

# 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)

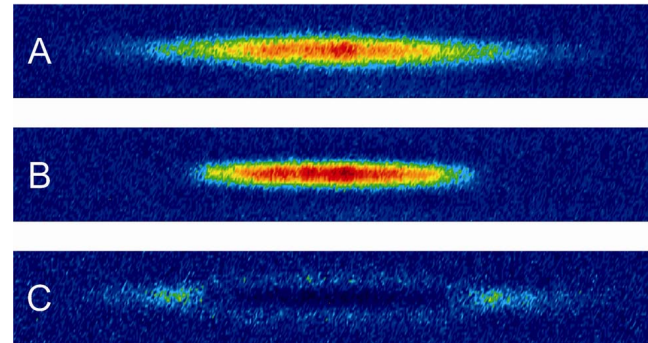
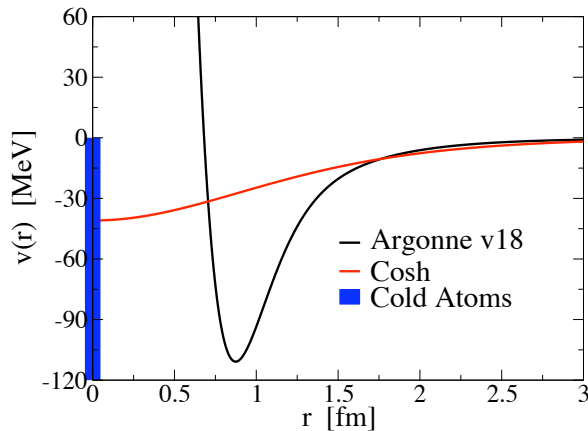
- Energies and Saturation

- Comparing ab-initio energies with Skyrme

- Single-Particle Energies

## ■ Outlook

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



## Computational Approach:

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

GFMC: sum over spin/isospin explicitly

Diffusion MC: spin-independent (s-wave interactions)

AFDMC: Monte-Carlo sums over spin/isospin

## Neutron Matter Diffusion Monte Carlo

~65 particles (scales like  $N^3$ )

Gap from even/odd staggering

Need  $\ll 1$  MeV accuracy

## Caveats:

Fixed-node (Upper Bound)

Finite System Size

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

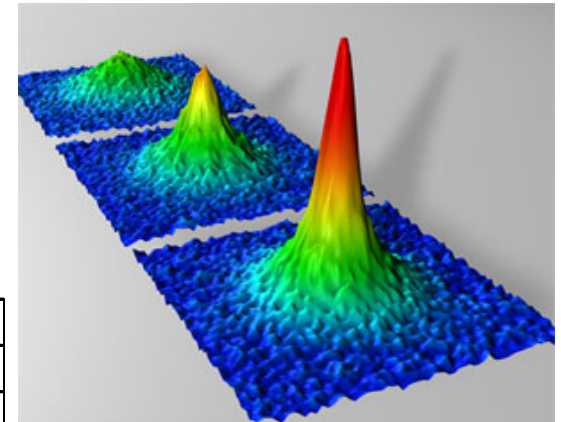
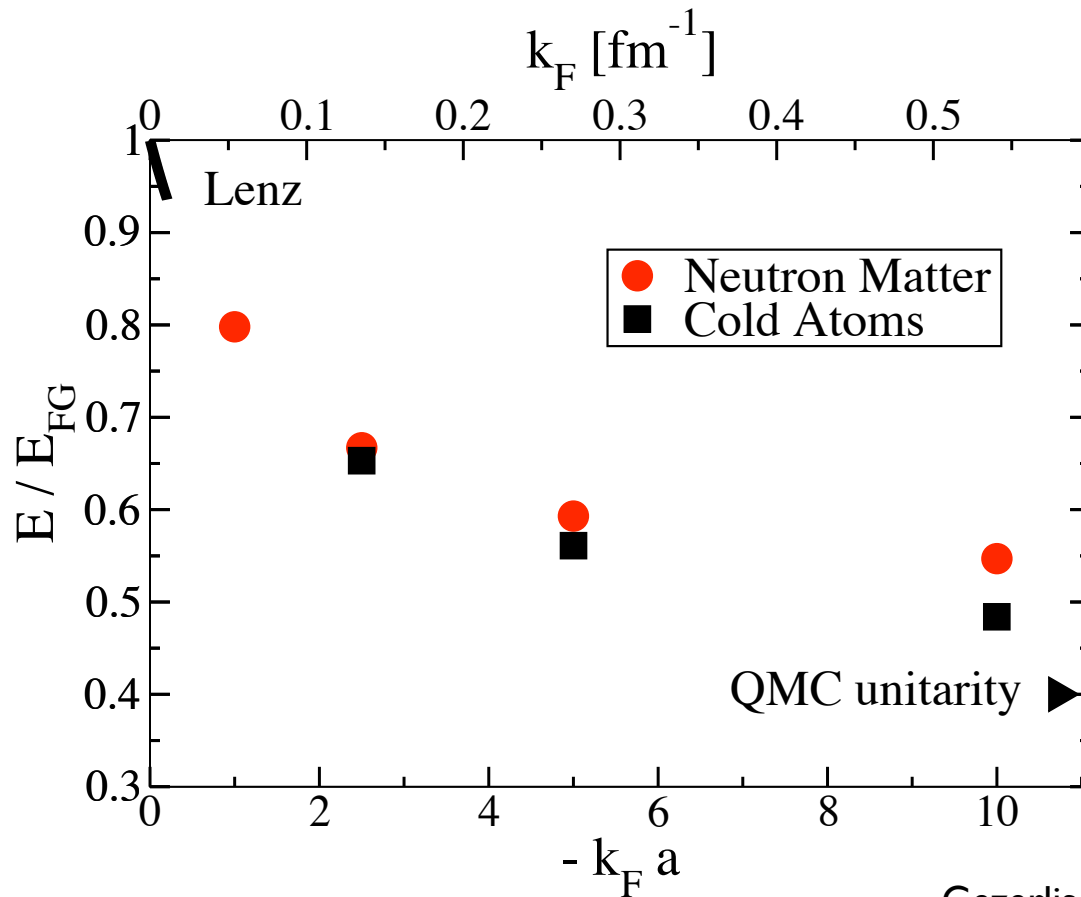
approximately 1 Tflop on Franklin

