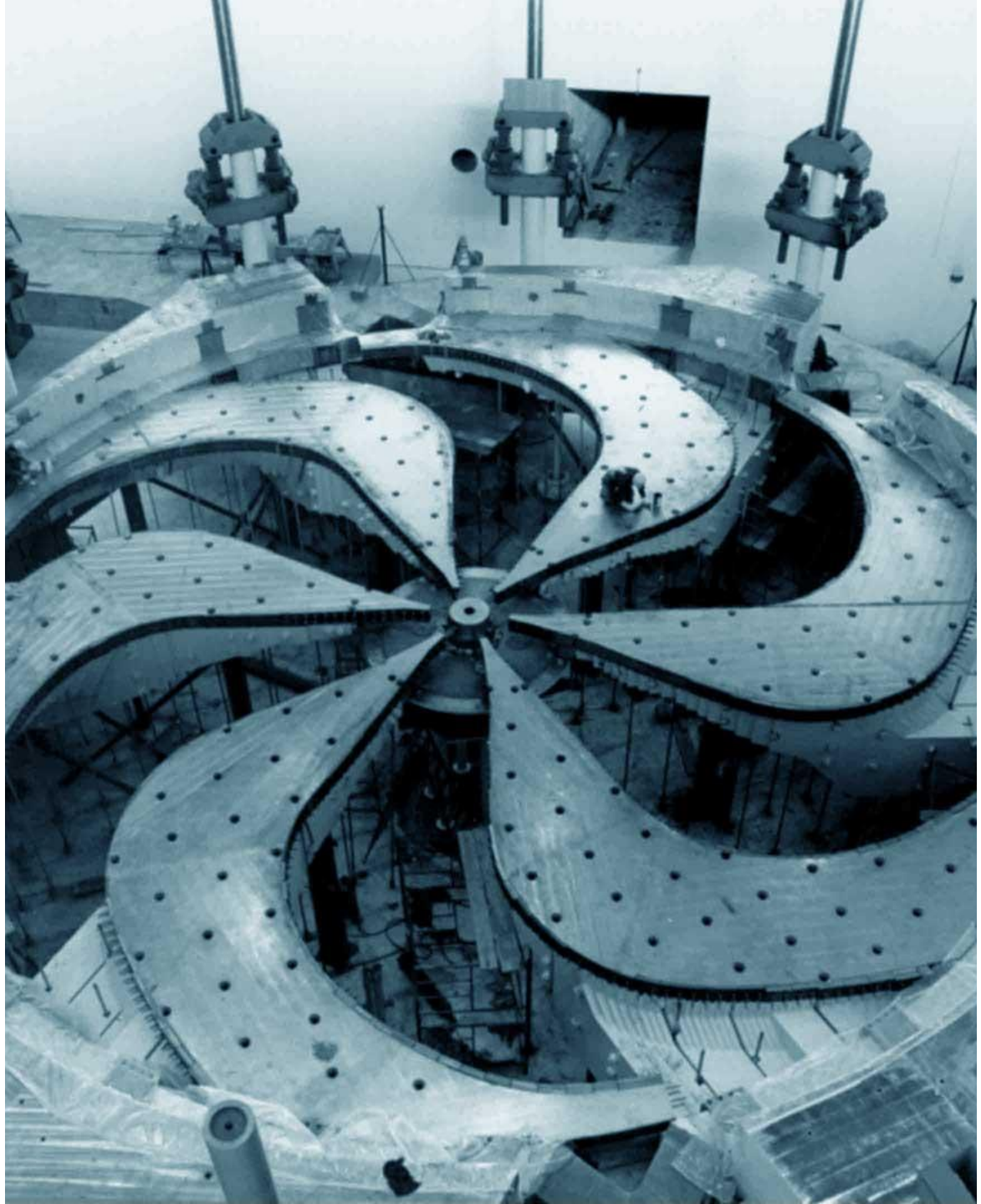
# Ab Initio Theory for New Physics Searches

Jason D. Holt
TRIUMF, McGill University
INVISIBLES Workshop, CERN
September 1, 2025

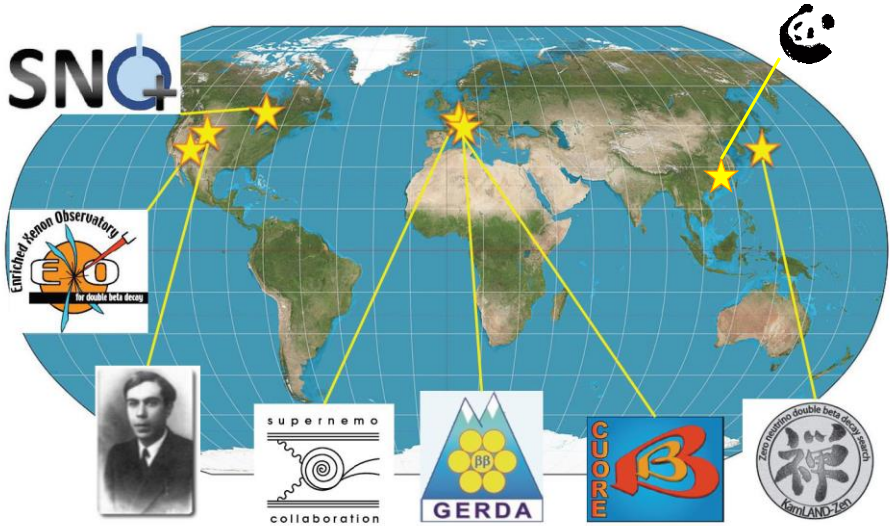


Discovery, accelerated

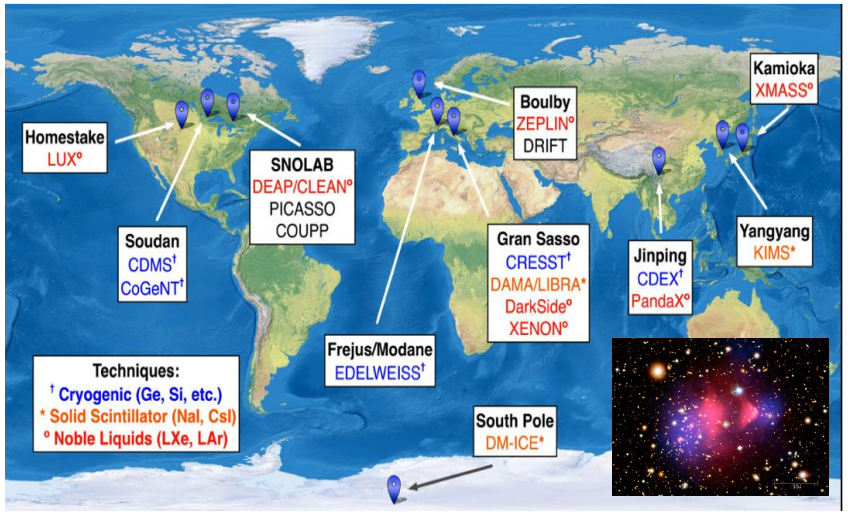
# Major BSM Searches Worldwide

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

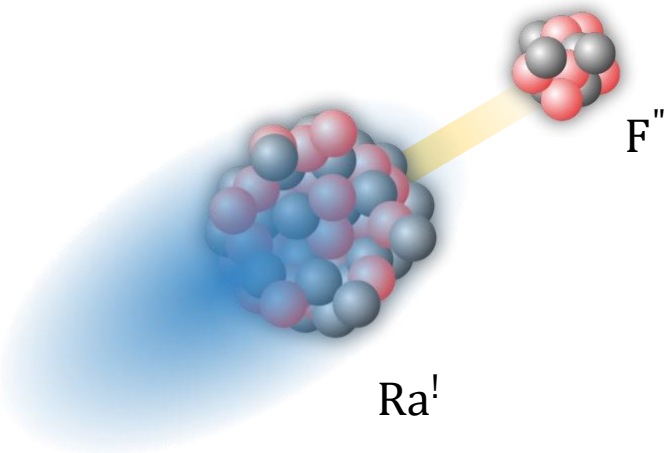
## 0νββ Decay




## Dark Matter Direct Detection




## Symmetry Violation

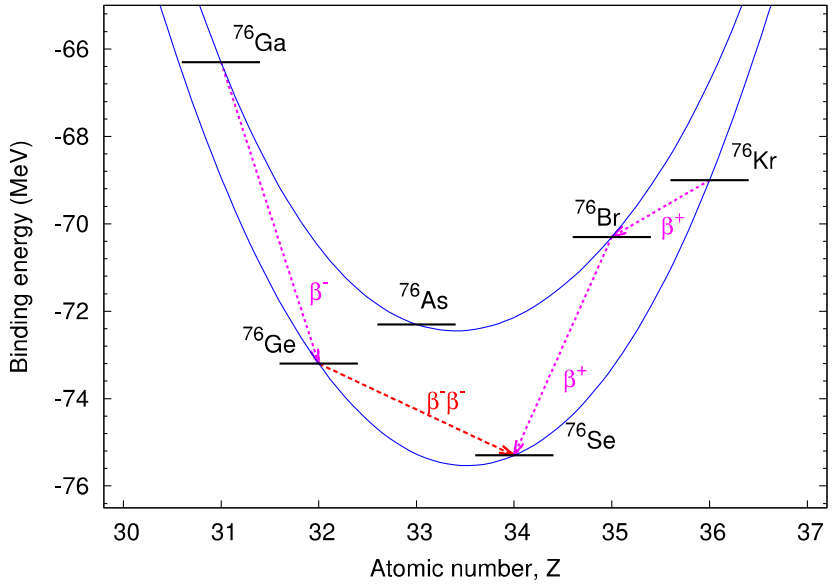


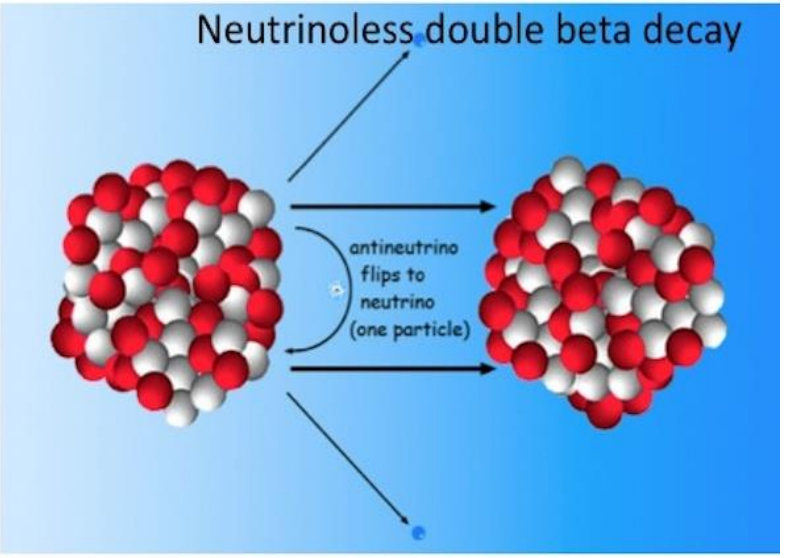

**Billions invested worldwide – theory of the nucleus is essential**

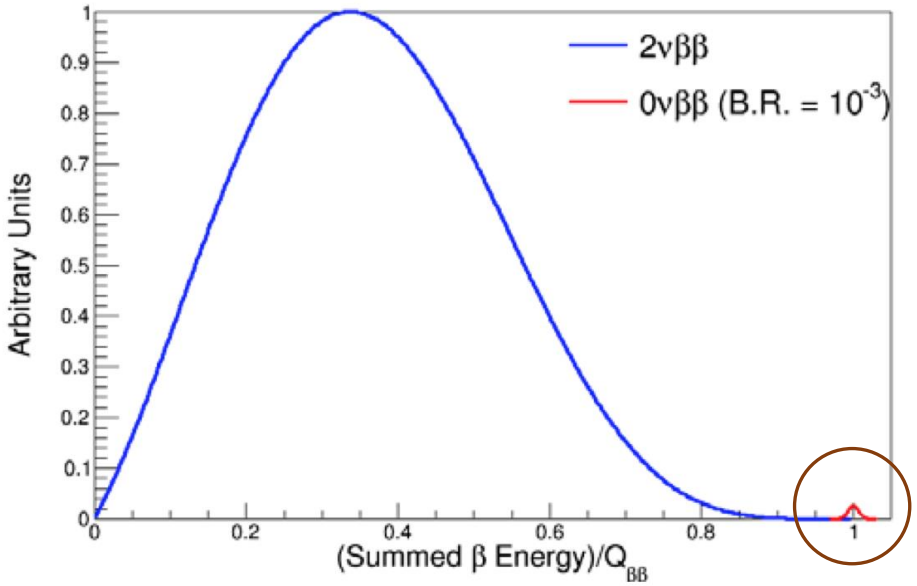
Strategic planning for discovery (**motivation**) + **interpretation**

# 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

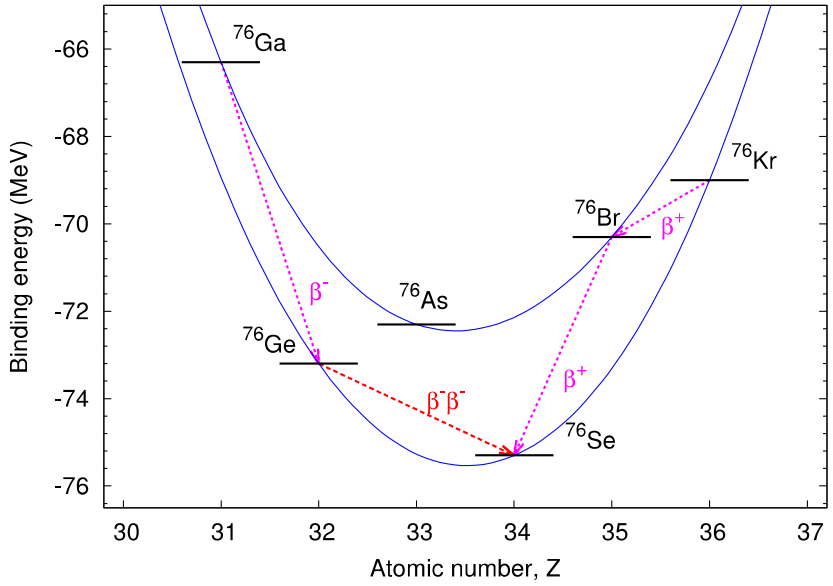
Matter/antimatter asymmetry

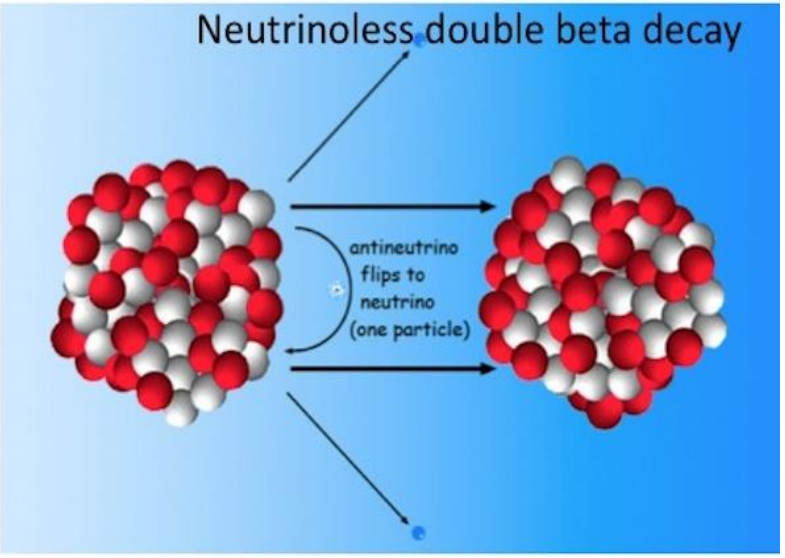
**Absolute neutrino mass scale**

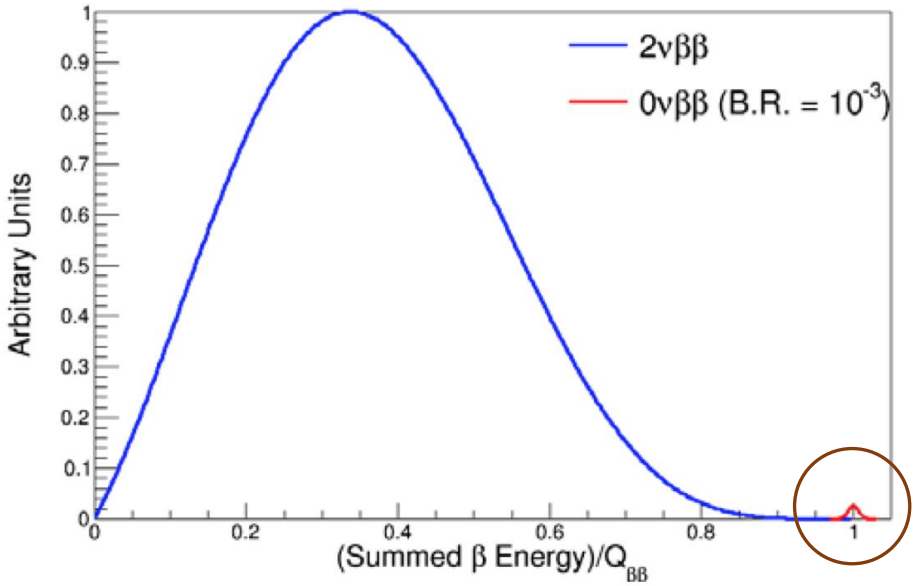
$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2 \quad \langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei} m_i\right|$$

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

Neutrino own antiparticle $\Longleftrightarrow$ 0νββ decay




**Tremendous impact on BSM physics**

Lepton-number violation

Majorana character of neutrino

Matter/antimatter asymmetry

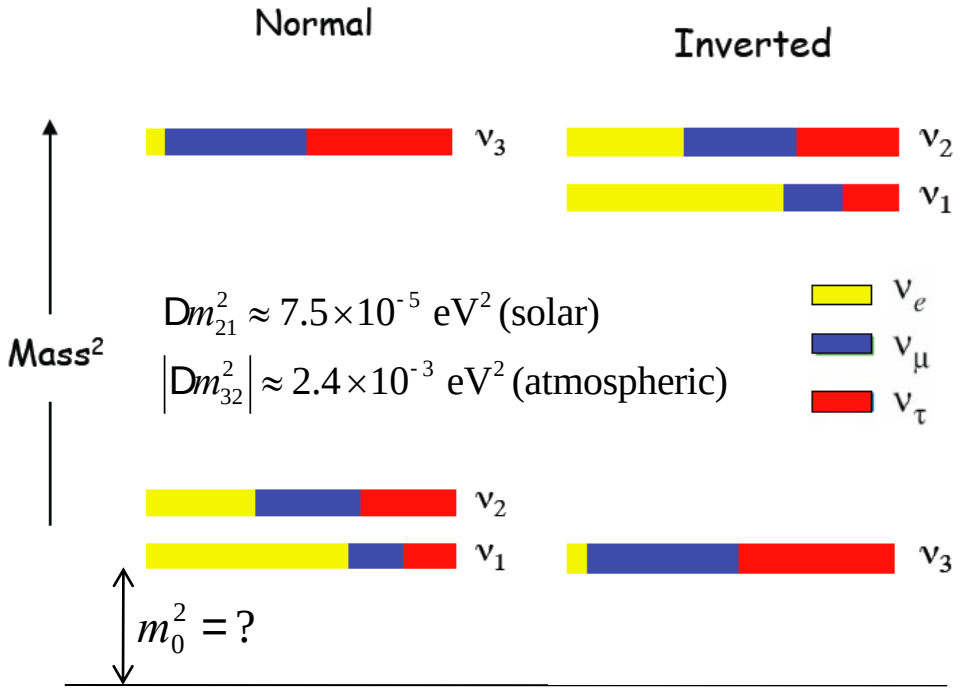
**Absolute neutrino mass scale**

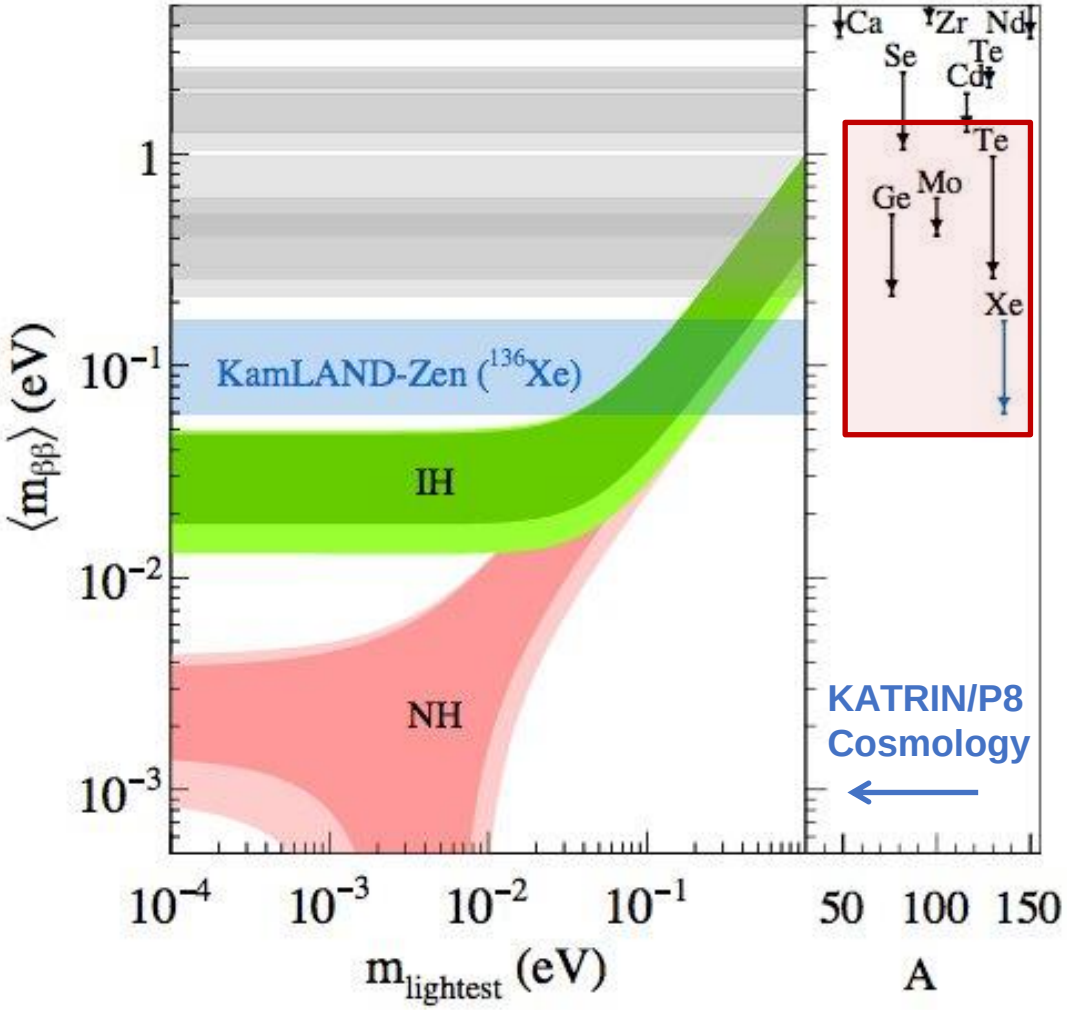
$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2\left\langle m_{\beta\beta}\right\rangle^2 \quad \left\langle m_{\beta\beta}\right\rangle = \left|\sum_{i=1}^{3} U_{ei} m_i\right|$$

**NME not observable: must be calculated**

# Nature of Neutrino: 0νββ Decay

Next-generation searches probe **Inverted Hierarchy**



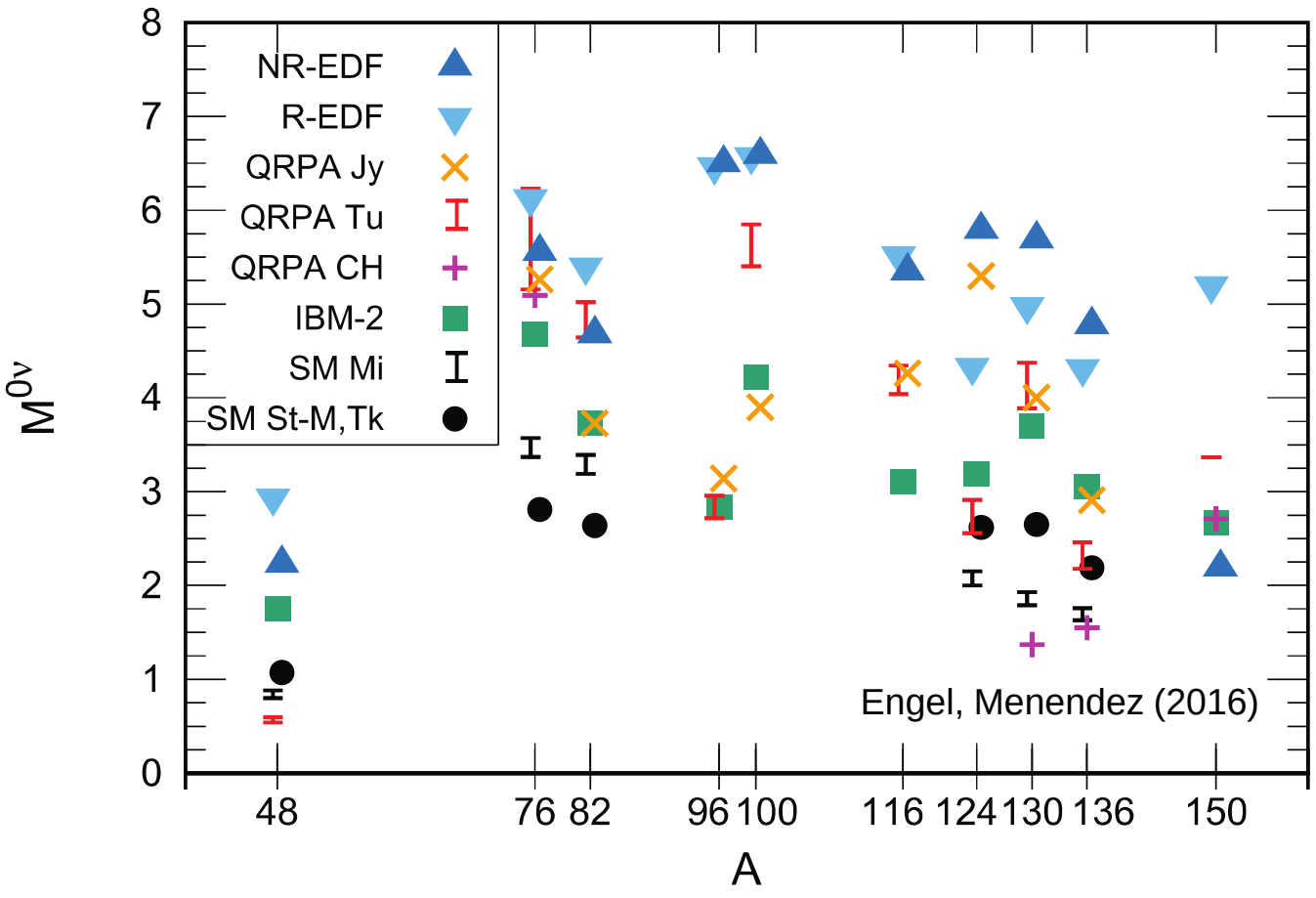




$$\left(T^{0\nu\beta\beta}_{1/2}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2 \quad \langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei} m_i\right|$$

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

# Status of 0νββ-Decay Matrix Elements

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

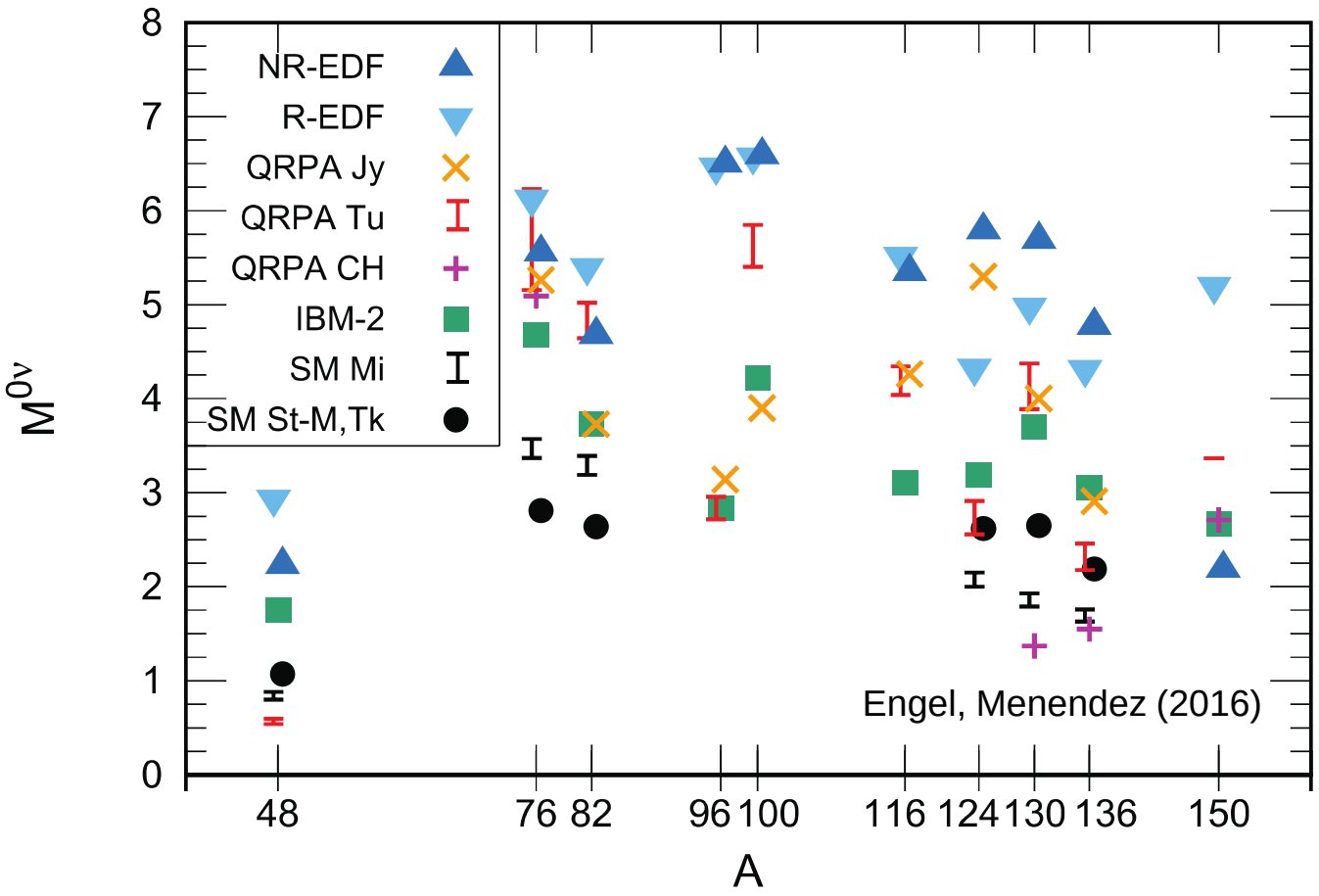


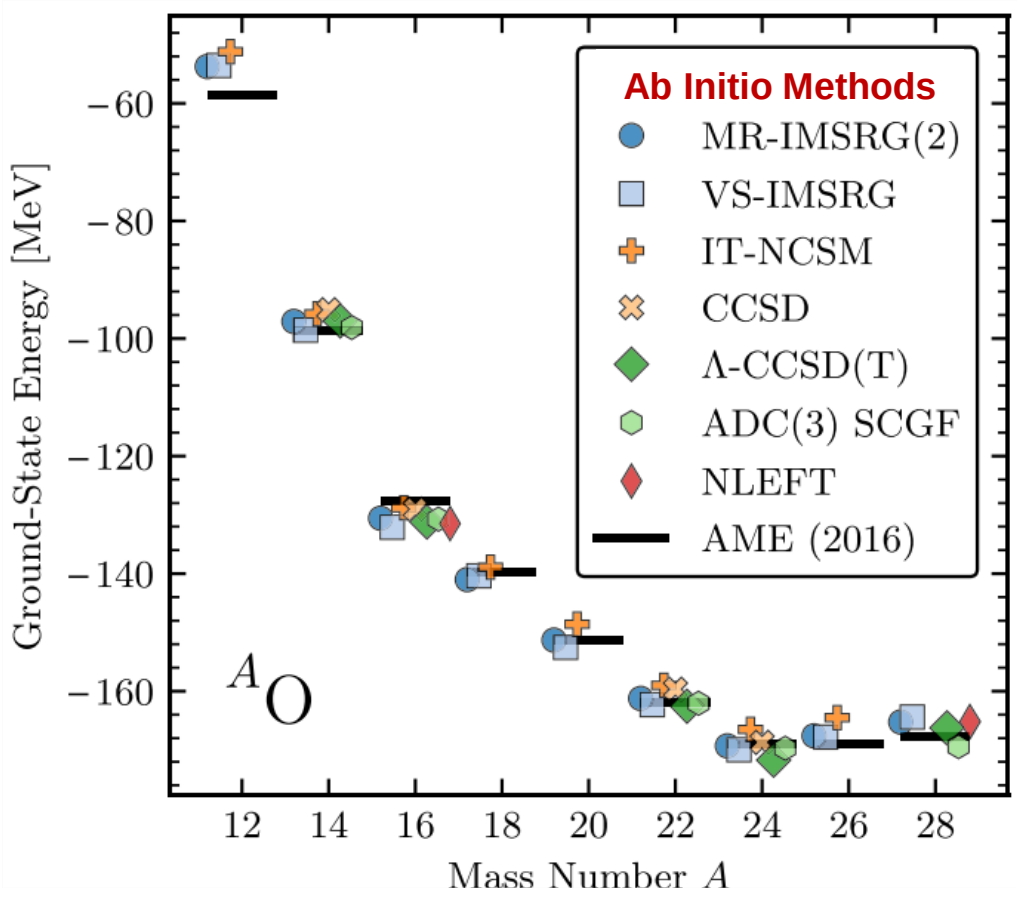

All models missing essential physics: correlations, single-particle levels, two-body currents

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

# Status of 0νββ-Decay Matrix Elements

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



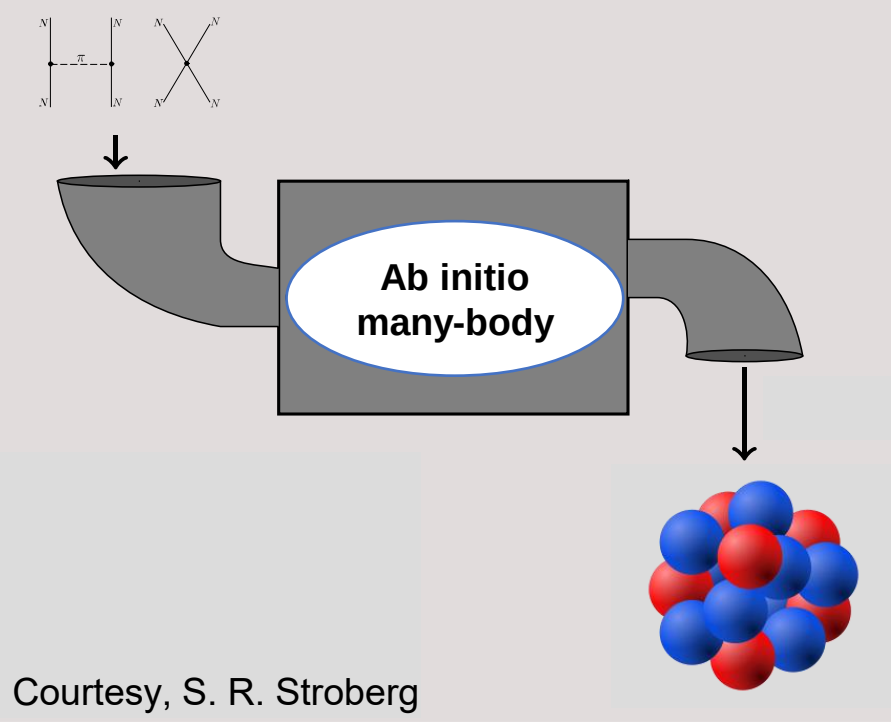

New approach to NME calculations: **ab initio theory** consistent results when extrapolated

# 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

$$H\psi_n = E_n\psi_n$$



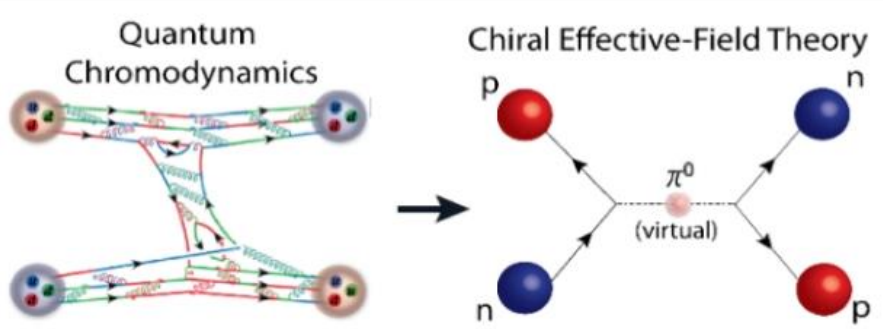

Courtesy, S. R. Stroberg

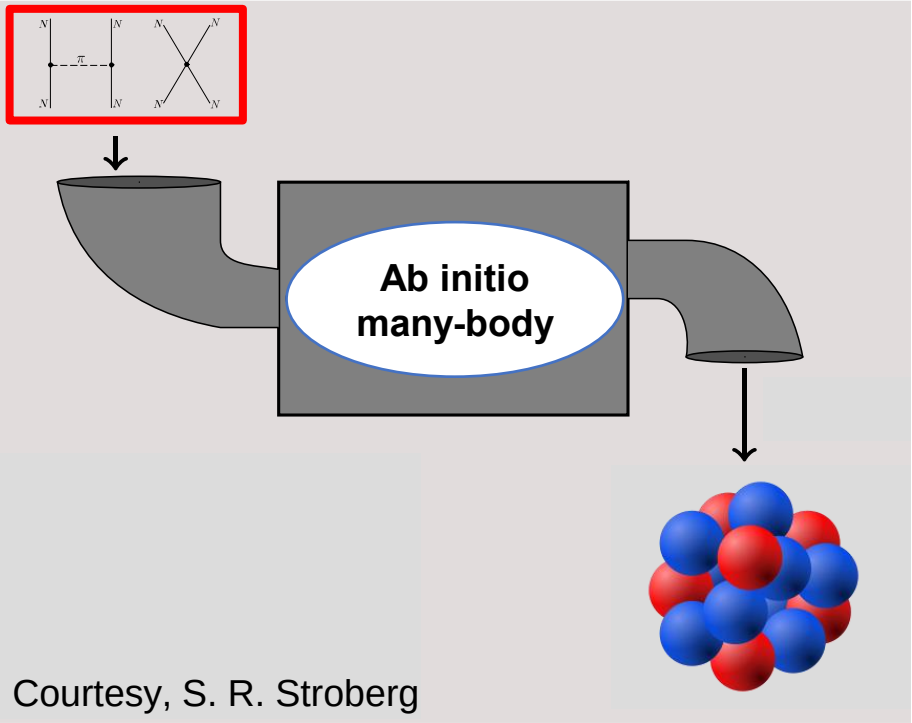
# Ingredient I: Nuclear Forces

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

High-energy information encoded in contact terms

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




Courtesy, S. R. Stroberg

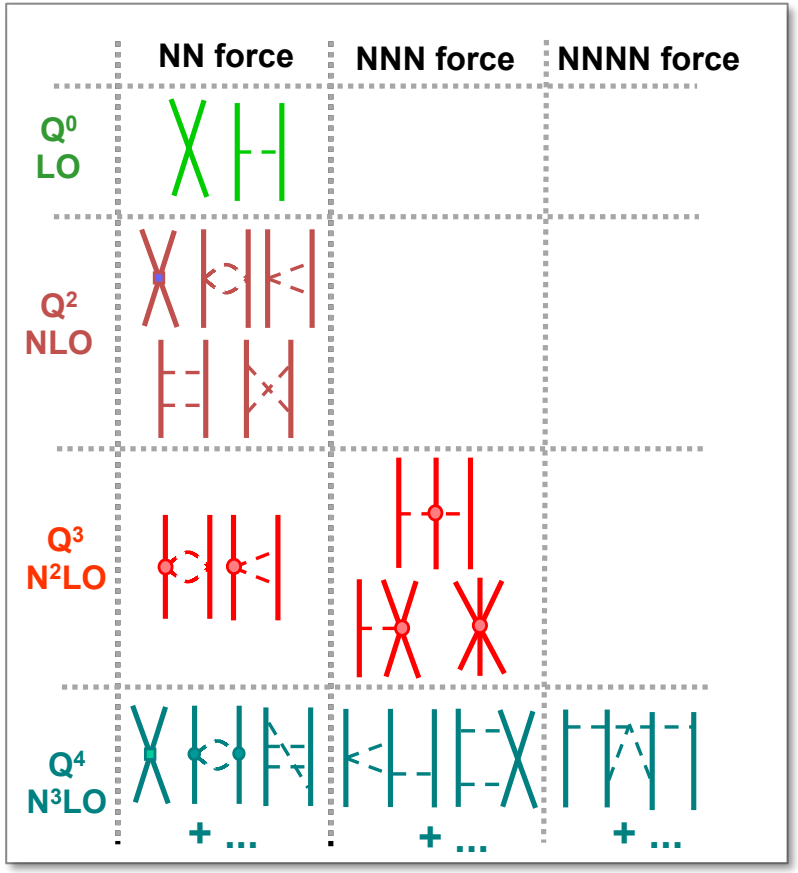
Chiral Effective Field Theory

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

Quantifiable uncertainties

Interactions

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

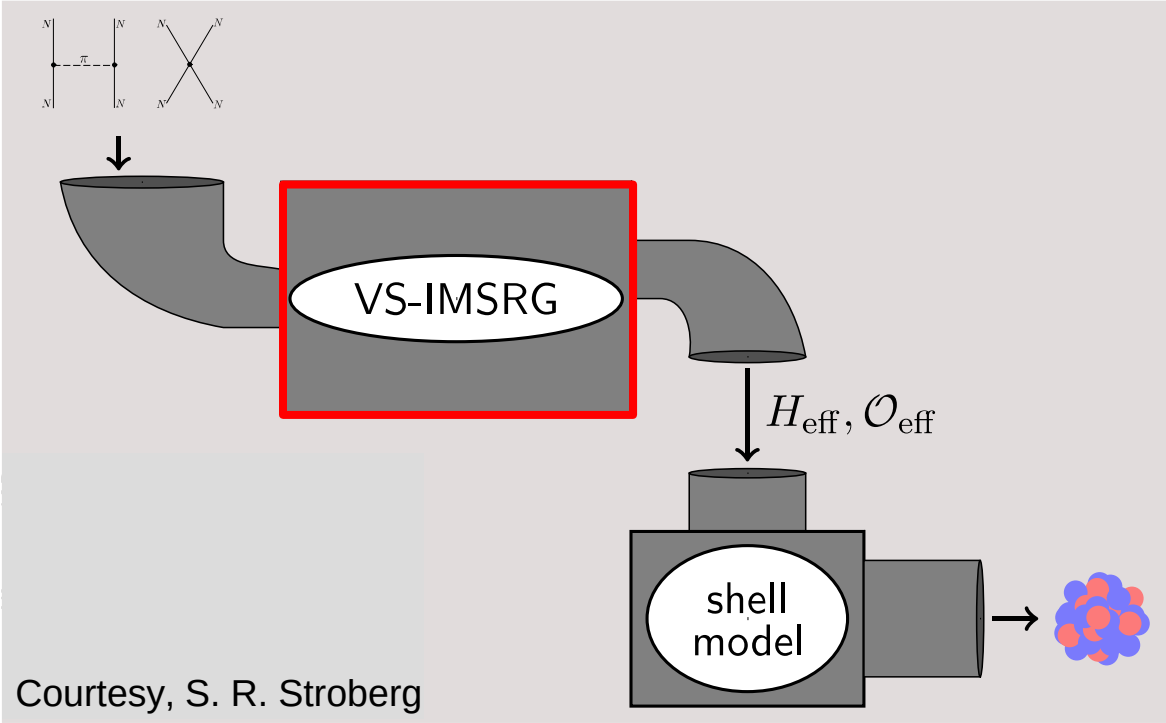


# *Key Advance* Valence-Space Approach

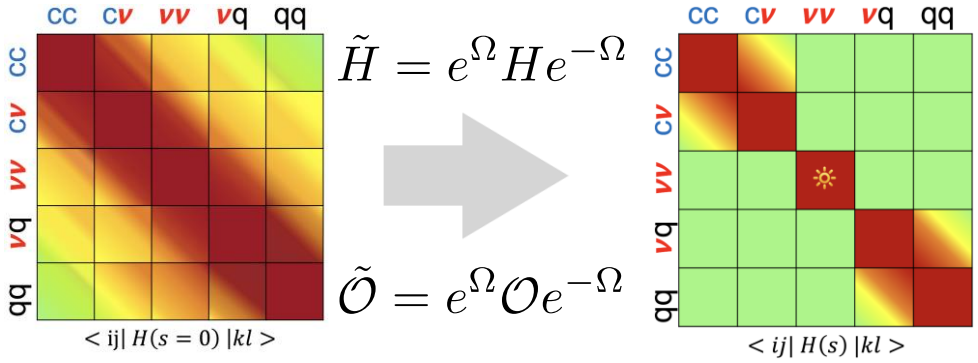
Polynomially scaling methods tailored for doubly magic, semi-magic chains

