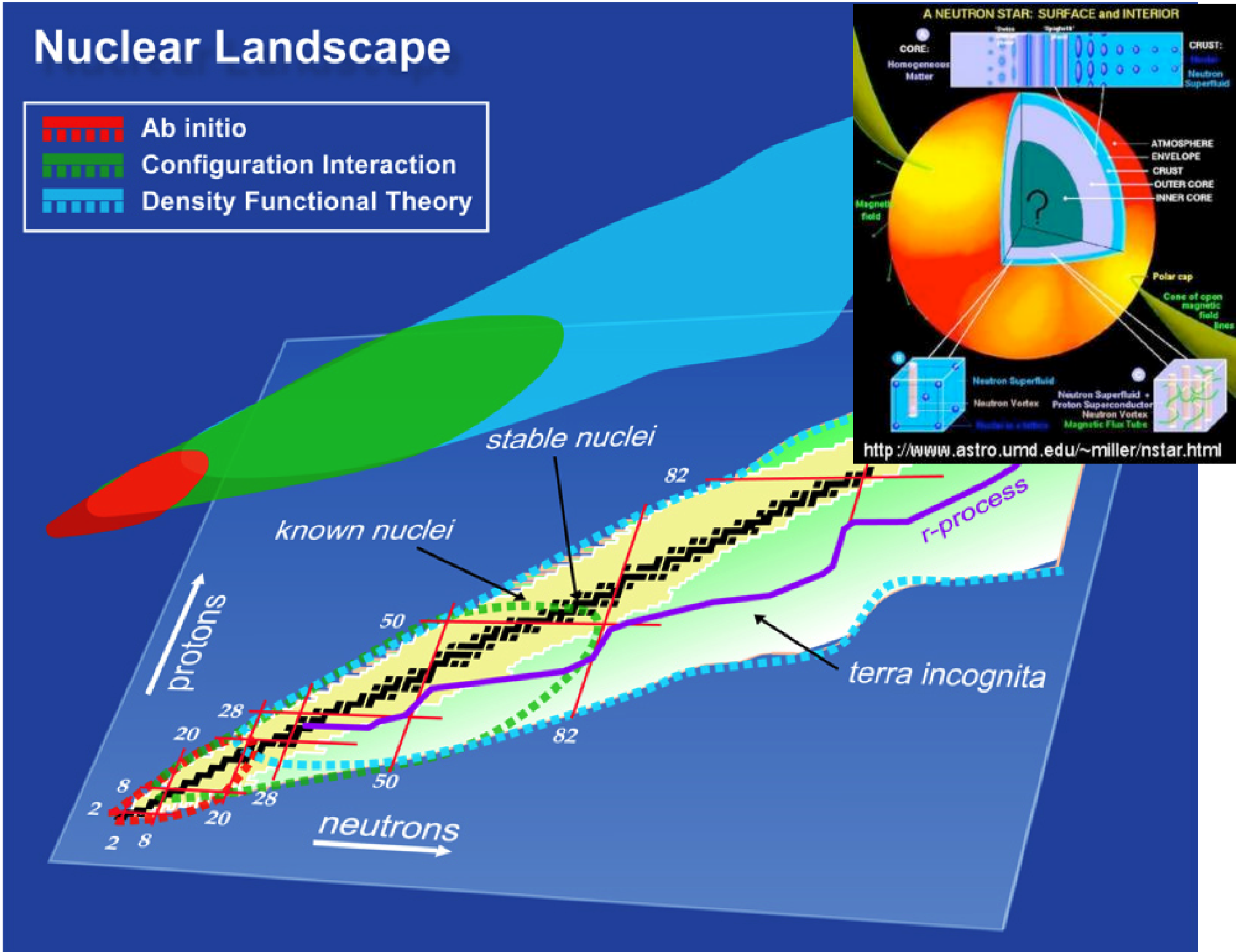
Neutron-rich matter from chiral EFT interactions

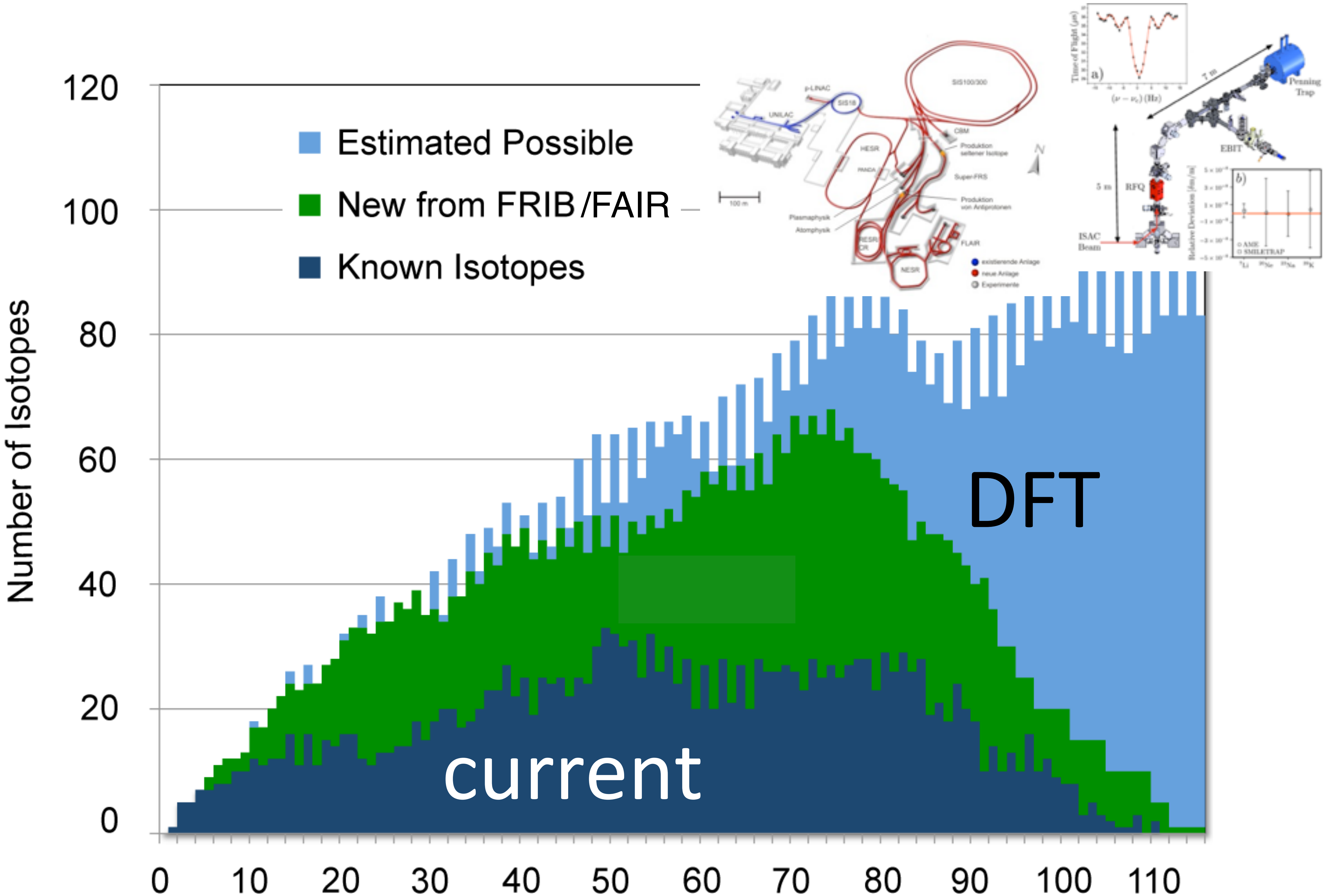
Kai Hebeler

Darmstadt, Nov. 10, 2014

EMMI Physics Days 2014


Nuclear Landscape
Ab initio
Configuration Interaction
Density Functional Theory
stable nuclei
known nuclei
r-process
terra incognita
protons
neutrons
2
8
20
28
50
82
A NEUTRON STAR: SURFACE and INTERIOR
CORE:
Homogeneous Matter
CRUST:
Neutron Superfluid
ATMOSPHERE
ENVELOPE
CRUST
OUTER CORE
INNER CORE
Magnetic field
Polar cap
Cone of open magnetic field lines
Neutron Superfluid
Neutron Vortex
Neutron Superfluid + Proton Superconductor
Neutron Vortex
Magnetic Flux Tube
http ://www.astro.umd.edu/~miller/nstar.html

New frontiers from rare isotope facilities



Balantekin et al. , Mod. Phys. Lett. A29, 1430010 (2014)

Exciting recent developments on many fronts...

LETTER

nature
doi:10.1038/nature12522

Evidence for a new nuclear 'magic number' from the level structure of ^{54}Ca

D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]

LETTER

nature
doi:10.1038/nature11188

The limits of the nuclear landscape

Jochen Erler[1,2], Noah Birge[1], Markus Kortelainen[1,2,3], Witold Nazarewicz[1,2,4], Erik Olsen[1,2], Alexander M. Perhac[1] & Mario Stoitsov[1,2]‡

LETTER

nature
doi:10.1038/nature12226

Masses of exotic calcium isotopes pin down nuclear forces

F. Wienholtz[1], D. Beck[2], K. Blaum[3], Ch. Borgmann[3], M. Breitenfeldt[4], R. B. Cakirli[3,5], S. George[1], F. Herfurth[2], J. D. Holt[6,7], M. Kowalska[8], S. Kreim[3,8], D. Lunney[9], V. Manea[9], J. Menéndez[6,7], D. Neidherr[2], M. Rosenbusch[1], L. Schweikhard[1], A. Schwenk[7,6], J. Simonis[6,7], J. Stanja[10], R. N. Wolf[1] & K. Zuber[10]

LETTER

nature
doi:10.1038/nature09466

A two-solar-mass neutron star measured using Shapiro delay

P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

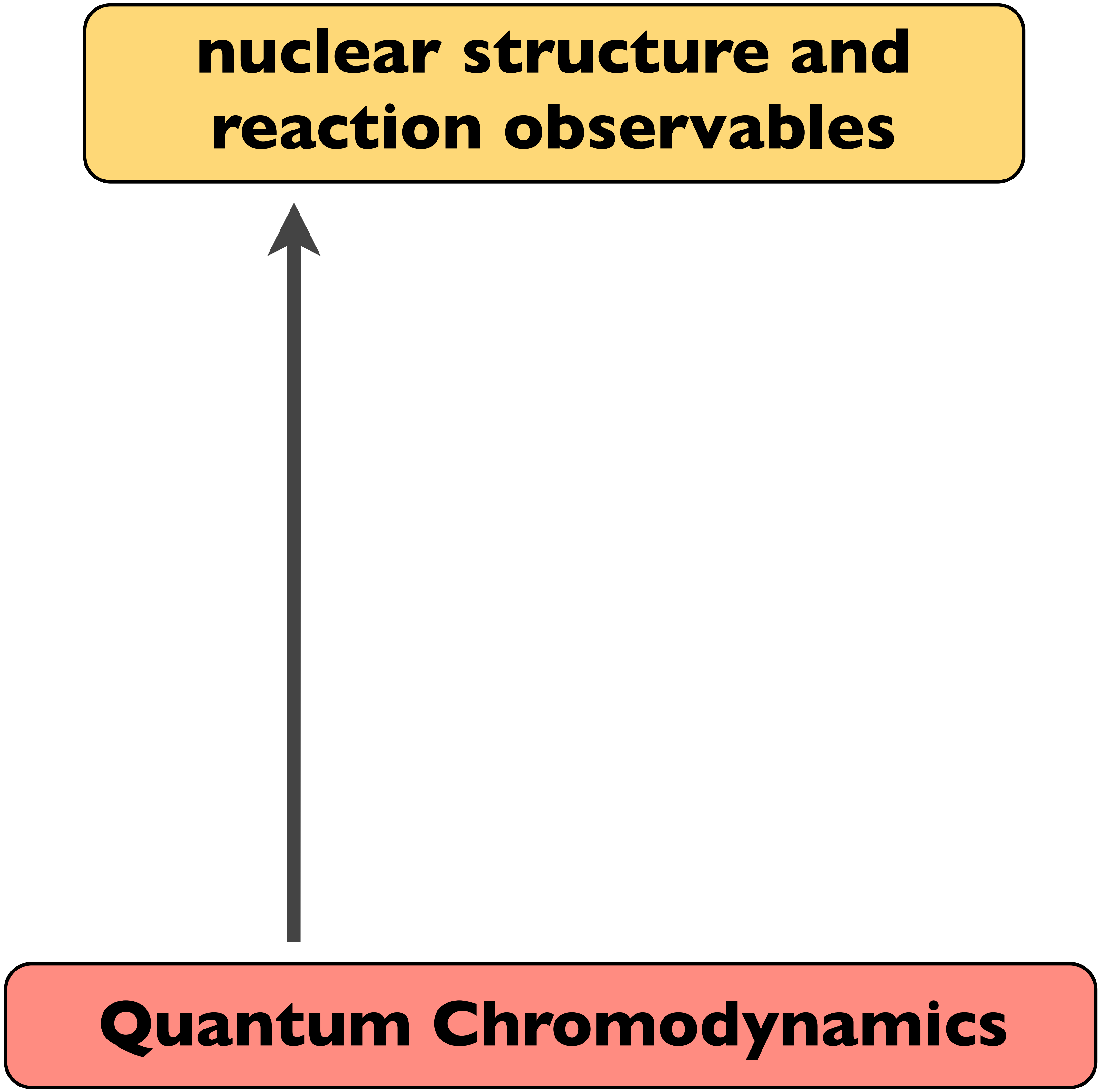
RESEARCH ARTICLE SUMMARY

Science

A Massive Pulsar in a Compact Relativistic Binary

John Antoniadis,* Paulo C. C. Freire, Norbert Wex, Thomas M. Tauris, Ryan S. Lynch, Marten H. van Kerkwijk, Michael Kramer, Cees Bassa, Vik S. Dhillon, Thomas Driebe, Jason W. T. Hessels, Victoria M. Kaspi, Vladislav I. Kondratiev, Norbert Langer, Thomas R. Marsh, Maura A. McLaughlin, Timothy T. Pennucci, Scott M. Ransom, Ingrid H. Stairs, Joeri van Leeuwen, Joris P. W. Verbiest, David G. Whelan

Ab initio nuclear structure theory



Ab initio nuclear structure theory

nuclear structure and reaction observables

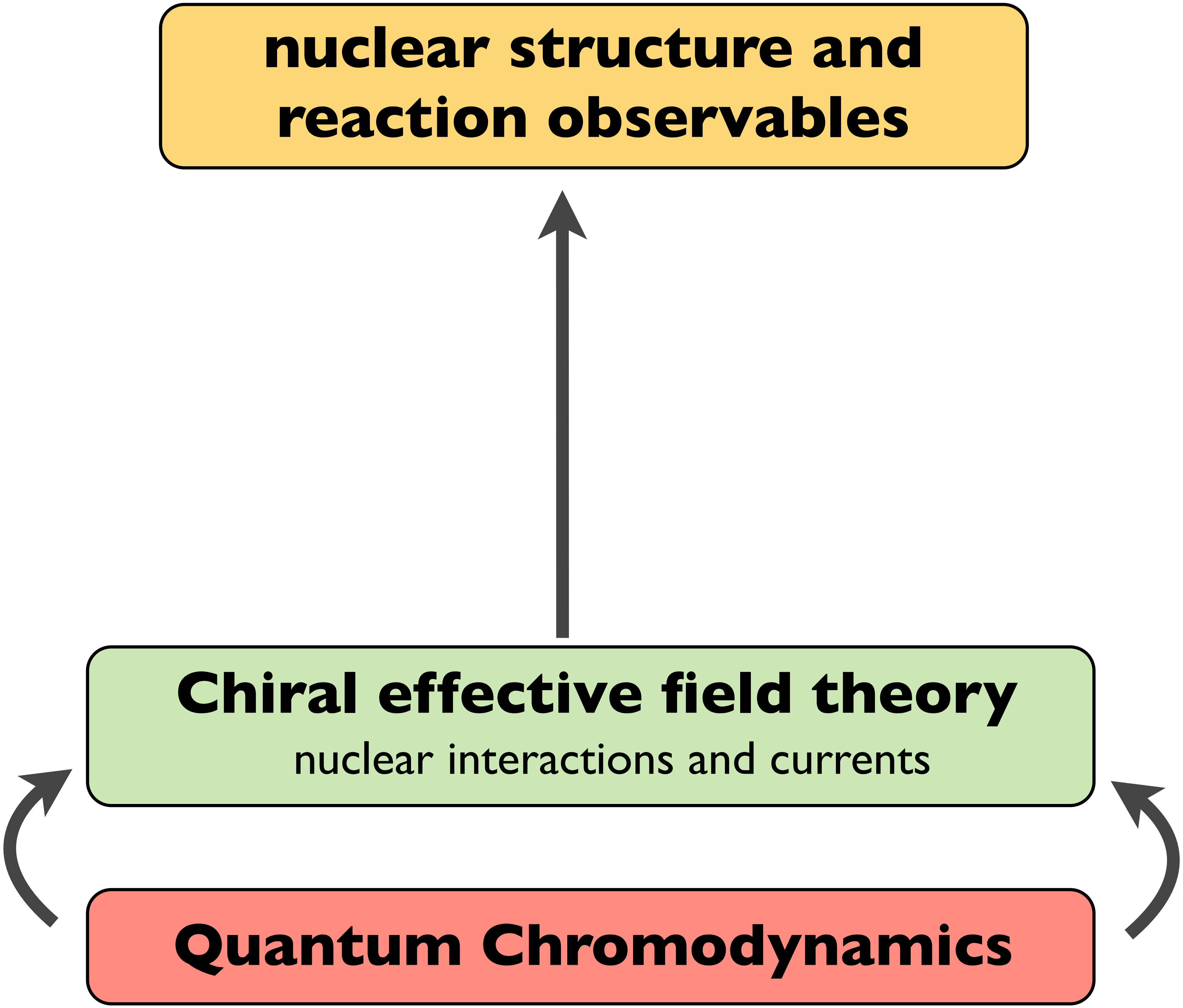
↑

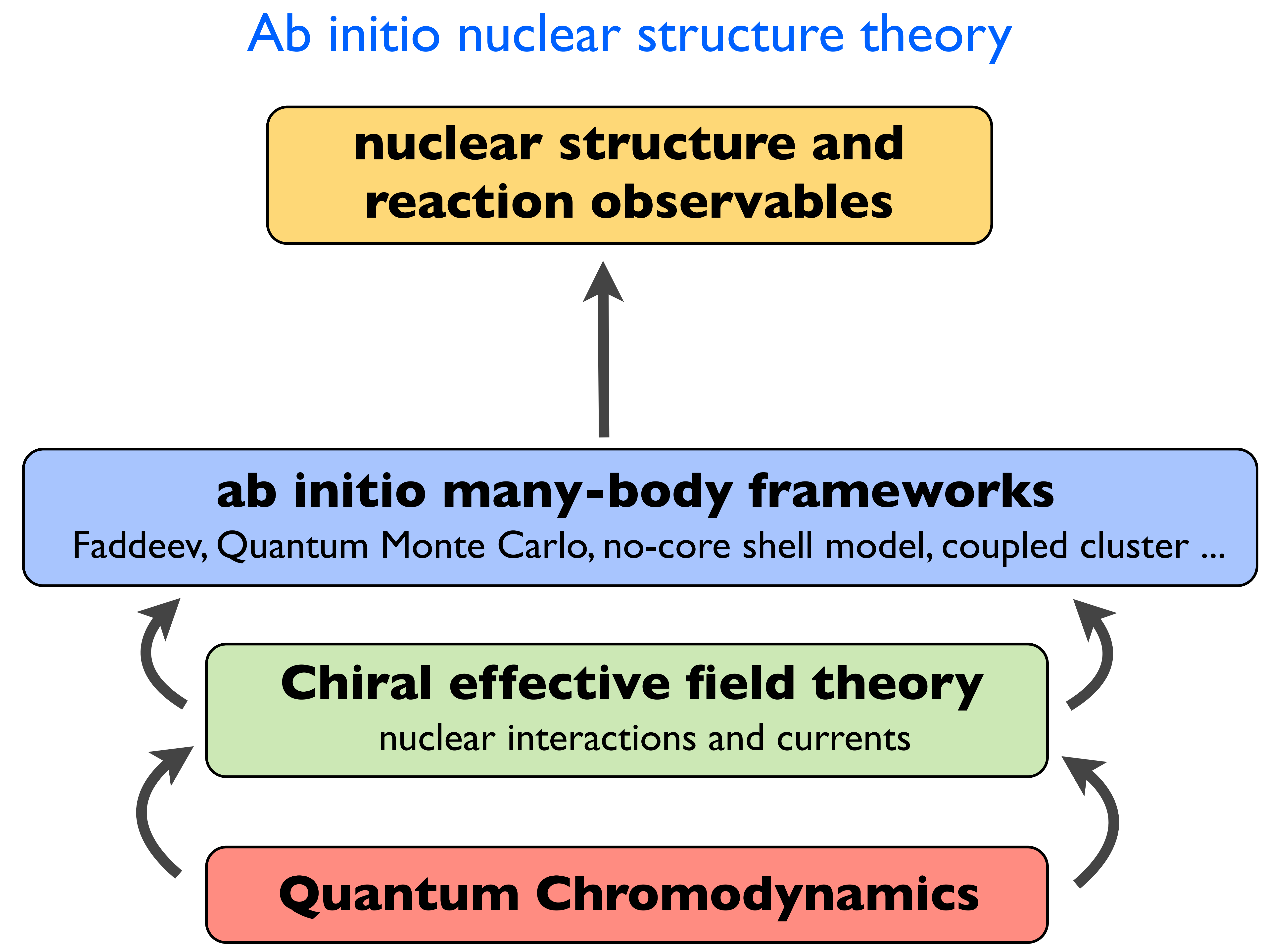
Lattice QCD

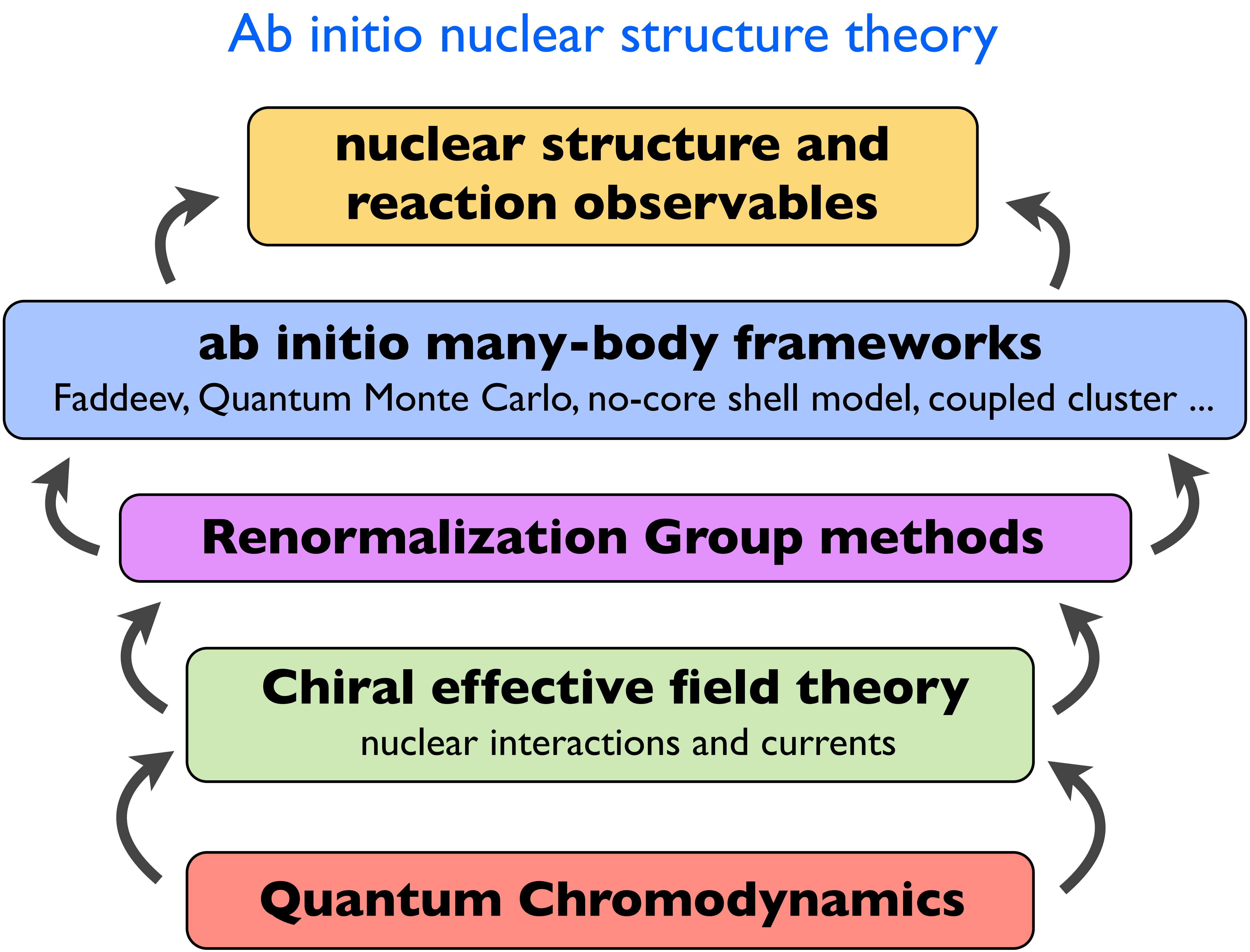
- requires extreme amounts of computational resources
- currently limited to 1- or 2-nucleon systems
- current accuracy insufficient for precision nuclear structure

Quantum Chromodynamics

Ab initio nuclear structure theory




Ab initio nuclear structure theory
nuclear structure and reaction observables
ab initio many-body frameworks
Faddeev, Quantum Monte Carlo, no-core shell model, coupled cluster ...
Chiral effective field theory
nuclear interactions and currents
Quantum Chromodynamics


Ab initio nuclear structure theory
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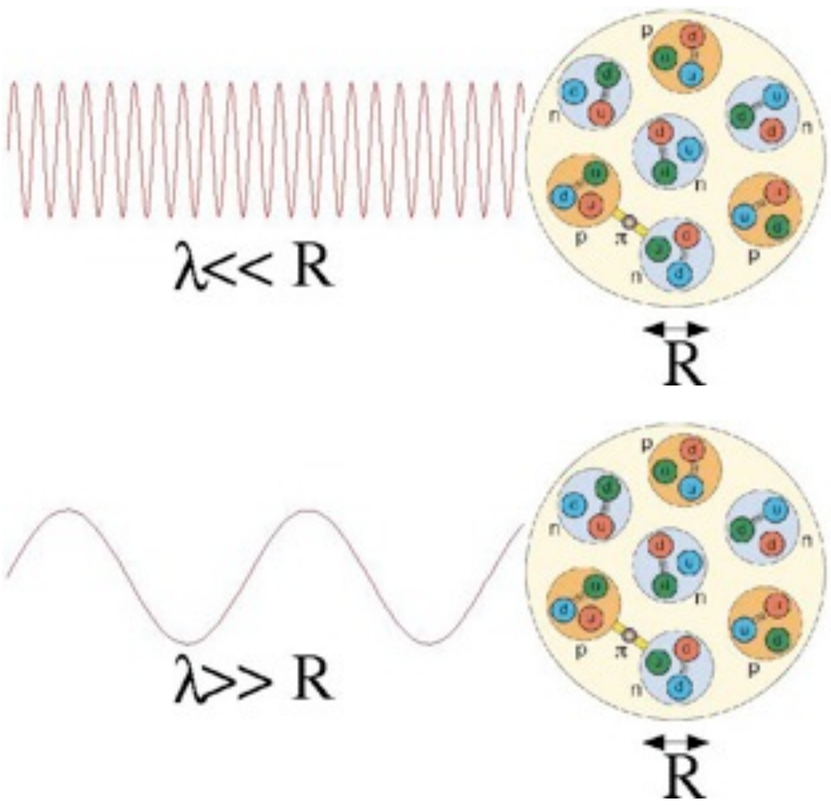
ab initio many-body frameworks
Faddeev, Quantum Monte Carlo, no-core shell model, coupled cluster ...
Renormalization Group methods
Chiral effective field theory
nuclear interactions and currents
Quantum Chromodynamics

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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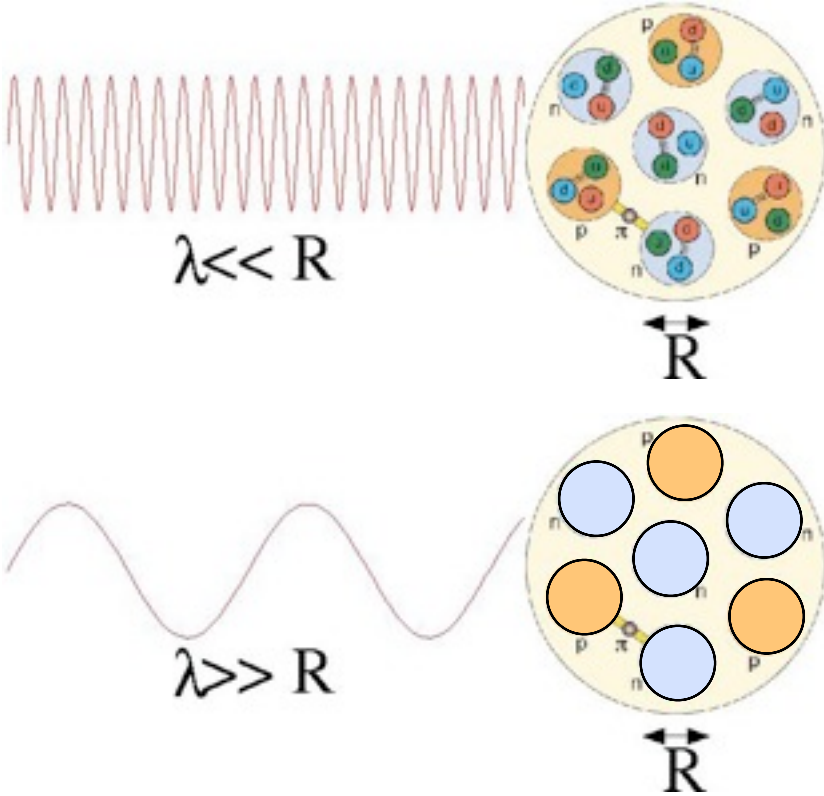
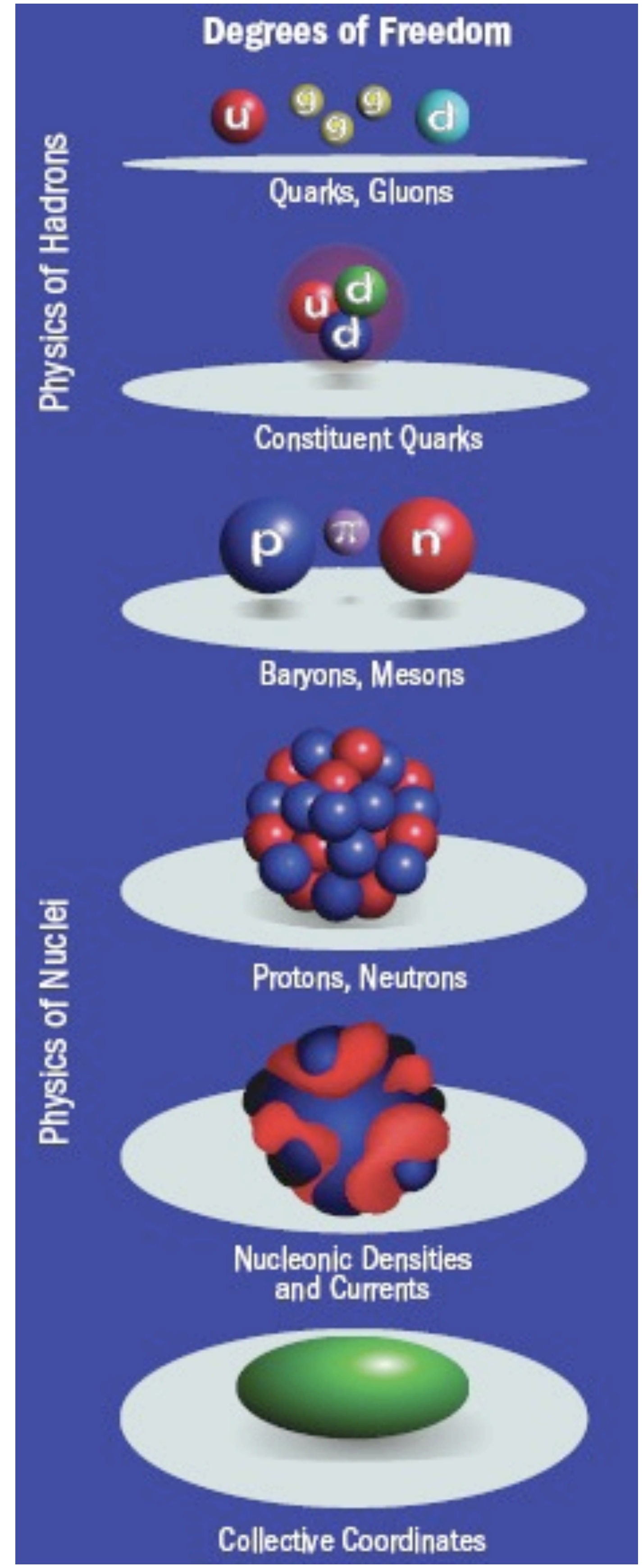




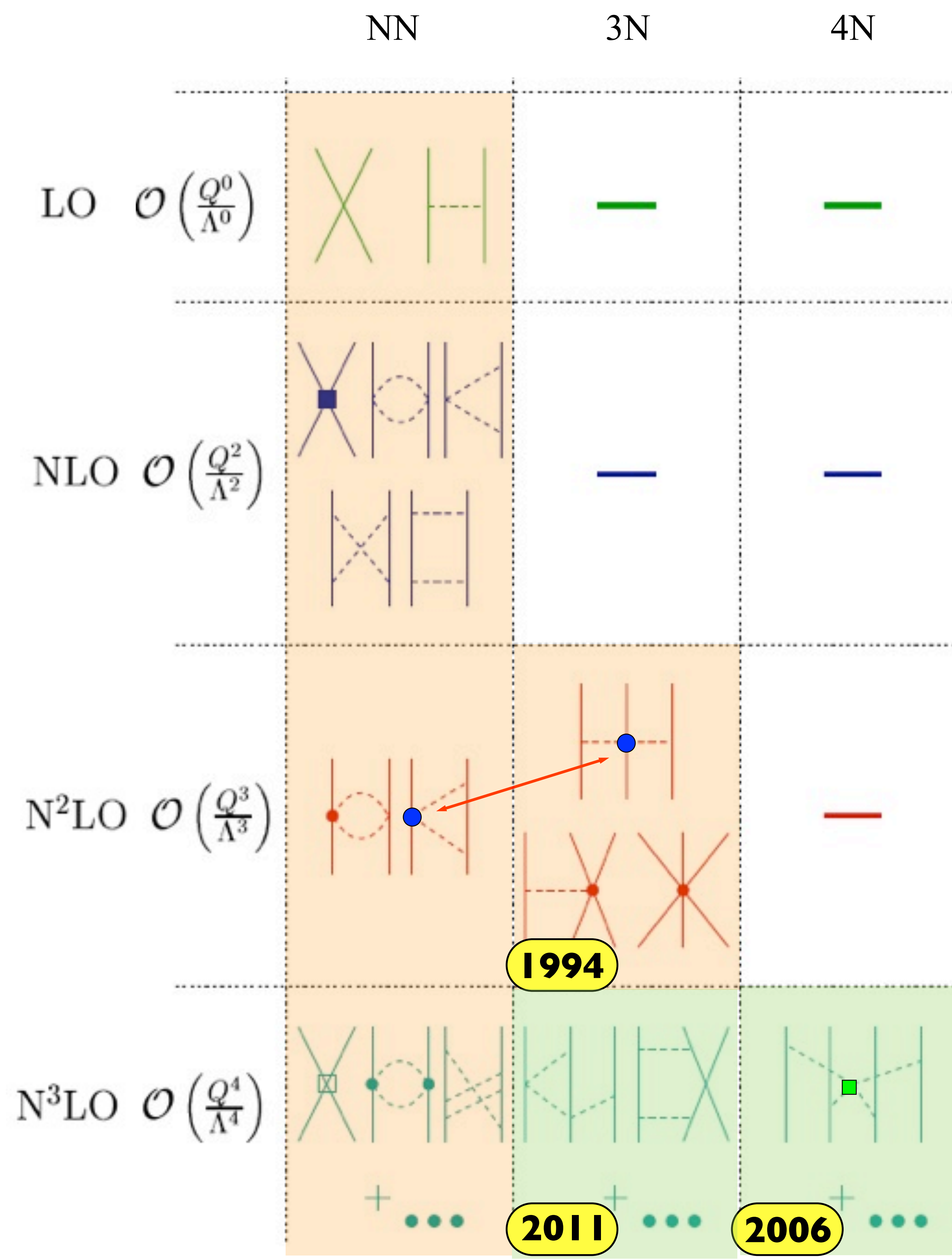
Resolution ↓

- 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 (like multipole expansion), low-energy observables unchanged

