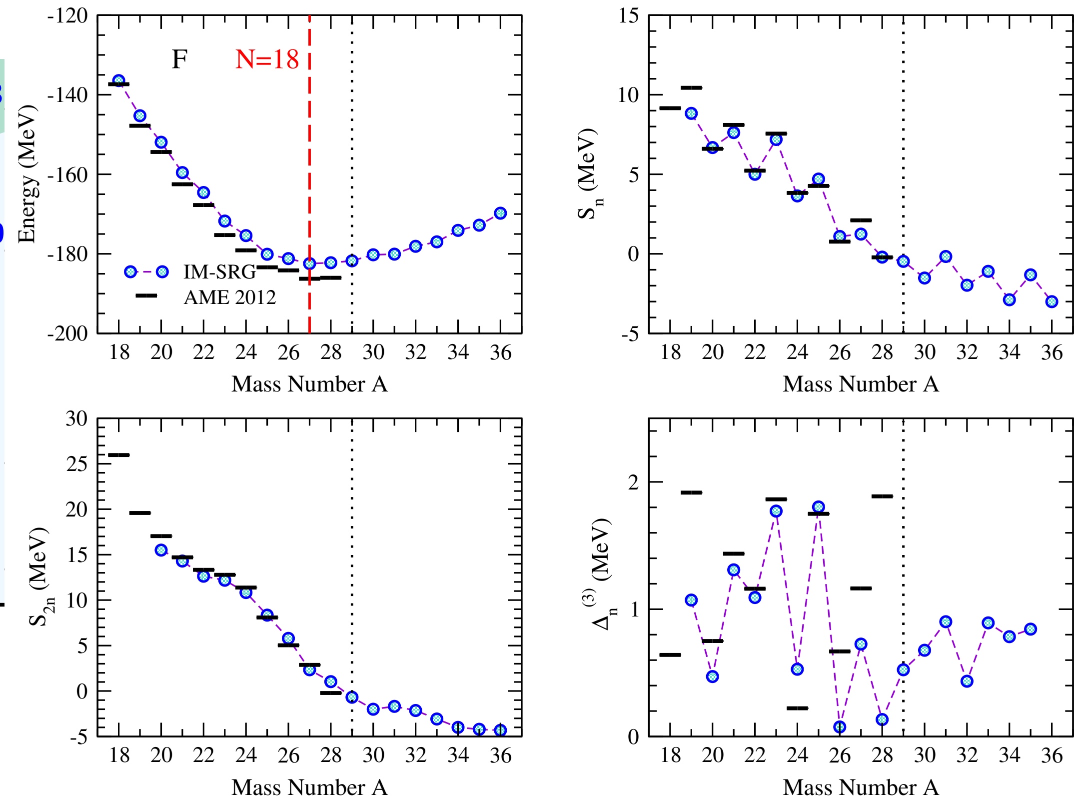


How well does it work across broad regions of nuclei?

Ground-State Properties in sd-Shell: F (Z=9)

Explore ground-state properties throughout medium-mass region





Remarkable agreement with experiment

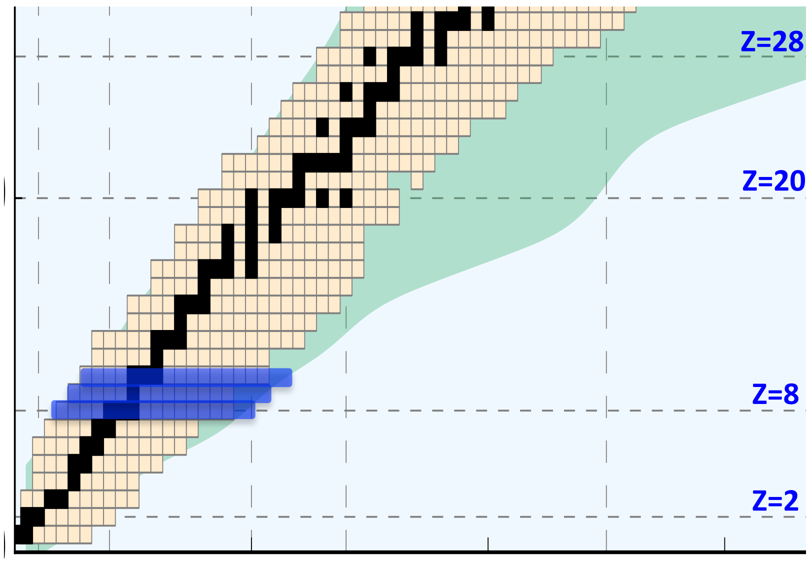
Probe dripline and beyond

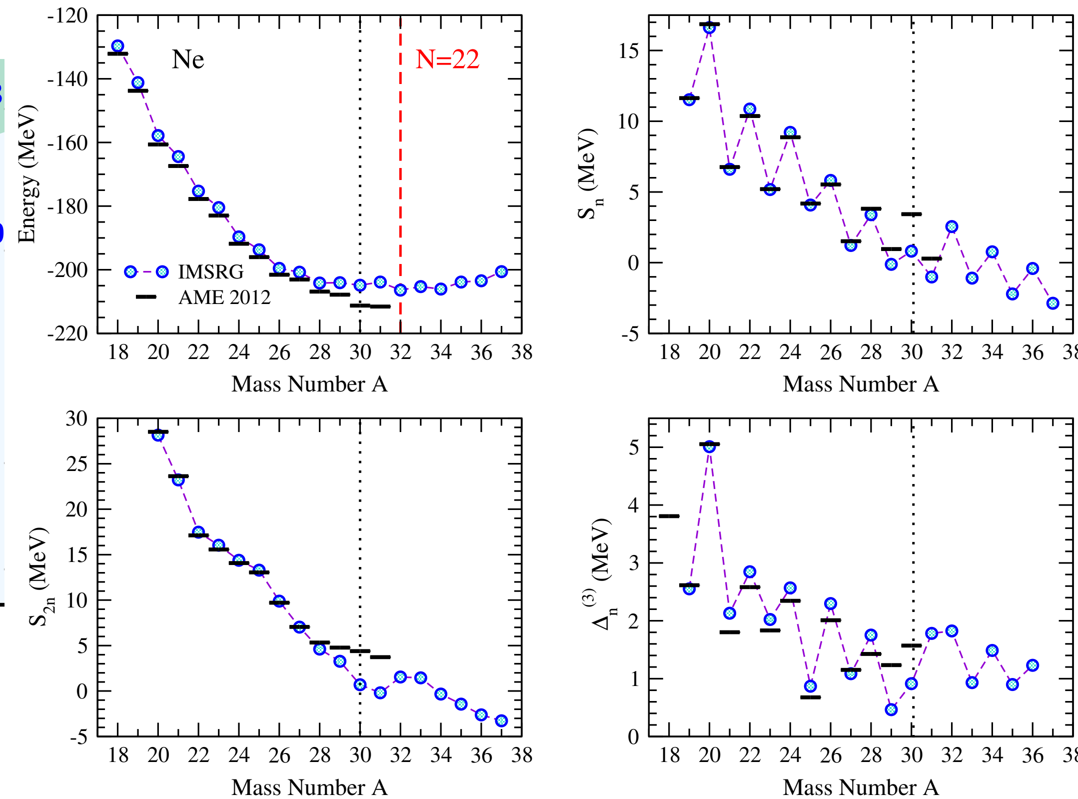
Artifacts at neutron N=20 gap

JDH, Stroberg, et al., in preparation

Ground-State Properties in sd-Shell: Ne (Z=10)

Explore ground-state properties throughout medium-mass region





Remarkable agreement with experiment

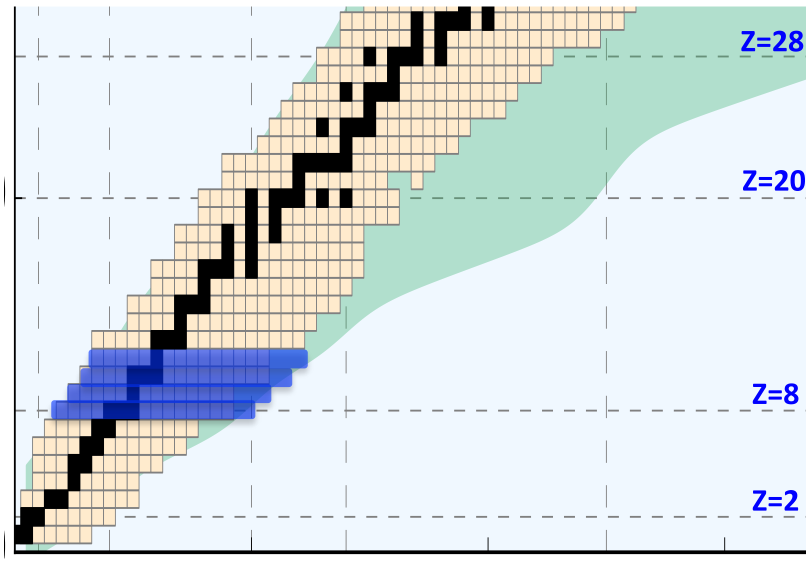
Probe dripline and beyond

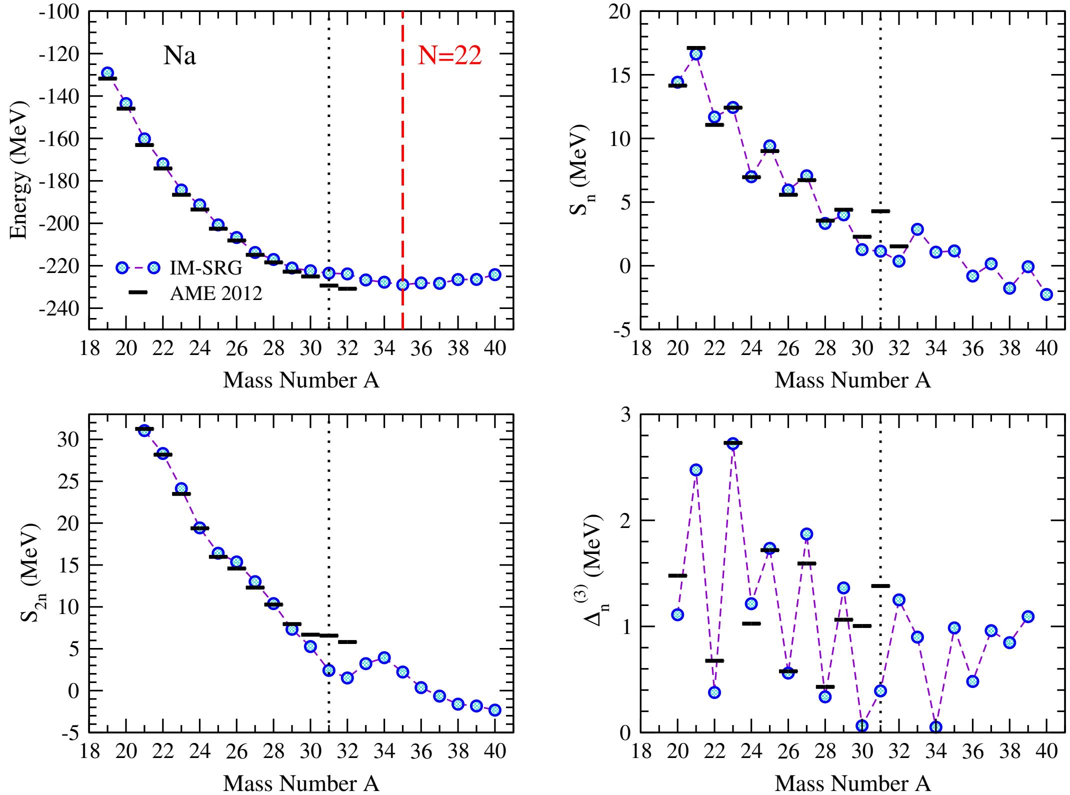
Artifacts at neutron N=20 gap

JDH, Stroberg, et al., in preparation

Ground-State Properties in sd-Shell: Na (Z=11)

Explore ground-state properties throughout medium-mass region





Remarkable agreement with experiment

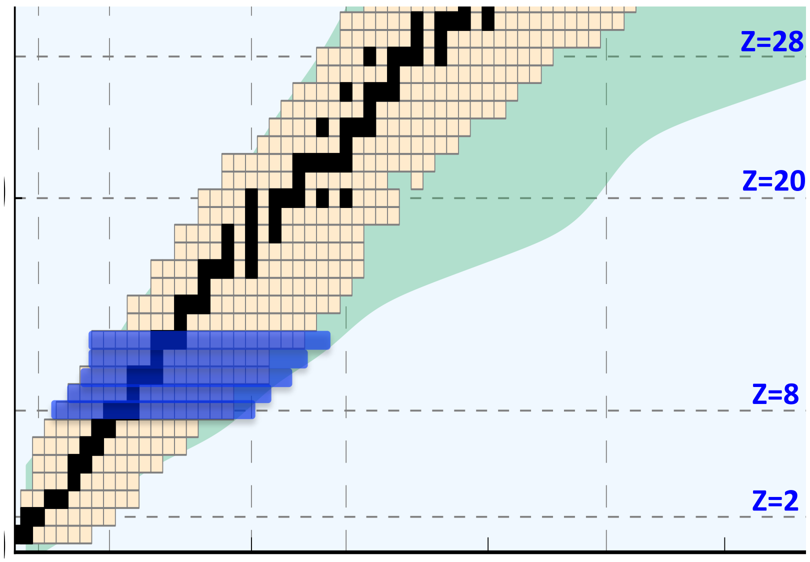
Probe dripline and beyond

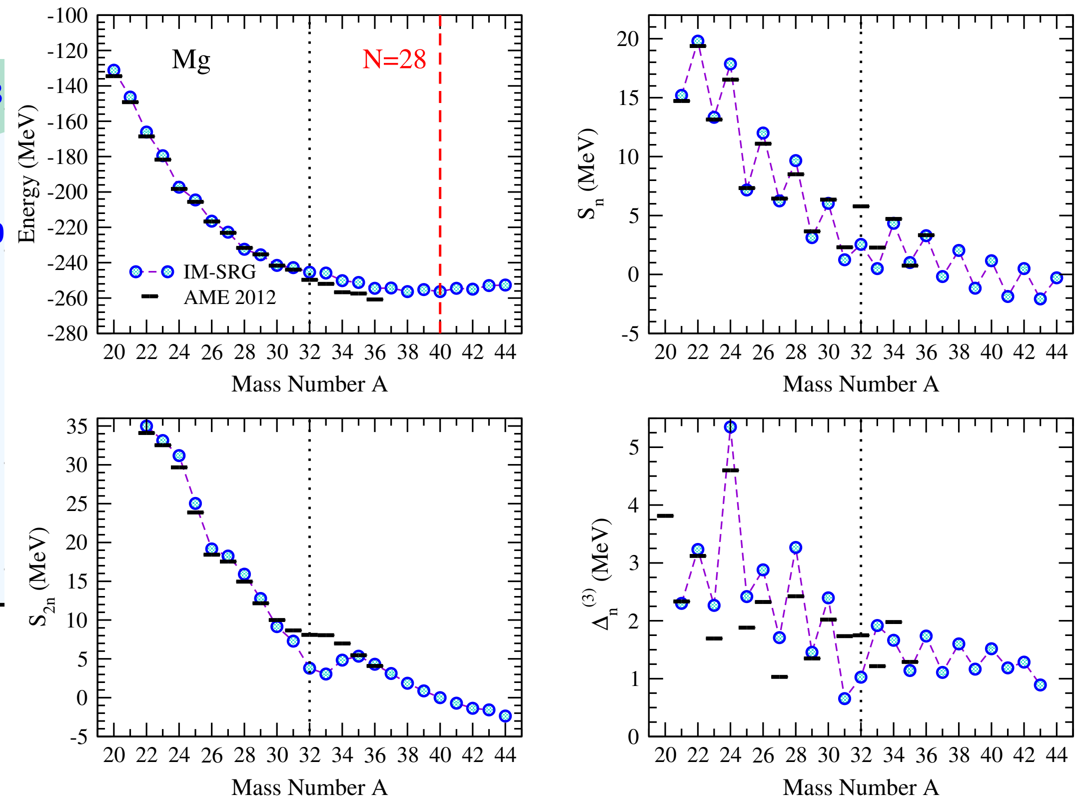
Artifacts at neutron N=20 gap

JDH, Stroberg, et al., in preparation

Ground-State Properties in sd-Shell: Mg (Z=12)

Explore ground-state properties throughout medium-mass region





Remarkable agreement with experiment

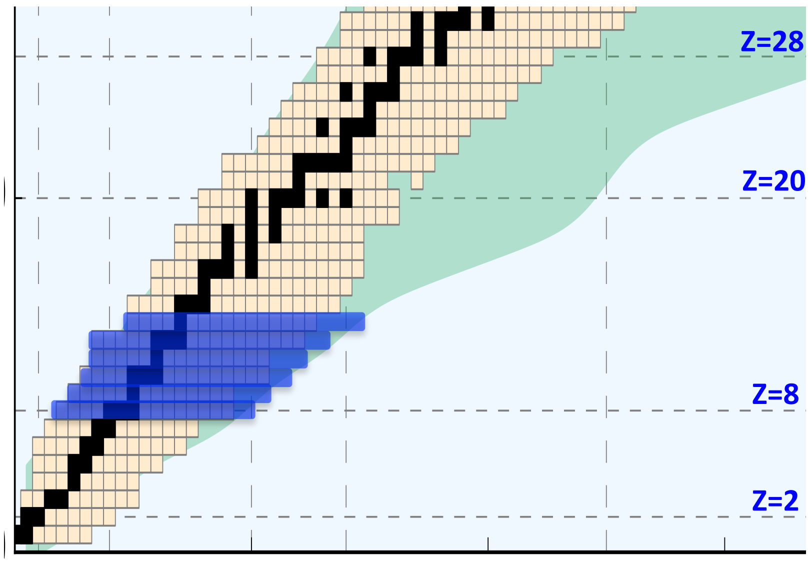
Probe dripline and beyond

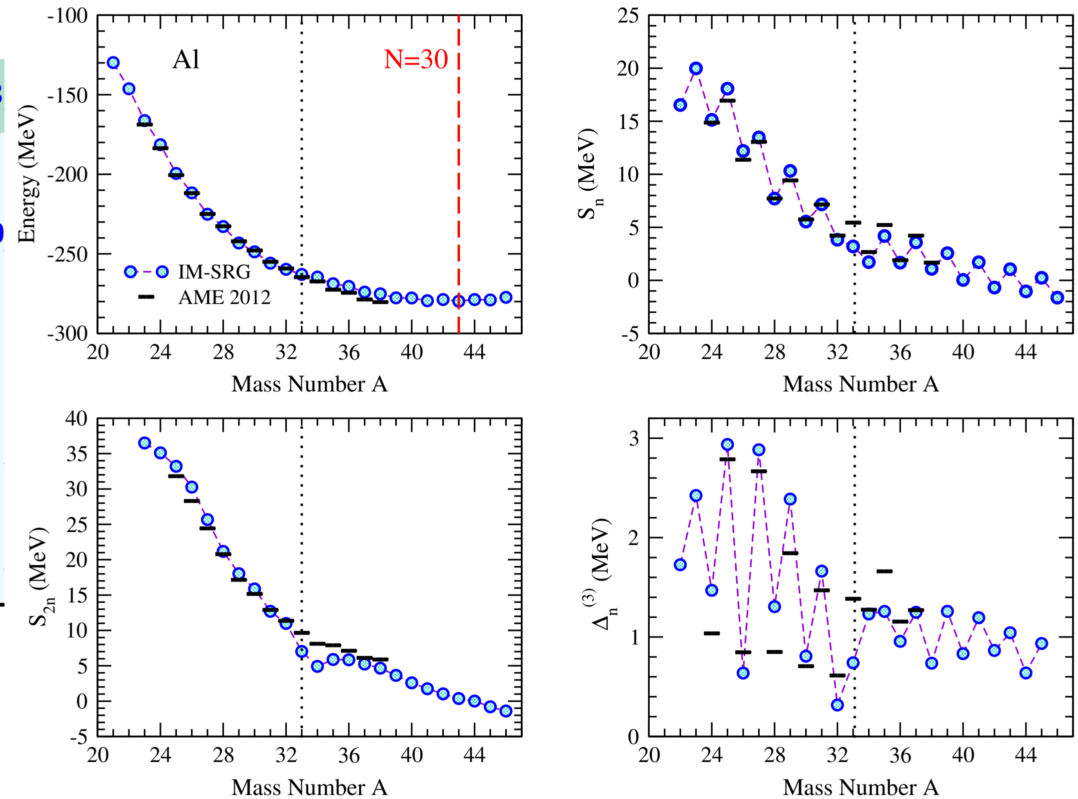
Artifacts at neutron N=20 gap

JDH, Stroberg, et al., in preparation

Ground-State Properties in sd-Shell: Al (Z=13)

