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McGill UNIVERSITY

Ab initio nuclear theory for neutrino physics

Jason D. Holt
Scientist, Theory Department
CAP Congress
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NSERC CRSNG

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

NRC·CNRC

Discovery, accelerated

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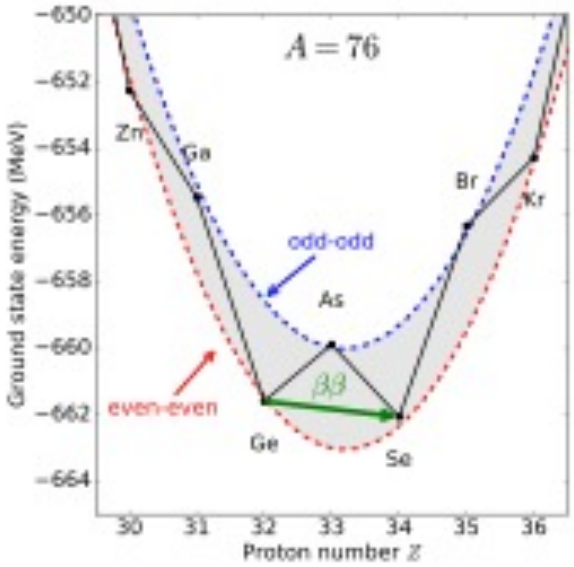
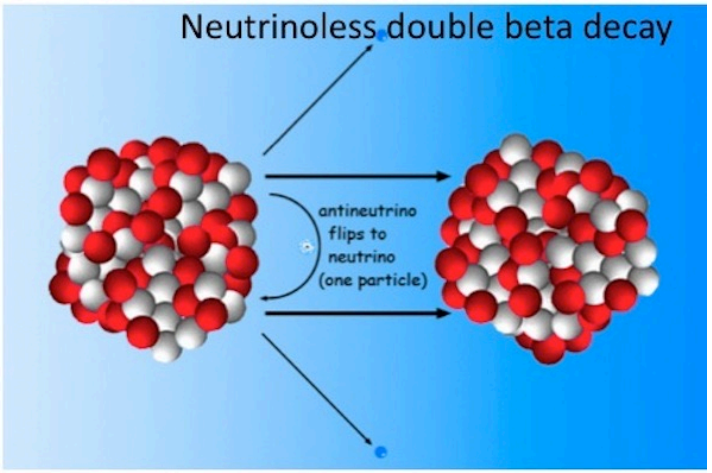
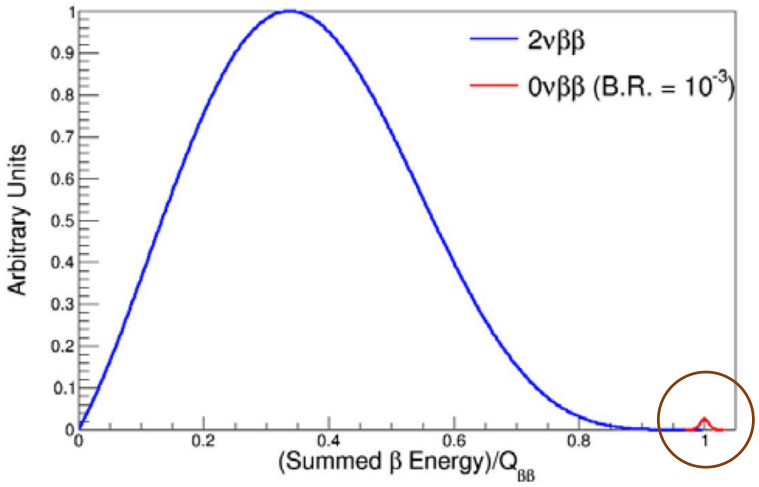
Nature of Neutrino: 0νββ-decay

Neutrino own antiparticle $\Longleftrightarrow$ 0νββ decay







Tremendous impact on BSM physics:

Lepton-number violating process

Majorana character of neutrino

Absolute neutrino mass scale

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

NME not observable: must be calculated

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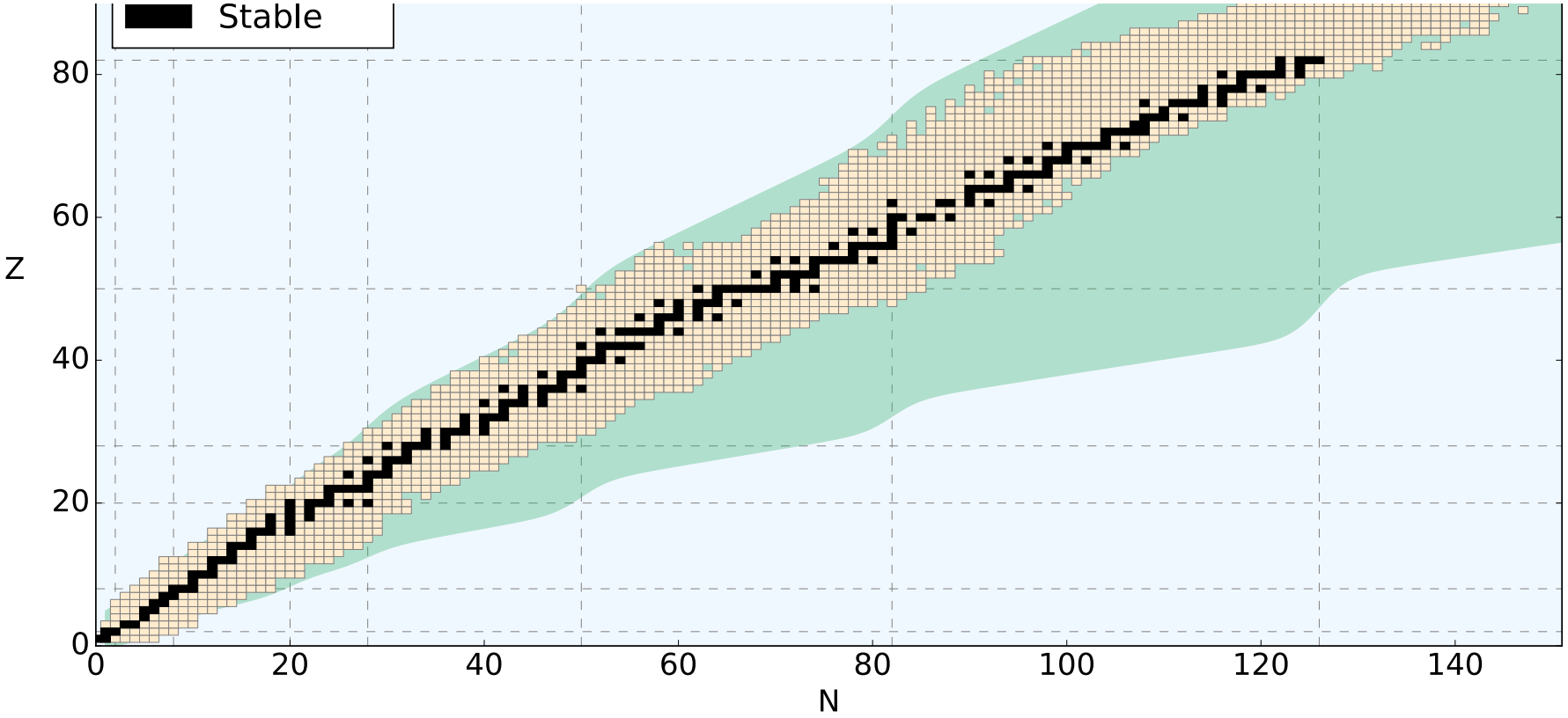
VS-IMSRG for Atomic Nuclei

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

$$H\psi_n = E_n\psi_n$$



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Obligatory Super Technical Theory Slide

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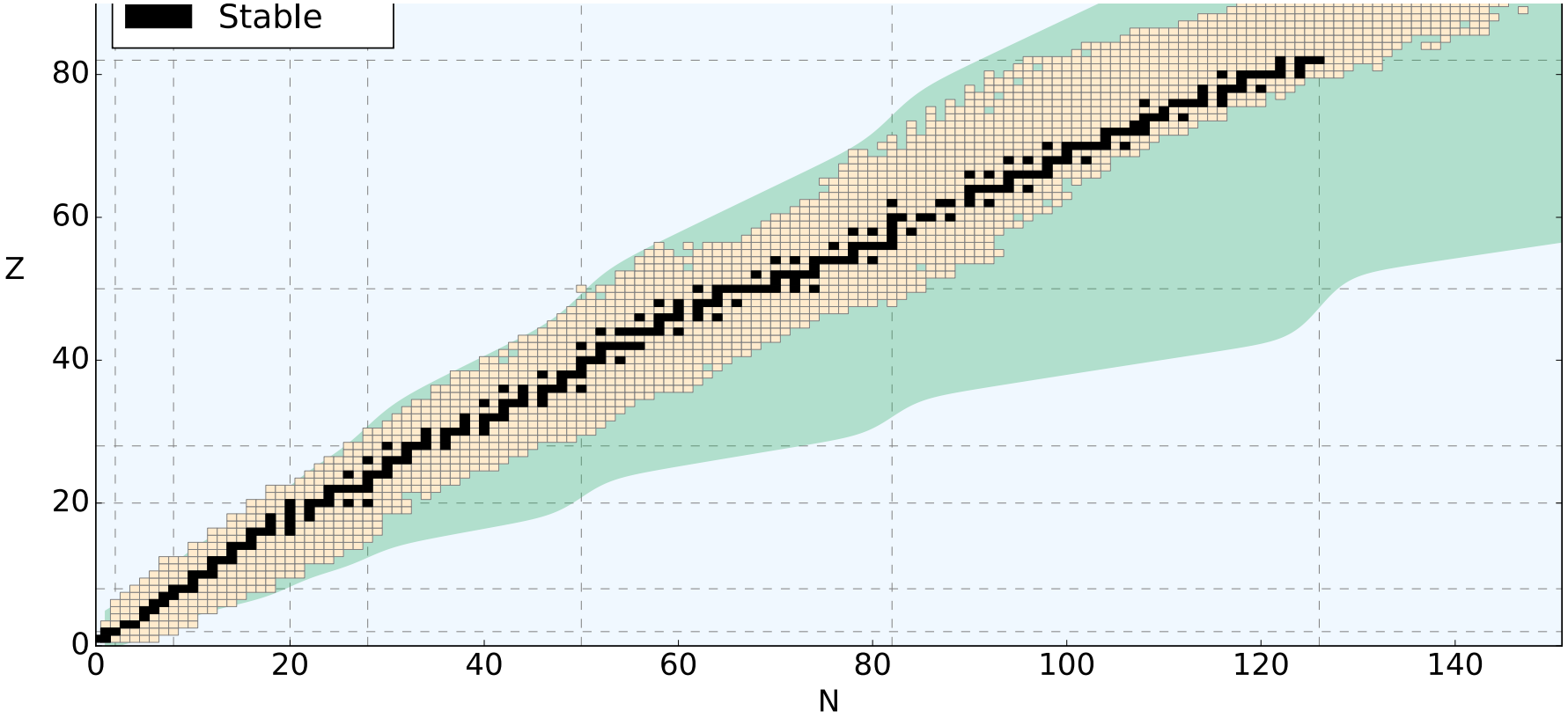

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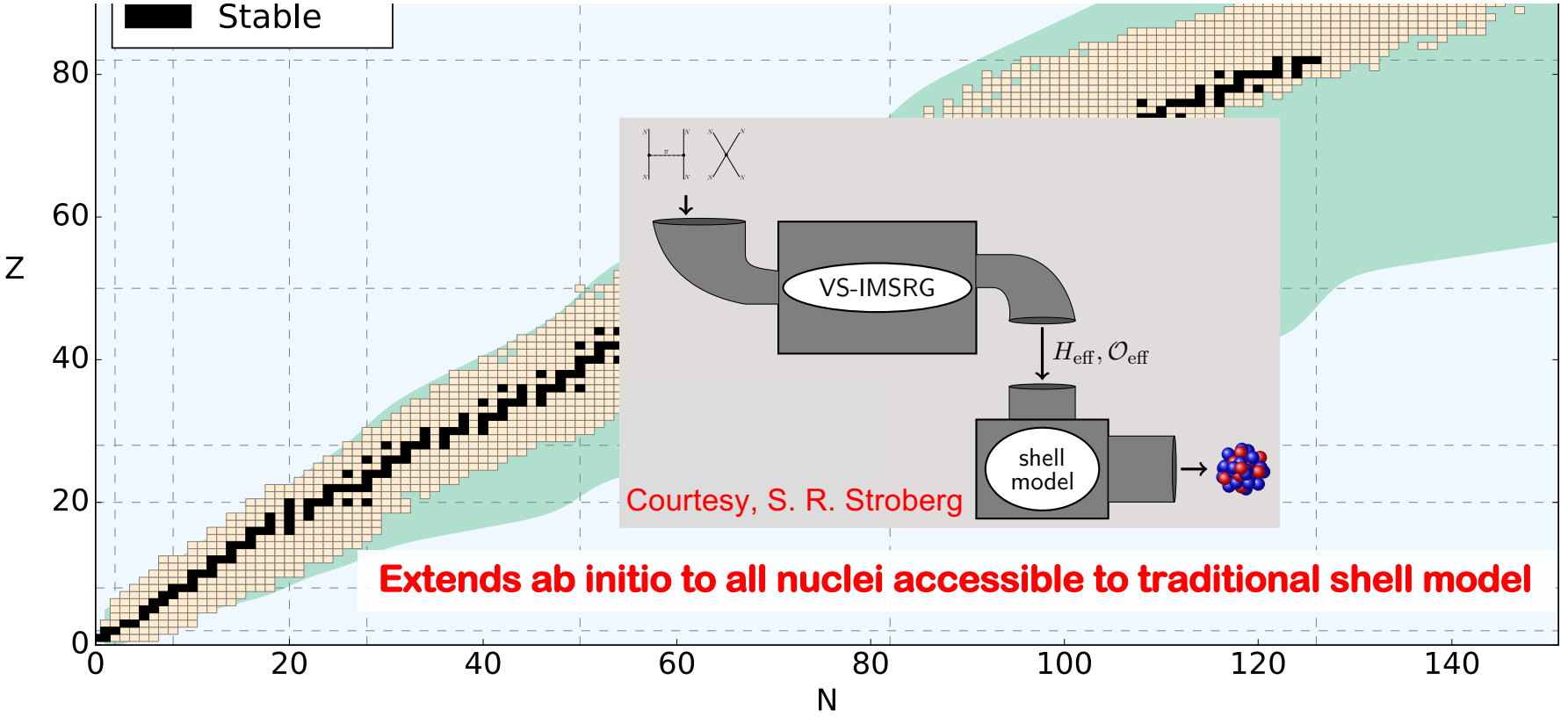

Extends ab initio to all nuclei accessible to traditional shell model

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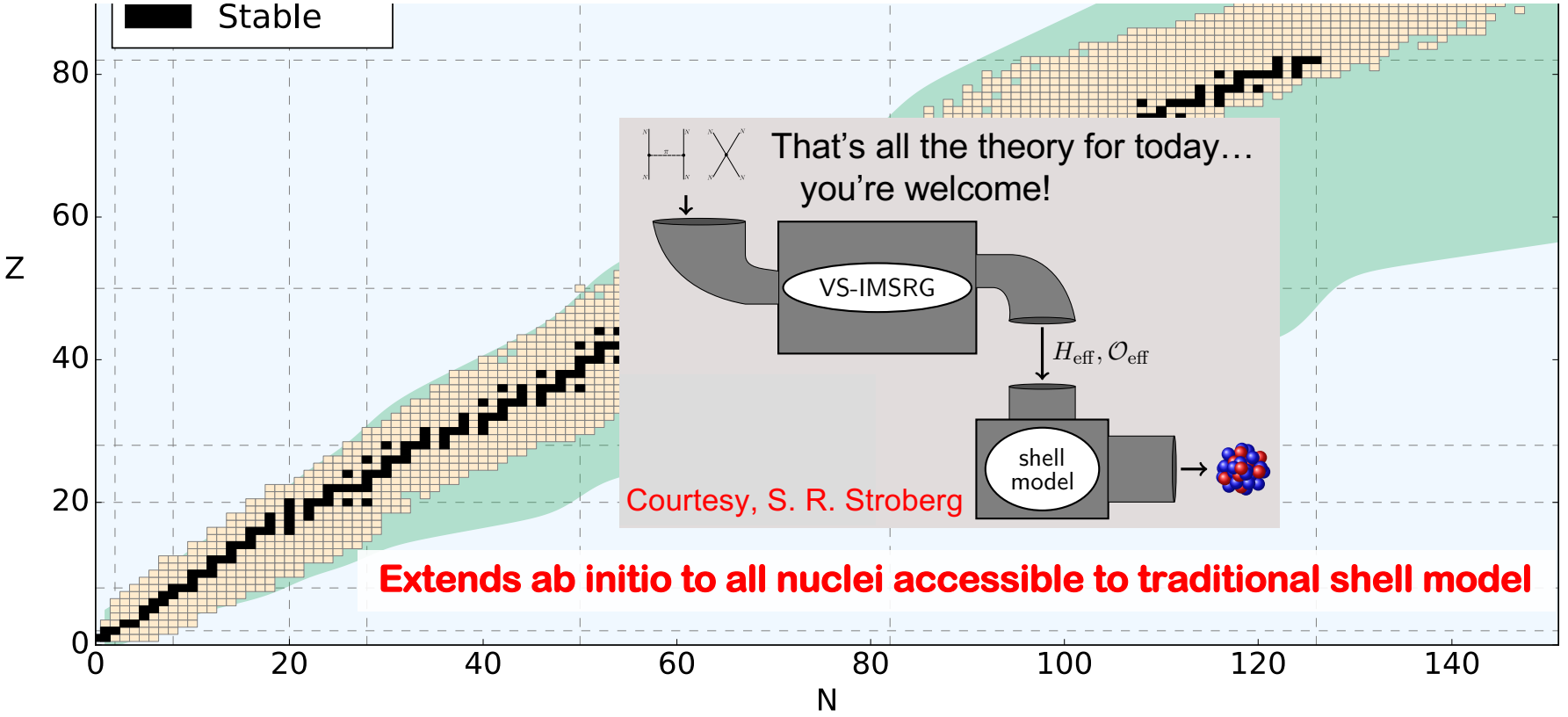

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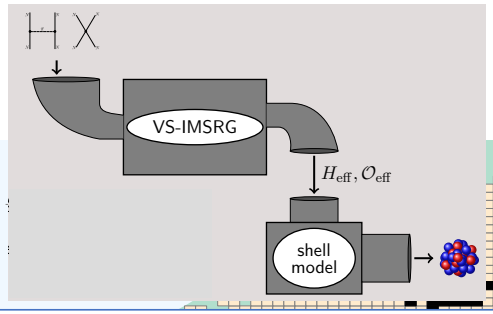

Major Nuclear Structure Questions/Developments Underway

1) How do basic properties of nuclei emerge from fundamental interactions?