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

Expt at Unitarity

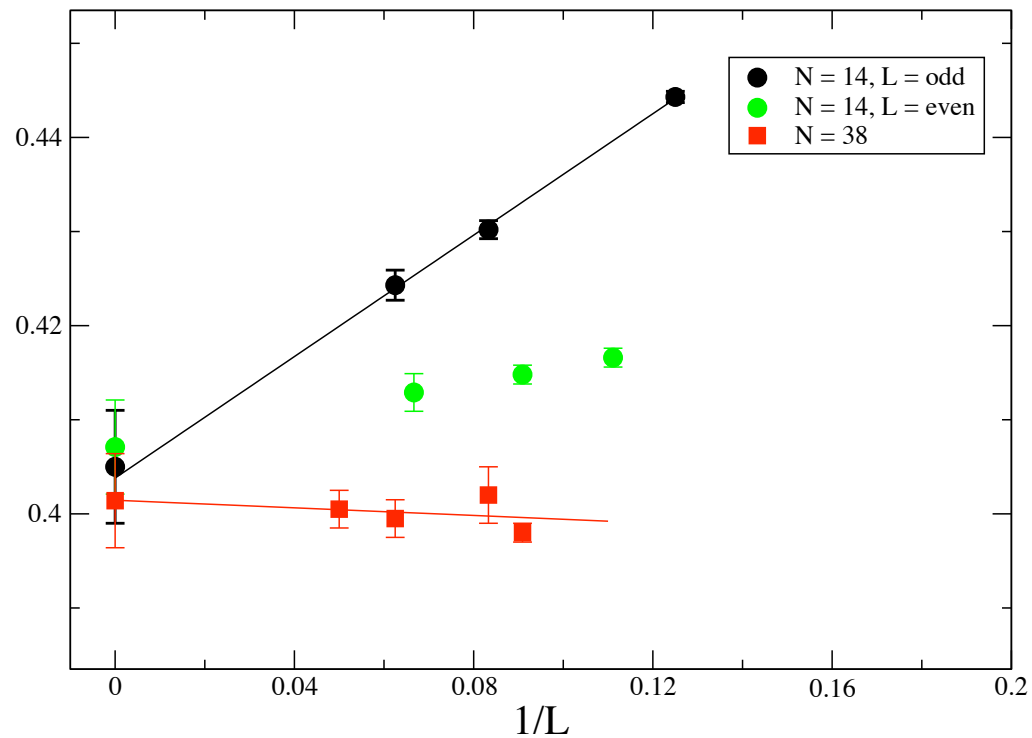
L. Luo and J. E. Thomas,  
 J. Low. Temp. Phys., 154, 1 (2009)