Explore ground-state properties throughout medium-mass region





Remarkable agreement with experiment

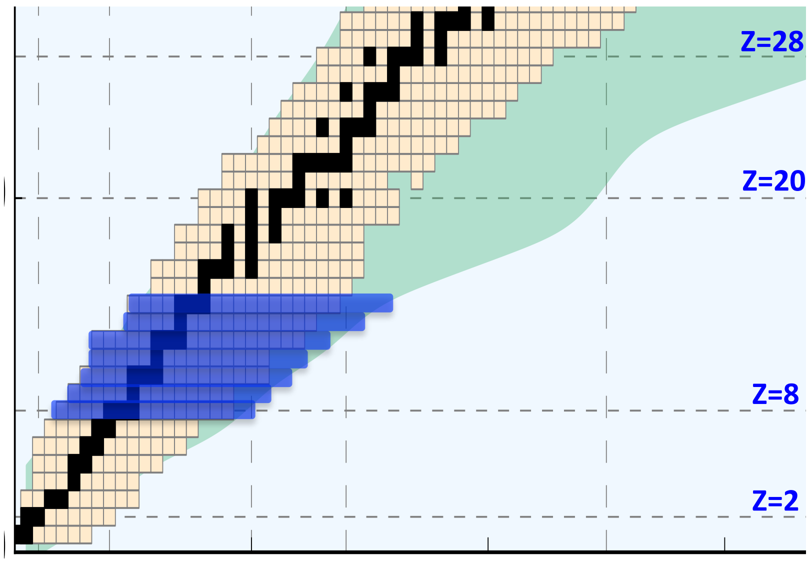
Probe dripline and beyond

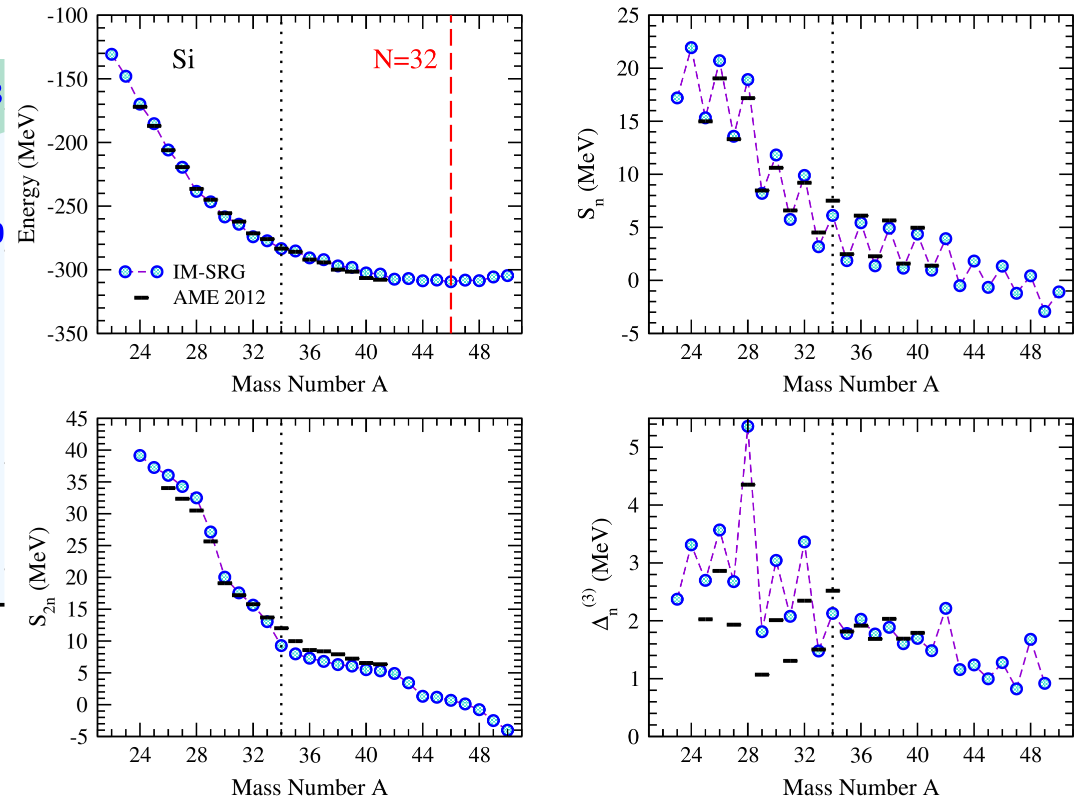
Artifacts at neutron N=20 gap

JDH, Stroberg, et al., in preparation

Ground-State Properties in sd-Shell: Si (Z=14)

Explore ground-state properties throughout medium-mass region





Remarkable agreement with experiment

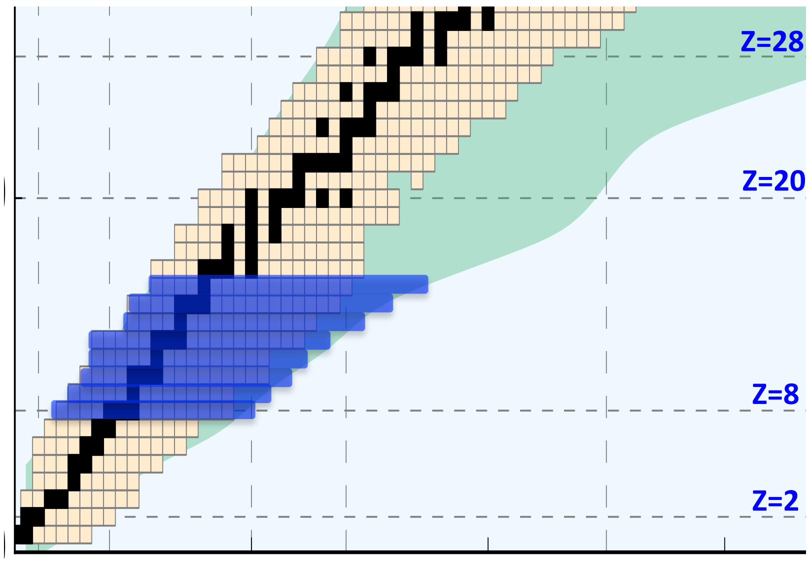
Probe dripline and beyond

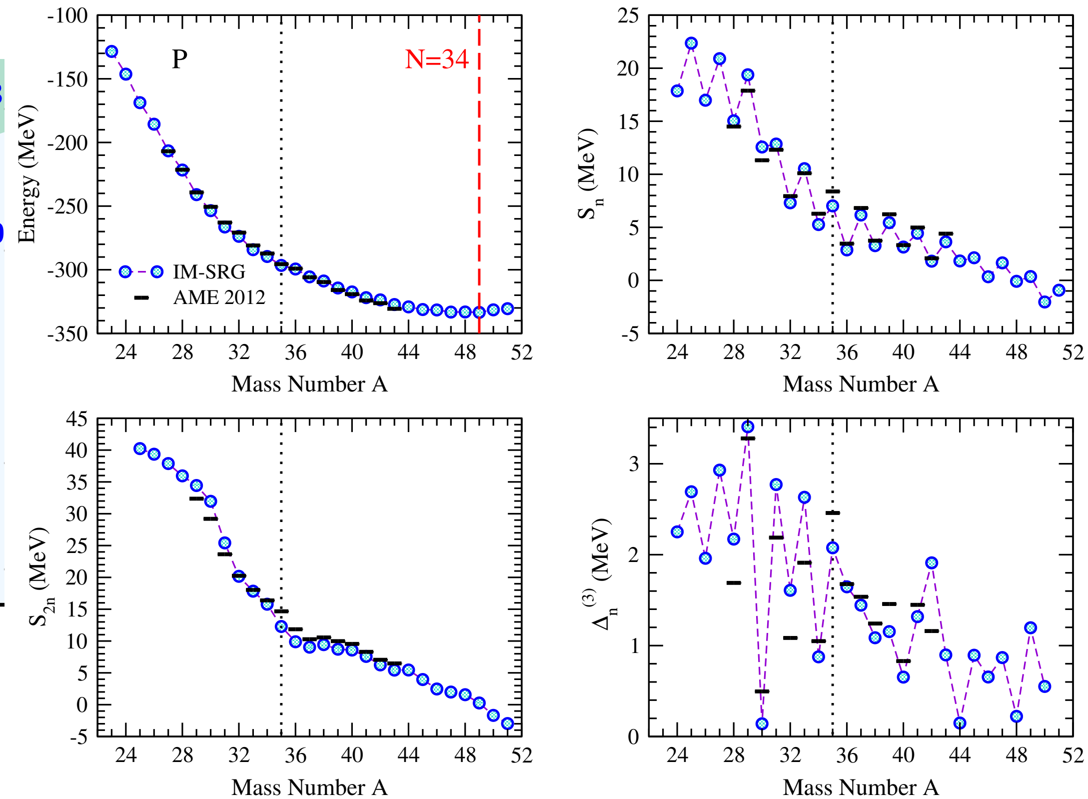
Artifacts at neutron N=20 gap

JDH, Stroberg, et al., in preparation

Ground-State Properties in sd-Shell: P (Z=15)

Explore ground-state properties throughout medium-mass region





Remarkable agreement with experiment

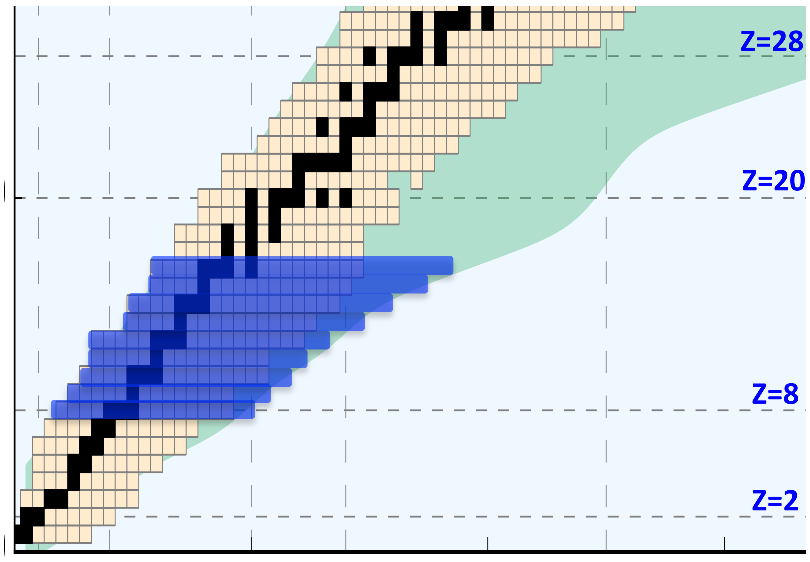
Probe dripline and beyond

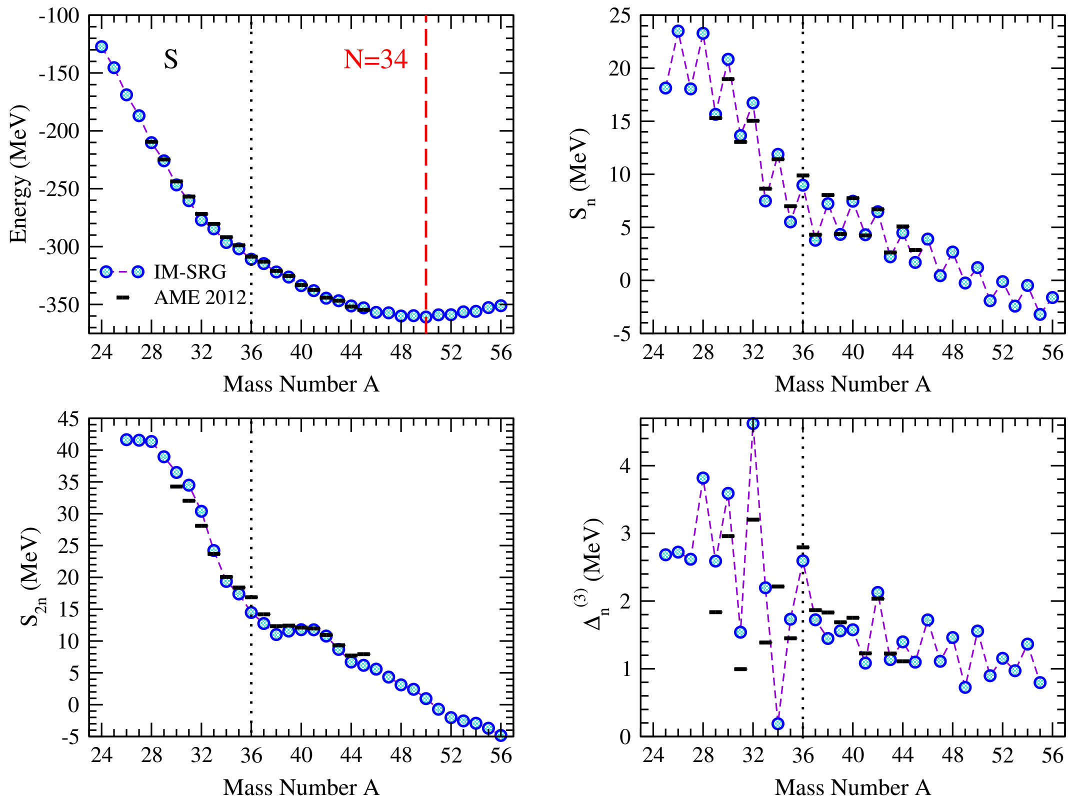
Artifacts at neutron N=20 gap

JDH, Stroberg, et al., in preparation

Ground-State Properties in sd-Shell: S (Z=16)

Explore ground-state properties throughout medium-mass region





Remarkable agreement with experiment

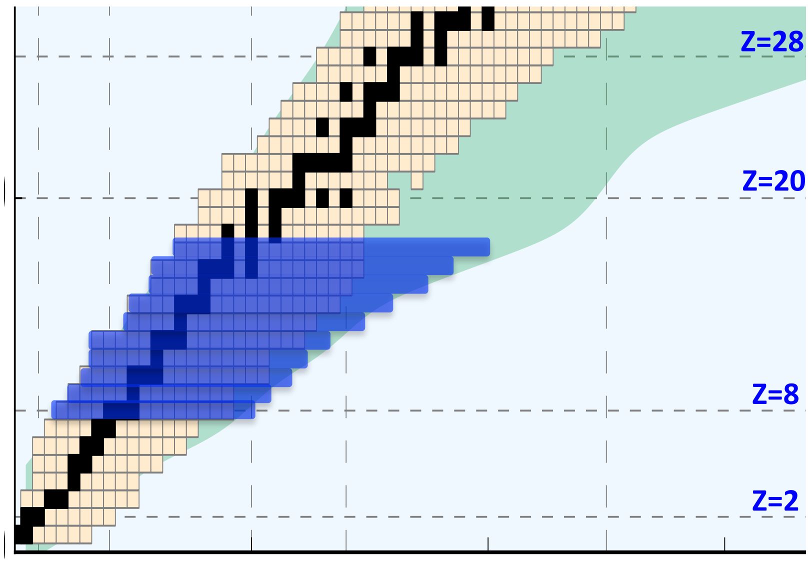
Probe dripline and beyond

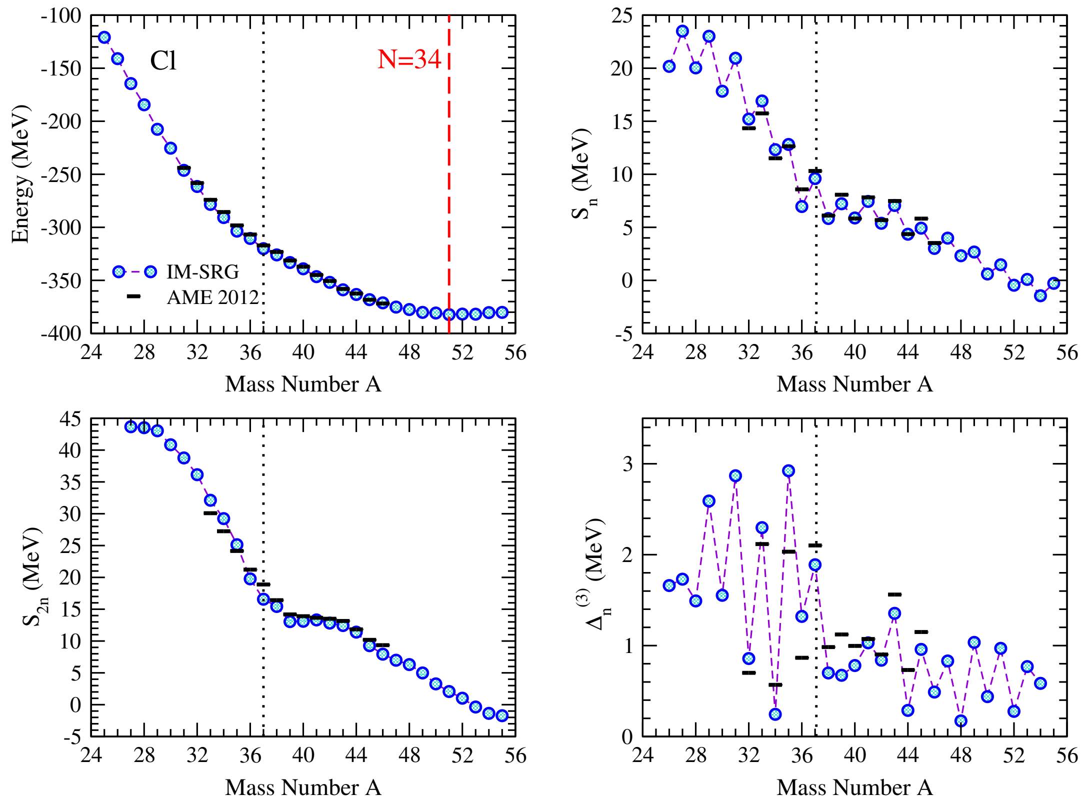
Artifacts at neutron N=20 gap

JDH, Stroberg, et al., in preparation

Ground-State Properties in sd-Shell: Cl (Z=17)

Explore ground-state properties throughout medium-mass region





Remarkable agreement with experiment

Probe dripline and beyond

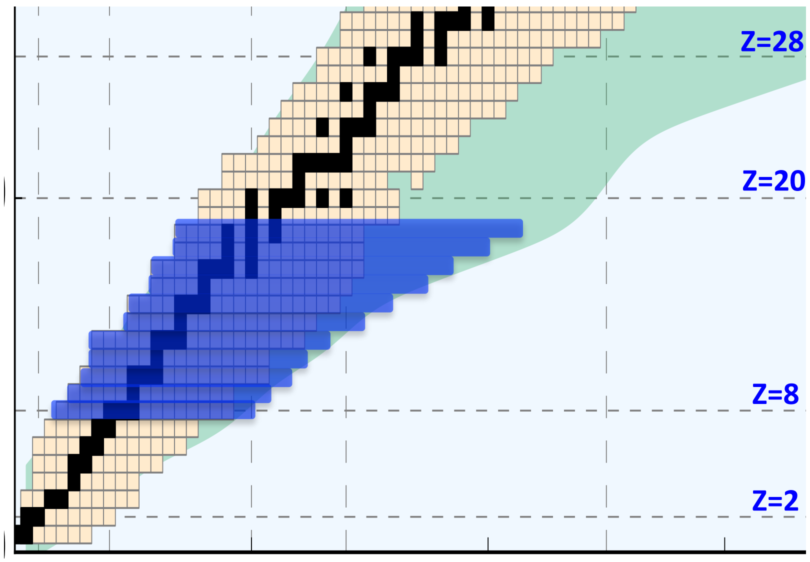
Artifacts at neutron N=20 gap

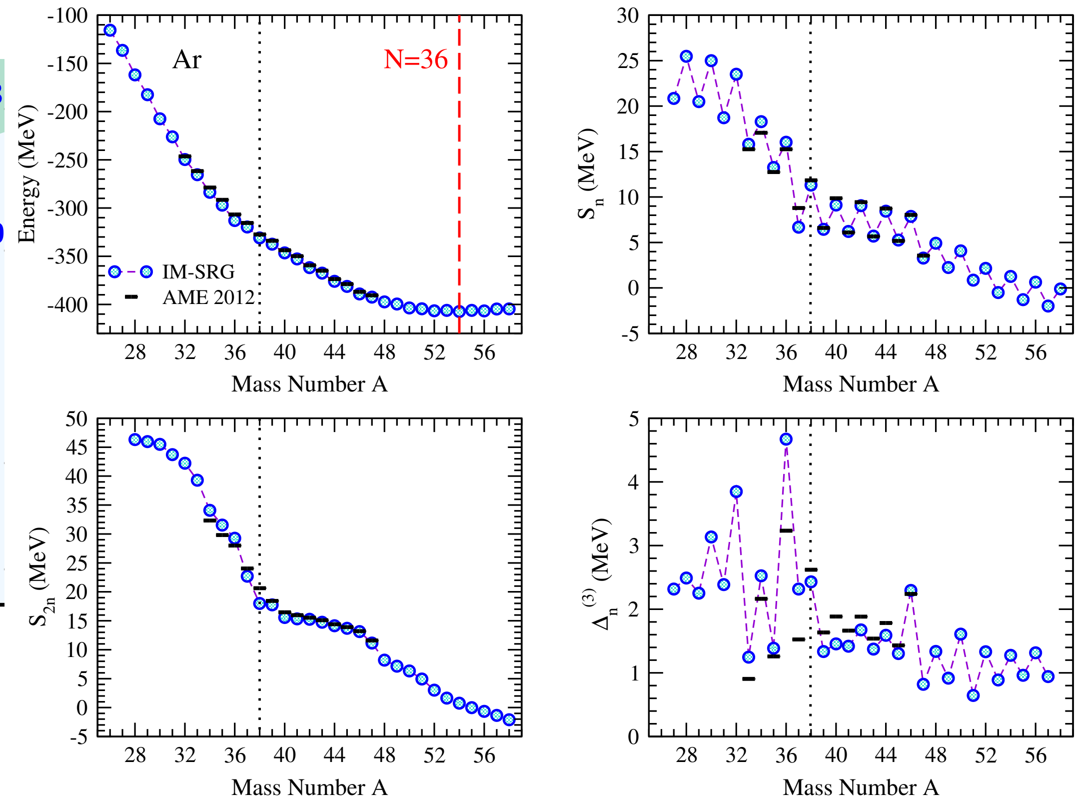
JDH, Stroberg, et al., in preparation

Ground-State Properties in sd-Shell: Ar (Z=18)

