Living on the edge of stability, challenges to nuclear theory in the FRIB era

Morten Hjorth-Jensen

National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, U.S.A.

Department of Physics, University of Oslo, Oslo, Norway

Nuclear Talent course 2017

Big Questions in nuclear physics today (NAS report)

- How did matter come into being and how does it evolve?
- How does subatomic matter organize itself and what phenomena emerge?
- Are the fundamental interactions that are basic to the structure of matter fully understood?
- How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?

- **Fundamental aspects**
  - Nature of building blocks (nuclear degrees of freedom)
  - Nature of nuclear interactions
- **Self-organization of building blocks**
  - Nature of composite structures and phases
  - Origin of simple patterns in complex systems

The Nuclear Landscape

- QCD transition (color singlets formed): 10 μs after Big Bang (13.8 billion years ago)
- D, 3,4He, 7Be/7Li formed 3-50 min after Big Bang
- Other nuclei born later in heavy stars and supernovae

Many-body theories 2005, Barrett, Dean, MHJ, Vary, 2004, JPG **31**

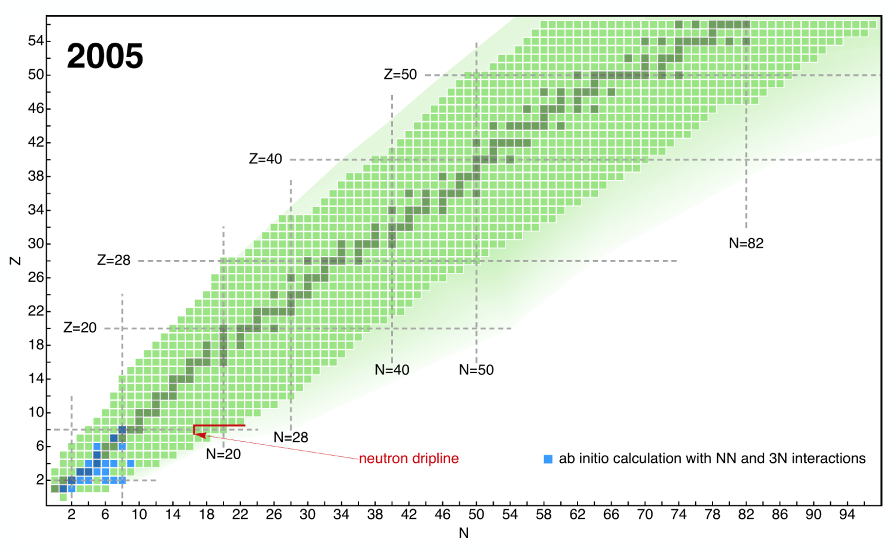
It is our firm belief that new developments in many-body theories for nuclear problems should contain as many as possible of the following ingredients:

- It should be fully microscopic and start with present two- and three-body interactions derived from *e.g.*, effective field theory;
- It can be improved upon systematically, e.g., by inclusion of three-body interactions and more complicated correlations;
- It allows for description of both closed-shell systems and valence systems;
- For nuclear systems where shell-model studies are the only feasible ones, viz., a small model space requiring an effective interaction, one should be able to derive effective two and three-body equations and interactions for the shell model;

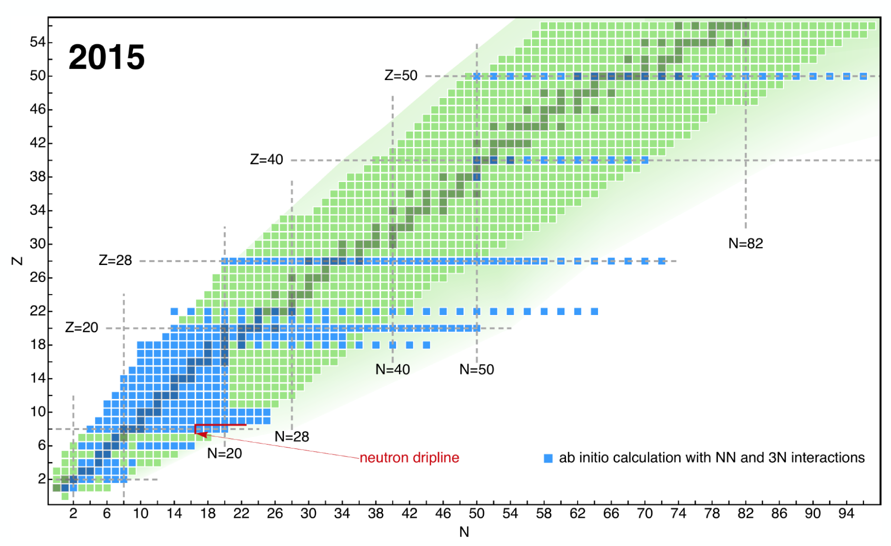
Many-body theories 2005, Barrett, Dean, MHJ, Vary, 2004, JPG **31**