2) What are the limits of existence of matter?

3) How do magic numbers evolve?

4) Accessing the heaviest nuclei and r-process region (T. Miyagi)

5) Incorporate coupling to continuum (B. Hu)

6) Cross-shell physics for Islands of Inversion (T. Miyagi)

7) Constraining properties relevant to neutron star physics (B. Hu)

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VS-IMSRG for Atomic Nuclei

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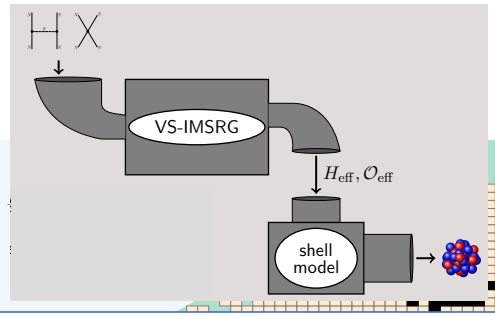

BSM Physics and Other Applications

1) Neutrinoless double beta decay (A. Belley, I. Ginnett, T. Miyagi)

2) WIMP-Nucleus scattering (M. Bruneault, J. Padua, B. Hu)

3) Superallowed Fermi transitions (E. Love, M. Martin)

4) Symmetry-violating moments (EDM, anapole) (T. Miyagi)

5) Atomic systems (G. Tenkila, H. Patel, T. Miyagi)

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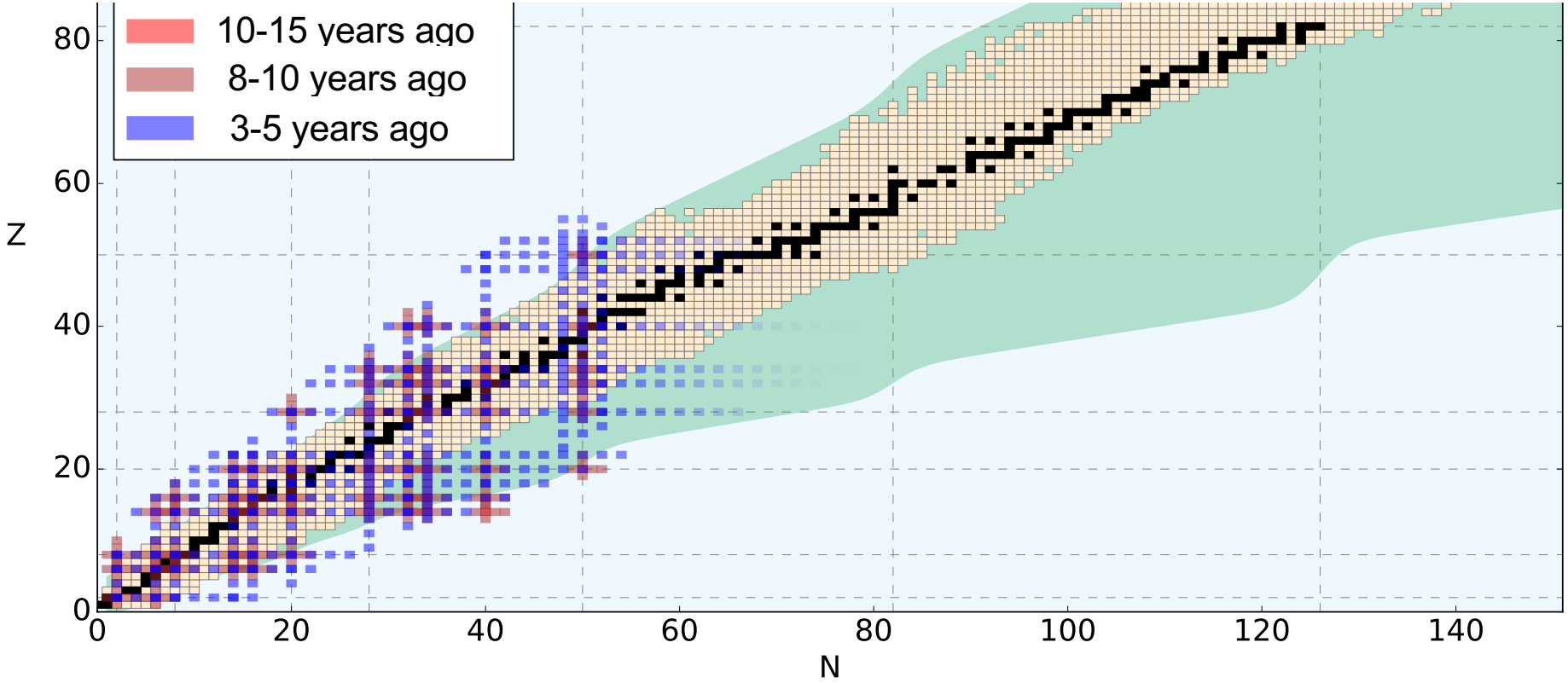
Breadth of Ab Initio Theory

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

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

$$H\psi_n = E_n\psi_n$$



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Towards Global Ab Initio Calculations

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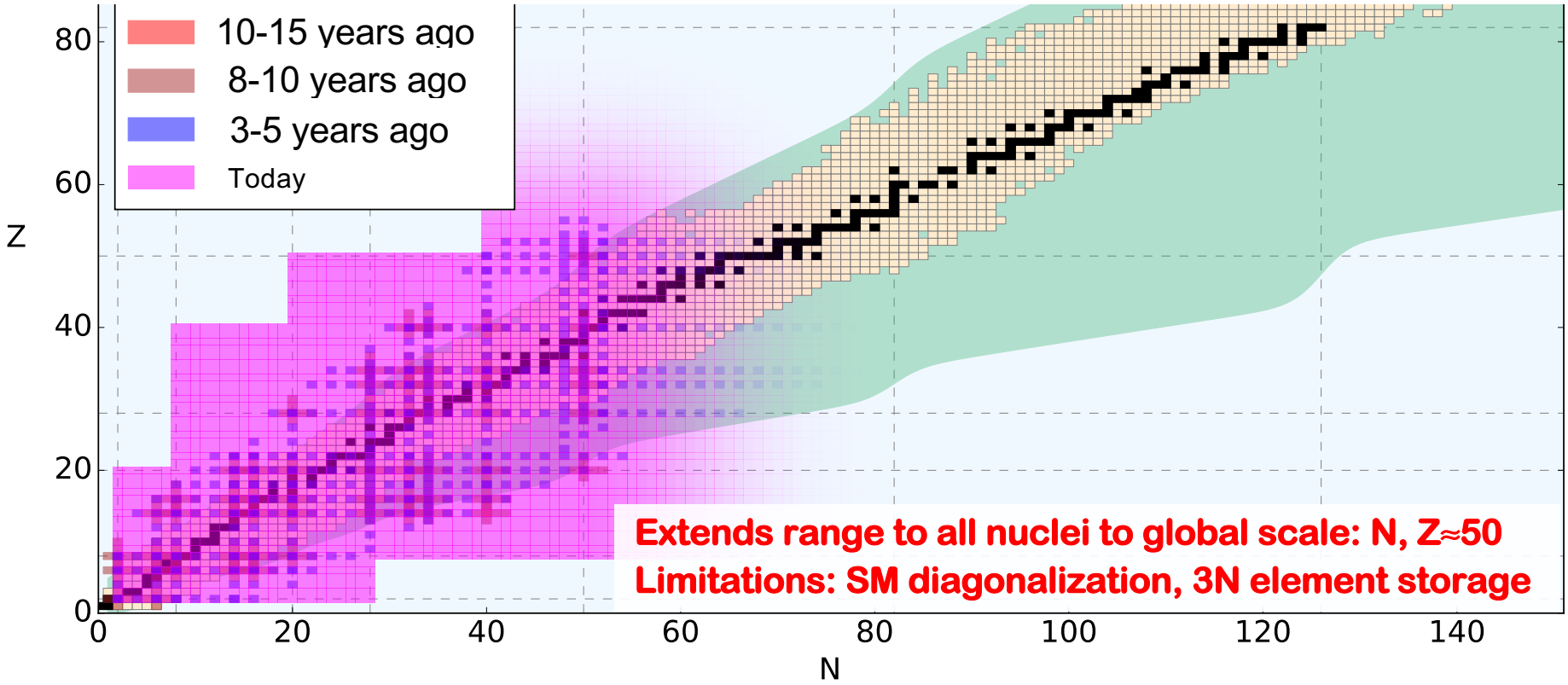

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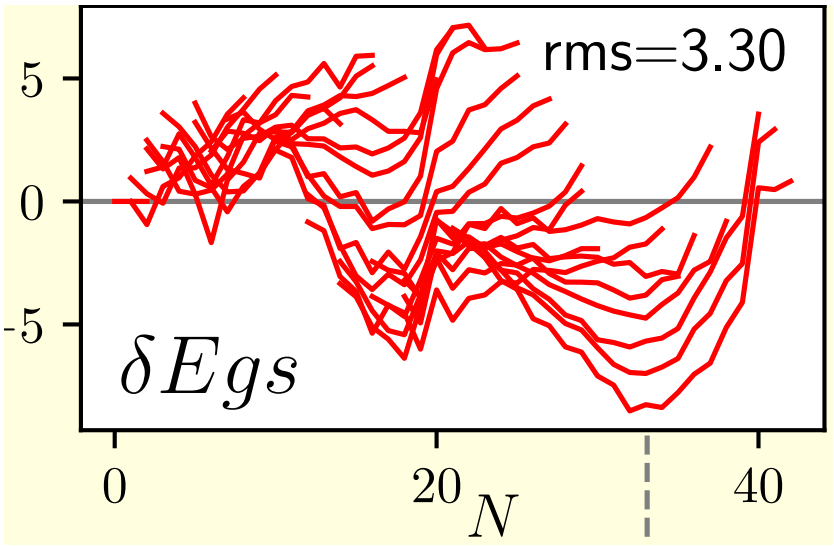
Global Ground-State Energy Residuals

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

Stroberg et al., PRL (2021)

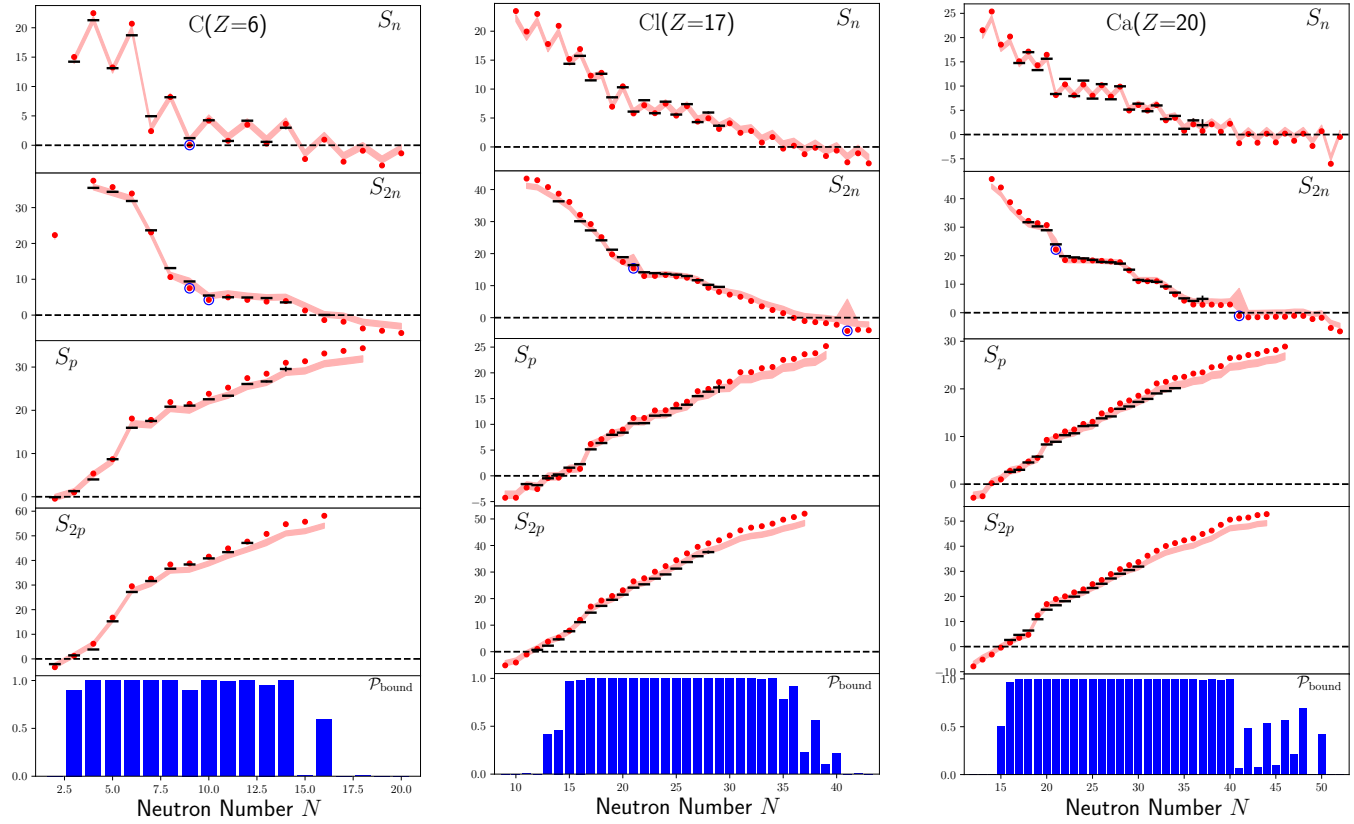
rms deviation at level of BW Mass formula, approaching EDF models

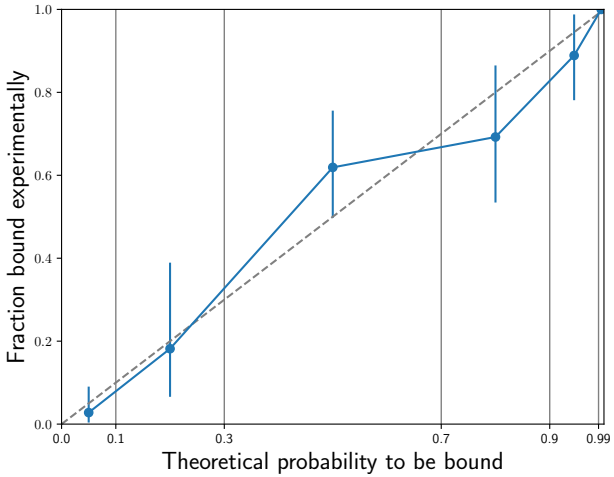
Input Hamiltonians fit to A=2,3,4 – not biased towards known data

What is deviation for separation energies? **Apply to proton/neutron driplines**

Estimating Dripline Uncertainites

Determine rms deviation from experiment – extrapolate this uncertainty beyond data