Gezerlis & Carlson, PRC 2008

# Lattice Results at Unitarity

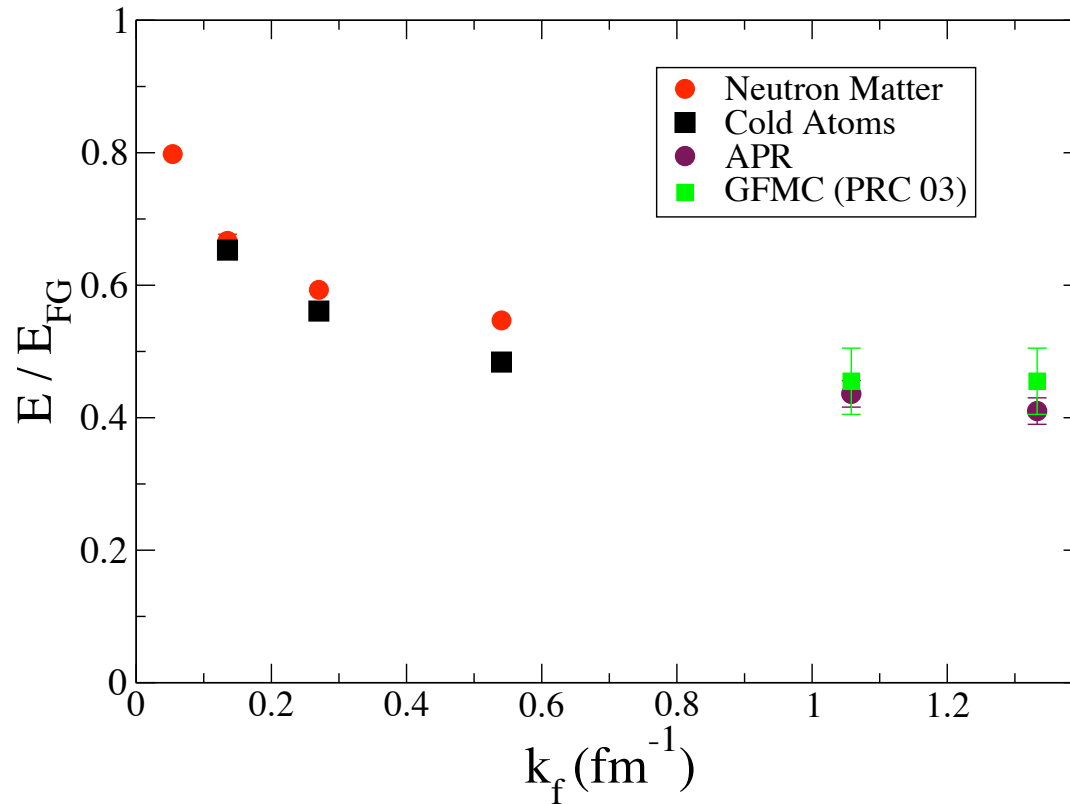
lattice has no fixed-node error

Unitarity Limit



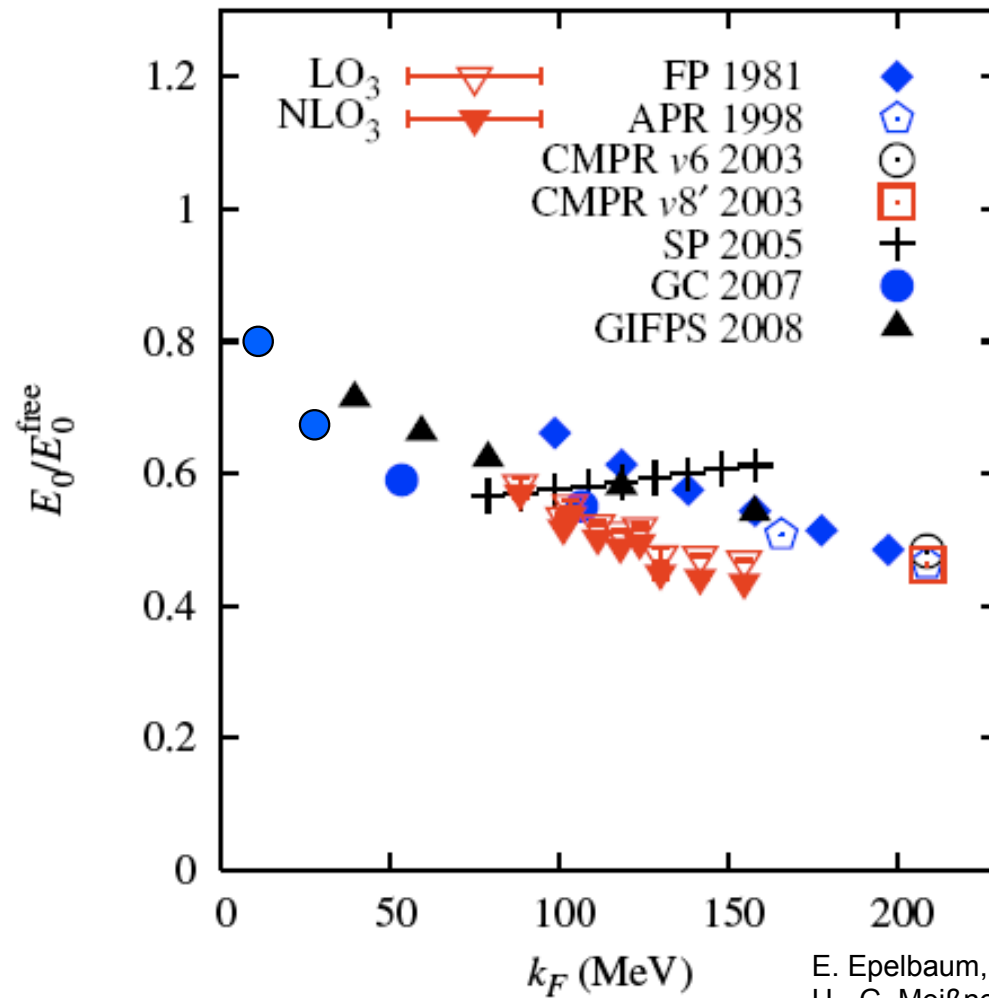
Good agreement between lattice, continuum

# Low Density Neutron Matter EOS very well determined



Skyrmes typically fit at  $k_f = 0$  and  $\sim 1.3 \text{ fm}^{-1}$ ,  
but not between

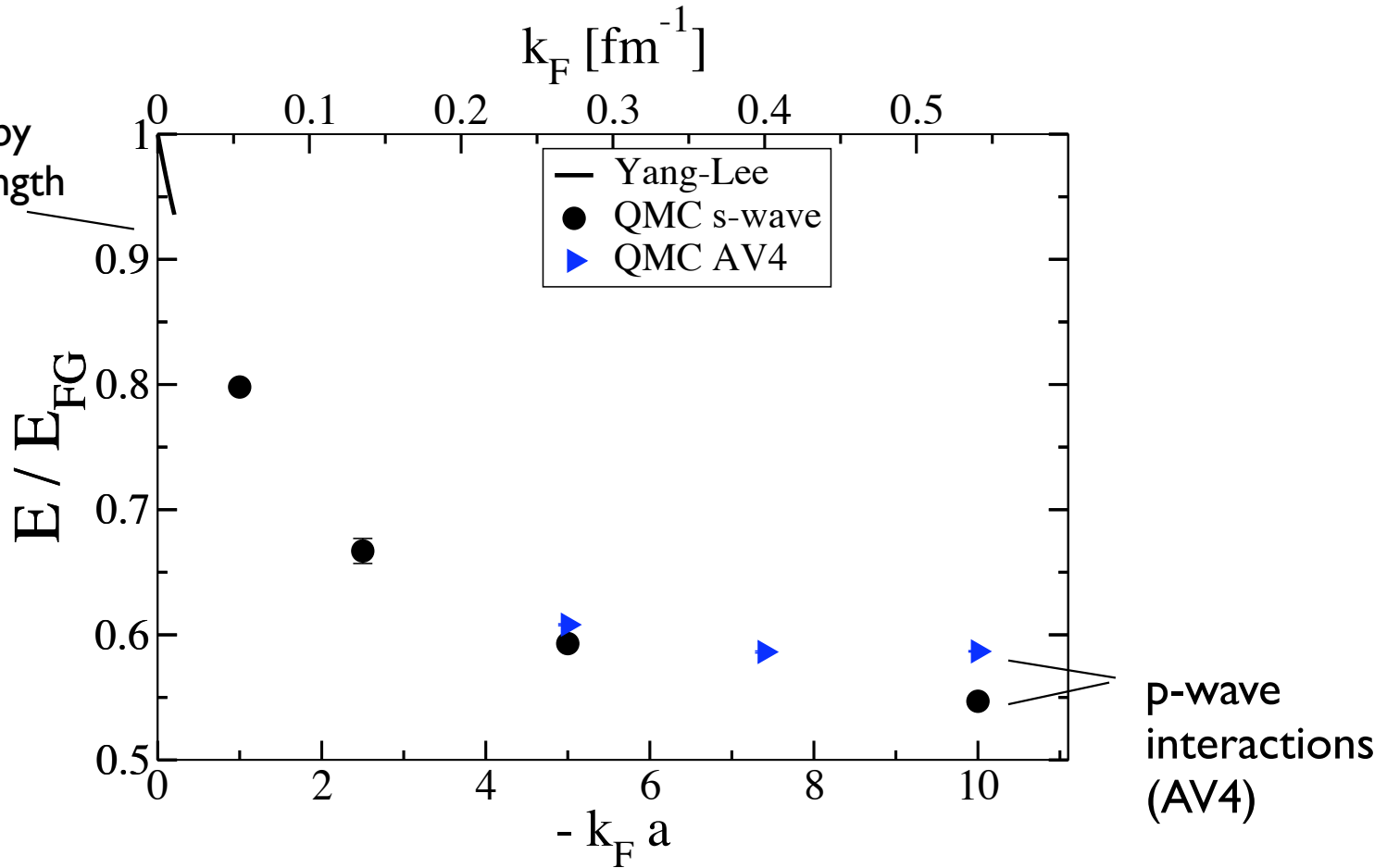
# Equation of State Quantitatively Established



