NSAC Long Range Plan Town Hall Meeting on Nuclear Structure, Reactions and Astrophysics

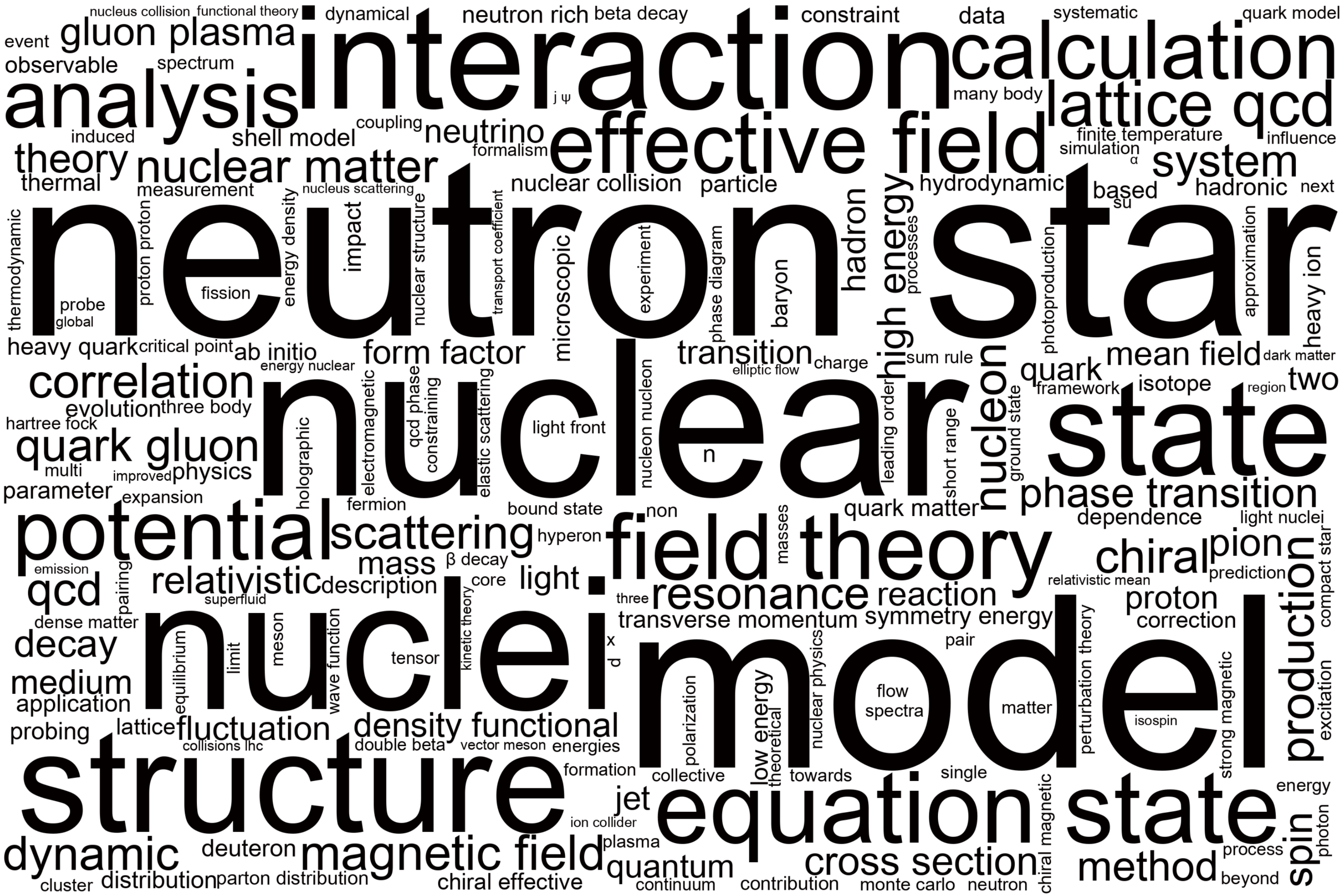
Predictive theory of nuclei and their interactions

Thomas Papenbrock
University of Tennessee & Oak Ridge National Laboratory

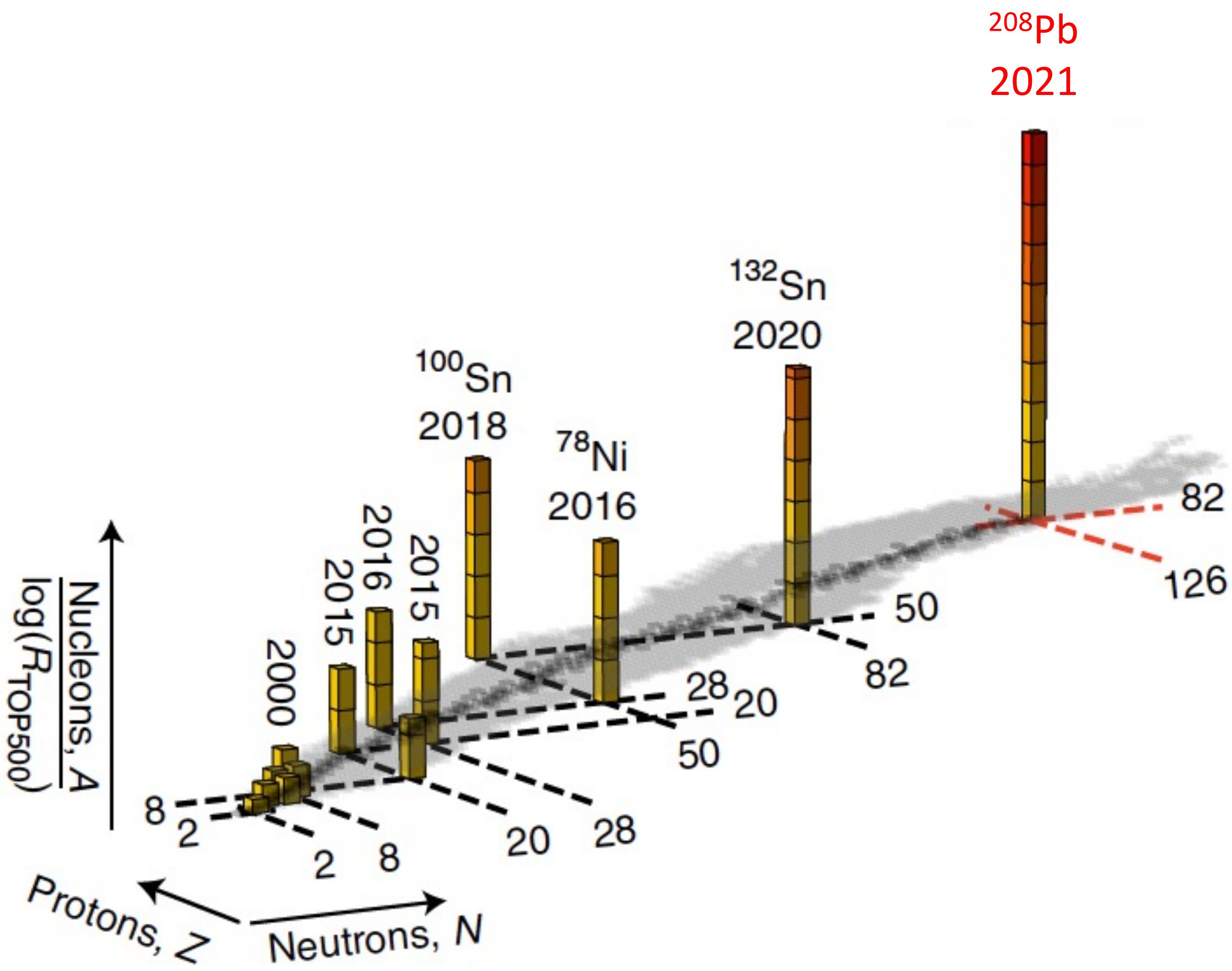
Argonne National Laboratory, 11/14/2022

Work supported by the US Department of Energy

arXiv [nucl-th] titles 2016-2022 (w/o rel. heavy ion collisions)



Progress in computing nuclei from EFT Hamiltonians

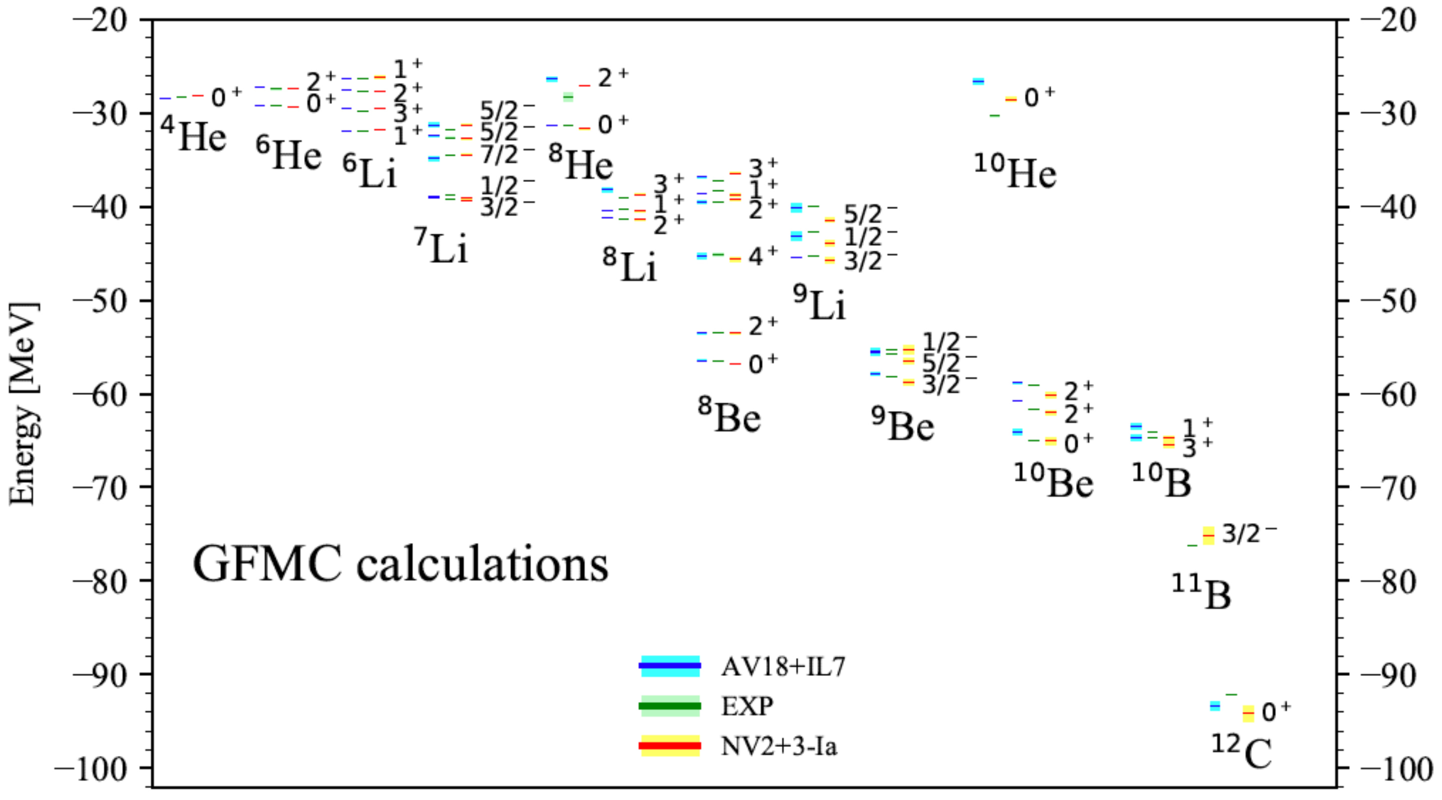


Phys. Rev. C 105, 014302 (2022)
Nature Physics 18, 1196 (2022)