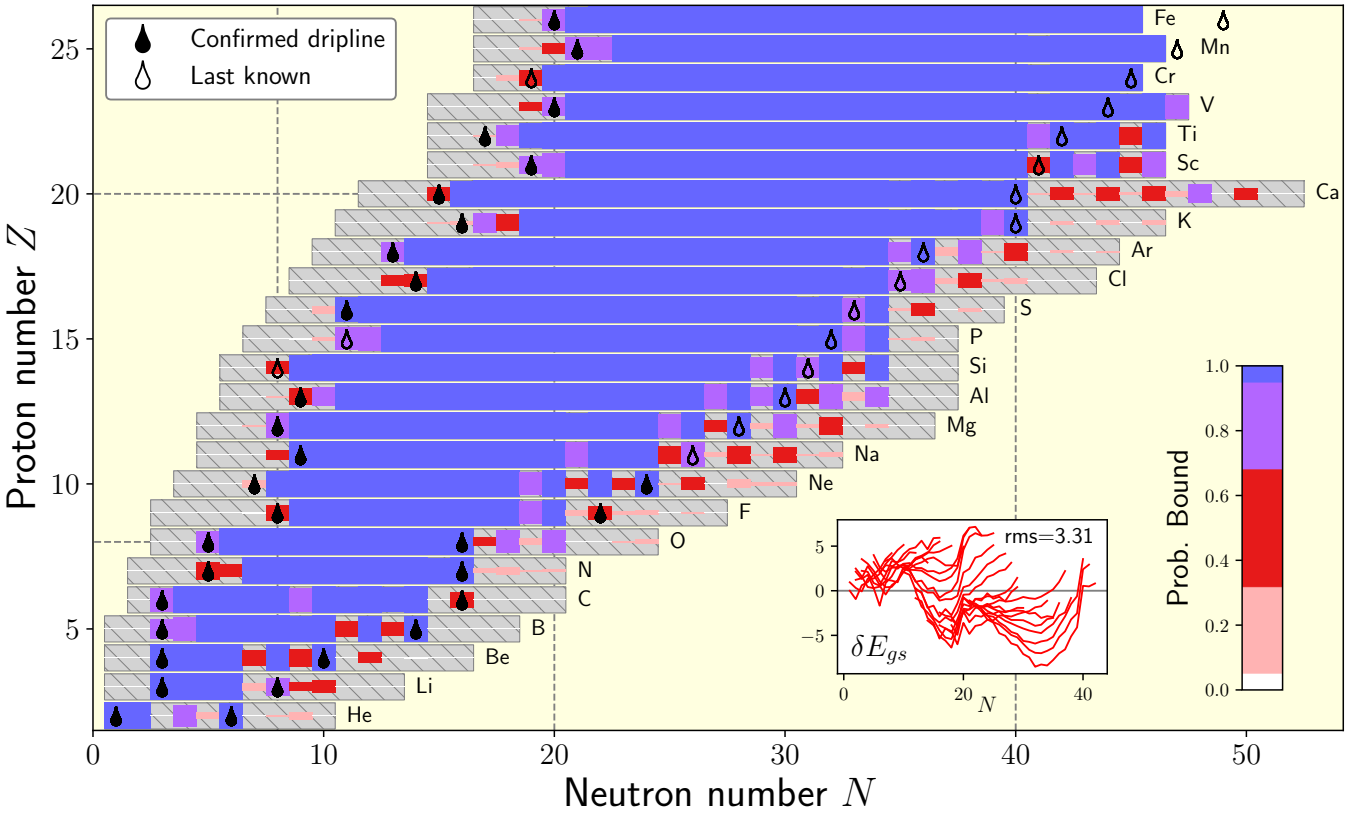


Determine range of likely separation energies reaching 0 Stroberg et al. PRL (2021)

Assign probability that a particular nucleus is bound

Dripline Predictions to Fe Isotopes

First predictions of proton and neutron driplines from first principles



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

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

Stroberg et al. PRL (2021)

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

Provide ab initio predictions for neutron-rich region

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Towards Neutrinoless Double Beta Decay

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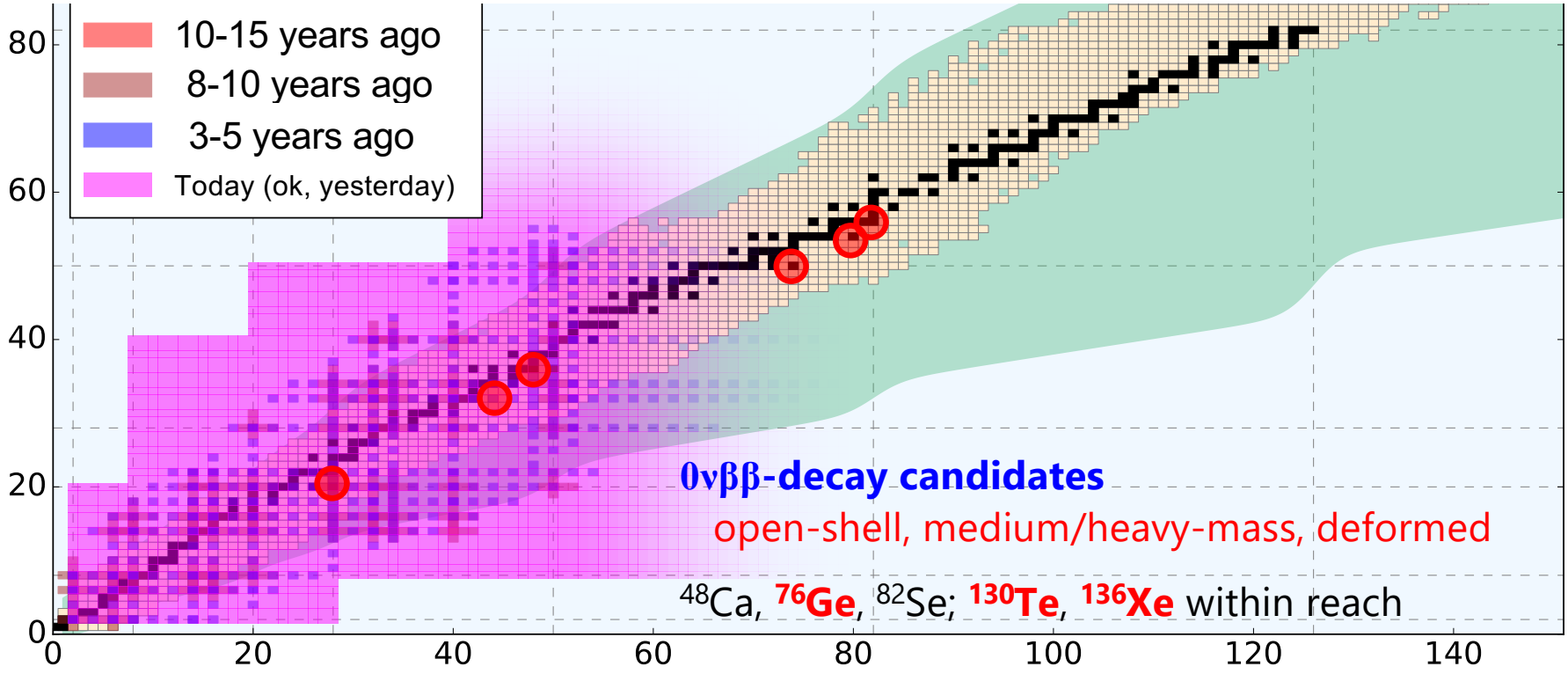

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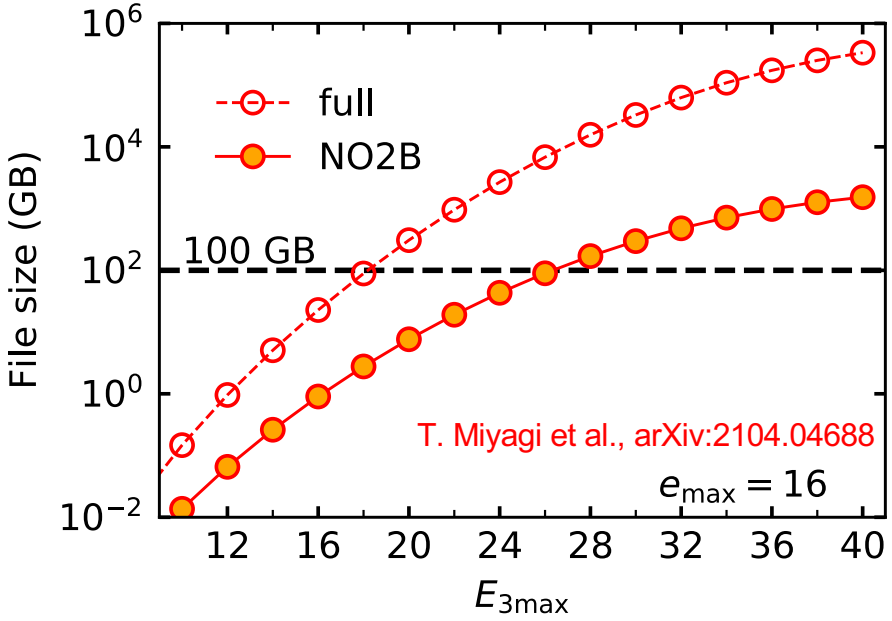
Towards Heavy Nuclei: ^{132}Sn

Improvements in (clever) storage of 3N MEs *greatly* expands reach of ab initio theory!

Previous limit E_{3max}=16/18



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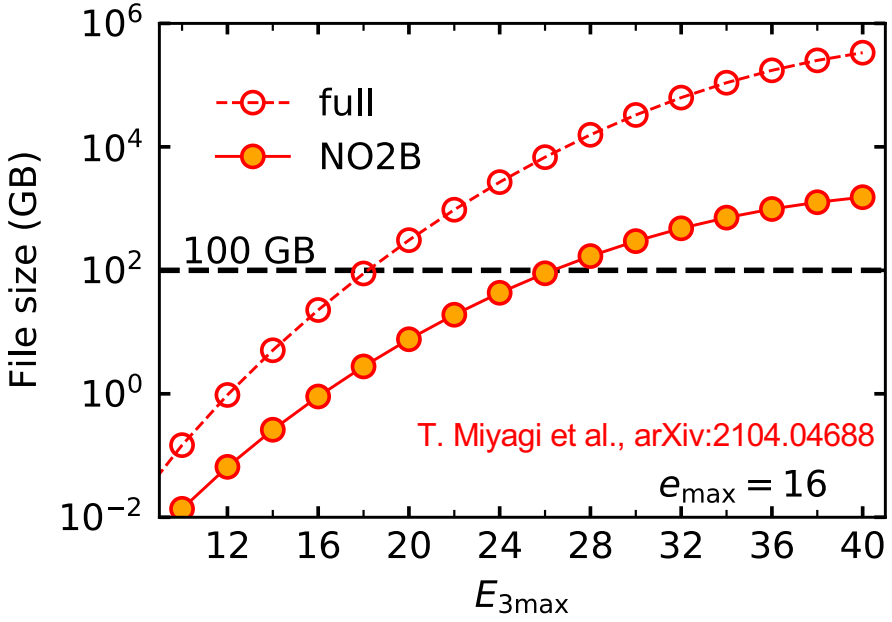
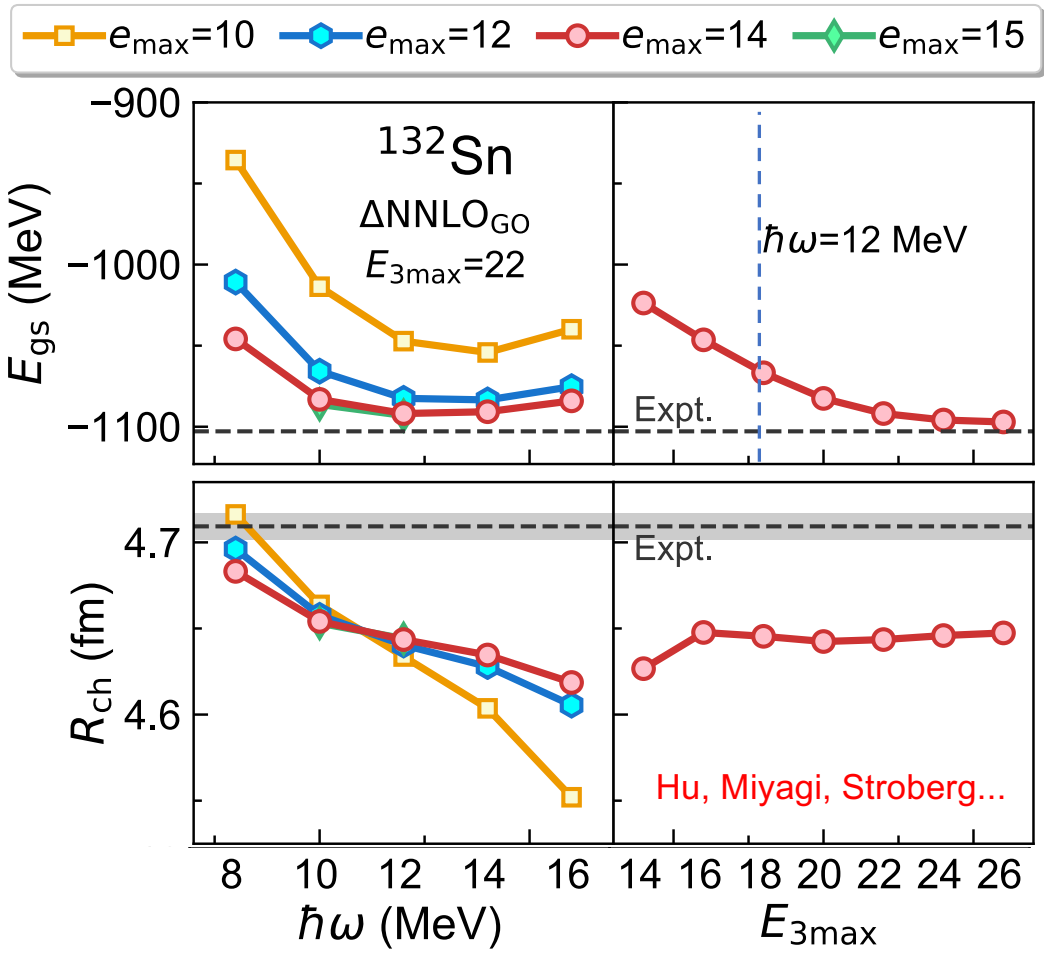


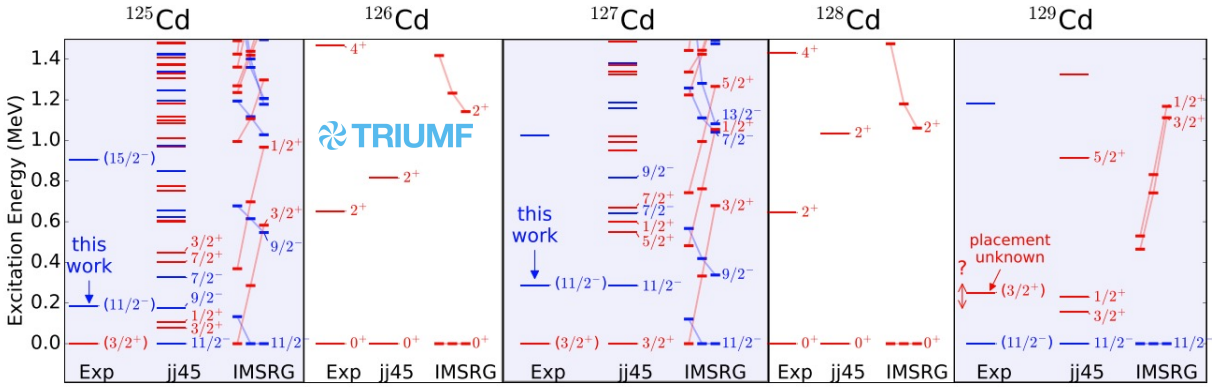


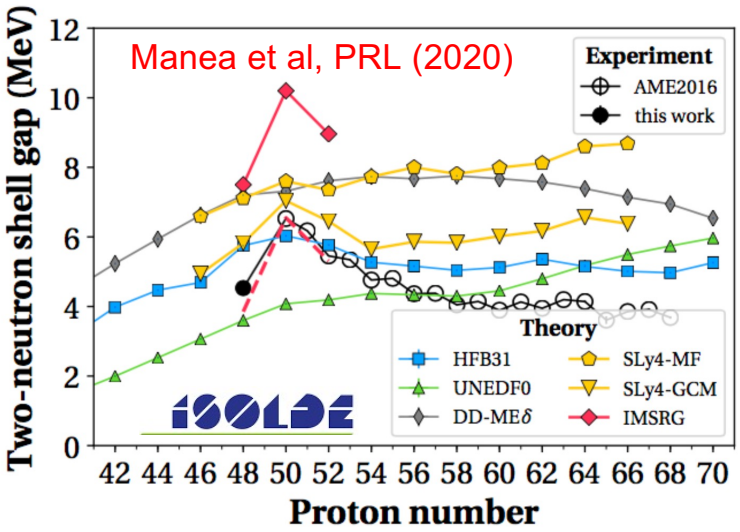
First converged calculations of ^{132}Sn

Opens heavy region to ab initio theory!