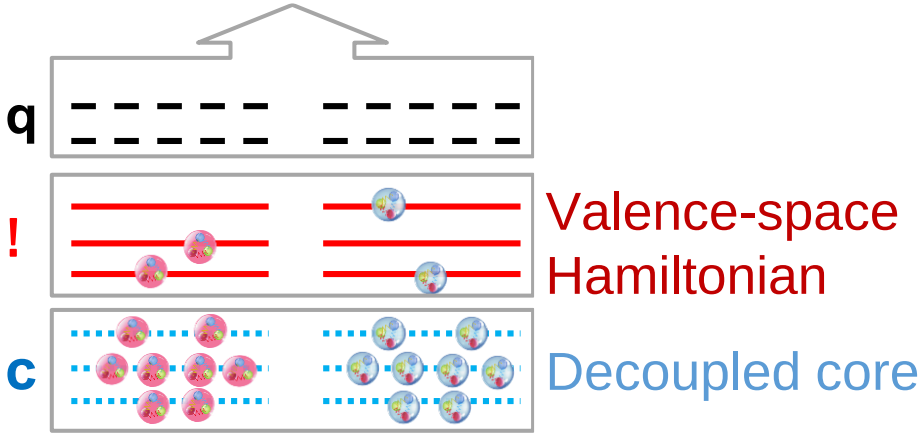
**Valence-space IMSRG**: Novel approach for all open-shell nuclei

$$H\psi_n = E_n\psi_n$$




Courtesy, S. R. Stroberg



**Ragnar Stroberg**

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

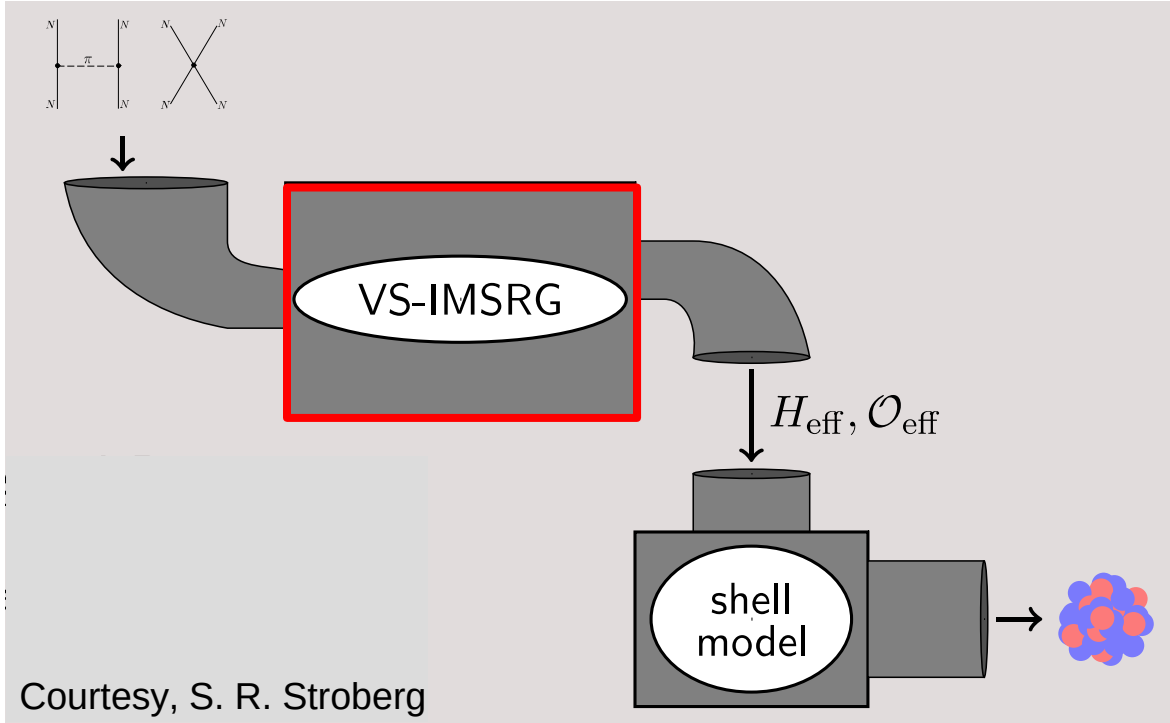
**Ab initio → scope of nuclear shell model**

# 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

$$H\psi_n = E_n\psi_n$$



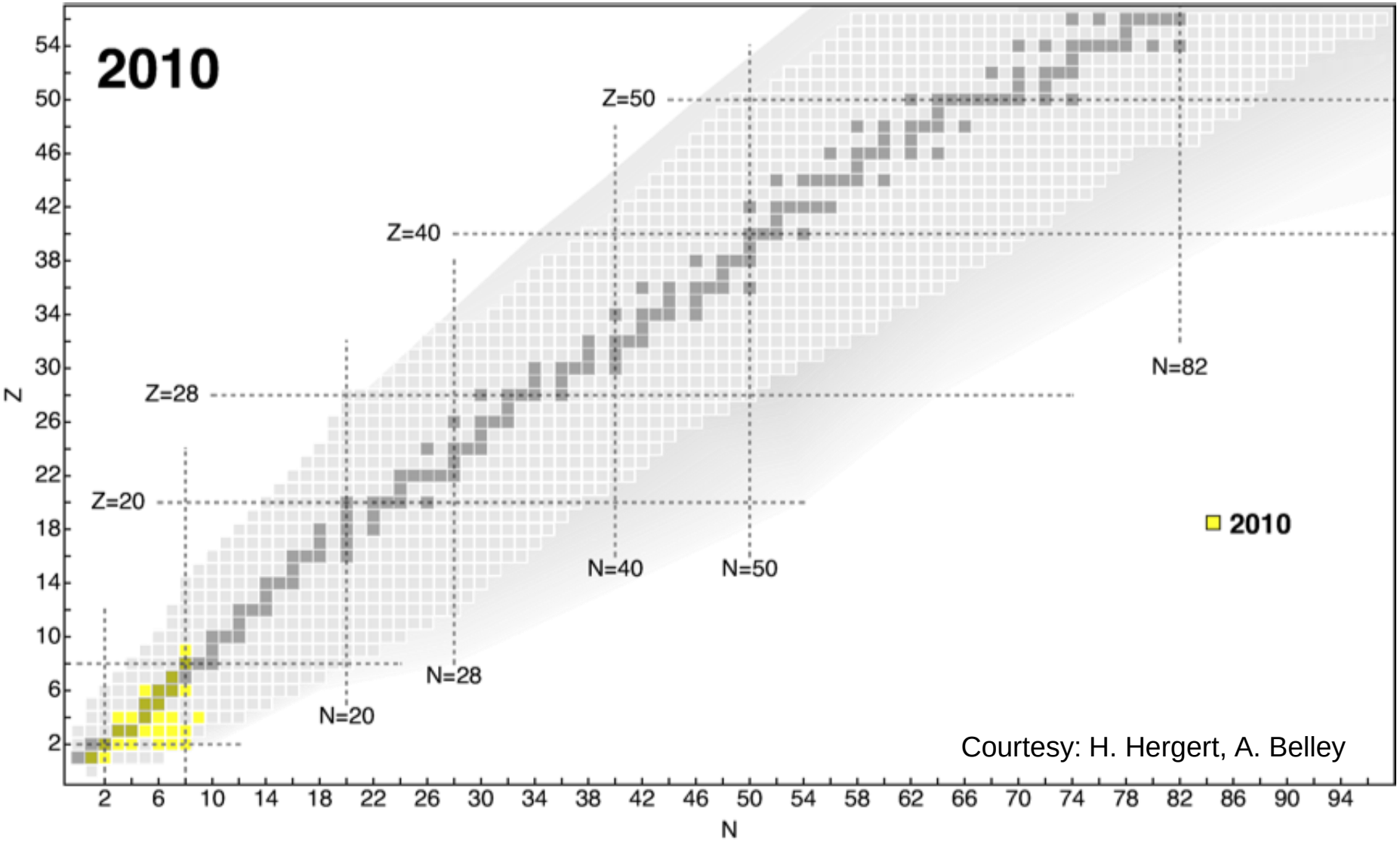

Courtesy, S. R. Stroberg

**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)**

# Scope of Ab Initio: 2010

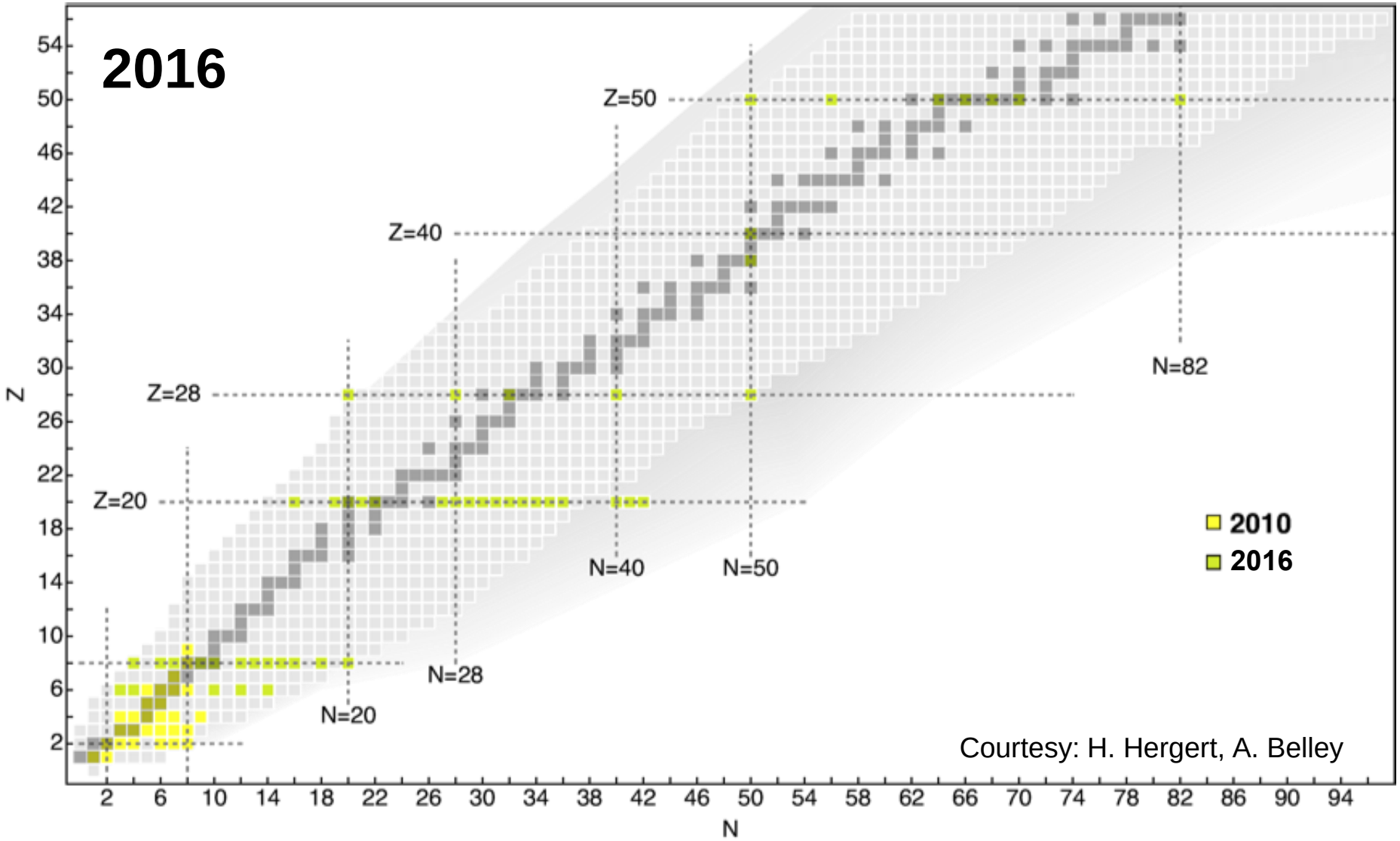
**2010** Quasi-exact methods for light nuclei ($^{16}O$); limited capability for 3N forces



# Scope of Ab Initio: 2016

**2016** Polynomially scaling methods emerge (Coupled Cluster, IMSRG, etc.)

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

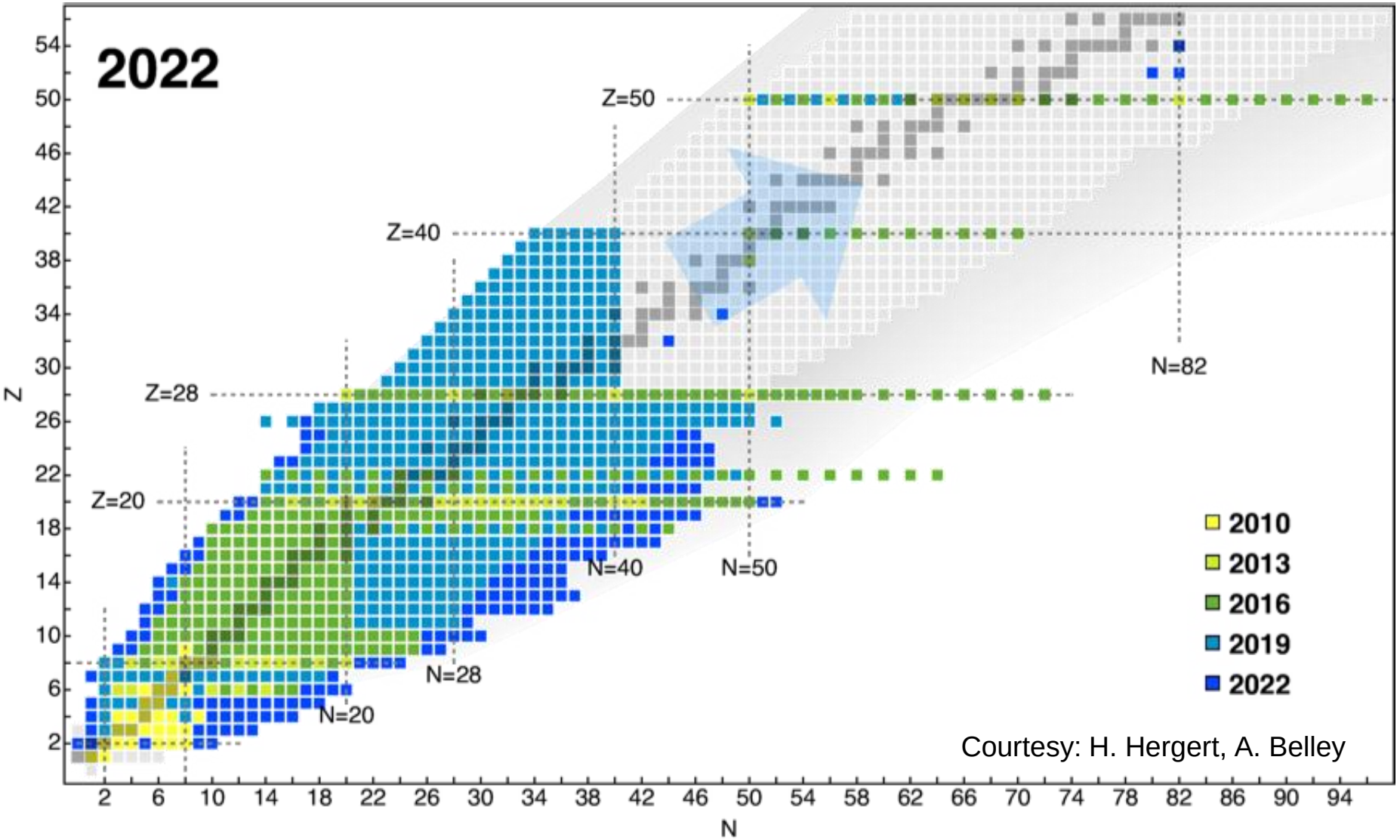



Courtesy: H. Hergert, A. Belley

# The Six-Year Revolution: Ab Initio 2022

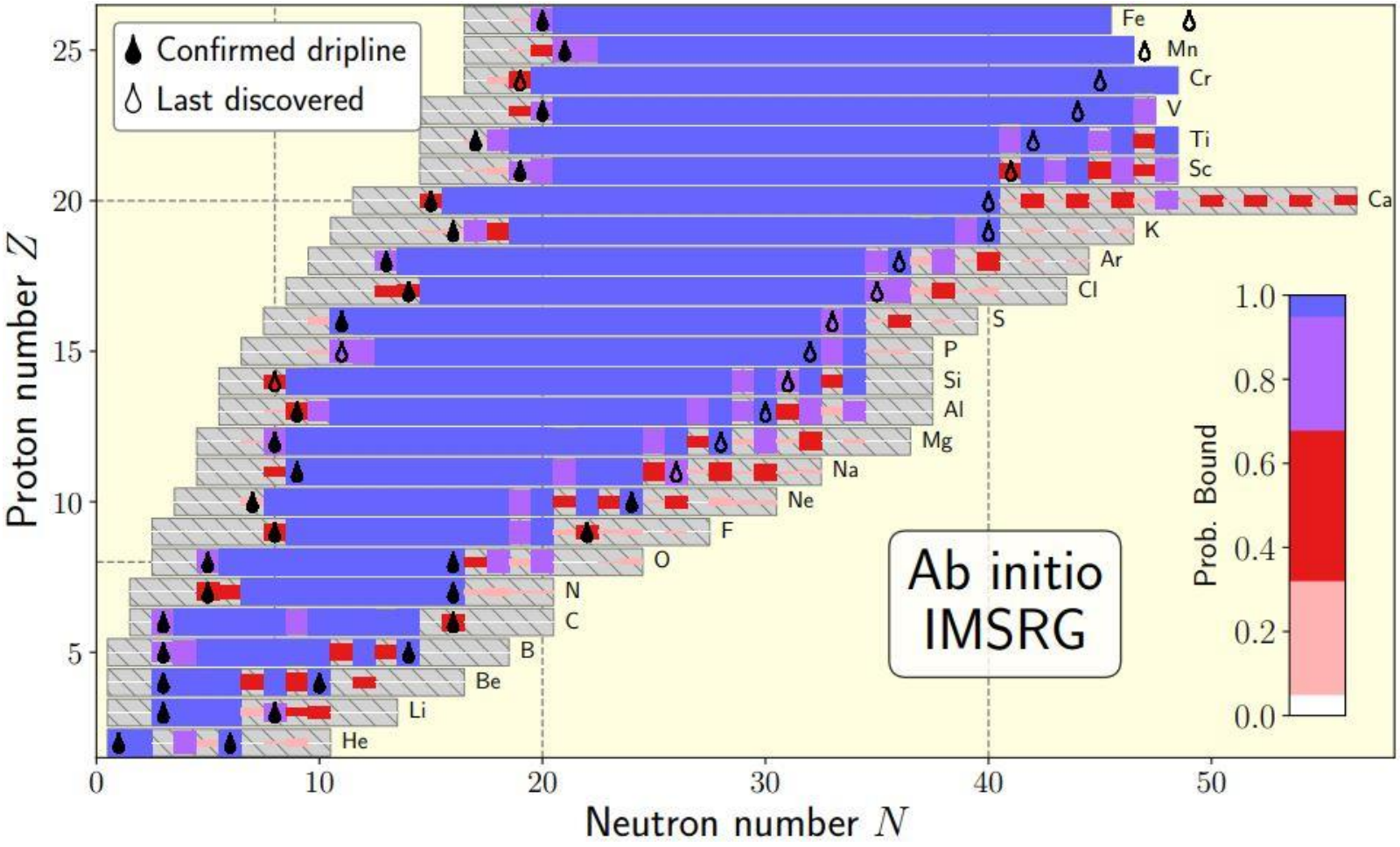
**2022** Valence-space approach: essentially *all* properties of *all* nuclei

**What can we do with this advance?**

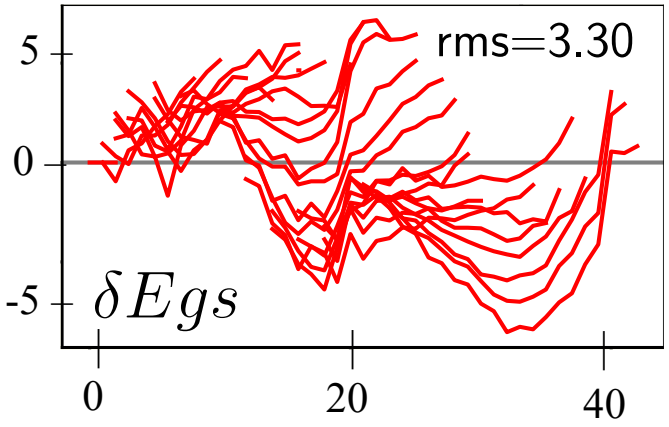


# Predicting Ab Initio Limits of Atomic Nuclei

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




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




Input NN+3N fit to 2,3,4-body

*Not biased towards existing data*

**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

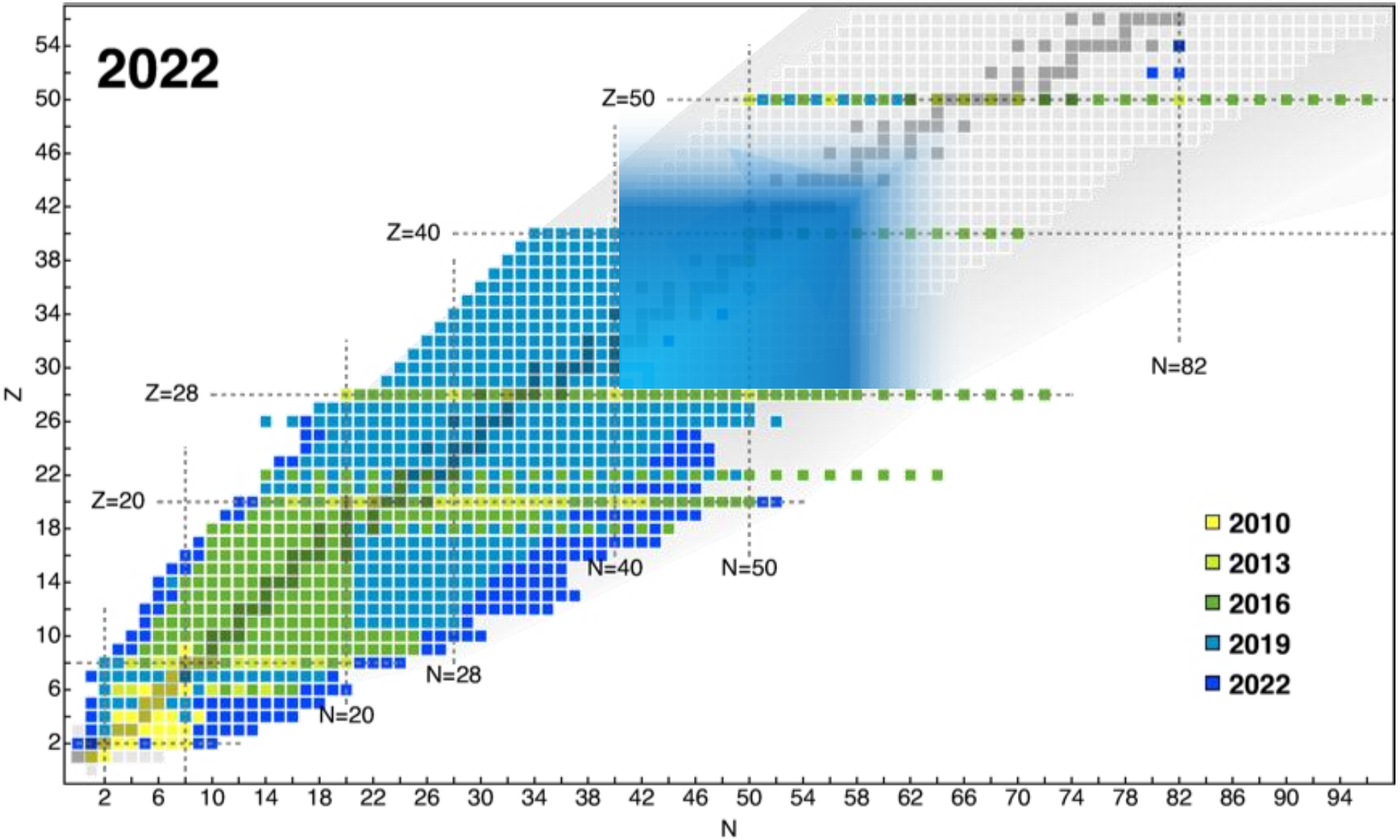
Known drip lines predicted within uncertainties

**Ab initio guide for neutron-rich driplines**

# Ab Initio Progress: How Heavy Can We Go?

Tremendous progress in ab initio reach, largely due to valence-space IMSRG

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




Key Limitation

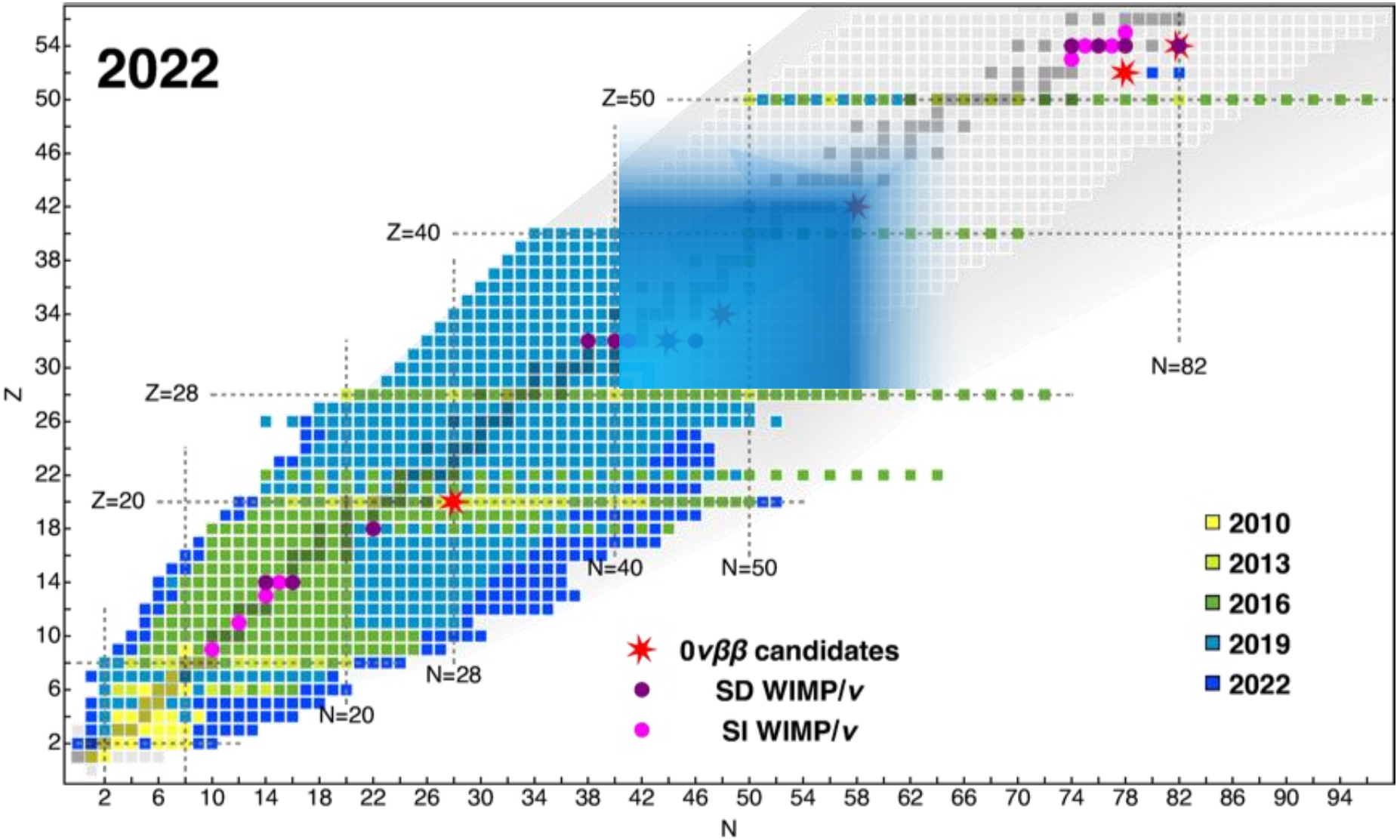
**3NF matrix element storage**

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

# Ab Initio Progress: How Heavy Can We Go?

Tremendous progress in ab initio reach, largely due to valence-space IMSRG

Calculate essentially *all* properties *all* of nuclei… **to N, Z ~ 50 (key nuclei just out of reach!)**




Key Limitation

**3NF matrix element storage**

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

TRIUMF

*KEY ADVANCE*

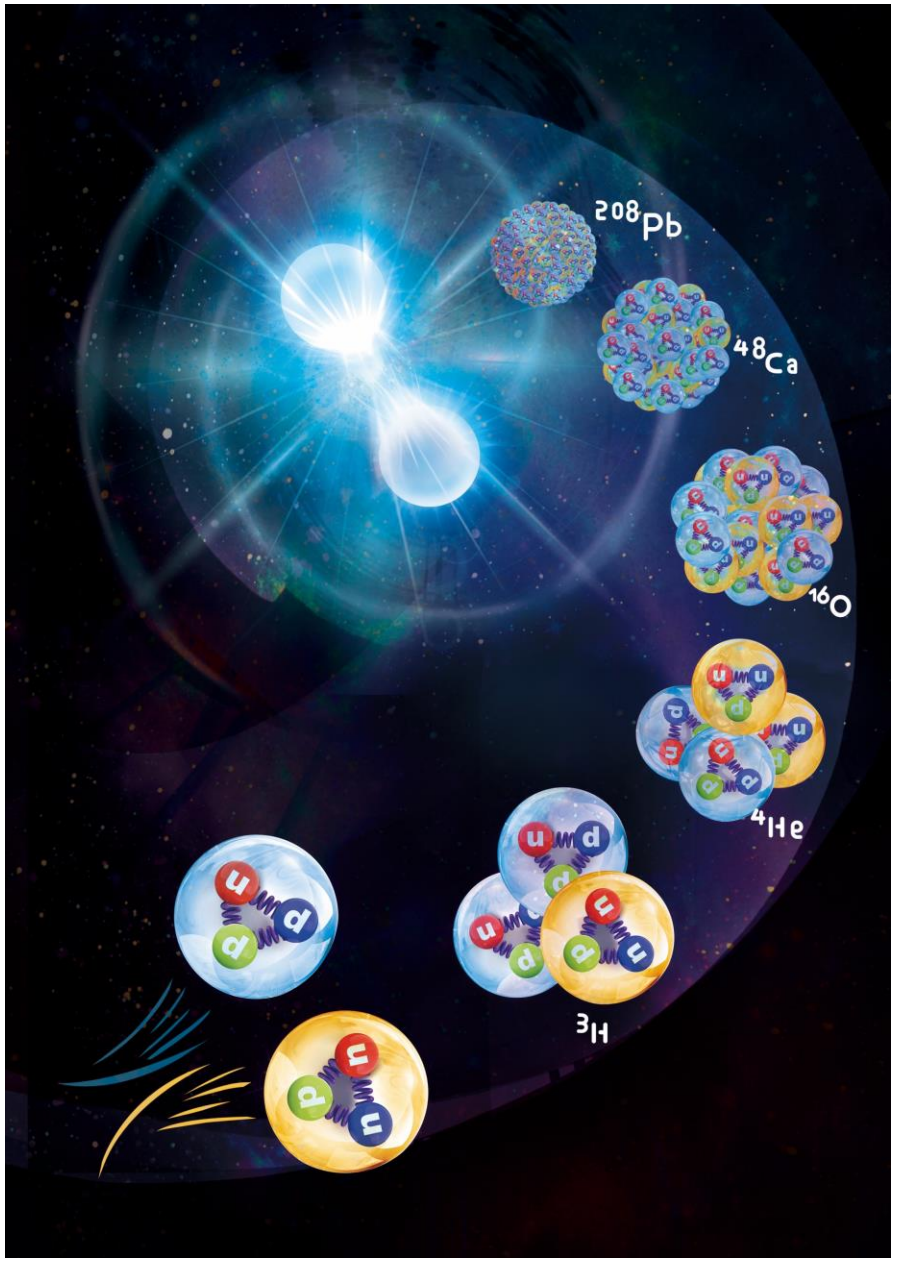
# Converged Calculations of Heavy Nuclei

筑波大学
University of Tsukuba

Takayuki Miyagi

Converged *ab initio* calculations of heavy nuclei

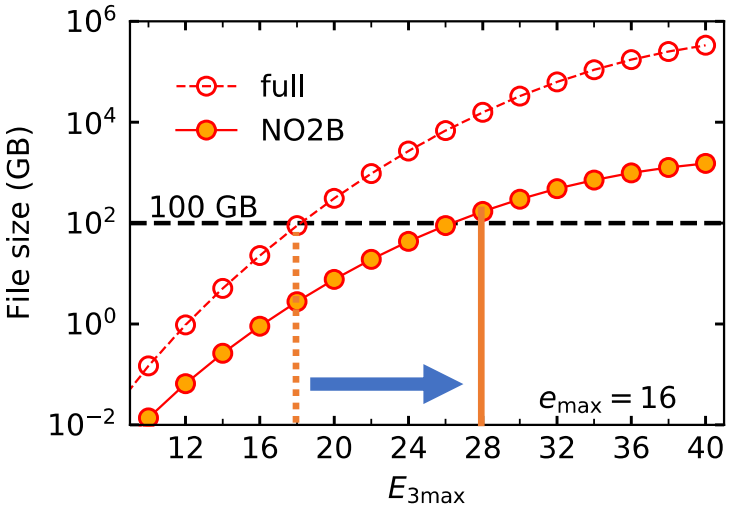
T. Miyagi, S. R. Stroberg, P. Navrátil, K. Hebeler, and J. D. Holt
Phys. Rev. C **105**, 014302 – Published 3 January 2022

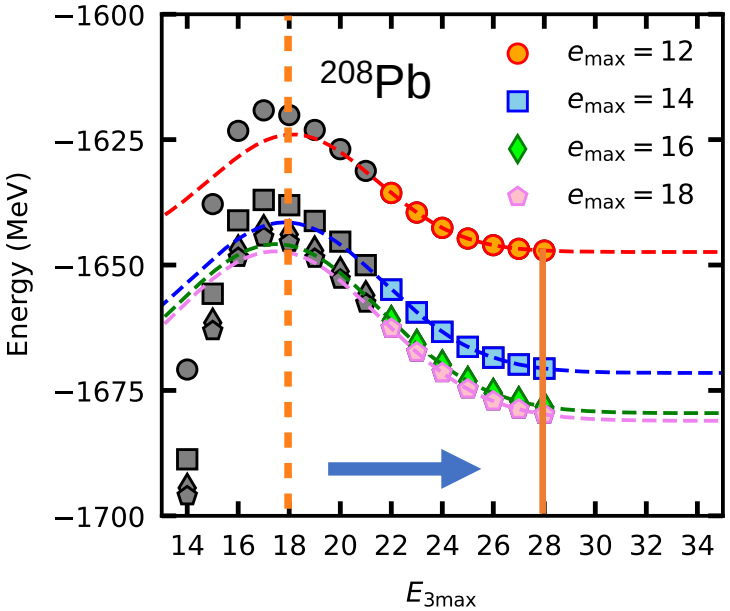


# Ab Initio Calculations of Heavy Nuclei

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

## Clever storage reduces needs: TB → GB



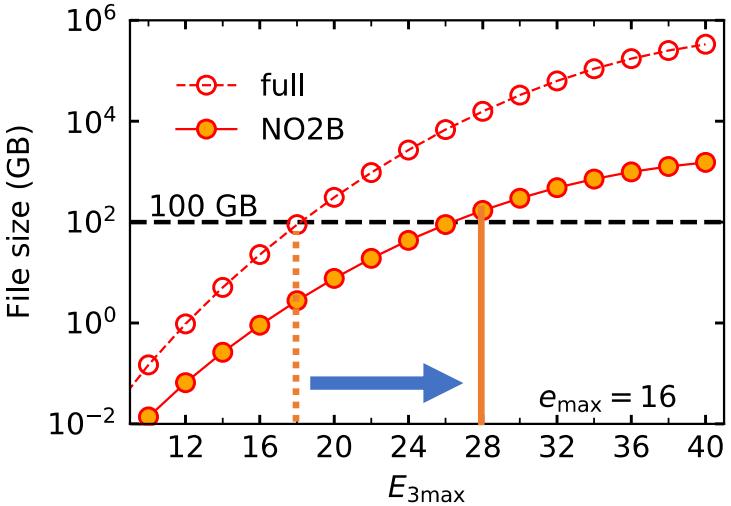

$^{208}$Pb now straightforward:

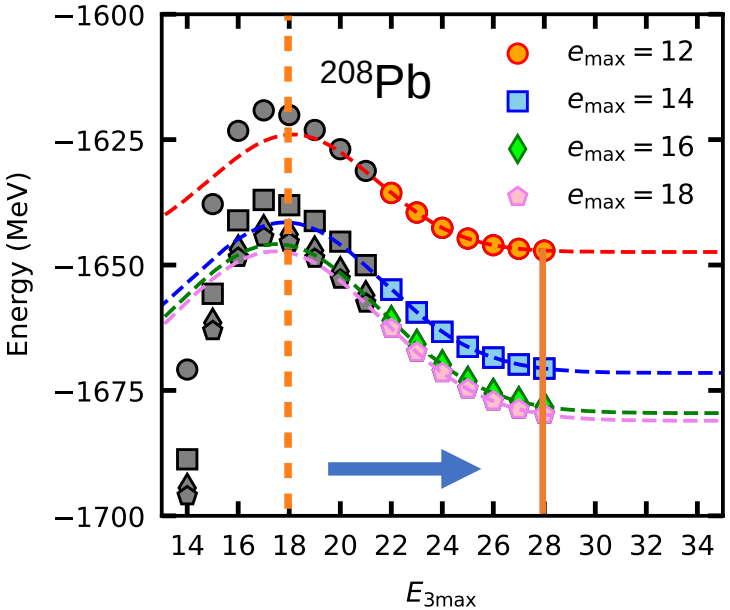
Solving the Schrödinger equation for 200+ nucleons!

# Ab Initio Calculations of Heavy Nuclei

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

## Clever storage reduces needs: TB → GB



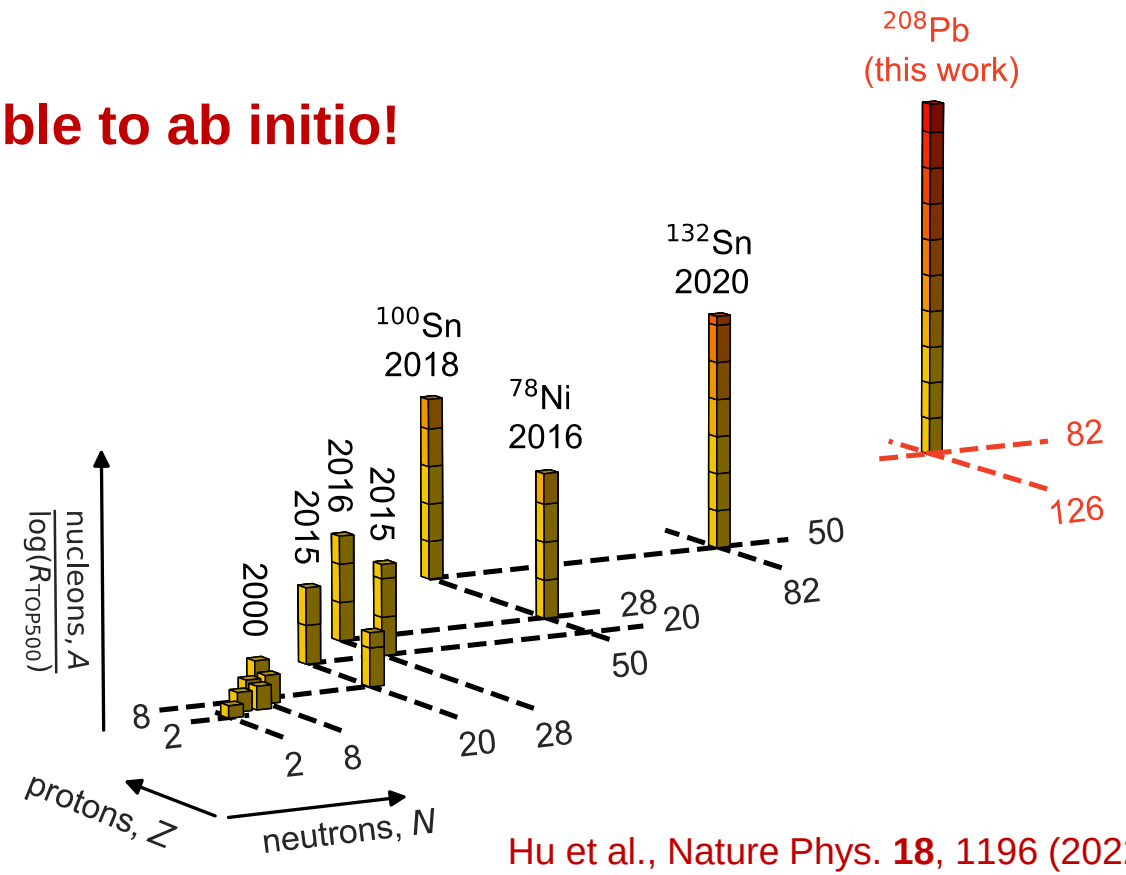

$^{208}$Pb now straightforward:

Solving the Schrödinger equation for 200+ nucleons!