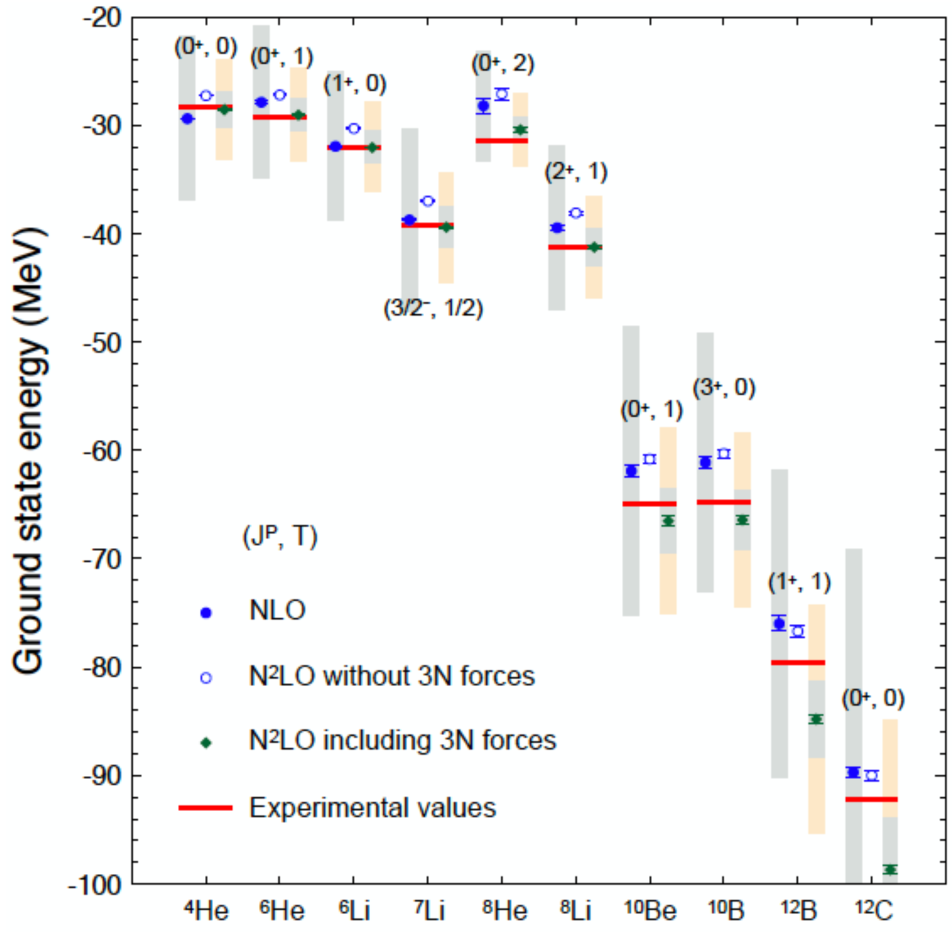
Tremendous progress

- Ideas from EFT and RG
- Methods that scale polynomially with mass number
- Collaboration with computer scientists and statisticians
- Quantified uncertainties
- Fast emulators enabled by machine learning
- Ever-increasing computing power

Ab initio computations of light nuclei

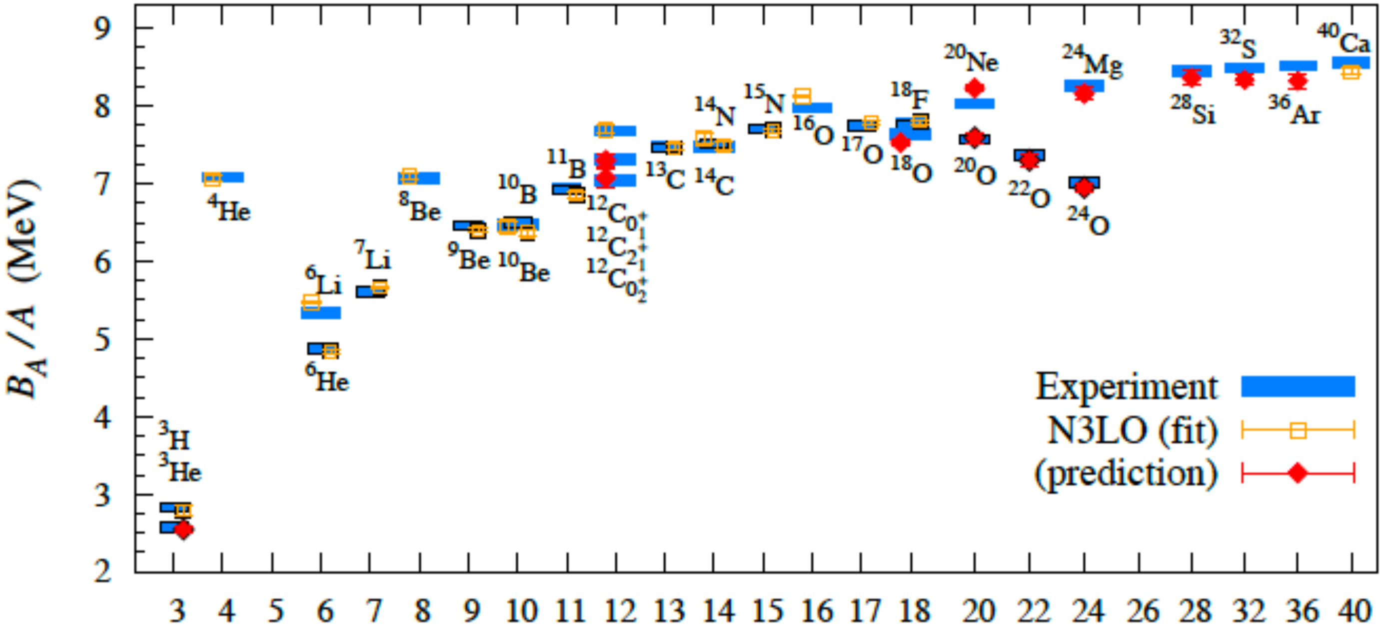


Energies in light nuclei from Δ-chiral EFT and Argonne potentials, compared to data.
Phys. Rev. Lett. 120, 052503 (2018)

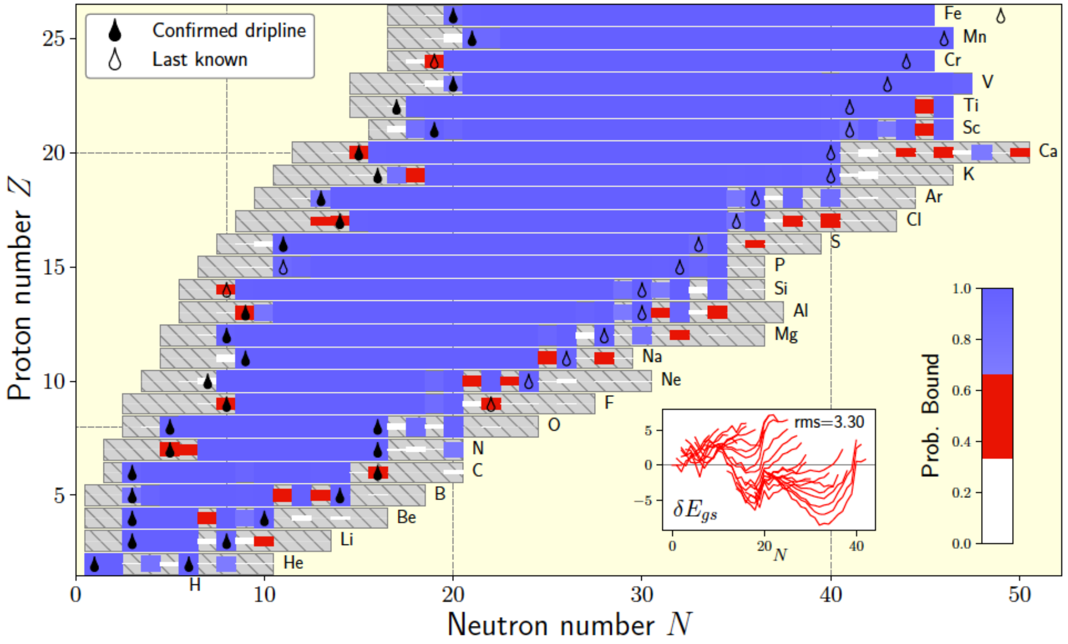


Ground-state energies of light nuclei from semi-local chiral EFT and compared to data.
Phys. Rev. C 103, 054001 (2021)

Computations of medium-mass nuclei from EFT forces



arXiv:2210.17488



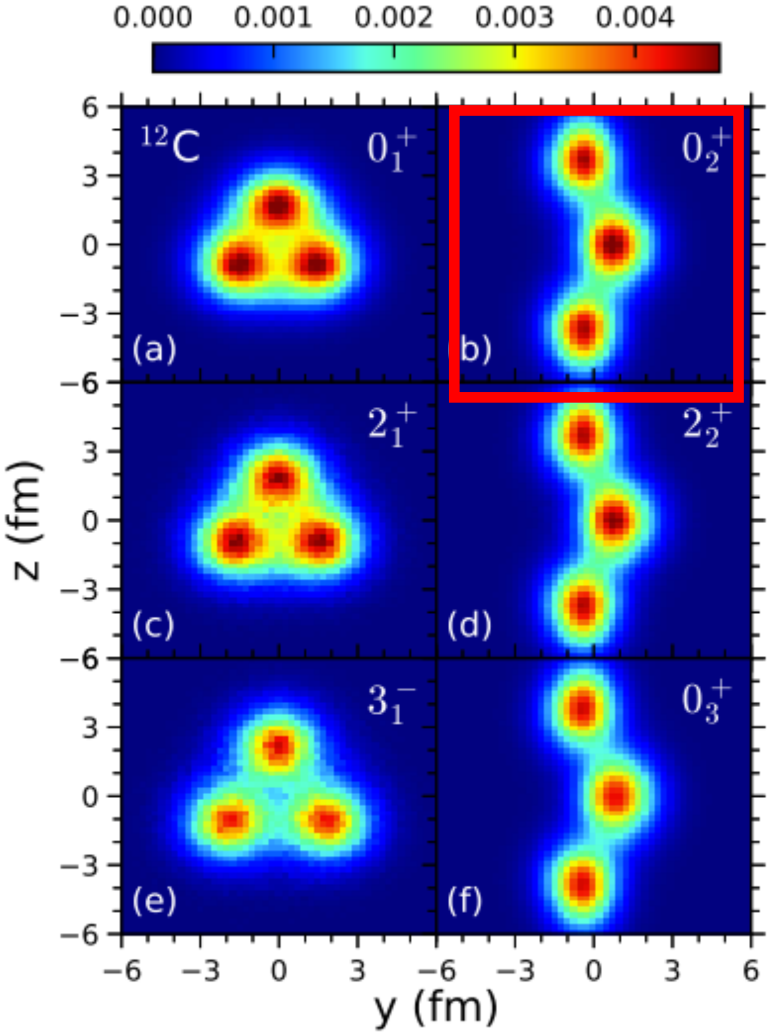
Phys. Rev. Lett. 126, 022501 (2021)

Have: interactions from EFT that yield accurate binding energies and charge radii for medium-mass nuclei; see also Phys. Rev. C 91, 051301 (2015)

