Neutron Matter: EOS, Spin and Density Response

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How can microscopic theories constrain mean-field theories
and properties of neutron-rich matter?

- Neutron Matter
  - EOS
  - 1- and 2-body distribution functions
- Spin Response
  - Pairing Gap
- Density Response (Drops)
  - Energies and Saturation
  - Comparing ab-initio energies with Skyrme
  - Single-Particle Energies
- Outlook

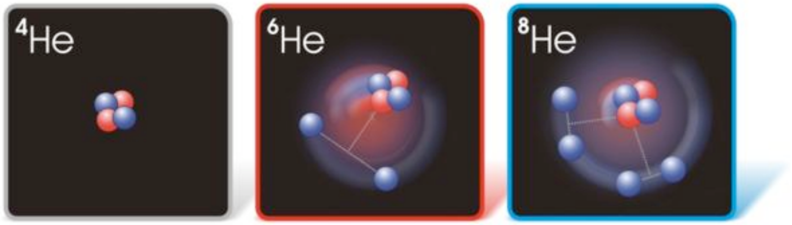
Computational Approach:

$$| \psi_0 > = \exp [- H \tau] | \psi_t >$$

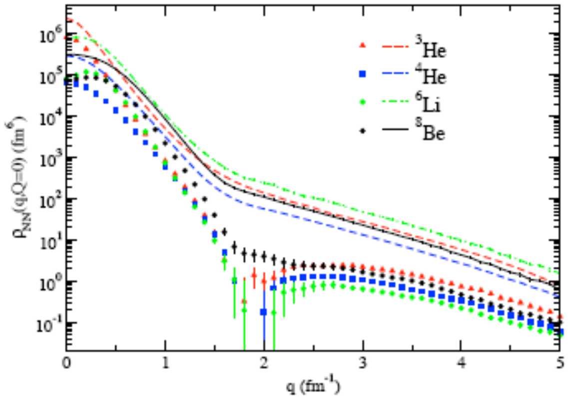
GFMC: sum over spin/isospin explicitly
Diffusion MC: spin-independent (s-wave interactions)
AFDMC: Monte-Carlo sums over spin/isospin

Mostly calculations on light nuclei

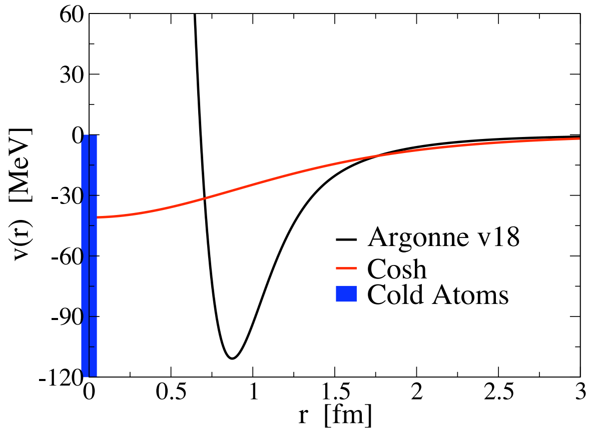
Nuclear Structure

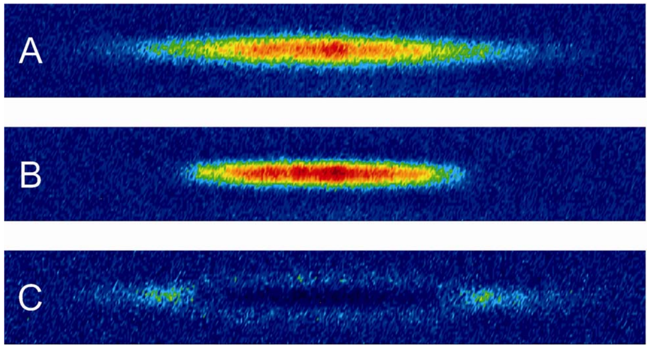


High-Momentum Pairs



$$\mathcal{H} = \sum_{k=1}^{A}\left(-\frac{\hbar^2}{2m_k}\nabla_k^2\right) + \sum_{i<j} v(r_{ij})$$





Caveats:

Fixed-node (Upper Bound)
Finite System Size

Neutron Matter Diffusion Monte Carlo

~65 particles (scales like N^3)
Gap from even/odd staggering
Need << 1 MeV accuracy

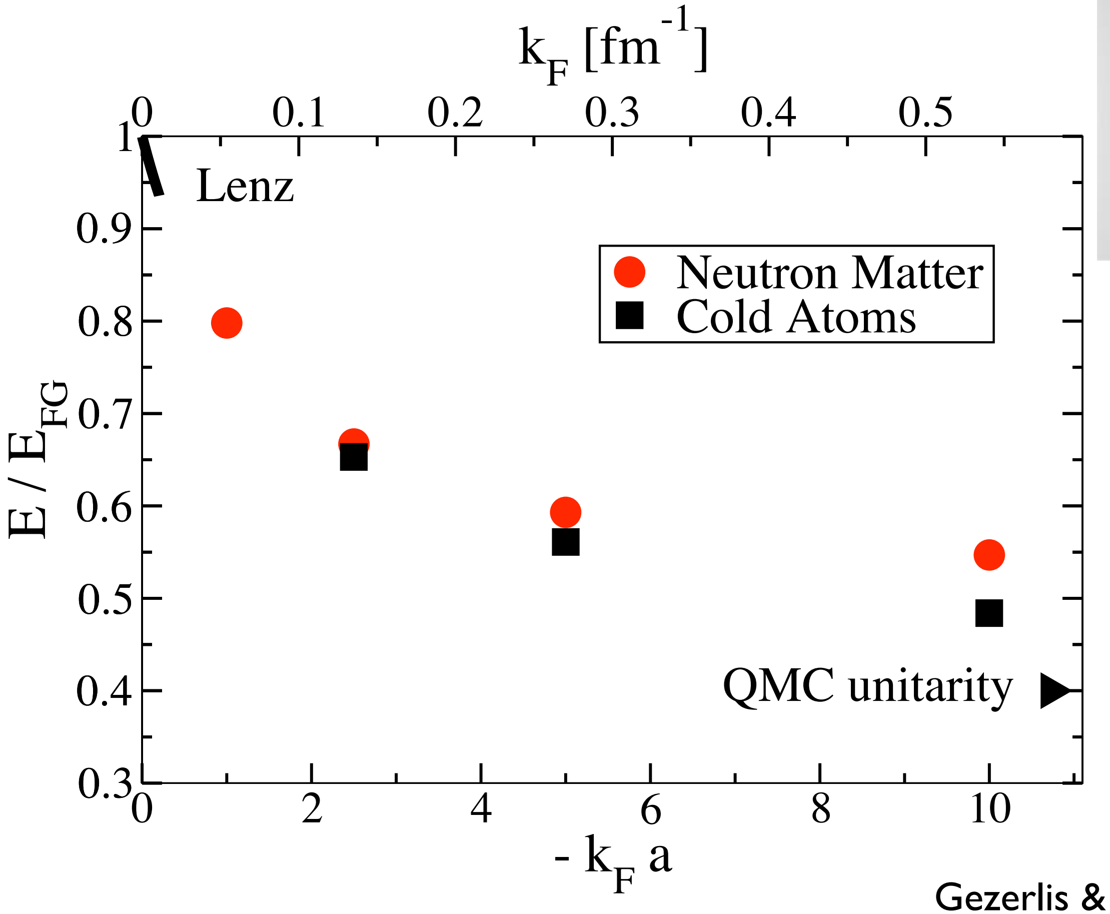
Each calculation (fixed ρ,N, k) takes of order 1/2 day on 1000 processors

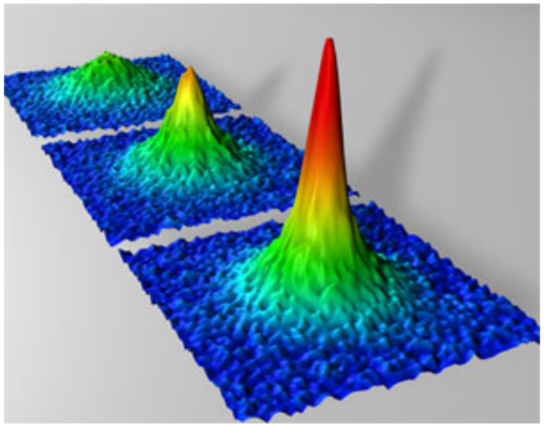
approximately 1 Tflop on Franklin
90% parallel efficiency up to 1000 processors

