FRIB science (lecture 2)

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overview

Lecture 1:

- basic concepts and language
- big science questions
- cool phenomena
- production of the exotic stuff
- what is FRIB?

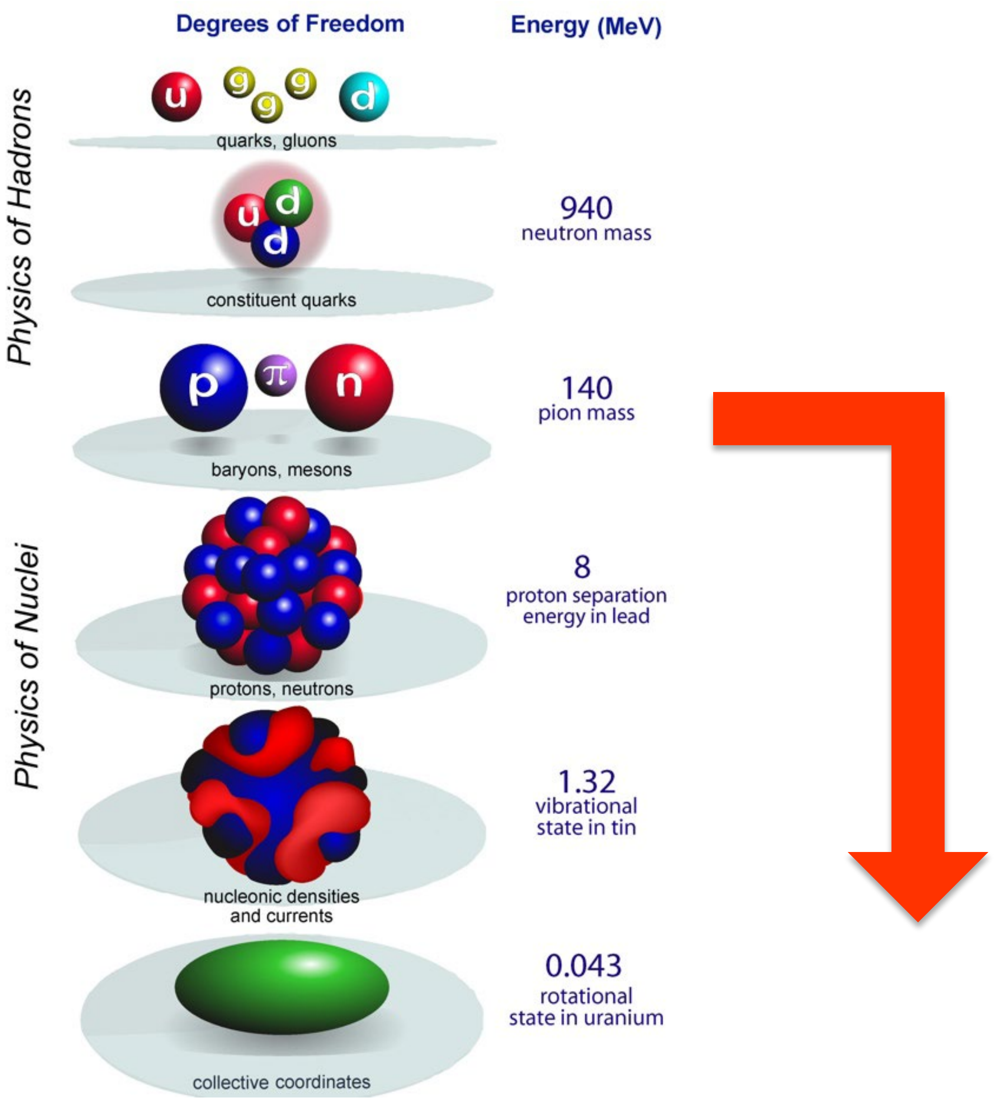
Lecture 2

- connection to QCD
- the many-body problem
- forces and EFT
- various applications
- current status for nuclear structure

Lecture 3

- nuclear reactions as a tool
- basics concepts in nuclear reactions
- some examples from my research

Multiple scales in nuclear physics



Our building blocks are nucleons

nuclei: a tough many-body problem

$$H_A = -\sum_{i=1}^{A} \frac{\hbar^2}{2m_i}\nabla^2_{\mathbf{r}_i} + \frac{\hbar^2}{2M}\nabla^2_{\mathbf{S}} + \sum_{i>j}^{A} V^{(2)}(\mathbf{r}_i - \mathbf{r}_j) + \sum_{i>j>k}^{A} V^{(3)}(\mathbf{r}_i - \mathbf{r}_j, \mathbf{r}_i - \mathbf{r}_k),$$

$$H_A \Phi_{I\mu}(\boldsymbol{\rho}_1, \ldots, \boldsymbol{\rho}_{A-1}) = E_I \Phi_{I\mu}$$

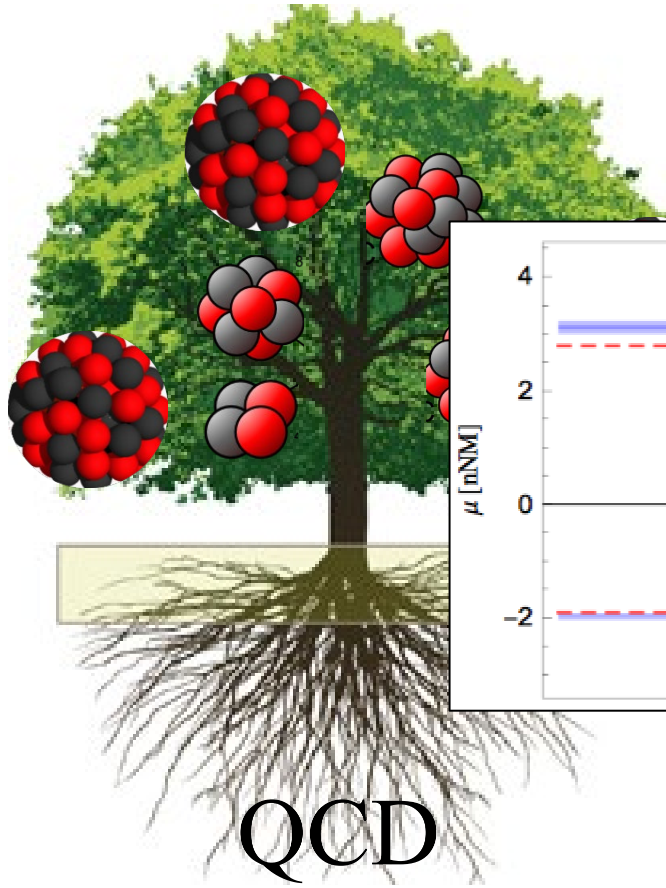
$$\lim_{\boldsymbol{\rho}_i \to \infty} \Phi_{I\mu}(\ldots, \boldsymbol{\rho}_i, \ldots) = 0$$

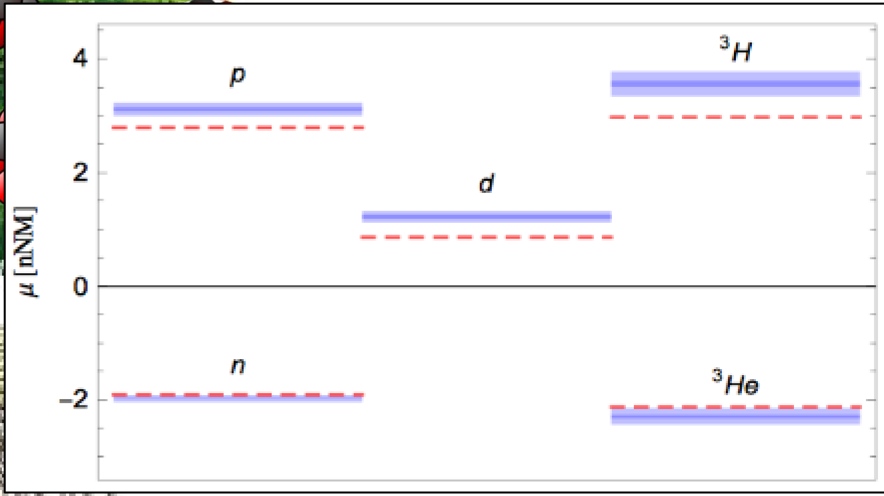
$$\int \mathrm{d}\boldsymbol{\rho}_1 \ldots \int \mathrm{d}\boldsymbol{\rho}_{A-1} |\Phi_{I\mu}(\boldsymbol{\rho}_1, \ldots, \boldsymbol{\rho}_{A-1})|^2 = 1$$

non-relativistic!

The fundamental theory: QCD

A reliable theory for nuclei needs to be rooted in QCD!





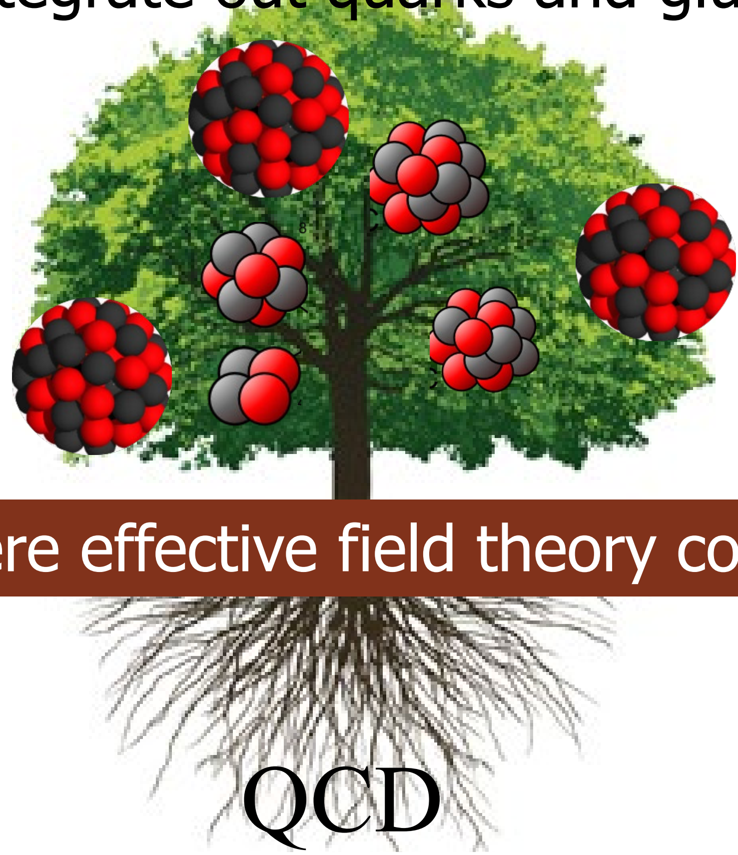
LQCD predictions for magnetic moments A<4

The fundamental theory: QCD

QCD may one day calculate the lightest nuclei

but what about ^{238}U?

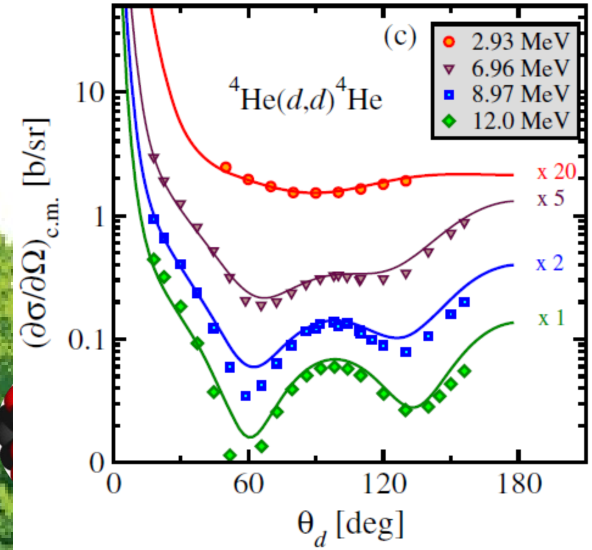
we need to integrate out quarks and gluons...



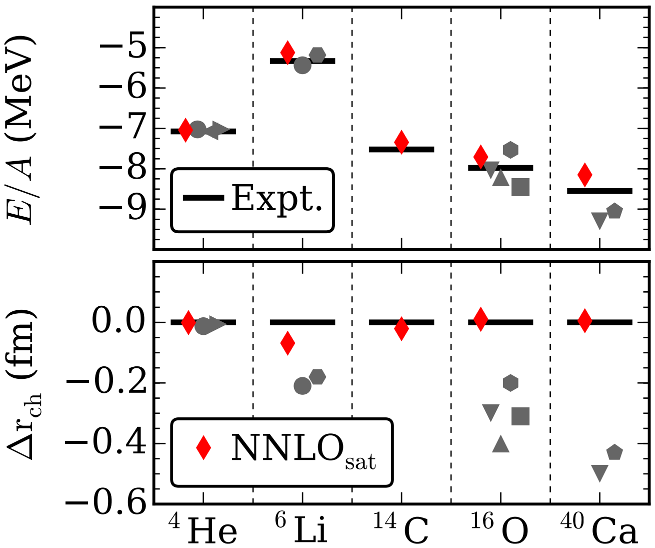
This is where effective field theory comes in

Rooting nuclei in QCD

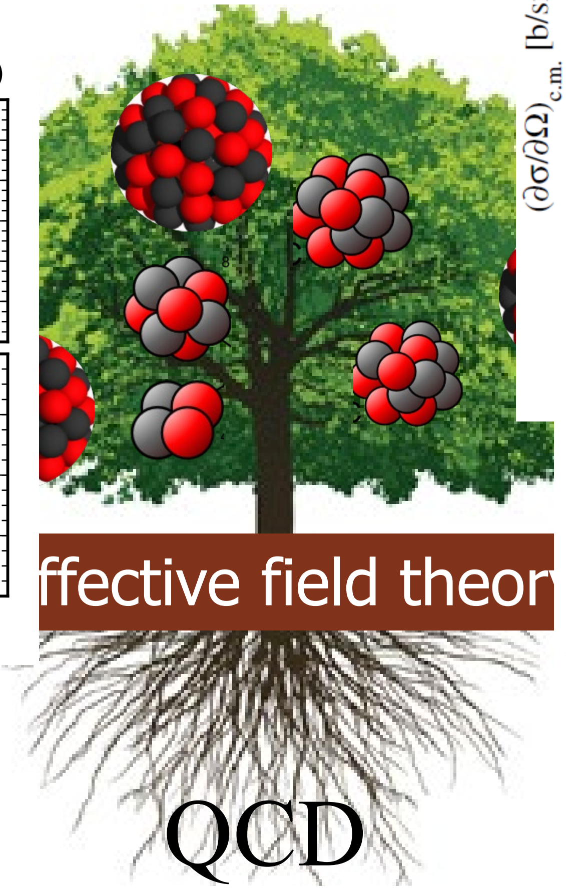
Hupin et al., Phys. Rev. Lett. **114**, 212502



Ekstrom et al, Phys. Rev. C **91**, 051301(R)