- It is amenable to parallel computing;
- It can be used to generate excited spectra for nuclei like where many shells are involved (It is hard for the traditional shell model to go beyond one major shell. The inclusion of several shells may imply the need of complex effective interactions needed in studies of weakly bound systems); and
- Finally, nuclear structure results should be used in marrying microscopic many-body results with reaction studies. This will be another hot topic of future *ab initio* research.

Many-body theories 2005

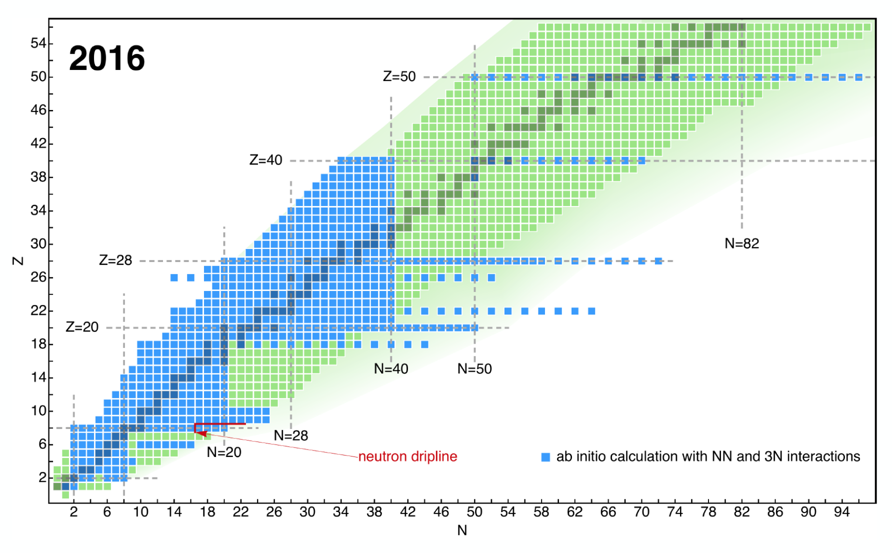


In 2015



2015
Z=50
Z=40
Z=28
Z=20
N=20
N=28
N=40
N=50
N=82
neutron dripline
ab initio calculation with NN and 3N interactions
Z
N
54
50
46
42
38
34
30
26
22
18
14
10
6
2
2
6
10
14
18
22
26
30
34
38
42
46
50
54
58
62
66
70
74
78
82
86
90
94

And in 2016



2016
Z=50
Z=40
Z=28
Z=20
N=20
N=28
N=40
N=50
N=82
neutron dripline
ab initio calculation with NN and 3N interactions
Z
N

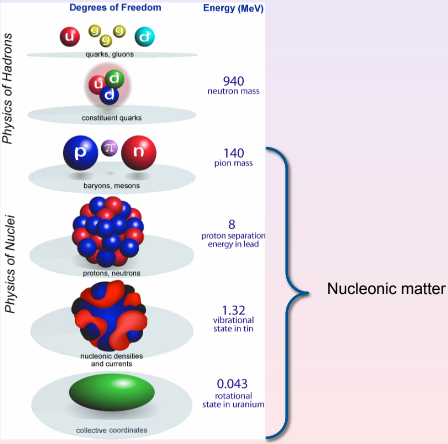
Huge progress in many-body theories

- Lattice QCD and lattice effective field theory
- FCI quantum Monte Carlo
- Full configuration interaction theory (Shell Model and Variants)
- In-Medium Similarity Renormalization Group
- Coupled Cluster theory
- Self-Consistent Green's Functions
- Various Monte Carlo methods
- Density functional theories
- Now and the future: quantum computing and machine learning
- And several other approaches

