Course Summary

Nuclear Talent course 2018 at Henan Normal University

Kevin Fossez, Morten Hjorth-Jensen, Thomas Papenbrock, Ragnar Stroberg, and Yu-Min Zhao

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:

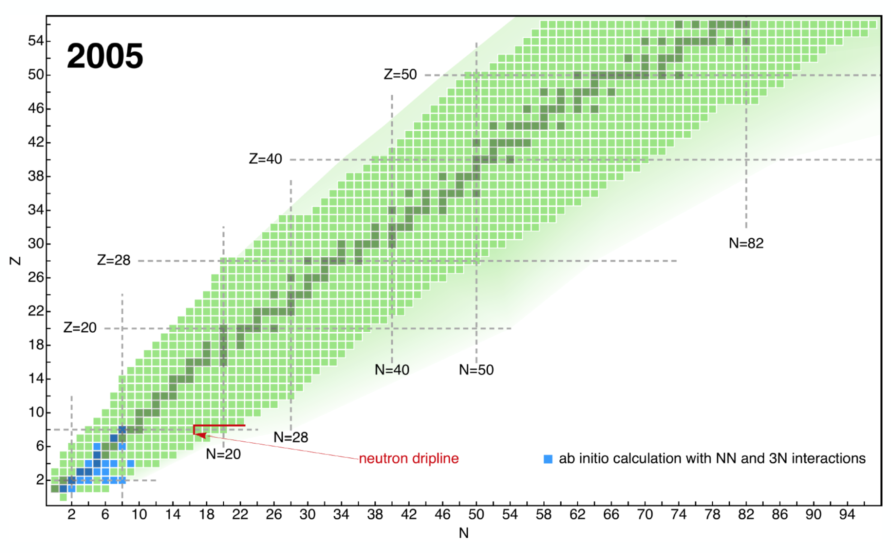
- It should be fully microscopic and start with present two- and three-body interactions derived from *e.g.*, effective field theory;
- It can be improved upon systematically, e.g., by inclusion of three-body interactions and more complicated correlations;
- It allows for description of both closed-shell 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**

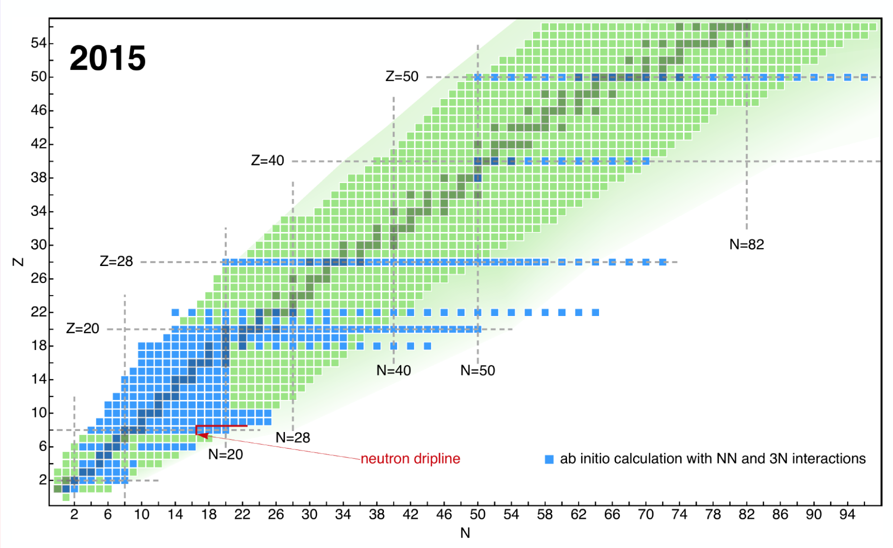
- It is amenable to parallel computing;
- It can be used to generate excited spectra for nuclei like where many shells are involved (It is hard for the traditional shell model to go beyond one major shell. The inclusion of several shells may imply the need of complex effective interactions needed in 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.

Most of these topics are nowadays standard ingredients in most many-body methods

Many-body theories 2005

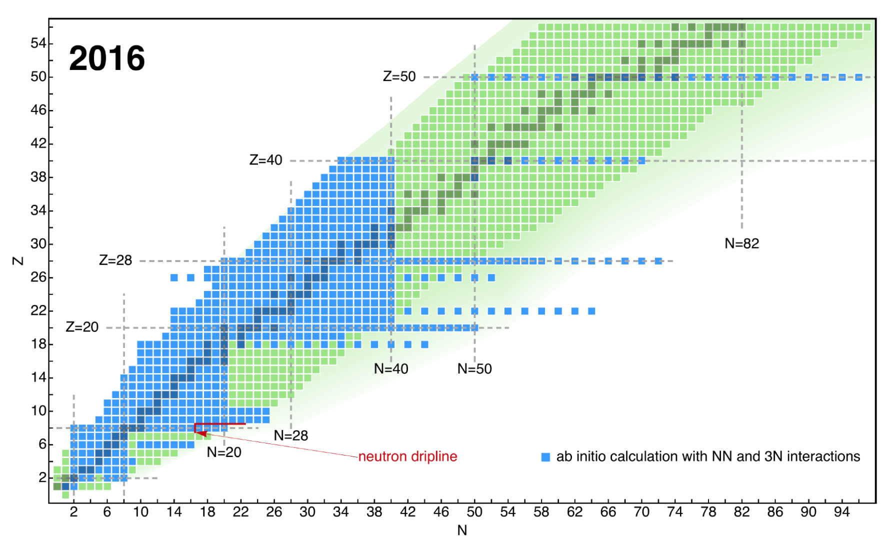


In 2015



2015
Z=50
Z=40
Z=28
Z=20
N=82
N=40
N=50
N=28
N=20
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 2018 (not complete)



