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McGill UNIVERSITY

Ab initio nuclear theory for beyond standard-model physics

Jason D. Holt

Scientist, Theory Department

Conference on Neutrino and Nuclear Physics

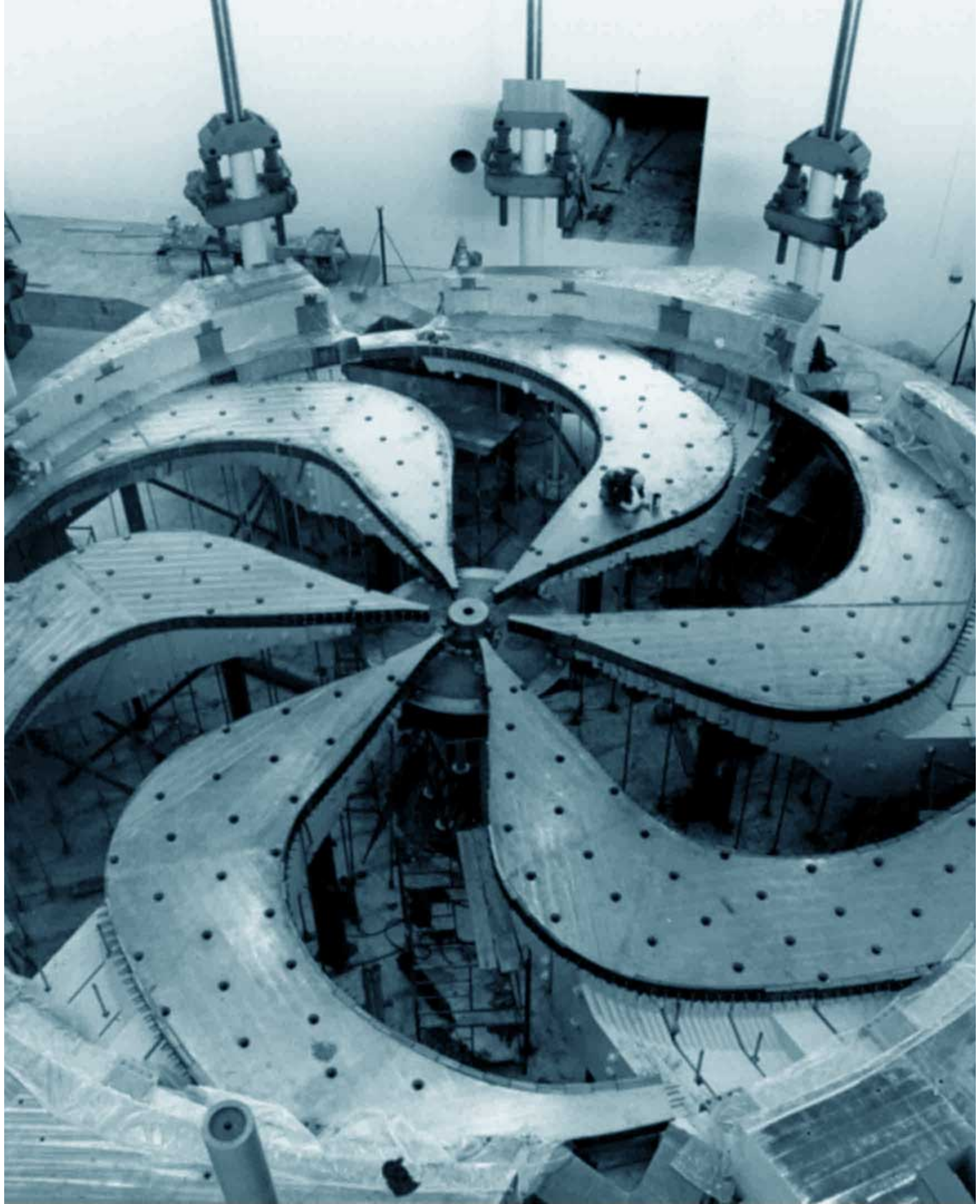
February 26, 2020

work of S.R. Stroberg, T. Miyagi

NSERC CRSNG

Arthur B. McDonald Canadian Astroparticle Physics Research Institute

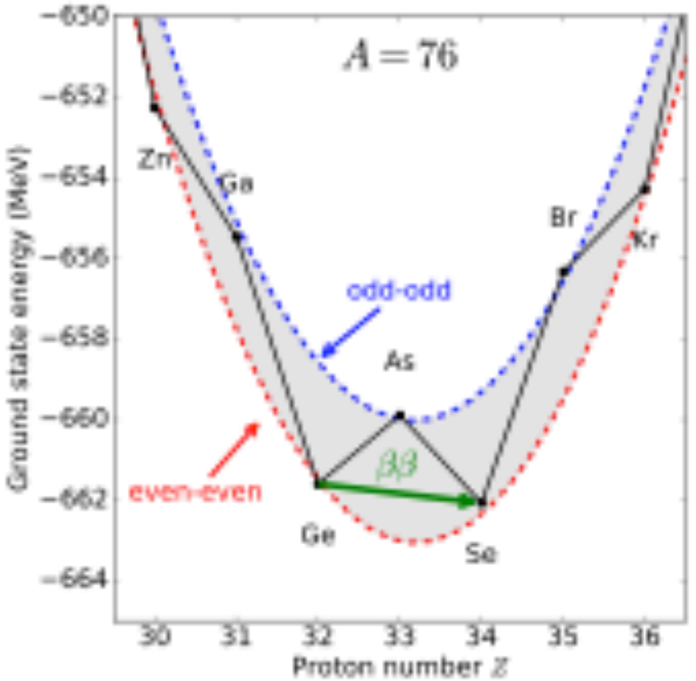
NRC·CNRC

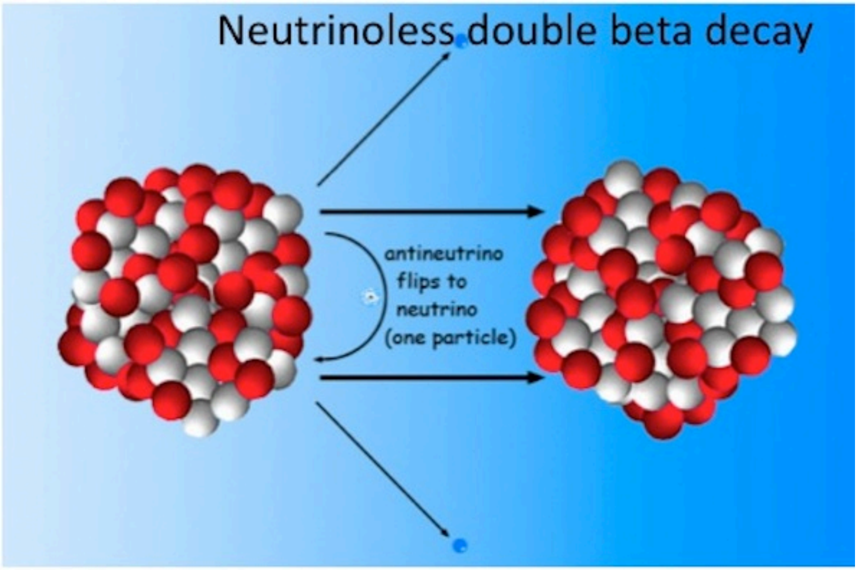


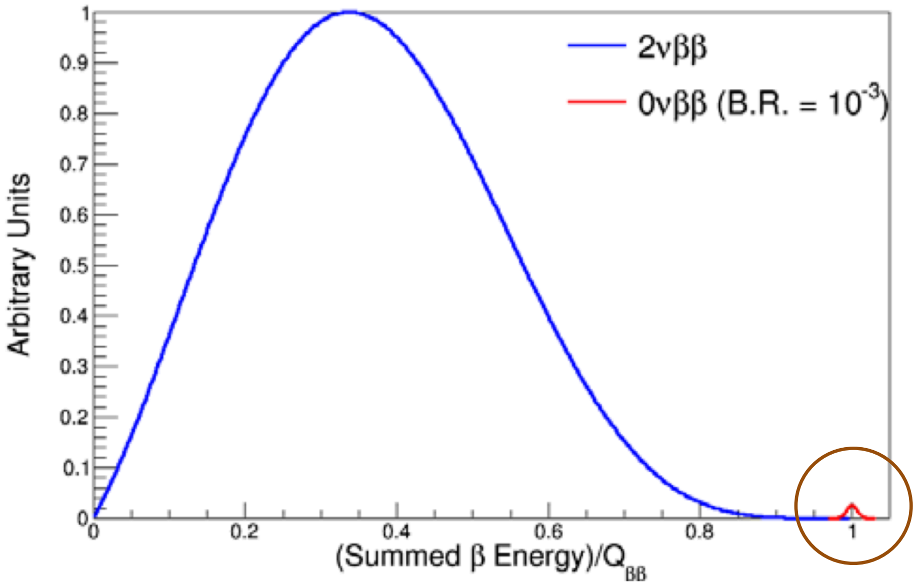
Discovery, accelerated

$0\nu\beta\beta$-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

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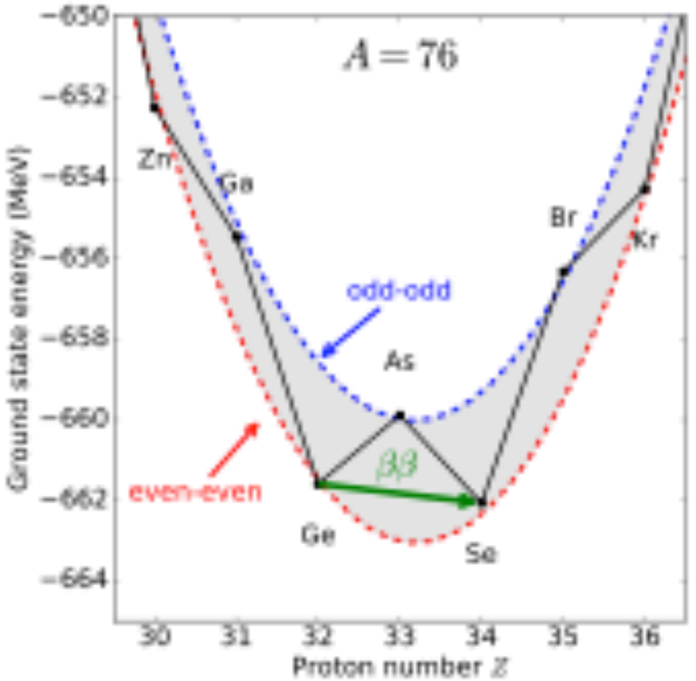

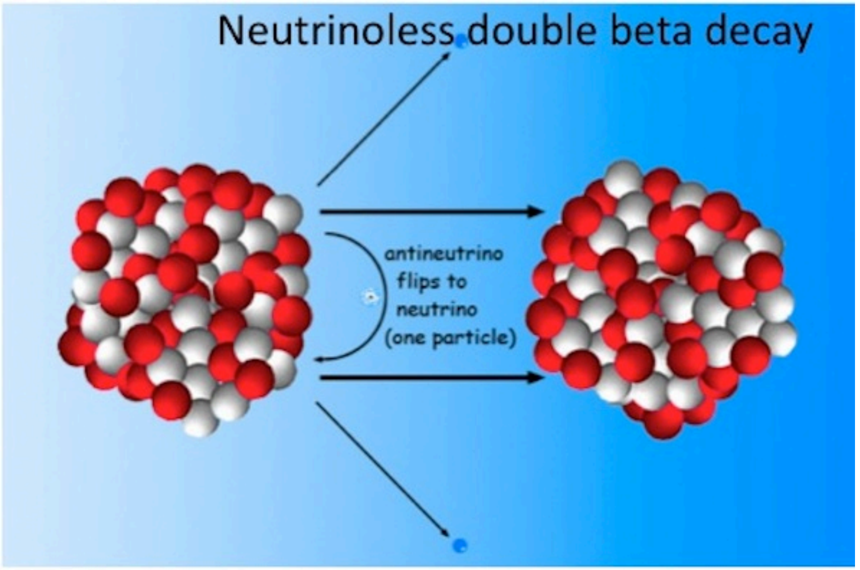

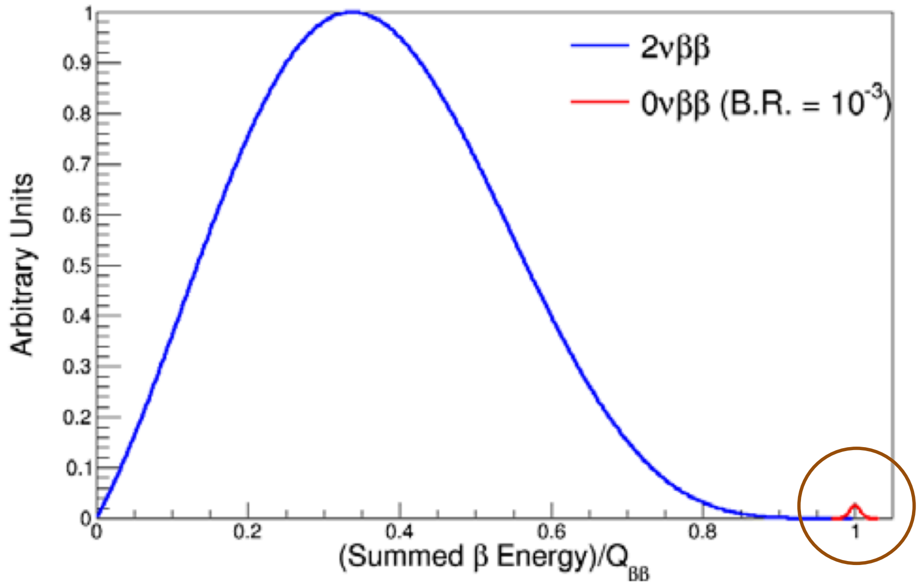

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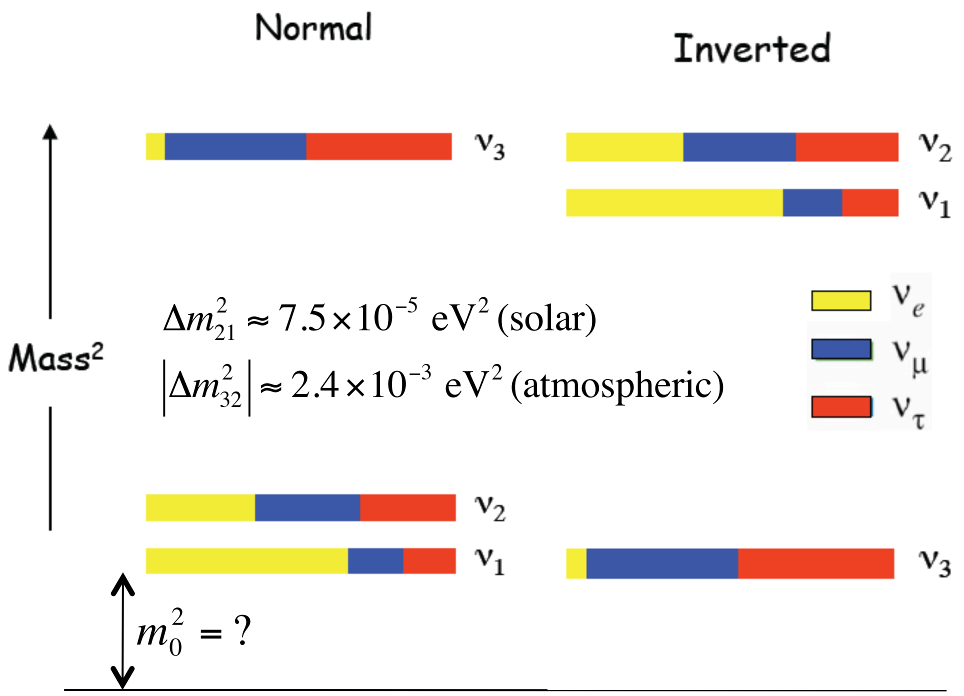
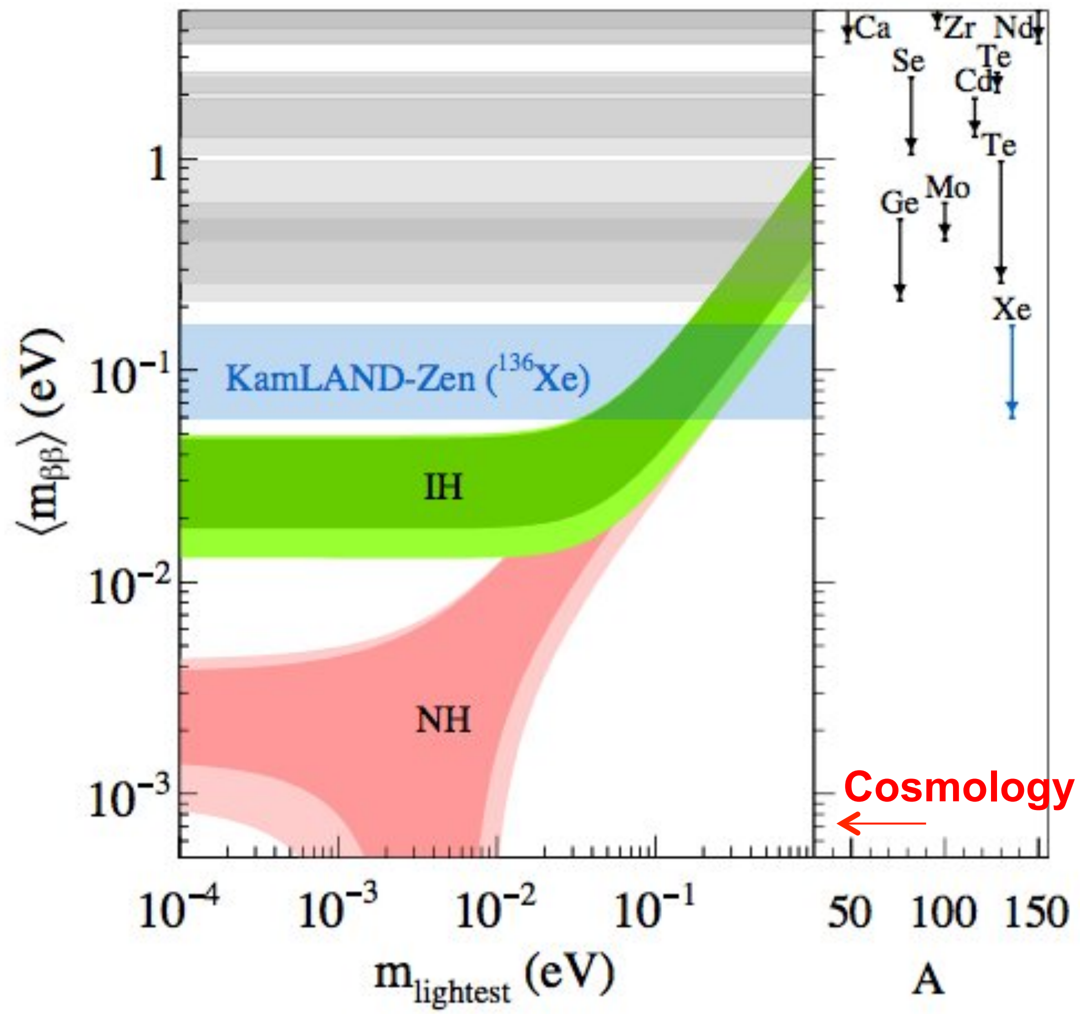
$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2 \qquad \langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei} m_i\right|$$

NME not observable: must be calculated

0νββ-decay

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



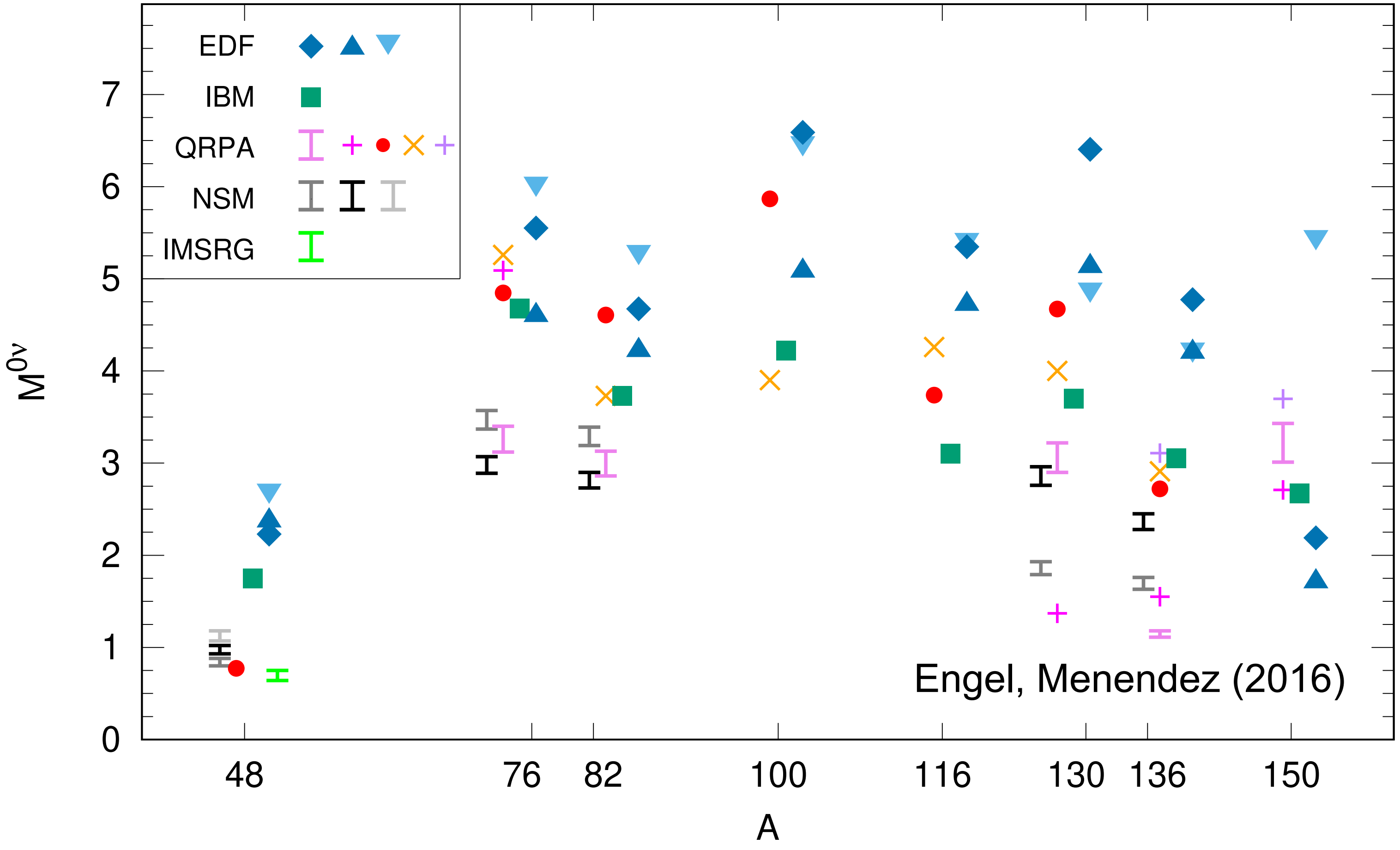


$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu}\,|M^{0\nu}|^2\,\langle m_{\beta\beta}\rangle^2 \quad \langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei} m_i\right|$$

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

Status of 0νββ-decay Matrix Elements

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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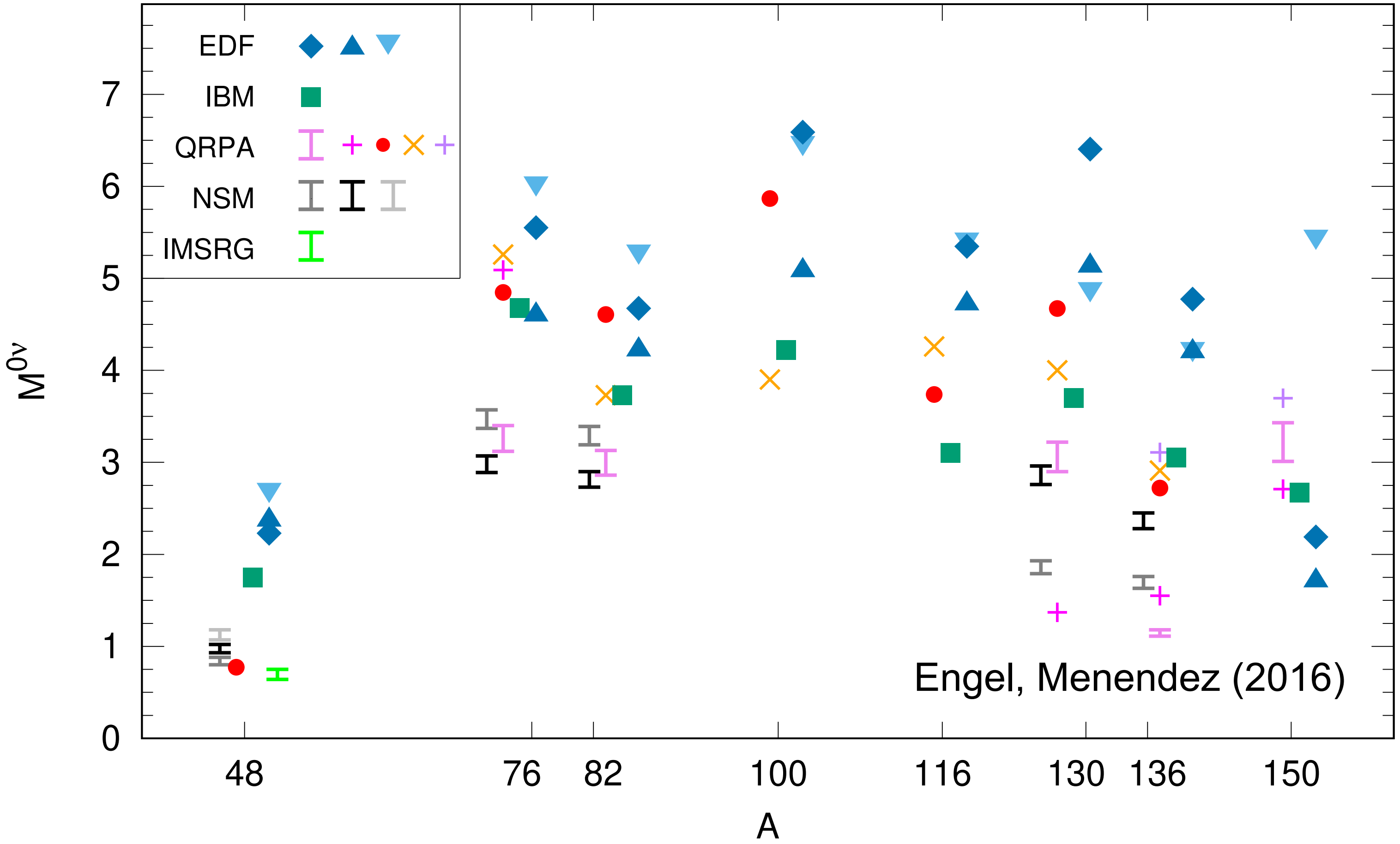


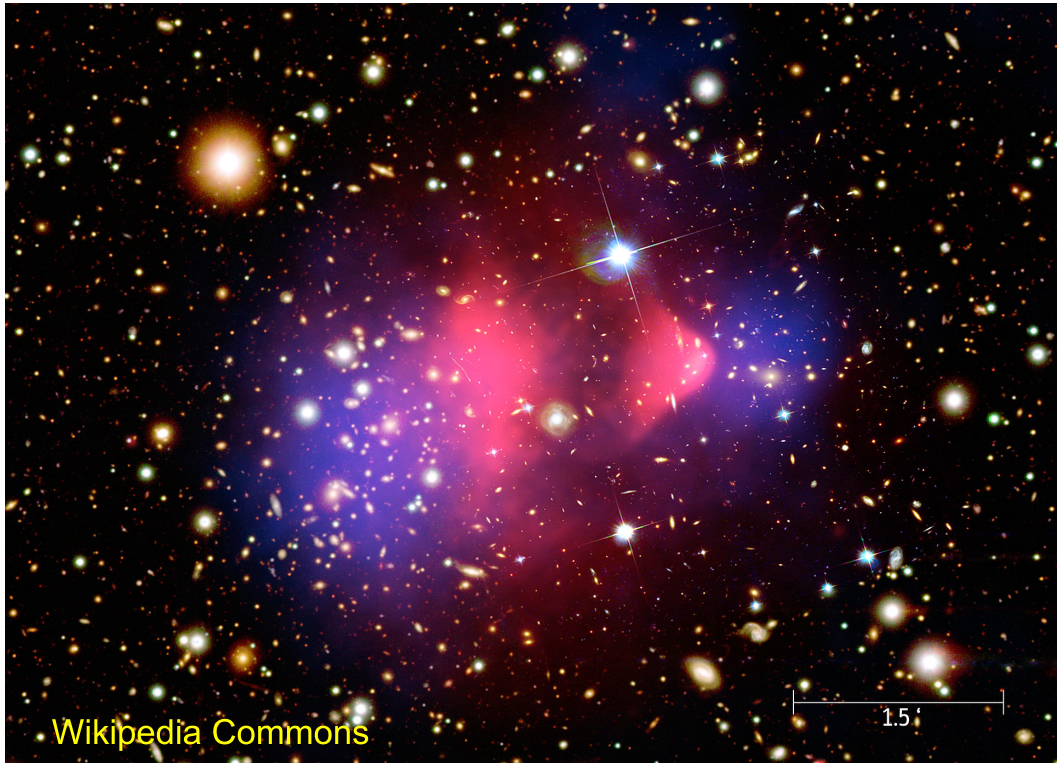
All models missing essential physics

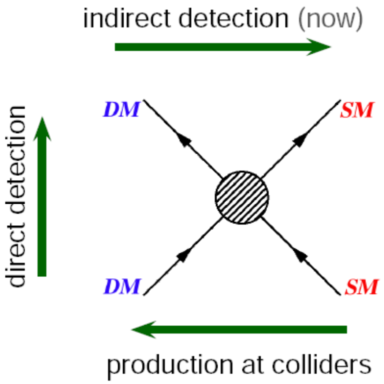
Impossible to assign rigorous uncertainties

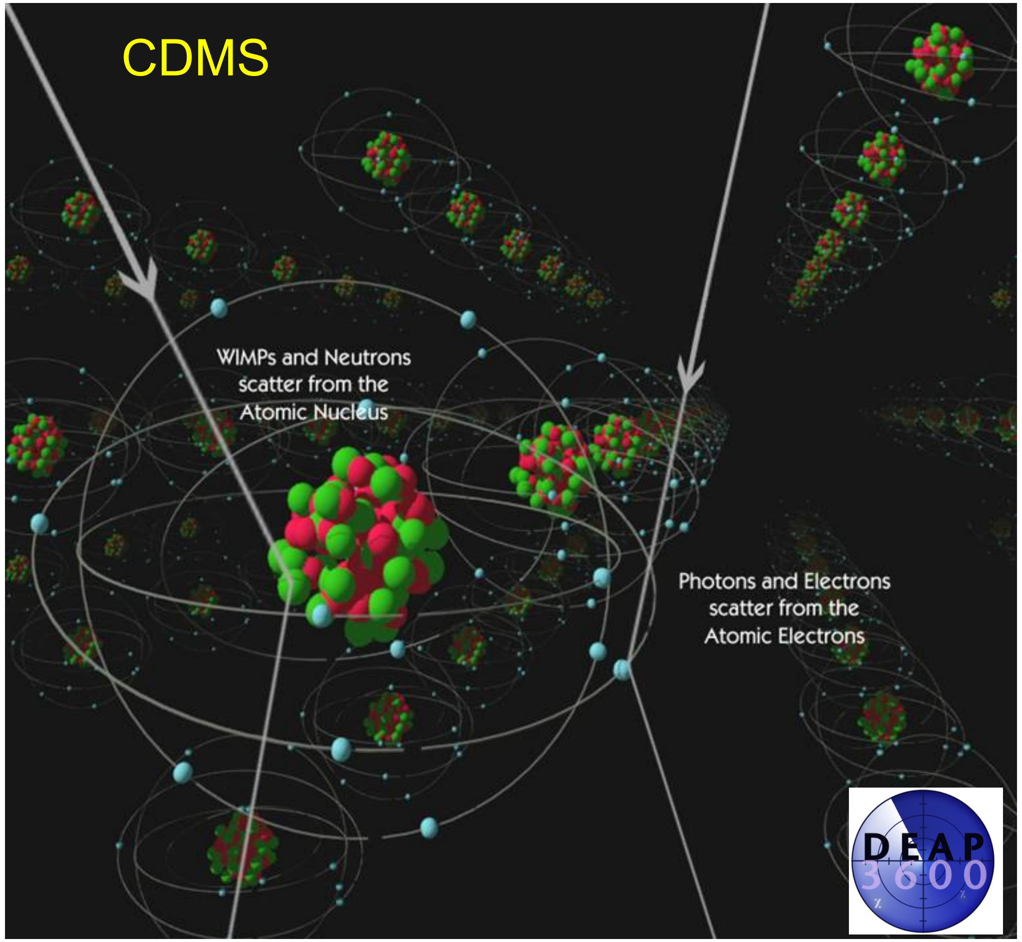
Explore new approaches to nuclear theory

Dark Matter Direct Detection

Large-scale direct-detection searches underway worldwide







Observation of nuclear recoil

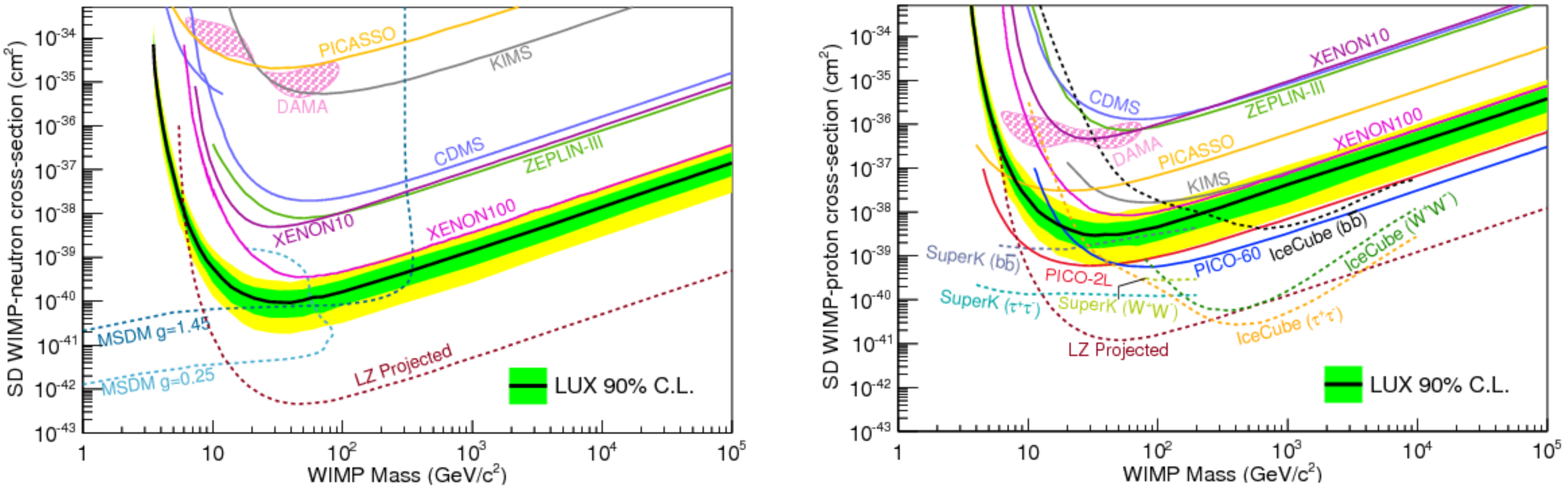
Direct detection: $X\,\mathrm{SM} \to X\,\mathrm{SM}$

Leading candidates: neutralinos, …?

Couple to scalar and axial-vector currents in atomic nuclei

Dark Matter Direct Detection

Exclusion plots for WIMP-nucleon total cross section require nuclear structure



Differential cross section: compare results from different target nuclei

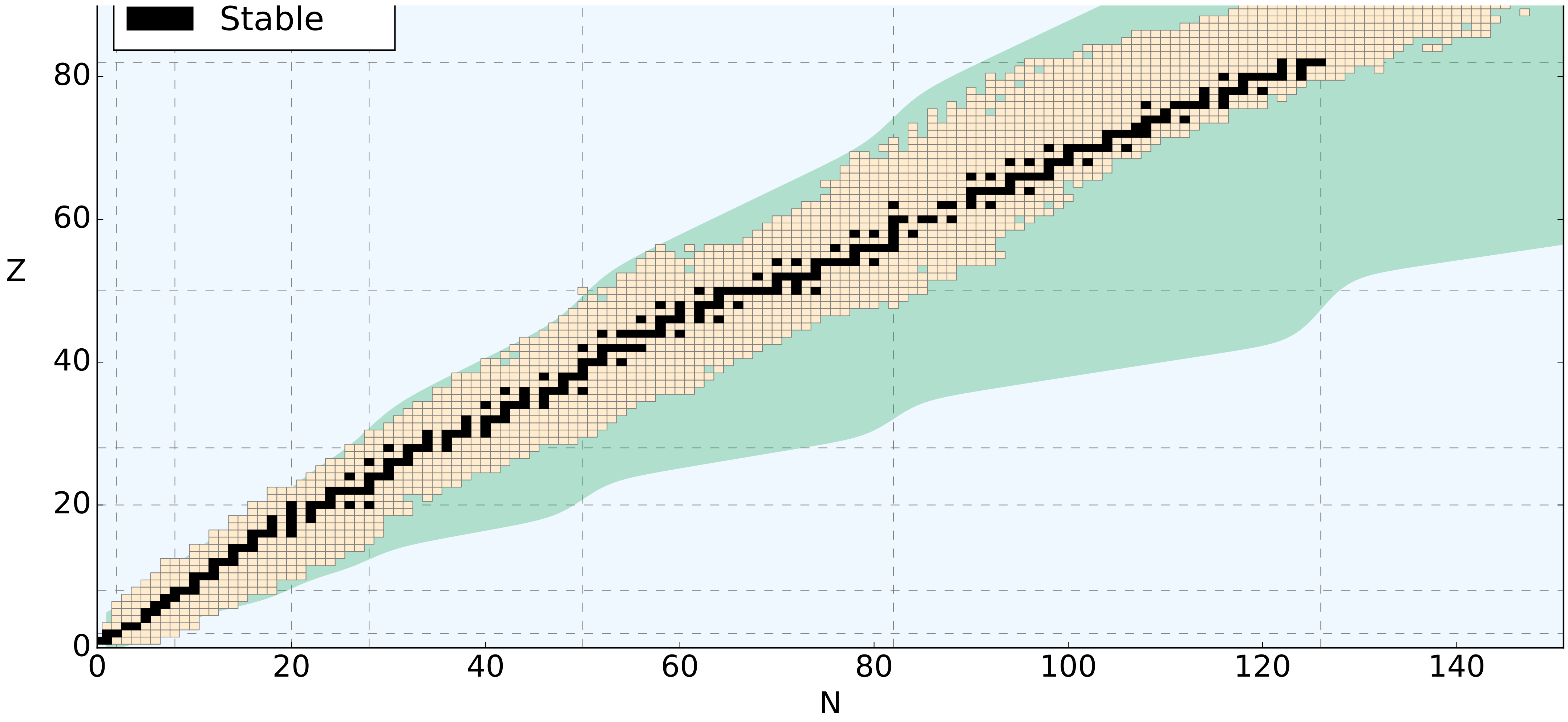
$$\frac{\mathrm{d}\sigma}{\mathrm{d}p^2} = \frac{8G_F^2}{(2J_i+1)v^2} S_A(p)$$

Structure functions required from nuclear theory

Ab Initio Theory for Atomic Nuclei

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

$$H\psi_n = E_n\psi_n$$



Ab Initio Theory for Atomic Nuclei

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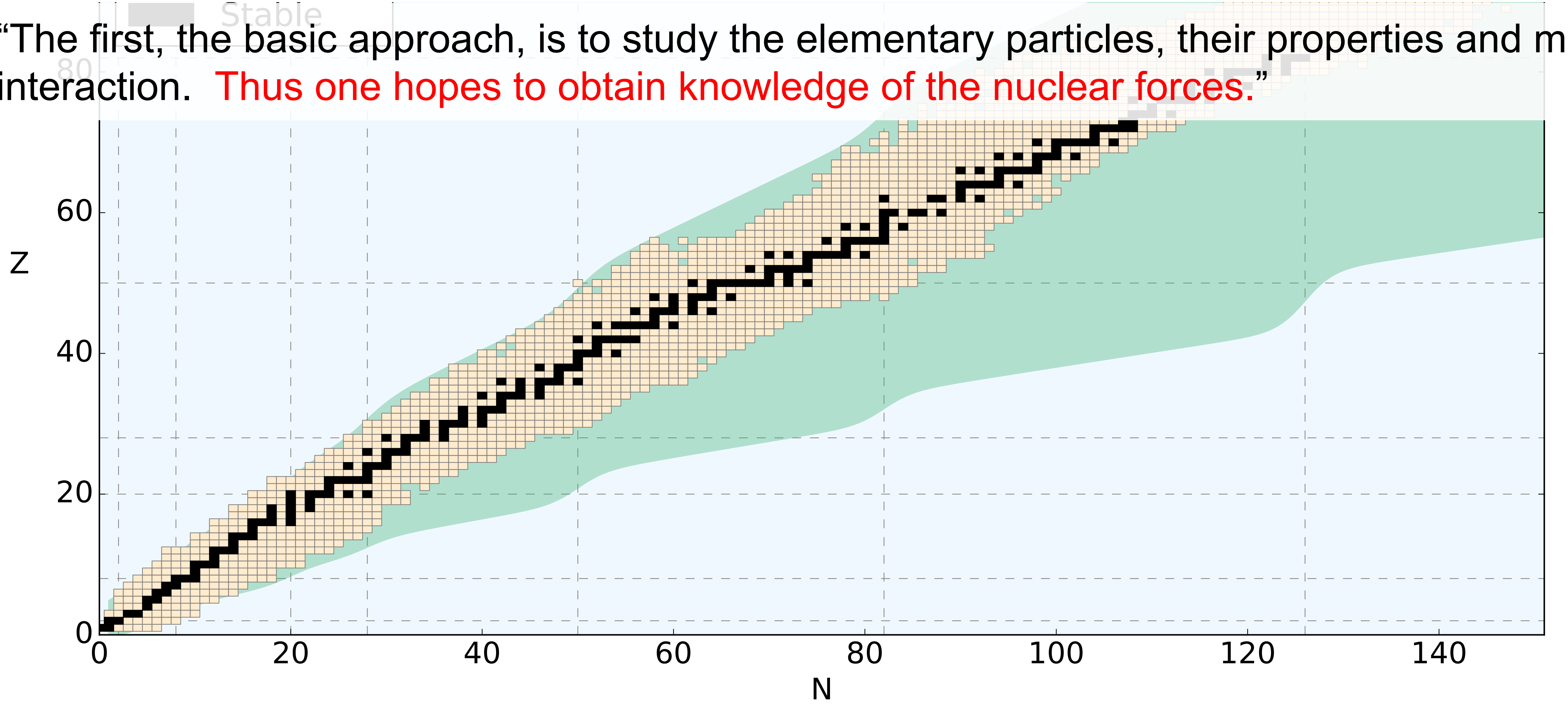
Aim of modern nuclear theory: Develop unified *first-principles* picture of structure and reactions

- 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."



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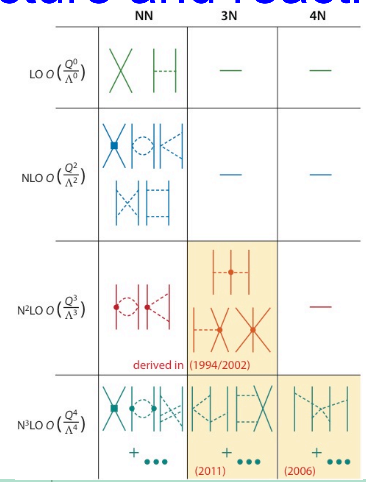
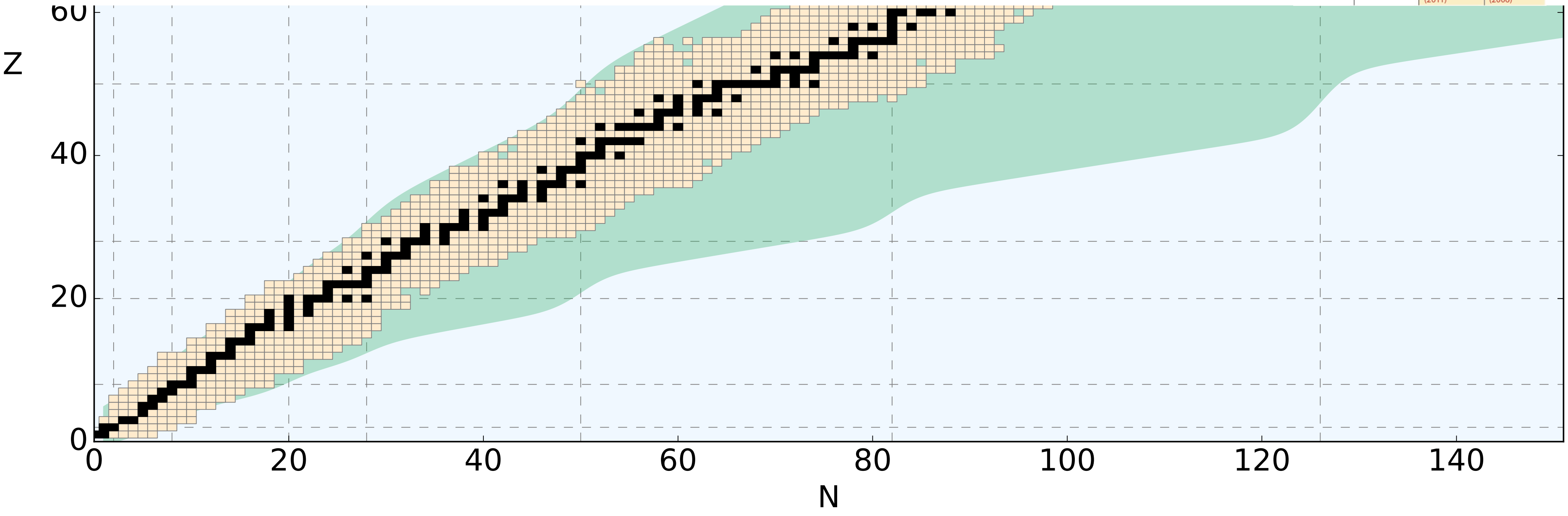


Chiral effective field theory: systematic expansion of nuclear interactions

Consistent 3N forces, electroweak currents

Quantifiable uncertainties possible



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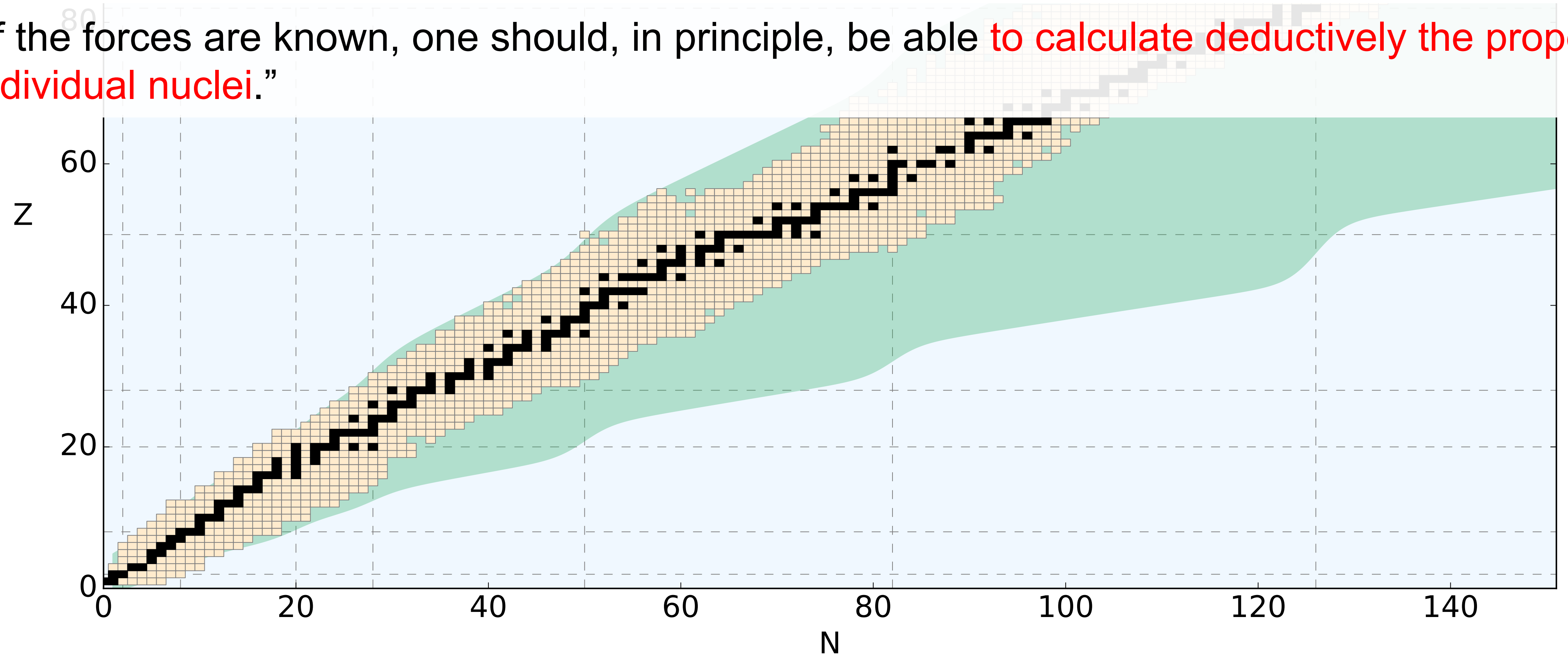
- **Nuclear many-body problem**

$$H\psi_n = E_n\psi_n$$

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



Chronological Reach of Ab Initio Theory

Moore's law: exponential growth in computing power

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

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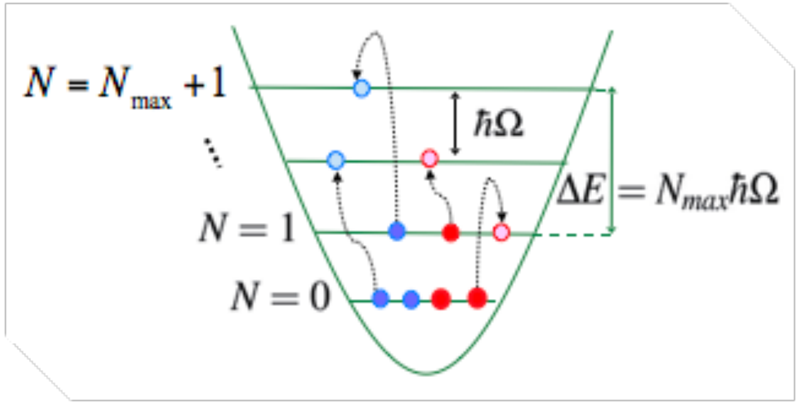
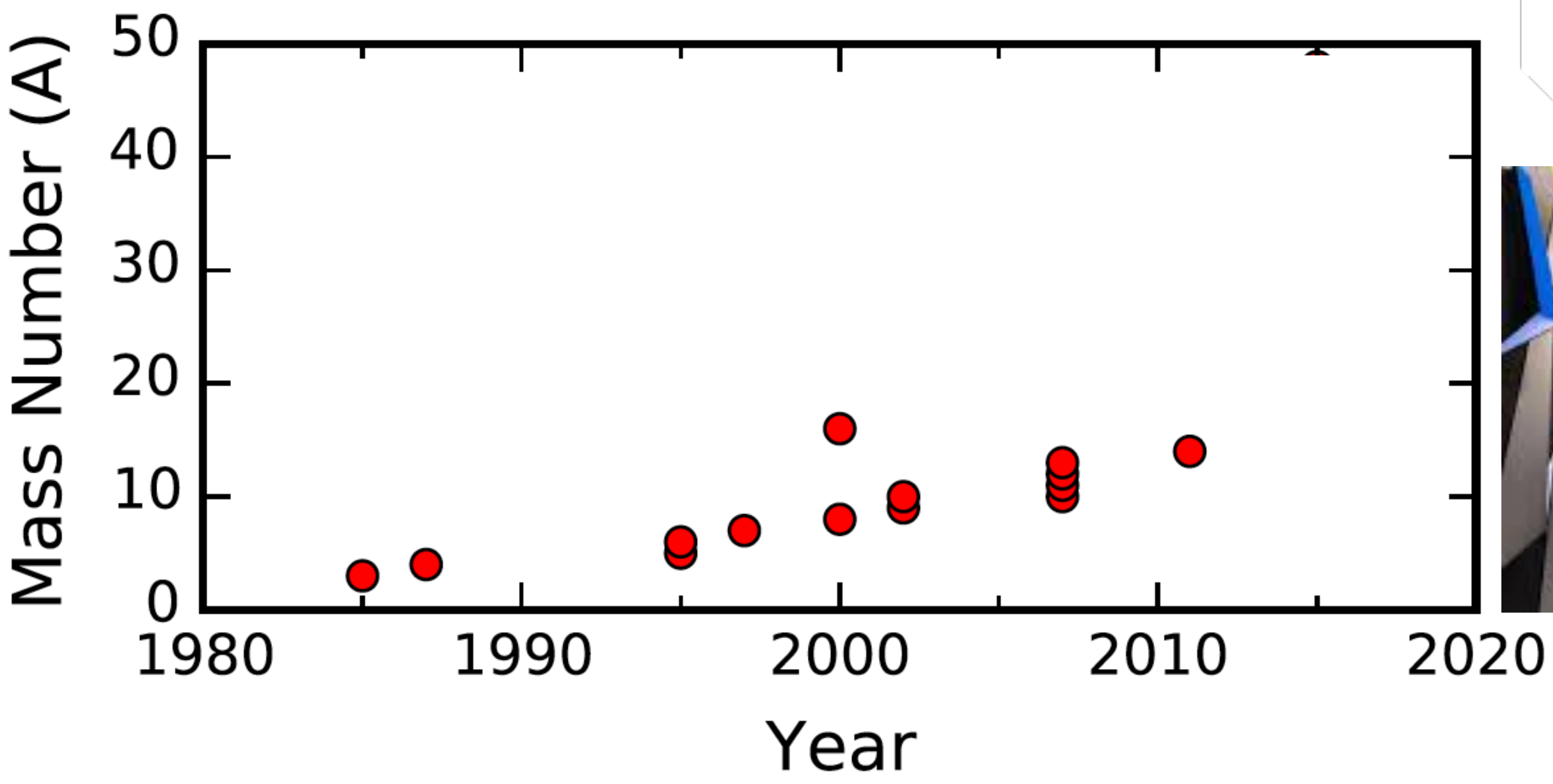




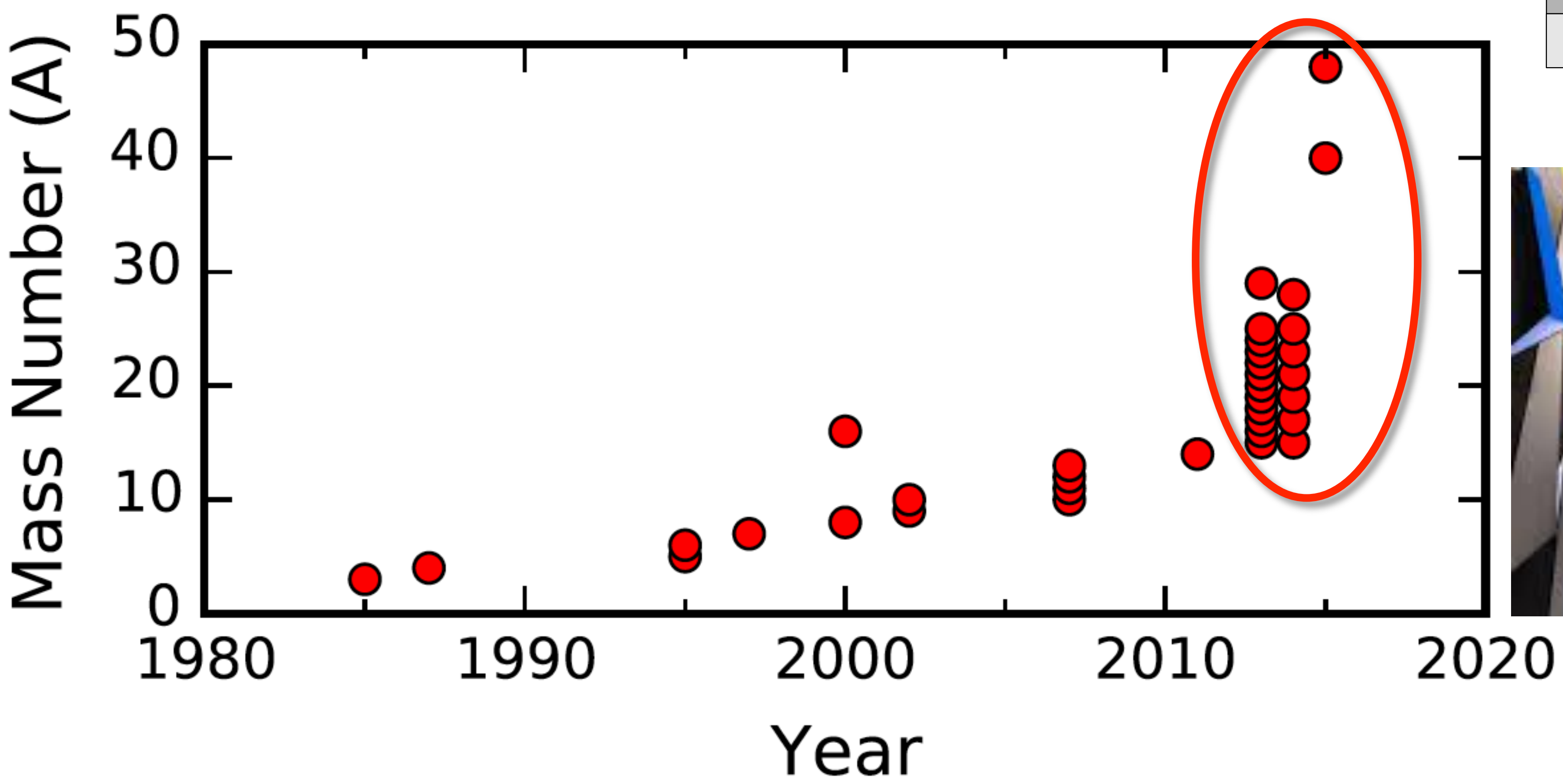
Chronological Reach of Ab Initio Theory

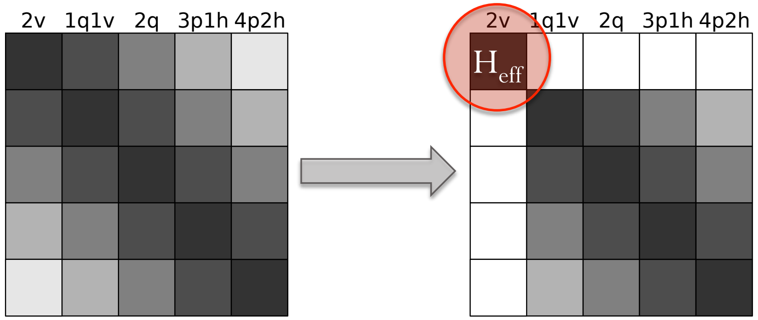
Moore's law: exponential growth in computing power

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

Polynomial scaling methods developed (**CC**, **IMSRG**, SCGF)

Explosion in limits of ab initio theory





$$H(s=0) \rightarrow H(\infty)$$

Chronological Reach of Ab Initio Theory

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Moore's law: exponential growth in computing power

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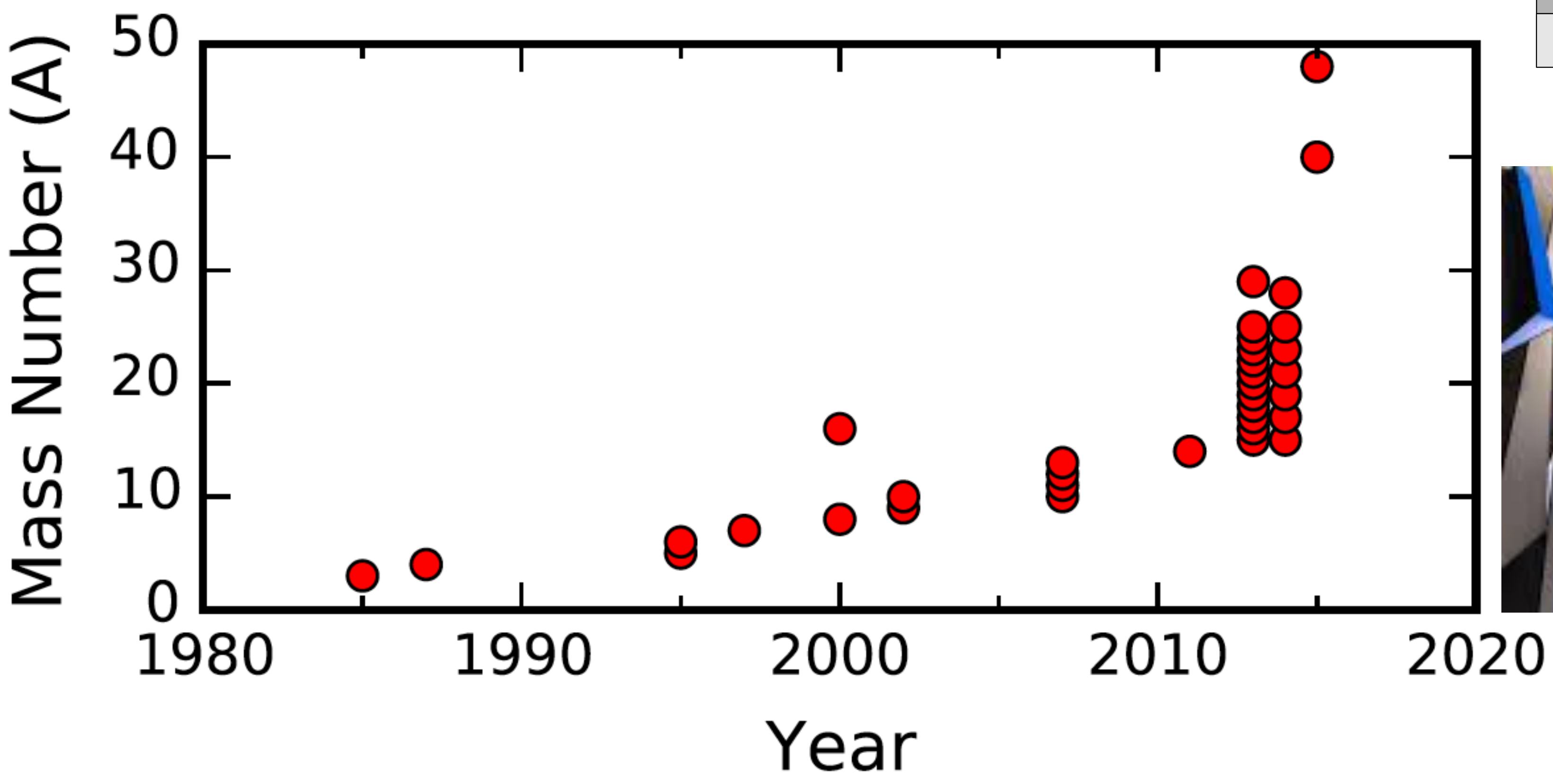

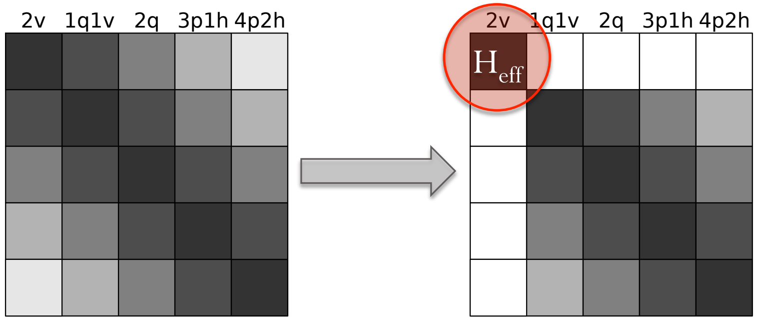

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Breadth of Ab Initio Theory

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- **Nuclear many-body problem**

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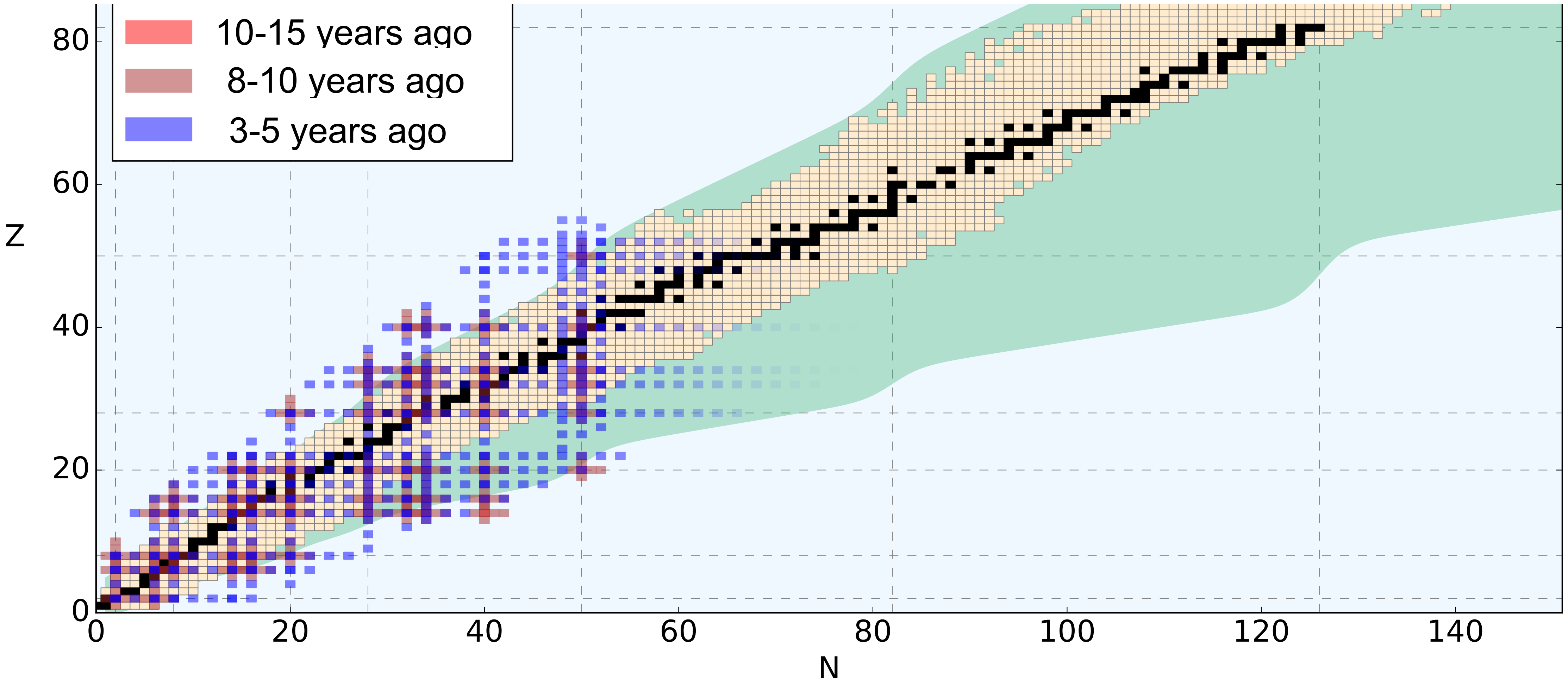

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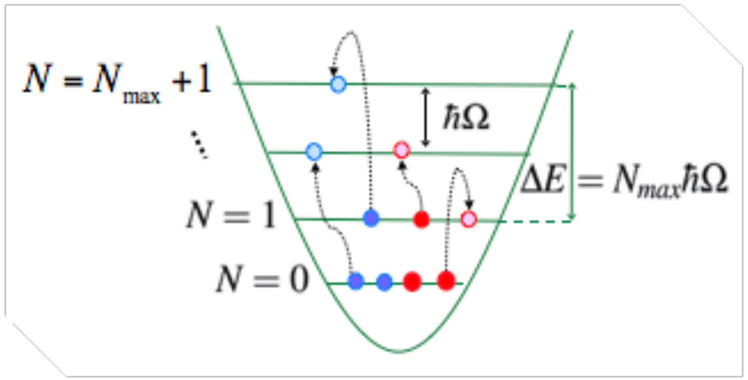
Valence-Space IMSRG

Explicitly construct unitary transformation from sequence of rotations

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

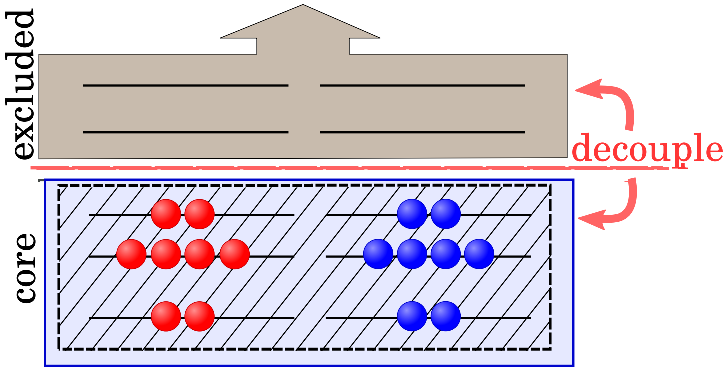
$$\tilde{H} = e^{\Omega} H e^{-\Omega} = H + [\Omega, H] + \frac{1}{2}[\Omega, [\Omega, H]] + \cdots$$



All operators truncated at two-body level IMSRG(2)
IMSRG(3) in progress (S.R. Stroberg)

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

Step 1: Decouple core



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

Can we achieve accuracy
of large-space methods?

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

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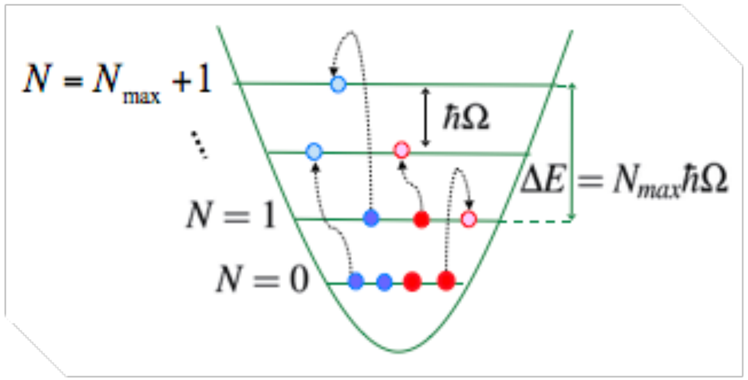

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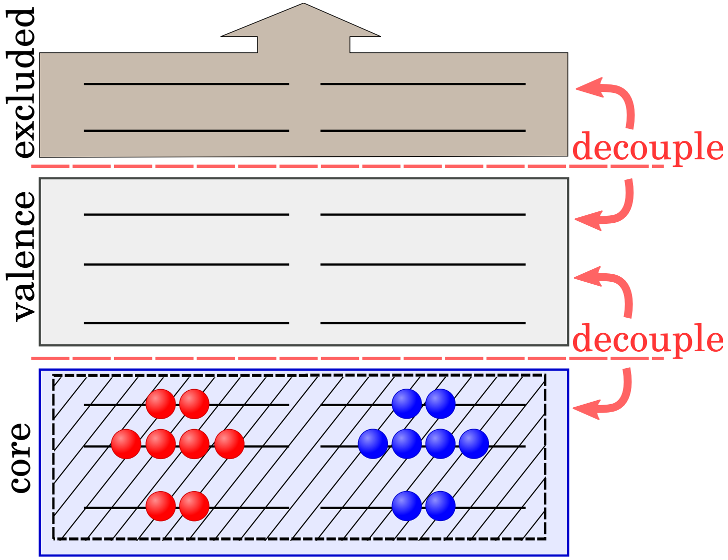

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Step 1: Decouple core
Step 2: Decouple valence space H

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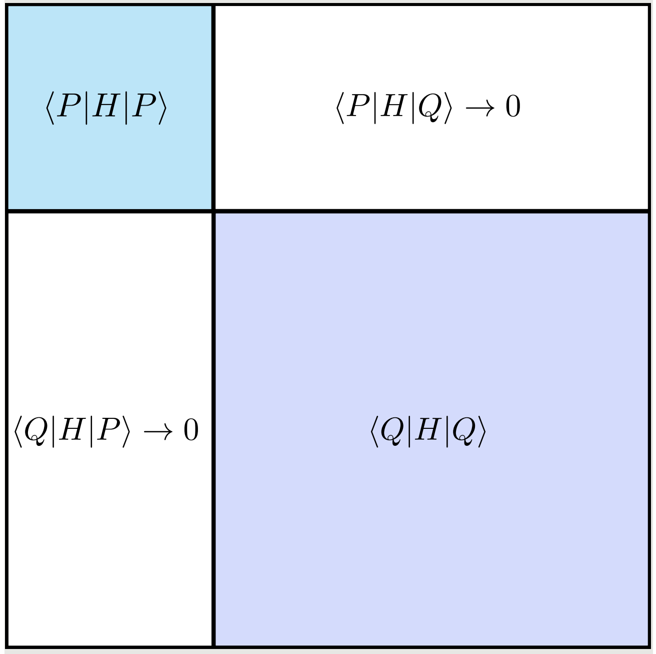

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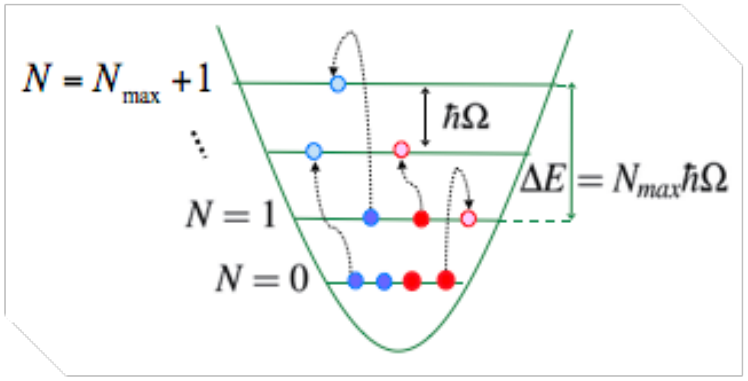

$$\tilde{H} = e^{\Omega} H e^{-\Omega} = H + [\Omega, H] + \frac{1}{2}[\Omega, [\Omega, H]] + \cdots$$

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

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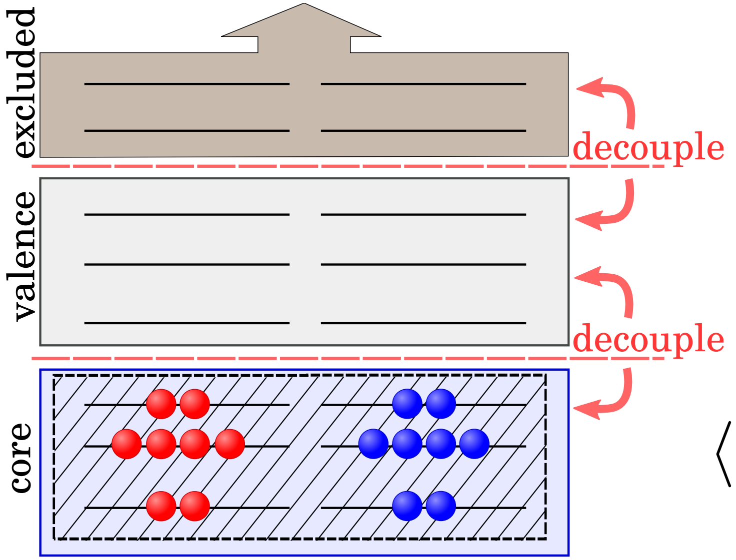


$|\Phi_0\rangle = |^{16}\mathrm{O}\rangle$

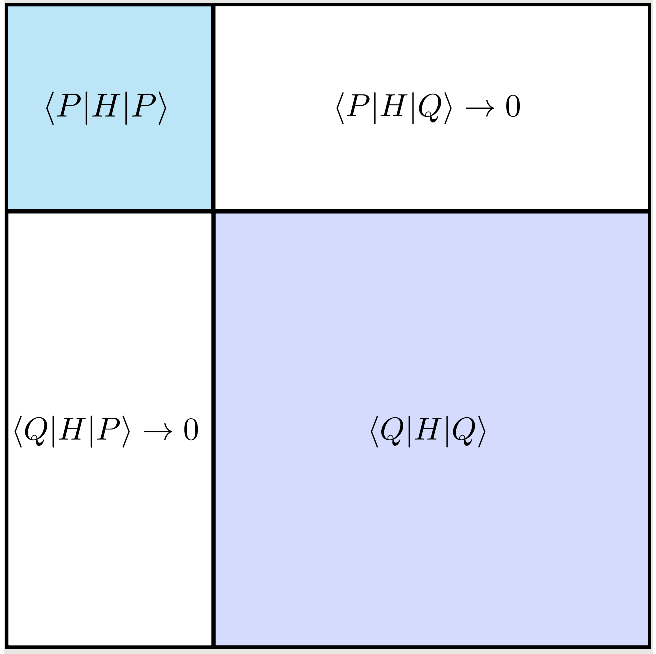
Step 1: Decouple core

Step 2: Decouple valence space H

Step 3: Transform additional operators

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

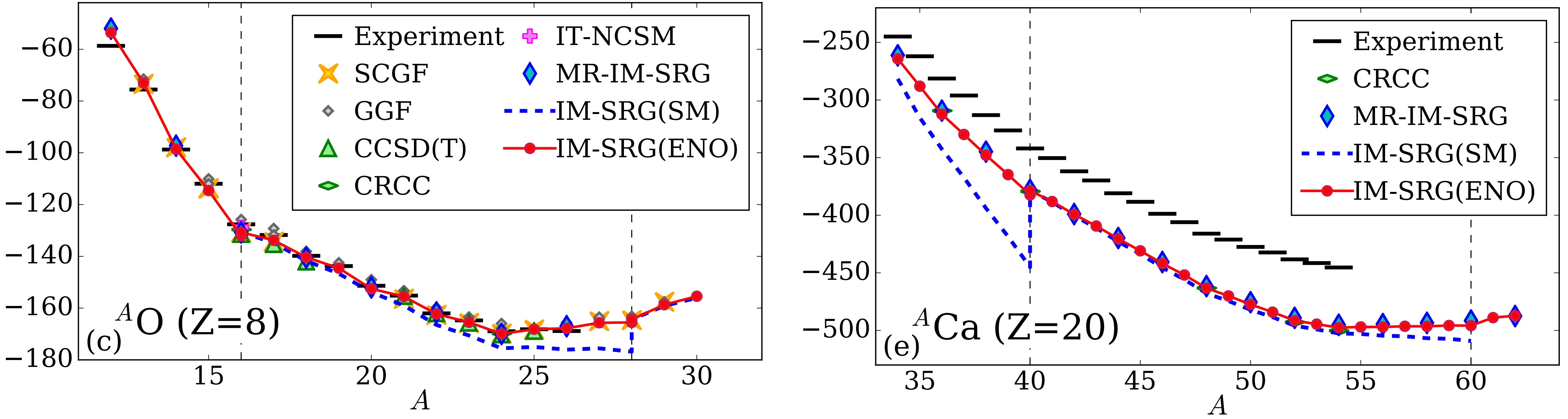
$$\langle \tilde{\Psi}_n | P \tilde{M}_{0\nu} P \mid \tilde{\Psi}_n \rangle \approx \langle \Psi_i | M_{0\nu} | \Psi_i \rangle$$



Careful benchmarking essential!

