

Title: Spin-polarized low-density neutron matter

Date: Jun 20, 2011 11:40 AM

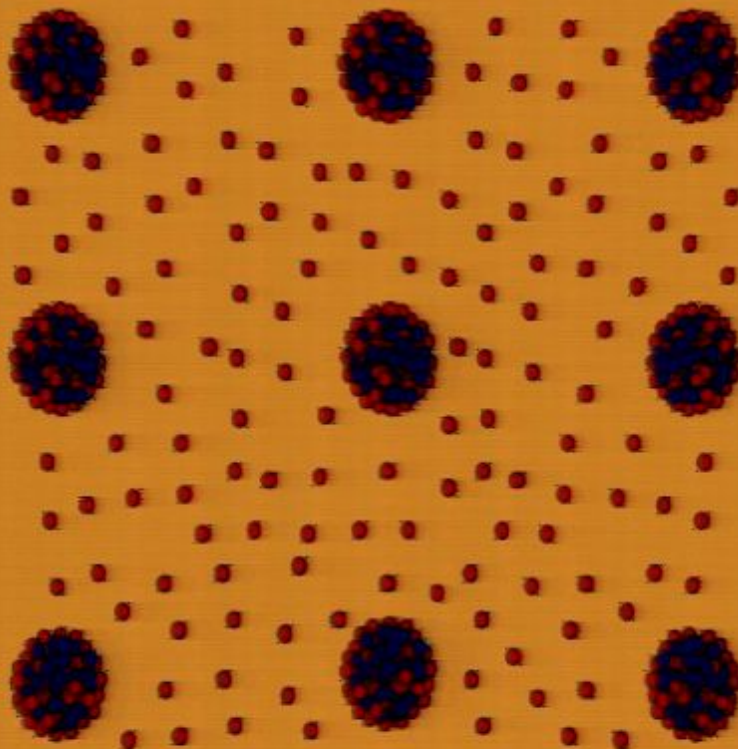
URL: <http://pirsa.org/11060016>

Abstract: Low-density neutron matter is relevant to the study of neutron-rich nuclei and neutron star crusts. Unpolarized neutron matter has been studied extensively over a number of decades, while experimental guidance has recently started to emerge from the field of ultracold atomic gases. We study population-imbalanced neutron matter (possibly relevant to magnetars and to density functionals of nuclei) applying a Quantum Monte Carlo method that has proven successful in the field of cold atoms. We report on the first ab initio simulations of superfluid low-density polarized neutron matter. For systems with small imbalances, we find a linear dependence of the energy on the polarization, the proportionality coefficient changing with the density. We also present results for the momentum and pair distributions of the two fermionic components.

Neutron star inner crust

Low-density neutron matter in ion lattice

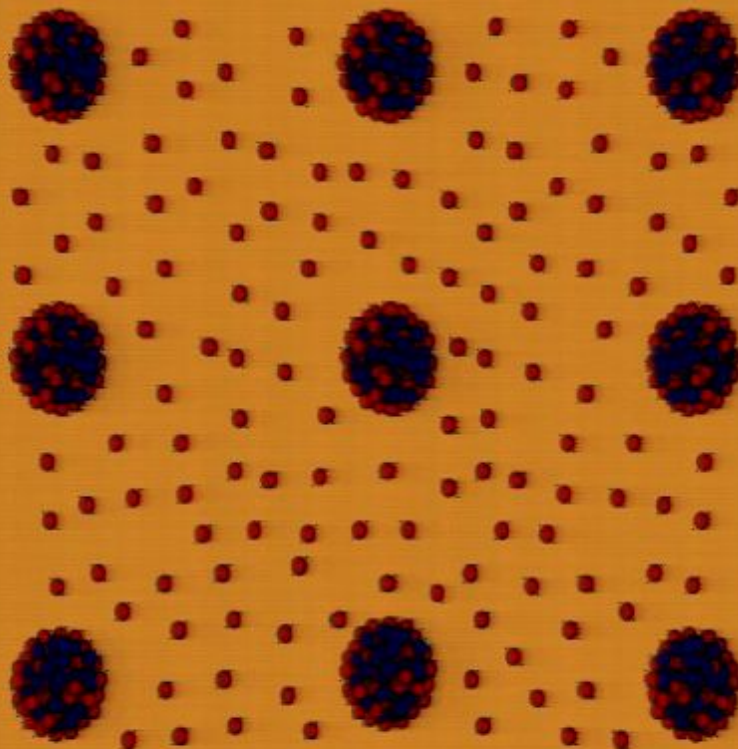
- Pairing significant: singlet in matter, possibly triplet in nuclei
- Nuclear toy problem of physical relevance



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Properties

- Scattering length (a)
- Effective range (r_e)
- Density (ρ) or (k_F)

“Observables”

- Energy (E/E_{FG})
- Pairing gap (Δ/E_F)

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No Signal

VGA-1

No Signal

VGA-1

No Signal

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The meaning of it all

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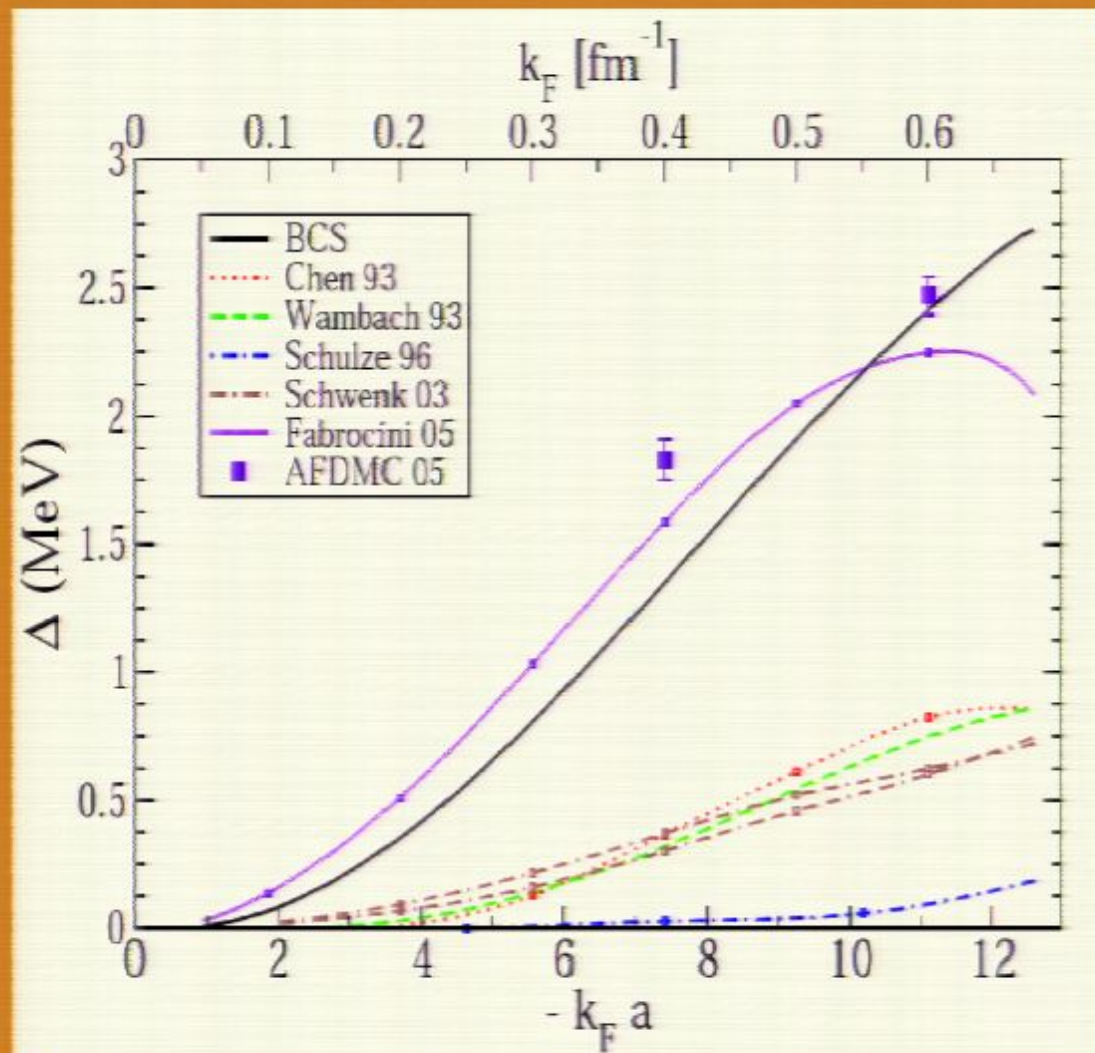
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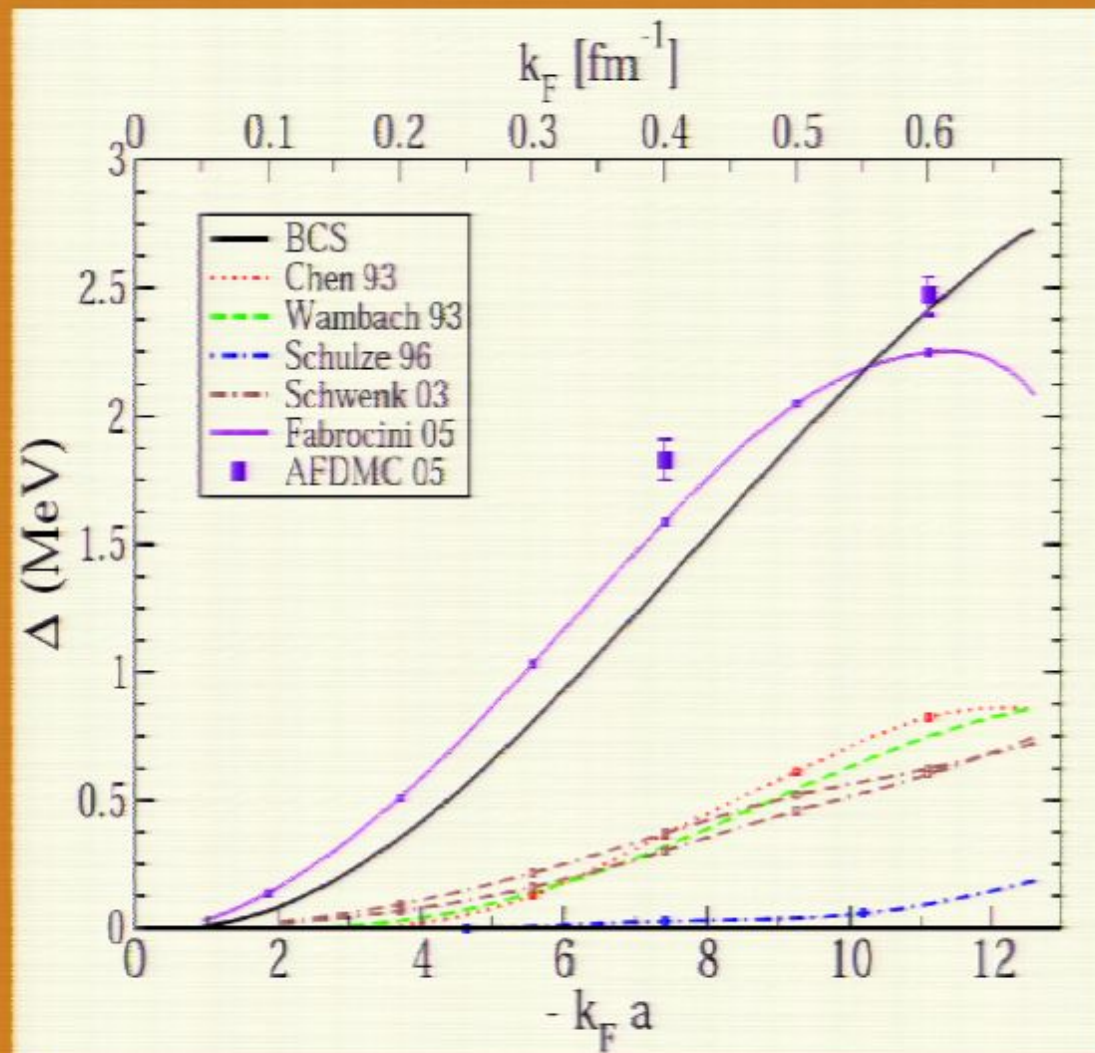
1S_0 neutron matter pairing gap

