TRIUMF

McGill UNIVERSITY

Ab Initio Approach to Superallowed Fermi Transitions

Jason D. Holt
TRIUMF, Theory Department

MITP Workshop: Electroweak Precision Physics

October 27, 2022

NSERC CRSNG

Arthur B. McDonald Canadian Astroparticle Physics Research Institute

NRC·CNRC

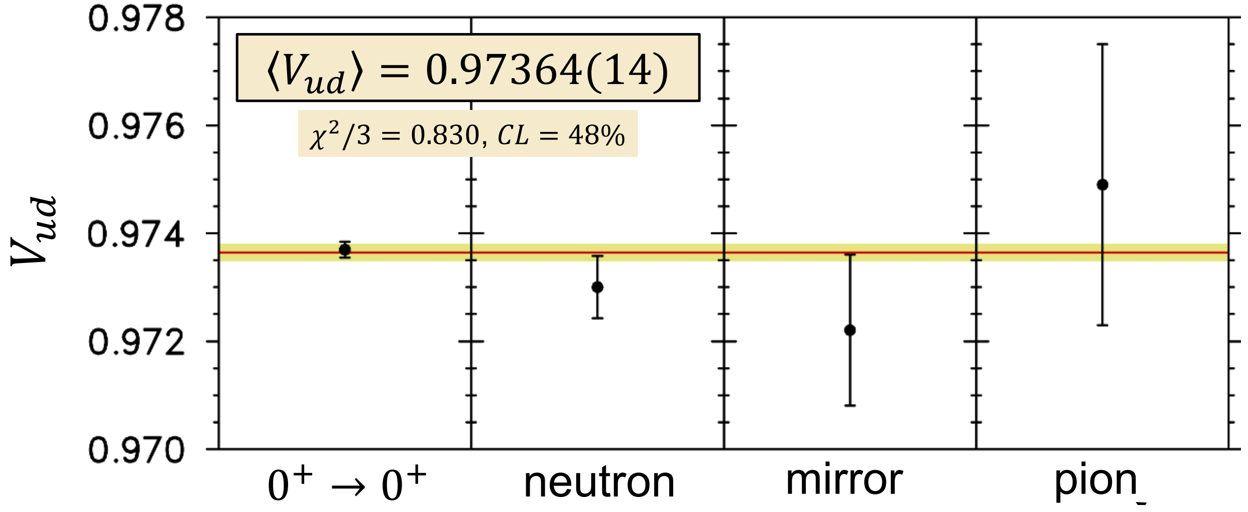
Discovery, accelerated

Superallowed Fermi Transitions

$0^+ \rightarrow 0^+$ transitions: most stringent constraint on V_{ud} from corrected (parameterized) lifetime

$$G_V = G_F V_{ud}, \text{ where } ft = \frac{K}{2G_V^2} \quad \text{(isospin limit)}$$

$$\mathcal{F}t = ft(1+\delta'_R[1-(\delta_C - \delta_{NS})] = \frac{K/G_F^2}{2V_{ud}^2(1+\Delta_R^V)}$$

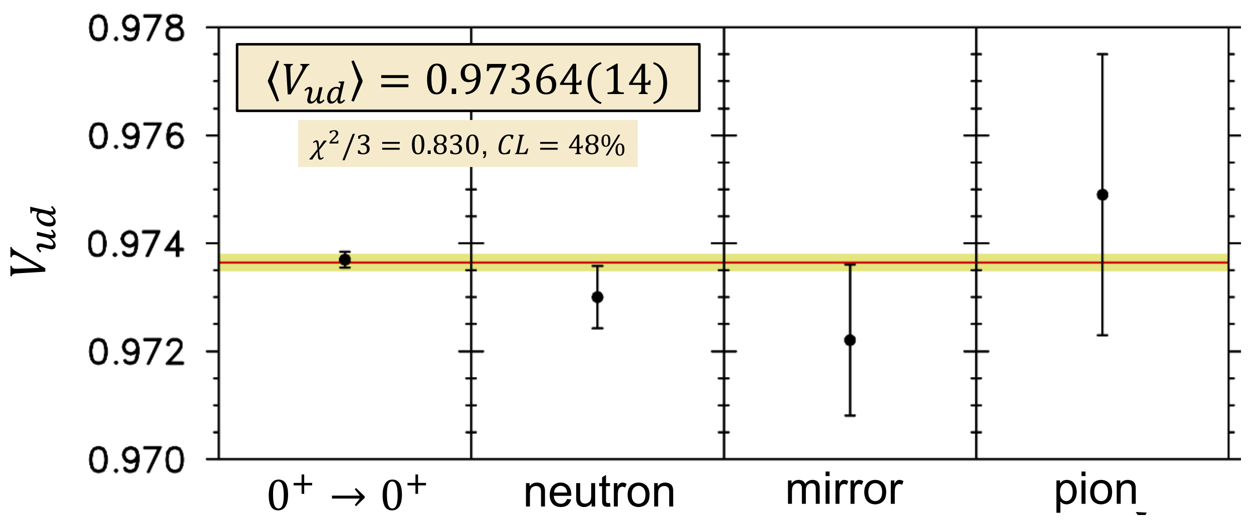


Superallowed Fermi Transitions

$0^+ \rightarrow 0^+$ transitions: most stringent constraint on V_{ud} from corrected (parameterized) lifetime

$$G_V = G_F V_{ud}, \text{ where } ft = \frac{K}{2G_V^2} \quad \text{(isospin limit)}$$

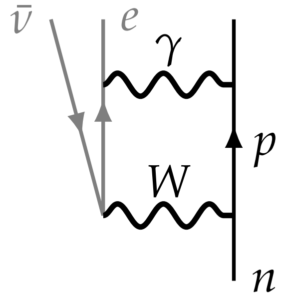
$$\mathcal{F}t = ft(1+\delta_R'[1-(\delta_C-\delta_{NS})] = \frac{K/G_F^2}{2V_{ud}^2(1+\Delta_R^V)}$$



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

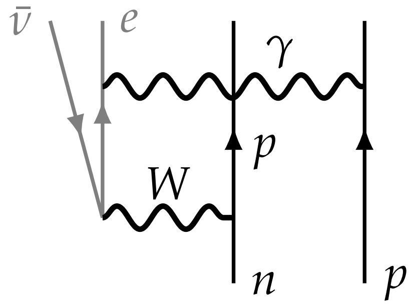
Isospin-symmetry breaking

$\delta_R' \sim$



Structure-independent radiative correction

$\delta_{NS} \sim$



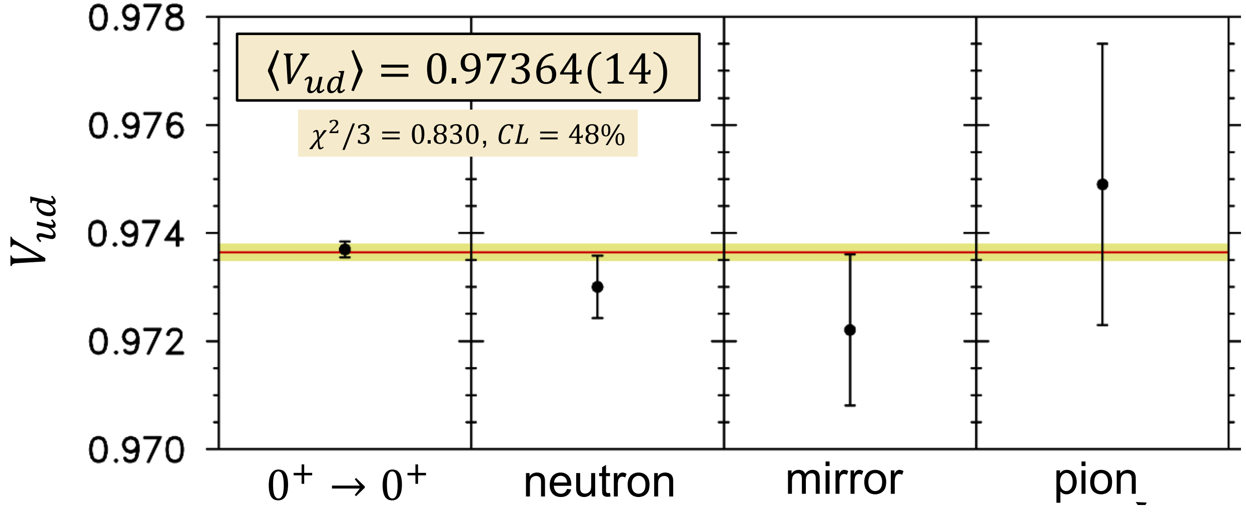
Structure-dependent radiative correction

Superallowed Fermi Transitions

$0^+ \rightarrow 0^+$ transitions: most stringent constraint on $\mathrm{V_{ud}}$ from corrected (parameterized) lifetime

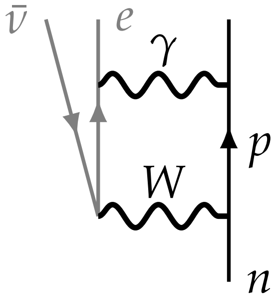
$$G_V = G_F V_{ud}, \text{ where } ft = \frac{K}{2G_V^2} \quad \text{(isospin limit)}$$

$$\mathcal{F}t = ft(1+\delta'_R[1-(\delta_C - \delta_{NS})] = \frac{K/G_F^2}{2V_{ud}^2(1+\Delta_R^V)}$$



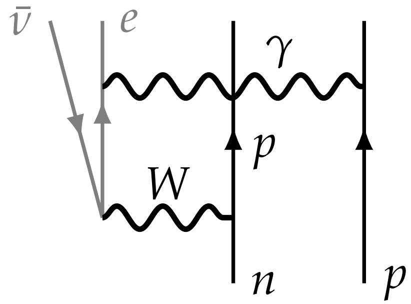
$$|M_F|^2 = |M_F^0|^2(1+\delta_C)$$ Isospin-symmetry breaking

$\delta'_R \sim$



Structure-independent radiative correction

$\delta_{NS} \sim$



Structure-dependent radiative correction

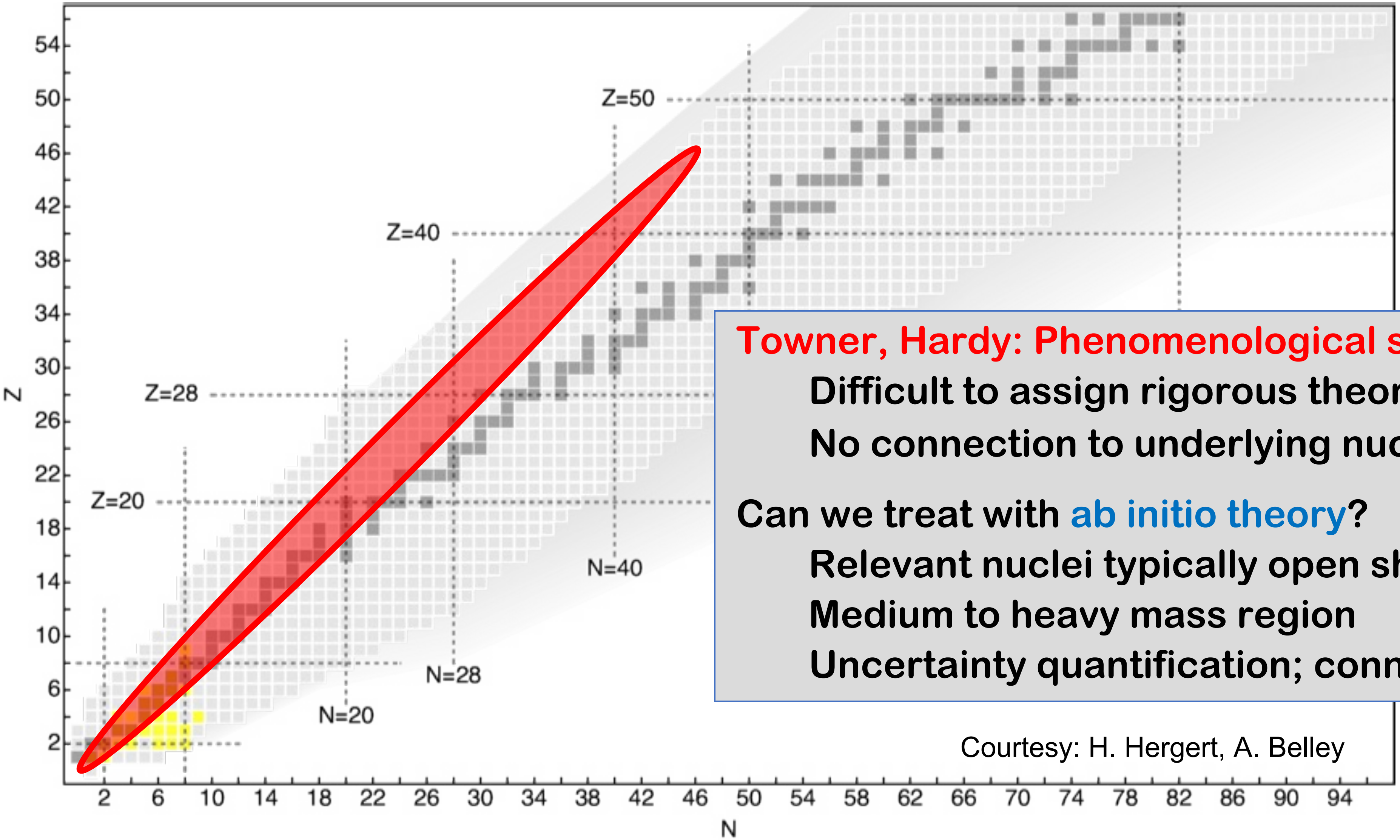
Nuclear structure theory

Isospin symmetry correction

dominates uncertainty in medium/heavy nuclei (and simple operator to calculate)

Progress of Ab Initio Theory Since 2010

2010: Limited capabilities for 3N forces; ^{16}O heaviest



Towner, Hardy: Phenomenological shell model

- Difficult to assign rigorous theoretical uncertainties
- No connection to underlying nuclear/weak forces

Can we treat with ab initio theory?

- Relevant nuclei typically open shell
- Medium to heavy mass region
- Uncertainty quantification; connection to QCD

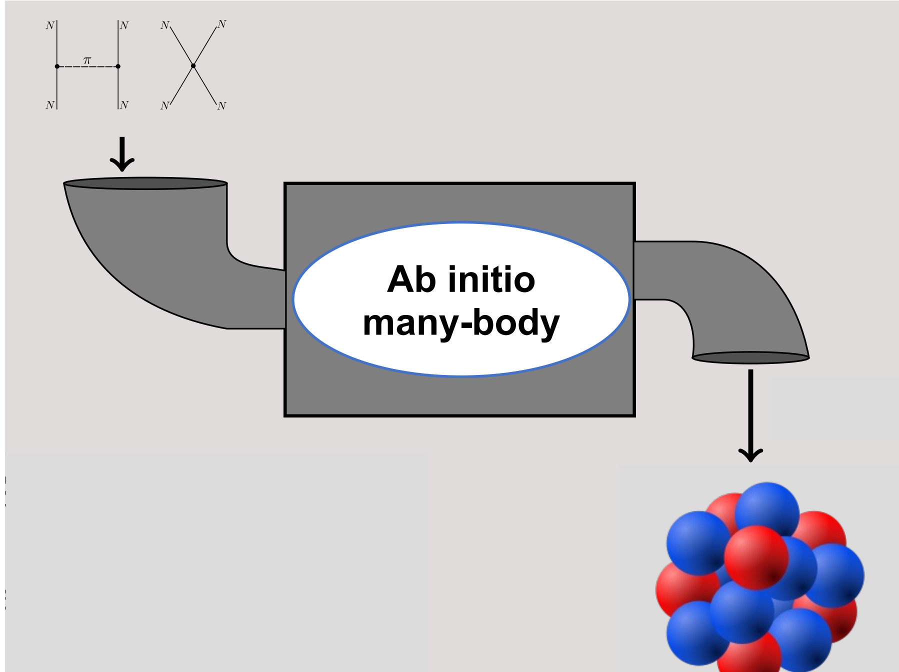
Courtesy: H. Hergert, A. Belley

Ab Initio Approach to Nuclear Structure

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

(Approximately) solve nonrelativistic Schrödinger equation

$$H\psi_n = E_n\psi_n$$



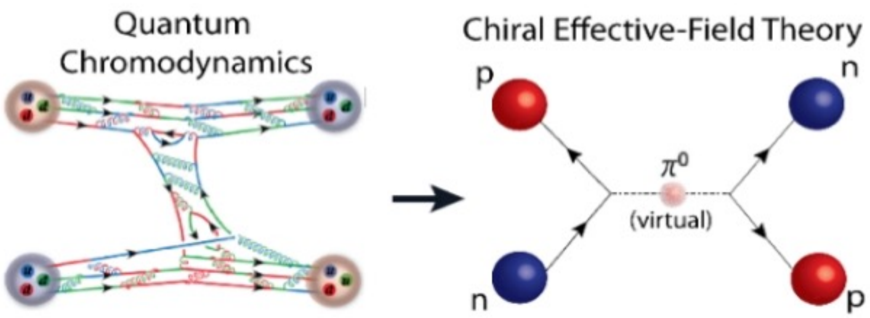
Courtesy, S. R. Stroberg

TRIUMF

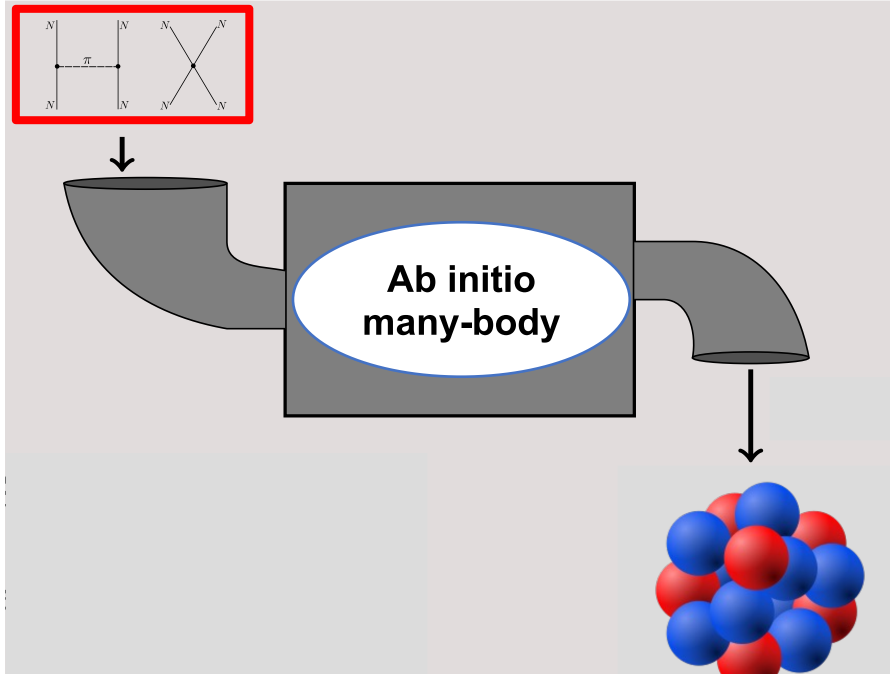
Ab Initio Approach to Nuclear Structure

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

(Approximately) solve nonrelativistic Schrödinger equation



$$\boxed{H}\psi_n = E_n\psi_n$$

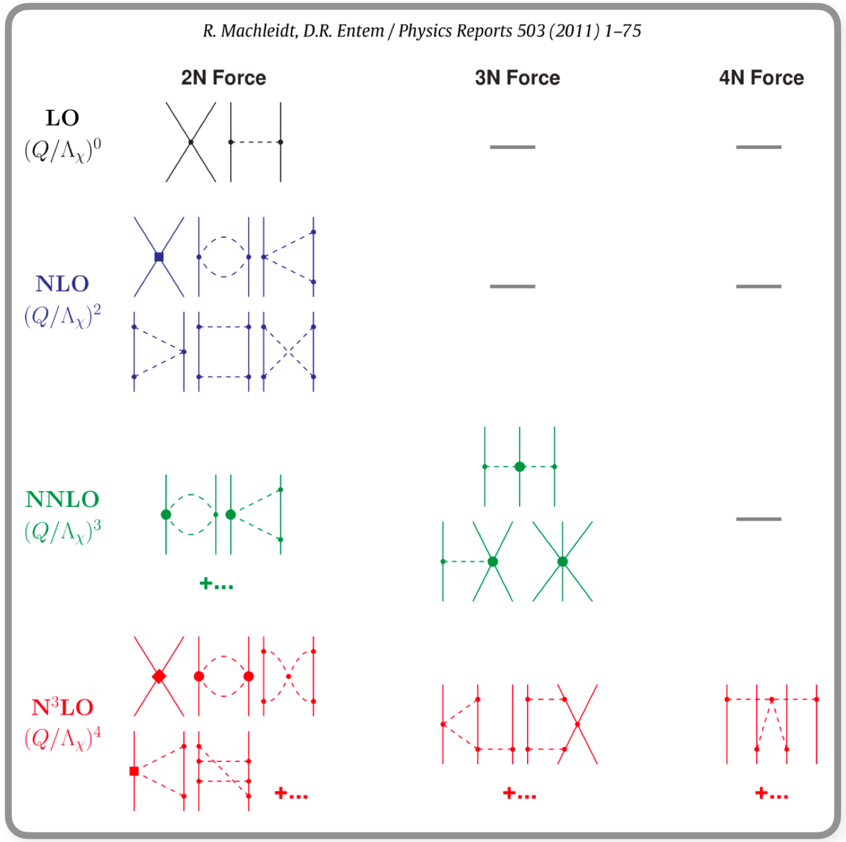


Courtesy, S. R. Stroberg

Chiral Effective Field Theory

Consistent treatment of
- 2N, 3N, 4N, … forces
- Electroweak physics

Quantifiable uncertainties

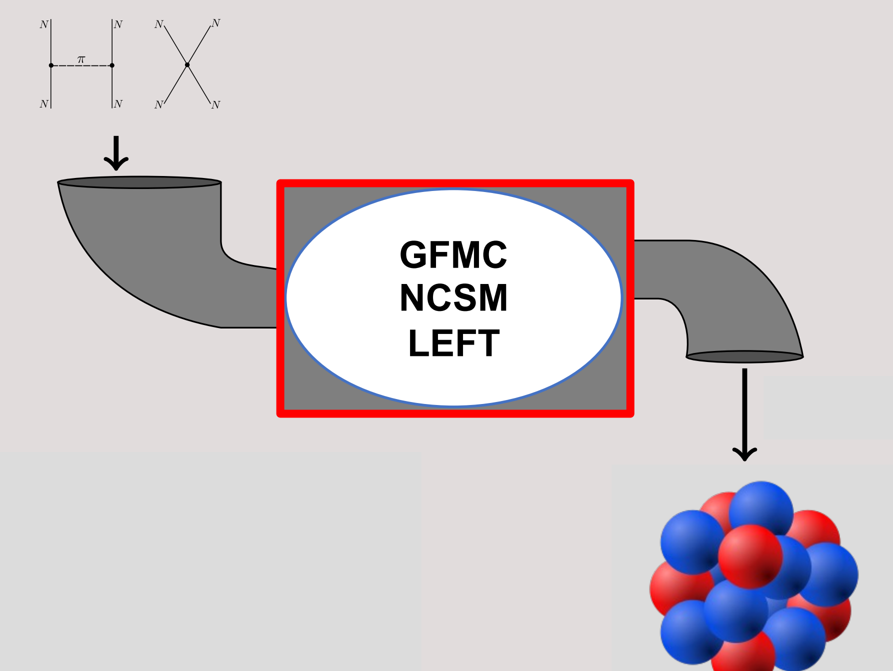


Ab Initio Approach to Nuclear Structure

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

(Approximately) solve nonrelativistic Schrödinger equation

$$\boxed{H\psi_n = E_n\psi_n}$$

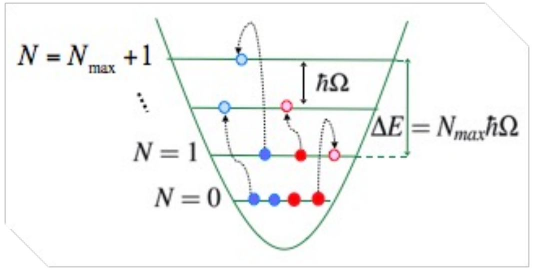


Courtesy, S. R. Stroberg

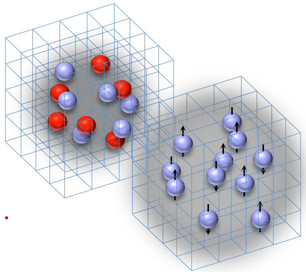
Ab Initio Cheat Sheet (quasi-exact methods)

