Equation of state constraints from nuclear physics and observation

Kai Hebeler

Hirschegg, January 19, 2017

Neutron star mergers:
from gravitational waves to nucleosynthesis

SFB 1245

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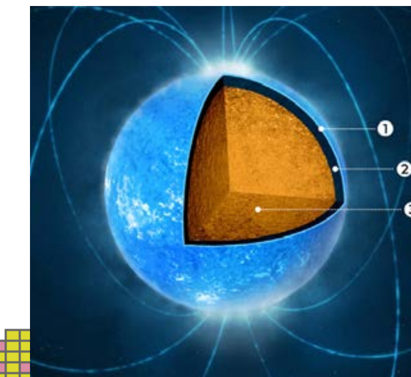
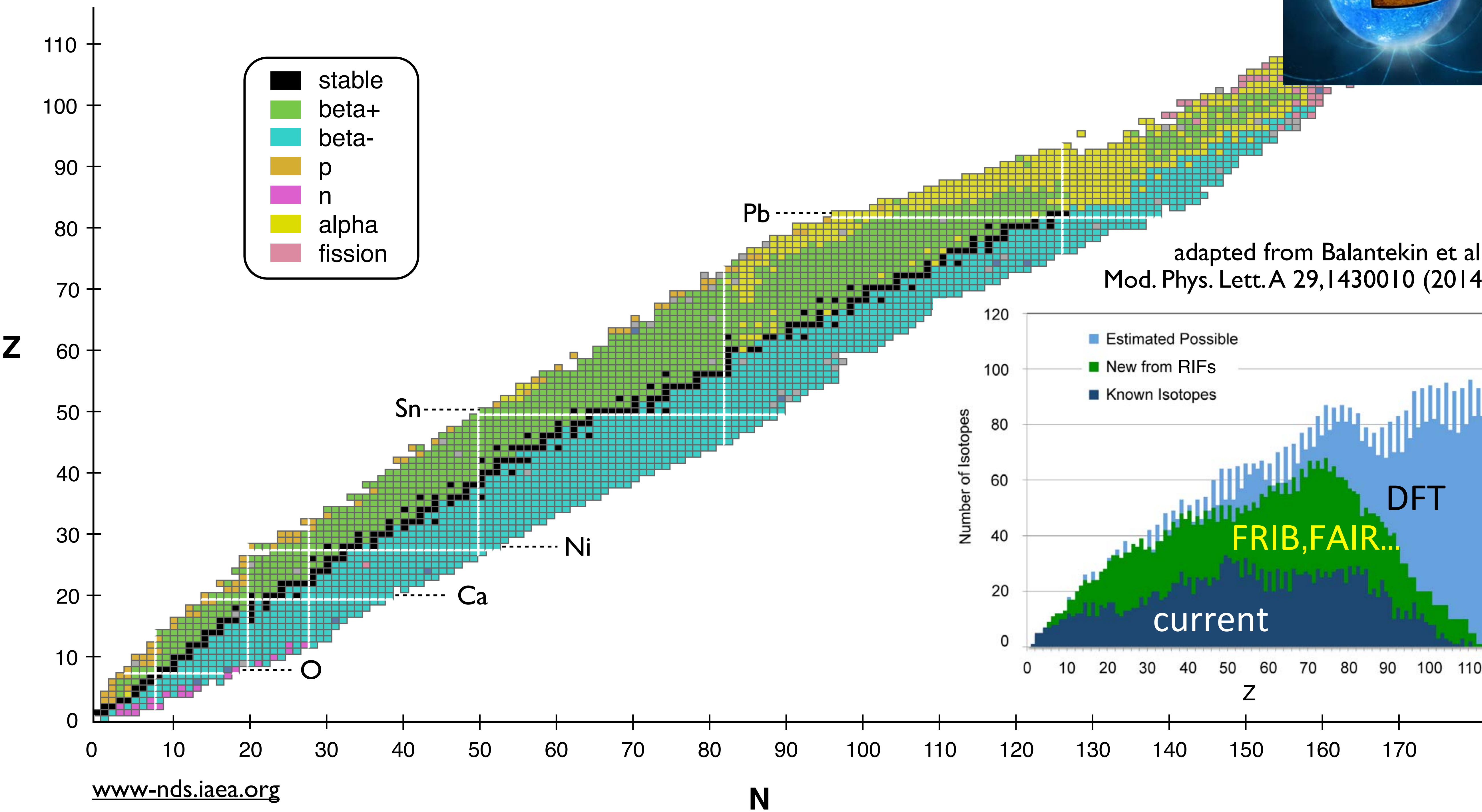
The nuclear landscape:
New frontiers from rare isotope facilities





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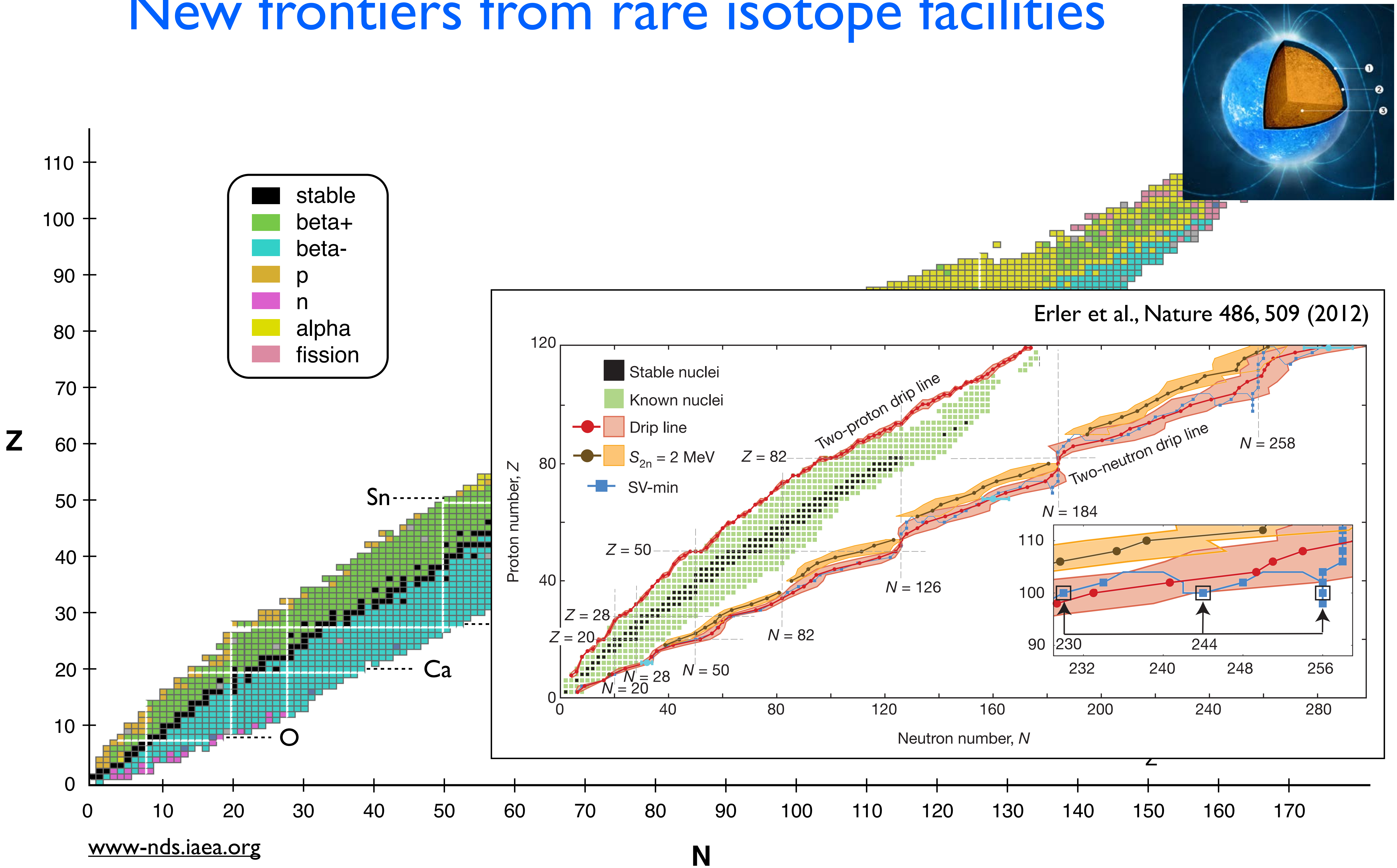

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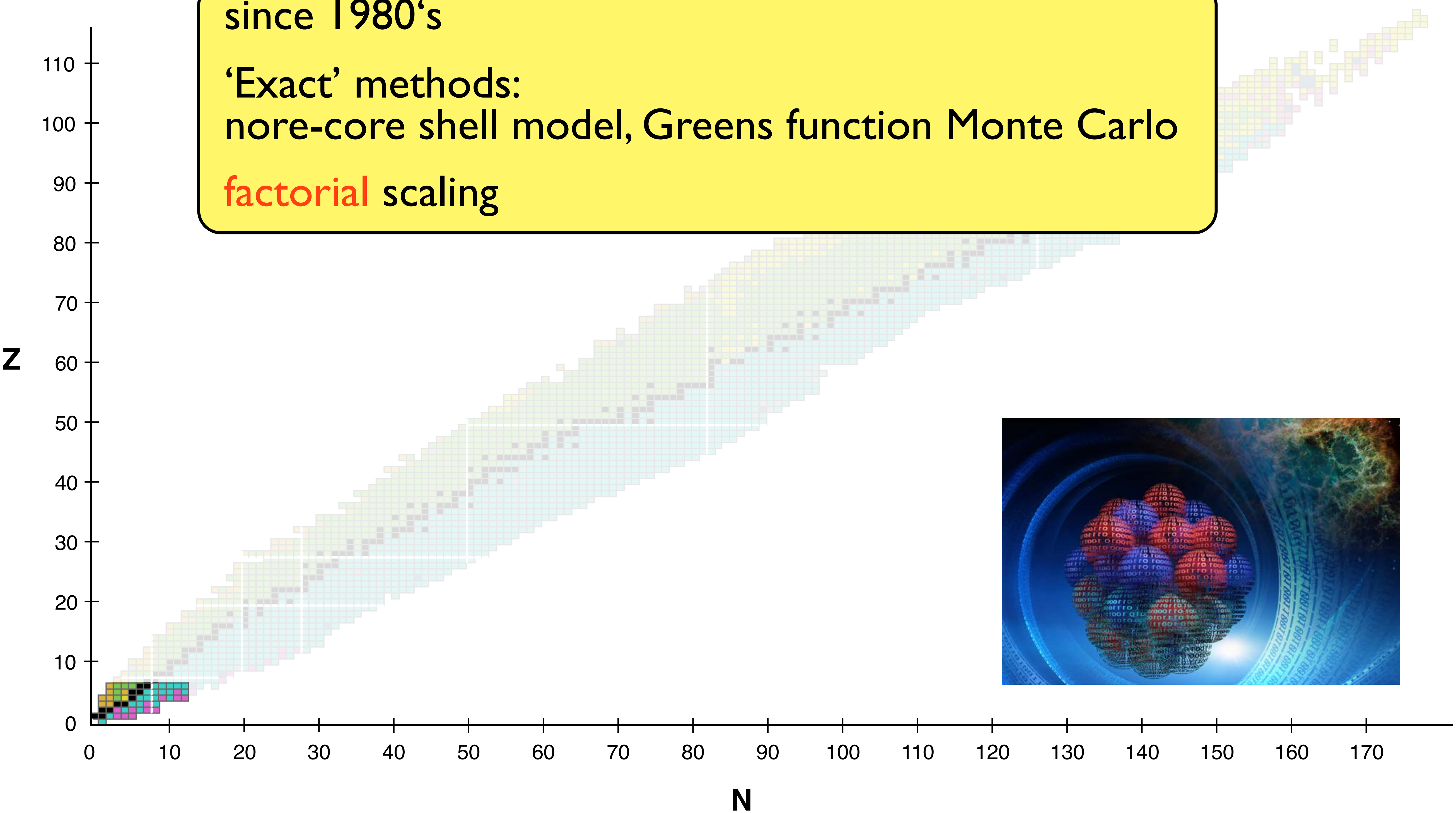
The theoretical nuclear landscape: Scope of ab initio methods for atomic nuclei

since 1980‘s

‘Exact’ methods:
nore-core shell model, Greens function Monte Carlo

factorial scaling



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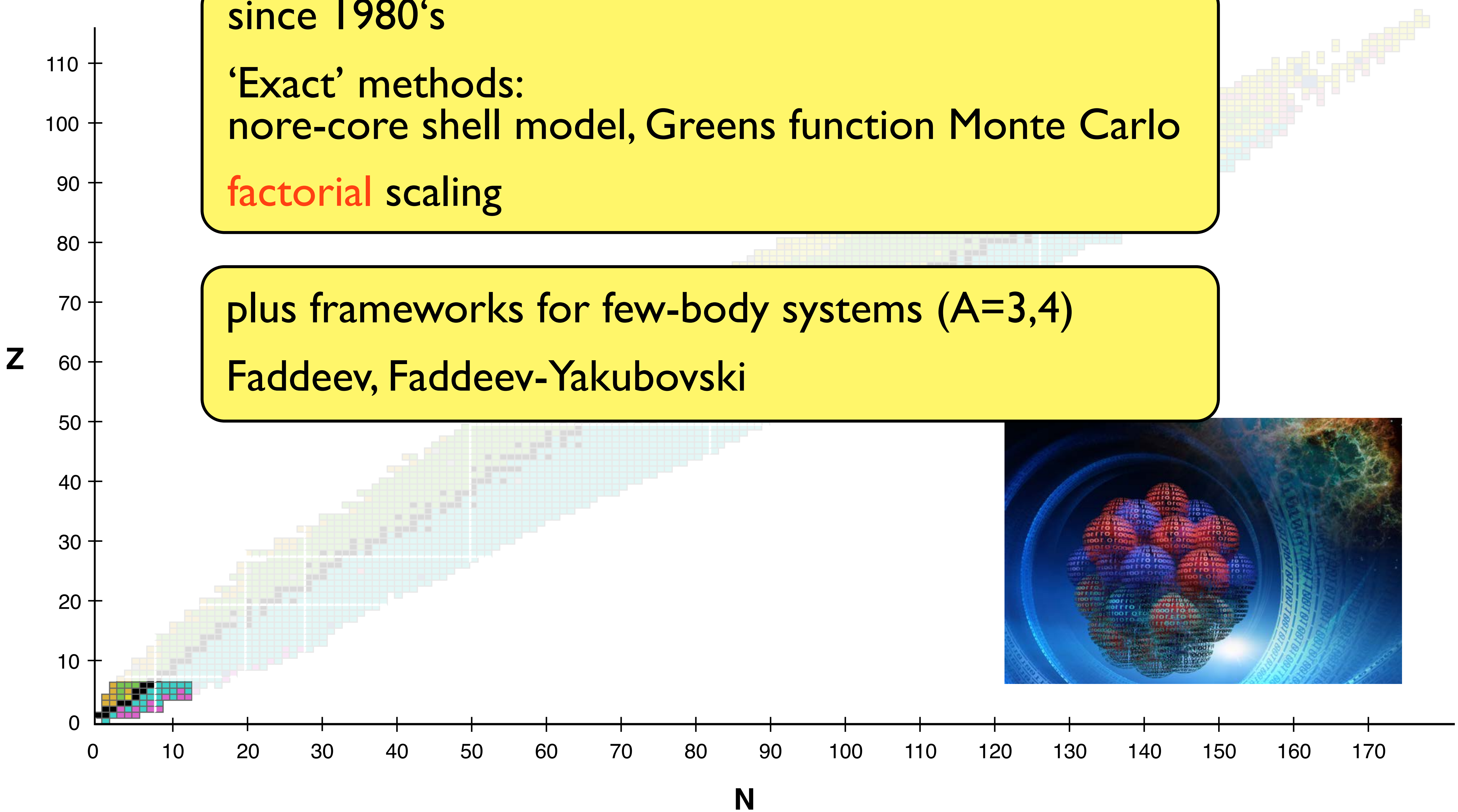
since 1980's

'Exact' methods:
nore-core shell model, Greens function Monte Carlo

factorial scaling

plus frameworks for few-body systems (A=3,4)

Faddeev, Faddeev-Yakubovski

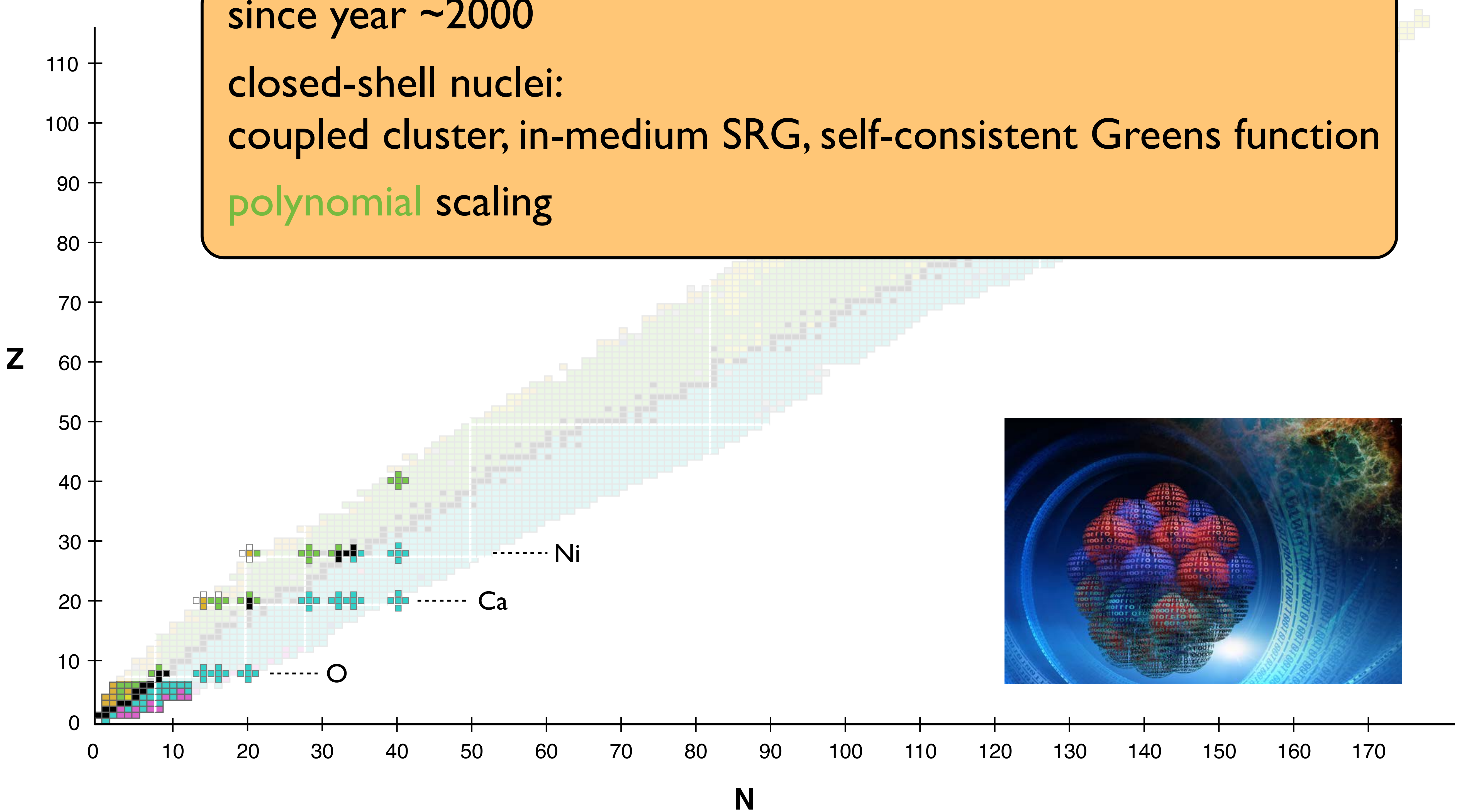


The theoretical nuclear landscape: Scope of ab initio methods for atomic nuclei

since year ~2000

closed-shell nuclei:
coupled cluster, in-medium SRG, self-consistent Greens function

polynomial scaling

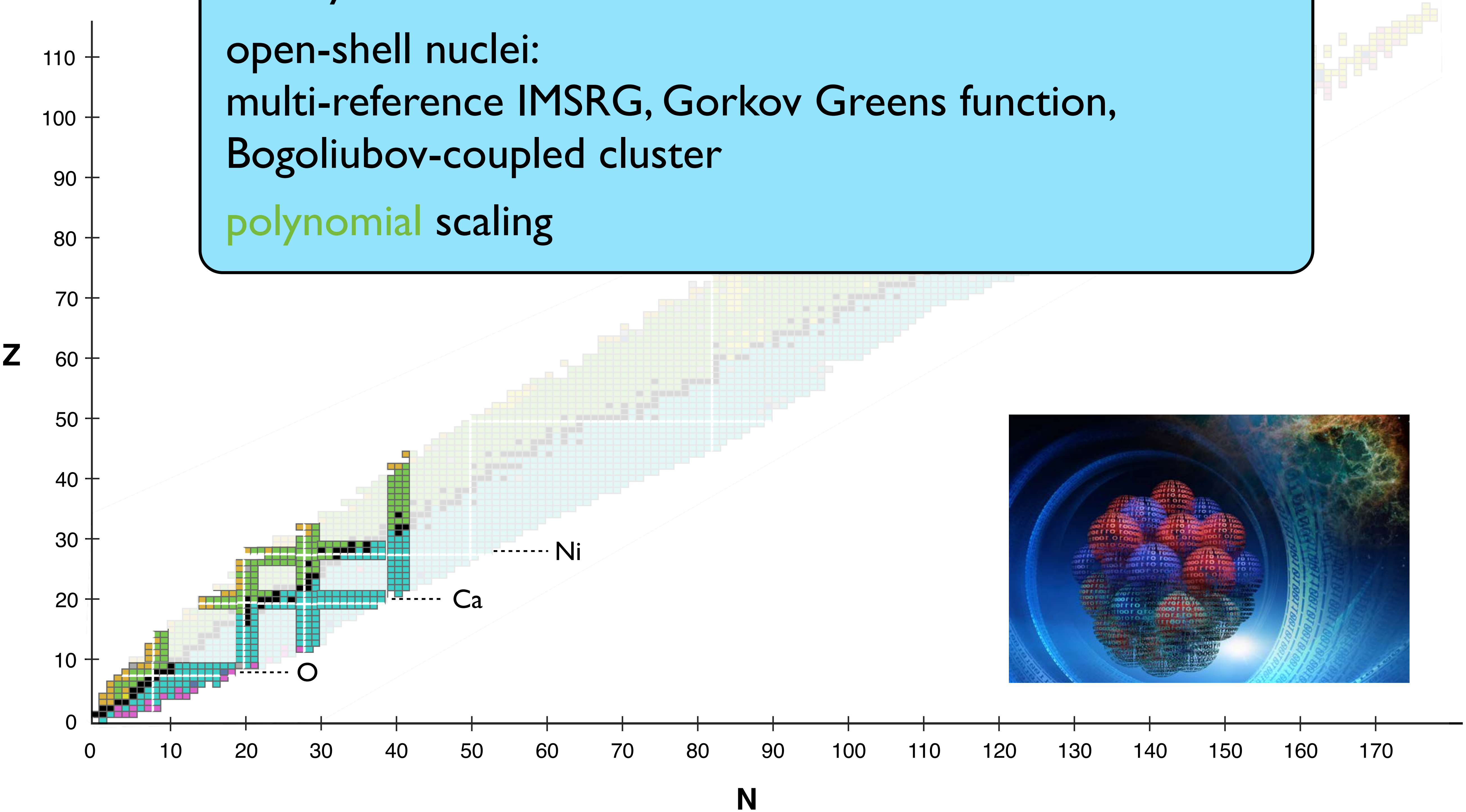


The theoretical nuclear landscape: Scope of ab initio methods for atomic nuclei

since year ~2010

open-shell nuclei:
multi-reference IMSRG, Gorkov Greens function,
Bogoliubov-coupled cluster

polynomial scaling

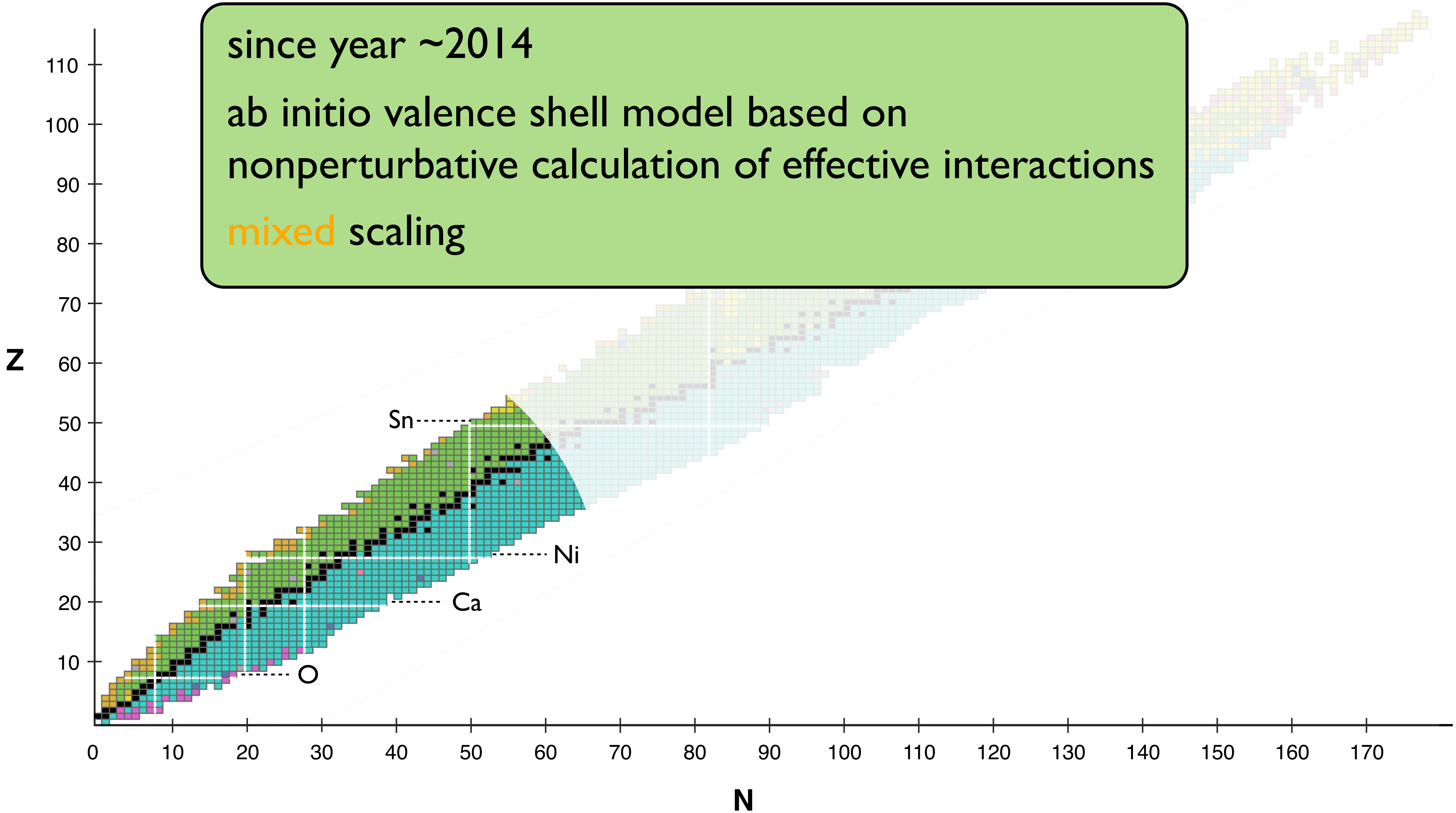


The theoretical nuclear landscape: Scope of ab initio methods for atomic nuclei

since year ~2014

ab initio valence shell model based on nonperturbative calculation of effective interactions

mixed scaling



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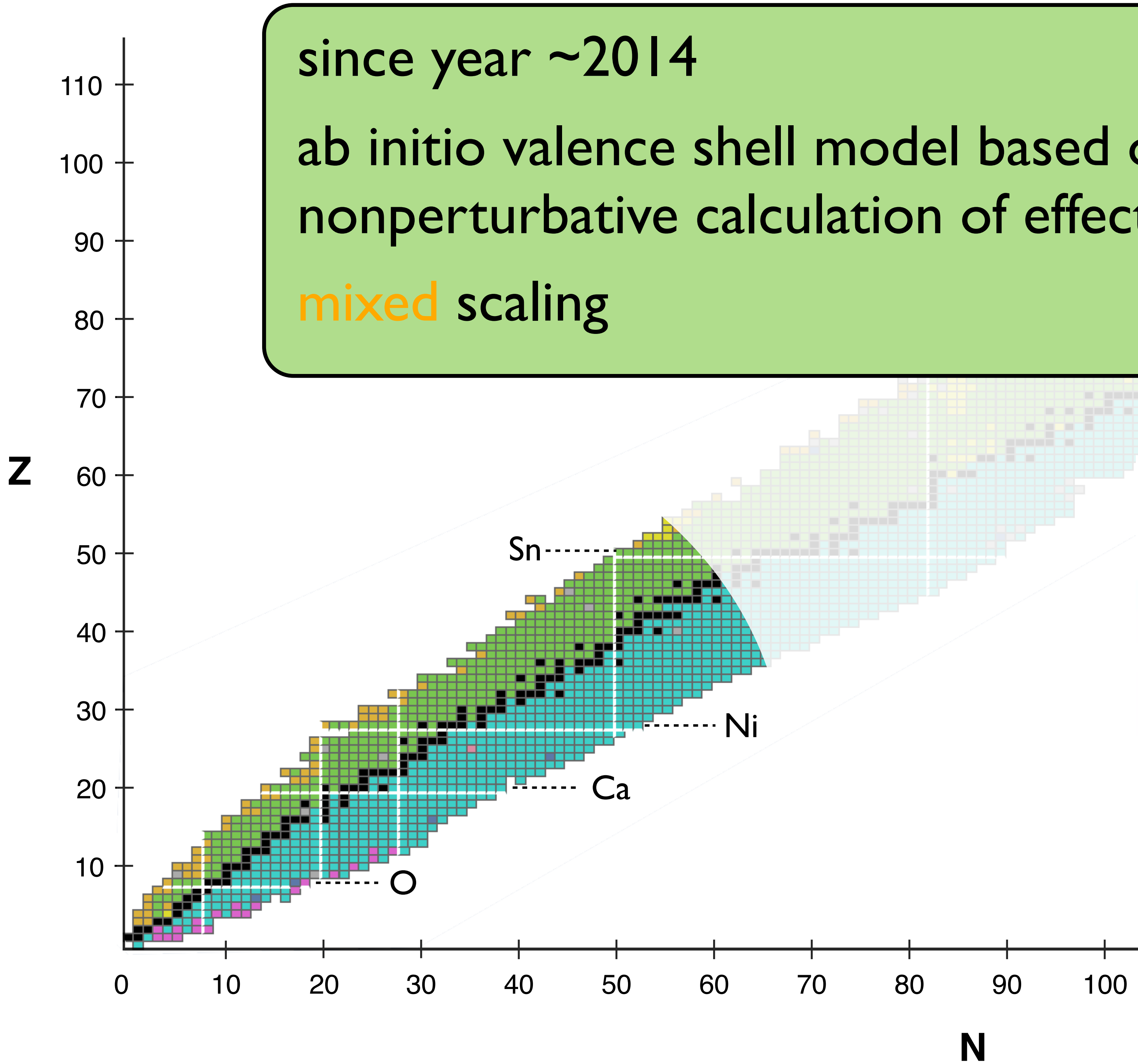
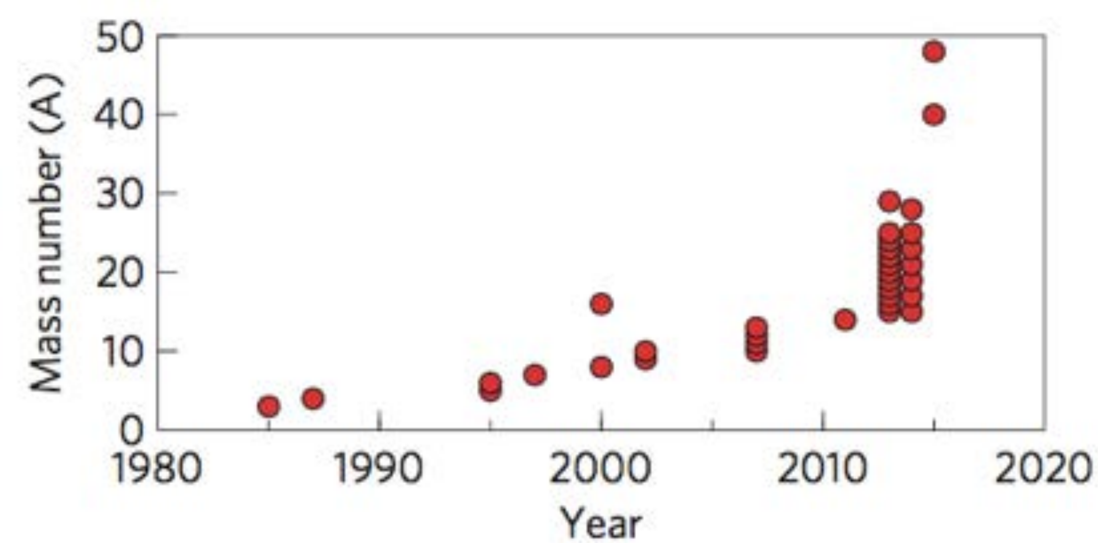




Hagen et al., Nature Physics 12, 186 (2016)

Ab initio nuclear structure and reaction theory

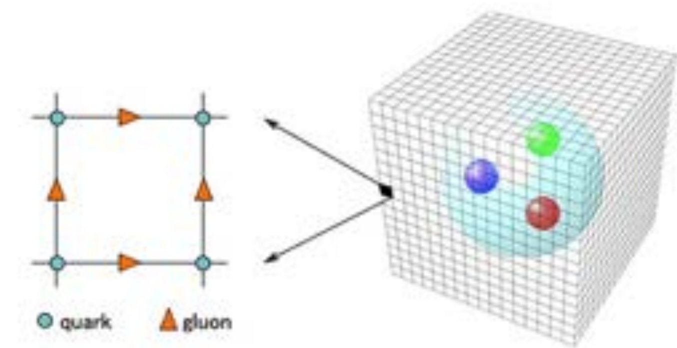
nuclear structure and reaction observables