TRIUMF

Explore ground-state properties throughout medium-mass region





Remarkable agreement with experiment

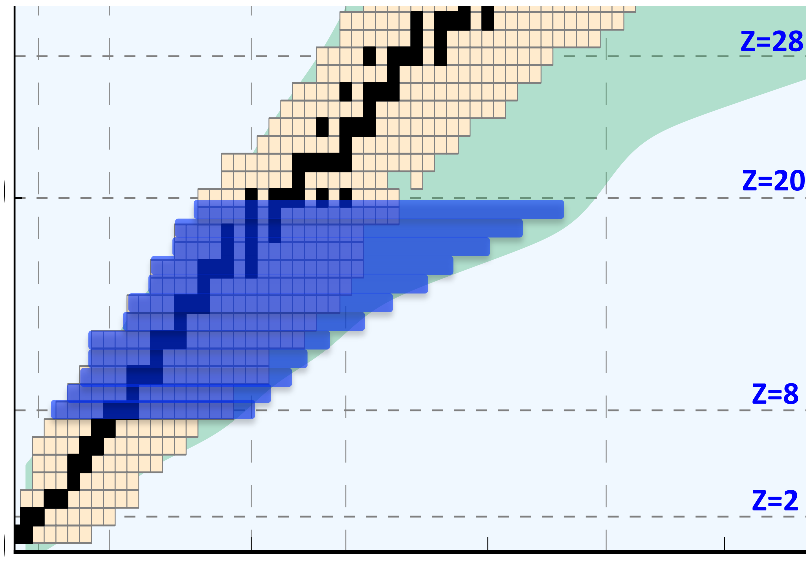
Probe dripline and beyond

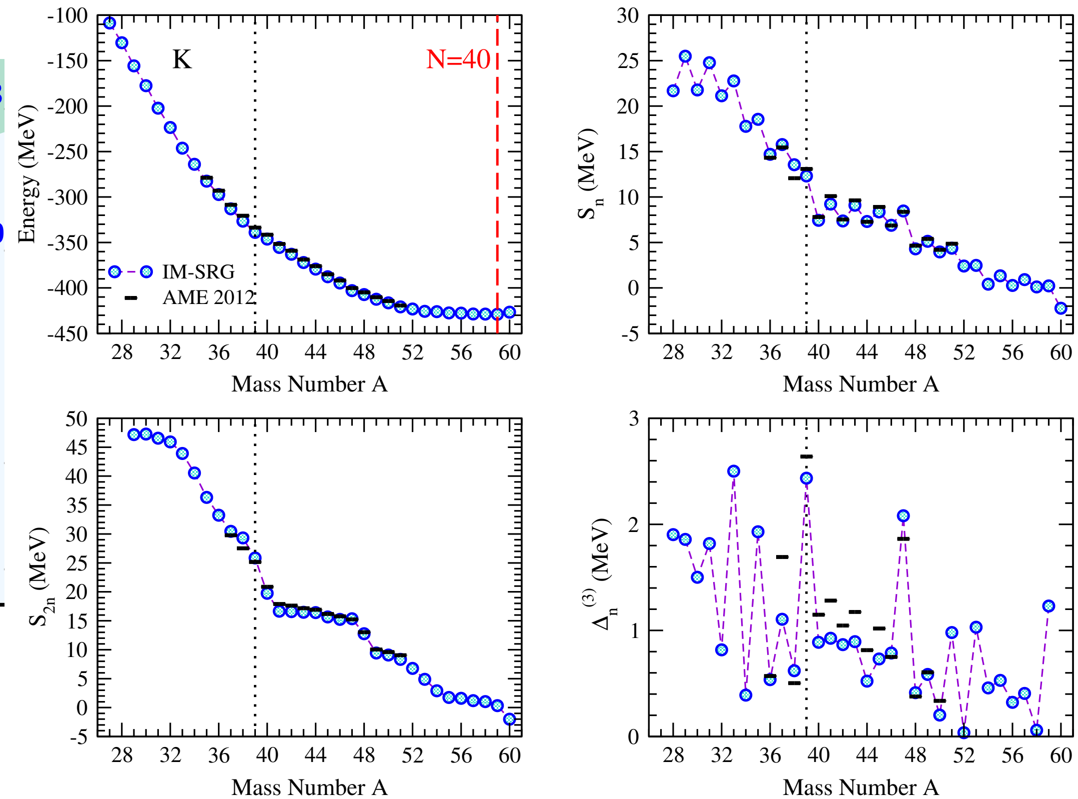
Artifacts at neutron N=20 gap

JDH, Stroberg, et al., in preparation

Ground-State Properties in sd-Shell: K (Z=19)

Explore ground-state properties throughout medium-mass region





Remarkable agreement with experiment

Probe dripline and beyond

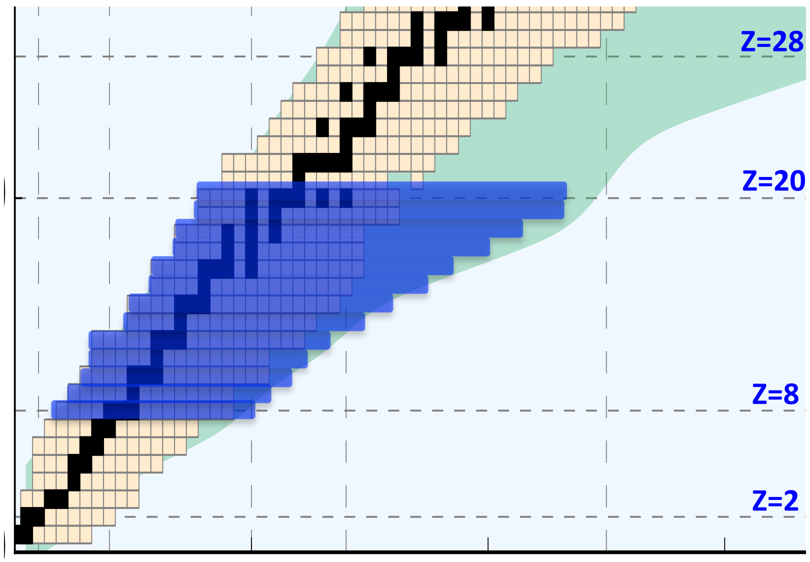
Artifacts at neutron N=20 gap

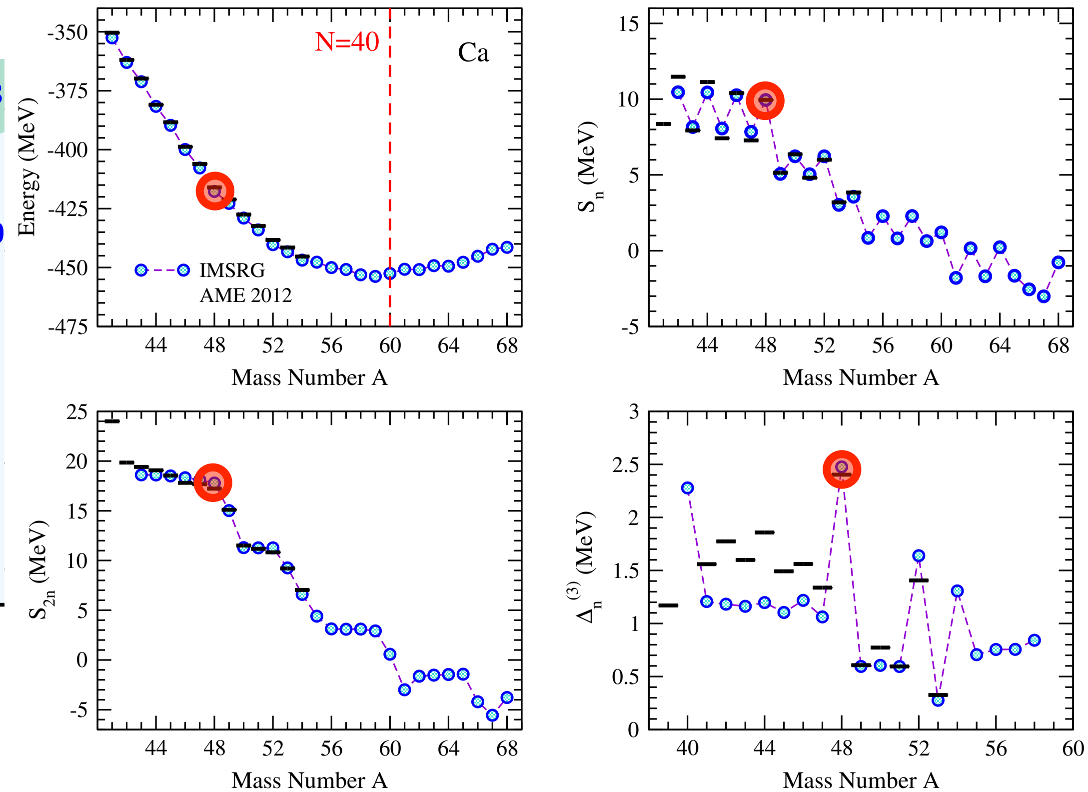
JDH, Stroberg, et al., in preparation

TRIUMF

Ground-State Properties in pf-Shell: Ca (Z=20)

Explore ground-state properties throughout medium-mass region





Remarkable agreement with experiment

Probe dripline and beyond

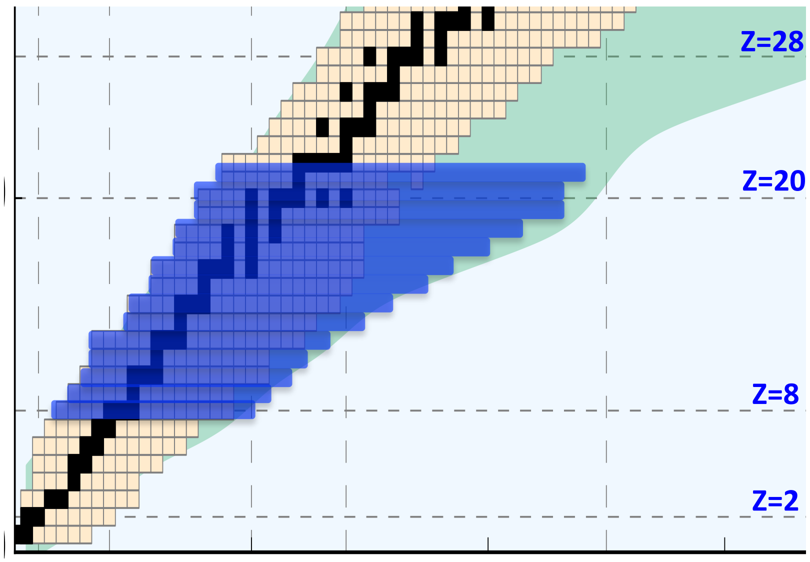
Artifacts at neutron N=40 gap

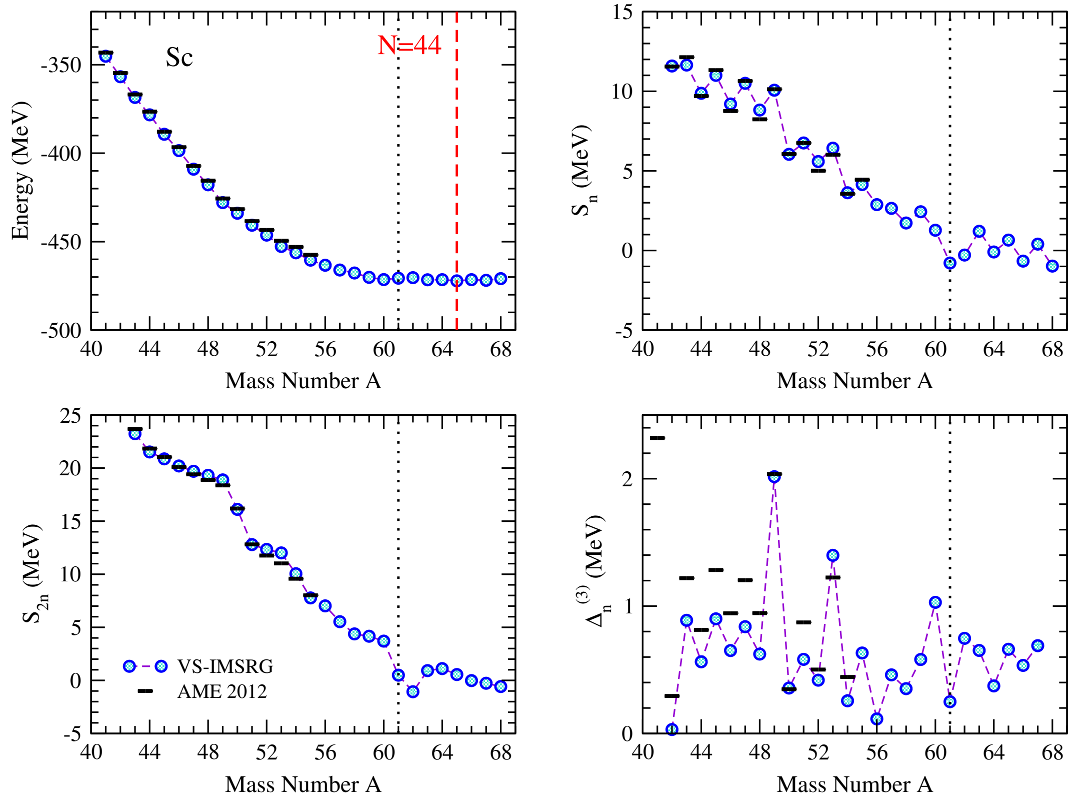
JDH, Stroberg, et al., in preparation

TRIUMF

Ground-State Properties in pf-Shell: Sc (Z=21)

Explore ground-state properties throughout medium-mass region





Remarkable agreement with experiment

Probe dripline and beyond

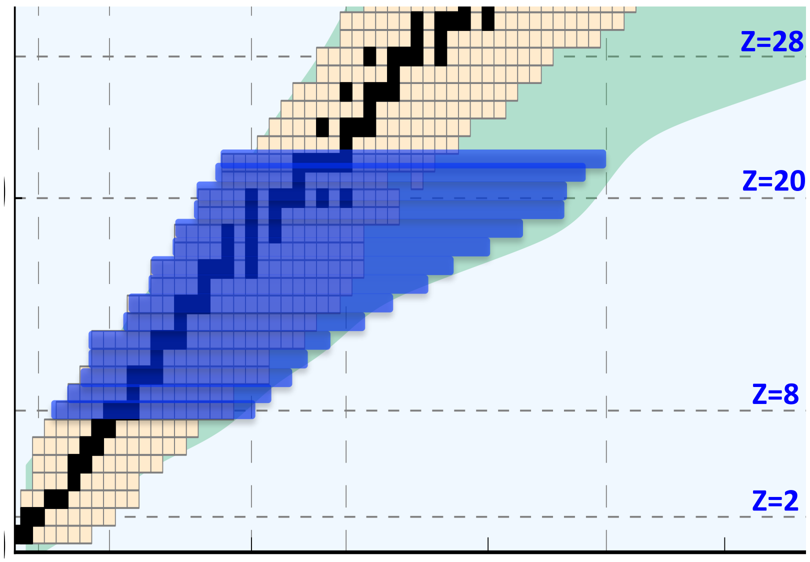
Artifacts at neutron N=40 gap

JDH, Stroberg, et al., in preparation

Ground-State Properties in pf-Shell: Ti (Z=22)

TRIUMF

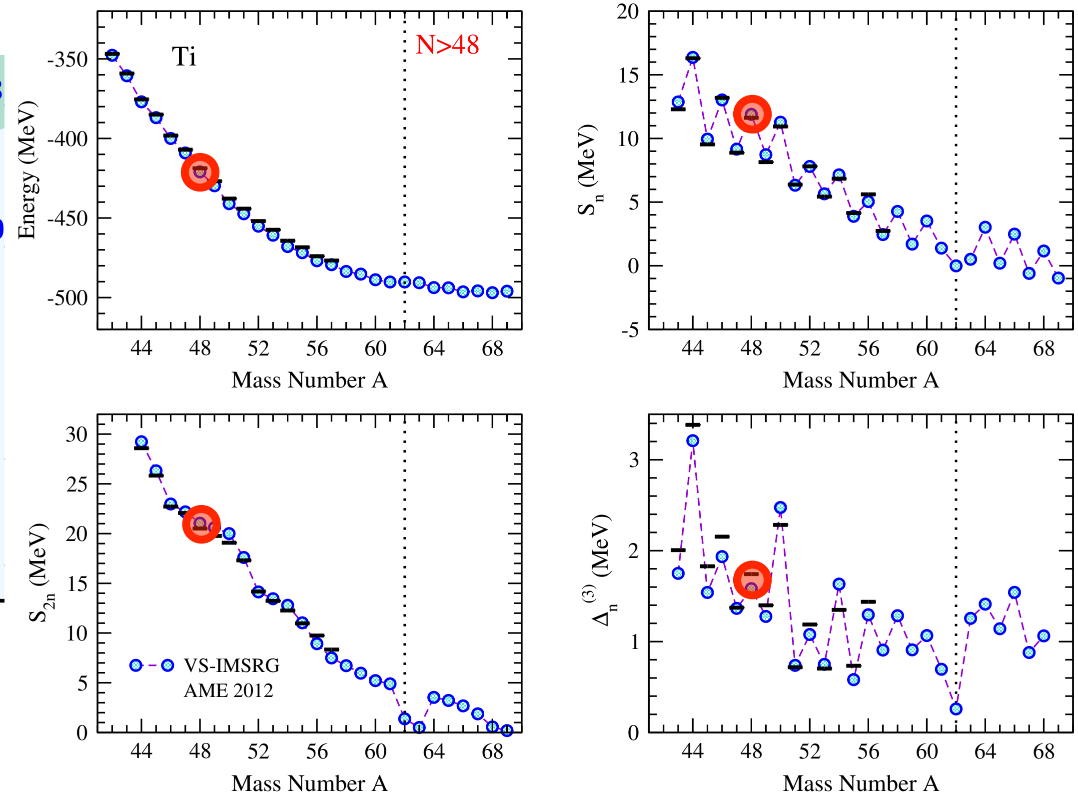
Explore ground-state properties throughout medium-mass region