Clustering in nuclei; astrophysical reactions

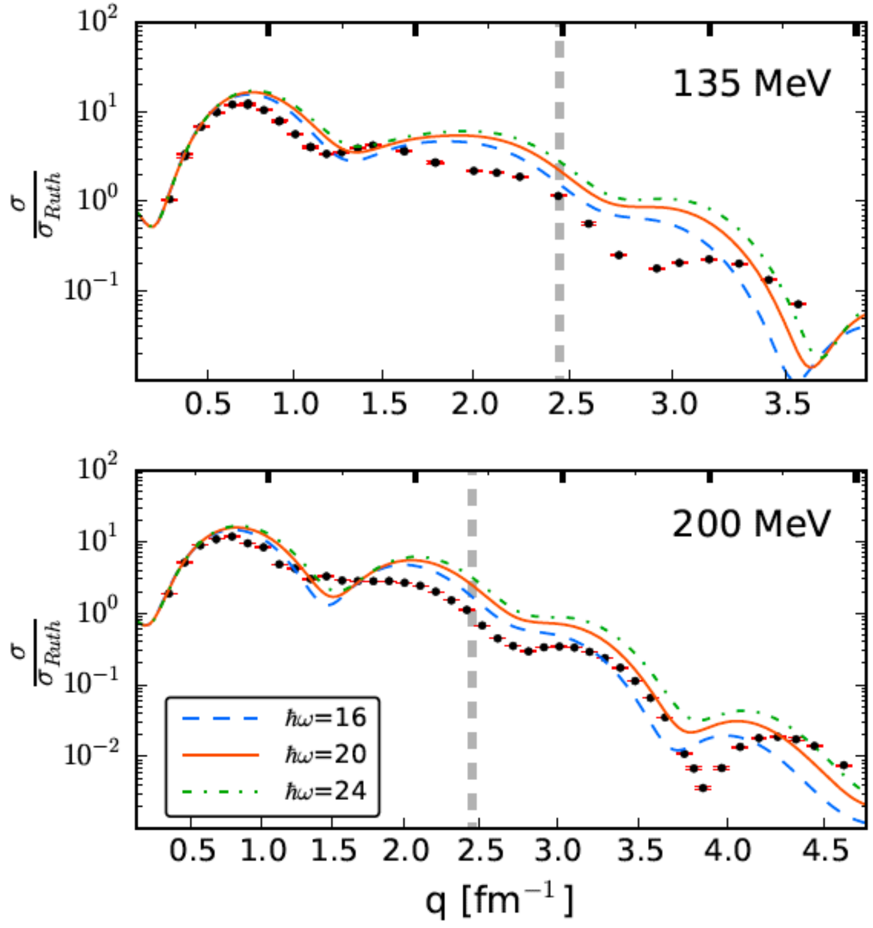
Clustering in ^{12}C

Hoyle State (triple α resonance)



arXiv:2202.13596 (2022)

Elastic proton scattering from ^{16}O using a microscopic optical potential

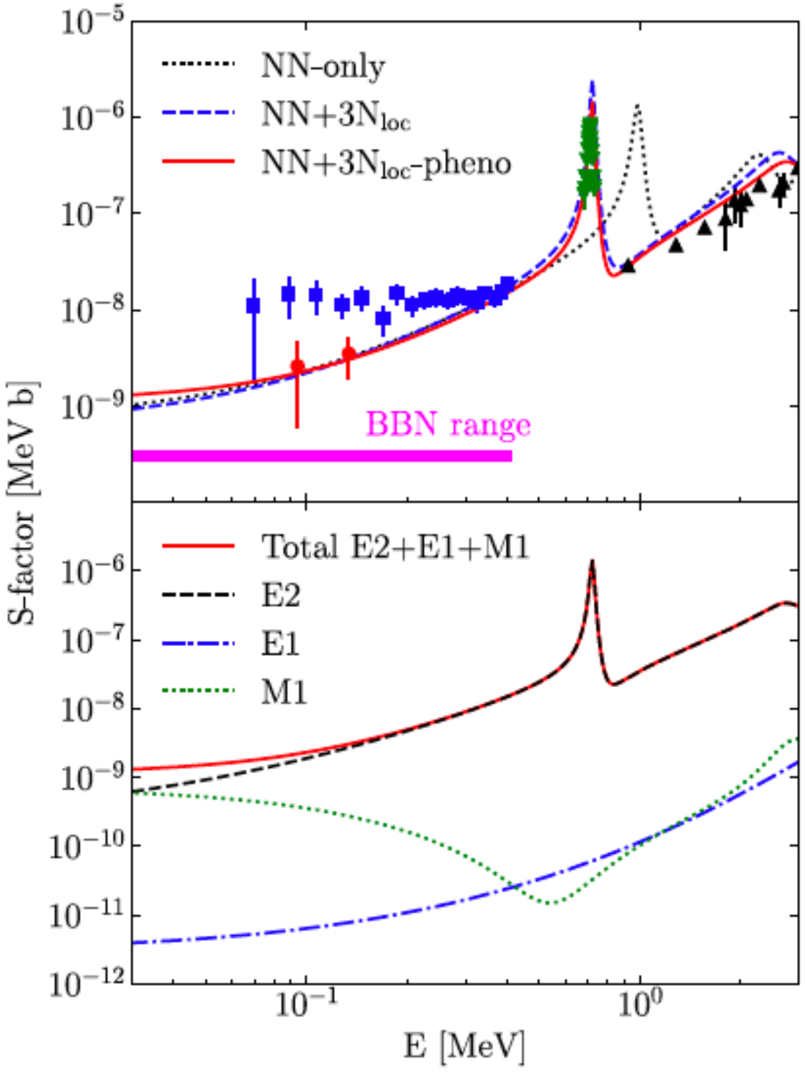


Phys. Rev. C 99, 044603 (2019)

Phys. Rev. C 95, 024315 (2017)

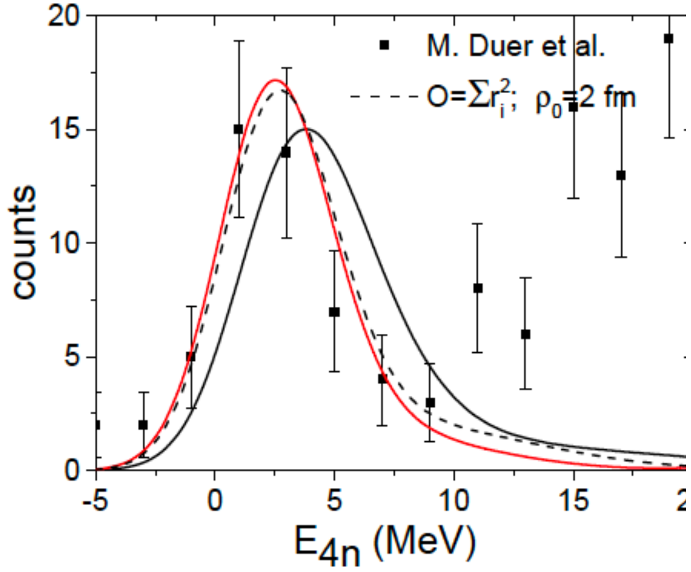
Astrophysical reactions and four-neutron system

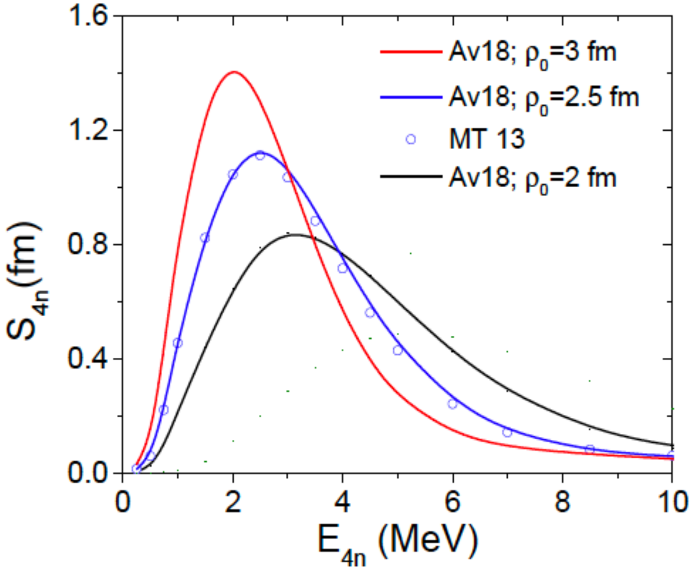
$^{4}He(d,\gamma)^{6}Li$ big bang radiative capture



Phys. Rev. Lett. 129, 042503 (2022)

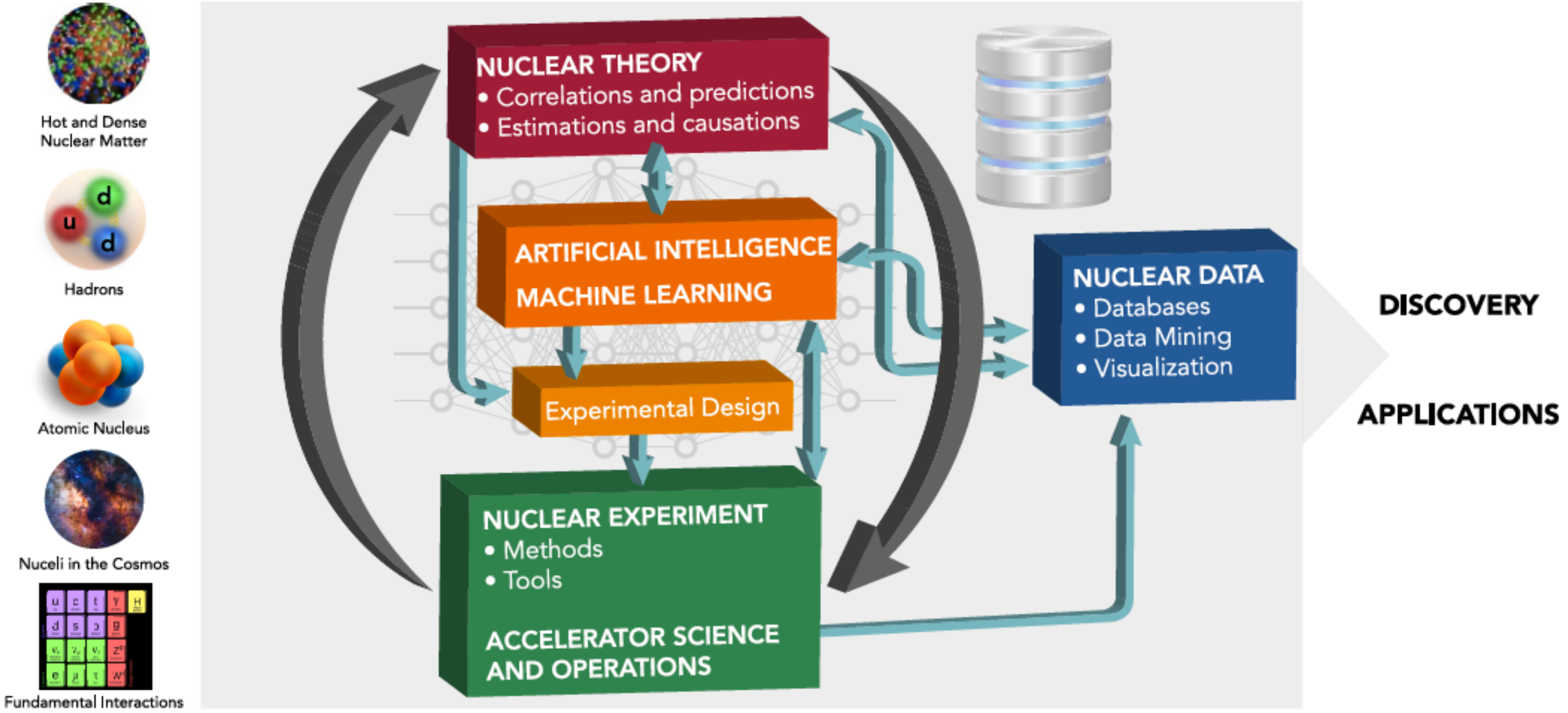
A model with four neutrons coupled to a ^{4}He core in the continuum describes the experimental results [M. Duer et al, Nature 606, 678 (2022)] and exhibits sensitivity to the range of the core-n-n interaction, see arXiv:2207.07575