GFMC: Green's function Monte Carlo

NCSM: No-core shell model



LEFT: Lattice effective field theory



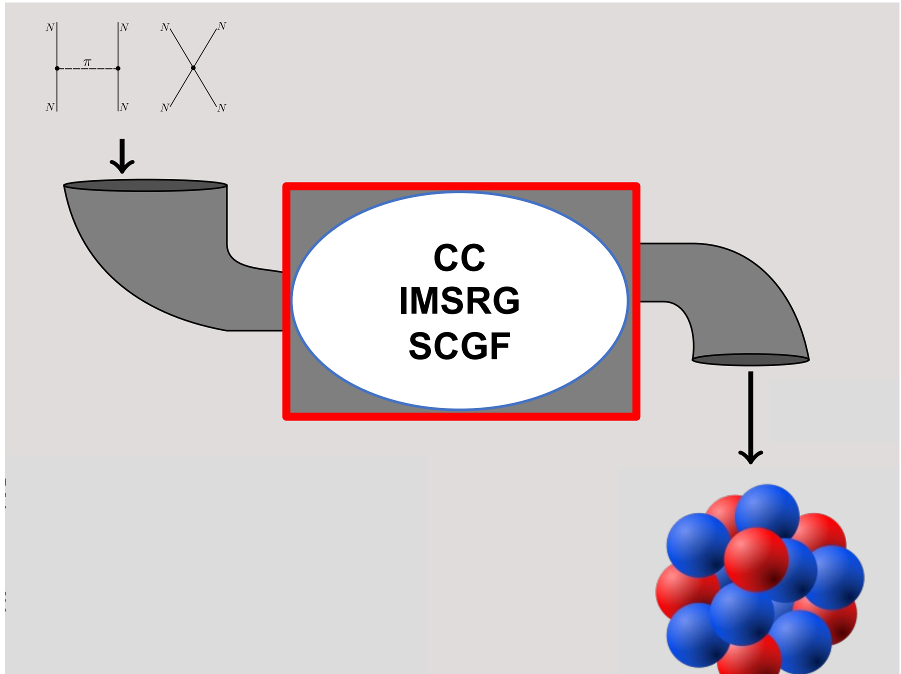
TRIUMF

Ab Initio Approach to Nuclear Structure

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

(Approximately) solve nonrelativistic Schrödinger equation

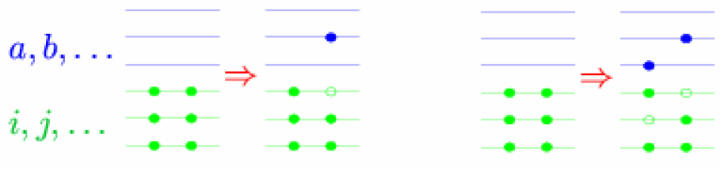
$$\boxed{H\psi_n = E_n\psi_n}$$



Courtesy, S. R. Stroberg

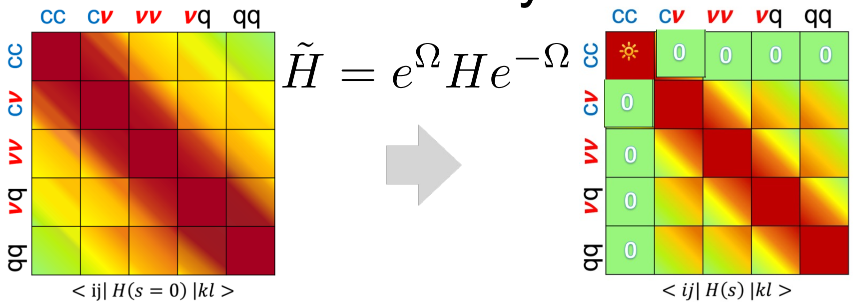
Ab Initio Cheat Sheet (polynomial scaling methods)

CC: Coupled cluster theory

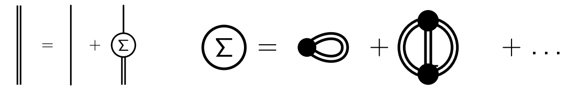


$$\begin{aligned} E &= \langle \Phi | \overline{H} | \Phi \rangle \\ 0 &= \langle \Phi_i^a | \overline{H} | \Phi \rangle \\ 0 &= \langle \Phi_{ij}^{ab} | \overline{H} | \Phi \rangle \\ \overline{H} &\equiv e^{-T} H e^{T} = \left(H e^{T} \right)_c \end{aligned}$$

IMSRG: In-medium similarity renormalization group



SCGF: Self-consistent Green's function



Valence-Space IMSRG

Explicitly construct unitary transformation from sequence of rotations

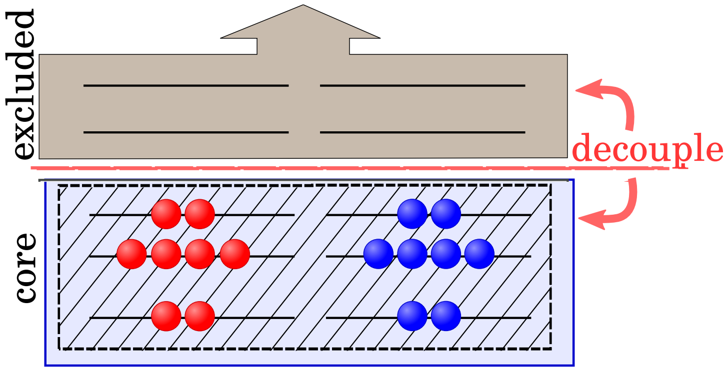
$$U = e^{\Omega} = e^{\eta_n} \dots e^{\eta_1} \qquad \eta = \frac{1}{2}\arctan\left(\frac{2H_{\mathrm{od}}}{\Delta}\right) - \mathrm{h.c.}$$

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

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

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?

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

TRIUMF

Valence-Space IMSRG

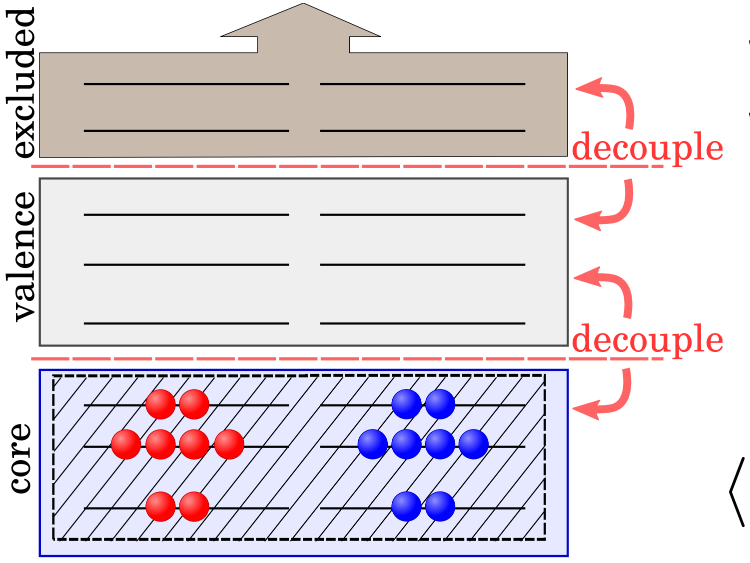
Explicitly construct unitary transformation from sequence of rotations

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

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

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

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

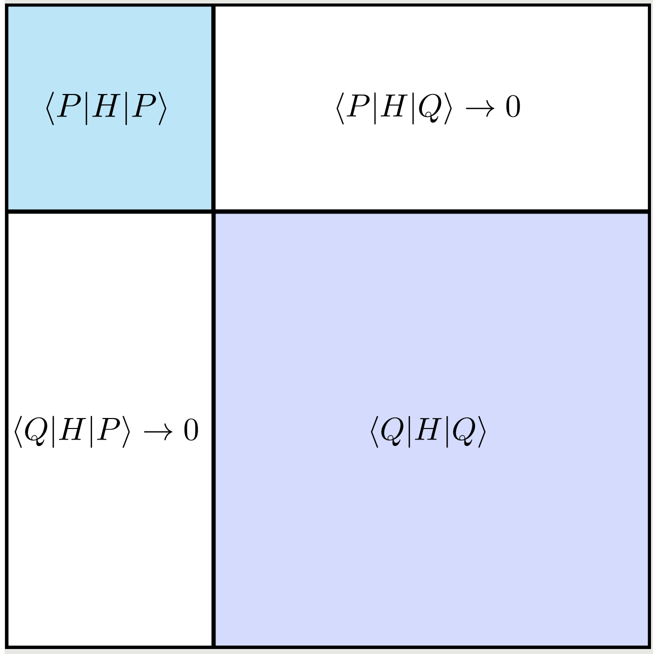


$|\Phi_0\rangle = |^{16}\mathrm{O}\rangle$

Step 1: Decouple core
Step 2: Decouple valence space

Can we achieve accuracy of large-space methods?

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



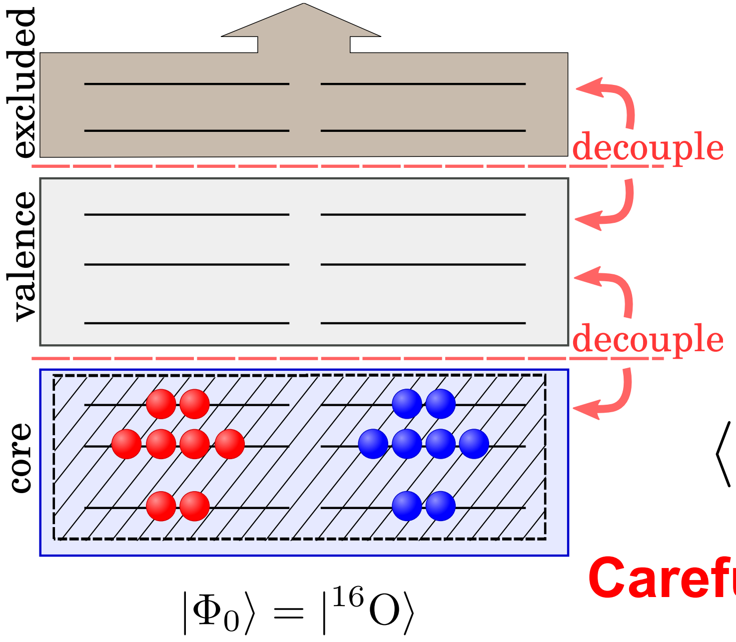
Valence-Space IMSRG

Explicitly construct unitary transformation from sequence of rotations

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

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

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



Step 1: Decouple core

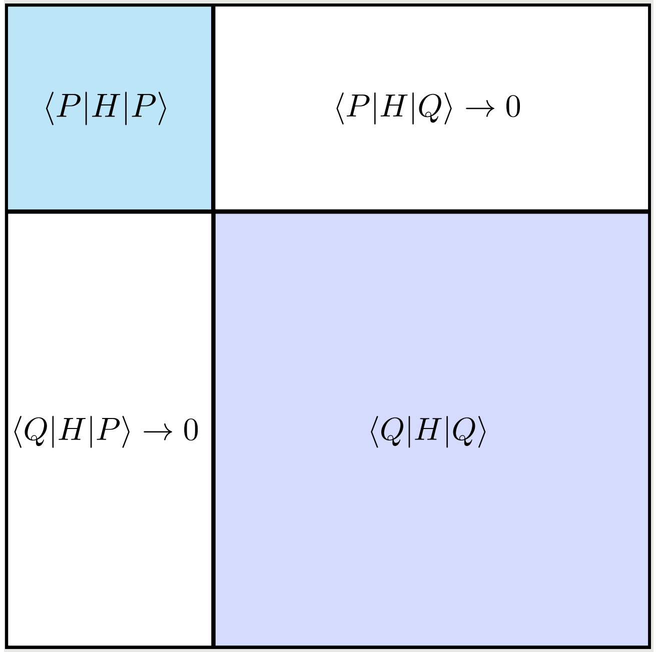
Step 2: Decouple valence space

Step 3: Decouple additional operators

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

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

Careful benchmarking essential

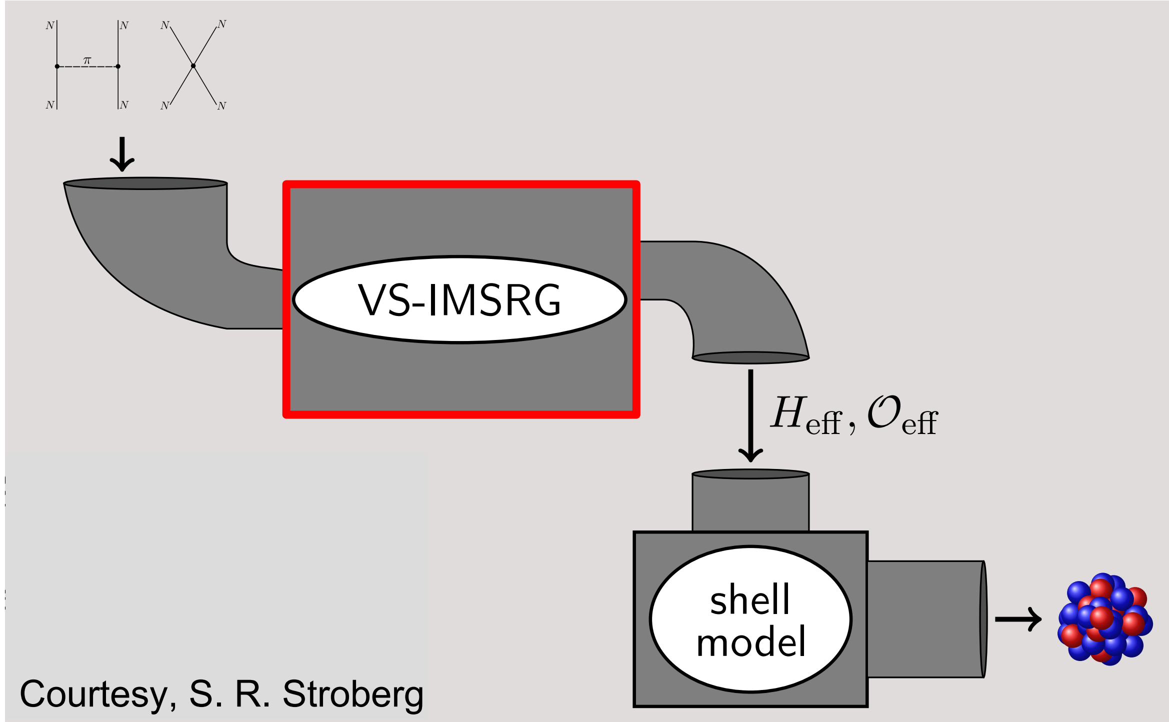


Ab Initio Approach to Nuclear Structure

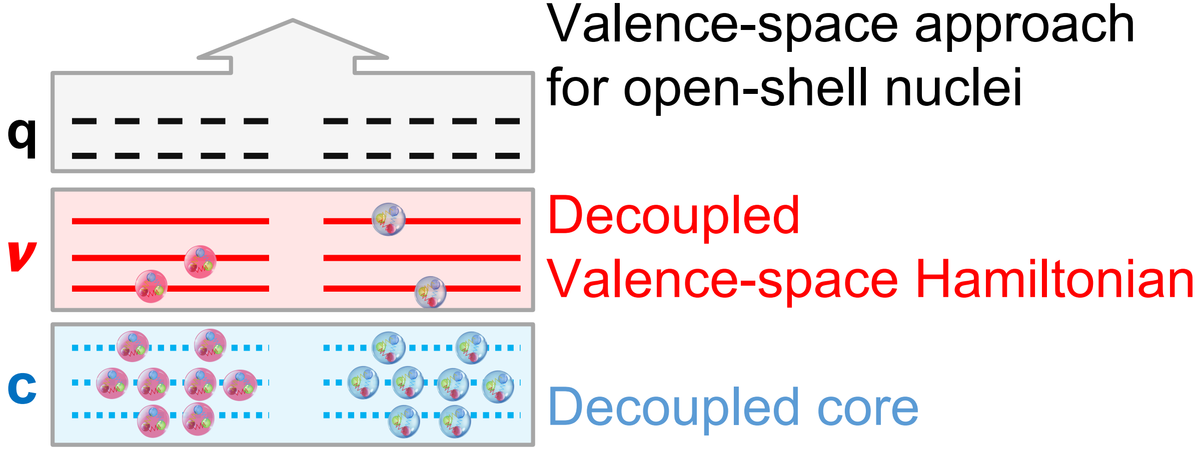
Aim of modern nuclear theory: develop unified *first-principles* picture of structure and reactions

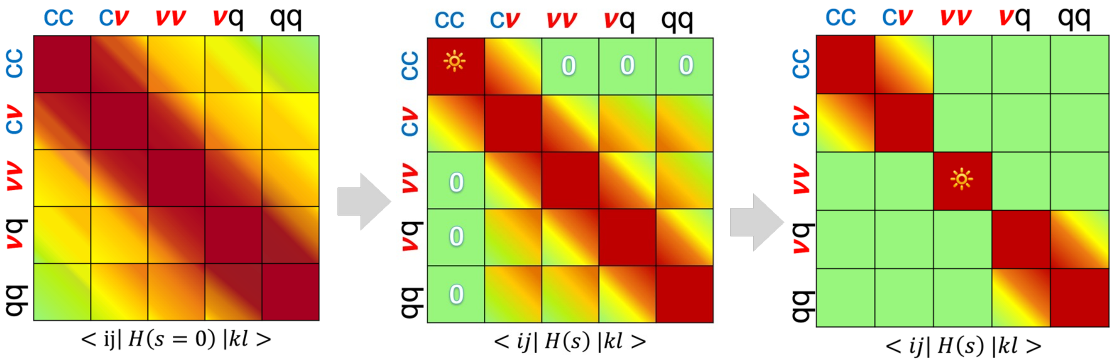
(Approximately) solve nonrelativistic Schrödinger equation

$$\boxed{H\psi_n = E_n\psi_n}$$



Courtesy, S. R. Stroberg





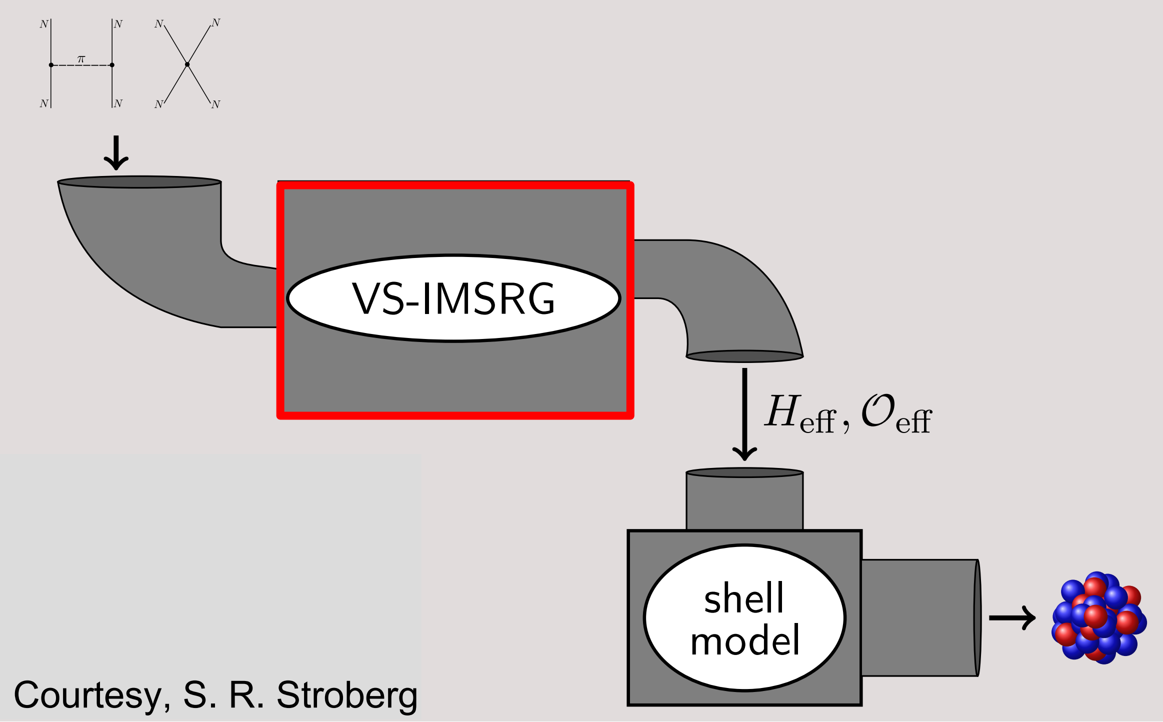
Extends ab initio to scope of traditional nuclear shell model

Ab Initio Approach to Nuclear Structure

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

(Approximately) solve nonrelativistic Schrödinger equation

$$\boxed{H\psi_n = E_n\psi_n}$$



Courtesy, S. R. Stroberg

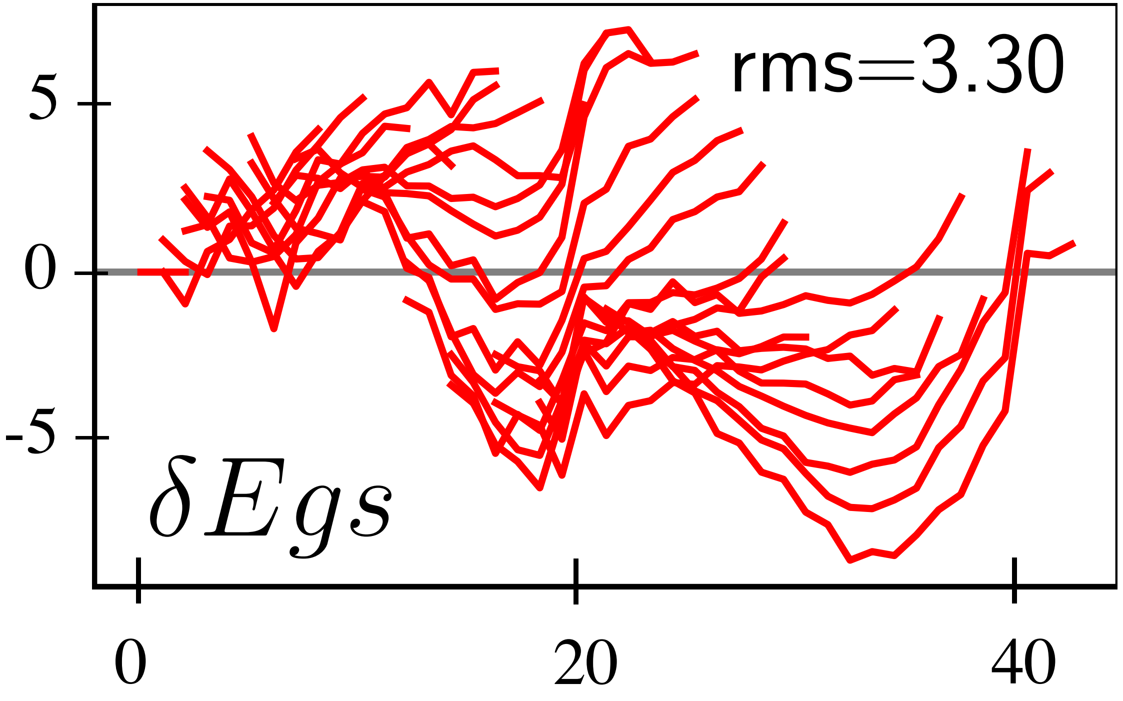
Methods Exact up to Truncations

- ✅ **Single-particle basis** $e_{\max} = 2n + l$
- ❌ **Storage limits of 3N forces** $e_1 + e_2 + e_3 \leq E_{3\max}$
- 🤷 **Many-body operators: e.g., CCSD(T), IMSRG(2)**

Ab Initio Goes Global!

Long considered the domain of DFT or shell model

Ab initio calculations of ~700 nuclei from He to Fe!