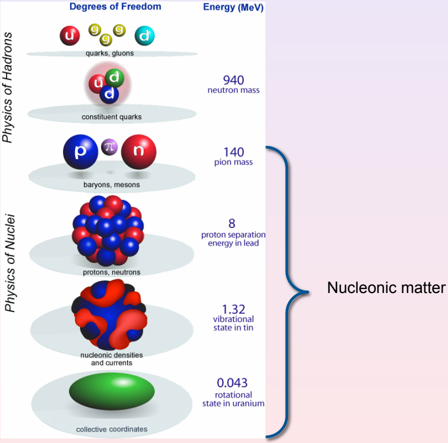
Huge progress in many-body theories

- 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

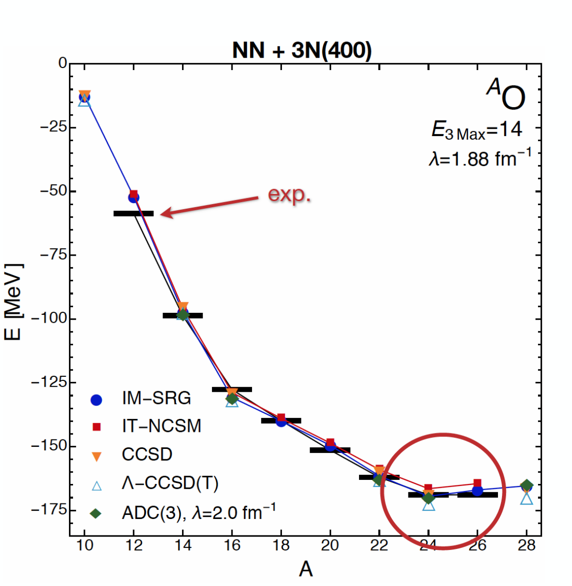
Important questions from QCD to the nuclear many-body problem

- 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?

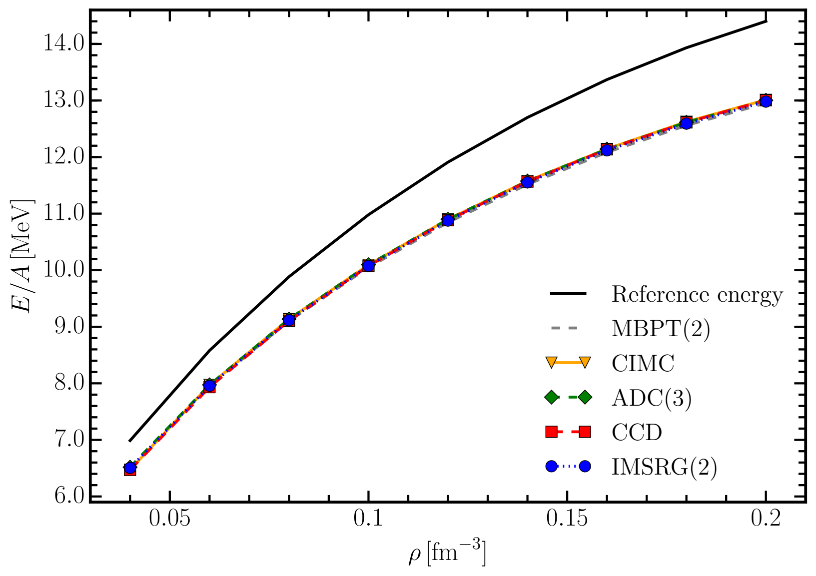
The many scales pose a severe challenge to *ab initio* descriptions of nuclear systems.



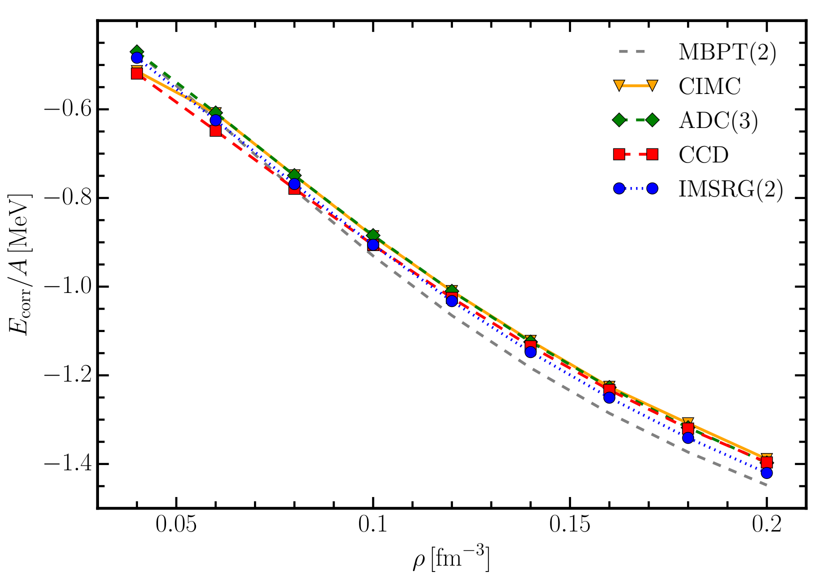
Consistency between many-body theories (Courtesy of Heiko Hergert@MSU)



