Neutron matter and pairing from low-momentum interactions

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Outline

1. Neutron matter based on large scattering length and effective range

with C.J. Pethick and P.T. Reuter PRL 95 (2005) 160401; and in prep.

NORDITA
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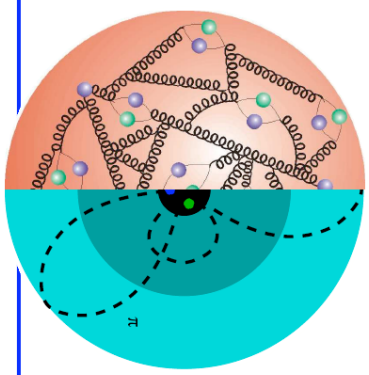
2. based on low-momentum interactions

with B. Friman, K. Hebeler, L. Tolos PL B648 (2007) 176; and arXiv:0711.3613.

GSI

Resolution Scale dependence of nuclear interactions

with high-energy probes:
deconfined quarks+gluons



Lattice QCD

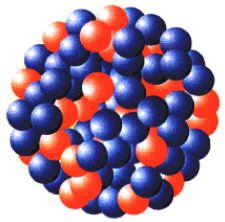
Effective theory for NN, many-N interactions, operators depend on resolution scale Λ

$$H(\Lambda) = T + V_{\rm NN}(\Lambda) + V_{\rm 3N}(\Lambda) + V_{\rm 4N}(\Lambda) + \ldots$$

$\Lambda_{\rm chiral}$

momenta $Q \sim \lambda^{-1} \sim m_\pi$: chiral effective field theory

nucleons interacting via pion exchanges + contact interactions



typical Fermi momenta in nuclei $\sim m_\pi$

$\Lambda_{\rm pionless}$

$Q \ll m_\pi$=140 MeV - pion not resolved:

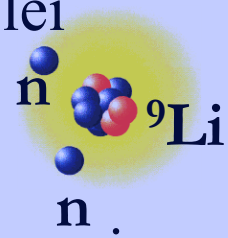
pionless effective field theory

large scattering lengths + corrections

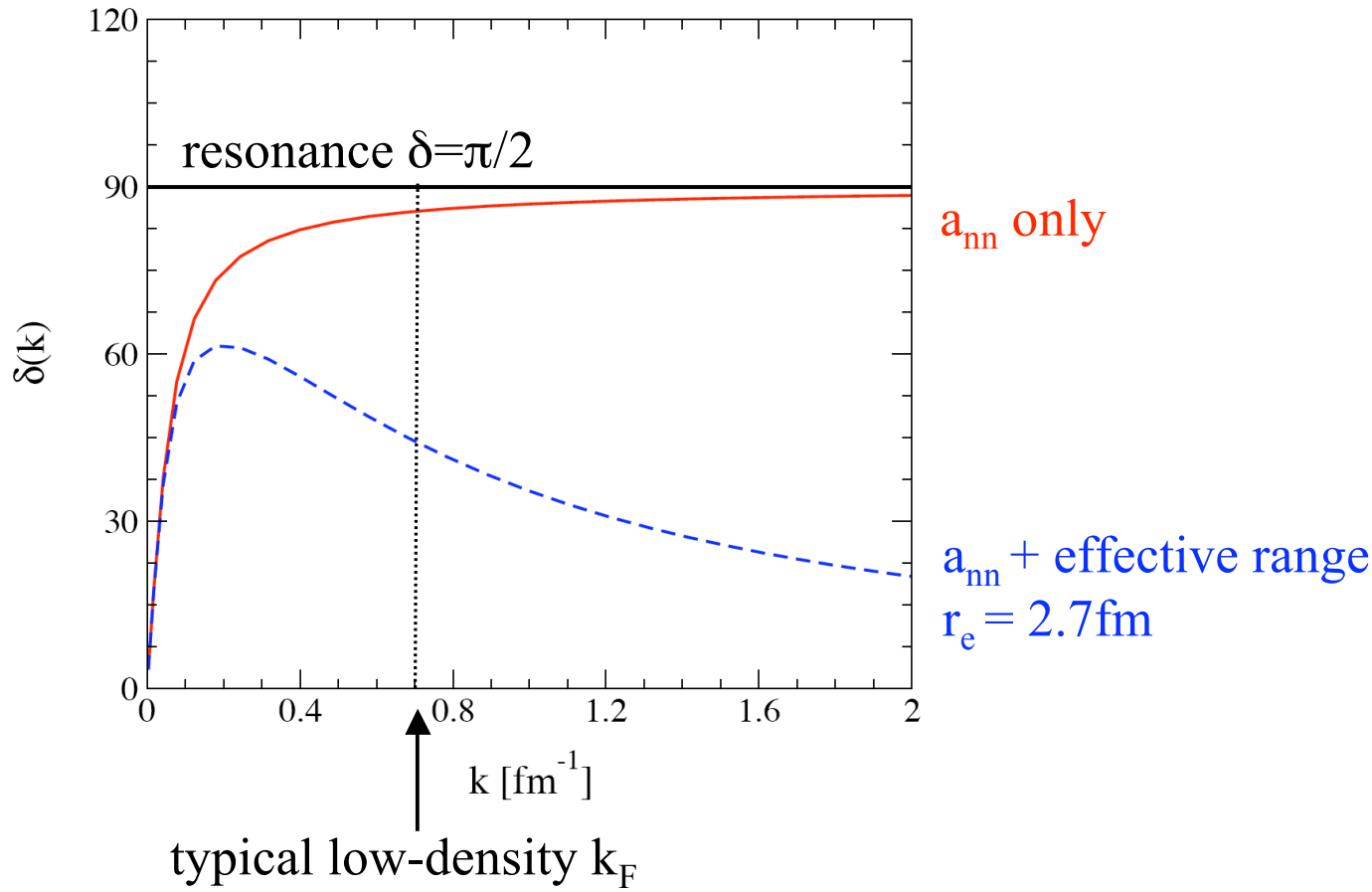
applicable to loosely-bound, dilute systems, reactions at astro energies