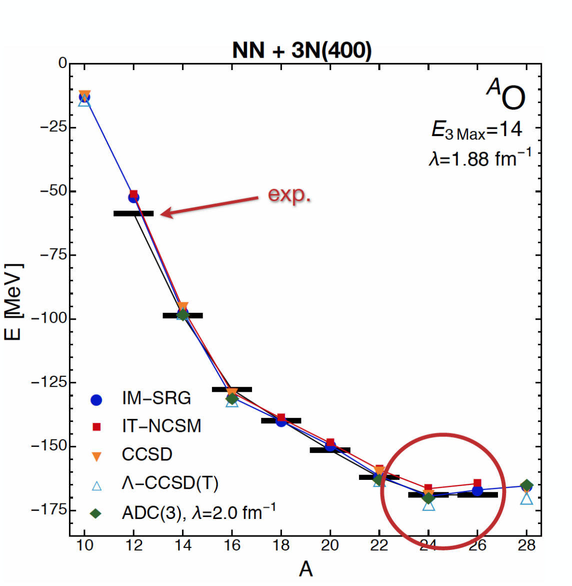
Important questions from QCD to the nuclear many-body problem

- How to derive the in medium nucleon-nucleon interaction from basic principles?
- How does the nuclear force depend on the proton-to-neutron ratio?
- What are the limits for the existence of nuclei?
- How can collective phenomena be explained from individual motion?
- Shape transitions in nuclei?

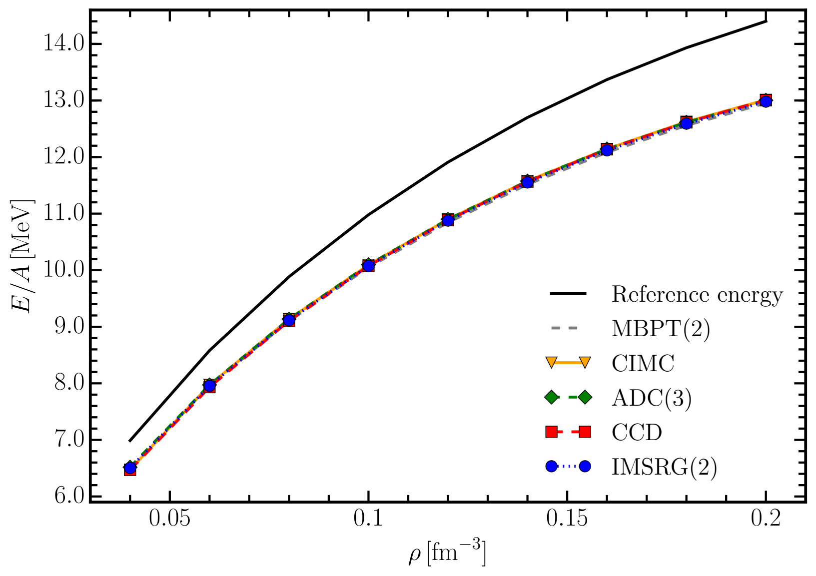
The many scales pose a severe challenge to *ab initio* descriptions of nuclear systems.



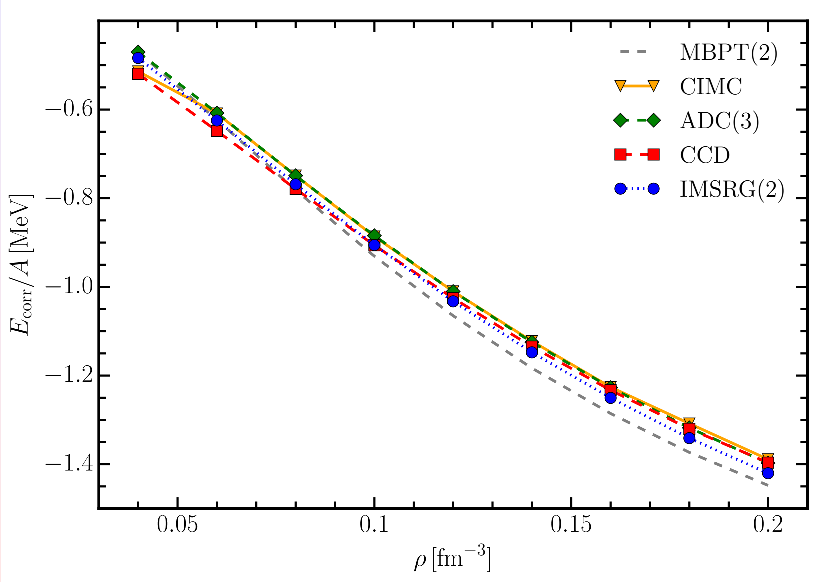
Consistency between many-body theories (Courtesy of Heiko Hergert@MSU)