E. Epelbaum, H. Krebs, D. Lee, and  
U. -G. Meißner, arXiv:0812.3653

# Adding p-wave interactions

Very low  
densities  
determined by  
scattering length

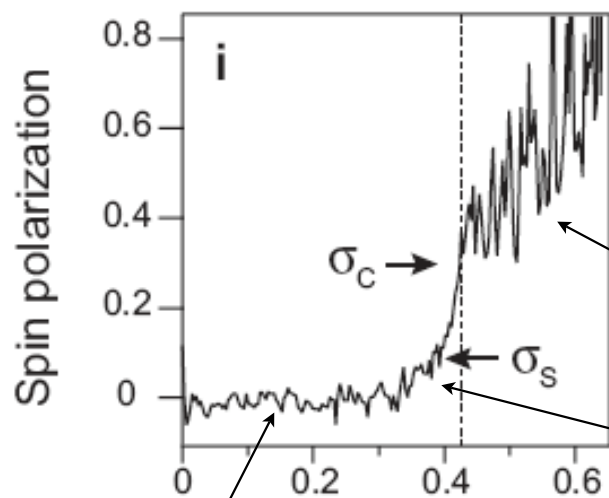
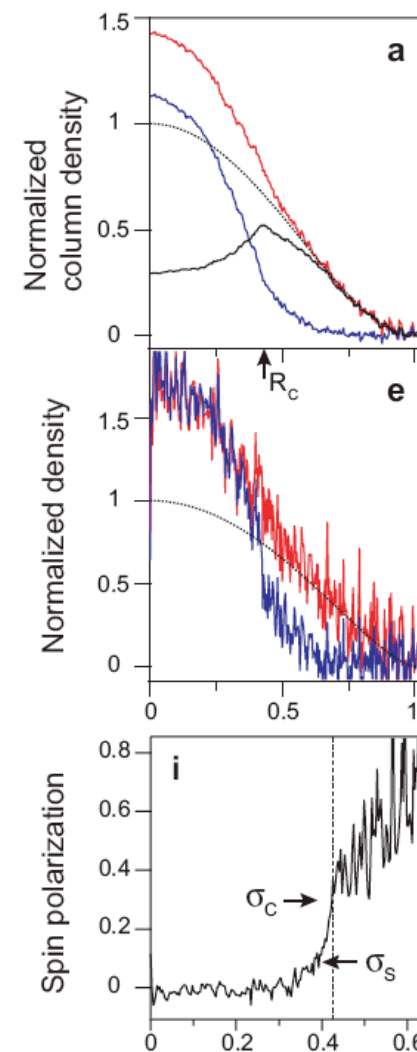
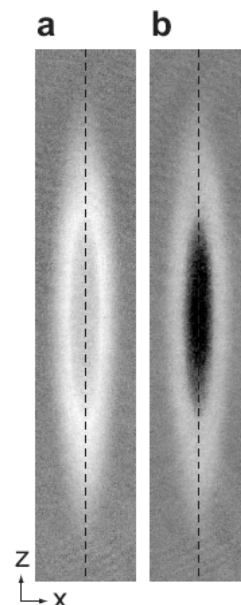