halo nuclei

……



1. Neutron matter based on large a_s and r_e



effective range appreciable, weakens interactions at higher momenta

fewer particles interact strongly

large effective range makes problem simpler

EFT for low-density neutron matter

di-fermion effective field theory for large a_s and large r_e

Kaplan (1997), Bedaque, van Kolck (1998), Beane, Savage (2001), following Weinberg (1963)

both a_s and r_e are low-momentum scales, need to be iterated to all orders

$$\mathcal{L} = \psi^\dagger \left(i\partial_0 + \frac{\nabla^2}{2} \right) \psi - d^\dagger \left(i\partial_0 + \frac{\nabla^2}{4} - \Delta \right) d - g \left(d^\dagger \psi\psi + d\,\psi^\dagger \psi^\dagger \right)$$

Δ, g: low-energy constants, matched to a_s and r_e, reliable for $k < 0.8\ \mathrm{fm}^{-1}$

Leading order: cutoff independence requires summing ladders

leads to effective coupling $\sim 4\pi \left[\frac{1}{a_s} - \frac{r_e k^2}{2} - \frac{k_F + \frac{P}{2}}{\pi} + \ldots \right]^{-1}$

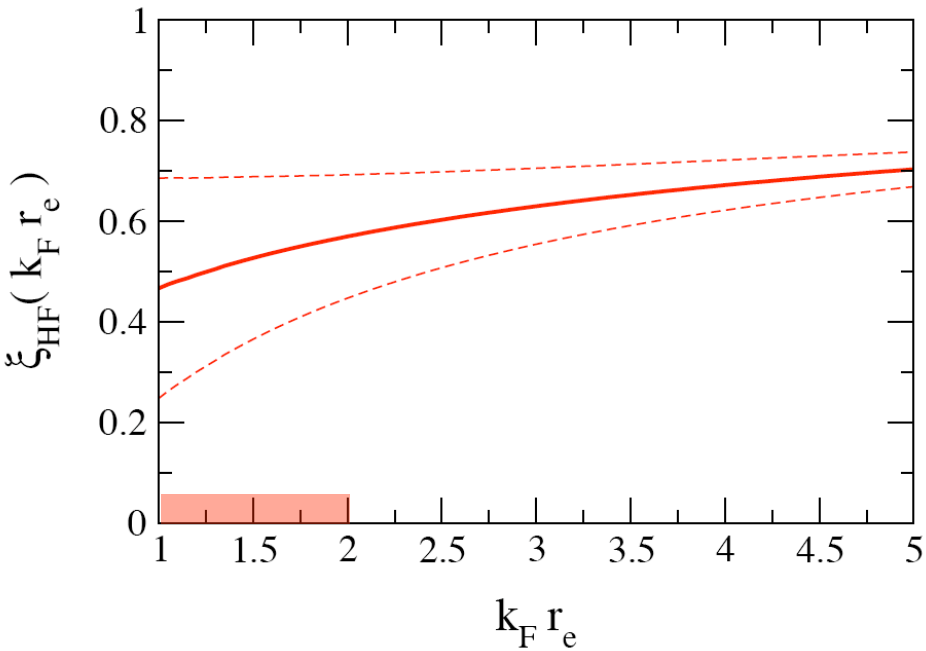
energy per particle $\frac{E}{N} = \xi(k_F r_e) \frac{3k_F^2}{10m}$ from effective interaction in HF

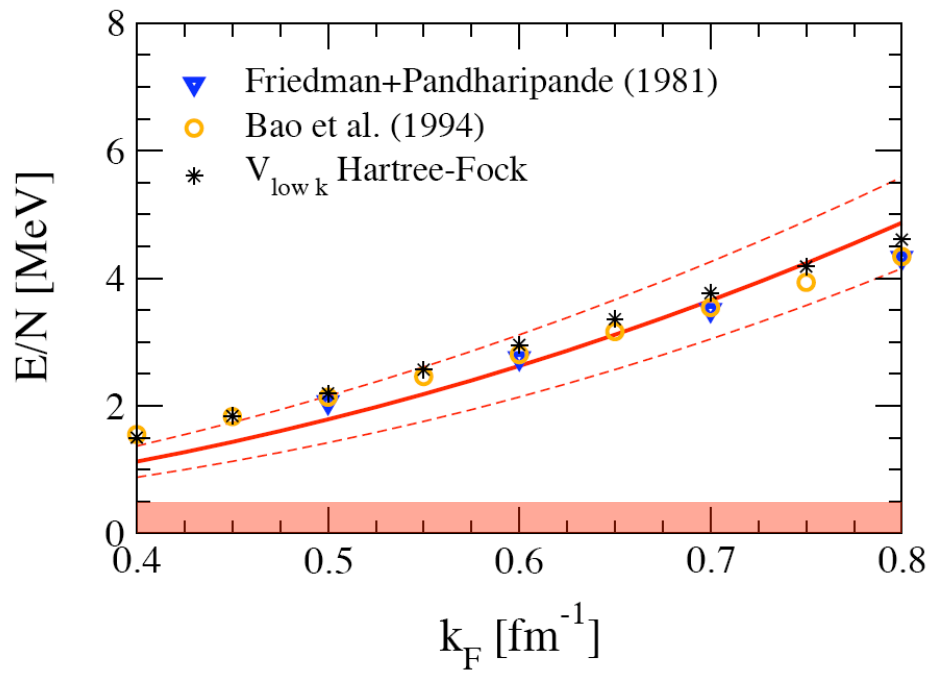
with errors beyond ladders $\Delta\xi = 0.077 \left(U_0 \left(1 + 0.27\, k_F r_e \right) \right)^{-3}$

weak pairing $\xi_{sf} \approx -0.01$

Results for neutron matter

gives neutron matter E/N for $k_F r_e \lesssim 2$ or $\rho < 0.02\,\mathrm{fm}^{-3}$