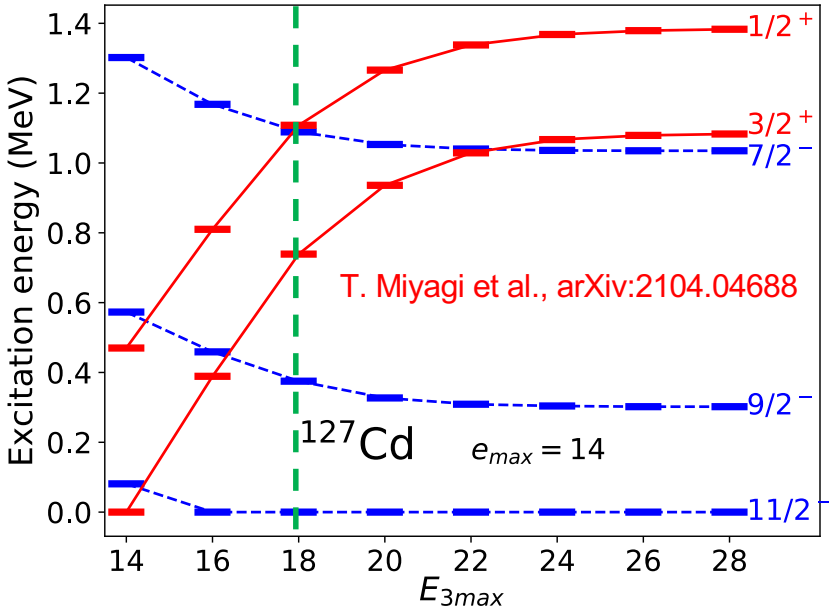
Convergence of N=82 Gap

Size of N=70 gap not converged at E_{3max}=18: for neutron-rich Sn, In, Cd…





Lascar et al PRC (2017)



Resorted to unreliable extrapolations…

New capabilities: converged spectra in N=82 region

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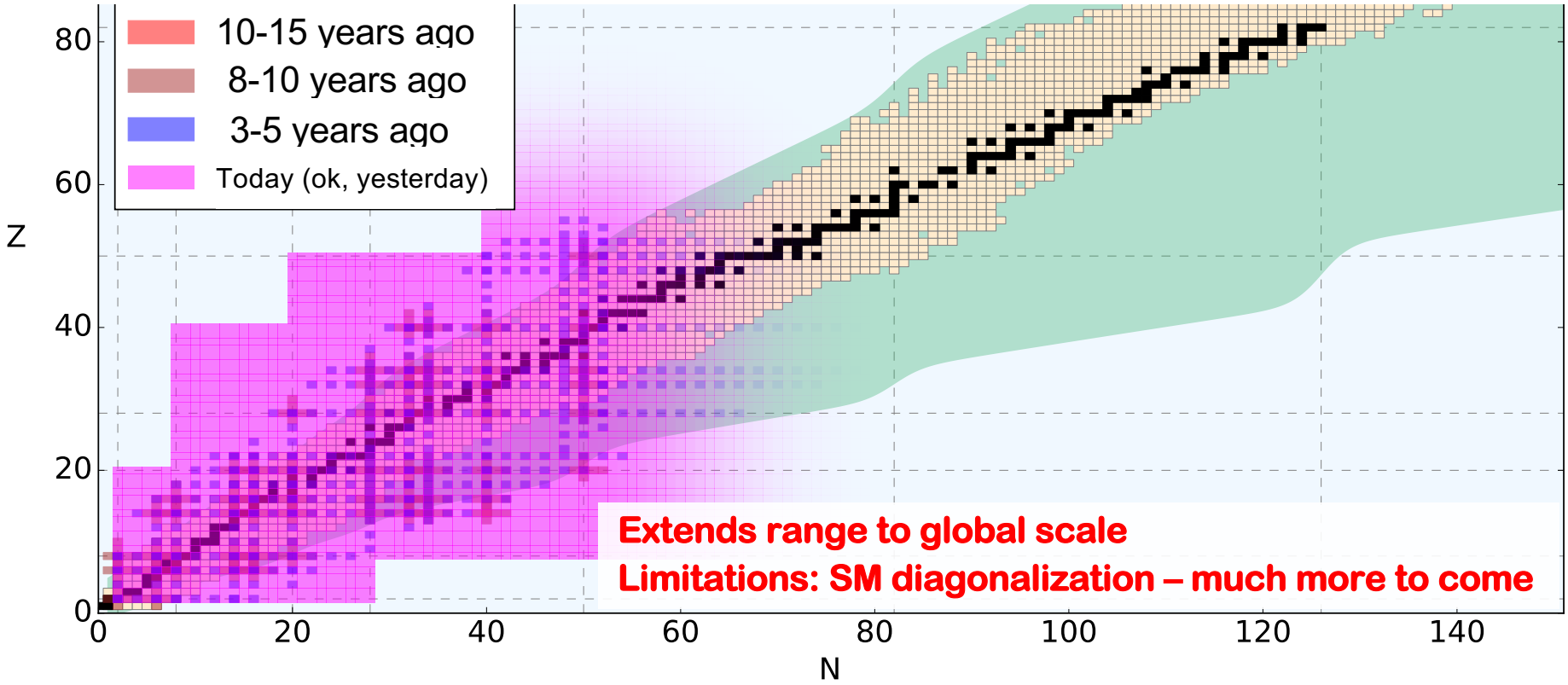

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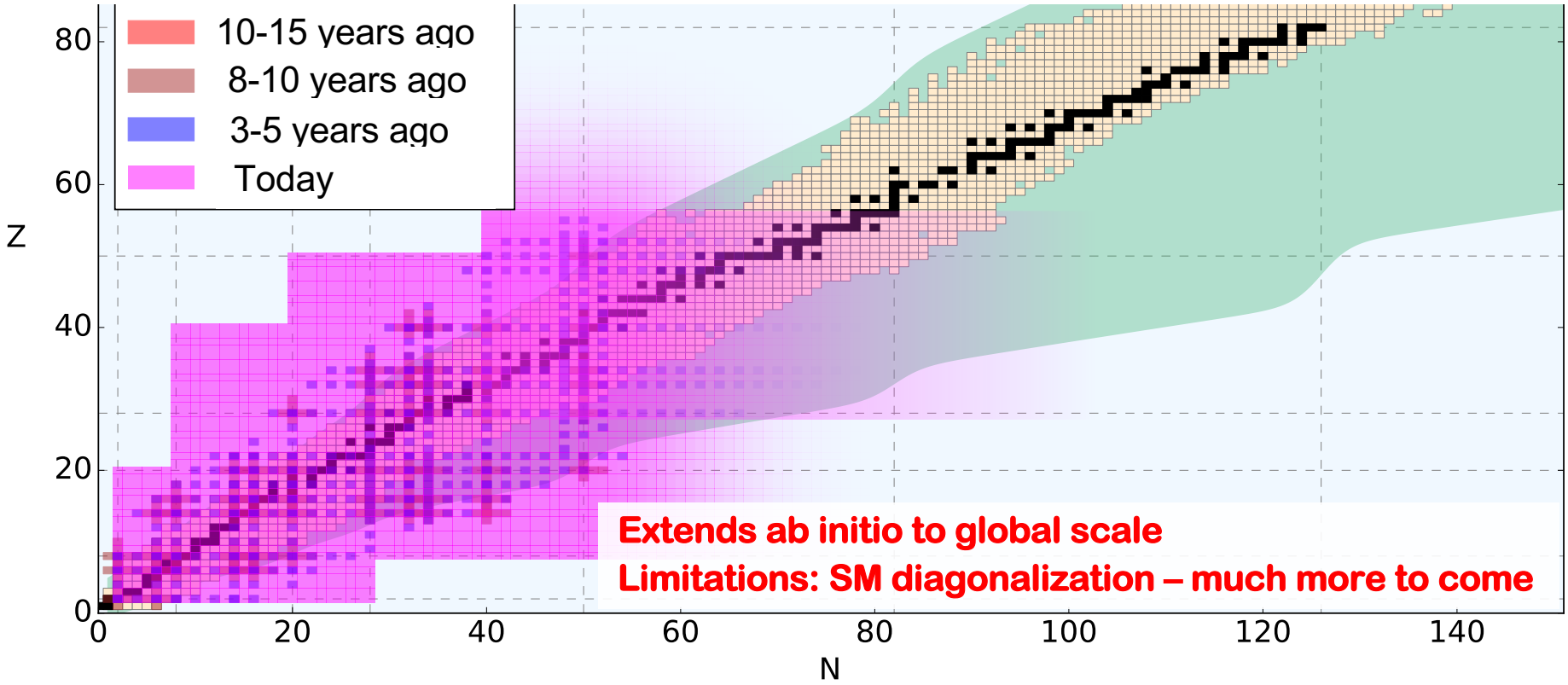

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One more thing… Can we go heavier?

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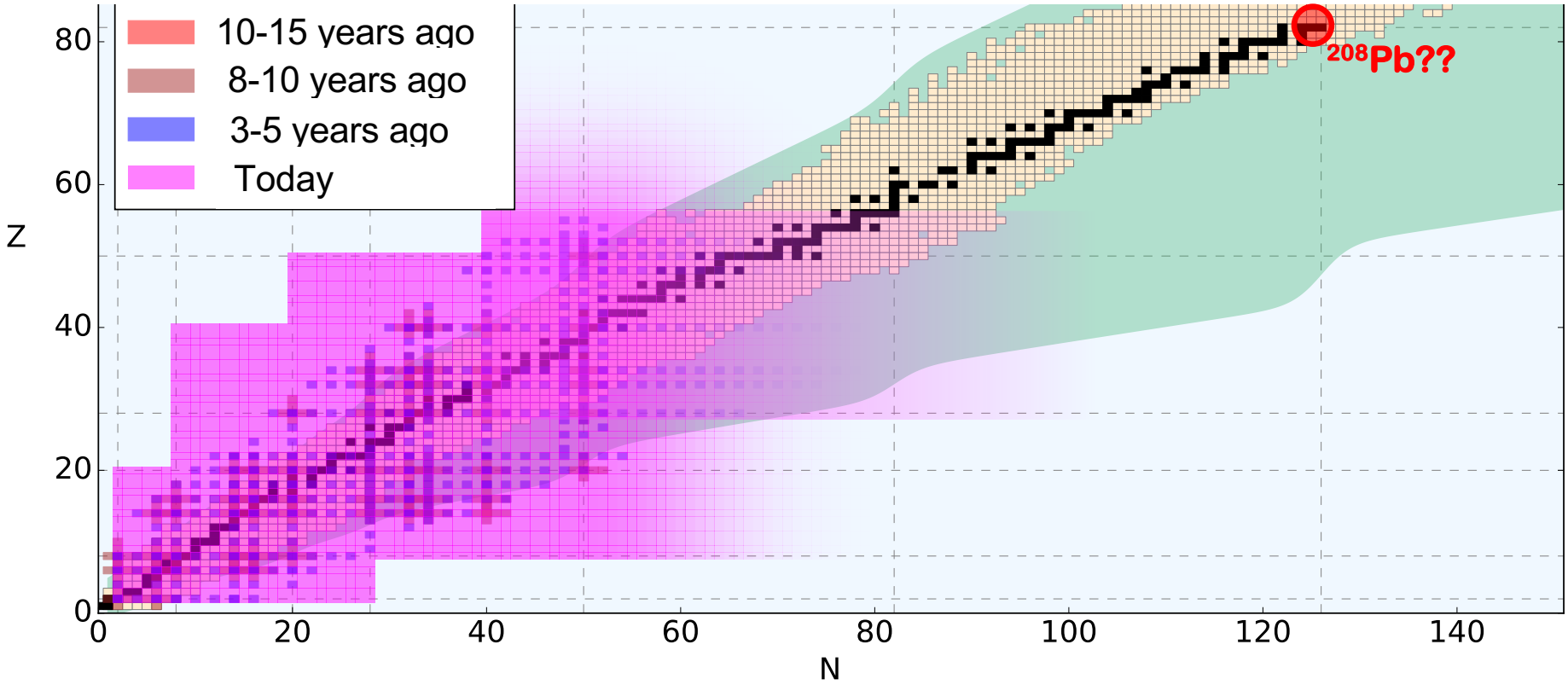

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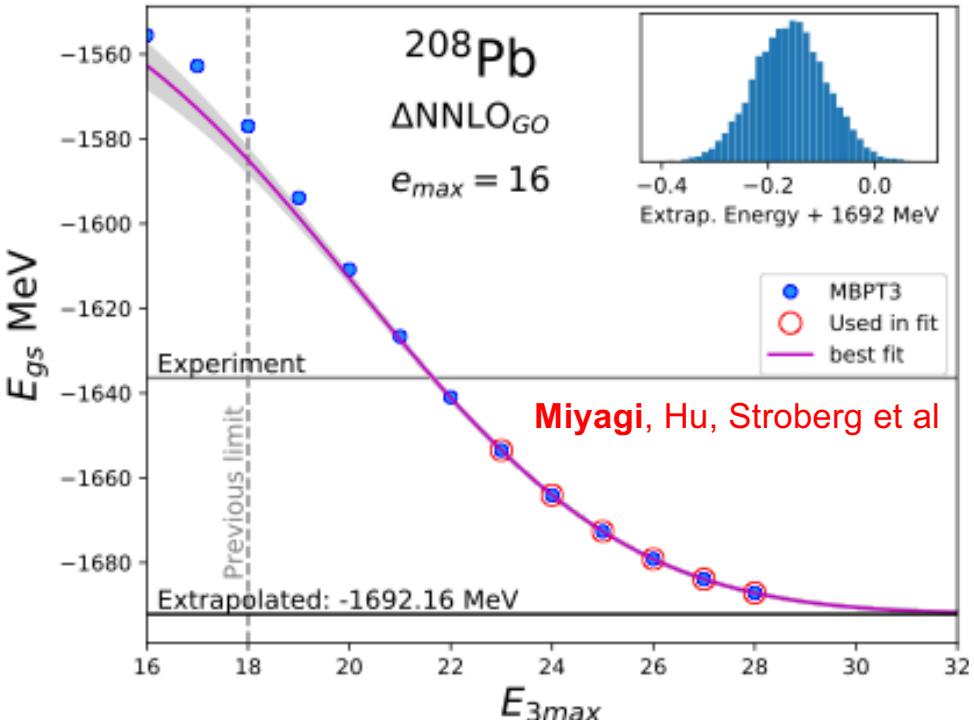
Can We Ever Compute ^{208}Pb?

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

Increased E_{3max} range allows first reliable convergence of ^{208}Pb



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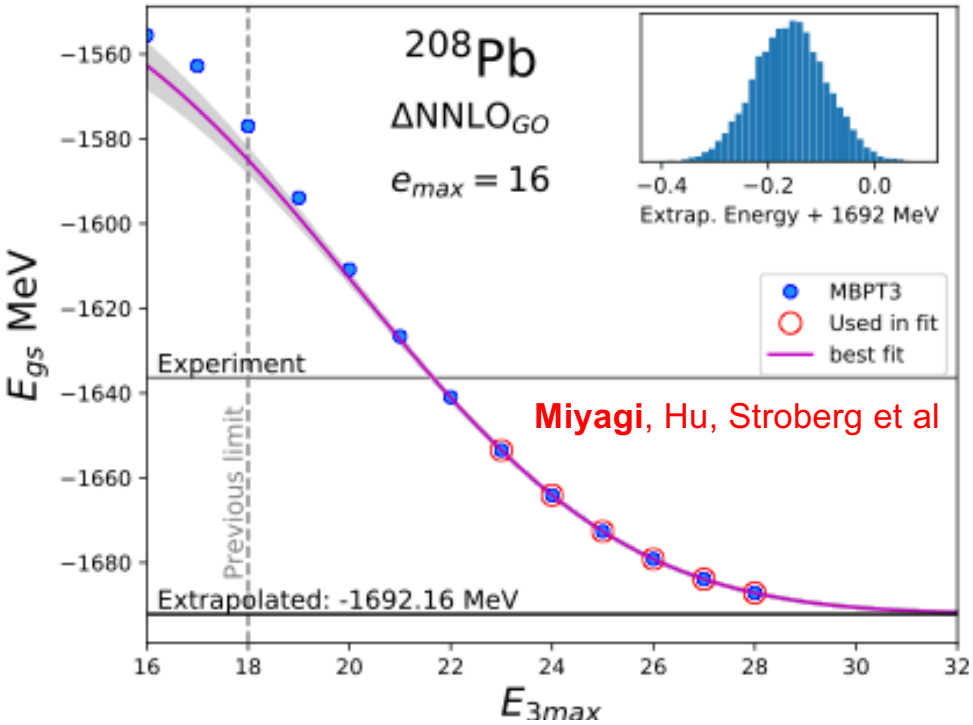

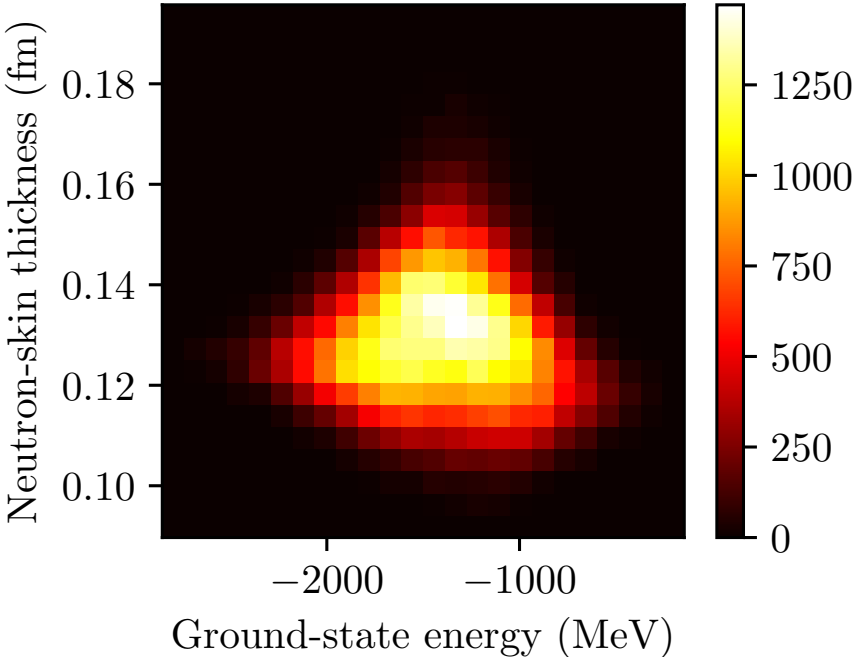

Machine learning: sample "all" chiral interactions - 10^8 ^{208}Pb calculations in progress

