TRIUMF

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

Ab Initio Theory for Neutrinoless Double-Beta Decay

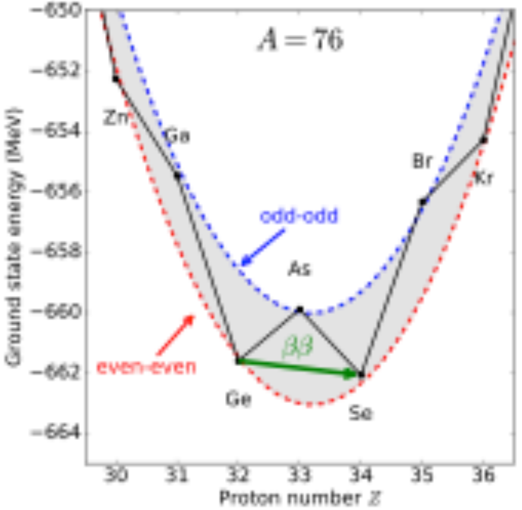
Jason D. Holt

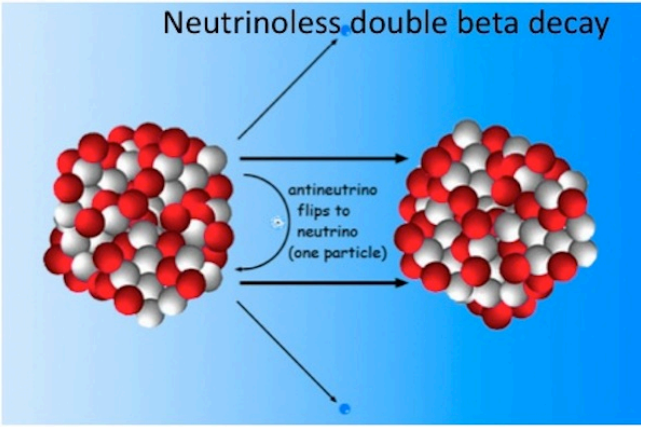
with Ragnar Stroberg, Takayuki Miyagi, Baishan Hu (soon)

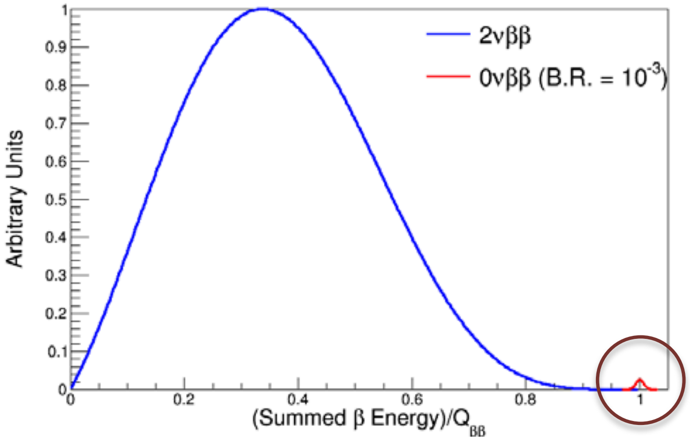
Trento, April 17, 2019

The Next Big Discovery: 0νββ-decay?

Neutrino own antiparticle $\Longleftrightarrow$ 0νββ decay







Tremendous impact on BSM physics:

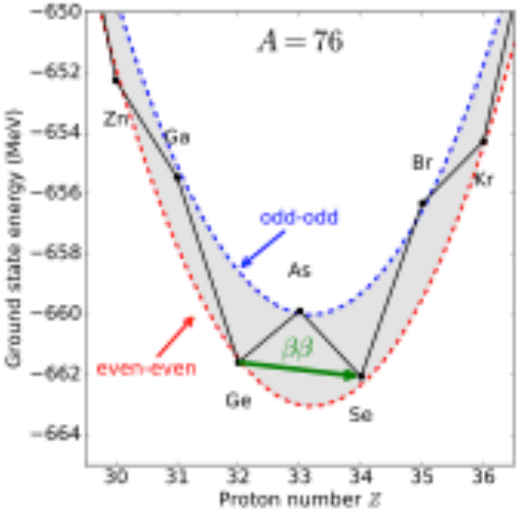
Lepton-number violating process

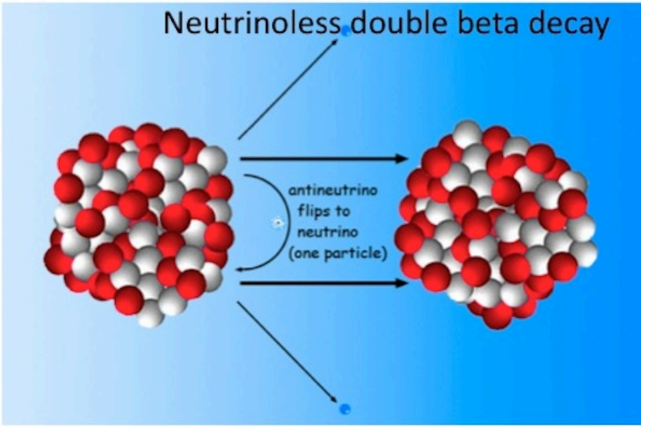
Majorana character of neutrino

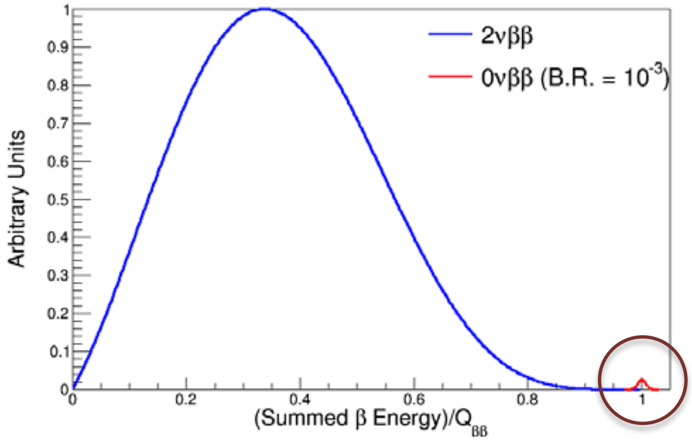
Absolute neutrino mass scale

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

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







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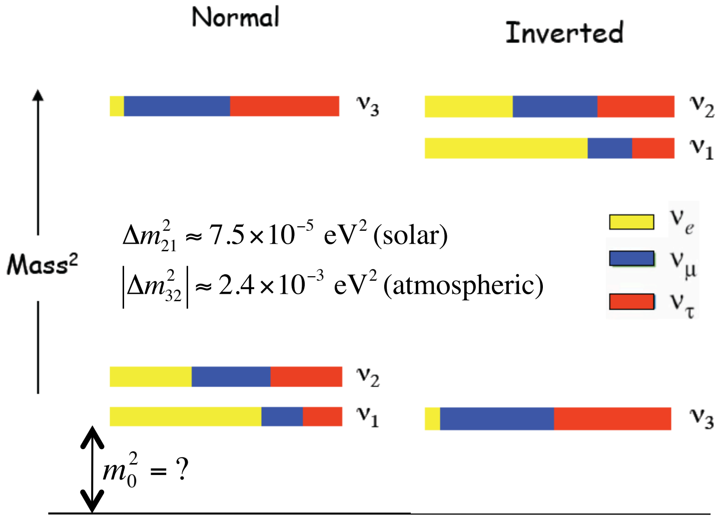
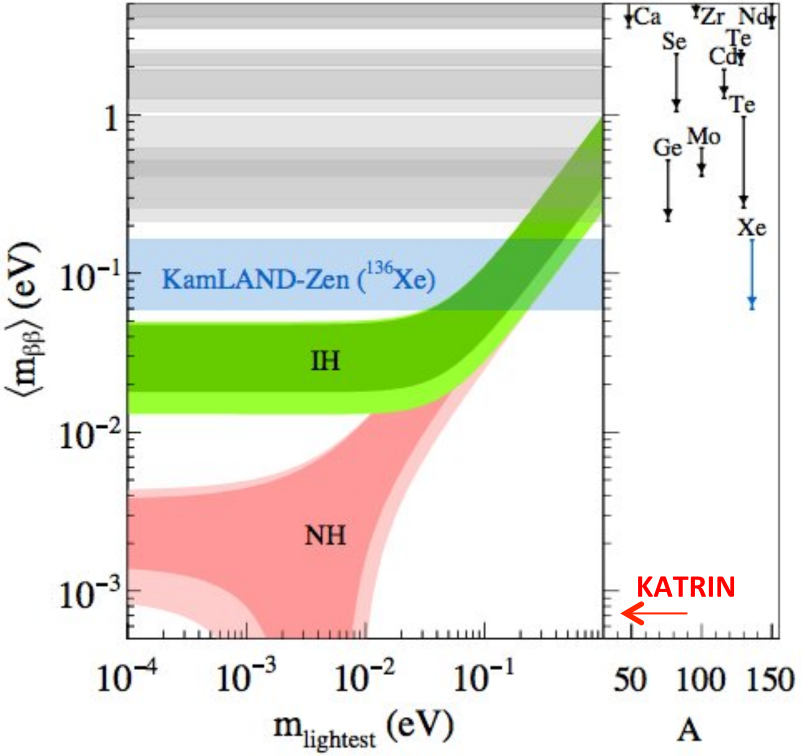
$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2 \qquad \langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei} m_i\right|$$

The Next Big Discovery: 0νββ-decay?

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





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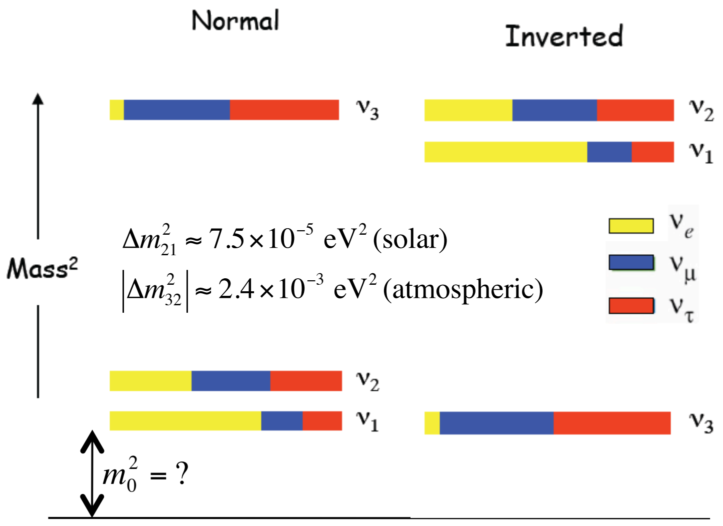

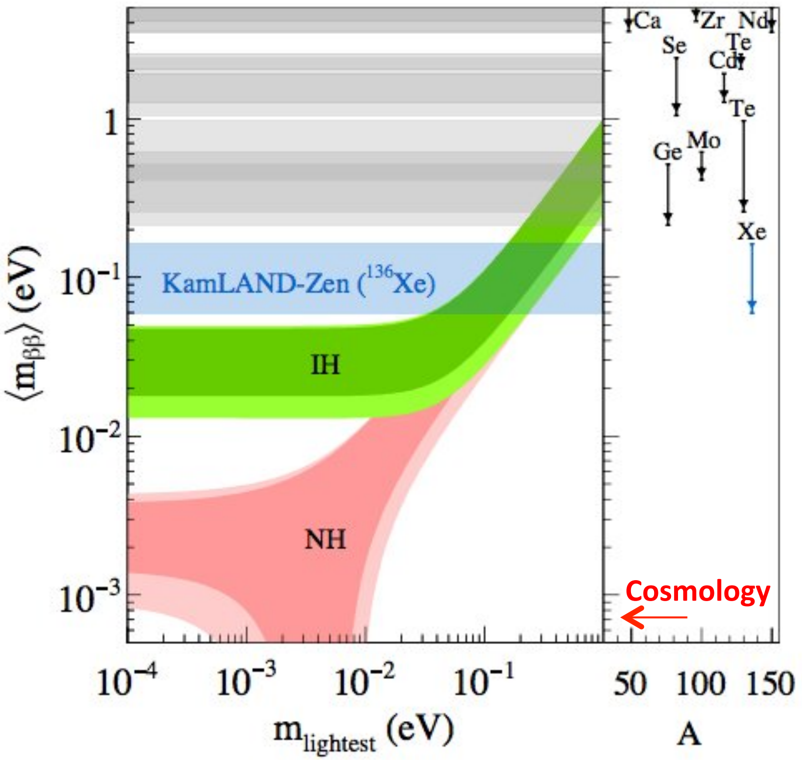

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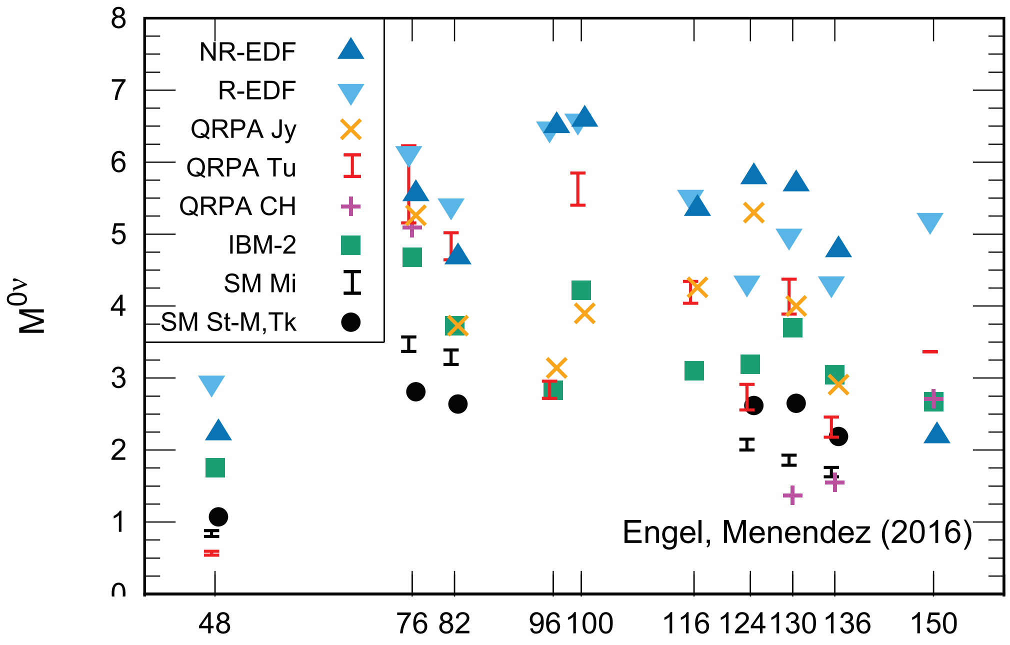
Uncertainty from **Nuclear Matrix Element**; bands do not represent rigorous uncertainties

0νββ-Decay Nuclear Matrix Element Status

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



All models missing essential physics

Impossible to assign rigorous uncertainties

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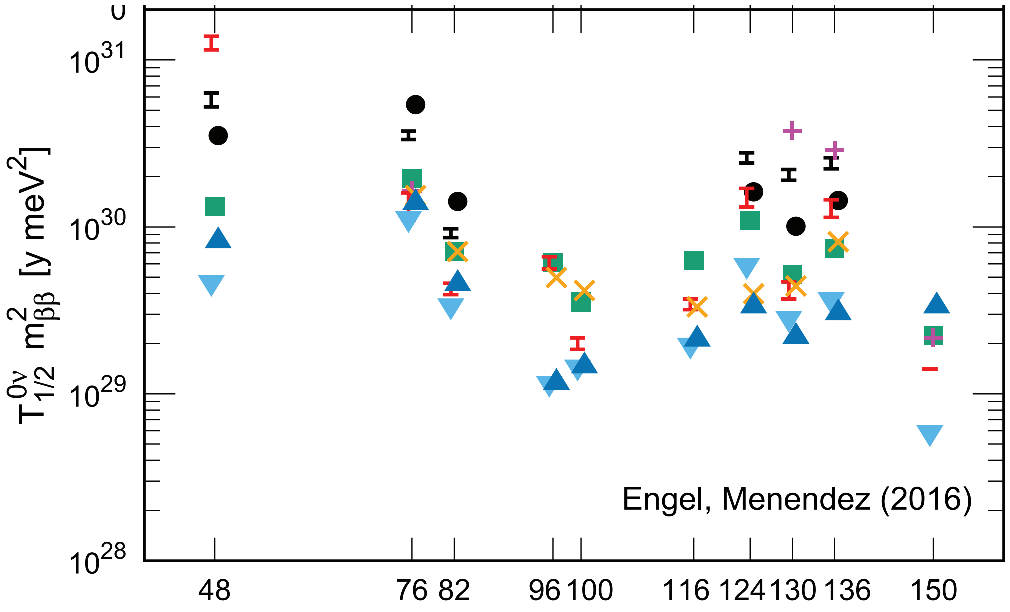


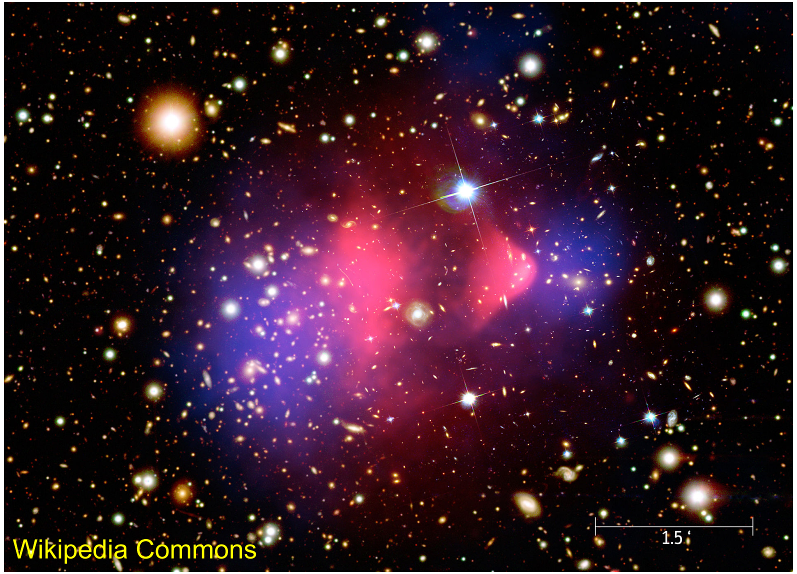
All models missing essential physics

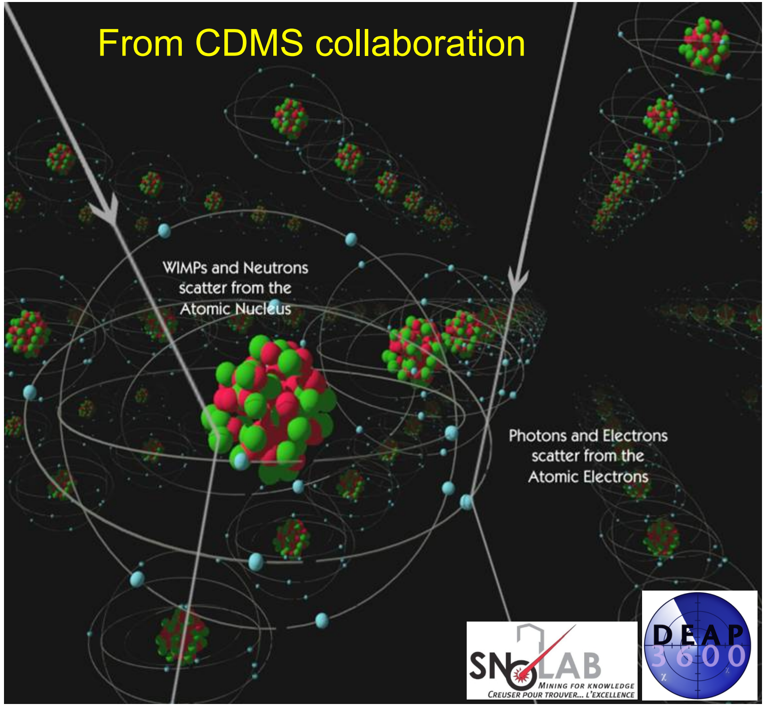
Impossible to assign rigorous uncertainties

Rethink approach to nuclear structure!

Next Big Discovery: Nature of Dark Matter?

Many direct-detection searches underway worldwide





Observation of nuclear recoil

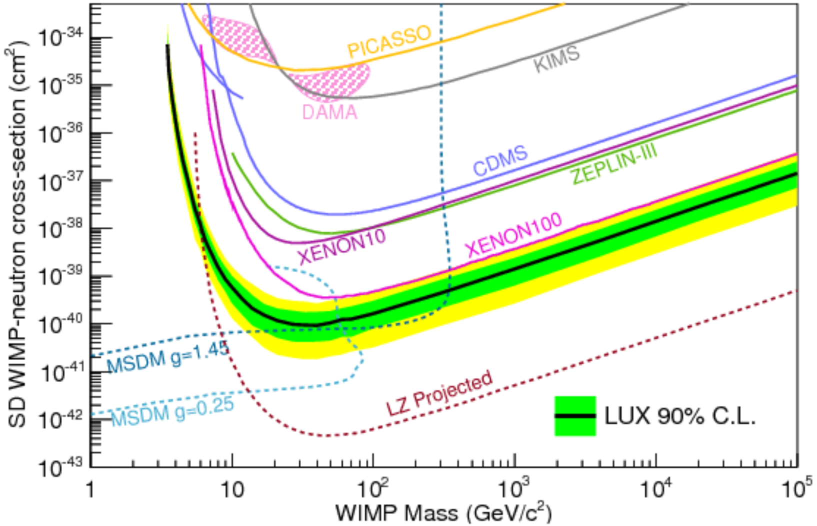
Direct detection: $X\,\mathrm{SM} \to X\,\mathrm{SM}$

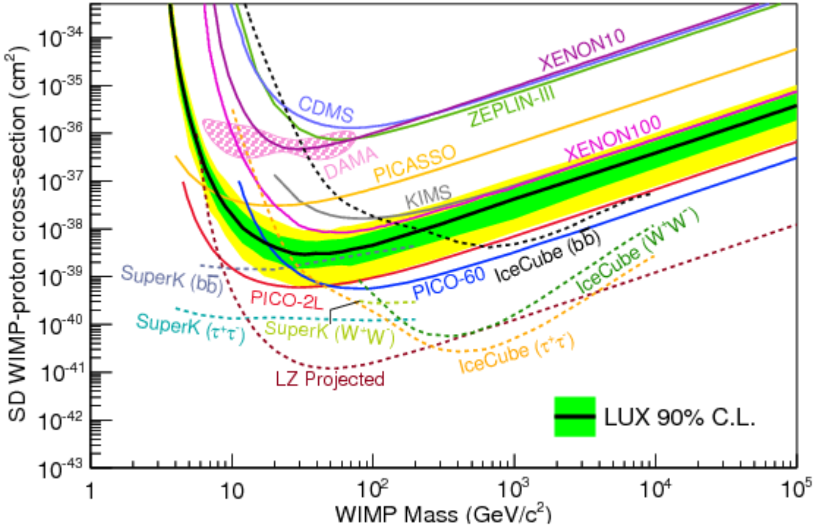
Leading candidates: neutralinos

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

Next Big Discovery: Nature of Dark Matter?

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





Differential cross section: compare results from different target nuclei

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

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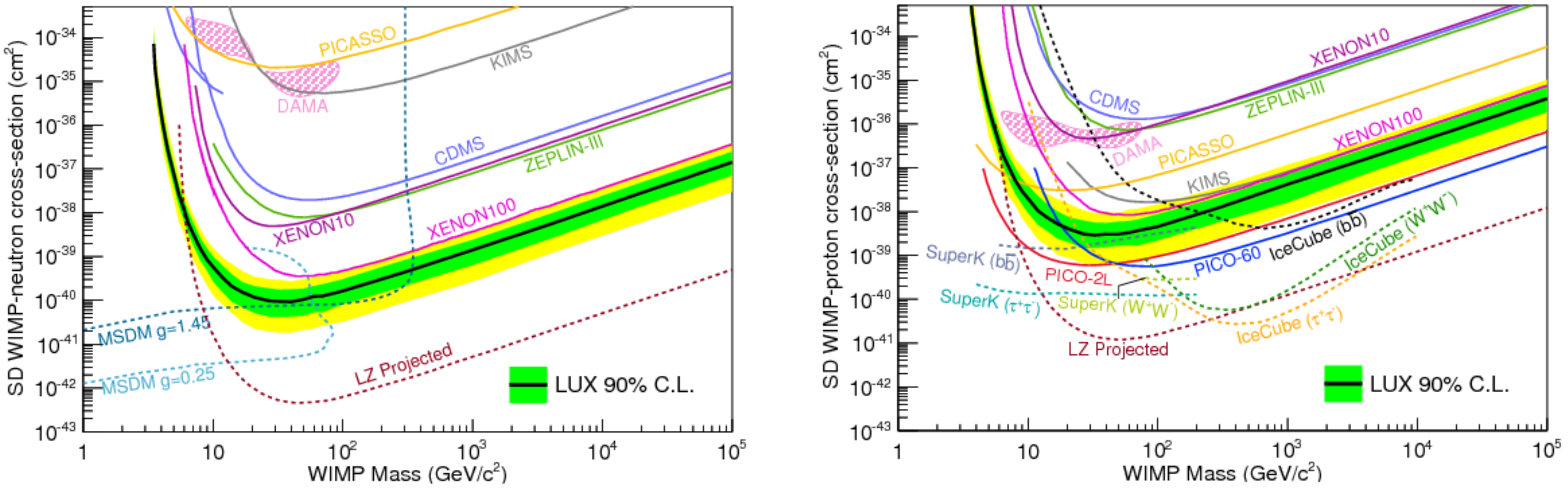


Differential cross section: compare results from different target nuclei

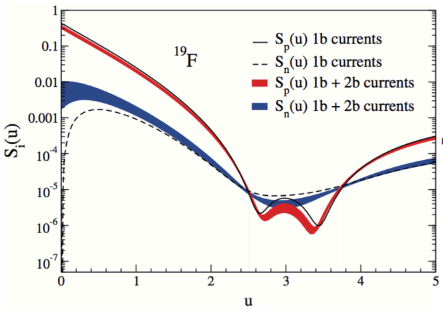
$$\frac{d\sigma}{dp^2} = \frac{8G_F^2}{(2J_i+1)v^2} S_A(p)$$

Structure functions required from nuclear theory

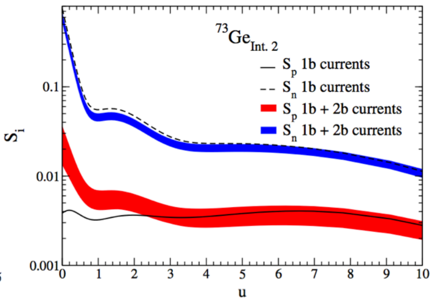
Spin-Dependent Structure Factors

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

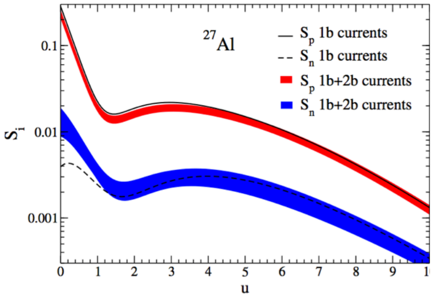
$$S_A(p) = \sum_{L\geqslant 0} |\langle J_f \| \mathcal{L}_L \| J_i \rangle|^2 + \sum_{L\geqslant 0} \left(|\langle J_f \| \mathcal{T}_L^{\mathrm{el}} \| J_i \rangle|^2 + |\langle J_f \| \mathcal{T}_L^{\mathrm{mag}} \| J_i \rangle|^2 \right)$$



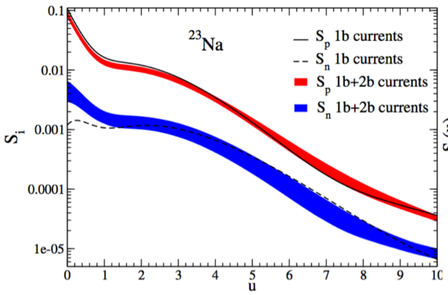
PICASSO, COUPP, SIMPLE



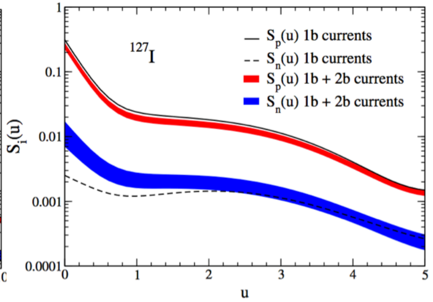
CDMS, EDELWEISS, EURECA



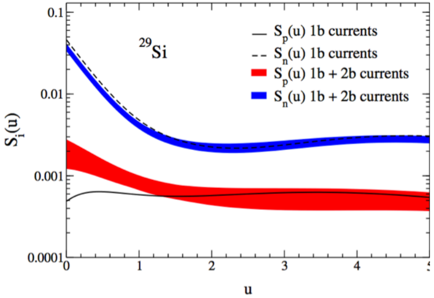
CRESST



DAMA, ANAIS, DM-Ice



DAMA, ANAIS, DM-Ice, KIMS

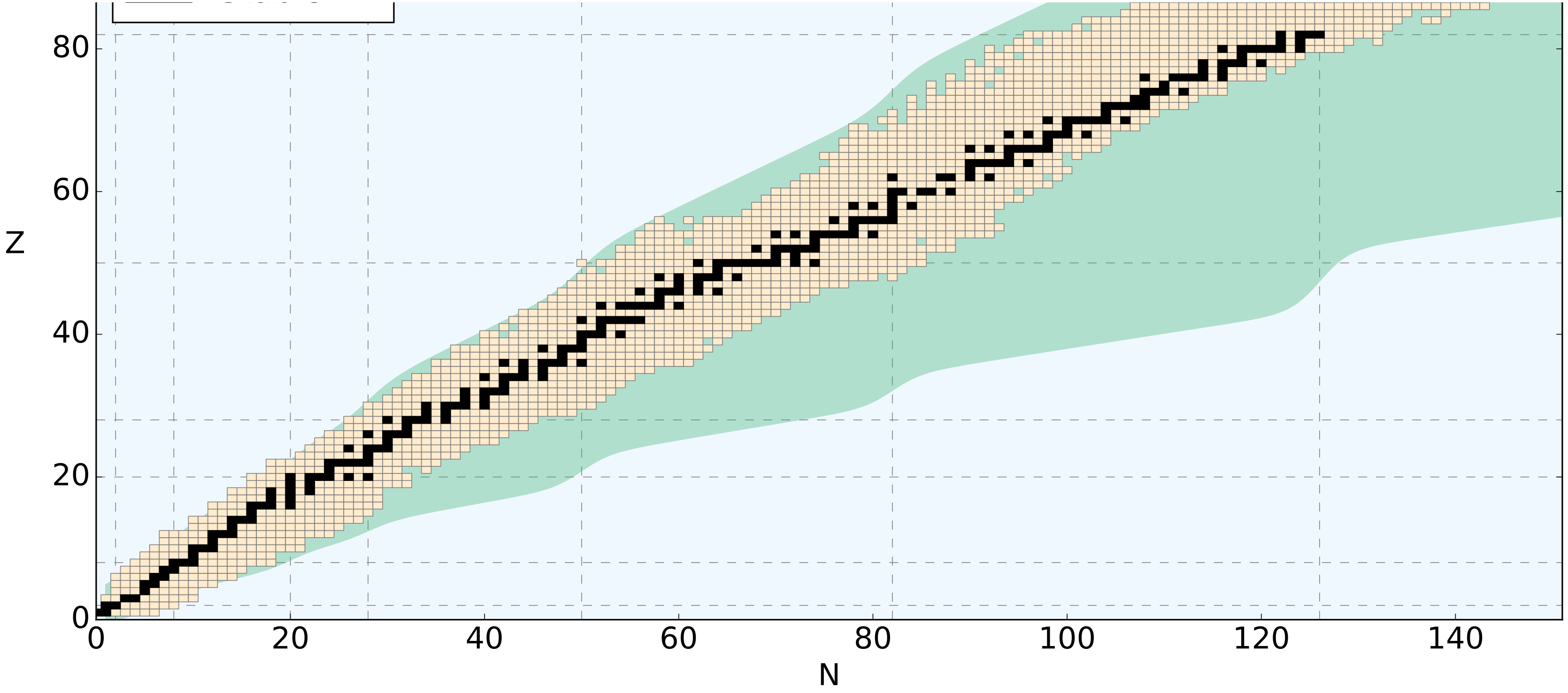


CDMS-II

Klos et al, PRD (2013)