No experiment \rightarrow no consensus



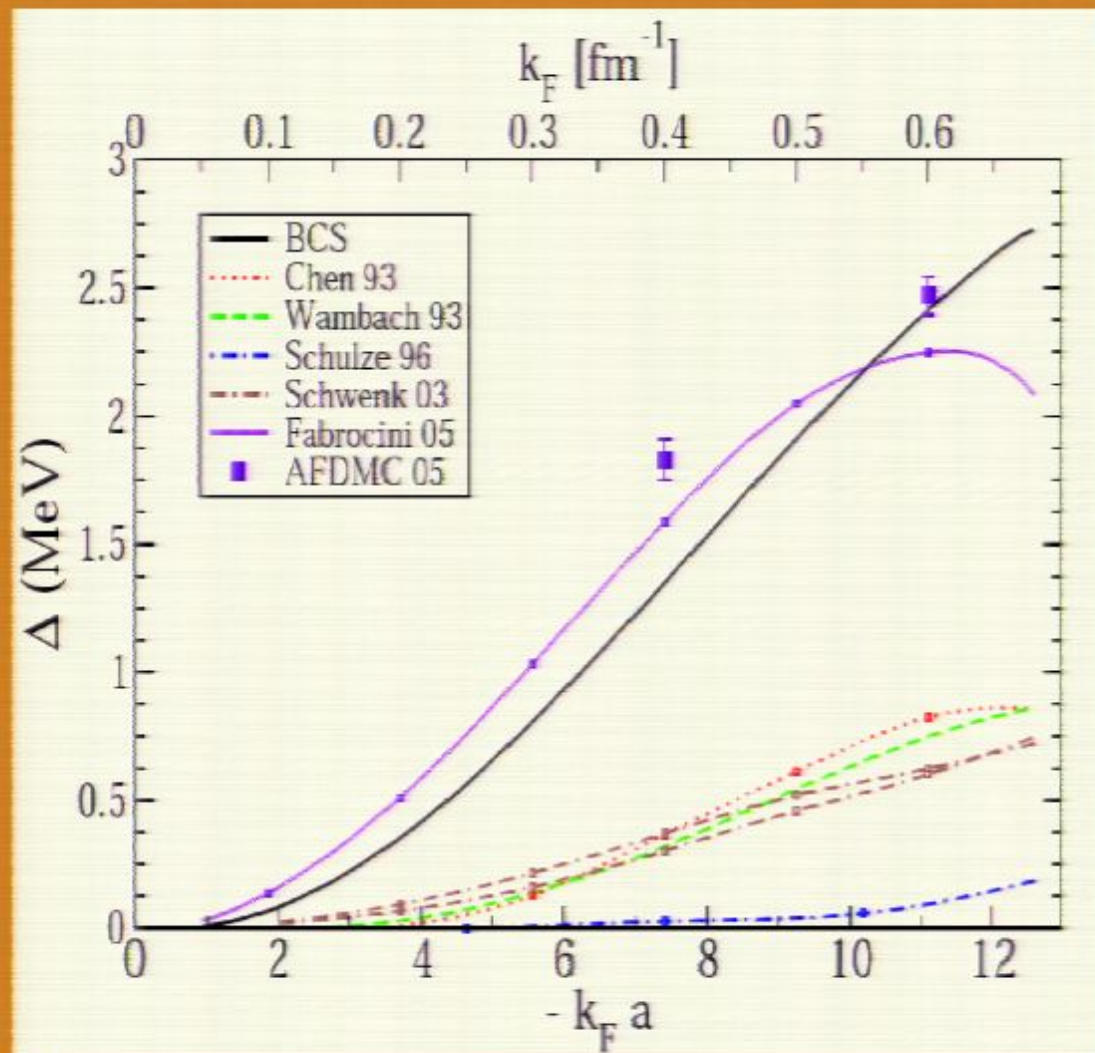
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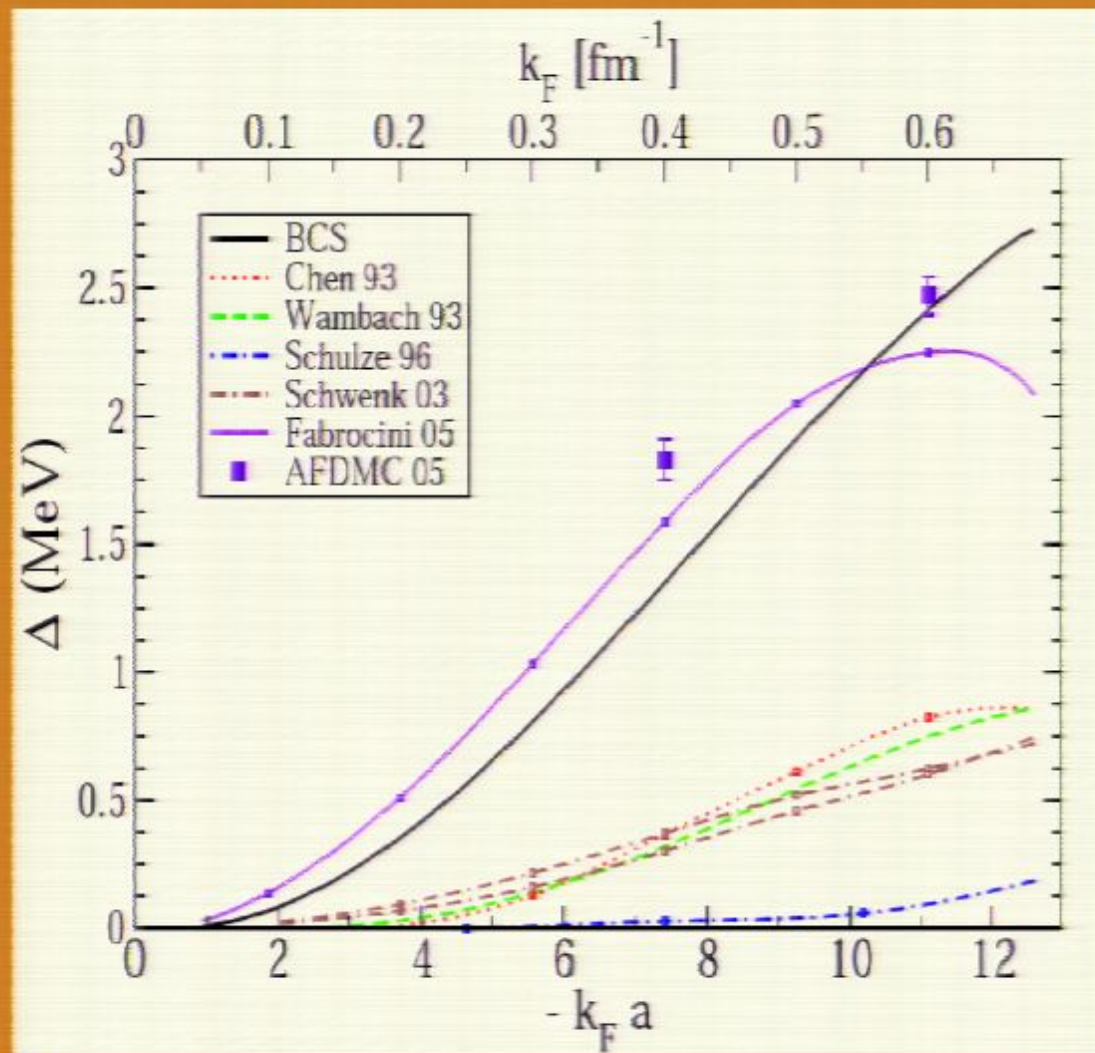
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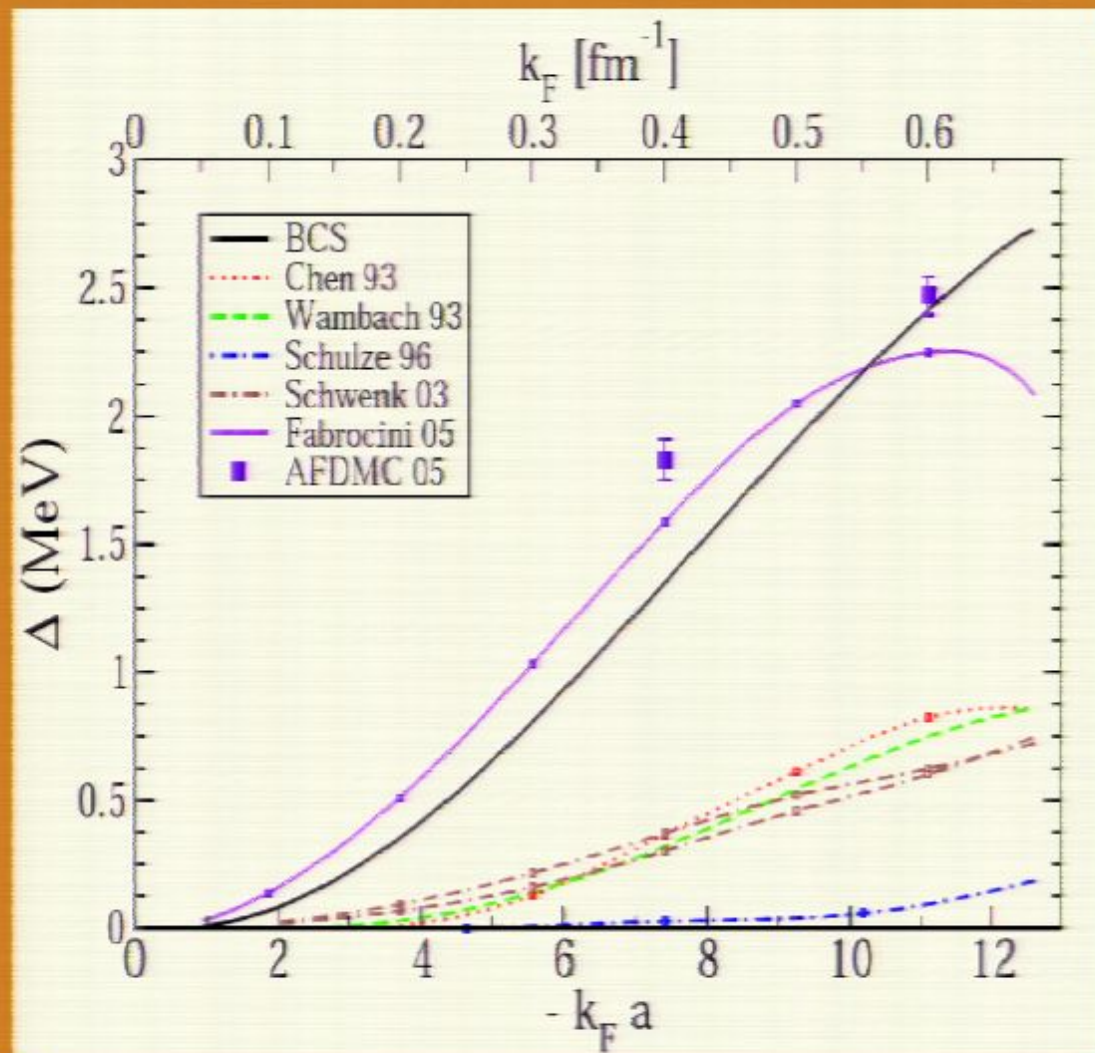
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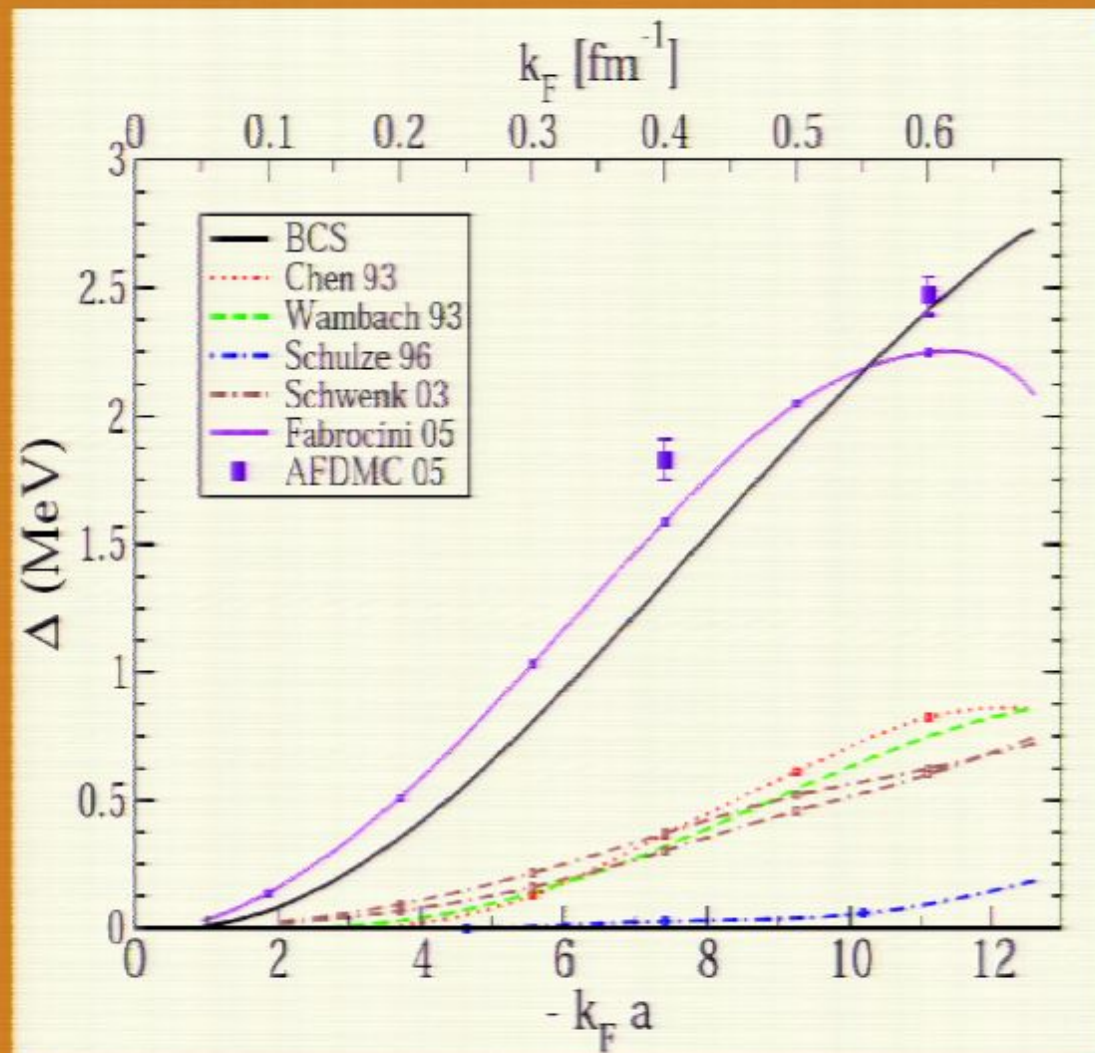
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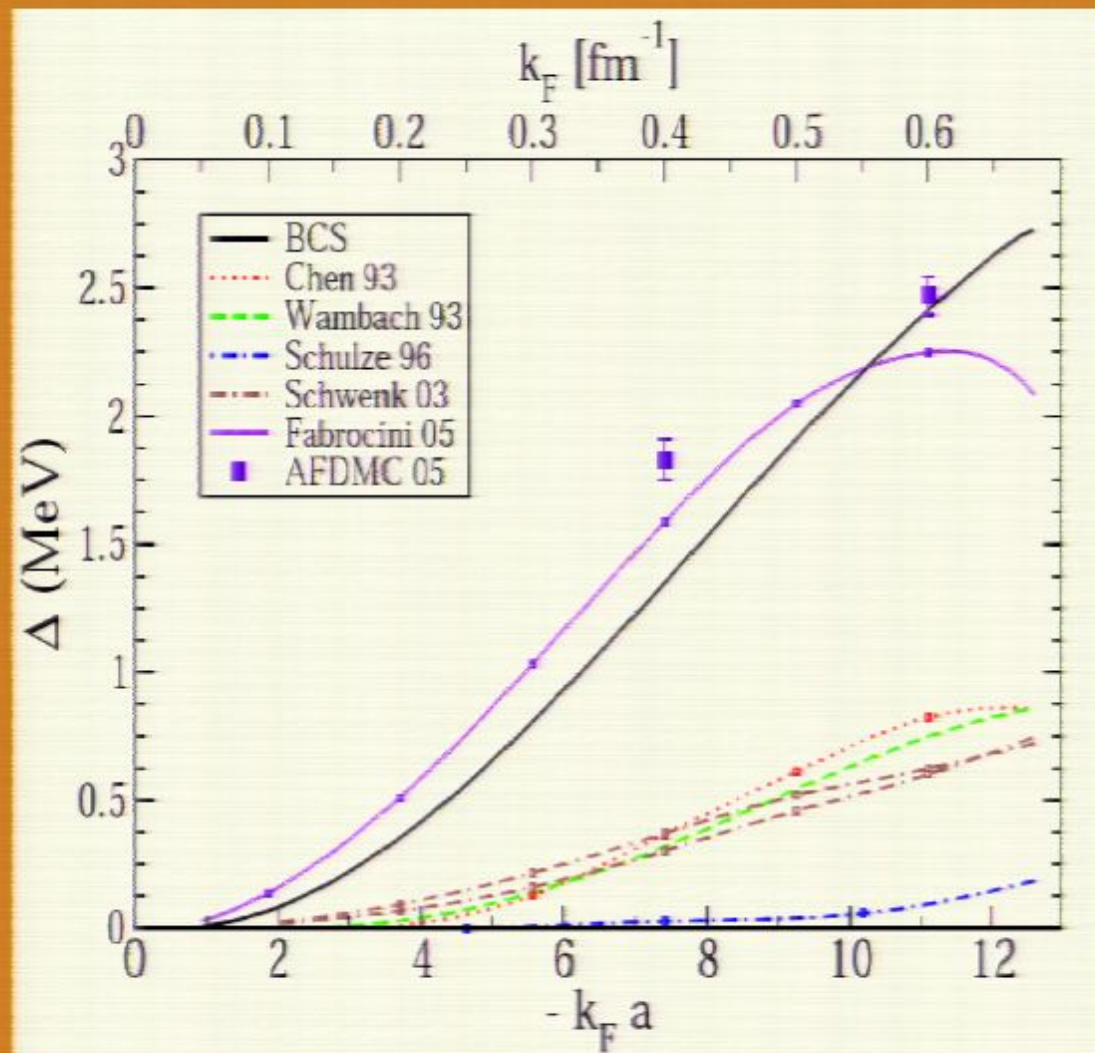
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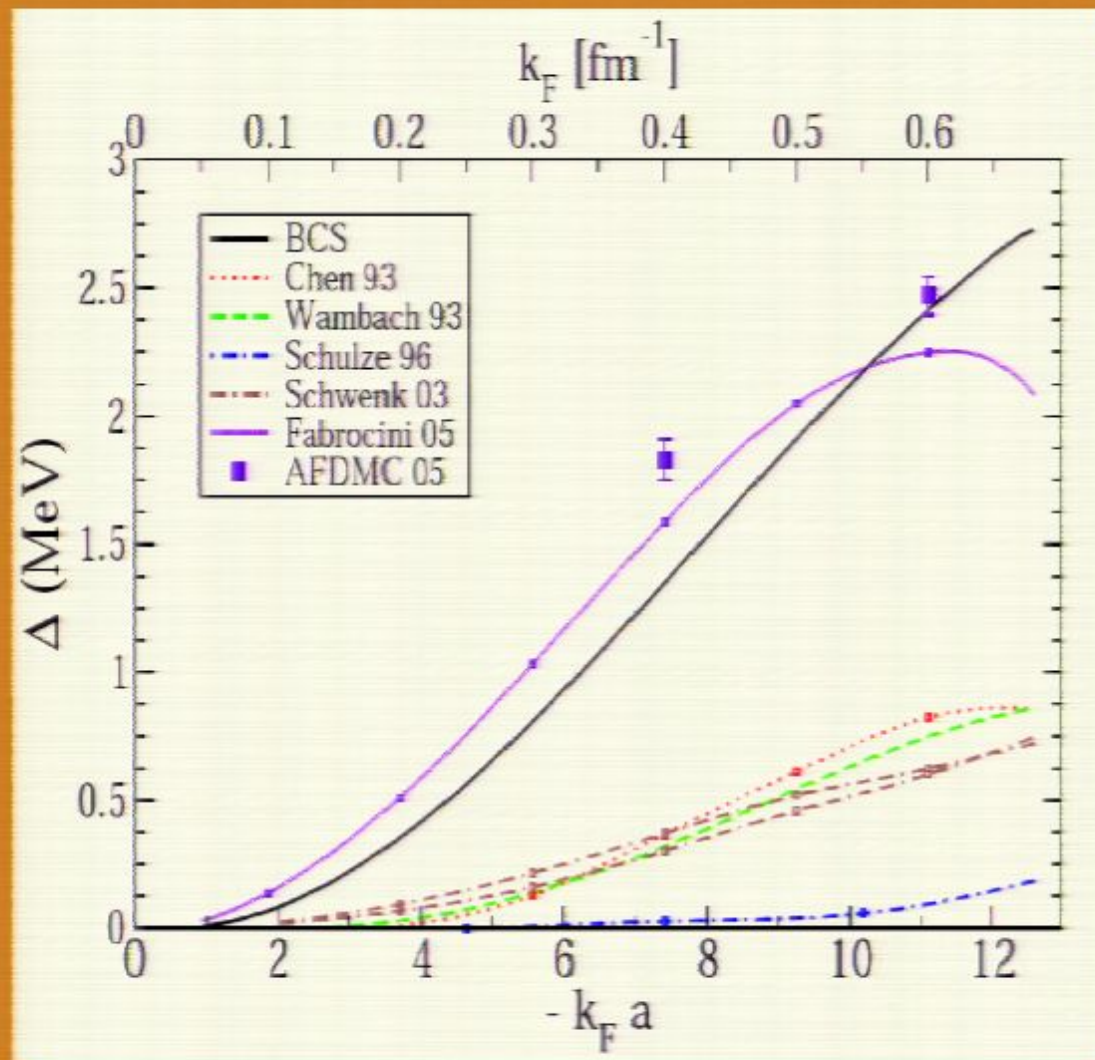
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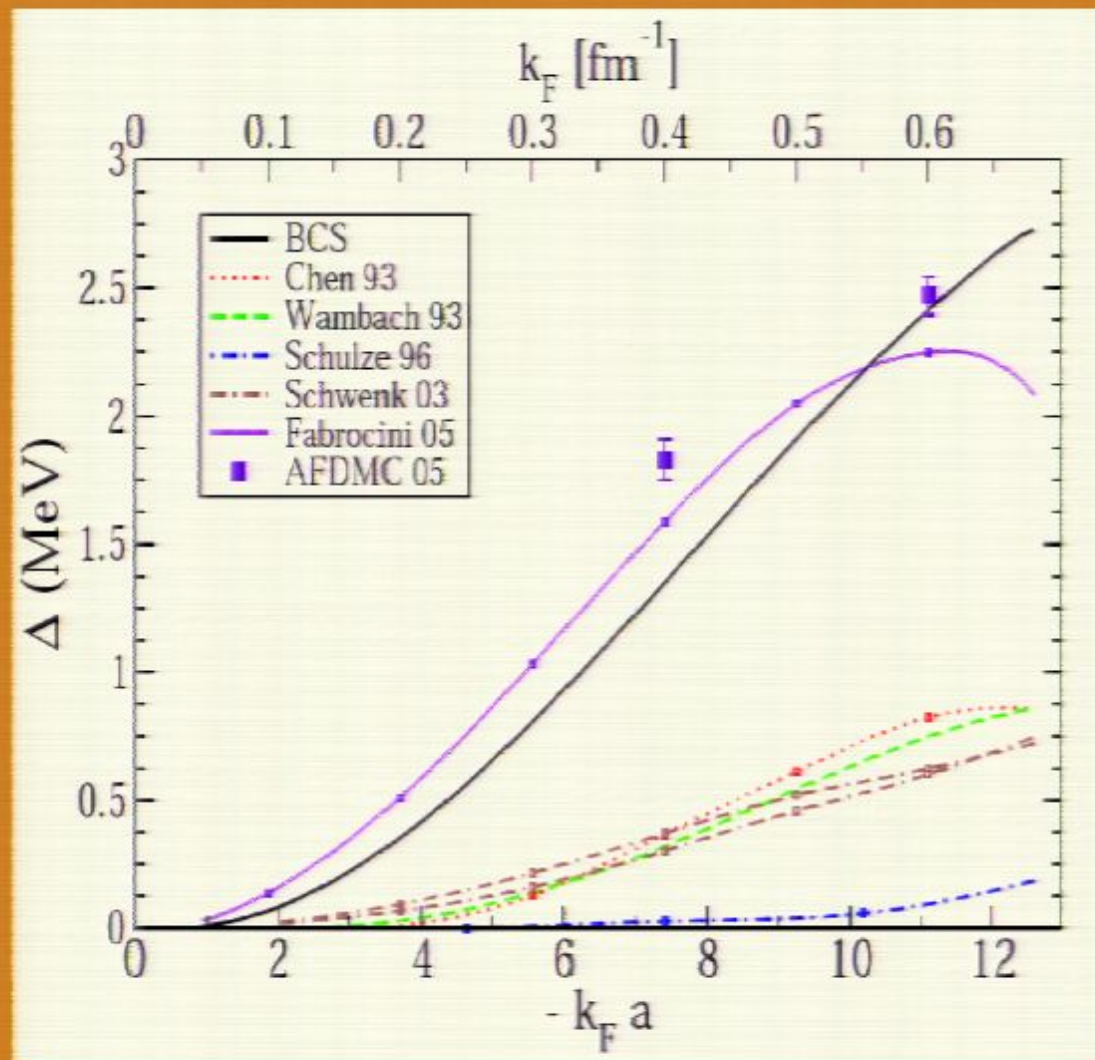
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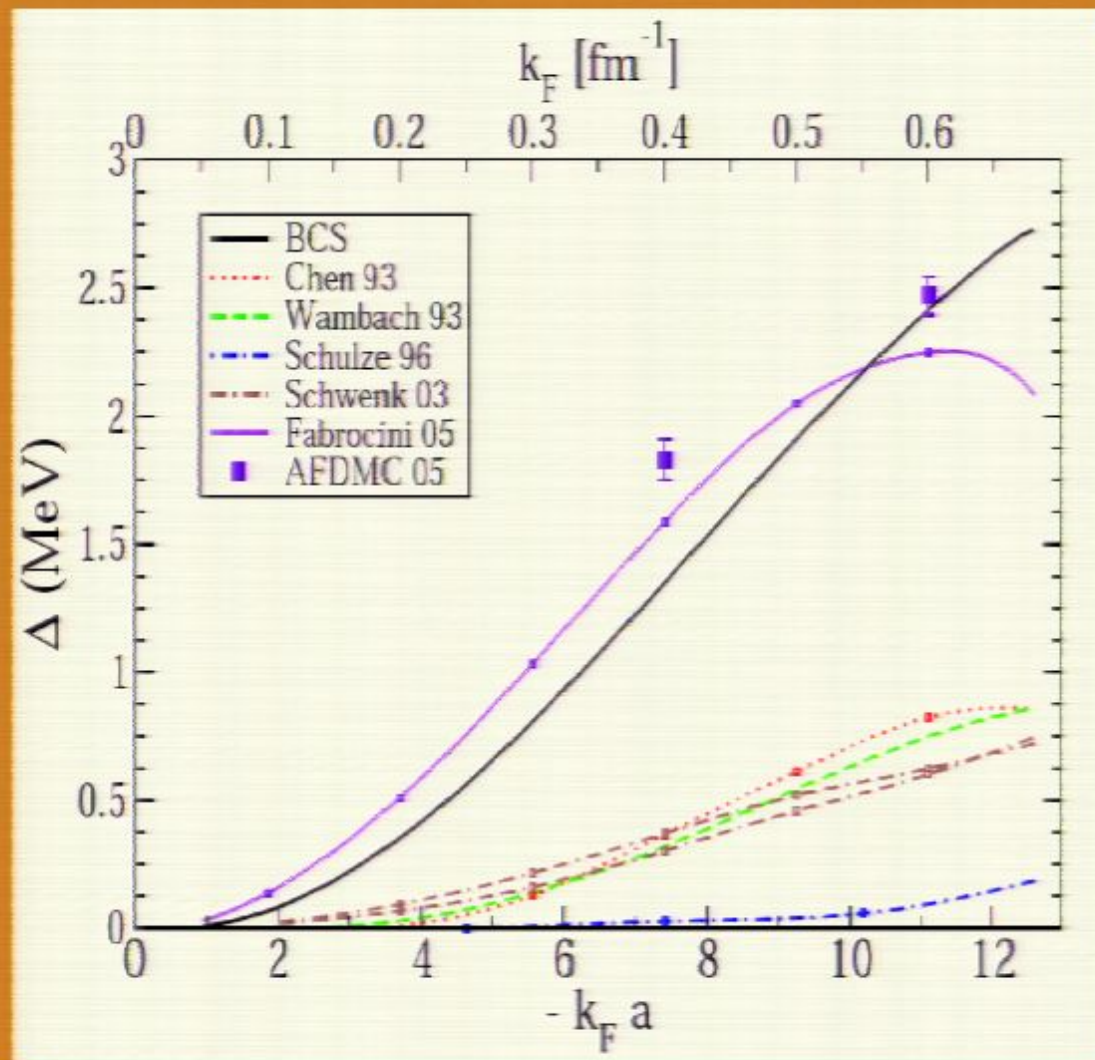
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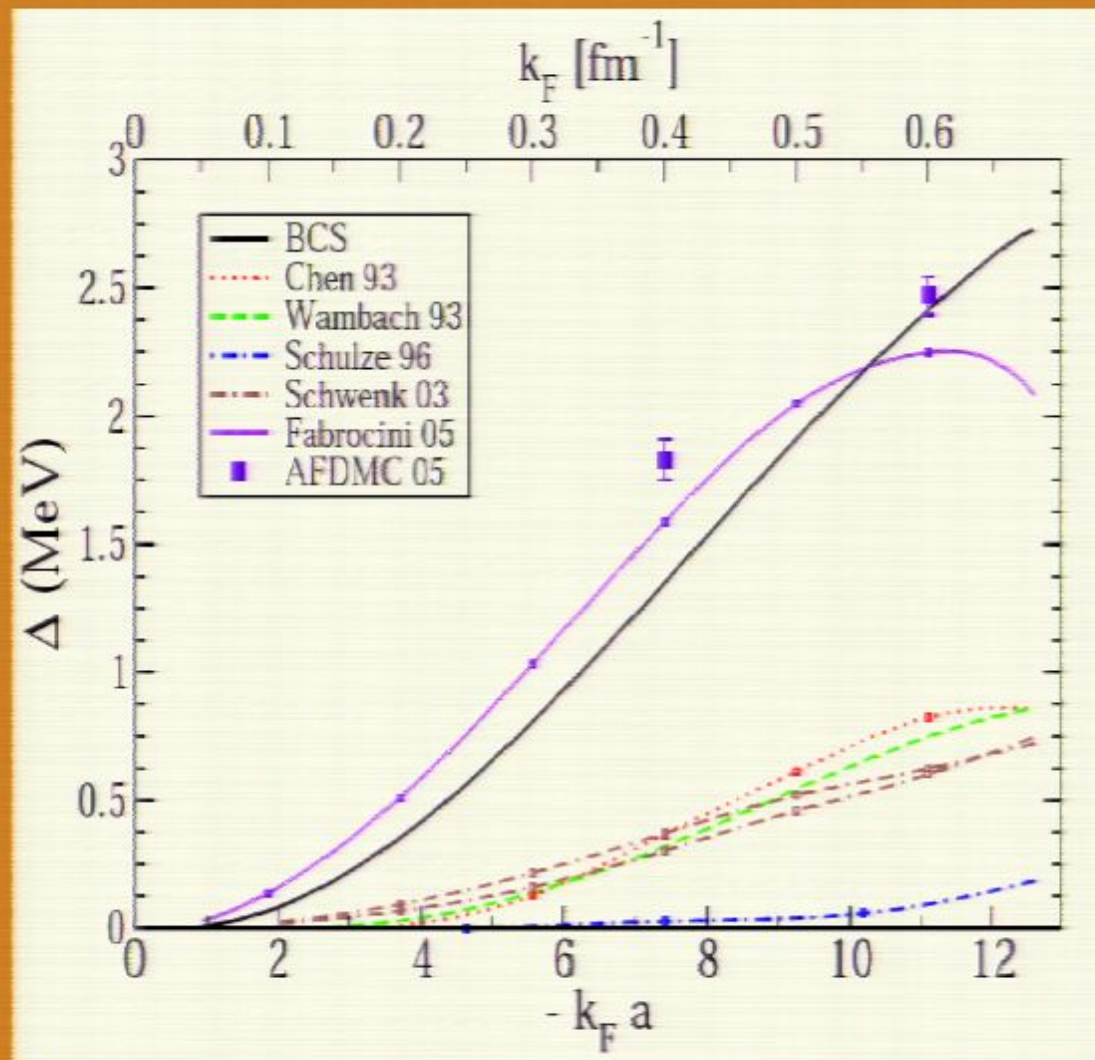
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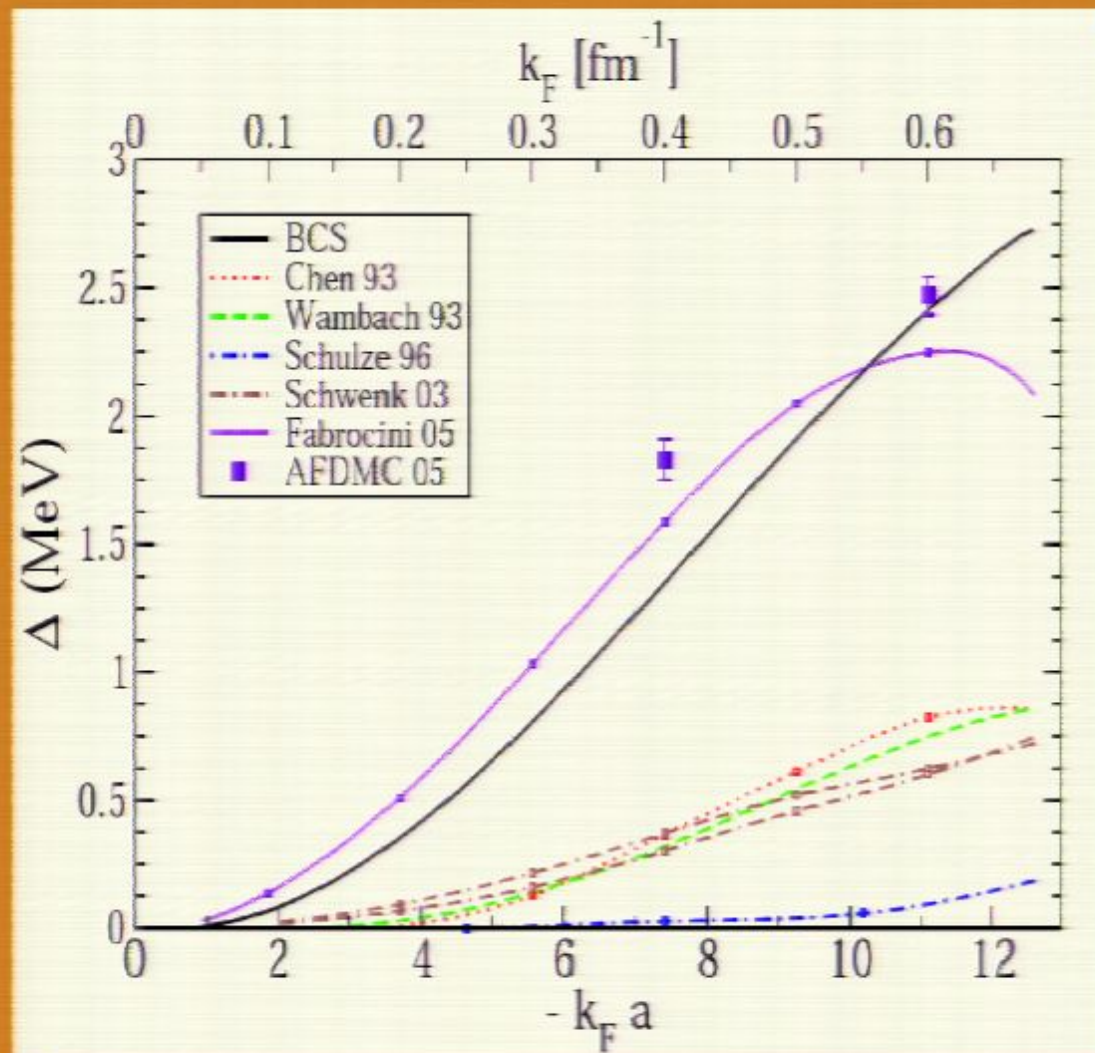
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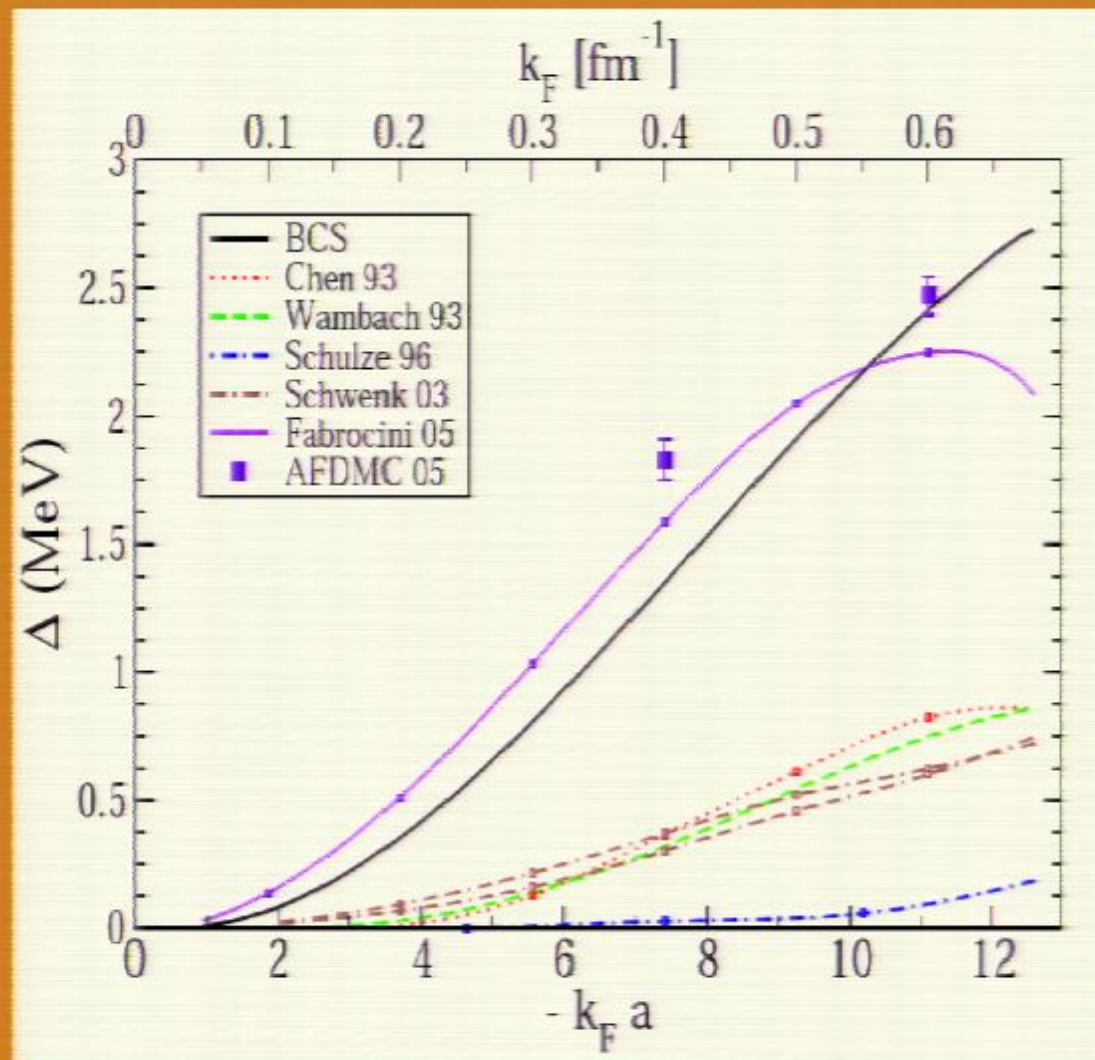
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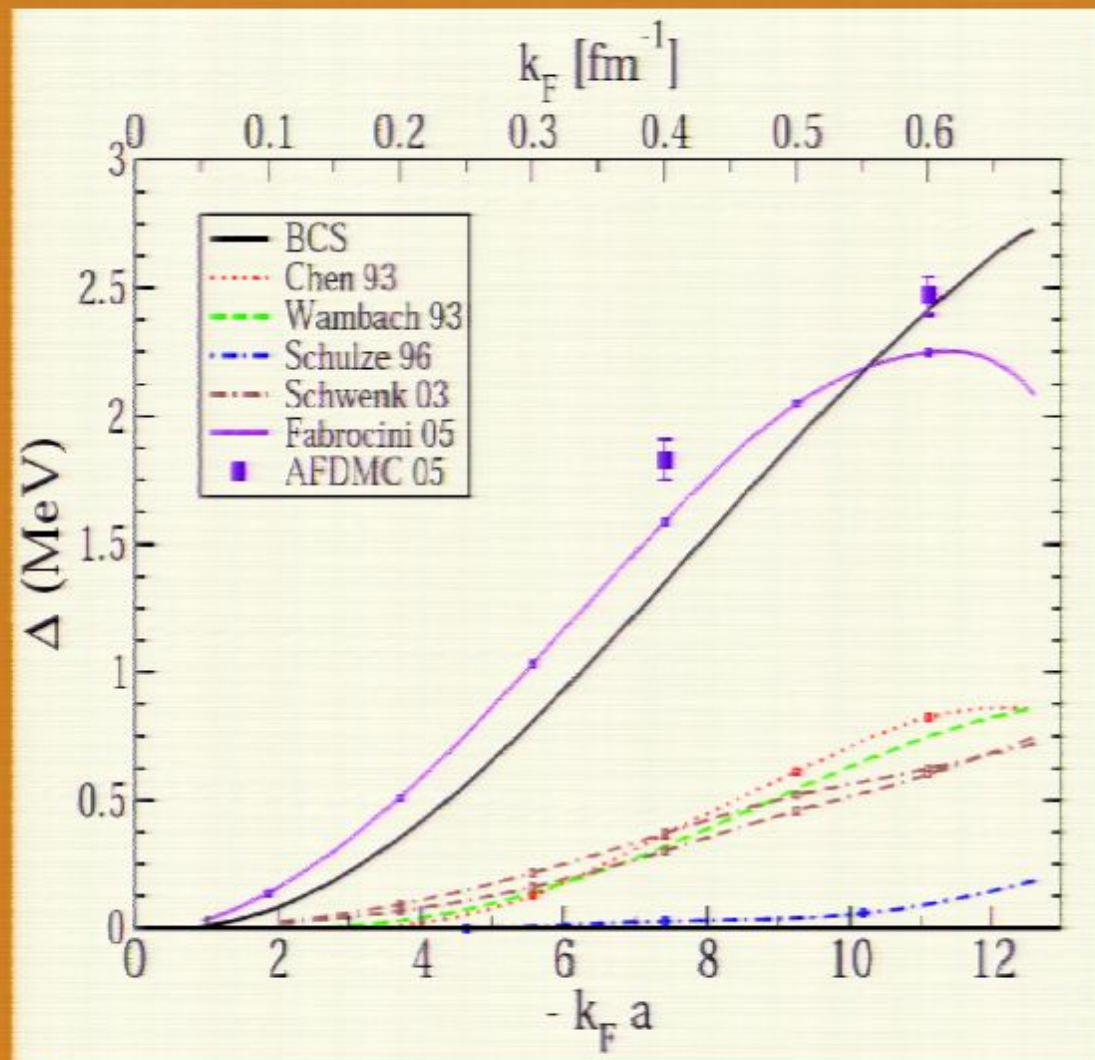
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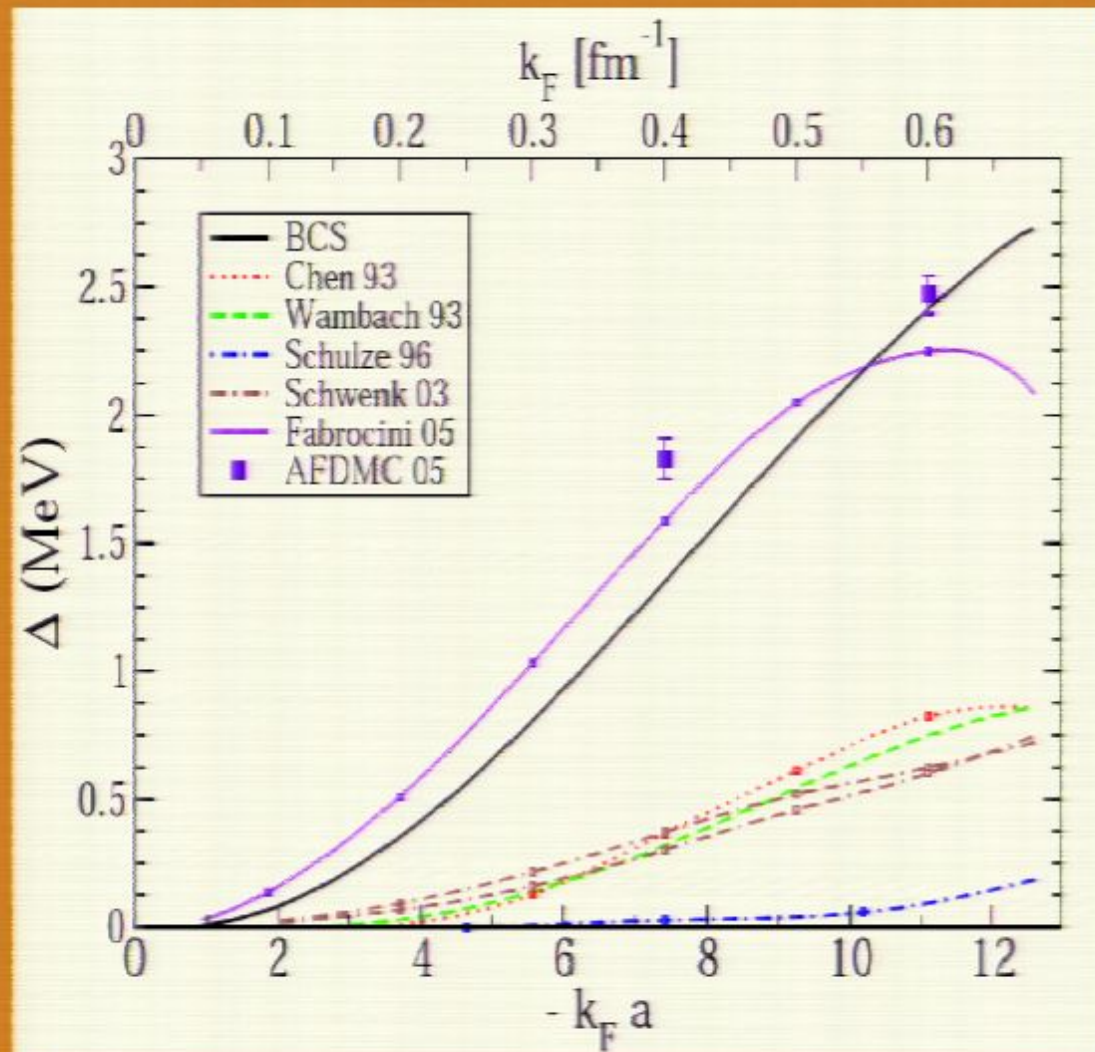
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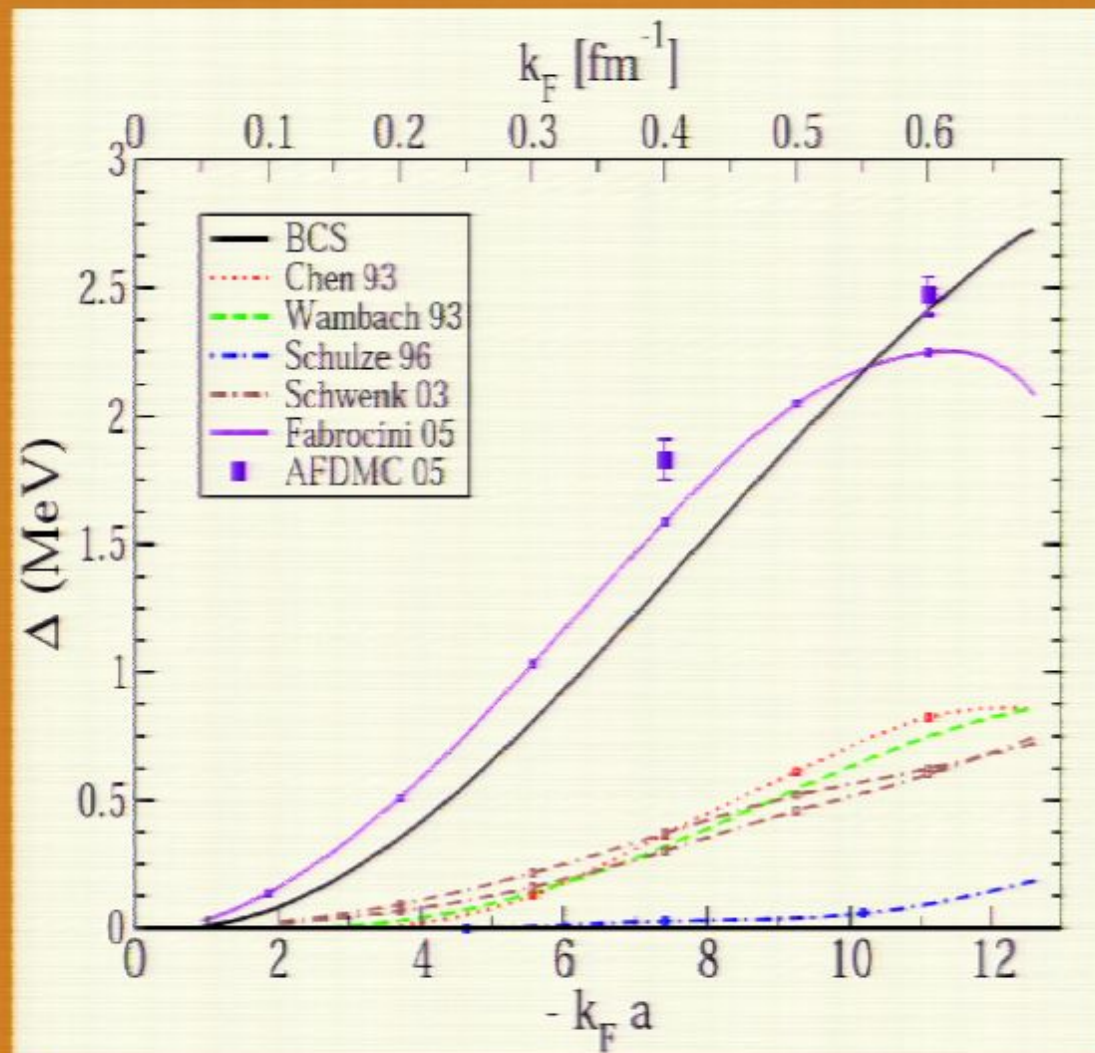
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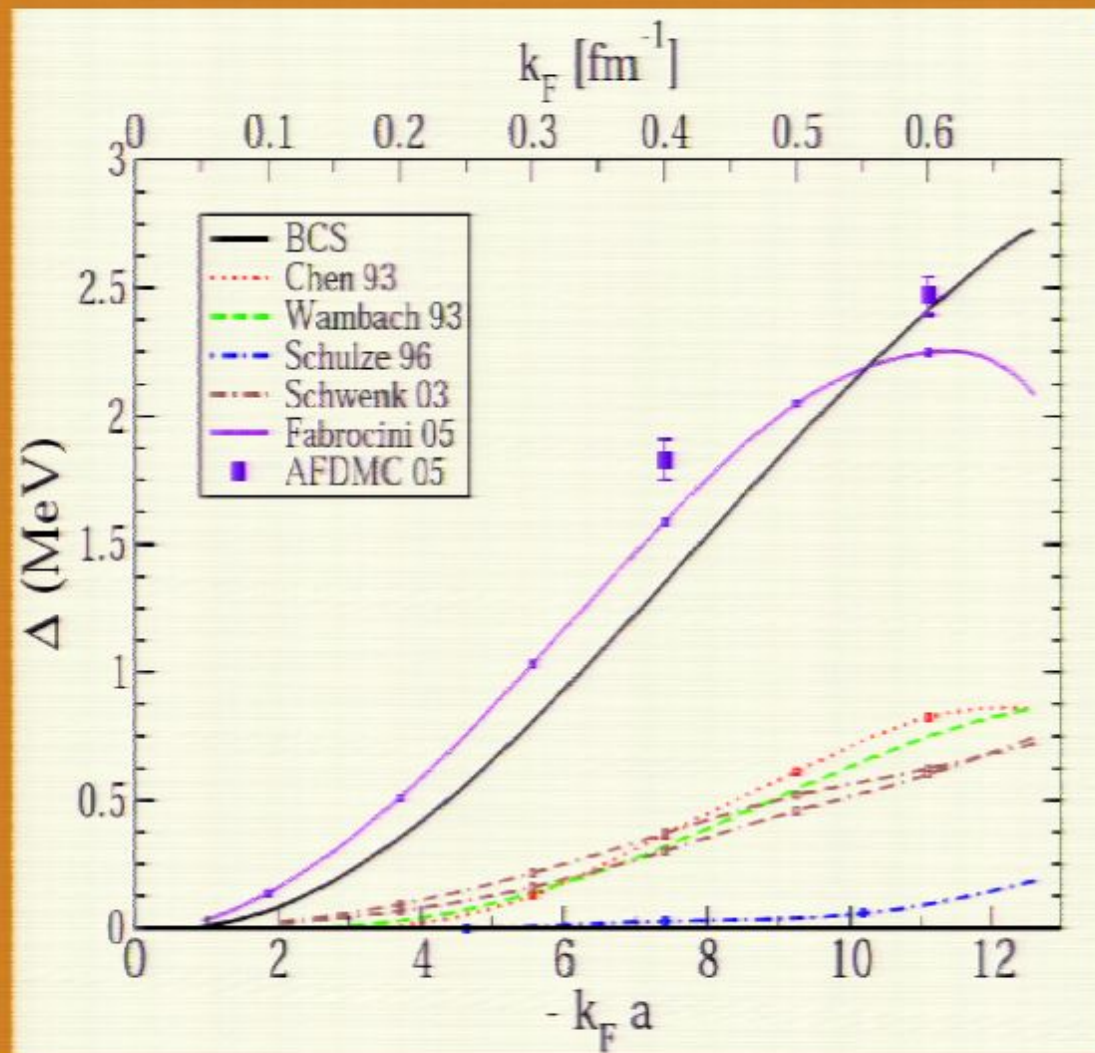
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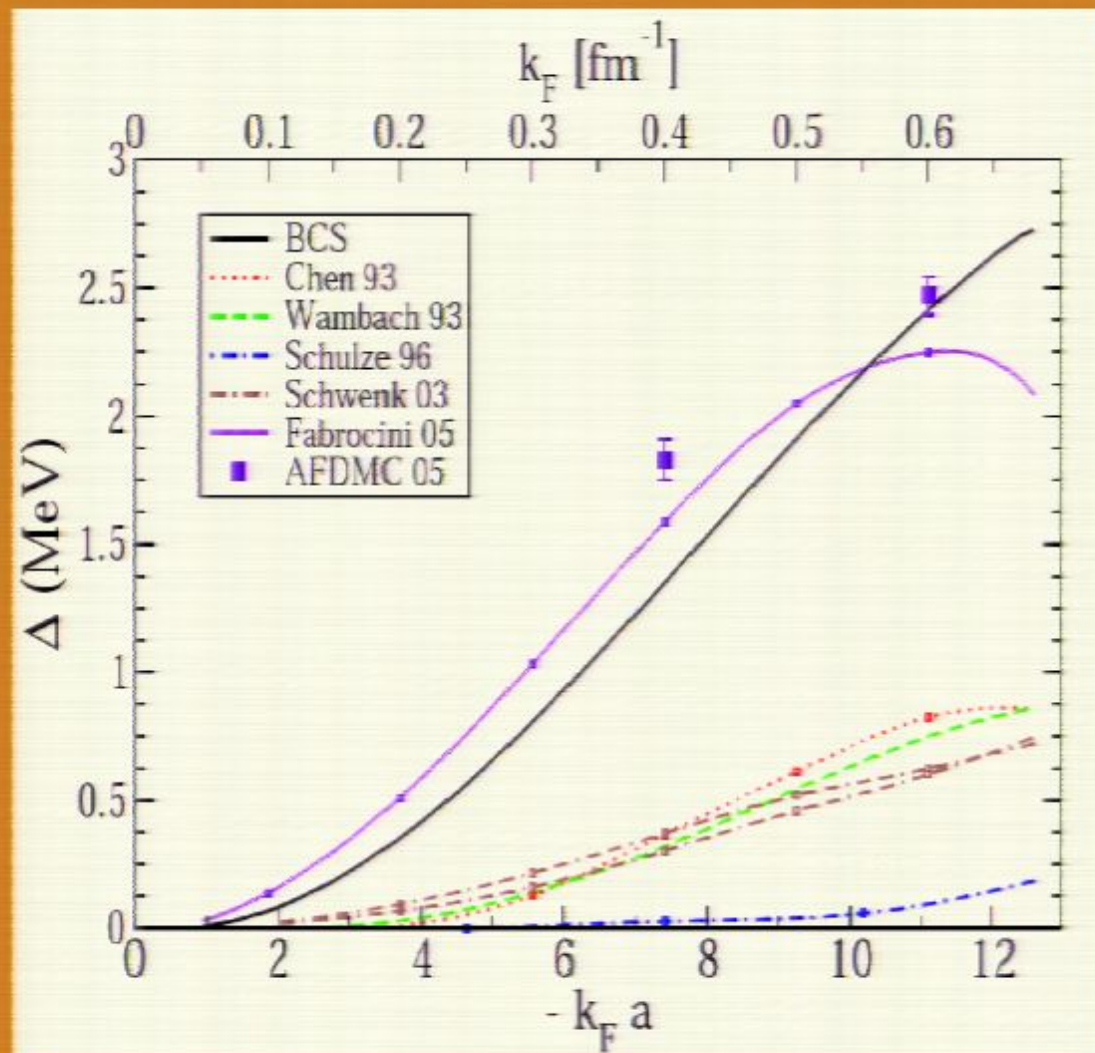
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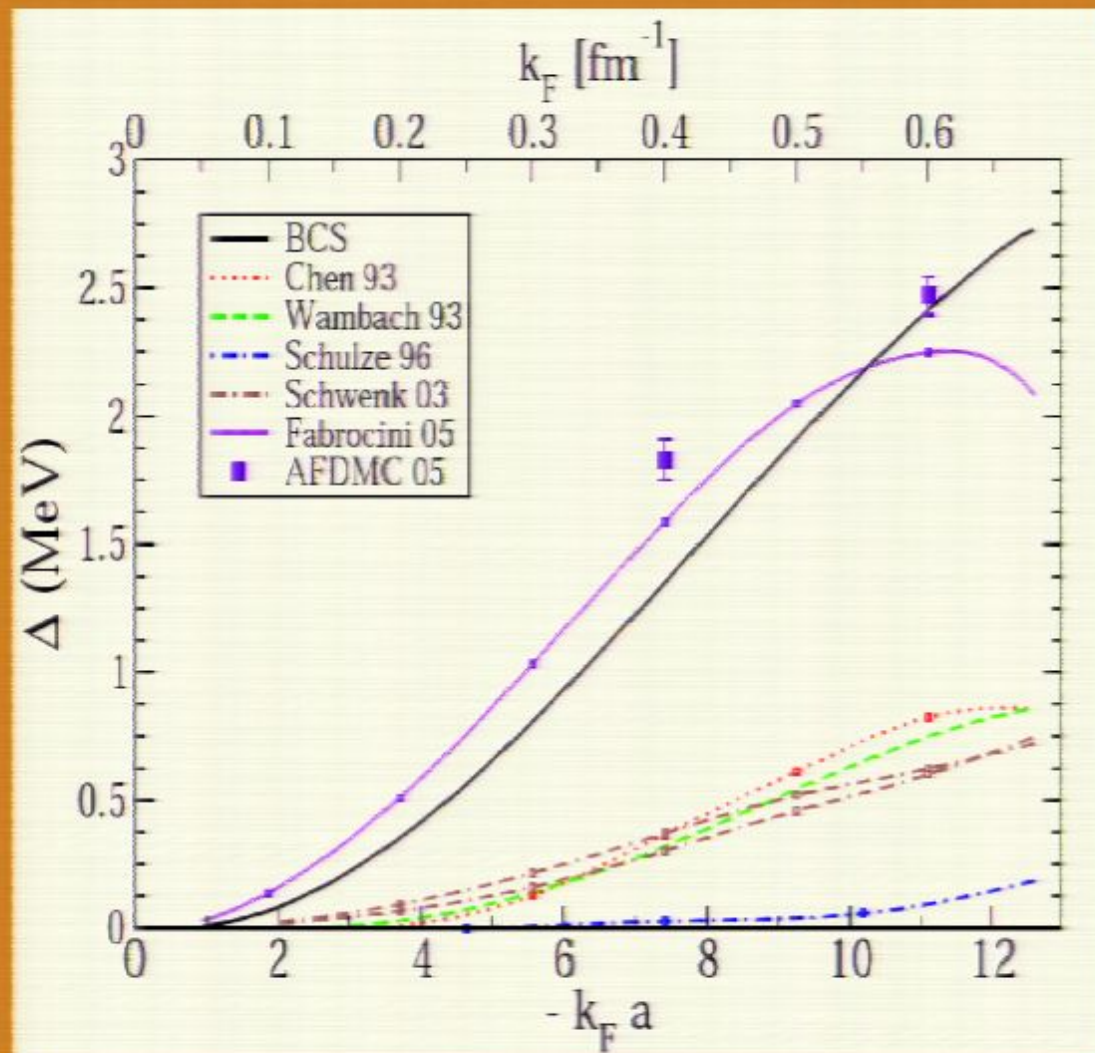
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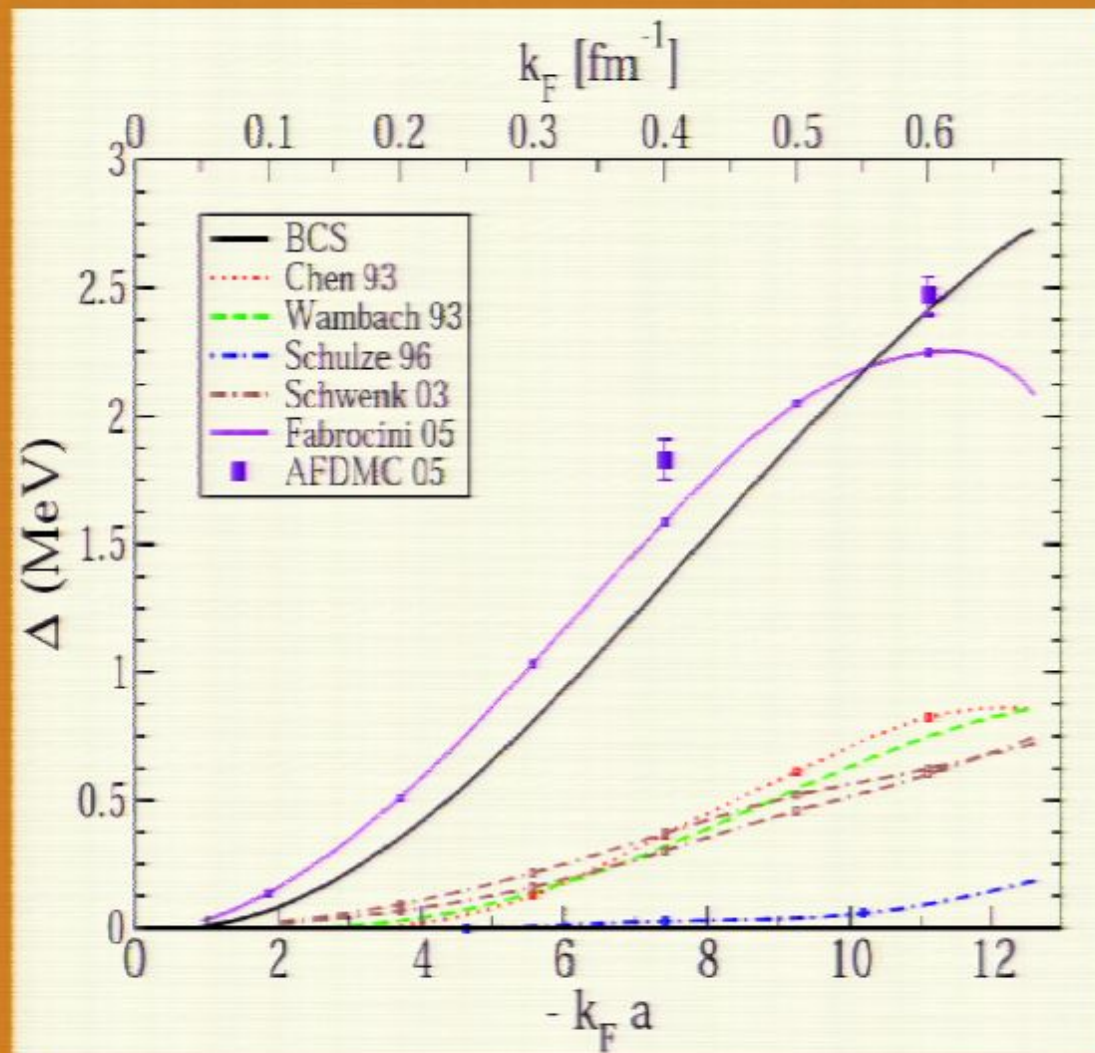
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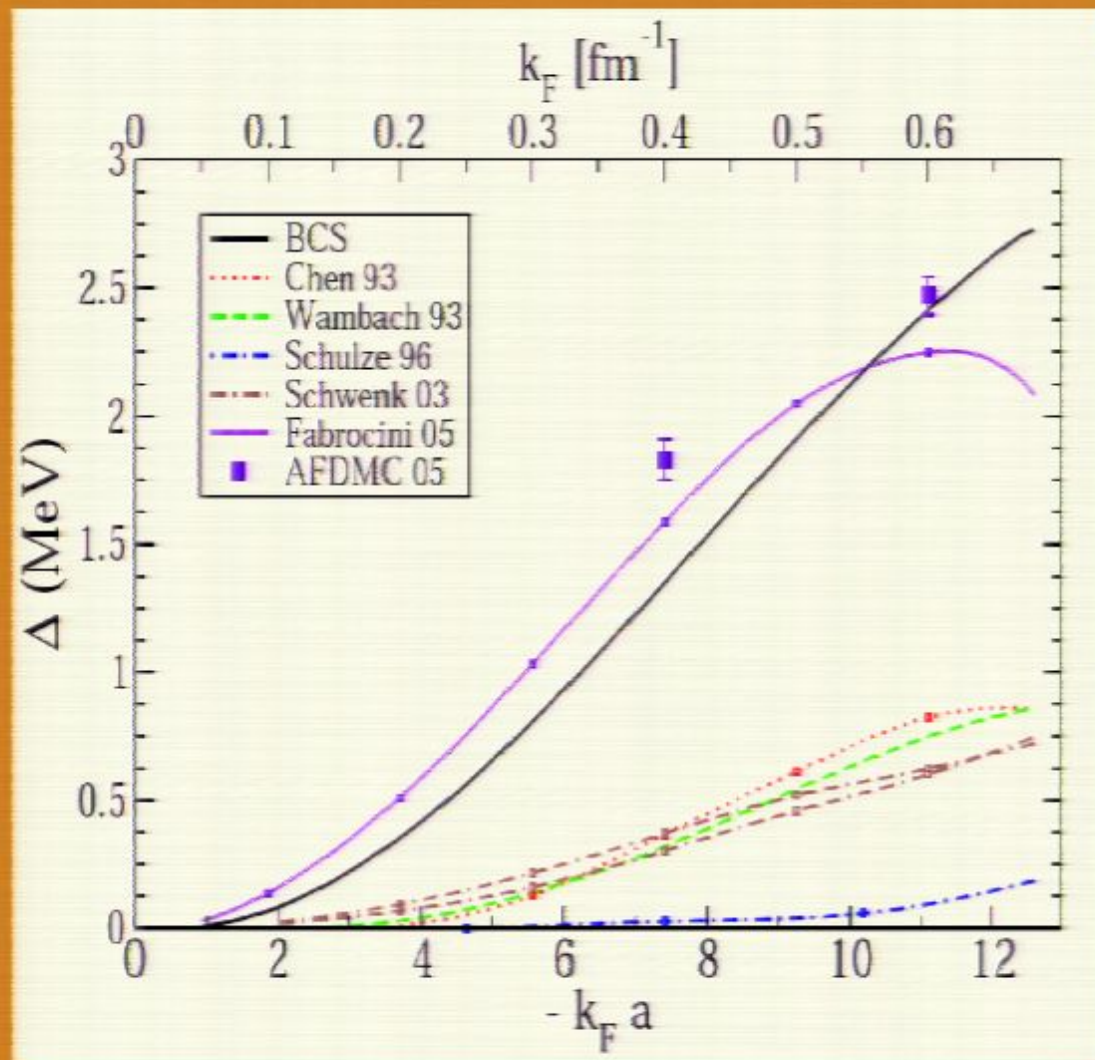
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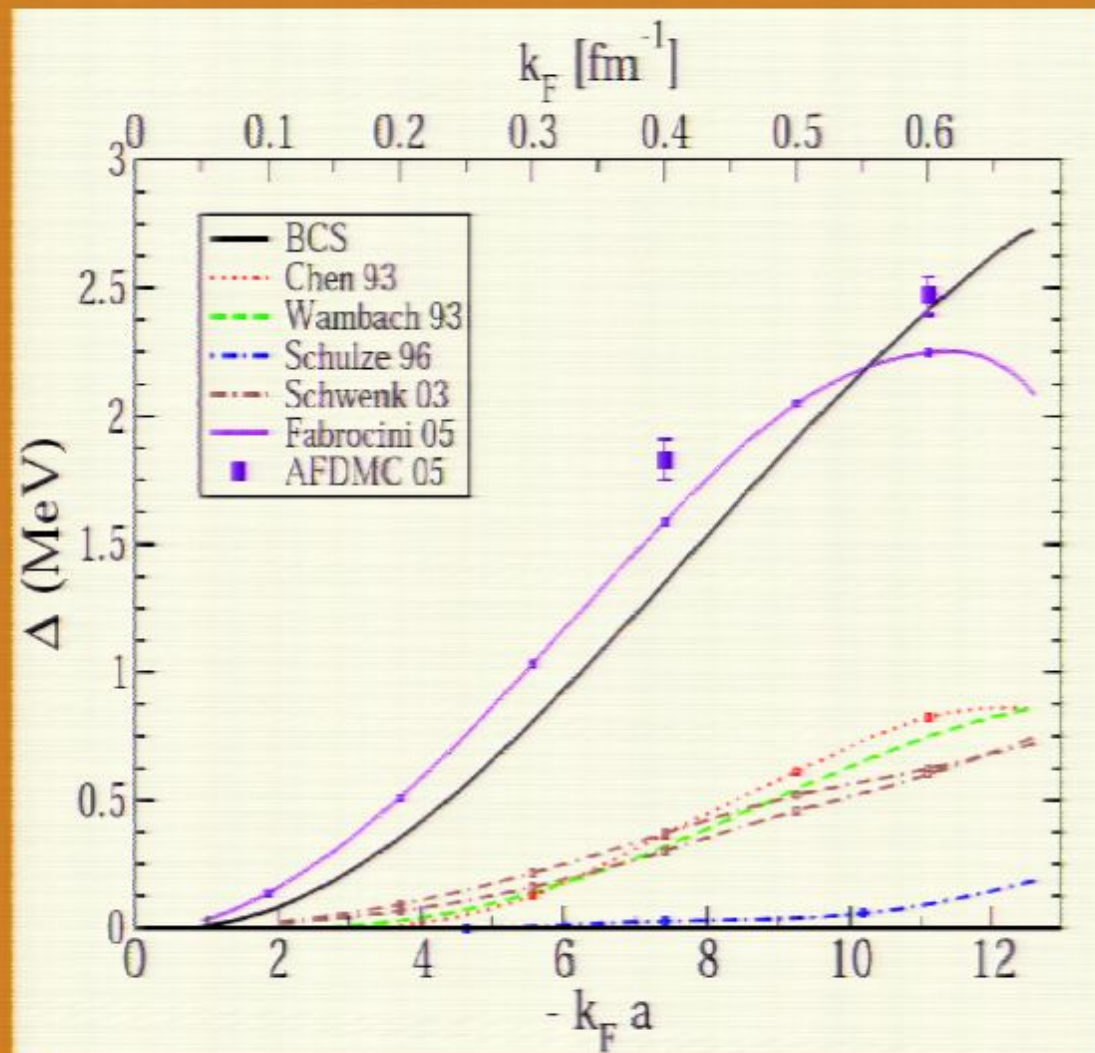
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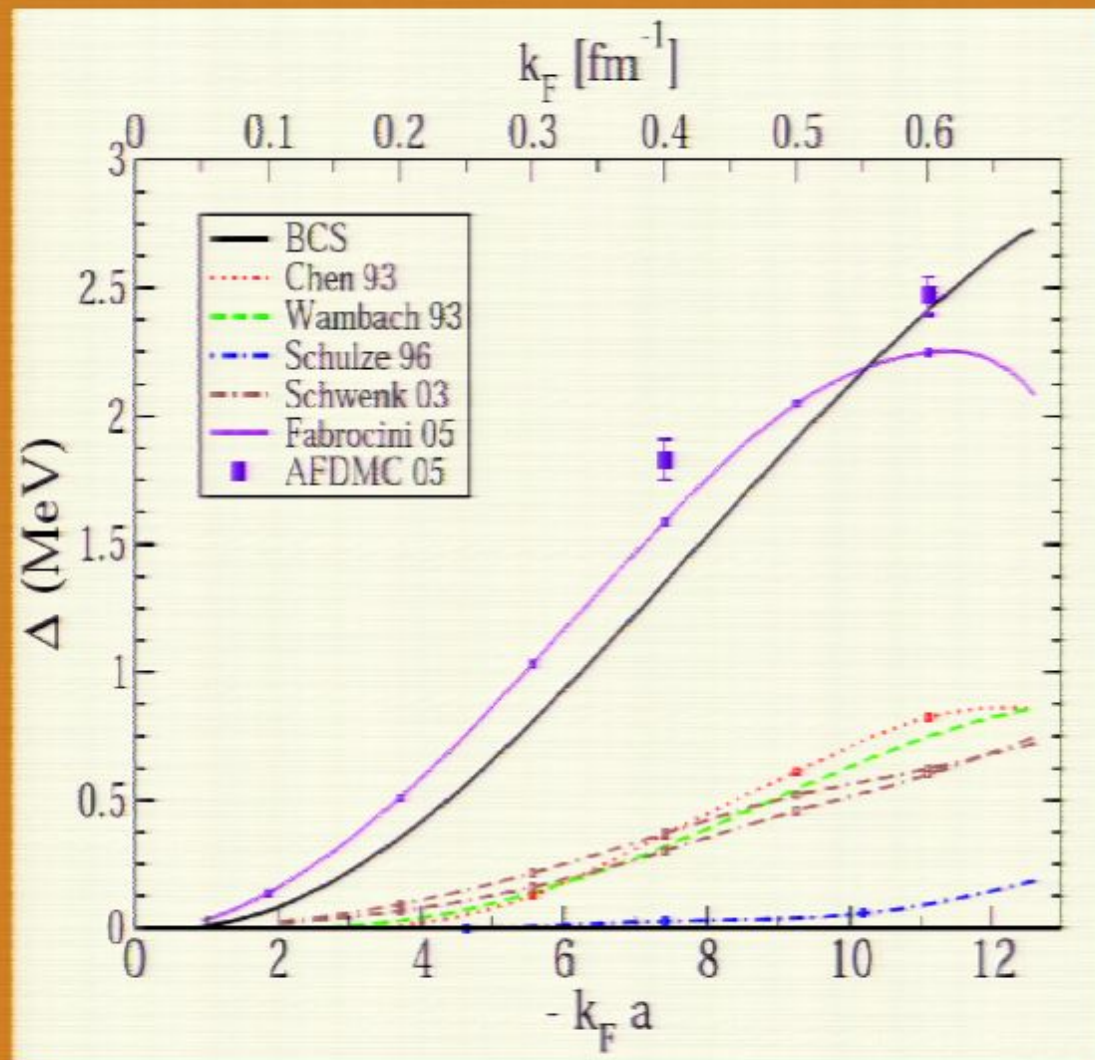
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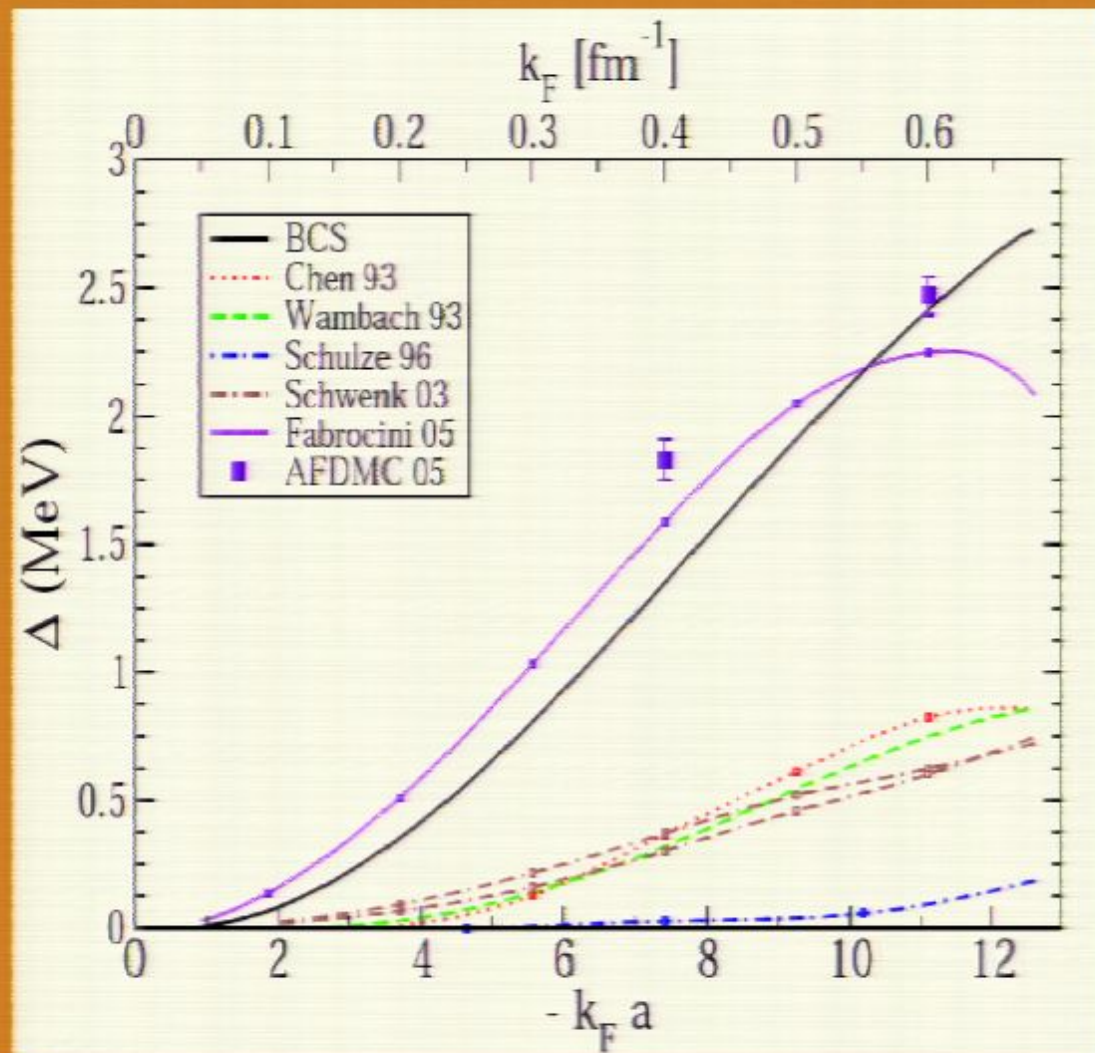
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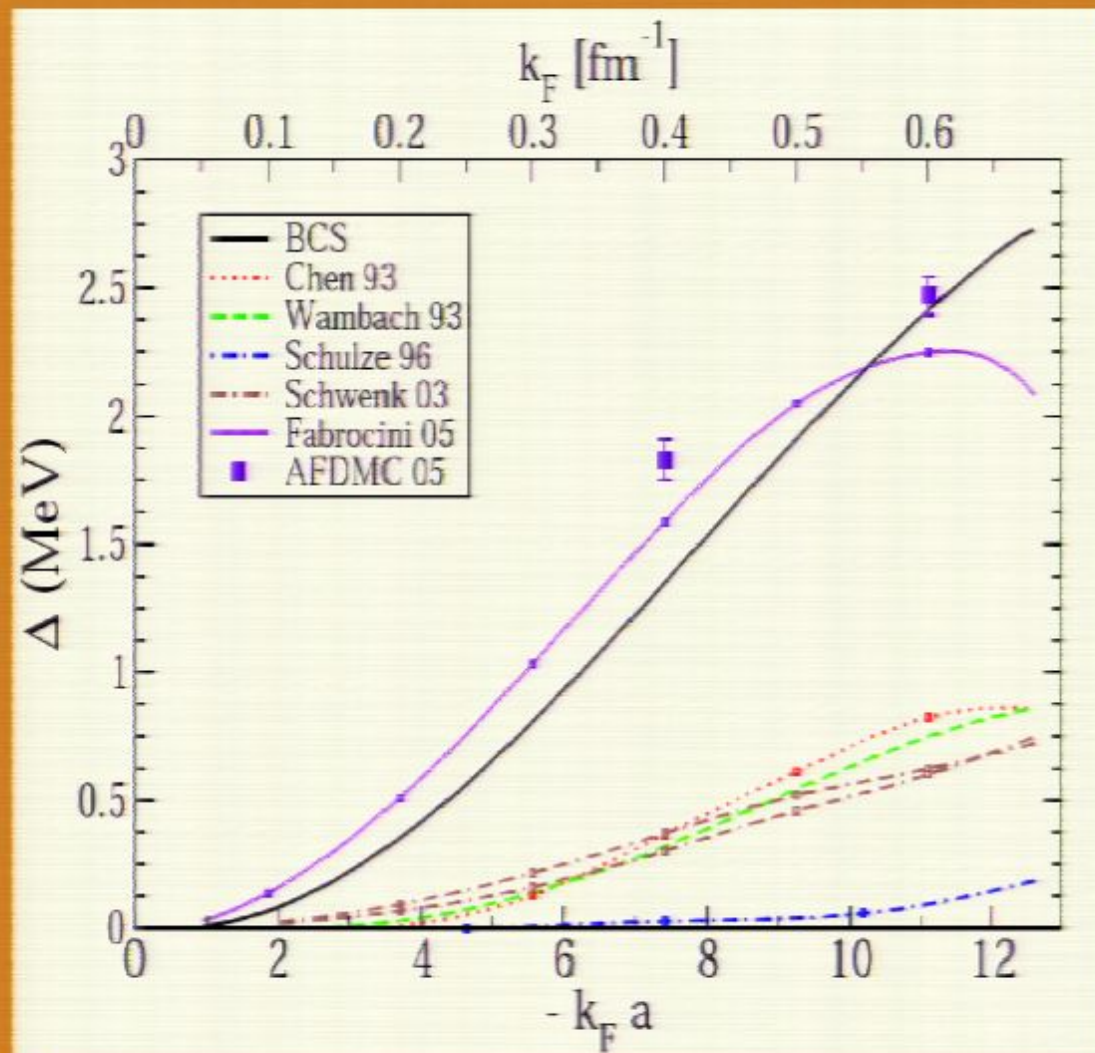
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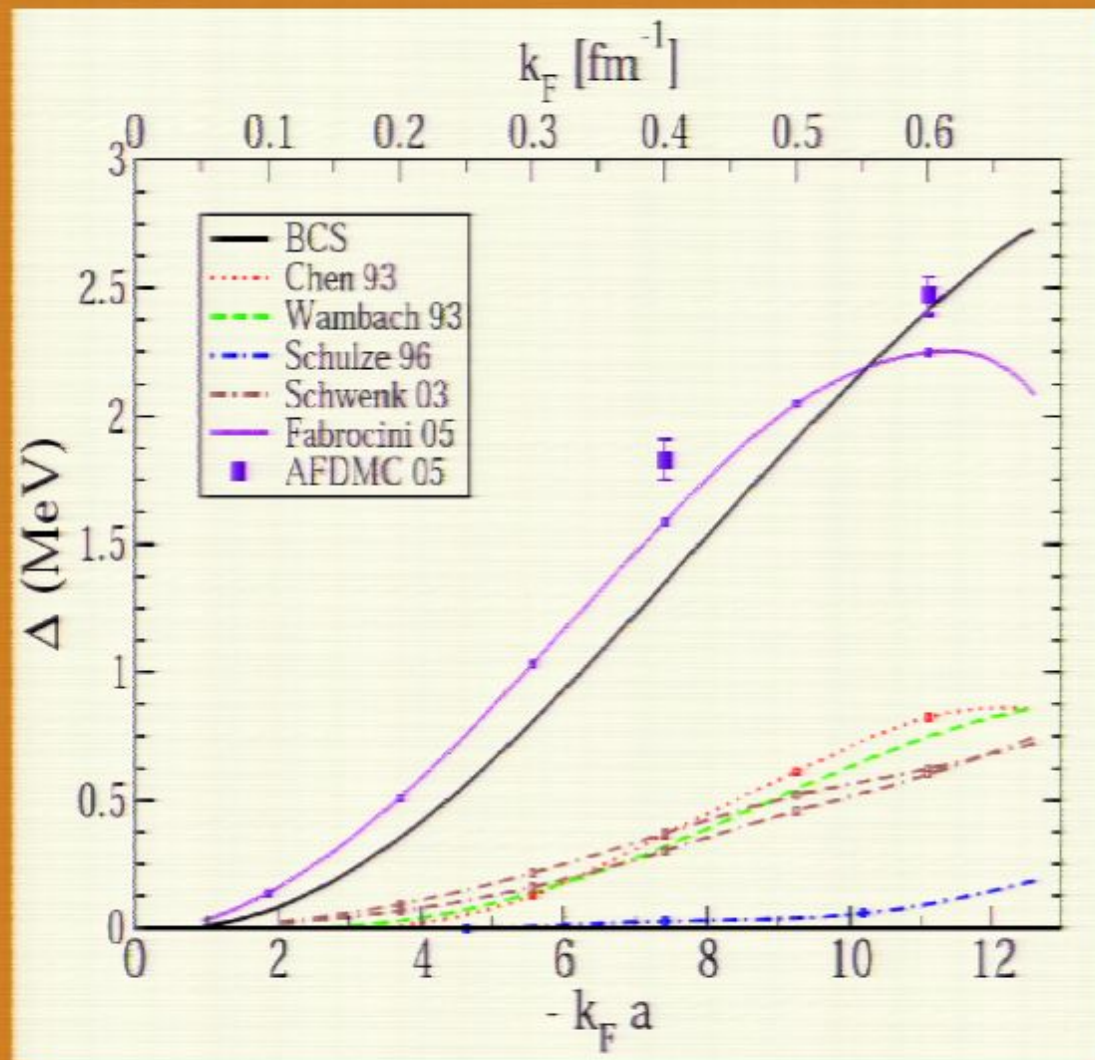
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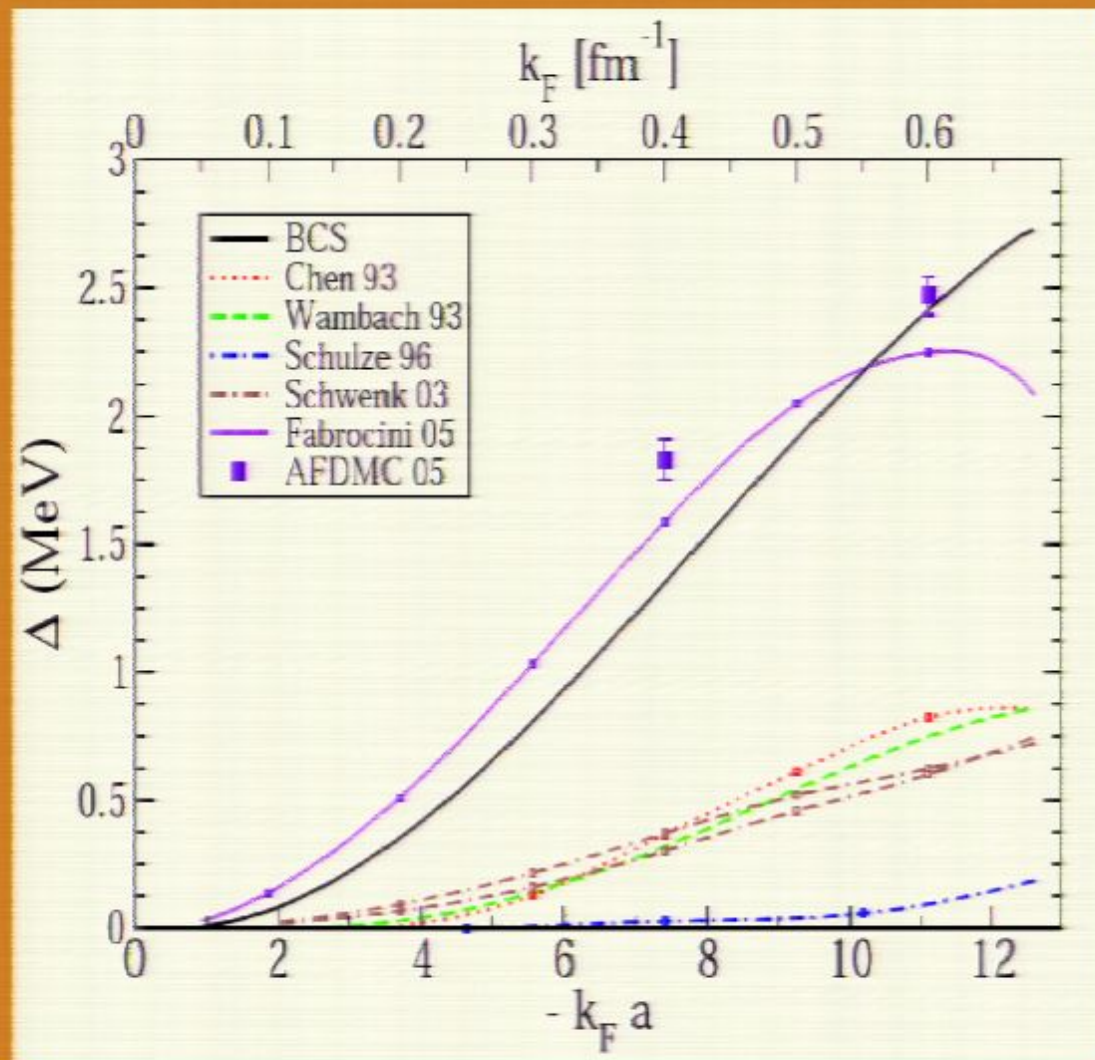
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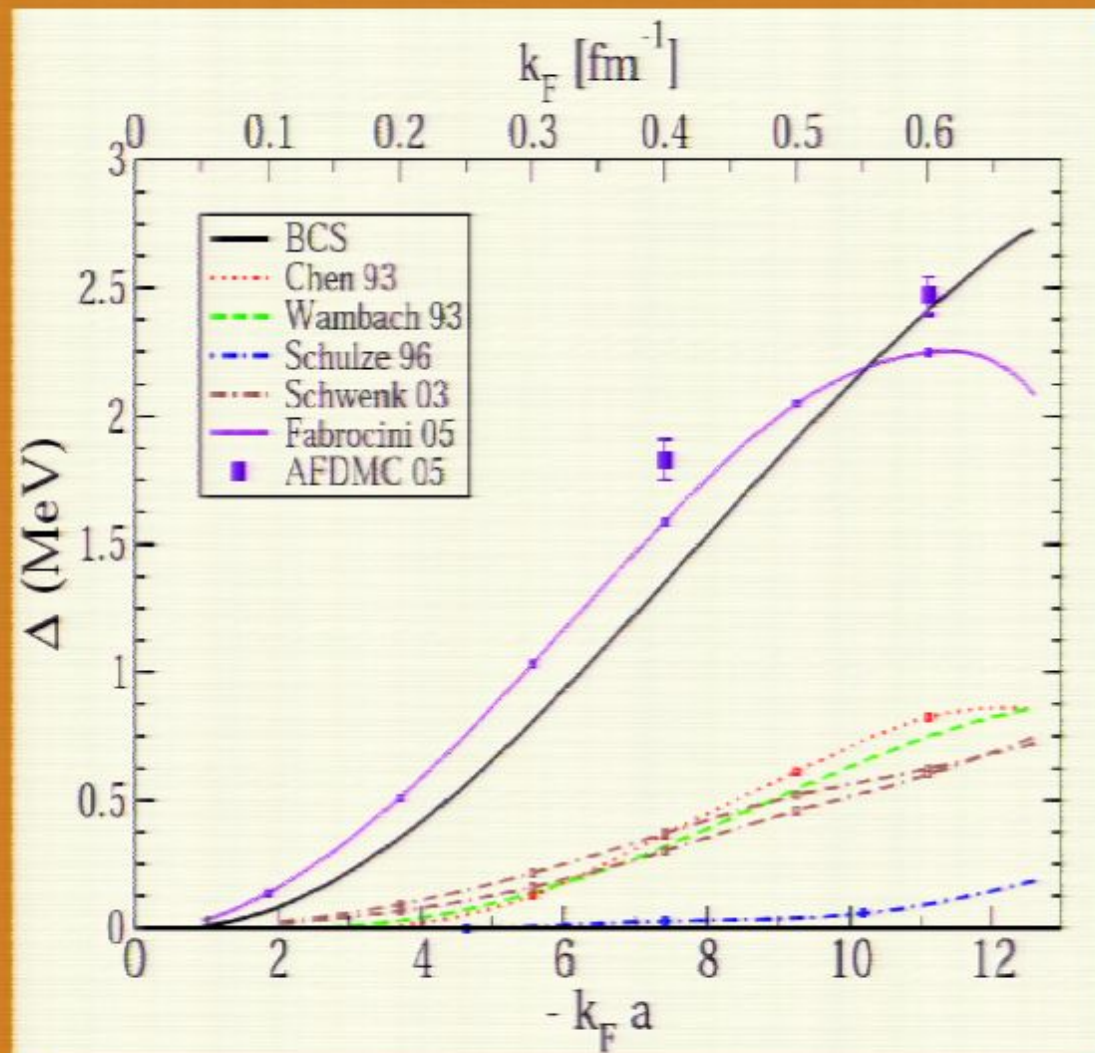
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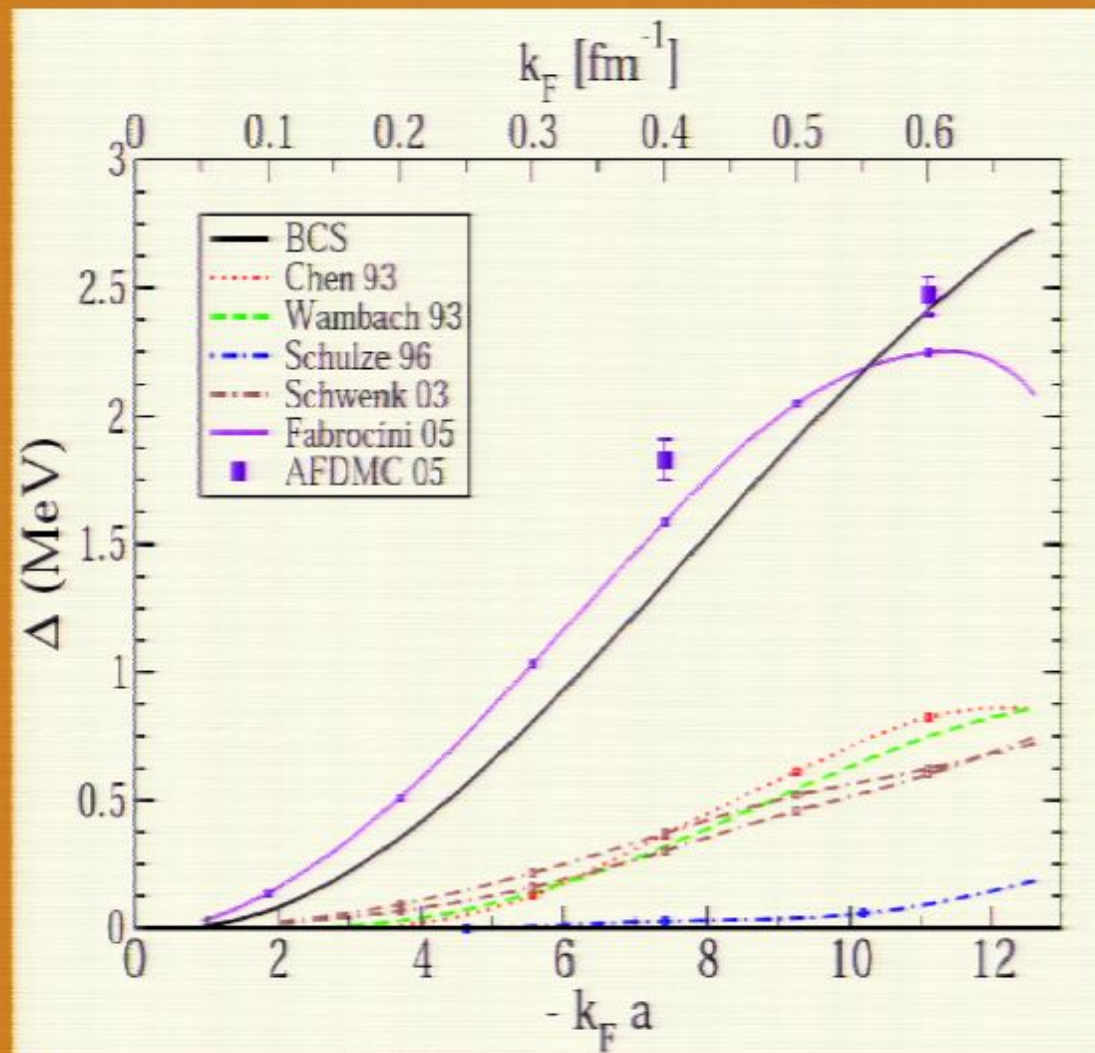
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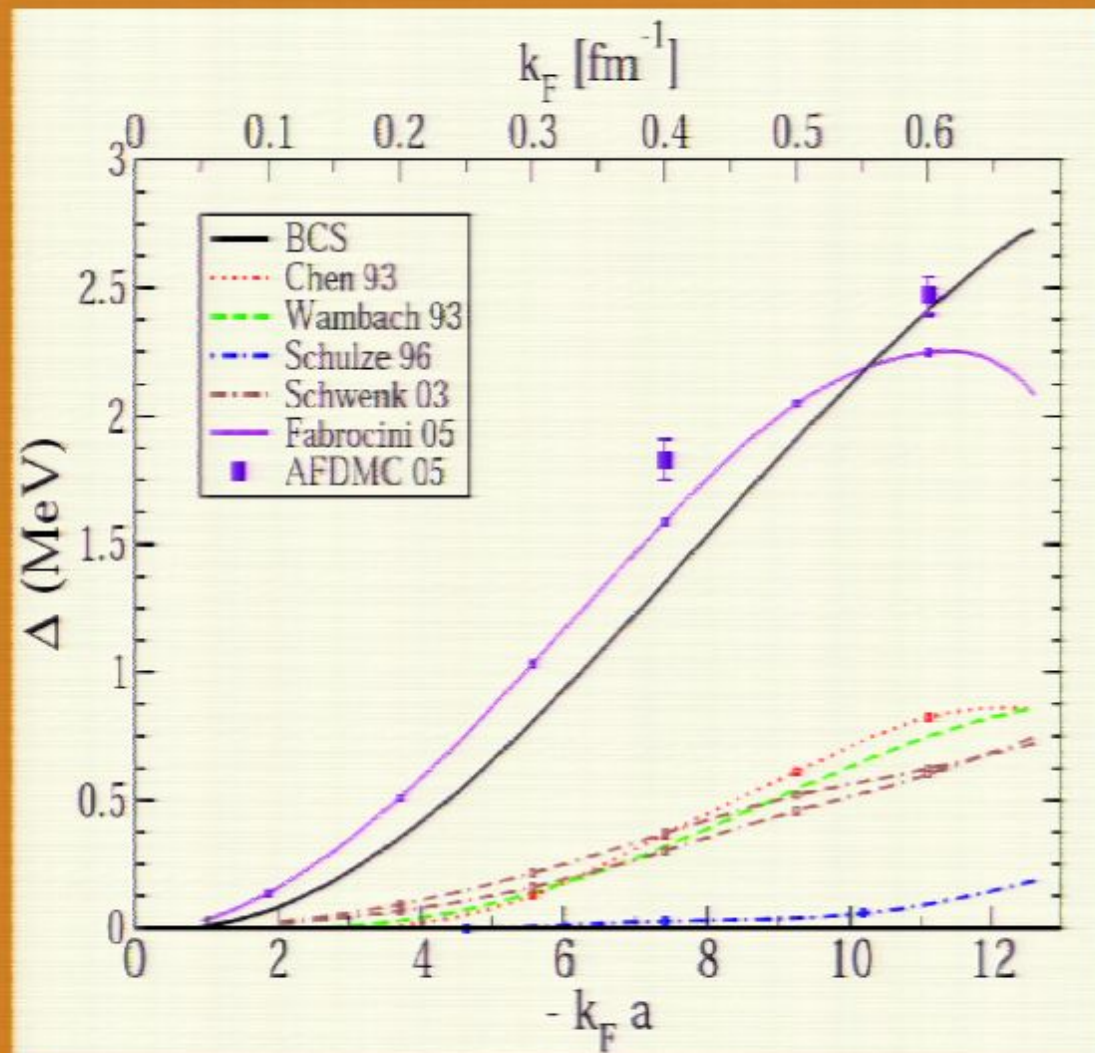
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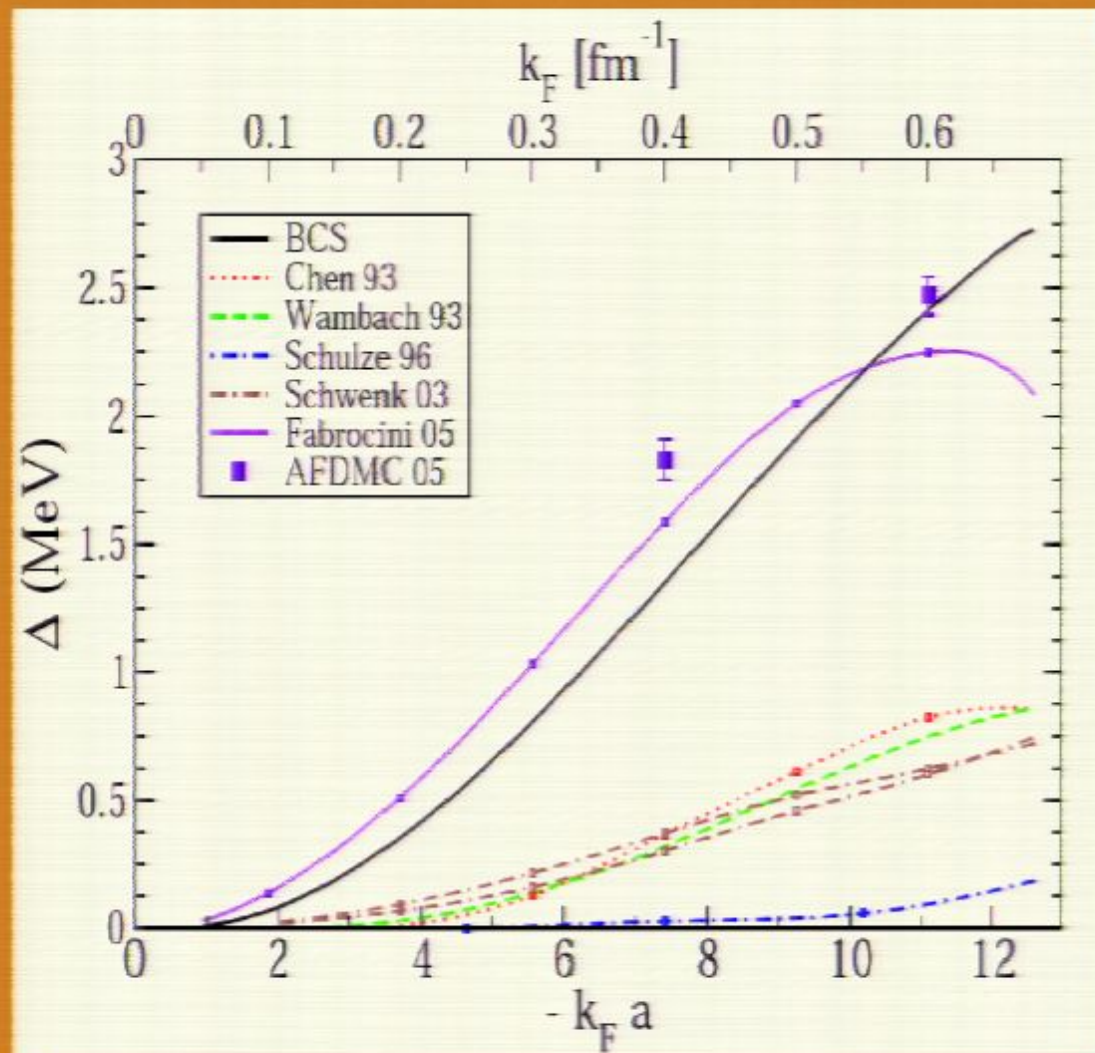
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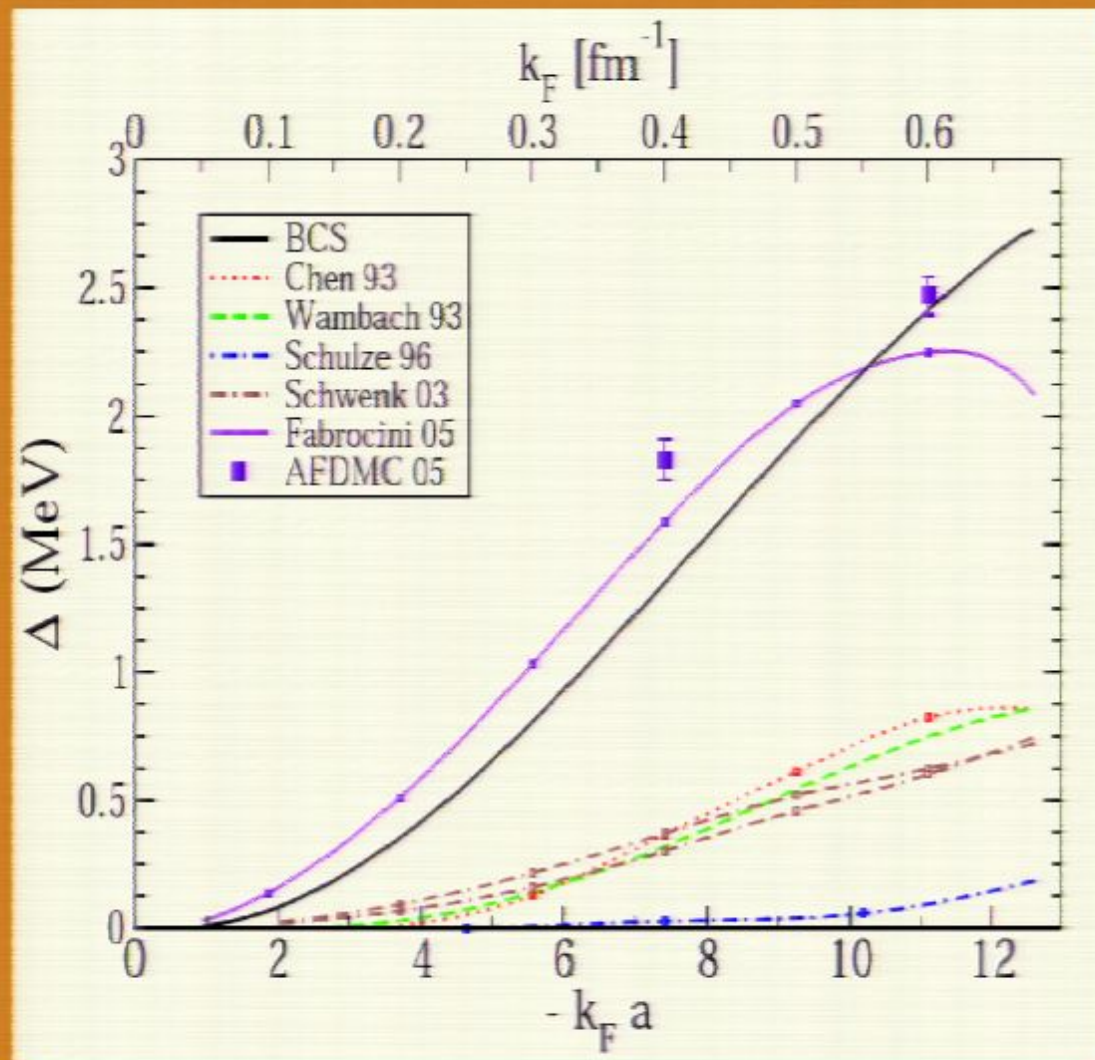
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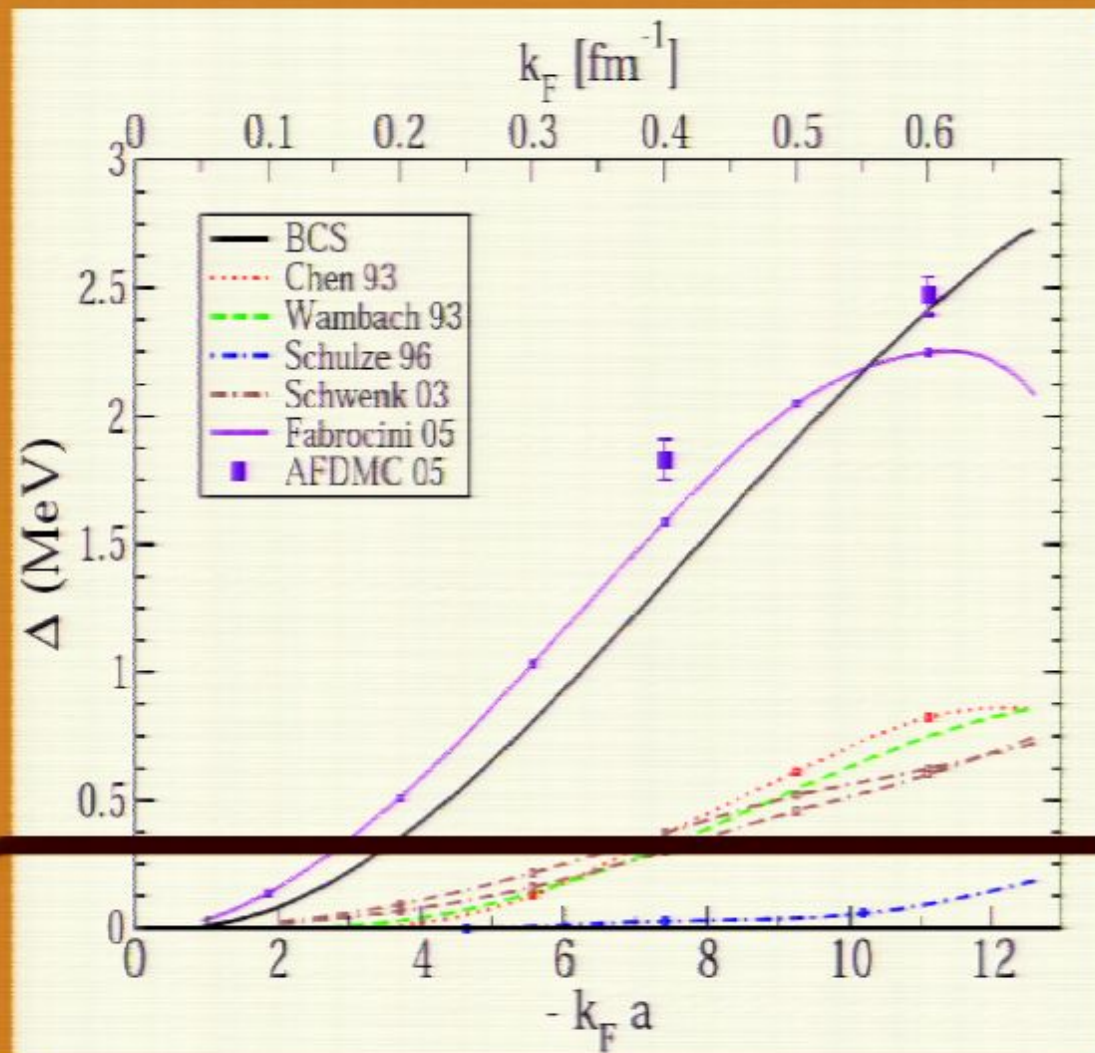
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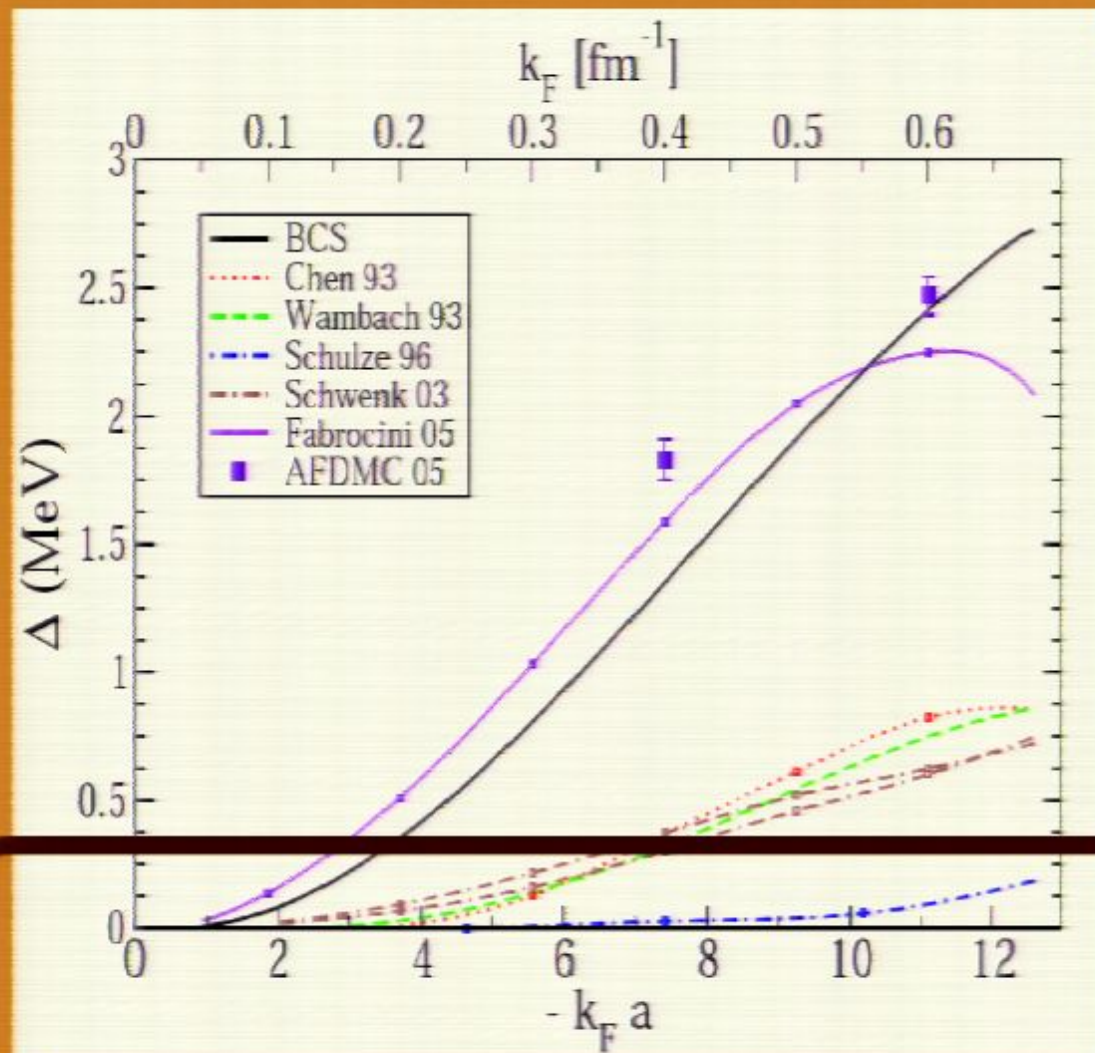
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Cold atoms to the rescue