**(Super)heavy accessible to ab initio!**

16 years: $^{16}$O → $^{56}$Ni

6 years: $^{56}$Ni → $^{208}$Pb




Hu et al., Nature Phys. **18**, 1196 (2022)

TRIUMF

*Milestone Result*

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

nature physics

ARTICLES

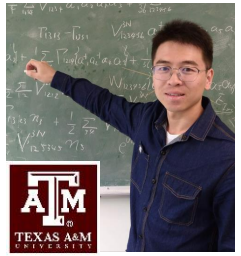
https://doi.org/10.1038/s41567-022-01715-8

OPEN

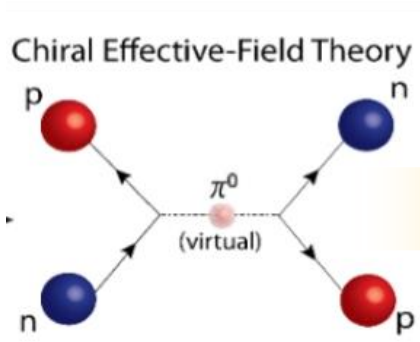
## Ab initio predictions link the neutron skin of $^{208}$Pb to nuclear forces

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]

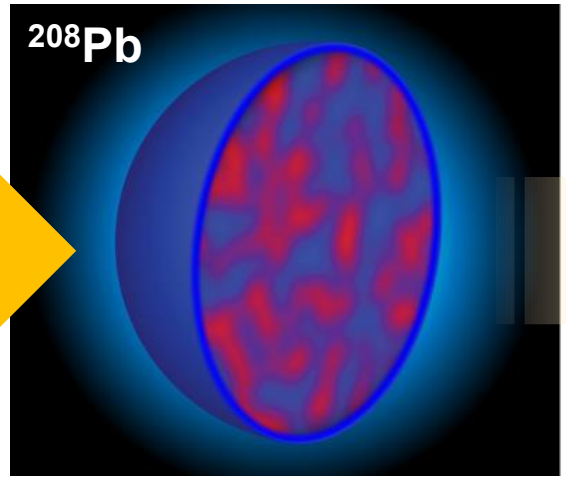
Takayuki Miyagi



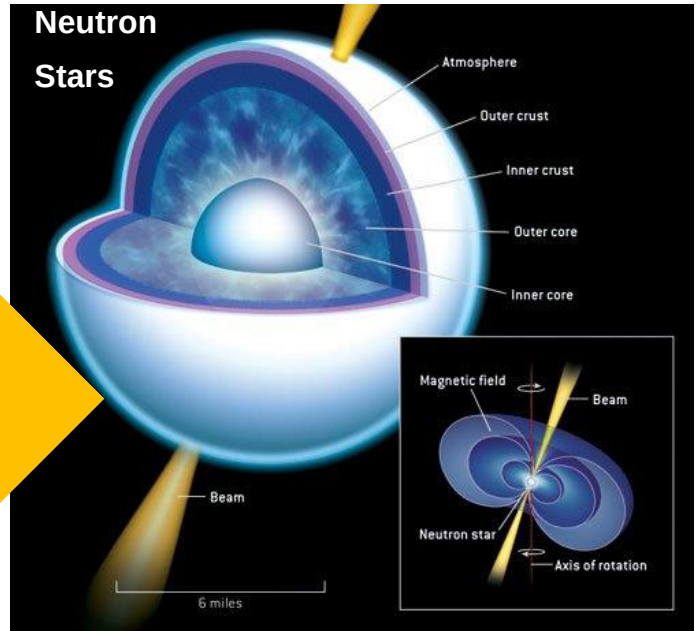

Baishan Hu




Ab Initio




Nuclear EOS



TRIUMF

*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

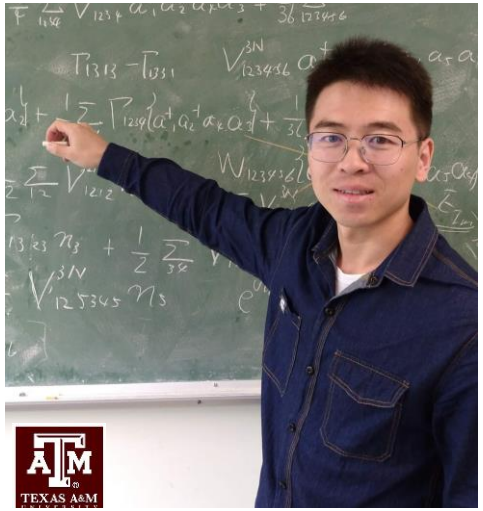
OPEN

## 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]

280

Takayuki Miyagi




IUPAP EARLY CAREER SCIENTIST PRIZES IN NUCLEAR PHYSICS 2025

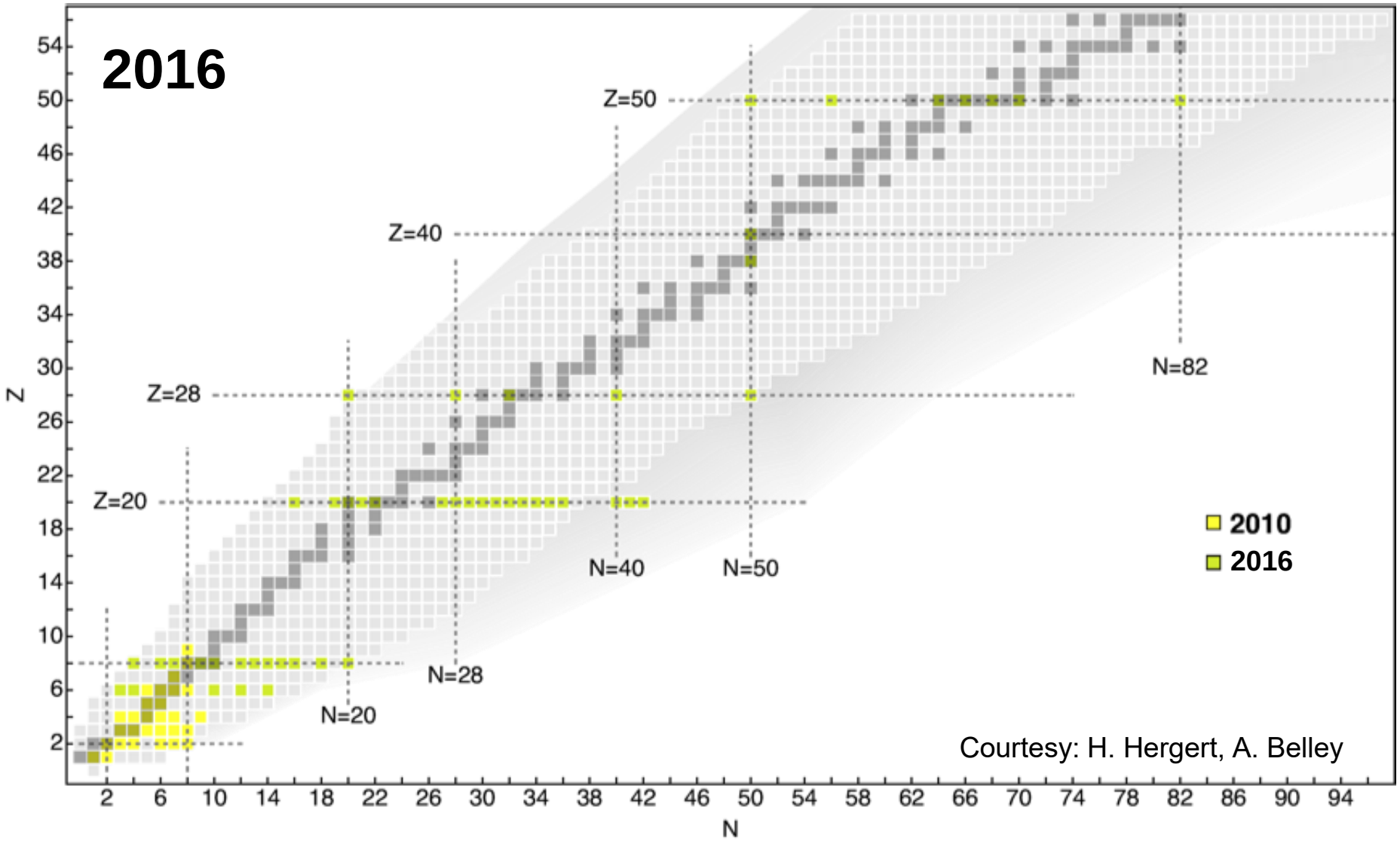
## Baishan Hu

Baishan Hu received his prize *"for pioneering ab initio nuclear theories that extend precision calculations to heavy and strongly deformed nuclei—advancing our understanding of nuclear structure, dense nuclear matter, and physics beyond the Standard Model."*

# Scope of Ab Initio: 2016

**2016** Polynomially scaling methods (Coupled Cluster, IMSRG)

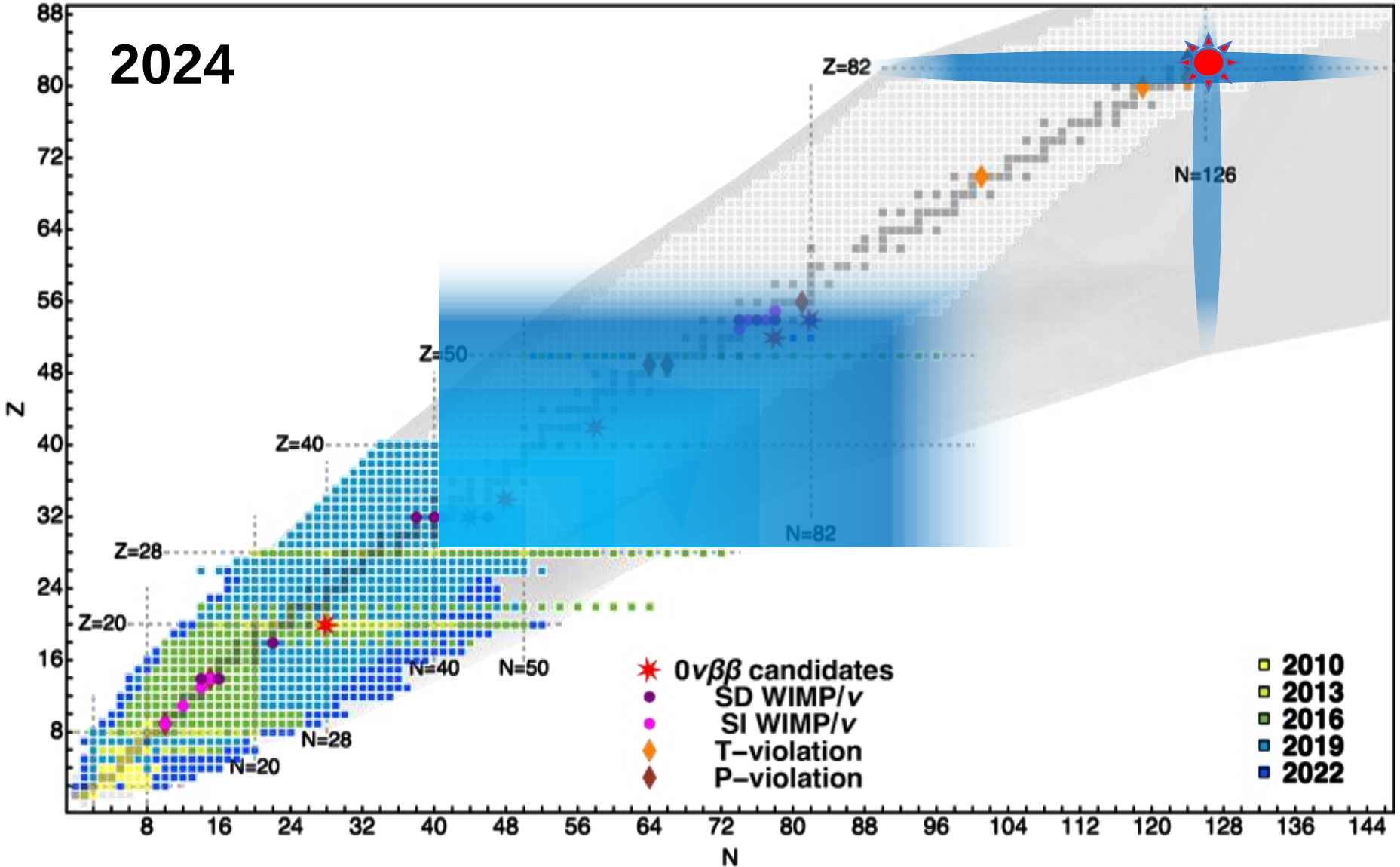
Progress to doubly magic $^{56/78}$Ni + semi-magic chains



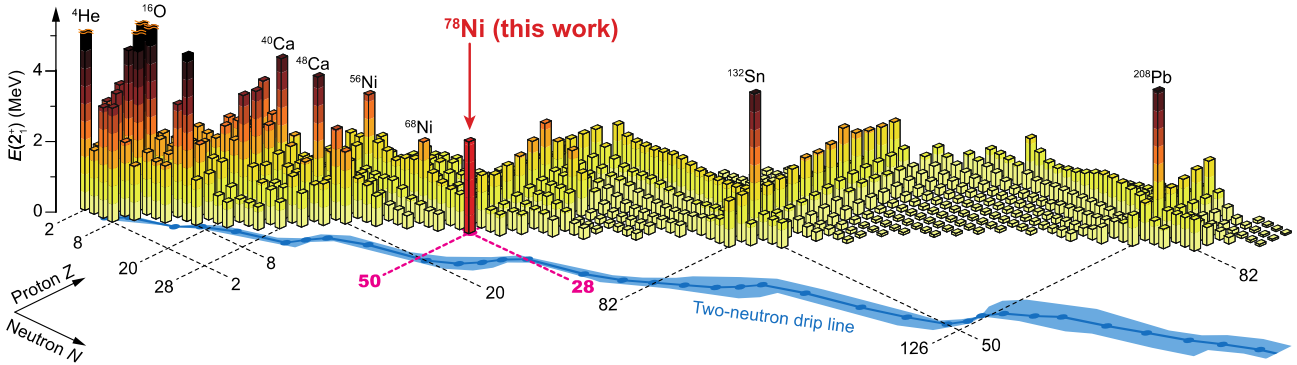
# Scope of Ab Initio Theory: Today

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

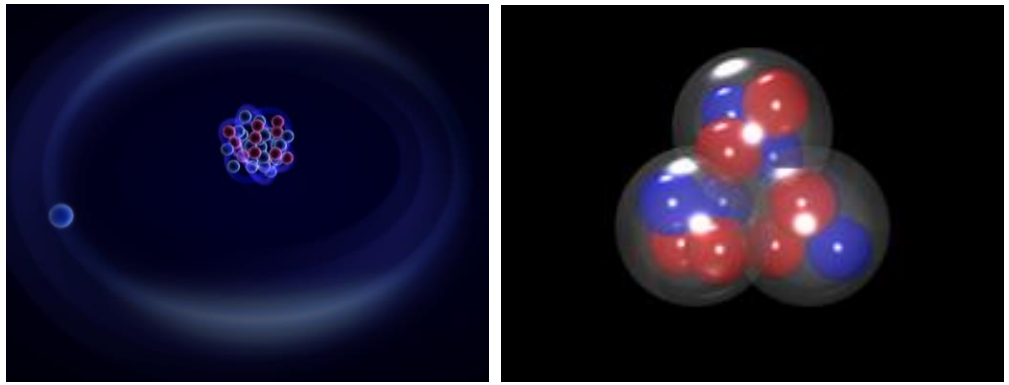
Exciting applications to searches for BSM physics!



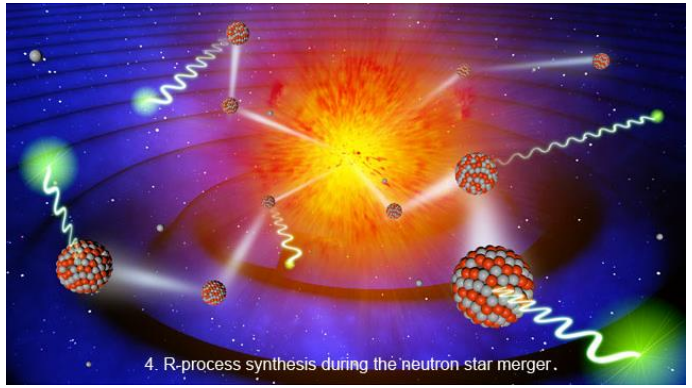
# Major Questions in Nuclear Structure/Astrophysics



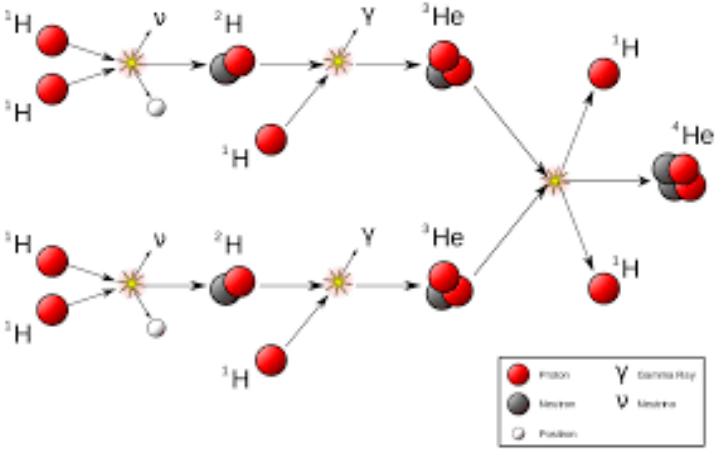

Limits of existence + formation/evolution of magic numbers



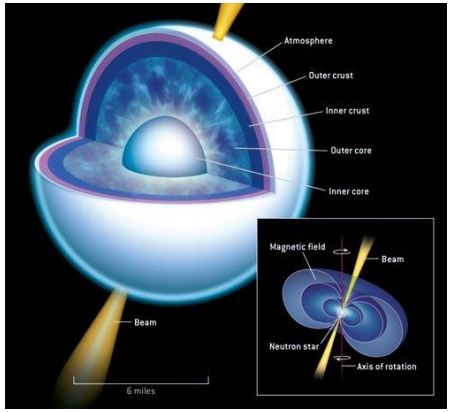
Nuclear skins/halos/clusters




Heavy Element Nucleosynthesis




Continuum and nuclear reactions




Infinite matter/Neutron stars

# Ab Initio VS-IMSRG Campaign: Masses and Charge Radii

Expansive campaign for nuclear structure, astrophysics, and BSM physics searches

**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)

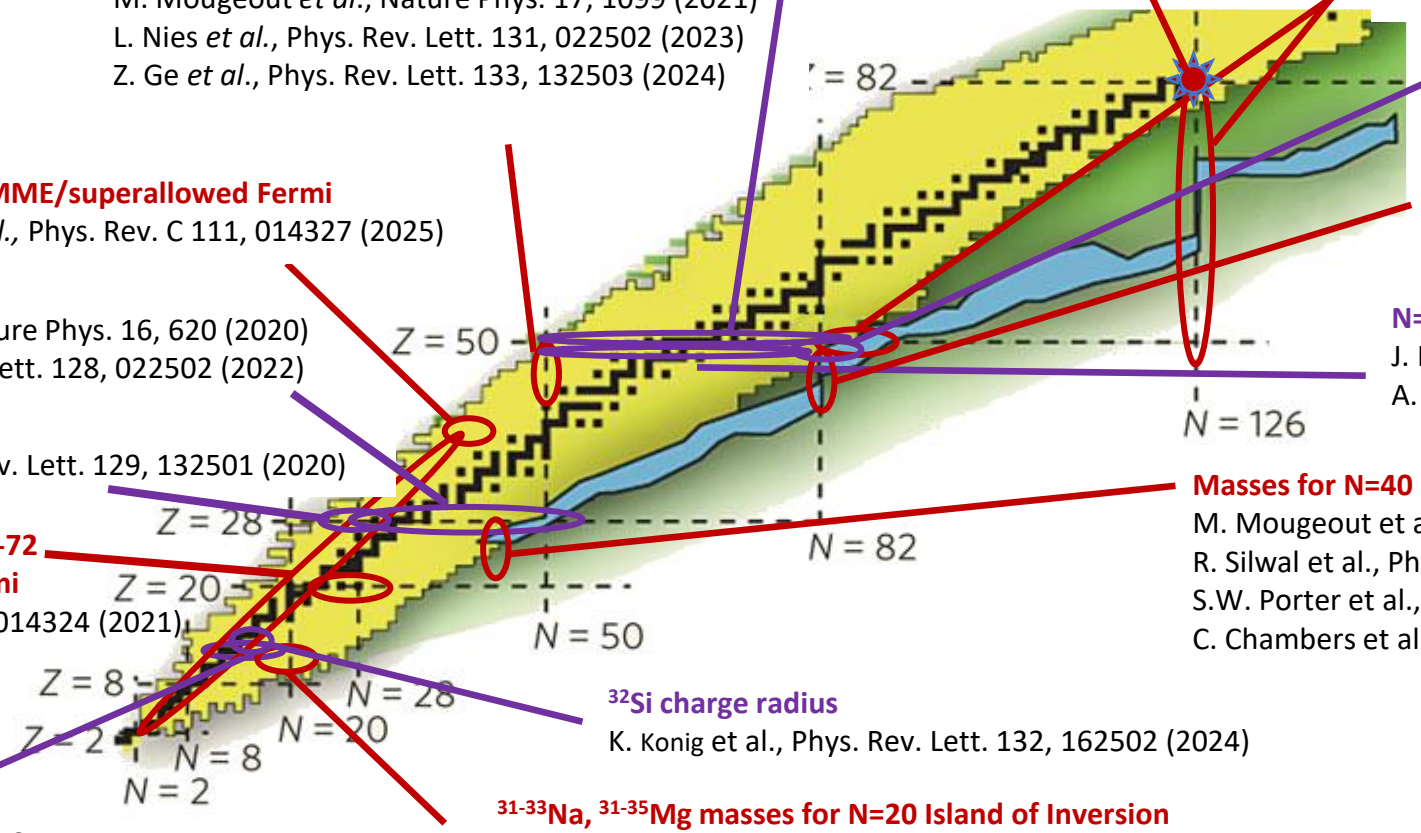
**N=28-50 Ni and Cu radii**
R.P. de Groote *et al.*, Nature Phys. 16, 620 (2020)
S. Malbrunot Phys. Rev. Lett. 128, 022502 (2022)

**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

Expansive campaign for nuclear structure, astrophysics, and BSM physics searches

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

**Spectroscopy of $^{126\text{-}136}$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)

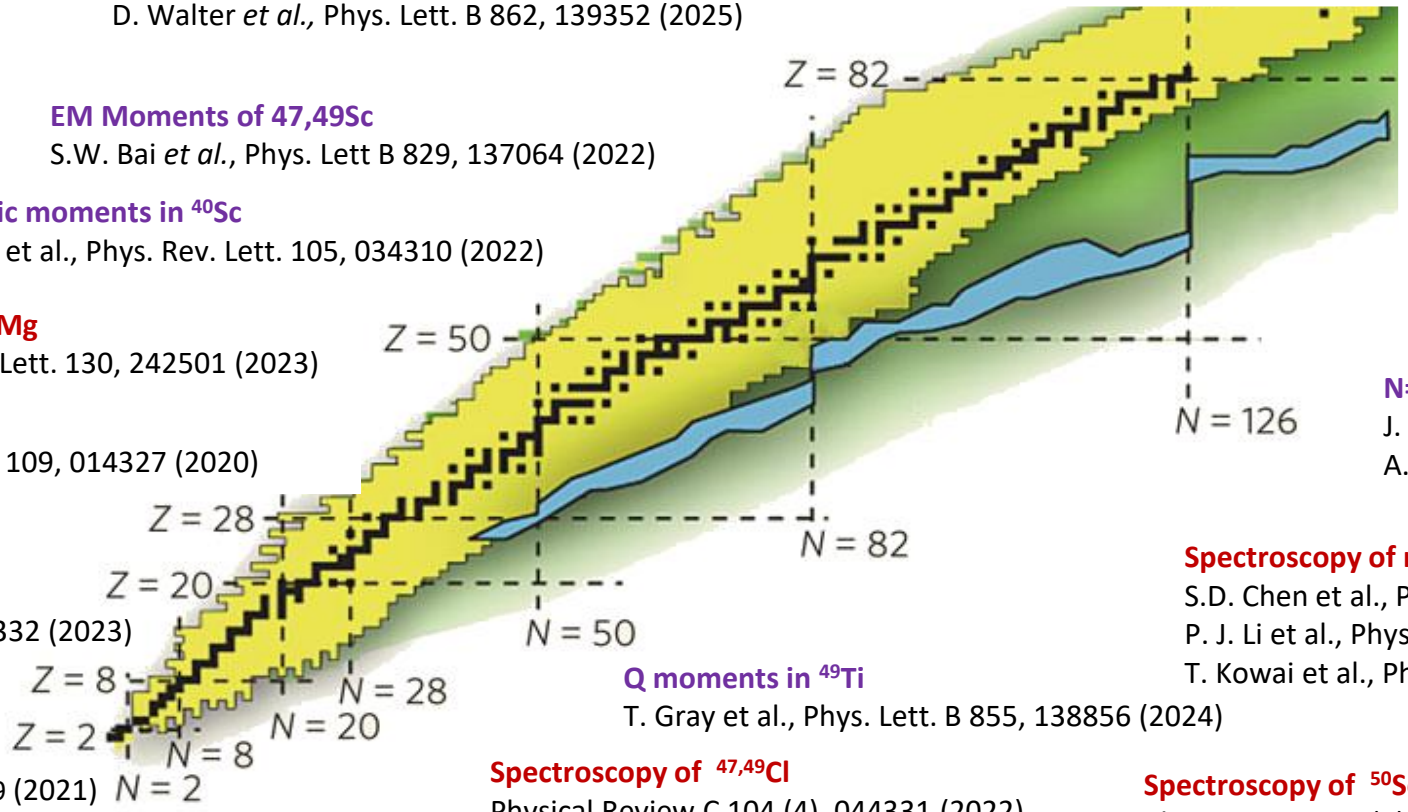
**Magnetic moments in $^{40}$Sc**
R Powel et al., Phys. Rev. Lett. 105, 034310 (2022)

**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)

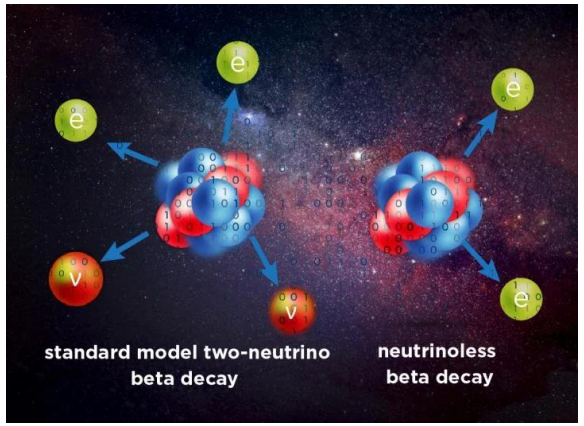
**Spectroscopy of $^{47,49}$Cl**
Physical Review C 104 (4), 044331 (2022)

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

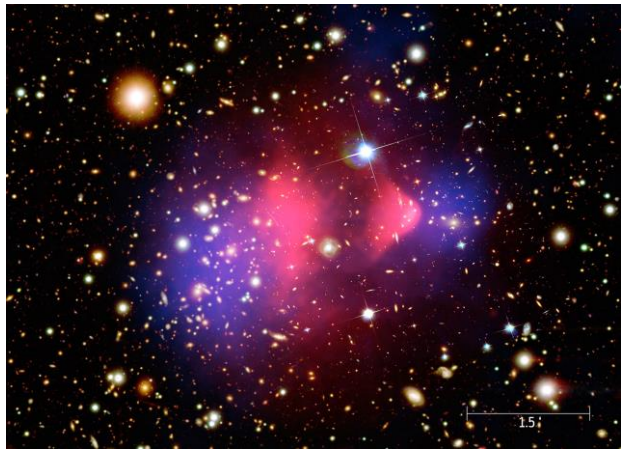
**Spectroscopy of $^{23}$F**
H. Crawford *et al.*, Phys. Rev. C 103, L061303 (2022)

**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)

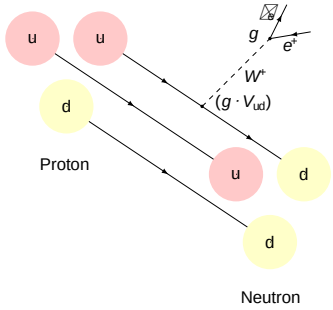
# Searches for BSM Physics



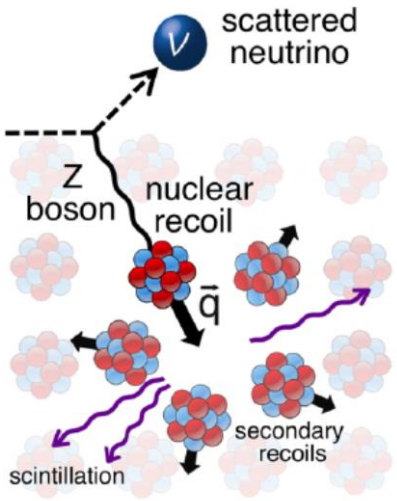

**Neutrinoless double-beta decay**



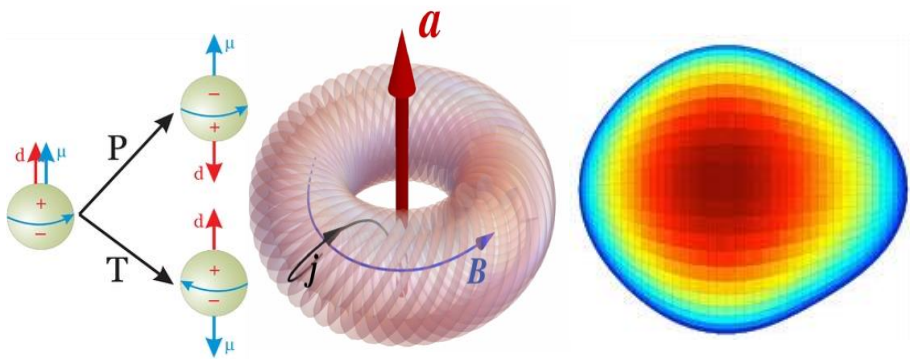
**Dark matter direct detection**



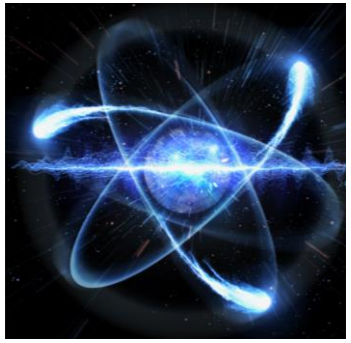

**Super-allowed Fermi transitions**




**Neutrino scattering**




**Symmetry-violating moments**



**Atomic theory**

TRIUMF

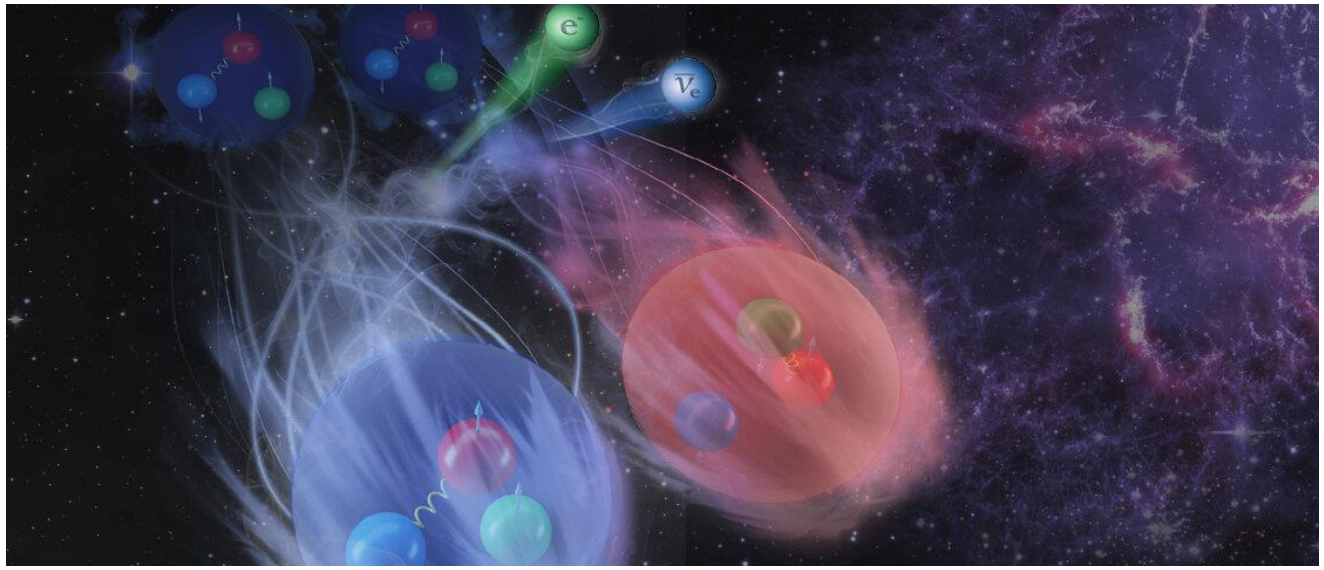
*Milestone Result*

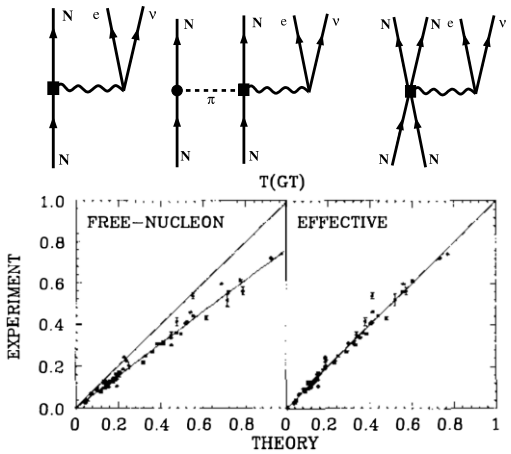
# Two-Body Currents for Gamow-Teller Transitions and $g_A$ Quenching

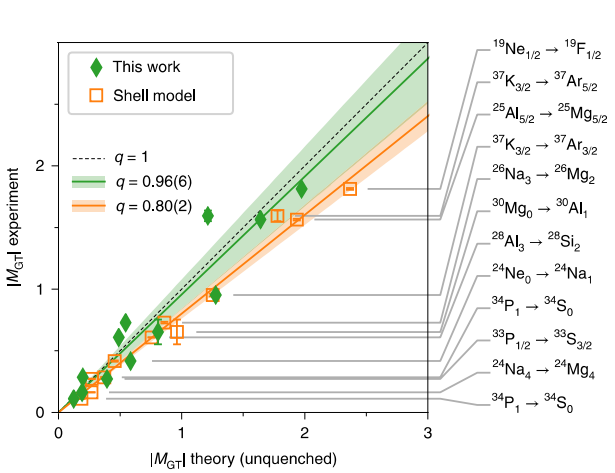
Ab initio survey of **GT matrix elements**

- 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

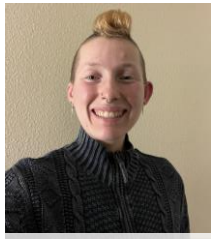
P. Gysbers[1,2], G. Hagen[3,4*], J. D. Holt[1], G. R. Jansen[3,5], T. D. Morris[3,4,6], P. Navrátil[1], T. Papenbrock[3,4], S. Quaglioni[7], A. Schwenk[8,9,10], S. R. Stroberg[1,11,12] and K. A. Wendt[7]

TRIUMF

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

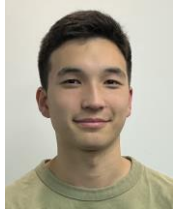
A. Belley

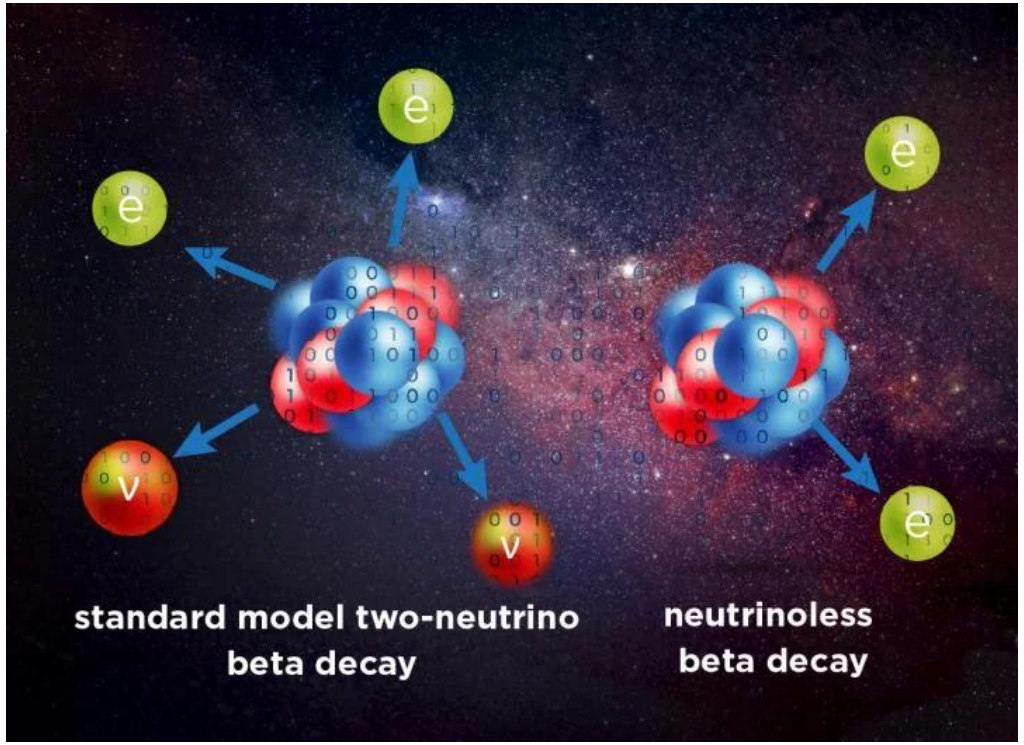
L. Jokiniemi


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

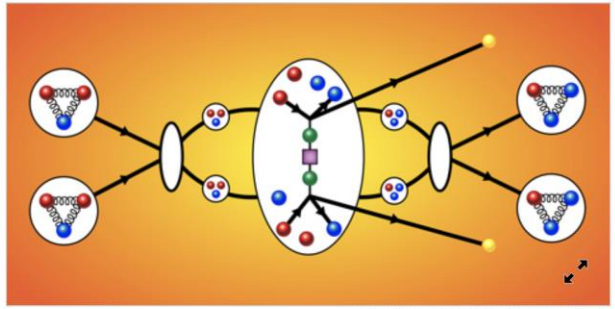
## Proper renormalization requires short-range contact term at leading order

Physics — SYNOPSIS

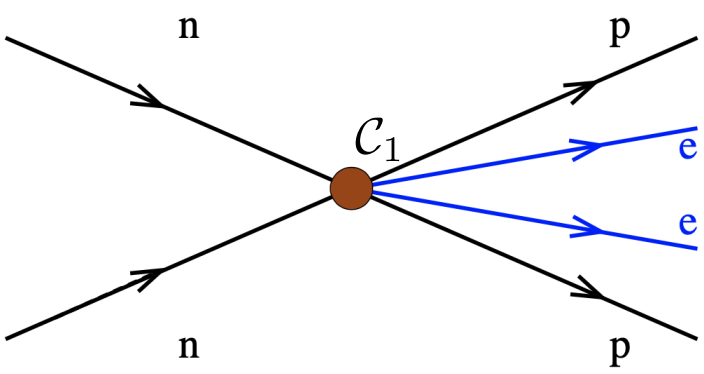
### A Missing Piece in the Neutrinoless Beta-Decay Puzzle

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)*

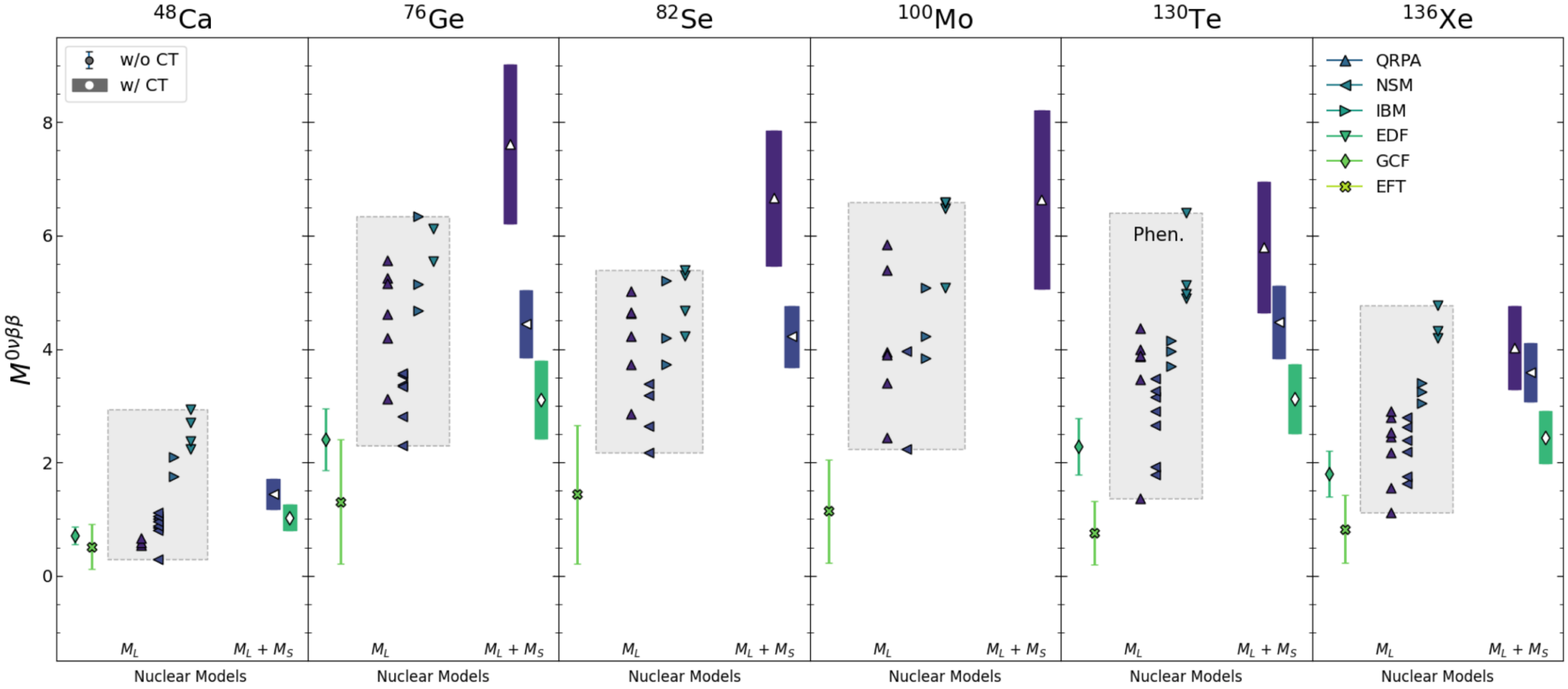
New paradigm for $0\nu\beta\beta$ decay: include long- and short-range terms

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

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

# (More) Current Status of NMEs

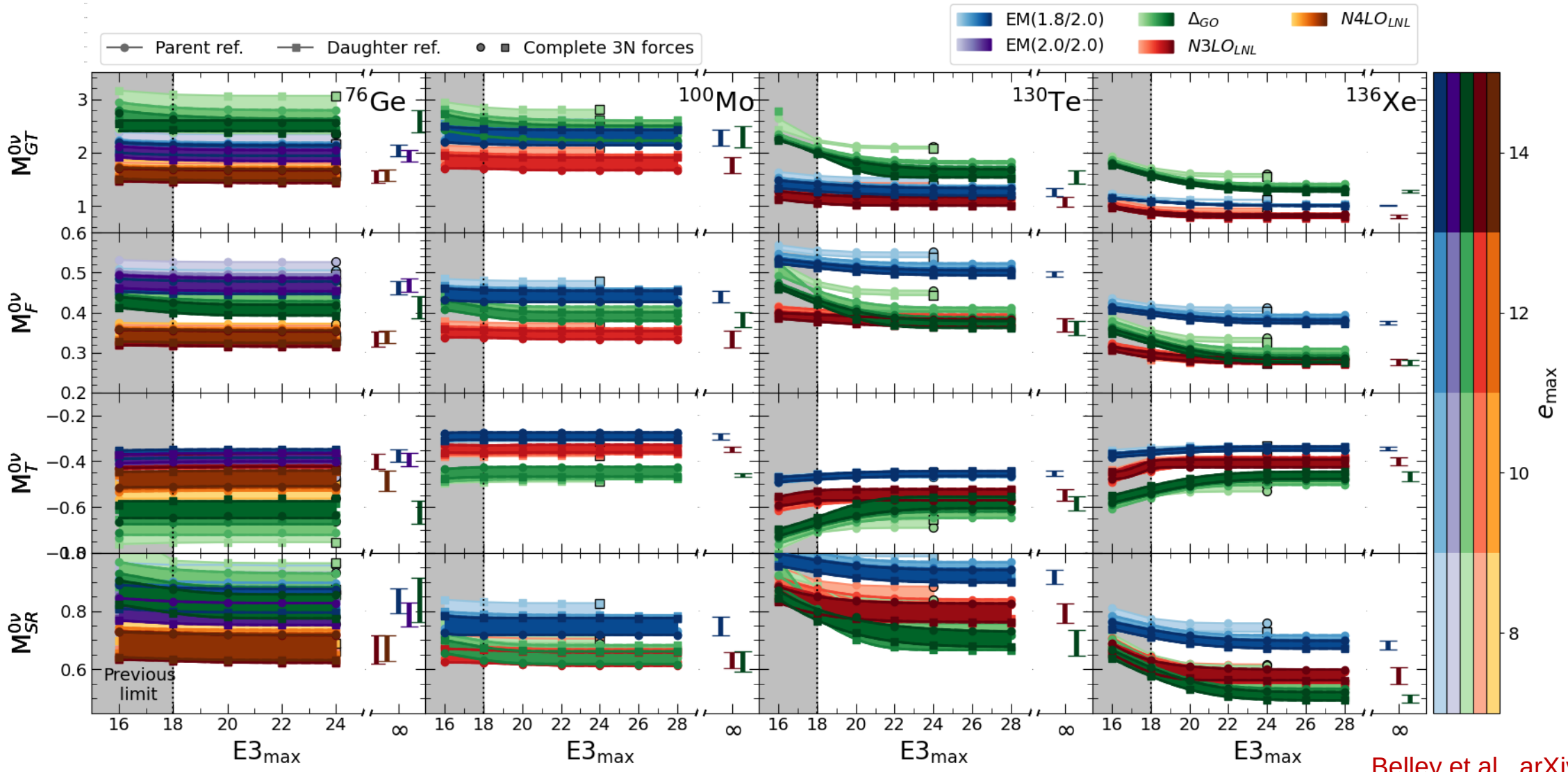
Compiled values updated w/ phenomenology + short-range contact