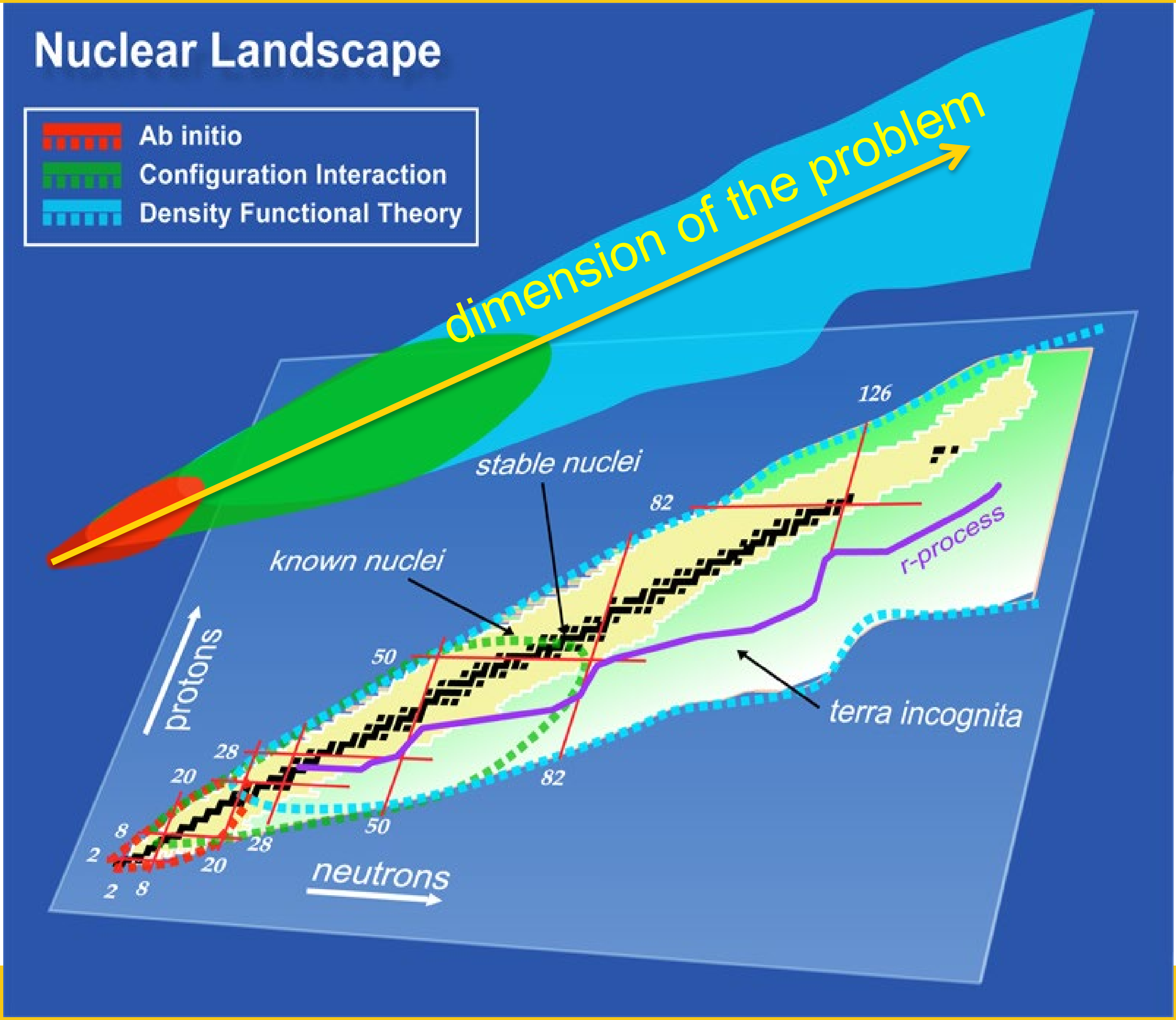


Coupled cluster predictions of binding energies and radii



No Core Shell Model with continuum predictions for d-α elastic scattering

The nuclear many-body problem



Interactions and methods

Poorly known

interactions

Well known

DFT

↑

Shell model

↑

Ab-initio

↑

Soft interactions

↑

Chiral EFT

↑

Lattice QCD

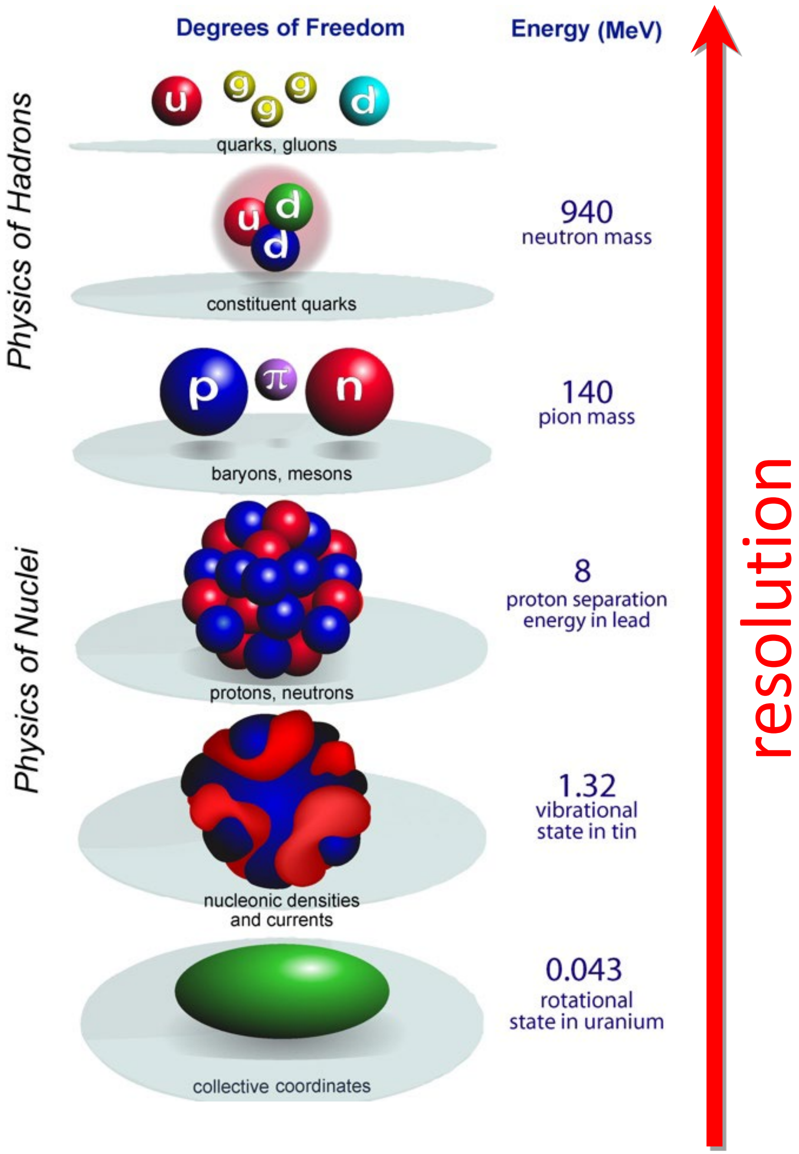
easy to solve

QM many-body problem

hard to solve

[Scott Bogner]

Multiple scales and resolution



Ratio of scales => small parameters!

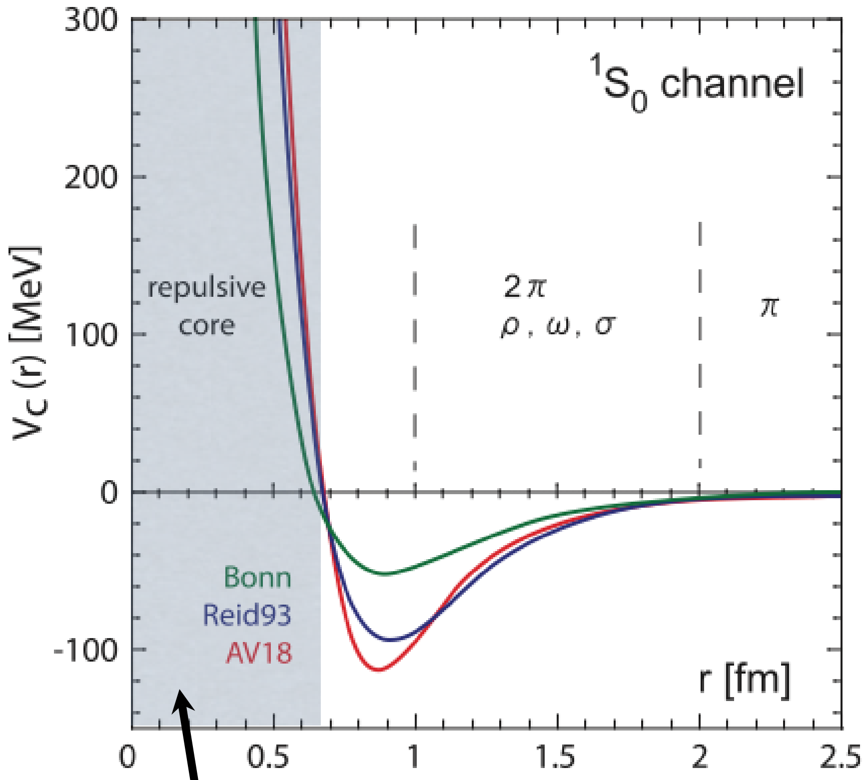
• Effective theories at each scale connected by renormalization group

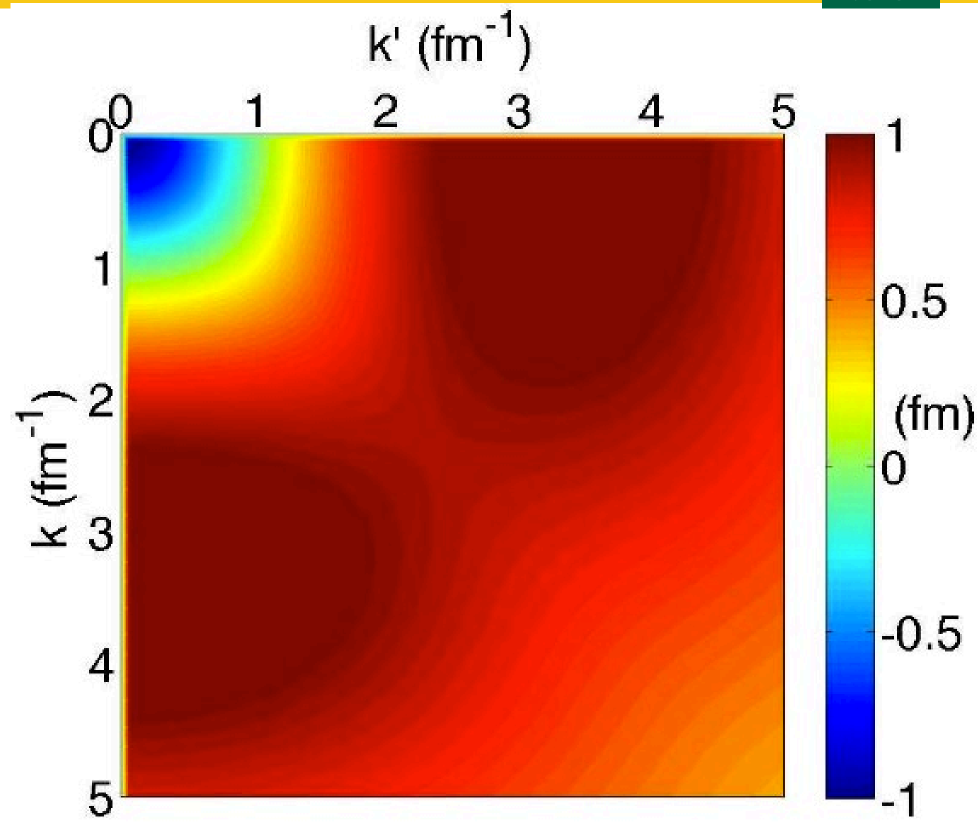
$$V(\Lambda) = V_{2N}(\Lambda) + V_{3N}(\Lambda) + \cdots$$

Use RG to pick a convenient Λ "resolution scale"

[Scott Bogner]

Why are nuclear many-body problems hard?





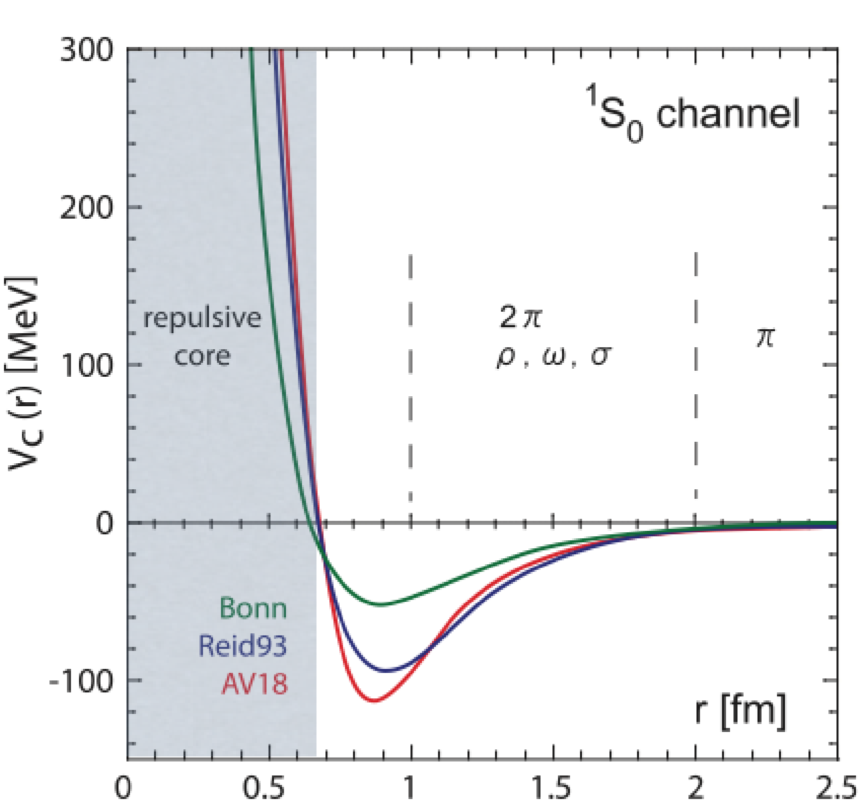
“hard-core” of V(r) => strong offdiagonal V(k,k’)

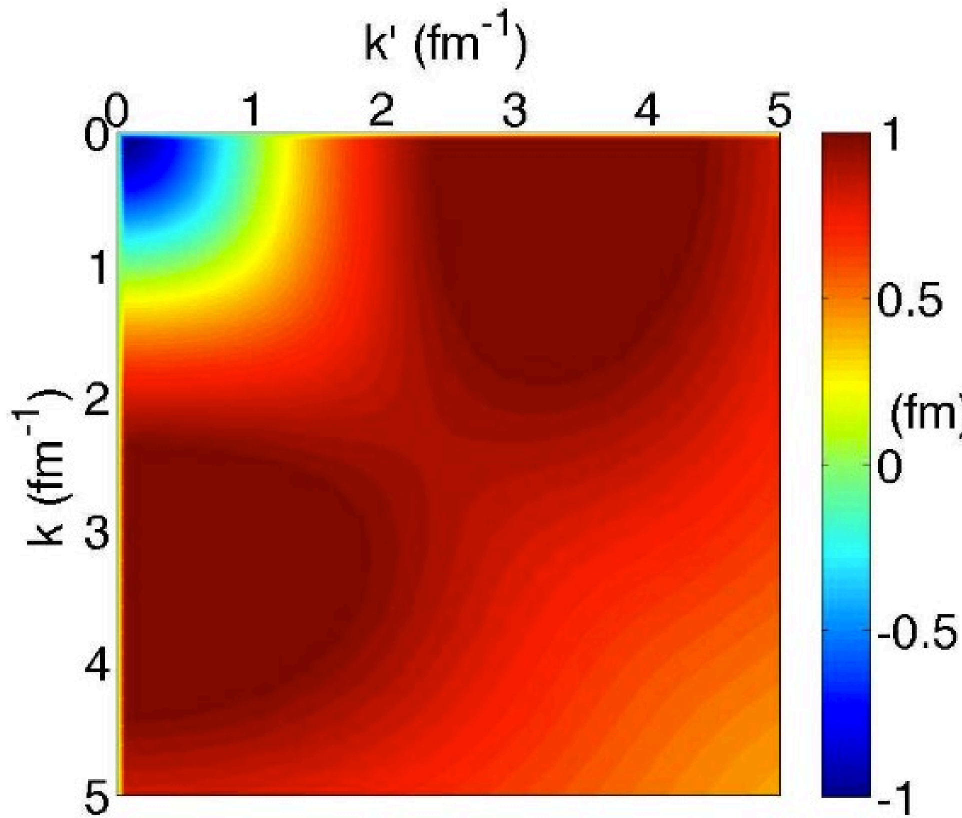
$$V_{l=0}(k,k') = \int d^3r\, j_0(kr)\, V(r)\, j_0(k'r')$$

Characteristic $k_F \sim 1\ \mathrm{fm}^{-1}$

[Scott Bogner]

Why are nuclear many-body problems hard?



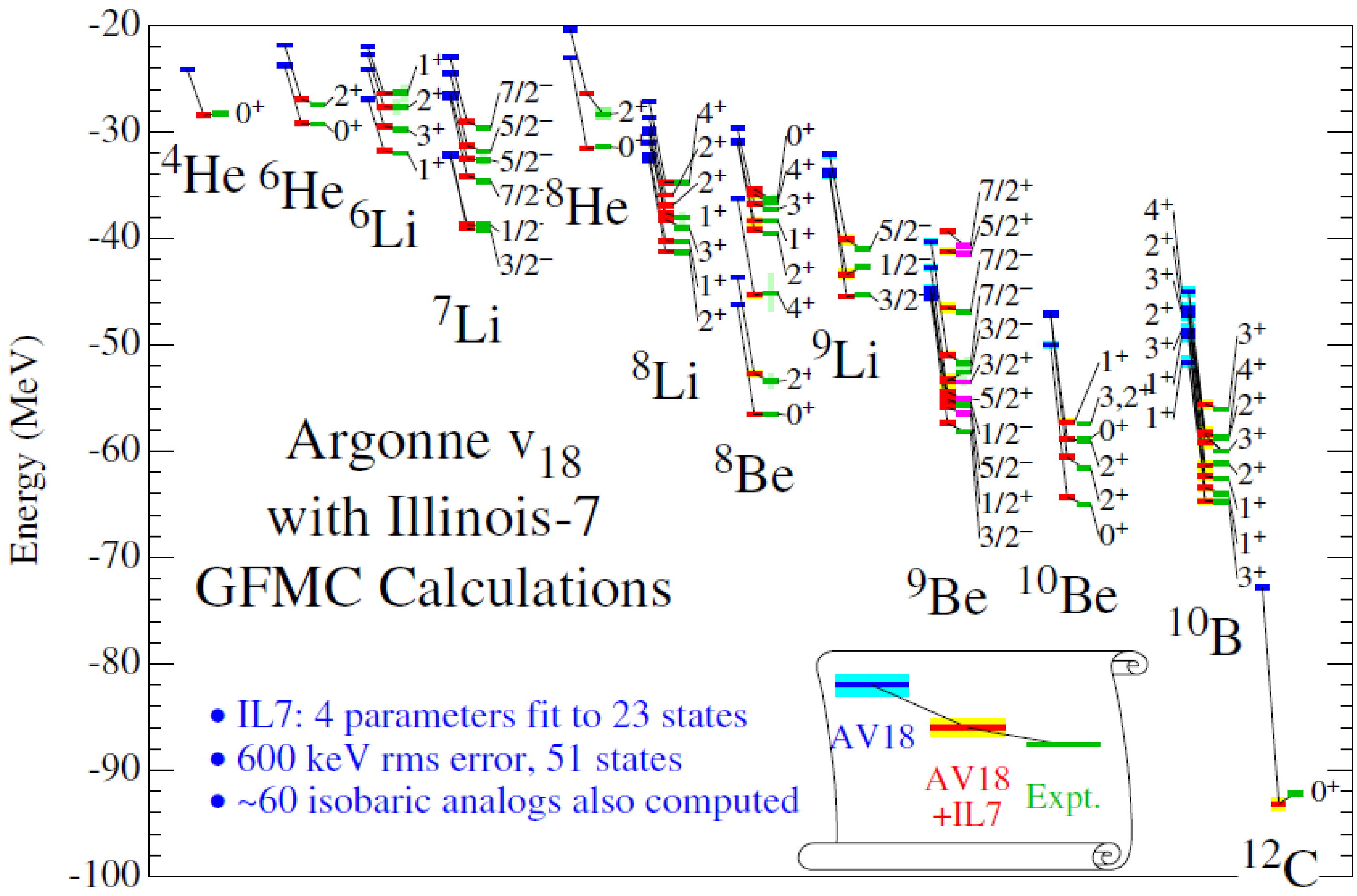


Complications: strong correlations, non-perturbative, poorly convergent basis expansions, ...