Quantum Chromodynamics

Ab initio nuclear structure and reaction theory

nuclear structure and reaction observables

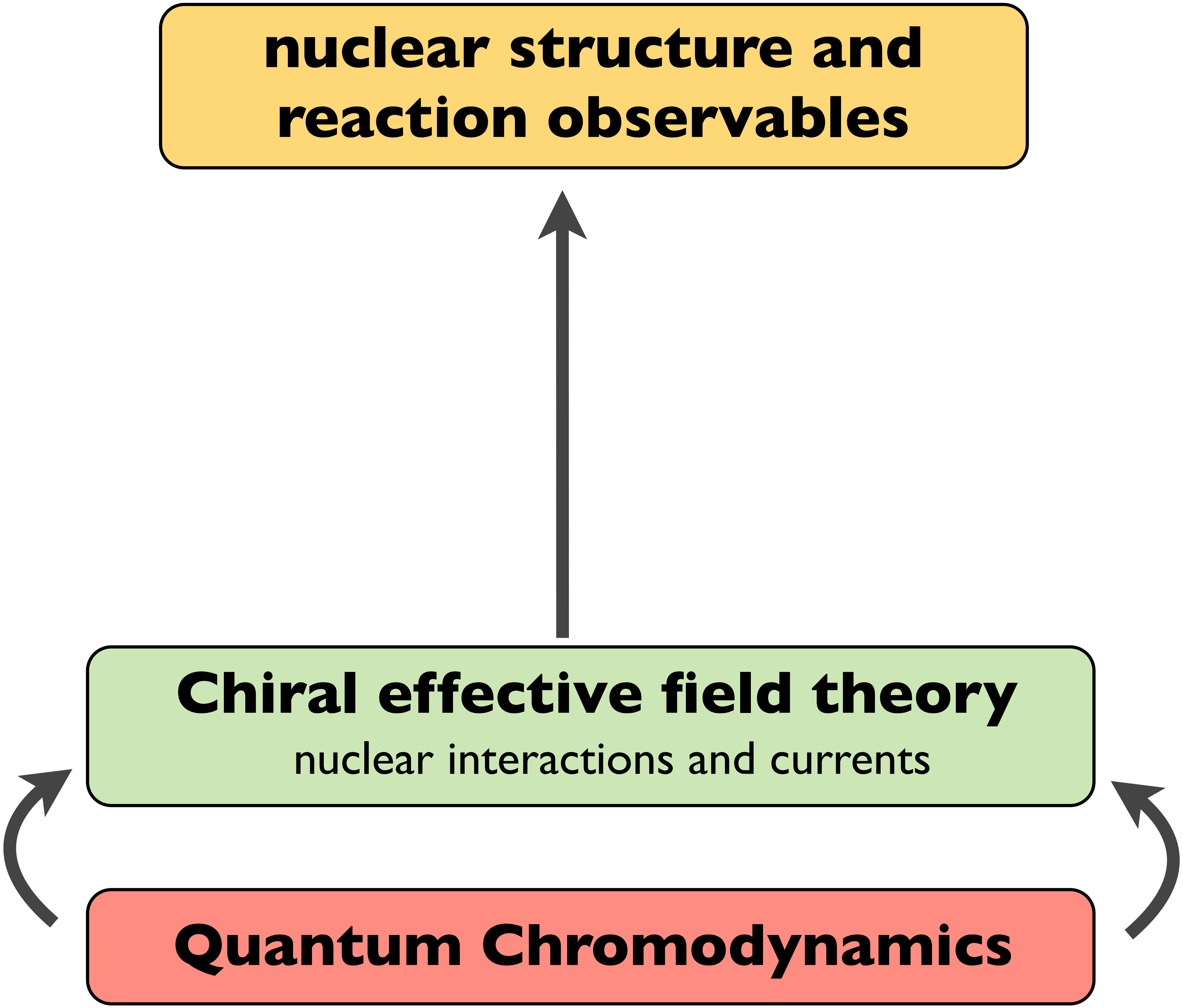
Lattice QCD



- requires extreme amounts of computational resources
- currently limited to 1- or 2-nucleon systems
- current accuracy insufficient for precision nuclear structure

Quantum Chromodynamics

Ab initio nuclear structure and reaction theory



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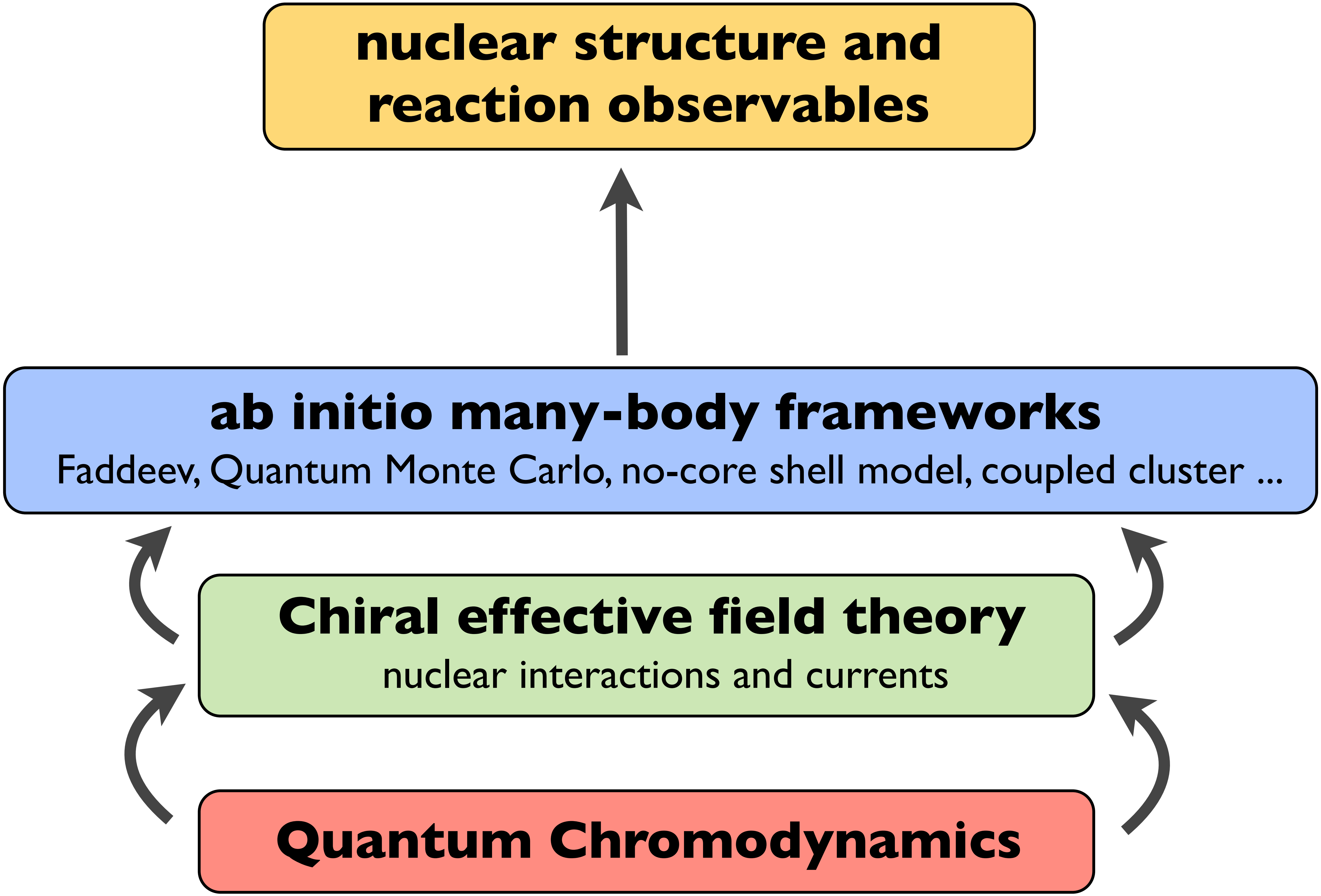

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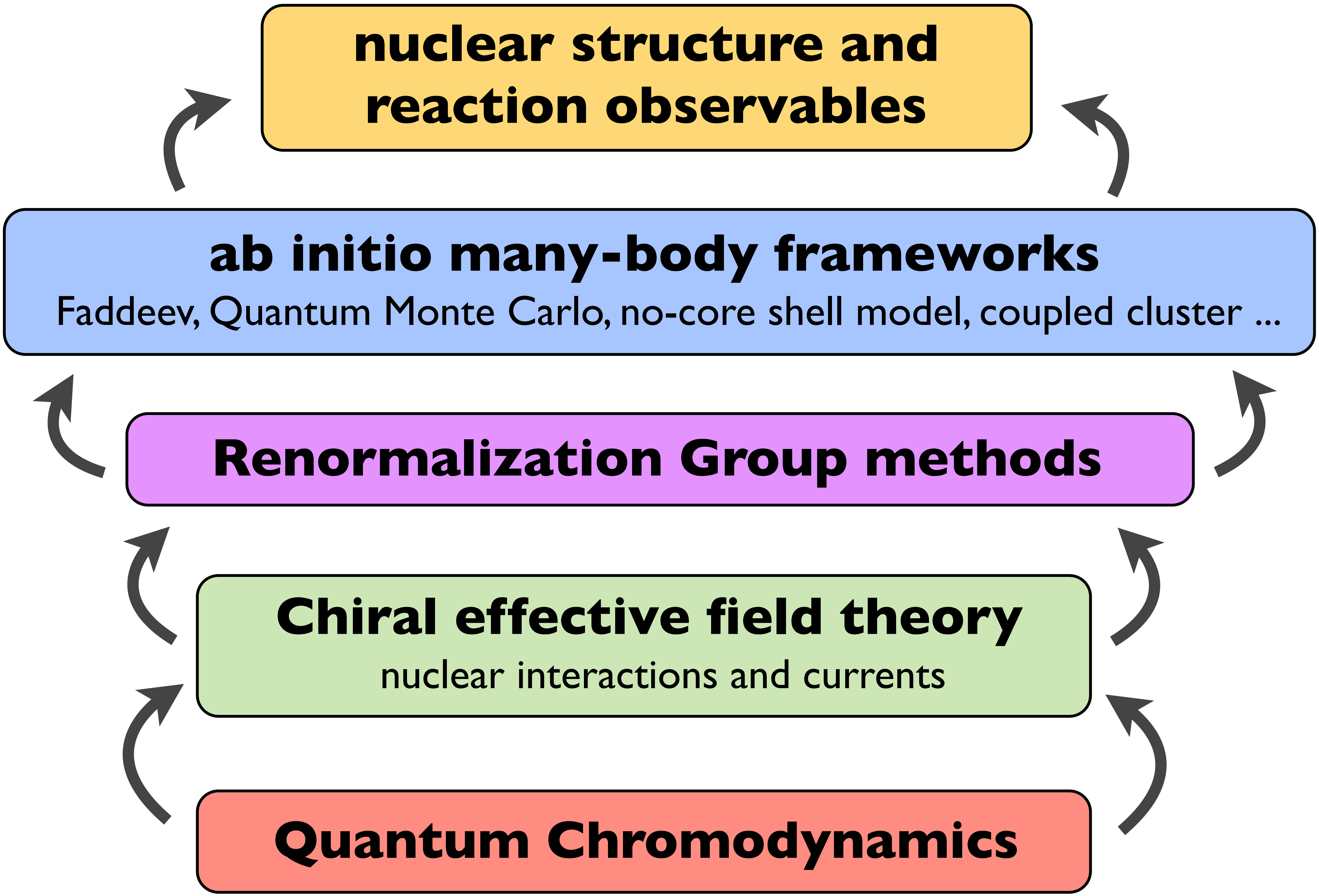
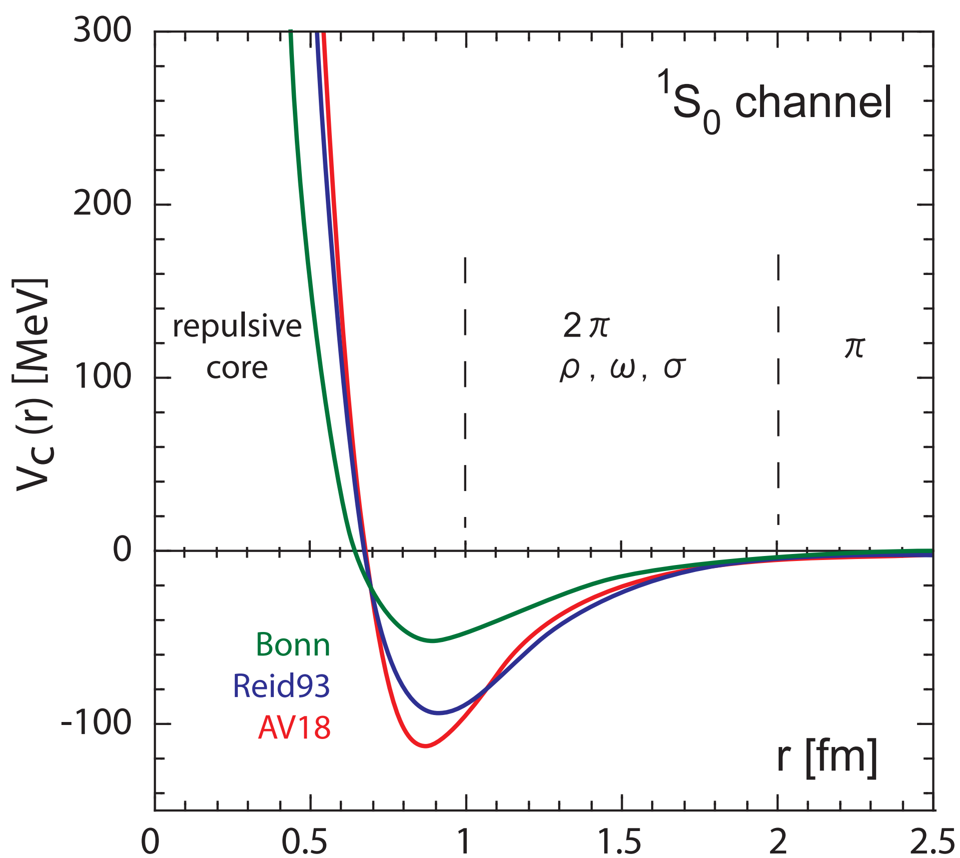
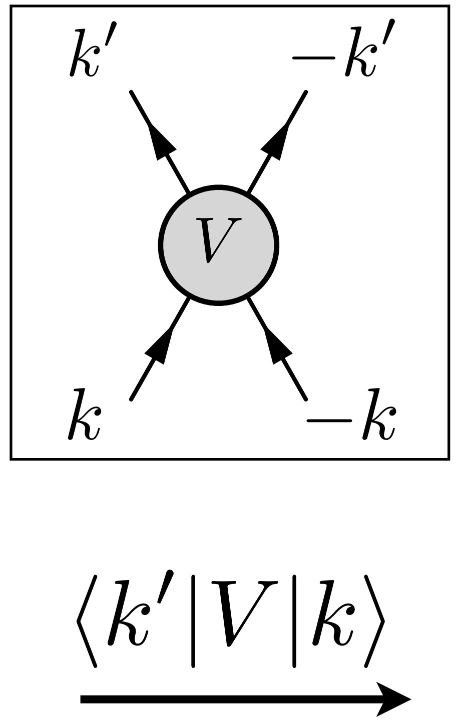
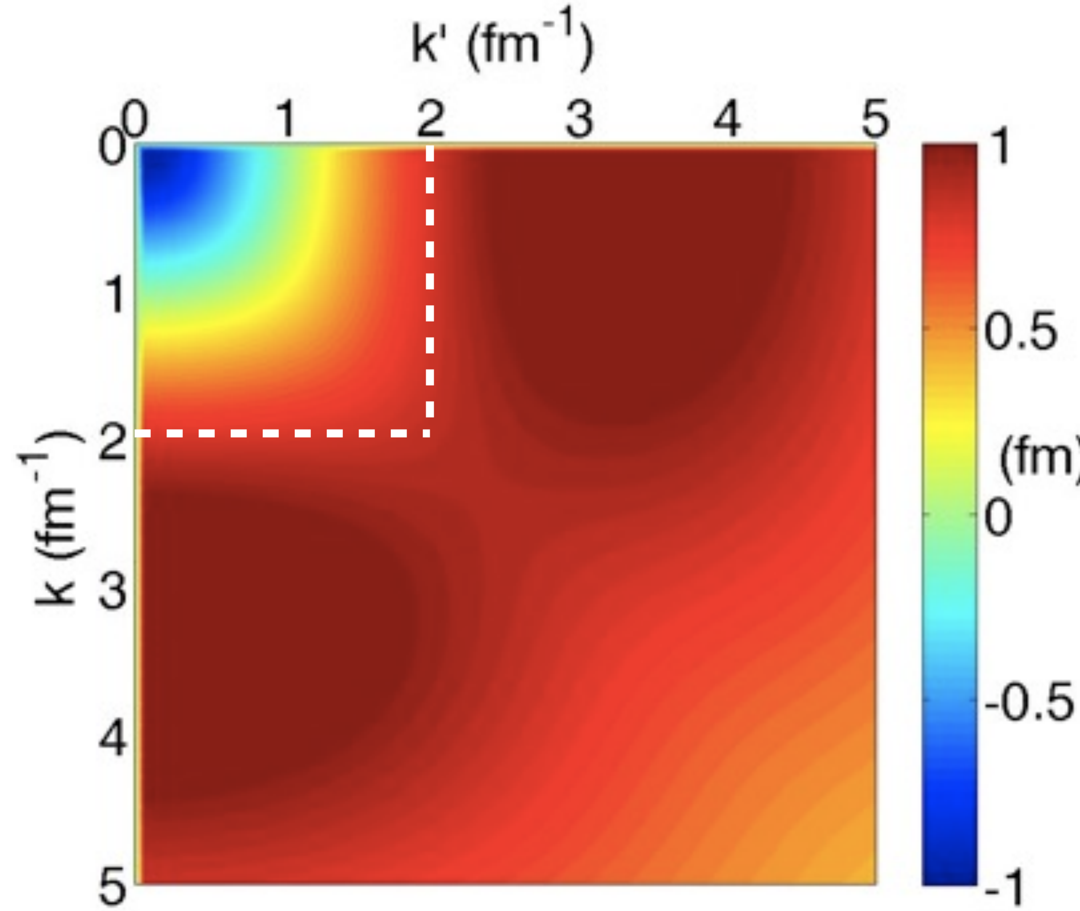


“Traditional” NN interactions







- constructed to fit NN scattering data (long-wavelength information)
- long-range part dominated by one pion exchange interaction
- short range part strongly model dependent!
- traditional NN interactions contain strongly repulsive core at small distance
  - many-body problem hard to solve using basis expansion!

Systematic decoupling of high-momentum physics: The Similarity Renormalization Group

- generate unitary transformation which decouples low- and high momenta:

$$\boxed{H_\lambda = U_\lambda H U_\lambda^\dagger}$$ with the resolution parameter λ

- change resolution systematically in small steps: $$\boxed{\frac{dH_\lambda}{d\lambda} = [\eta_\lambda, H_\lambda]}$$

- generator η_λ can be chosen and tailored to different applications

- observables are preserved due to unitarity of transformation

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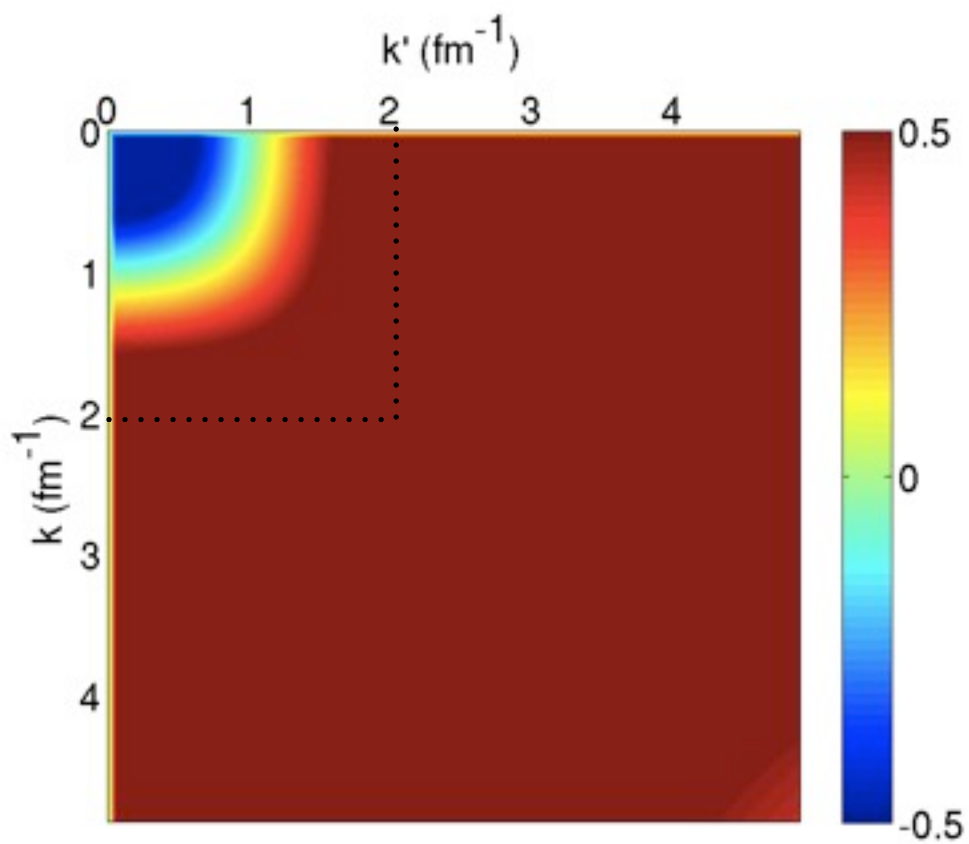
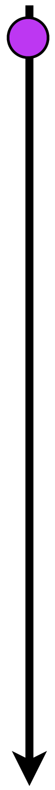


Resolution λ



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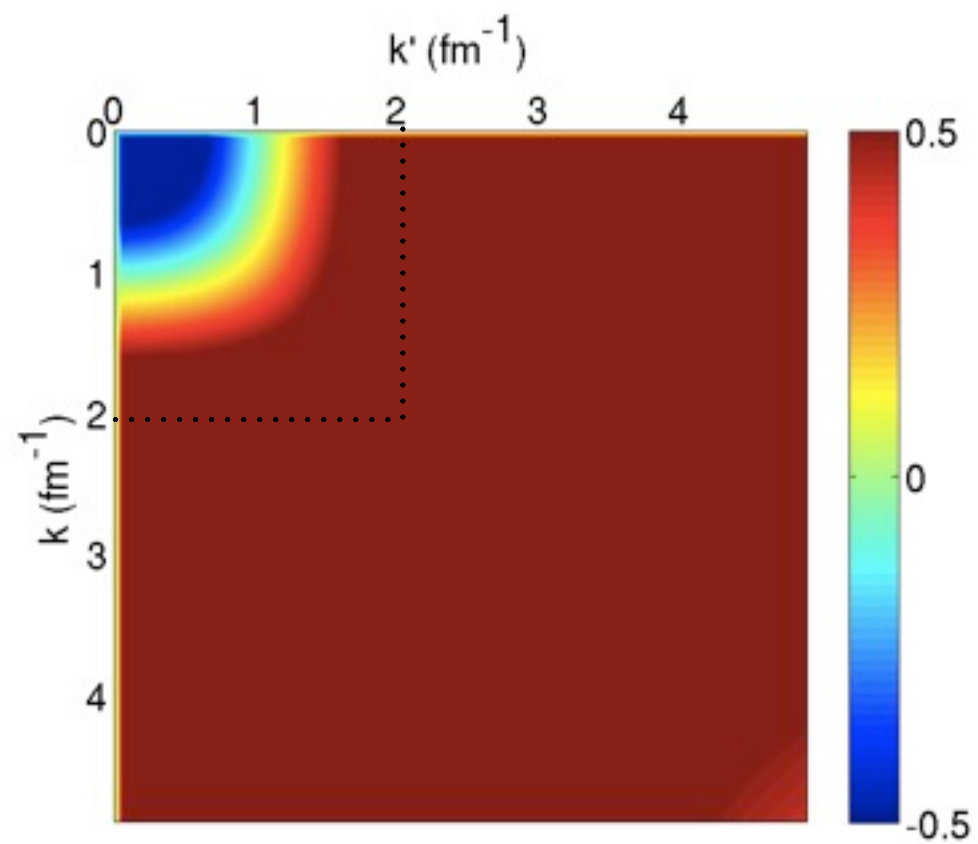

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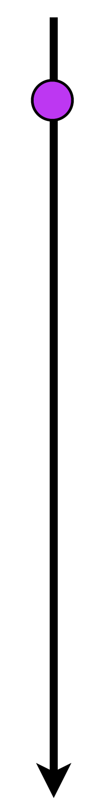

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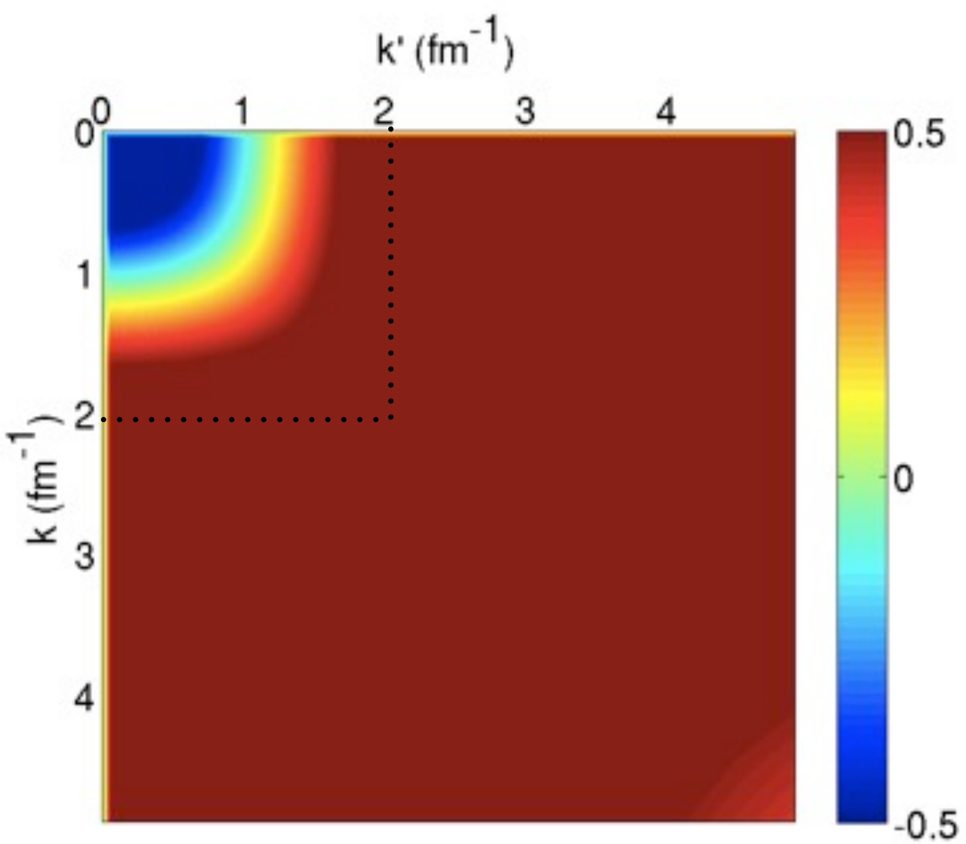

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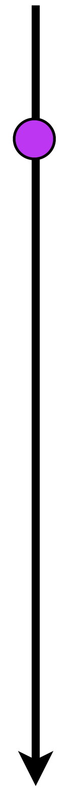

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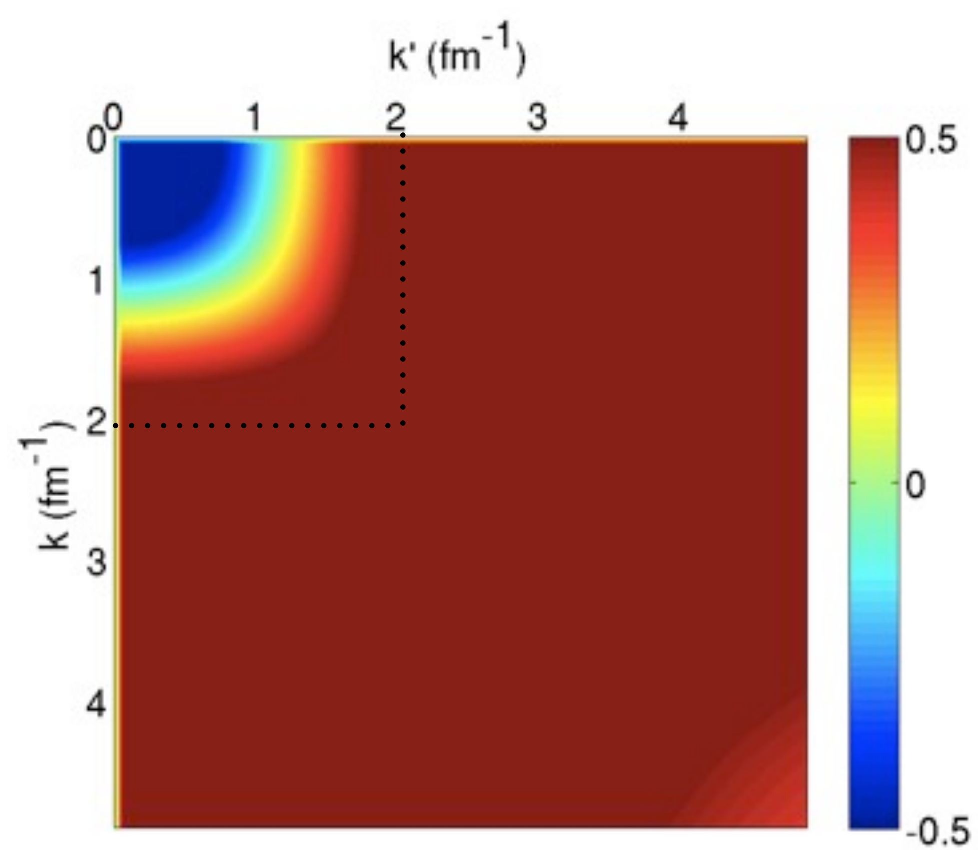

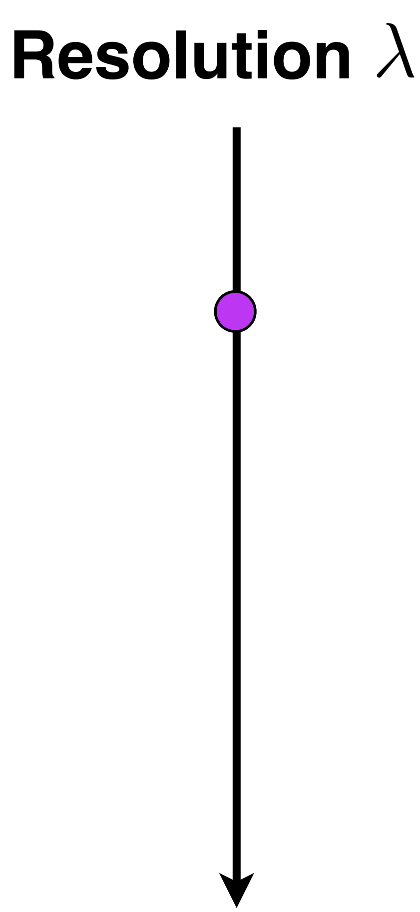

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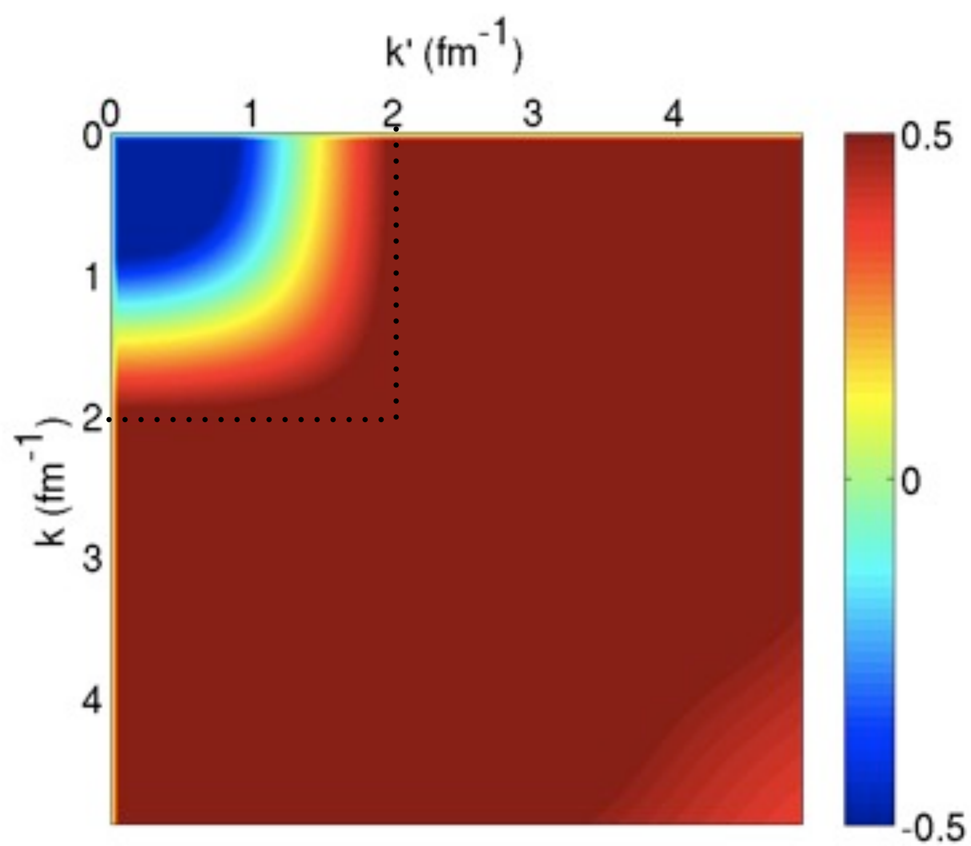