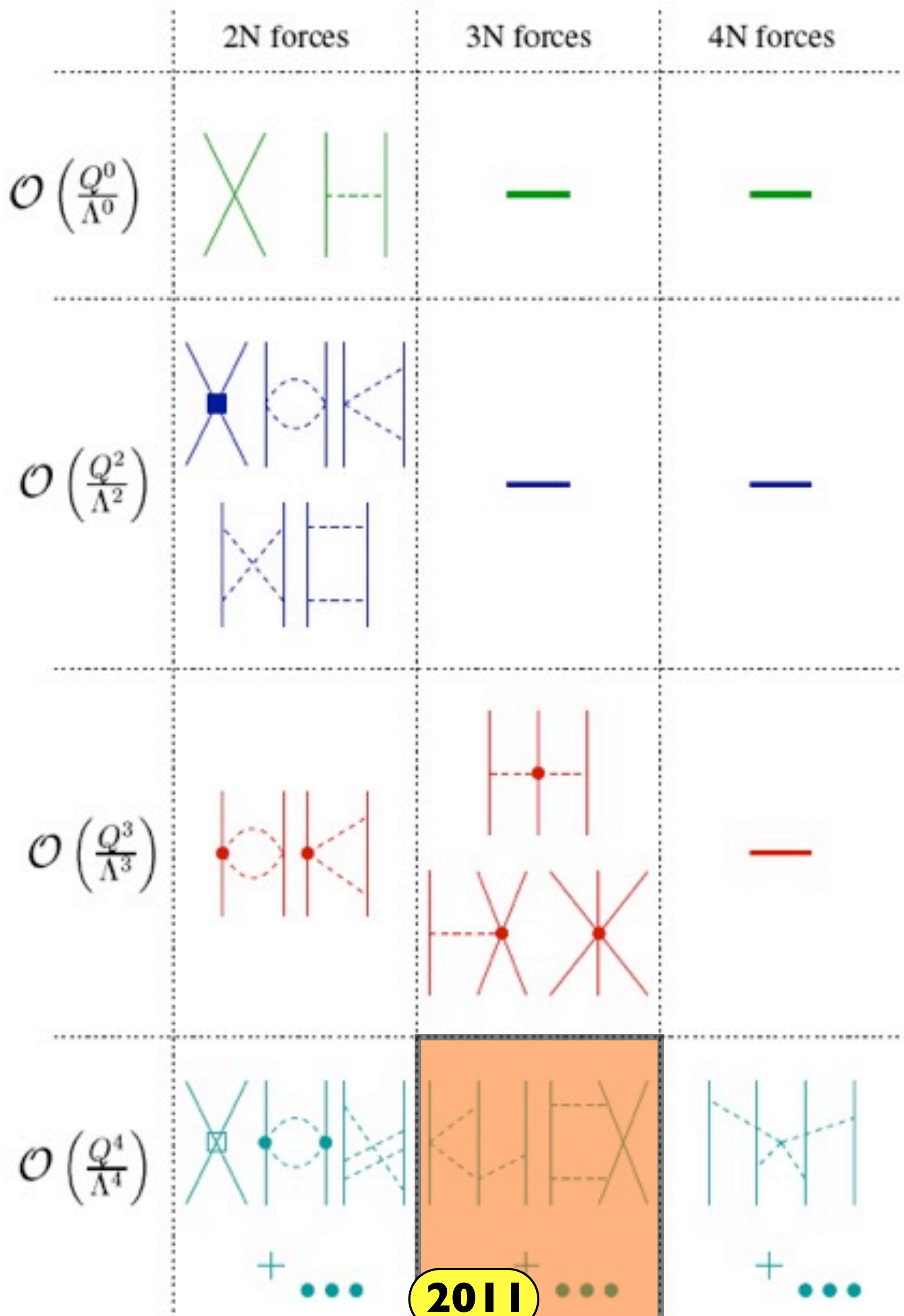
→ effective field theory

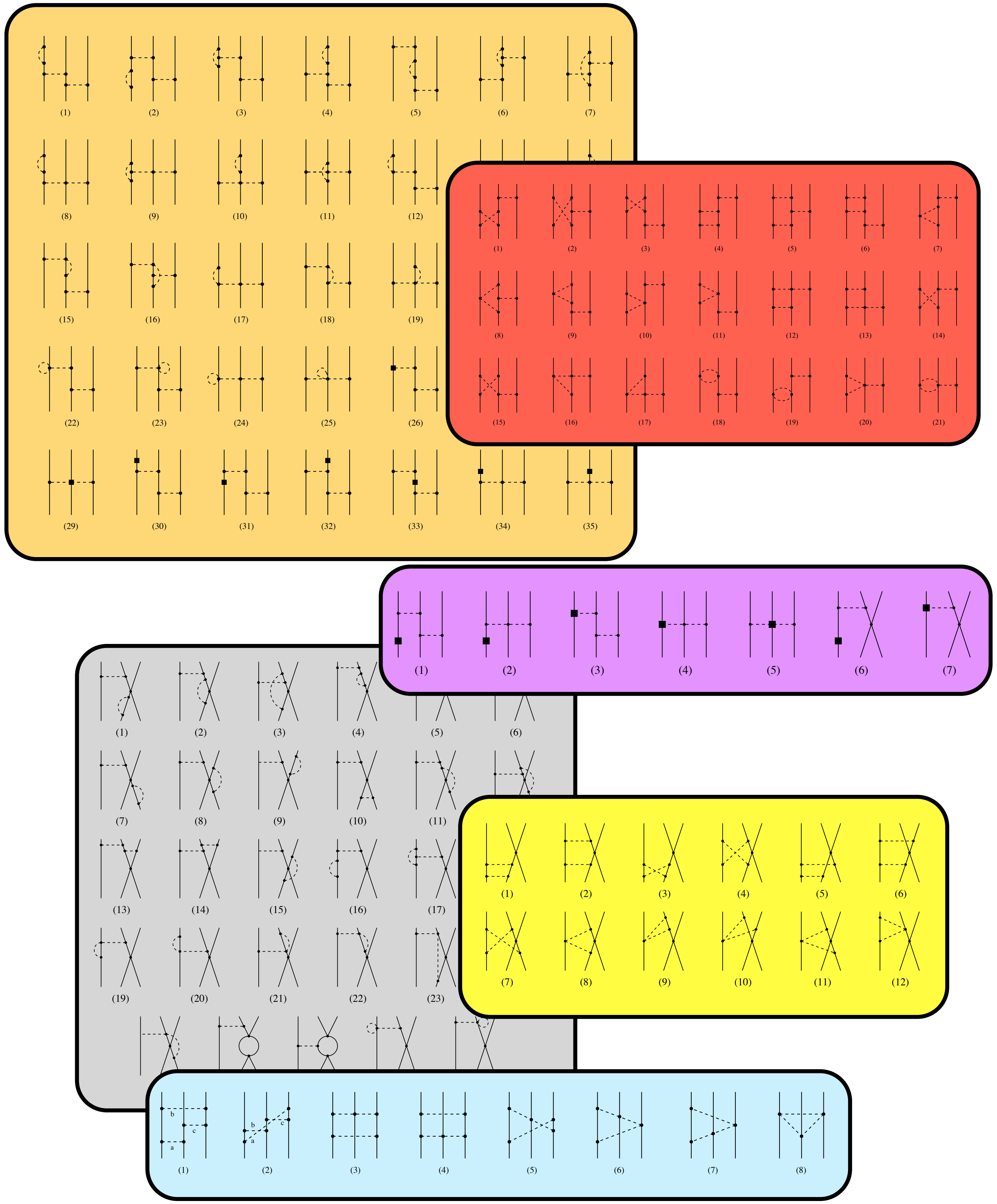
Chiral effective field theory for nuclear forces

- choose relevant degrees of freedom: here nucleons and pions
- operators constrained by symmetries of QCD
- short-range physics captured in few short-range couplings
- separation of scales: $Q << \Lambda_b$, breakdown scale Λ_b~500 MeV
- power-counting: expand in powers Q/Λ_b
- systematic: work to desired accuracy, obtain error estimates



Chiral 3N forces at subleading order (N^3LO)





Bernard et al., PRC 77, 064004 (2008)
Bernard et al., PRC 84, 054001 (2011)

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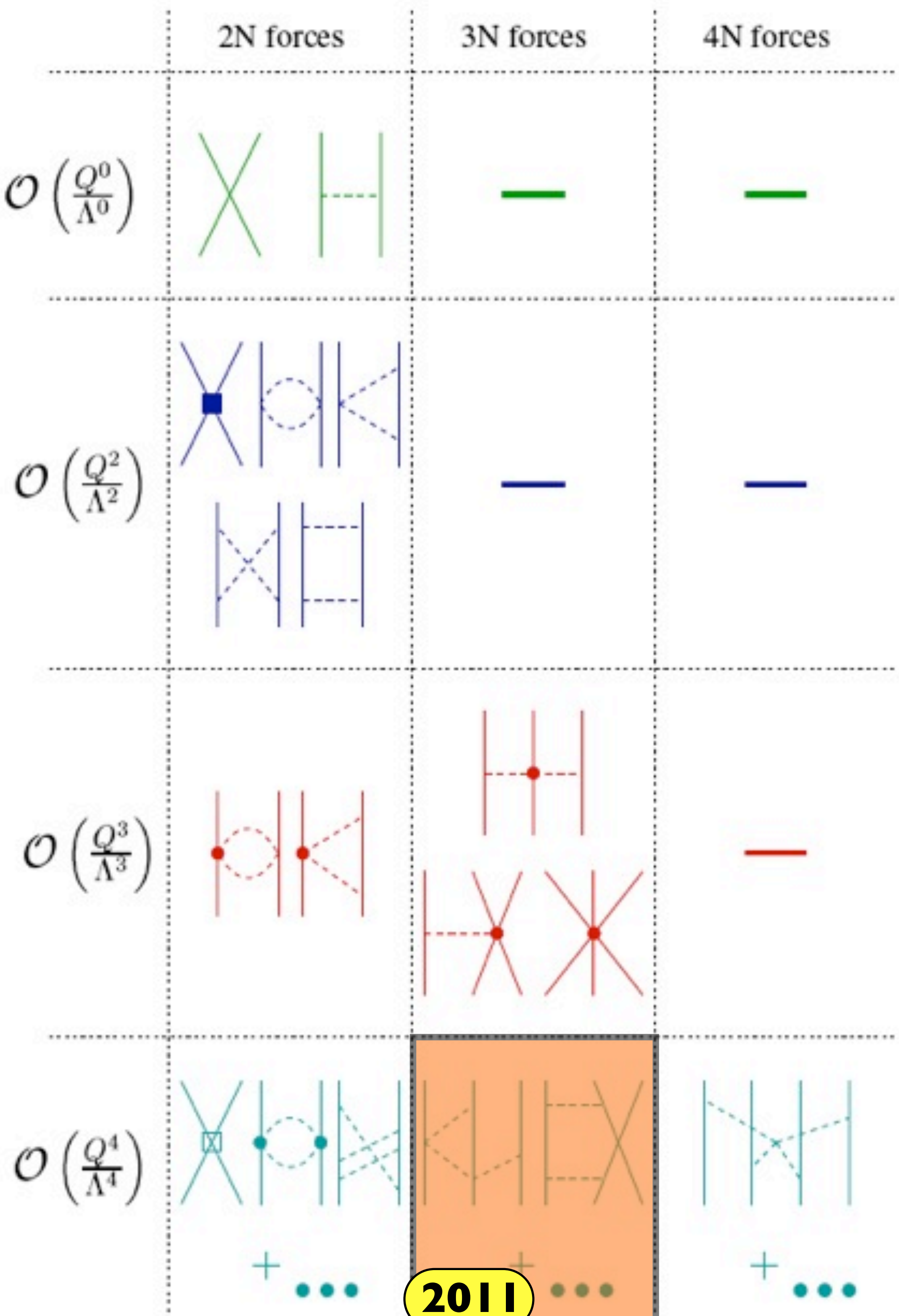
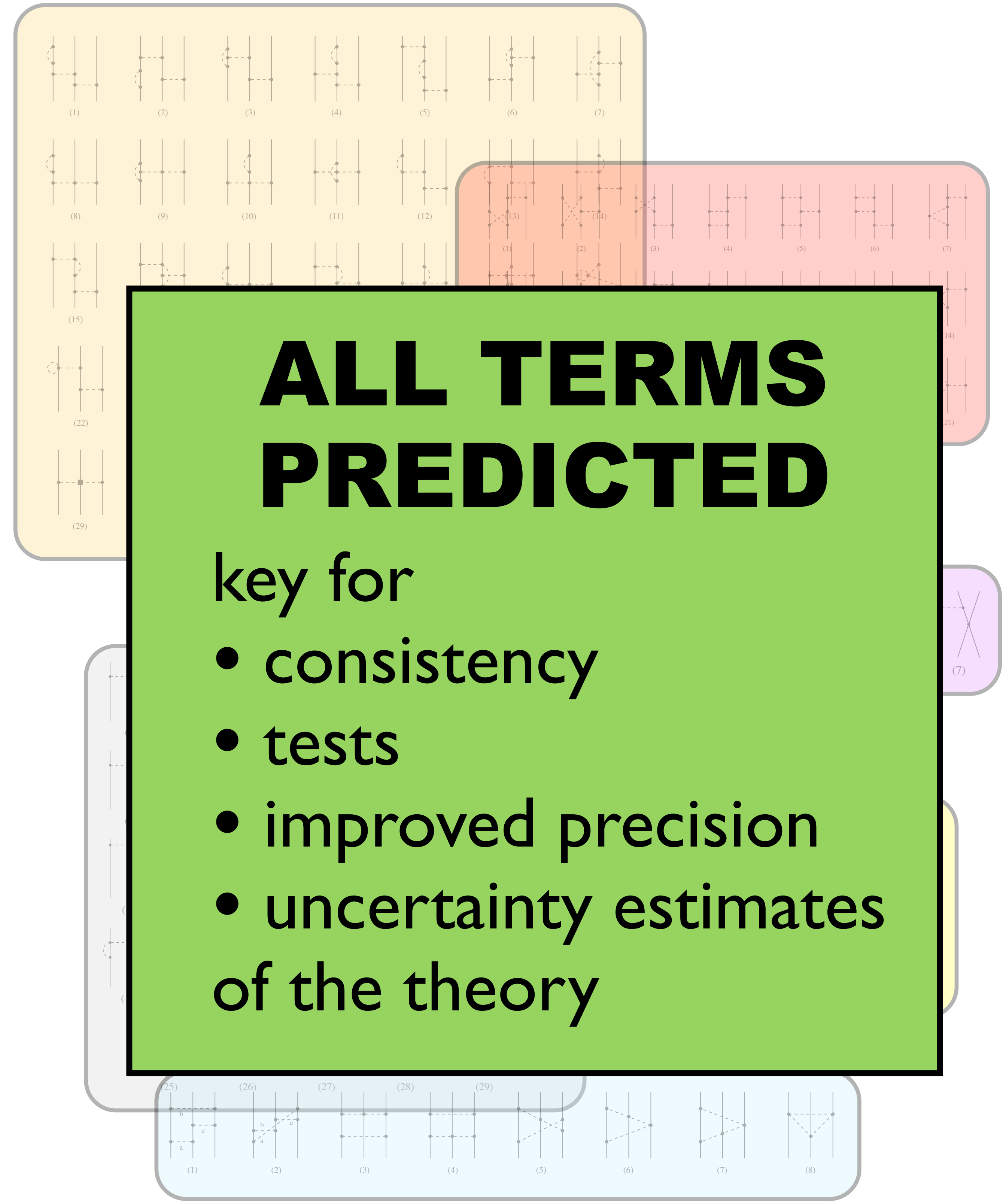




ALL TERMS PREDICTED

key for
- consistency
- tests
- improved precision
- uncertainty estimates

of the theory

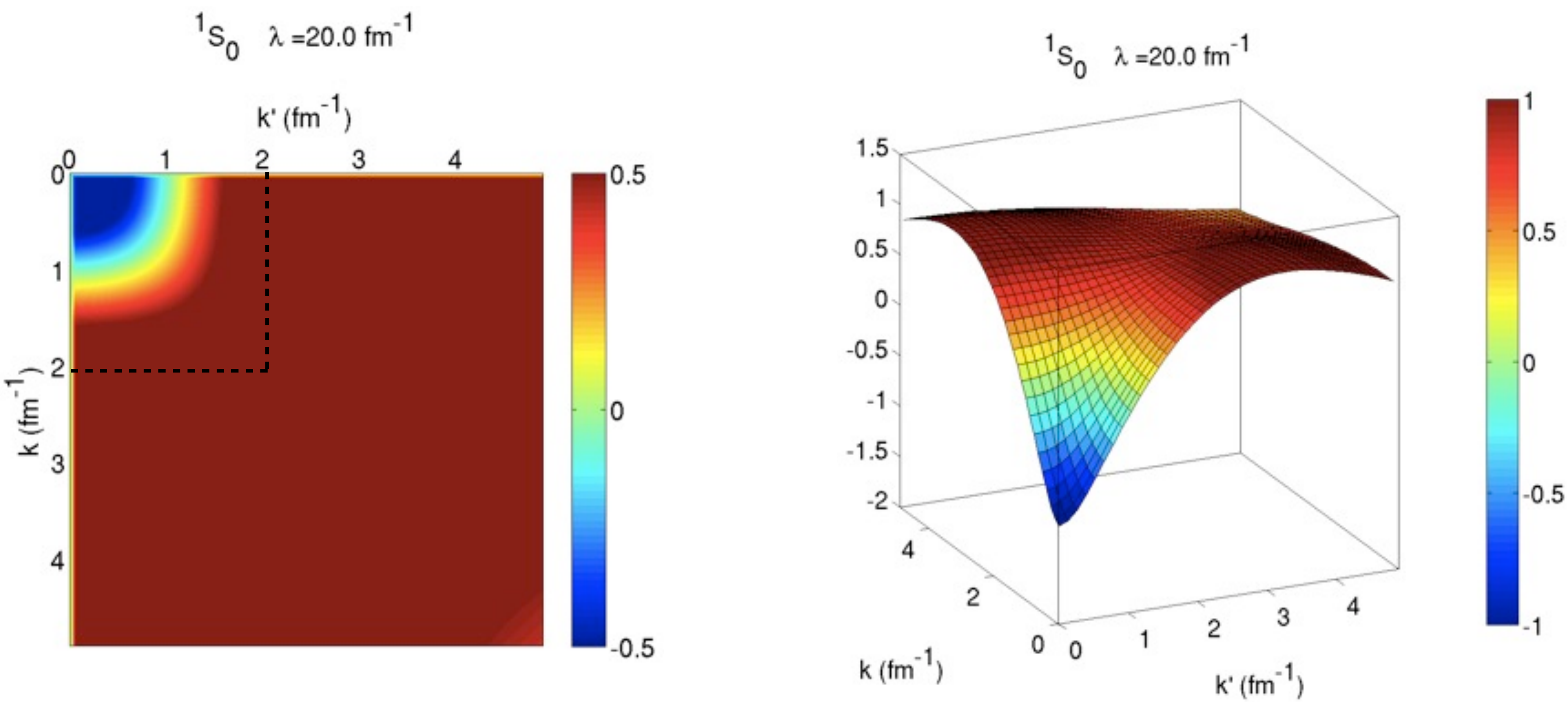
Bernard et al., PRC 77, 064004 (2008)
Bernard et al., PRC 84, 054001 (2011)

The Similarity Renormalization Group

- generate unitary transformation which decouples low- and high momenta

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

- basic idea: change resolution successively in small steps: $\frac{dH_\lambda}{d\lambda} = [\eta_\lambda, H_\lambda]$
- generator η_λ can be chosen and tailored to different applications
- observables are preserved due to unitarity of transformation



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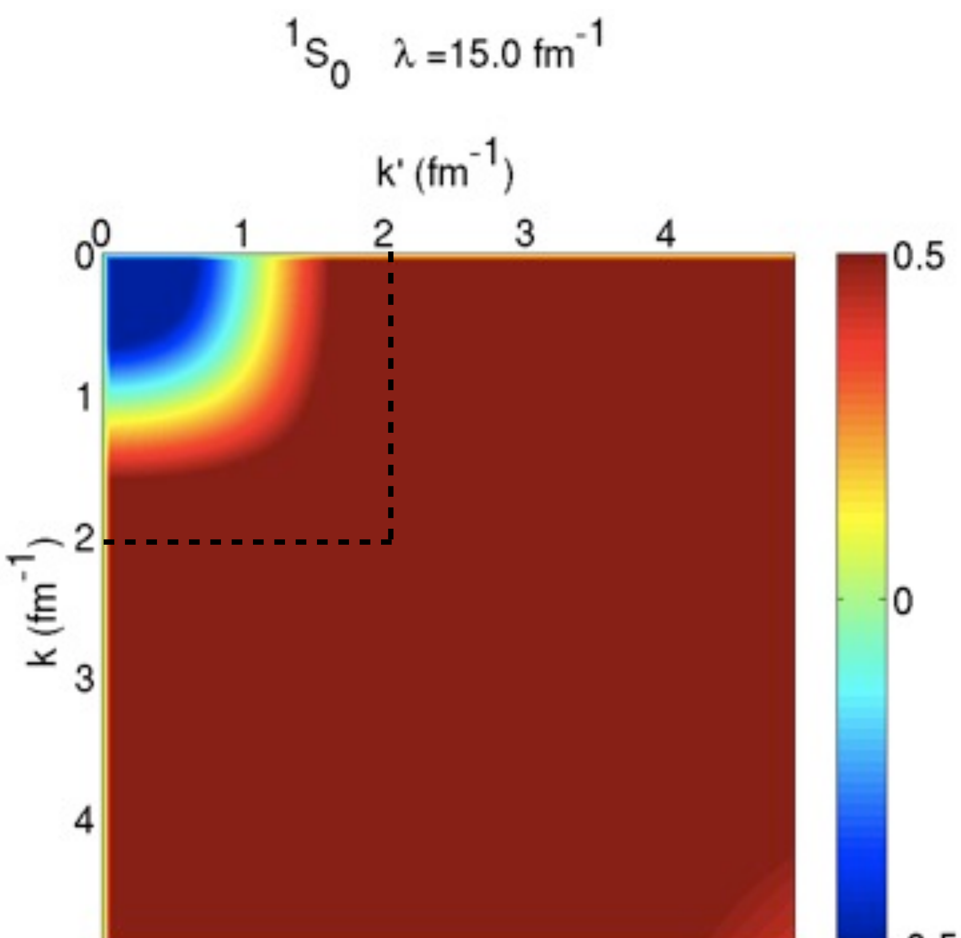

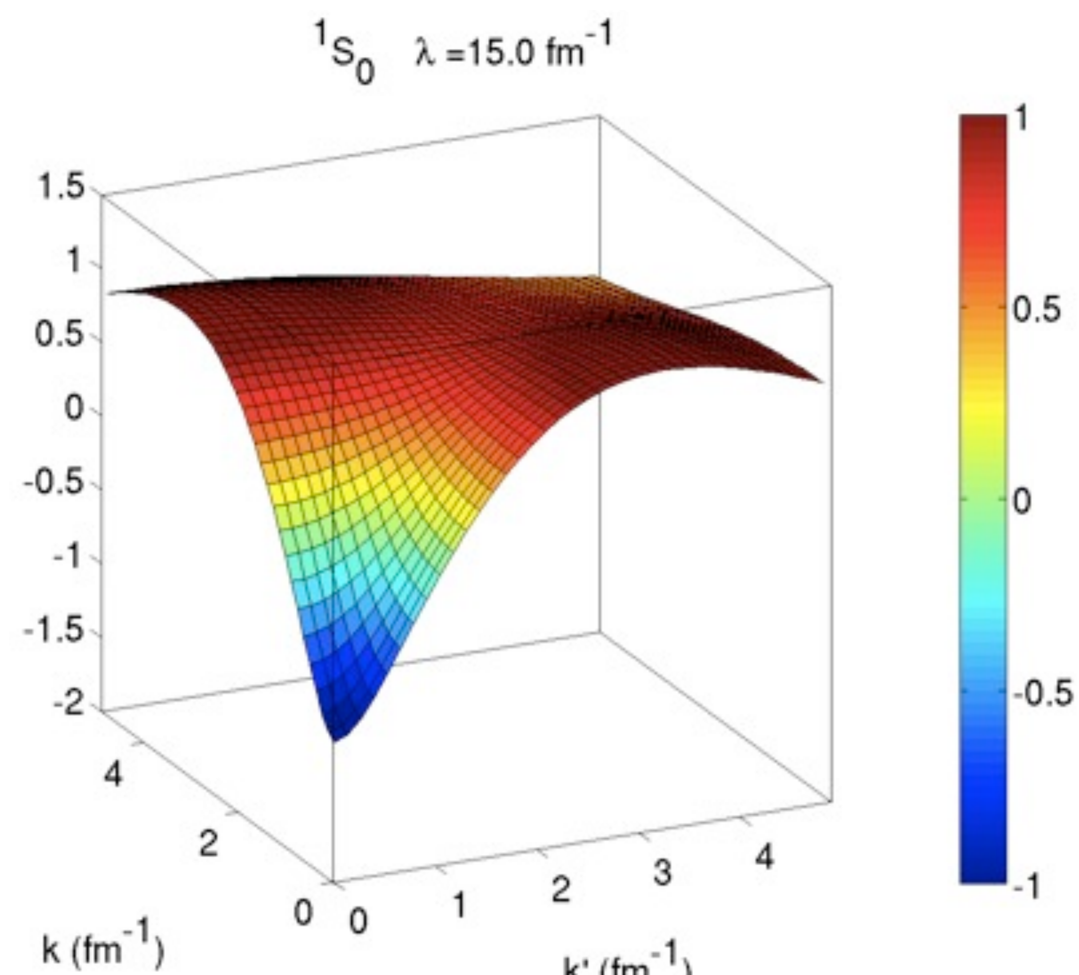

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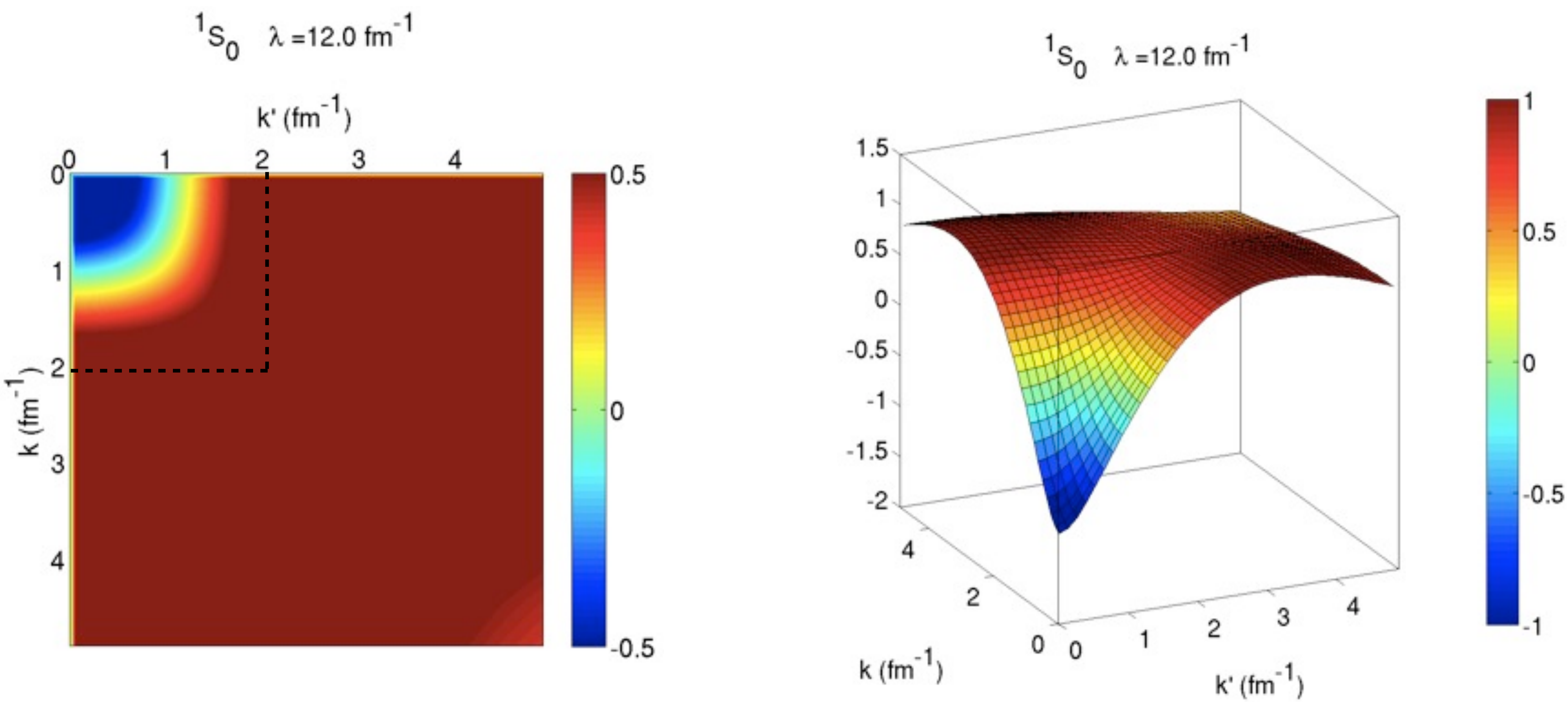

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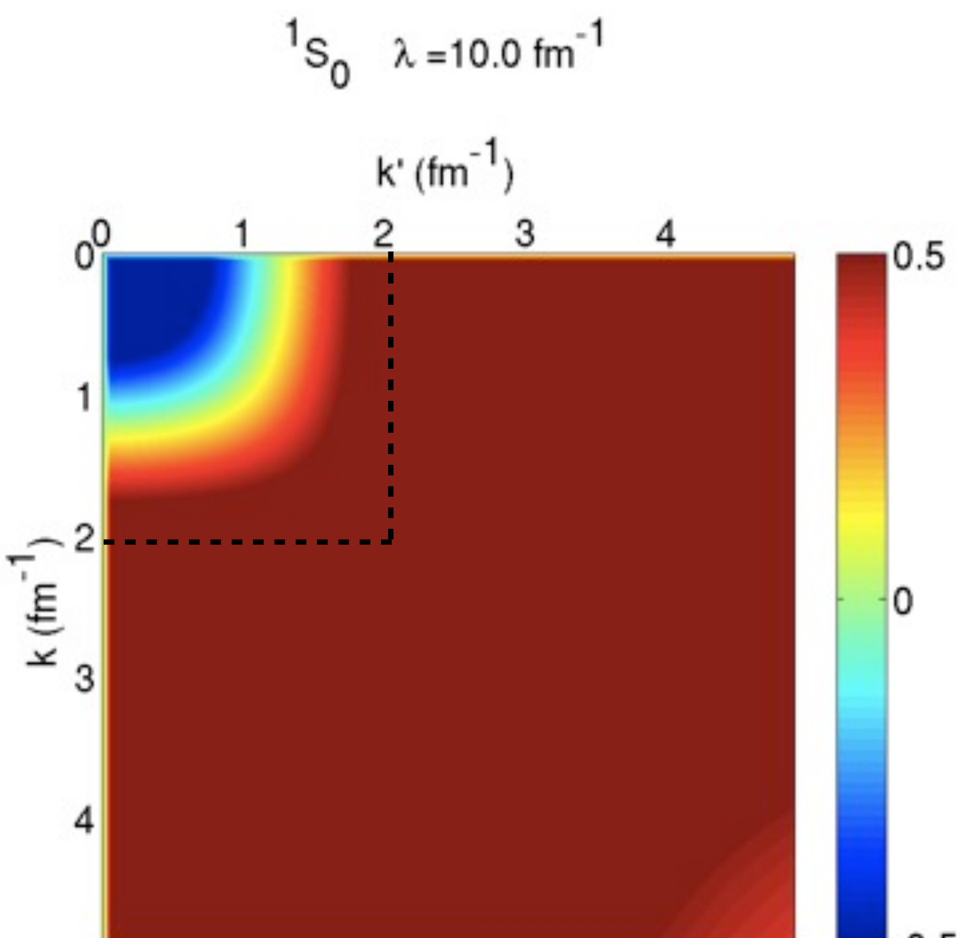

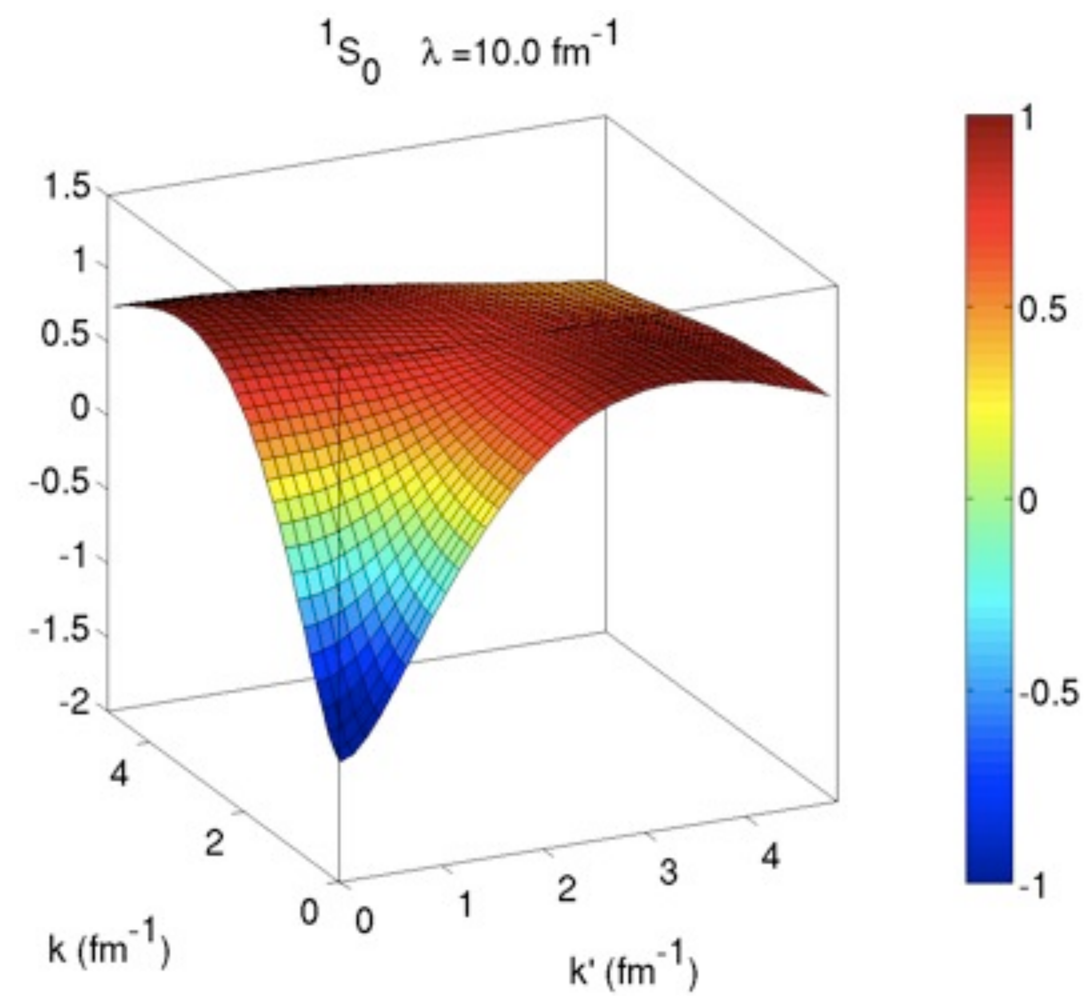

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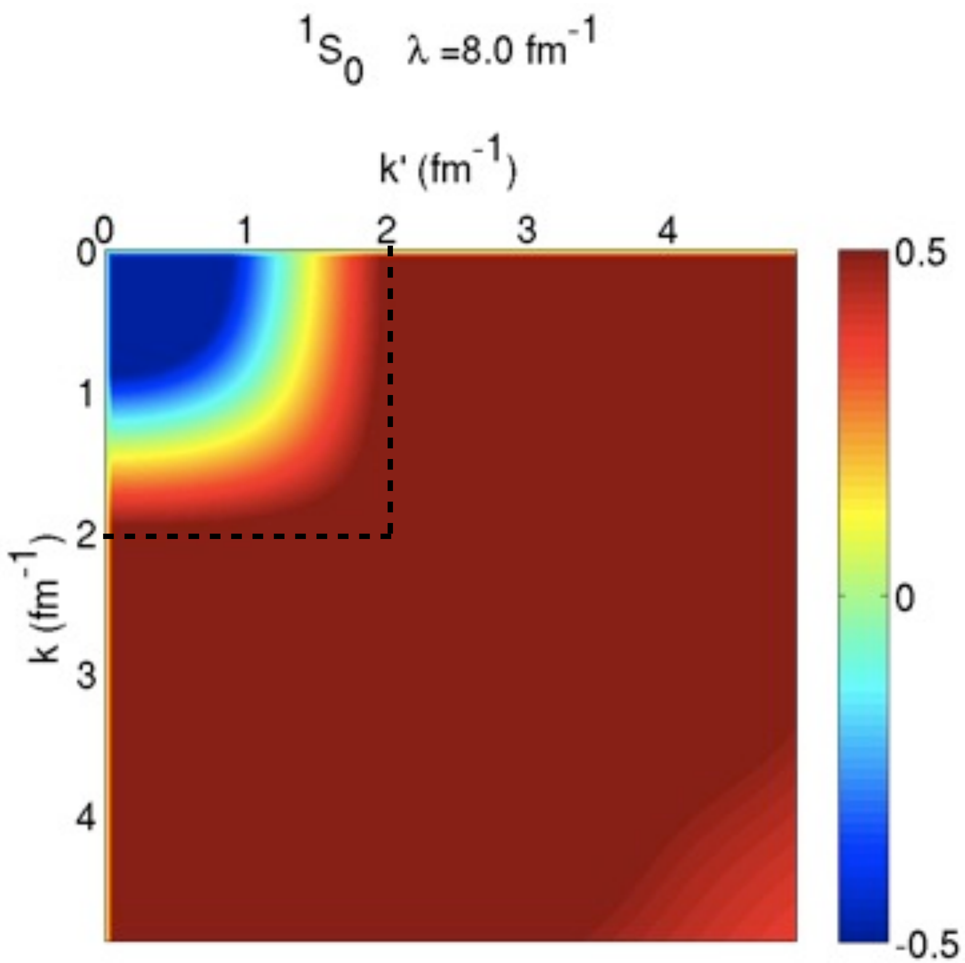