Characteristic $k_F \sim 1\ \mathrm{fm}^{-1}$

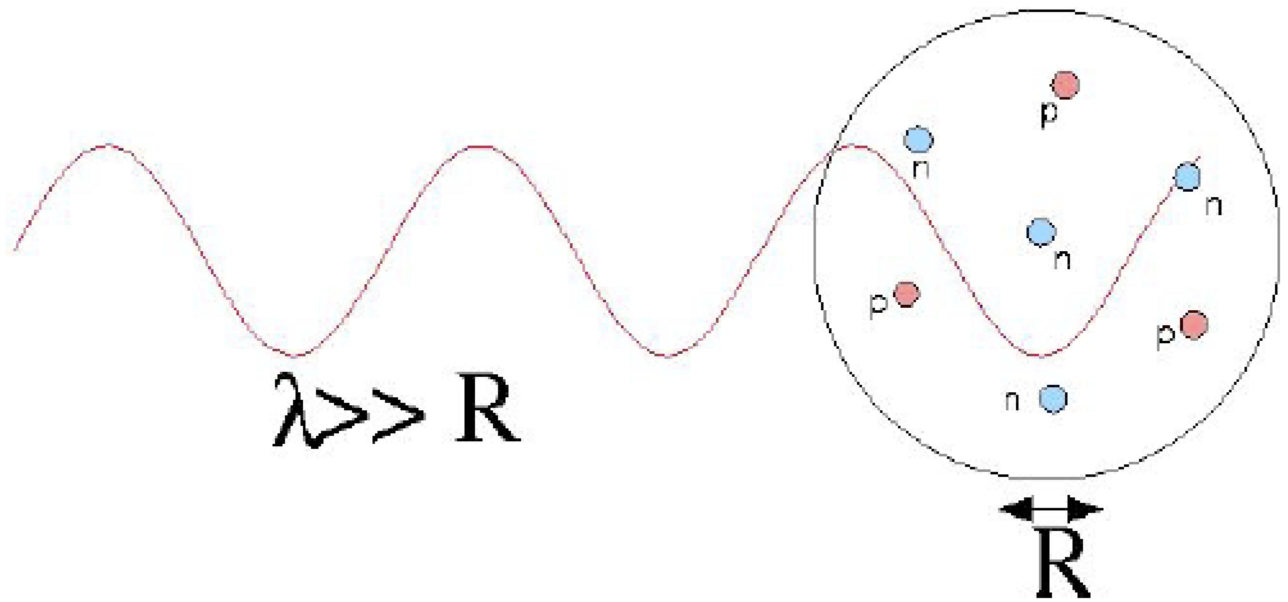
[Scott Bogner]

Some many-body techniques use "phenomenological" interactions (bare interactions)



Already the three-body force shows up!
Most techniques needs a "softer" interaction…

Principles of low energy effective theories



- If a system is probed at low energies, fine details not resolved
- Use convenient dof to describe low-energy processes
- Complicated short-distance structure replaced by something simpler without distorting low-E observables

Low energy effective theories

Generic form of the effective theory

$$V_{eff} = V_L + \delta V_{c.t.}(\Lambda)$$

$$\delta V_{ct} = C_0(\Lambda)\delta^3(\mathbf{r}) + C_2(\Lambda)\nabla^2\delta^3(\mathbf{r}) + \cdots$$

encodes the effects of integrated dof on low-E physics

universal form; depends only on symmetries

The complicated short-distance structure of the "true" theory is encoded in a few numbers that can be calculated from the underlying theory

OR

in cases where the short-distance structure is unknown or too complicated, can be extracted from low energy data

Effective Field Theory (EFT) is based on these ideas

Nuclear forces from Chiral EFT

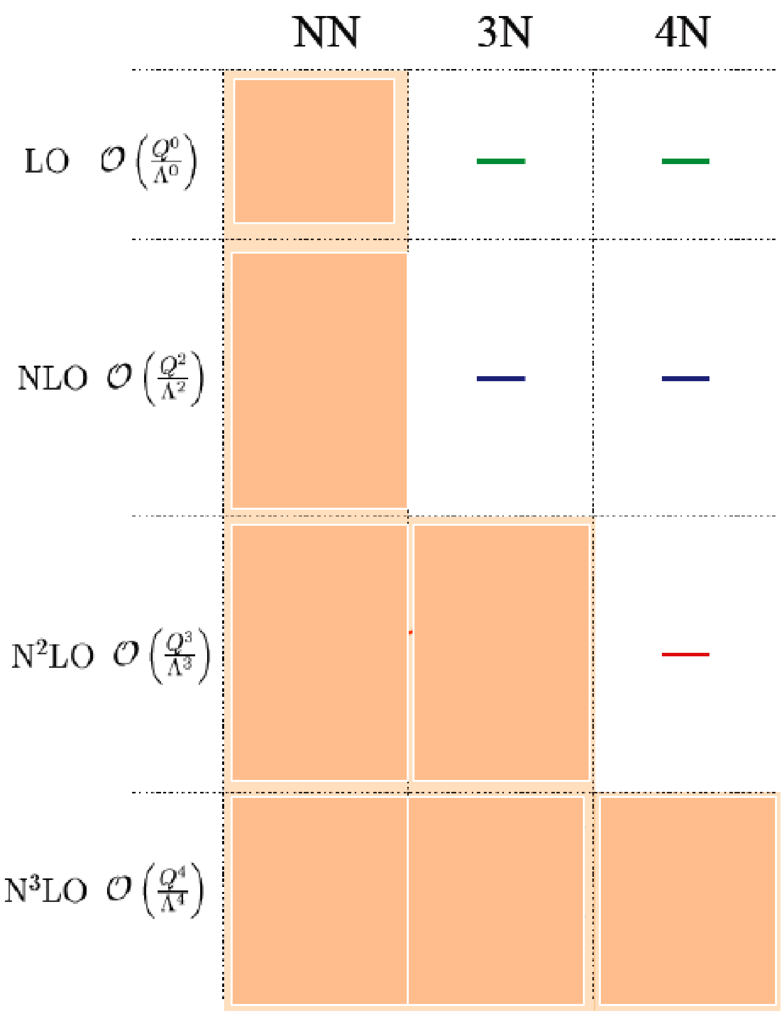
Separation of scales: low momenta Q << Λ_b (breakdown scale)

- Include long-range pion physics explicitly

- Short-distance **details** not resolved, Encoded in short-range couplings fit to data once

- Systematic: can work to desired accuracy

$$\Delta \mathcal{O}_\nu \sim \left(\frac{Q}{\Lambda}\right)^{\nu+1}$$

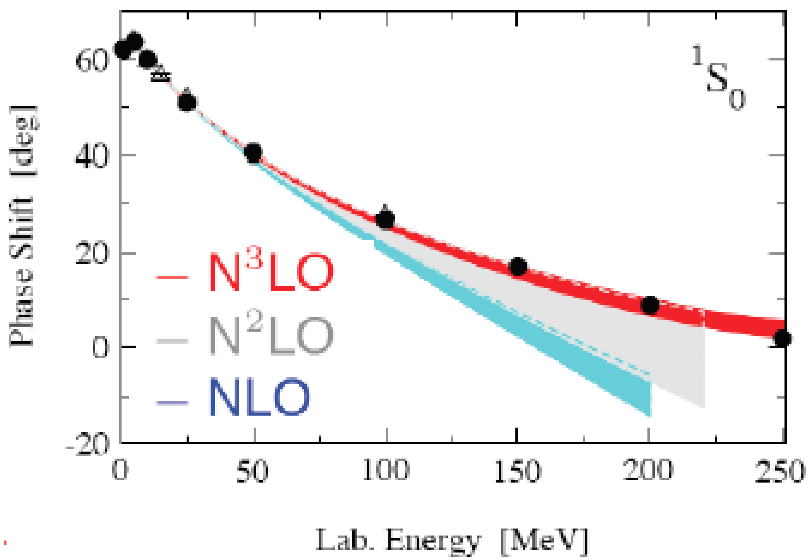


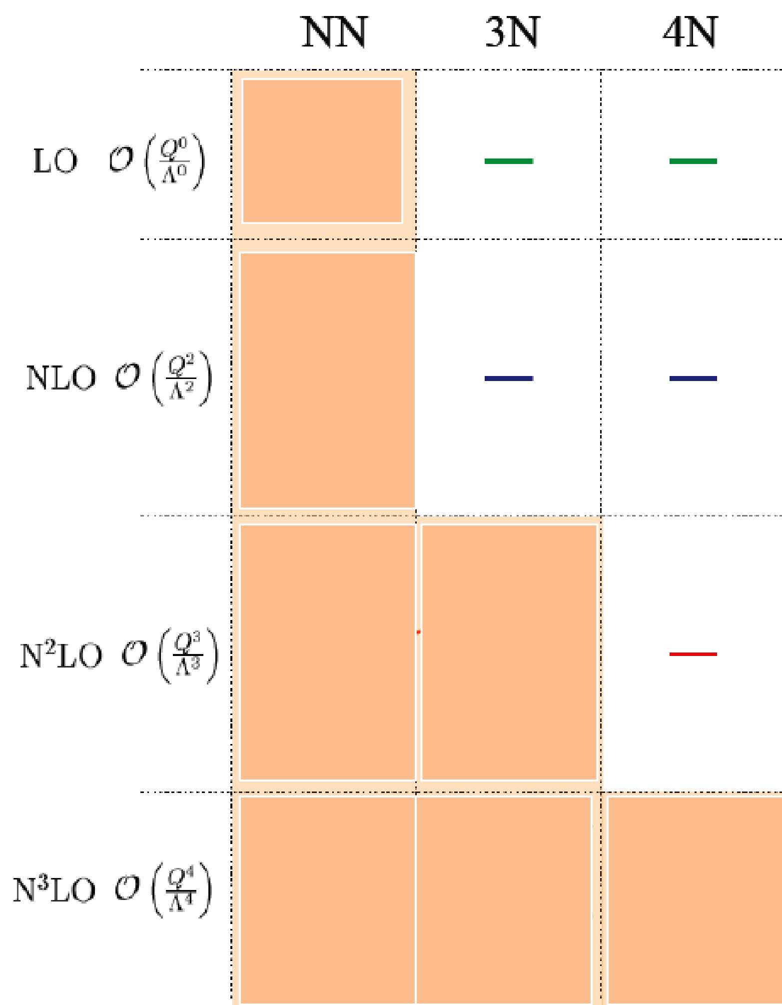
Weinberg, van Kolck, Epelbaum, Meissner, Machleidt, …

Nuclear forces from Chiral EFT

Separation of scales: low momenta Q << Λ_b breakdown scale

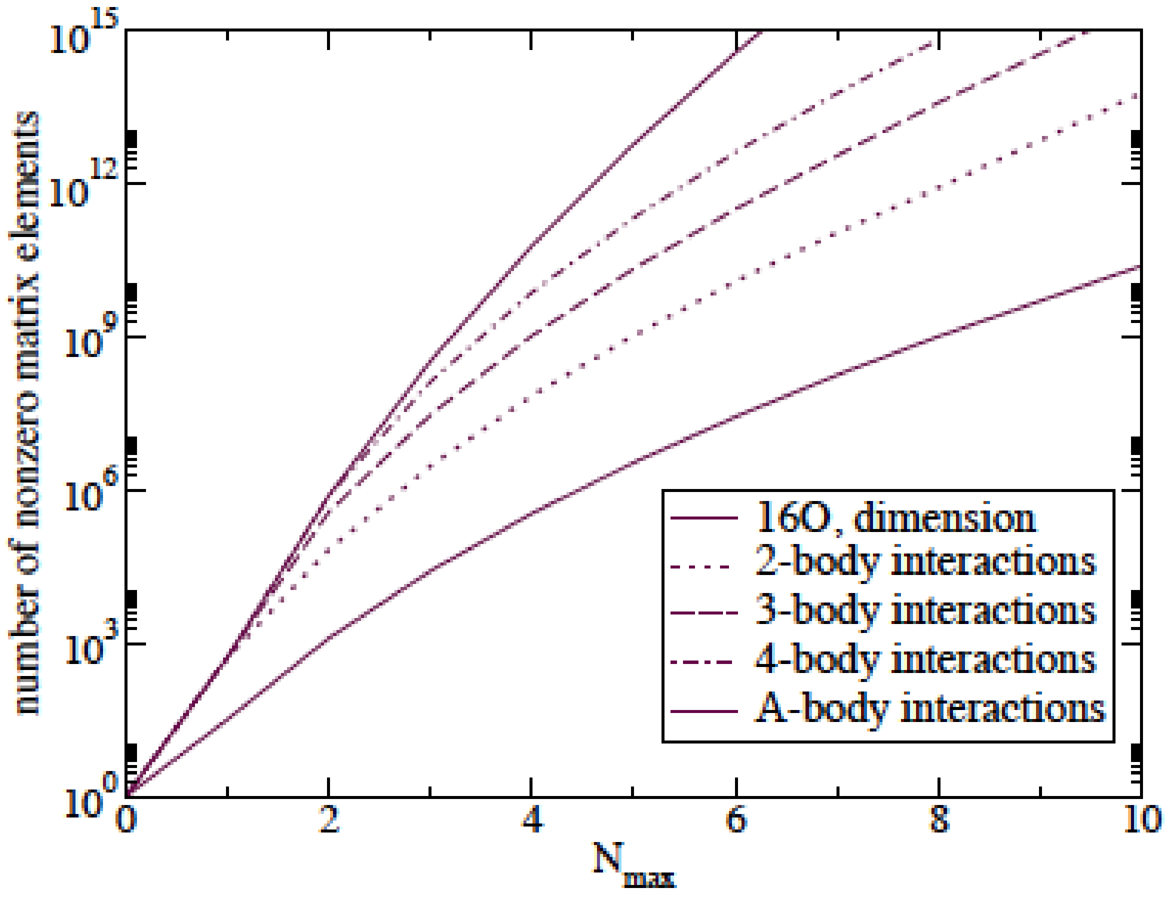
- Explains why 2N>3N>4N
- Error determined from Λ variation





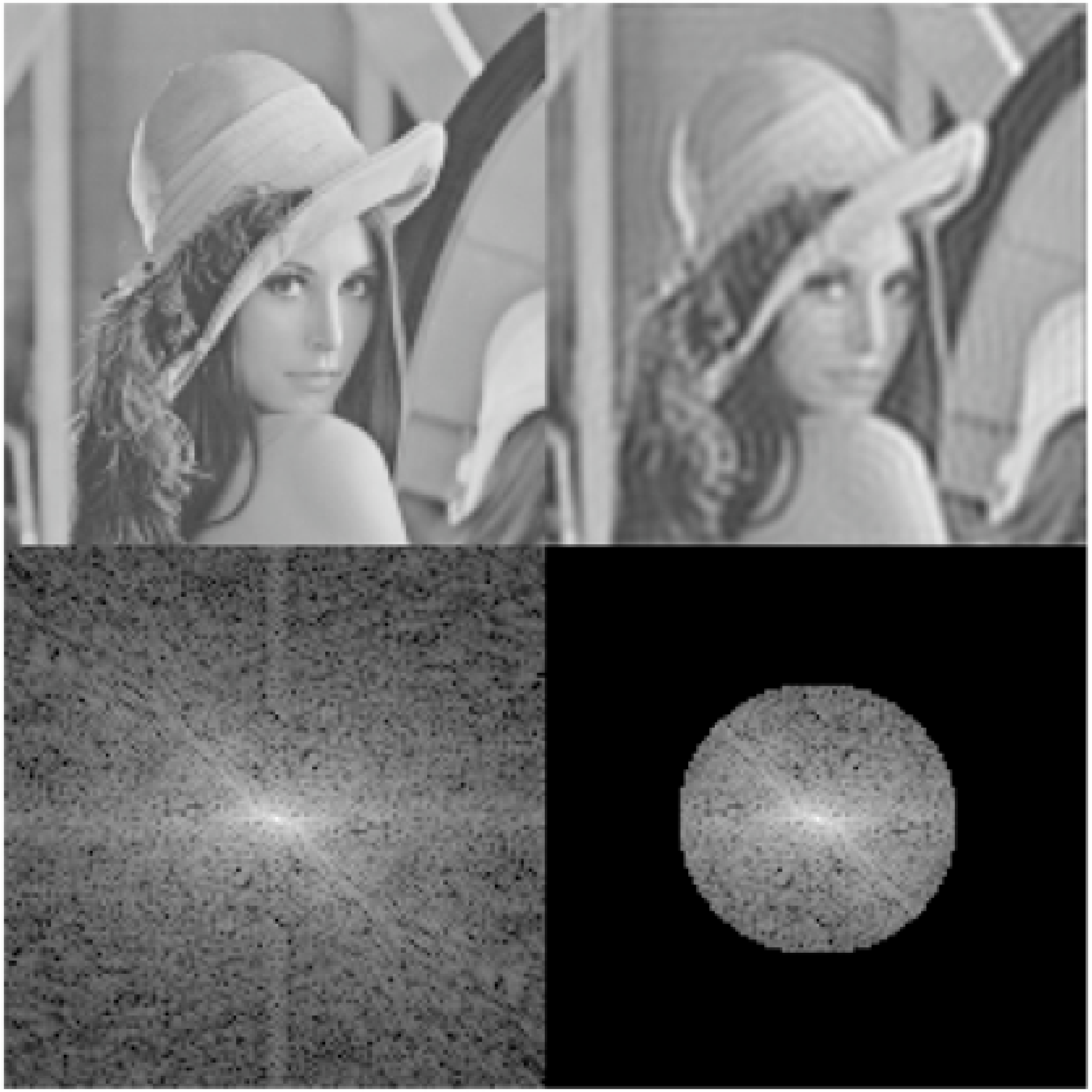
Weinberg, van Kolck, Epelbaum, Meissner, Machleidt, …

No free lunch: beyond two-body forces



Higher-order forces are a computational nightmare!