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

B-W Mass formula: ~3.5MeV (Z<28)

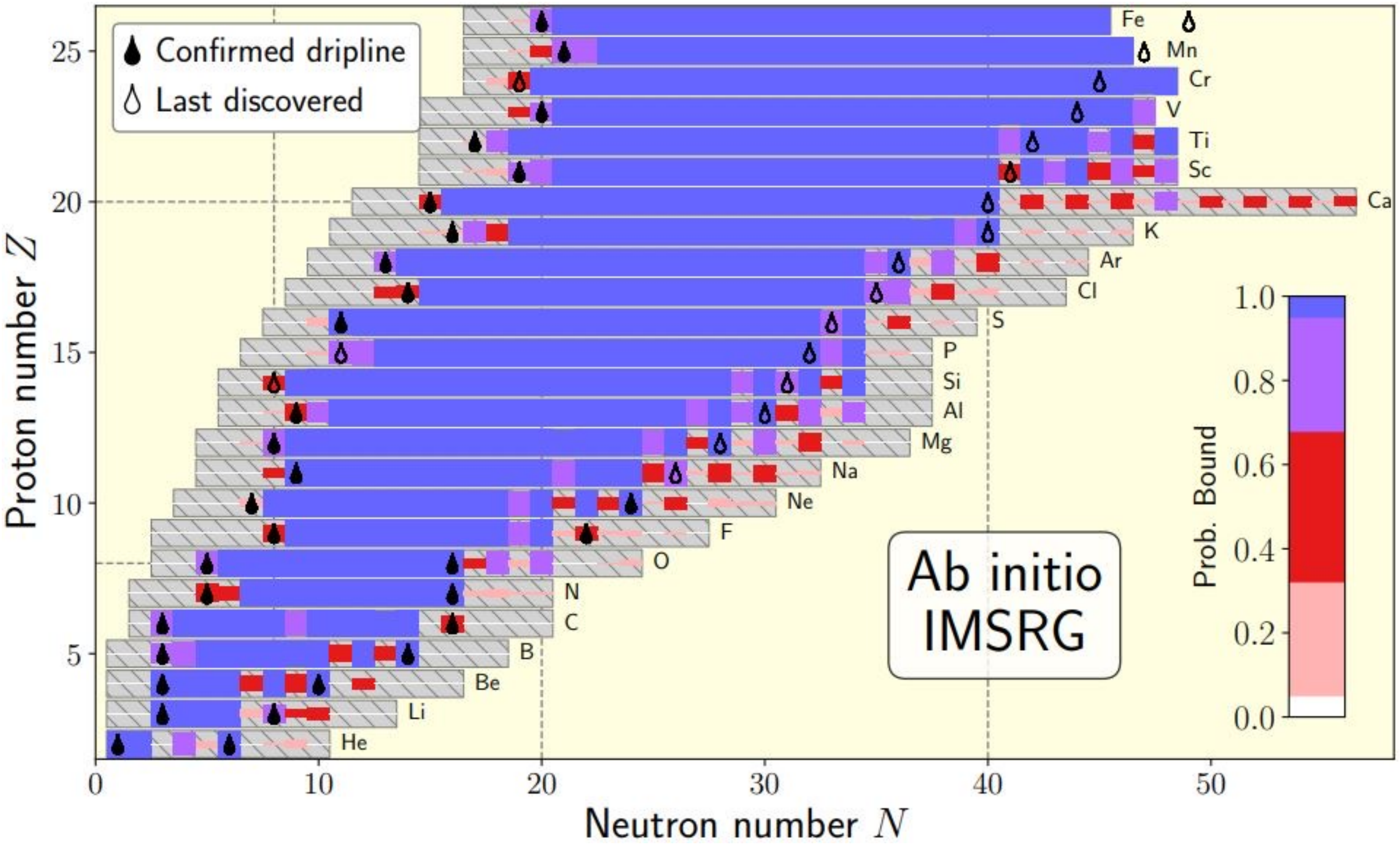
DFT: 0.6-2.0 MeV

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

Apply to proton/neutron driplines separation energies?

Dripline Predictions to Medium Mass Region

Predictions of proton and neutron driplines from first principles



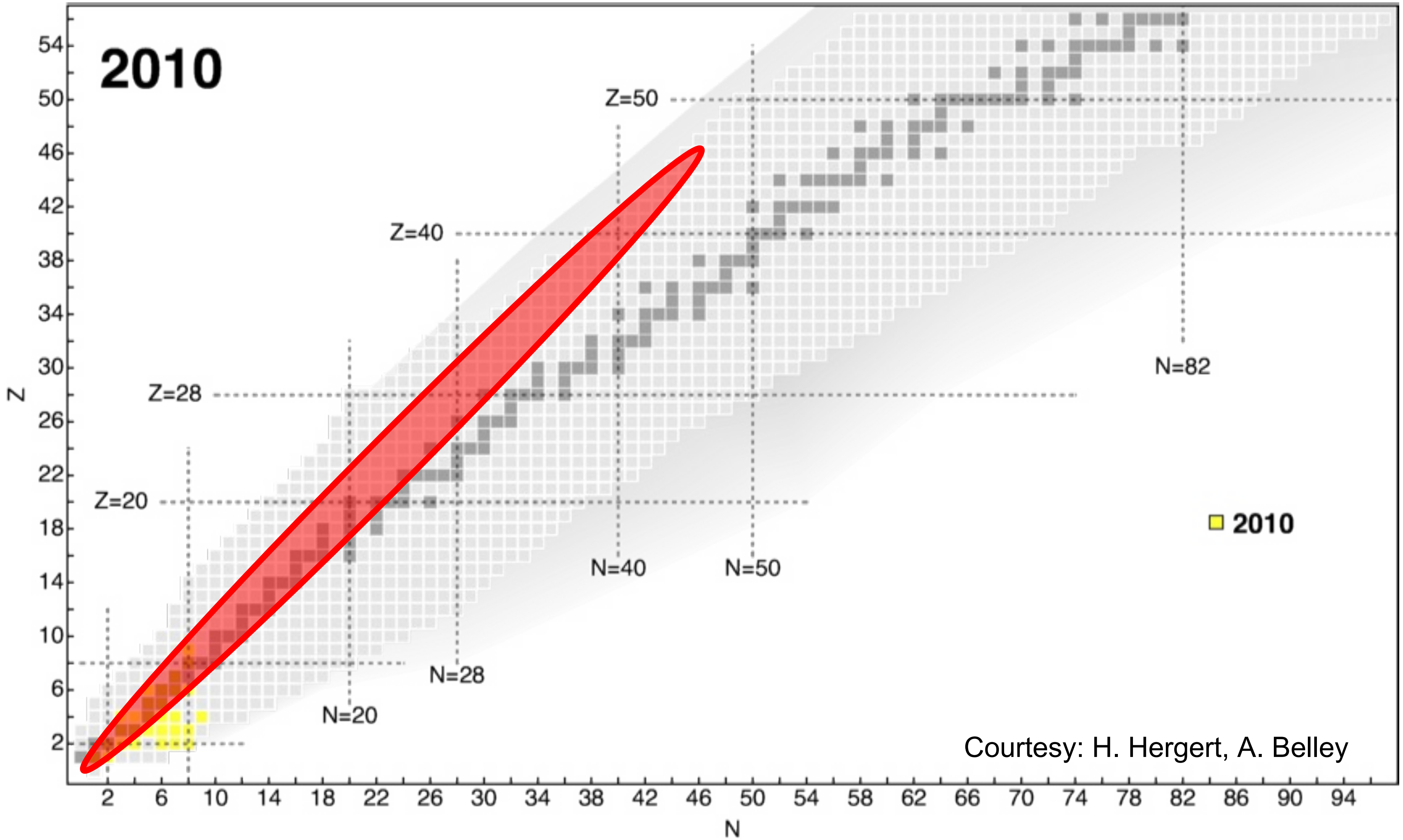
Known drip lines predicted within uncertainties (artifacts at shell closures)

Ab initio guide for neutron-rich driplines

TRIUMF

Progress of Ab Initio Theory Since 2010

2010: Limited capabilities for 3N forces; ^{16}O heaviest

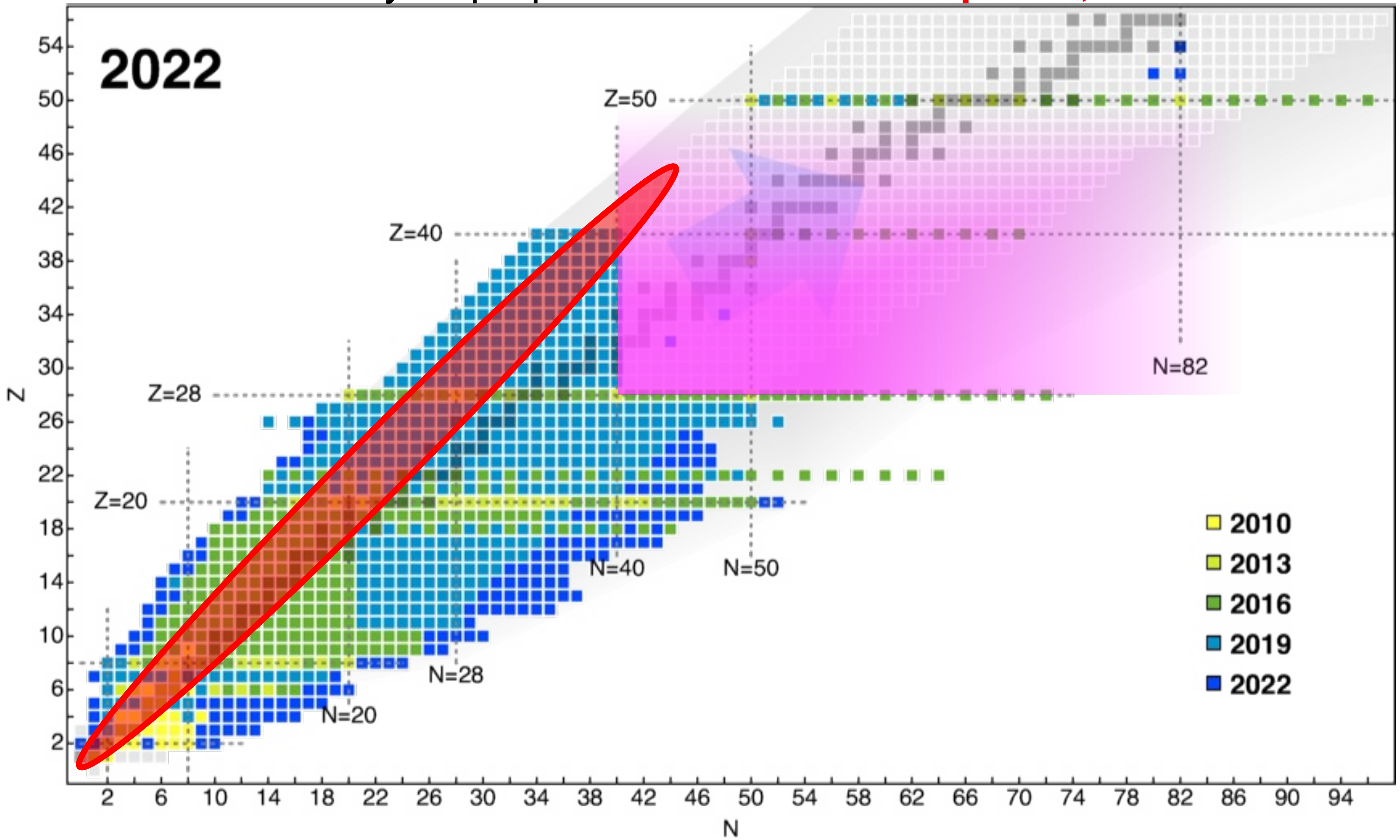


TRIUMF

Ab Initio Progress: How Heavy Can We Go?

Tremendous progress in ab initio reach, largely due to polynomially scaling methods!

Calculate essentially all properties all of nuclei… **up to N, Z ~ 50**



Key Limitation

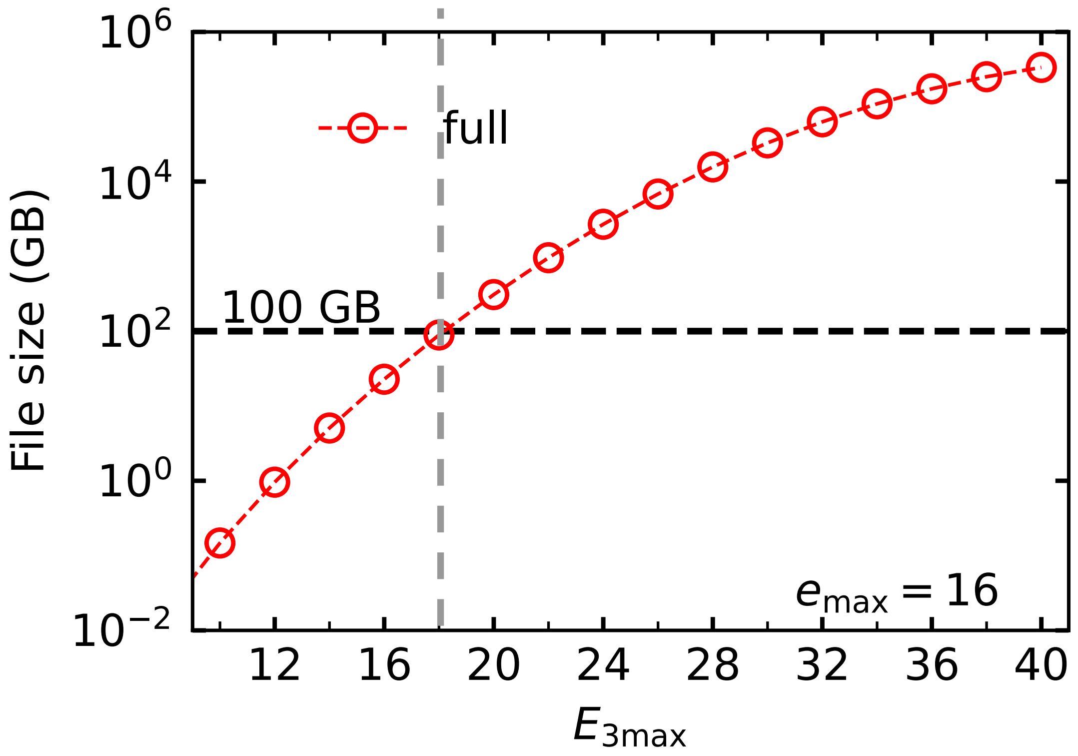
3NF matrix element storage

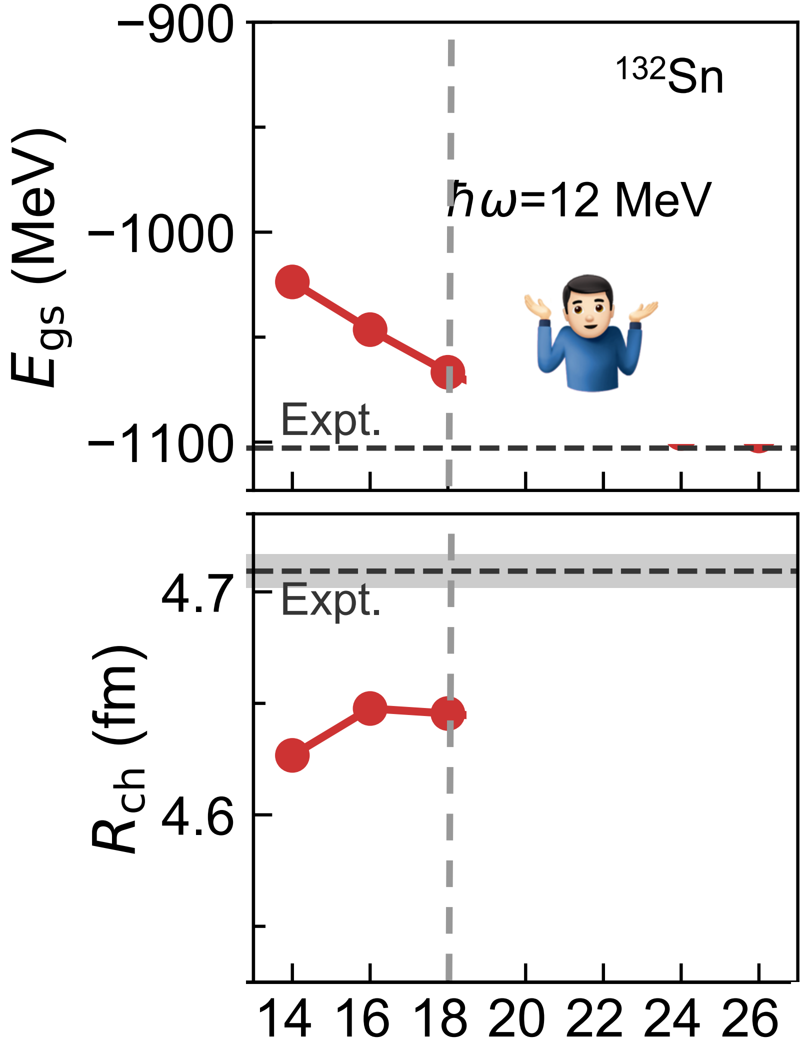
$$e_1 + e_2 + e_3 \leq E_{3\max}$$

Ab Initio Calculations of Heavy Nuclei

Limited by typical memory/node: $e_1 + e_2 + e_3 \leq E_{3\max} = 18$

No sign of convergence in ^{132}Sn - E_{gs} or R_{ch}

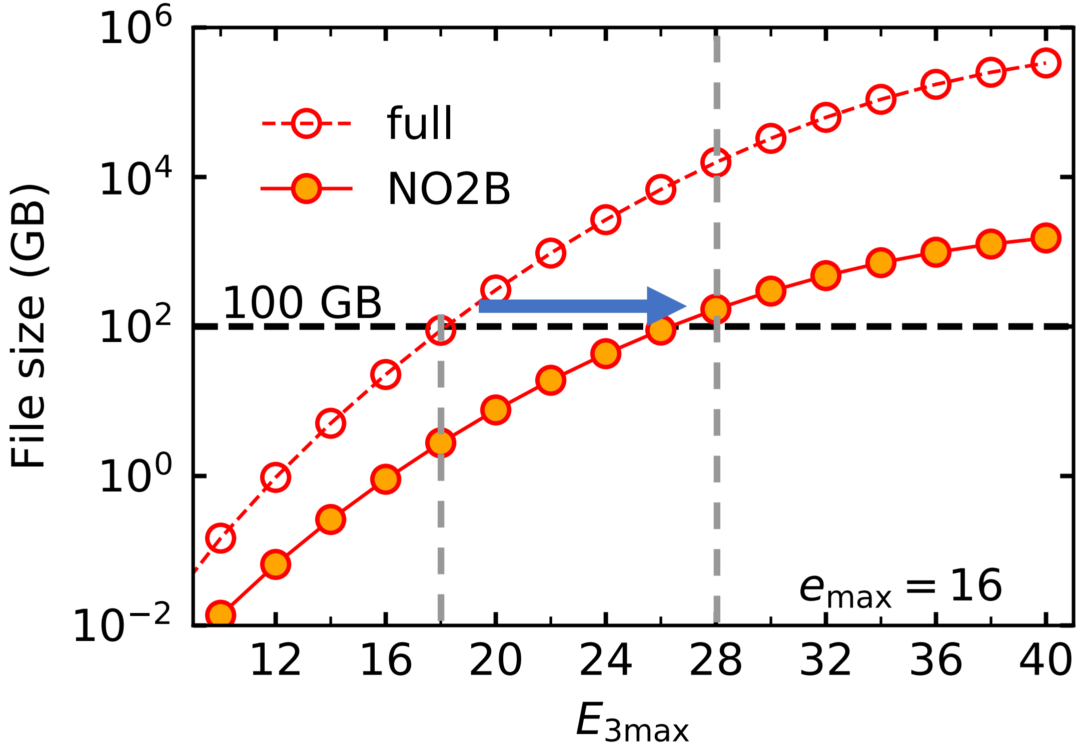


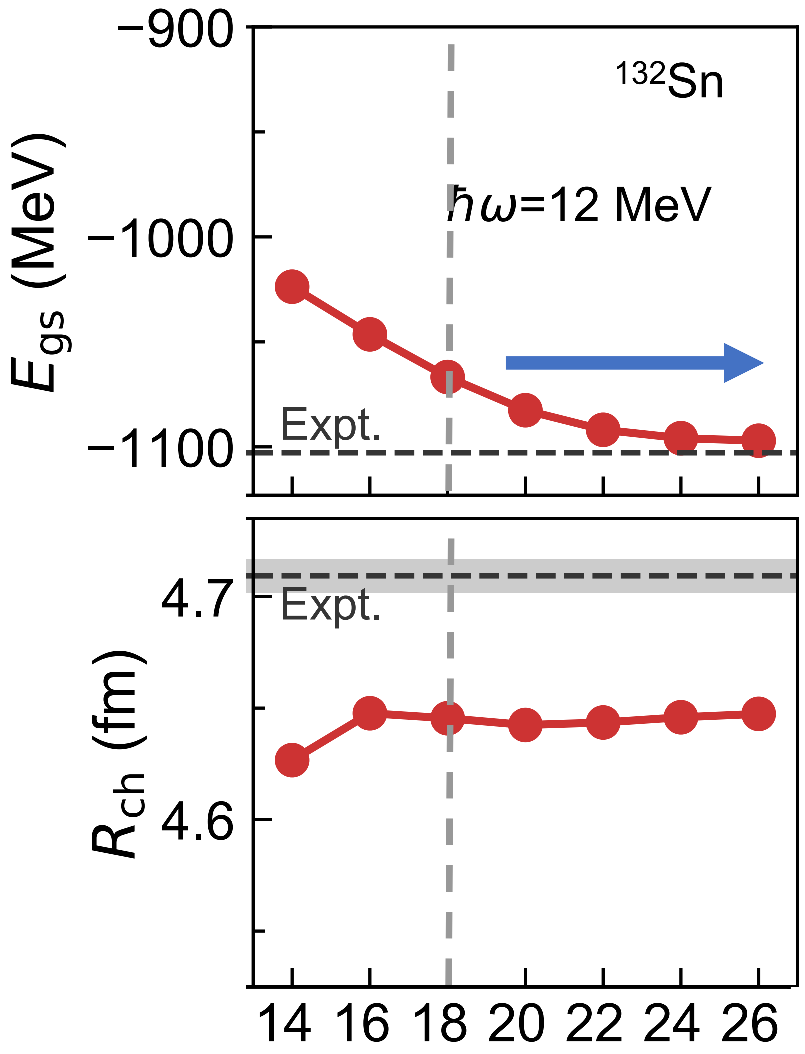


Ab Initio Calculations of Heavy Nuclei

Limited by typical memory/node: $e_1 + e_2 + e_3 \leq E_{3\mathrm{max}} = 18$

Clever storage reduces needs by factor of 100!





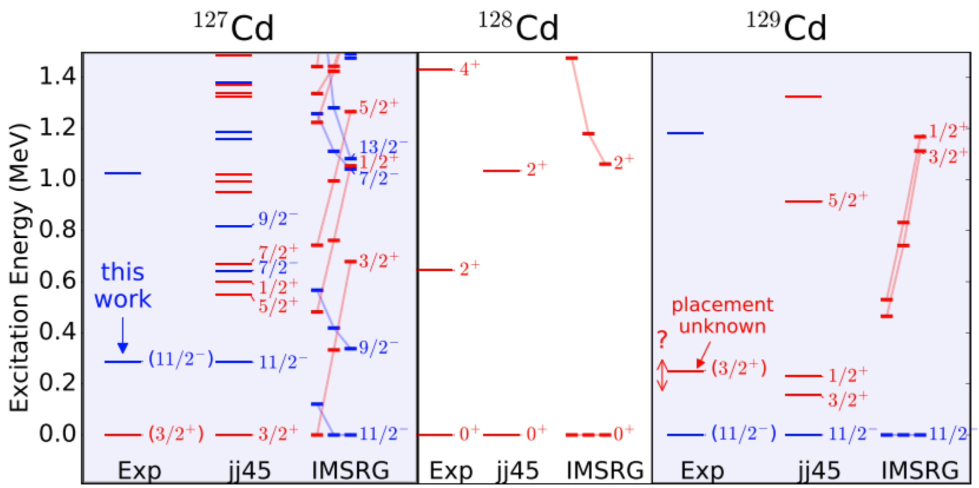
First converged ground-state properties of ^{132}Sn!