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

$$H\psi_n = E_n\psi_n$$



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

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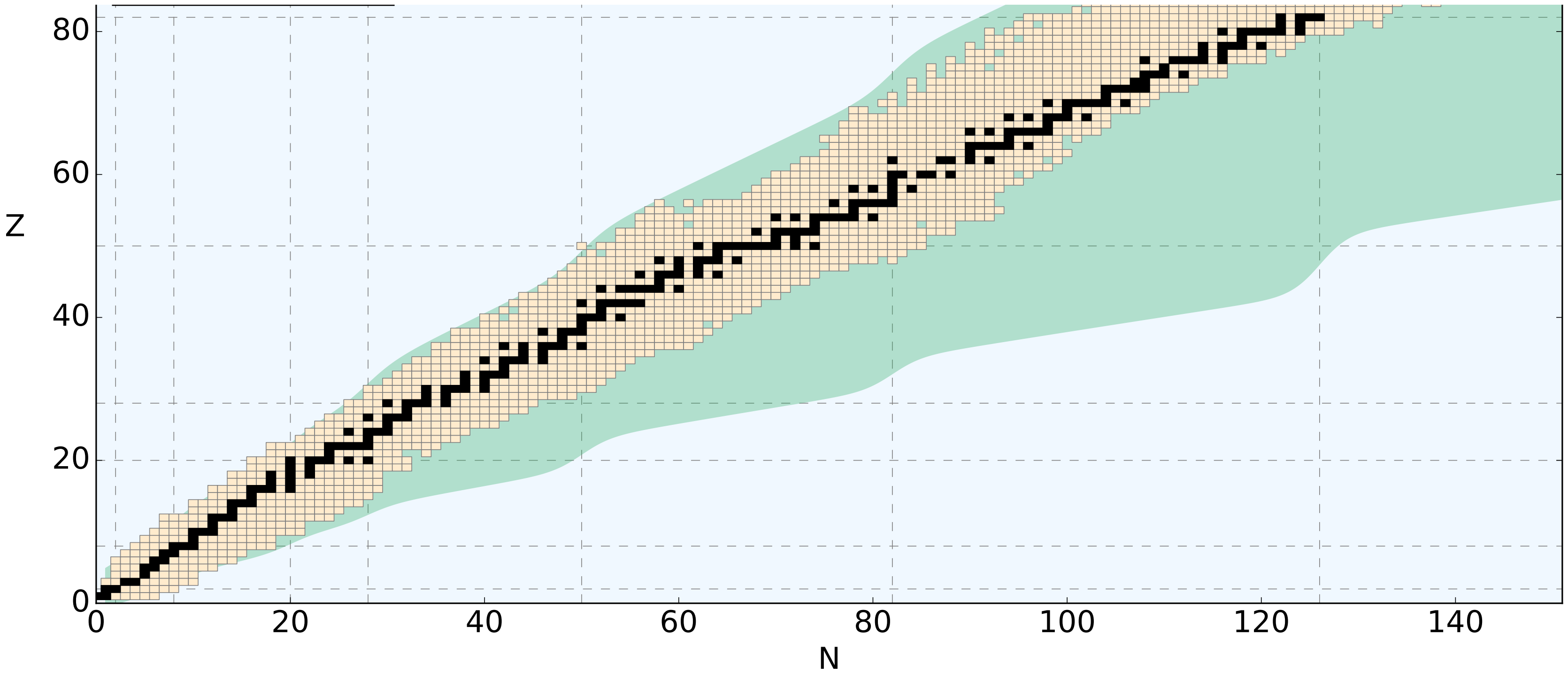

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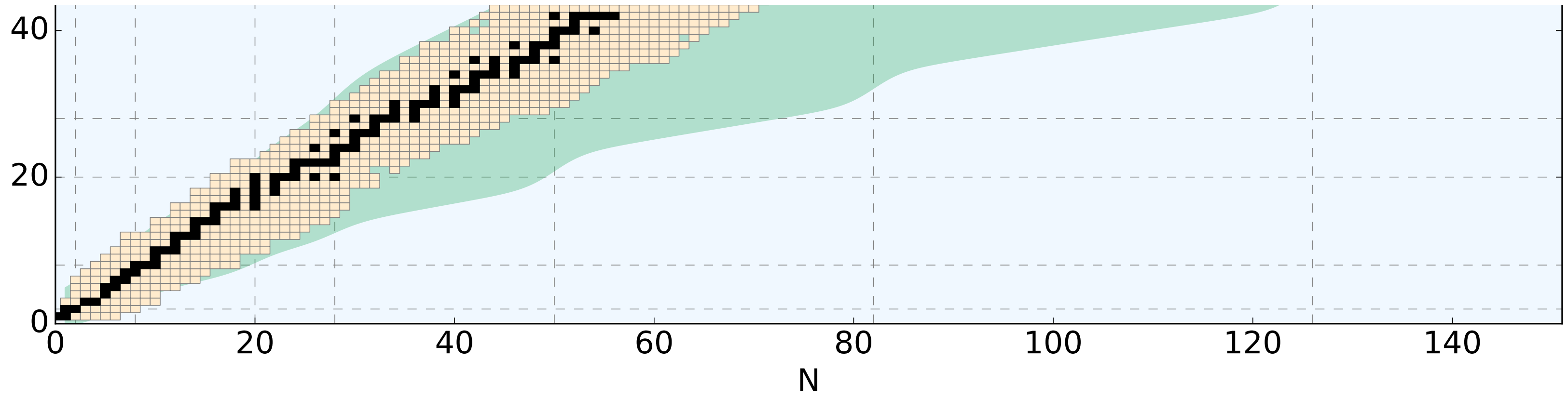
Chiral effective field theory, in principle

Systematic expansion of nuclear interactions

Consistent 3N forces, electroweak currents

Quantifiable uncertainties possible

In practice, use EFT as guidance - all available Hamiltonians exhibit some deficiencies



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

- Nuclear forces, electroweak physics
- **Nuclear many-body problem**

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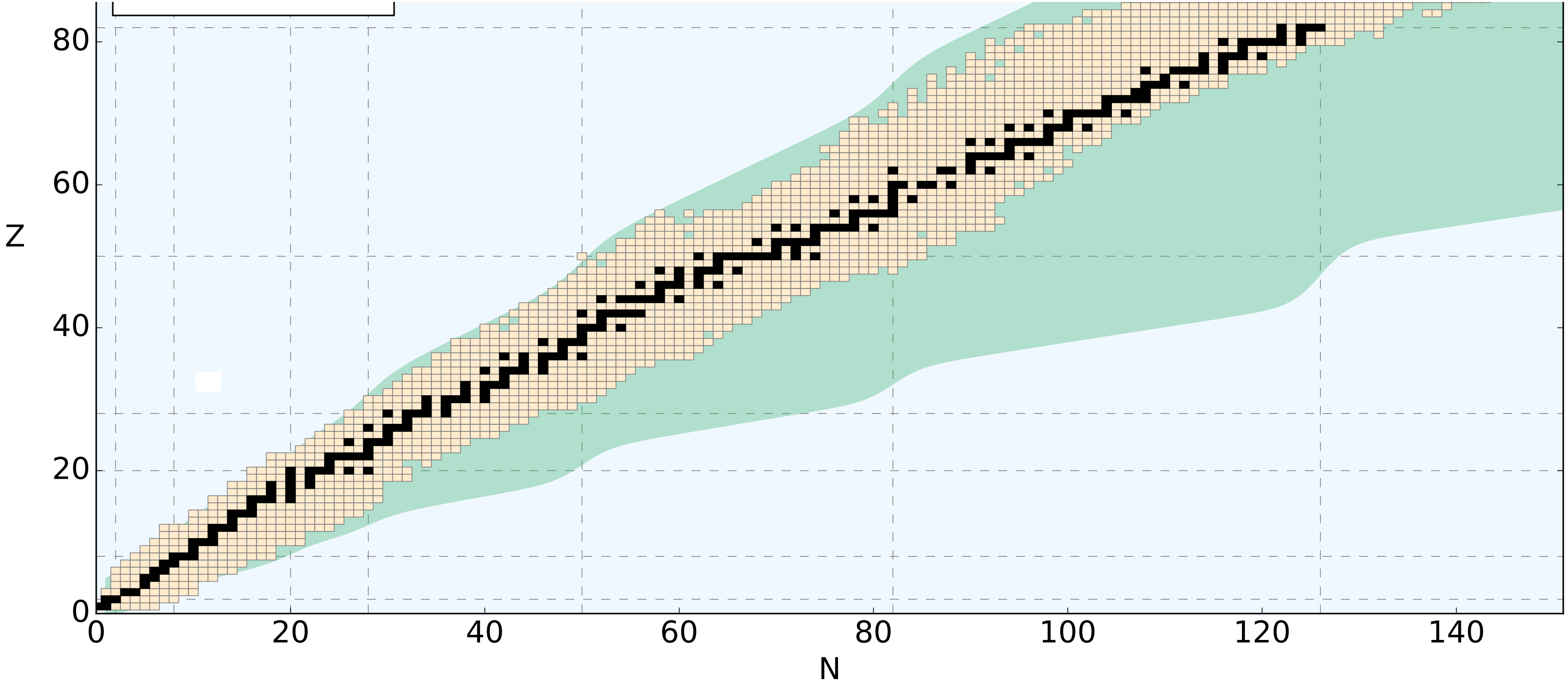

Breadth of Ab Initio Many-Body Methods

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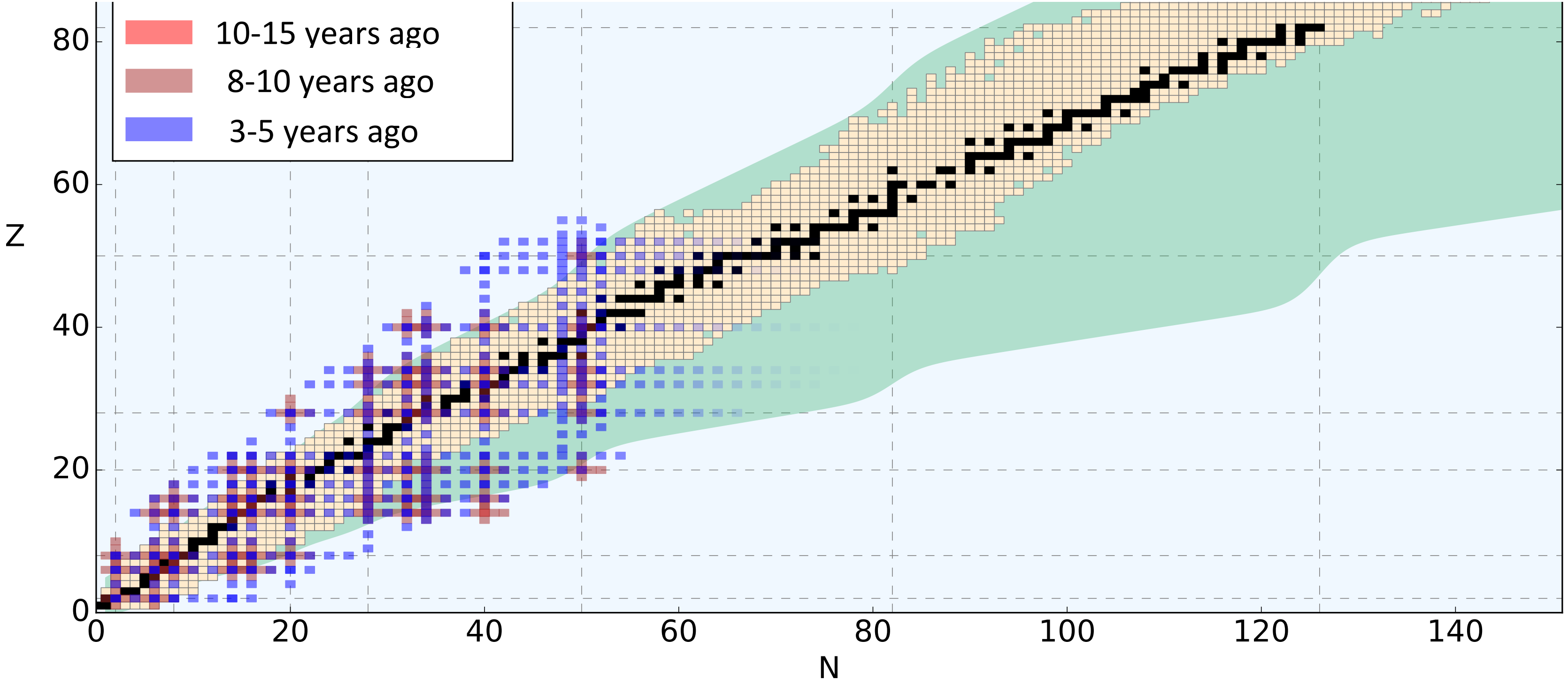

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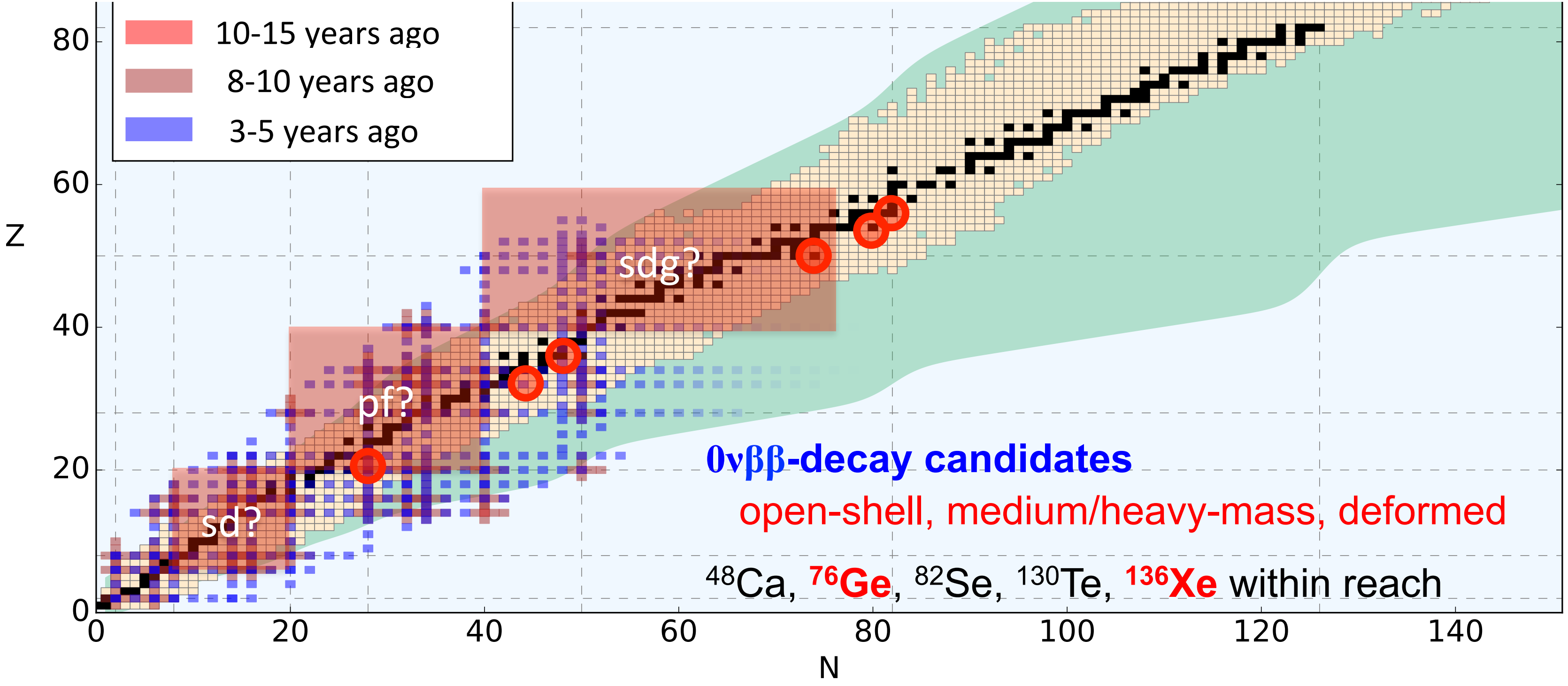


0νββ-decay candidates

open-shell, medium/heavy-mass, deformed

^{48}Ca, **^{76}Ge**, ^{82}Se, ^{130}Te, **^{136}Xe** within reach

Explicitly construct unitary transformation from sequence of rotations

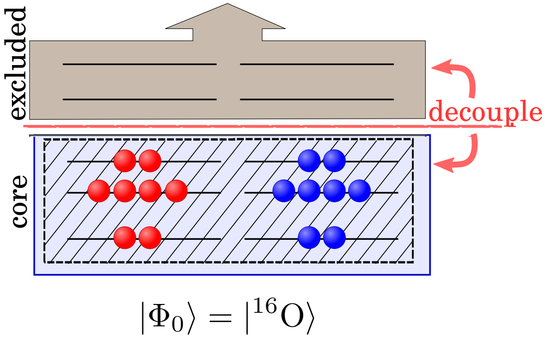
$$U = e^{\Omega} = e^{\eta_n} \dots e^{\eta_1} \qquad \eta = \frac{1}{2}\arctan\left(\frac{2H_{\rm od}}{\Delta}\right) - {\rm h.c.}$$

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

All operators truncated at two-body level IMSRG(2)
IMSRG(3) in progress

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

Step 1: Decouple core



Can we achieve accuracy of large-space methods?

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

Valence-Space In-Medium SRG

Explicitly construct unitary transformation from sequence of rotations

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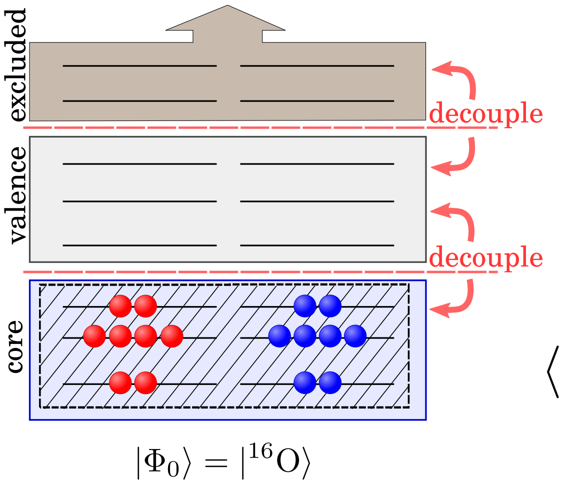

Step 1: Decouple core
Step 2: Decouple valence space

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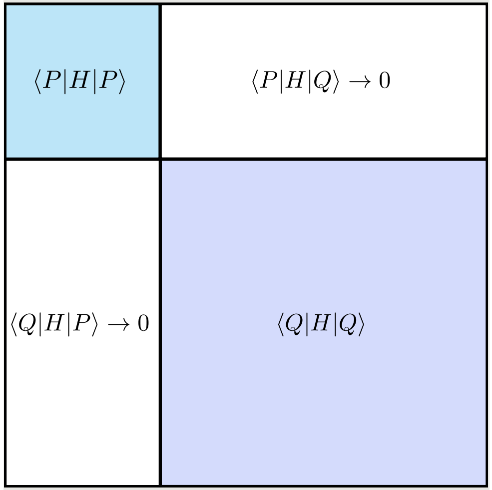

Effective Valence-Space In-Medium SRG Operators

Explicitly construct unitary transformation from sequence of rotations

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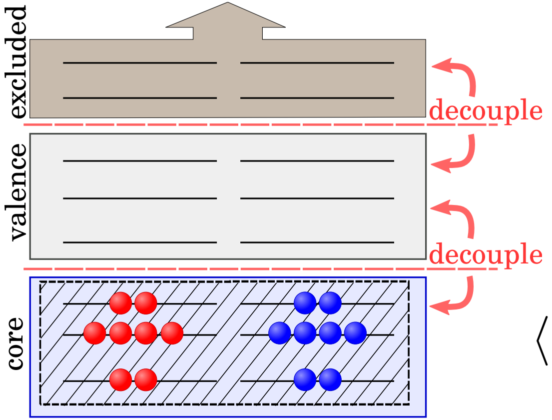
$$\tilde{H} = e^{\Omega} H e^{-\Omega} = H + [\Omega, H] + \frac{1}{2}[\Omega, [\Omega, H]] + \cdots$$

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



$|\Phi_0\rangle = |^{16}\text{O}\rangle$

Step 1: Decouple core

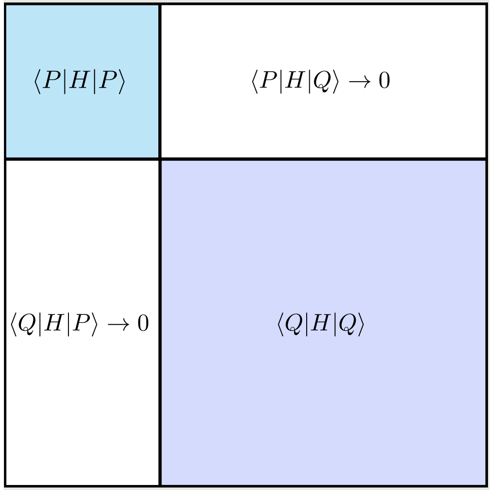
Step 2: Decouple valence space

Step 3: Decouple additional operators

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

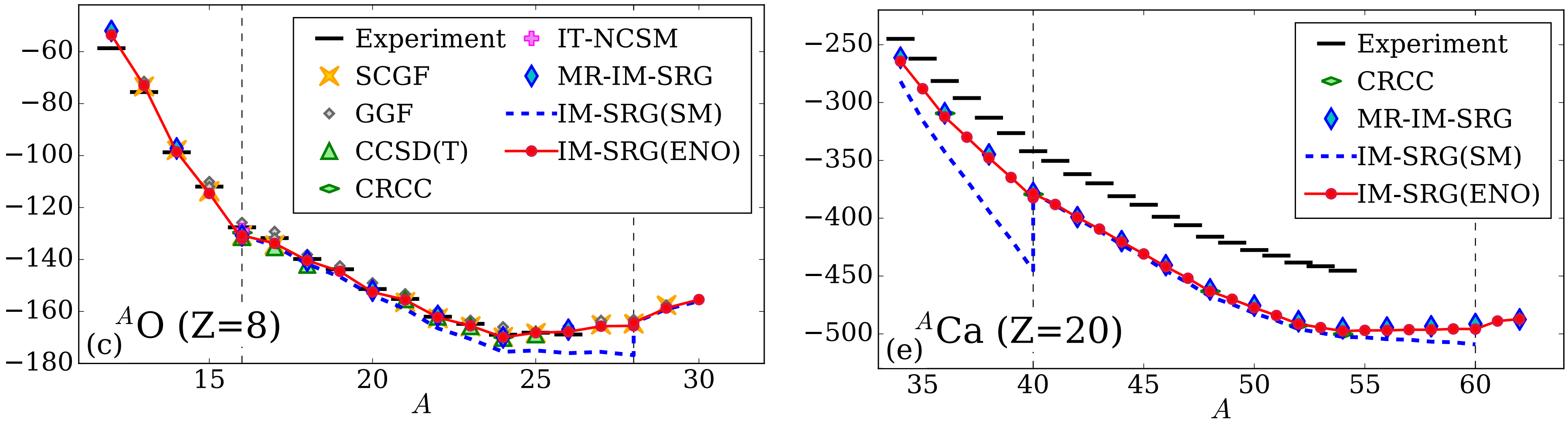
$$\langle \tilde{\Psi}_n | P\tilde{M}_{0\nu}P \mid \tilde{\Psi}_n \rangle \approx \langle \Psi_i | M_{0\nu} | \Psi_i \rangle$$

Careful benchmarking essential



Valence-Space IMSRG: From Oxygen to Nickel

New approach accesses *all* nuclei: agrees to 1% with large-space methods



Stroberg et al., PRL (2017)

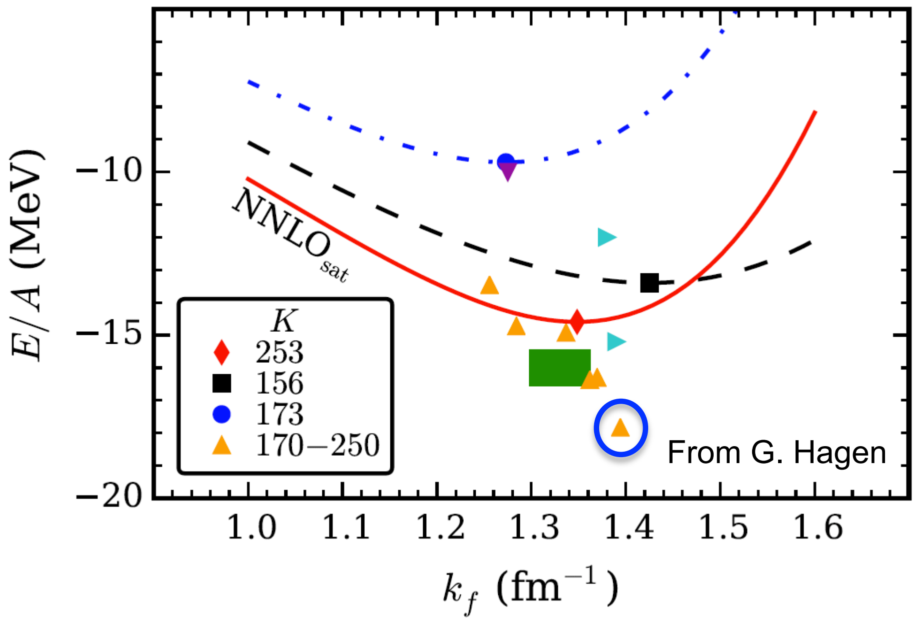
Agreement with *experiment* deteriorates for heavy chains (due to input Hamiltonian)

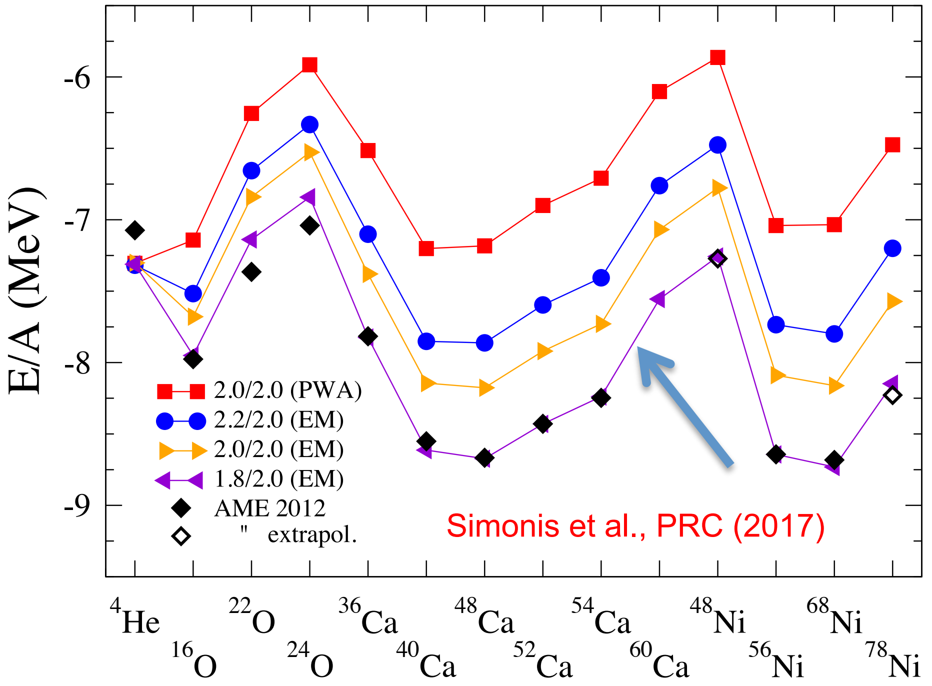
Significant gain in applicability with little/no sacrifice in accuracy

Low computational cost: ~1 node-day/nucleus

Connection to Infinite Matter: Saturation as a Guide for Nuclei

NN+3N force with good reproduction of ground-state energies (but poor radii)



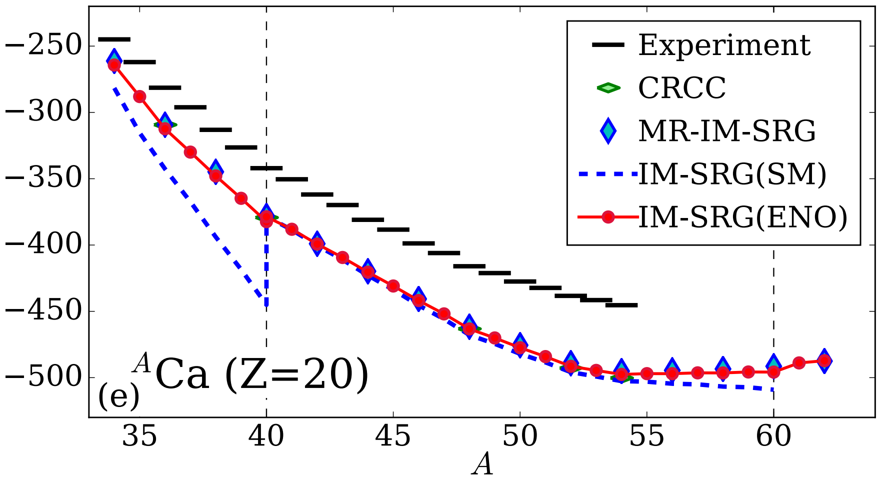


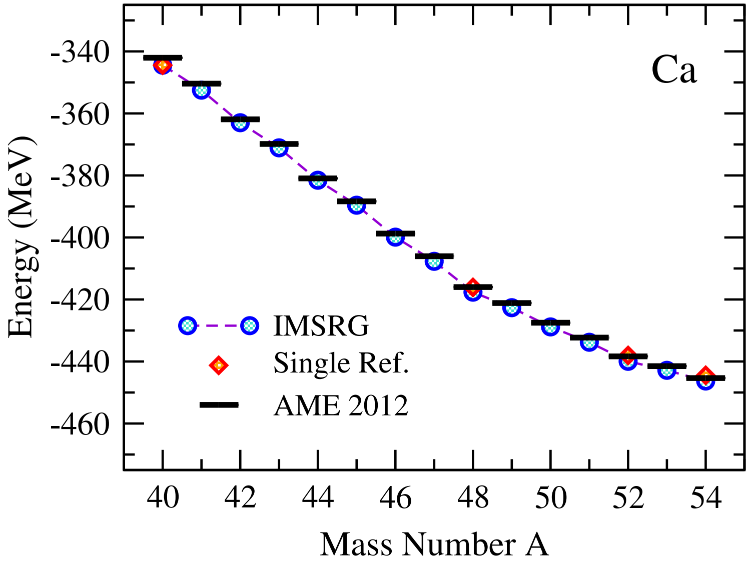
1.8/2.0 (EM) reproduces ground-state energies through ^{78}Ni

Slight underbinding for neutron-rich oxygen

Forces with good saturation

Isotopic chains: dramatic improvement with respect to experimental data





Opens possibility for reliable ab initio predictions across the nuclear chart!

Accesses **all** properties of **all** nuclei:

- Ground states, excited states, radii, electroweak transitions…

Breadth of Ab Initio Many-Body Methods

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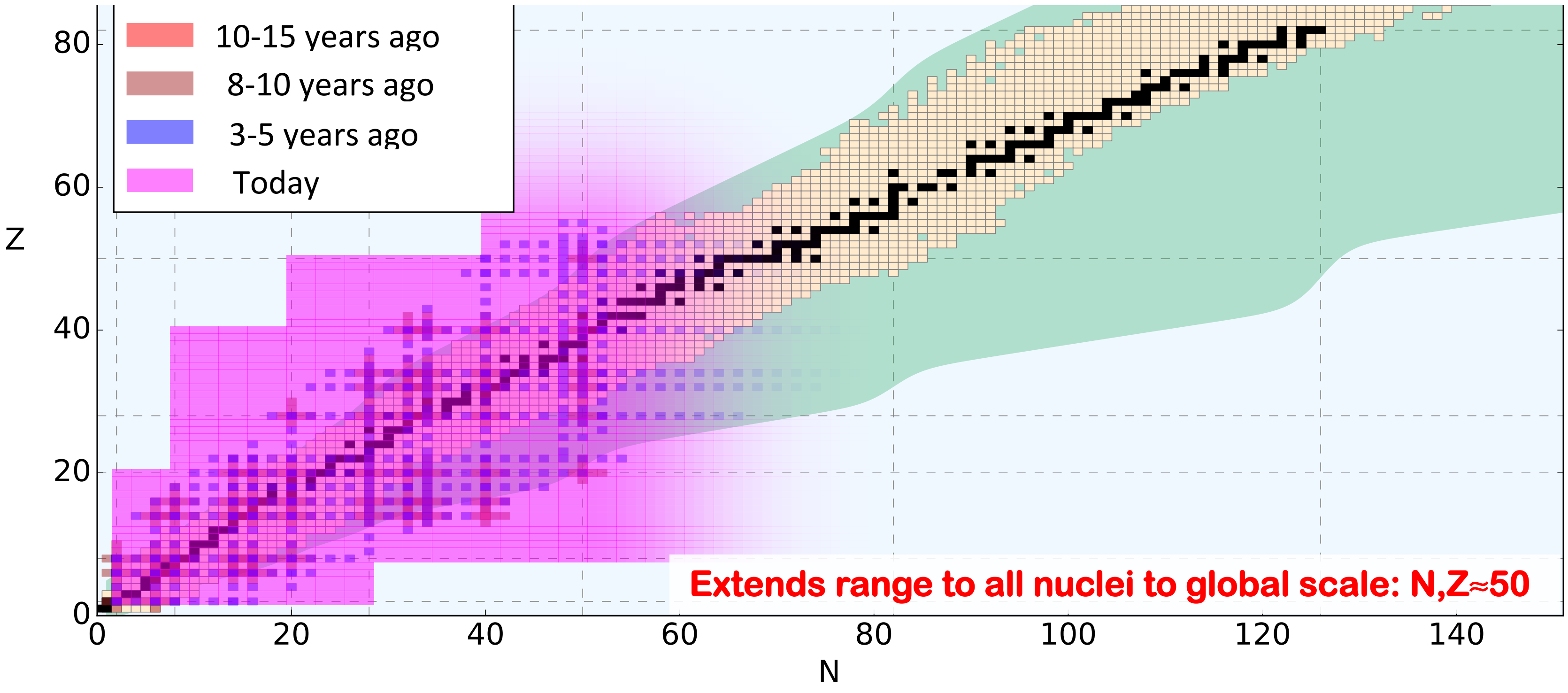
$$H\psi_n = E_n\psi_n$$

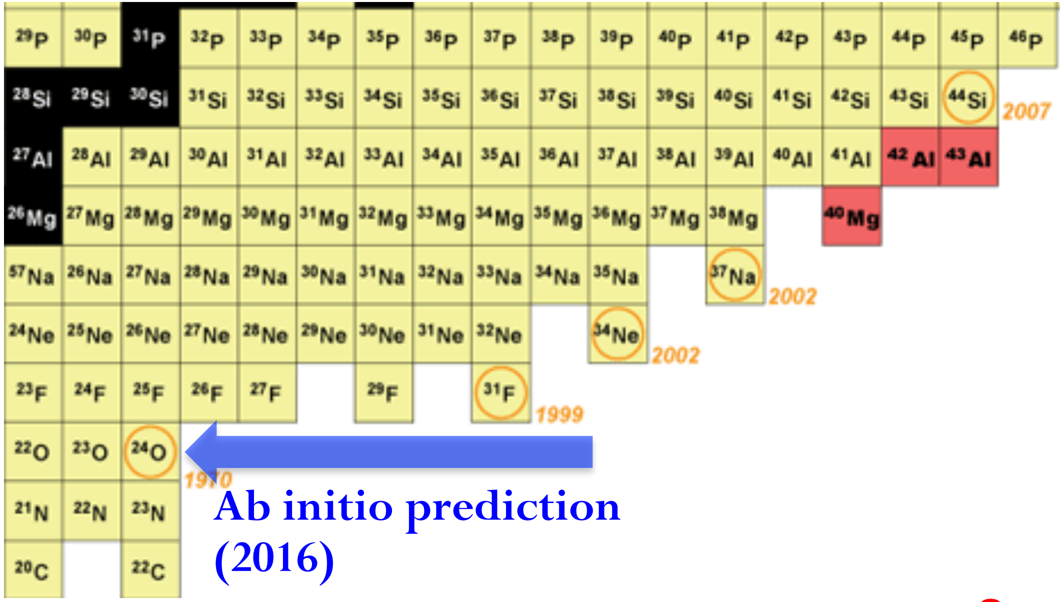


Where (and what) is the nuclear dripline?