Ex: Low-pass filter on fourier transform of a 2d-imag

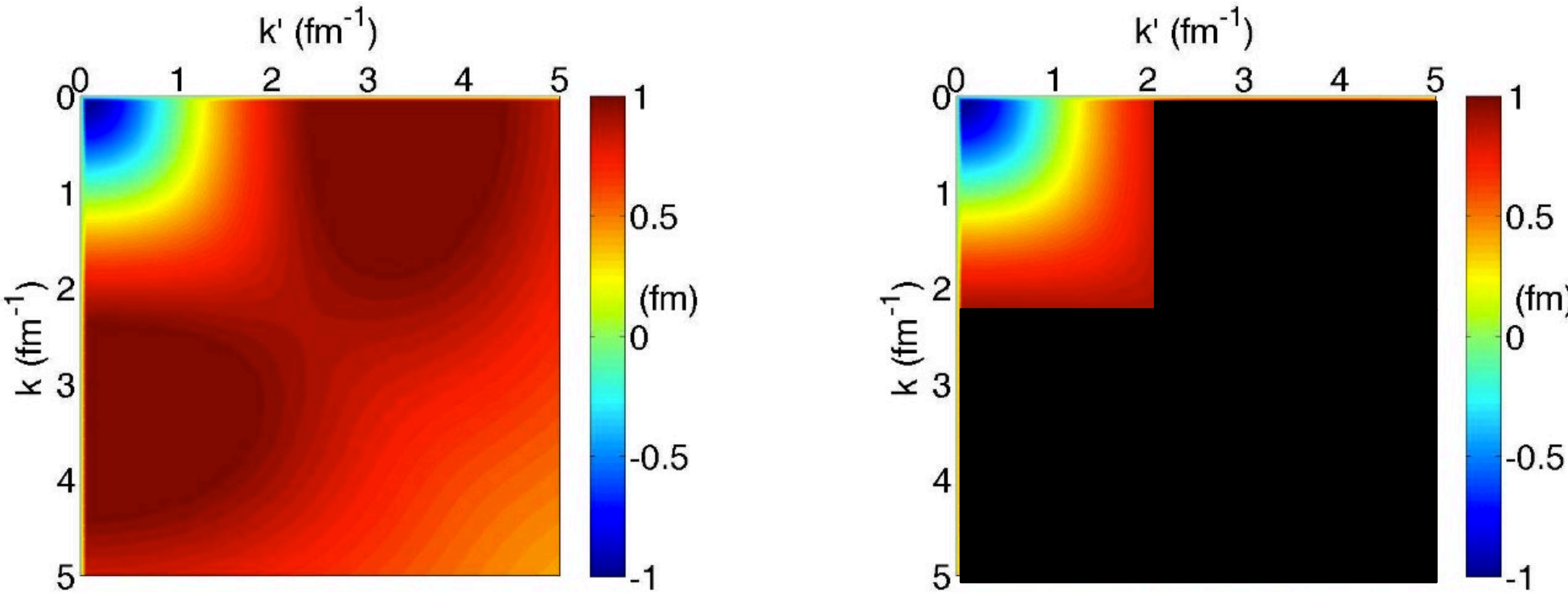


filtered image contains much less information

BUT

Long-wavelength info preserved

Try a naive "low-pass" filter on V:

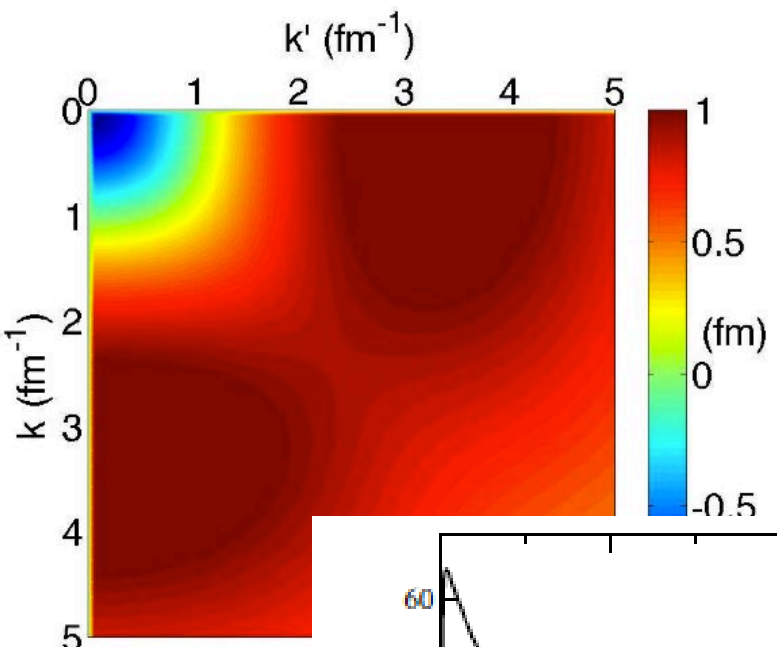


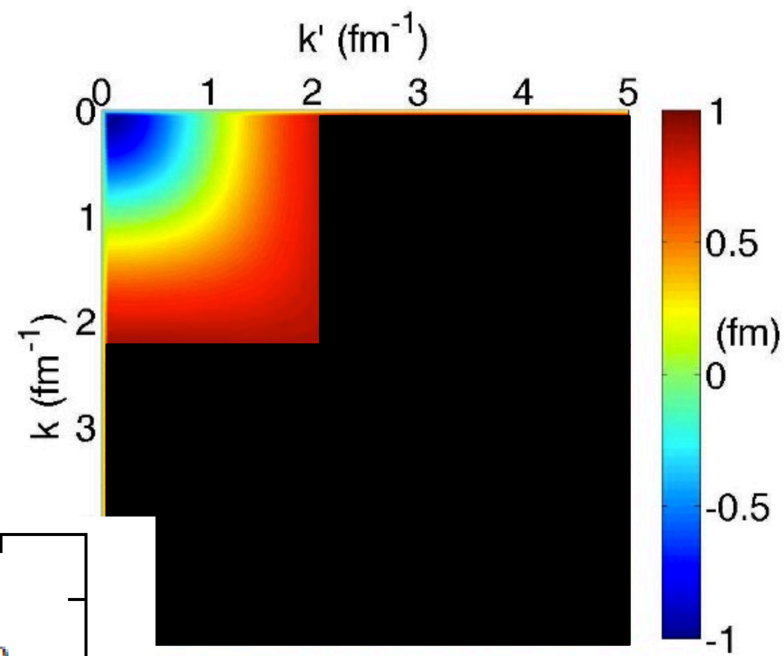
$$V_{filter}(k', k) \equiv 0 \quad k, k' > 2.2 \text{ fm}^{-1}$$

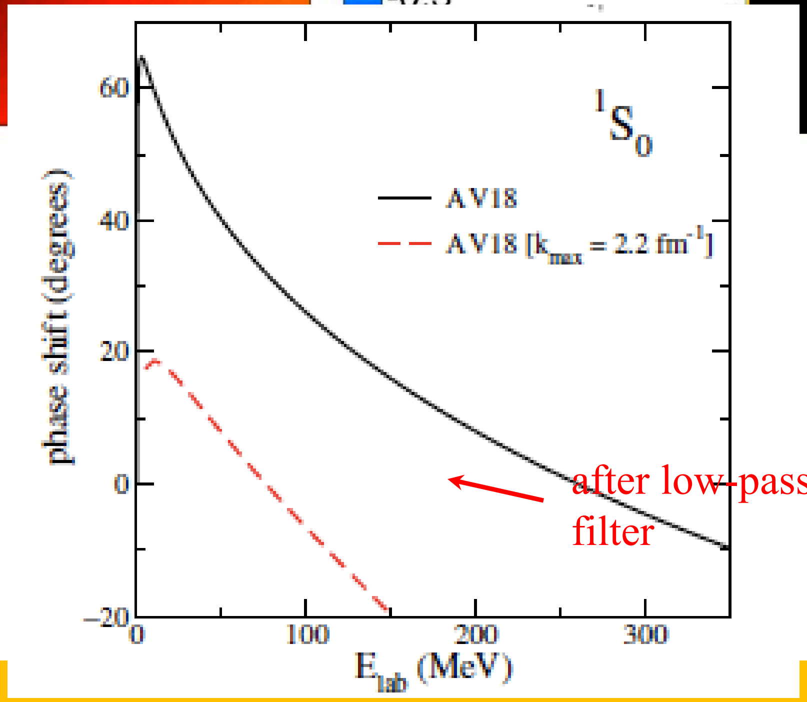
Now calculate low E observables (e.g., NN scattering) and see what happens...

[Scott Bogner]

Try a naive "low-pass" filter on V:



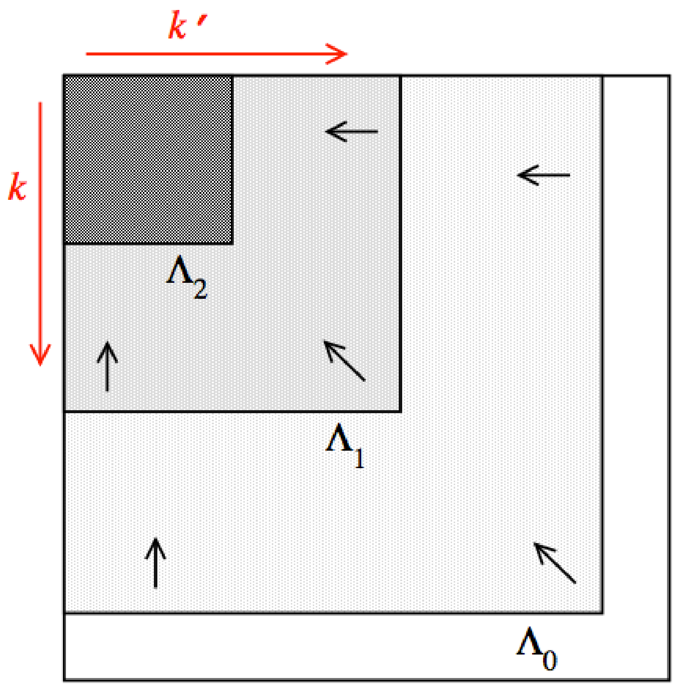


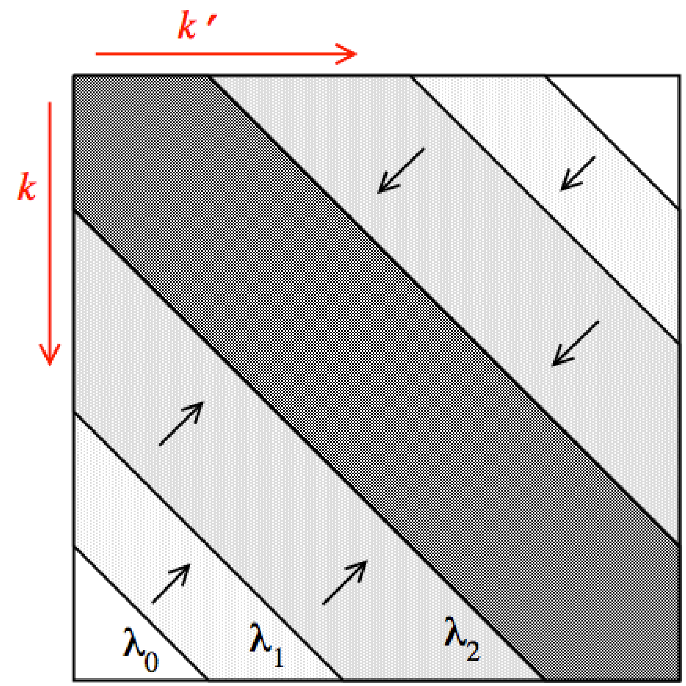


δ(E) totally **wrong** with V_{filter}

[Scott Bogner]

2 Types of Renormalization Group Transformations





"$V_{\text{low k}}$"

integrate-out high k states

preserves observables for $k < \Lambda$

"Similarity RG"

eliminate far off-diagonal coupling

preserves "all" observables

Identical simplifications despite differences in appearance!

Bogner, Furnstahl, Schwenk, Prog. Part. Nucl. Phys. **65** (2010)

nuclei: a tough many-body problem

$$H_A = -\sum_{i=1}^{A} \frac{\hbar^2}{2m_i} \nabla^2_{\mathbf{r}_i} + \frac{\hbar^2}{2M} \nabla^2_{\mathbf{S}} + \sum_{i>j}^{A} V^{(2)}(\mathbf{r}_i - \mathbf{r}_j) + \sum_{i>j>k}^{A} V^{(3)}(\mathbf{r}_i - \mathbf{r}_j, \mathbf{r}_i - \mathbf{r}_k),$$

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$$\int \mathrm{d}\boldsymbol{\rho}_1 \ldots \int \mathrm{d}\boldsymbol{\rho}_{A-1} |\Phi_{I\mu}(\boldsymbol{\rho}_1, \ldots, \boldsymbol{\rho}_{A-1})|^2 = 1$$

soft forces make it more like quantum chemistry
lead to approximations/controlled truncations

Exciting developments in ab-initio methods

- no core shell model (NCSM)
  - based on harmonic oscillators
  - good for energies, not so good for other observables
  - up to A=16
  - extension to include continuum and specific reaction channels

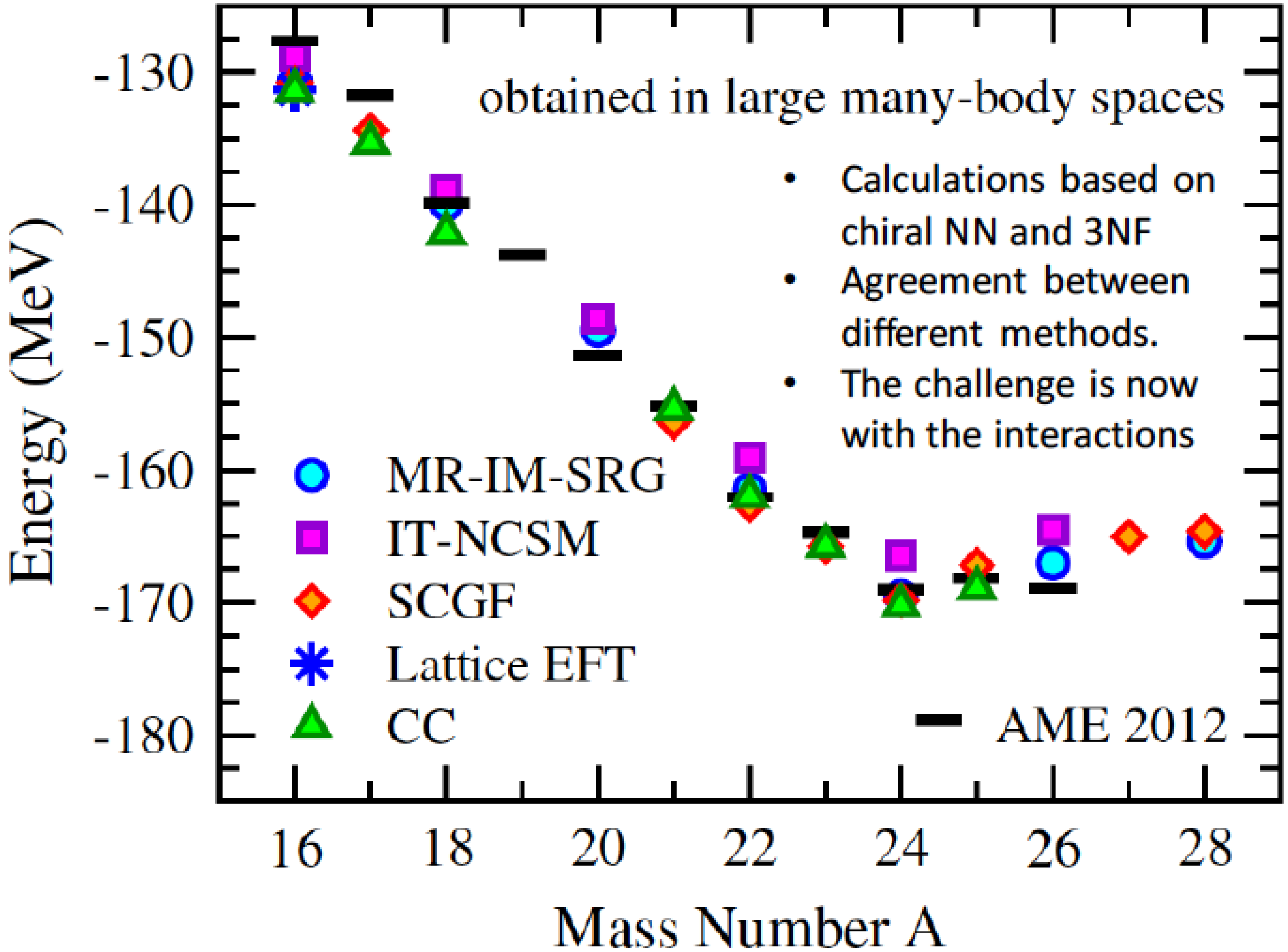
- green's function monte carlo (GFMC)
  - need a good starting variational wavefunction
  - implemented for specific forces
  - computationally demanding: hard limit A=12