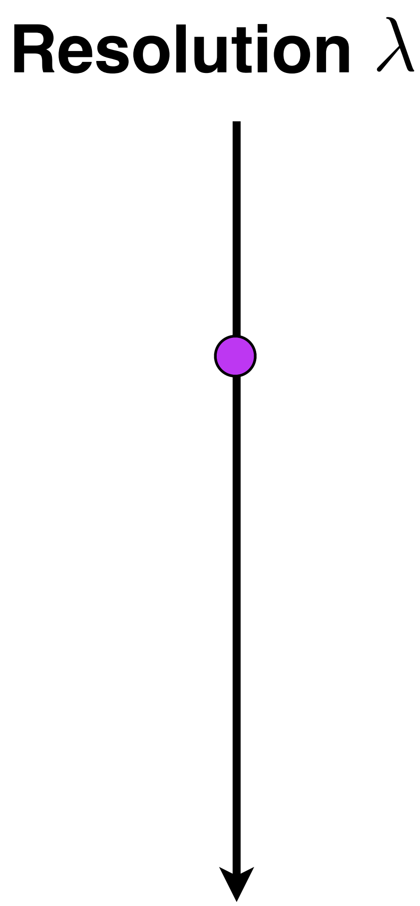

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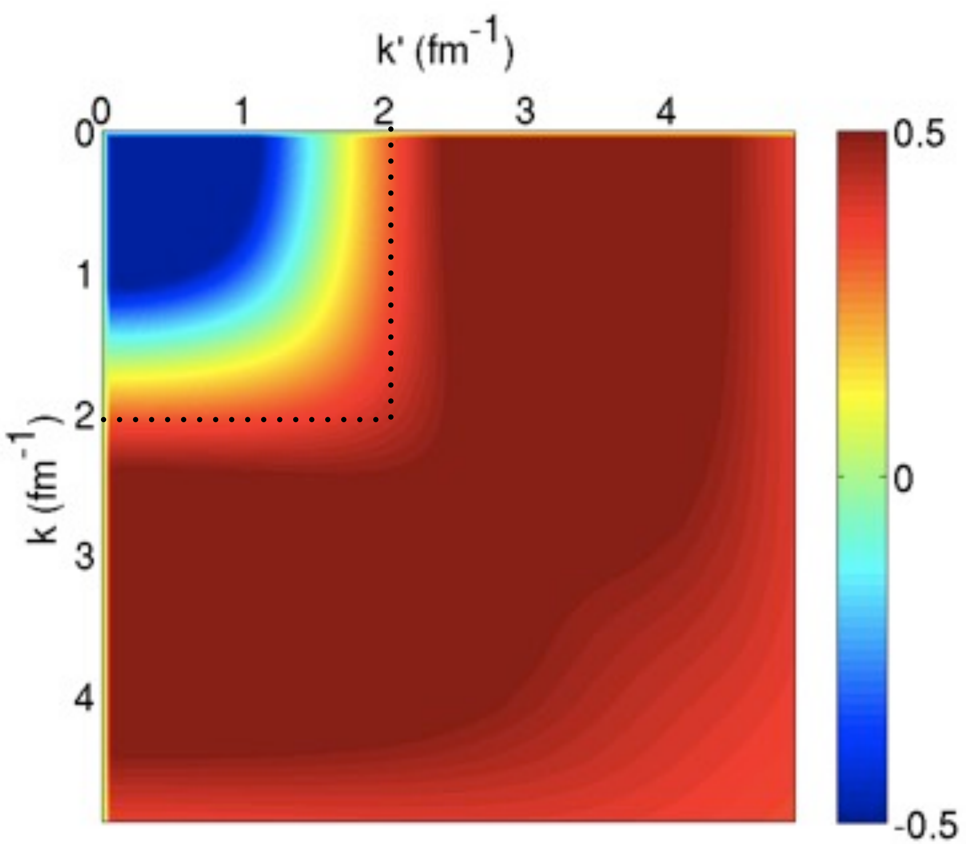

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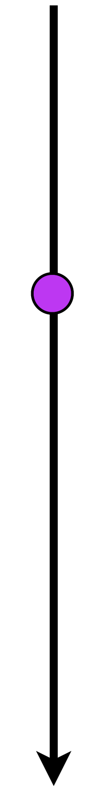

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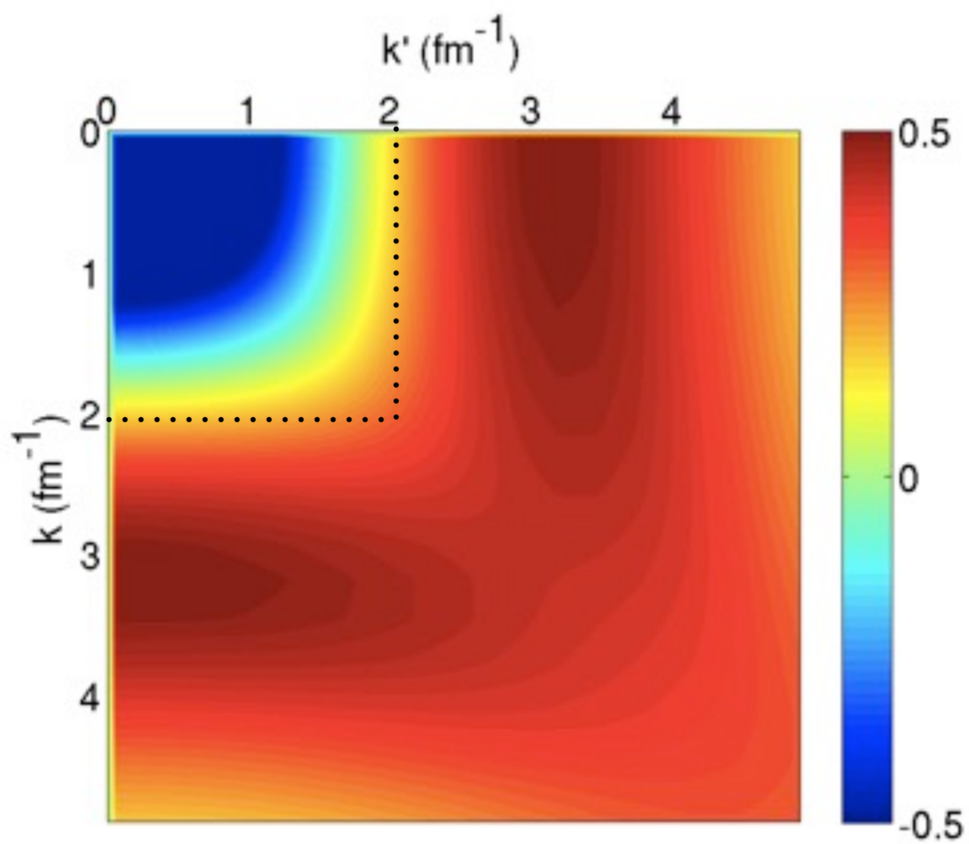

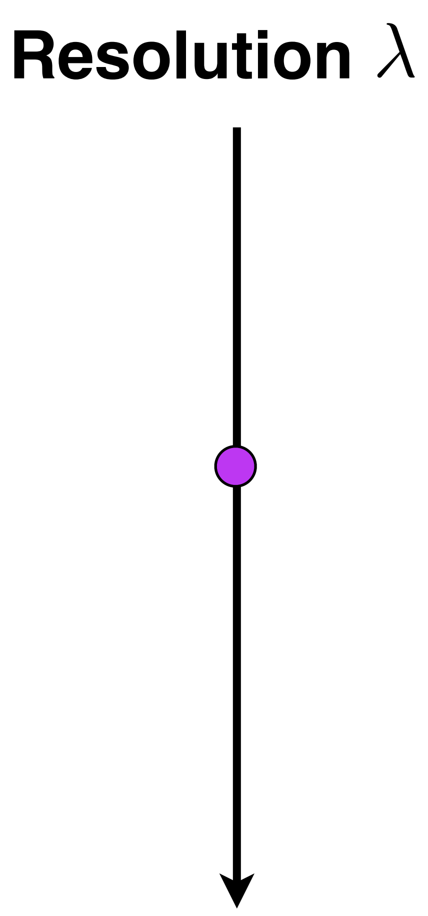

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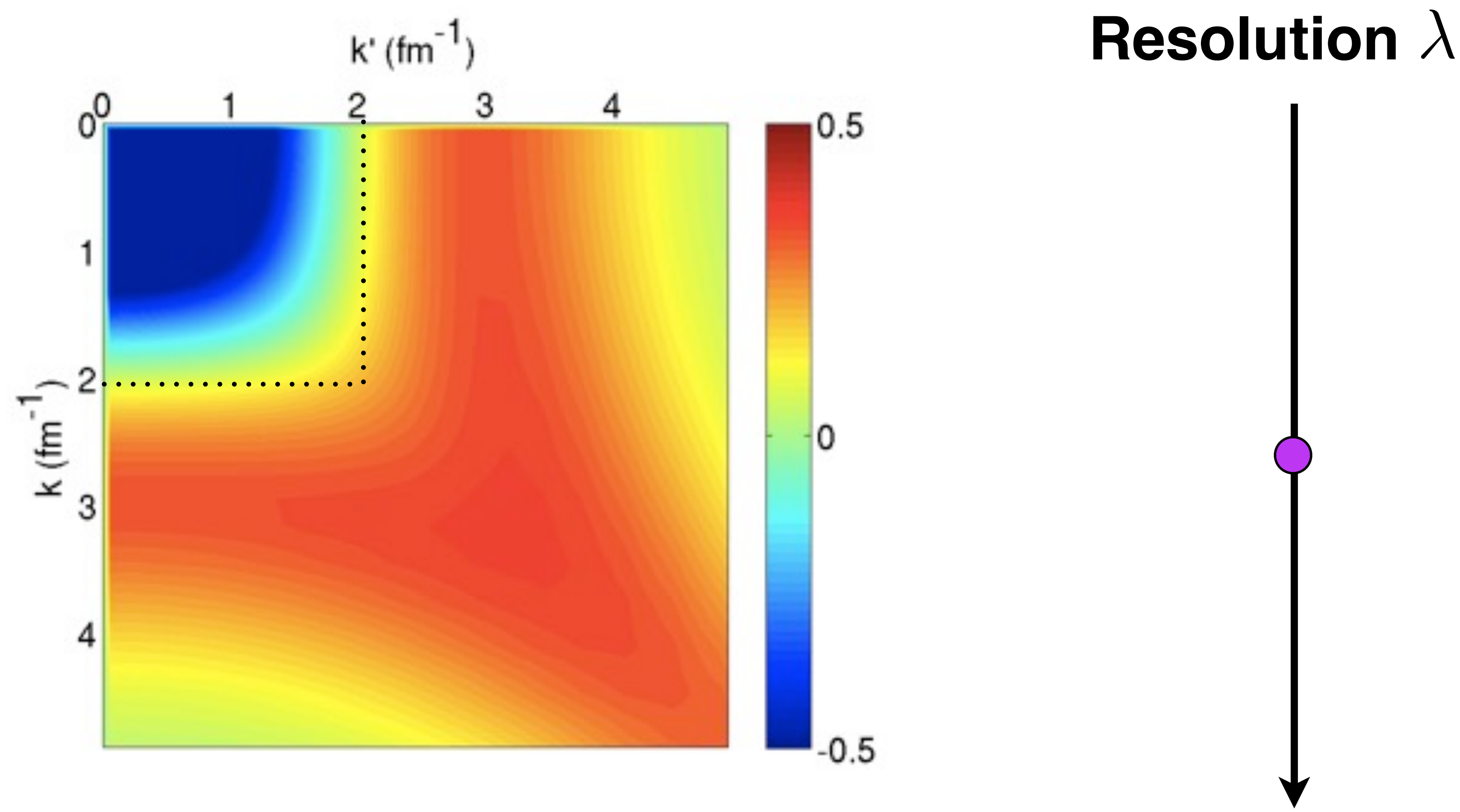

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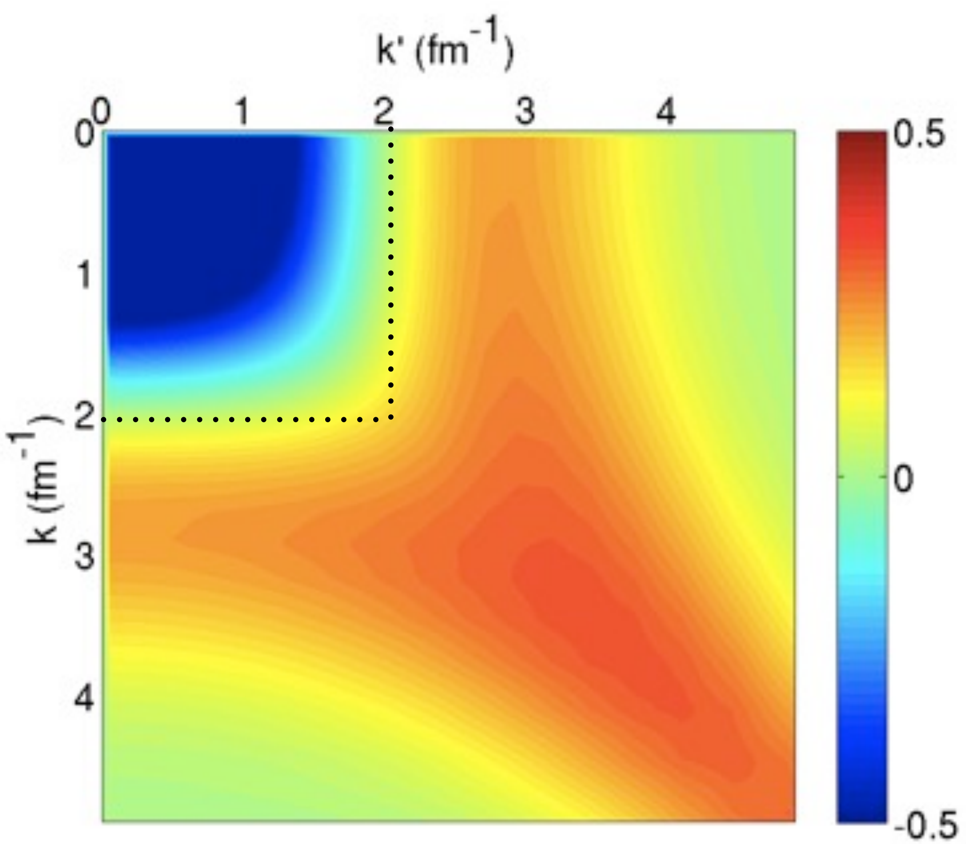

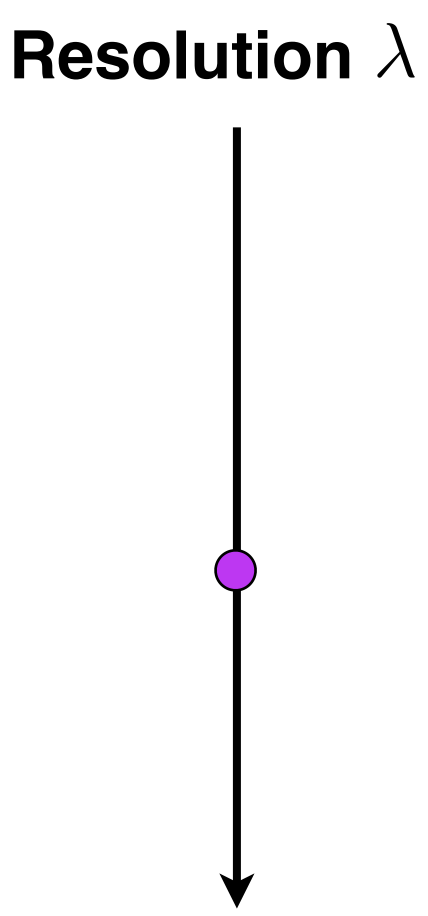

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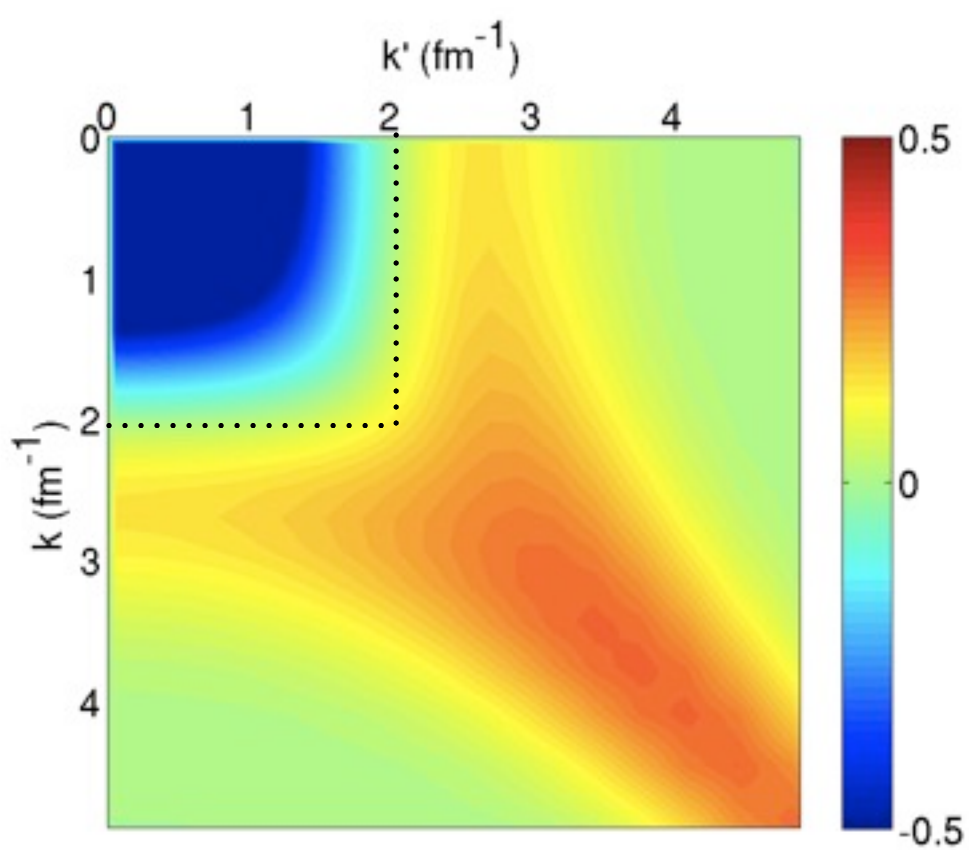

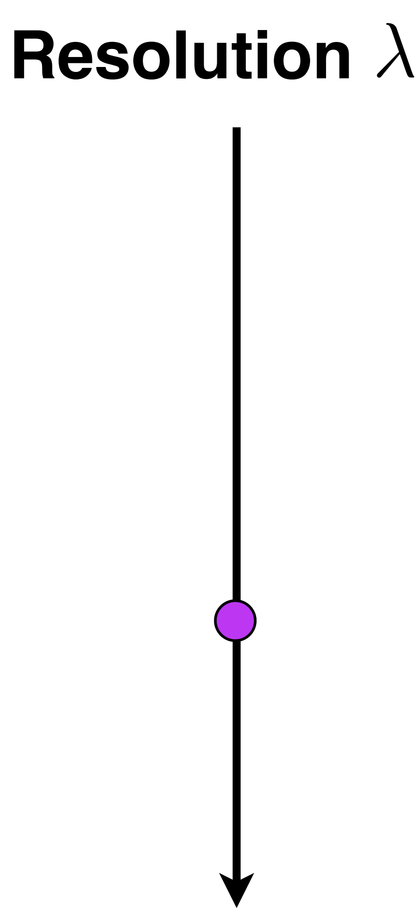

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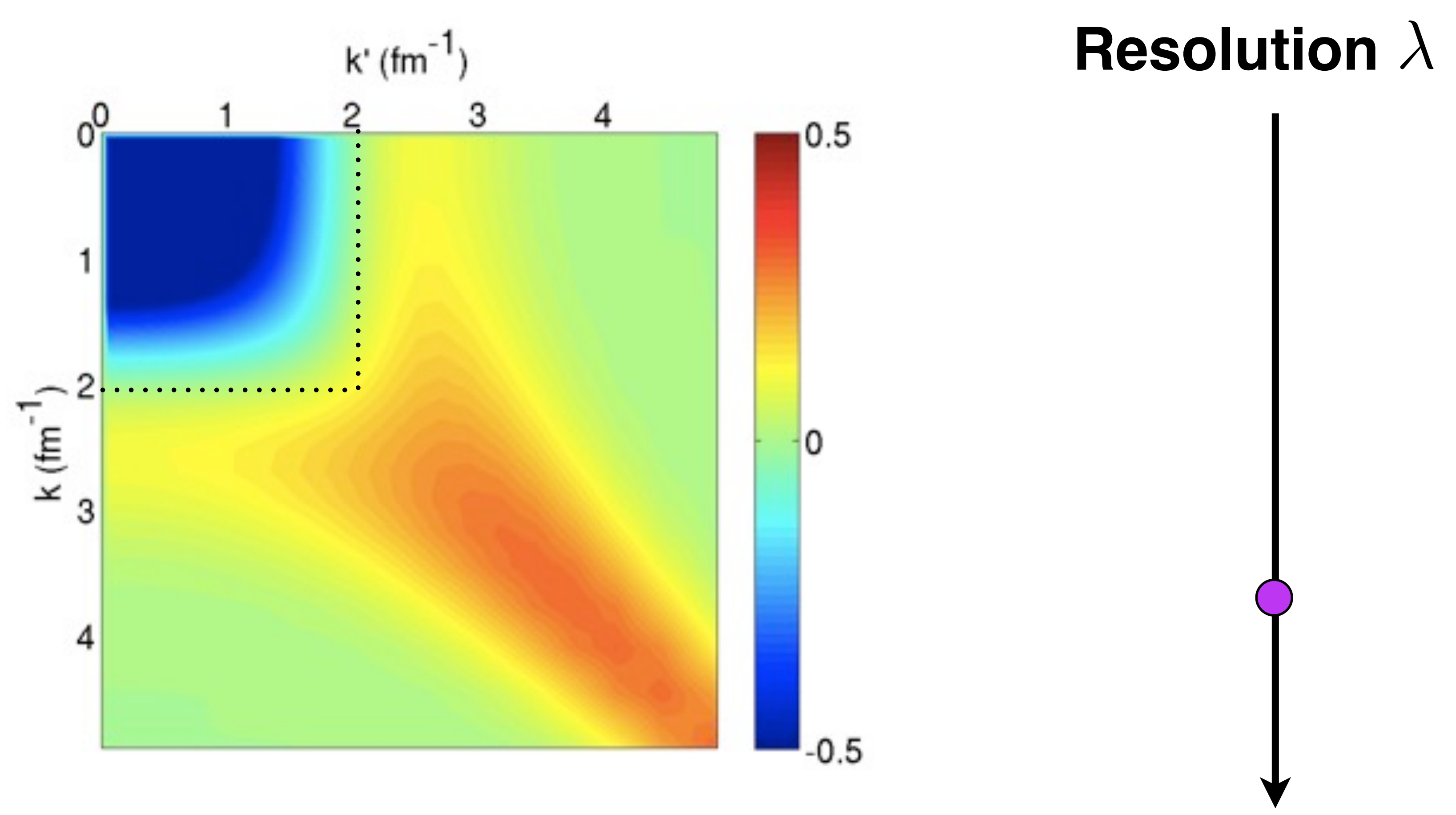

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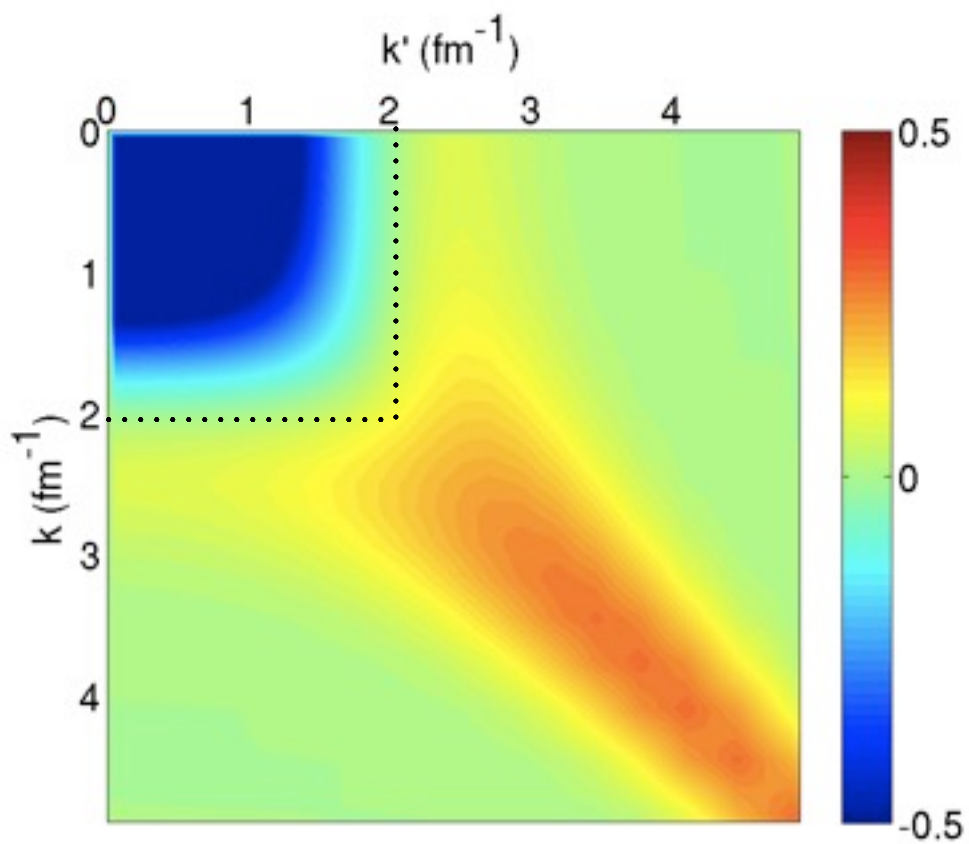

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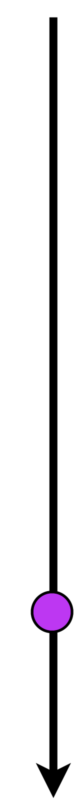

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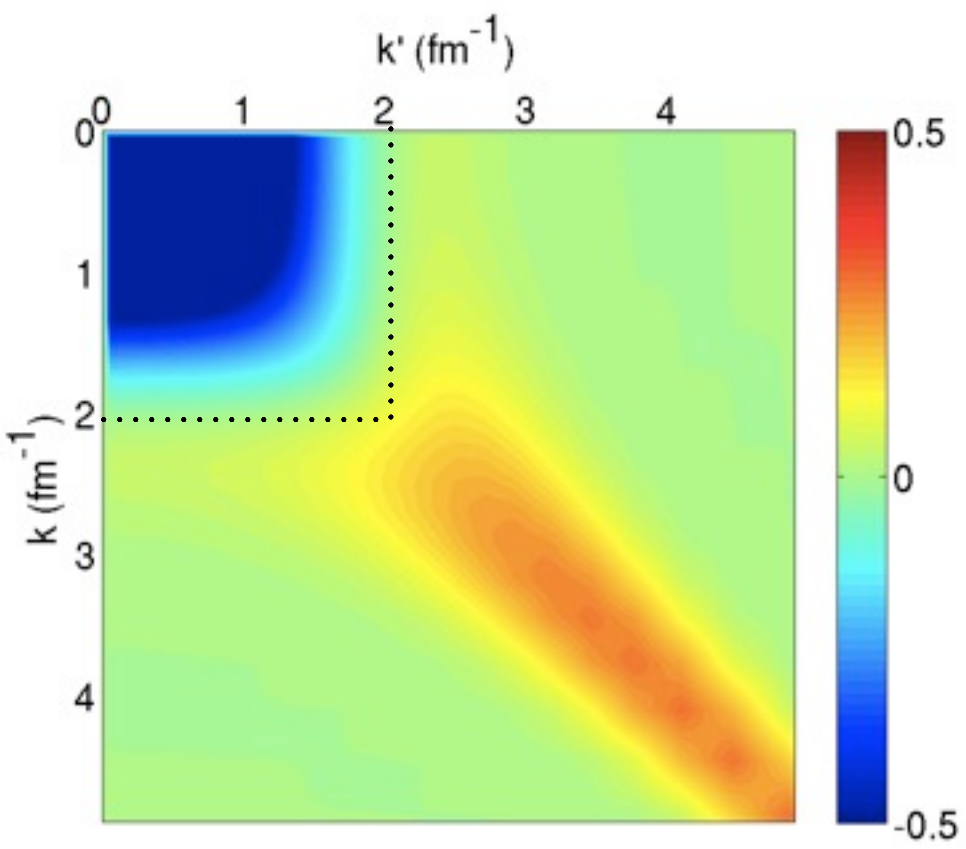

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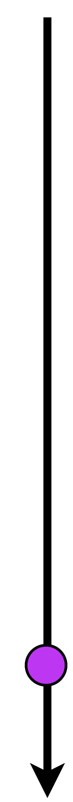

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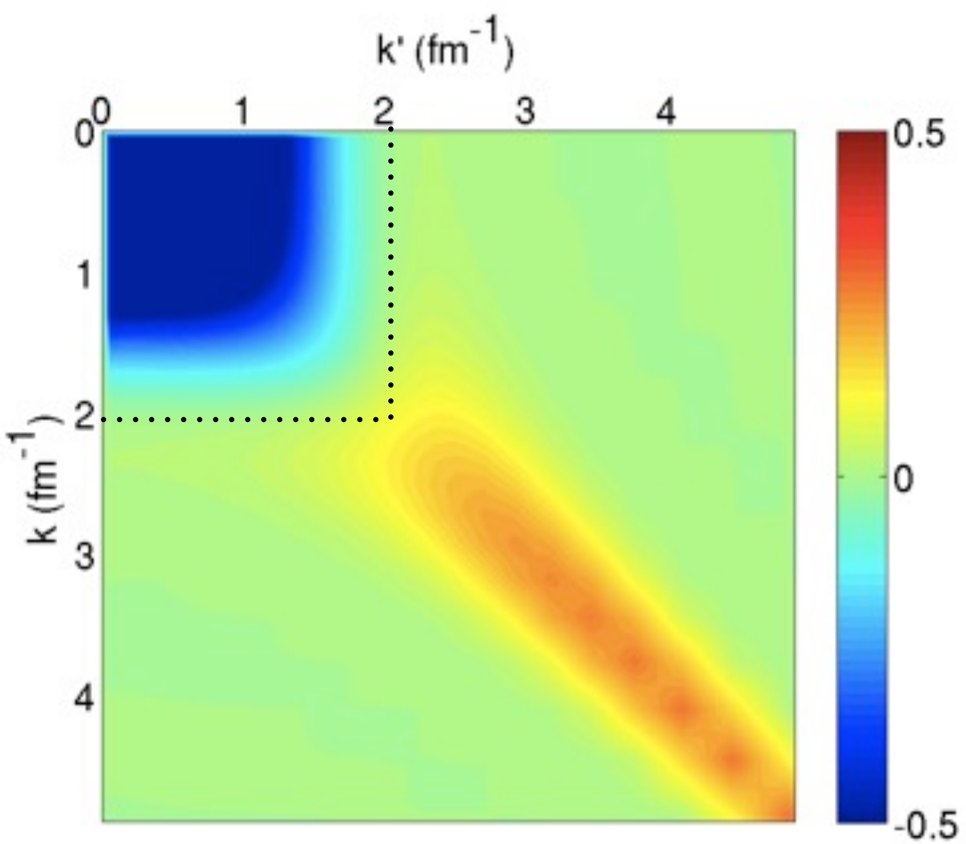
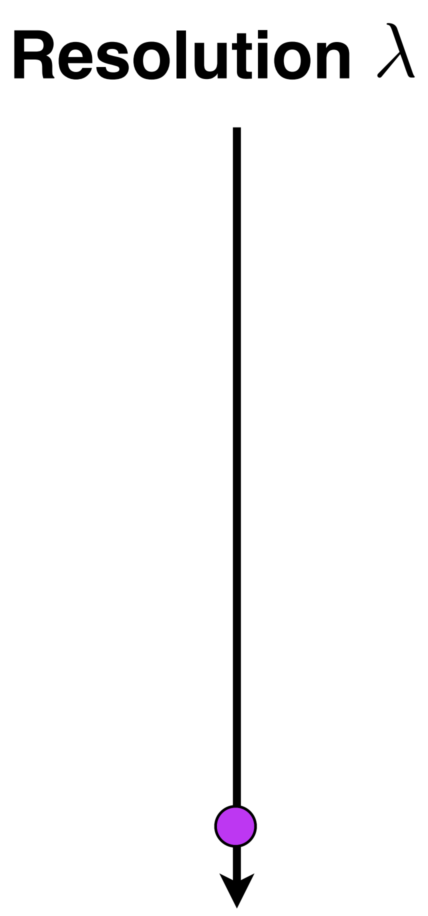
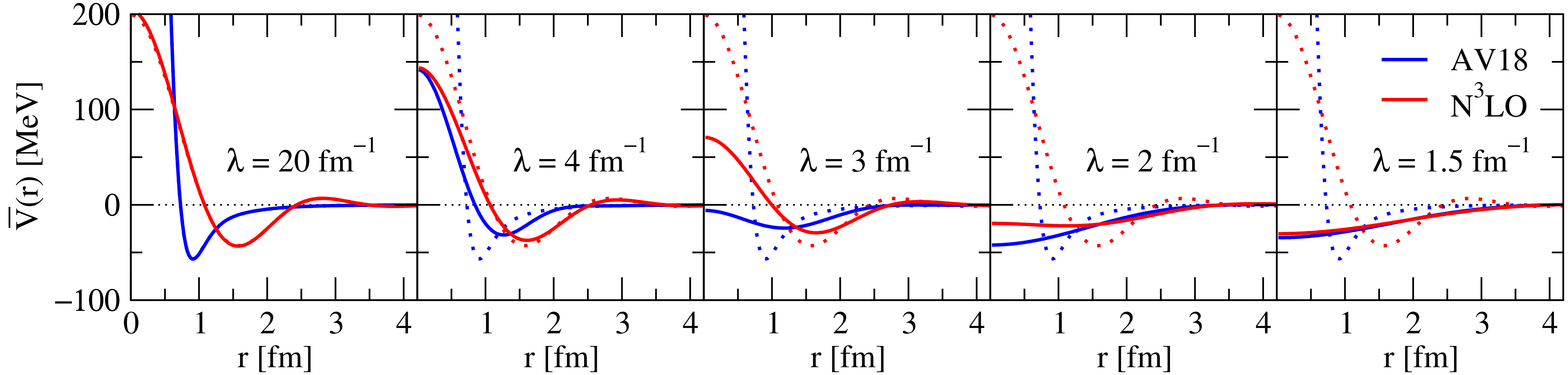
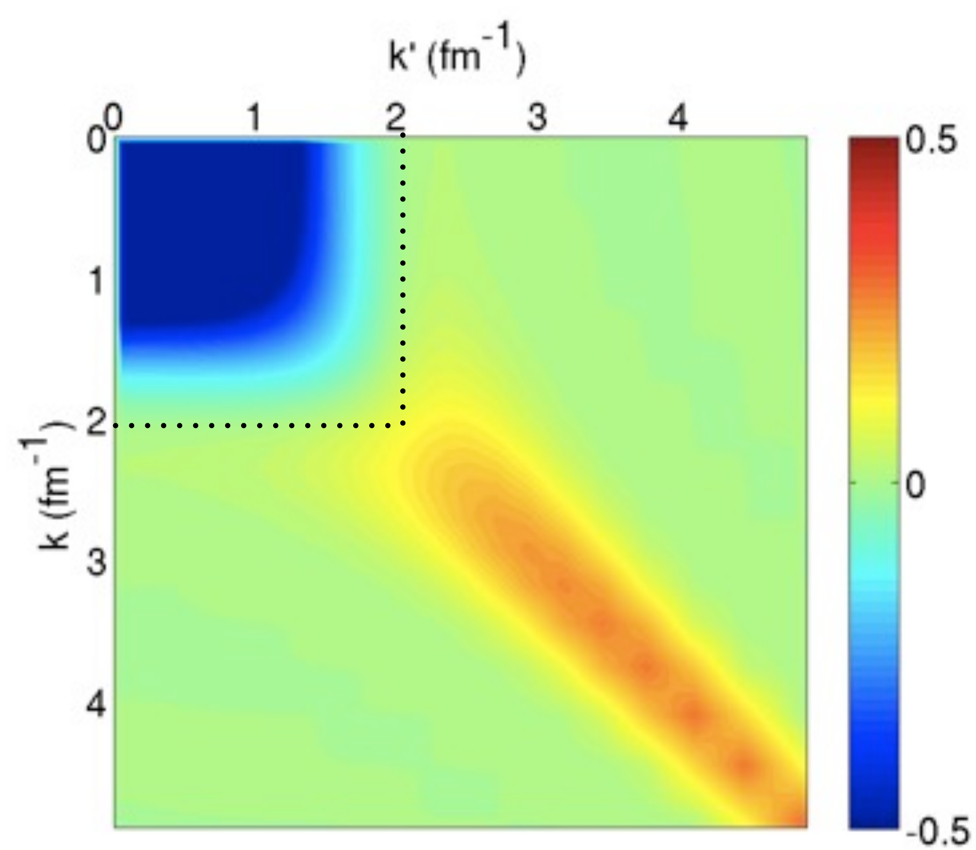