Neutron Matter EOS

Neutron Matter properties less well-known than Nuclear Matter near equilibrium density
Ab Initio calculations can provide guidance to the density functional

Equation of State at Low Densities



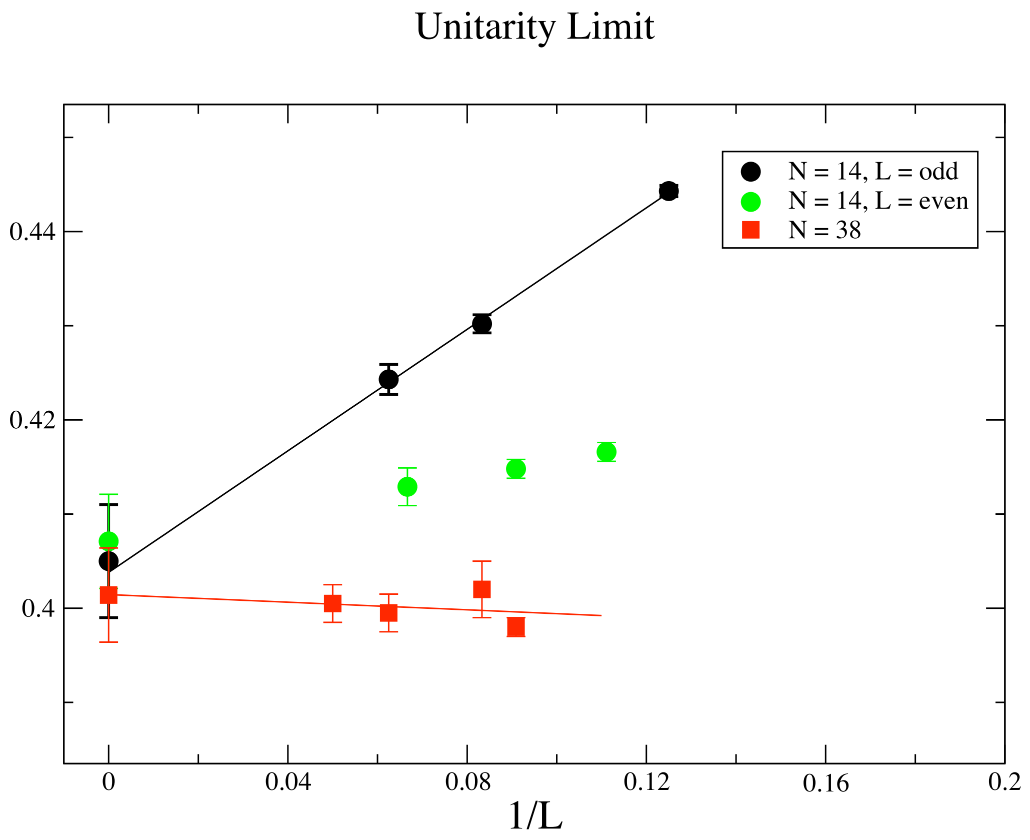


From JILA

Gezerlis & Carlson, PRC 2008

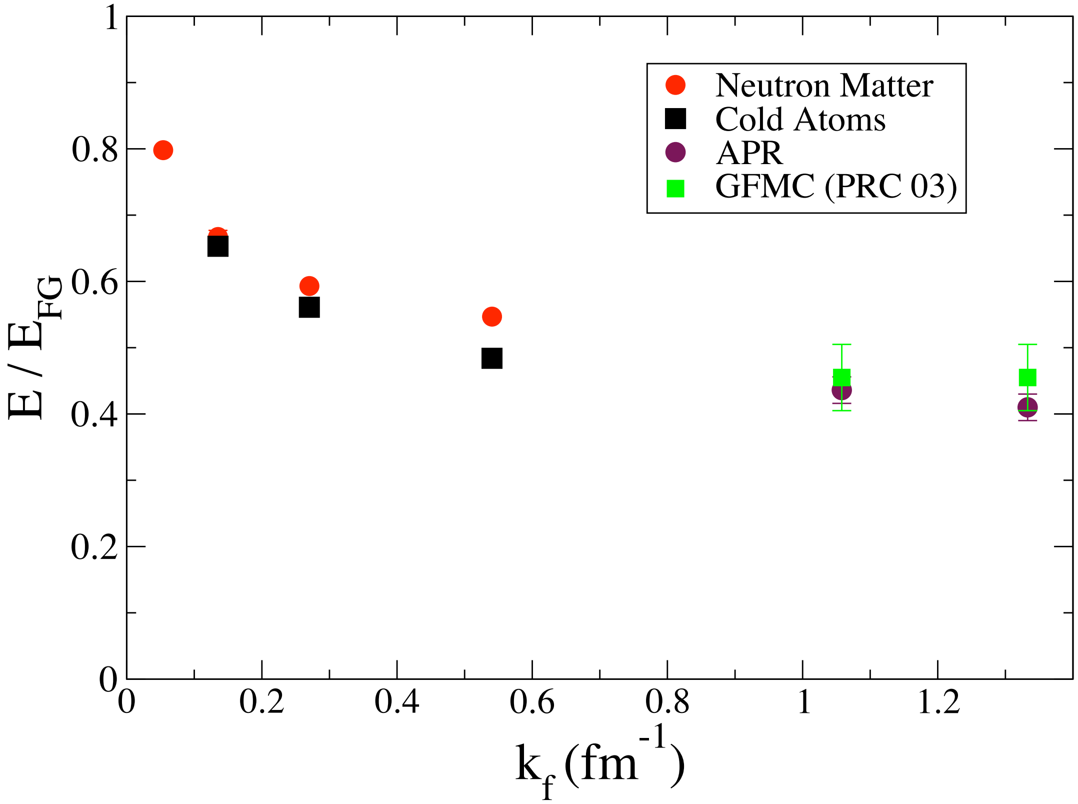
Lattice Results at Unitarity