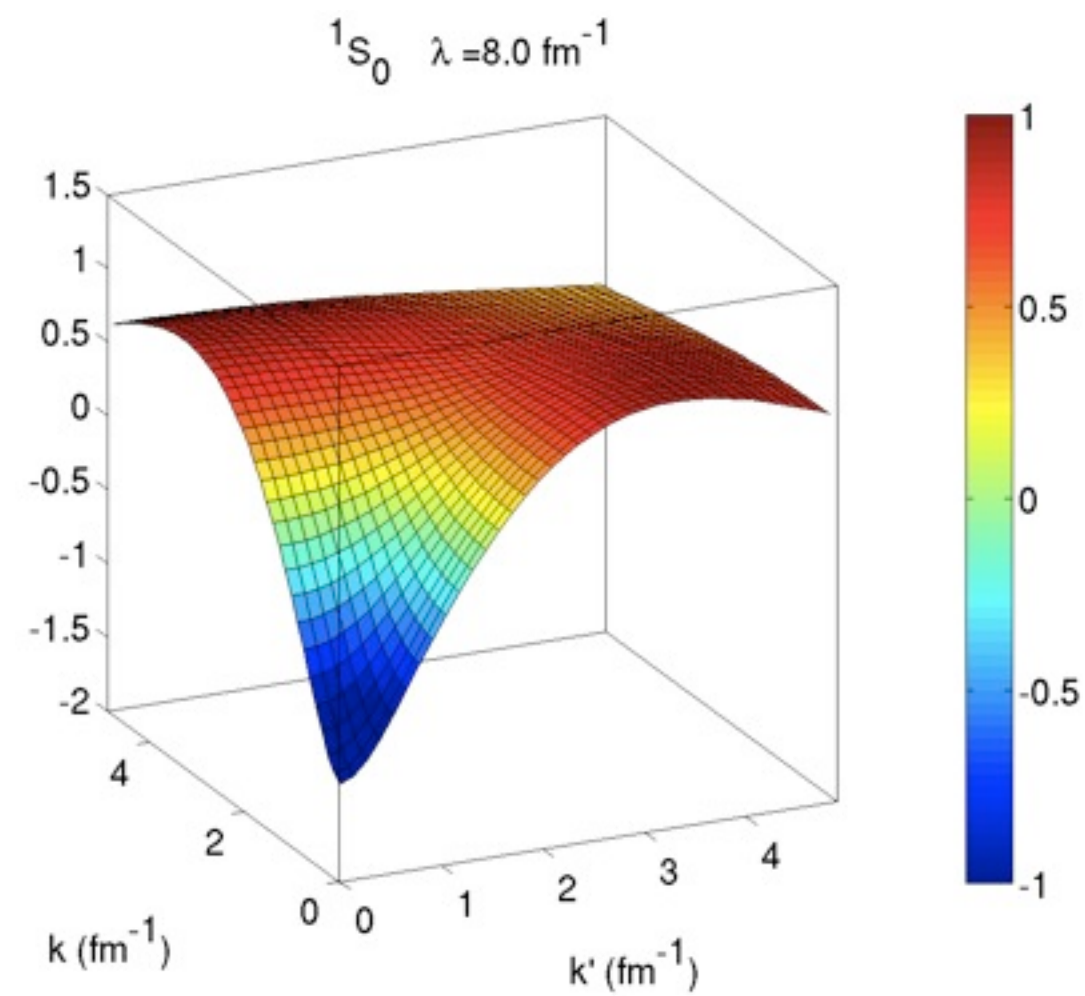

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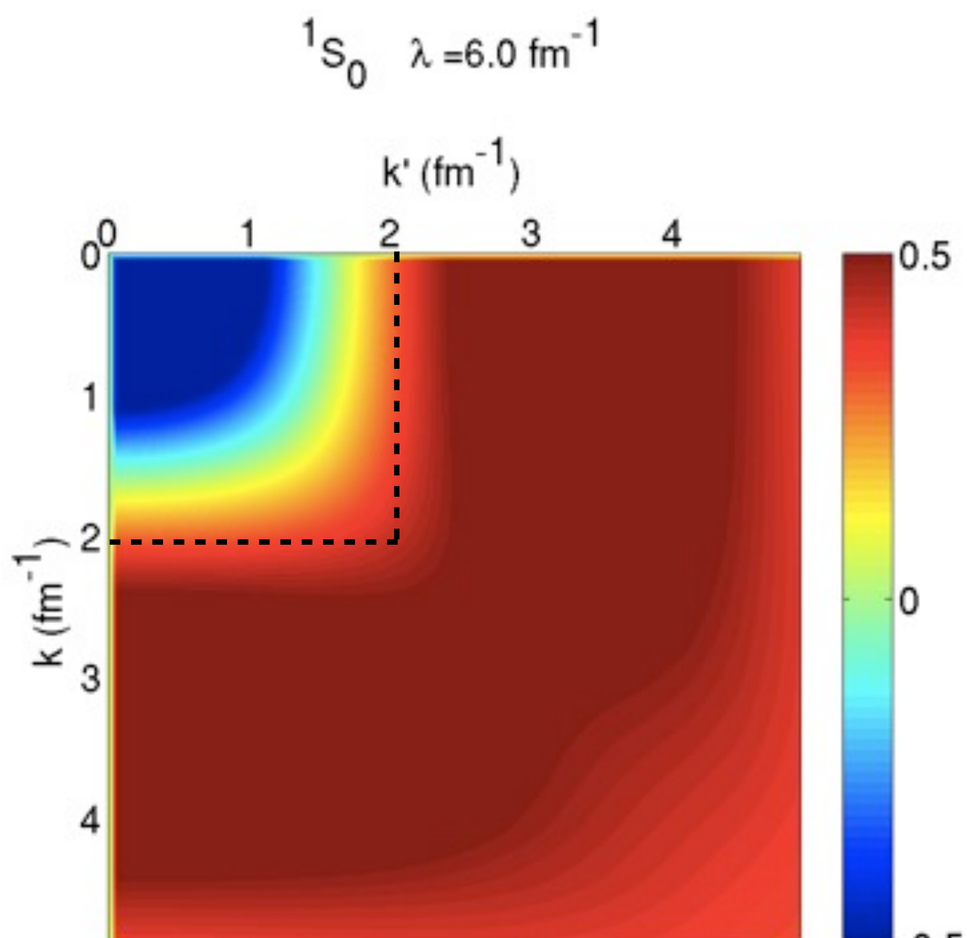

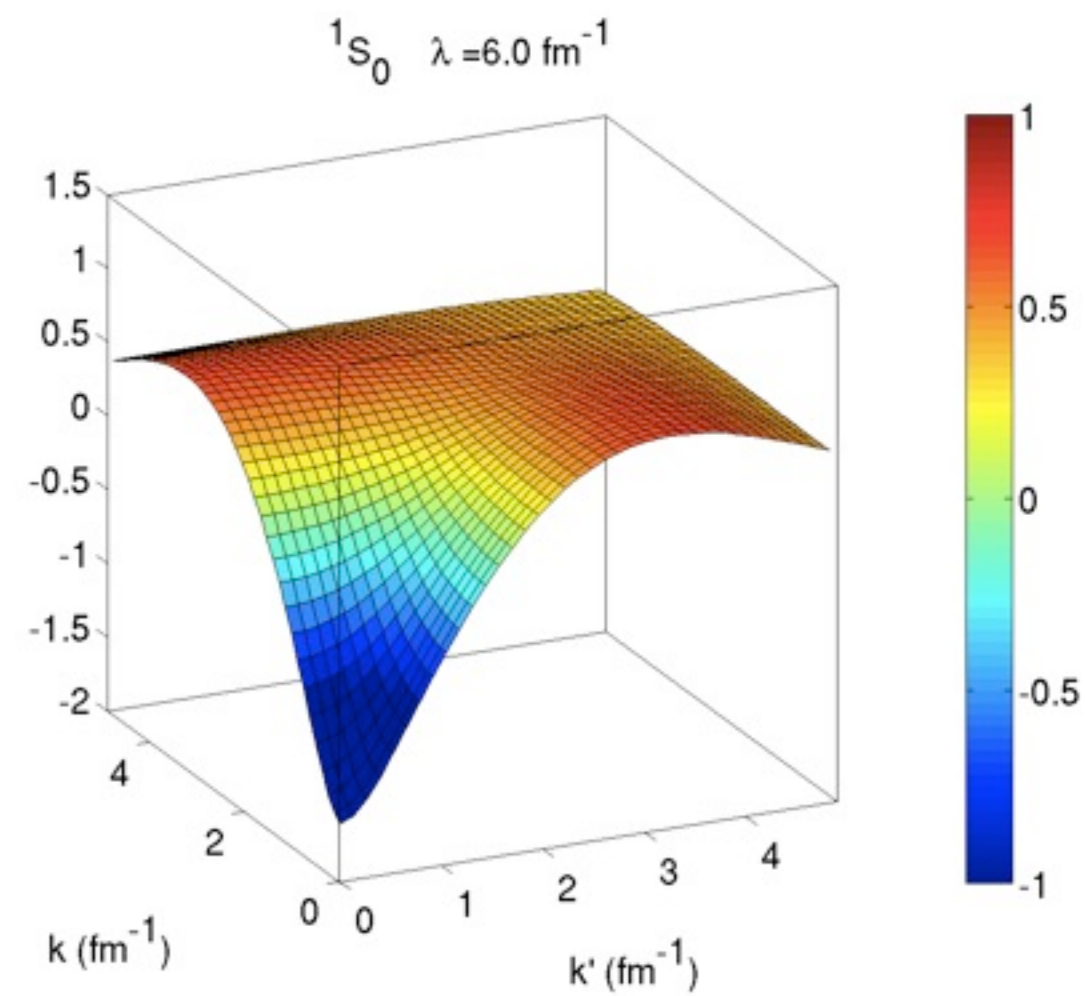

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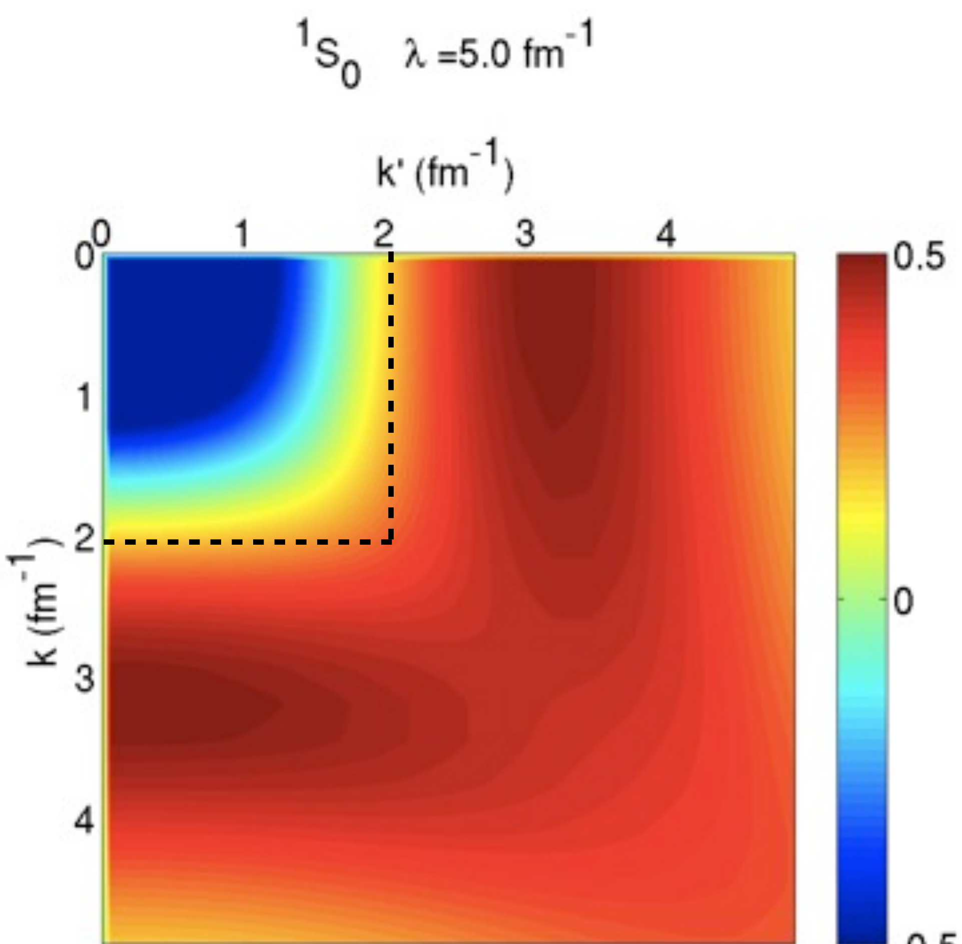

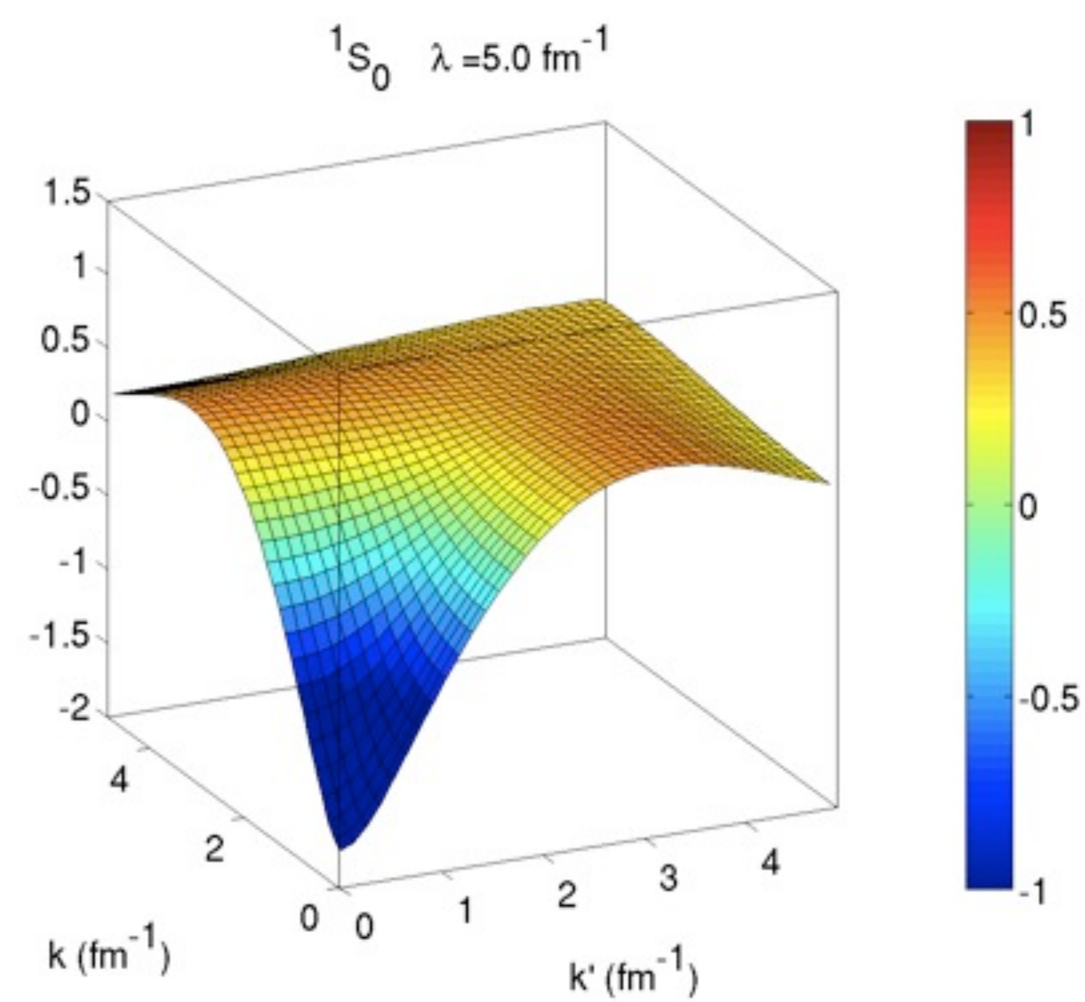

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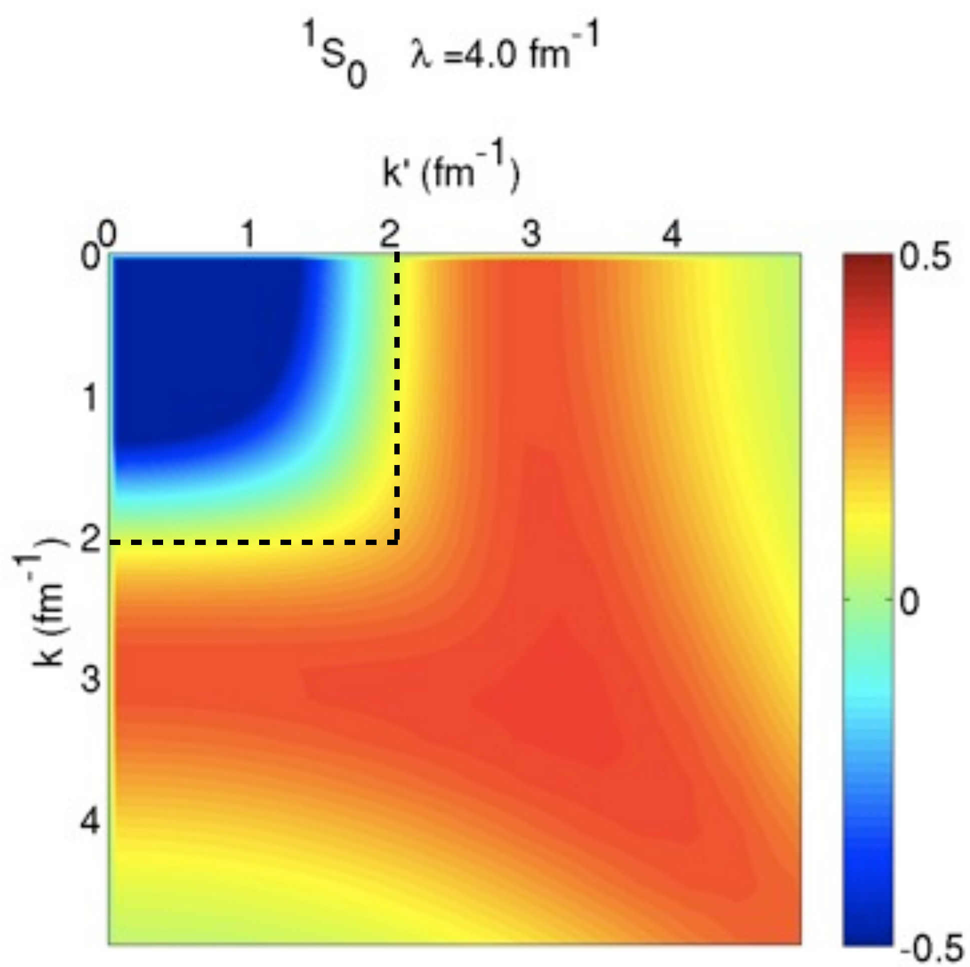

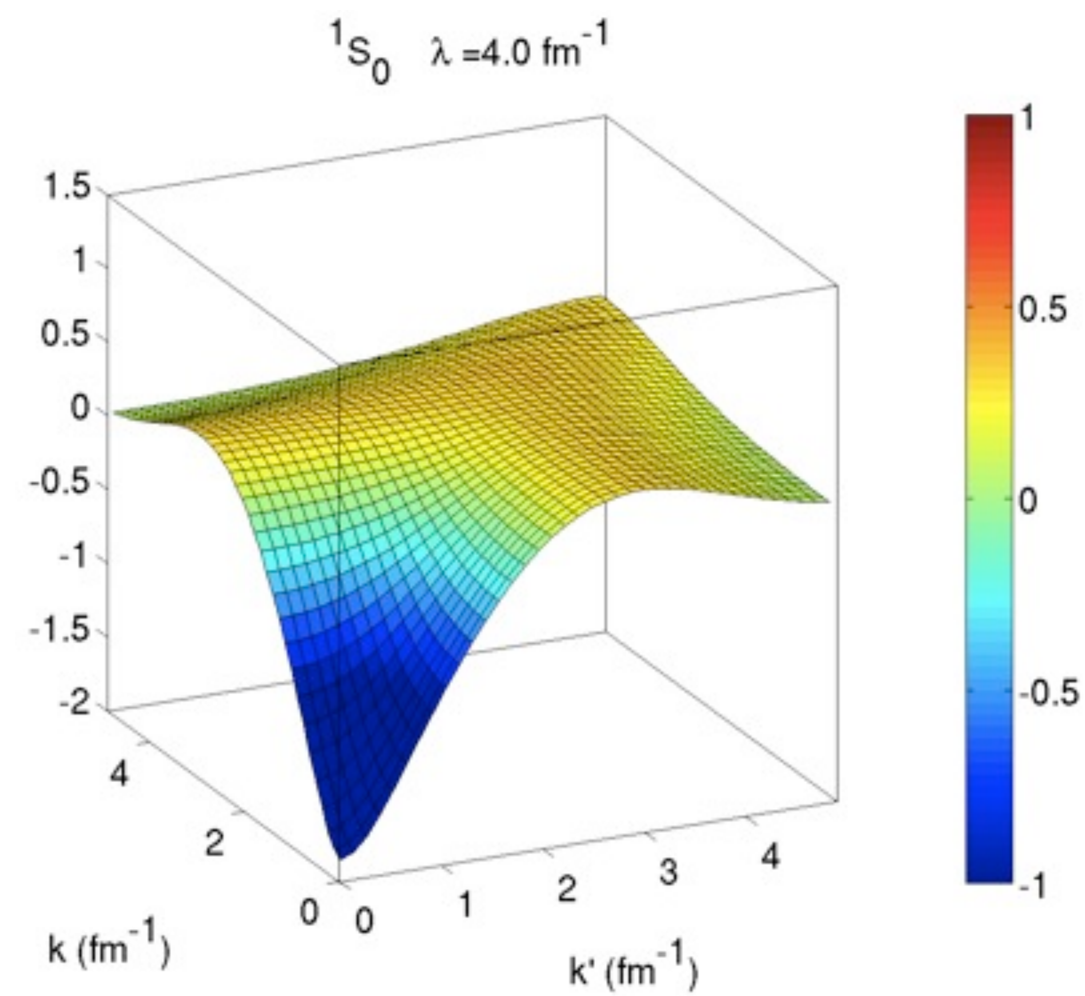

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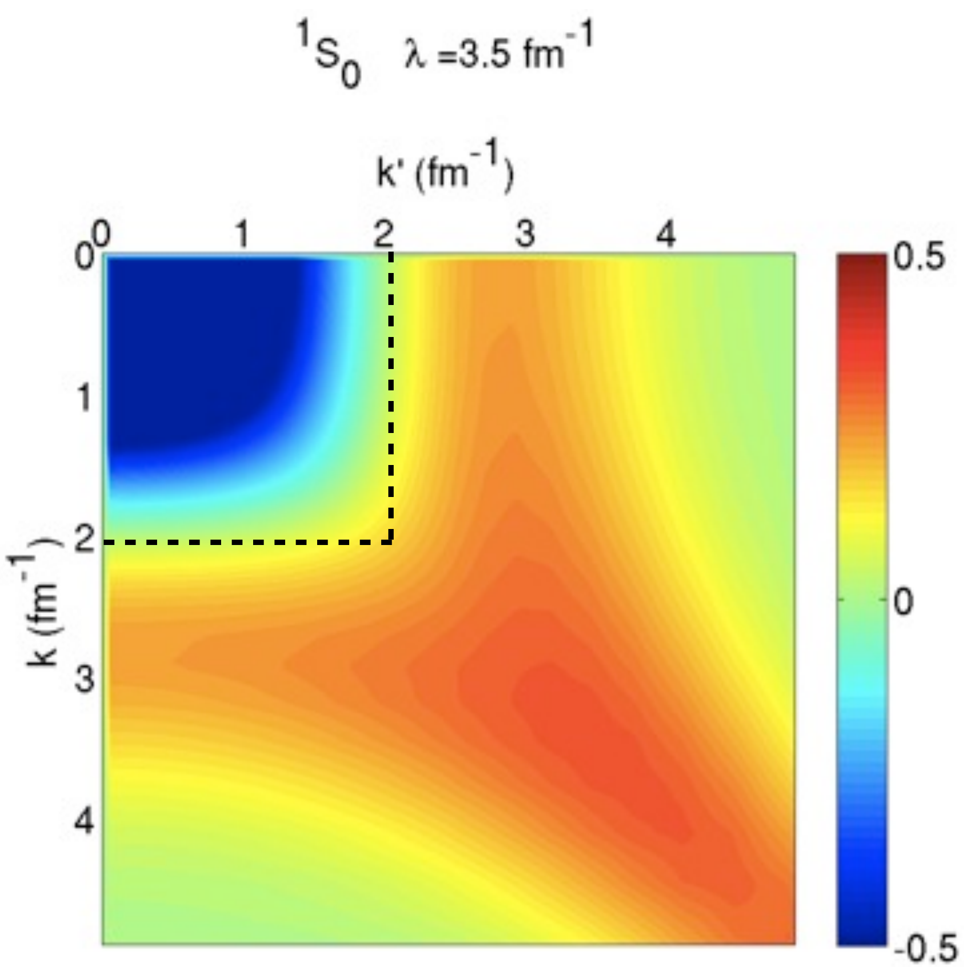

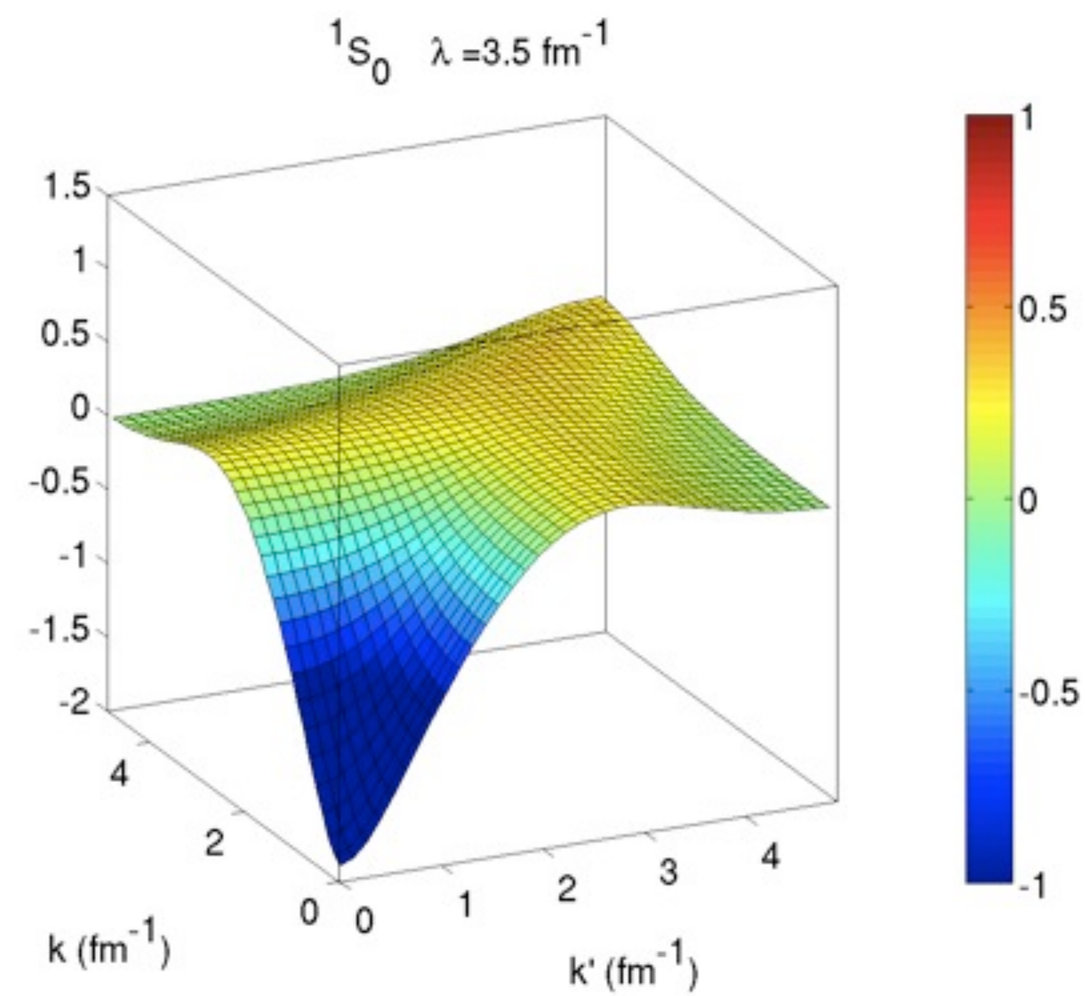

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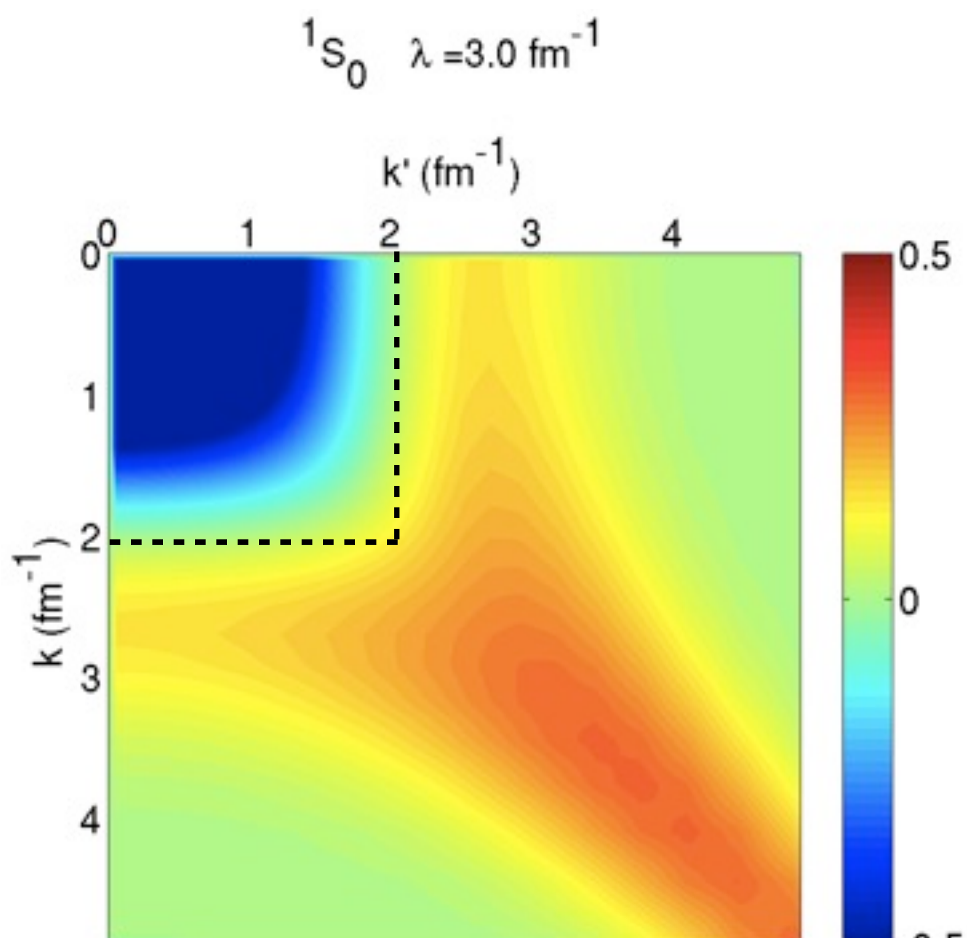

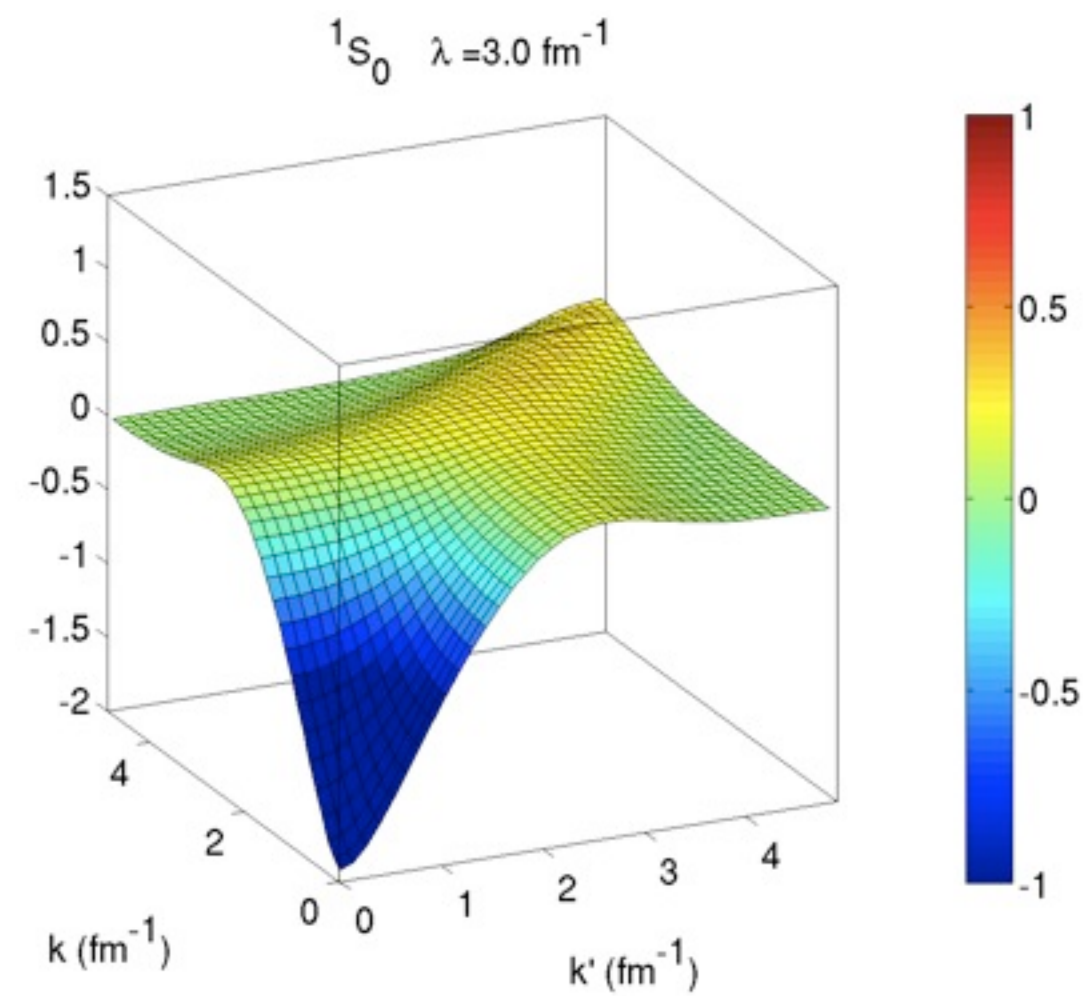

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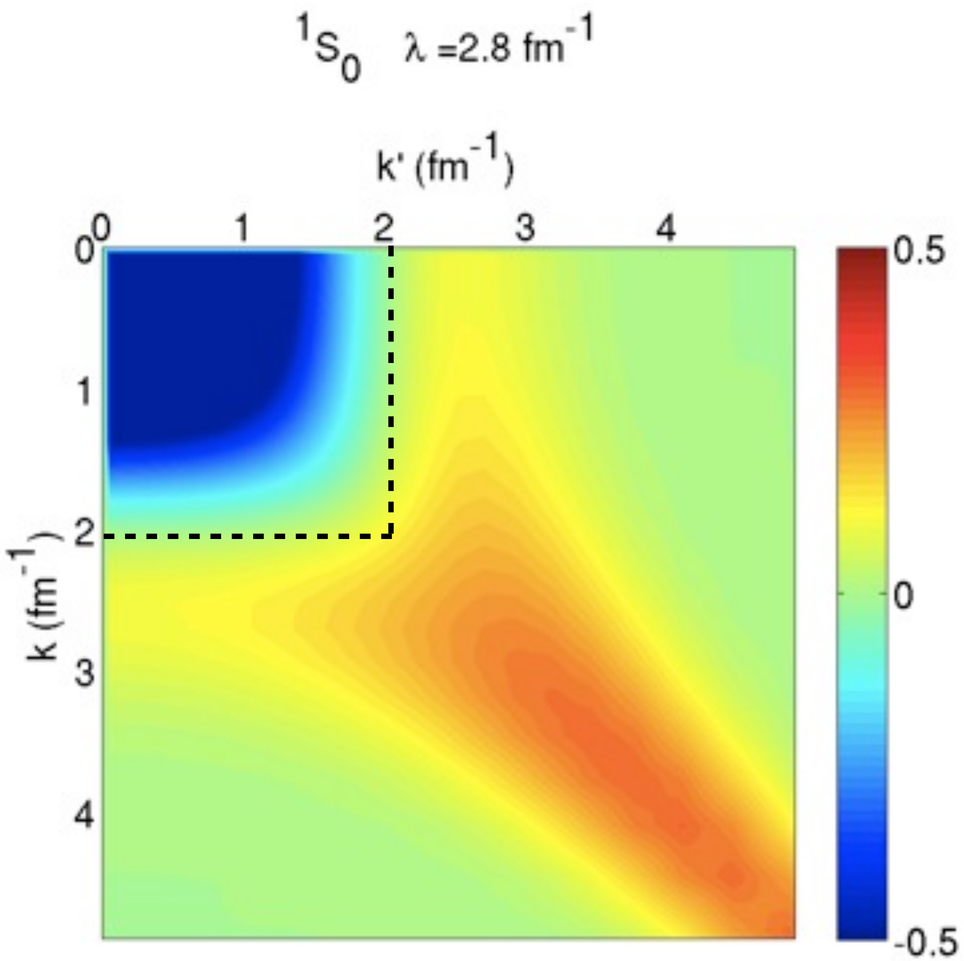