Benchmarking VS-IMSRG: from Oxygen to Calcium

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



Stroberg et al., PRL (2017)

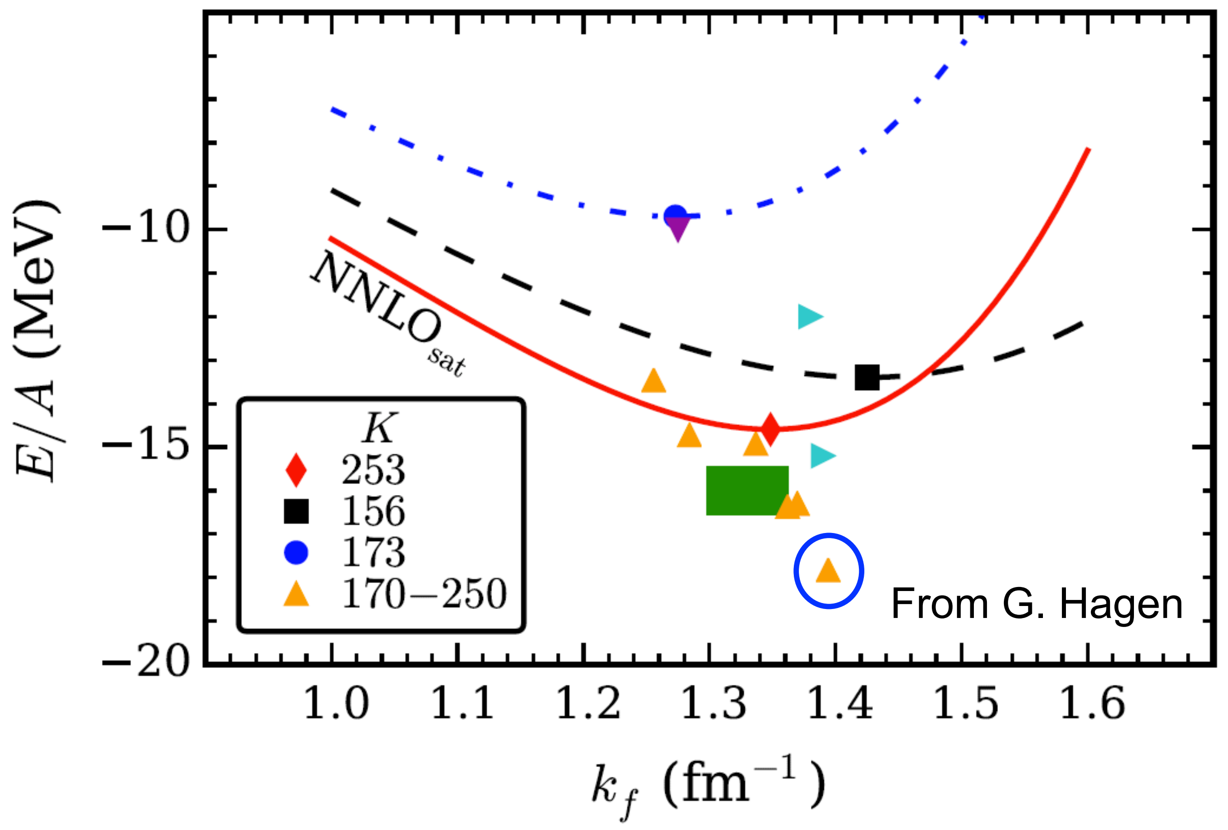
Agreement with *experiment* deteriorates for heavy chains (due to input Hamiltonian)

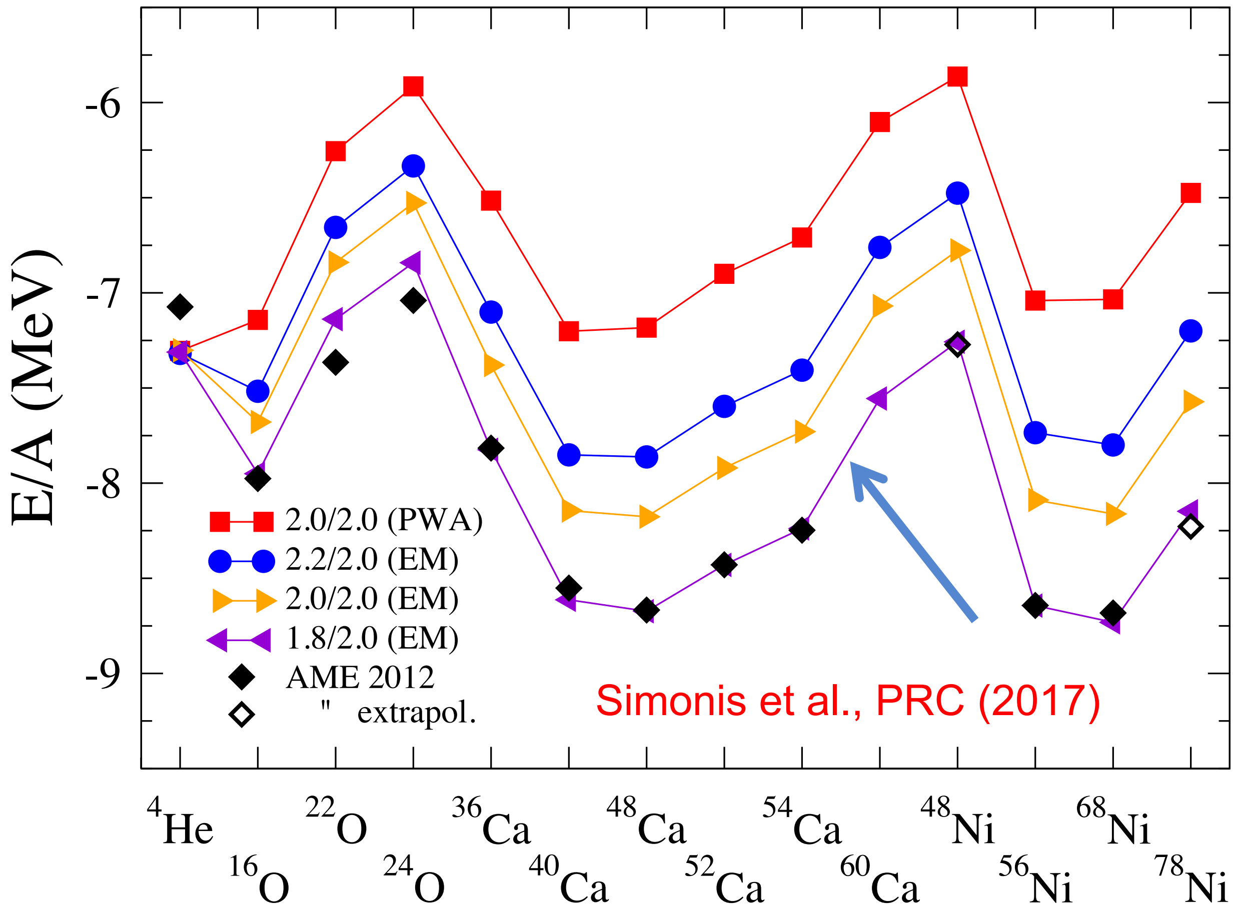
Significant gain in applicability with little/no sacrifice in accuracy; **Any operator can be calculated**

Low computational cost: ~1 node-day/nucleus

Connection to Infinite Matter: Saturation as a Guide

NN+3N force with good reproduction of ground-state energies



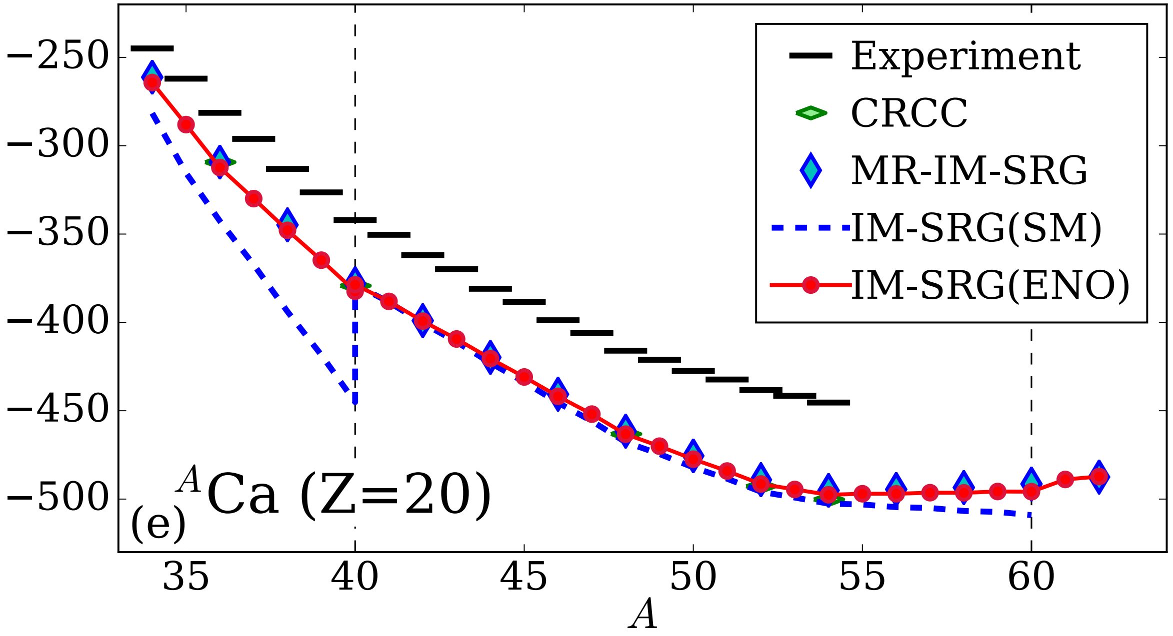


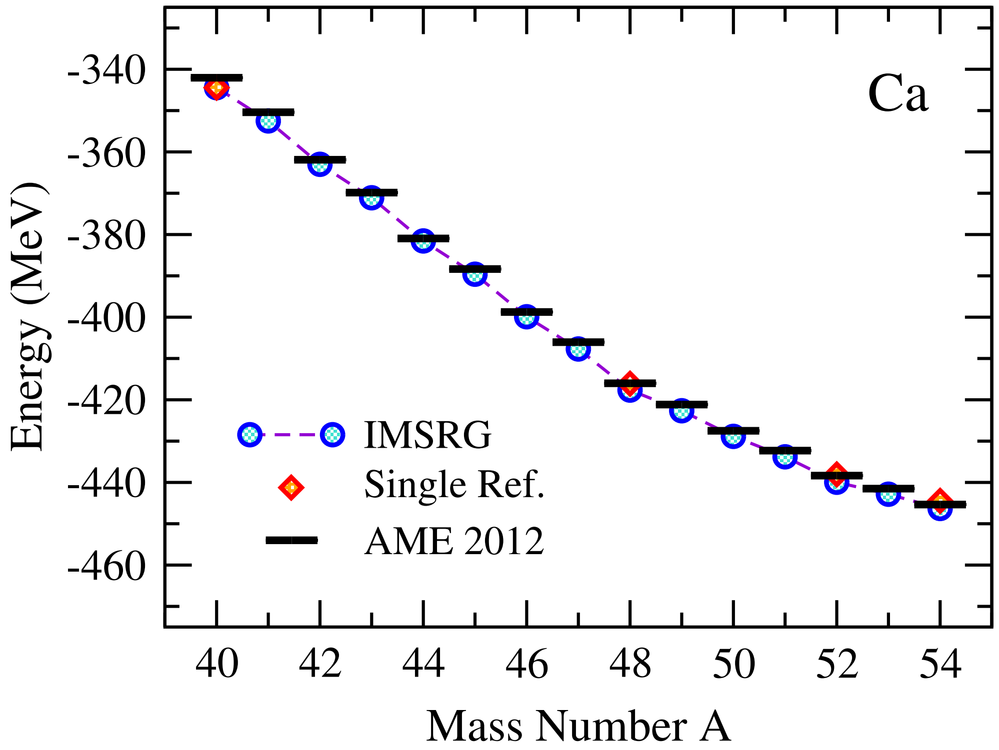
1.8/2.0 (EM) reproduces ground-state energies through ^{78}Ni

Slight underbinding for neutron-rich oxygen

NN+3N Forces with Good Saturation Properties

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, charge radii, electroweak transitions…
- Test nuclear forces across wide range of nuclei

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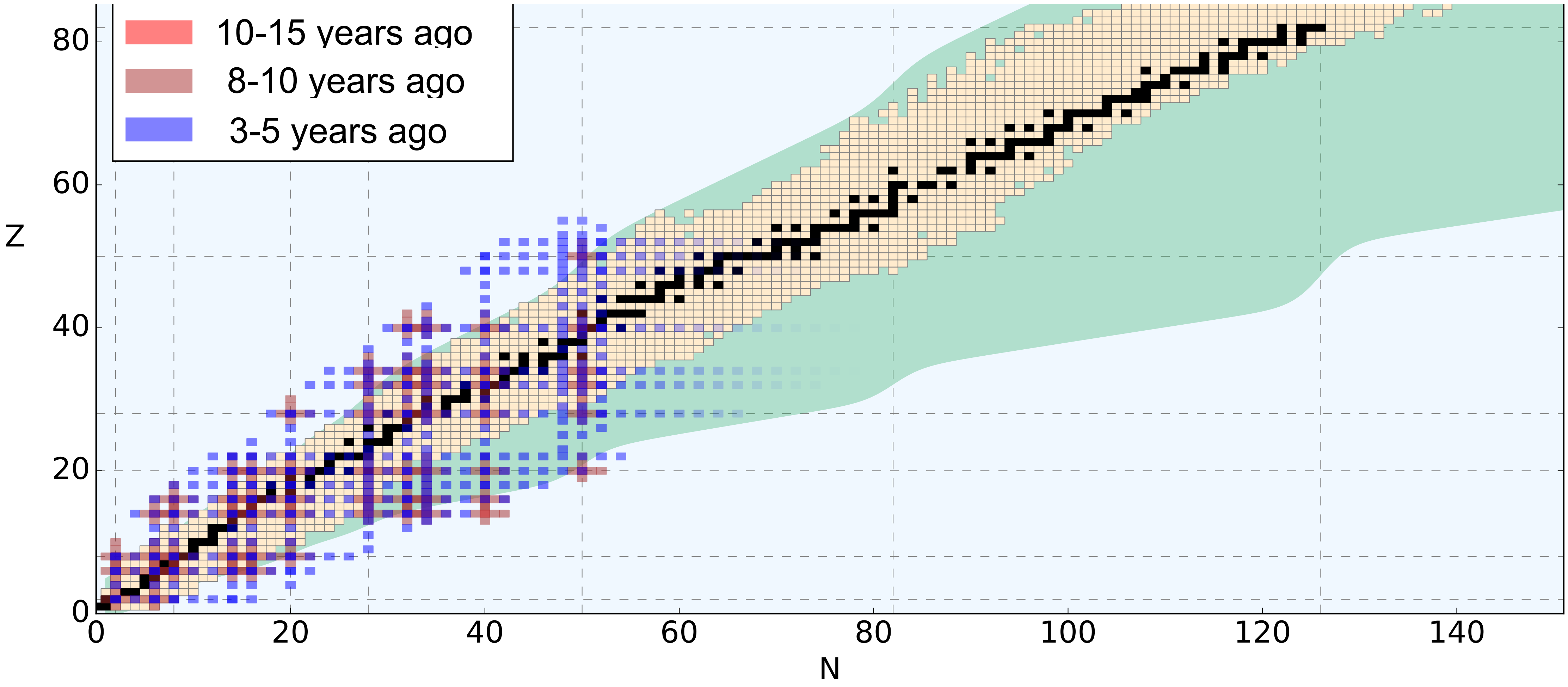
Breadth of Ab Initio Theory

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

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

$$H\psi_n = E_n\psi_n$$



Towards Global Ab Initio Calculations

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

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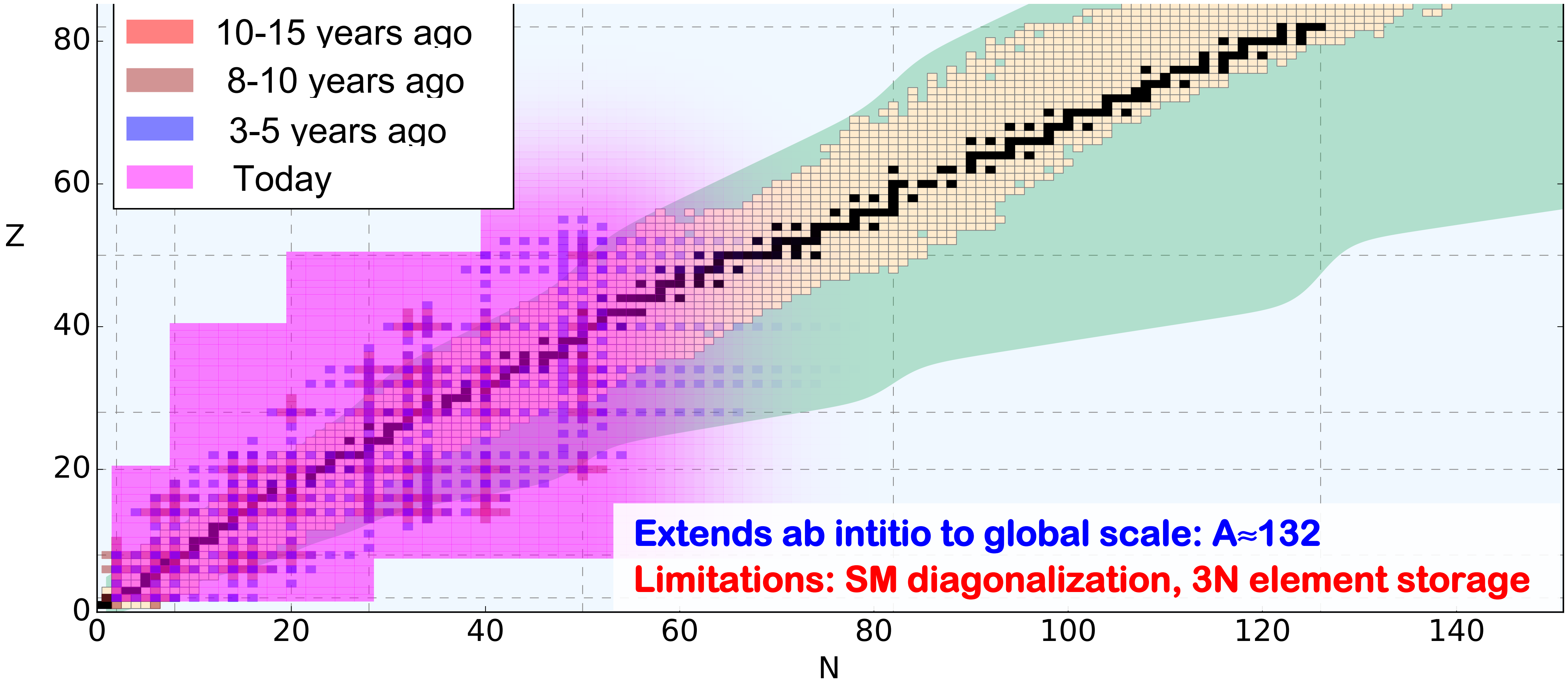

Extends ab intitio to global scale: A≈132

Limitations: SM diagonalization, 3N element storage

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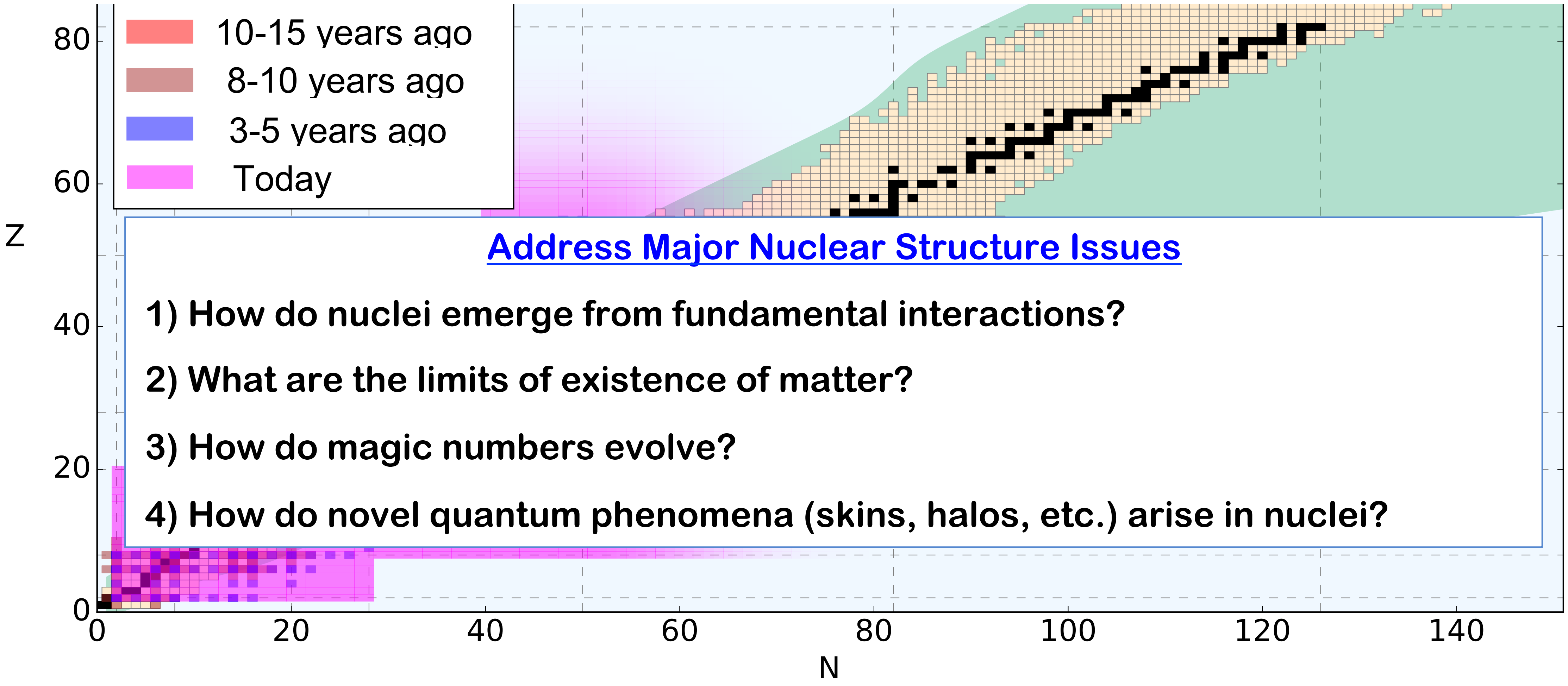

Address Major Nuclear Structure Issues

1) How do nuclei emerge from fundamental interactions?

2) What are the limits of existence of matter?

3) How do magic numbers evolve?

4) How do novel quantum phenomena (skins, halos, etc.) arise in nuclei?

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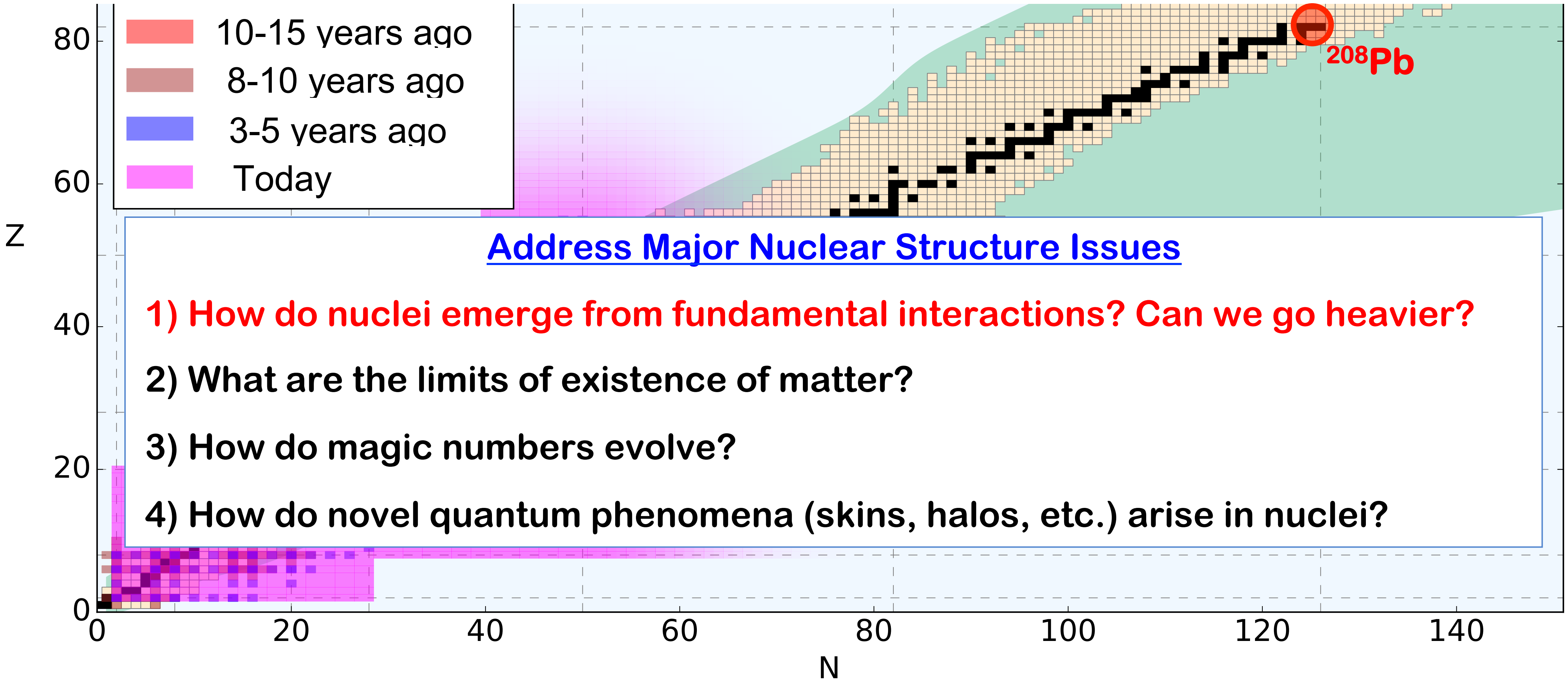

Address Major Nuclear Structure Issues

1) How do nuclei emerge from fundamental interactions? Can we go heavier?

2) What are the limits of existence of matter?

3) How do magic numbers evolve?

4) How do novel quantum phenomena (skins, halos, etc.) arise in nuclei?

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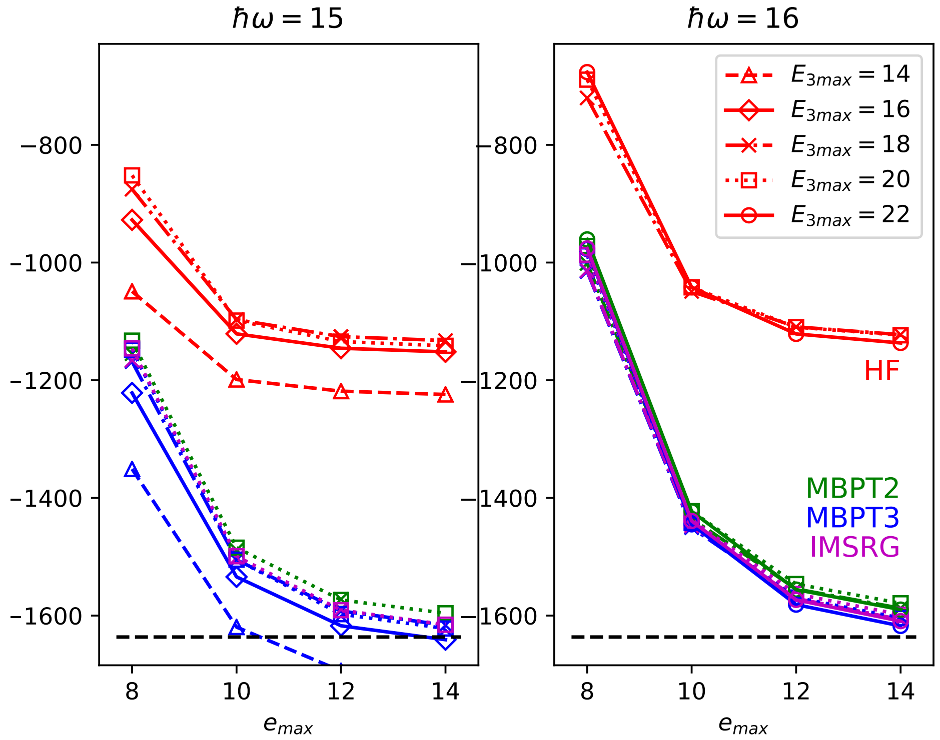
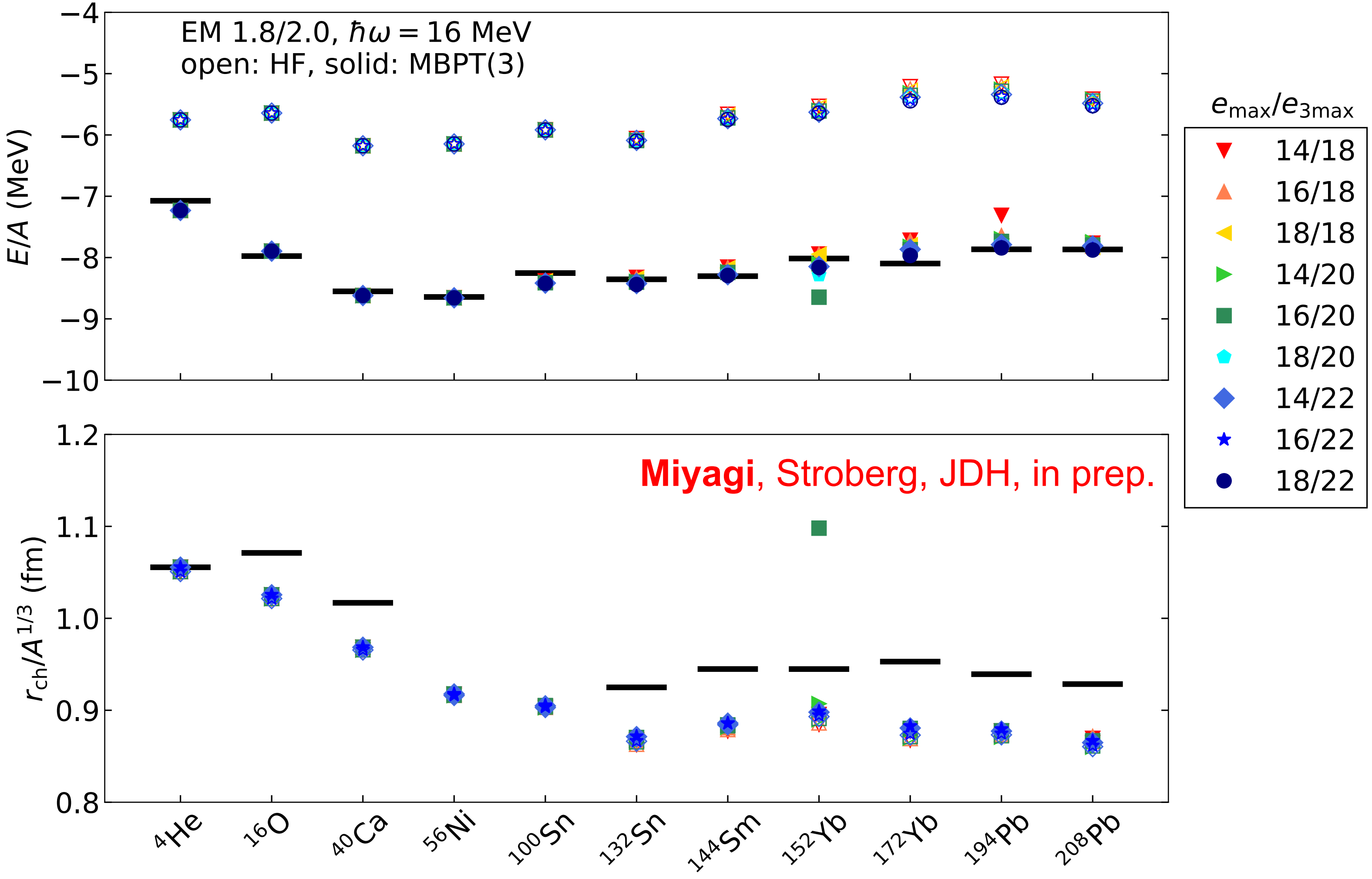
Will We Ever Compute ^{208}Pb?

Improvements in storage of 3N matrix elements greatly expands reach of ab initio theory!





Preliminary results

Promising for converged calculations in region of heavy Pb isotopes!

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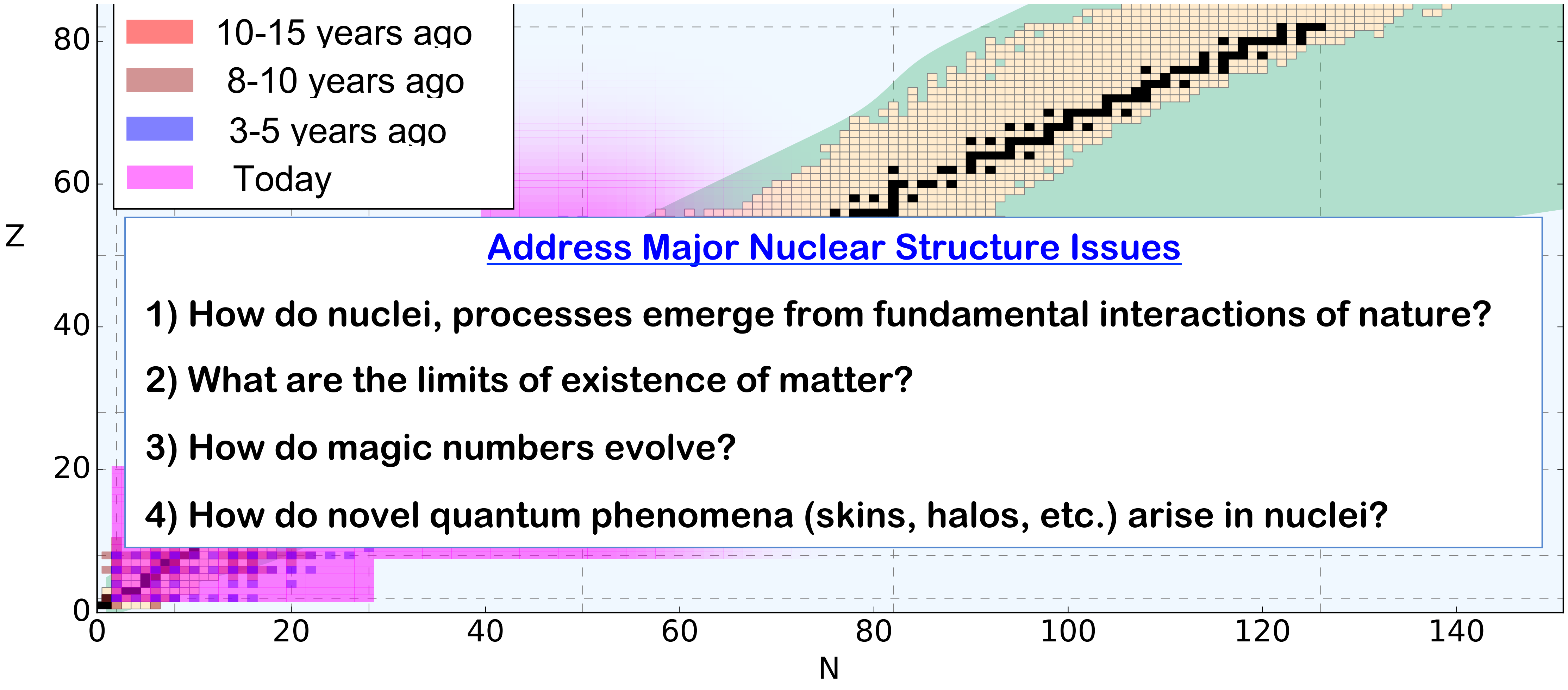

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1) How do nuclei, processes emerge from fundamental interactions of nature?

2) What are the limits of existence of matter?

3) How do magic numbers evolve?

4) How do novel quantum phenomena (skins, halos, etc.) arise in nuclei?

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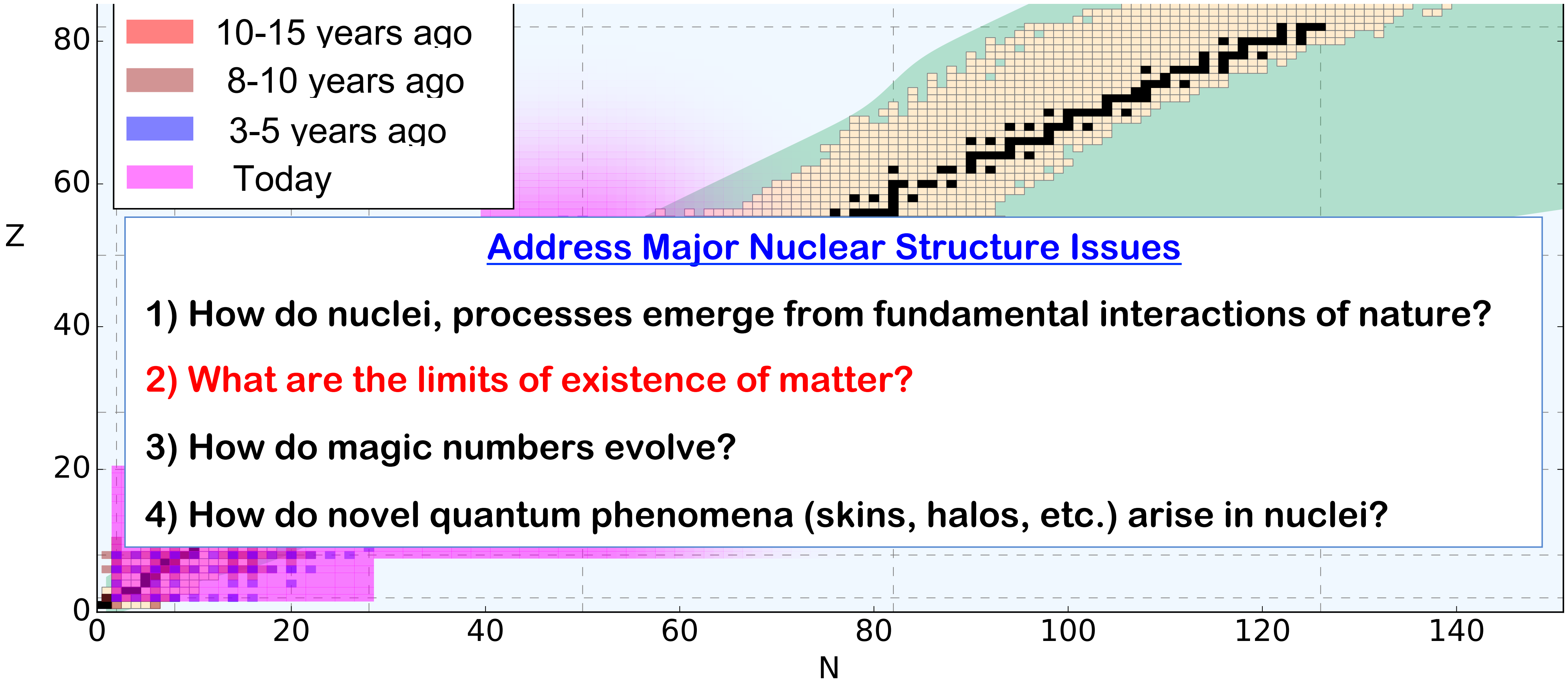


Address Major Nuclear Structure Issues

1) How do nuclei, processes emerge from fundamental interactions of nature?

2) What are the limits of existence of matter?

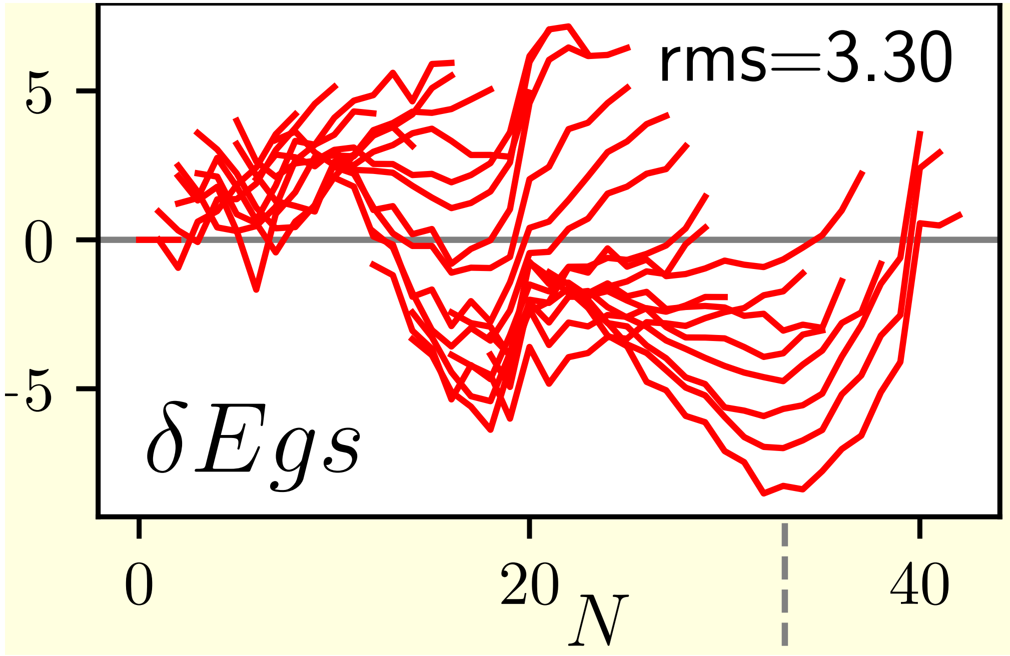
3) How do magic numbers evolve?

4) How do novel quantum phenomena (skins, halos, etc.) arise in nuclei?

TRIUMF

Global Ground-State Energy Residuals

Ab initio calculations of nearly 700 nuclei… how to analyze uncertainties?



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

B-W Mass formula: 3.1MeV Z<28

3.5MeV Z<20

DFT: 0.6-2.0 MeV

JDH, Stroberg, Schwenk, Simonis, arXiv:1905.10475

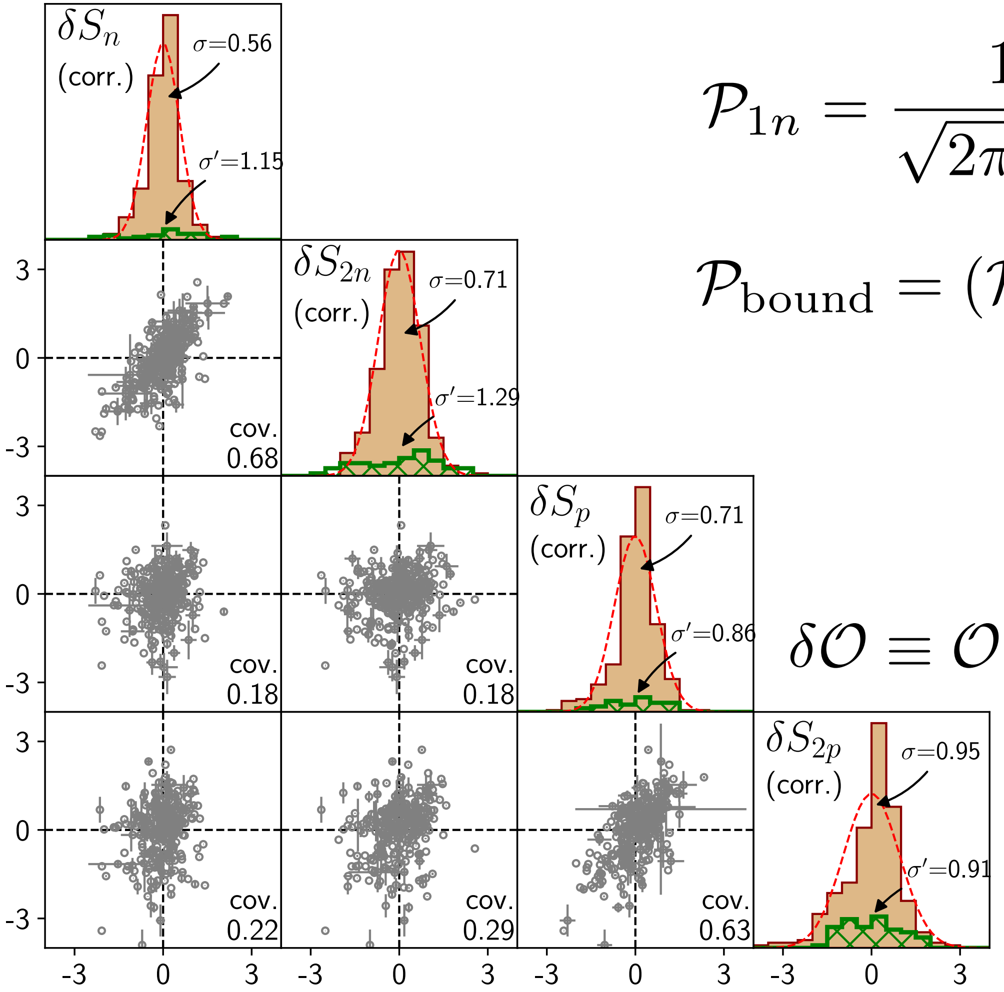
rms deviation at level of BW Mass formula, approaching EDF models

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

What is deviation for separation energies? **Apply to nuclear driplines**

TRIUMF Deviations from Experimental Separation Energies

All corrected distributions approximately Gaussian centered at 0



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

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

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

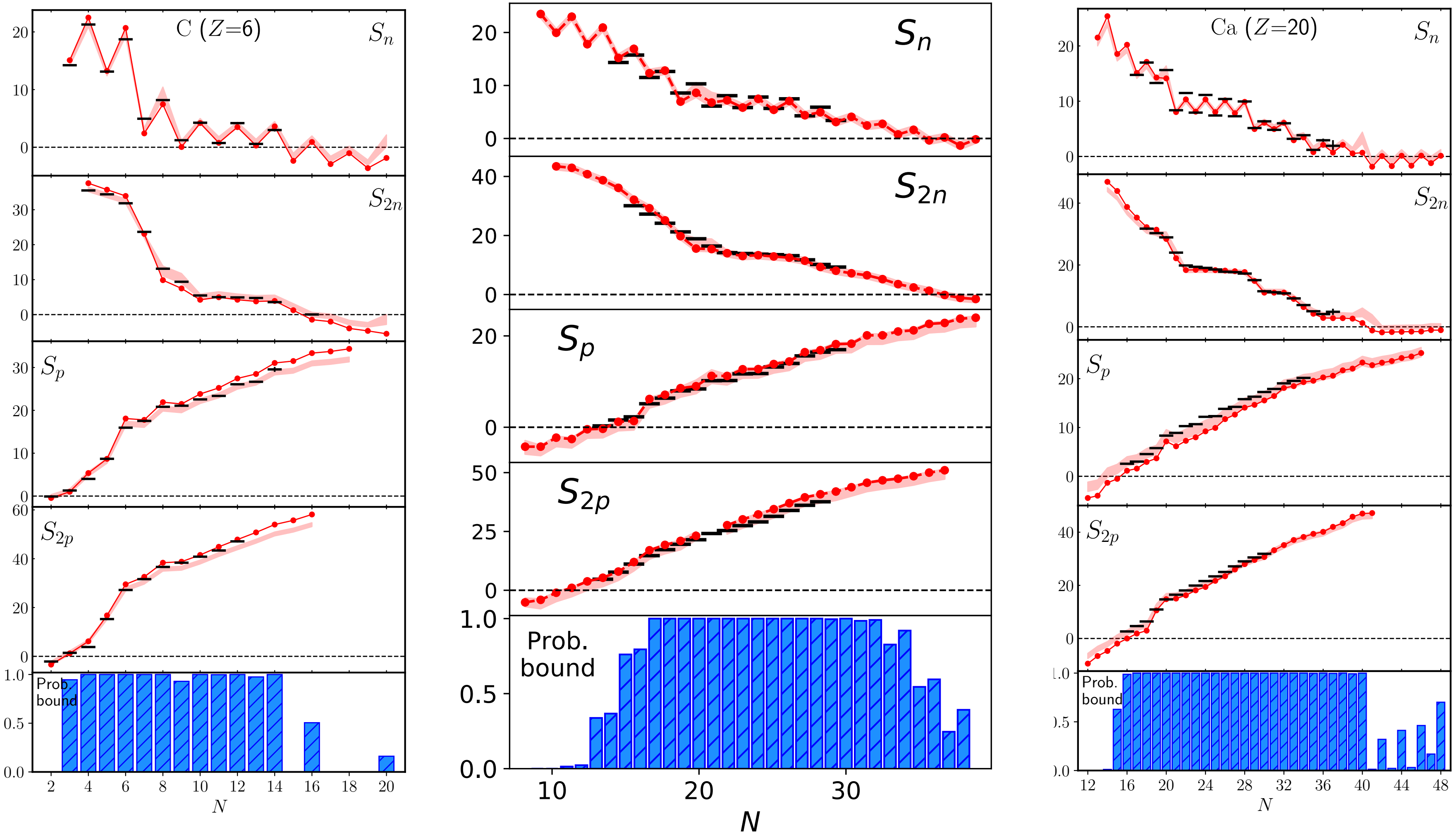
JDH, Stroberg, Schwenk, Simonis, arXiv:1905.10475

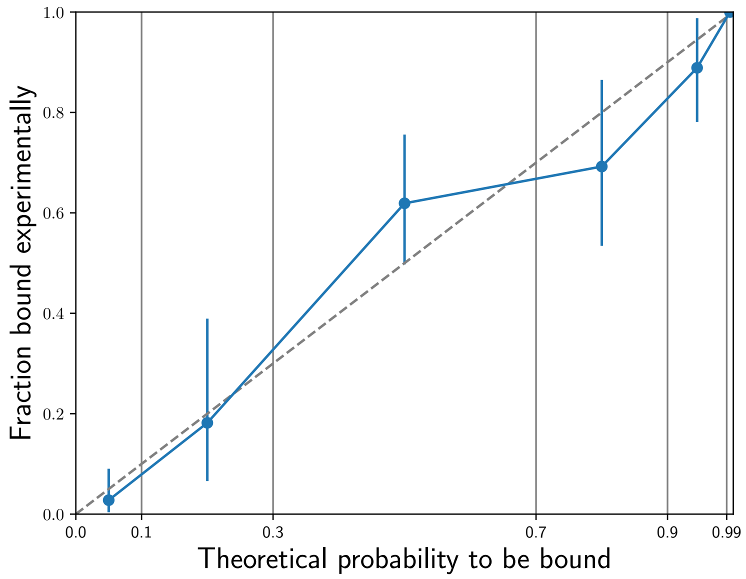
Certain residuals correlated – must correct for this in probabilities

Assume unmeasured nuclei also follow this distribution

Estimating Dripline Uncertainites

Determine rms deviation from experiment – extrapolate this uncertainty beyond data





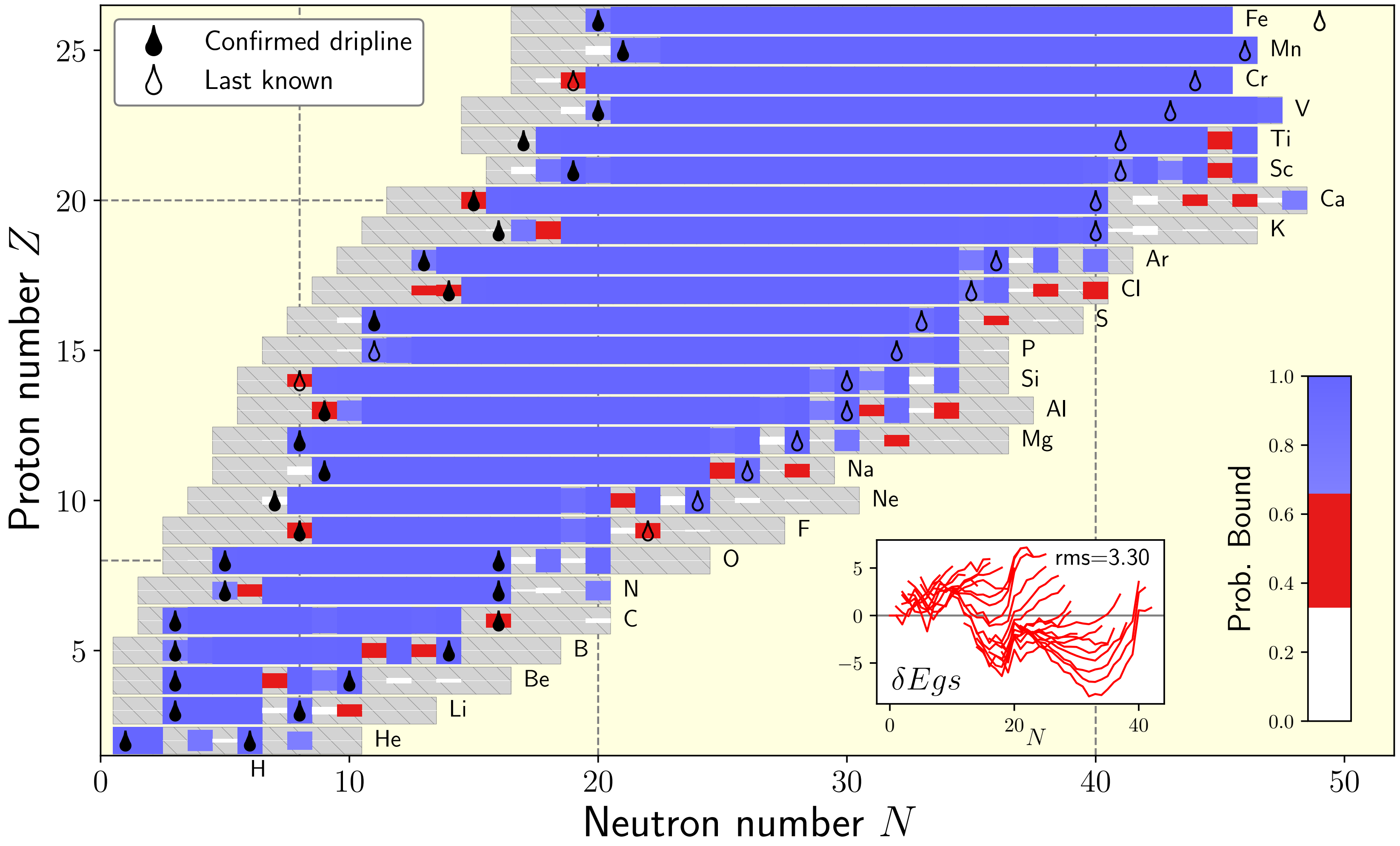
Determine range of likely separation energies reaching 0

Assign probability that a particular nucleus is bound

JDH, Stroberg, Schwenk, Simonis, arXiv:1905.10475

Dripline Prediction to Iron Isotopes

First predictions of proton and neutron driplines from first principles



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JDH, Stroberg, Schwenk, Simonis, arXiv:1905.10475

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

Provide ab initio predictions for neutron-rich region

Breadth of Ab Initio: Towards Global Calculations

TRIUMF

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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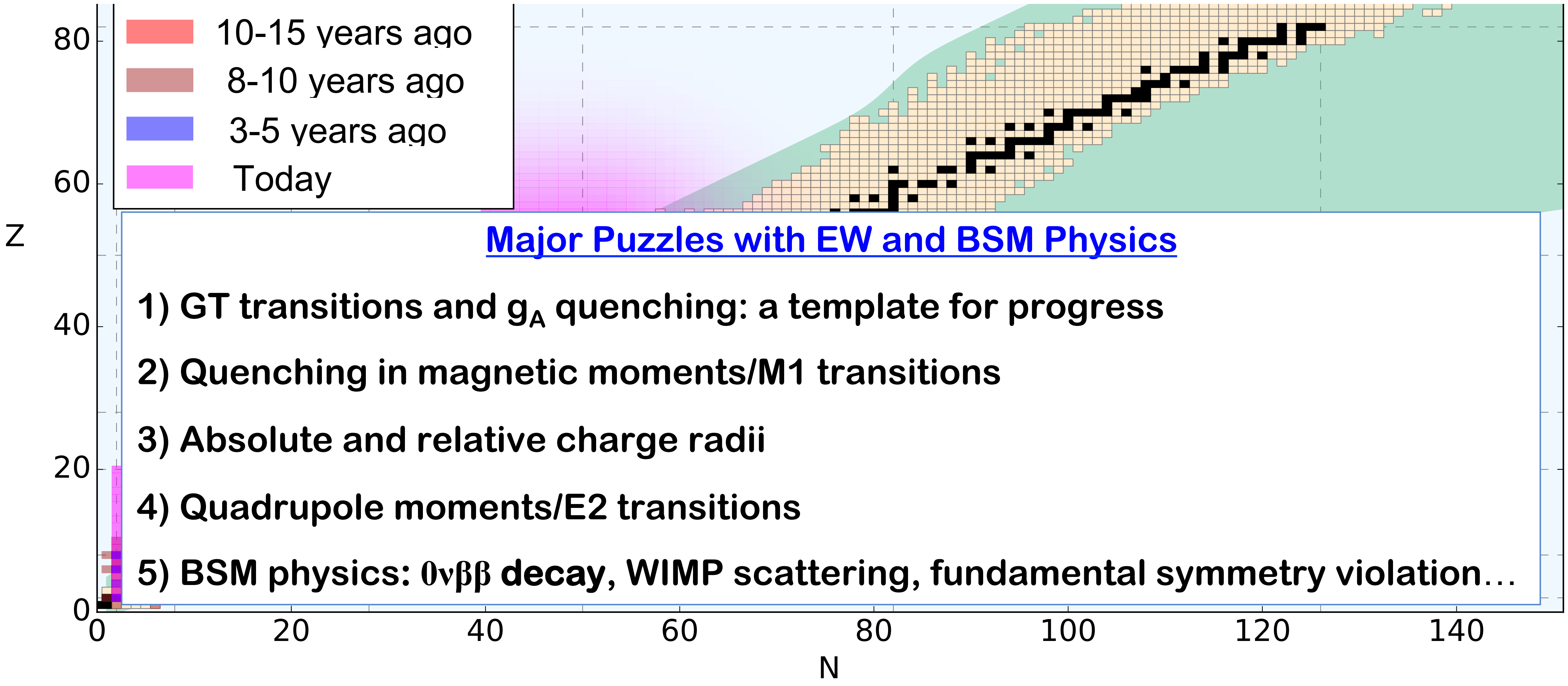

Major Puzzles with EW and BSM Physics

1) GT transitions and g_A quenching: a template for progress

2) Quenching in magnetic moments/M1 transitions

3) Absolute and relative charge radii

4) Quadrupole moments/E2 transitions

5) BSM physics: $0\nu\beta\beta$ decay, WIMP scattering, fundamental symmetry violation…

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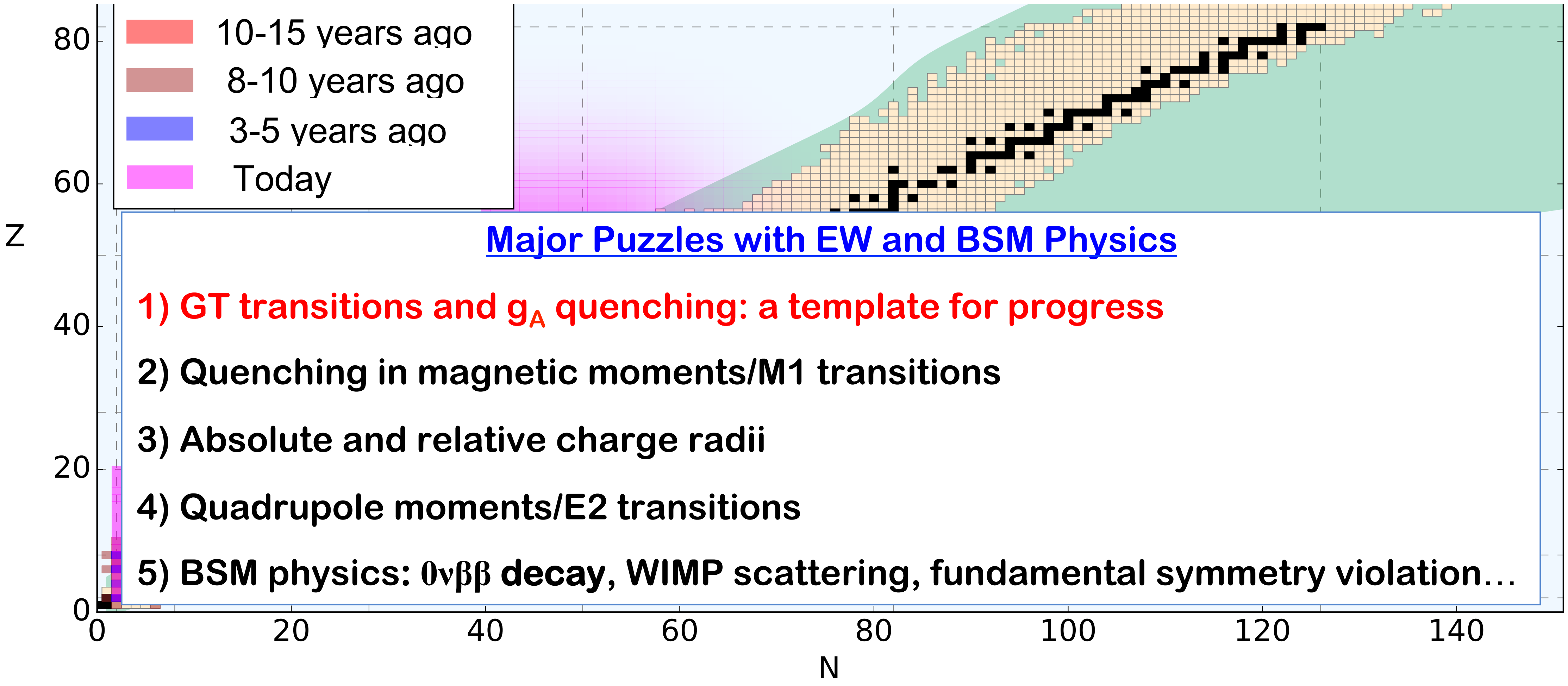

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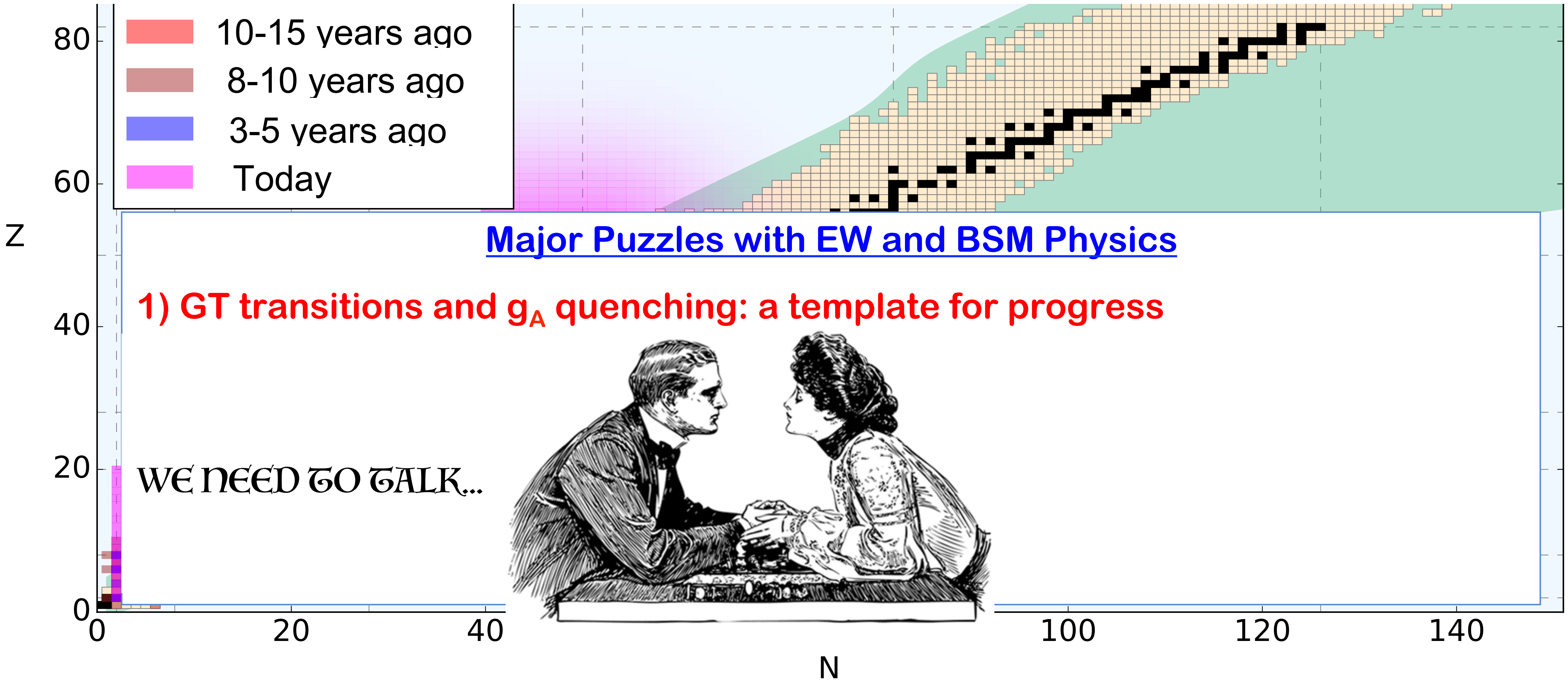

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WE NEED TO TALK...

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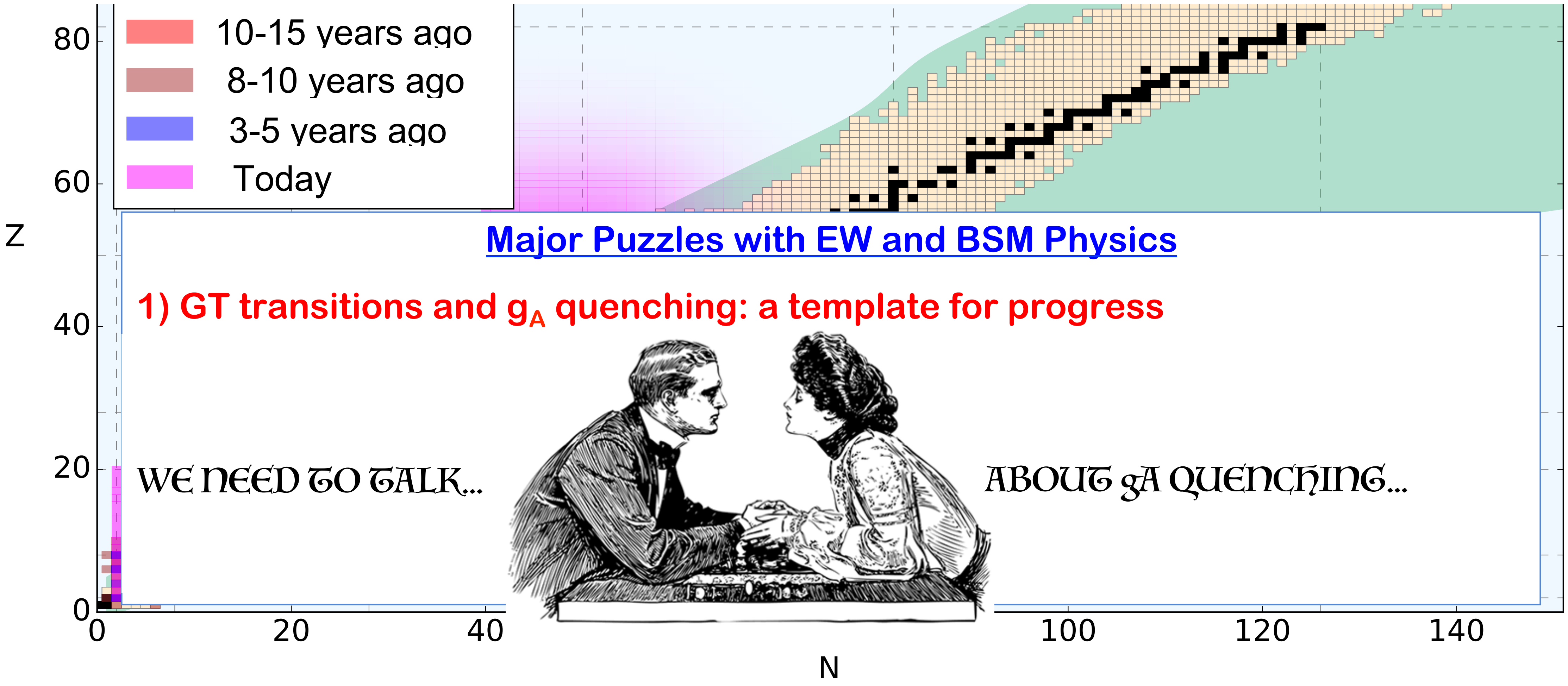

Major Puzzles with EW and BSM Physics

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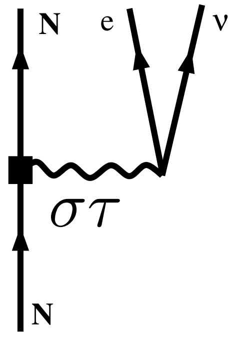
WE NEED TO TALK...

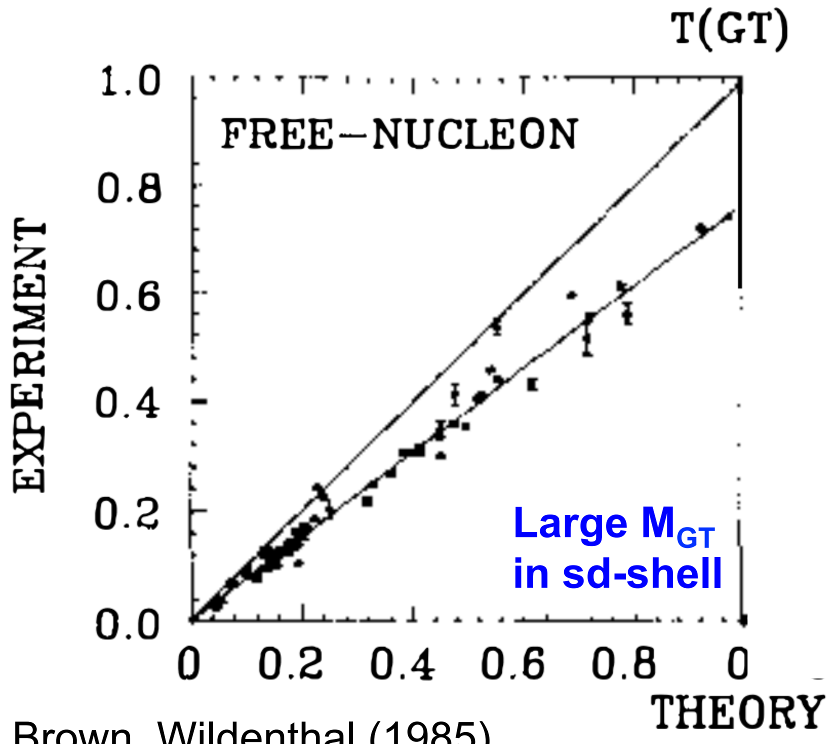
ABOUT gA QUENCHING...

Beta-Decay "Puzzle": Quenching of g_A

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

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





Brown, Wildenthal (1985)

[1] papers from the 1970's

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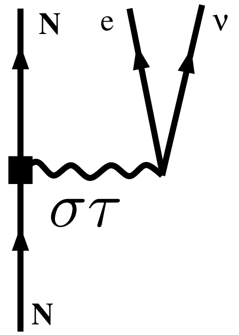
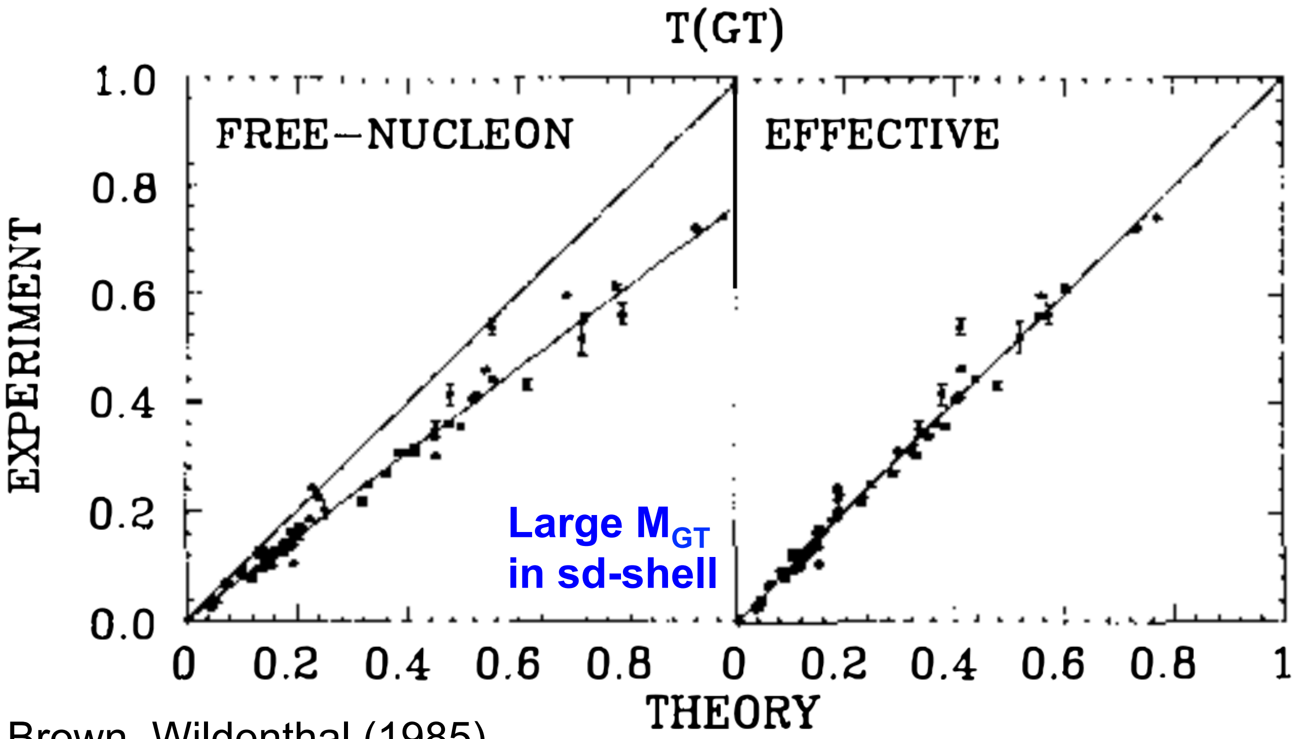


Using $g_A^{\mathrm{eff}} \approx 0.77 \times g_A^{\mathrm{free}}$ agrees with data



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- Should g_A be quenched in medium?

TRIUMF

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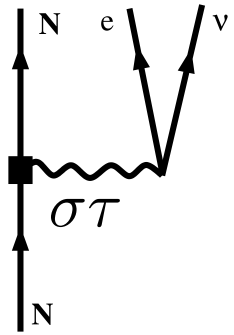
OTHER STUFF



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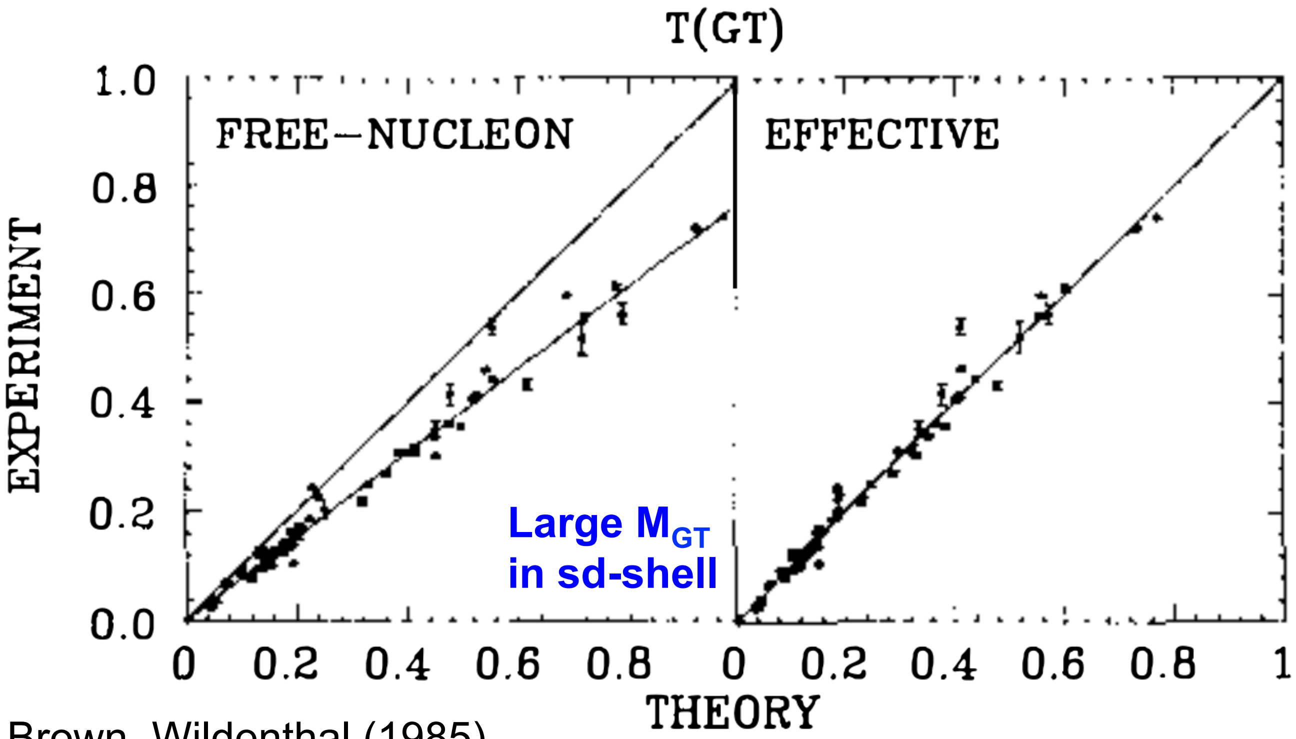

Brown, Wildenthal (1985)

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What about all the other stuff?