See also Phys. Rev. Lett. 116, 052501 (2016); Phys. Rev. Lett. 117, 182502 (2016); Phys. Rev. Lett. 118, 232501 (2017); Phys. Rev. Lett. 119, 032501 (2017); Phys. Rev. Lett. 125, 052501 (2020)

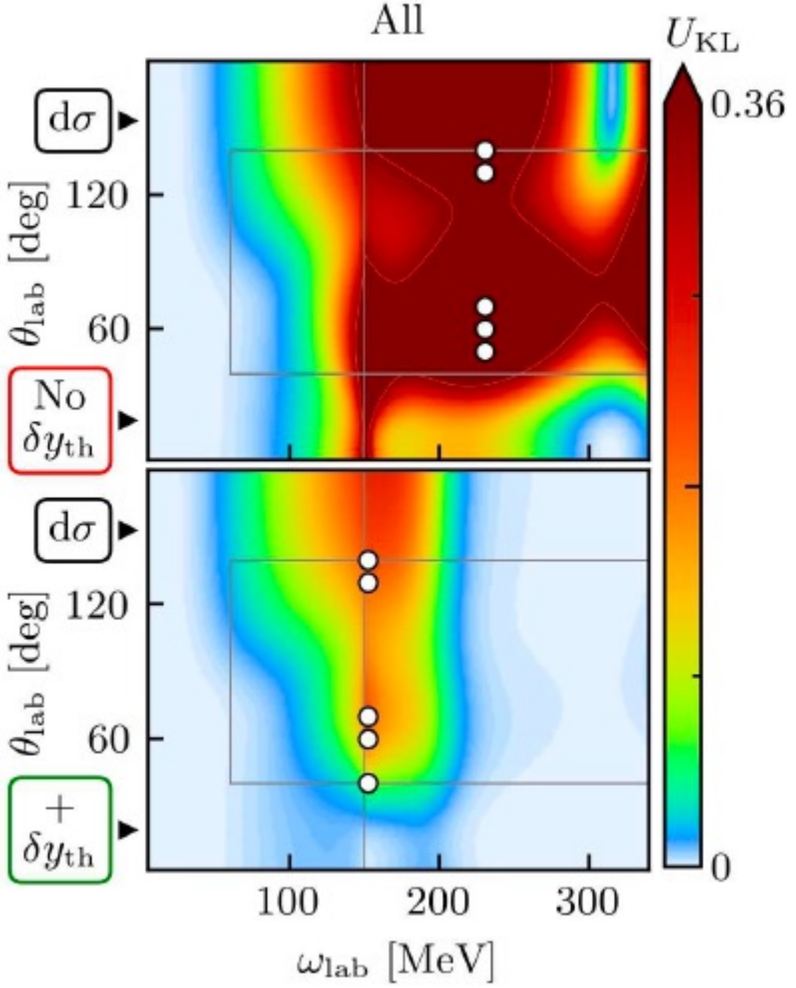
Bayesian inference, machine learning, and emulators



New possibilities are on the horizon: Emulators, built using ML and HPC, could enable real-time analysis of experiments
Rev. Mod. Phys. 94, 031003 (2022), arXiv:2112.02309

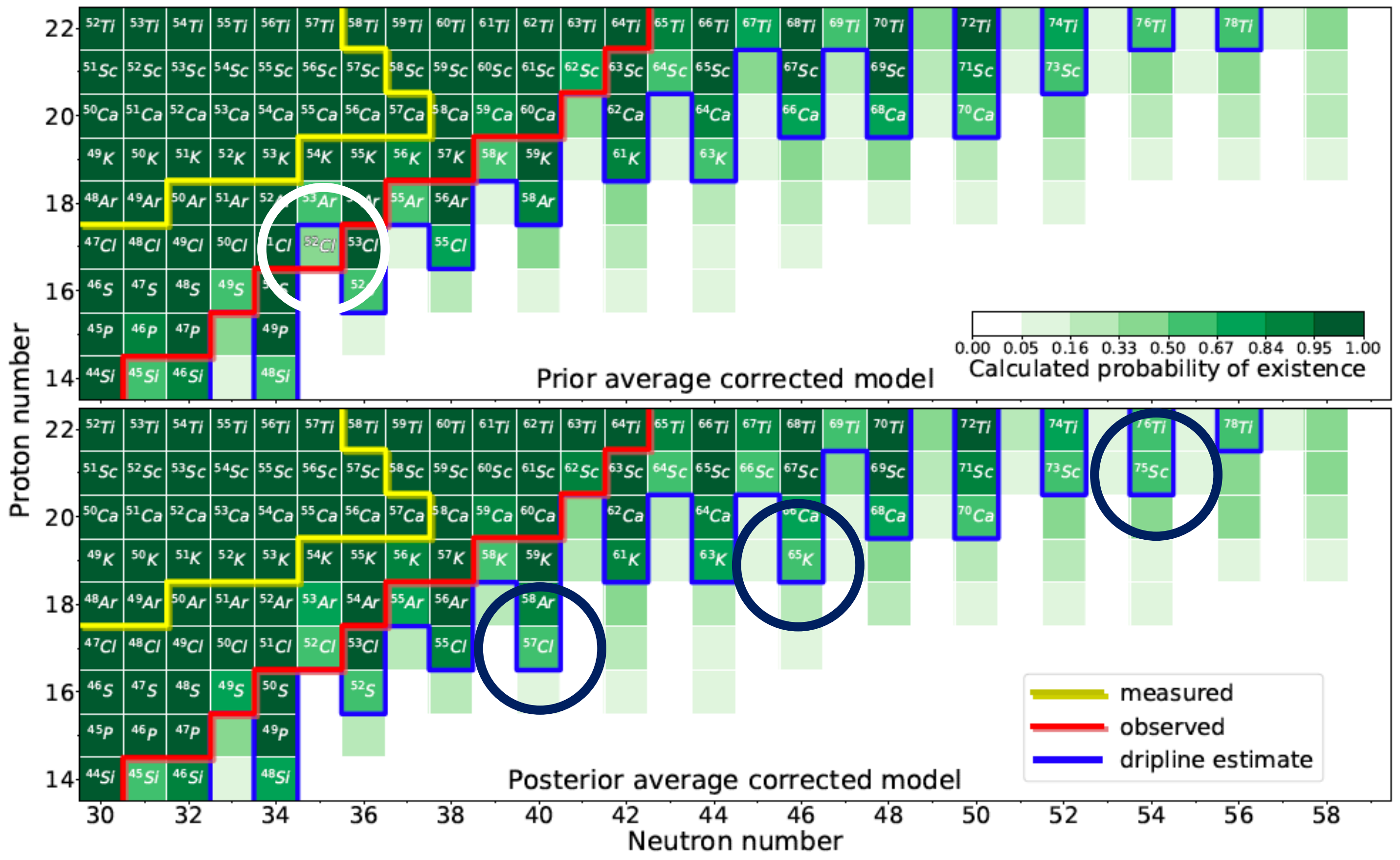
Experimental design & impact on theory

Expected utility of measuring proton-Compton scattering



EPJA 57, 81 (2021)

Bayesian model averaging impacts neutron drip line

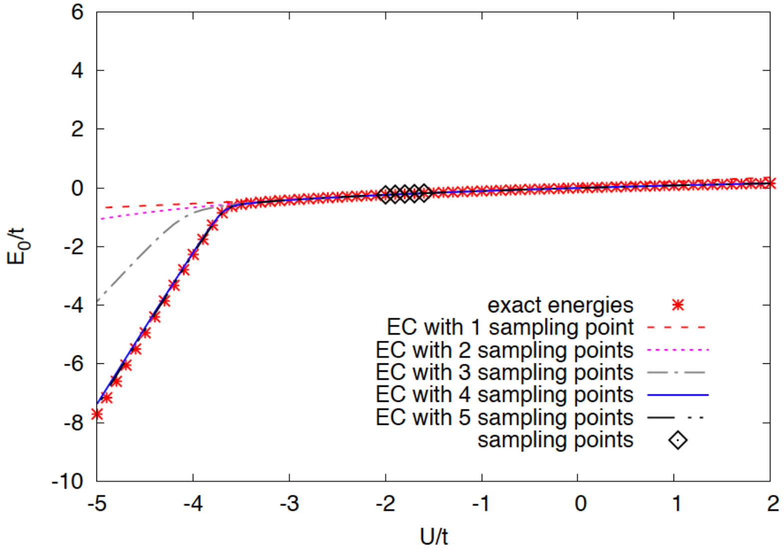


Phys. Rev. Lett. 122, 062502 (2019)

Uncertainty quantification & Bayesian machine learning have advanced nuclear theory

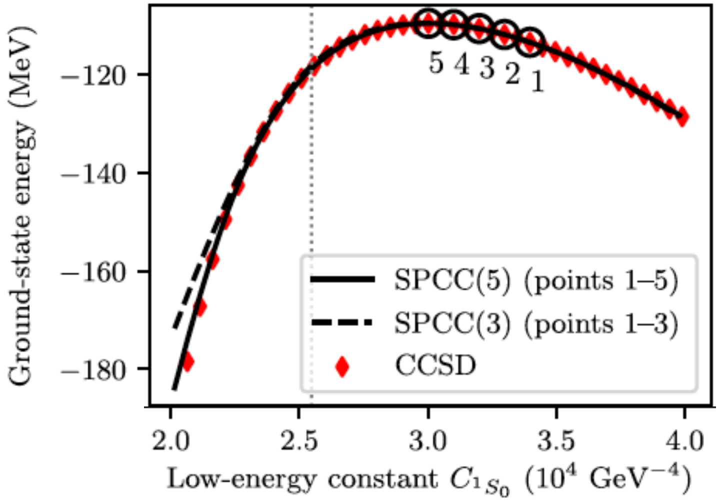
Eigenvector continuation enables emulators

Eigenvector continuation identifies low-dimensional subspace and permits non-perturbative solutions;



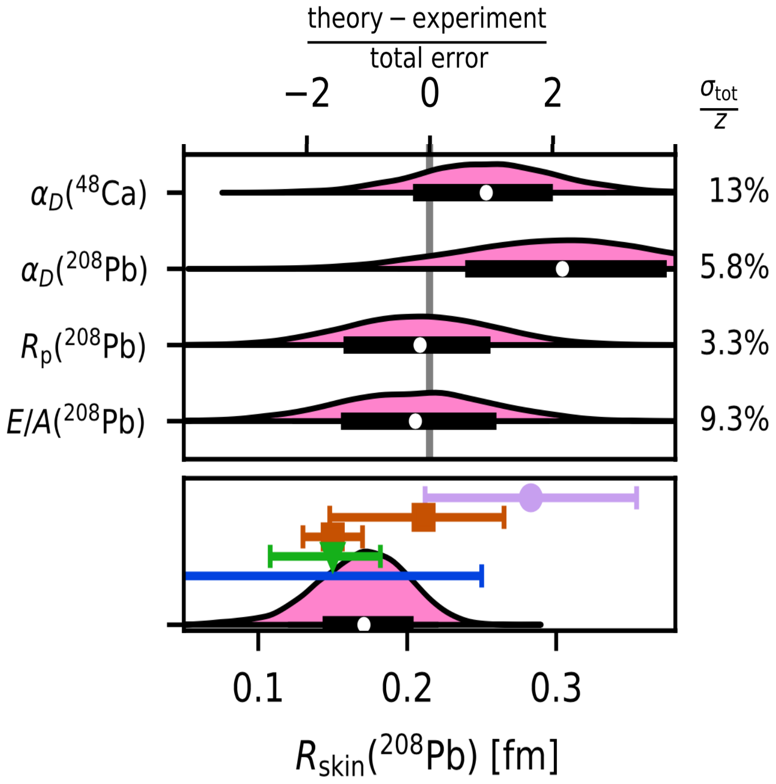
Phys. Rev. Lett. 121, 032501 (2018)