Neutron matter calculations with simple Minnesota model for the force, Lecture Notes in Physics **936** (2017)



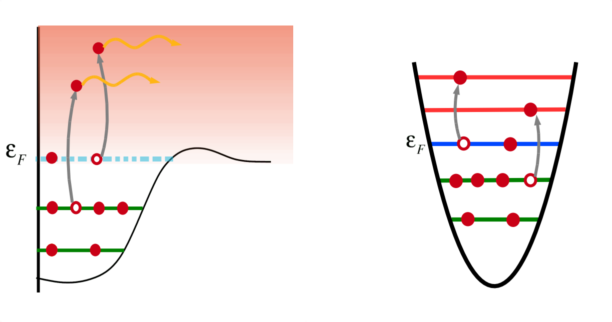
Neutron matter correlation energy, Lecture Notes in Physics **936** (2017)



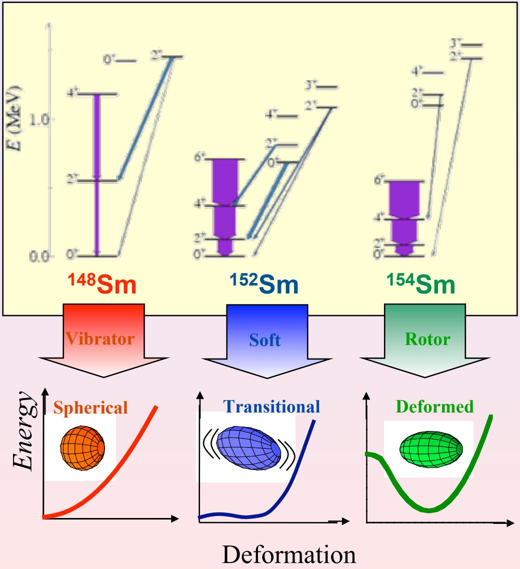
Halo nuclei and moving towards the limits of nuclear stability

Open Quantum System.
Coupling with continuum needs to be taken into account.

Closed Quantum System.
No coupling with external continuum.



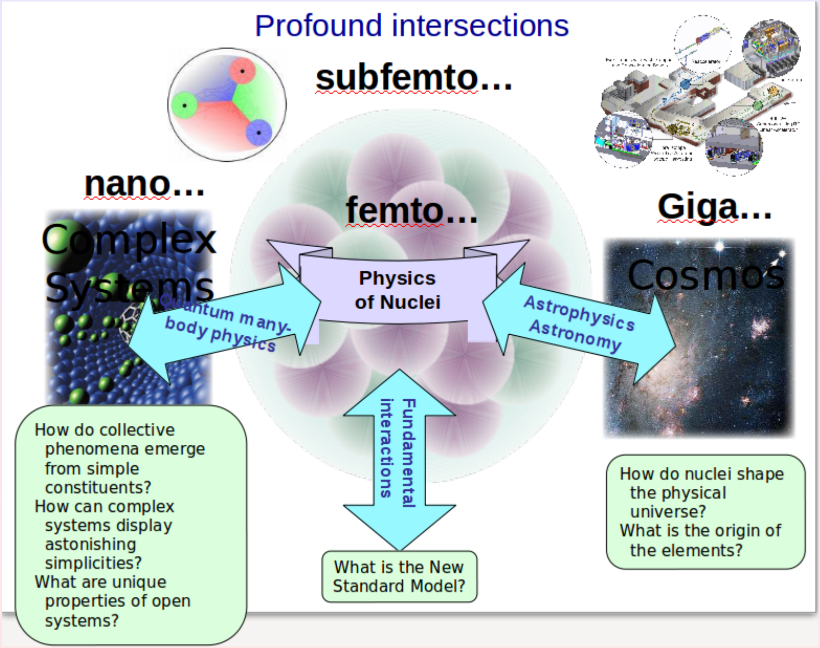
Shape coexistence and transitions, a multiscale challenge



