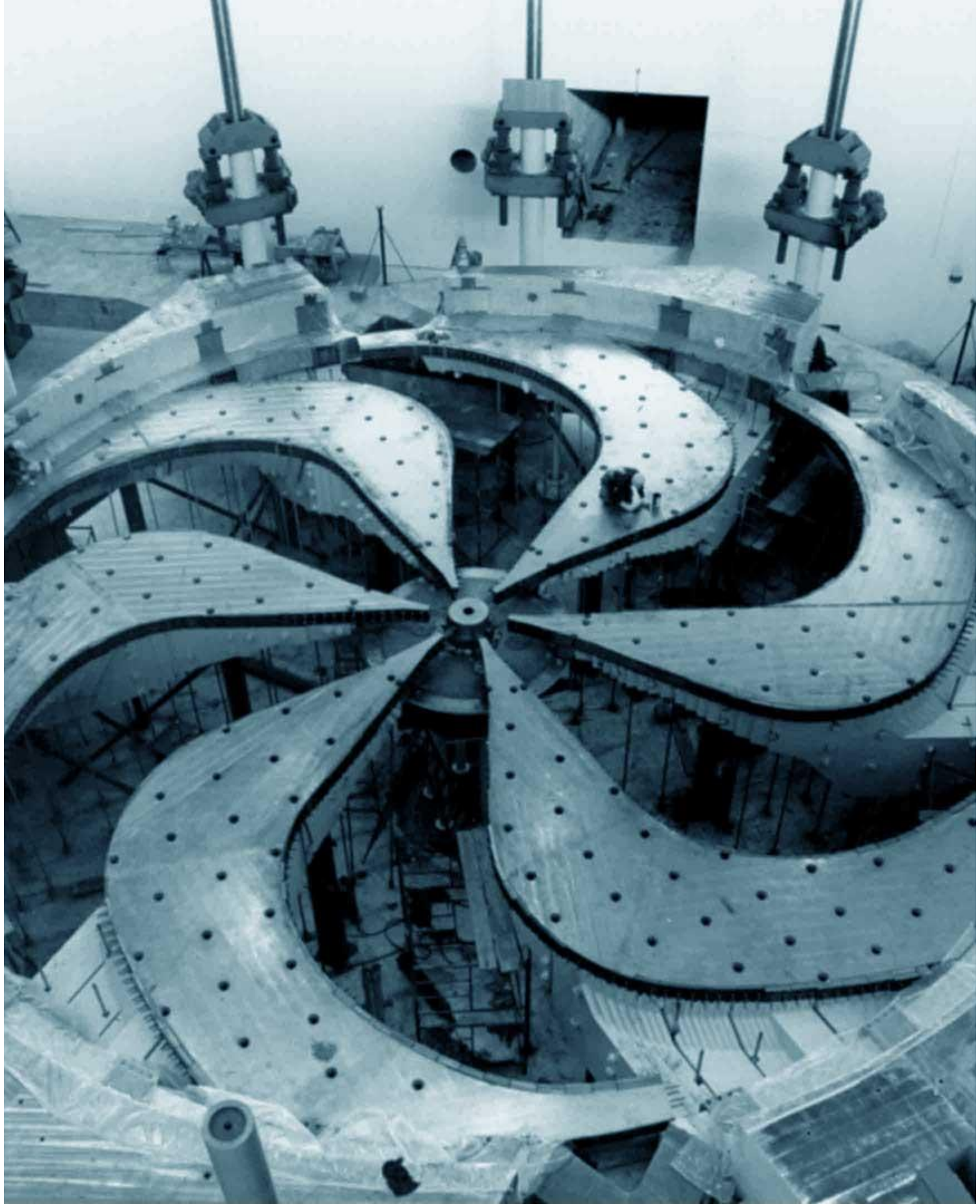
(Ab Initio) Theory Status for Neutrinoless Double Beta Decay NMEs

Jason D. Holt
TRIUMF, McGill University
Next-Gen Xe; Montreal QC
Nov 12, 2025



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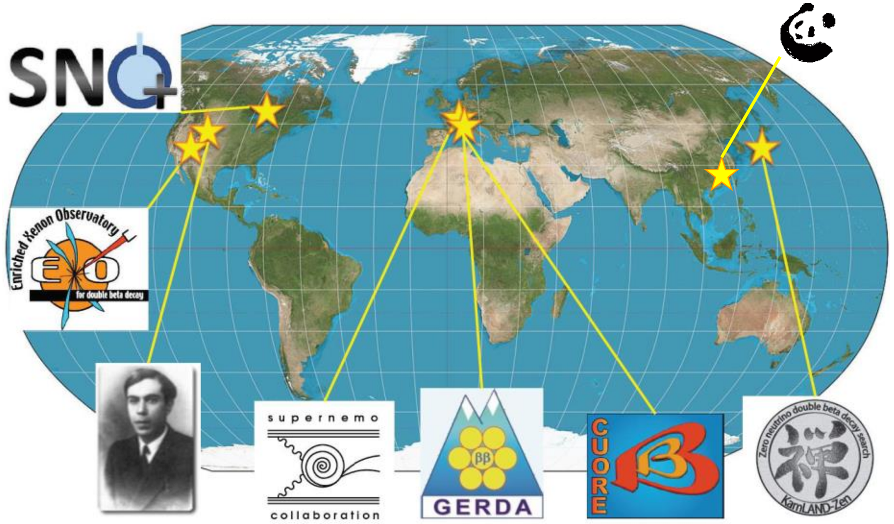
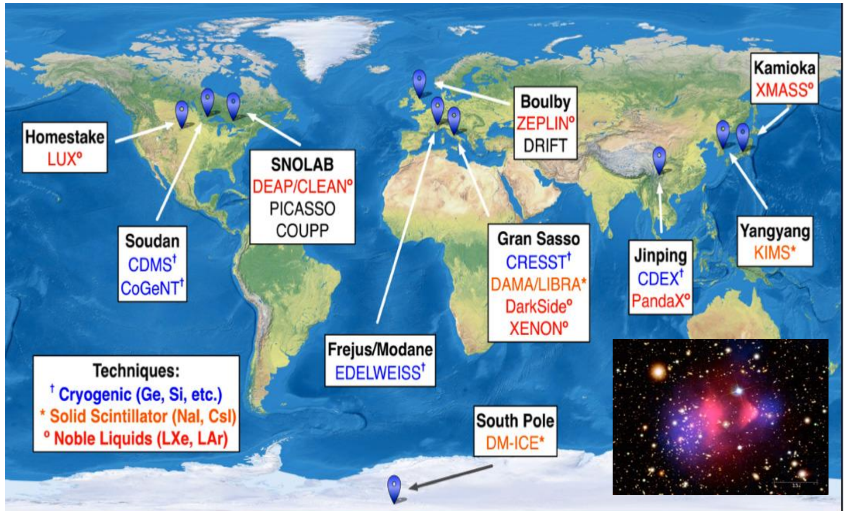
Major BSM Searches Worldwide

Worldwide search for BSM physics w/ neutrinos, dark matter, and radioactive molecules!

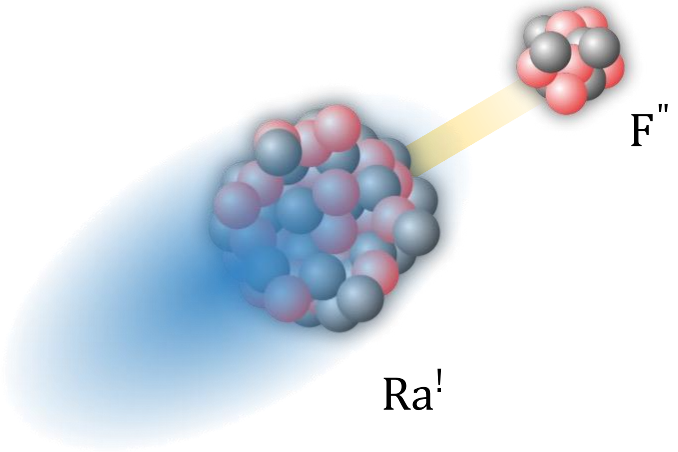
$0\nu\beta\beta$ Decay



Dark Matter Direct Detection



Symmetry Violation

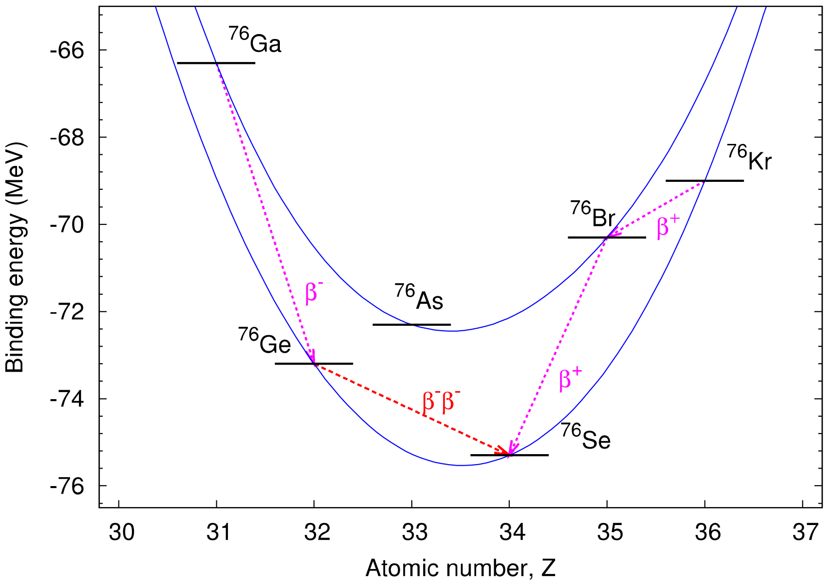


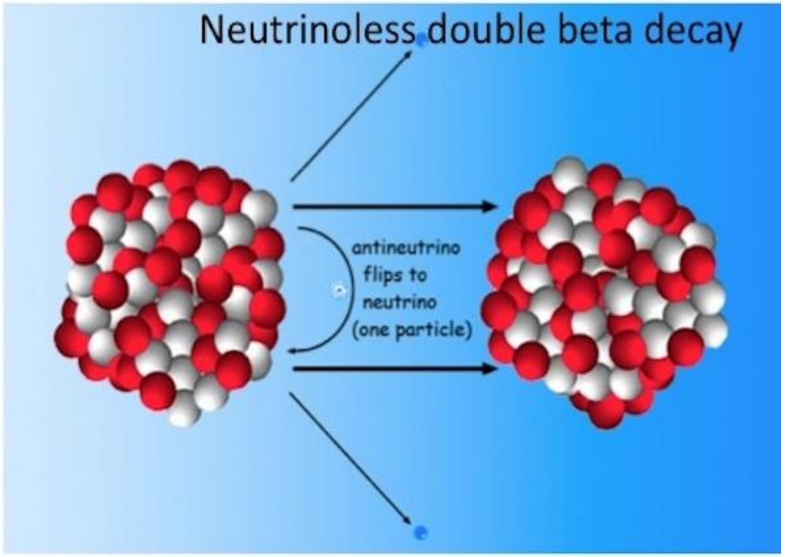
Billions invested worldwide – theory of the nucleus is essential

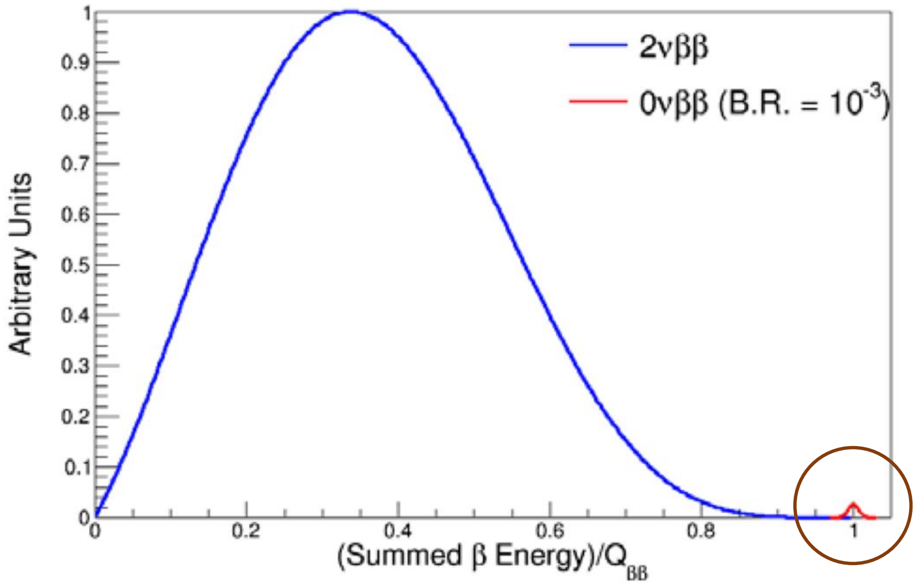
Strategic planning for discovery (**motivation**) + **interpretation**

Neutrino-less (0ν) Double-Beta (ββ) Decay

Neutrino own antiparticle $\Longleftrightarrow$ 0νββ decay







Tremendous impact on BSM physics

Lepton-number violation

Majorana character of neutrino

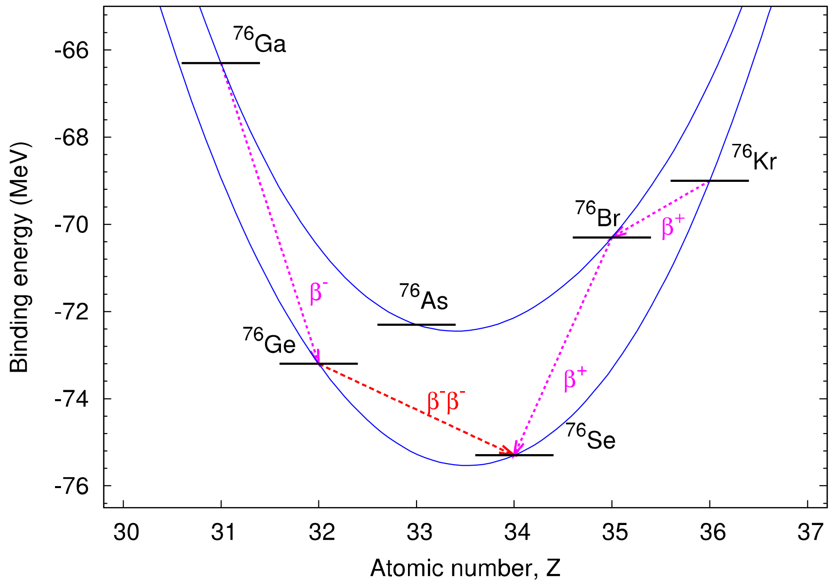
Matter/antimatter asymmetry

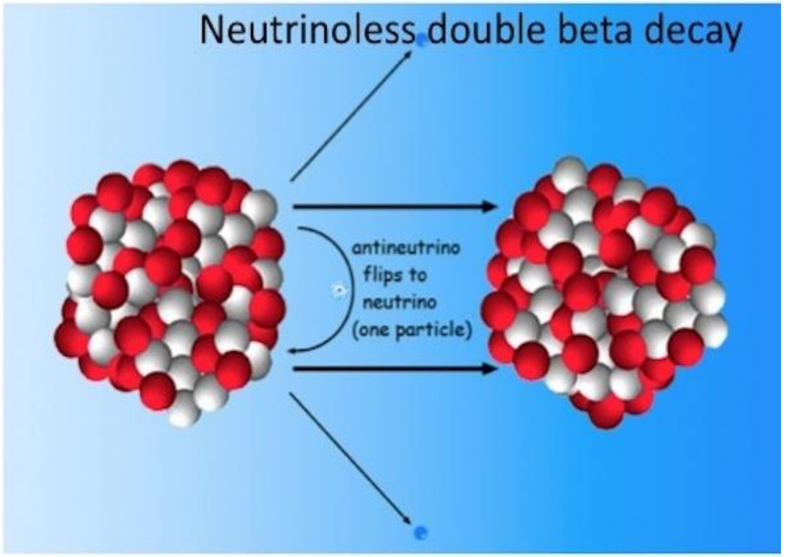
Absolute neutrino mass scale

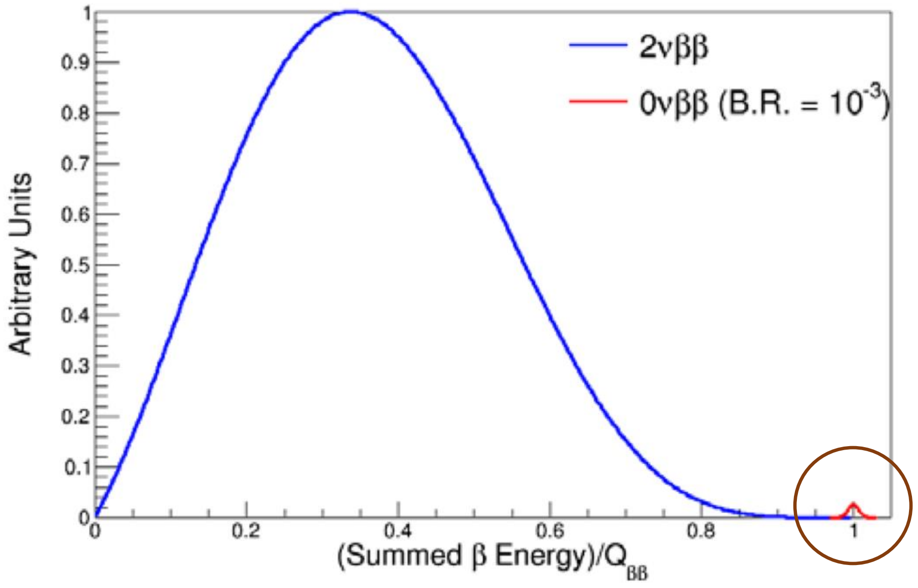
$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 \boxed{\langle m_{\beta\beta}\rangle^2} \quad \langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei} m_i\right|$$

Neutrino-less (0ν) Double-Beta (ββ) Decay

Neutrino own antiparticle $\Longleftrightarrow$ 0νββ decay







Tremendous impact on BSM physics

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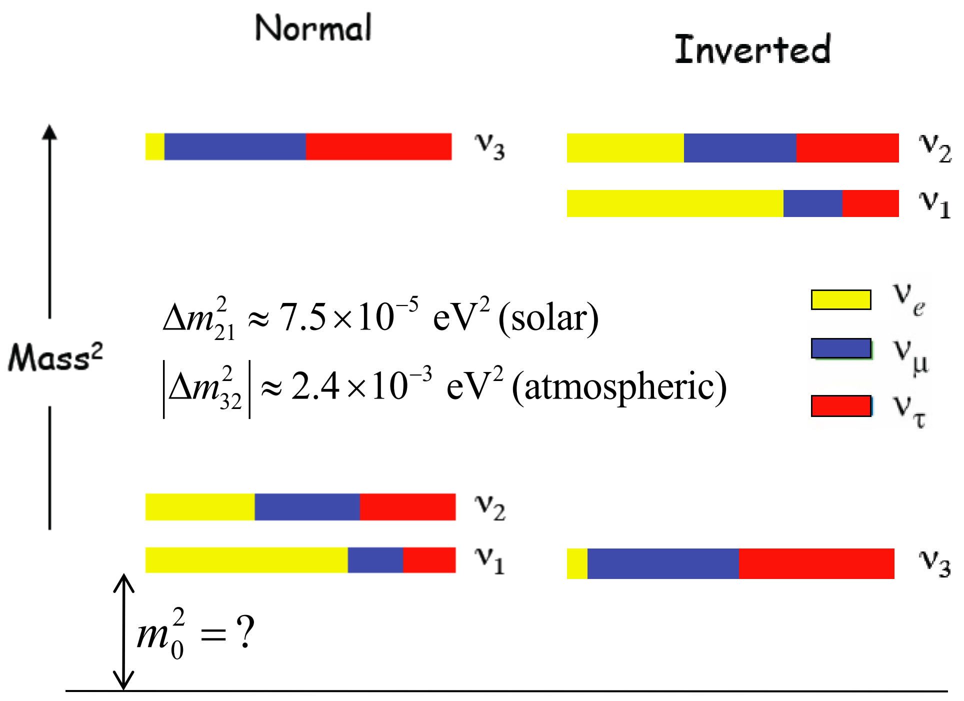
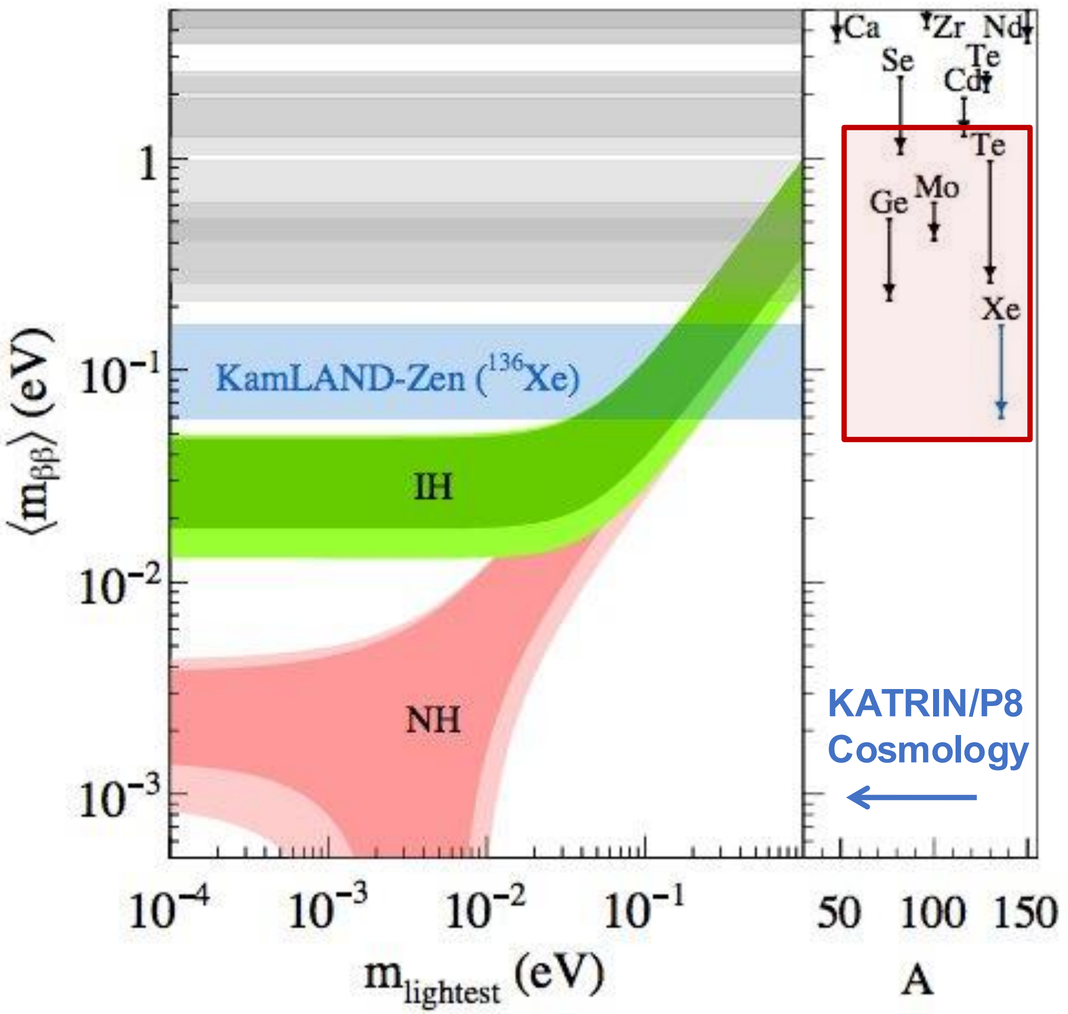
$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2 \quad \langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei} m_i\right|$$

NME not observable: must be calculated

Nature of Neutrino: 0νββ Decay

Next-generation searches probe **Inverted Hierarchy**



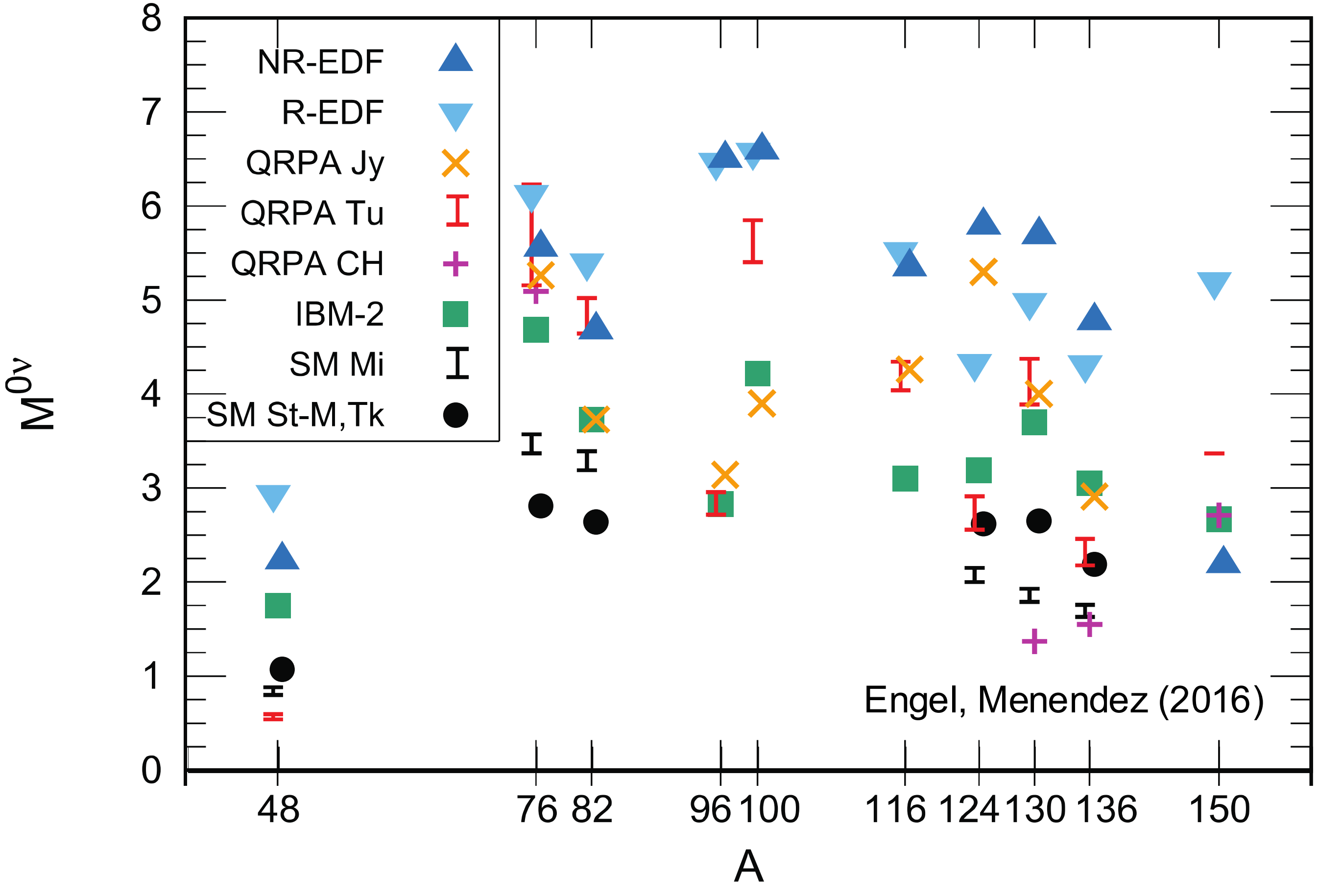


$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2 \quad \langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei} m_i\right|$$

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

Status of $0\nu\beta\beta$-Decay Matrix Elements

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



All models missing essential physics: correlations, single-particle levels, two-body currents

Impossible to assign rigorous uncertainties… but, hey, could be worse

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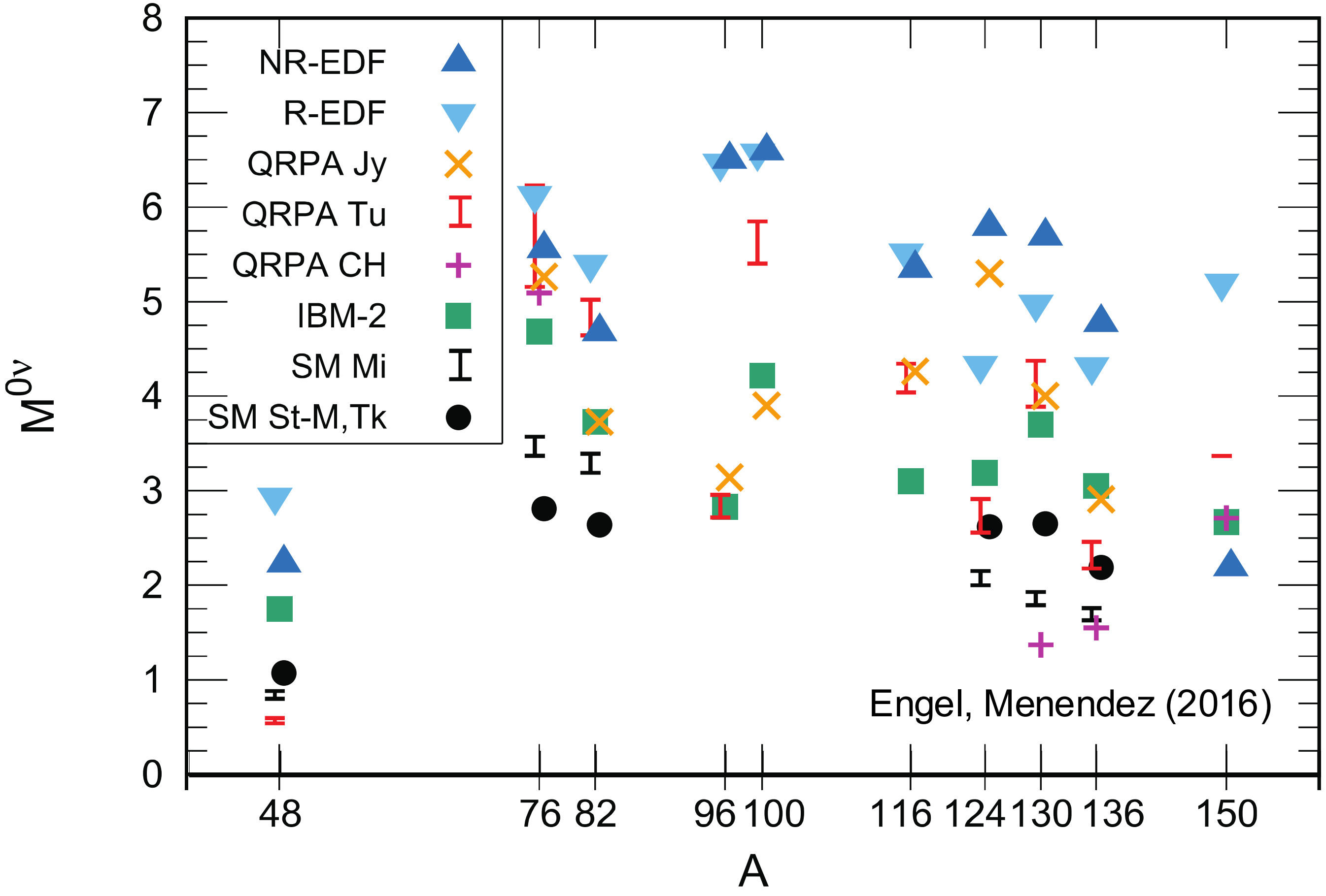
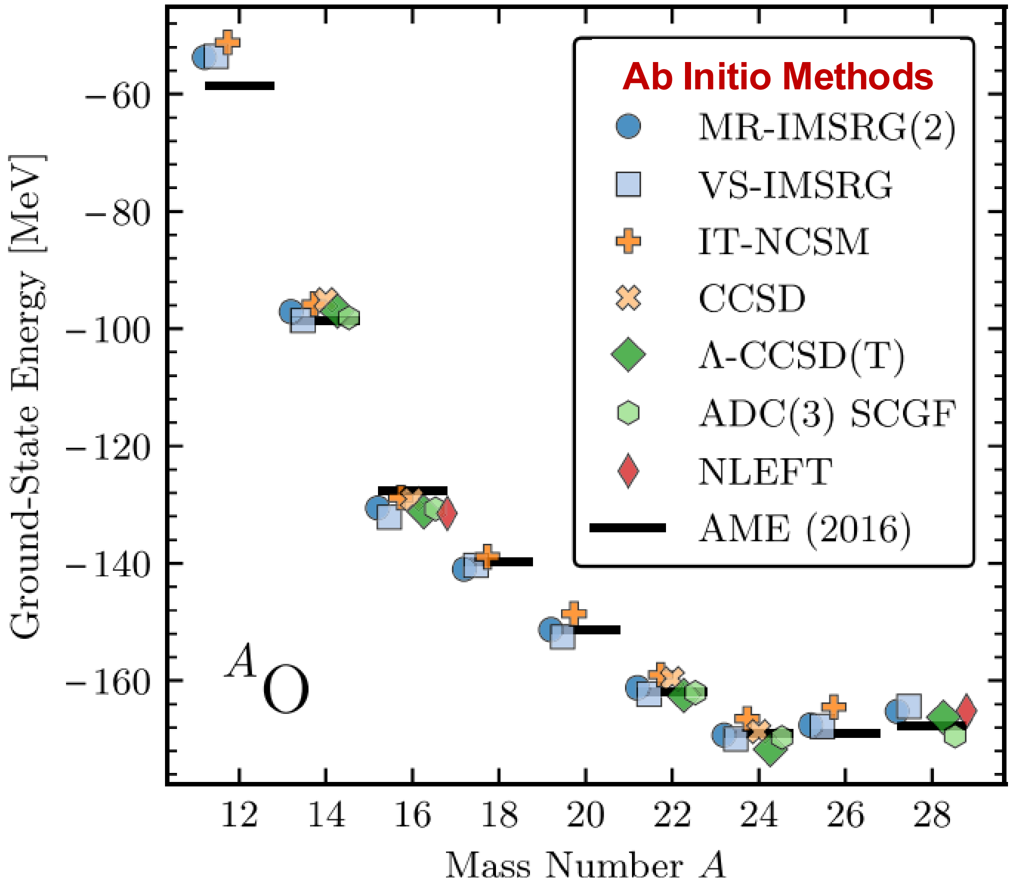
Status of 0νββ-Decay Matrix Elements