Other Quantities (Gap, etc.) much more difficult

# Spin Degrees of Freedom

Superfluid pairing gap  
in strong coupling testable in cold atoms

Magnetic Fields or different  
chemical potentials can break superfluidity



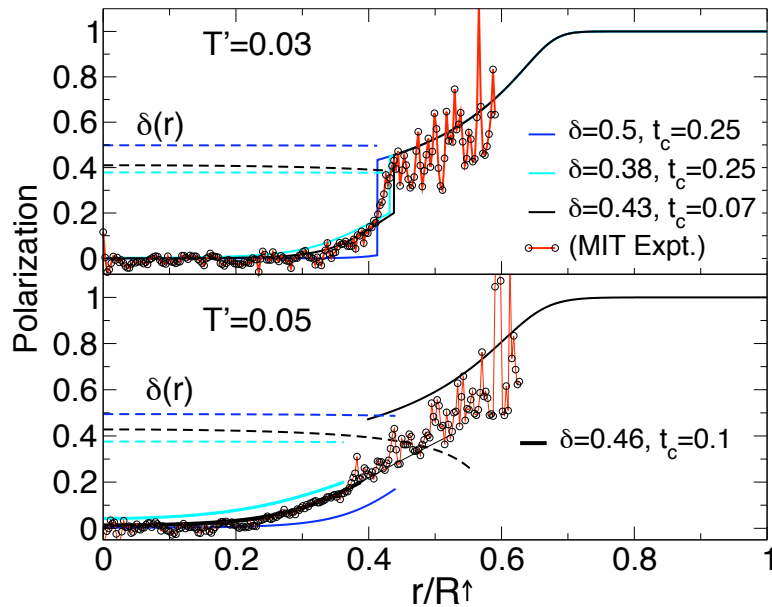
Unpolarized Superfluid

Polarized Normal State

Thermally populated  
quasiparticles in superfluid

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

# Neutron Matter Pairing Gap

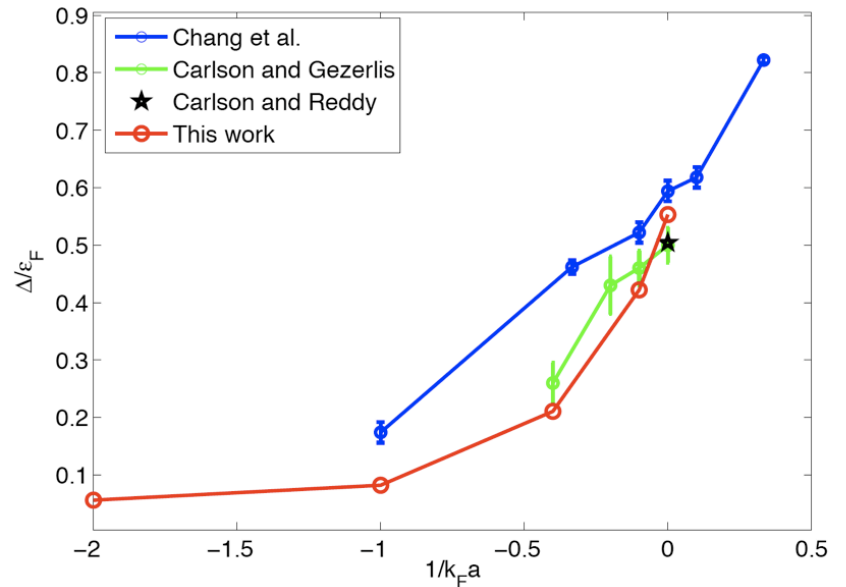


Analysis of cold atom experiments gives  $\Delta/E_f = 0.45$  (05).