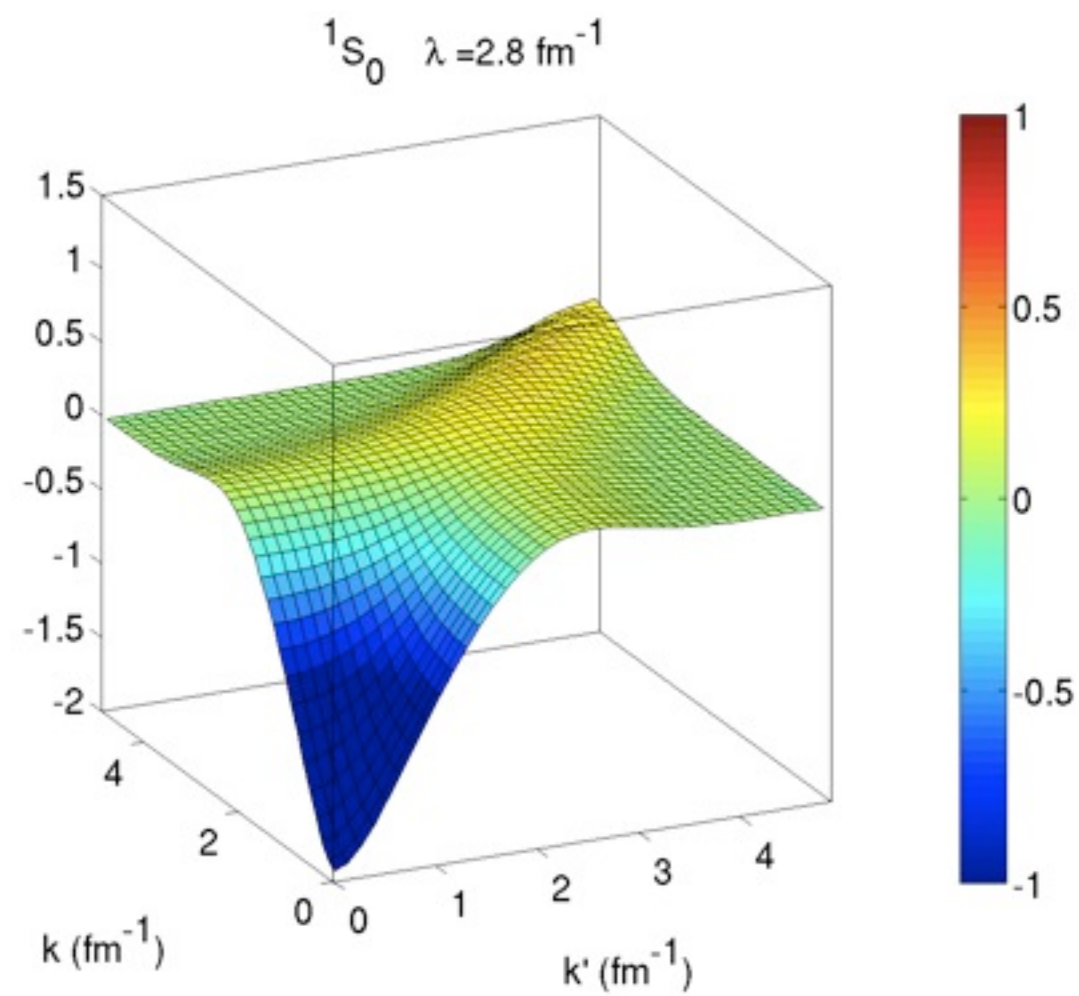

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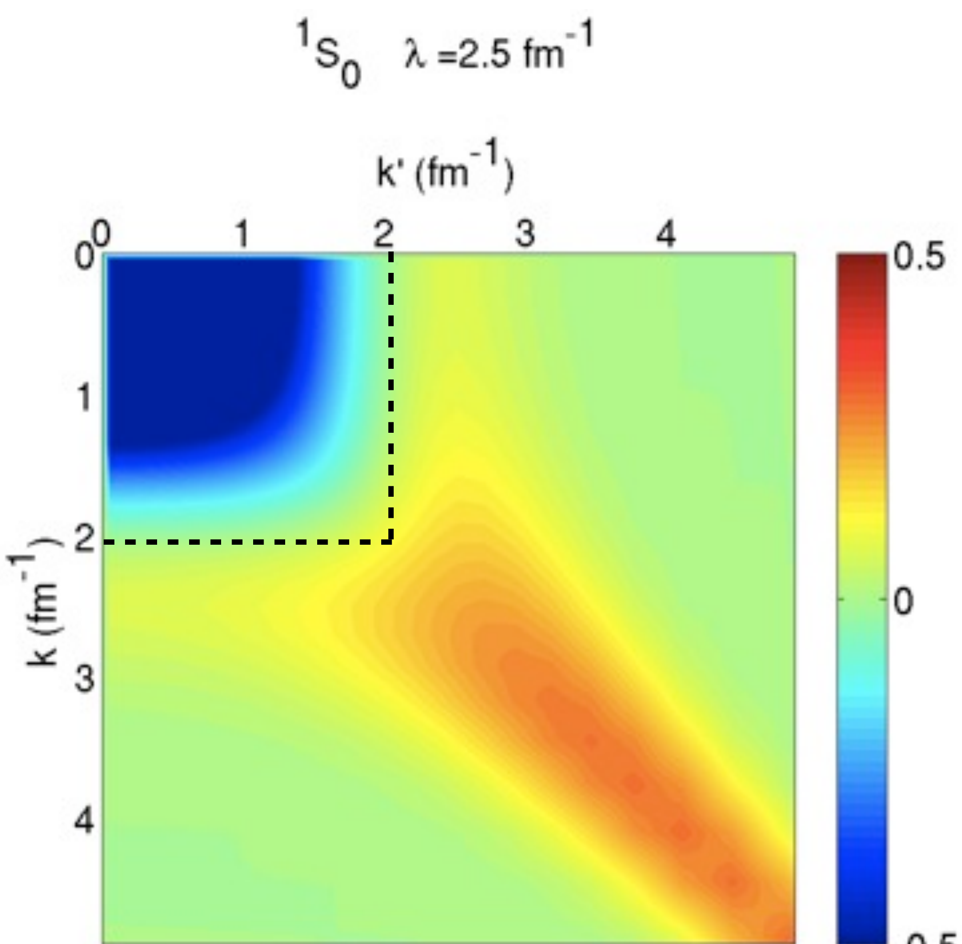

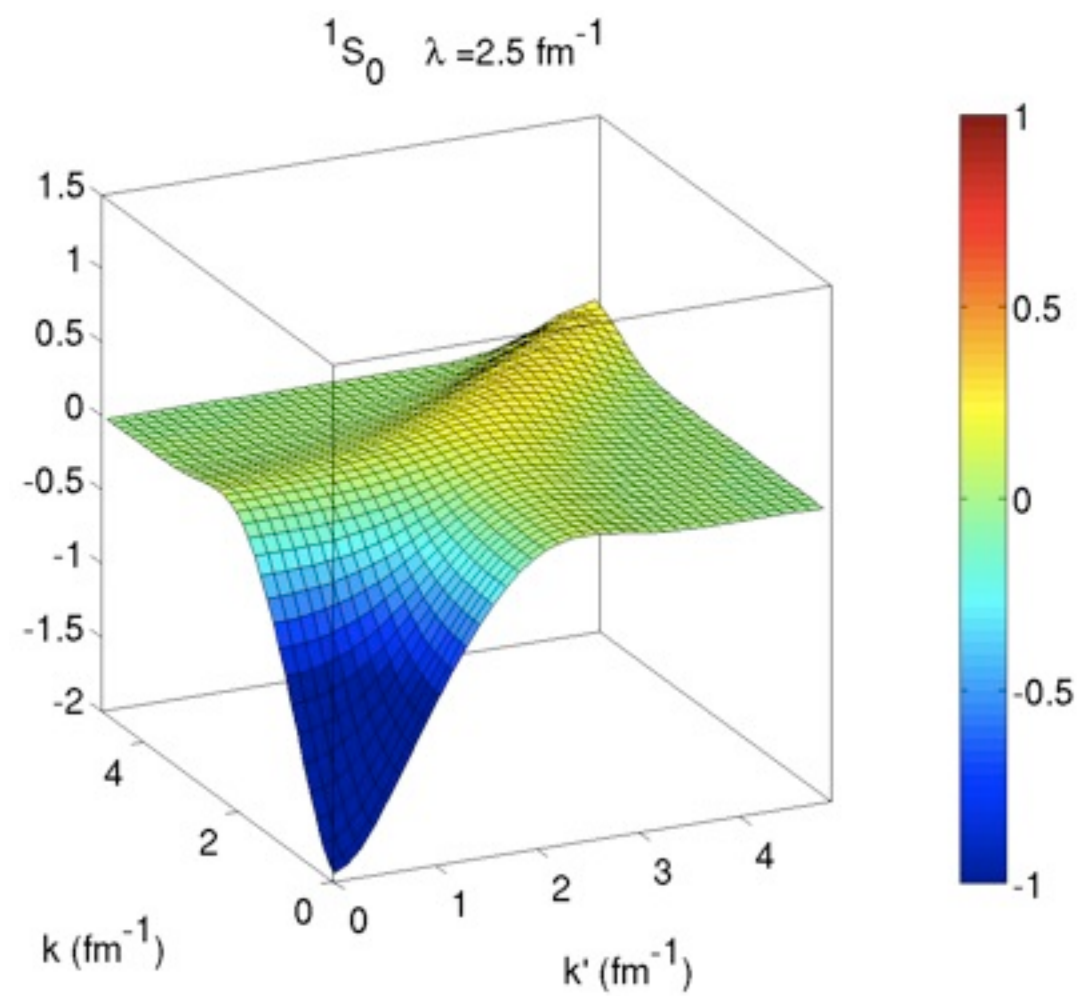

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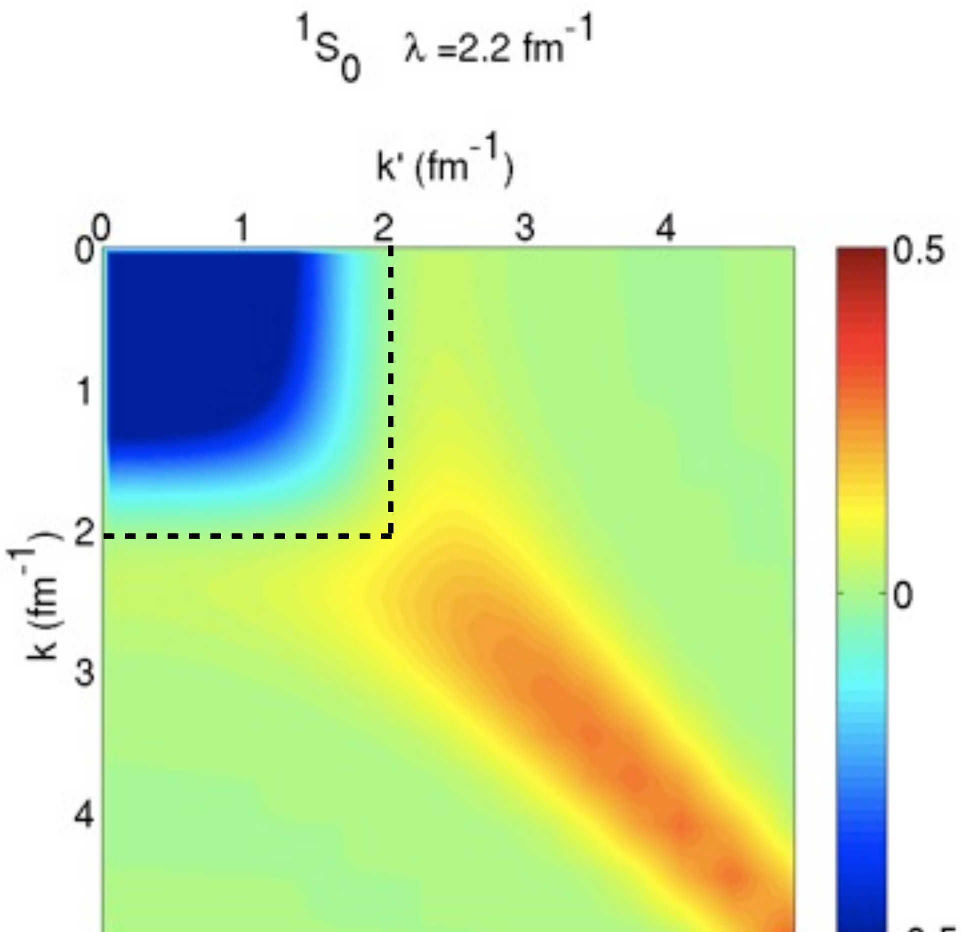

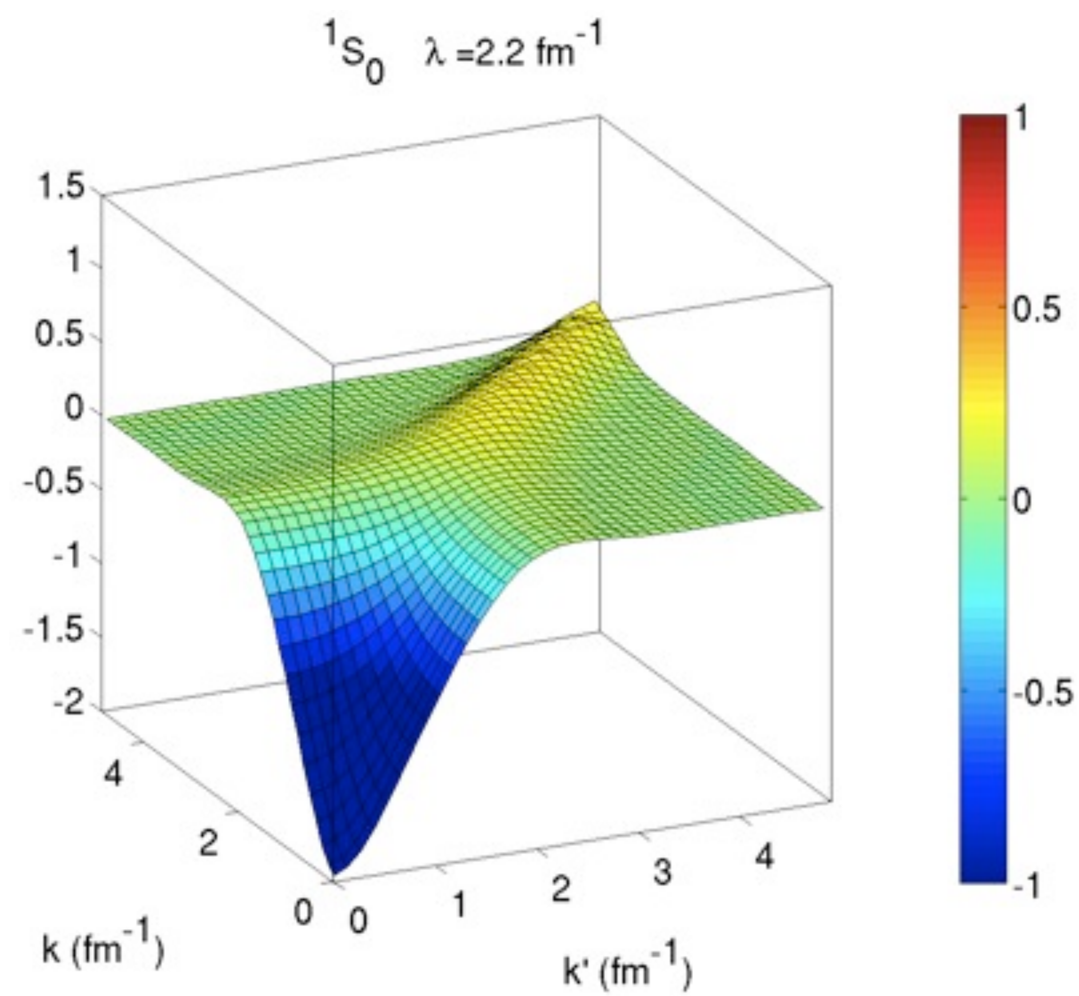

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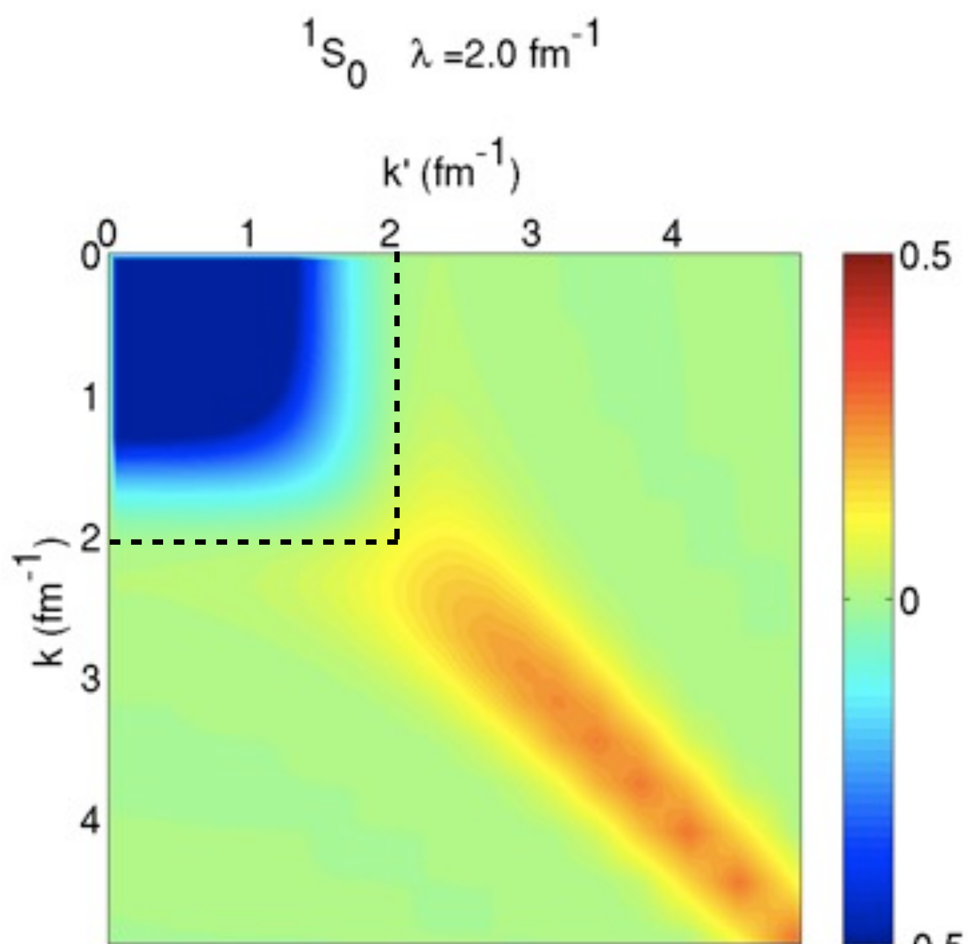
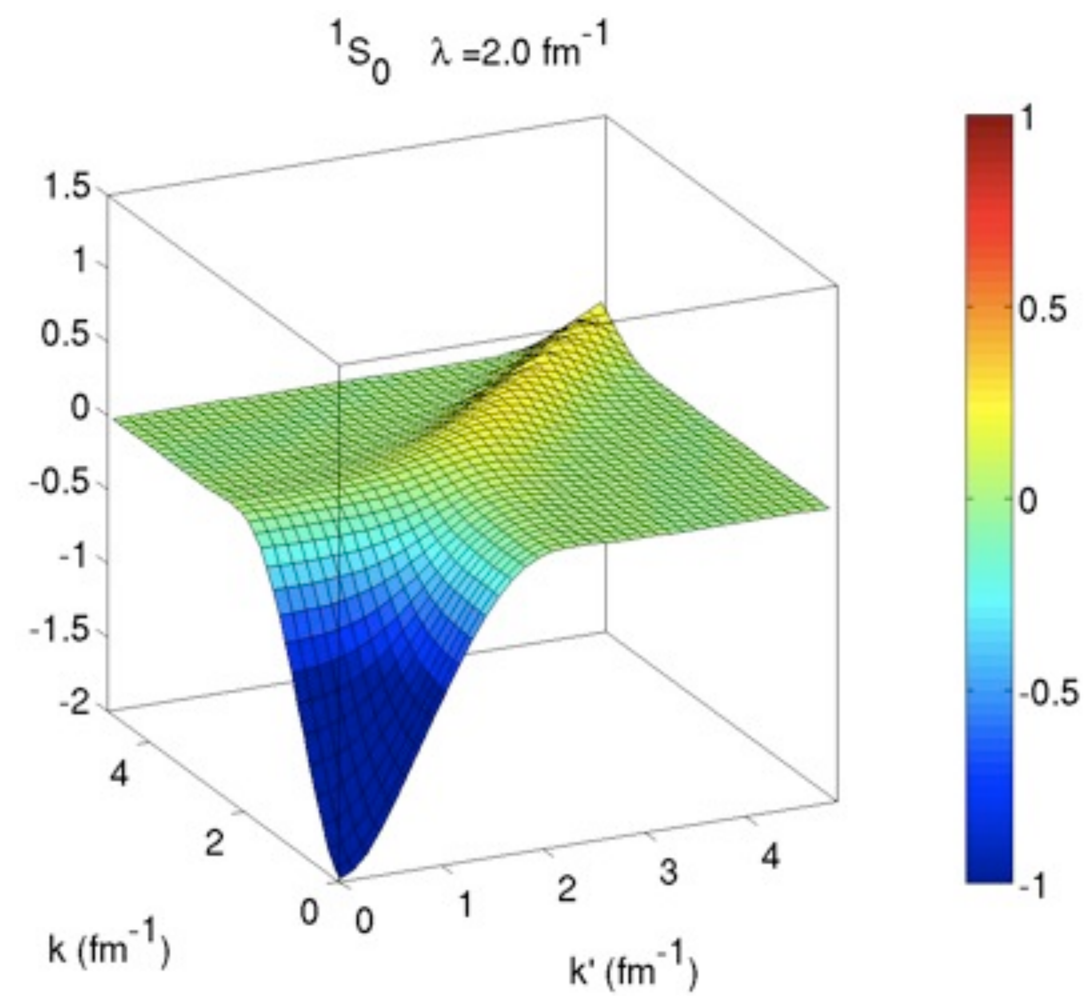
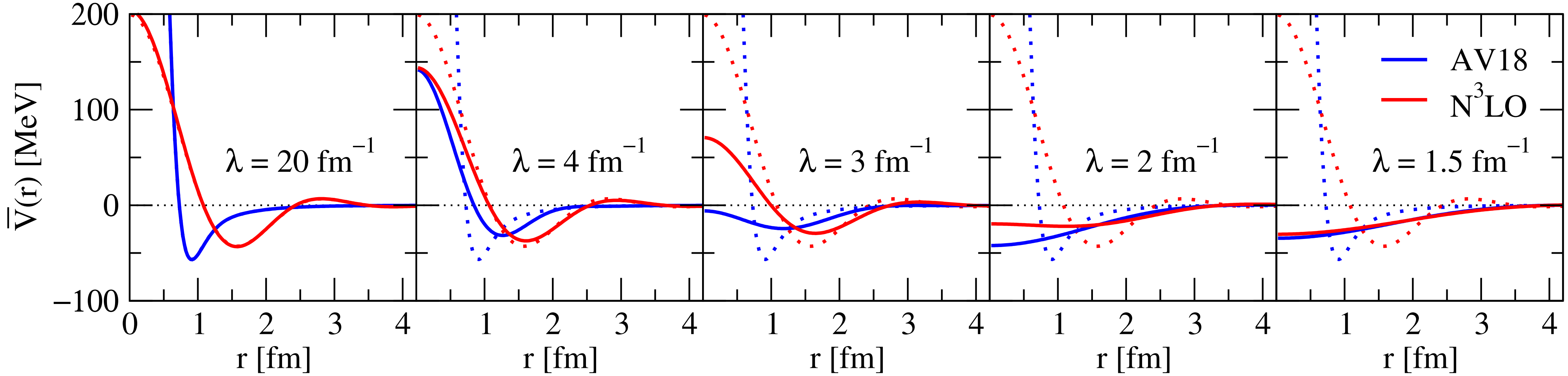
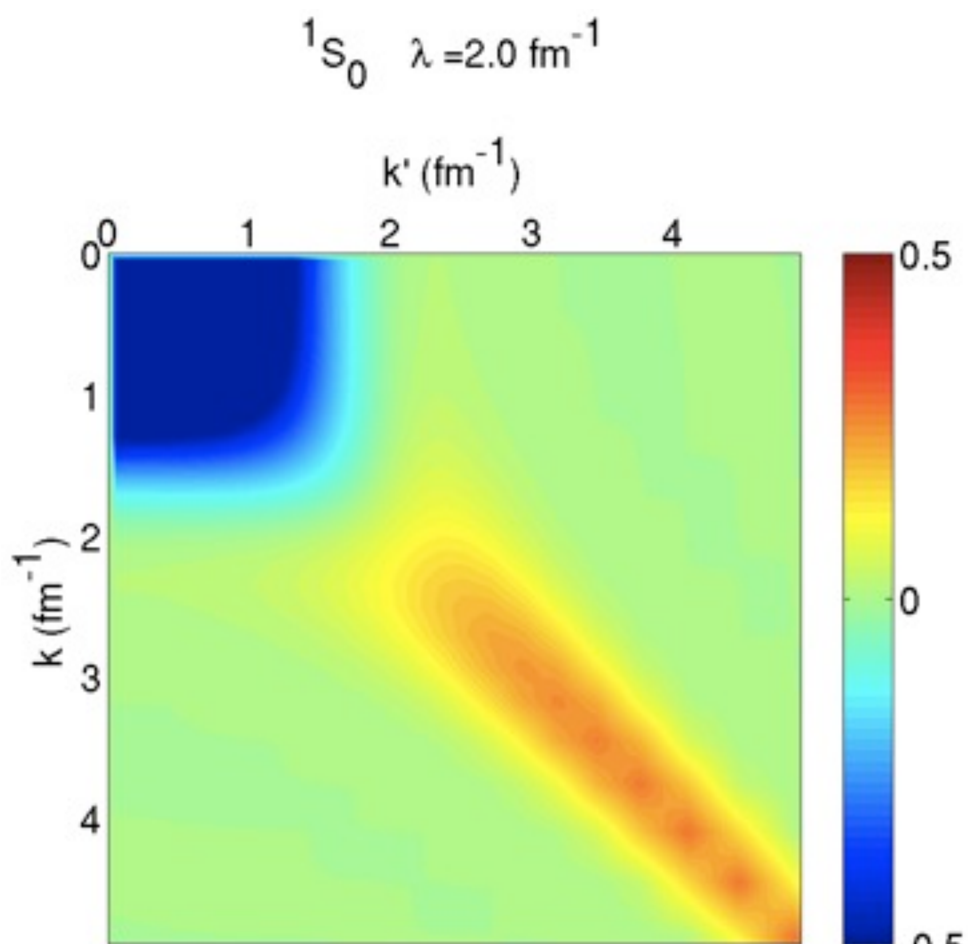


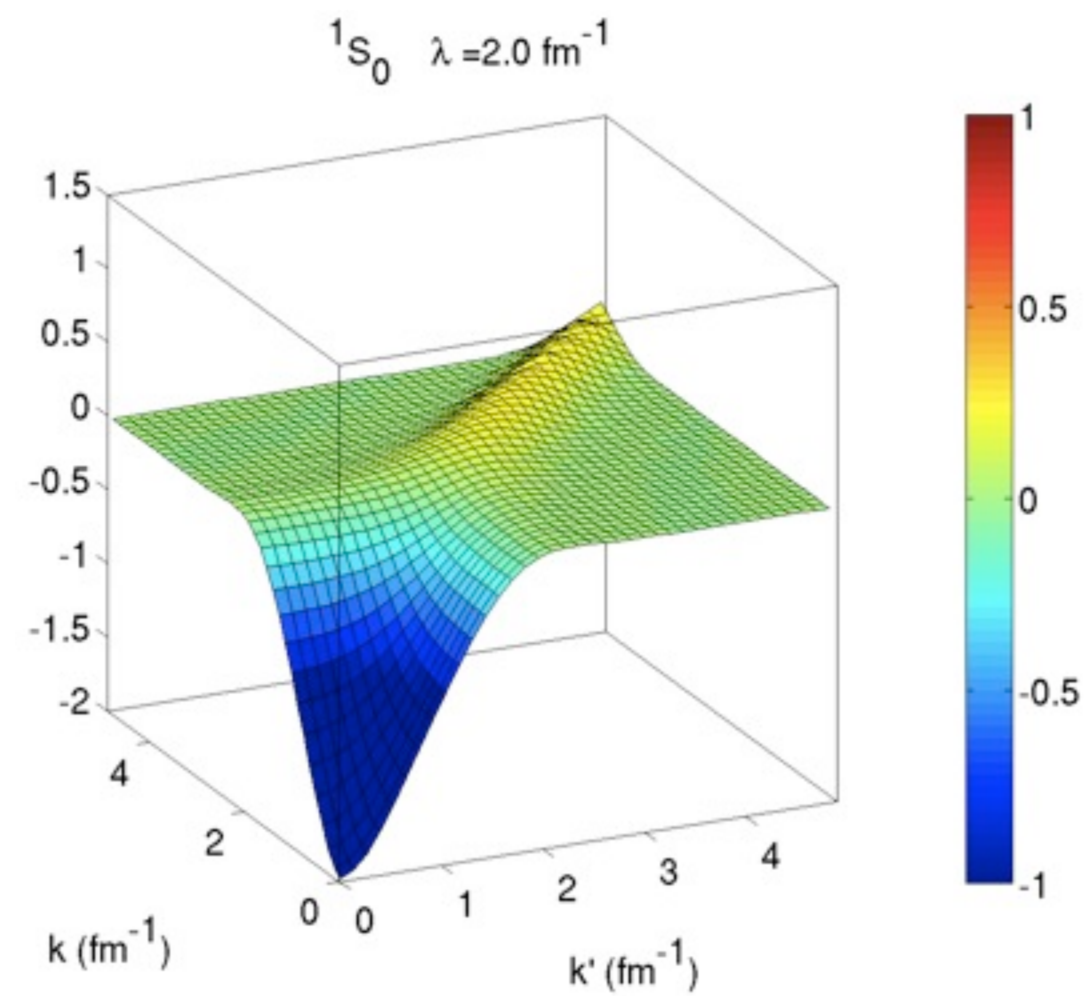


Systematic decoupling of high-momentum physics: The Similarity Renormalization Group

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







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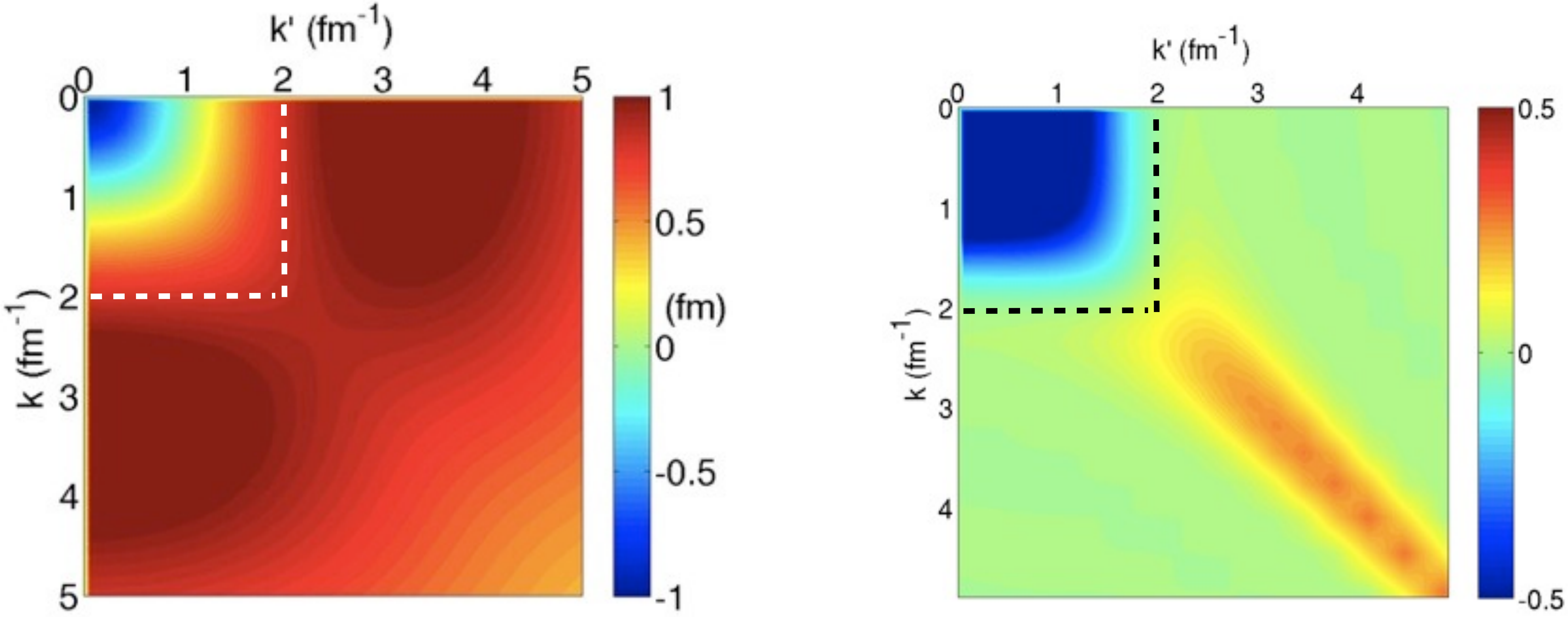
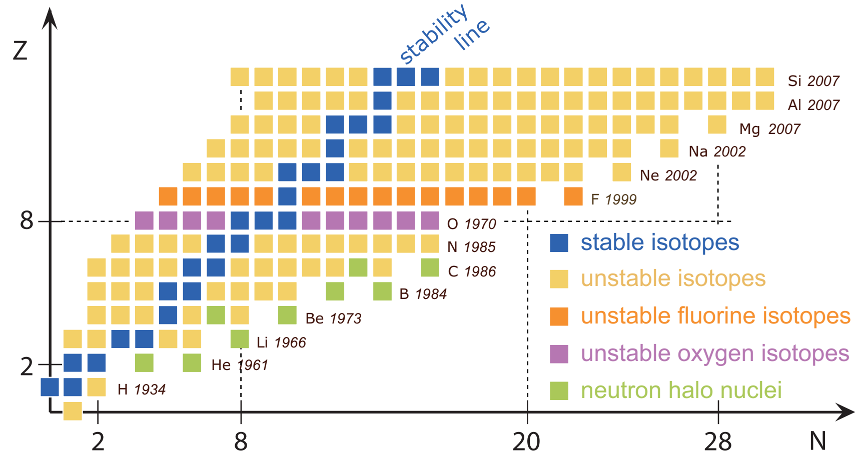


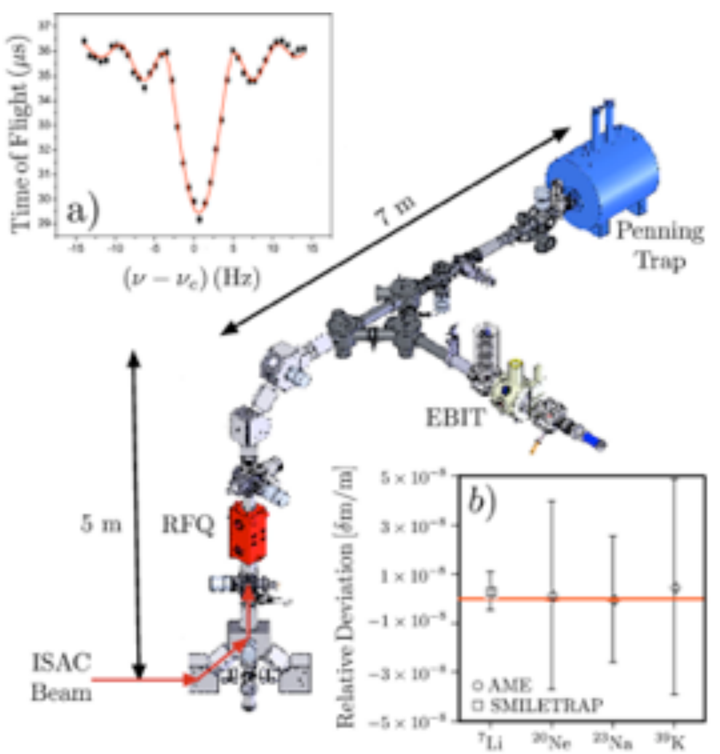
- elimination of coupling between low- and high momentum components,
  ⟶ simplified many-body calculations
- observables unaffected by resolution change (for exact calculations)
- residual resolution dependences can be used as tool to test calculations

Not the full story:
RG transformation also changes three-body (and higher-body) interactions.