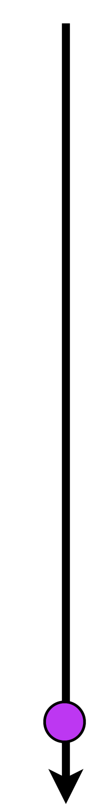


Systematic decoupling of high-momentum physics: The Similarity Renormalization Group

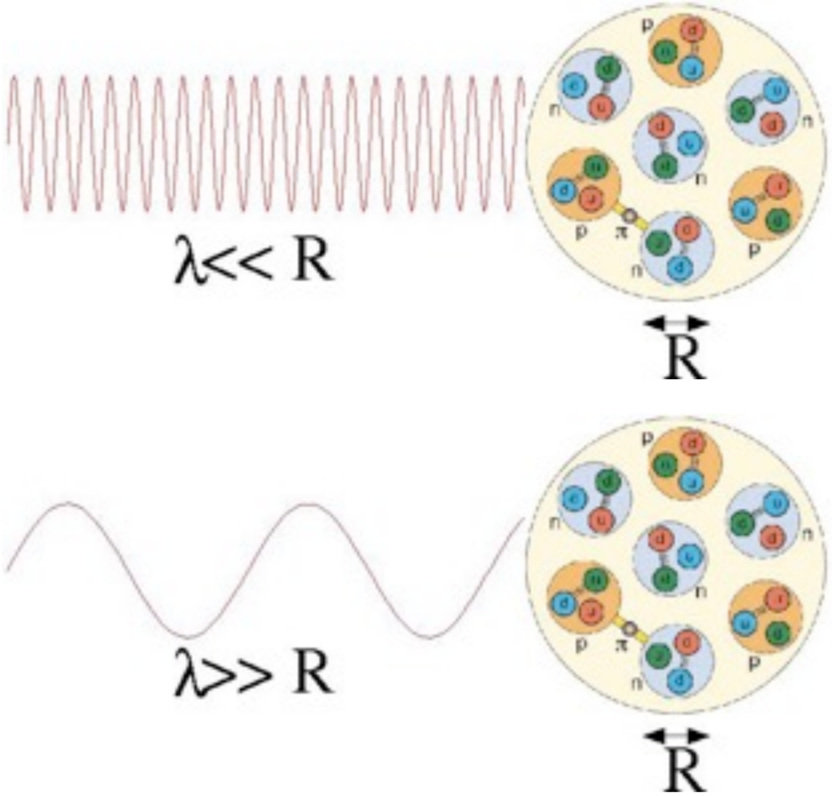
$$\overline{V}_{\lambda}(r) = \int dr' r'^2 V_{\lambda}(r, r')$$







Nuclear effective degrees of freedom



- if a nucleus is probed at high energies, nucleon substructure is resolved
- at low energies, details are not resolved

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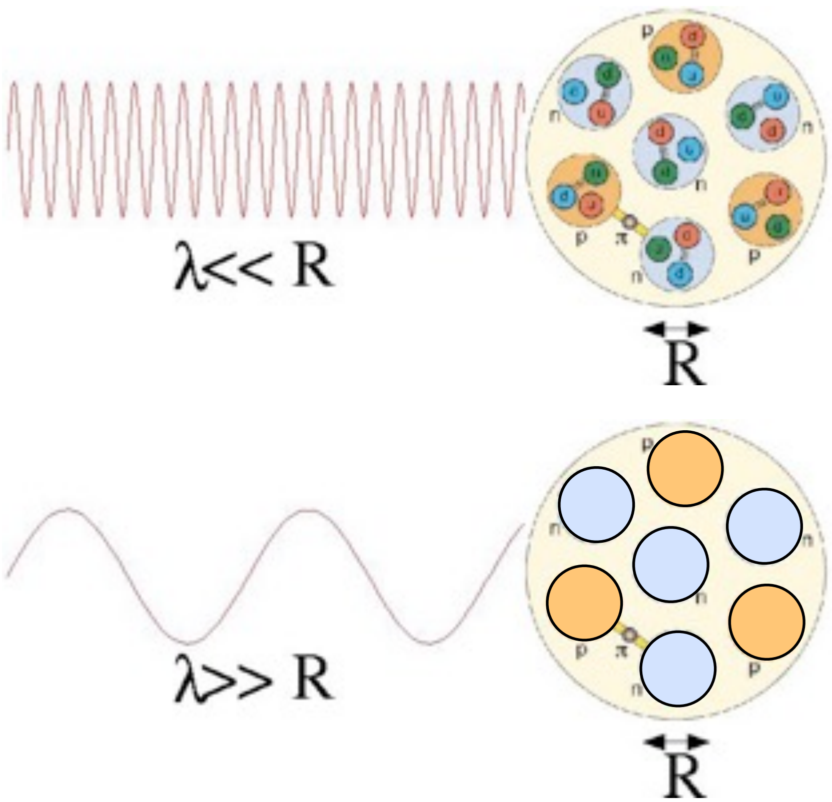
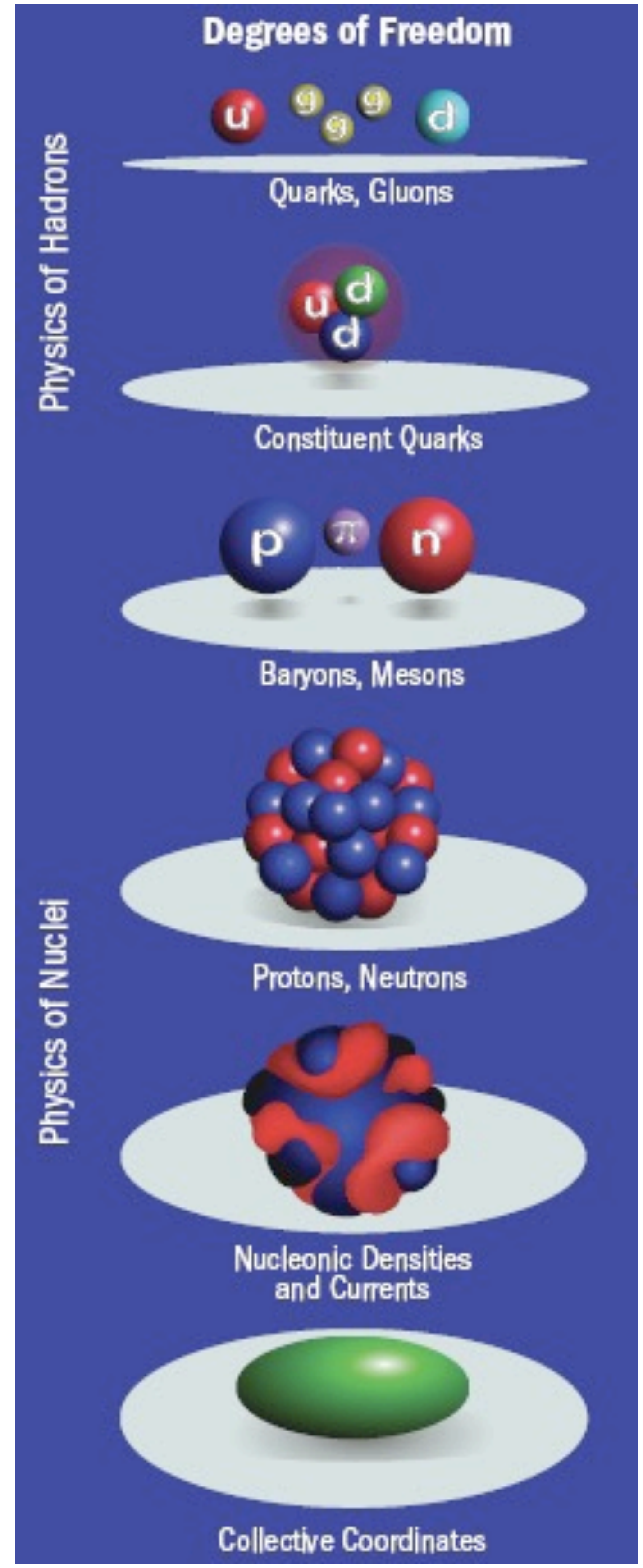


- if a nucleus is probed at high energies, nucleon substructure is resolved
- at low energies, details are not resolved
- replace fine structure by something simpler (compare multipole expansion)

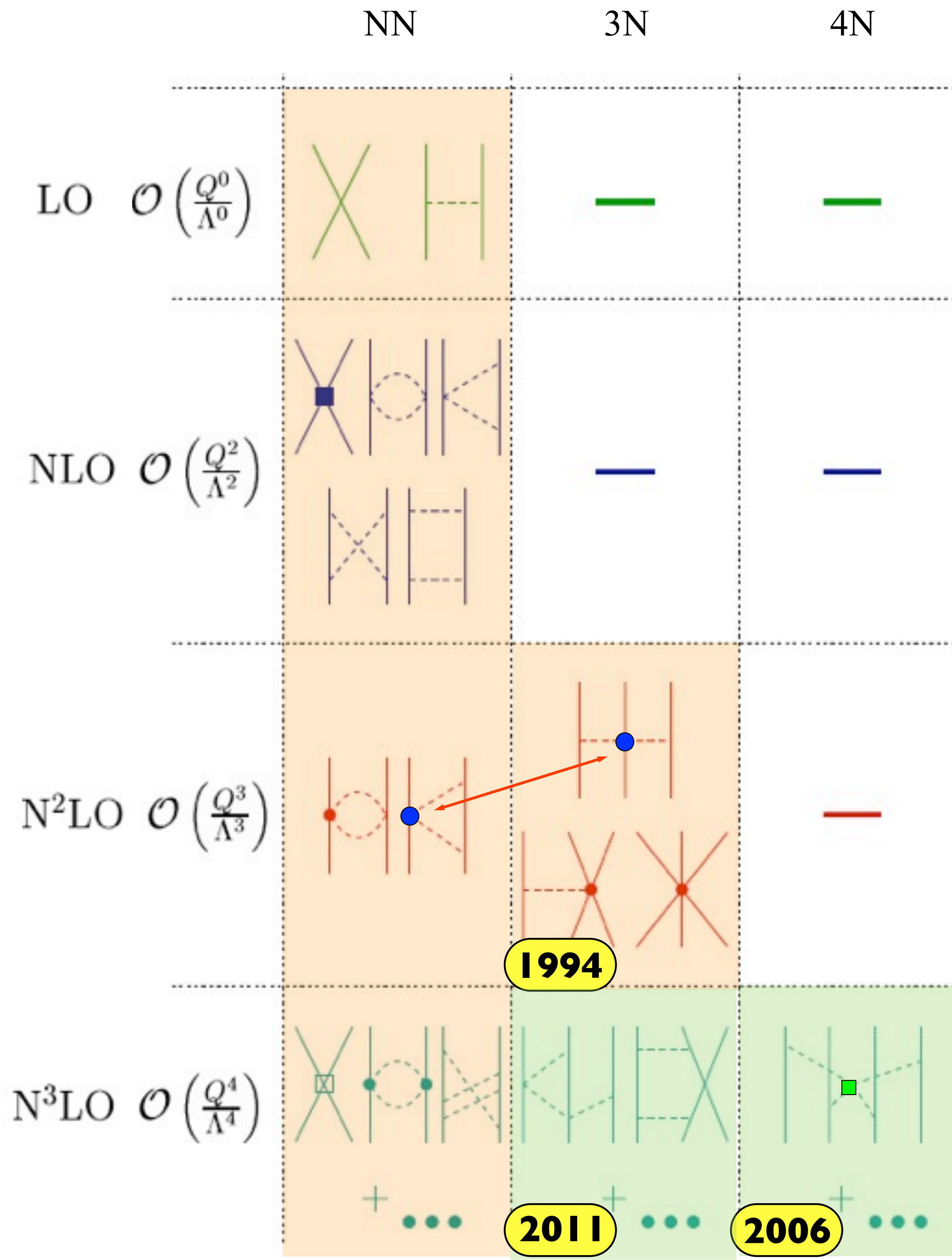
⟶ effective field theory



Resolution

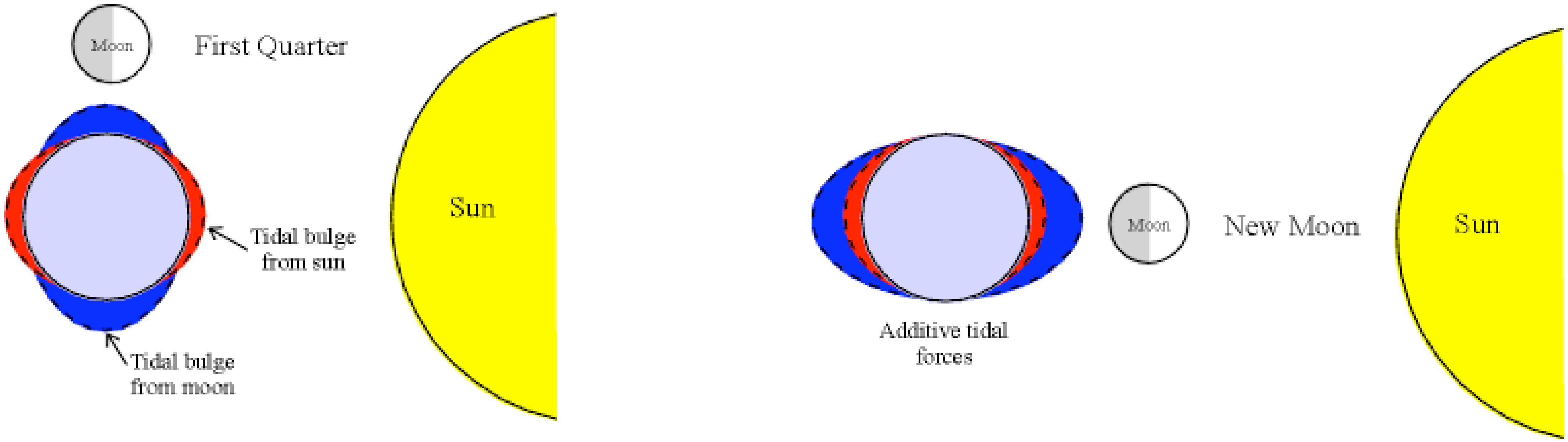
Chiral effective field theory for nuclear forces

- choose relevant degrees of freedom: here nucleons and pions
- operators constrained by symmetries of QCD
- short-range physics captured in short-range couplings
- separation of scales: Q << Λ_b, breakdown scale Λ_b~500 MeV
- power-counting: expand in Q/Λ_b
- systematic, obtain error estimates
- many-body forces appear naturally



Aren't 3N forces unnatural? Do we really need them?

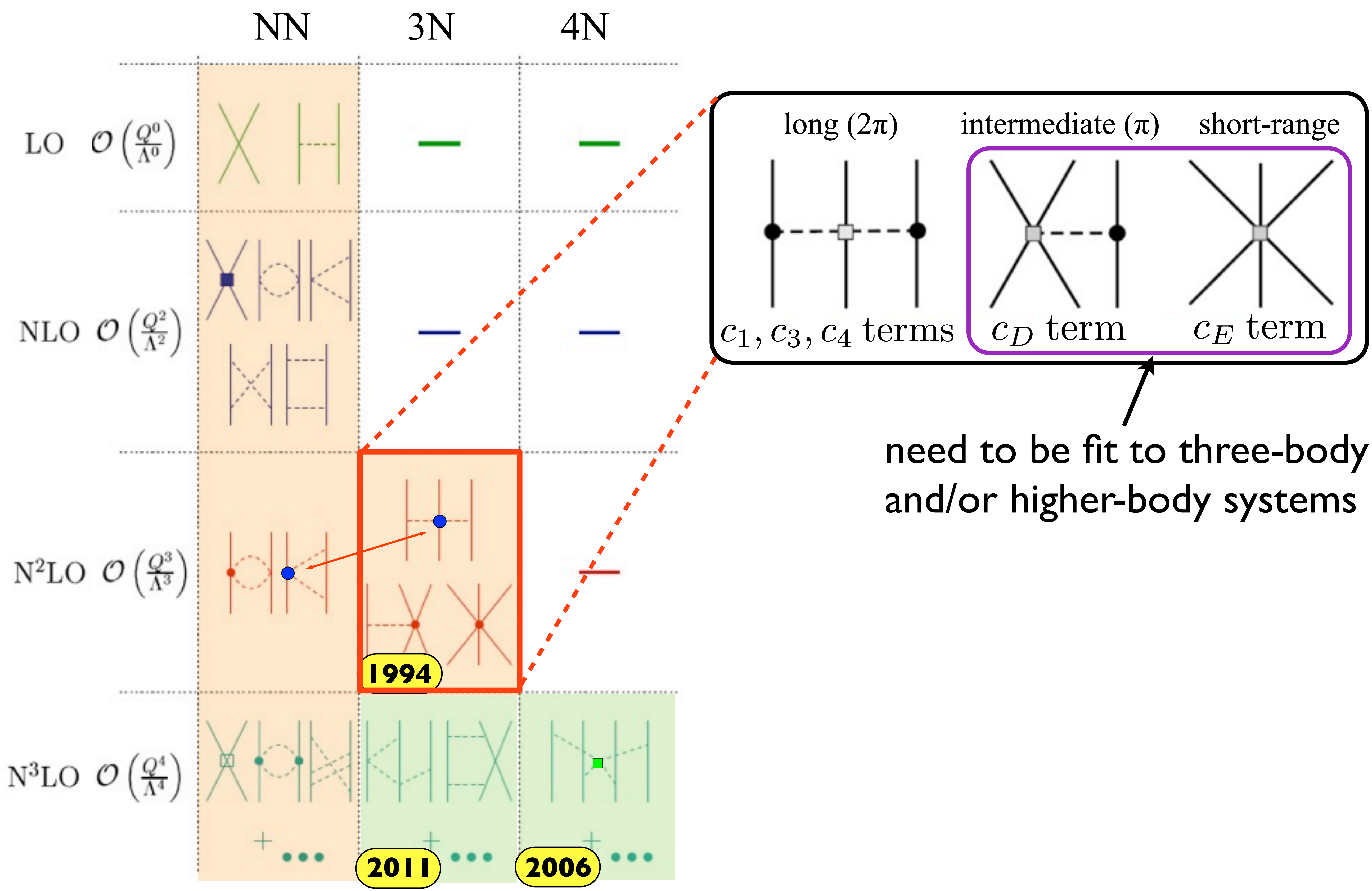
Consider classical analog: tidal effects in earth-sun-moon system



- force between earth and moon depends on the position of sun
- tidal deformations represent internal excitations
- describe system using point particles $\longrightarrow$ 3N forces inevitable!

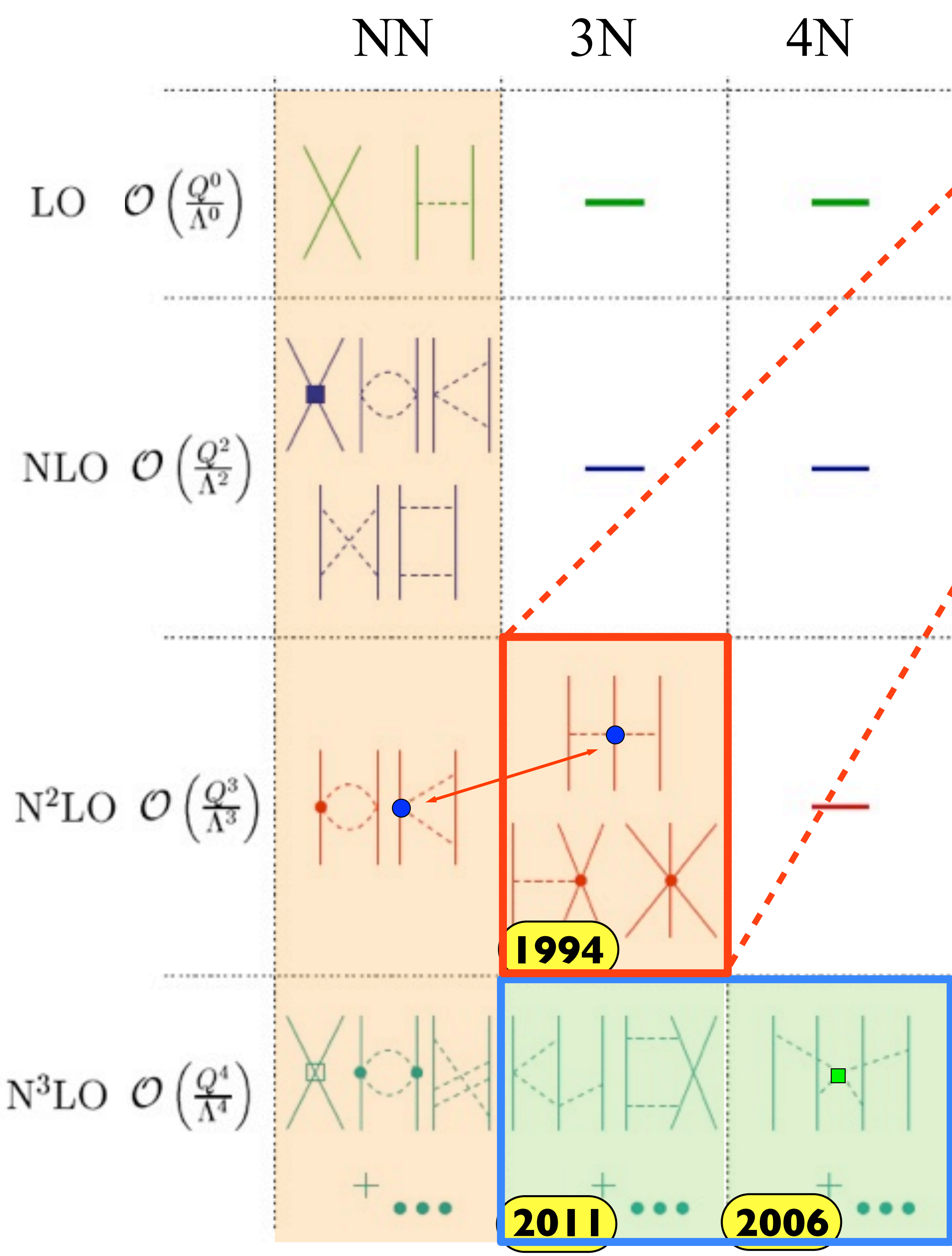
- nucleons are composite particles, can also be excited
- change of resolution change excitations that can be described explicitly
  - existence of three-nucleon forces natural
  - crucial question: how important are their contributions?

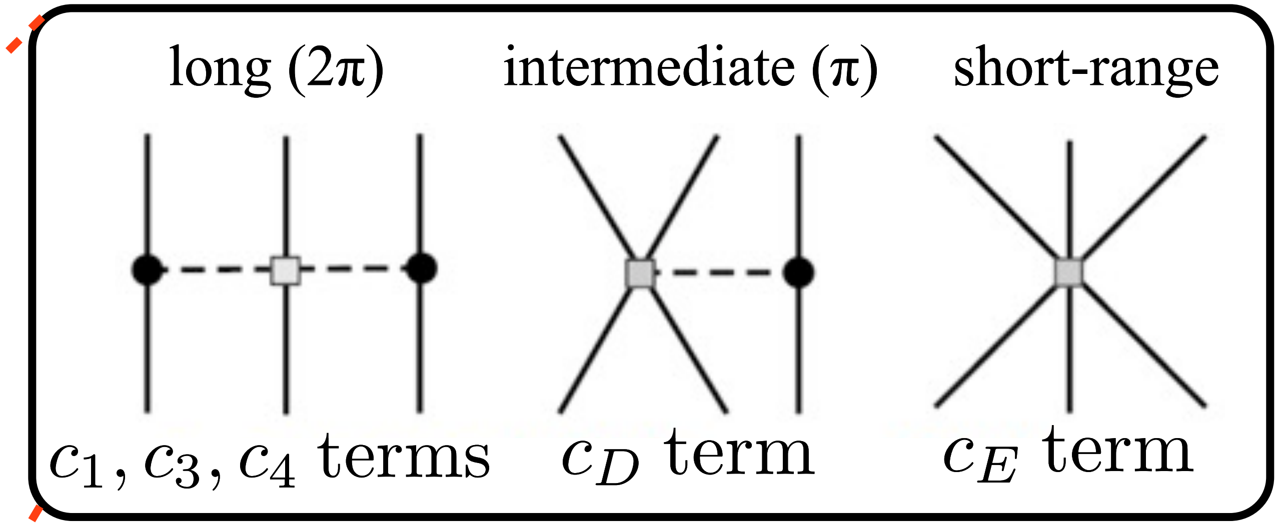
Many-body forces in chiral EFT



need to be fit to three-body and/or higher-body systems

Many-body forces in chiral EFT





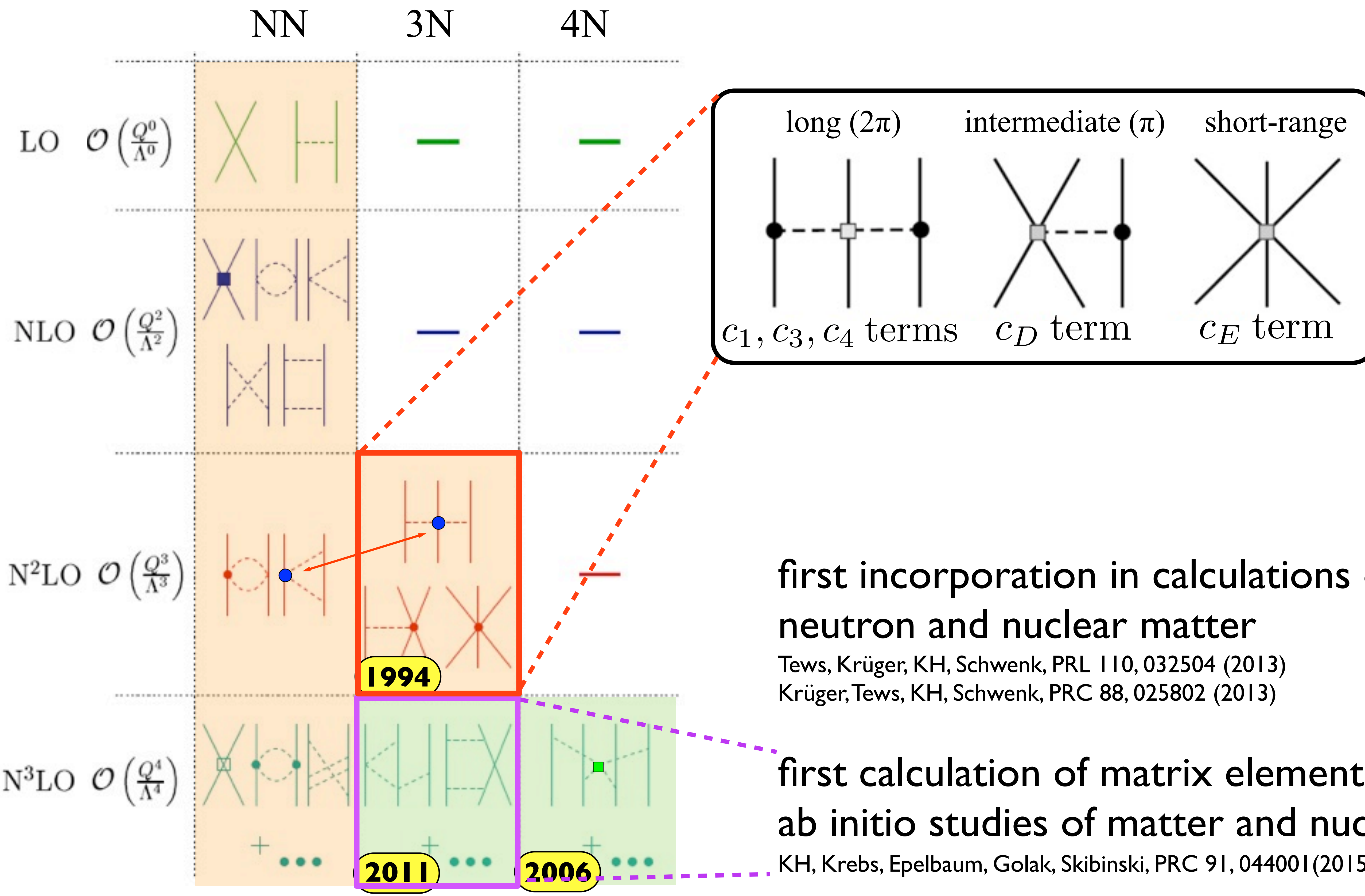
values of LECs c_1, c_3, c_4 still contain large uncertainties!

first incorporation in calculations of neutron and nuclear matter

Tews, Krüger, KH, Schwenk, PRL 110, 032504 (2013)
Krüger, Tews, KH, Schwenk, PRC 88, 025802 (2013)

all terms predicted
(no new low-energy couplings)

Many-body forces in chiral EFT



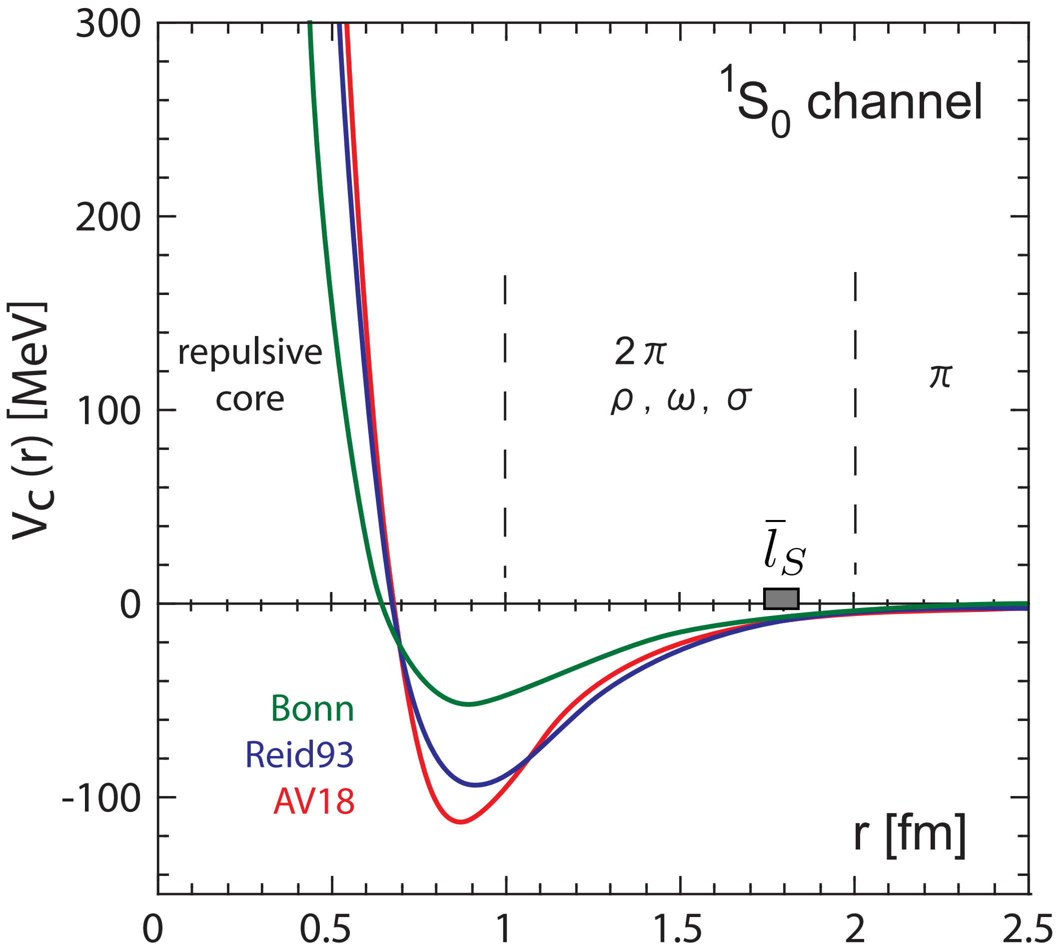
first incorporation in calculations of neutron and nuclear matter