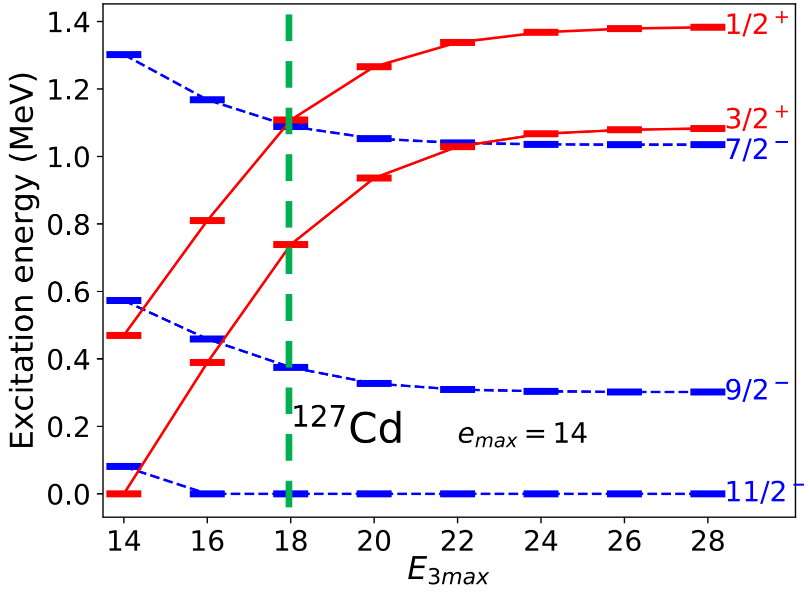
Opens heavy region to ab initio…

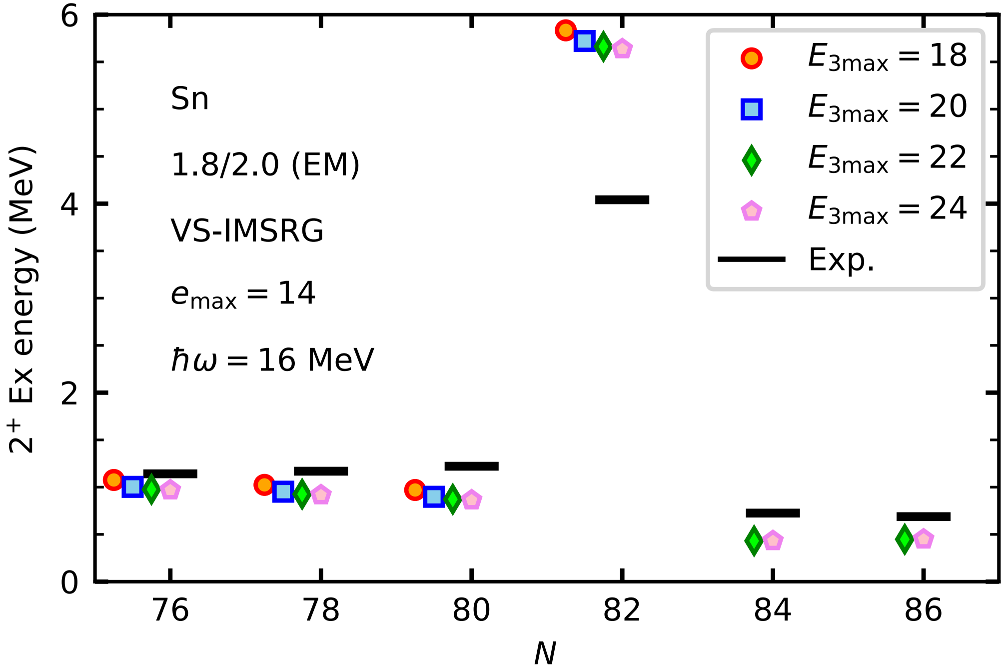
TRIUMF

Convergence of N=82 Gap

Size of N=70 gap **well** converged at E_{3max}=28 for neutron-rich Sn, In, Cd!







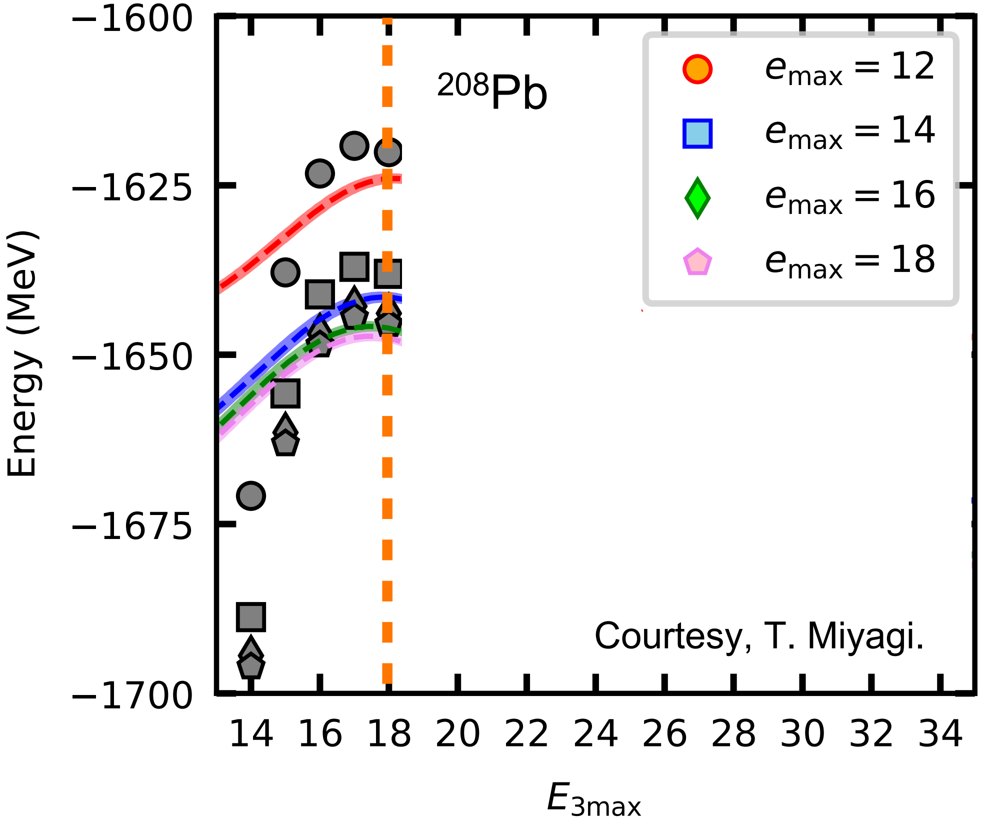
New capabilities: converged spectra in N=82 region

Converged (overpredicted) doubly magic ^{132}Sn

Can we go heavier?

Convergence in Heavy Nuclei: ^{208}Pb

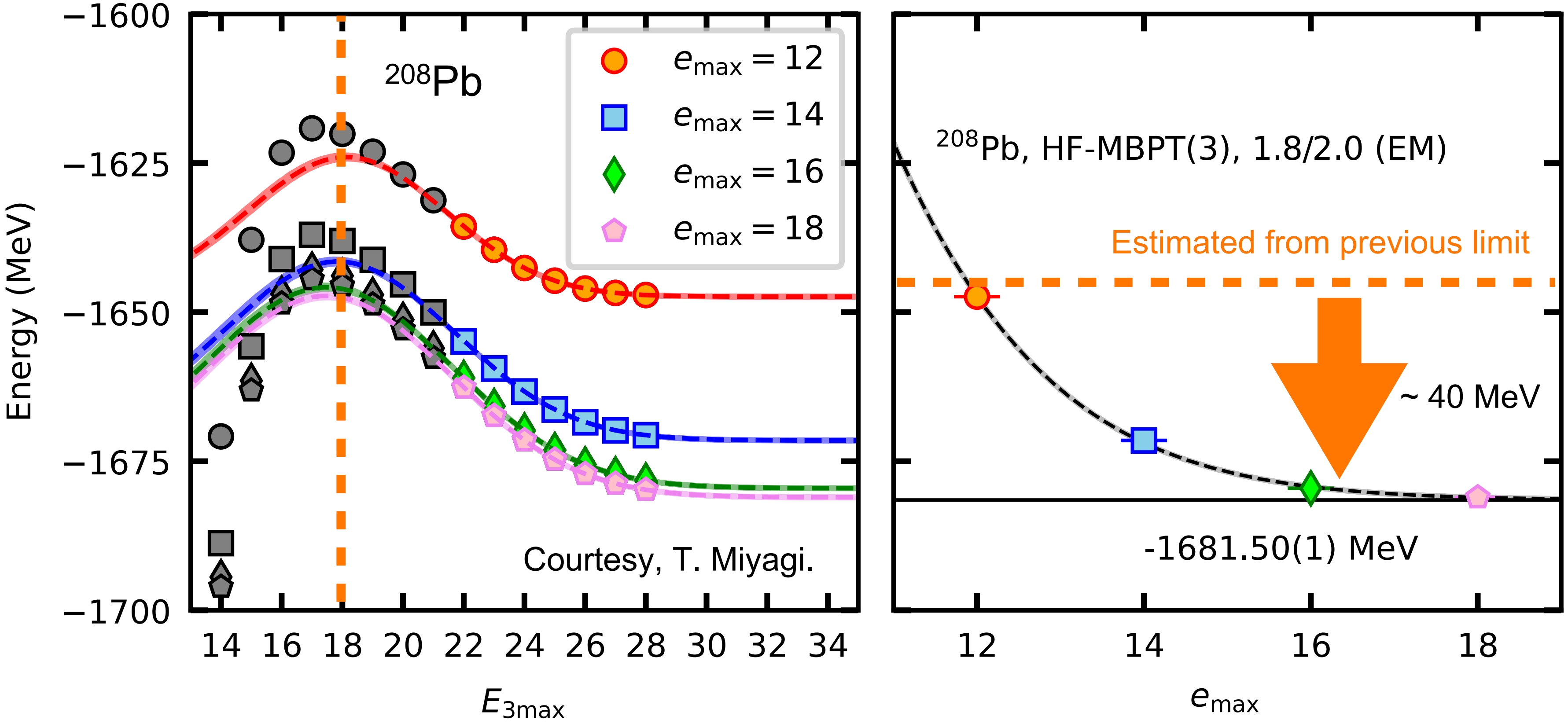
Previous limit, no hope of convergence in ^{208}Pb g.s. energy…



Convergence in Heavy Nuclei: ^{208}Pb

Previous limit, no hope of convergence in ^{208}Pb g.s. energy

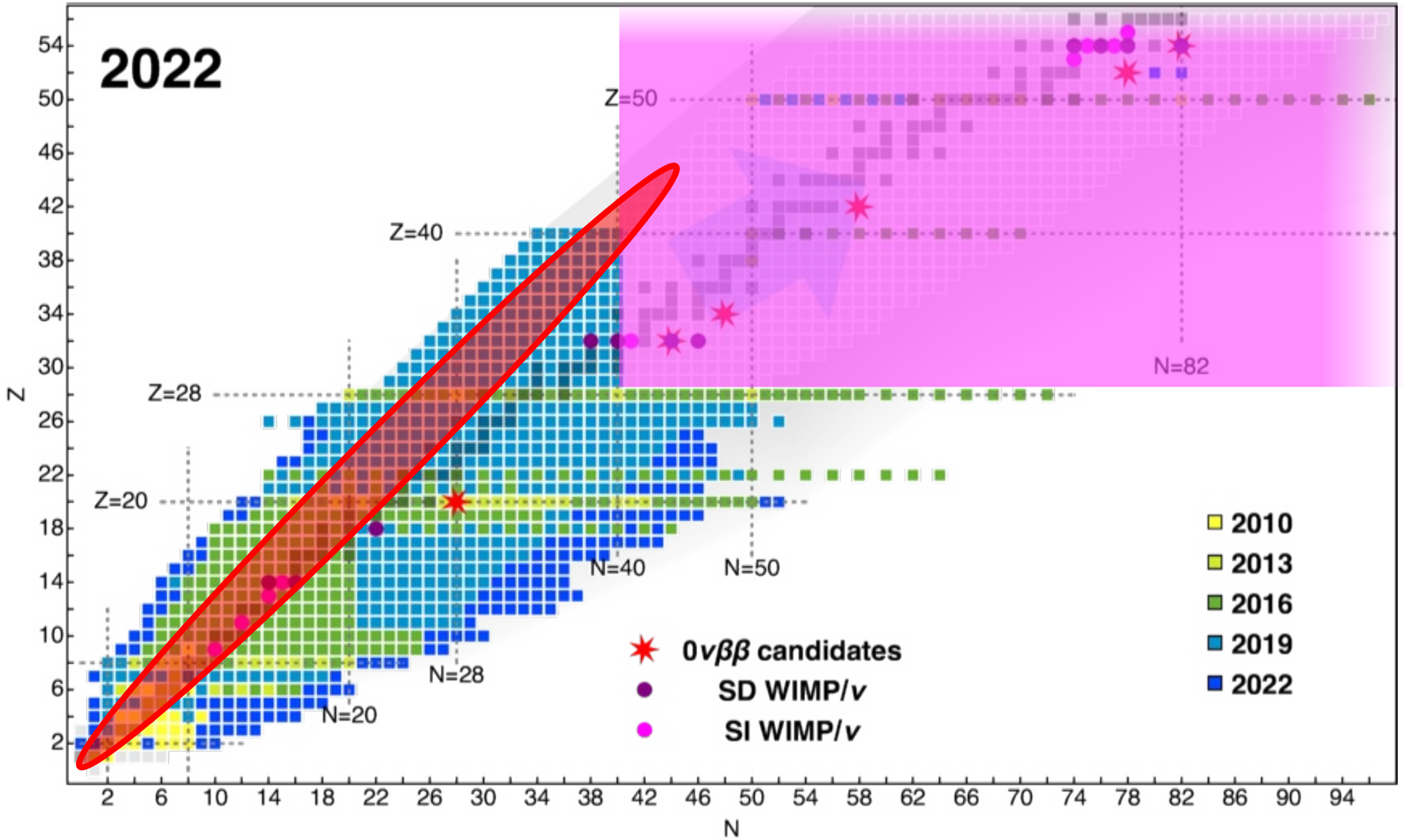
Improved $E_{3\max} = 18 \to 28$ clear convergence



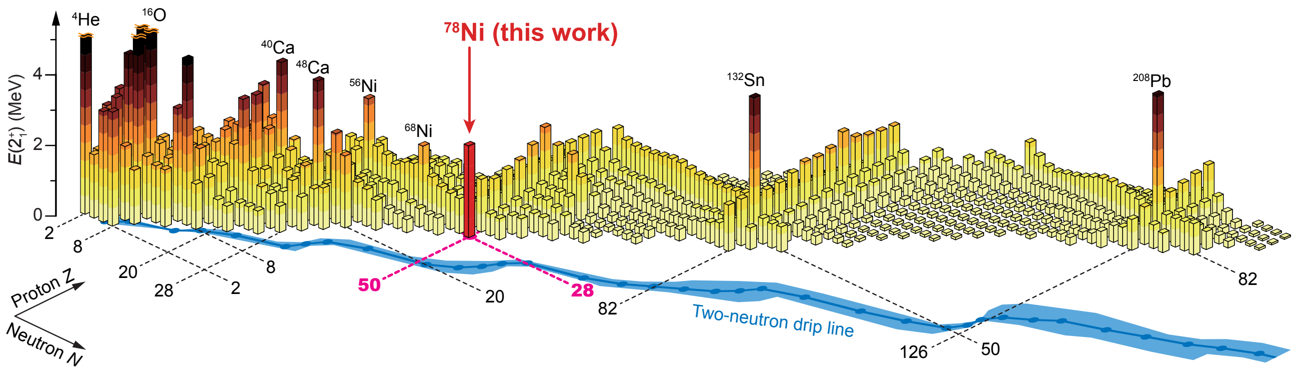
First converged ab initio calculation of ^{208}Pb!

Recalibrating Ab Initio Progress

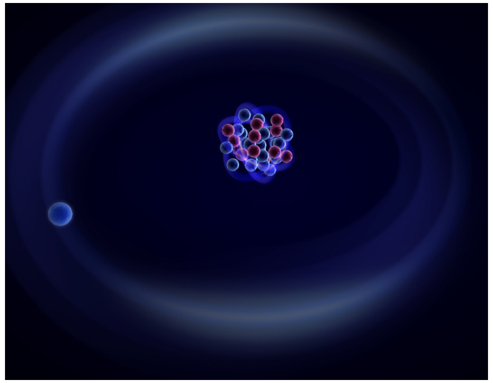
Rapid progress in ab initio reach, due to valence-space approach… up to...