Theoretical many-body problem formulated by
George Bertsch more than 10 years ago:

“What is the ground-state energy of a gas
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$$E = \xi E_{FG} \quad E_{FG} = \frac{3}{5} N \frac{\hbar^2 k_F^2}{2m}$$

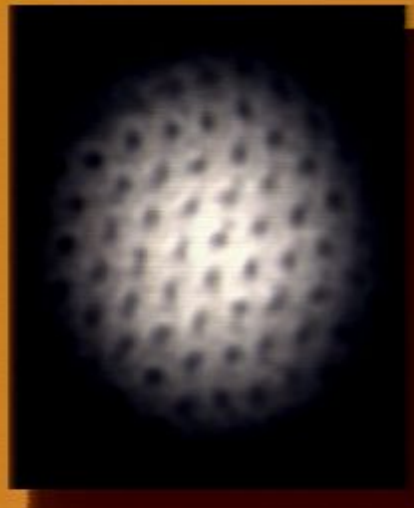
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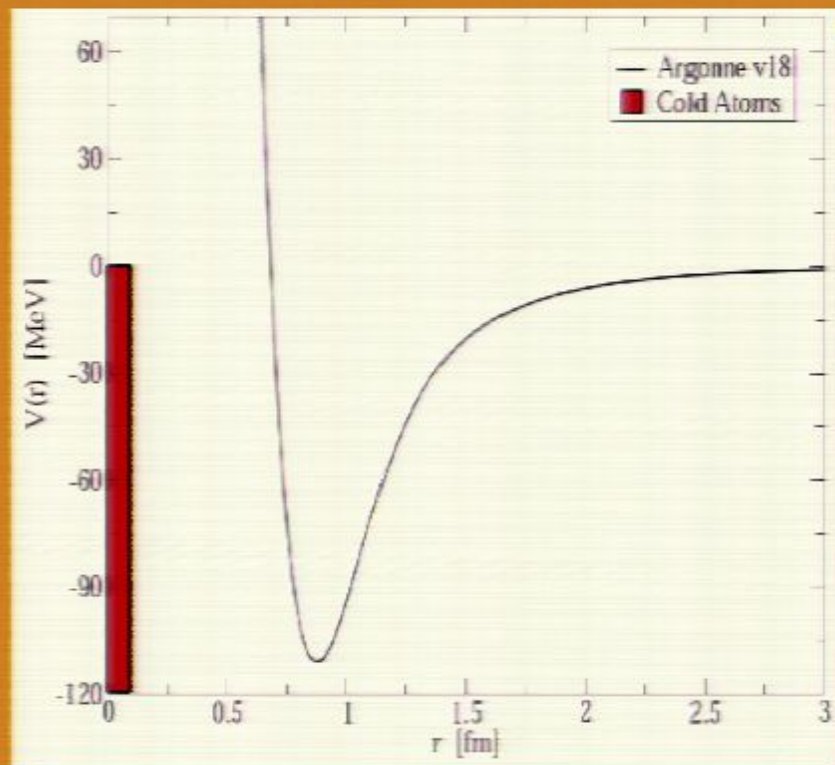
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Now within *direct* experimental reach!



Hamiltonian: unity in diversity

$$\mathcal{H} = -\frac{\hbar^2}{2m} \sum_{k=1}^N \nabla_k^2 + \sum_{i < j'} v(r_{ij'})$$



Neutron matter

1S_0 channel of AV18 – later AV4

060076

$a = -18.5 \text{ fm}$, $r_c = 2.7 \text{ fm}$

Cold atoms

modified Pöschl-Teller potential

Page

$a = \text{tunable}$, $r = \text{tunable/infinitesimal}$

What do we know for sure?

Weak Coupling

Equation of state:
$$\frac{E}{E_{FG}} = 1 + \frac{10}{9\pi} k_F a + \frac{4}{21\pi^2} (11 - 2 \ln 2) (k_F a)^2$$

Pairing gap:
$$\frac{\Delta}{E_F} = \frac{1}{(4e)^{1/3}} \Delta_{\text{BCS}}$$

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Strong Coupling

Mean-field BCS is easy but unreliable:

$$\Delta(\mathbf{k}) = - \sum_{\mathbf{k}'} \langle \mathbf{k} | V | \mathbf{k}' \rangle \frac{\Delta(\mathbf{k}')}{2\sqrt{\xi(\mathbf{k})^2 + \Delta(\mathbf{k})^2}}$$

Ab initio GFMC is difficult but accurate:

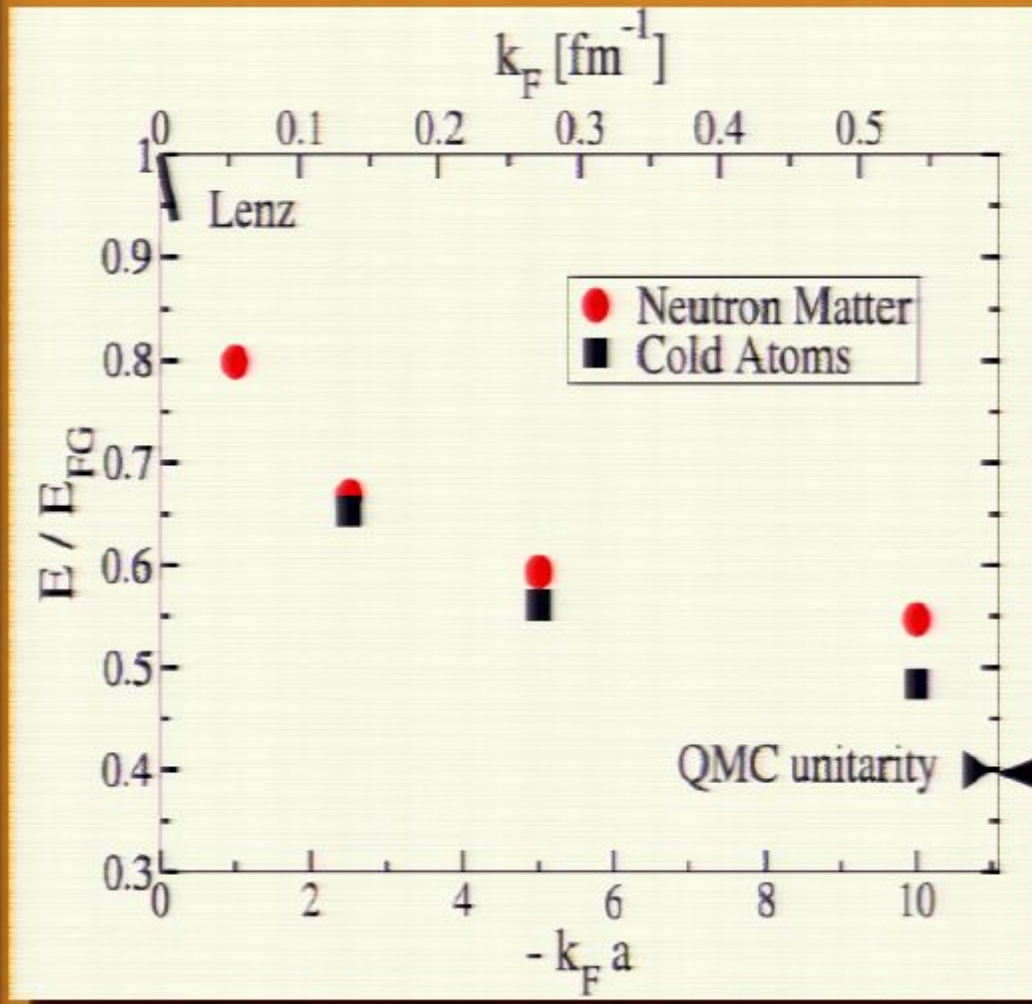
$$\Psi_V = \prod_{i < j} f(r_{ij}) \mathcal{A}[\prod \phi(r_{ij})]$$

Equal Populations

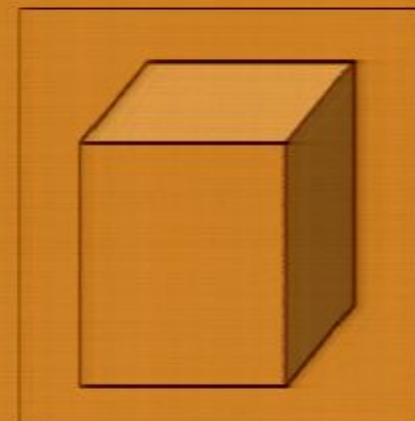
Equation of state



Equations of state: results

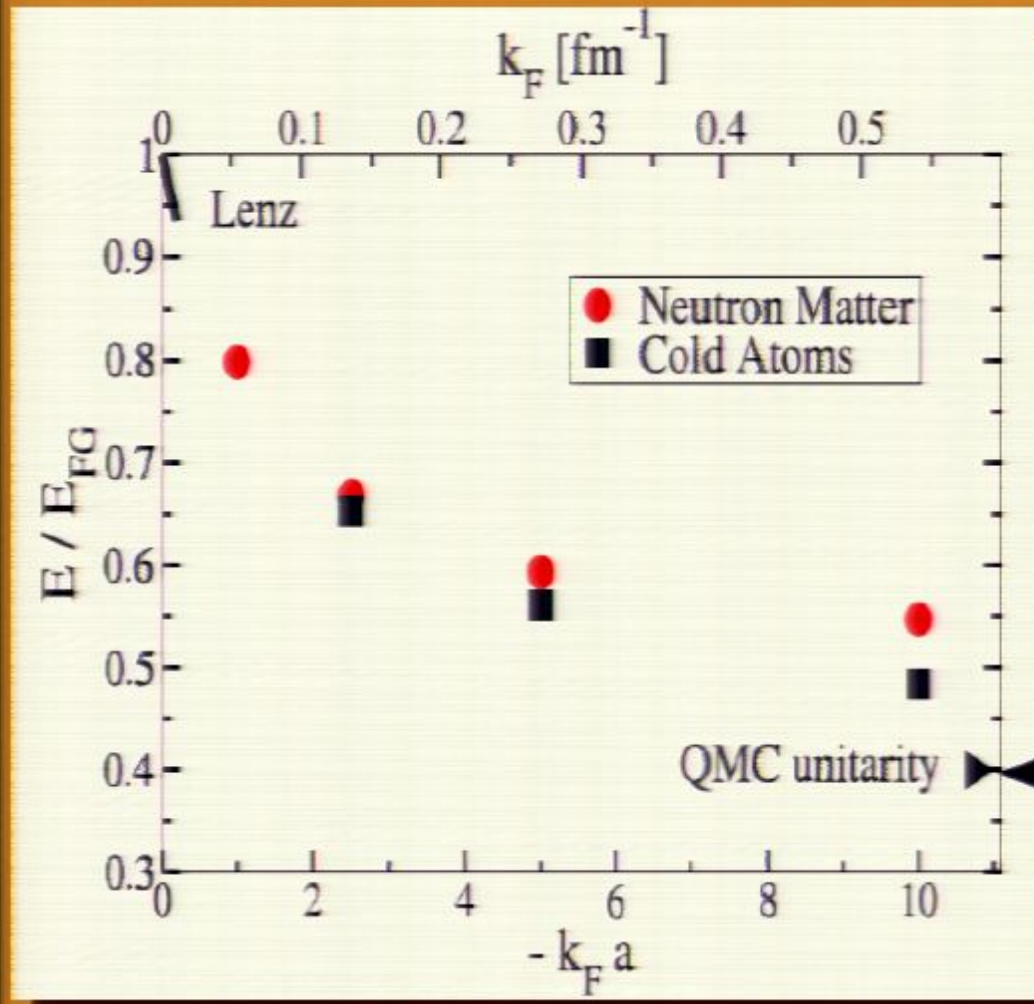


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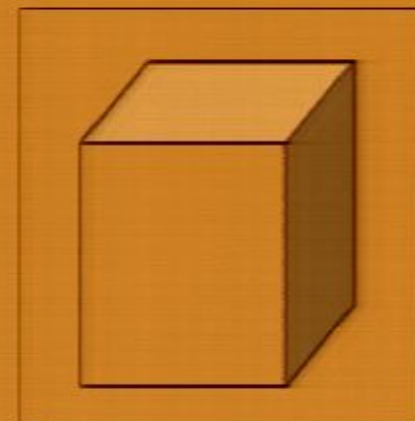