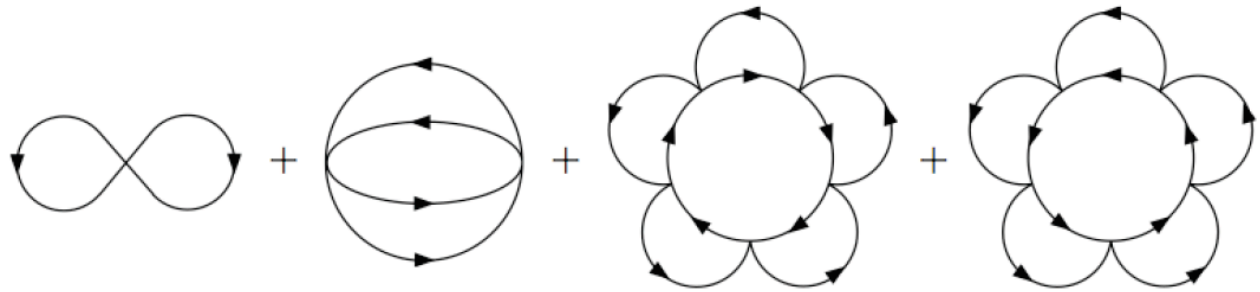


all microscopic results lie within errors of lowest-order di-fermion EFT

Pairing at low densities

Reuter, AS, in prep.

Effective action in Gorkov basis to subleading order,
based on ladders and leading particle-hole loop

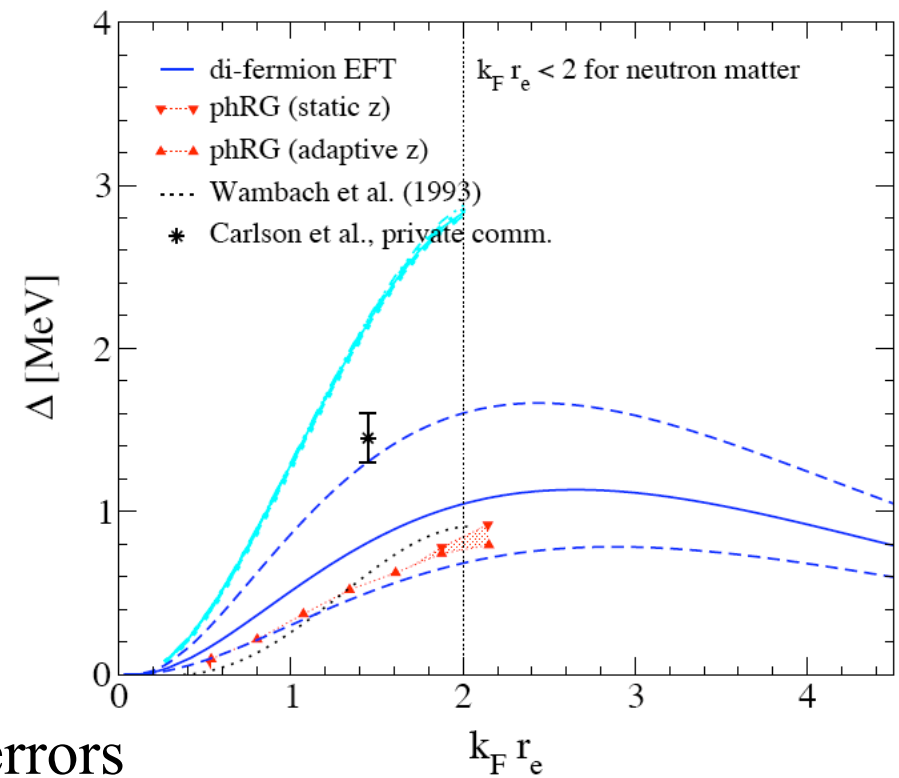
$\Gamma[\mathcal{G}] =$ 

expansion in effective coupling

$$\frac{1}{g} \equiv \frac{1}{a_s k_F} - \frac{r_e k_F}{2} - \frac{4}{\pi}$$

with S-wave gap to subleading order

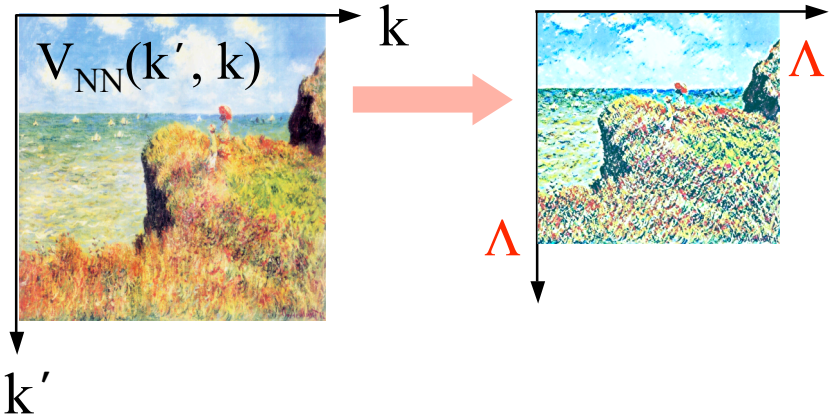
$$\Delta = 8\,\epsilon_F \exp\left(\frac{\pi}{2\,g} + \ln(0.45) + c\,g + \cdots\right)$$

