Nuclear Science: Fundamental knowledge and broader impact

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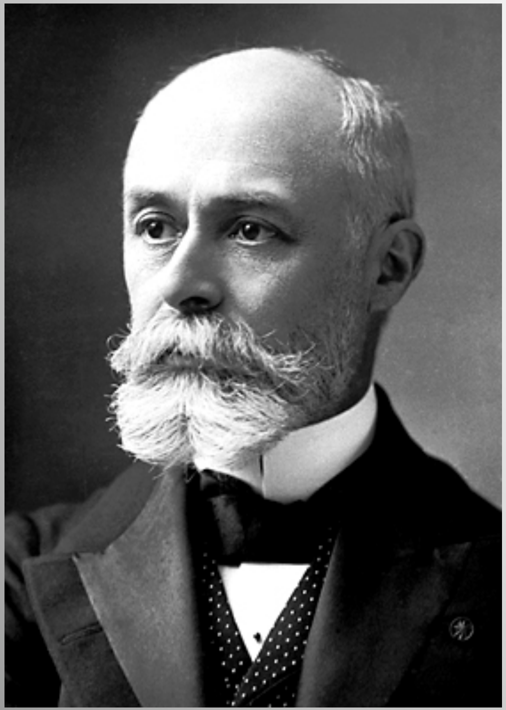
This program funds collaborations between the two nations towards theoretical and computational advances in nuclear structure and nuclear matter.

Historical overview

Our evolving understanding of nuclear science has been closely intertwined with the revolutions that transformed physics in the 20th century.

Initial discovery of radioactive decays (1896)

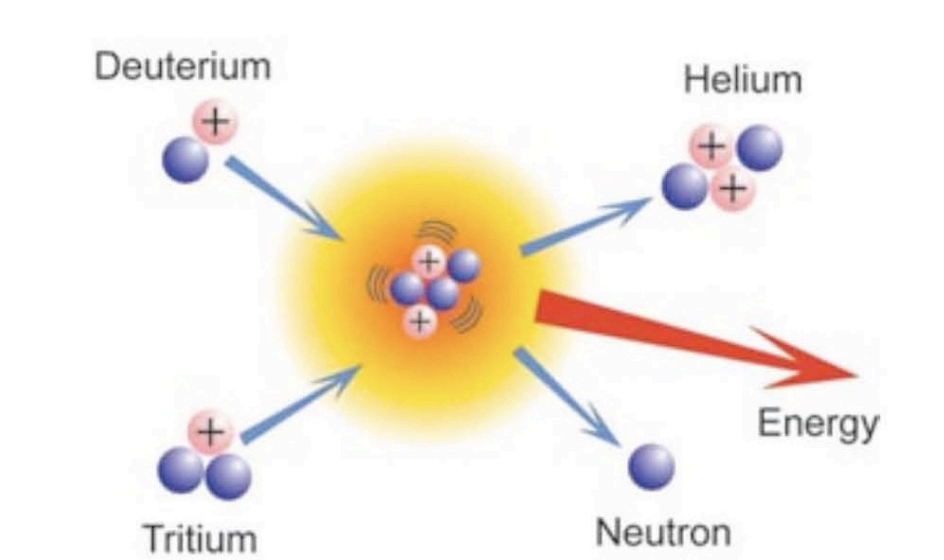


Quantum Mechanics begins to provide a theoretical foundation for the field, together with the realization that energy and mass are interchangeable.
(Beginning 20th century.)

Middle of the 20th century: the Shell Model provides crucial insight into nuclear structure.

Realization that nuclear reactions provide the energy driving the cosmos; new links with astrophysics.

"The marriage between particle physics and astrophysics is still fairly new……" (M.A. Ruderman & W.A. Fowler, 1971)



Discovery of point-like structures in the proton shed new light on the fundamental building blocks in QCD (SLAC, 1967-1973).

Two facilities completed in 1990:

CEBAF at Jefferson Laboratory

RHIC at Brookhaven National Laboratory

Experiments at these facilities have advanced our understanding of QCD.

Upcoming facilities:

MSU is soon to become the site of another new facility, FRIB.
Meantime, advances in nuclear structure and nuclear astrophysics are happening at NSCL at MSU.

Search for new particles at the LHC

Dark matter, dark energy

Neutrino oscillations and neutrino mass

Nuclear science today is focused on three broad frontiers (items mentioned above belong to one or the other):

1) Structure of nuclei and properties of nuclear matter
   with realistic nuclear forces;
   limits/drip lines; connection to astrophysics