lattice has no fixed-node error

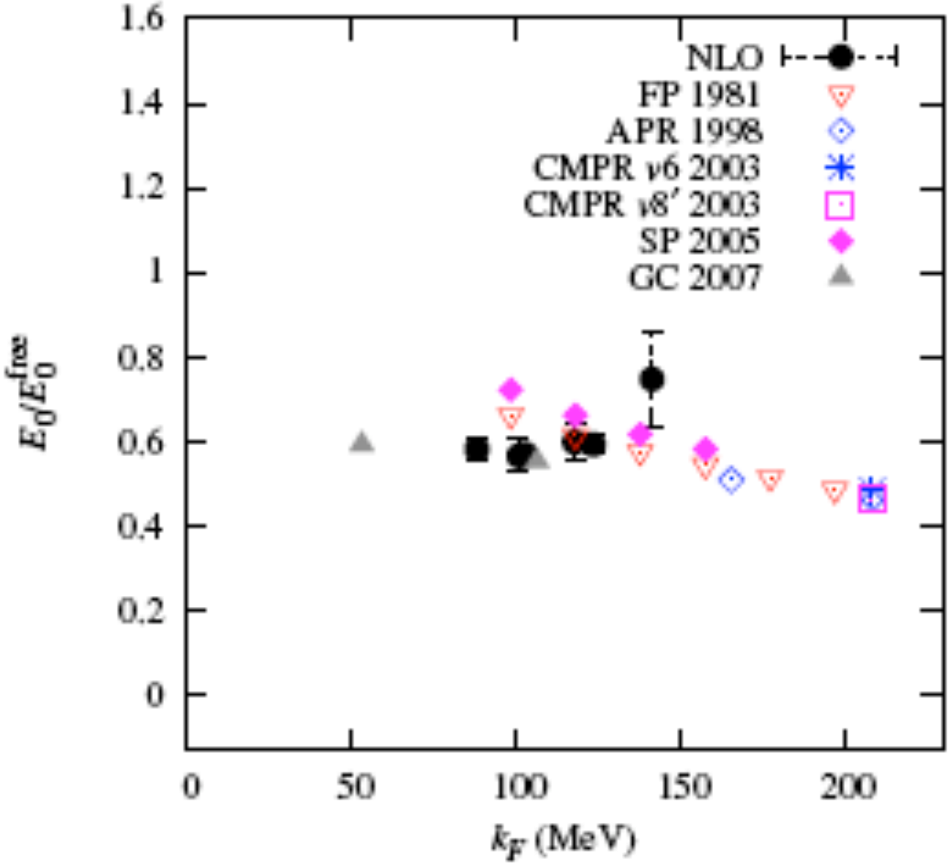


Good agreement between lattice, continuum

Low Density Neutron Matter
EOS very well determined



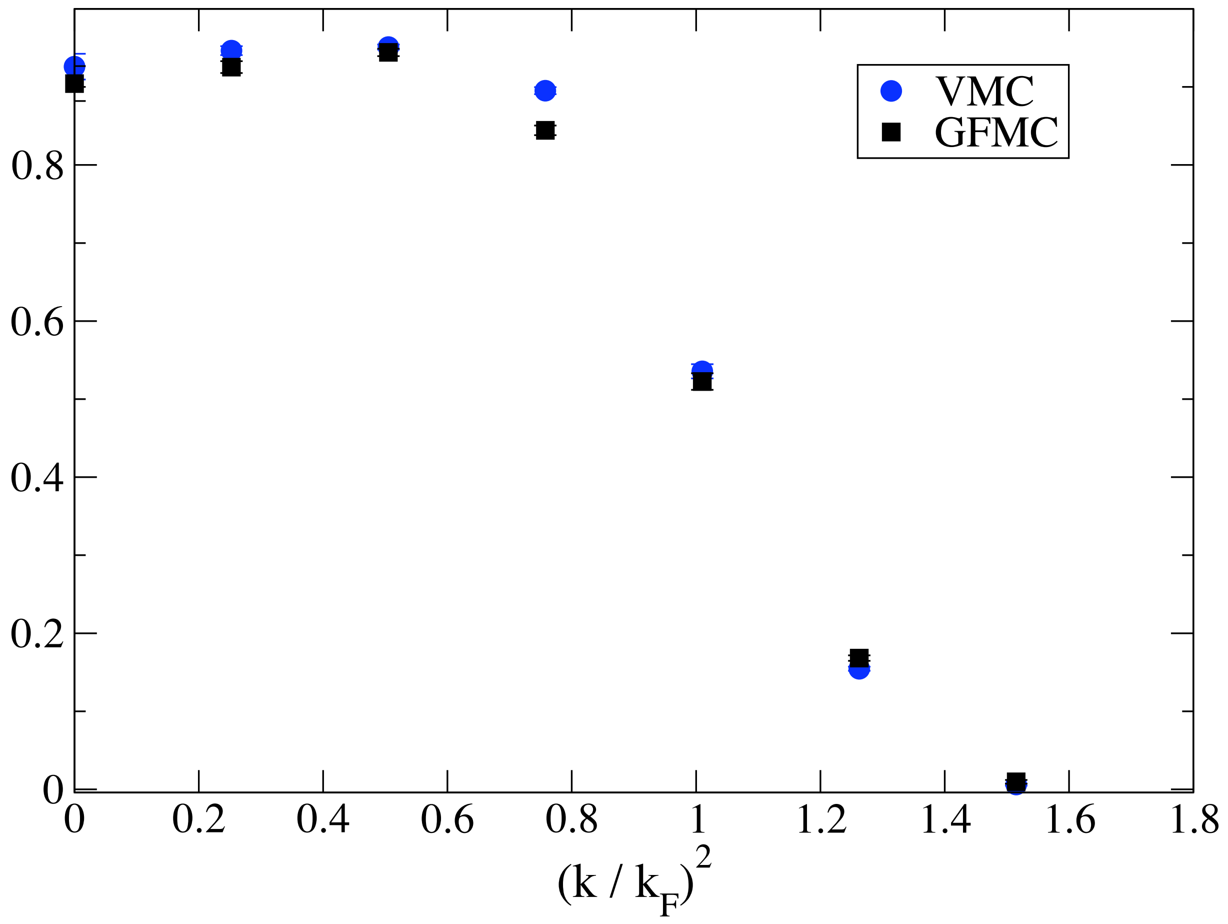
Skyrmes typically fit at k_f = 0 and ~ 1.3 fm^{-1}, but not between



Dean Lee, arXiv:0804.350

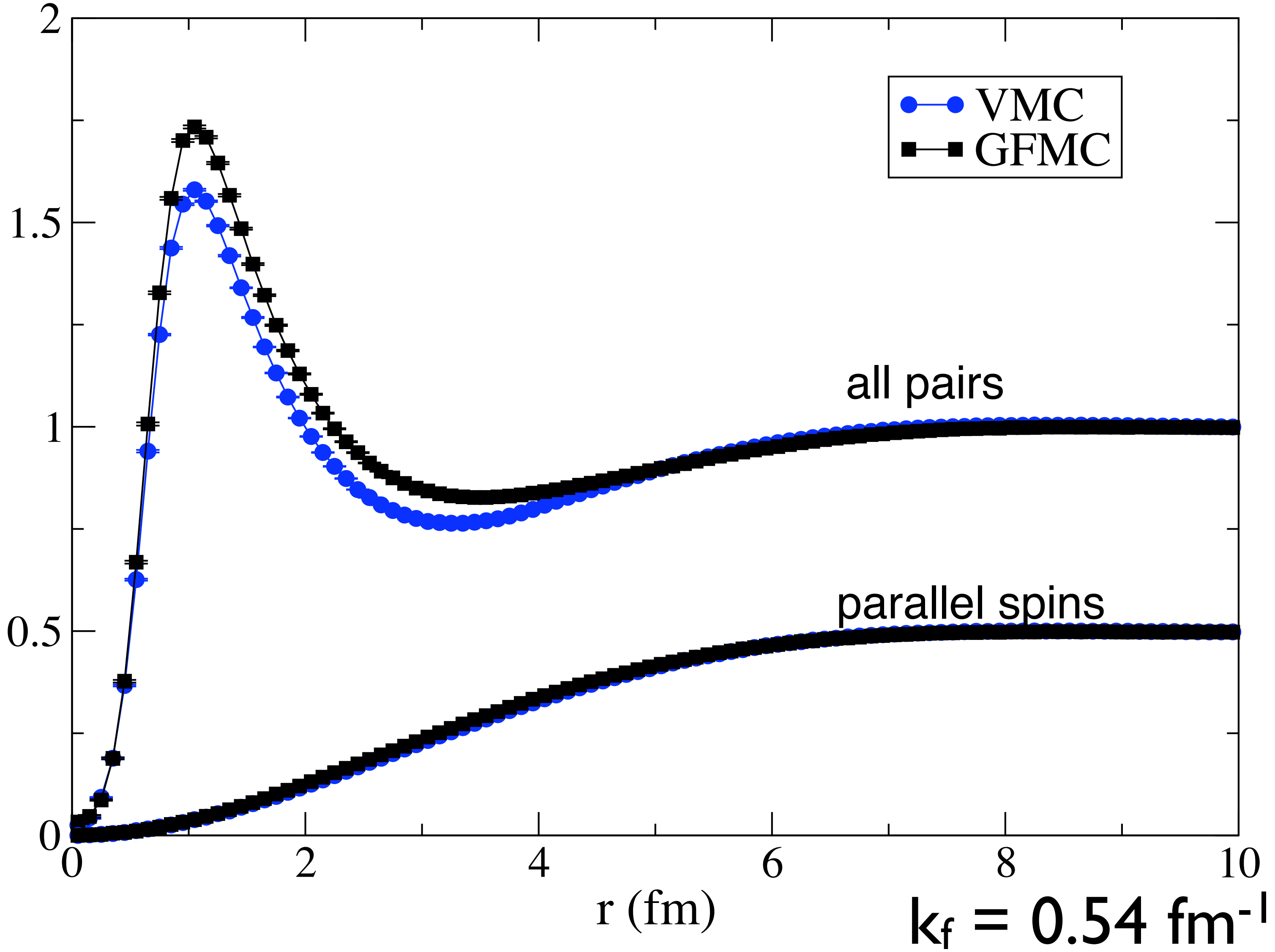
Other Quantities:

Momentum Distributions



$k_f = 0.54\ \mathrm{fm}^{-1}$

Pair Distribution Functions

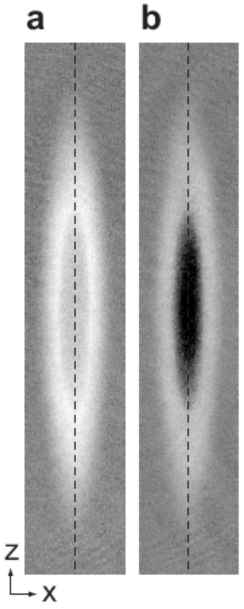


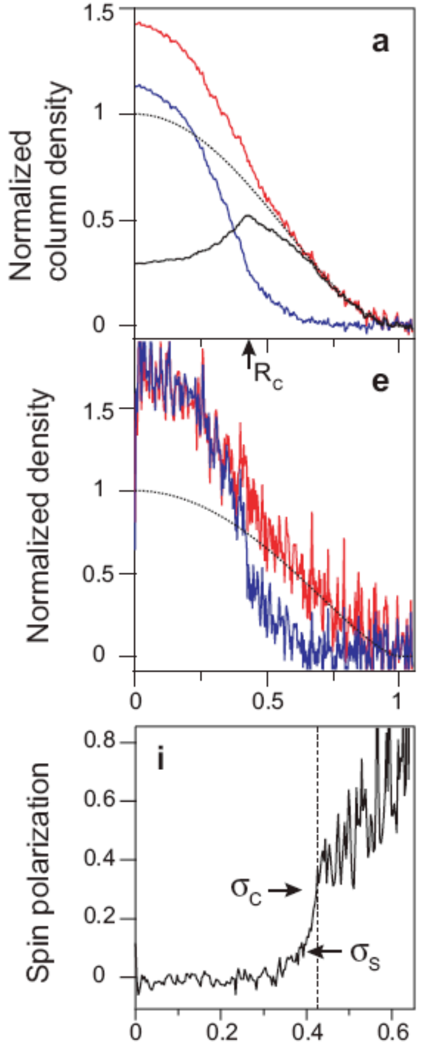
$k_f = 0.54\ \mathrm{fm}^{-1}$

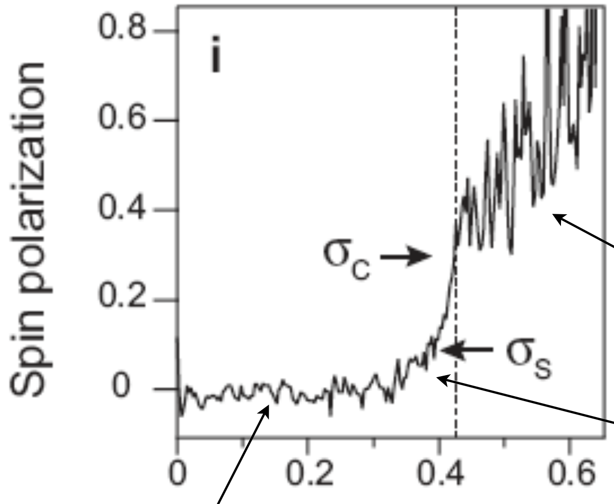
Spin Degrees of Freedom

Superfluid pairing gap
in strong coupling testable in cold atoms

Magnetic Fields or different
chemical potentials can break superfluidity







Polarized Normal State

Thermally populated
quasiparticles in superfluid

Unpolarized Superfluid

Figures from Shin, et al, Nature 459, 689-U1, 2008

Universal Parameters

Superfluid State (P=0)

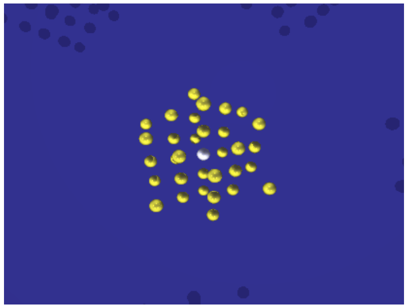
$\chi = 0.40\ (02)$ Superfluid Energy / Fermi Gas Energy

$\Delta = 0.50\ (03)$ Gap / Fermi Energy

Carlson, et al, PRL 2003,
Giorgini, et al., PRL 2004,
Carlson and Reddy, PRL 2005, ...

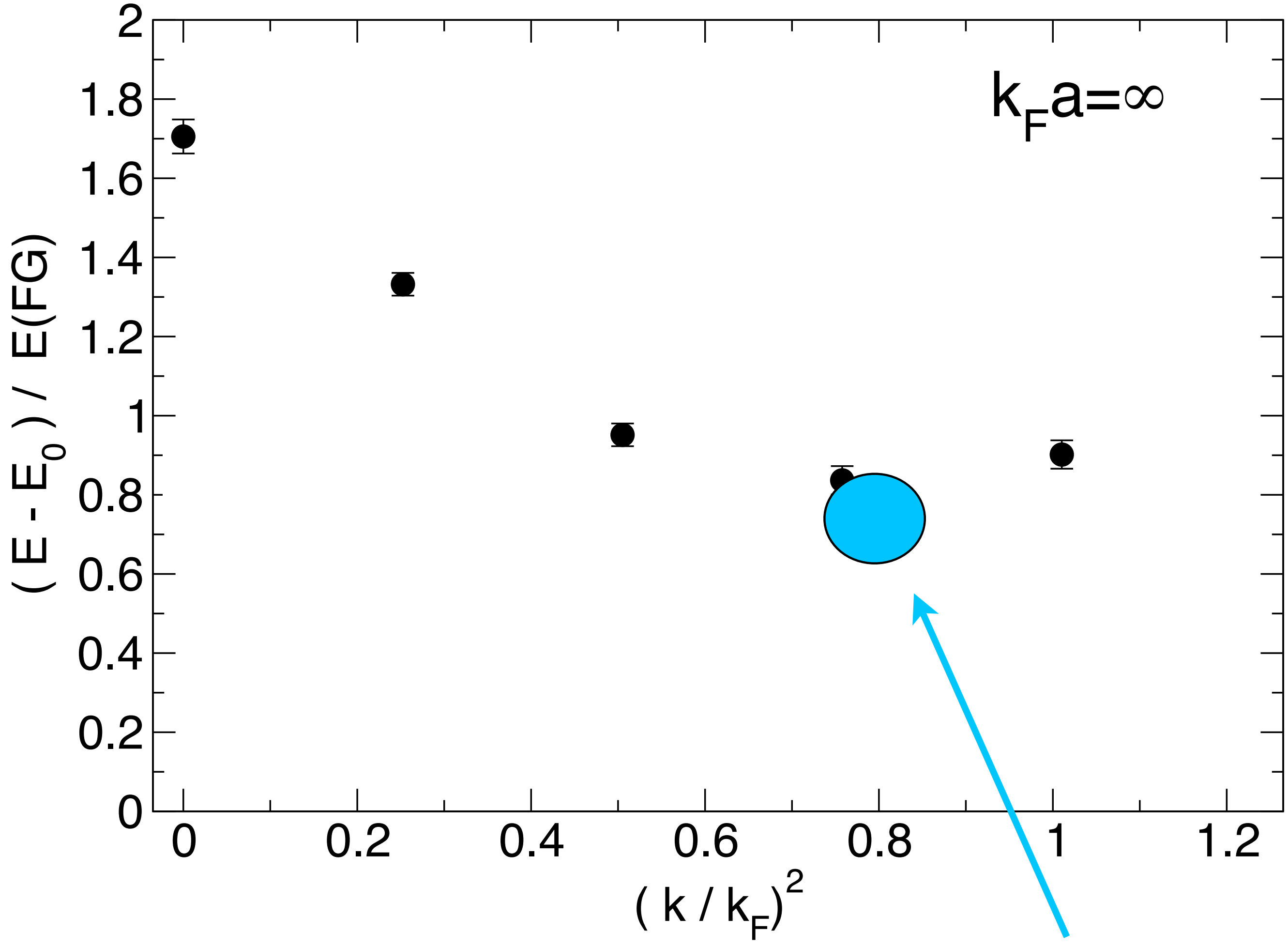
Normal State (P=1)