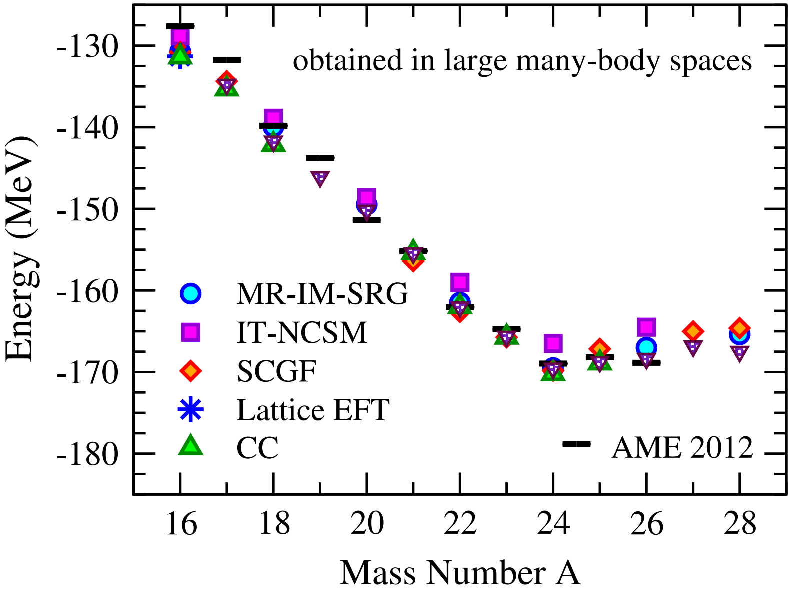
Limits defined as last isotope with positive neutron separation energy

- Nucleons “drip” out of nucleus

Neutron dripline experimentally established to Z=8



Ab initio prediction (2016)

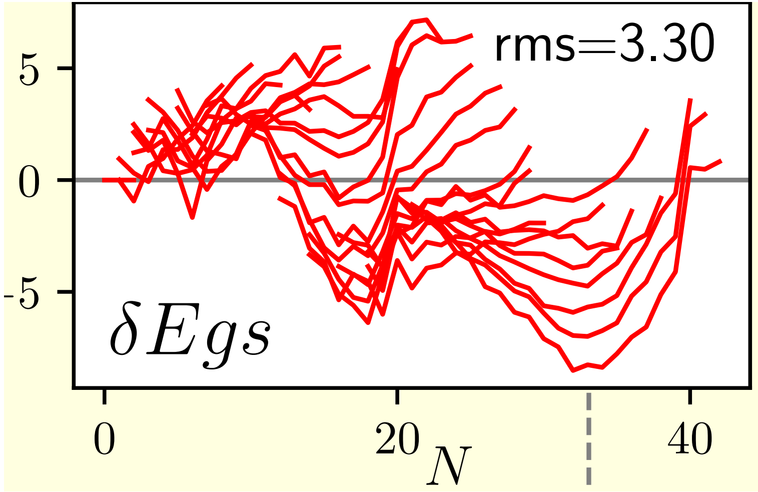


Same result from same input NN+3N forces

Already well beyond where fit to data!

Global Ab Initio Calculations

Effectively takes ab initio calculations to a global scale – up to N,Z~50



B-W Mass formula: 3.1 Z<28

3.5 Z<20

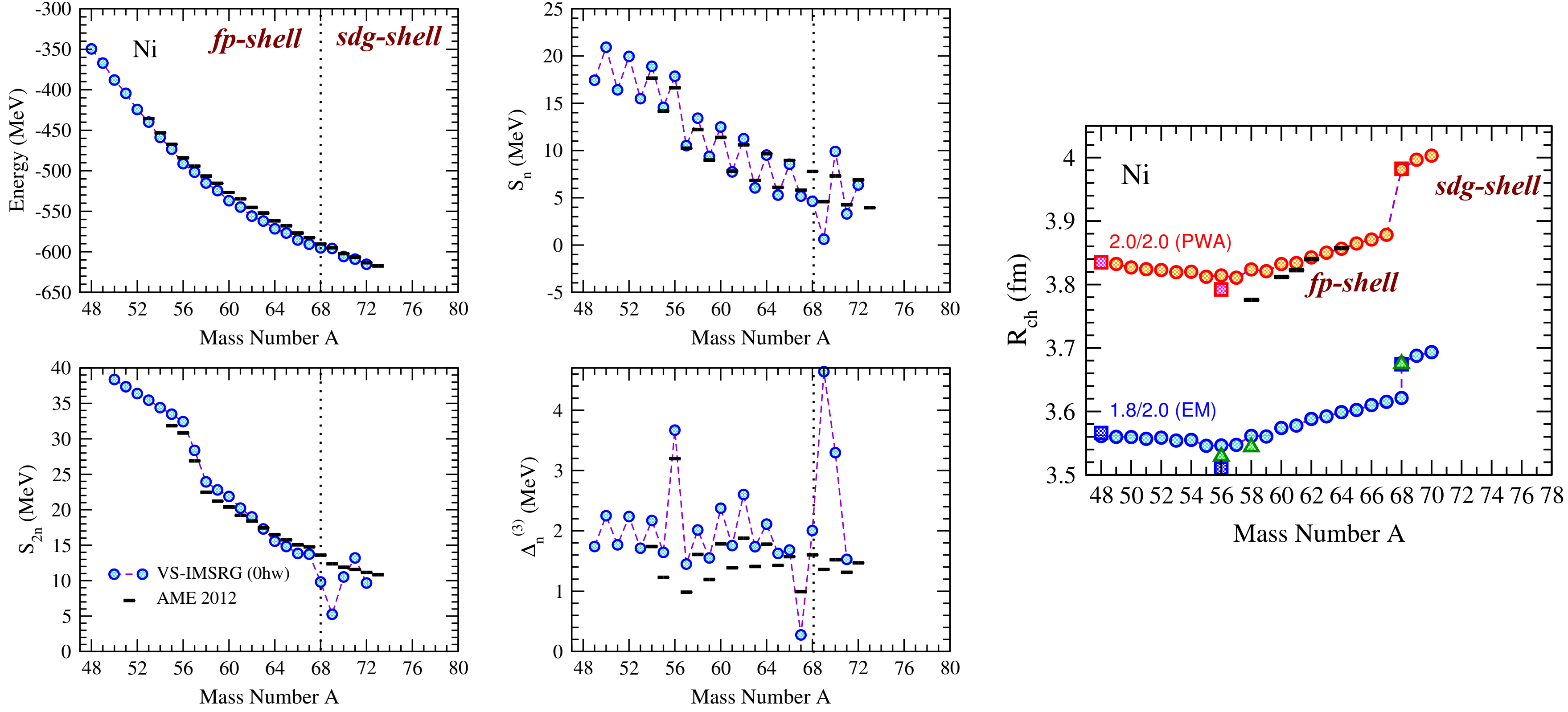
rms deviation at level of BW Mass formula (EDF models; UNEDF1 rms=1.8MeV)

Input Hamiltonians fit to A=2,3,4 – not biased towards known data

How does deviation from experiment look for separation energies (relevant for drip lines)?

Shell Closures in Neutron-Rich Ni

Defect 1: Clear artifacts when changing valence spaces



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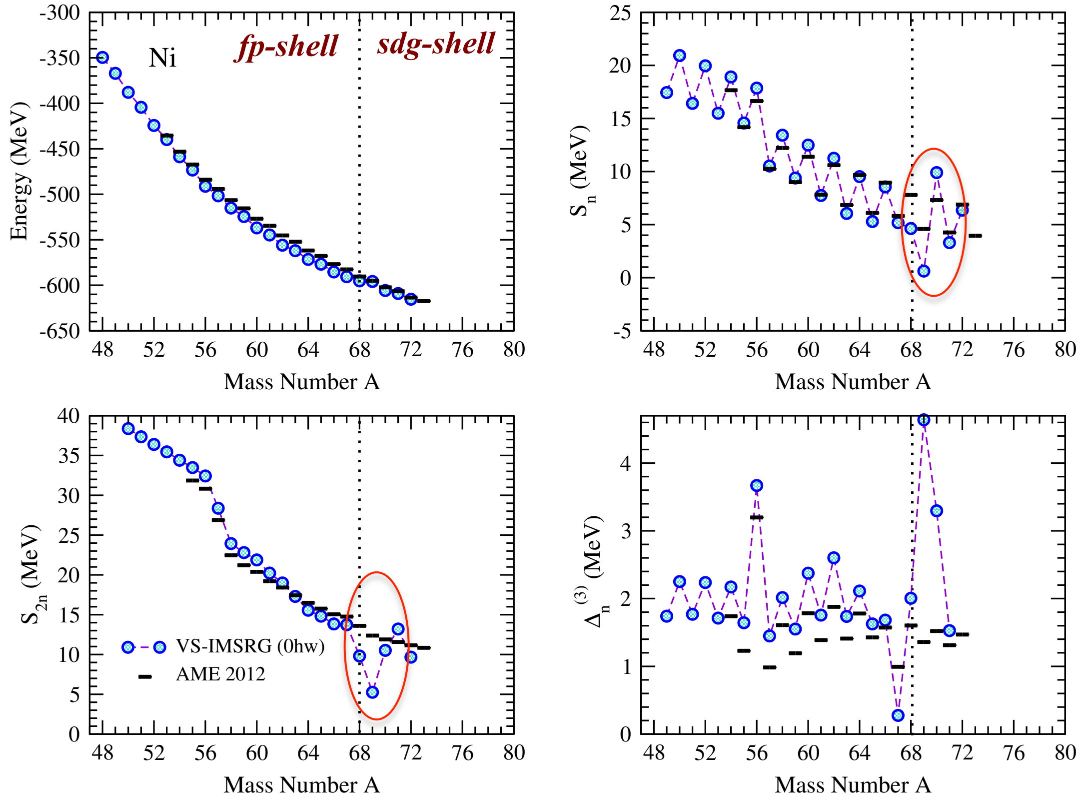
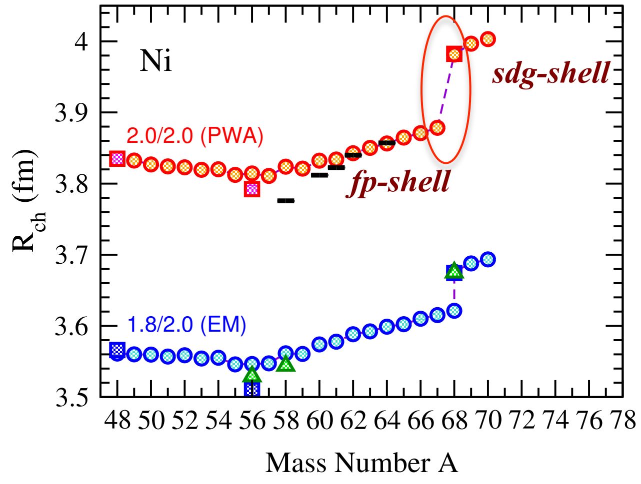


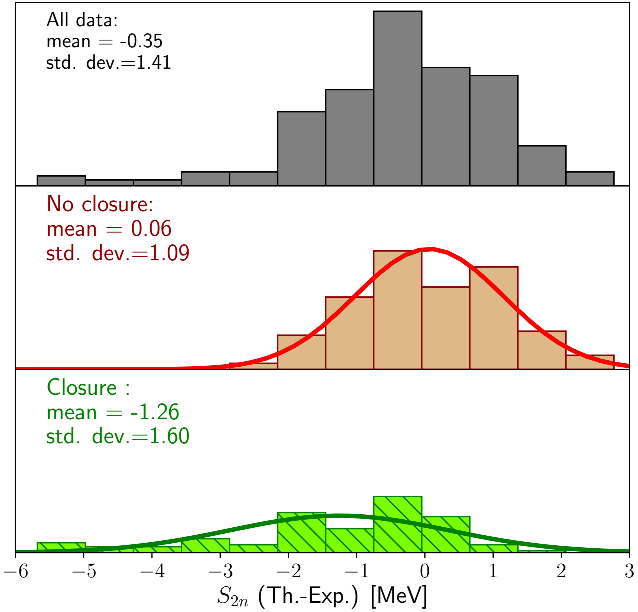


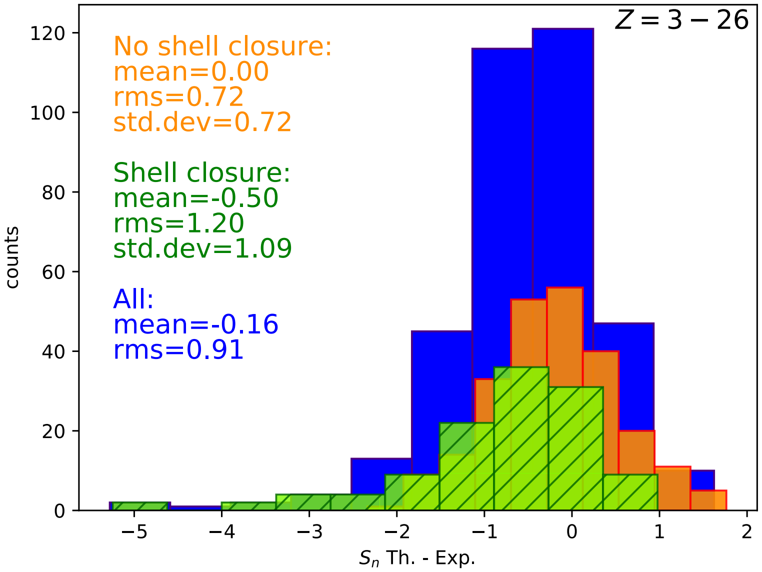
Introduces errors for separation energies near HO shell closures

Global Ab Initio Calculations

Potential errors at shell closures from changing valence spaces

Differentiate between “closure” and “no closure” cases





$$\delta\mathcal{O} \equiv \mathcal{O}^{(th)} - \mathcal{O}^{(exp)}$$

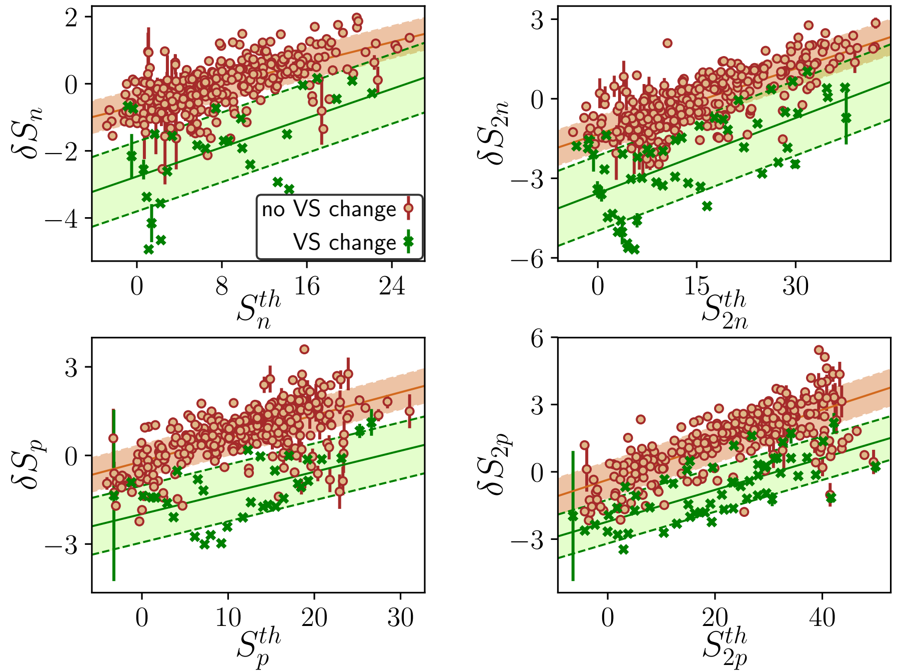
JDH, Stroberg, Schwenk in prep

Distributions approximately Gaussian

Non closed shells approximately centered at 0; rms approximately 1MeV

Distribution of Separation Energies

Defect 2: Incomplete infrared convergence near threshold – clear trend in residuals



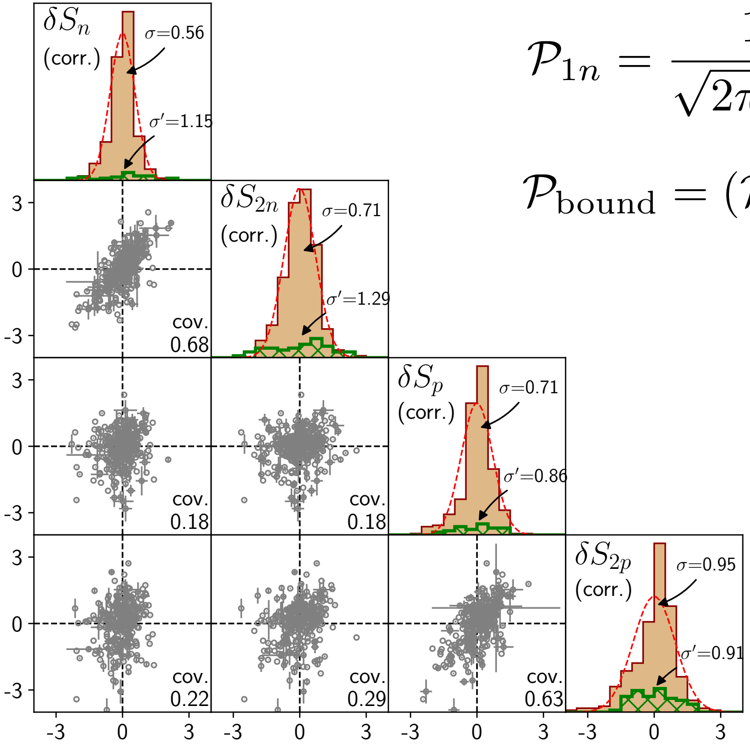
$$\delta\mathcal{O} \equiv \mathcal{O}^{(th)} - \mathcal{O}^{(exp)}$$

JDH, Stroberg, Schwenk in prep

Separate trends for VS change and no change

Correct VS-IMSRG results with linear fit of residuals

All corrected distributions approximately Gaussian centered at 0



$$\mathcal{P}_{1n} = \frac{1}{\sqrt{2\pi}\sigma_{1n}} \int_0^\infty \exp\left[\frac{(x - S_n^{th.corr})^2}{2\sigma_{1n}^2}\right] dx$$

$$\mathcal{P}_{\text{bound}} = (\mathcal{P}_{1n}\mathcal{P}_{2n} + \xi_{1n,2n})(\mathcal{P}_{1p}\mathcal{P}_{2p} + \xi_{1p,2p})$$

JDH, Stroberg, Schwenk in prep

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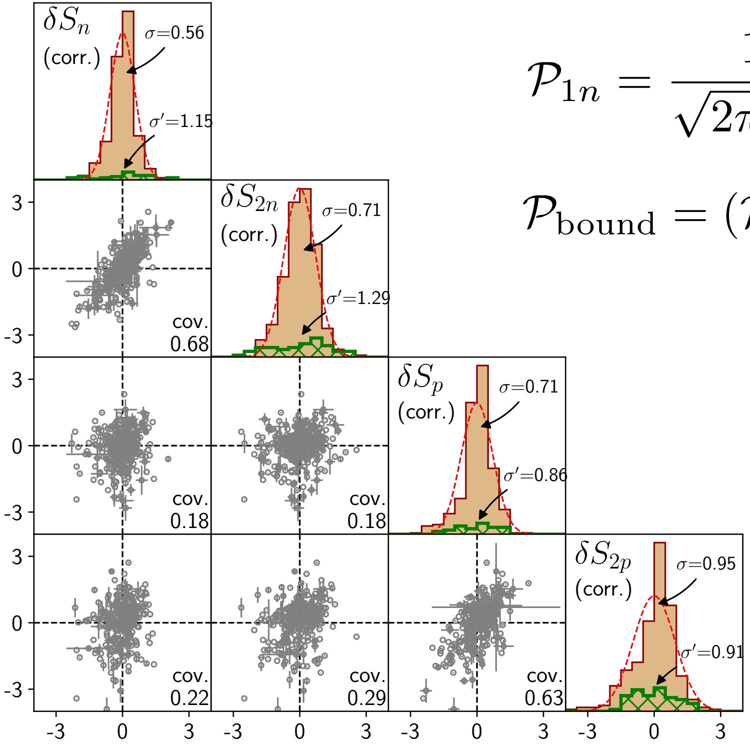

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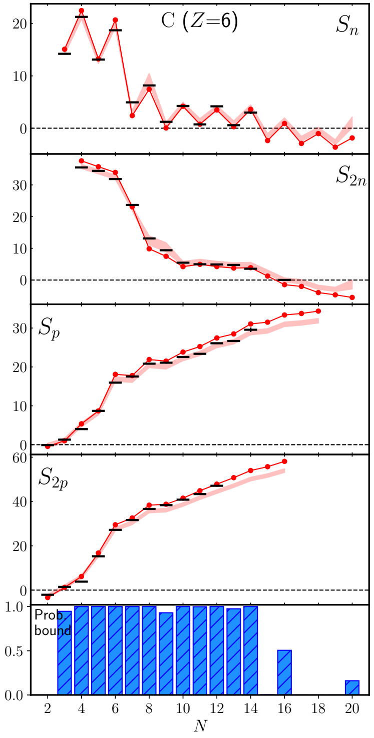
JDH, Stroberg, Schwenk in prep

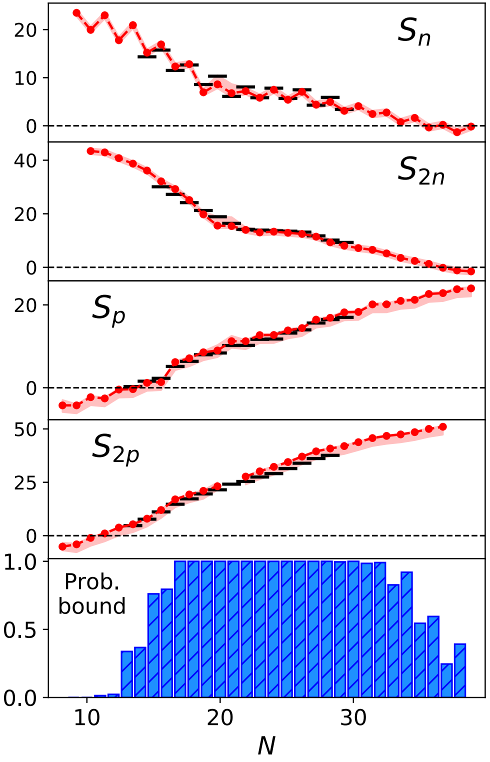
Certain residuals correlated – must correct for this in probabilities

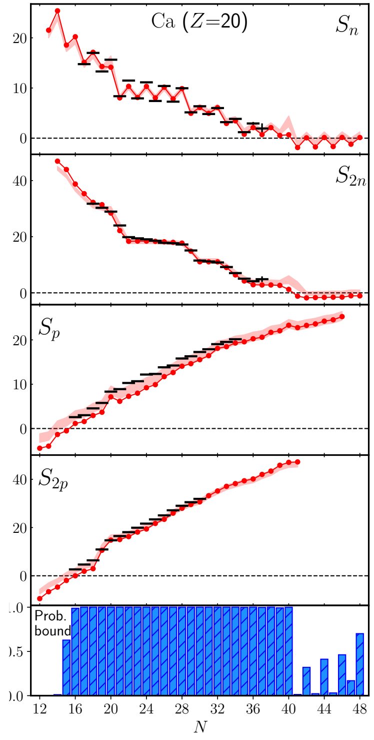
Assume unmeasured nuclei also follow this distribution

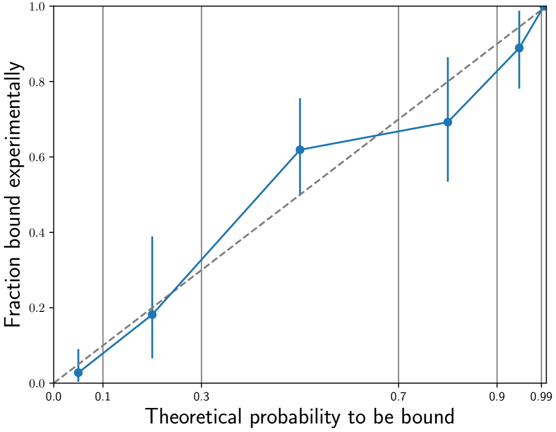
Estimating Dripline Uncertainties

Determine rms deviation from experiment – extrapolate this uncertainty beyond data









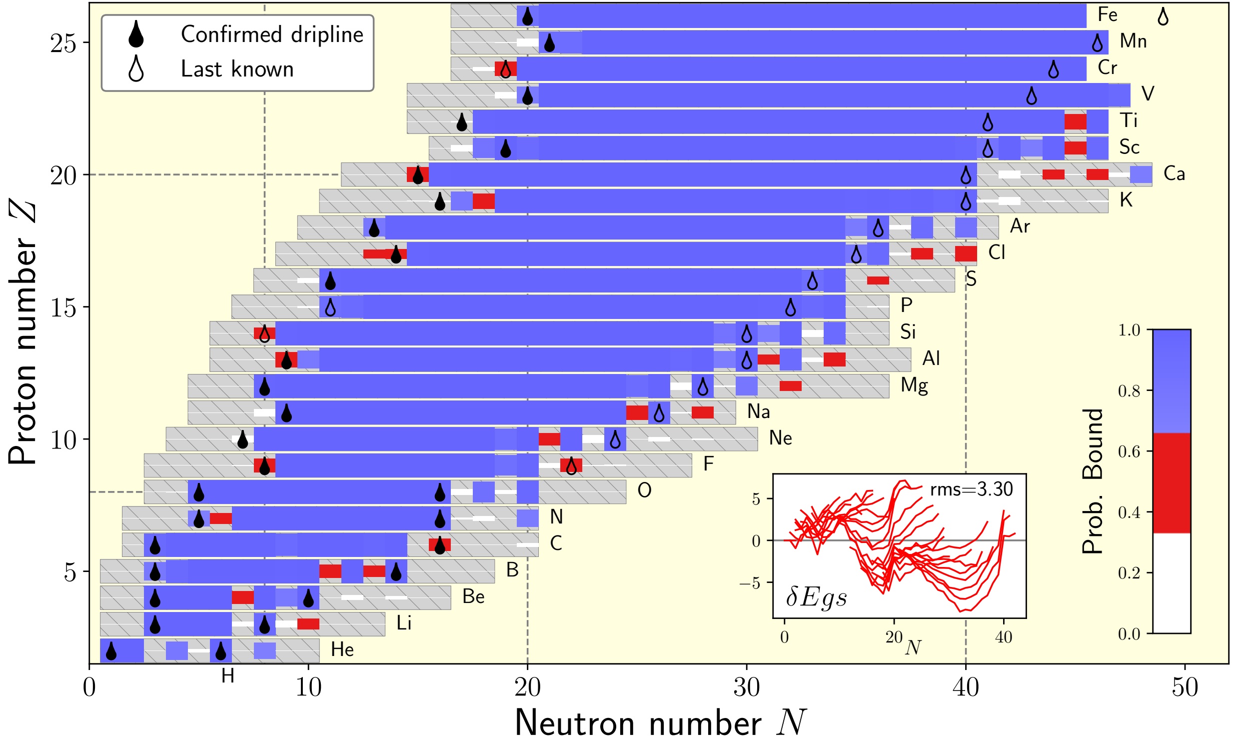
Determine range of likely separation energies reaching 0

Assign probability that a particular nucleus is bound

JDH, Stroberg, Schwenk in prep

Estimating Dripline Uncertainties

First predictions of proton and neutron driplines from first principles



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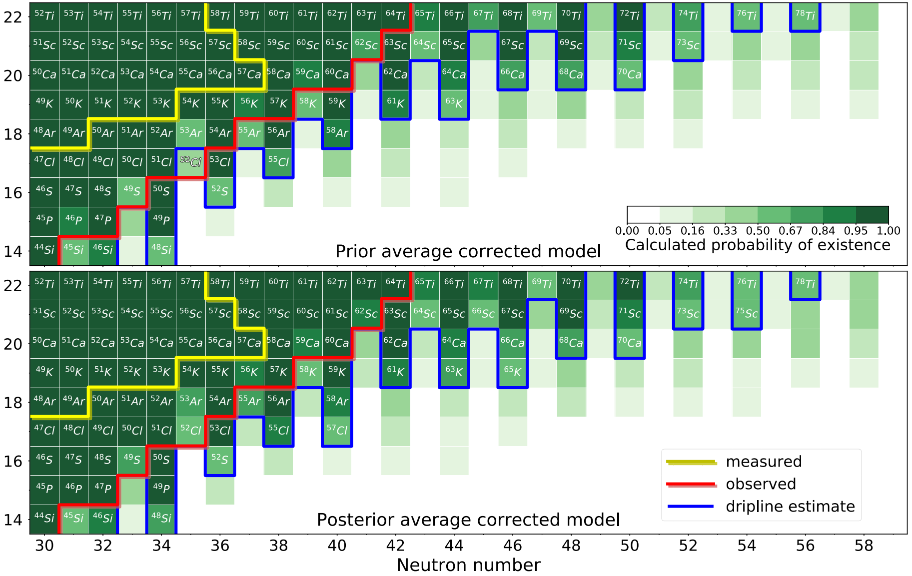
JDH, Stroberg, Schwenk in prep

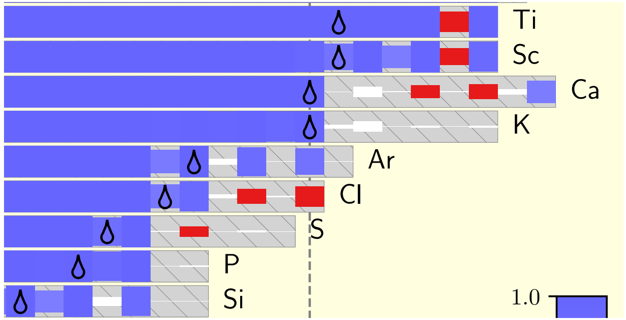
Known drip lines largely predicted within uncertainties (issues remain at shell closures)