2) QCD: Quark confinement, structure of p and n

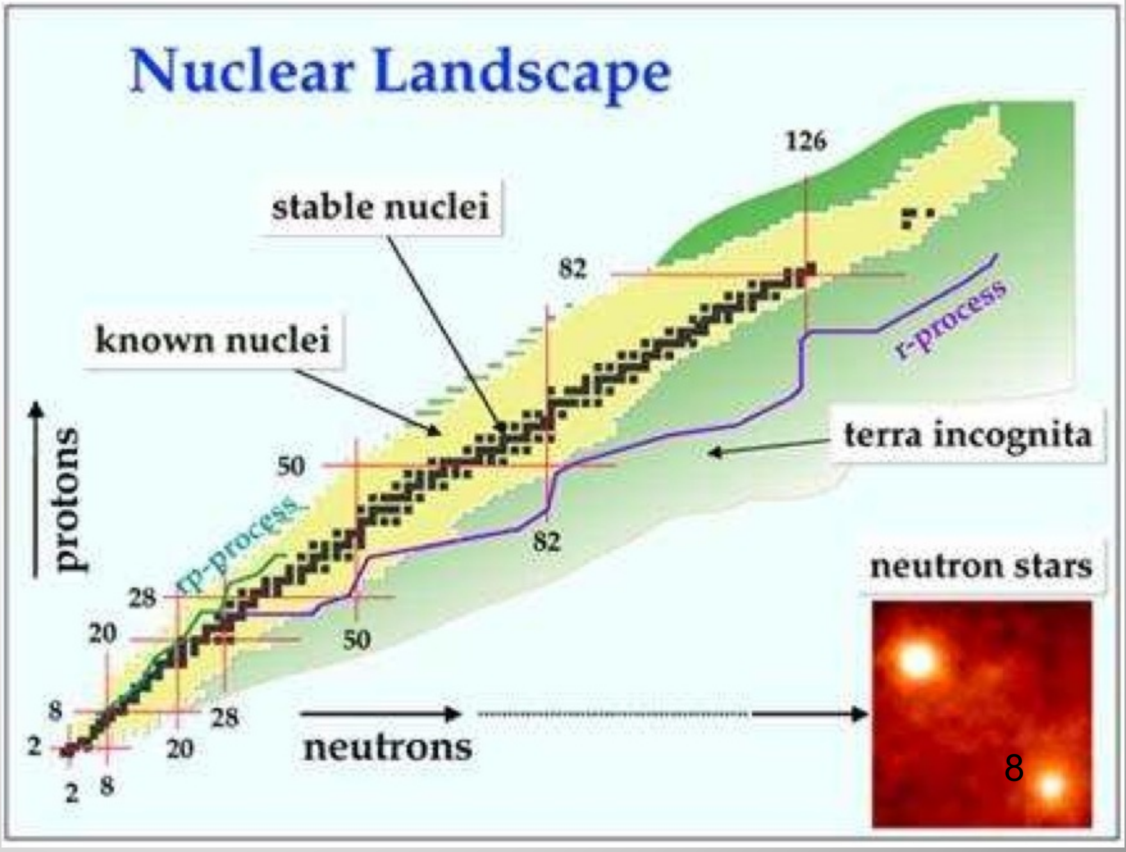
3) Physics beyond the Standard Model.

Within item 1):

What is the nature of the force which binds neutrons and protons in stable nuclei and rare isotopes?

Origin of patterns in complex nuclei?

What is the nature of dense matter in neutron stars?



Within the FRIB program, one wants to probe the limits of stability:

How many neutrons can we add to a stable nucleus before it cannot hold any more?

We know the answer to this question only for the lightest elements. As we push measurements to more neutron-rich isotopes, we learn new features of the strong interaction.

Recent measurements at the NSCL indicate that the drip lines for Al and Mg is likely further from the line of stability than previously thought.

Mapping the neutron drip line will provide a wealth of information on how the nuclear force saturates.

Experiments need theoretical guidance.
Thus, we need reliable theoretical calculations.

The goal of microscopic nuclear physics:

To derive the properties of nuclear systems from the basic few-nucleon interactions
(AB INITIO)

***Ab initio*:**

realistic free-space few-nucleon forces are applied in the nuclear many-body problem.

Most important aspect of the *ab initio* approach:
No free parameters in the medium.

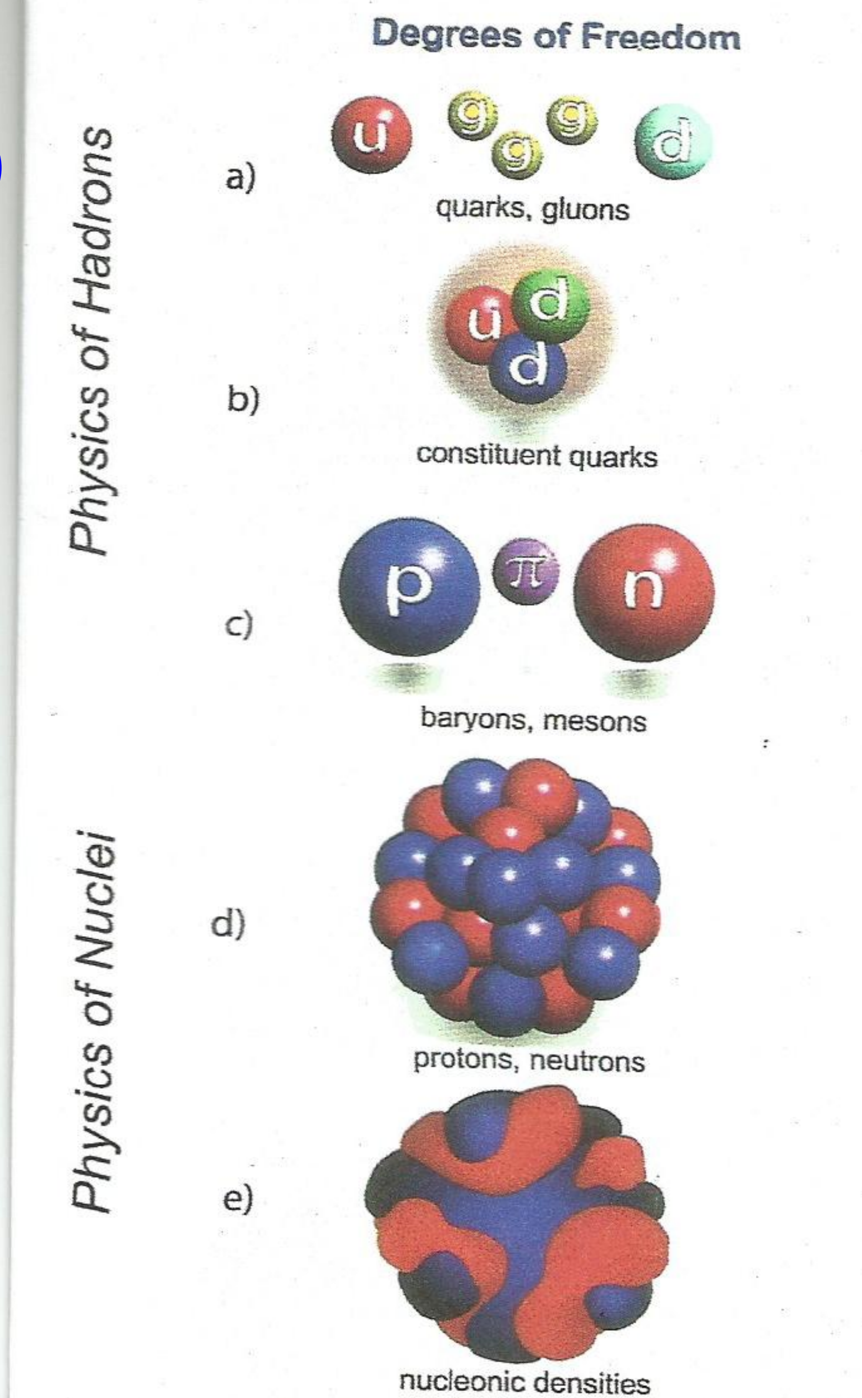
First question is: How to best develop nuclear forces?