Tews, Krüger, KH, Schwenk, PRL 110, 032504 (2013)
Krüger, Tews, KH, Schwenk, PRC 88, 025802 (2013)

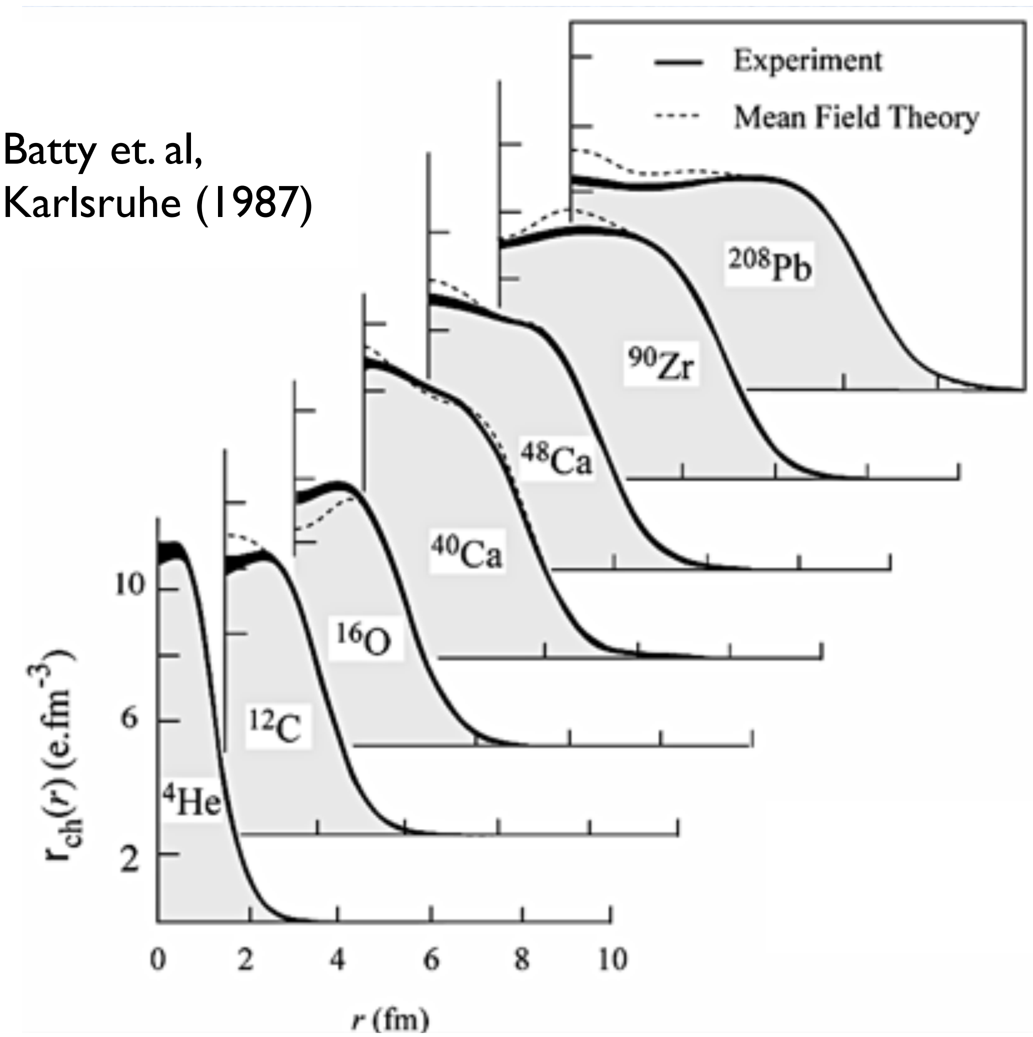
first calculation of matrix elements for ab initio studies of matter and nuclei

KH, Krebs, Epelbaum, Golak, Skibinski, PRC 91, 044001(2015)

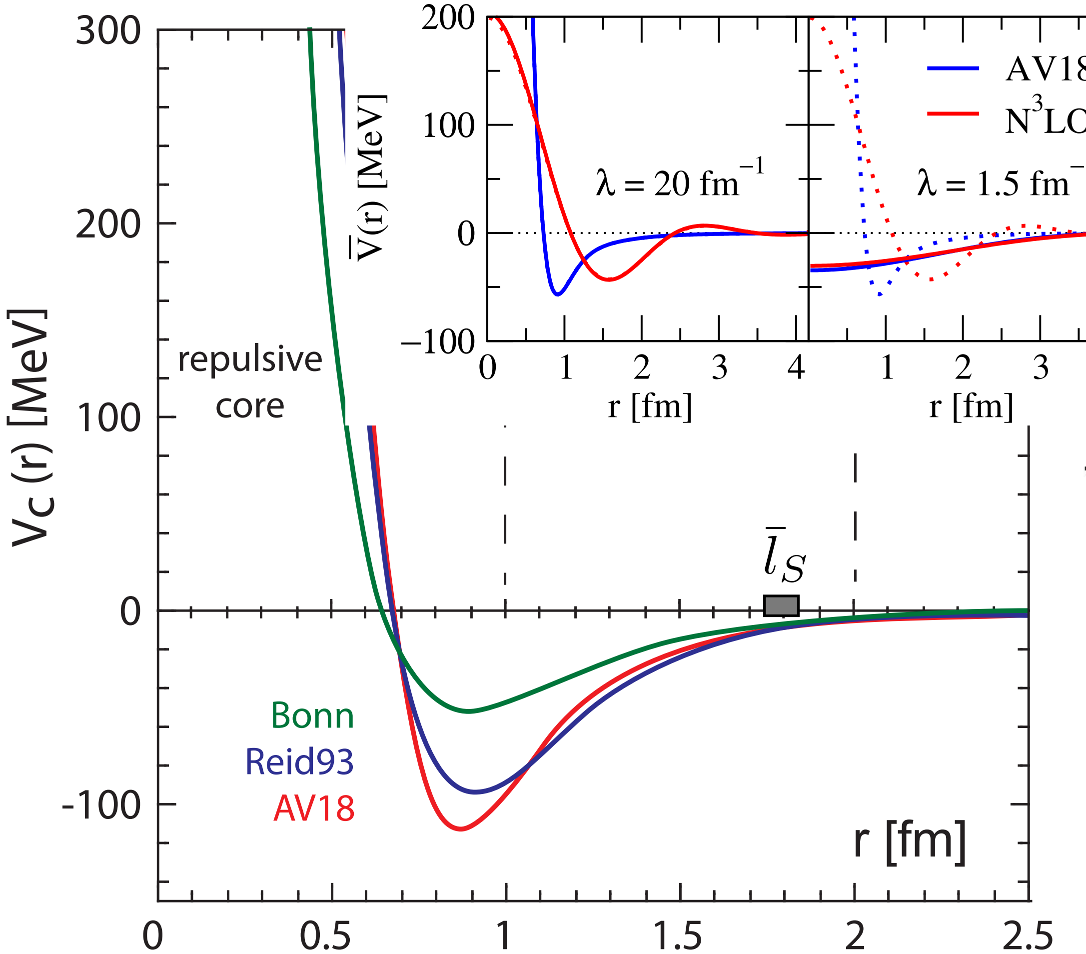
Equation of state of symmetric nuclear matter: nuclear saturation

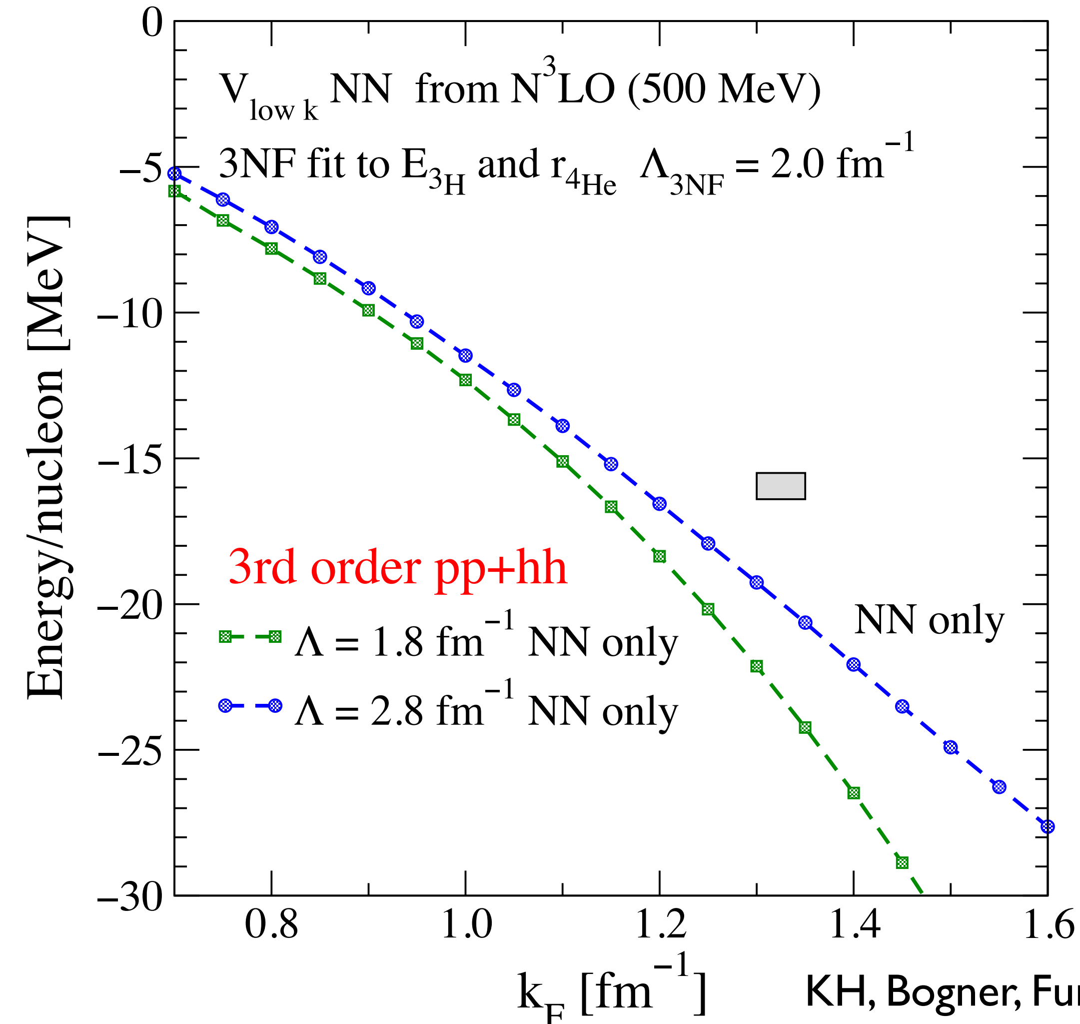


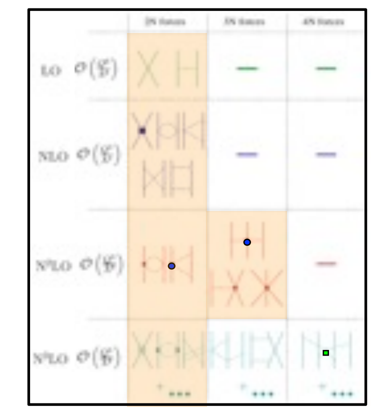
Batty et. al,
Karlsruhe (1987)



Equation of state of symmetric nuclear matter: nucle

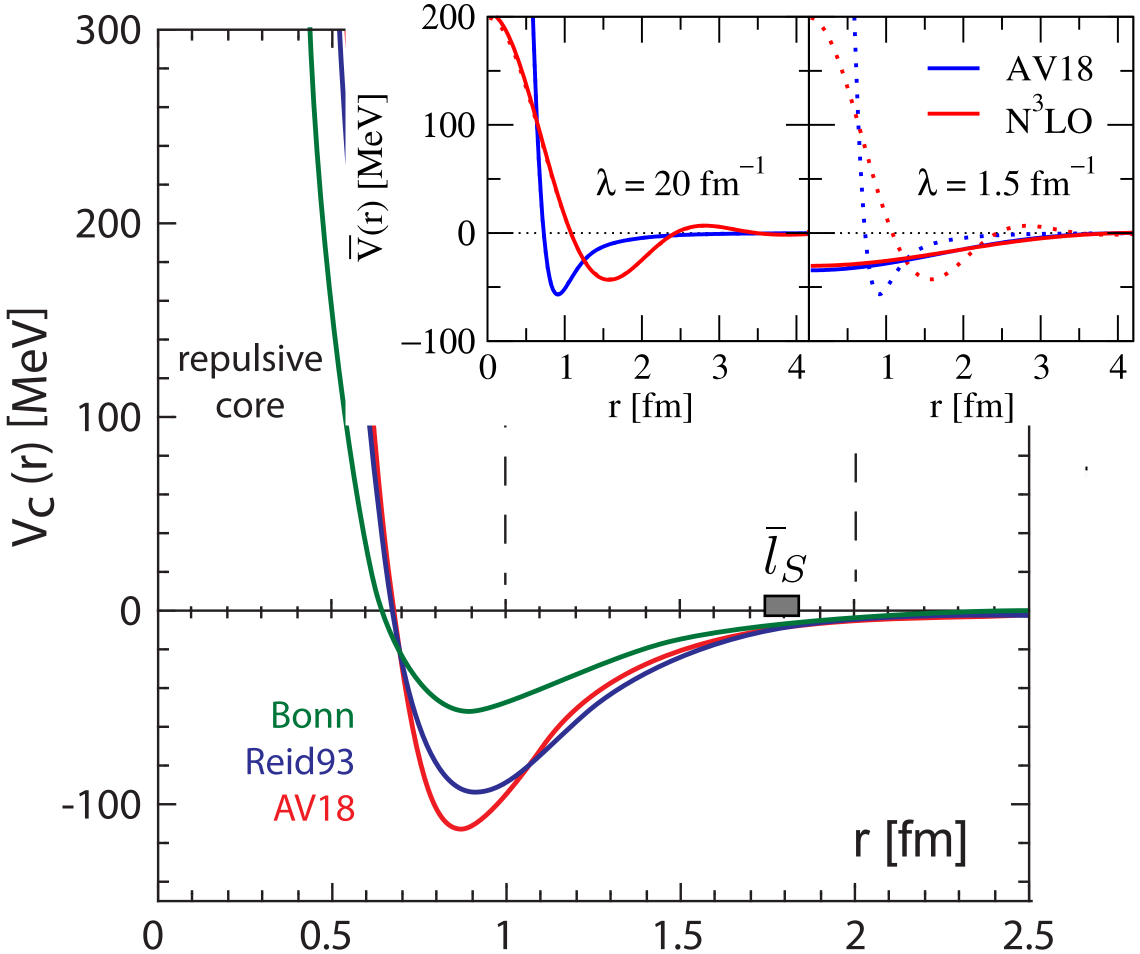


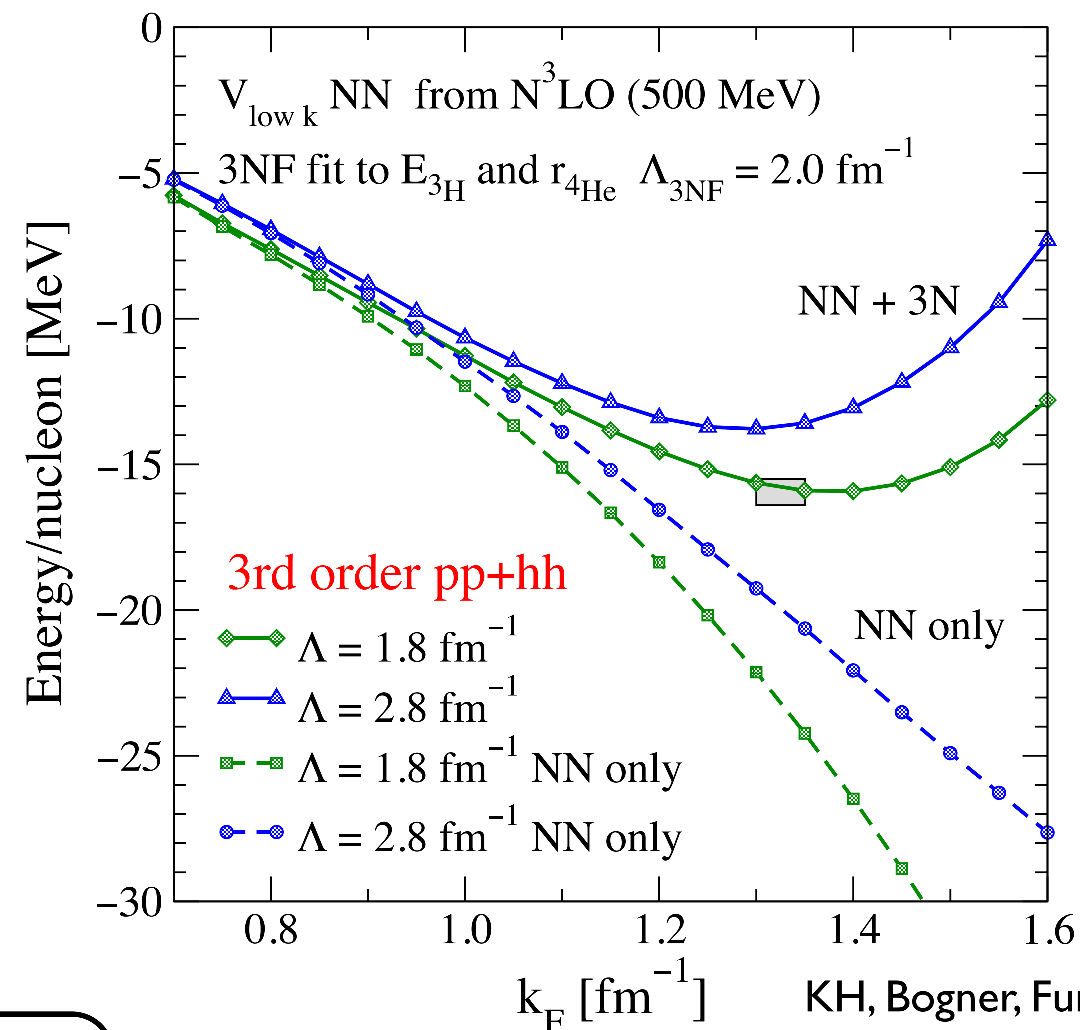


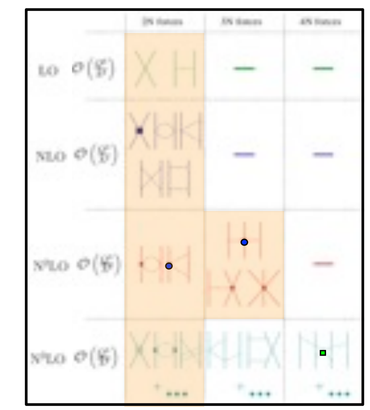


KH, Bogner, Furnstahl, Nogga, PRC(R) 83, 031301 (2011)

Equation of state of symmetric nuclear matter: nuclear saturation



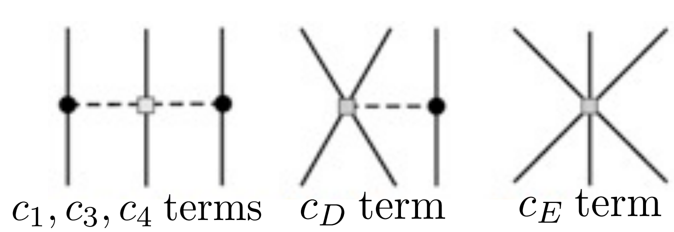




KH, Bogner, Furnstahl, Nogga, PRC(R) 83, 031301 (2011)

intermediate (c_D) and short-range (c_E) 3NF couplings fitted to few-body systems at different resolution scales:

$$E_{^3\text{H}} = -8.482\,\text{MeV} \qquad r_{^4\text{He}} = 1.464\,\text{fm}$$



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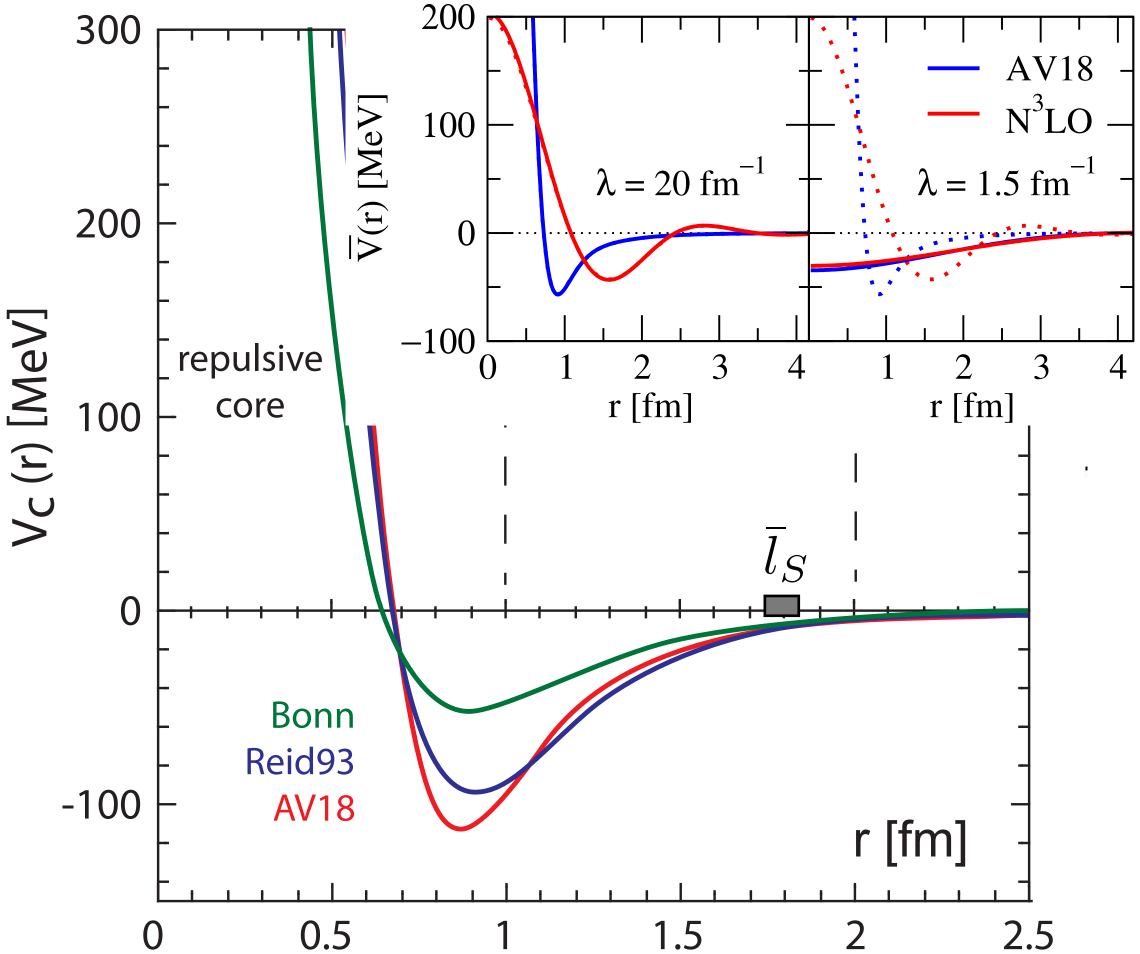

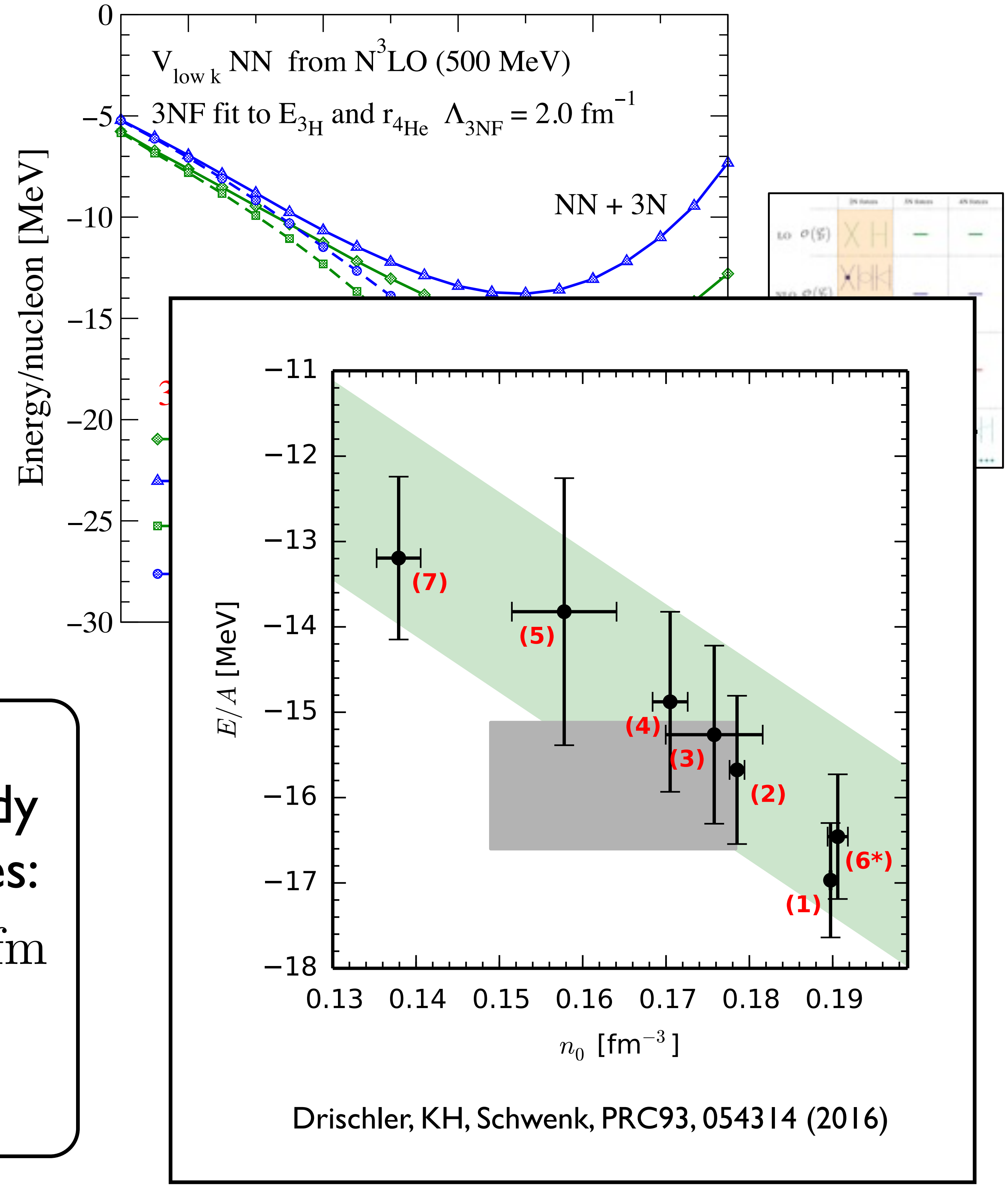

Drischler, KH, Schwenk, PRC93, 054314 (2016)

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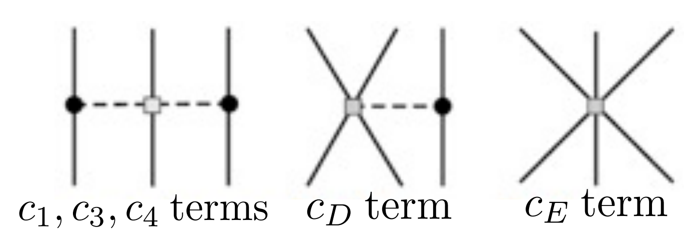
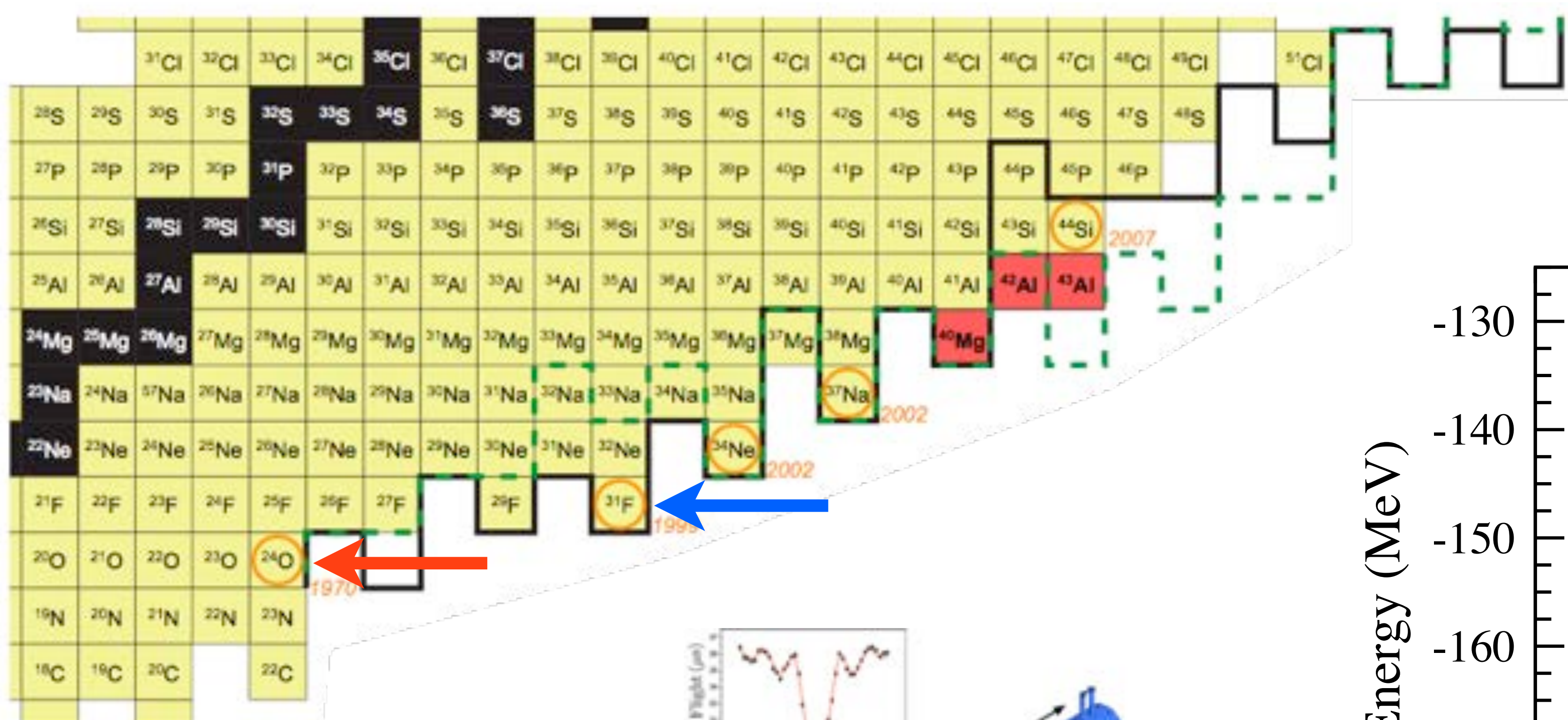
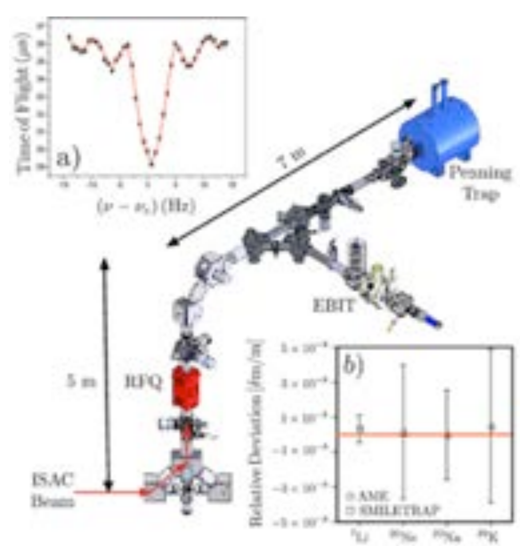


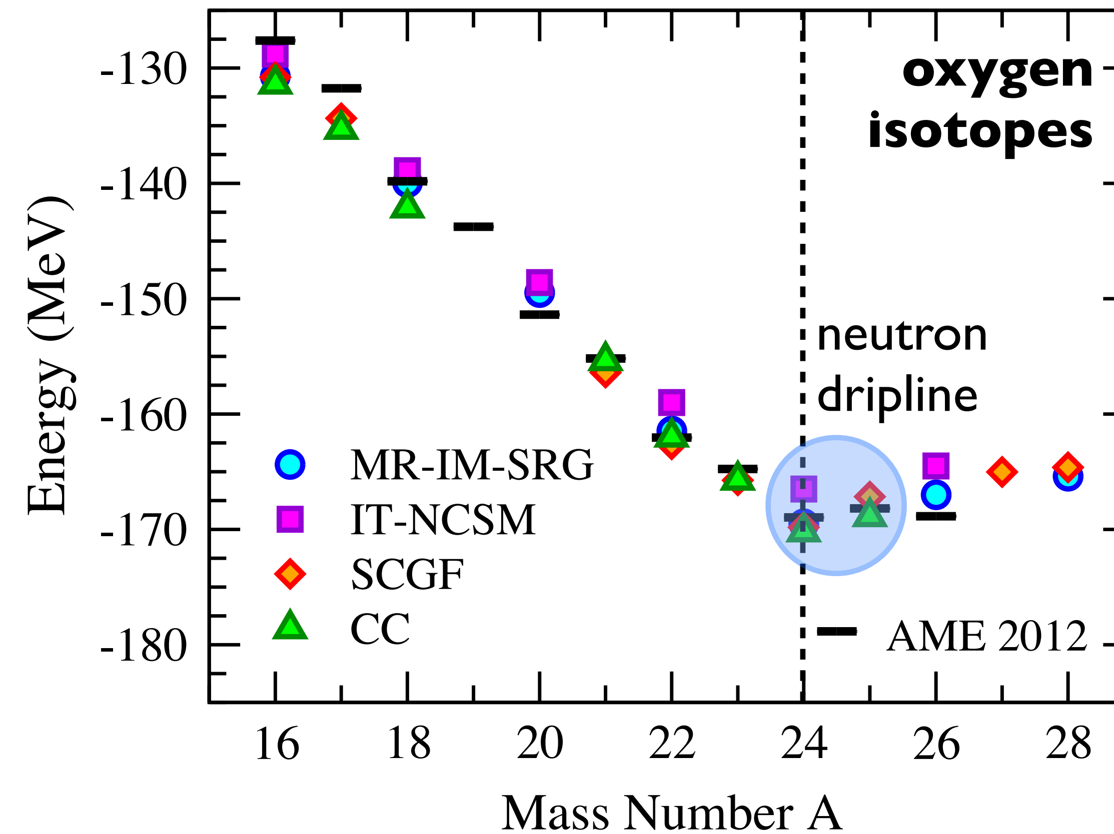
Studies of neutron-rich nuclei:
Neutron dripline and the oxygen anomaly