Provide ab initio predictions for neutron-rich region

Comparison with DFT Dripline Predictions

Recent DFT analysis from Si-Ti based on Bayesian machine learning

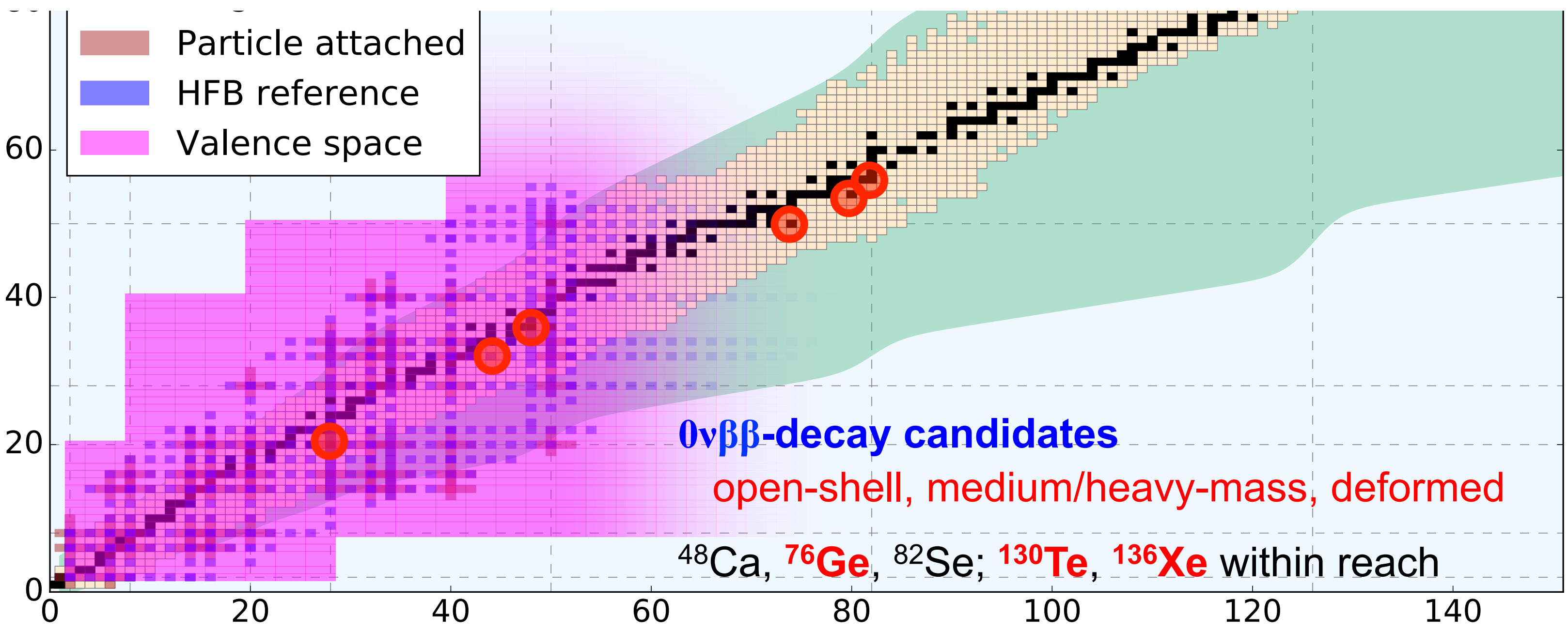




Largely consistent prediction of drip line

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

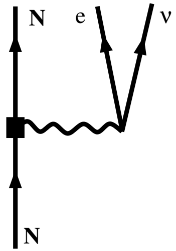
- Nuclear forces (low-energy QCD)
- Electroweak physics
- Nuclear many-body problem

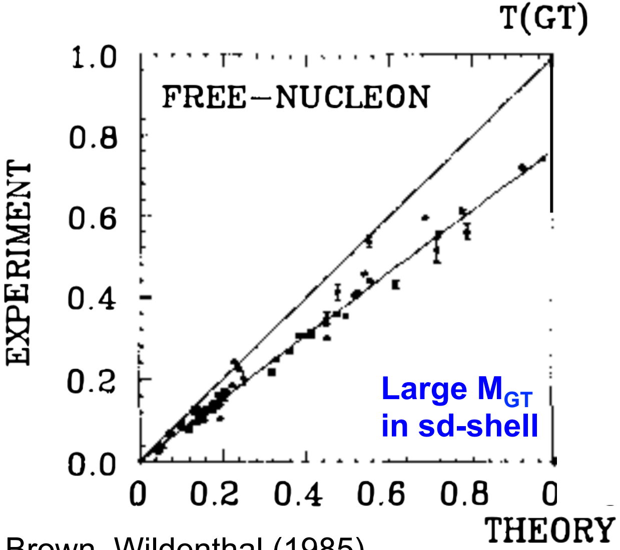


Beta-decay puzzle: "Quenching" of g_A

"Long-standing problem"[1] in weak decays: experimental values systematically smaller than theory

$$M_{\rm GT} = g_A \langle f | \mathcal{O}_{\rm GT} | i \rangle \quad \mathcal{O}_{\rm GT} = \mathcal{O}^{1b}_{\sigma\tau} + \mathcal{O}^{2b}_{2BC}$$





Brown, Wildenthal (1985)

1 papers from the 1970's

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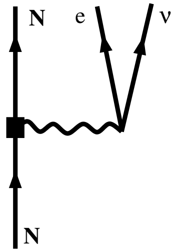
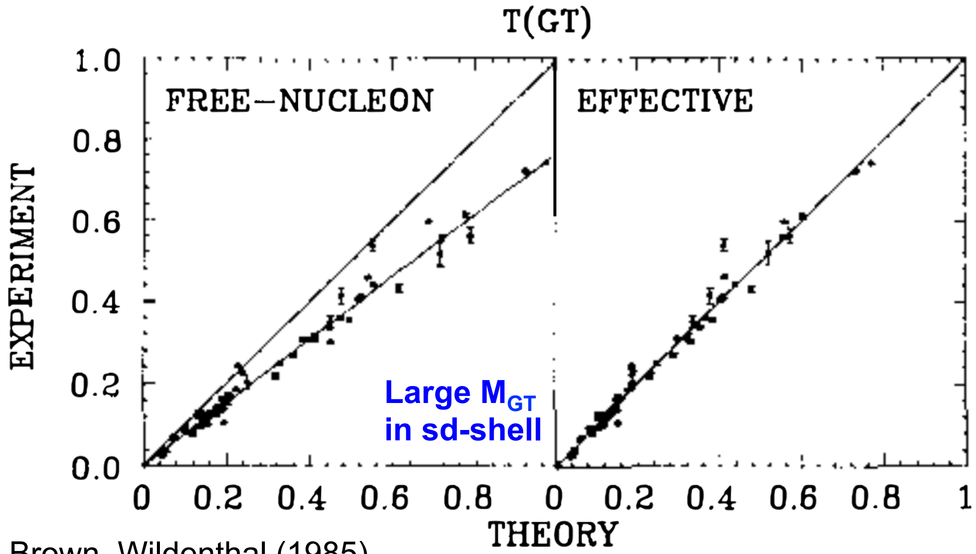


Using $g_A^{\mathrm{eff}} \approx 0.77 \times g_A^{\mathrm{free}}$ agrees with data



Brown, Wildenthal (1985)

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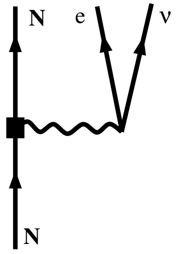

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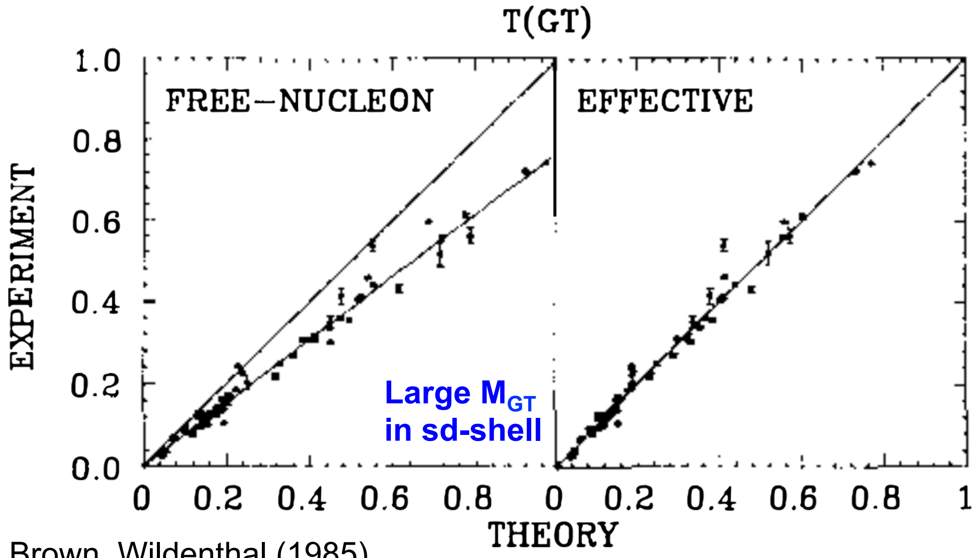

Brown, Wildenthal (1985)

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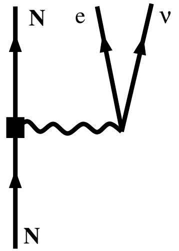
$\mathcal{O}_{\rm eff}$



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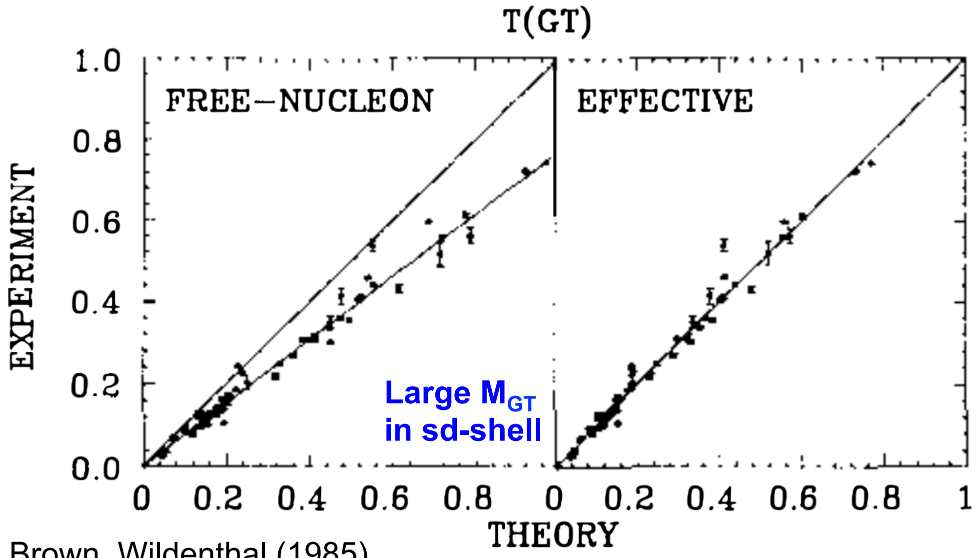

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- **Renormalized VS operator?**

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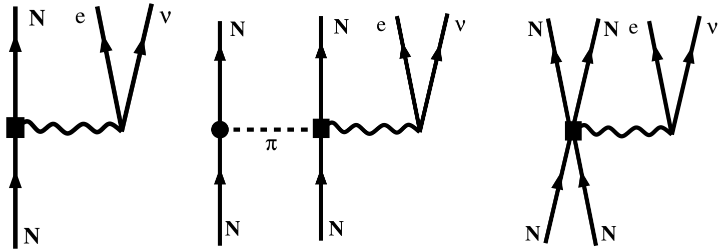

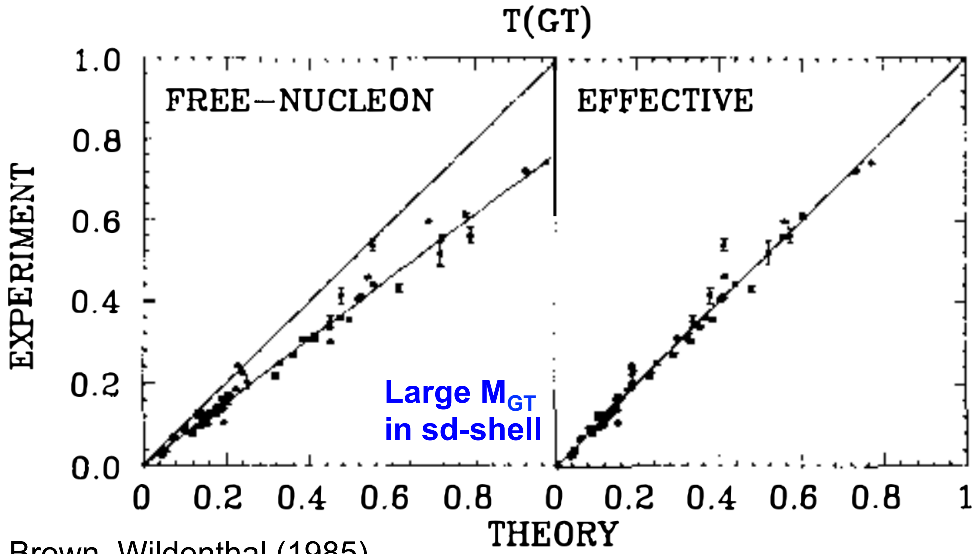

Brown, Wildenthal (1985)

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- **Neglected two-body currents?**

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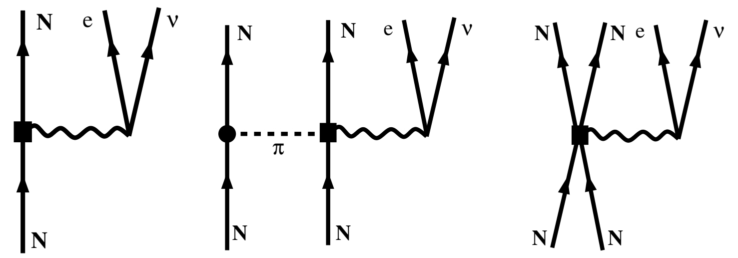

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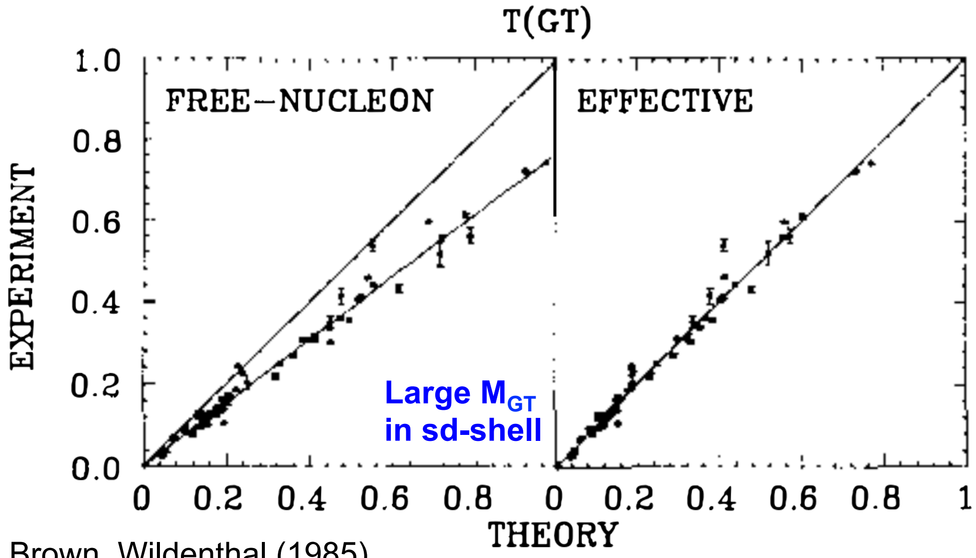


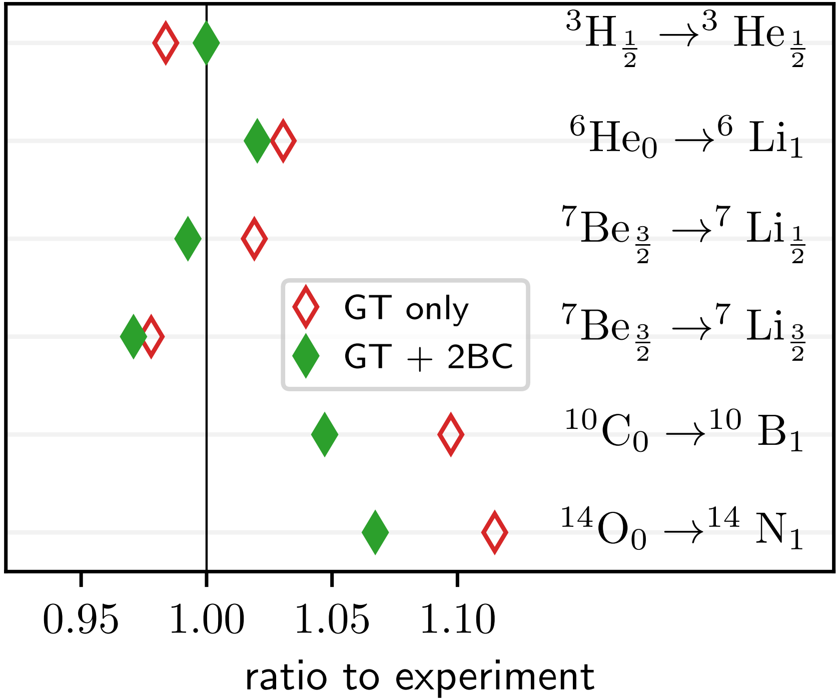
Brown, Wildenthal (1985)

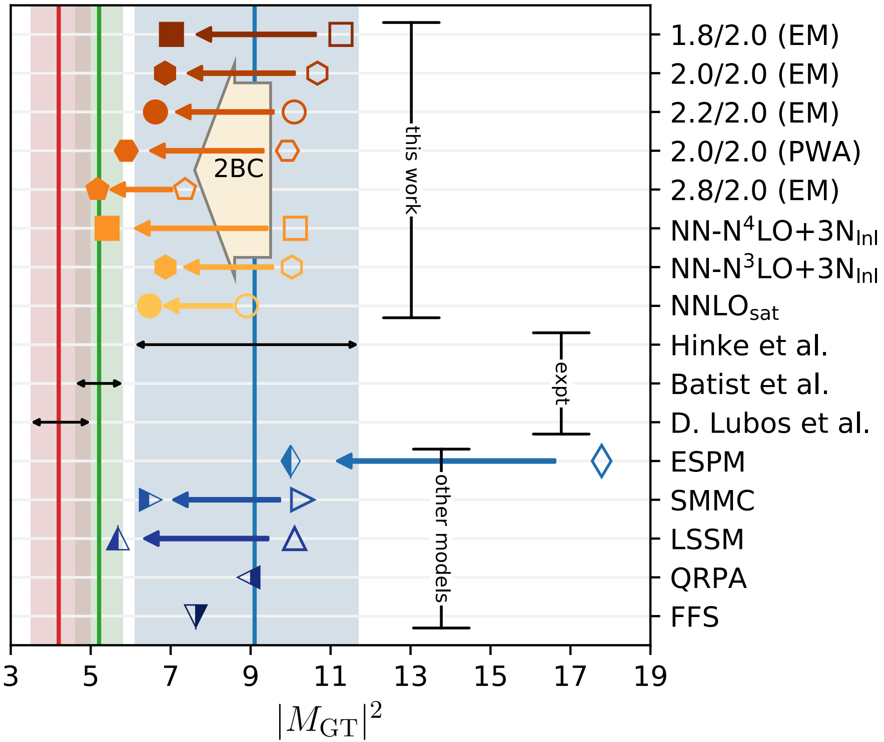
- Should g_A be quenched in medium?
- Missing wavefunction correlations
- Renormalized VS operator?
- Neglected two-body currents?
- Model-space truncations?

Explore in ab initio framework

GT Transition in light and heavy nuclei

NCSM in light nuclei, CC calculations of GT transition in ^{100}Sn from different forces





Large quenching effect from correlations

Gysbers et al., Nature Phys. (2019)

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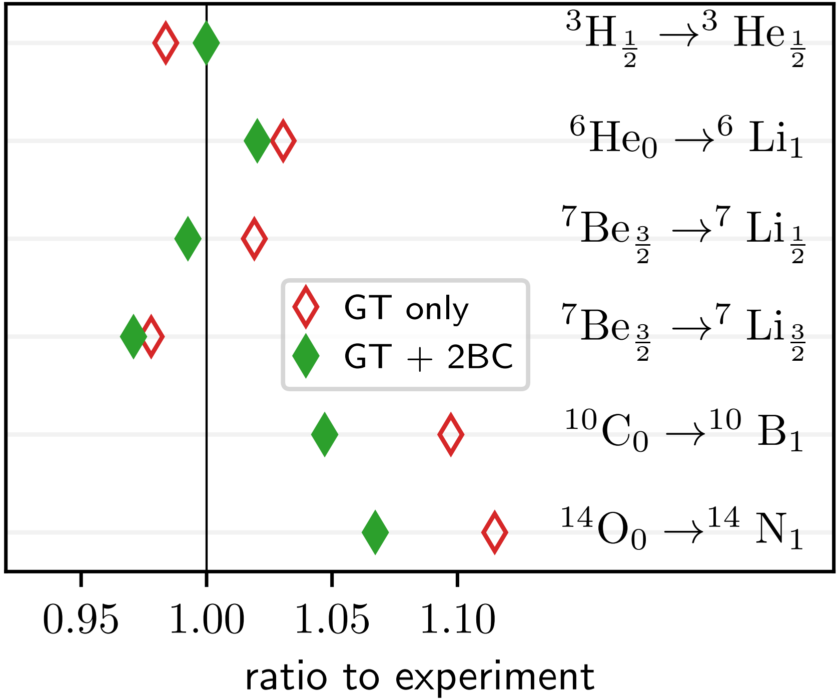

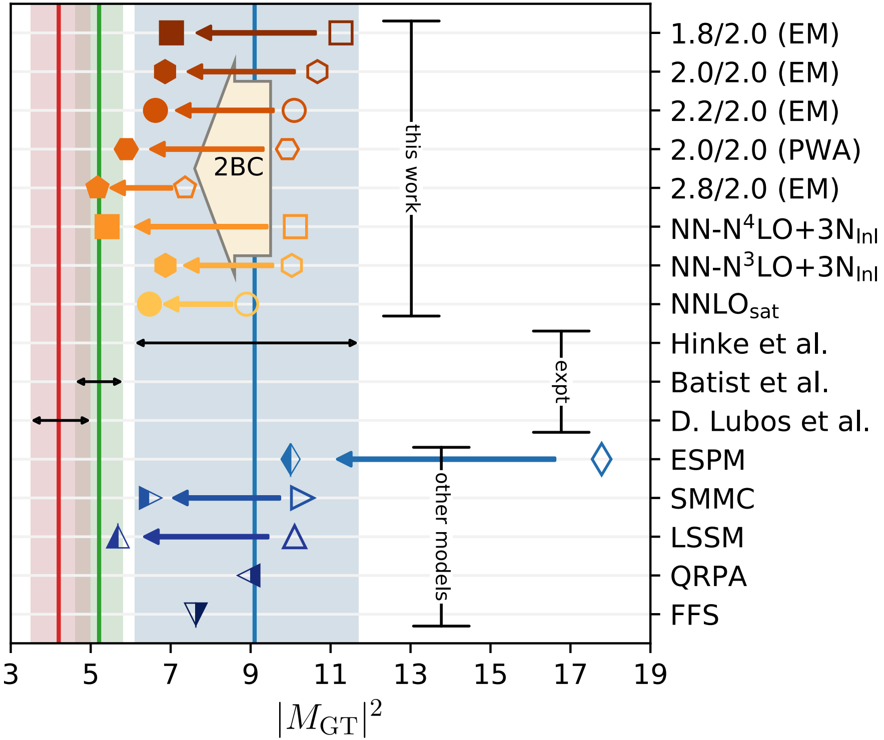

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Addition of 2BC further quenches and reduces spread in results

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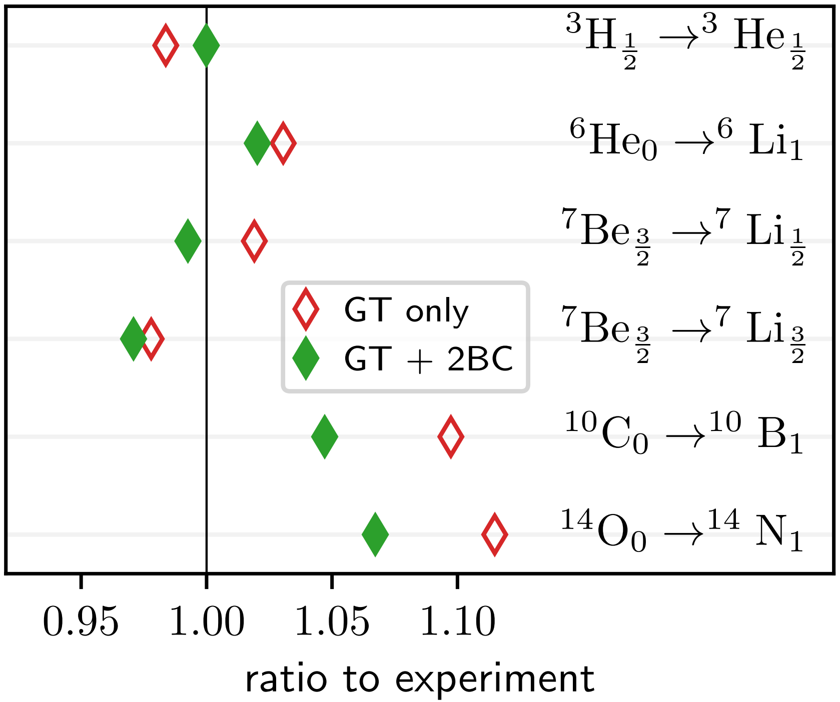

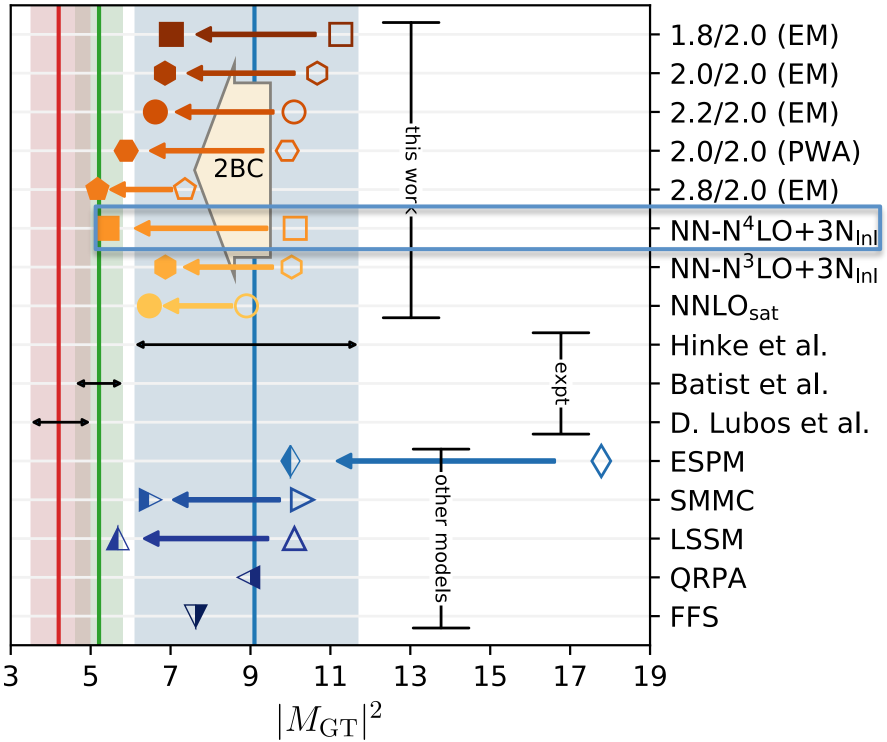

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Convergence and method benchmarks of VS-IMSRG GT transitions

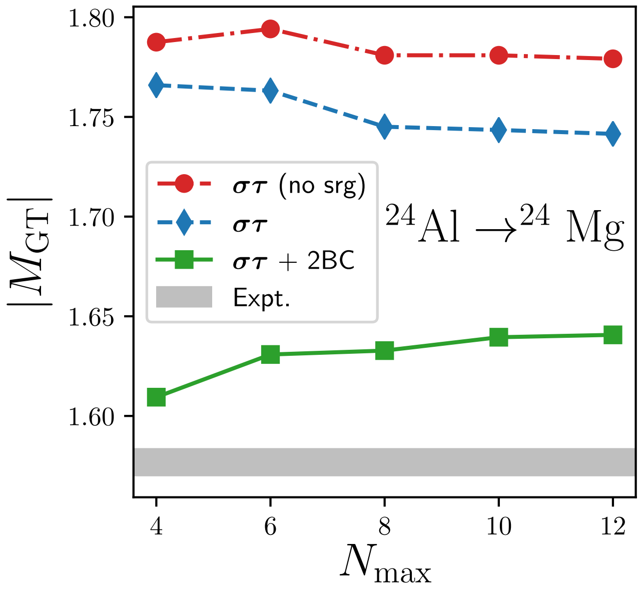


TABLE IV. Gamow Teller (GT) transition strength in ^{10}C to the first 1_1^+ in ^{10}B for the NN-N^{4}LO +3N$_{\rm lnl}$ interaction calculated in the VS-IMSRG(2) and NCSM approaches.

Method	$\lvert M_{\rm GT}(\boldsymbol{\sigma\tau})\rvert$	$\lvert M_{\rm GT}\rvert$
VS-IMSRG(2)	1.94	1.88
NCSM	2.01	1.92

TABLE III. Gamow Teller (GT) transition strength in ^{14}O to the second 1_2^+ in ^{14}N for the NNLO$_{\rm sat}$ and NN-N^{4}LO +3N$_{\rm lnl}$ interactions calculated in the EOM-CCSD, EOM-CCSDT-1, VS-IMSRG, and NCSM approaches.

