NUCLEAR STRUCTURE AND FUNDAMENTAL SYMMETRIES

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Computational Nuclear Physics and AI/ML Workshop

Argonne NATIONAL LABORATORY

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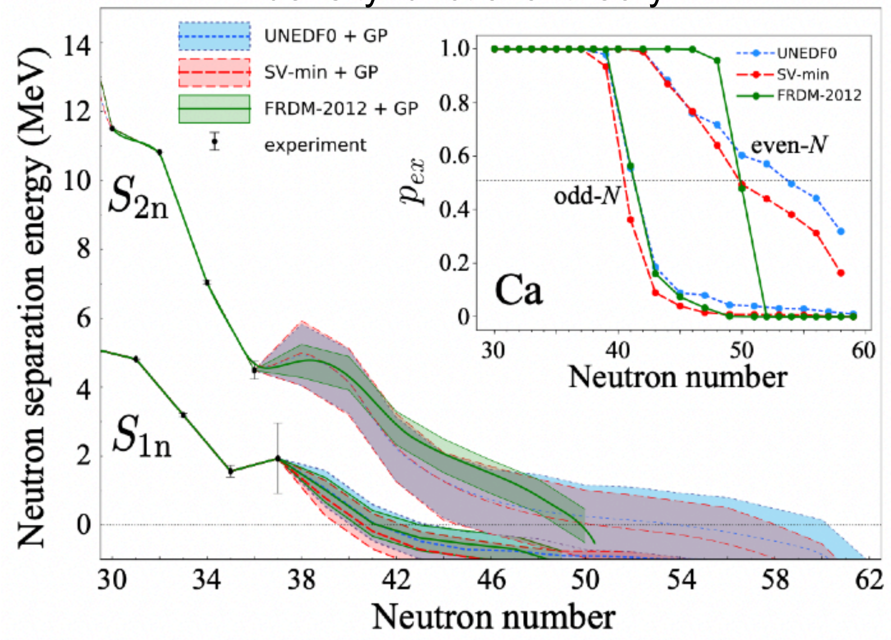
TREMENDOUS PROGRESS SINCE 2015

Tremendous progress since 2015 in quantified many-body approaches

density functional theory



L. Neufcourt et al. Phys. Rev. Lett. 122, 062502 (2019)

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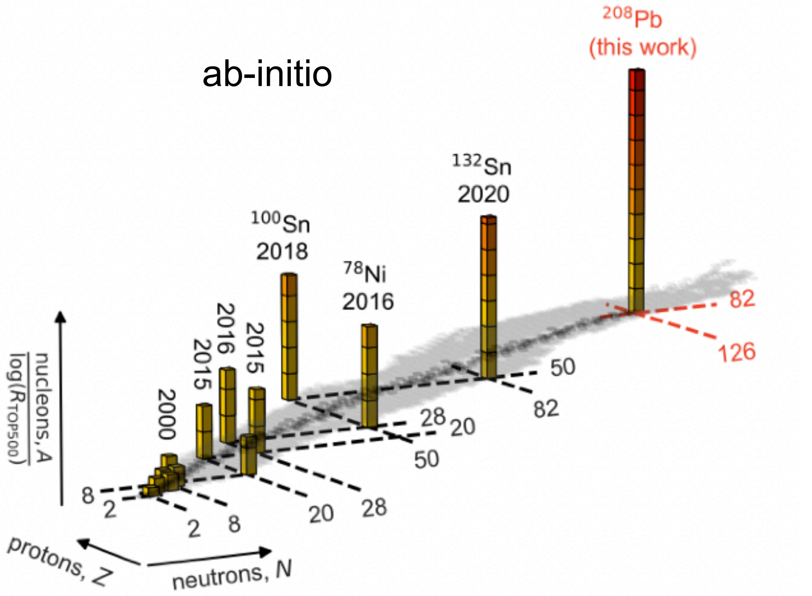