$\beta = 0.60\ (01)$ Binding Energy of one spin down in Fermi sea of spin up



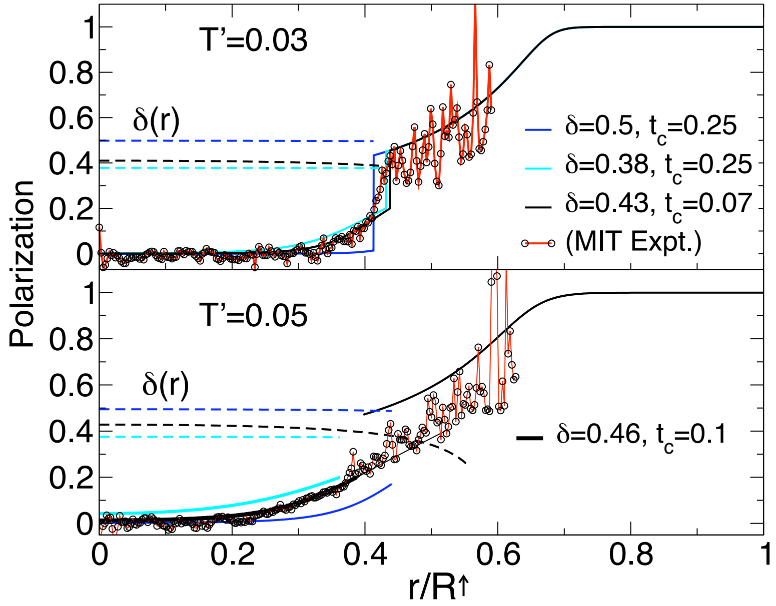
Lobo, et al, PRL, 2006

Cold Atom Dispersion



Shin, Ketterle, ... 2008

Neutron Matter Pairing Gap

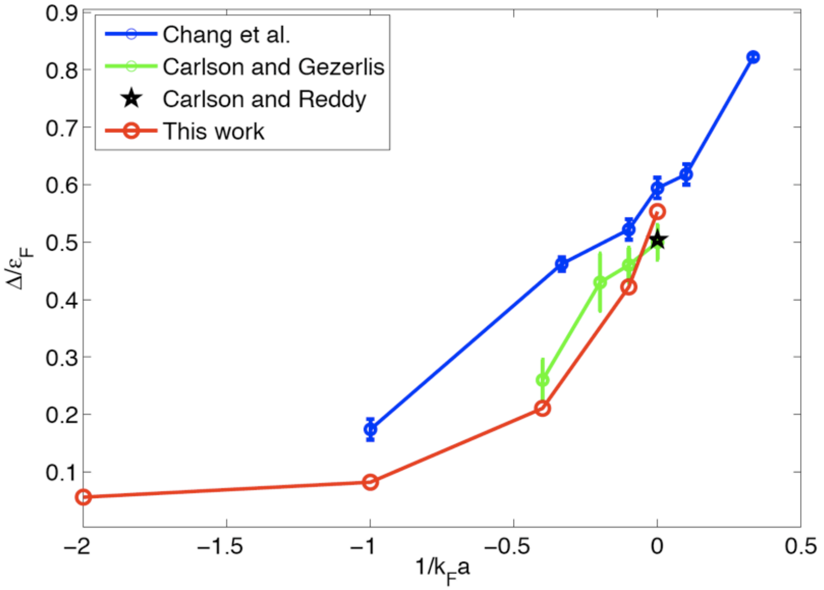


Analysis of cold atom experiments gives Δ/E_f = 0.45 (05).

Largest Δ/E_f in any system!

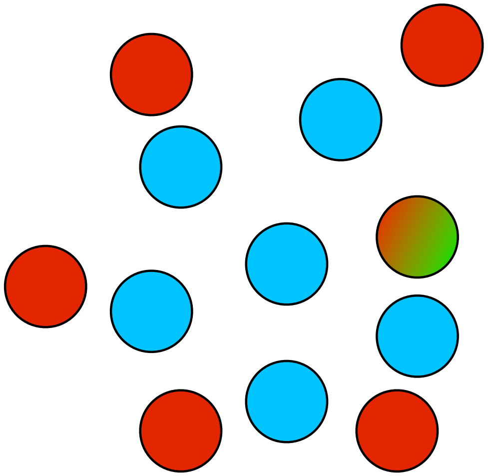
Carlson and Reddy, PRL 08

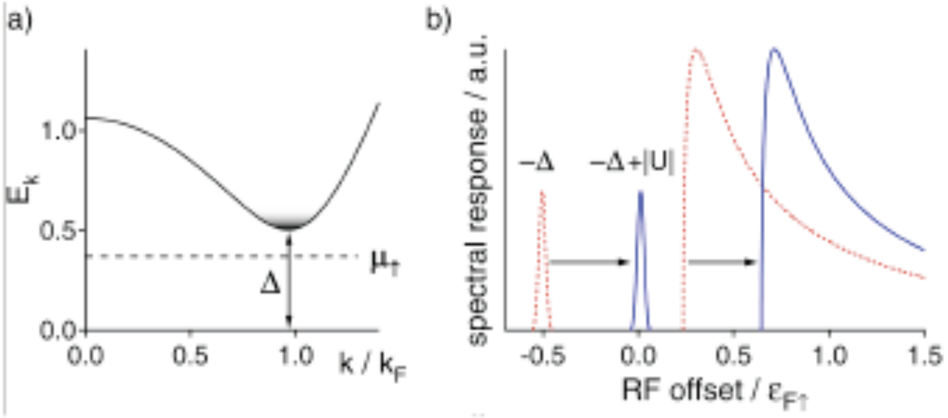
Pairing Gap for Atomic Gas
Experimentally confirmed to ~10%