TRIUMF

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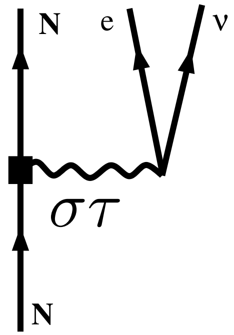

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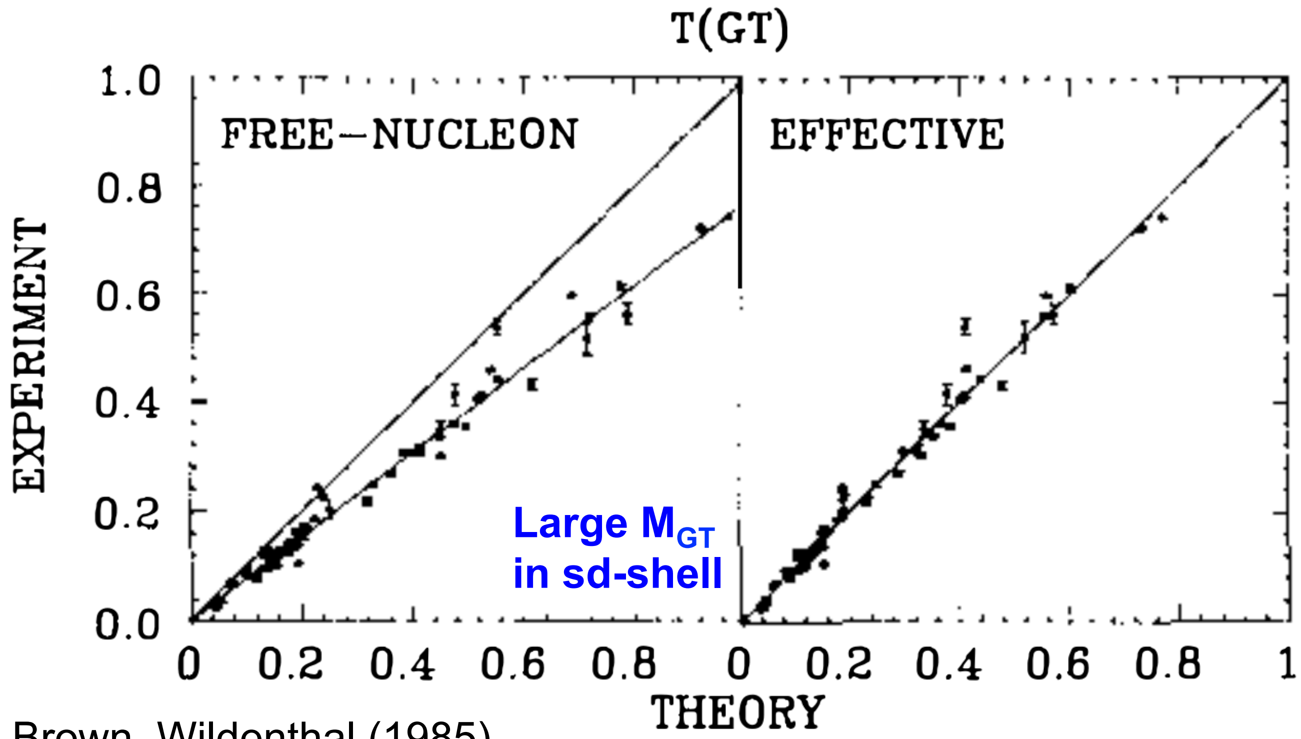

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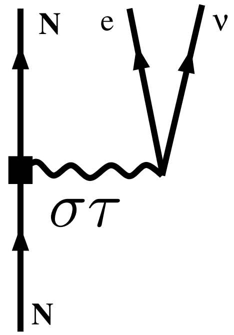

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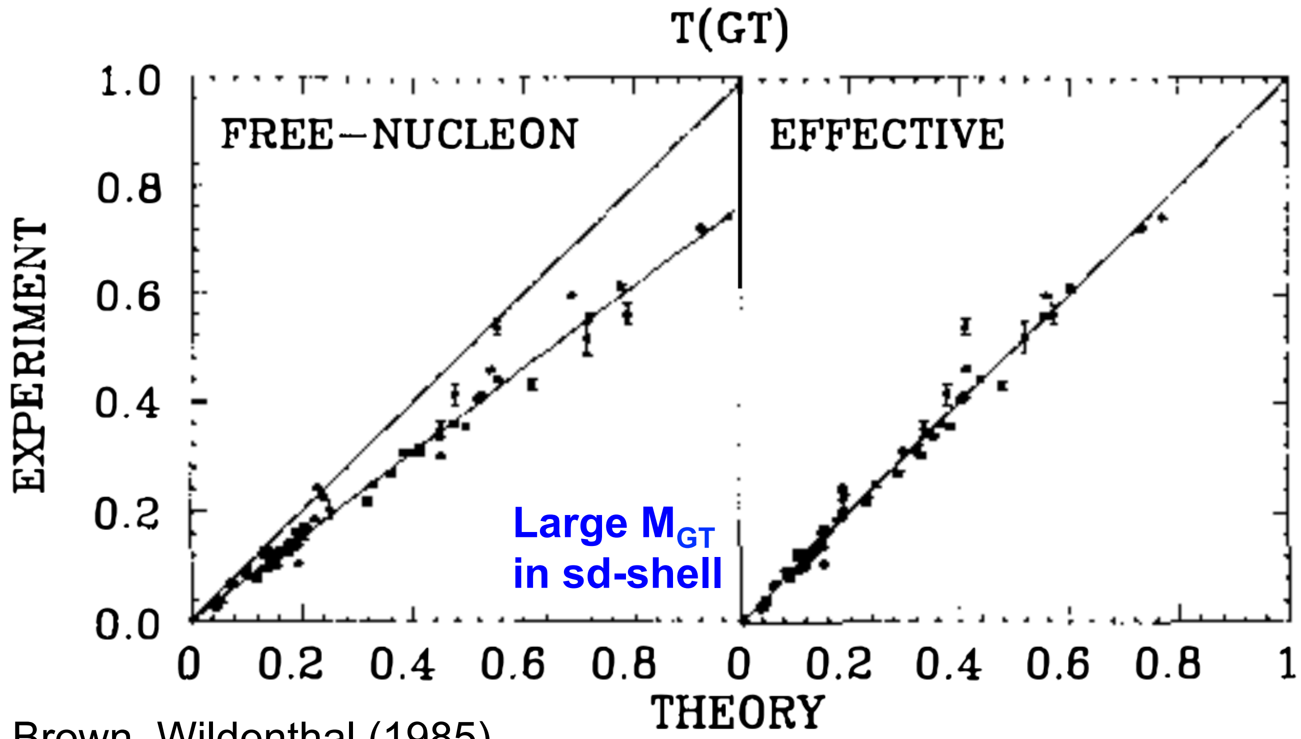

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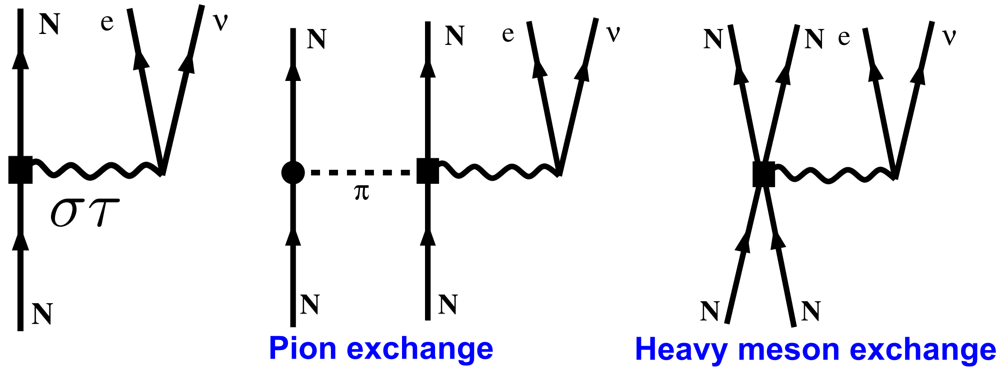

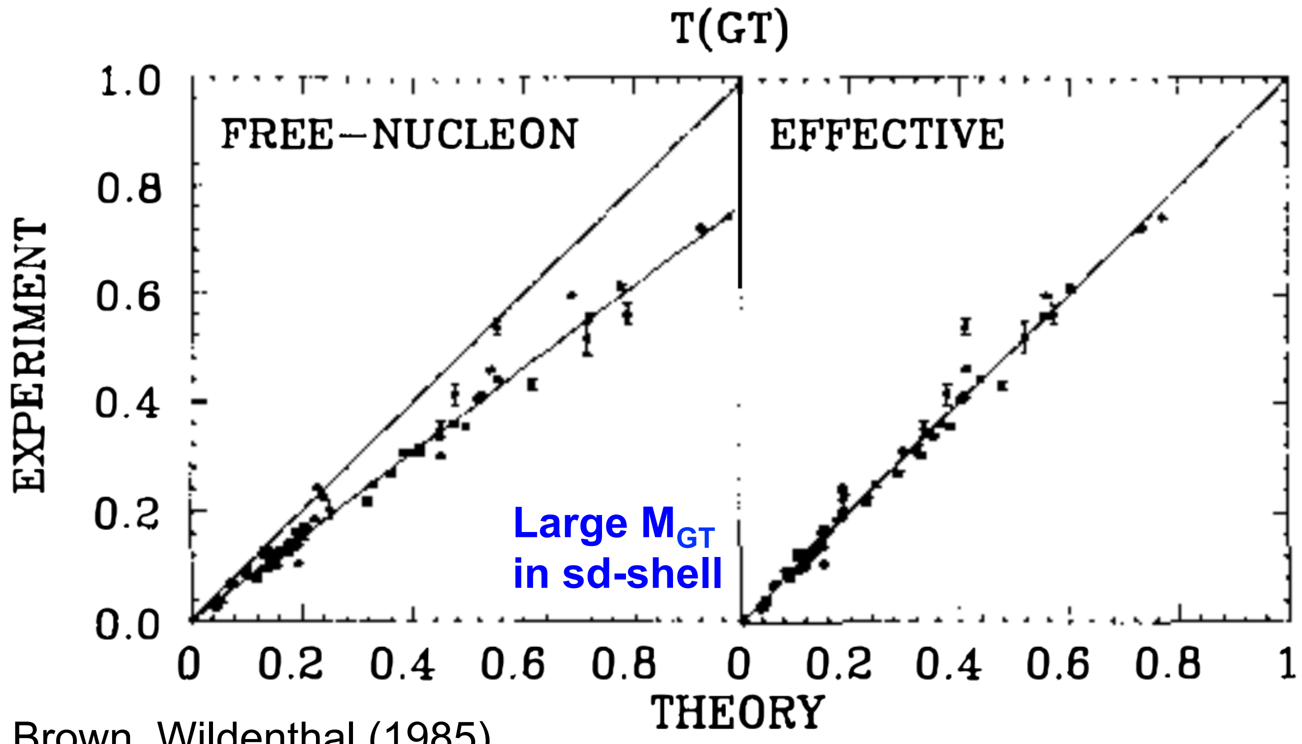

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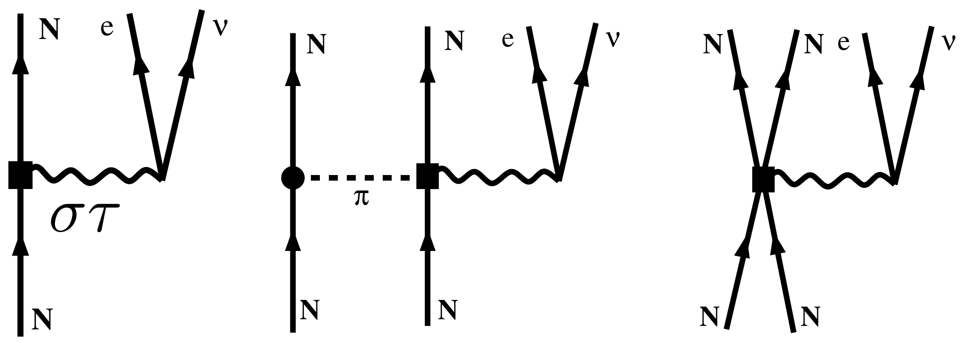

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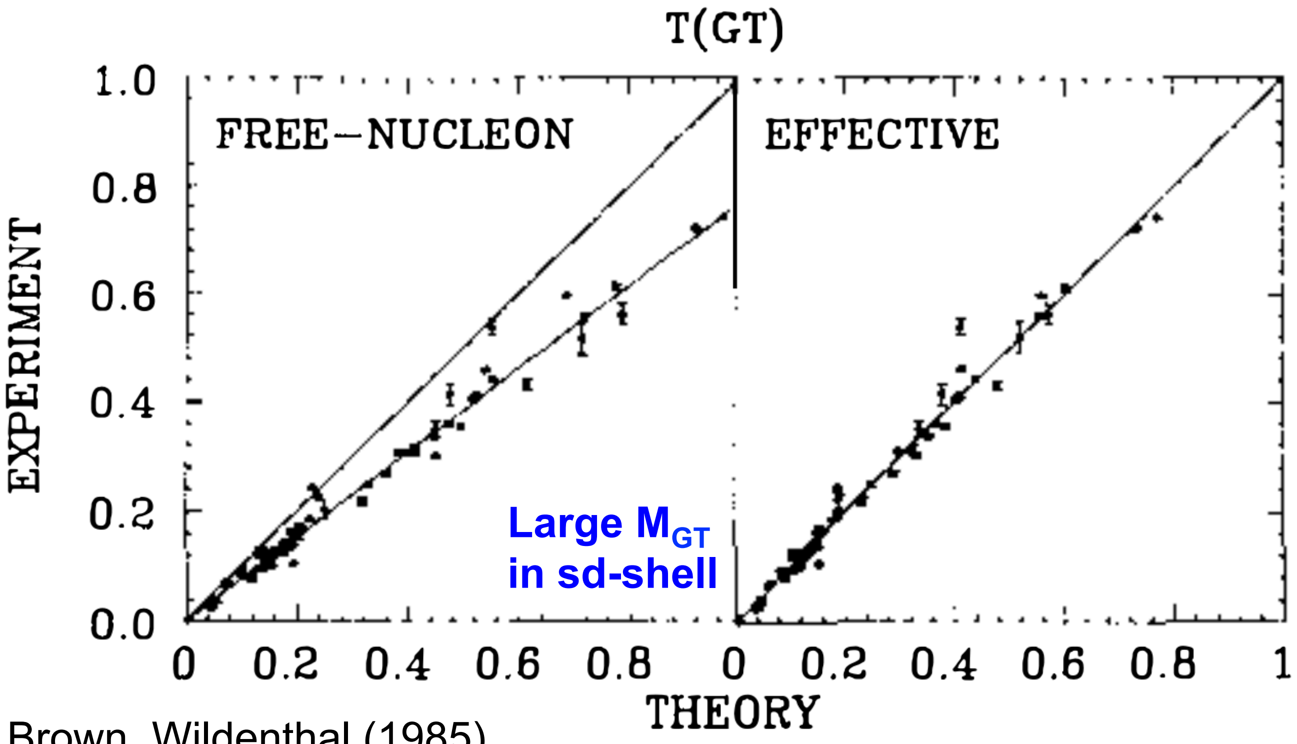

Brown, Wildenthal (1985)

- Should g_A be quenched in medium?
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- Neglected two-body currents?
- Model-space truncations?

Explore in ab initio framework

TRIUMF

Large-Scale Efforts for Ab Initio GT Transitions

Calculate large GT matrix elements

$$M_{\mathrm{GT}} = g_A \langle f | \mathcal{O}_{\mathrm{GT}} | i \rangle$$

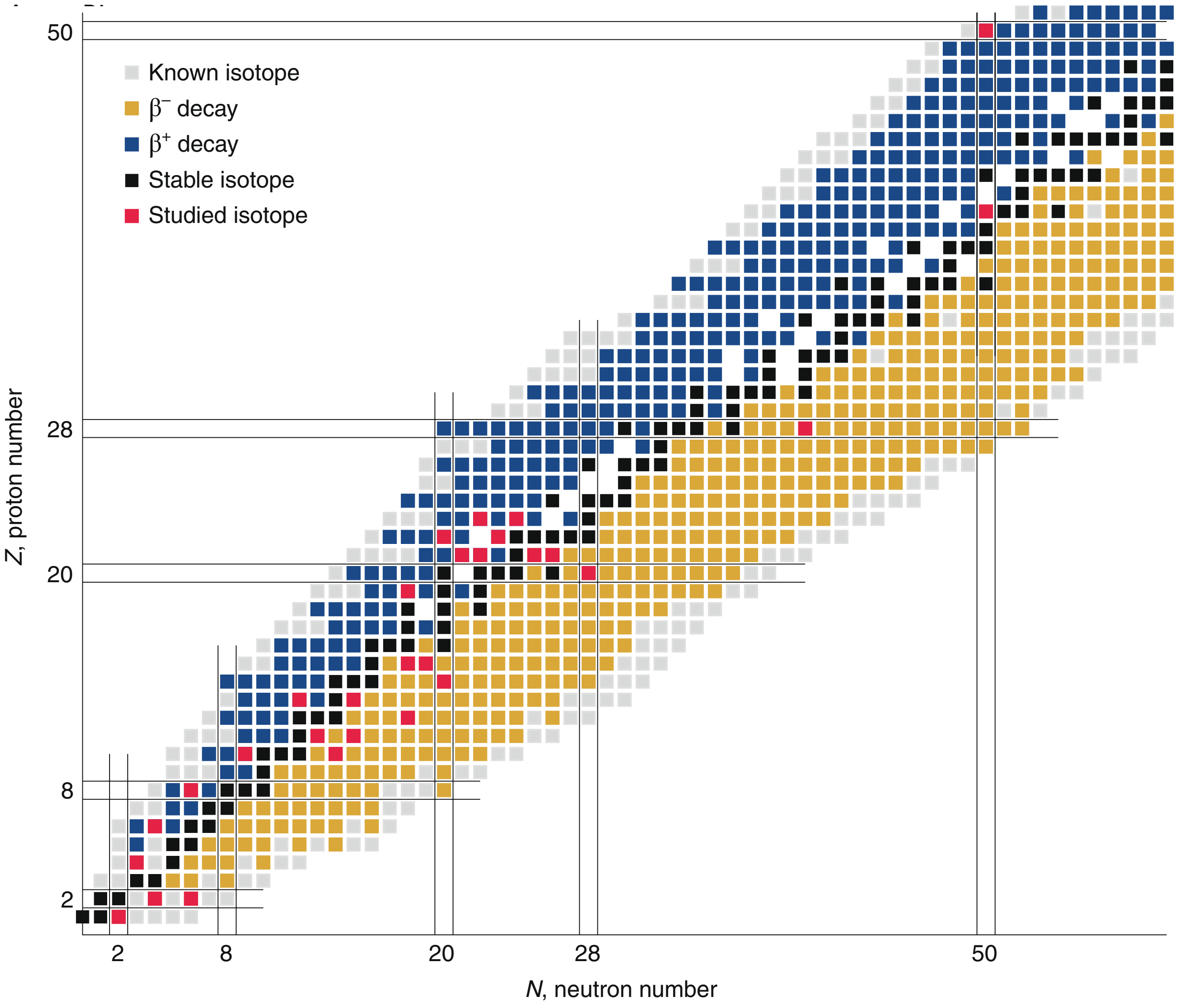
$$\mathcal{O}_{\mathrm{GT}} = \mathcal{O}^{1\mathrm{b}}_{\sigma\tau} + \mathcal{O}^{2\mathrm{b}}_{2BC}$$

- Light, medium, and heavy regions
- Benchmark different ab initio methods
- Wide range of NN+3N forces
- Consistent inclusion of 2BC

NUCLEAR PHYSICS

Beta decay gets the ab initio treatment

One of the fundamental radioactive decay modes of nuclei is β decay. Now, nuclear theorists have used first-principles simulations to explain nuclear β decay properties across a range of light- to medium-mass isotopes, up to ^{100}Sn.



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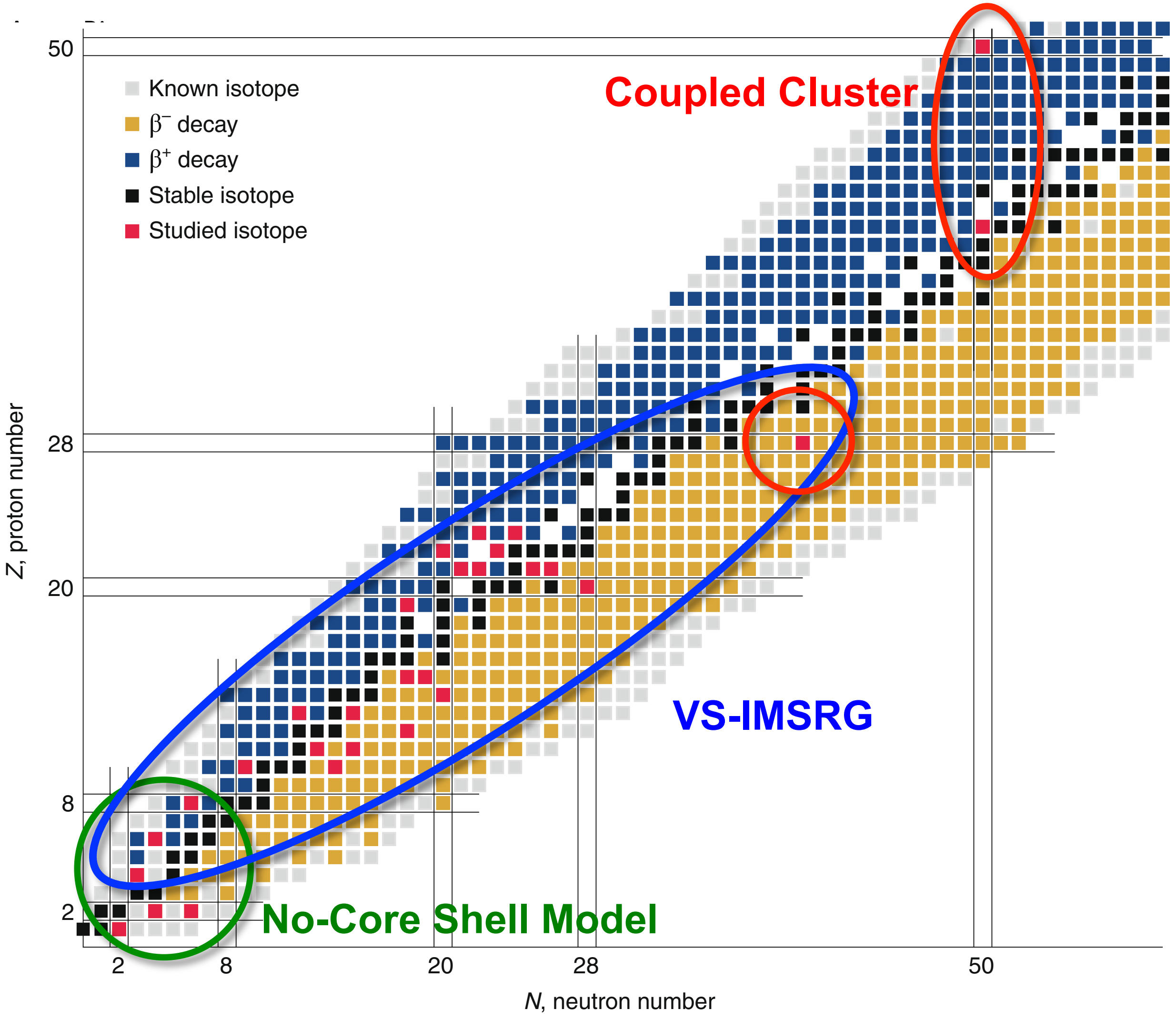
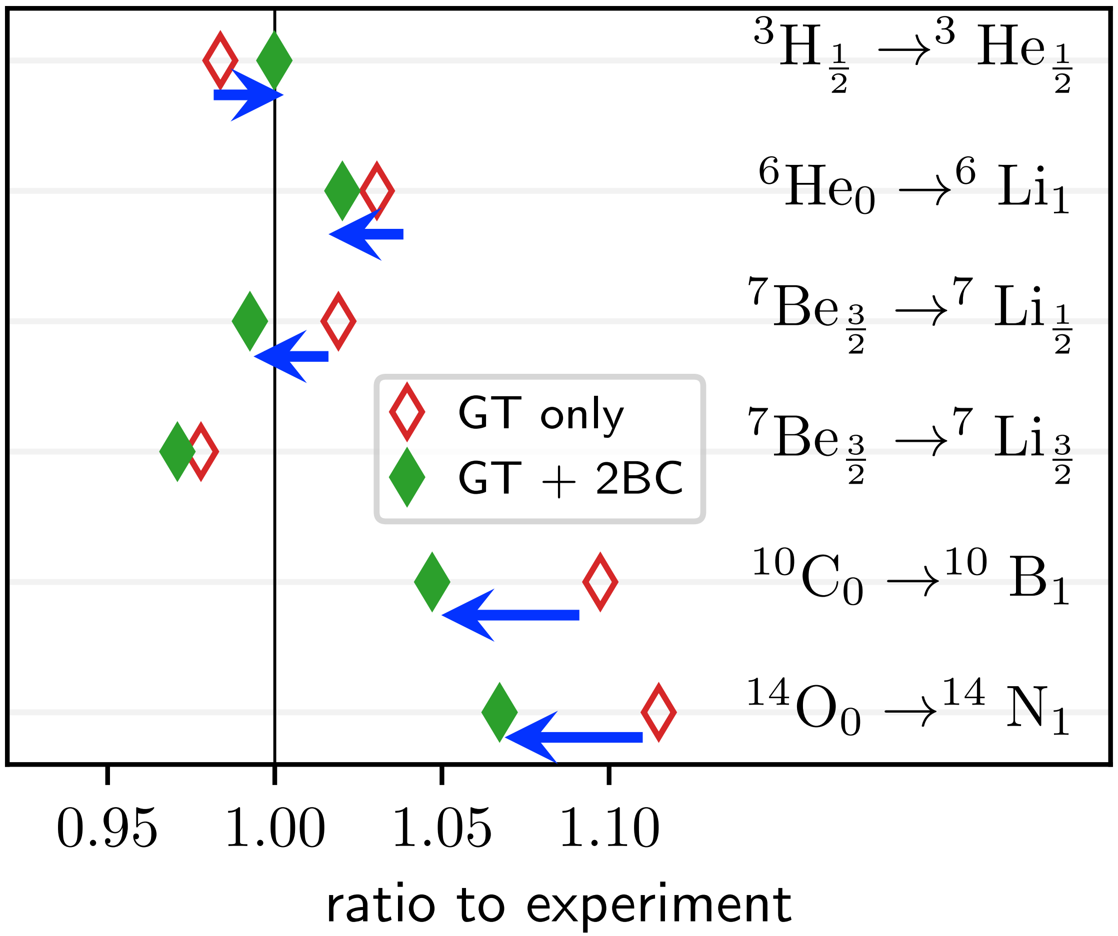
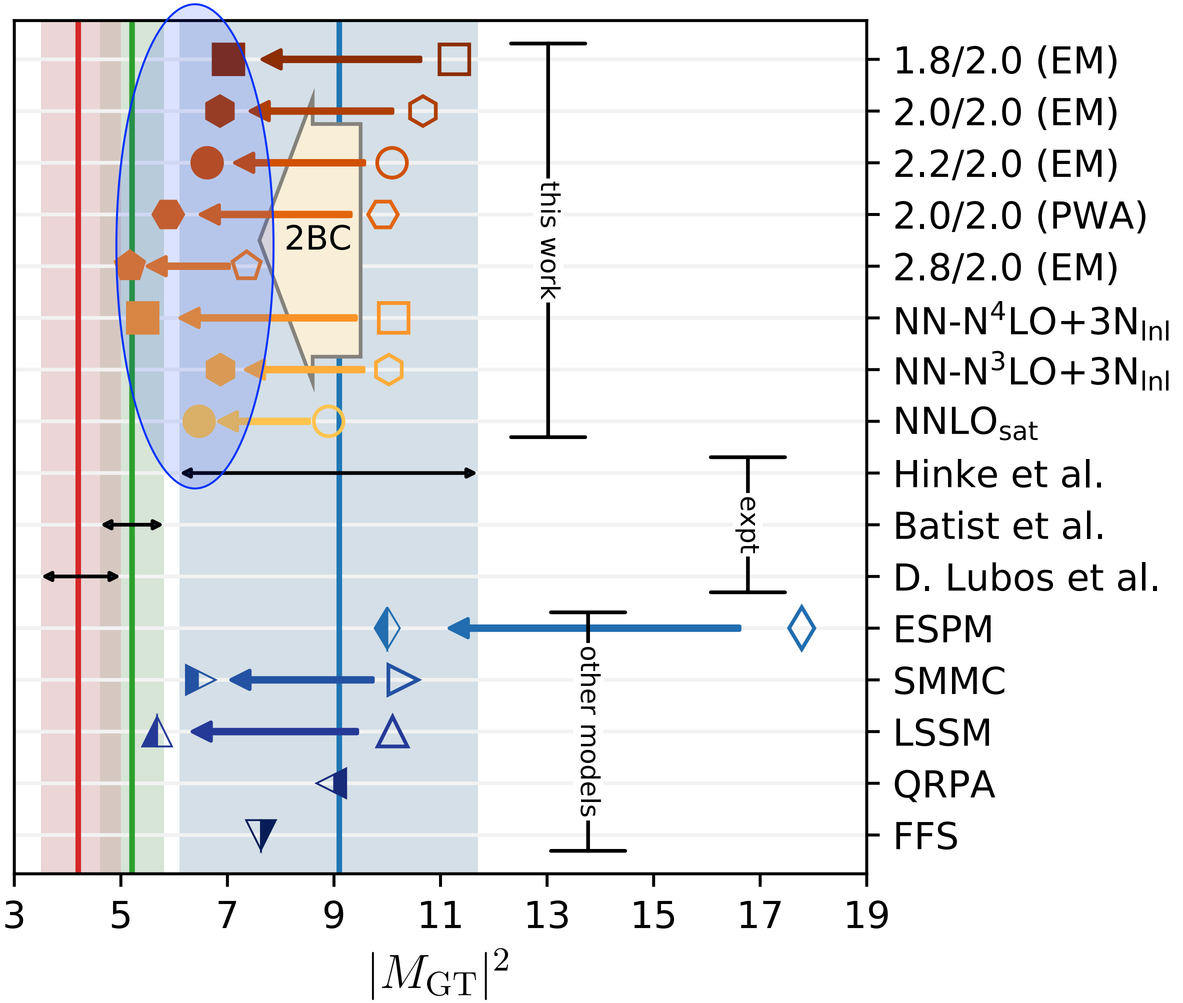


TRIUMF

GT Transitions in Light nuclei and ^{100}Sn

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)

Addition of 2BC further quenches and reduces spread in results

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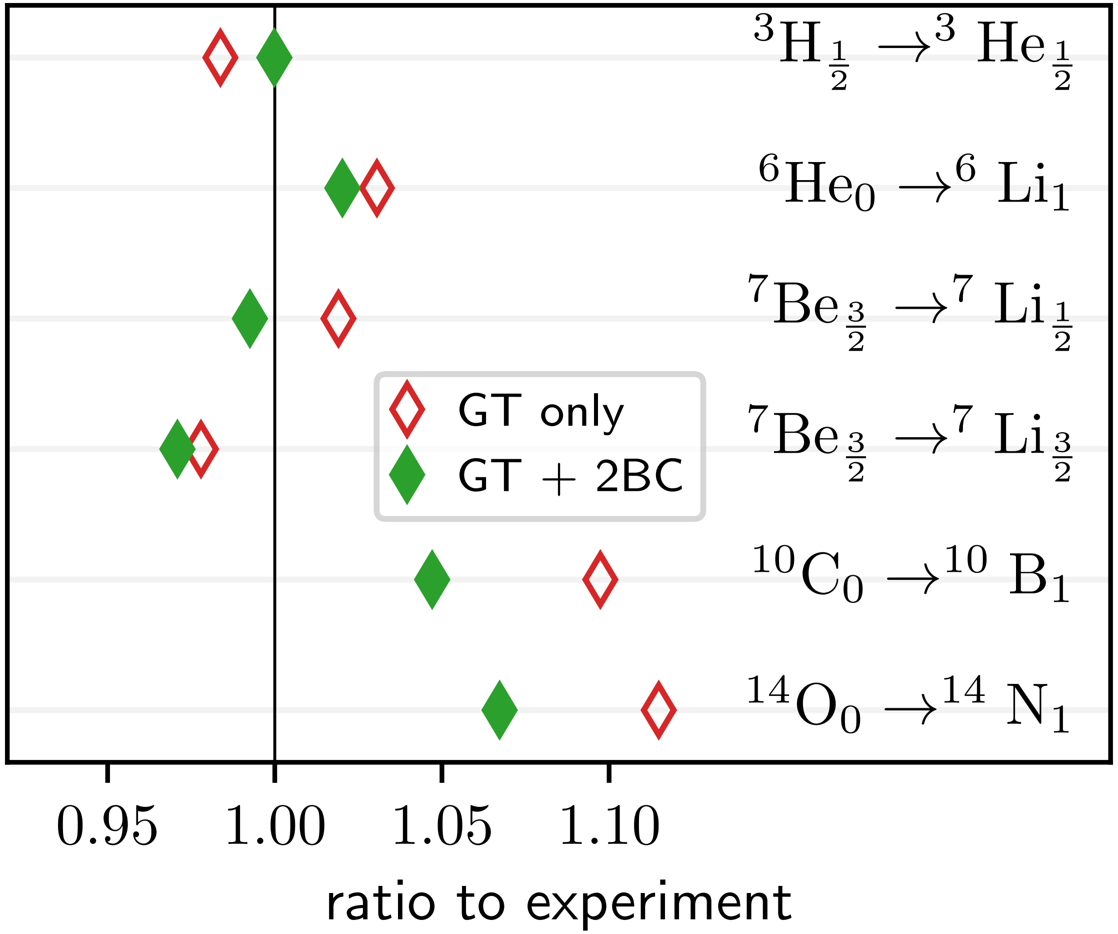

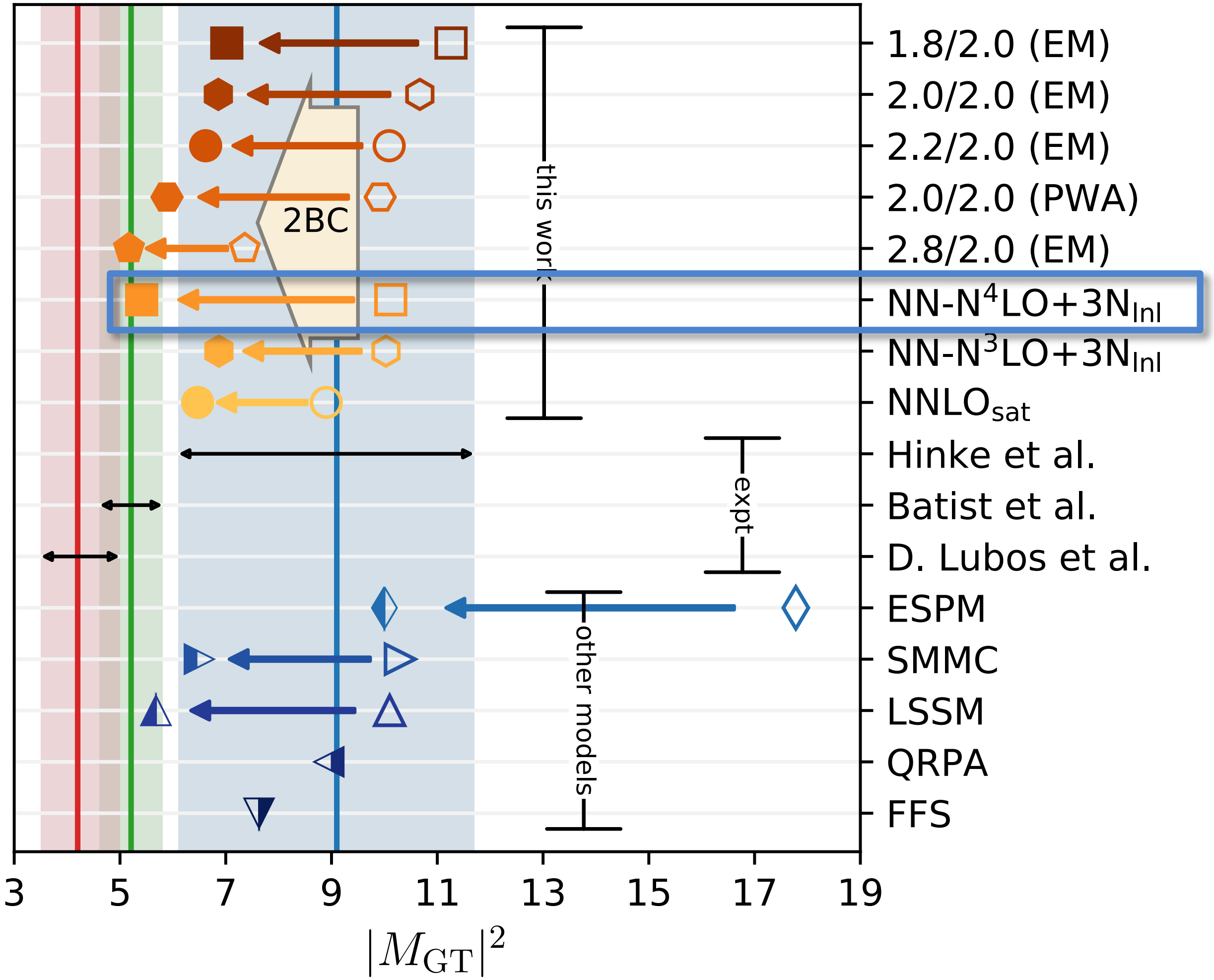

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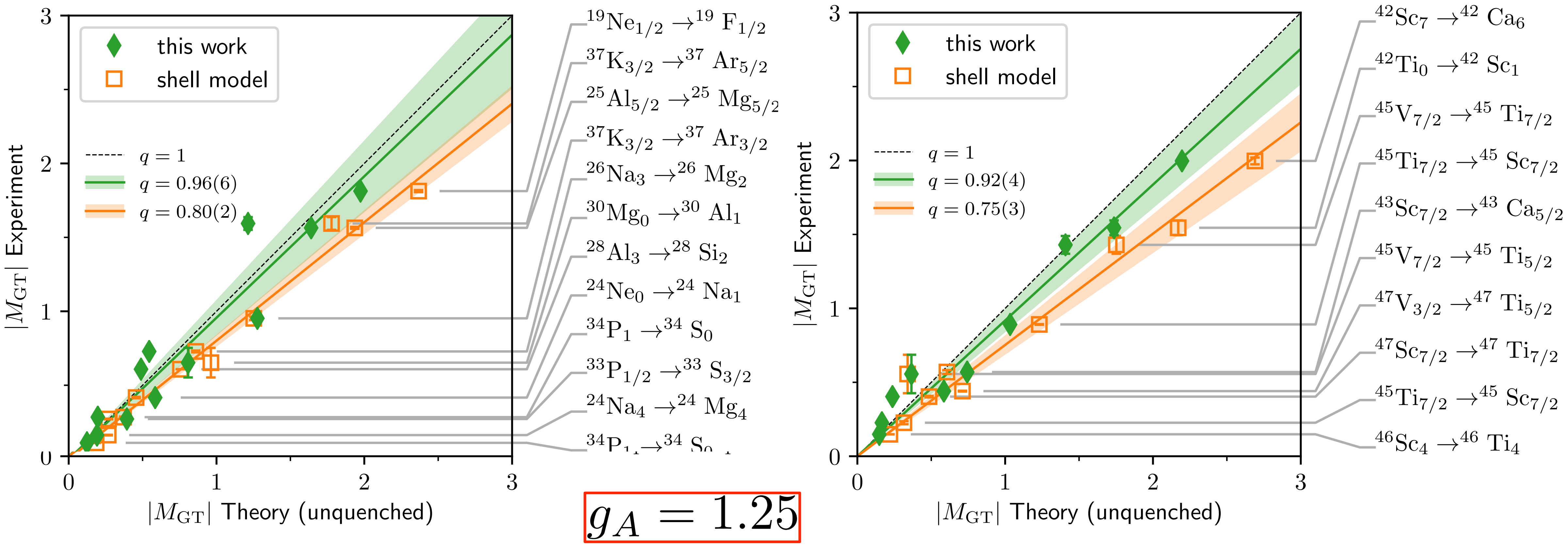
Gysbers et al., Nature Phys. (2019)

Ab Initio GT Decays in Medium-Mass Region

TRIUMF

Comparison to standard phenomenological shell model

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



Gysbers et al., Nature Phys. (2019)

Refine results with improvements in forces and many-body methods

In progress: muon capture

Breadth of Ab Initio: Towards Global Calculations

TRIUMF

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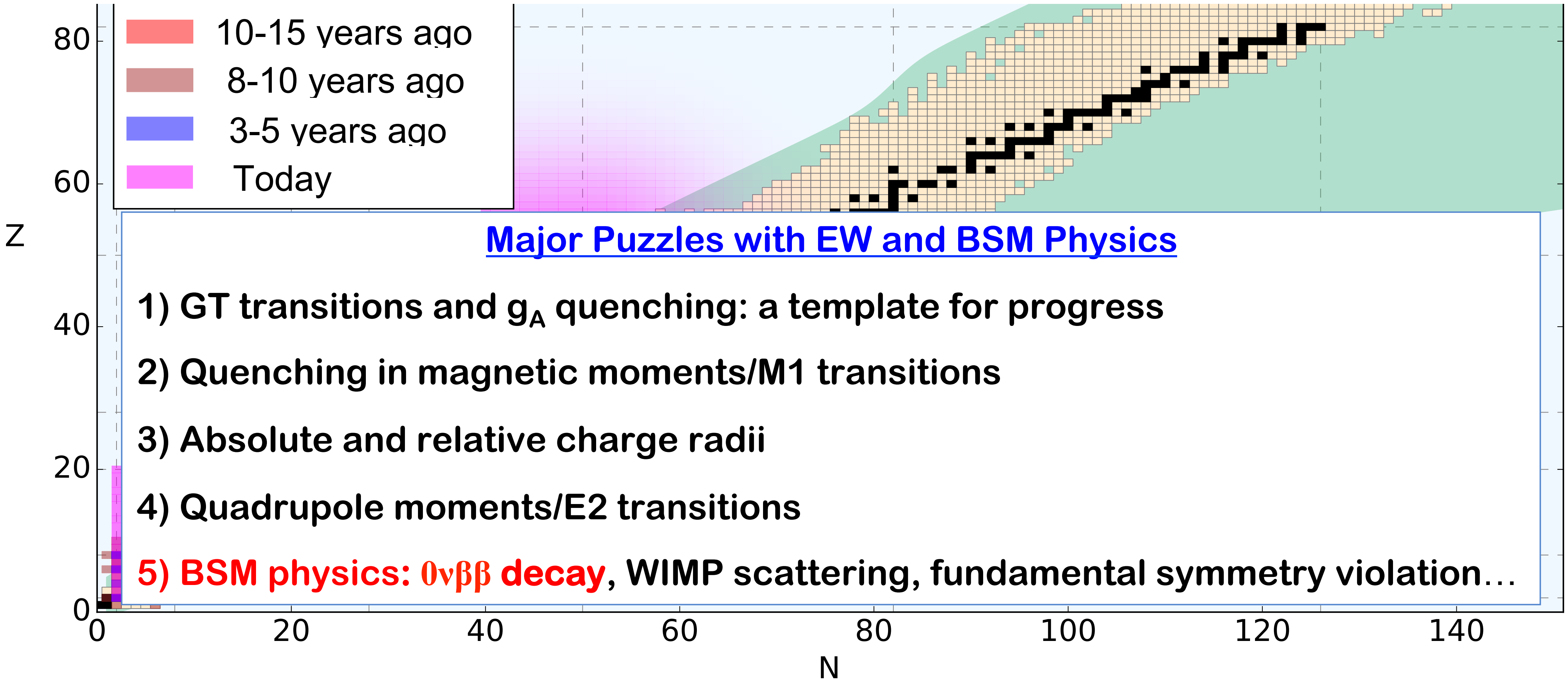

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Towards 0νββ Decay

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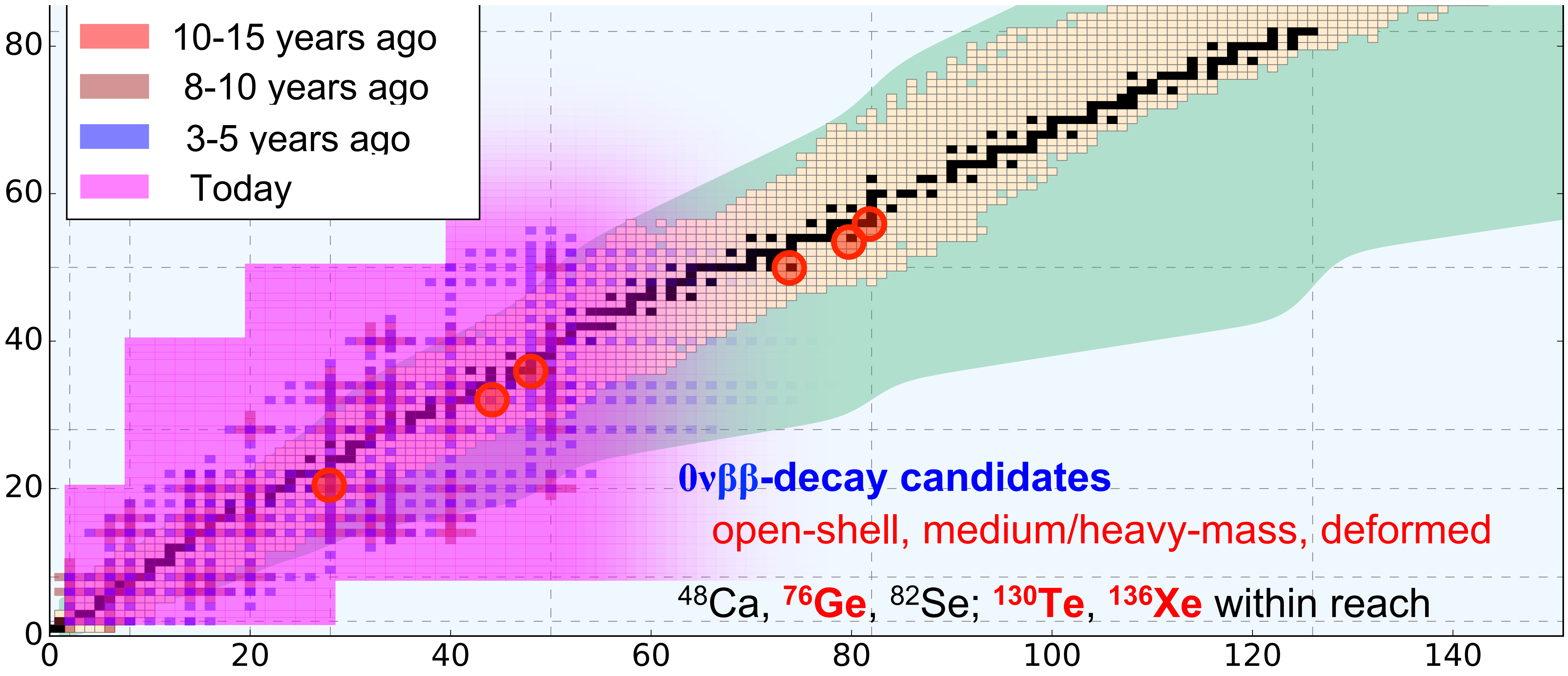
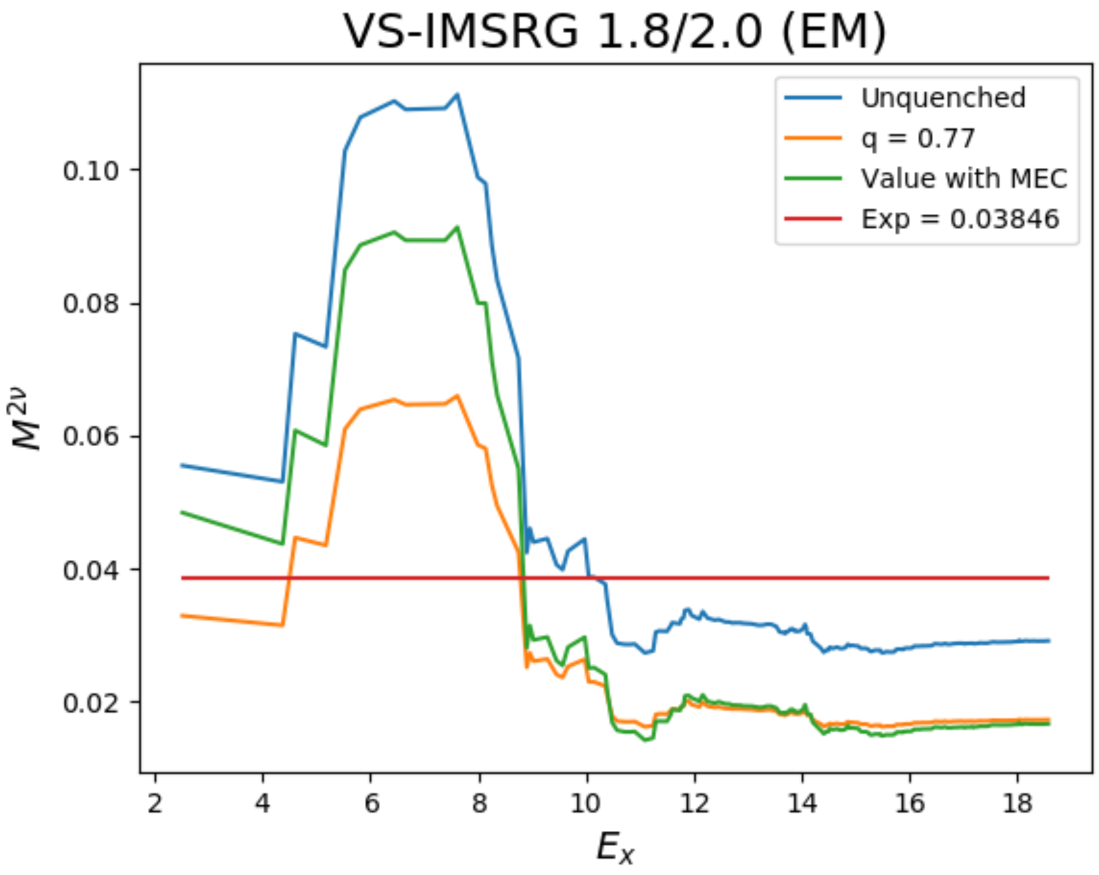
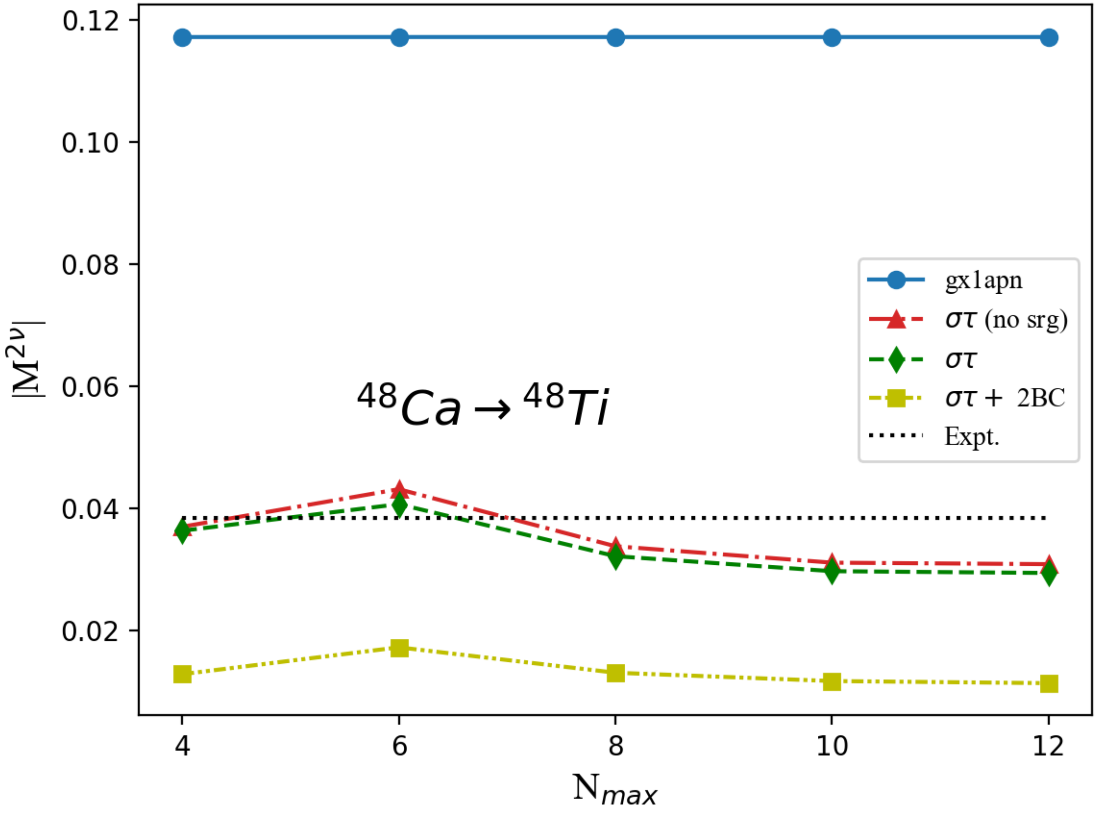


Ab Initio $2\nu\beta\beta$ Decay: ^{48}Ca

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





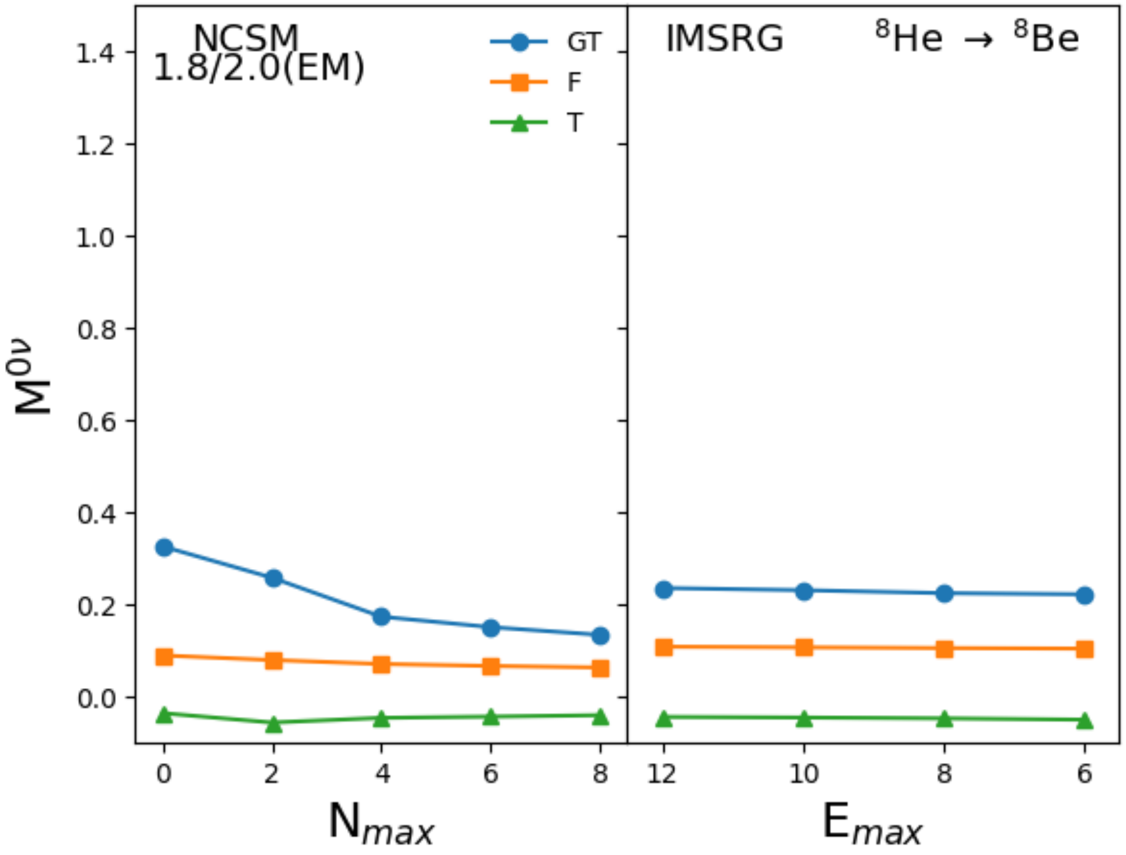
Belley, **Payne**, Stroberg, JDH, in prep

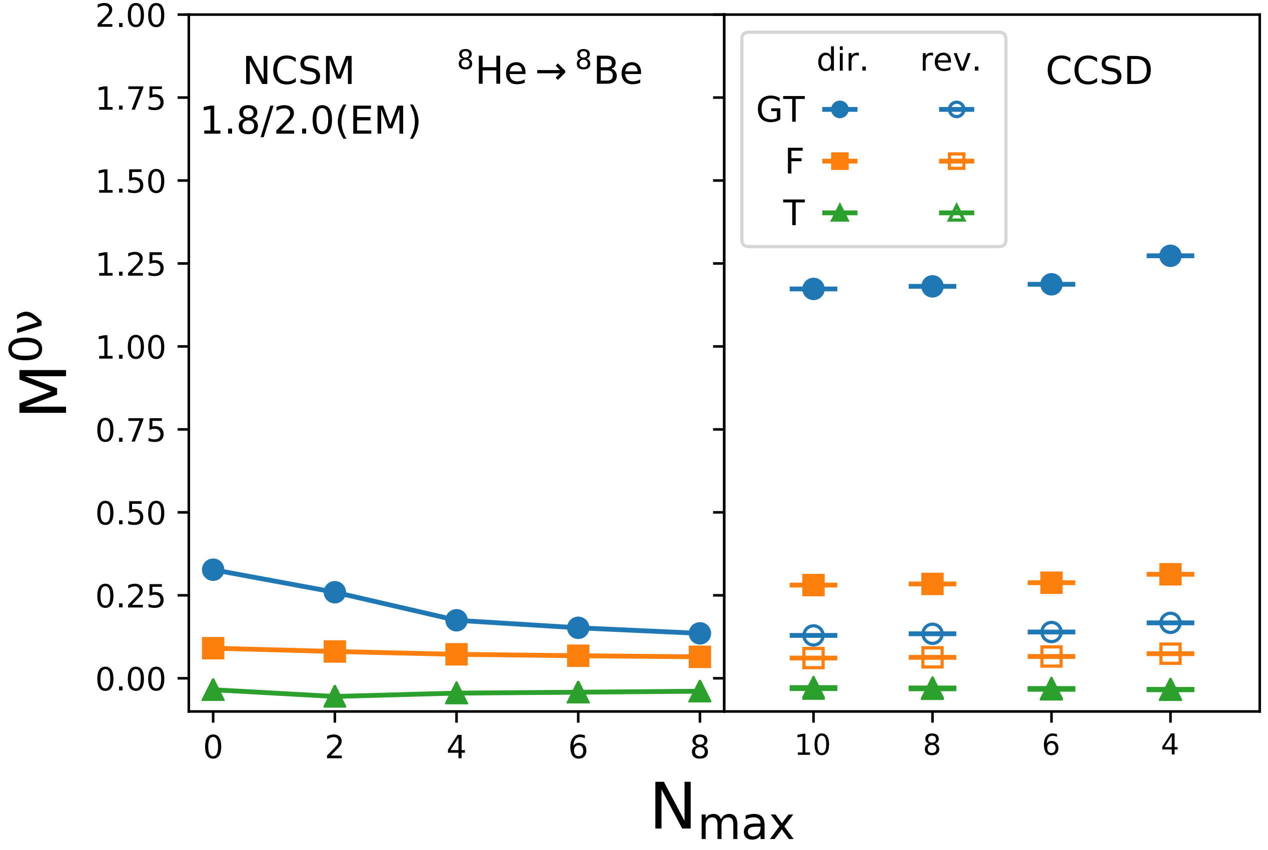
VS-IMSRG: decrease in final matrix element

Potential issues: limited 1^+ states, missing IMSRG(3)... benchmarks with CC underway…

Benchmarking 0νββ Decay in Light Nuclei: ^{8}He

Benchmark with quasi-exact NCSM and CC theory in light systems





Reasonable/good agreement in all cases!

Belley, Payne, Stroberg, JDH, in prep

Benchmarking $0\nu\beta\beta$ Decay in Light Nuclei: ^{10}He

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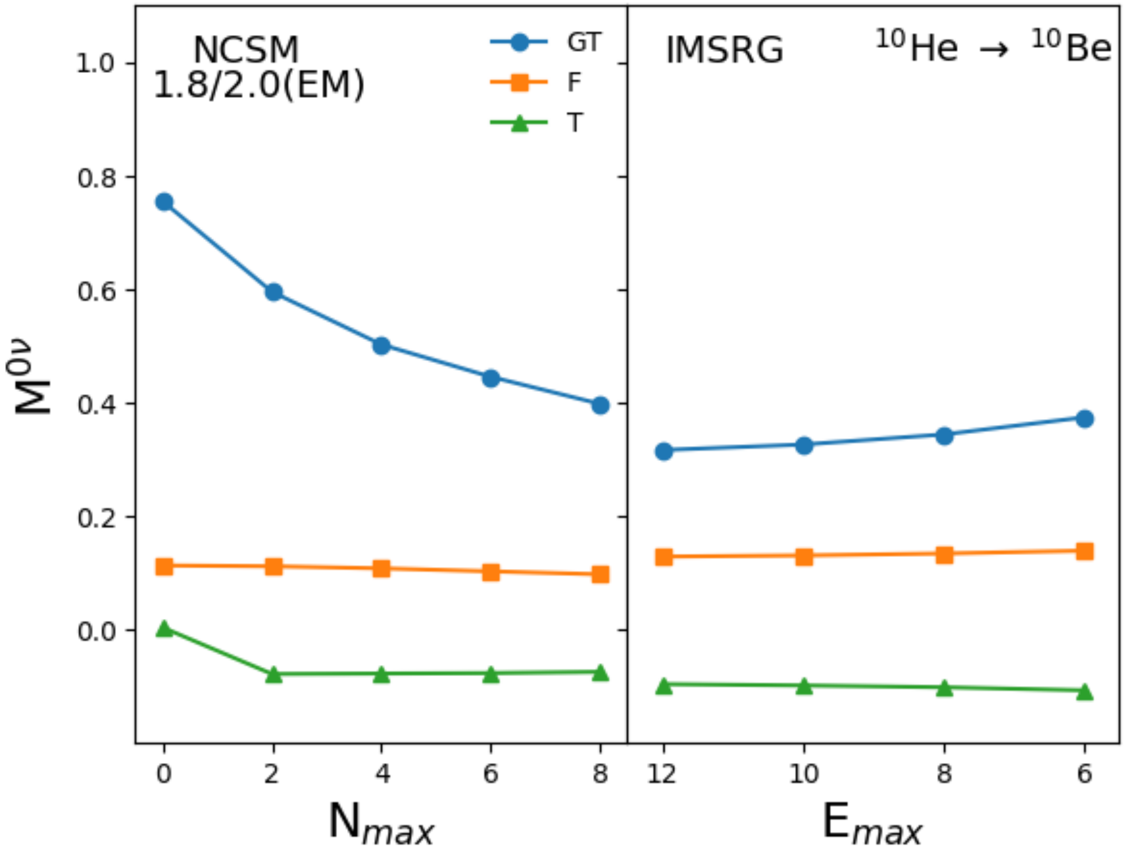

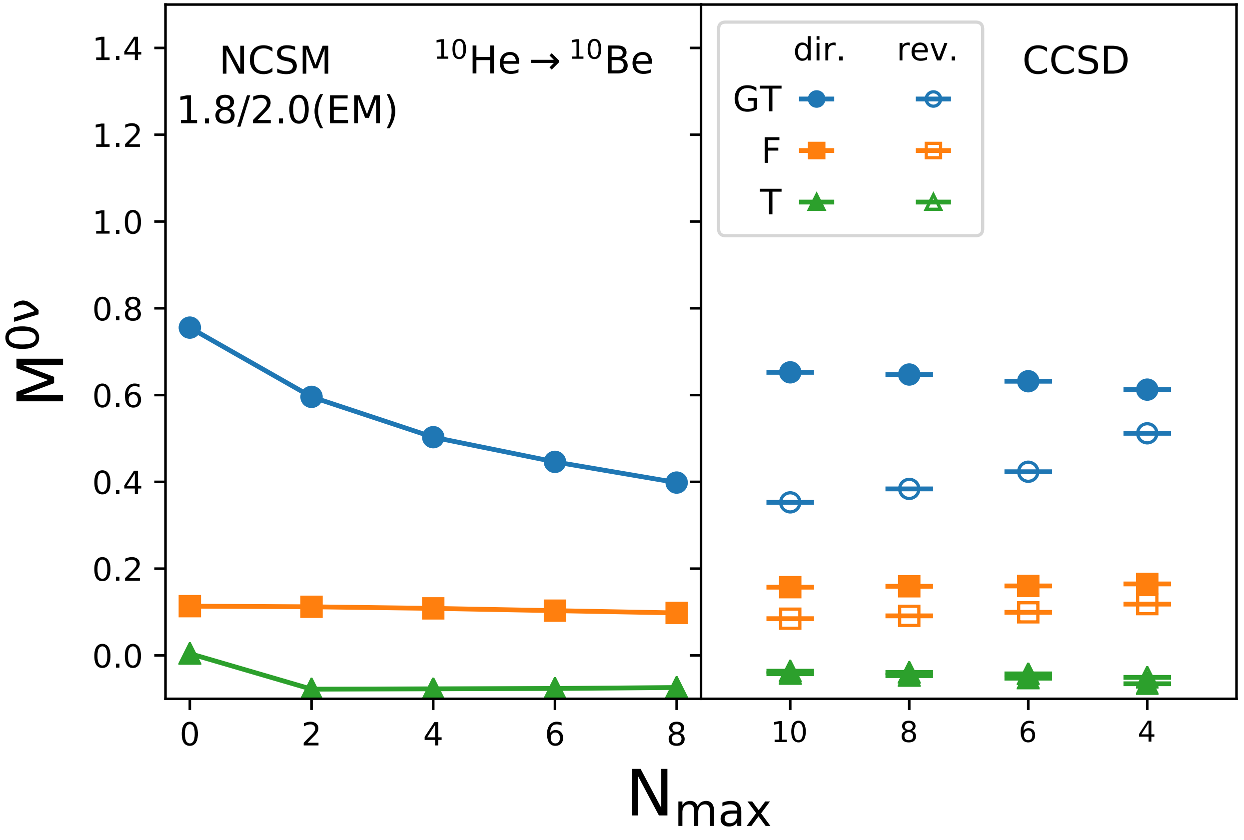

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Belley, Payne, Stroberg, JDH, in prep

TRIUMF

Benchmarking $0\nu\beta\beta$ Decay in Light Nuclei: ^{14}C

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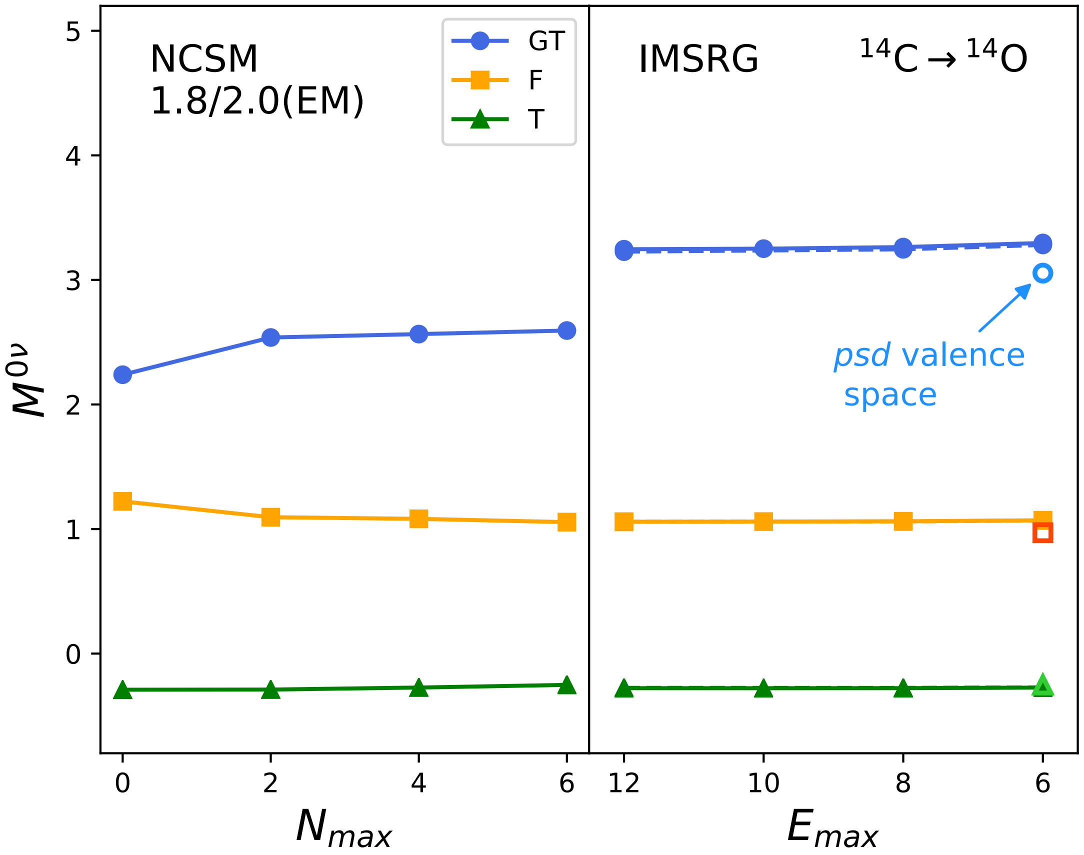

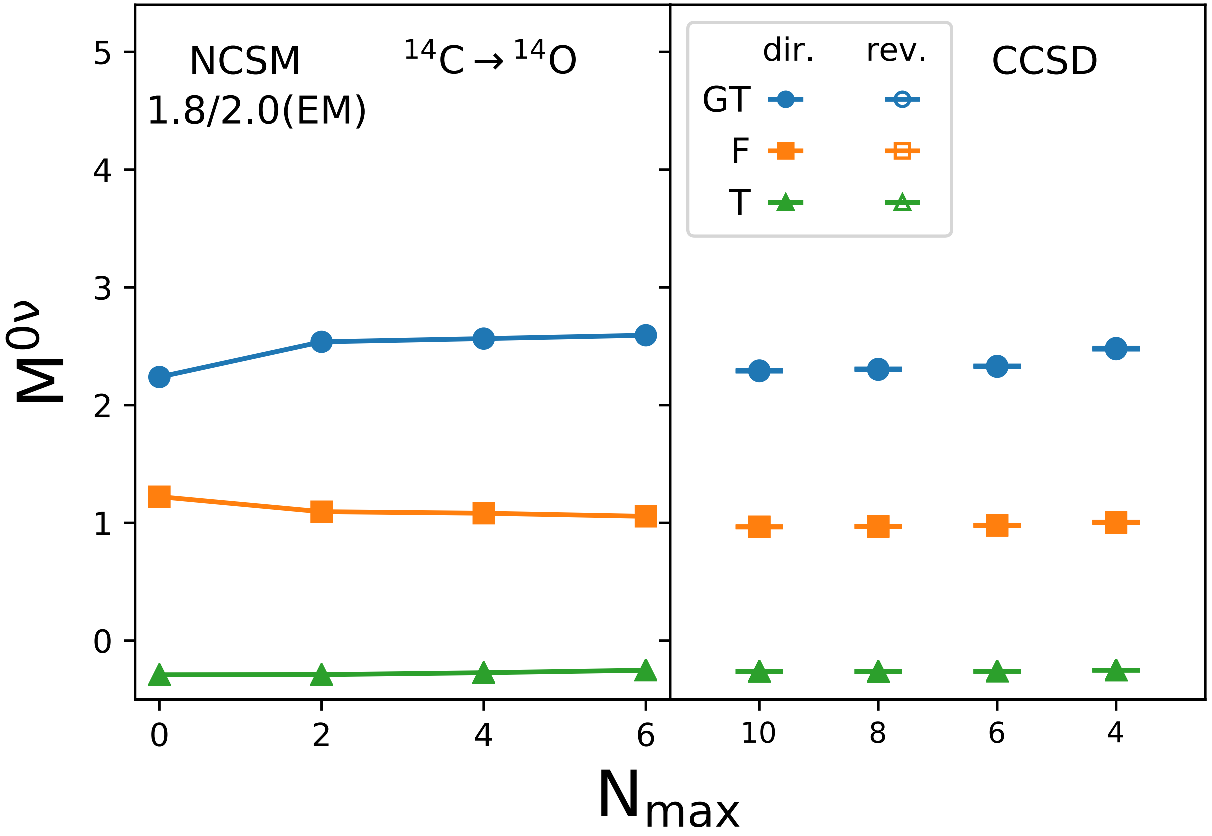

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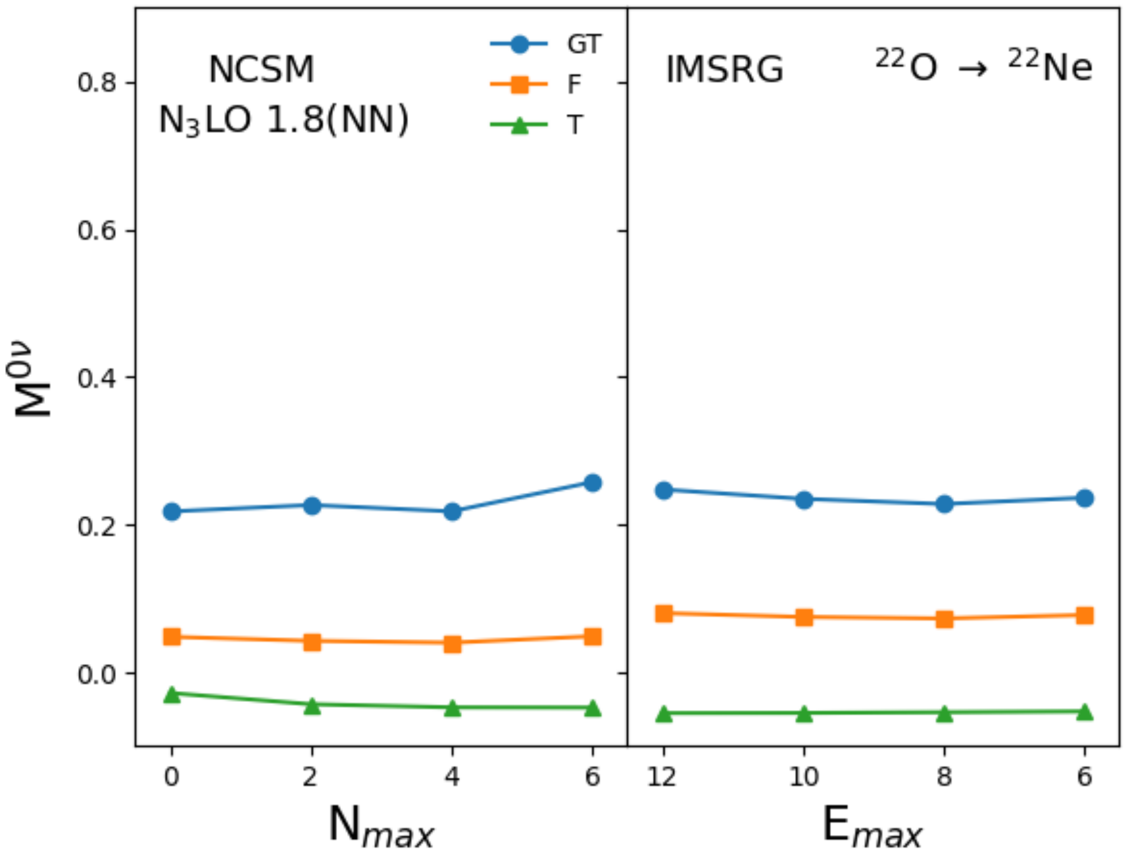
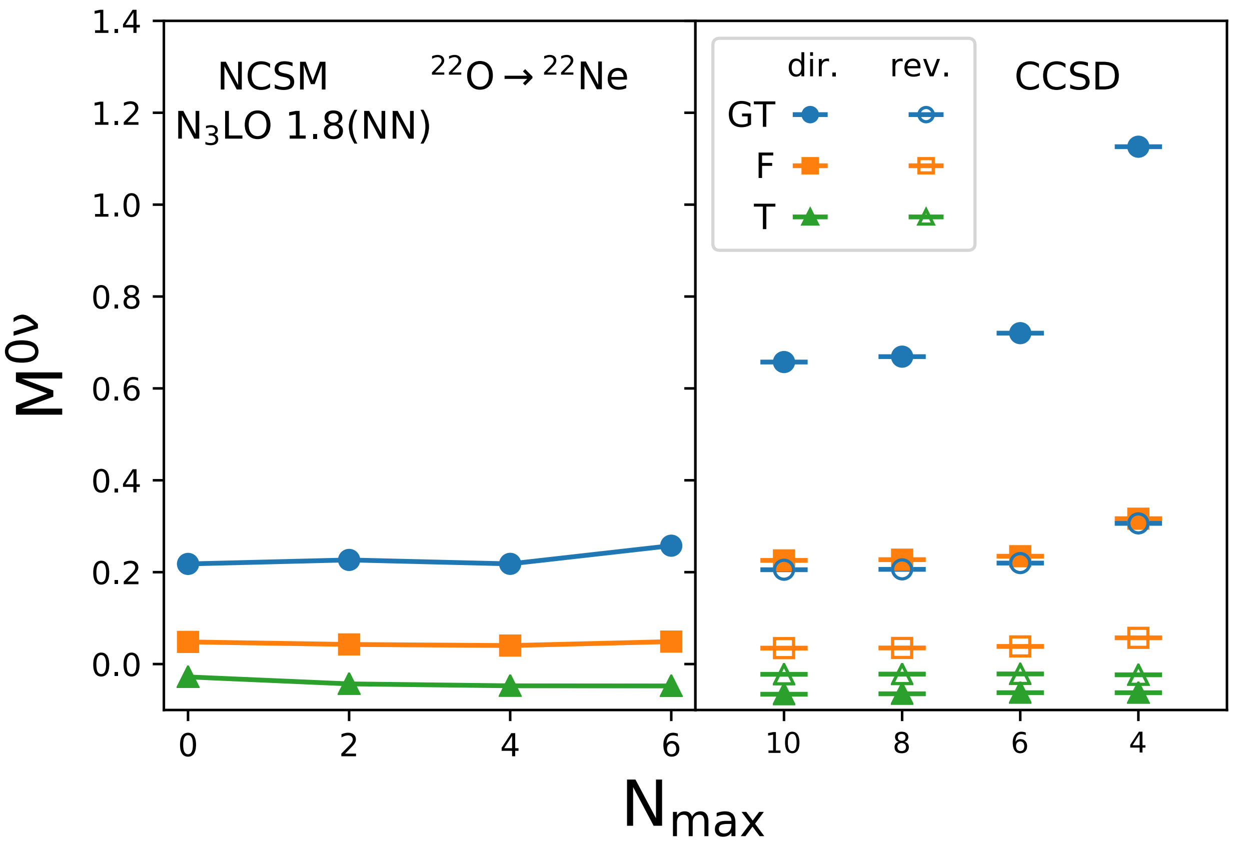
Belley, Payne, Stroberg, JDH, in prep

Benchmarking $0\nu\beta\beta$ Decay in Light Nuclei: ^{22}O

Benchmark with quasi-exact NCSM and CC theory in light systems



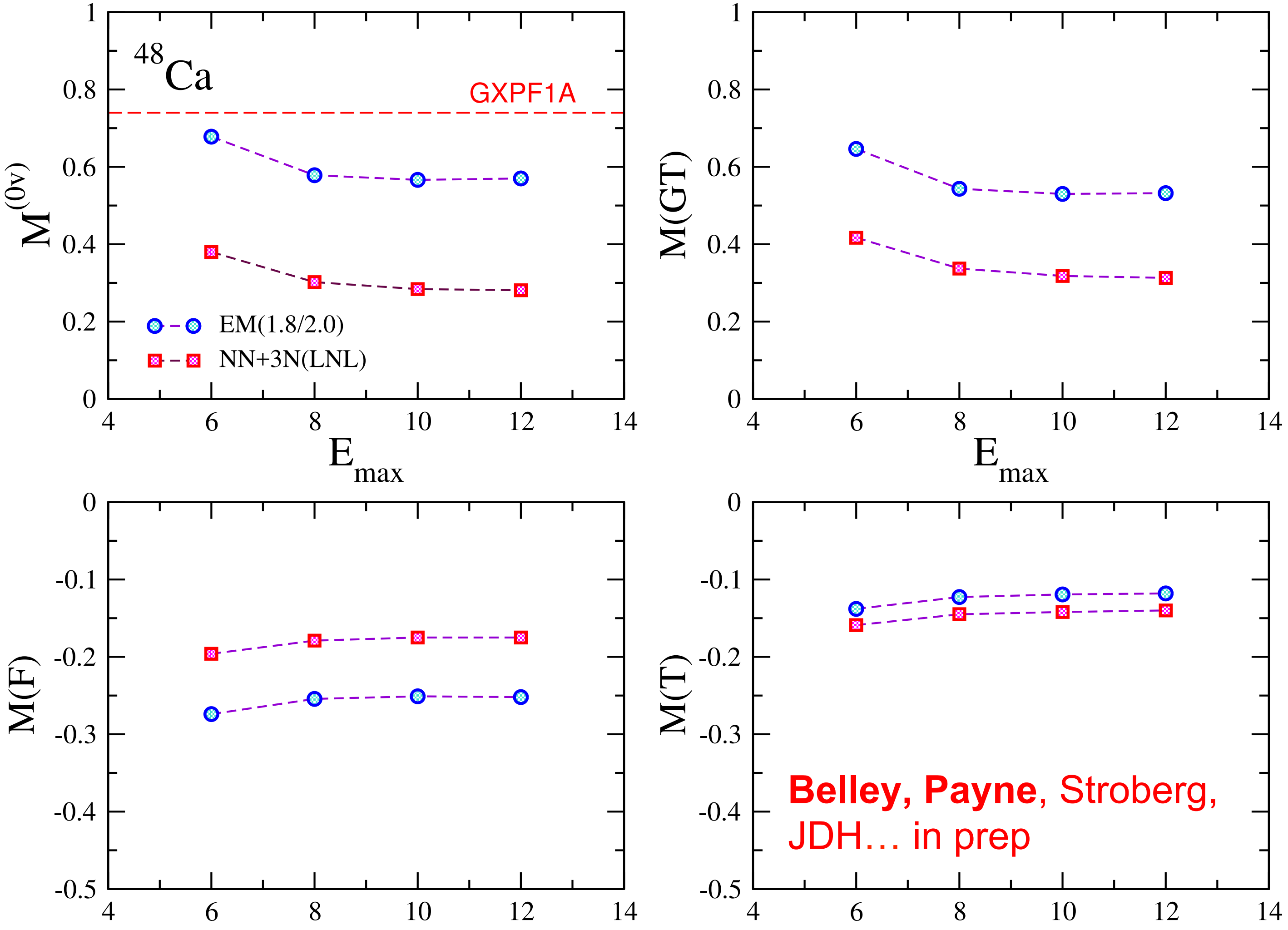


Belley, Payne, Stroberg, JDH, in prep

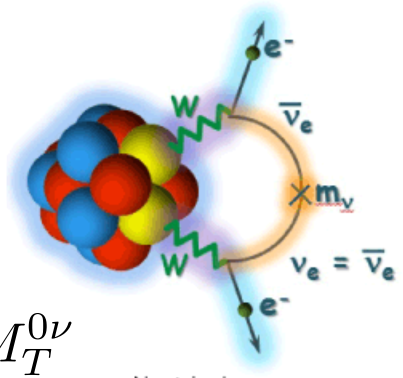
Reasonable to good agreement in all cases!