A. Gezerlis and J. Carlson, Phys. Rev. C 77, 032801 (2008)

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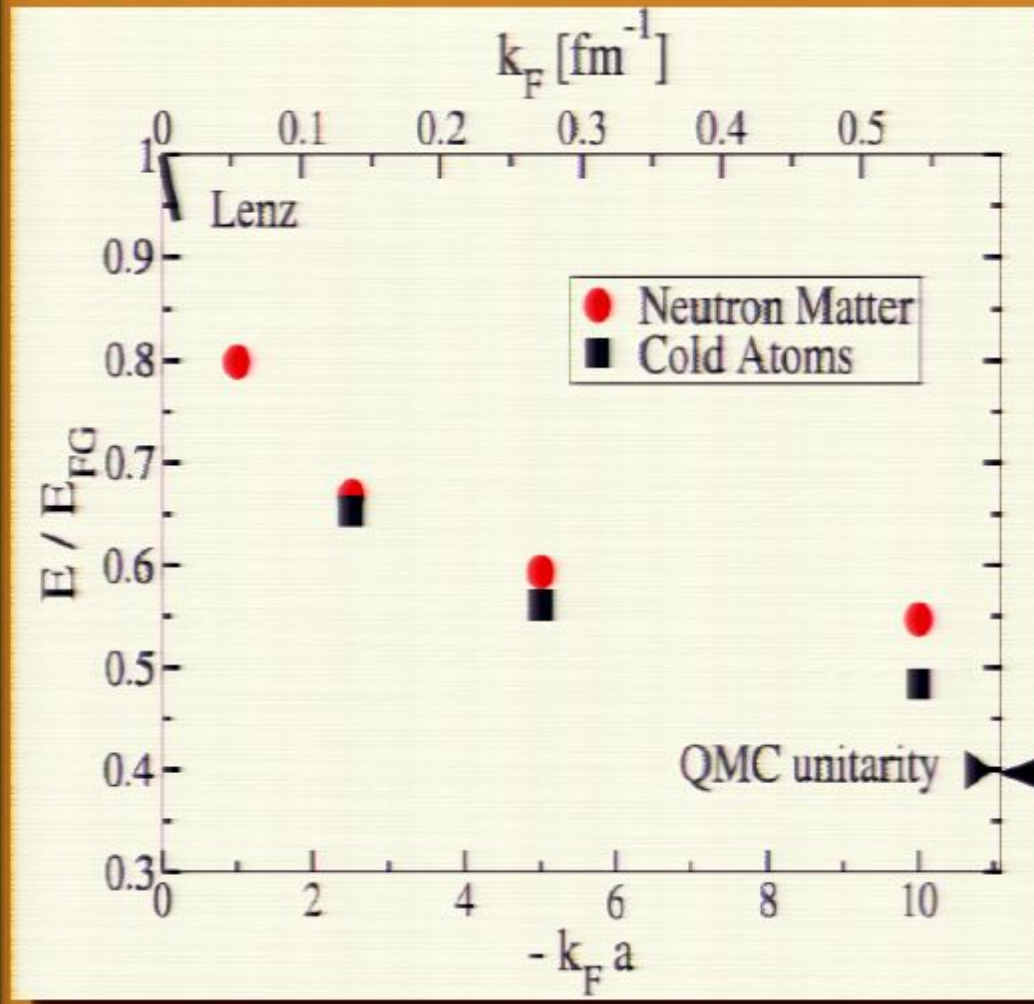


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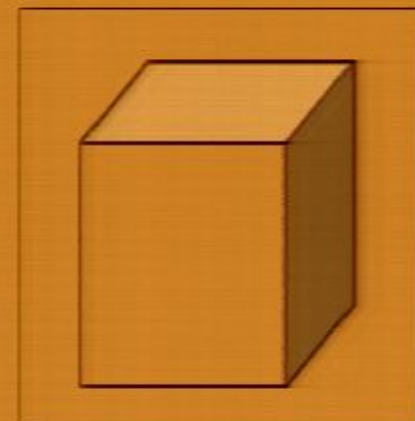


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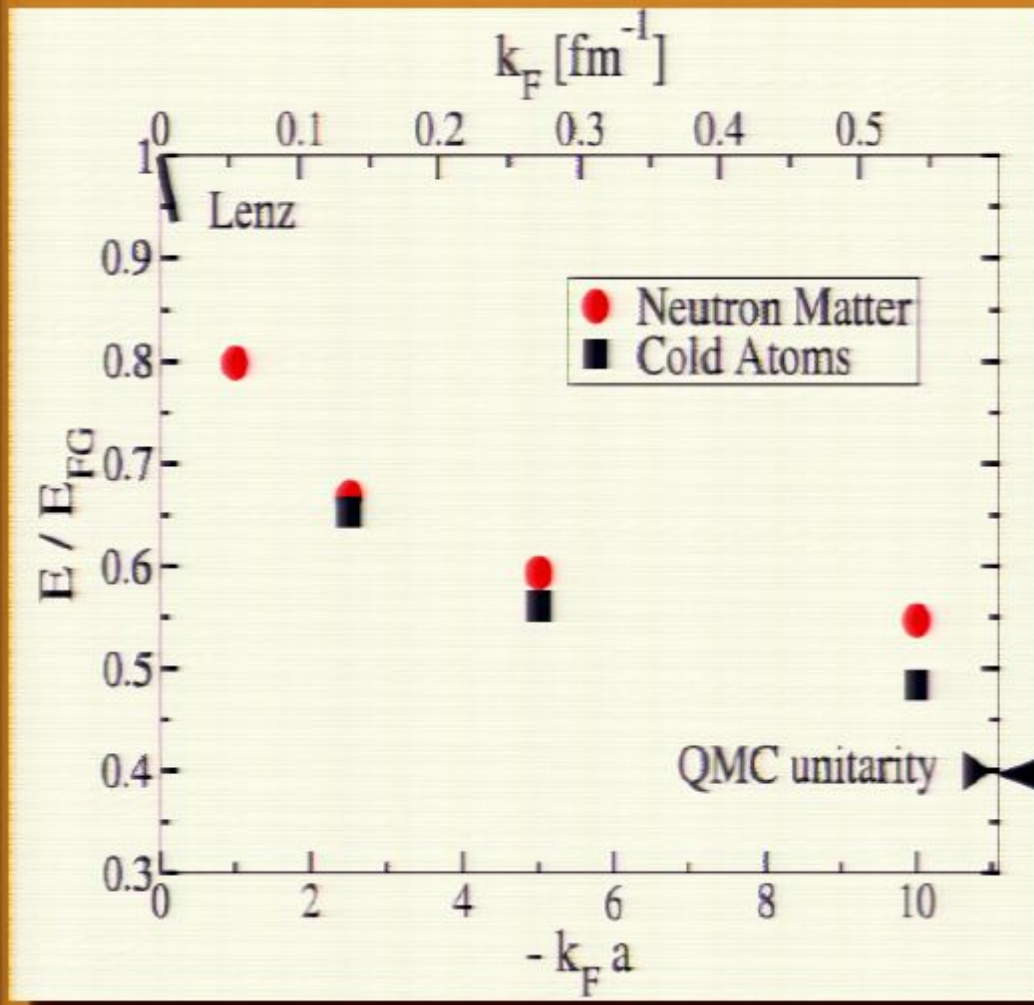


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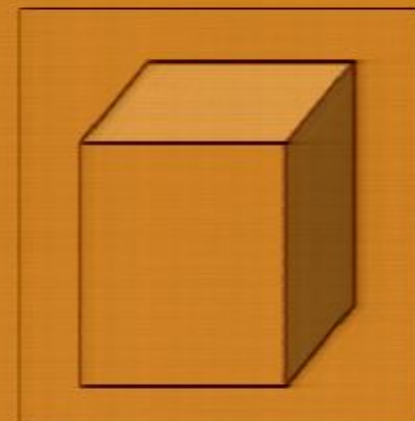


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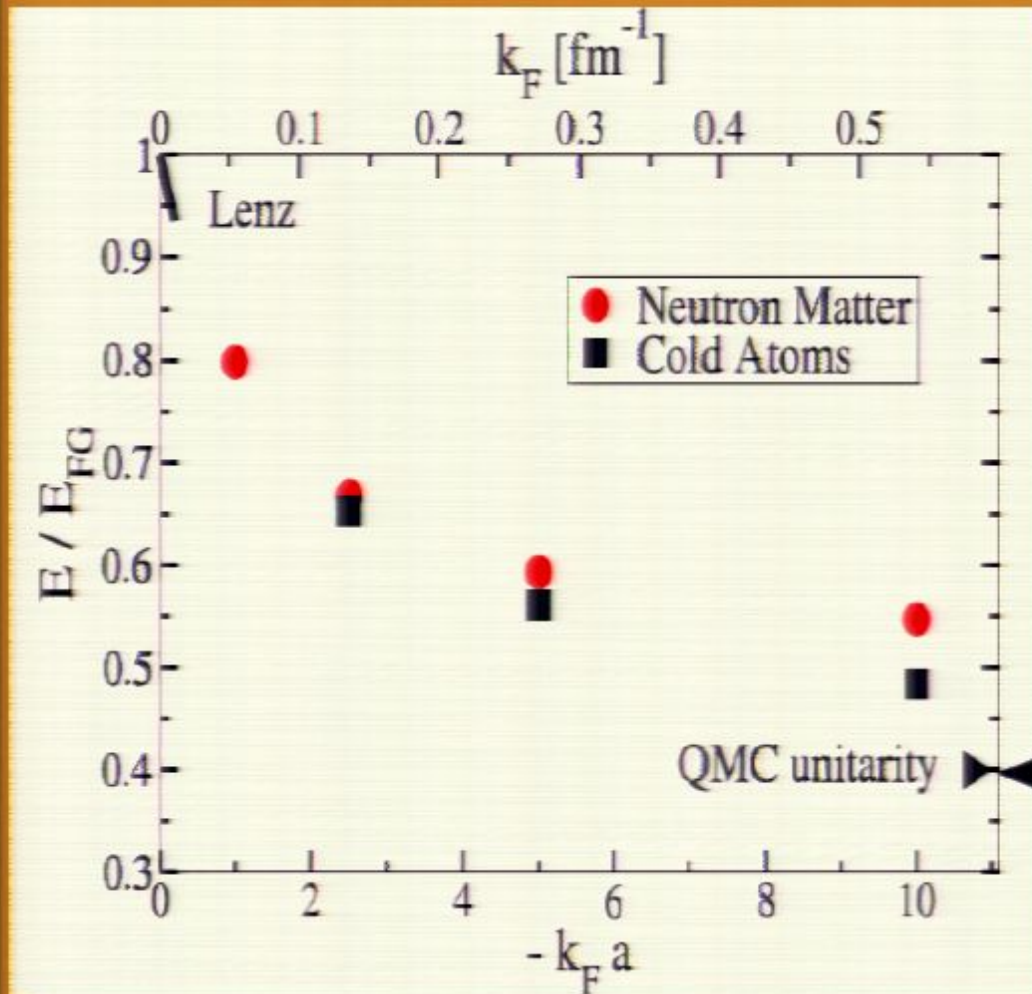


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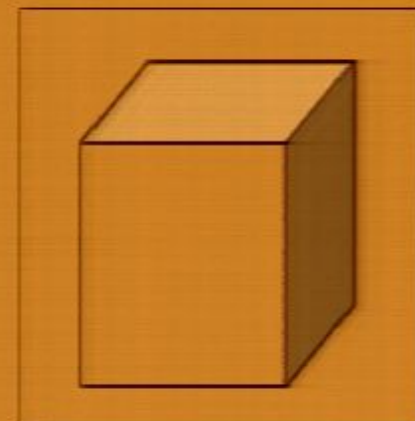


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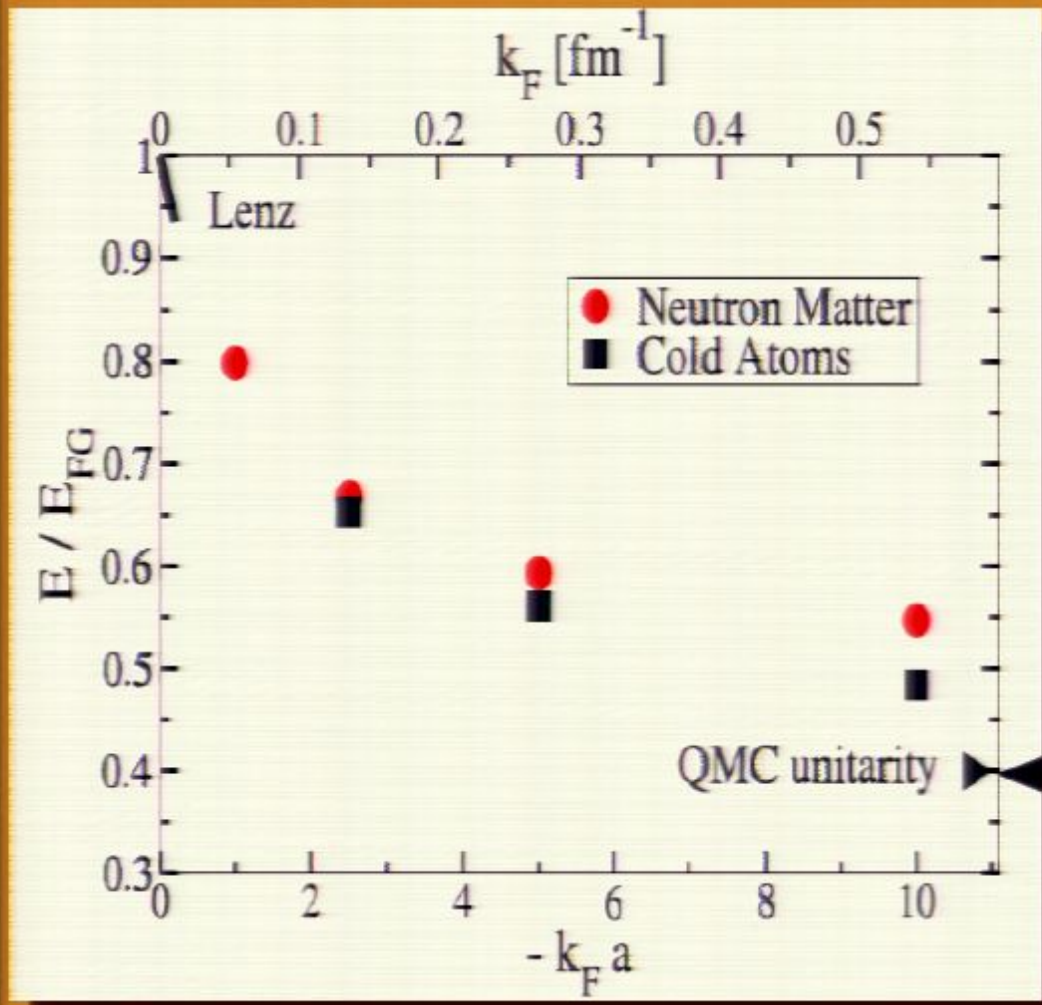


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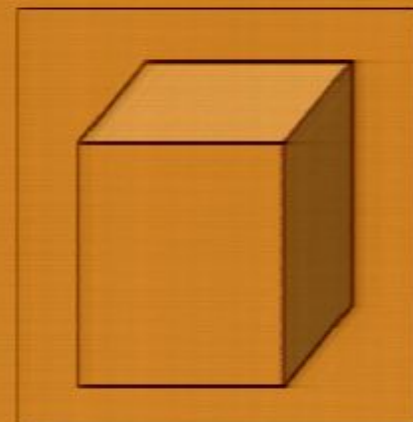


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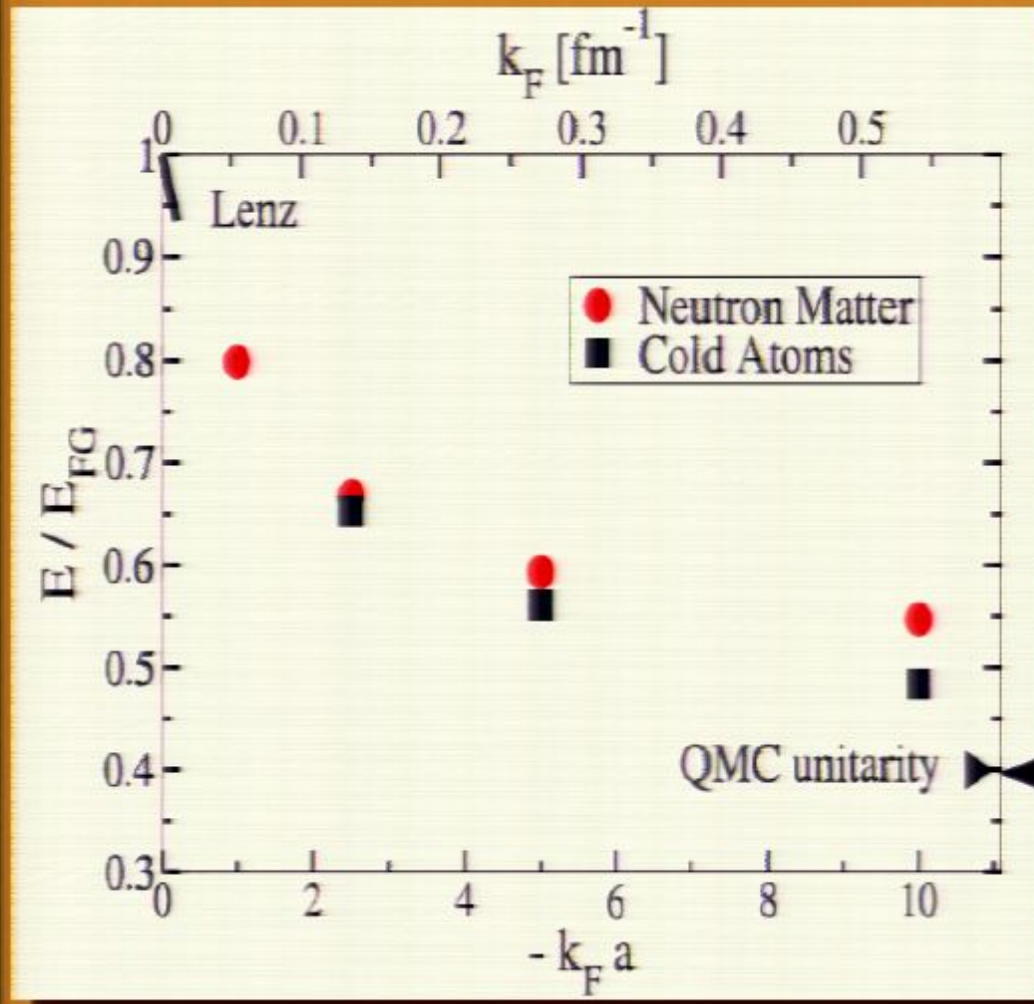


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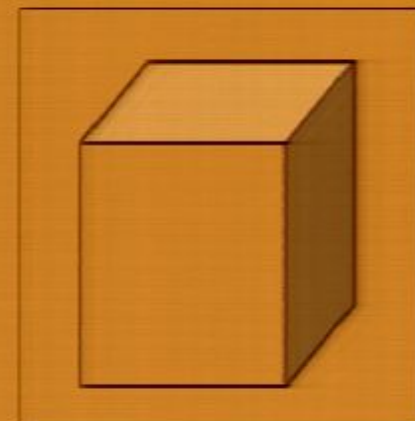


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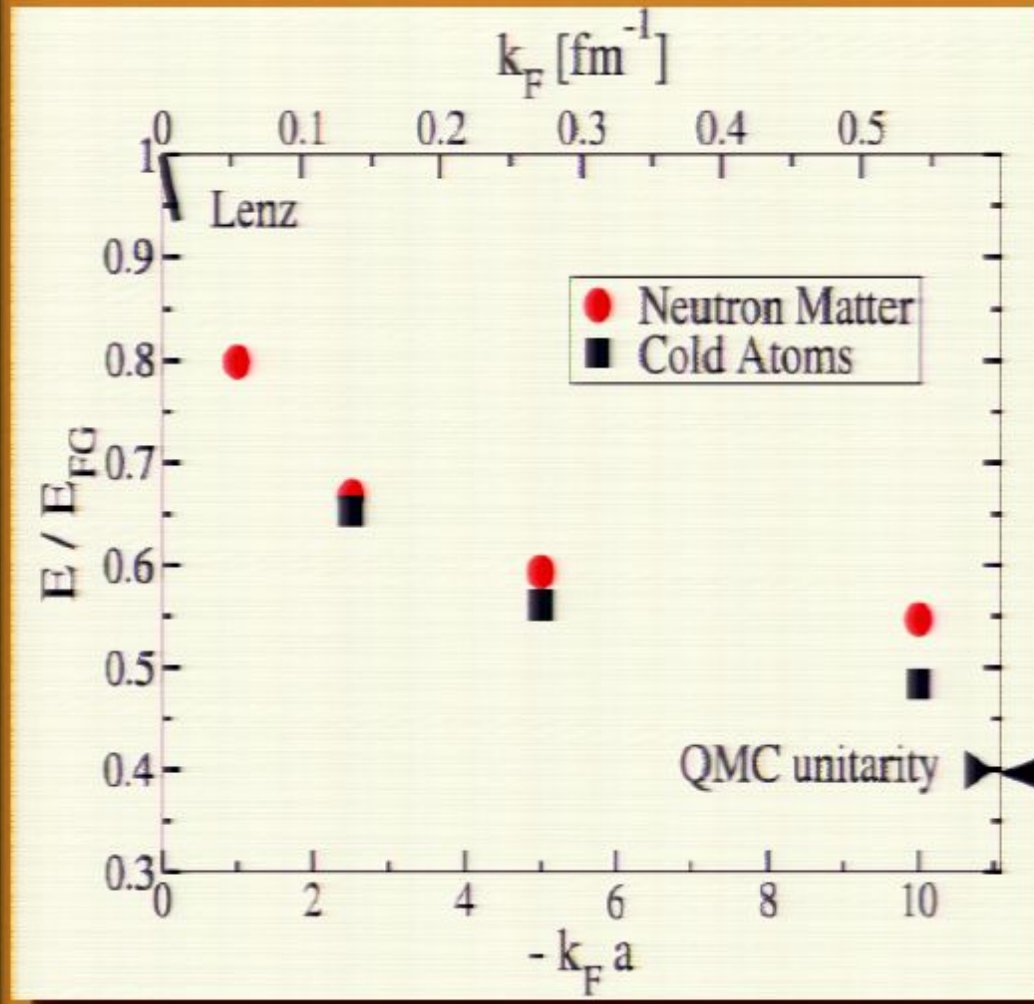


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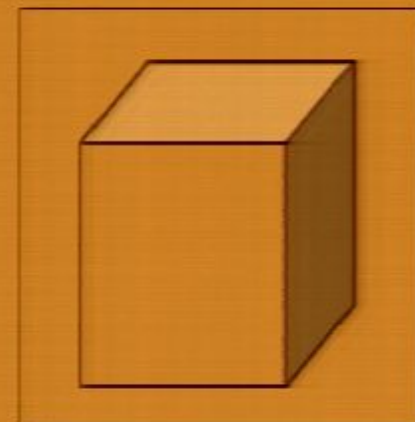


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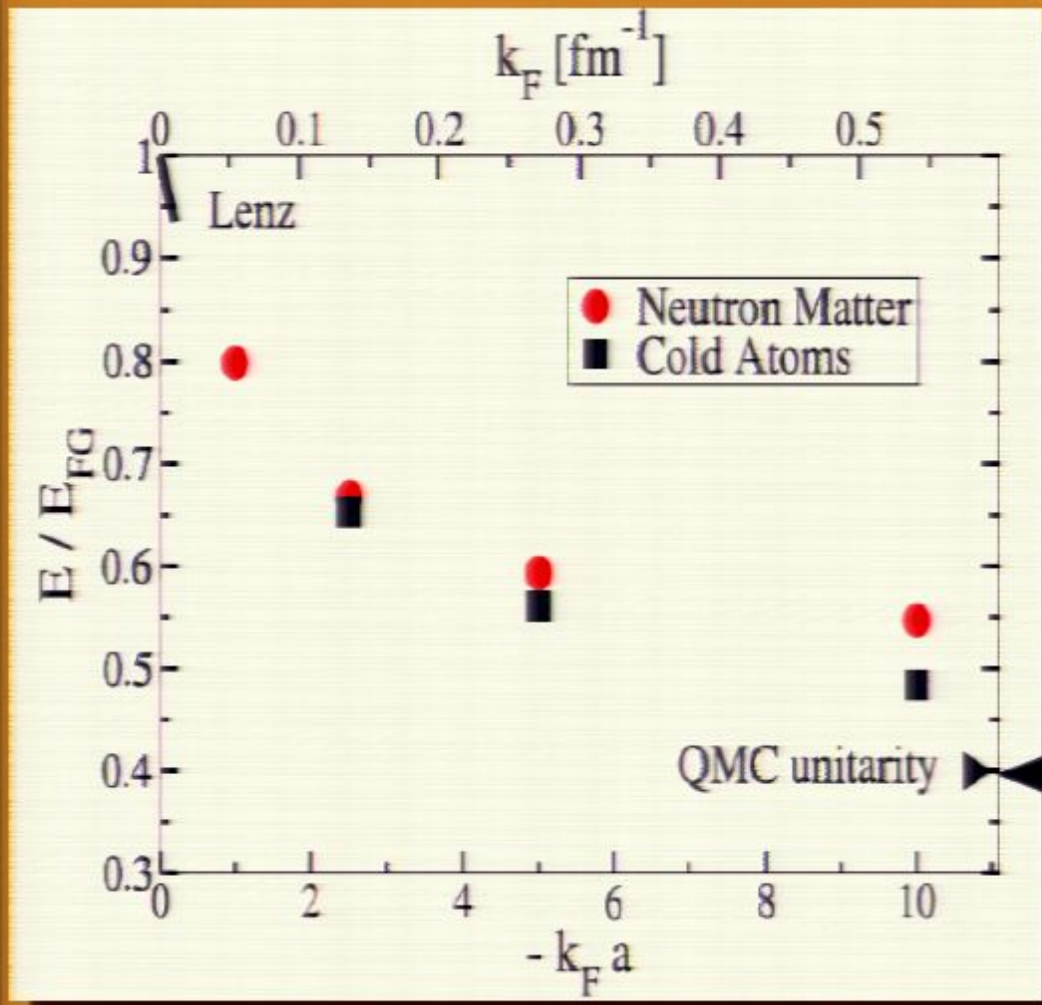


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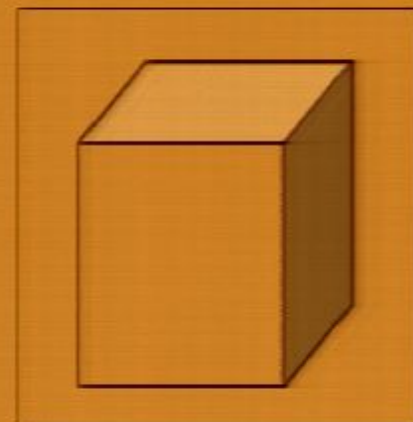


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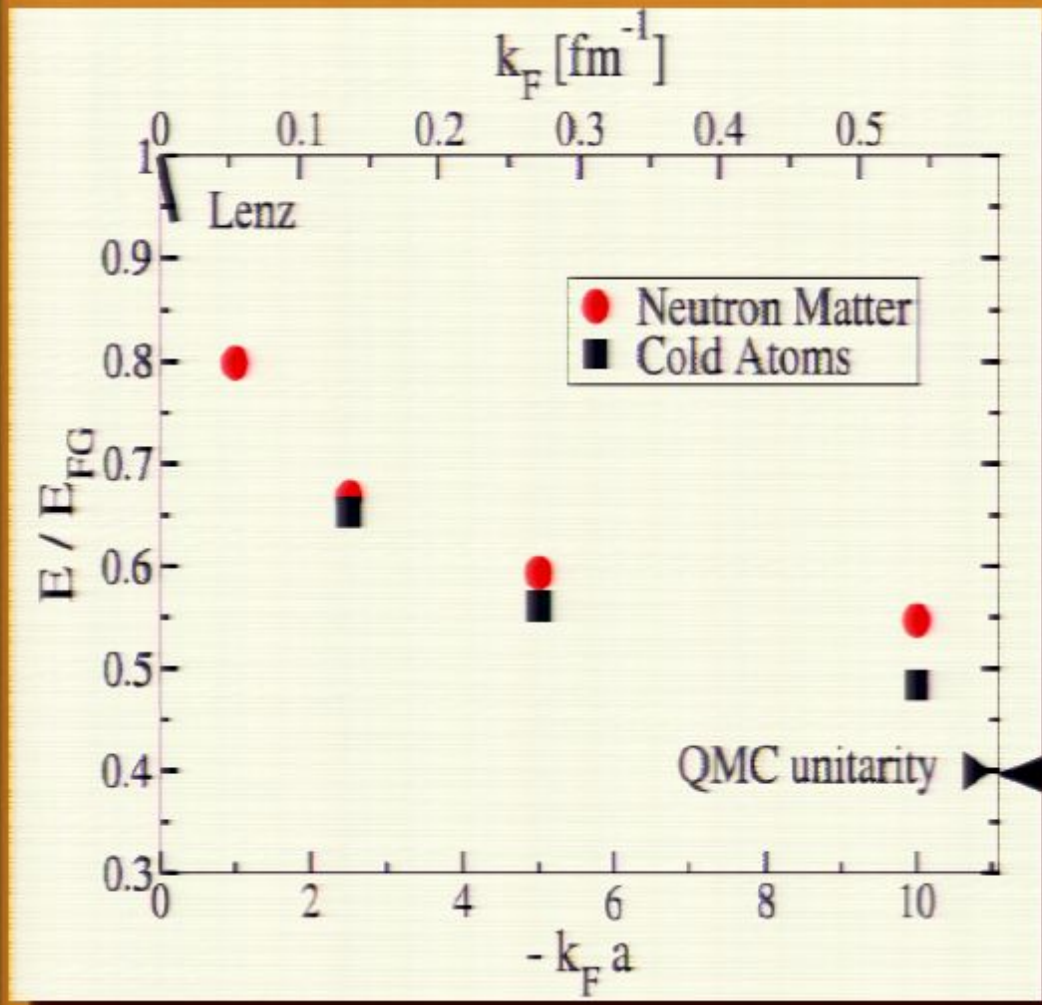


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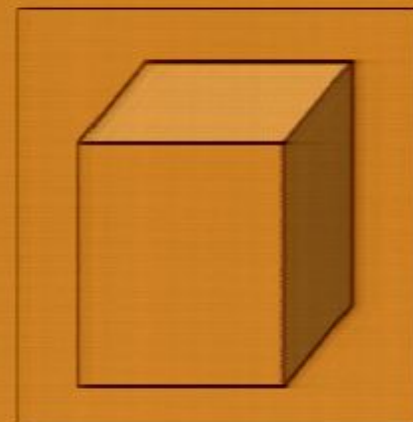


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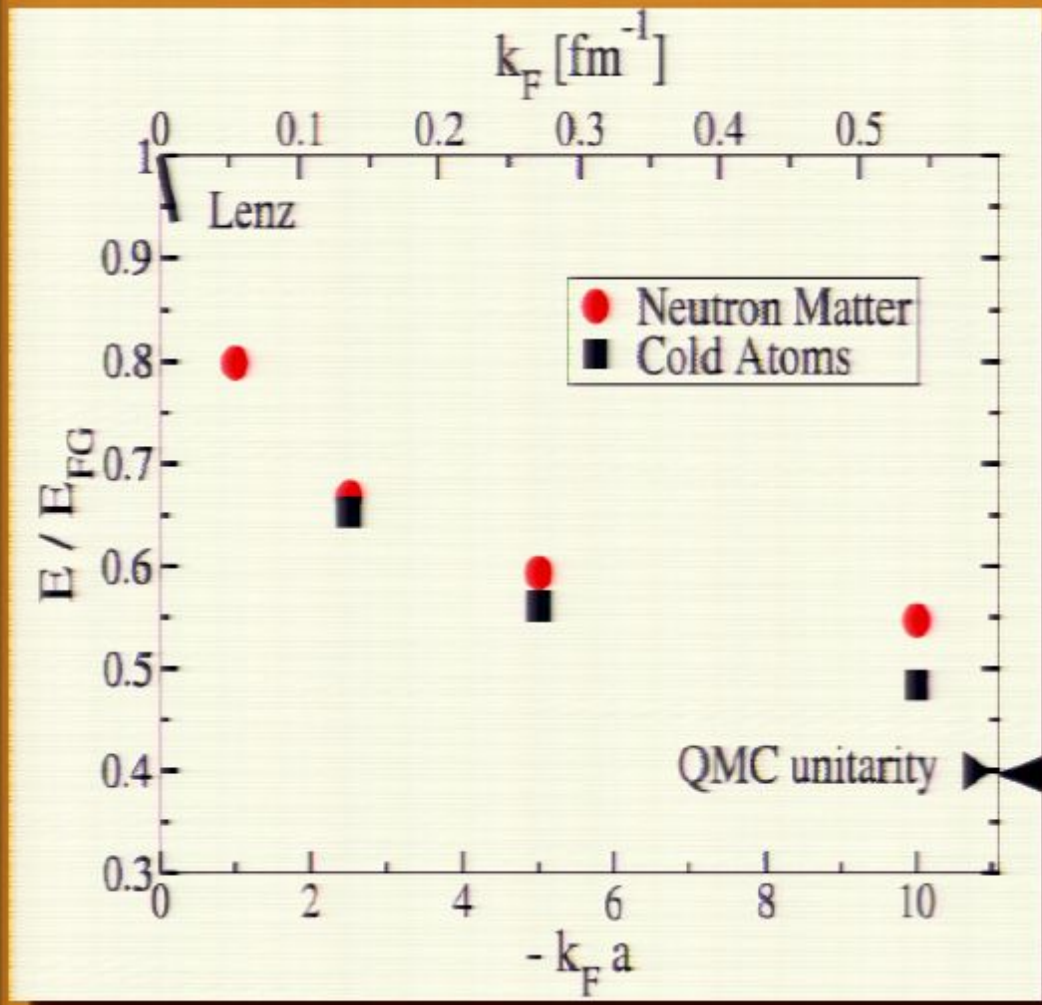


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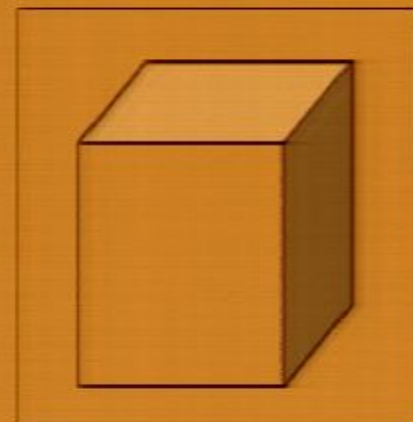


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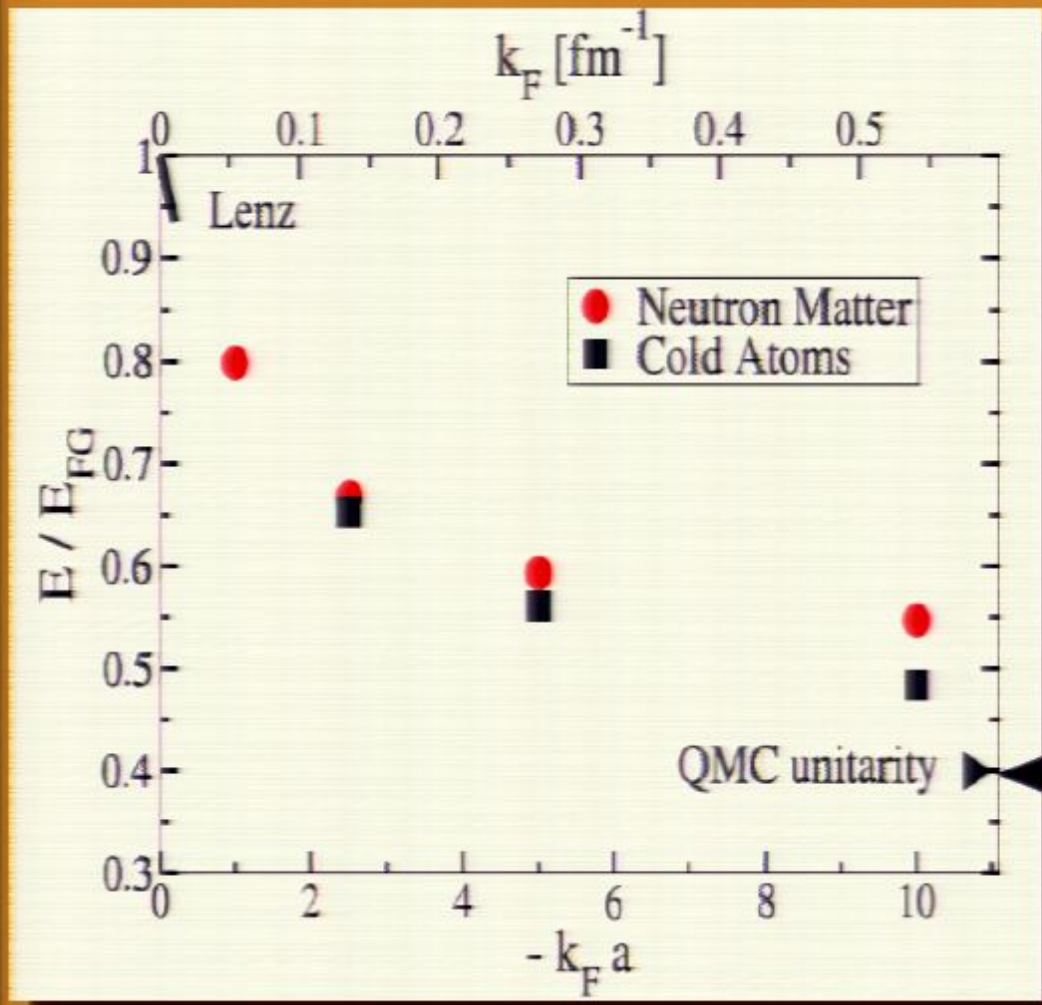


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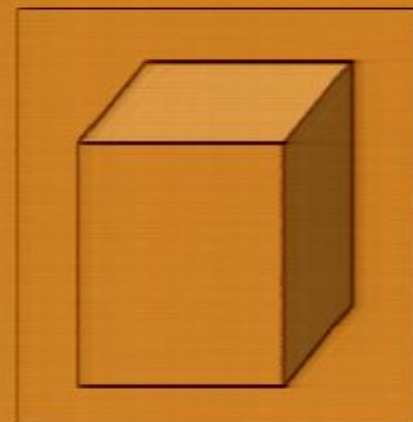


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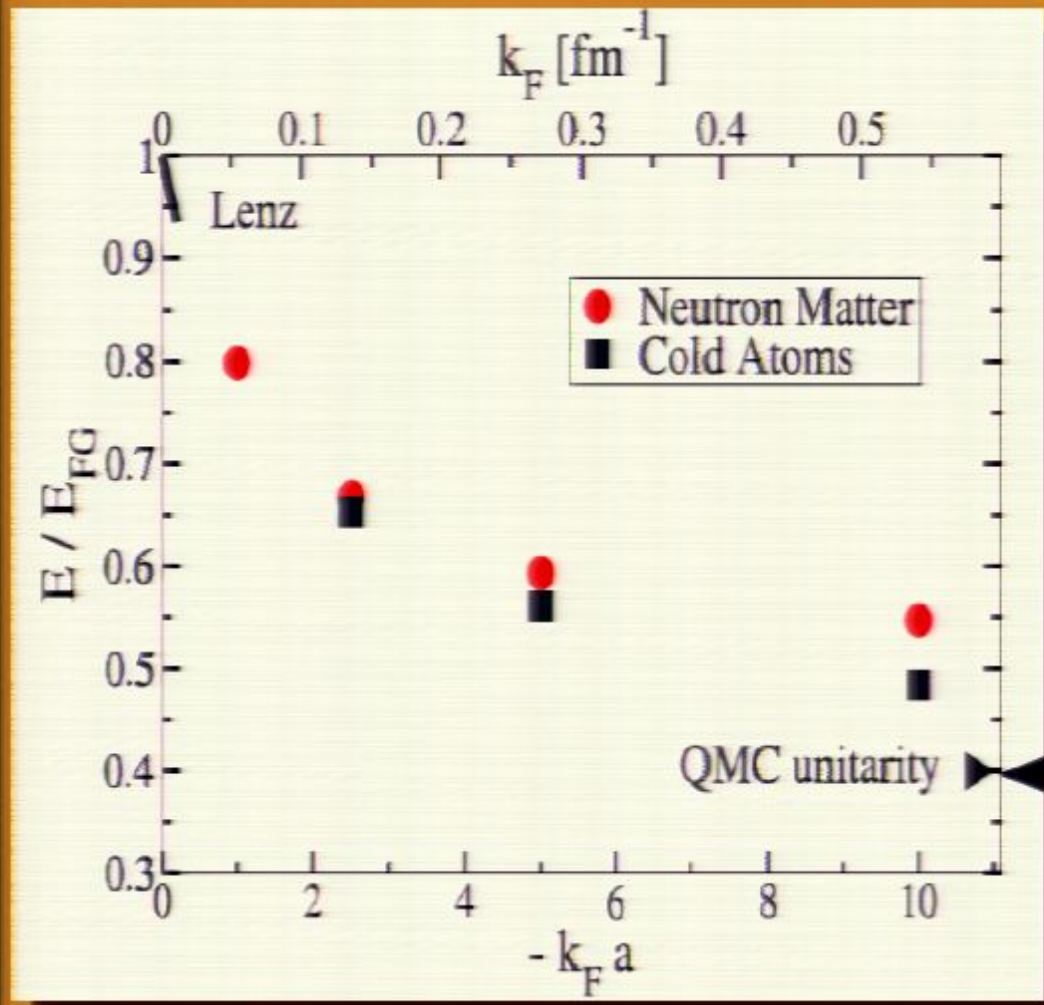


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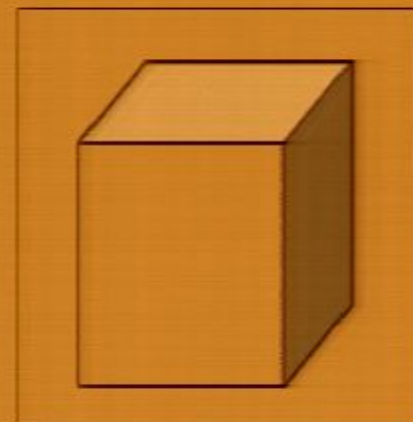


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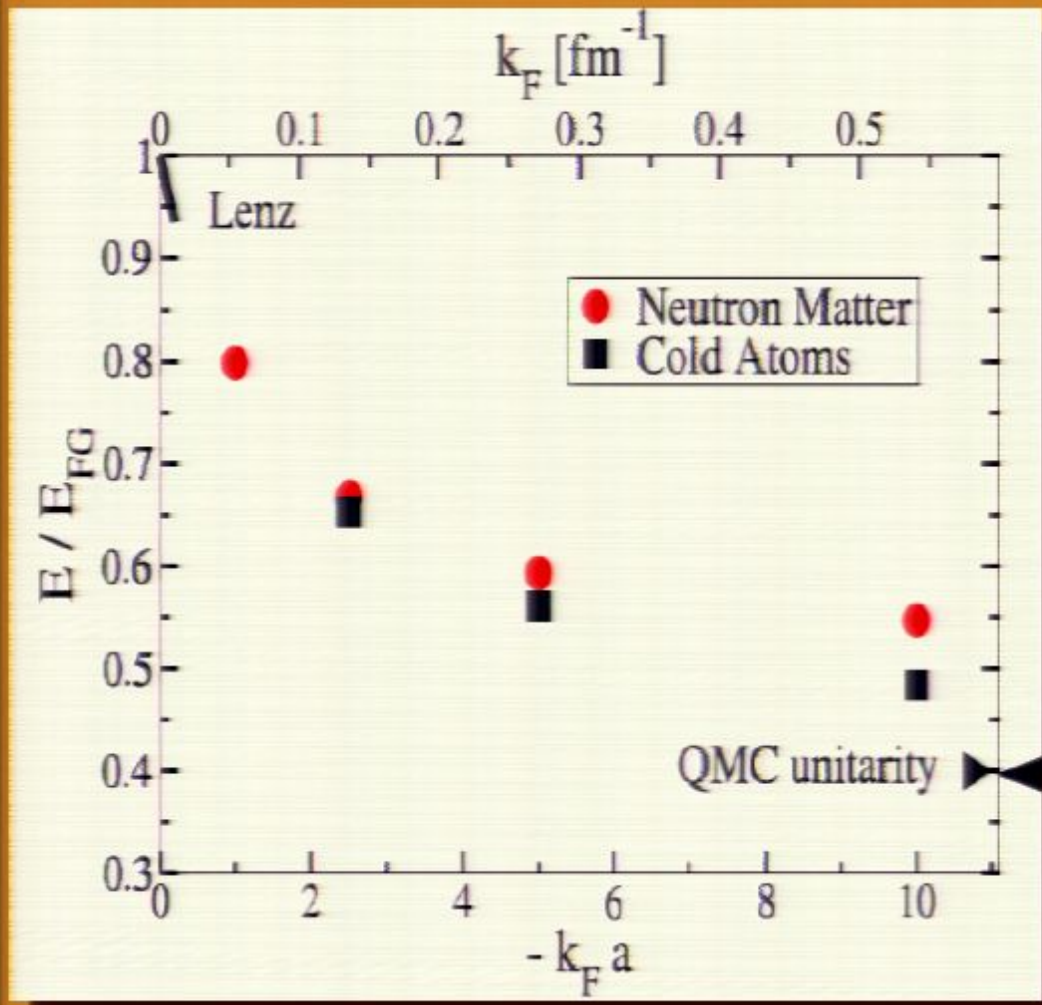


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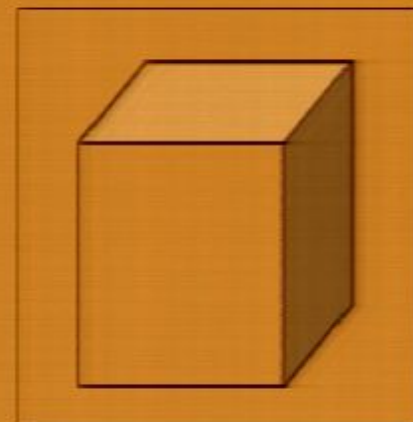