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





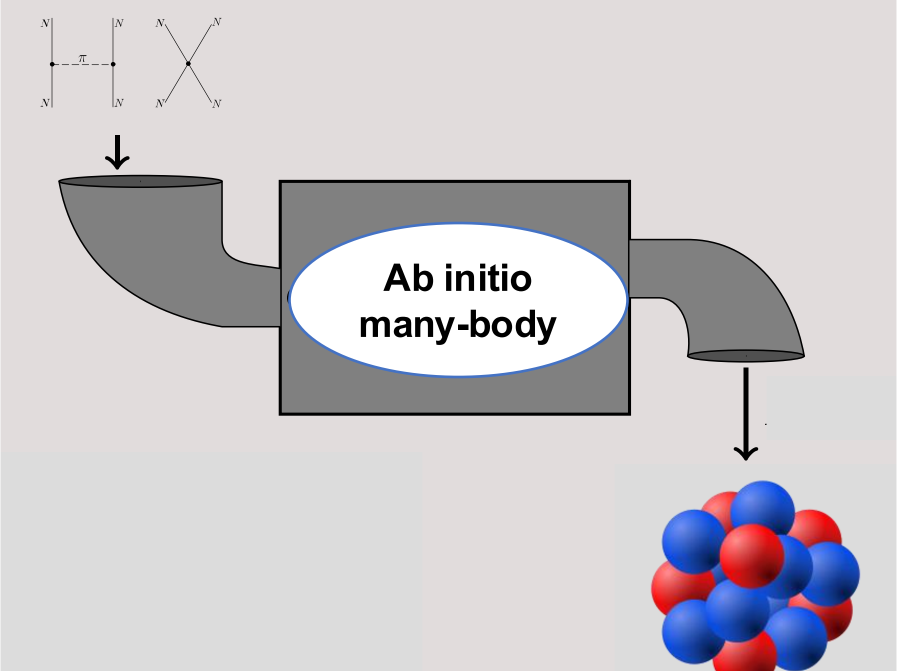
New approach to NME calculations: **ab initio theory** consistent results when extrapolated

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

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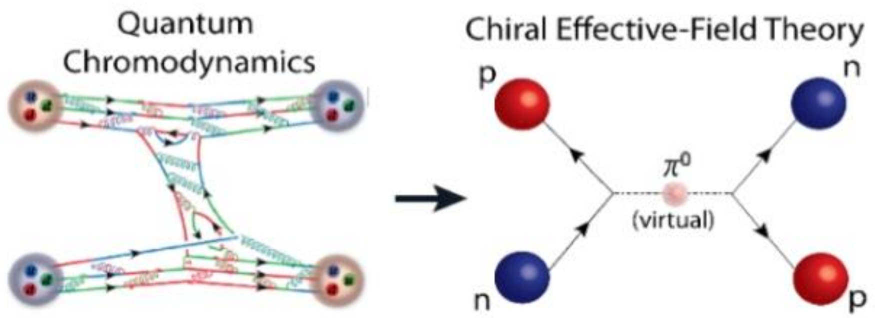
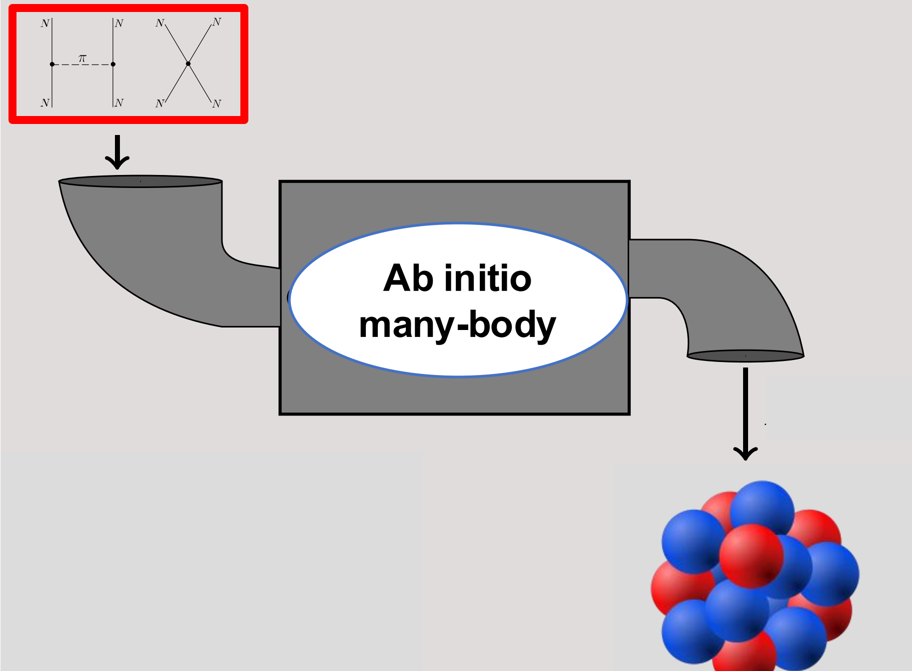
Ingredient I: Nuclear Forces

Chiral Effective Field Theory: low-energy expansion of QCD, nucleons + pions

High-energy information encoded in contact terms

$$H\psi_n = E_n\psi_n$$





Courtesy, S. R. Stroberg

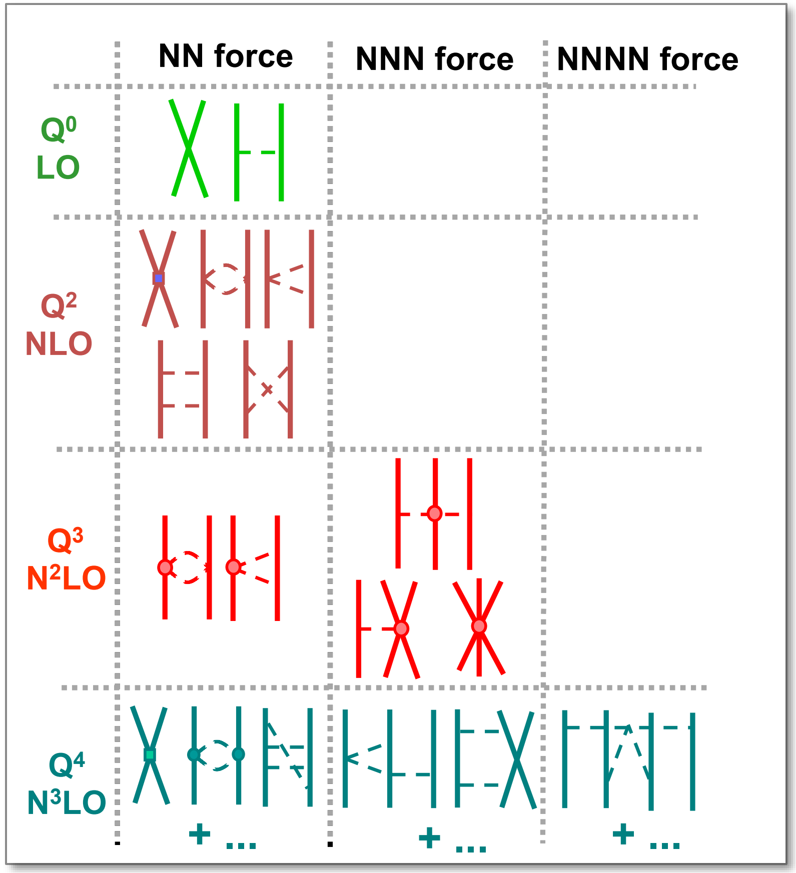
Chiral Effective Field Theory

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

Quantifiable uncertainties

Interactions

1.8/2.0, N2LO$_{GO}$, N3LO$_{LNL}$
34 non-implausible

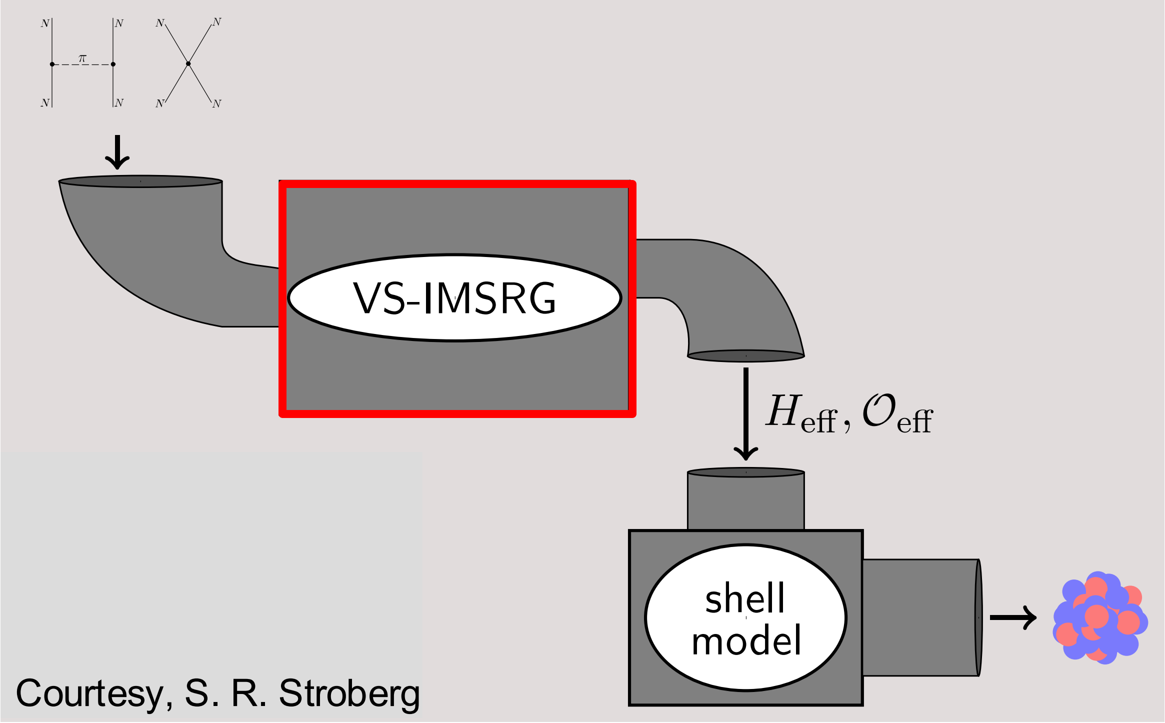


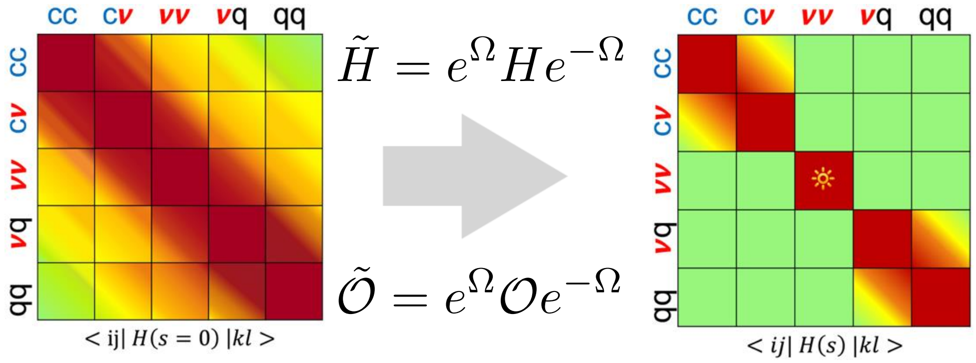
Key Advance Valence-Space Approach

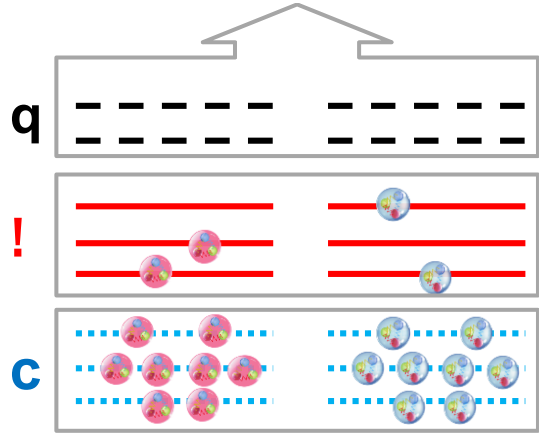
Polynomially scaling methods tailored for doubly magic, semi-magic chains

Valence-space IMSRG: Novel approach for all open-shell nuclei

$$H\psi_n = E_n\psi_n$$







Ragnar Stroberg

Ab initio → scope of nuclear shell model

Nucleus-Dependent Valence-Space Approach to Nuclear Structure

S. R. Stroberg, A. Calci, H. Hergert, J. D. Holt, S. K. Bogner, R. Roth, and A. Schwenk

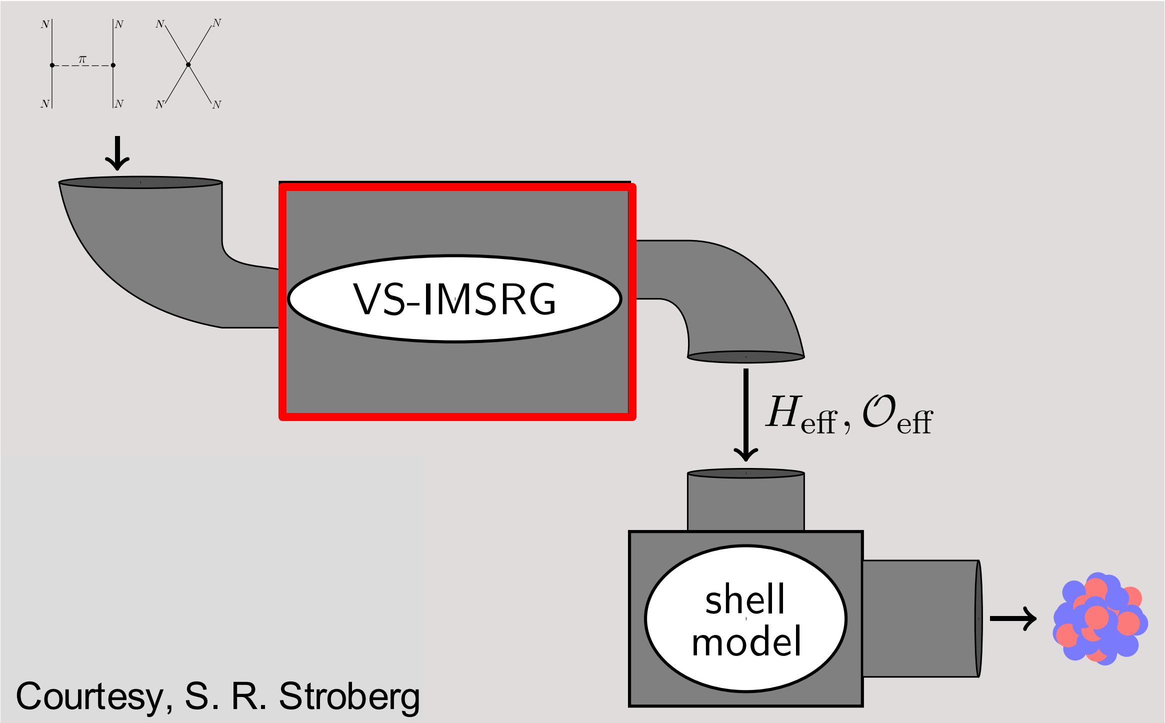
Phys. Rev. Lett. **118**, 032502 – Published 20 January 2017

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

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)

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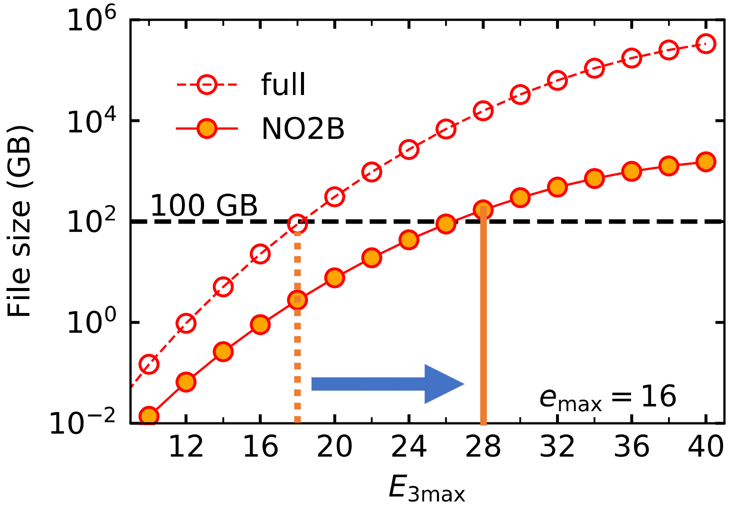
Ab Initio Calculations of Heavy Nuclei

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

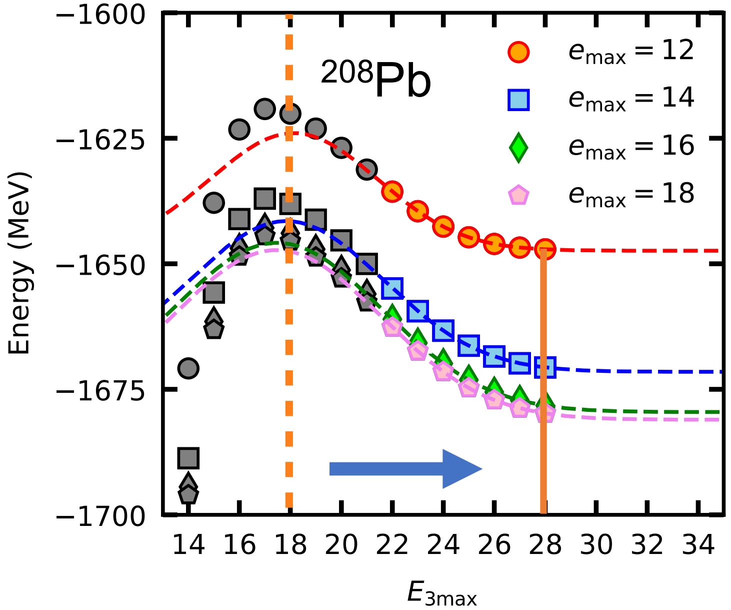
Clever storage reduces needs: TB → GB



^{208}Pb now straightforward:

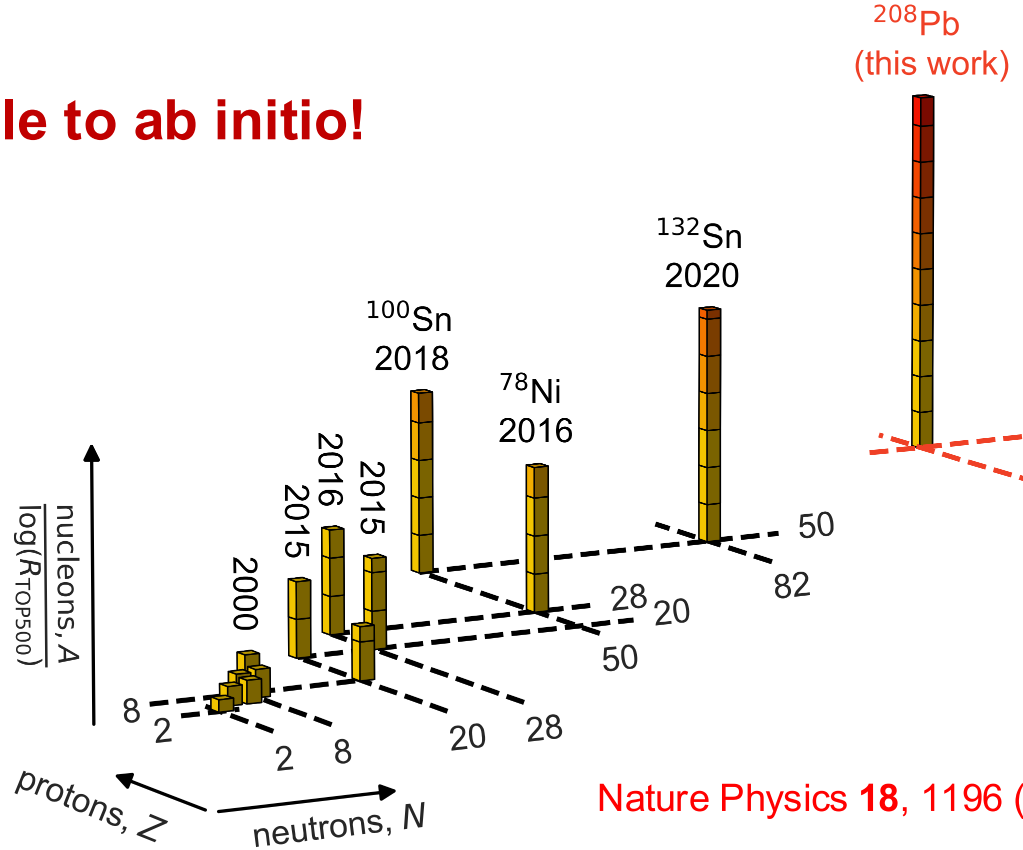
Solving the Schrödinger equation for 200+ nucleons!

(Super)heavy accessible to ab initio!



16 years: $^{16}O \rightarrow {}^{56}Ni$

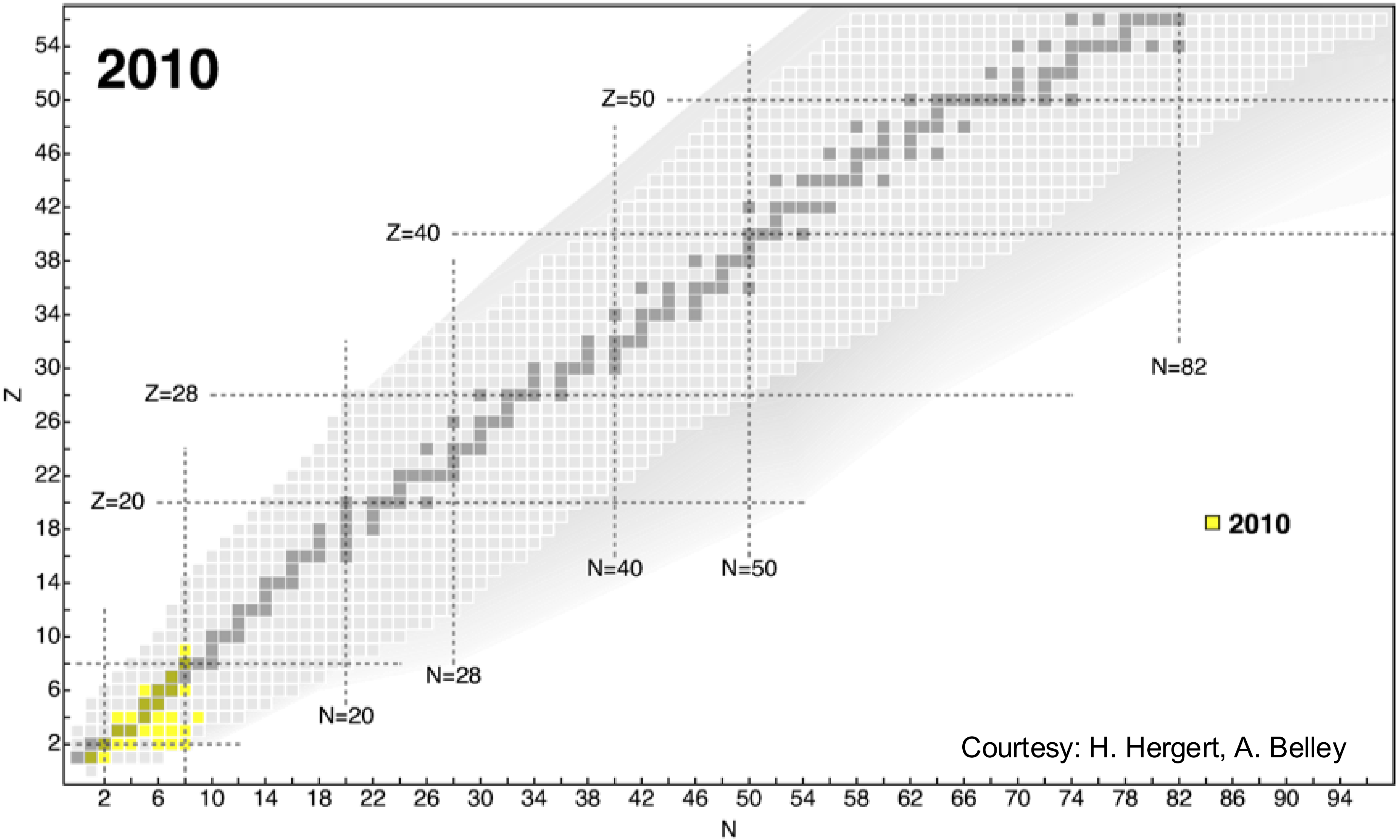
6 years: $^{56}Ni \rightarrow {}^{208}Pb$



Nature Physics **18**, 1196 (2022)

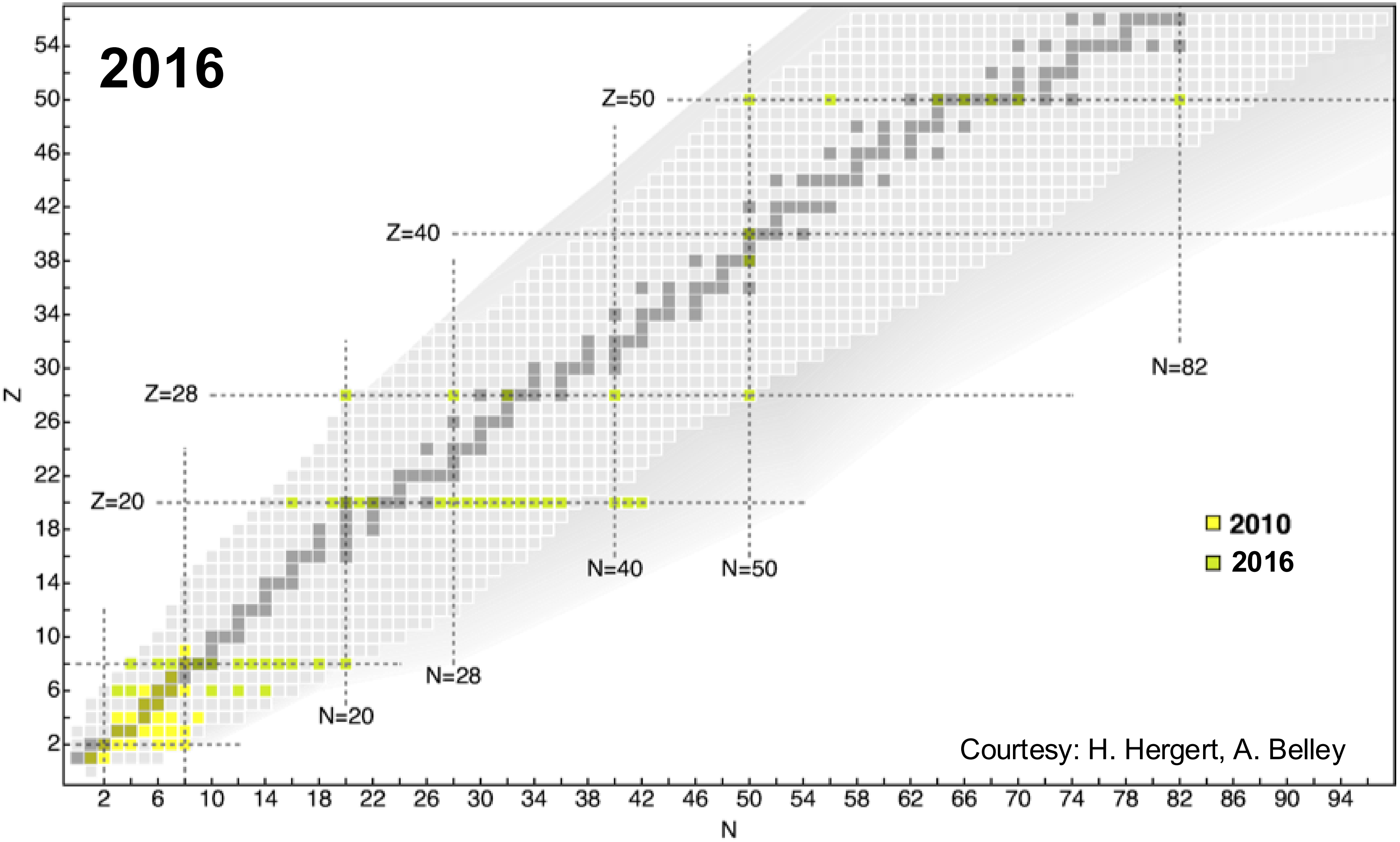
Ab Initio 2010

2010 Quasi-exact methods for light nuclei (^{16}O); limited capability for 3N forces



2016 Polynomially scaling methods (Coupled Cluster, IMSRG)

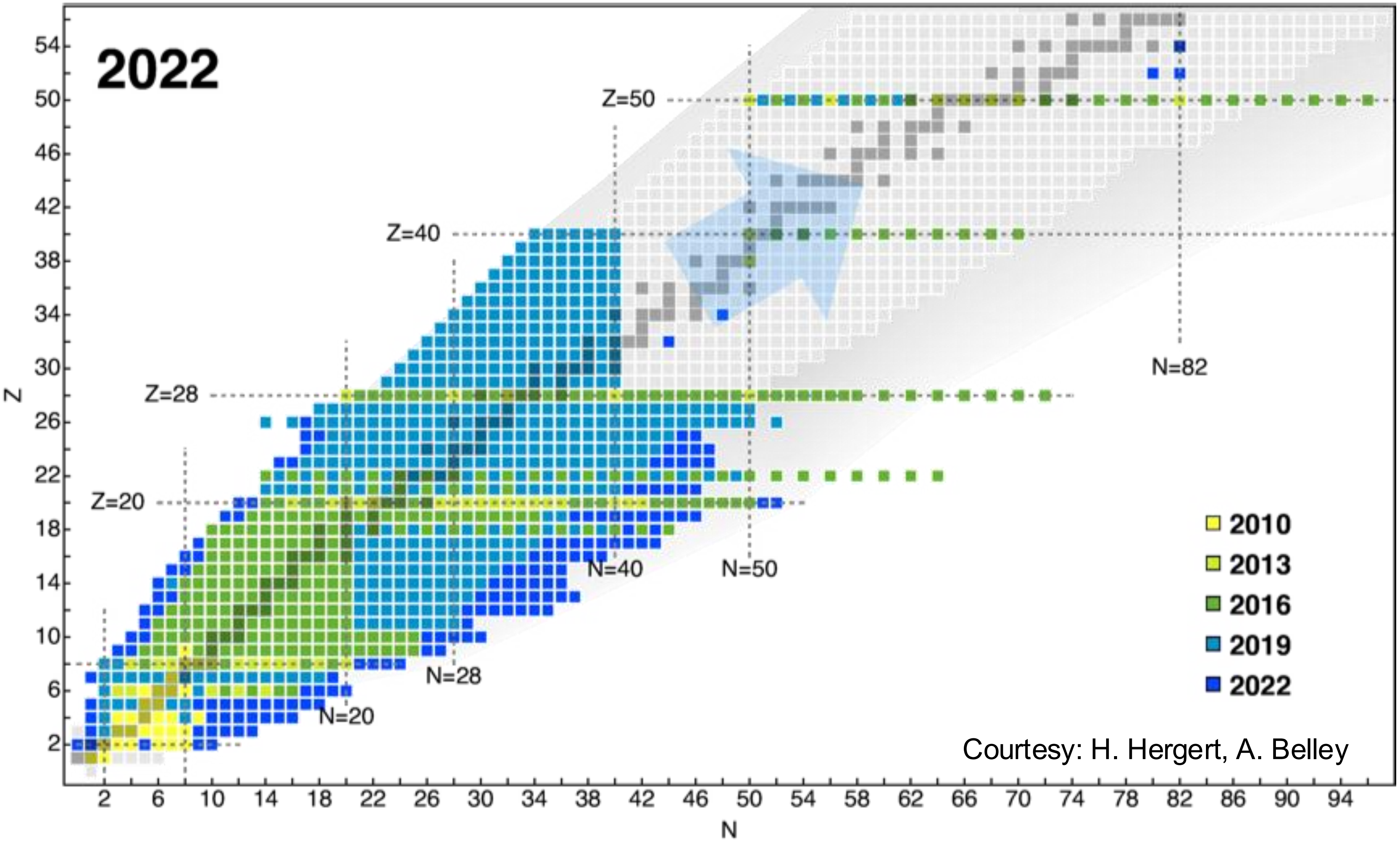
Progress to doubly magic $^{56/78}$Ni + semi-magic chains