Our (still incomplete) knowledge of the nuclear force is the result of decades of struggle.

Nuclear Theory:

A hierarchy of

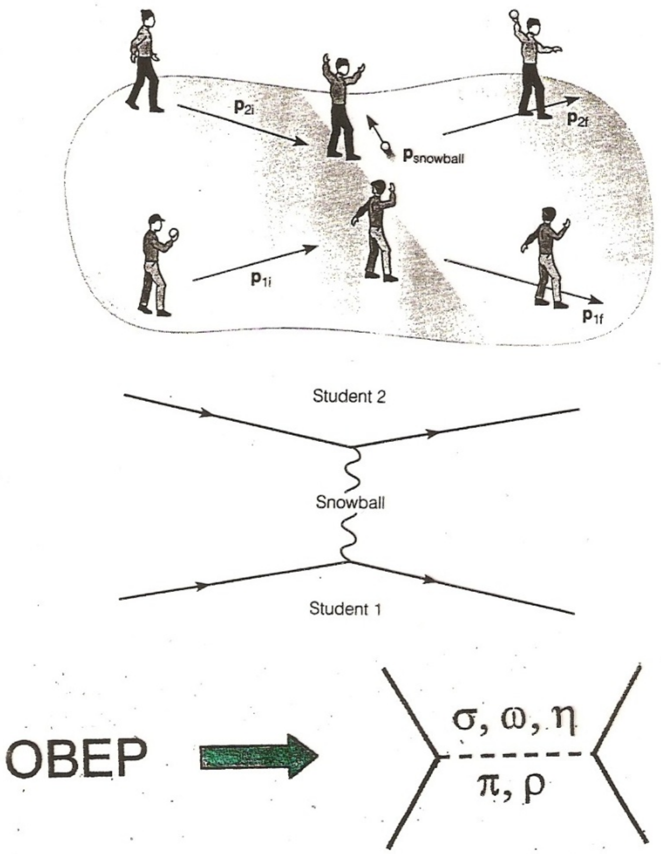
scales.



A popular approach has been Meson Theory

Mesons=Boson fields

OBEP=One-Boson-Exchange Potential



First meson-exchange idea: Yukawa, 1935 (Nobel 1949)

A different approach to the development of nuclear forces:

High-quality OBEP continue to be applied in contemporary nuclear structure calculations, but the more recent Chiral Effective Field Theory (EFT) is presently considered a superior framework.

Firm connection with QCD

Allows for a systematic expansion---> at each order the uncertainty associated with a particular prediction can be controlled.