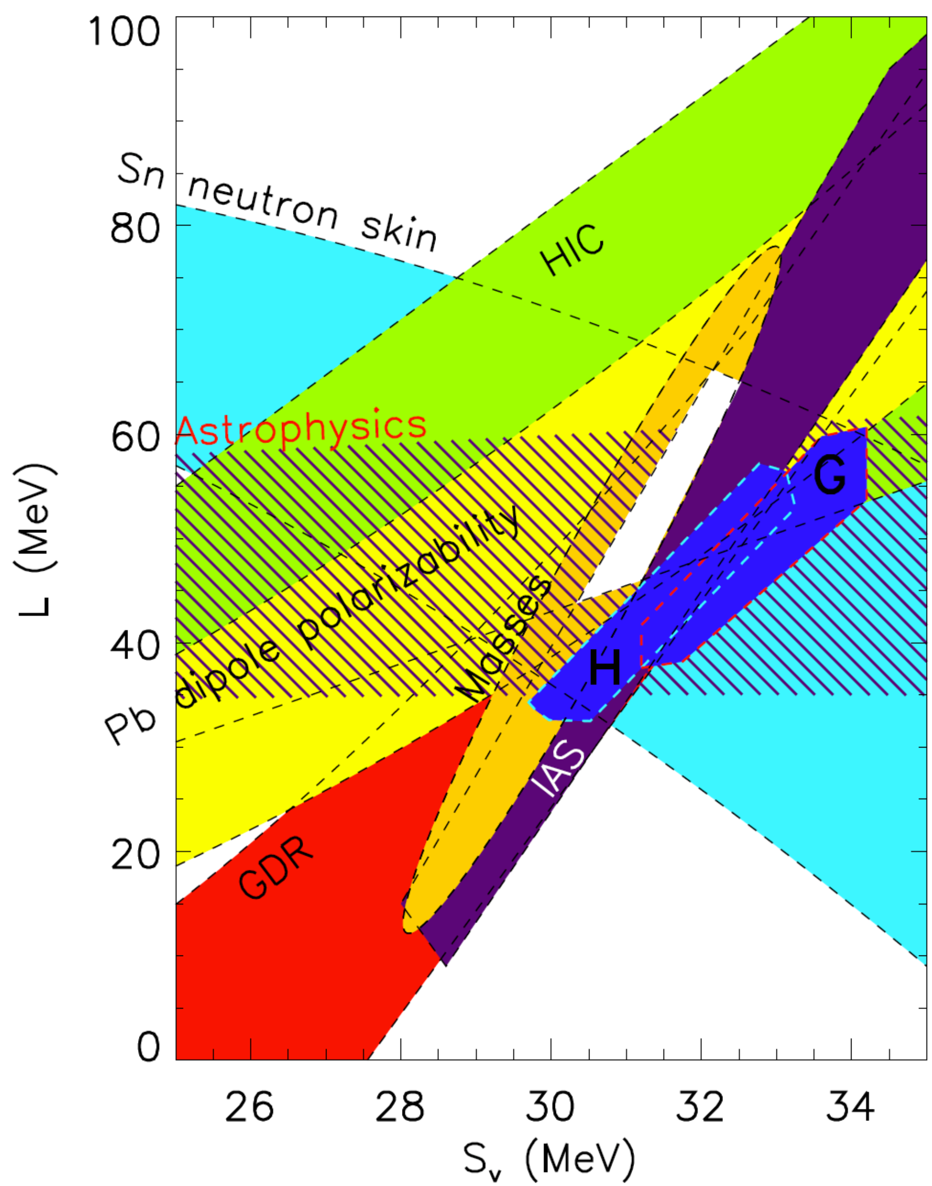
Neutron matter calculations with simple Minnesota model for the force, Lecture Notes in Physics **936** (2017)