**Largest  $\Delta/E_f$  in any system!**

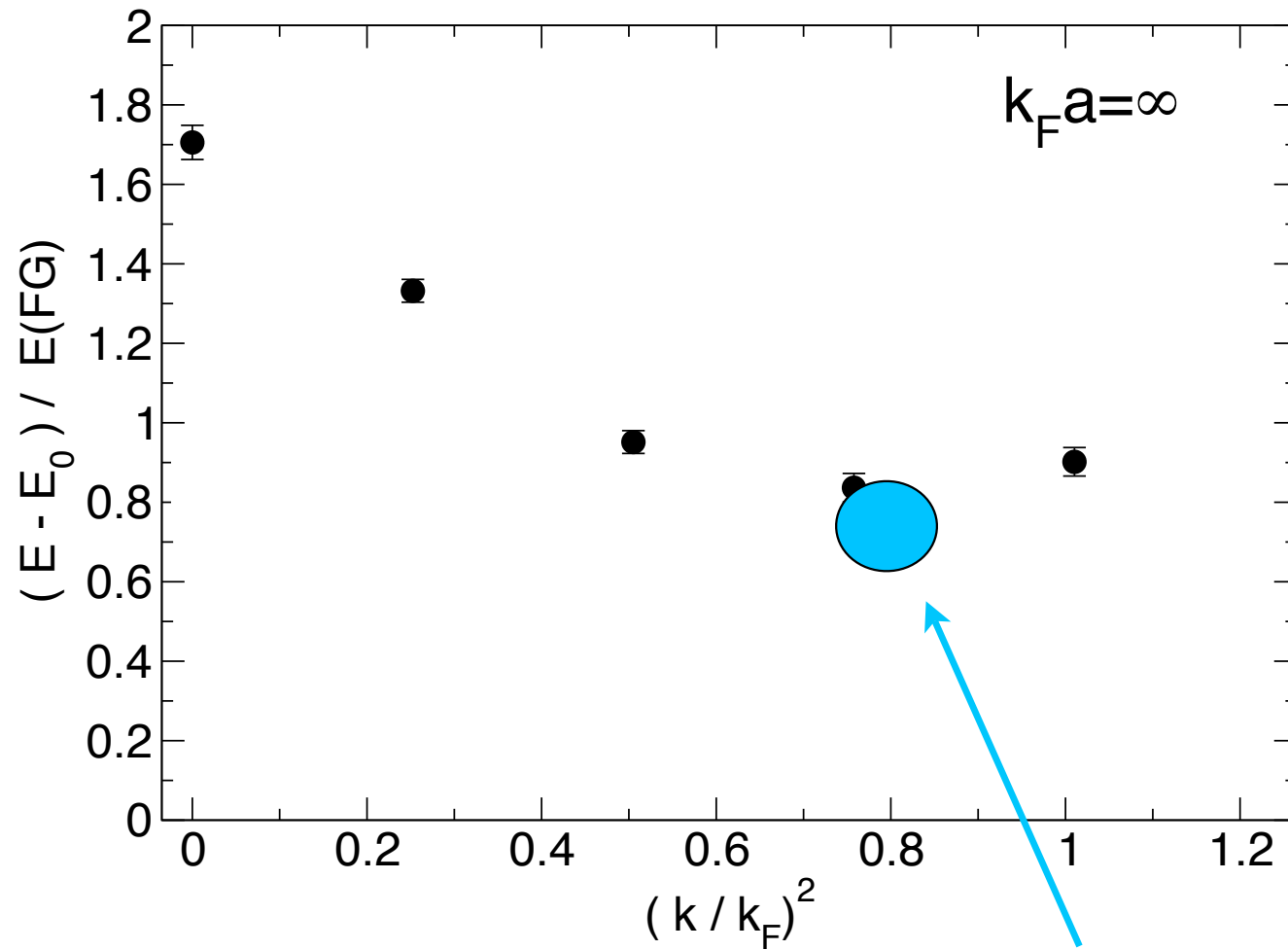
Carlson and Reddy, PRL 08

Pairing Gap for Atomic Gas  
Experimentally confirmed to ~10%



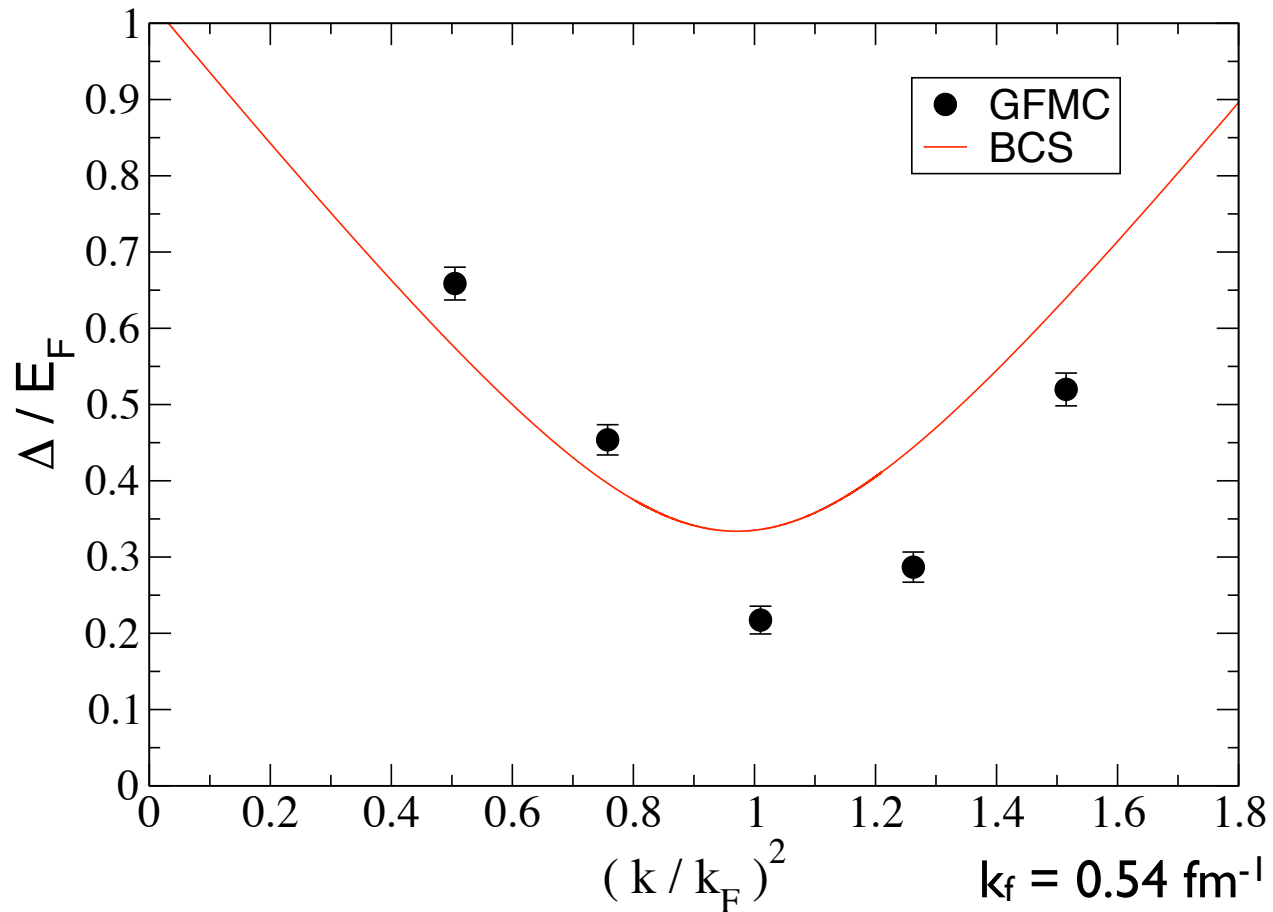
Calculations also agree; new AFDMC calculation much closer to DMC