Ab Initio $0\nu\beta\beta$ Decay: ^{48}Ca

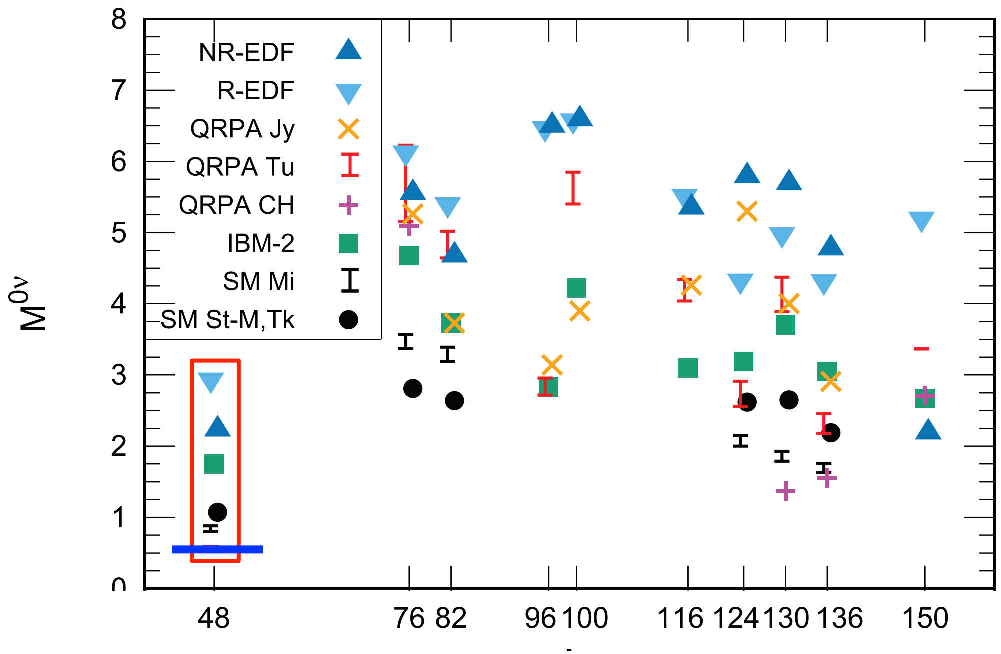
Consistent many-body wfs/operators from chiral NN+3N forces (**no 2b currents**)



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



Neutrinoless double beta decay



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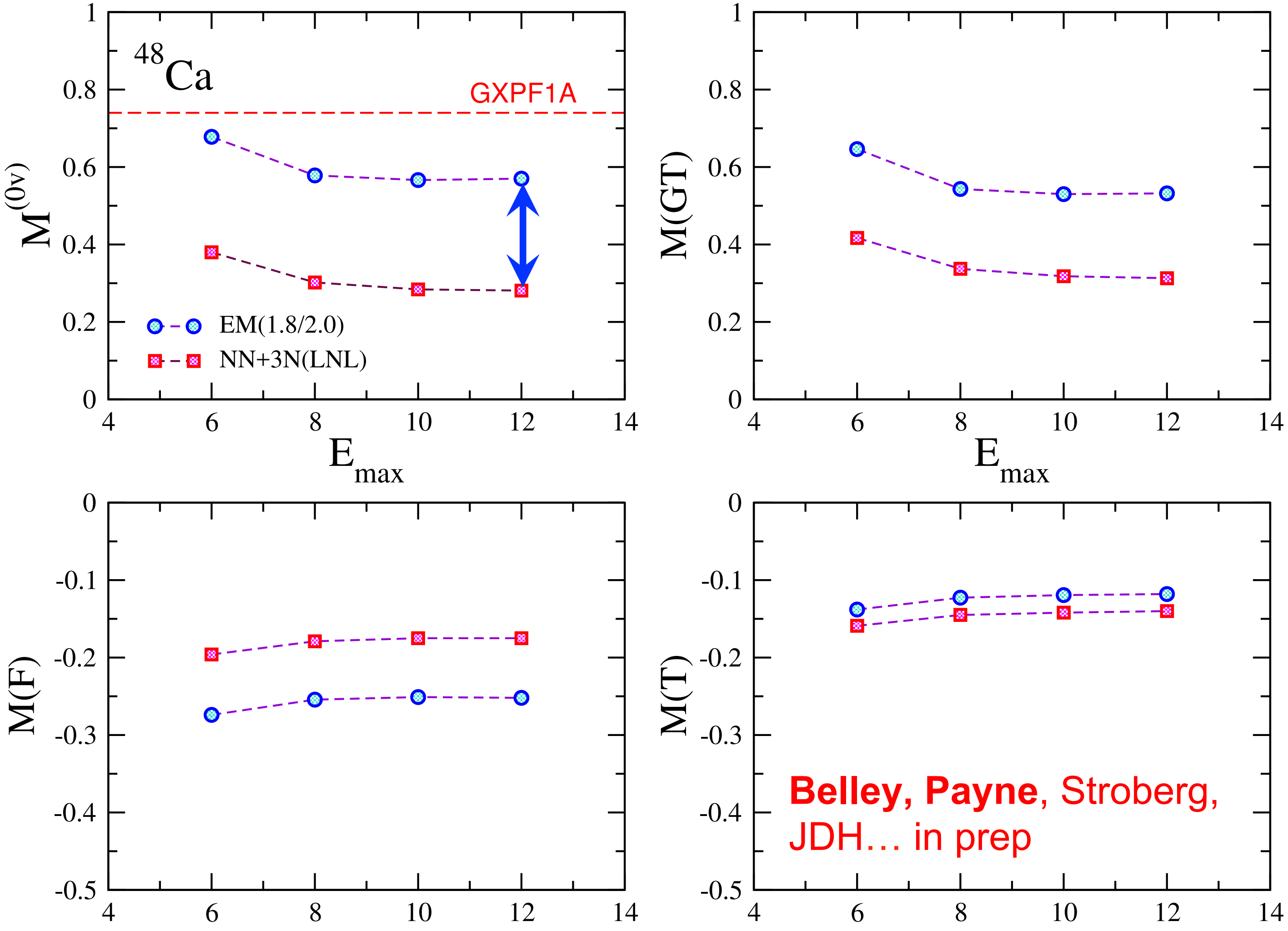
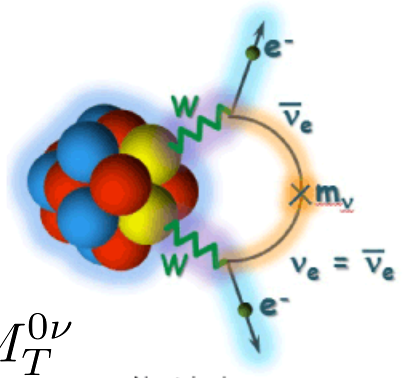
Consistent many-body wfs/operators from chiral NN+3N forces (**no 2b currents**)

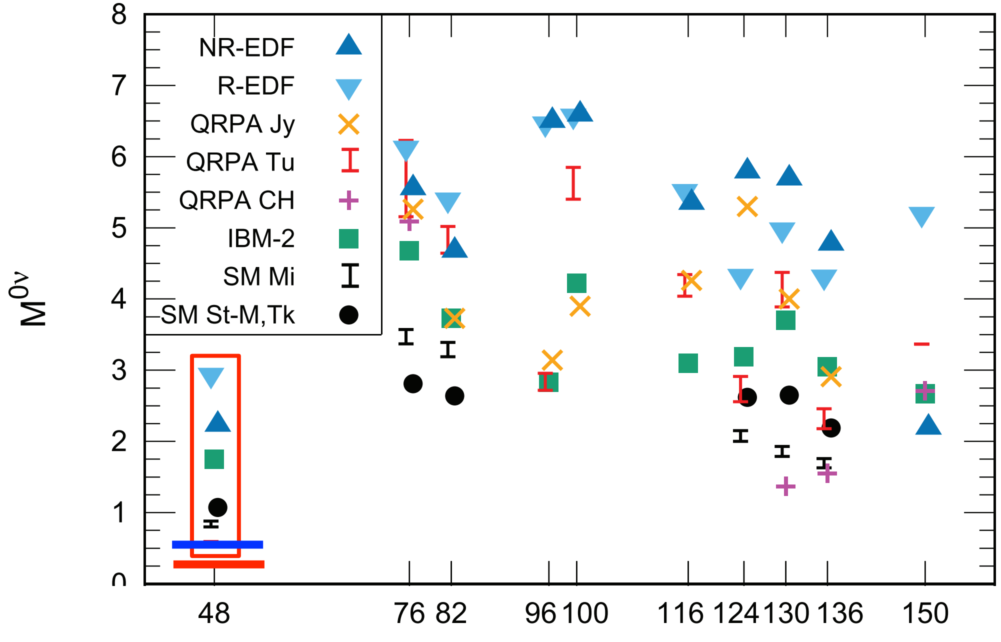


Belley, Payne, Stroberg, JDH… in prep

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



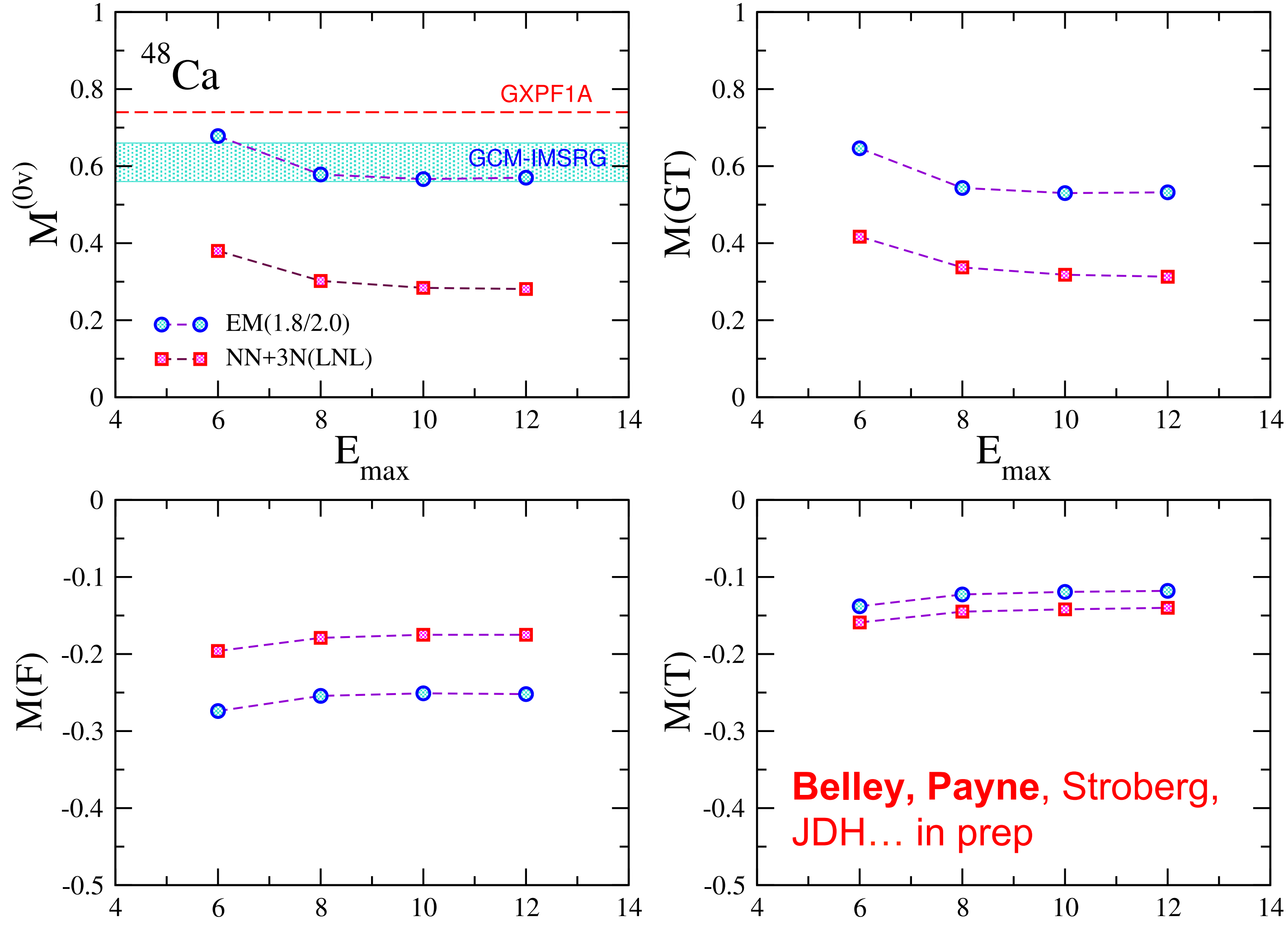
Neutrinoless double beta decay



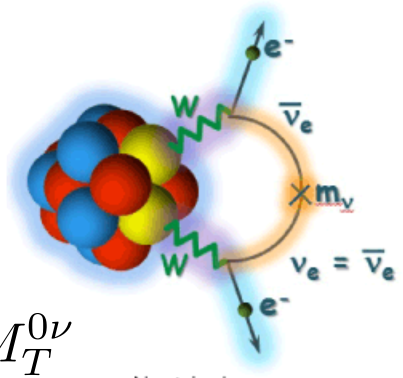
TRIUMF

Ab Initio 0νββ Decay: ^{48}Ca

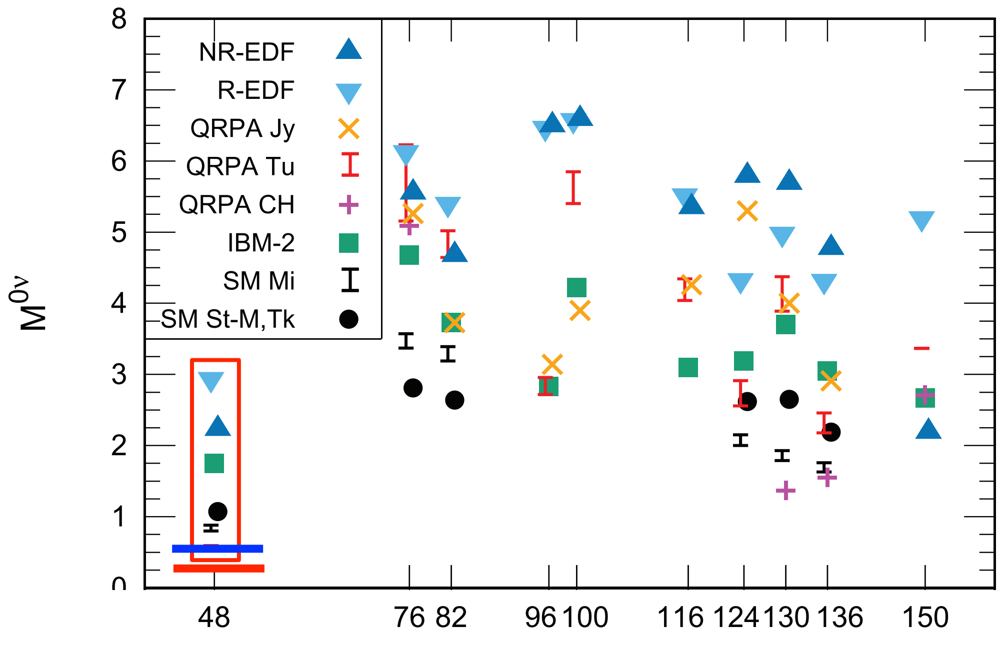
Consistent many-body wfs/operators from chiral NN+3N forces (**no 2b currents**)



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



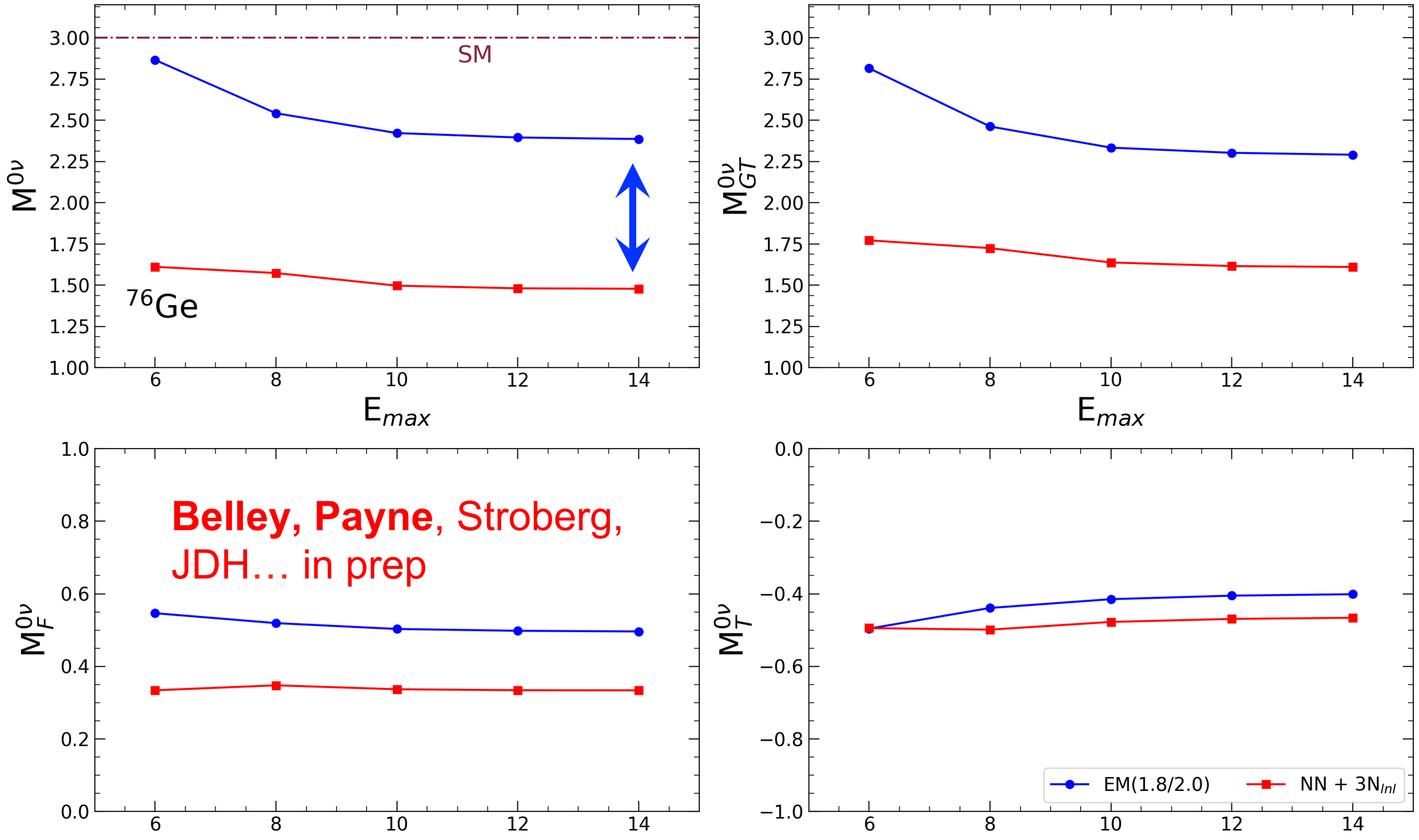
Neutrinoless double beta decay



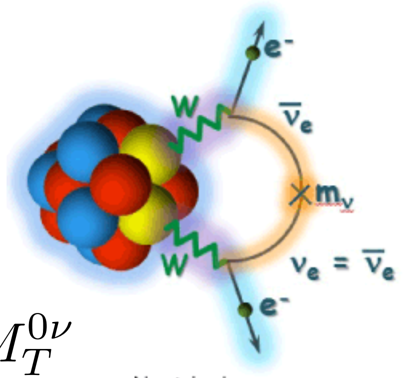
Good agreement with GCM-IMSRG (tentative)… Further benchmarks underway

Ab Initio 0νββ Decay: ^{76}Ge

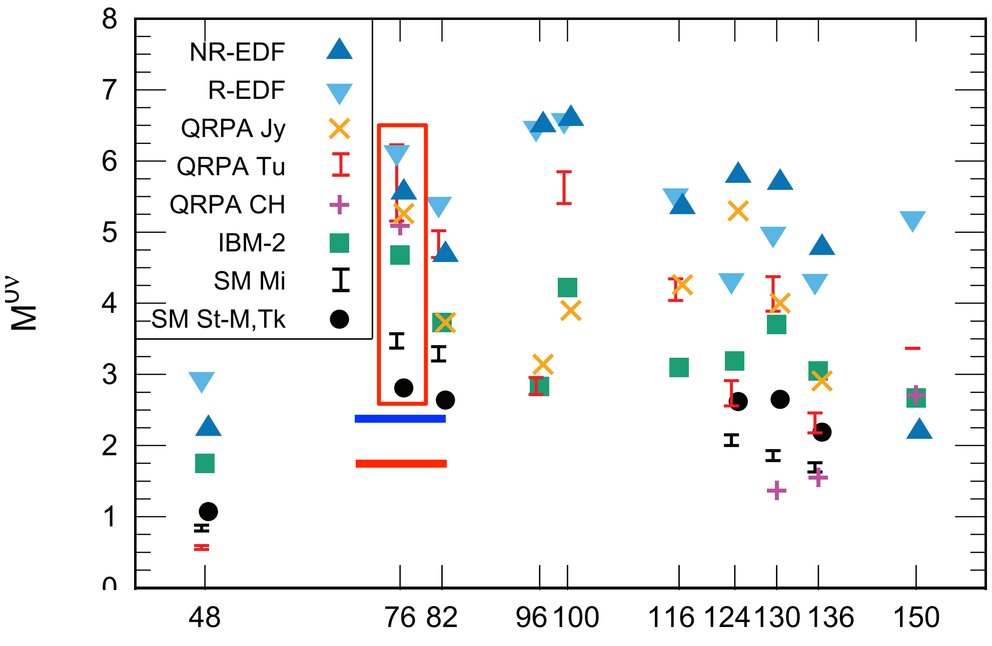
Consistent many-body wfs/operators from chiral NN+3N forces (**no 2b currents**)



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

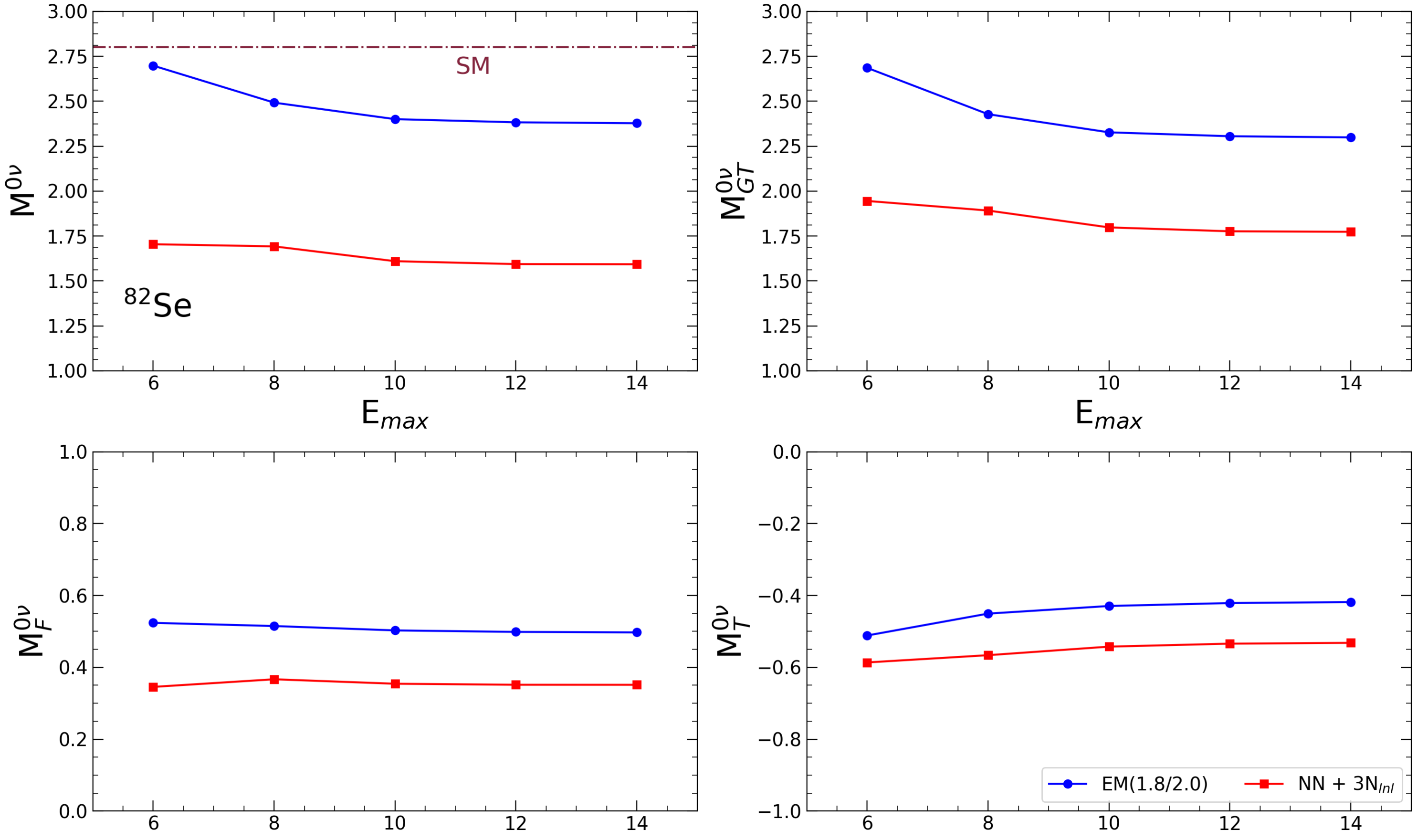


Neutrinoless double beta decay

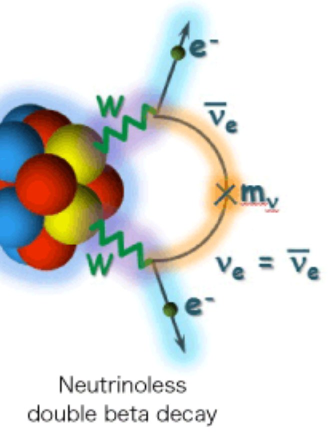


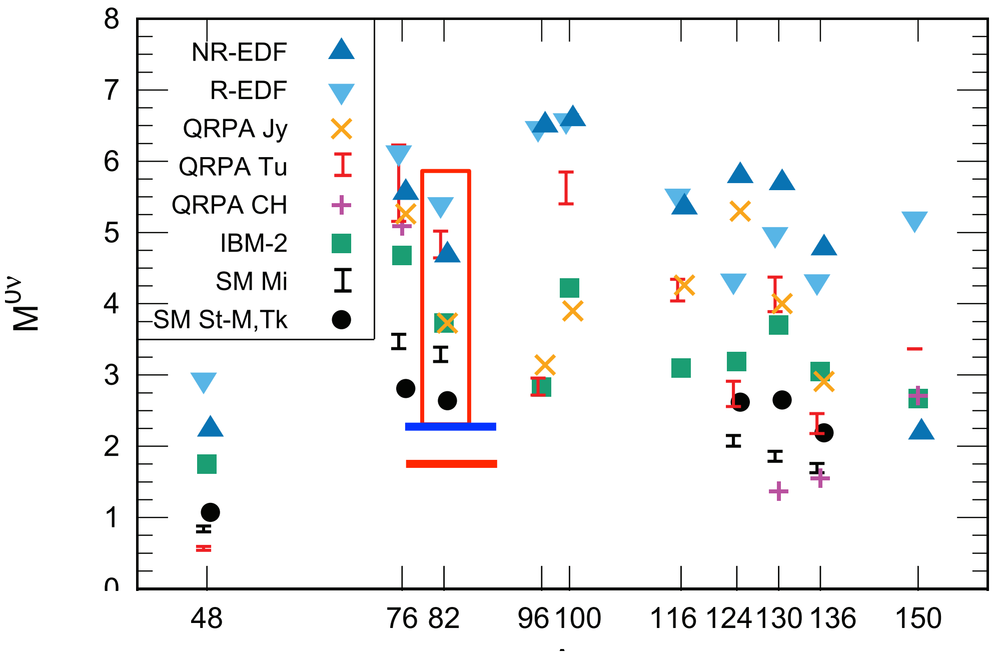
Ab Initio 0νββ Decay: ^{82}Se

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



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



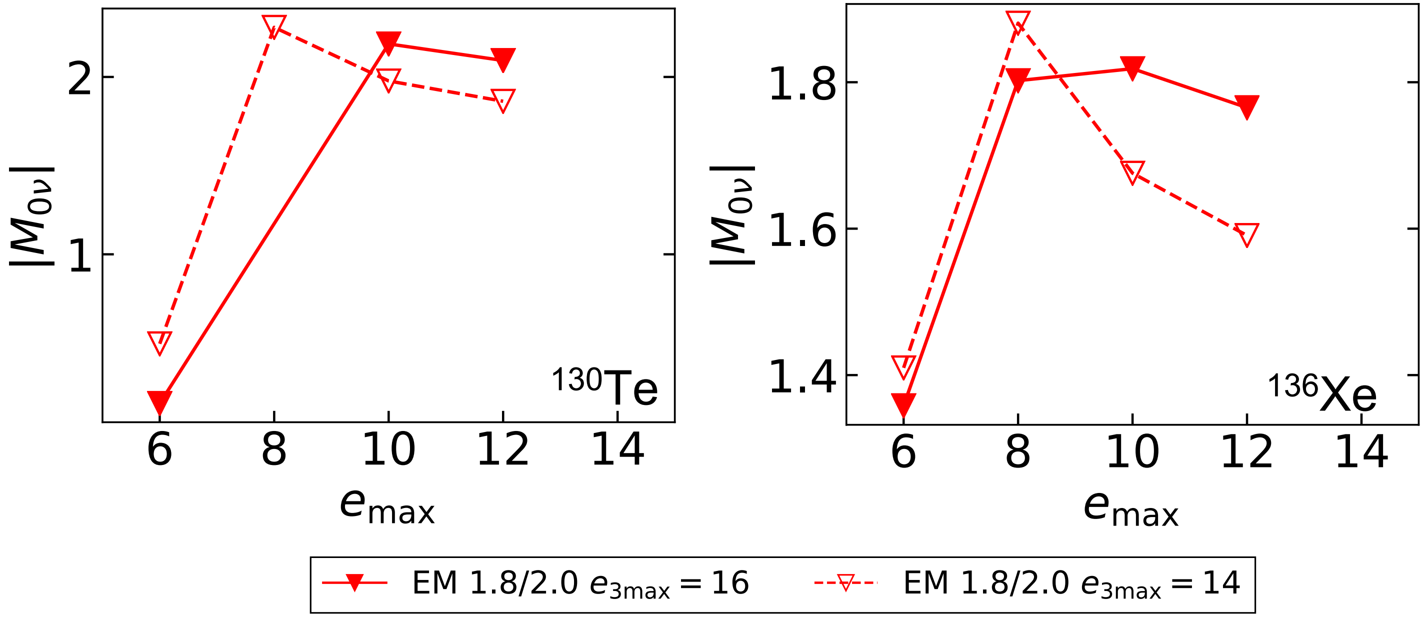


Results consistently below lowest model predictions…

TRIUMF

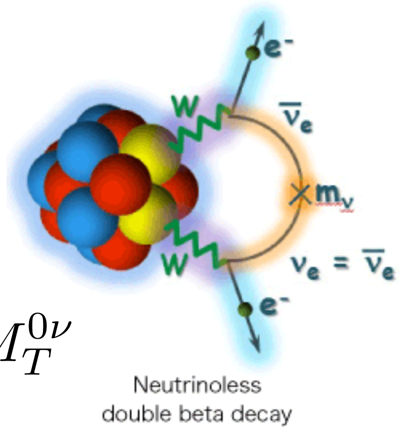
Ab Initio 0νββ Decay: ^{130}Te, ^{136}Xe

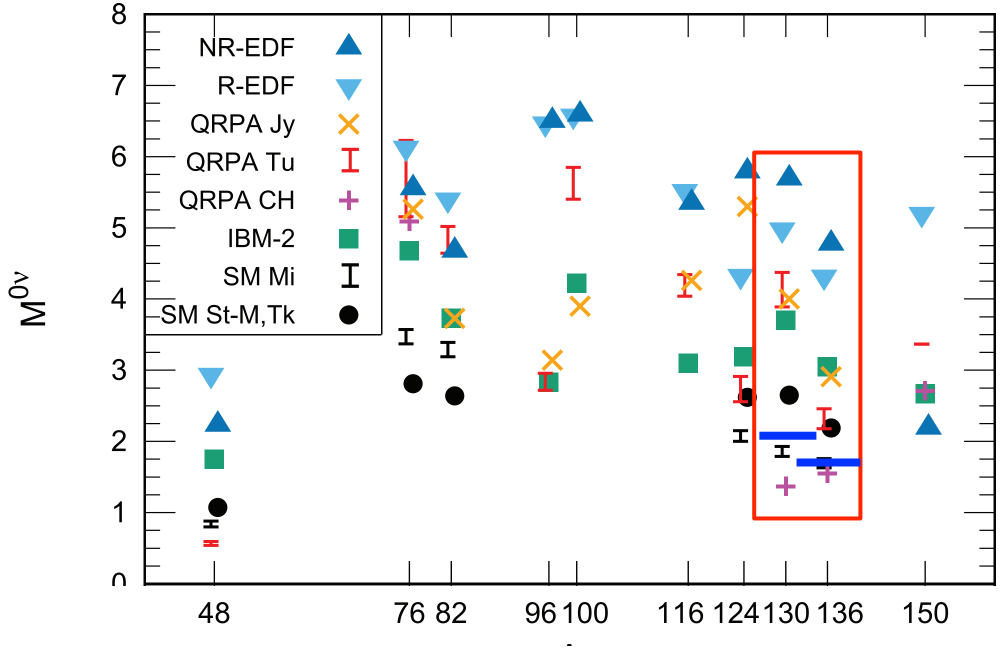
Consistent many-body wfs/operators from chiral NN+3N forces (**no 2b currents**)



Belley, Payne, Stroberg, JDH… in prep

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





***Very Preliminary* - results consistently below lowest SM predictions…**

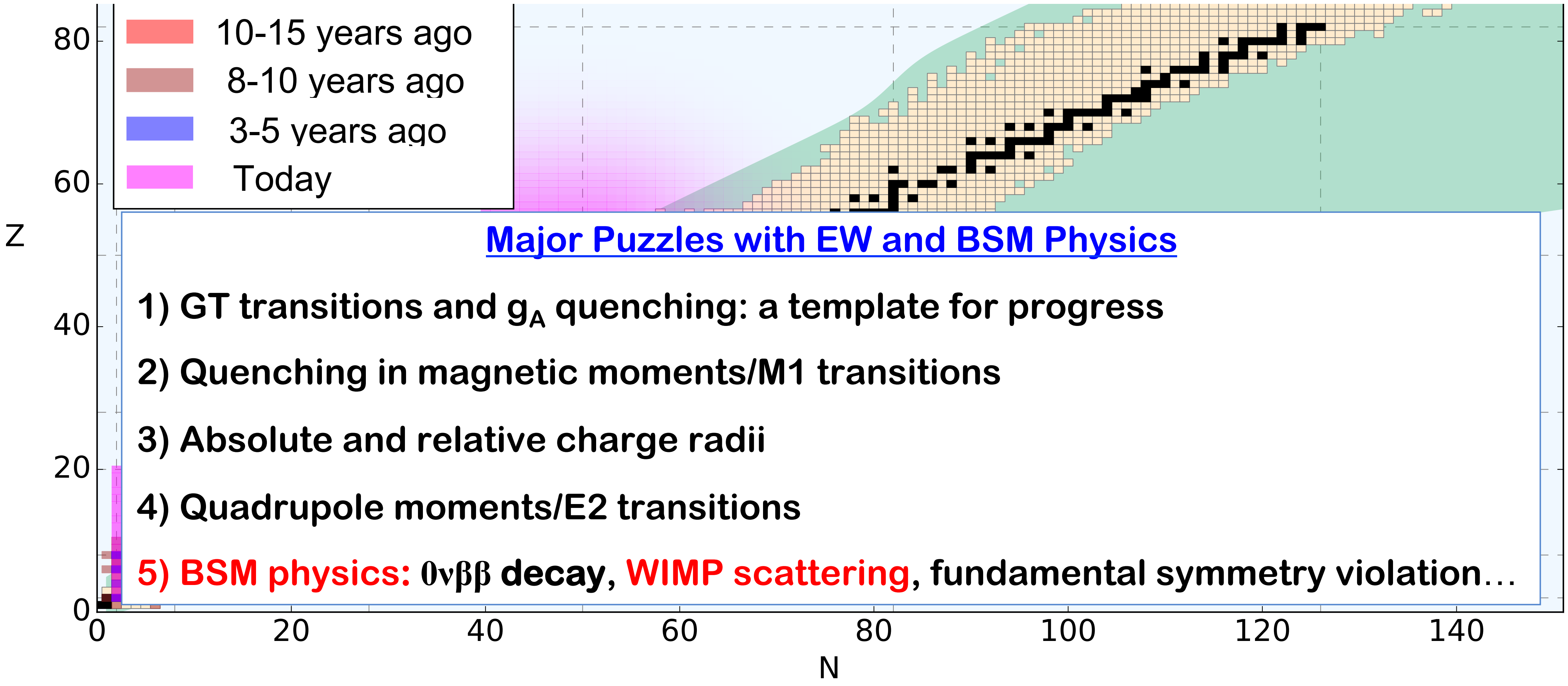
TRIUMF

Breadth of Ab Initio: Towards Global Calculations

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

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

$$H\psi_n = E_n\psi_n$$



Major Puzzles with EW and BSM Physics

1) GT transitions and g_A quenching: a template for progress

2) Quenching in magnetic moments/M1 transitions

3) Absolute and relative charge radii

4) Quadrupole moments/E2 transitions

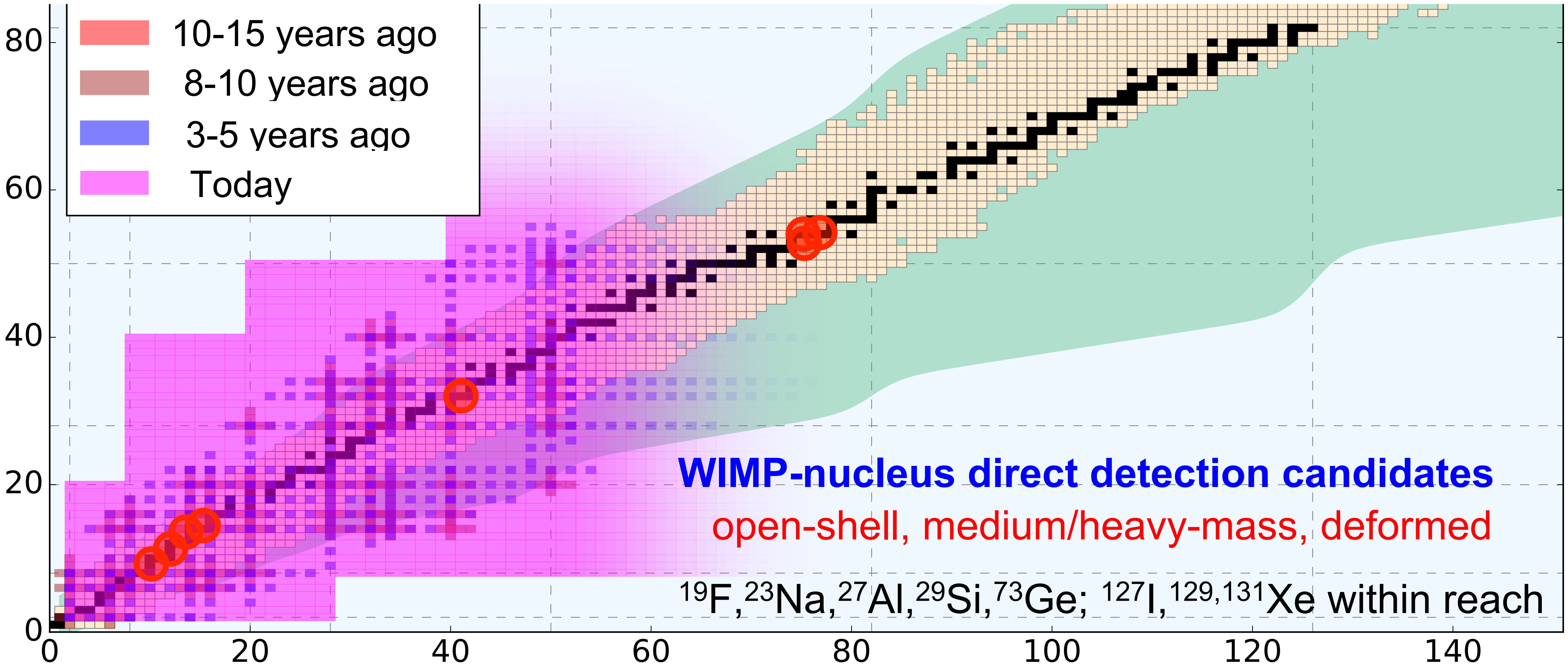
5) BSM physics: $0\nu\beta\beta$ decay, WIMP scattering, fundamental symmetry violation…

WIMP-Nucleus Scattering

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

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

$$H\psi_n = E_n\psi_n$$



WIMP-nucleus direct detection candidates

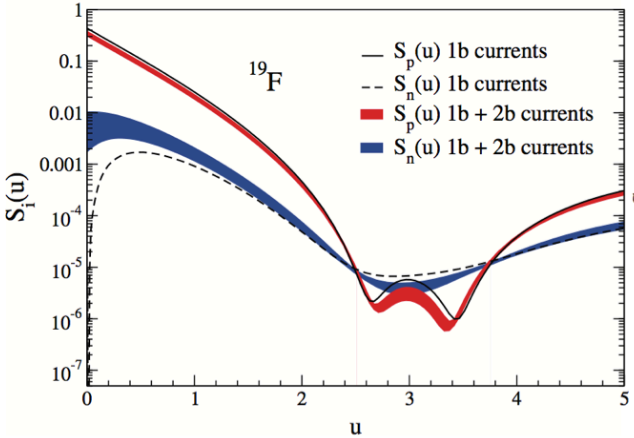
open-shell, medium/heavy-mass, deformed

^{19}F, ^{23}Na, ^{27}Al, ^{29}Si, ^{73}Ge; ^{127}I, $^{129,131}Xe$ within reach

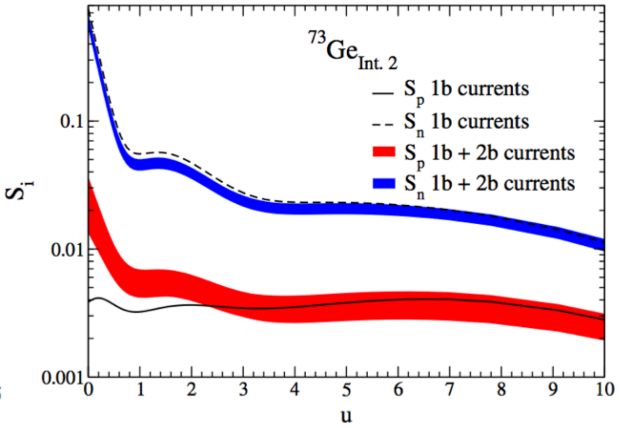
Structure Functions from Phenomenological Shell Model

Previous advances: phenomenological wfs + bare operator (**axial currents**)

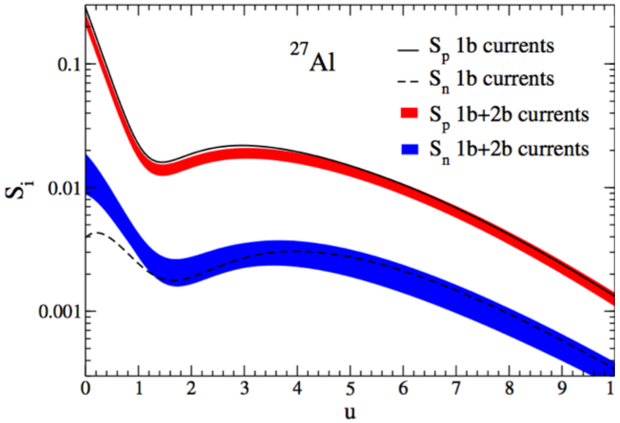
$$S_A(p) = \sum_{L\geqslant 0} |\langle J_f \| \mathcal{L}_L \| J_i \rangle|^2 + \sum_{L\geqslant 0} \left(|\langle J_f \| \mathcal{T}_L^{\text{el}} \| J_i \rangle|^2 + |\langle J_f \| \mathcal{T}_L^{\text{mag}} \| J_i \rangle|^2 \right)$$



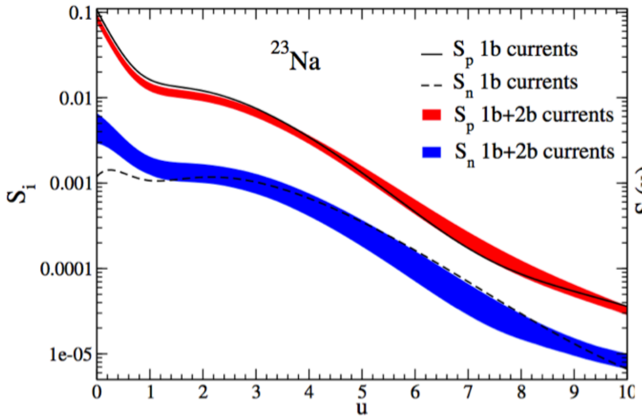
PICASSO, COUPP, SIMPLE



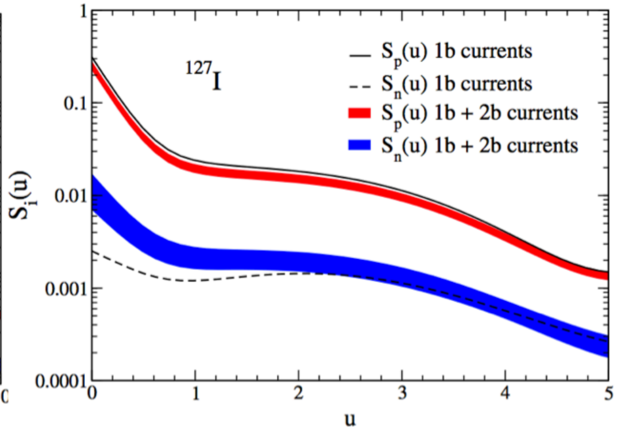
CDMS, EDELWEISS, EURECA



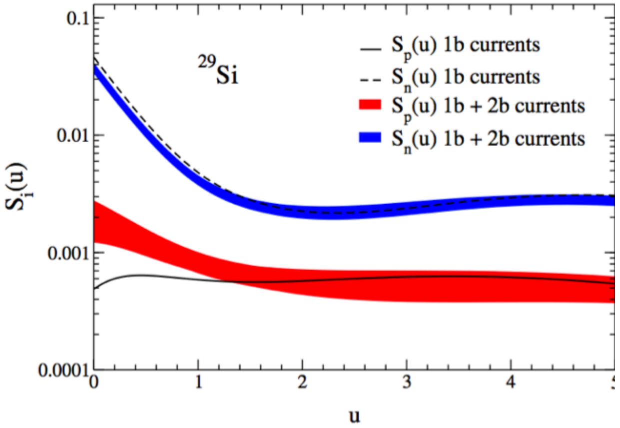
CRESST



DAMA, ANAIS, DM-Ice



DAMA, ANAIS, DM-Ice, KIMS



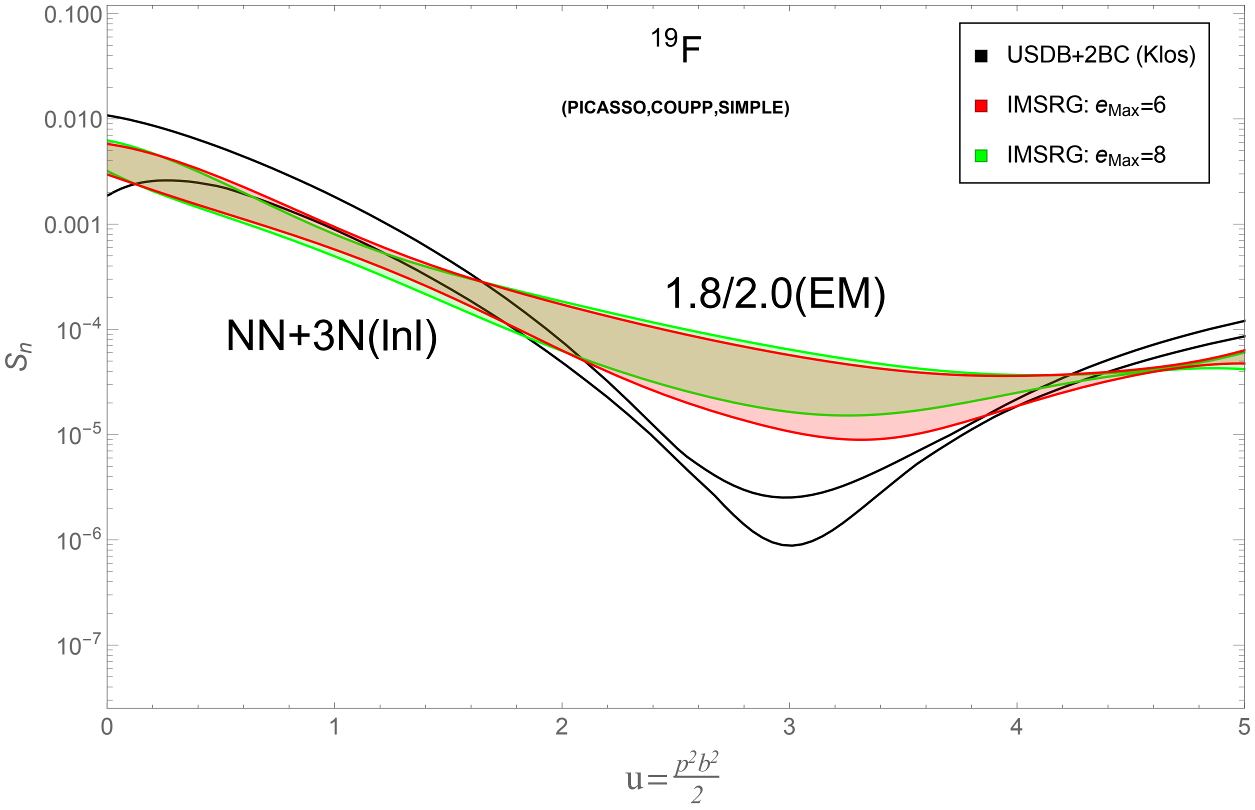
CDMS-II

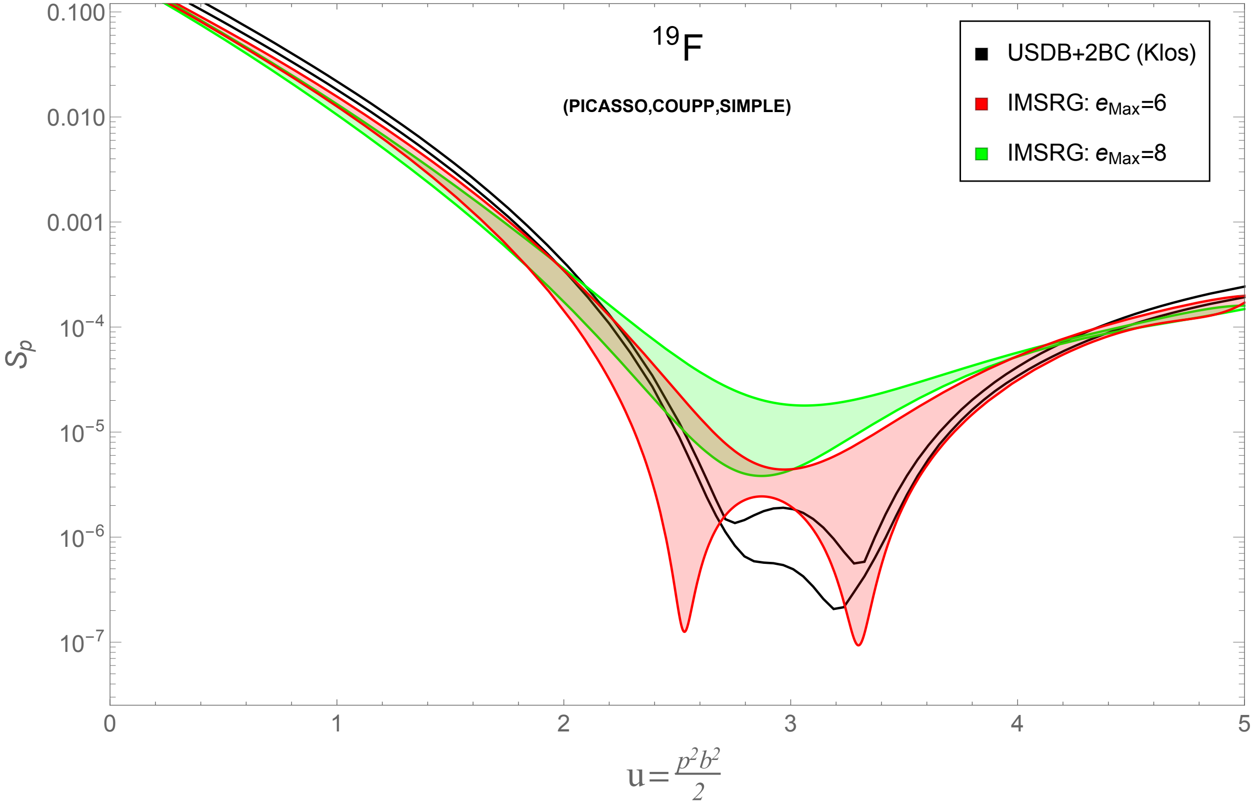
Klos et al, PRD (2013)

SD WIMP-Nucleus Response: Benchmarking ^{19}F

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

Two NN+3N interactions: 1.8/2.0(EM), NN+3N(LNL)



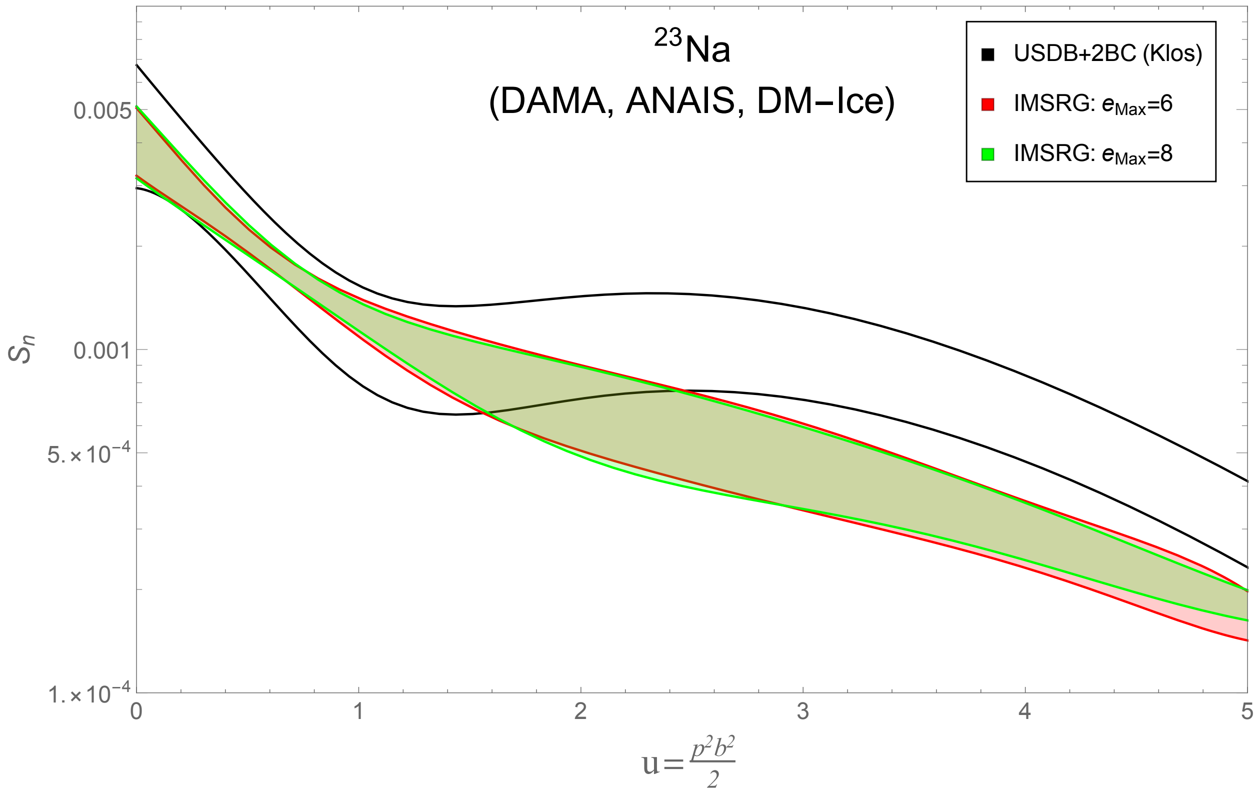


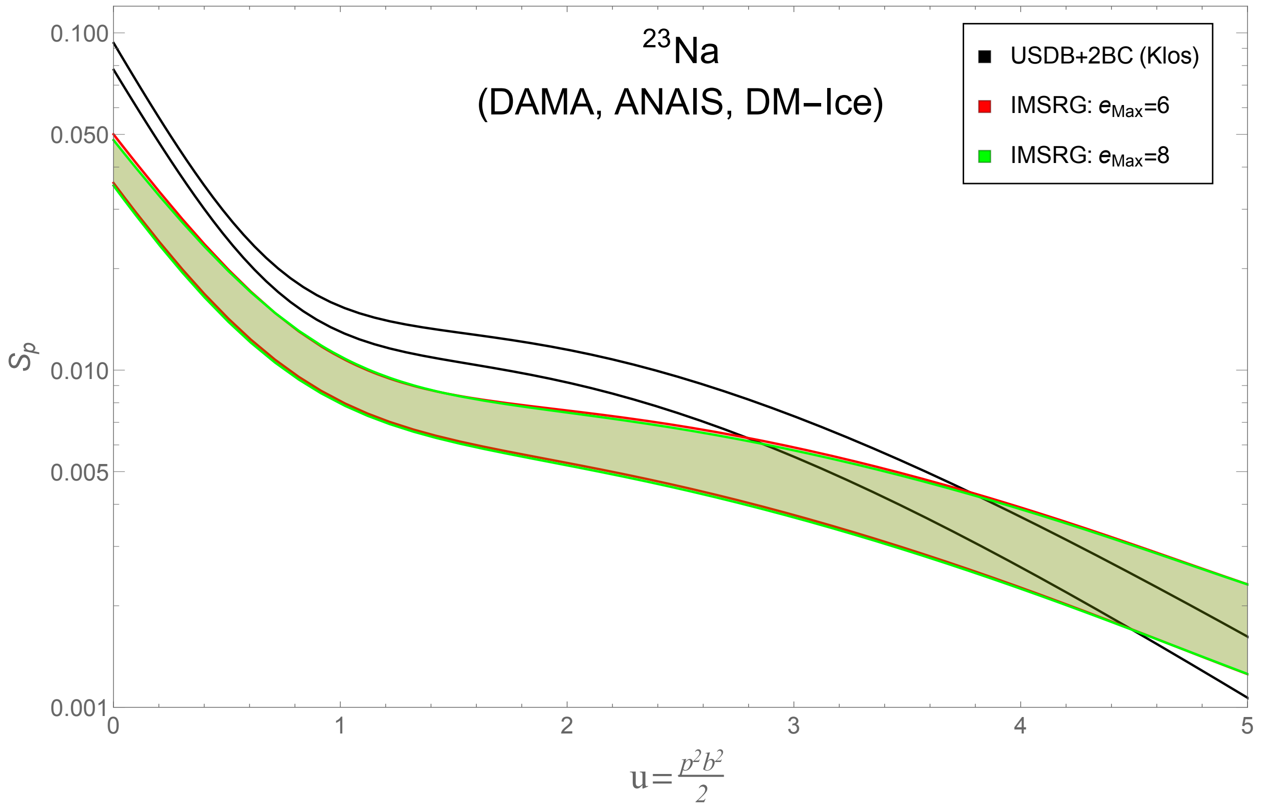
Padua, Leutheusser, Stroberg, JDH, in prep.

SD WIMP-Nucleus Response: Benchmarking ^{23}Na

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

Two NN+3N interactions: 1.8/2.0(EM), NN+3N(LNL)



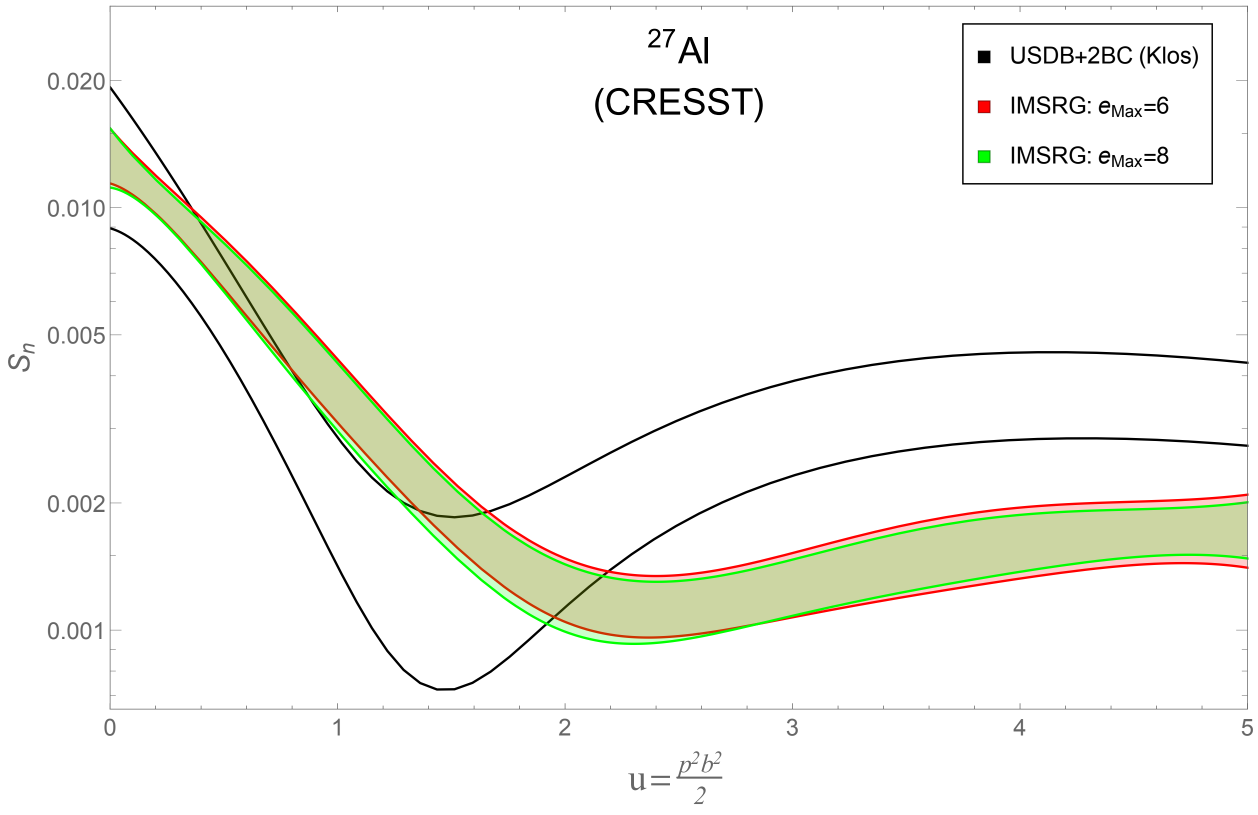


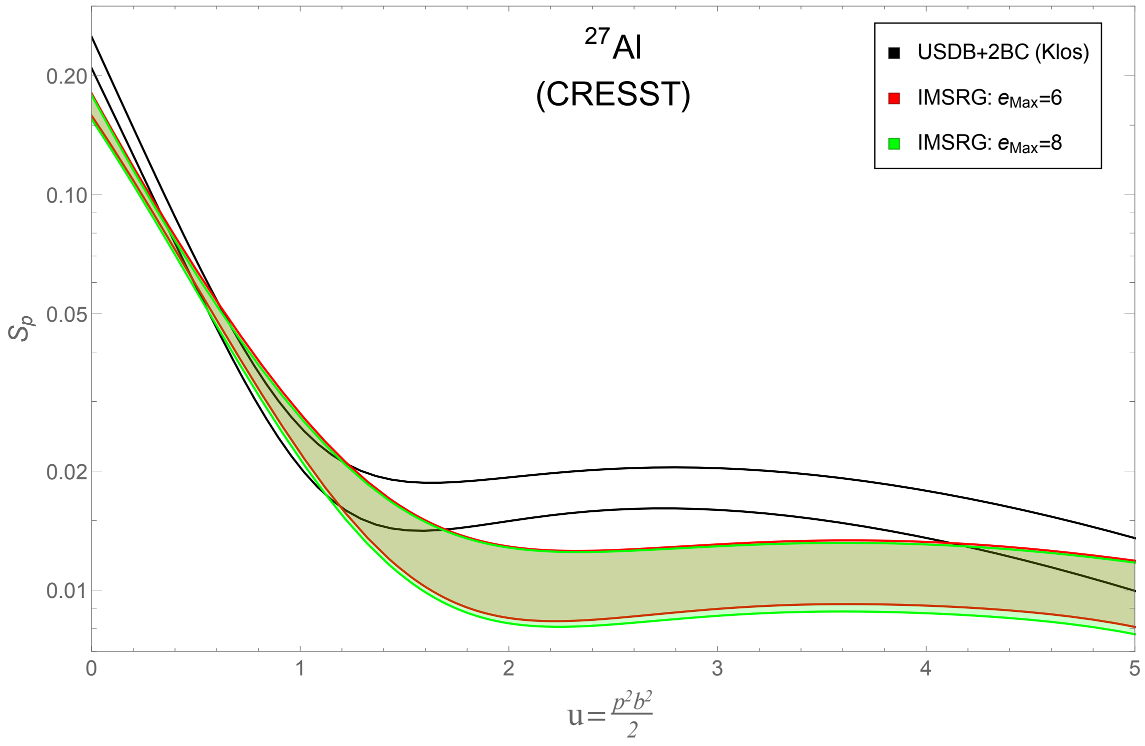
Padua, Leutheusser, Stroberg, JDH, in prep.

SD WIMP-Nucleus Response: Benchmarking ^{27}Al

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

Two NN+3N interactions: 1.8/2.0(EM), NN+3N(LNL)



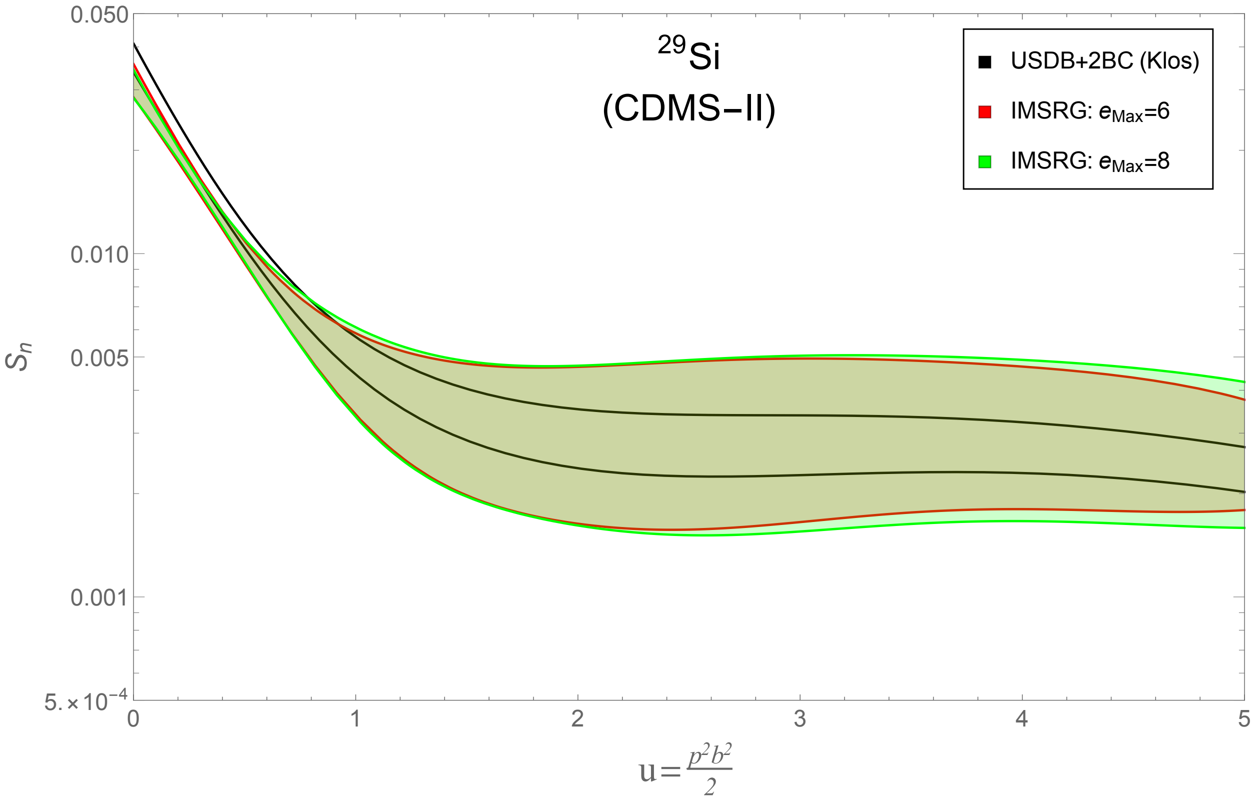


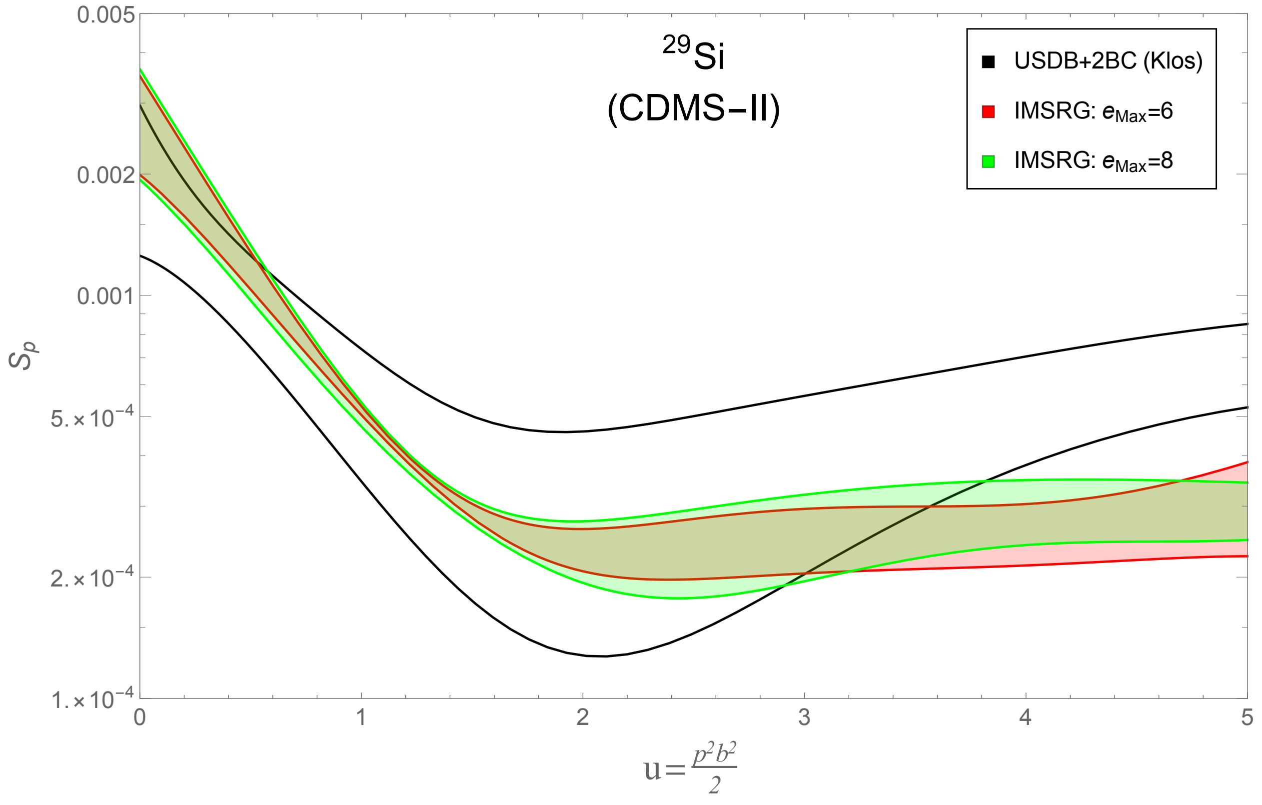
Padua, Leutheusser, Stroberg, JDH, in prep.