Gallant et al.
PRL 109, 032506 (2012)

Wienholtz et al.
Nature 498, 346 (2013)

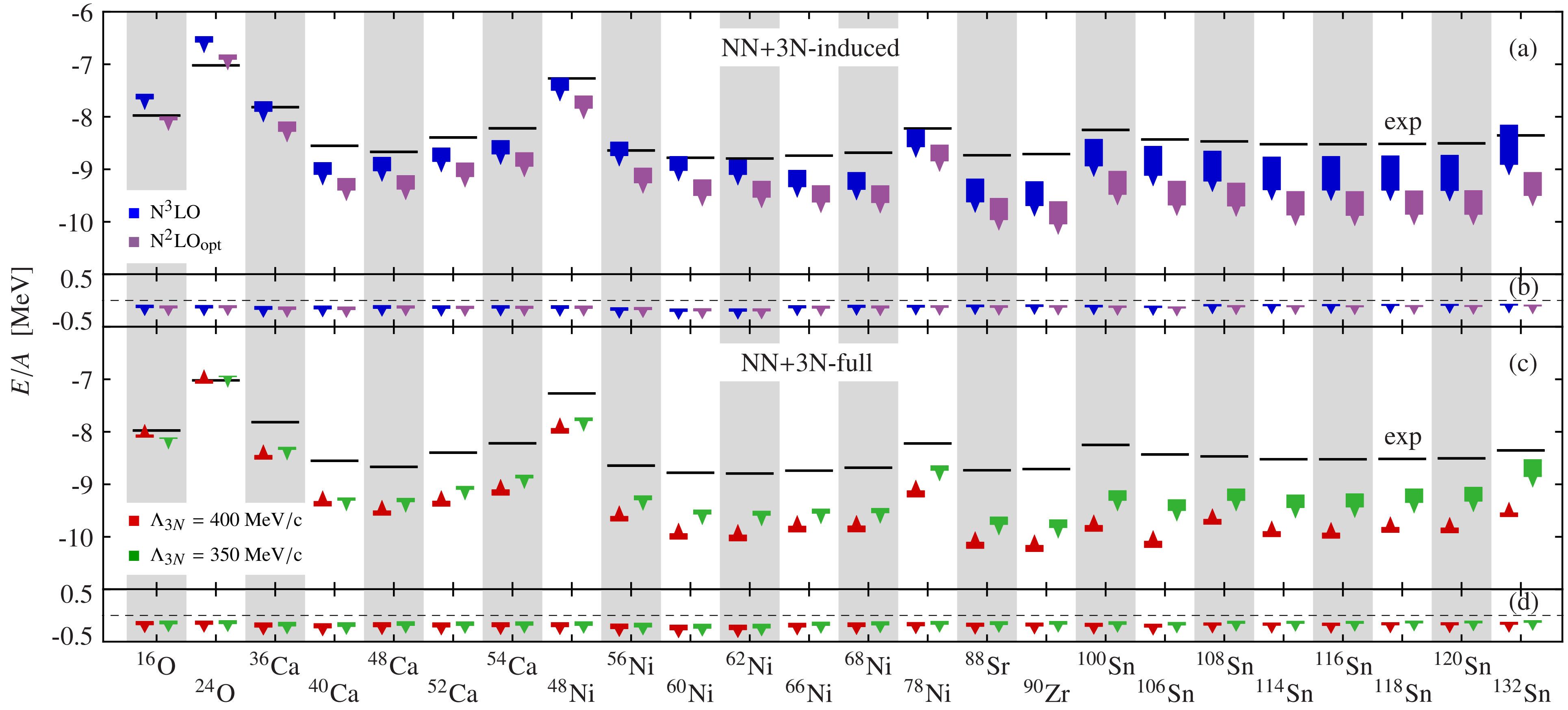


adapted from
KH et al. , Ann. Rev. Nucl. Part. Sci.165, 457 (2015)

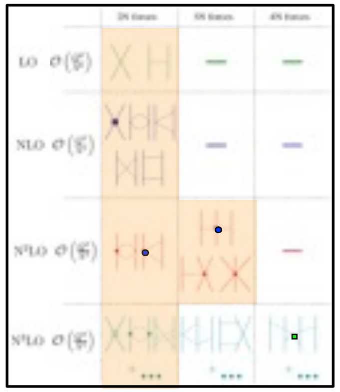
- remarkable agreement between different many-body frameworks
- very good agreement between theory and experiment for masses of oxygen and calcium isotopes based on specific chiral interactions
- contributions from 3N force play important role for drip line

Ab initio calculations of heavier nuclei

coupled cluster (CC) framework



Binder et al., Phys. Lett B 736, 119 (2014)



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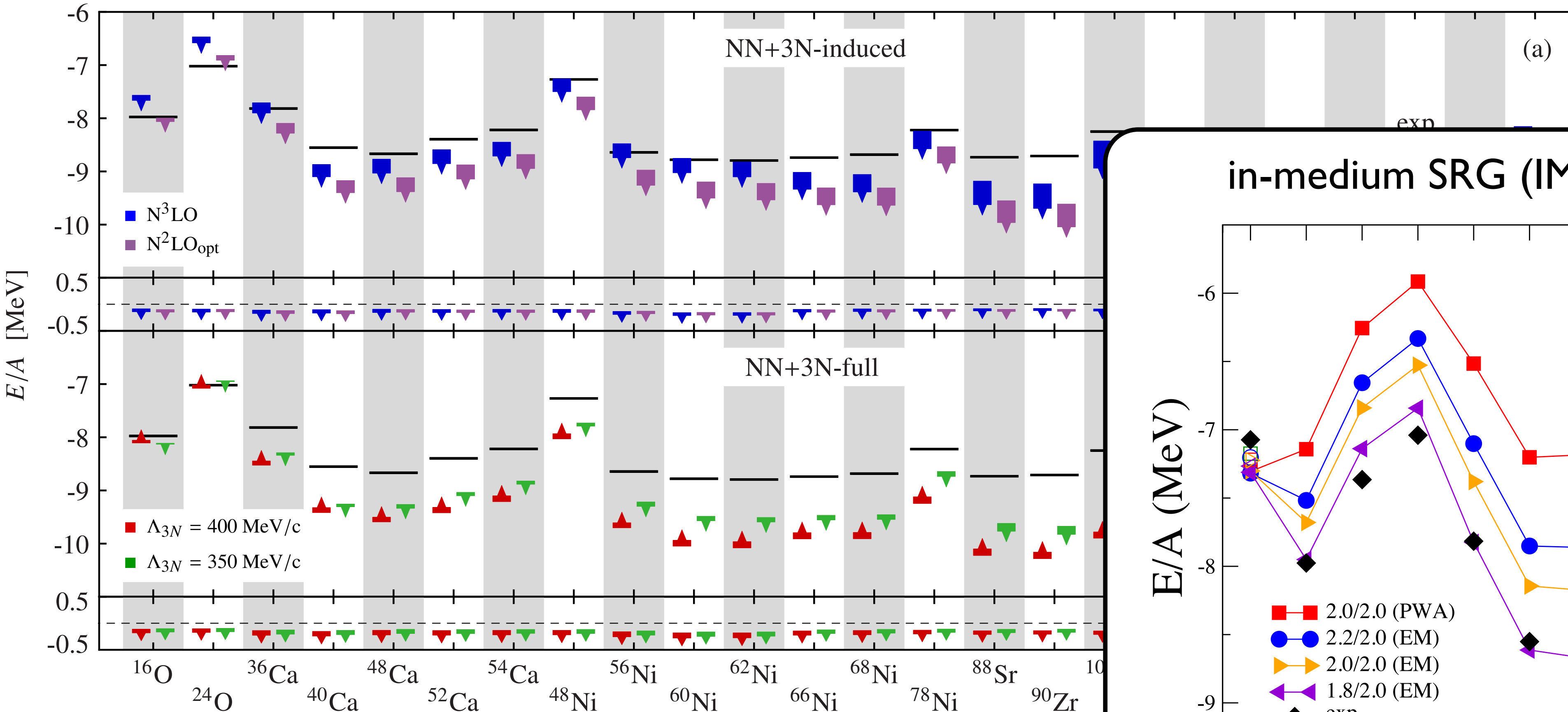
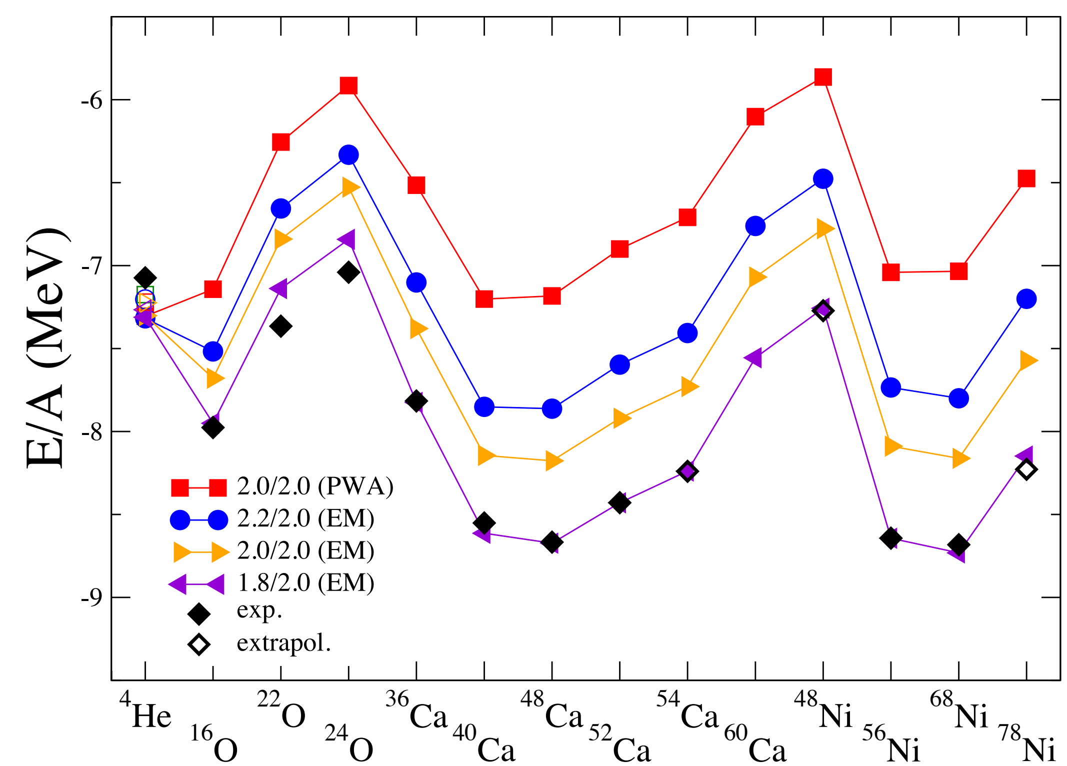


Binder et al., Phys. Lett B 736, 119 (2014)

in-medium SRG (IMSRG) framework



Simonis, Stroberg et al., in preparation

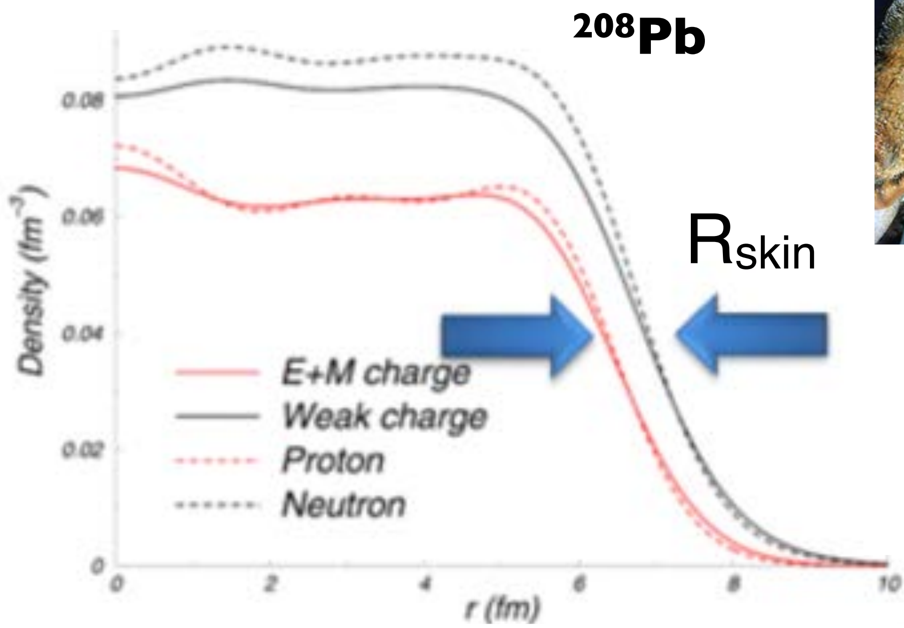
- spectacular increase in range of applicability of ab initio many body frameworks
- significant discrepancies to experimental data for heavy nuclei for

(most of) presently used nuclear interactions

- need to quantify theoretical uncertainties

The size of the atomic nucleus: challenges from novel high-precision measurements

Horowitz

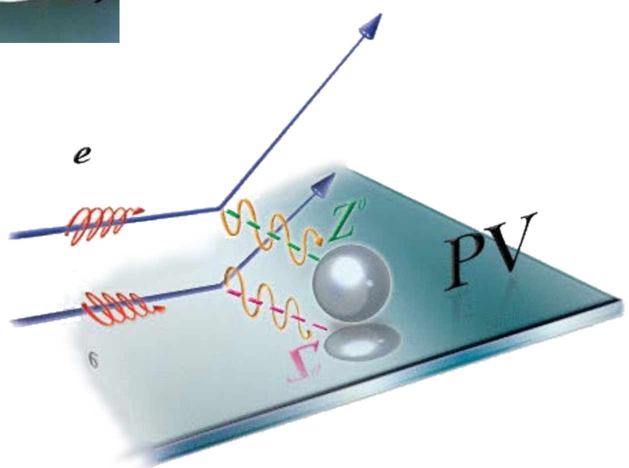


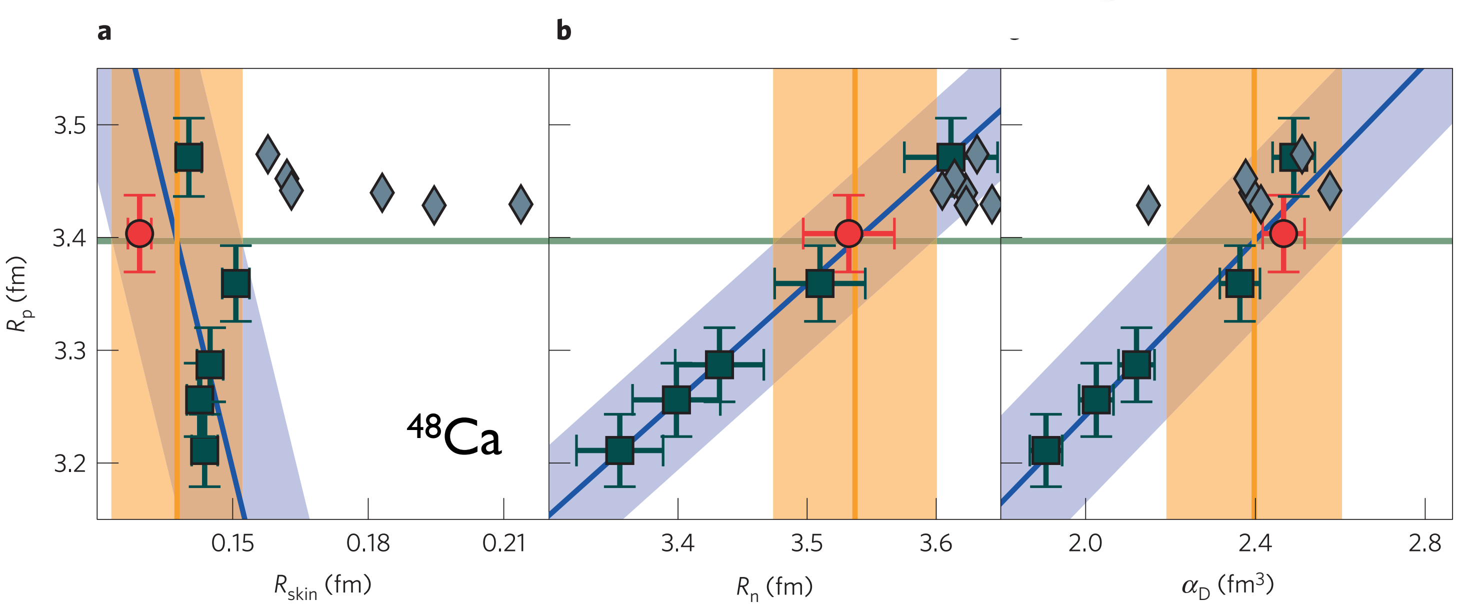
PREX

Pb Radius Experiment

CREX

Ca Radius Experiment

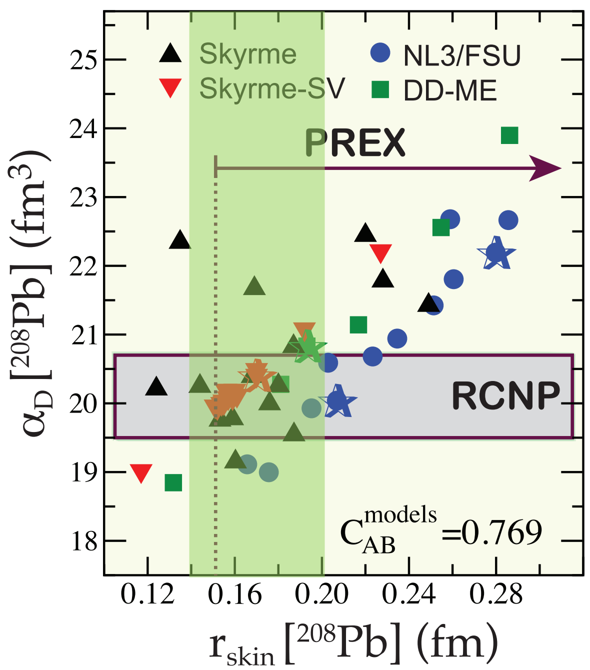




Hagen. et al.. Nature Phys. 12, 186 (2015)

The size of the atomic nucleus: challenges from novel high-precision measurements

Piekarewicz, PRC 85, 041302 (2012)



PREX

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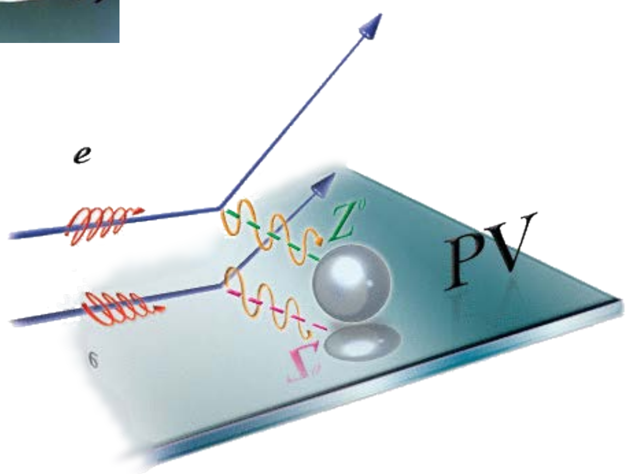

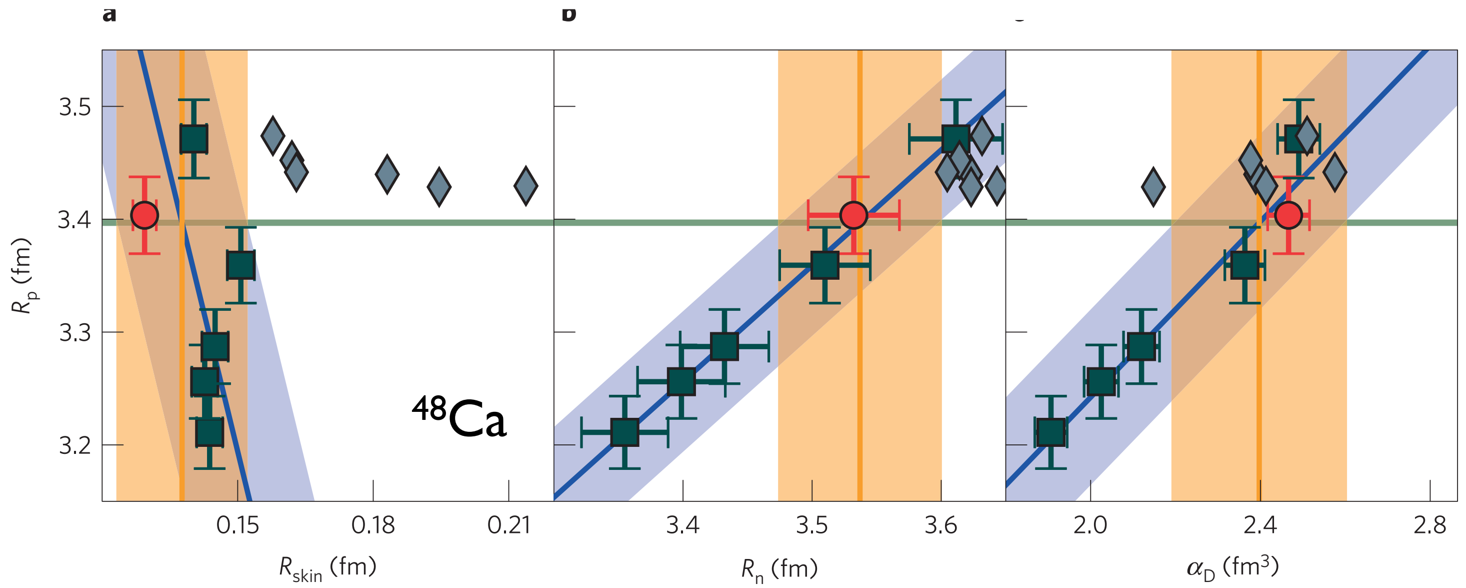

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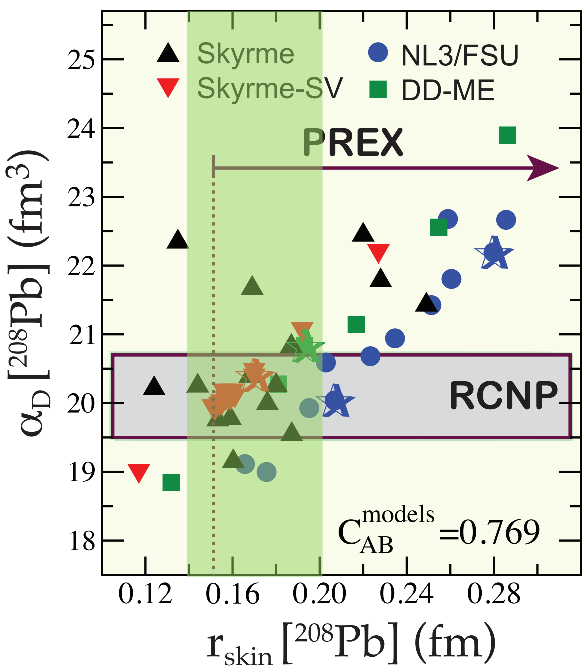

PREX
Pb Radius Experiment
CREX
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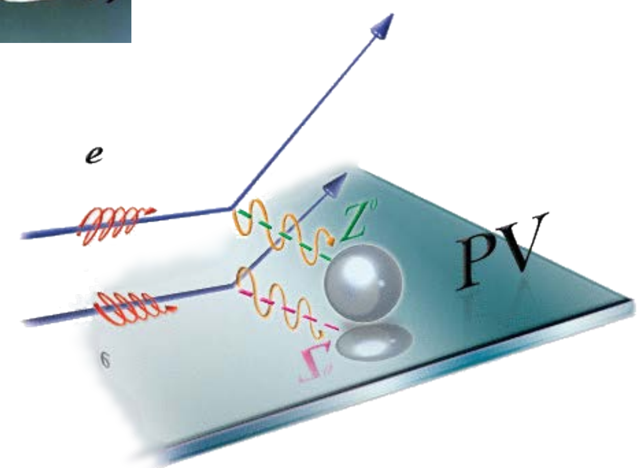
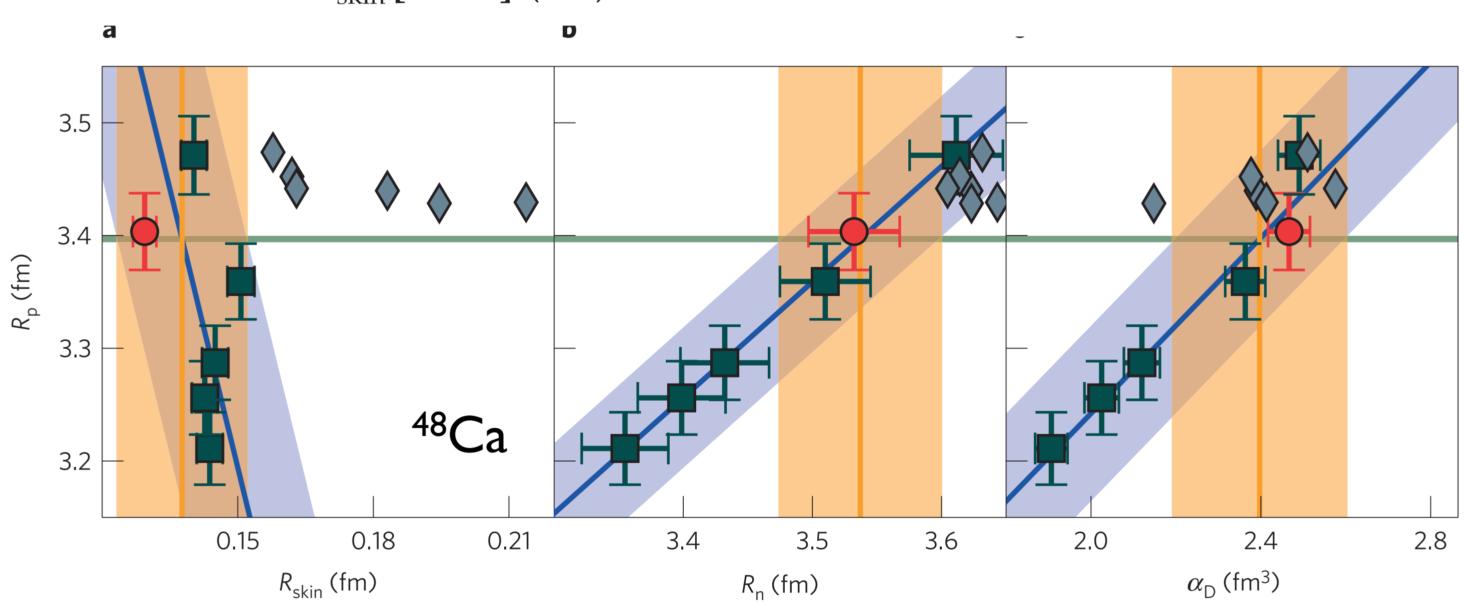
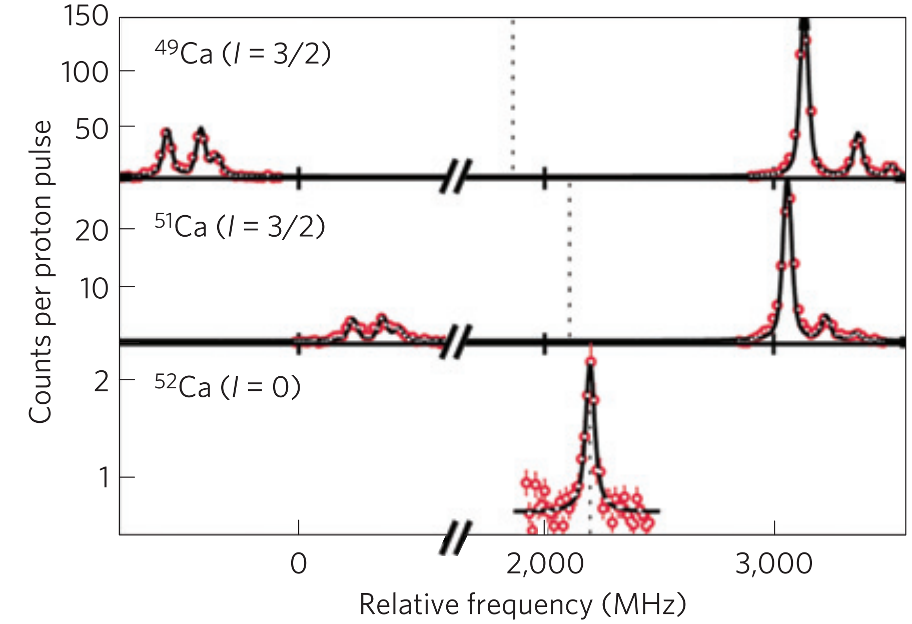
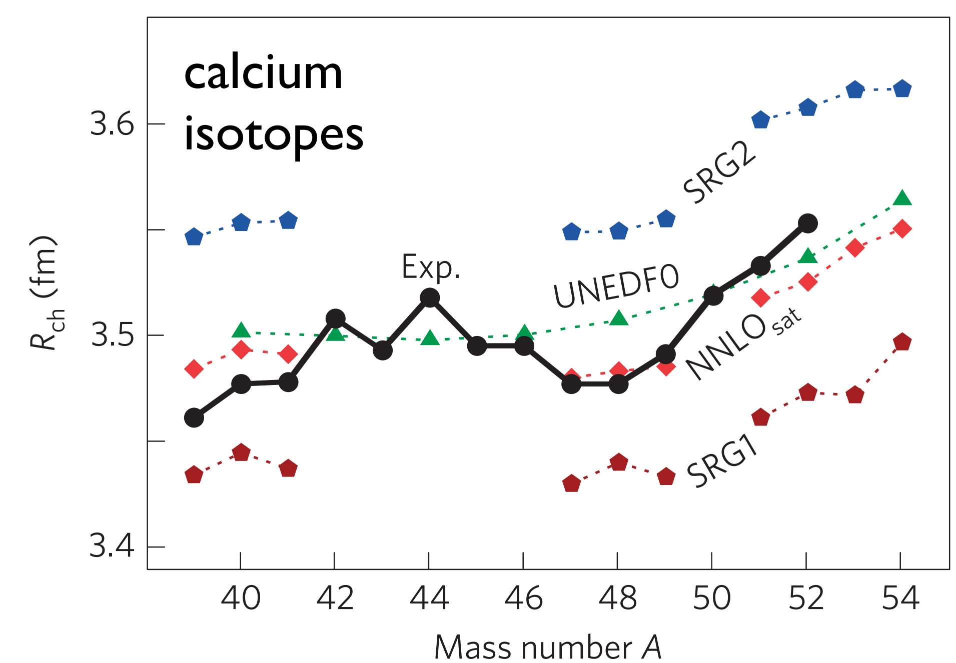




Hagen. et al.. Nature Phys. 12, 186 (2015)





Garcia Ruiz. et al.,
Nature Phys. 12, 594 (2016)

The size of the atomic nucleus: challenges from novel high-precision measurements