Emulators for ground-state energy of ^{16}O for different values of interaction parameter



Phys. Rev. Lett. 123, 252501 (2019);
Phys. Lett. B 810, 135814 (2020);
Phys. Lett. B 821, 136608 (2021);
Phys. Rev. C 104, 064001 (2021)…

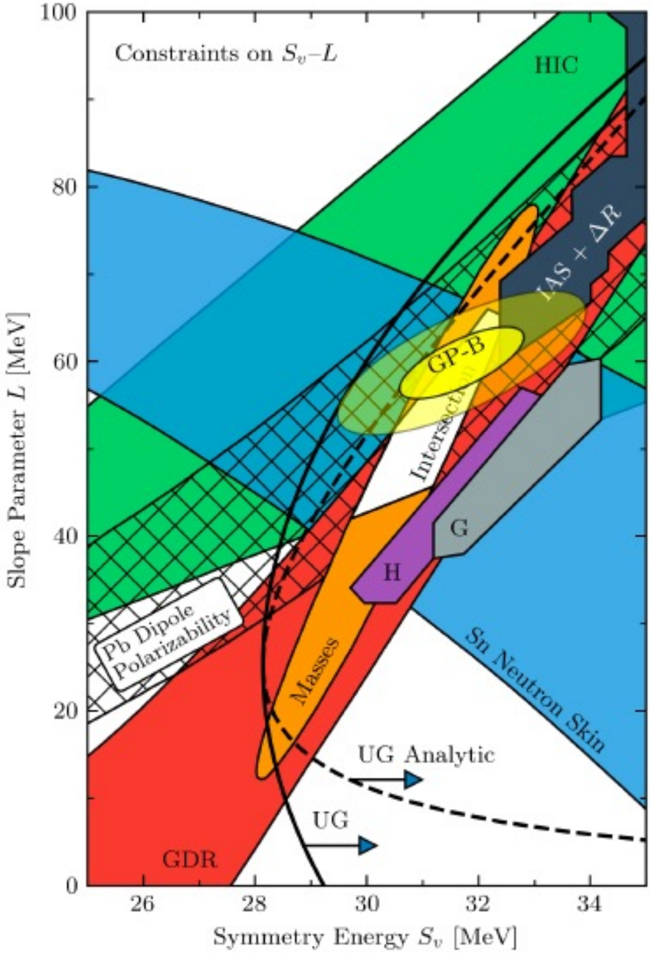
Emulators sieved through 10^8 EFT interactions; 34 non-implausible forces yield $R_{skin}(^{208}Pb)$ = 0.14 – 0.20 fm



Nature Physics 18, 1196 (2022)

CREX, PREX, and nuclear structure, EOS

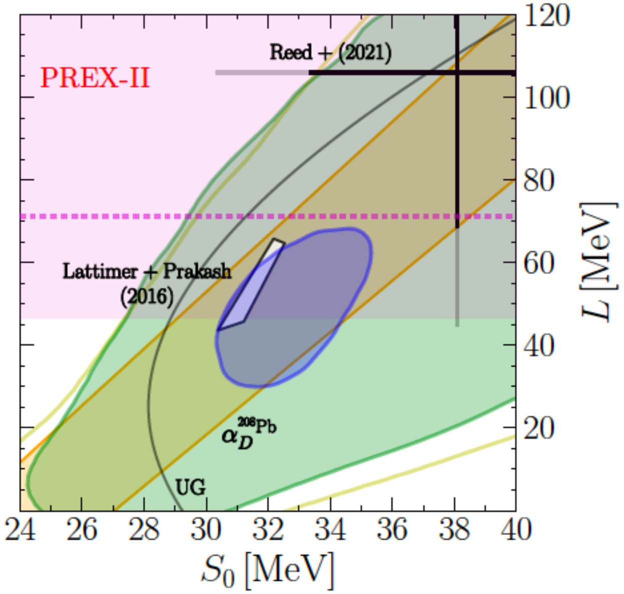
Symmetry energy and its slope constrained by experiment and theory



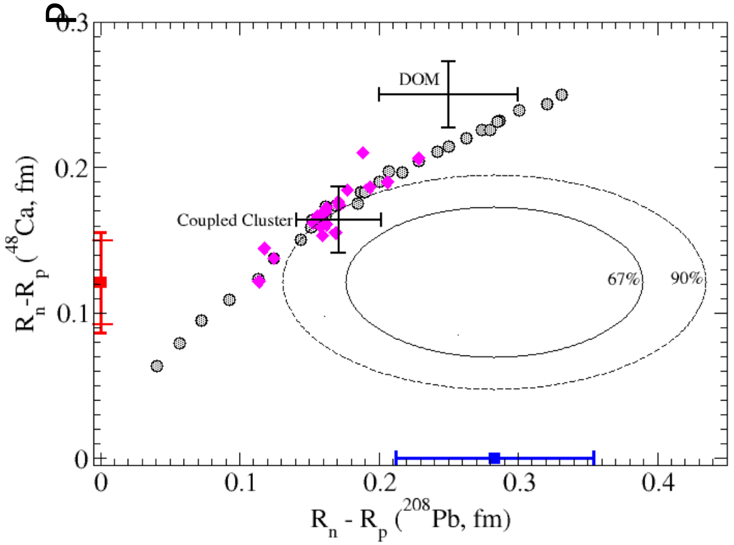
Phys. Rev. Lett. 125, 202702 (2020)

Phys. Rev. Lett. 126, 172503 (2021)

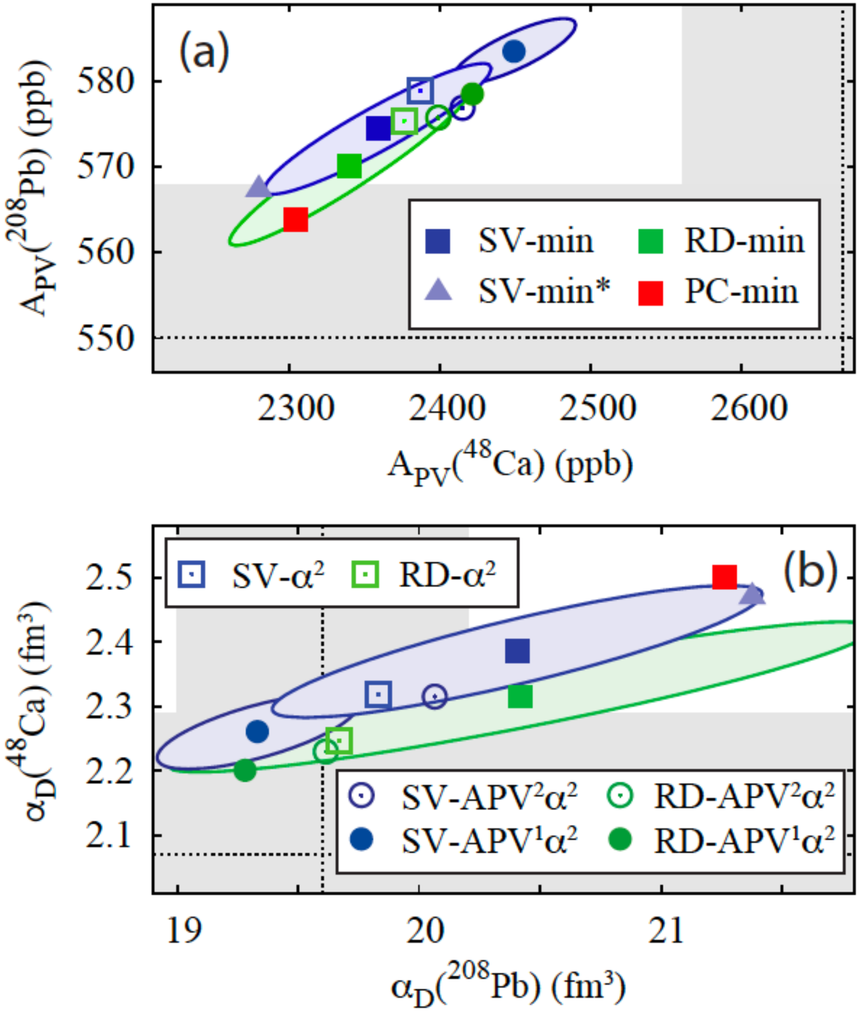
Phys. Rev. C 104, 065804 (2021)



Phys. Rev. Lett. 129, 042501 (2022)



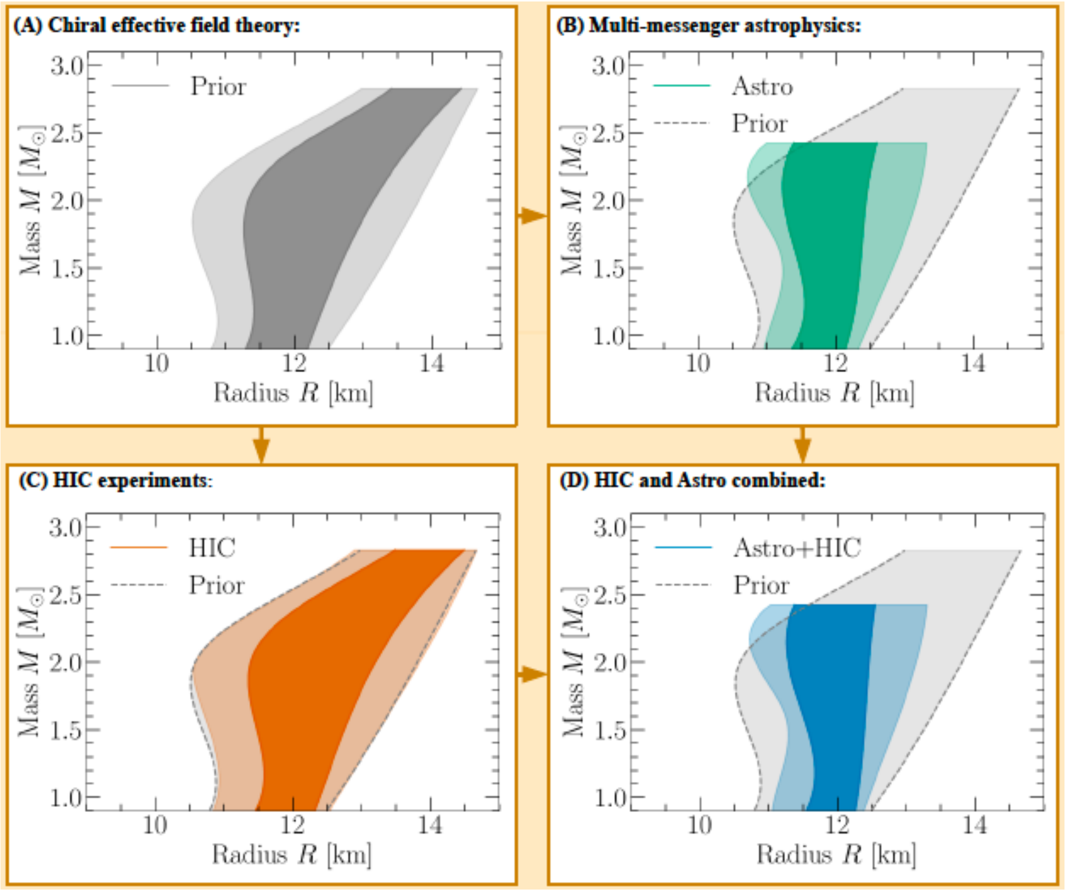
EDFs on dipole polarizabilities and parity-violating asymmetries