The 5-Year Revolution: 2022

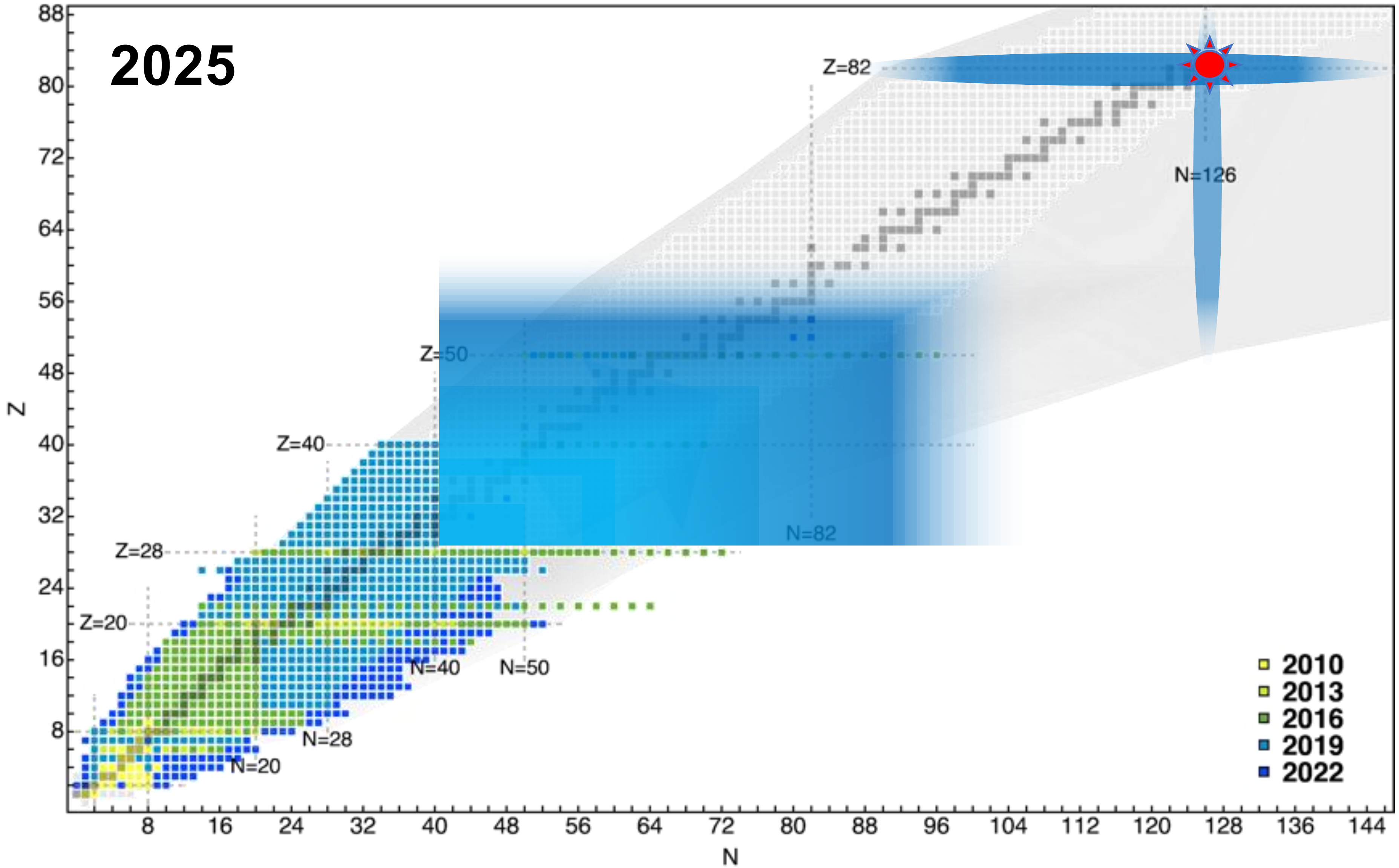
2022 Valence-space approach: essentially *all* properties of *all* nuclei

What can we do with this advance?



New Scope of Ab Initio Theory

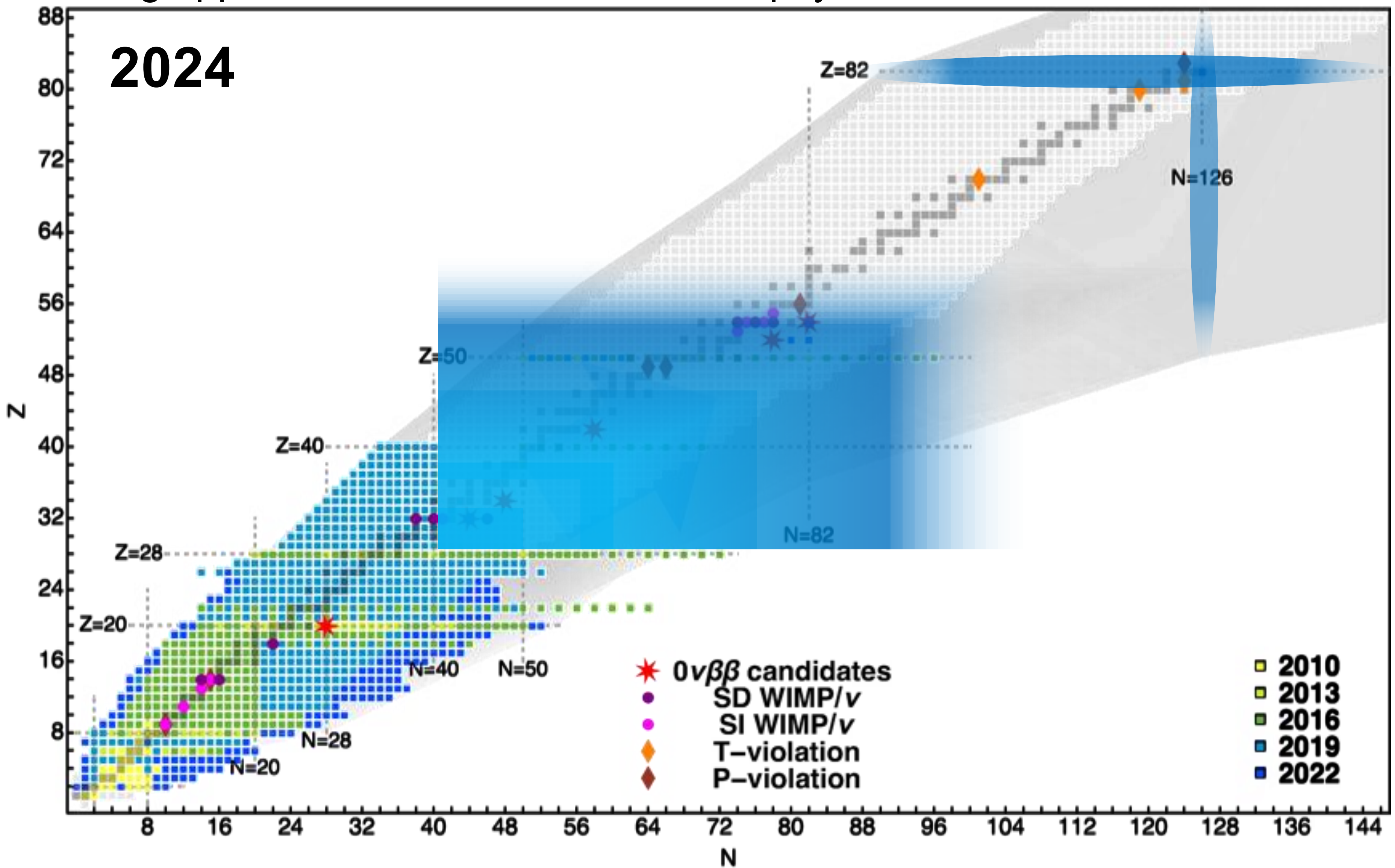
Rapid progress in ab initio reach: **global + heavy**



New Scope of Ab Initio Theory

Rapid progress in ab initio reach: **global + heavy**

Exciting applications to searches for BSM physics!



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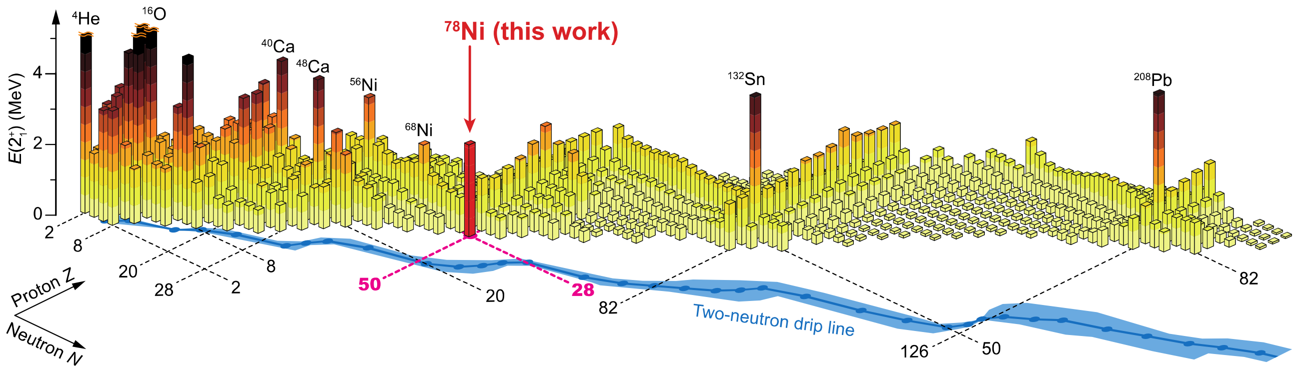
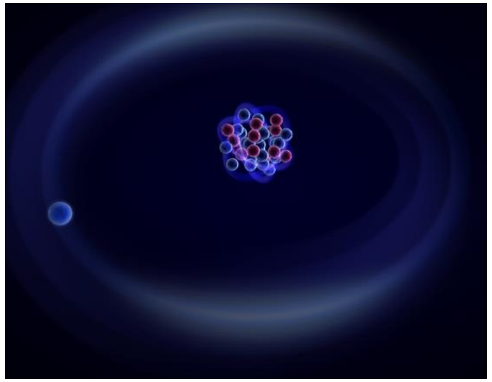
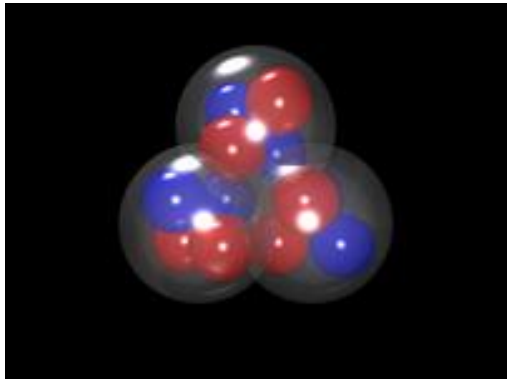
Major Questions in Nuclear Structure/Astrophysics

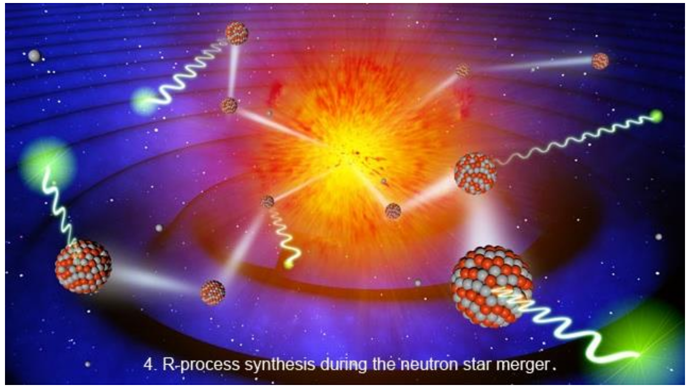


Limits of existence + formation/evolution of magic numbers

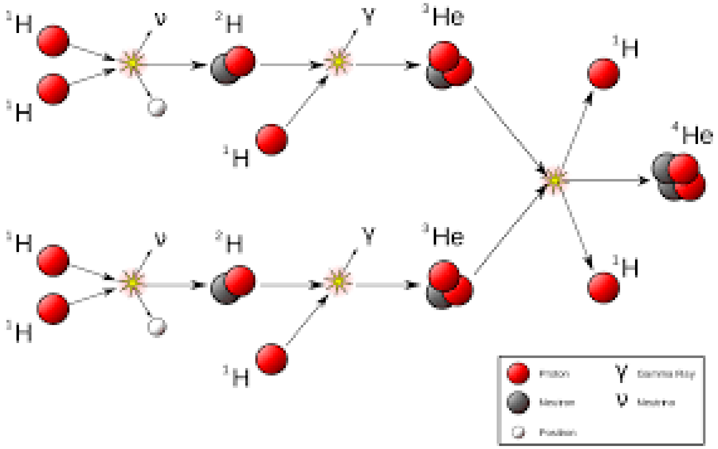




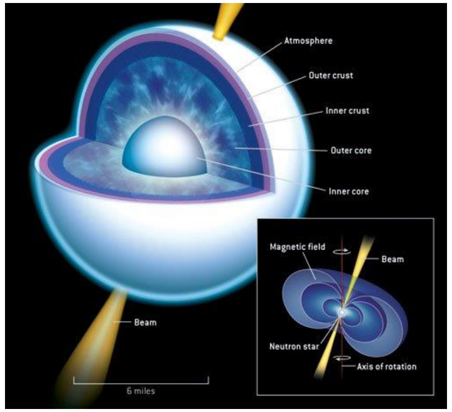
Nuclear skins/halos/clusters



Heavy Element Nucleosynthesis



Continuum and nuclear reactions



Infinite matter/Neutron stars

Ab Initio VS-IMSRG Campaign: Masses and Charge Radii

Extensive campaign for nuclear structure, nuclear astrophysics, and searches for physics beyond the standard model

Neutron skin of ^{208}Pb
B. Hu *et al.*,
Nature Physics **18**, 1196

N=124-128: Ab initio masses for r-process nucleosynthesis
B. Hu *et al.* (in preparation)

N=50-82 Sn charge radii
P.F. Gustaffson *et al.*, Phys. Rev. Lett (under review)

In – Ag masses for structure of ^{100}Sn
M. Mougeout *et al.*, Nature Phys. 17, 1099 (2021)
L. Nies *et al.*, Phys. Rev. Lett. 131, 022502 (2023)
Z. Ge *et al.*, Phys. Rev. Lett. 133, 132503 (2024)

$^{132-140}$Sn masses for r-process nucleosynthesis
A. Mollaebrahimi *et al.*, Phys. Rev. Lett. (under review)

Reduced size of excited state isomer in ^{129,131}In
A. Vernon et al., Phys. Rev. Lett. (under review)

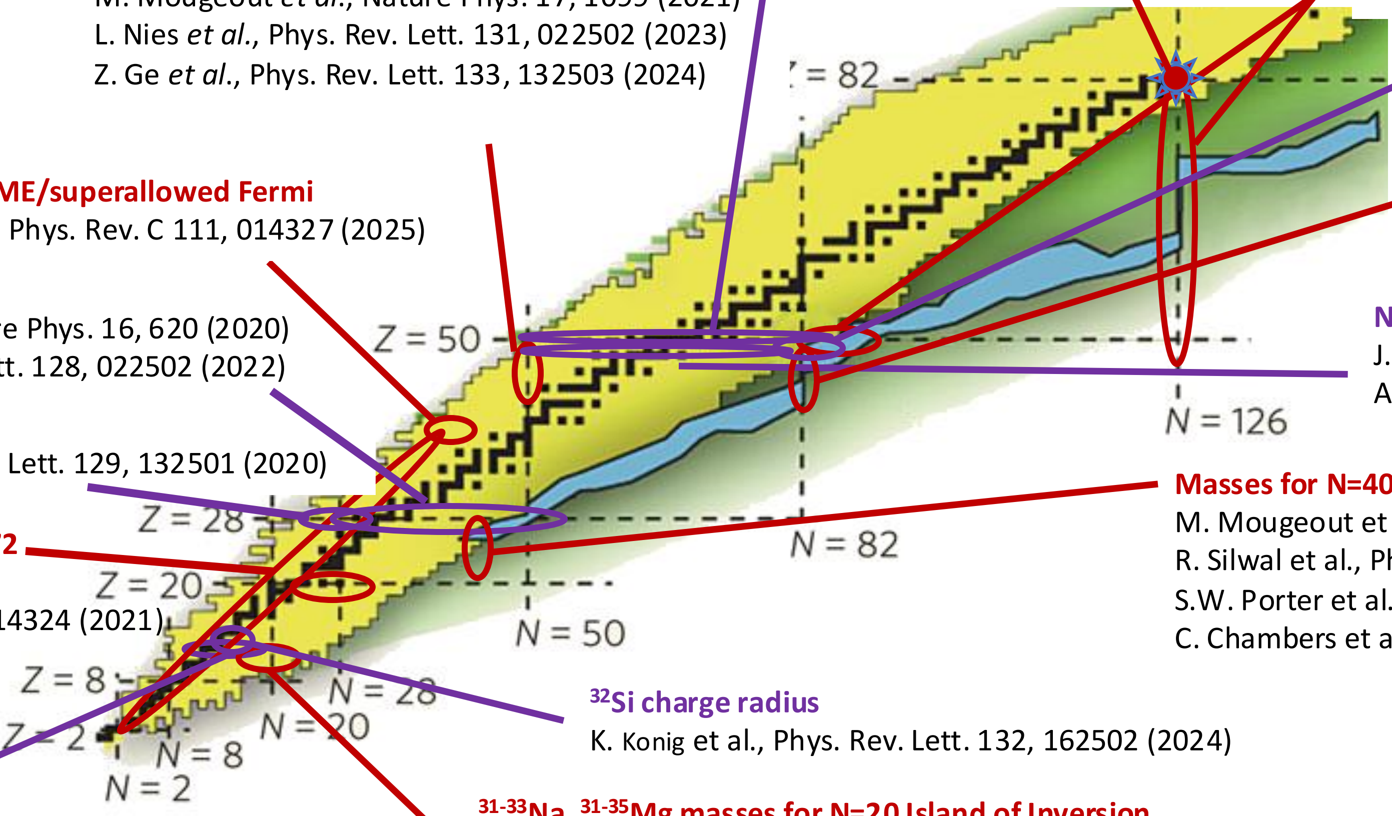
$^{74-76}$Sr masses for IMME/superallowed Fermi
Z. Hockenberry *et al.*, Phys. Rev. C 111, 014327 (2025)

Masses of Cd isotopes for N=82 shell closure
V. Manea et al., Phys. Rev. Lett. 124, 092502 (2020)

N=28-50 Ni and Cu radii
R.P. de Groote *et al.*, Nature Phys. 16, 620 (2020)
S. Malbrunot Phys. Rev. Lett. 128, 022502 (2022)

N=50-82 In radii for structure of ^{100}Sn
J. Karthein *et al.*, Nature Phys. 20, 1719 (2024)
A. R. Vernon et al., Phys. Rev. C (under review)

^{55,56}Ni radii
F. Sommer *et al.*, Phys. Rev. Lett. 129, 132501 (2020)



Masses for N=40 Island of Inversion
M. Mougeout et al., Phys. Rev. Lett. 120, 232501 (2018)
R. Silwal et al., Phys. Lett. B 833, 137288 (2022)
S.W. Porter et al., Phys Rev C 105, L041301 (2022)
C. Chambers et al., Phys. Rev. C (under review)

Isospin triplets from A=10-72 for ISB/Superallowed Fermi
M. Martin *et al.*, PRC 104, 014324 (2021)

^{32}Si charge radius
K. Konig et al., Phys. Rev. Lett. 132, 162502 (2024)

$^{27-32}$Al radii
H. Heylen *et al.*, Phys. Rev. C 103, 014318 (2021)

$^{31-33}$Na, $^{31-35}$Mg masses for N=20 Island of Inversion
E.M. Lykiardopoulou et al., Phys. Rev. Lett. 134, 052503 (2025)

Ab Initio VS-IMSRG Campaign: Spectra and EM Moments

Extensive campaign for nuclear structure, nuclear astrophysics, and searches for physics beyond the standard model

Magnetic moments from O to Bi
T.Miyagi *et al.*, Phys. Rev. Lett 104, 014324 (2021)

Spectroscopy of $^{126-136}$Sn and ^{129}Cd
T. Miyagi *et al.*, Phys. Rev. C 105, 014302 (2022)

0$^+$ states in ^{90}Kr
D. Walter *et al.*, Phys. Lett. B 862, 139352 (2025)

Spectroscopy of ^{132}Sn, ^{132}In and ^{131}Sb
K. Whitmore *et al.*, Phys. Rev. C 102, 024327 (2020)

EM Moments of 47,49Sc
S.W. Bai *et al.*, Phys. Lett B 829, 137064 (2022)

Reduced size of excited state isomer in ^{129,131}In
A. Vernon et al., Phys. Rev. Lett. (under review)

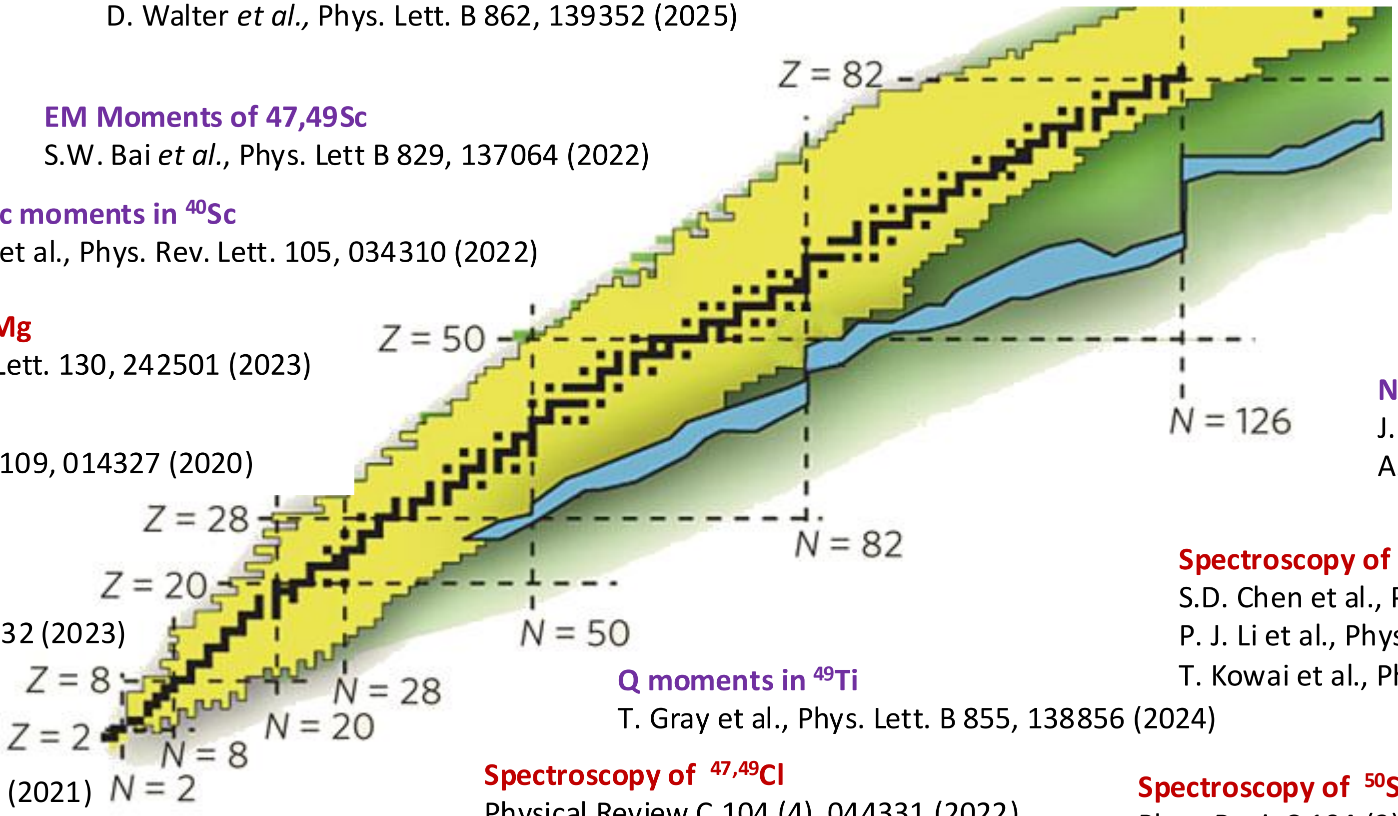
Magnetic moments in ^{40}Sc
R Powel et al., Phys. Rev. Lett. 105, 034310 (2022)

EM moments of neutron-rich Sb isotopes
S. Lecher *et al.*, Phys. Lett. B 847, 138278 (2024)

Microsecond Isomer in ^{32}Mg
T.J. Gray *et al.*, Phys. Rev. Lett. 130, 242501 (2023)

N=50-82 In EM moments
J. Karthein *et al.*, Nature Phys. 20, 1719 (2024)
A. R. Vernon et al., Phys. Rev. C (under review)

Q moments of ^{32}Si
J. Heery *et al.*, Phys. Rev. C 109, 014327 (2020)



Spectroscopy of neutron-rich Ca isotopes
S.D. Chen et al., Phys. Lett. B 843 138025 (2023)
P. J. Li et al., Phys. Lett. B 855, 138828 (2024)
T. Kowai et al., Phys. Lett. B 827, 136952 (2022)

B(E2) in ^{23}Mg
Physical Review C 105, 034332 (2023)

Q moments in ^{49}Ti
T. Gray et al., Phys. Lett. B 855, 138856 (2024)

Spectroscopy of ^{42}Sc
Physics Letters B 819, 136439 (2021)

Spectroscopy of ^{47,49}Cl
Physical Review C 104 (4), 044331 (2022)

Spectroscopy of ^{50}Sc and ^{50}Ti
Phys. Revi. C 104 (2), 024314 (2021)

Spectroscopy of ^{23}F
H. Crawford *et al.*, Phys. Rev. C 103, L061303 (2022)

Spectroscopy of ^{49,50}Ar for N=32
B.D. Linh et al., Phys. Rev. C 109, 043312 (2024)
Physical Review C 102 (6), 064320 (2020)

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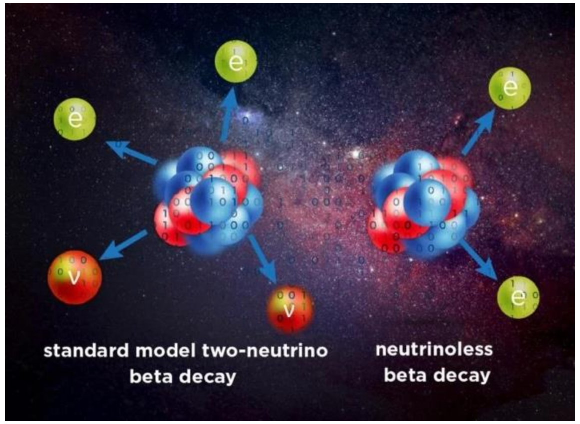
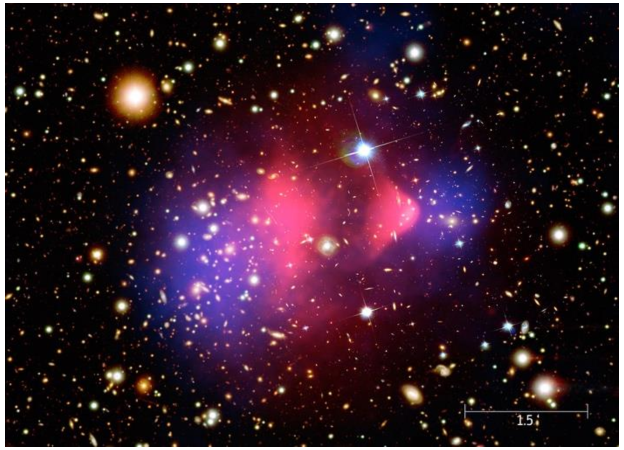
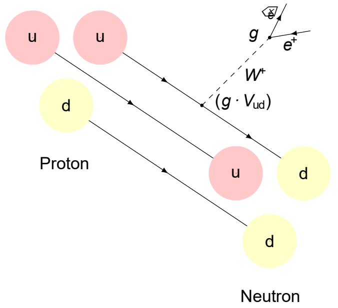
Searches for BSM Physics



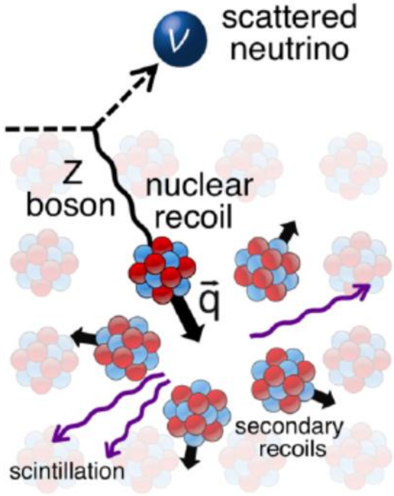
Neutrinoless double-beta decay



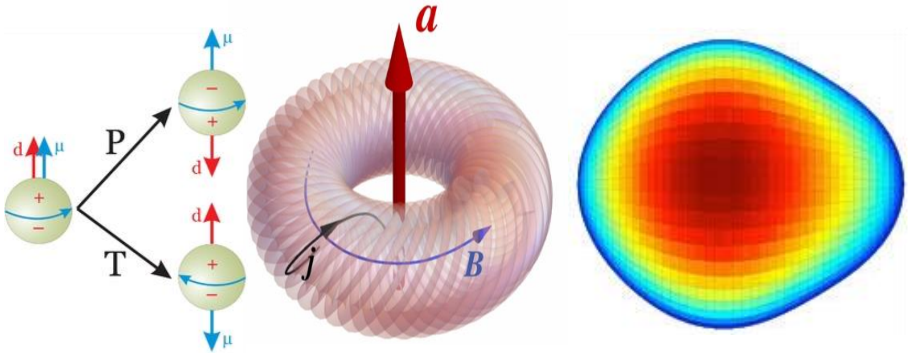
Dark matter direct detection



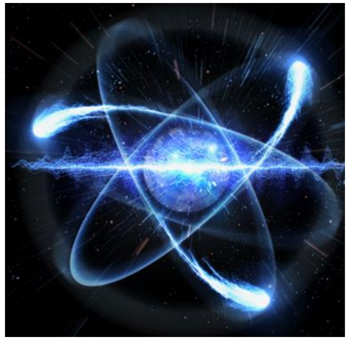
Superallowed Fermi transitions



Neutrino scattering



Symmetry-violating moments



Atomic theory

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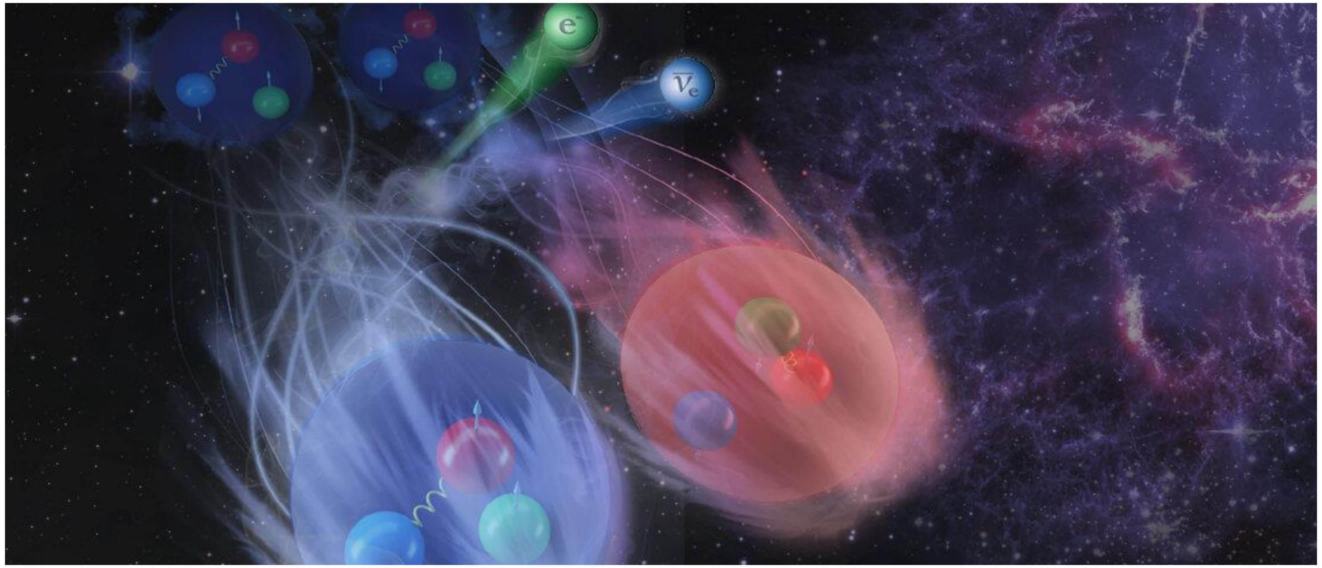
Milestone Result