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

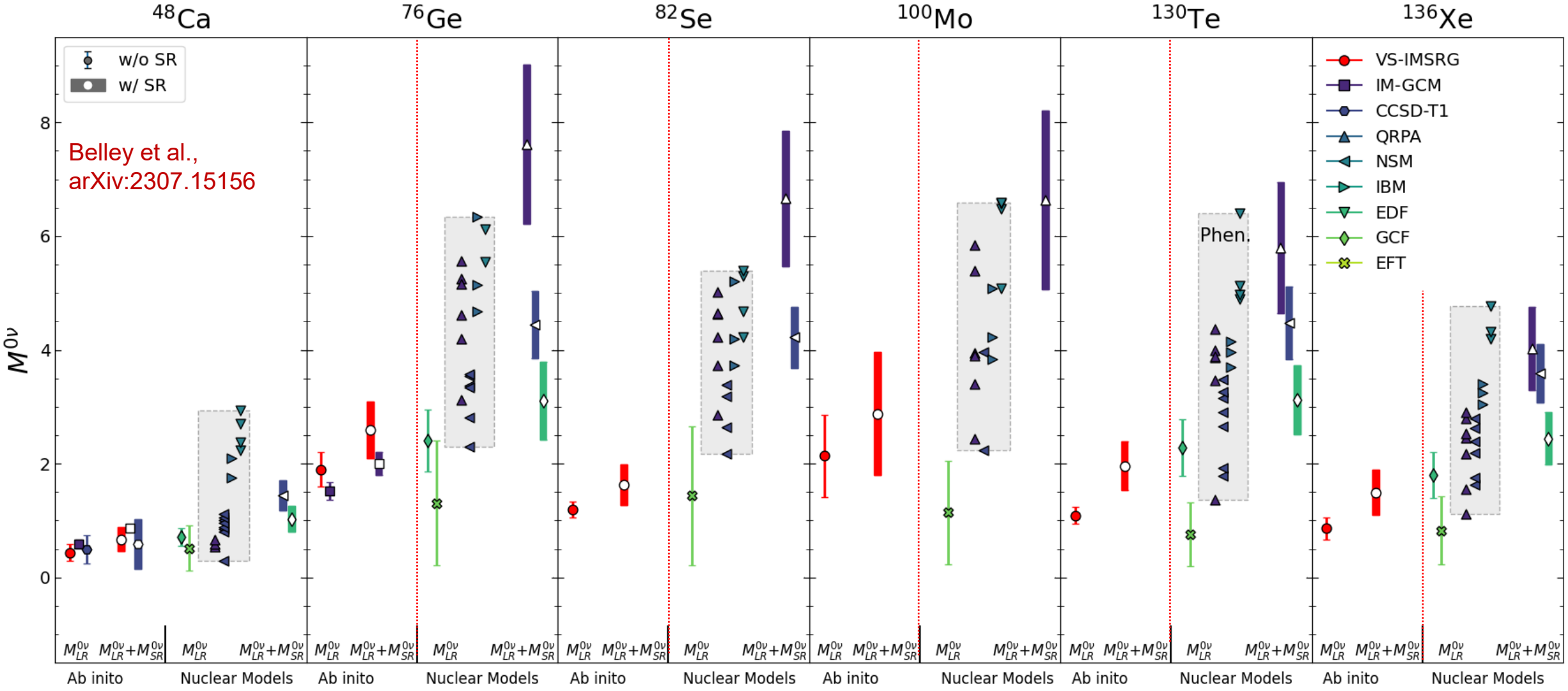



Belley et al., arXiv:2307.15156
Nature (under review)

# Ab Initio Strategy: Predict in Heavy Nuclei

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

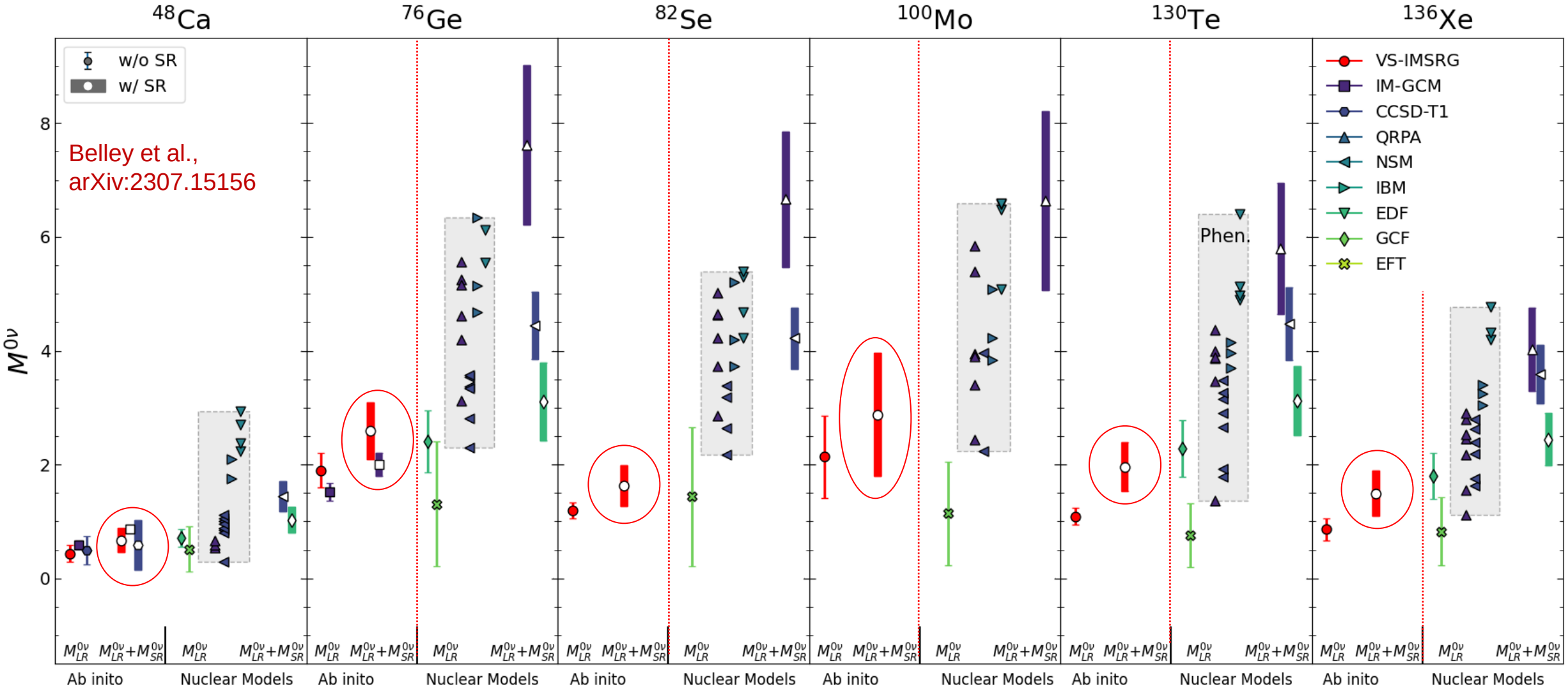
Ab initio results: differences from models; **large NMEs *strongly* disfavored**



# Ab Initio Strategy: Predict in Heavy Nuclei

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

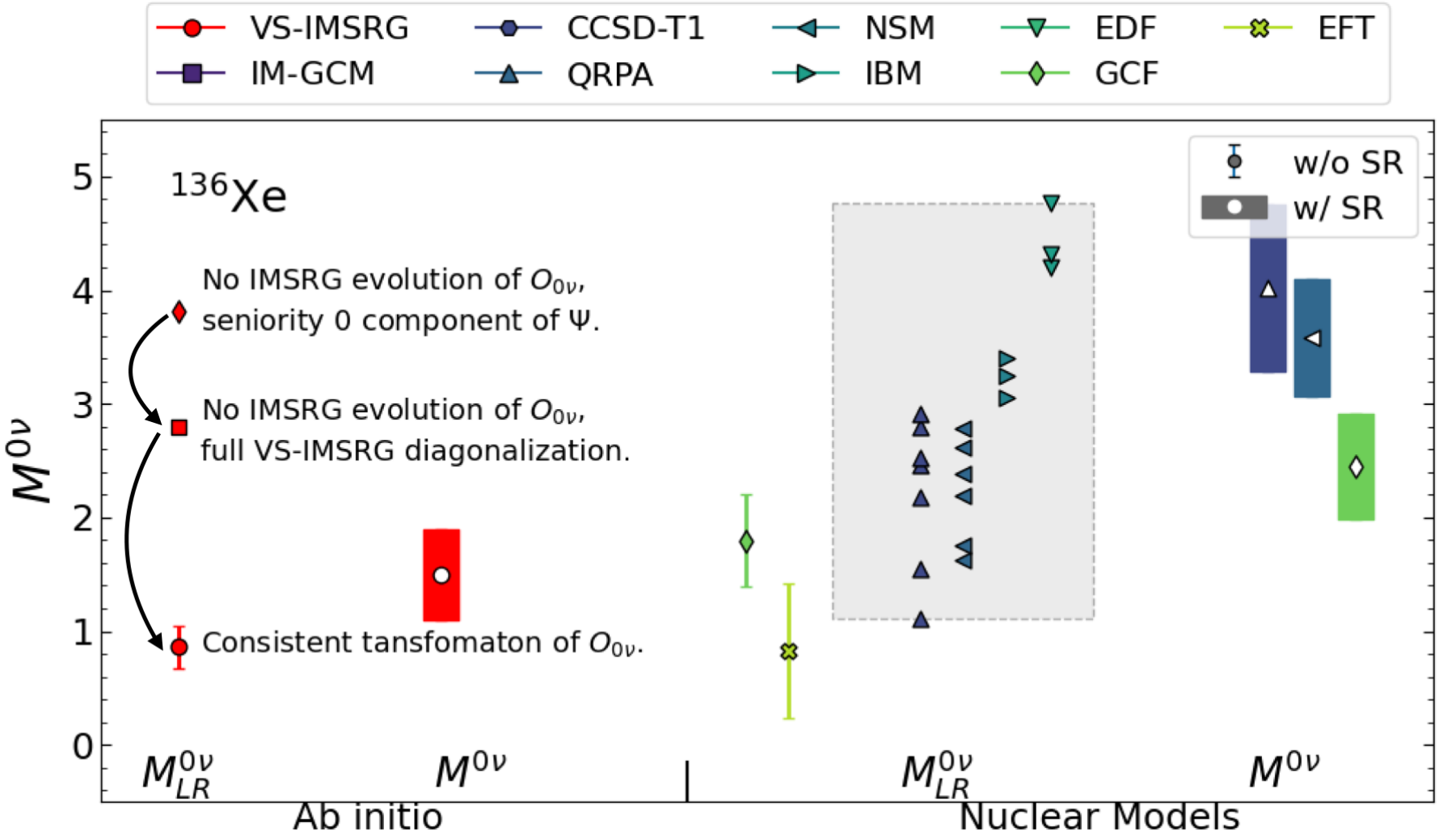
Ab initio results: differences from models; **large NMEs *strongly* disfavored**



# Why Small Matrix Elements?

## Correlations in wavefunction and operator drive small NMEs

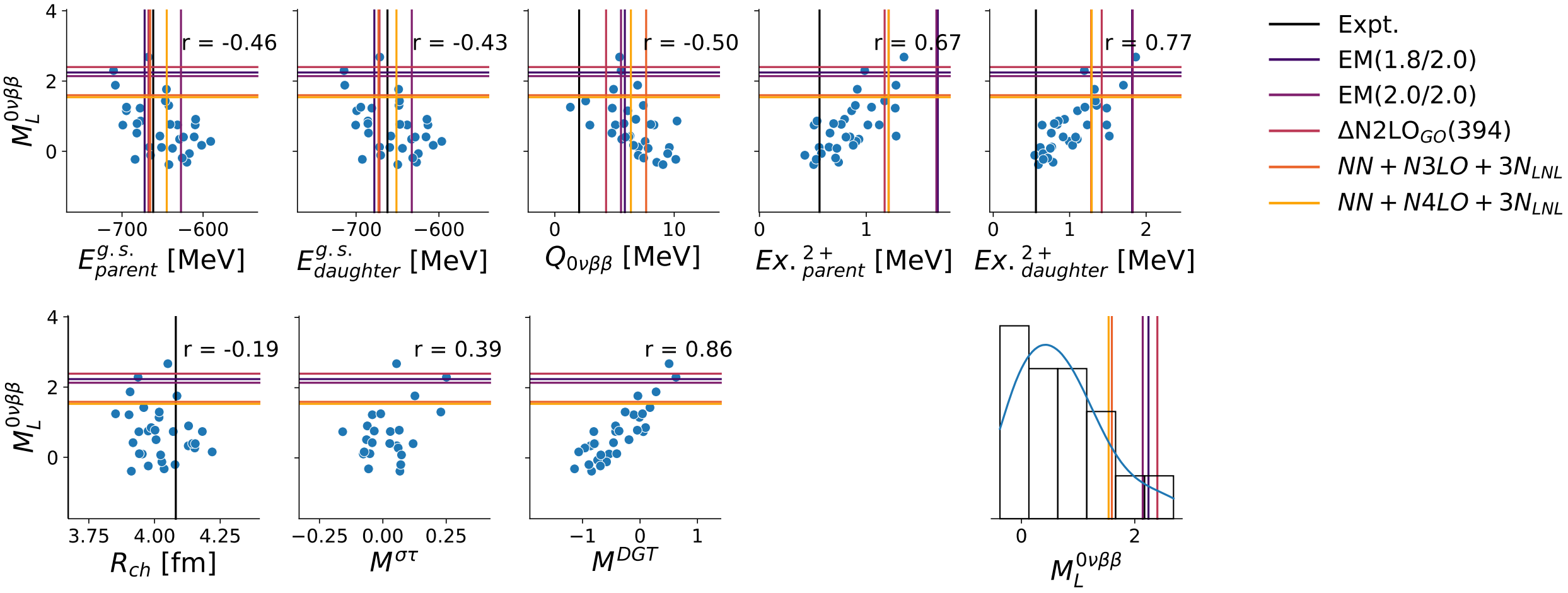
Ab initio results: differences from models; **large NMEs *strongly* disfavored**



# Ab Initio Strategy: Explore Correlations

## $^{76}$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)

# Machine Learning for Sensitivity Analysis

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

Use gaussian processes as an emulator

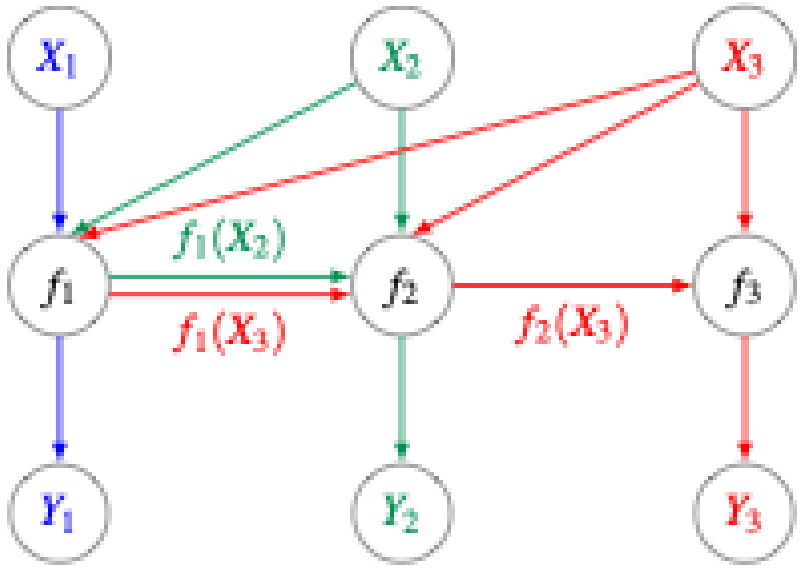
**Multi-Fidelity Gaussian Process**: connects few (complicated) high-fidelity data points (e.g., full IMSRG) w/ many low-fidelity data points (HF, low $e_{max}$, etc)

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)**

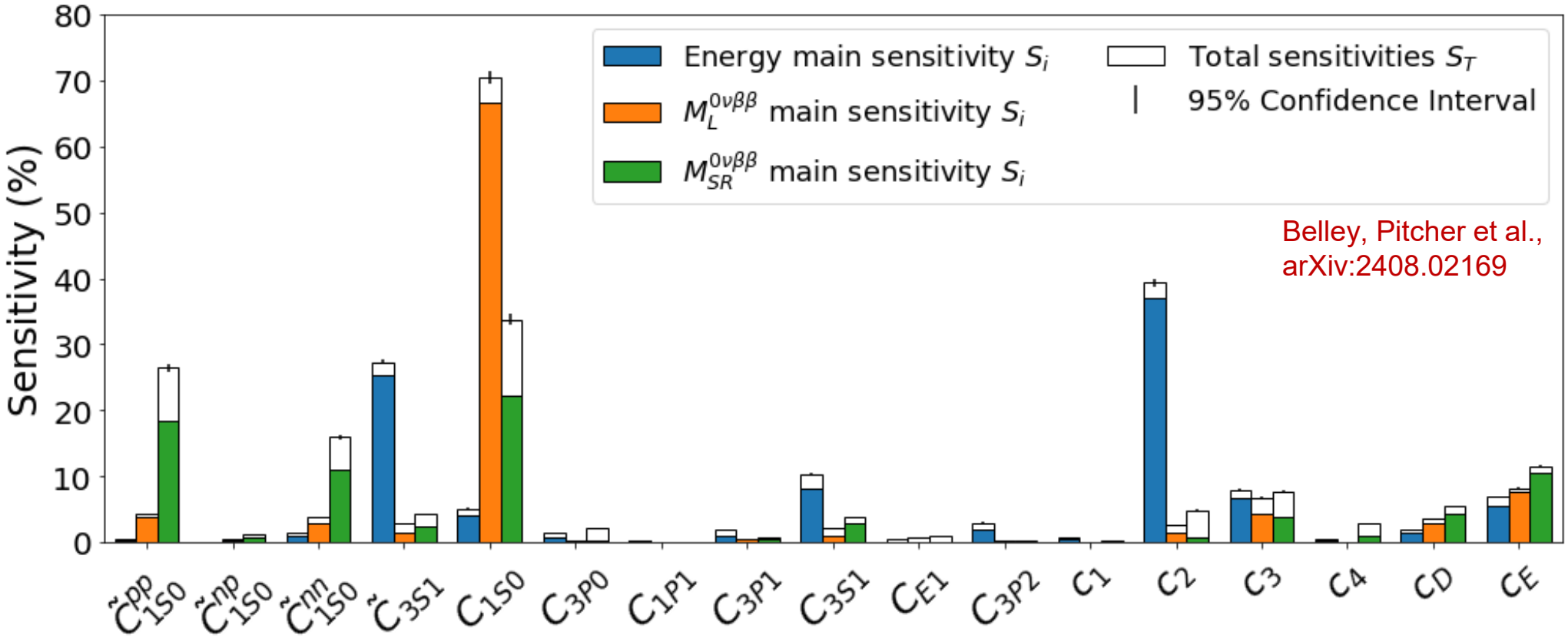



Belley, Pitcher et al., in preparation

# MM-DGP Emulator for IMSRG: Sensitivity Analysis

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

**Sensitivity analysis:** **Connect long-range 0νββ decay to terms in nuclear forces**

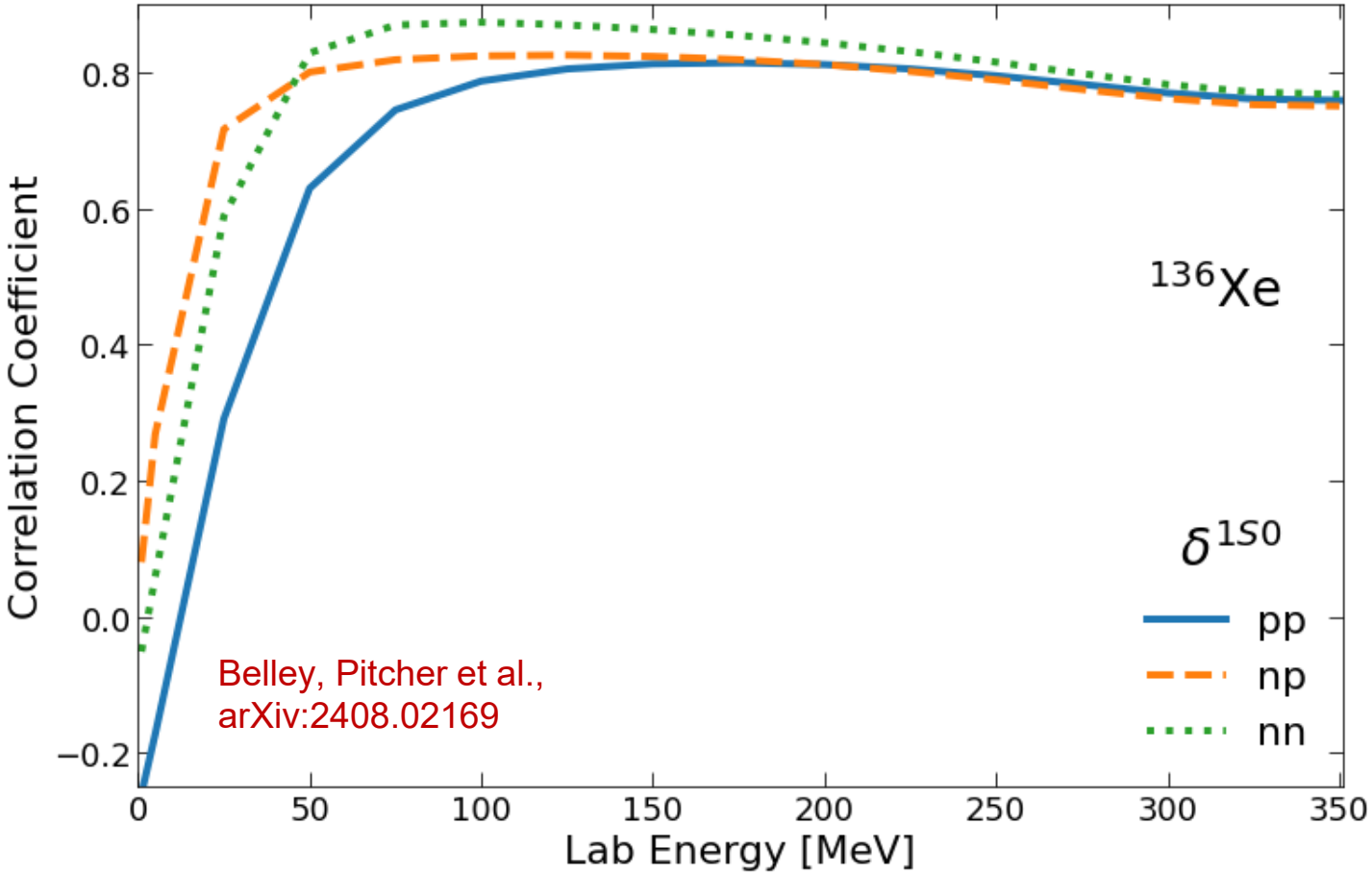



**Highly sensitive to single constant "C1S0"** – related to $^1S_0$ phase shift

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

## Clear correlation with $^1S_0$ phase-shift

Strong correlation emerges for energies > 50MeV

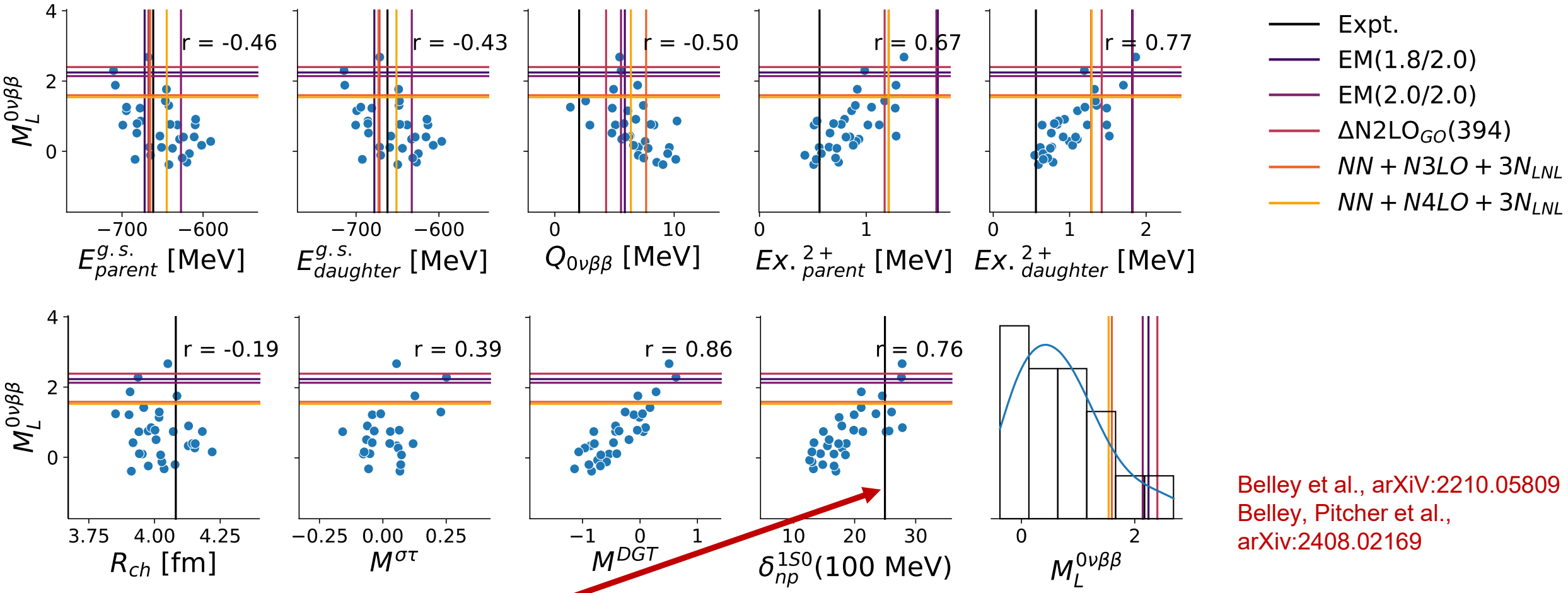



Constrained by part of interaction for the two nucleons when “close” to each other

# 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!

# Rigorous Ab Initio Uncertainties for $^{76}$Ge

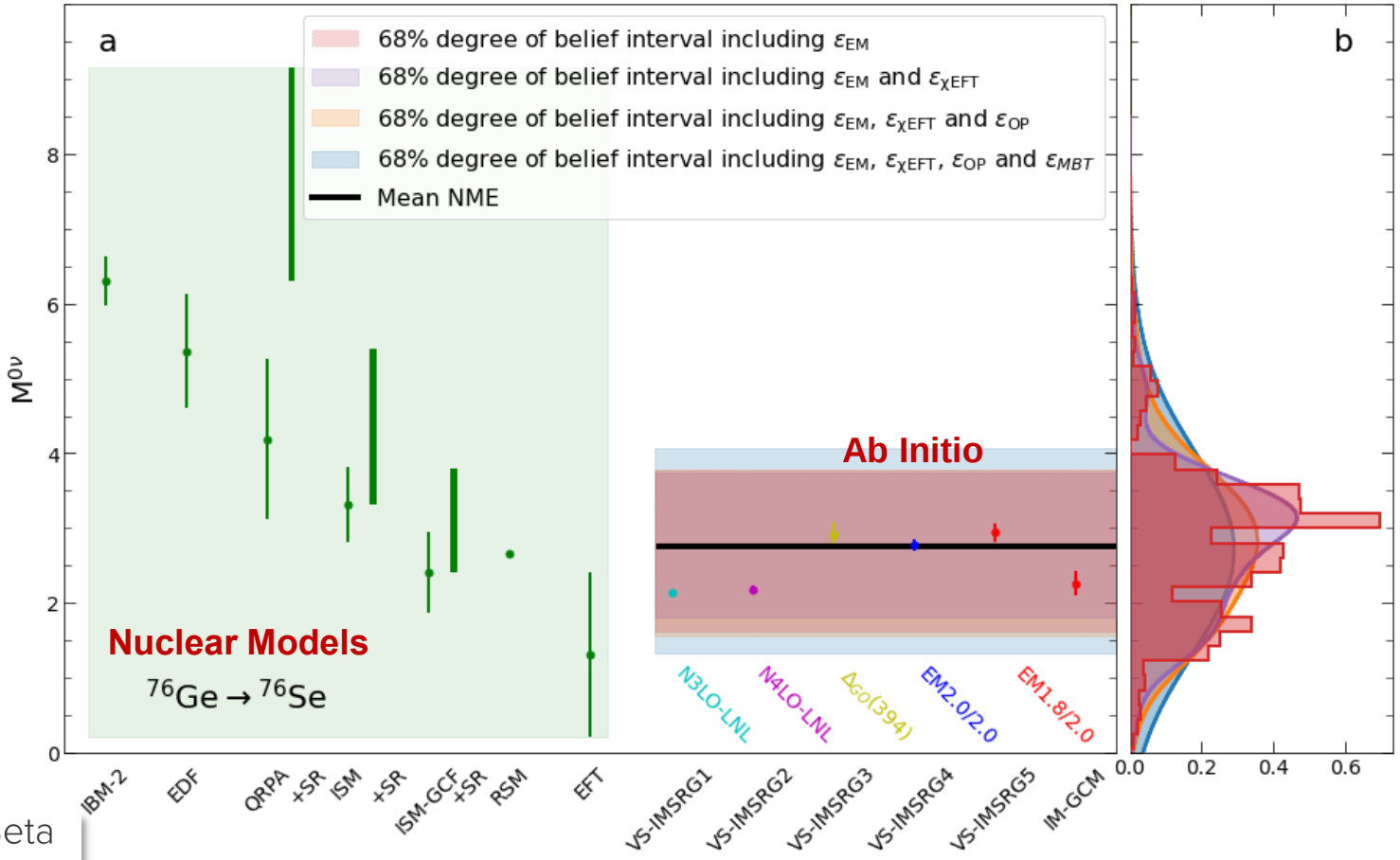
Consider *all* physics contributing to theoretical error in $0\nu\beta\beta$ decay

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

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

Construct PPD for NME in $^{76}$Ge

**Dramatically reduced uncertainty compared to nuclear models**



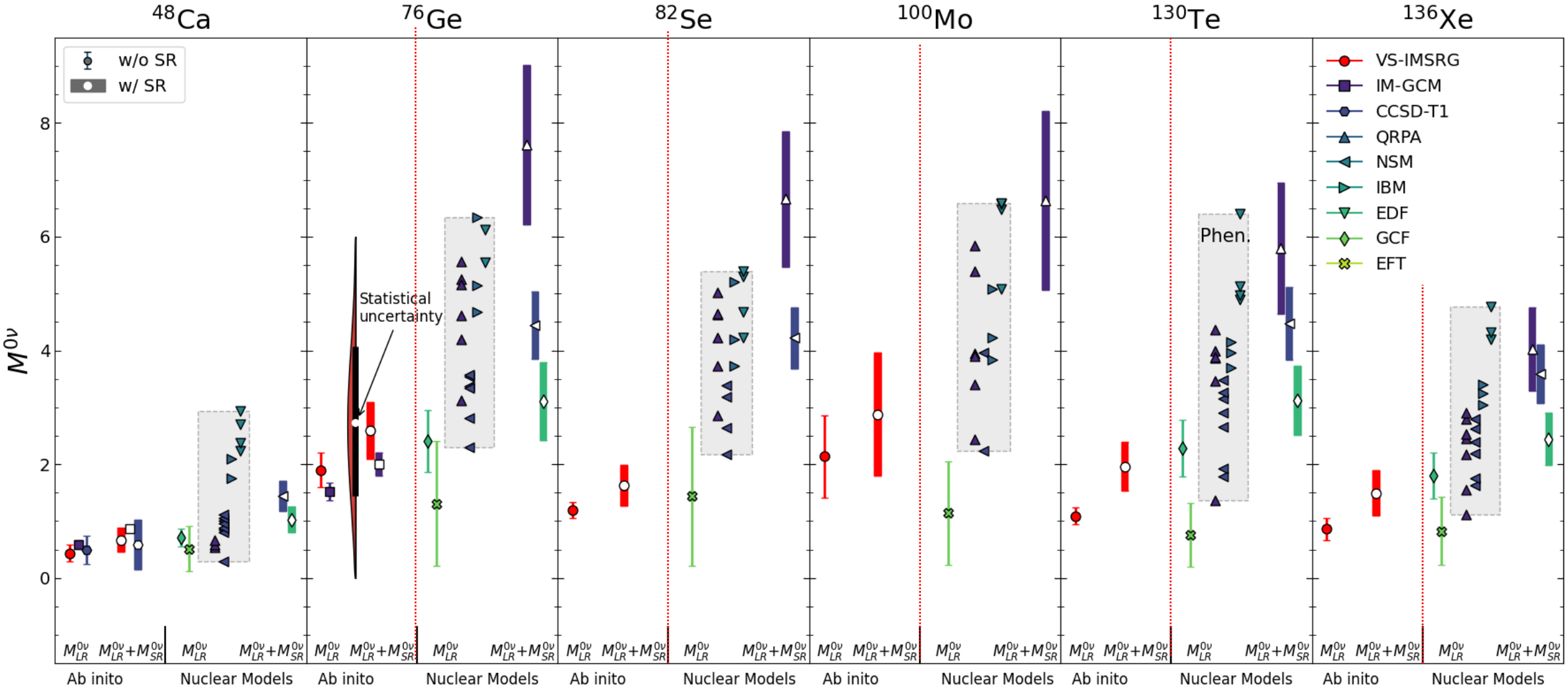

*Ab Initio* Uncertainty Quantification of Neutrinoless Double-Beta Decay in $^{76}$Ge

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

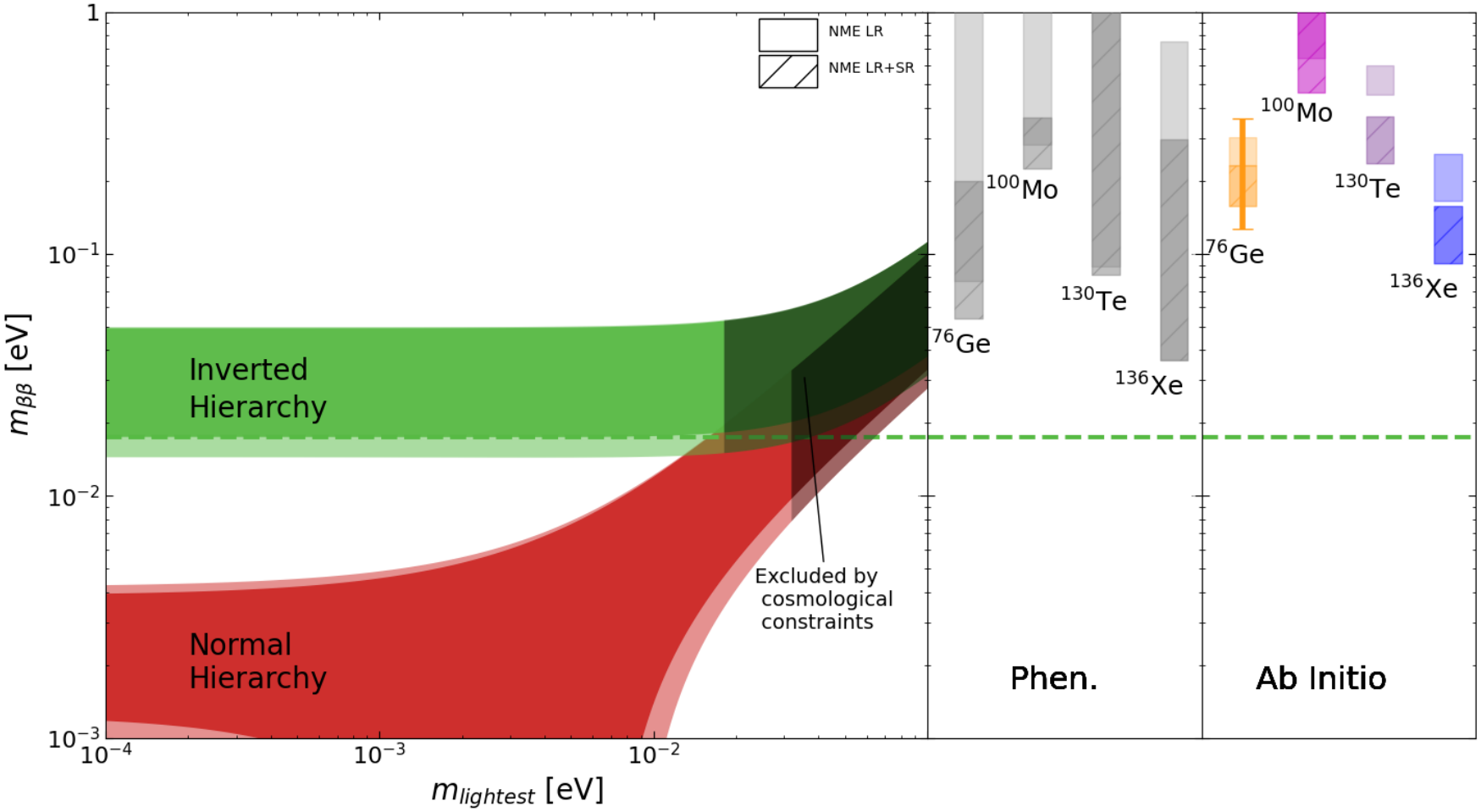
**Independent PPD agrees with previous spread**



# 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



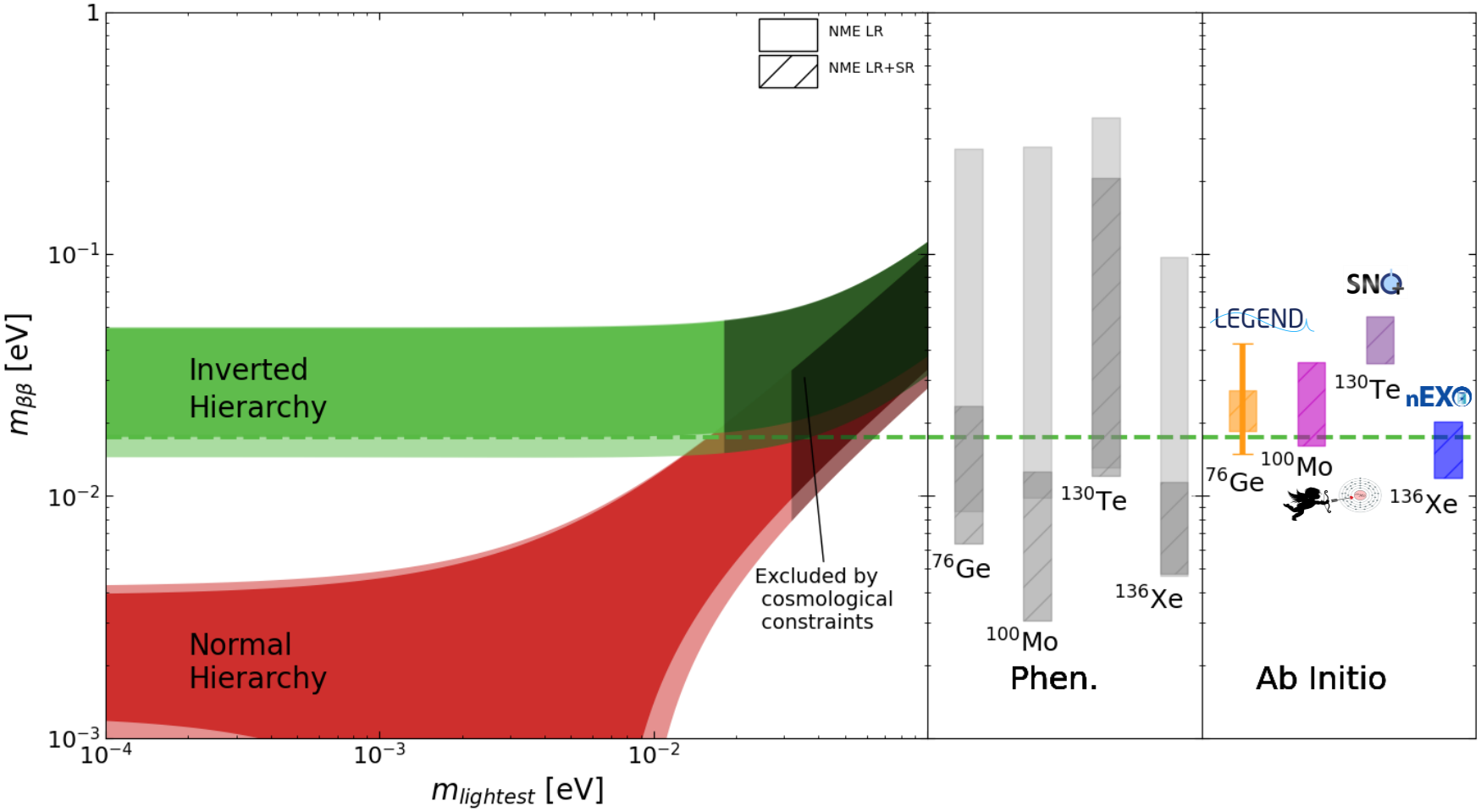

***Highly unlikely*** **inverted Hierarchy has been probed**

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*!**

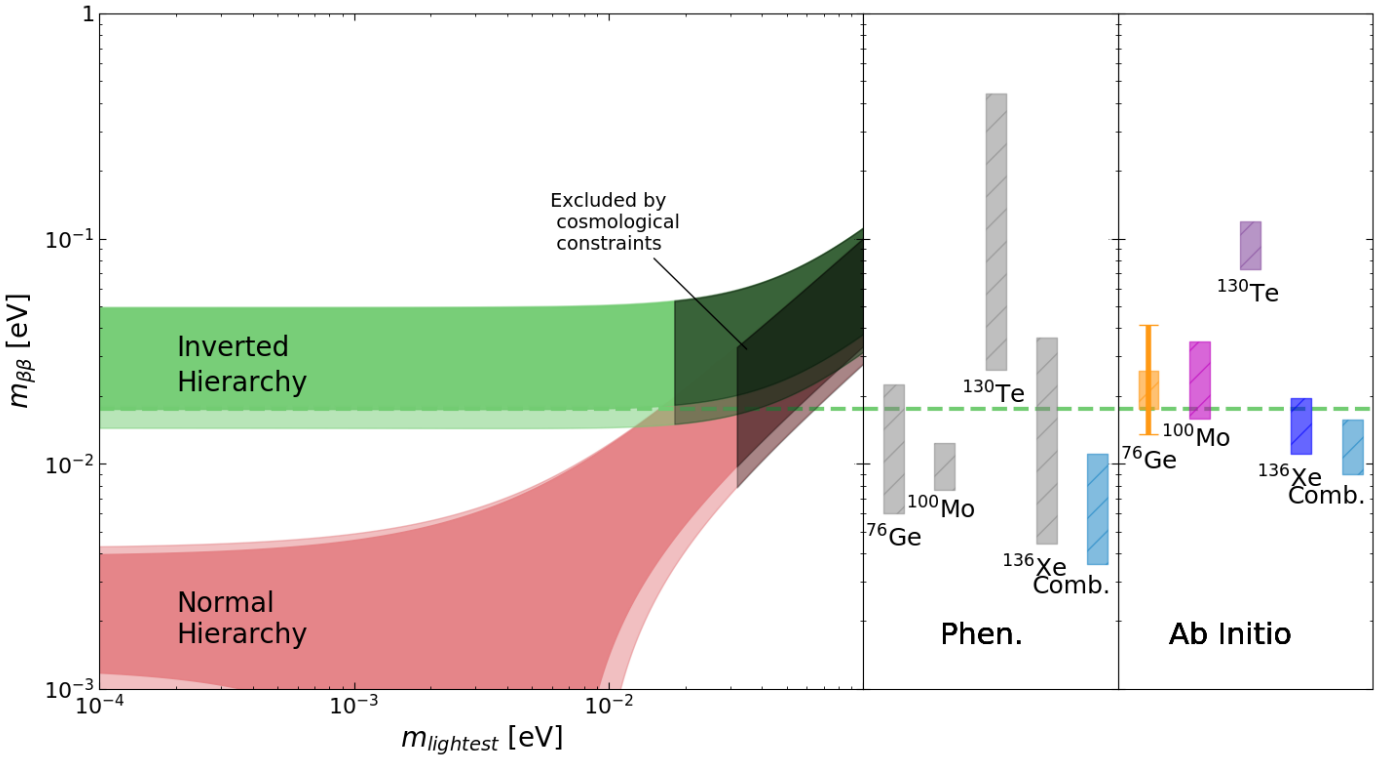
Belley et al, arXiv:2307.15156
Nature (under review)

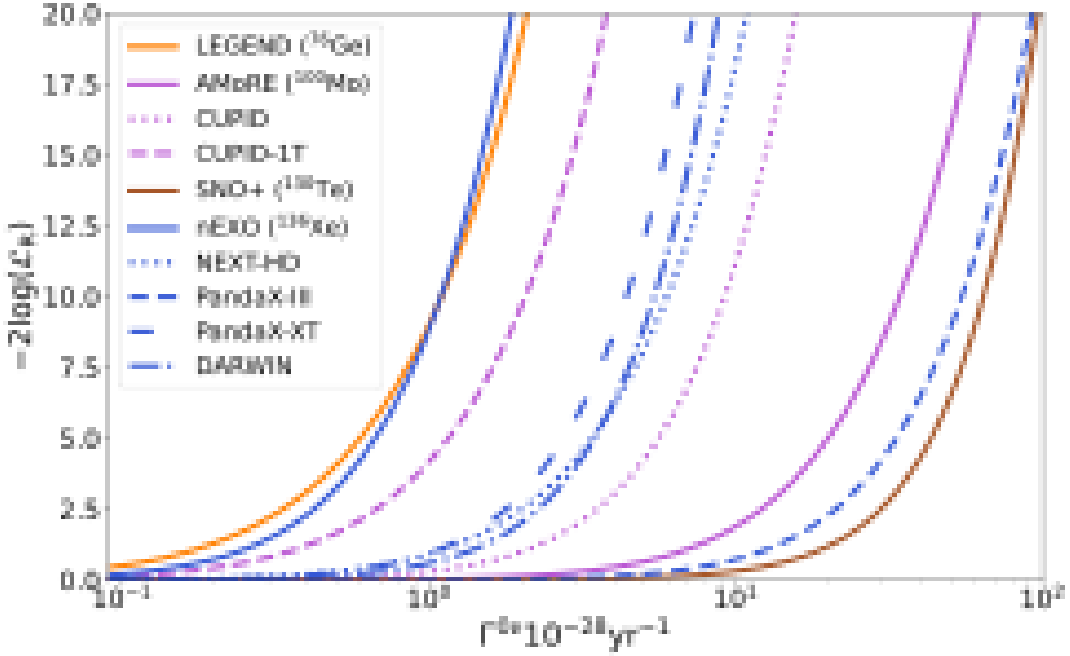
# Combined Limits: Likelihood Functions

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

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

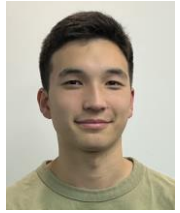
Likelihoods allow combined limit via Bayes' Theorem