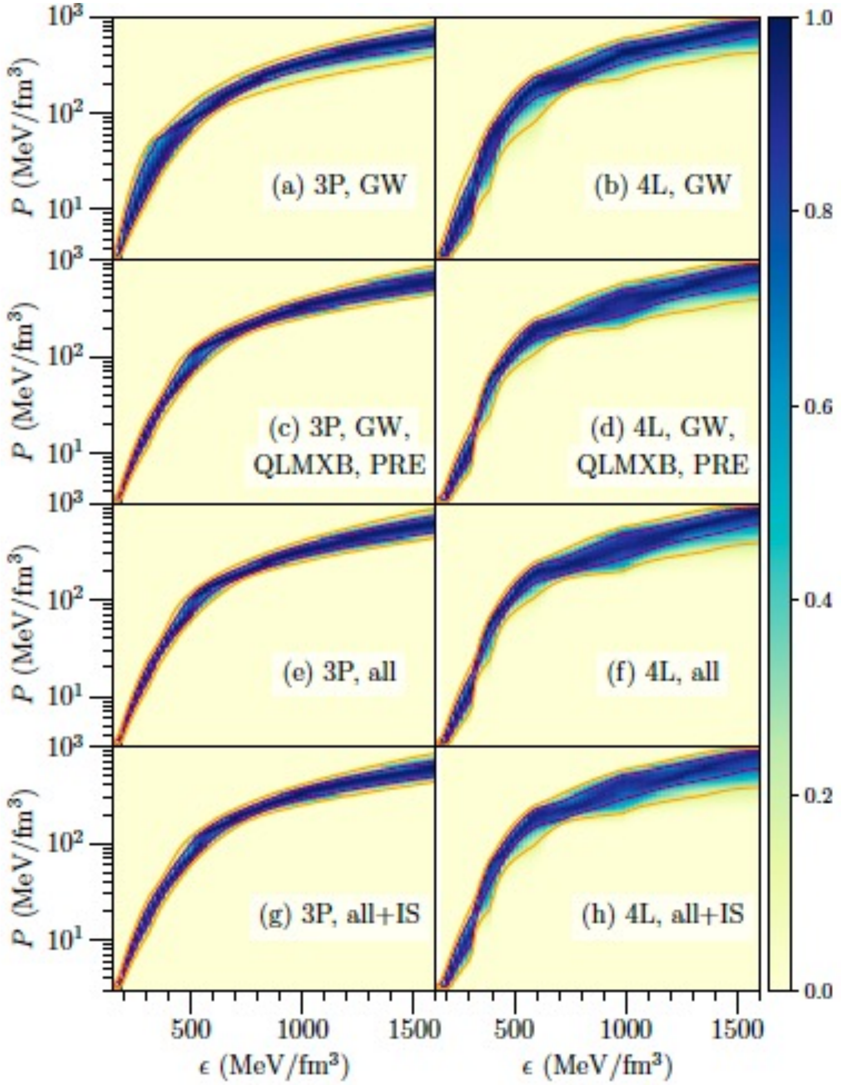


arXiv:2206.03134

Tremendous progress in quantifying uncertainties; PREX not precise enough to strongly constrain theory…

Multi-messenger constraints on neutron stars





Nature 606, 276 (2022)

Phys. Rev. Lett. 126, 061101 (2021)

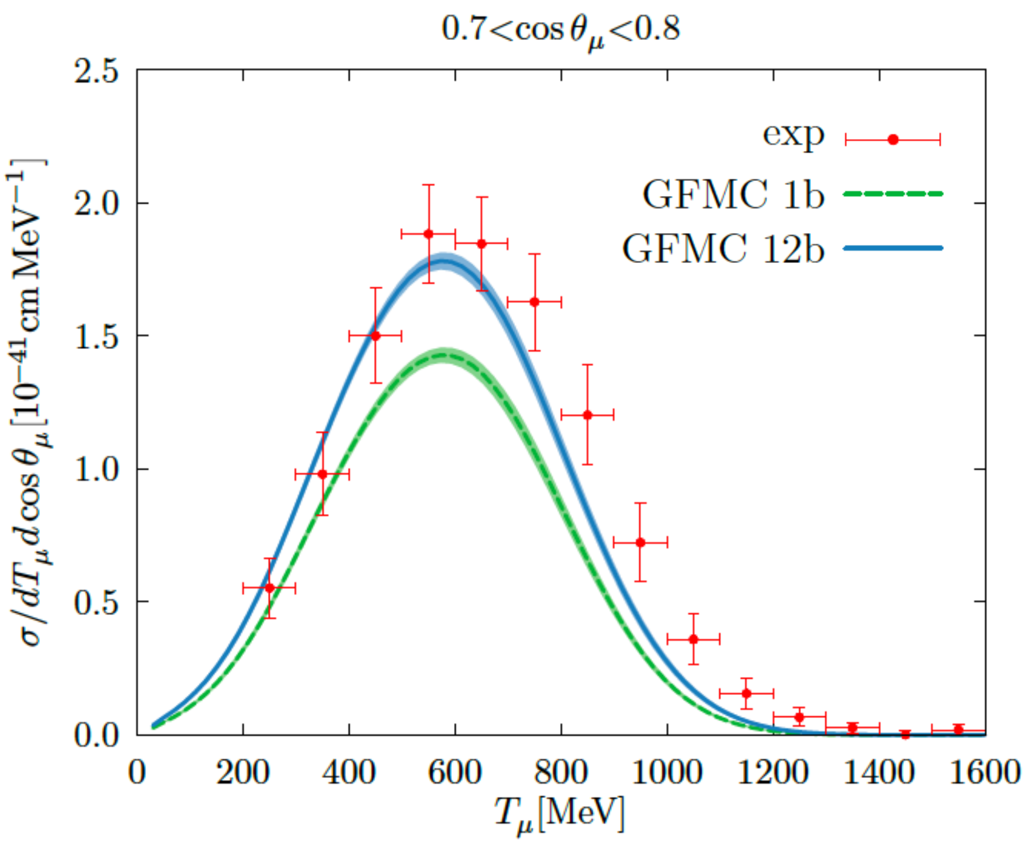
Astrophys. J. Lett. 908, L1 (2021)

Nat. Astron. 4, 625 (2020)

Science 370, 1450 (2020)

Strong constraints on neutron-star mass-radius relation

Progress in neutrino-nucleus scattering



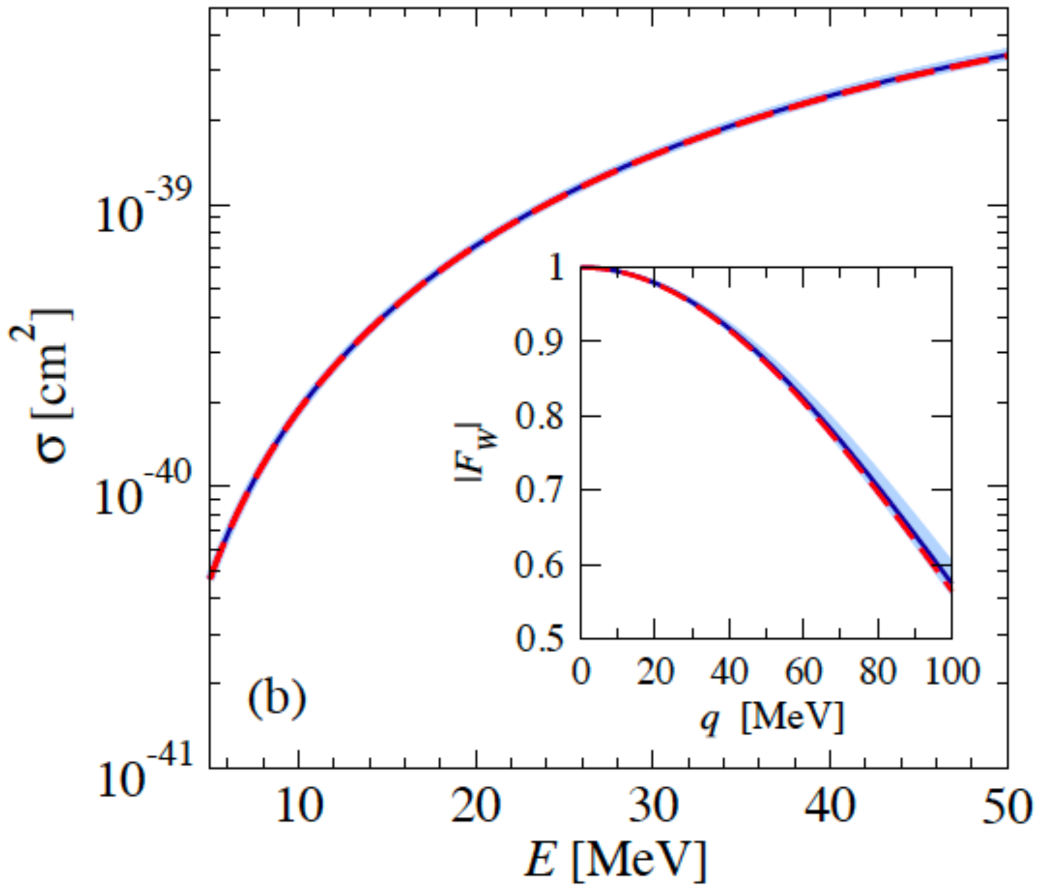
Neutrino scattering on ^{12}C with one (green) and one plus two-body currents (blue) compared to MiniBooNE experimental data.

Phys. Rev. X 10, 031068 (2020)

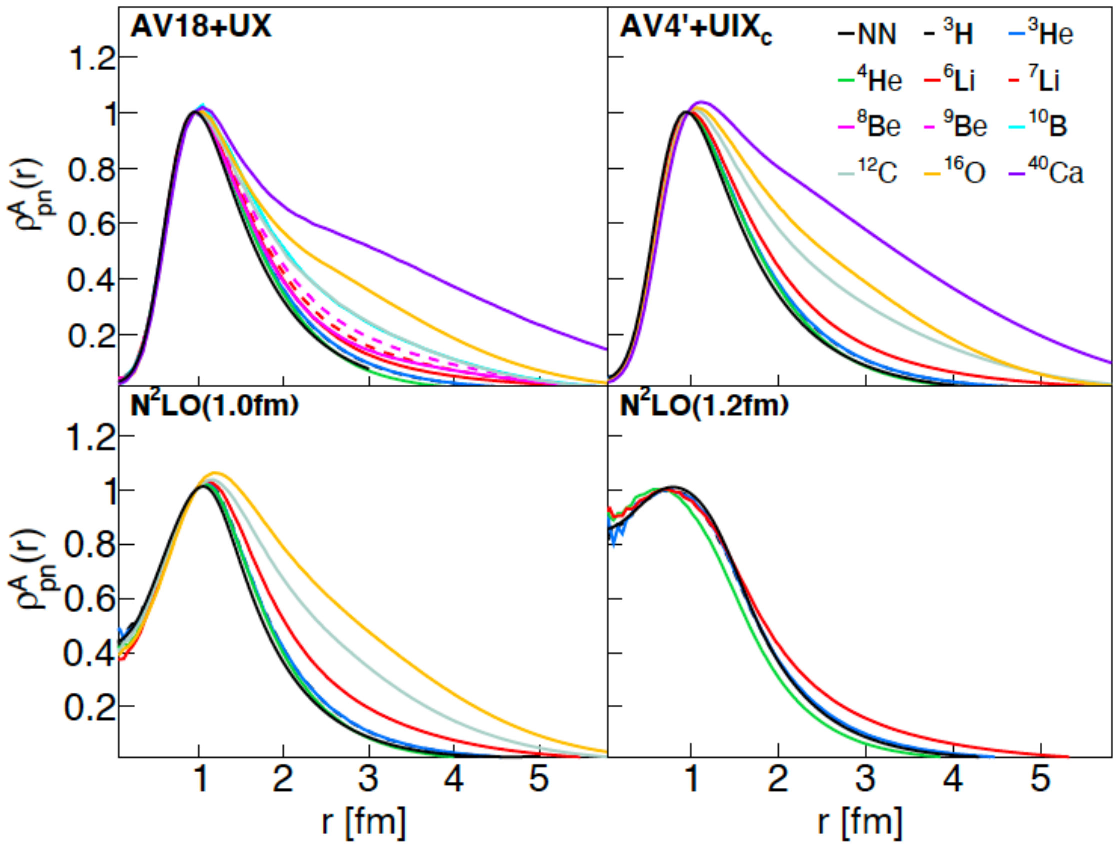
Cross section for CEνNS for ^{40}Ar

Phys. Rev. C 100, 061304 (2019)