Studies of neutron-rich nuclei

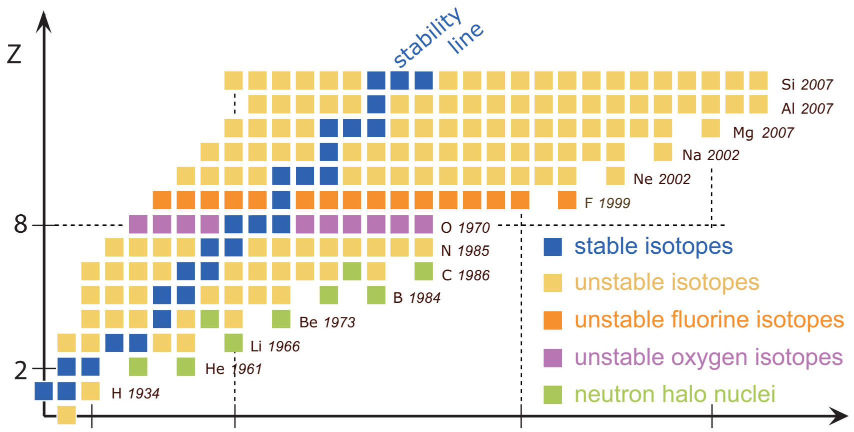


Otsuka et al.,
PRL 105, 032501 (2010)



Studies of neutron-rich nuclei

Wienholtz et al.
Nature 498, 346 (2013)



Otsuka et al.,
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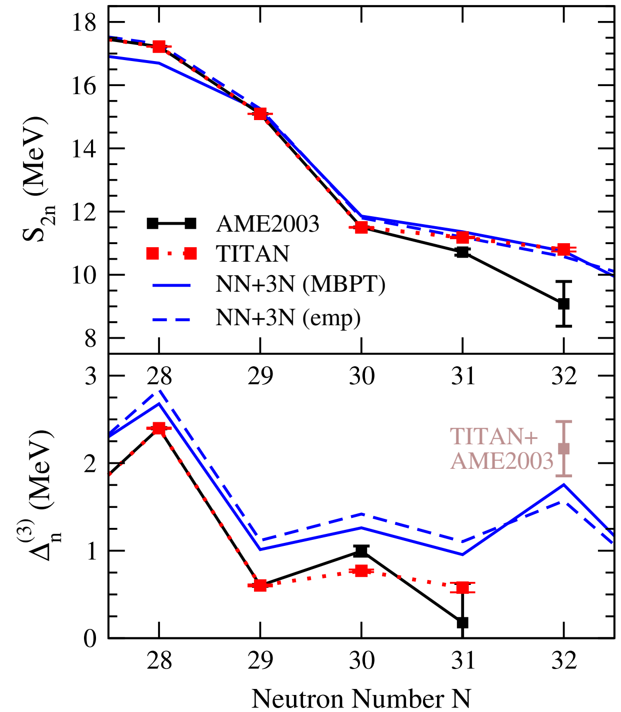
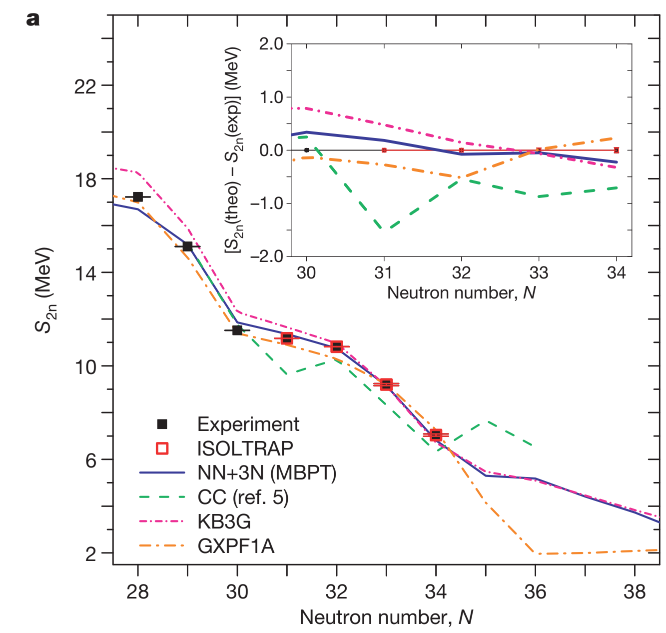
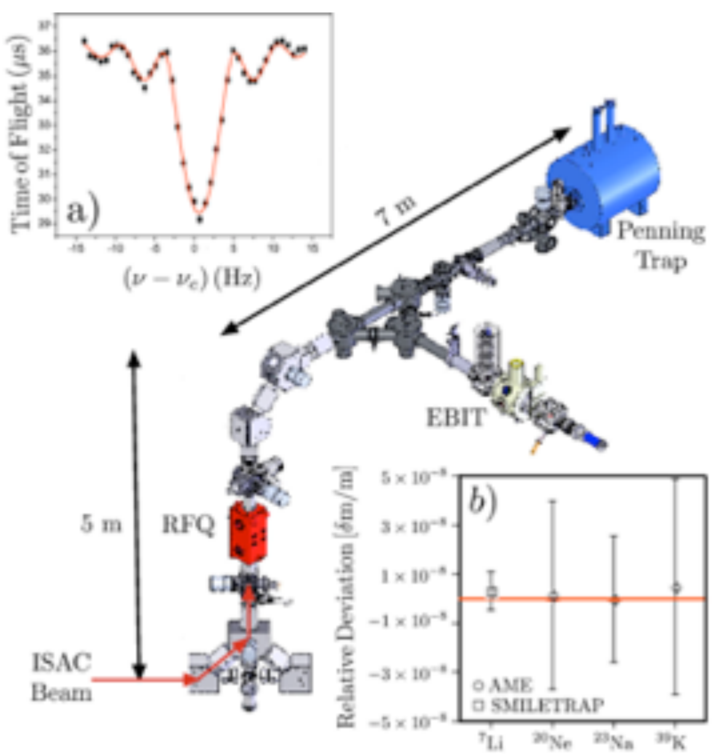
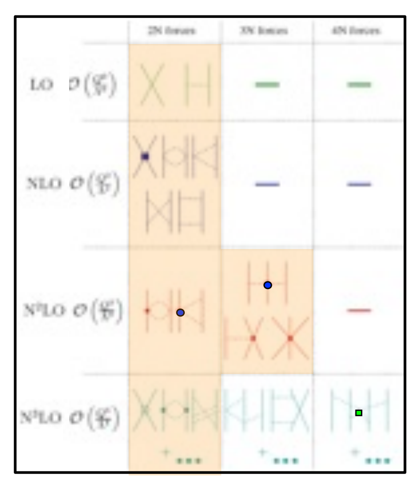


Gallant et al.
PRL 109, 032506 (2012)







- excellent agreement between theory and experiment for medium-mass nuclei

Studies of neutron-rich nuclei

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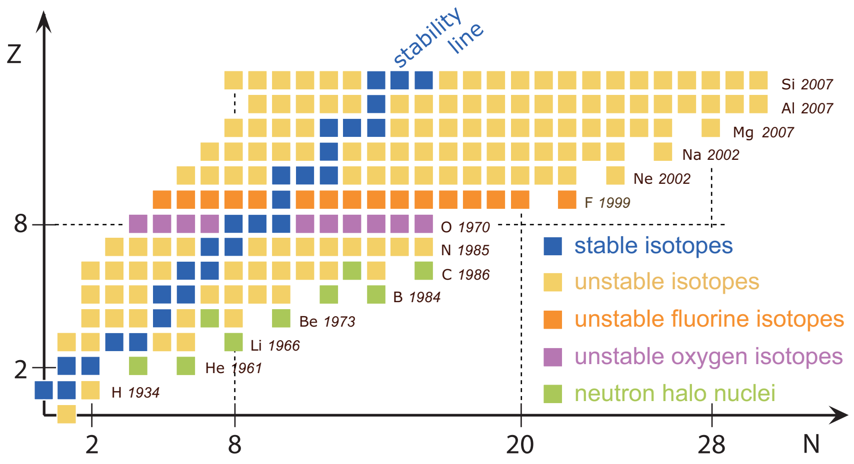
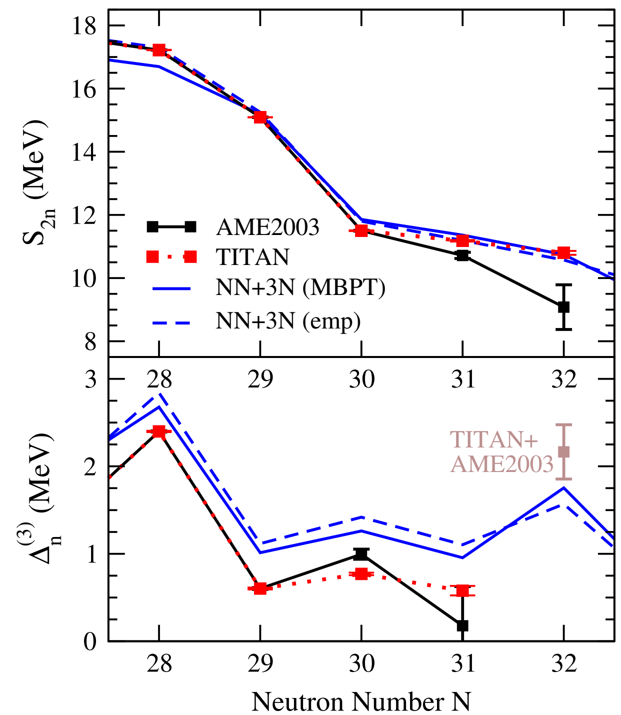
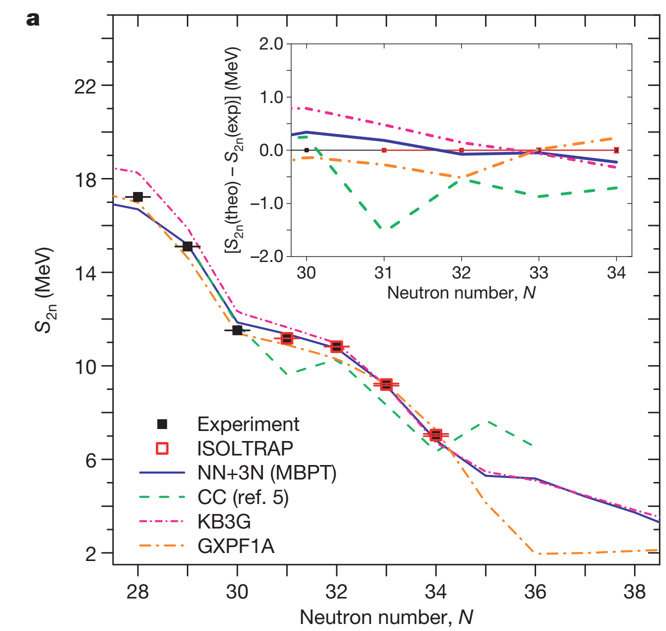
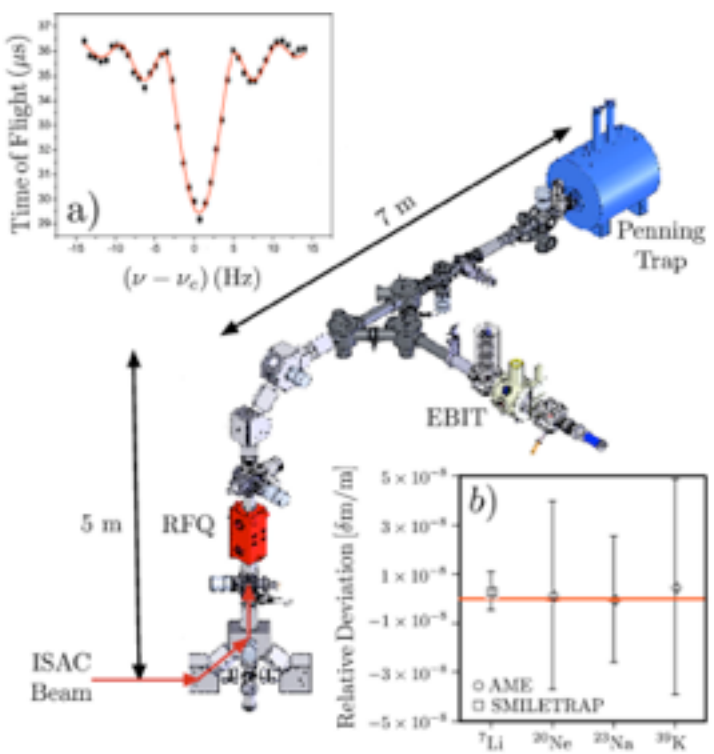


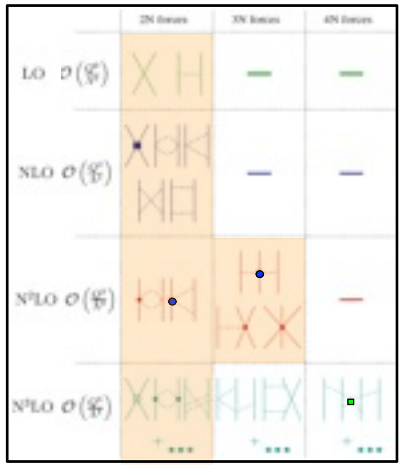
Otsuka et al.,
PRL 105, 032501 (2010)

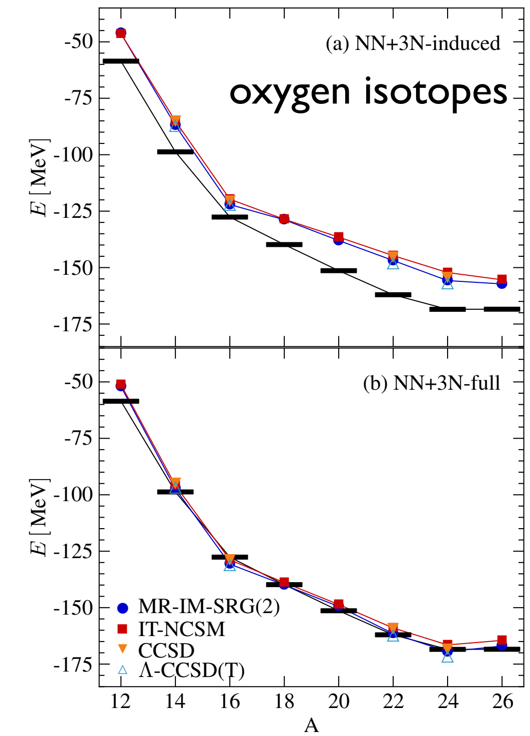


Gallant et al.
PRL 109, 032506 (2012)







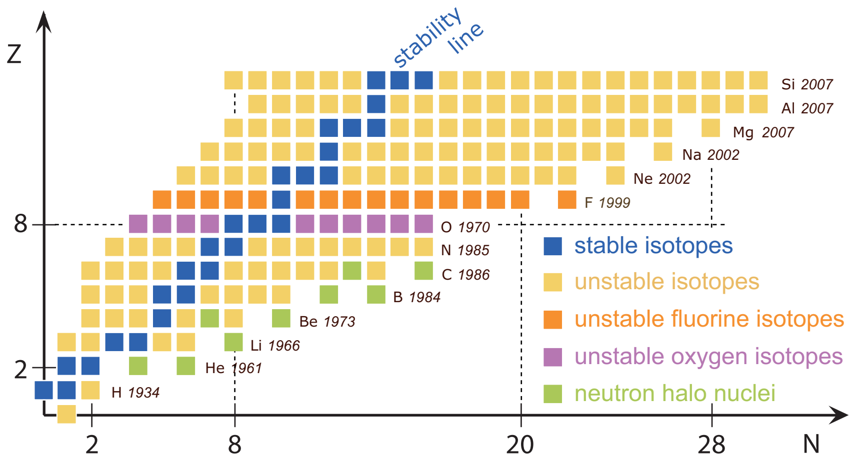


Hergert et al., PRL 110, 242501 (2013)

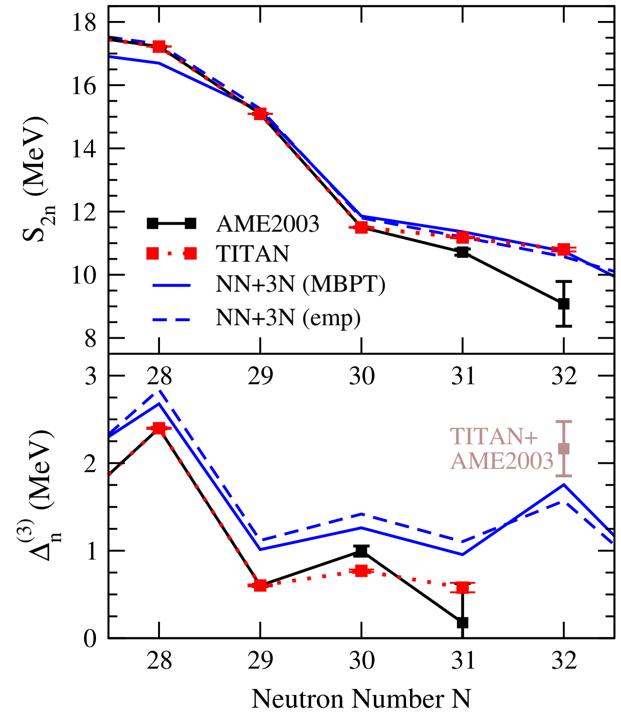
- excellent agreement between theory and experiment for medium-mass nuclei
- remarkable agreement between different many-body frameworks

Studies of neutron-rich nuclei

Wienholtz et al.
Nature 498, 346 (2013)



Otsuka et al.,
PRL 105, 032501 (2010)



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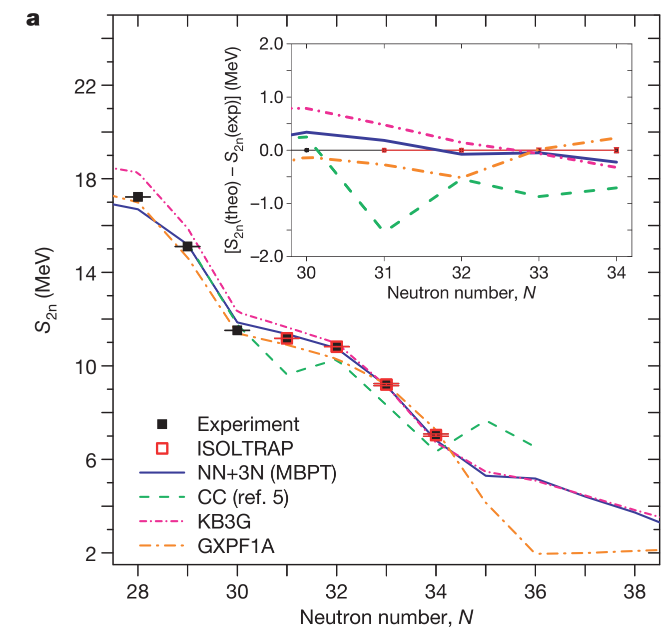
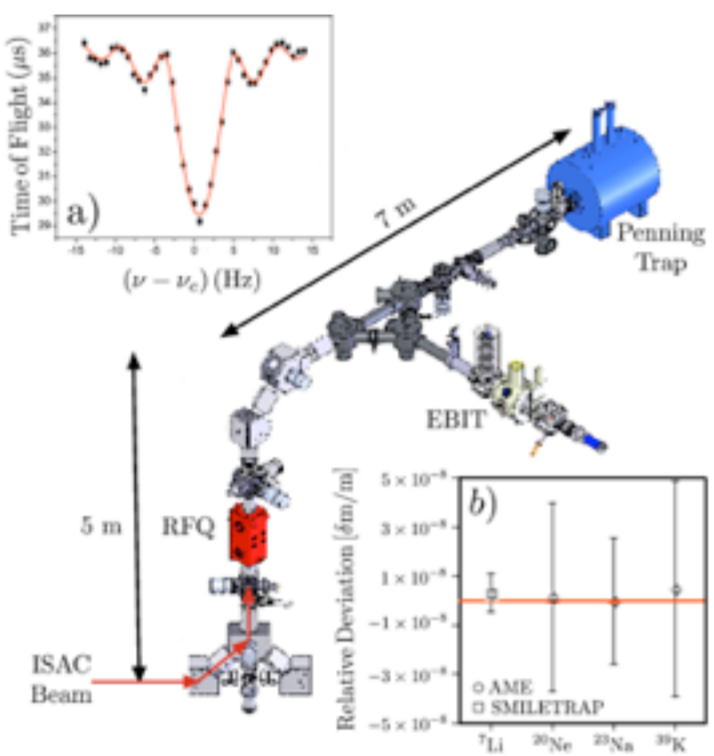
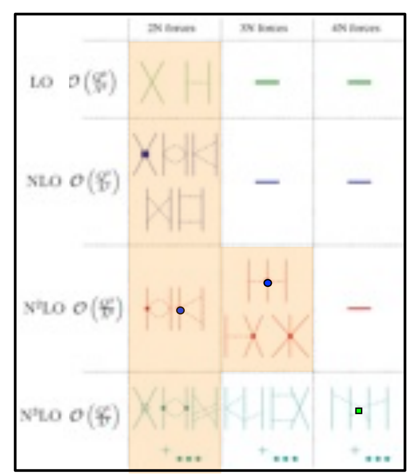
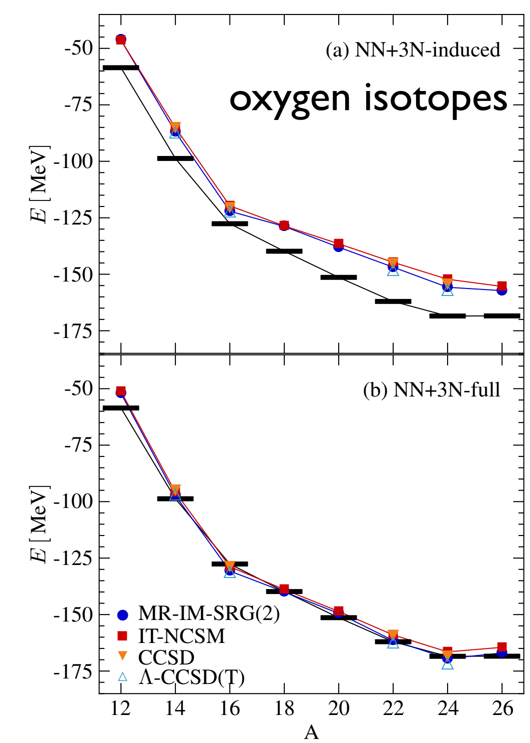




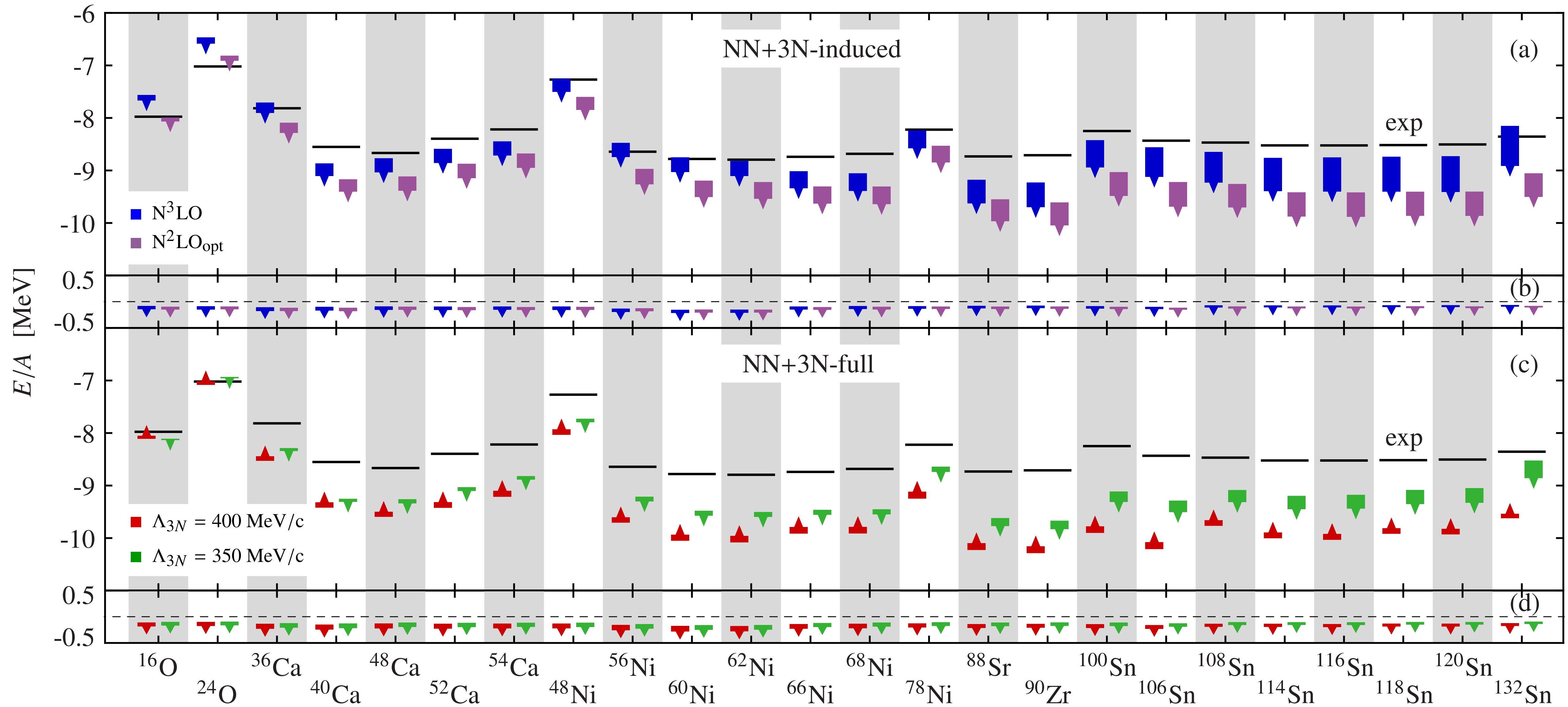




Hergert et al. , PRL 110, 242501 (2013)

- excellent agreement between theory and experiment for medium-mass nuclei
- remarkable agreement between different many-body frameworks
- need to quantify theoretical uncertainties

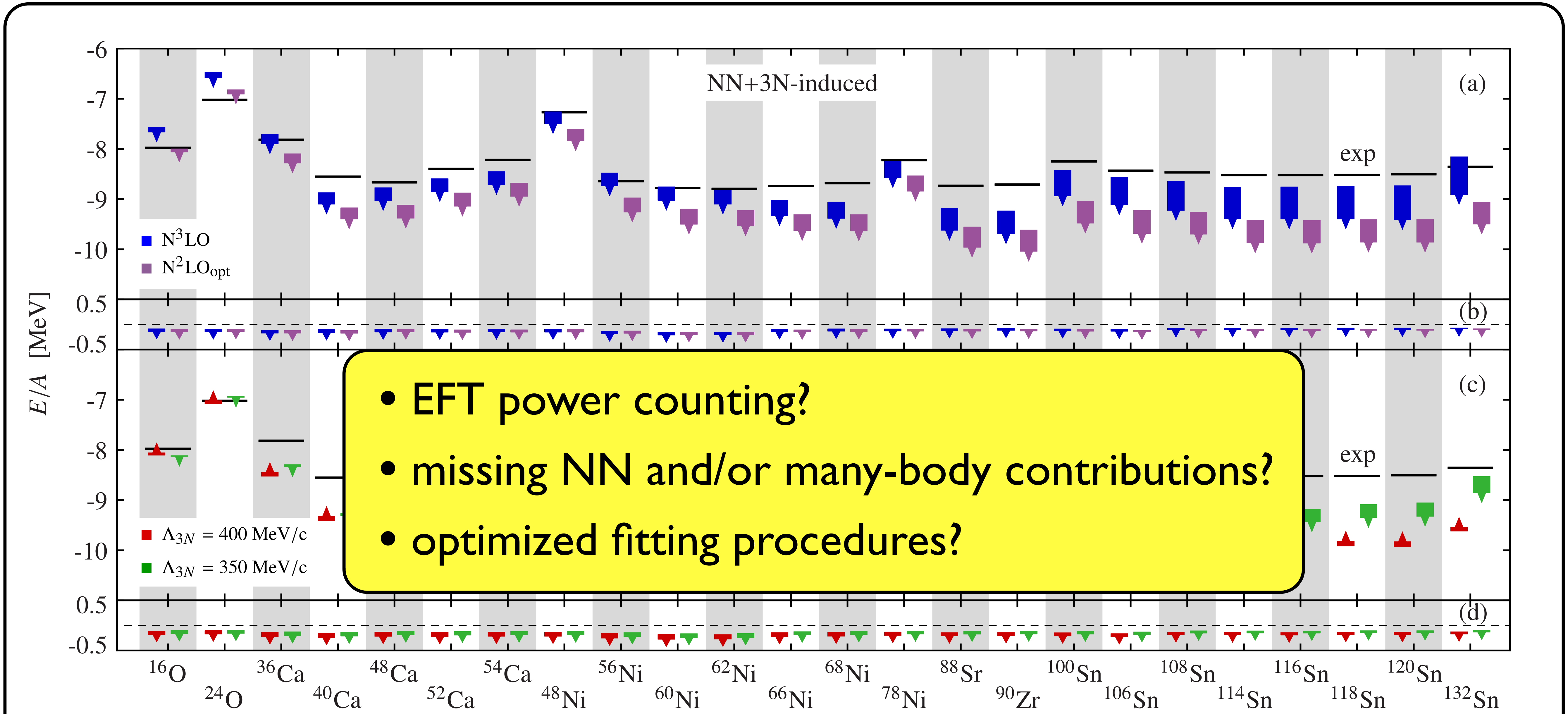
Ground state energies of medium-mass and heavy nuclei



Binder et al., arXiv:1312.5685 (2014)

- remarkable agreement of different many-body calculations for given Hamiltonian
- strong dependence on cutoff scale in 3NF for heavier nuclei
- significant overbinding of heavy nuclei
- need to quantify and reduce theoretical uncertainties

Ground state energies of medium-mass and heavy nuclei



- EFT power counting?
- missing NN and/or many-body contributions?
- optimized fitting procedures?

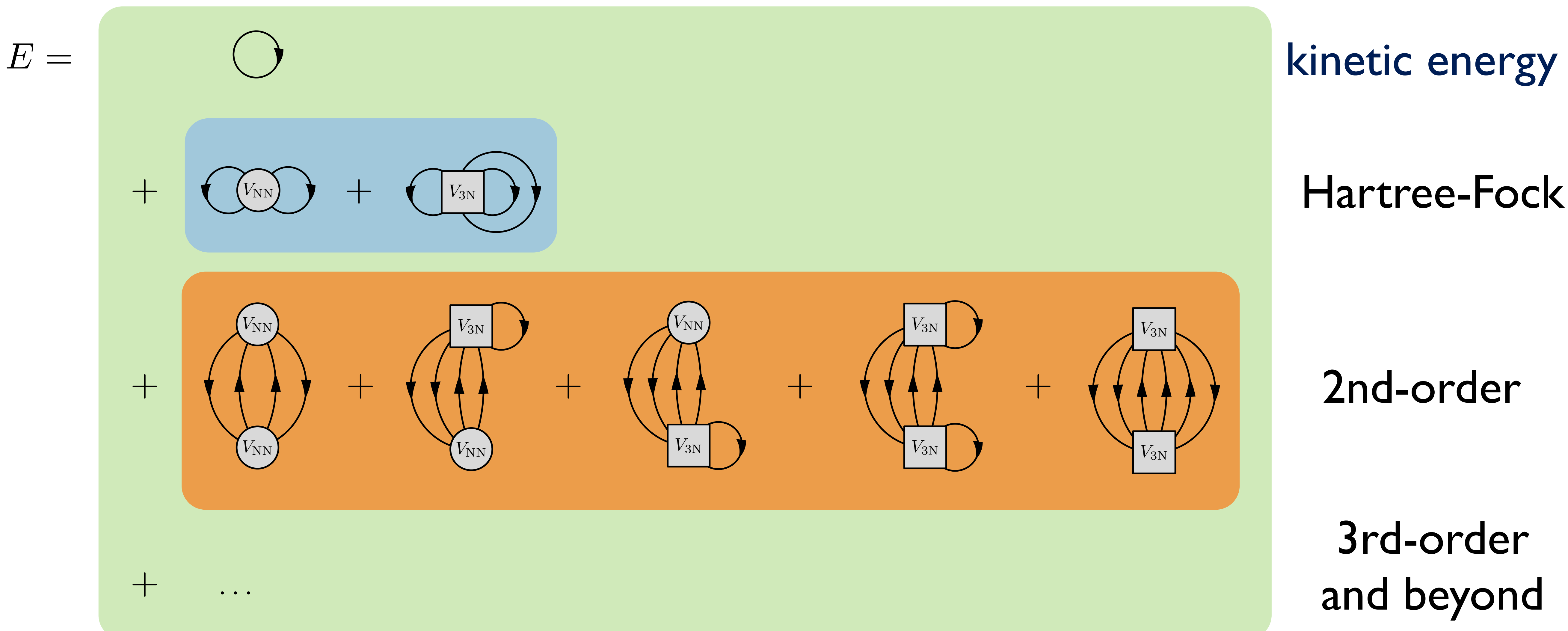
Binder et al., arXiv:1312.5685 (2014)

- remarkable agreement of different many-body calculations for given Hamiltonian
- strong dependence on cutoff scale in 3NF for heavier nuclei
- significant overbinding of heavy nuclei
- need to quantify and reduce theoretical uncertainties

Equation of state: Many-body perturbation theory

central quantity of interest: energy per particle E/N

$$H(\lambda) = T + V_{\mathrm{NN}}(\lambda) + V_{\mathrm{3N}}(\lambda) + \ldots$$

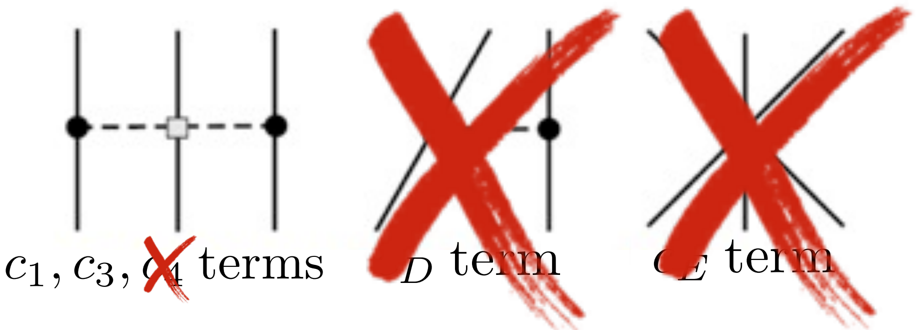


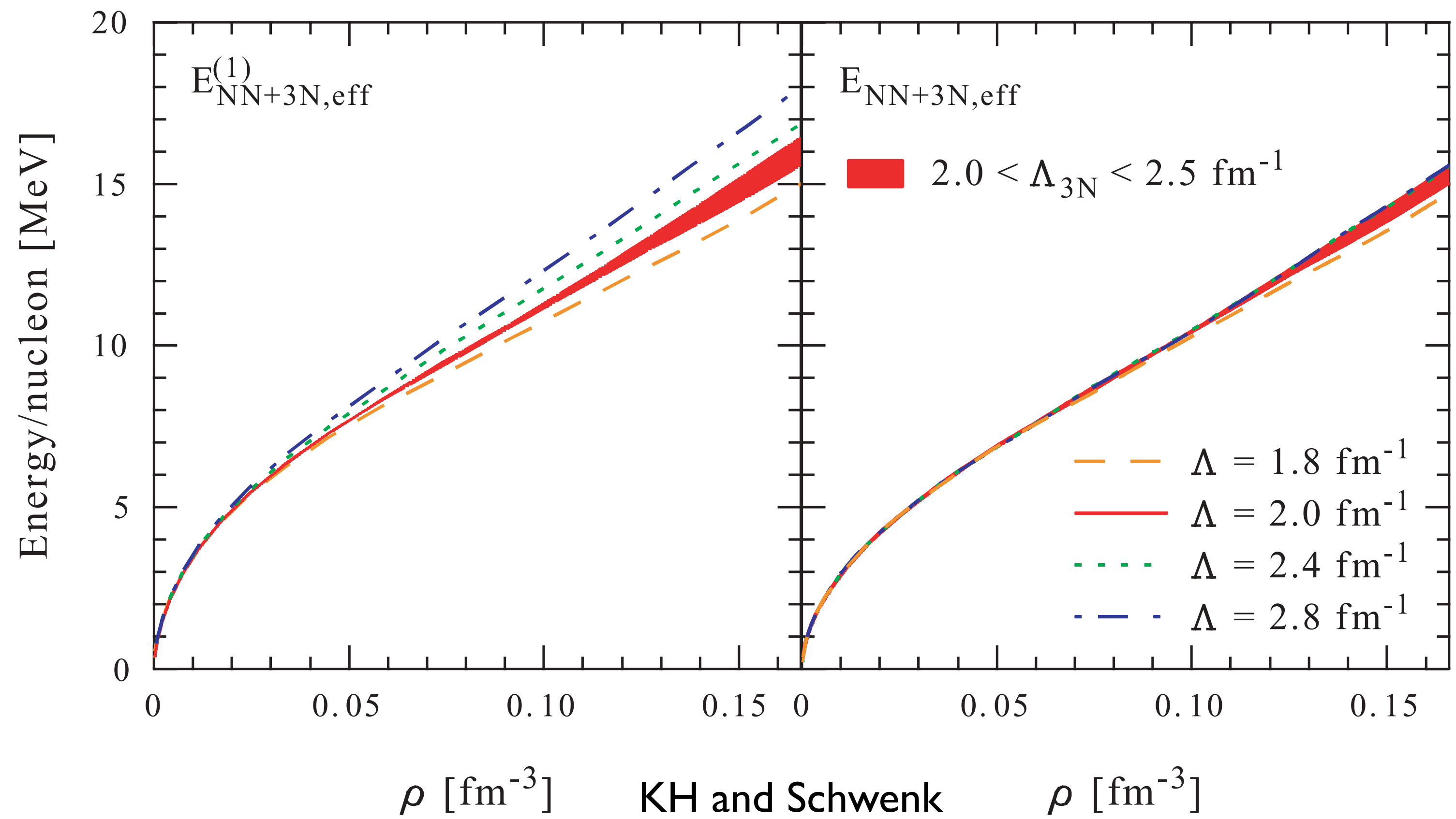
- “hard” interactions require non-perturbative summation of diagrams
- with low-momentum interactions much more perturbative
- inclusion of 3N interaction contributions crucial!