Heat map of neutron skin/ground state energy - constraints on equation of state and neutron stars

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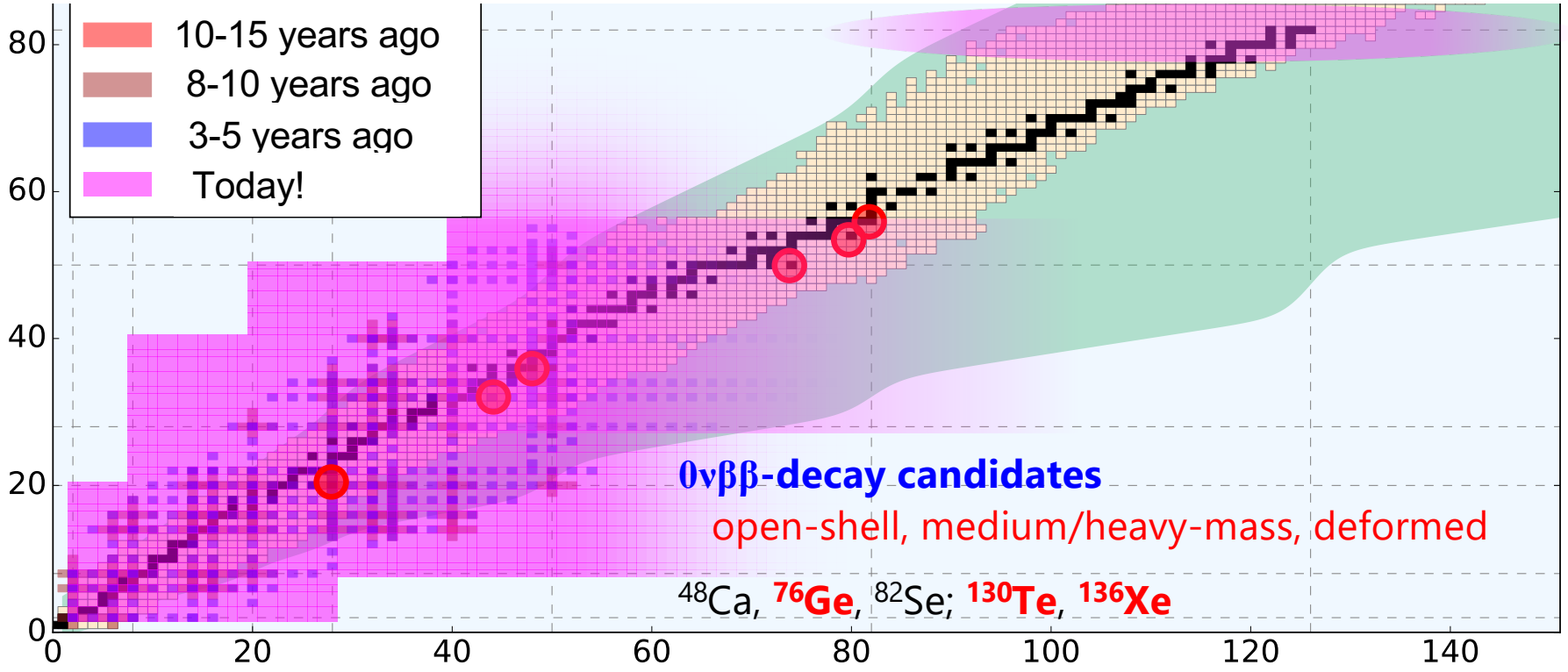

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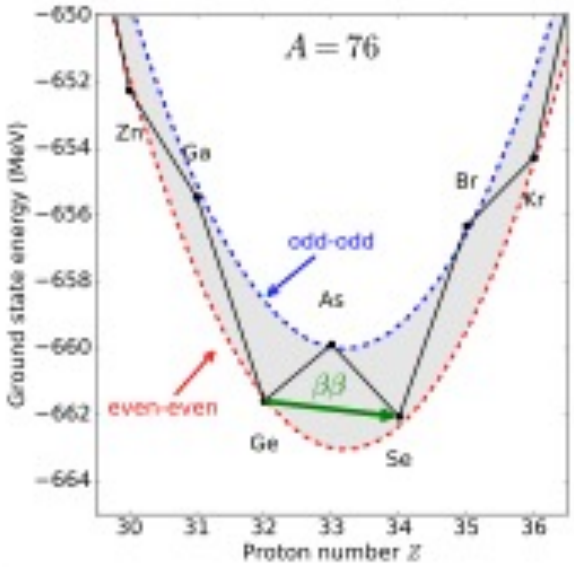
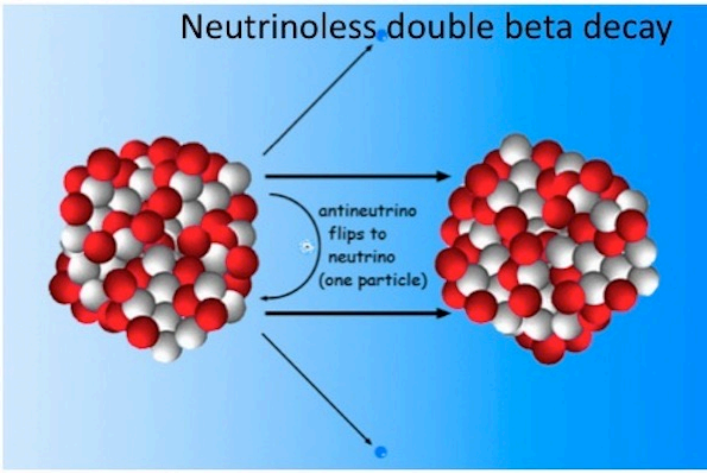
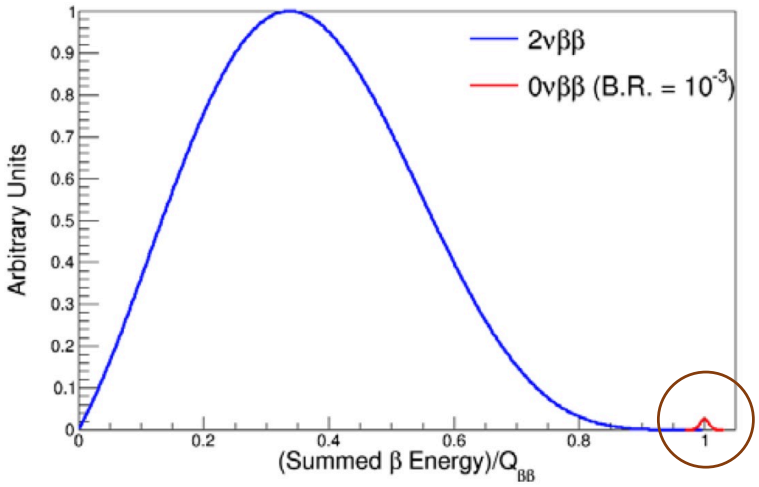
0νββ-decay

Neutrino own antiparticle $\Longleftrightarrow$ 0νββ decay







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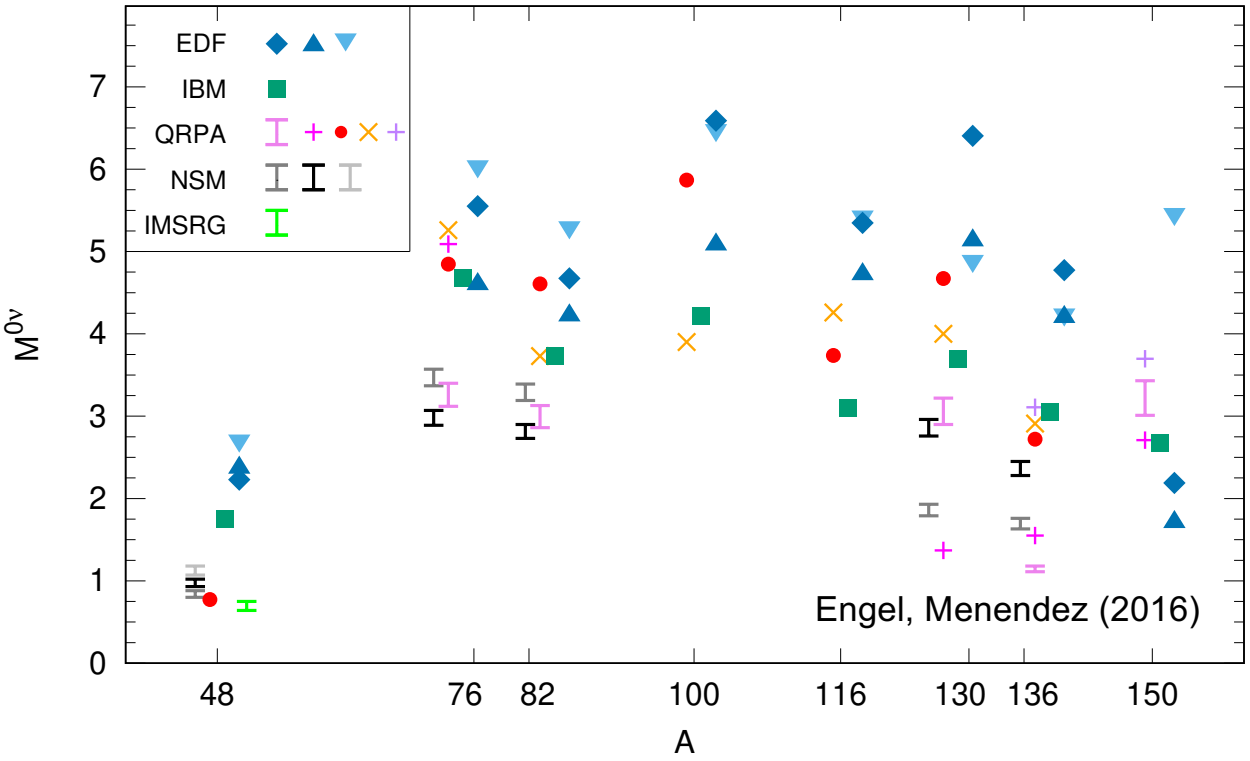
Status of 0νββ-decay Matrix Elements

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



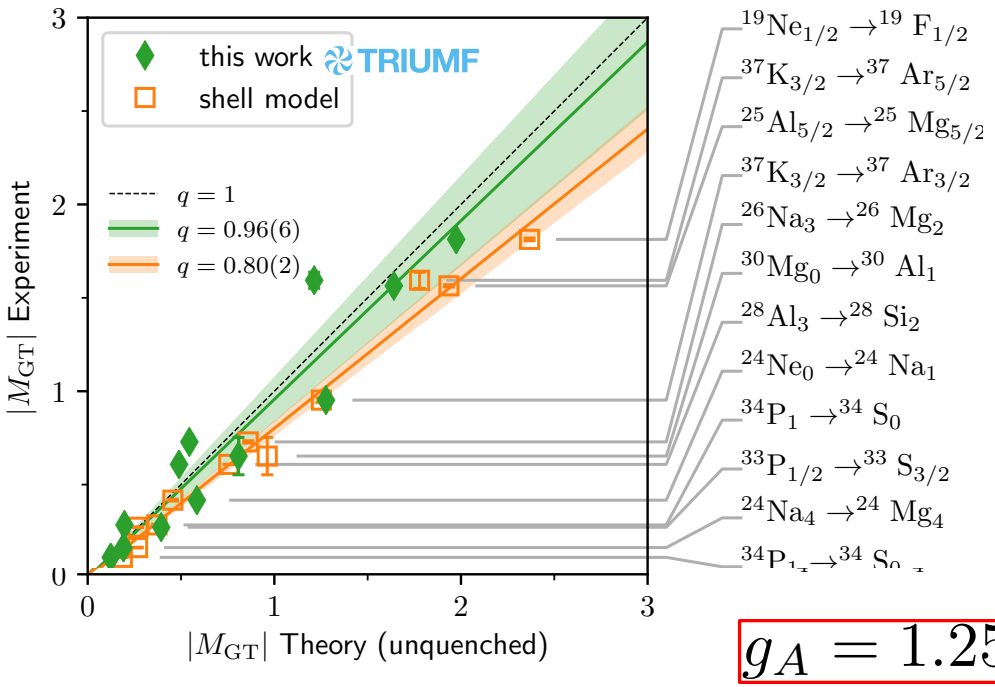
All models missing essential physics

Impossible to assign rigorous uncertainties

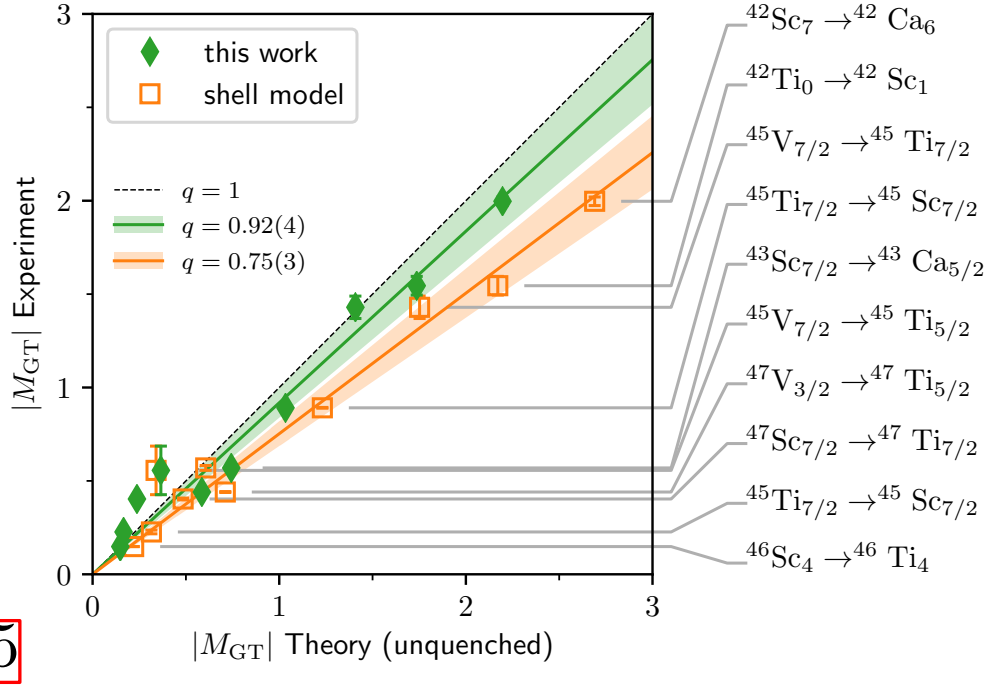
Ab Initio GT Decays in Medium-Mass Region