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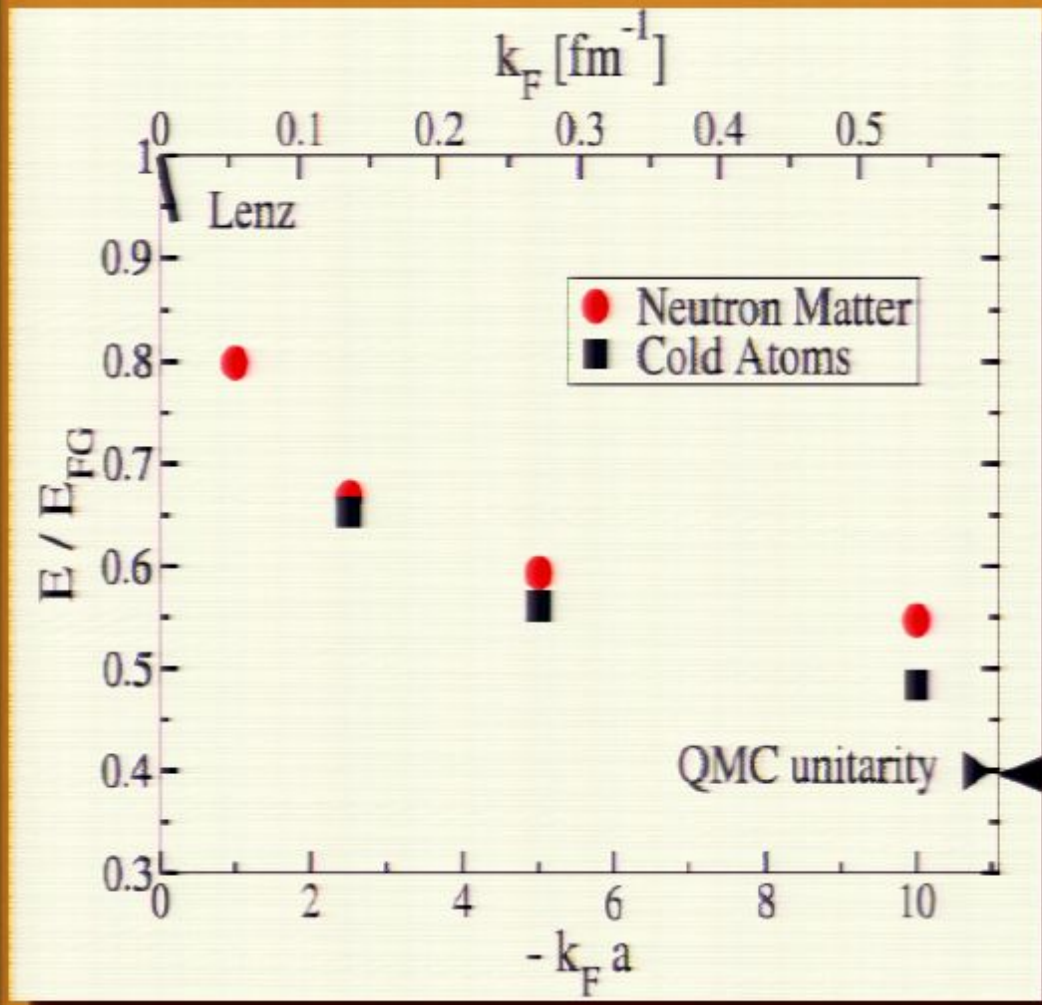


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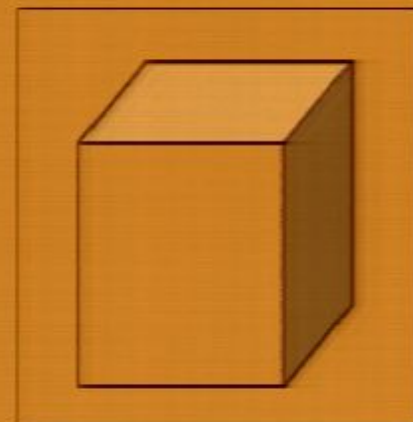


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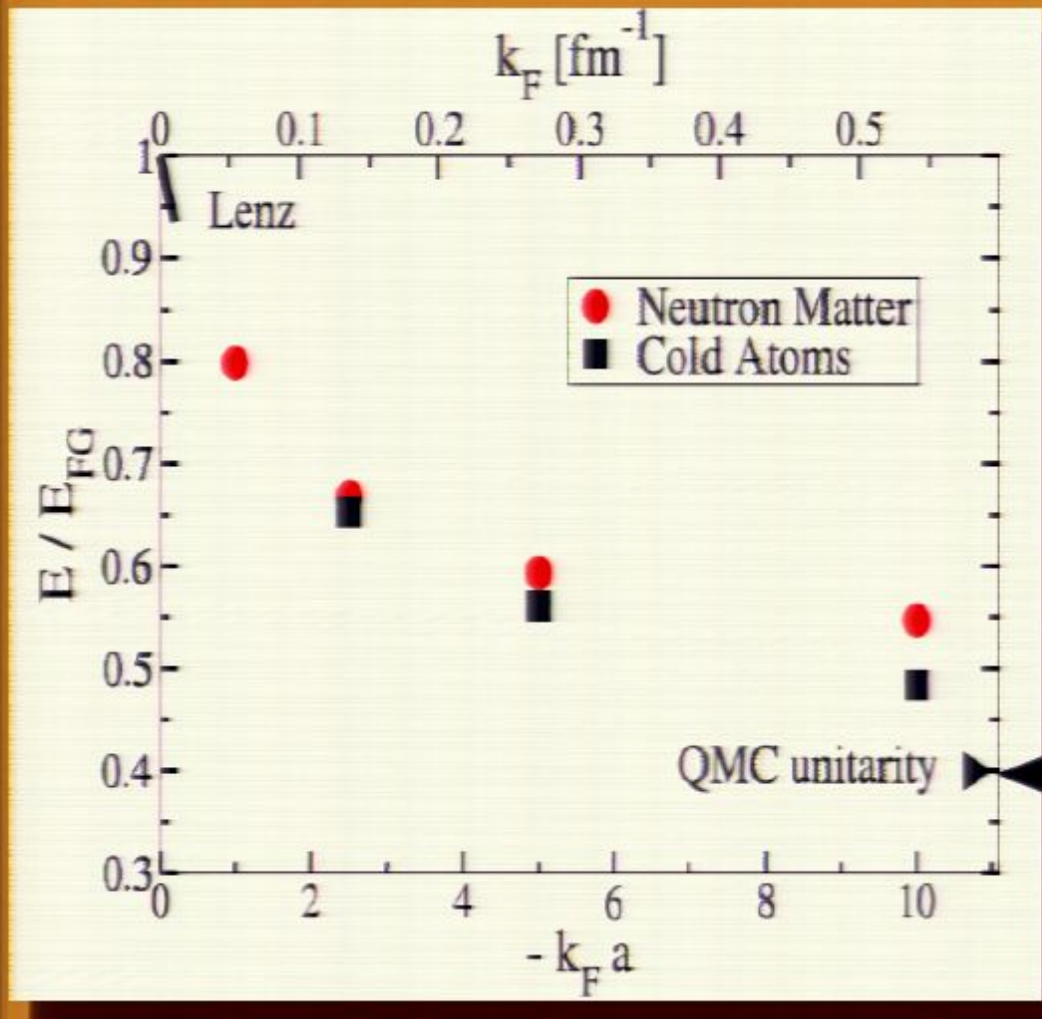


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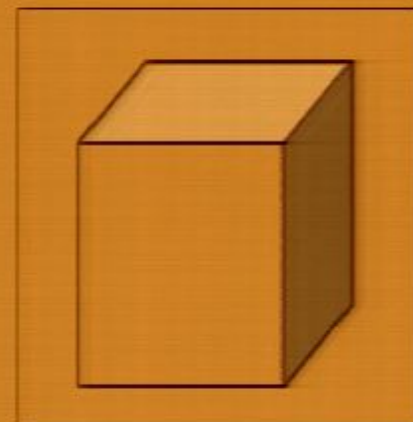


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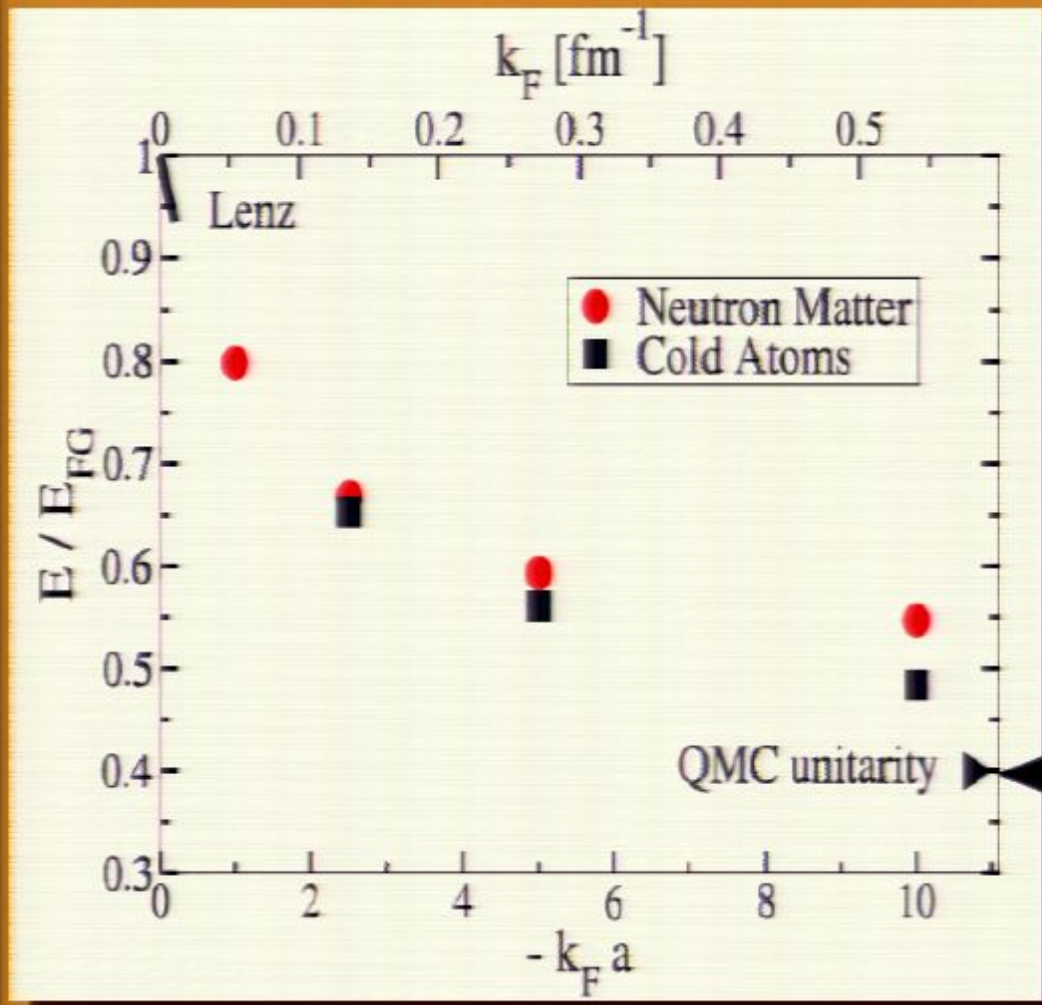


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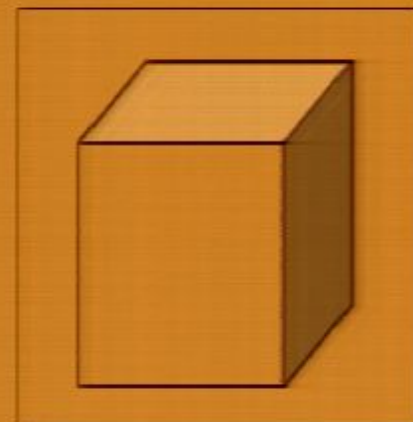


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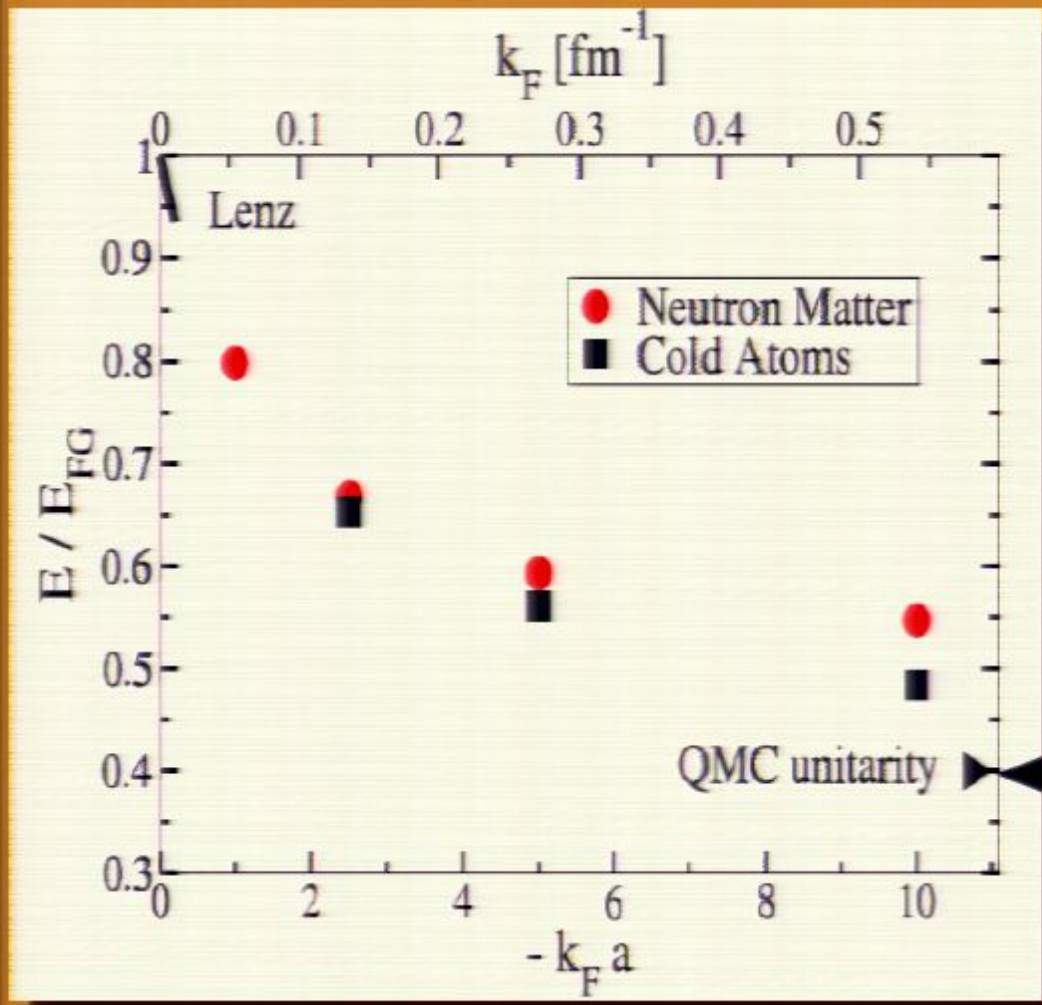


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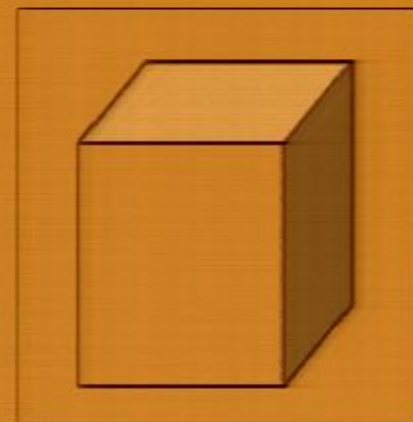


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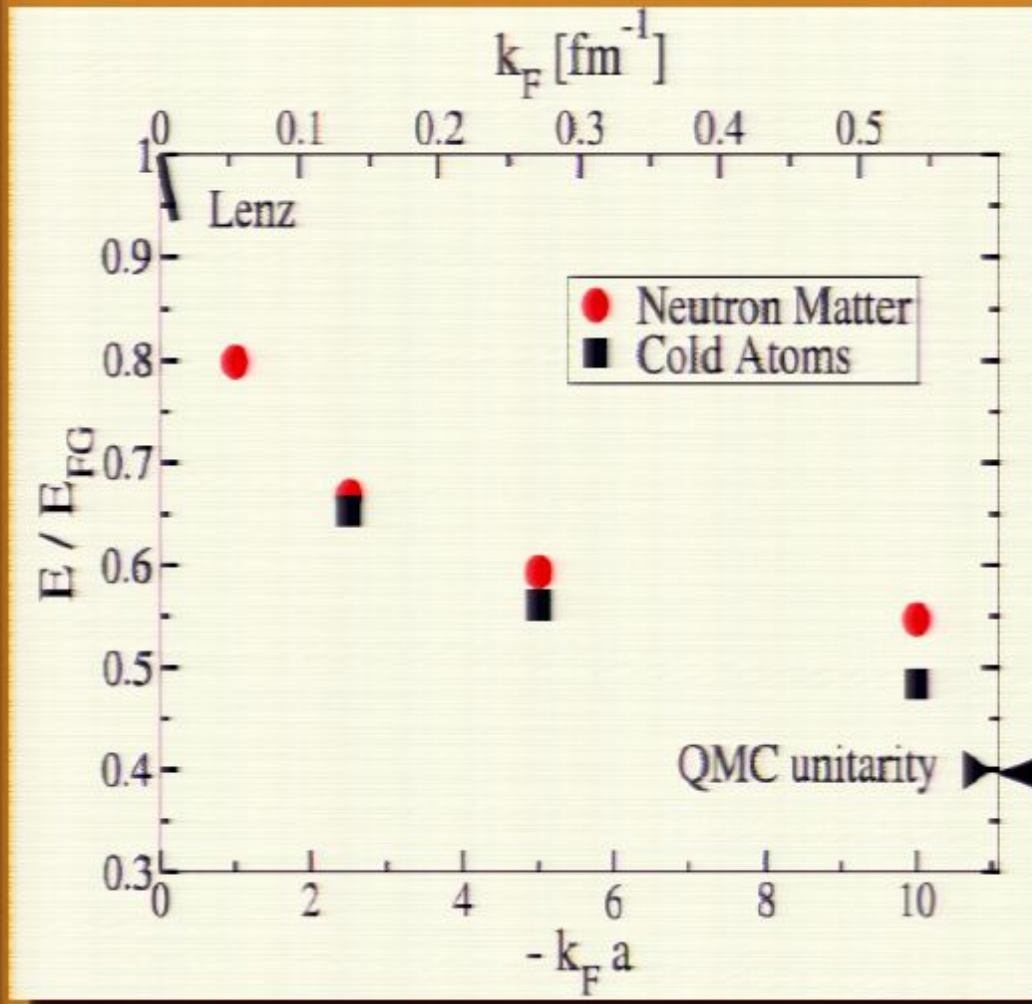


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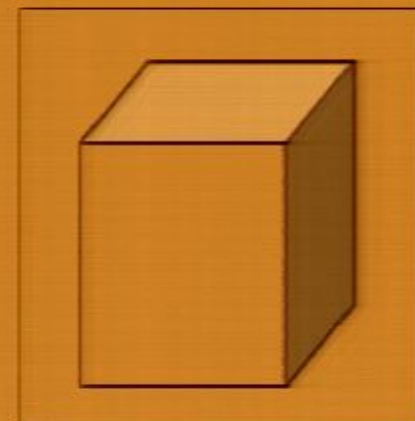


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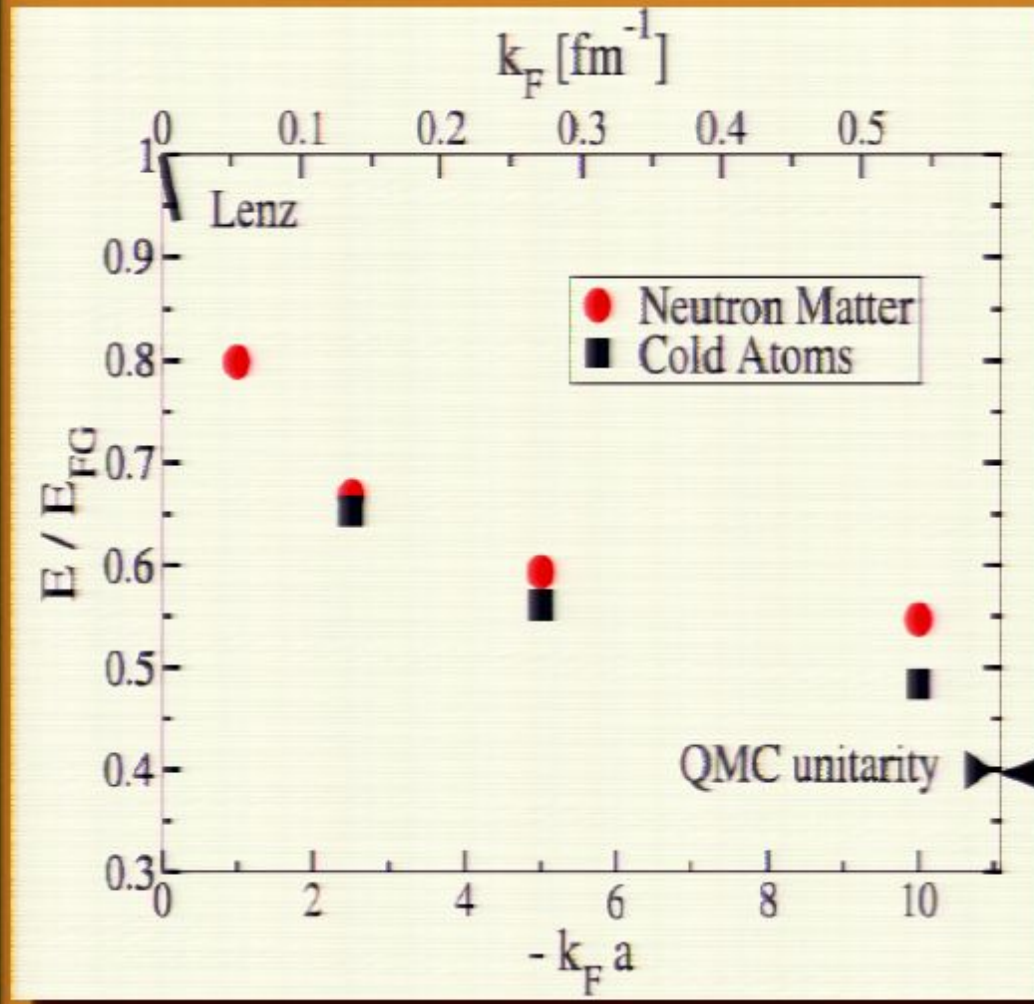


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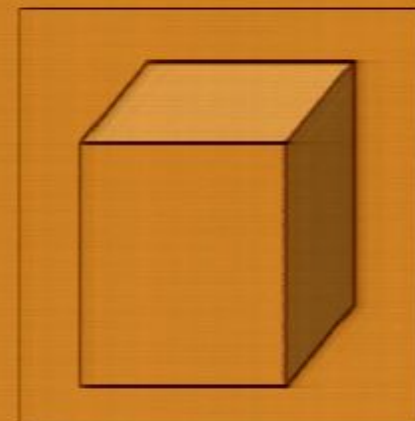


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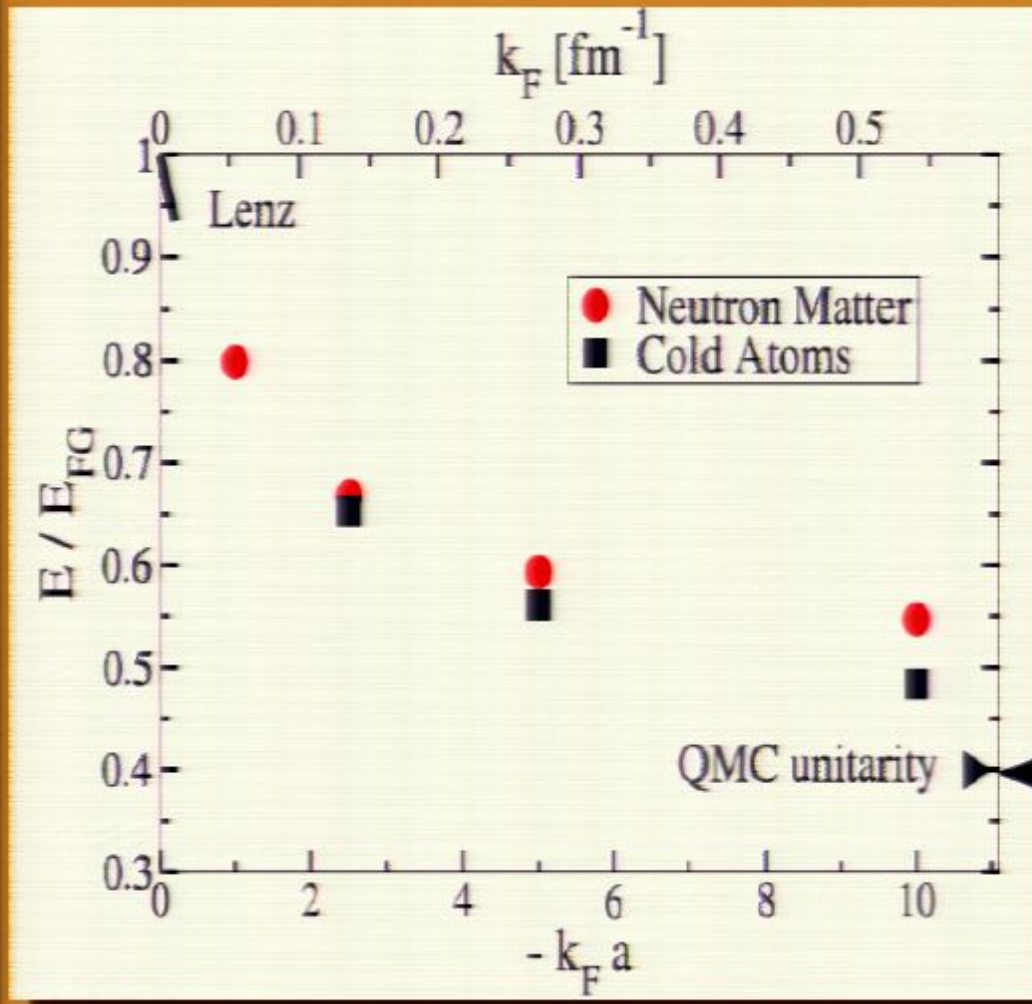


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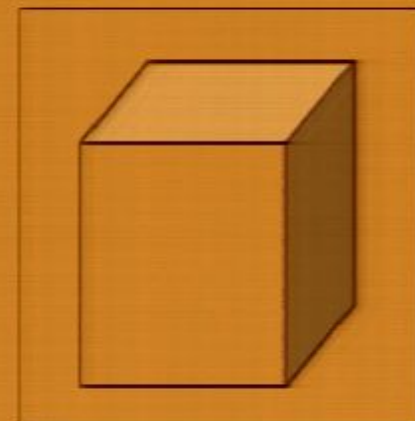


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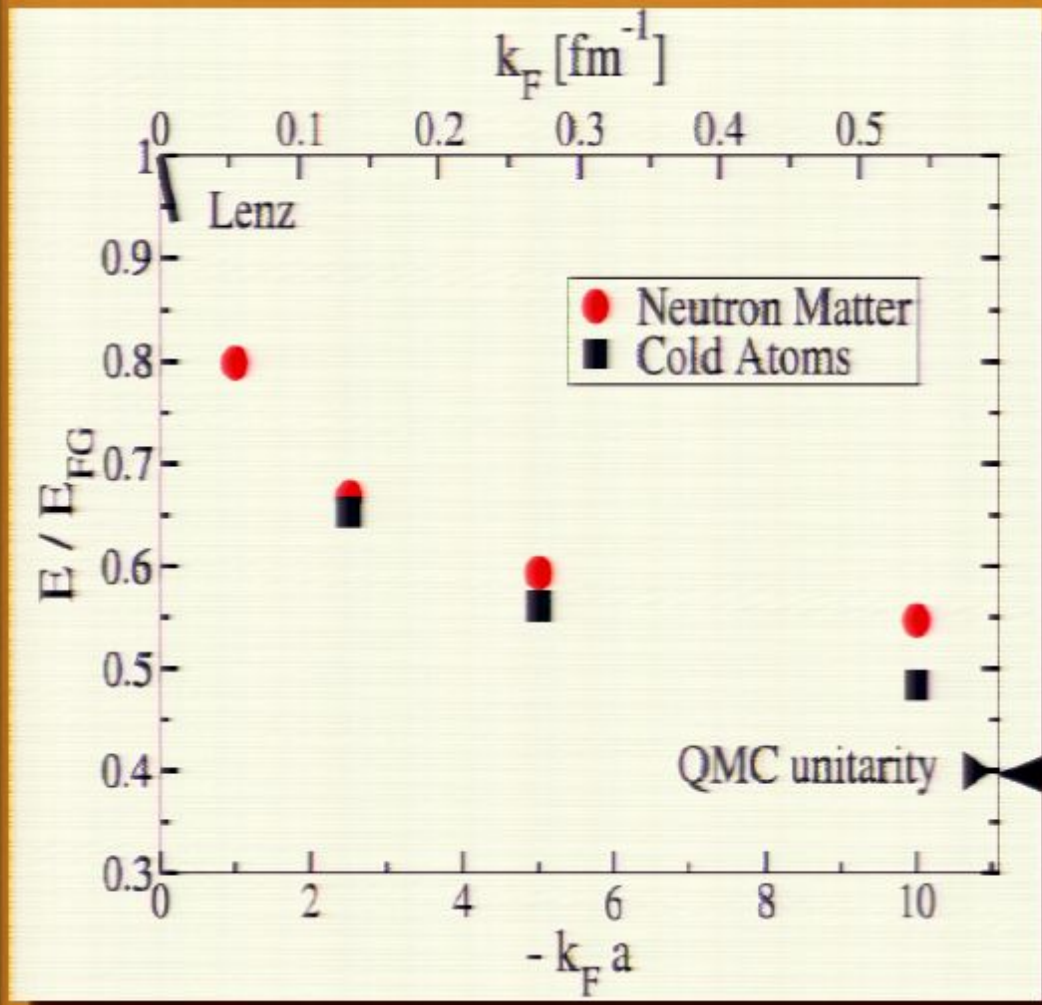


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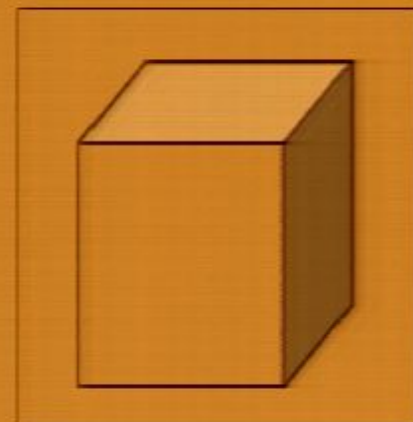


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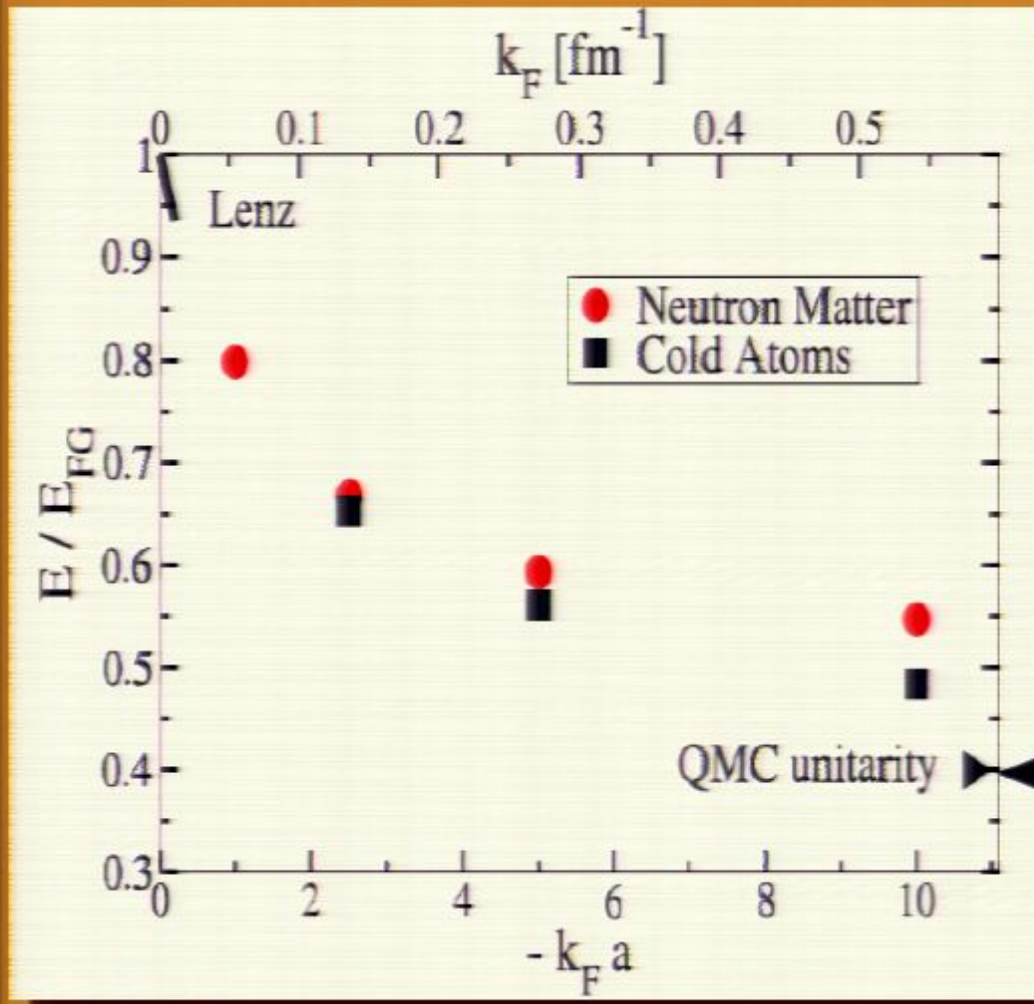


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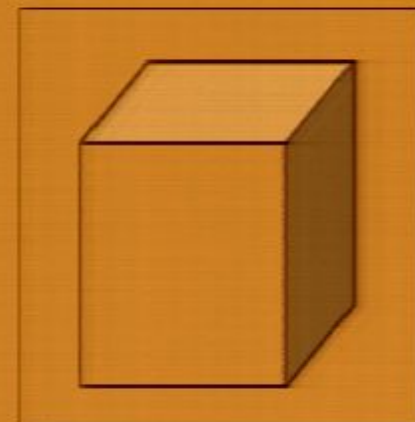


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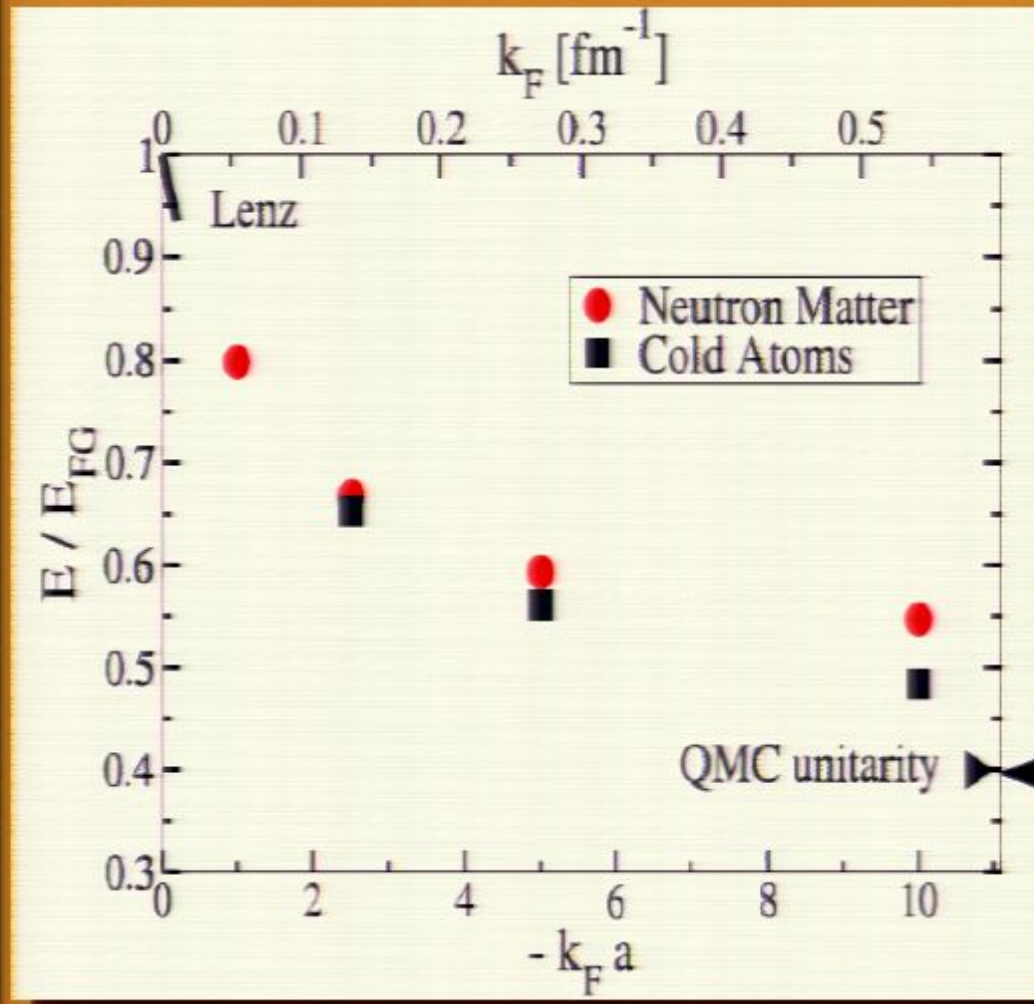


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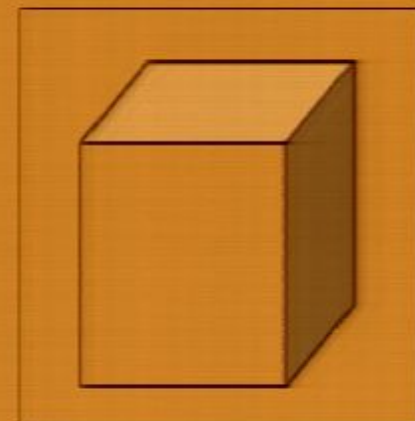


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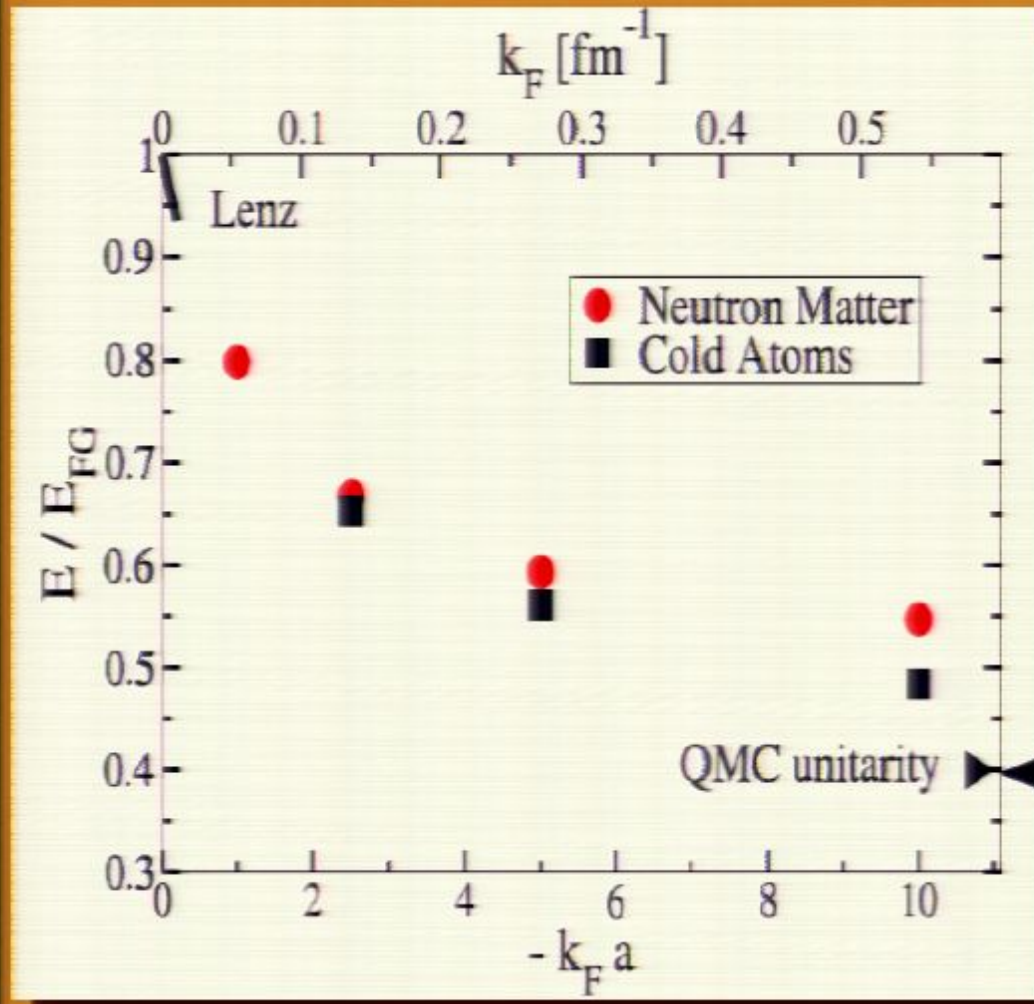


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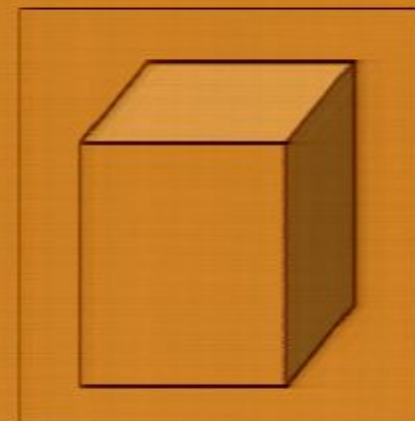


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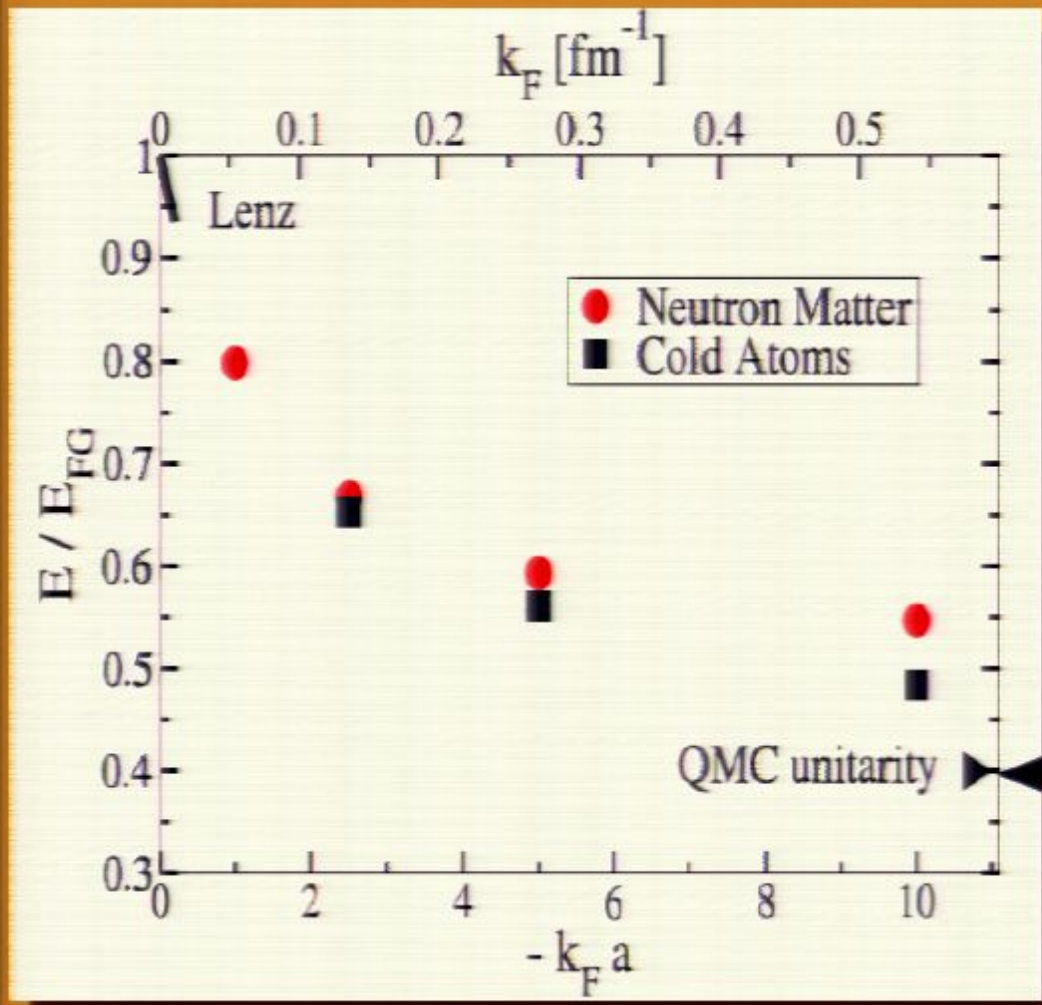


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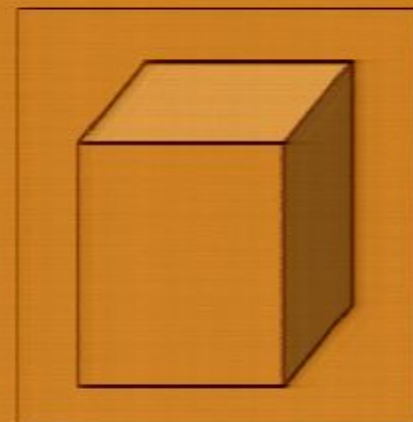


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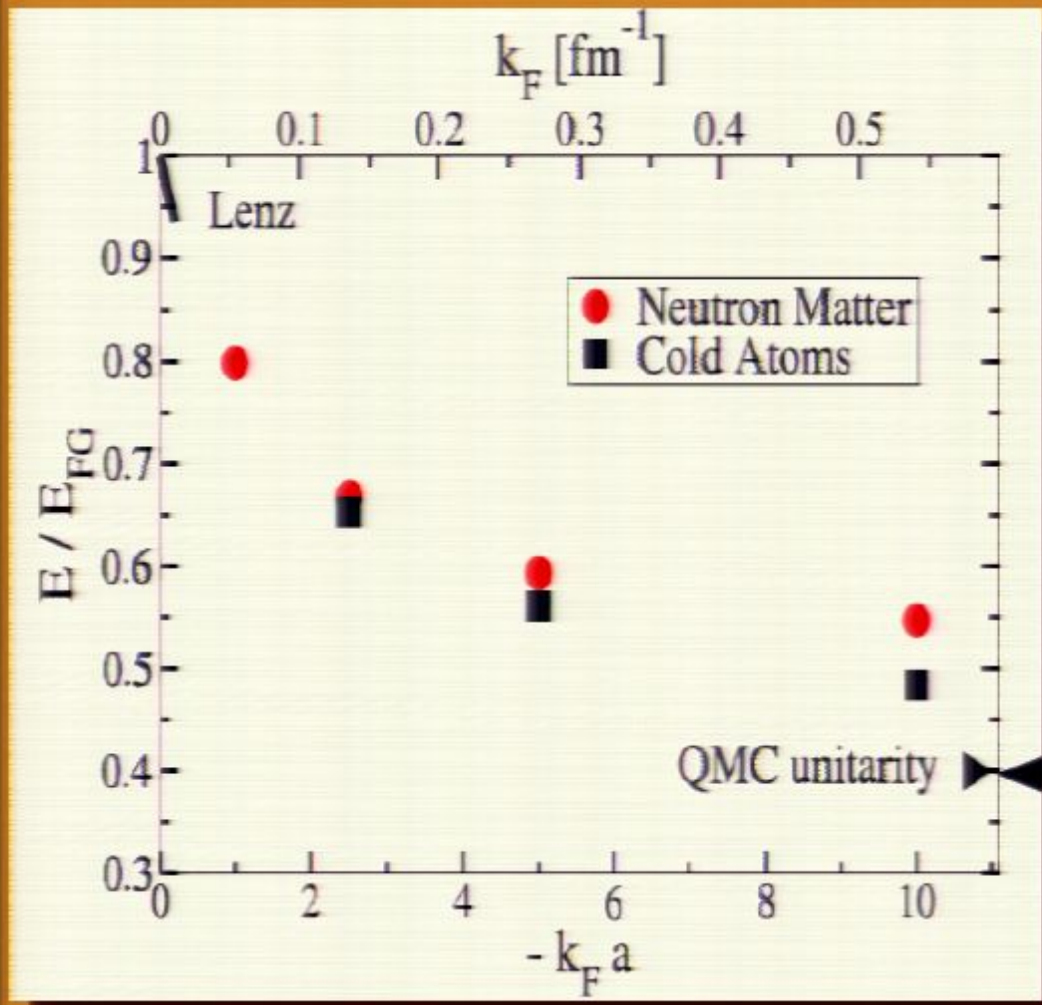