- coupled cluster method (CC)
  - widely used in quantum chemistry
  - ansatz contains correlations in the exponential
  - scaling better than NCSM
  - implemented with the gamow basis (continuum)
  - applications up to 2 nucleons away from closed sub-shell

- in medium Similarity Renormalization Group method (IMSRG)
  - applies a flow equation to obtain a diagonal matrix
  - scaling similar to coupled cluster
  - extension to ab-initio type shell model

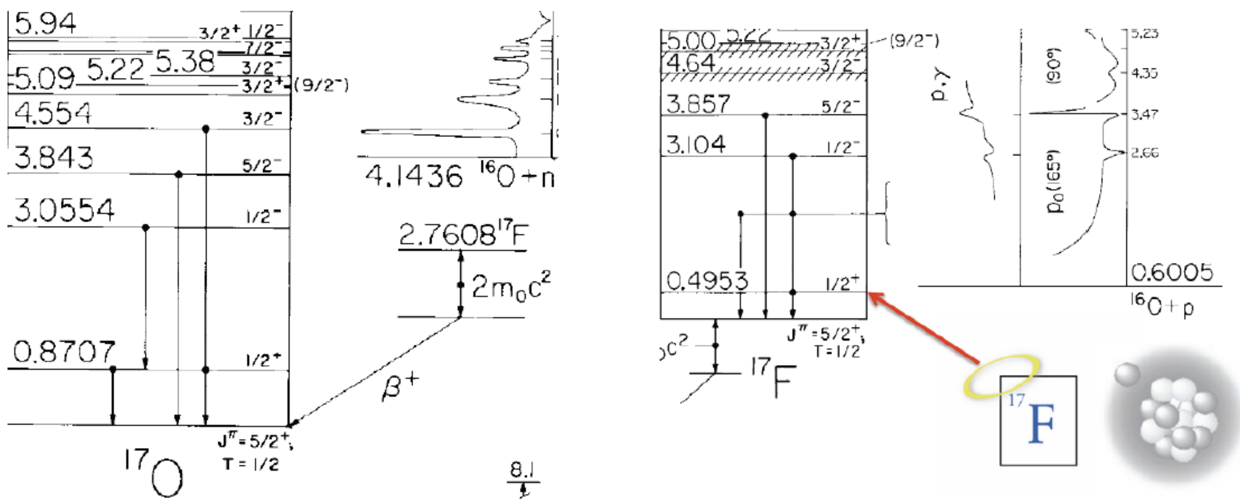
Benchmarking many-body theories

Oxgyen chain with interactions from chiral EFT



Hebeler, Holt, Menendez, Schwenk, Annu. Rev. Nucl. Part. Sci. 65, 457 (2015)

Ab-initio methods: coupled cluster for halos



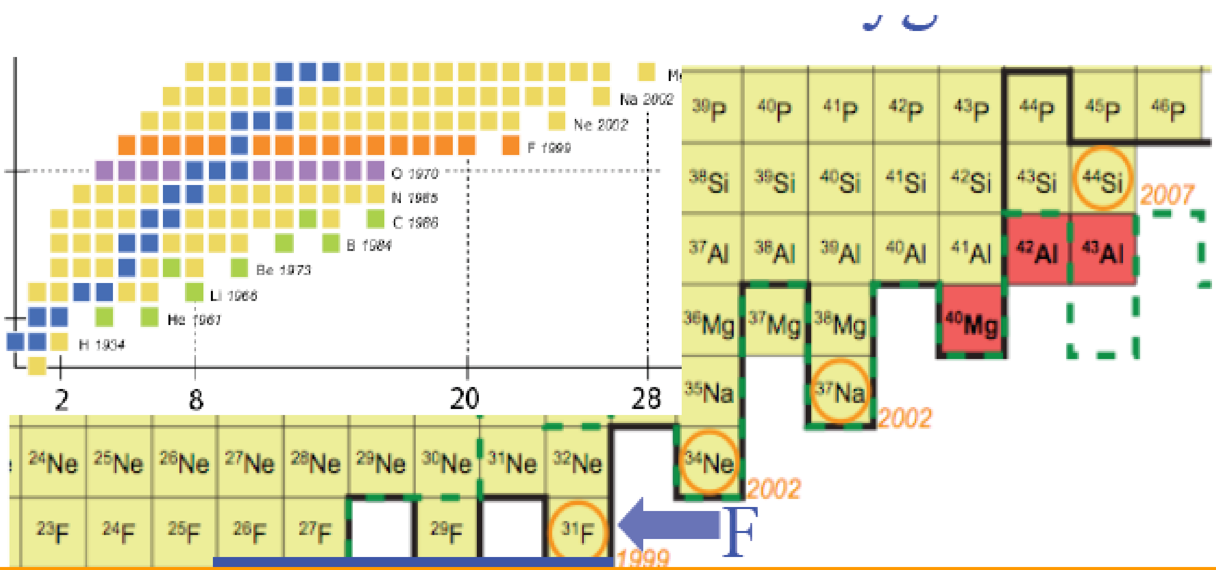
	^{17}O			^{17}F		
	$(1/2)_1^+$	$(5/2)_1^+$	$E_{s.o.}$	$(1/2)_1^+$	$(5/2)_1^+$	$E_{s.o.}$
OHF	-1.888	-2.955	4.891	0.976	0.393	4.453
GHF	-2.811	-3.226	4.286	-0.082	0.112	3.747
Exp.	-3.272	-4.143	5.084	-0.105	-0.600	5.000

	^{17}O $(3/2)_1^+$		^{17}F $(3/2)_1^+$	
	Re[E_{sp}]	Γ	Re[E_{sp}]	Γ
PA-EOMCCSD	1.059	0.014	3.859	0.971
Experiment	0.942	0.096	4.399	1.530

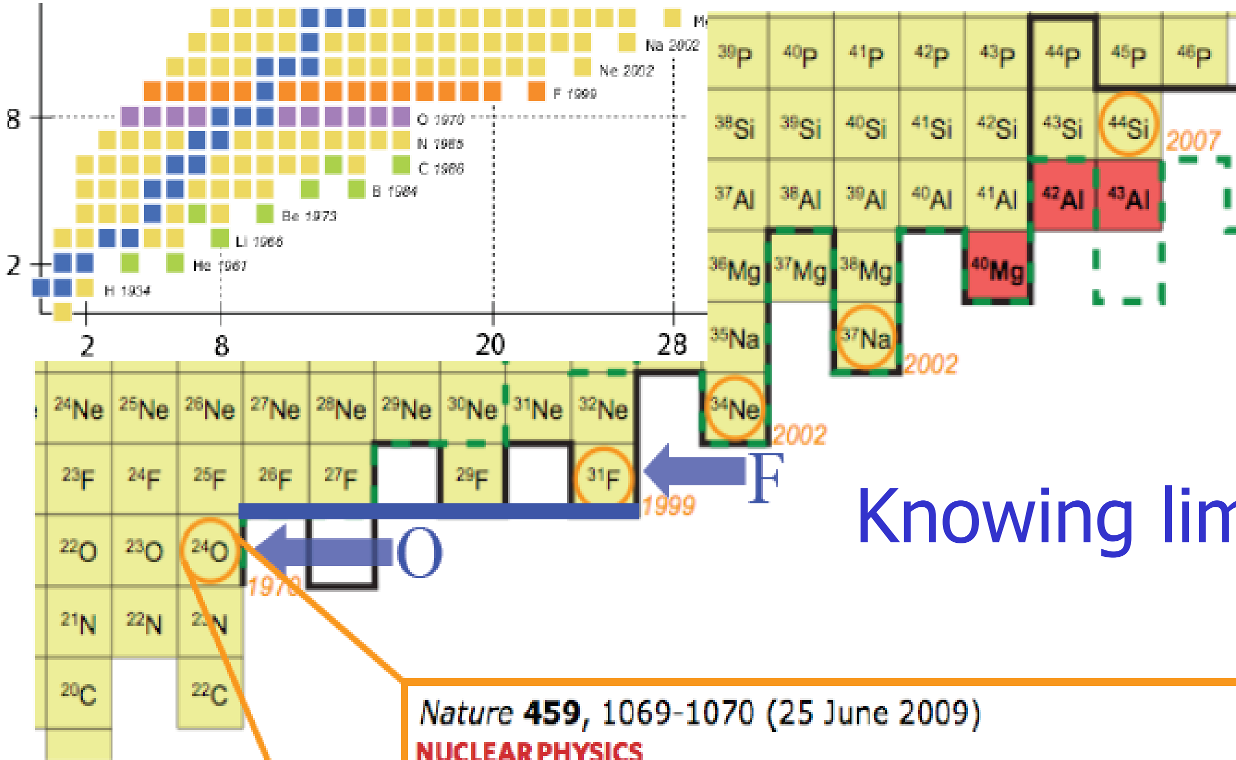
QUESTION TIME

1. When solving the many-nucleon problem, what is the price you pay in using RG techniques to soften NN forces?

2. What is the dripline of Z=8 isotopes? First have a guess using only the nuclear chart provided below. Then you can google…



understanding nuclei



Knowing limits of stability

Nature **459**, 1069-1070 (25 June 2009)

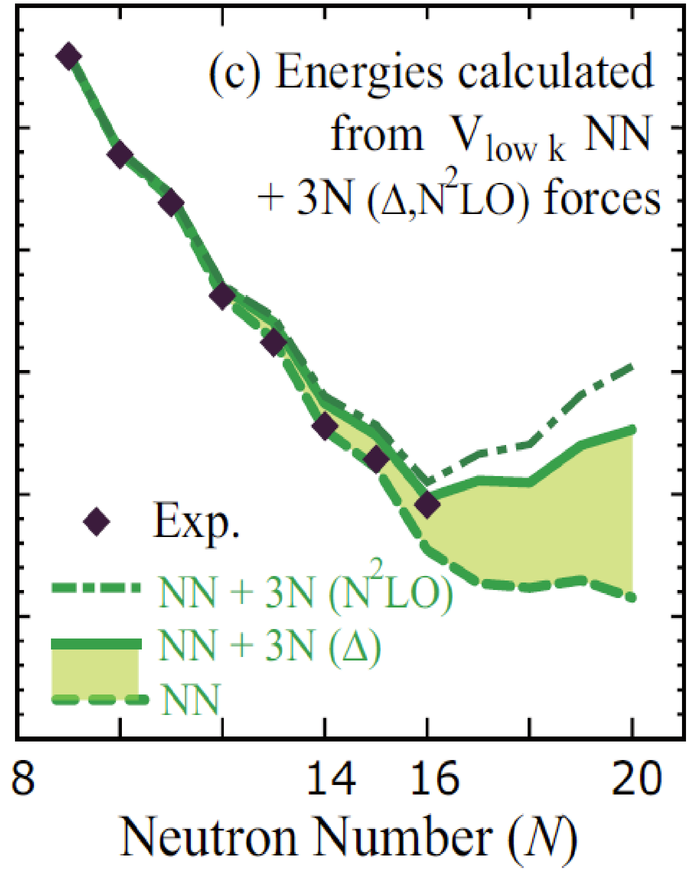
NUCLEAR PHYSICS

Unexpected doubly magic nucleus

Robert V. F. Janssens

Nuclei with a 'magic' number of both protons and neutrons, dubbed doubly magic, are particularly stable. The oxygen isotope ^{24}O has been found to be one such nucleus — yet it lies just at the limit of stability.

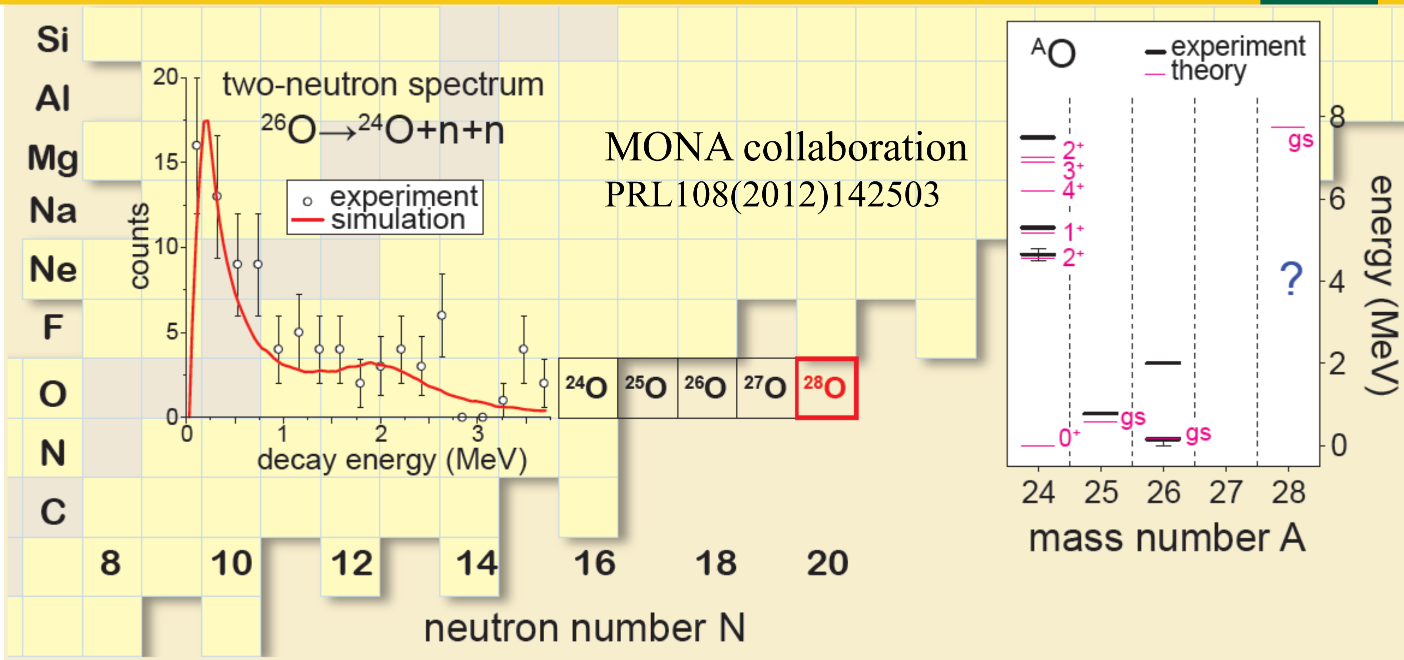
three-body force for Oxygen isotopes

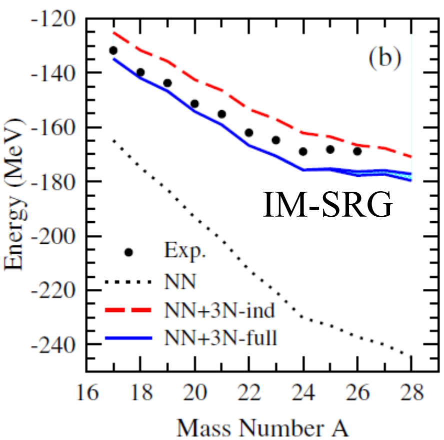


Otsuka, Suzuki, Holt, Schwenk, Akaishi, PRL (2009)

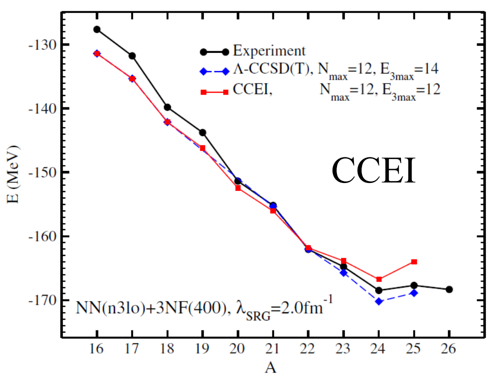
Exotic nuclei impose stringent tests on theory

Surprises with the Oxygen isotopes, at and beyond stability, have provided crucial information to constrain the effective nuclear force!