Comparison to standard phenomenological shell model

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



$g_A = 1.25$

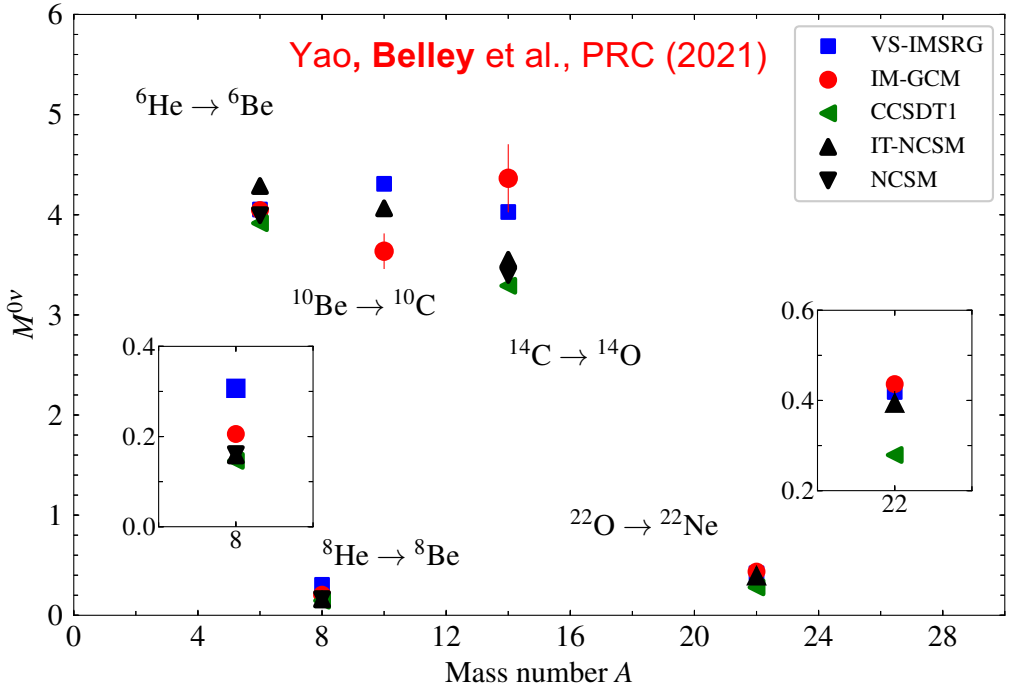


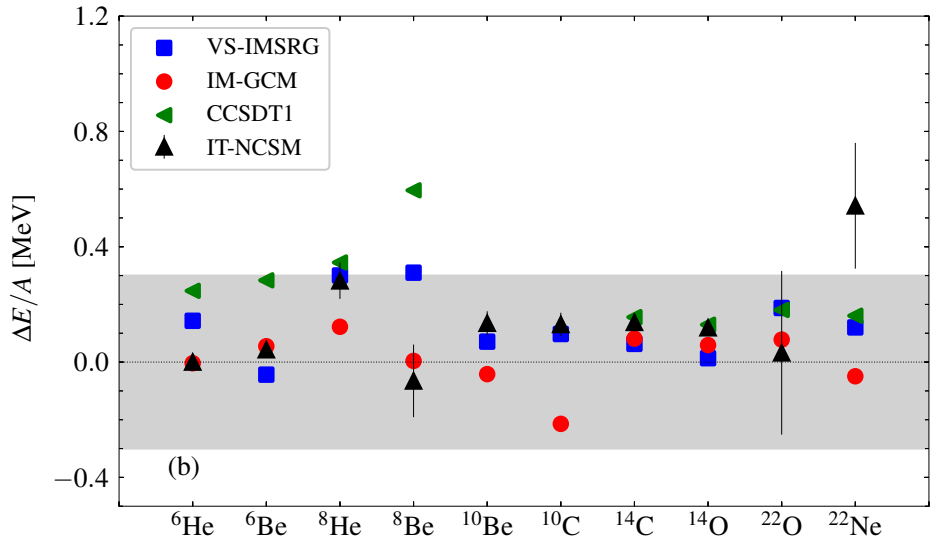
Gysbers et al., Nature Phys. (2019)

Refine results with improvements in forces and many-body methods

Benchmarking $0\nu\beta\beta$ Decay in Light Nuclei: Summary

Benchmark with quasi-exact NCSM, IT-NCSM, IM-GCM, and CC in light systems: A=6-22





Reasonable to good agreement in all cases! Pursue true double-beta decay nuclei

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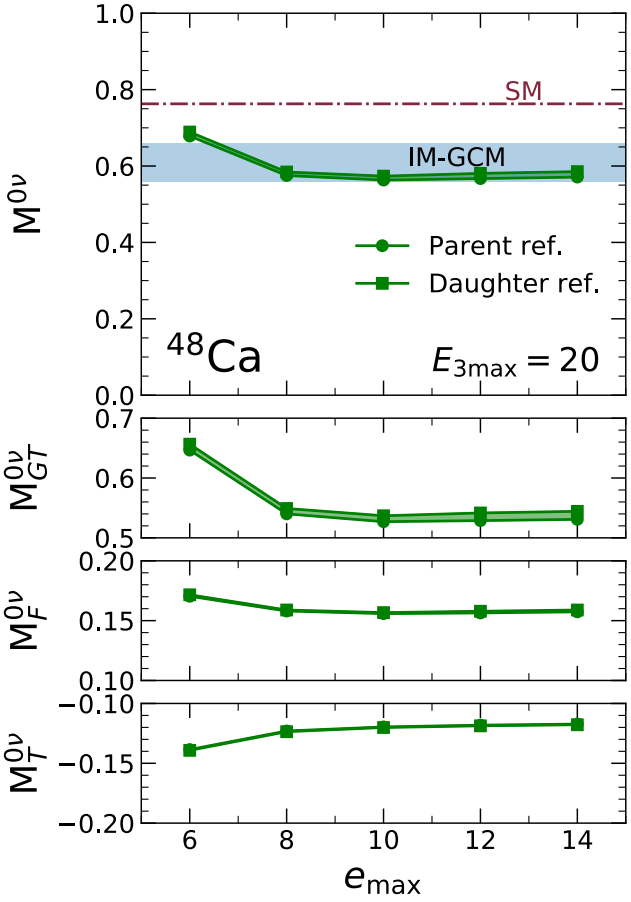
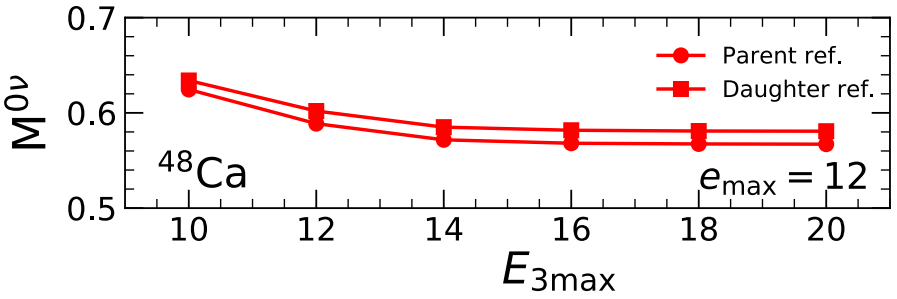
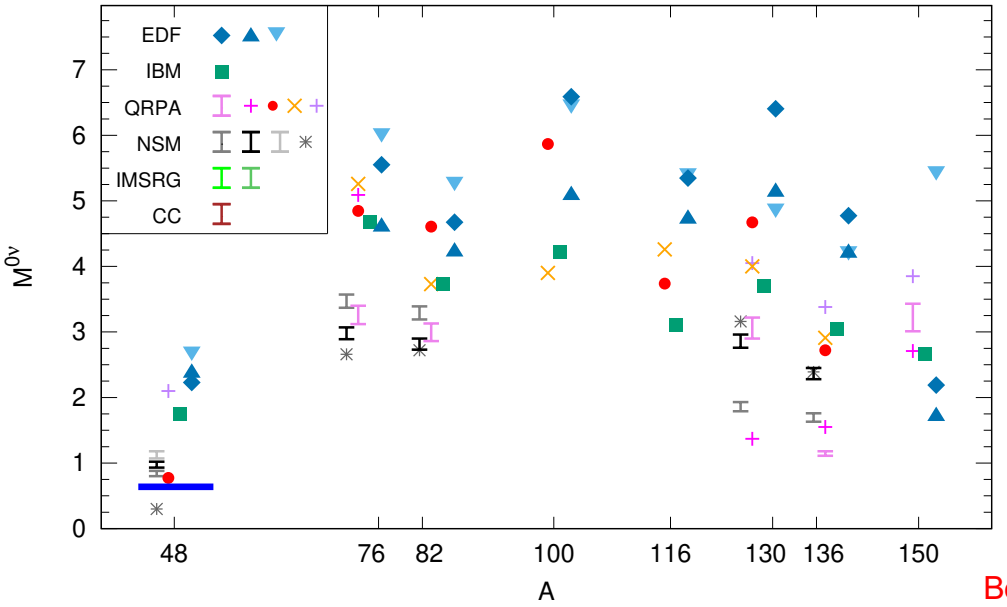
Ab Initio 0νββ Decay: ^{48}Ca

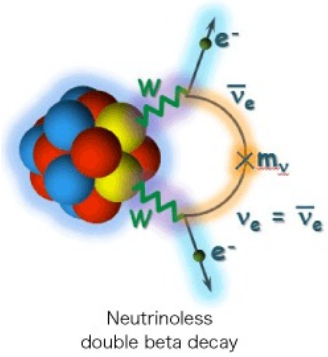
Ab initio: consistent many-body wfs/operators from chiral NN+3N forces (**no 2b currents**)

Small uncertainty from NO reference indicated; well converged in e_{max}, E_{3max}







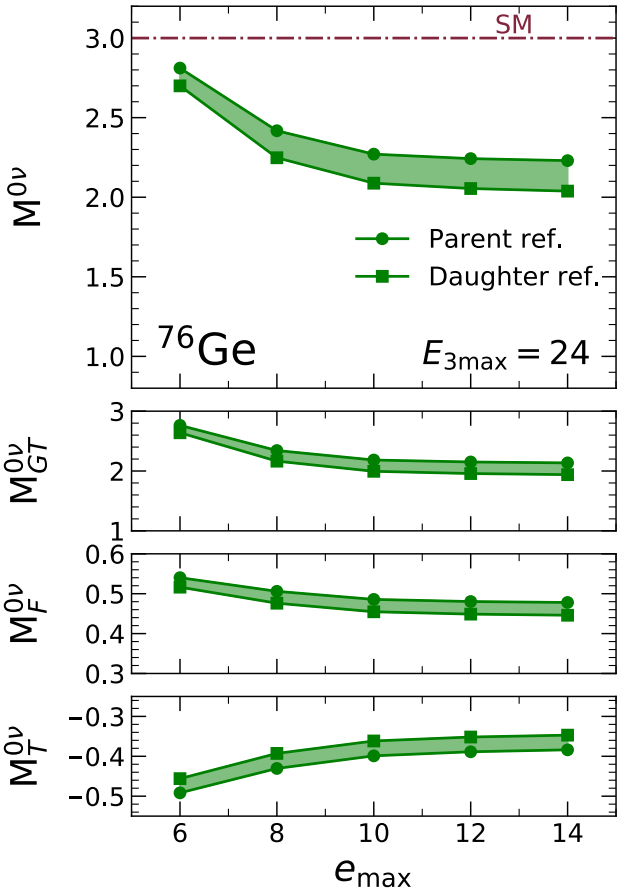


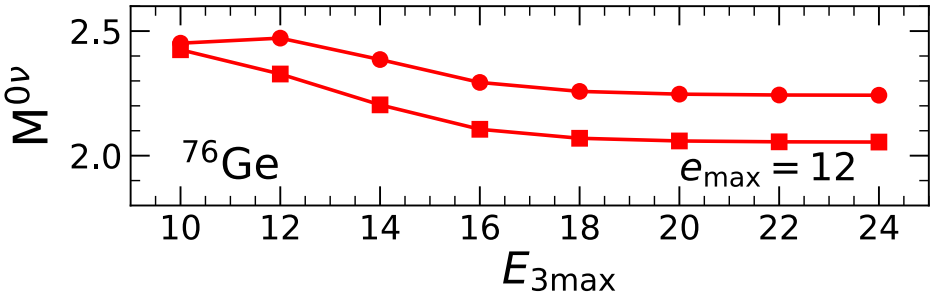
Belley et al., PRL (2021)

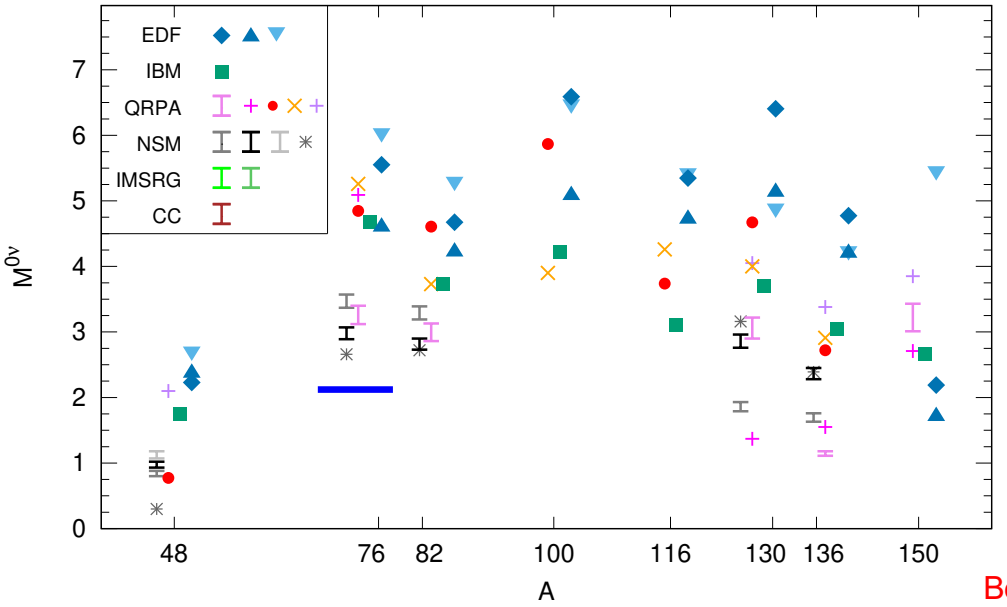
Ab Initio 0νββ Decay: ^{76}Ge

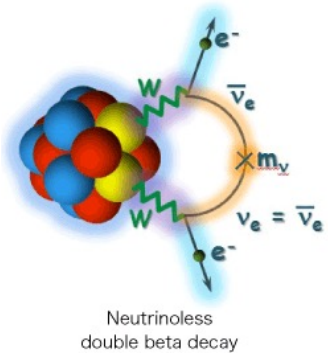
Key nucleus in worldwide searches

NME smaller than all previous calculations…









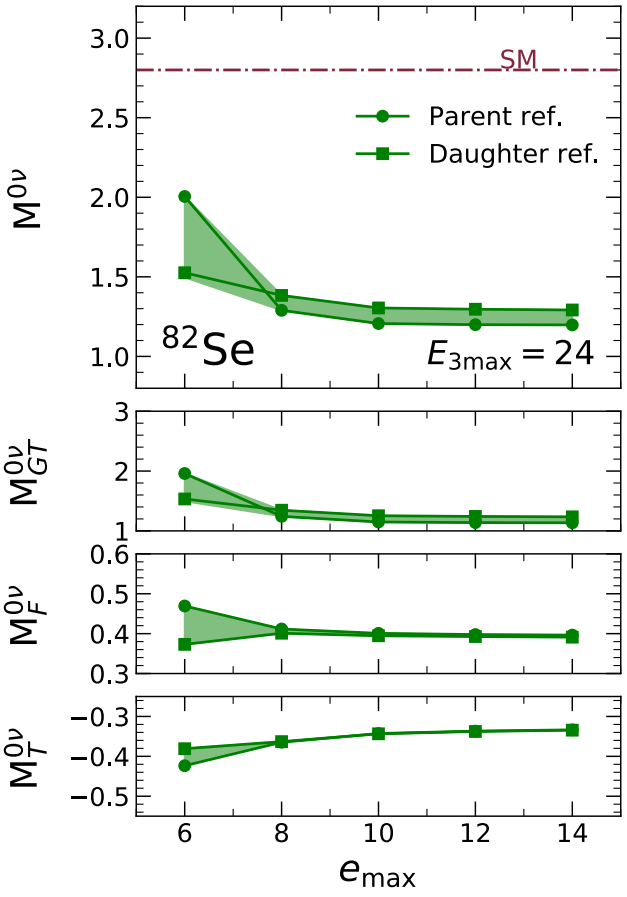
Belley et al., PRL (2021)

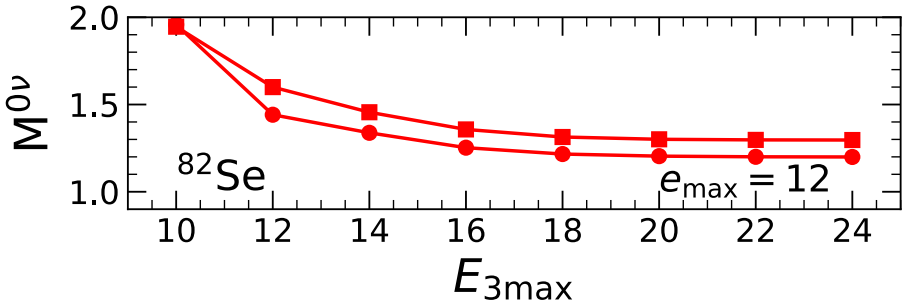
TRIUMF

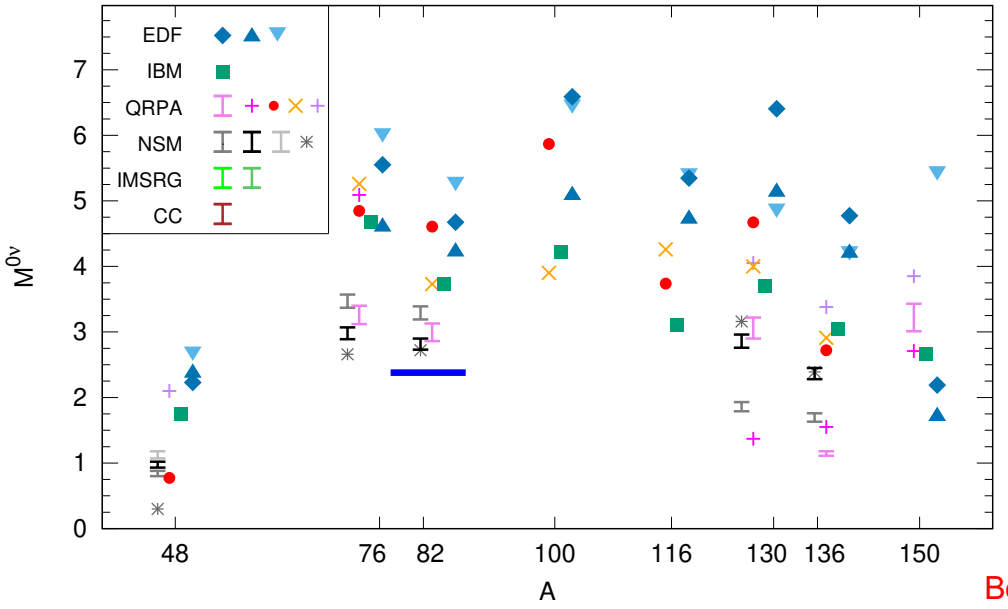
Ab Initio 0νββ Decay: ^{82}Se

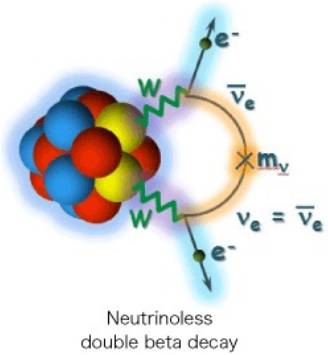
Ab initio: consistent many-body wfs/operators from chiral NN+3N forces (**no 2b currents**)