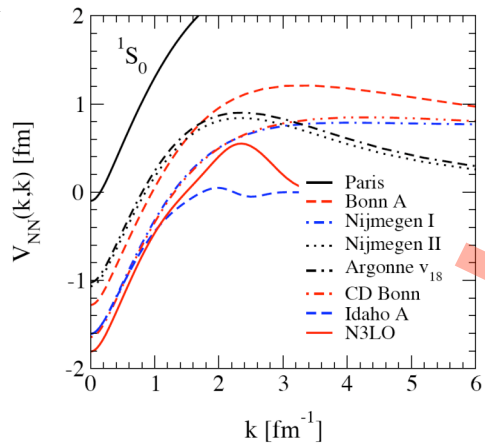


first error estimate possible,
existing reliable S-wave gaps within errors

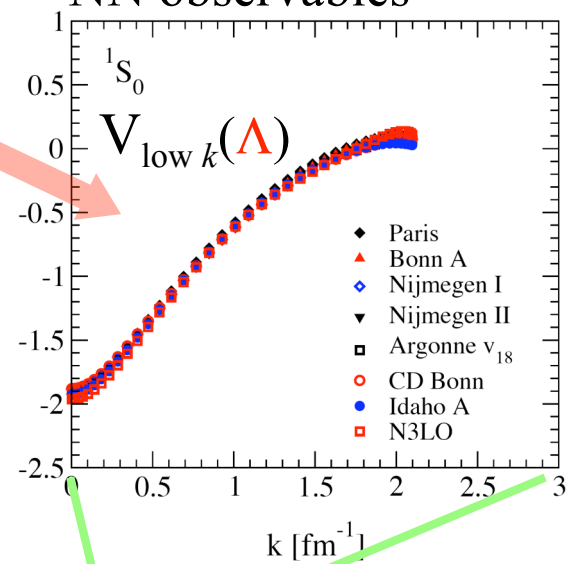
2. Neutron matter based on low-momentum interactions

evolve to lower resolution/cutoffs by integrating out high-momenta, can be carried out exactly for NN interactions Bogner, Kuo, AS (2003)





reproduces low-energy NN observables

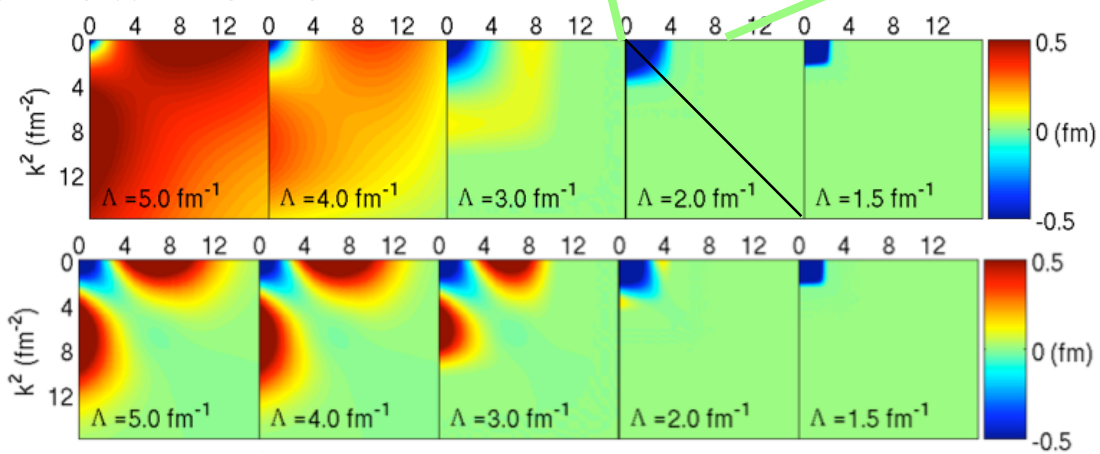


implemented by discretized RG equation or equivalent Lee-Suzuki transformation

leads to universal interaction for low momenta

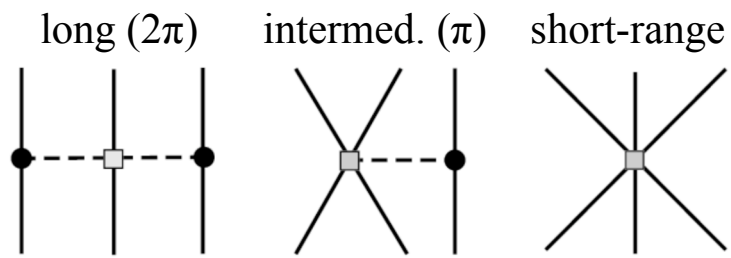
evolution to $V_{low\ k}(\Lambda)$ weakens off-diagonal coupling

enables model-independent calculations



Corresponding 3N interactions

from leading N^2LO chiral EFT ~ $(Q/\Lambda)^3$ van Kolck (1994), Epelbaum et al. (2002)



c_1,c_3,c_4 terms D(Λ) term E(Λ) term

c_i from πN, consistent with NN $c_1 = -0.9^{+0.2}_{-0.5}$, $c_3 = -4.7^{+1.2}_{-1.0}$, $c_4 = 3.5^{+0.5}_{-0.2}$