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

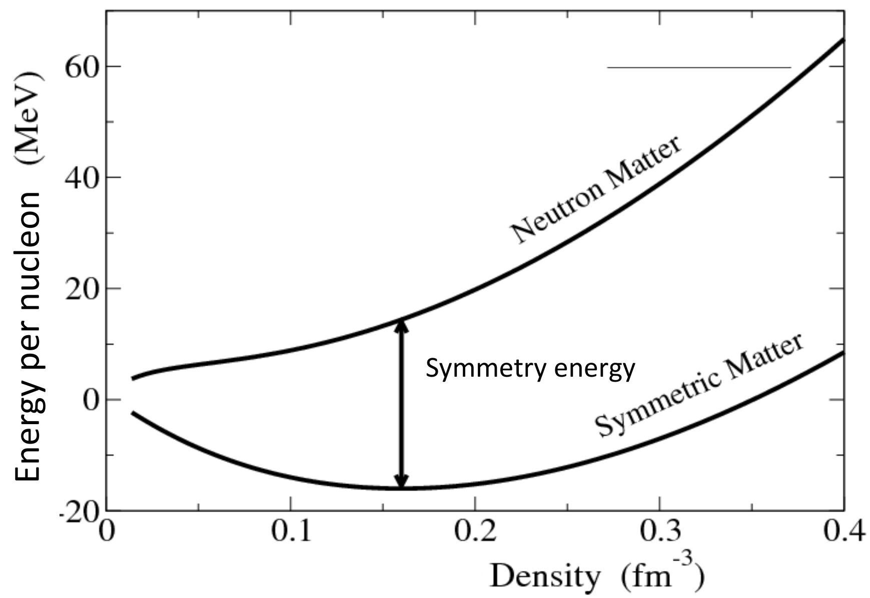


Nuclear matter connects neutron stars and nuclei

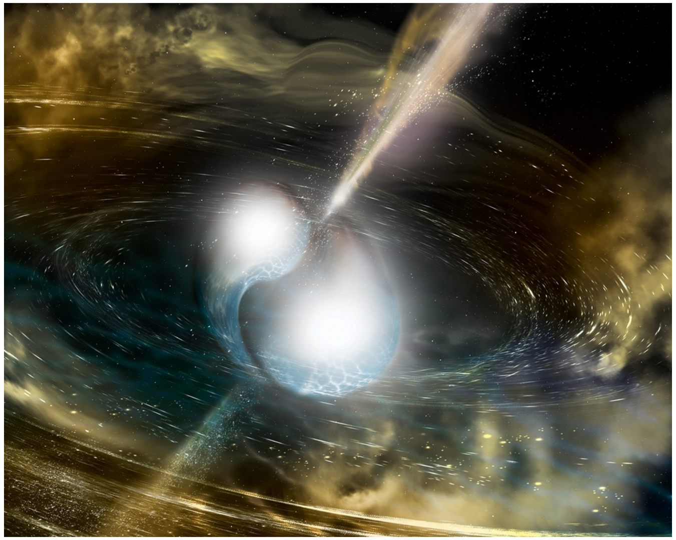


Lattimer & Lim 2013; Lattimer & Steiner 2014

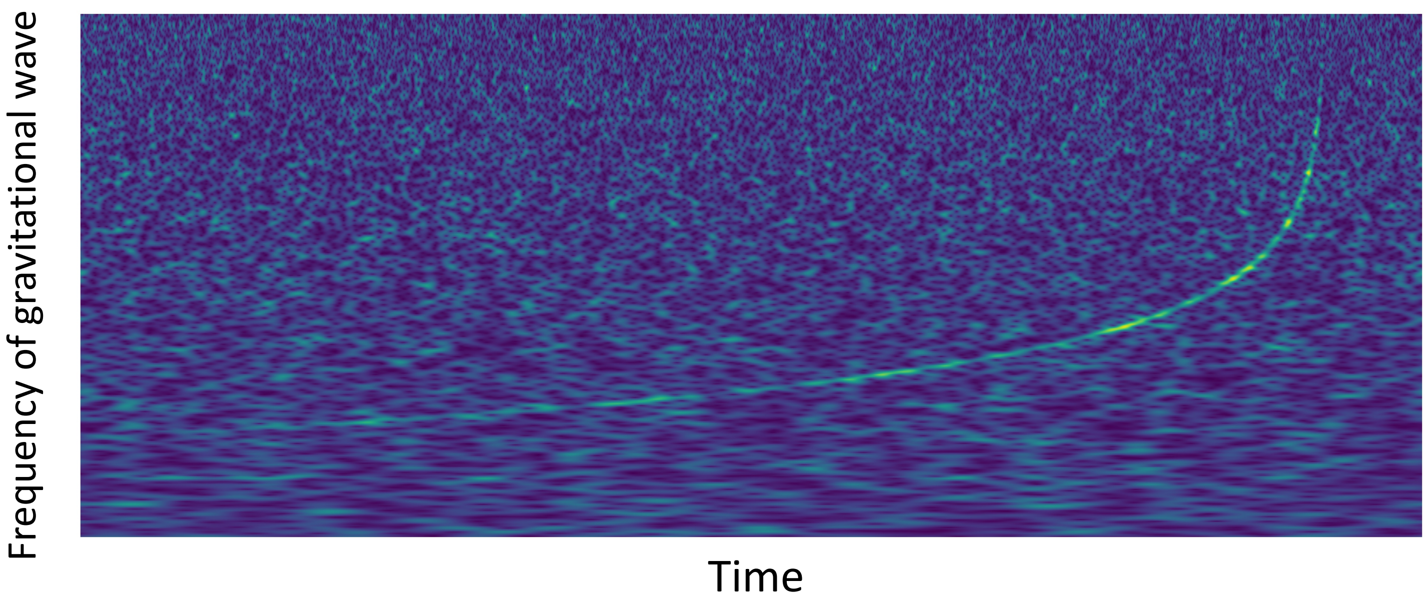
Symmetry energy connects neutron stars to nuclei, see review by Tsang et al., Phys. Rev. C (2012)



Nuclear equation of state from neutron star mergers



Nuclear equation of state describes "ring down" signal of gravitational waves from neutron star merger
(pictures from LIGO website)



Some Extensions to Your Projects

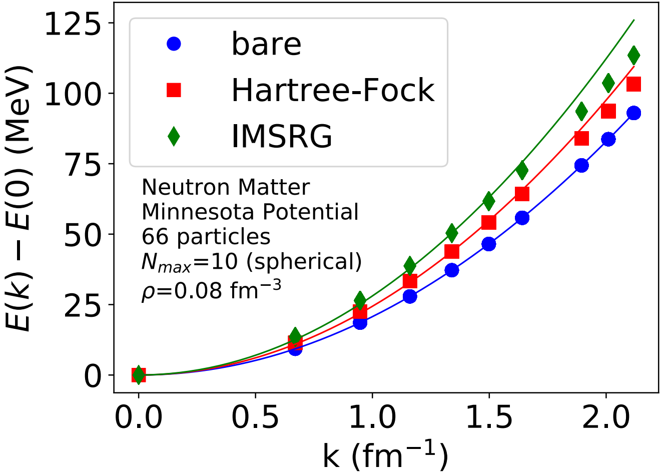
TALENT School 2018

Profiling

```
================== TIMES ======================
       0.0886           Interaction::MinnesotaPotential
     998.1878           Solvers::IMSRG::Commutator
     266.0298           Solvers::IMSRG::Commutator_Mpp/Mhh_loop
      60.1362           Solvers::IMSRG::Commutator_[1,2]->2
      51.6677           Solvers::IMSRG::Commutator_ph_antisymmetrize
     113.9078           Solvers::IMSRG::Commutator_ph_matmult
     260.9087           Solvers::IMSRG::Commutator_ph_transform
     220.2985           Solvers::IMSRG::Commutator_undo_ph_transform
    1185.9728           Solvers::IMSRG::EvolveMagnus
       0.1314           Solvers::MBPT2
       7.2504           Solvers::MBPT3
================= COUNTERS ==================
          514           Solvers::IMSRG::Commutator
```

Dispersion

Just print out the 1-body piece of $\bar{H}$ or $H(s)$:

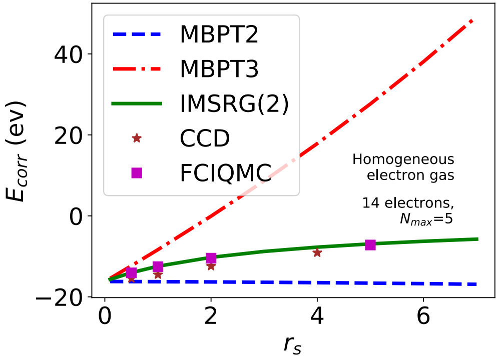


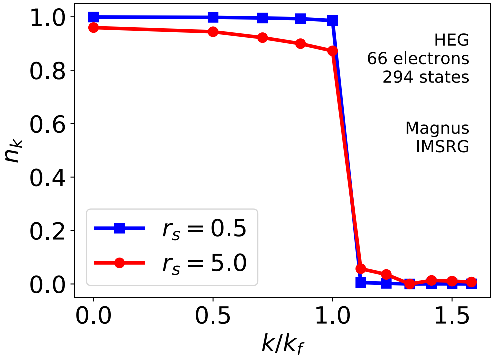
Homogeneous Electron Gas

$$\langle \vec{k}' | V_{coul} | \vec{k} \rangle = \frac{1}{L^3} \frac{e^2}{|\vec{q}|^2}$$

$$n_k = \frac{1}{\mathcal{N}_k} \sum_{s',\vec{k}'} \delta_{k^2,k'^2} \langle \psi | a^\dagger_{\vec{k}',s'} a_{\vec{k}',s'} | \psi \rangle$$

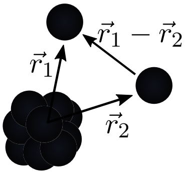
$$\mathcal{O}(s) = e^{\Omega(s)} \mathcal{O}(0) e^{-\Omega(s)}$$





Wigner-Seitz radius r_s: $\frac{4\pi}{3}(r_s a_0)^3 = \frac{1}{\rho}$

Finite Nuclei



- Harmonic oscillator basis
  $\phi(\vec{r}, s) = \mathcal{R}_{nl}(r) Y_\ell^m(\theta, \phi) \chi_s$
- Potential depends on *relative* coordinate:
  $V(\vec{r}_1 - \vec{r}_2)$ (normal ordering?)
- Switch to relative/COM coordinates
  $|\phi(\vec{r}_1), s_1, \phi(\vec{r}_2), s_2\rangle \Rightarrow |\phi(\vec{r}), \phi(\vec{R}), S\rangle$
- Talmi-Moshinsky Transformation:
  $|n_1 \ell_1 n_2 \ell_2 L\rangle =$
  $\sum_{nN\lambda\Lambda} \langle n_1 \ell_1 n_2 \ell_2 | n \lambda N \Lambda \rangle_L | n \lambda N \Lambda L\rangle$

$j - j$ coupling

$$(\ell, s) \to j, \quad (j_1 j_2) \to J$$

$$|\alpha_p j_p m_p, \alpha_q j_q m_q\rangle = \frac{1}{\sqrt{1 + \delta_{pq}}} \sum_{JM} \mathcal{C}^{JM}_{j_p m_p j_q m_q} |\alpha_p j_p, \alpha_q j_q JM\rangle$$

H is block-diagonal in J, and independent of M.

Need these savings to reach medium-mass nuclei.

Neutron matter from EFT potentials

Structure of nucleon-nucleon potentials

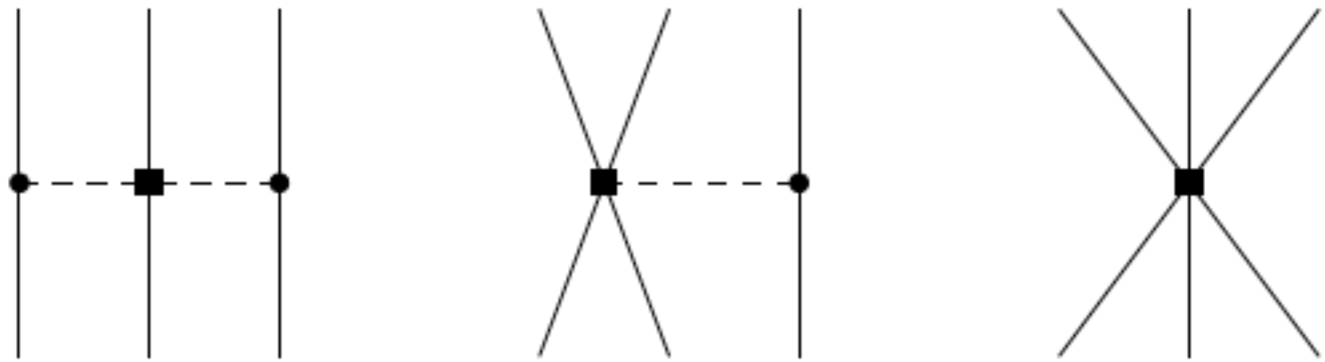
$$
\begin{aligned}
V(\vec{p}\,', \vec{p}) \;=\;& V_C + \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 W_C \\
&+ [V_S + \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 W_S]\, \vec{\sigma}_1 \cdot \vec{\sigma}_2 \\
&+ [V_{LS} + \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 W_{LS}] \left(-i\vec{S} \cdot (\vec{q} \times \vec{k})\right) \\
&+ [V_T + \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 W_T]\, \vec{\sigma}_1 \cdot \vec{q}\, \vec{\sigma}_2 \cdot \vec{q} \\
&+ [V_{\sigma L} + \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 W_{\sigma L}]\, \vec{\sigma}_1 \cdot (\vec{q} \times \vec{k})\, \vec{\sigma}_2 \cdot (\vec{q} \times \vec{k})
\end{aligned}
$$

V_α and W_α ($\alpha = C, S, LS, T, \sigma L$) can be expressed as functions of q and k

$$
\begin{aligned}
\vec{q} &\equiv \vec{p}\,' - \vec{p} && \text{is the momentum transfer,} \\
\vec{k} &\equiv \tfrac{1}{2}(\vec{p}\,' + \vec{p}) && \text{the average momentum,} \\
\vec{S} &\equiv \tfrac{1}{2}(\vec{\sigma}_1 + \vec{\sigma}_2) && \text{the total spin,}
\end{aligned}
$$

See, e.g., Machleidt & Entem, Phys. Rep. (2011) for details on the functions V_α and W_α. You could implement this! There are several new forces for which we do not know the saturation properties. How do local vs. nonlocal cutoffs behave?