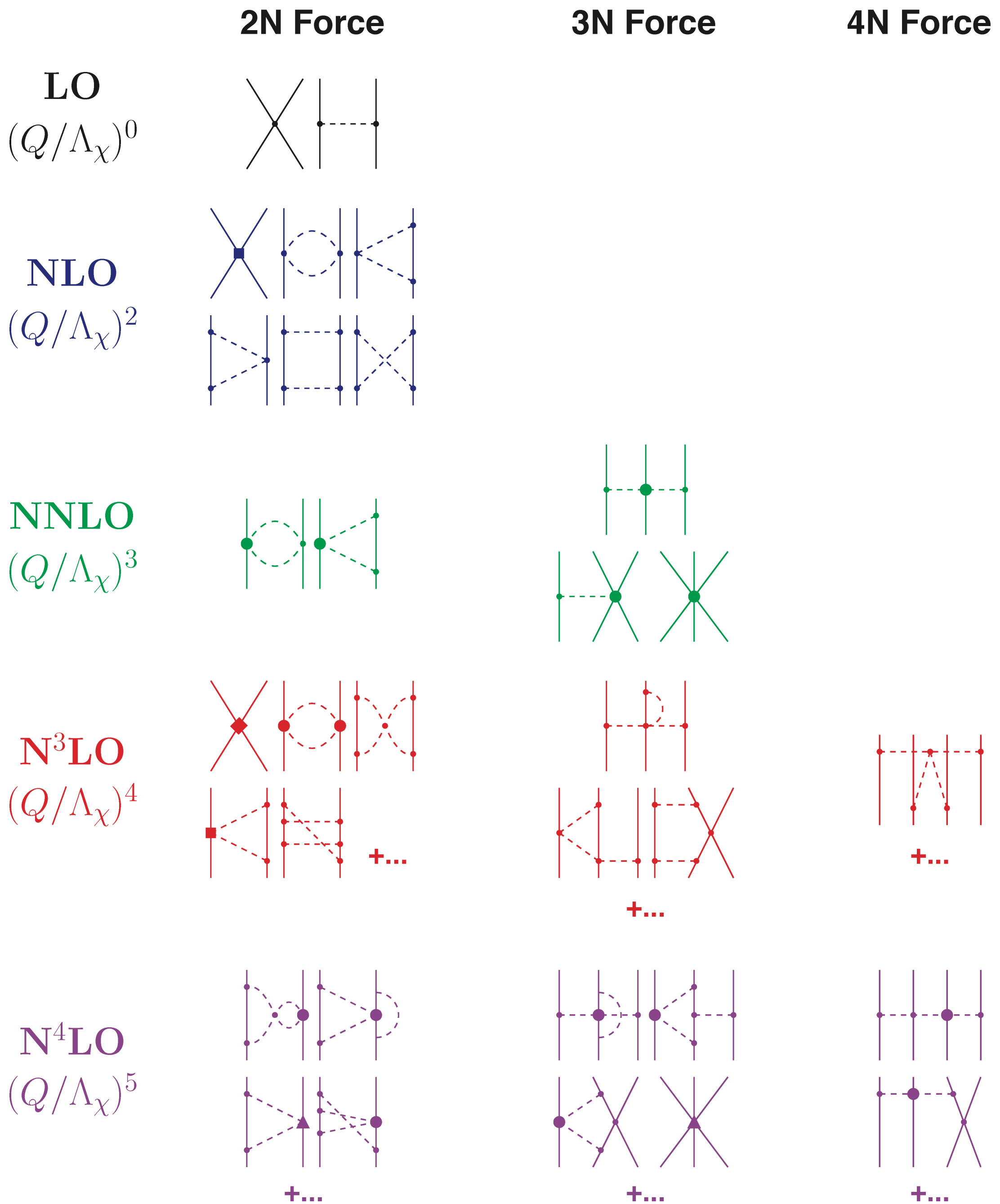
The philosophy of EFT:

To provide a well-defined path to calculate observables whose truncation error decreases systematically as higher orders are included.

EFT: A framework in which the properties governed by low-energy physics are specified by the choice of degrees of freedom and symmetries, and can be computed systematically.

Power counting: an organizational scheme to rank-order the various diagrams.

Nuclear two- and few-body forces emerge on equal footing in a controlled hierarchy.