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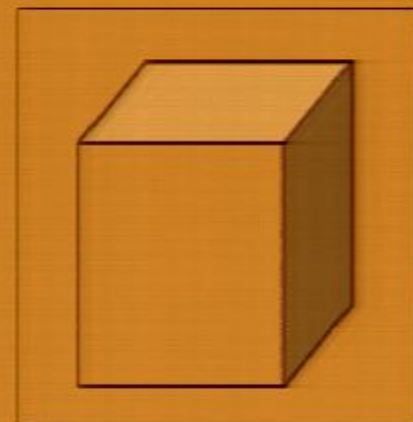


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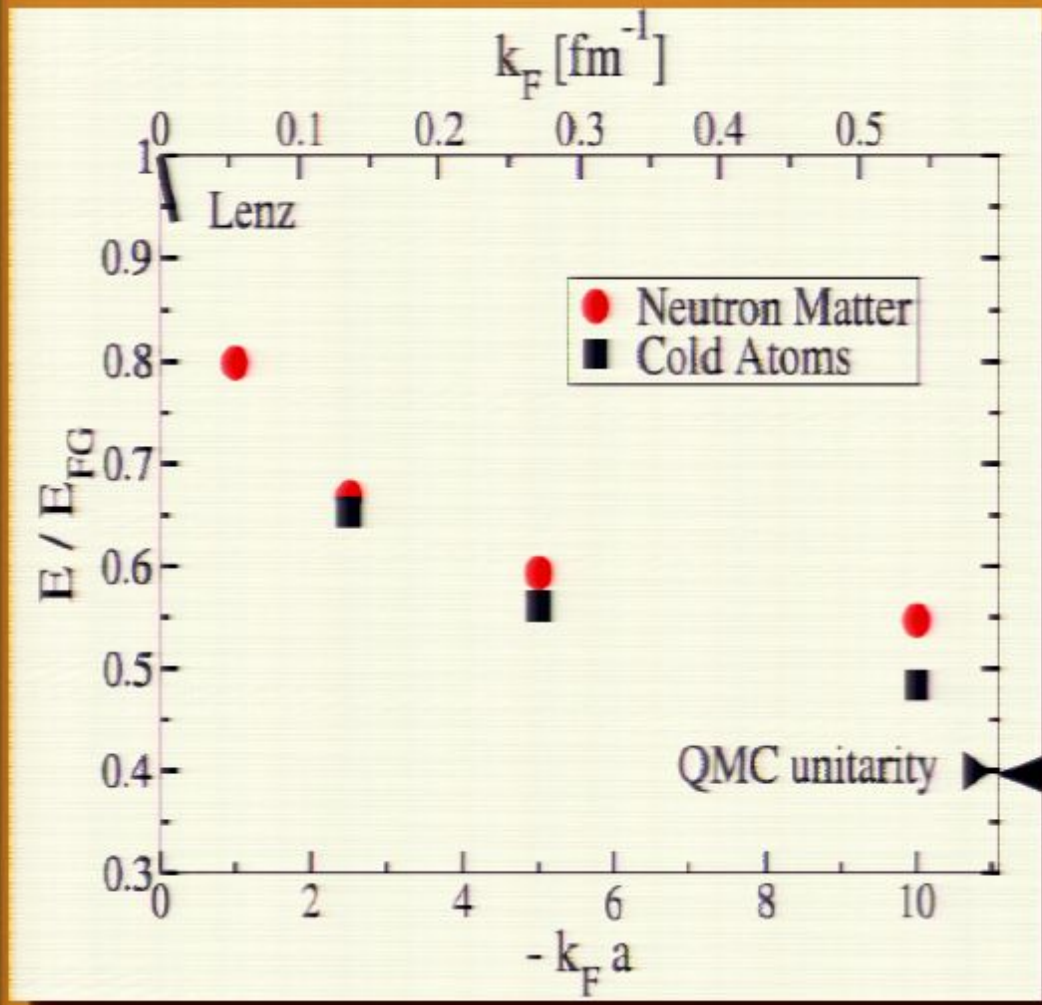


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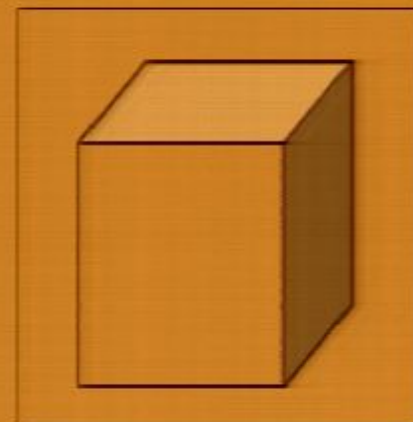


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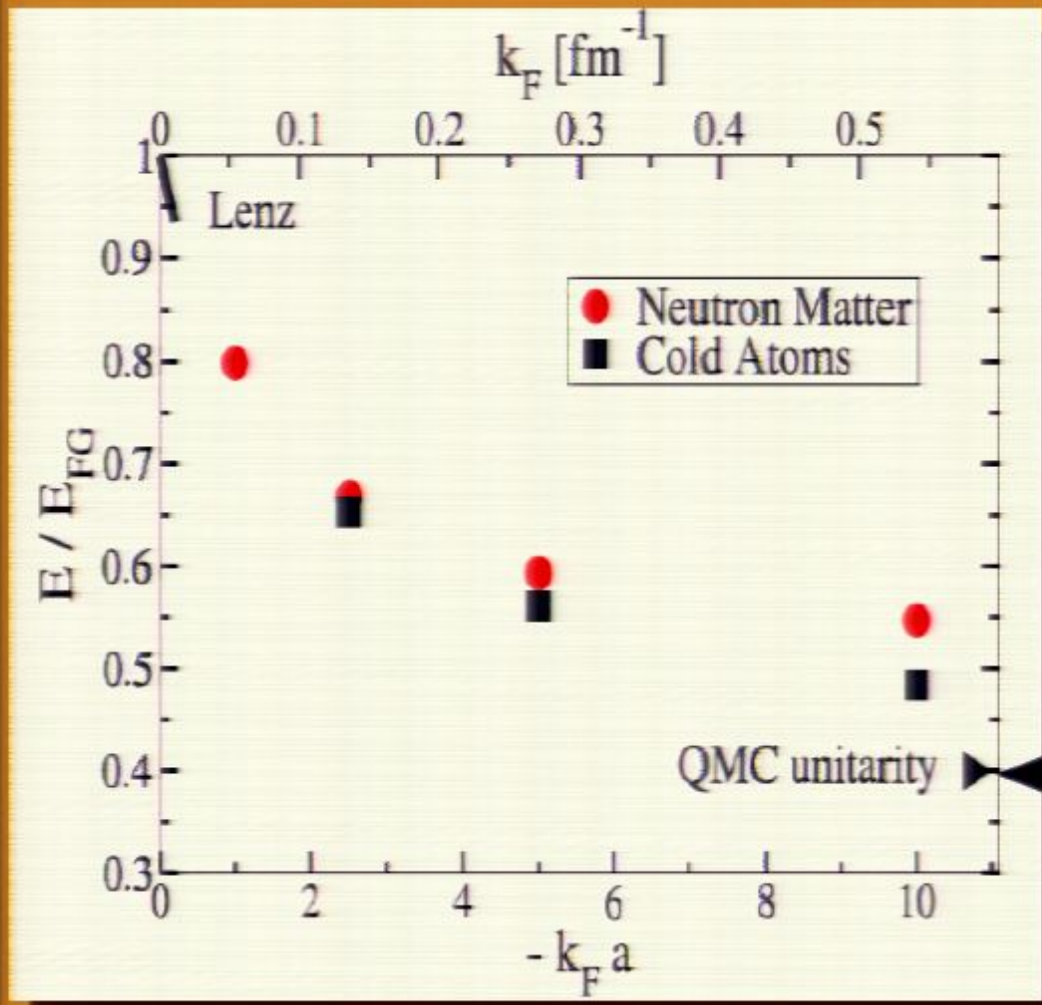


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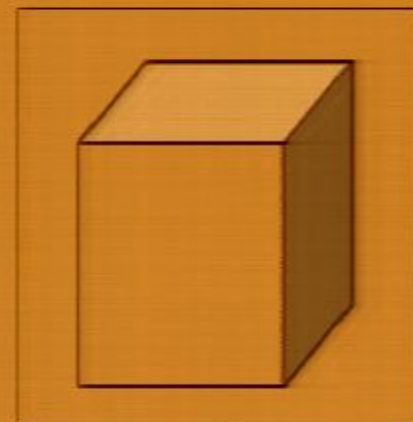


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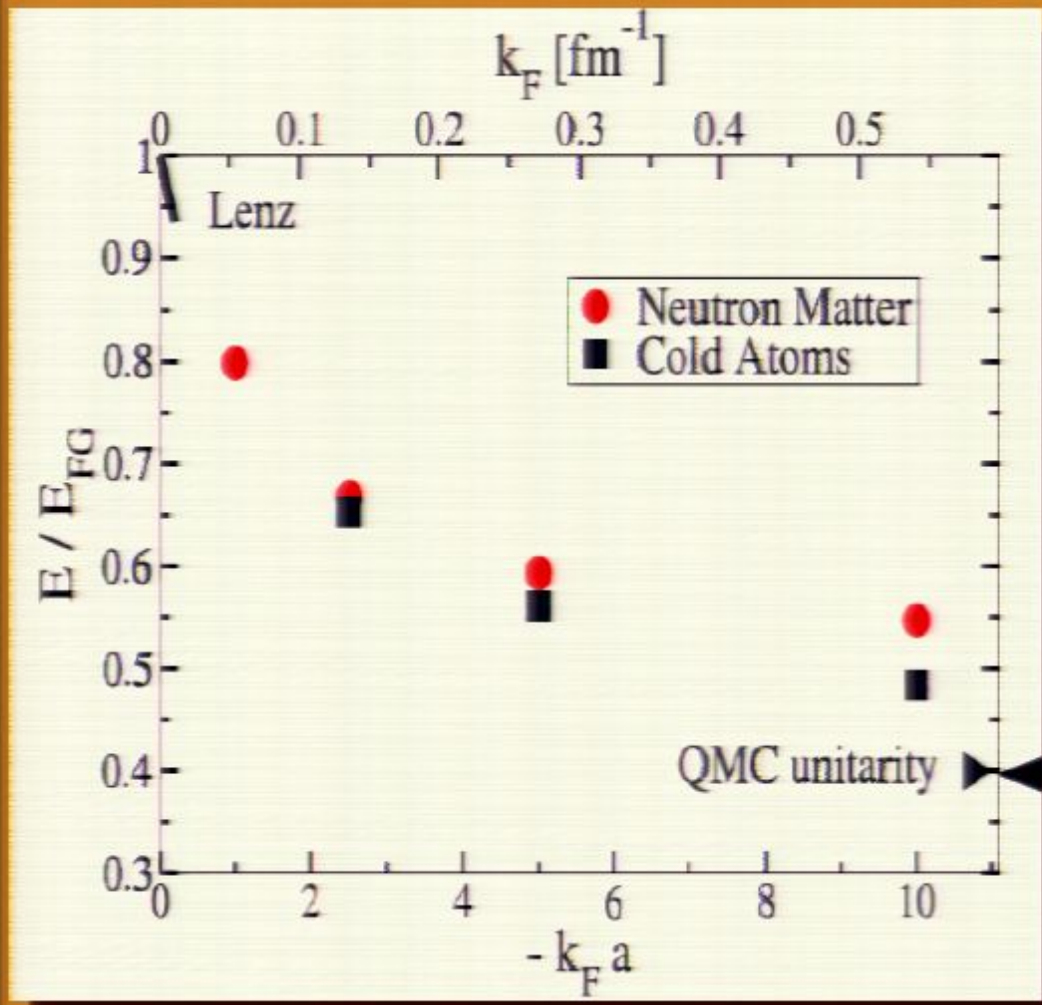


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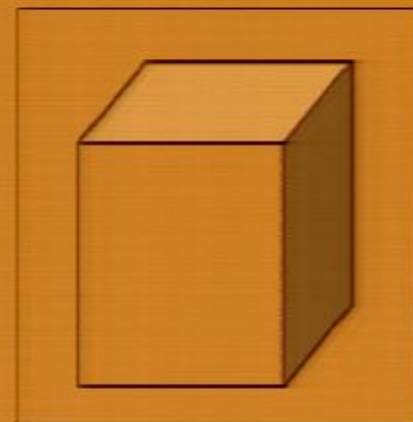


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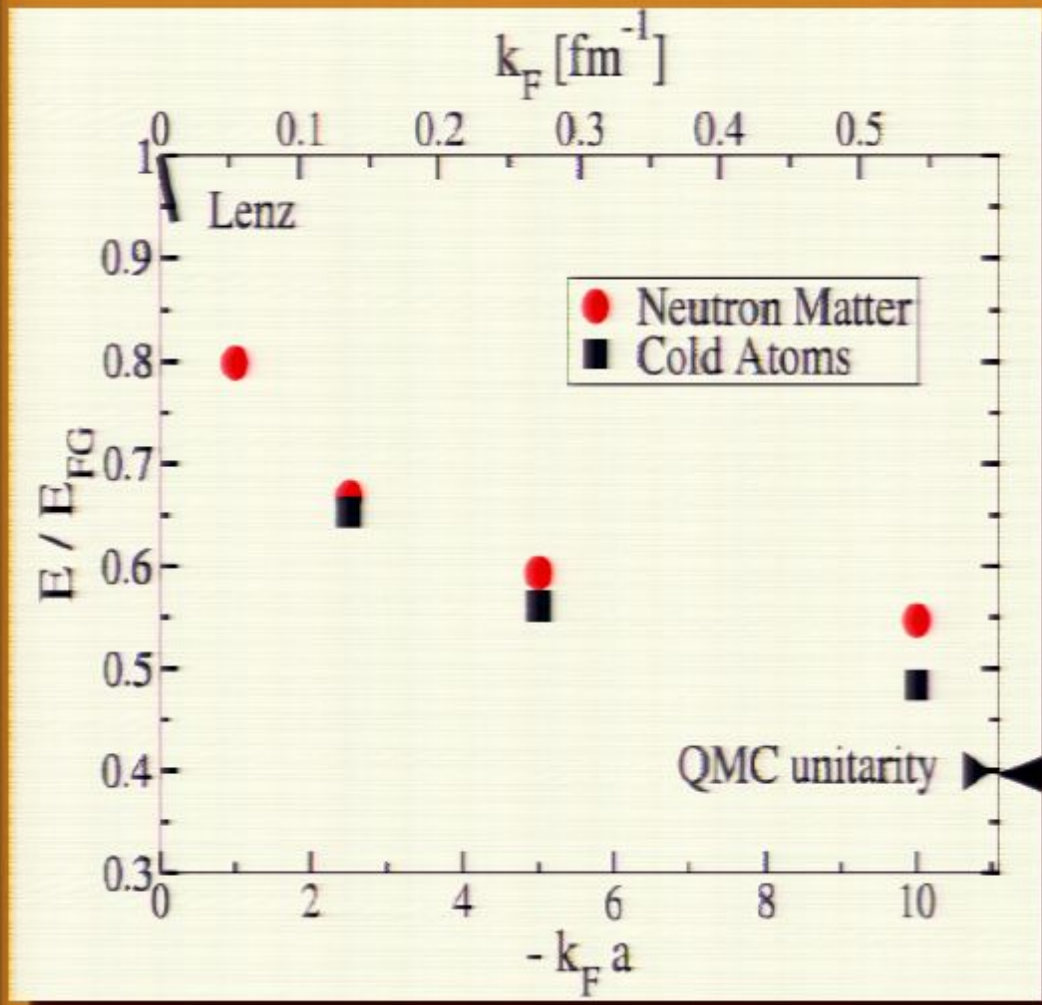


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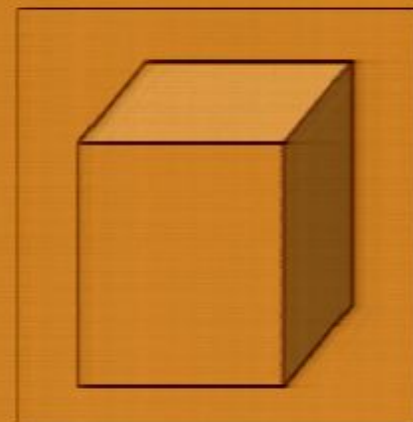


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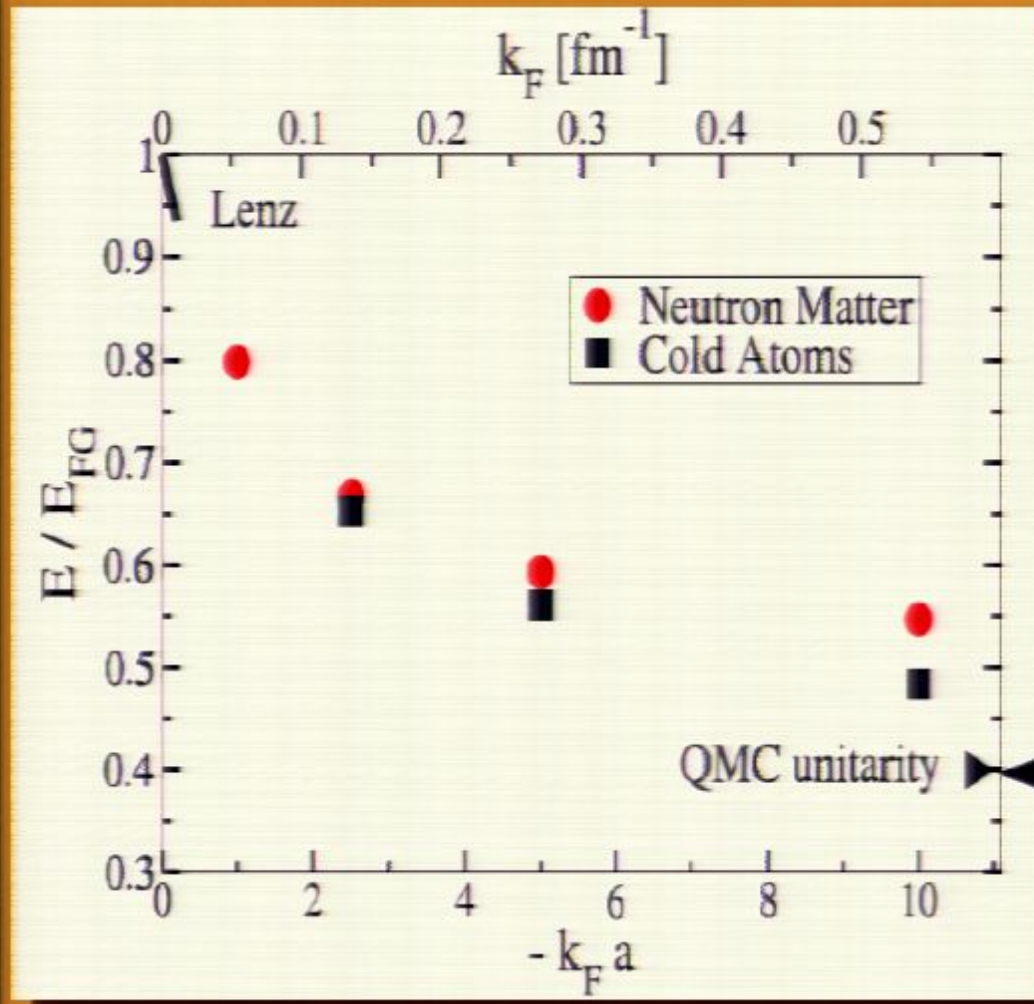


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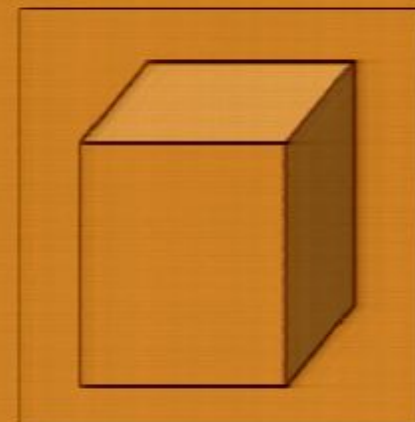


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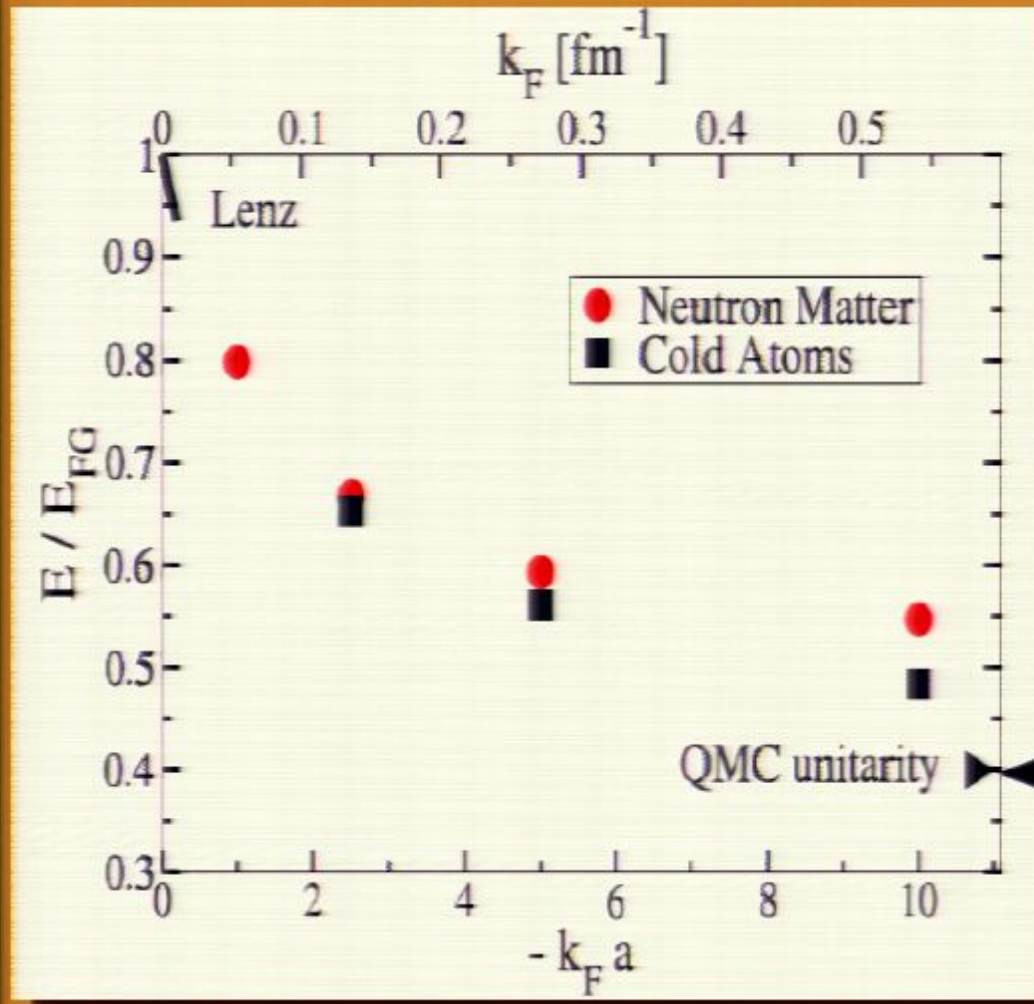


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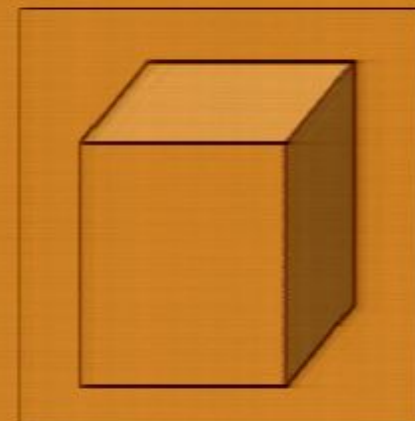


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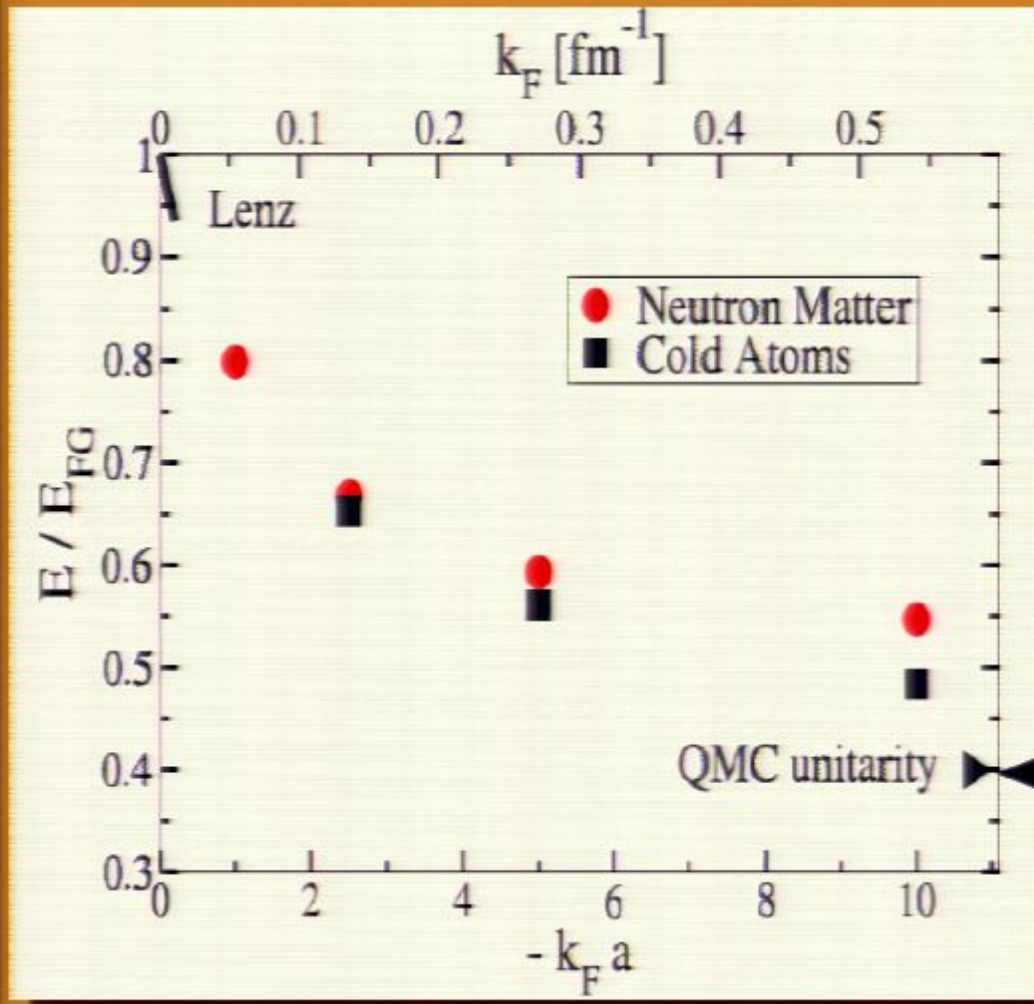


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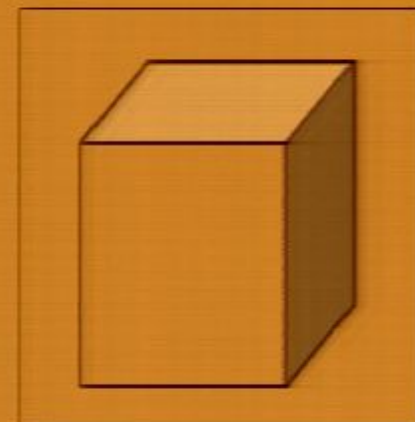


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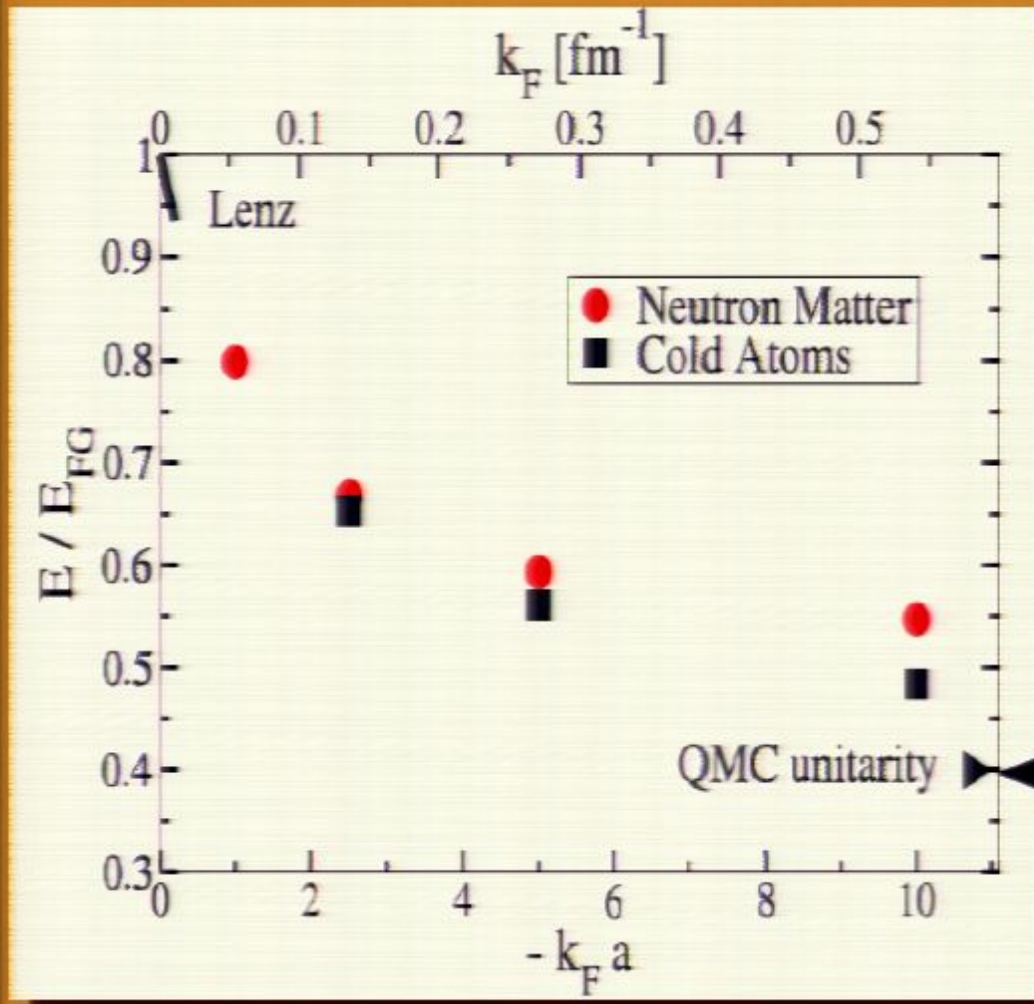


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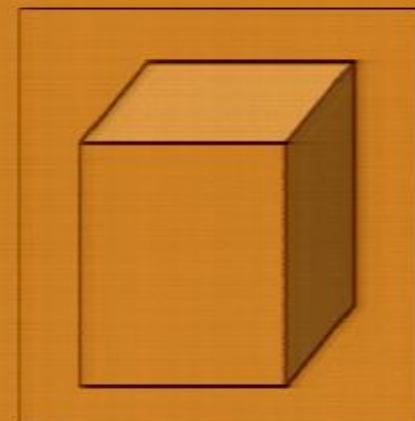


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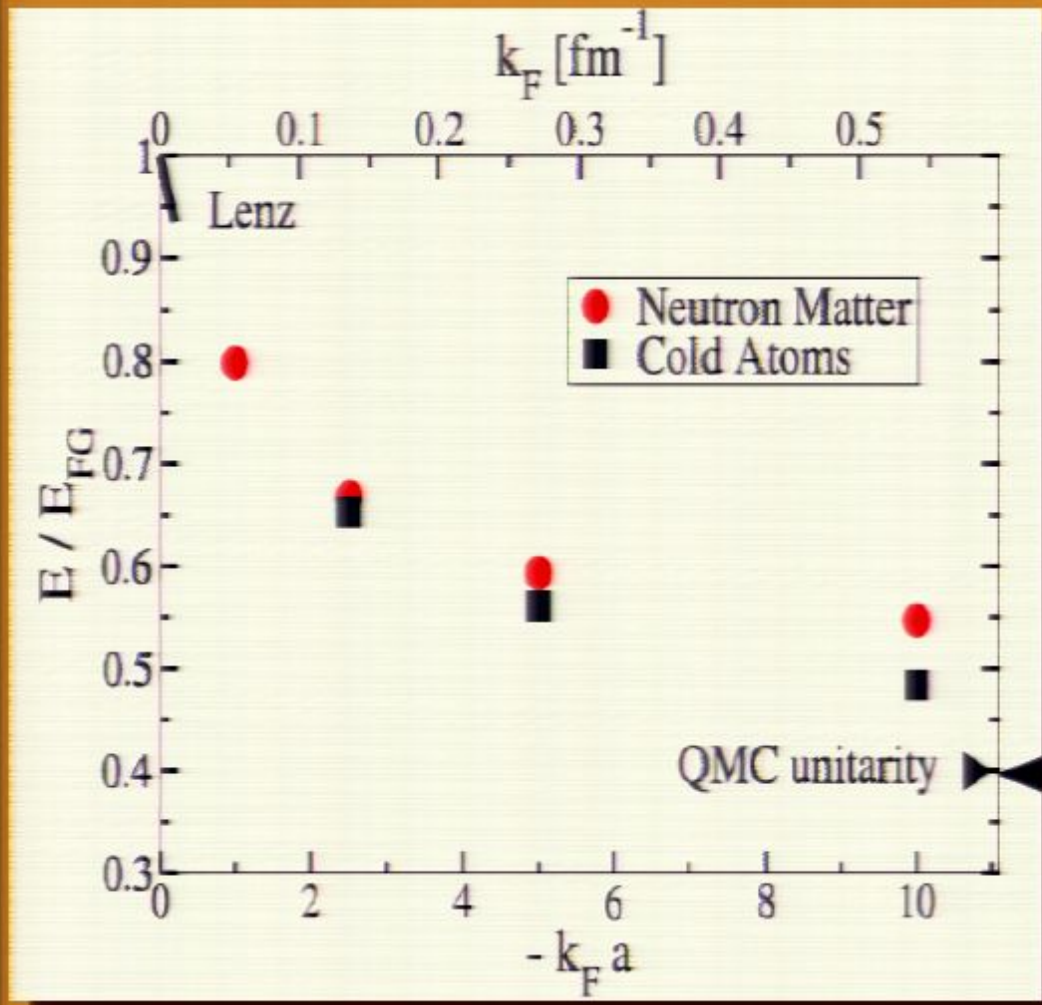


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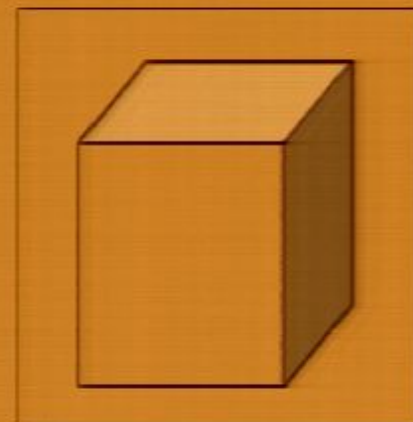


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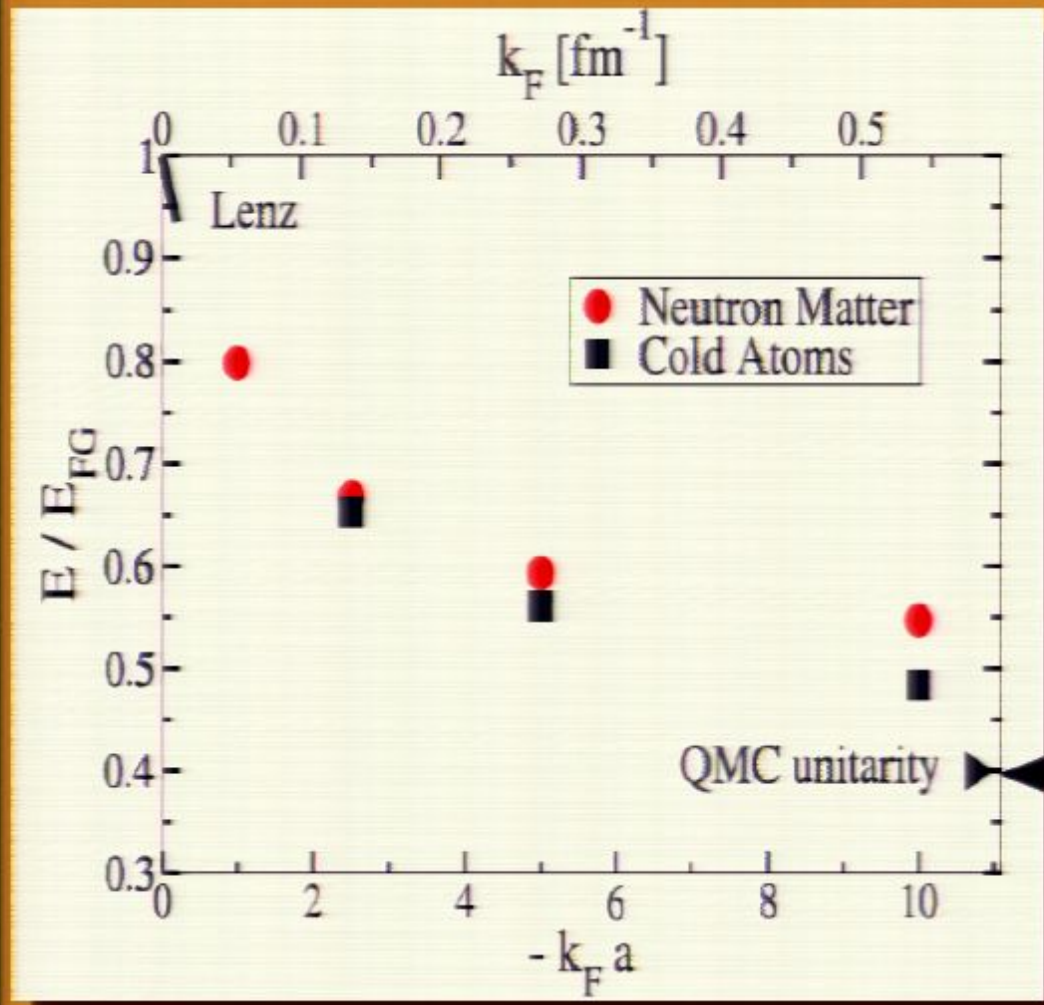


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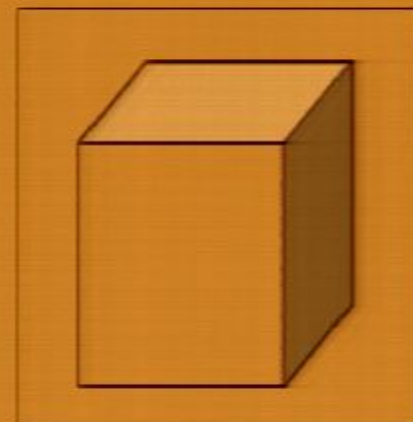


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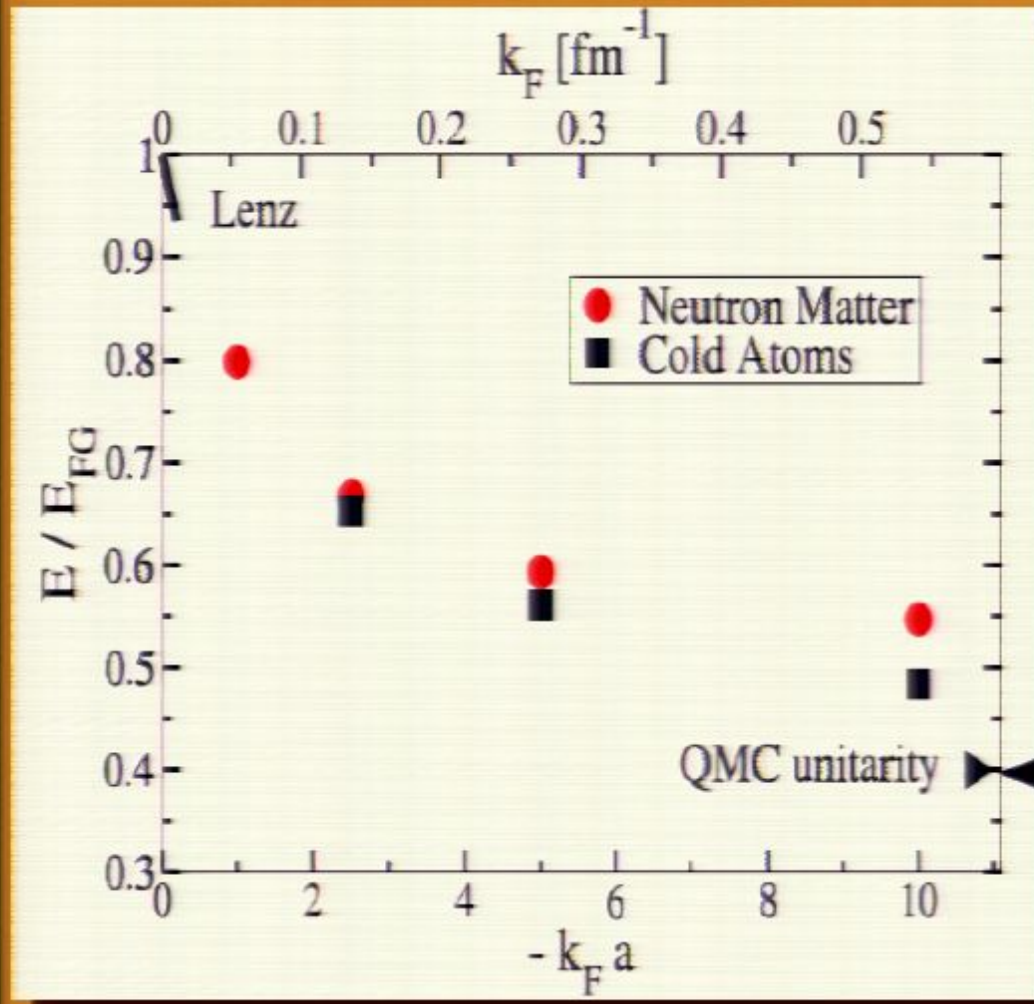


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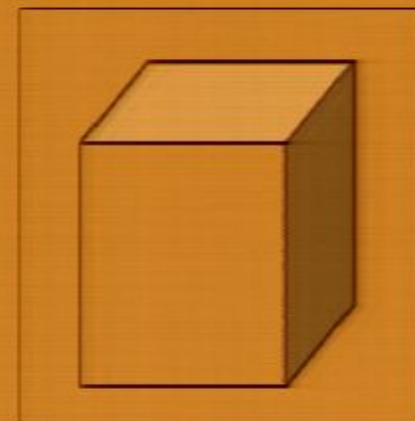


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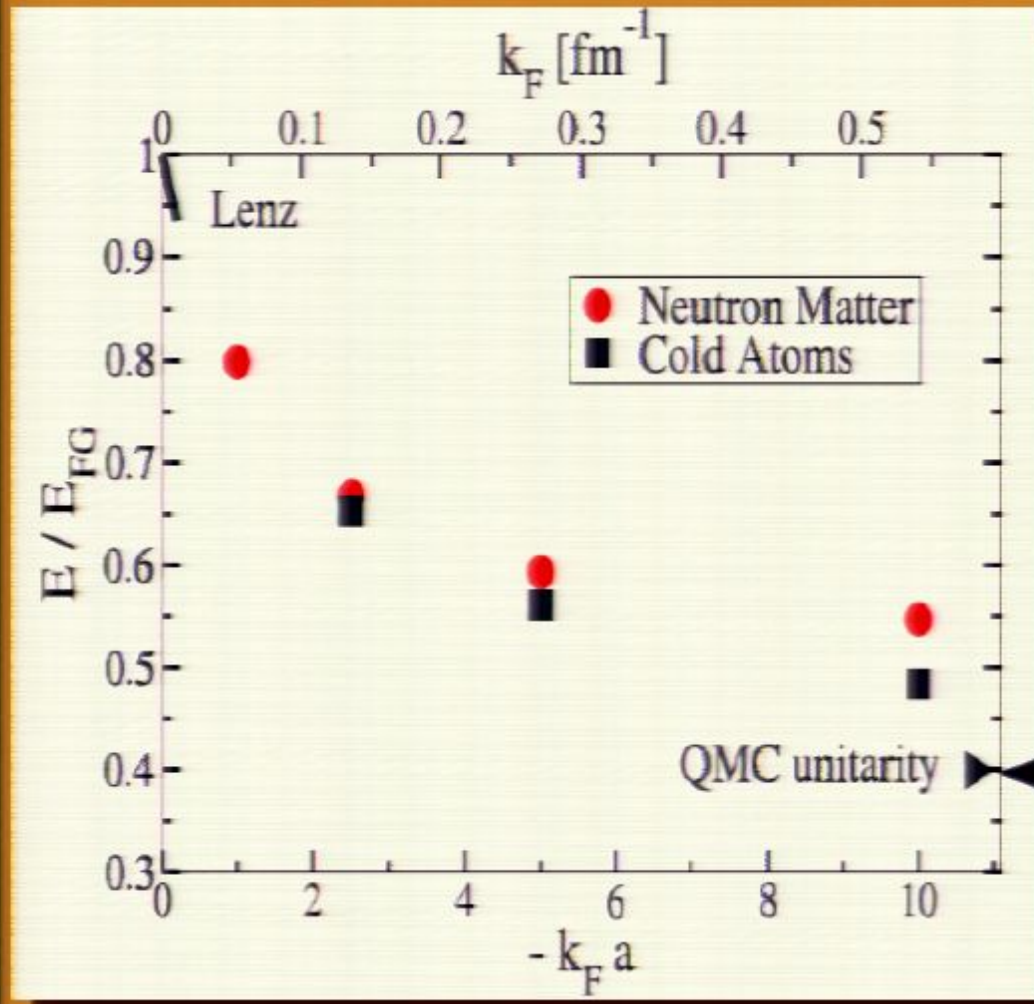


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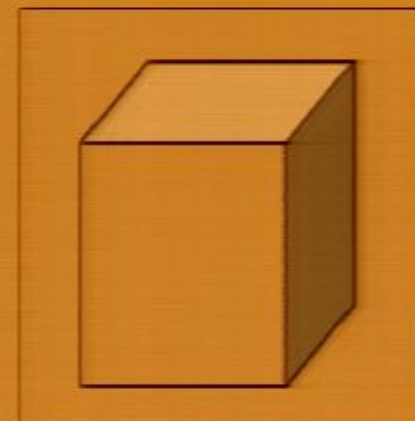