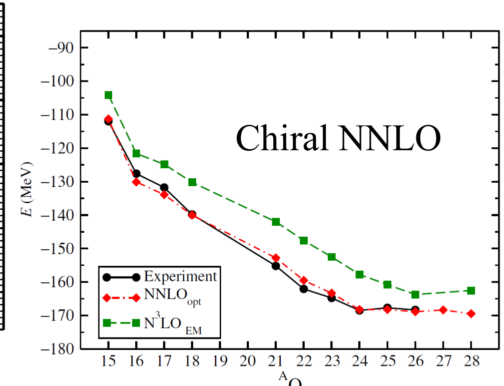




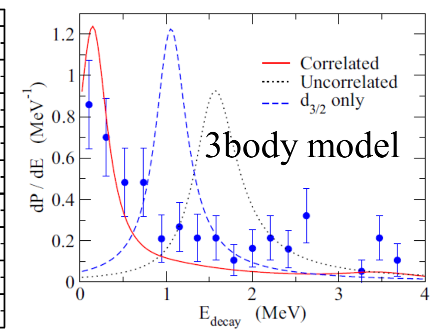
S.K. Bogner et al.
PRL113(2014)142501



G.R. Jansen et al.
PRL113(2015)142502



A. Ekström et al.
PRL110(2013)192502



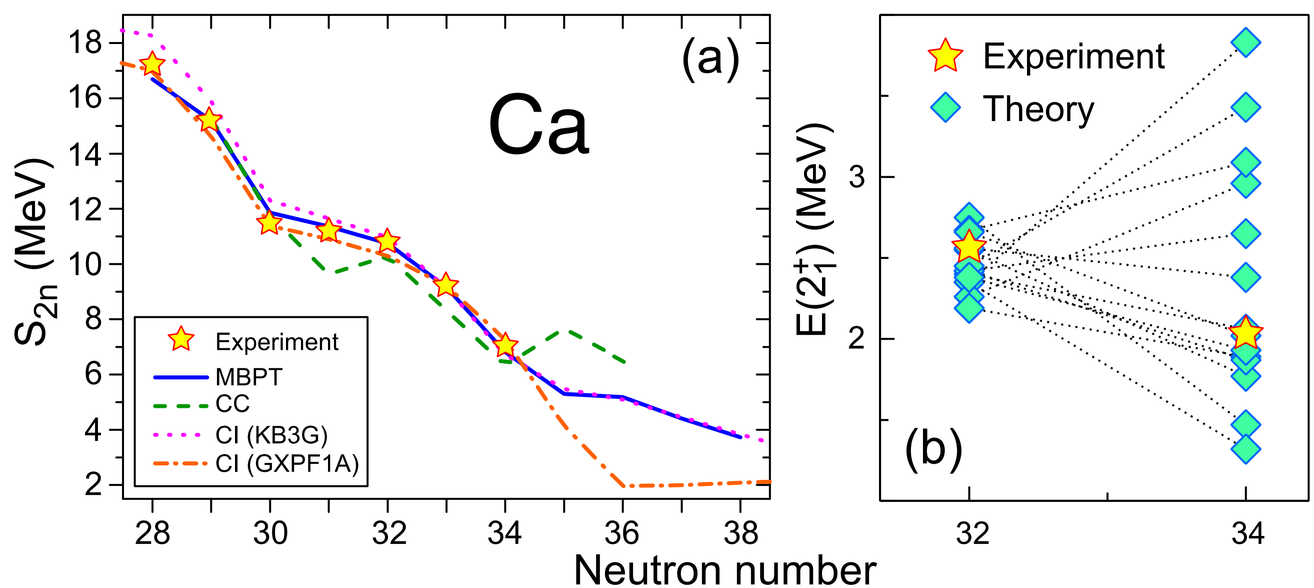
K. Hagino and H. Sagawa
PRC89(2014)014331

Enhancing the coupling between experiment and theory

- Theory and experiment work hand-in-hand:

  experiment guides theory --- theory guides experiment

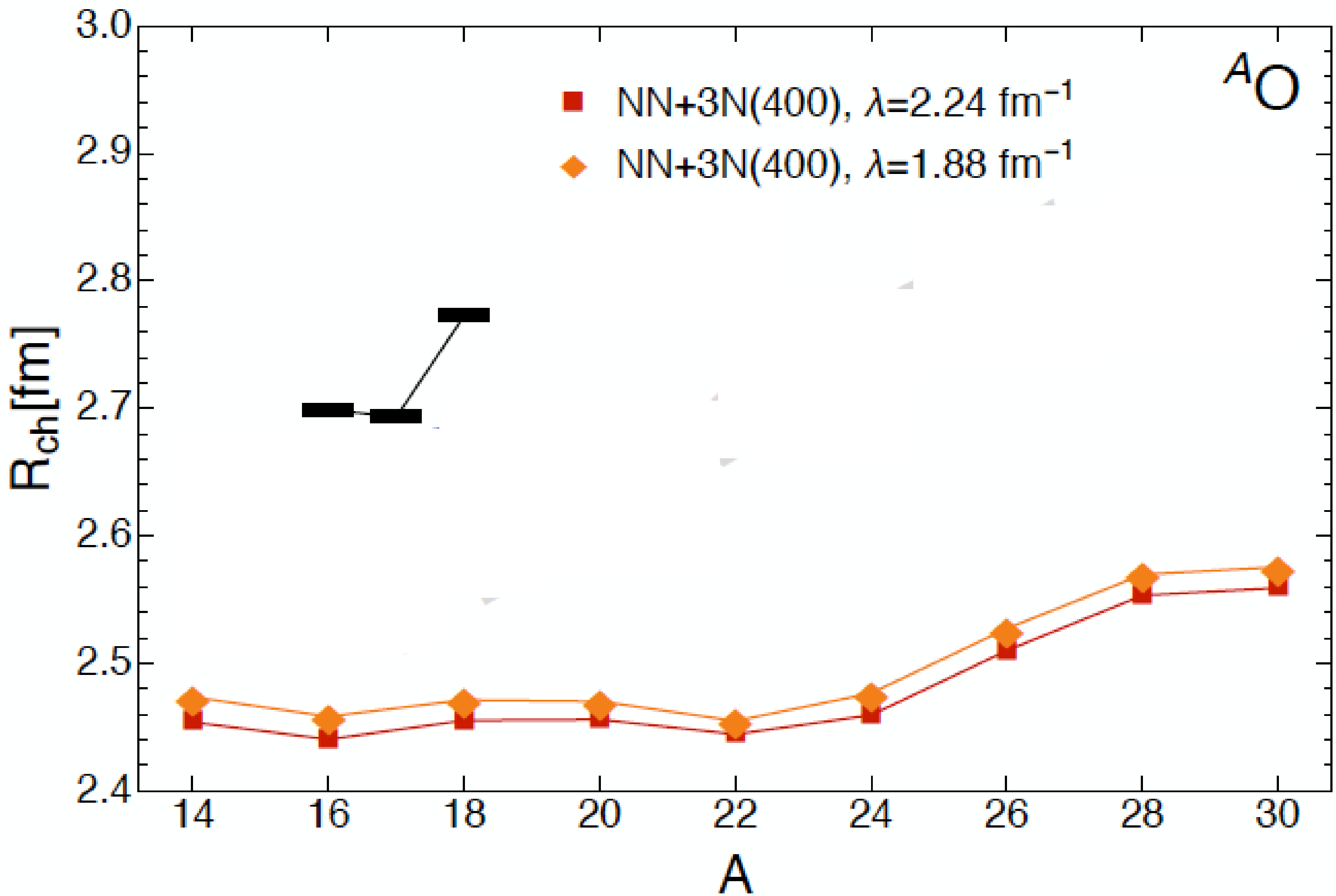
- Need to integrate theory and experiment to exploit FRIB's full potential and optimize its research.



F. Wienholtz *et al.*, *Nature* **498**, 346 (2013).
D. Steppenbeck *et al.*, *Nature* **502**, 207 (2013)

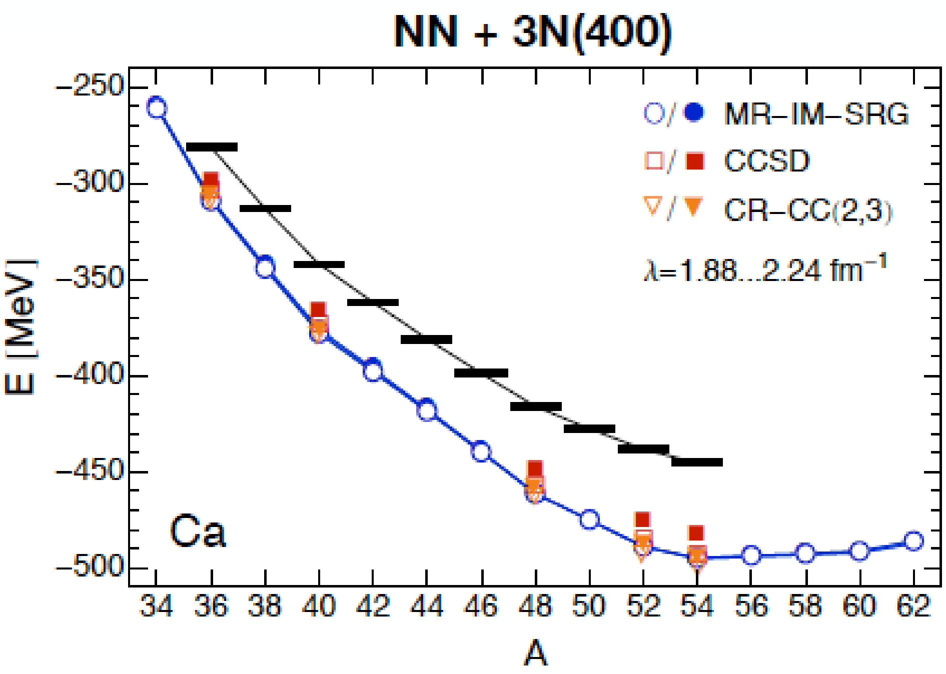
problems with our forces? radii for Oxygen

V. Lapoux, V. Somà, C. Barbieri, H. H., J. D. Holt, and S. R. Stroberg,



Other issues with Chiral EFT forces

*HH et al., PRC **90**, 041302(R) (2014)*



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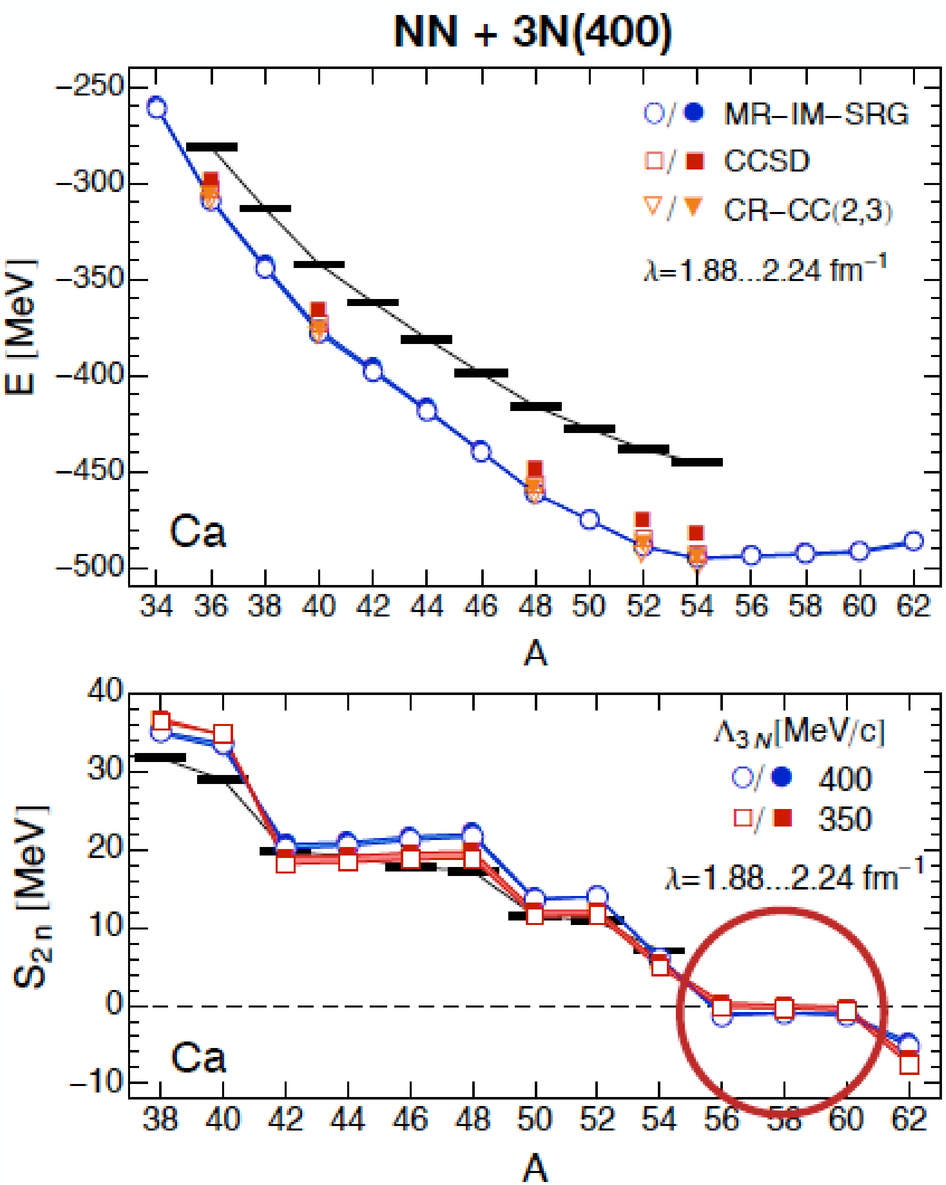
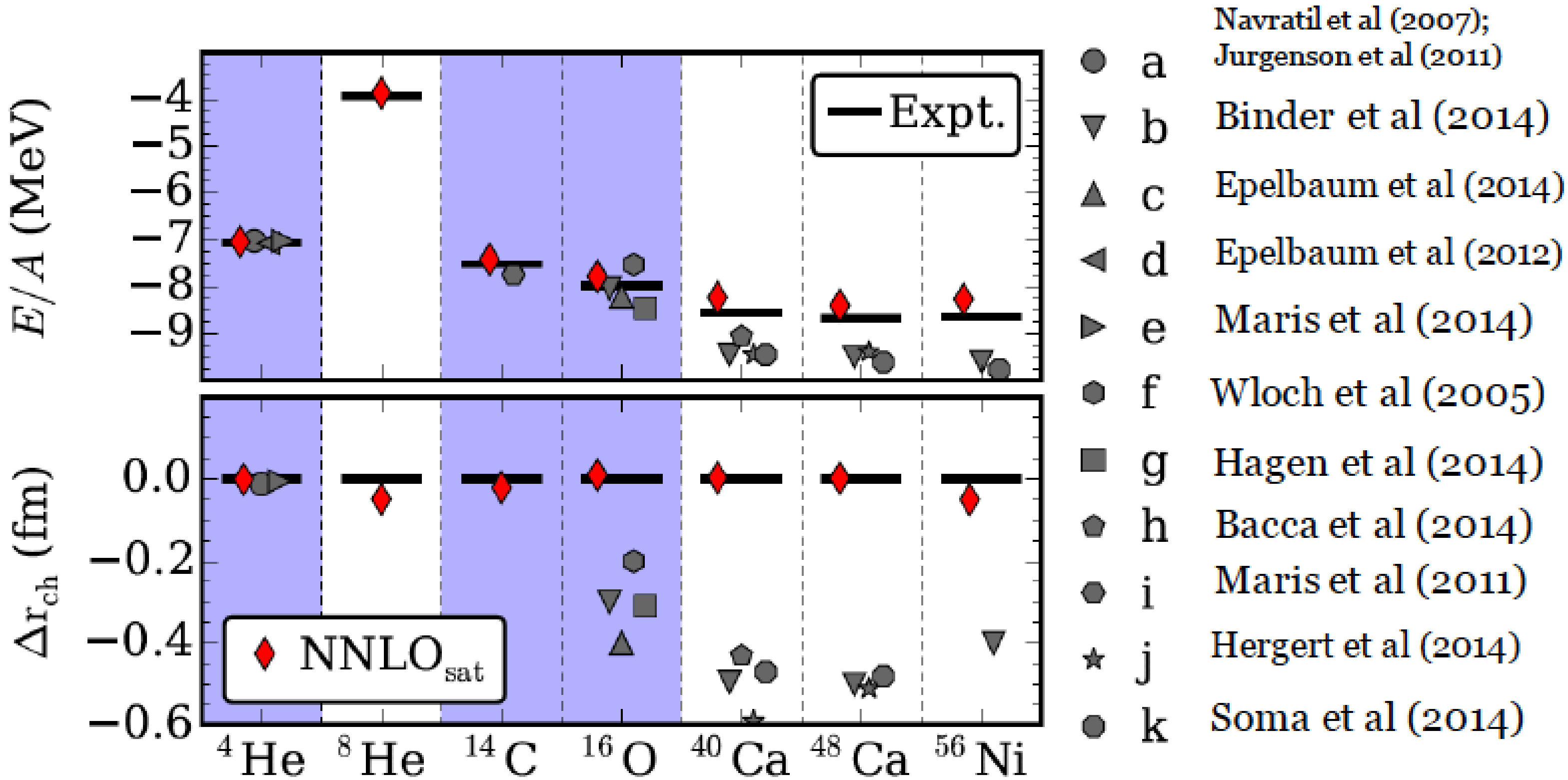


- differential observables (S_{2n}, spectra,...) filter out interaction components that cause overbinding
- predict flat trends for g.s. energies/S_{2n} beyond ^{54}Ca - await experimental data
- ^{52}Ca, ^{54}Ca magic for these NN+3N interactions
- no continuum coupling yet, other S_{2n} uncertainties < 1MeV

Refitting EFT parameters to include nuclei

Accurate nuclear binding energies and radii from a chiral interaction



Simultaneous optimization of NN and 3NFs

Include charge radii and binding energies of ^{3}H, $^{3,4}He$, ^{14}C, ^{16}O in the optimization ($NNLO_{sat}$)