B. S. Hu et al., Nature Phys. (2022)

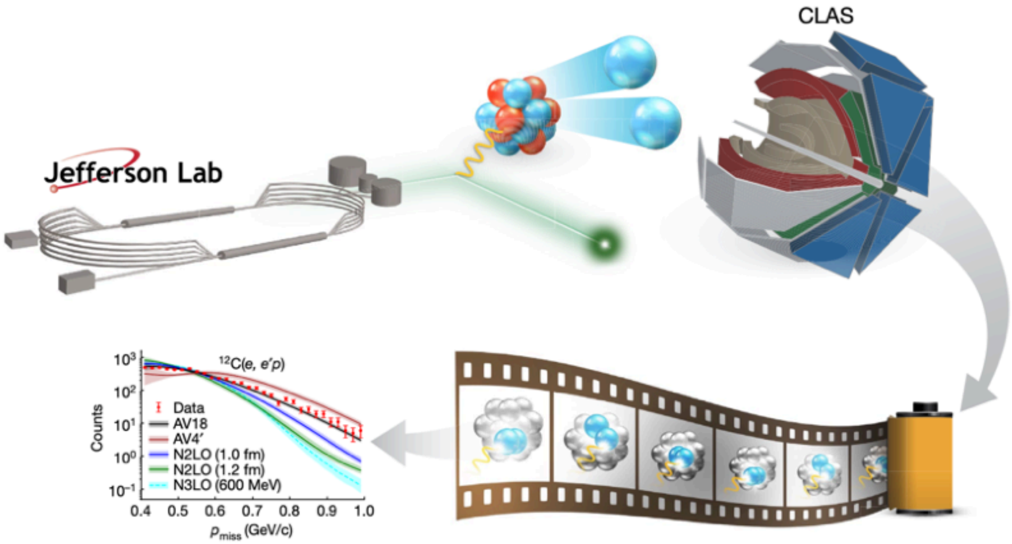
PRESENT AND FUTURE EXPERIMENTS (1)

Diverse and complementary capabilities across Low Energy Nuclear Physics Facilities, including:

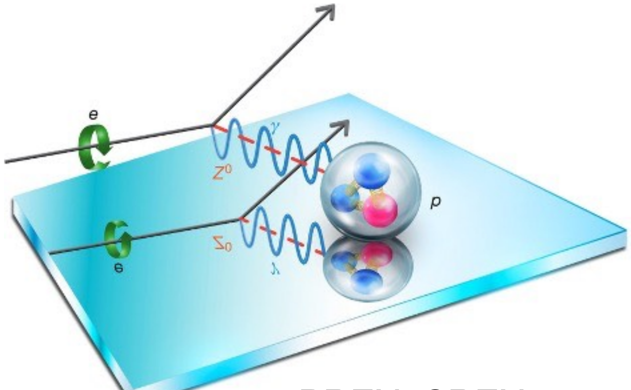
- National User Facilities:
  - ✳ FRIB: World-leading facility for intense beams of rare isotopes;
  - ✳ ATLAS: High-intensity stable beams, radioactive beam program;
- Association for Research at University Nuclear Accelerators (ARUNA)
  - ✳ Nuclear astrophysics, low- energy nuclear physics, fundamental symmetries and applications

PRESENT AND FUTURE EXPERIMENTS (2)

Electron-scattering experiments are critical to elucidate short- and long-range nuclear dynamics



A. Schmidt et al. Nature ***578***, 540 (2020)



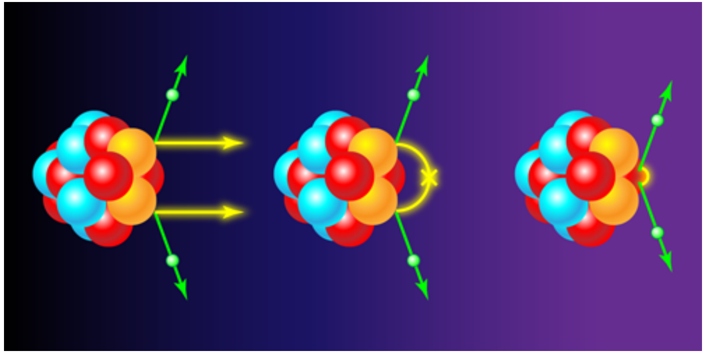
PREX, CREX

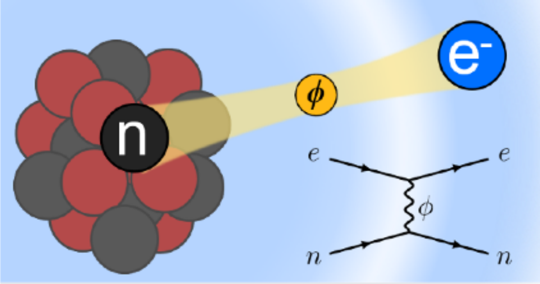
D. Adhikari et al. Phys. Rev. Lett. ***126****, 172502 (2021) and Phys. Rev. Lett.* ***129****, 042501 (2022)*

PRESENT AND FUTURE EXPERIMENTS (3)

Nuclear physics plays a prominent role in the search for new physics through a targeted program of fundamental symmetries and neutrino research that includes:

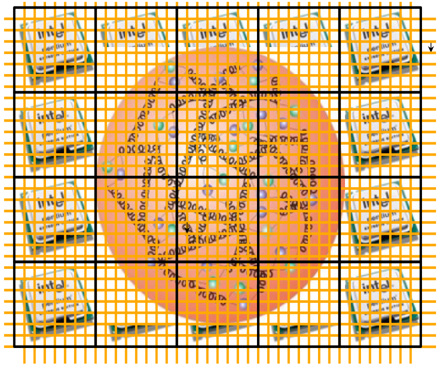
- High precision measurements of SM-allowed processes and properties (β-decay, nucleus-electron interactions, parity-violating electron scattering, and the muon anomalous magnetic moment);
- Searches for rare or SM-forbidden processes that break approximate or exact symmetries of the SM 0νββ, permanent EDMs, μ→e conversion in nuclei, and neutron-antineutron oscillations;
- Experiments that explore properties of existing and hypothetical light weakly-coupled particles such as active neutrinos, sterile neutrinos, axions, dark photons

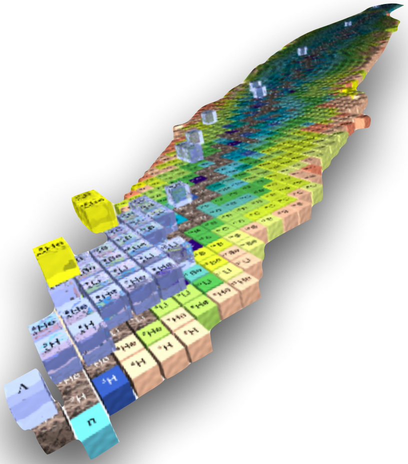


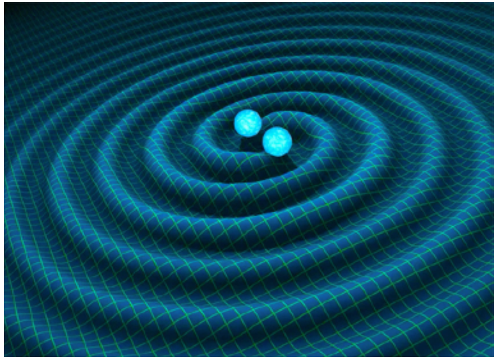


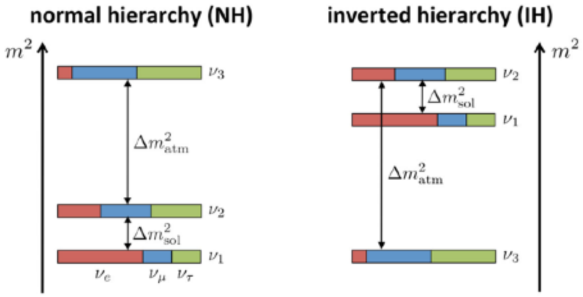
NUCLEAR MANY-BODY SYNERGIES

Synergies between LQCD, many-body theory, nuclear astrophysics, and fundamental symmetries critical to guide and support the experimental program