*Analysis based on S. Biller PRD (2021)*

Combined ab initio limits:
IH fully probed with multiple isotopes

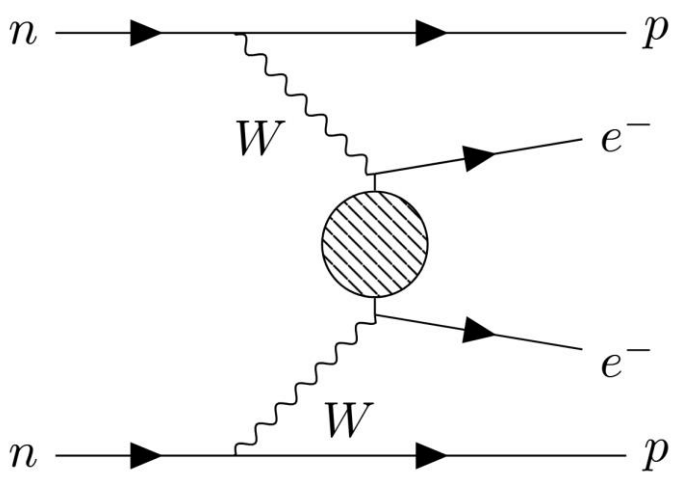


Shickele et al., in prep

# NMEs for Heavy Sterile Neutrino Exchange

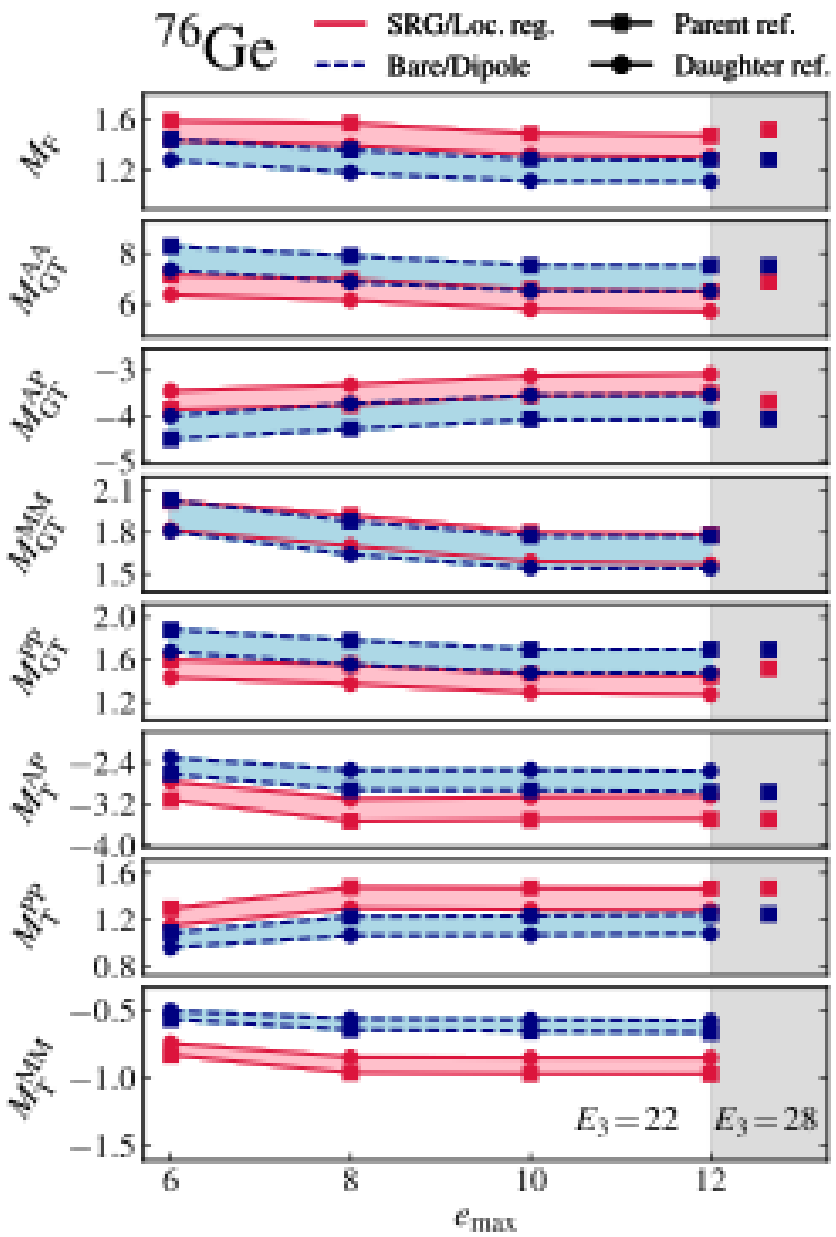
Explore other possible exchange mechanisms

**Heavy sterile neutrinos**: complicated operator structures

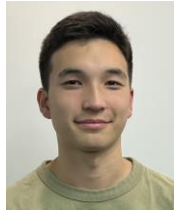



*V. Cirigliano et al.*
*J. High Energy Phys. (2018)*

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



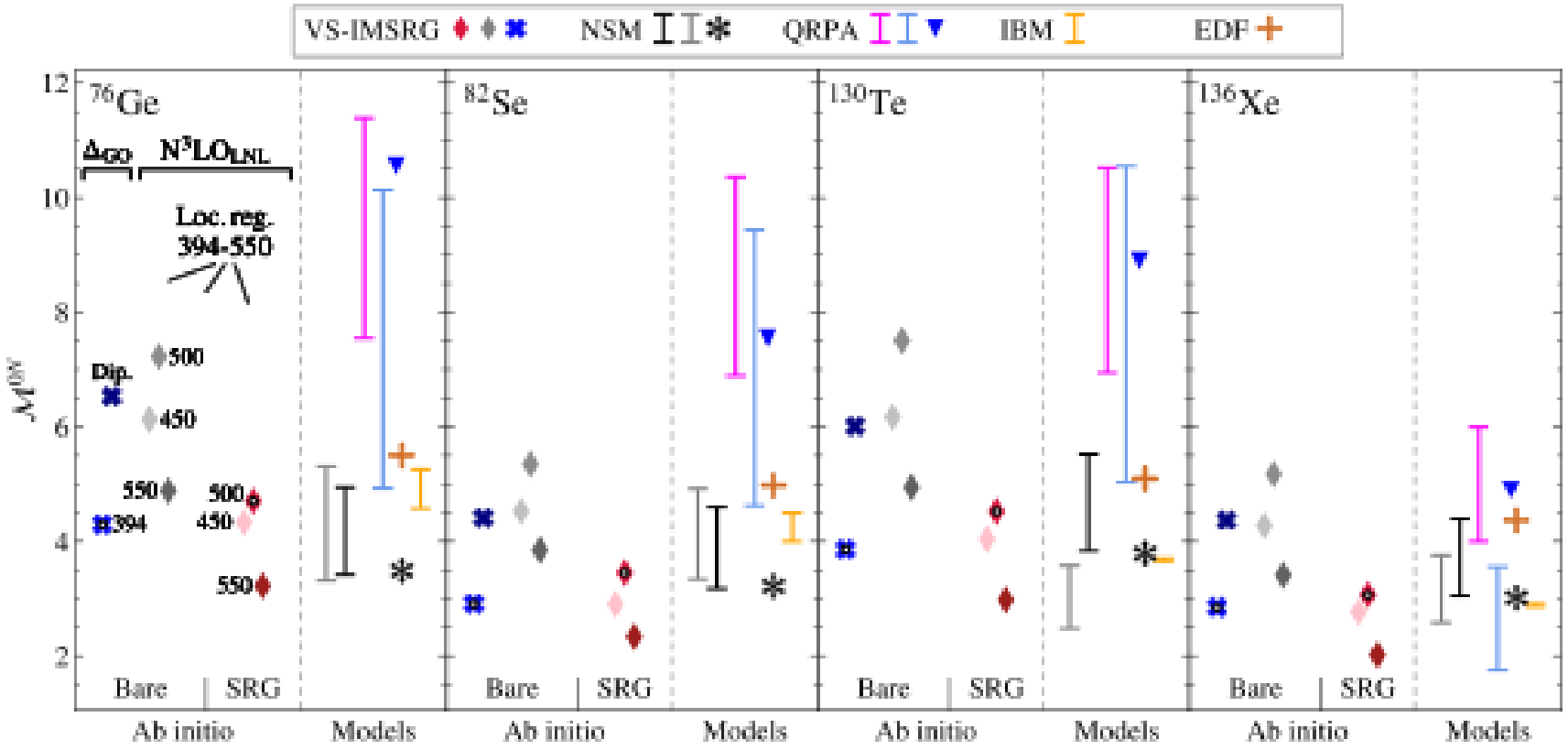

Converged heavy NMEs for all major candidates



Todd, Shickele et al., in prep

# NMEs for Heavy Sterile Neutrino Exchange

Generally smaller values (and spread) than nuclear models

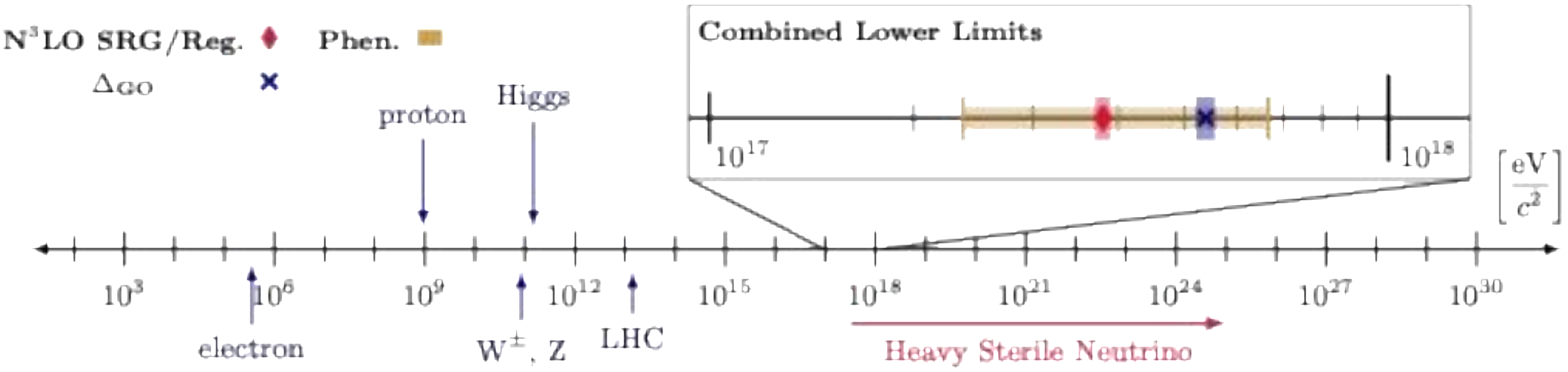



Todd, Shickele et al., in prep

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

# NMEs for Heavy Sterile Neutrino Exchange

Generally smaller values (and spread) than nuclear models




Todd, Shickele et al., in prep

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

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

TRIUMF

# Standard Model EFT meets Chiral EFT (SMEFT meets ChEFT)

September 29, 2025 to October 3, 2025
TRIUMF
US/Pacific timezone

Enter your search term

- Overview
- Local Information
- Code of Conduct
- Registration
- Participant List

Contact


cdelima@triumf.ca
gpalkanoglou@triumf.ca
mckeen@triumf.ca
navratil@triumf.ca


**SMEFT meets ChEFT:**

The core goal of this effective field theory (EFT) workshop is to bring together the Standard Model EFT (SMEFT) and Chiral EFT (ChEFT) communities to discuss the recent advances and current obstacles that lay at the forefront of EFT development. In SMEFT, one utilizes EFTs to explore the effects of Beyond Standard Model (BSM) physics in a model independent way, while similar techniques are used in ChEFT to describe strongly interacting systems involving nucleons. The related experimental searches have the potential to address fundamental questions in physics, such as testing fundamental symmetries, the nature of neutrinos, and dark matter as well as the matter-antimatter asymmetry of the universe.

Interdisciplinary collaboration between SMEFT and ChEFT practitioners is crucial to correctly interpret the results of these experiments. This workshop seeks to strengthen connections and establish communication channels between the communities, facilitate discussion of recent advances and, foster interdisciplinary collaboration in tackling the current challenges at the fields' interface. This will be especially encouraged by the workshop's mixed schedule consisting of talks and time for discussion.

*This is an invitation-only event. If you want to participate and were not invited, please contact one of the organizers.*

**Organizing committee:**

Carlos Henrique de Lima, *TRIUMF*
Georgios Palkanoglou, *TRIUMF*
Michael Gennari, *University of Victoria / TRIUMF*
Mehdi Drissi, *TU Darmstadt*
Lotta Jokiniemi, *TRIUMF*
Douglas Tuckler, *TRIUMF/Simon Fraser University*

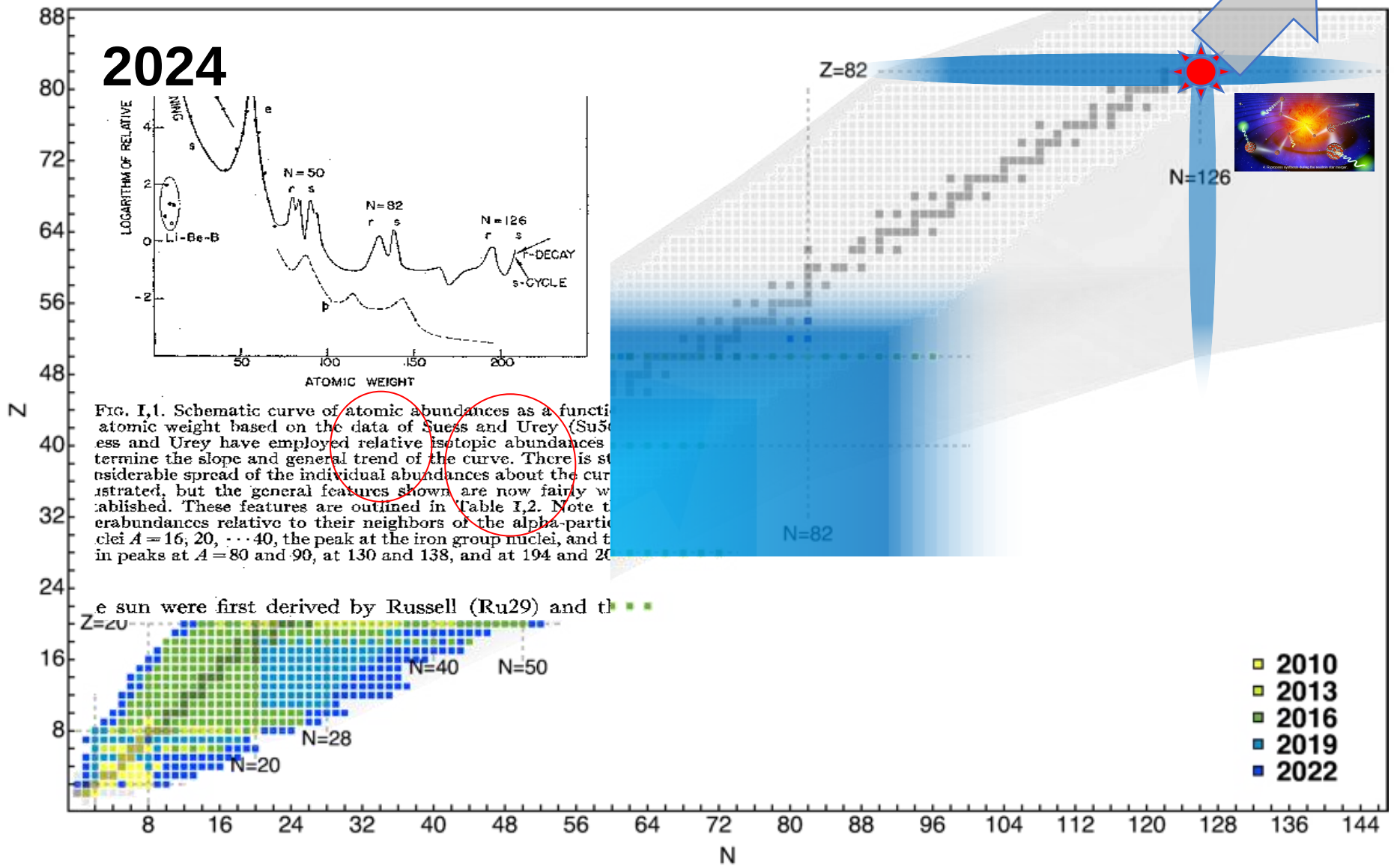
**New collaborations welcome!**

Workshop @ TRIUMF
particle + nuclear theory

jholt@triumf.ca

# Future of Ab Initio Theory

(Not so) Bold predictions: many new directions in the next 5 years

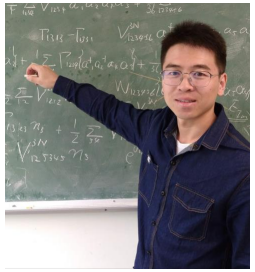


## Nucleosynthesis

Ab initio input for r-process

Nicole Vassh

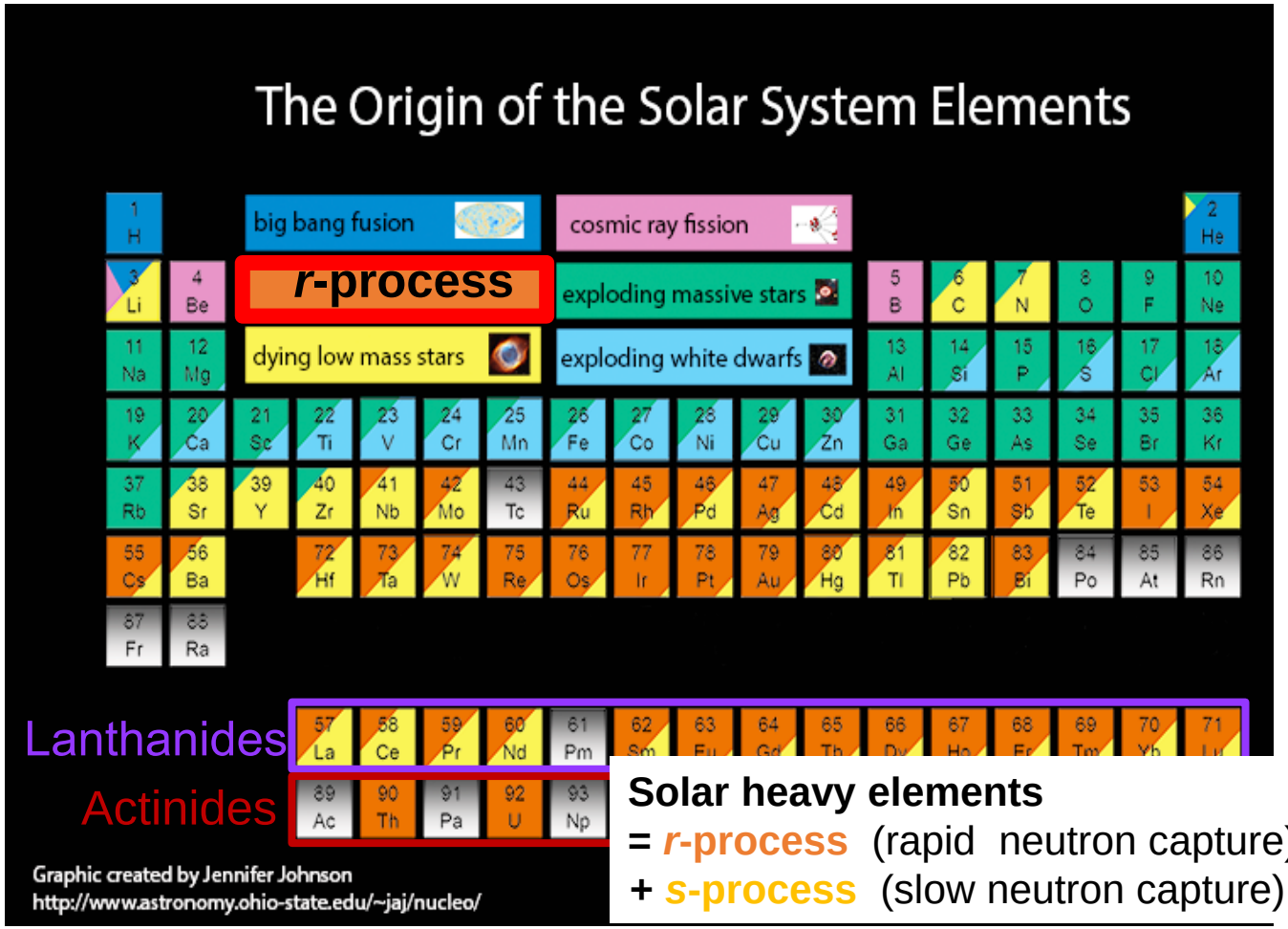
Maude Larivière



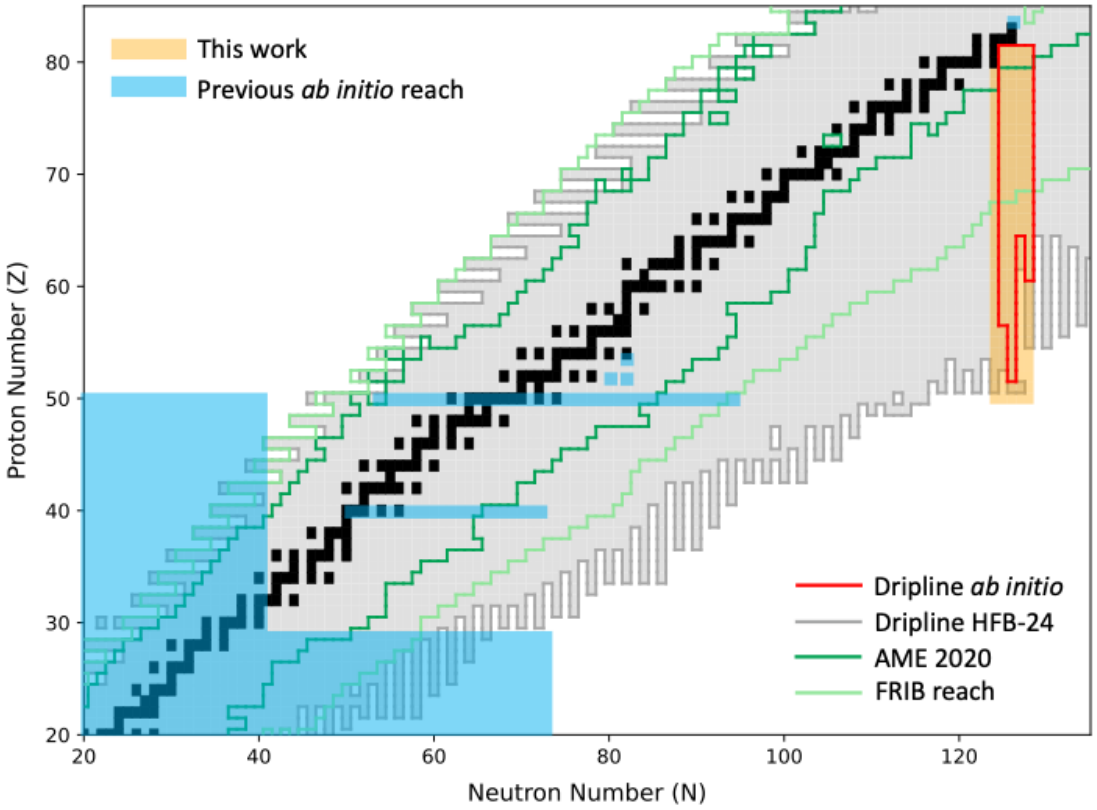
Baishan Hu

# Ab Initio Theory for Origin of Heavy Elements

Most heavy elements created via rapid-neutron capture process (r-process)



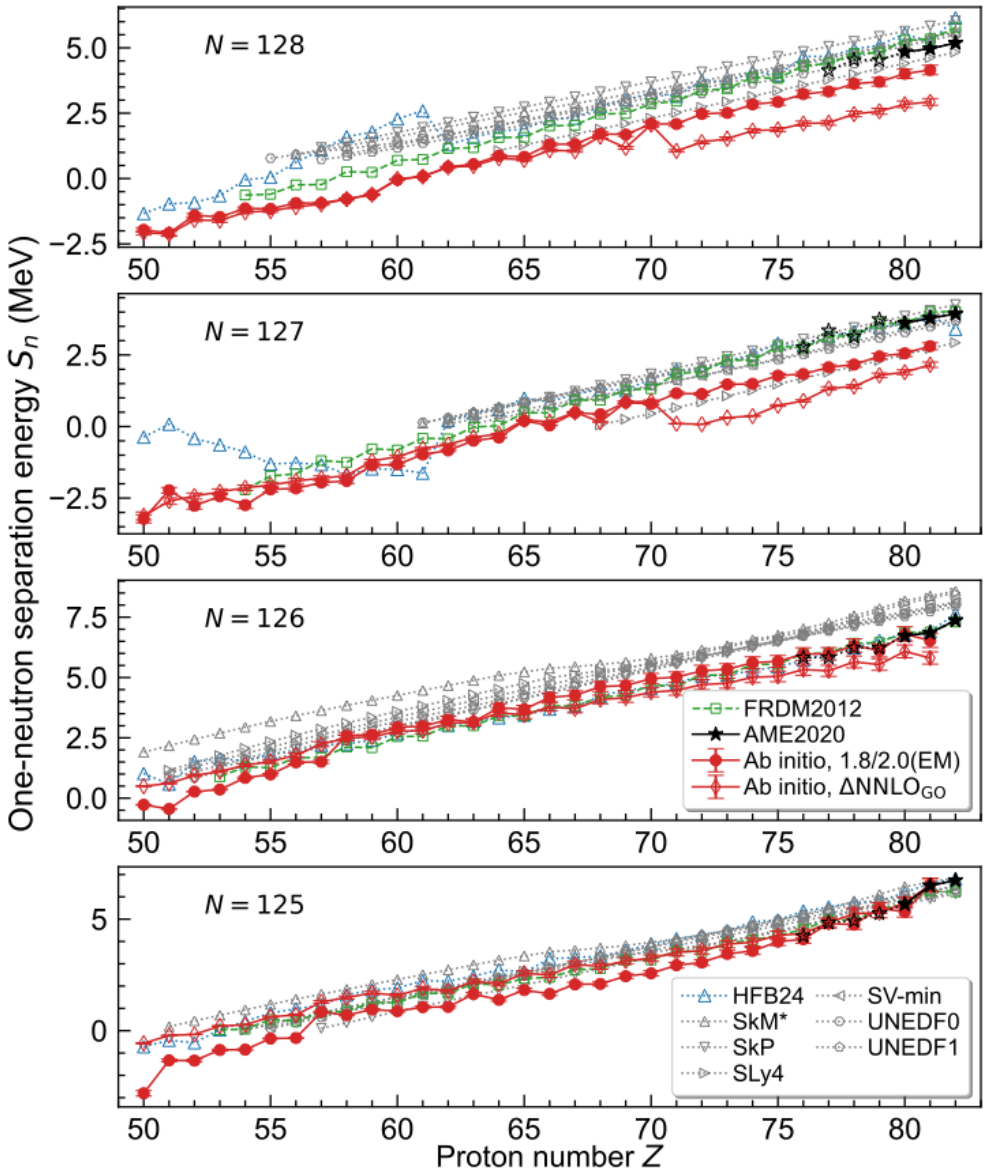

**Solar heavy elements**
= ***r*-process** (rapid neutron capture)
+ ***s*-process** (slow neutron capture)

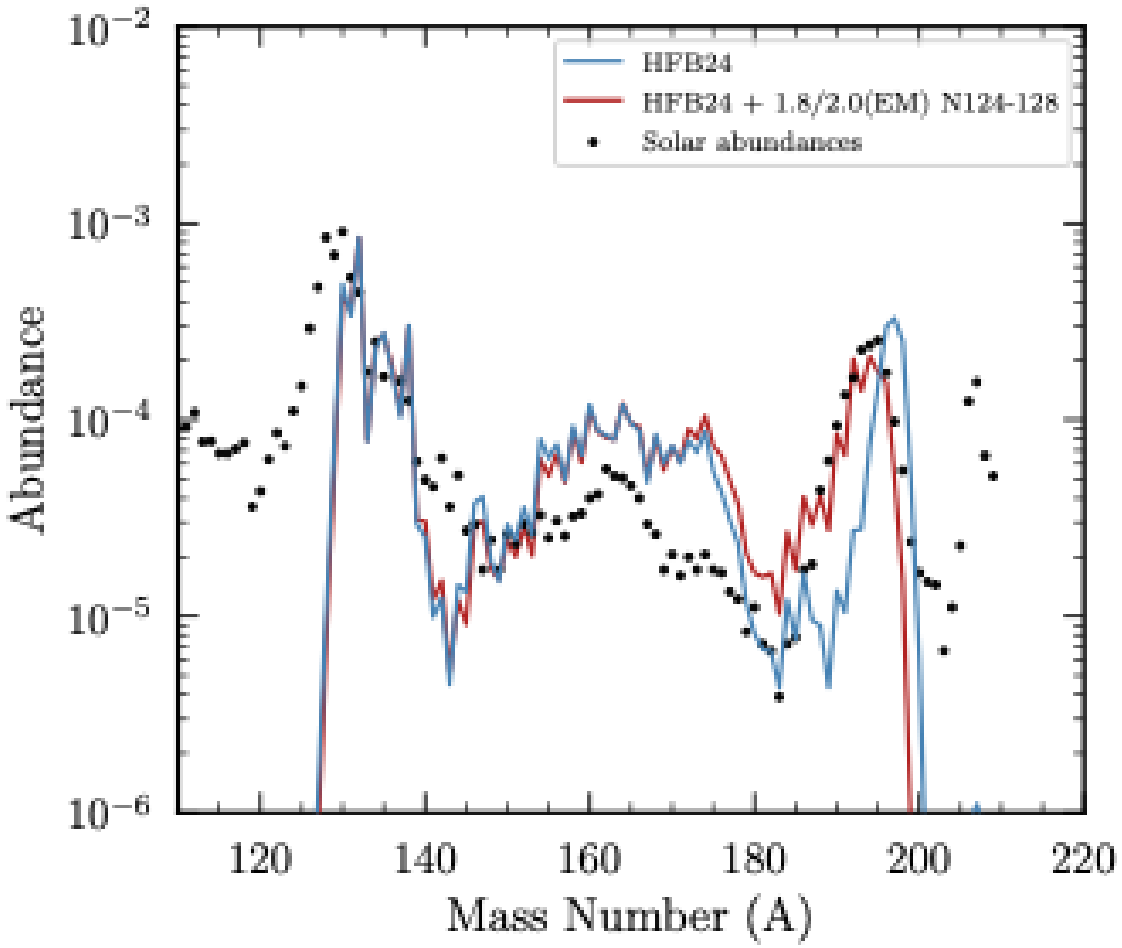



Theory input is crucial where no data exists – little known "south" of $^{208}$Pb

# Ab Initio Impact on r-Process Simulations

Separation energies, Q-values calculated to N=12x driplines for r-process inputs

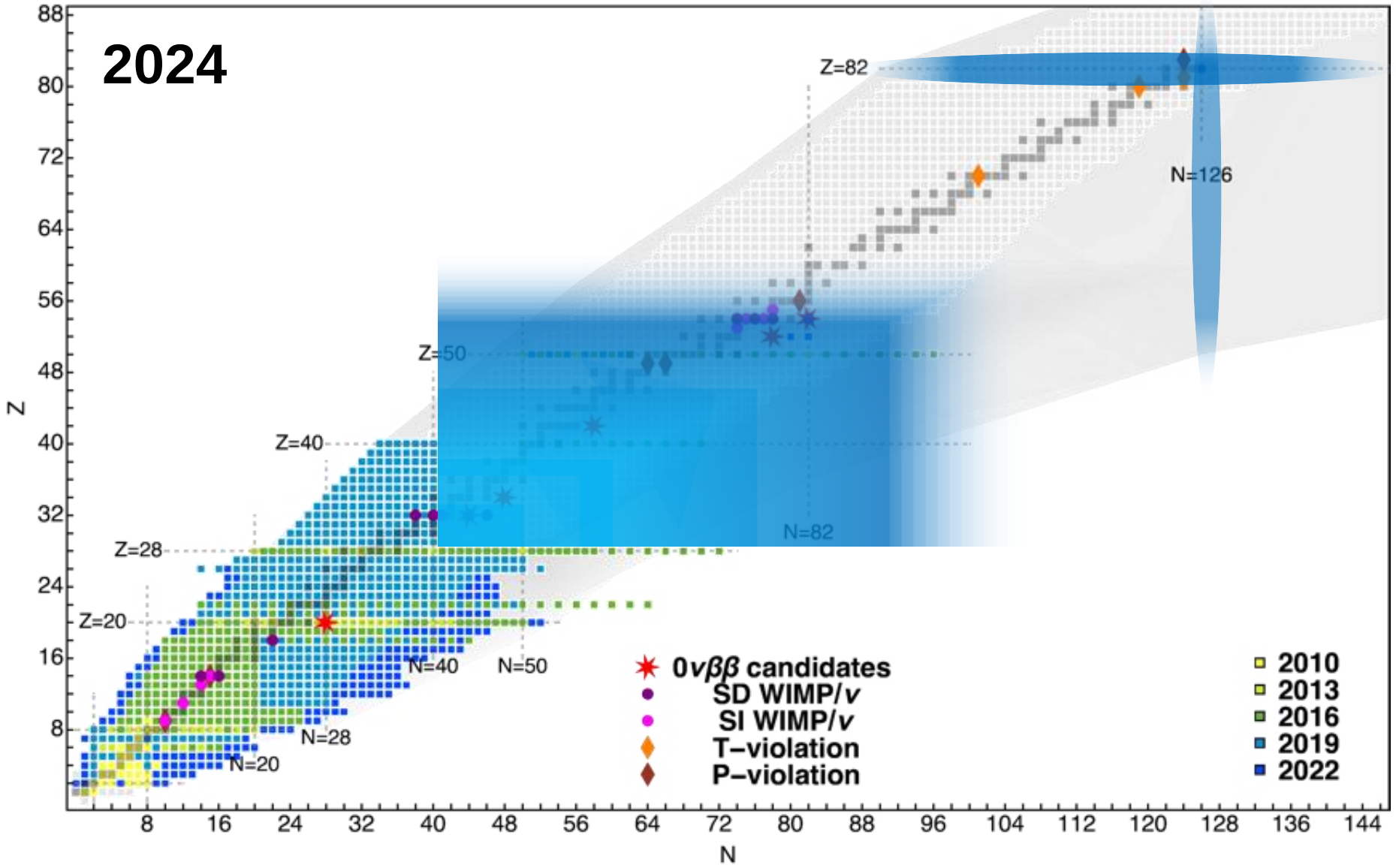



**Significant improvement in 3rd abundance peak!**

# Future of Ab Initio Theory

(Not so) Bold predictions: many new directions in the next 5 years

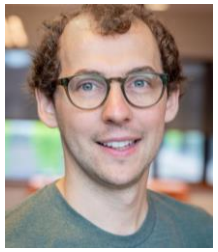



**Nucleosynthesis**

Ab initio input for r-process

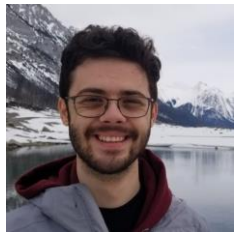
**Dark Matter/ν Scattering**

Ab initio structure functions

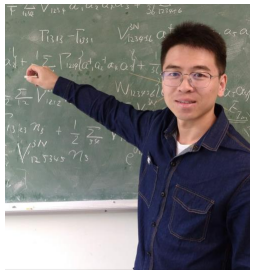


Sam Leutheusser

Jose Padua



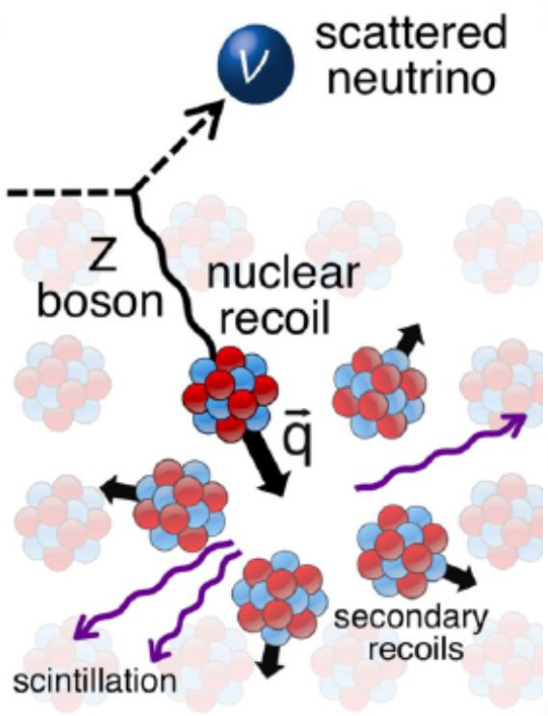
Mathieu Bruneault

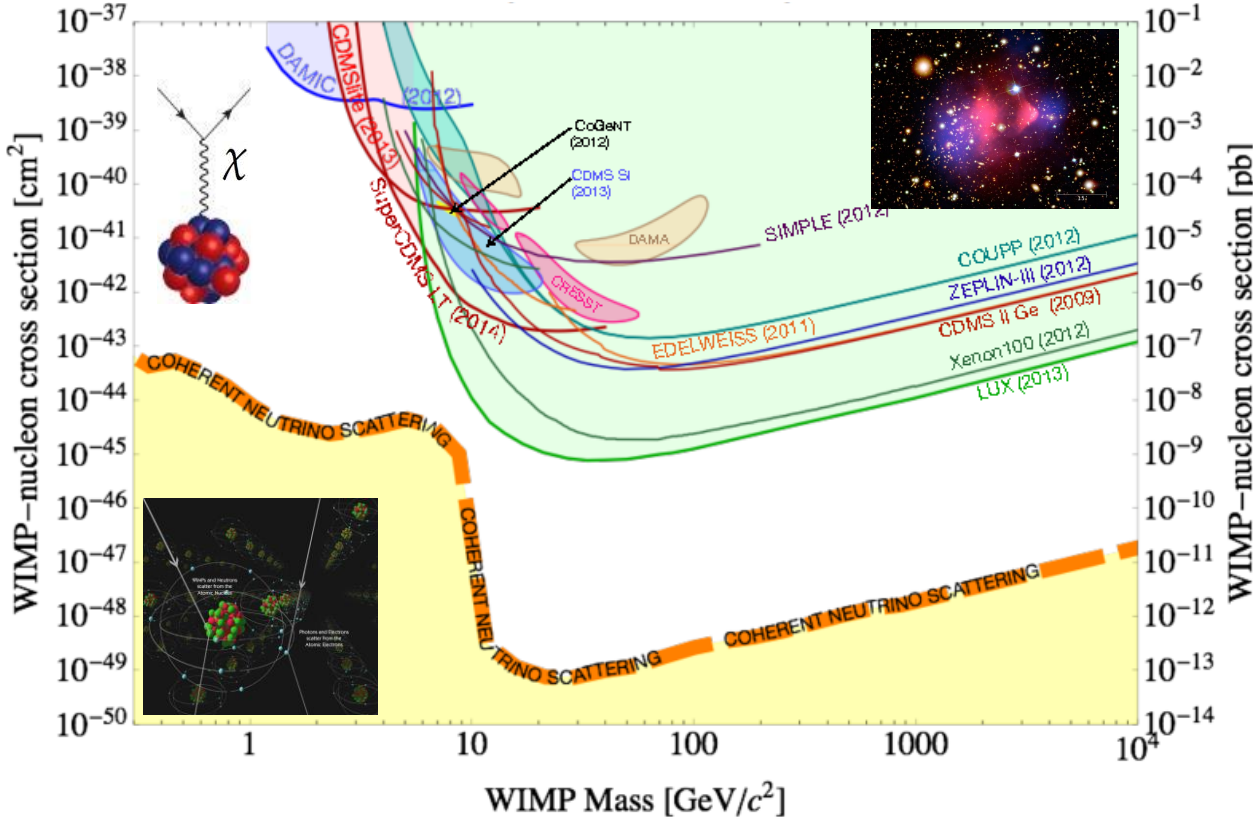


Baishan Hu

# Nuclear Theory for BSM Searches

Dark matter direct detection and CEνNS require similar ab initio theory






Differential cross section, well-defined in SM

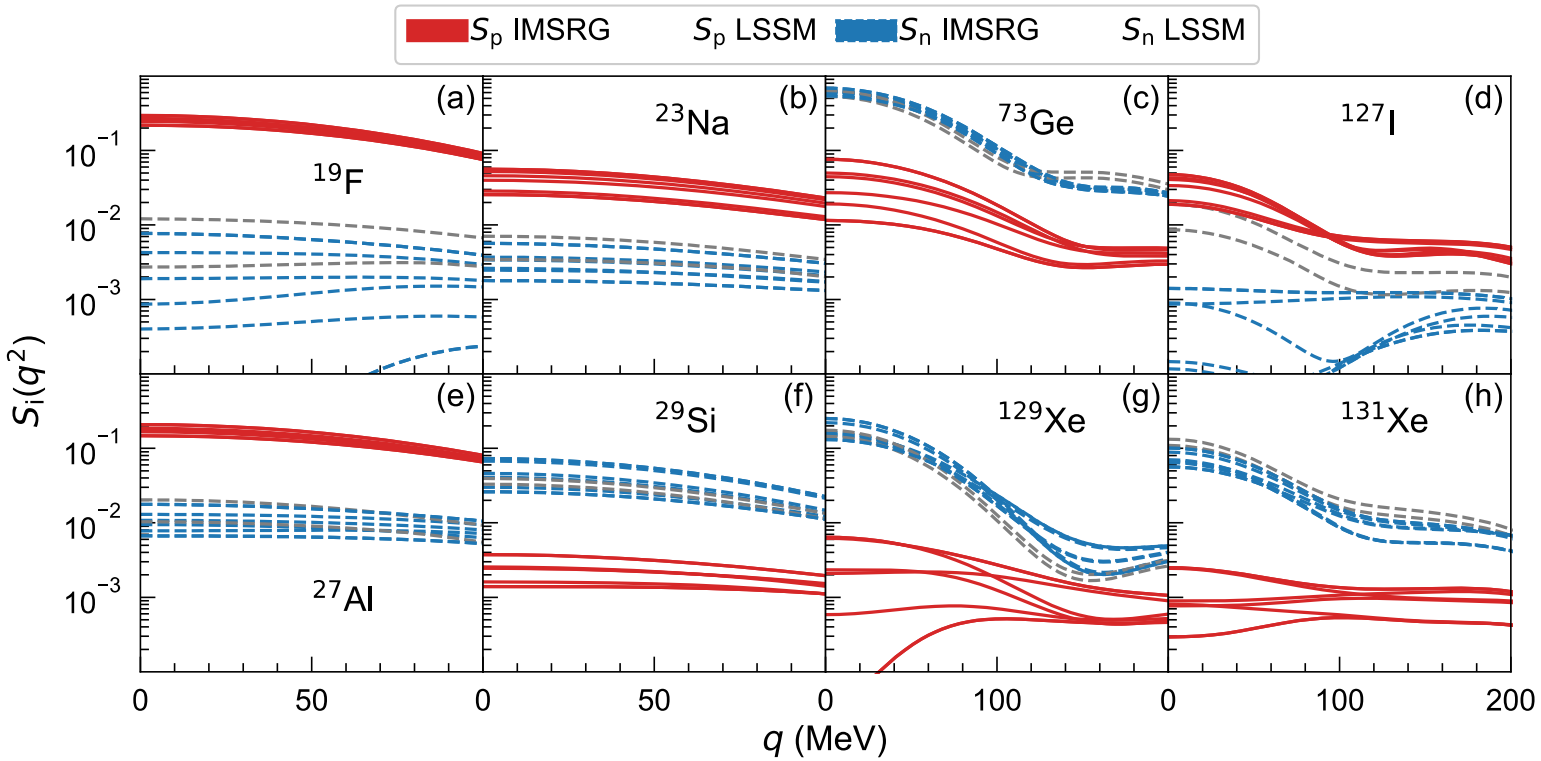
$$\frac{\mathrm{d}\sigma_A}{\mathrm{d}T}(E_\nu, T) = \frac{G_F^2 M_A}{4\pi}\left(1 - \frac{M_A T}{2E_\nu^2} - \frac{T}{E_\nu}\right) Q_{\mathrm{w}}^2 \left|F_{\mathrm{w}}(\mathbf{q}^2)\right|^2 + \frac{G_F^2 M_A}{4\pi}\left(1 + \frac{M_A T}{2E_\nu^2} - \frac{T}{E_\nu}\right) F_A(\mathbf{q}^2)$$

$$\frac{d\sigma}{dq^2} = \frac{8G_{\mathrm{F}}^2}{(2J+1)v^2} S_A(\mathbf{q}^2)$$

**Weak/Axial form factors** from nuclear theory

# Ab Initio SD WIMP-Nucleus Response Overview

## Ab initio structure functions for Spin-Dependent *all* dark-matter direct detection candidates




Result overall similar to phenomenology at low *q;* Largest discrepancies in $^{127}$I