SD WIMP-Nucleus Response: Benchmarking ^{29}Si

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

Two NN+3N interactions: 1.8/2.0(EM), NN+3N(LNL)



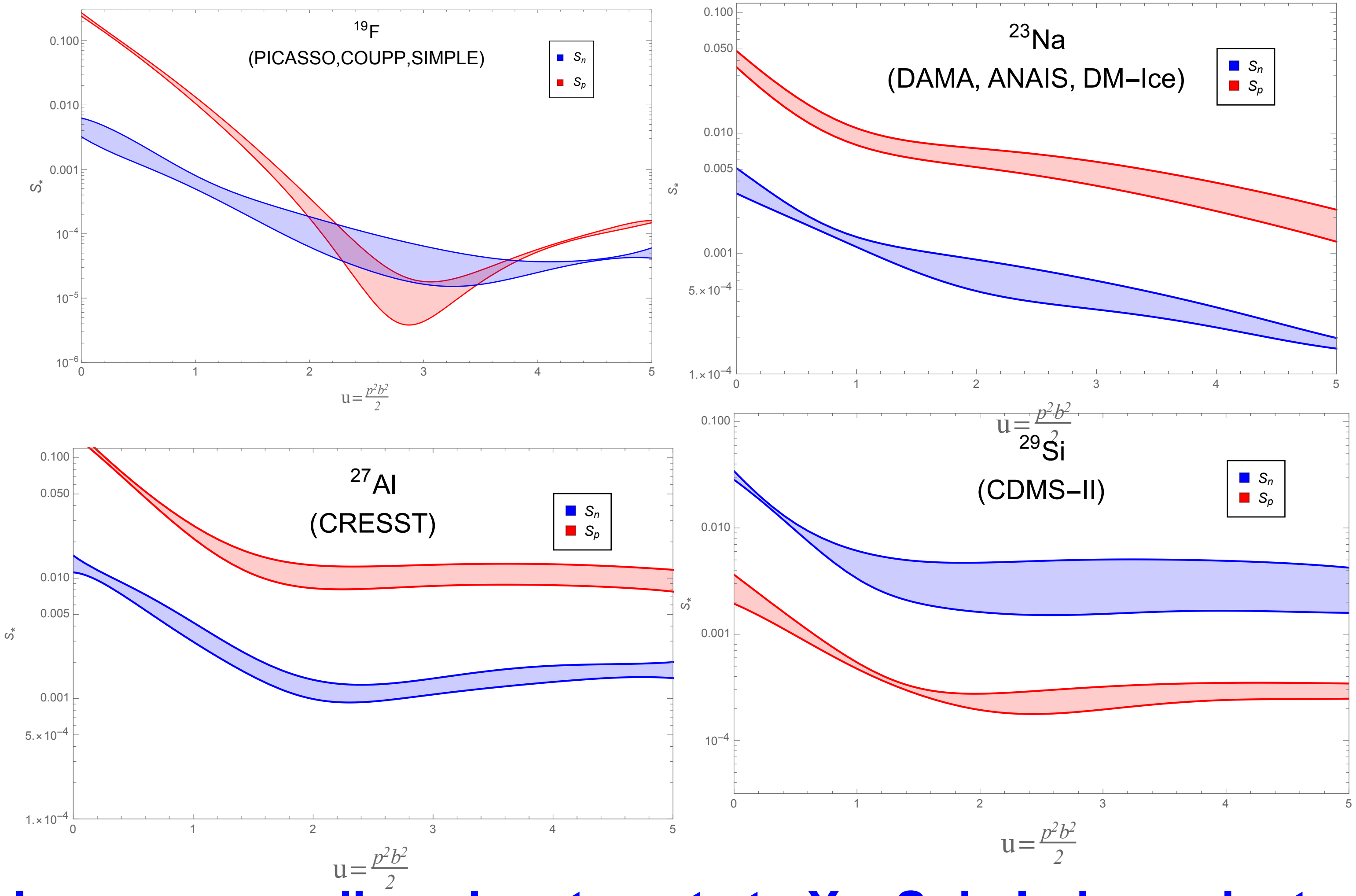


Padua, Leutheusser, Stroberg, JDH, in prep.

Ab Initio SD WIMP-Nucleus Response: ^{19}F, ^{23}Na, ^{27}Al, ^{29}Si

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

Two NN+3N interactions: 1.8/2.0(EM), NN+3N(LNL)



Padua, Leutheusser, Stroberg, JDH, in prep.

In progress: all nuclear targets to Xe, Spin Independent

TRIUMF

Present and Future for VS-IMSRG

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

Nuclear Structure

Development of forces and currents[1]

Dripline predictions for medium-mass

Evolution of magic numbers from masses, radii, spectroscopy, EM transitions: ^{78}Ni

Multi-shell theory:

- **Island of inversion[2]**
- **Forbidden decays[3]**

Atomic systems[4]

Fundamental Symmetries/BSM Physics

- **Effective electroweak operators: GT quenching**
- **Effective $0\nu\beta\beta$ decay operator[5]**
- **WIMP-Nucleus scattering[6]**
- **Superallowed Fermi transitions[7]**
- **Symmetry-violating moments [molecules][8]**

Outstanding issues

- **Controlled IMSRG(3) approximation***
- **E2 operators/collectivity problematic**
- **Understand discrepancies with CC**
- **Quantify uncertainties**

TRIUMF, McGill University, The University of British Columbia

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C. Gwak[3,8]
D. Livermore[4]
G. Tenkila[4]
A. Belley[5]
C. Payne[5]
J. Padua[6]
S. Leutheusser[6]

The University of Tennessee Knoxville: T. Morris, G. Hagen, T. Papenbrock

Technische Universität Darmstadt: A. Schwenk

東京大学 The University of Tokyo: J. Menéndez

Michigan State University: H. Hergert, S. Bogner

The University of North Carolina at Chapel Hill: J. Engel

Colorado School of Mines: M. Martin[7], K. G. Leach

JGU: J. Simonis[1]

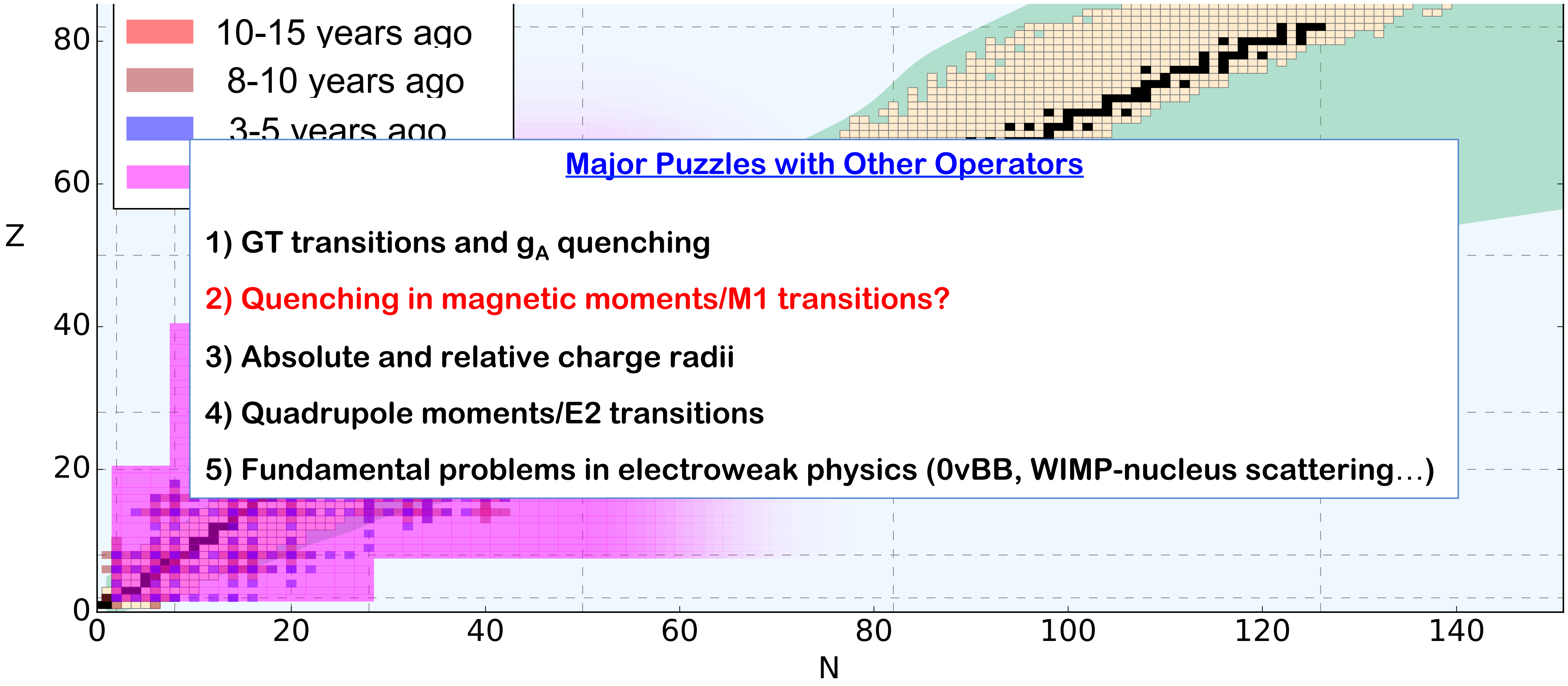
Massachusetts Institute of Technology: R. F. Garcia-Ruiz[8]

Breadth of Ab Initio: Towards Global Calculations

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

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

$$H\psi_n = E_n\psi_n$$



Major Puzzles with Other Operators

1) GT transitions and g_A quenching

2) Quenching in magnetic moments/M1 transitions?

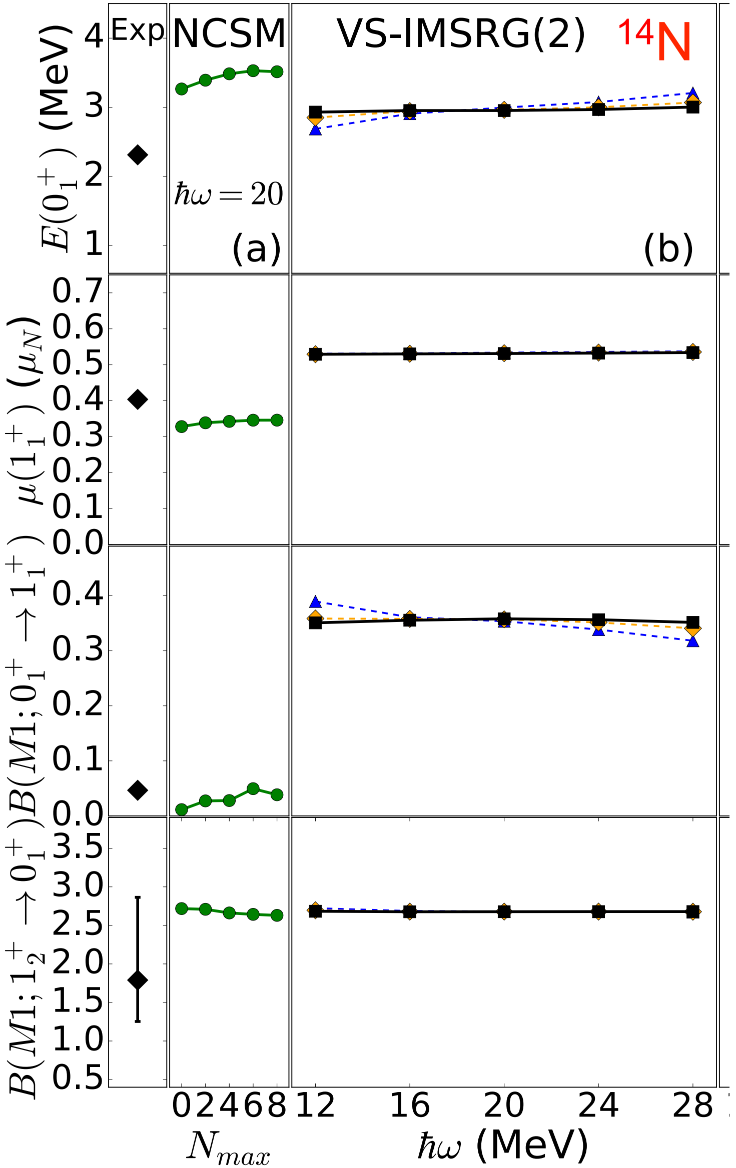
3) Absolute and relative charge radii

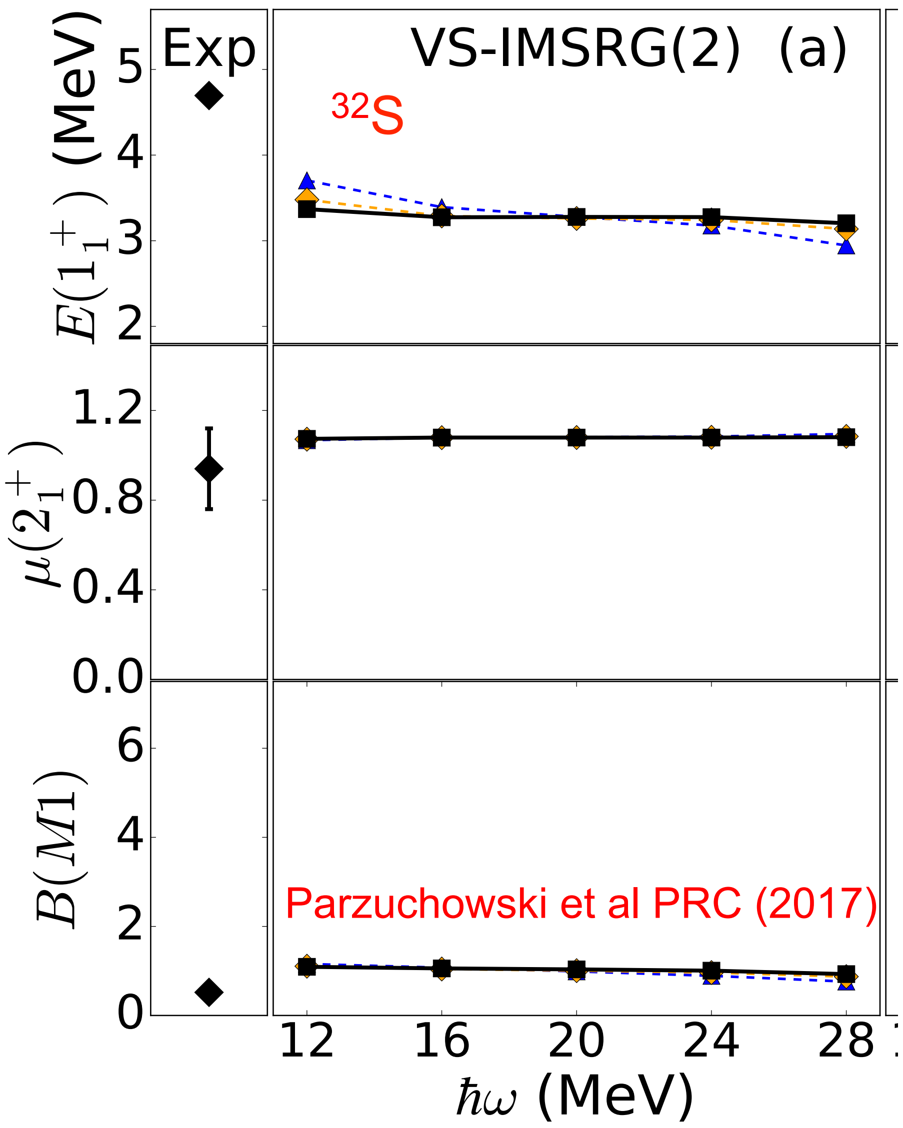
4) Quadrupole moments/E2 transitions

5) Fundamental problems in electroweak physics (0vBB, WIMP-nucleus scattering…)

Similar: Quenching of Magnetic Moments?

Similar effects expected as in GT quenching: renormalized operator + 2BC ~0.75-0.8





Reasonable experimental agreement: additional quenching needed

No inclusion of 2BC yet - developments underway…

TRIUMF

Breadth of Ab Initio: Towards Global Calculations

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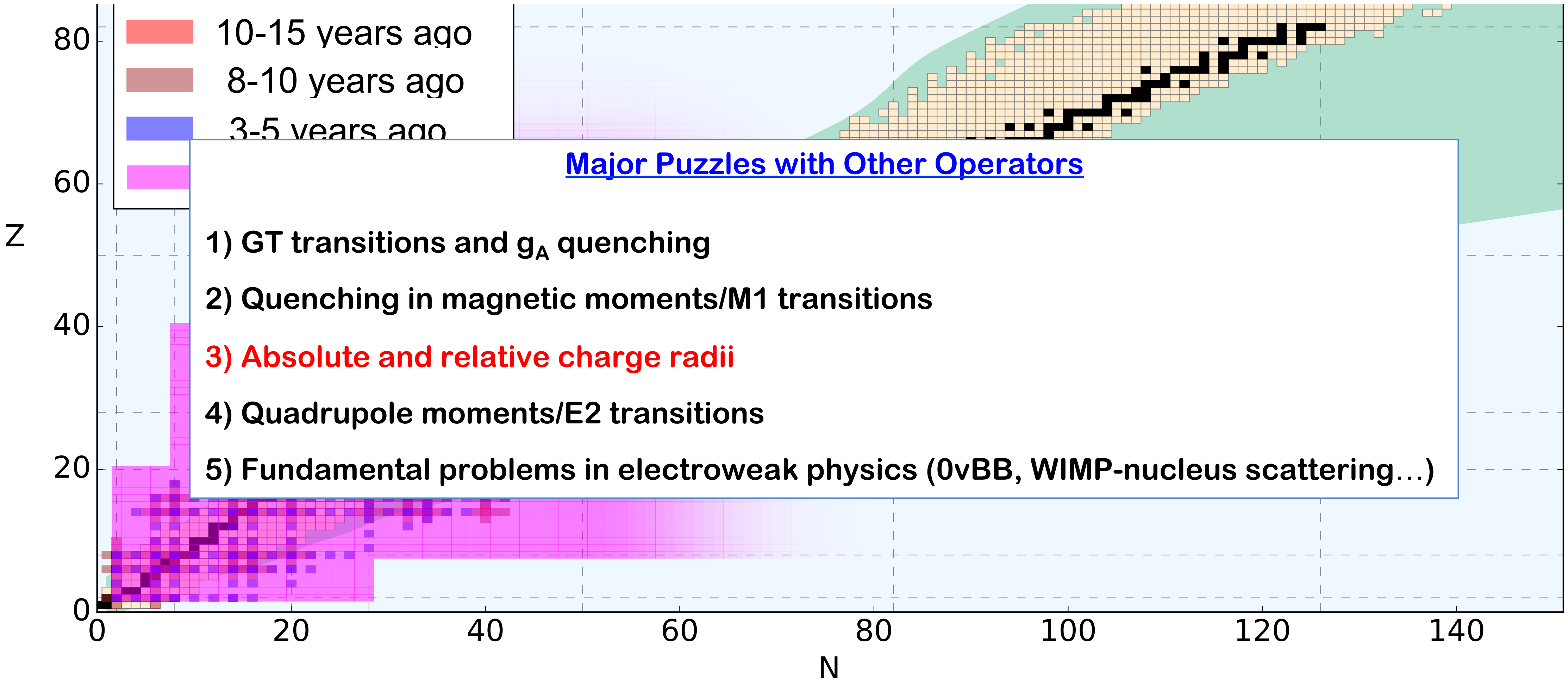

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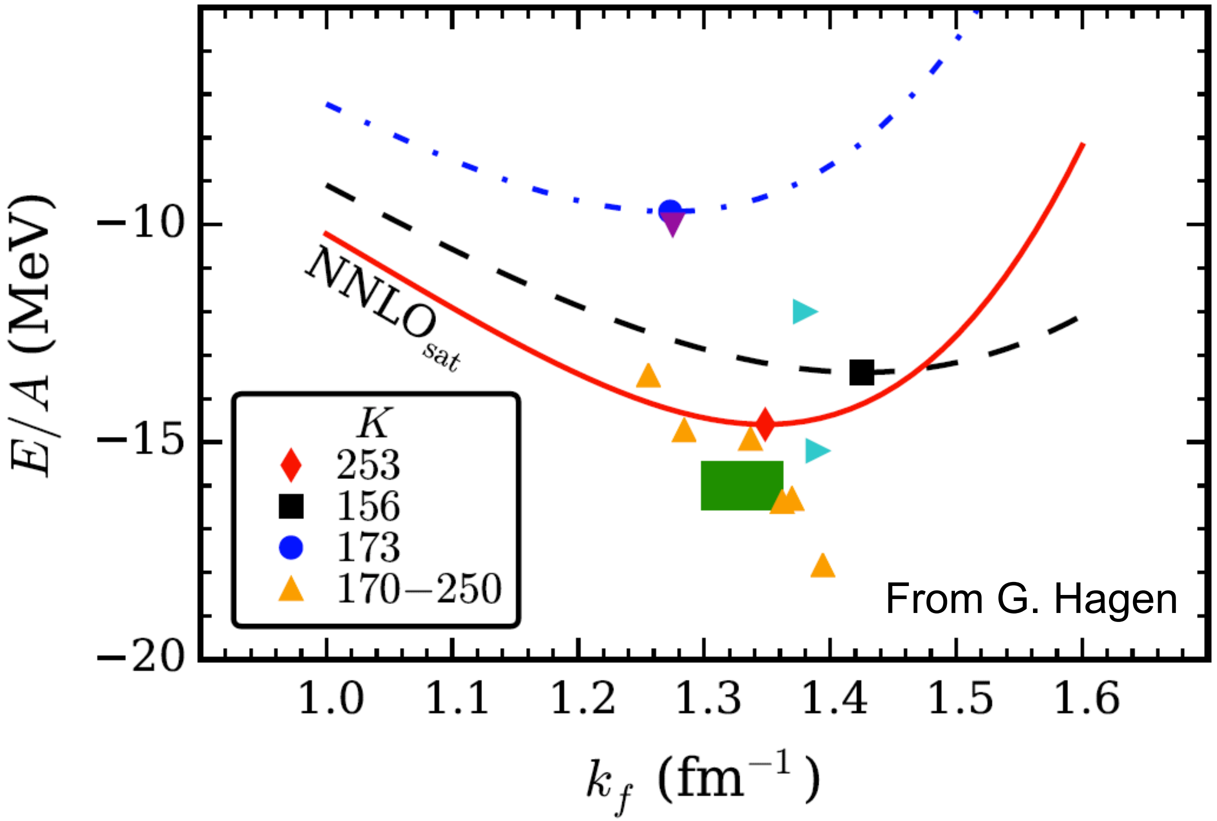
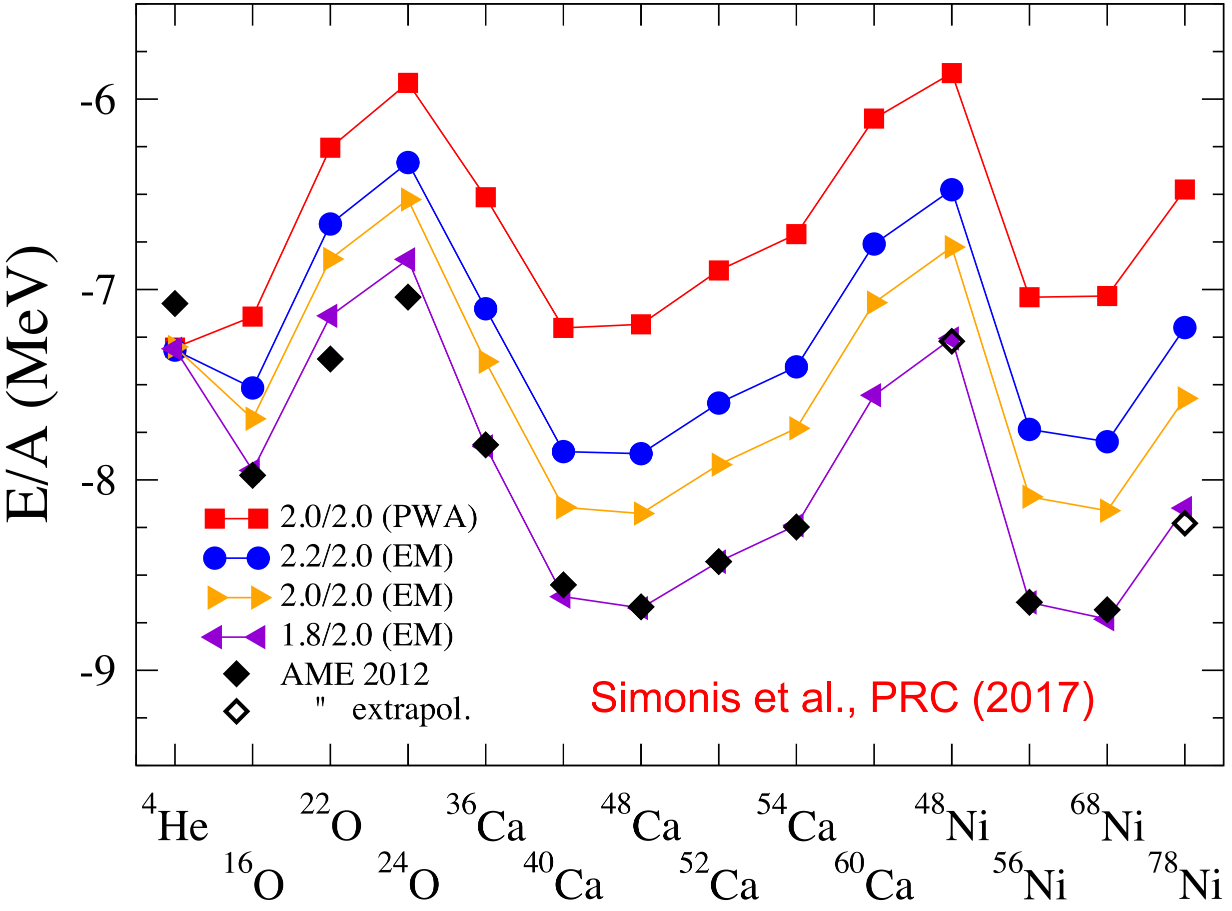
Connection to Infinite Matter: Saturation as a Guide

NN+3N force with good reproduction of ground-state energies



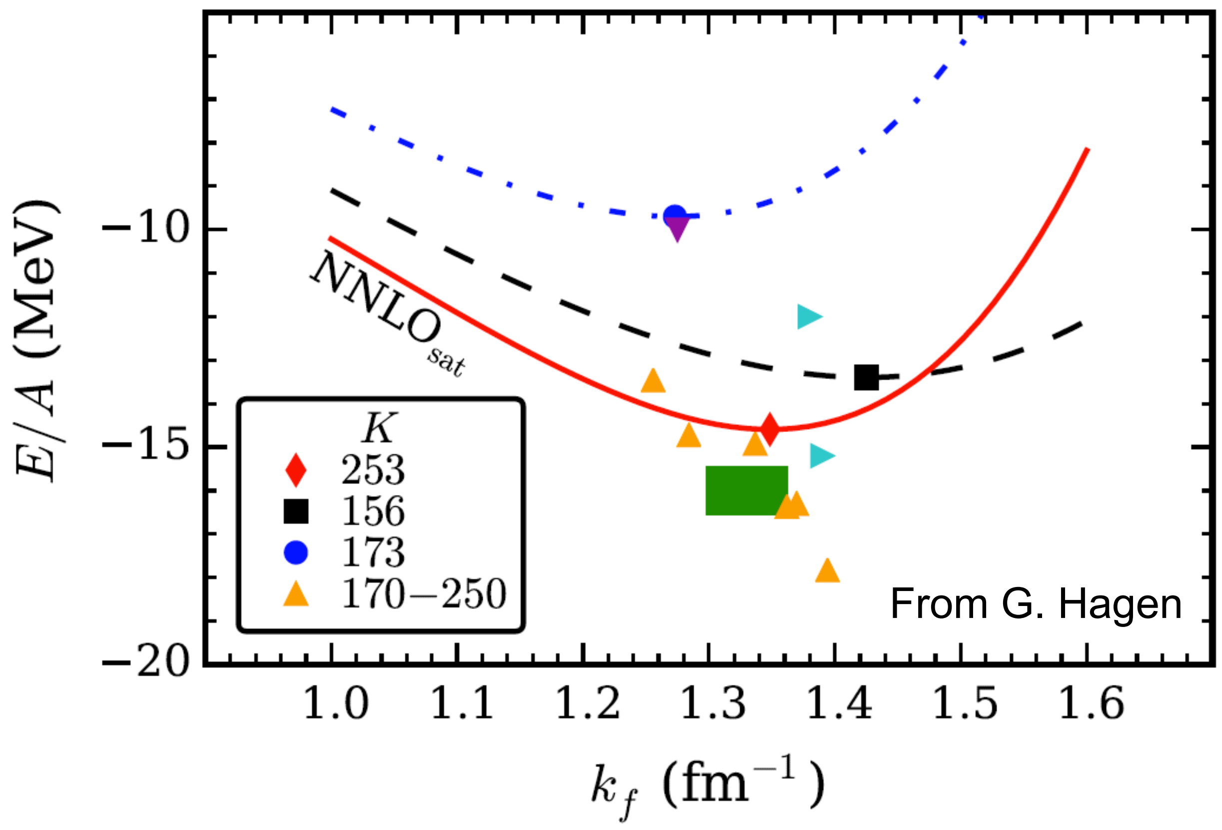


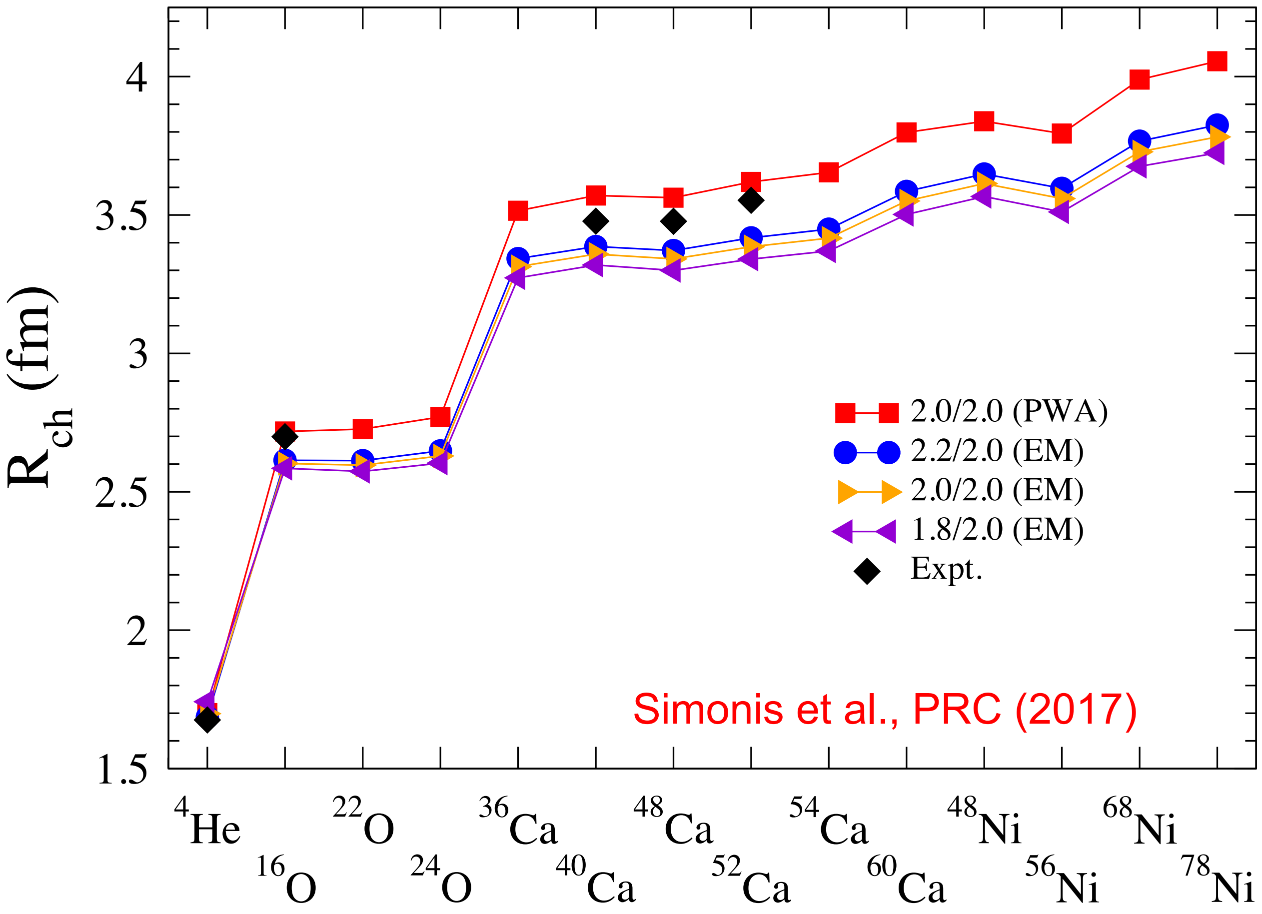
1.8/2.0 (EM) reproduces ground-state energies through ^{78}Ni

Slight underbinding for neutron-rich oxygen

Connection to Infinite Matter: Saturation as a Guide

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



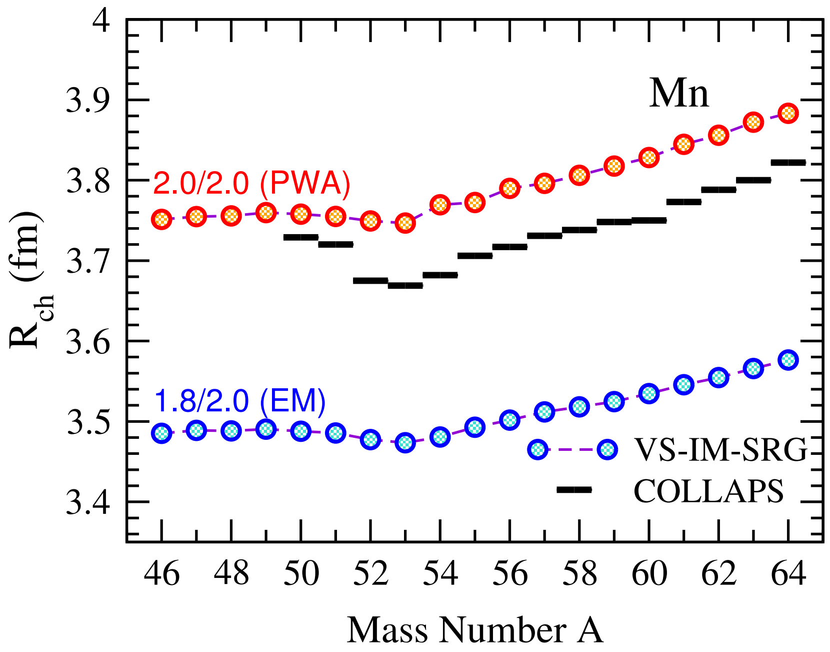


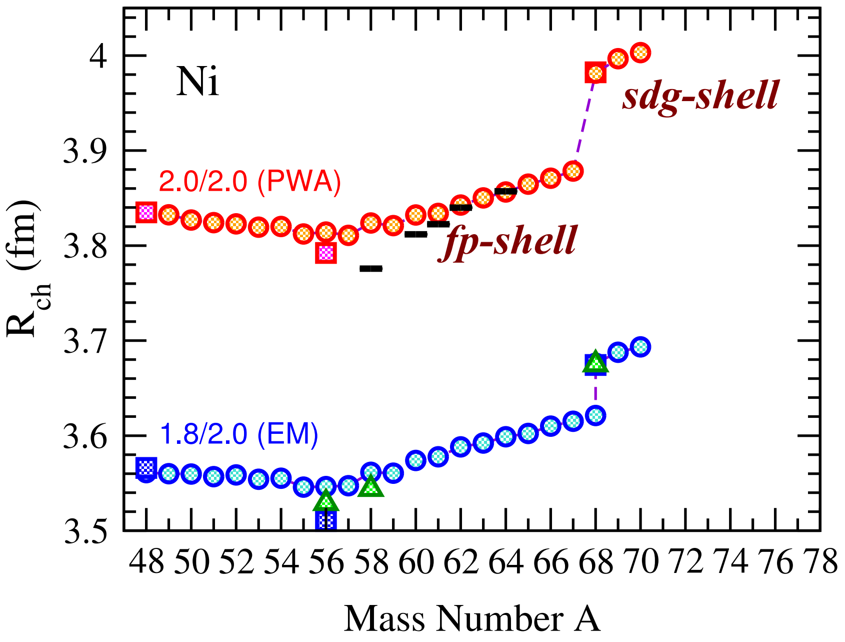
Description of radii depends on saturation density

No interactions reproduces perfectly total charge radii

Charge Radii Across Isotopic Chains

Study charge radii across isotopic chains: $\langle R^2 \rangle = \left\langle \Phi_0 \mid \tilde{R}^2 \mid \Phi_0 \right\rangle + \left\langle \Phi_{SM} \mid \tilde{R}^2 \mid \Phi_{SM} \right\rangle$



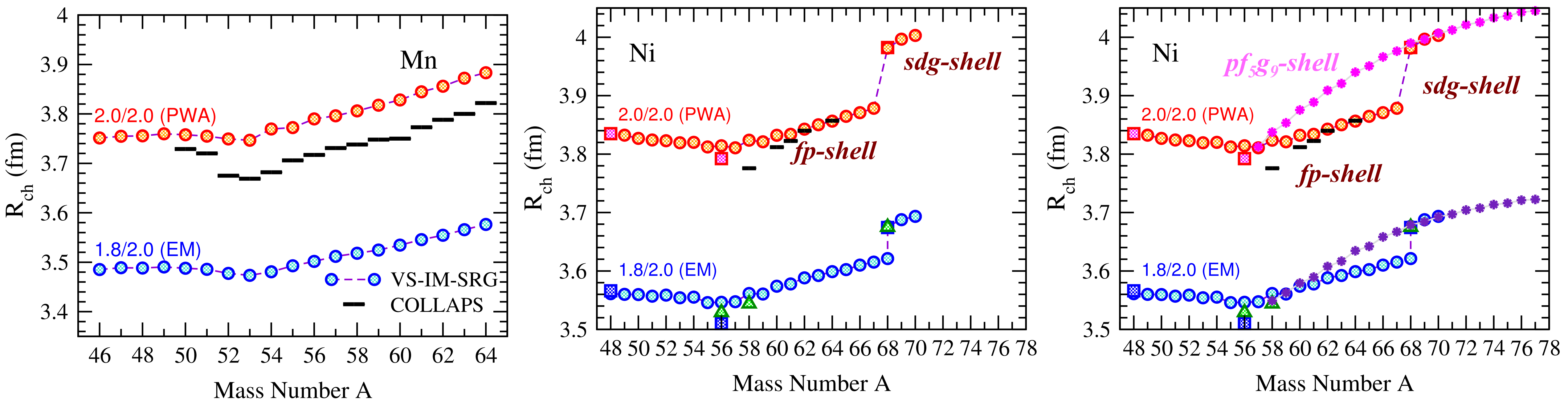


2.0/2.0 (PWA) “best” results: overpredicts experiment, less pronounced trends

Clear discrepancy at ^{68}Ni: benchmark against CC and GGF in progress

Charge Radii Across Isotopic Chains

Study charge radii across isotopic chains: $\left\langle R^2 \right\rangle = \left\langle \Phi_0 \mid \tilde{R}^2 \mid \Phi_0 \right\rangle + \left\langle \Phi_{\rm SM} \mid \tilde{R}^2 \mid \Phi_{\rm SM} \right\rangle$



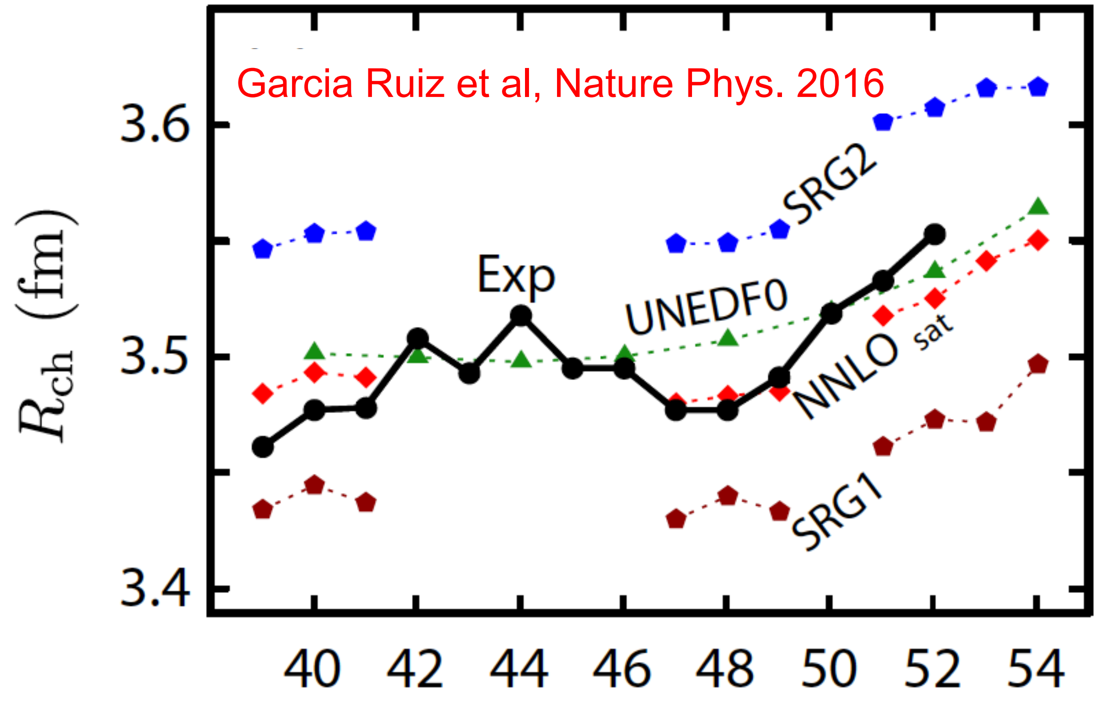
2.0/2.0 (PWA) “best” results: overpredicts experiment, less pronounced trends

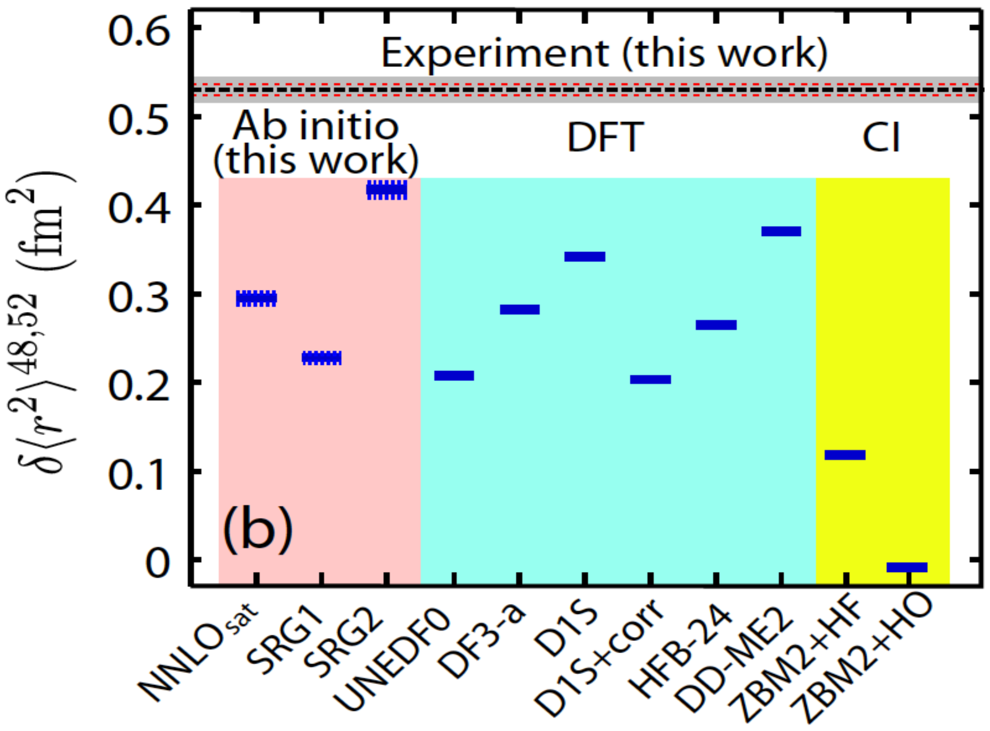
Clear discrepancy at ^{68}Ni: benchmark against CC and GGF in progress

Multi-shell VS-IMSRG in progress…

N=32 Magic Number: Charge Radii

Charge radii of $^{49-52}$Ca measured from laser spectroscopy at COLLAPS, CERN



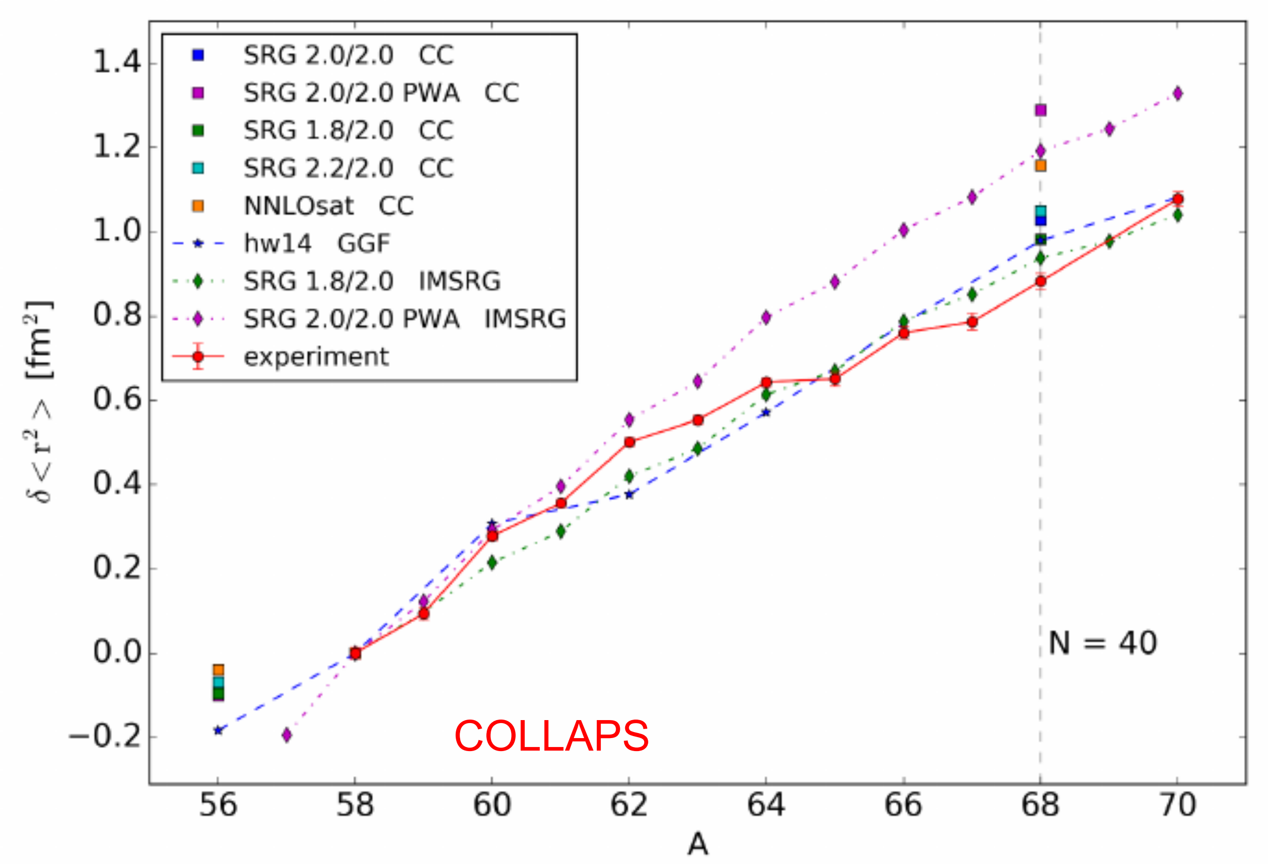


Unexpected increase in charge radius questions magicity of ^{52}Ca

Theory underestimates this increase – challenge for future

Relative Charge Radii Across Isotopic Chains: Ni

Study charge radii across isotopic chains: $$\langle R^2 \rangle = \left\langle \Phi_0 \mid \tilde{R}^2 \mid \Phi_0 \right\rangle + \left\langle \Phi_{\rm SM} \mid \tilde{R}^2 \mid \Phi_{\rm SM} \right\rangle$$

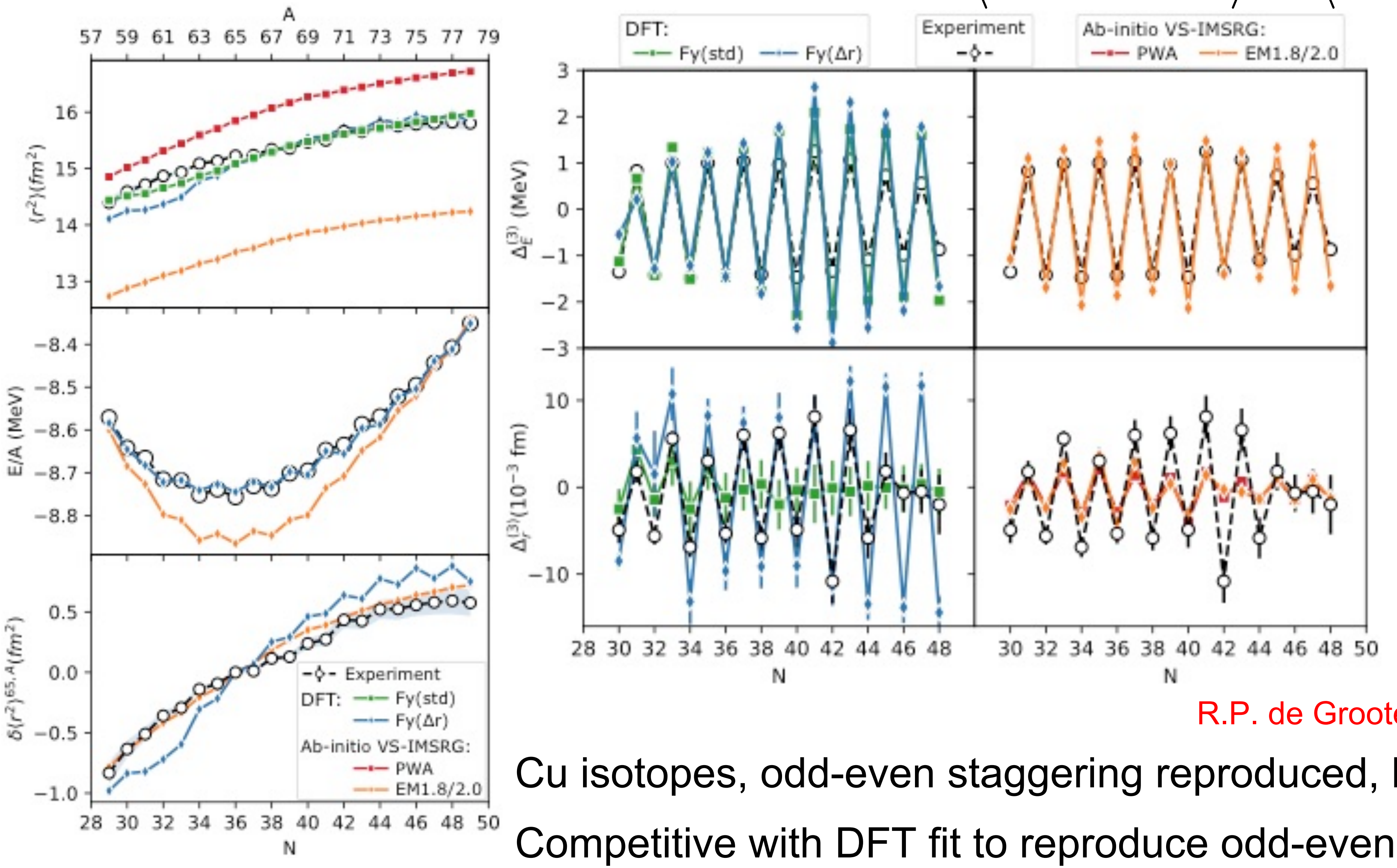


Study radii normalized to reference (as measured in laser spec. experiments)

1.8/2.0(EM) reproduces trends more accurately in Ni isotopes

Charge Radii Across Isotopic Chains: Cu

Study charge radii across isotopic chains: $\langle R^2 \rangle = \left\langle \Phi_0 \mid \tilde{R}^2 \mid \Phi_0 \right\rangle + \left\langle \Phi_{SM} \mid \tilde{R}^2 \mid \Phi_{SM} \right\rangle$



R.P. de Groote et al., Nat. Phys. (2020)

Cu isotopes, odd-even staggering reproduced, but still deficient

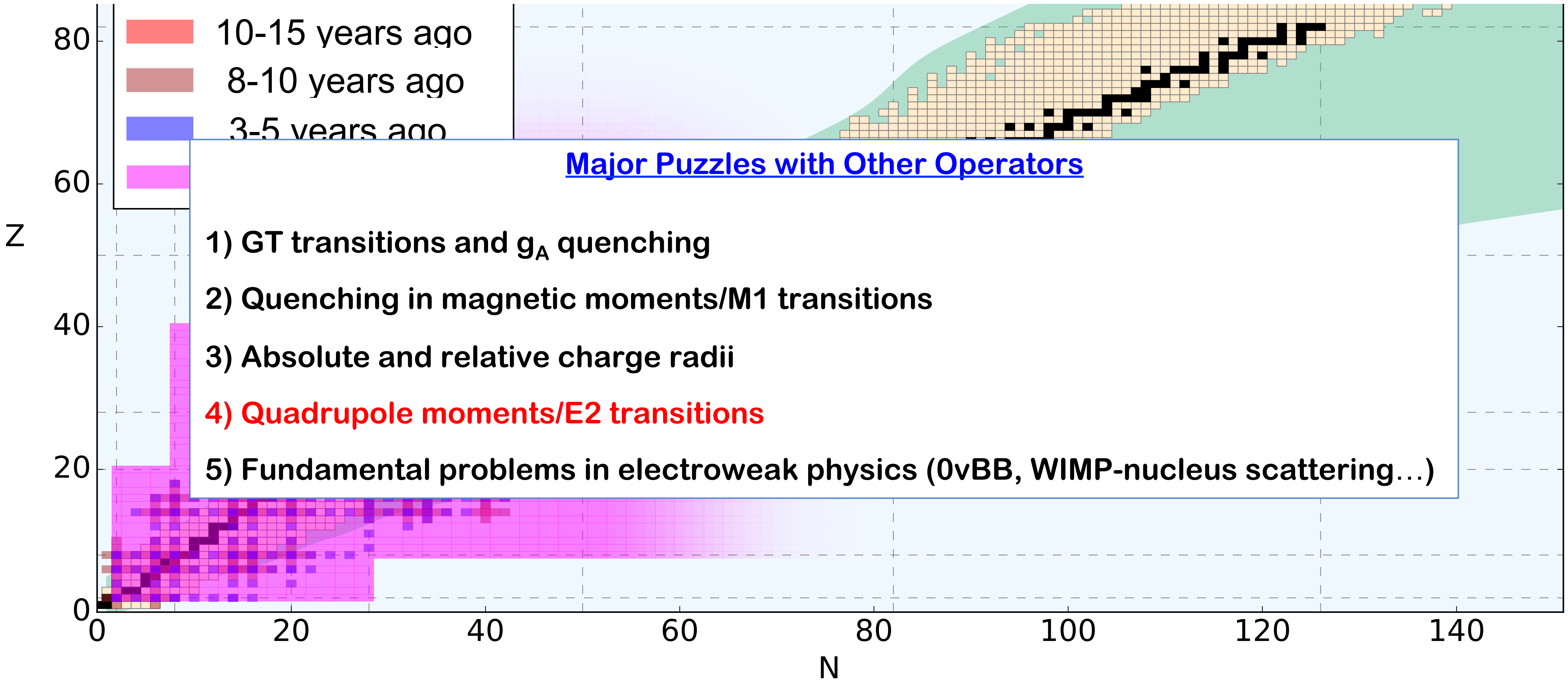
Competitive with DFT fit to reproduce odd-even staggering in region

Breadth of Ab Initio: Towards Global Calculations

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

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

$$H\psi_n = E_n\psi_n$$



Major Puzzles with Other Operators

1) **GT transitions and g_A quenching**

2) **Quenching in magnetic moments/M1 transitions**

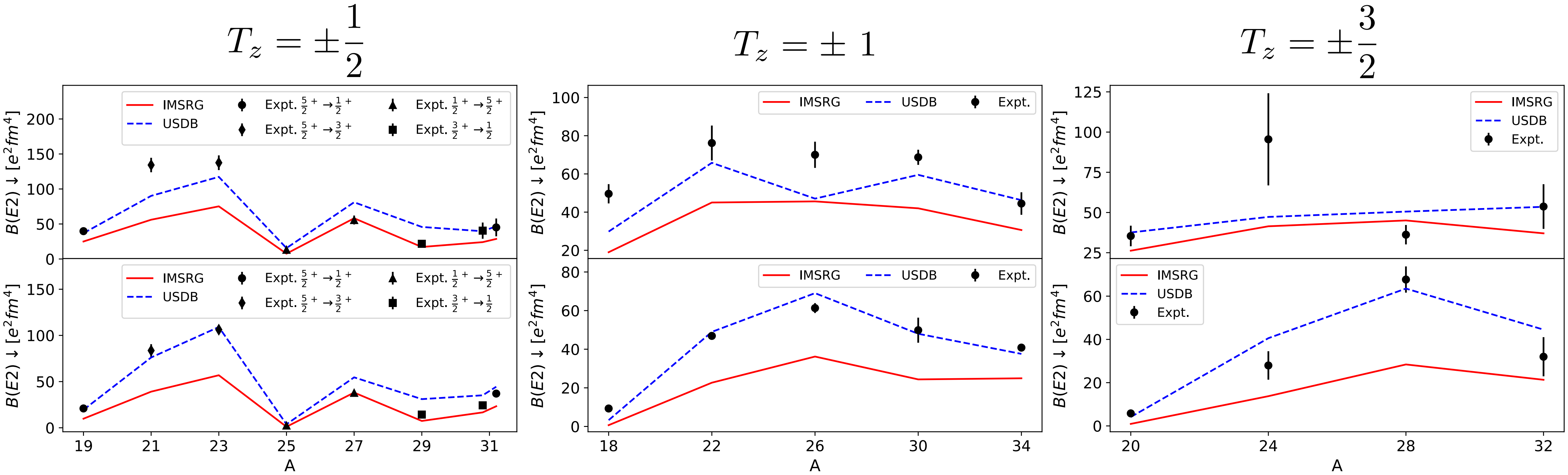
3) **Absolute and relative charge radii**

4) **Quadrupole moments/E2 transitions**

5) **Fundamental problems in electroweak physics (0vBB, WIMP-nucleus scattering…)**

Global Trends in Absolute B(E2): sd Shell

Study charge E2 transitions across sd-shell



USDB with effective charges typically reproduces absolute values well

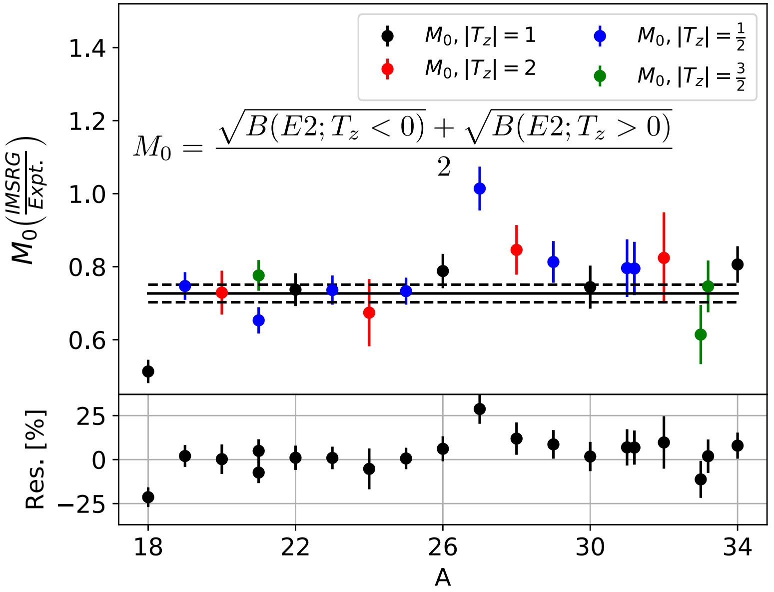
VS-IMSRG (**no effective charges**) typically underpredicts experiment

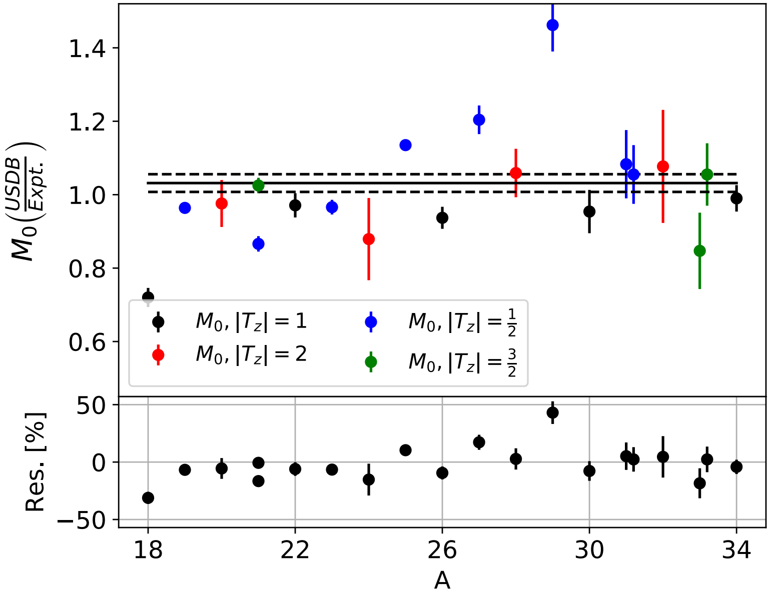
Trends well reproduced in both…

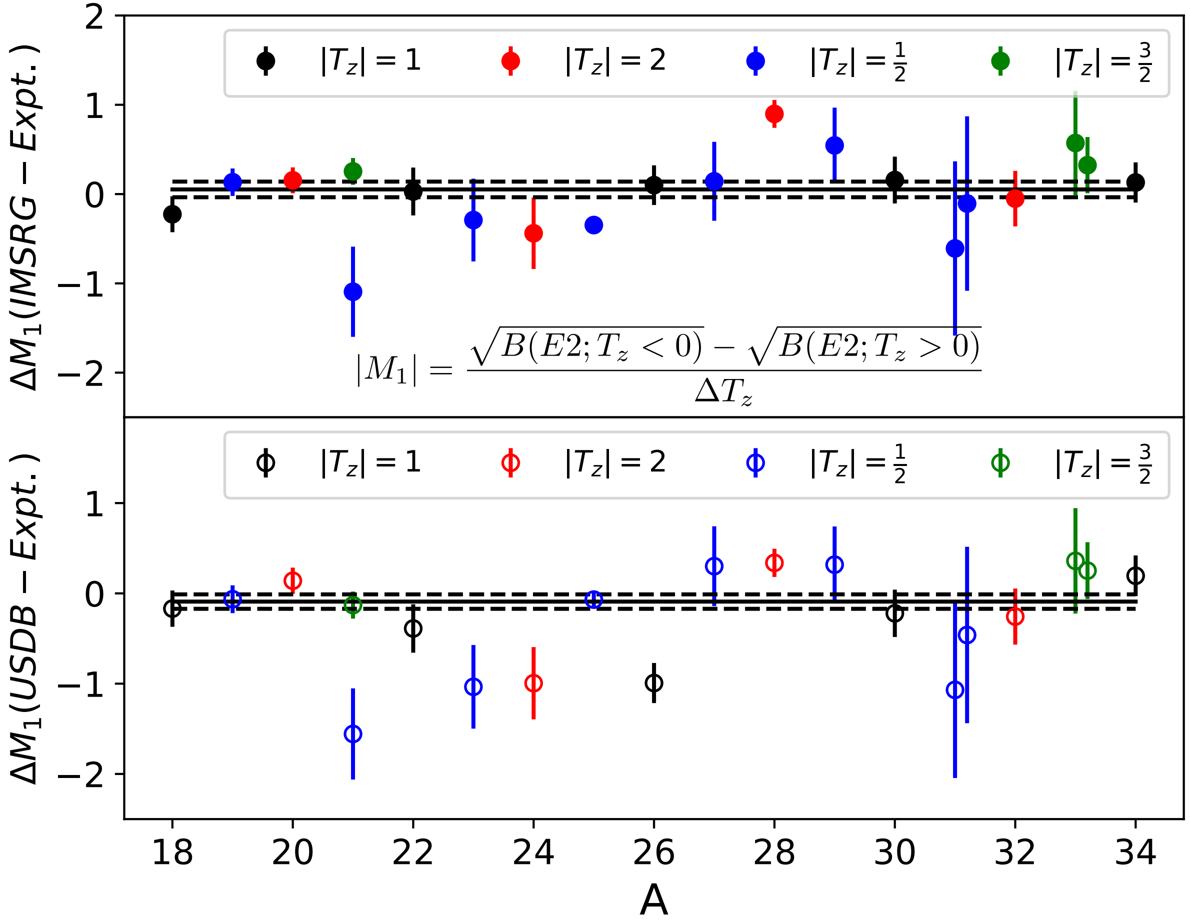
TRIUMF

Global Trends in B(E2): IS/IV Components

Study charge E2 transitions across sd-shell: IS (M_0) and IV (M_1)







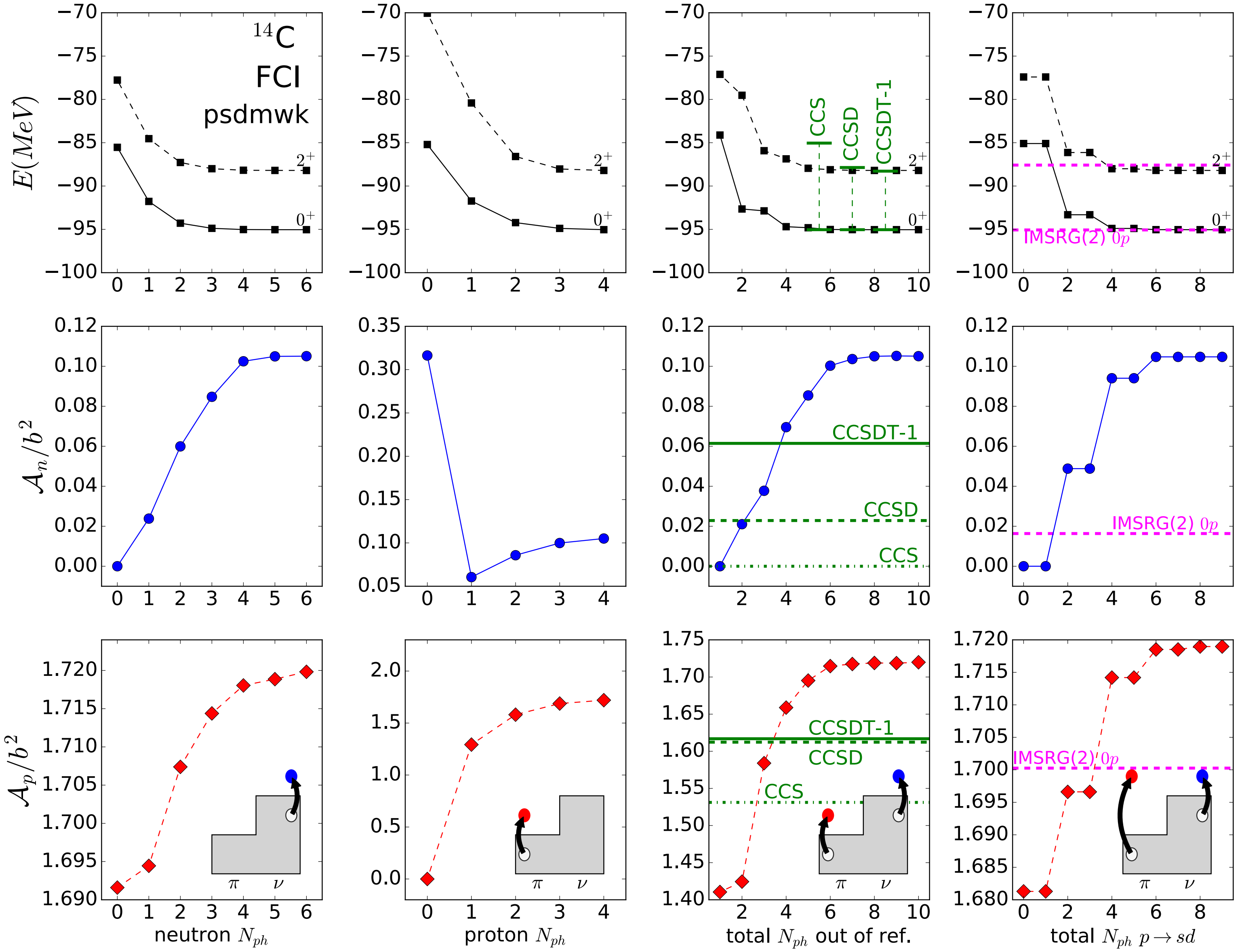
IS: USDB good agreement, VS-IMSRG systematically small

IV: Both agree well

Deficiencies in IS only

Origin of E2 Puzzle ^{14}C in psd Shell

Perform CC and VS-IMSRG calculations of ^{14}C in toy psd space with phenomenological potential



Energies well converged all around

p/n amplitudes increase with p/h ex.

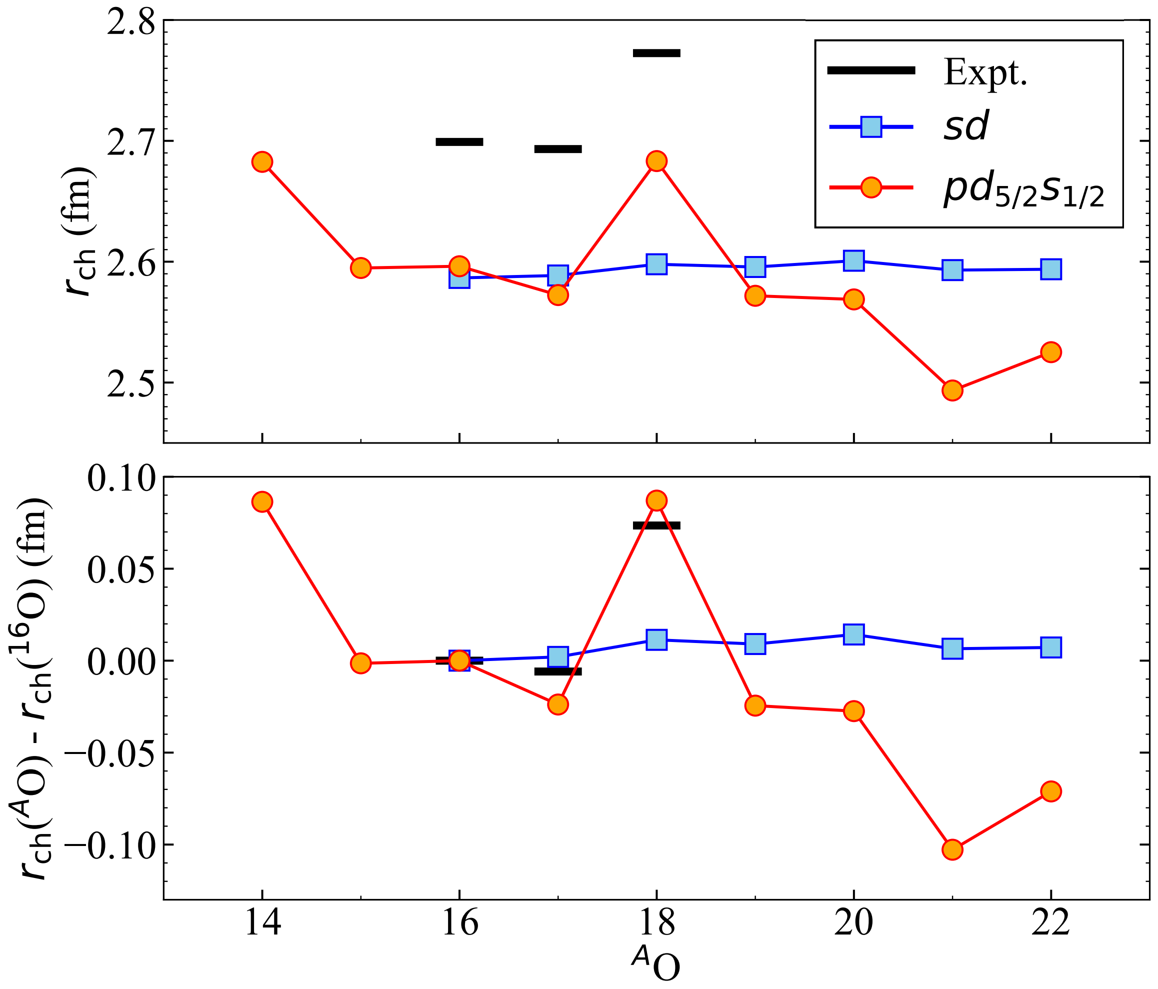
Only converged at 6-8 Nph

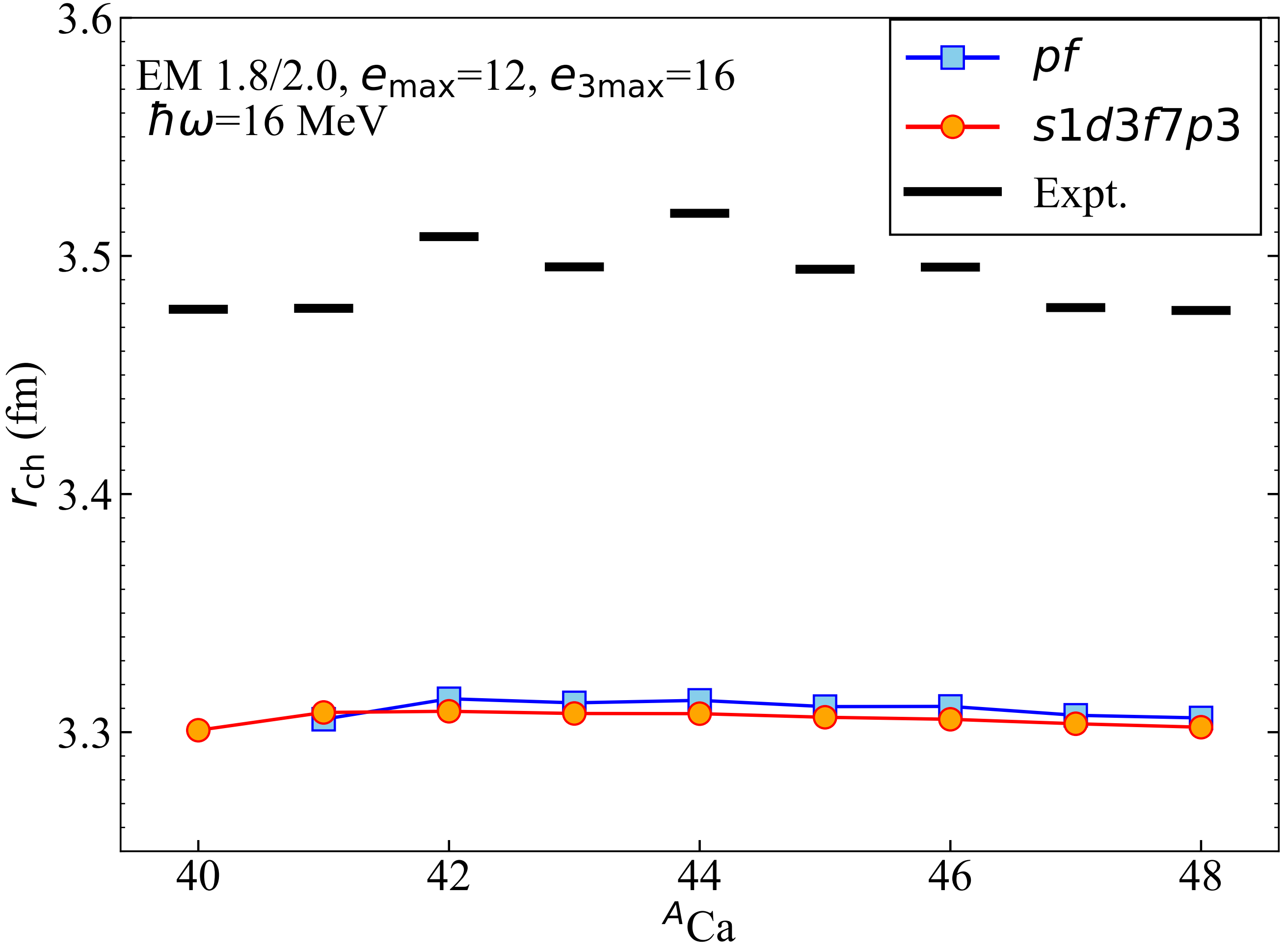
Not possible to capture in CC/IMSRG

Do Cross-Shell Spaces Improve Radii?

Improved trends across oxygen isotopes with pd5s1 space!