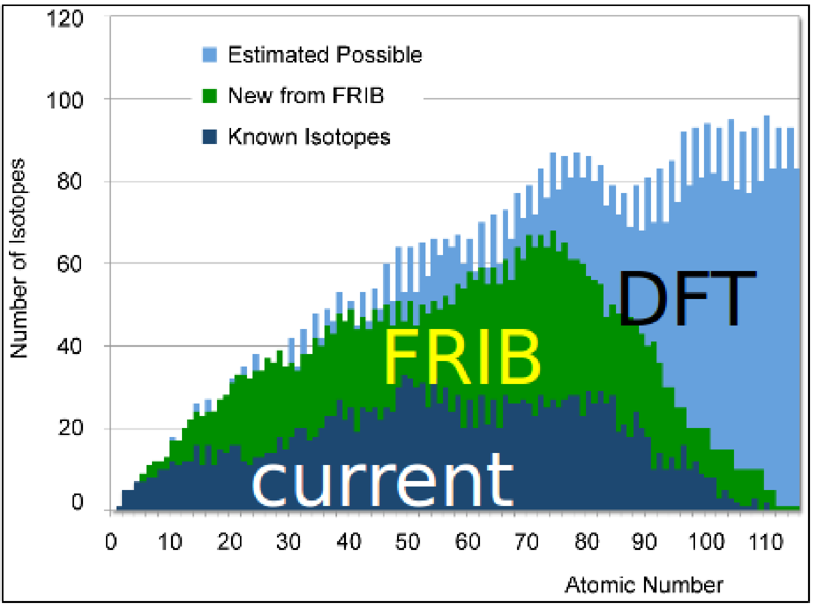
Challenges for theory

- Possible shape transitions, huge spaces needed to describe properly.
- Theory: need to marry *ab initio* methods with density functional theories in order to describe such systems
- Need a large wealth of experimental data to constrain theory

The many interesting intersections

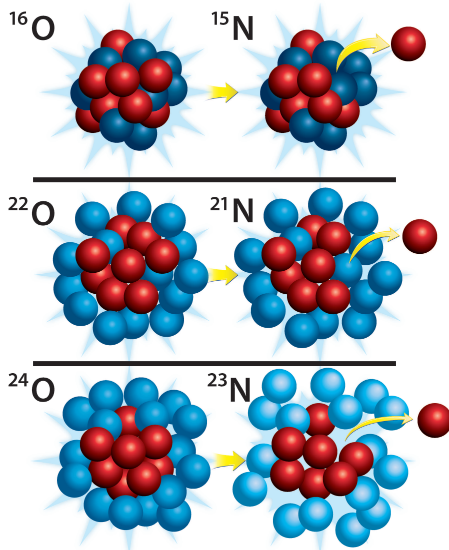


Known nuclei and predictions



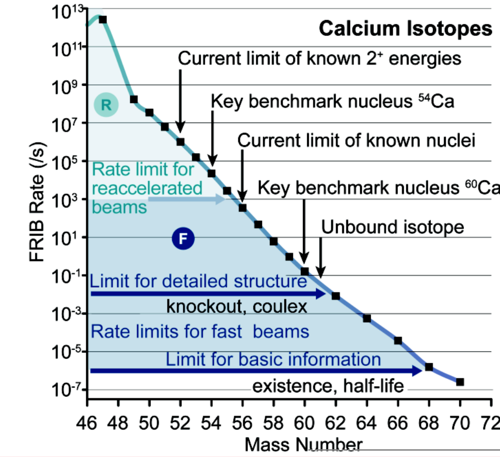
Do we understand the physics of dripline systems?

- The oxygen isotopes are the heaviest isotopes for which the drip line is well established.
- Two out of four stable even-even isotopes exhibit a doubly magic nature, namely ^{22}O ($Z = 8$, $N = 14$) and ^{24}O ($Z = 8$, $N = 16$).
- The structure of ^{22}O and ^{24}O is assumed to be governed by the evolution of the $1s_{1/2}$ and $0d_{5/2}$ one-quasiparticle states.
- The isotopes ^{25}O ^{26}O, ^{27}O and ^{28}O are outside the drip line, since the $0d_{3/2}$ orbit is not bound.