Interaction	NNLO$_{\rm sat}$		NN-N^{4}LO+3N$_{\rm lnl}$	
Method	$\lvert M_{\rm GT}(\boldsymbol{\sigma\tau})\rvert$	$\lvert M_{\rm GT}\rvert$	$\lvert M_{\rm GT}(\boldsymbol{\sigma\tau})\rvert$	$\lvert M_{\rm GT}\rvert$
EOM-CCSD	2.15	2.08	2.26	2.06
EOM-CCSDT-1	1.77	1.69	1.97	1.86
VS-IMSRG(2)	1.72	1.76	1.83	1.83
NCSM	1.80	1.69	1.86	1.78

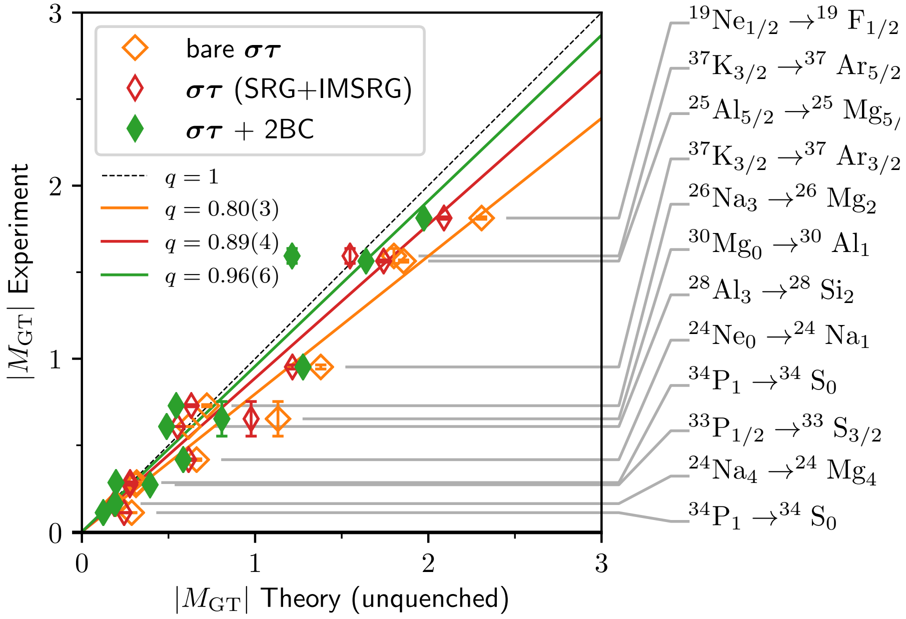
Well converged and good agreement with other ab initio methods

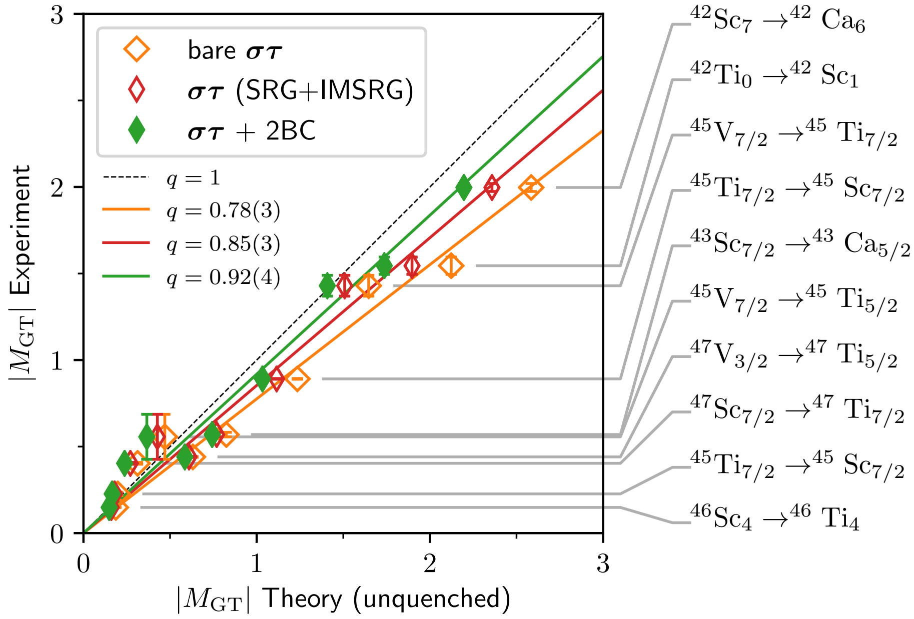
Ab Initio GT Decays in Medium-Mass Region

Ab initio calculations of **large** GT transitions in *sd*, *pf* shells

Bare operator similar to phenomenological shell model

Modest quenching from consistent ab initio wavefunctions and operators





Gysbers et al., Nature Phys. (2019)

Further modest quenching from 2BC

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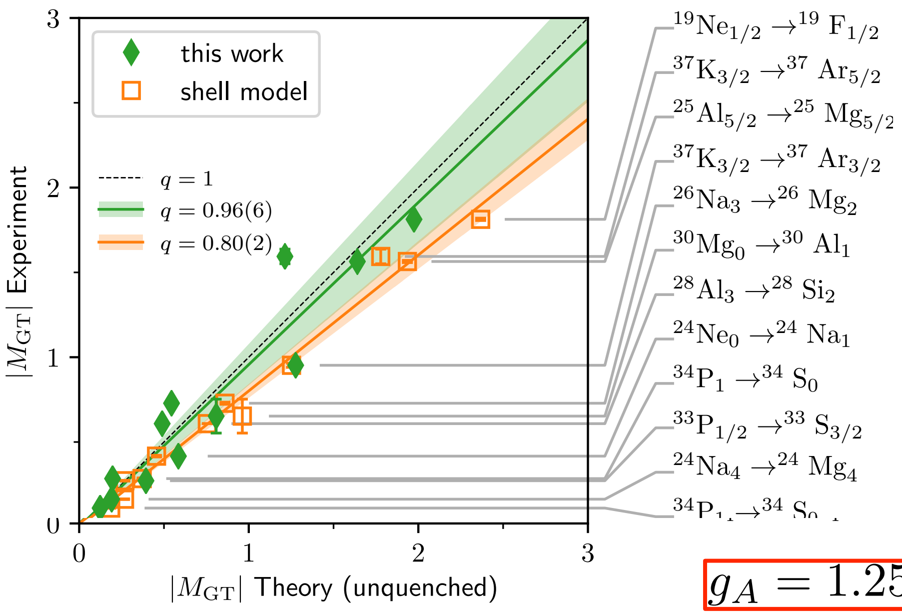
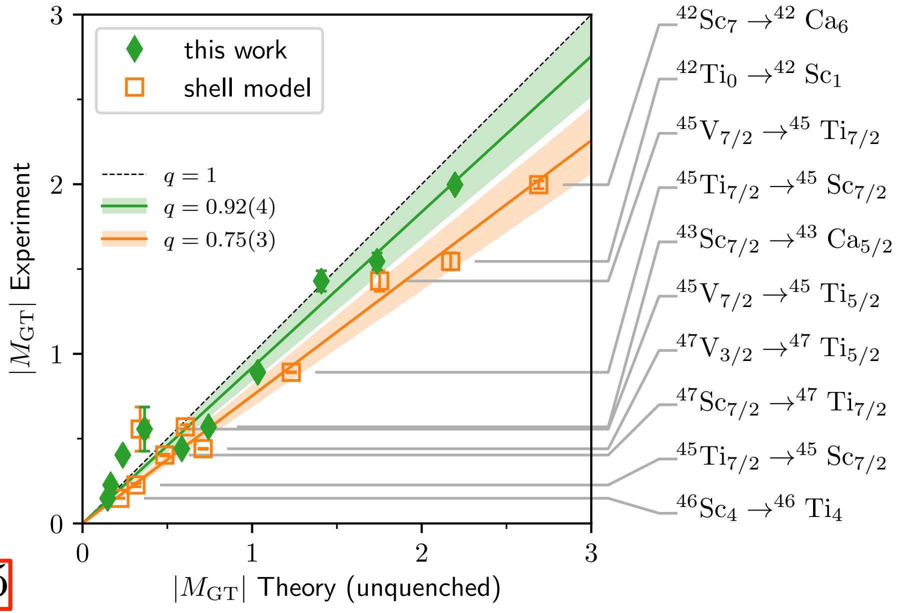
Comparison to standard phenomenological shell model

Ab initio calculations across the chart explain data with free-space g_A



$g_A = 1.25$



Gysbers et al., Nature Phys. (2019)

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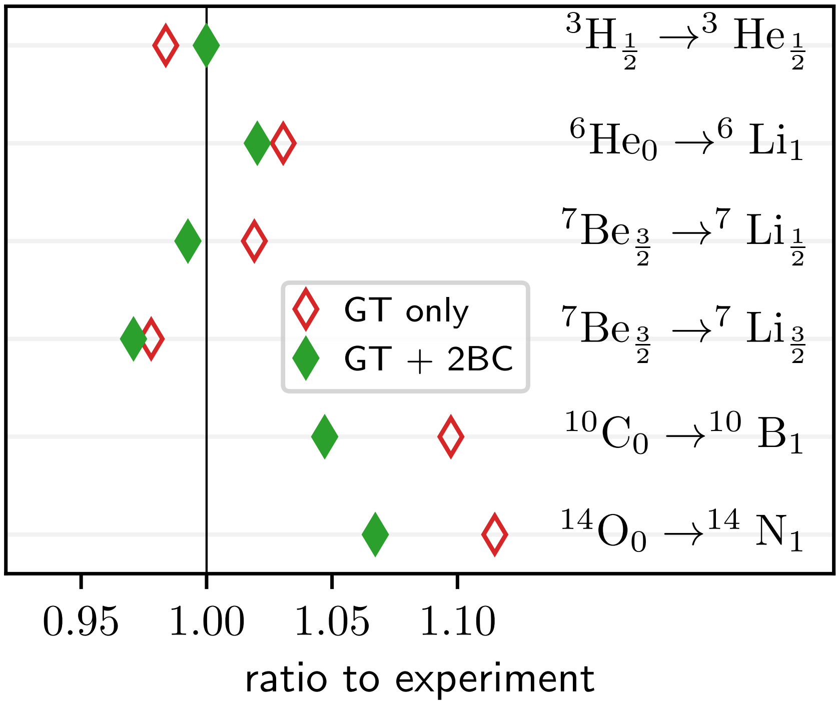

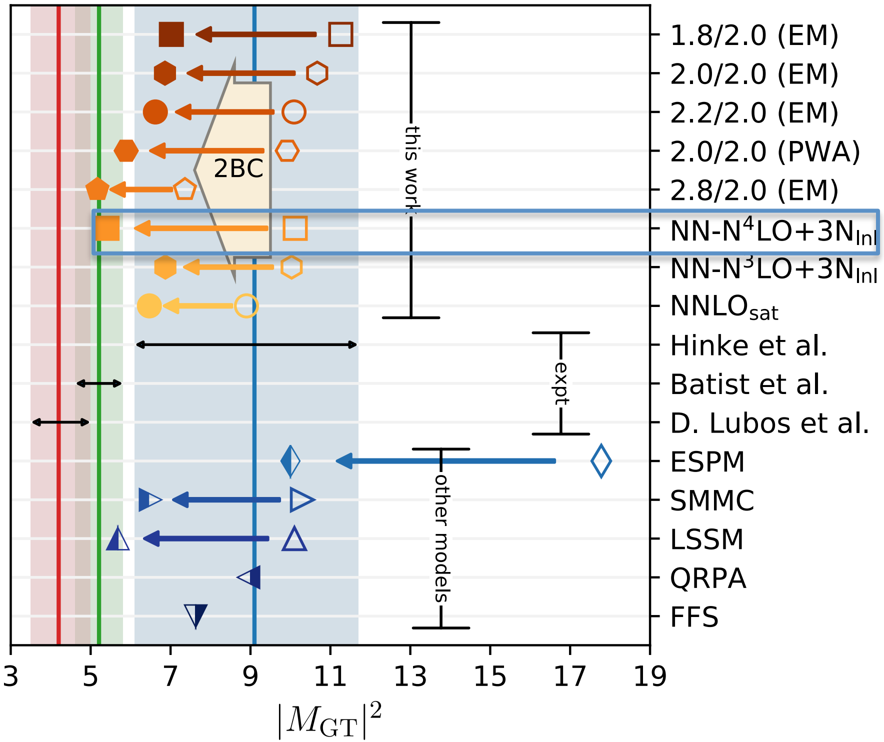

Large quenching effect from correlations

Gysbers et al., Nature Phys. (2019)

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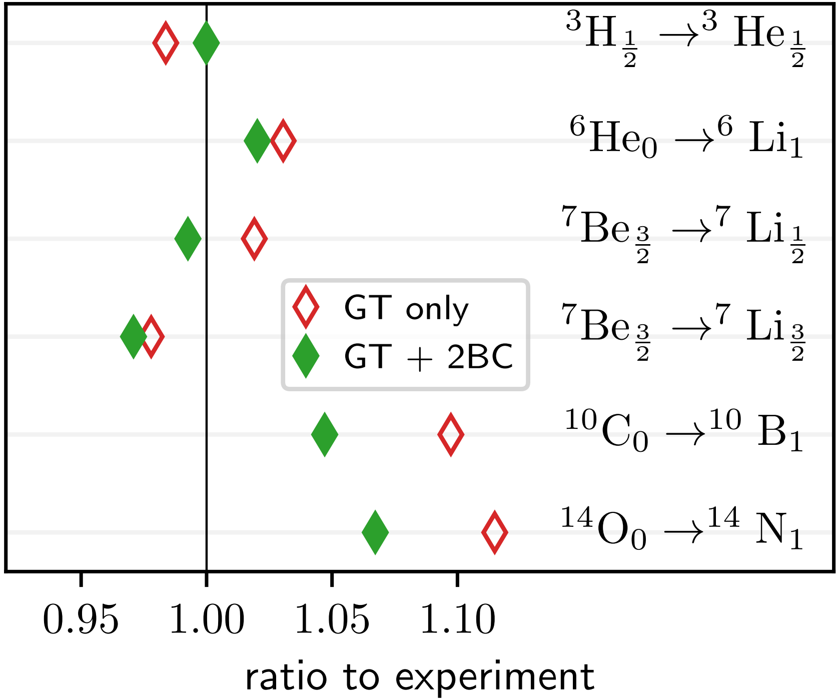

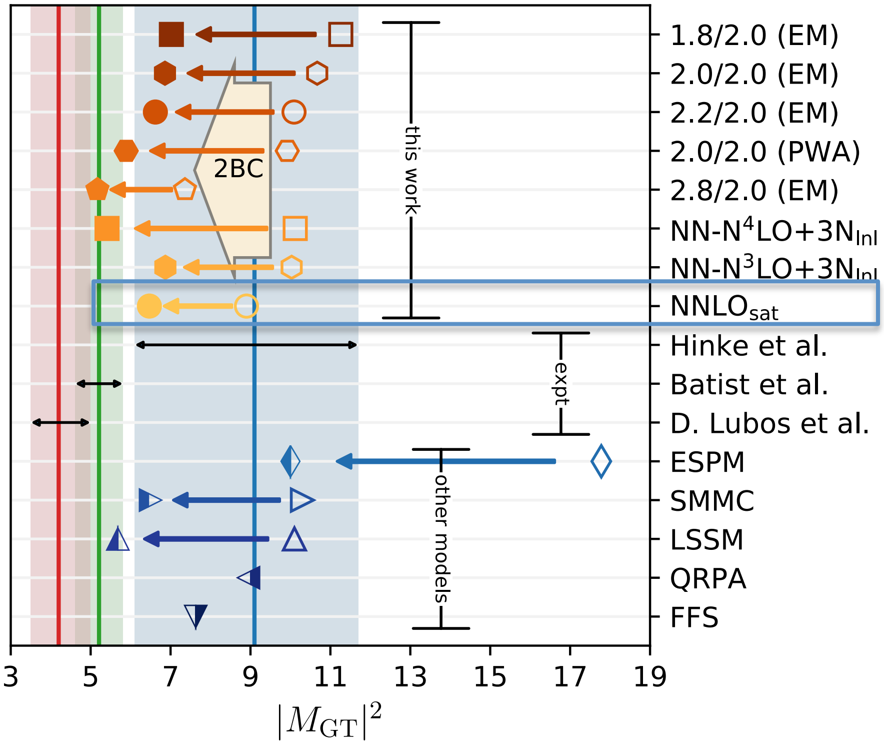

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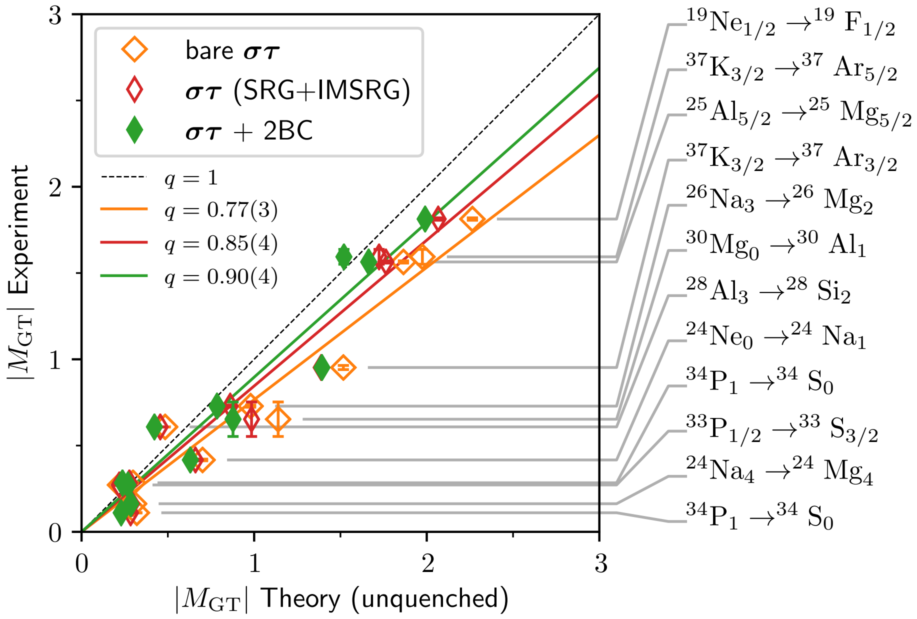

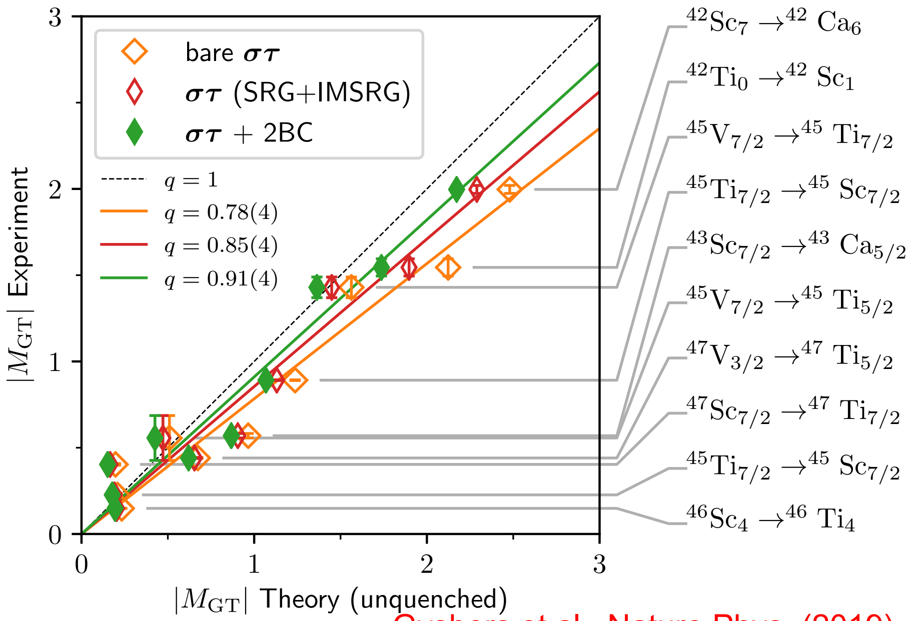

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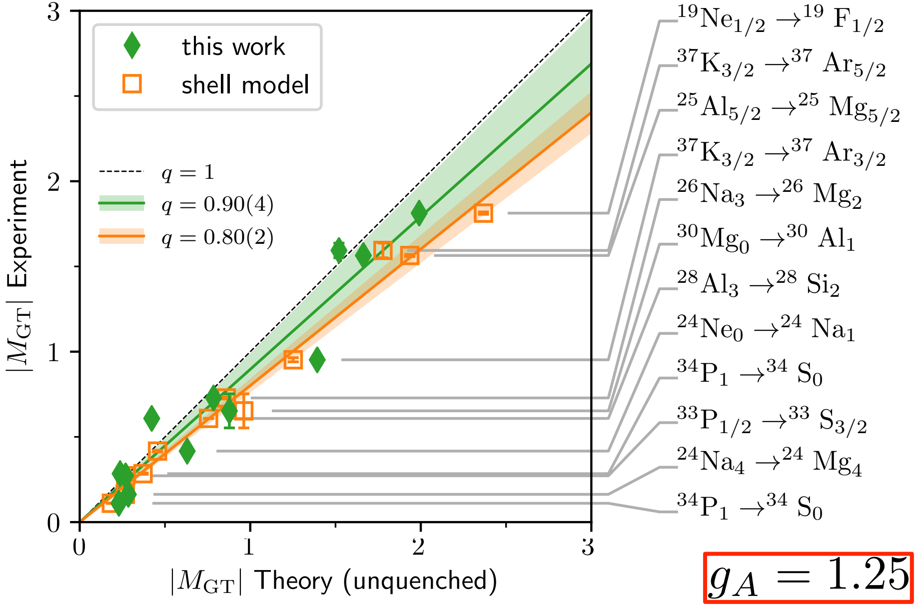

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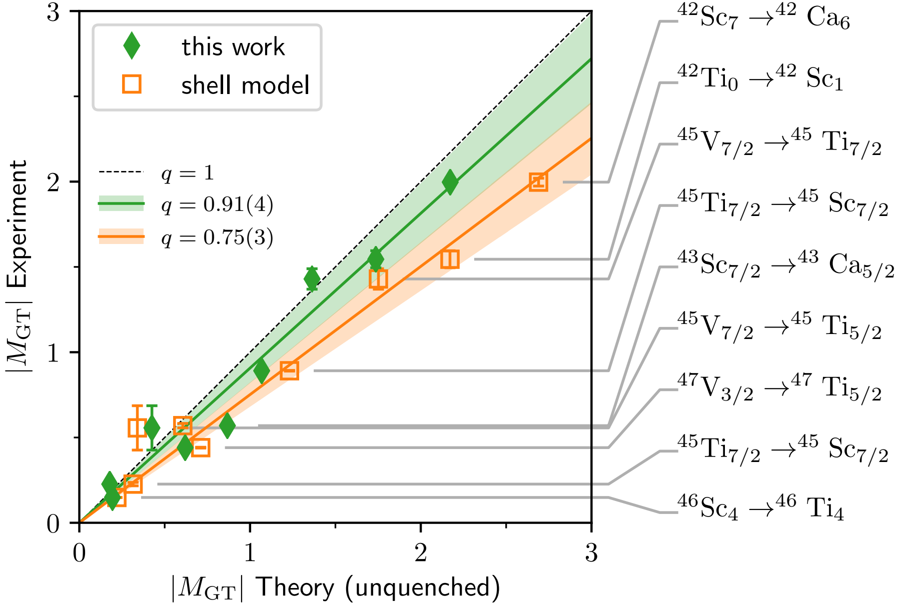
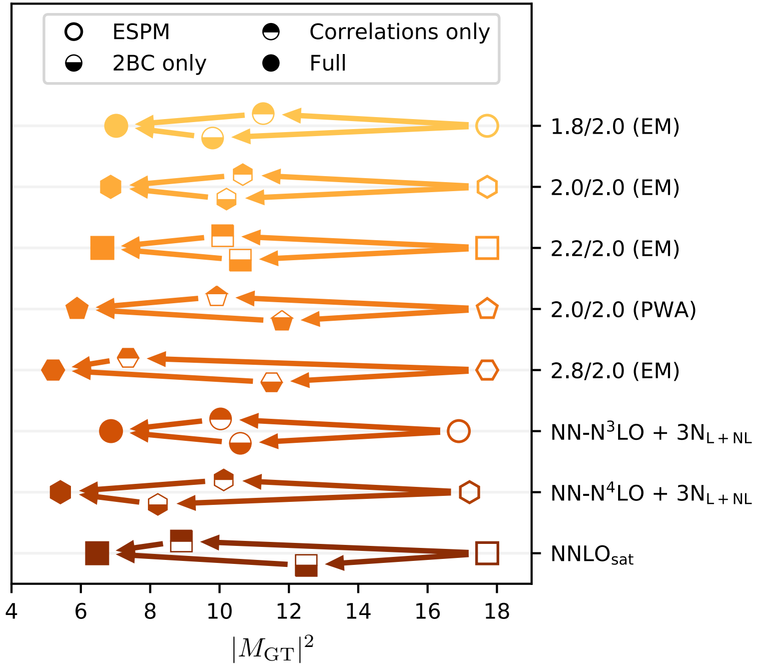


Gysbers et al., Nature Phys. (2019)

Refine results with improvements in forces and many-body methods

Role of Correlations vs Currents

^{100}Sn examine the relative importance of correlations vs. two-body currents

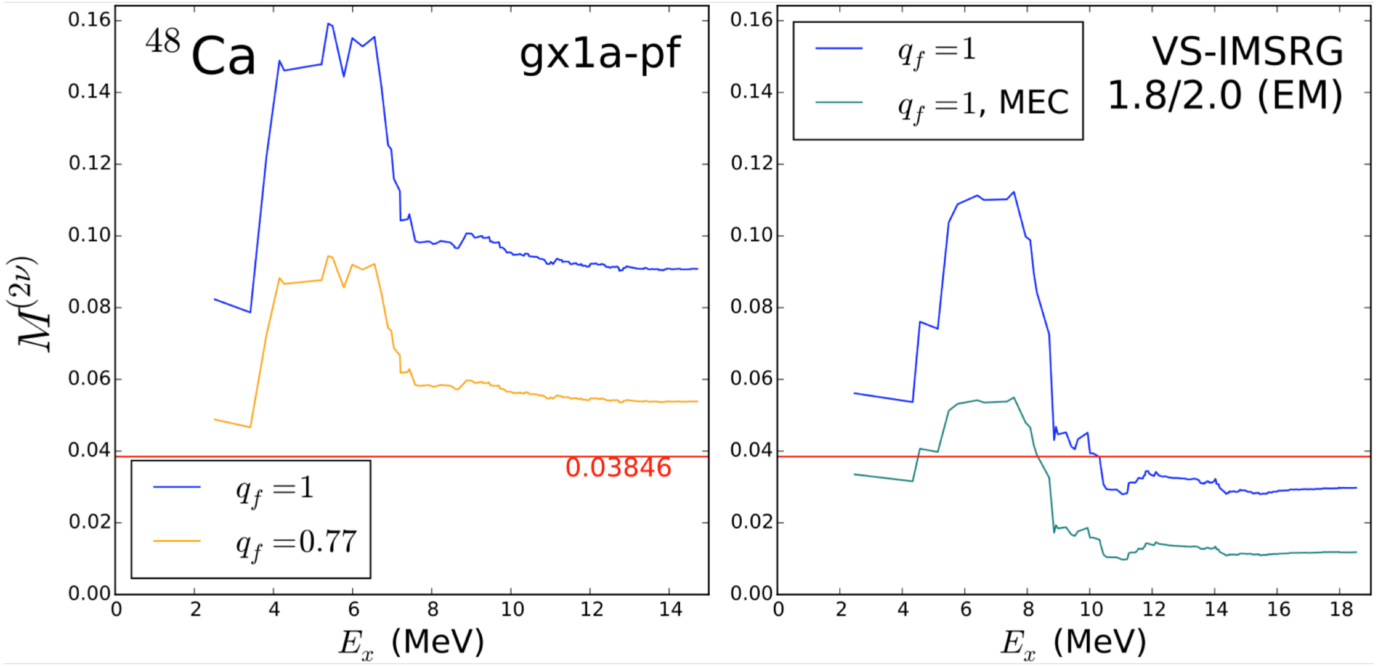


Harder interactions more impact from correlations, less from currents

"Importance" is a scale/scheme-dependent notion

Ab Initio 2νββ-decay

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



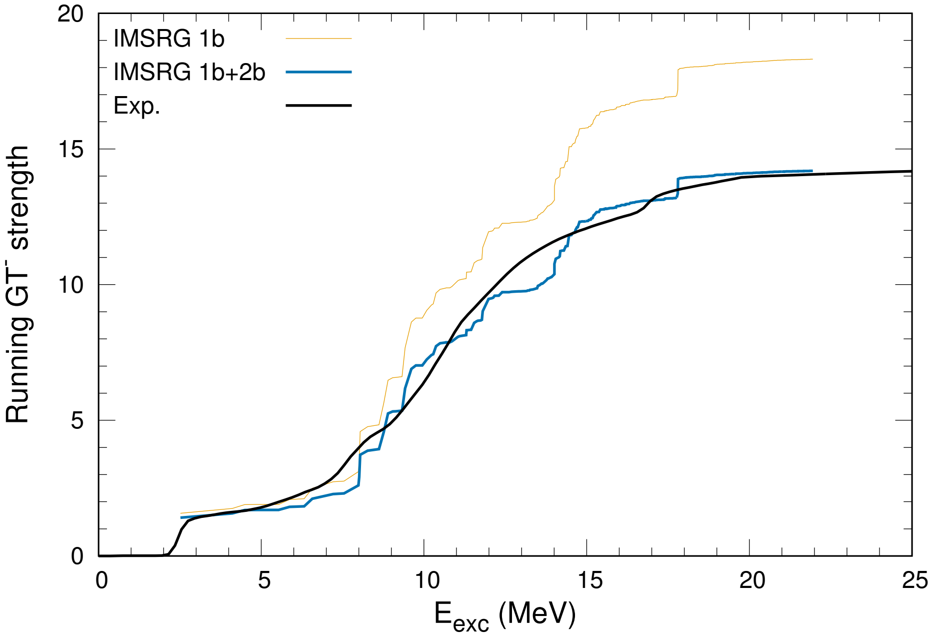
Payne, Stroberg, JDH, et al., in prep

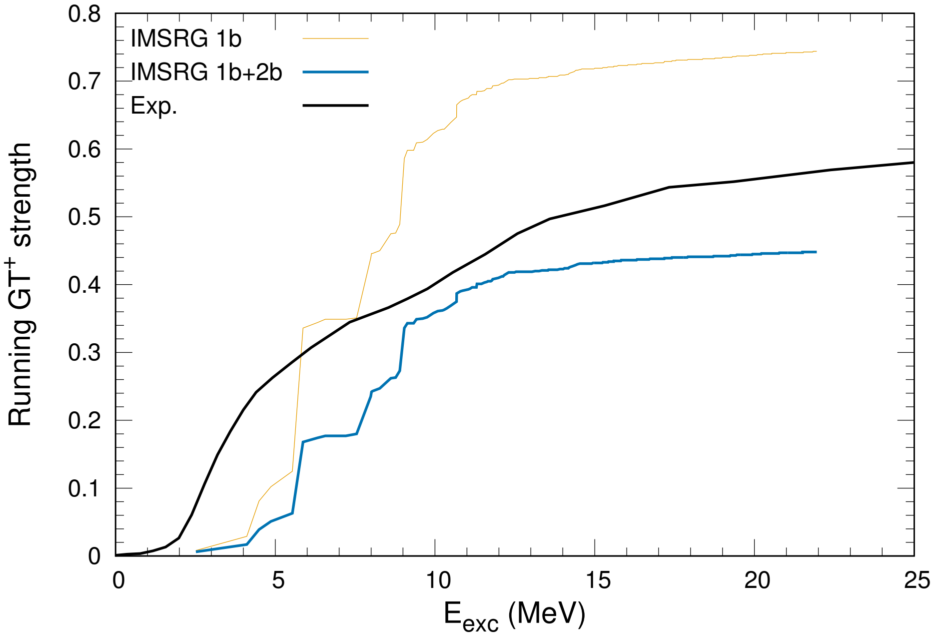
VS-IMSRG: decrease in final matrix element

Potential issues: valence-space limitations for 1+ states or missing correlations

Gamow-Teller Strengths for A=48

Running GT strengths for ^{48}Ca(p,n)^{48}Sc and ^{48}Ti(n,p)^{48}Sc

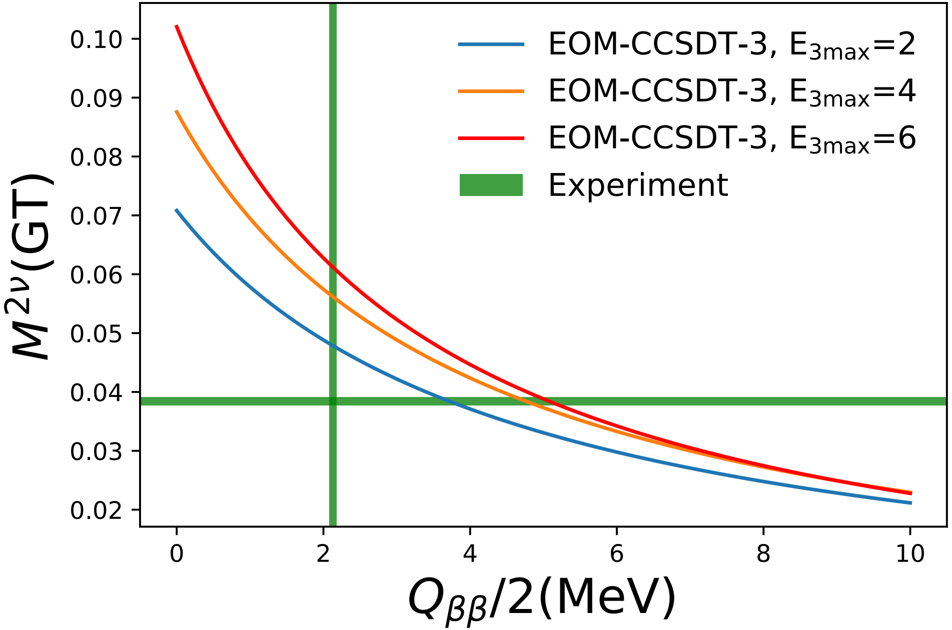


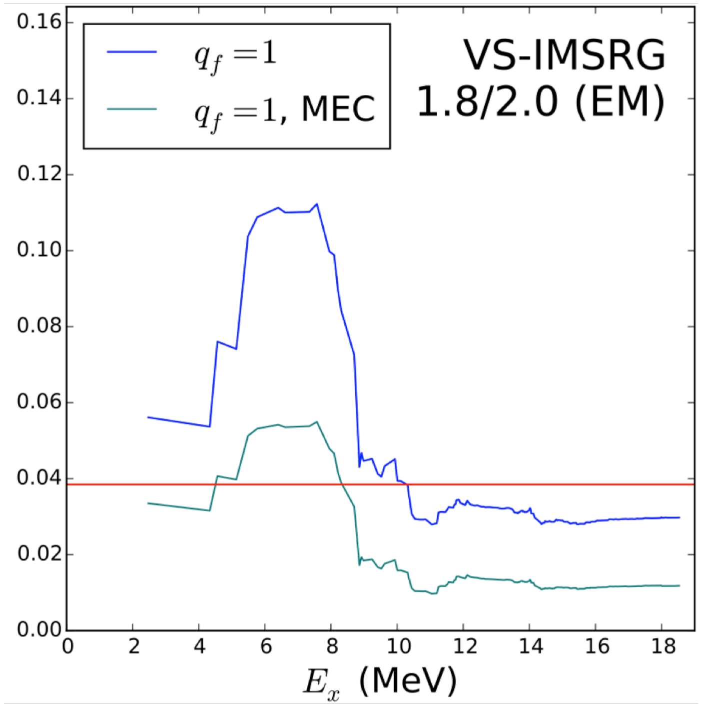


Significant improvement with effects of 2BC – good agreement with experiment

Ab Initio 2νββ-decay: Role of Correlations?