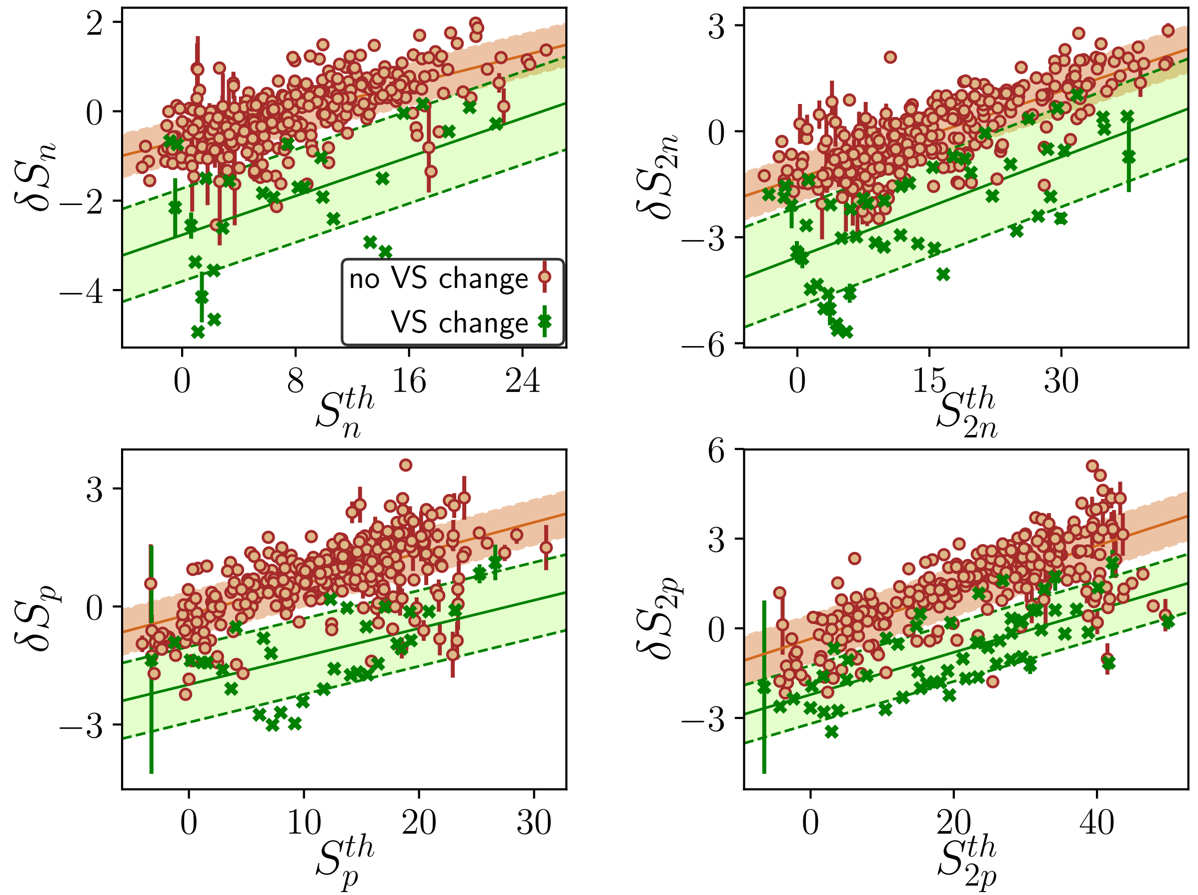
Calcium… not so much…





Shell Closures in Neutron-Rich Ni

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



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

JDH, Stroberg, Schwenk, Simonis, arXiv:1905.10475

Separate trends for VS change and no change

Correct VS-IMSRG results with linear fit of residuals

Present and Future for VS-IMSRG

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

Nuclear Structure

Development of forces and currents[1]

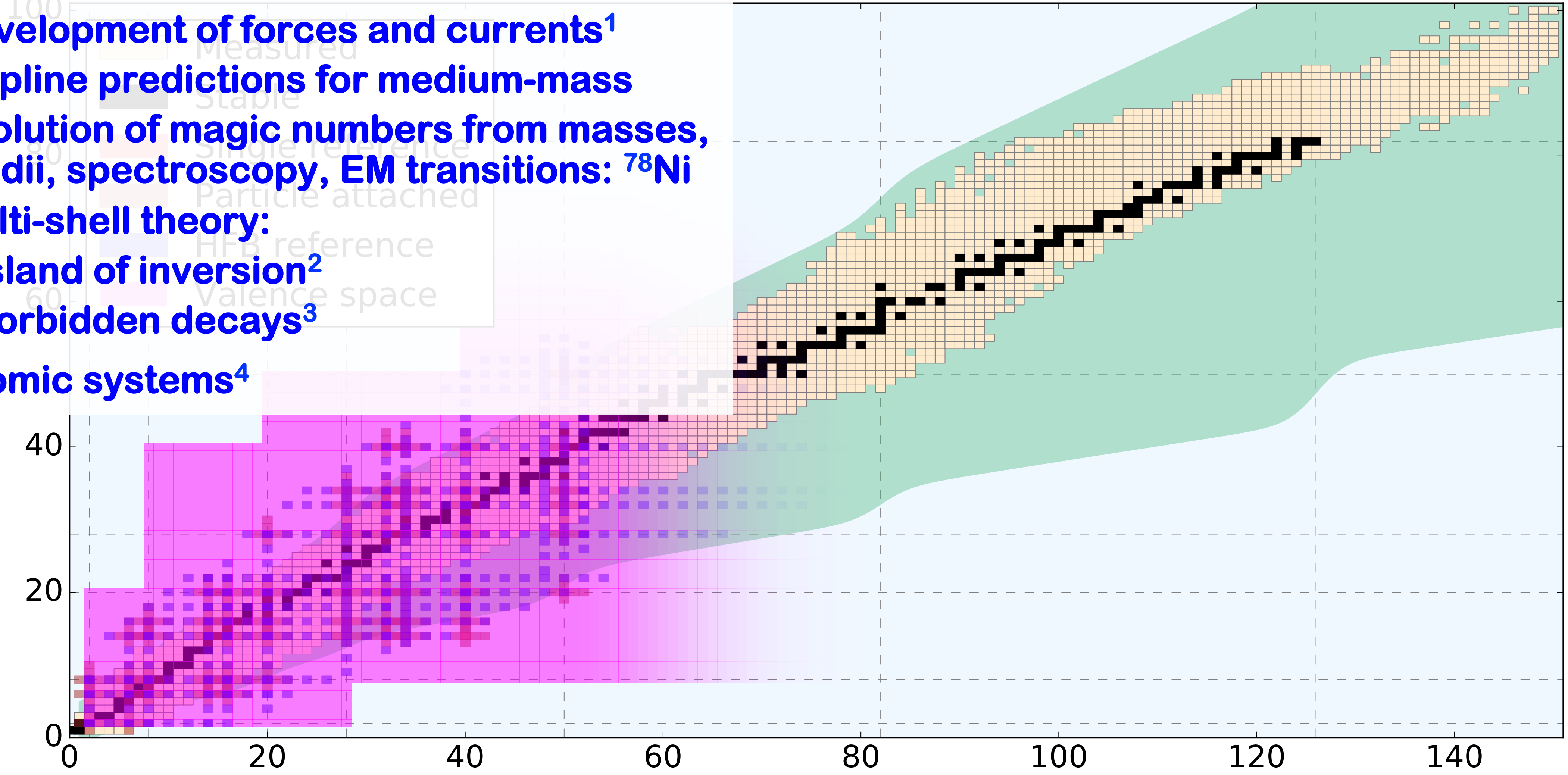
Dripline predictions for medium-mass

Evolution of magic numbers from masses, radii, spectroscopy, EM transitions: ^{78}Ni

Multi-shell theory:

- **Island of inversion[2]**
- **Forbidden decays[3]**

Atomic systems[4]



Present and Future for VS-IMSRG

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

Nuclear Structure

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Evolution of magic numbers from masses, radii, spectroscopy, EM transitions: ^{78}Ni

Multi-shell theory:

- **Island of inversion[2]**
- **Forbidden decays[3]**

Atomic systems[4]

Fundamental Symmetries/BSM Physics

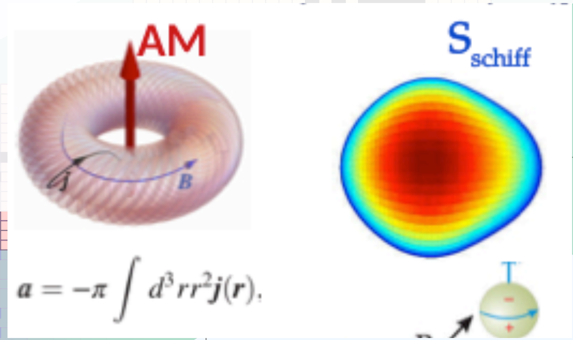
Effective electroweak operators: GT quenching

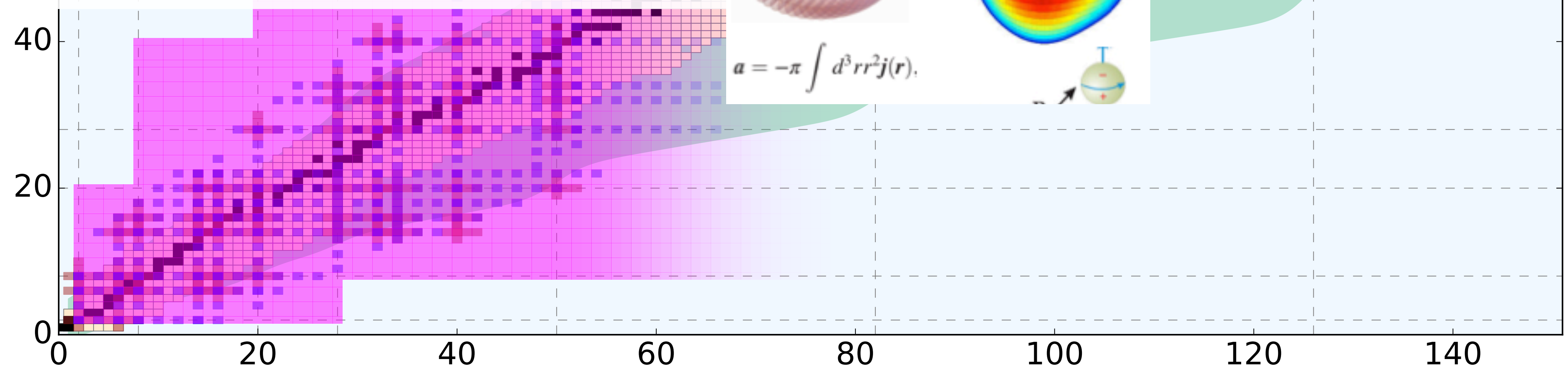
Effective $0\nu\beta\beta$ decay operator[5]

WIMP-Nucleus scattering[6]

Superallowed Fermi transitions[7]

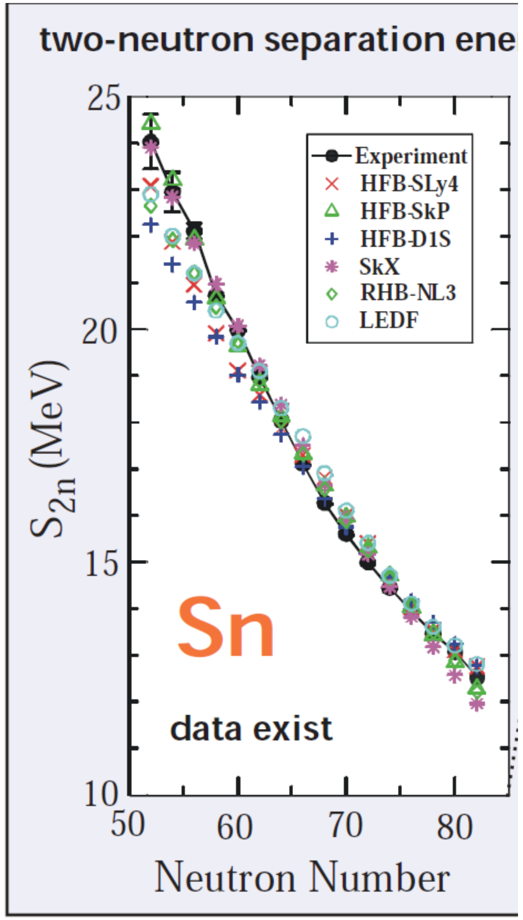
Symmetry-violating moments [molecules][8]





Predictions with Nuclear Models

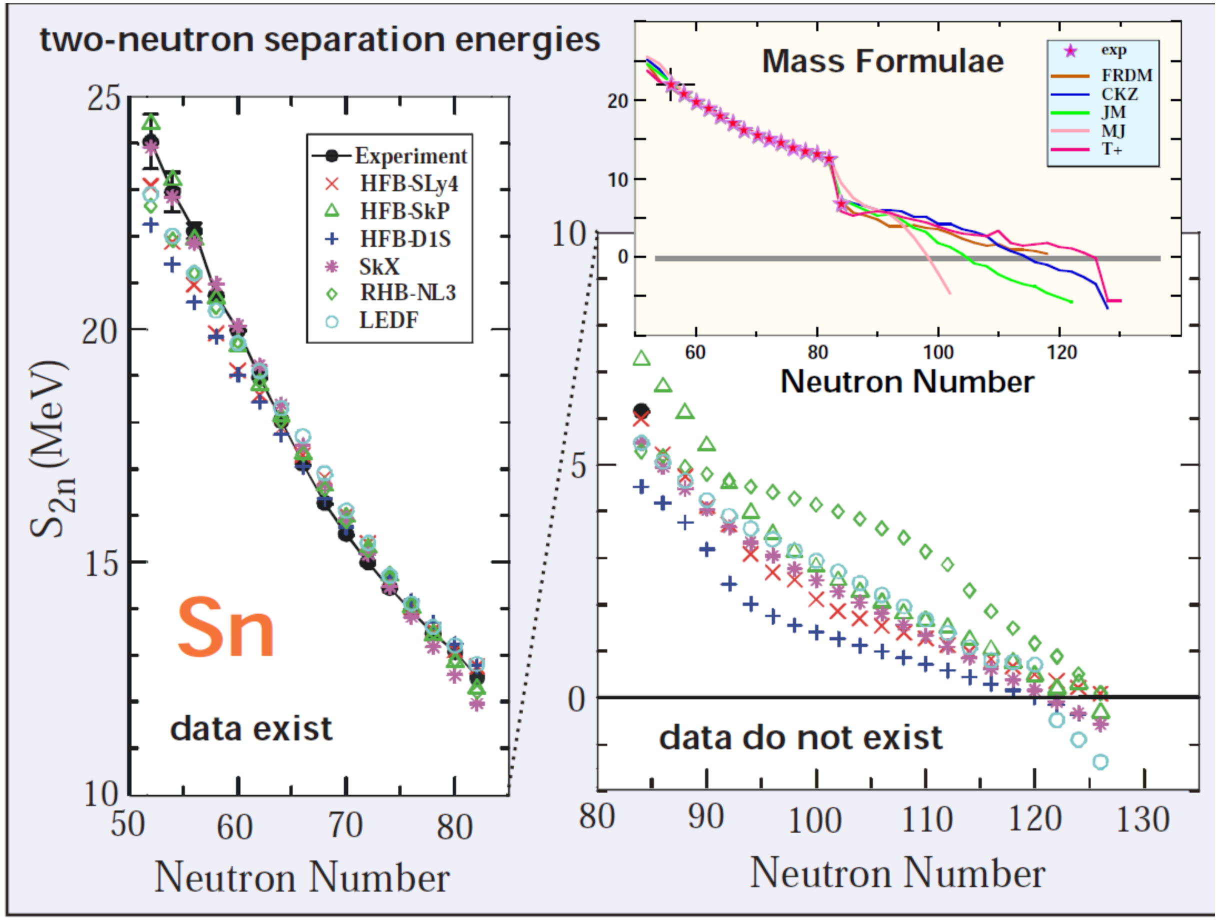
How well can nuclear models motivate experiments, predict beyond data?



Work well where informed by data

Predictions with Nuclear Models

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



Models can extrapolate unreliably

Spread in results ≠ meaningful uncertainty

Predictions with Nuclear Models

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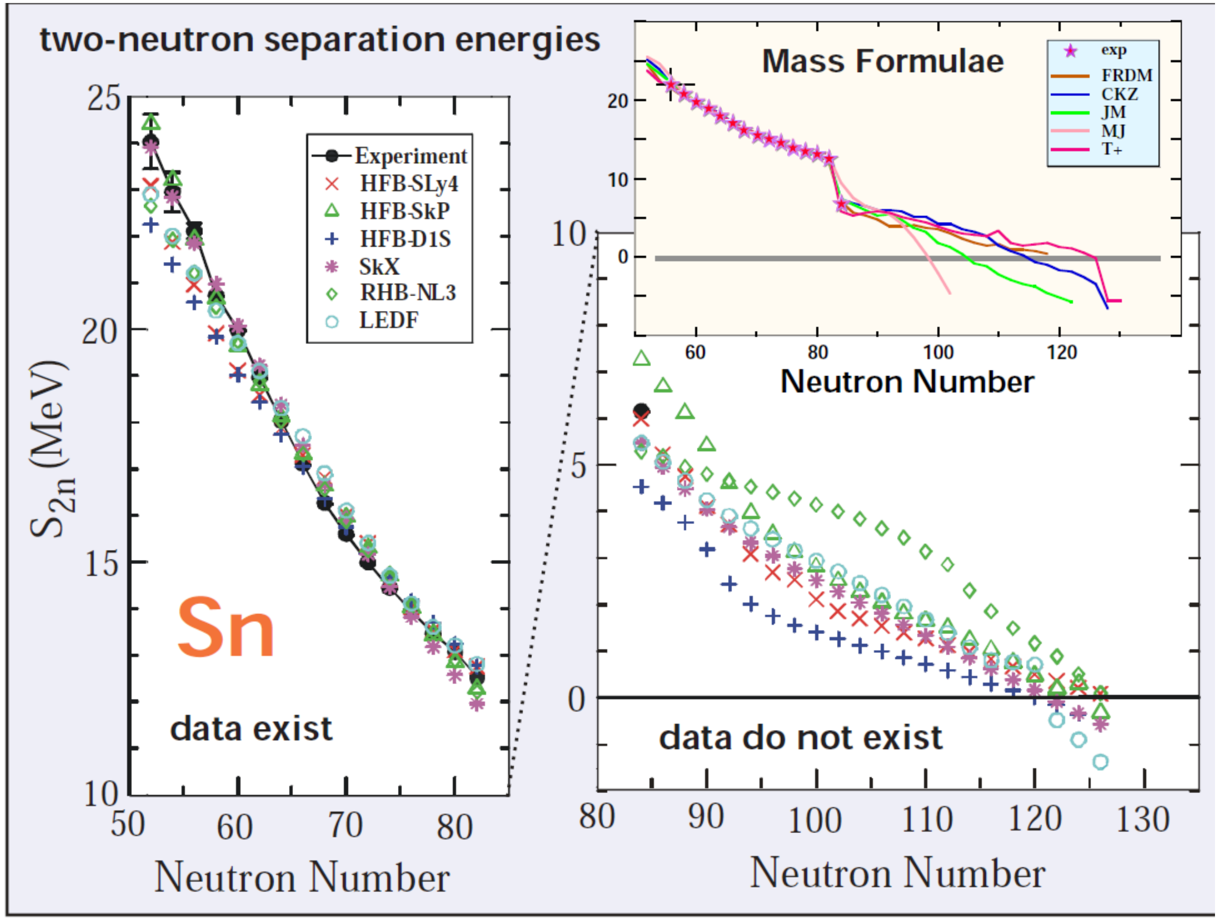
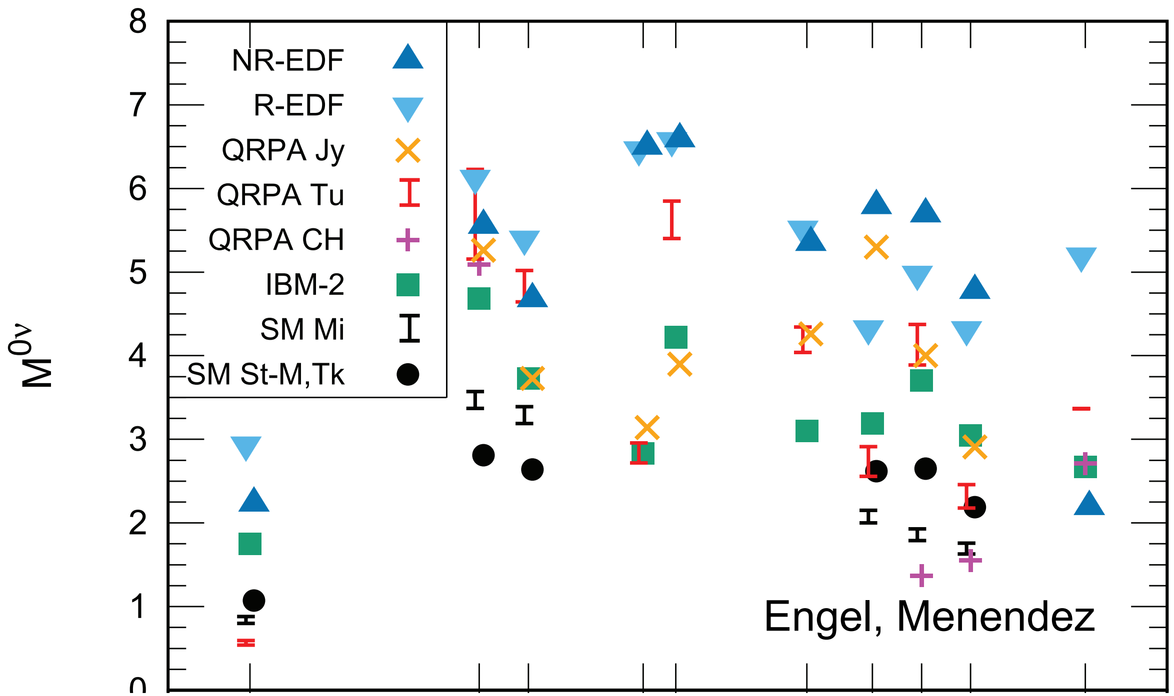


Analogous picture in $0\nu\beta\beta$ decay

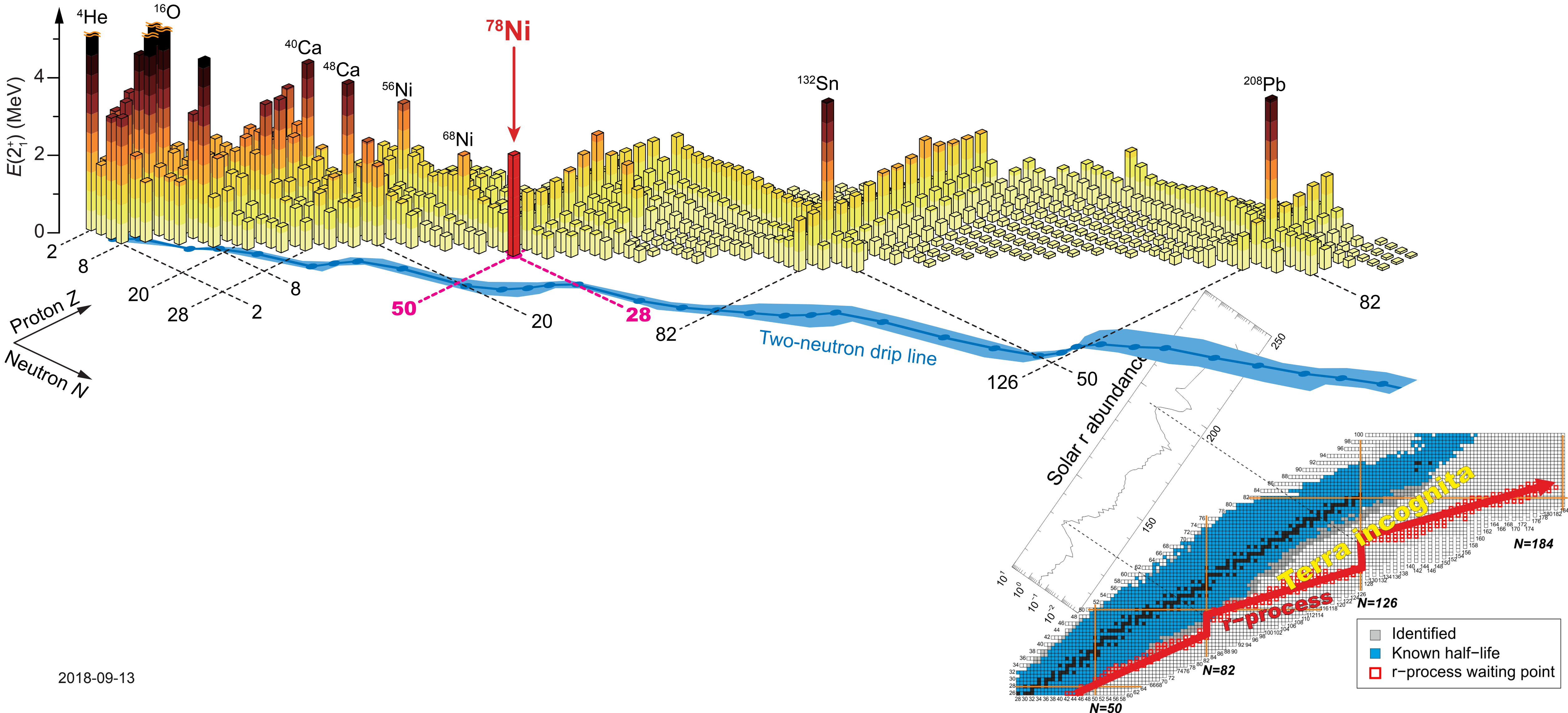


Models can extrapolate unreliably

Spread in results ≠ meaningful uncertainty

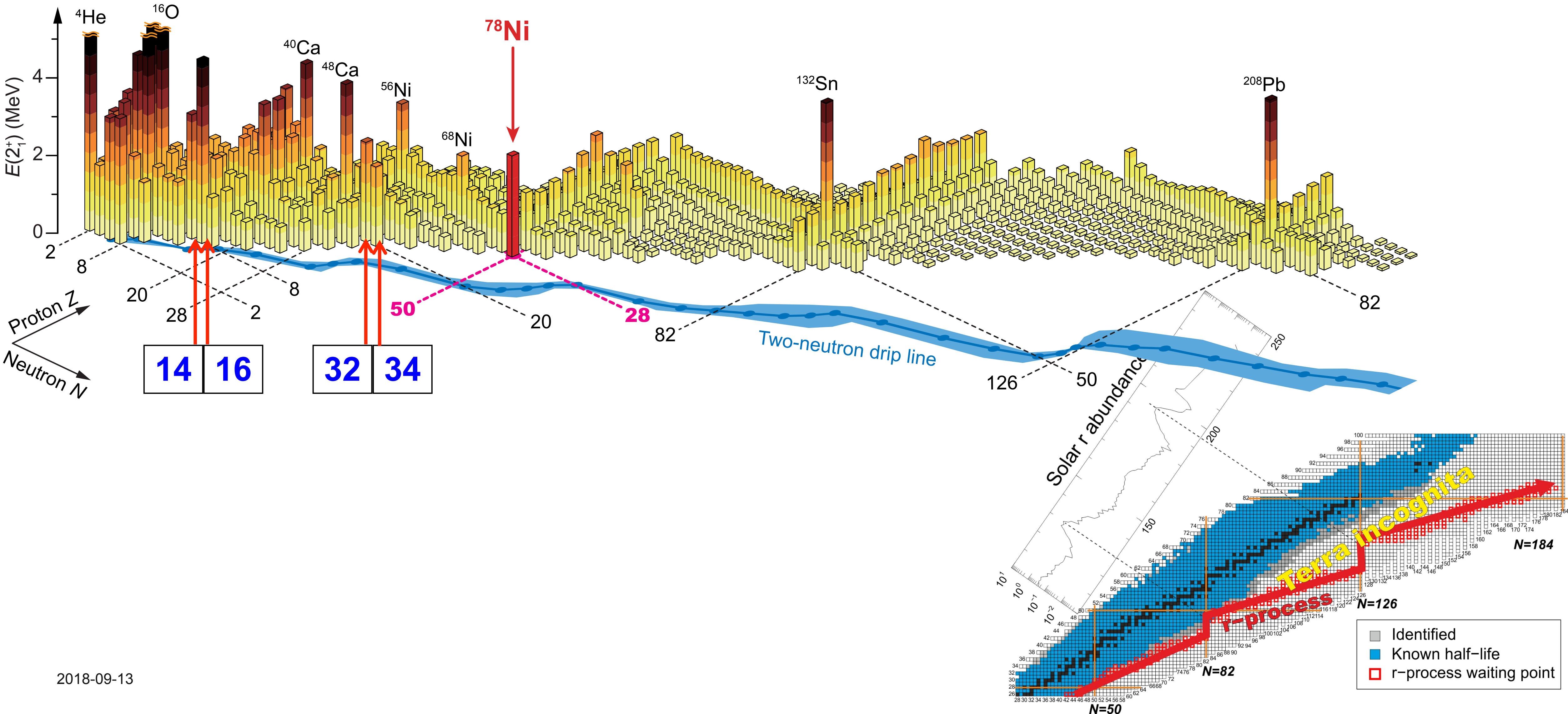
Major Issue II: Magic Numbers in Nuclei

Magic numbers: pillars of nuclear structure, vital for r-process nucleosynthesis



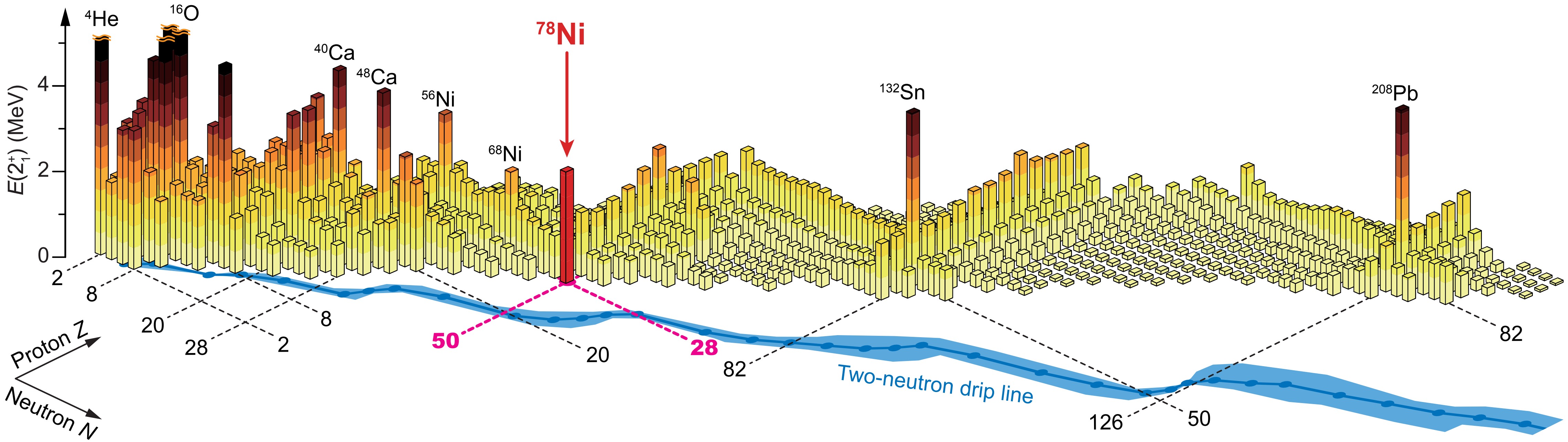
Magic Numbers in Nuclei

Magic numbers: pillars of nuclear structure, **novel evolution in exotic nuclei**



Magic Numbers in Nuclei

Magic numbers: pillars of nuclear structure, novel evolution in exotic nuclei



Signatures of Magic Numbers

Sharp decrease in separation energy (masses)

Elevated first excited 2+ energy (spectroscopy)

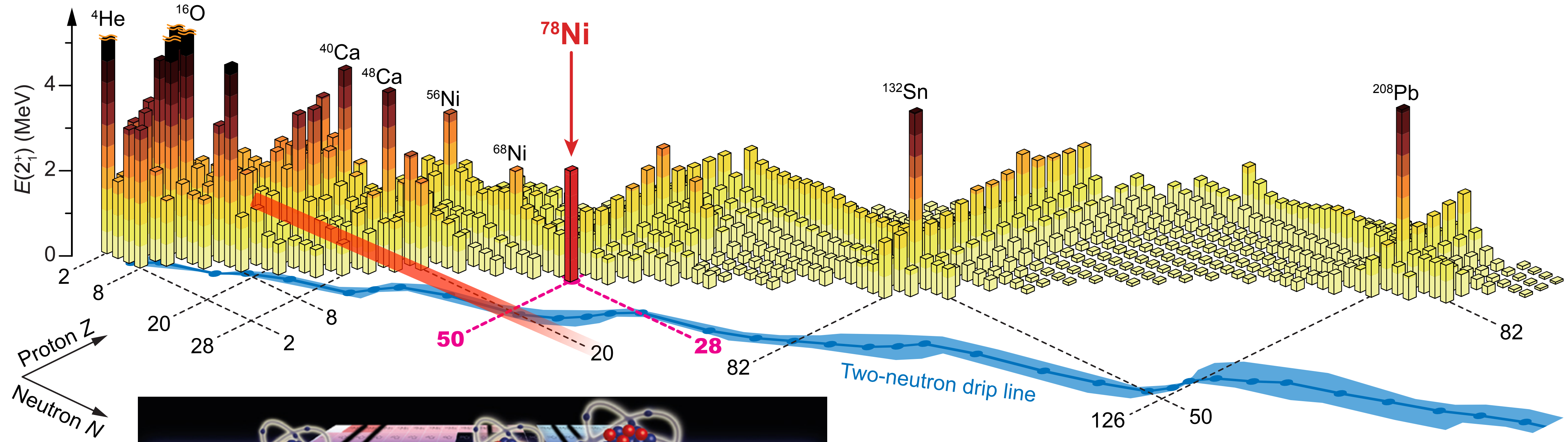
Tightly bound (decreased radii)

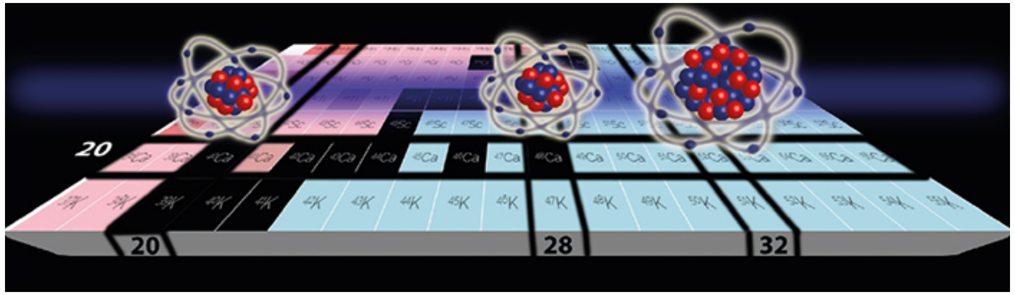
Must observe all signatures – many experiments (and calculations) needed!

TRIUMF

Evolution of N=32,34 Magic Numbers

Magic numbers: pillars of nuclear structure, novel evolution in exotic nuclei





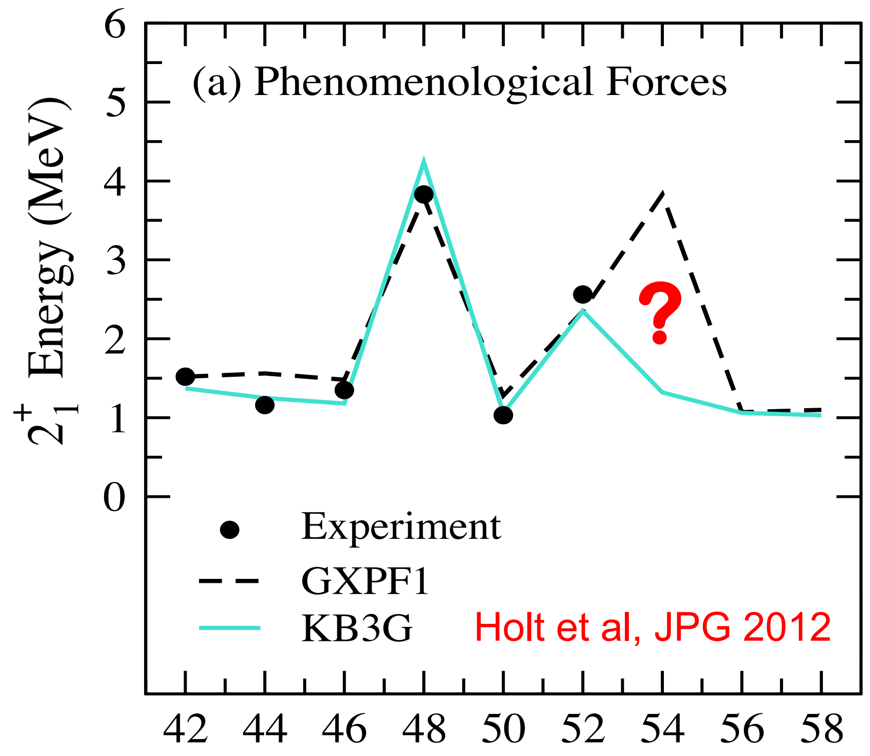
Highlight of TRIUMF theory and experiment:

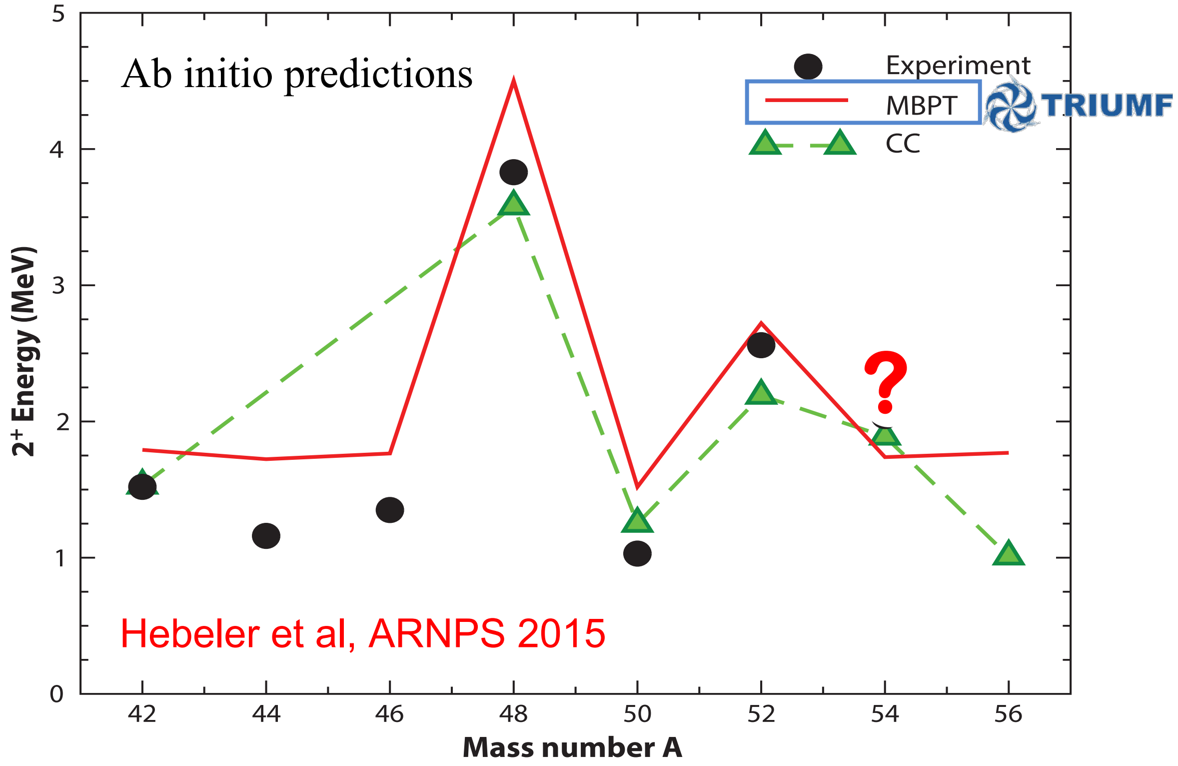
Discovery and evolution of new N=32,34 magic numbers in calcium region

Discovery, accelerated

Classic Picture of Magic Numbers

2013 potentially new magic numbers from 2^+ energies: N=32,34





Phenomenological Models

Reproduce magic N=28,32; discrepancy at N=34 (beyond data)

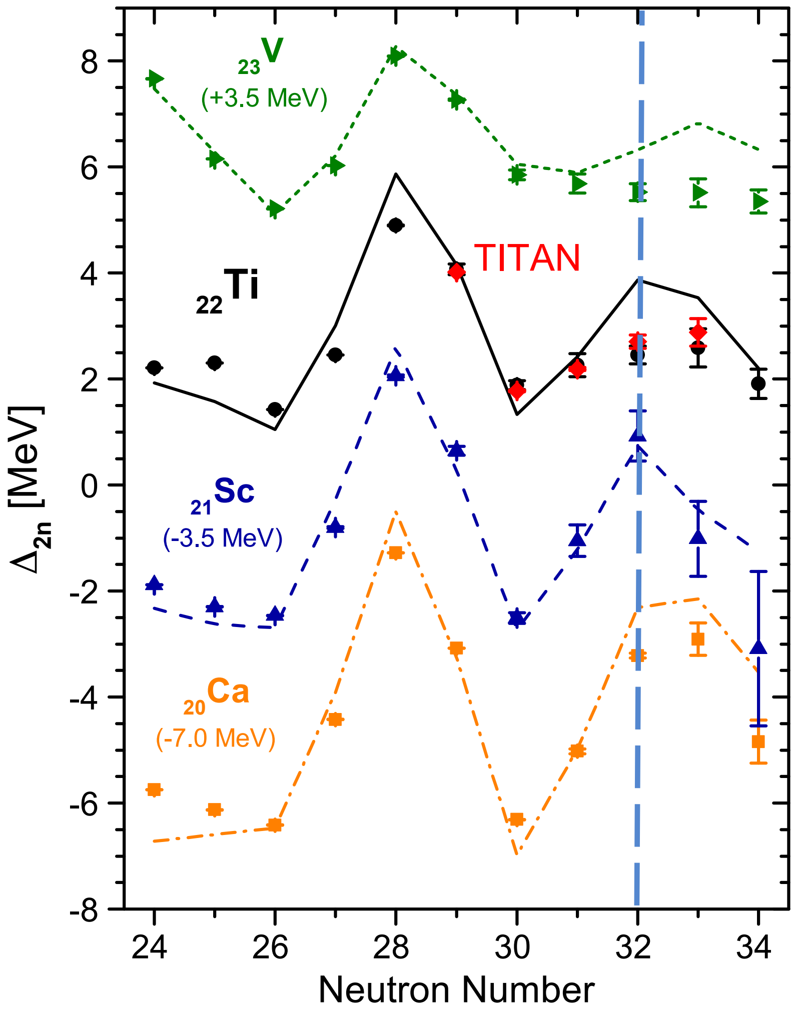
Ab initio theories

Predict all magic numbers; **consistent at N=34**

Evolution of N=32 Magic Number: Masses

Further questions: how do magic numbers evolve with proton number?

Current frontier of measurements and theory



New TITAN Measurements of Ti masses

Probe "dawning" of N=32 magic number

Ab Initio from NN+3N

Generally good agreement, but predicts appearance too early

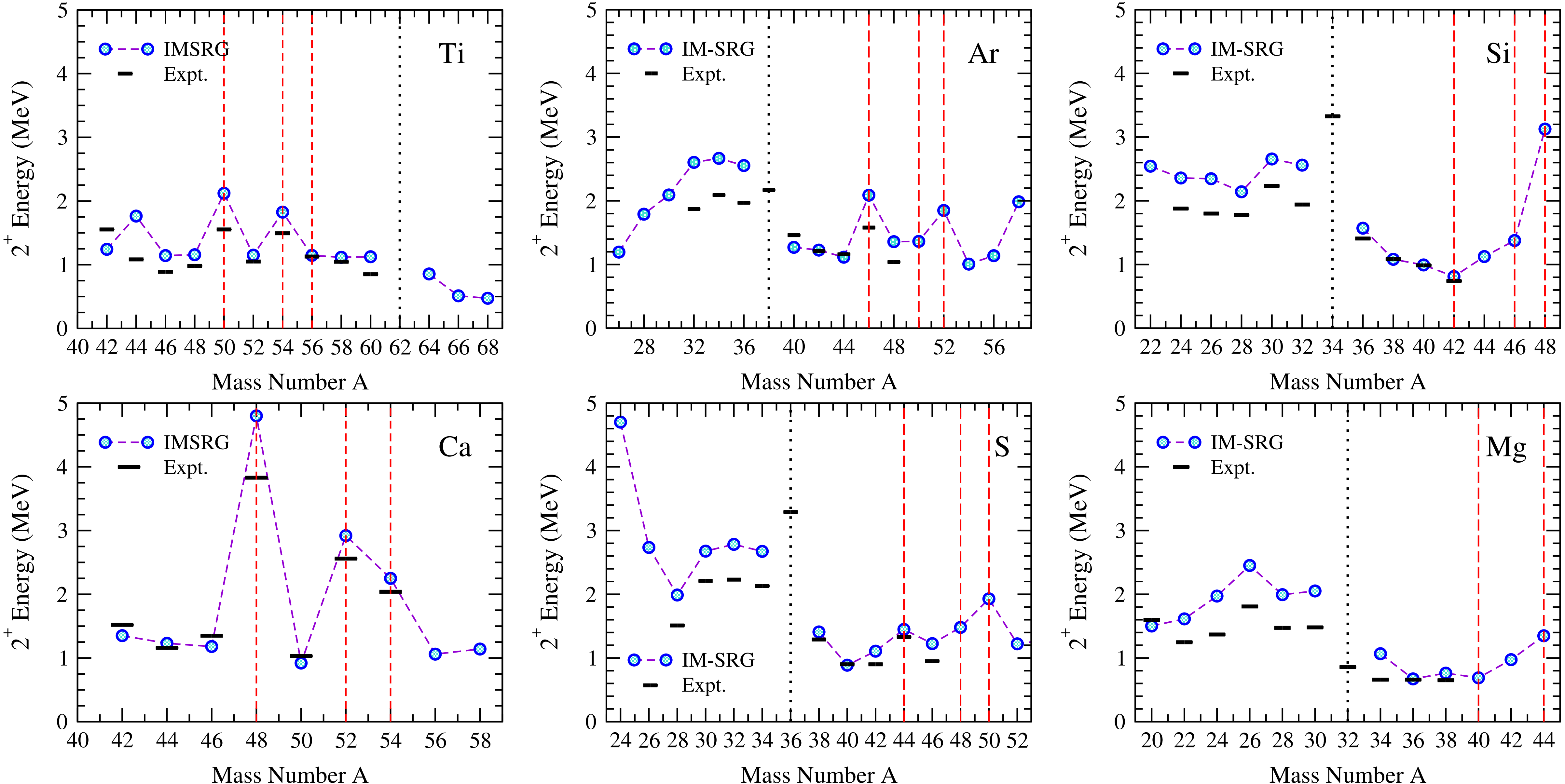
Future: Evolution to be measured in Ar, Cl

Leistenschneider et al, PRL 2018

TRIUMF

Future: Evolution of N=28,32,34 Magic Numbers

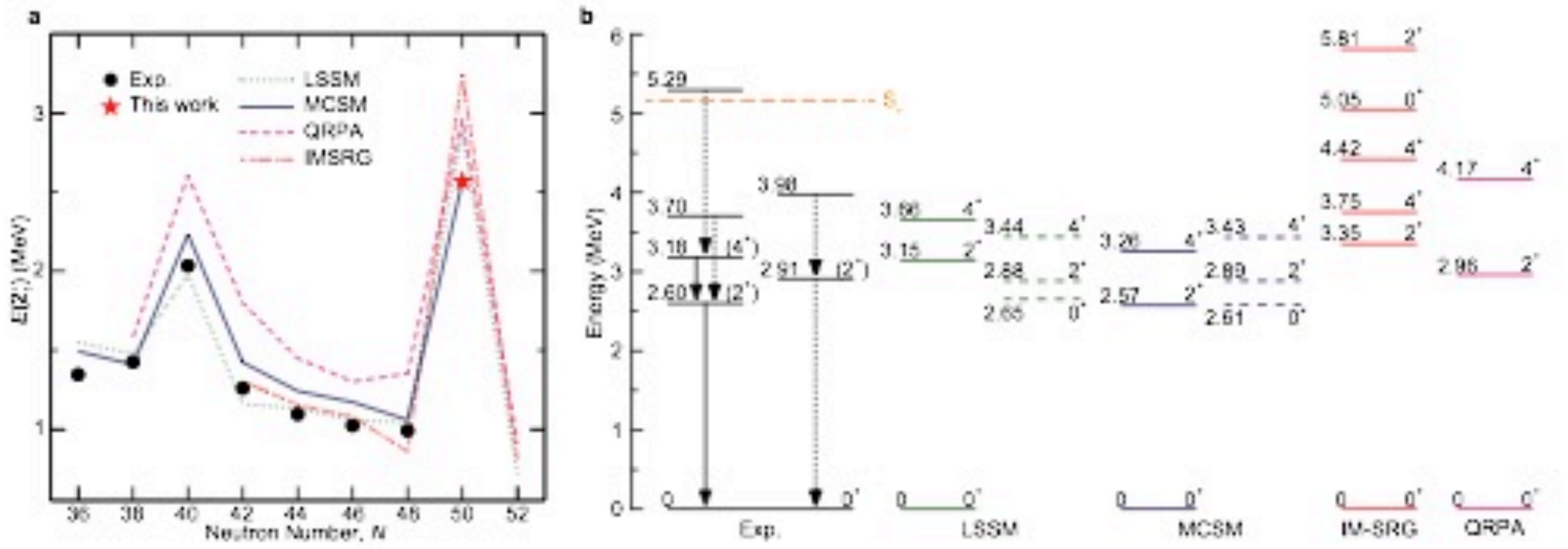
Ab initio predictions from above calcium towards oxygen – **persistence of N=34**



Discovery, accelerated

Missing Pillar: Magicity of ^{78}Ni?

New measurement at RIKEN 2^+ energy in ^{78}Ni – clear peak compared to ^{76}Ni



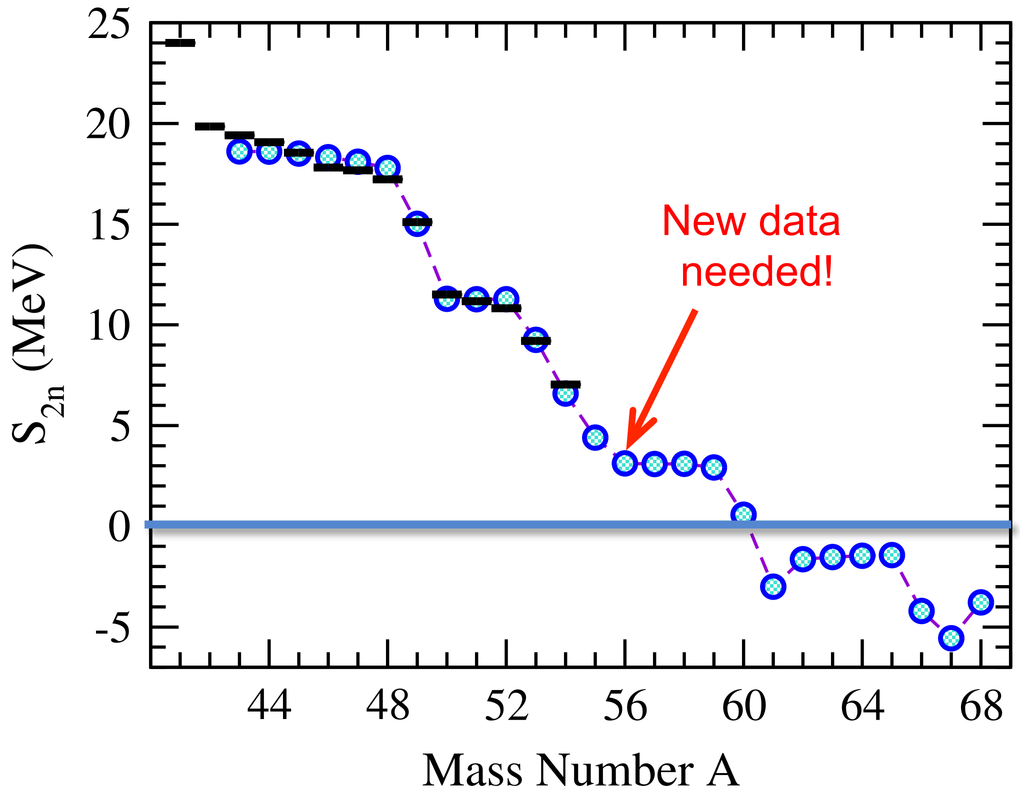
Peak wrt neighboring systems well predicted by IMSRG (also phenomenology)

First evidence for the (double) magicity of ^{78}Ni!

N=34 Magic Number in Calcium: Masses

2013-2018 impressive series of experiments; ideal example of theory/exp overlap

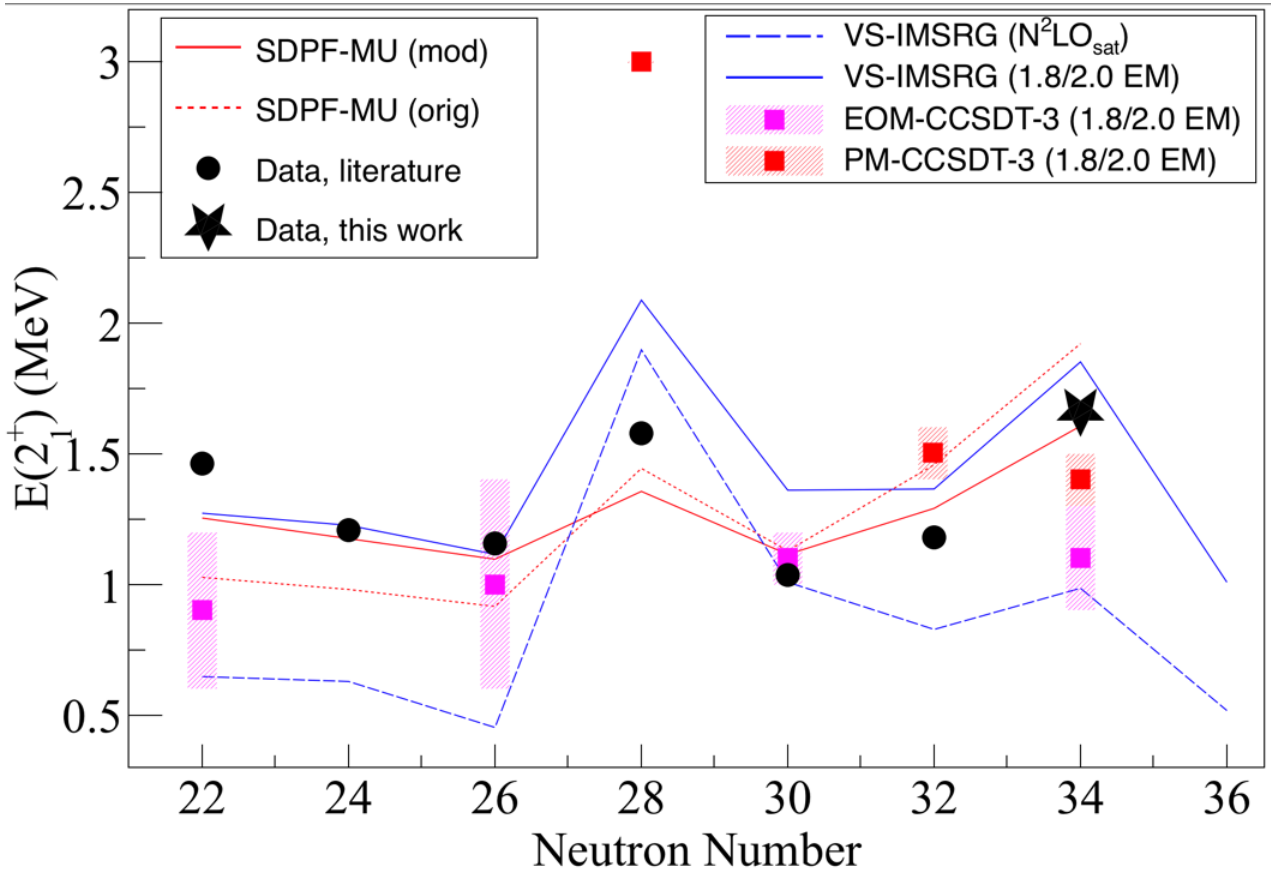
Story continues at ???



2017:
Updated ab initio theory predicts shell closure

Persistence of N=34 Magic Number

New measurement at RIKEN: 2^+ energy in ^{52}Ar – clear peak at N=34

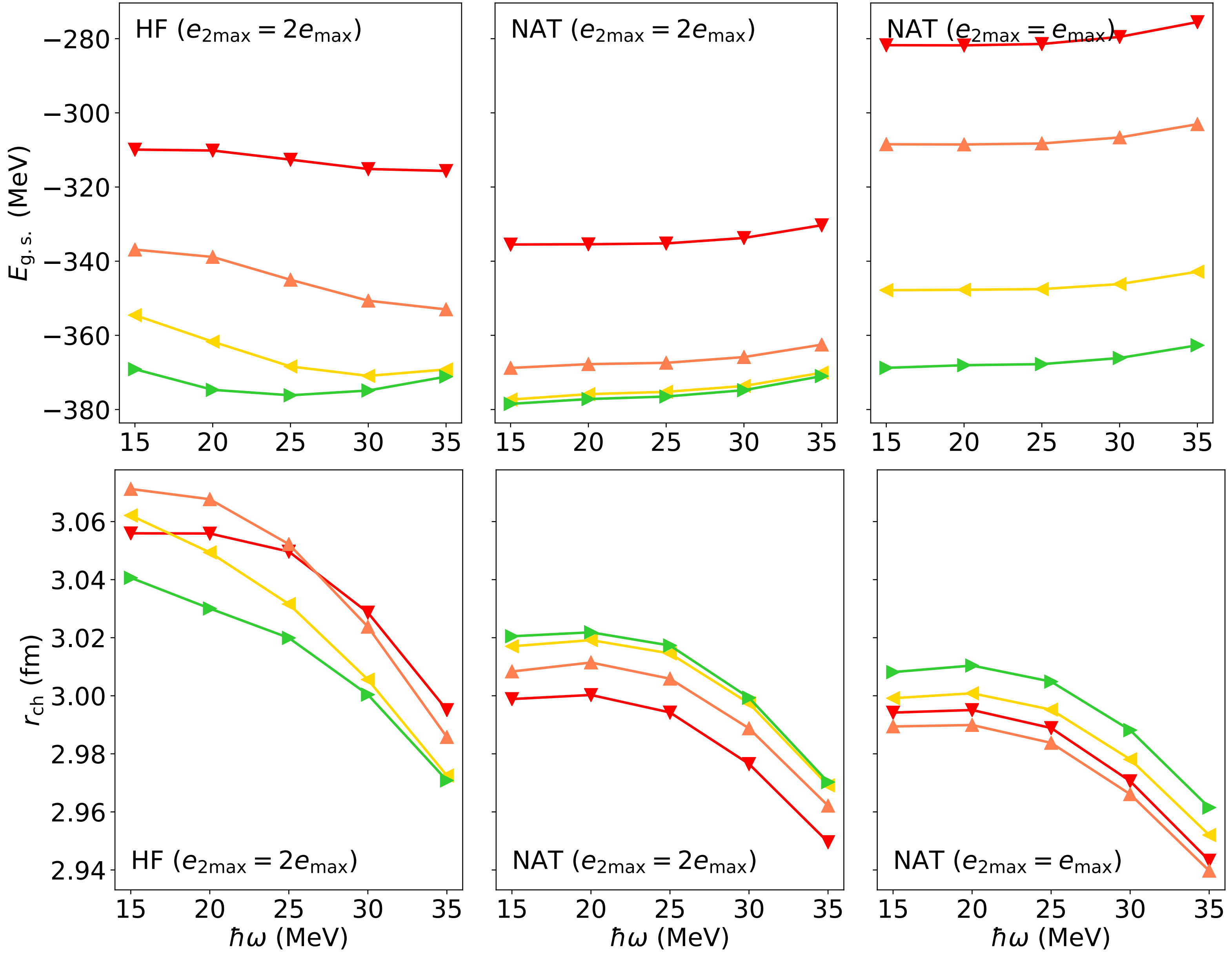


Agreement with IMSRG and other ab initio predictions (coupled cluster theory)

First evidence for persistence of N=34 magic number away from calcium!

Natural Orbitals in IMSRG

They work! Next, test in VS formulation…

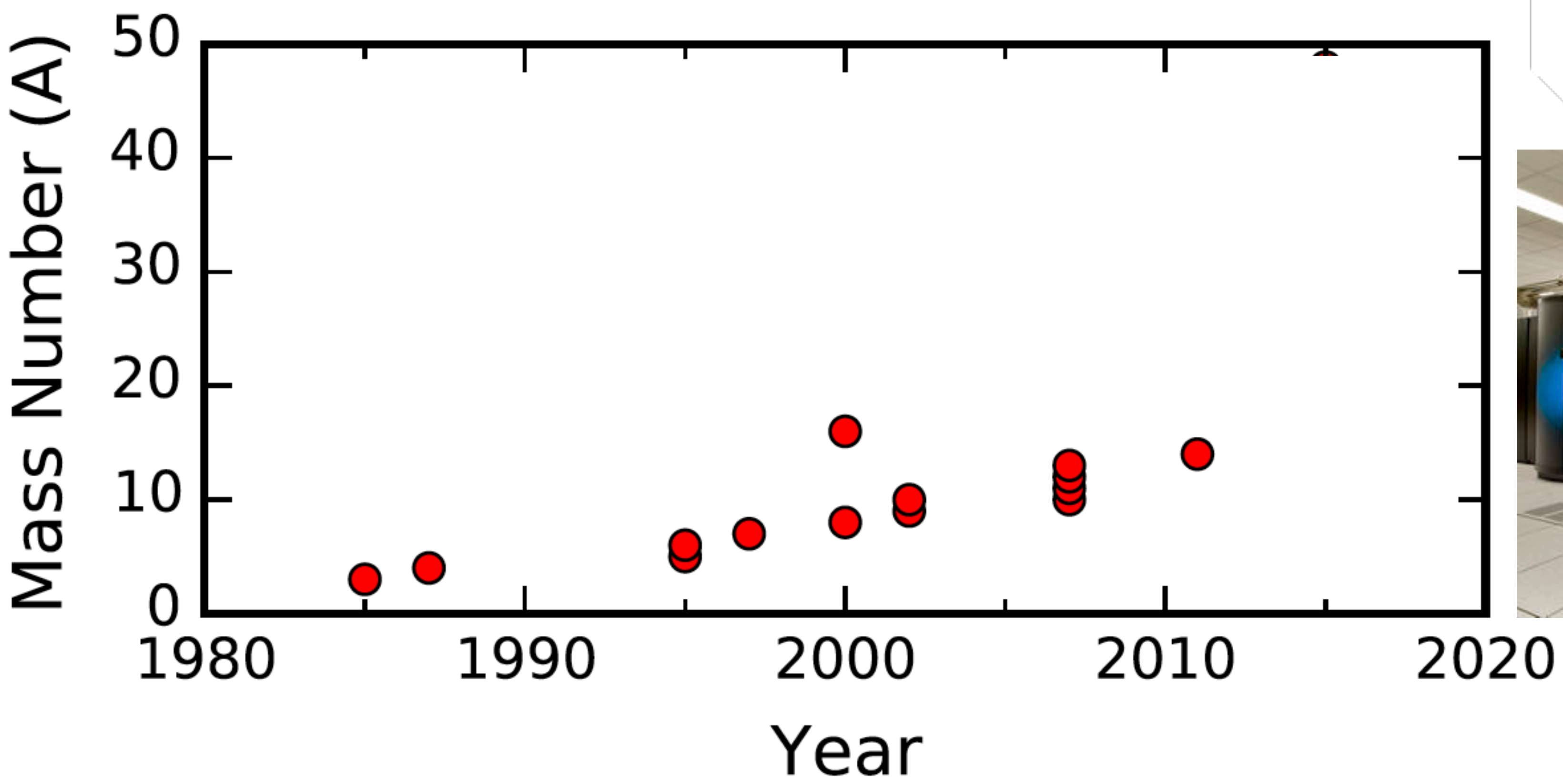


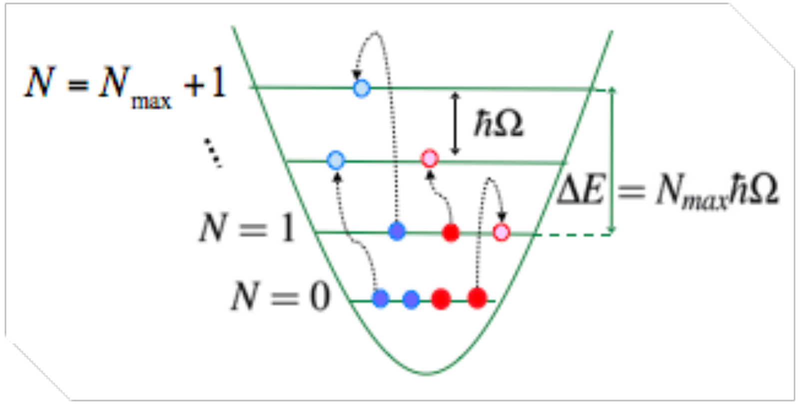
Miyagi, Stroberg, JDH… in prep

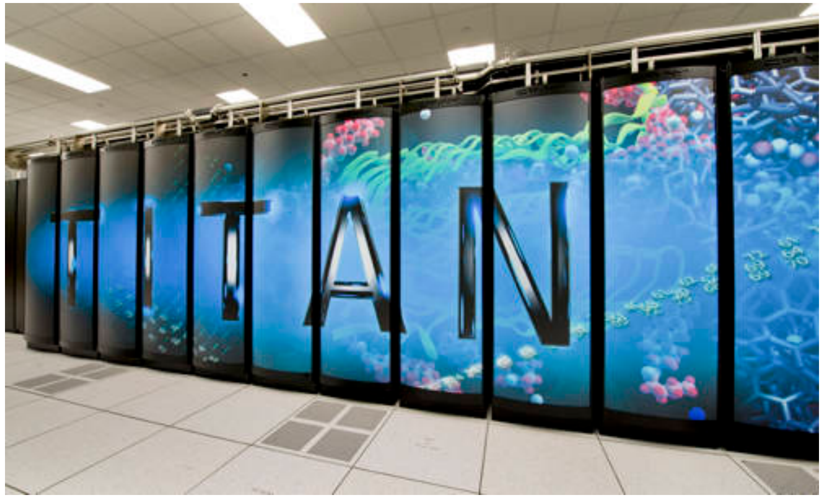
Chronological Reach of Ab Initio Theory

Moore's law: exponential growth in computing power

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





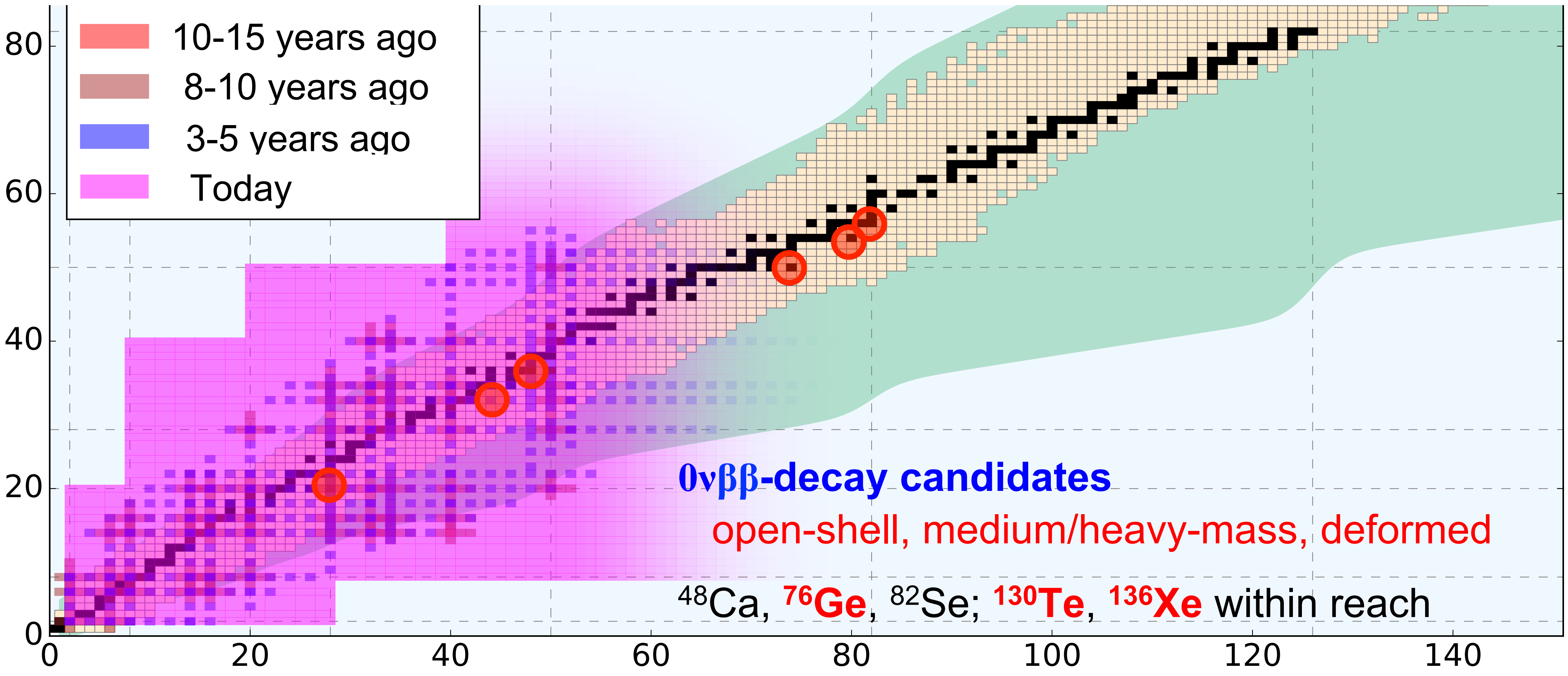


TRIUMF

Towards Neutrinoless Double Beta Decay

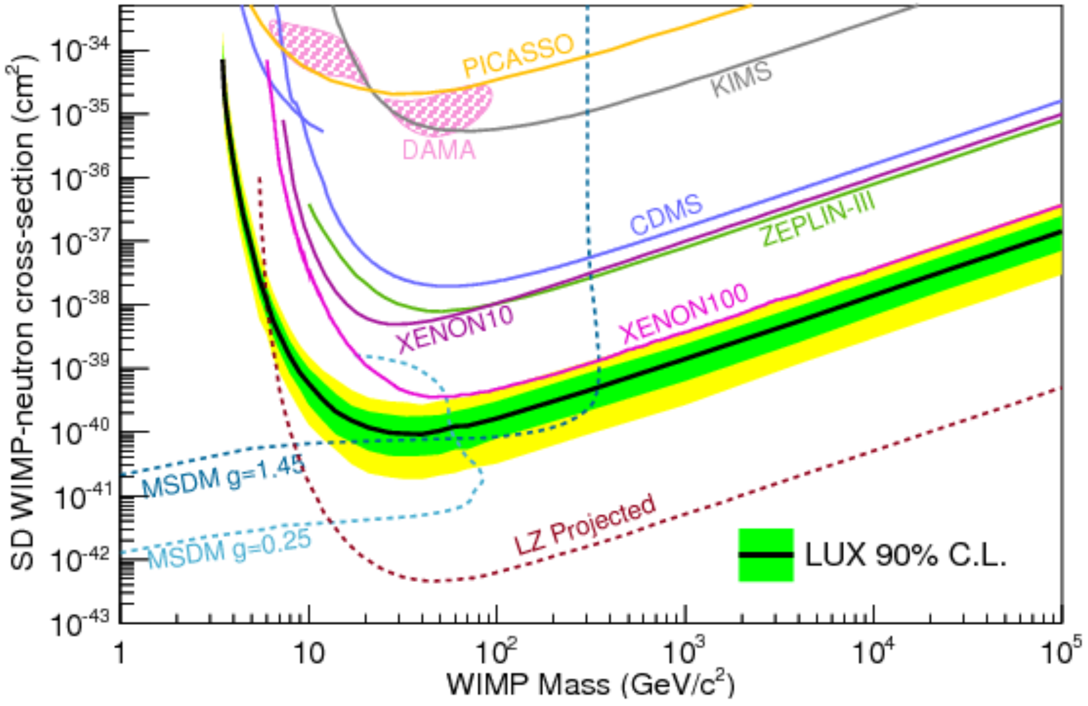
Aim of modern nuclear theory: Develop unified *first-principles* picture of structure and reactions

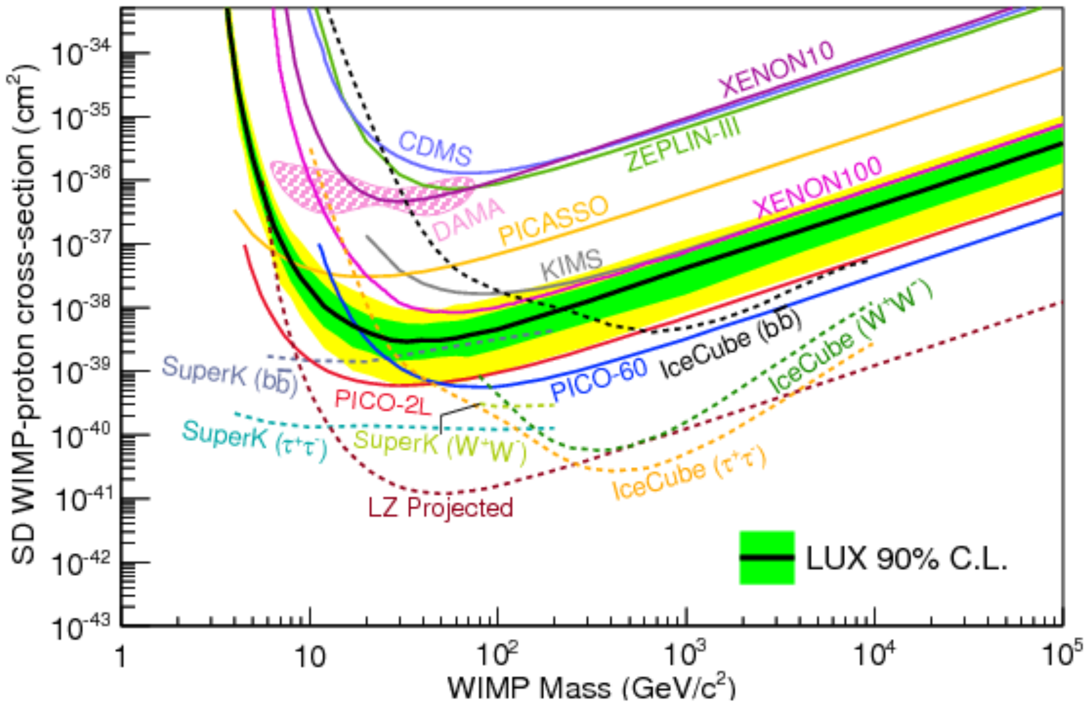
- Nuclear forces, electroweak physics
- Nuclear many-body problem



Nature of Dark Matter: WIMP-Nucleus Scattering

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



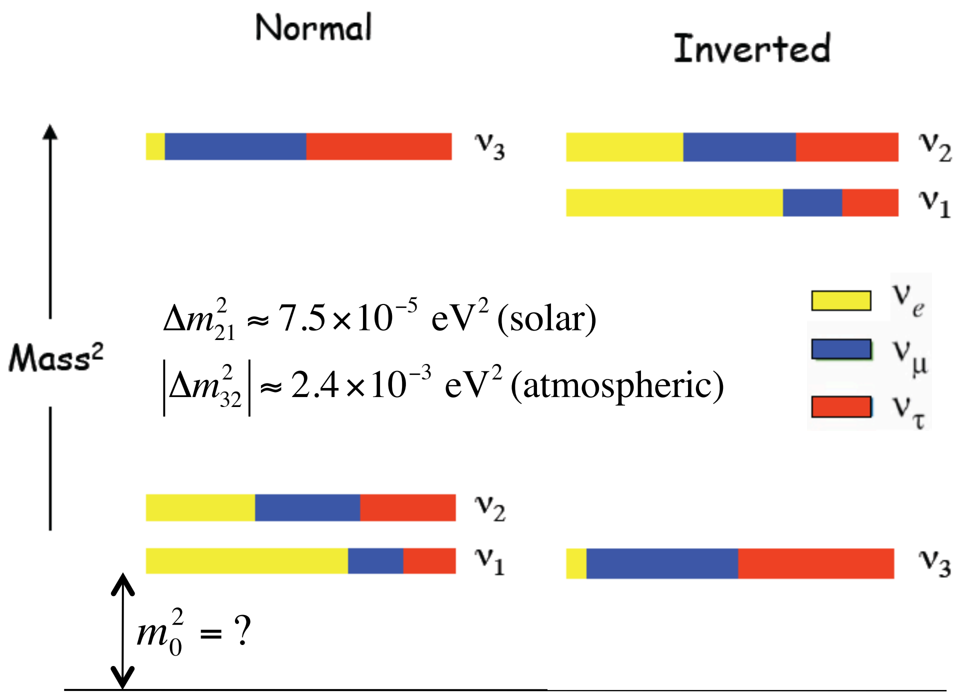


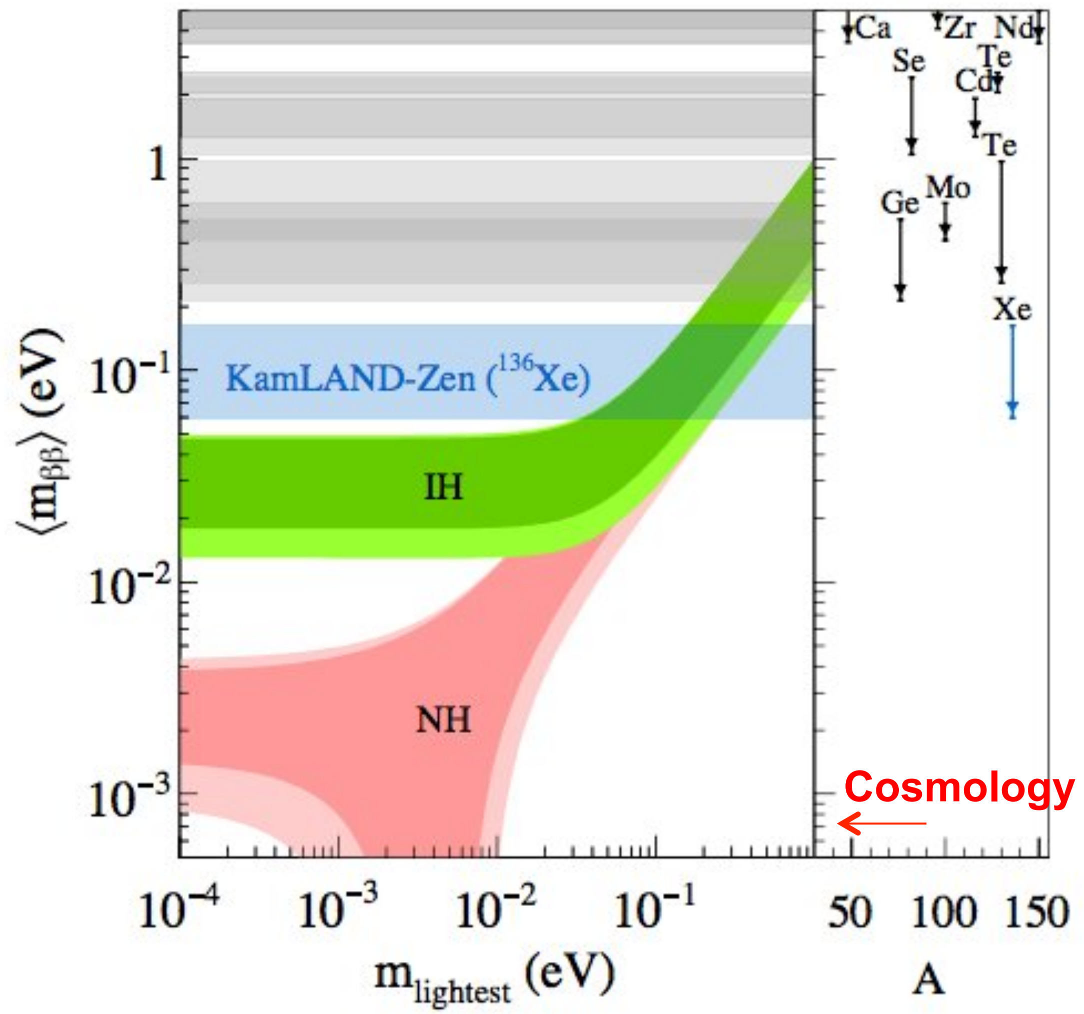
Differential cross section: compare results from different target nuclei