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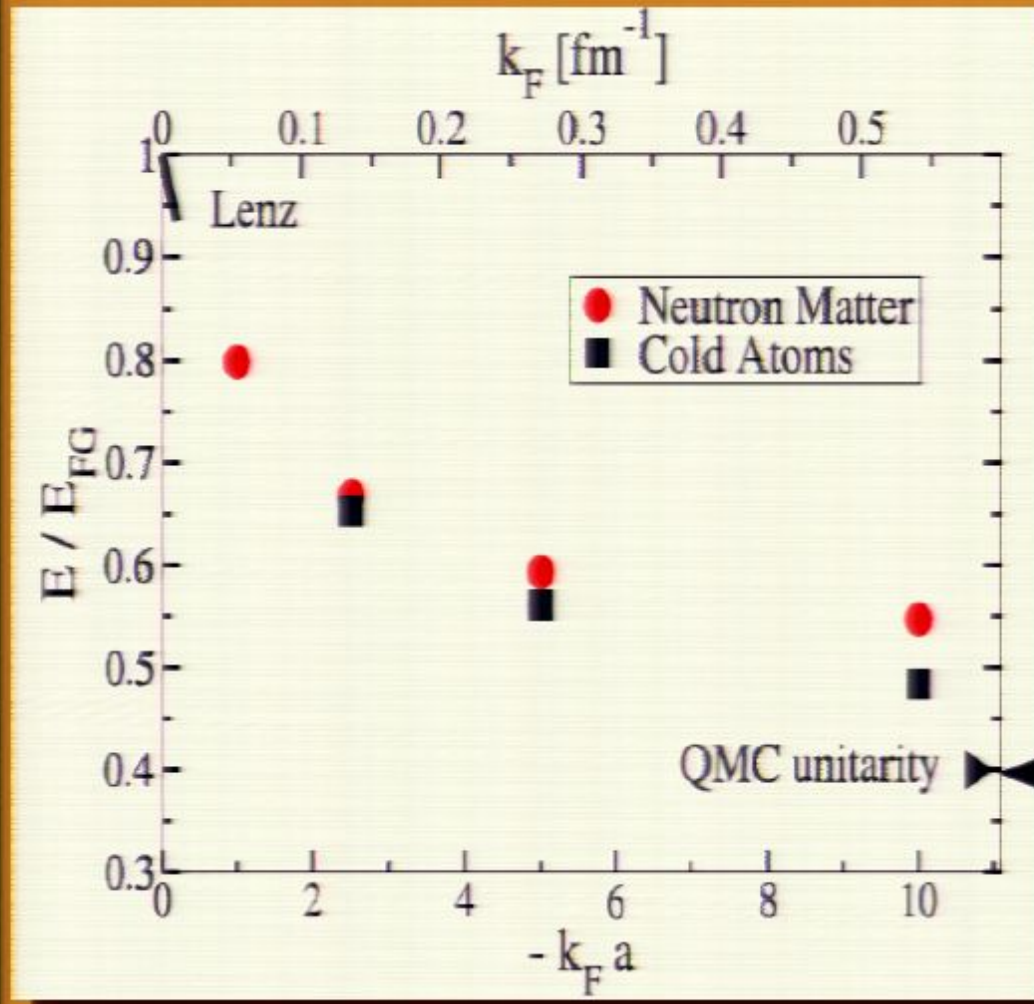


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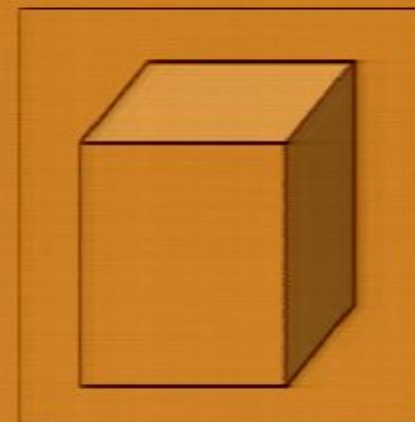


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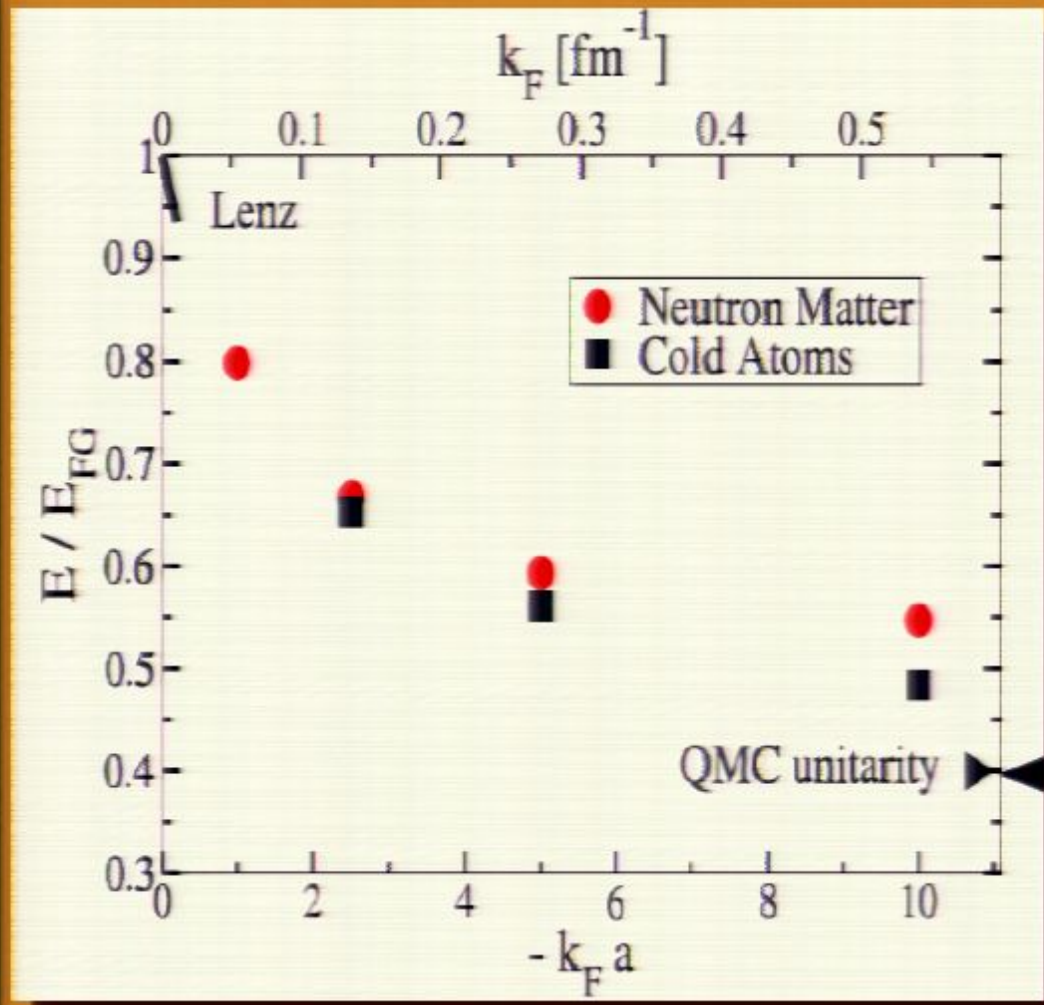


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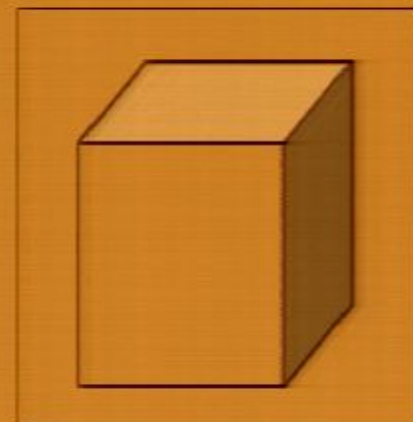


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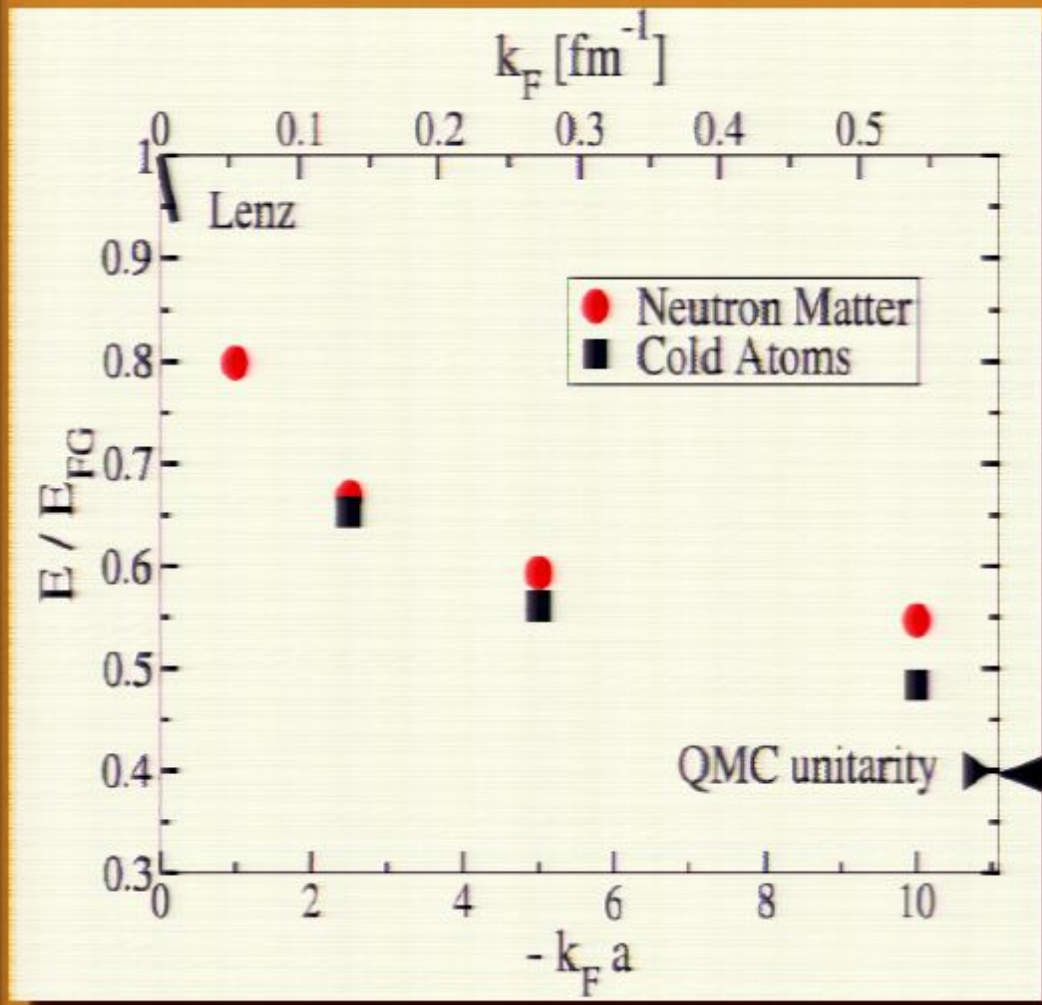


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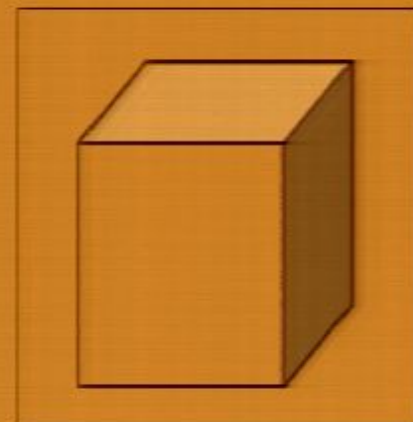


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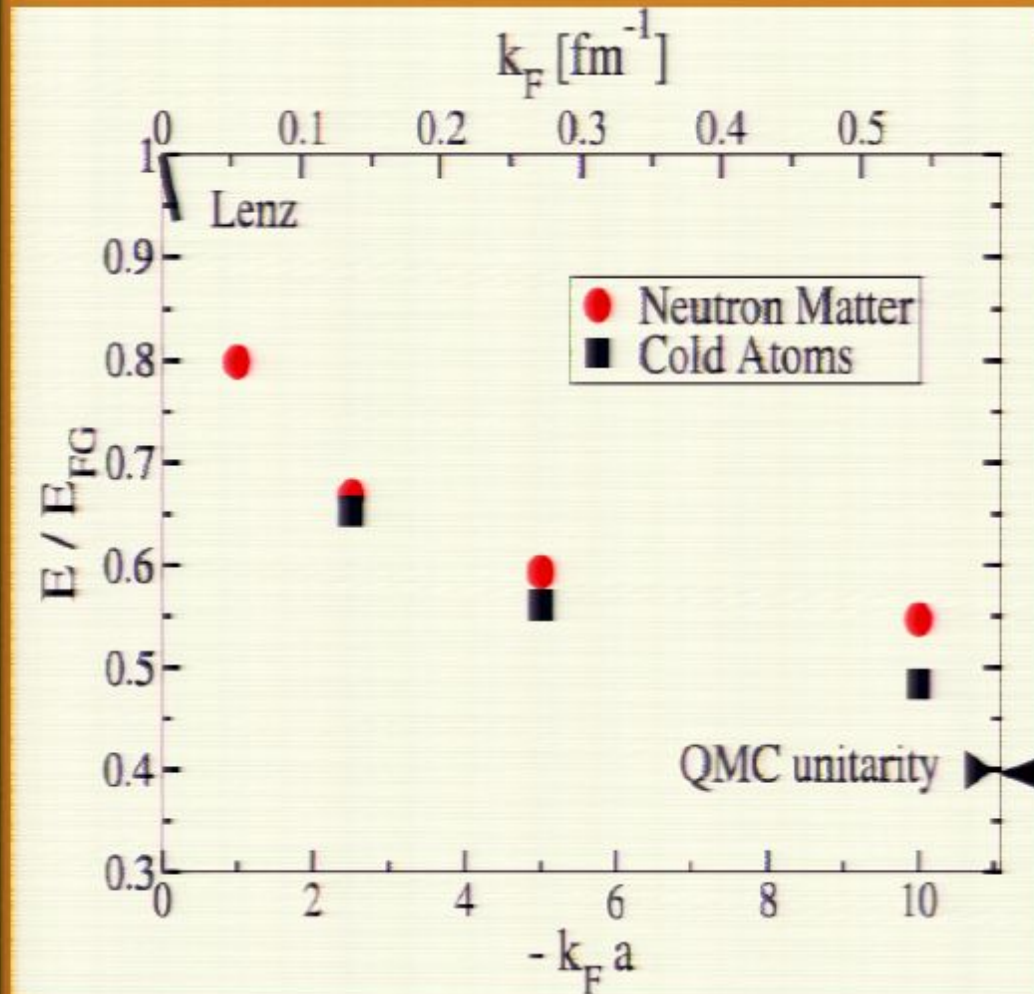


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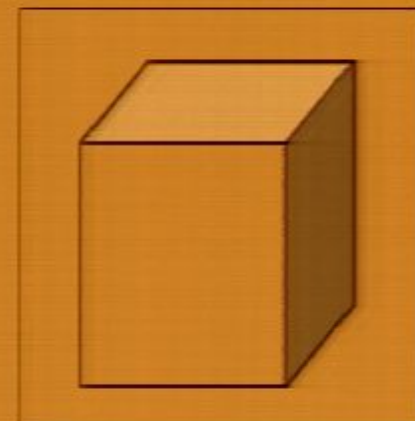


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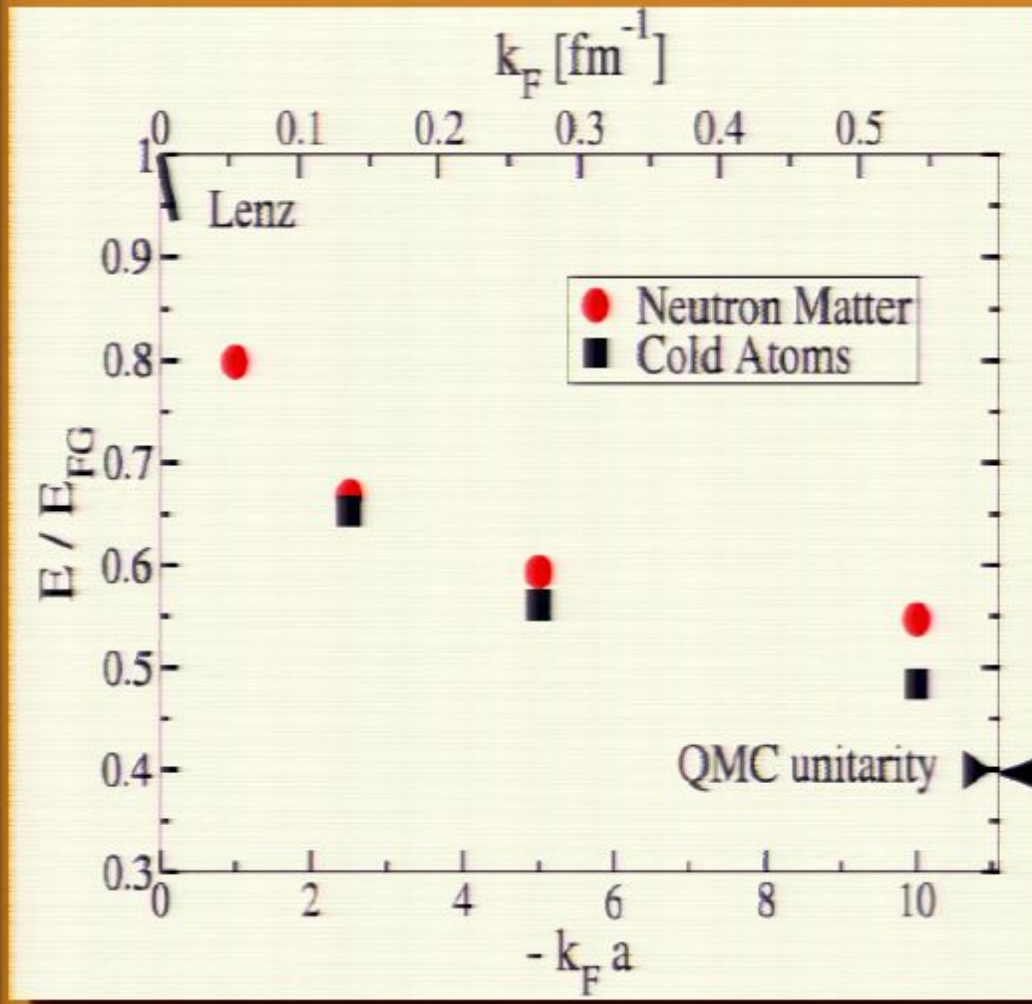


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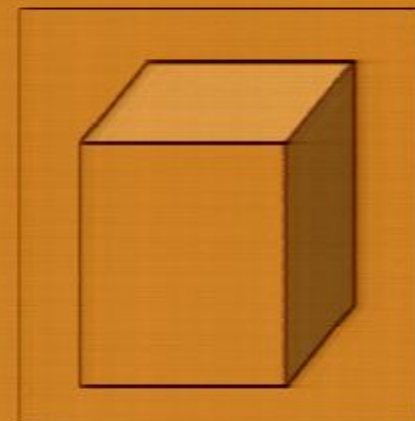


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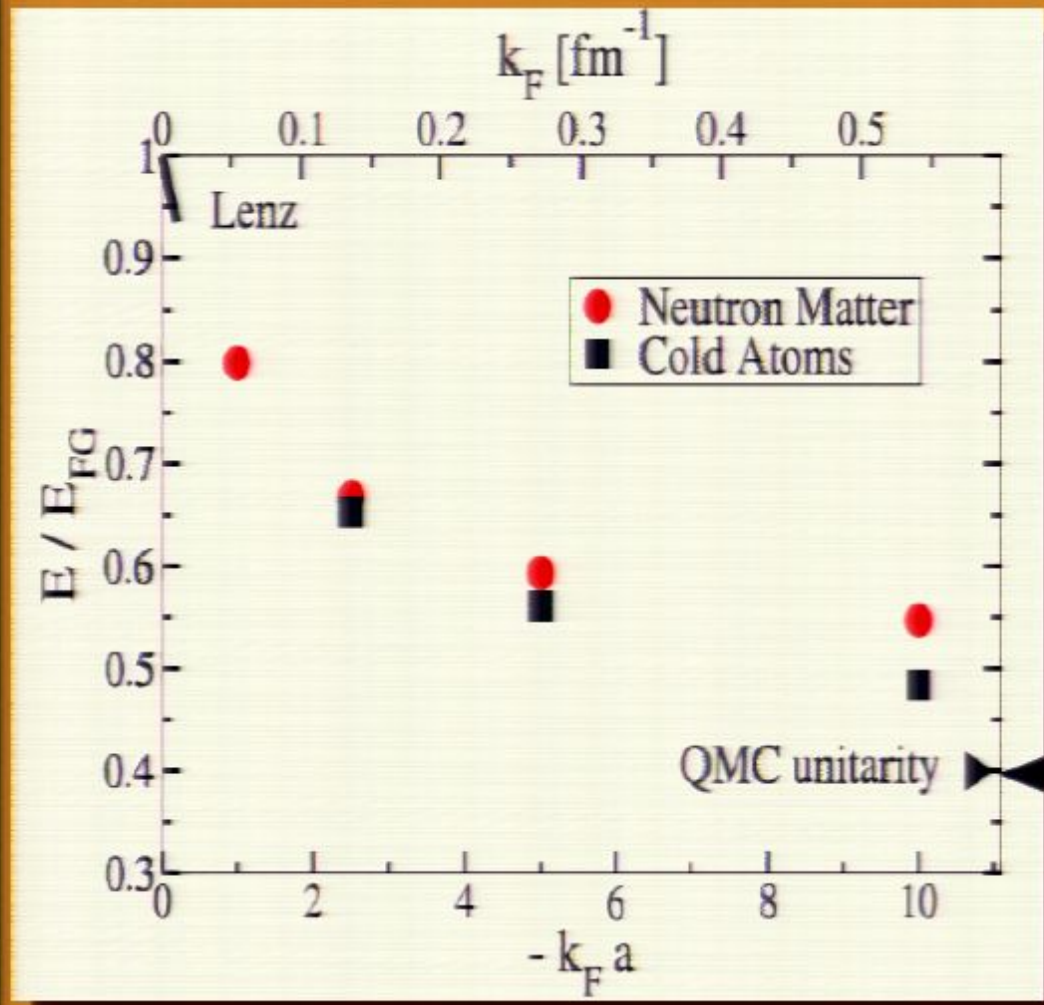


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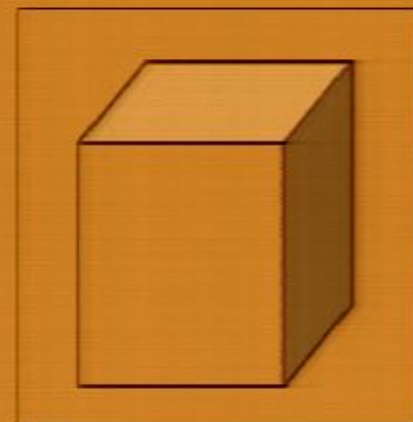


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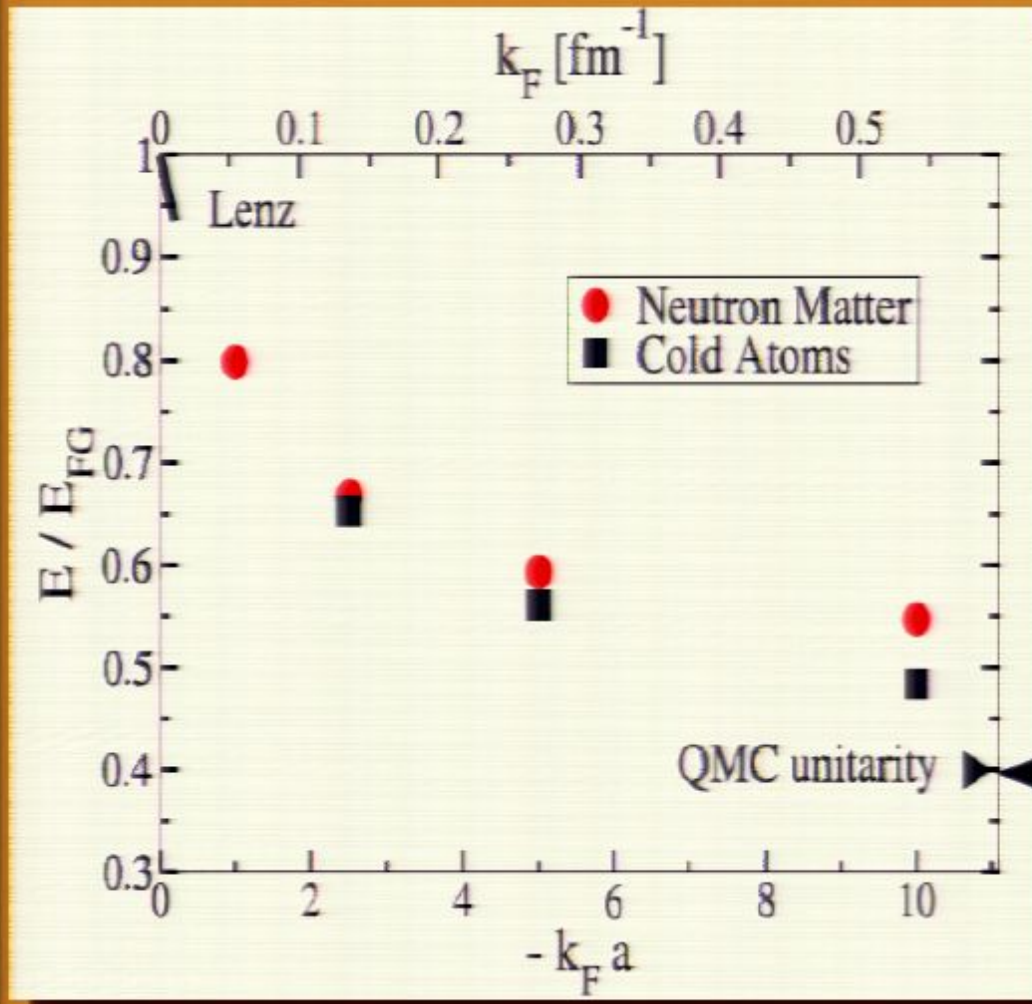


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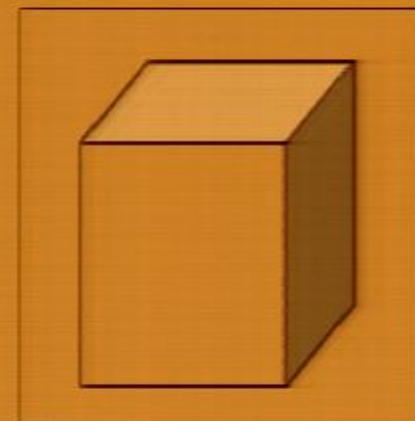


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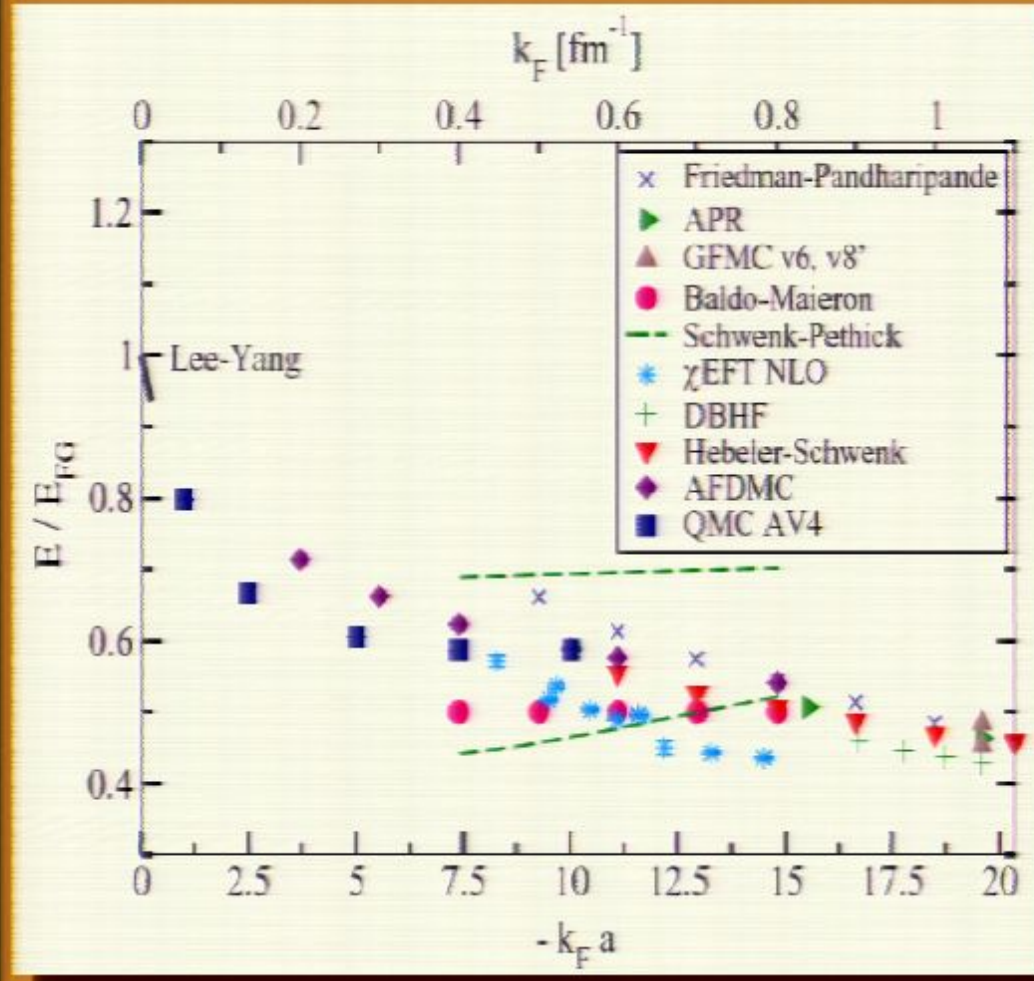


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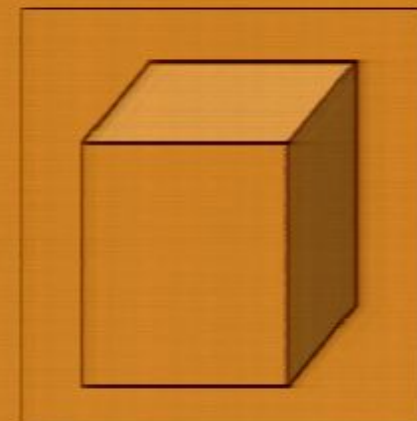


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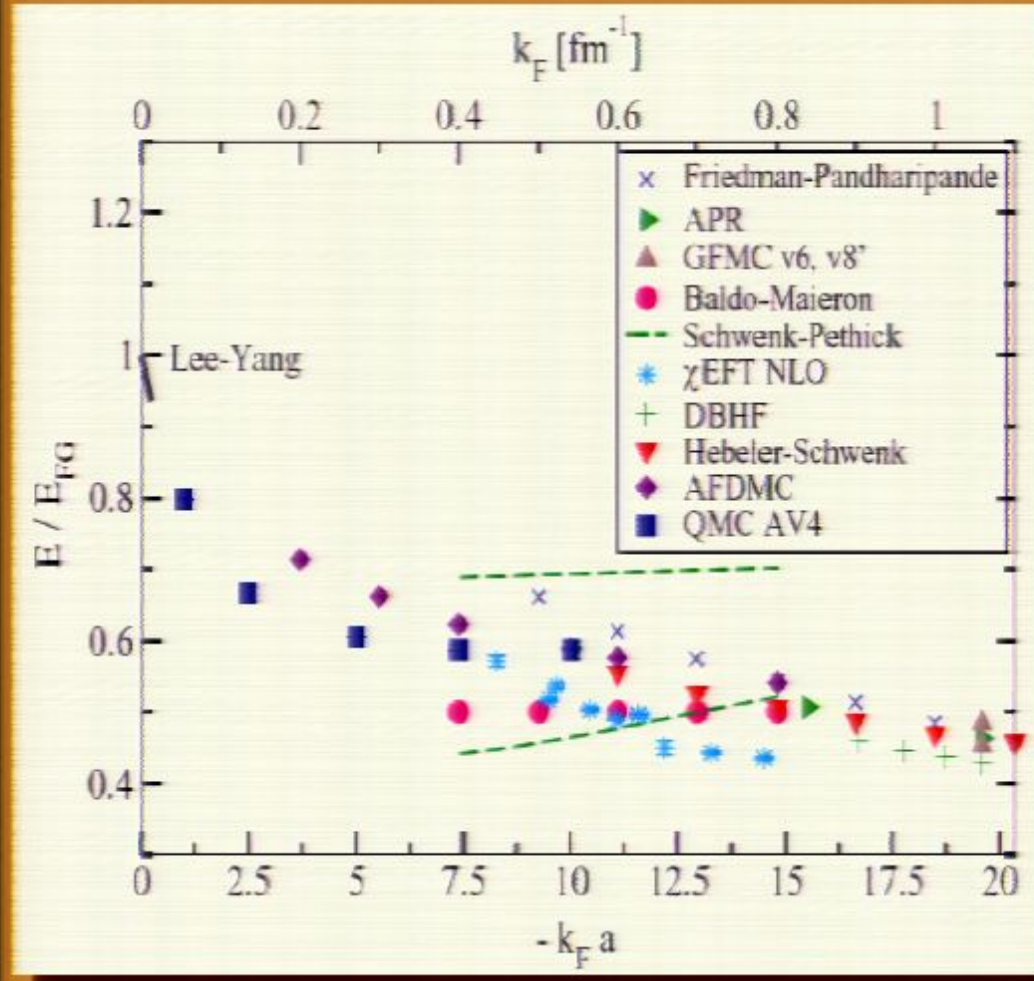
Equations of state: comparison



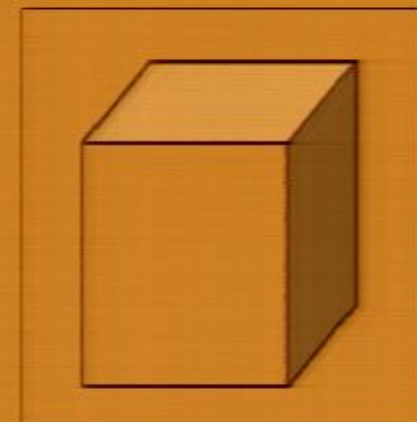
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- At higher densities all calculations are in qualitative agreement



Equations of state: comparison

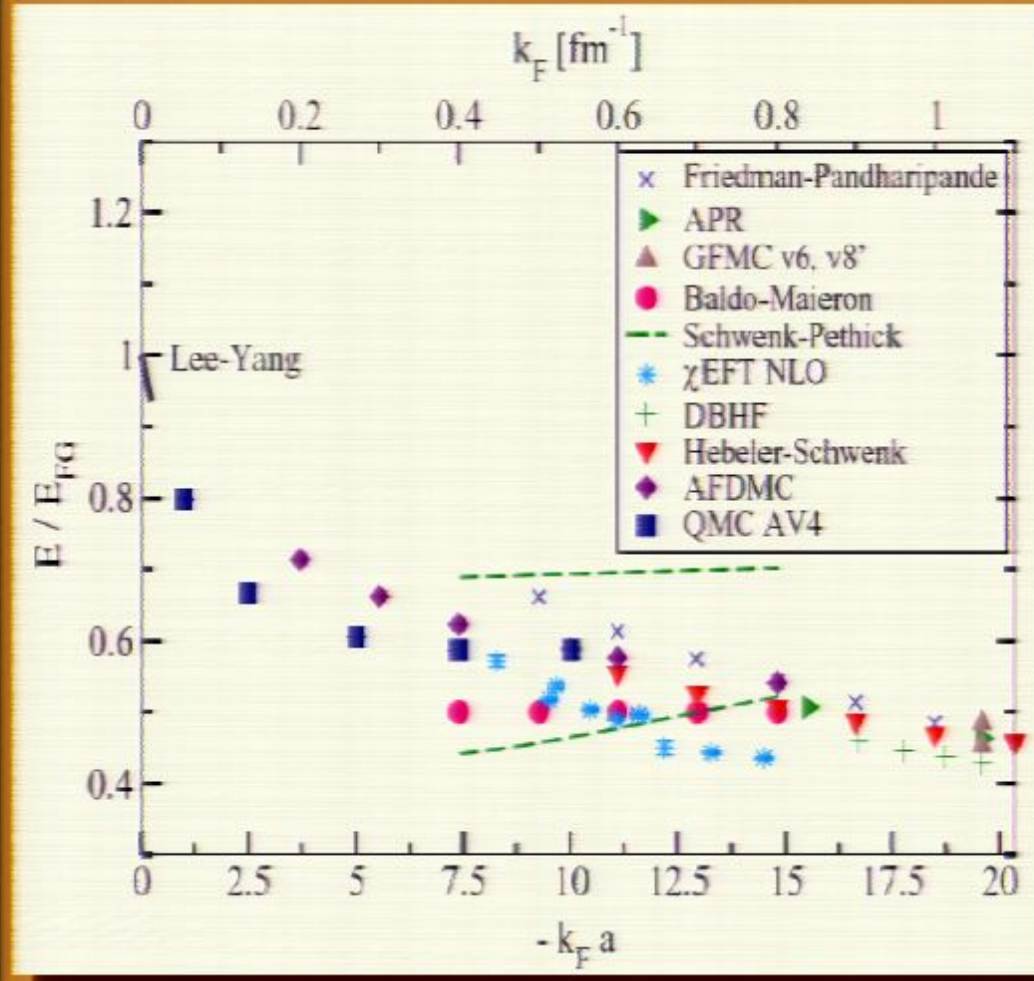


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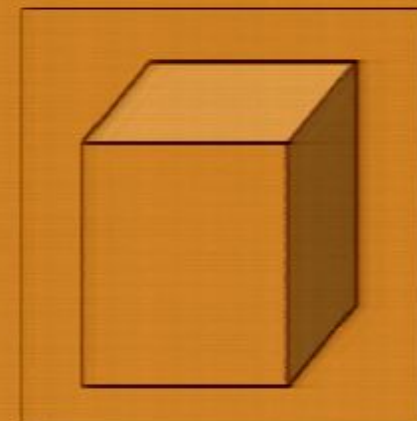


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Equations of state: comparison

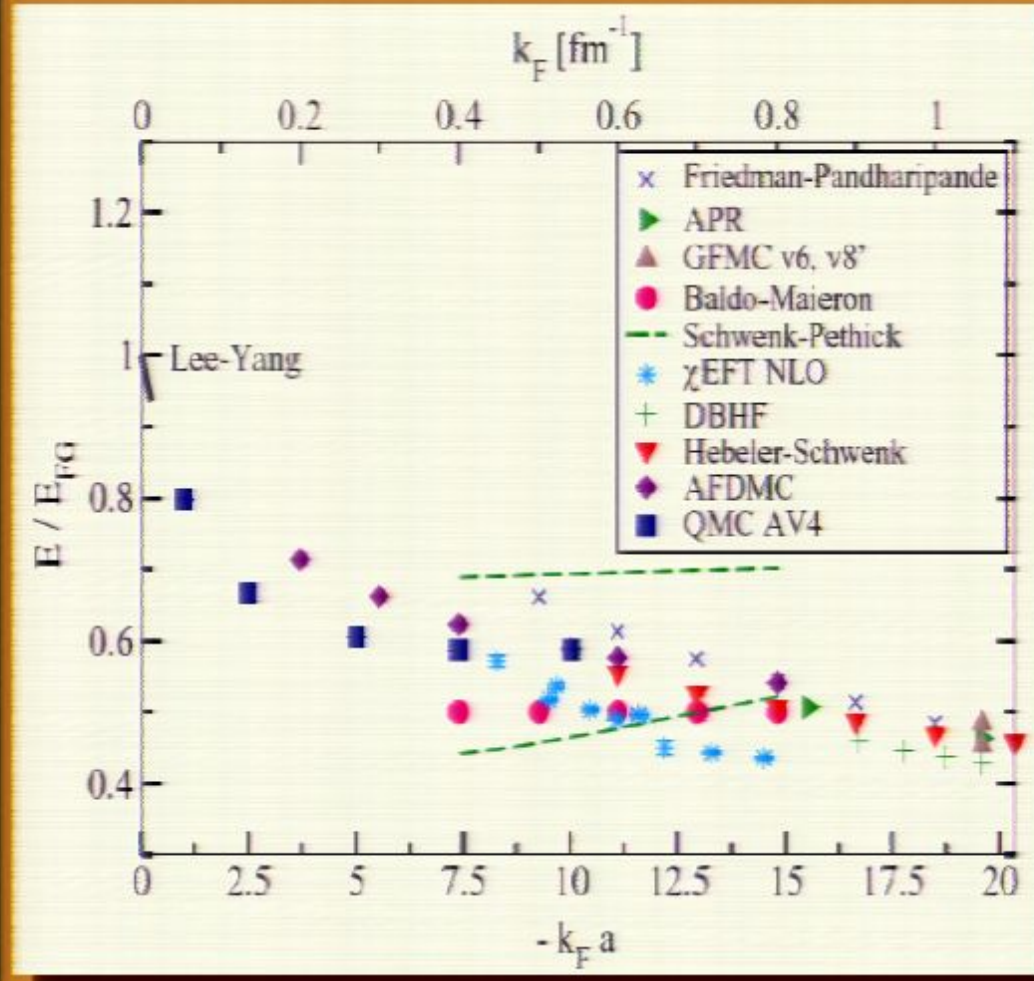


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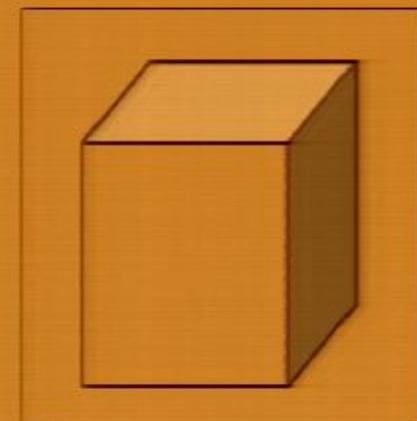


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Equations of state: comparison

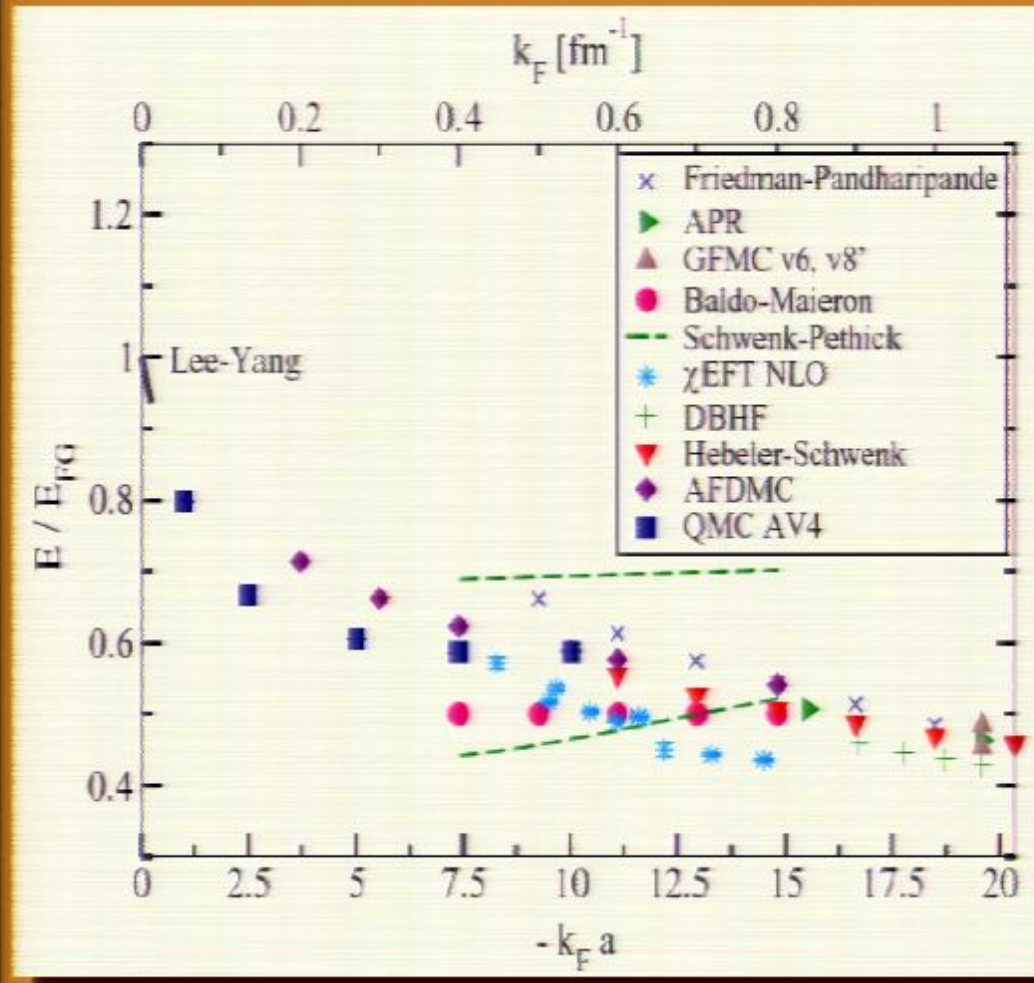


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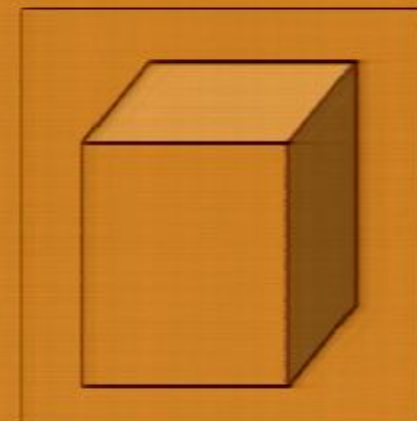