Meissner (2007)

c_3,c_4 important for structure, large uncertainties at present

4N interactions: E/A~1 MeV not unreasonable in nuclear matter

$V_{3N}(\Lambda)$ based on fit of D,E to A=3,4 binding energies for range of cutoffs

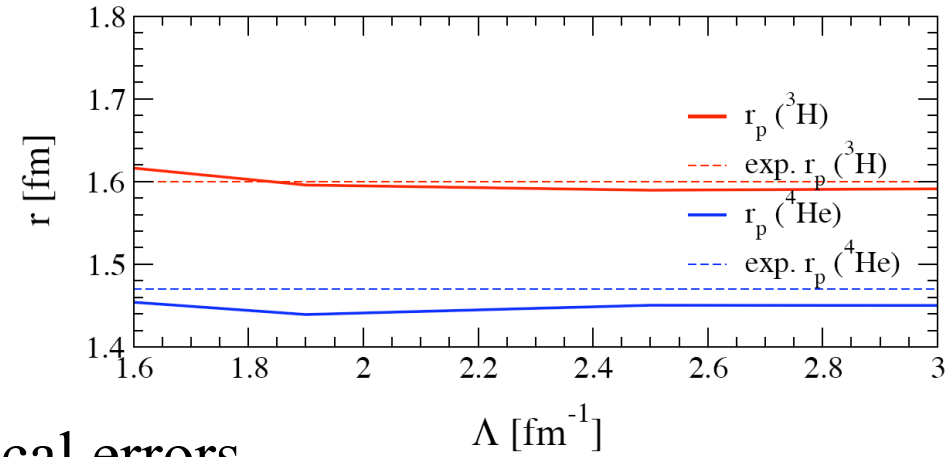
chiral EFT is complete basis → 3N up to truncation errors

3N interactions perturbative for $\Lambda \lesssim 2\,\mathrm{fm}^{-1}$ Nogga, Bogner, AS (2004)

Theoretical uncertainties

Cutoff variation estimates errors due to neglected parts in H(Λ)

Radii of light nuclei approximately cutoff-independent, agree with exp.



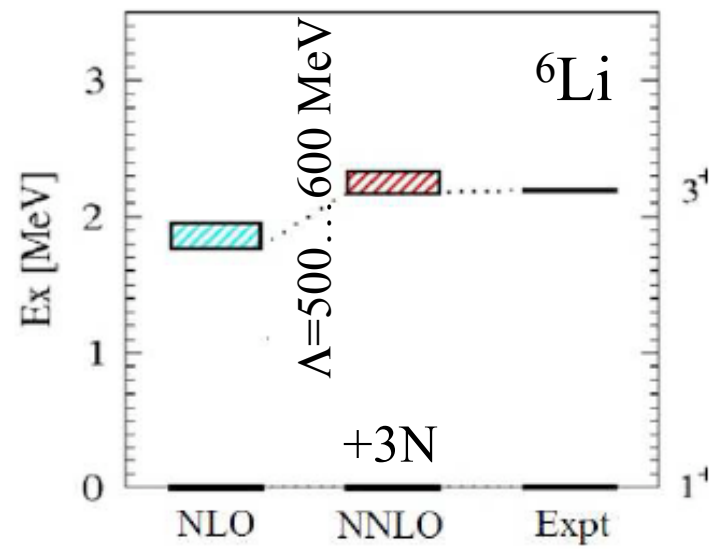
Can provide lower limits on theoretical errors

long-term: uncertainties of matrix elements needed in fundamental symmetry tests

neutrinoless double-beta decay

atomic EDMs

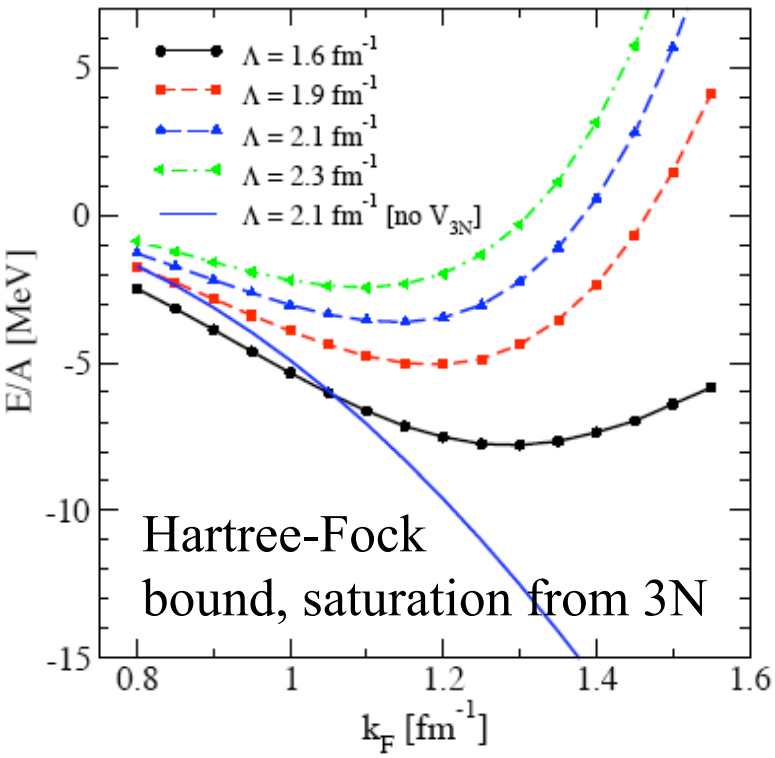
isospin-symmetry breaking corrections for V_{ud} ……