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

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

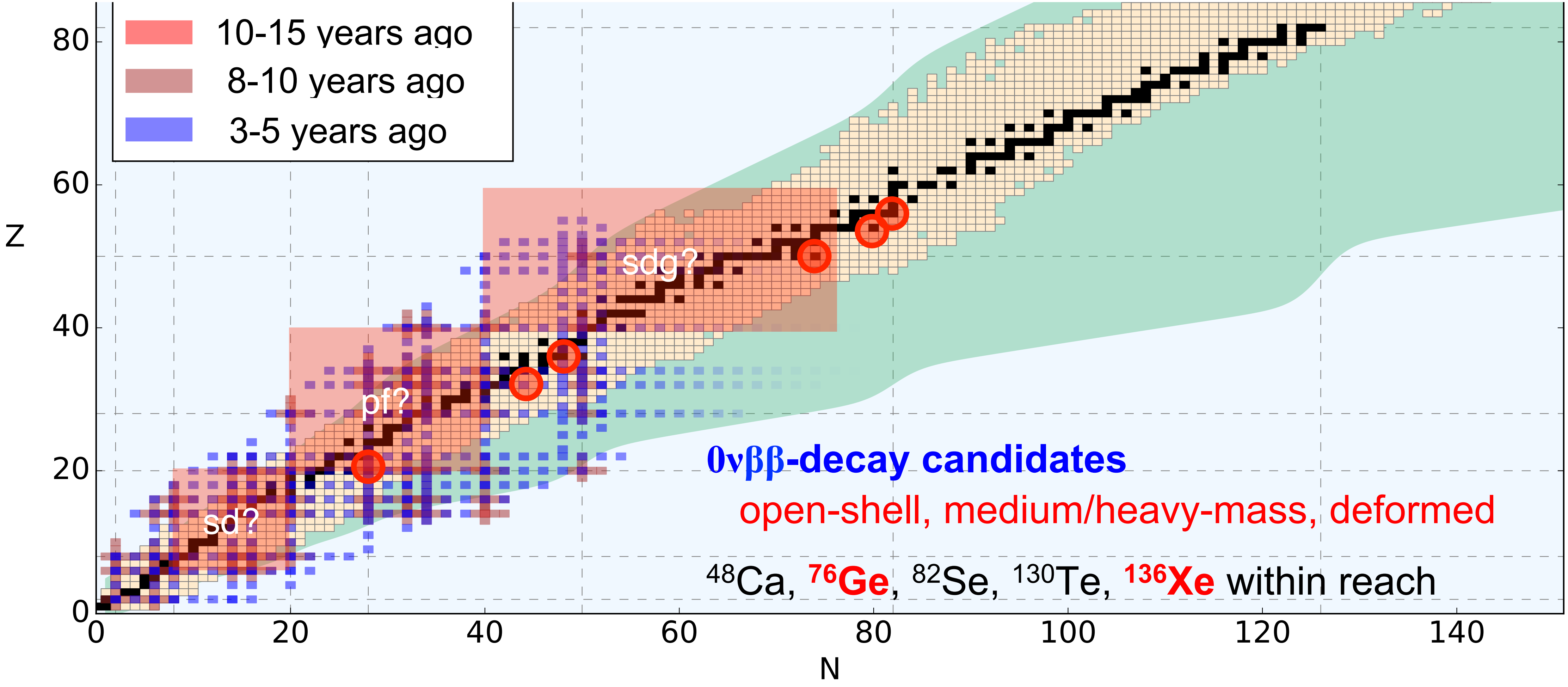
TRIUMF

Breadth of Ab Initio Theory

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

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

$$H\psi_n = E_n\psi_n$$



0νββ-decay candidates

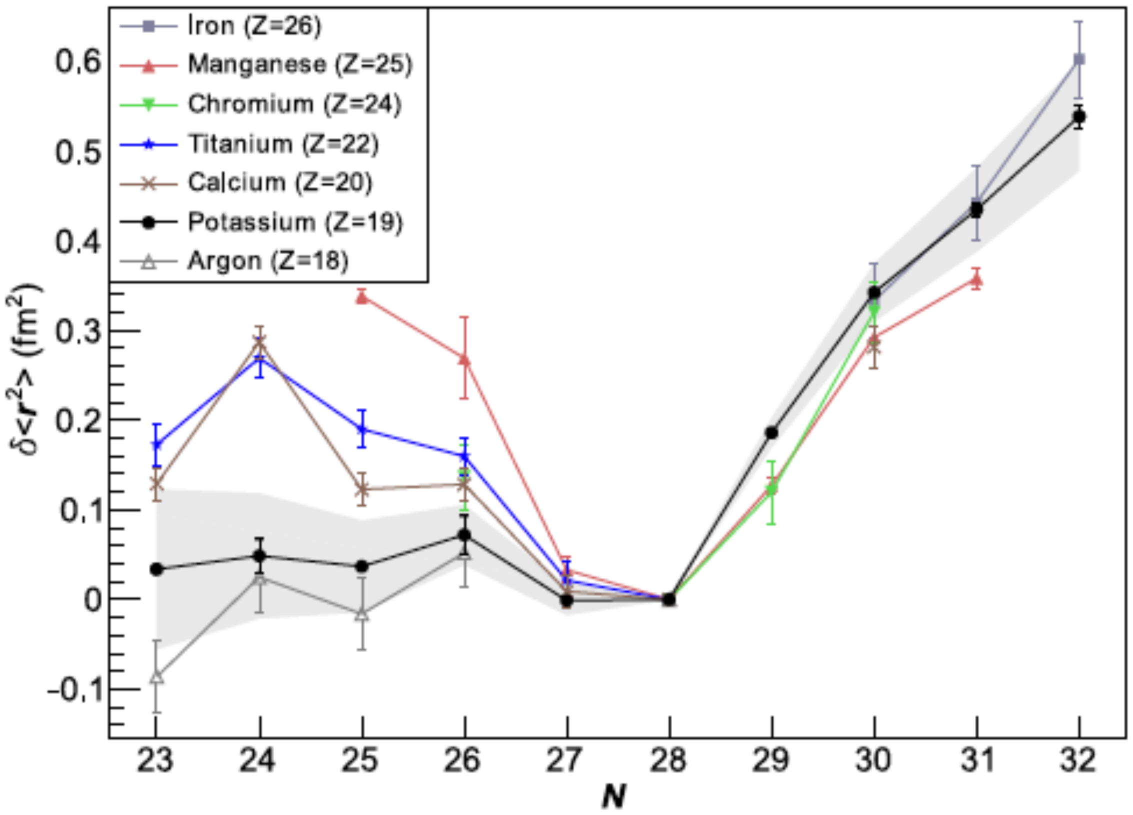
open-shell, medium/heavy-mass, deformed

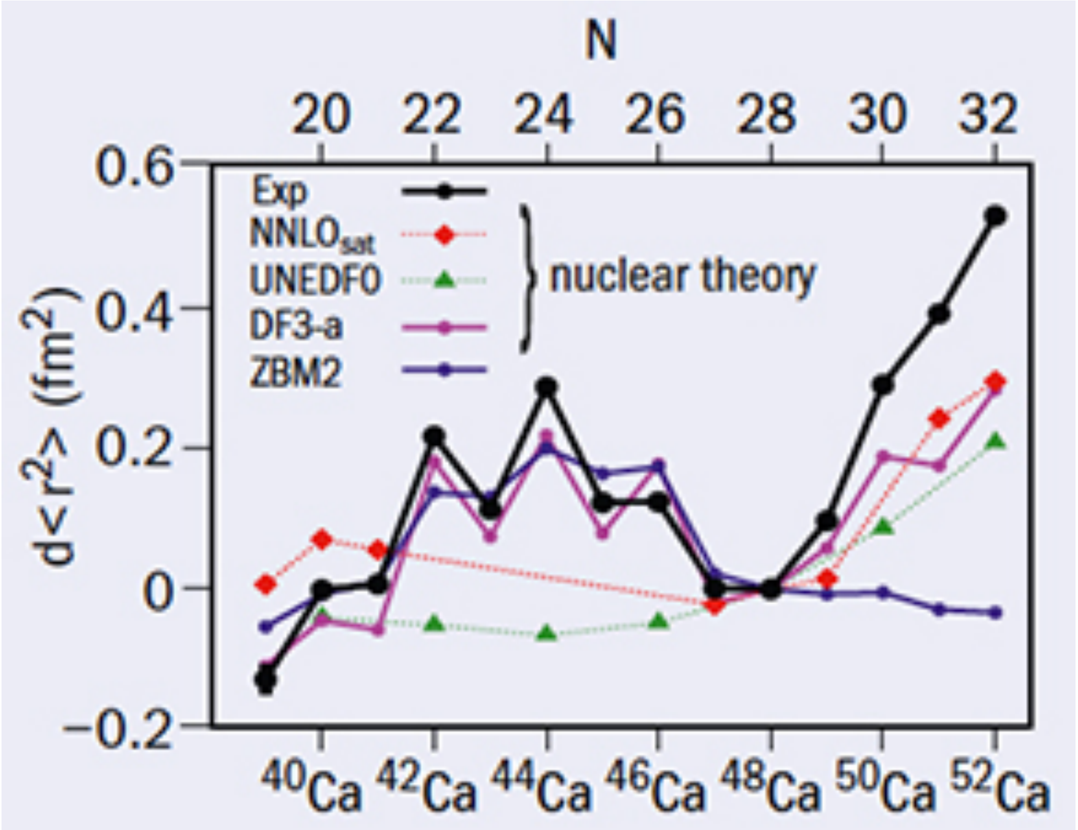
^{48}Ca, **^{76}Ge**, ^{82}Se, ^{130}Te, **^{136}Xe** within reach

Evolution of N=32 Magic Number: Charge Radii

Charge radii of $^{49,51,52}Ca$, obtained from laser spectroscopy experiments at COLLAPS, CERN

Unexpected large increase in charge radius questions the magicity of ^{52}Ca





Theoretical models all underestimate the charge radius

Ab-initio calculations reproduce the trend of charge radii

Approaches to Nuclear Structure

"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. If the forces are known, one should, in principle, be able to calculate deductively the properties of individual nuclei. ***Only after this has been accomplished can one say that one completely understands nuclear structure…***

–M. Goeppert-Mayer, Nobel Lecture

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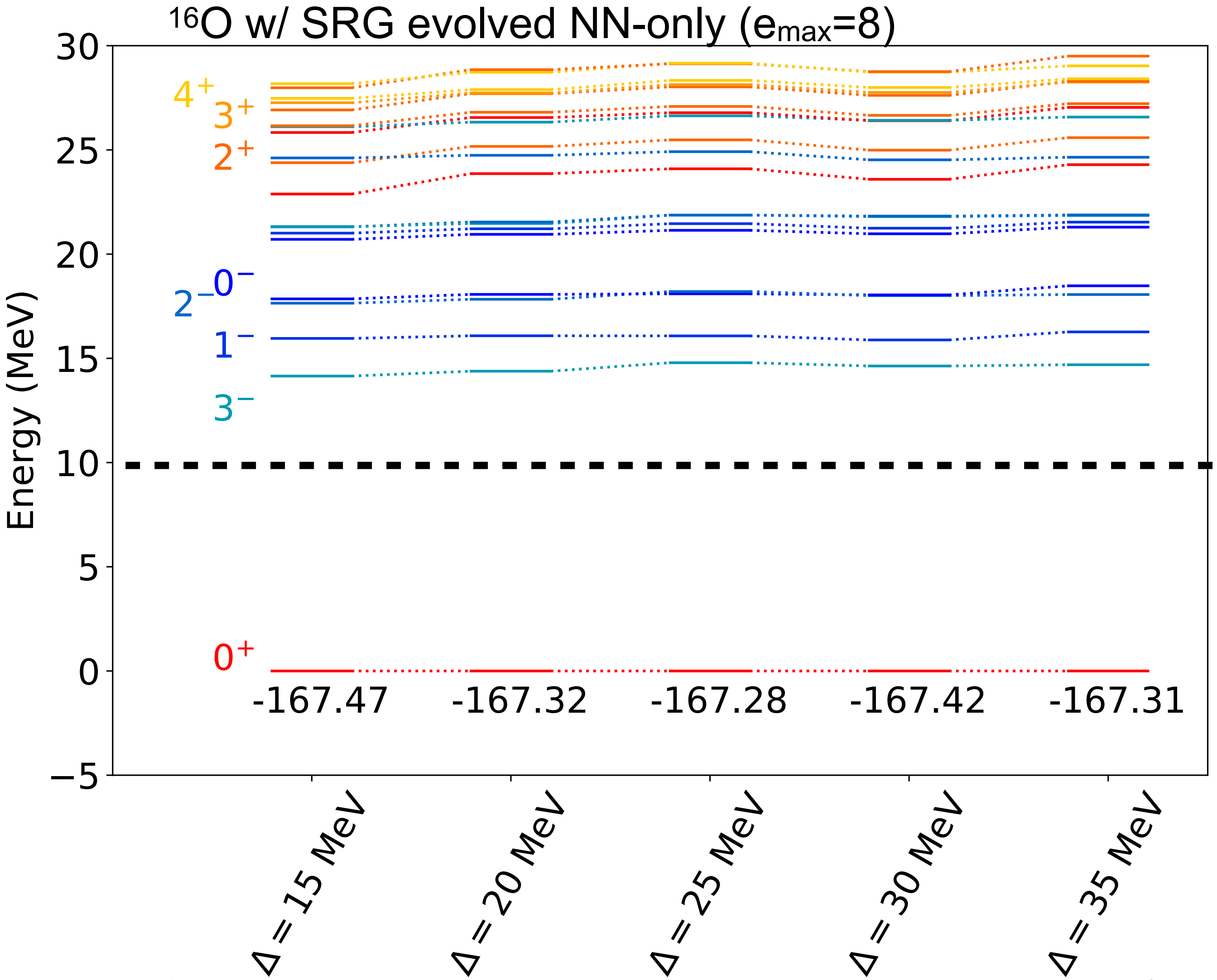
The other approach is that of the experimentalist and consists in obtaining by direct experimentation as many data as possible for individual nuclei. One hopes in this way to find regularities and correlations which give a clue to the structure of the nucleus… The shell model, although proposed by theoreticians, really corresponds to the experimentalist's approach."

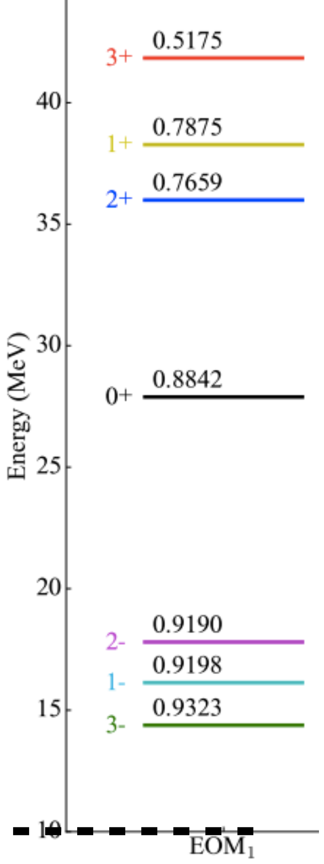
–*M. Goeppert-Mayer, Nobel Lecture*

Ab initio approach vs. *phenomenological models*

To date, nuclear physics largely phenomenological

Comparison with EOM method





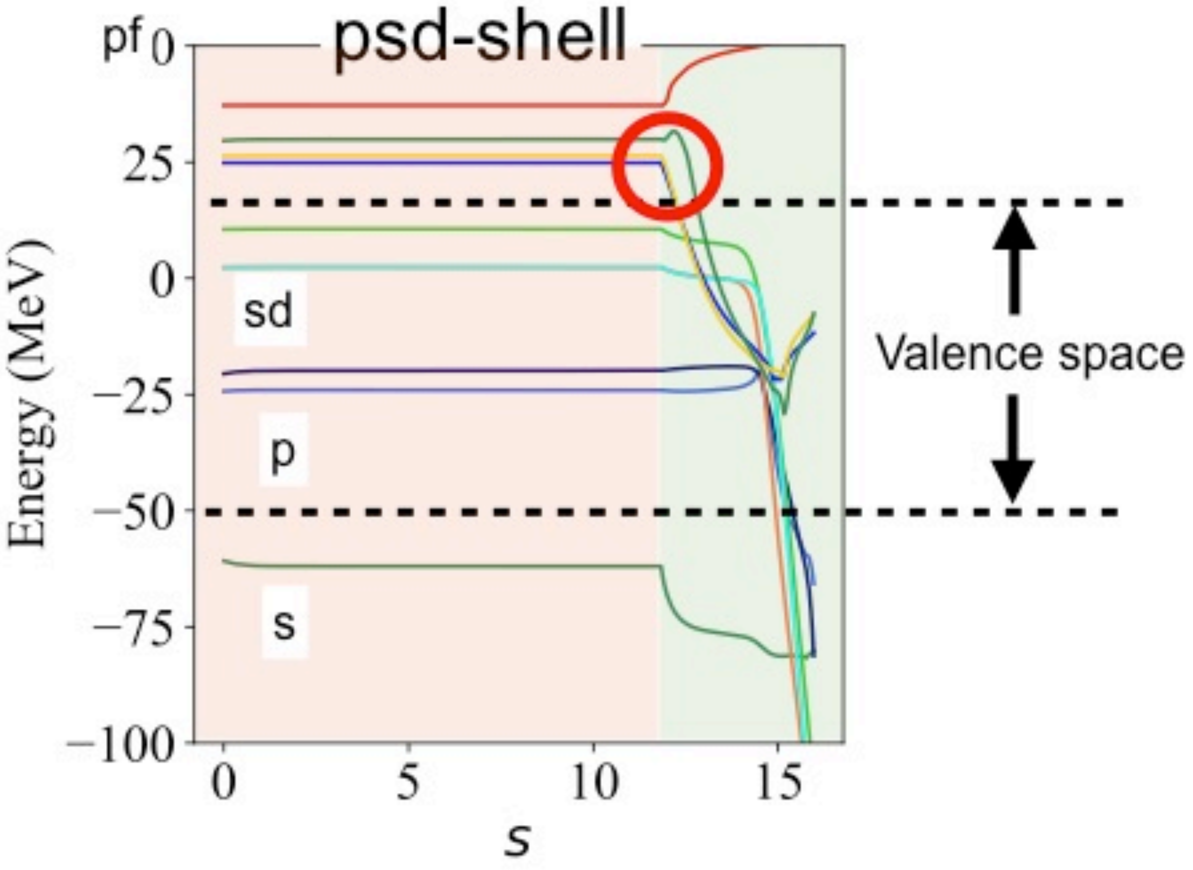
1p1h dominant lowest 3^-, 1^-, 2^- agree well with the EOM-IMSRG results.

Miyagi, Stroberg, JDH… in prep

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

Typical IMSRG Failure

- Flow of single-particle energies
  - At the very beginning of valence-decoupling flow, some of pf-shell orbits come down.
  - Intuitively, we expect that P- and Q-space single particle energies do not mix.
  - At the beginning of the flow, the slope of single-particle energies (df/ds) seems to be crucial.



Chronological Reach of Ab Initio Theory

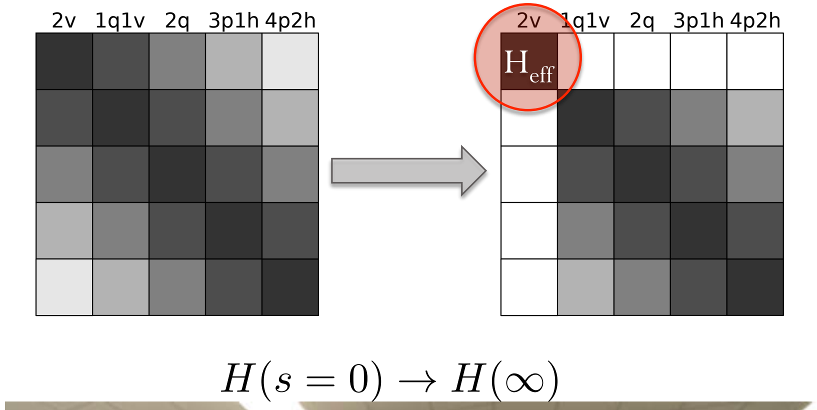
2019: A>100

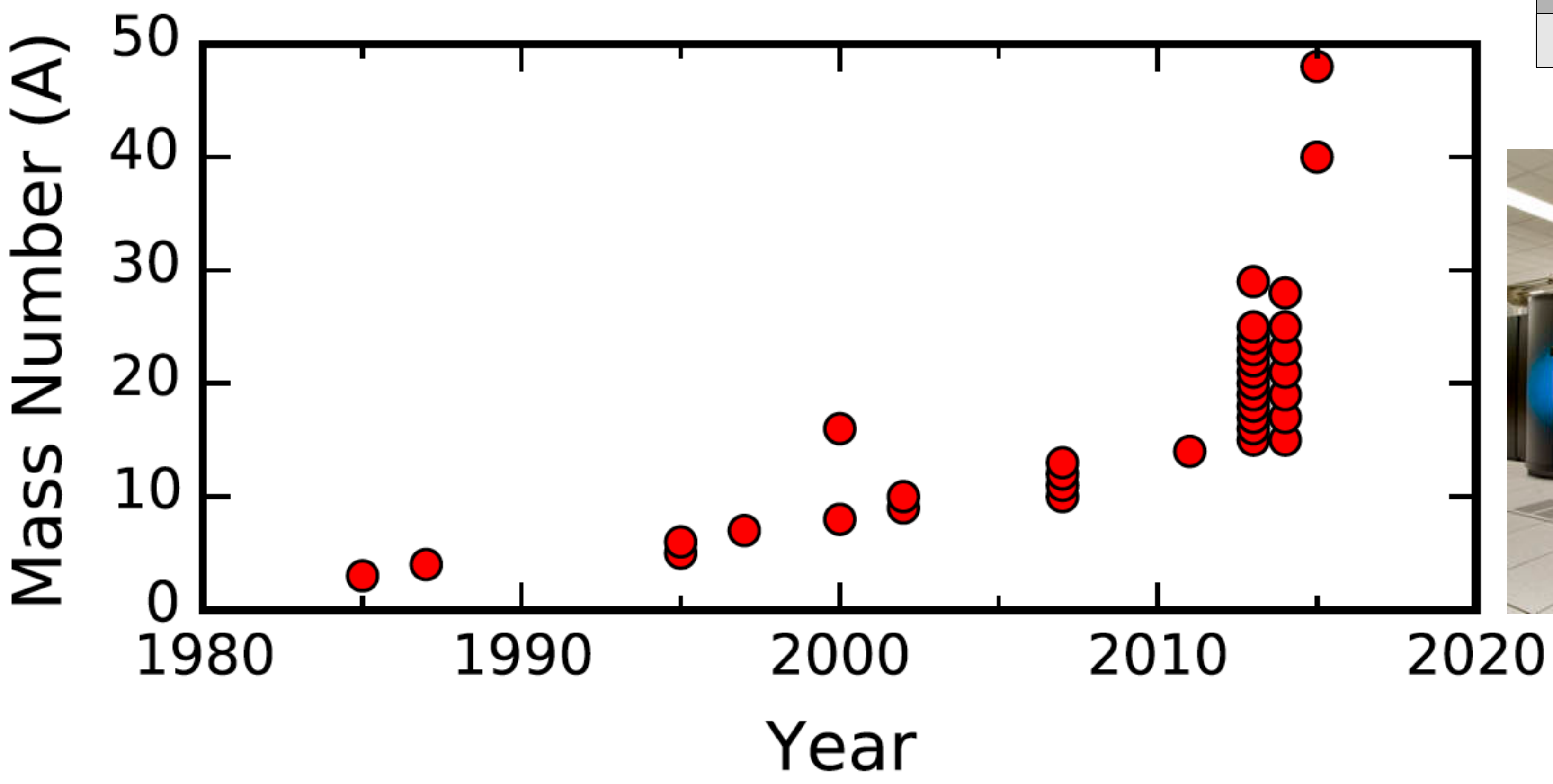
Moore's law: exponential growth in computing power

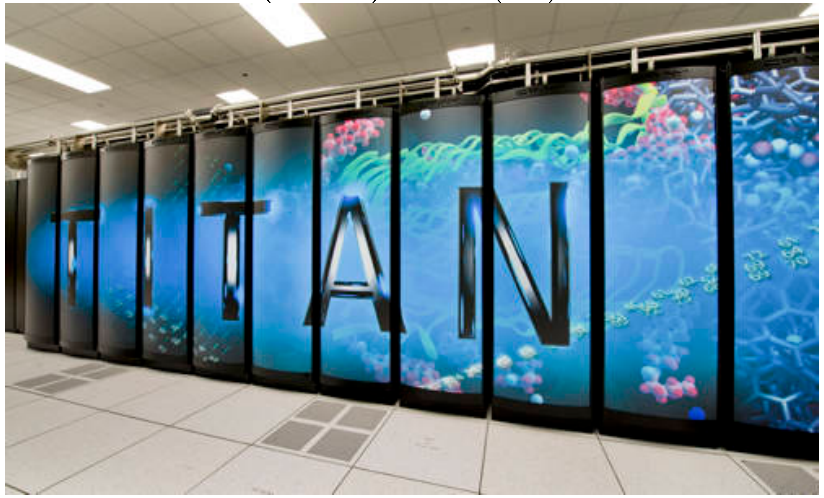
Methods for light nuclei (QMC, NCSM) scale exponentially with mass

Polynomial scaling methods developed (CC, IMSRG, SCGF…)

Explosion in limits of ab initio theory



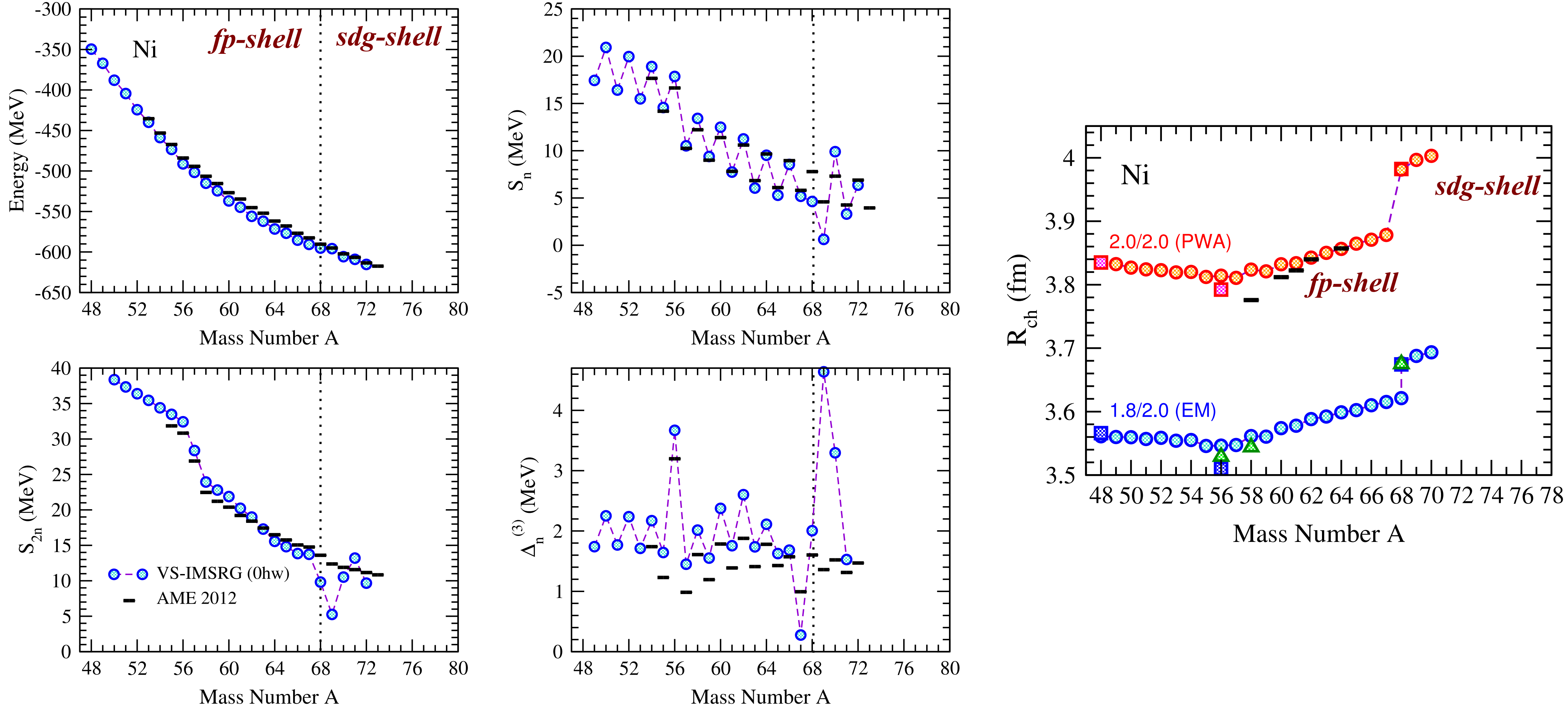




Shell Closures in Neutron-Rich Ni

Deviations from Experimental Separation Energies

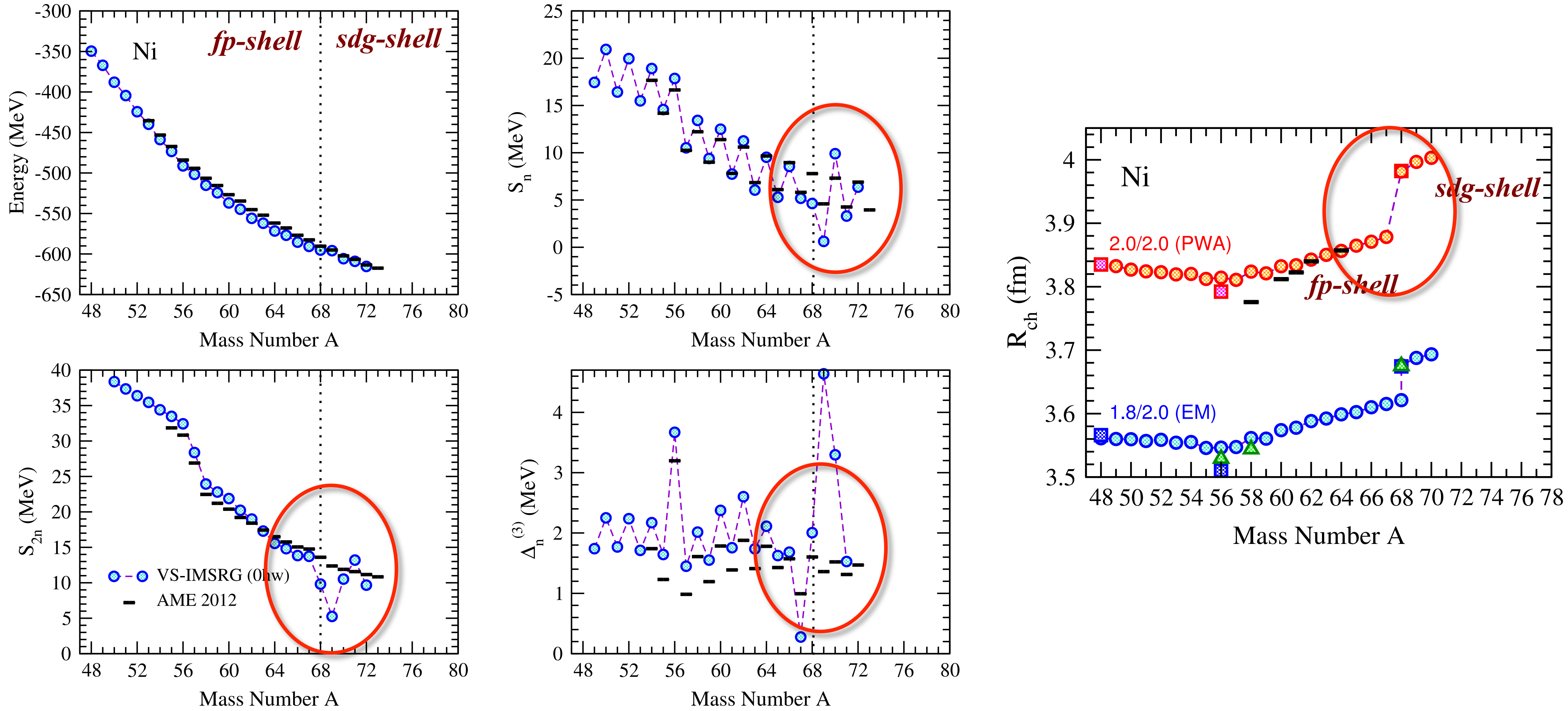
Defect 1: Clear artifacts when changing valence spaces



TRIUMF

Deviations from Experimental Separation Energies

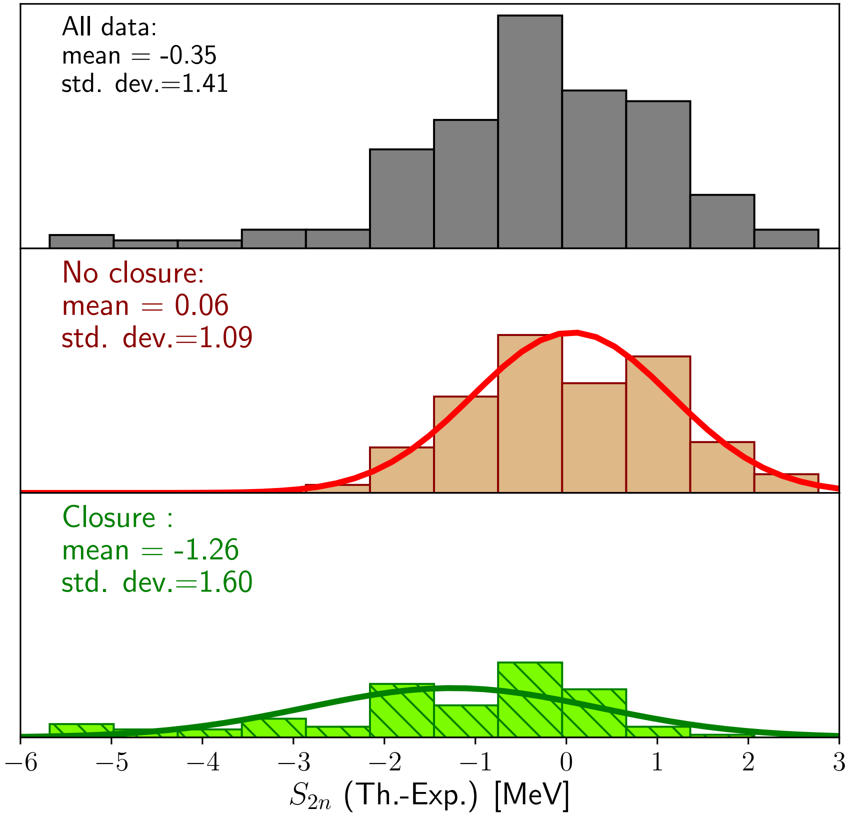
Defect 1: Clear artifacts when changing valence spaces

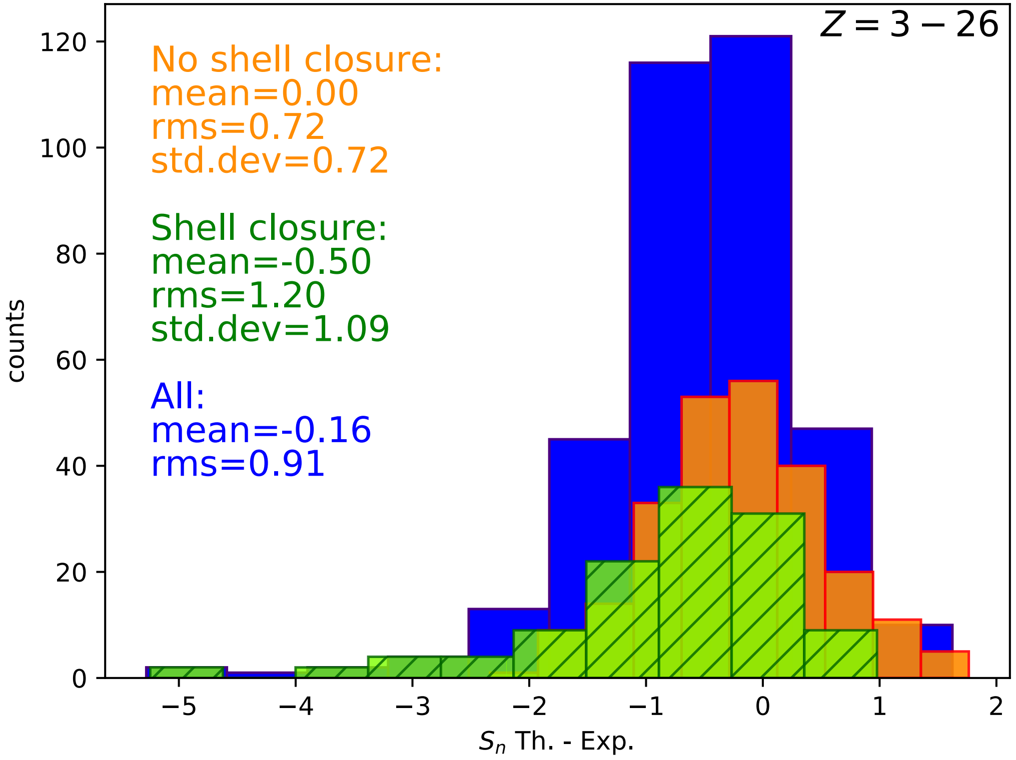


Residuals at Shell/Non-Shell Closures

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, Simonis, arXiv:1905.10475

Distributions approximately Gaussian

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

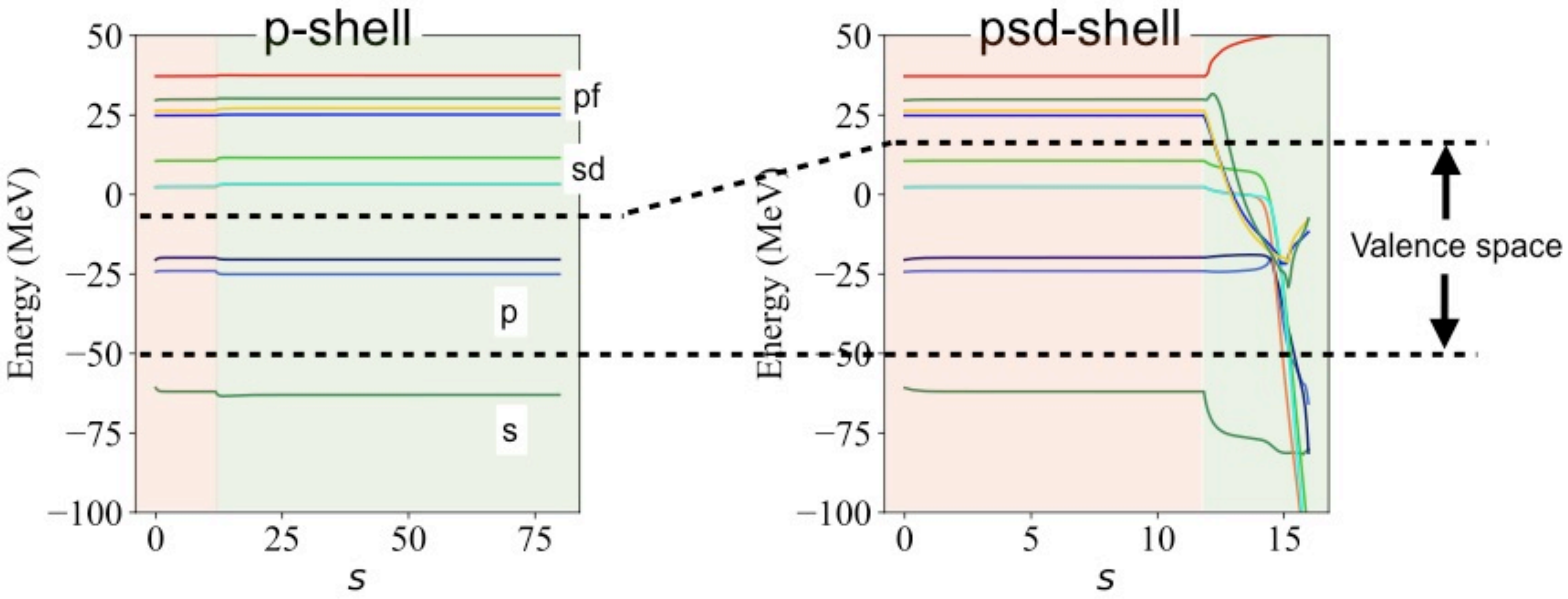
TRIUMF

Improve Cross-Shell Physics: Multi-Shell Spaces

Essential for many applications: island of inversion, forbidden transitions, heavier beta decay cases

IMSRG typically fails!

- Flow of single-particle energies



Proposed Fix: Modified Generator

Proposed fix: modify generator to give constant shift to energy denominator

Never have negative energy denominators if on order of hw…

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

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

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

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

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

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

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

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

Miyagi, Stroberg, JDH… in prep

Proposed Fix: Modified Generator

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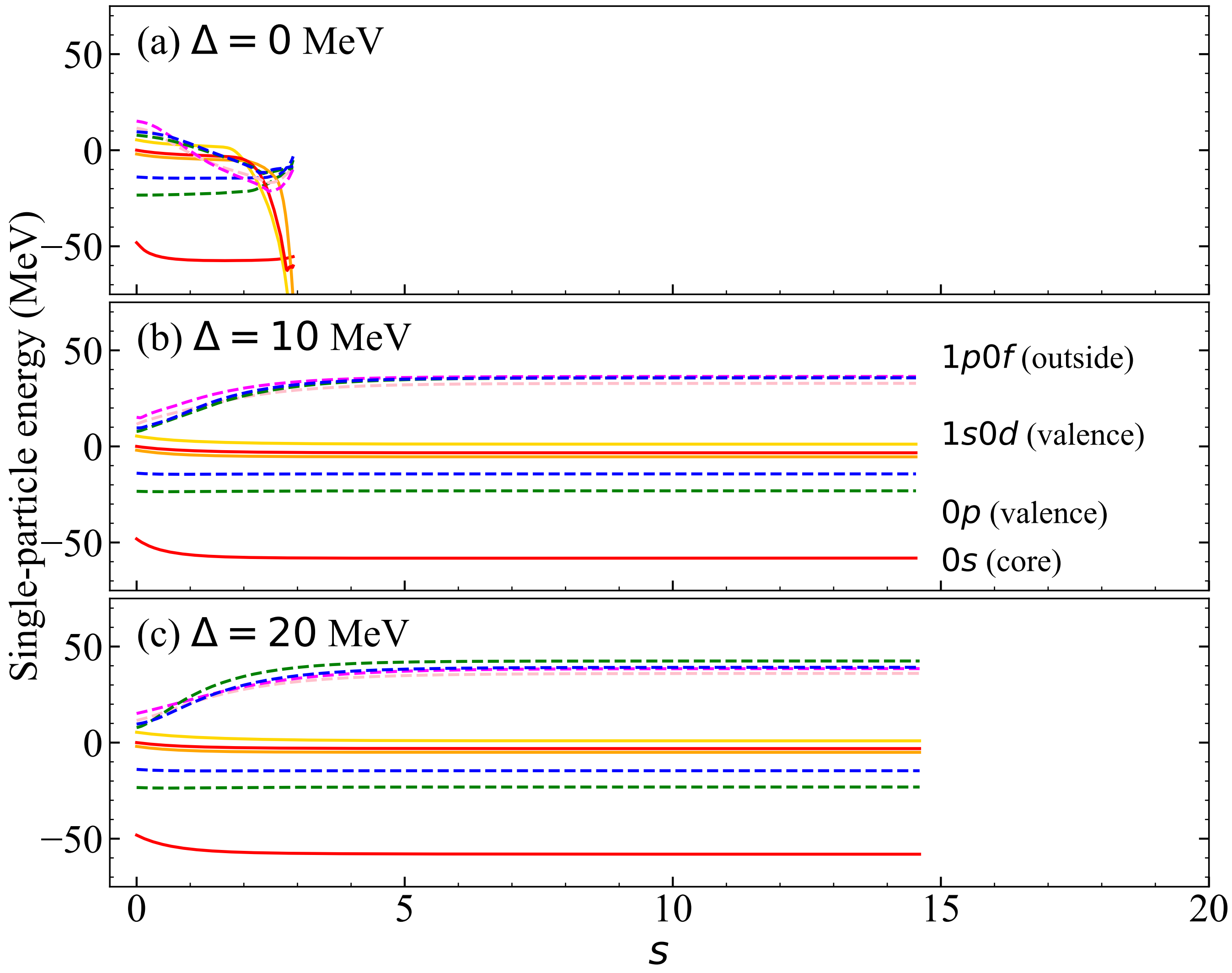


Miyagi, Stroberg, JDH… in prep

Approaches to Nuclear Structure

"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. If the forces are known, one should, in principle, be able to calculate deductively the properties of individual nuclei. ***Only after this has been accomplished can one say that one completely understands nuclear structure…***

–M. Goeppert-Mayer, Nobel Lecture

Approaches to Nuclear Structure

"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. If the forces are known, one should, in principle, be able to calculate deductively the properties of individual nuclei. ***Only after this has been accomplished can one say that one completely understands nuclear structure…***

The other approach is that of the experimentalist and consists in obtaining by direct experimentation as many data as possible for individual nuclei. One hopes in this way to find regularities and correlations which give a clue to the structure of the nucleus… The shell model, although proposed by theoreticians, really corresponds to the experimentalist's approach."

–*M. Goeppert-Mayer, Nobel Lecture*

Ab initio approach vs. *phenomenological models*

To date, nuclear physics largely phenomenological

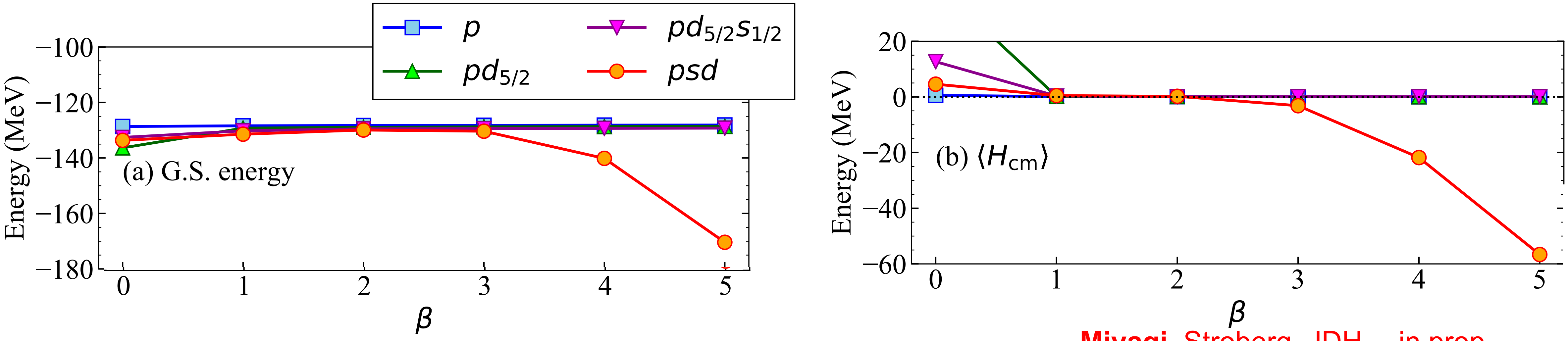
Major Issue: Center of Mass

- So far, we added the center-of-mass Hamiltonian at the shell-model calculation stage:

$$H \longrightarrow H_{\mathrm{VS}} + \beta H_{\mathrm{cm}} \longrightarrow \text{energies}$$

- But, H_{VS} is no longer represented in HO basis. We should add H_{cm} from the beginning:

$$H + \beta H_{\mathrm{cm}} \longrightarrow H_{\mathrm{VS}} \longrightarrow \text{energies}$$

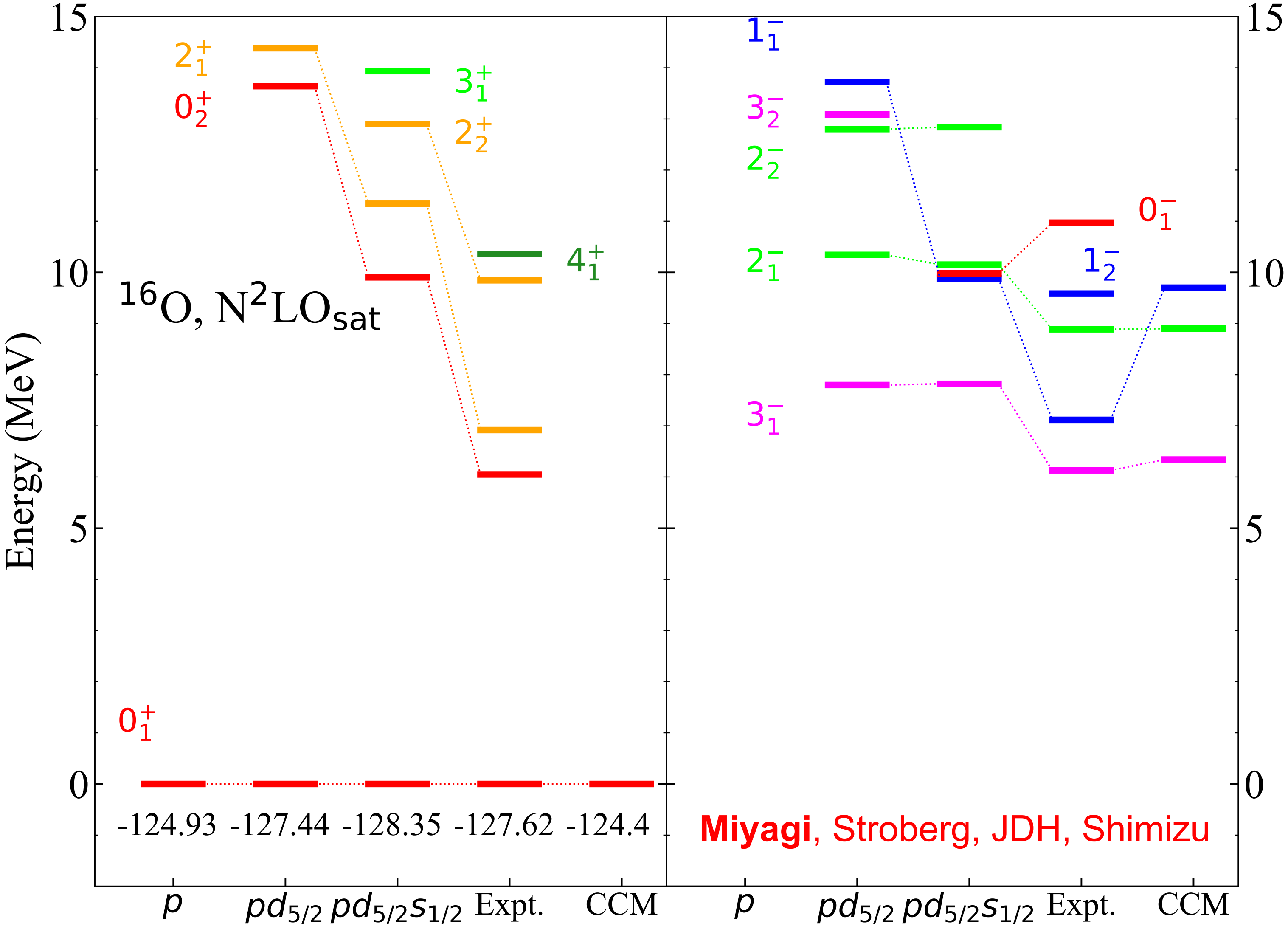


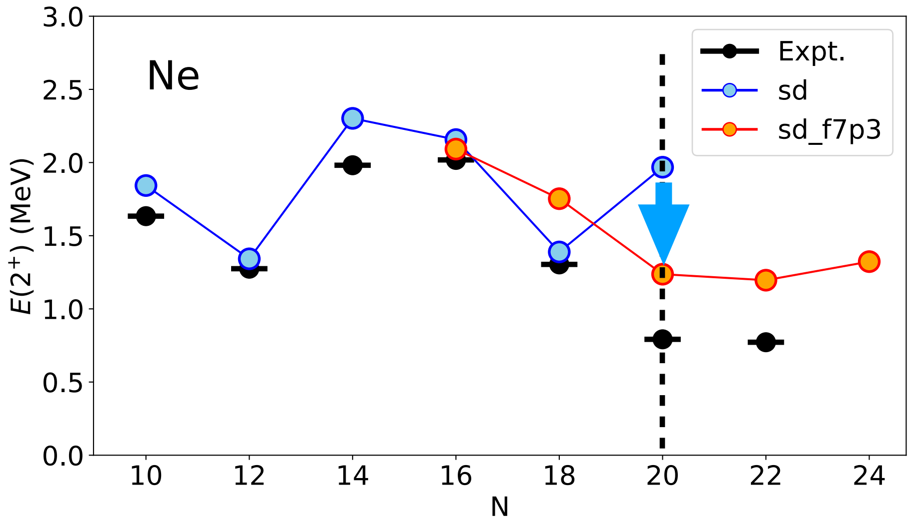
Miyagi, Stroberg, JDH… in prep

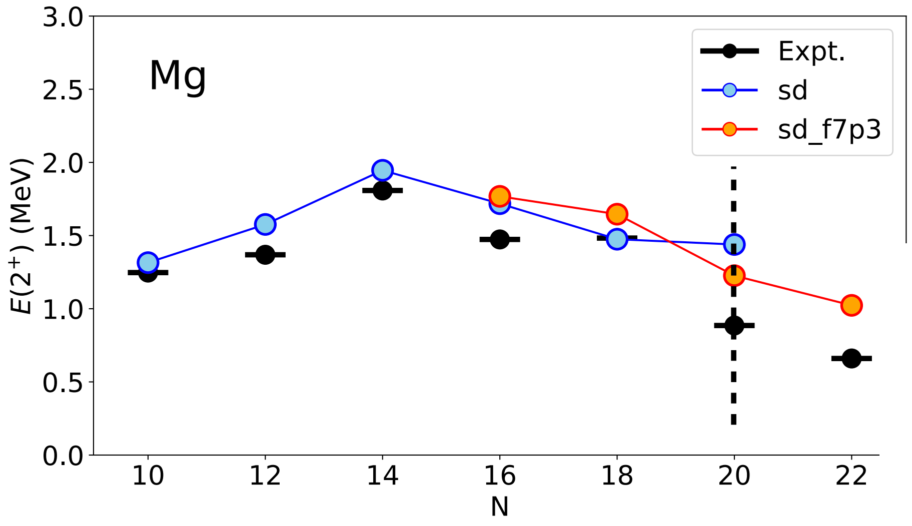
First Results

With selected orbitals, free of CoM contamination

Excited states in ^{16}O, Island of Inversion

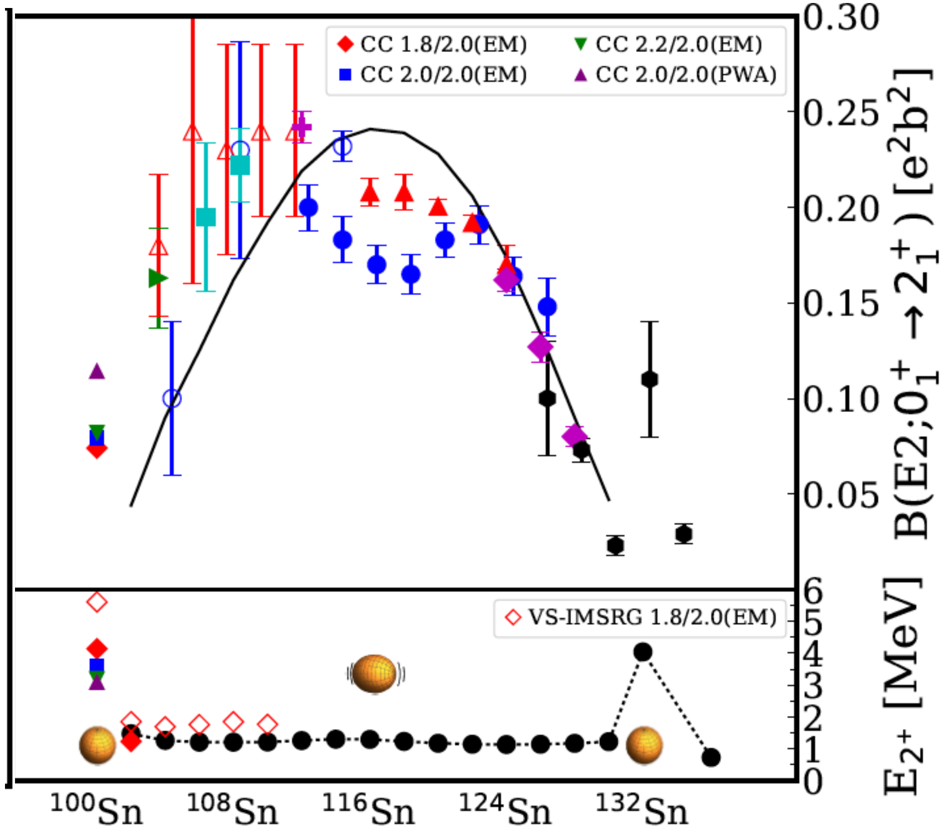




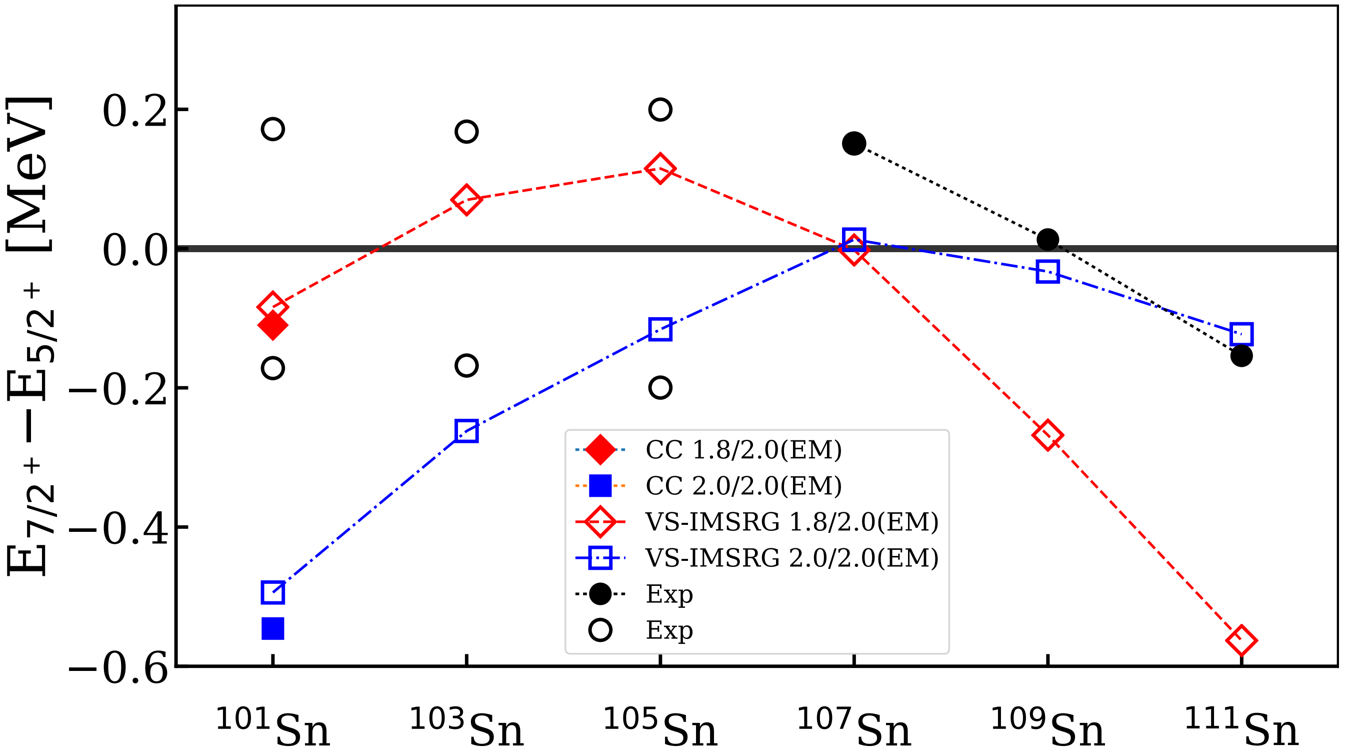


Structure of Light Tin Isotopes

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



Morris et al., PRL (2018)

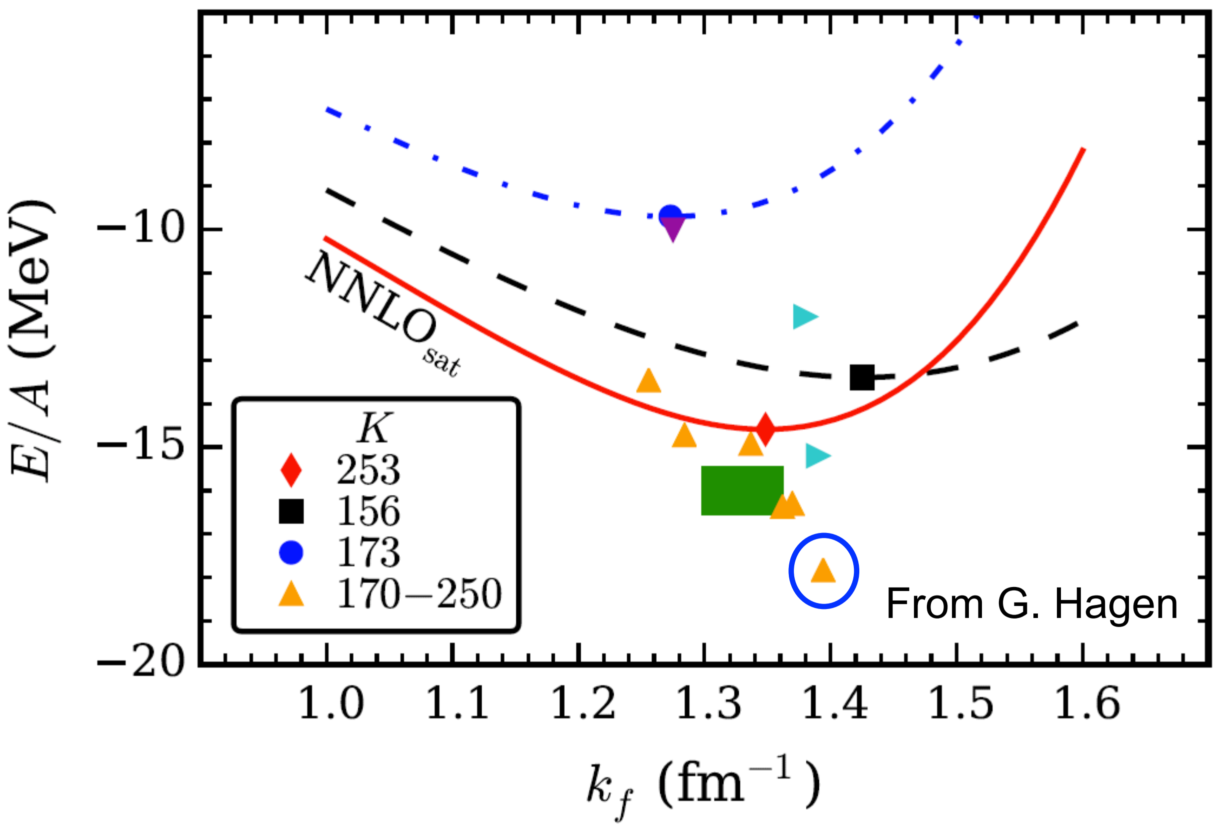


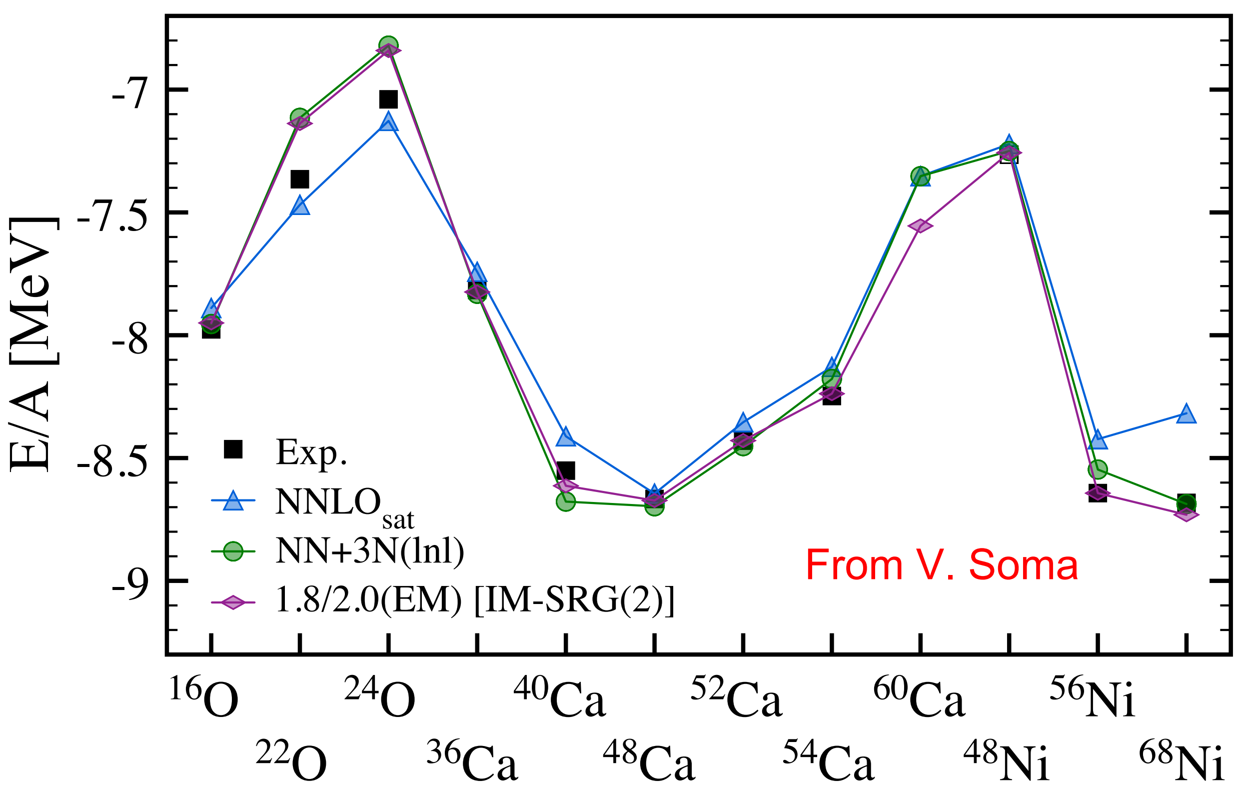
Predicts doubly magic nature from
2$^+$ energies and B(E2) systematics

Both calculations predict 5/2+ ground state

Connection to Infinite Matter: Saturation as a Guide

NN+3N force with good reproduction of ground-state energies





1.8/2.0 (EM), new LNL potential reproduce ground-state energies through ^{78}Ni

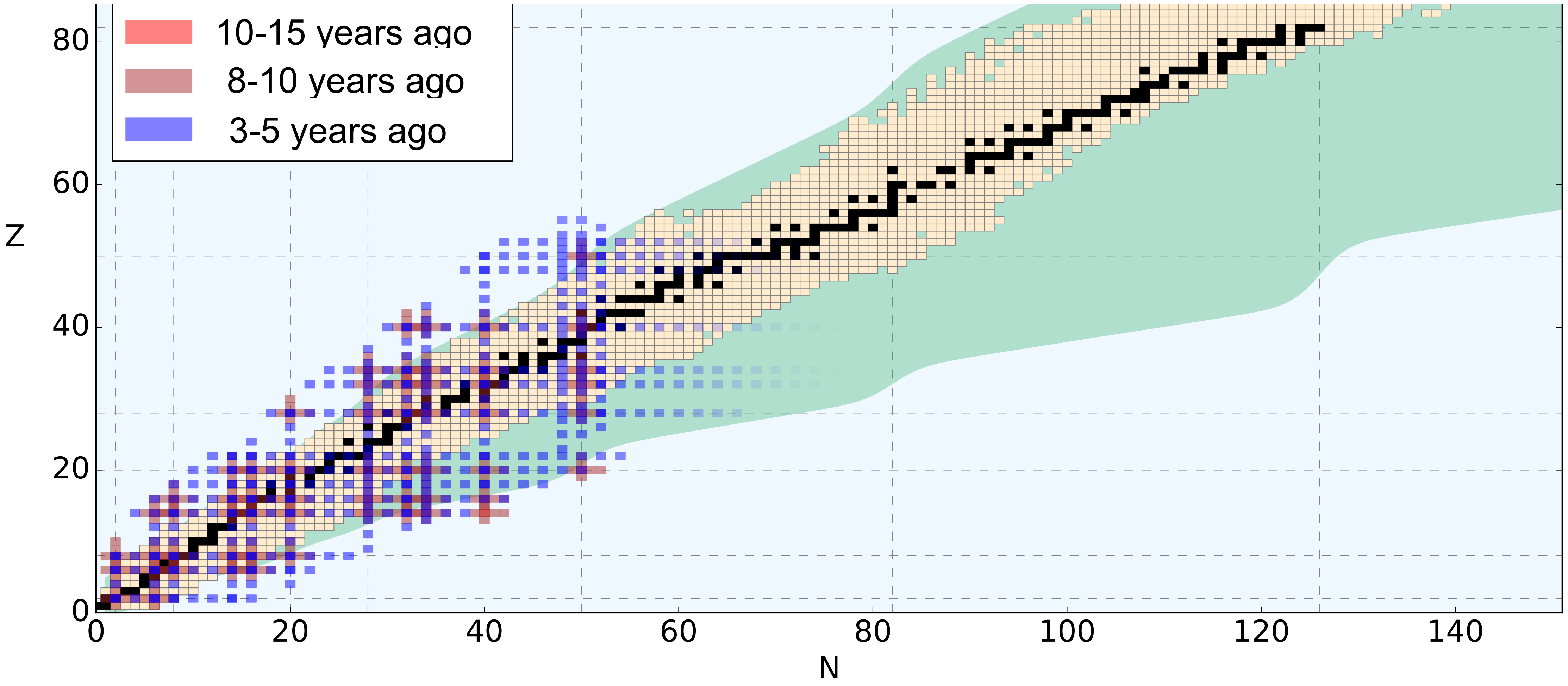
NNLOsat, typically underbinds

Breadth of Ab Initio Theory

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

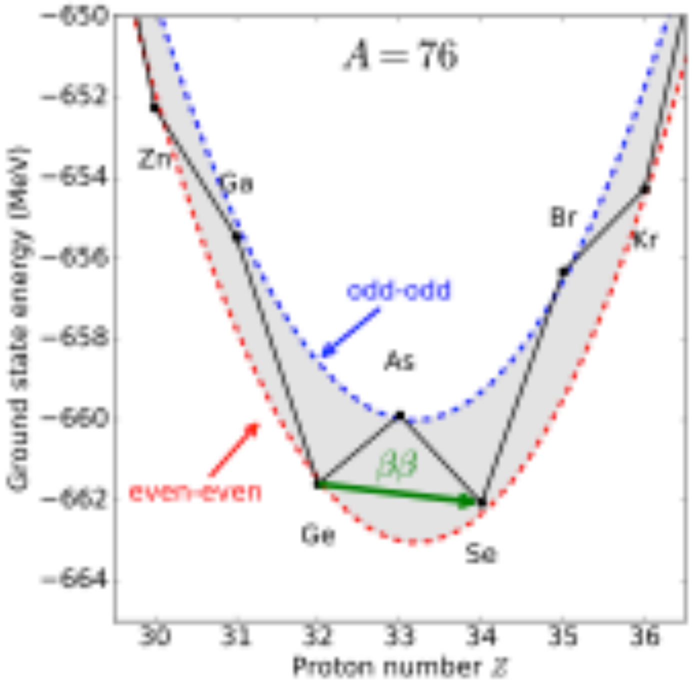
- Nuclear forces, electroweak physics
- **Nuclear many-body problem**

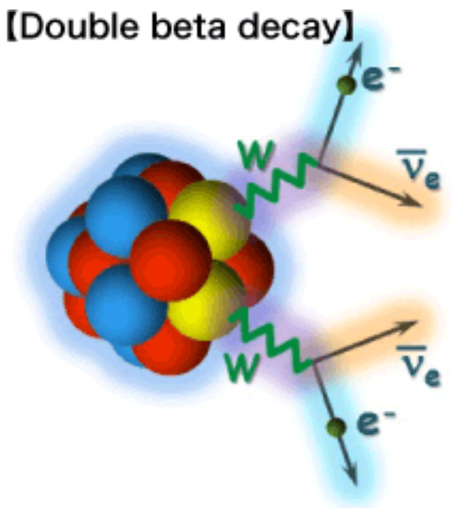
$$H\psi_n = E_n\psi_n$$

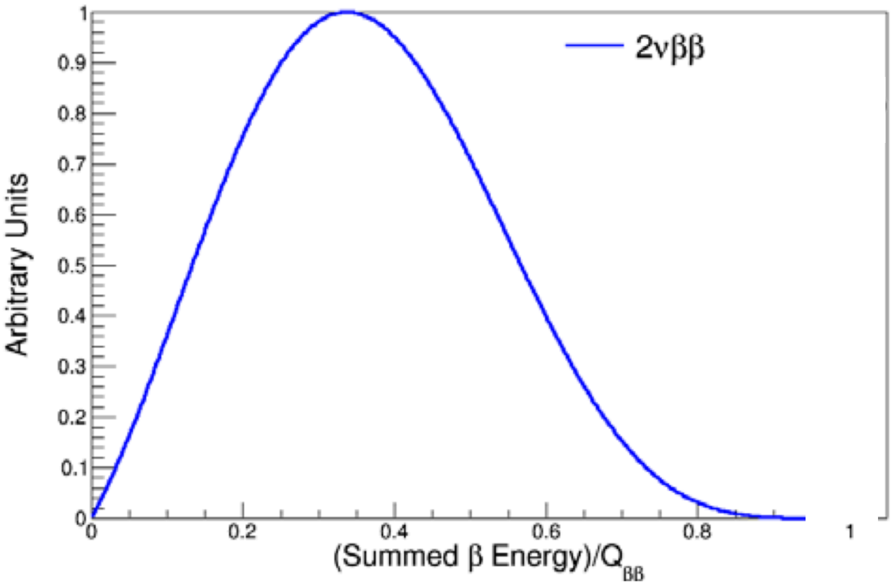


(Two-Neutrino) Double-Beta Decay

In rare cases beta decay is energetically forbidden – simultaneous beta decays







2nd-order weak process allowed by standard model

$$\left(T_{1/2}^{2\nu\beta\beta}\right)^{-1} = G^{2\nu}\left(Q_{\beta\beta}, Z\right)\left|M^{2\nu}\right|^2$$

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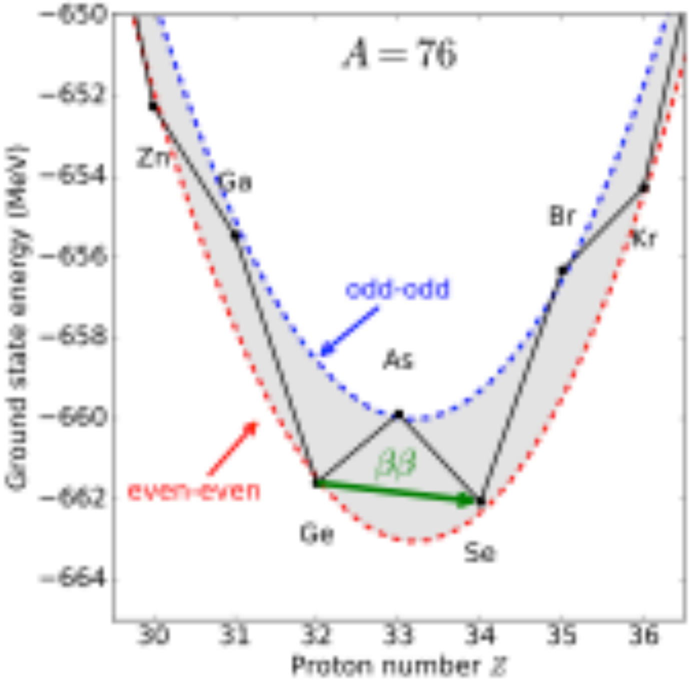
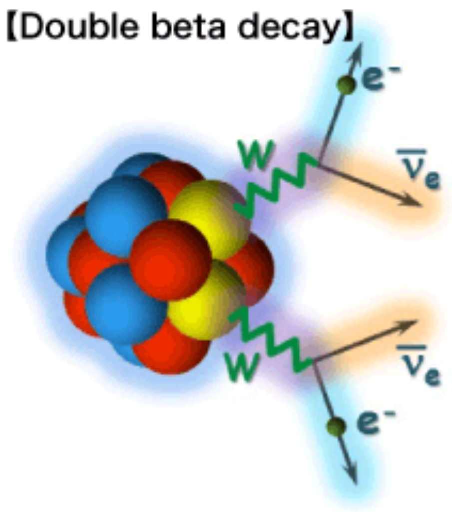
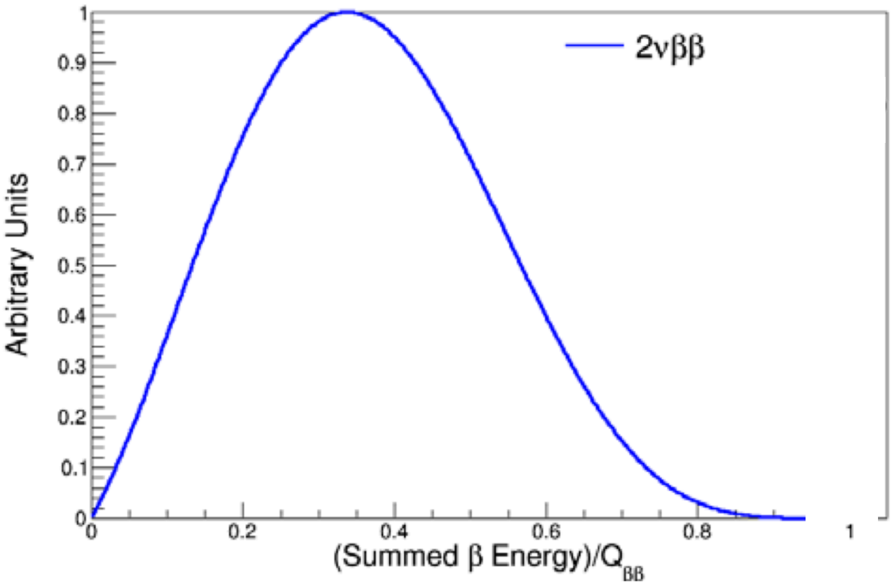