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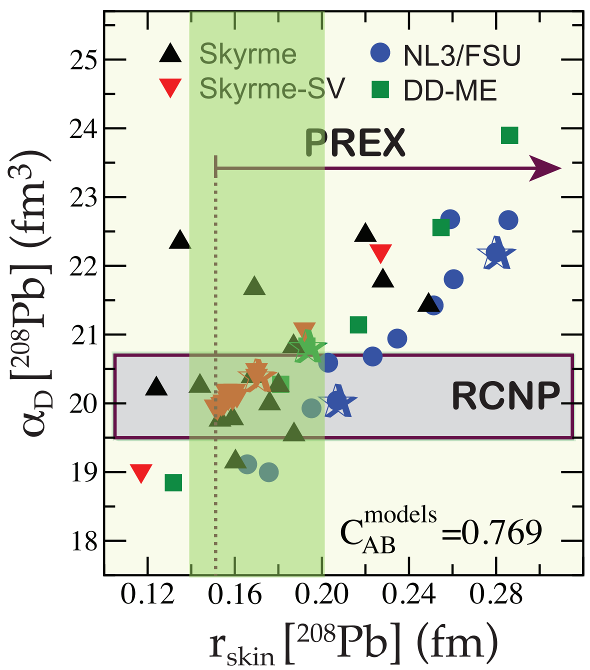
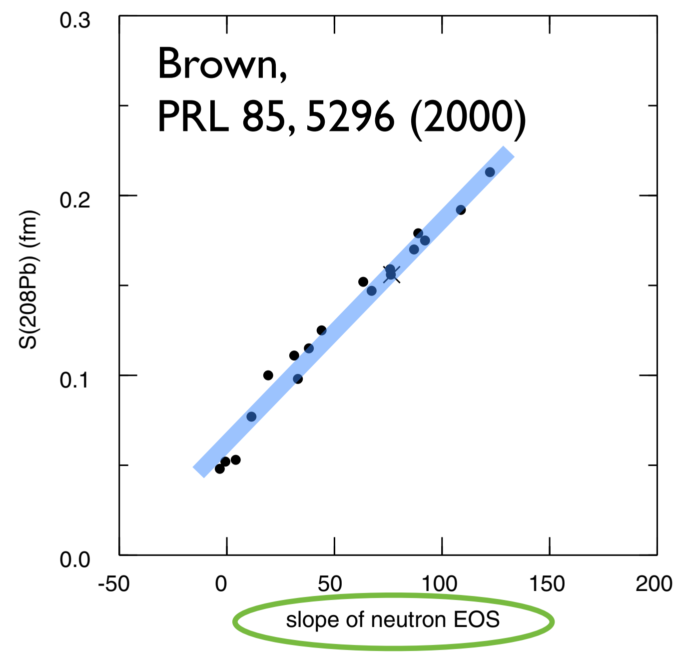
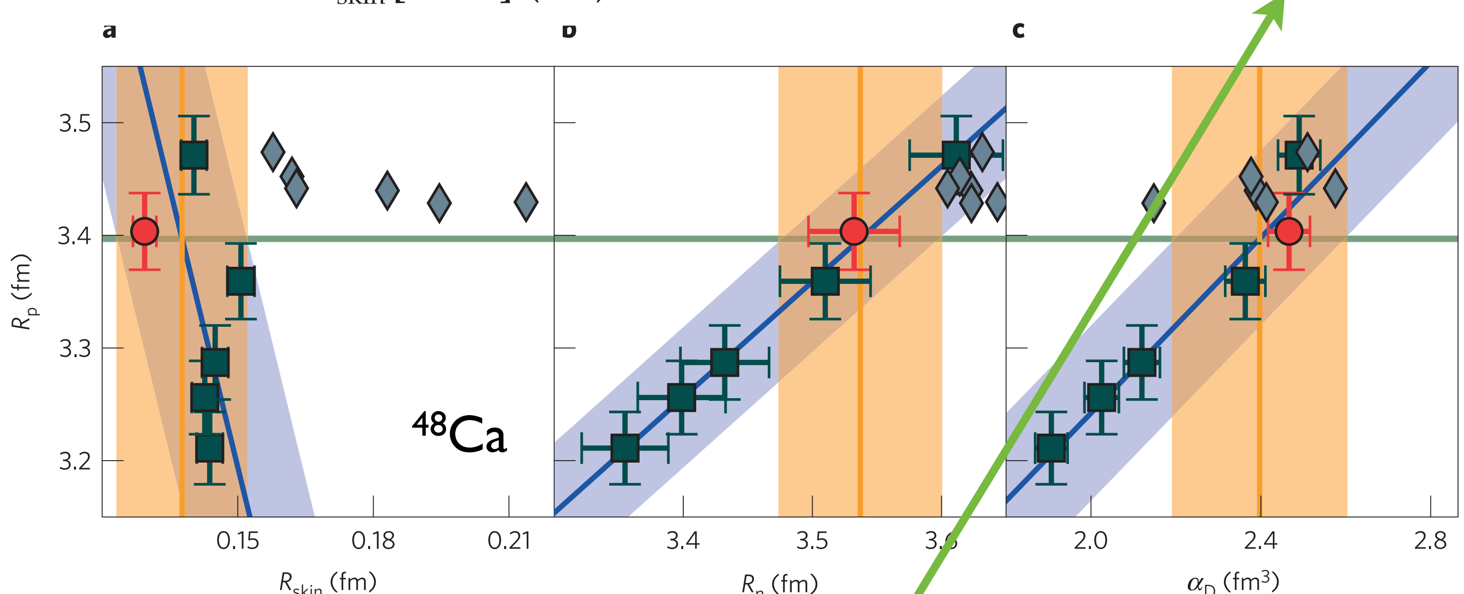
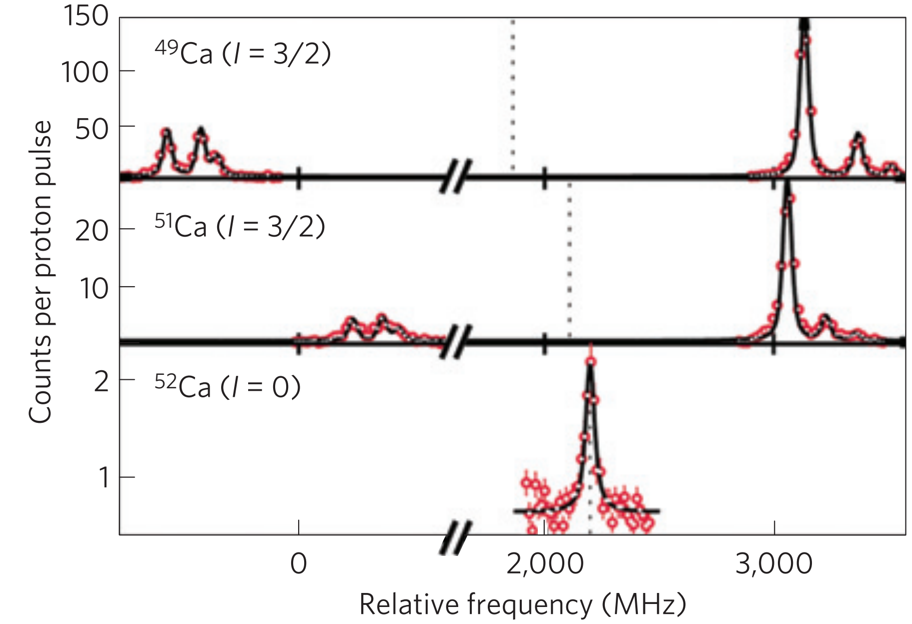


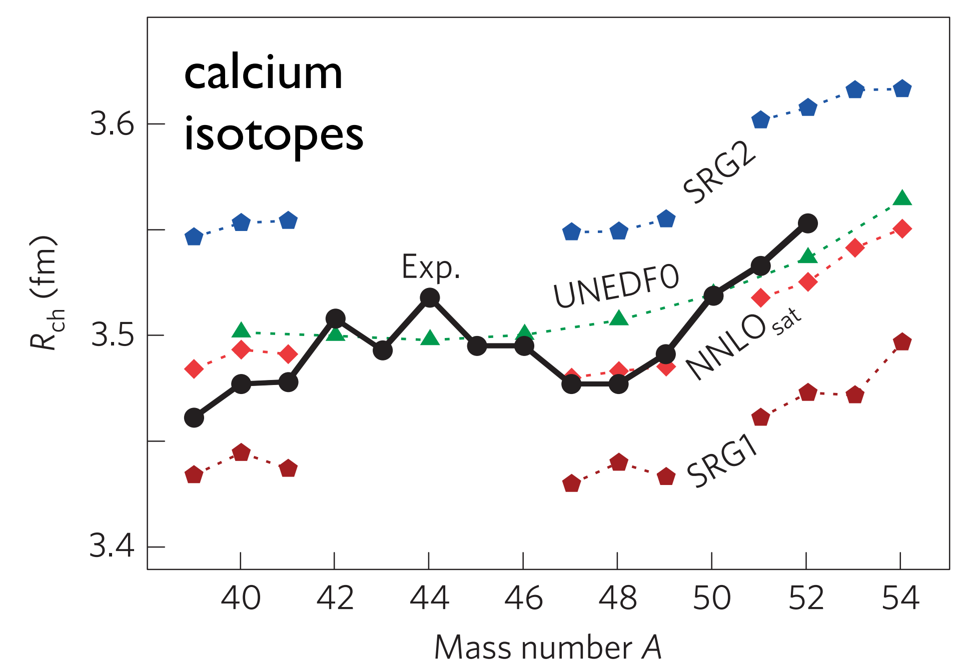




Hagen. et al.. Nature Phys. 12, 186 (2015)

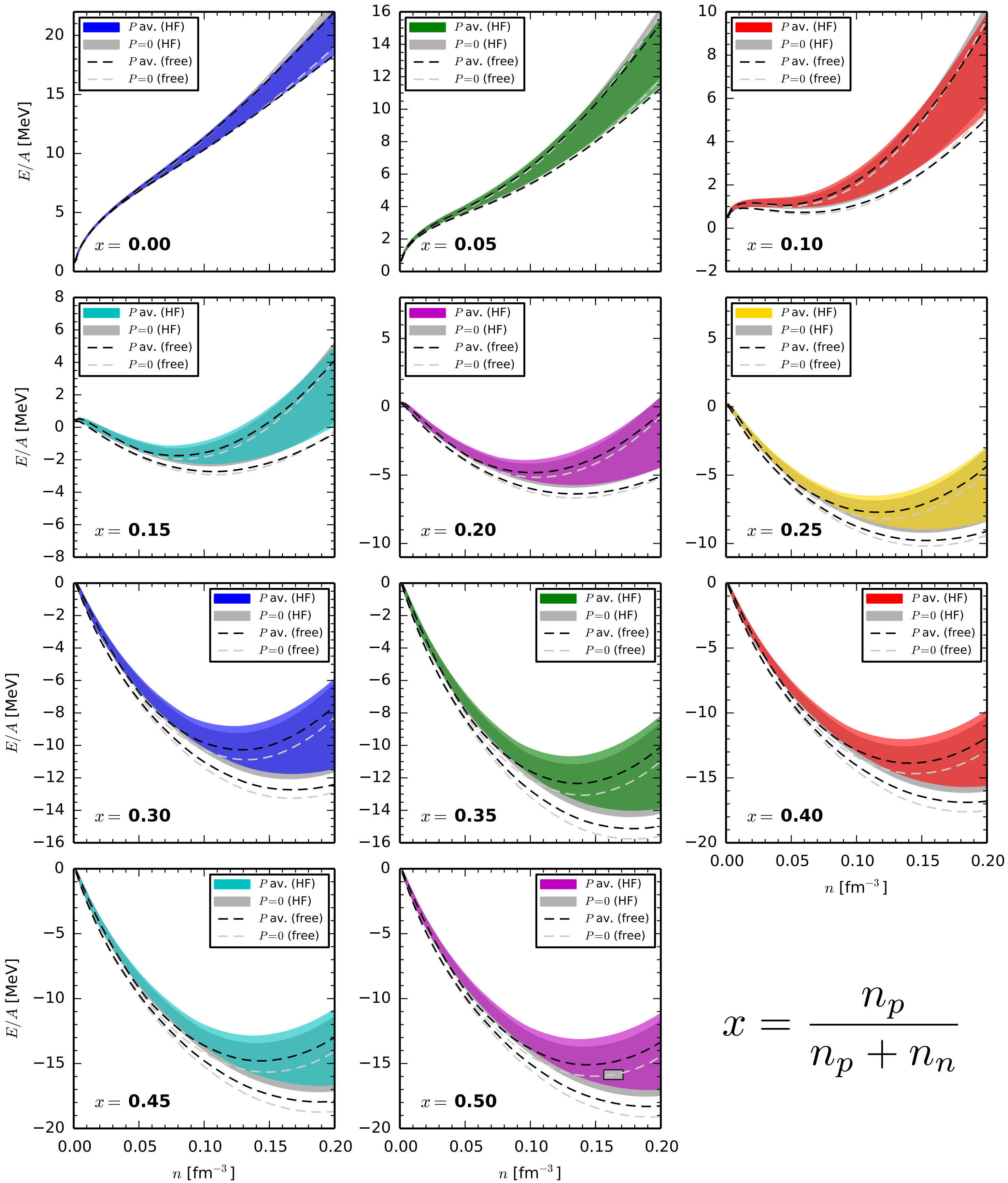
direct connections to astrophysics!





Garcia Ruiz. et al., Nature Phys. 12, 594 (2016)

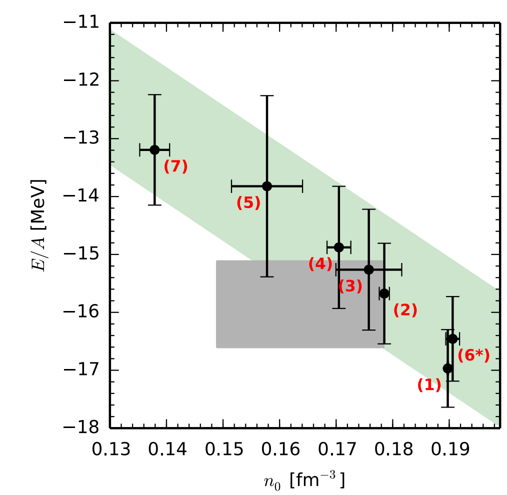
Microscopic calculations of the equation of state



$$x = \frac{n_p}{n_p + n_n}$$

- microscopic framework to calculate equation of state for general proton fractions

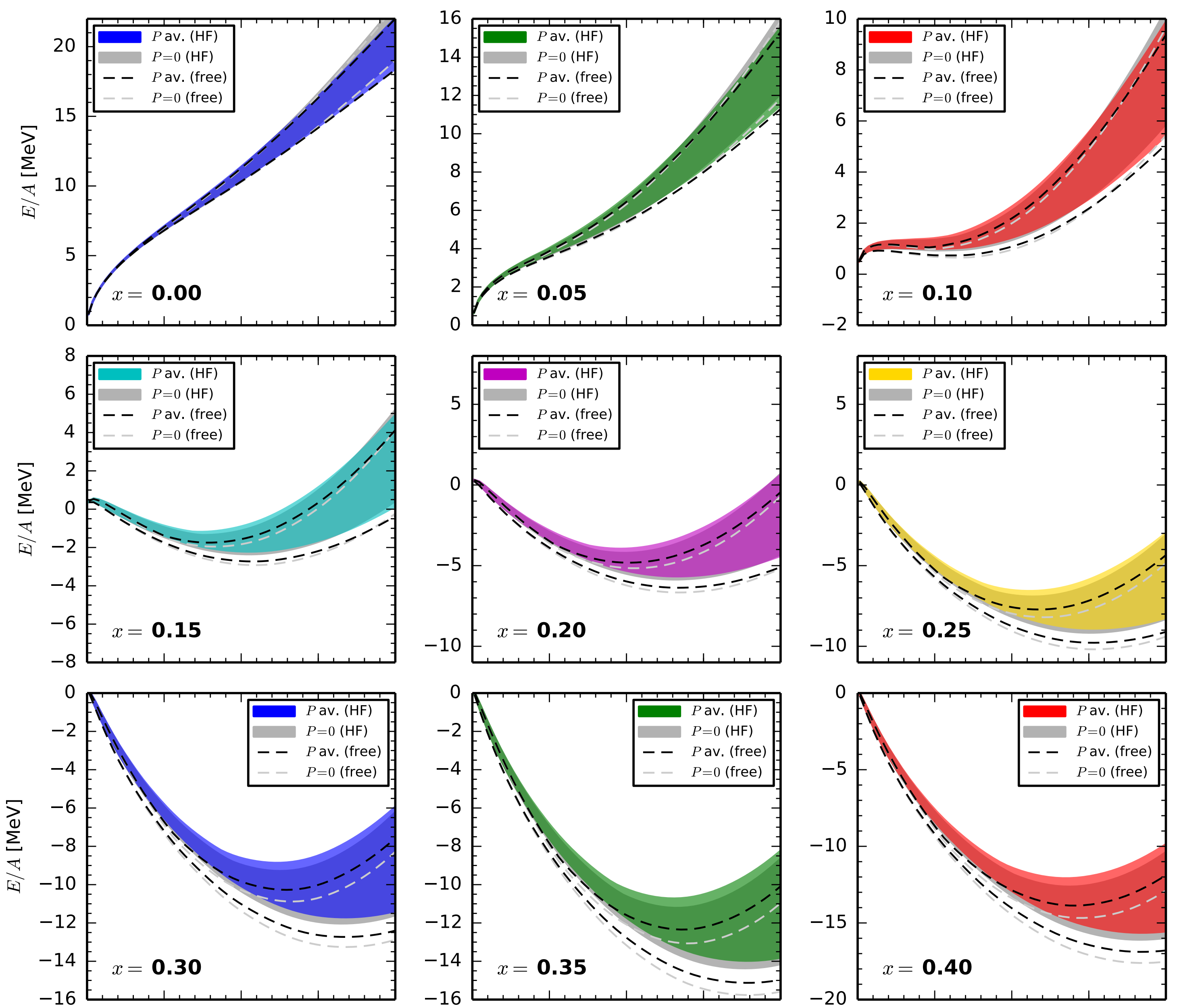
- uncertainty bands determined by set of 7 Hamiltonians



- many-body framework allows treatment of general 3N interaction

Drischler, KH, Schwenk,
PRC 054314 (2016)

Microscopic calculations of the equation of state



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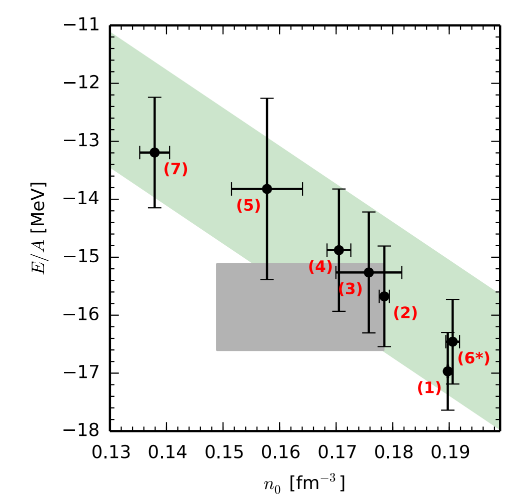


- many body framework allows

Problem:

Calculation of neutron star properties require EOS up to high densities.

Reliable calculations only possible up to $\sim 1\text{-}2\, n_{sat}$.

Strategy:

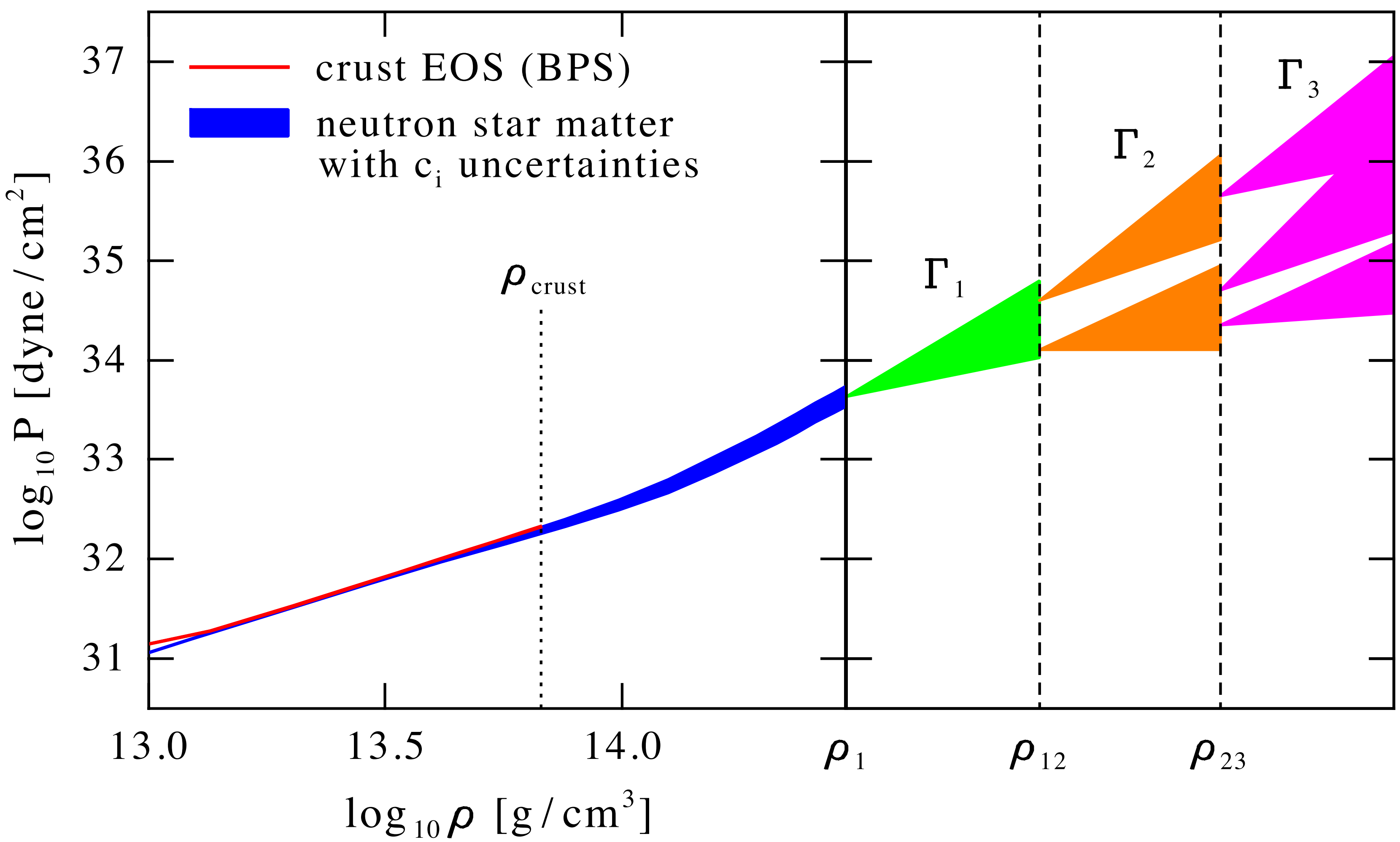
Use observations to constrain the high-density part of the nuclear EOS.

Neutron star radius constraints

incorporation of beta-equilibrium: neutron matter $\longrightarrow$ neutron star matter

parametrize our ignorance via piecewise high-density extensions of EOS:

- use polytropic ansatz $p \sim \rho^\Gamma$ (results insensitive to particular form)
- range of parameters $\Gamma_1, \rho_{12}, \Gamma_2, \rho_{23}, \Gamma_3$ limited by physics



KH, Lattimer, Pethick, Schwenk, ApJ 773, 11 (2013)
KH, Lattimer, Pethick, Schwenk, PRL 105, 161102 (2010)

Constraints on the nuclear equation of state

use the constraints:

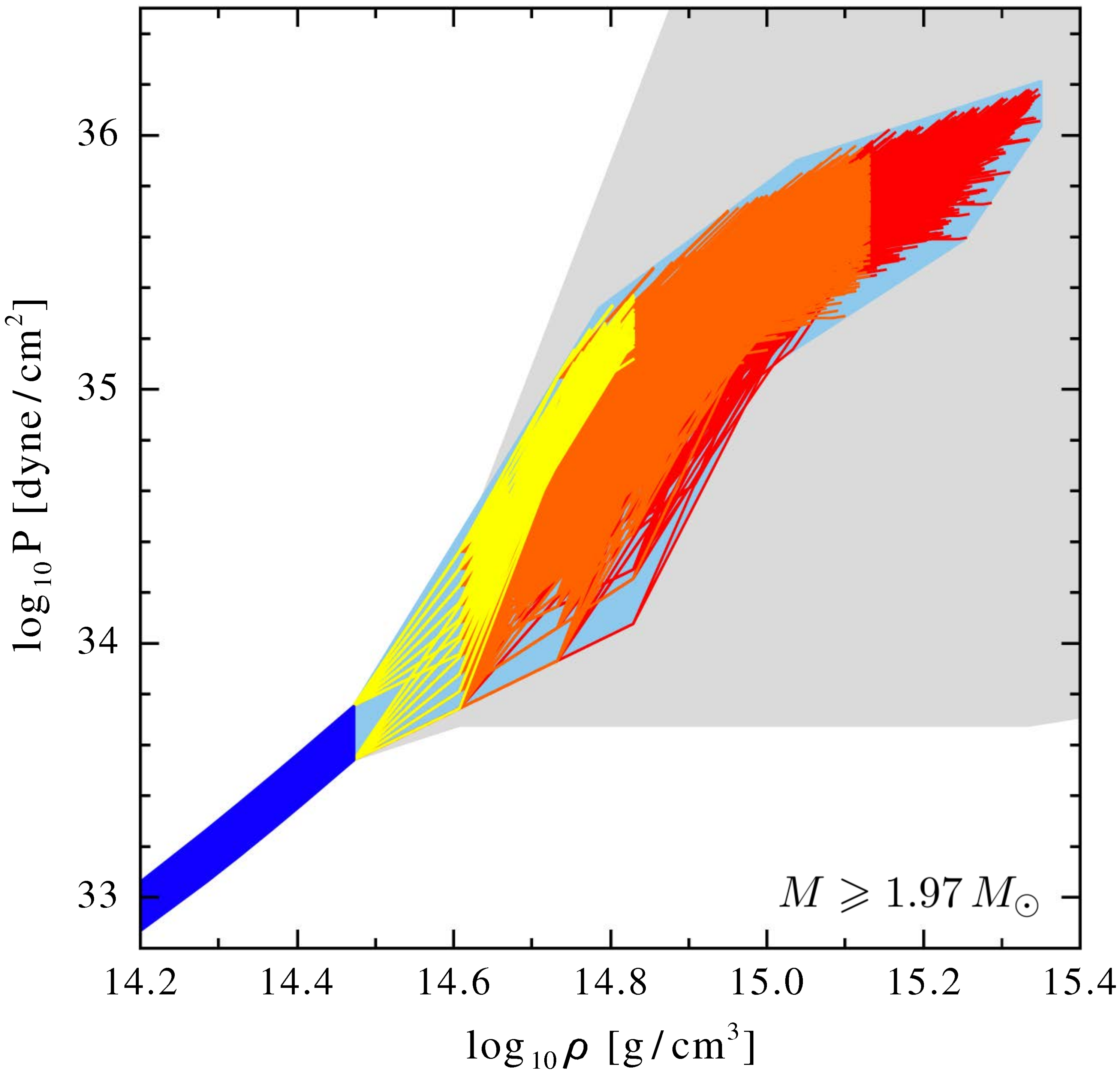
recent NS observations

$$M_{\rm max} > 1.97\, M_\odot$$

causality

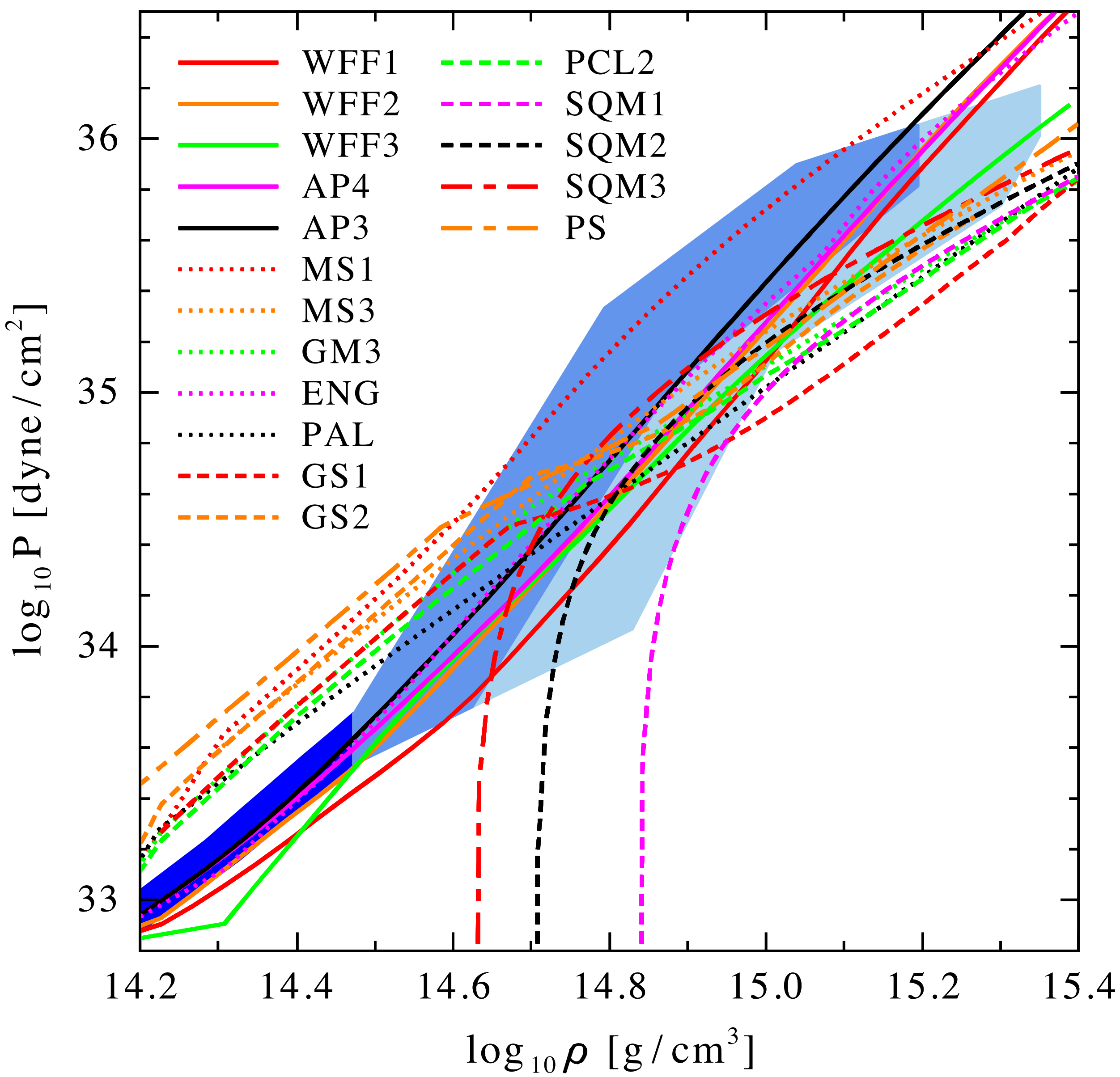
$$v_s(\rho) = \sqrt{dP/d\varepsilon} < c$$

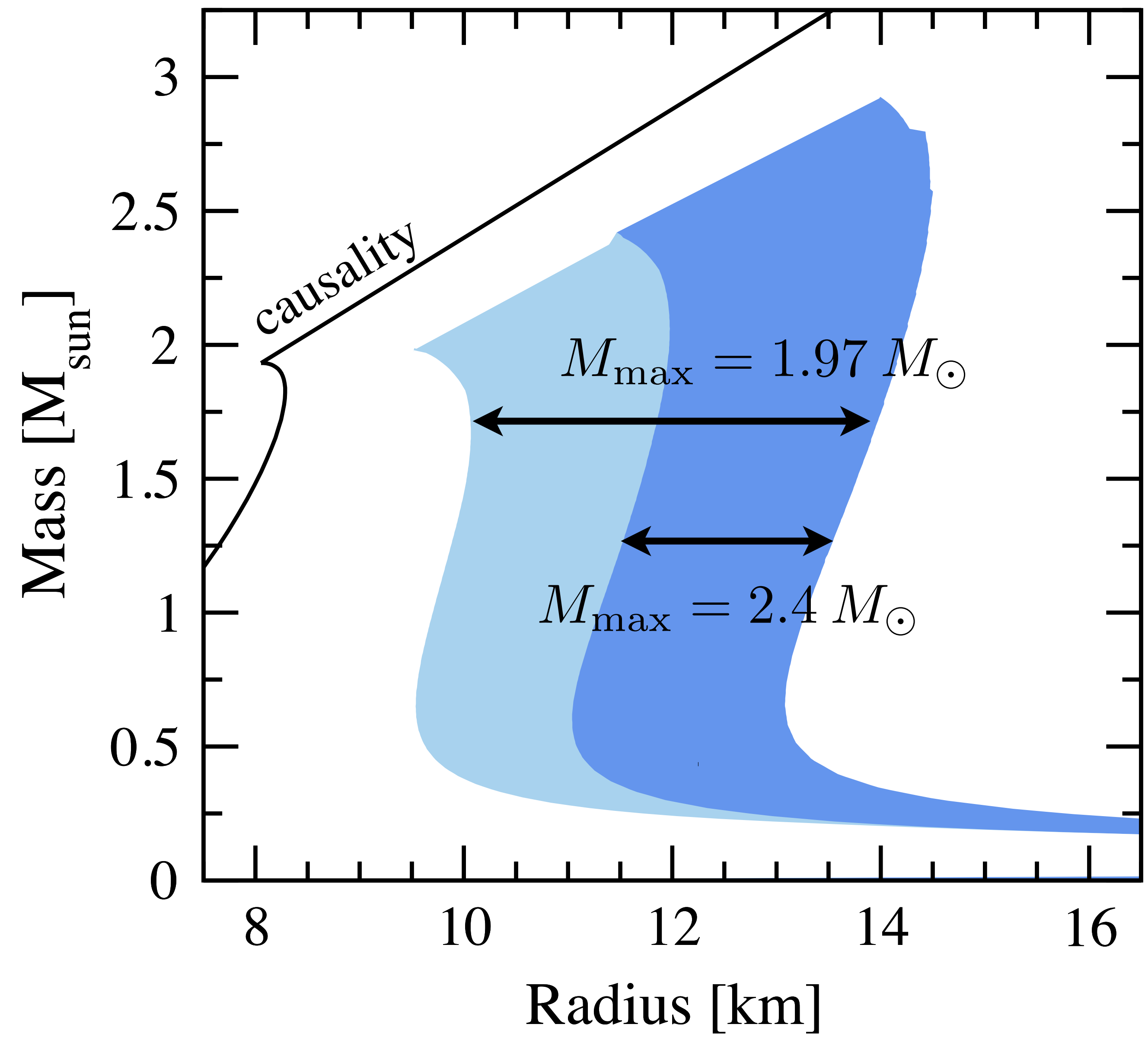
KH, Lattimer, Pethick, Schwenk, ApJ 773, 11 (2013)



constraints lead to significant reduction of EOS uncertainty band

Constraints on neutron star radii





KH, Lattimer, Pethick, Schwenk, ApJ 773, 11 (2013)
KH, Lattimer, Pethick, Schwenk, PRL 105, 161102 (2010)

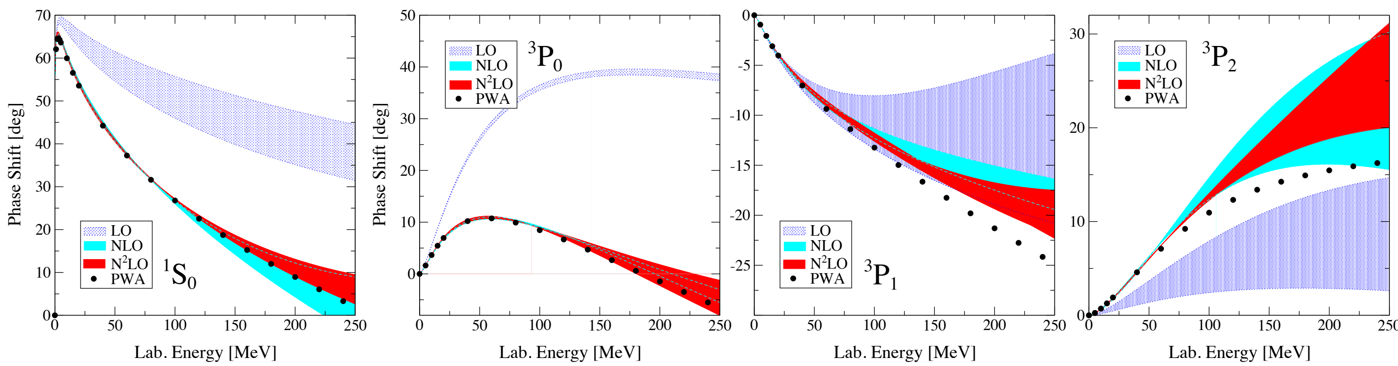
- low-density part of EOS sets scale for allowed high-density extensions