*Ab Initio* Structure Factors for Spin-Dependent Dark Matter Direct Detection

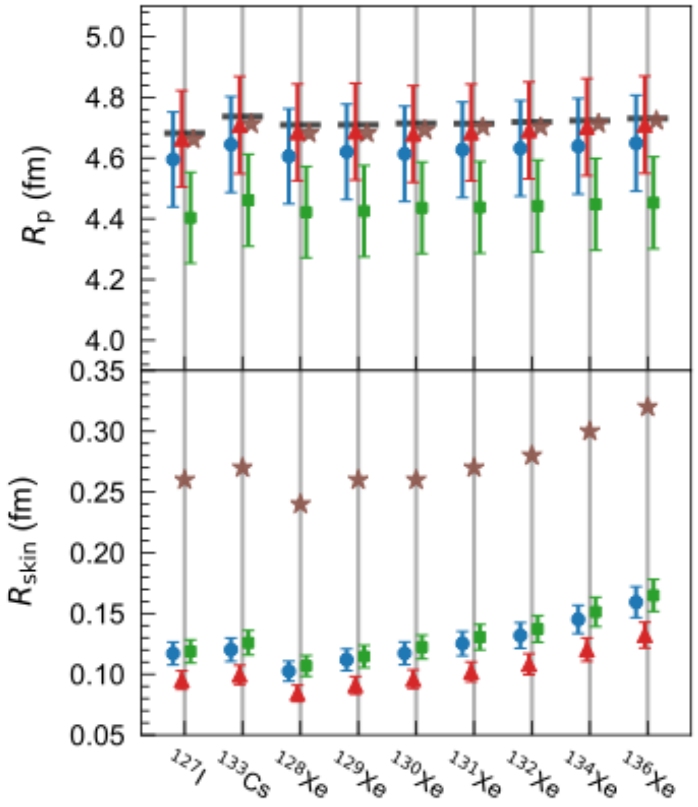
B. S. Hu, J. Padua-Argüelles, S. Leutheusser, T. Miyagi, S. R. Stroberg, and J. D. Holt
Phys. Rev. Lett. **128**, 072502 – Published 17 February 2022

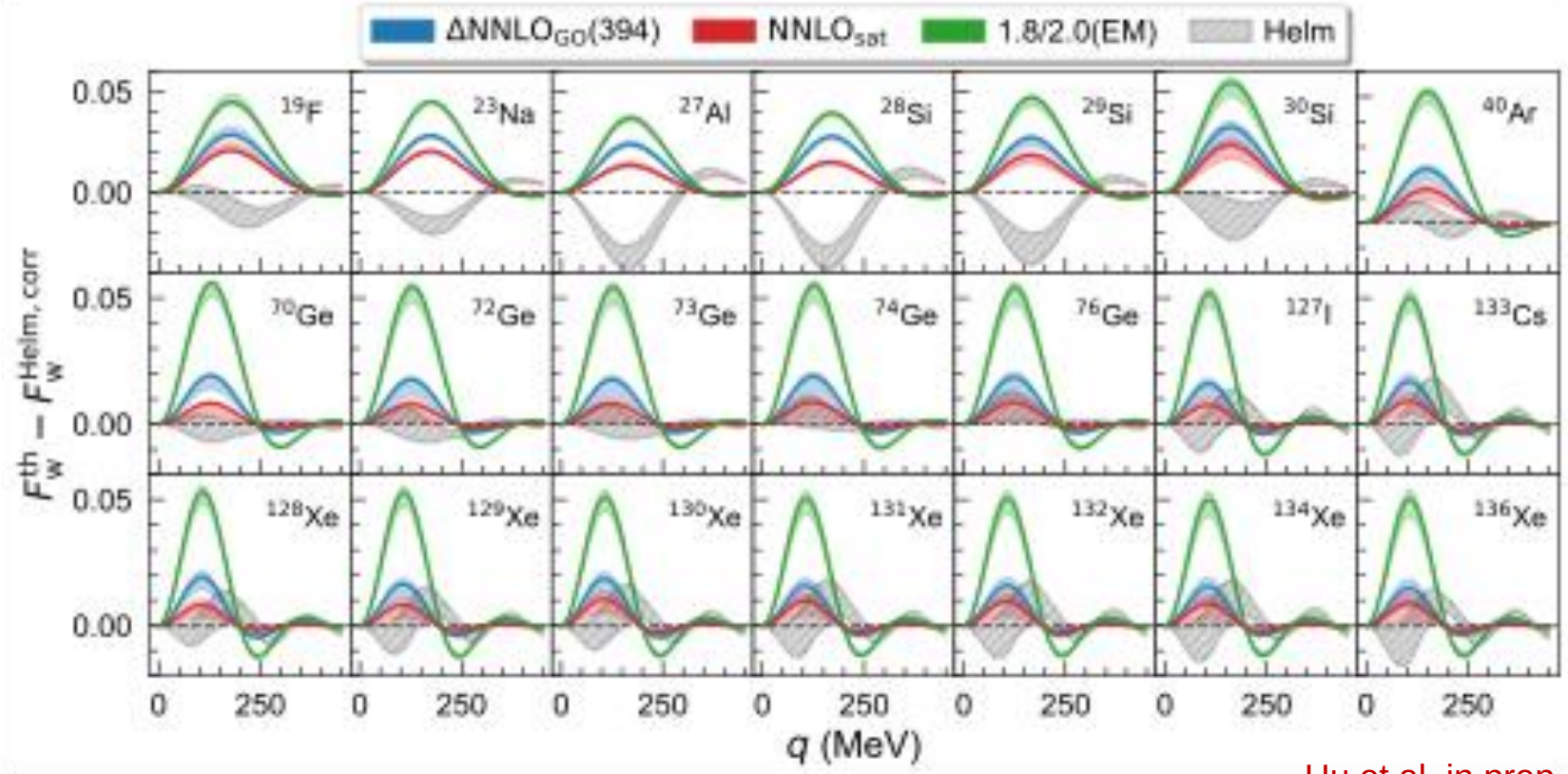
# Ab Initio WIMP/ν-Nucleus Responses

## Structure functions for dark matter direct detection and CEνNS

Typically use phenomenological form factors (Helm, etc.) same for p/n

CE□NS sensitive to neutron distribution in nuclei – **neutron skin calculations improve Helm**




Hu et al. in prep.

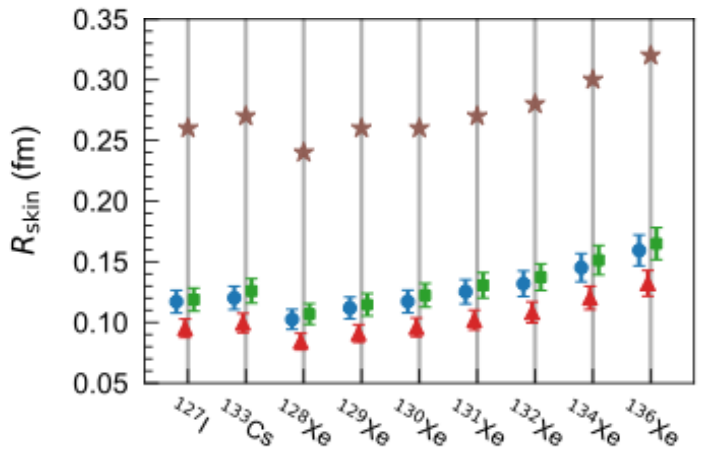
Comparison with ab initio calculations shows refined Helm well reproduces ab initio

# Ab Initio WIMP/ν-Nucleus Responses

## Structure functions for dark matter direct detection and CEνNS

Typically use phenomenological form factors (Helm, etc.) same for p/n

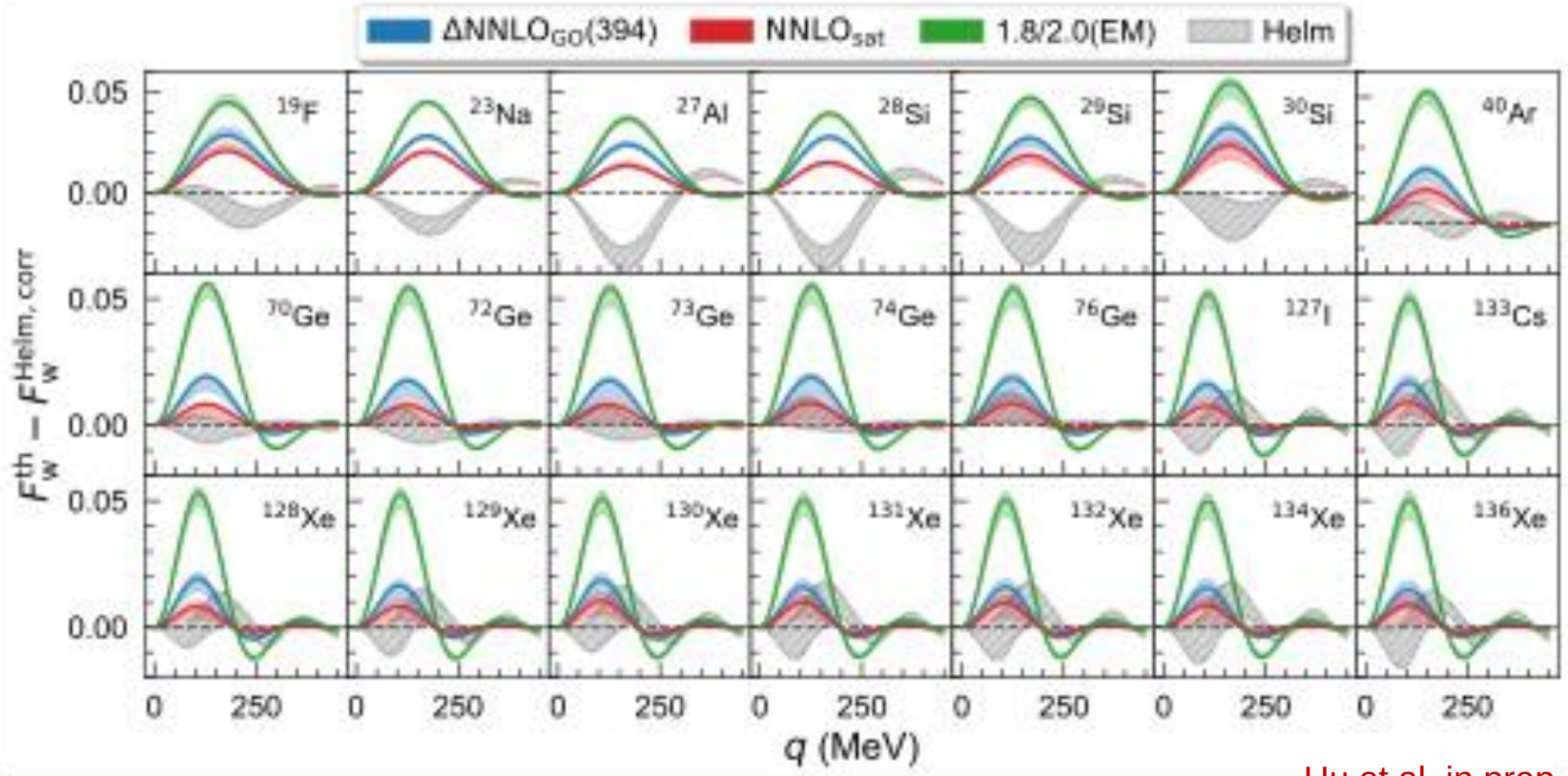
CE□NS sensitive to neutron distribution in nuclei – neutron skin calculations improve Helm




$$\mathcal{F}^{\rm Helm}(q^2) = \frac{3j_1(qR_0)}{qR_0} e^{-q^2 s^2/2},$$

$$R_0^2 = (1.23A^{1/3} - 0.60)^2 + \tfrac{7}{3}\pi^2 a^2 - 5s^2$$

| | $a$ (fm) | $s$ (fm) |
|---|---|---|
| Standard | 0.52 | 0.90 |
| Refined (proton) | $0.50 \pm 0.02$ | $0.88 \pm 0.10$ |
| Refined (neutron) | $0.52 \pm 0.02$ | $0.90 \pm 0.09$ |

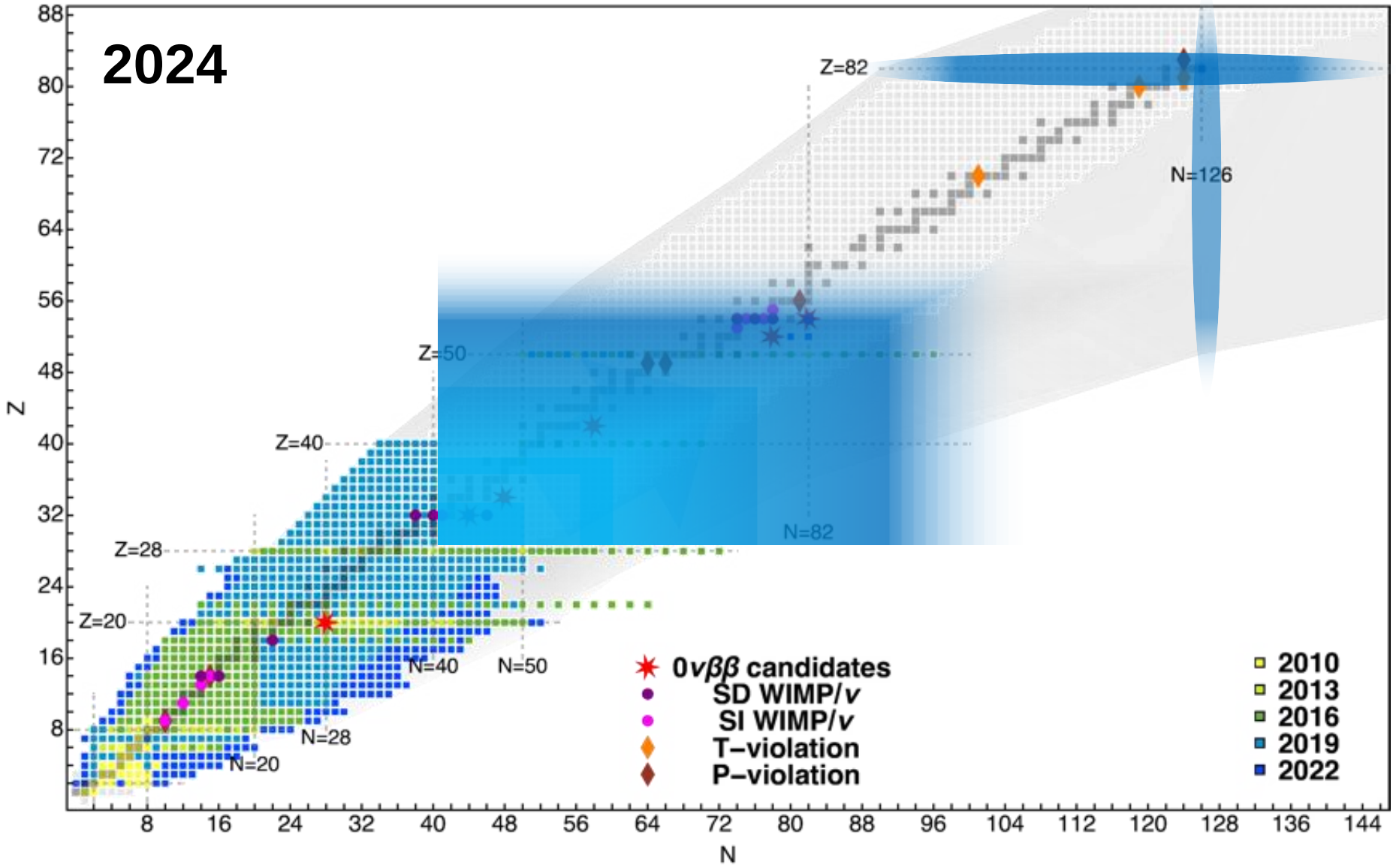



Hu et al. in prep.

**Provide refined "ab initio" Helm form factor for use by all in community**

# Future of Ab Initio Theory

(Not so) Bold predictions: many new directions in the next 5 years




**Nucleosynthesis**

Ab initio input for r-process

**Dark Matter/ν Scattering**

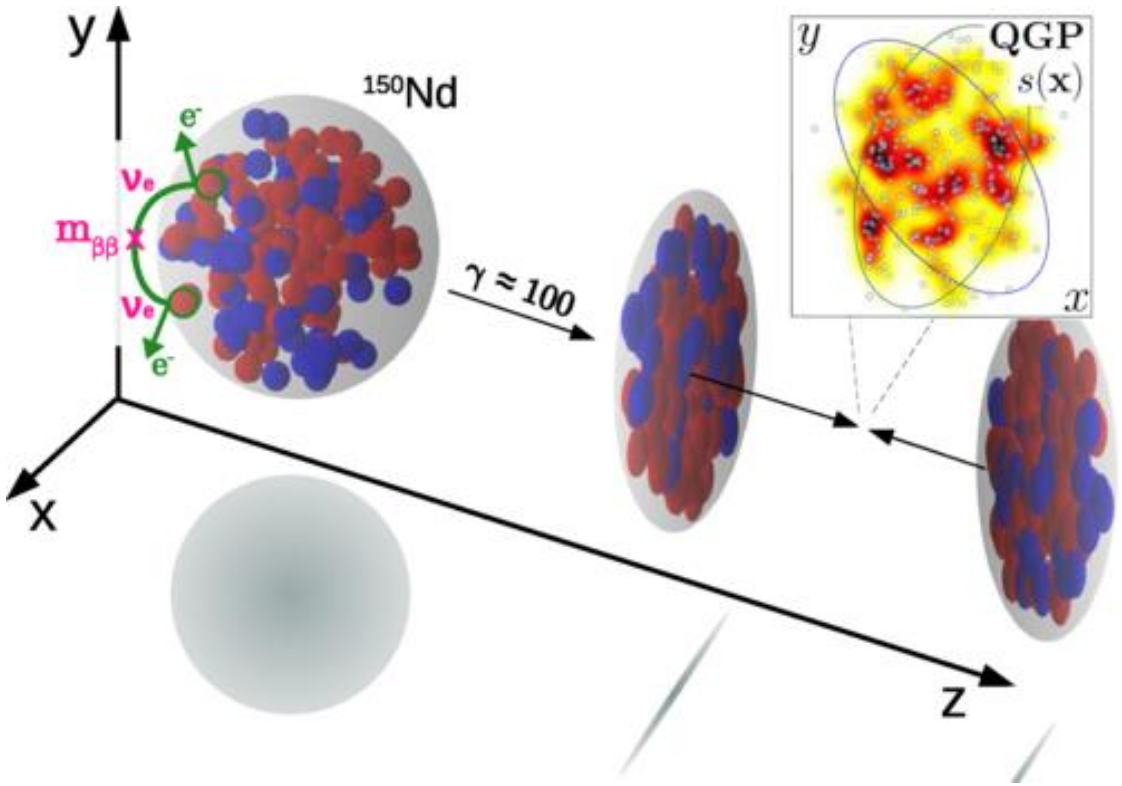
Ab initio structure functions

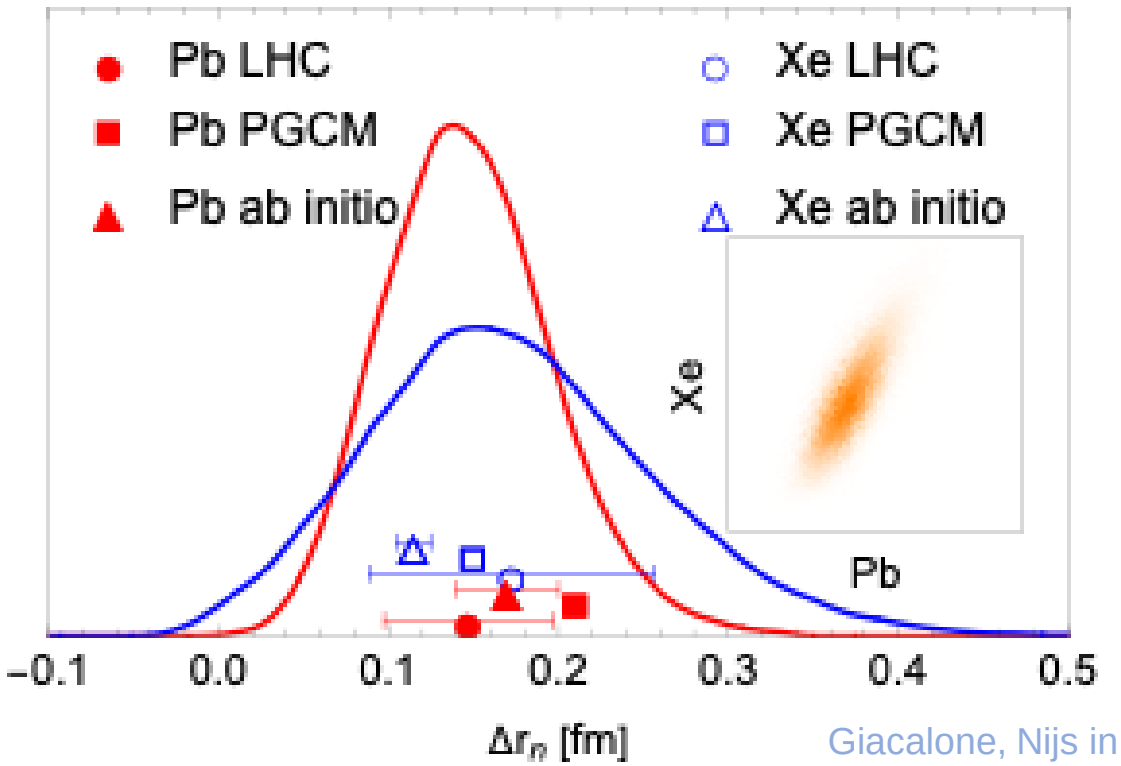
**Heavy Ion Collisions**

Nuclear structure/NMEs

# Nuclear Properties from Heavy-Ion Collisions

Utilize heavy ion collision data @ LHC for novel insights into nuclei and $0\nu\beta\beta$ decay!



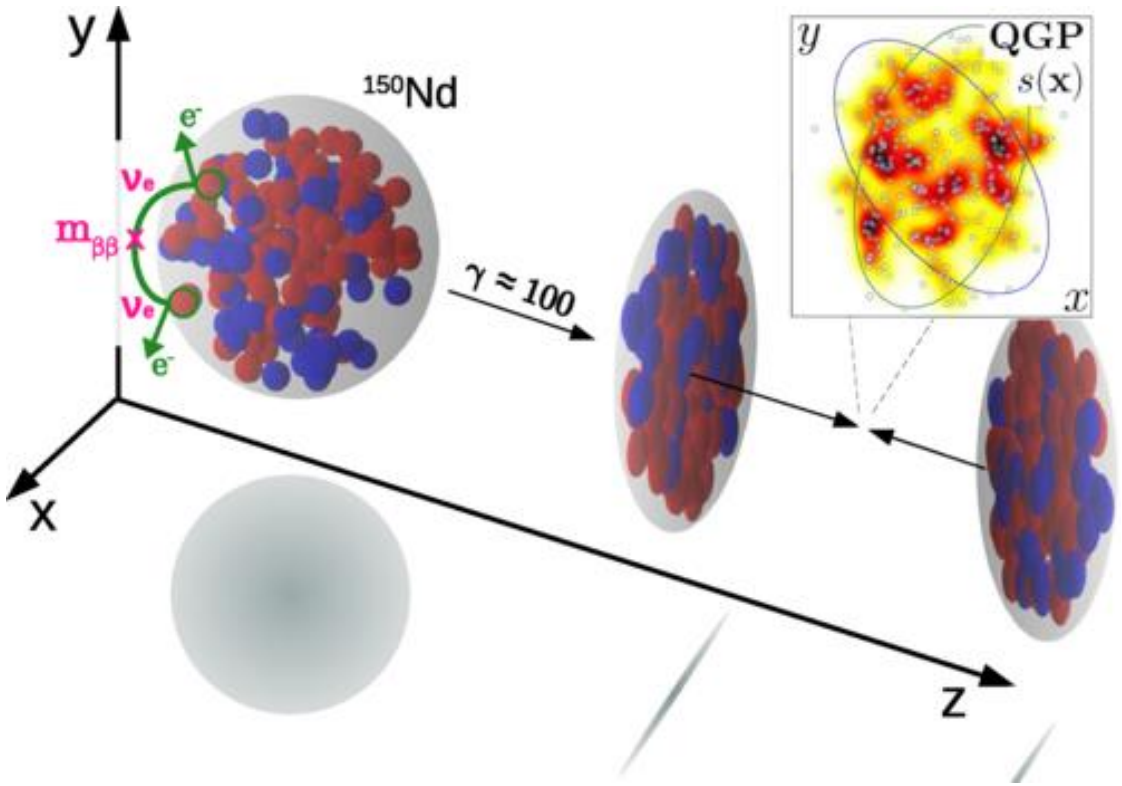



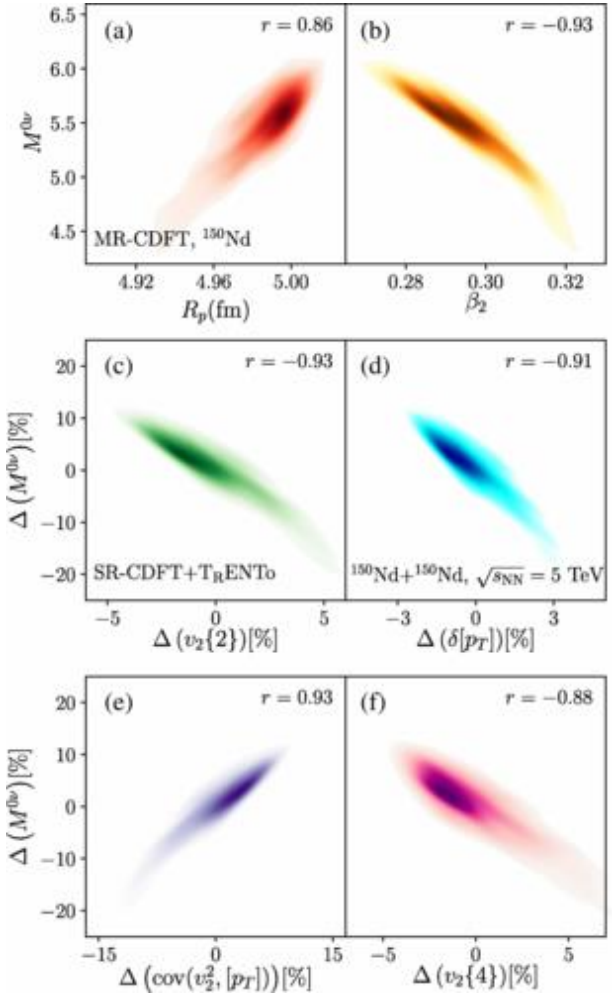

Giacalone, Nijs in prep.

Xe-Xe collisions provide first such determination of **neutron skins, consistent with ab initio**

# Nuclear Properties from Heavy-Ion Collisions

Utilize heavy ion collision data @ LHC for novel insights into nuclei and $0\nu\beta\beta$ decay!



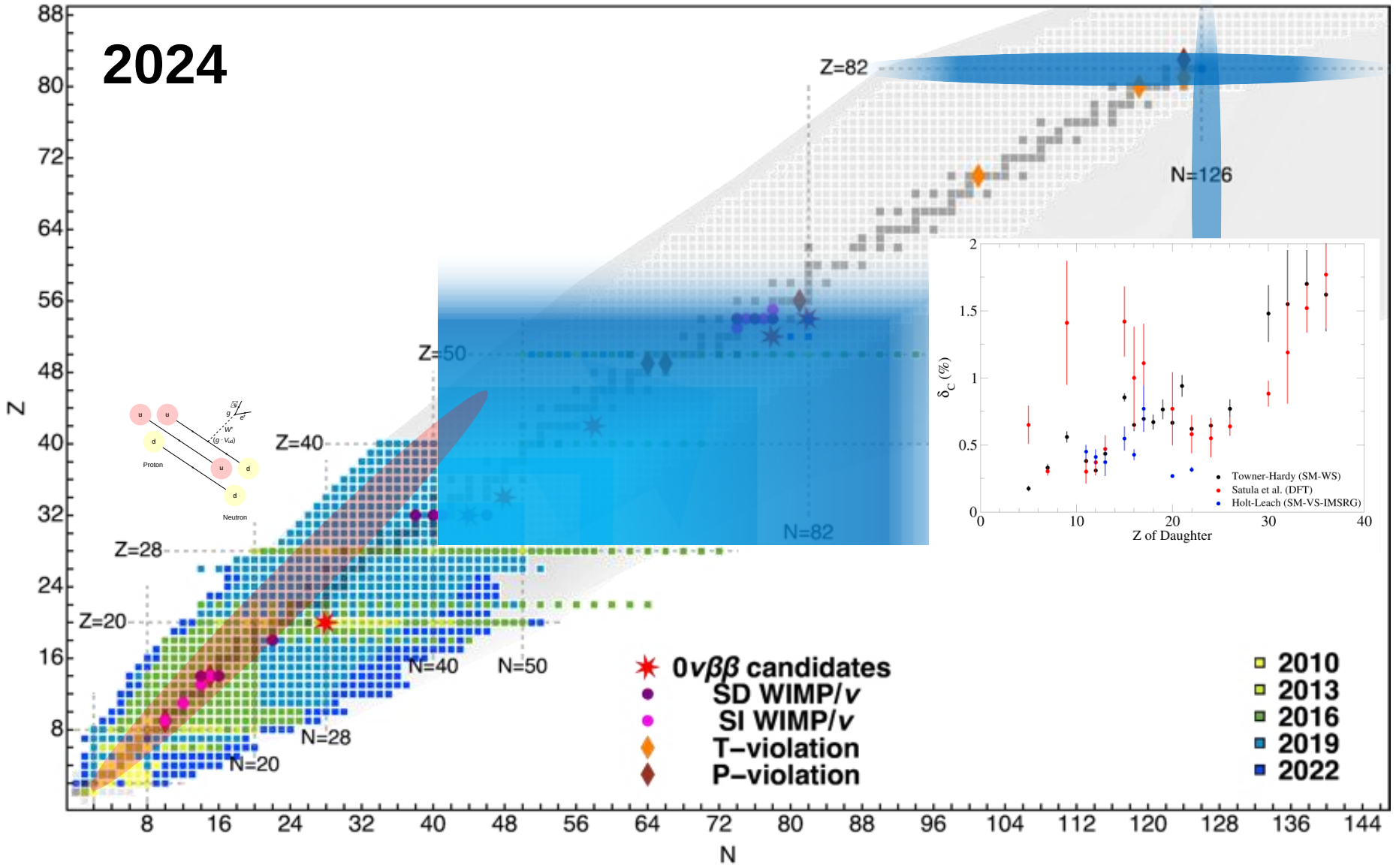

Y, Li et al., PRL (2025)

Xe-Xe collisions provide first such determination of neutron skins, consistent with ab initio

CERN/Canada **NME@LHC** collaboration: refine NME from **ab initio** and **Ge-Ge collisions**!

# Future of Ab Initio Theory

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




**Nucleosynthesis**

Ab initio input for r-process

**Dark Matter/ν Scattering**

Ab initio structure functions

**Heavy Ion Collisions**

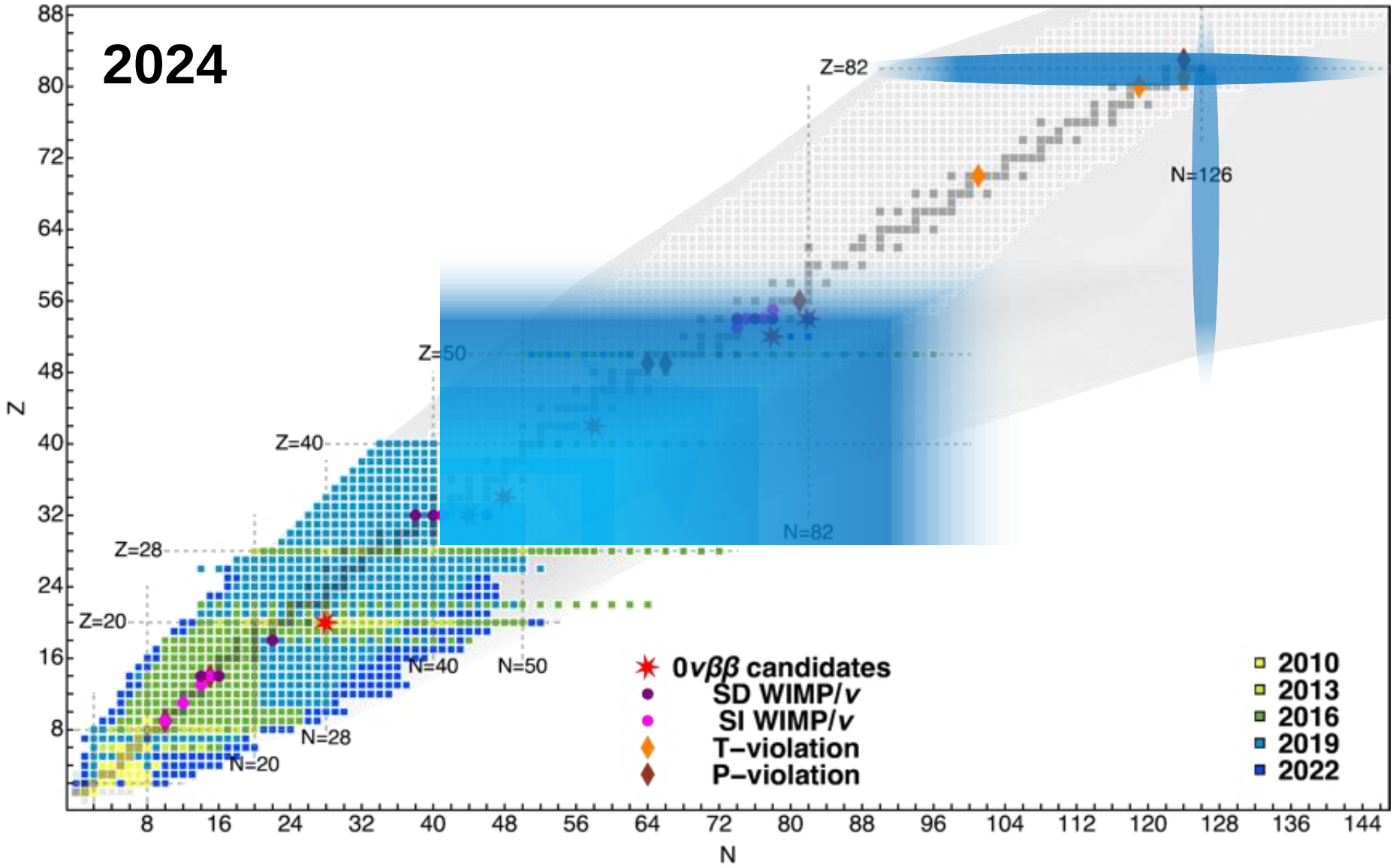
Nuclear structure/NMEs

**CKM Unitarity ($V_{ud}$)**

Superallowed Fermi

# Future of Ab Initio Theory

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




**Nucleosynthesis**

Ab initio input for r-process

**Dark Matter/ν Scattering**

Ab initio structure functions

**Heavy Ion Collisions**

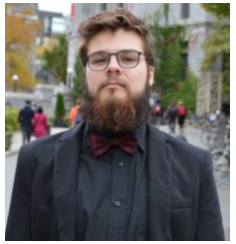
Nuclear structure/NMEs

**CKM Unitarity ($V_{ud}$)**

Superallowed Fermi

**Symmetry Violation**

P/T-violating moments



Antoine Belley

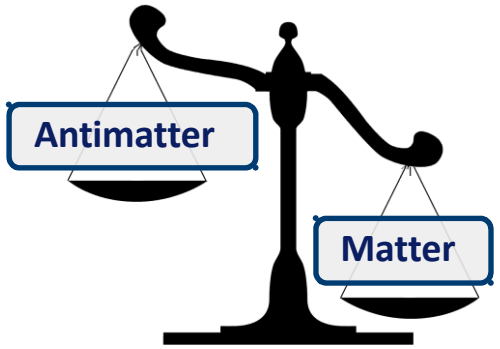
Jose Munoz

# The Magic of Molecules: CP Violation

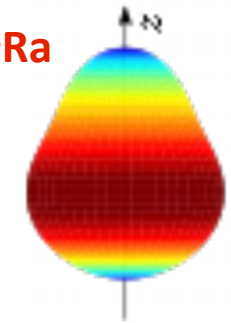
"One of the most compelling mysteries in all of science is how matter came to dominate over antimatter in the universe." – NSAC LRP

**CP violation** required beyond our current observations

Searches for CP violation ongoing for 50+ yr
neutron/atoms - $^{199}$Hg EDM world leader



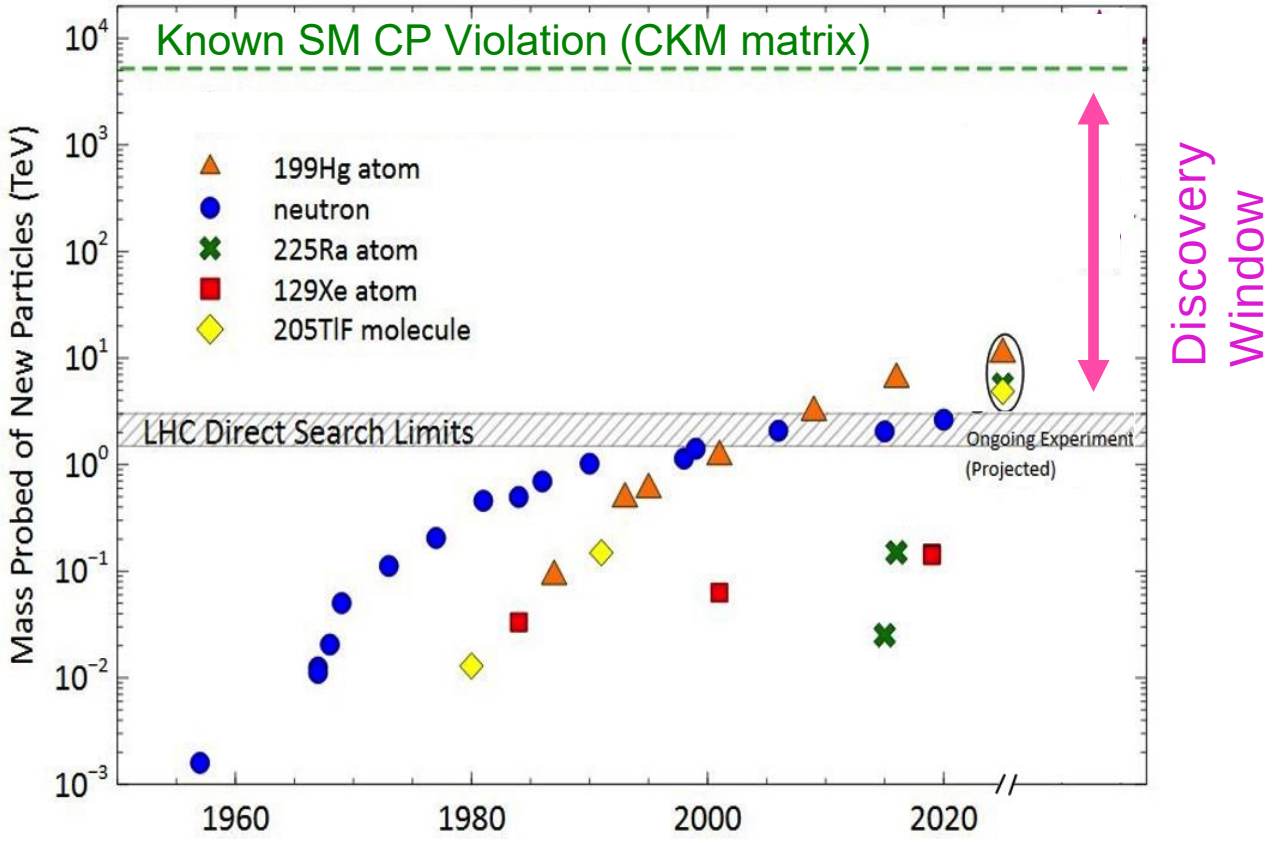

$^{225}$Ra



$$\sim \frac{Z A^{2/3} \beta_2 \beta_3^2}{E_+^N - E_-^N} \sim 10^3$$

Effects enhanced in:

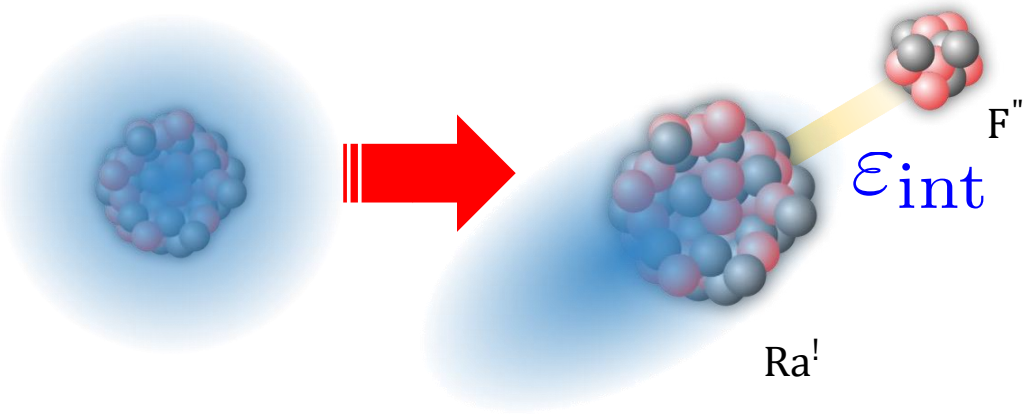
Heavy systems, Octupole deformed



# The Magic of Molecules: CP Violation

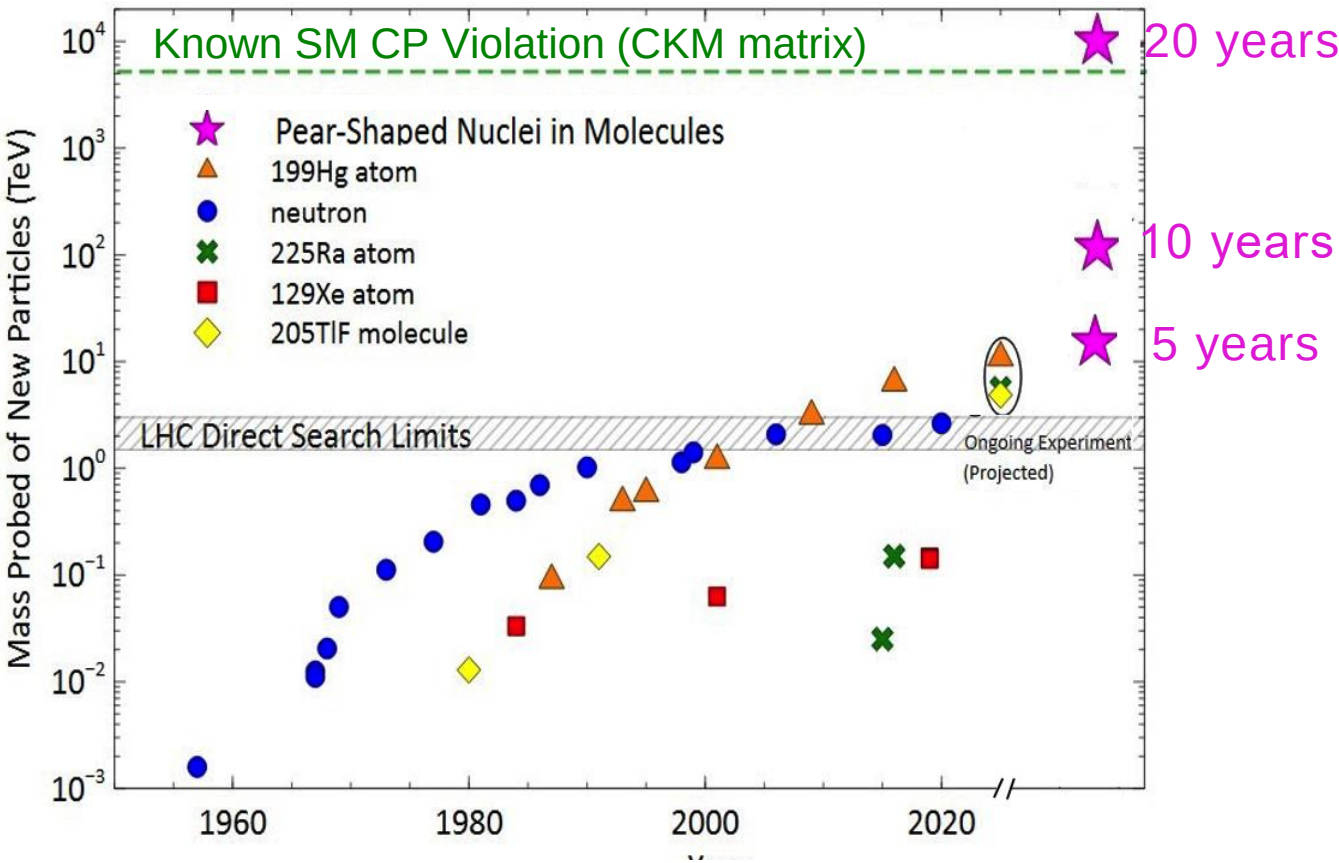
Worldwide race to exploit power of **Radioactive Molecules**

Generate internal fields orders of magnitude above lab possibilities




Enhancements in molecules vs atoms **>4000**

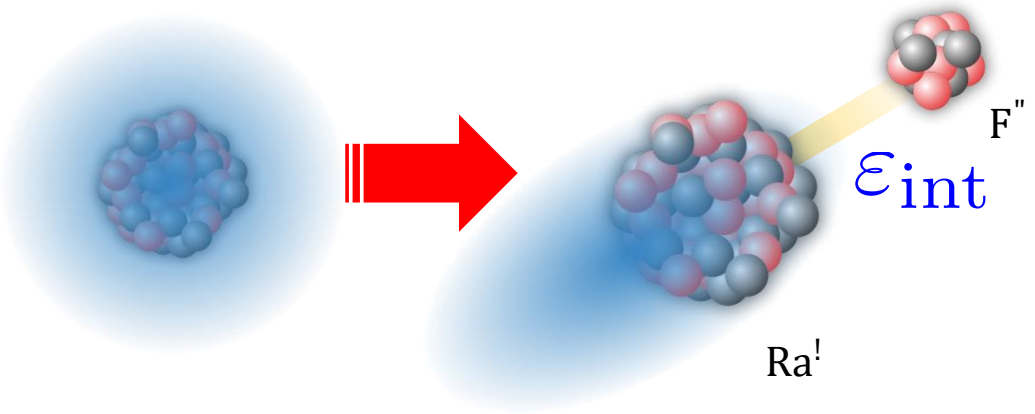
Probe **1000TeV scale** in our lifetimes!