Critical ingredient:
Three-nucleon forces with non-local regulators

A. Ekström *et al*, Phys. Rev. C **91**, 051301(R) (2015).

G. Hagen et al, arXiv:1601.08203 (2016).

Slide from Gaute Hagen, 2016

problems with our forces? radii for Oxygen

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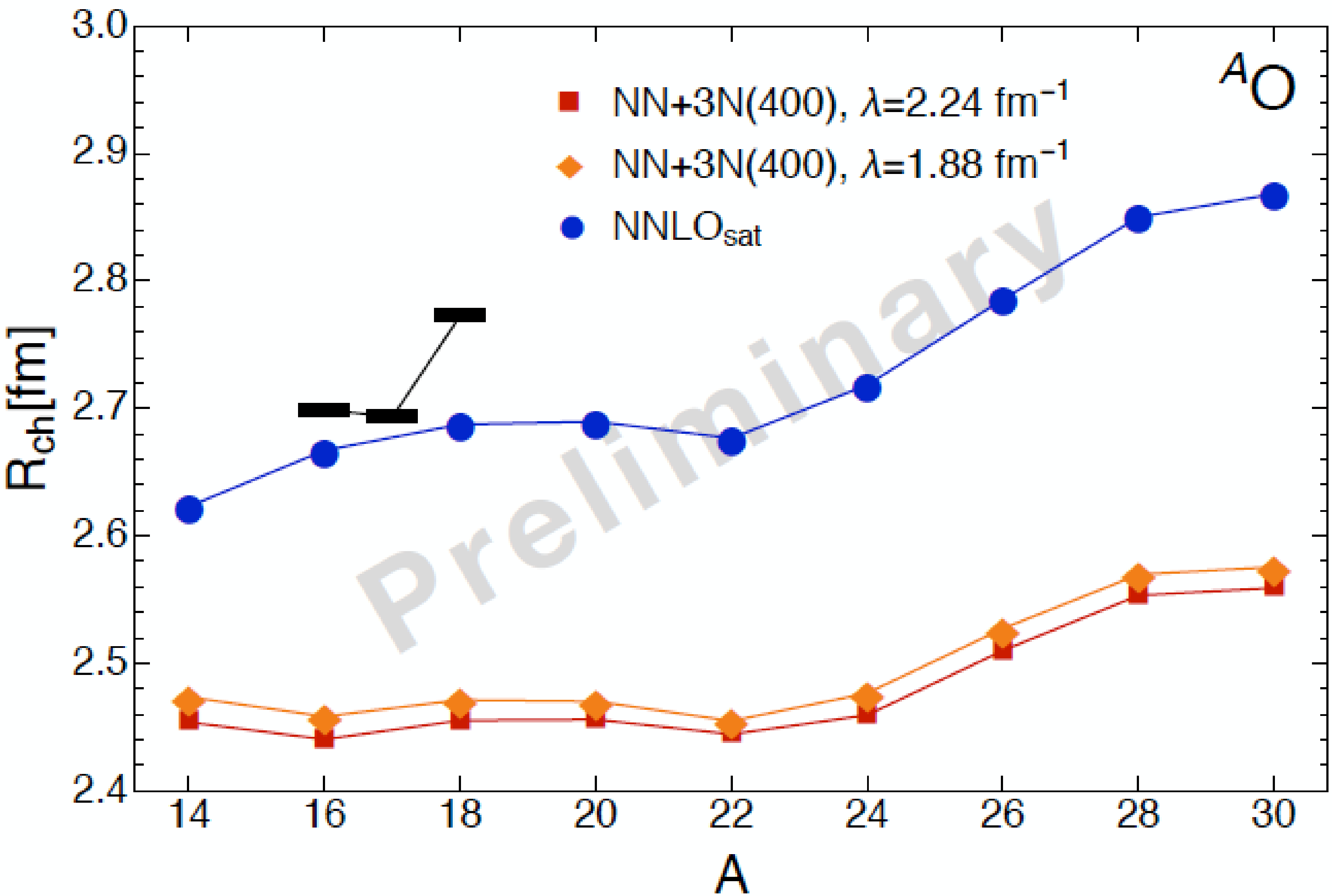
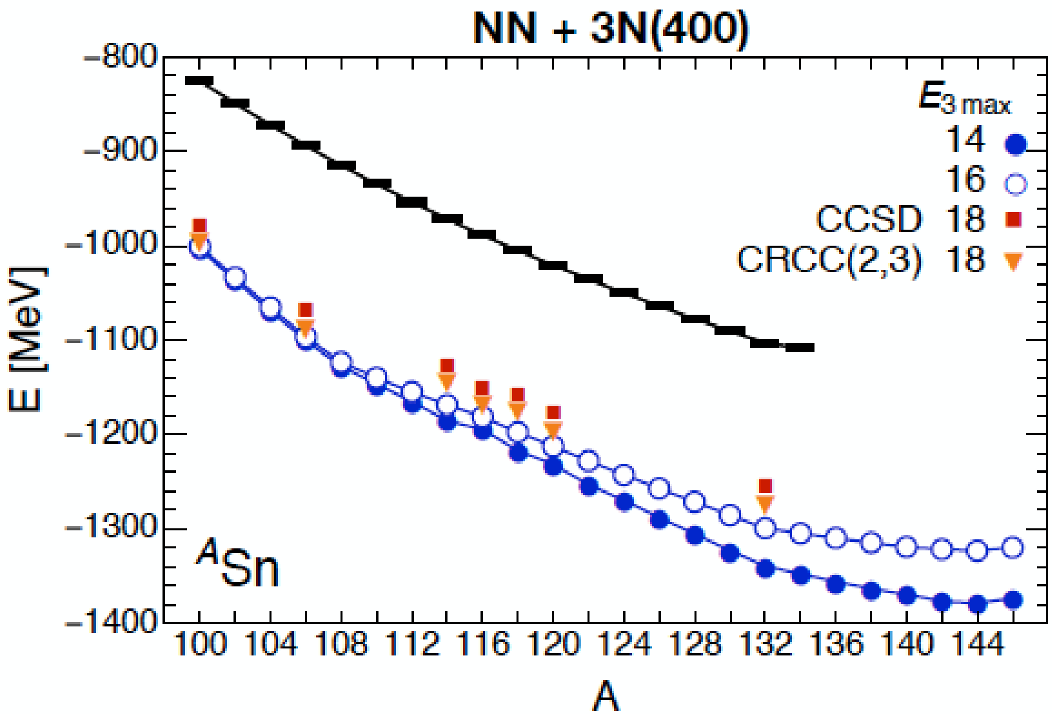


The mass frontier with ab-initio: Tin

HH, in preparation



E_{3max}	memory (float) [GB]
14	5
16	~20
18	100+

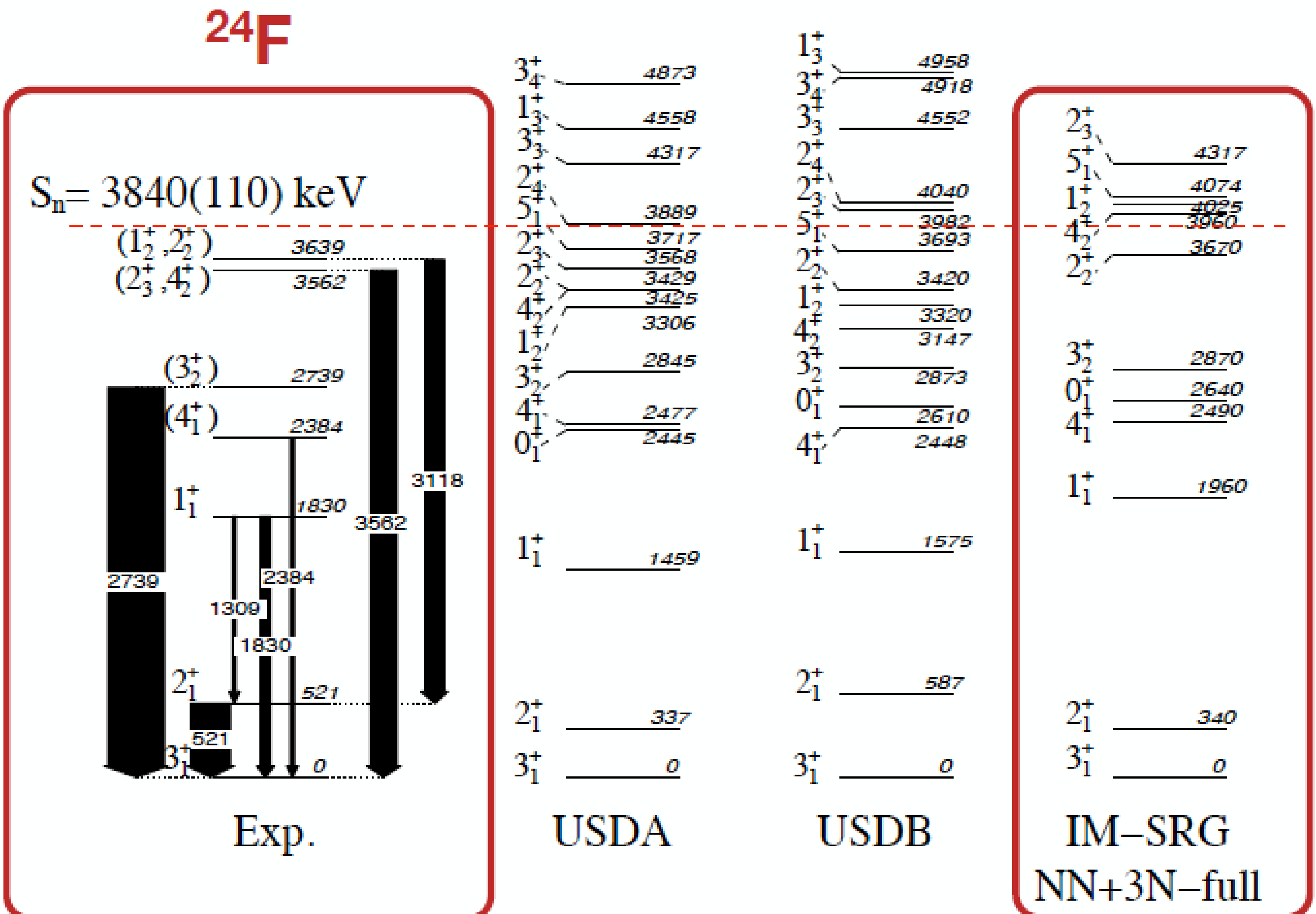
- systematics of overbinding similar to Ca/Ni
- not converged with respect to 3N matrix element truncation:

$$e_1 + e_2 + e_3 \leq E_{3max}$$

($e_{1,2,3}$: SHO energy quantum numbers)

- need technical improvements to go further

Detailed spectroscopy with ab-initio theories

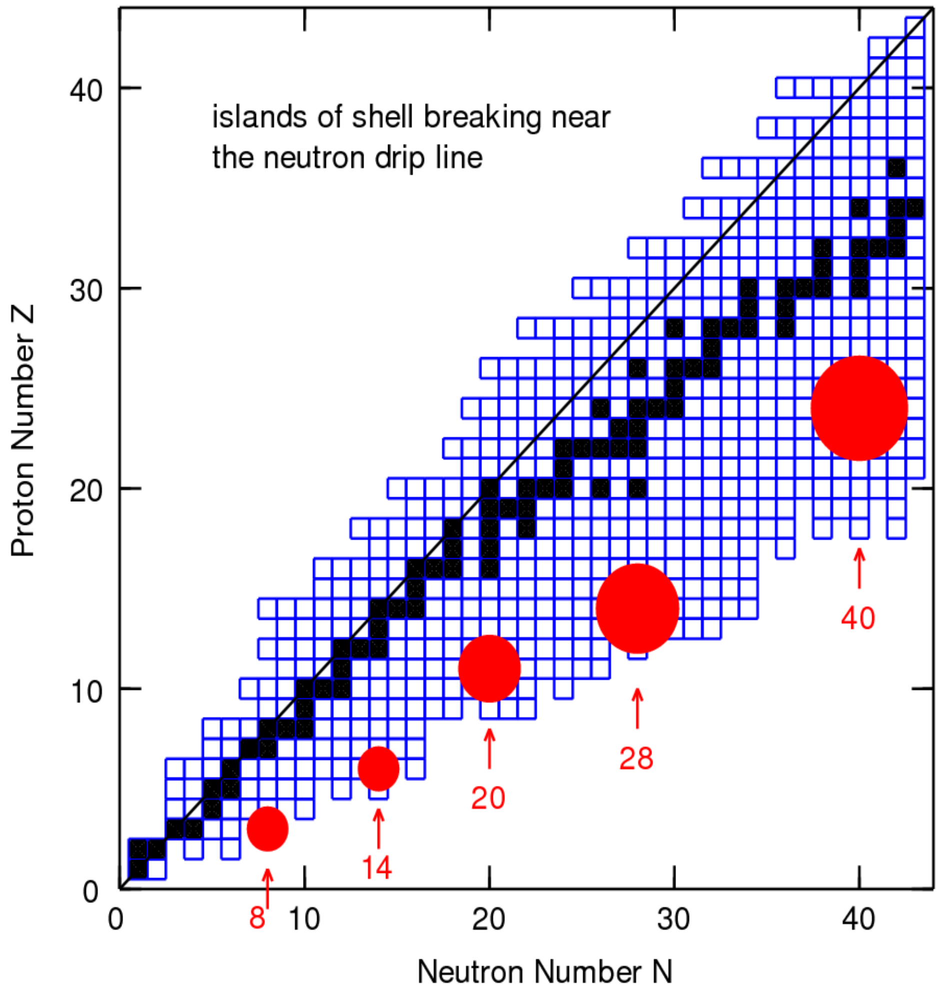


L. Caceres et al., PRC92, 014327 (2015)

shell structure away from stability

what happened to our magic numbers?