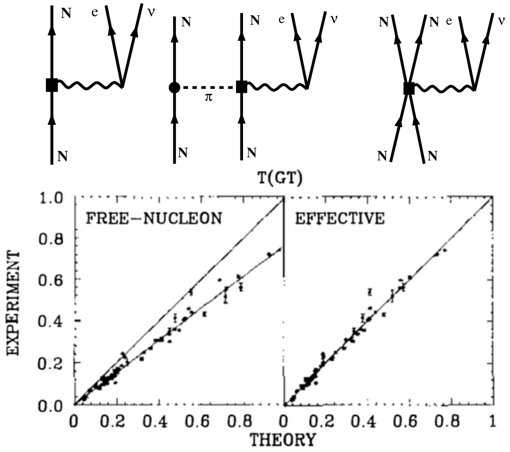
Two-Body Currents for Gamow-Teller Transitions and g_A Quenching

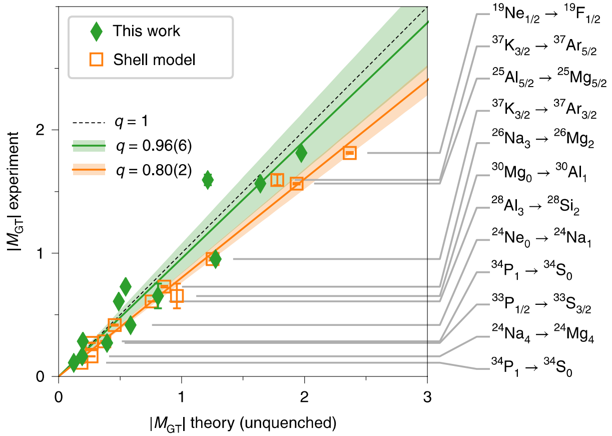
Ab initio survey of **GT matrix elements**

- Many-body correlations
- Consistent NN+3N forces + 2BC

Broad experimental agreement with g_A=1.25







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

$0\nu\beta\beta$ Decay for All Major Players: ^{76}Ge ^{100}Mo, ^{130}Te, ^{136}Xe

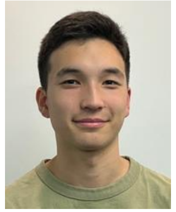
A. Belley

L. Jokiniemi

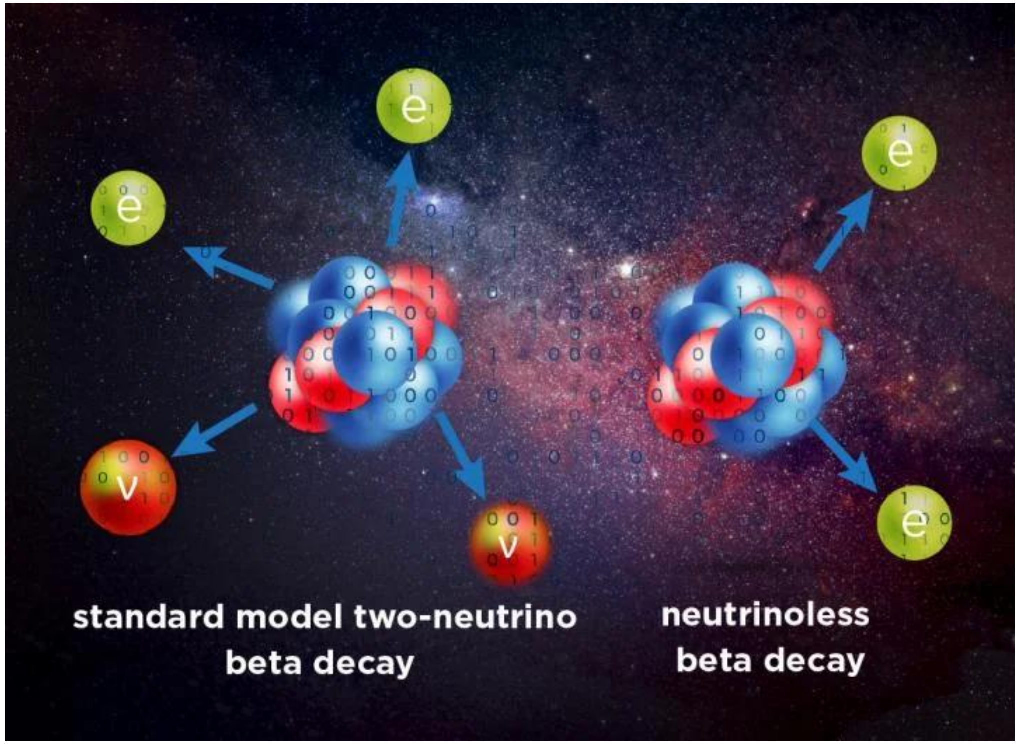
I. Ginnett

J. Pitcher

A. Todd



T. Shickele



Ab Initio Neutrinoless Double-Beta Decay Matrix Elements for ^{48}Ca, ^{76}Ge, and ^{82}Se

A. Belley, C. G. Payne, S. R. Stroberg, T. Miyagi, and J. D. Holt
Phys. Rev. Lett. **126**, 042502 – Published 29 January 2021

Ab initio uncertainty quantification of neutrinoless double-beta decay in Ge

Phys. Rev. Lett.

A. Belley, J. M. Yao, B. Bally, J. Pitcher, J. Engel, H. Hergert, J. D. Holt, T. Miyagi, T. R. Rodríguez, A. M. Romero, S. R. Stroberg, and X. Zhang

Physical Sciences - Article

Ab initio calculations of neutrinoless $\beta\beta$ decay refine neutrino mass limits

Status: Under Review

Jason Holt, Antoine Belley, Takayuki Miyagi, Steven Stroberg

nature portfolio

The Year(s) We Lost Hope: Leading-Order Contact

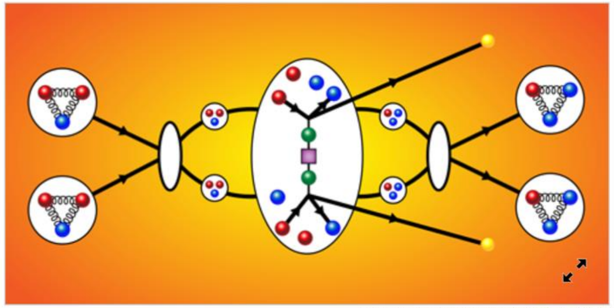
Proper renormalization requires short-range contact term at leading order

Physics — SYNOPSIS

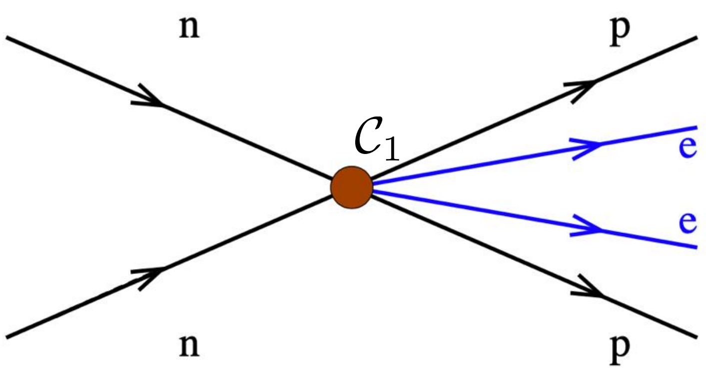
A Missing Piece in the Neutrinoless Beta-Decay Puzzle

May 16, 2018 • *Physics* 11, s58

The inclusion of short-range interactions in models of neutrinoless double-beta decay could impact the interpretation of experimental searches for the elusive decay.



J. de Vries/Nikhef; adapted by APS/Alan Stonebraker



New physics inside blob:
High-energy ν exchange

V. Cirigliano et al. PRL (2018), PRL (2022)

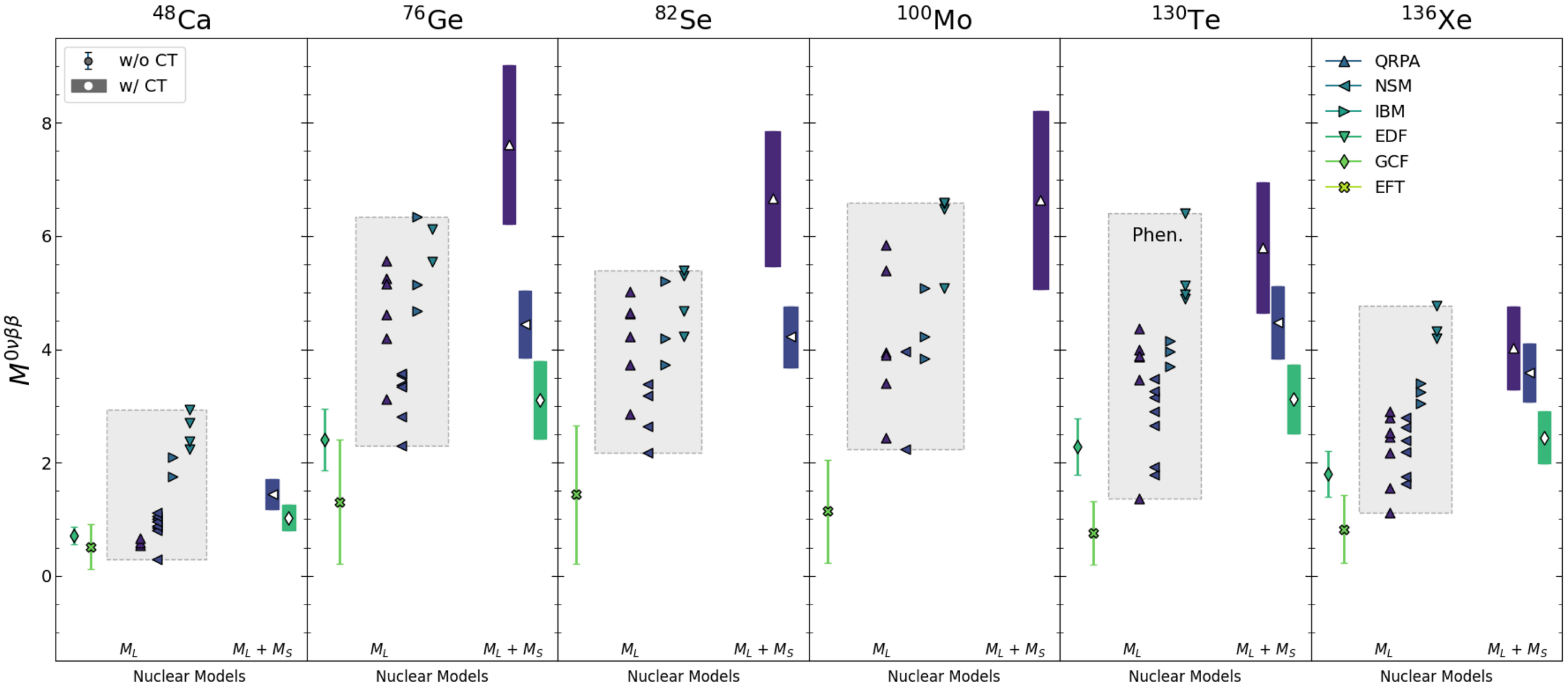
New paradigm for 0νββ decay: include long- and short-range terms

$$M^{0\nu} \rightarrow M_{\rm L} + M_{\rm S} = M_{\rm GT} + \frac{M_{\rm F}}{g_A^2} + M_{\rm T} + M_{\rm CT}$$

Estimated to ~30% - no consistent way to assess with phenomenology

(More) Current Status of NMEs

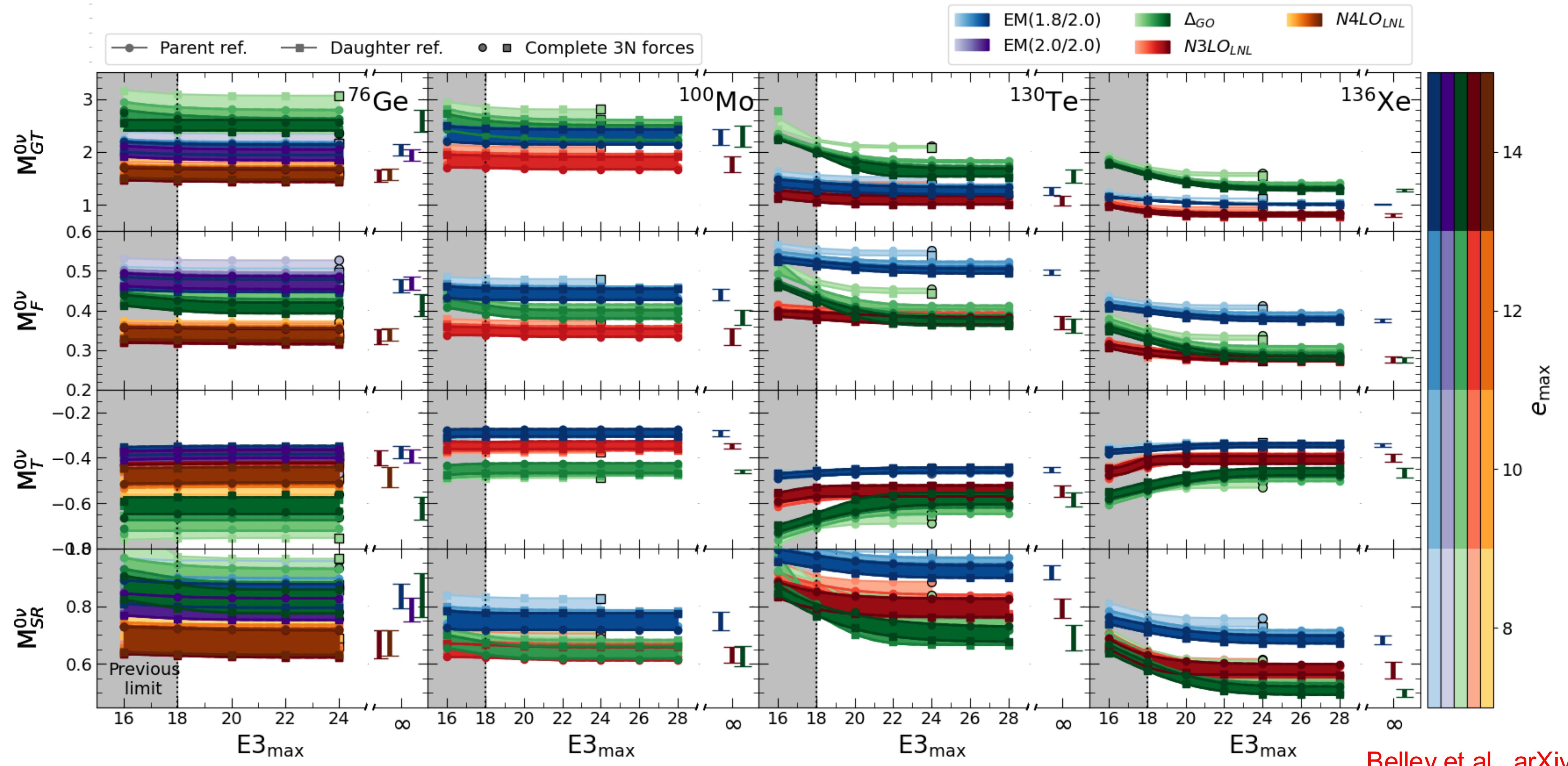
Compiled values updated w/ phenomenology + short-range contact



New(er) results increase factors up to >10 uncertainty 😬 can we do better?

Ab Initio Strategy: Predict in Heavy Nuclei

Converged NMEs for major players in global searches: ^{76}Ge, ^{100}Mo, ^{130}Te, ^{136}Xe



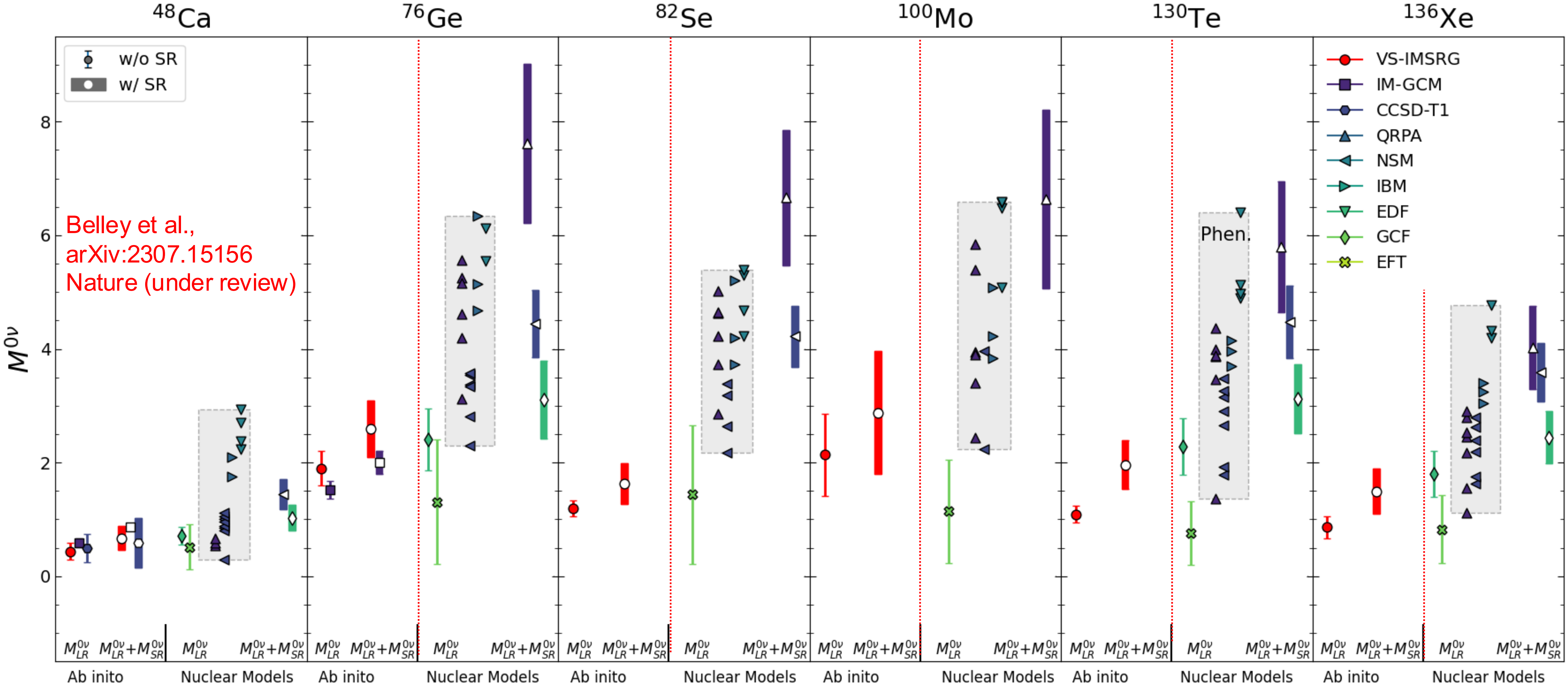
Belley et al., arXiv:2307.15156
Nature (under review)

TRIUMF

Ab Initio Strategy: Predict in Heavy Nuclei

Converged NMEs for major players in global searches: ^{76}Ge, ^{100}Mo, ^{130}Te, ^{136}Xe

Ab initio results: differences from models; **large NMEs *strongly* disfavored**



TRIUMF

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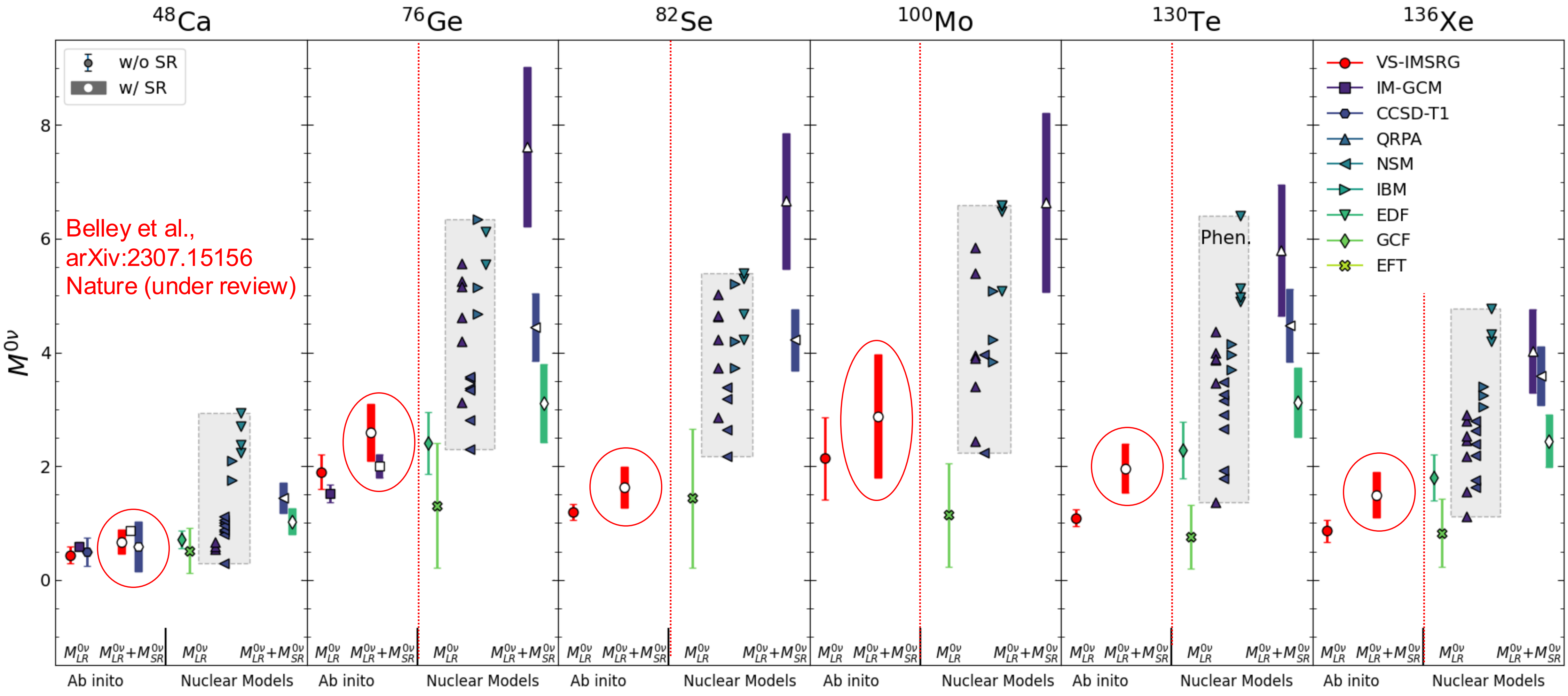
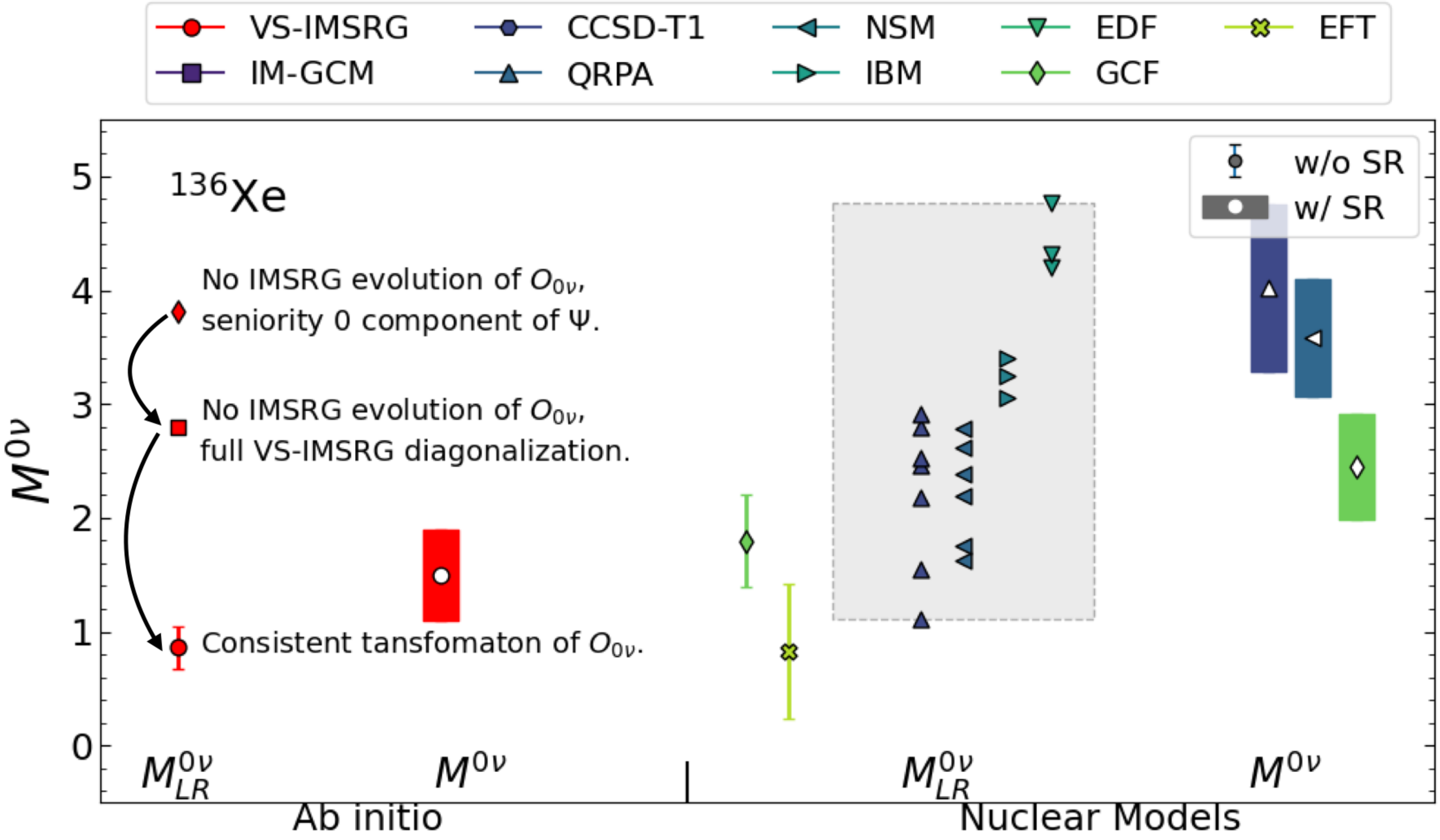


Why Small Matrix Elements?

Correlations in wavefunction and operator drive small NMEs

Ab initio results: differences from models; **large NMEs *strongly* disfavored**

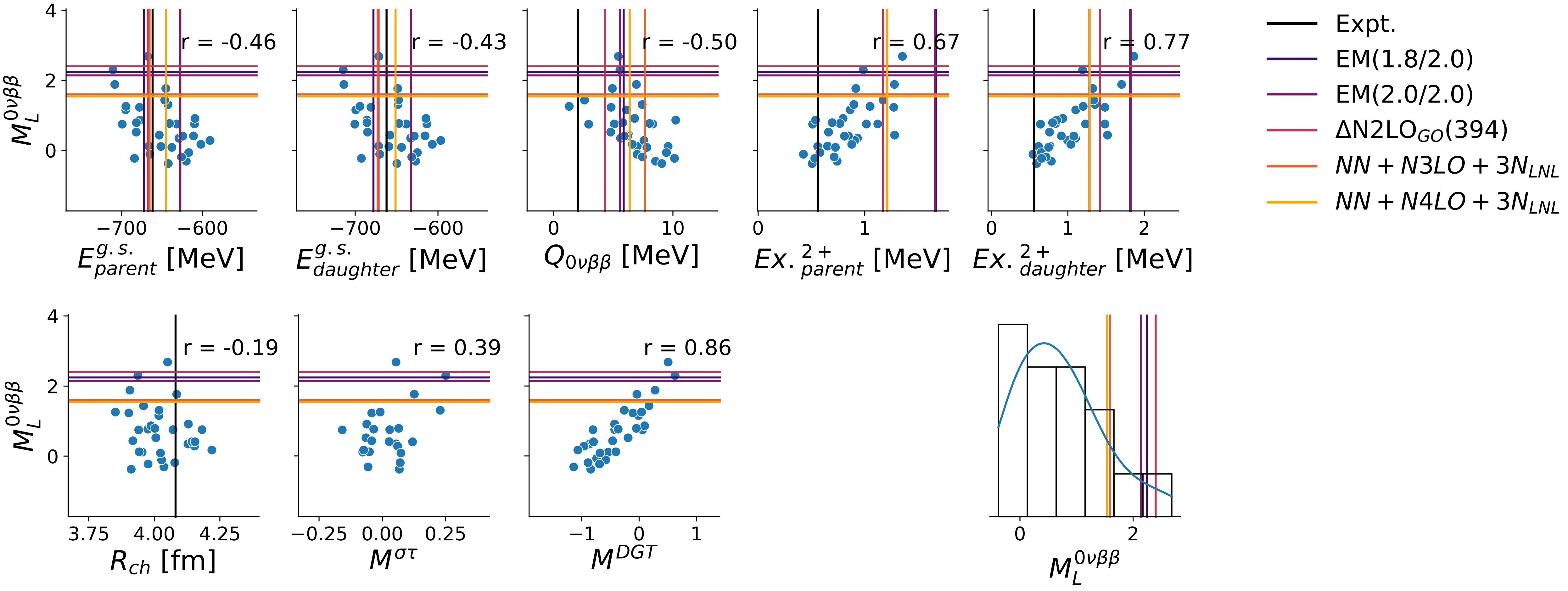


Ab Initio Strategy: Explore Correlations

TRIUMF

^{76}Ge: Explore correlations with other observables from 34 interactions

No obvious correlations, except DGT



Use machine learning for further insights?