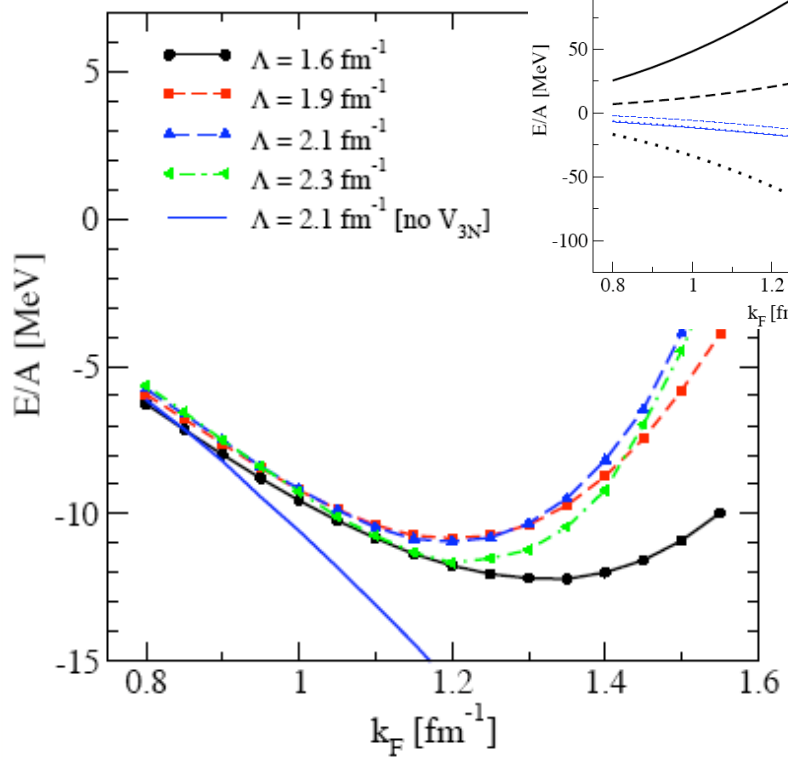


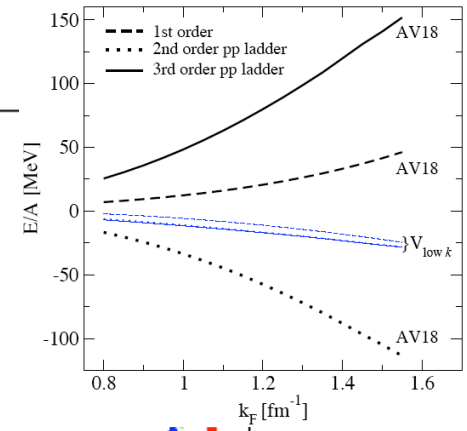
from A. Nogga

Possibility of perturbative nuclear matter with NN and 3N

motivated by Weinberg eigenvalue analysis





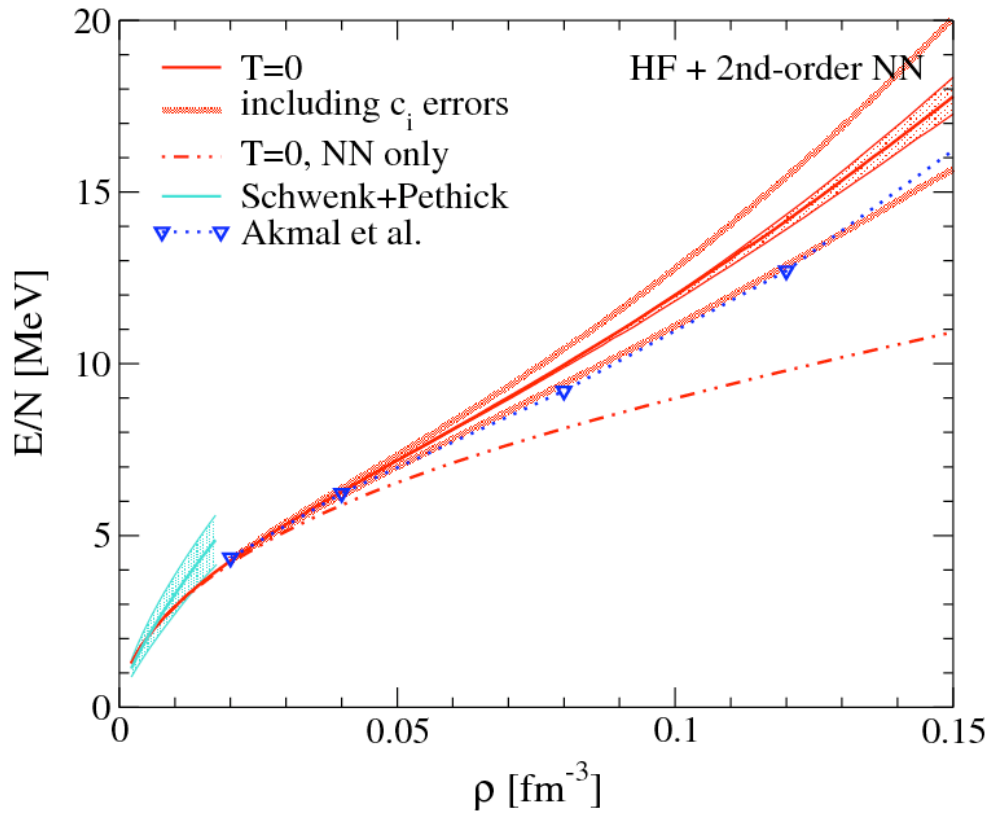


Hartree-Fock + ≈2nd-order
cutoff dep. strongly reduced
Bogner, AS, Furnstahl, Nogga (2005)