Results for the neutron matter equation of state

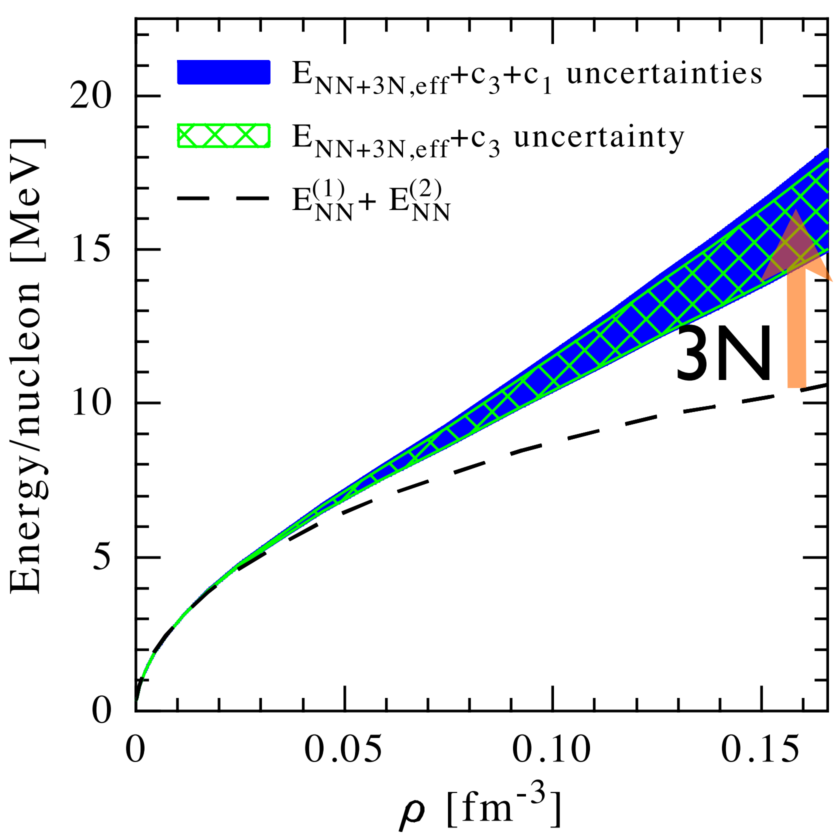
neutron matter is a **unique system** for chiral EFT:

only long-range 3NF contribute in leading order



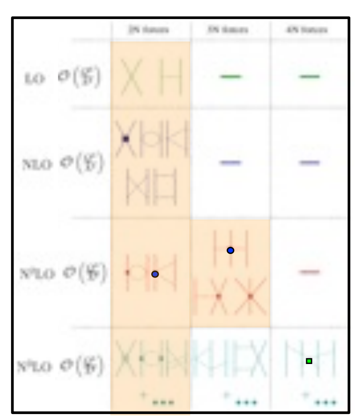


KH and Schwenk
PRC 82, 014314 (2010)



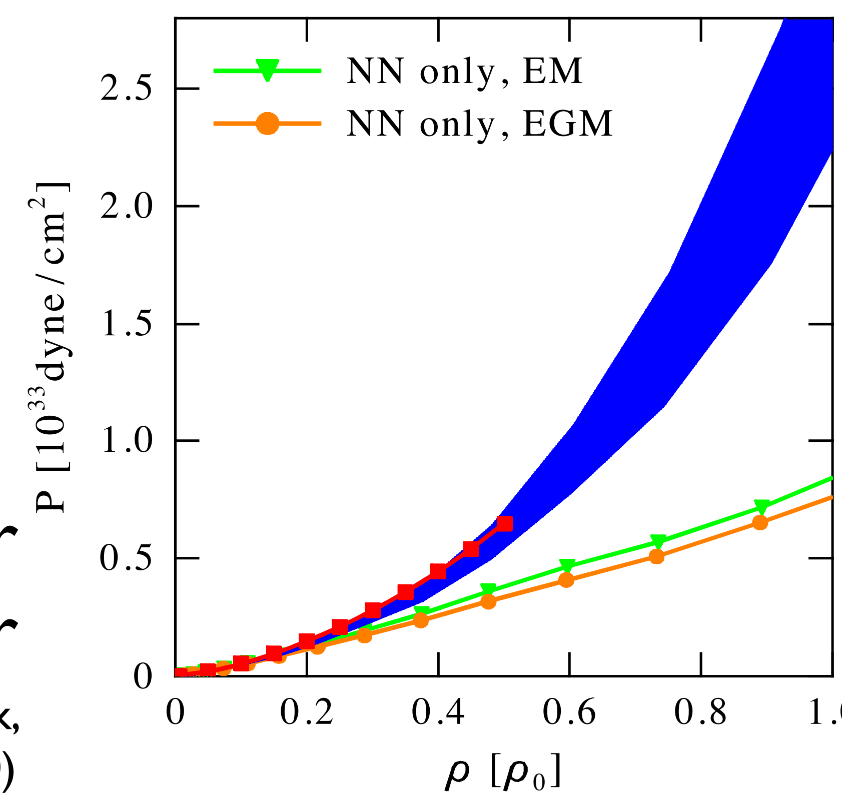
pure neutron matter

KH and Schwenk PRC 82, 014314 (2010)

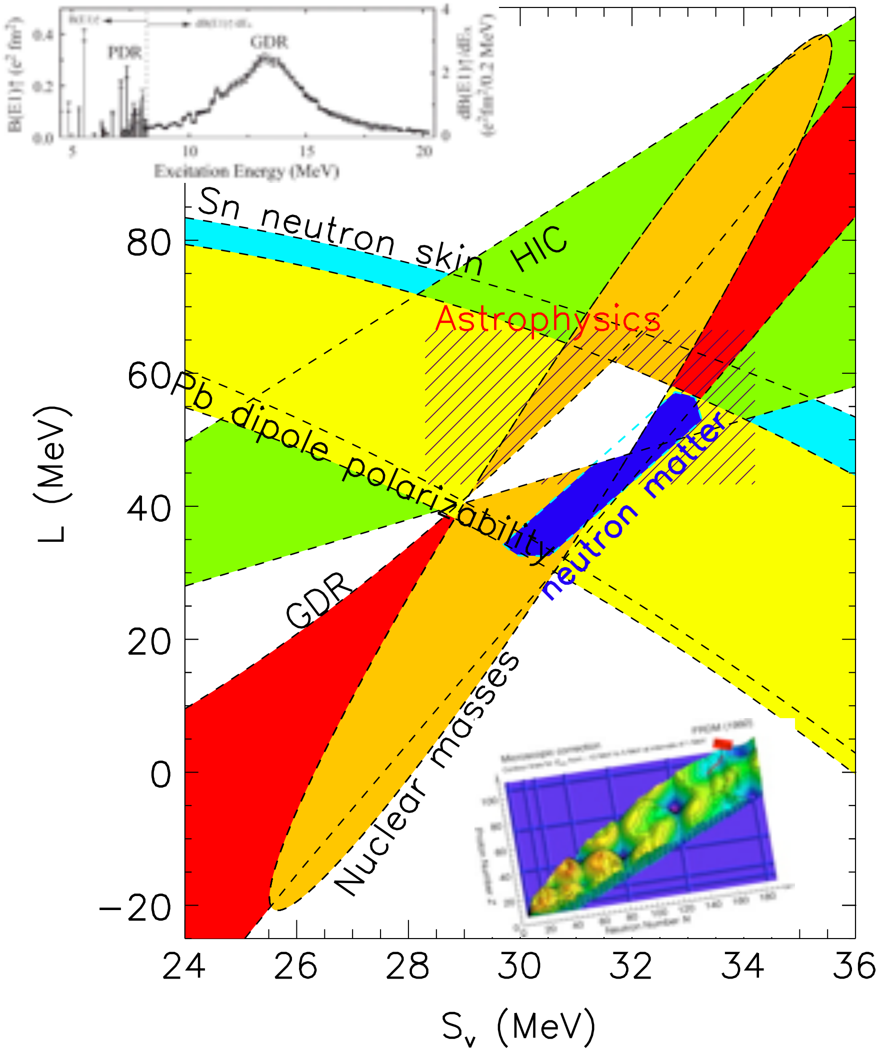


neutron star matter

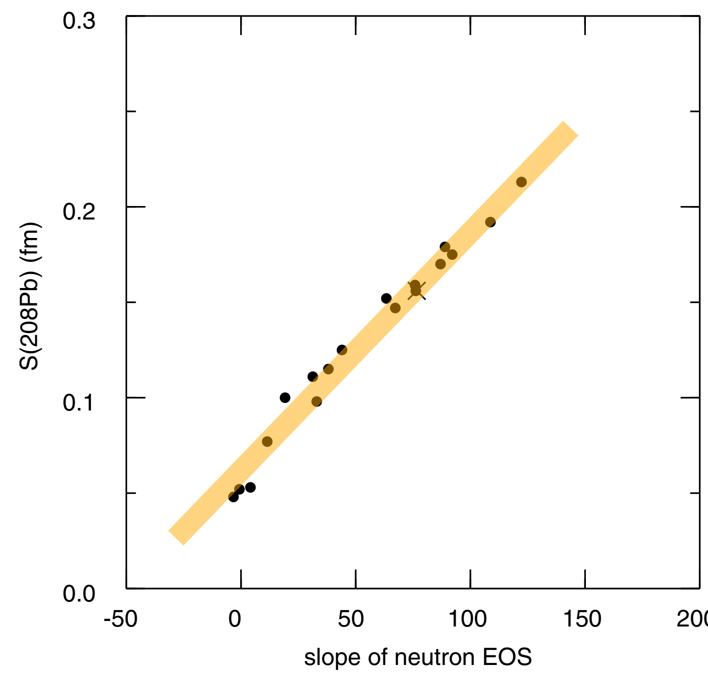
KH, Lattimer, Pethick, Schwenk,
PRL 105, 161102 (2010)



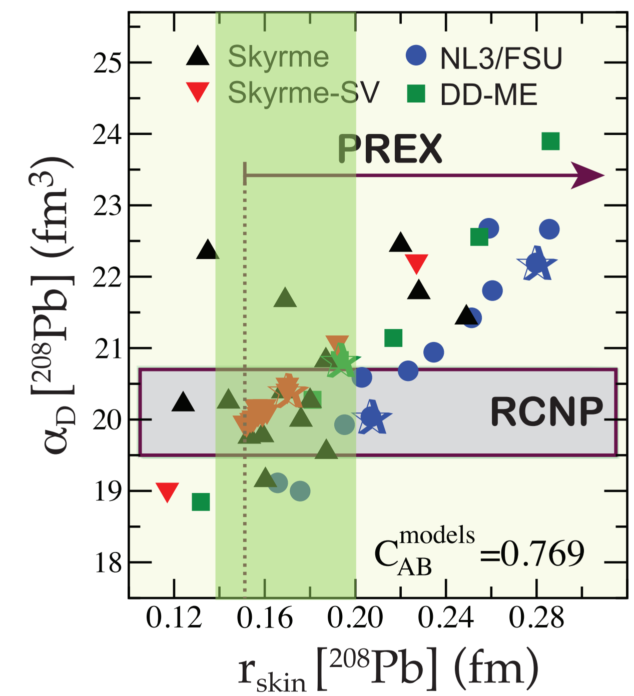
Symmetry energy and neutron skin constraints



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



Brown,
PRL 85, 5296 (2000)



Piekarewicz,
PRC 85, 041302 (2012)

$$S_v = \left.\frac{\partial^2 E/N}{\partial^2 x}\right|_{\rho=\rho_0, x=1/2}$$

$$L = \frac{3}{8} \left.\frac{\partial^3 E/N}{\partial\rho\partial^2 x}\right|_{\rho=\rho_0, x=1/2}$$

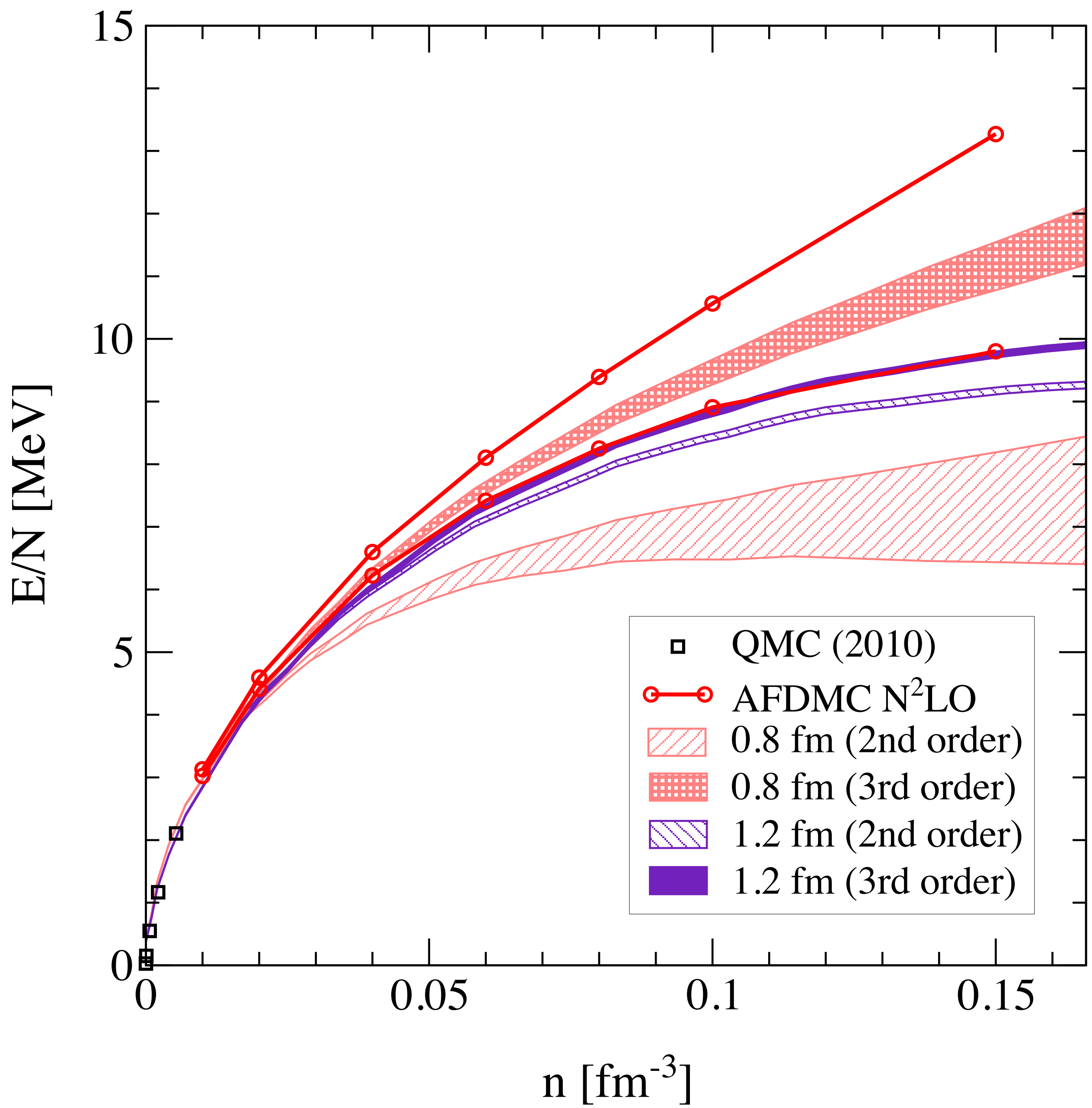
neutron skin constraint from neutron matter results:

$$r_{\rm skin}[^{208}{\rm Pb}] = 0.14 - 0.2 \text{ fm}$$

KH, Lattimer, Pethick, Schwenk, PRL 105, 161102 (2010)

- neutron matter give tightest constraints
- in agreement with all other constraints

First Quantum Monte Carlo based on chiral EFT interactions

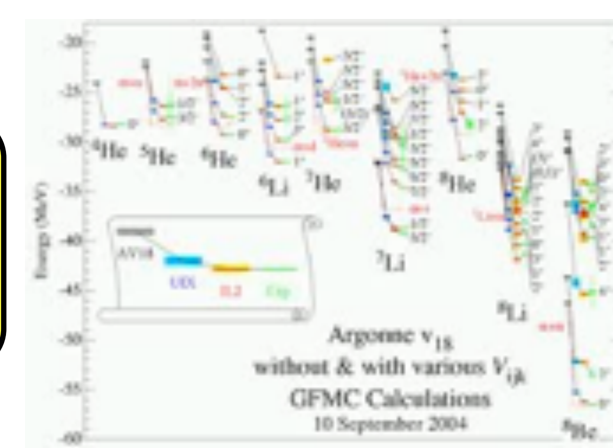


perfect agreement for soft interactions, first direct validation of perturbative calculations

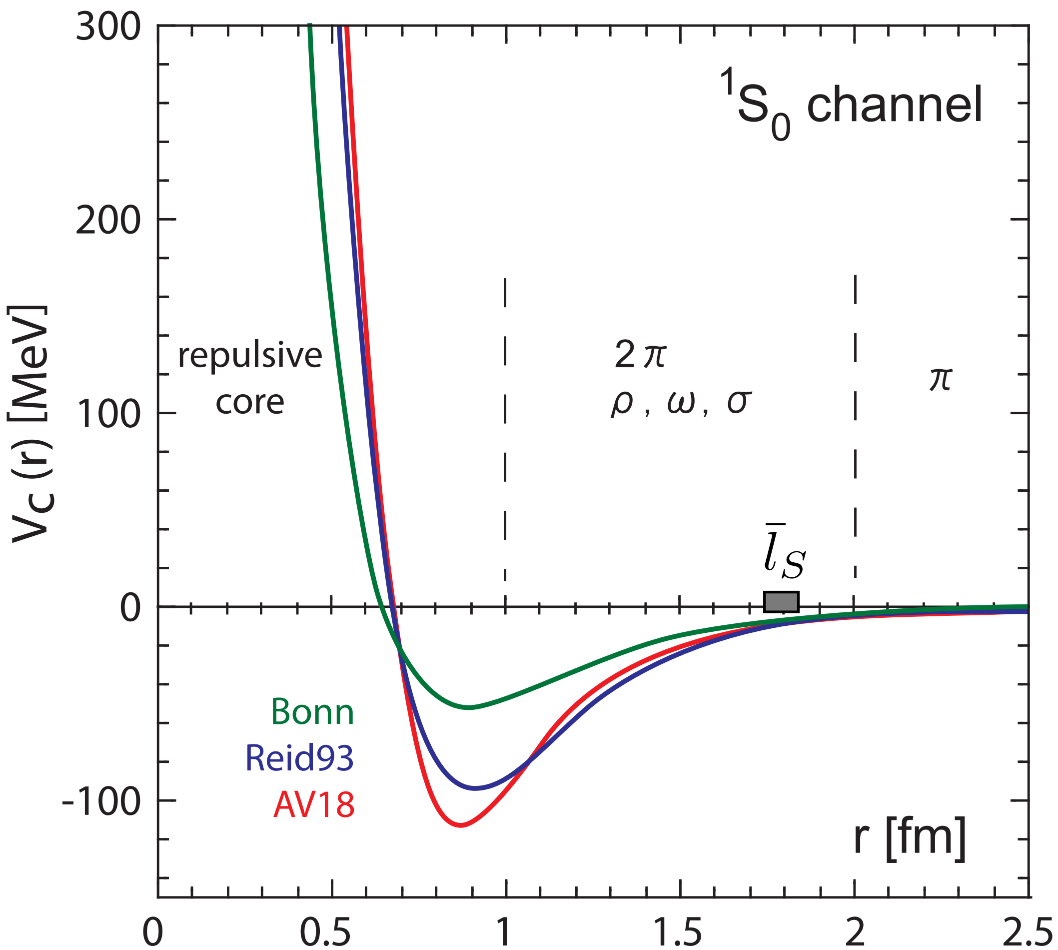
Gezerlis, Tews, Epelbaum, Gandolfi, KH, Nogga, Schwenk
PRL 111, 032501 (2013)

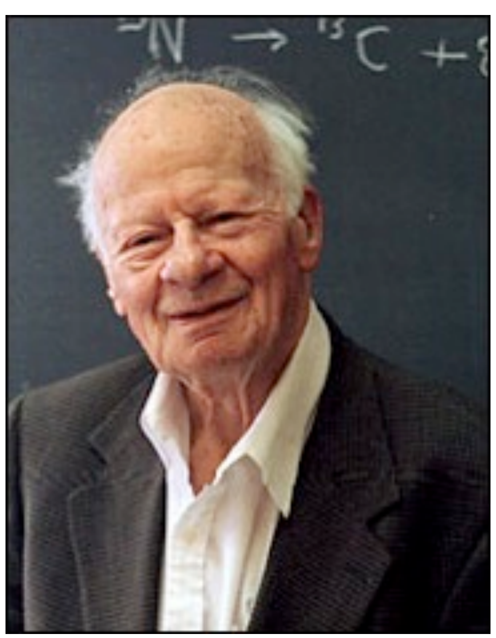
In progress: Greens Function Monte Carlo calculations for light nuclei based on chiral interactions

Lynn, Carlson, Epelbaum, Gandolfi, Gezerlis, Schwenk
PRL 113, 192501 (2014)



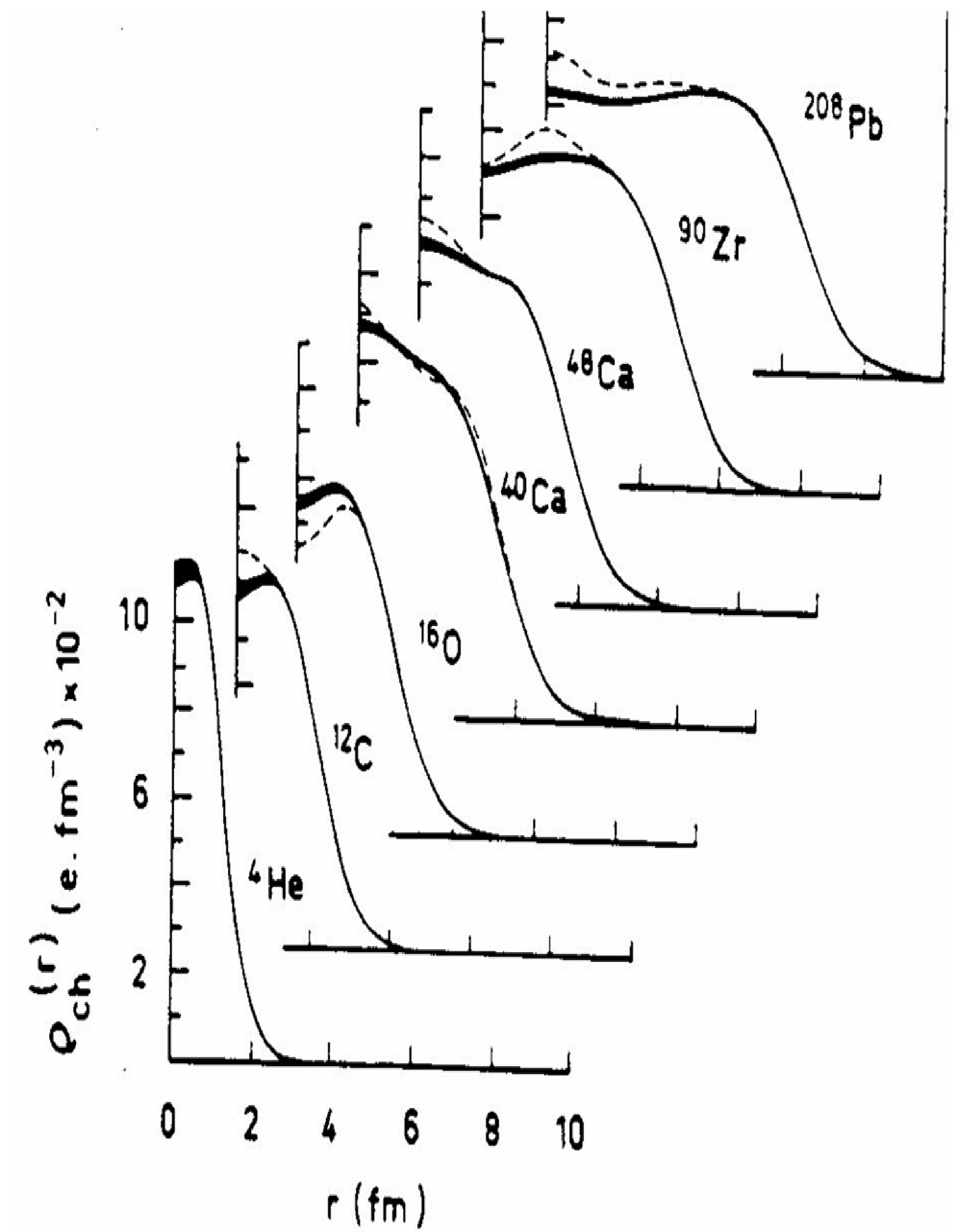
Equation of state of symmetric nuclear matter, nuclear saturation



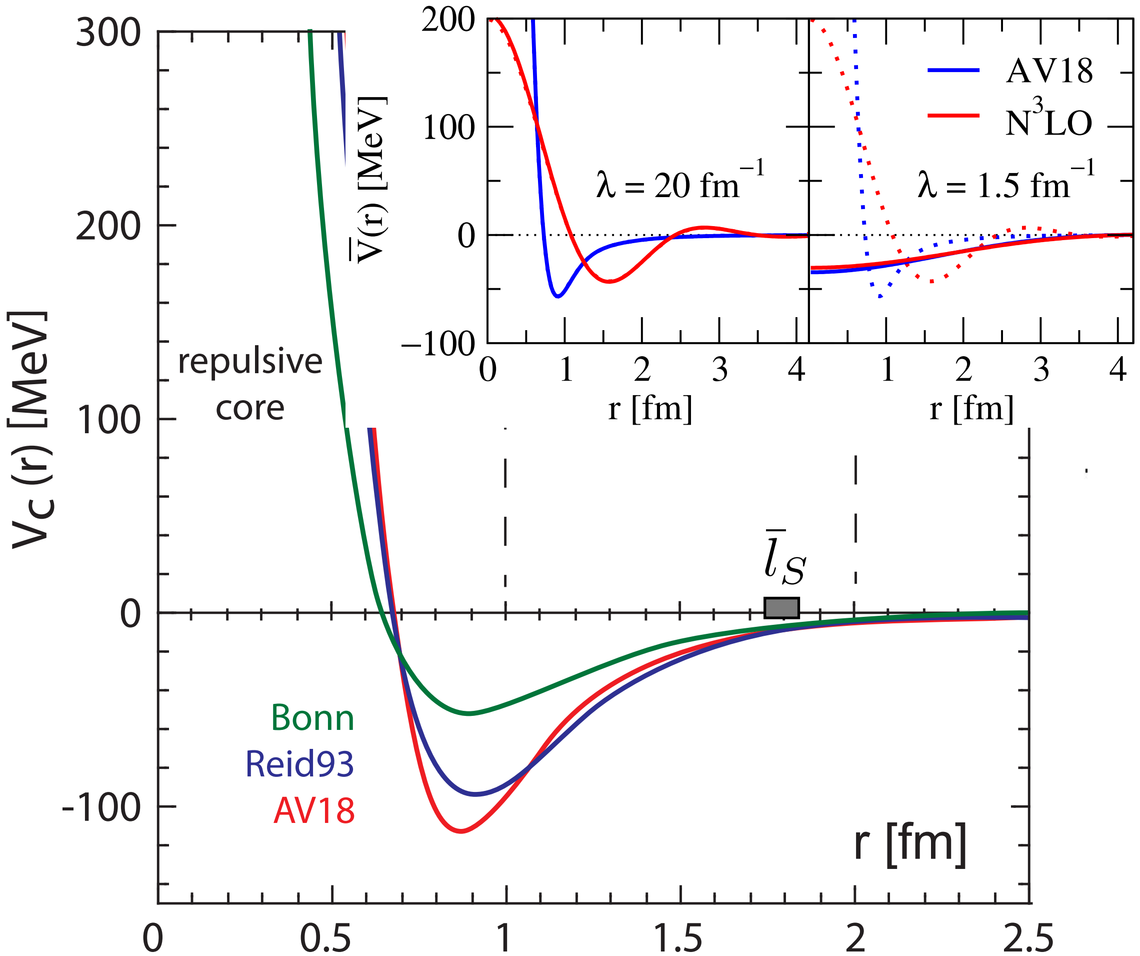


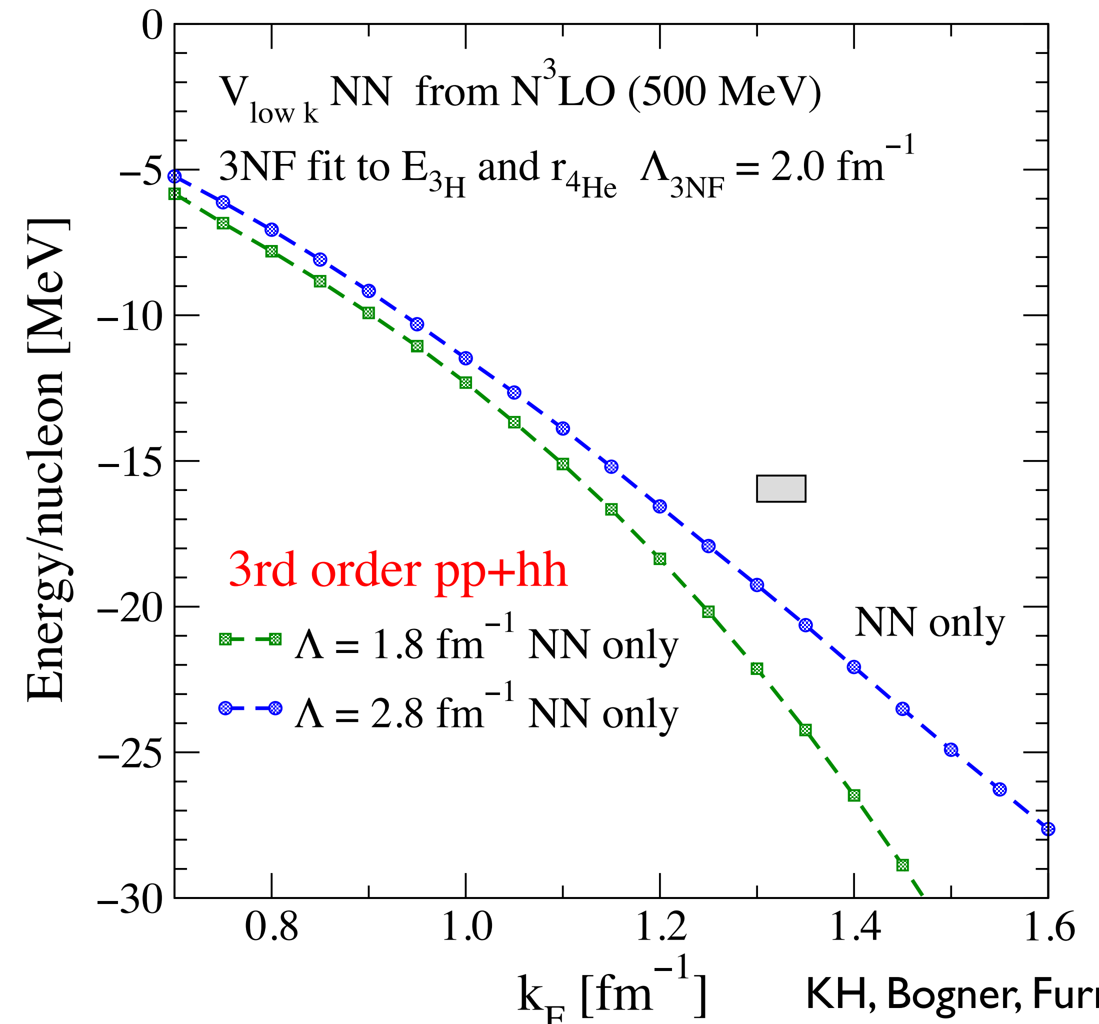
"Very soft potentials must be excluded because they do not give saturation; they give too much binding and too high density. In particular, a substantial tensor force is required."

Hans Bethe (1971)

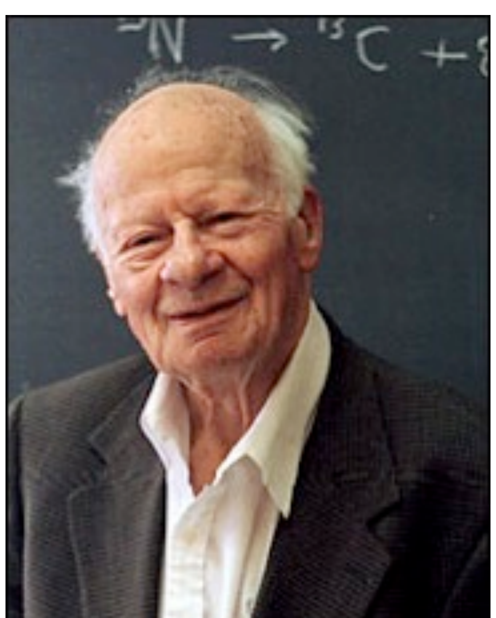


Equation of state of symmetric nuclear matter, nuclear saturation





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

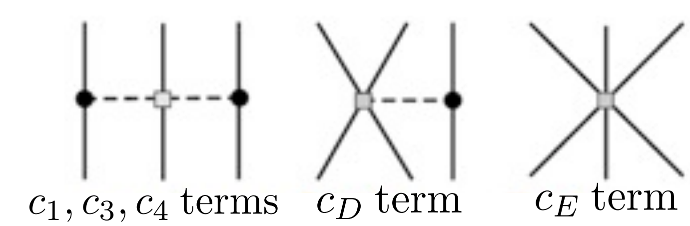


"Very soft potentials must be excluded because they do not give saturation; they give too much binding and too high density. In particular, a substantial tensor force is required."

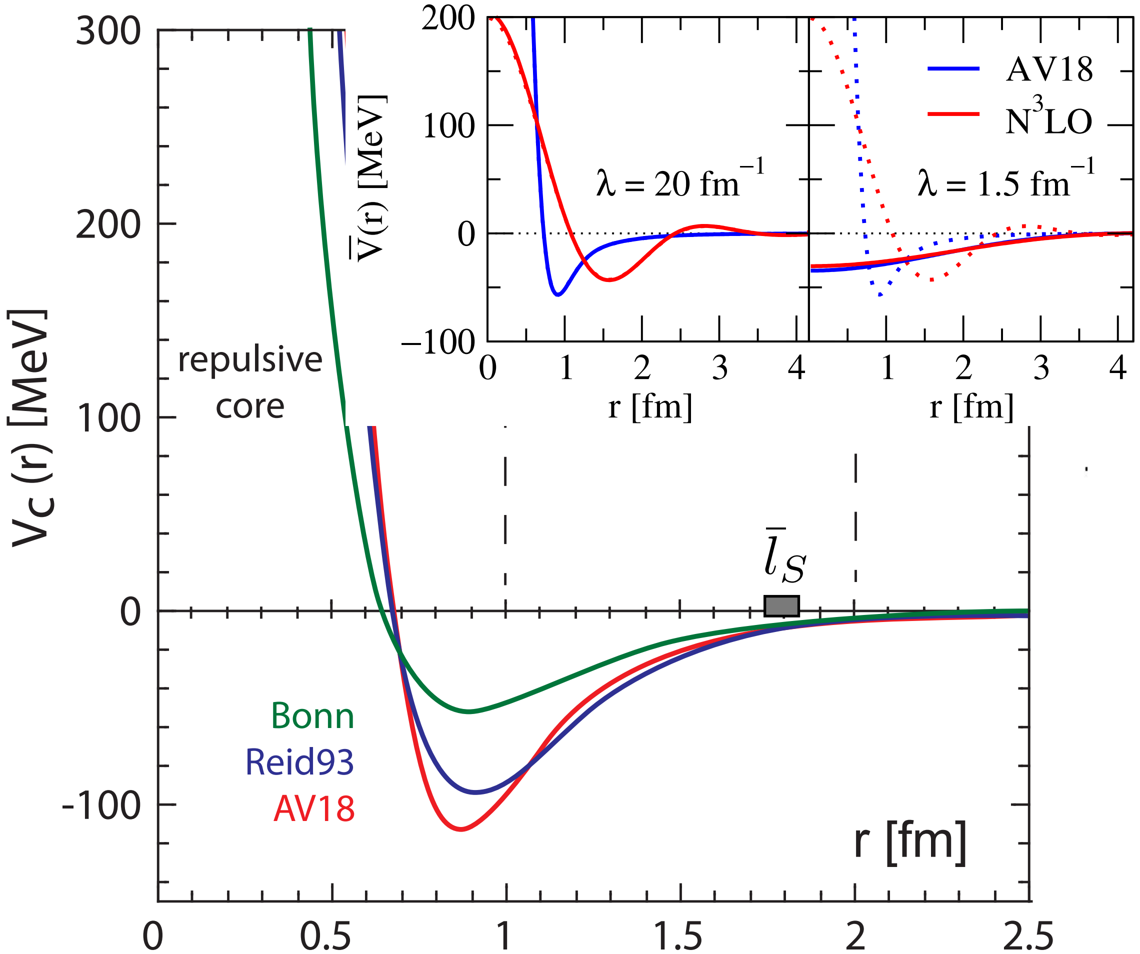
Hans Bethe (1971)

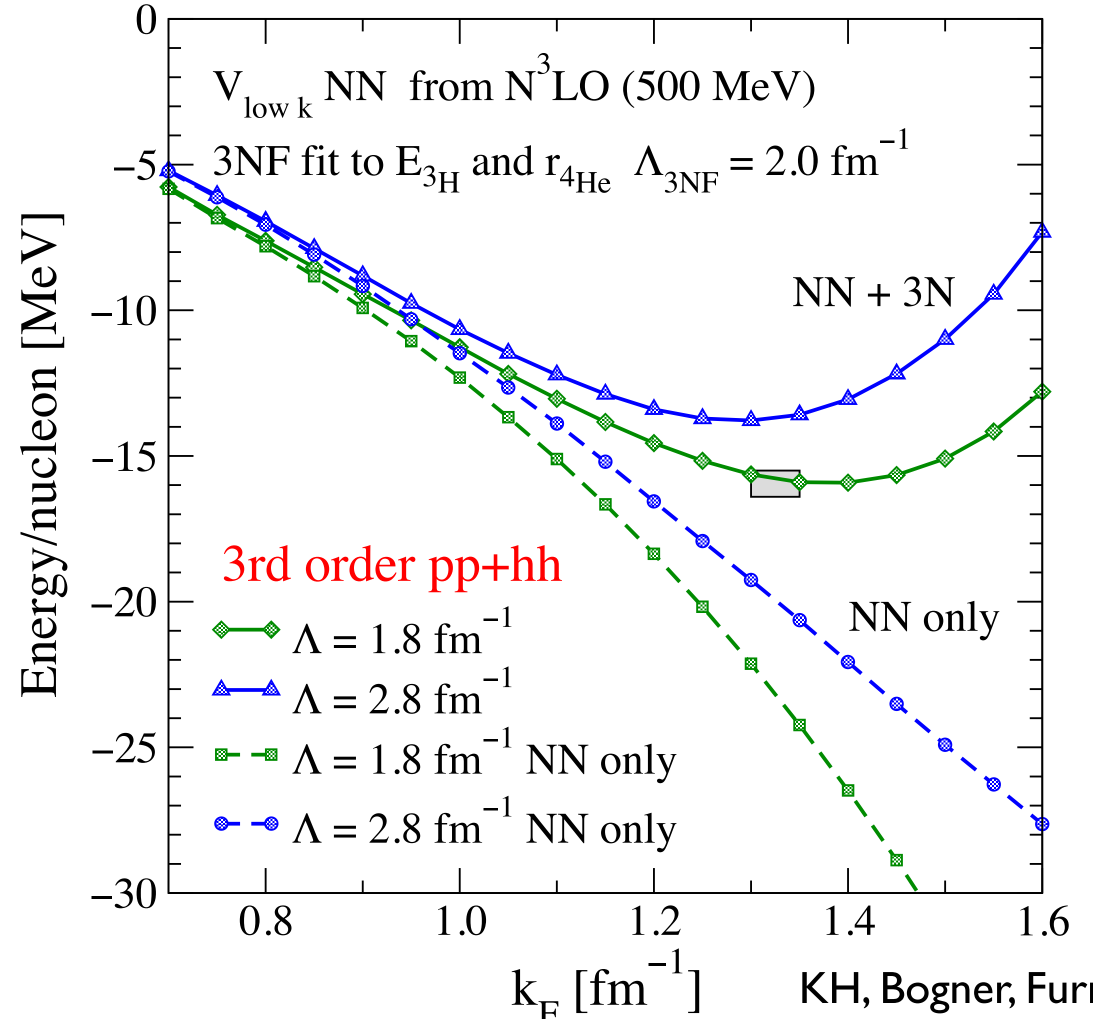
intermediate (c_D) and short-range (c_E) 3NF couplings fitted to few-body systems at different resolution scales:

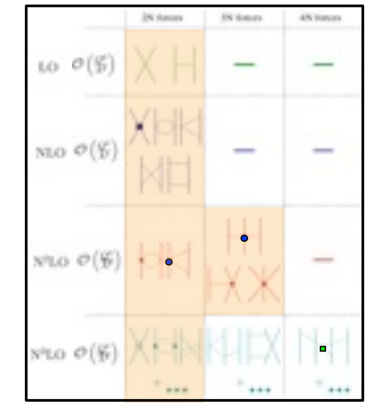
$$E_{^3\mathrm{H}} = -8.482\,\mathrm{MeV} \qquad r_{^4\mathrm{He}} = 1.464\,\mathrm{fm}$$



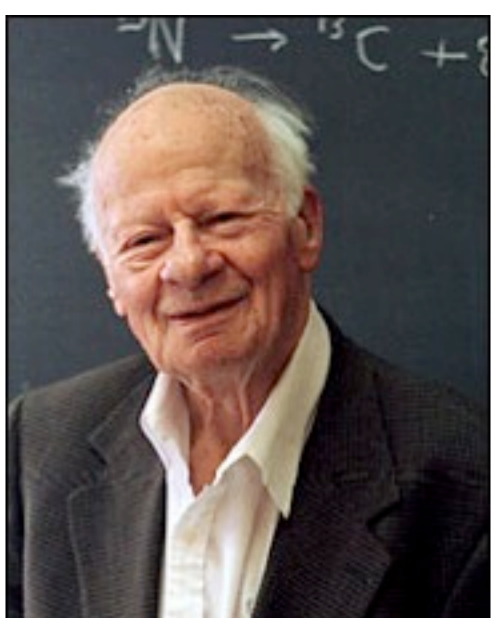
Equation of state of symmetric nuclear matter, nuclear saturation







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



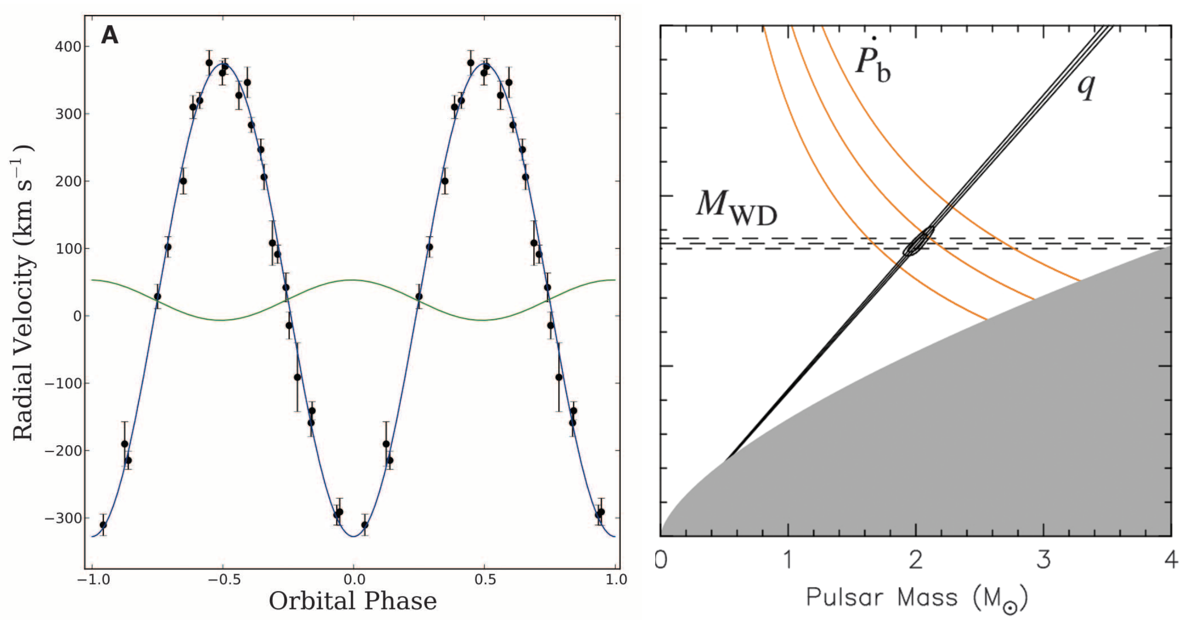
"Very soft potentials must be excluded because they do not give saturation;
they give too much binding and too high density. In particular, a substantial tensor force is required."