Role of correlations addressed in CC theory



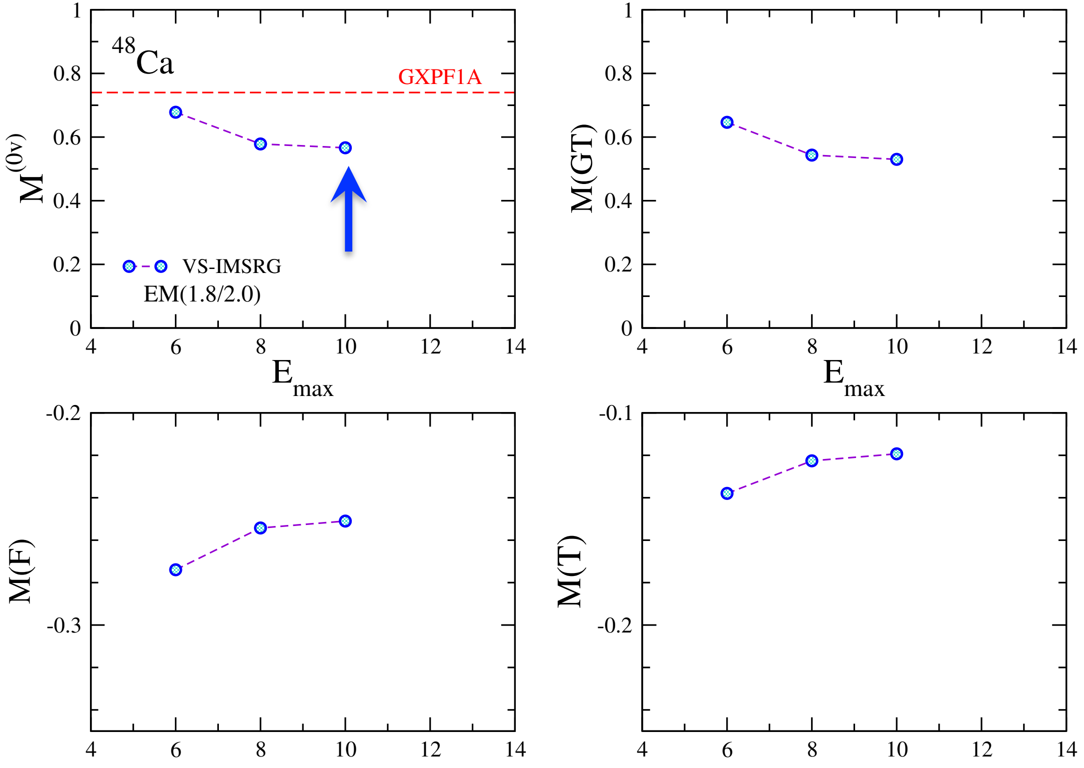


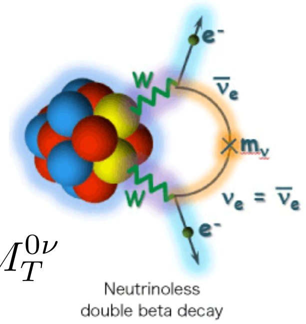
Including triples perturbatively increases value of NME

IMSRG(2) results similar to CCSD results – missing many-body correlations

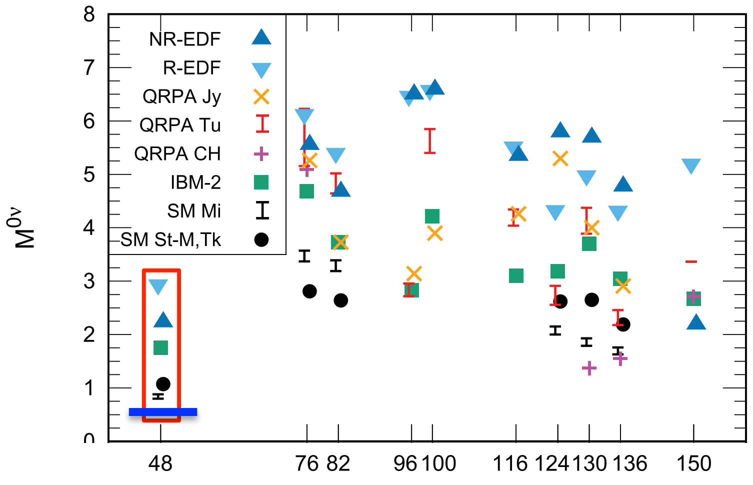
Ab Initio 0νββ-decay

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



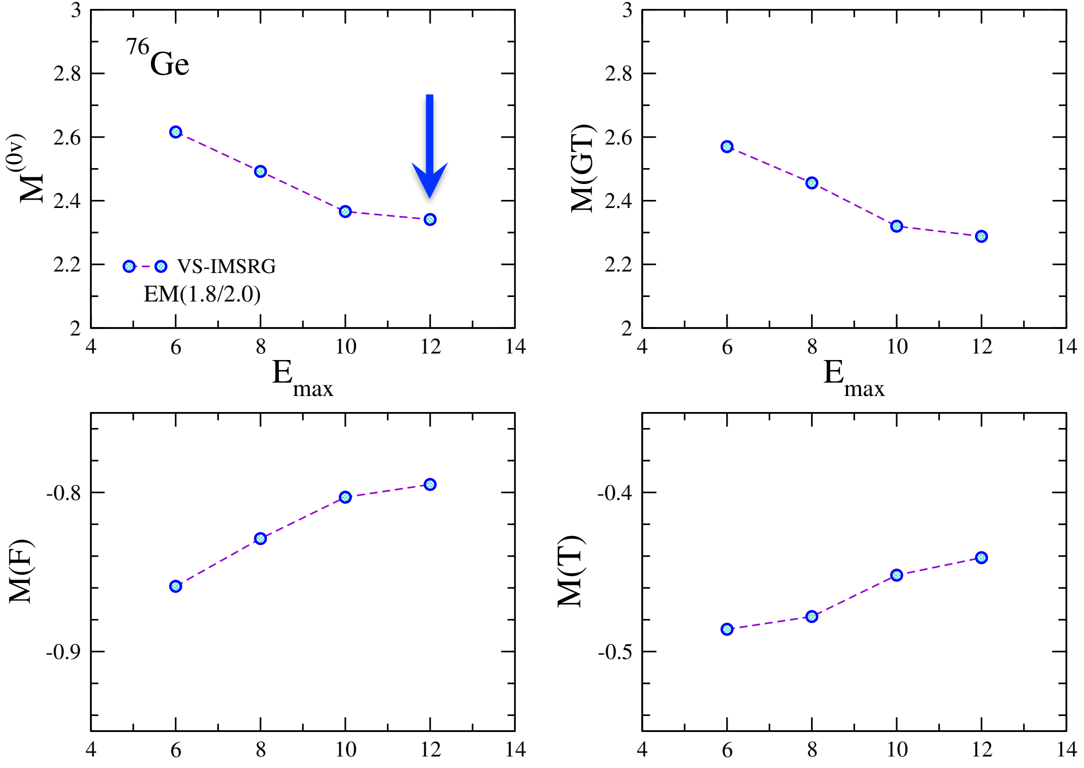


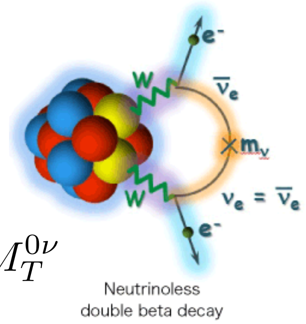
$$M^{0\nu} = M^{0\nu}_{GT} - \frac{M^{0\nu}_F}{g_A^2} + M^{0\nu}_T$$



CC: Factor of 2 larger! Benchmarks underway to understand…

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





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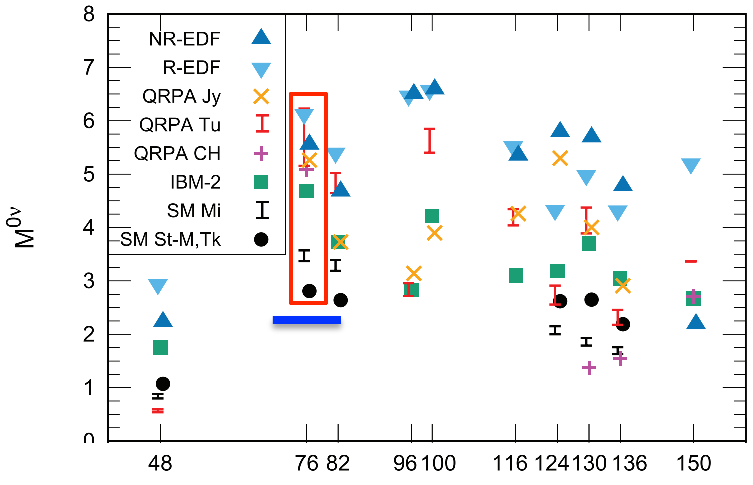
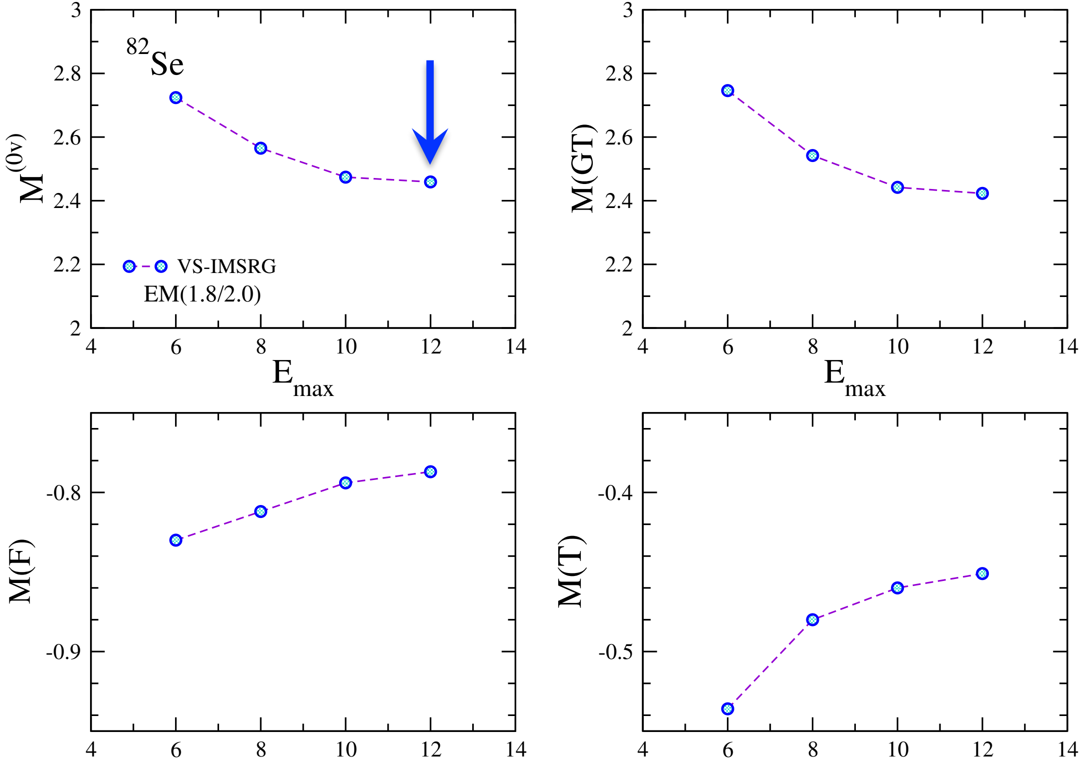


General cancellation between Fermi and Tensor contributions

Ab Initio 0νββ-decay

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



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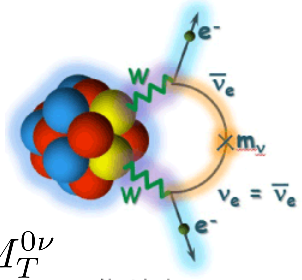
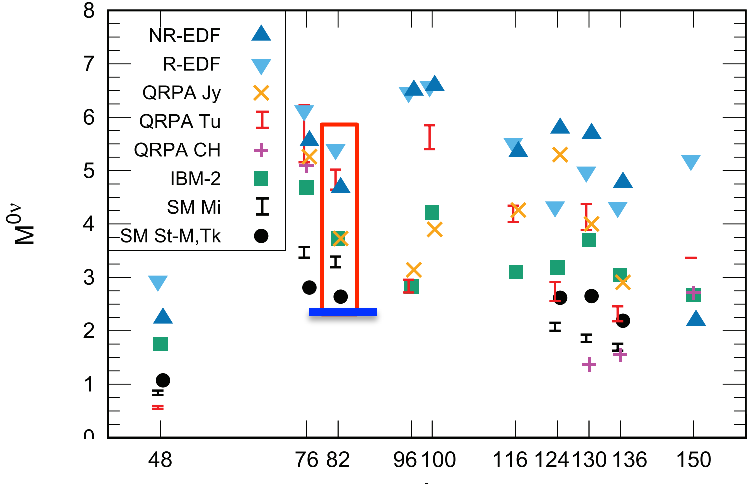


Neutrinoless double beta decay



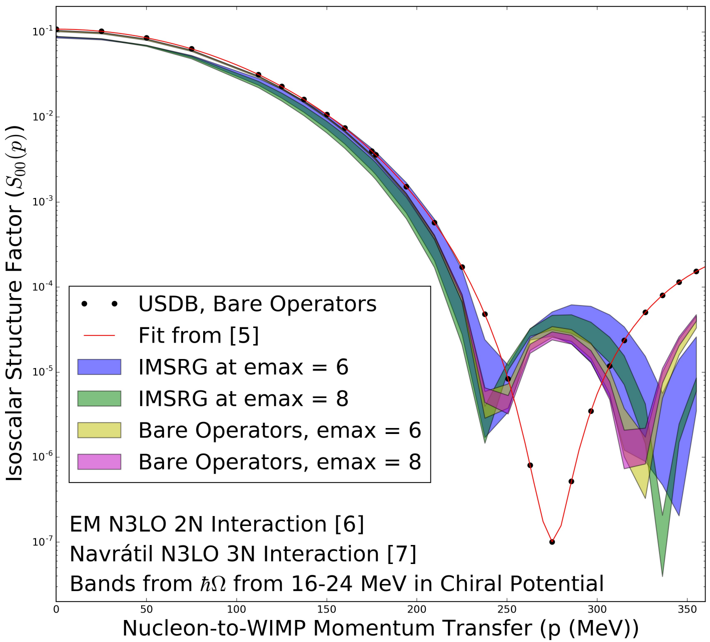
General cancellation between Fermi and Tensor contributions

Ab Initio WIMP-Nucleus Response Functions (Isoscalar)

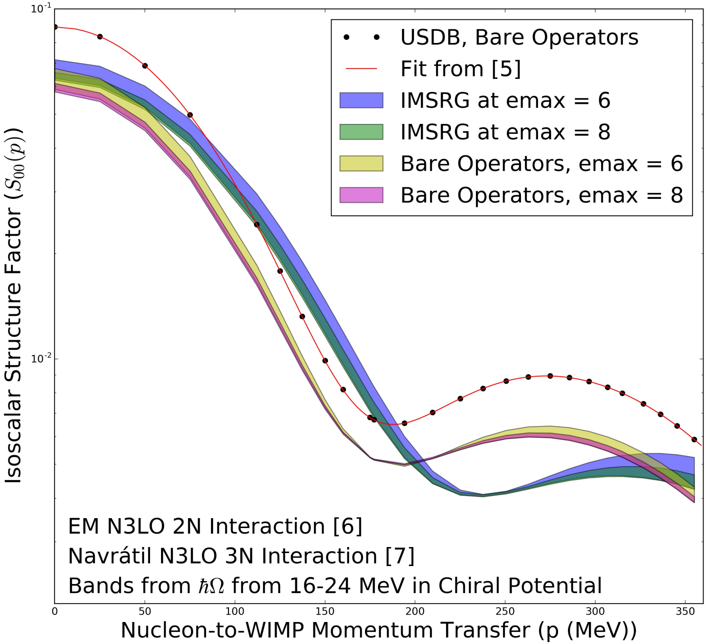
Ab initio: Consistent many-body wfs/operators from chiral NN+3N forces + 2b currents

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

S_{00}(p) for ^{19}F



S_{00}(p) for ^{27}Al



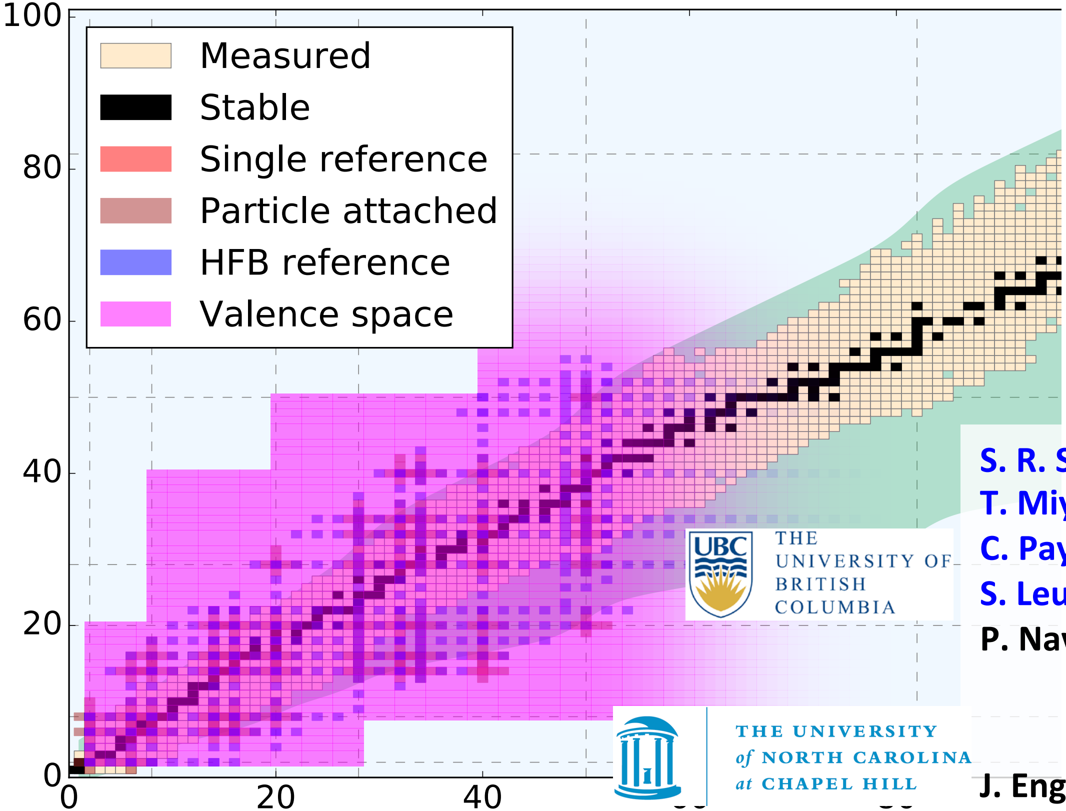
Leutheusser, Stroberg, Holt

Outlook

Ab initio valence-shell Hamiltonians

First ab initio prediction of nuclear driplines

Multi-shell spaces: Island of inversion/forbidden decays



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/collectivity problematic

Understand discrepancies with CC

Quantify uncertainties

THE UNIVERSITY OF BRITISH COLUMBIA

S. R. Stroberg
T. Miyagi
C. Payne
S. Leutheusser
P. Navrátil

MICHIGAN STATE UNIVERSITY

H. Hergert
S. Bogner

TECHNISCHE UNIVERSITÄT DARMSTADT

J. Simonis
A. Schwenk

THE UNIVERSITY of TENNESSEE KNOXVILLE

T. Morris
G. Hagen, T. Papenbrock

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

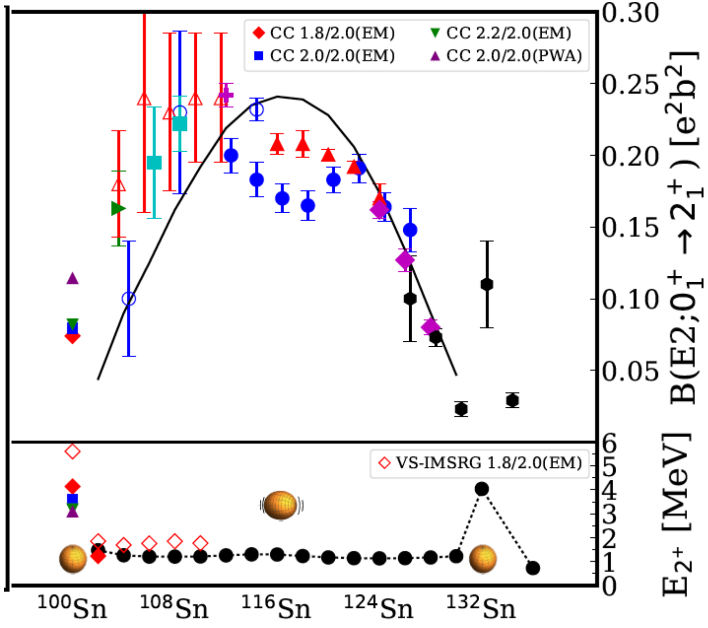
J. Engel

東京大学 THE UNIVERSITY OF TOKYO

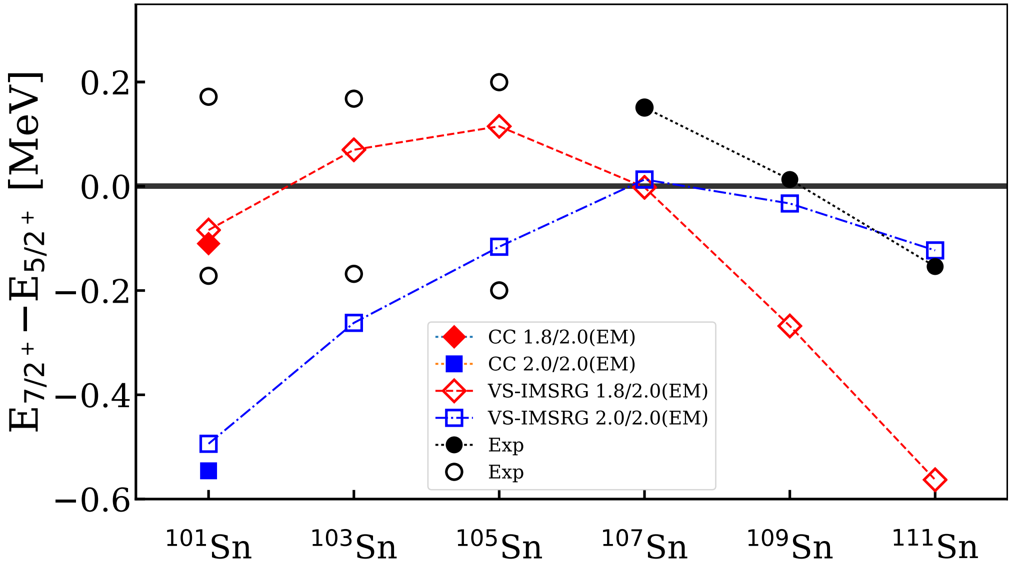
J. Menéndez

Structure of Lightest Tin Isotopes

Extend ab initio to heavy-mass region: magicity of ^{100}Sn, controversial level ordering in ^{101}Sn



Morris et al., PRL (2018)



Predicts doubly magic nature from 2^+ energies and B(E2) systematics

Both calculations predict 5/2+ ground state

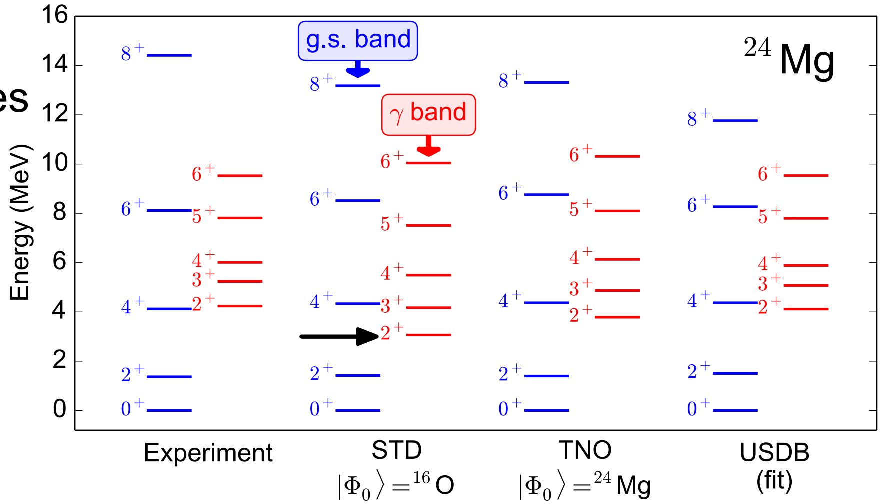
Ab Initio 0νββ-Decay Predictions from Valence-Space IMSRG

Conventional SM: phenomenological wavefunctions

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

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

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



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

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

Deformation challenging for large-space methods

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

Conventional SM: phenomenological wavefunctions

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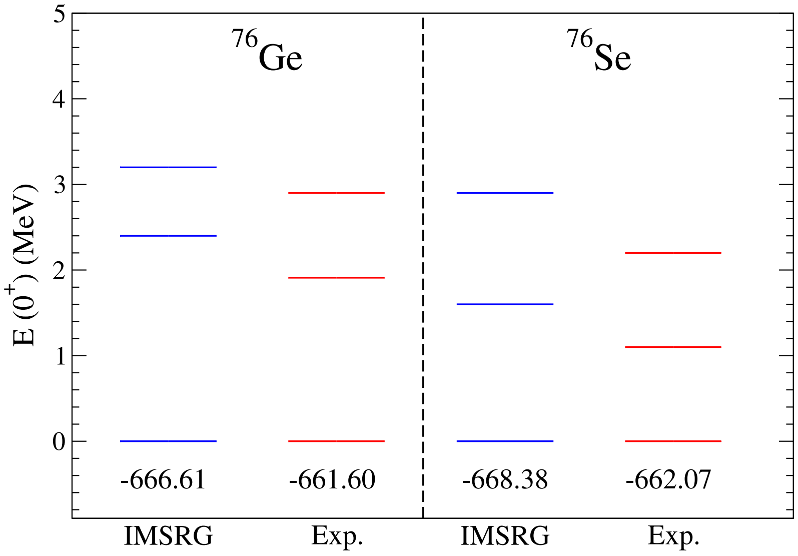


1) ✓ Ab initio energies in medium/heavy-mass region

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

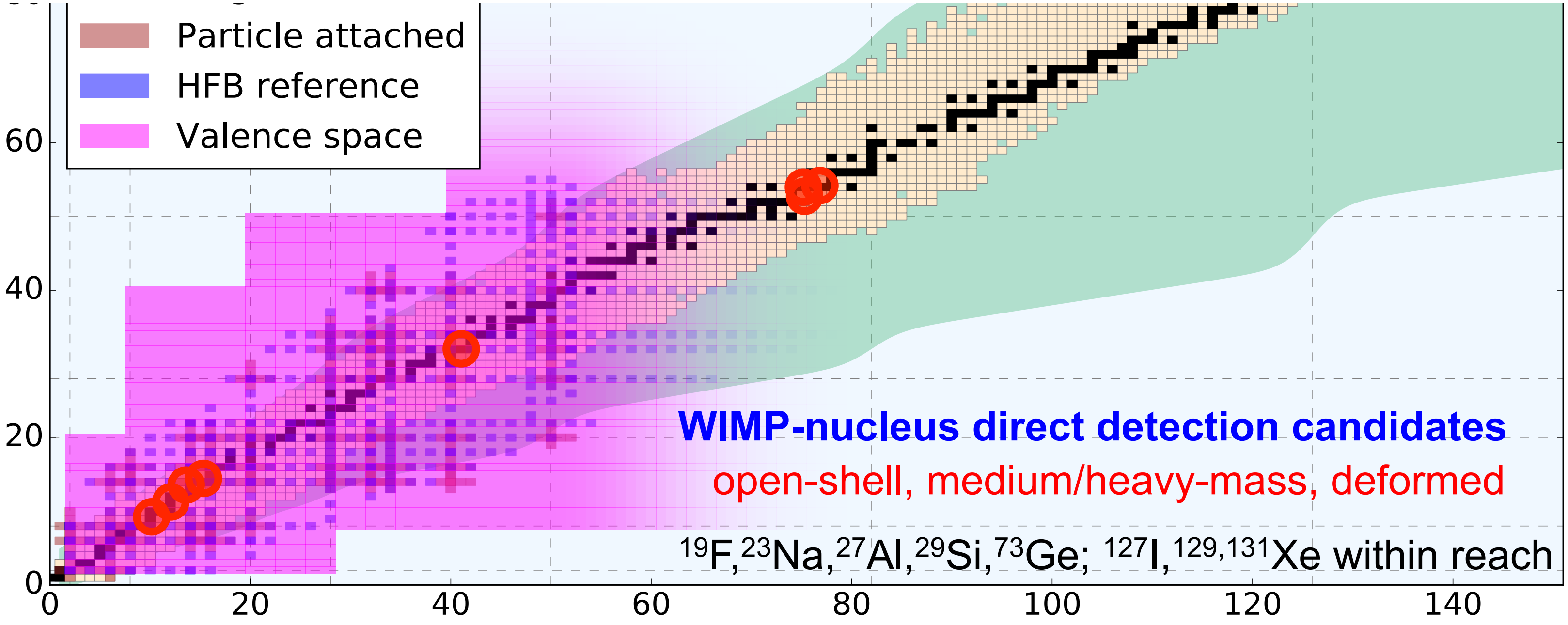
Deformation challenging for large-space methods

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

Towards big questions: WIMP-Nucleus Scattering

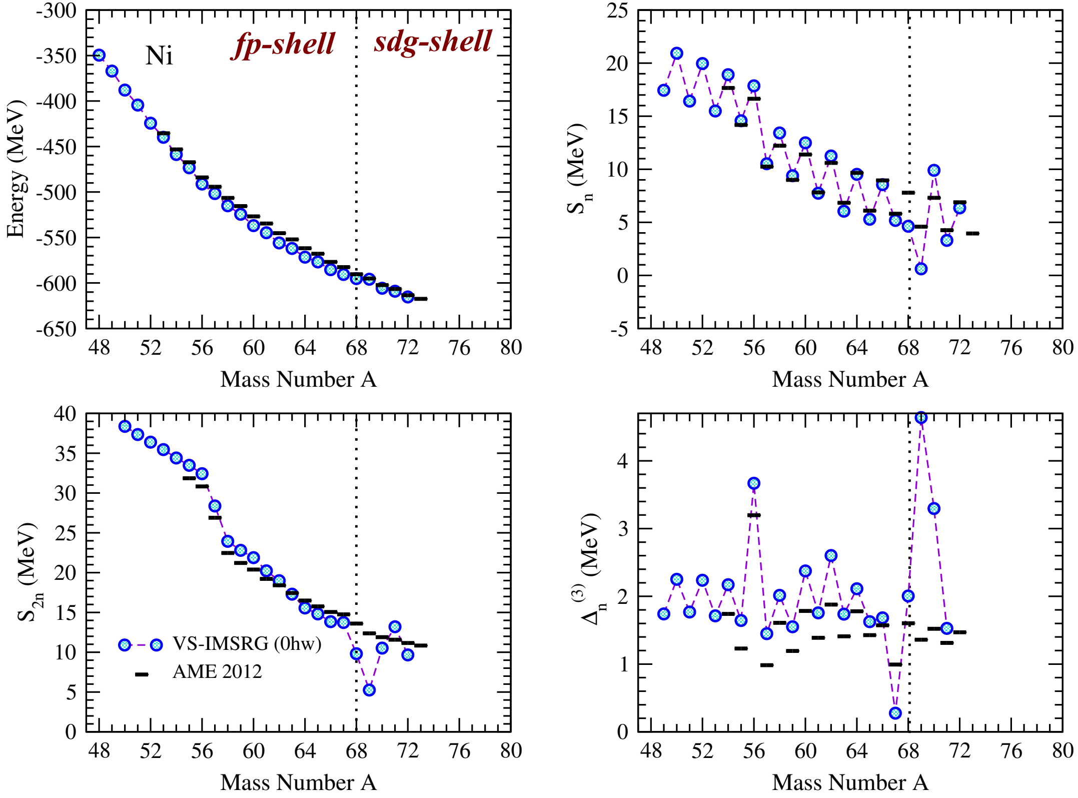
Aim of modern nuclear theory: Develop unified *first-principles* picture of structure and reactions

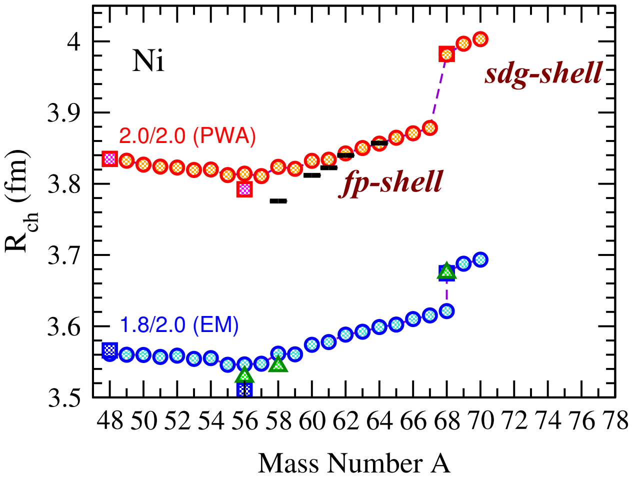
- Nuclear forces (low-energy QCD)
- Electroweak physics
- Nuclear many-body problem



Shell Closures in Neutron-Rich Ni

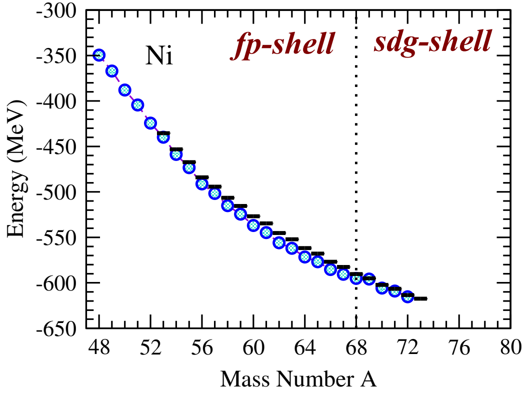
Clear artifacts when changing valence spaces

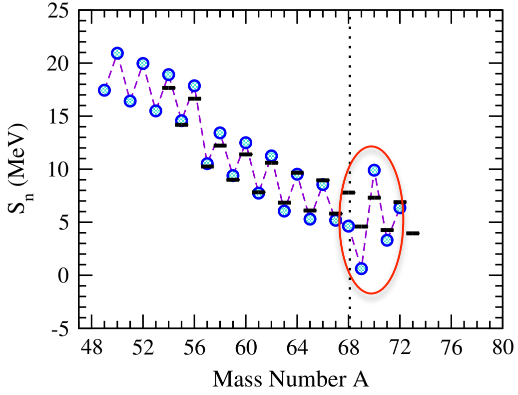


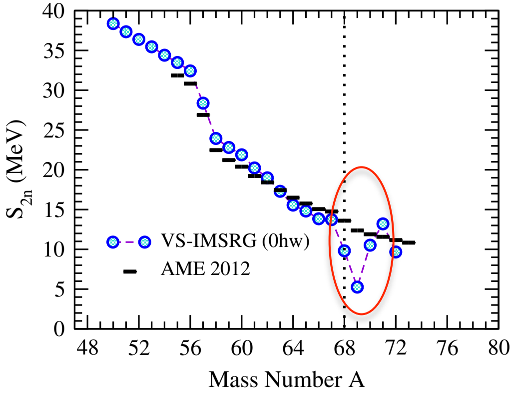


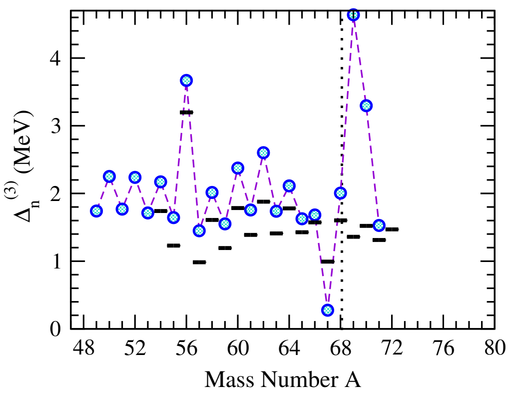
Shell Closures in Neutron-Rich Ni

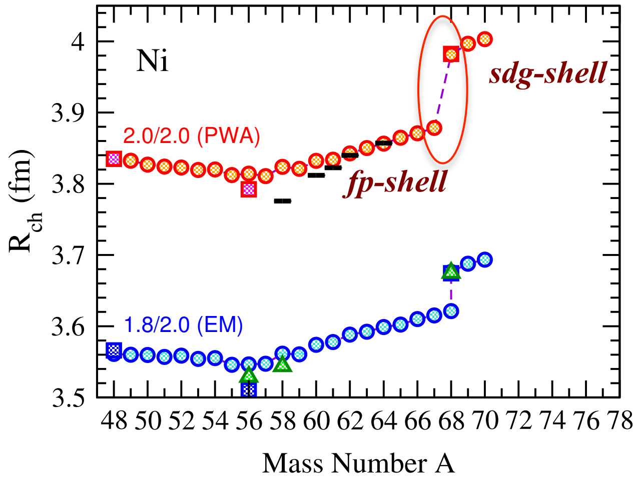
Clear artifacts when changing valence spaces: can we decouple a cross-shell space?