Three nucleon forces



$$V_{2\mathrm{PE}}^{3\mathrm{NF}} = \left(\frac{g_A}{2f_\pi}\right)^2 \frac{1}{2} \sum_{i\neq j\neq k} \frac{(\vec{\sigma}_i \cdot \vec{q}_i)(\vec{\sigma}_j \cdot \vec{q}_j)}{(q_i^2 + m_\pi^2)(q_j^2 + m_\pi^2)} F_{ijk}^{\alpha\beta}\, \tau_i^\alpha \tau_j^\beta$$

$$F_{ijk}^{\alpha\beta} = \delta^{\alpha\beta} \left[-\frac{4c_1 m_\pi^2}{f_\pi^2} + \frac{2c_3}{f_\pi^2}\, \vec{q}_i \cdot \vec{q}_j \right] + \frac{c_4}{f_\pi^2} \sum_\gamma \epsilon^{\alpha\beta\gamma}\, \tau_k^\gamma\, \vec{\sigma}_k \cdot [\vec{q}_i \times \vec{q}_j]$$

$$V_{1\mathrm{PE}}^{3\mathrm{NF}} = D\, \frac{g_A}{8f_\pi^2} \sum_{i\neq j\neq k} \frac{\vec{\sigma}_j \cdot \vec{q}_j}{q_j^2 + m_\pi^2} (\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j)(\vec{\sigma}_i \cdot \vec{q}_j)$$

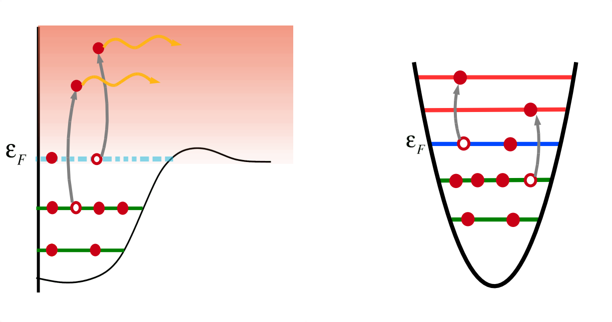
$$V_{\mathrm{ct}}^{3\mathrm{NF}} = E\, \frac{1}{2} \sum_{j\neq k} \boldsymbol{\tau}_j \cdot \boldsymbol{\tau}_k$$

You could implement this as normal-ordered two-body forces!

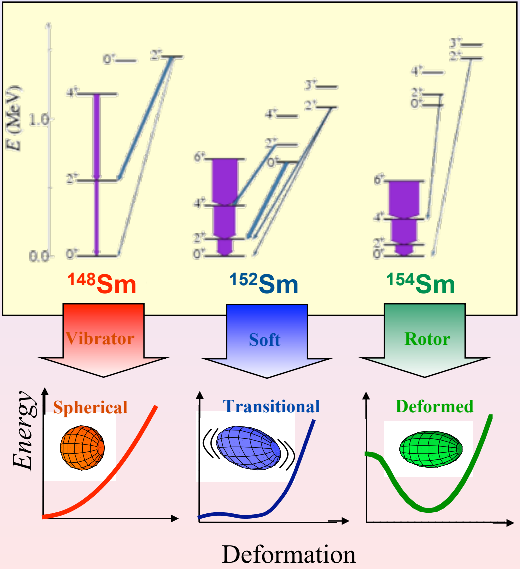
Halo nuclei and moving towards the limits of nuclear stability

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

Closed Quantum System.
No coupling with external continuum.



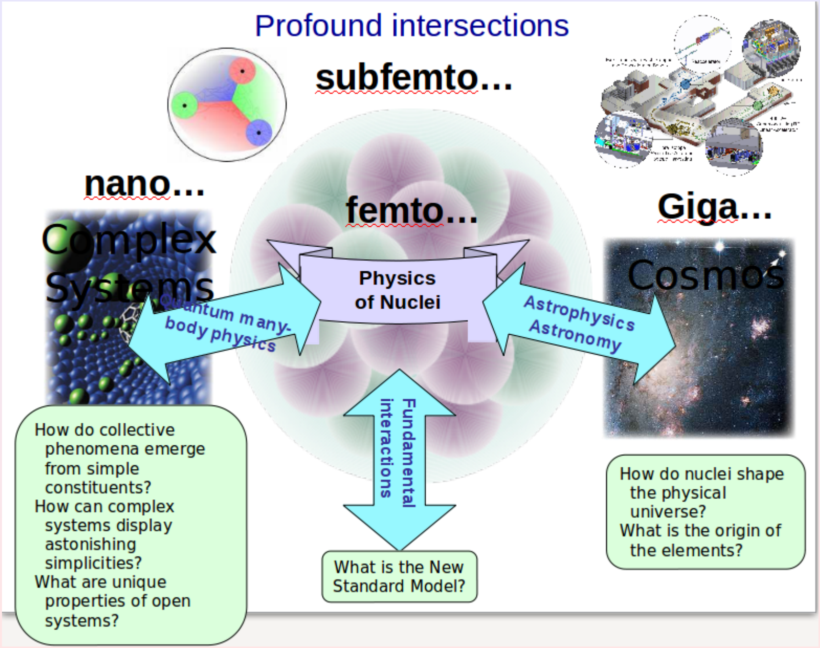
Shape coexistence and transitions, a multiscale challenge