Hans Bethe (1971)

Reproduction of saturation point
without readjusting parameters!

Constraints on the nuclear equation of state (EOS)

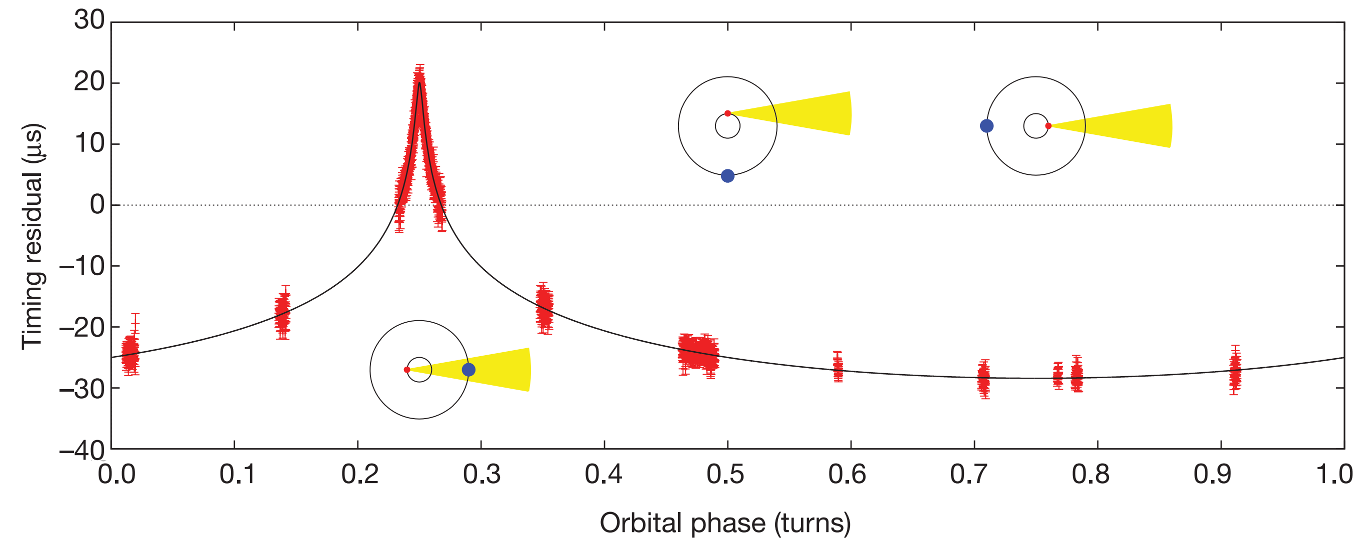
Science — A Massive Pulsar in a Compact Relativistic Binary



Antoniadis et al., Science 340, 448 (2013)

nature — A two-solar-mass neutron star measured using Shapiro delay

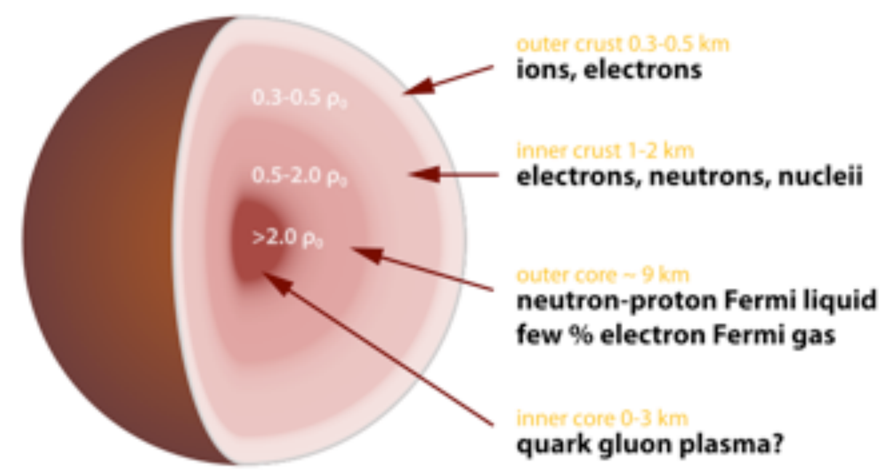
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]



Demorest et al., Nature 467, 1081 (2010)

New constraints from recent observations:

$$M_{\mathrm{max}} = 1.65 M_\odot \rightarrow 1.97 \pm 0.04\, M_\odot$$
$$\rightarrow 2.01 \pm 0.04\, M_\odot$$



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

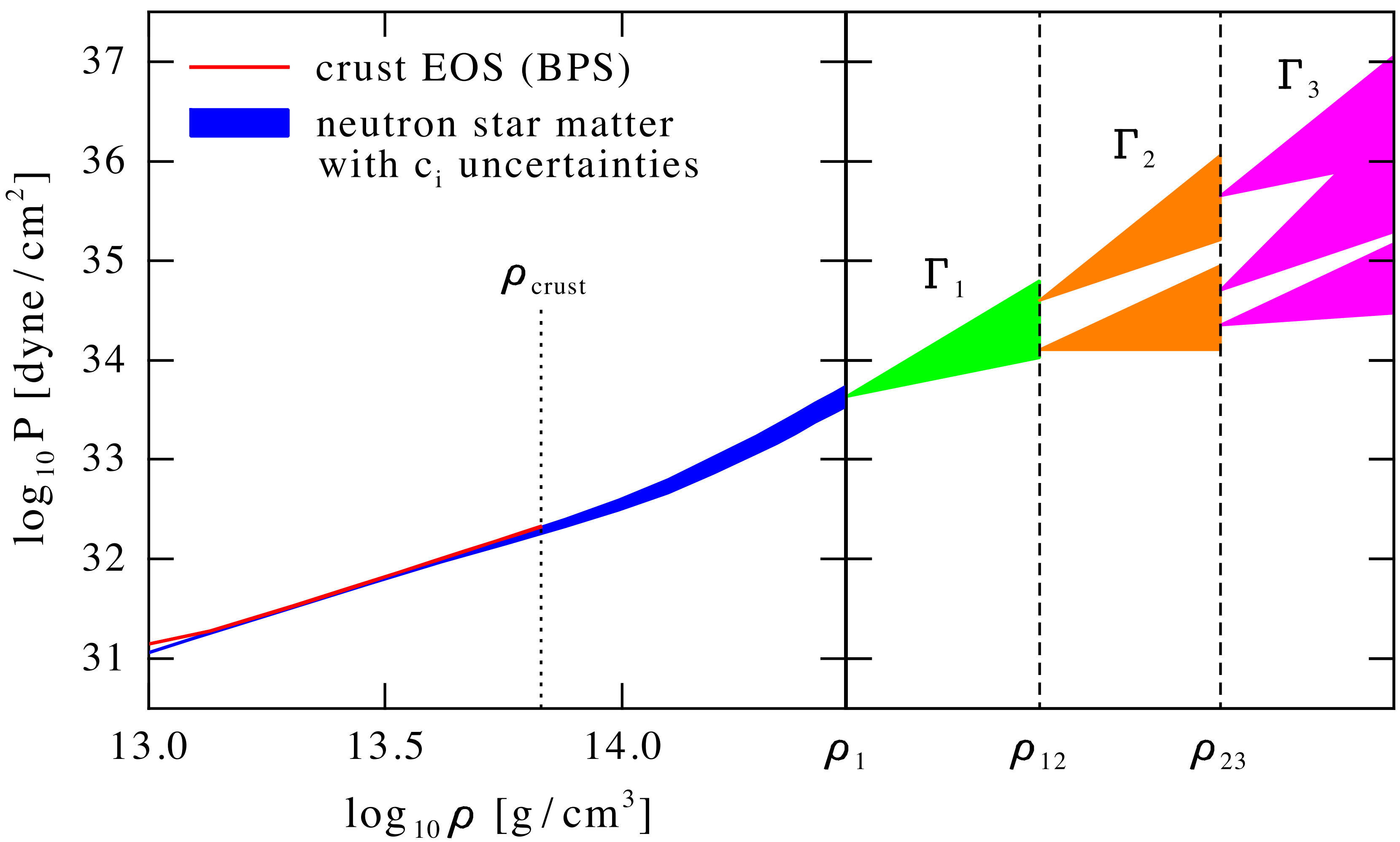
Strategy:
Use observations to constrain the high-density part of the nuclear EOS.

Neutron star radius constraints

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

parametrize piecewise high-density extensions of EOS:

- use polytropic basis functions $p \sim \rho^{\Gamma}$
- 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:

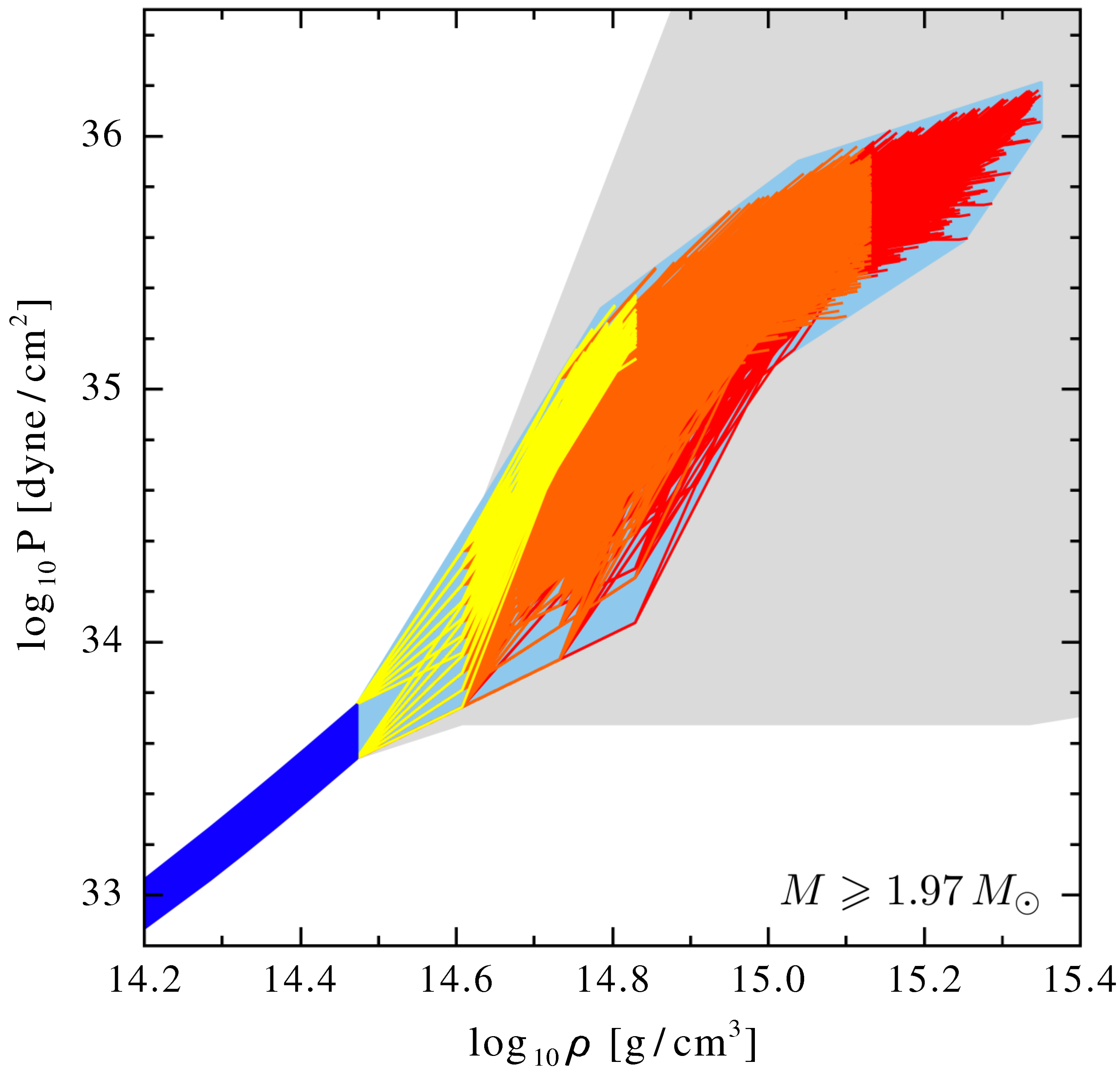
recent NS observations

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

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 the nuclear equation of state

use the constraints:

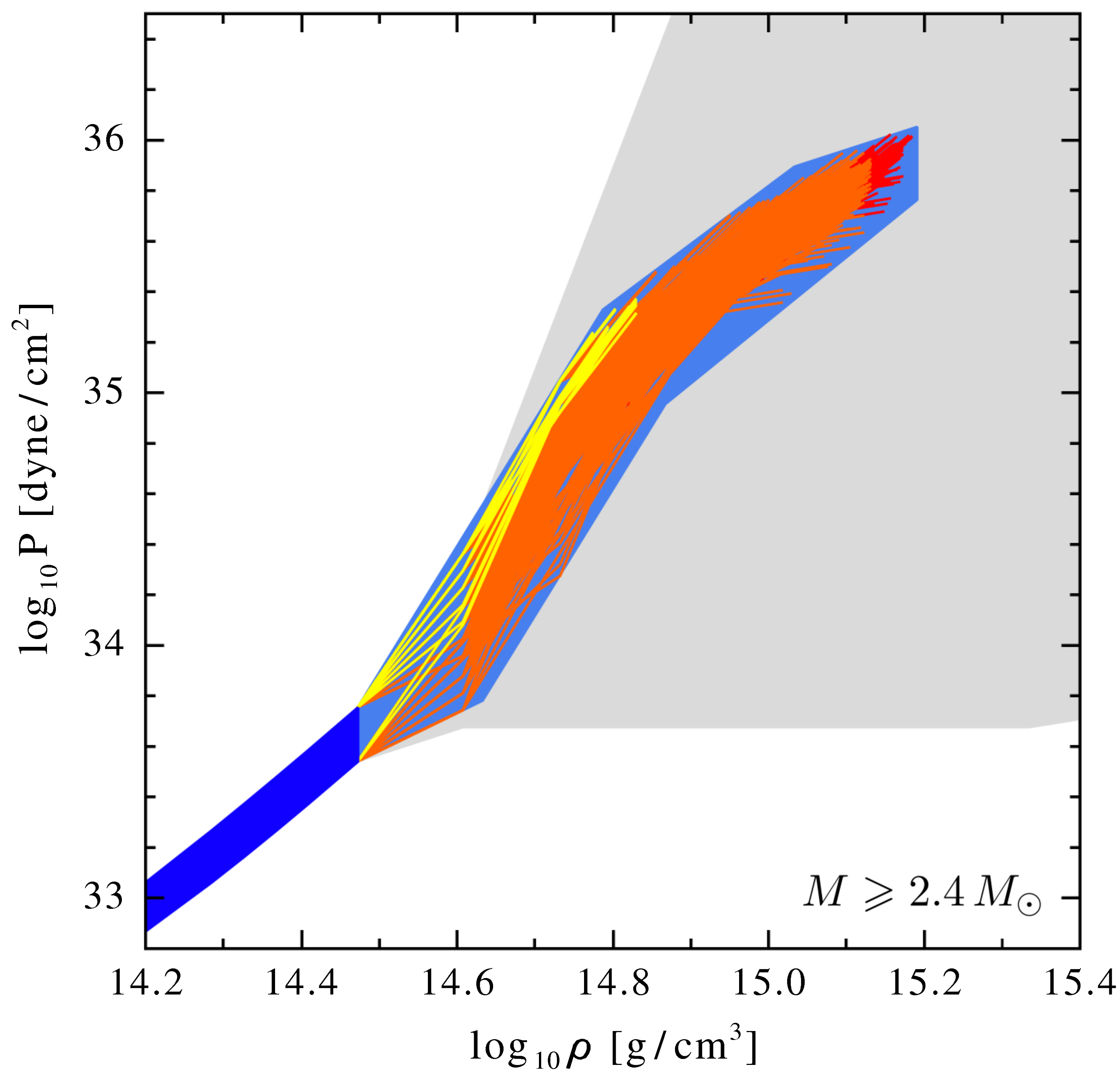
fictitious NS mass

$$M_{\max} > 2.4\, M_\odot$$

causality

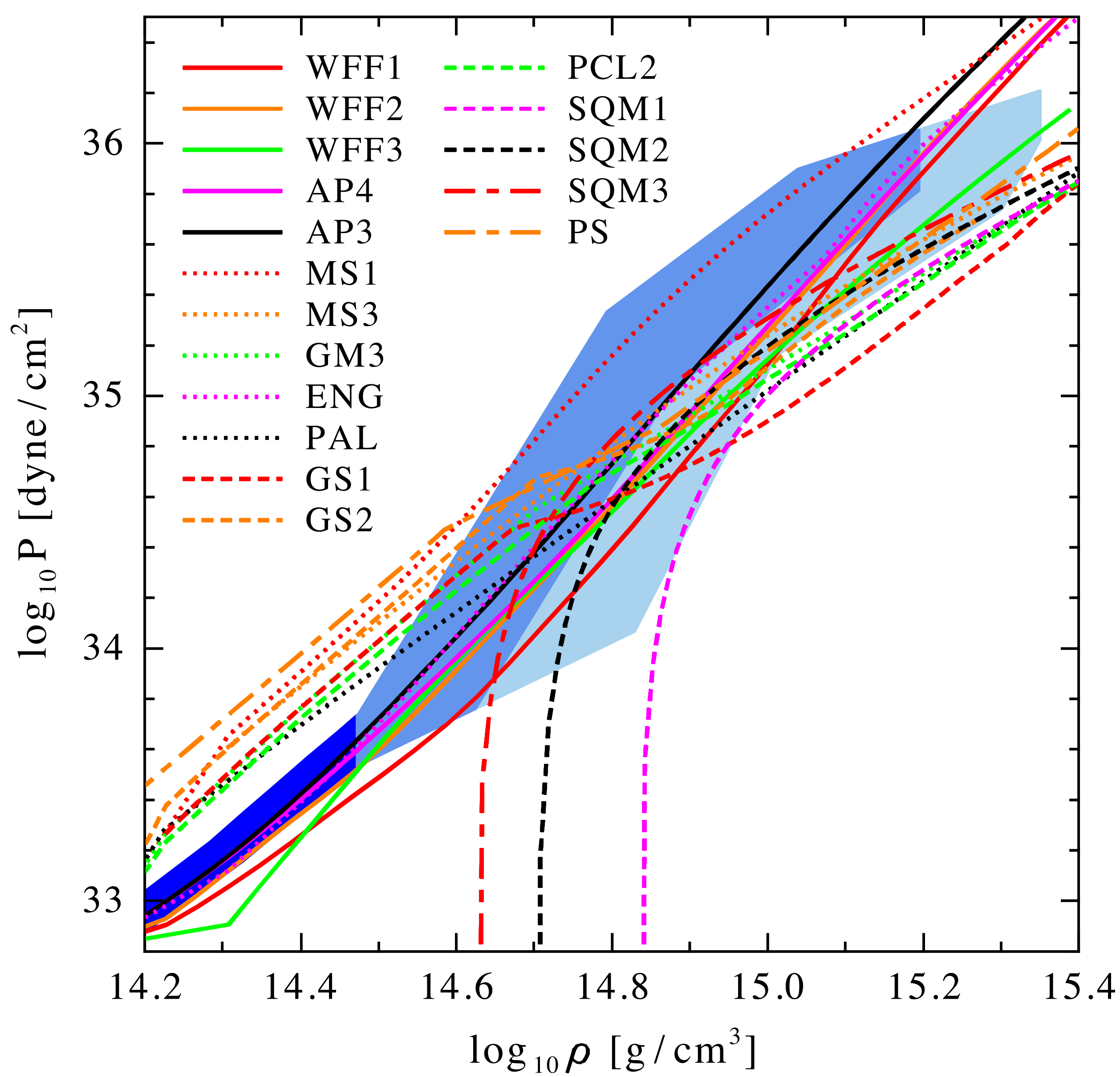
$$v_s(\rho) = \sqrt{dP/d\varepsilon} < c$$

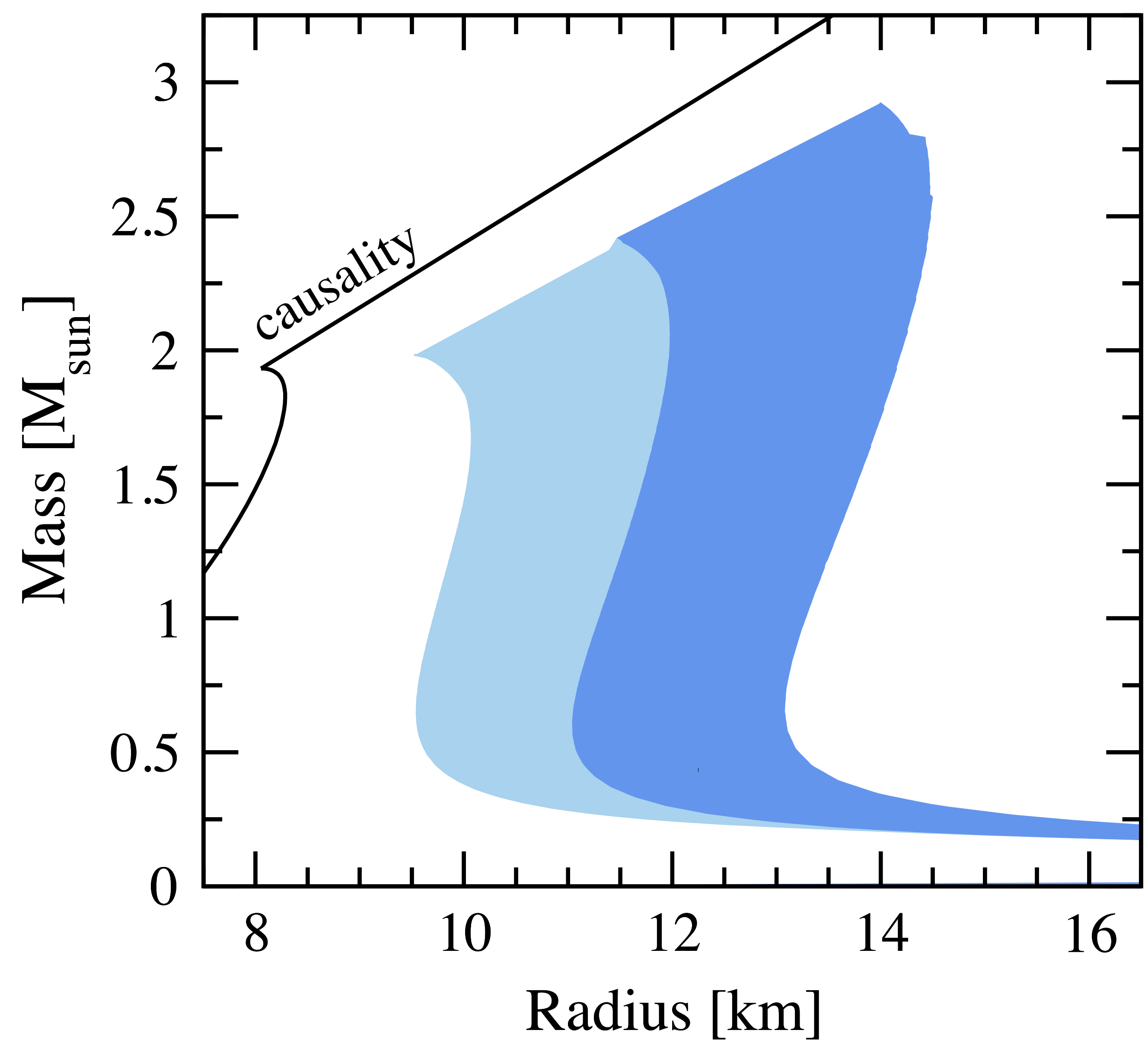
KH, Lattimer, Pethick, Schwenk, ApJ 773, 11 (2013)



increased $M_{\max}$ systematically reduces width of band

Constraints on neutron star radii

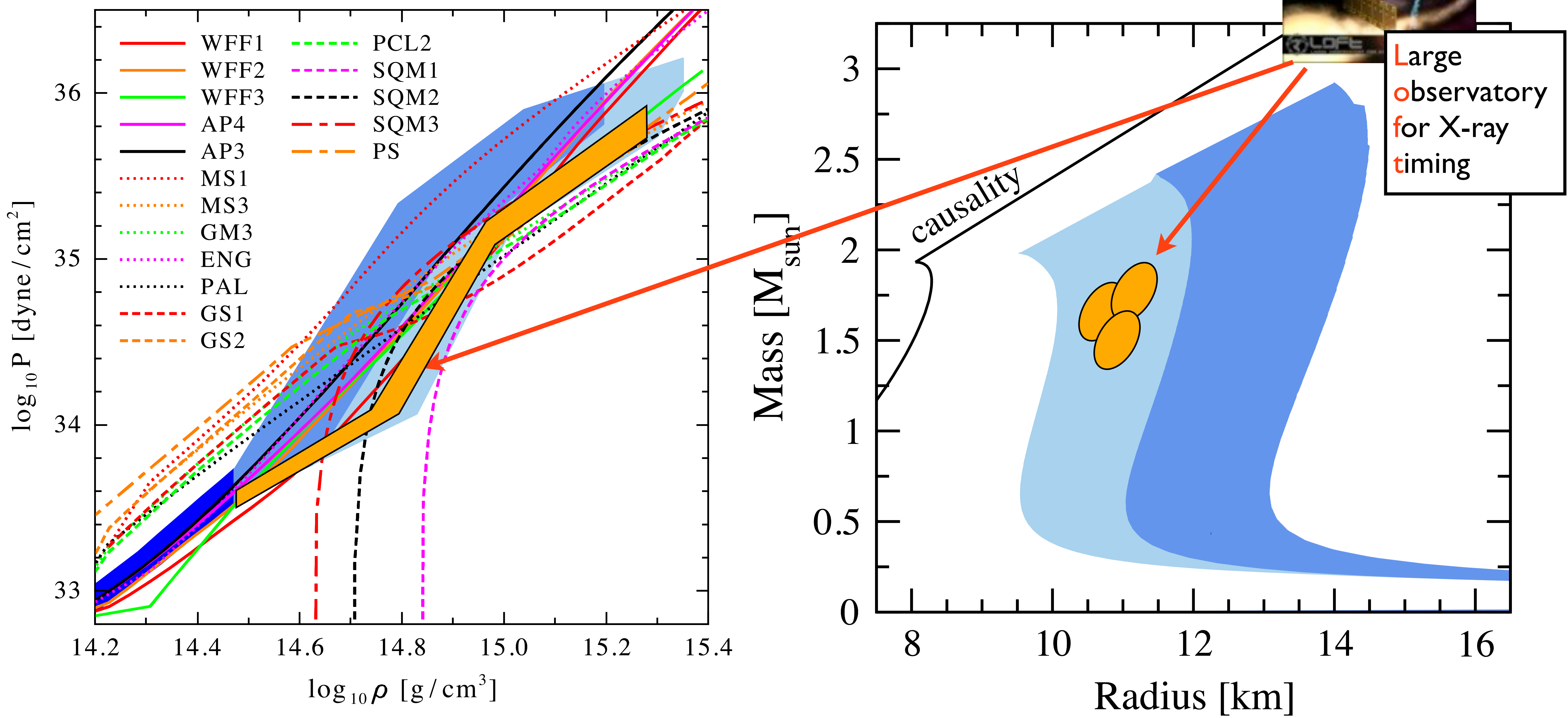




KH, Lattimer, Pethick, Schwenk, ApJ 773, 11 (2013)
see also KH, Lattimer, Pethick, Schwenk, PRL 105, 161102 (2010)

- low-density part of EOS sets scale for allowed high-density extensions
- current radius prediction for typical $1.4\,M_\odot$ neutron star: $9.7 - 13.9\,\mathrm{km}$

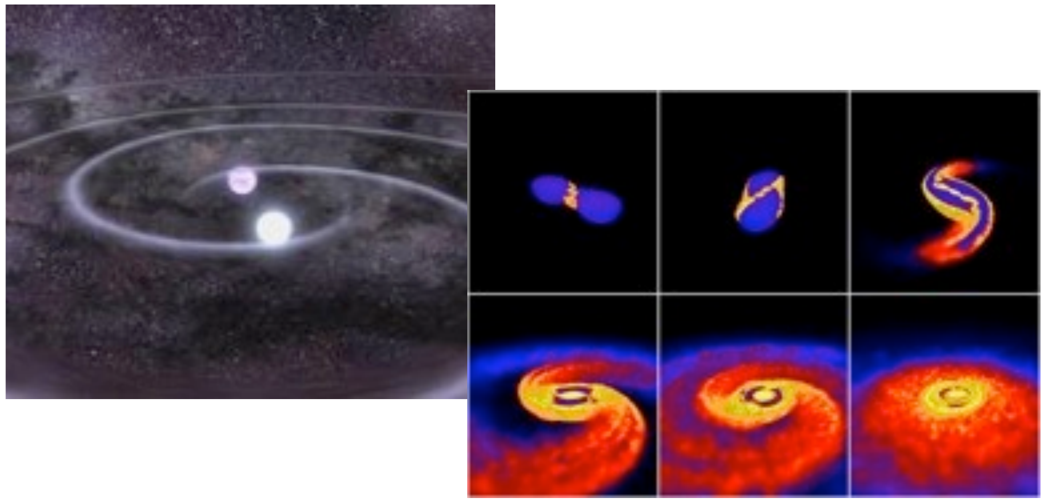
Constraints on neutron star radii

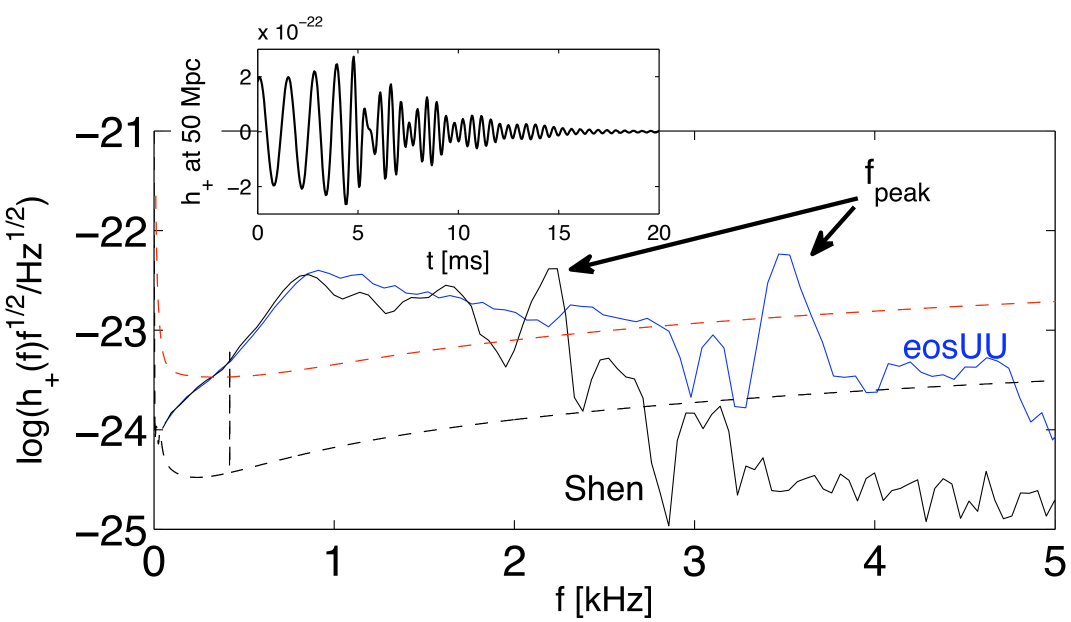


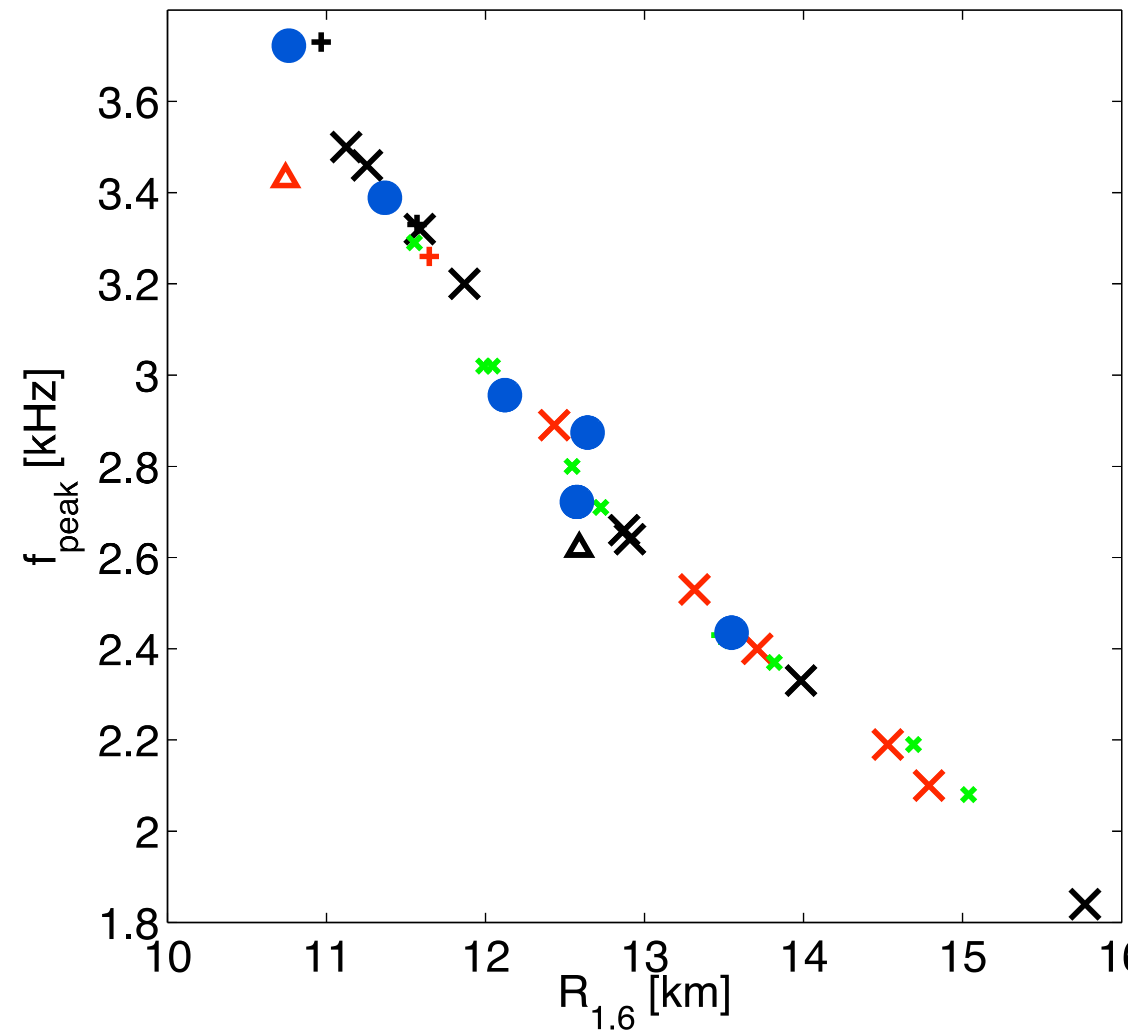
KH, Lattimer, Pethick, Schwenk, ApJ 773, 11 (2013)
see also KH, Lattimer, Pethick, Schwenk, PRL 105, 161102 (2010)