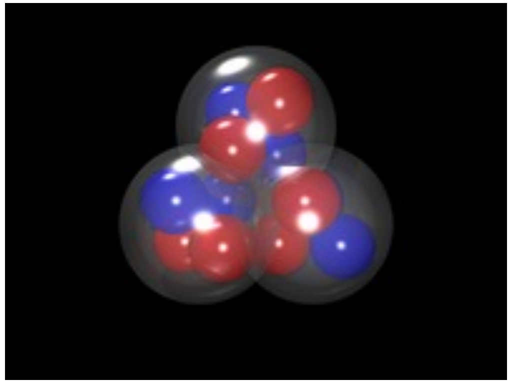


TRIUMF Major Questions in Nuclear Structure

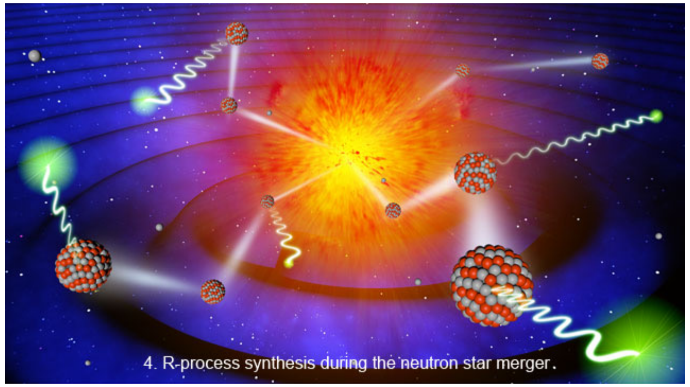


Limits of existence + formation/evolution of magic numbers

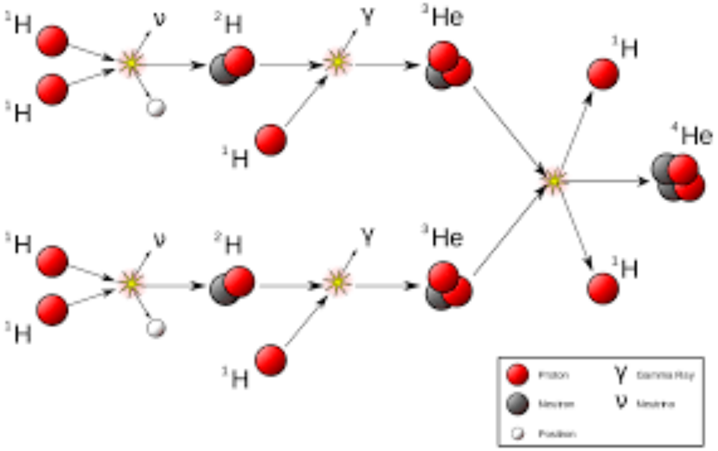




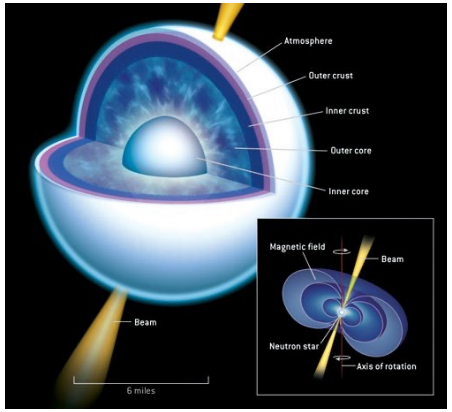
Nuclear skins/halos/clusters



Heavy Nuclei + r-process

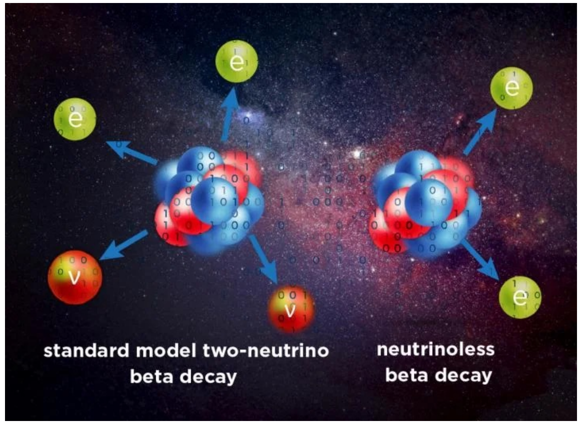


Continuum and nuclear reactions

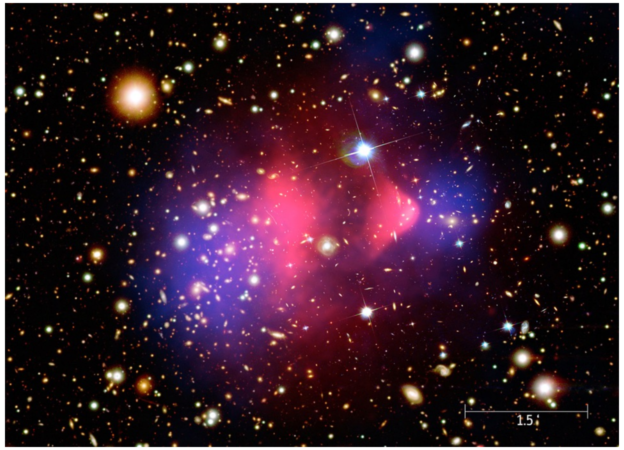


Infinite matter/Neutron stars

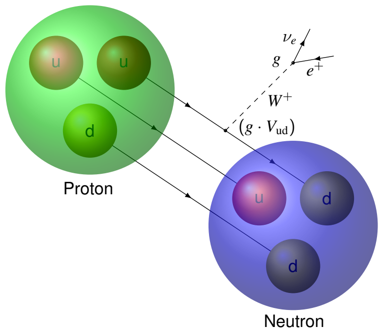
Searches for BSM Physics



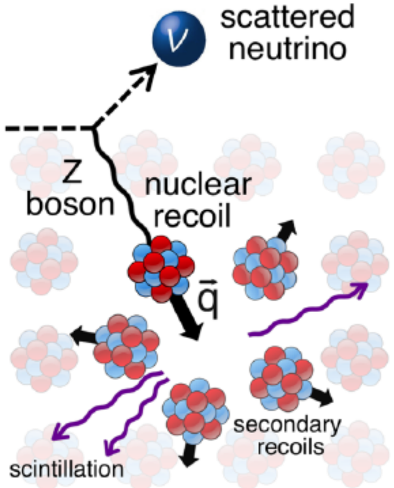
Neutrinoless double beta decay



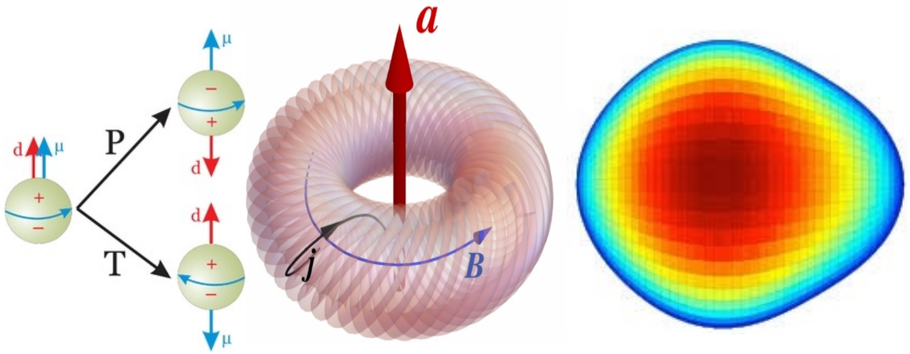
Dark matter direct detection



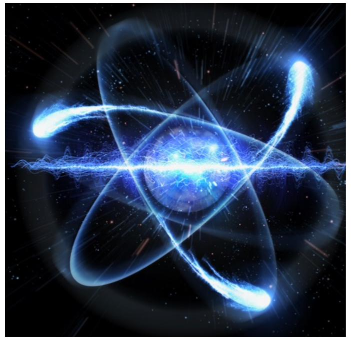
Superallowed Fermi transitions



Neutrino scattering

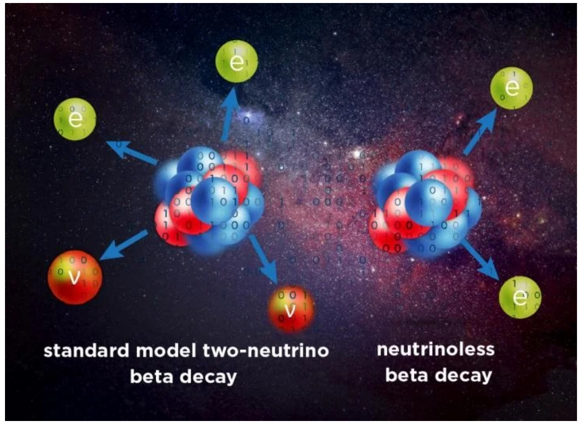


Symmetry-violating moments

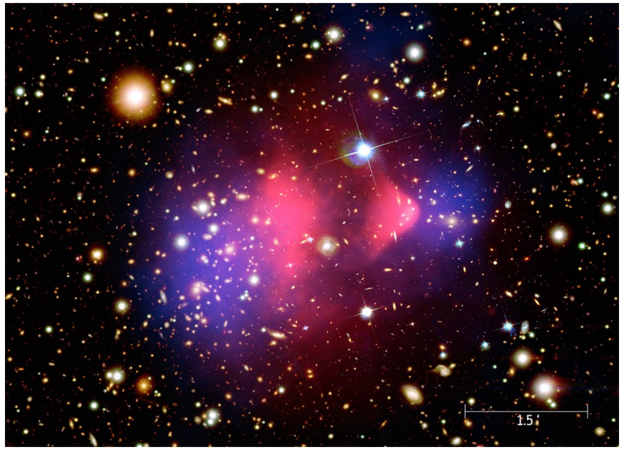


Atomic theory

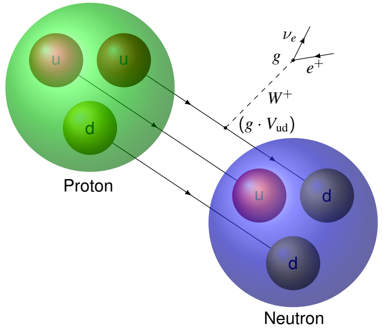
Searches for BSM Physics



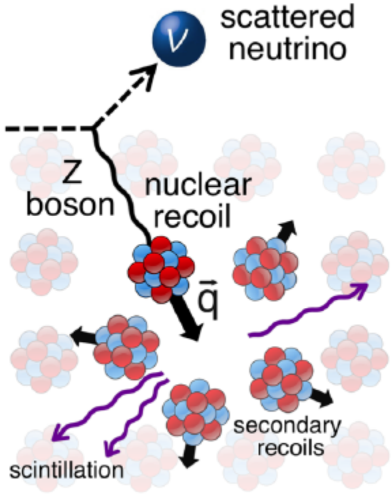
Neutrinoless double beta decay



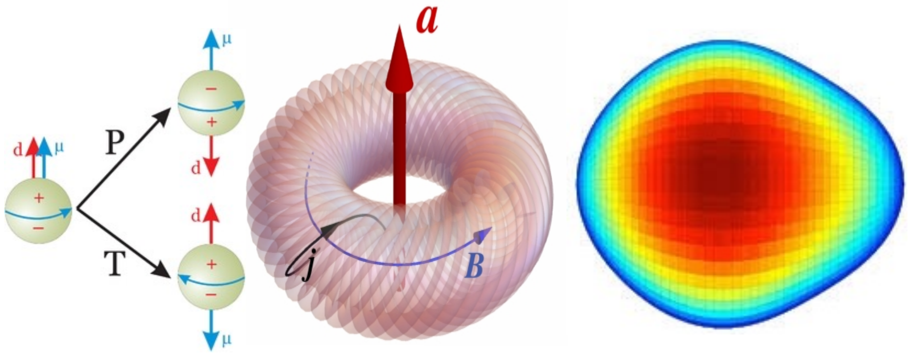
Dark matter direct detection



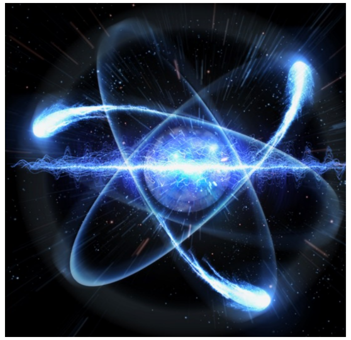
Superallowed Fermi transitions



Neutrino scattering



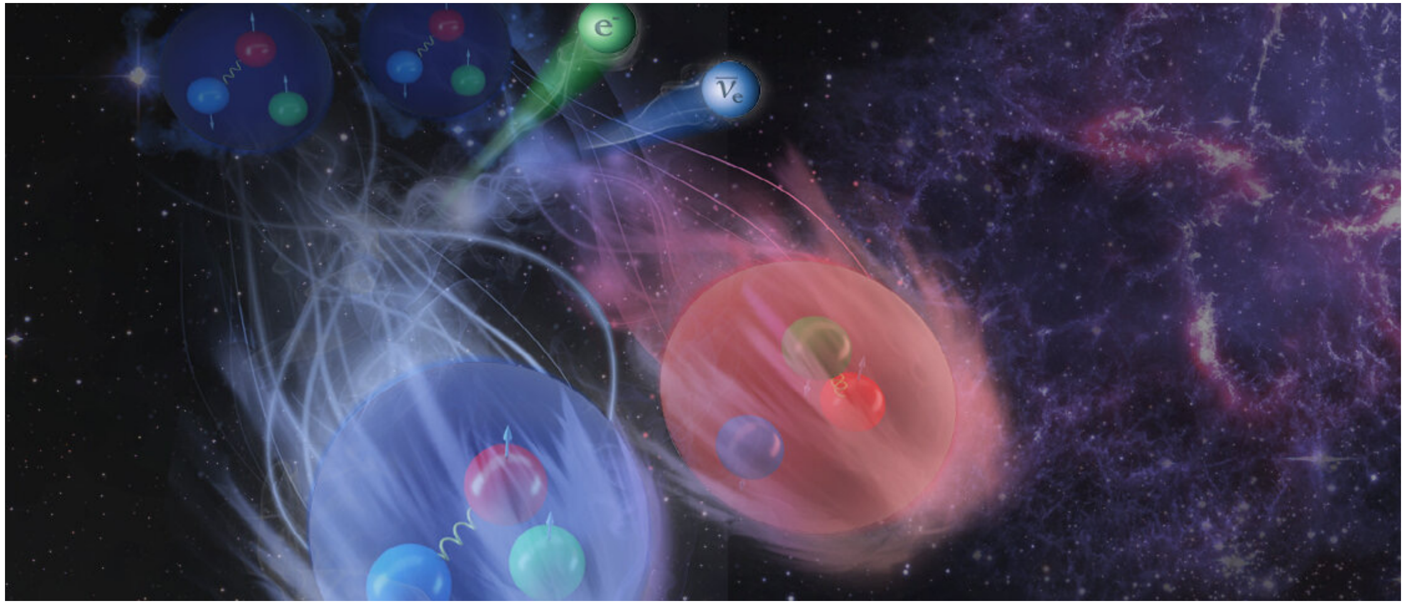
Symmetry-violating moments



Atomic theory

TRIUMF

Two-Body Currents for Gamow-Teller Transitions and g_A Quenching



LETTERS
https://doi.org/10.1038/s41567-019-0450-7
nature physics

Discrepancy between experimental and theoretical β-decay rates resolved from first principles

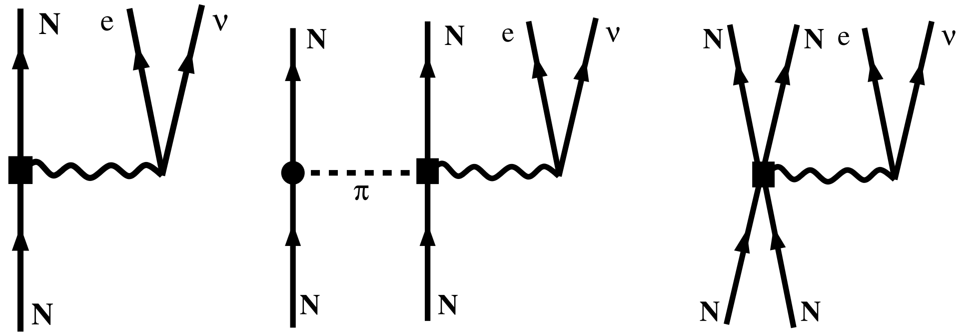
P. Gysbers[1,2], G. Hagen[3,4*], J. D. Holt[1], G. R. Jansen[3,5], T. D. Morris[3,4,6], P. Navrátil[1], T. Papenbrock[3,4], S. Quaglioni[7], A. Schwenk[8,9,10], S. R. Stroberg[1,11,12] and K. A. Wendt[7]

TRIUMF

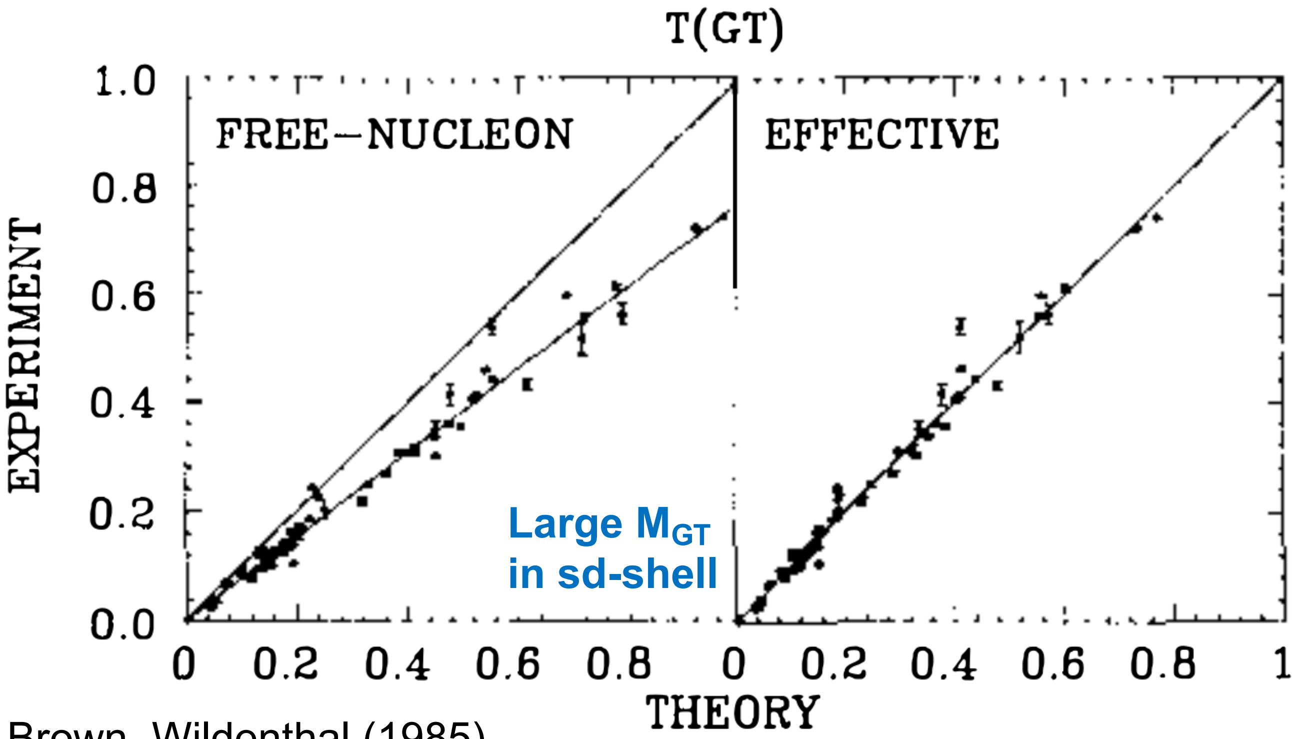
Beta-Decay "Puzzle": Quenching of g_A

Long-standing problem in weak decays: experimental values systematically smaller than theory

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



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



Brown, Wildenthal (1985)

- Missing wavefunction correlations
- Renormalized VS operator?
- 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**

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

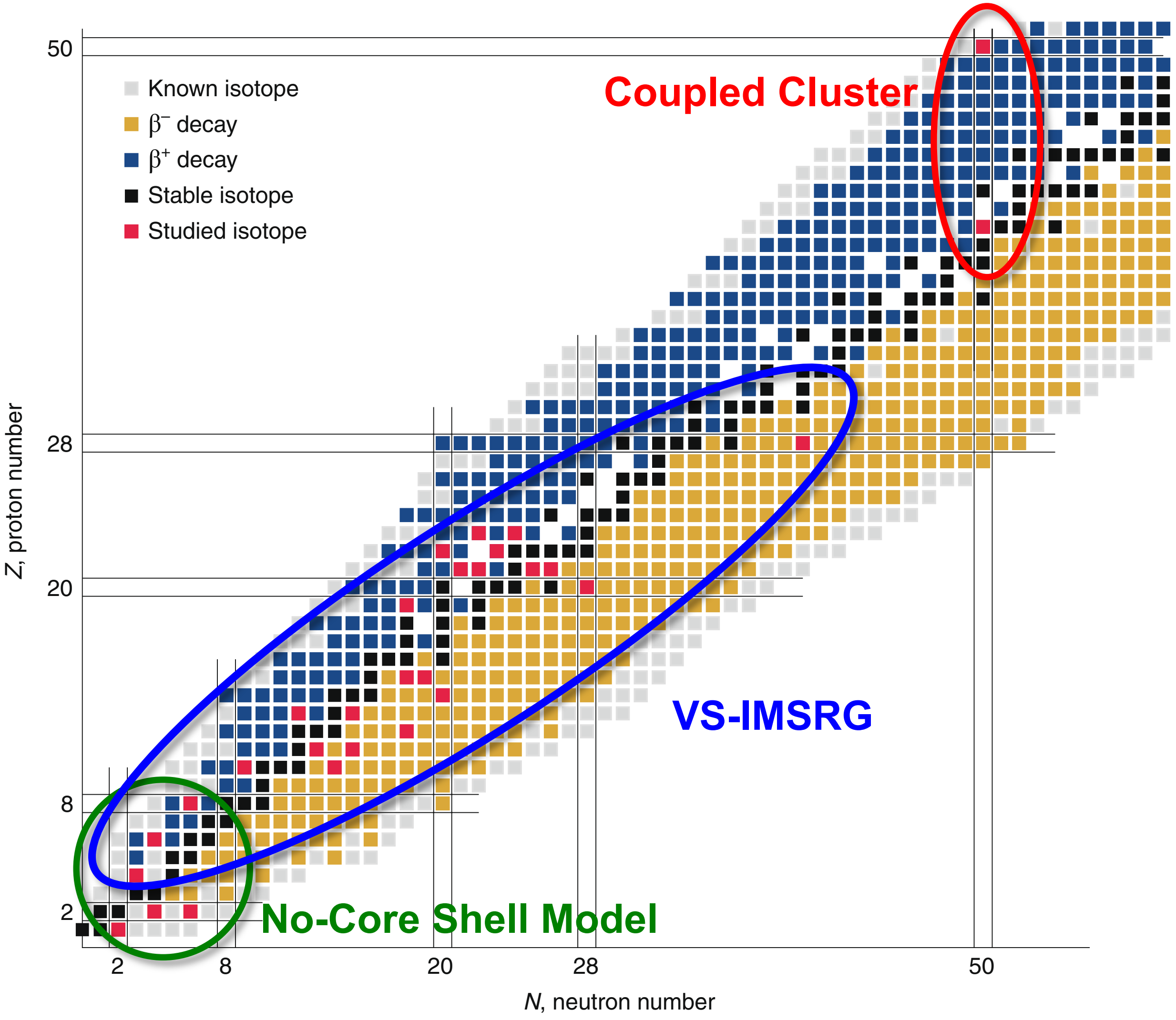
$$\mathcal{O}_{\mathrm{GT}} = \mathcal{O}^{1\mathrm{b}}_{\sigma\tau} + \mathcal{O}^{2\mathrm{b}}_{2BC}$$

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

NUCLEAR PHYSICS

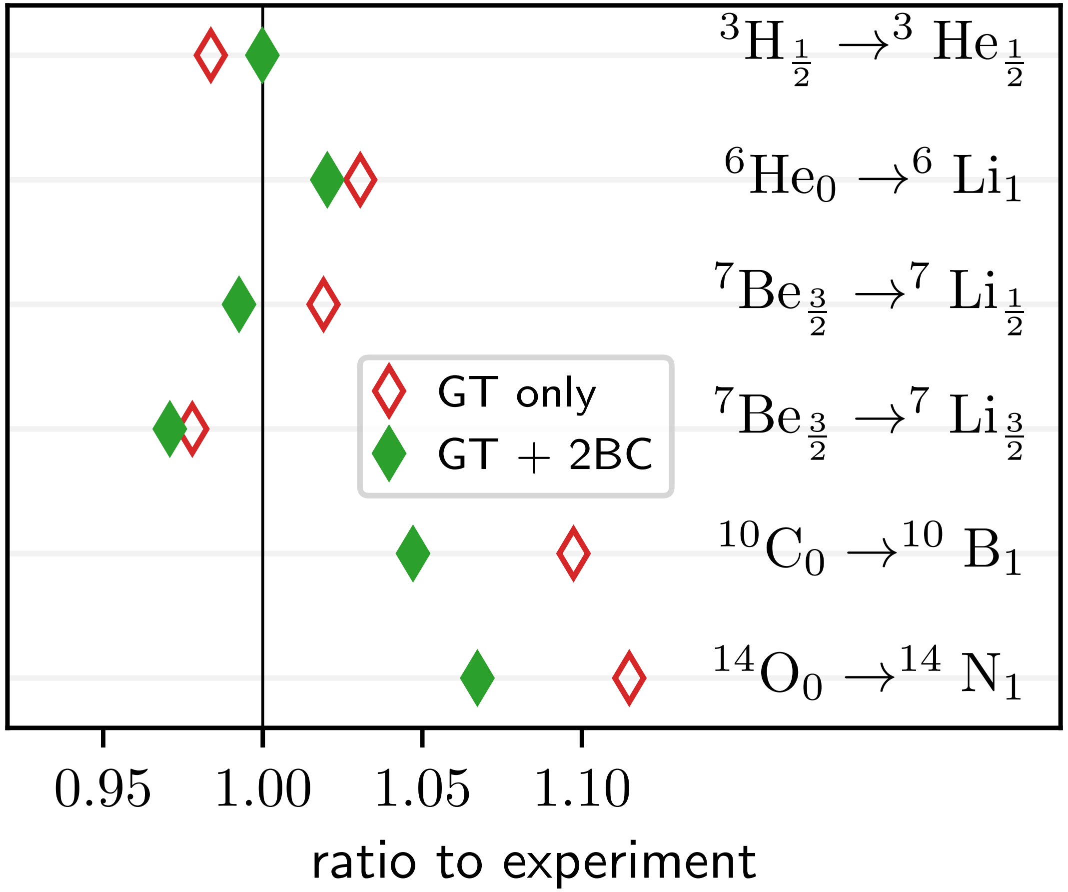
Beta decay gets the ab initio treatment

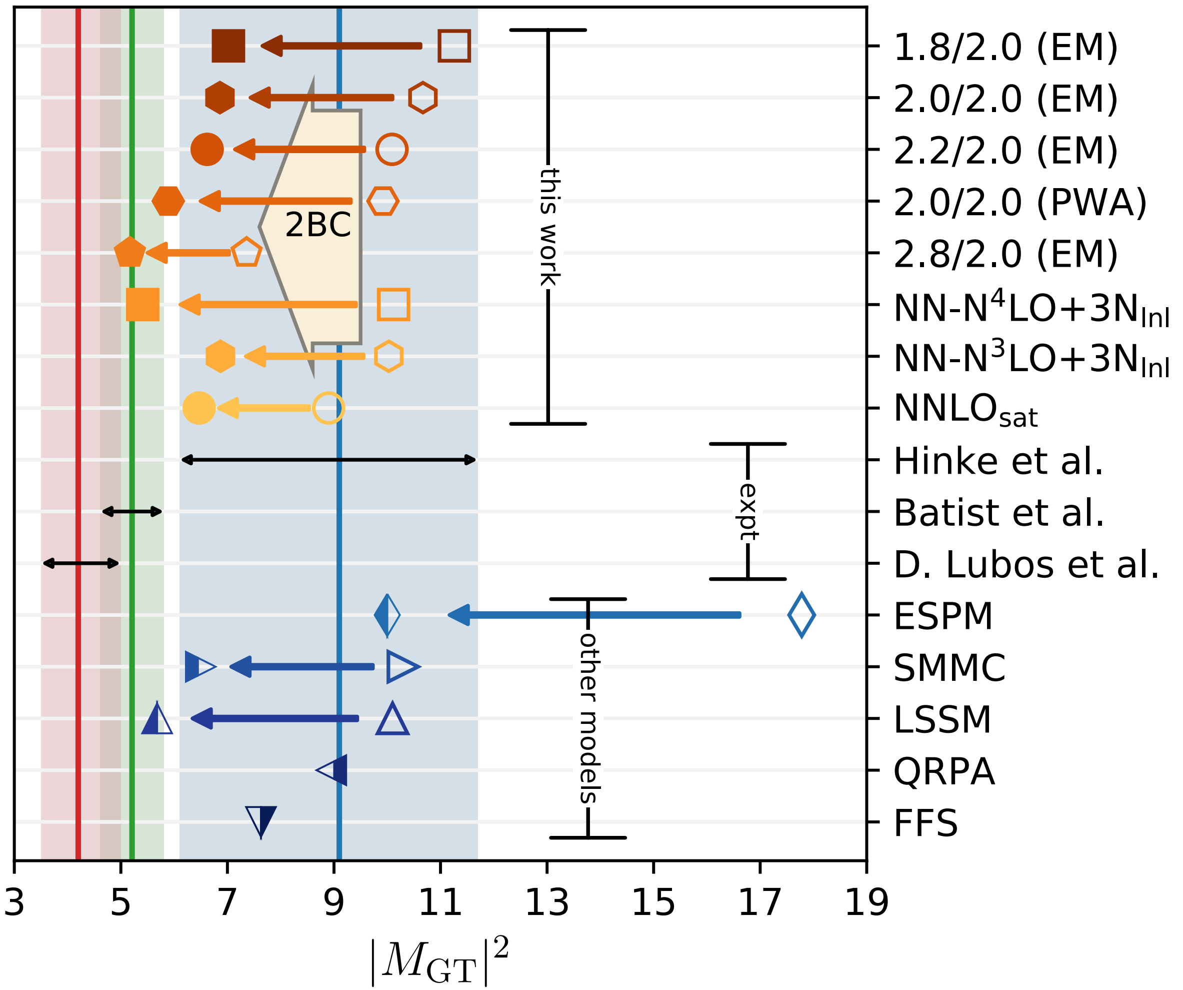
One of the fundamental radioactive decay modes of nuclei is β decay. Now, nuclear theorists have used first-principles simulations to explain nuclear β decay properties across a range of light- to medium-mass isotopes, up to ^{100}Sn.