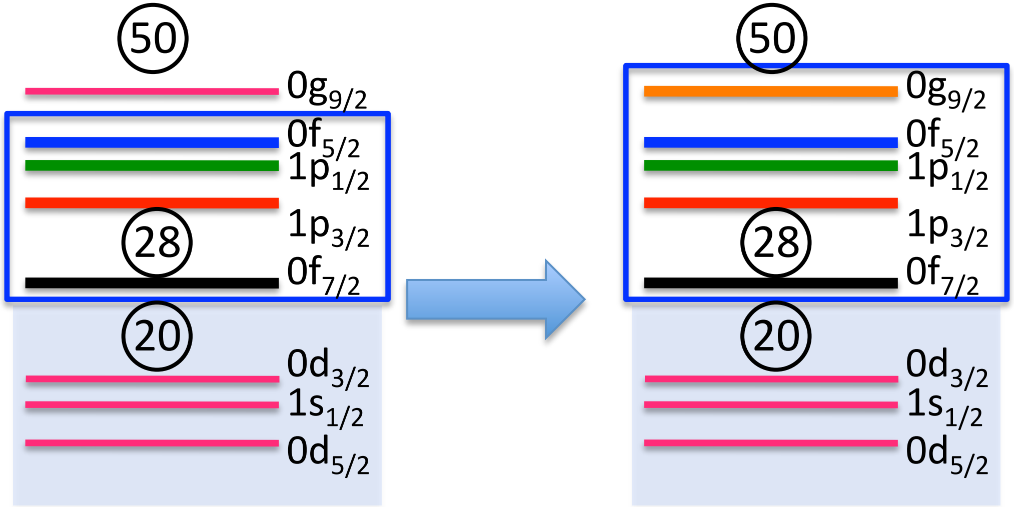




Exploring Cross-Shell Valence Spaces

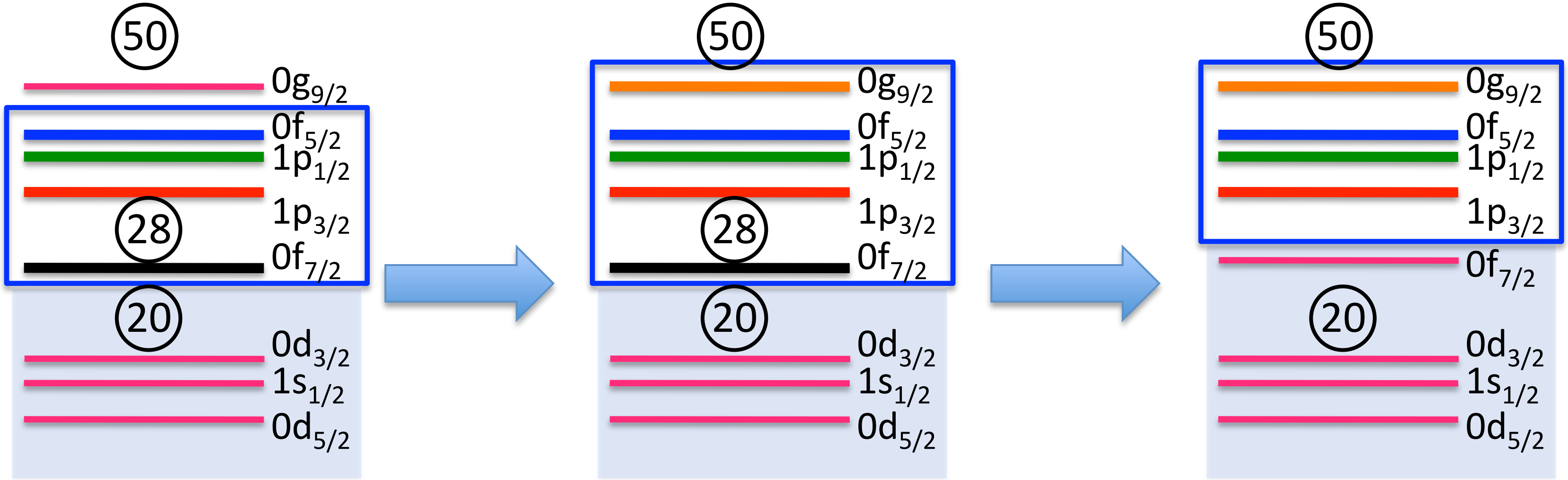
First try: extend pf to include g9/2, etc

IMSRG fails to decouple such valence spaces



Exploring Cross-Shell Valence Spaces

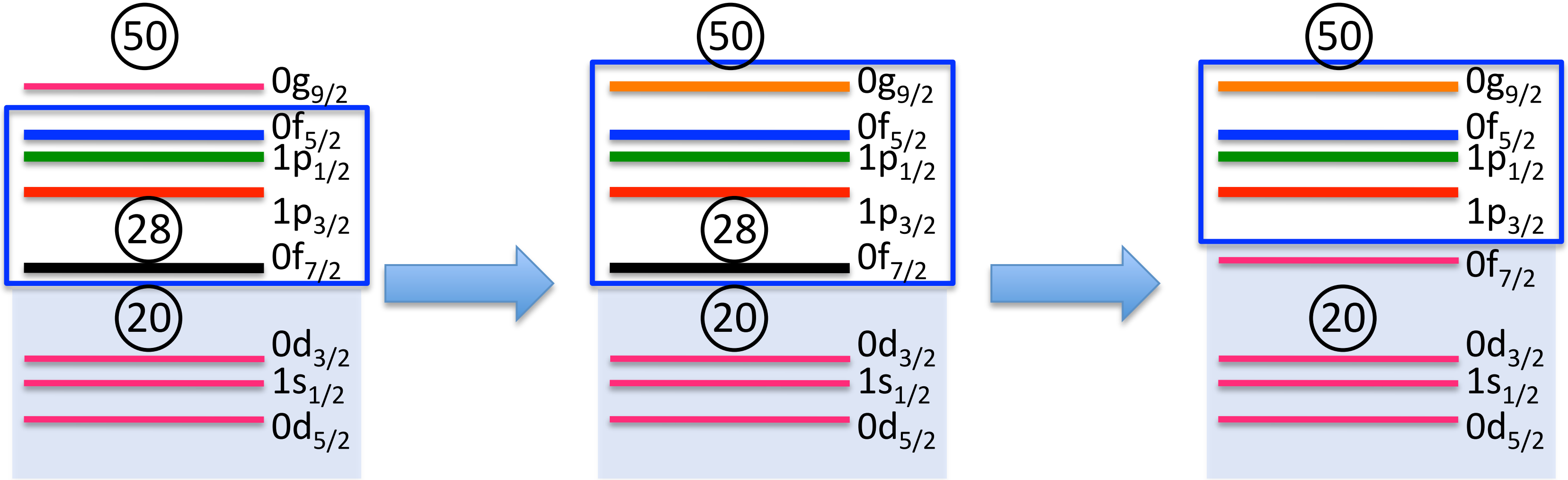
Next try: extend to include g9/2, but exclude f7/2



Exploring Cross-Shell Valence Spaces

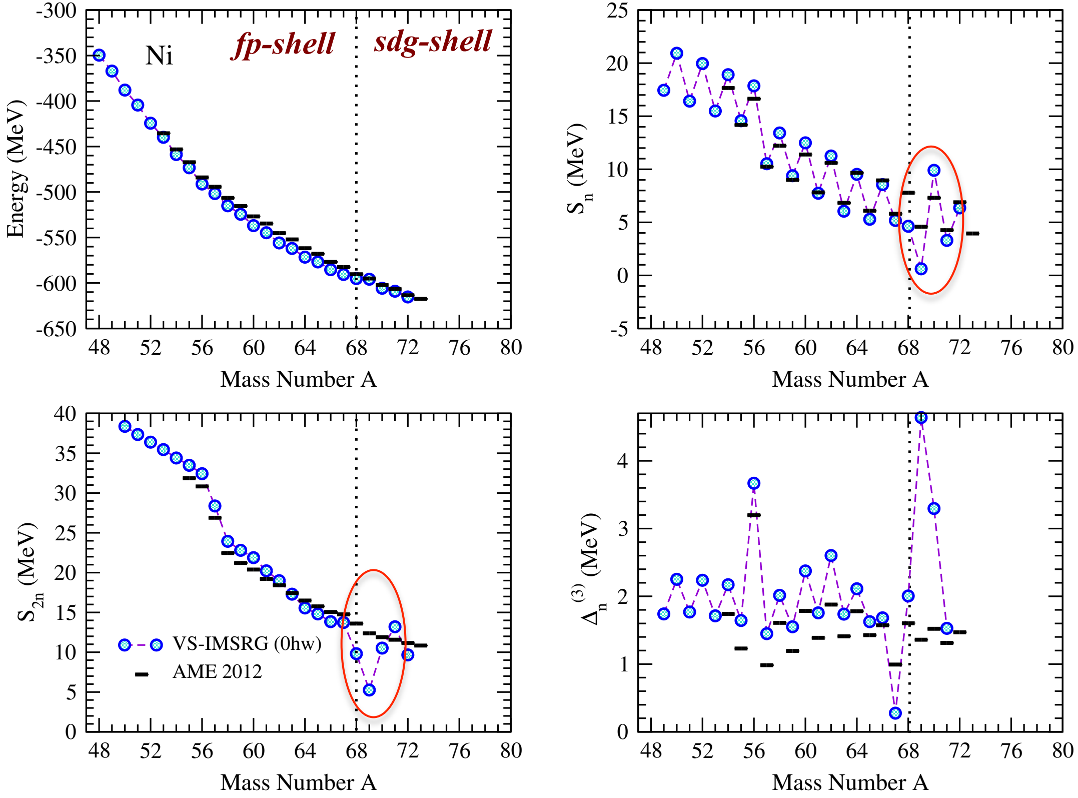
Next try: extend to include g9/2, but exclude f7/2

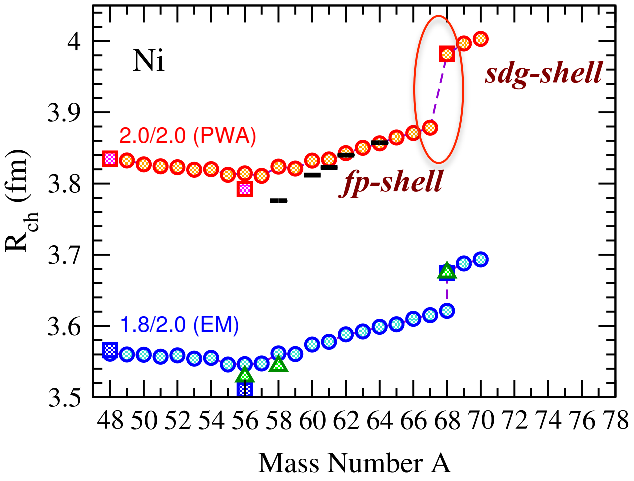
IMSRG successfully decouples (usually) such valence spaces!



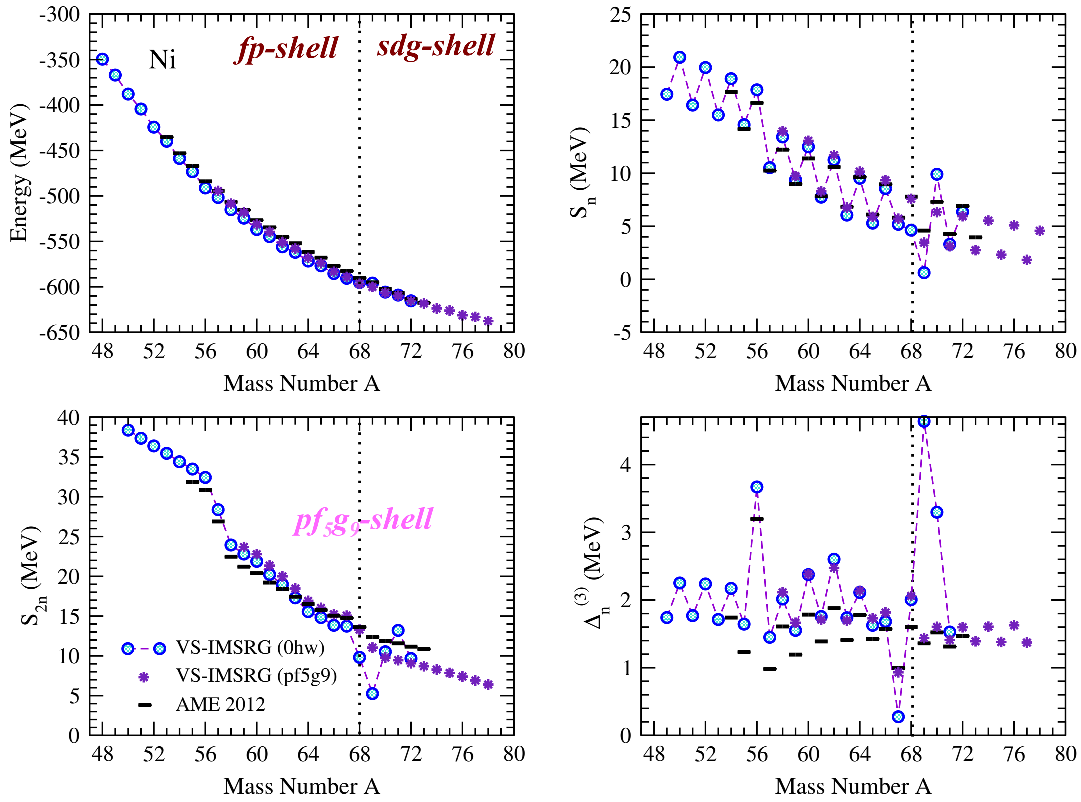
Shell Closures in Neutron-Rich Ni

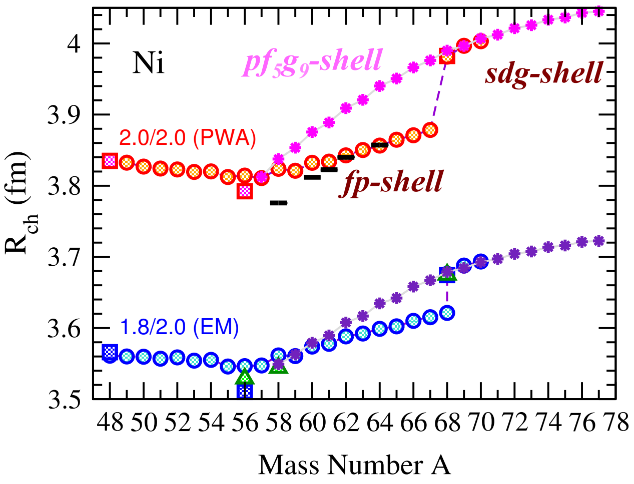
Clear artifacts when changing valence spaces





Cross-shell valence space interpolates smoothly through pf/sdg spaces





IM-SRG (Quick reminder)

$$H_{\mathrm{N.O.}} = E_0 + \sum_{ij} f_{ij} \left\{a_i^\dagger a_j\right\} + \frac{1}{4}\sum_{jkl} \Gamma_{ijkl} \left\{a_i^\dagger a_j^\dagger a_l a_k\right\} + \frac{1}{36}\sum_{ijklmn} W_{ijklmn} \left\{a_i^\dagger a_j^\dagger a_k^\dagger a_l a_m a_n\right\}$$

- In-medium similarity renormalization group:

Generator is chosen to suppress the off diagonal component:

$$\eta_{12} = \frac{f_{12}}{f_{11} - f_{22} + \Gamma_{1212}}$$

$$\eta_{1234} = \frac{\Gamma_{1234}}{f_{11} + f_{22} - f_{33} - f_{44} + A_{1234}}$$

$$A_{1234} = \Gamma_{1212} + \Gamma_{3434} - \Gamma_{1313} - \Gamma_{2424} - \Gamma_{1414} - \Gamma_{2323}$$

f_{12}, Γ_{1234} : matrix element we want to suppress

$$\frac{dE}{ds} = \sum_{ab}(n_a - n_b)\eta_{ab} f_{ba} + \frac{1}{2}\sum_{abcd} \eta_{abcd}\Gamma_{cdab} n_a n_b \overline{n}_c \overline{n}_d$$

$$\frac{df_{12}}{ds} = \sum_a (1 + P_{12})\eta_{1a} f_{a2} + \frac{1}{2}\sum_{ab}(n_a - n_b)(\eta_{ab}\Gamma_{b1a2} - f_{ab}\eta_{b1a2}) + \frac{1}{2}\sum_{abc}(n_a n_b \overline{n}_c + \overline{n}_a \overline{n}_b n_c)(1 + P_{12})\eta_{c1ab}\Gamma_{abc2}$$

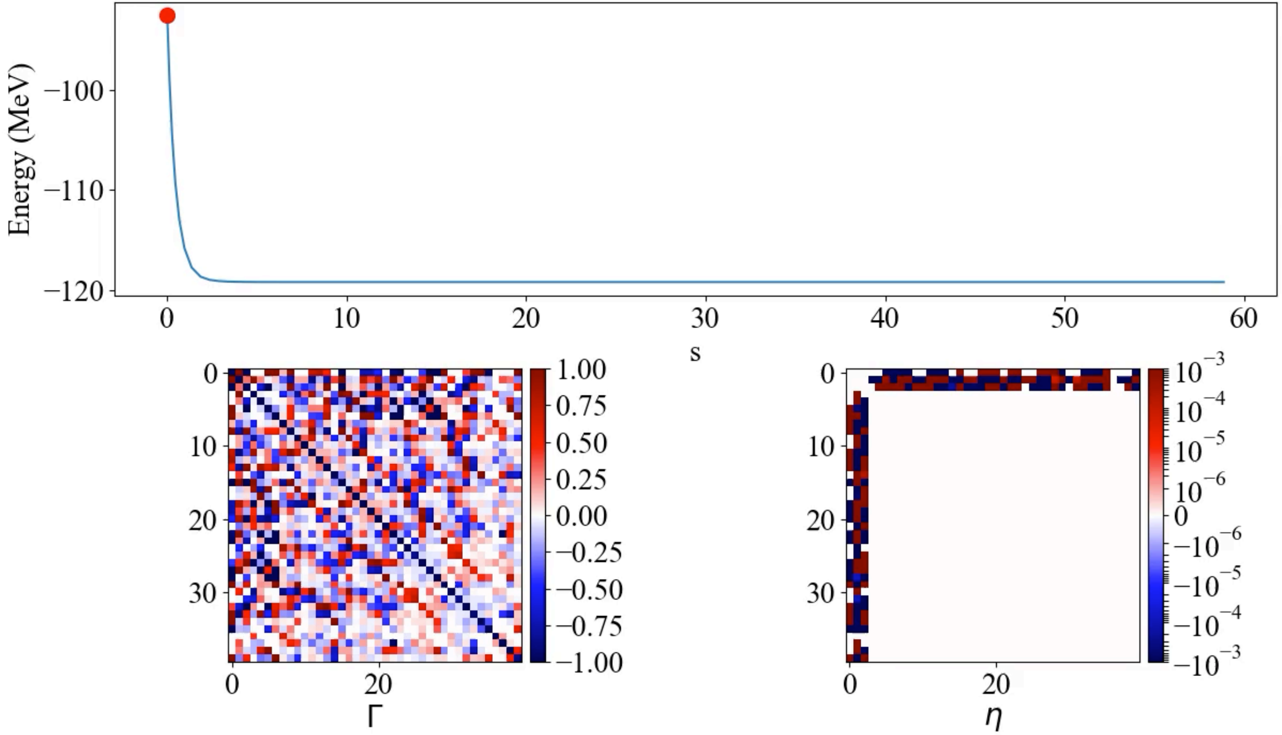
$$\frac{d\Gamma_{1234}}{ds} = \sum_a [(1 - P_{12})(\eta_{1a}\Gamma_{a234} - f_{1a}\eta_{a234}) - (1 - P_{34})(\eta_{a3}\Gamma_{12a4} - f_{a3}\eta_{12a3})] + \frac{1}{2}\sum_{ab}(1 - n_a - n_b)(\eta_{12ab}\Gamma_{ab34} - \Gamma_{12ab}\eta_{ab34}) - \sum_{ab}(n_a - n_b)(1 - P_{12})(1 - P_{34})\eta_{b2a4}\Gamma_{a1b3}$$

n_a : occupation number

$\overline{n}_a = 1 - n_a$

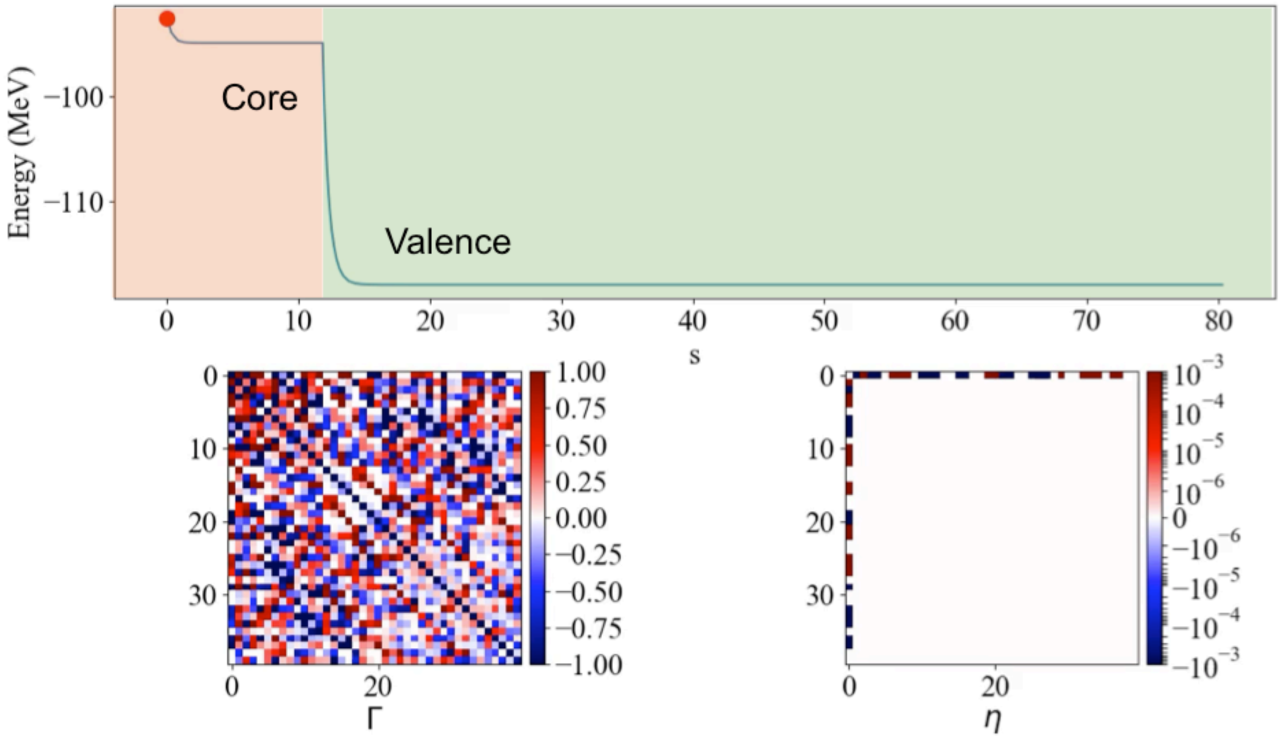
IM-SRG (Quick reminder)

Evolution for single reference problem (^{14}C w/ SRG evolved NN-only)



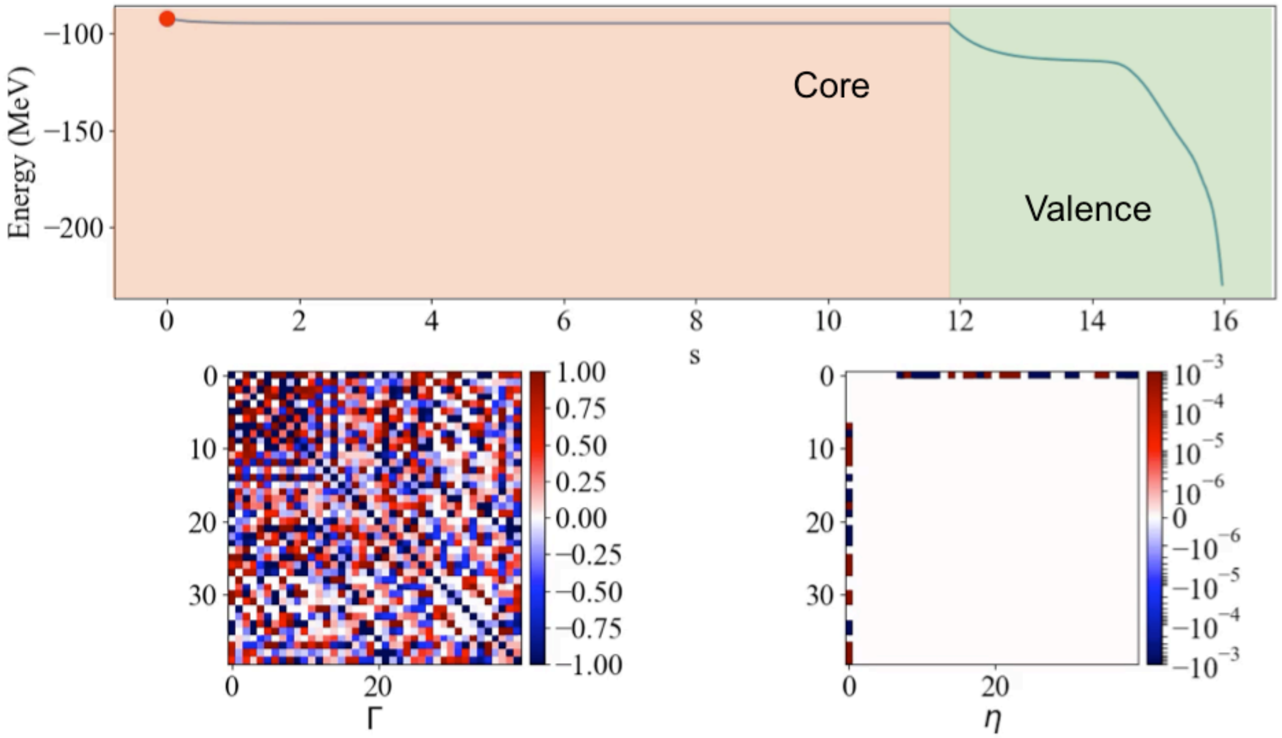
IM-SRG (Quick reminder)

Evolution for p-shell problem (^{14}C [^{4}He core] w/ SRG evolved NN-only)



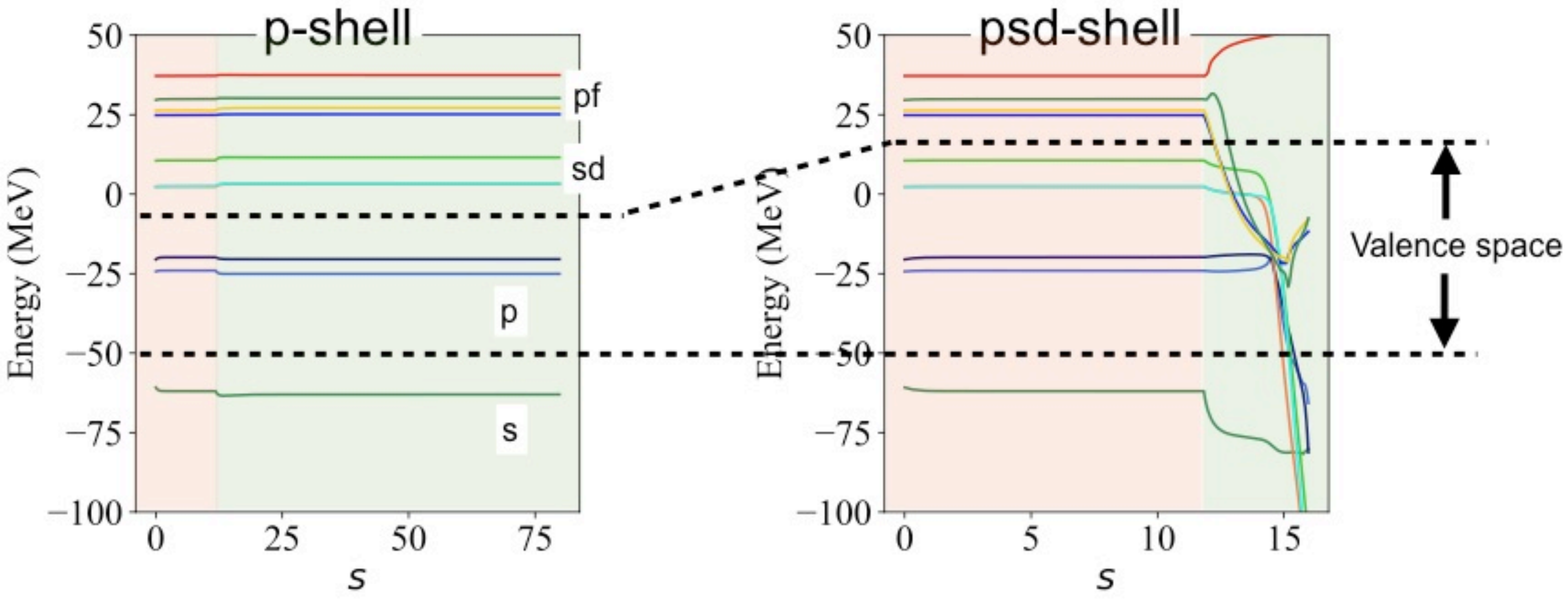
IM-SRG for two-major shell valence space problem

Evolution for psd-shell problem (^{14}C [^{4}He core] w/ SRG evolved NN-only)



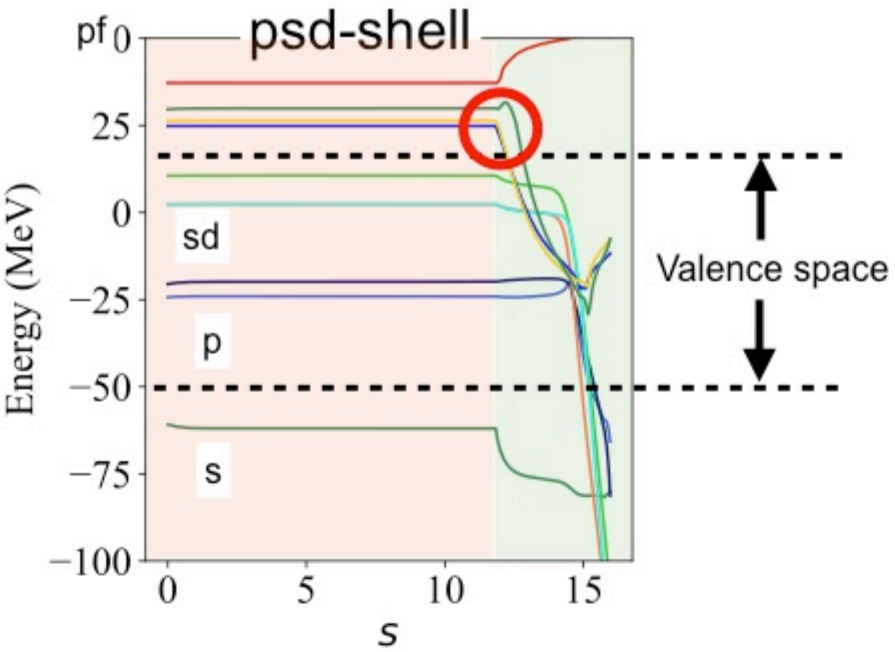
How it fail

- Flow of single-particle energies



How it fail

- Flow of single-particle energies
  - ✦ At the very beginning of valence-decoupling flow, some of pf-shell orbits come down.
  - ✦ Intuitively, we expect that Q-space single particle energies rise during evolution.
  - ✦ At the beginning of the flow, the slope of single-particle energies (df/ds) seems to be crucial.