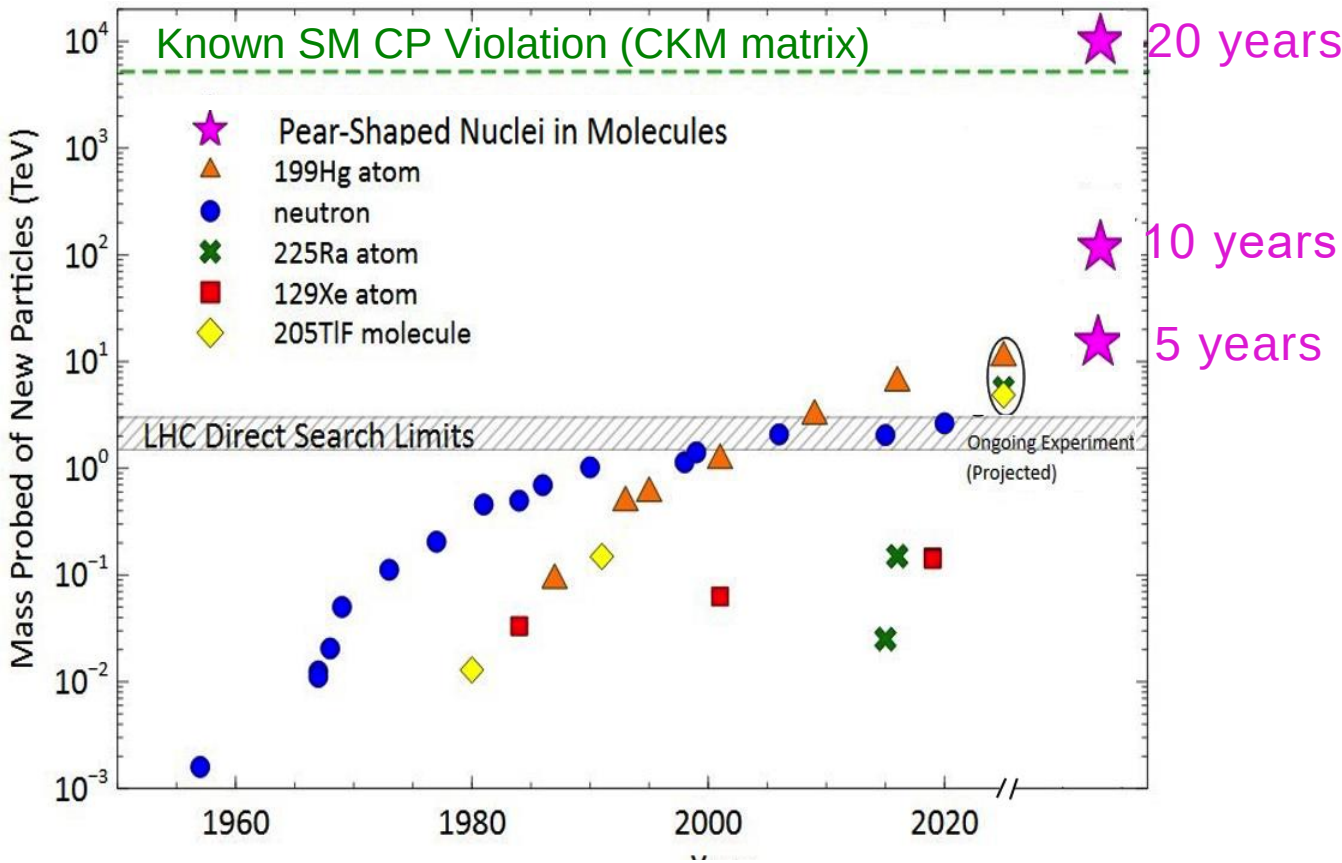


# The Magic of Molecules: CP Violation

Worldwide race to exploit power of **Radioactive Molecules**

Generate internal fields orders of magnitude above lab possibilities




Enhancements in molecules vs atoms **>4000**

Probe **1000TeV scale** in our lifetimes

**To date, no rigorous nuclear theory**

(motivation, interpretation)

Measurement — Nuclear structure — P,T odd NN int

$$S = \langle \Psi_0 | S_z | \Psi_0 \rangle = \frac{\langle \Psi_+ | S_z | \Psi_- \rangle \langle \Psi_+ | V_{PT} | \Psi_- \rangle}{E_+ - E_-}$$

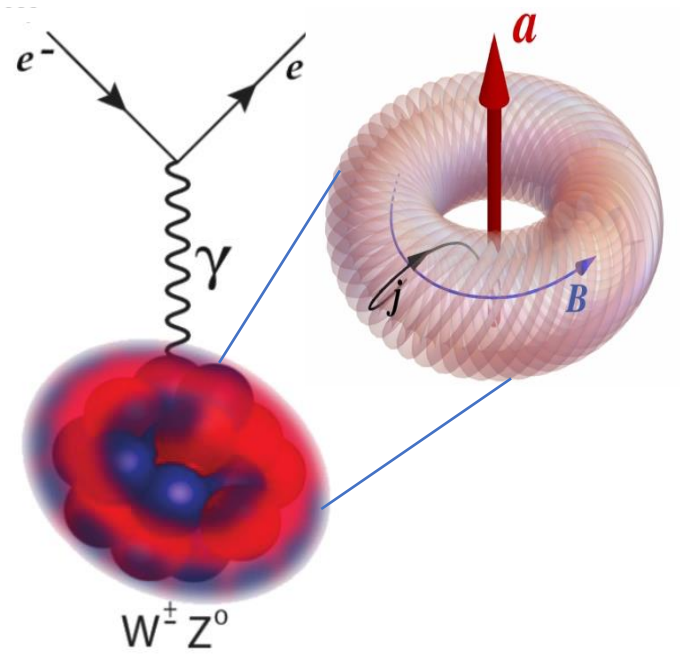
**New physics**

Experiment

# The Magic of Molecules: Weak Structure of Nuclei

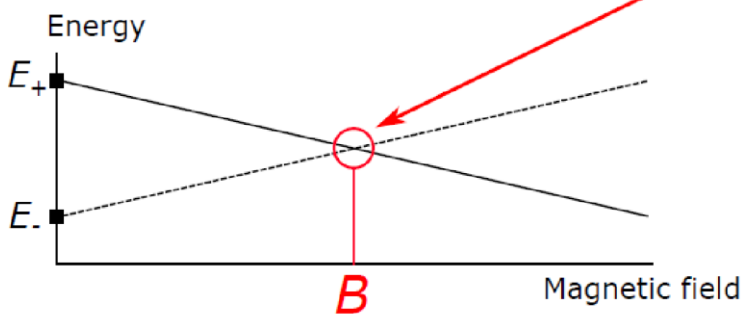
**Hadronic P violation** – probe the **weak structure** of the atomic nucleus!

W,Z exchange between nucleons generates **anapole moment**

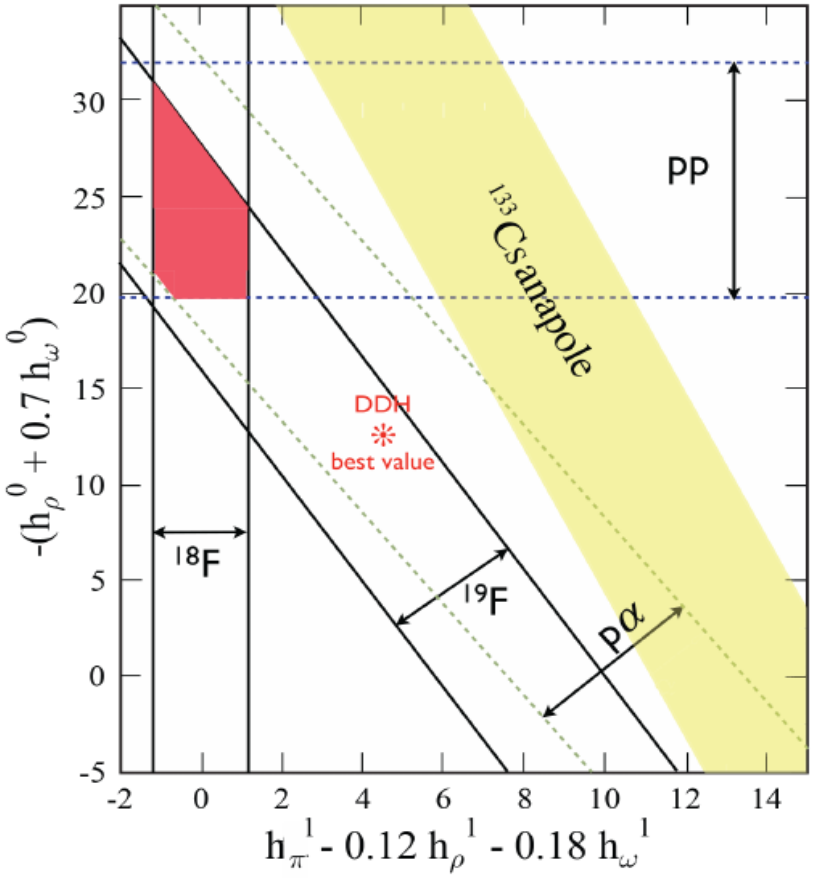



$$E_{PV} \sim \frac{\langle \psi_\uparrow^+ | H_\pm | \psi_\downarrow^- \rangle}{E_- - E_+}$$

$> 10^{11}$ molecular enhancement




Experimental tuning enhances $>10^{11}$




C. S. Wood et al., Science (80-. ). 275, 1759 (1997).

RESEARCH ARTICLE

**Measurement of Parity Nonconservation and an Anapole Moment in Cesium**

C. S. Wood, S. C. Bennett, D. Cho,* B. P. Masterson,† J. L. Roberts, C. E. Tanner,‡ C. E. Wieman§

**To date, no rigorous nuclear theory**

Nuclear structure — P-odd NN int

$$\langle IM | a_{10}^{\rm pol} | IM \rangle \sim \sum_n \frac{\langle I^\pi || a_1 || I_n^{-\pi} \rangle \langle I_n^{-\pi} | V_{\rm PV} | I^\pi \rangle}{E_{\rm g.s.} - E_n}$$

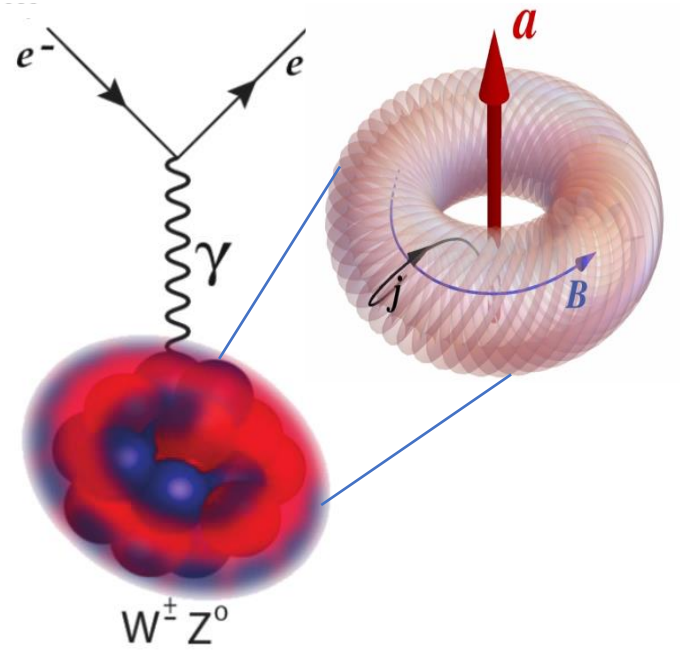
Experiment

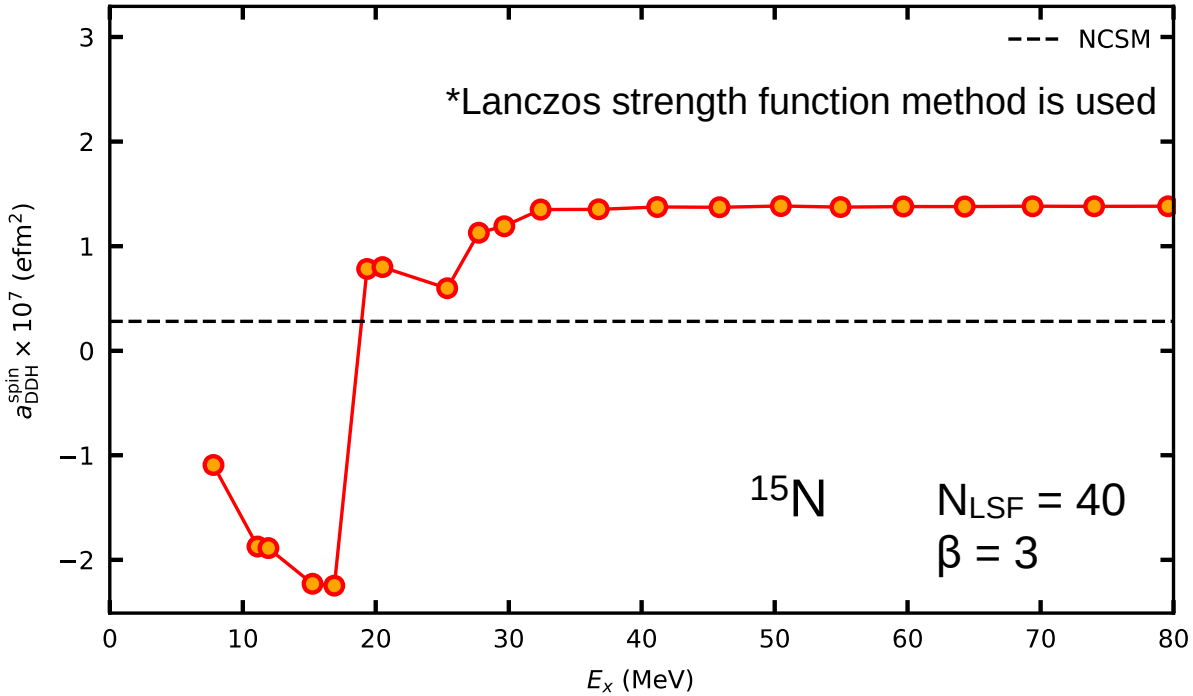
**New P-violating physics**

# The Magic of Molecules: Weak Structure of Nuclei

**Hadronic P violation** – probe the weak structure of the atomic nucleus!

W,Z exchange between nucleons generates **anapole moment**




**To date, no rigorous nuclear theory**

**$^{133}$Cs underway!**

Nuclear structure — P-odd NN int

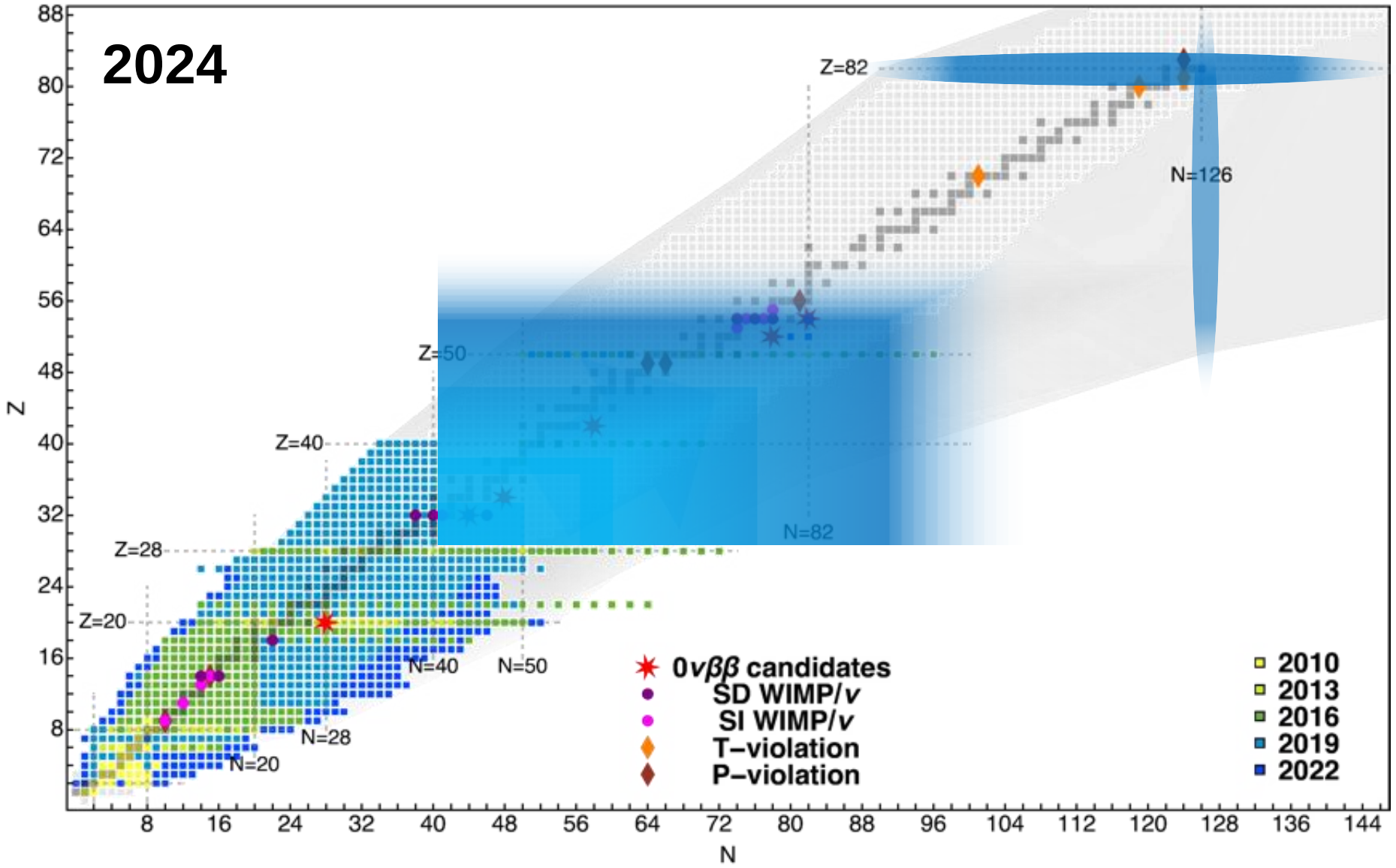
$$\langle IM|a_{10}^{\rm pol}|IM\rangle \sim \sum_n \frac{\langle I^\pi||a_1||I_n^{-\pi}\rangle\langle I_n^{-\pi}|V_{\rm PV}|I^\pi\rangle}{E_{\rm g.s.}-E_n}$$

Experiment

**New P-violating physics**

# Future of Ab Initio Theory

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




**Nucleosynthesis**
Ab initio input for r-process

**Dark Matter/ν Scattering**
Ab initio structure functions

**Heavy Ion Collisions**
Nuclear structure/NMEs

**CKM Unitarity ($V_{ud}$)**
Superallowed Fermi

**Symmetry Violation**
Schiff/anapole moments

**Atomic/molecular/QC**

**AI/Machine Learning**
New emulators

TRIUMF

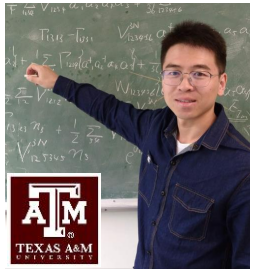
# Future of Ab Initio Theory

## (Former) Postdoctoral Fellows

Ragnar Stroberg

Takayuki Miyagi

Lotta Jokiniemi

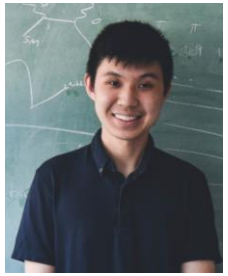

Baishan Hu

## 0νββ Decay

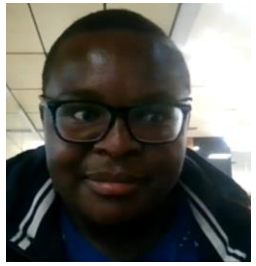
Antoine Belley

Isabella Ginnette

Alex Todd

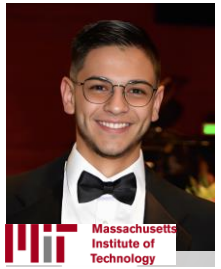

Michael Liudeng

## Structure + Astrophysics


Kanting Motimele

Maude Larivière

## Symmetry Violation


Jose Munoz

Jack Pitcher

## CKM Unitarity

Emily Love

Matt Martin

## AI/Machine Learning

## Atomic Systems

Gaurav Tenkila

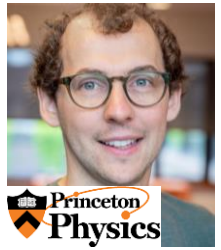
Hrishi Patel

Vijay Chand

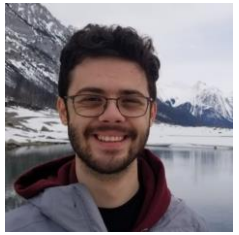
# Just the beginning: join our revolution!

# jholt@triumf.ca

## Dark Matter/ν Scattering


Sam Leutheusser

Jose Padua


Mathieu Bruneault

# Valence-Space IMSRG

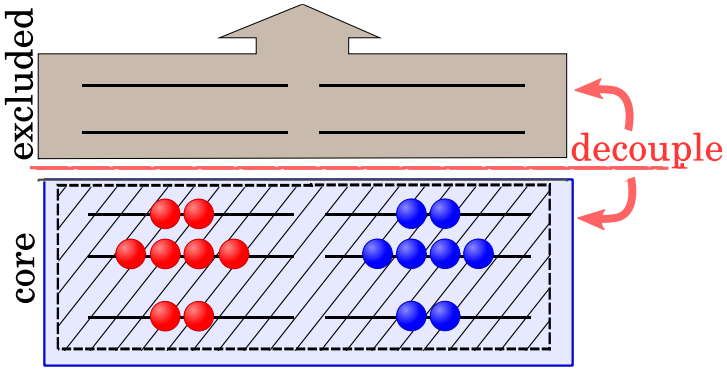
Explicitly construct unitary transformation from sequence of rotations

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

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

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

**Step 1: Decouple core**




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

Can we achieve accuracy of large-space methods?

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

# Valence-Space IMSRG

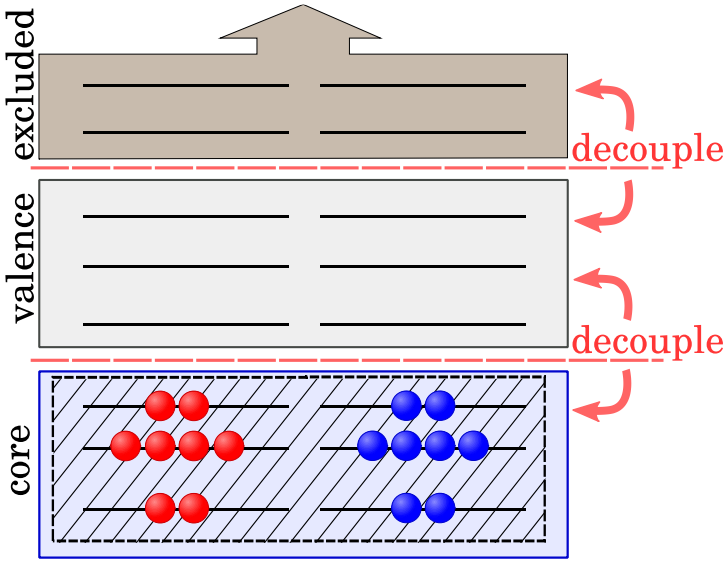
Explicitly construct unitary transformation from sequence of rotations

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

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

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

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

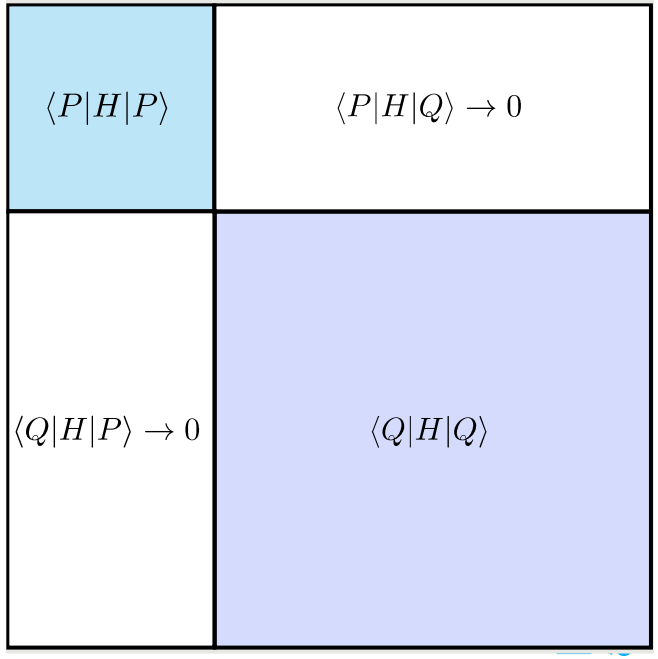



$|\Phi_0\rangle = |^{16}\mathrm{O}\rangle$

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

Can we achieve accuracy of large-space methods?

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



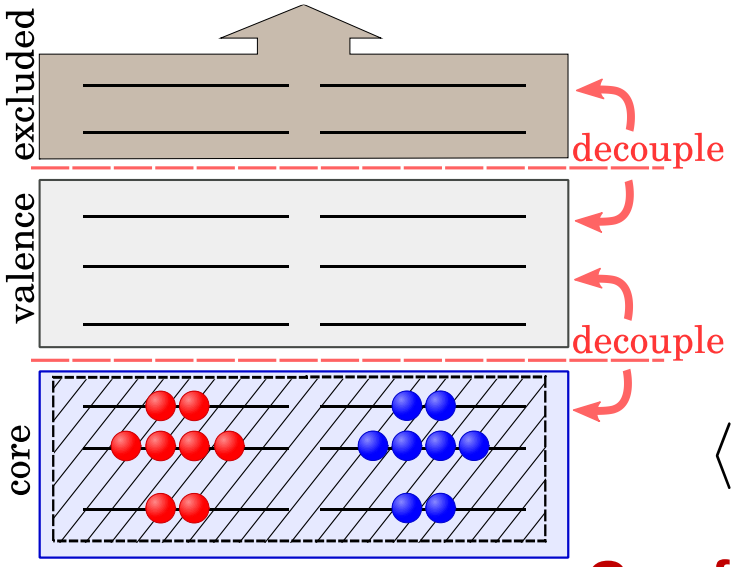
# Valence-Space IMSRG

Explicitly construct unitary transformation from sequence of rotations

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

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

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




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

**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**

| | |
|---|---|
| $\langle P\|H\|P\rangle$ | $\langle P\|H\|Q\rangle \to 0$ |
| $\langle Q\|H\|P\rangle \to 0$ | $\langle Q\|H\|Q\rangle$ |

# Ab Initio Strategy IV: Rigorous Uncertainties

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

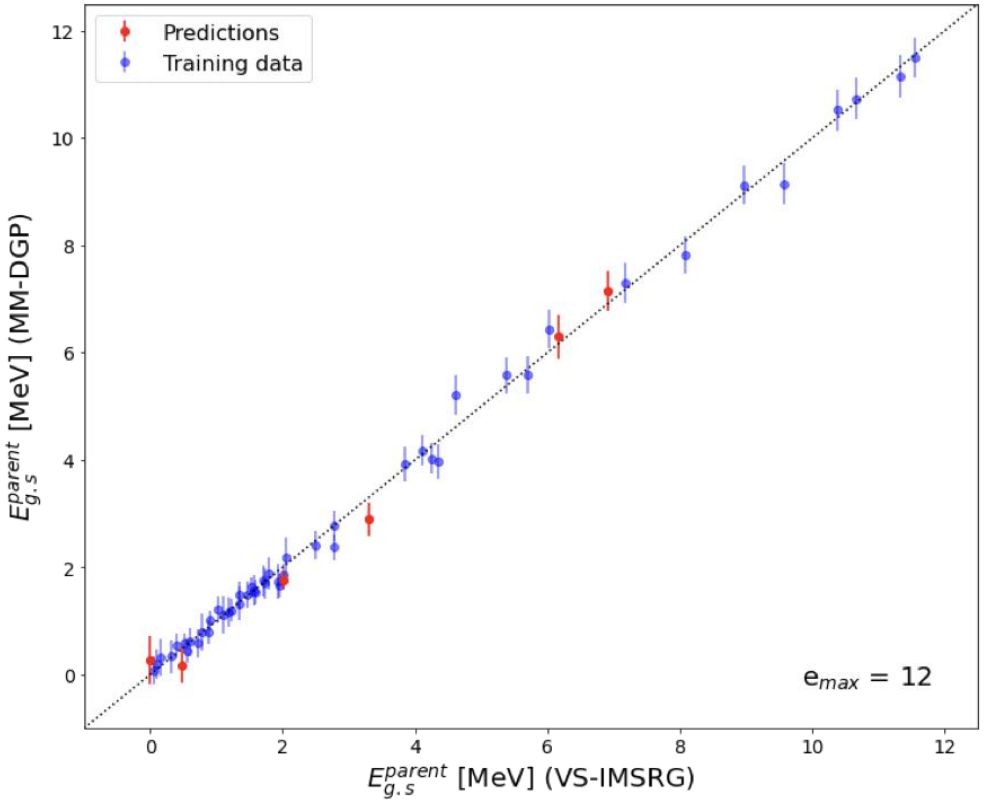
Consider all physics contributing to systematic error

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

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



# Ab Initio Strategy IV: Rigorous Uncertainties

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

Consider all physics contributing to systematic error

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

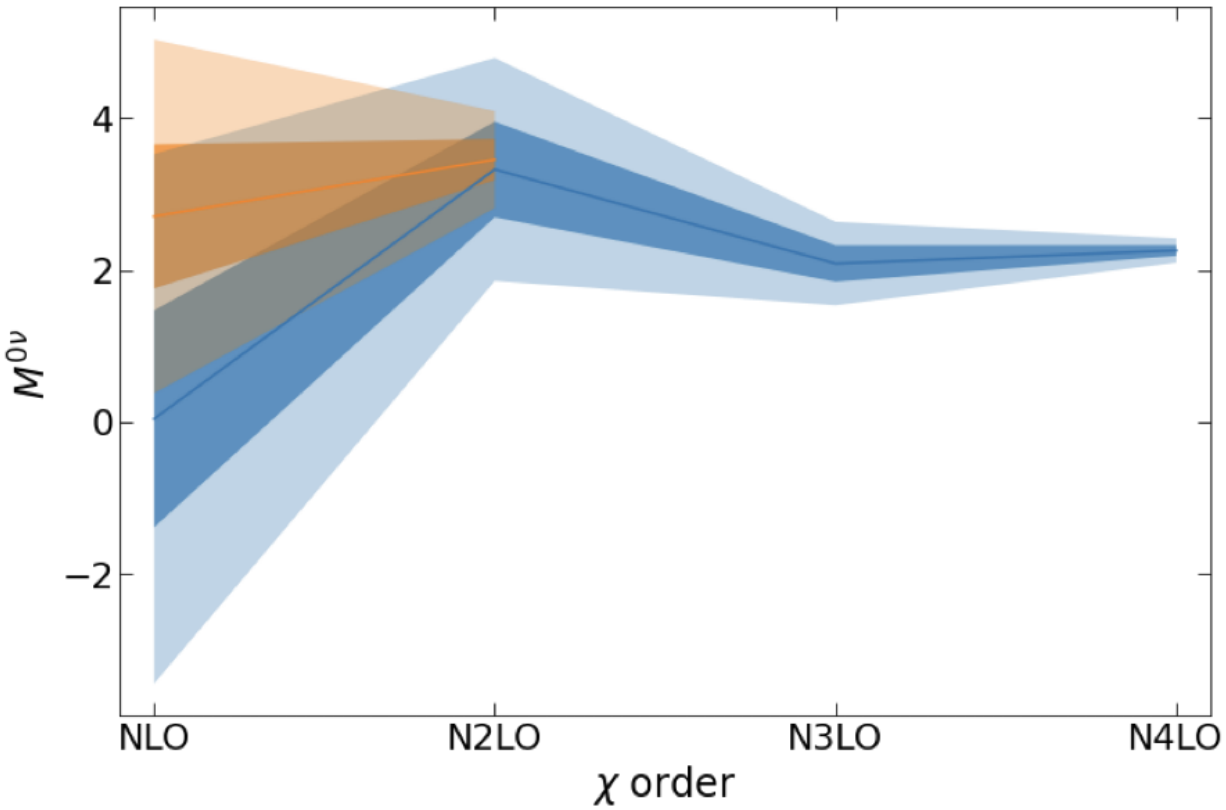
Use 8100+NN+3N forces - weighted by np $^1S_0$ phase shift

Solve many-body problem with MM-DGP

Emulator: from process itself

**EFT**: Truncation in nuclear forces

Belley et al, arXiv:2308.15634



# Ab Initio Strategy IV: Rigorous Uncertainties

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

Consider all physics contributing to systematic error

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

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

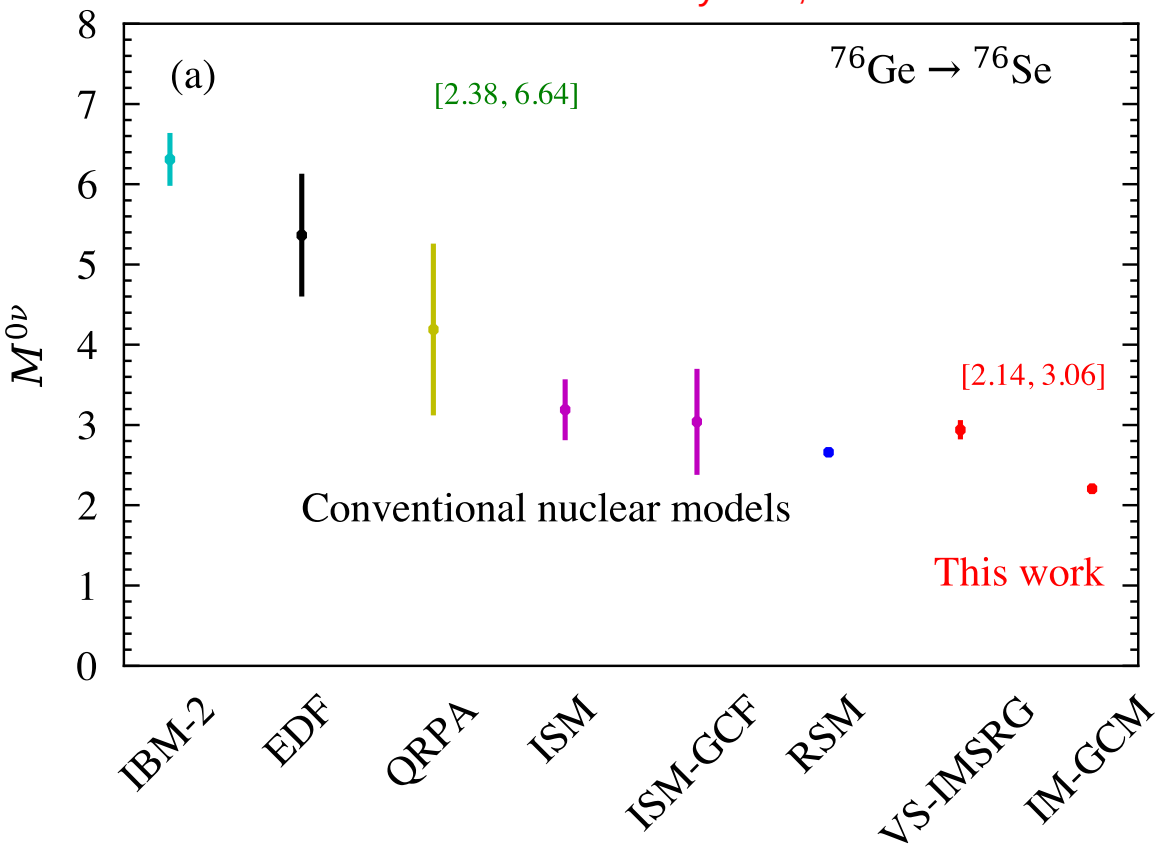
Solve many-body problem with MM-DGP

Emulator: from process itself

EFT: Truncation in nuclear forces

**Many-body**: Truncation in many-body physics

Belley et al, arXiv:2308.15634



# Ab Initio Strategy IV: Rigorous Uncertainties

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

Consider all physics contributing to systematic error

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

Belley et al, arXiv:2308.15634

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

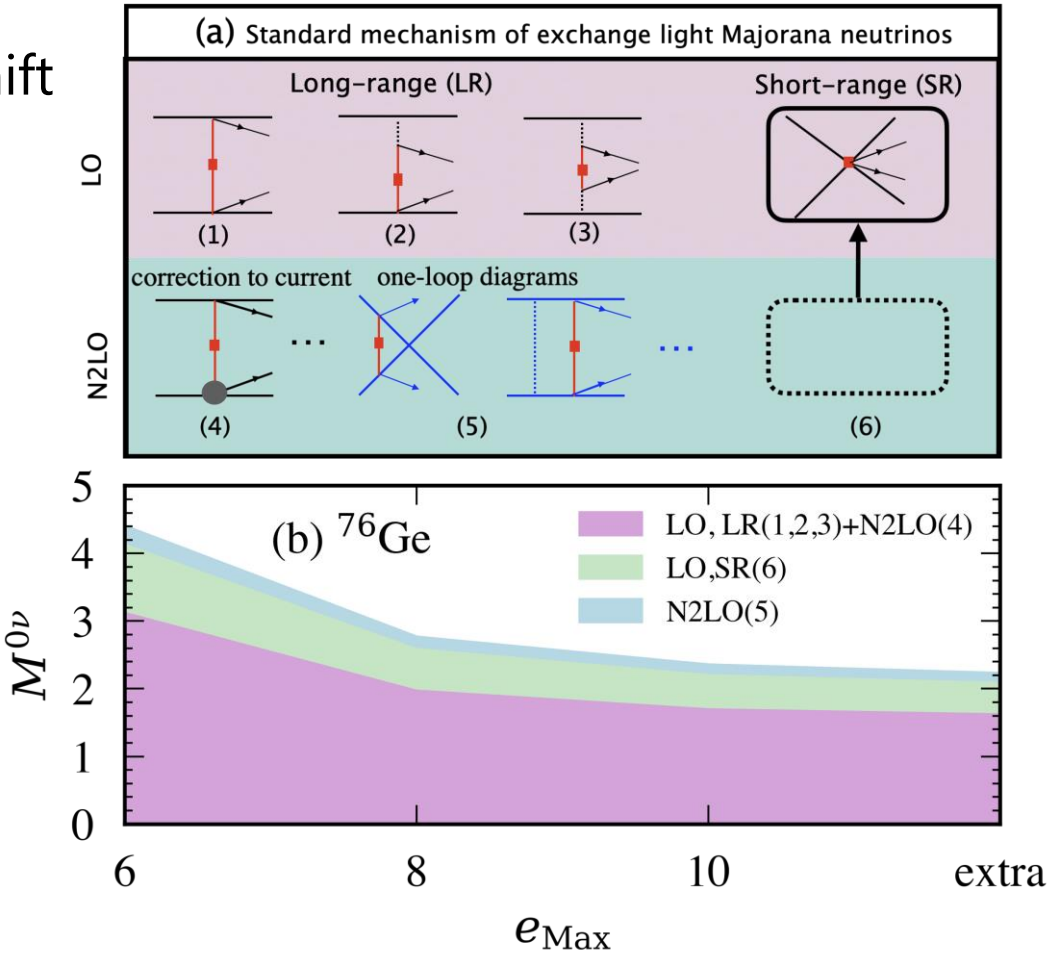
Solve many-body problem with MM-DGP

Emulator: from process itself

EFT: Truncation in nuclear forces

Many-body: Truncation in many-body physics

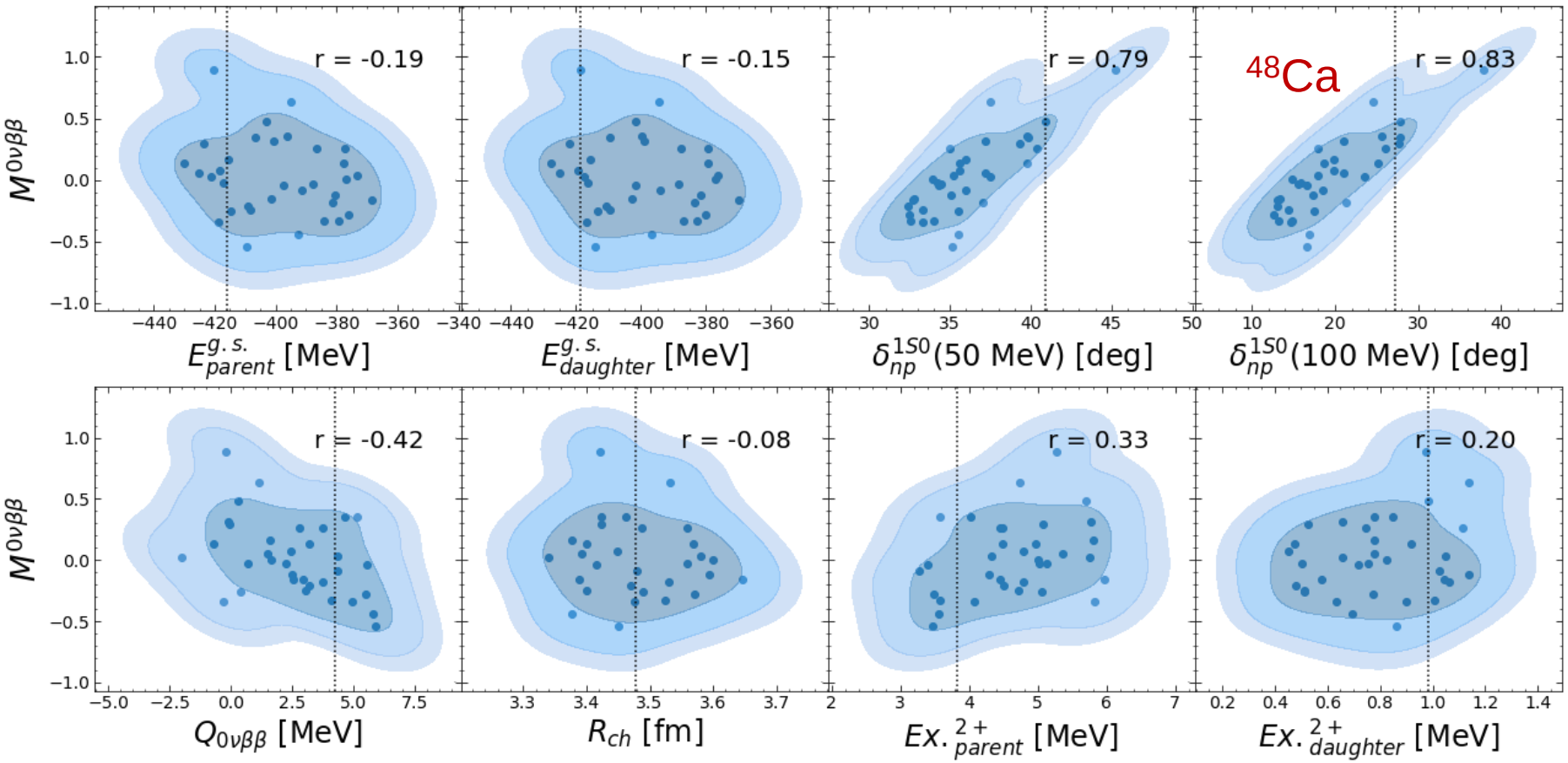
**Operator**: higher order contributions to operator



# Ab Initio Strategy: Explore Correlations

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

**No ab initio correlations**, except DGT



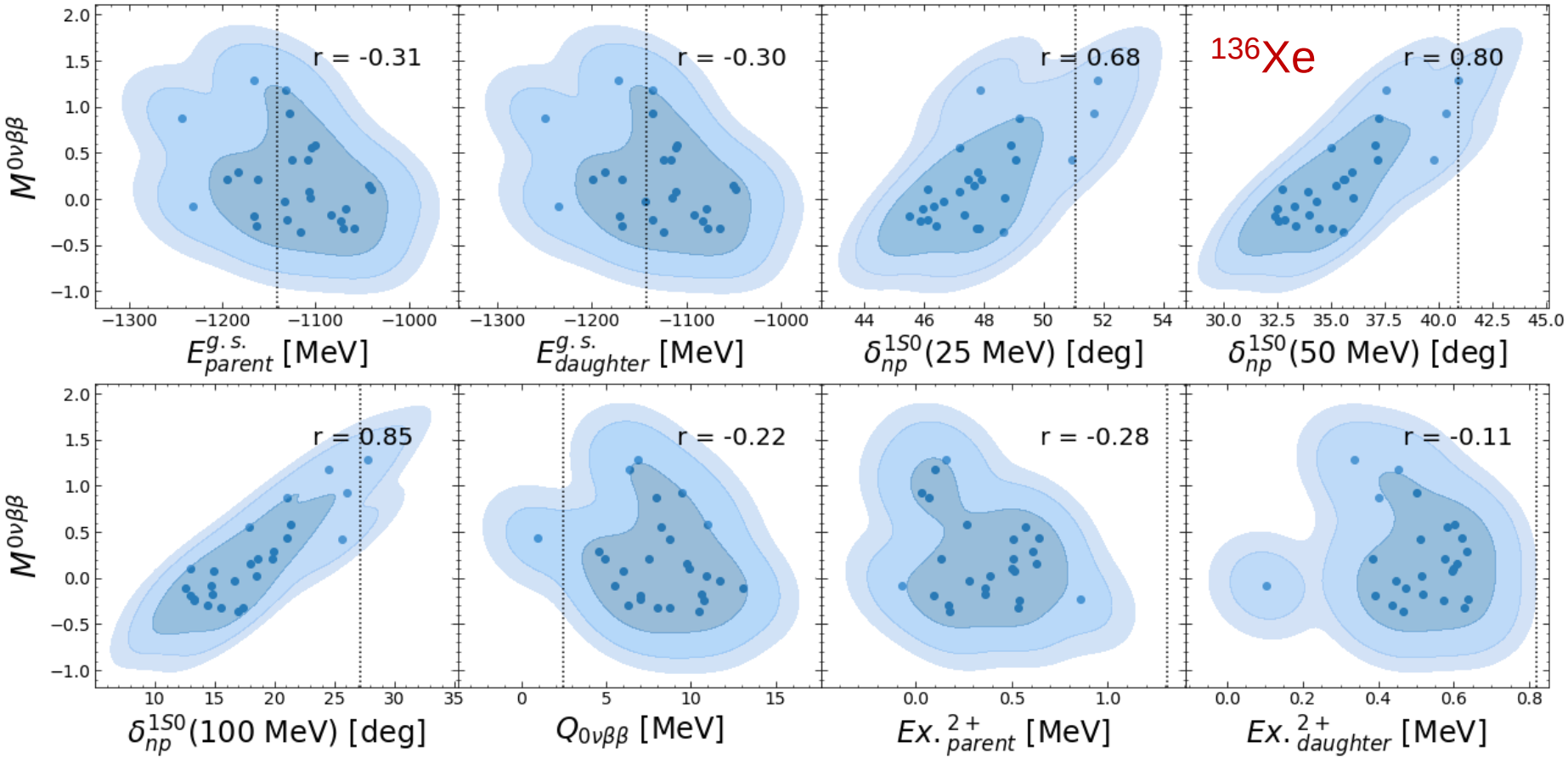

Use machine learning for further insights?