Belley et al., arXiV:2210.05809
Yao, Ginnett, Belley et al., PRC (2022)

Ab Initio Strategy: Explore Correlations

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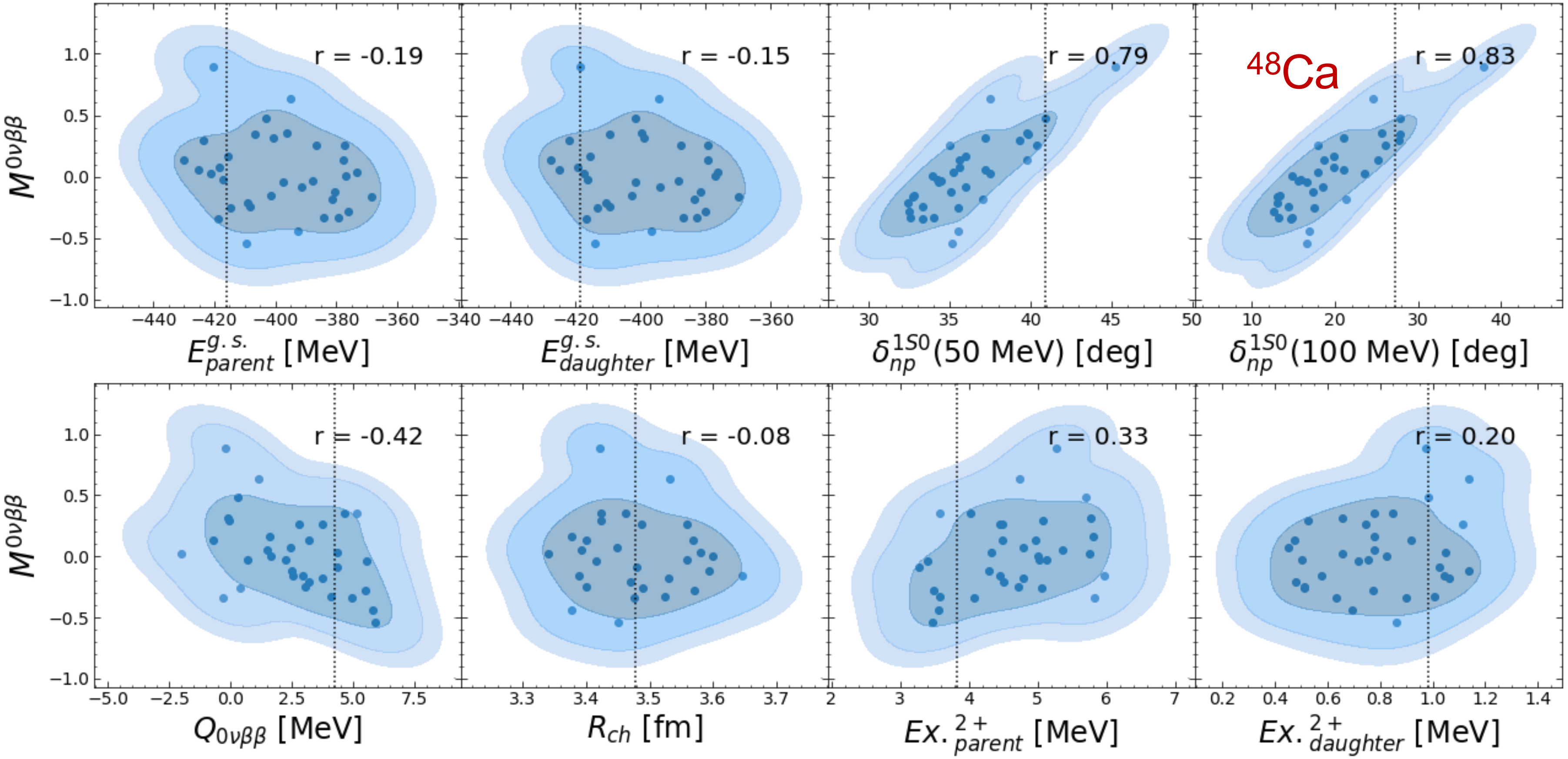

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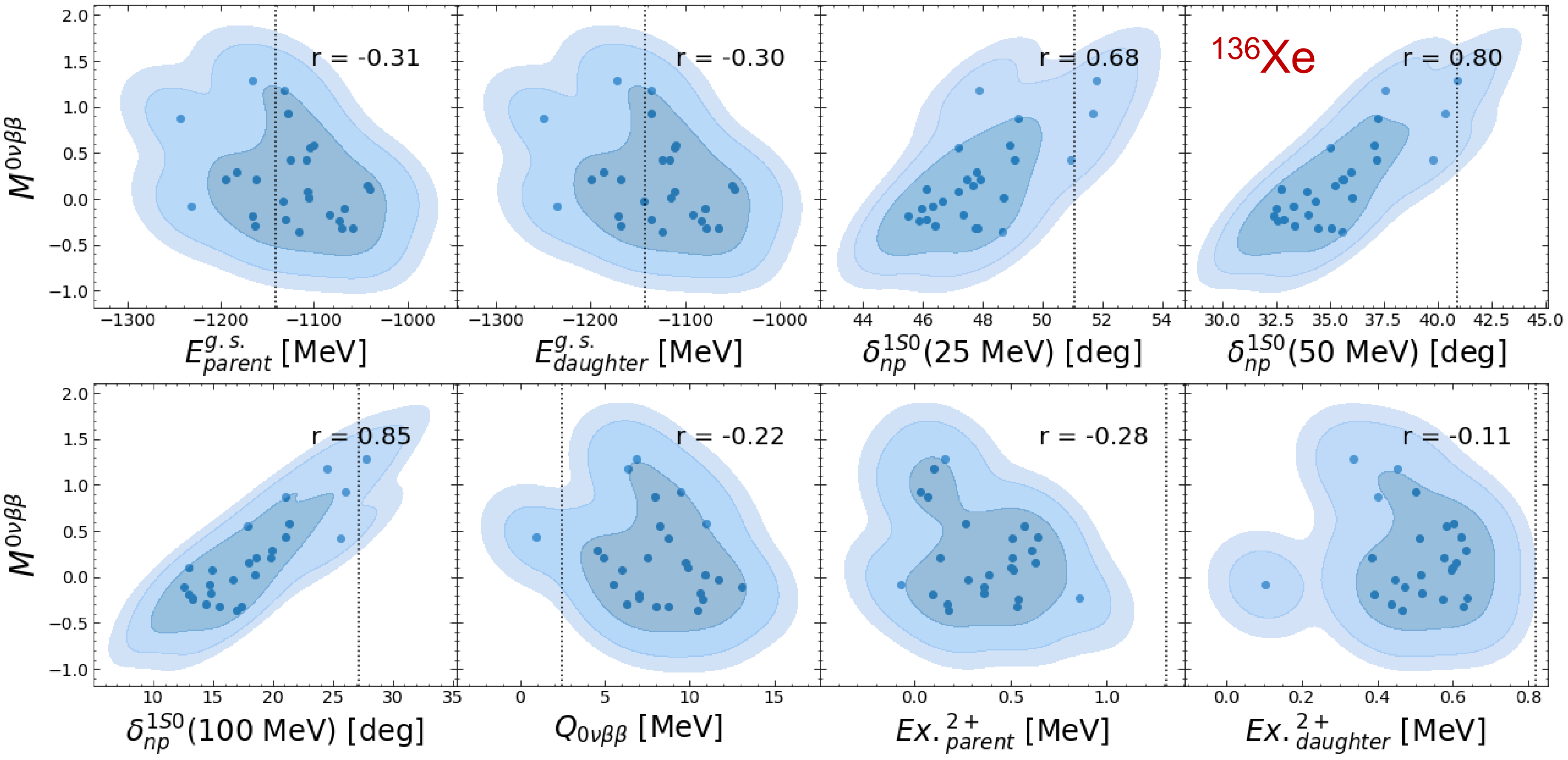


Use machine learning for further insights?

Belley et al., arXiV:2210.05809
Yao, Ginnett, Belley et al., PRC (2022)

Machine Learning for Sensitivity Analysis

TRIUMF

Explore dependence on chiral EFT LECs: requires many samples (as in ^{208}Pb)

Use gaussian processes as an emulator

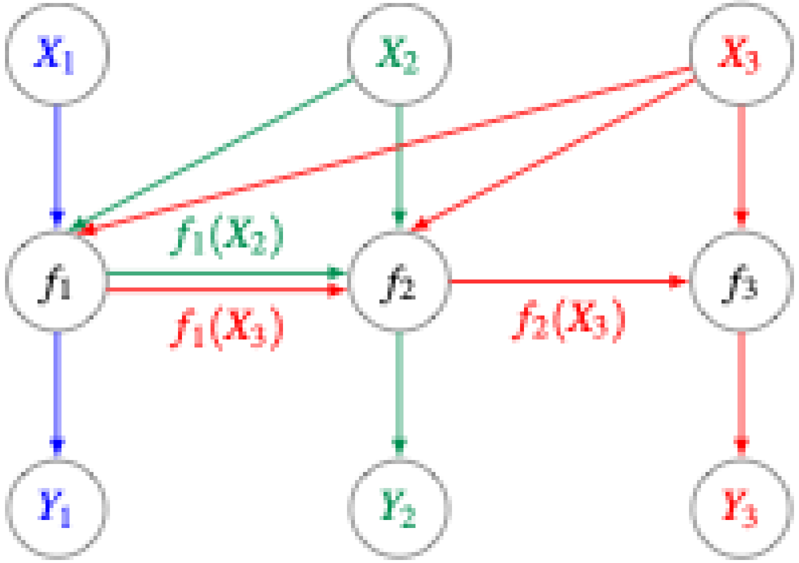
Multi-Fidelity Gaussian Process: connects few (complicated) high-fidelity data points (e.g., full IMSRG) w/ many low-fidelity data points (HF, low e_{max}, etc)

Difference function fit with Gaussian process: predict HF from LF

Deep Gaussian Process: Neural network links multiple GP

Include outputs of previous fidelity as new HF point:
  Improves modeling of difference between LF and HF

Adapted for multi output:
Multi-Output Multi-Fidelity Deep Gaussian Process (MM-DGP)

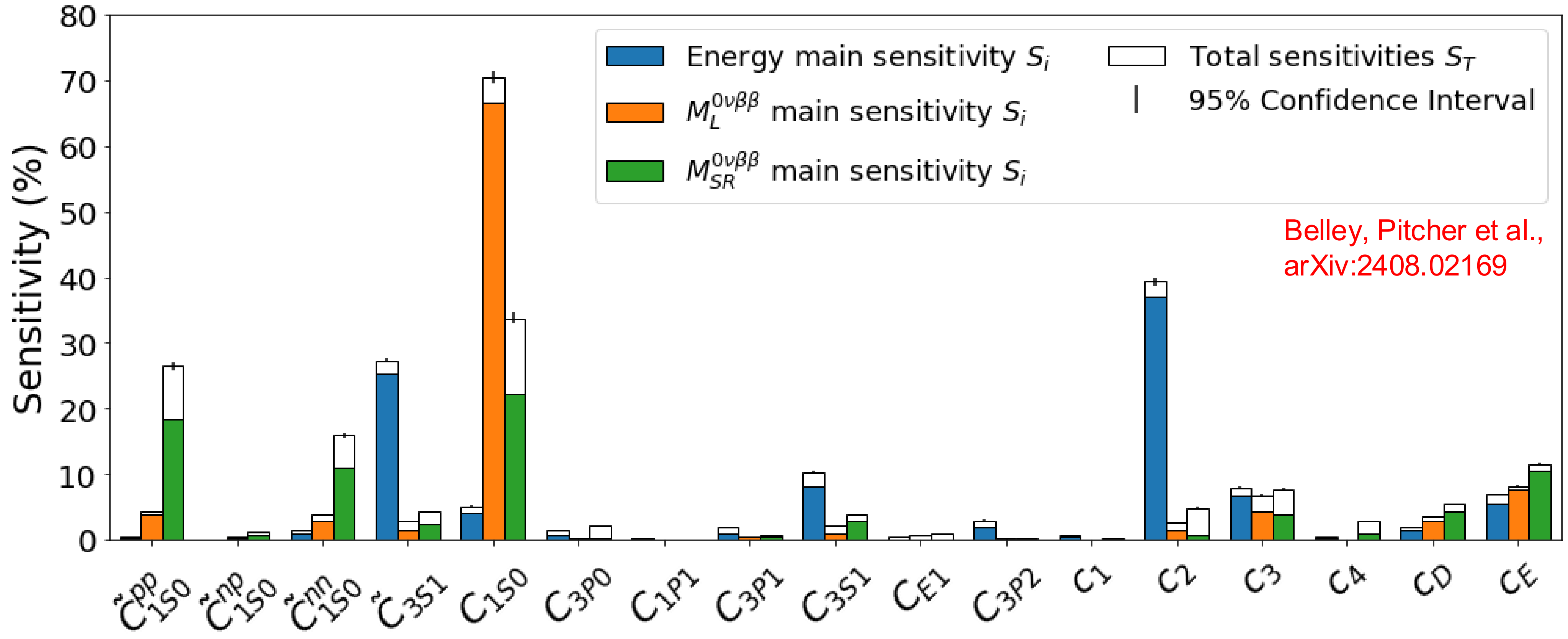


Belley, Pitcher et al., in preparation

MM-DGP Emulator for IMSRG: Sensitivity Analysis

Newly developed MM-DGP data-driven emulator for VS-IMSRG

Sensitivity analysis: Connect long-range $0\nu\beta\beta$ decay to terms in nuclear forces



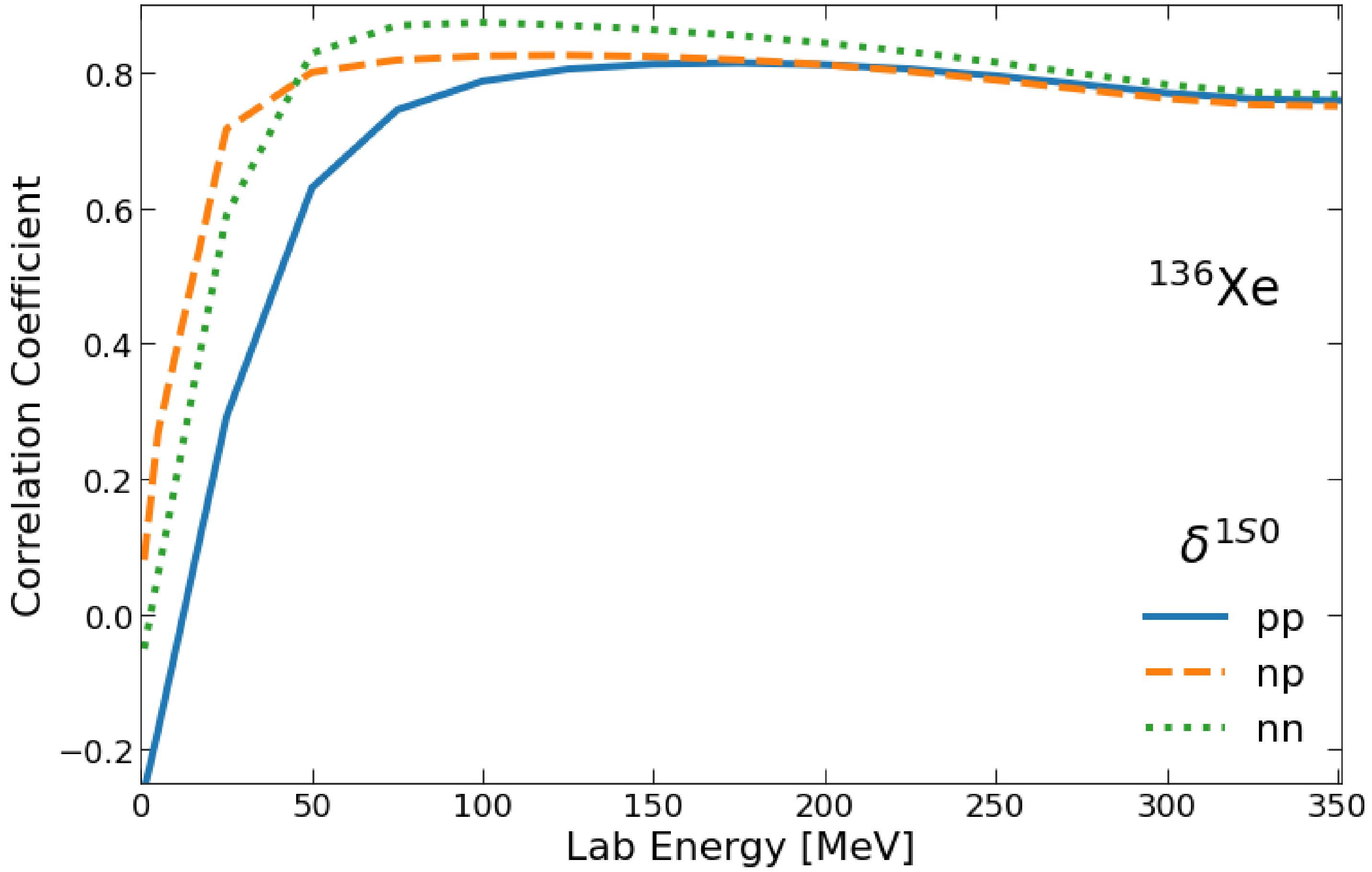
Belley, Pitcher et al., arXiv:2408.02169

Highly sensitive to single constant "C1S0" – related to $^1S_0$ phase shift

MM-DGP Emulator: Correlation w/ $^1S_0$ Phase Shift

Clear correlation with $^1S_0$ phase-shift

Strong correlation emerges for energies > 50MeV



Belley, Pitcher et al., arXiv:2408.02169

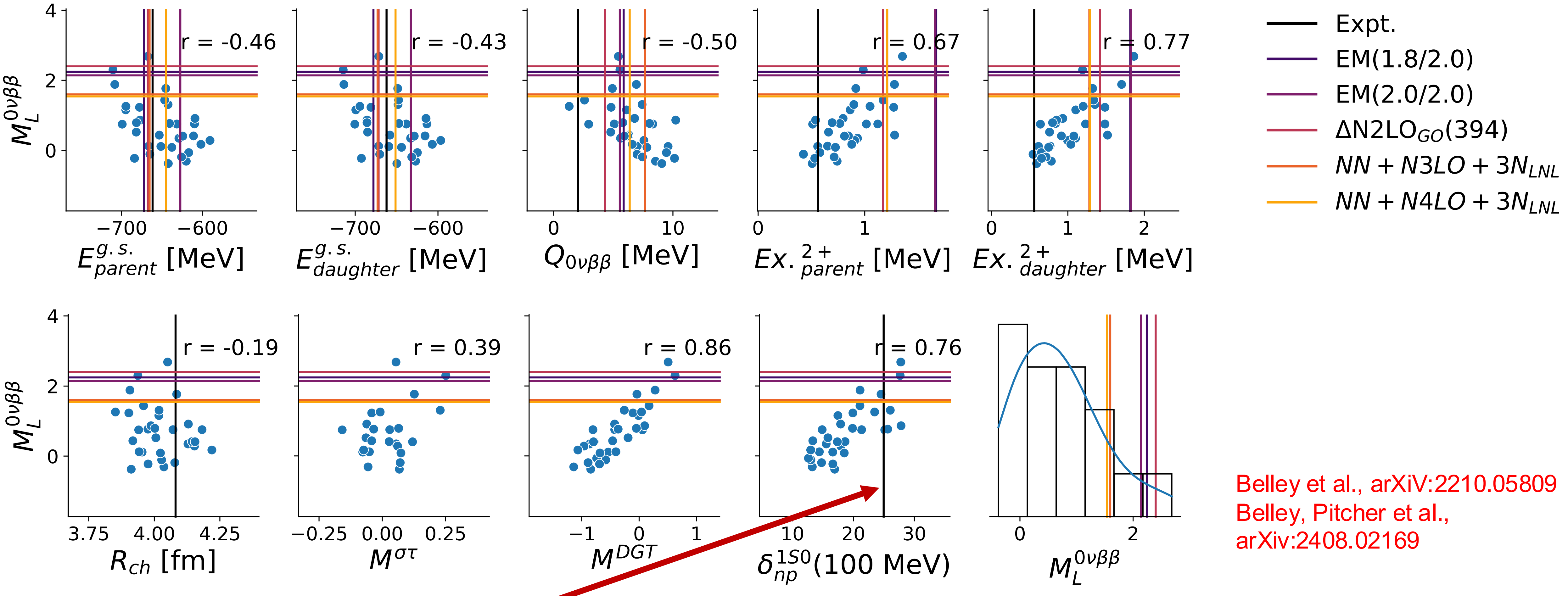
Constrained by part of interaction for the two nucleons when “close” to each other

TRIUMF

Ab Initio Strategy: Explore Correlations

Explore correlations with other observables from systematic analysis (34 interactions)

Few clear correlations, except DGT in ^{76}Ge



Belley et al., arXiV:2210.05809
Belley, Pitcher et al., arXiv:2408.02169

Novel correlation with **measured** $^1S_0$ phase shift!

TRIUMF

Rigorous Ab Initio Uncertainties for ^{76}Ge

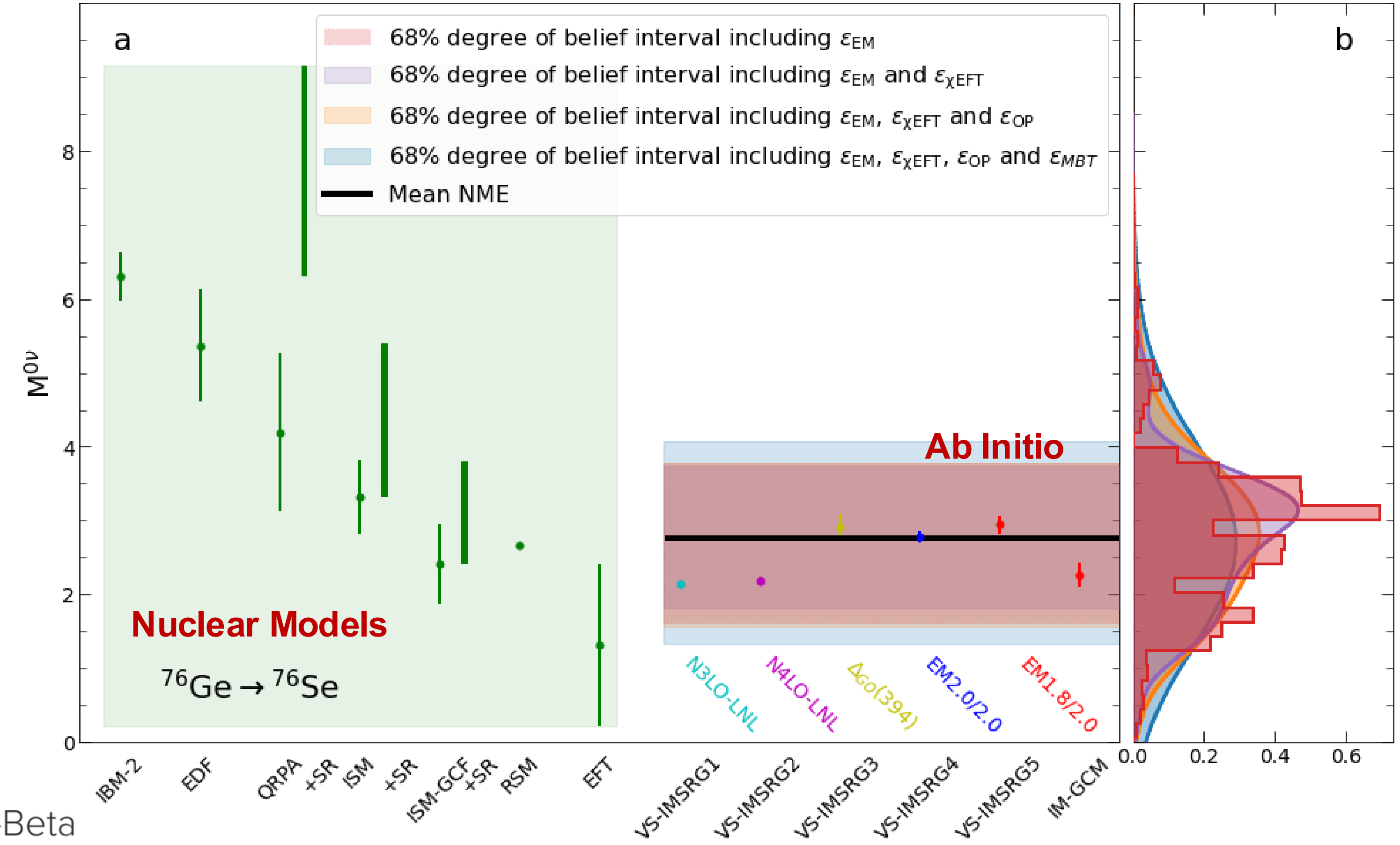
Consider *all* physics contributing to theoretical error in $0\nu\beta\beta$ decay

$$y = y_{\mathrm{MM-DDGP}} + \epsilon_{\mathrm{emulator}} + \epsilon_{\mathrm{EFT}} + \epsilon_{\mathrm{many-body}} + \epsilon_{\mathrm{operator}}$$

Nuclear many-body problem treated w/ newly developed ML emulators

Construct PPD for NME in ^{76}Ge

Dramatically reduced uncertainty compared to nuclear models



Ab Initio Uncertainty Quantification of Neutrinoless Double-Beta Decay in ^{76}Ge

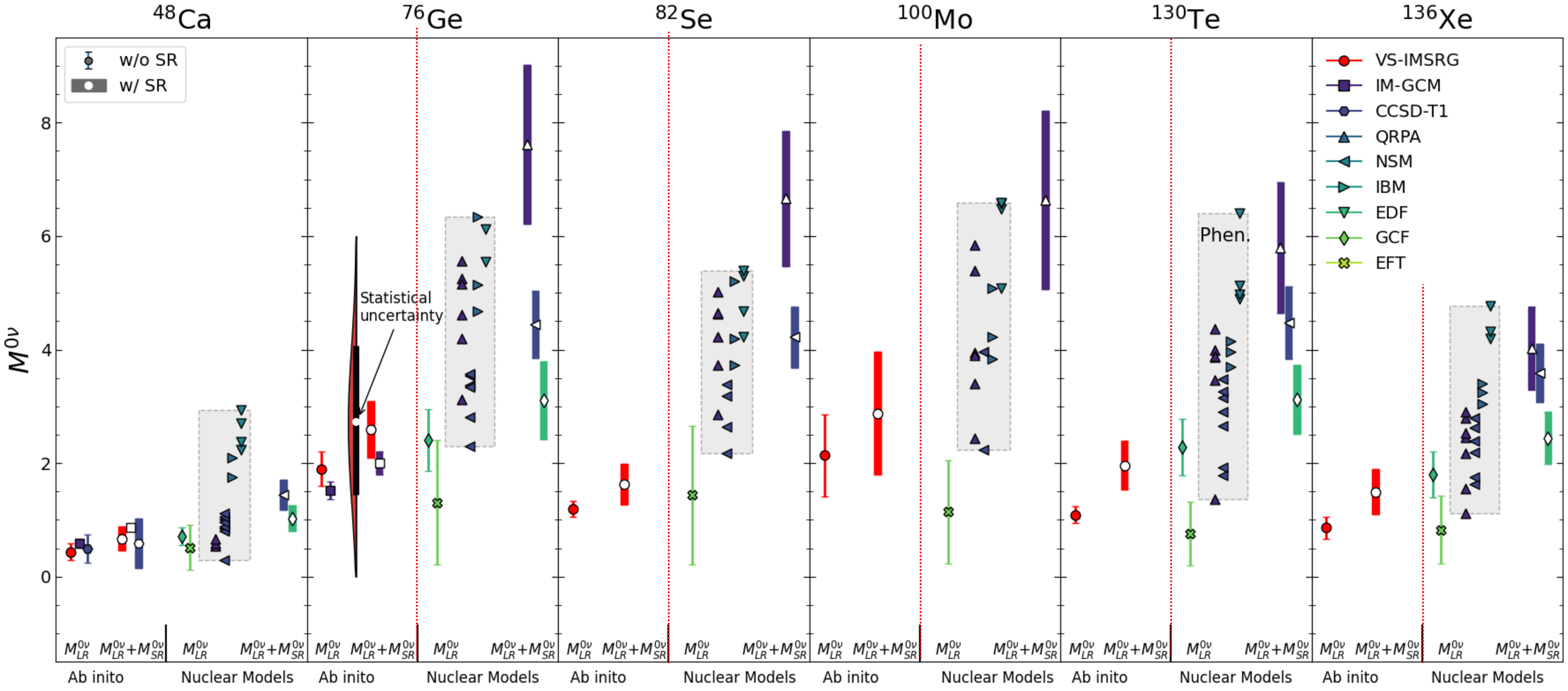
A. Belley, J. M. Yao (尧江明), B. Bally, J. Pitcher, J. Engel, H. Hergert, J. D. Holt, T. Miyagi, T. R. Rodríguez, A. M. Romero, S. R. Stroberg, and X. Zhang (张馨)

Phys. Rev. Lett. **132**, 182502 – Published 30 April 2024

Updated Predictions in Heavy Nuclei

Converged NMEs for major players in global searches: ^{76}Ge, ^{100}Mo ^{130}Te, ^{136}Xe

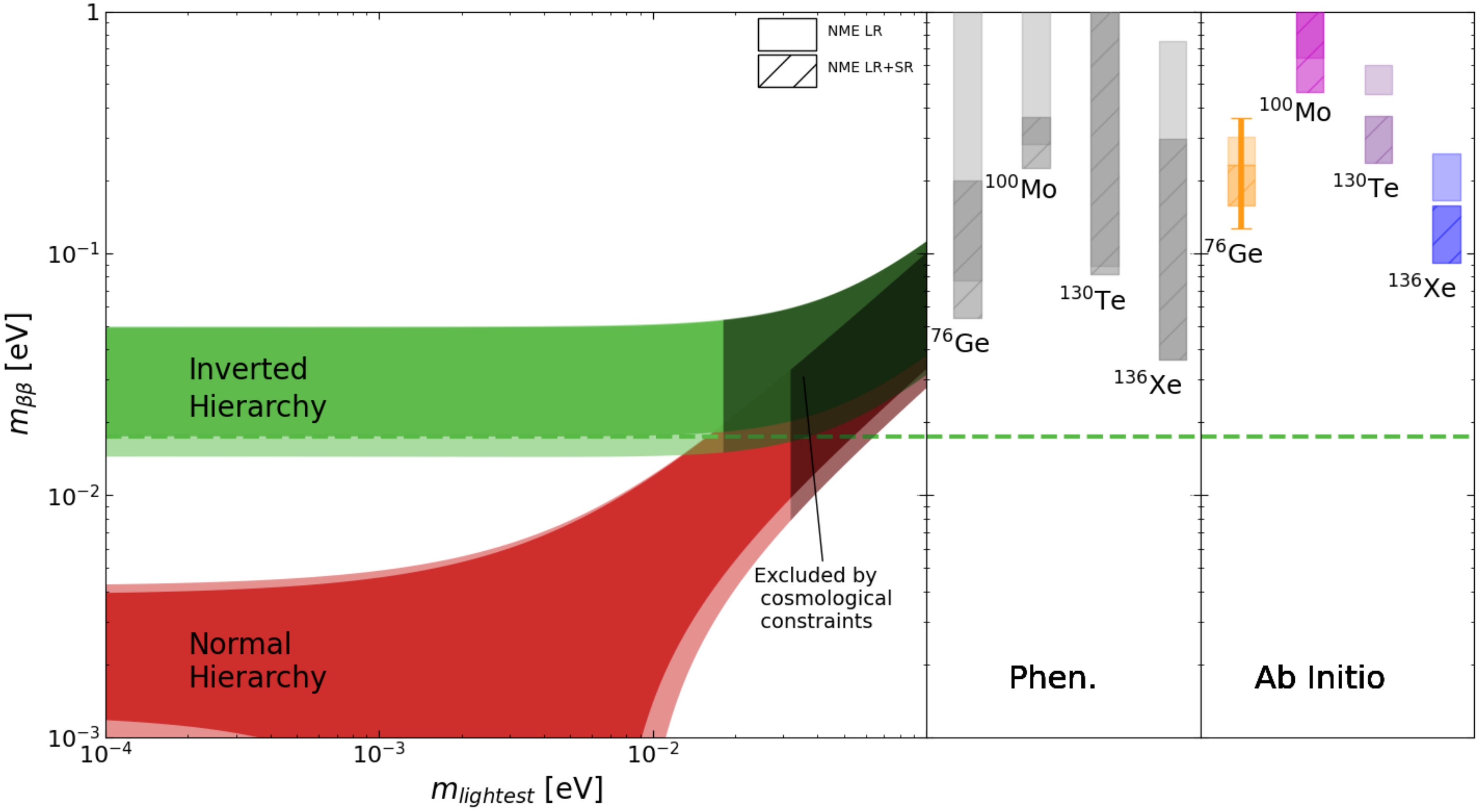
Independent PPD agrees with previous spread



Ab Initio Strategy: Impact on Worldwide Searches

Impact for current searches: large matrix elements disfavored, lowers expected rates