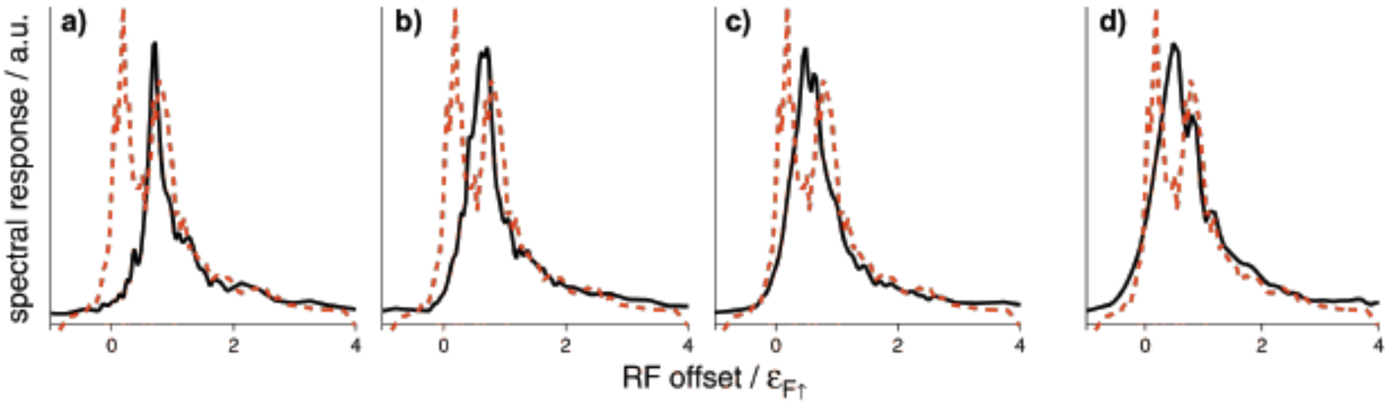


Calculations also agree; new AFDMC calculation much closer to DMC

RF response



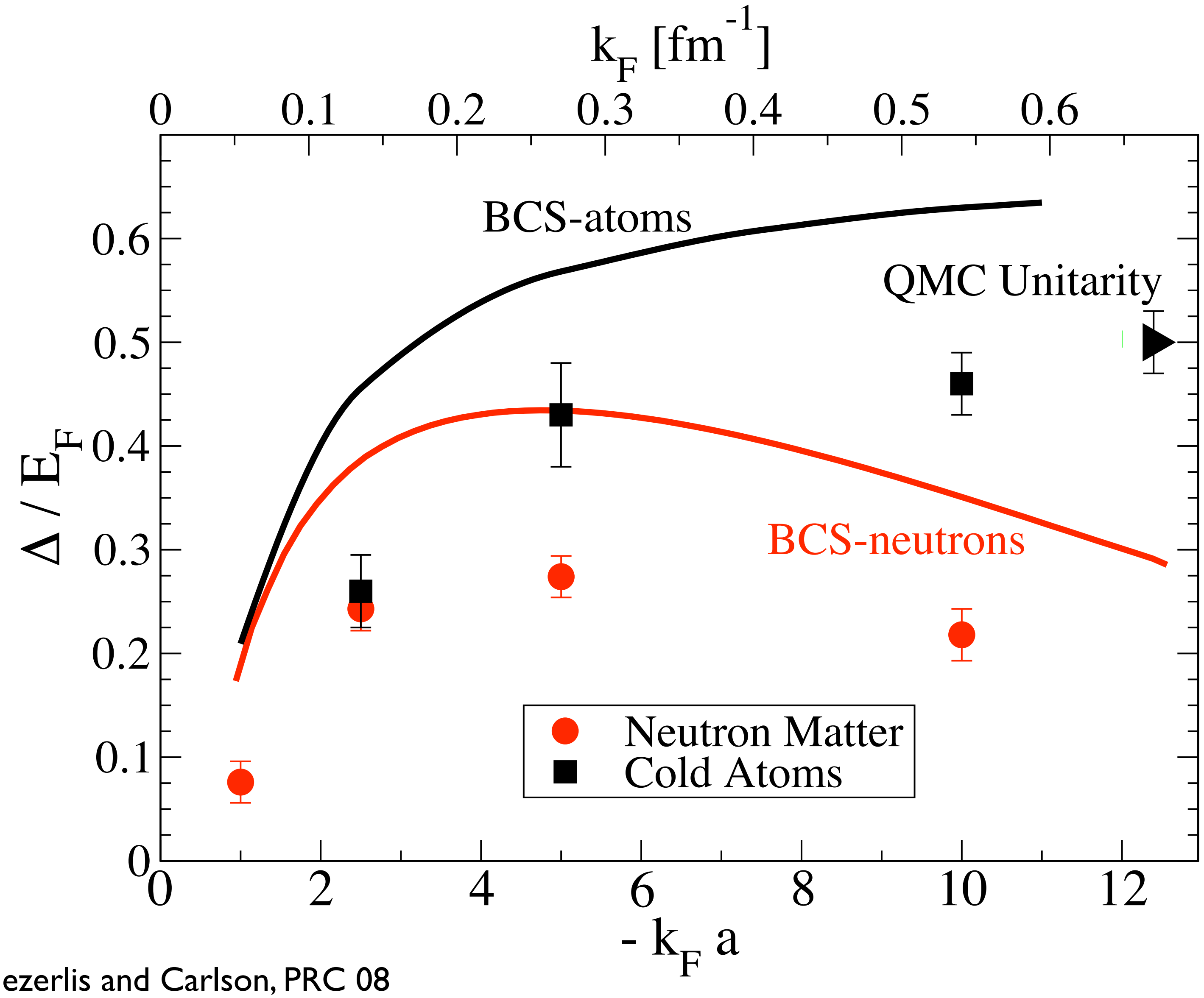




Increasing T

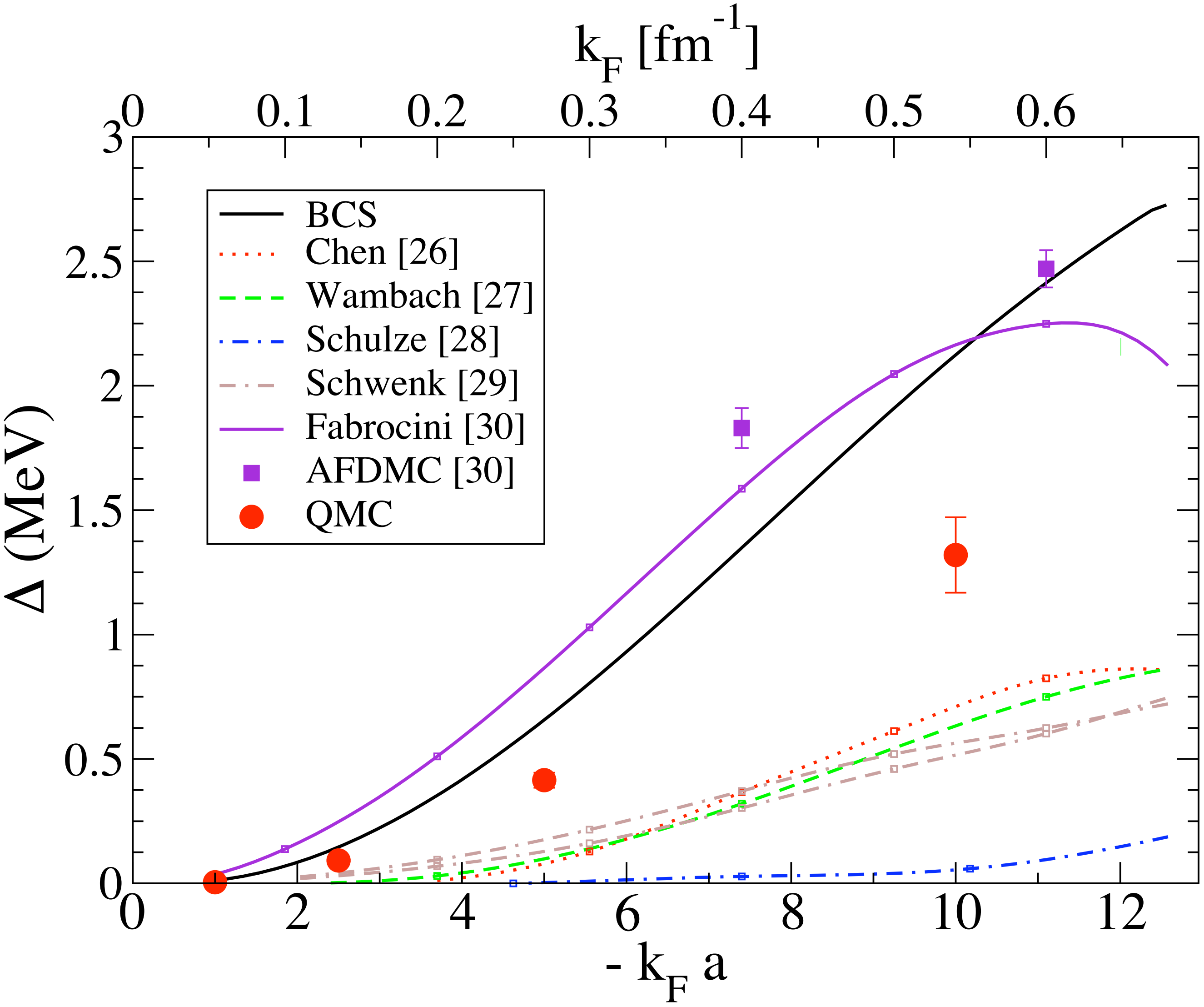
Shin, Ketterle, ... 2008

Neutron Matter Pairing Gap

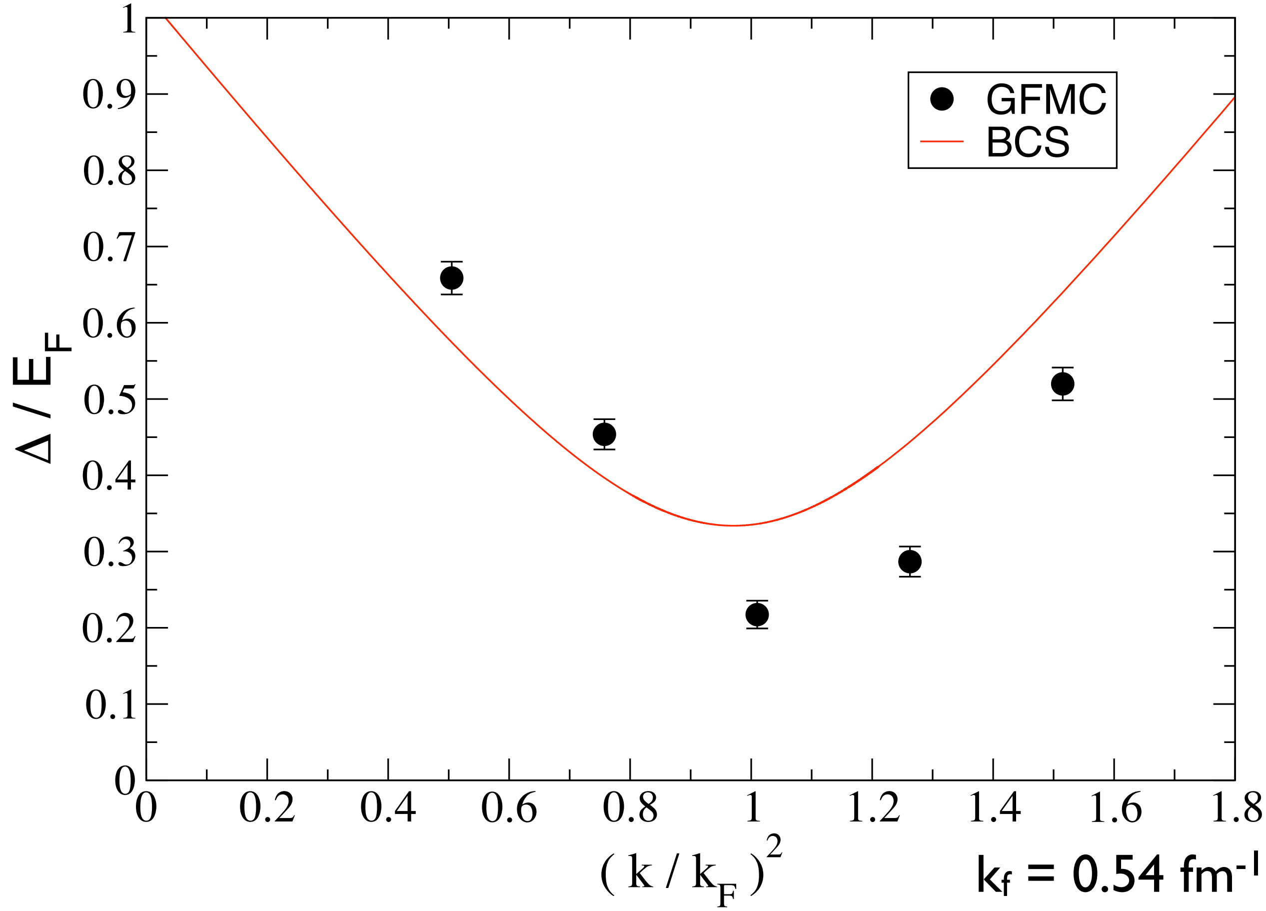


Gezerlis and Carlson, PRC 08

Pairing Gap at Low Densities



New Calculations:
Dispersion of Single-Particle States

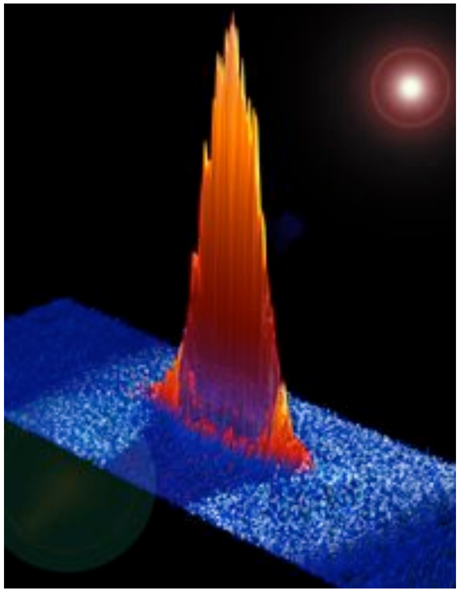


k_f = 0.54 fm^{-1}

Can be a constraint to Mean Field models