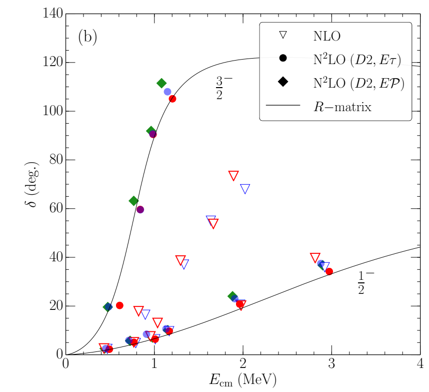
⟶ **see talk by Svenja Greif**

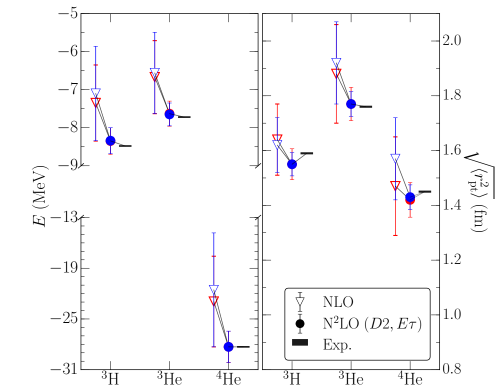
Recent and current developments of novel nuclear interactions

1. local EFT interactions, suitable for Quantum Monte Carlo calculations

status: NN plus 3N up to N2LO, calculations of few-body systems and neutron matter







Gezerlis et al.,
PRL 111, 032501 (2013)

Gezerlis et al.,
PRC 90, 054323 (2014)

Lynn et al.,
PRL 116, 062501 (2016)

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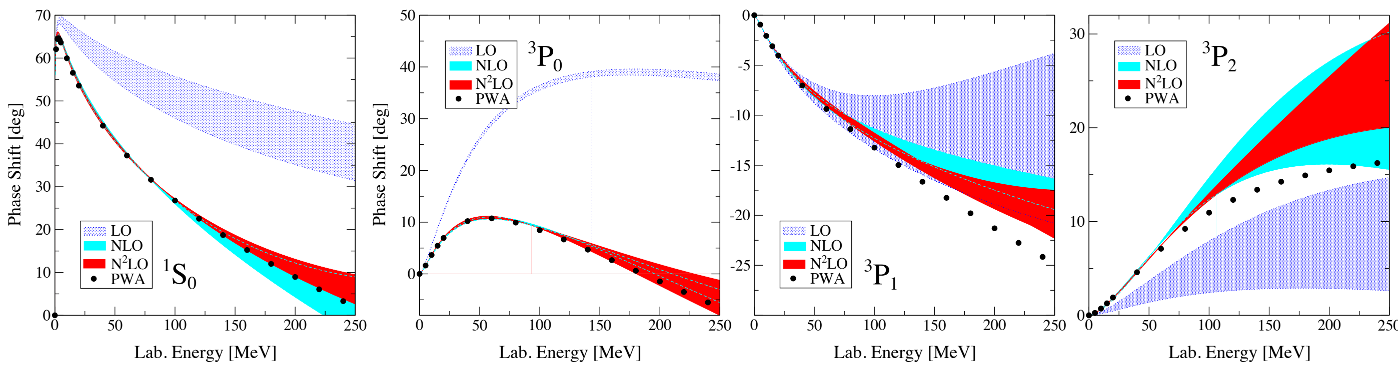

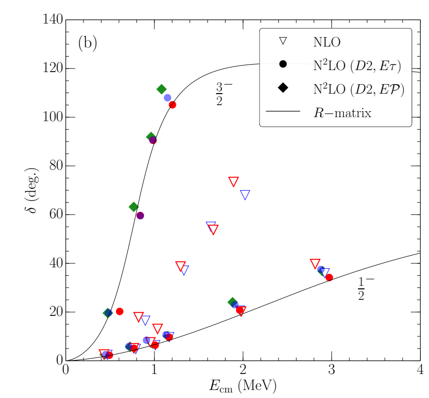

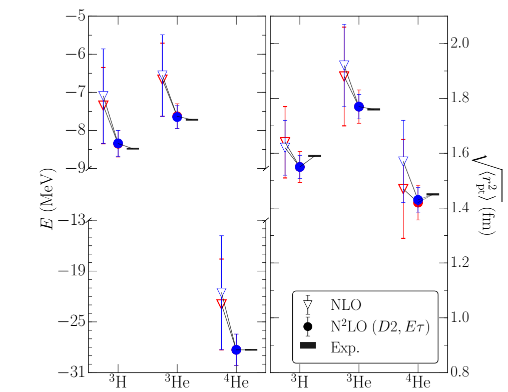

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Lynn et al.,
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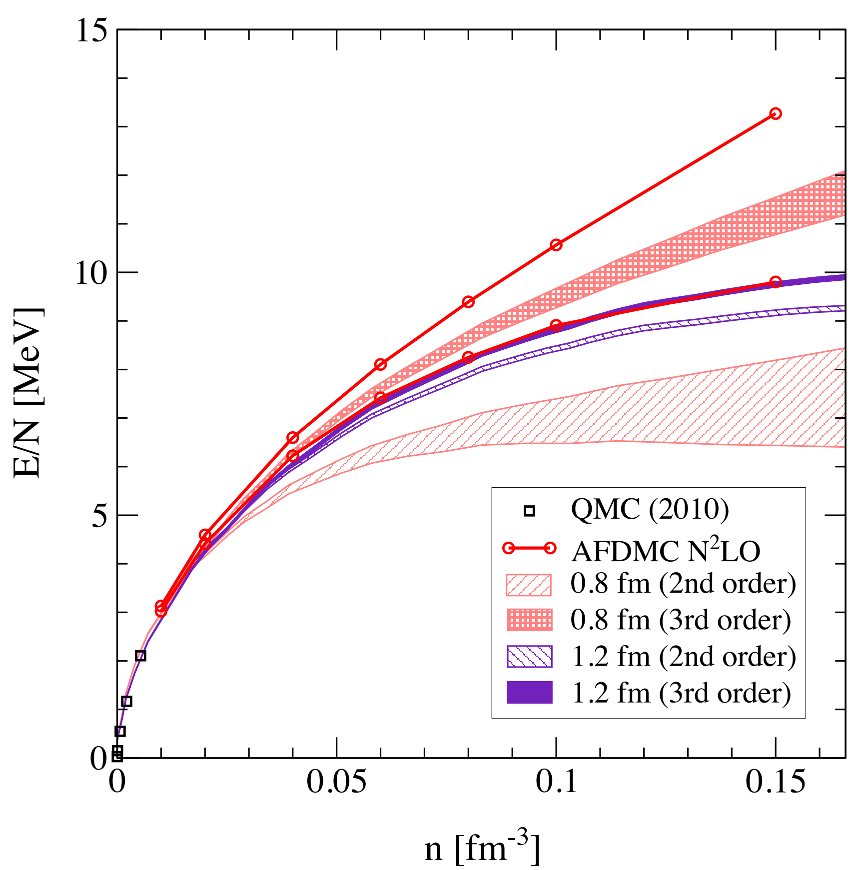


first Quantum Monte Carlo of neutron matter based on chiral EFT interactions

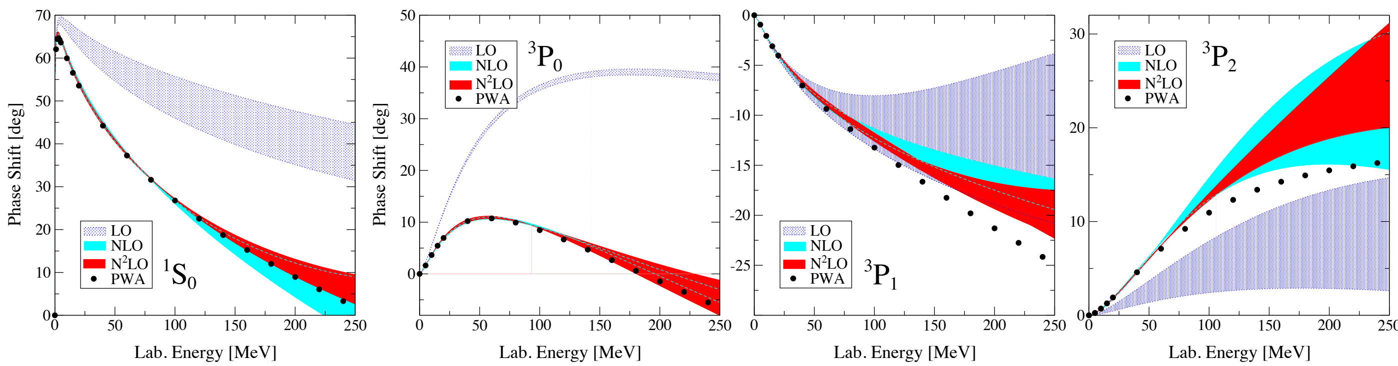
perfect agreement for soft interactions, first direct validation of calculations within many-body perturbation theory

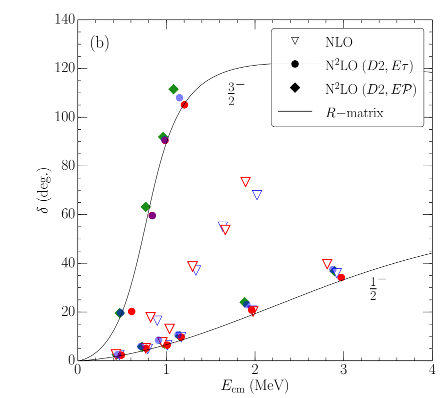
Gezerlis et. al,
PRL 111, 032501 (2013)

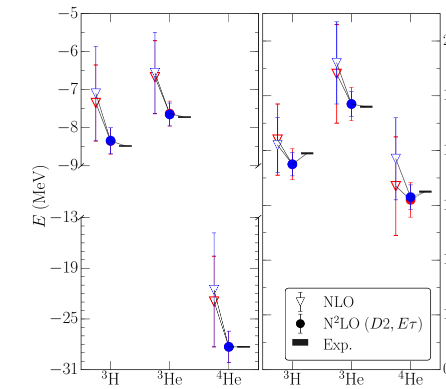
Recent and current developments of novel nuclear interactions

1. local EFT interactions, suitable for Quantum Monte Carlo calculations

status: NN plus 3N up to N2LO, calculations of few-body systems and neutron matter







Gezerlis et al.,
PRL 111, 032501 (2013)

Gezerlis et al.,
PRC 90, 054323 (2014)

Lynn et al.,
PRL 116, 062501 (2016)

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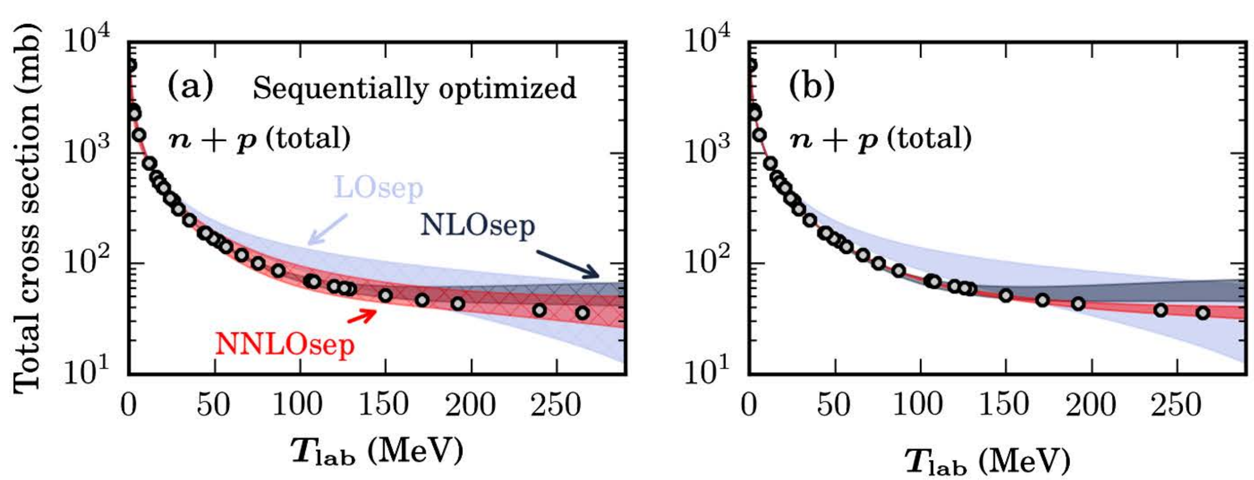
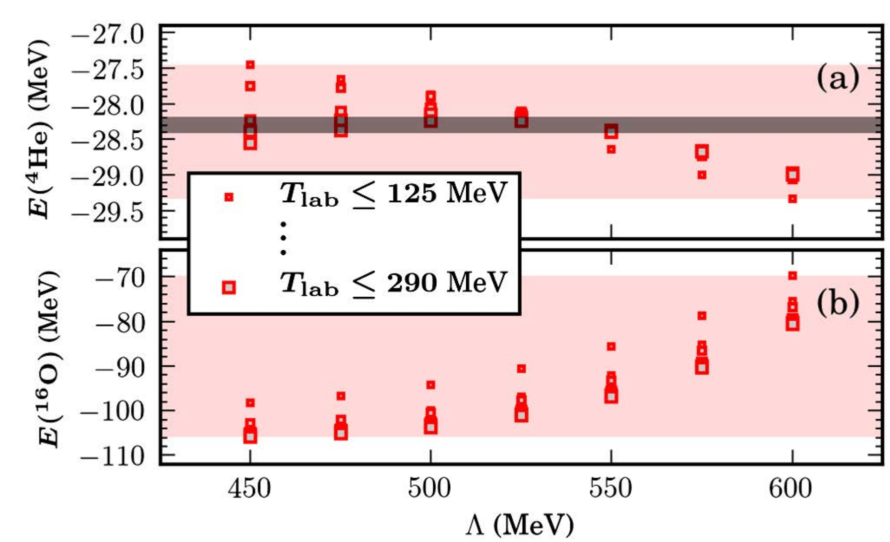
2. simultaneous fit of NN and 3N forces to two- and few-body observables

status: NN plus 3N up to N2LO, N3LO currently in development



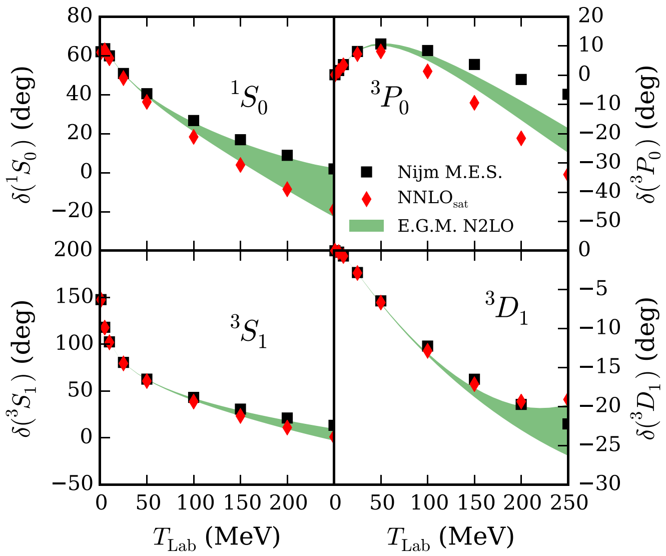


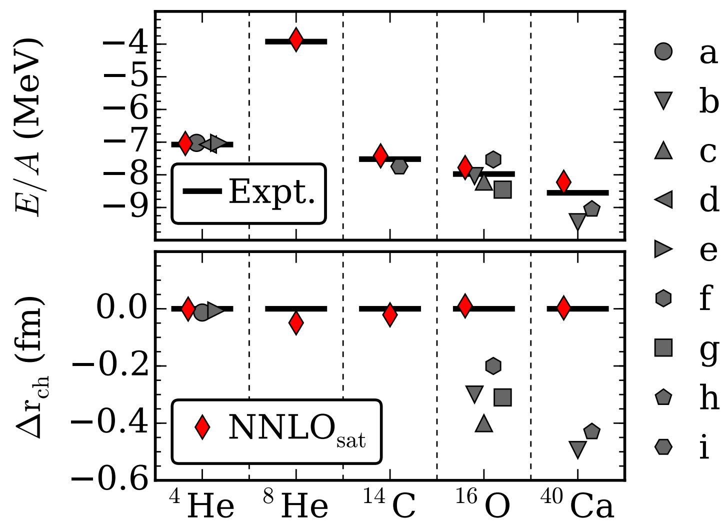
Carlsson et al.,
PRX 6, 011019 (2016)

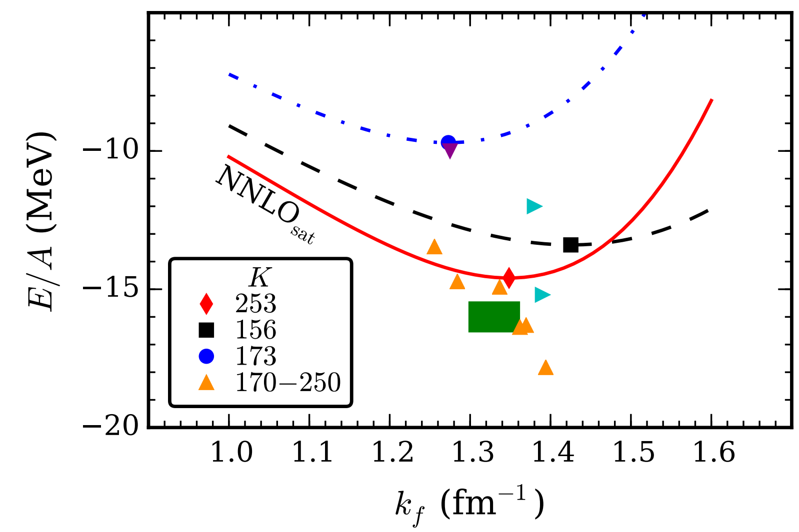
Recent and current developments of novel nuclear interactions

3. fits of NN plus 3N forces to two-, few- and many-body observables

status: NN plus 3N up to N2LO, NN phase shifts only fitted up to T_{lab}~35 MeV







Ekström et al., PRC91, 051301 (2015)

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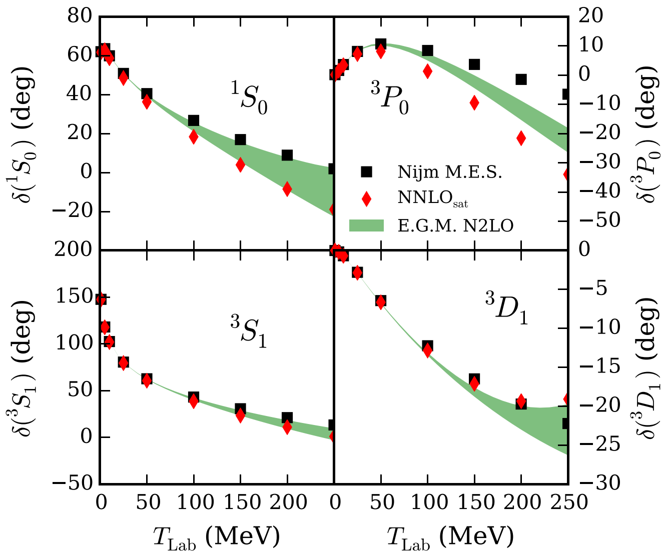

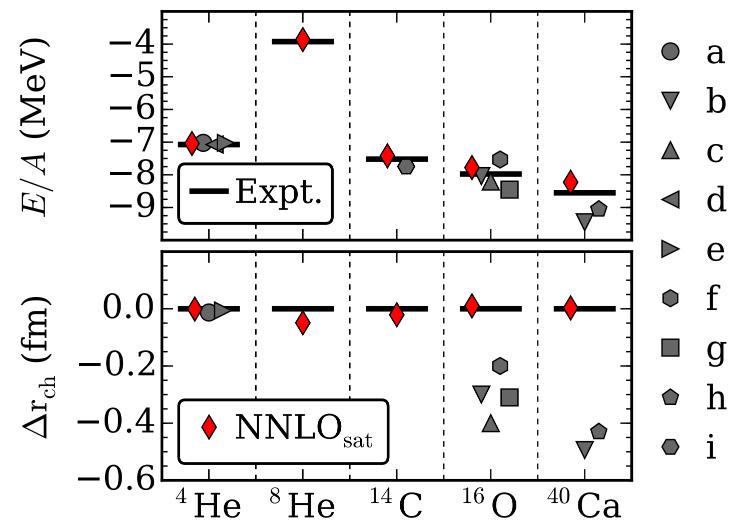

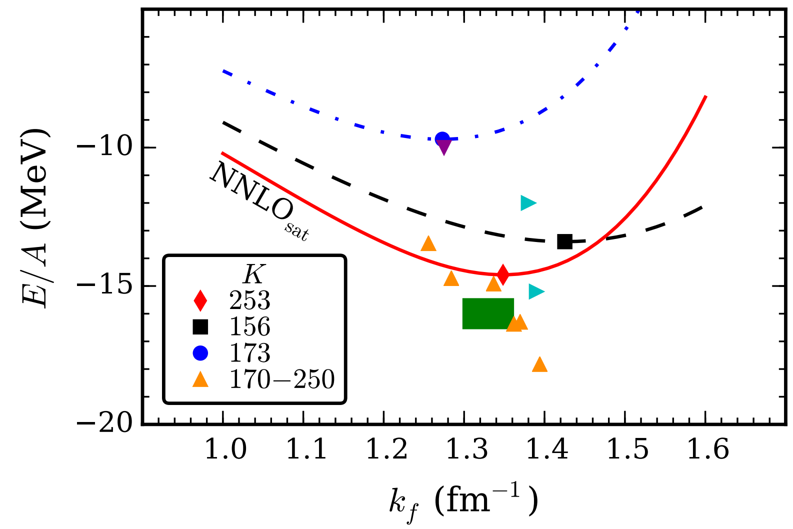

Ekström et al., PRC91, 051301 (2015)

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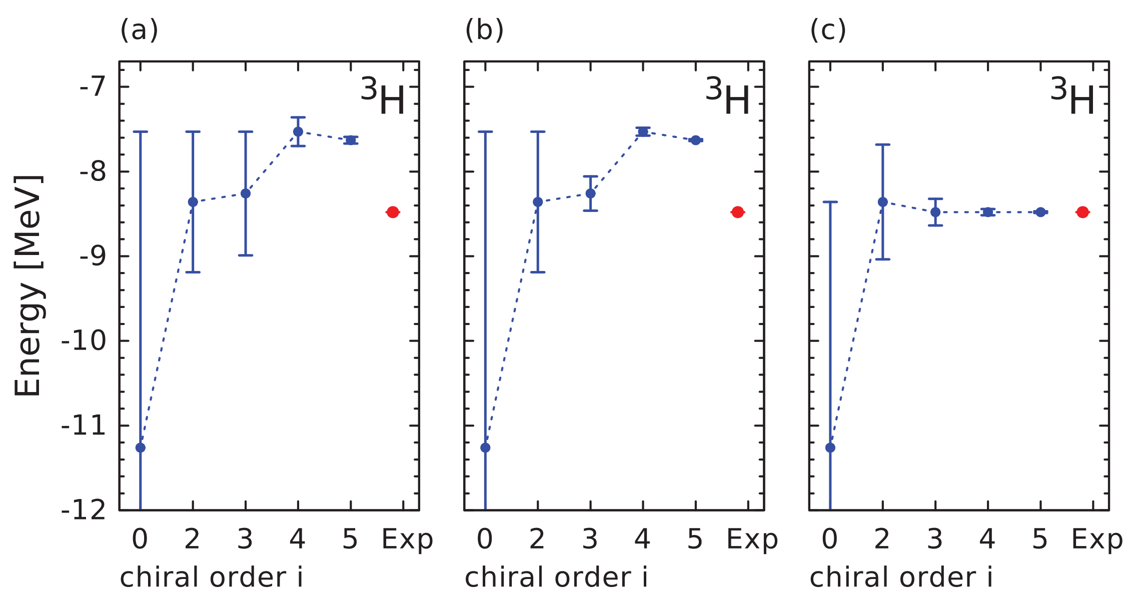
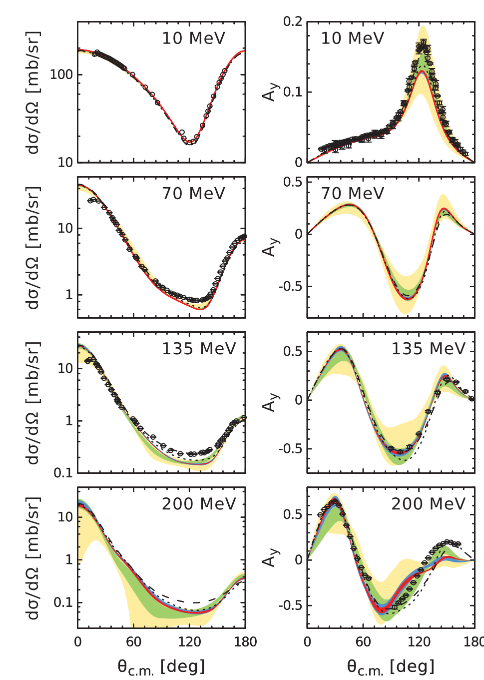
4. semilocal NN forces, development of improved method to estimate uncertainties

status: NN up to N4LO, 3N interactions in development (almost finished :-))





LENPIC

Epelbaum, Krebs, Meißner,
PRL 115, 122301 (2015)

Binder et al.,
PRC 93, 044002 (2016)

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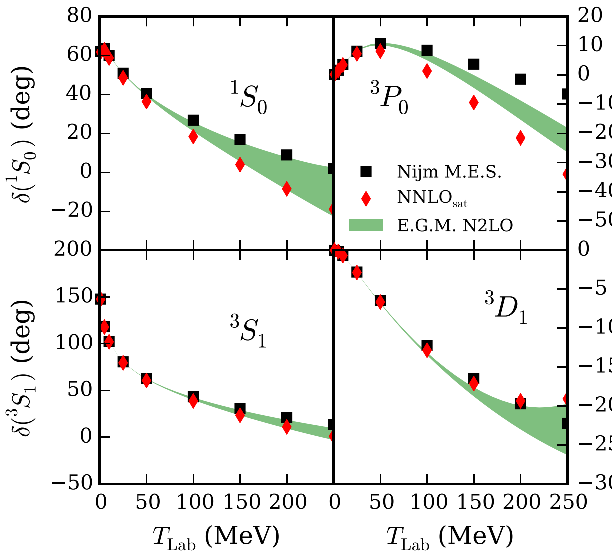

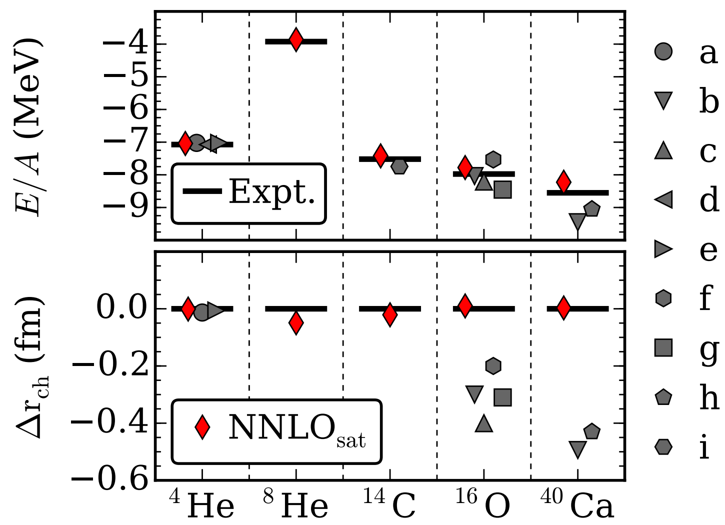

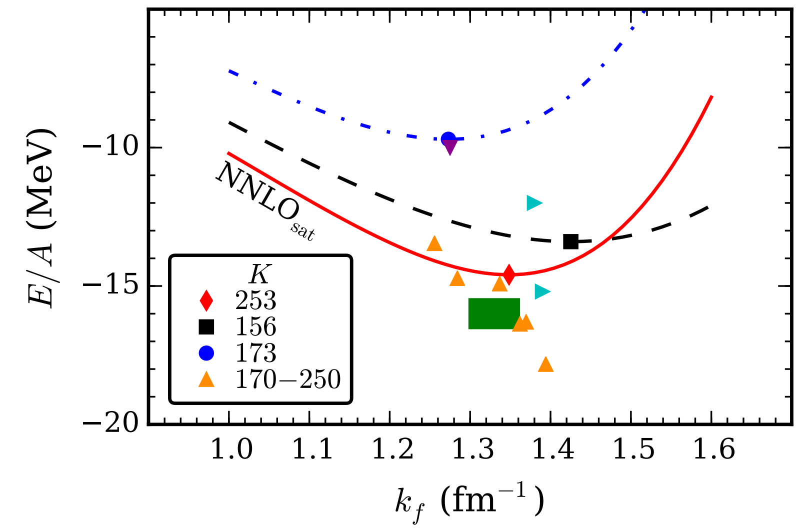

Ekström et al.,PRC91, 051301 (2015)

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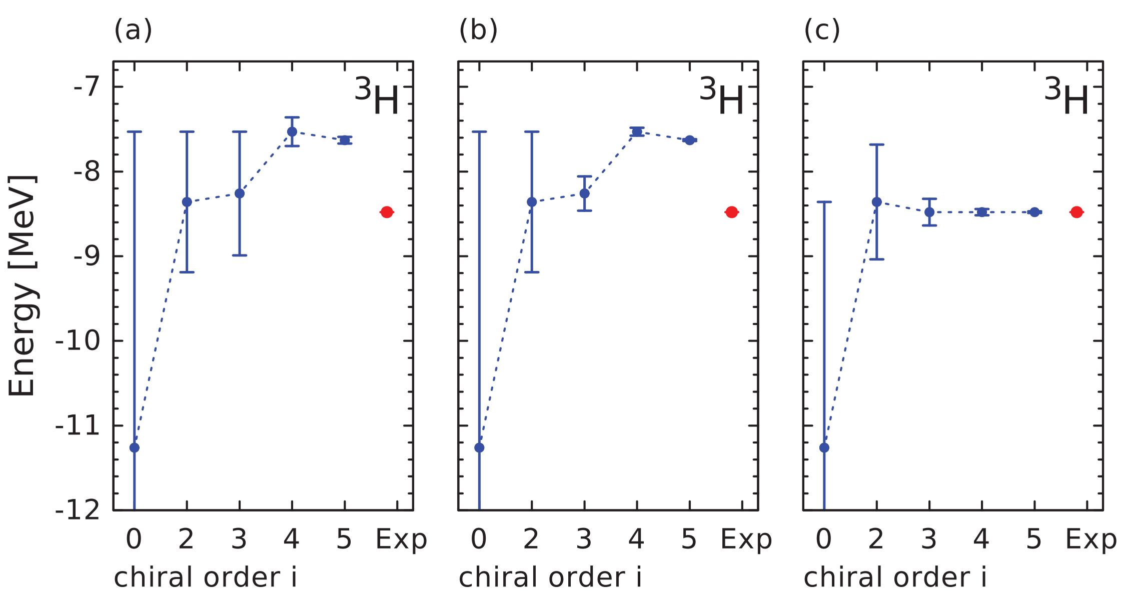
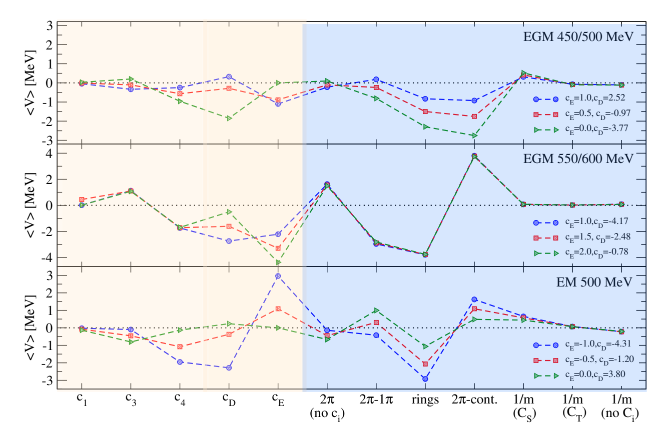


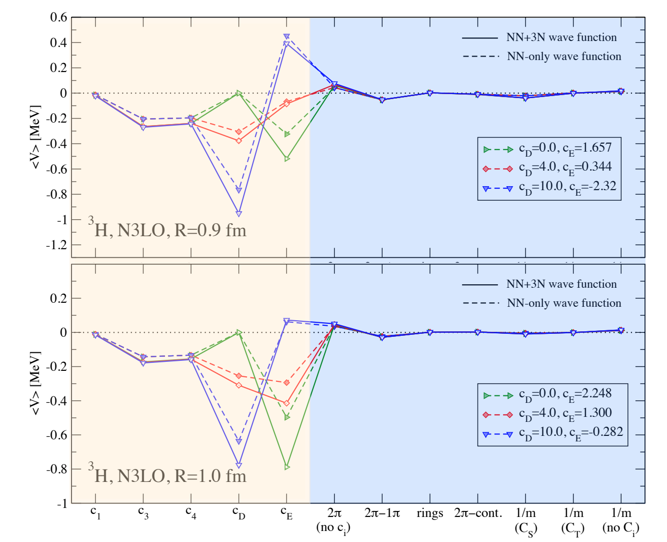
nonlocal

N2LO N3LO



semilocal

N2LO N3LO



Epelbaum, Krebs, Meißner,
PRL 115, 122301 (2015)

Binder et al.,
PRC 93, 044002 (2016)

KH et al.,
PRC 91, 044001 (2015)

Status and achievements

significant increase in scope of ab initio many-body frameworks

remarkable agreement between different ab intio many-body methods

discrepancies to experiment dominated by deficiencies of present nuclear interactions

Current developments and open questions

presently active efforts to develop improved nucleon interactions (fits of LECs, power counting, regularization...)

Key goals

unified study of atomic nuclei, nuclear matter and reactions based on novel interactions

systematic estimates of theoretical uncertainties