Remarkable agreement with experiment

Probe dripline and beyond

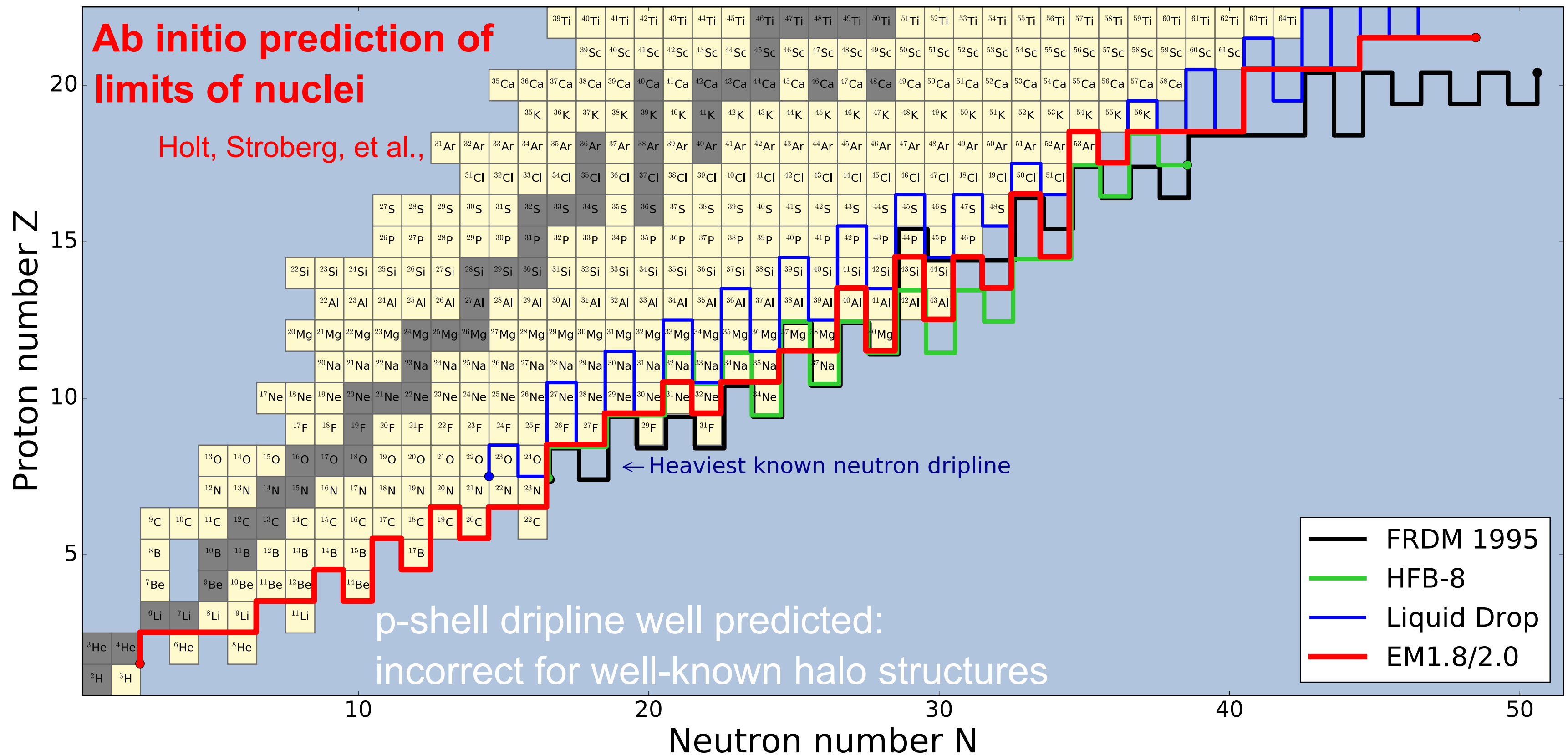
Artifacts at neutron N=40 gap



JDH, Stroberg, et al., in preparation

TRIUMF

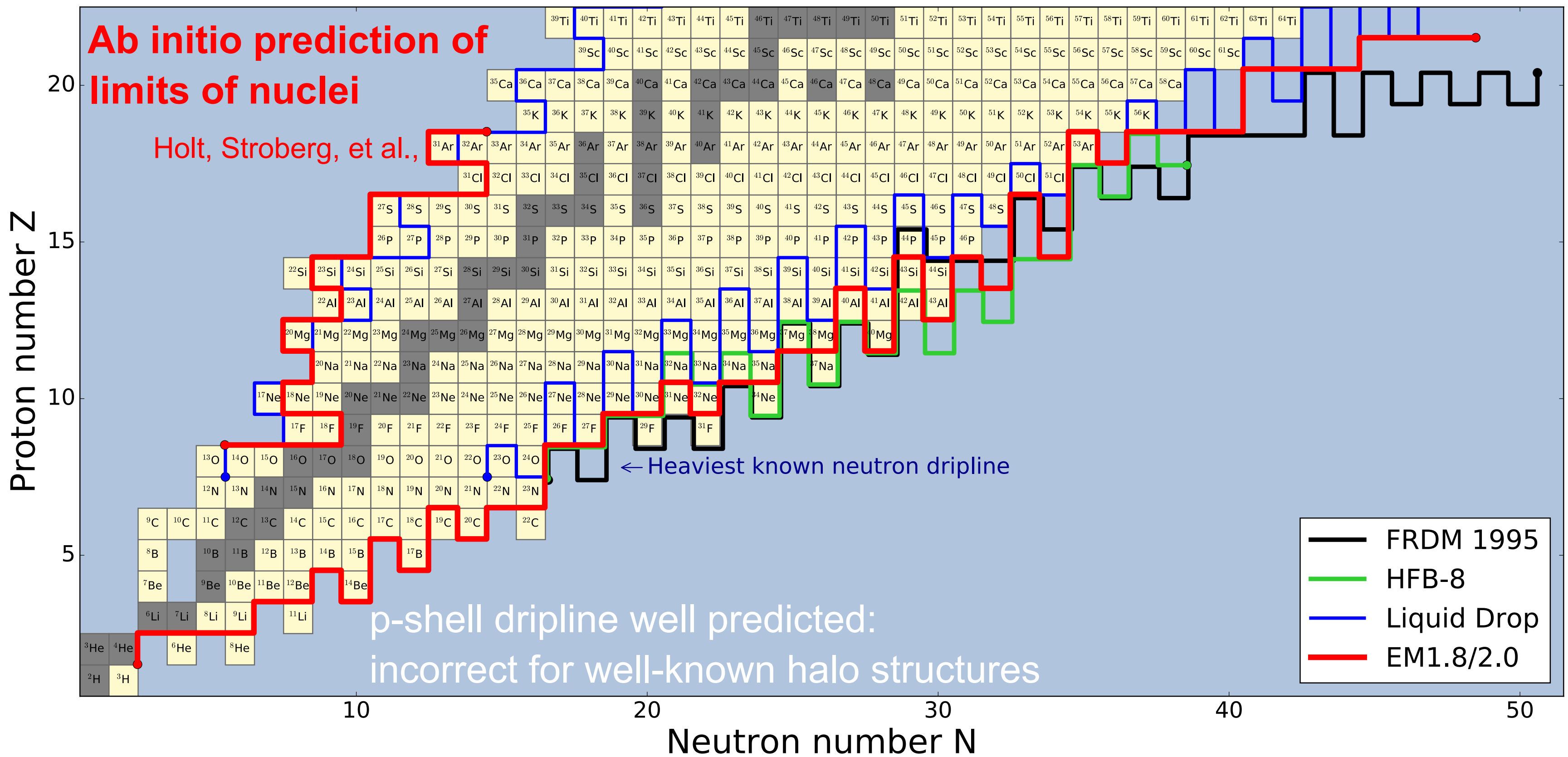
Ab Initio Dripline Prediction



General agreement with model predictions

Significant differences arise for heavy nuclei

Ab Initio Dripline Prediction

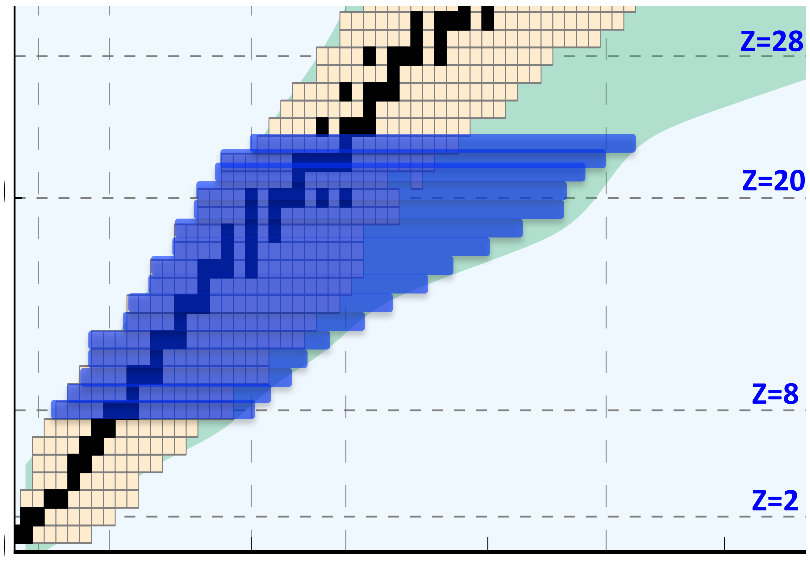


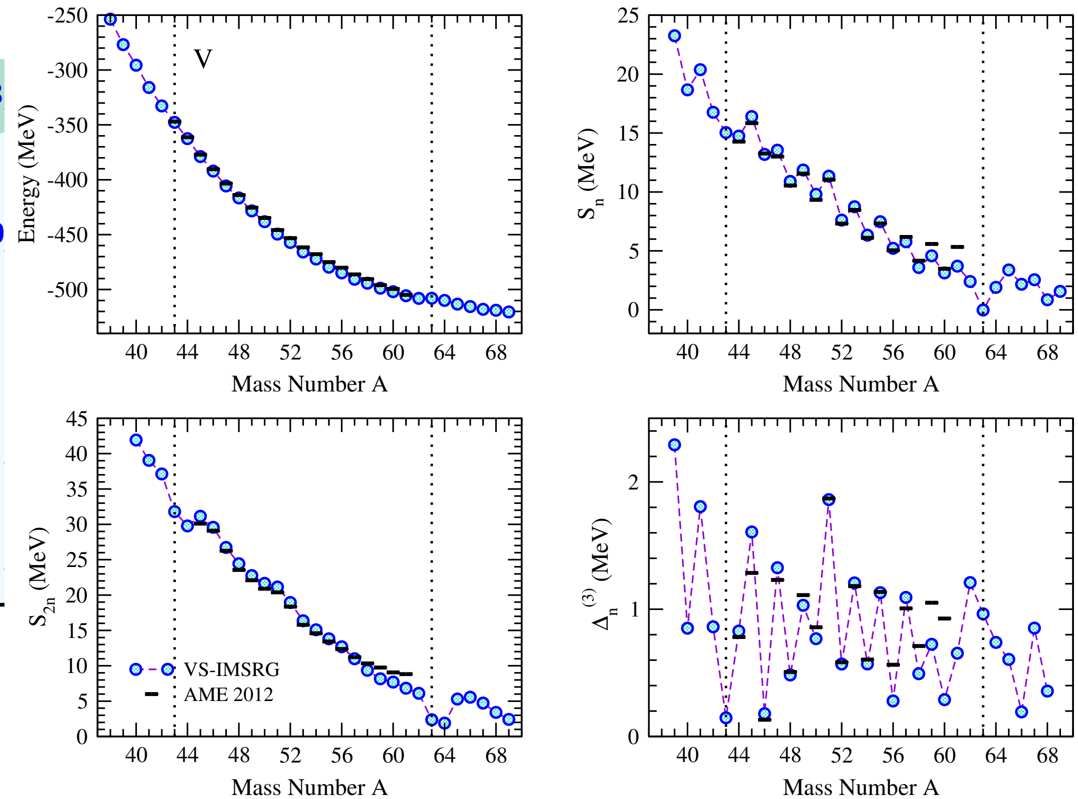
General agreement with model predictions

Proton dripline: very good agreement with experiment

Ground-State Properties in pf-Shell: V (Z=23)

Explore ground-state properties throughout medium-mass region





Remarkable agreement with experiment

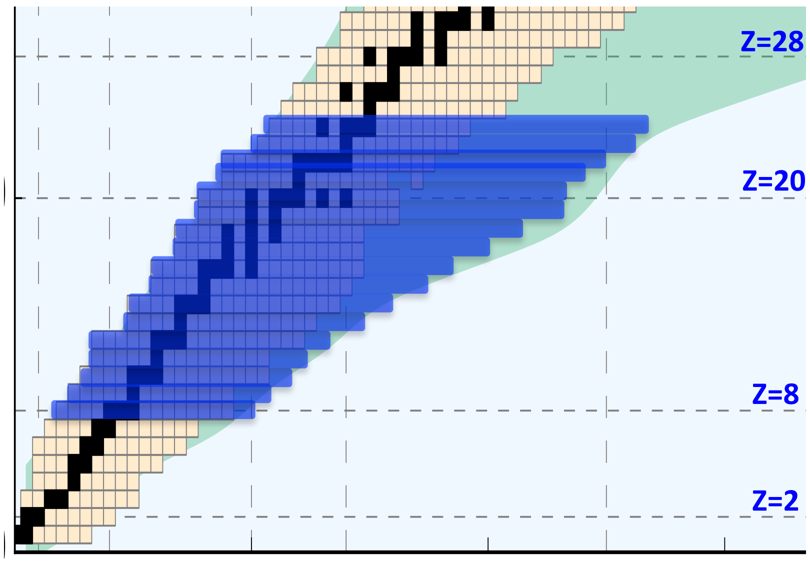
Probe dripline and beyond

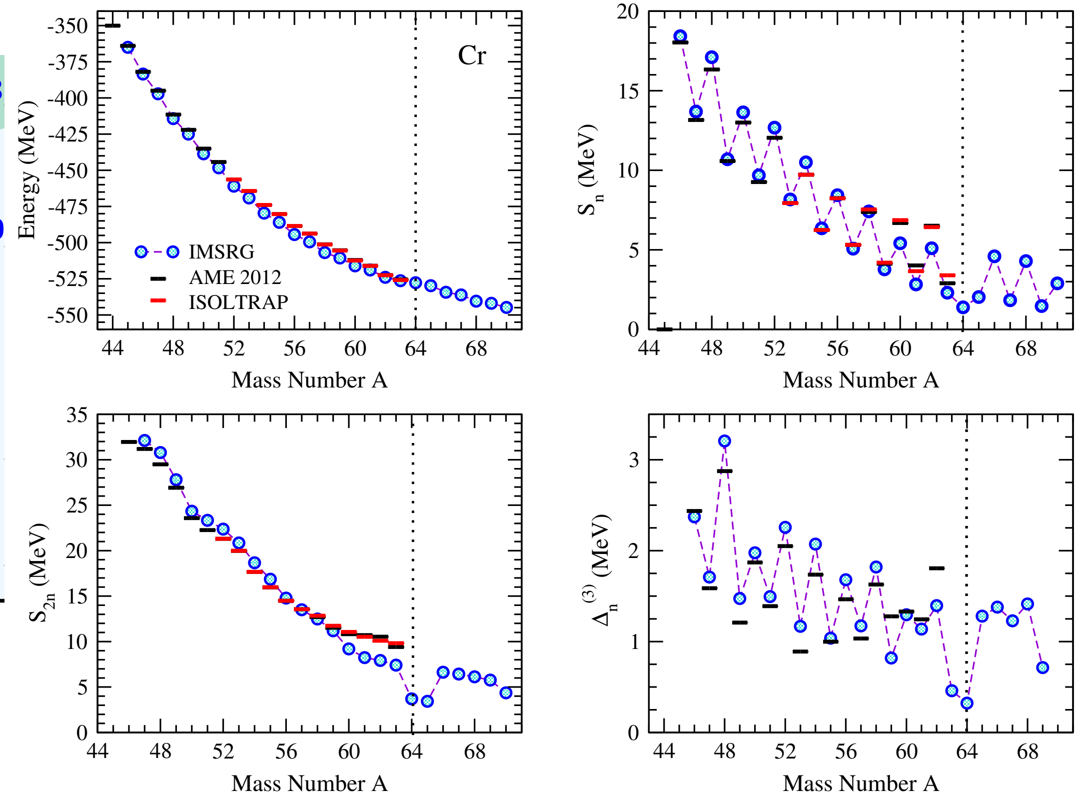
Artifacts at neutron N=40 gap

JDH, Stroberg, et al., in preparation

Ground-State Properties in pf-Shell: Cr (Z=24)

Generally deformed, new data from ISOLTRAP

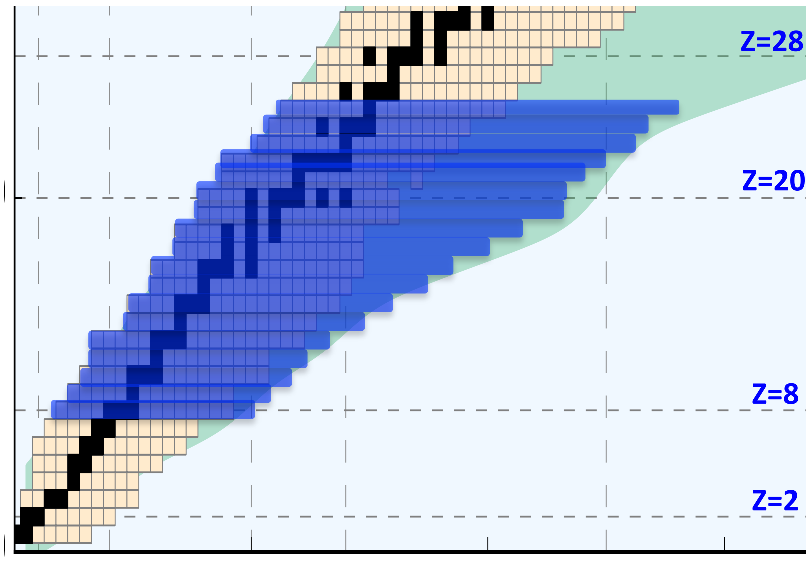


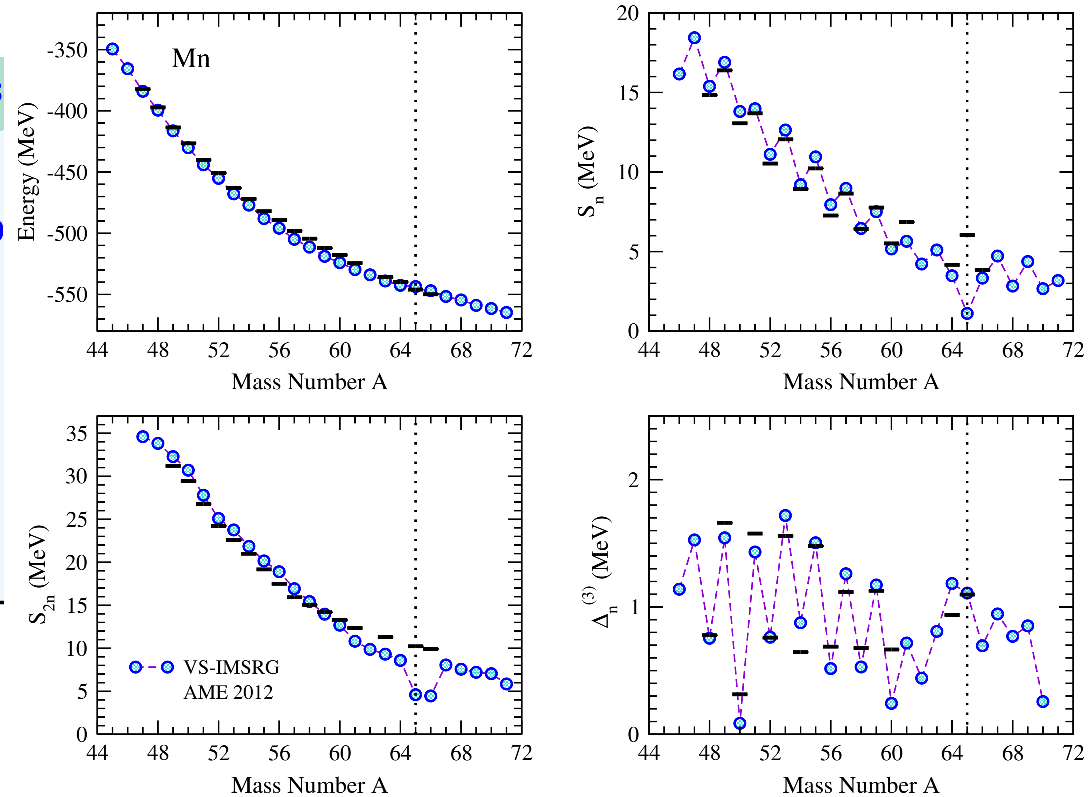


JDH, Stroberg, et al., in preparation

Ground-State Properties in pf-Shell: Mn (Z=25)