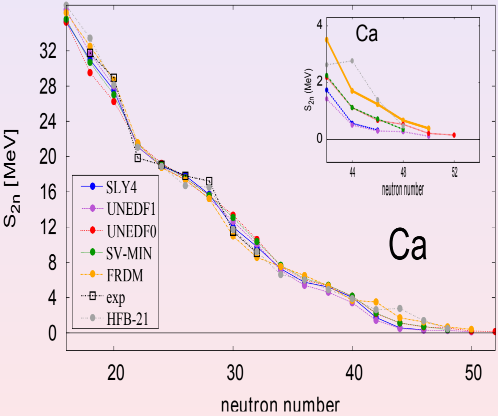
Calcium isotopes and FRIB plans and capabilities

- The Ca isotope exhibit several possible closed-shell nuclei ^{40}Ca, ^{48}Ca, ^{52}Ca, ^{54}Ca, and ^{60}Ca.
- Magic neutron numbers are then $N = 20, 28, 32, 34, 40$.
- Masses available up to ^{54}Ca, Gallant *et al.*,Phys. Rev. Lett. **109**, 032506 (2012) and K. Baum *et al*, Nature **498**, 346 (2013).
- Heaviest observed ^{57,58}Ca. NSCL experiment, O. B. Tarasov *et al.*, Phys. Rev. Lett. **102**, 142501 (2009). Cross sections for ^{59,60}Ca assumed small ($< 10^{-12}$mb).
- Which degrees of freedom prevail close to ^{60}Ca?



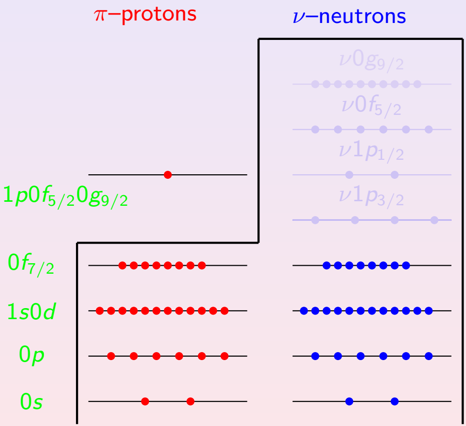
More on Calcium Isotopes

- **Mass models and mean field models predict the dripline at $A \sim 70$!** Important consequences for modeling of nucleosynthesis related processes.
- Can we predict reliably which is the last stable calcium isotope?
- And how does this compare with popular mass models on the market?
- And which parts of the underlying forces are driving the physics towards the dripline?



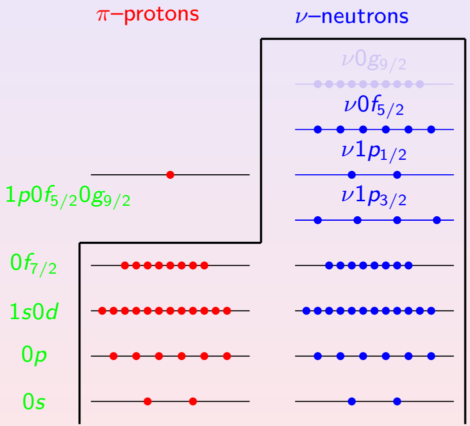
Other chains of isotopes of crucial interest for FRIB like physics: nickel isotopes

- This chain of isotopes exhibits four possible closed-shell nuclei ^{48}Ni, ^{56}Ni, ^{68}Ni and ^{78}Ni. **FRIB plans systematic studies from ^{48}Ni to ^{88}Ni.**
- Neutron skin possible for ^{84}Ni at FRIB.
- Which is the best closed-shell nucleus? And again, which part of the nuclear forces drives it? Is it the strong spin-orbit force, the tensor force, or ..?



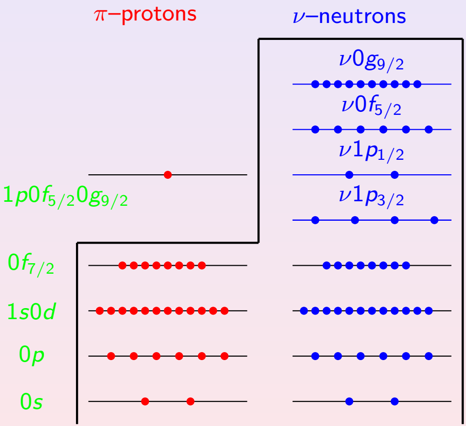
Other chains of isotopes of crucial interest for FRIB like physics: nickel isotopes

- This chain of isotopes exhibits four possible closed-shell nuclei ^{48}Ni, ^{56}Ni, ^{68}Ni and ^{78}Ni. **FRIB plans systematic studies from ^{48}Ni to ^{88}Ni.**
- Neutron skin possible for ^{84}Ni at FRIB.
- Which is the best closed-shell nucleus? And again, which part of the nuclear forces drives it? Is it the strong spin-orbit force, the tensor force, or ..?