3N drives saturation but expectation values natural, consistent with EFT

can provide guidance to microscopic DFT

Neutron matter from NN and 3N



Tolos, Friman, AS, arXiv:0711.3613.

uncertainties from c_i overwhelm errors due to cutoff variation, mainly c_3 for neutron matter

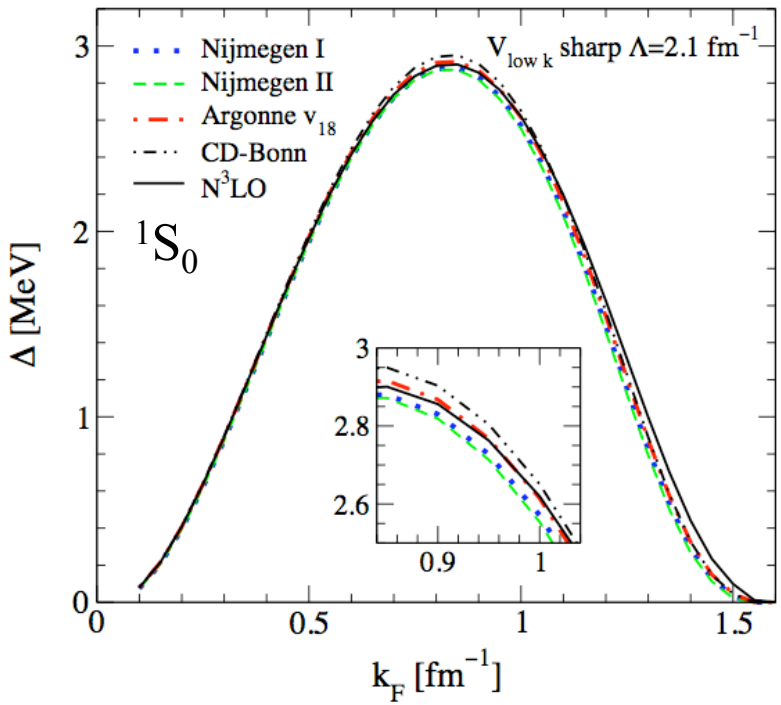
lower c_3 (Δ dominated): less repulsion, would add ~ -2 MeV in nuclear matter