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

# Ab Initio Strategy: Explore Correlations

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

**No ab initio correlations**, except DGT

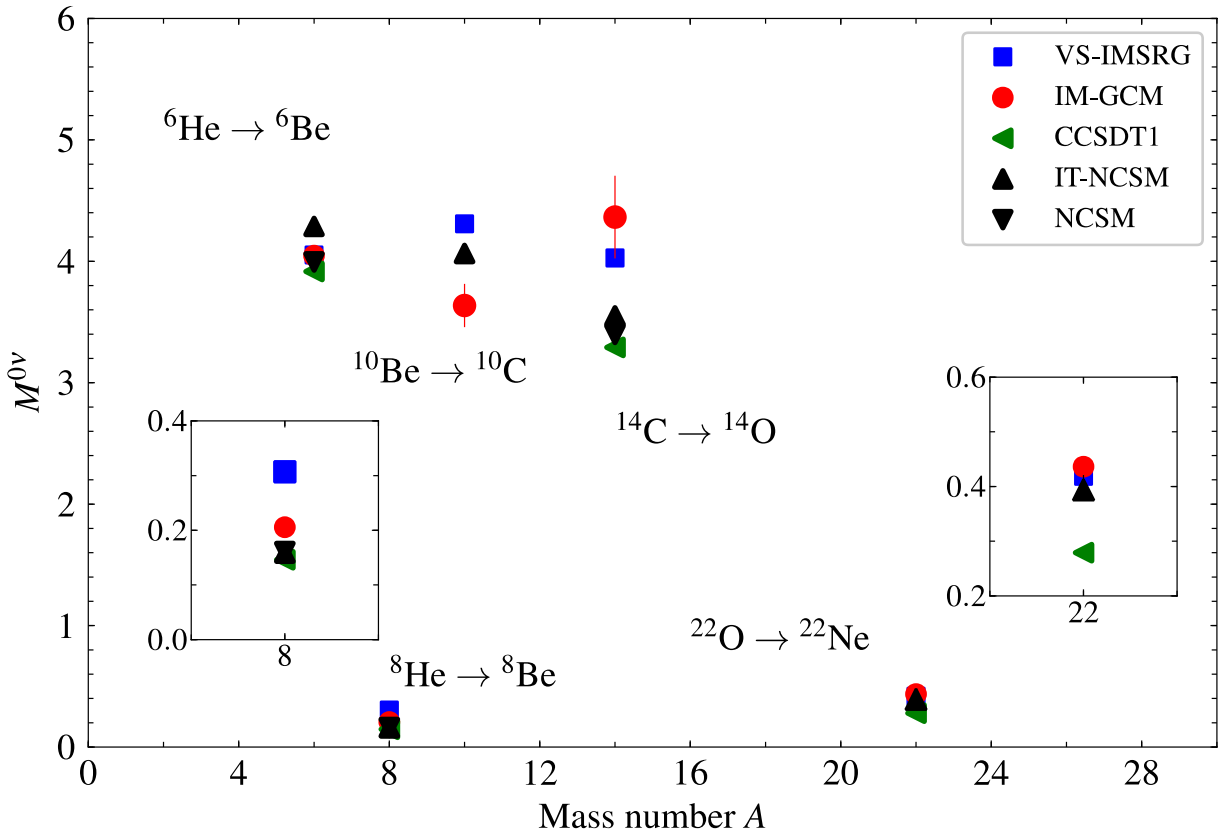


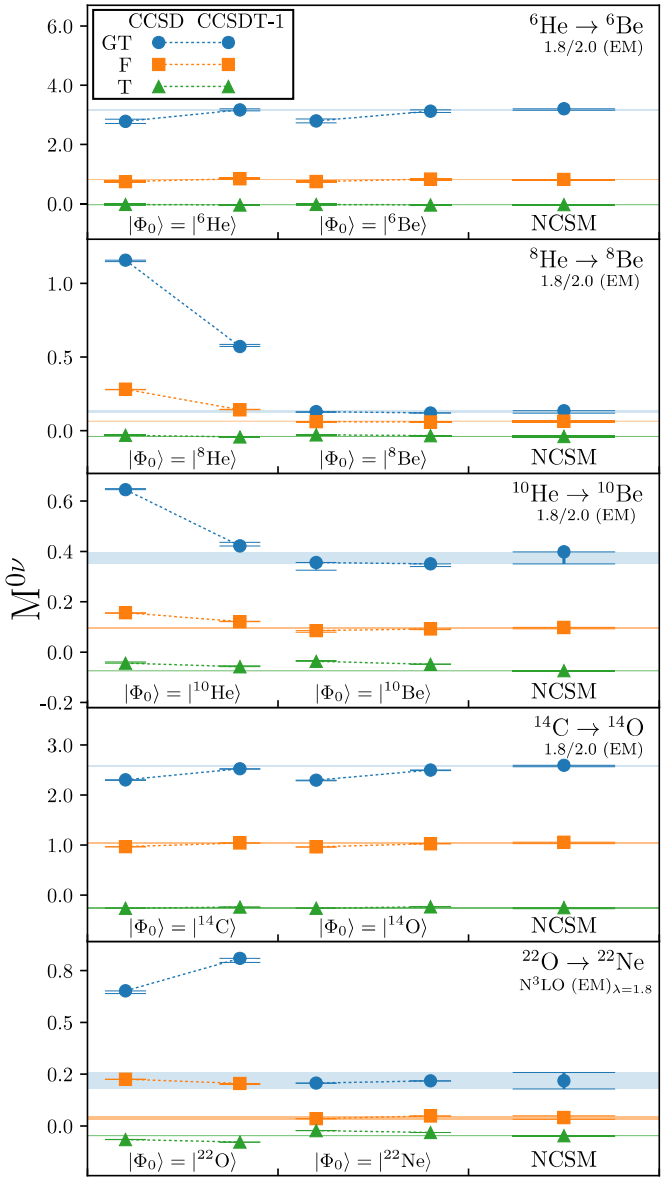

Use machine learning for further insights?

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

# Ab Initio Strategy 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)

# Ab Initio Neutron Skin of $^{208}$Pb

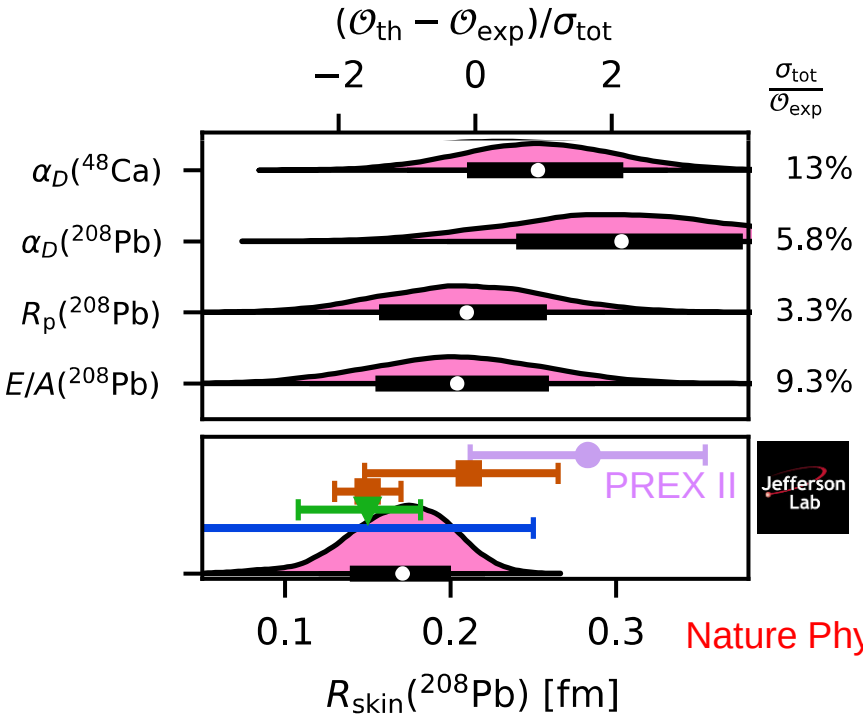
Combine ab initio + machine learning advances

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

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

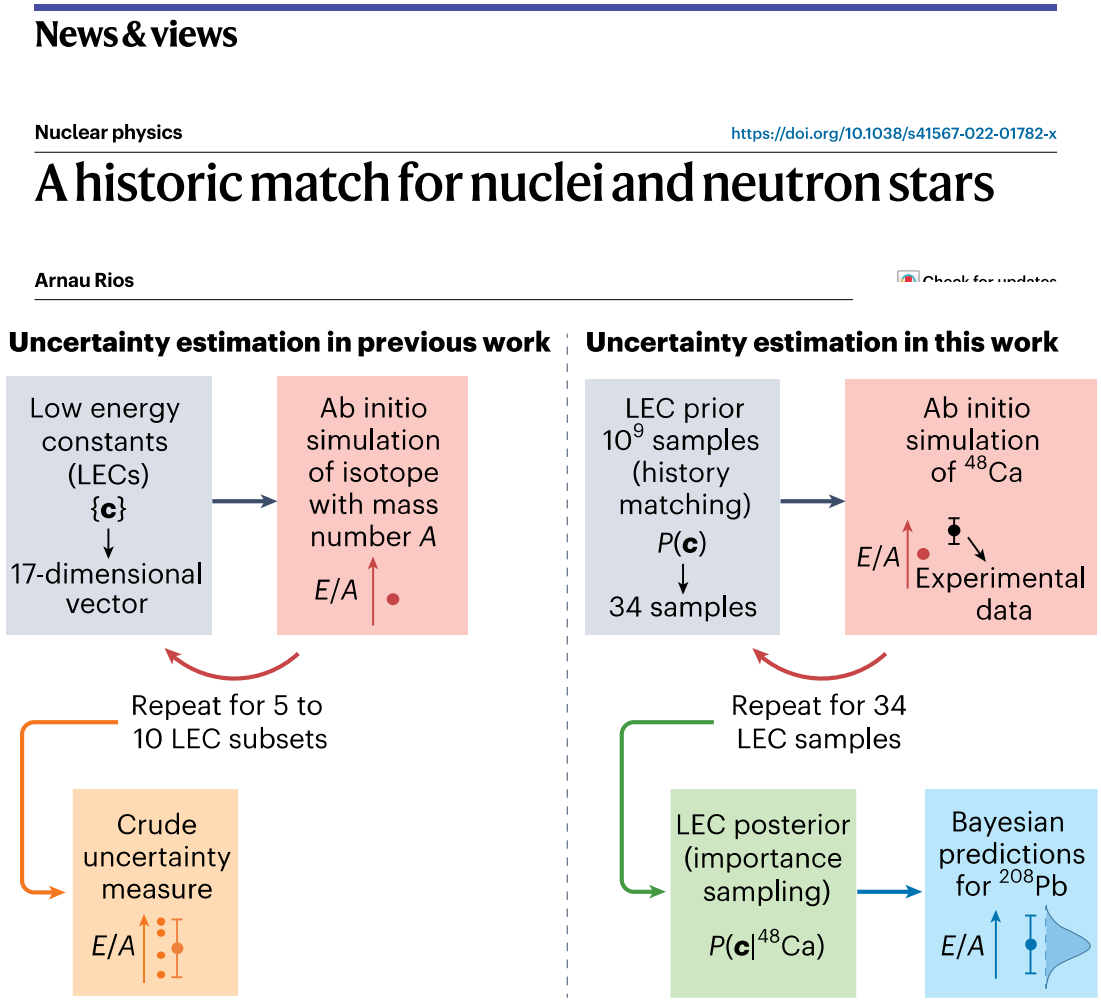
III: Validation: $^{208}$Pb properties from ab initio

**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$^2$LO

34 non-implausible interactions

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

Importance resampling – statistically weight interactions

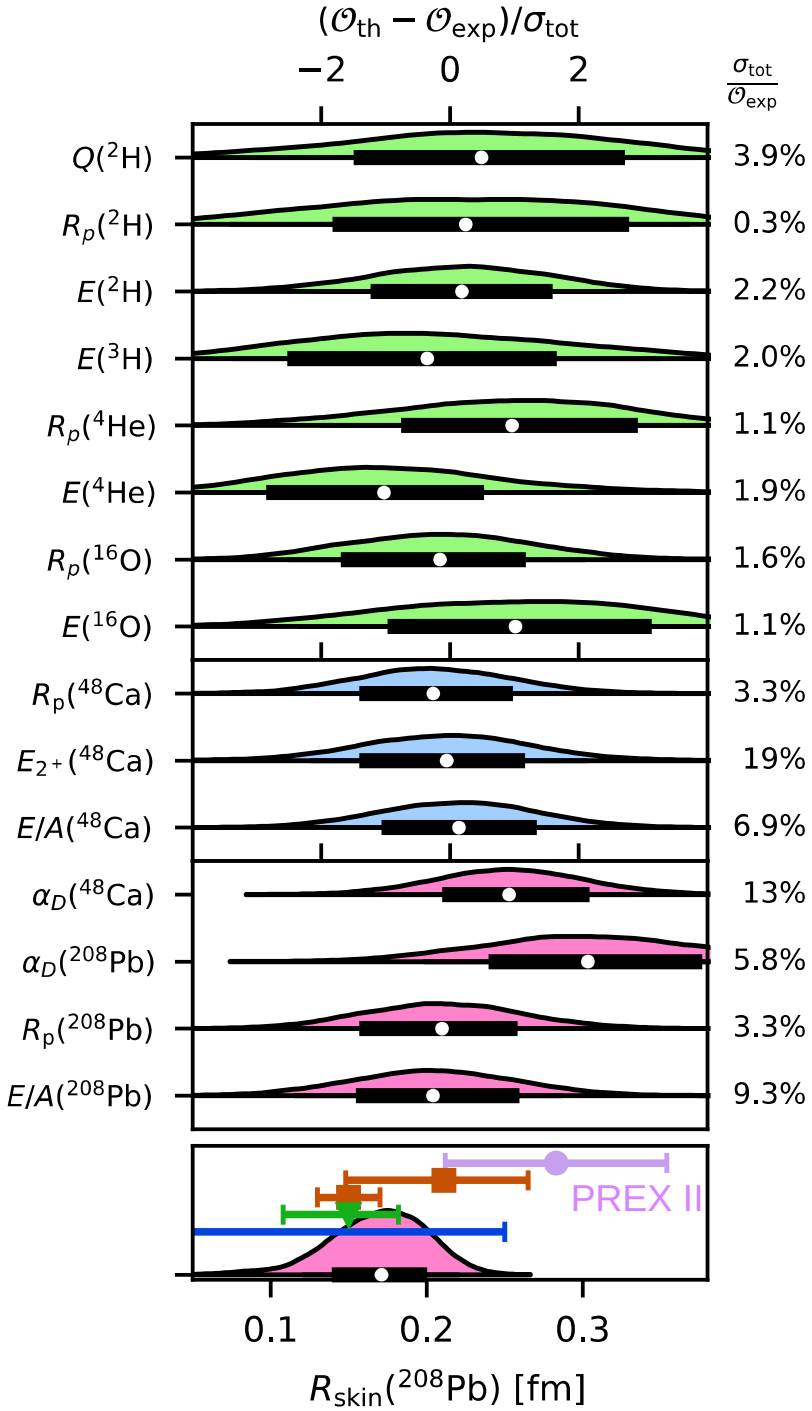
III: Validation $^{208}$Pb E/A, $R_p$ + $^{48}$Ca/$^{208}$Pb DP from ab initio

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**

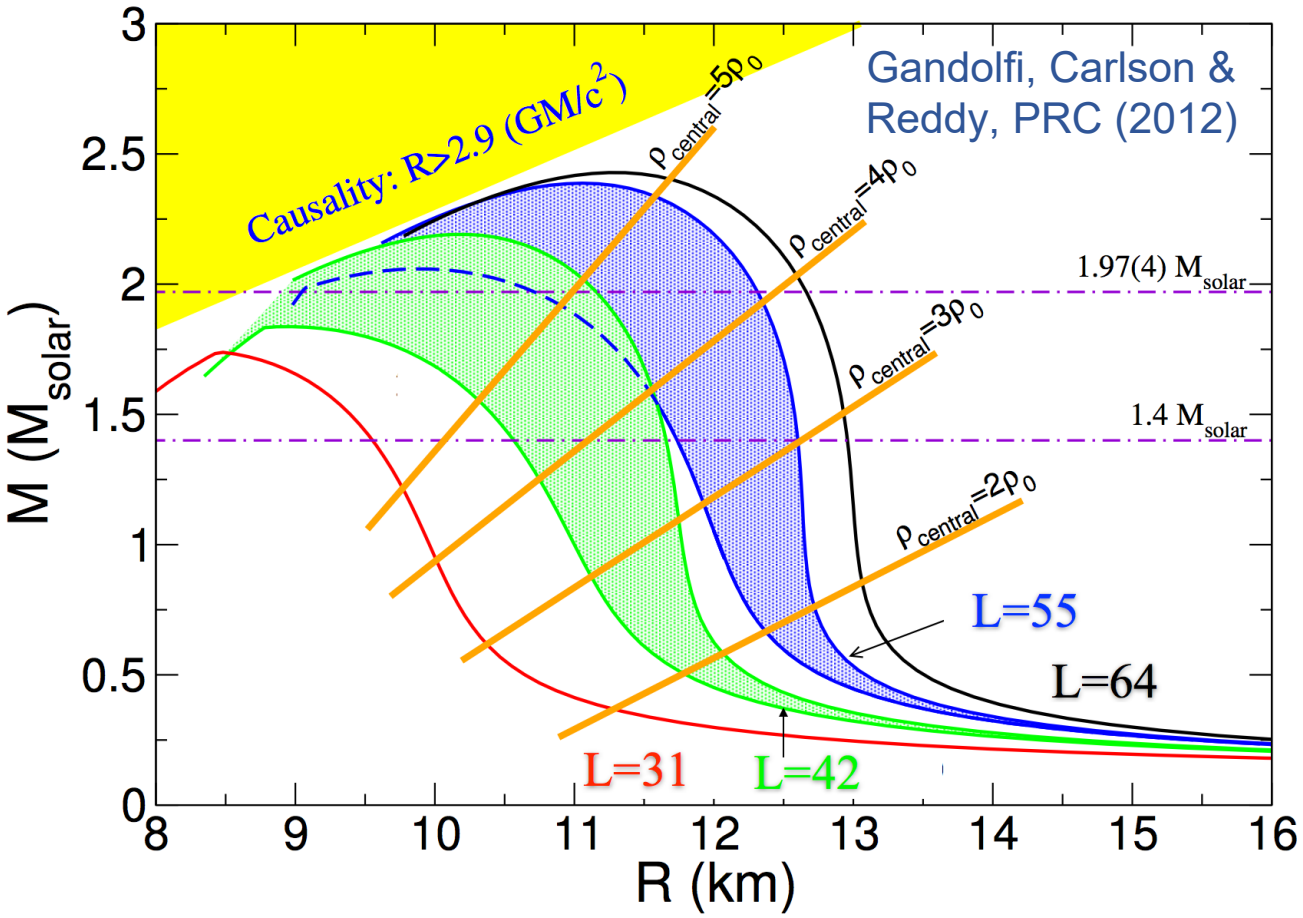


# Neutron Skin of $^{208}$Pb and Nuclear EOS

Slope of symmetry energy (**L**) related to NS pressure

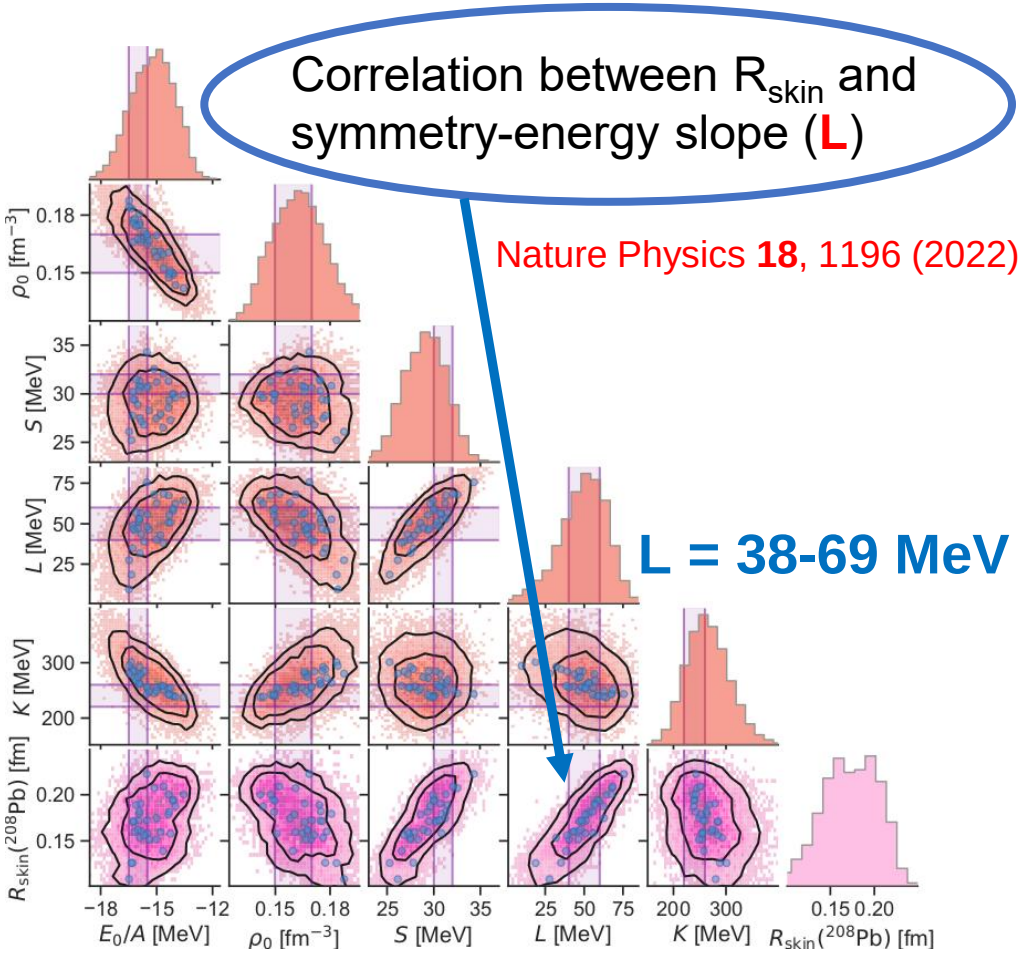
Crucial for mass-radii relationship

$$P = \rho^2 \frac{\partial(E/A)}{\partial\rho}$$




Mirror charge radii, dipole/quadrupole polarizabilities

Correlations from ab initio $^{208}$Pb




Potentially constrain nuclear forces:

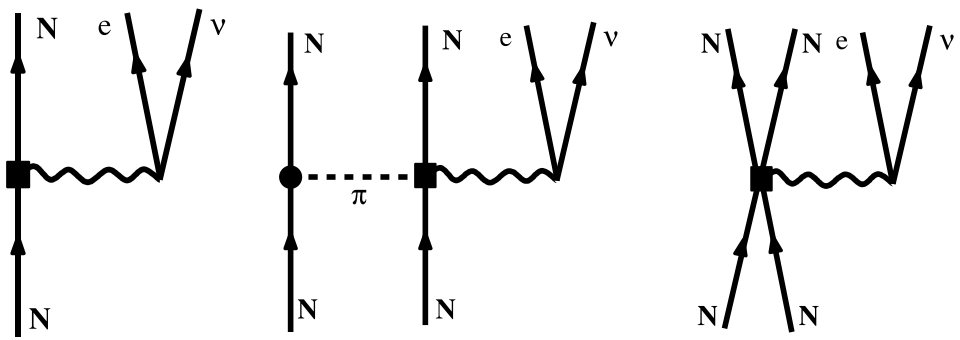
**Neutron star radii/mergers**

# Large-Scale Ab Initio GT Transitions

Ab initio survey of **large GT matrix elements**

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

2BC: Coupling of weak force to two nucleons



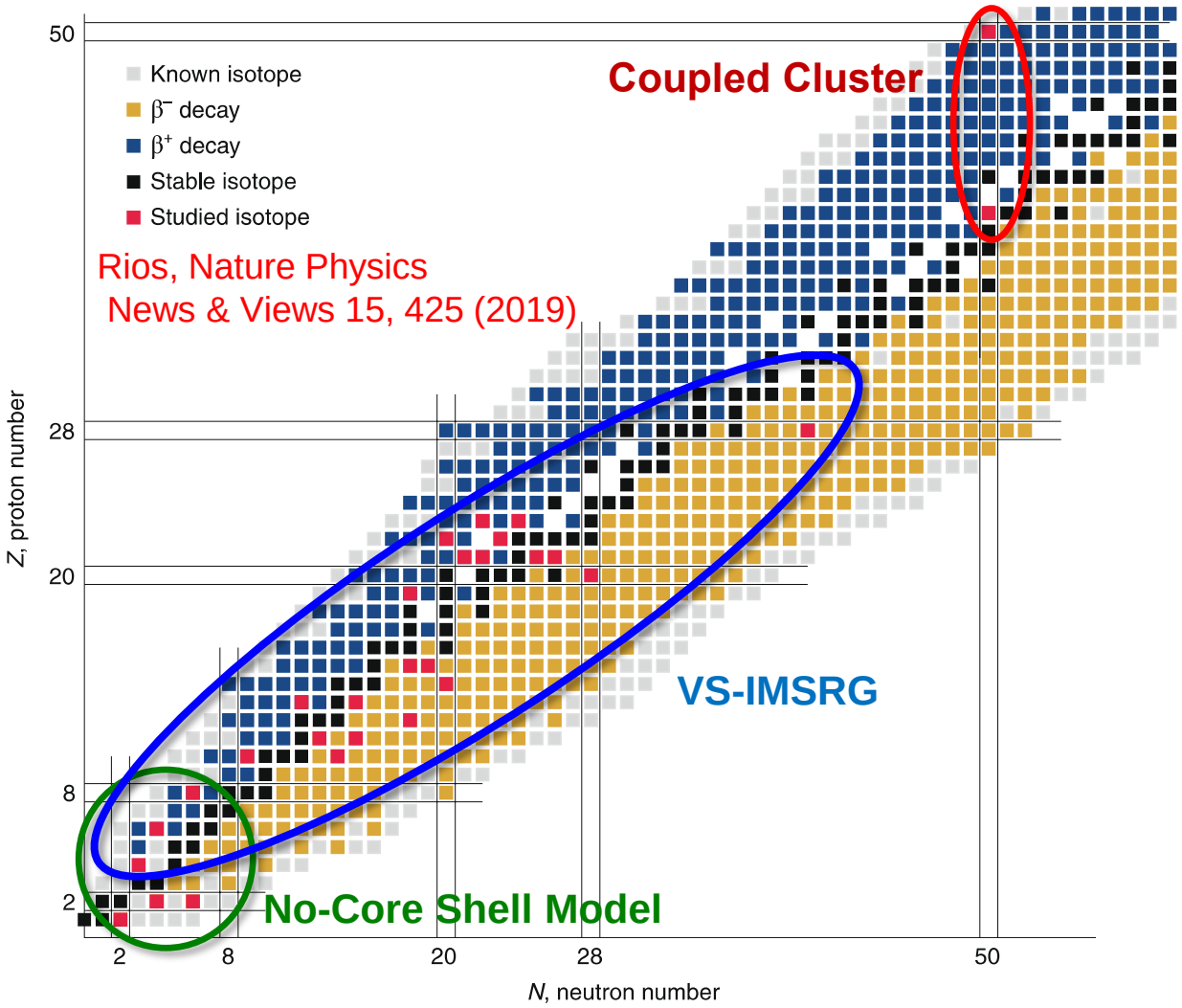

$$\mathcal{O}_{\mathrm{GT}} = \mathcal{O}^{1\mathrm{b}}_{\sigma\tau} + \mathcal{O}^{2\mathrm{b}}_{2BC}$$

- Light → heavy mass regions
- Many-body correlations
- Consistent NN+3N forces + 2BC

NUCLEAR PHYSICS news & views

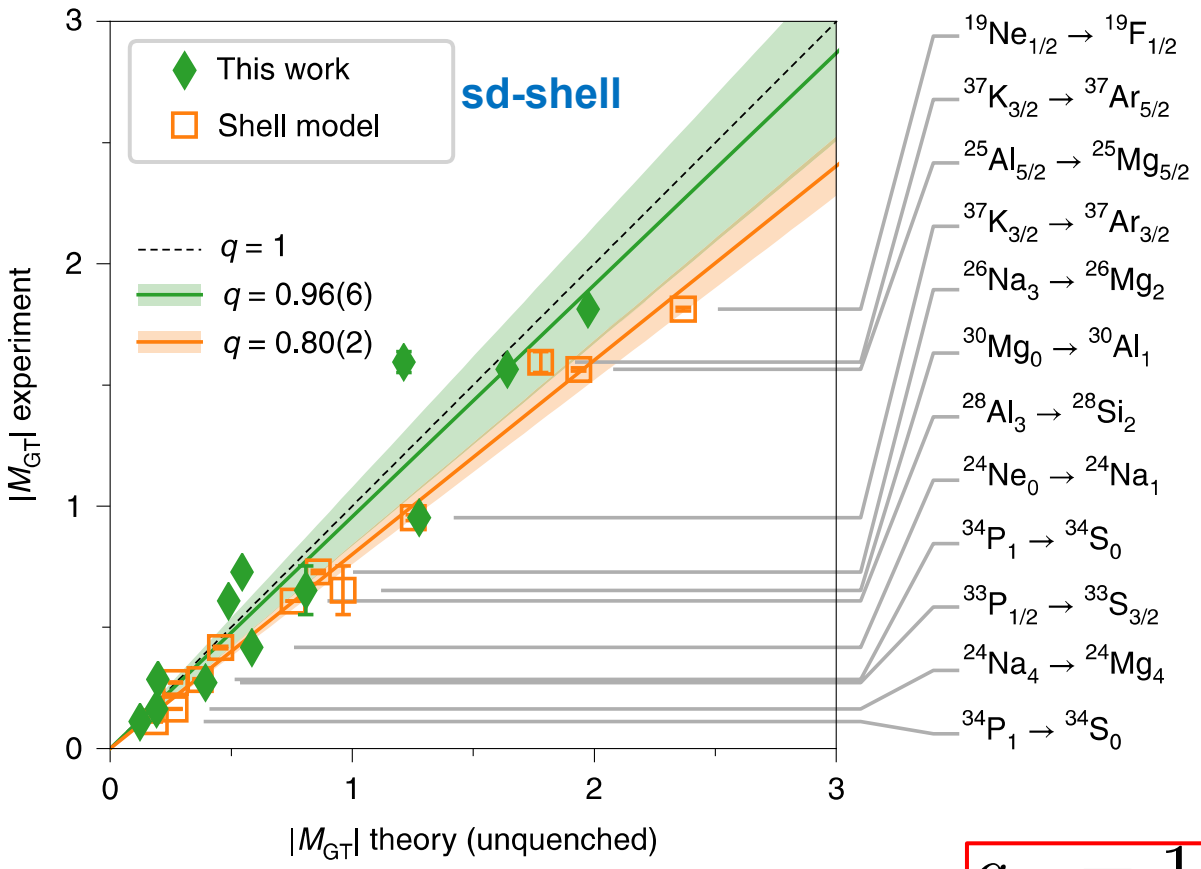
## Beta decay gets the ab initio treatment

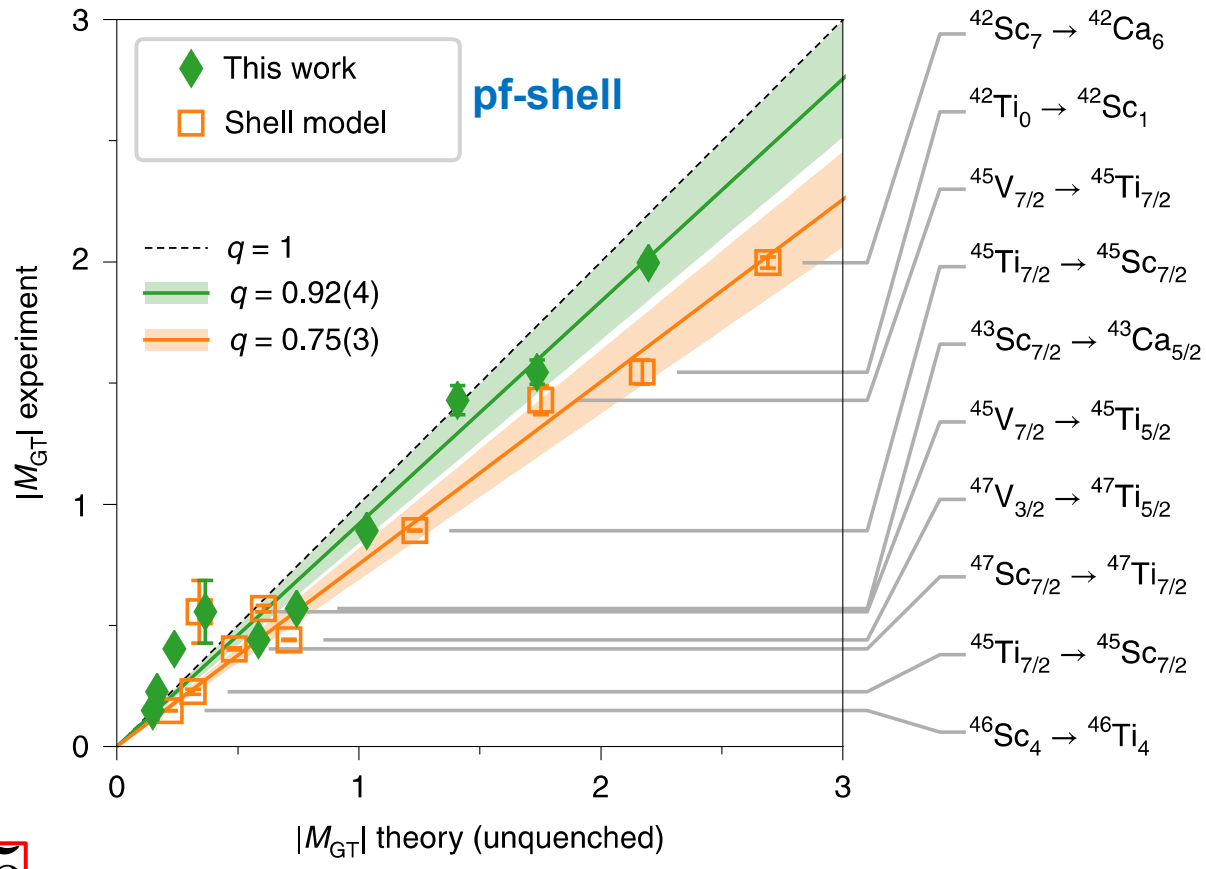
One of the fundamental radioactive decay modes of nuclei is β decay. Now, nuclear theorists have used first-principles simulations to explain nuclear β decay properties across a range of light- to medium-mass isotopes, up to $^{100}$Sn.



# Solution to $g_A$-Quenching Problem

**VS-IMSRG** calculations in regions from O → Ca (sd) and Ca→Ni (pf) shells




$$g_A = 1.25$$

**Ab initio calculations across the chart explain data with unquenched $g_A$**

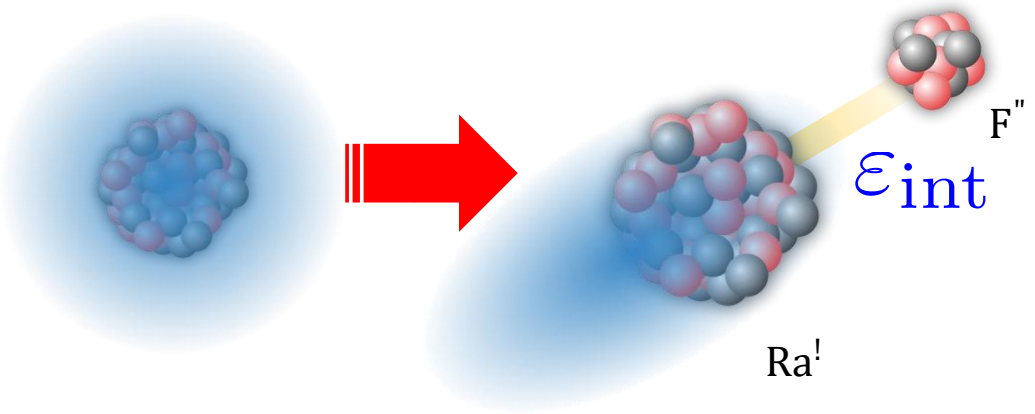
Next up: explore **double**-beta decays…

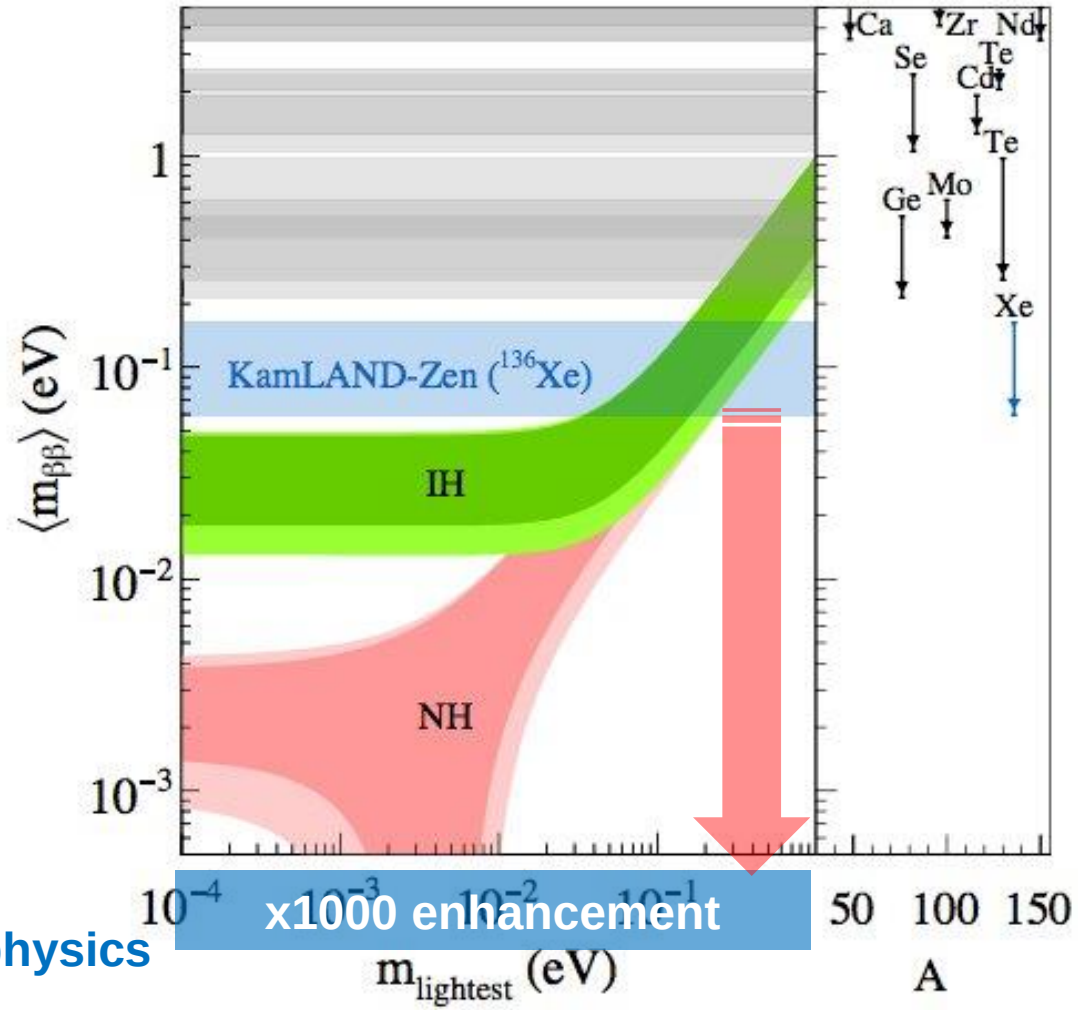
Nature Physics **15**, 428 (2019)

# The Magic of Molecules: CP Violation

Worldwide race to exploit power of **Radioactive Molecules**

Generate internal fields orders of magnitude above lab possibilities




Enhancements in molecules vs atoms **>4000**

Probe 1000TeV scale in our lifetimes

**To date, no rigorous nuclear theory**

(motivation, interpretation)

Measurement — Nuclear structure — P,T odd NN int

$$S = \langle \Psi_0 | S_z | \Psi_0 \rangle = \frac{\langle \Psi_+ | S_z | \Psi_- \rangle \langle \Psi_+ | V_{PT} | \Psi_- \rangle}{E_+ - E_-}$$

Experiment

**New physics**