Other chains of isotopes of crucial interest for FRIB like physics: nickel isotopes

- This chain of isotopes exhibits four possible closed-shell nuclei ^{48}Ni, ^{56}Ni, ^{68}Ni and ^{78}Ni. **FRIB plans systematic studies from ^{48}Ni to ^{88}Ni.**
- Neutron skin possible for ^{84}Ni at FRIB.
- Which is the best closed-shell nucleus? And again, which part of the nuclear forces drives it? Is it the strong spin-orbit force, the tensor force, or ..?

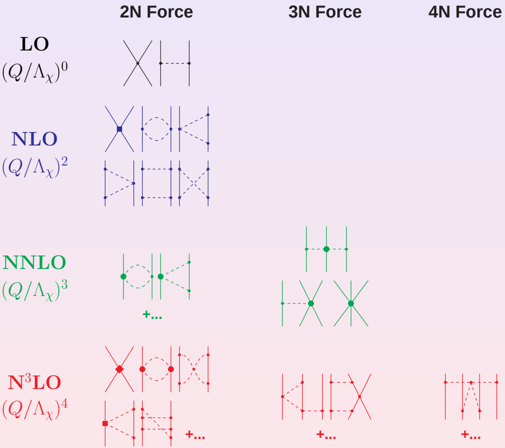


Tin isotopes

From ^{100}Sn to nuclei beyond ^{132}Sn

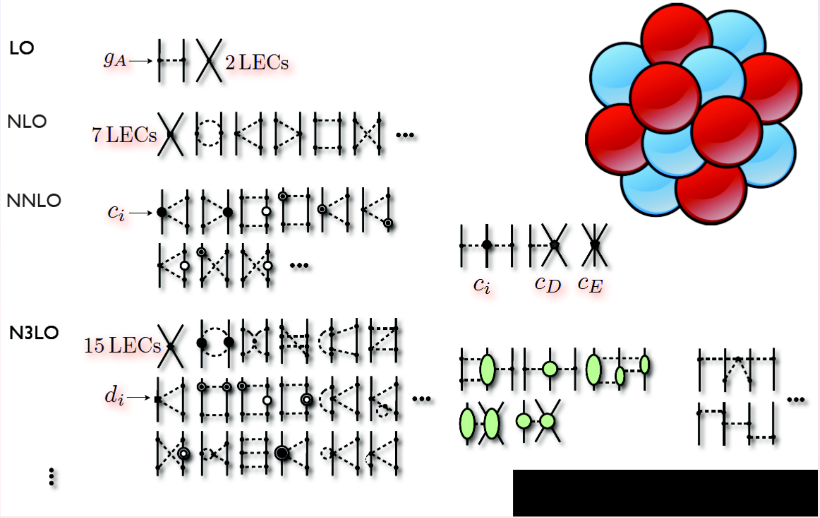
1. We will most likely be able to run coupled-cluster calculations for nuclei like ^{100}Sn, ^{114}Sn, ^{116}Sn, ^{132}Sn, ^{140}Sn and $A \pm 1$ and $A \pm 2$ nuclei within the next one to two years. FRIB can reach to ^{140}Sn. Interest also for EOS studies.
2. Can then test the development of many-body forces for an even larger chain of isotopes.
3. ^{137}Sn is the last reported neutron-rich isotope (with half-life).
4. To understand which parts of the nuclear Hamiltonian that drives the properties of such nuclei will be crucial for our understanding of the stability of matter.
5. Zr isotopes form also long chains of neutron-rich isotopes. **FRIB plans from ^{80}Zr to ^{120}Zr.**
6. And why neutron rich isotopes? **Here the possibility to constrain nuclear forces from in-medium results.**

Nuclear interactions from Effective Field Theory (Δ-less)



- Nucleons and Pions as effective degrees of freedom only. Most general Lagrangian consistent with all symmetries of low-energy QCD.
- Chiral perturbation theory for different orders (ν) of the expansion in terms of $(Q/\Lambda_\chi)^\nu$.
- At order $\nu = 4$ one should include four-body forces in many-body calculations! Not including these will result in what we call missing many-body correlations.

Forces in Nuclear Physics (without isobars)



[redacted]

The future: Hamiltonians from Lattice QCD