GT Transitions in Light Nuclei + ^{100}Sn

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



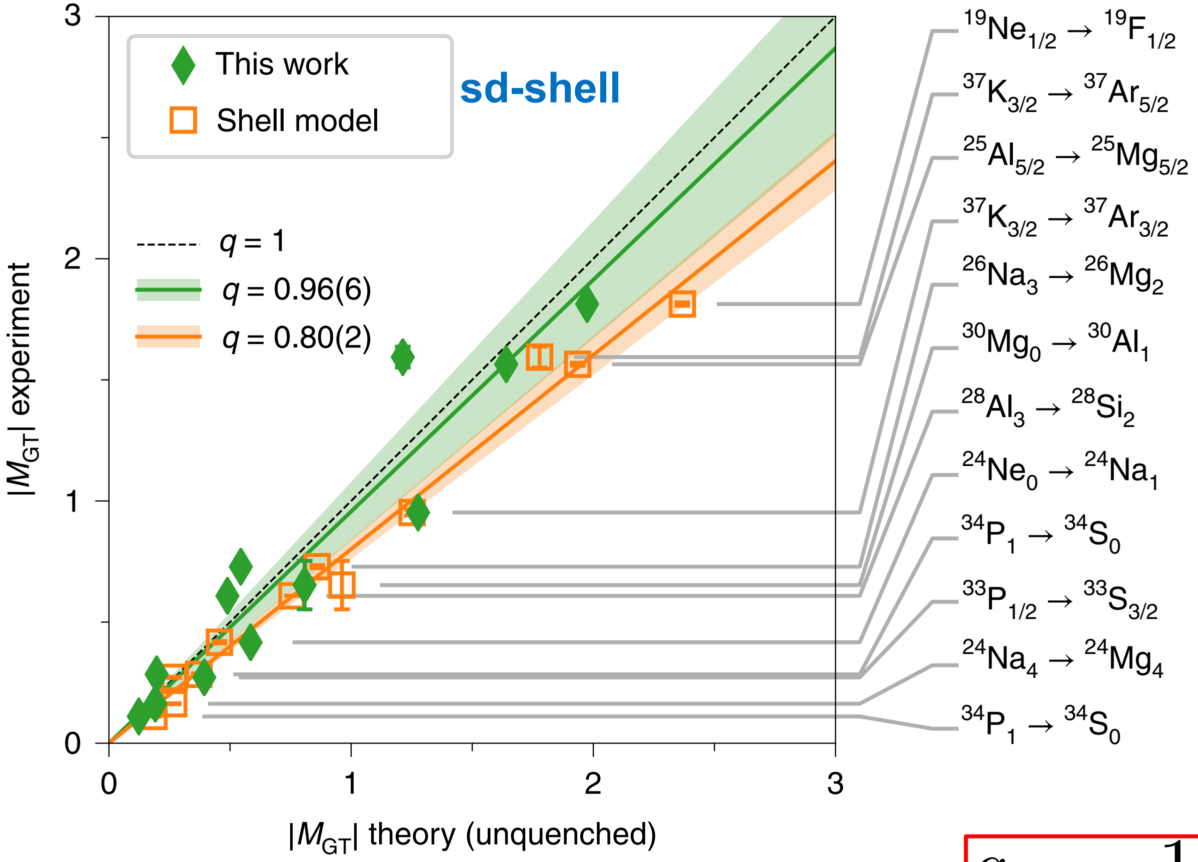


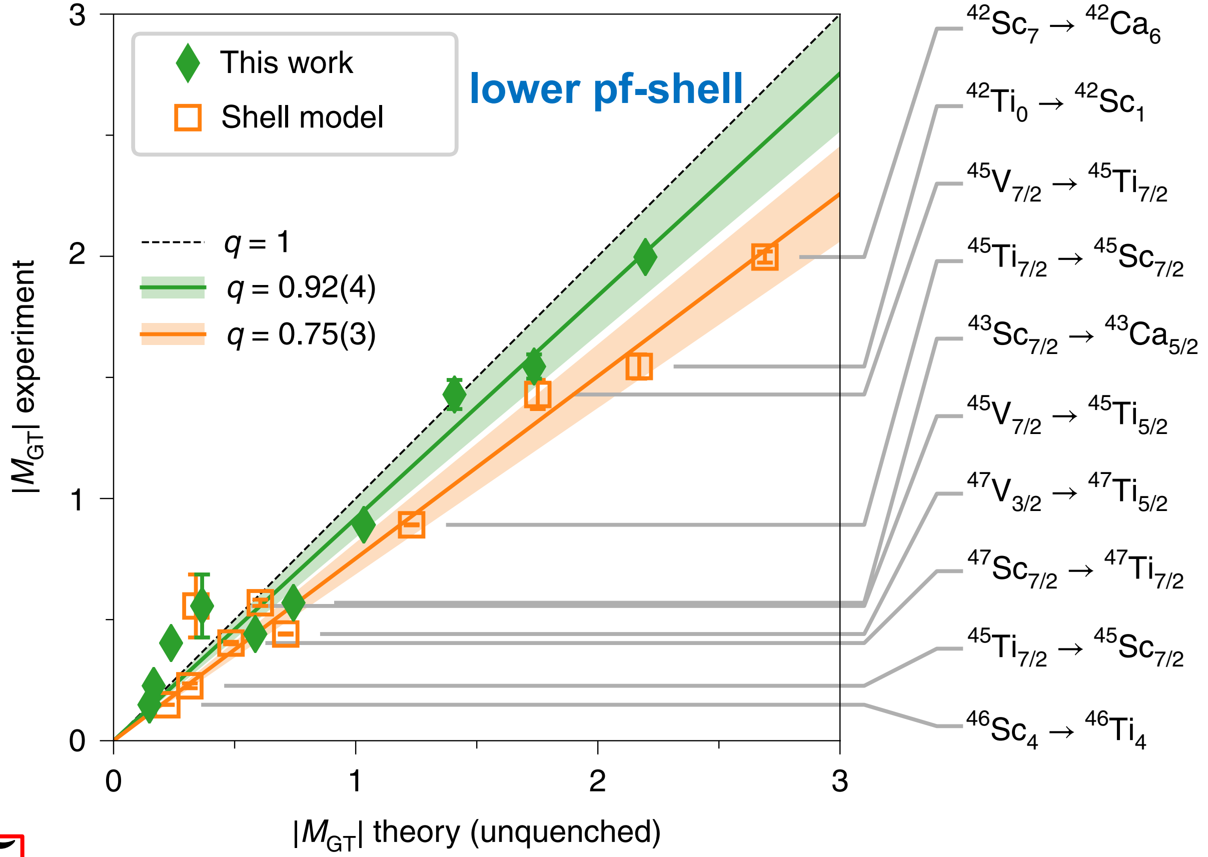
Large quenching from correlations in ^{100}Sn

Addition of 2BC further quenches; reduces spread in results

Solution to g_A-Quenching Problem

VS-IMSRG calculations throughout sd and pf shells





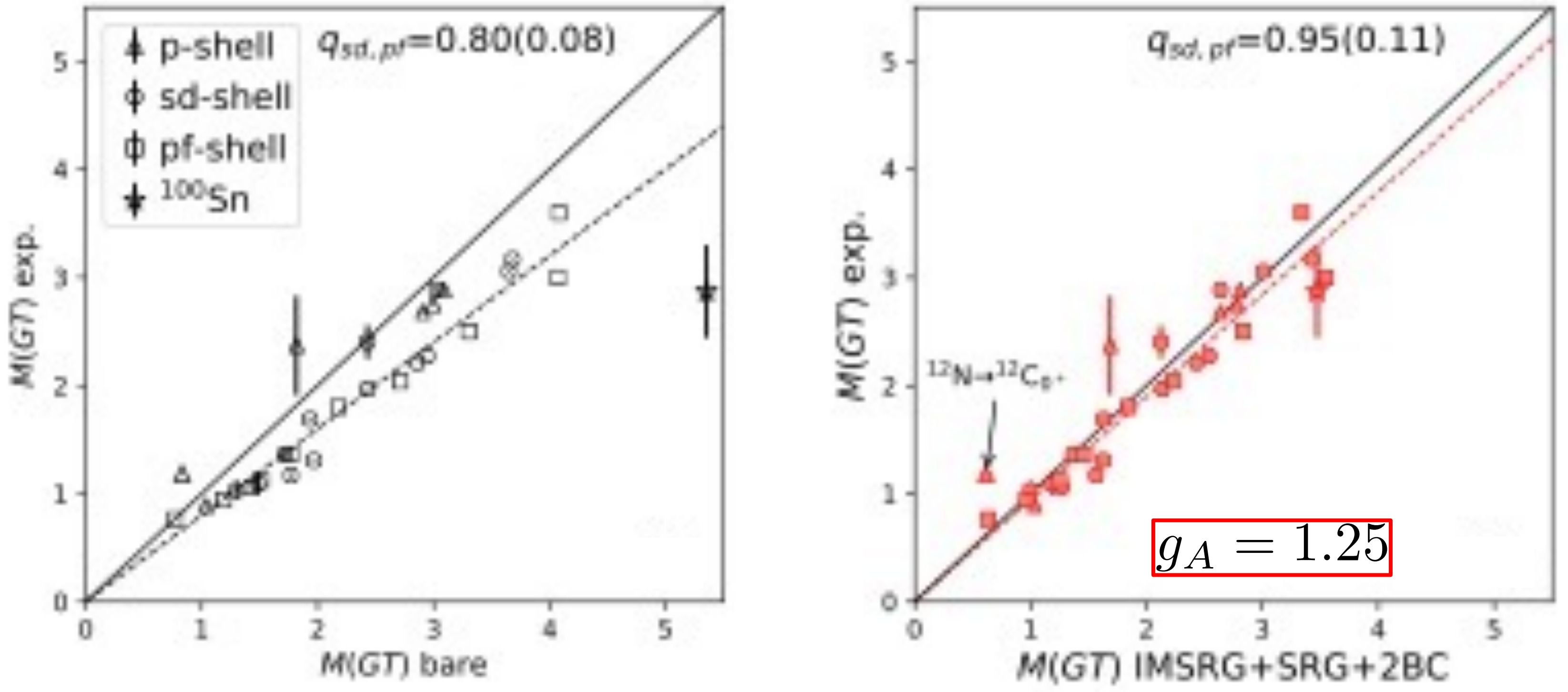
$$\boxed{g_A = 1.25}$$

Ab initio calculations across the chart explain data with unquenched g_A

Refine results: improvements in forces and many-body methods

Complete GT Picture: Light to ^{100}Sn

Ab initio calculations throughout sd and pf shells

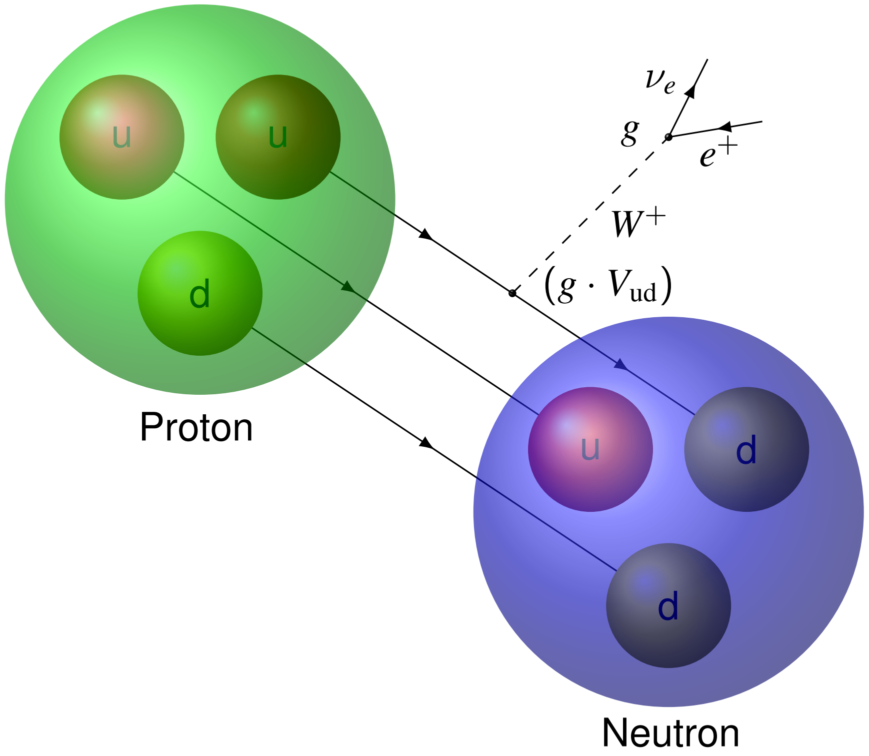


Stroberg (2021)

Ab initio calculations across the chart explain data with unquenched g_A

Including p-shell: q=0.99(21)

Ab Initio Approach to ISB and Superallowed $0^+ \rightarrow 0^+$



Editors' Suggestion

Testing isospin symmetry breaking in *ab initio* nuclear theory

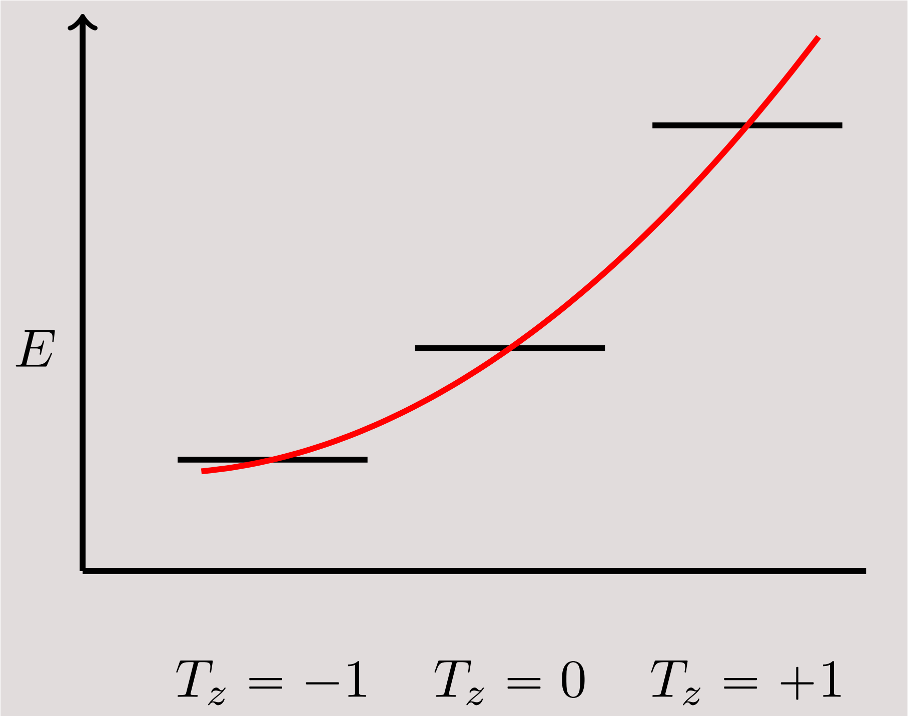
M. S. Martin, S. R. Stroberg, J. D. Holt, and K. G. Leach

Phys. Rev. C **104**, 014324 – Published 30 July 2021

Explore ab initio isospin symmetry breaking

Isobaric mass multiplet equation (IMME) relates energies between members of multiplets

$$E(T_z) = a + bT_z + cT_z^2$$



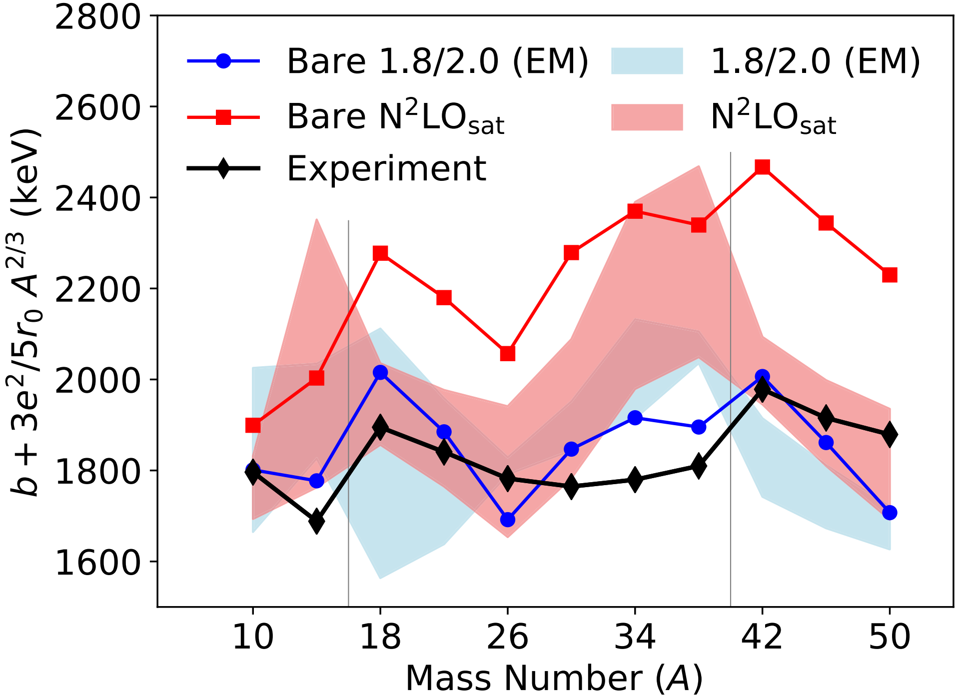
Compare ab initio with experimental determination of IMME coefficients to gauge success

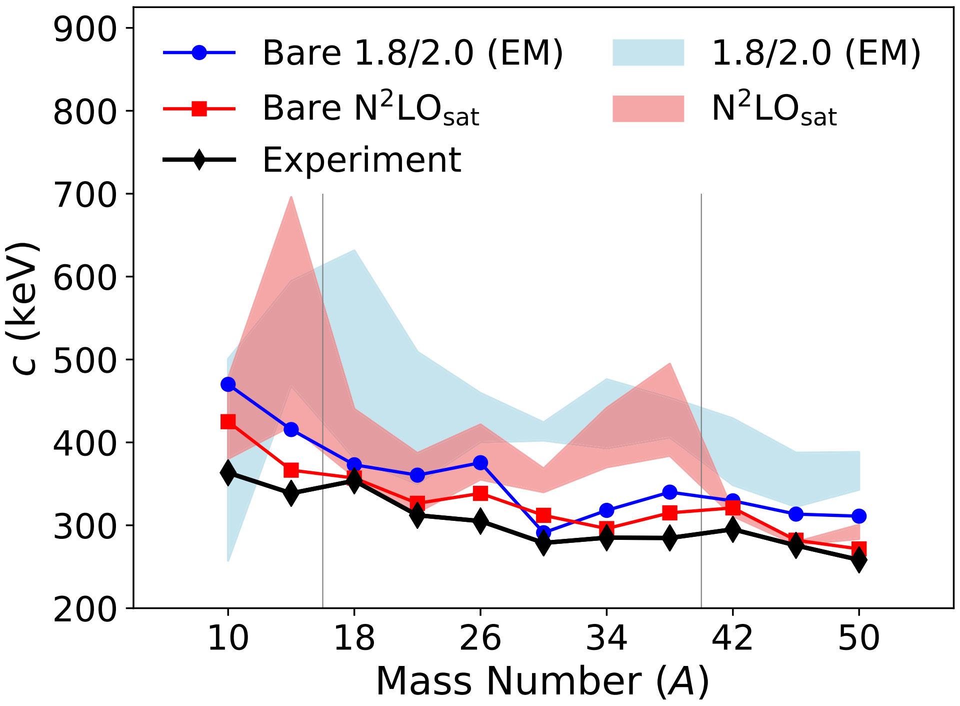
Calculate all nuclei relevant for superallowed transitions; 2 NN+3N forces

Ab initio IMME: bare vs IMSRG

Isobaric mass multiplet equation (IMME) relates energies between members of multiplets

$$E(T_z) = a + bT_z + cT_z^2$$





Bands: normal ordering reference dependence

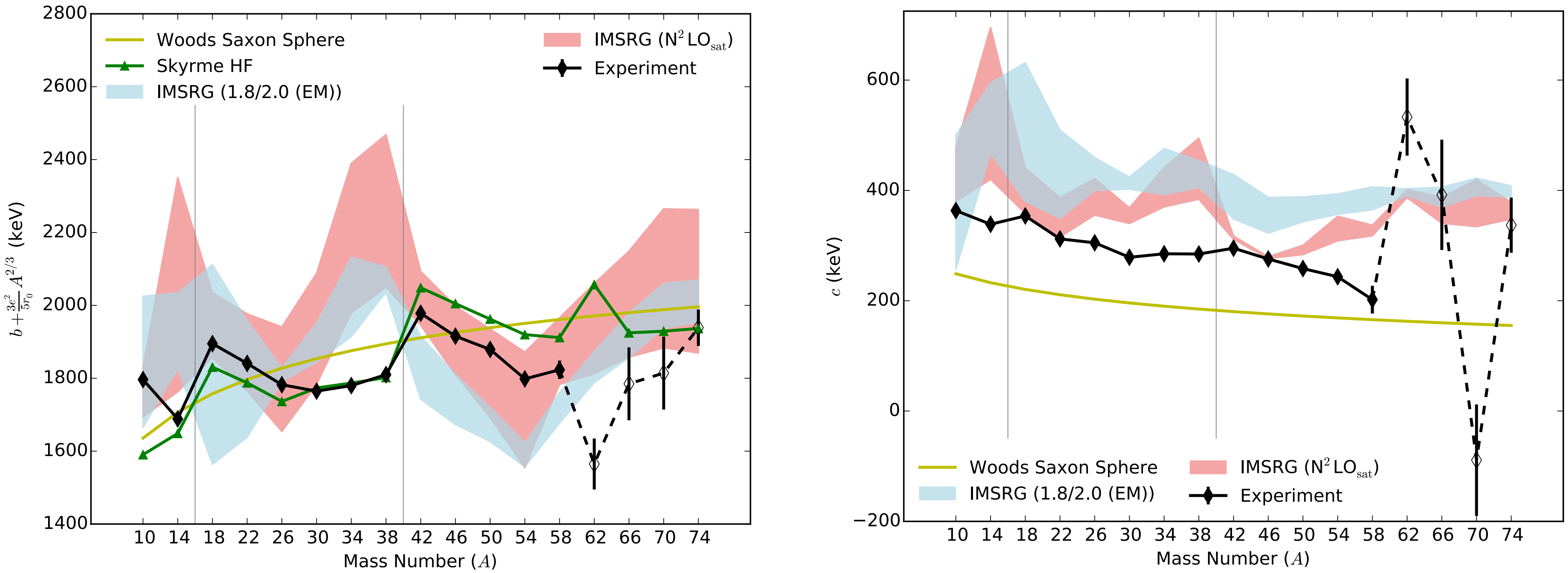
Overall little effect/improvement when applying IMSRG transformation for both b, c

Ab initio IMME: bare vs IMSRG

Isobaric mass multiplet equation (IMME) relates energies between members of multiplets

$$E(T_z) = a + bT_z + cT_z^2$$

Compare VS-IMSRG b, c coefficients to HF and results from a uniform charged sphere



Systematics already largely captured (better) by mean field or charged sphere

Ambiguous results… turn to superallowed Fermi transitions

Superallowed Fermi Transitions

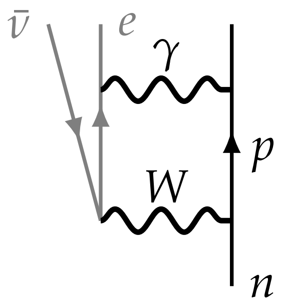
$0^+ \rightarrow 0^+$ transitions: most stringent constraint on V_{ud} from corrected (parameterized) lifetime

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

Isospin-symmetry breaking

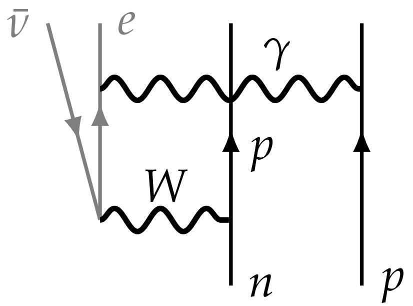
~ Effect of **correlations outside valence space**

$\delta'_R \sim$



Structure-independent radiative correction

$\delta_{NS} \sim$



Structure-dependent radiative correction

~ Effect of **two-body currents**

Superallowed Fermi Transitions

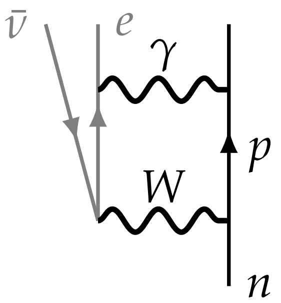
$0^+ \rightarrow 0^+$ transitions: most stringent constraint on V_{ud} from corrected (parameterized) lifetime

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

Isospin-symmetry breaking

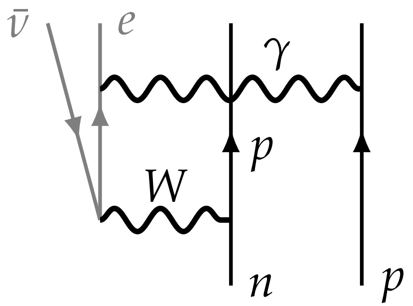
~ Effect of **correlations outside valence space**

$\delta'_R \sim$



Structure-independent radiative correction

$\delta_{NS} \sim$

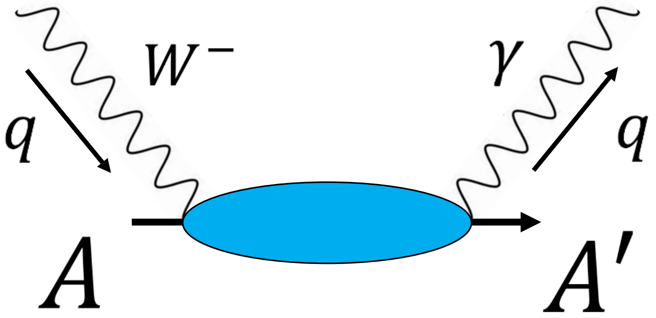


Structure-dependent radiative correction

~ Effect of **two-body currents**

Treatment of SD Radiative Corrections in NCSM

Compton amplitude in the NCSM



- Nuclear matrix elements for γW-box
  1) Express currents in momentum space
  2) Multipole expansion of current operators
  3) Connect currents to effective one–body operators

Lanczos continued fractions method to compute Green's functions!

$$T_3(q_0, Q^2) = -4\pi i \frac{q_0}{q}\sqrt{M_i M_f}\sum_{J=1}^{\infty}(2J+1)$$

$$\times \langle A\lambda_f J_f M_f | \Big[T_{J0}^{mag}(q) \boxed{G(M_f + q_0 + i\epsilon)} T_{J0}^{5,el}(q) + T_{J0}^{el}(q) \boxed{G(M_f + q_0 + i\epsilon)} T_{J0}^{5,mag}(q)$$