Brown, Viewpoint 2010

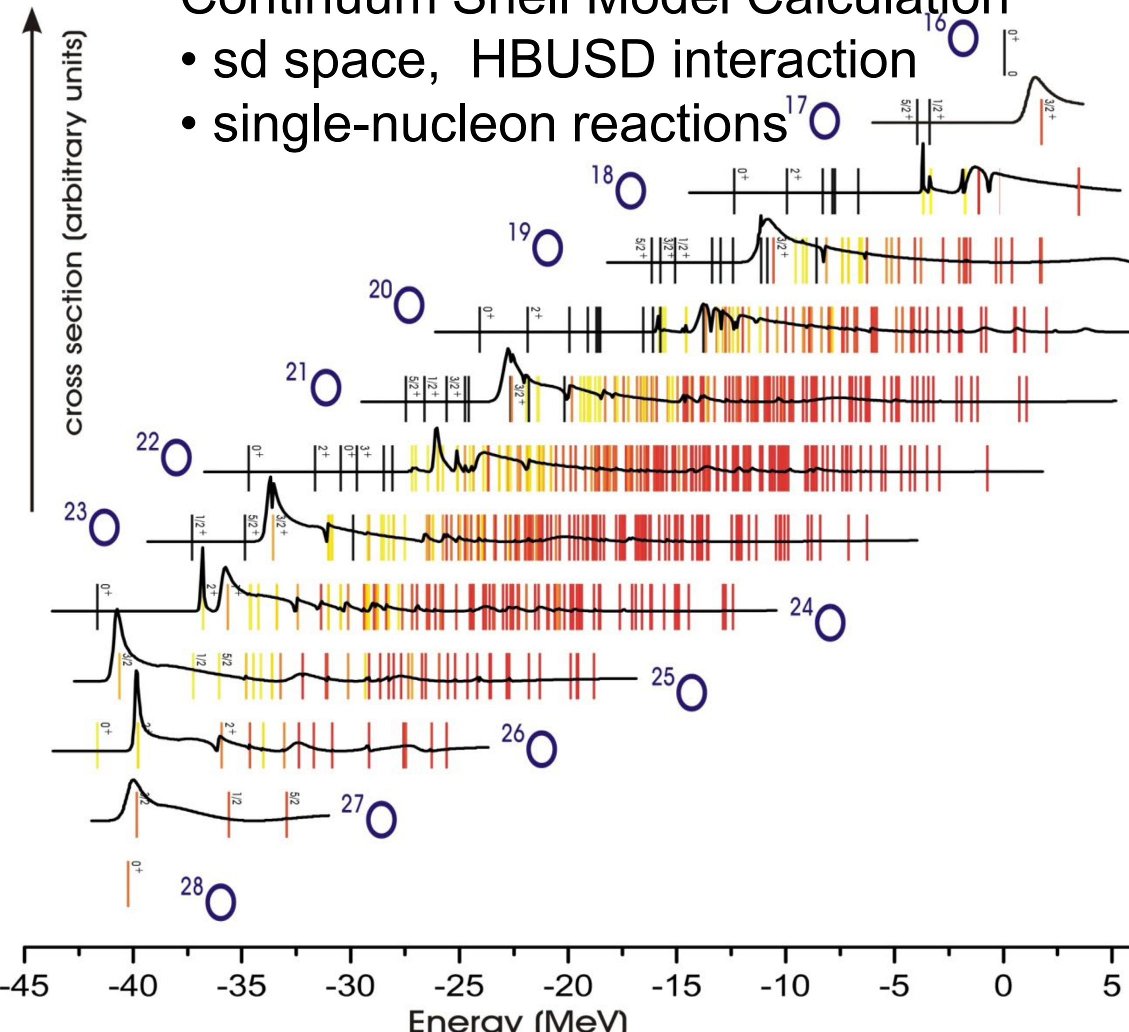


Continuum shell model

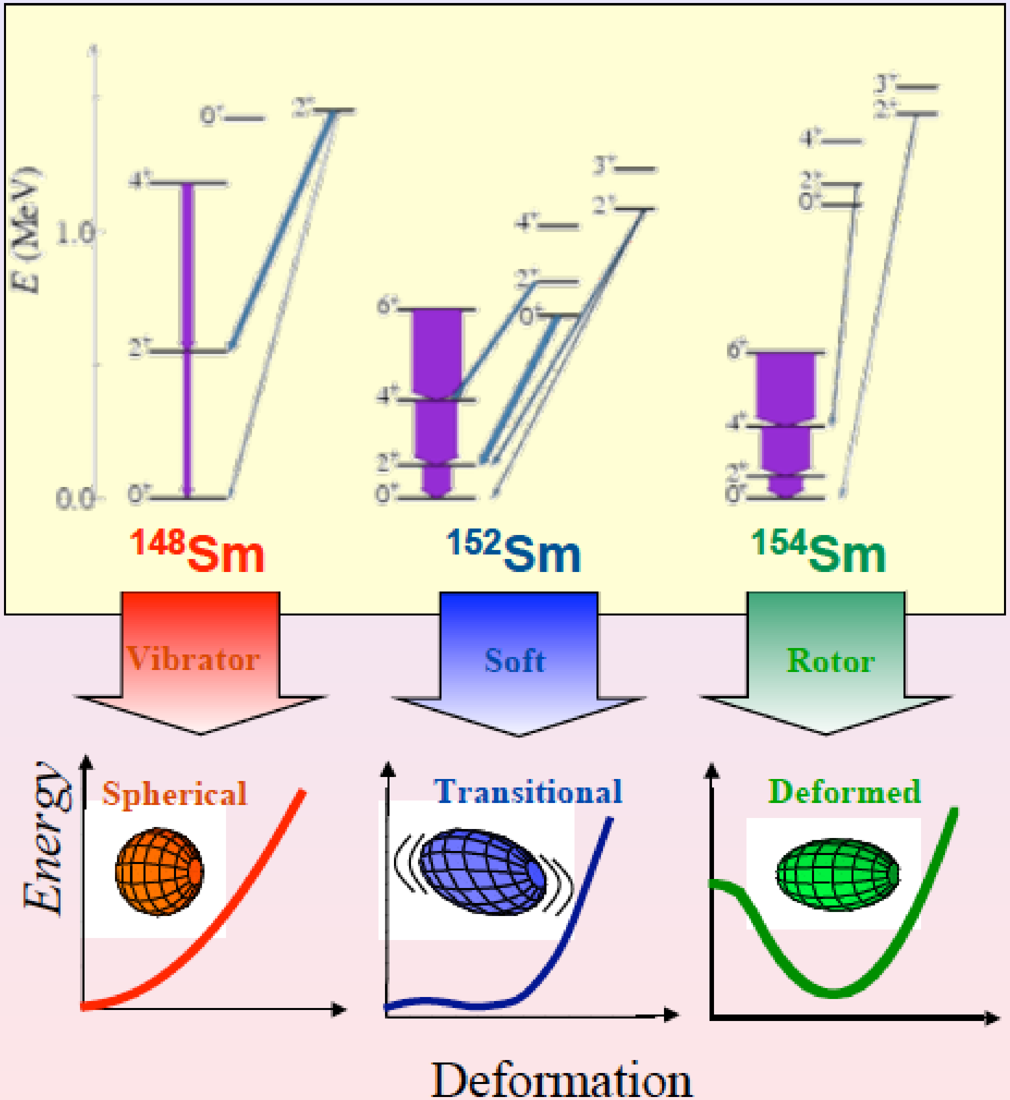
Oxygen Isotopes

Continuum Shell Model Calculation

- sd space, HBUSD interaction
- single-nucleon reactions



Collective effects are a real challenge for ab-initio



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

Density functional approach

- Hohenberg-Kohn: there exists a universal energy functional
- approximate the energy functional
- introduce orbitals and minimize energy functional
- self-consistent

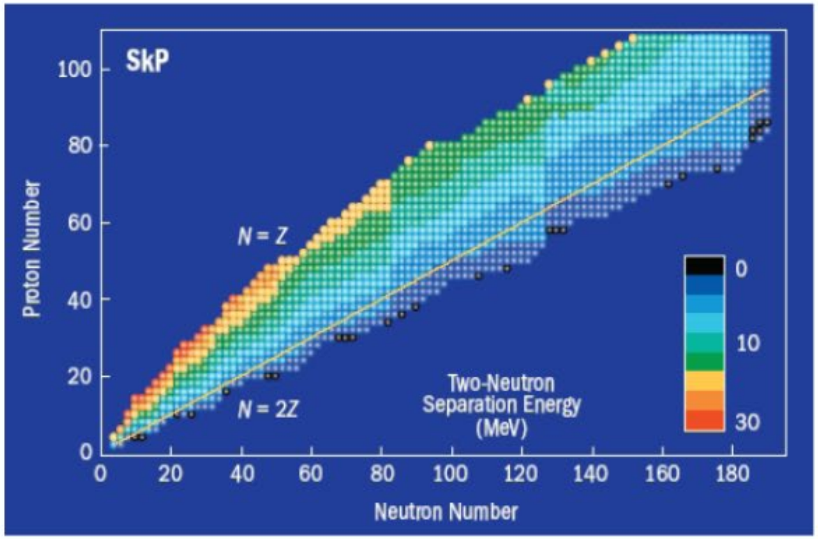
Phenomenological Skyrme Functionals

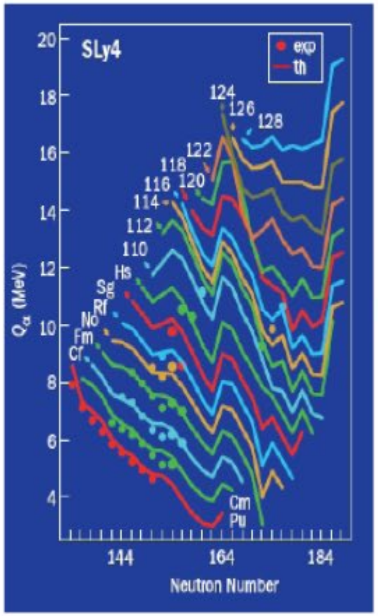
- Minimize $E = \int d\mathbf{x}\, \mathcal{E}[\rho(x), \tau(x), \mathbf{J}(\mathbf{x}), \ldots]$ (for $N = Z$):

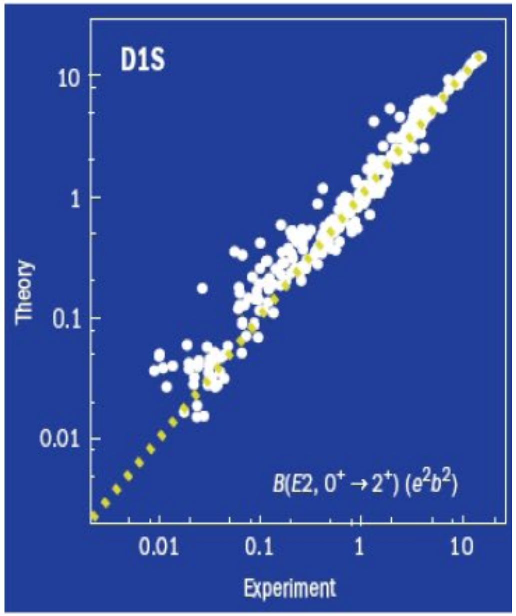
$$\mathcal{E}[\rho, \tau, \mathbf{J}] = \frac{1}{2M}\tau + \frac{3}{8}t_0\rho^2 + \frac{1}{16}t_3\rho^{2+\alpha} + \frac{1}{16}(3t_1 + 5t_2)\rho\tau + \frac{1}{64}(9t_1 - 5t_2)(\nabla\rho)^2 - \frac{3}{4}W_0\rho\nabla\cdot\mathbf{J} + \frac{1}{32}(t_1 - t_2)\mathbf{J}^2$$

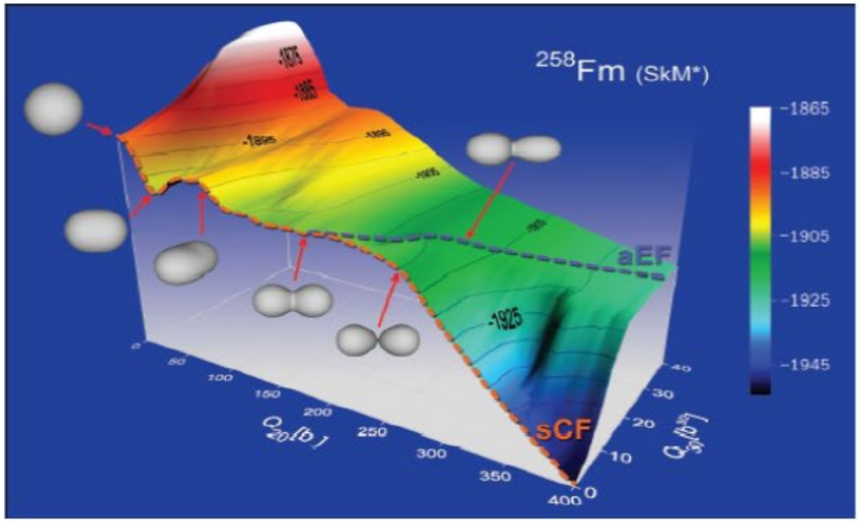
- where $\rho(x) = \sum_i |\phi_i(x)|^2$ and $\tau(x) = \sum_i |\nabla\phi_i(x)|^2$ (and $\mathbf{J}$)

Density functional approach





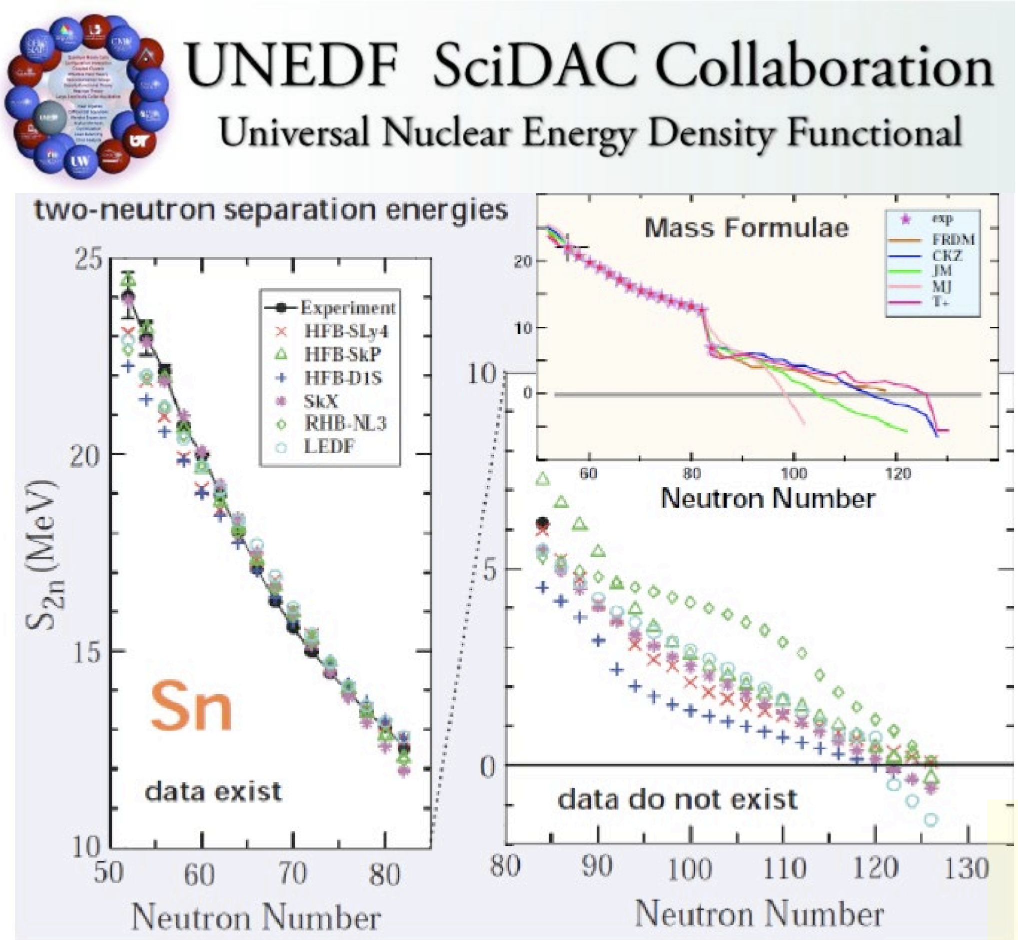




2N separation energies, Quadrupole and BE2 values, Fission energy surfaces, mass tables in a day, plus many other impressive feats

BUT…

Density functional approach



What is missing from Skyrme?

- Simplistic density dependence
- No connection to pion-exchange (NN+NNN)
- Does not capture different spin-orbit NN and NNN mechanisms (short versus long range)

Turn to underlying NN+NNN forces + microscopic many-body theories for guidance

Why exotic stuff?

Nuclear forces constrained in the valley of stability

predict diverging properties away from stability

need exotic nuclei for reliability

feeds back into our understanding of stable matter

Moving along an isotopic line: provides sensitivity to isospin

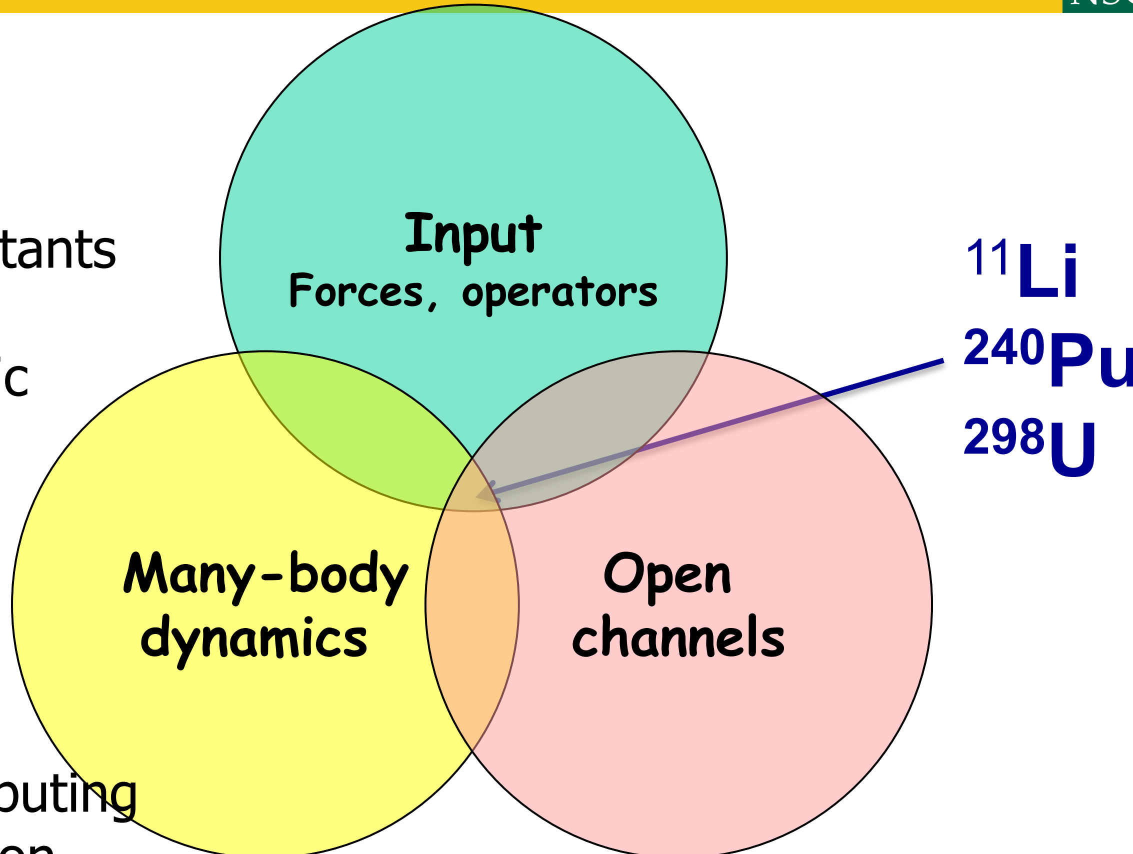
Moving to low binding energies: sensitivity to 3N (or higher)

Moving toward nuclear dripline: probes density dependence

Wider variety of nuclear phenomena away from stability

Physics of nuclei is demanding

- rooted in QCD – EFT expansions
- many-body interactions
- low-energy coupling constants optimized to NN data
- crucial insights from exotic nuclei



- many-body techniques
- high-performance computing
- uncertainty quantification
- interdisciplinary connections

- nuclear structure impacted by couplings to reaction and decay channels
- clustering, alpha decay, and fission still remain major challenges for theory
- unified picture of structure and reactions

[Nazarewicz]

QUESTION TIME

Go and explore DFTs

massexplorer.frib.msu.edu

Compare the predictions of binding energy for ^{40}Ca and ^{60}Ca for a number of different functionals.

Where is the Ca dripline for these various functionals?

Questions?

Reaching towards the FRIB benchmark ^{60}Ca

G. Hagen *et al*, arXiv:1601.08203 (2016).