NEXT-GENERATION COMPUTING RESOURCES

Tremendous computing power available through heterogeneous CPU/GPU machines

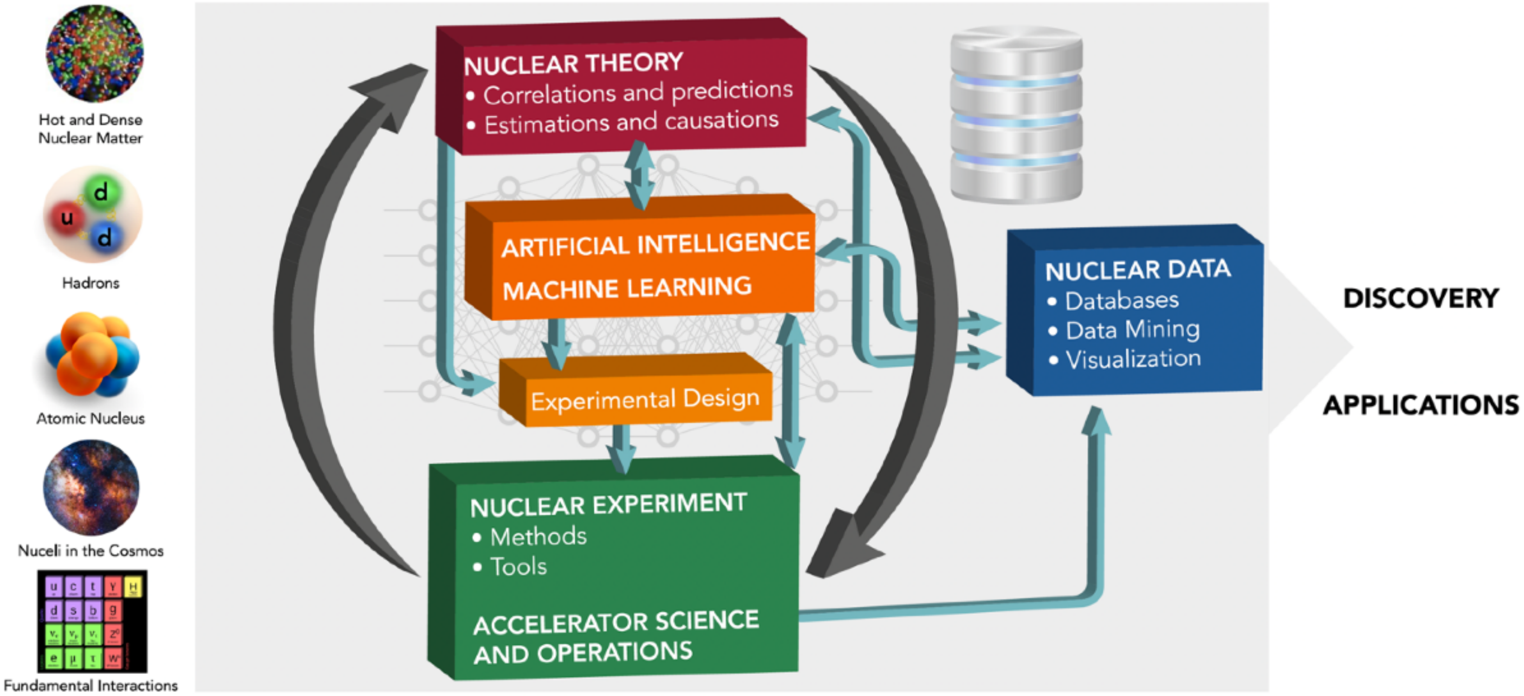
CHALLENGES FOR NUCLEAR MANY-BODY THEORY

- Exotic nuclei relevant for FRIB physics;
- Consistent picture of nuclear structure and reactions;
- Electroweak transitions, including β-decay, electromagnetic moments… ;
- Long- and short-range nuclear dynamics on the same footing;
- Real-time dynamics (fission, heavy-ion fusion, particle decay, lepton-nucleus scattering…);
- Equation of state of infinite nuclear matter (at large densities and finite temperatures);
- Uncertainty quantification, model reduction, emulators, correlations;
- and more…

SCIENTIFIC CASE FOR NUCLEAR PHYSICS

- What are the critical scientific questions that need to be explored where computational physics, combined with AI/ML and UQ techniques can provide insights?
- How do current and future planned experimental capabilities within nuclear physics enable advances in nuclear physics theory?
- How will computational nuclear physics be utilized to guide and interpret the next generation of experiments?
- How will computational physics algorithms capitalize on heterogeneous next-generation computing resources?
- How can we get access to next-generation architectures and how we make sure support of existing algorithms is guaranteed?

HPC and ML help speeding-up the cycle of the scientific method



A. Boehnlein et al., Rev. Mod. Phys. in press

MULTI-FACETED STRATEGY

1) Strengthen and expand programs and partnerships dedicated to computational excellence in Nuclear Physics, such as, but not limited to SciDAC

- Continued support and development for HPC to exploit evolving hardware,
- Support for the development of novel algorithmic approaches such as those capitalizing on AI/ML tools;
- Development of emerging technologies such as quantum computing.

What is an effective strategy to pursue this strategy in a sustainable way? Make sure to highlight synergies and avoid effort duplications.

Take advantage of synergies with existing theoretical efforts (FRIB Theory Alliance, DOE topical collaborations, NSF frameworks,…)

MULTI-FACETED STRATEGY

2) Expand nuclear theory access to computational resources which are essential for progress.

- Ideally a mix of hardware resources including traditional HPC and GPU computing and disk storage, programmatic resources (such as USQCD), and DOE and NSF HPC allocations.

- How to expand currently available allocation programs?

- How to guarantee access to new architectures that are not available commercially?

MULTI-FACETED STRATEGY

3) Establish programs to support the development of a multi-disciplinary workforce in high-performance computing including quantum and AI/ML-based research;

- How can we take the best advantage of emerging technologies to attract talented students to the field?
- Is it possible to explore partnerships with industry?

4) Build the literacy of the NP community, enhance the educational activities in high-performance computing, AI/ML, and quantum computing.

- Existing extremely successful example: TALENT. Can we take inspiration from it?
- How to make the training accessible to more experienced researchers?