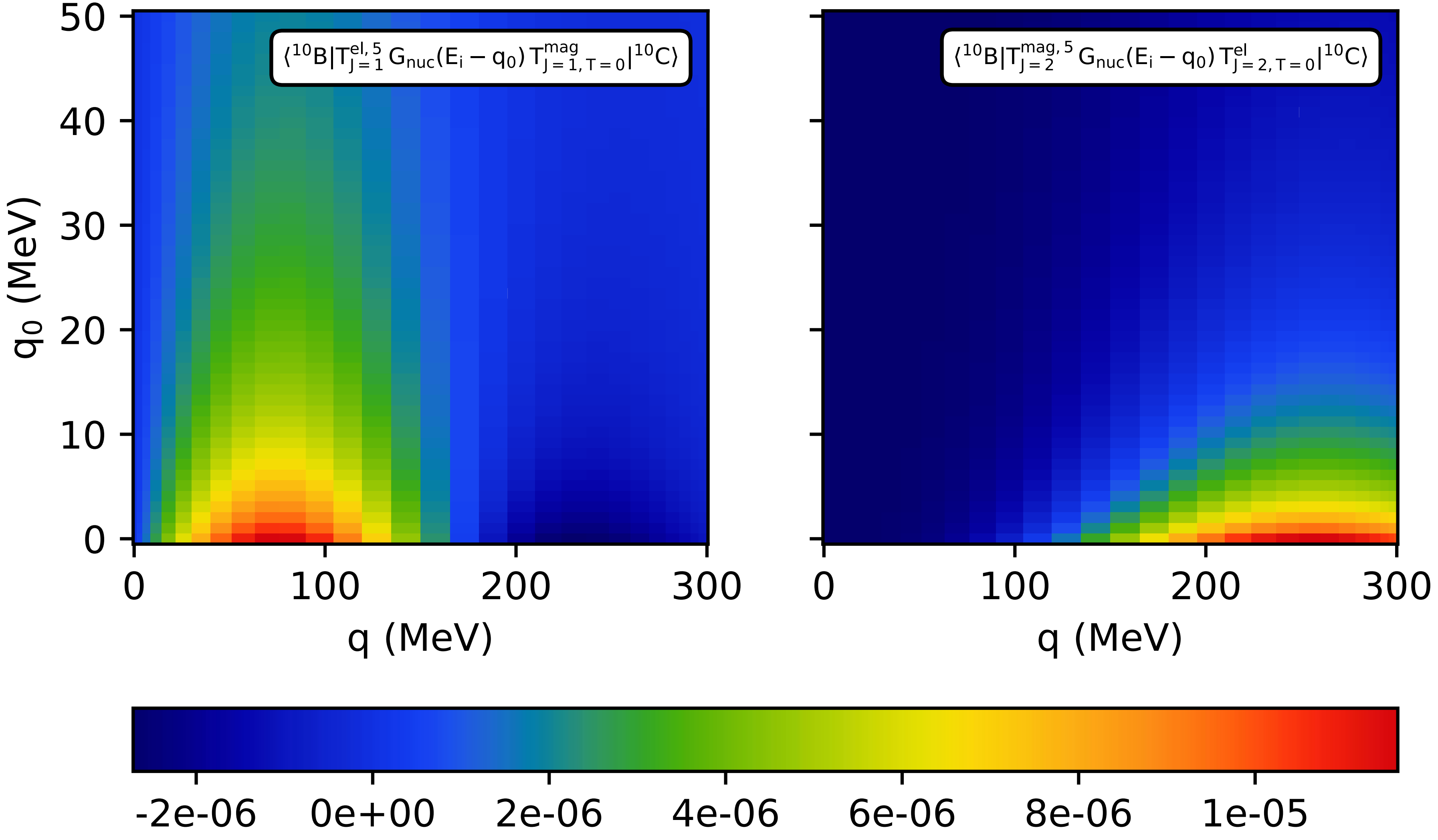
$$+ T_{J0}^{5,mag}(q) \boxed{G(M_i - q_0 + i\epsilon)} T_{J0}^{el}(q) + T_{J0}^{5,el}(q) \boxed{G(M_i - q_0 + i\epsilon)} T_{J0}^{mag}(q) \Big] | A\lambda_i J_i M_i \rangle$$

Courtesy, M. Gennari

Treatment of SD Radiative Corrections in NCSM

$G(M_i - q_0 + i\epsilon)$ terms: $T = 0$ EM current

Preliminary

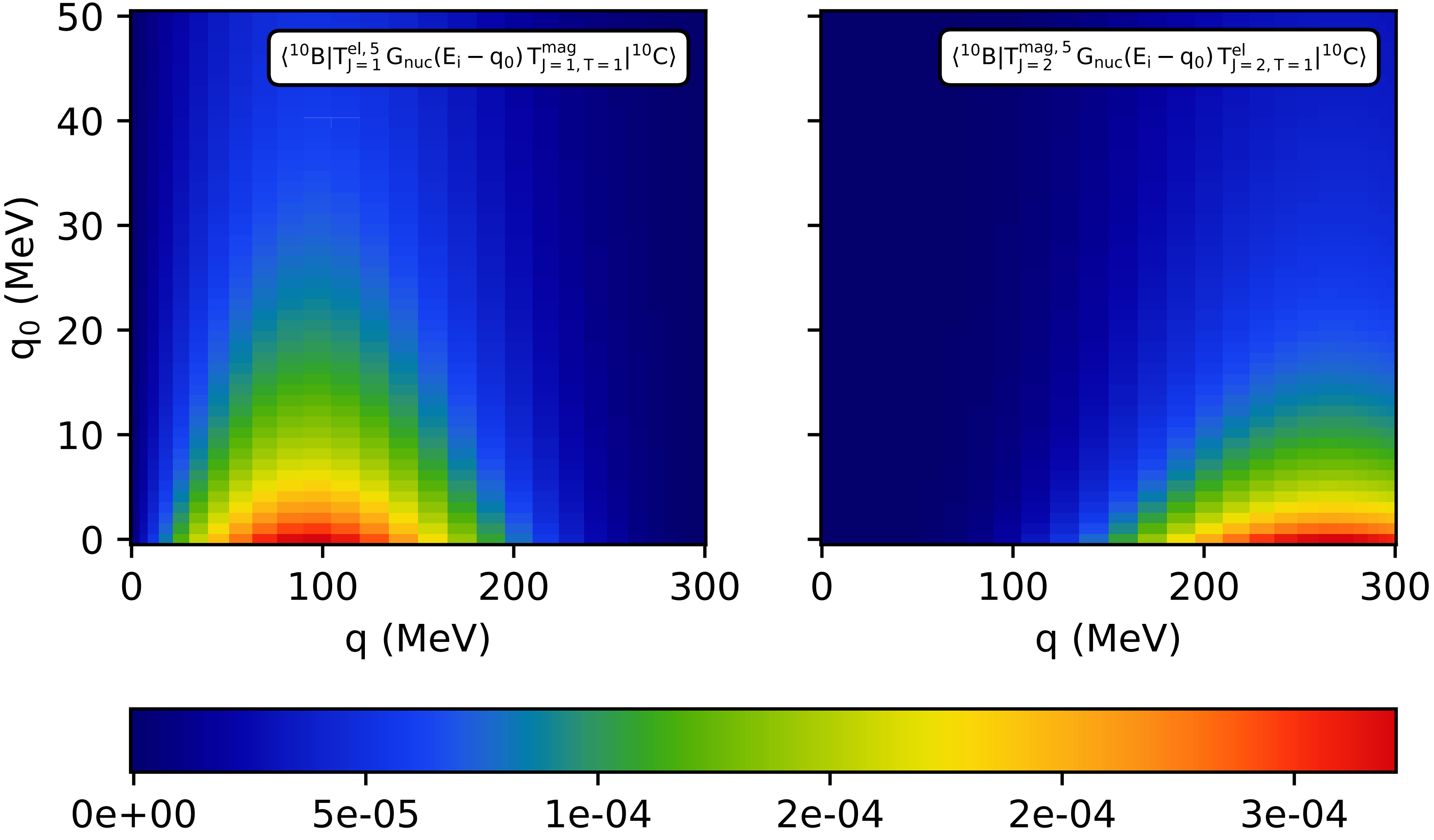


Courtesy, M. Gennari

Treatment of SD Radiative Corrections in NCSM

$G(M_i - q_0 + i\epsilon)$ terms: $T = 1$ EM current

Preliminary

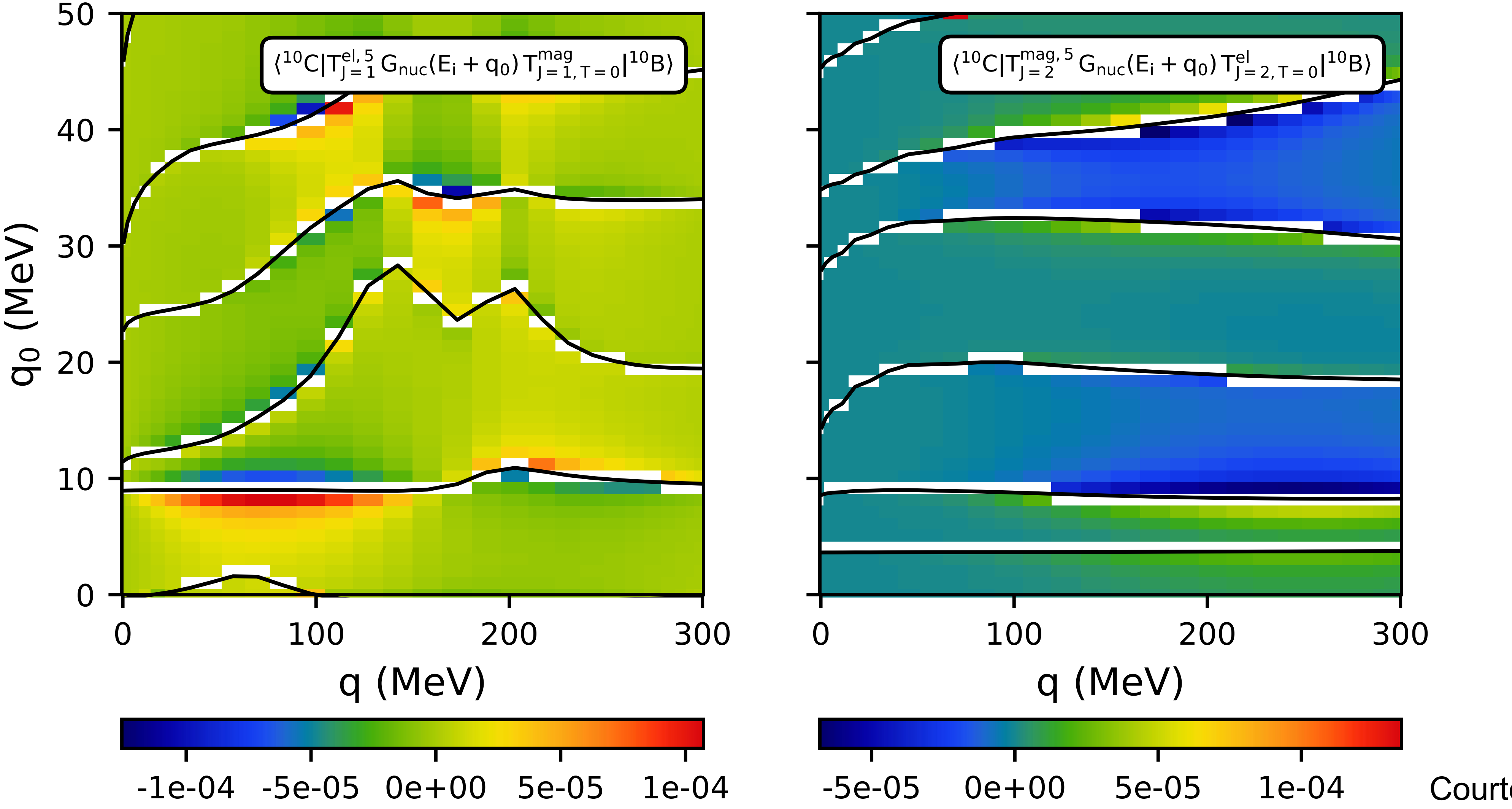


Courtesy, M. Gennari

Treatment of SD Radiative Corrections in NCSM

$G\left(M_f + q_0 + i\epsilon\right)$ terms: $T = 0$ EM current

Preliminary

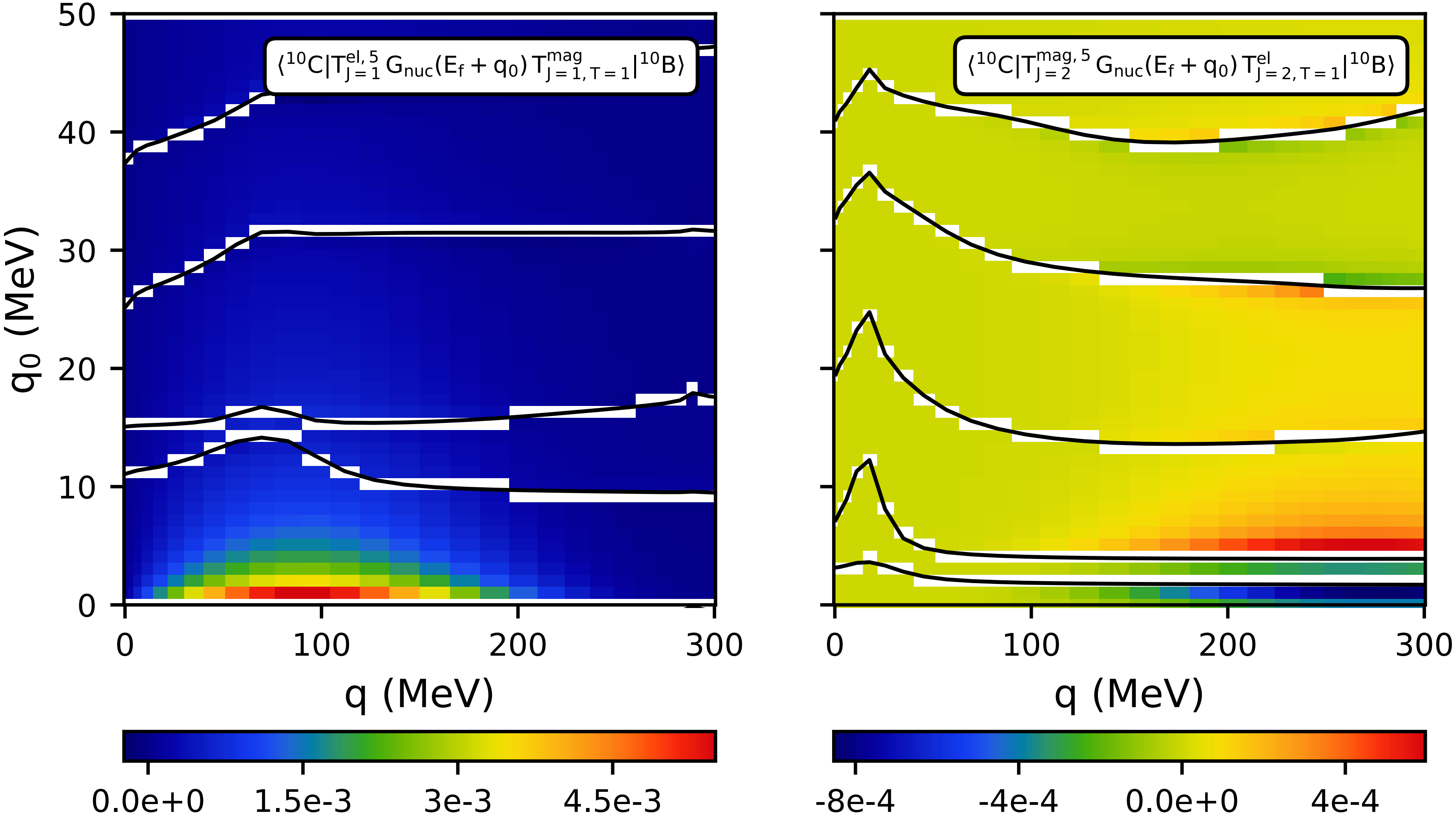


Courtesy, M. Gennari

Treatment of SD Radiative Corrections in NCSM

$G(M_f + q_0 + i\epsilon)$ terms: $T = 1$ EM current

Preliminary

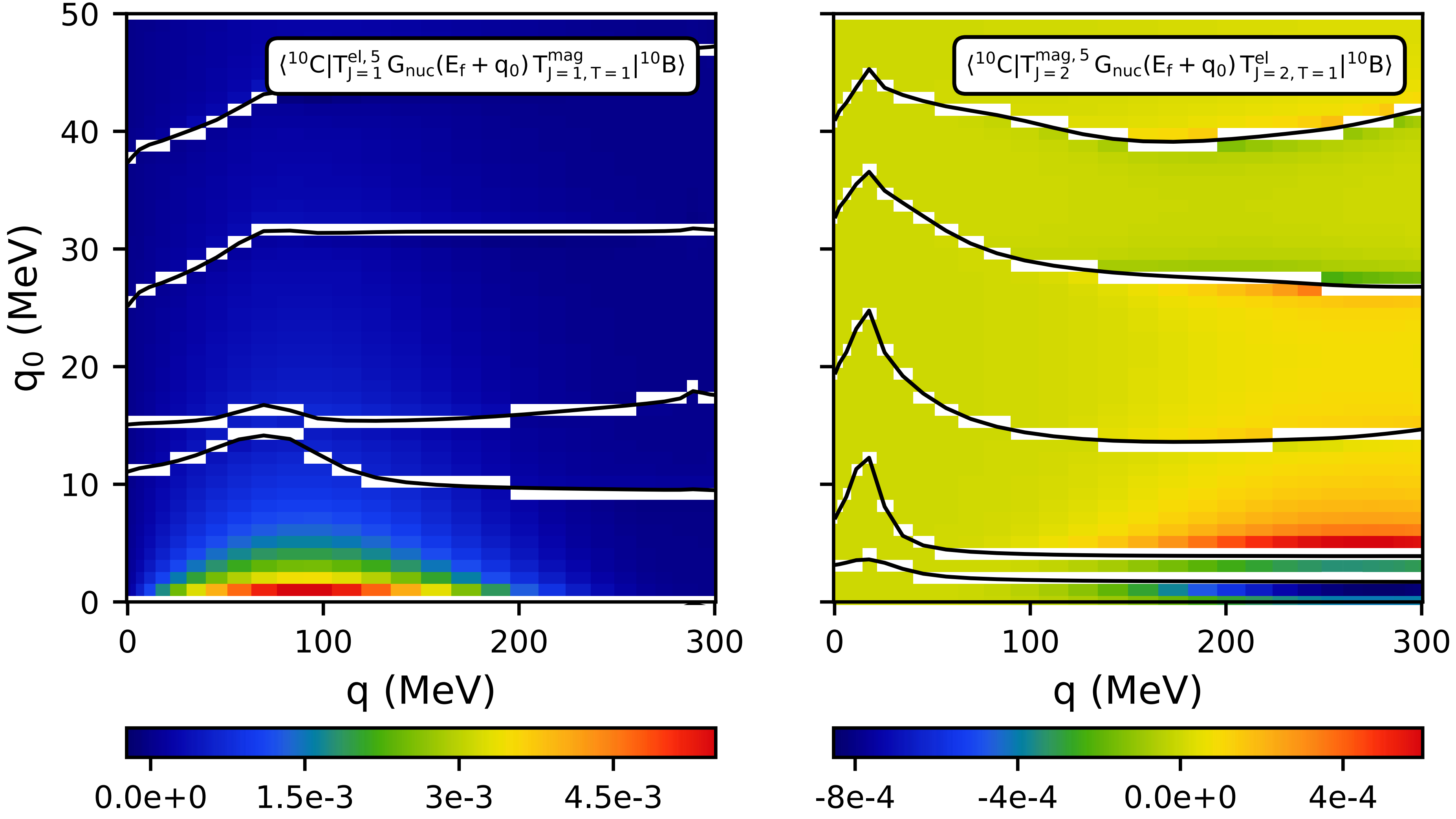


Courtesy, M. Gennari

Treatment of SD Radiative Corrections in NCSM

$G\left(M_f + q_0 + i\epsilon\right)$ terms: $T = 1$ EM current

Preliminary

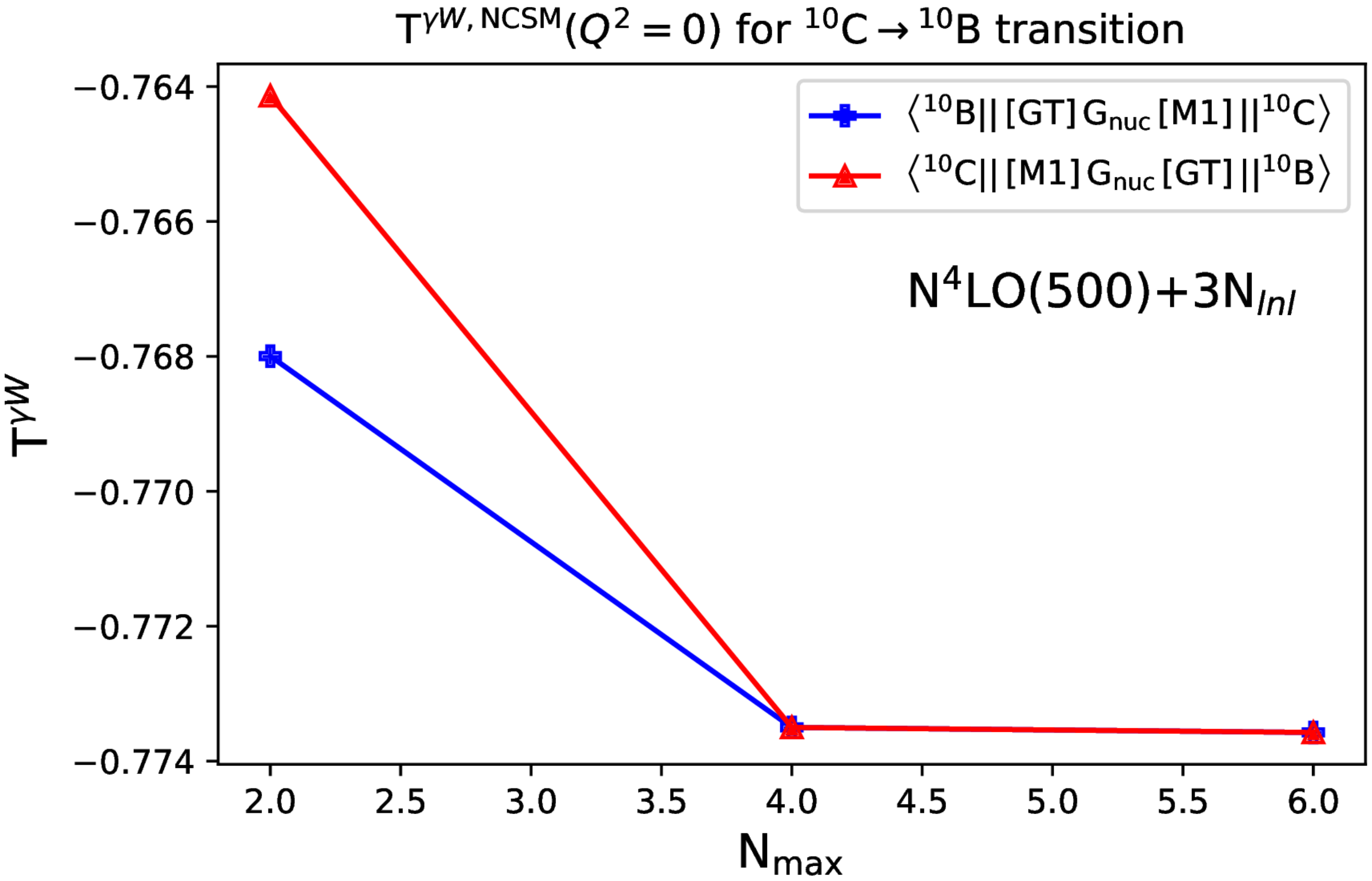


Courtesy, M. Gennari

Treatment of SD Radiative Corrections in NCSM

Comment on many-body convergence

Preliminary



Next step: implement in VS-IMSRG for all superallowed nuclei

Courtesy, M. Gennari

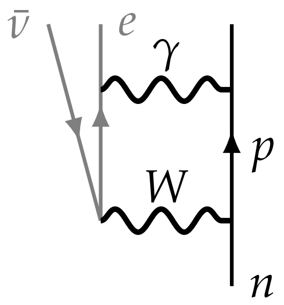
Superallowed Fermi Transitions

$0^+ \rightarrow 0^+$ transitions: most stringent constraint on V_{ud} from corrected (parameterized) lifetime

$$|M_F|^2 = |M_F^0|^2(1 + \delta_C)$$ Isospin-symmetry breaking

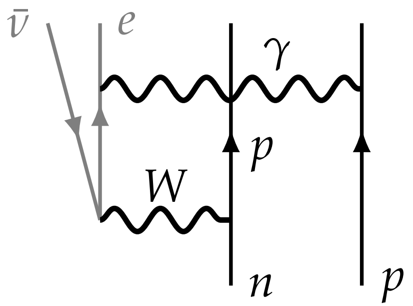
~ Effect of **correlations outside valence space**