Small uncertainty from NO reference indicated; well converged in e_{max}, E_{3max}







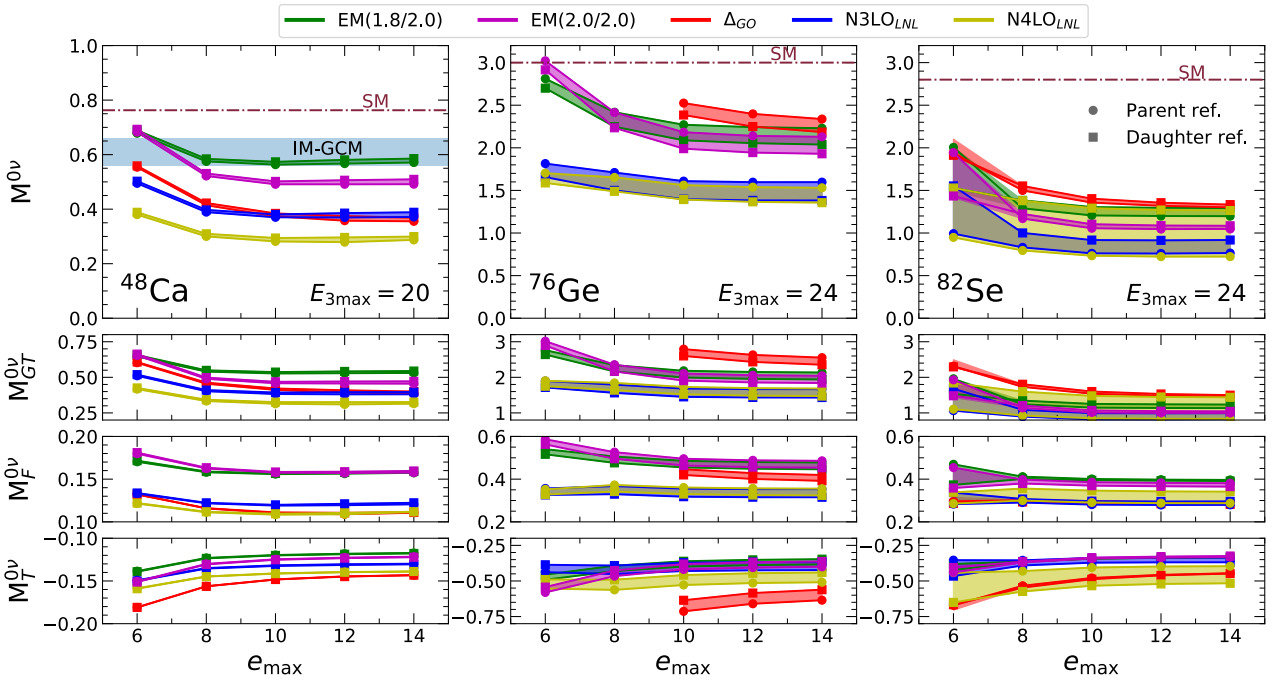


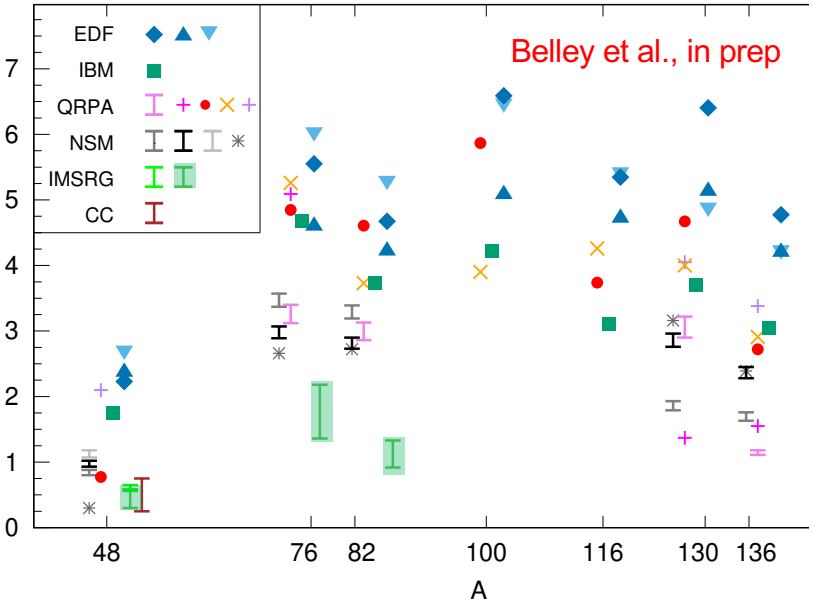
Belley et al., PRL (2021)

Ab Initio $0\nu\beta\beta$ Decay: Multiple Interactions

Study uncertainty from input NN+3N forces with **5 chiral interactions**

Convergence in virtually all cases: globally smaller than phenomenology, much less spread



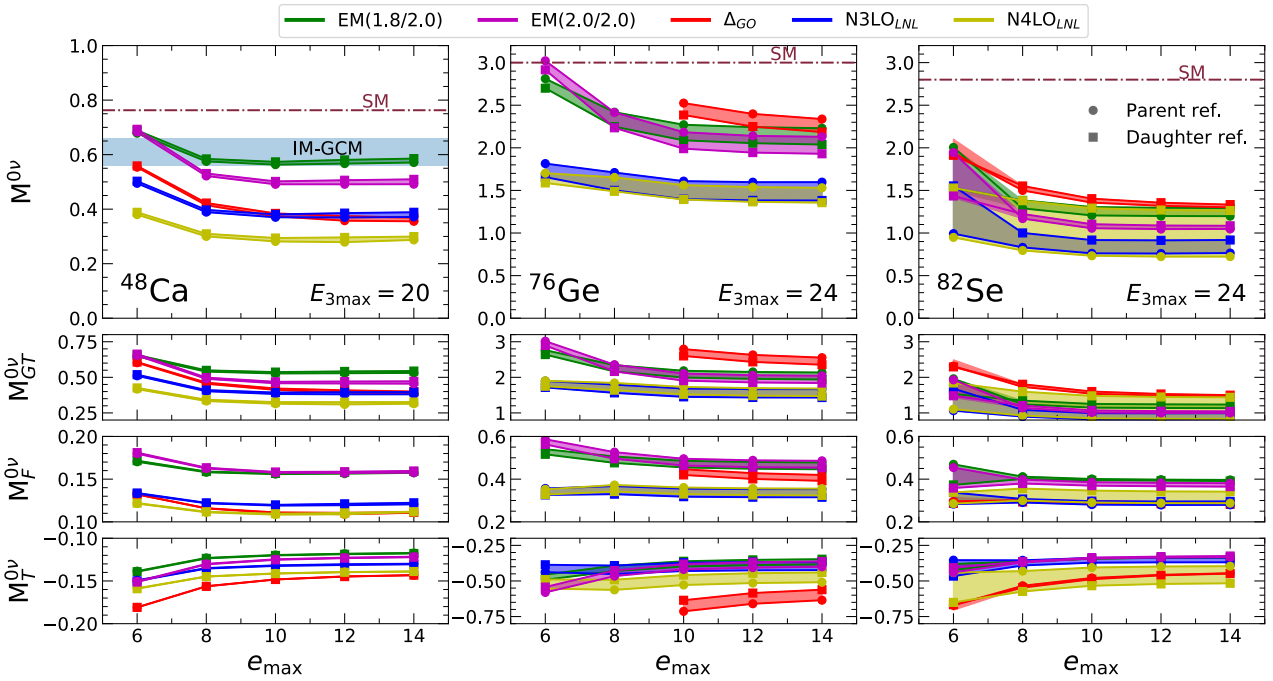


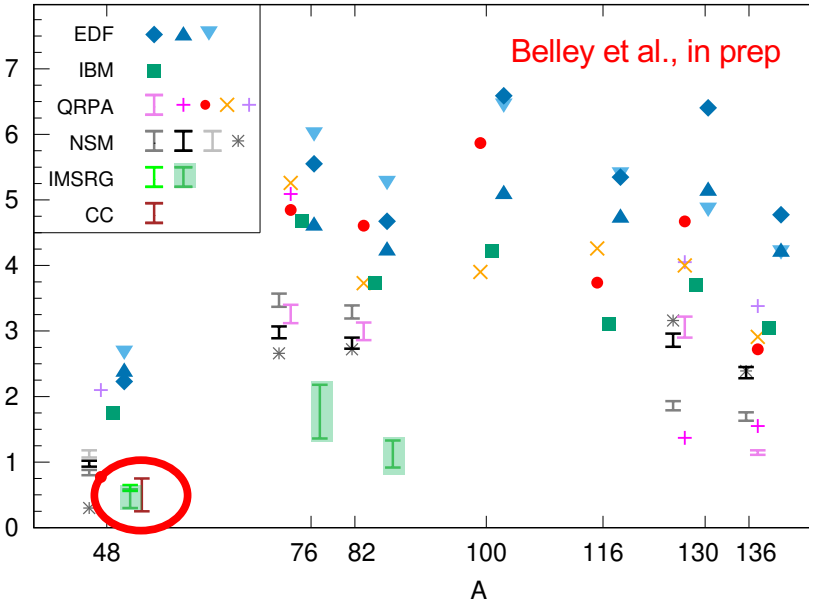
Ab Initio $0\nu\beta\beta$ Decay: Multiple Interactions

Study uncertainty from input NN+3N forces with **5 chiral interactions**

Convergence in virtually all cases: globally smaller than phenomenology, much less spread

In agreement with other ab initio approaches in ^{48}Ca





Still missing physics: IMSRG(3), valence-space variation, two-body currents…

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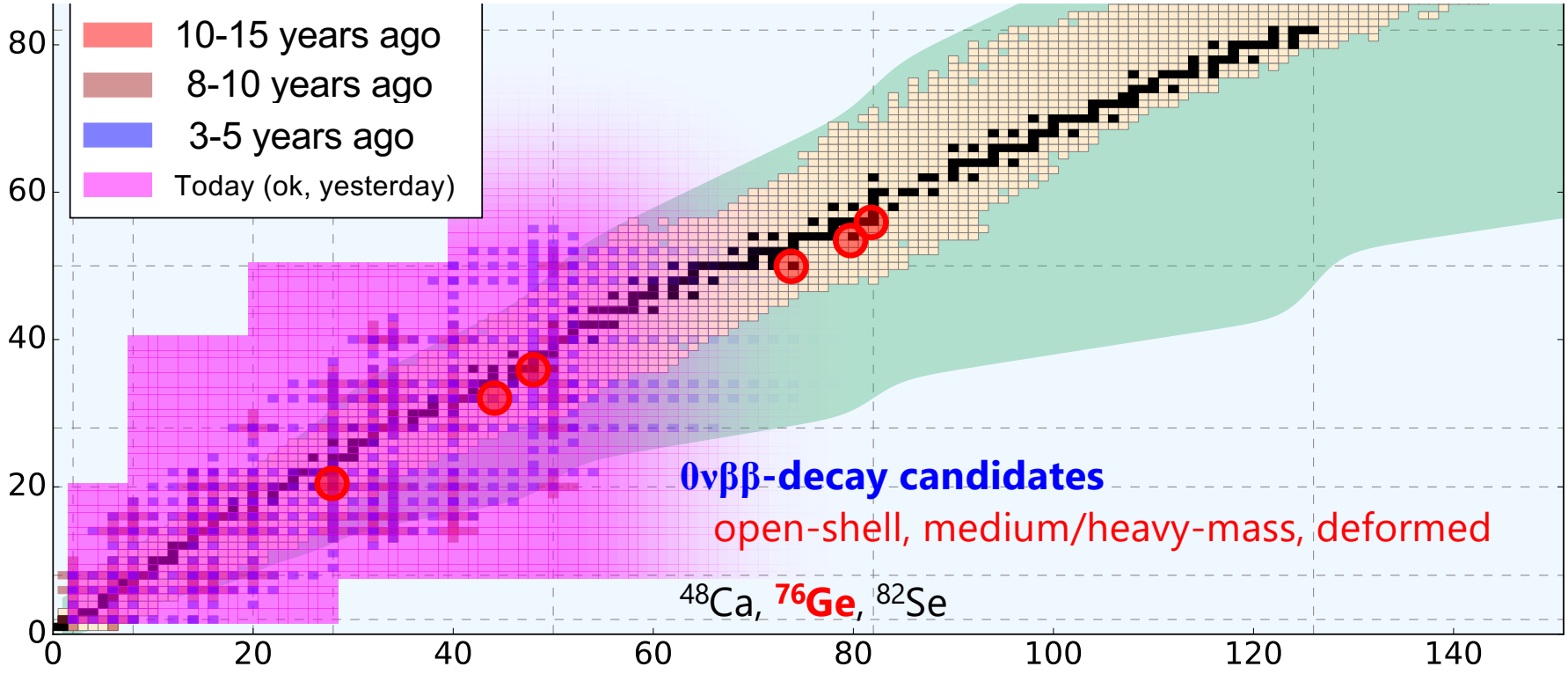
Towards Neutrinoless Double Beta Decay

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

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



TRIUMF

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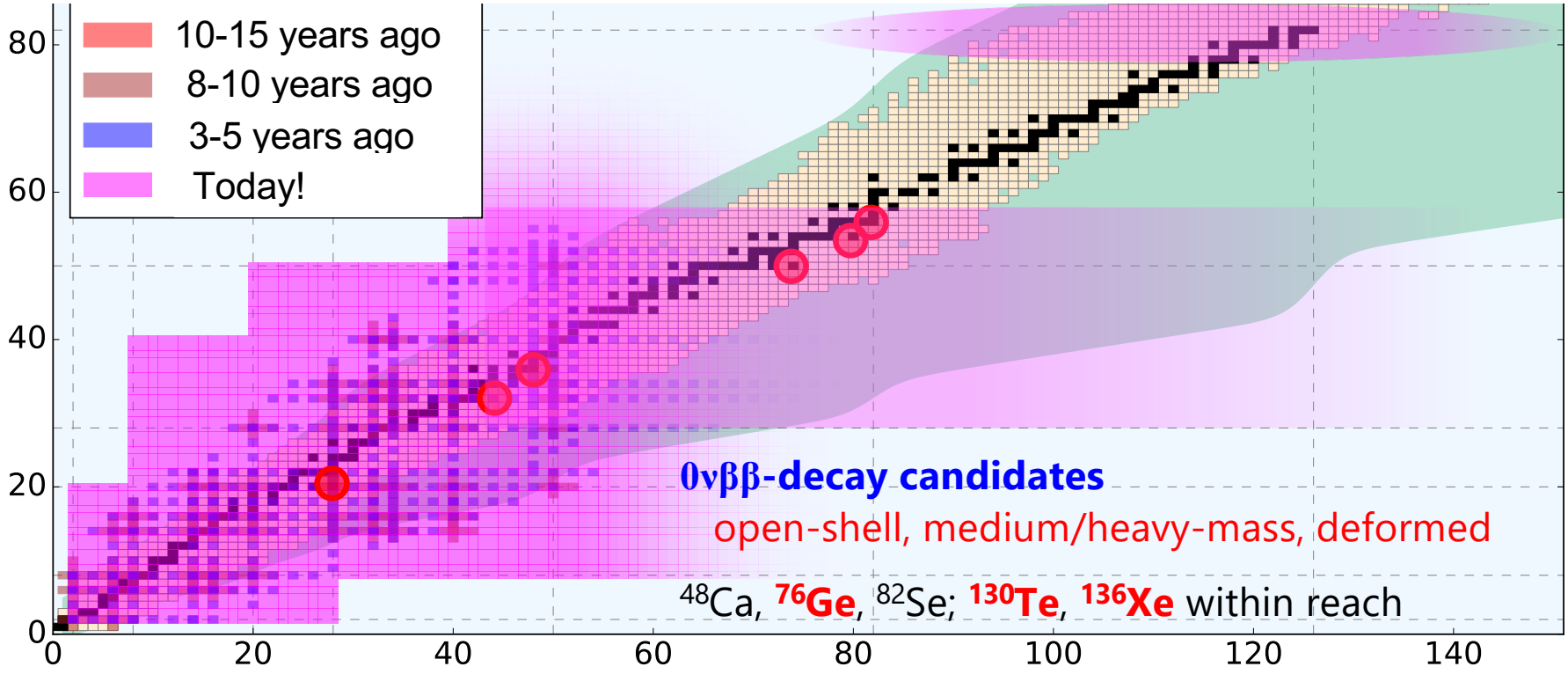