Current experimental reach – improved with effects of contact term



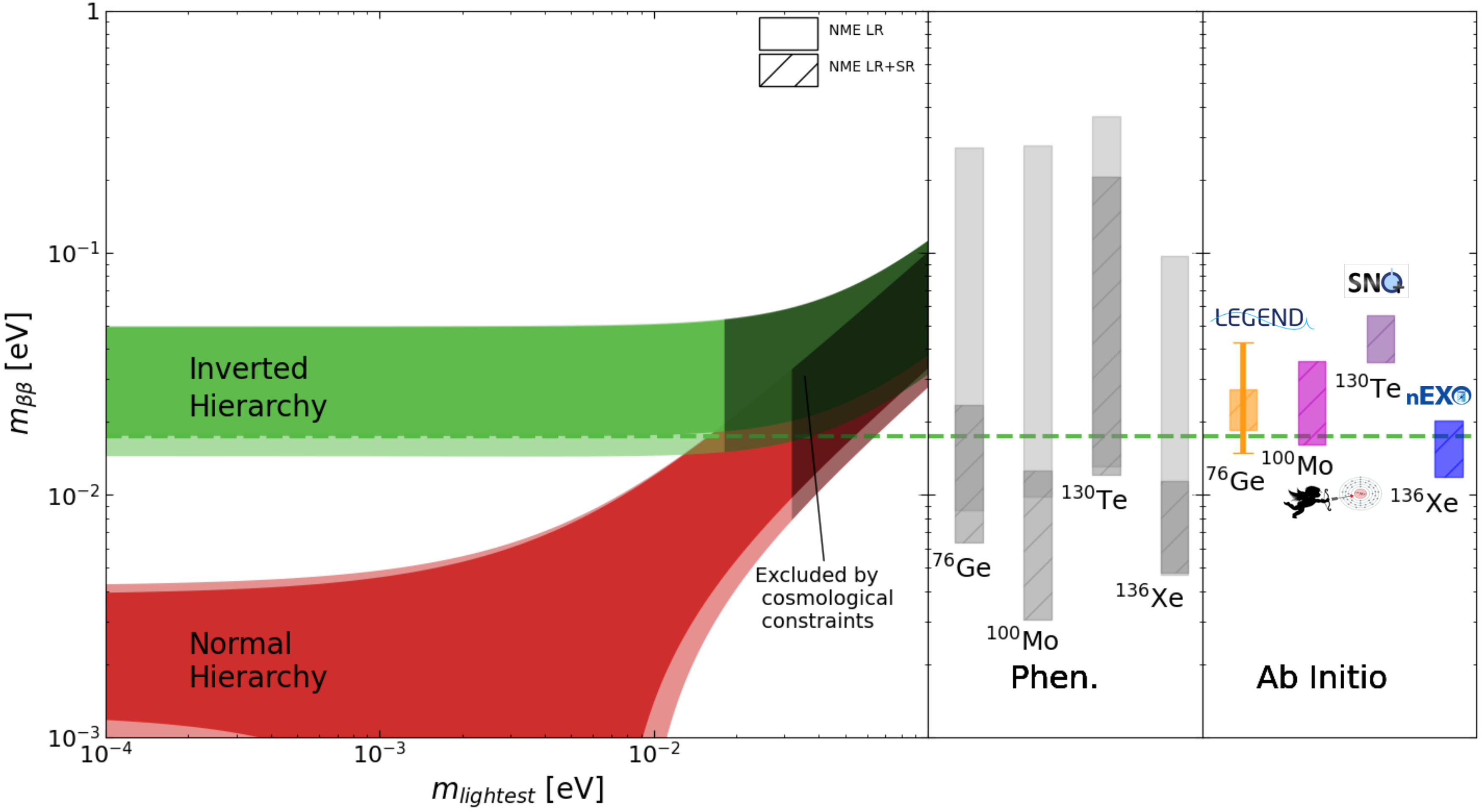
***Highly unlikely* inverted Hierarchy has been probed**

Belley et al, arXiv:2307.15156
Nature (under review)

Ab Initio Strategy: Impact on Ton-Scale Searches

Impact for next-generation searches: sensitivities from LEGEND, SNO+, nEXO, CUPID

Effect of short-range term improves experimental reach… **^{100}Mo now a major player**



Uncertainty reduced by ***over one order of magnitude*!**

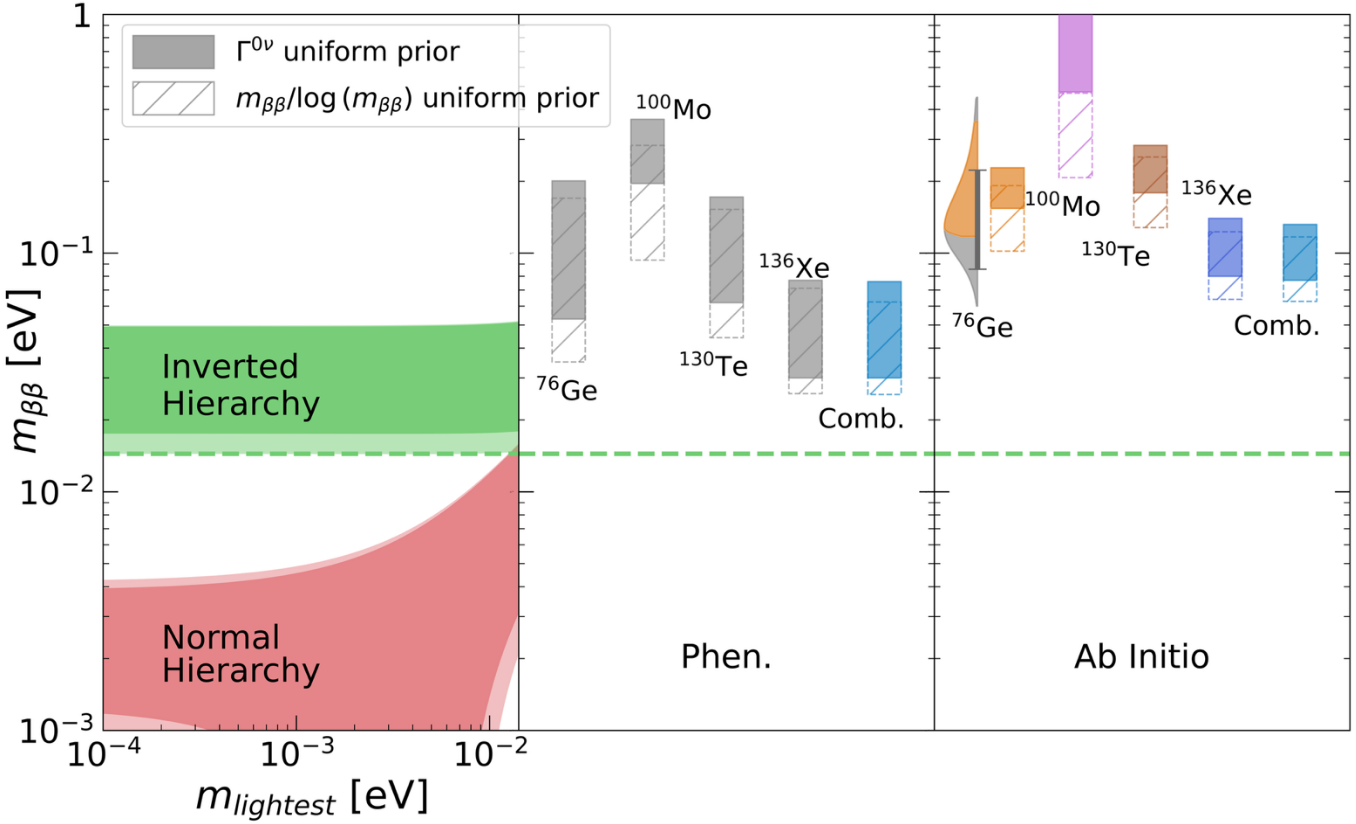
Belley et al, arXiv:2307.15156
Nature (under review)

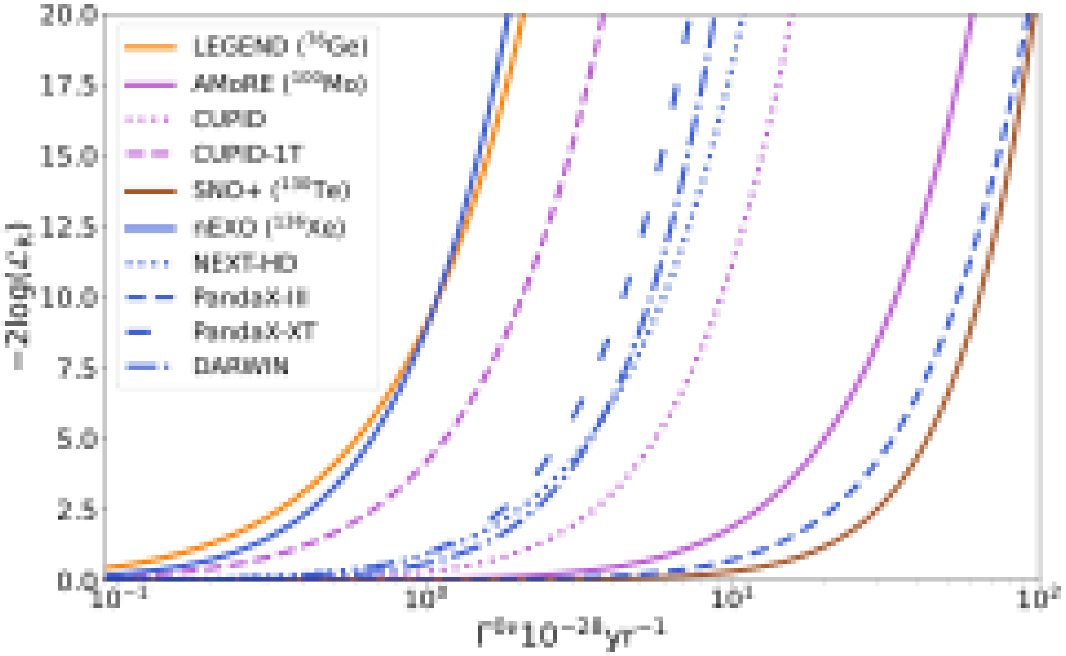
Combined Limits: Likelihood Functions

Obtain likelihood functions from experiments – convert decay rates to $m_{\beta\beta}$

$$m_{\beta\beta} = \frac{m_e}{g_A^2 |M^{0\nu}|} \sqrt{\frac{\Gamma^{0\nu}}{G^{0\nu} \log 2}}$$

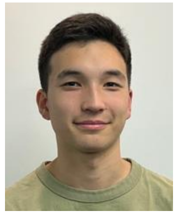
Likelihoods allow combined limit via Bayes' Theorem





Analysis based on S. Biller PRD (2021)

Combined ab initio limits:
IH fully probed with multiple isotopes



Shickele et al., in prep

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TRIUMF

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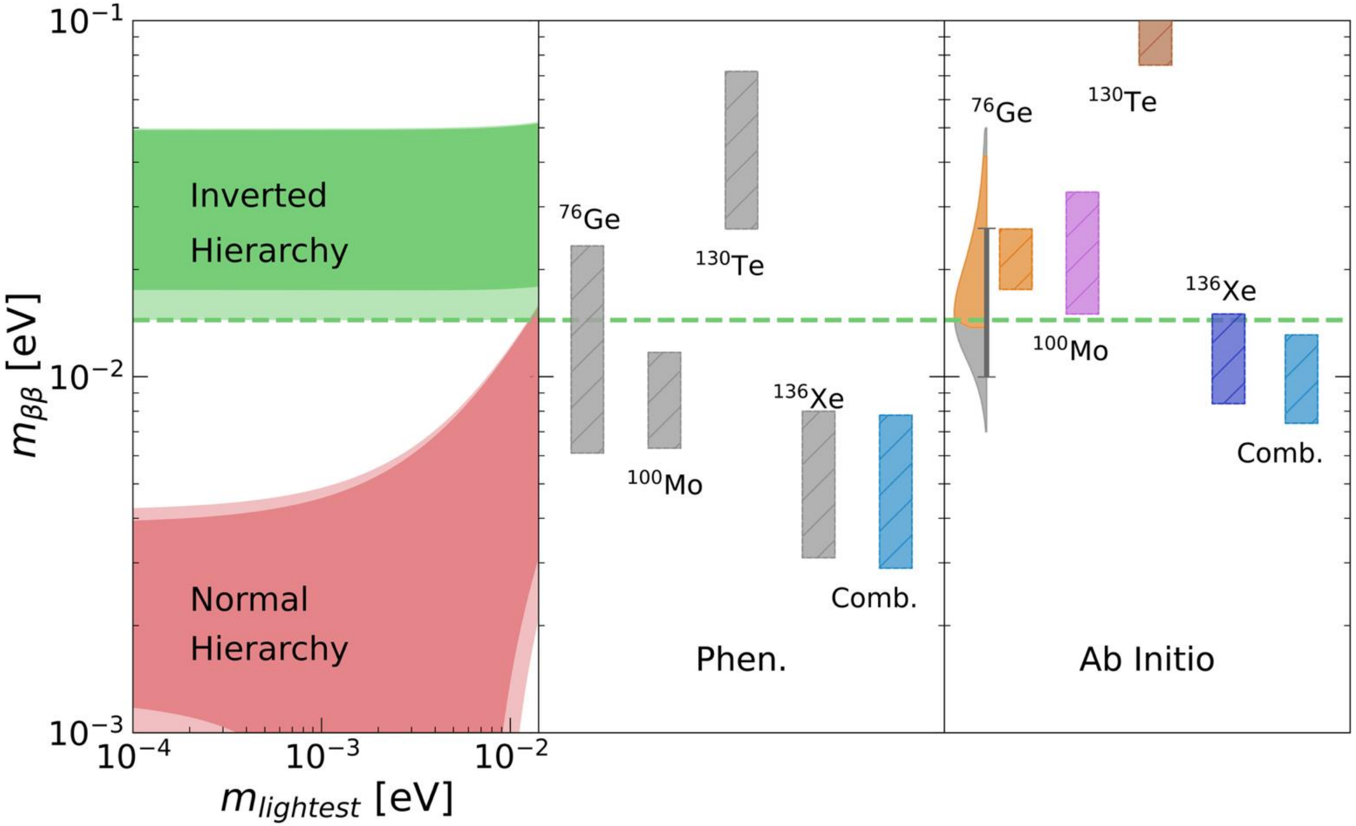

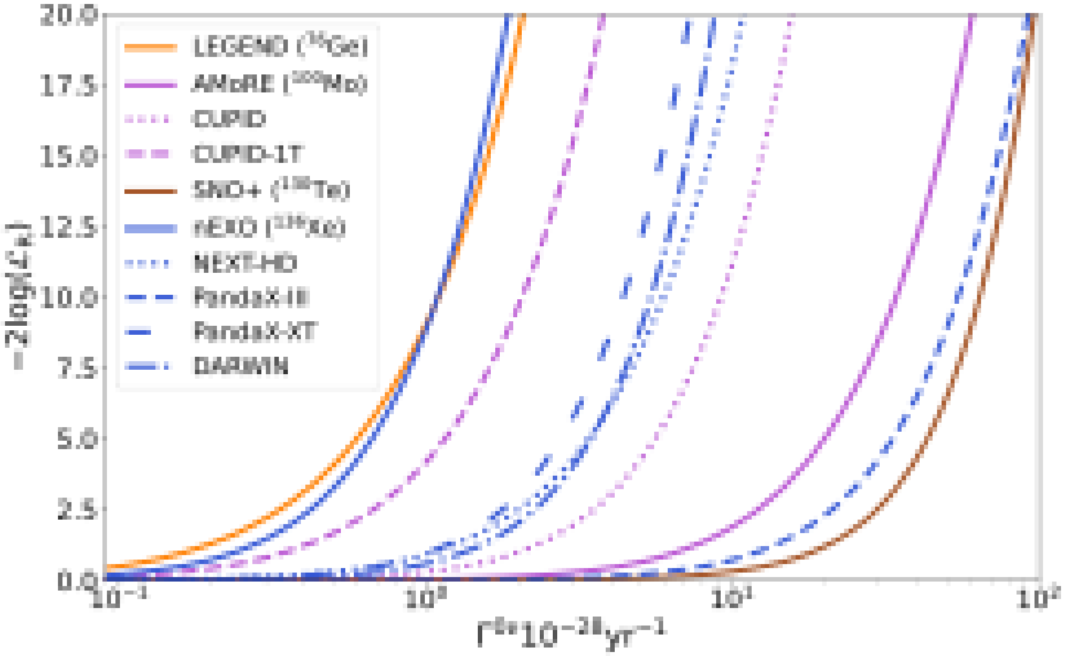

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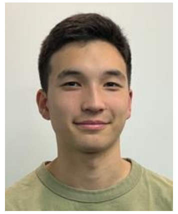

Shickele et al., in prep

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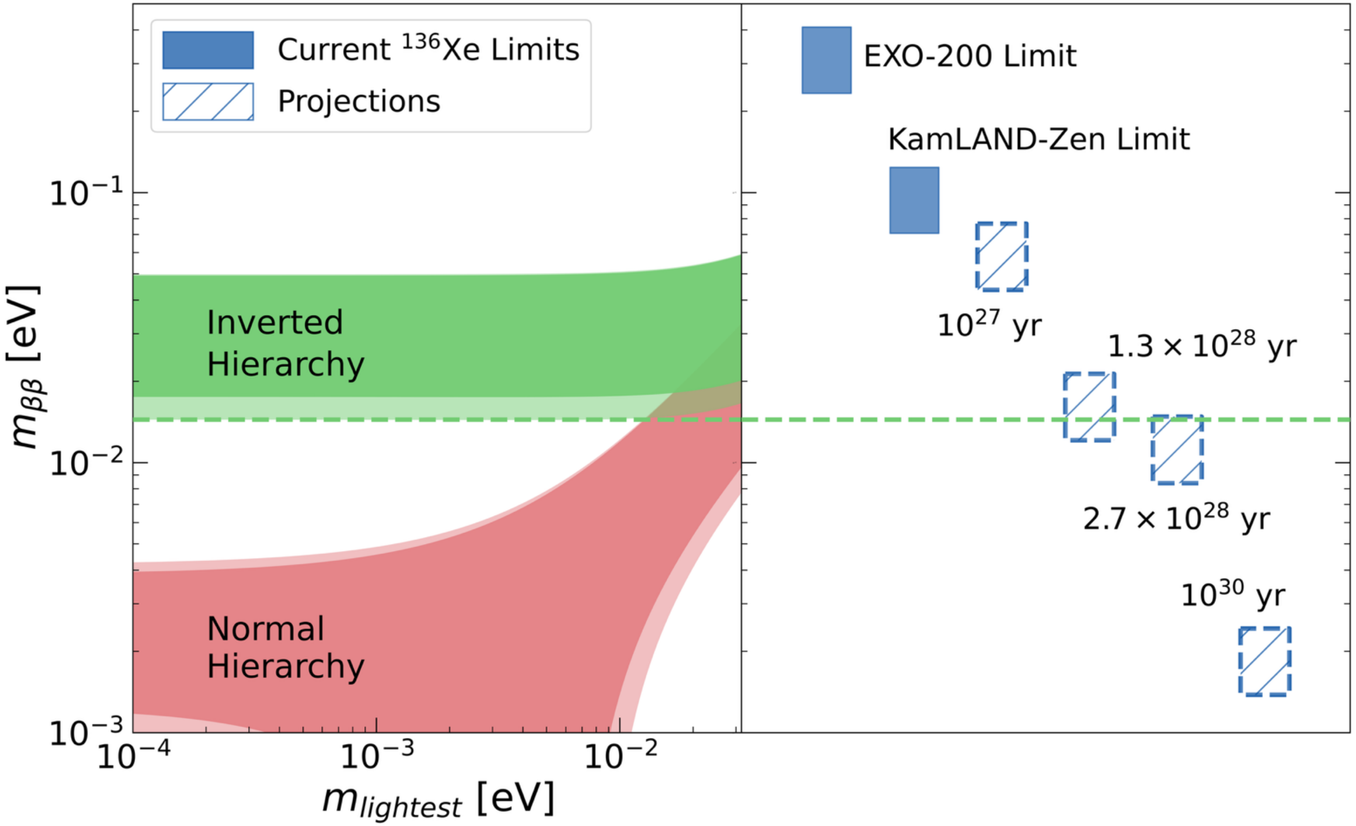

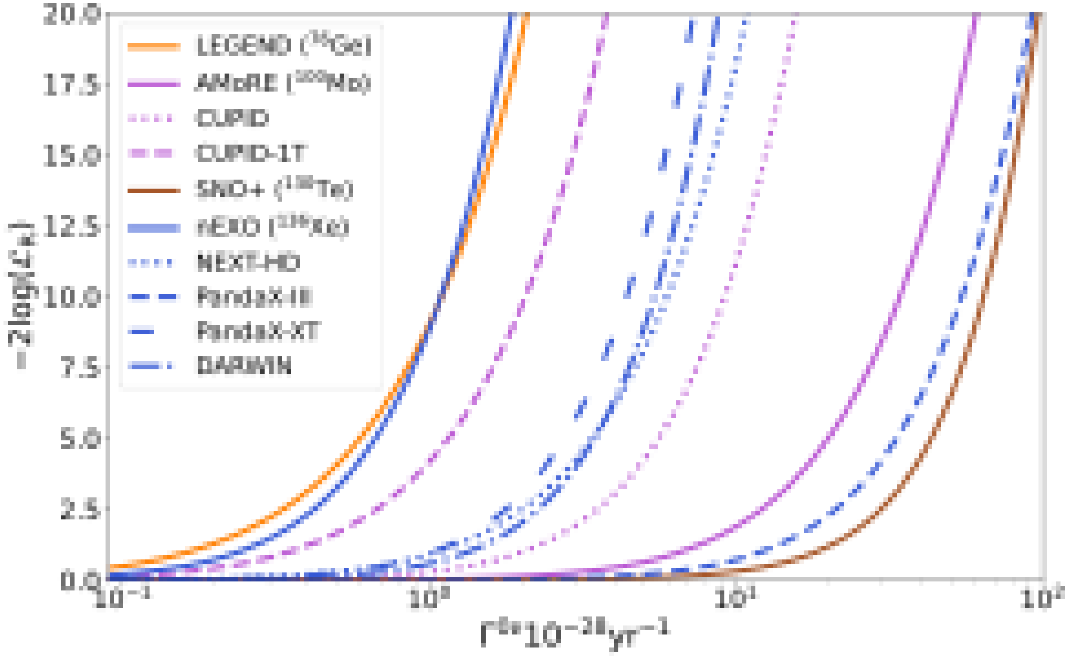

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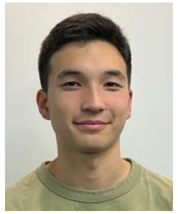

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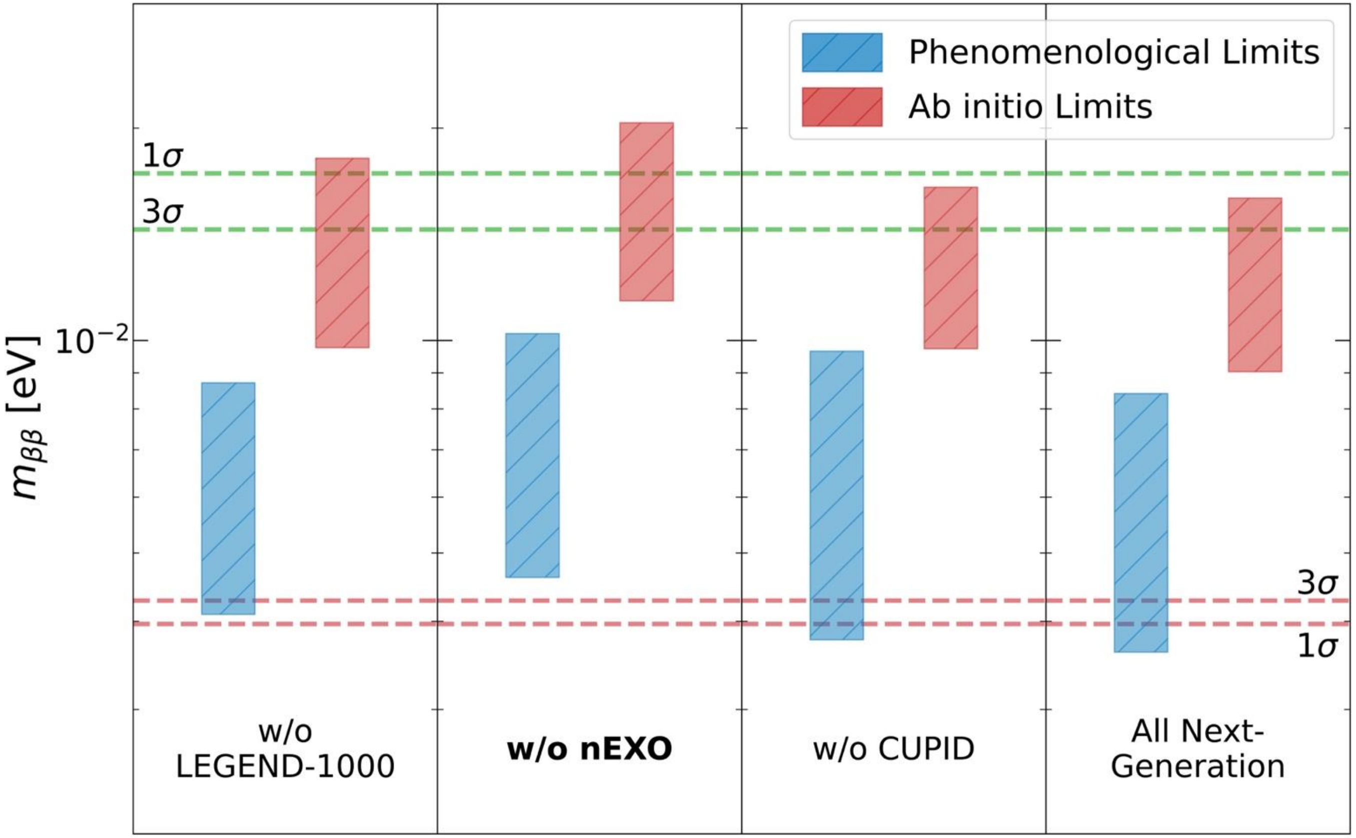

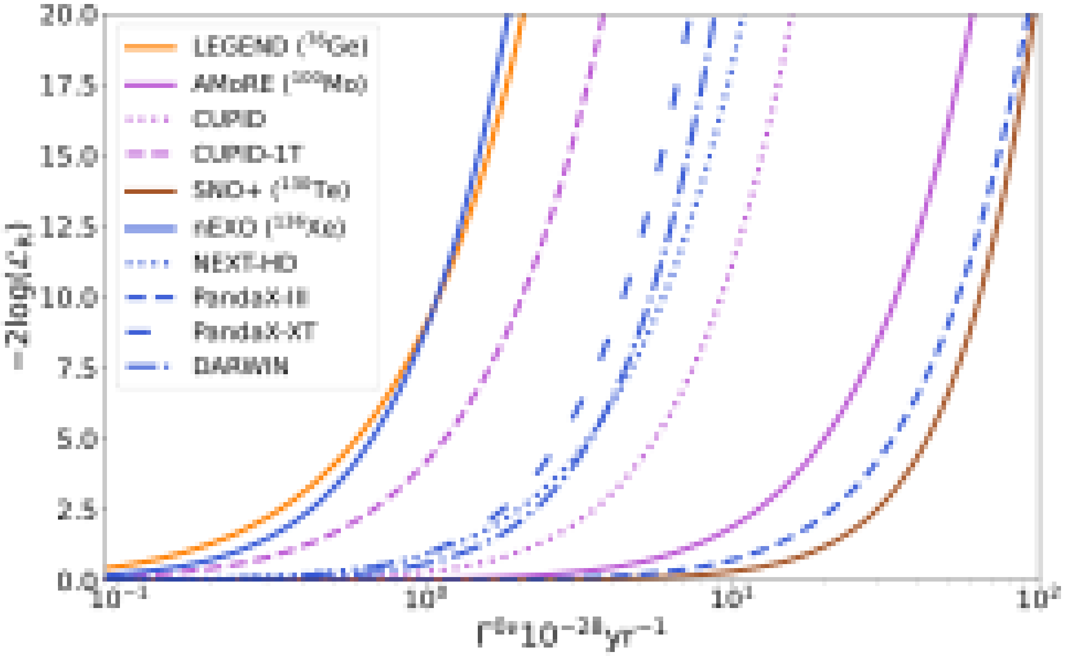

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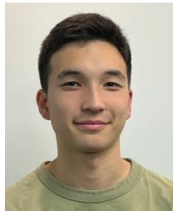


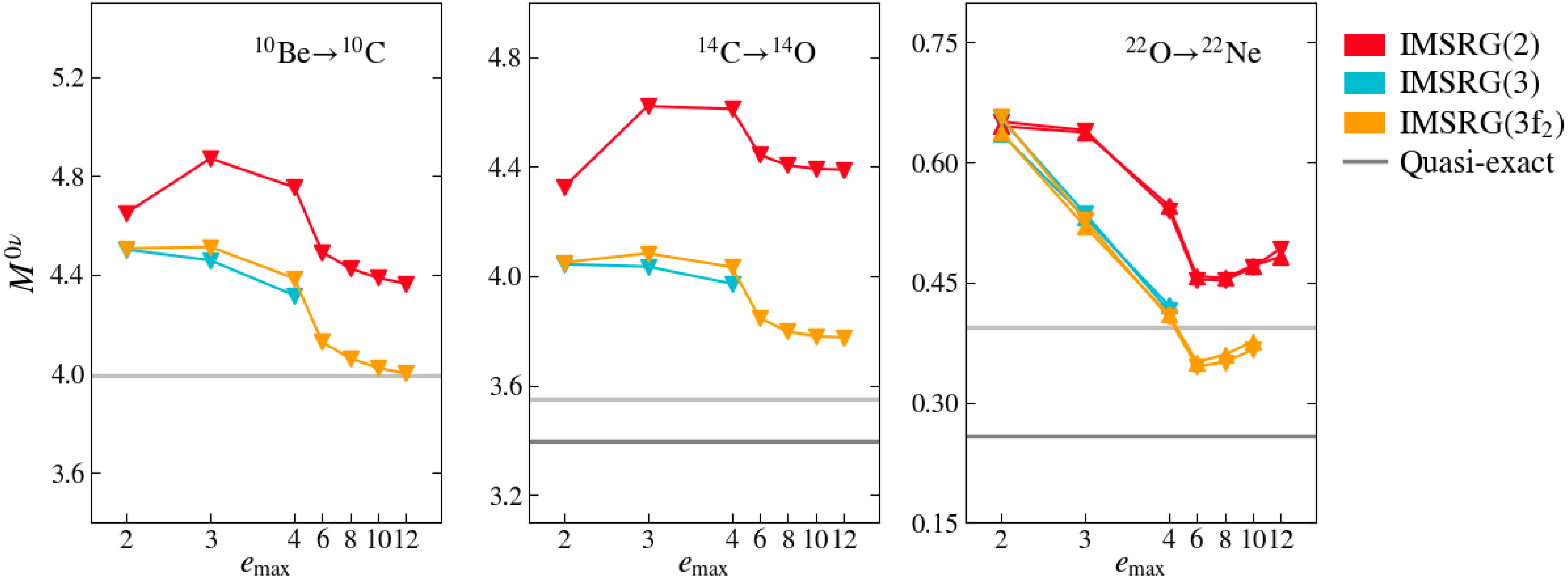
Shickele et al., in prep

Next Steps: Evaluate Many-Body Physics

Many-body largest source of uncertainty, need some estimation of higher-body operators

Compare with other (quasi-exact) ab initio method

Evaluate next order in IMSRG(2→3f2→3):



IMSRG(3f2) very well approximates IMSRG(3)

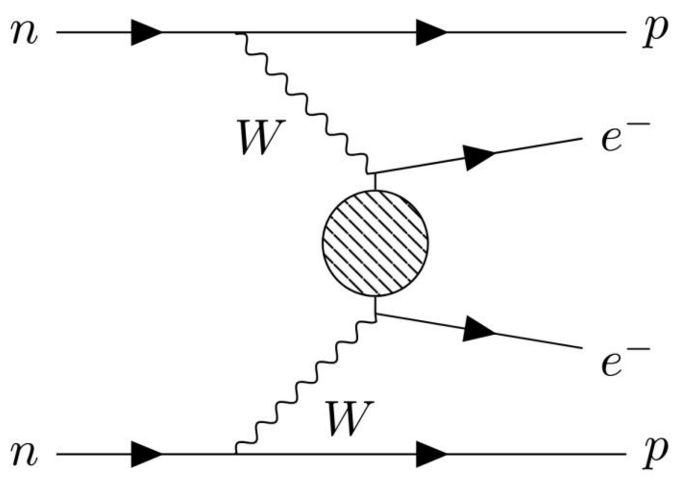
In all cases: lowers NMEs, reproduces quasi-exact results