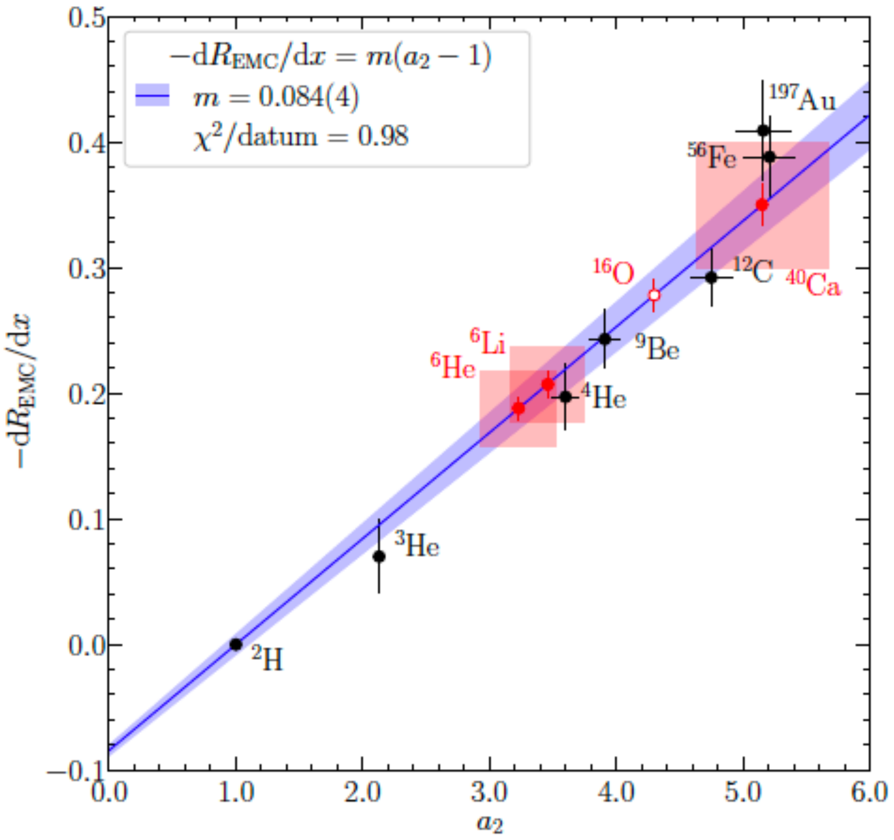
Phys. Rev. C 100, 062501 (2019)



Short-range correlations and EMC effect: Effective field theory and the renormalization group



Short-range correlations are nucleus independent and model dependent, Nature Physics 17, 306 (2021); Phys. Rev. C 101, 044612 (2020)



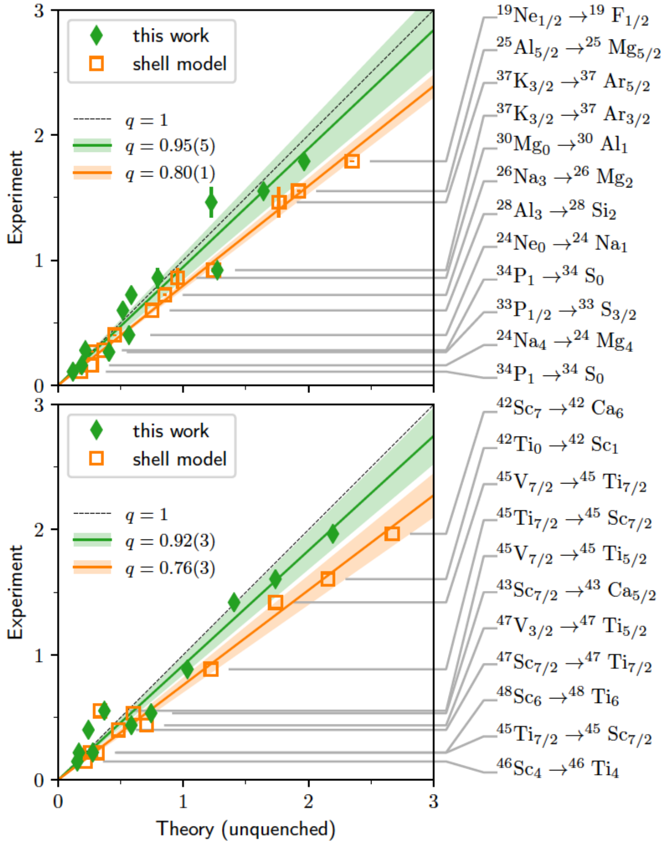
EFT and RG explains the relation between short-range correlations and EMC effect.

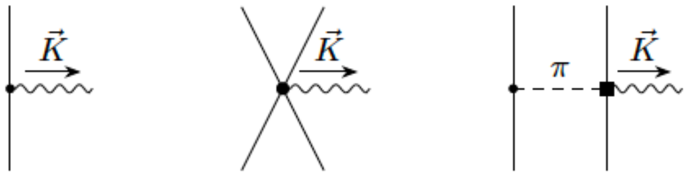
Phys. Rev. C 104, 034311 (2021)

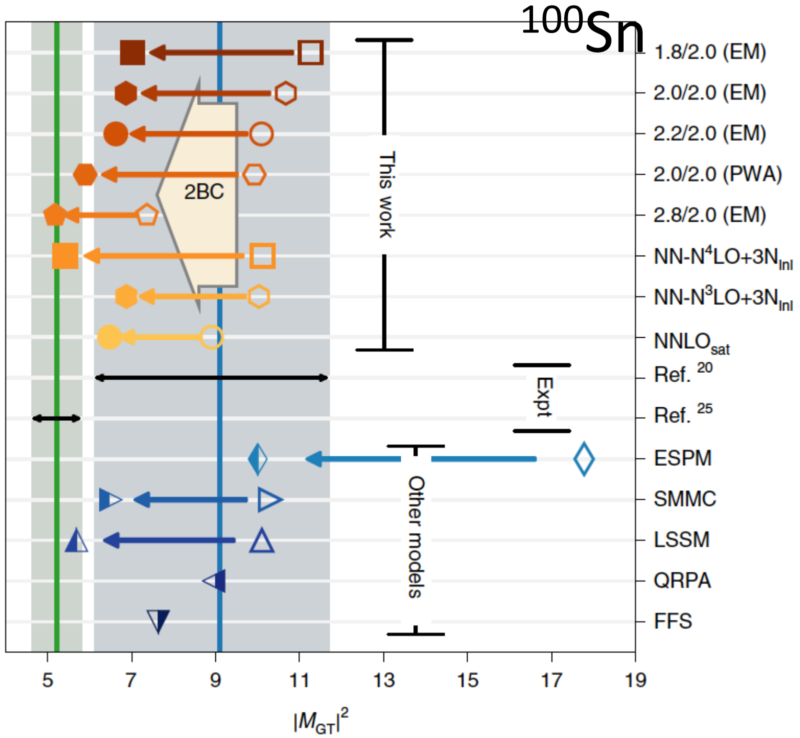
J. Phys. G 47 (2020) 045109

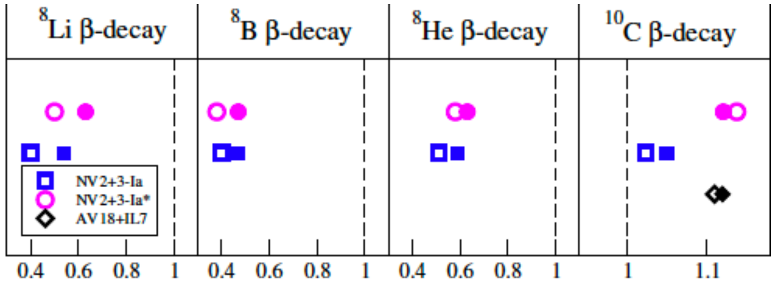
Phys. Rev. Lett. 119, 262502 (2017)

Quenching of β-decays





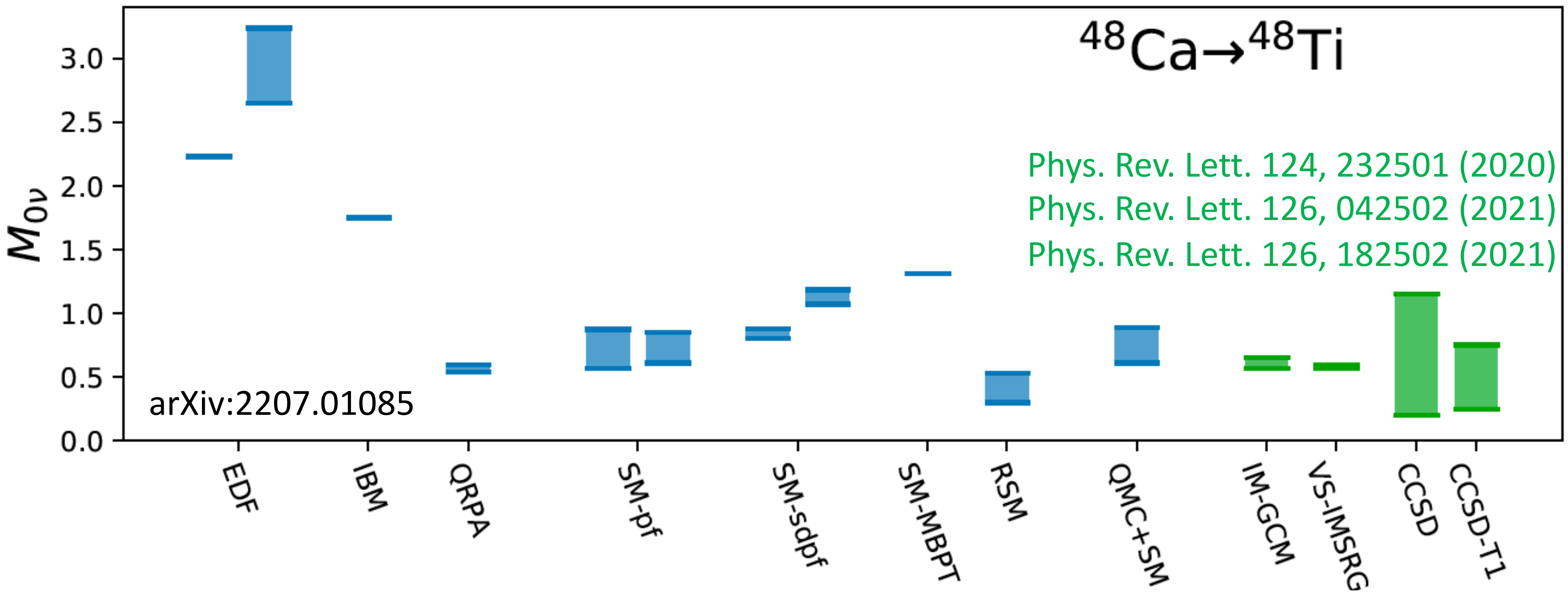




Light nuclei are different.
Phys. Rev. C 102, 025501 (2020)