Explore ground-state properties throughout medium-mass region





Remarkable agreement with experiment

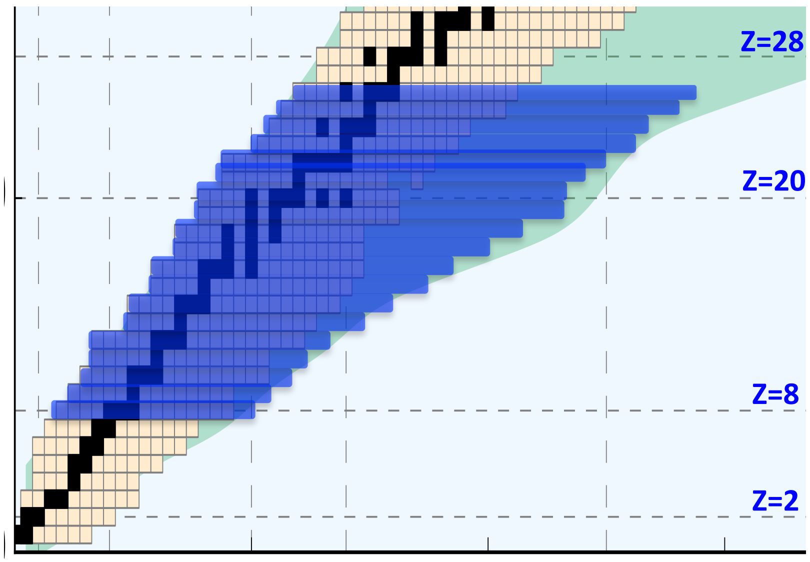
Probe dripline and beyond

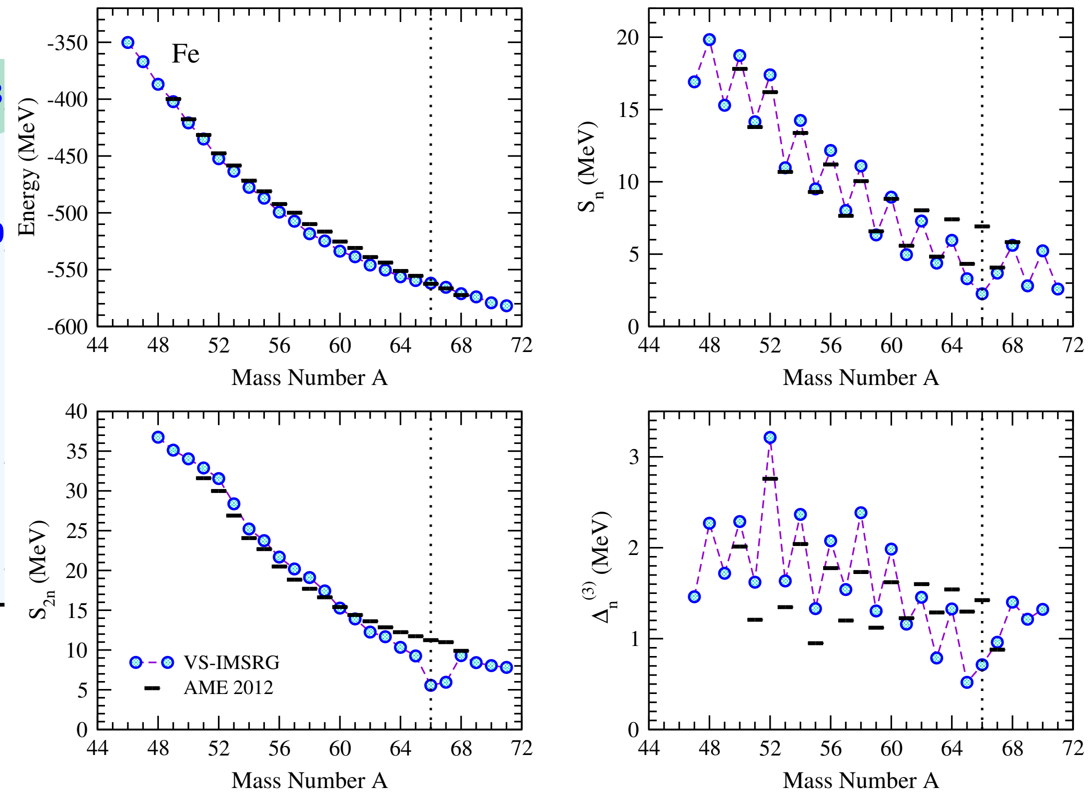
Artifacts at neutron N=40 gap

JDH, Stroberg, et al., in preparation

Ground-State Properties in pf-Shell: Fe (Z=26)

Explore ground-state properties throughout medium-mass region





Remarkable agreement with experiment

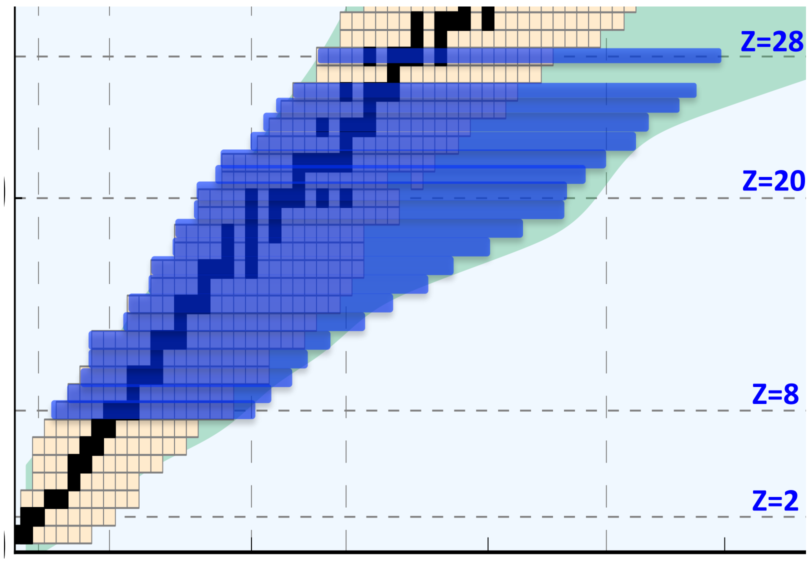
Probe dripline and beyond

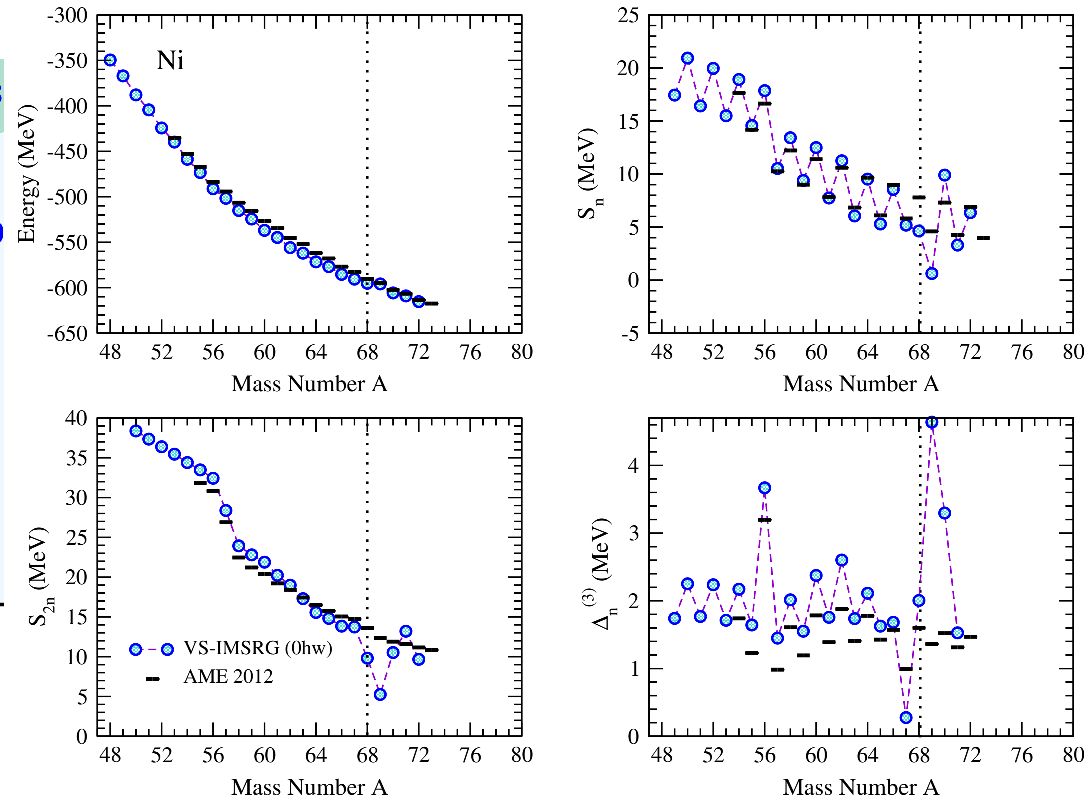
Artifacts at neutron N=40 gap

JDH, Stroberg, et al., in preparation

Ground-State Properties in pf-Shell: Ni (Z=28)

Explore ground-state properties throughout medium-mass region





Remarkable agreement with experiment

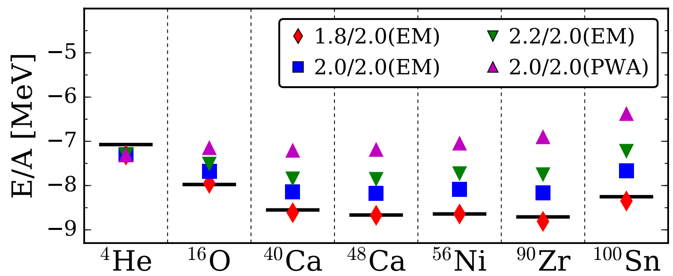
Probe dripline and beyond

Artifacts at neutron N=40 gap

JDH, Stroberg, et al., in preparation

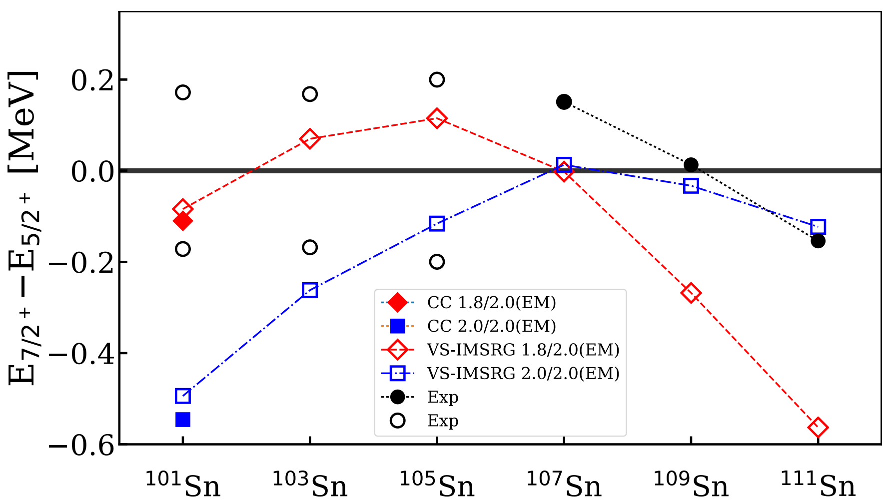
Ab Initio for Structure of Lightest Tin Isotopes

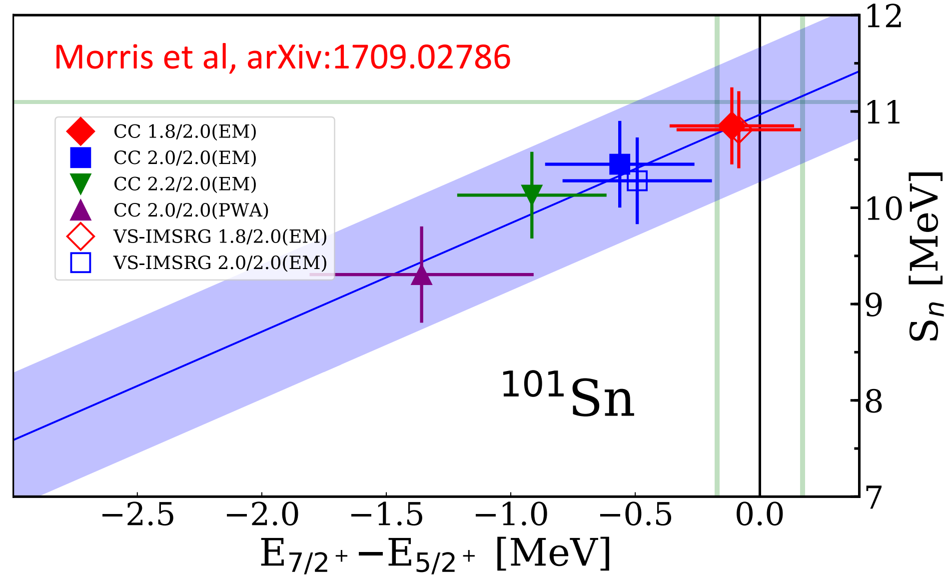
Level ordering near ^{101}Sn controversial and unknown: insights from ab initio valence-space IMSRG



1.8/2.0(EM) reproduces gs energies across chart

Use in study of Sn isotopes



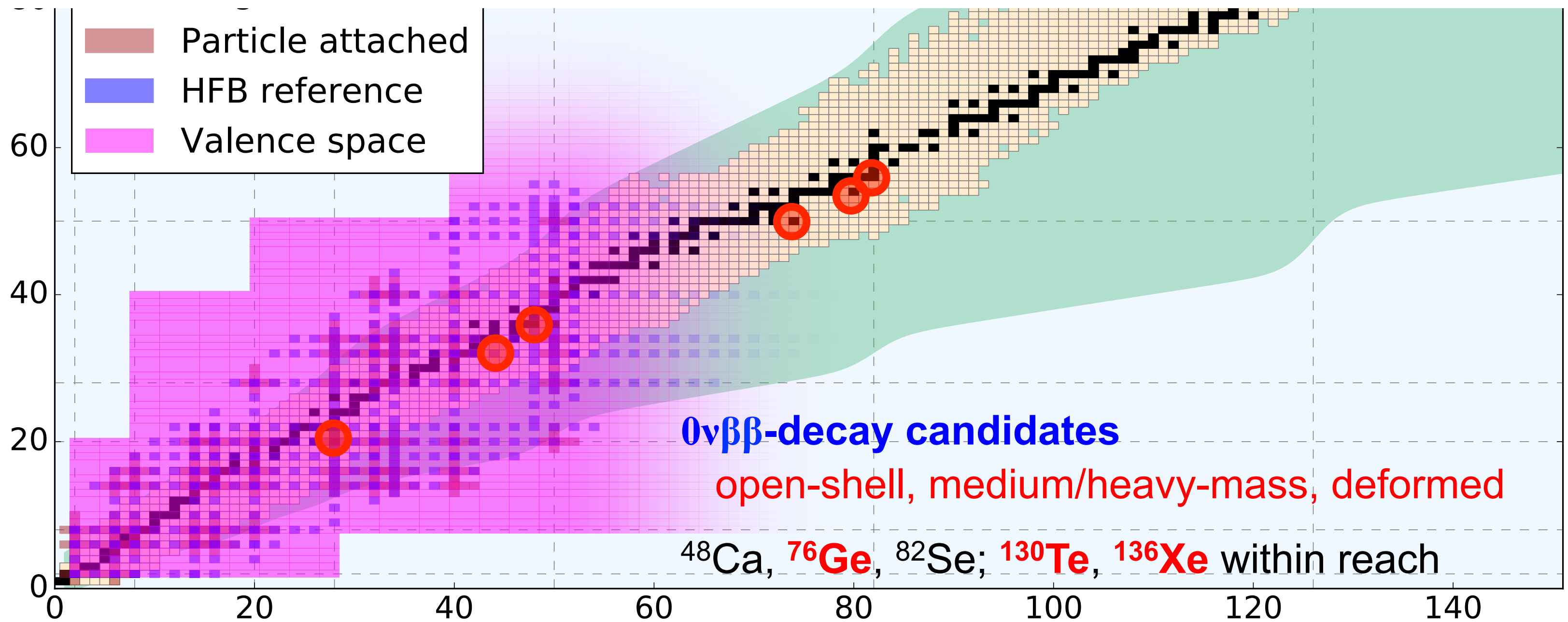


Ab initio predicts $5/2^+$ ground state, but within theoretical uncertainties

Towards big questions: $0\nu\beta\beta$-decay

Aim of modern nuclear theory: Develop unified *first-principles* picture of structure and reactions

- Nuclear forces (low-energy QCD)
- Electroweak physics
- Nuclear many-body problem



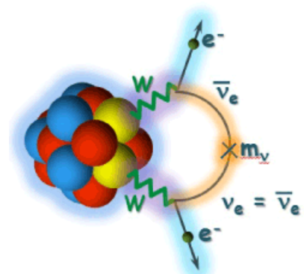
TRIUMF Ab Initio 0νββ-Decay Predictions from Valence-Space IMSRG

Conventional SM: phenomenological wavefunctions

Ab initio SM: wavefunctions from chiral NN+3N forces

$$M^{0\nu} = M^{0\nu}_{GT} - \frac{M^{0\nu}_{F}}{g_A^2} + M^{0\nu}_{T}$$

$$M^{0\nu}_{GT} = \langle f | \sum_{ab} H(r_{ab}) \sigma_a \cdot \sigma_b \, \tau_a^+ \tau_b^+ | i \rangle$$



Neutrinoless double beta decay

1) Ab initio energies in medium/heavy-mass region

Valence-space IM-SRG for all medium-mass nuclei

TRIUMF Ab Initio 0νββ-Decay Predictions from Valence-Space IMSRG

Conventional SM: phenomenological wavefunctions

Ab initio SM: wavefunctions from chiral NN+3N forces

$$M^{0\nu} = M^{0\nu}_{GT} - \frac{M^{0\nu}_F}{g_A^2} + M^{0\nu}_T$$

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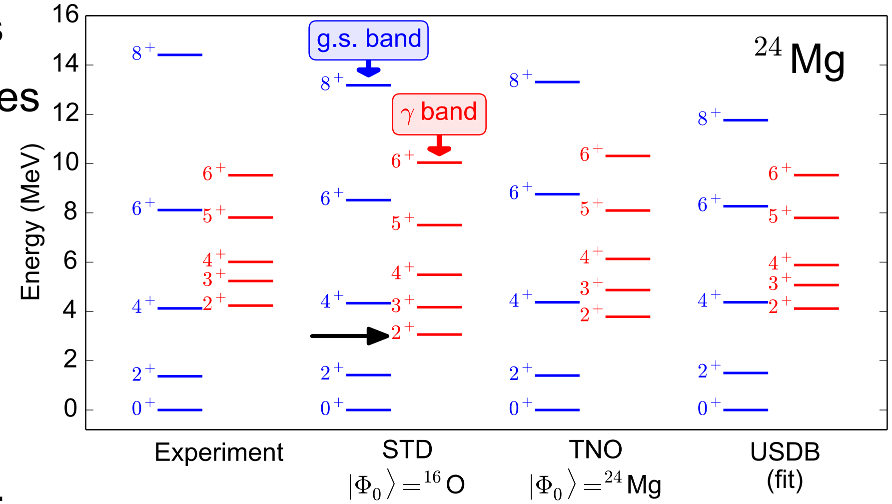

1) Ab initio energies in medium/heavy-mass region

Valence-space IM-SRG for all medium-mass nuclei

Deformation challenging for large-space methods

TRIUMF

Ab Initio 0νββ-Decay Predictions from Valence-Space IMSRG

Conventional SM: phenomenological wavefunctions

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$$M^{0\nu} = M^{0\nu}_{GT} - \frac{M^{0\nu}_{F}}{g_A^2} + M^{0\nu}_{T}$$

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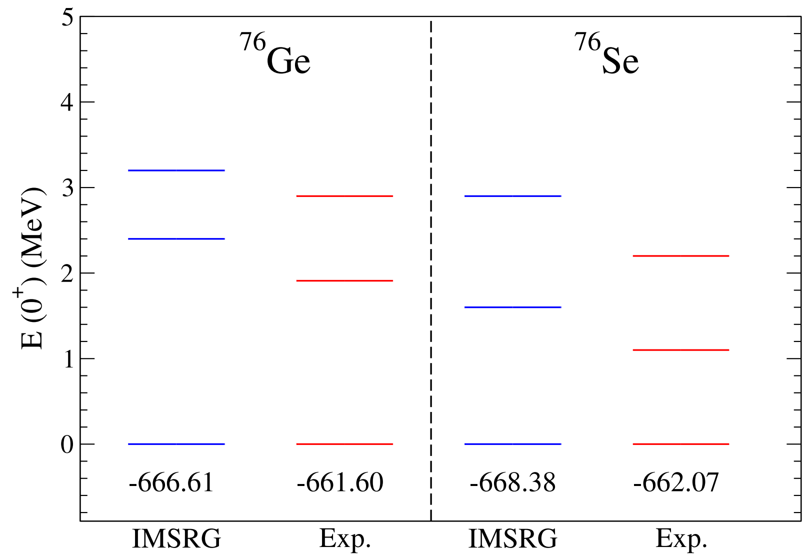