Observed in ~15 nuclei

Isotope	$T_{1/2}(2\nu)$ (years)	Isotope	$T_{1/2}(2\nu)$ (years)
^{48}Ca	$4.4^{+0.6}_{-0.5} \times 10^{19}$	^{116}Cd	$(2.8 \pm 0.2) \times 10^{19}$
^{76}Ge	$(1.5 \pm 0.1) \times 10^{21}$	^{128}Te	$(1.9 \pm 0.4) \times 10^{24}$
^{82}Se	$(0.92 \pm 0.07) \times 10^{20}$	^{130}Te	$(6.8^{+1.2}_{-1.1}) \times 10^{20}$
^{96}Zr	$(2.3 \pm 0.2) \times 10^{19}$	^{150}Nd	$(8.2 \pm 0.9) \times 10^{18}$
^{100}Mo	$(7.1 \pm 0.4) \times 10^{18}$	^{150}Nd-^{150}Sm(0_1^+)	$1.33^{+0.45}_{-0.26} \times 10^{20}$
^{100}Mo-^{100}Ru(0_1^+)	$5.9^{+0.8}_{-0.6} \times 10^{20}$	^{238}U	$(2.0 \pm 0.6) \times 10^{21}$

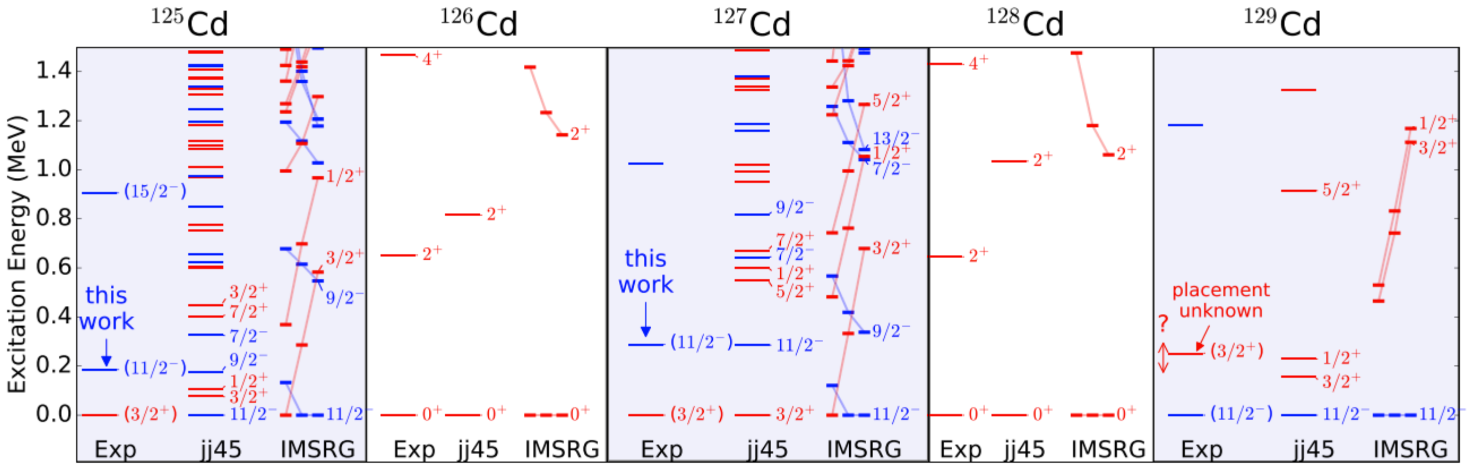
2nd-order weak process allowed by standard model

$$\left(T_{1/2}^{2\nu\beta\beta}\right)^{-1} = G^{2\nu}\left(Q_{\beta\beta}, Z\right)\boxed{\left|M^{2\nu}\right|^{2}}$$

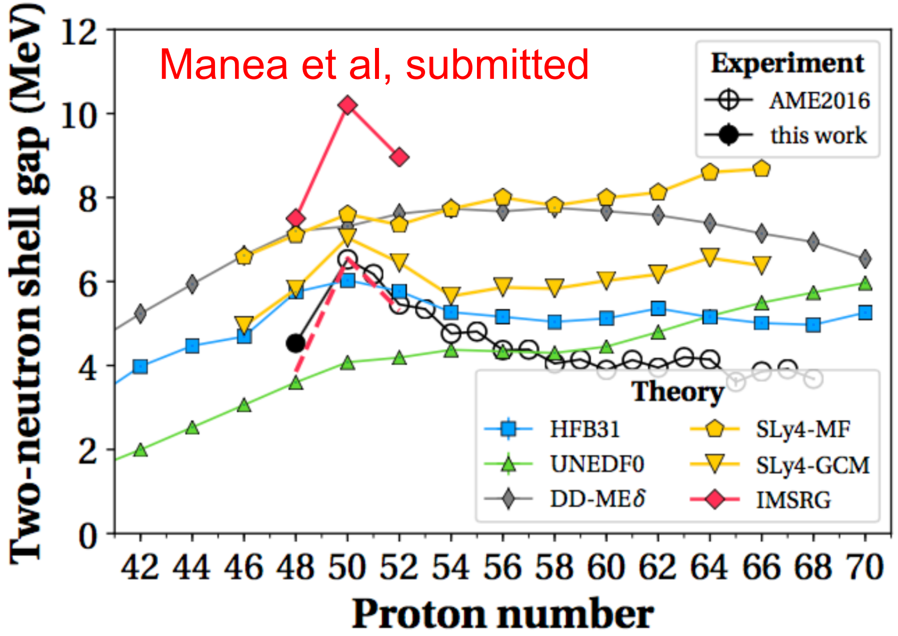
Lifetimes ~ 10^{20} years: **governed by NME**

Convergence of N=40 Gap

Size of N=70 gap clearly not converged wrt E3max – for neutron-rich Sn, In, Cd…



Lascar et al PRC (2017)



Resorted to unreliable extrapolations…

TRIUMF Convergence of N=40 Gap

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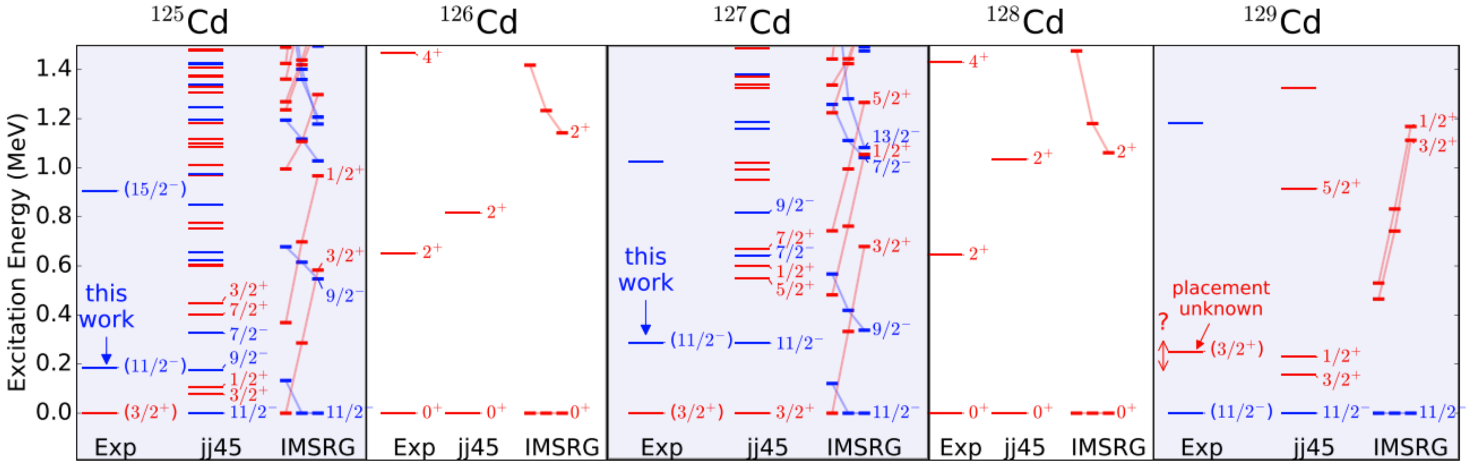

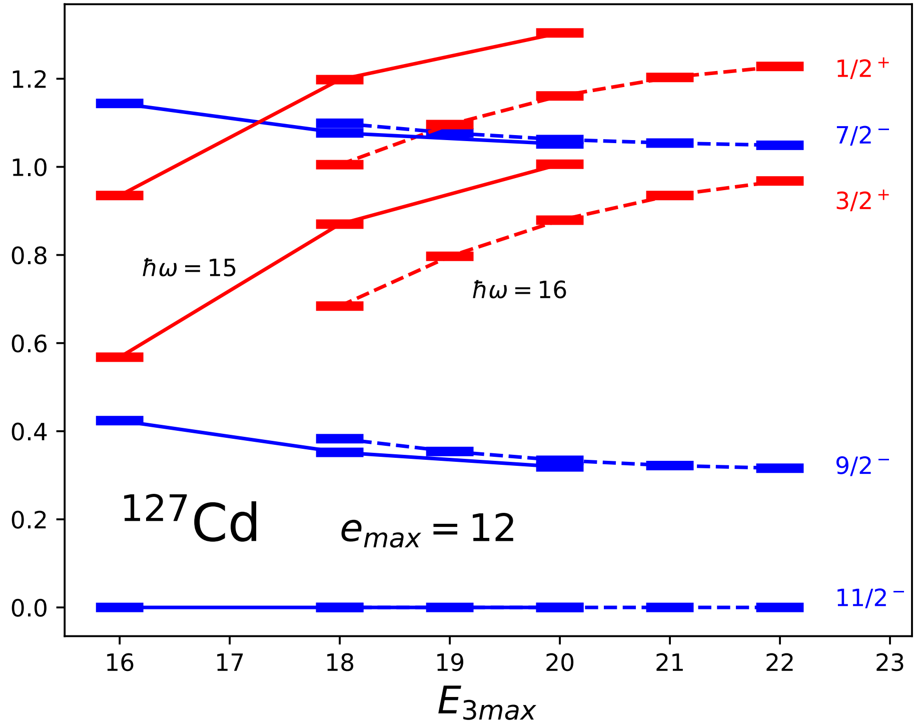

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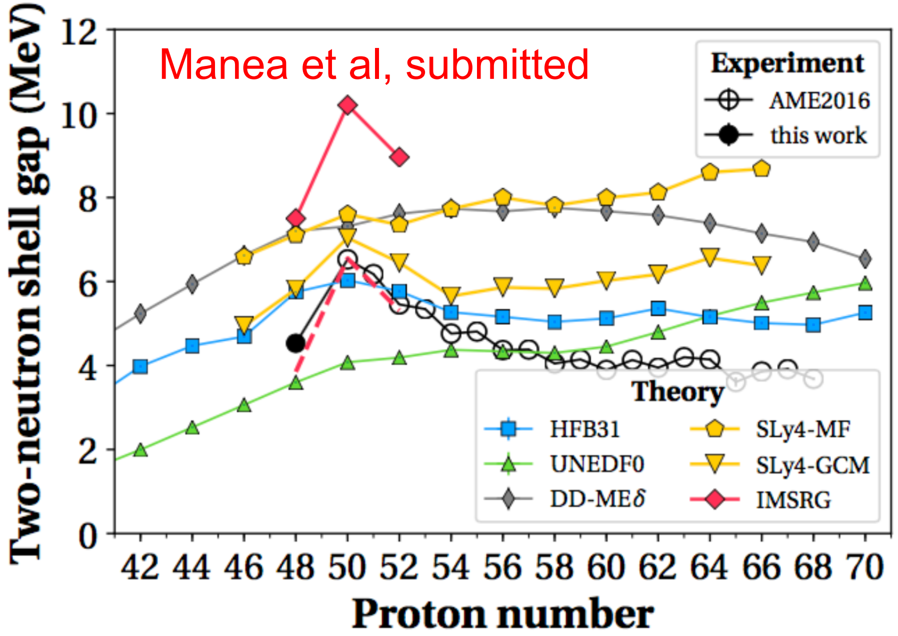


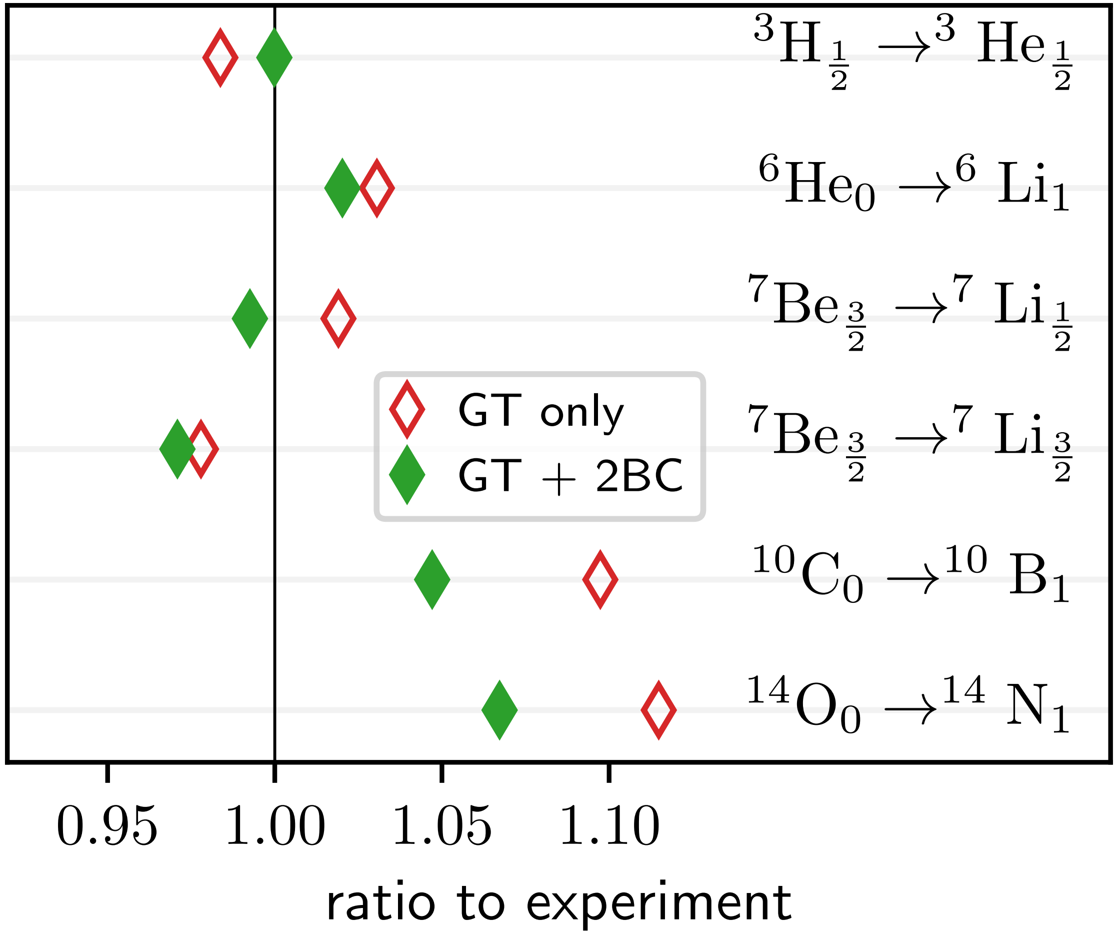
Resorted to unreliable extrapolations…

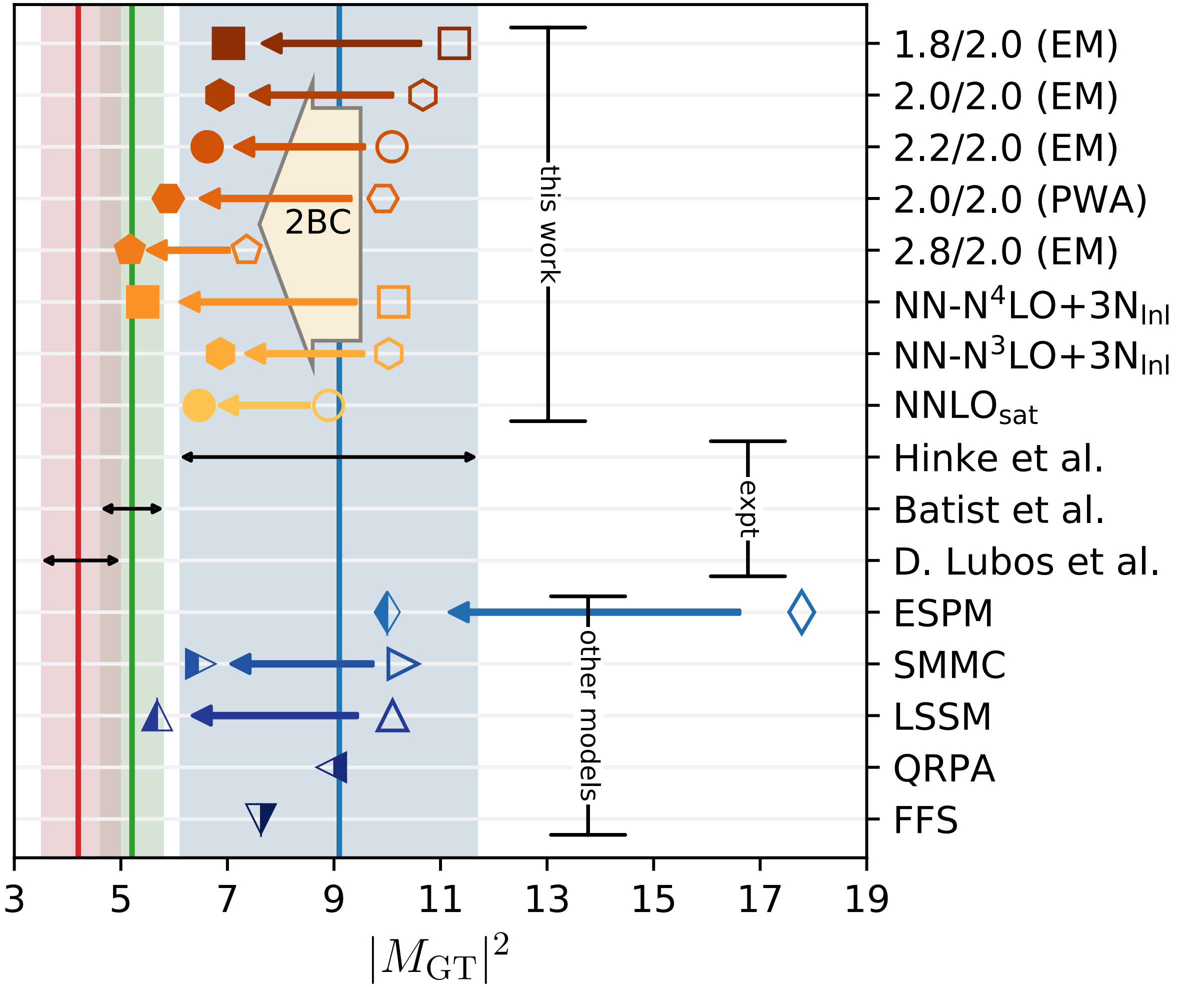
New capabilities: converged spectra in N=82 region!

Explore new physics near ^{132}Sn!

GT Transitions in Light nuclei and ^{100}Sn

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



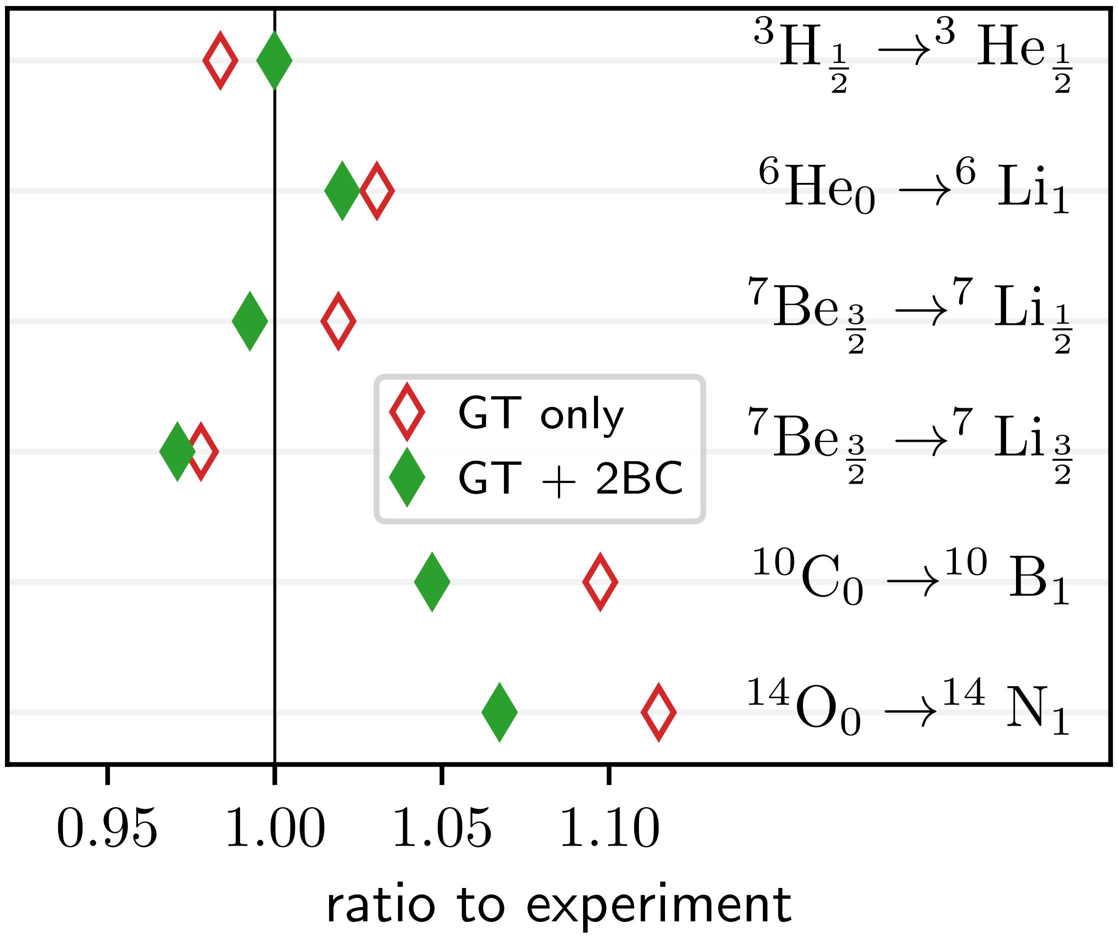


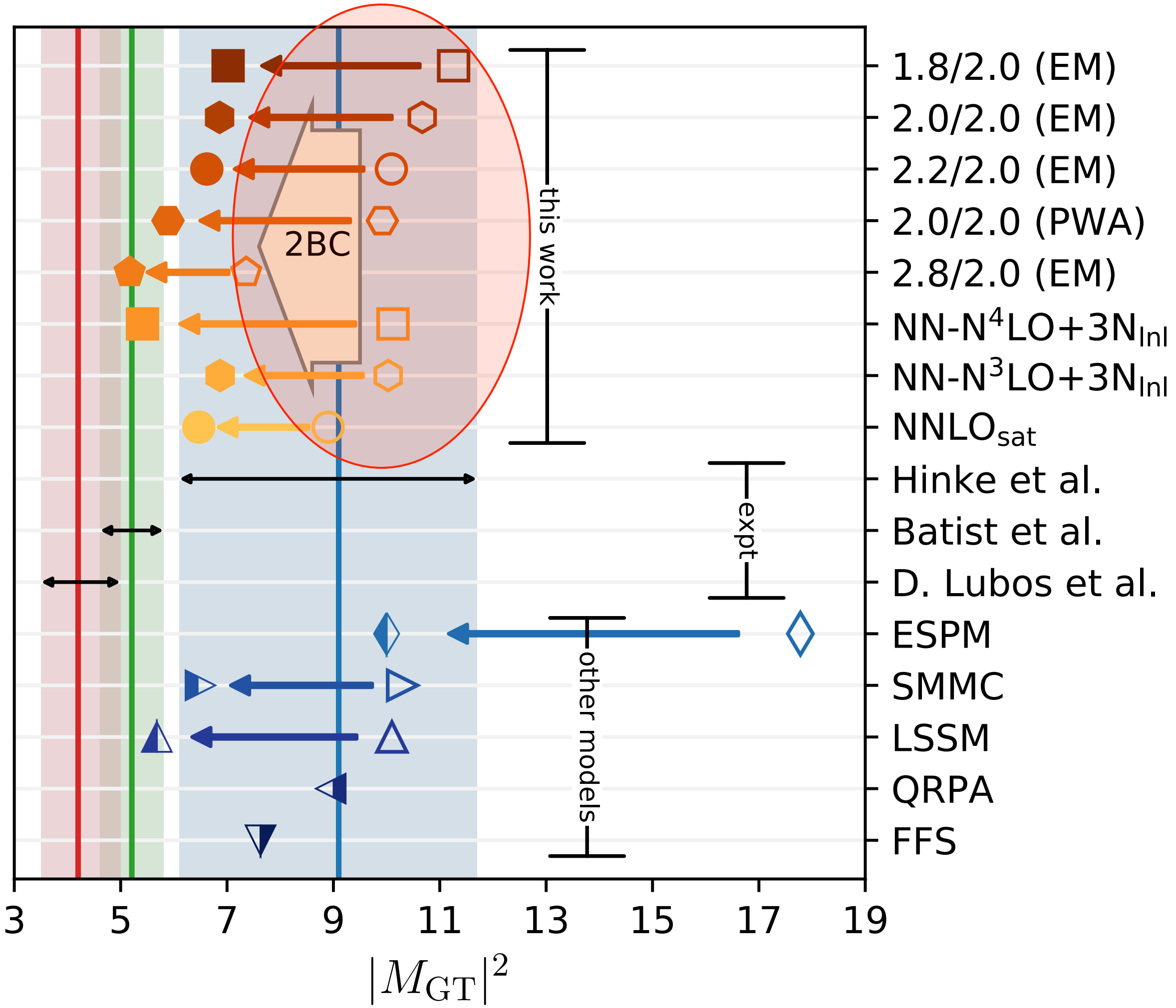
Large quenching effect from correlations

Gysbers et al., Nature Phys. (2019)

GT Transitions in Light nuclei and ^{100}Sn

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





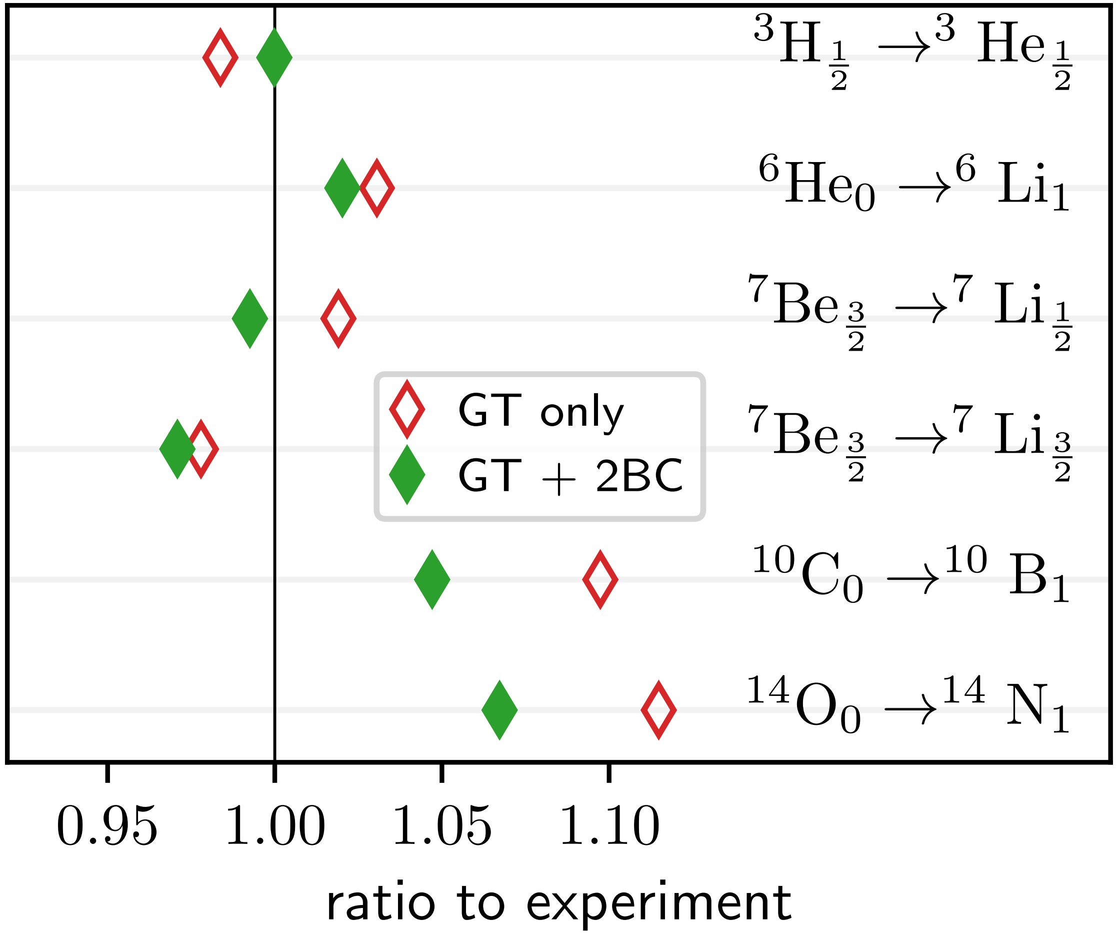
Large quenching effect from correlations

Without 2B currents, large spread in results

Gysbers et al., Nature Phys. (2019)

GT Transitions in Light nuclei and ^{100}Sn

NCSM in light nuclei



Gysbers et al., Nature Phys. (2019)

GT Transitions in Light nuclei and ^{100}Sn

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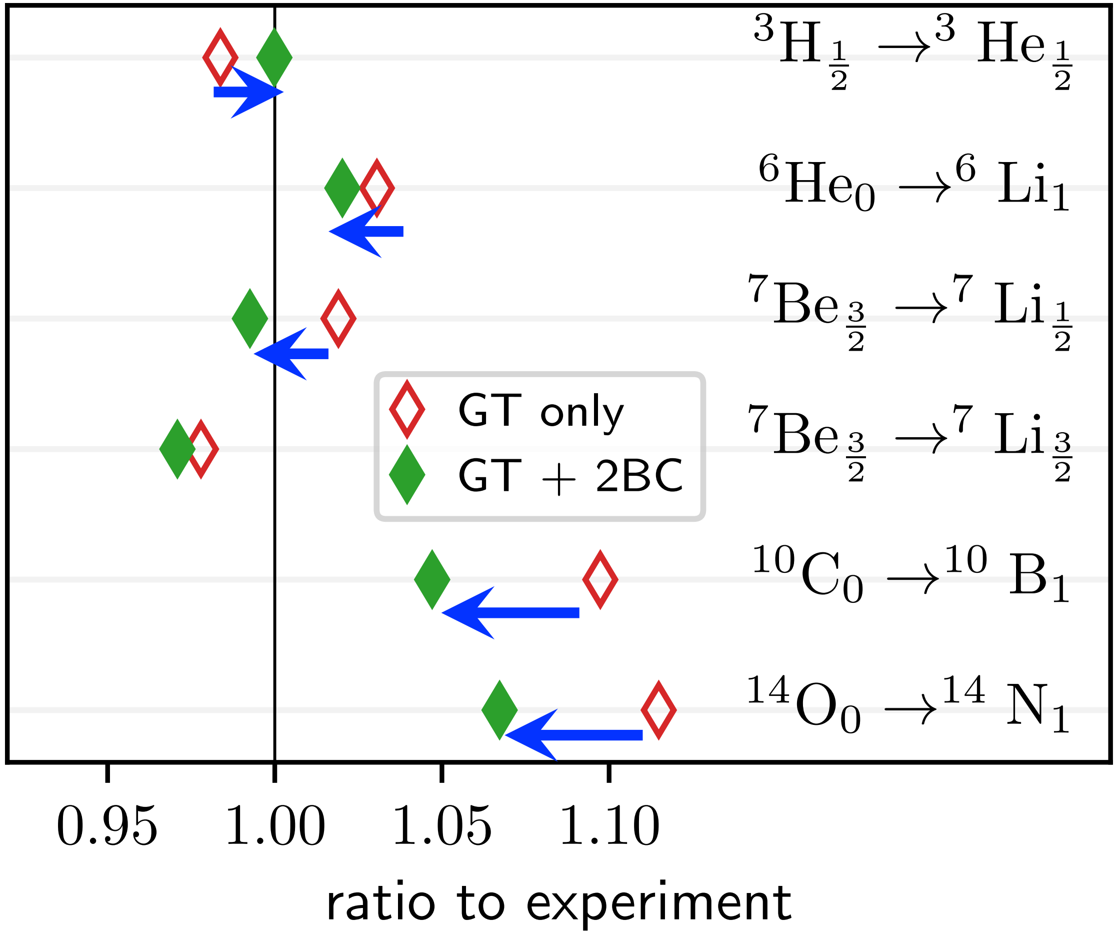


Gysbers et al., Nature Phys. (2019)

2BC provide modest quenching in most cases

VS-IMSRG Benchmarks

Convergence and method benchmarks of VS-IMSRG GT transitions

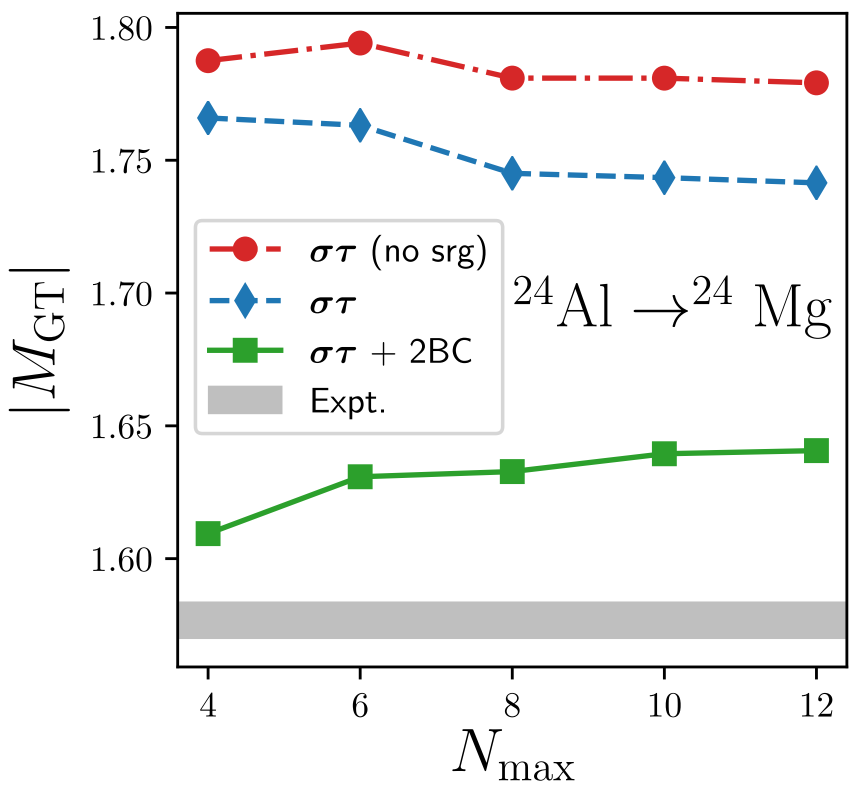


TABLE IV. Gamow Teller (GT) transition strength in ^{10}C to the first 1_1^+ in ^{10}B for the NN-N^{4}LO +3N$_{\rm lnl}$ interaction calculated in the VS-IMSRG(2) and NCSM approaches.

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

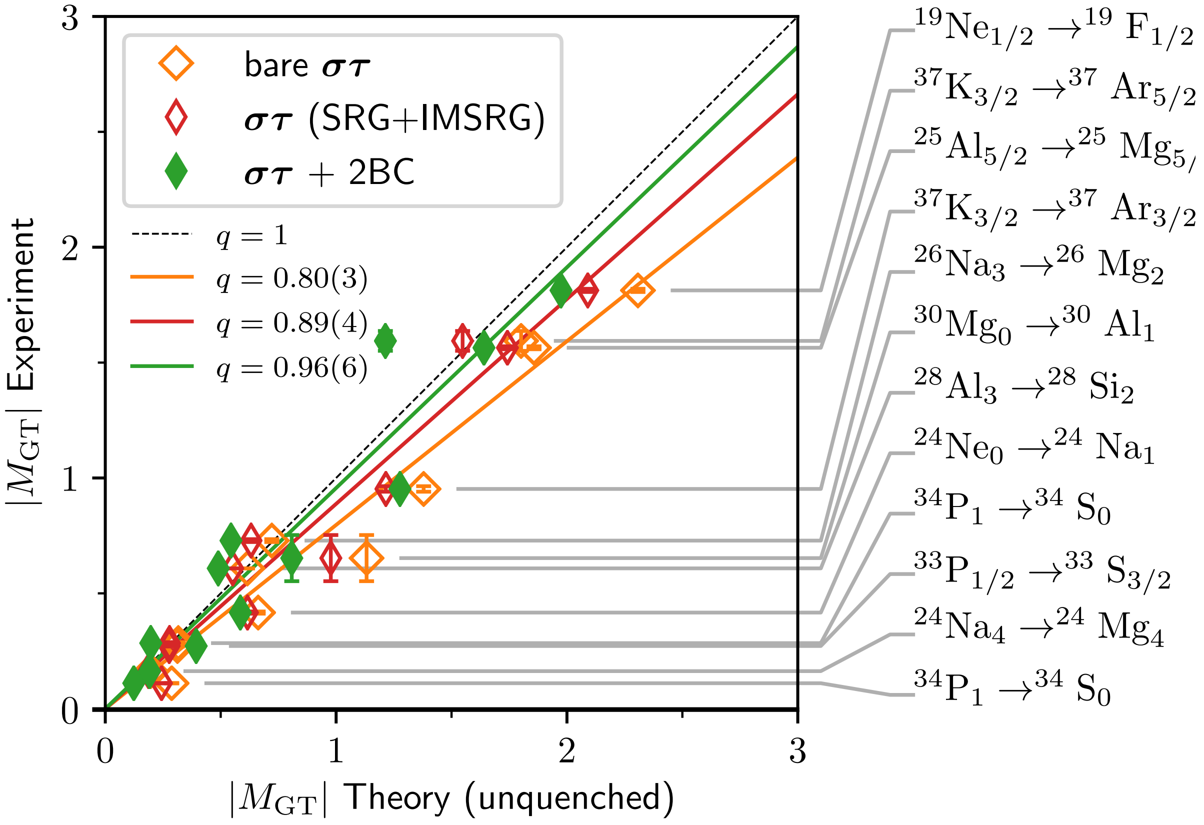
Well converged and good agreement with other ab initio methods

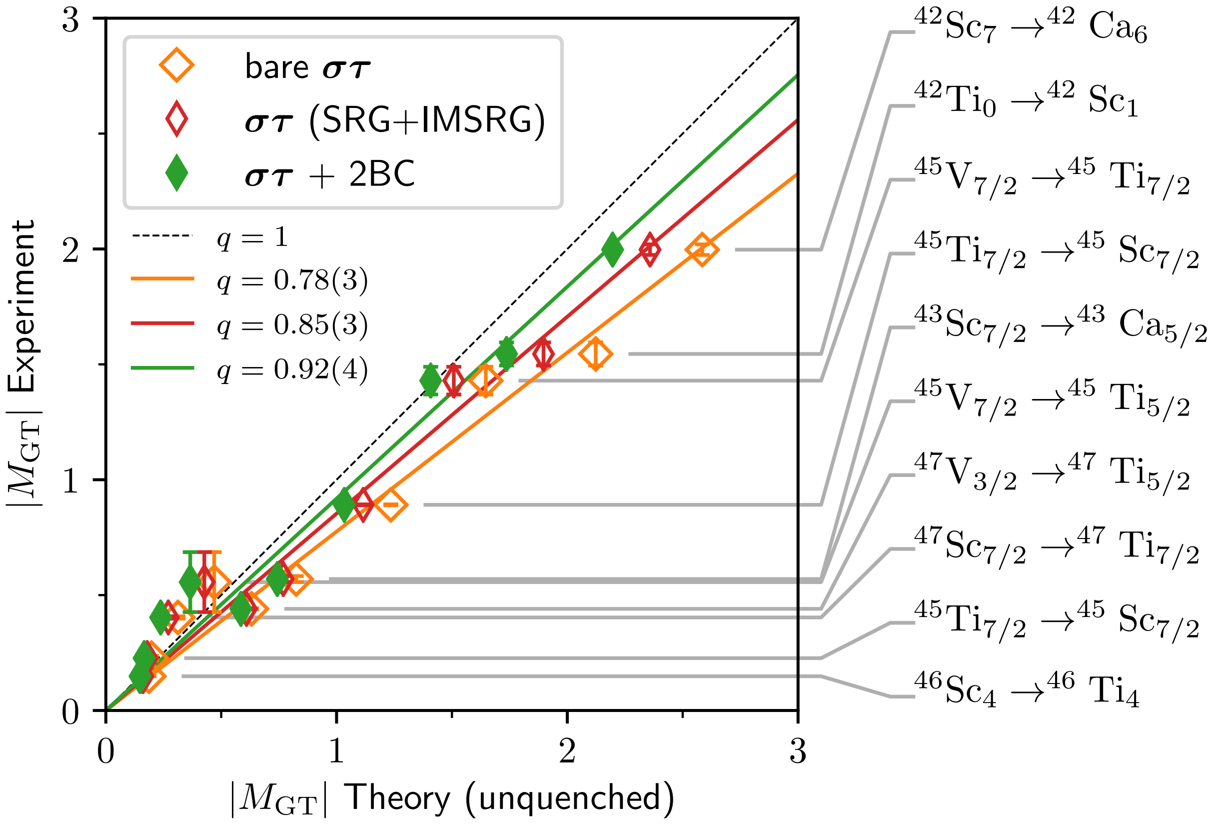
Ab Initio GT Decays in Medium-Mass Region

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



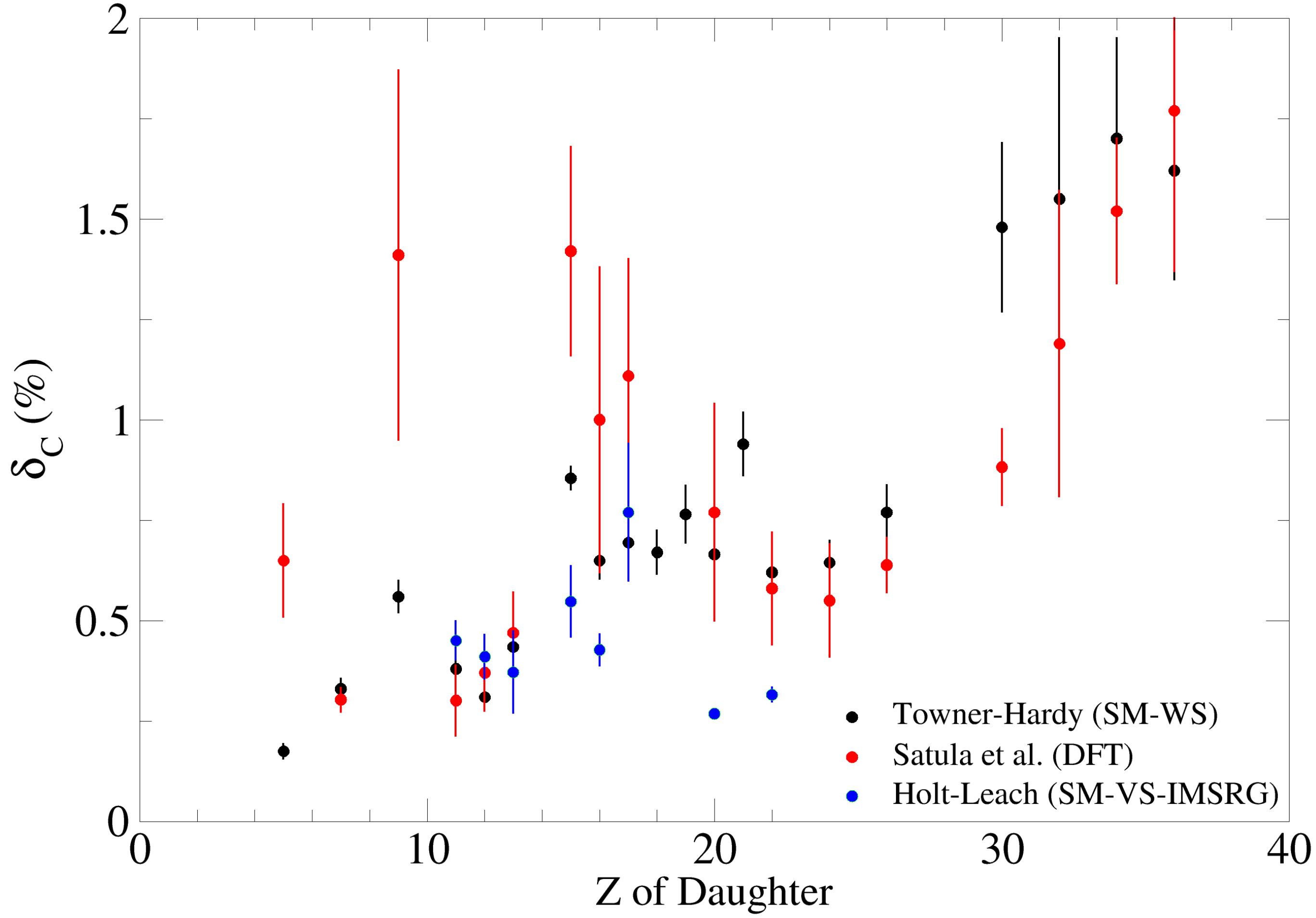


Gysbers et al., Nature Phys. (2019)

Further modest quenching from 2BC

Superallowed Fermi Transitions

Essential for determinination of V_{ud}



Standard approach (T/H):

$$\delta_C = \underbrace{\delta_{C1}}_{\text{configuration mixing}} + \underbrace{\delta_{C2}}_{\text{wave function mismatch}}$$

Ab initio approach

$$|M_F|^2 = |M_F^0|^2(1-\delta_C)$$

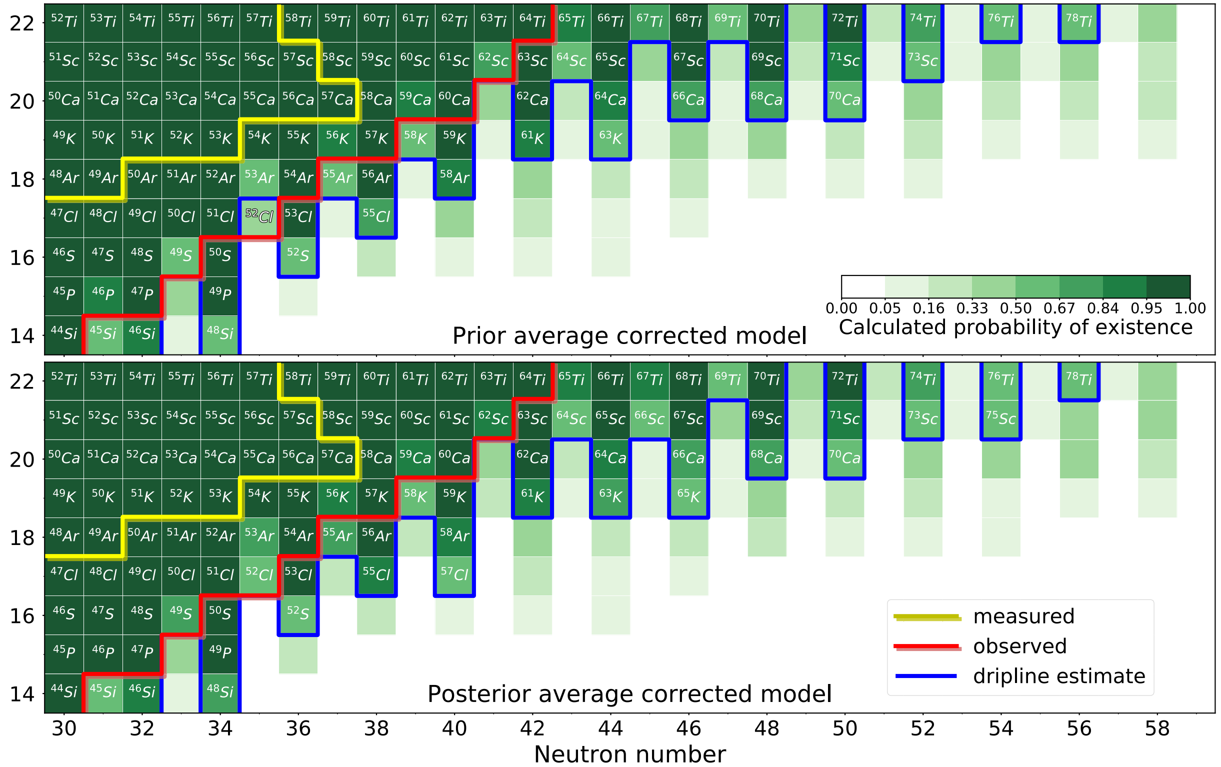
$$\delta_C = \left\{H_{pp}(s) \neq H_{nn}(s) \neq H_{pn}(s)\right\} + \left\{\tau(s) = U(s)\tau U^{\dagger}(s)\right\} + \left\{\langle \phi_p^{HF}|\tau|\phi_n^{HF}\rangle \neq 1\right\}$$

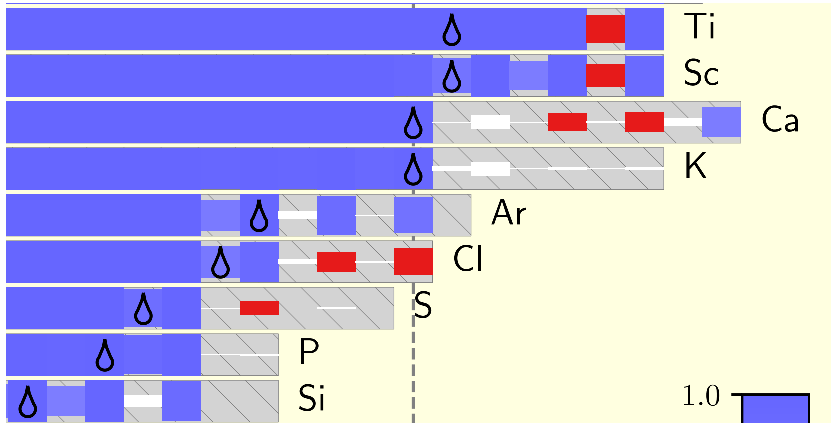
Martin, JDH, Leach, Stroberg, in prep.

TRIUMF

Comparison with DFT/Machine Learning Predictions

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





Largely consistent prediction of drip line

TRIUMF

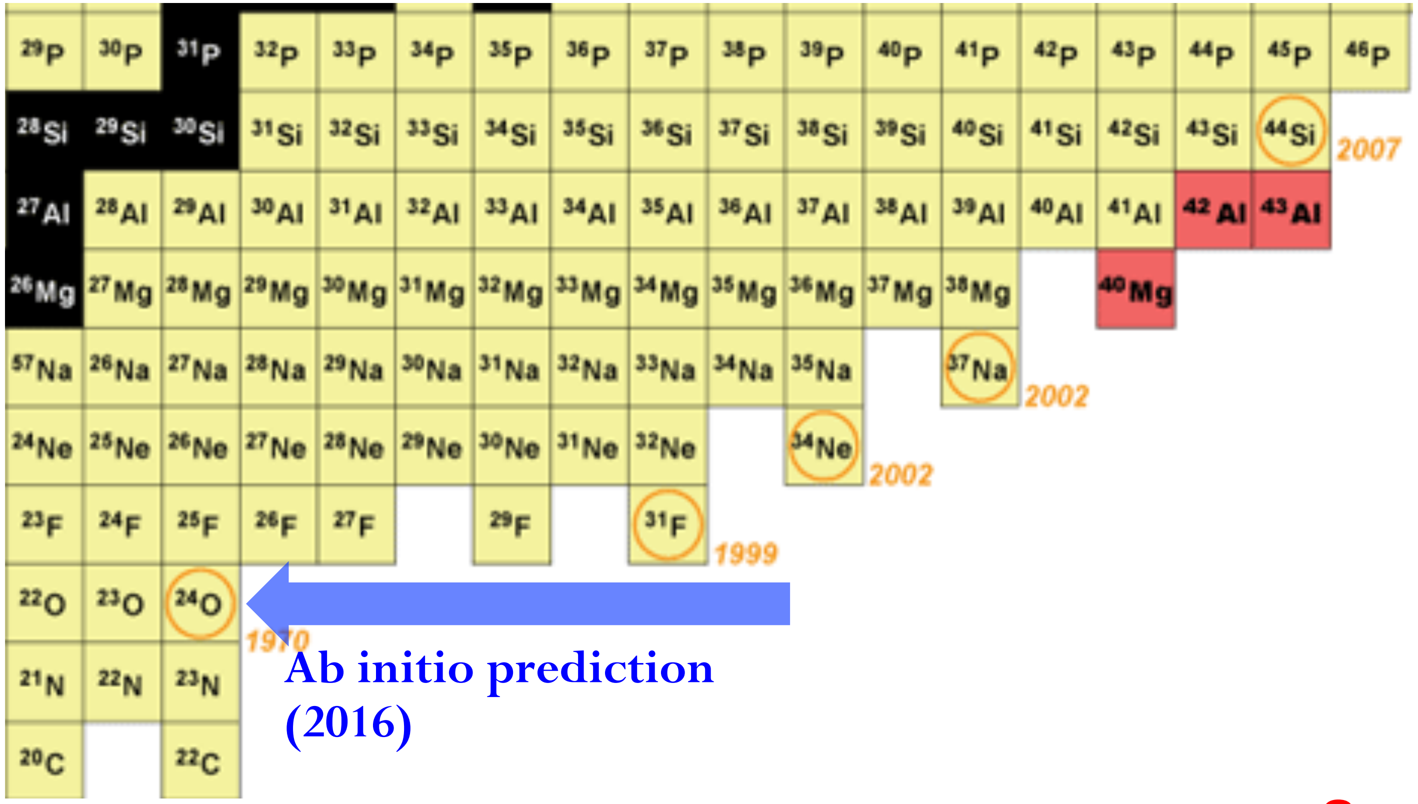
Major Issue I: Limits of Existence of Nuclei

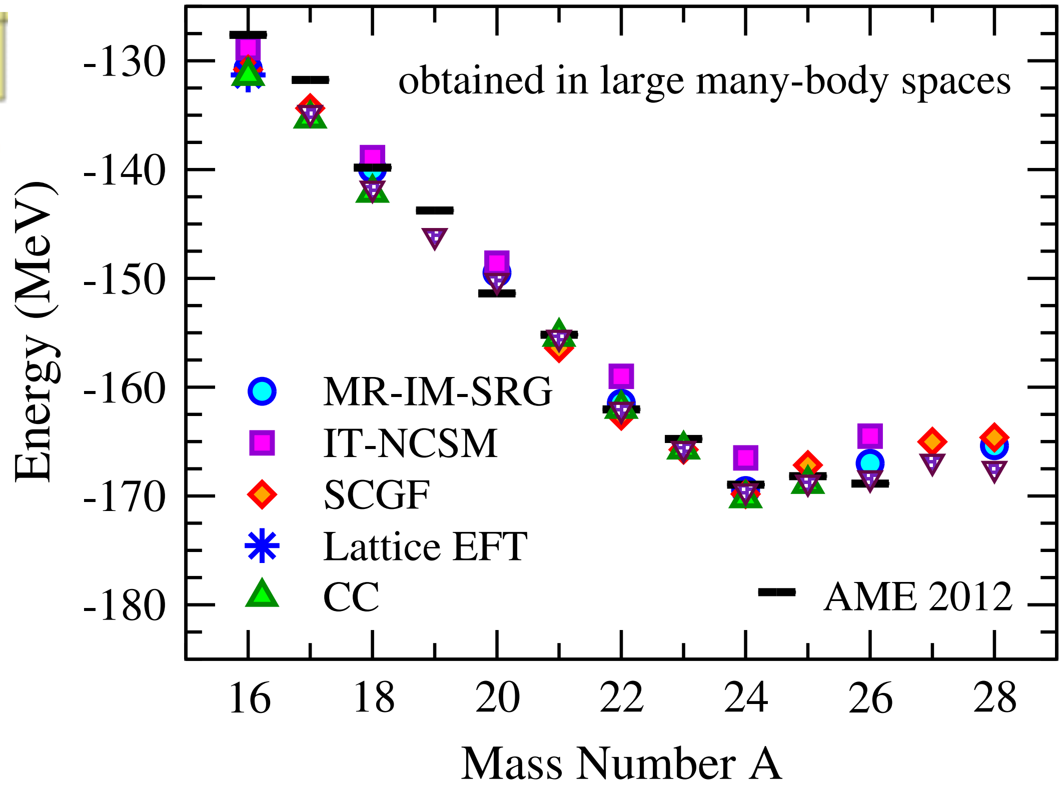
Where (and what) is the nuclear dripline?

Limits defined as last isotope with positive neutron separation energy

- Nucleons "drip" out of nucleus

Neutron dripline experimentally established to Z=8





Same result from same input NN+3N forces

Already well beyond where fit to data!

Valence-Space IMSRG

Explicitly construct unitary transformation from sequence of rotations

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

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

$$\tilde{\mathcal{O}} = e^{\Omega}\mathcal{O}e^{-}$$

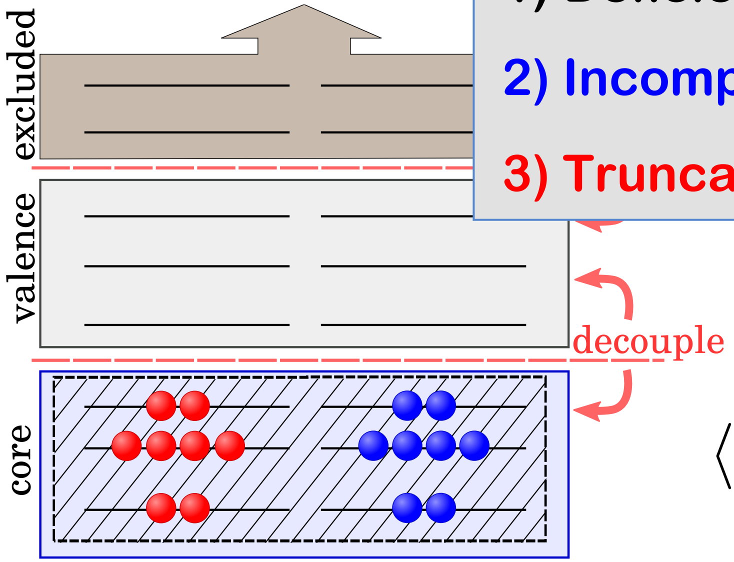
…, Bogner, Schwenk, PRC 2012
…rzuchowski, Bogner, PRC 2015

Potential sources of error

1) Deficiencies in nuclear forces / neglected EW currents

2) Incomplete convergence in basis ✔ (N,Z < 50)

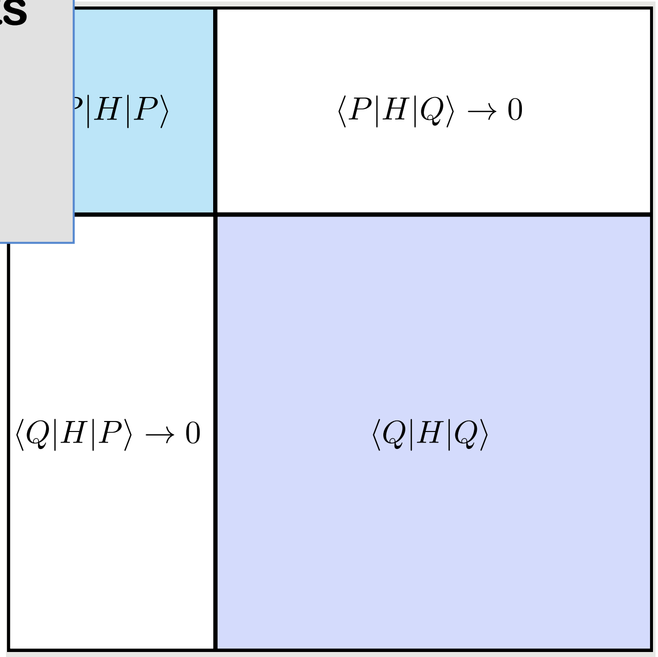
3) Truncations in many-body operators?



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

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

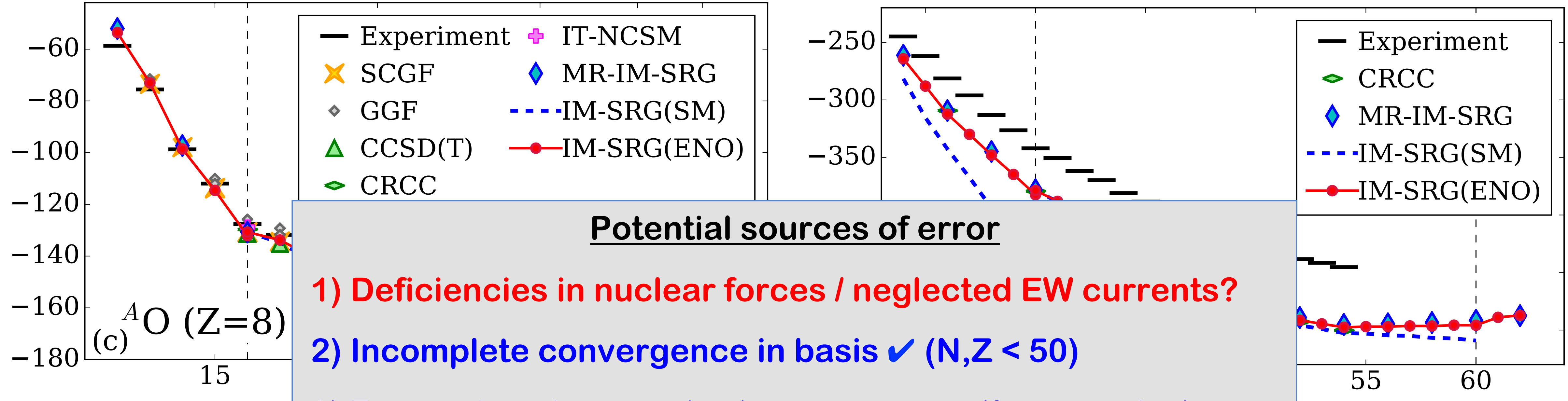
$$\langle \tilde{\Psi}_n | P\tilde{M}_{0\nu}P \mid \tilde{\Psi}_n\rangle \approx \langle \Psi_i | M_{0\nu} | \Psi_i\rangle$$



Careful benchmarking essential!

Benchmarking VS-IMSRG: from Oxygen to Calcium

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



Potential sources of error

1) Deficiencies in nuclear forces / neglected EW currents?

2) Incomplete convergence in basis ✔ (N,Z < 50)

3) Truncations in many-body operators ✔ (for energies)

Stroberg et al., PRL (2017)

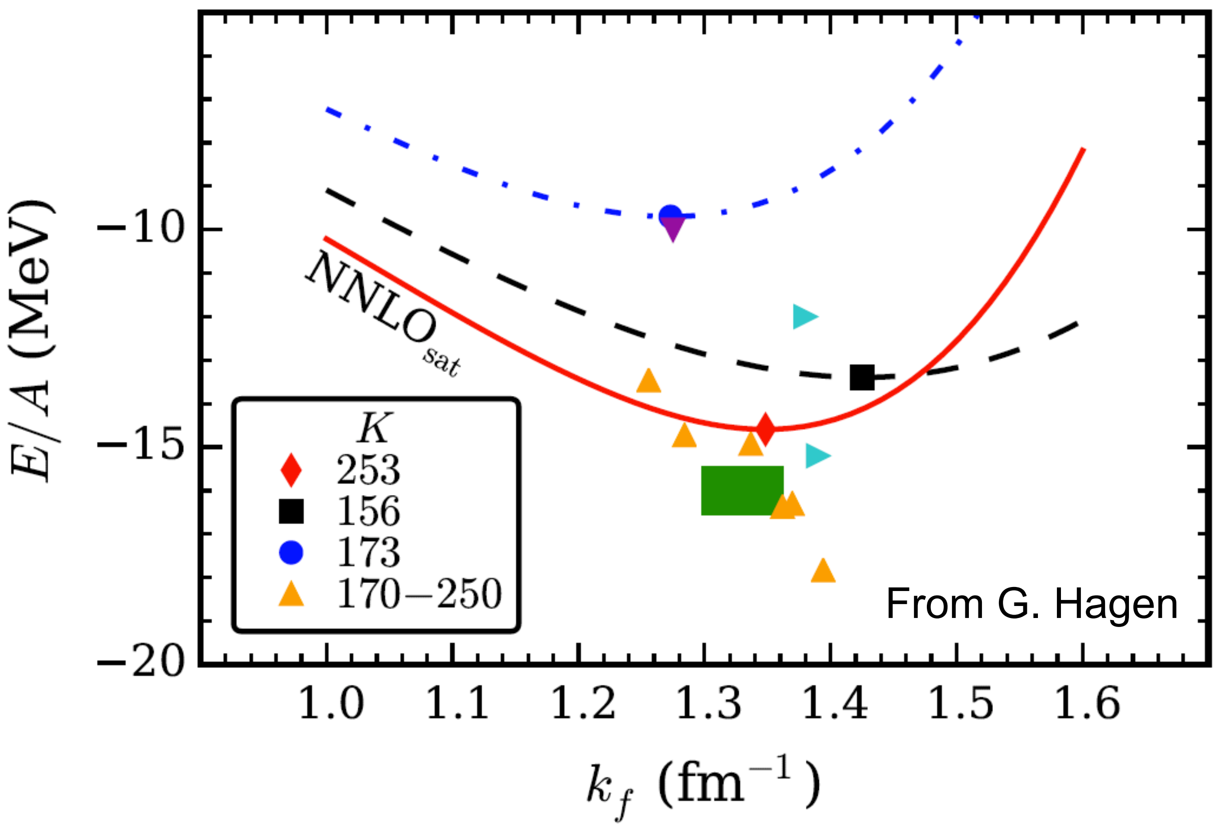
Agreement with *experiment* deteriorates for heavy chains (due to input Hamiltonian)

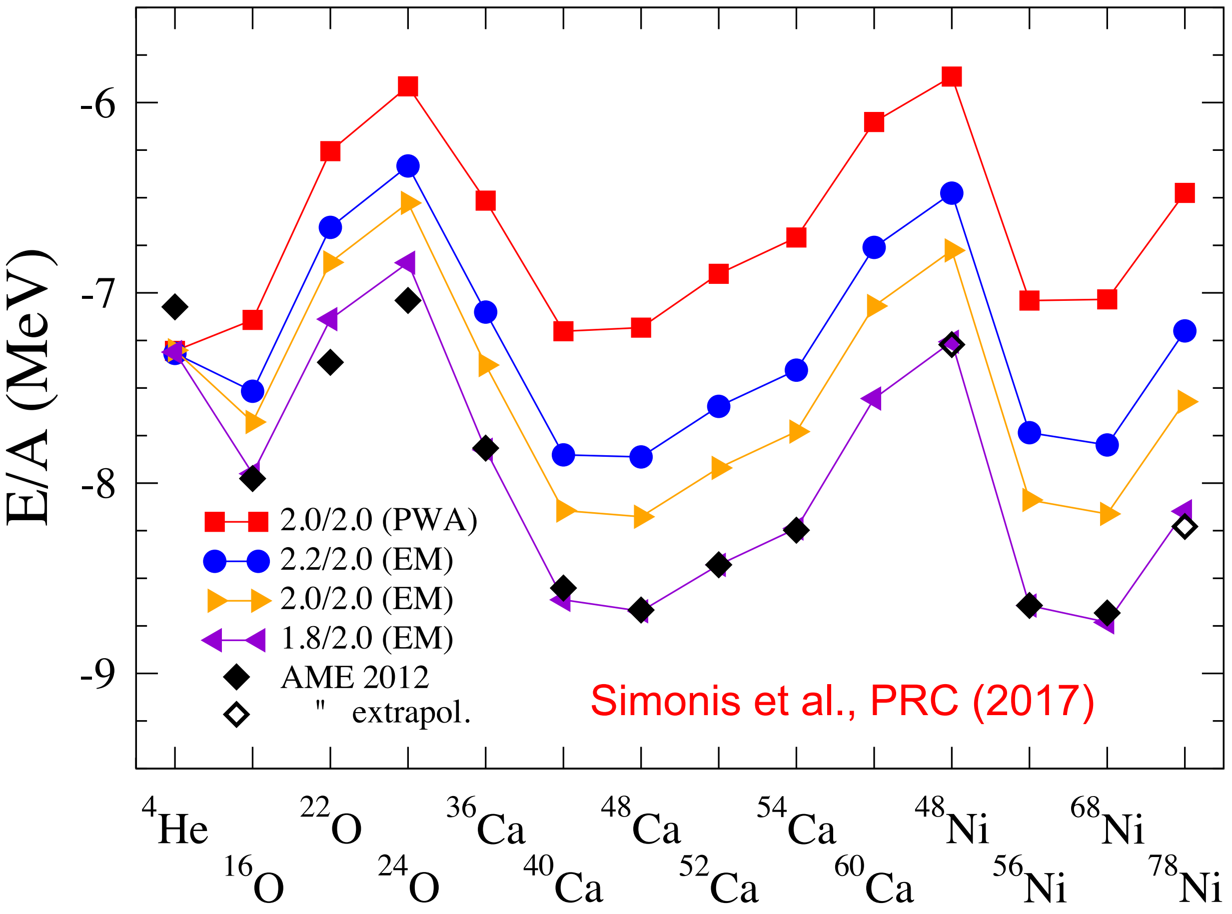
Significant gain in applicability with little/no sacrifice in accuracy; **Any operator can be calculated**

Low computational cost: ~1 node-day/nucleus

TRIUMF Connection to Infinite Matter: Saturation as a Guide

NN+3N force with good reproduction of ground-state energies





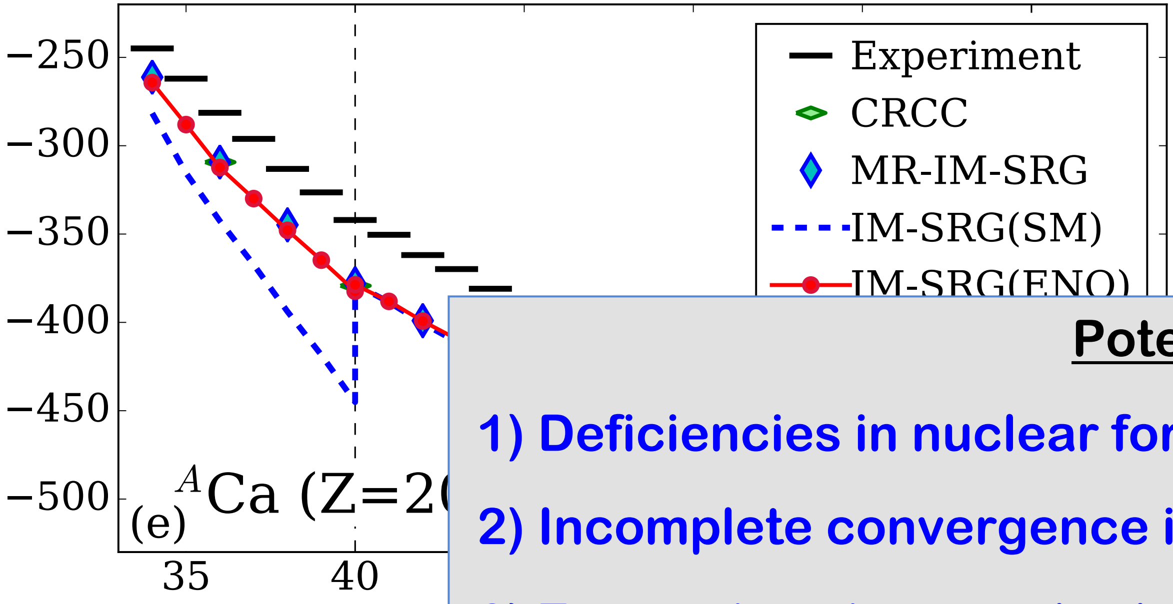
1.8/2.0 (EM) reproduces ground-state energies through ^{78}Ni

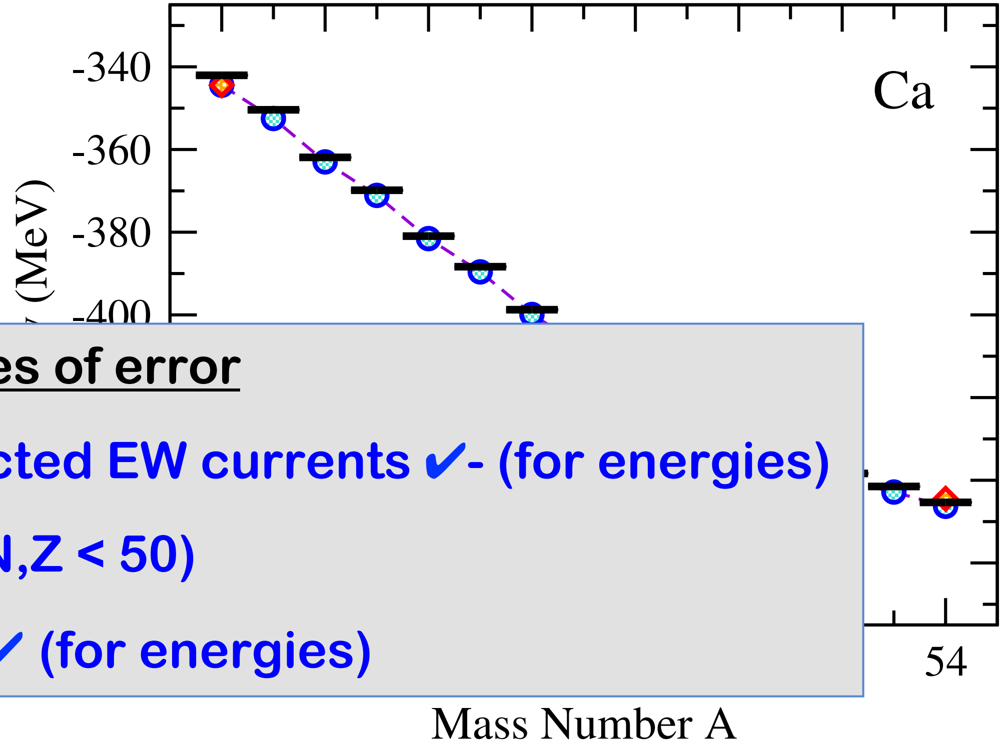
Slight underbinding for neutron-rich oxygen

TRIUMF

NN+3N Forces with Good Saturation Properties

Dramatic improvement with respect to experimental data





Potential sources of error

1) Deficiencies in nuclear forces / neglected EW currents ✔- (for energies)

2) Incomplete convergence in basis ✔ (N,Z < 50)

3) Truncations in many-body operators ✔ (for energies)

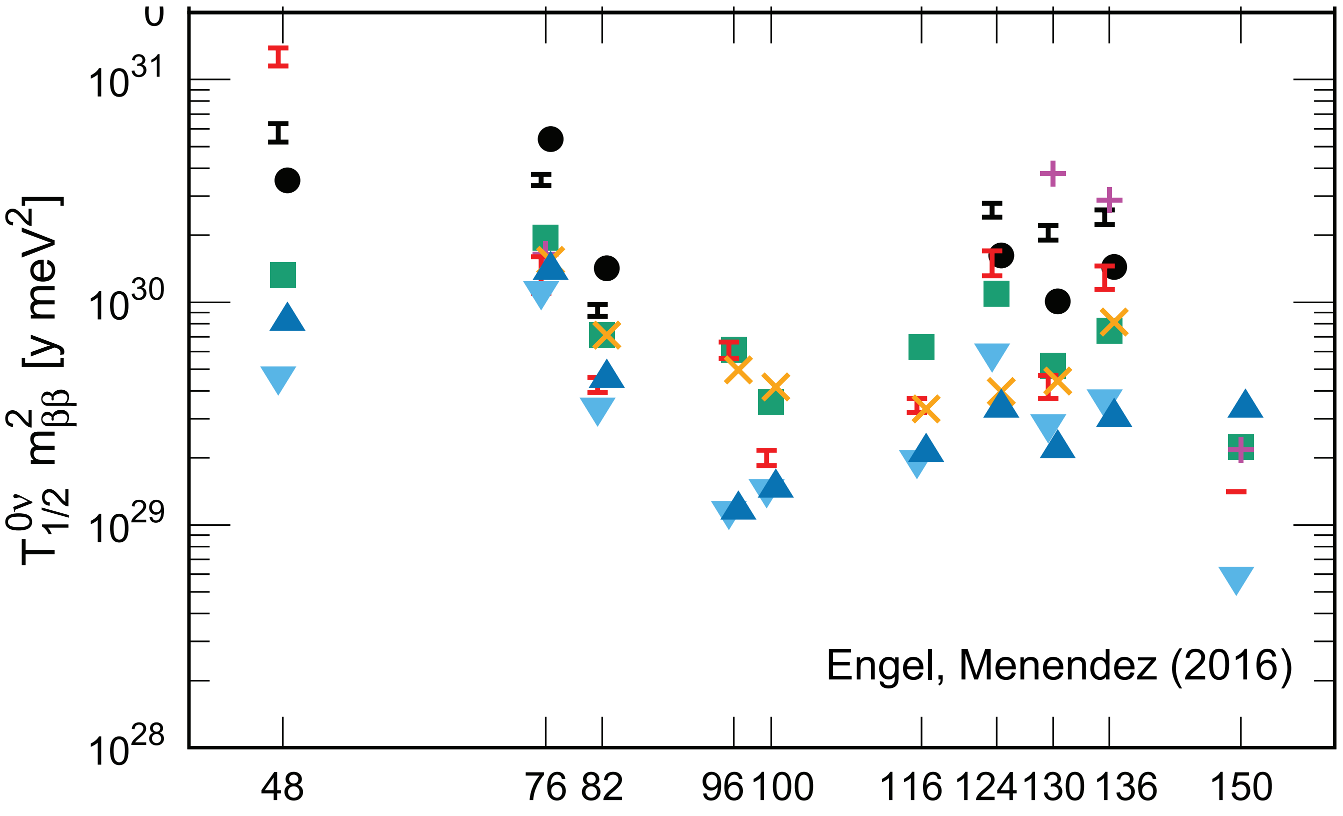
Opens possibility for reliable ab initio predictions across the nuclear chart!

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

- Ground states, excited states, charge radii, electroweak transitions…
- Test nuclear forces across range of nuclei

Status of 0νββ-decay Matrix Elements

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



All models missing essential physics

Impossible to assign rigorous uncertainties – **explore new approach to nuclear theory!**