$\delta'_R \sim$



Structure-independent radiative correction

$\delta_{NS} \sim$



Structure-dependent radiative correction

~ Effect of **two-body currents**

Superallowed Fermi Transitions

Ab initio calculations of all cases with 1.8/2.0 (EM) interaction

Standard approach (T/H): Split contribution

$$\delta_C = \delta_{C1} + \delta_{C2}$$

Configuration mixing

wavefunction mismatch

Ab initio approach: calculate directly

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

$$\delta_C = 1 - \frac{|M_F|^2}{2}$$

$$M_F = \langle \Psi_F || \tau || \Psi_i \rangle$$

TRIUMF

Superallowed Fermi Transitions

Ab initio calculations of all cases with 1.8/2.0 (EM) interaction

Standard approach (T/H): Split contribution

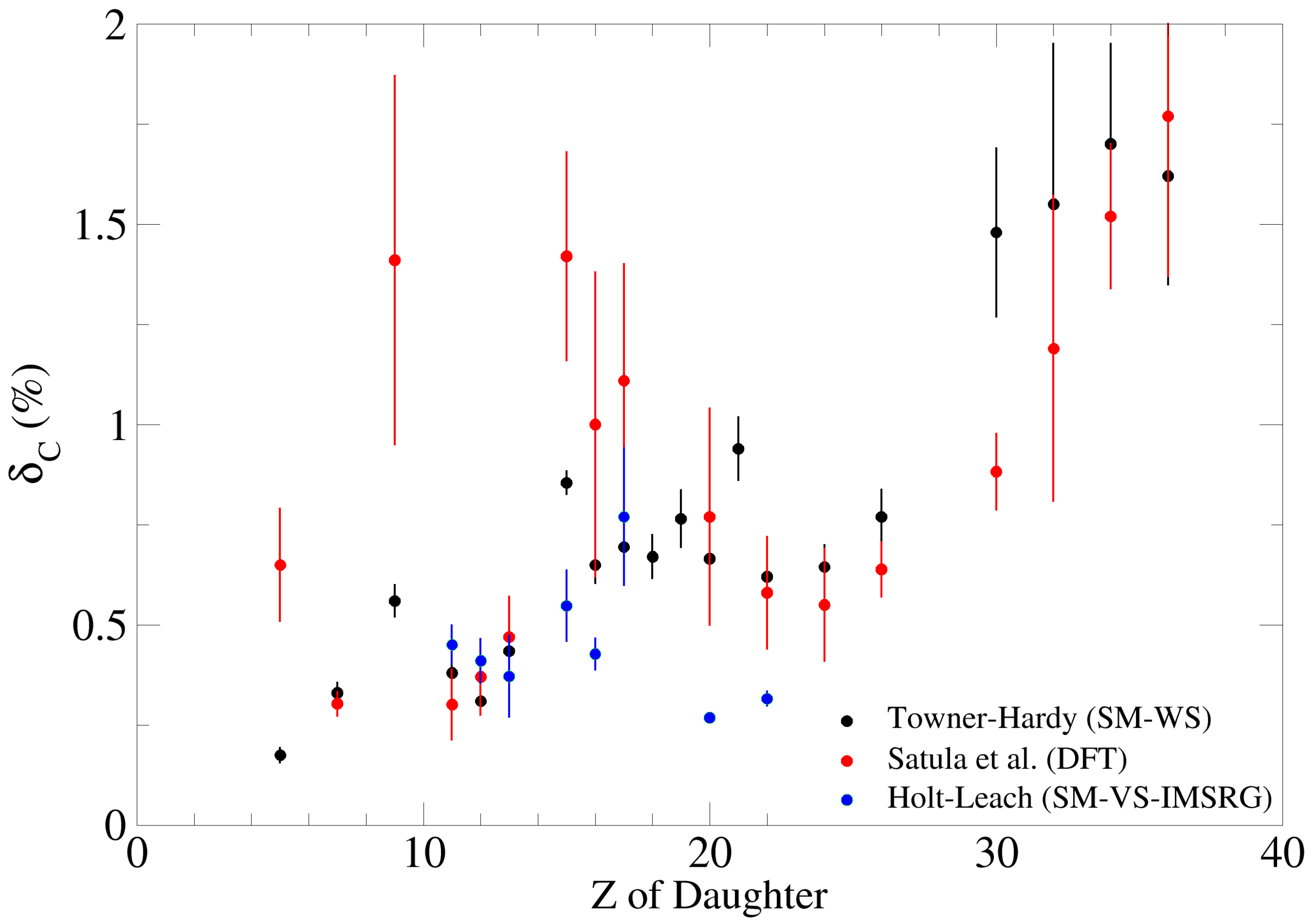
$$\delta_C = \underbrace{\delta_{C1}}_{\text{Configuration mixing}} + \underbrace{\delta_{C2}}_{\text{wavefunction mismatch}}$$

Ab initio approach: calculate directly

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

$$\delta_C = 1 - \frac{|M_F|^2}{2}$$

$$M_F = \langle \Psi_F || \tau || \Psi_i \rangle$$

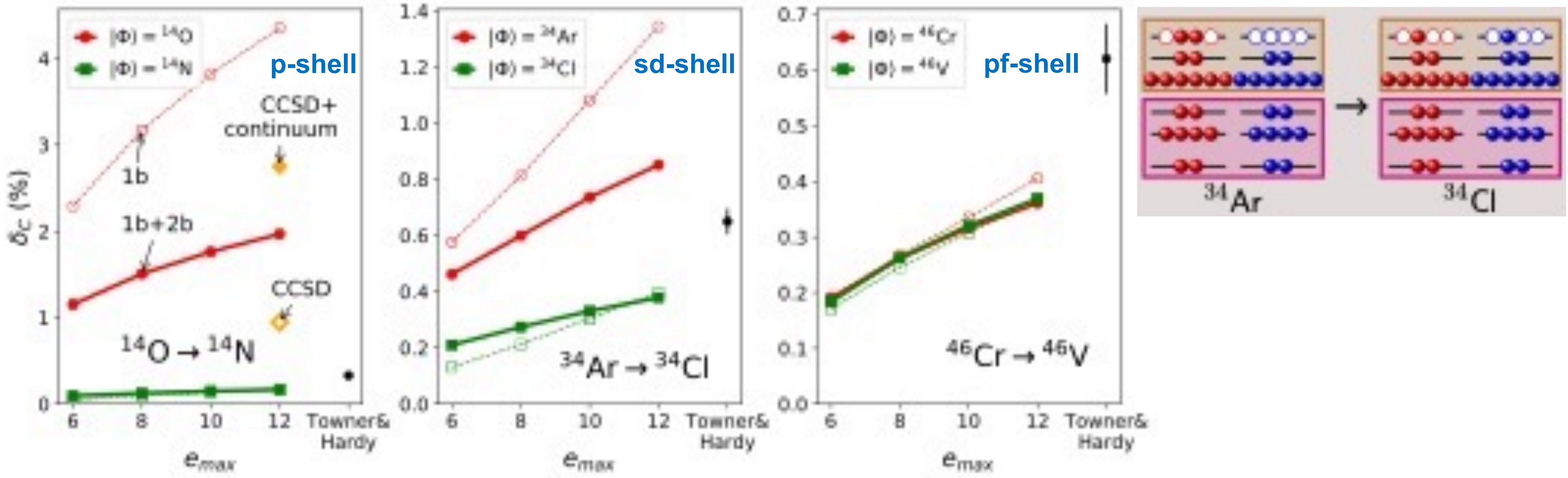


Leach, Holt, arXiv:1809.10793

Results comparable to T-H and DFT

Convergence Issues

Can we provide rigorous uncertainty estimates?



Significant effect from 1b to 1b+2b

Significant reference-state dependence in some cases; unclear convergence with e_{max}

Large effect from CC with continuum indicates generally difficult for ab inito

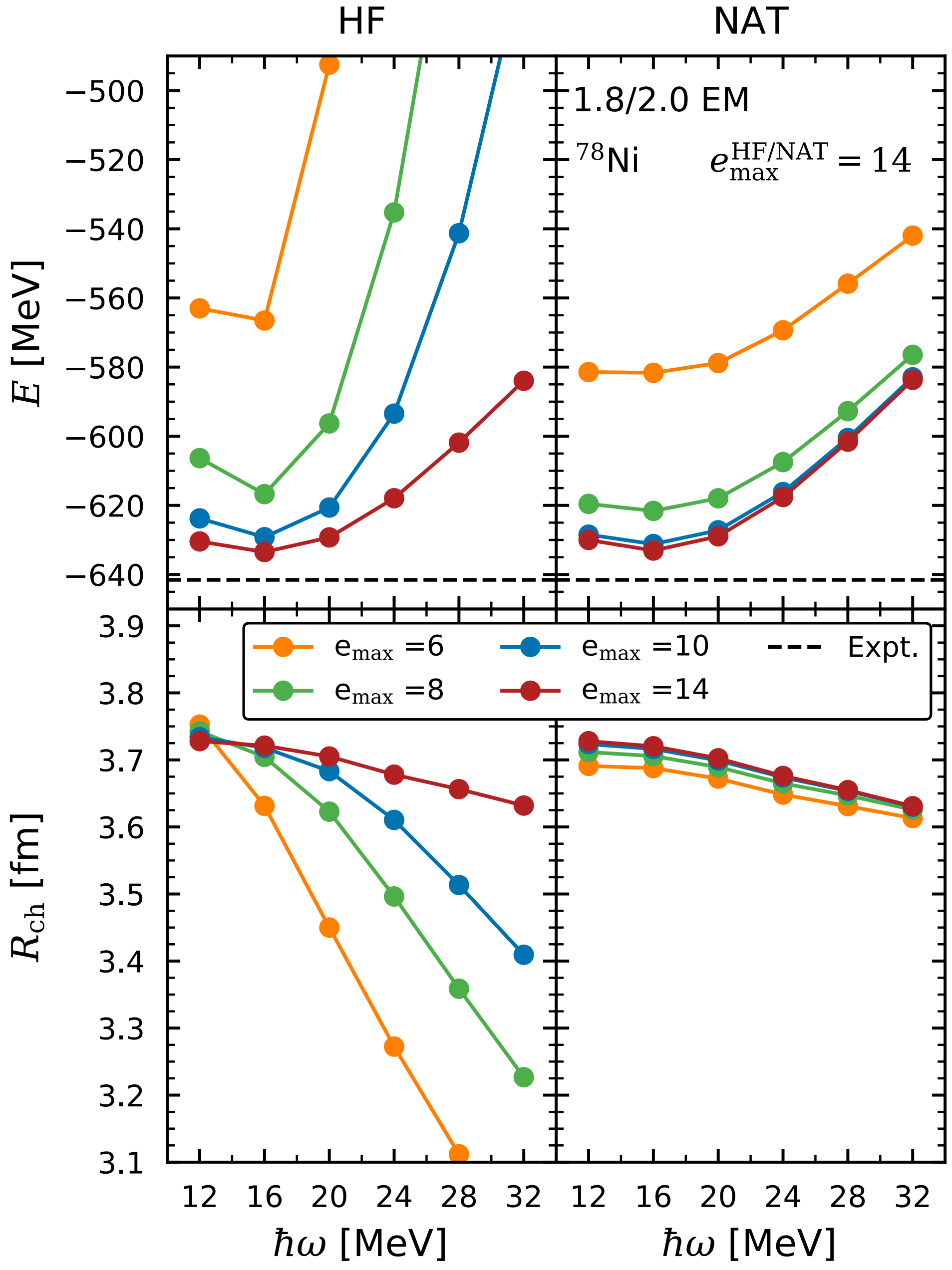
Potential Improvement: Natural Orbitals Basis

Natural Orbitals (perturbatively improved) basis:

Add *perturbations* caused by interactions between particles to the HF-basis system

$$|\Psi\rangle = |\Phi\rangle + \sum_{n=1}^{\infty} \left(\frac{H_I}{H_0 - E^{(0)}} \right)^n |\Phi\rangle$$

$$E = E^{(0)} + \sum_{n=1}^{\infty} \left\langle \Phi | H_I \left(\frac{H_I}{H_0 - E^{(0)}} \right)^n |\Phi \right\rangle$$



Dramatic improvement in energies and radii

Can it help with superallowed convergence?

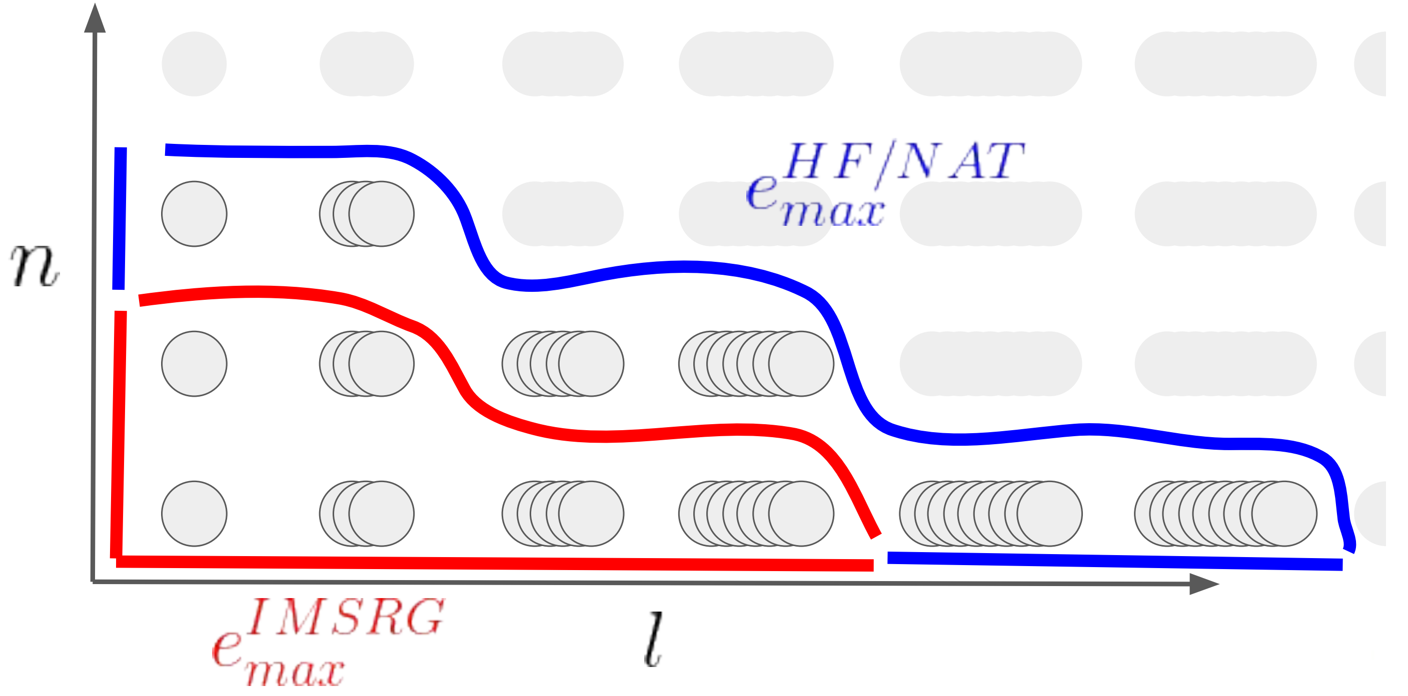
Potential Improvement: Natural Orbitals Basis

Natural Orbitals (perturbatively improved) basis:

Add *perturbations* caused by interactions between particles to the HF-basis system

$$|\Psi\rangle = |\Phi\rangle + \sum_{n=1}^{\infty} \left(\frac{H_I}{H_0 - E^{(0)}}\right)^n |\Phi\rangle$$

$$E = E^{(0)} + \sum_{n=1}^{\infty} \left\langle \Phi | H_I \left(\frac{H_I}{H_0 - E^{(0)}}\right)^n |\Phi\right\rangle$$



Dramatic improvement in energies and radii

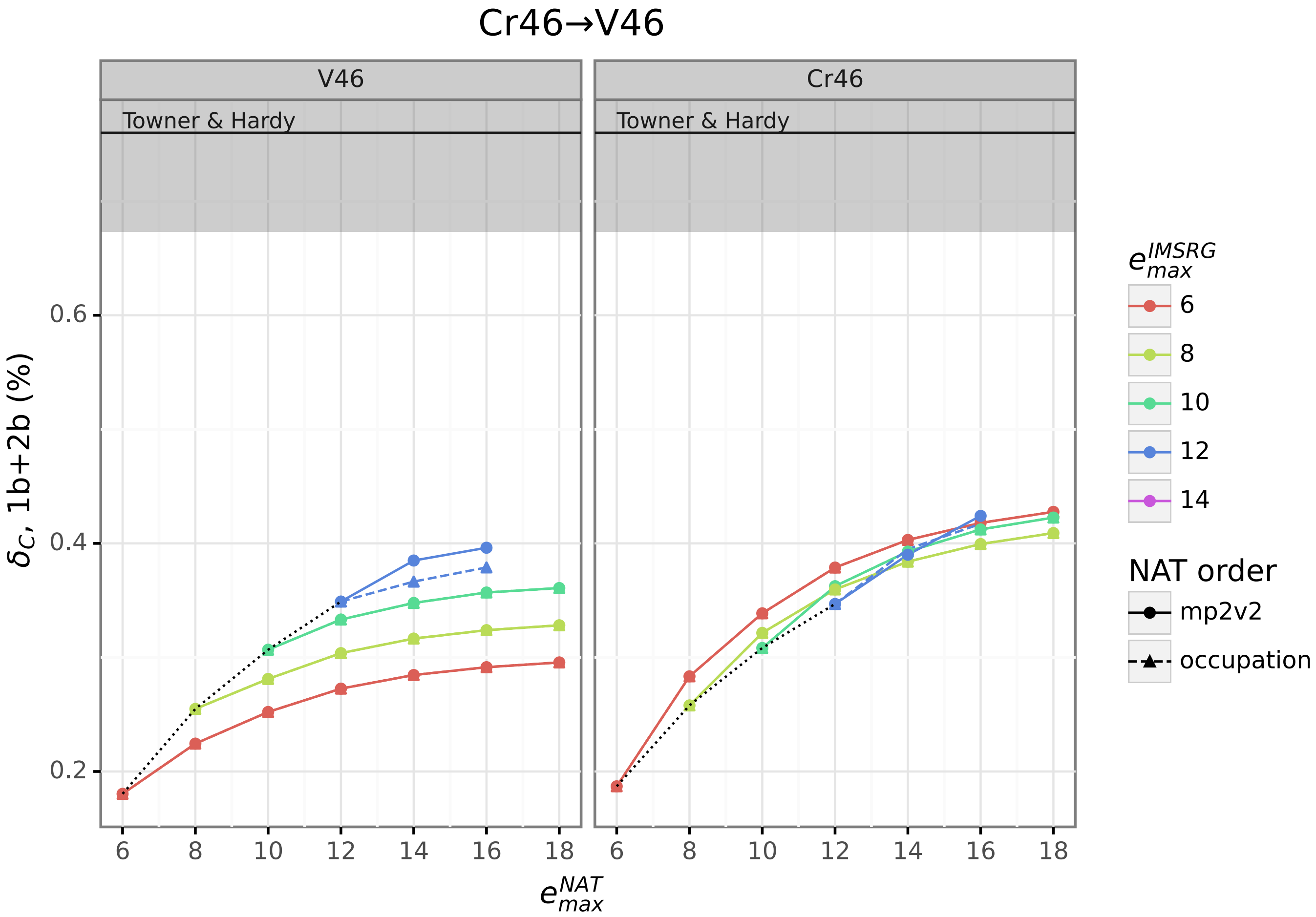
Can it help with superallowed convergence?

Potential Improvement: Natural Orbitals Basis

Natural Orbitals (perturbatively improved) basis:

Medium mass:

- consistent results for NAT orbitals chosen
- potentially small reference-state dependence
- still unclear e_{max} convergence



Potential Improvement: Natural Orbitals Basis

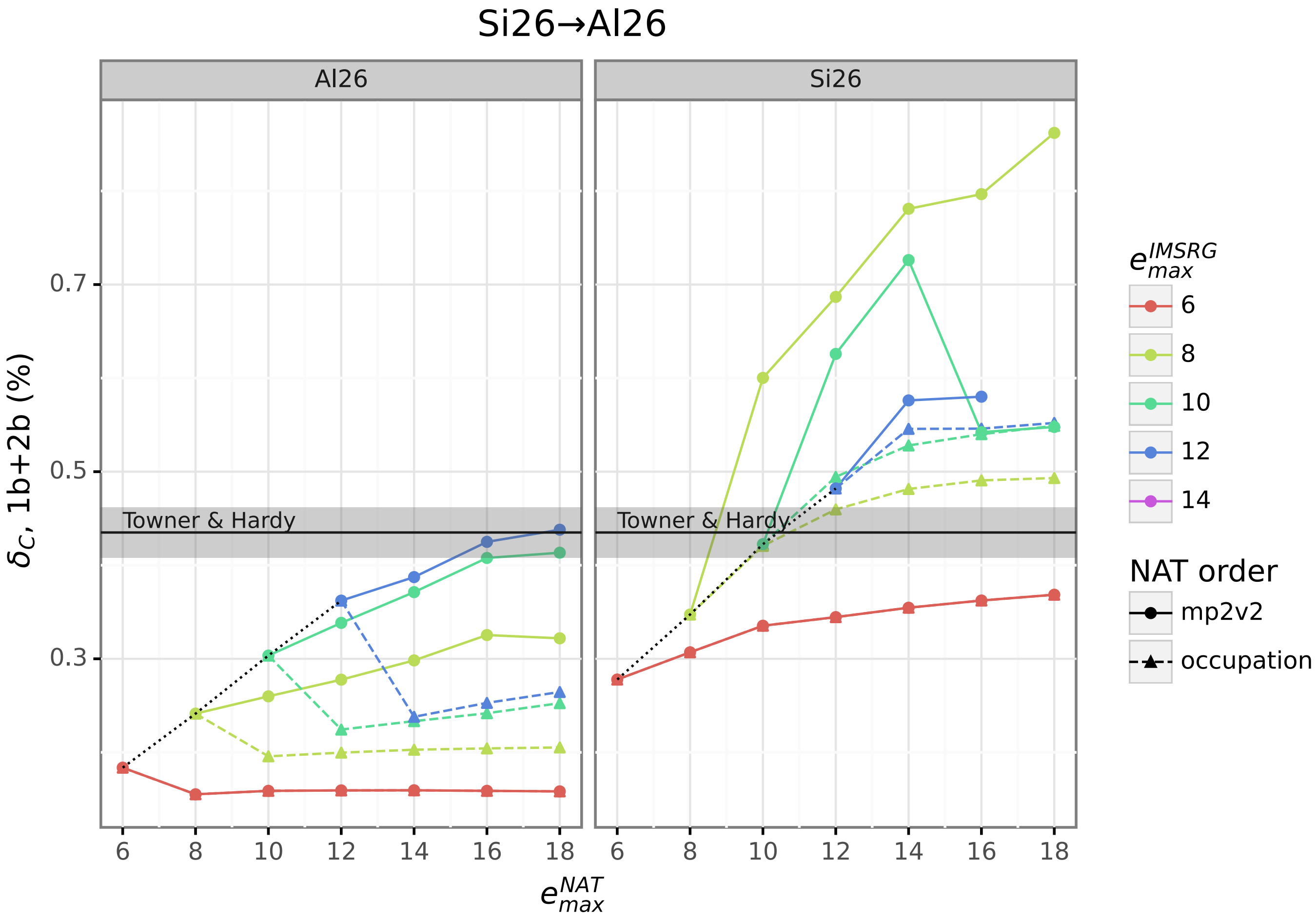
Natural Orbitals (perturbatively improved) basis:

Medium mass:

- consistent results for NAT orbitals chosen
- potentially small reference-state dependence
- still unclear e_{max} convergence

Lighter systems

- “quirks” in convergence…



Work still in progress…

TRIUMF

Present and Future for Ab Initio Theory

Nuclear Structure/Astrophysics

Development of forces and currents

Ab initio to ^{208}Pb: neutron skin, r-process

Dripline predictions to medium-masses

Evolution of magic numbers:

masses, radii, spectra, EM transitions

Multi-shell theory:

Islands of inversion, forbidden decays

Nuclear EOS/Neutron star properties

Atomic systems

Fundamental Symmetries/BSM Physics

EW operators: GT quenching, muon capture

$0\nu\beta\beta$ decay matrix elements + DGT/ECEC/Dg

WIMP-Nucleus scattering for dark matter detection

Coherent elastic neutrino-nucleus scattering

Superallowed Fermi transitions

Symmetry-violating moments: EDM, anapole…

Work in progress

Higher-order many-body physics: IMSRG(3)

Monte Carlo shell model diagonalization

Extension to superheavy nuclei

TRIUMF

THE UNIVERSITY OF BRITISH COLUMBIA

McGill UNIVERSITY

T. Miyagi, B. S. Hu, L. Jokiniemi

A. Belley, I. Ginnett, C. G. Payne

M. Bruneault, J. Padua

S. Leutheusser

E. Love

K. Evidence, D. Kush

G. Tenkila, H. Patel, V. Chand

B. Wong, X. Cao

S. R. Stroberg N. Vassh

TECHNISCHE UNIVERSITÄT DARMSTADT A. Schwenk

THE UNIVERSITY of TENNESSEE UT KNOXVILLE G. Hagen, T. Papenbrock

MICHIGAN STATE UNIVERSITY J.M. Yao, H. Hergert

COLORADO SCHOOL OF MINES M. Martin, K. G. Leach

Massachusetts Institute of Technology R. F. Garcia-Ruiz

UNIVERSITAT DE BARCELONA J. Menéndez

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL J. Engel

TEXAS A&M UNIVERSITY J. W. Holt