1) ✓ Ab initio energies in medium/heavy-mass region

Valence-space IM-SRG for all medium-mass nuclei

Deformation challenging for large-space methods

First ab initio calculation of ^{76}Ge/^{76}Se

TRIUMF

Ab Initio 0νββ-Decay Predictions in the Shell Model

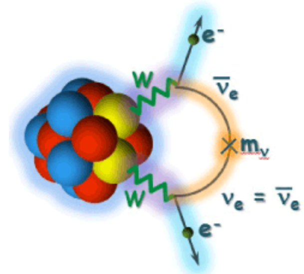
Conventional SM: phenomenological wavefunctions + **bare operator**

Ab initio SM: wavefunctions from chiral NN+3N forces + **consistent effective operator**

$$M^{0\nu} = M^{0\nu}_{GT} - \frac{M^{0\nu}_F}{g_A^2} + M^{0\nu}_T$$

$$M^{0\nu}_{GT} = \langle f | \sum_{ab} H(r_{ab}) \sigma_a \cdot \sigma_b \, \tau_a^+ \tau_b^+ | i \rangle$$

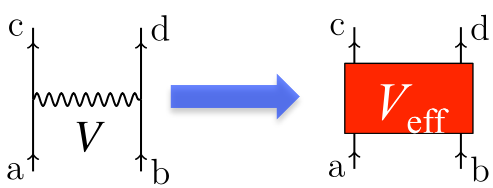
M_{eff}

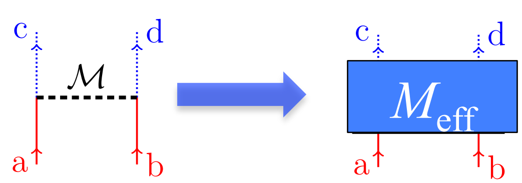


Neutrinoless double beta decay

1) ✓ Ab initio energies in medium/heavy-mass region

2) Effective decay operator: decouple valence-space operator (analogous to Hamiltonian)





Payne, Stroberg, JDH, Menendez, in preparation

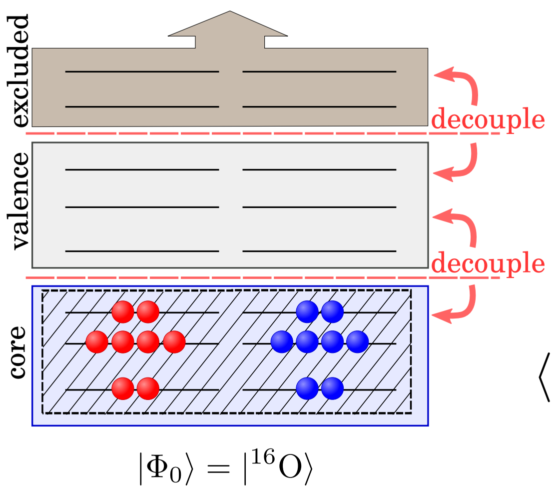
Effective Valence-Space In-Medium SRG Operators

Explicitly construct unitary transformation from sequence of rotations

$$U = e^{\Omega} = e^{\eta_n} \dots e^{\eta_1}$$

$$\tilde{H} = e^{\Omega} H e^{-\Omega} = H + [\Omega, H] + \frac{1}{2}[\Omega, [\Omega, H]] + \cdots$$

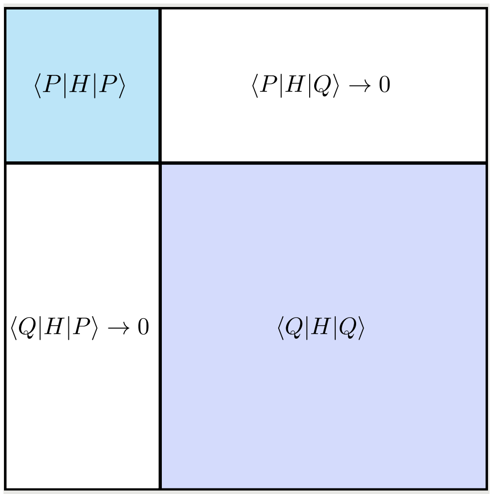
$$\tilde{\mathcal{O}} = e^{\Omega} \mathcal{O} e^{-\Omega} = \mathcal{O} + [\Omega, \mathcal{O}] + \frac{1}{2}[\Omega, [\Omega, \mathcal{O}]] + \cdots$$



Step 1: Decouple core
Step 2: Decouple valence space
Step 3: Decouple additional operators

$$\langle \tilde{\Psi}_n | P\tilde{H}P \mid \tilde{\Psi}_n \rangle \approx \langle \Psi_i | H | \Psi_i \rangle$$

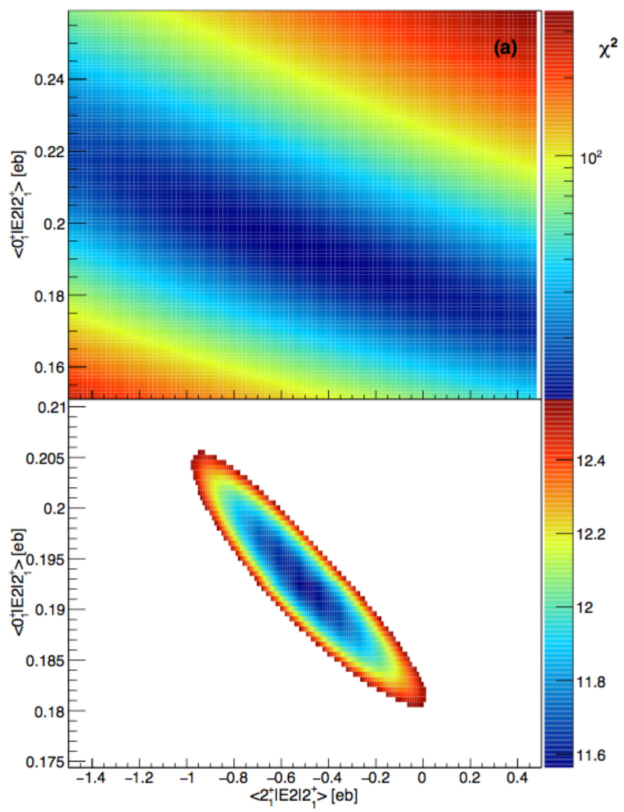
$$\langle \tilde{\Psi}_n | P\tilde{M}_{0\nu}P \mid \tilde{\Psi}_n \rangle \approx \langle \Psi_i | M_{0\nu} | \Psi_i \rangle$$

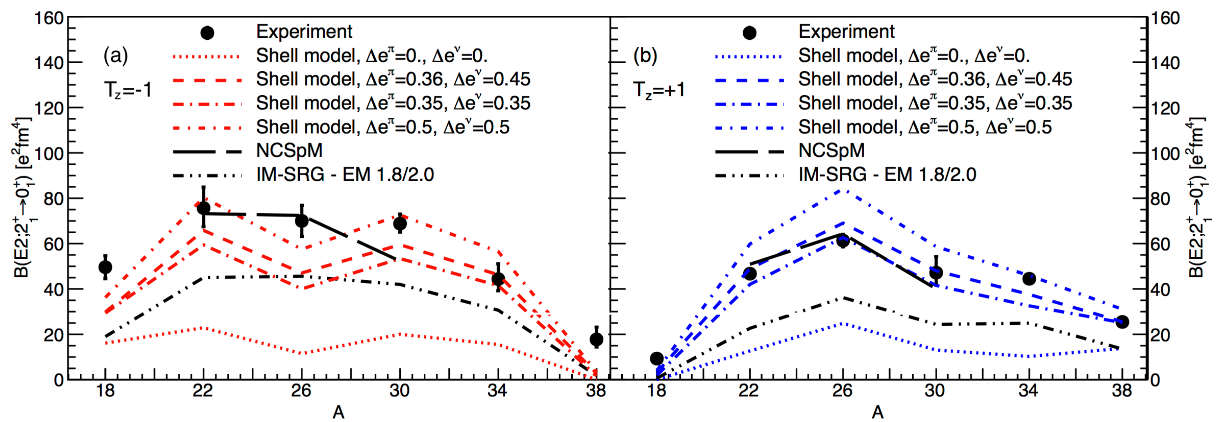


Testing microscopic descriptions of collectivity

- Use GOSIA Coulomb-excitation code to extract matrix elements

- Compare with NCSpM (LSU) and VS-IM-SRG (TRIUMF)
    - NCSpM - does excellent job - expensive calculations
    - VS-IM-SRG underpredicts strength - relatively inexpensive - qualitative description excellent





Henderson et al., PLB

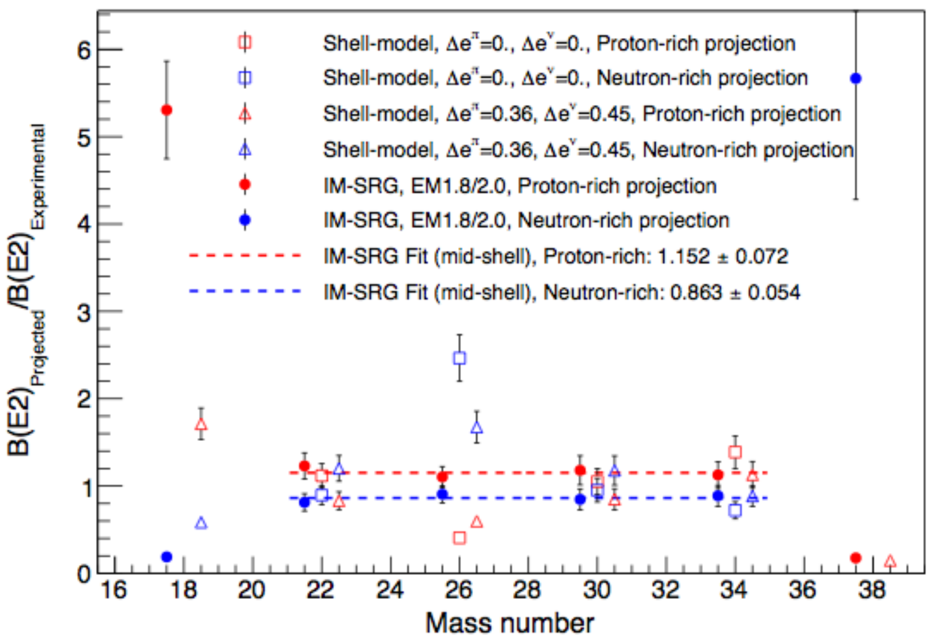
Testing microscopic descriptions of collectivity

Assess nature of missing VS-IM-SRG E2 strength:

$$B(E2)^{\text{Proj.}}_{T_z=-1} = B(E2)^{\text{Theory}}_{T_z=-1} \times \frac{B(E2)^{\text{Exp}}_{T_z=+1}}{B(E2)^{\text{Theory}}_{T_z=+1}},$$

If missing E2 strength isoscalar, expected "projected" B(E2) to match experiment

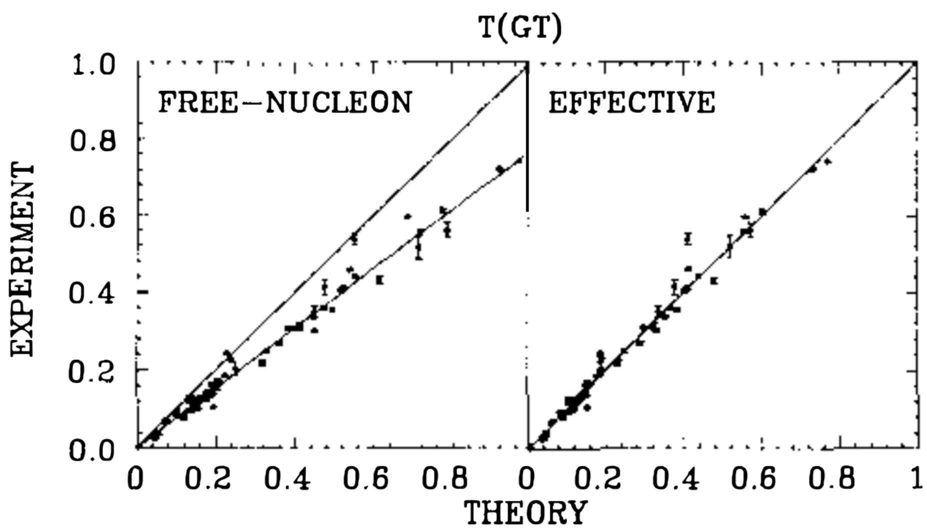
- Projected B(E2) consistently 15% over/under predicted by VS-IM-SRG
    - Missing strength has **consistent** isovector component
    - Promising for future development
- Shell model (USDB) shows no consistent behaviour



"Quenching" of g_A in Gamow-Teller Decays

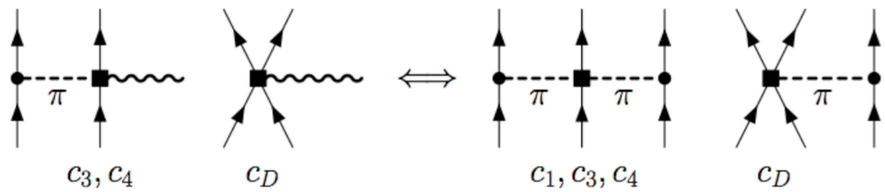
Long-standing problem in weak decays of nuclei: should g_A be "quenched"?

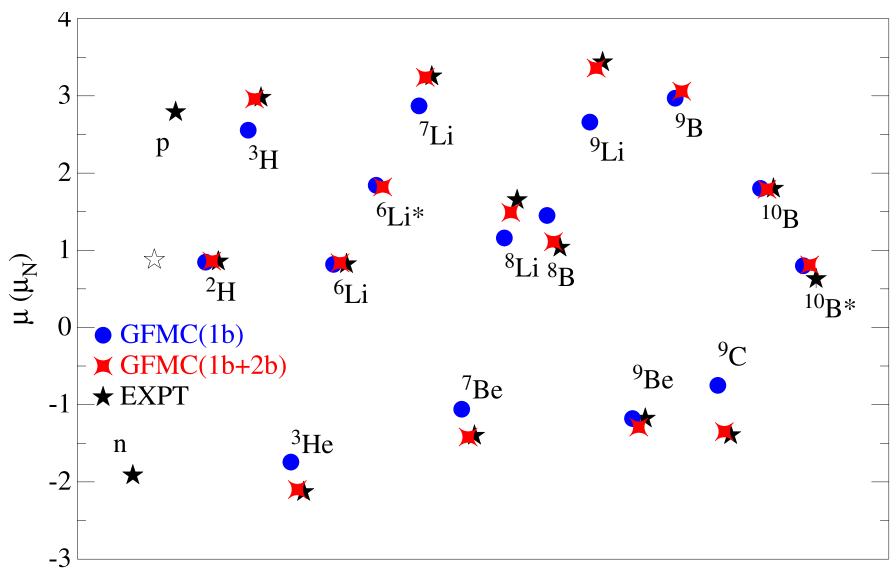
Using $g_A^{\mathrm{eff}} \approx 0.77 \times g_A^{\mathrm{free}}$ agrees with data

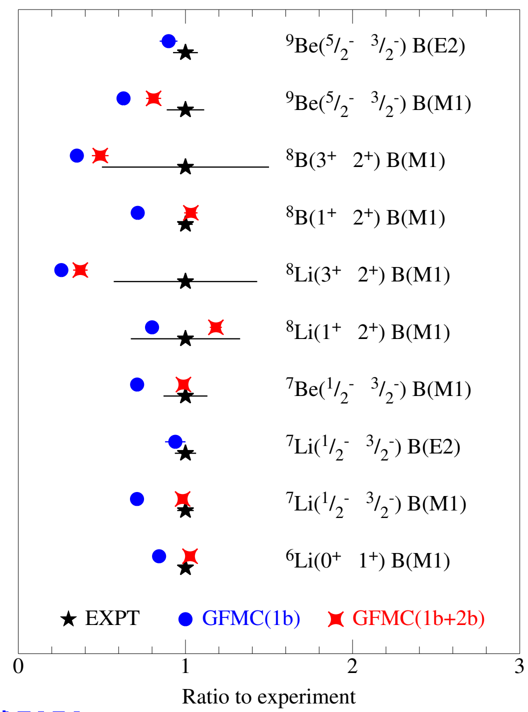


Two-body Currents in Nuclei

Chiral Effective Field Theory – electroweak currents consistent with nuclear forces

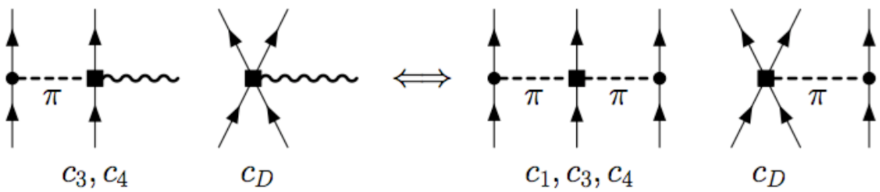


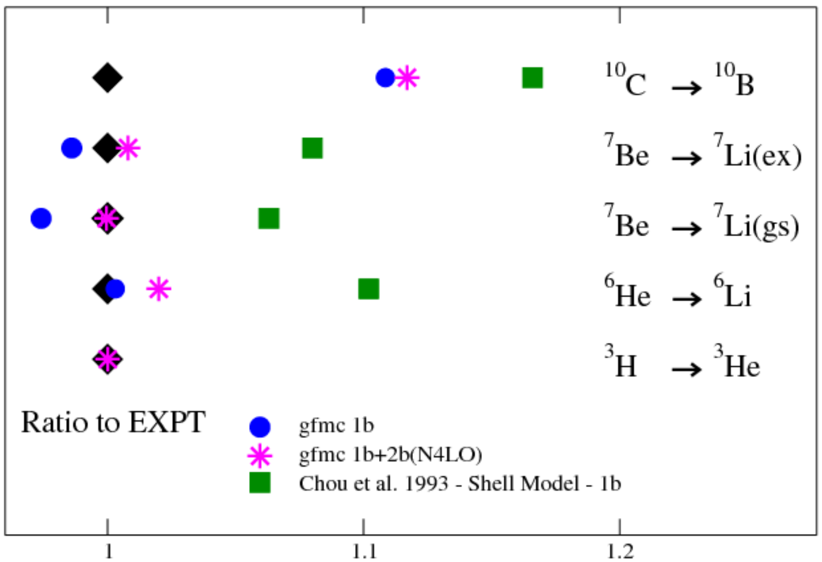




Clear Importance in for M1 transitions in light nuclei

Chiral Effective Field Theory – electroweak currents consistent with nuclear forces





Clear increase for GT transitions in GFMC – inconsistent forces/currents

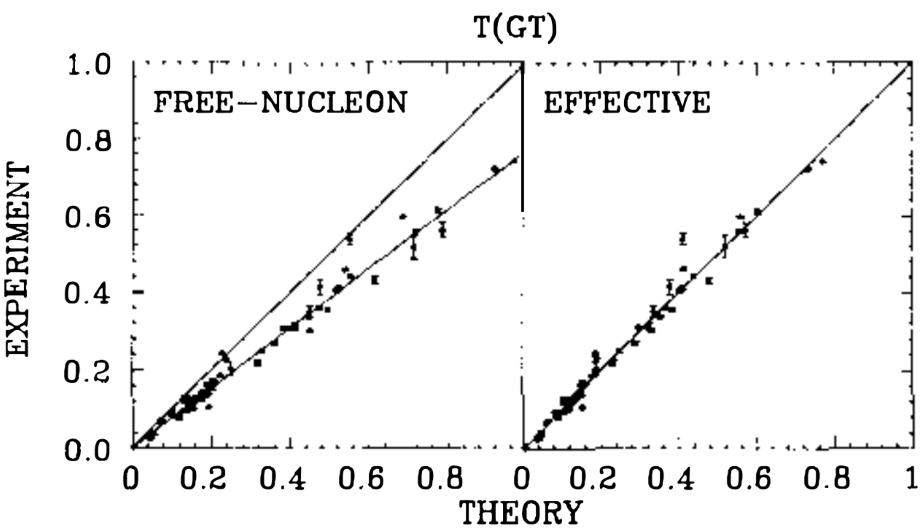
TRIUMF

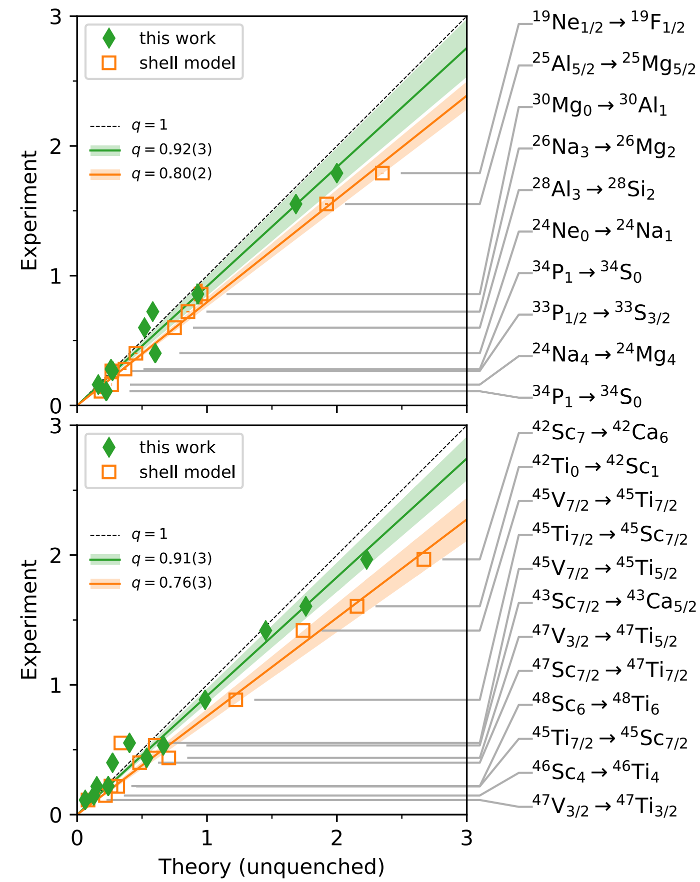
“Quenching” of g_A in Gamow-Teller Decays