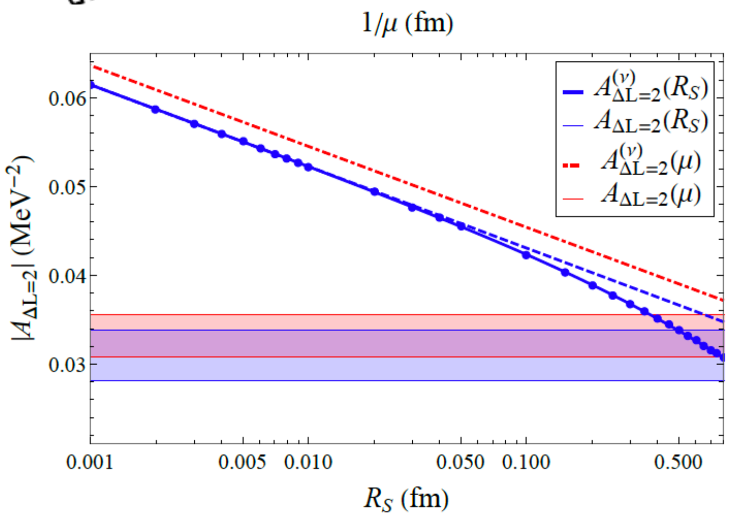
Two-body currents and correlations quench the β-decay rates.
Nature Physics 15, 428 (2019)

Nuclear matrix element for neutrinoless double beta decay



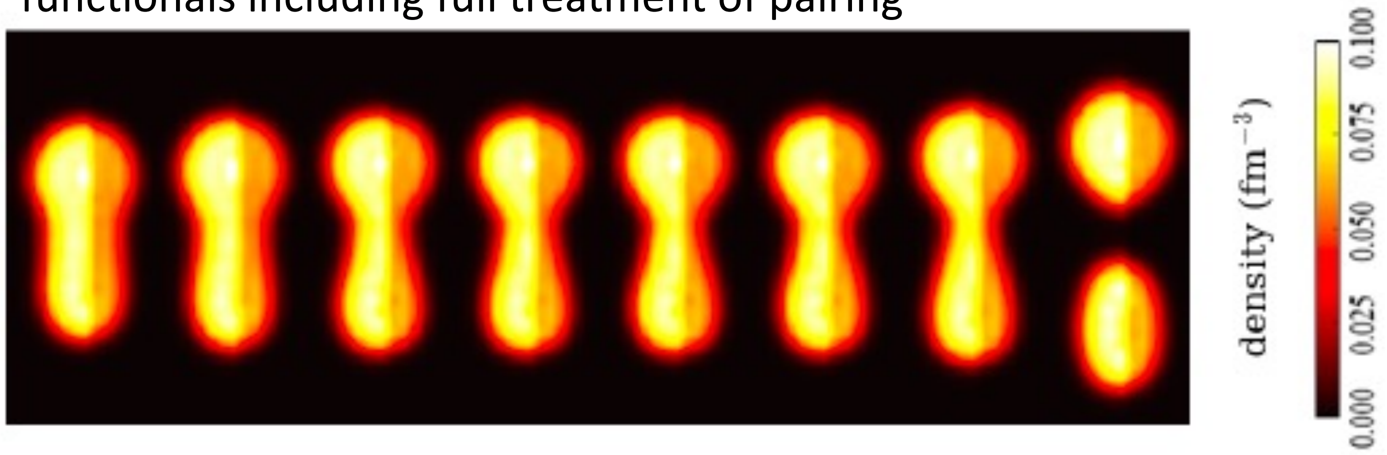
Unknown two-body contact needed for proper renormalization, see Phys. Rev. Lett. 120, 202001 (2018)

- Lattice QCD? Cottingham method?



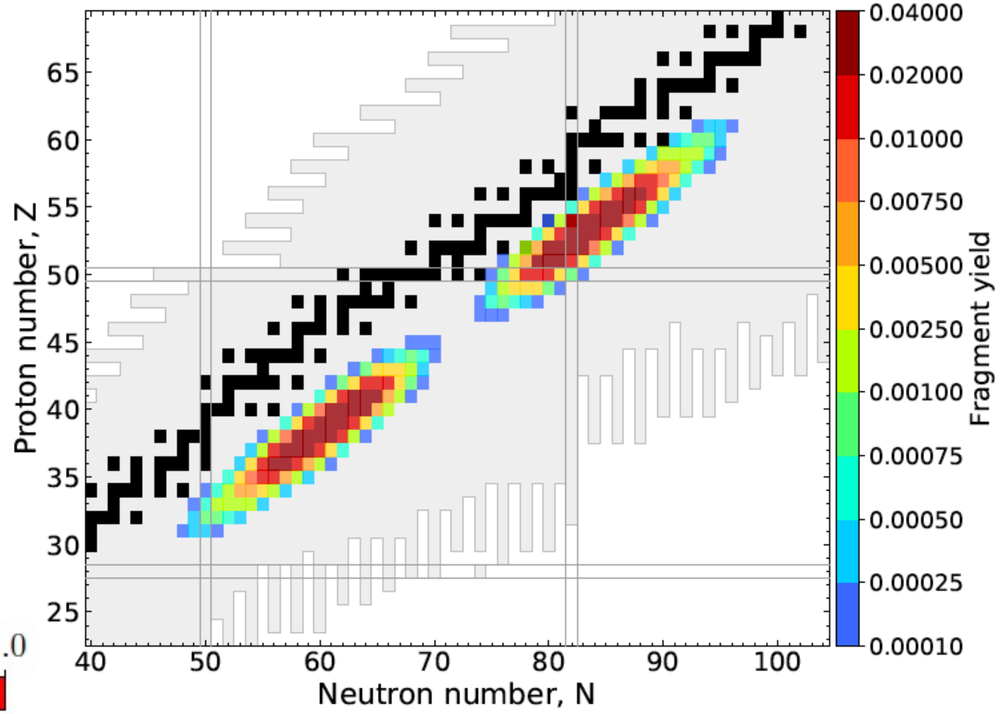
Real-time dynamics of fission and heavy-ion fusion; mass fragment distributions

Fission of ^{240}Pu within time-dependent nuclear energy density functionals including full treatment of pairing

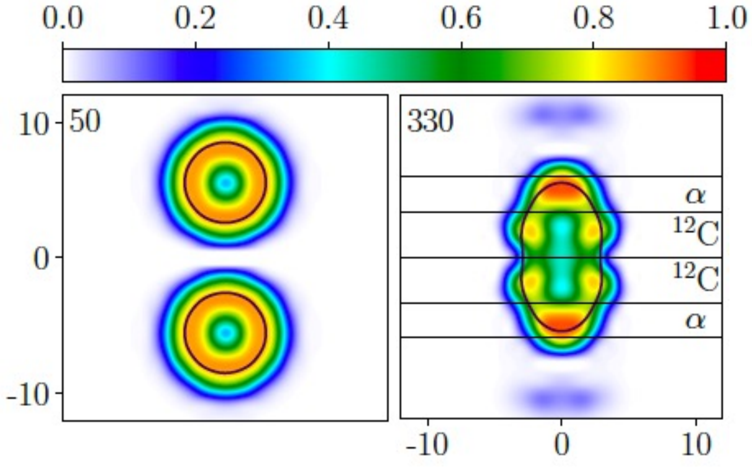


Phys. Rev. C 100, 034615 (2019);
Phys. Rev. Lett. 116, 122504 (2016);
Phys. Rev. C 94, 024605 (2016);

Mass yield from ^{236}U



Phys. Rev. C 101, 054607 (2020);
Phys. Rev. C 93, 054611 (2016);
Phys. Rev. C 99, 064316 (2019)



Visiualization via nucleon localization functions
Phys. Rev. C 96, 064608 (2017)

Growing the theory community in nuclear structure, reactions, and astrophysics

Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

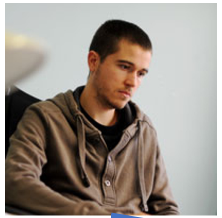
Year	2014	2015	2017	2020	2022
FRIB	Ground breaking		Civil construction completed	DOE-SC User Facility	Ribbon cutting; 1st experiment
FRIB-TA		Initiative in NP-LRP; 1st DOE award	2nd DOE award	3rd DOE award	

FRIB-TA Fellows

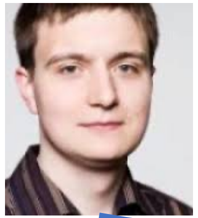
Diego Lonardoni

Gregory Potel

Kevin Fossez

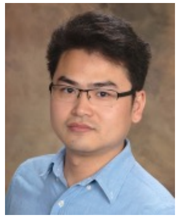


Christian Drischler



Chloe Hebborn

Xilin Zhang



Chieh-Yeah Seng

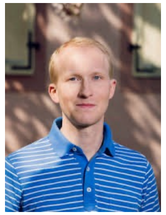
Anna McCoy

Now: staff at Nat'l Labs

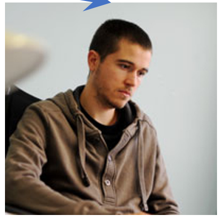
FRIB-TA Bridge Program

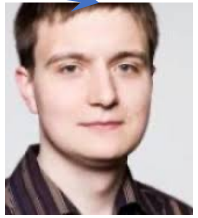
Maria Piarulli

Saori Pastore



Sebastian Koenig





FRIB-TA Activities

Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

- **Topical Programs**: bring together up to 30 theorists and experimentalists for a period of up to three weeks to address particular issues. Researchers discuss the problem, identify strategies and collaborate on solutions.
    - May 2023: Theoretical Justifications and Motivations for Early High-Profile FRIB Experiments
    - August 2022: Few-Body Clusters in Exotic Nuclei and Their Role in FRIB Experiments
    - May 2022: Nuclear Isomers in the Era of FRIB
    - March 2022: Optical Potentials in Nuclear Physics
- **Summer Schools**: hosted at FRIB and bring together graduate students, postdoctoral researches, and senior scientific experts.
    - 2022: Quantum Computing
    - 2021: A practical walk through formal scattering theory
- **Dialogues**: 30-minute presentation followed by a 30-minute Q&A and discussion session with panelists, moderated by a host.
- **International collaboration**: co-ordinate EUSTIPEN program, working on other international collaborative agreements.

Developments in funding since the 2015 LRP

Base funding flat for many years

Reduced summer research

Grant cycles reduced to two years

Tremendous theory progress since last LRP

- Computations of heavy nuclei with EFT Hamiltonians
- Ab initio densities / approaches for optical potentials; EFT approaches to reactions with scale separation
- Nuclear matter EOS constrained by microscopic physics and neutron-star mergers
- Development of high-quality energy density functionals for low-energy nuclear structure
- Real-time propagation for two-nucleon decays, heavy ion fusion, and fission
- Electroweak transitions and response functions include two-body currents
- Matrix elements for neutrinoless double beta decay
- Two-body currents and beta decays
- RG approach to electron-nucleon scattering
- Effective field theories from interactions between nucleons to halos to collective phenomena
- We have entered a precision era: field moves towards quantified uncertainties
- Emulators, machine learning, and Bayesian approaches promise to advance many capabilities