Spin susceptibility - of interest in neutron stars

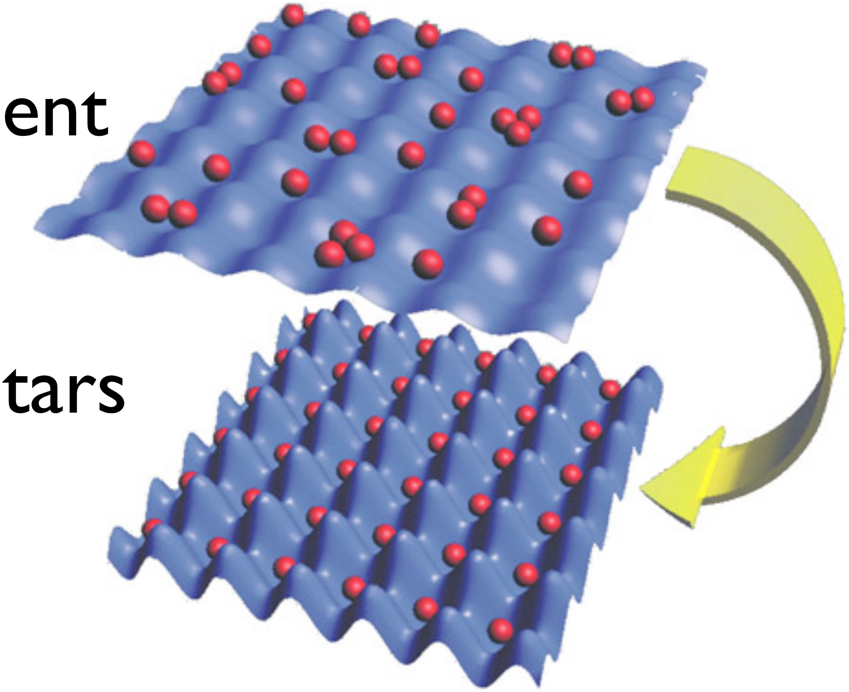
Density Perturbations



Static Susceptibility:

response to small long-wavelength potential

General response to external potentials



Relevant to generalized gradient terms in density functional:

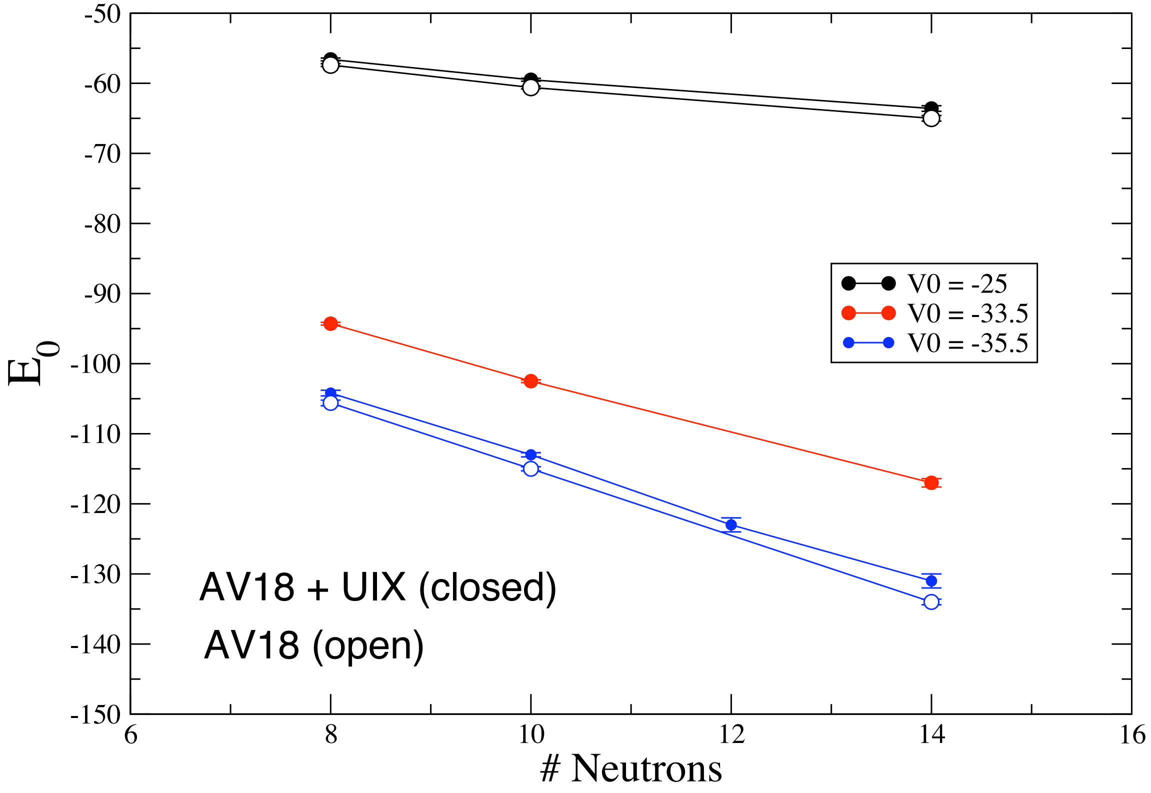
PREX

Inner Crust of Neutron Stars

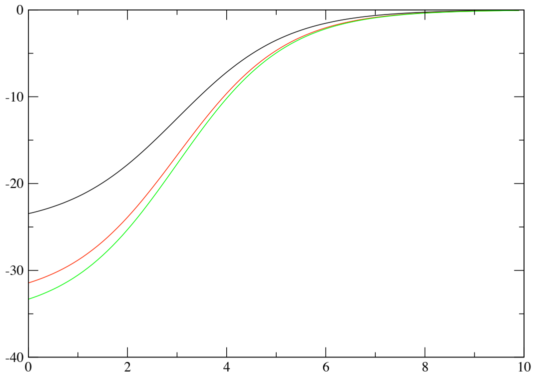
Neutron Drops

Woods-Saxon potential (r=3 fm, a=1.1fm) at various depths
also initial work on Harmonic Oscillators