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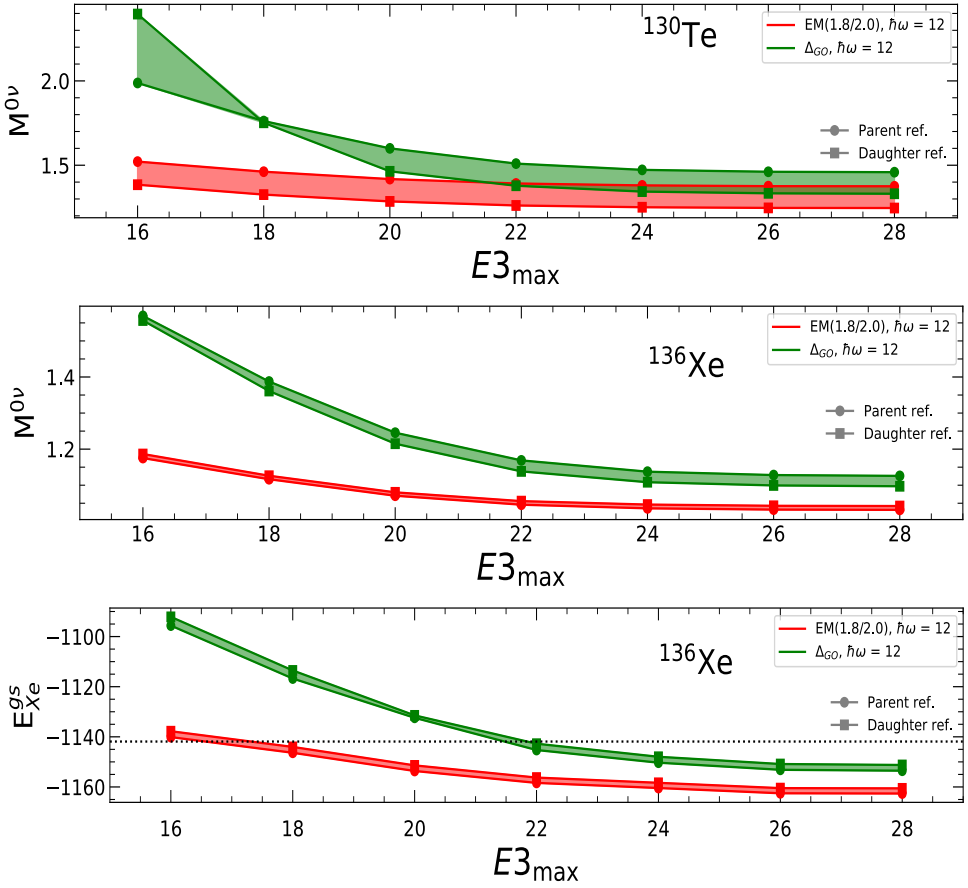
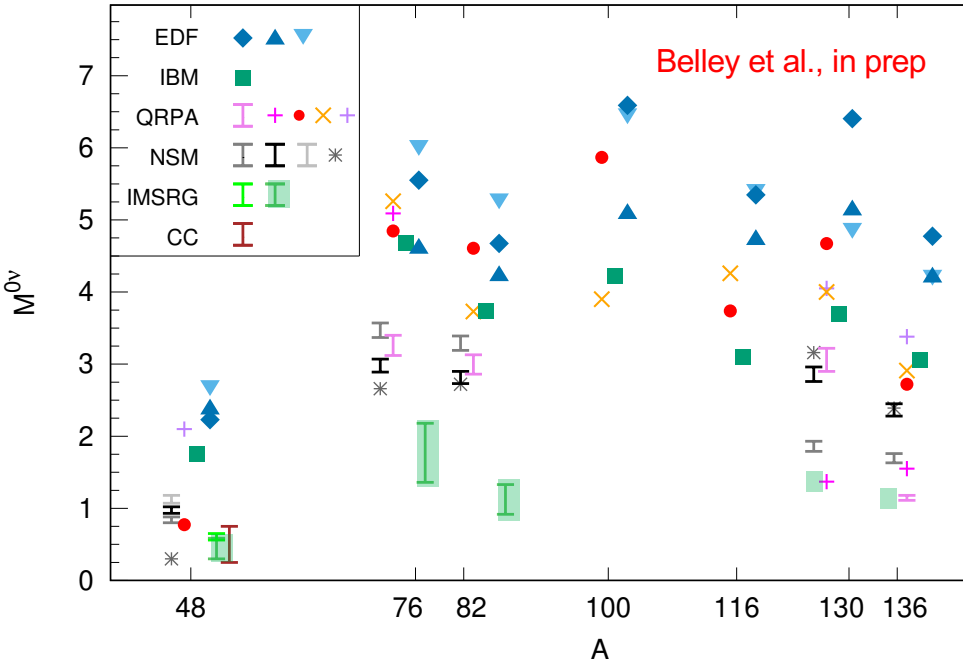
Ab Initio 0νββ Decay: ^{130}Te, ^{136}Xe

^{130}Te, ^{136}Xe major players in global searches

Increased E_{3max} allows first converged ab initio calculations: two NN+3N interactions





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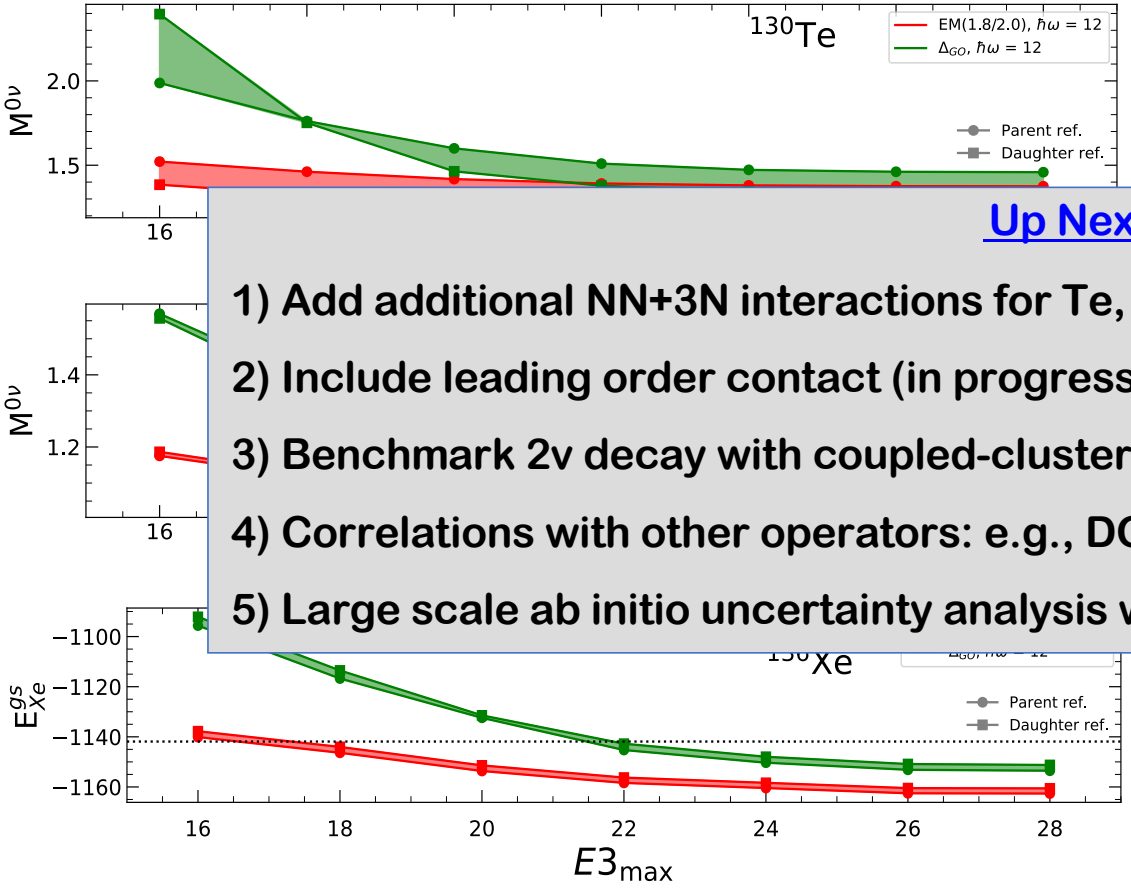
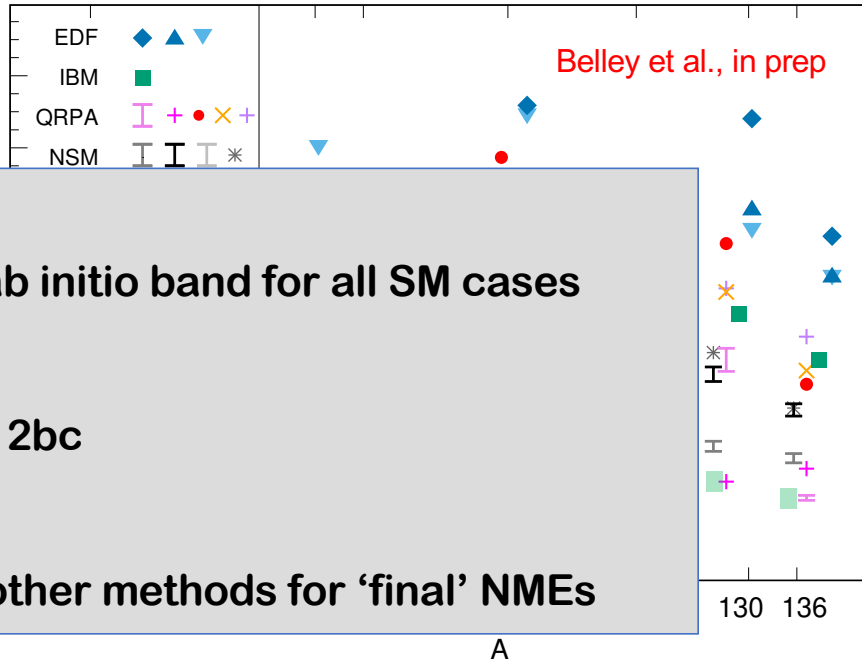




Up Next

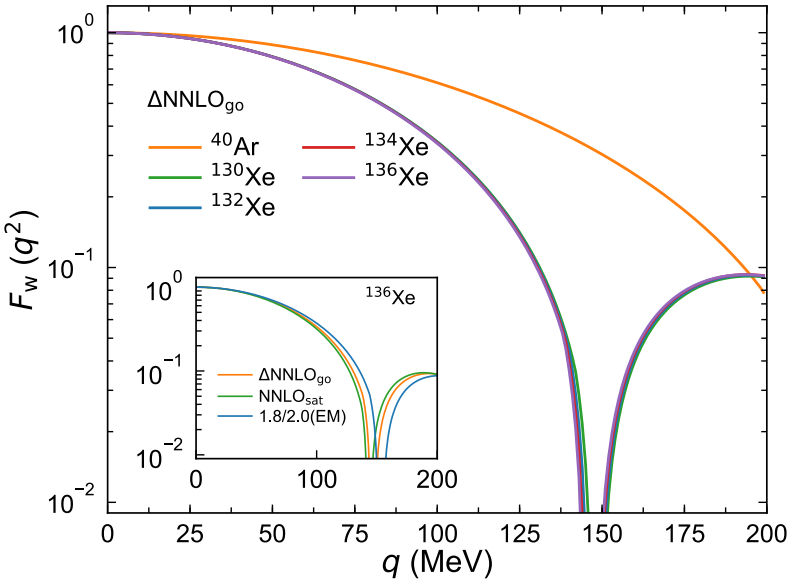
1) Add additional NN+3N interactions for Te, Xe: ab initio band for all SM cases
2) Include leading order contact (in progress)
3) Benchmark 2v decay with coupled-cluster with 2bc
4) Correlations with other operators: e.g., DGT
5) Large scale ab initio uncertainty analysis with other methods for 'final' NMEs

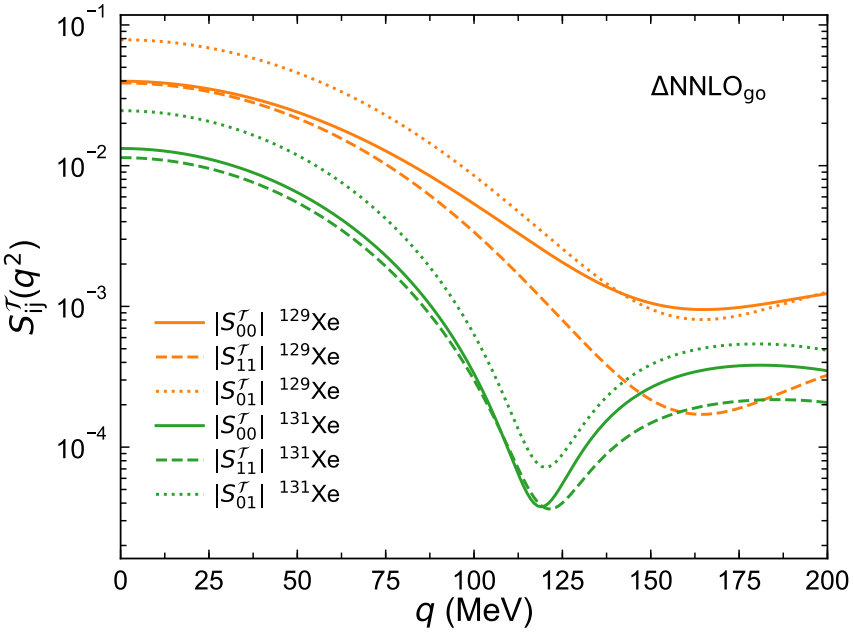
TRIUMF

Coherent Elastic Neutrino-Nucleus Scattering

^{130}Te, ^{136}Xe major players in global searches

Increased E_{3max} allows first converged ab initio calculations: two NN+3N interactions





Hu et al., in prep

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Present and Future for Theory

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

Nuclear Structure

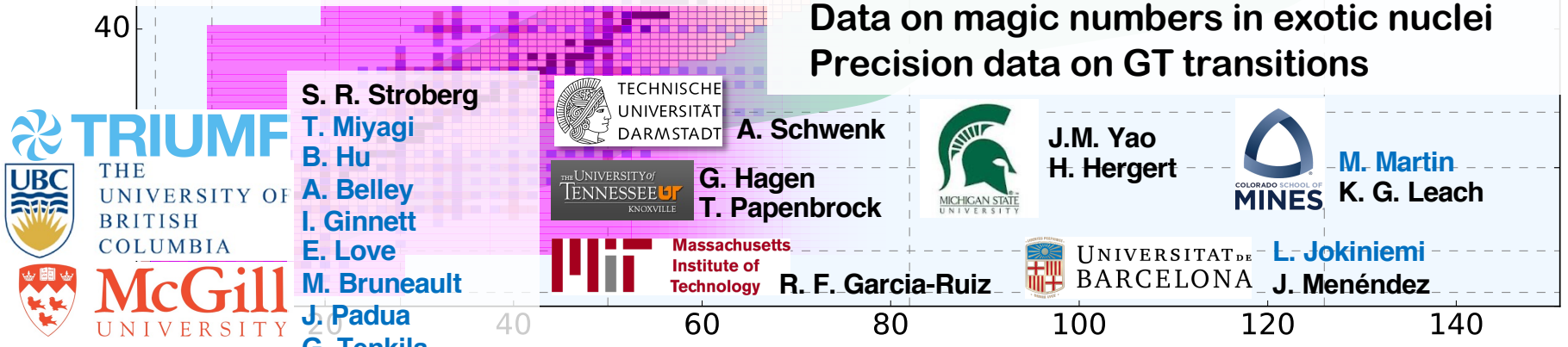
- Development of forces and currents
- Dripline predictions up to Fe
- Evolution of magic numbers:
  - masses, radii, spectra, EM transitions
- Multi-shell theory:
  - Islands of inversion
  - Forbidden decays
- Atomic systems

Fundamental Symmetries/BSM Physics

- EW operators: GT quenching, muon capture
- $0\nu\beta\beta$ decay matrix elements
- WIMP-Nucleus scattering
- Superallowed Fermi transitions
- Symmetry-violating moments [molecules]

Experimental overlap

- Best data for constraining nuclear forces
- New measurements of driplines
- Data on magic numbers in exotic nuclei
- Precision data on GT transitions



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THE UNIVERSITY OF BRITISH COLUMBIA

McGill UNIVERSITY

S. R. Stroberg
T. Miyagi
B. Hu
A. Belley
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E. Love
M. Bruneault
J. Padua
G. Tenkila
H. Patel

TECHNISCHE UNIVERSITÄT DARMSTADT — A. Schwenk

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

Massachusetts Institute of Technology — R. F. Garcia-Ruiz

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

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

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