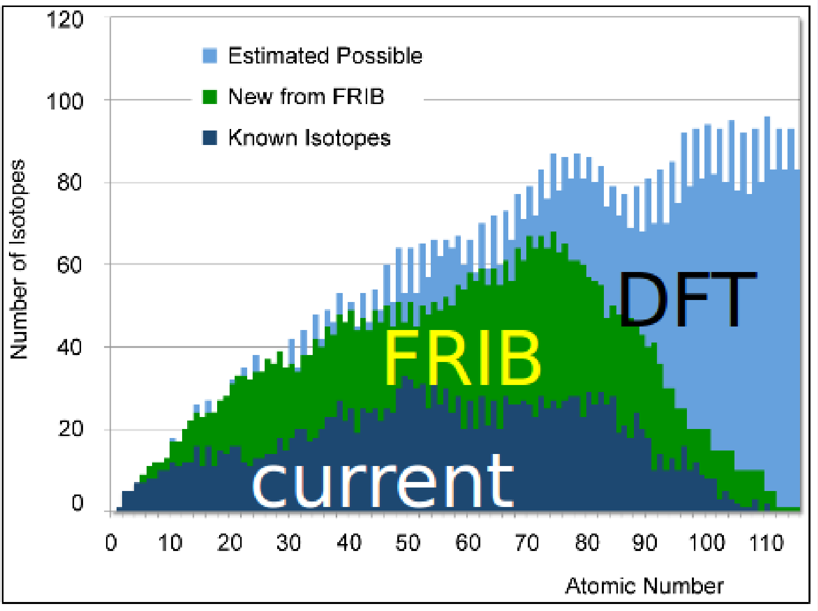
Challenges for theory

- 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

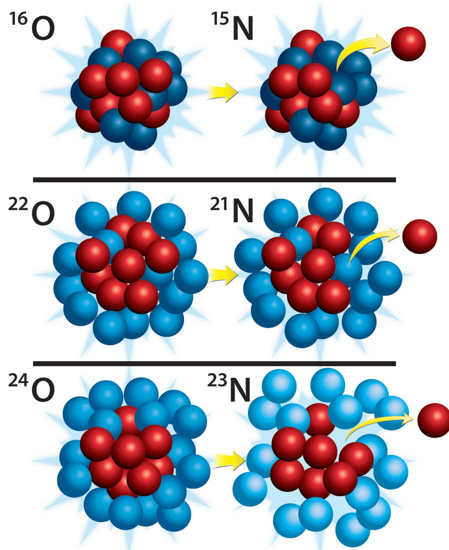


Known nuclei and predictions



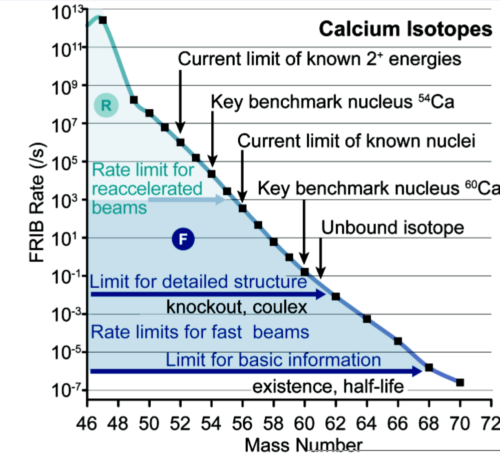
Do we understand the physics of dripline systems?

- 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.



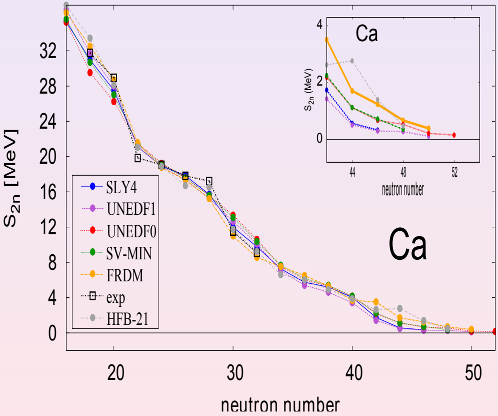
Calcium isotopes and FRIB plans and capabilities

- 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 ^{60}Ca. NSCL experiment, O. B. Tarasov *et al.*, Phys. Rev. Lett. **121**, 022501 (2018).
- Which degrees of freedom prevail close to ^{60}Ca?



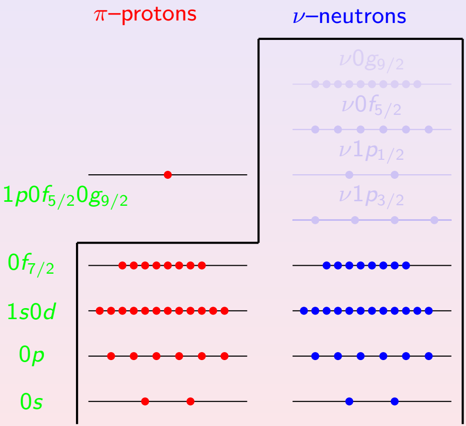
More on Calcium Isotopes

- **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 ..?



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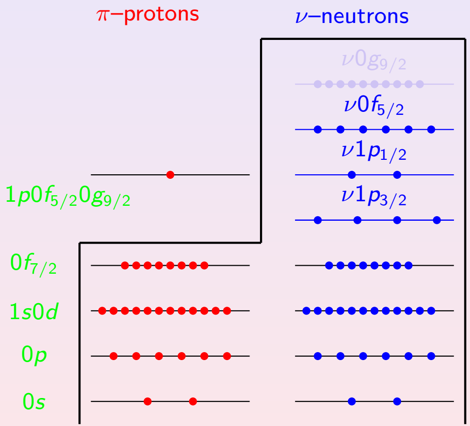