Binding Energy

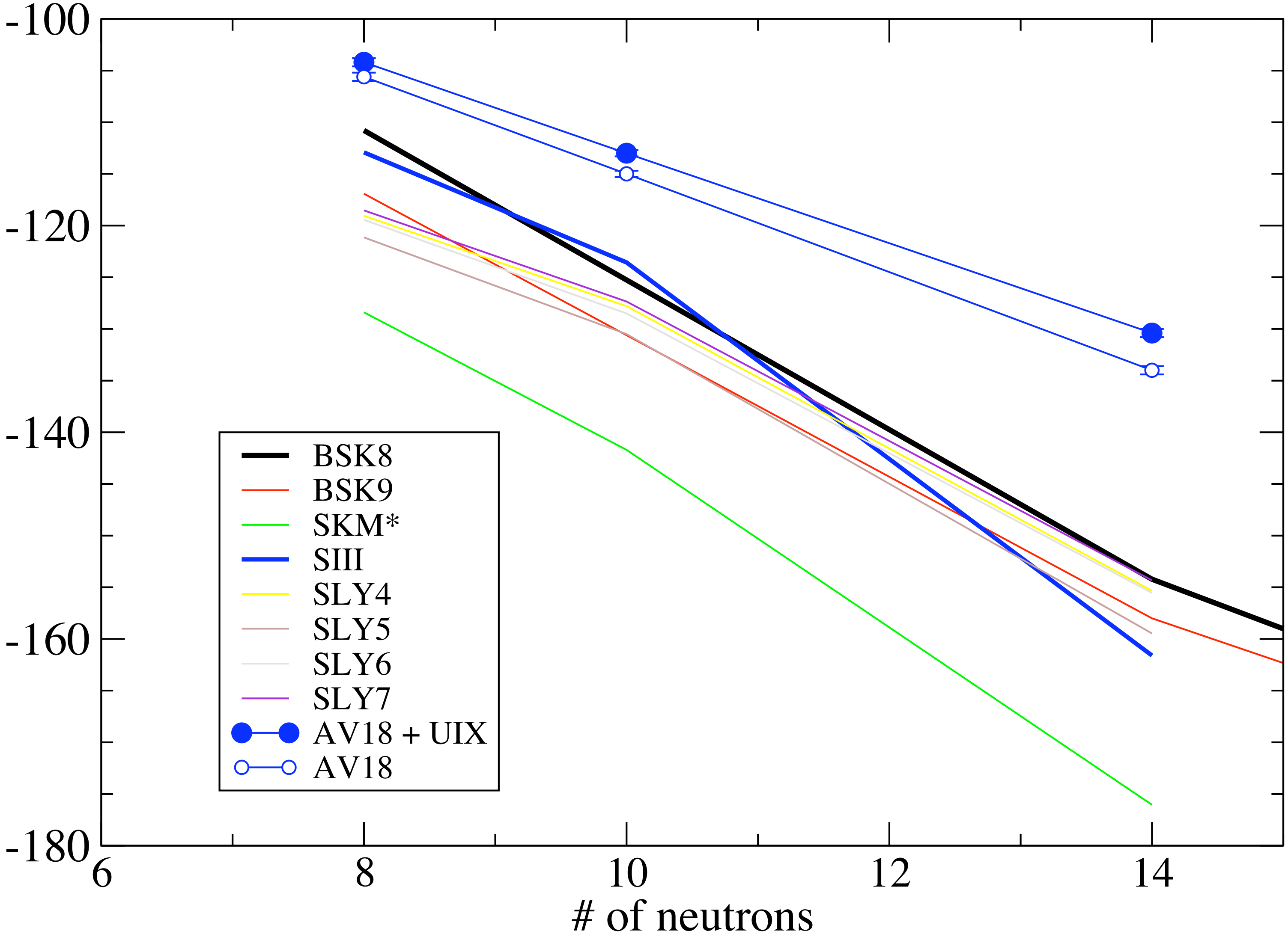


Potential

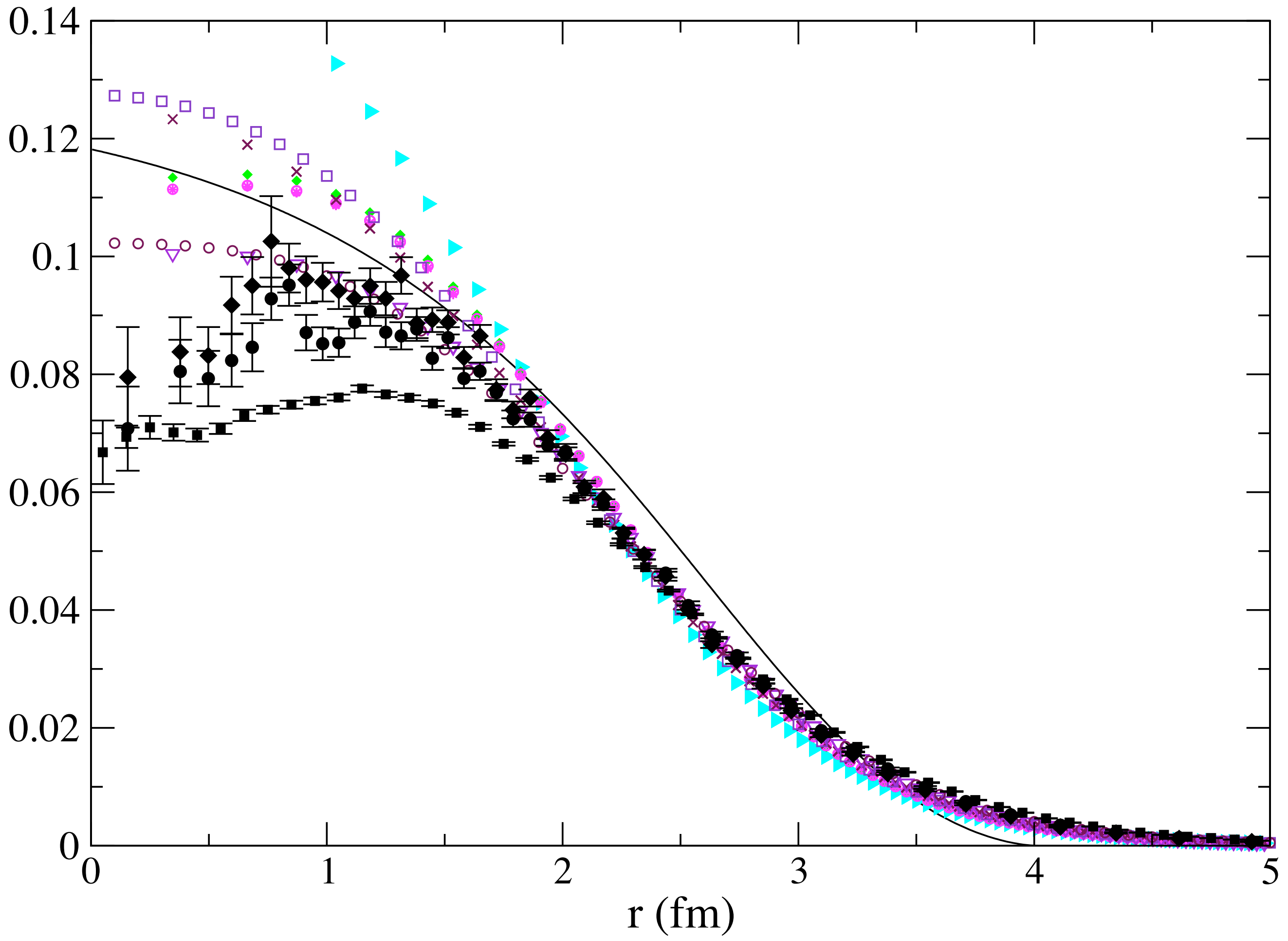


Small dependence upon three-nucleon force

Binding Energies: GFMC vs. present Skyrme



One-body Densities



Solid points: GFMC w/ various TNI
points w/o error bars: Skyrme Models

Generic overbinding/small radius

Summary and Outlook

Simplest properties of neutron matter at T=0
    rapidly becoming well understood: E/A, Δ

Similar systems (cold atoms) tested in experiment

Will require more advanced density functionals
Many more properties will be available shortly:
    Spin Susceptibility
    Generalized Static Resonse, ...

Toward direct studies of neutron-star matter