Flow equation for single-particle energies

- Modifying the generator
  - ✦Simple way is to give the constant shift to energy denominator

K. Suzuki, Prog. Theor. Phys. **58**, 1064 (1977).

N. Tsunoda, K. Takayanagi, M. Hjorth-Jensen, and T. Otsuka, Phys. Rev. C **89**, 024313 (2014).

$$\eta_{12} = \frac{f_{12}}{f_{11} - f_{22} + \Gamma_{1212}}$$
$$\eta_{1234} = \frac{\Gamma_{1234}}{f_{11} + f_{22} - f_{33} - f_{44} + A_{1234}}$$
$$A_{1234} = \Gamma_{1212} + \Gamma_{3434} - \Gamma_{1313} - \Gamma_{2424} - \Gamma_{1414} - \Gamma_{2323}$$

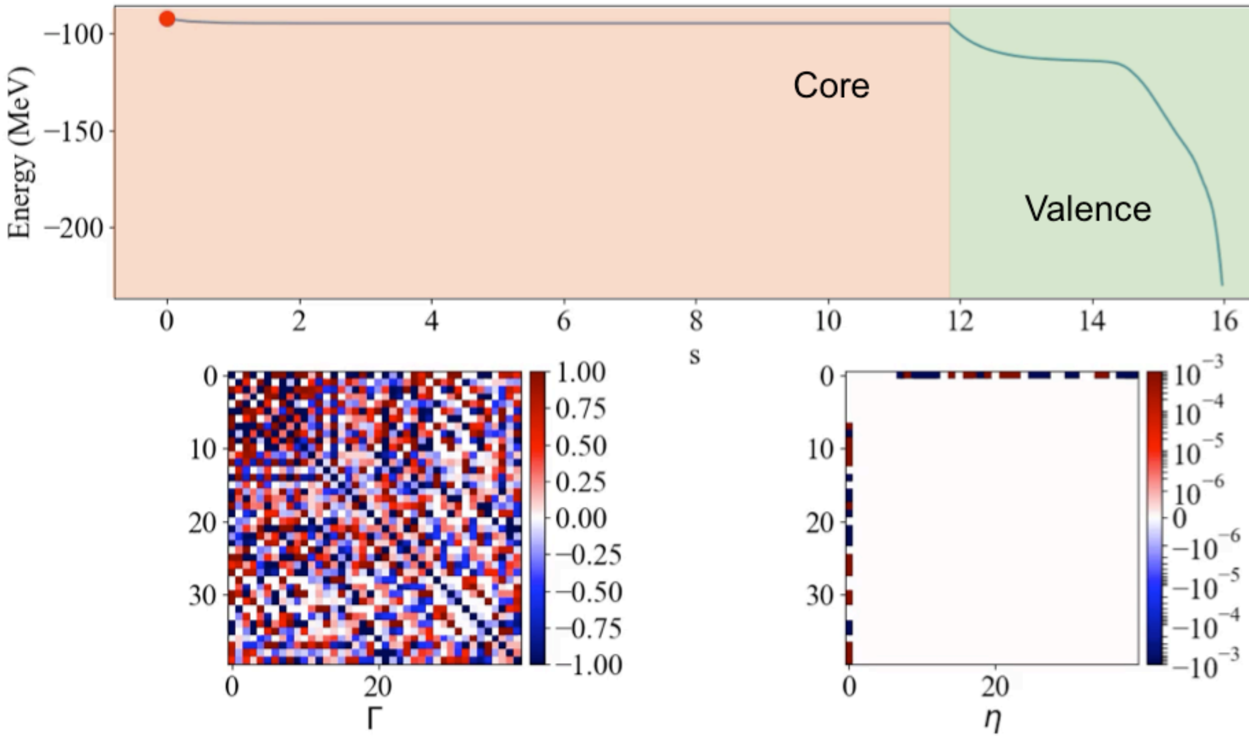
$\Rightarrow$

$$\eta_{12} = \frac{f_{12}}{f_{11} - f_{22} + \Gamma_{1212} + \Delta}$$
$$\eta_{1234} = \frac{\Gamma_{1234}}{f_{11} + f_{22} - f_{33} - f_{44} + A_{1234} + \Delta}$$
$$A_{1234} = \Gamma_{1212} + \Gamma_{3434} - \Gamma_{1313} - \Gamma_{2424} - \Gamma_{1414} - \Gamma_{2323}$$

  - ✦For our purpose, suitable choice of Δ would be comparable to hw.

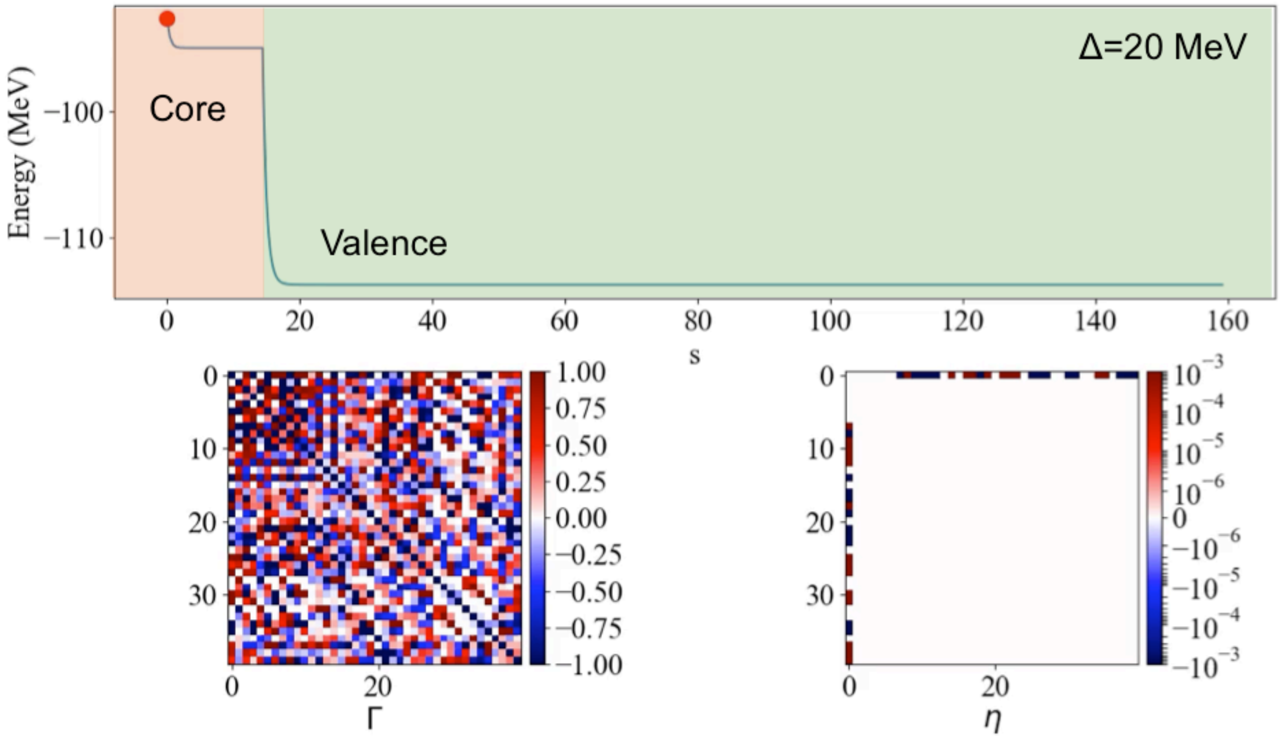
IM-SRG for two-major shell valence space problem

Evolution for psd-shell problem (^{14}C [^{4}He core] w/ SRG evolved NN-only)



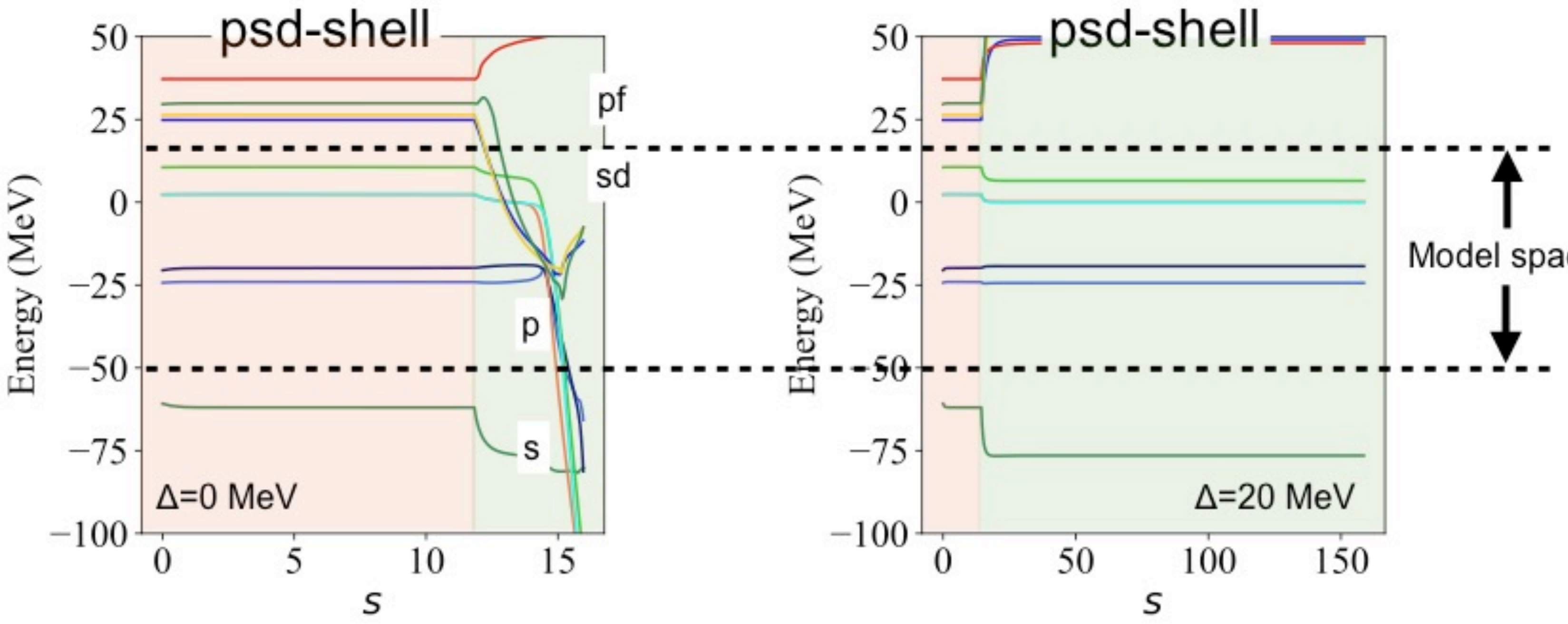
Does it really work?

Evolution for psd-shell problem (^{14}C [^{4}He core] w/ SRG evolved NN-only)

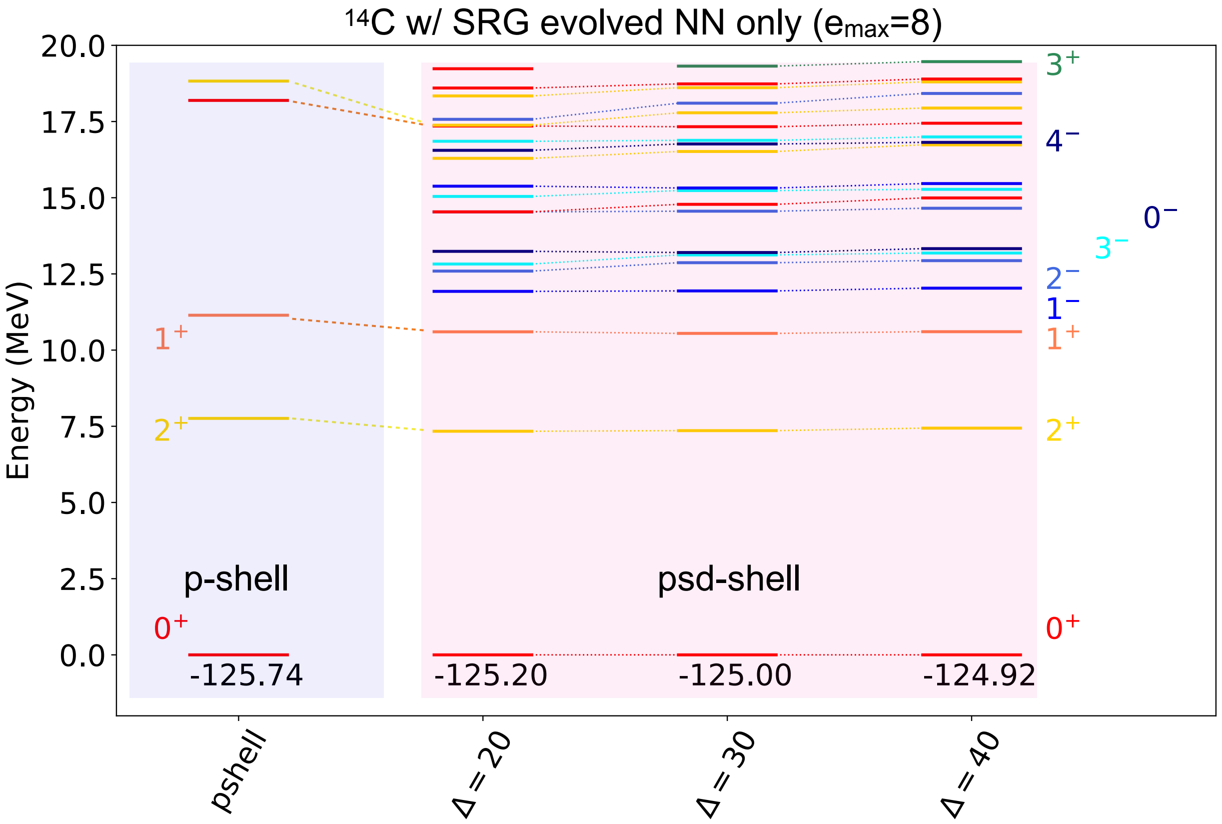


Does it really work?

- Flow of single-particle energies



Comparison with single major shell calculation



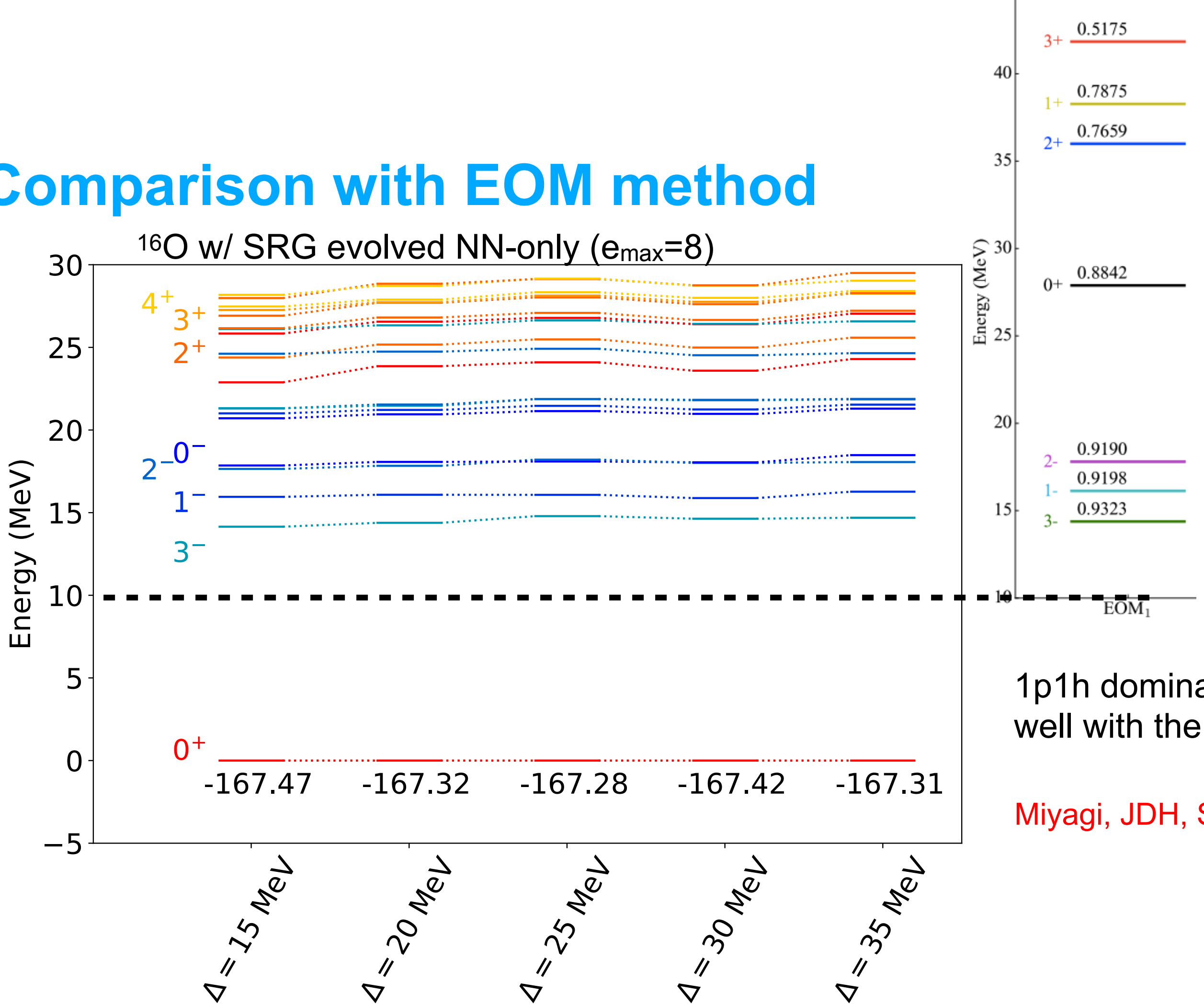
Including negative parity states, many states can appear from psd calculations.

For 0^+_1, 2^+_1, and 1^+_1, p-shell configurations are more than 90%. Also the energies are reasonably close to p-shell results.

Δ dependence is not unique

Miyagi, JDH, Stroberg in prep

Comparison with EOM method



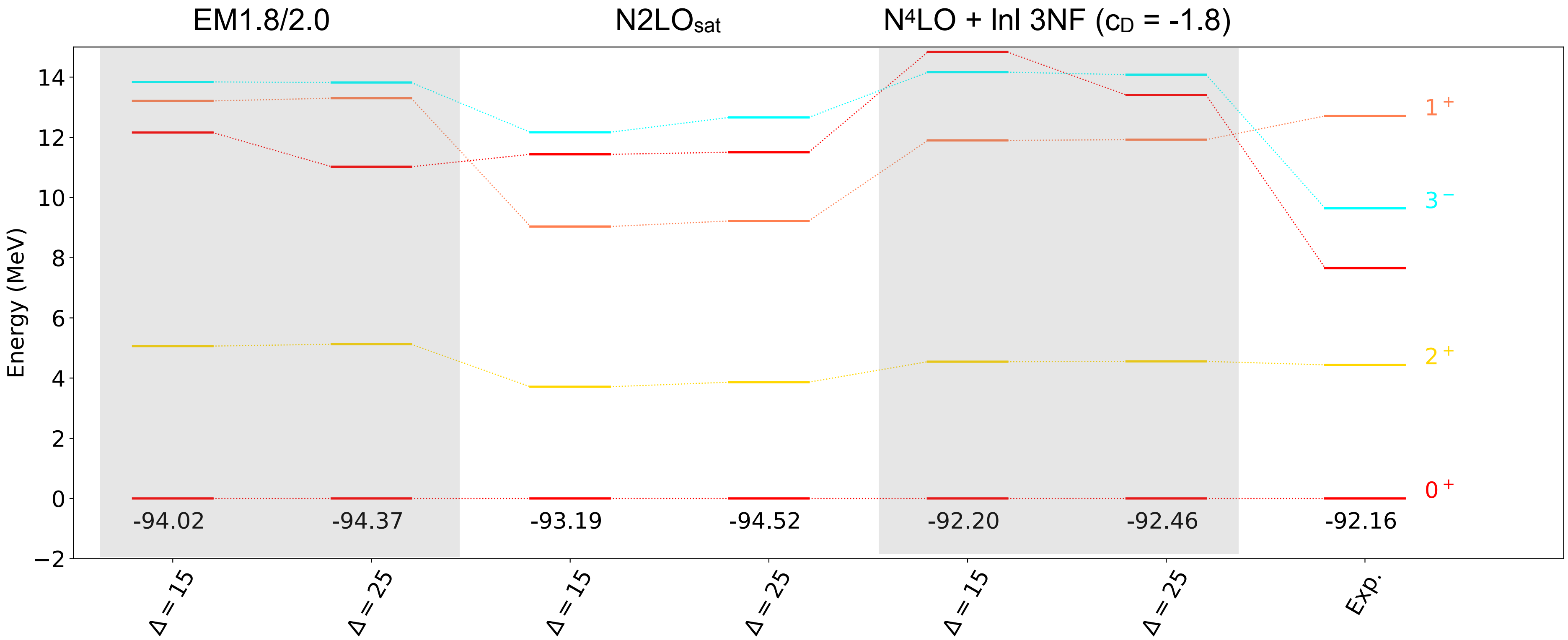
1p1h dominant lowest 3^-, 1^-, 2^- agree well with the EOM-IMSRG results.

Miyagi, JDH, Stroberg in prep

EOM-IMSRG results are take from N. M. Parzuchowski, T. D. Morris, and S. K. Bogner, Phys. Rev. C **95**, 044304 (2017).

^{12}C energies from *psd* calculations

All calculation results are obtained @ e_{max}=10

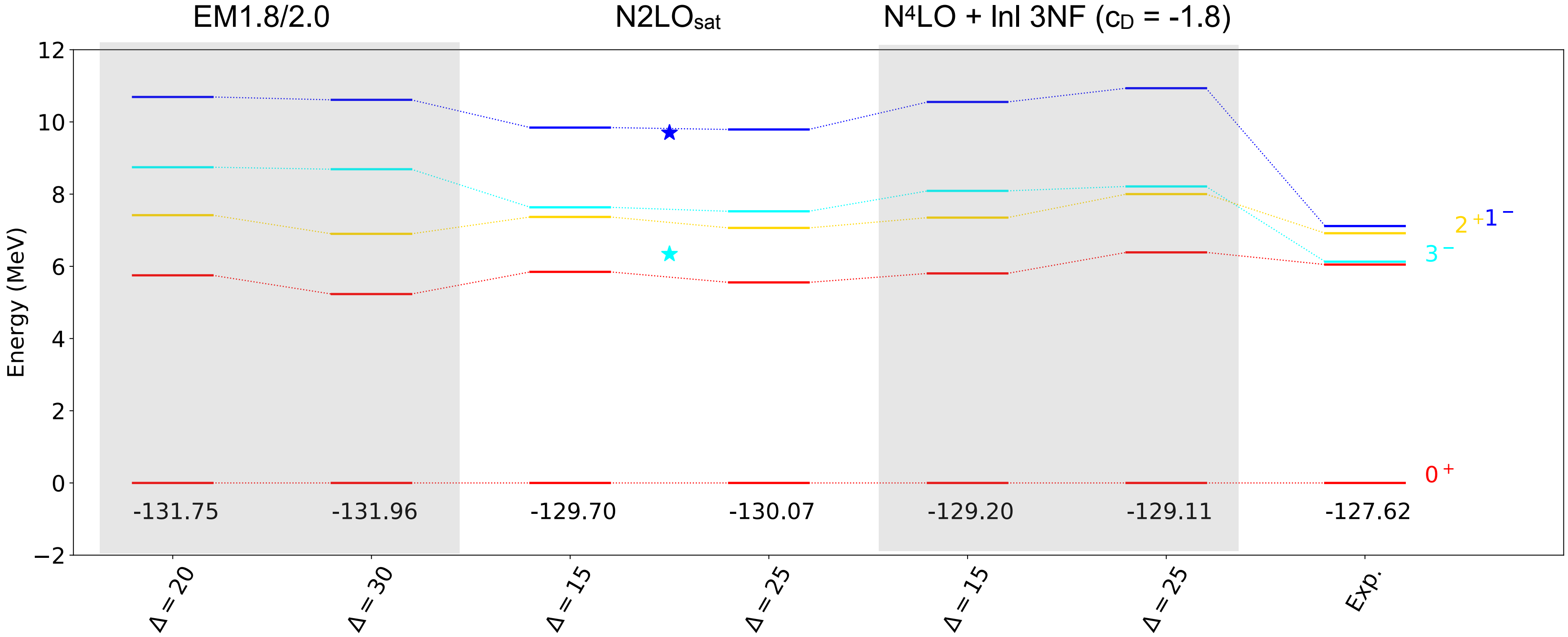


Miyagi, JDH, Stroberg in prep

★: EOM-CCM [A. Ekström,et al., Phys. Rev. C **91**, 051301 (2015).]

^{16}O energies from *psd* calculations

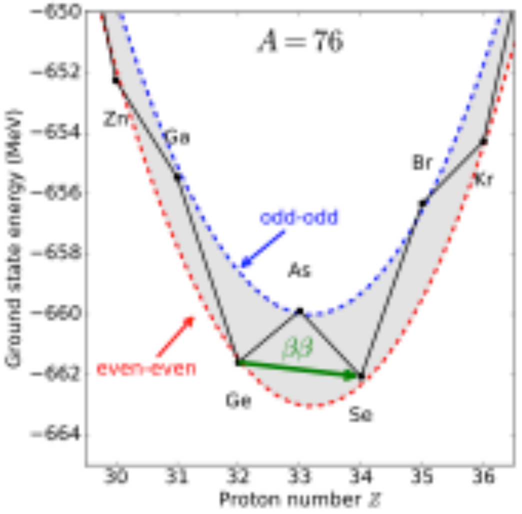
All calculation results are obtained @ e_{max}=10

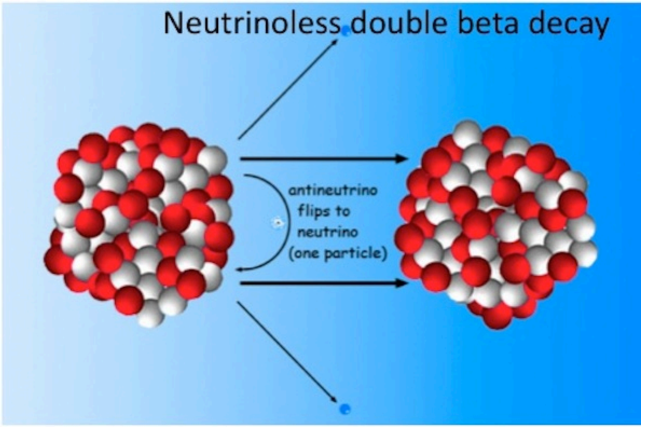


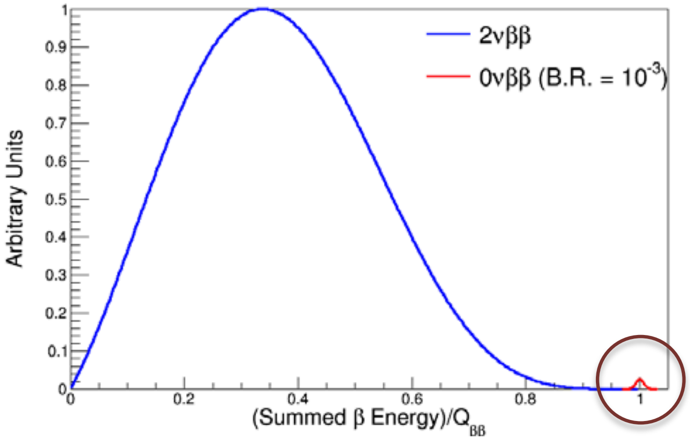
Miyagi, JDH, Stroberg in prep

The Next Big Discovery: 0νββ-decay?

Neutrino own antiparticle $\Longleftrightarrow$ 0νββ decay







Tremendous impact on BSM physics:

Lepton-number violating process

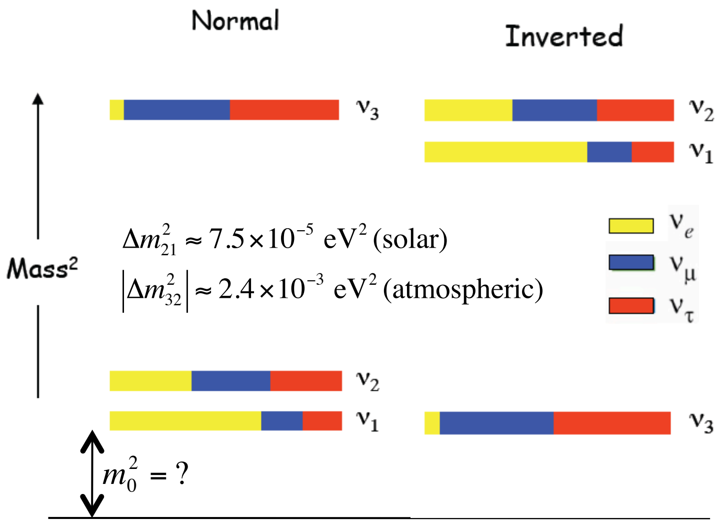
Majorana character of neutrino

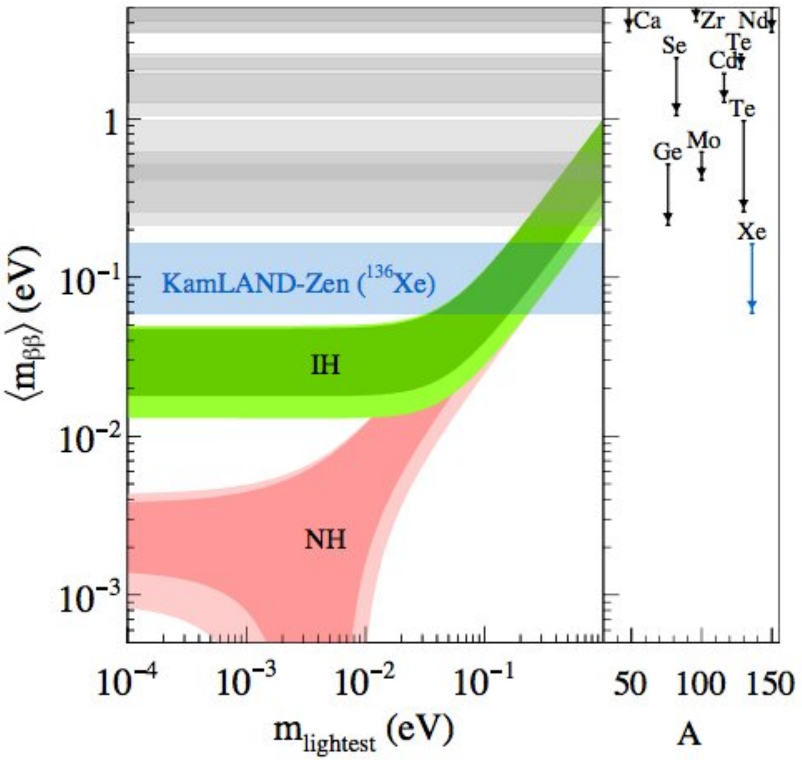
Absolute neutrino mass scale

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

The Next Big Discovery: 0νββ-decay?

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



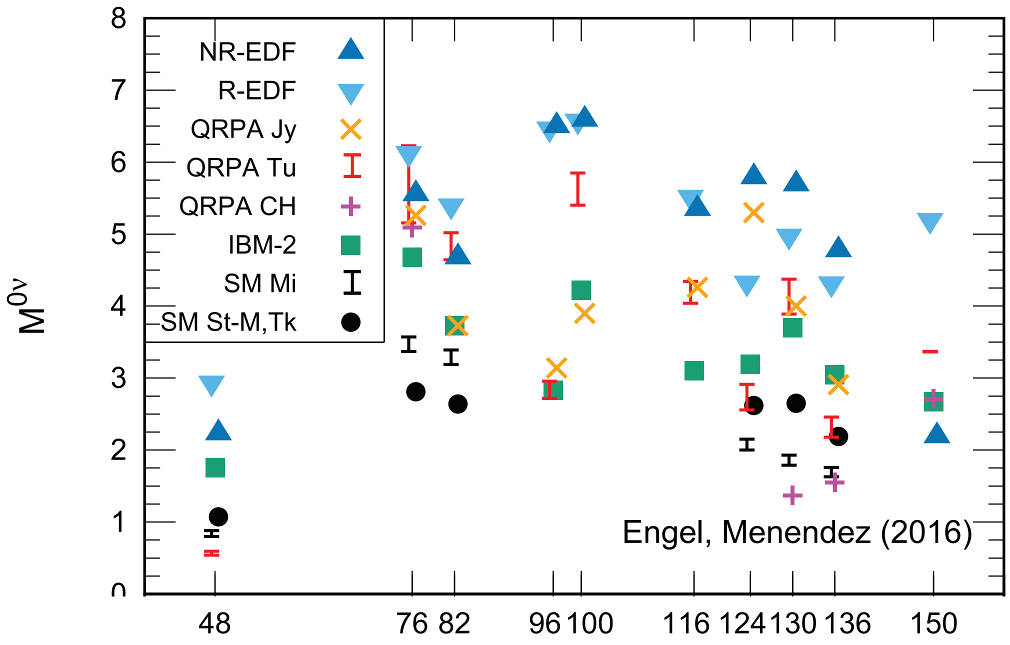


$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2 \quad \langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei} m_i\right|$$

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

$0\nu\beta\beta$-Decay Nuclear Matrix Element Status

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



All models missing essential physics

Impossible to assign rigorous uncertainties