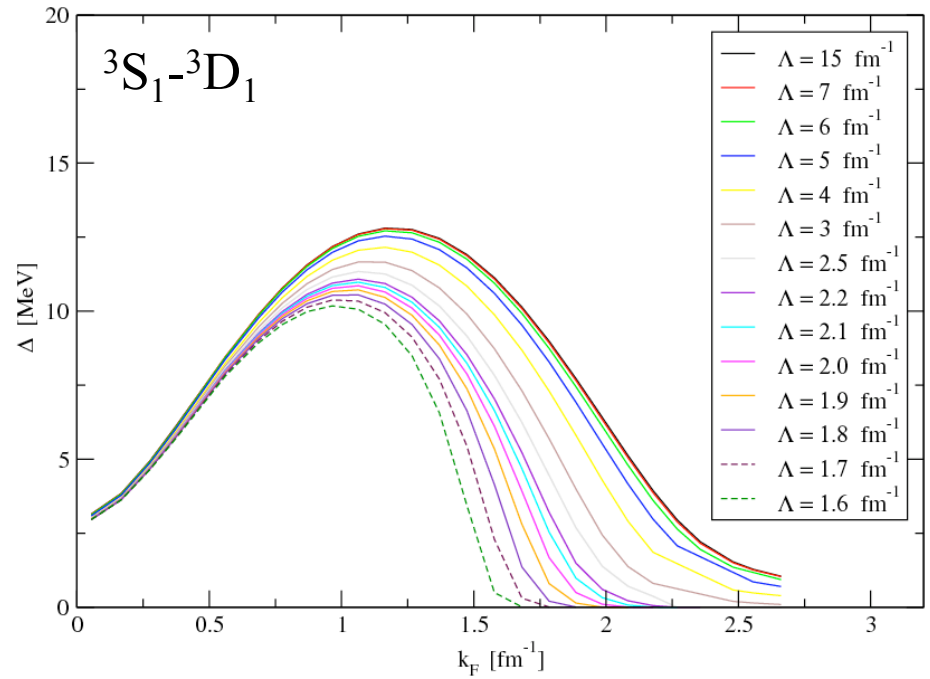
can provide guidance to constrain DFT

Pairing in nuclear matter

BCS gaps from nucleon-nucleon interactions and free dispersion

$^1S_0$ gaps well constrained for momenta < 2 fm^{-1} by phase shifts





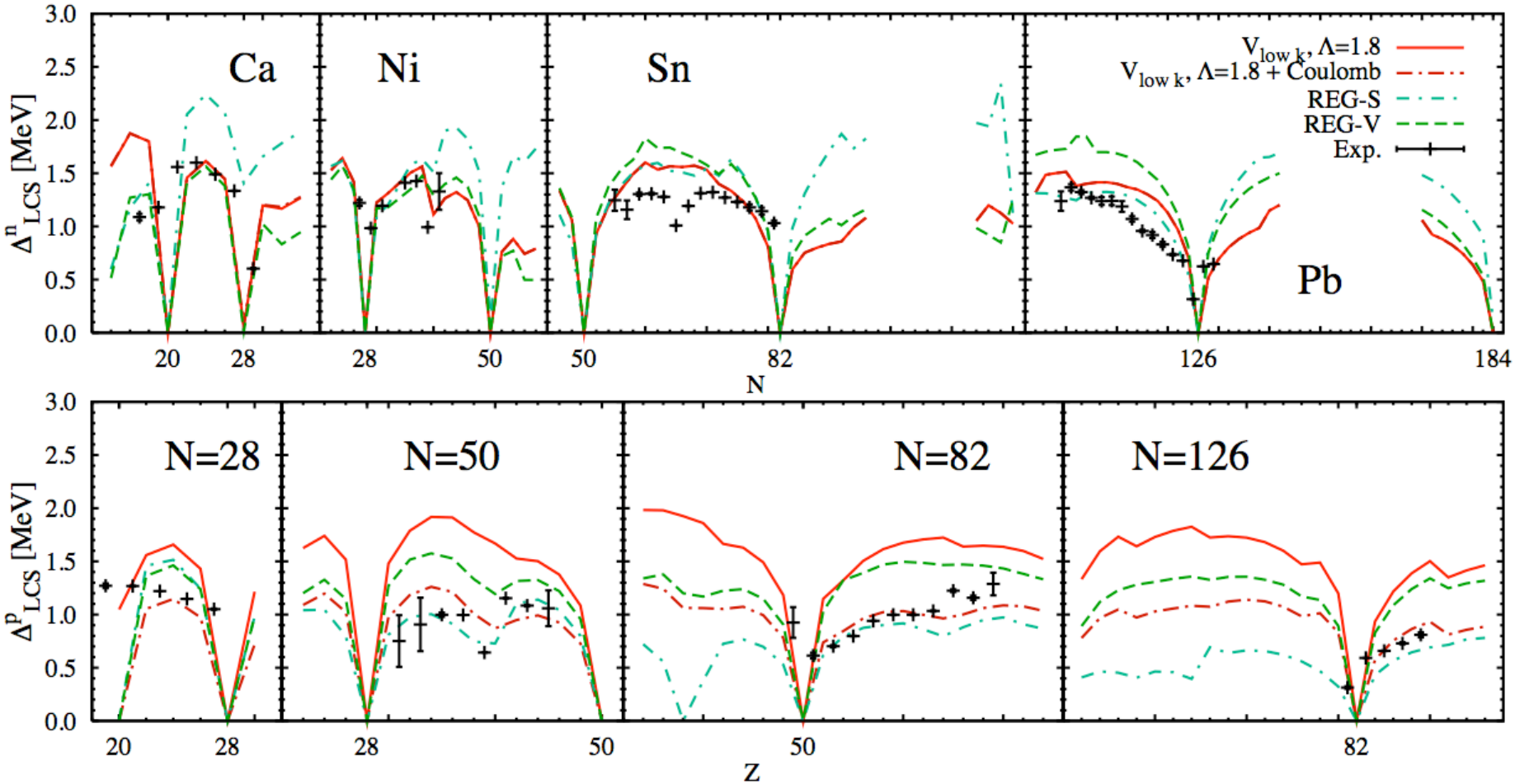
$^3S_1$-$^3D_1$ gaps cutoff dependent at higher density, points to 3N important

Hebeler et al. (2007) and in prep.

Towards a universal nuclear energy density functional

first microscopic pairing functional from low-momentum interactions

Lesinski, Duguet, Bennaceur arXiv:0711.4386 and in prep.



very exciting!

can study beyond BCS contributions to pairings gaps

INT program on CC theory

with Symposium on 50 years of CC theory, June 30 - July 2

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Application form

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Atomic, Chemical, and Nuclear Developments in Coupled Cluster Methods (INT-08-2a)

June 23 - July 25, 2008

One of the most promising ab initio microscopic theories that can potentially provide a highly accurate description of a variety of many-body physical systems, as small as atomic nuclei and as large as polyatomic molecules, as weakly bound as van der Waals molecules and as strongly bound as atomic nuclei, is coupled-cluster theory.

A systematic implementation of coupled-cluster theory for nuclei is underway. This effort utilizes the formalism of coupled-cluster developments in chemistry, but with both physical and computational twists inherent in the physics of nuclei. The nuclear problem requires as input an interaction that is less well understood than in the atomic and chemical cases and a close interaction between those who produce realistic nucleon-nucleon interactions and the many-body specialists is required. In light nuclear systems, some significant tests of interactions have been made with configuration-interaction and quantum Monte Carlo calculations. It would appear that a real three-body interaction is required to reliably predict nuclear properties. The introduction of three-body interactions into the coupled-cluster formalism constitutes one interesting discussion point for this program. A second point from nuclear physics involves efforts to utilize a single-particle basis that includes bound, continuum, and scattering states. The coupled-cluster problem then translates to a complex algorithm for weakly bound nuclei.

Recent significant advances in developing coupled-cluster theory have occurred in quantum chemistry. A variety of coupled-cluster methods for ground, excited, closed-shell, and open-shell, non-degenerate and quasi-degenerate states of atoms and molecules and molecular properties have been developed and coded, so that nowadays coupled-cluster methods are regarded by theoretical and experimental chemists as the best ab initio techniques for high-accuracy electronic structure calculations.

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Speakers and Topics:

A. Cumming (McGill) Neutron stars, X-ray bursts and superbursts
R. Furnstahl (OSU) Nuclear forces and density functional theory
K. Langanke (GSI) Nuclear reactions and nuclear astrophysics
A. Macchiavelli (LBNL) Pairing in nuclei
F. Nunes (MSU/NSCL) Nuclear reactions
T. Papenbrock (Tennessee/ORNL) Nuclear structure
M. Ramsey-Musolf (Wisconsin) Nuclei as laboratories for fundamental symmetries
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