# Cold Atom Dispersion



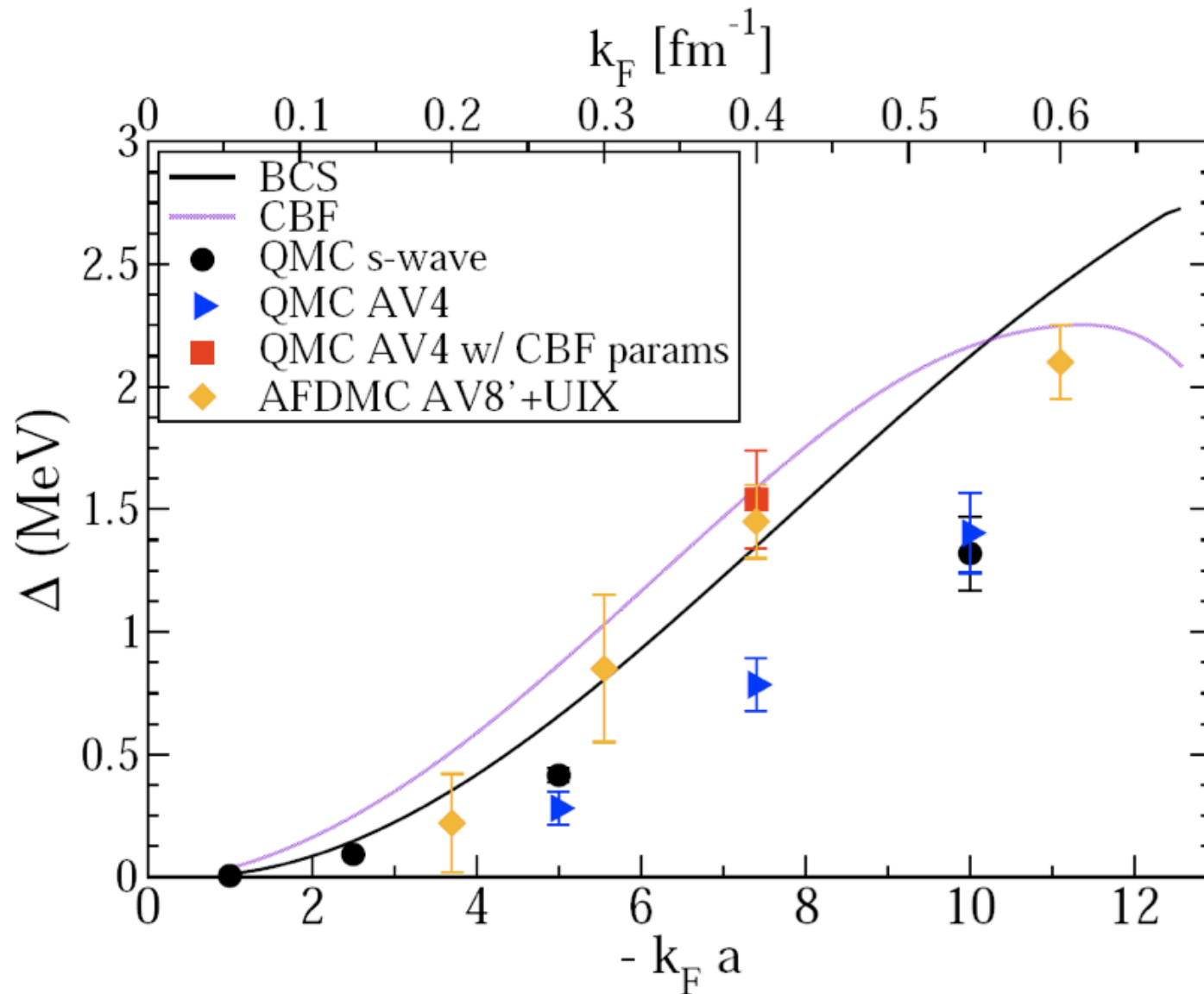
Shin, Ketterle, ... 2008

## New Calculations: Dispersion of Single-Particle States

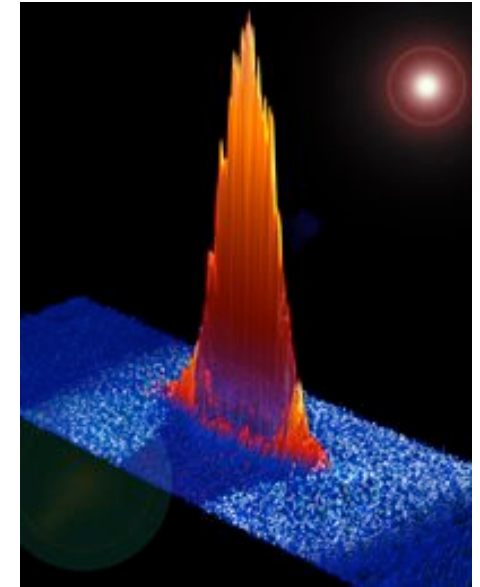


Can be a constraint to Mean Field models  
Spin susceptibility - of interest in neutron stars

# Pairing Gap at Low Densities



# Density Perturbations



**Static Susceptibility:**

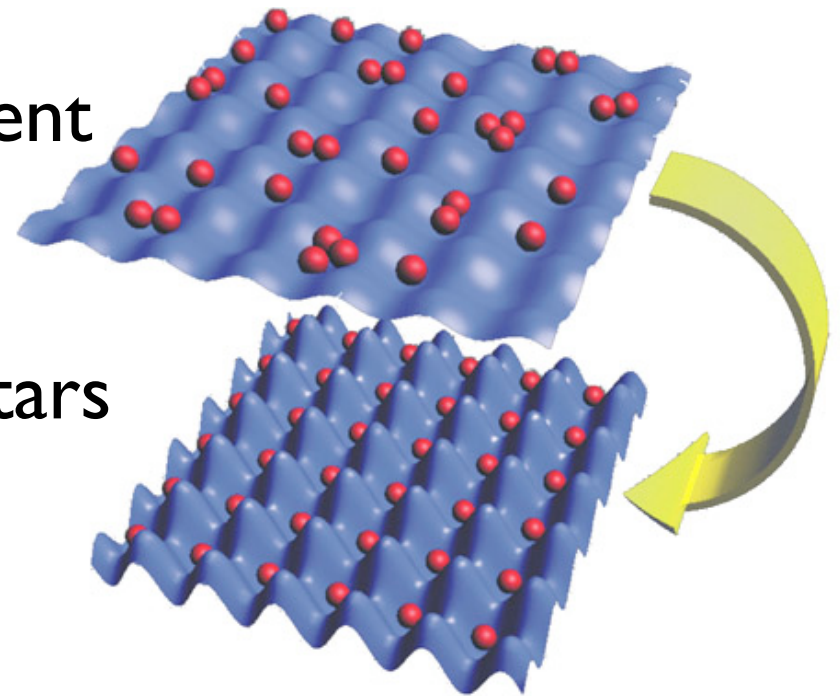
response to small long-wavelength potential

General response to external potentials

Relevant to generalized gradient terms in density functional:

PREX

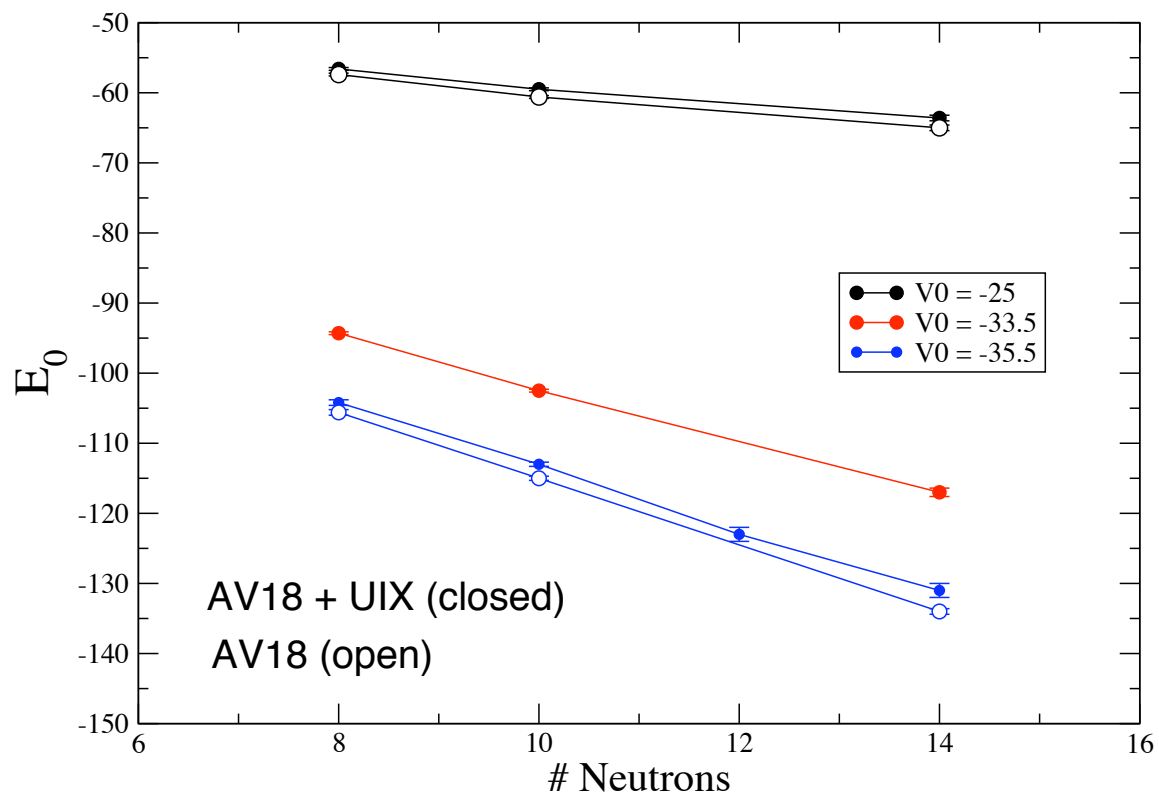
Inner Crust of Neutron Stars



# Neutron Drops

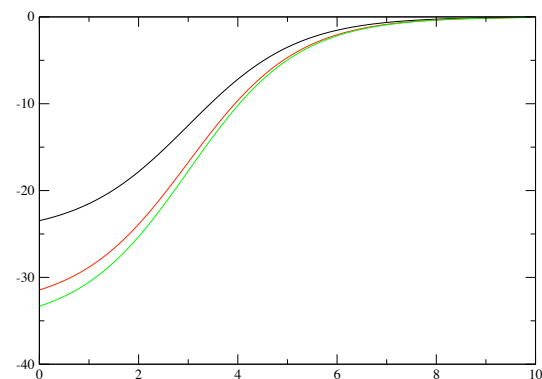
Woods-Saxon potential ( $r=3$  fm,  $a=1.1$  fm) at various depths  
also initial work on Harmonic Oscillators

## Binding Energy



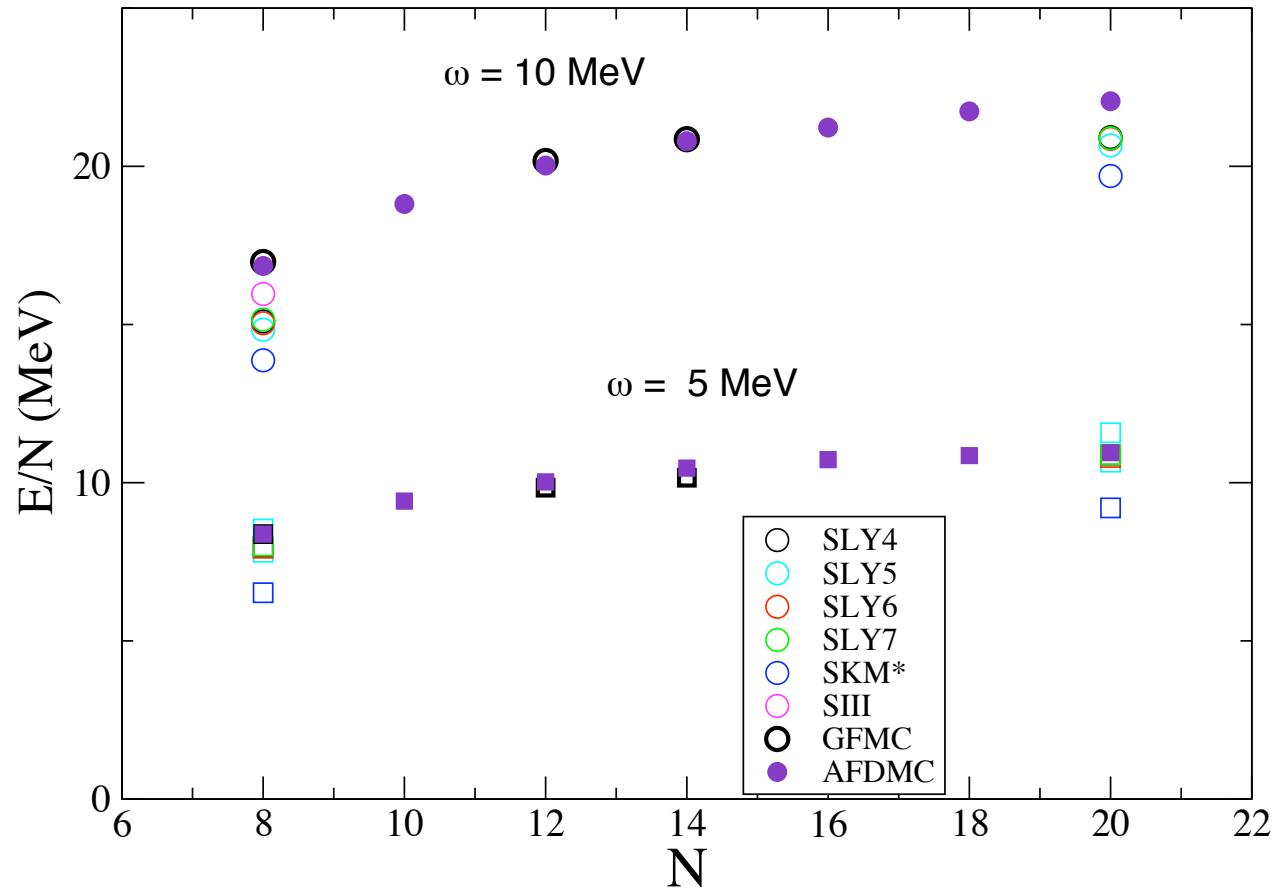
Small dependence upon three-nucleon force

## Potential





# Comparison - Harmonic Oscillator



## Summary and Outlook

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

Similar systems (cold atoms) tested in experiment

Will require more advanced density functionals

Many more properties will be available shortly:

Spin Susceptibility

Nearly Arbitrary External Potentials

Valuable Constraints on DF

Toward direct studies of neutron-star matter