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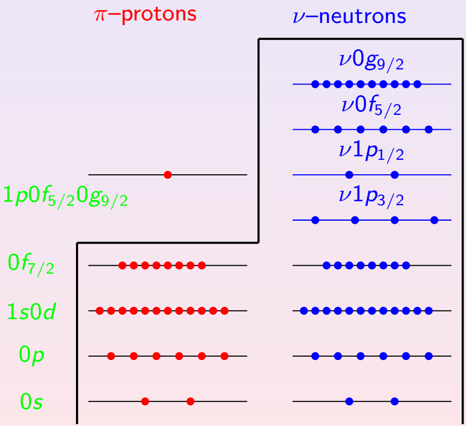
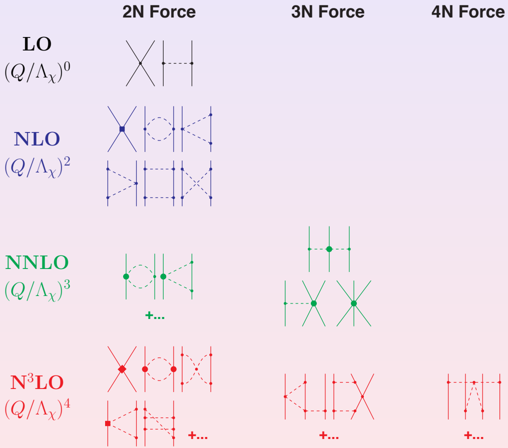


Tin isotopes

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

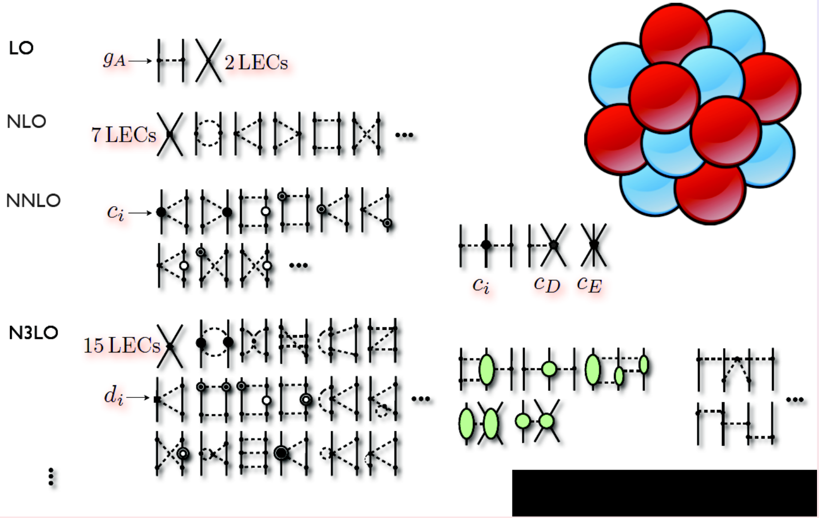
1. We are able to run coupled-cluster calculations for nuclei like ^{100}Sn and $A\pm 1$ and $A\pm 2$ nuclei, see Morris *et al*, Phys. Rev. Lett. **120**, 152503 (2018). FRIB can reach to ^{140}Sn. Interest also for EOS studies.
2. Can then test the development of many-body forces for an even larger 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)

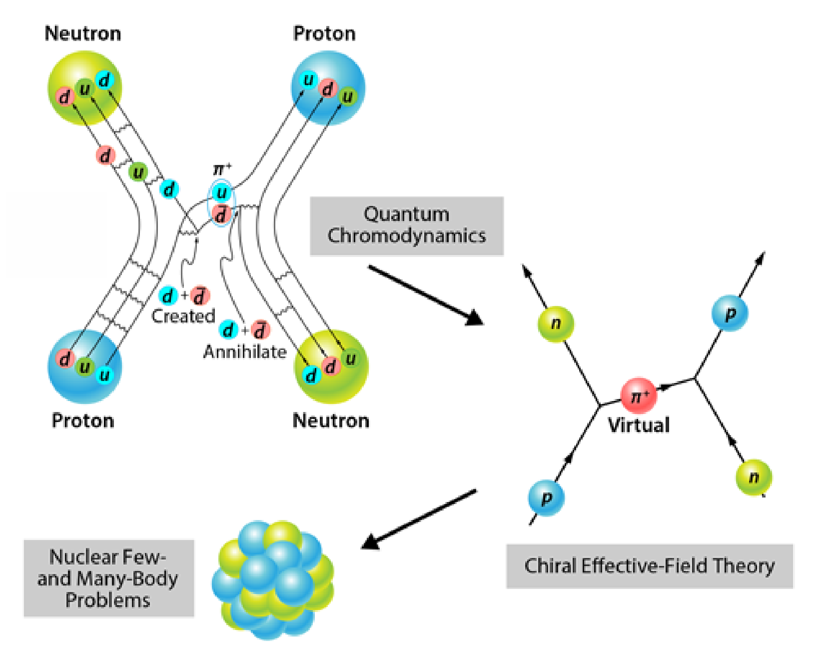


- Nucleons and Pions as effective degrees of freedom only. Most general Lagrangian consistent with all symmetries of low-energy QCD.
- Chiral perturbation theory for different orders (ν) of the expansion in terms of $(Q/\Lambda_\chi)^\nu$.
- At order $\nu = 4$ one should include four-body forces in many-body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

Forces in Nuclear Physics (without isobars)



The future: Hamiltonians from Lattice QCD



Talent courses in 2019

- Nuclear Forces: From Lattice QCD to nuclear effective field theories, approved and to be held at the ECT*, Trento, Italy during July or August 2019
- Nuclear Reaction theory, most likely at MSU or University of Ohio during summer 2019
- New course in China next year!!!

Thanks a million for a fantastic participation. We as teachers have truly enjoyed this time together with you all and it is sad to say that it has to end. You have all been incredible and we hope to see you all again in the near future. Best wishes from all of us and good luck with your thesis work and future projects.

Many thanks to

- The students for their active participation, many questions, dedication, hard work, and accomplishments
- The local organizers: Chunwang Ma, Furong Xu, and Shang-Gui Zhou
- Chunwang Ma for hosting this TALENT school at Henan Normal University
- Qiao Chunyuan for administrative support
- Baishan Hu, Weiguang Jiang, and Zhonghao Sun for their lectures, for answering questions, and for giving advise and help in the afternoons