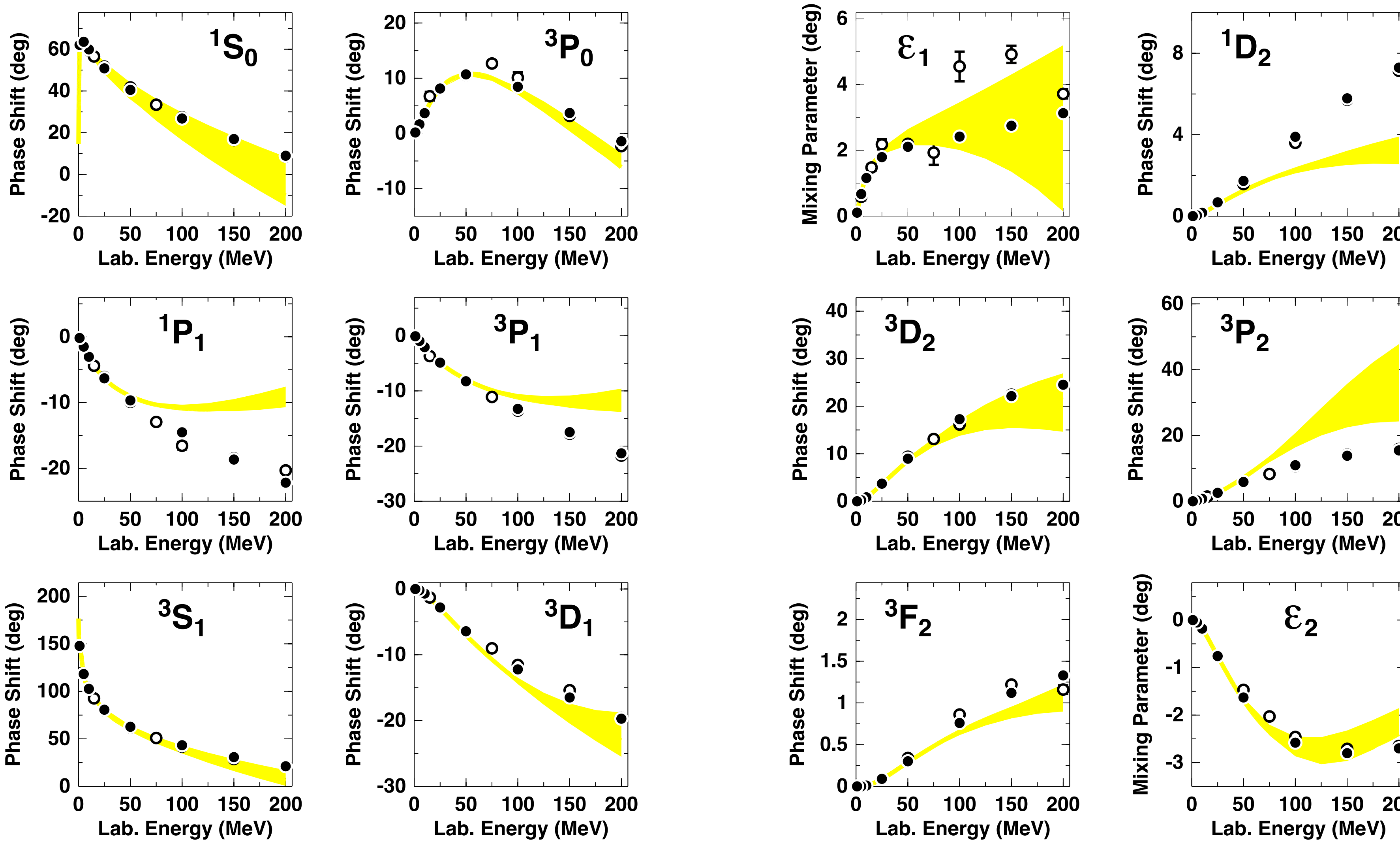

2N Force
3N Force
4N Force
LO
$(Q/\Lambda_\chi)^0$
NLO
$(Q/\Lambda_\chi)^2$
NNLO
$(Q/\Lambda_\chi)^3$
$\mathrm{N^3LO}$
$(Q/\Lambda_\chi)^4$
+...
+...
+...
$\mathrm{N^4LO}$
$(Q/\Lambda_\chi)^5$
+...
+...
+...

NEXT:

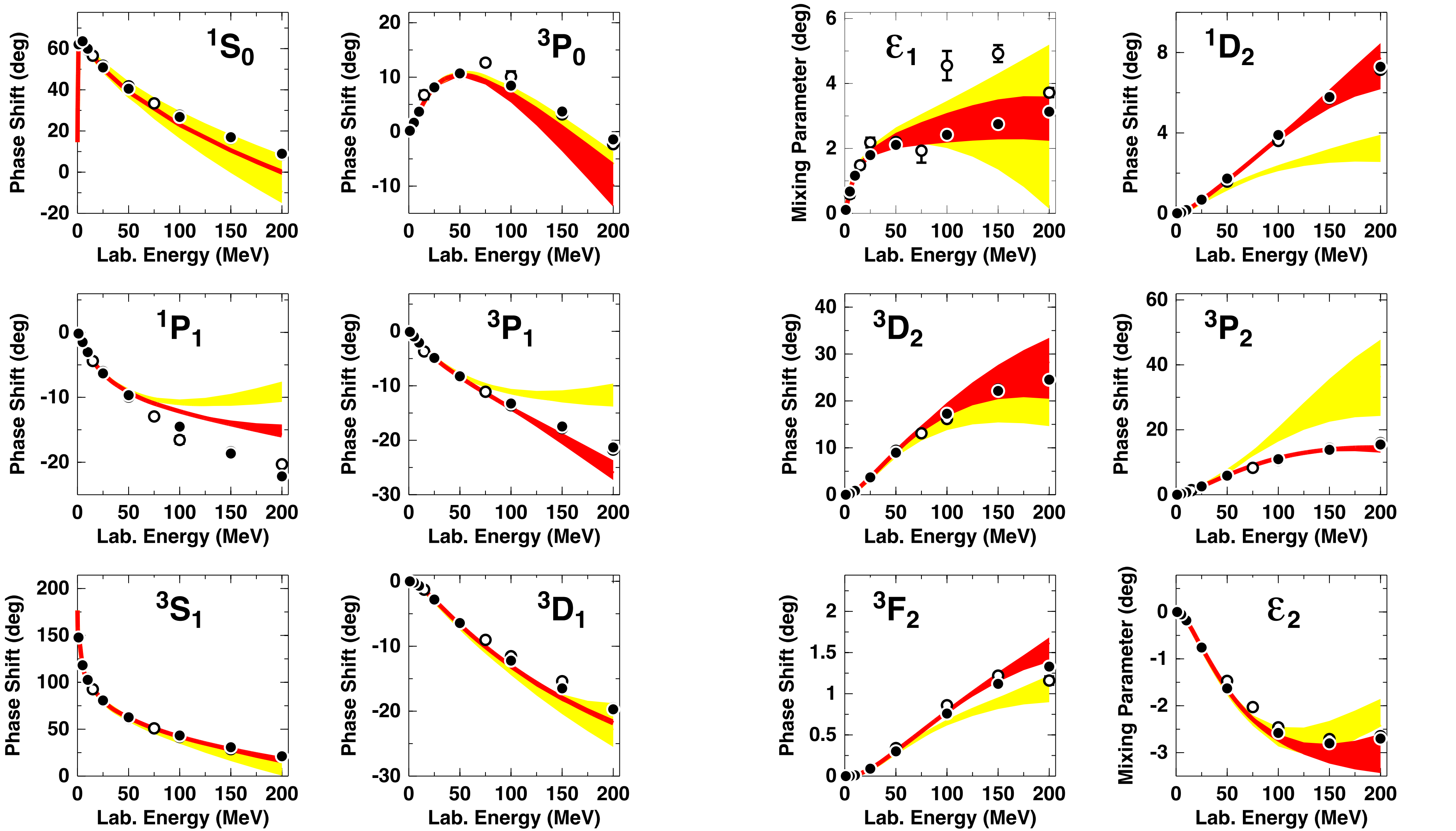
HOW GOOD IS THE CONVERGENCE WITH INCREASING ORDER?