- low-density part of EOS sets scale for allowed high-density extensions
- current radius prediction for typical $1.4\,M_\odot$ neutron star: $9.7 - 13.9\,\mathrm{km}$
- proposed LOFT mission could significantly improve constraints

Gravitational wave signals from neutron star binary mergers



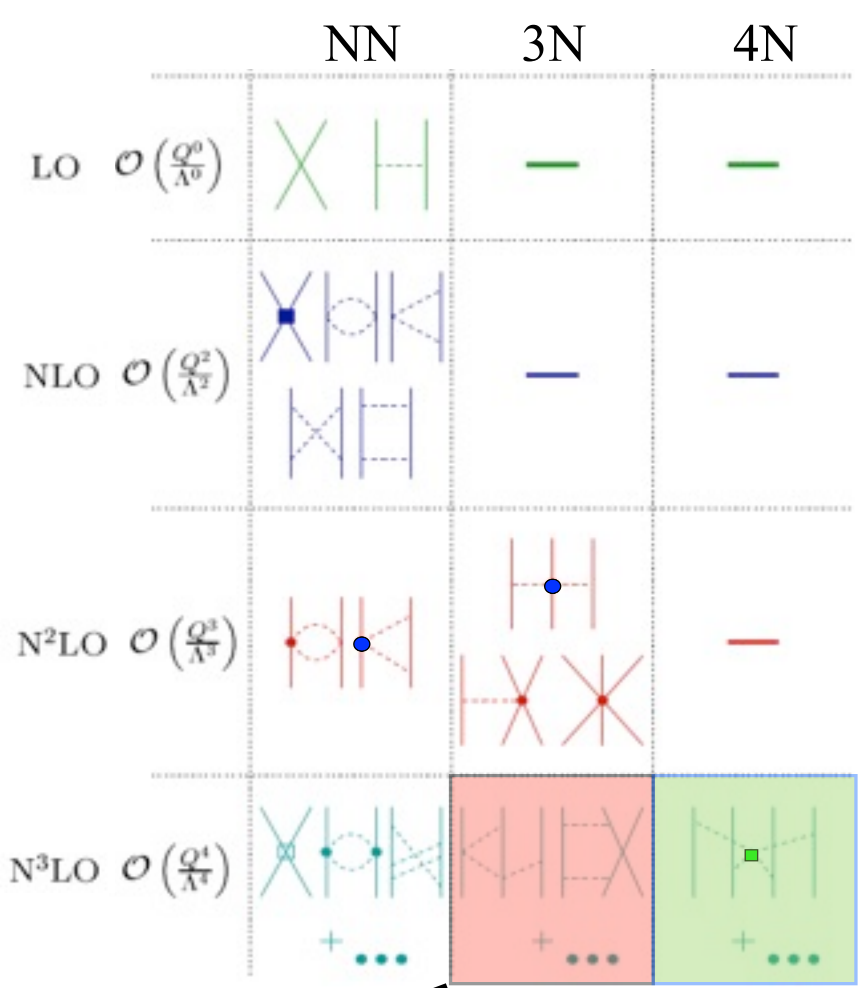




Bauswein and Janka, PRL 108, 011101 (2012),
Bauswein, Janka, KH, Schwenk, PRD 86, 063001

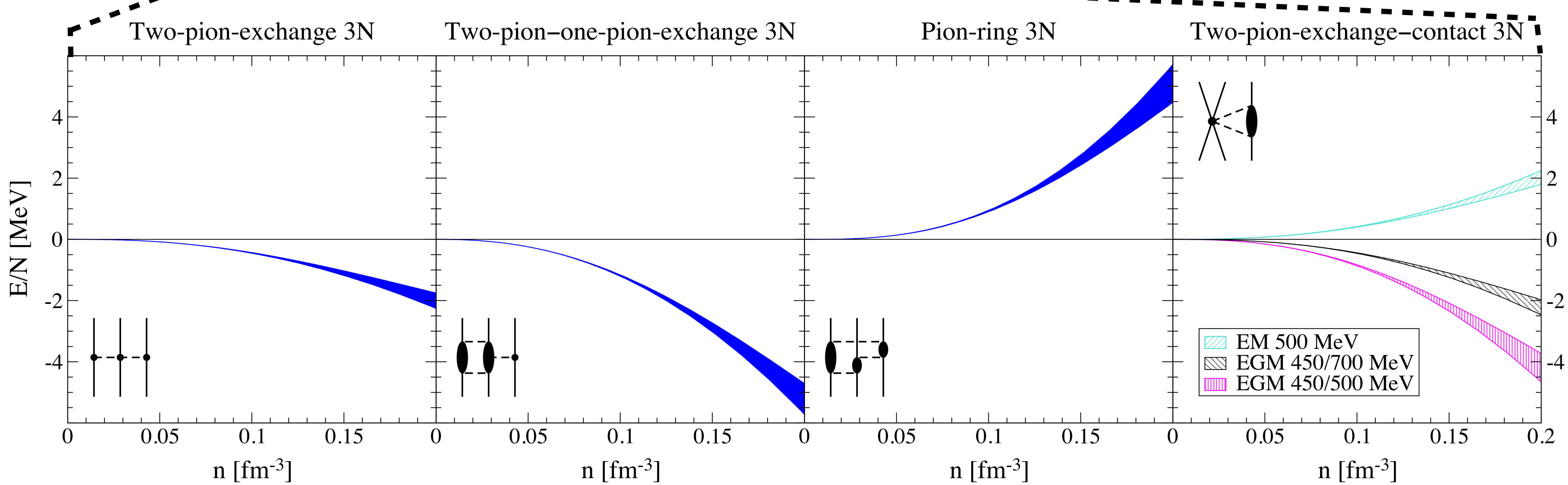
- simulations of NS binary mergers show strong correlation between between f_{peak} of the GW spectrum and the radius of a NS
- measuring f_{peak} is key step for constraining EOS systematically at large ρ

Contributions of many-body forces at N^{3}LO



- study chiral power counting in nuclear systems
- first calculations of N^{3}LO 3NF and 4NF contributions to EOS of neutron matter
- found large contributions, comparable to size of N^{2}LO contributions
- 4NF contributions small

Tews, Krüger, KH, Schwenk
PRL 110, 032504 (2013)



Calculation of many-body forces at N^3LO

Low
Energy
Nuclear
Physics
International
Collaboration

J. Golak, R. Skibinski, K. Tolponicki, H. Witala

E. Epelbaum, H. Krebs

A. Nogga

R. Furnstahl

S. Binder, A. Calci, K. Hebeler, J. Langhammer, R. Roth

P. Maris, J. Vary

H. Kamada

Goal

Calculate matrix elements in a form which is suitable for different few- and many-body frameworks

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Challenge

Due to the large number of matrix elements, the calculation is extremely expensive.

Strategy

Develop an efficient framework that allows to treat arbitrary 3N interactions. (Krebs and Hebeler)

Will enable improved calculations for nucleonic matter and nuclei based on the most advanced nuclear Hamiltonians.

Future directions:
Incorporation in different many-body frameworks

Hyperspherical harmonics

Bacca (TRIUMF), Barnea (Hebrew U.)

Faddeev, Faddeev-Yakubovski

Nogga (Juelich), Witala (Kracow)

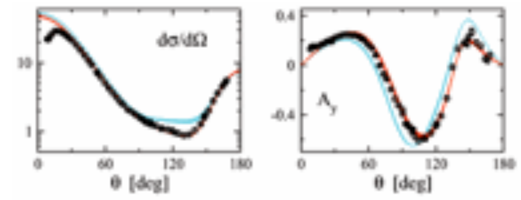


FIG. 4: Nd elastic observables at 65 MeV.

no-core shell model

Roth, Calci, Langhammer, Binder (TU Darmstadt)
Navratil (TRIUMF), Vary (Iowa)

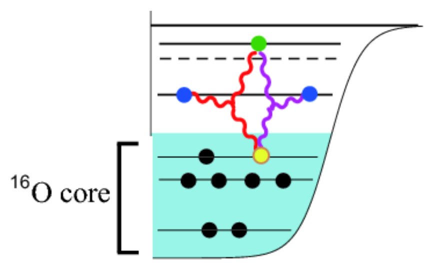
coupled cluster method

Ekstroem, Hagen, Papenbrock (Oak Ridge)

$$|\Psi\rangle = e^{\hat{T}}|\Phi_0\rangle = \left(1+\hat{T}+\frac{1}{2}\hat{T}^2+\frac{1}{3!}\hat{T}^3+\cdots\right)|\Phi_0\rangle,$$

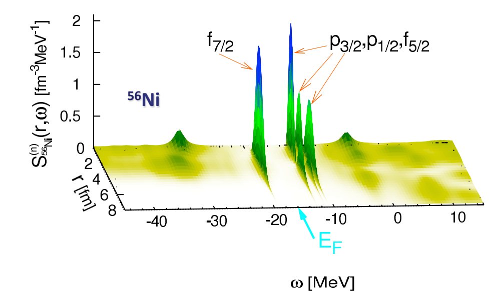
valence shell model

Holt, Menendez, Schwenk
(TU Darmstadt)

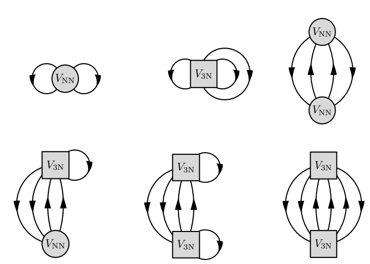


Self-consistent Greens function

Barbieri (Surrey), Duguet, Soma (CEA)

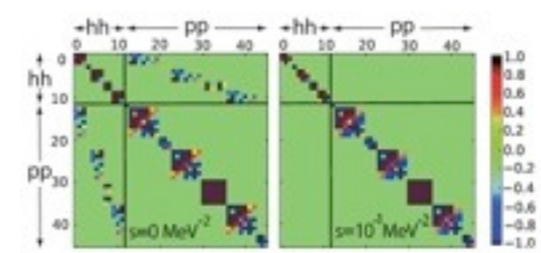


Many-body perturbation theory



In-medium SRG

Bogner (MSU), Hergert (OSU),
Holt (TU Darmstadt)



Required inputs:

1. consistent NN and 3N forces at N^3LO in partial-wave-decomposed form
2. softened forces for judging approximations and pushing to heavier nuclei

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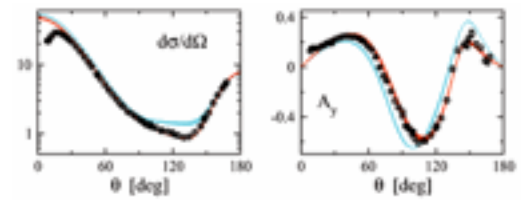

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no-core shell model
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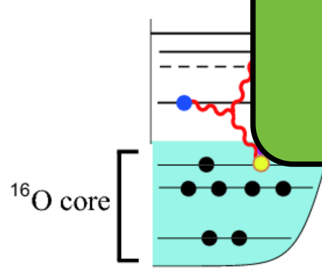
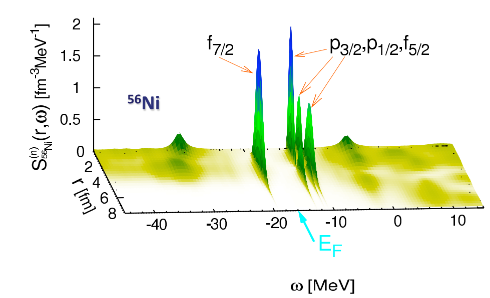


Stay tuned!

…tent …nction
Barbieri (Surrey), Duguet, Soma (CEA)



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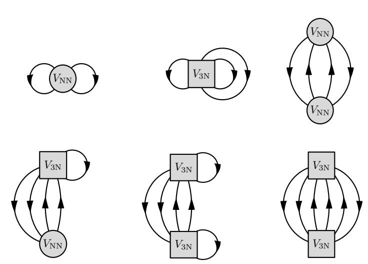

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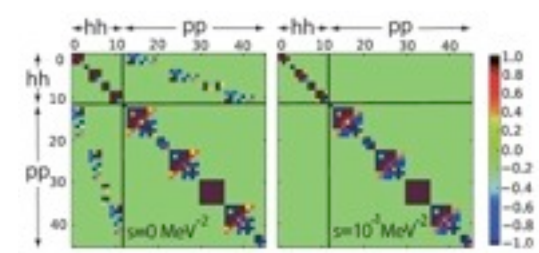

Required inputs:

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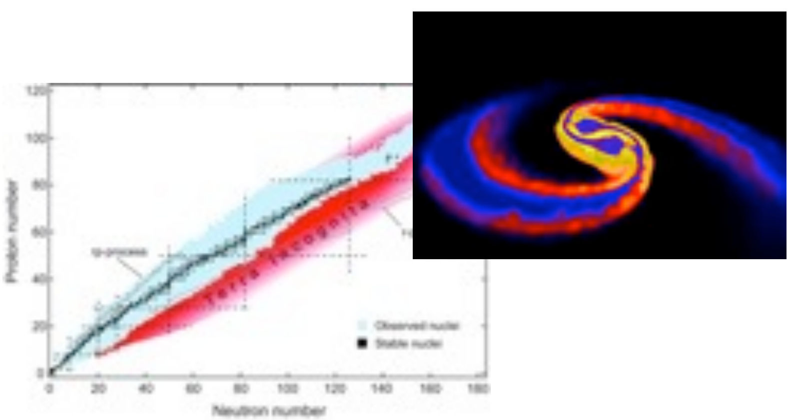
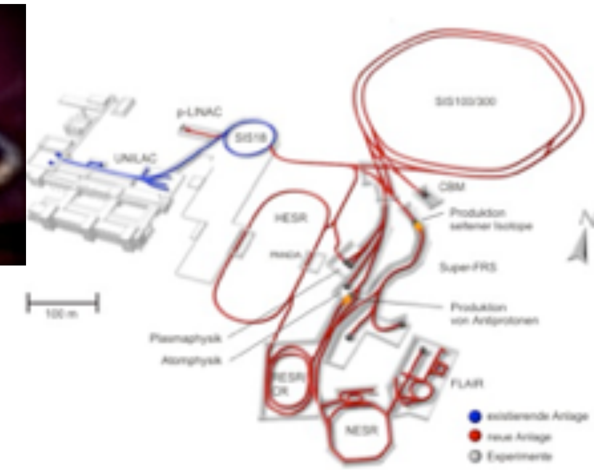
Summary

- chiral EFT provides systematic approach to nuclear interactions
- derived constraints for symmetry energy, EOS of neutron-rich matter and properties of neutron stars
- calculation of sub-leading 3NF forces for novel ab-initio studies
- observables resolution independent, interpretation can change!





Outlook

- study of neutron-rich nuclei and matter based on the same Hamiltonians (halo nuclei, drip line, nuclear saturation, ...)
- new EOS constraints at low and high densities (LOFT, GW waves)
- validation and optimization of nuclear interactions, power counting?
- derivation of systematic uncertainty estimates

In collaboration with:

TECHNISCHE UNIVERSITÄT DARMSTADT — A. Calci, C. Drischler, T. Krüger, R. Roth, A. Schwenk, I. Tews

S. Bogner, A. Ekstroem

A. Gezerlis,

J. Lattimer

J. Golak, R. Skibinski

R. Furnstahl, S. More

E. Epelbaum, H. Krebs

A. Nogga

C. Pethick

international collaborator in NUCLEI Nuclear Computational Low-Energy Initiative

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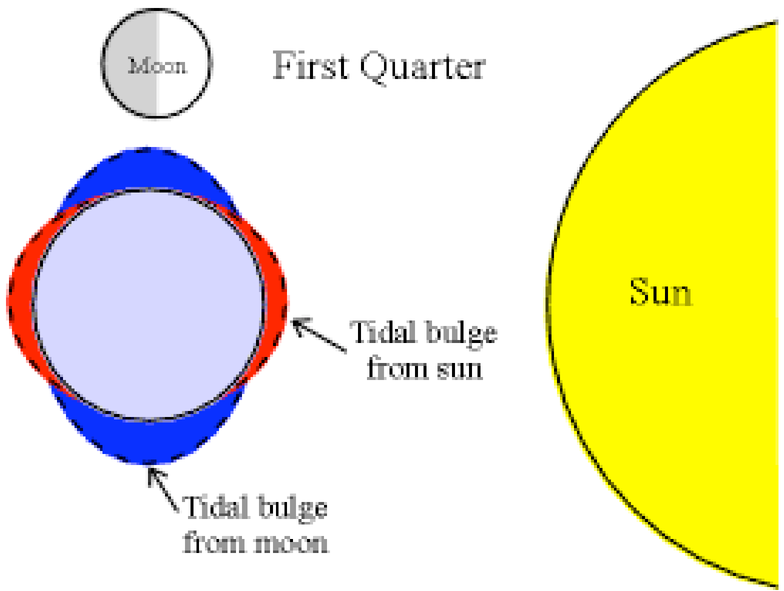
computing support:

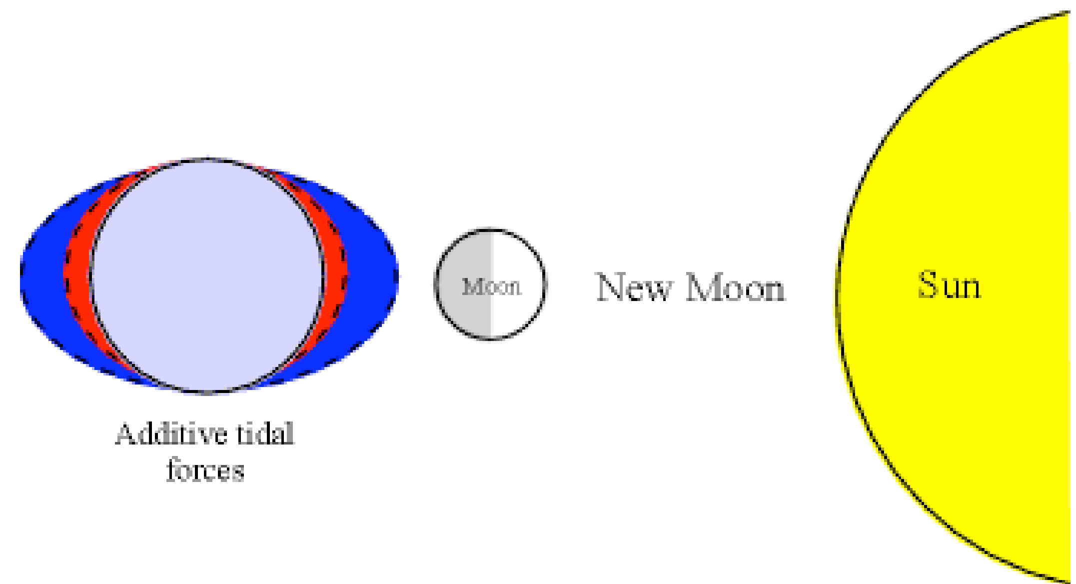
HRZ Hochschulrechenzentrum — SciDAC Scientific Discovery through Advanced Computing — Ohio Supercomputer Center — JÜLICH FORSCHUNGSZENTRUM JUROPA

Why are there 3N forces?

Classical analog

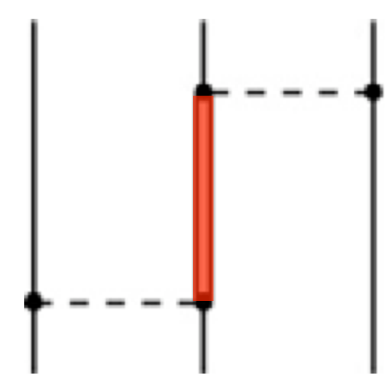
Tidal effects lead to 3N forces in earth-sun-moon system:



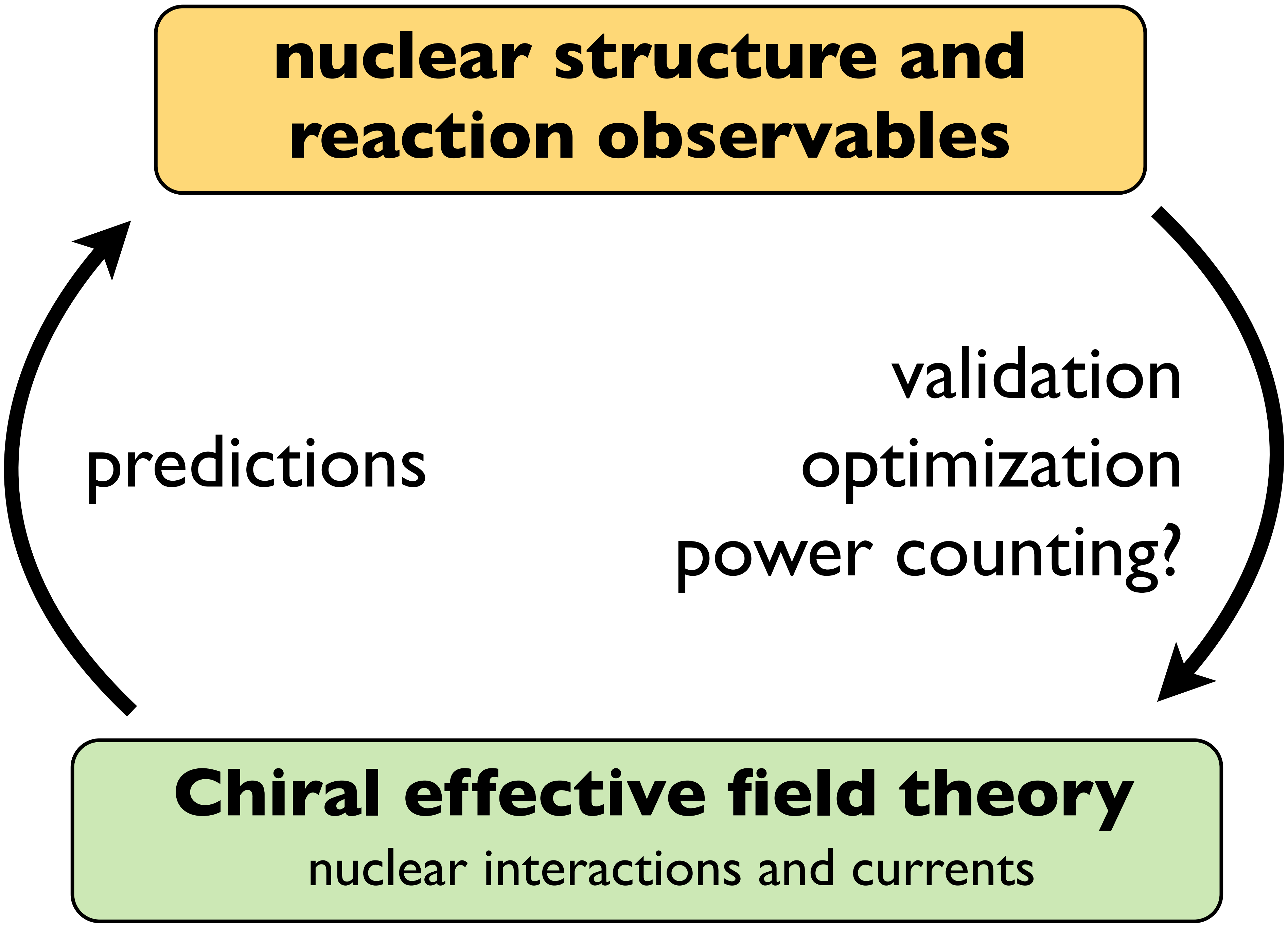


- force between earth and moon depends on the position of sun
- tidal deformations are internal excitations

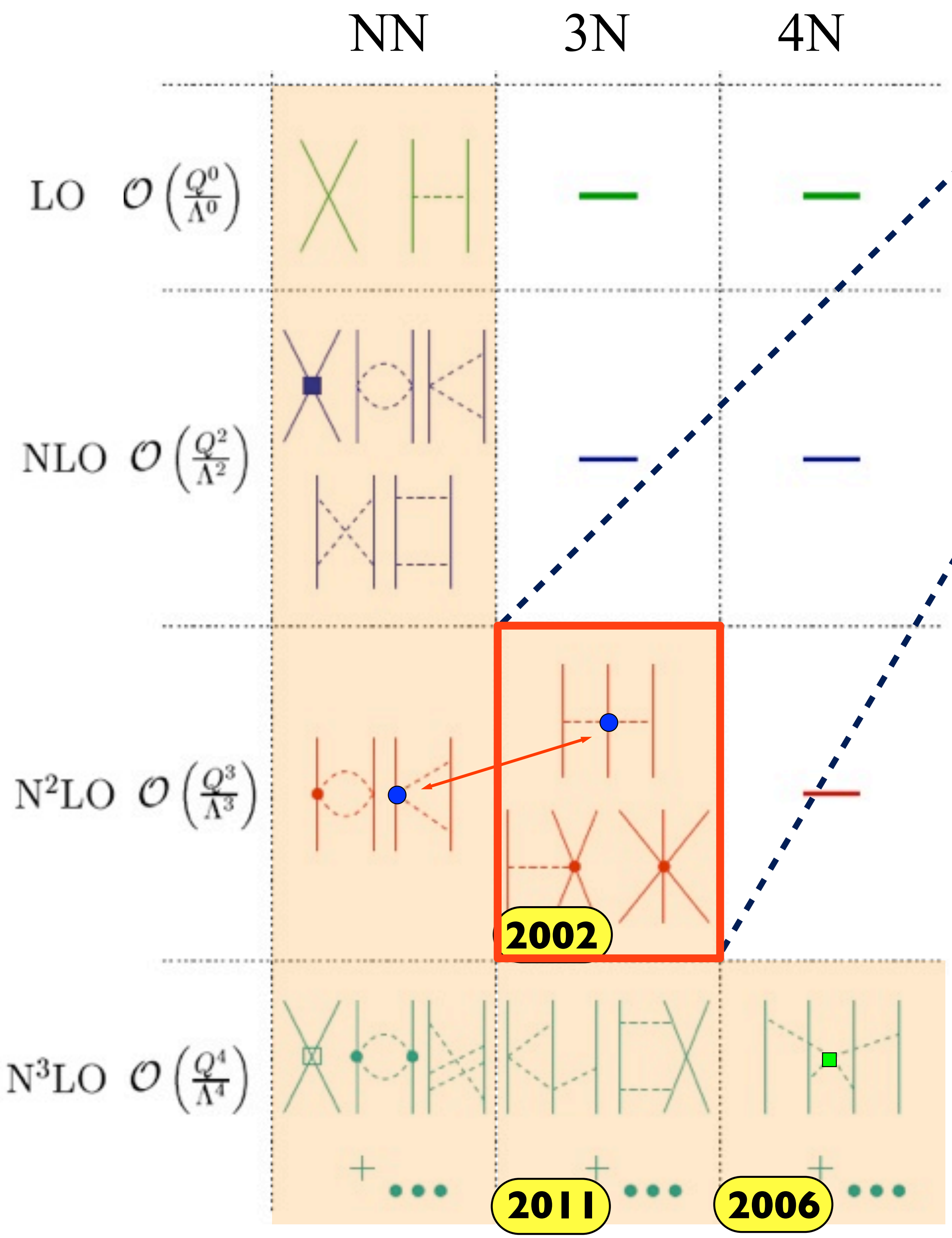
- nucleons are composite particles, can also be excited
- change of resolution changes the excitations that can be described explicitly ⟶ change of 3N force
- three-nucleon forces are crucial at low resolution!

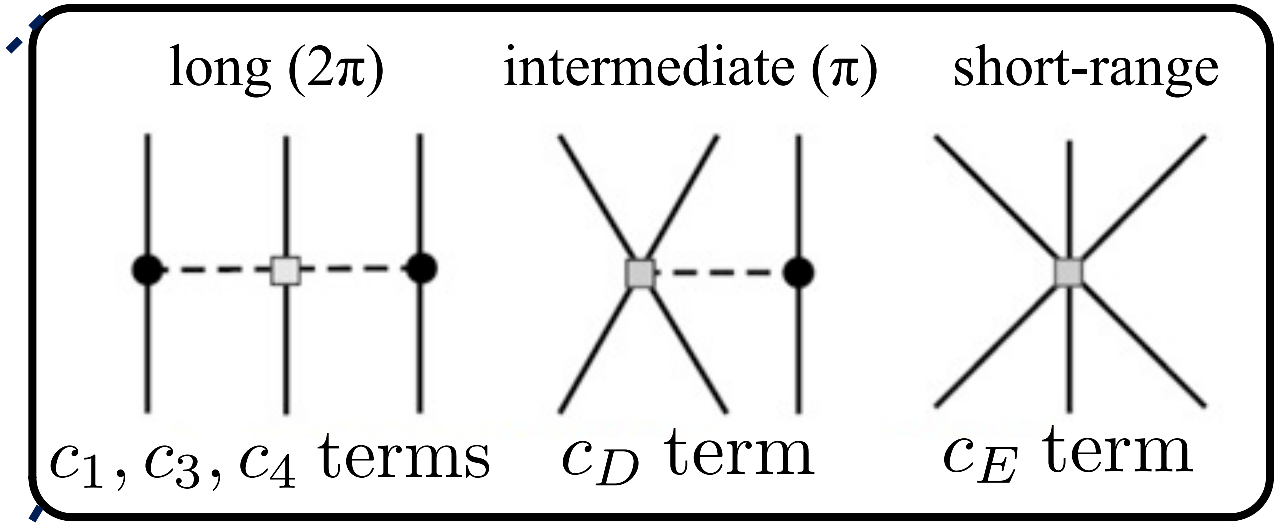


Ab initio nuclear structure theory



Chiral EFT for nuclear forces, leading order 3N forces





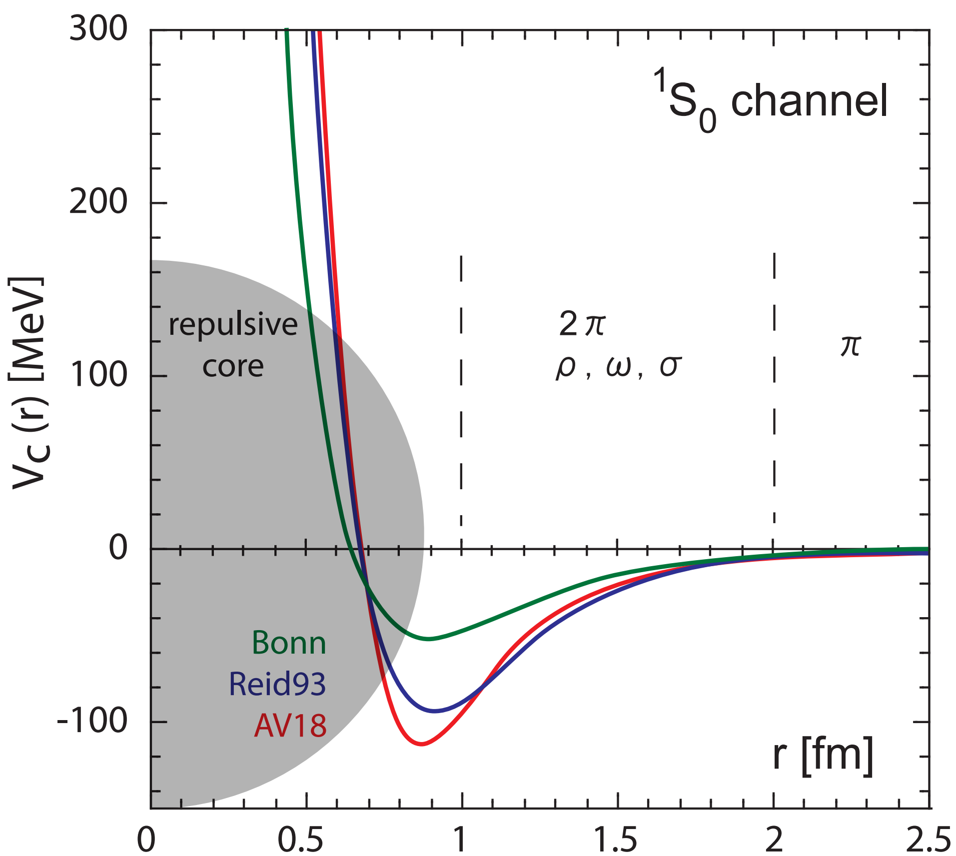
large uncertainties in coupling constants at present:

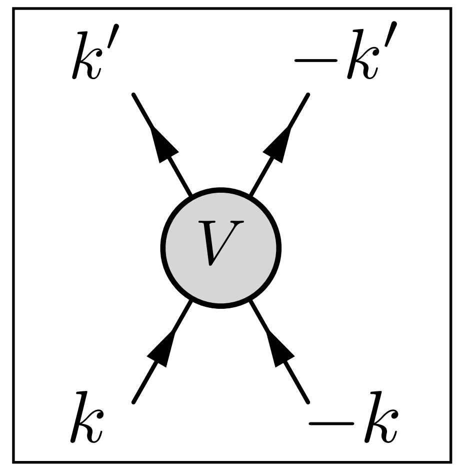
$$c_1 = -0.9^{+0.2}_{-0.5}\ ,\ c_3 = -4.7^{+1.5}_{-1.0}\ ,\ c_4 = 3.5^{+0.5}_{-0.2}$$

lead to theoretical uncertainties in many-body observables

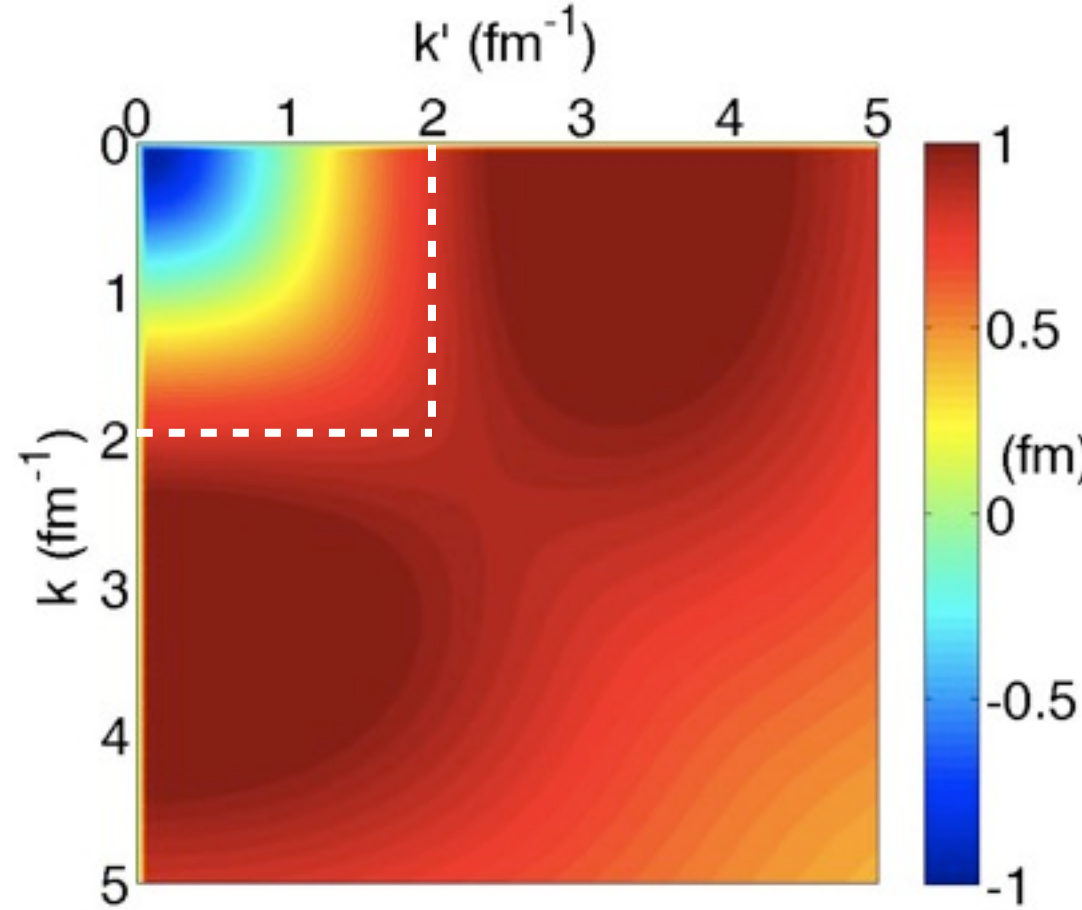
use chiral interactions as input for RG evolution

Problem: Traditional "hard" NN interactions





$$\langle k' | V | k \rangle$$



- constructed to fit scattering data (low-energy observables!)
- "hard" NN interactions contain repulsive core at small relative distance
- strong coupling between low and high-momentum components, hard to solve!

Claim:
Problems due to high resolution from interaction.