VS-IMSRG calculations of GT transitions in sd, pf shells

Minor effect from consistent effective operator

Significant effect from neglected 2-body currents

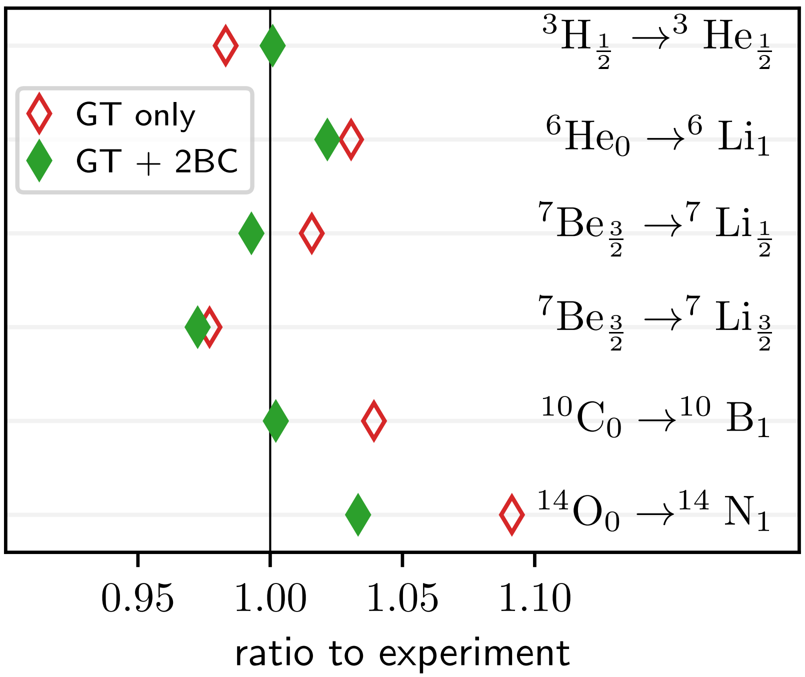


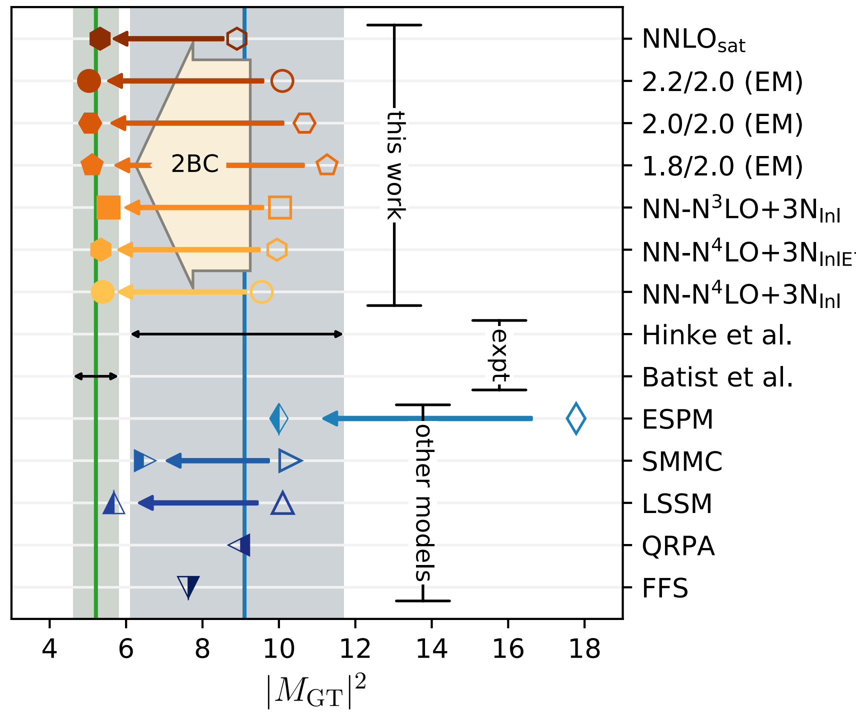


Ab initio calculations explain data with unquenched g_A

"Quenching" of g_A in Gamow-Teller Decays

Prediction from light nuclei to super allowed GT transition in 100Sn

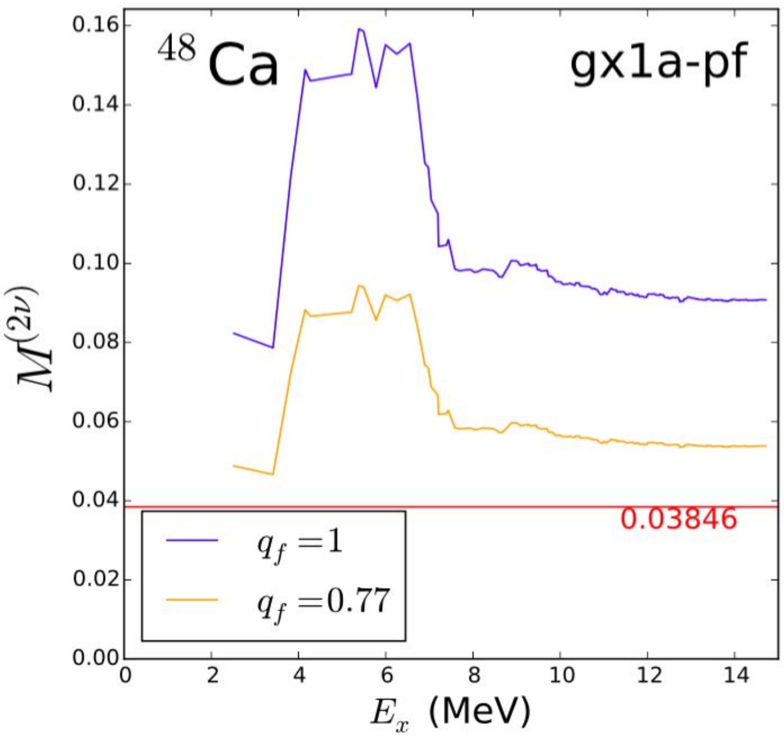




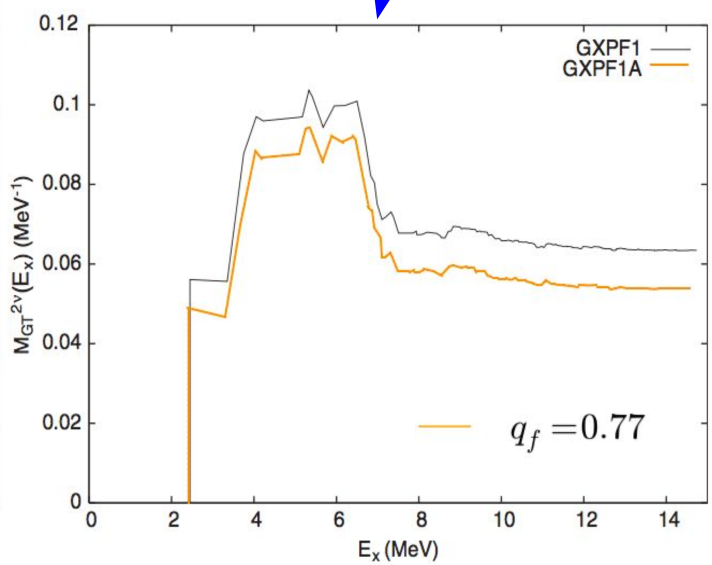
Agreement with data with no need for quenching

Ab Initio $2\nu\beta\beta$-decay

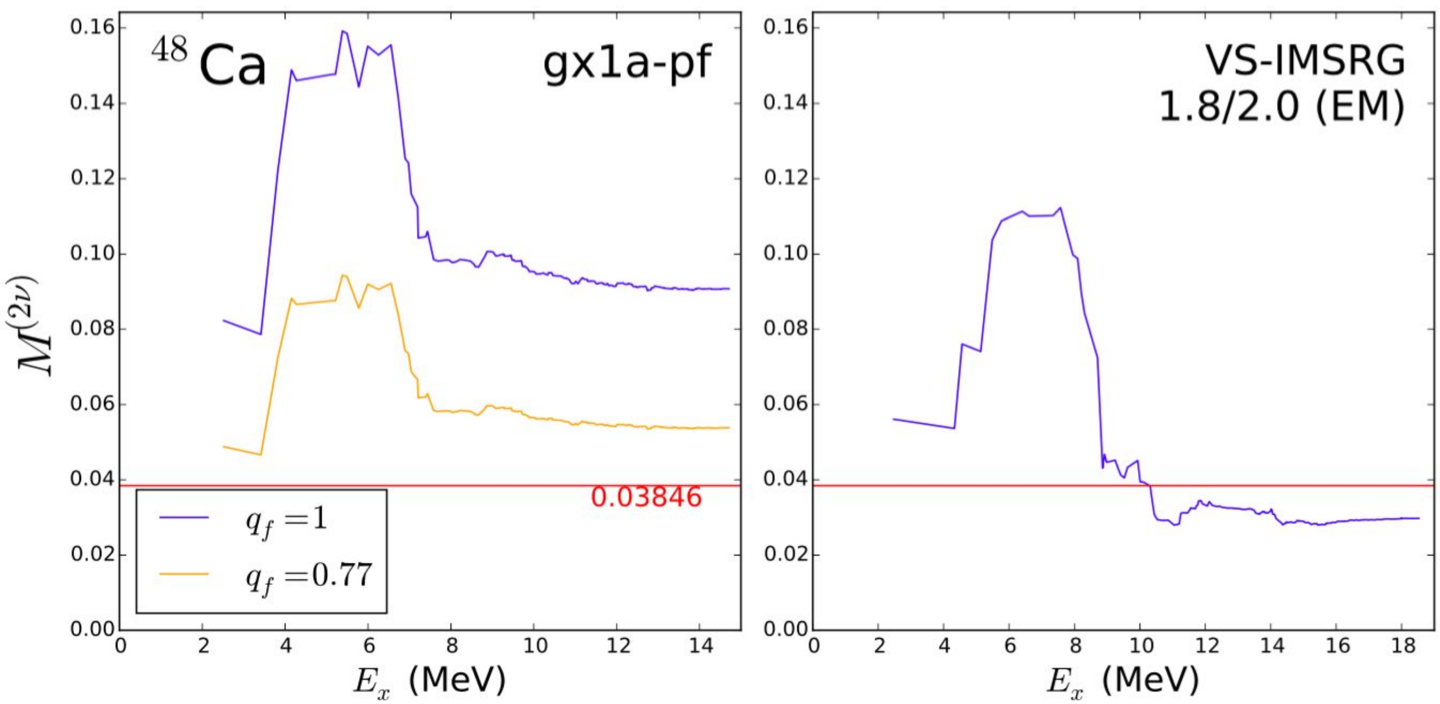
First benchmark to reproduce known shell-model results



VS = pf-shell, with **no** IMSRG evolution reproduces ShM results [6]



Consistent many-body wfs/operators from chiral NN+3N forces (no 2b currents)



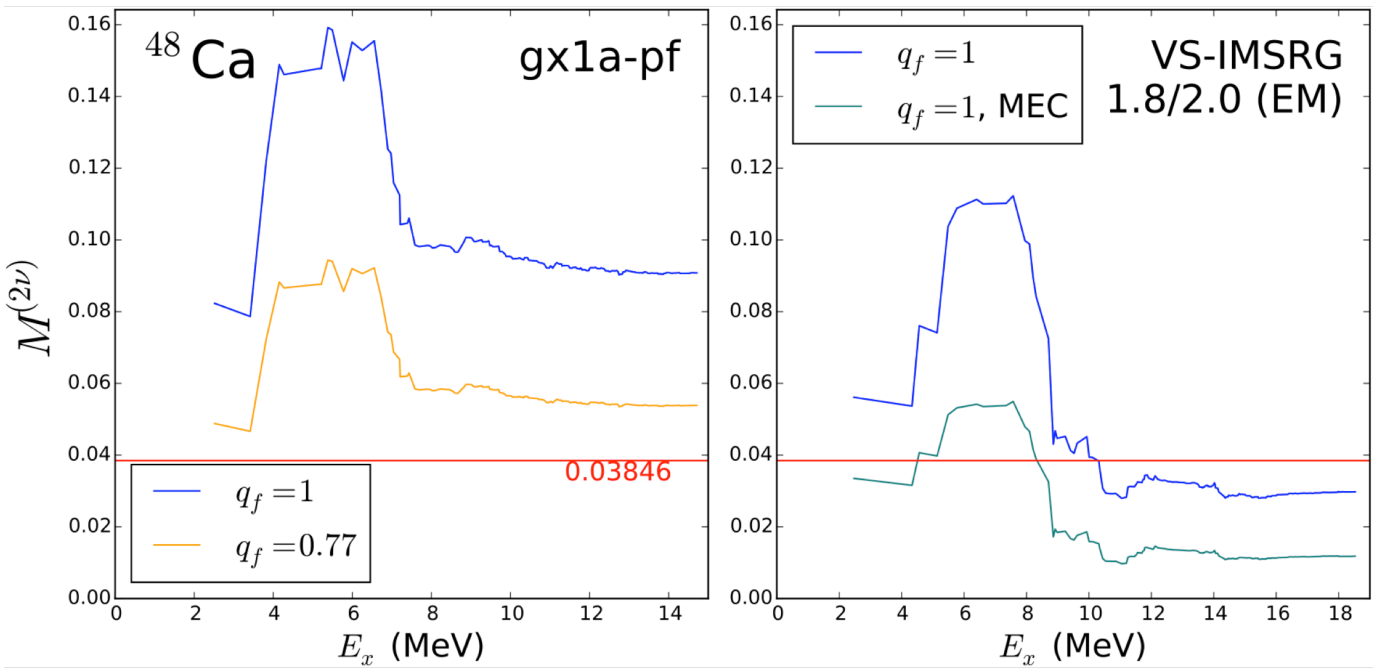
Payne, Stroberg, JDH, et al., in prep

VS-IMSRG: decrease in final matrix element

Likely missing contributions from intermediate states outside valence space

Ab Initio 2νββ-decay

Consistent many-body wfs/operators from chiral NN+3N forces (**with 2b currents**)



Payne, Stroberg, JDH, et al., in prep

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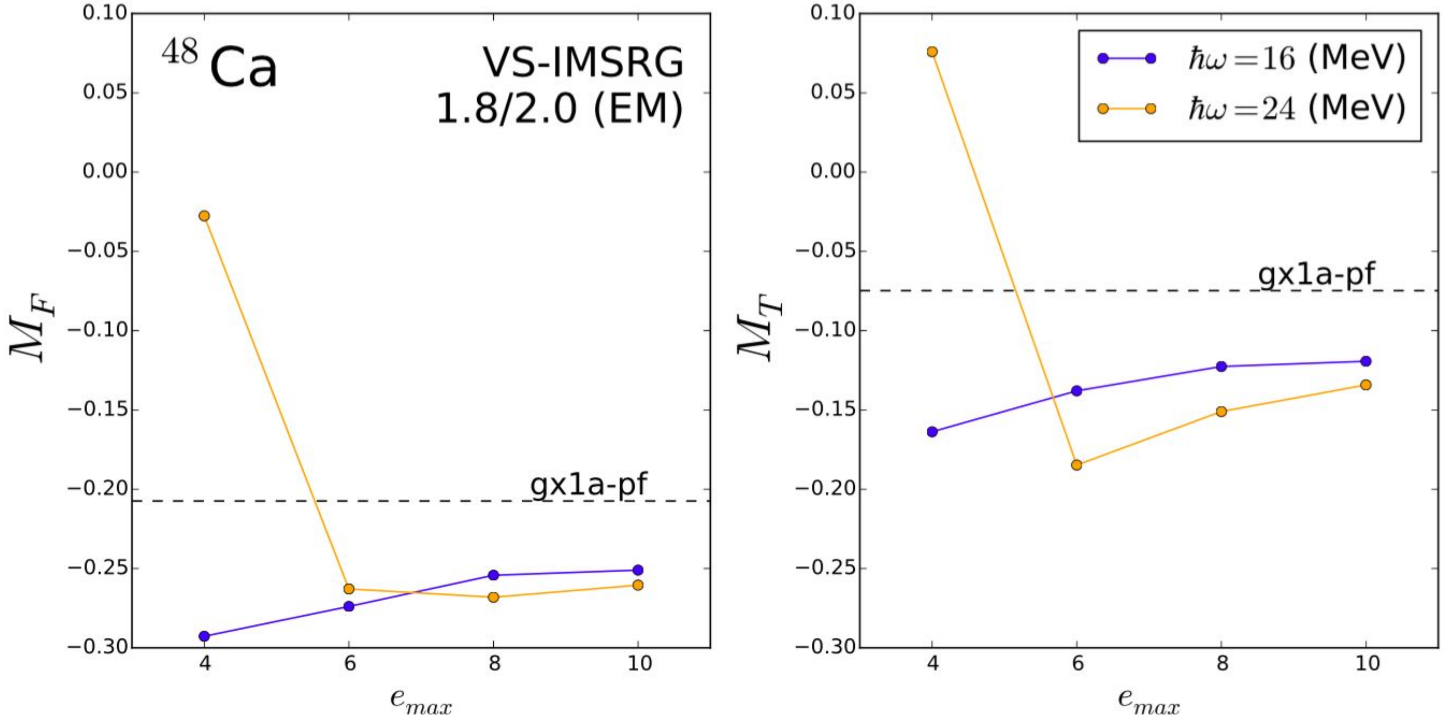
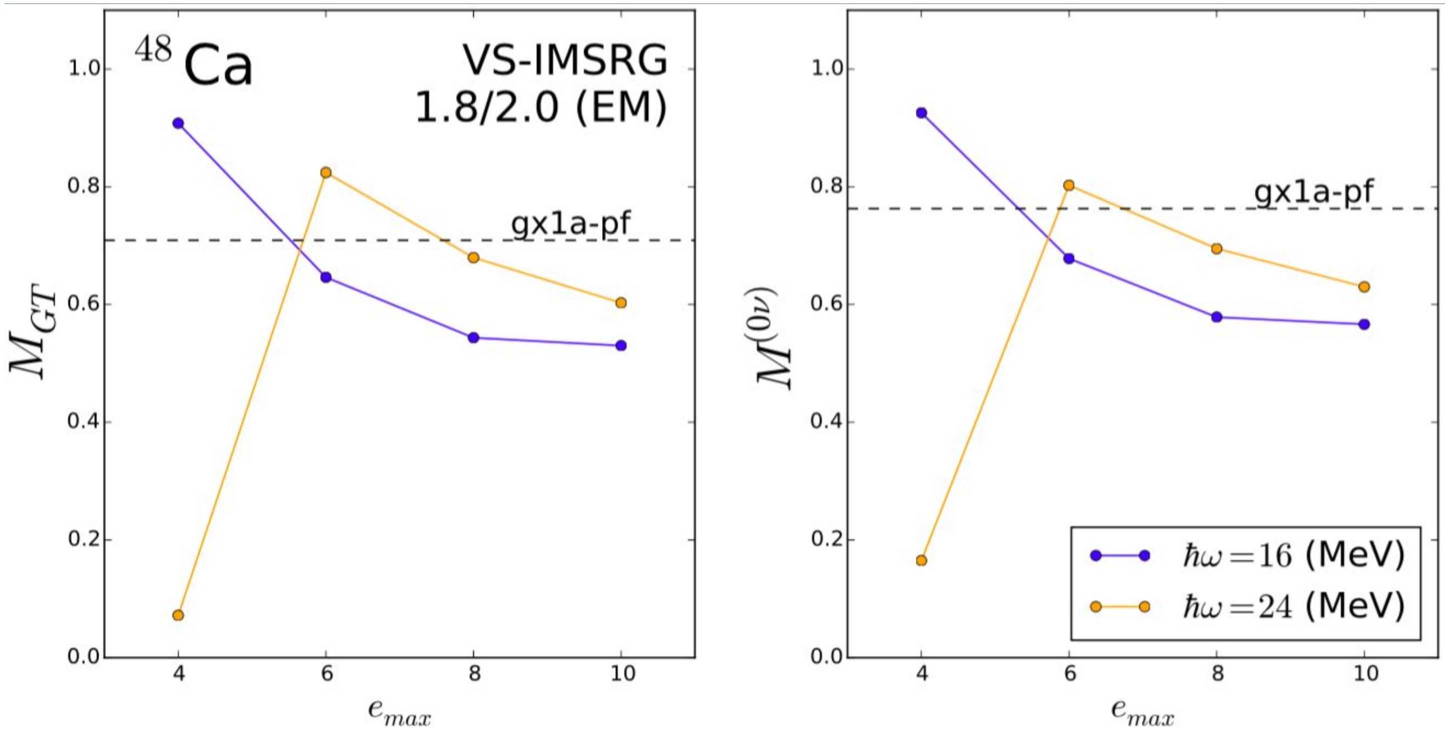