Todd, et al., in prep

NMEs for Heavy Sterile Neutrino Exchange

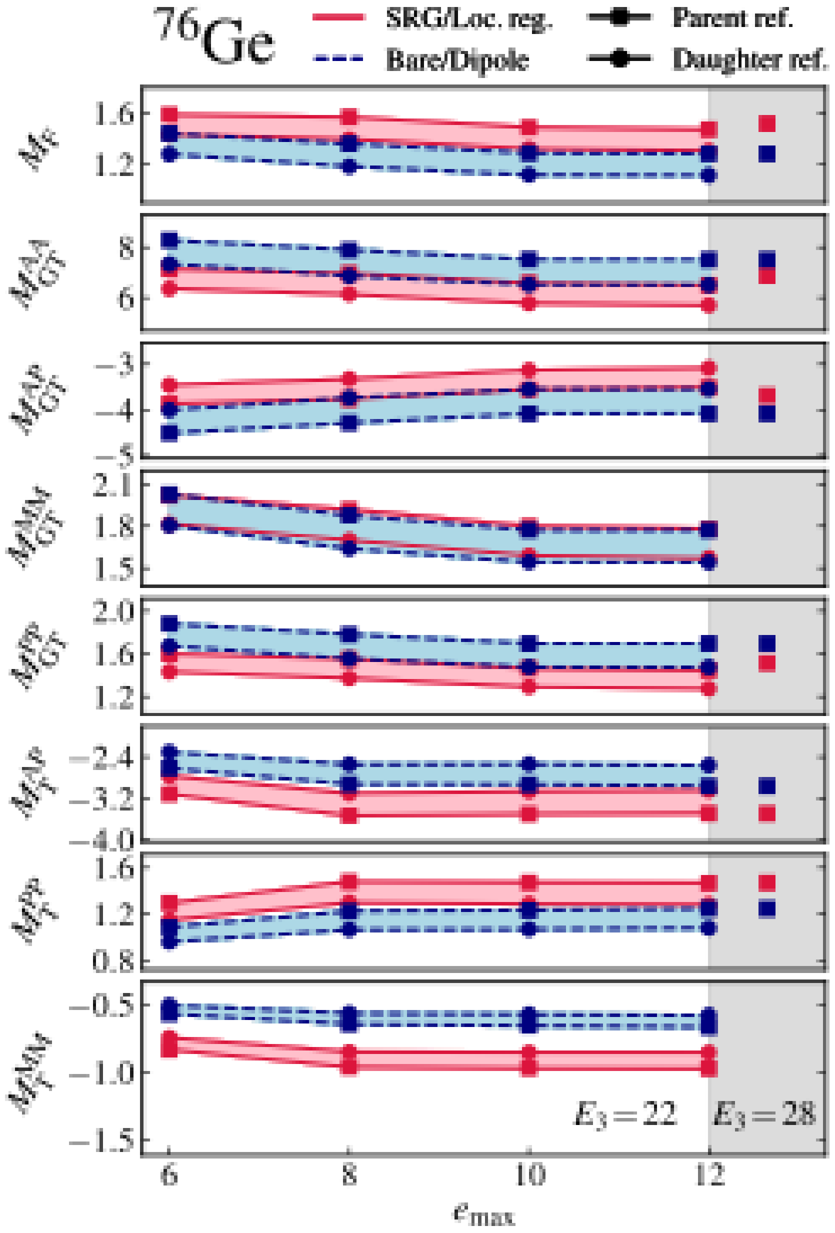
Explore other possible exchange mechanisms

Heavy sterile neutrinos: complicated operator structures

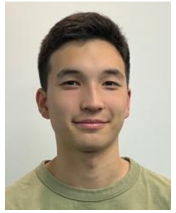


V. Cirigliano et al.
J. High Energy Phys. (2018)

$$\frac{1}{T_{1/2}^{0\nu}} = g_A^4 G^{0\nu} \left(|M_L^{0\nu}| \frac{m_{\beta\beta}}{m_e} + |M_H^{0\nu}| \frac{m_p}{M_{\beta\beta}} \right)^2$$



Converged heavy NMEs for all major candidates

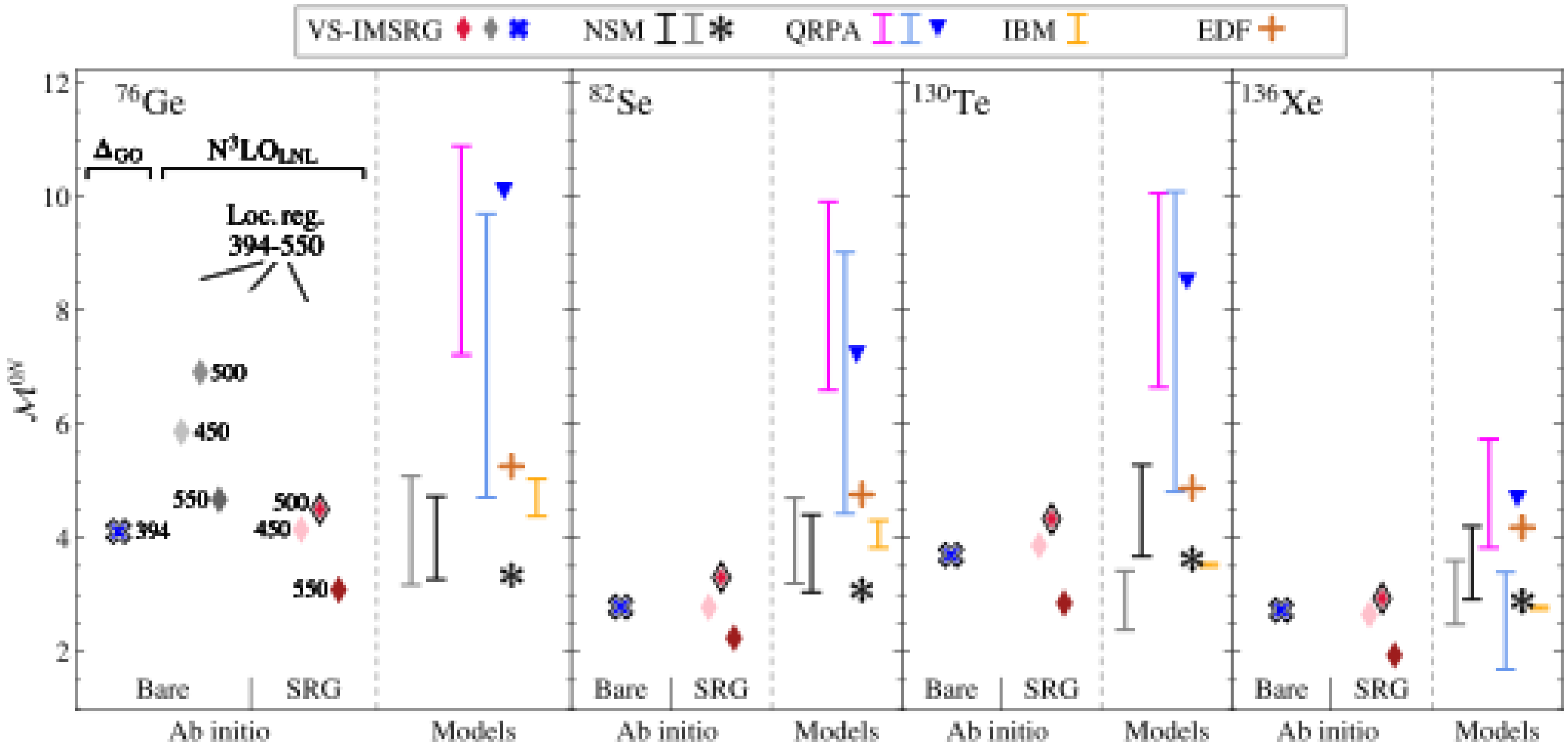


Todd, Shickele et al., PRL (under review)

TRIUMF

NMEs for Heavy Sterile Neutrino Exchange

Generally smaller values (and spread) than nuclear models



Todd, Shickele et al., PRL (under review)

Use ab initio 0νββ decay to obtain lower limits for sterile neutrino mass

NMEs for Heavy Sterile Neutrino Exchange

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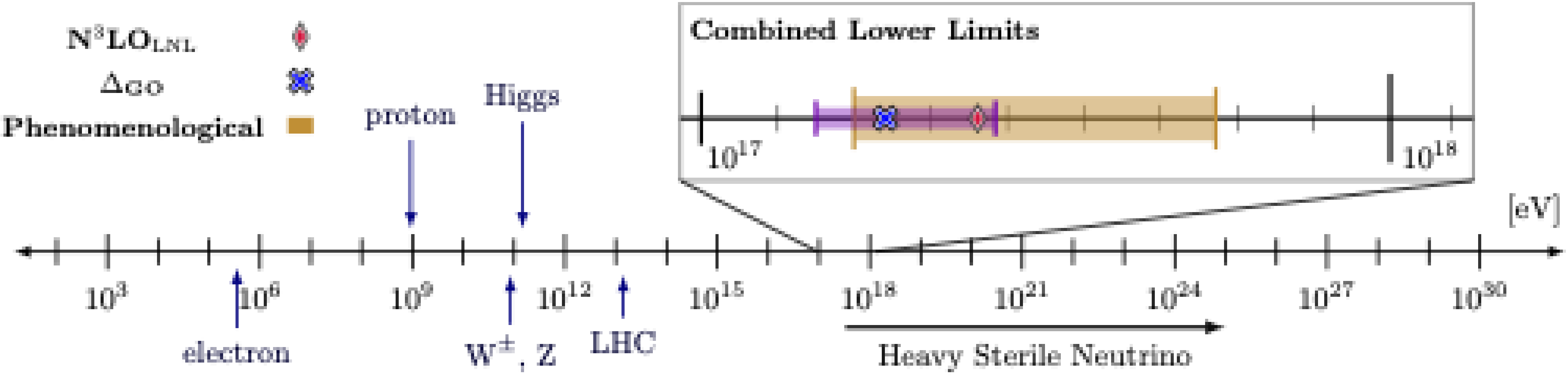


Todd, Shickele et al., PRL (under review)

Use ab initio $0\nu\beta\beta$ to obtain lower limits for sterile neutrino mass

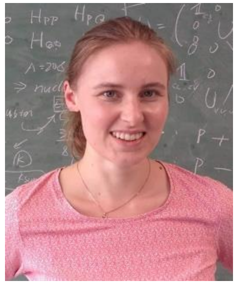
Results probe particle masses beyond the LHC: new collaborations w/ particle theory @TRIUMF

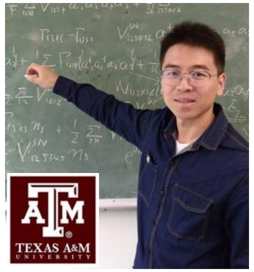
Future of Ab Initio Theory

(Former) Postdoctoral Fellows


Ragnar Stroberg

Takayuki Miyagi


Lotta Jokiniemi



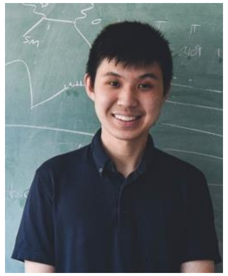
Baishan Hu

0νββ Decay

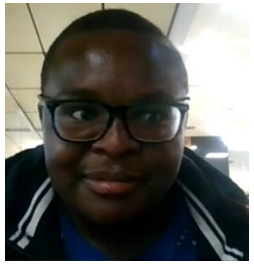
Antoine Belley

Isabella Ginnette


Alex Todd


Michael Liudeng

Structure + Astrophysics


Kanting Motimele


Maude Larivière

Symmetry Violation

Jose Munoz

Jack Pitcher

AI/Machine Learning

CKM Unitarity


Emily Love


Matt Martin

Atomic Systems

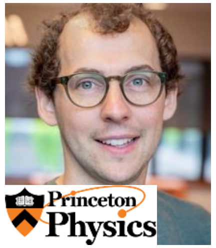
Gaurav Tenkila


Hrishi Patel


Vijay Chand

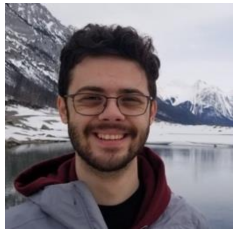
Just the beginning: join our revolution! jholt@triumf.ca

Dark Matter/ν Scattering



Sam Leutheusser

Jose Padua


Mathieu Bruneault

Ab Initio Strategy IV: Rigorous Uncertainties

Construct predictive posterior distribution for NMEs – first case ^{76}Ge

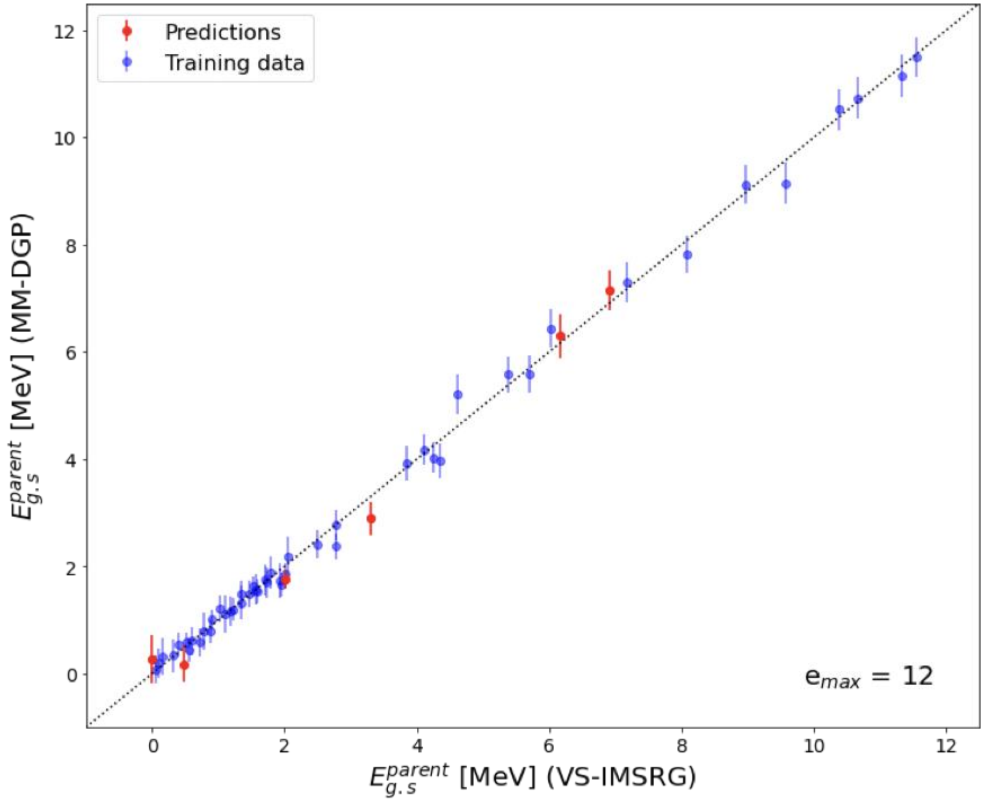
Consider all physics contributing to systematic error

$$y = y_{\mathrm{MM-DDGP}} + \epsilon_{\mathrm{emulator}} + \epsilon_{\mathrm{EFT}} + \epsilon_{\mathrm{many-body}} + \epsilon_{\mathrm{operator}}$$

Use 8100+ samplings of NN+3N forces - weighted by np $^1S_0$ phase shift

Solve many-body problem with MM-DGP

Emulator: from process itself



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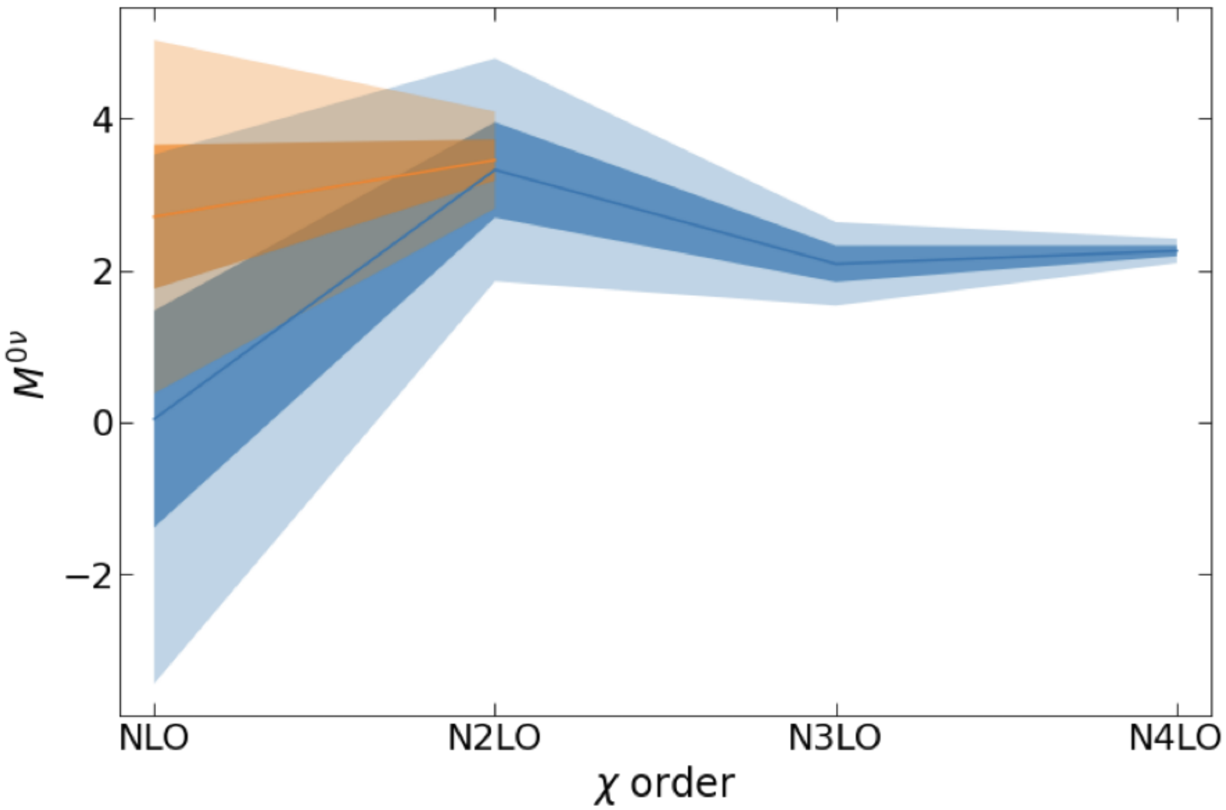
Belley et al, arXiv:2308.15634



Emulator: from process itself

EFT: Truncation in nuclear forces

TRIUMF

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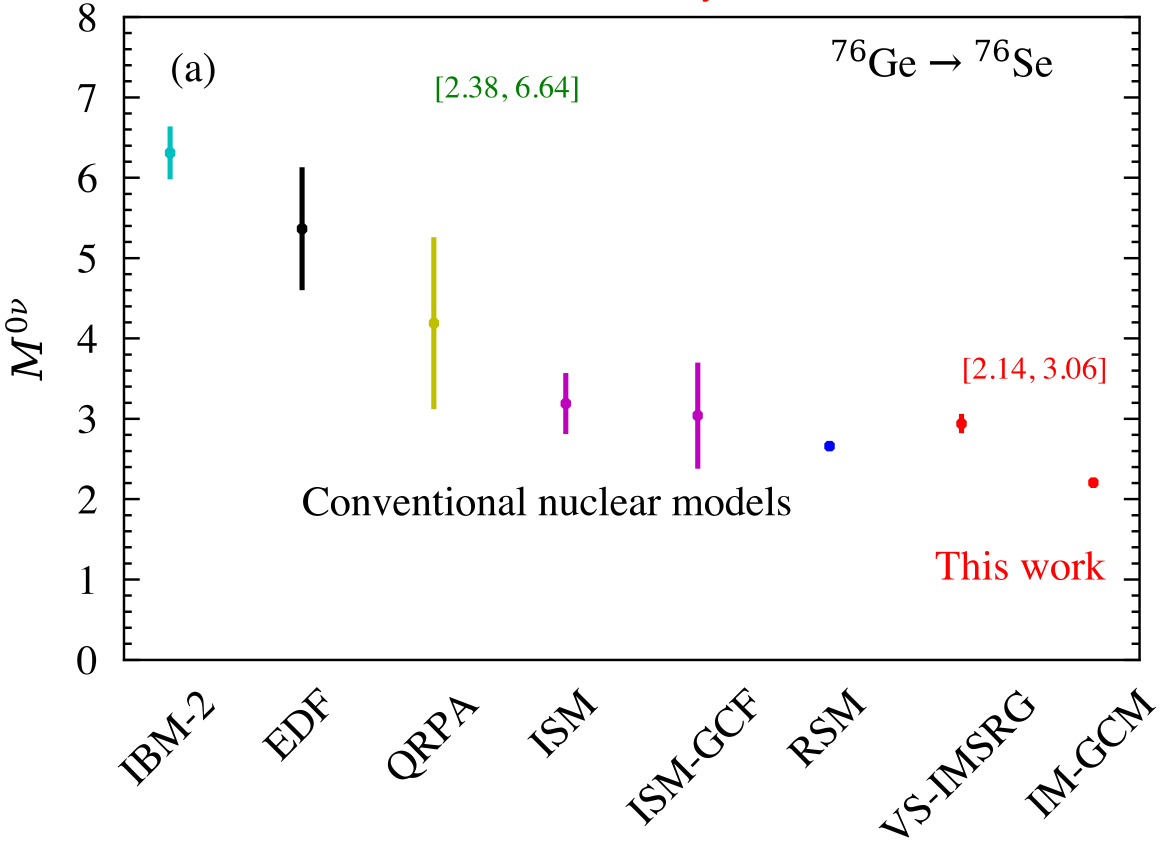

TRIUMF

Ab Initio Strategy IV: Rigorous Uncertainties

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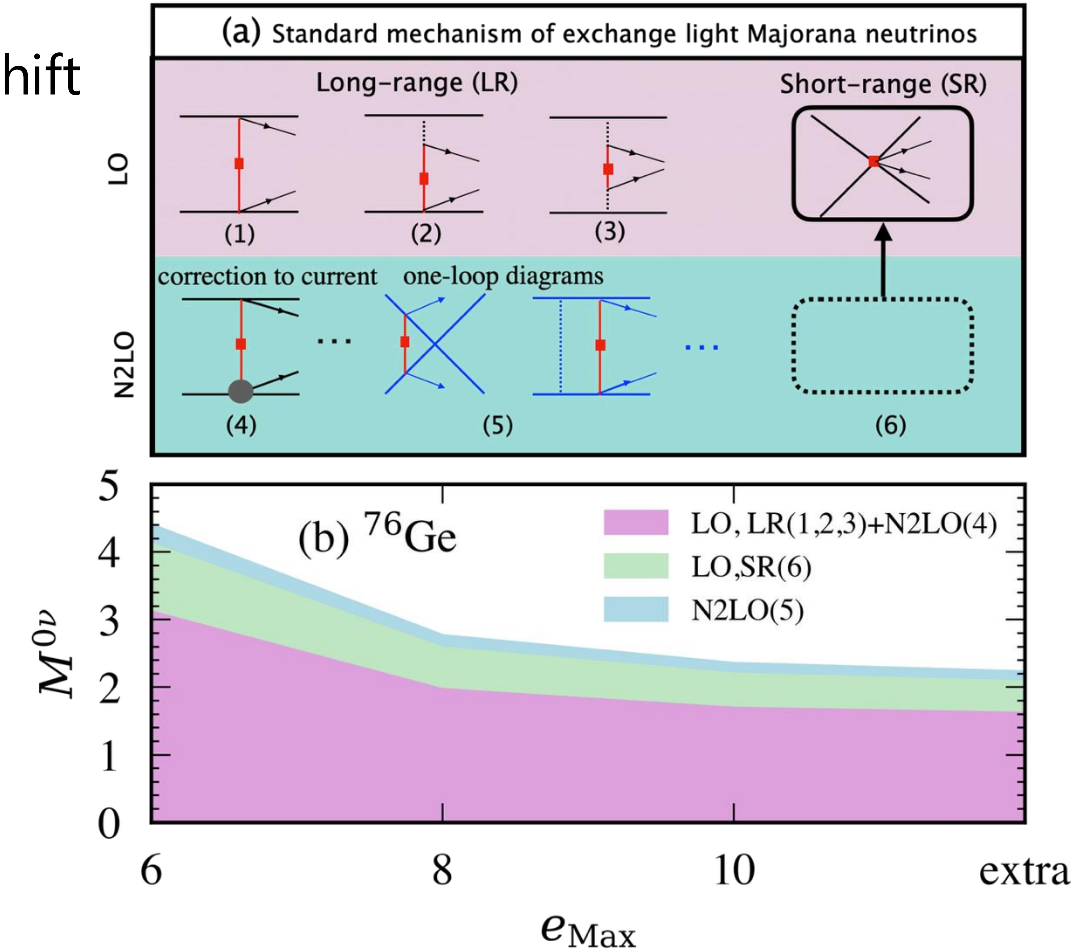
Solve many-body problem with MM-DGP

Emulator: from process itself

EFT: Truncation in nuclear forces

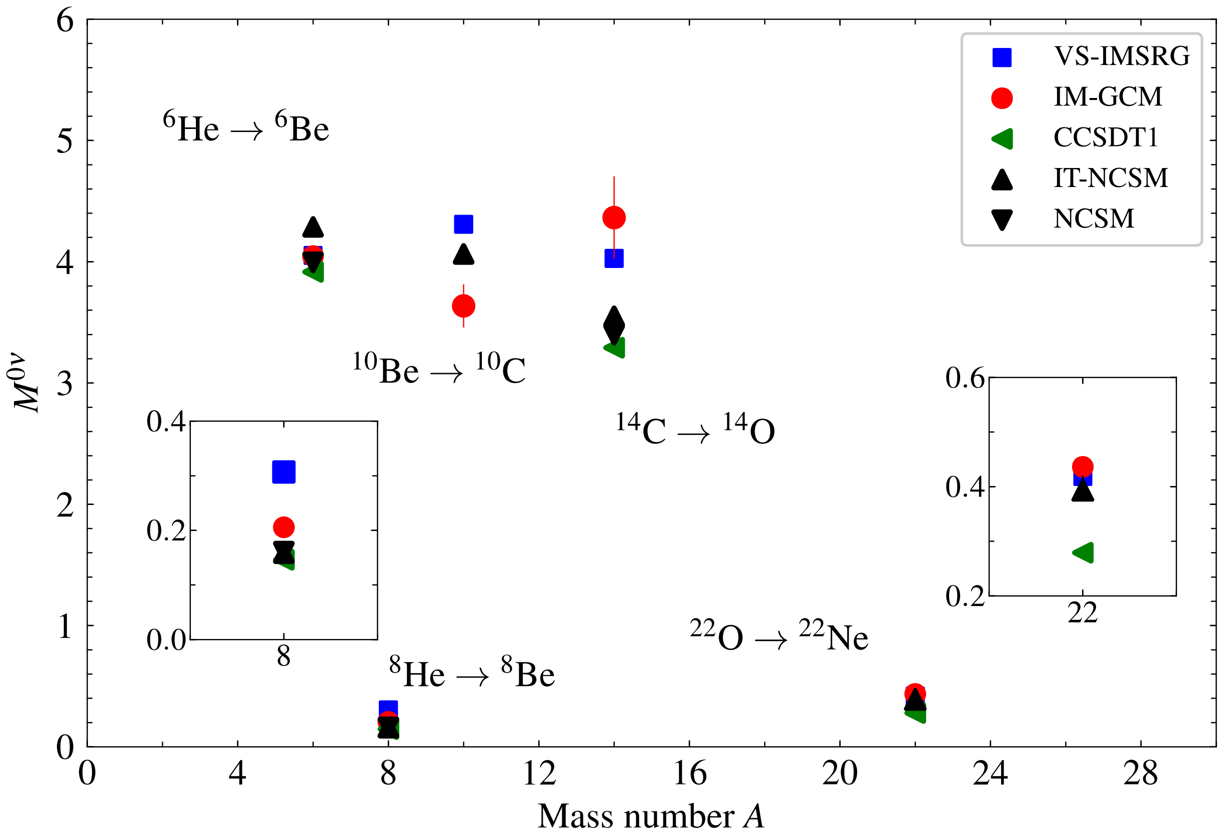
Many-body: Truncation in many-body physics

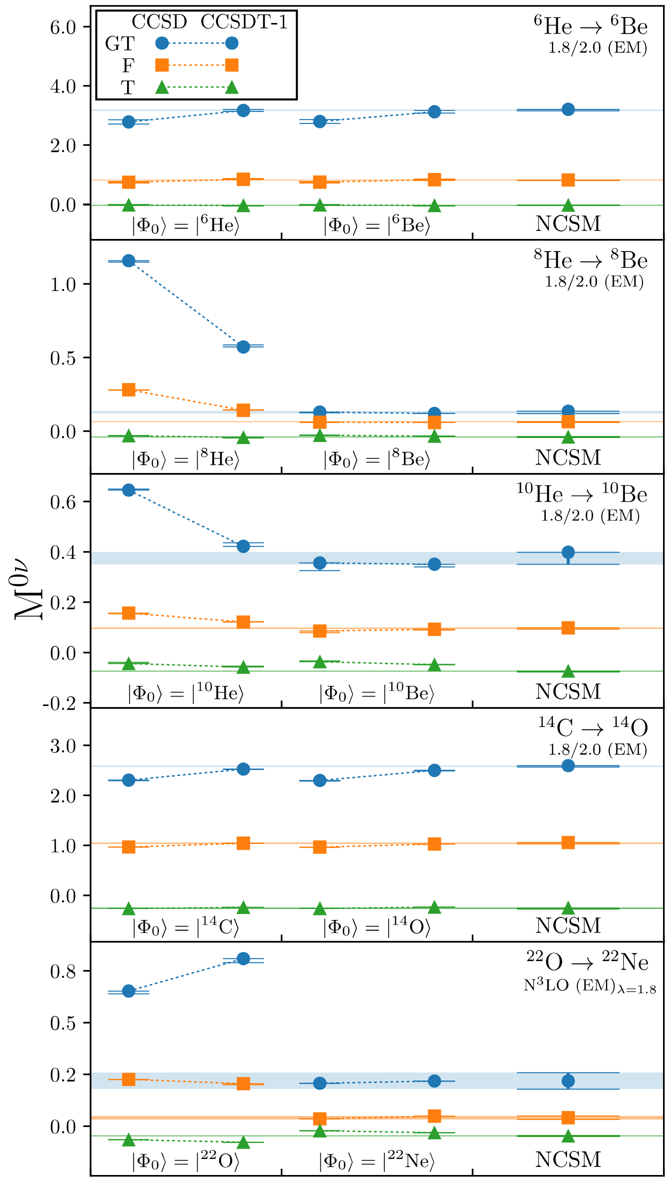
Operator: higher order contributions to operator



Ab Initio Strategy I: Benchmark in Light Nuclei

Benchmark with quasi-exact ab initio methods in light systems: A=6-22





Reasonable to good agreement in all cases

Pursue true double-beta decay candidates!

Yao, **Belley** et al., PRC (2020)

Valence-Space IMSRG

Explicitly construct unitary transformation from sequence of rotations

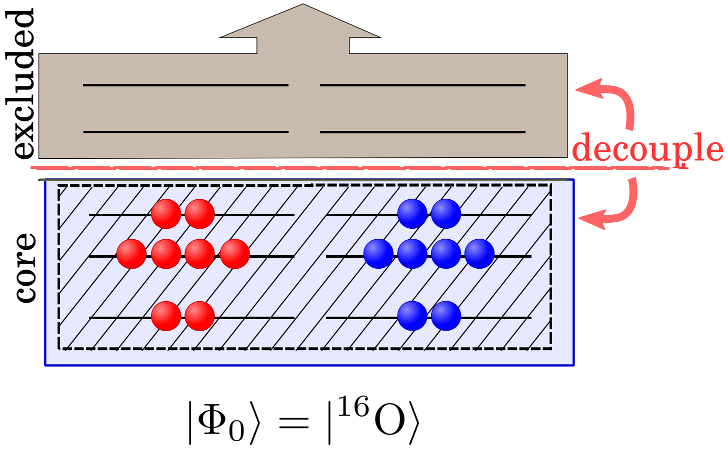
$$U = e^{\Omega} = e^{\eta_n} \dots e^{\eta_1} \qquad \eta = \frac{1}{2}\arctan\left(\frac{2H_{\text{od}}}{\Delta}\right) - \text{h.c.}$$

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

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

IMSRG(3) in progress

Step 1: Decouple core



Can we achieve accuracy of large-space methods?