NLO

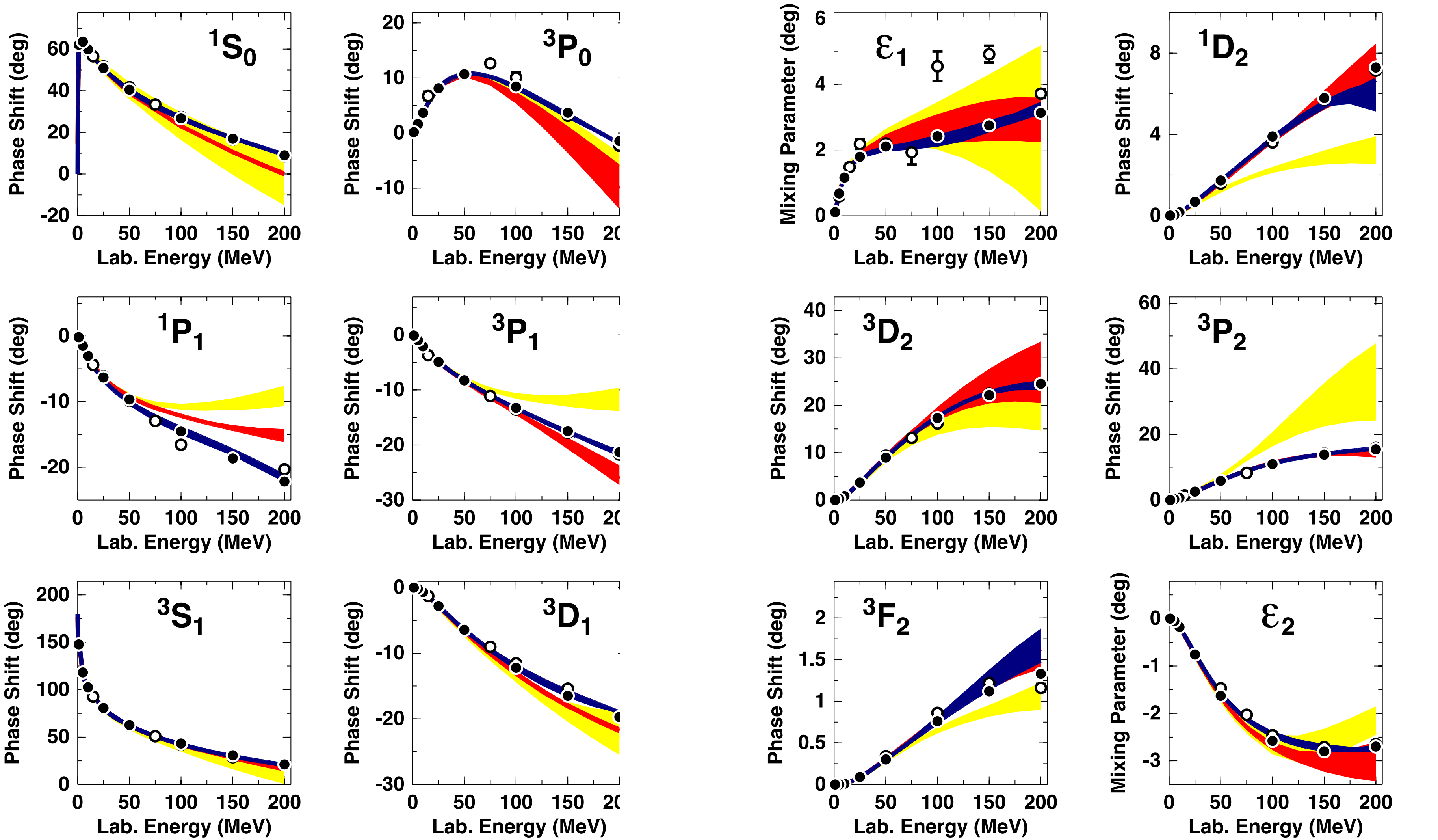
Cutoff = 450-800 MeV



NLO NNLO Cutoff = 450-800 MeV

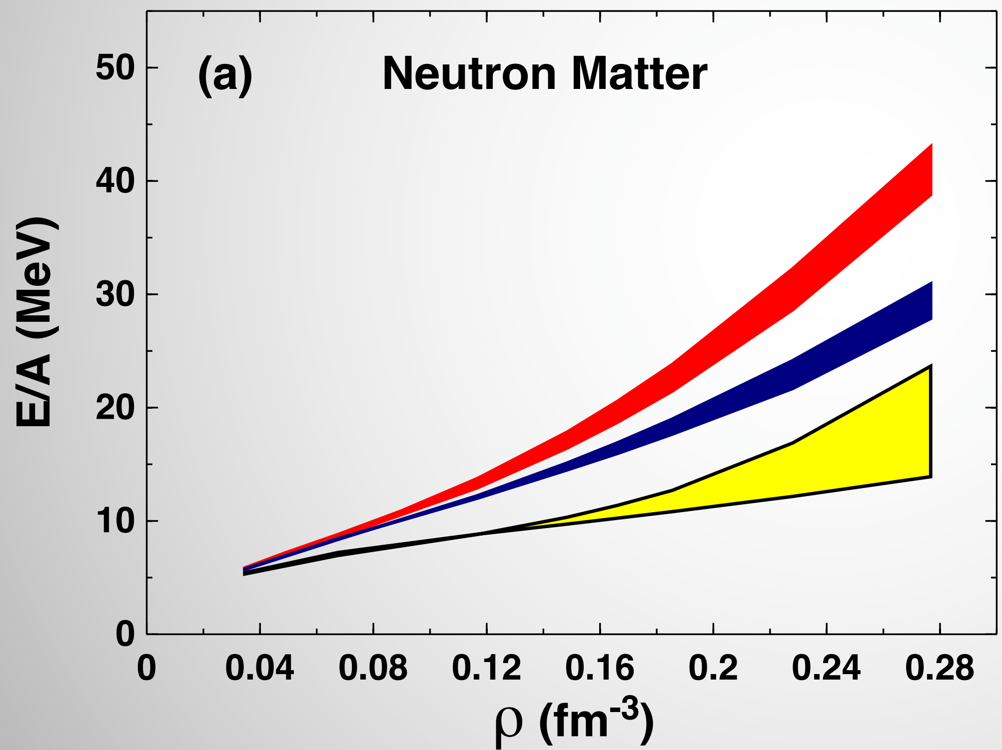


NLO NNLO N3LO Cutoff = 450-600 MeV



An example of EFT predictions in the many-body system:

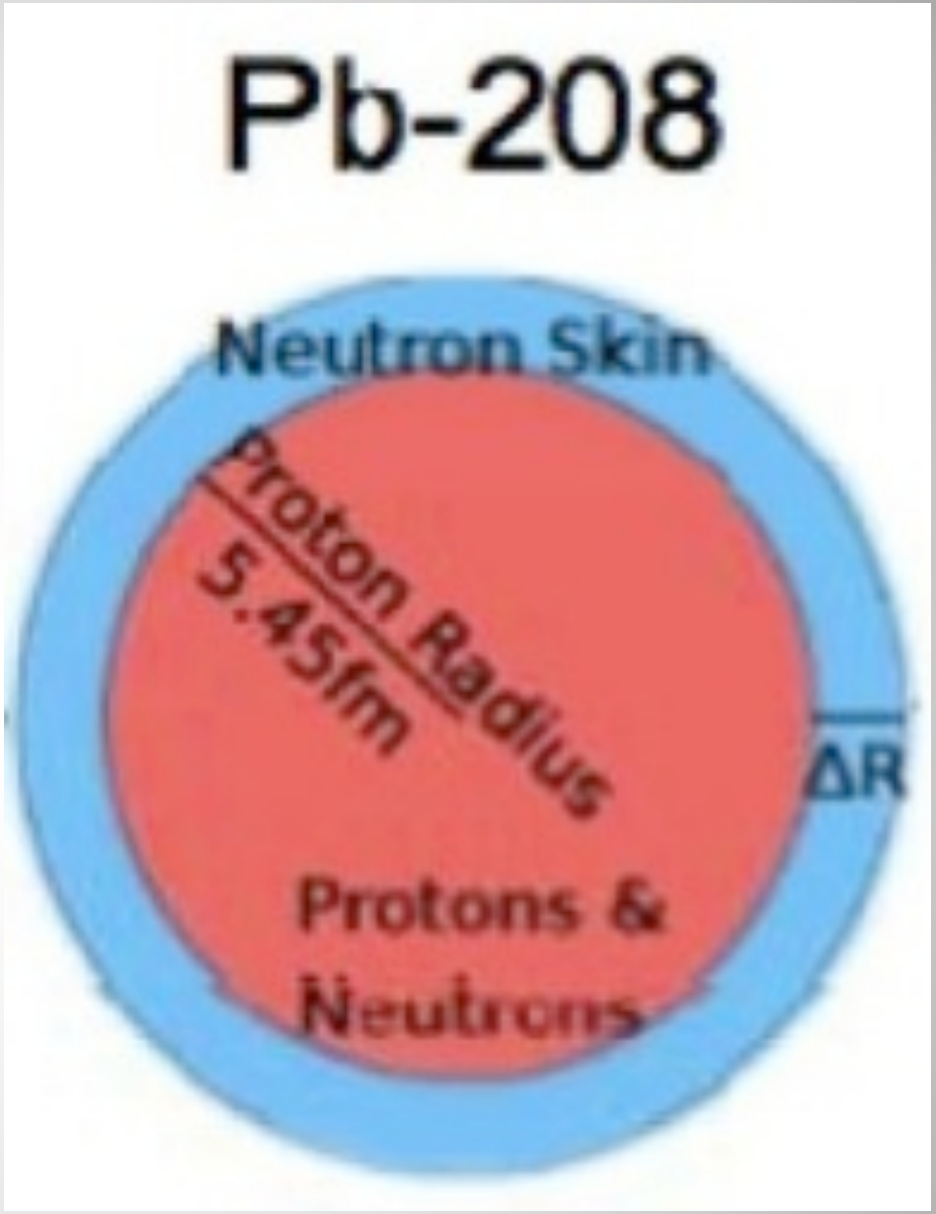
Energy/particle in neutron matter at various orders of chiral EFT and changing cutoff.



Yellow: NLO
Red: N2LO
Blue: N3LO

F. Sammarruca et al.,Phys. Rev. C 91, 054311 (2015)

An intuitive way to visualize the "neutron skin"



Corresponding predictions of the neutron skin in 208-Pb at different orders of EFT and changing cutoff:

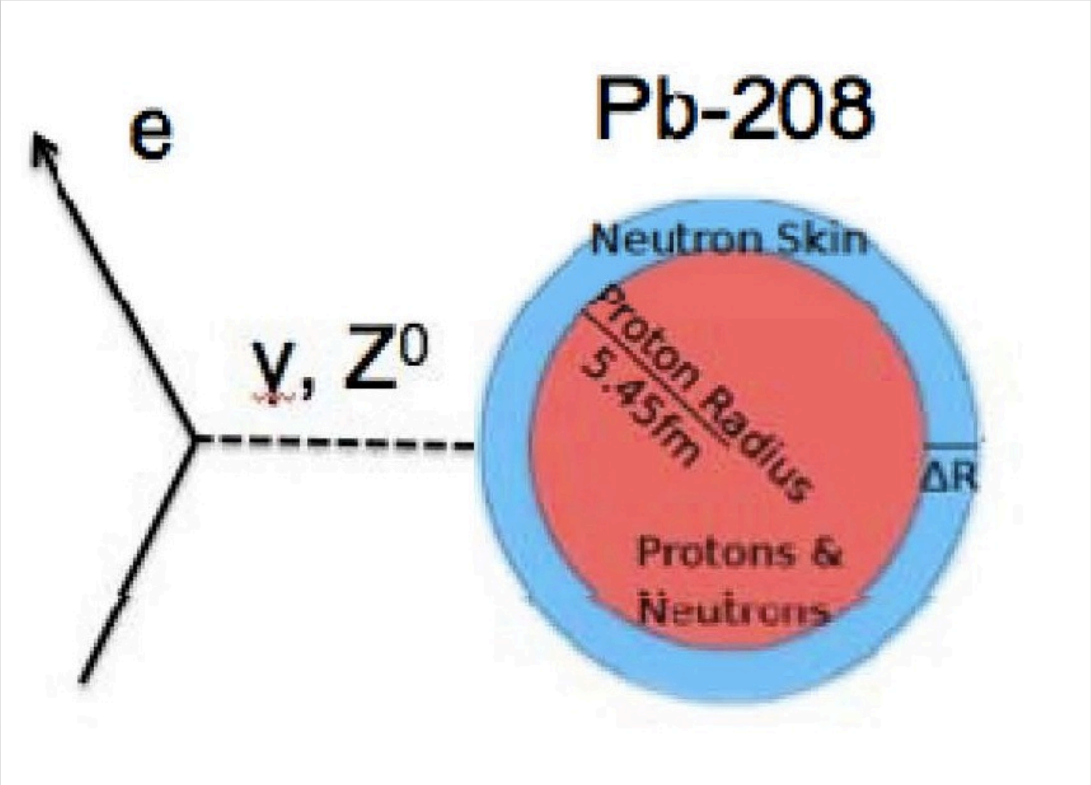
ORDER	S(fm)
NLO	0.126(+0.004,-0.003)
N^2LO	0.20(+0.01,-0.01)
N^3LO	0.172(+0.002,-0.005)

At N^3LO, we estimate:

S = 0.17 +/- 0.03 fm

F. Sammarruca, *Symmetry*, Special issue on "Symmetries in Hadrons and Nuclei", 7, 1646 (2015)

Electroweak scattering experiment:



Measured neutron Skin = 0.33 (+0.16,-0.18) fm

Target uncertainty of next measurements is a factor of 3 smaller.

We are now preparing a similar analysis of

neutron star properties.

J1614-2230 (Demorest et al., 2010) has a mass of 1.97 (0.04) solar masses.
More recently, a mass of 2.01 (0.04) has been observed (Antoniadis et al., 2013)

This value is the highest yet measured with this certainty and represents a strong constraint for theoretical models of the EoS.

Interaction with other fields and broader impact

Many-body problem in general:

Although interactions of nuclear physics differ from the e.m. interactions that dominate chemistry, materials, and molecules, theoretical methods and computational techniques necessary to solve the quantum many-body problem can be shared.

Nuclear scientists can contribute to other fields when applying their femto-scale methods to nano-scale problems.

High Performance Computing:

Technology to solve computational problems which require significant processing power and resources.

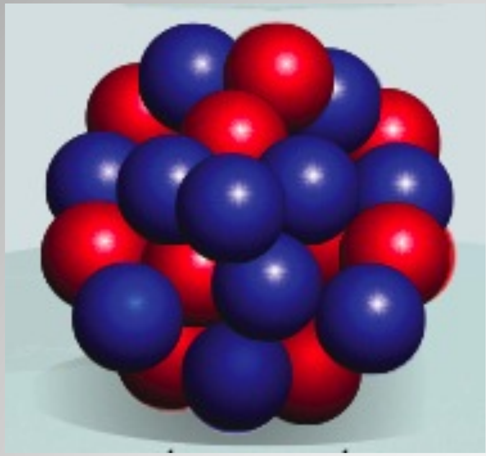
Goal:
Reduction in the execution time and ability to accommodate larger and more complex systems.

Computing and connection with Computer Science

A striking trend in contemporary nuclear physics is the increasing importance played by computational science.

The definition of “high-scale computing” changes continuosly.
Teraflop-hours (tera=10^12) of computing time/month needed to solve some of the current problems.

Both DOE and NSF are fostering collaborations between computer scientists and computational nuclear physicists.



Nuclear Hamiltonian

$$H = \sum_i K_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}$$

The Many-body Problem

Need to solve

$$\mathcal{H}\Psi(\vec{r}_1, \vec{r}_2, \cdots, \vec{r}_A; s_1, s_2, \cdots, s_A; t_1, t_2, \cdots, t_A)$$
$$= E\Psi(\vec{r}_1, \vec{r}_2, \cdots, \vec{r}_A; s_1, s_2, \cdots, s_A; t_1, t_2, \cdots, t_A)$$

s_i are nucleon spins: $\pm\frac{1}{2}$

t_i are nucleon isospins (proton or neutron): $\pm\frac{1}{2}$

$2^A \times \binom{A}{Z}$ complex coupled 2^{nd} order eqn in $3A-3$ variables

(number of isospin states can be reduced)

^{12}C: 270,336 coupled equations in 33 variables

CONCLUSIONS

A wealth of experimental and theoretical investigations are going on to answer fundamental questions in nuclear and particle physics.

Some of these questions have relevance which extends from nuclei to compact stars.

A typical complex problem to be addressed has two parts:

1) **The input few-nucleon force**
2) **The many-body theory**

The future of Nuclear Theory is microscopic nuclear physics.

CONCLUSIONS, cont.

Without new investments, the field will be dominated by scientists in Europe and Asia…..(LRP, from the NSAC)

Investments in new and upgraded facilities promise to yield applications in energy and homeland security.

Ph.D. production must increase by 20% to meet demands for new positions in industry, medicine, academia, and national labs.

Outreach to advance the public interest in nuclear science..

THE END