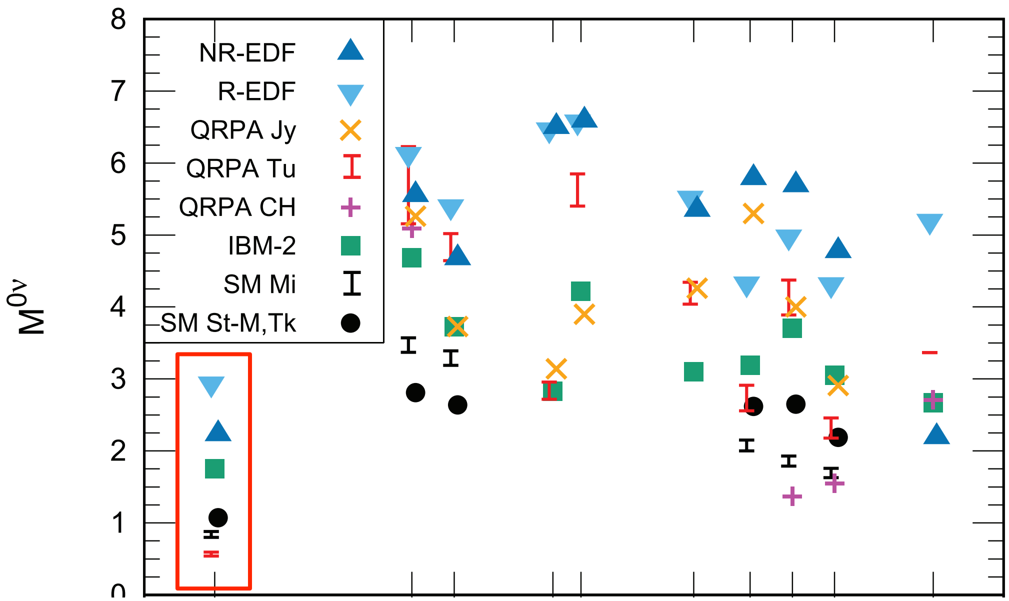
General cancellation between Fermi and Tensor contributions

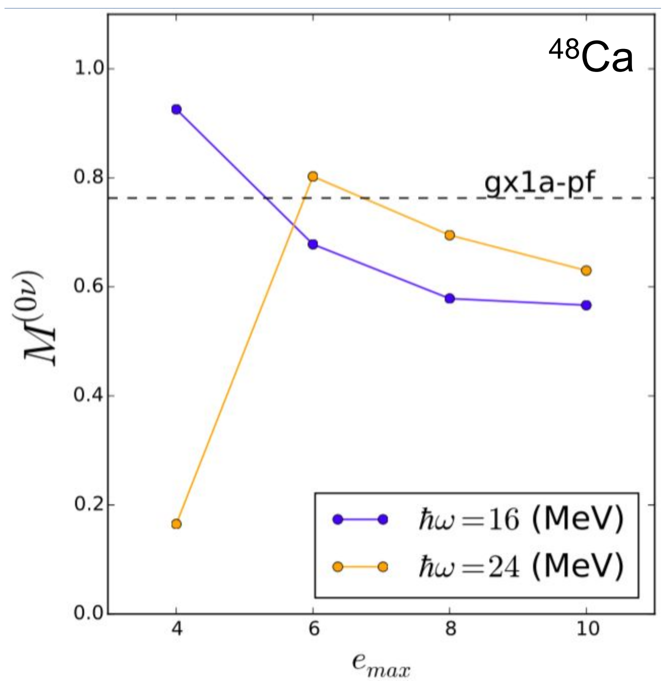
Consistent many-body wfs/operators from chiral NN+3N forces (no 2b currents)



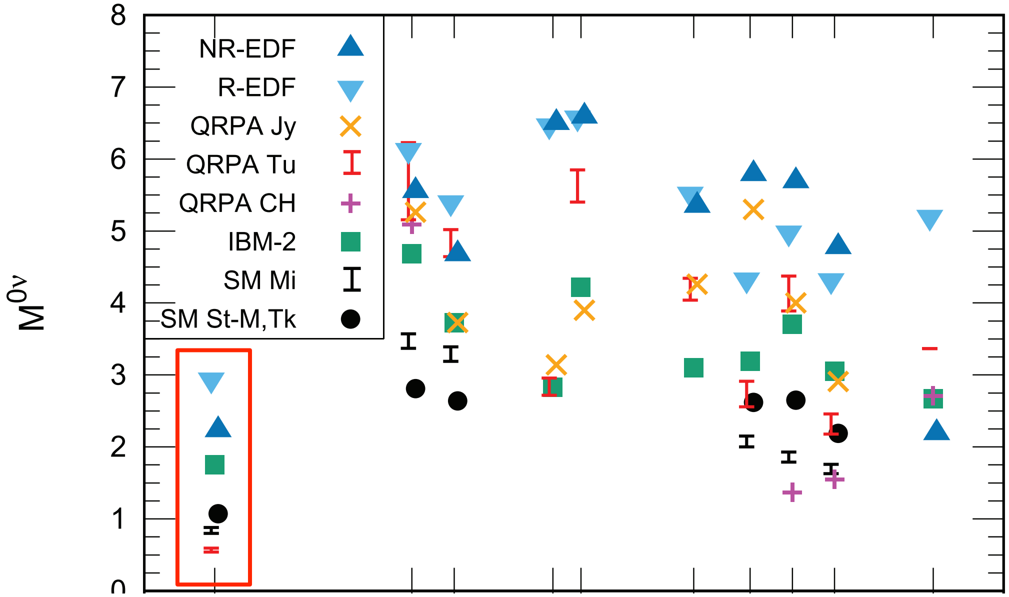
Final matrix element converged – significant decrease from phenomenology

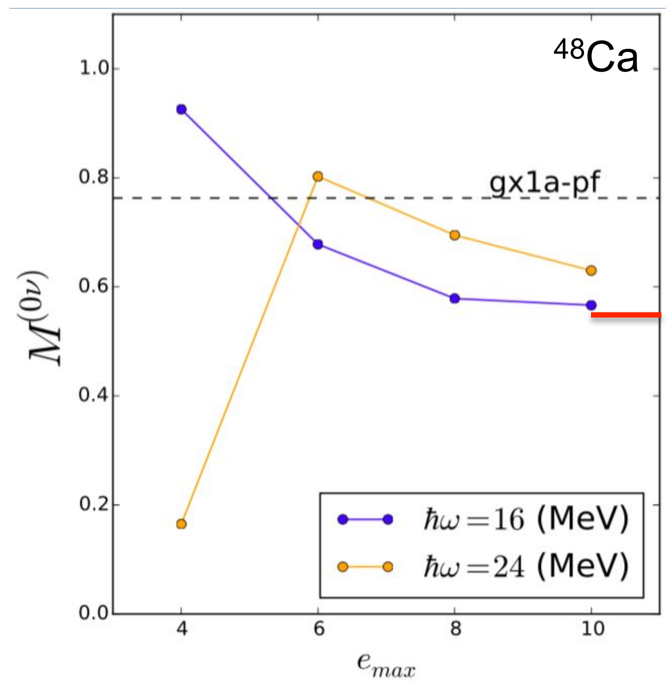
Ab initio: Consistent many-body wfs/operators from chiral NN+3N forces





Ab initio: Consistent many-body wfs/operators from chiral NN+3N forces





Consistent prediction from independent method

Two-body currents in progress – typically decrease NME

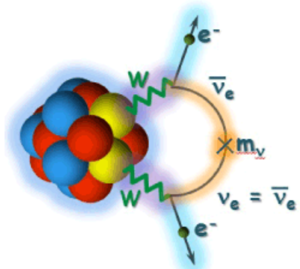
Ab Initio 0νββ-Decay Predictions in the Shell Model

Standard SM: phenomenological wavefunctions + bare operator

Ab initio SM: wavefunctions from chiral NN+3N forces + consistent effective operator

$$M^{0\nu} = M^{0\nu}_{GT} - \frac{M^{0\nu}_F}{g_A^2} + M^{0\nu}_T$$

$$M^{0\nu}_{GT} = \langle f | \sum_{ab} H(r_{ab}) \sigma_a \cdot \sigma_b \, \tau_a^+ \tau_b^+ | i \rangle$$



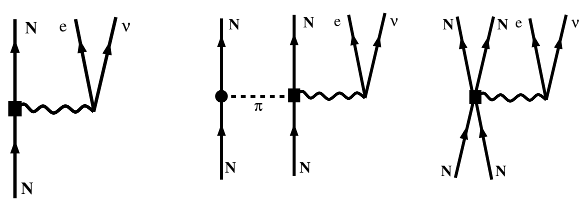
Neutrinoless double beta decay

1) ✓ Ab initio energies in medium/heavy-mass region

2) ✓ Effective decay operator: decouple valence-space operator

3) ⚠ Operator corrections

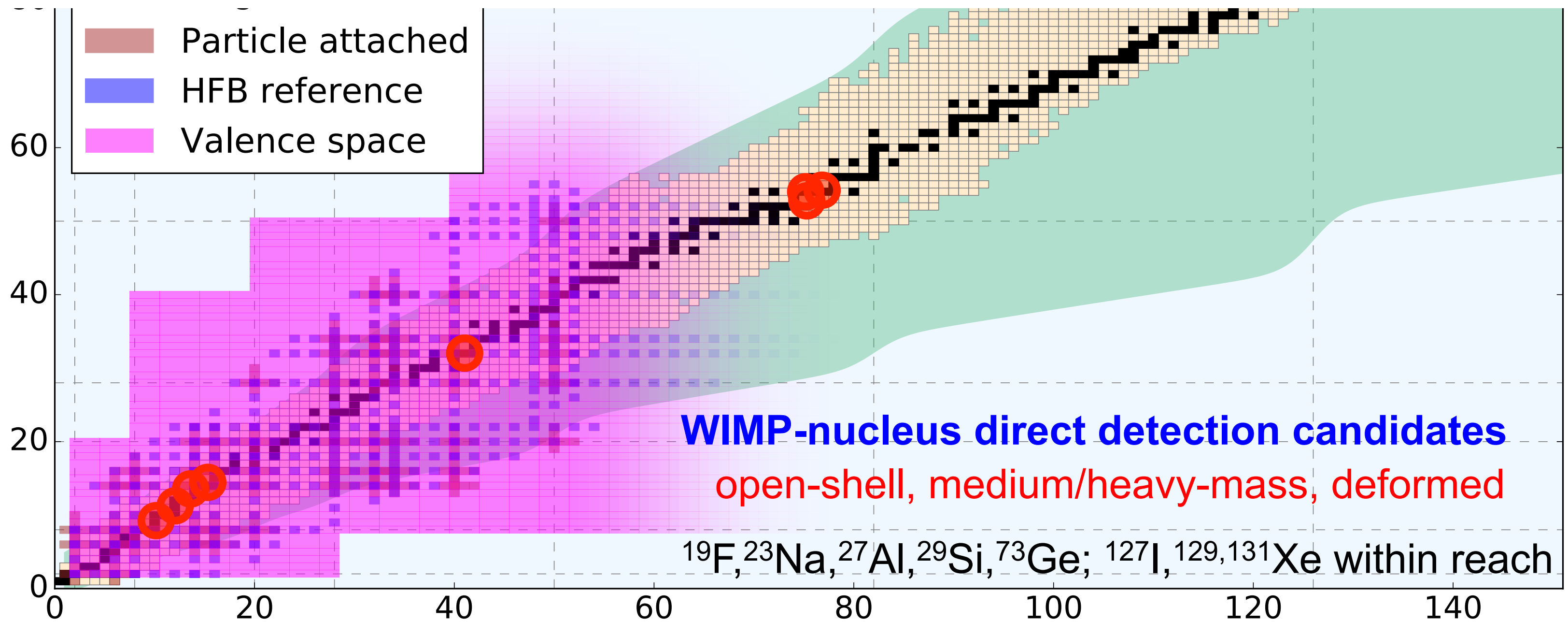
Two-body currents **S. Leutheusser** (UBC/MIT)



Towards big questions: WIMP-Nucleus Scattering

Aim of modern nuclear theory: Develop unified *first-principles* picture of structure and reactions

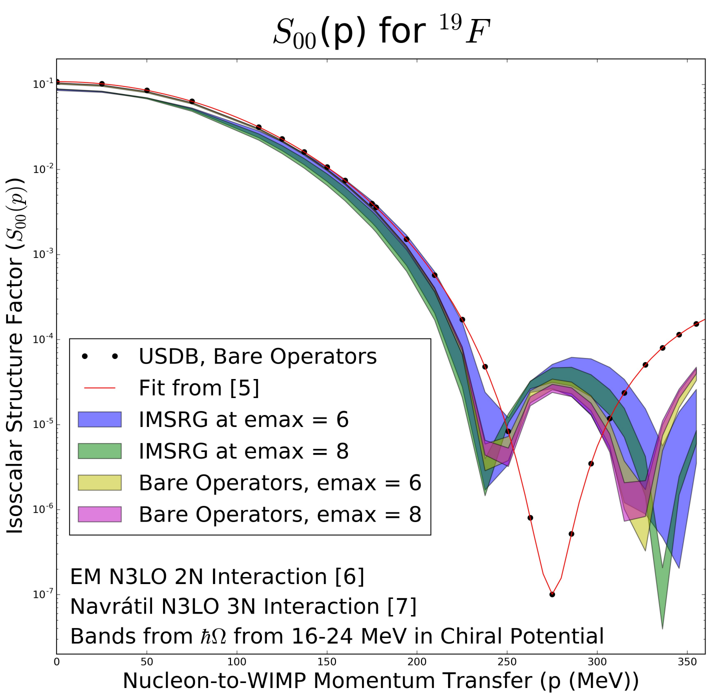
- Nuclear forces (low-energy QCD)
- Electroweak physics
- Nuclear many-body problem

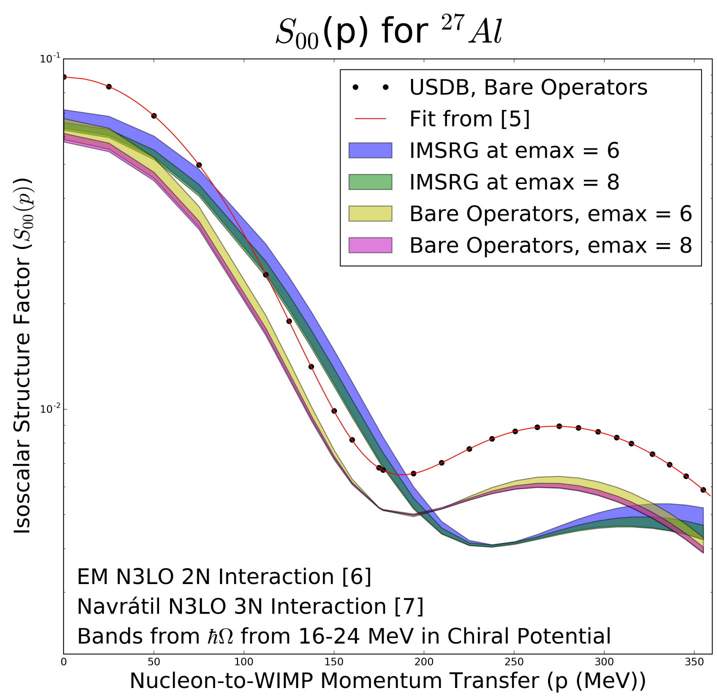


Ab Initio WIMP-Nucleus Response Functions (Isoscalar)

Ab initio: Consistent many-body wfs/operators from chiral NN+3N forces + 2b currents

$$S_A(p) = \sum_{L\geqslant 0} |\langle J_f \| \mathcal{L}_L \| J_i \rangle|^2 + \sum_{L\geqslant 0} \left(\left|\langle J_f \left\| \mathcal{T}_L^{\text{el}} \right\| J_i \rangle\right|^2 + |\langle J_f \| \mathcal{T}_L^{\text{mag}} \| J_i \rangle|^2 \right)$$





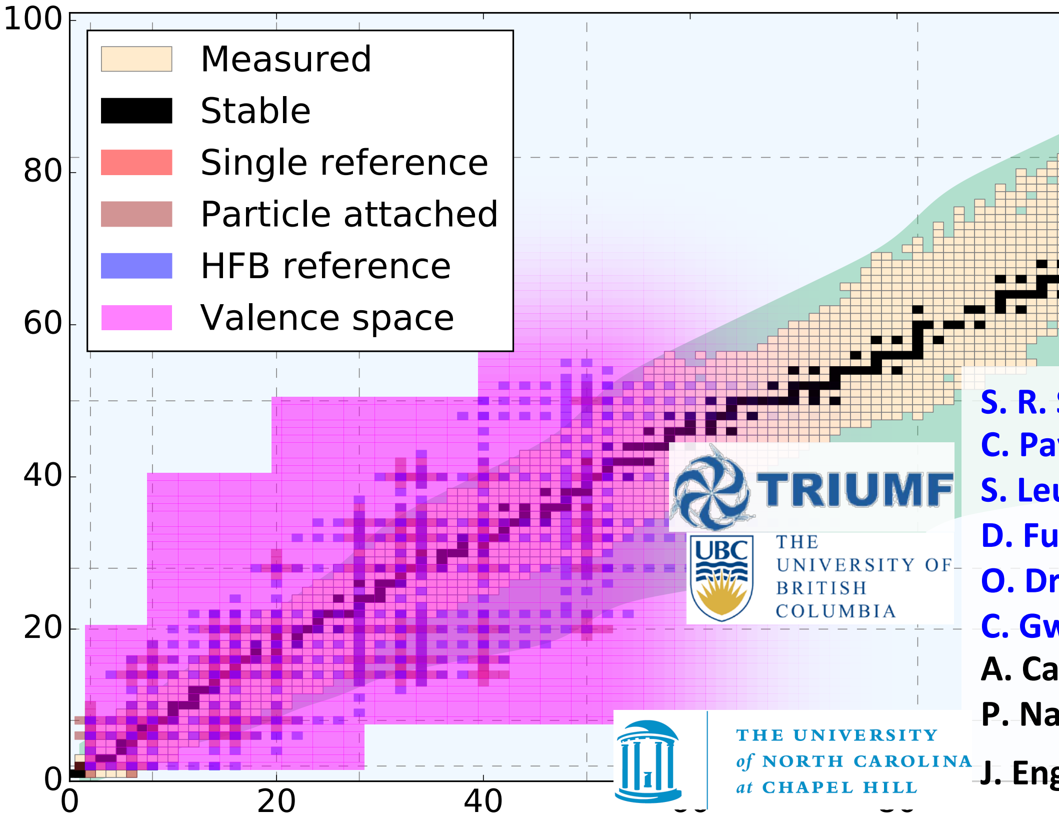
Leutheusser, Stroberg, Holt

Outlook

Ab initio valence-shell Hamiltonians

First ab initio prediction of nuclear driplines

Cross-shell spaces underway: Island of inversion



Fundamental physics

Effective electroweak operators: M1, GT,…

Effective $0\nu\beta\beta$ decay operator

WIMP-Nucleus scattering

Outstanding issues

Controlled IMSRG(3) approximation

E2 operators problematic

Continuum essential beyond stability

Too-high 2+ energies at closed shells

Quantify uncertainties

S. R. Stroberg
C. Payne
S. Leutheusser
D. Fullerton
O. Drozdowski
C. Gwak
A. Calci
P. Navrátil
J. Engel

H. Hergert
S. Bogner
N. Parzuchowski

J. Simonis
A. Schwenk

T. Morris
G. Hagen, T. Papenbrock

J. Menéndez