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

Valence-Space IMSRG

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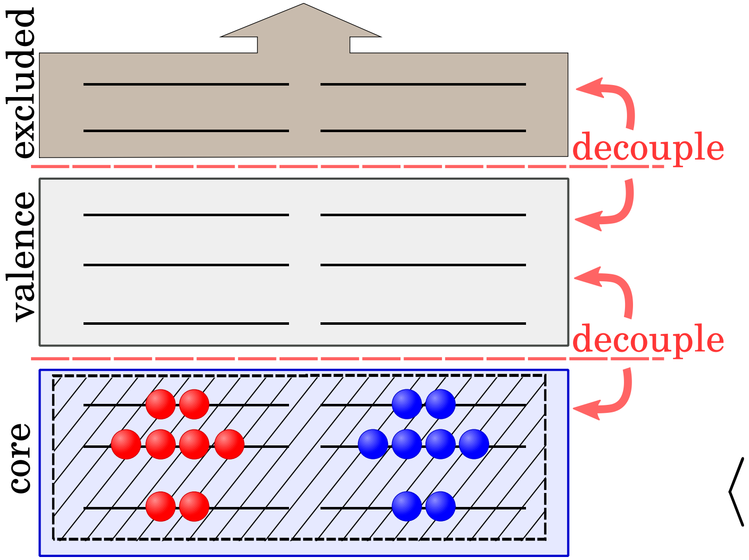
All operators truncated at two-body level IMSRG(2)

IMSRG(3) in progress

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



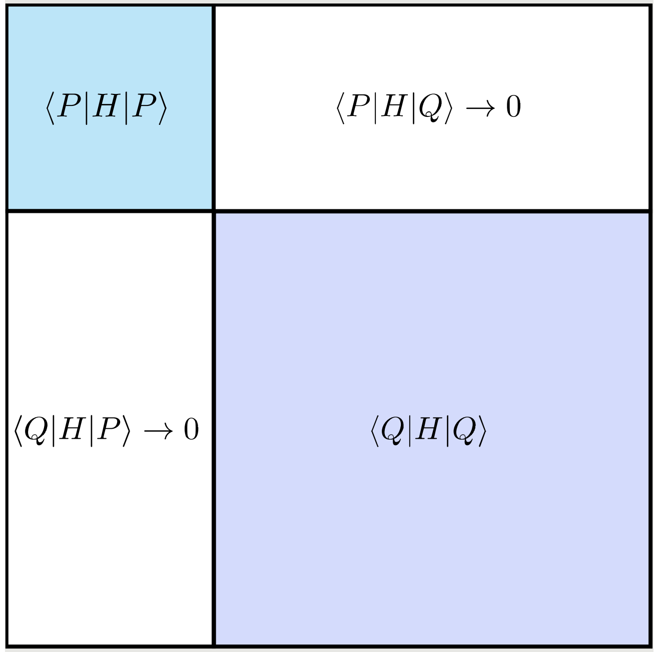
$|\Phi_0\rangle = |{}^{16}\mathrm{O}\rangle$

Step 1: Decouple core

Step 2: Decouple valence space

Can we achieve accuracy of large-space methods?

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



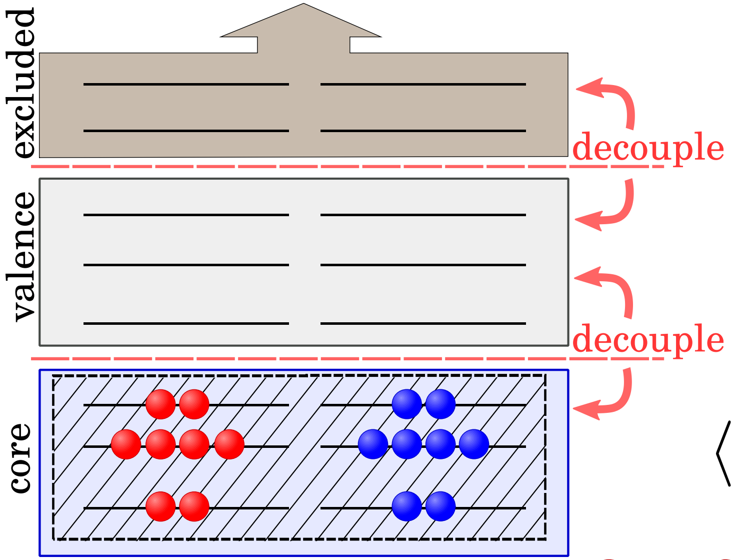
Valence-Space IMSRG

Explicitly construct unitary transformation from sequence of rotations

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

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

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



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

Step 1: Decouple core

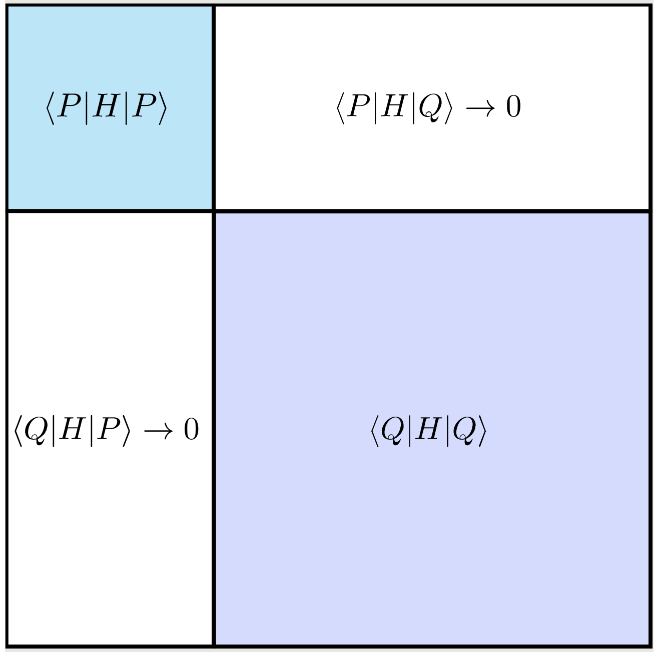
Step 2: Decouple valence space

Step 3: Decouple additional operators

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

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

Careful benchmarking essential



Ab Initio Neutron Skin of ^{208}Pb

TRIUMF

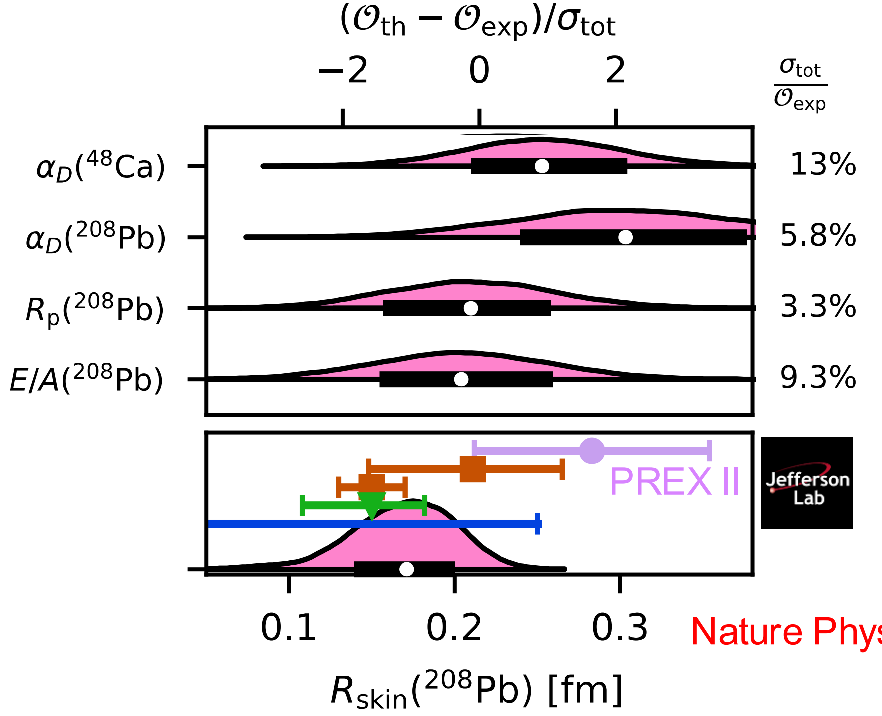
Combine ab initio + machine learning advances

I: History Matching: 34 “non-implausible” interactions

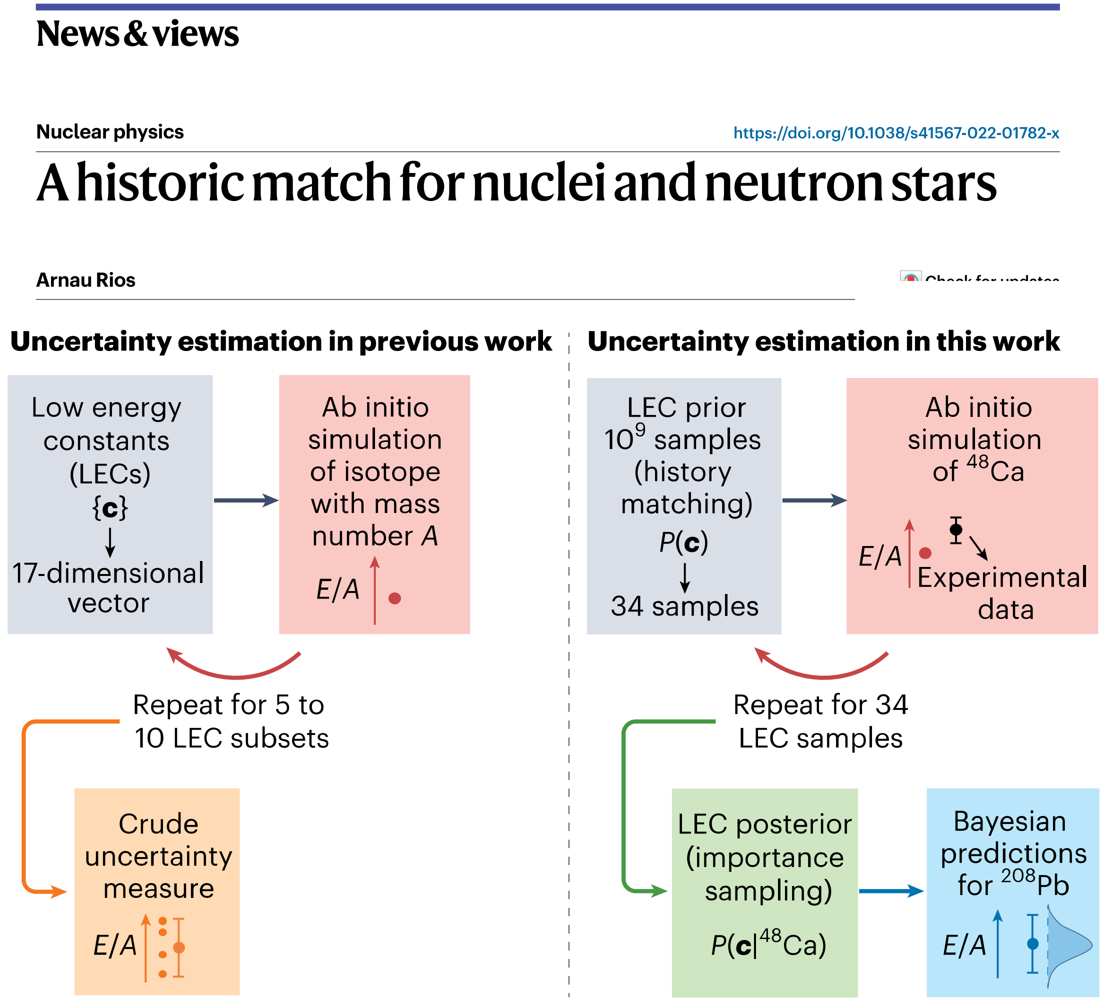
II: Calibration/importance sampling: ^{48}Ca properties

III: Validation: ^{208}Pb properties from ab initio

IV: Prediction: PPD for neutron skin



Nature Physics **18**, 1196 (2022)



$R_{skin}(^{208}Pb)$=0.14-0.20fm – consistent with **PREXII**

Neutron Skin of ^{208}Pb

Combine TRIUMF/ORNL/Chalmers advances!

I: History Matching confronted with A=2,3,4 data + ^{16}O

10^9 calculations spanning EFT parameter space at N^2LO

34 non-implausible interactions

II: Calibration use ^{48}Ca E/A, E(2^+), R_p, dipole polarizability

Importance resampling – statistically weight interactions

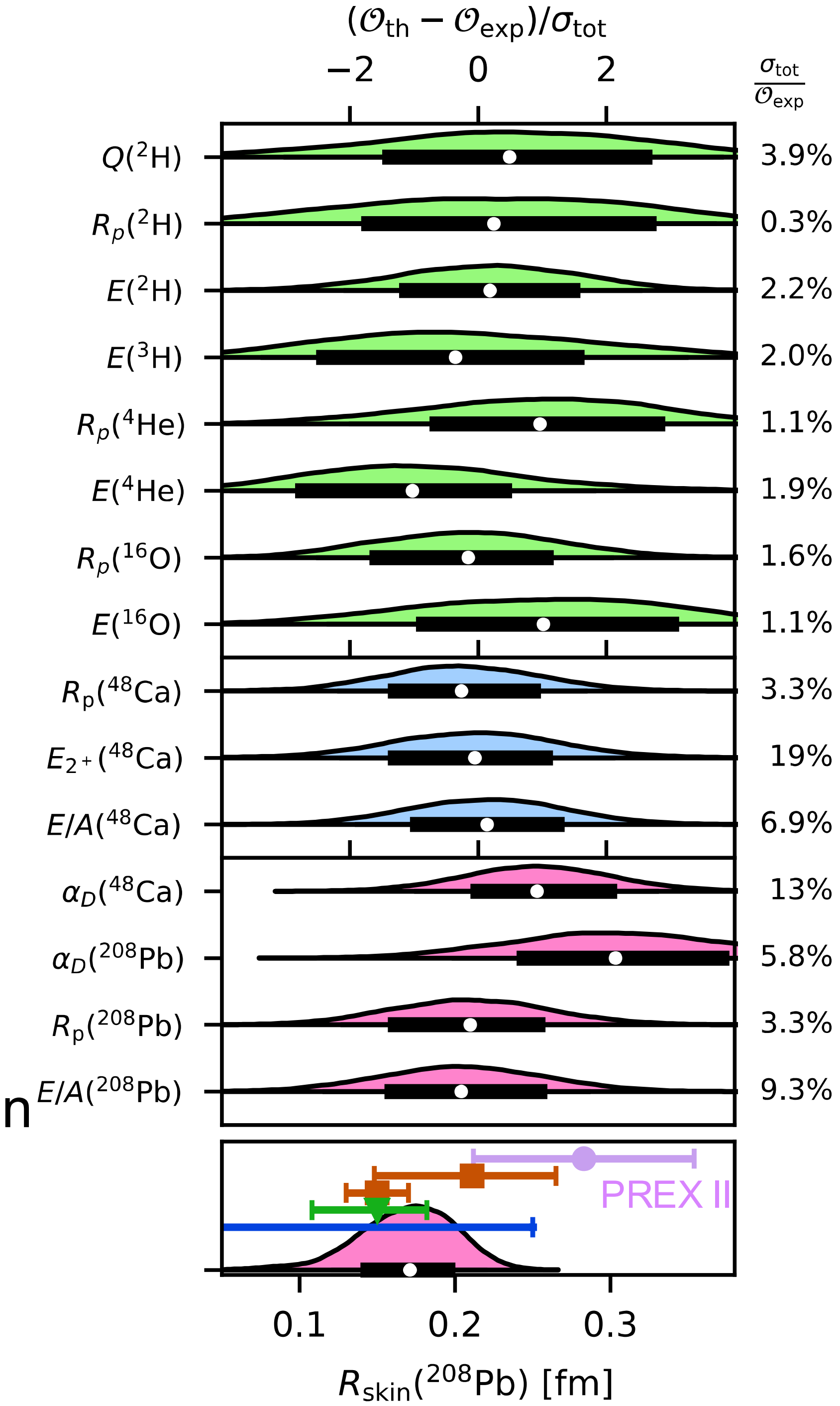
III: Validation ^{208}Pb E/A, R_p + ^{48}Ca/^{208}Pb DP from ab initio

Clear quality description of data

IV: Prediction - posterior predictive distribution for neutron skin

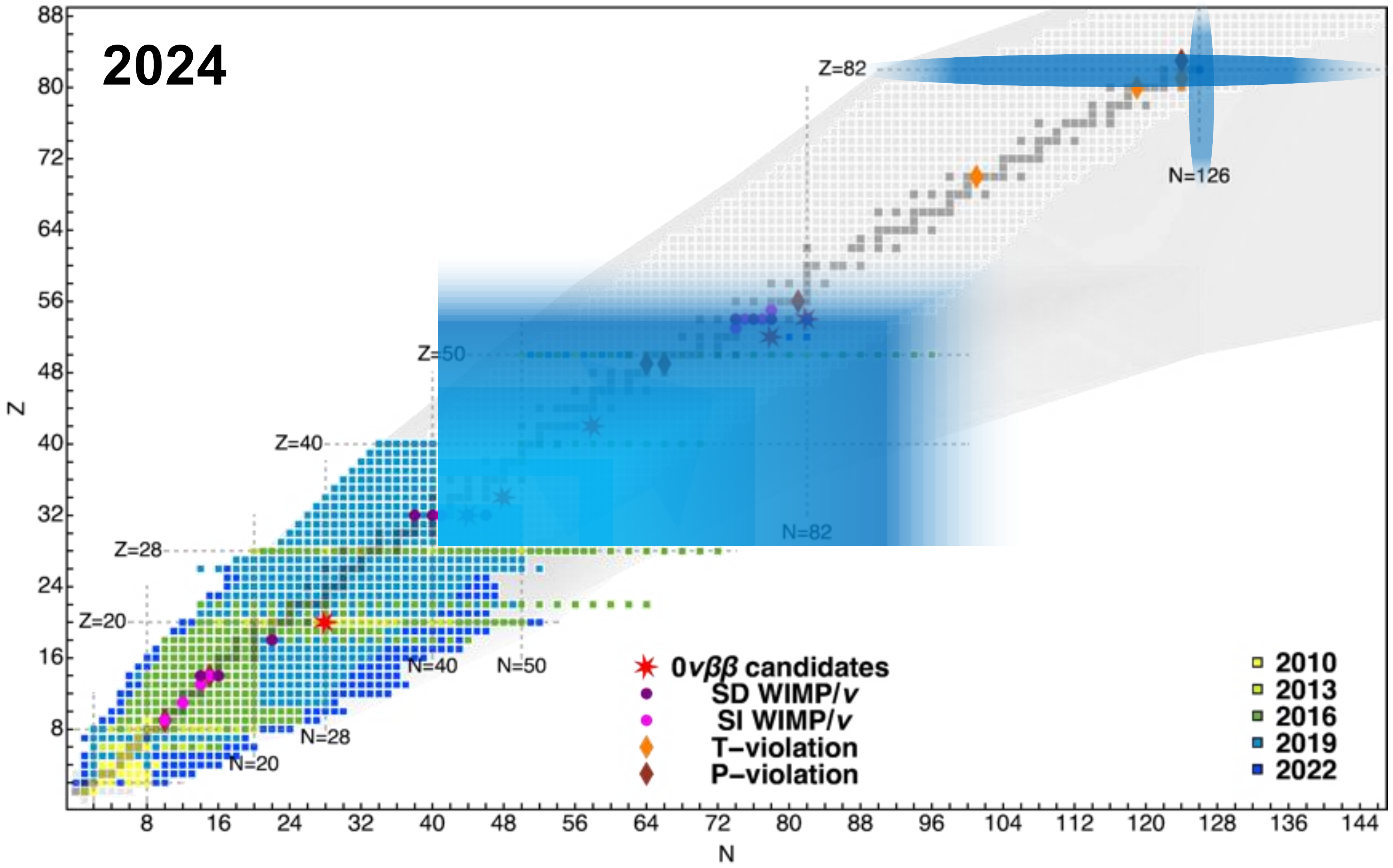
R_{skin}(^{208}Pb)= 0.14-0.20fm (68% credible level)

Consistent(ish) with extracted **PREXII result**



Act II Preview: Future of Ab Initio Theory

(Not so) Bold predictions: Five new direction in the next 5 years



Nucleosynthesis
Ab initio input for r-process

Dark Matter/ν Scattering
Ab initio structure functions

Symmetry Violation
Schiff/anapole moments

CKM Unitarity (V_{ud})
Superallowed Fermi

Atomic/molecular/QC(?)

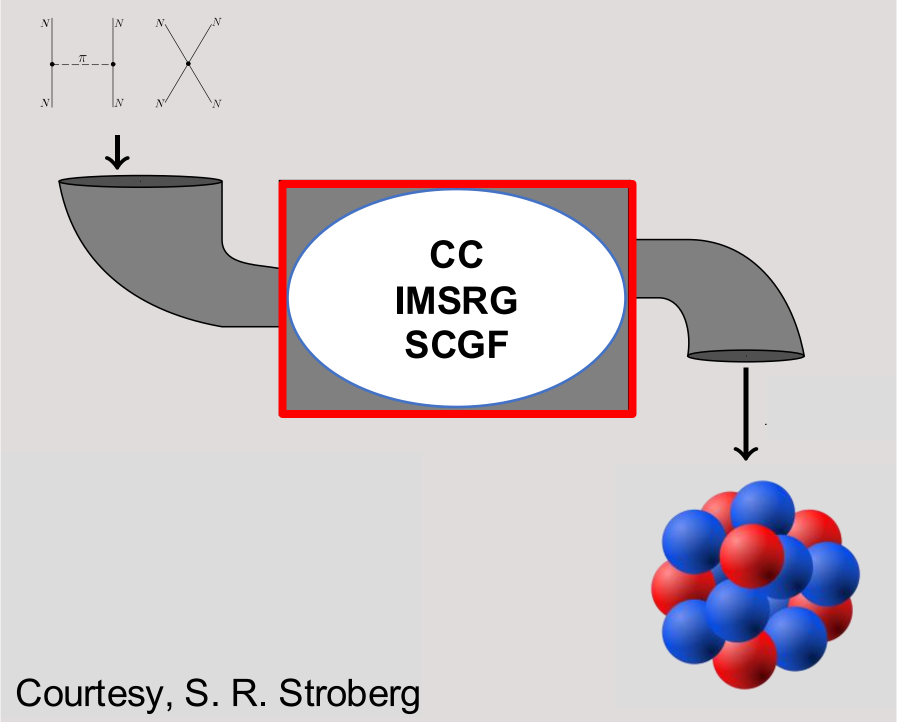
AI/Machine Learning
New emulators

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

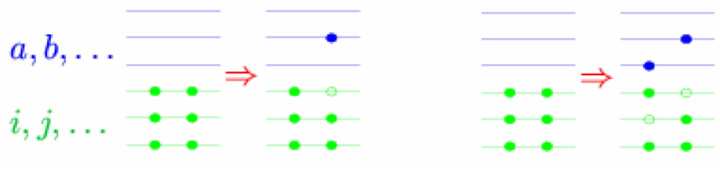
$$H\psi_n = E_n\psi_n$$



Courtesy, S. R. Stroberg

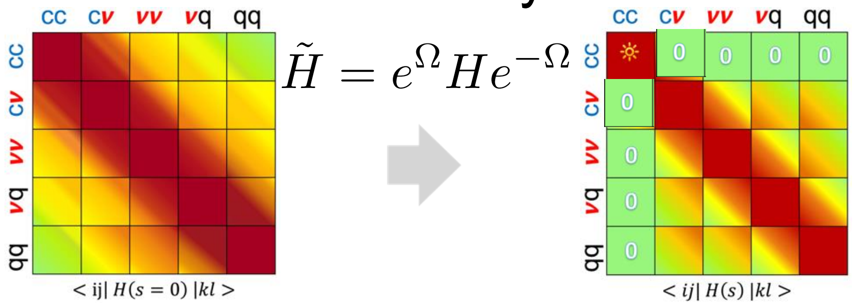
Ab Initio Cheat Sheet (polynomial scaling methods)

CC: Coupled cluster theory

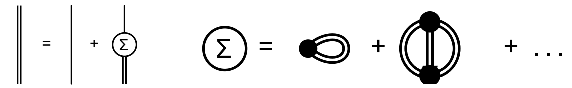


$$E = \langle\Phi|\overline{H}|\Phi\rangle$$
$$0 = \langle\Phi_i^a|\overline{H}|\Phi\rangle$$
$$0 = \langle\Phi_{ij}^{ab}|\overline{H}|\Phi\rangle$$
$$\overline{H} \equiv e^{-T}He^{T} = \left(He^{T}\right)_c$$

IMSRG: In-medium similarity renormalization group



SCGF: Self-consistent Green's function



TRIUMF

Milestone Result

Global Ab Initio Calculations: Limits of Nuclear Existence

Ragnar Stroberg

Featured in Physics | Editors' Suggestion

Ab Initio Limits of Atomic Nuclei

S. R. Stroberg, J. D. Holt, A. Schwenk, and J. Simonis

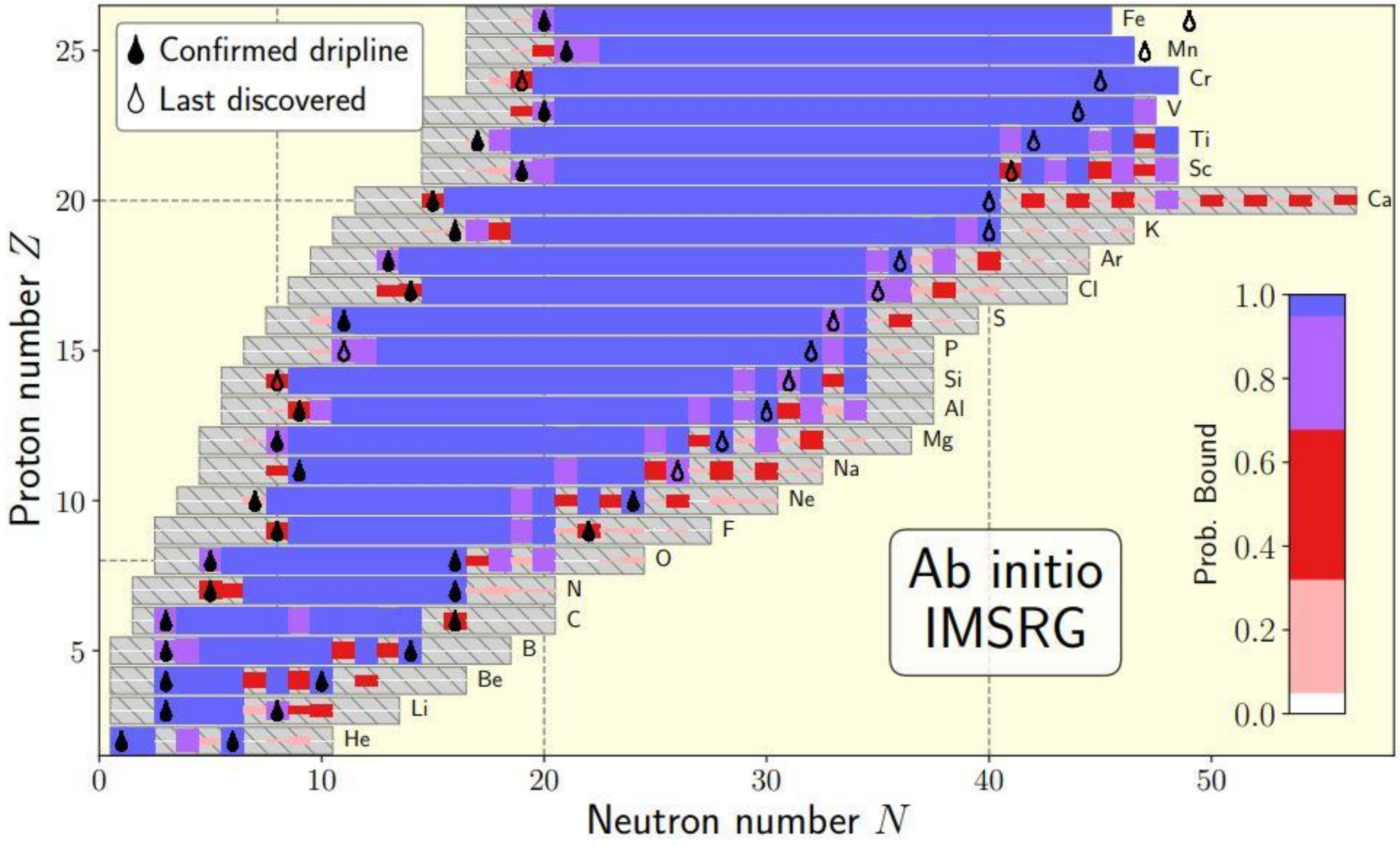
Phys. Rev. Lett. **126**, 022501 – Published 12 January 2021

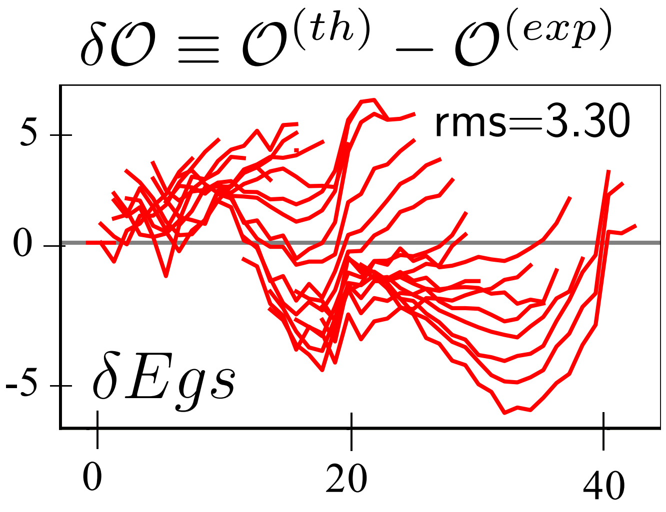
Physics See synopsis: Predicting the Limits of Atomic Nuclei

TRIUMF

Limits of Existence in Medium-Mass Region

Ab initio calculations of ~700 nuclei from He to Fe





Input H fit to 2,3,4-body

Not biased towards existing data

Known drip lines predicted within uncertainties

Ab initio guide for neutron-rich driplines

Featured in Physics | Editors' Suggestion

Ab Initio Limits of Atomic Nuclei

S. R. Stroberg, J. D. Holt, A. Schwenk, and J. Simonis
Phys. Rev. Lett. **126**, 022501 – Published 12 January 2021

Physics See synopsis: Predicting the Limits of Atomic Nuclei

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Milestone Result

Ab Initio Neutron Skin of ^{208}Pb Linked to Neutron Star Properties

nature physics

ARTICLES

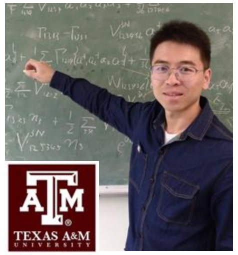
https://doi.org/10.1038/s41567-022-01715-8

OPEN

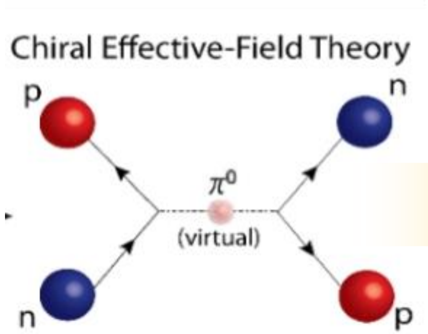
Ab initio predictions link the neutron skin of ^{208}Pb to nuclear forces

Baishan Hu[1,11], Weiguang Jiang[2,11], Takayuki Miyagi[1,3,4,11], Zhonghao Sun[5,6,11], Andreas Ekström[2], Christian Forssén[2], Gaute Hagen[1,5,6], Jason D. Holt[1,7], Thomas Papenbrock[5,6], S. Ragnar Stroberg[8,9] and Ian Vernon[10]

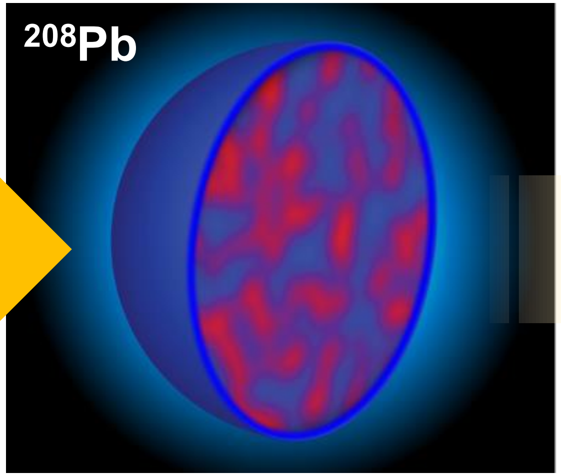
Takayuki Miyagi



Baishan Hu



Ab Initio



Nuclear EOS