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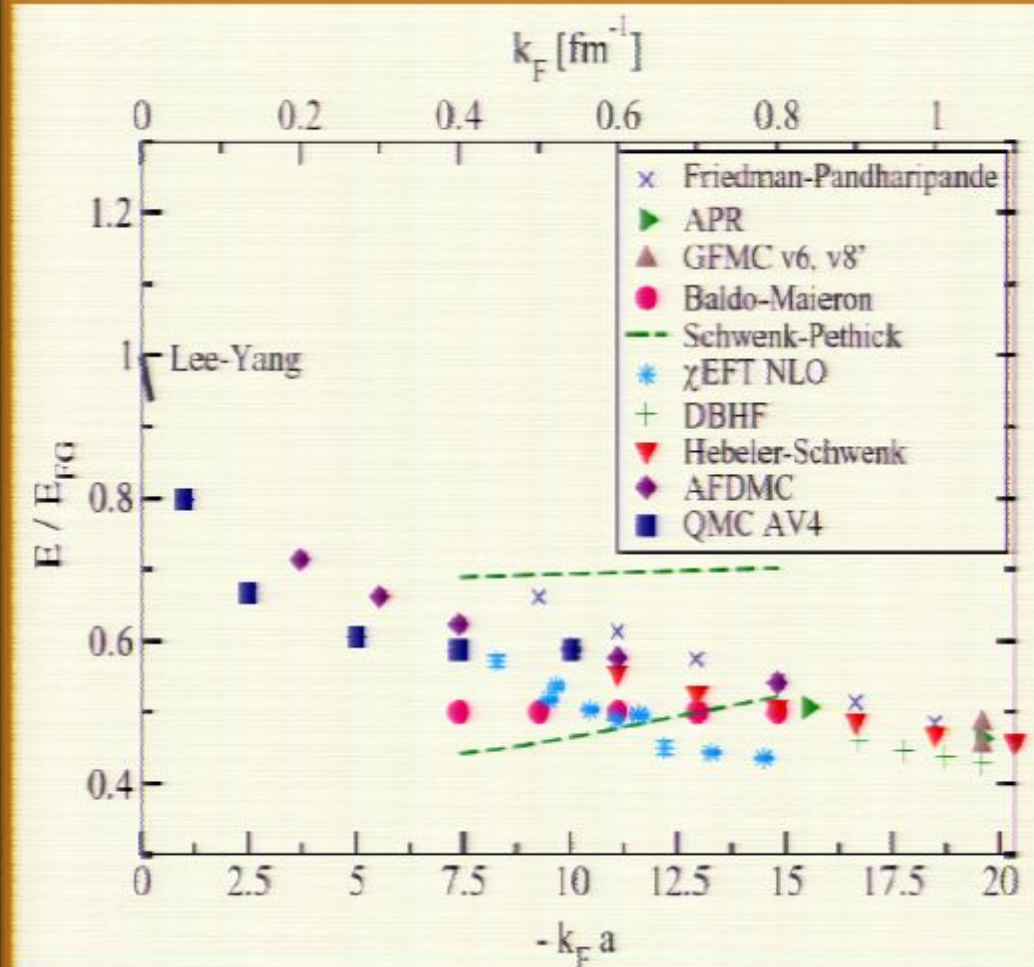


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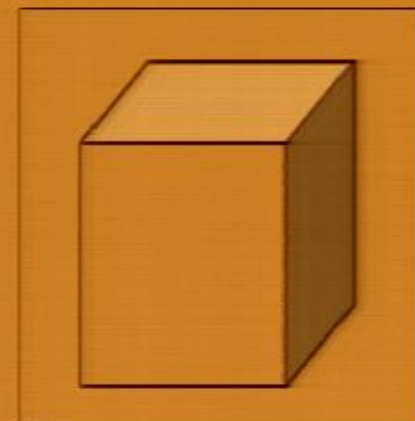


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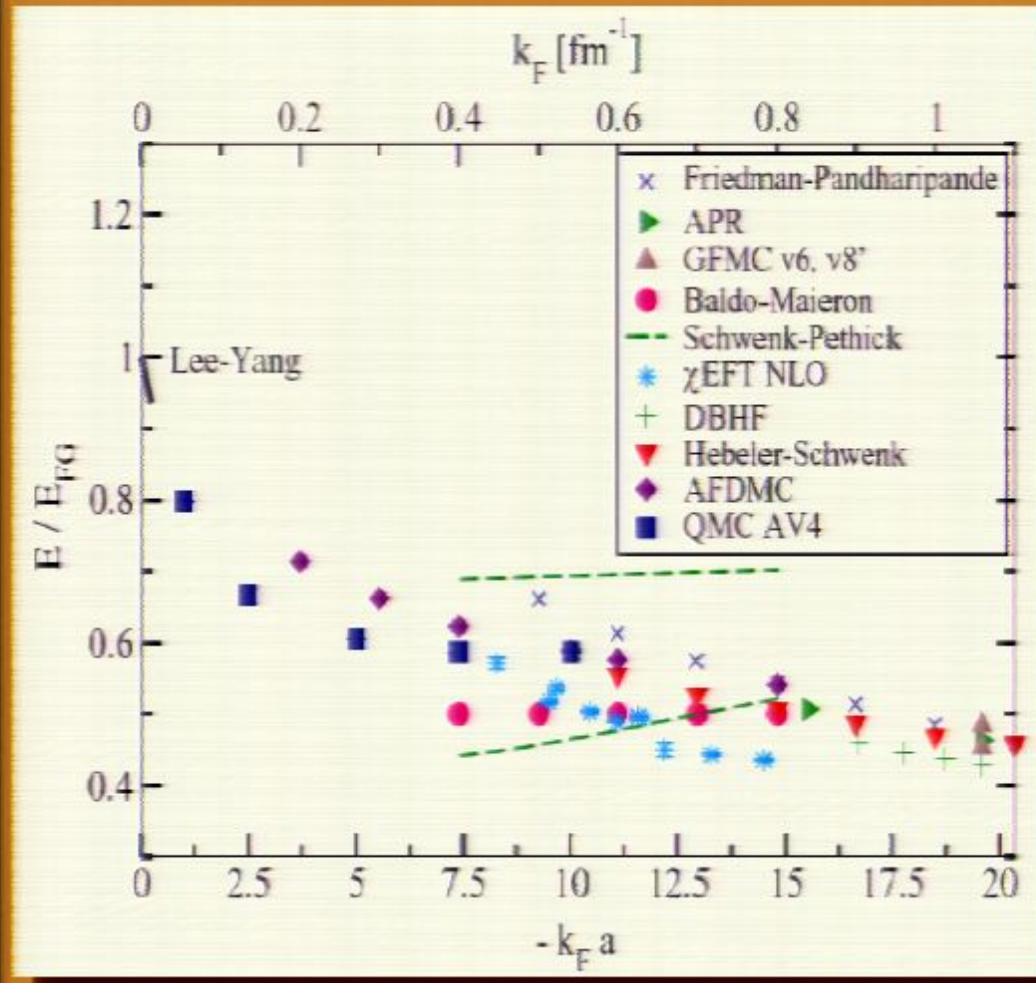


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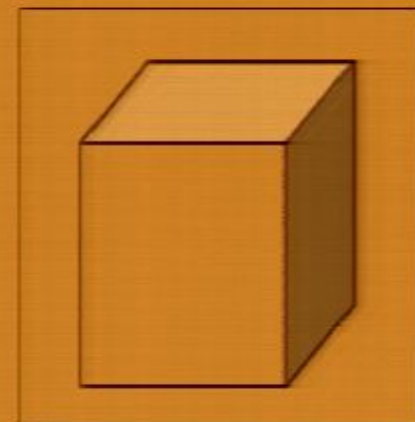


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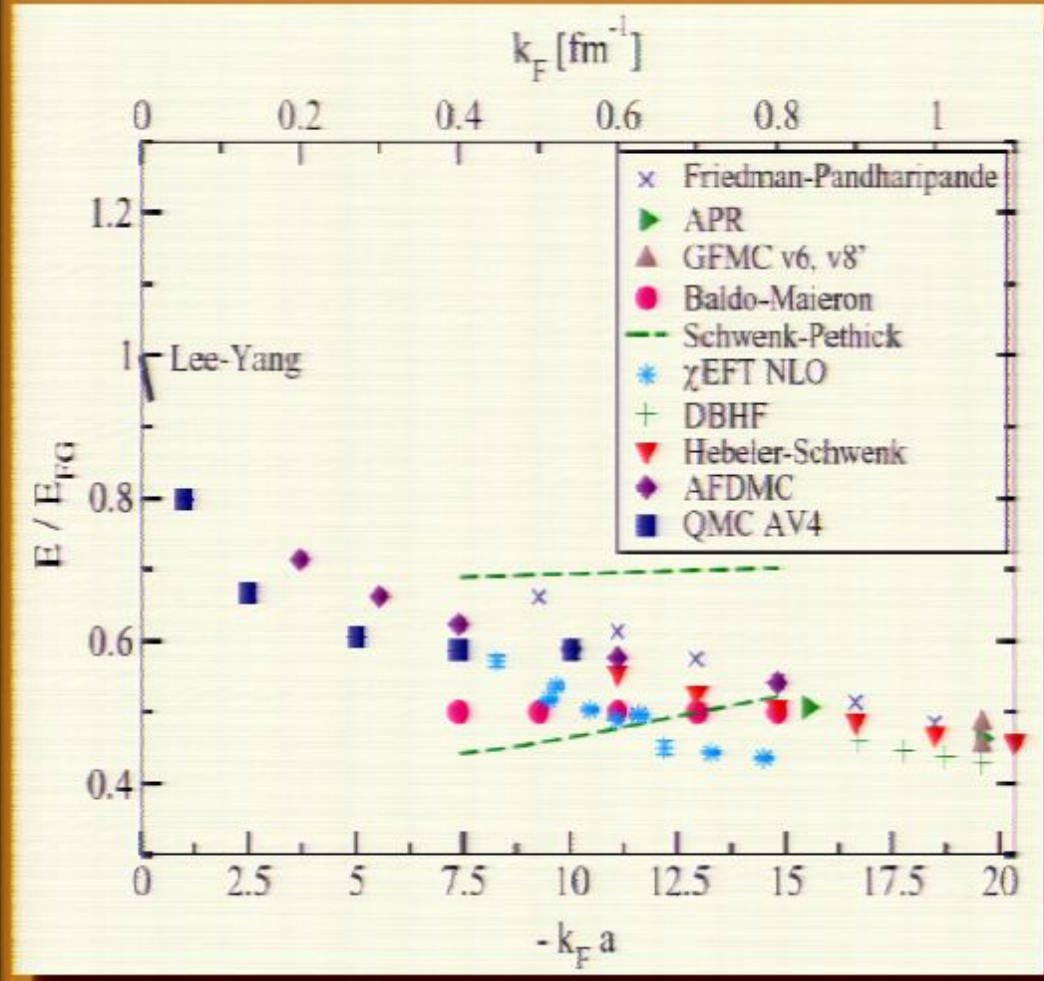


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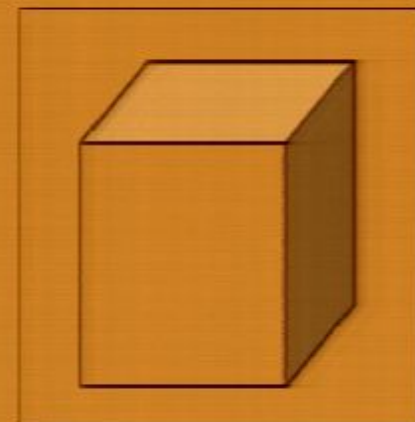


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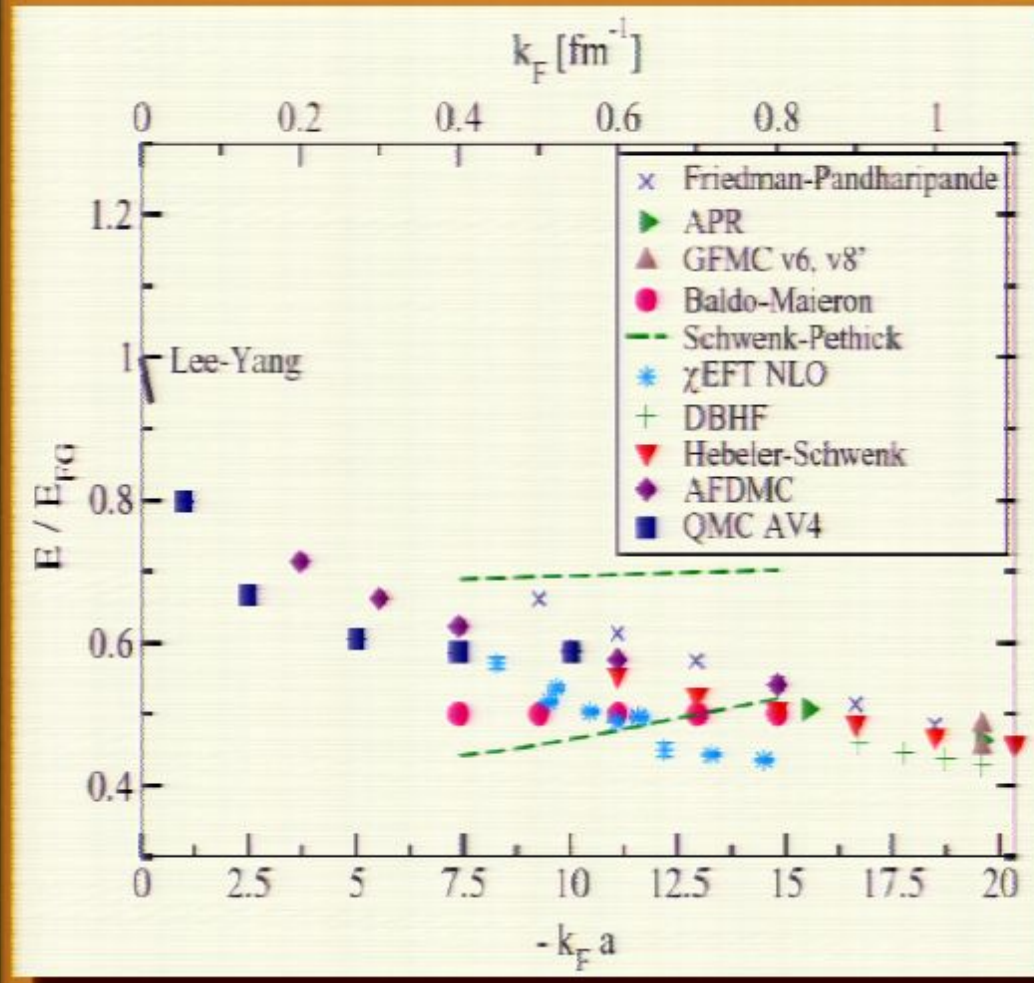


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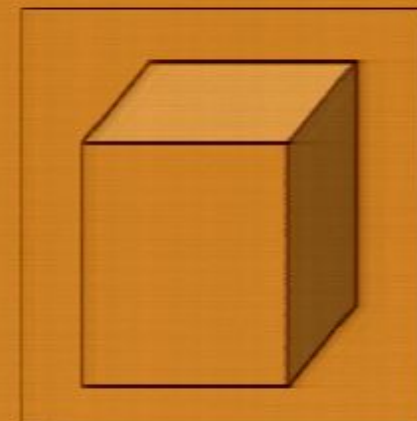


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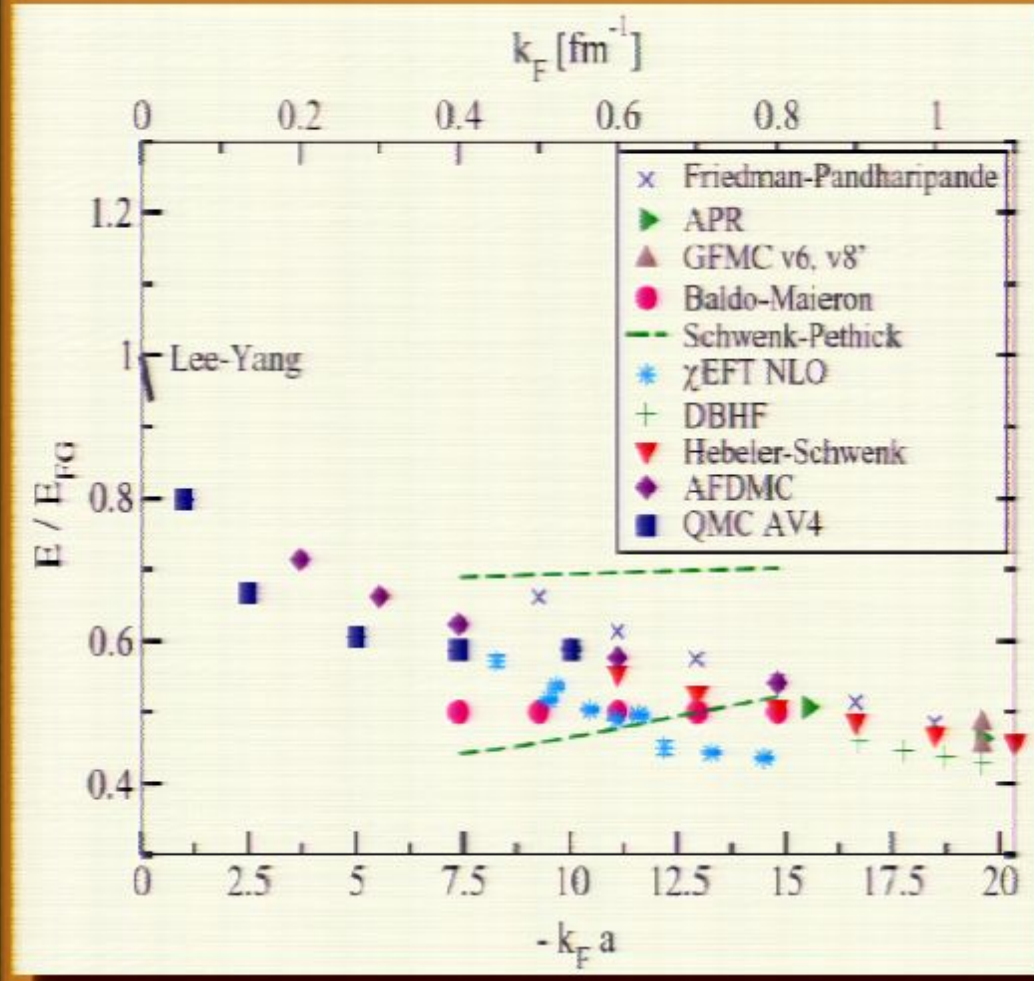


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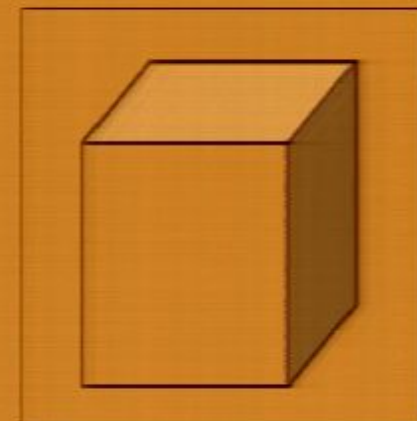


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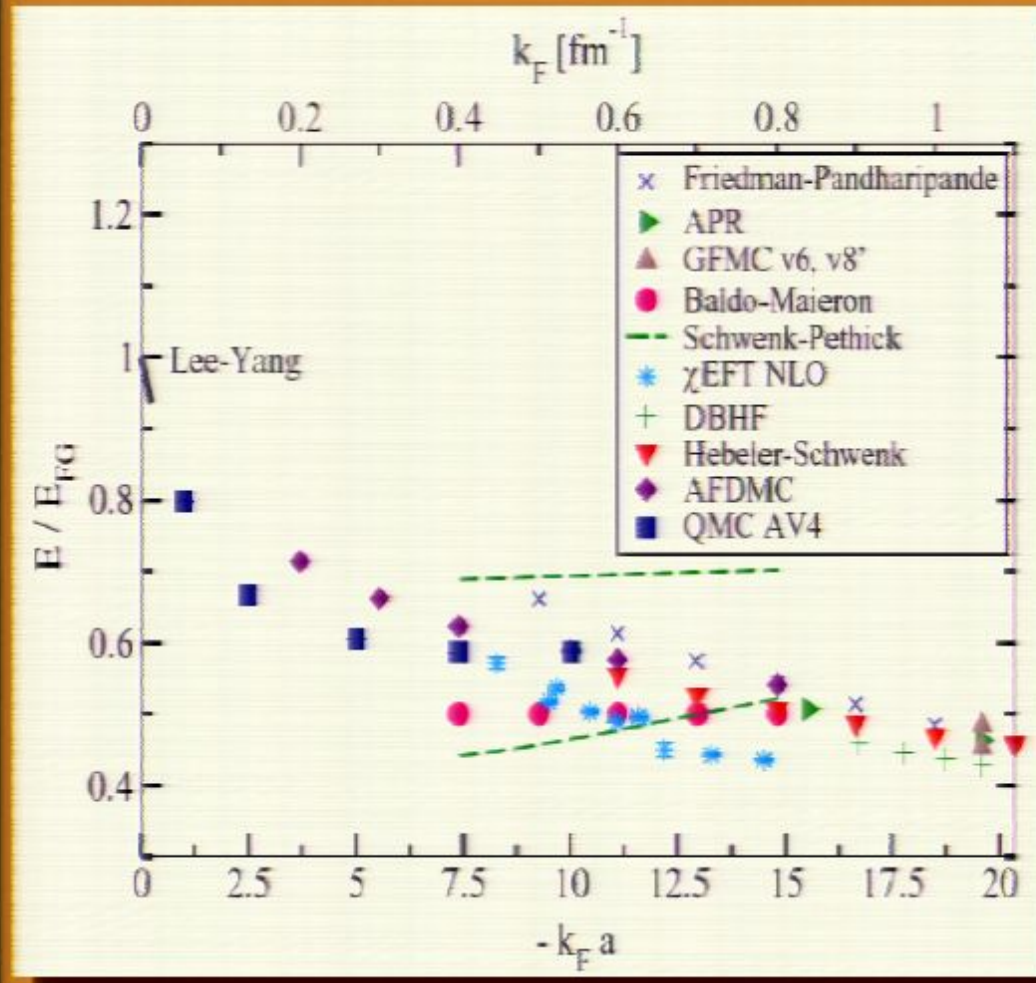


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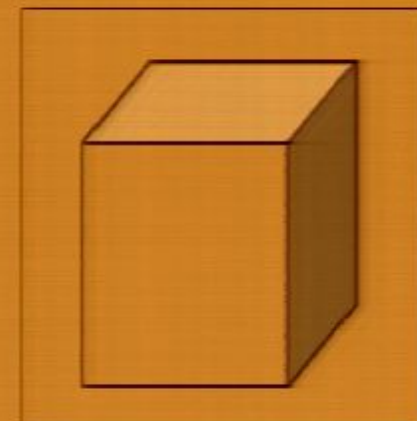


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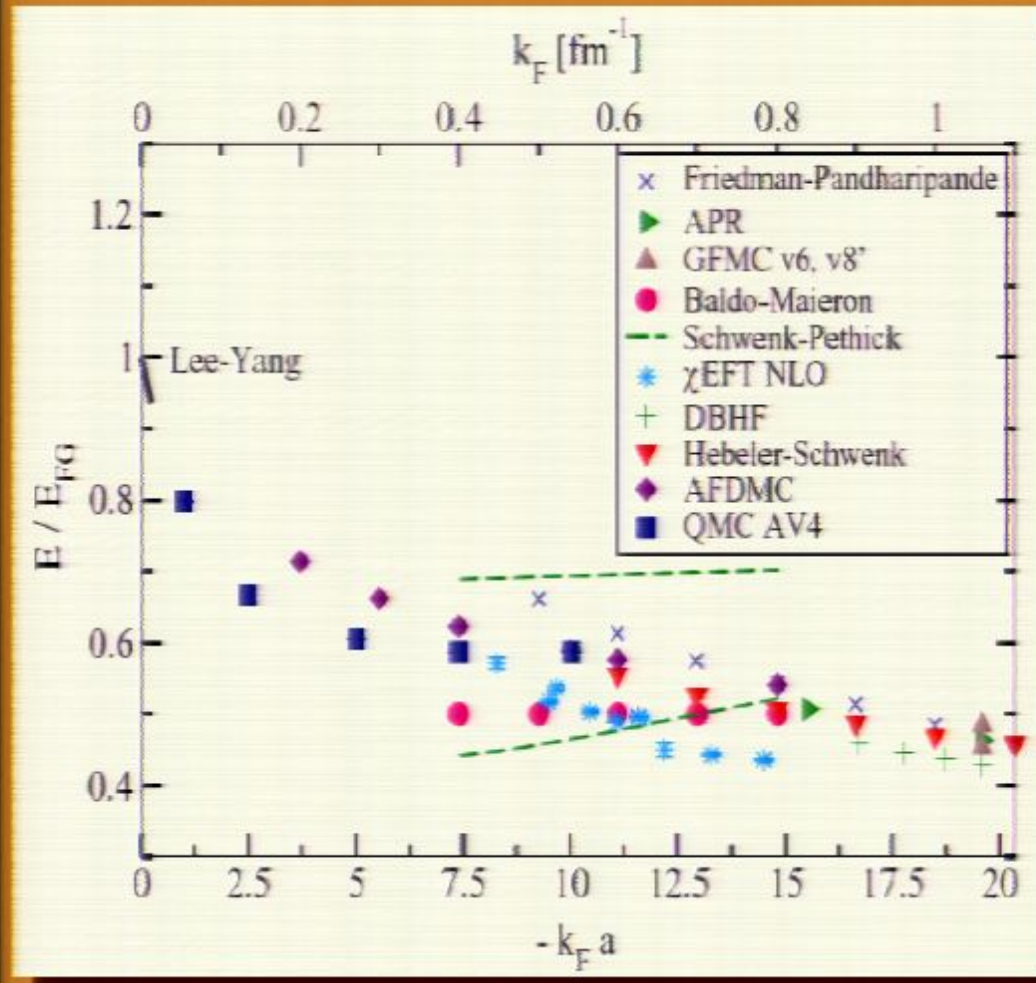


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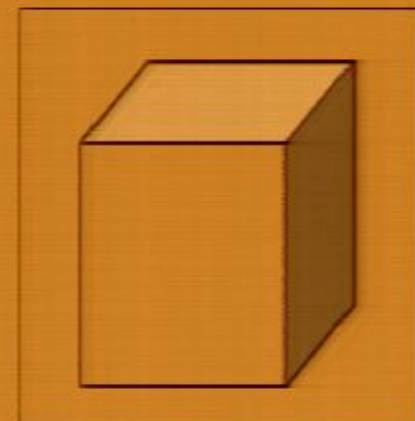


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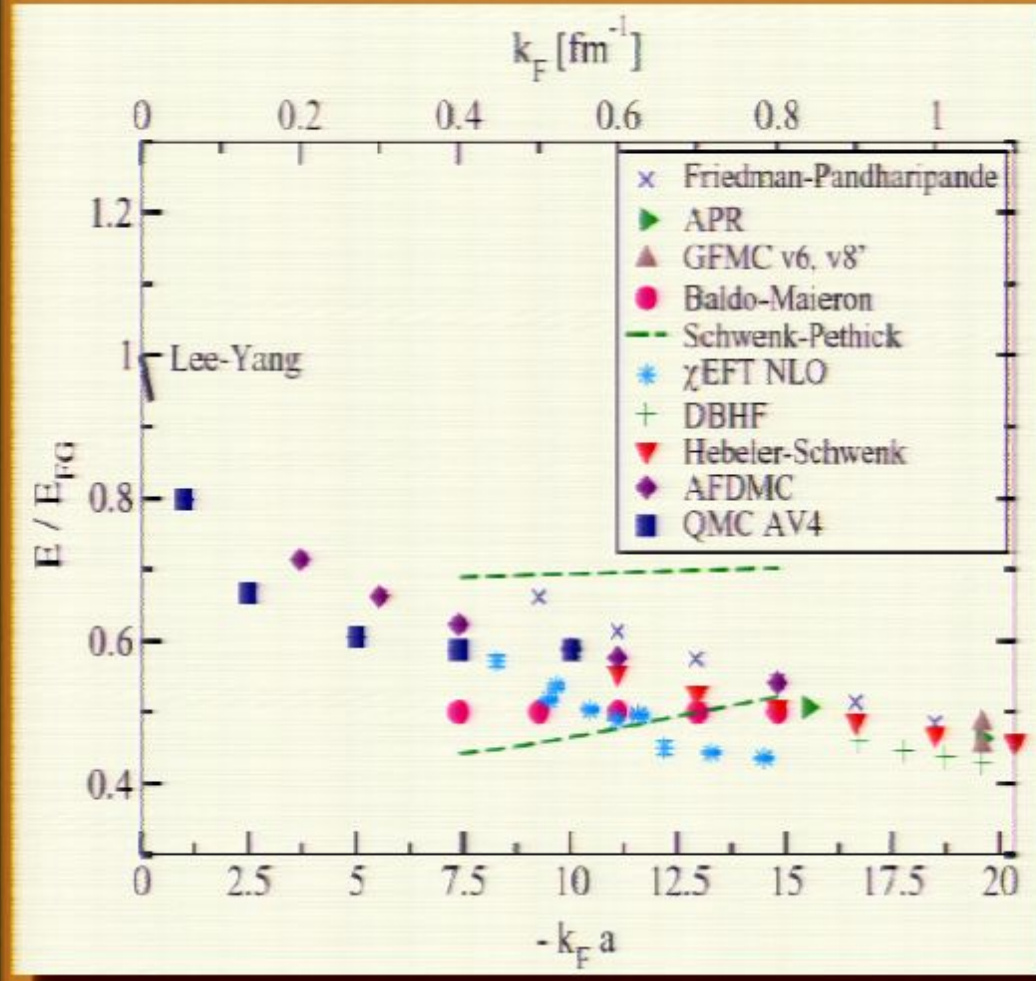


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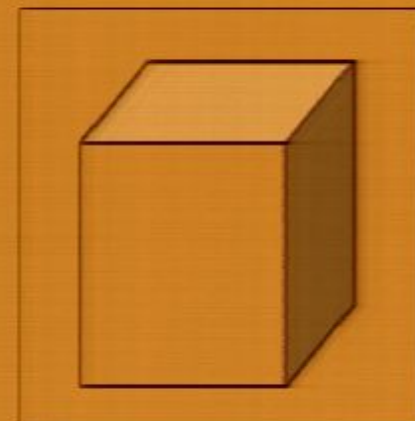


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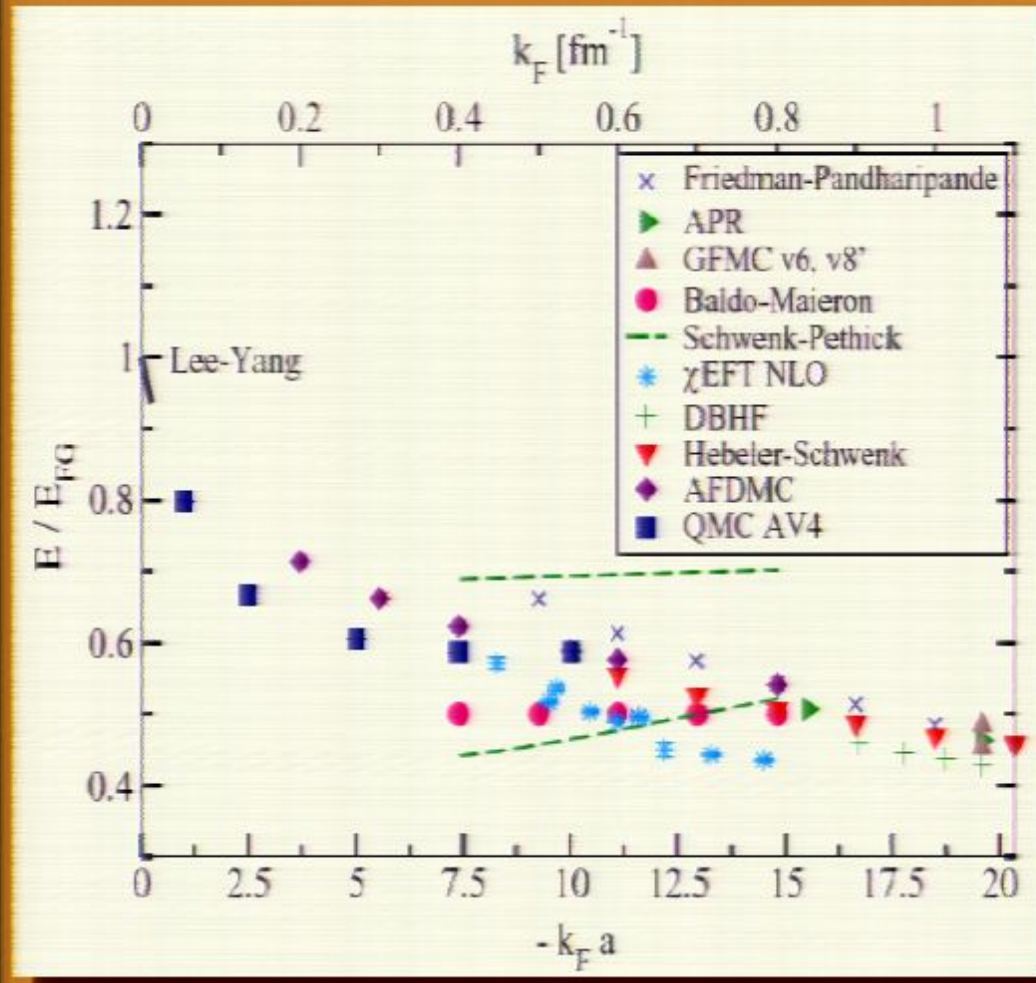


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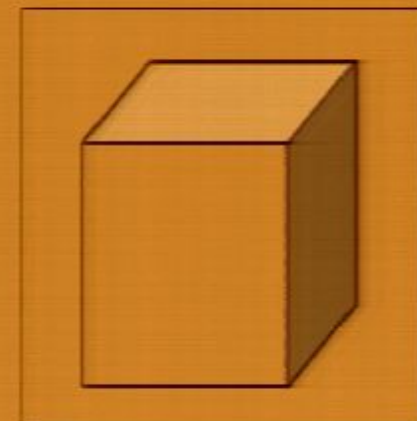


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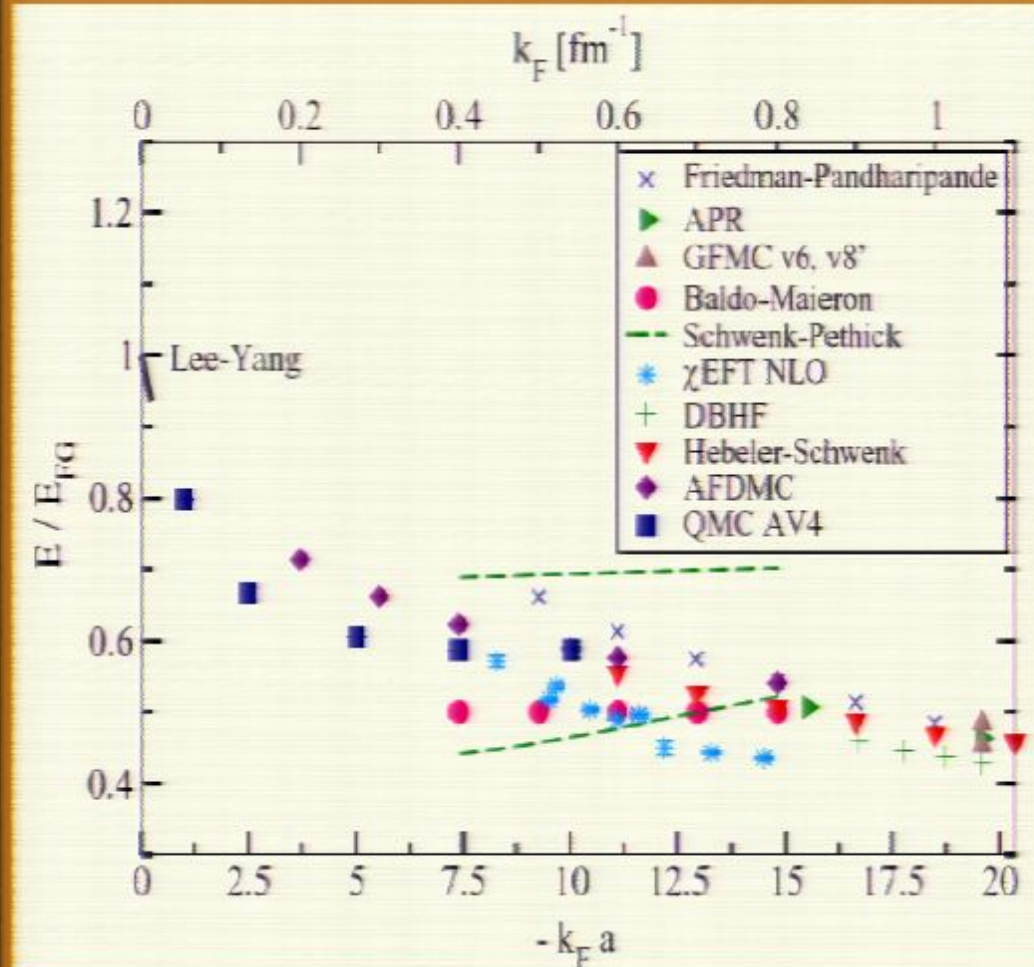


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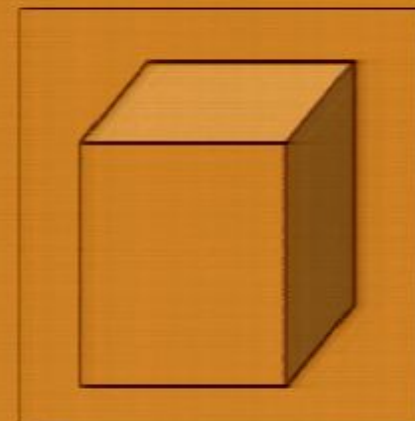


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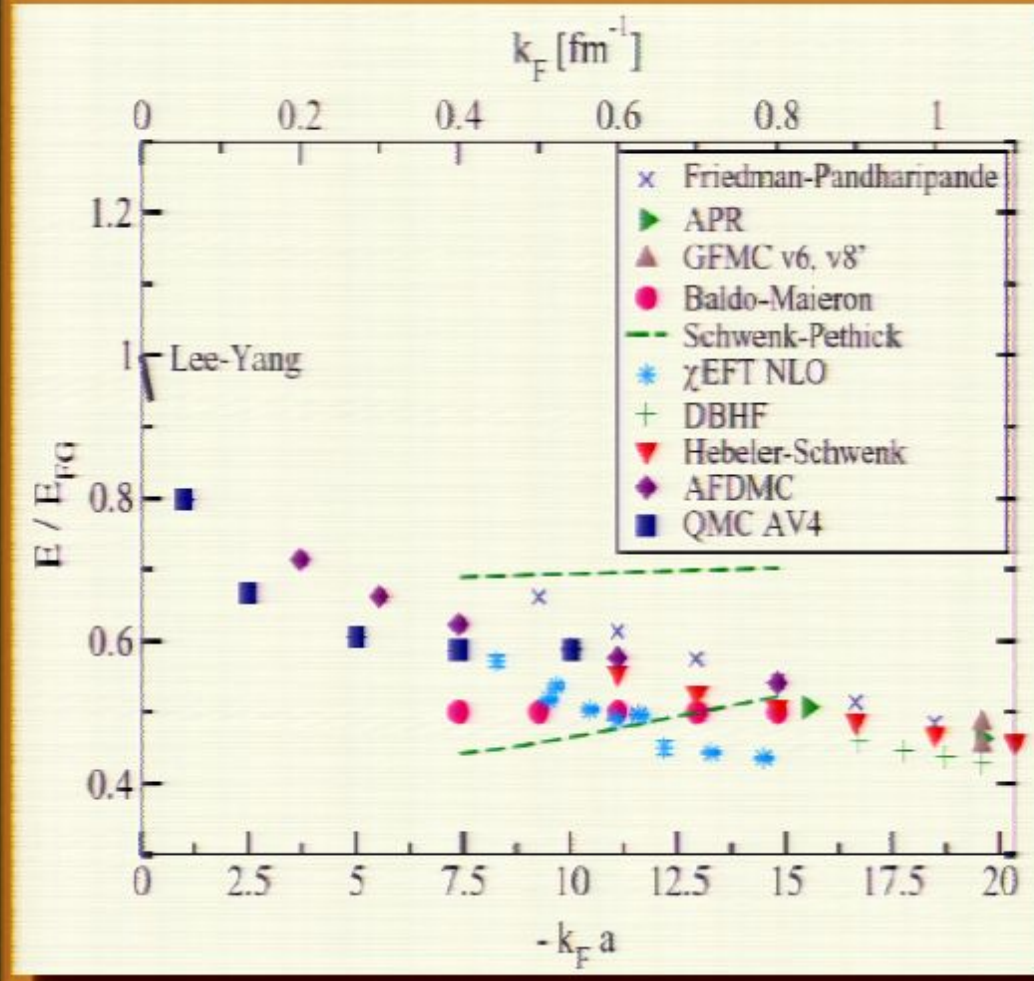
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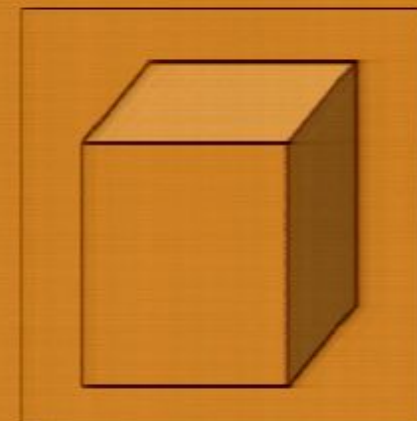
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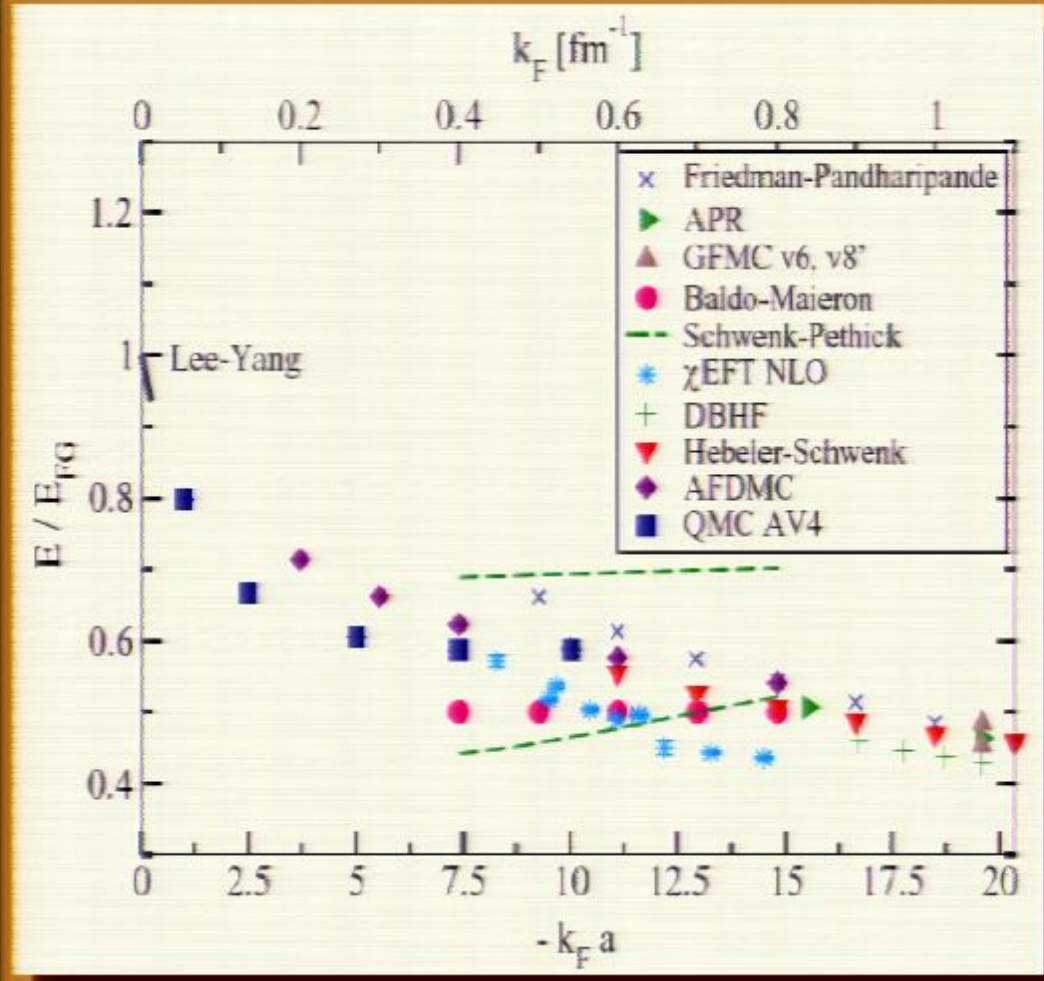


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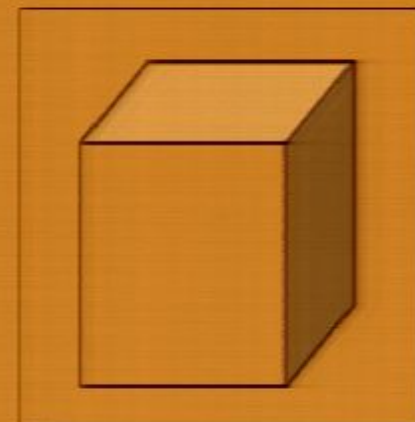


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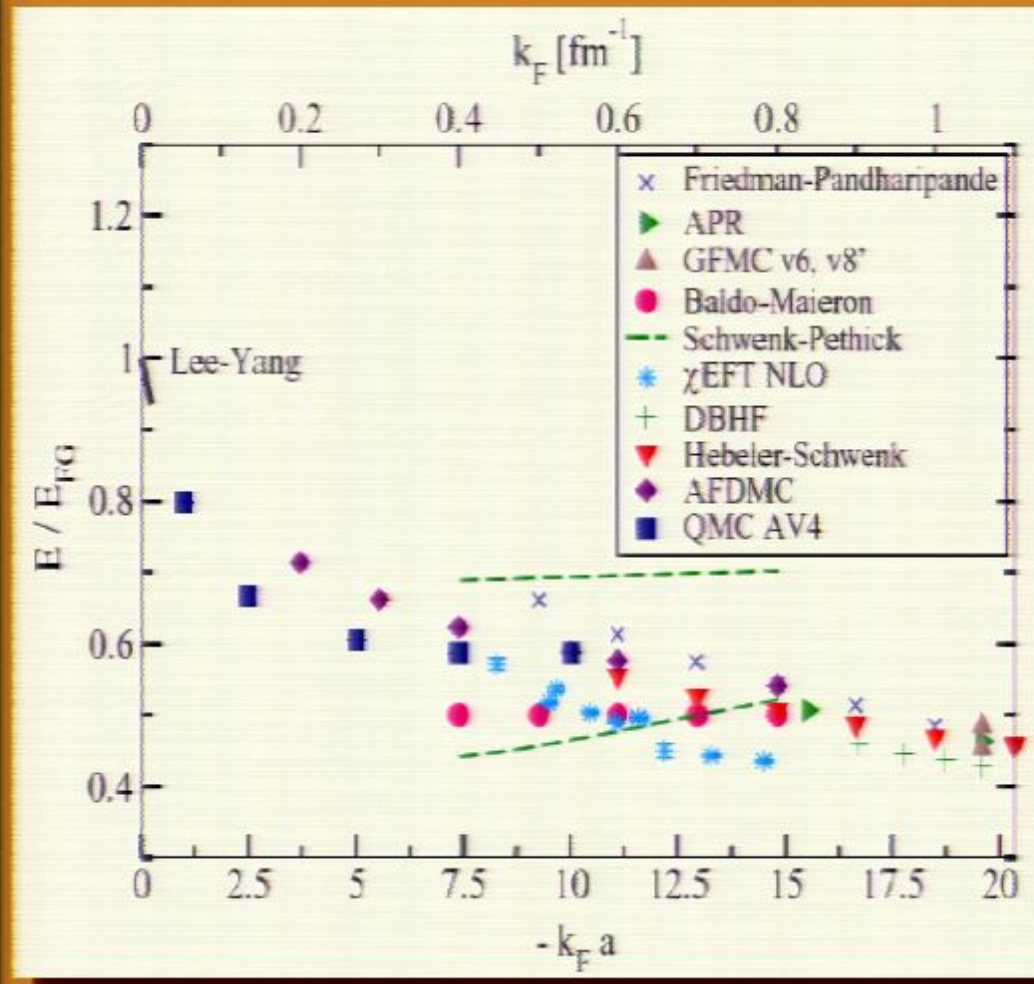


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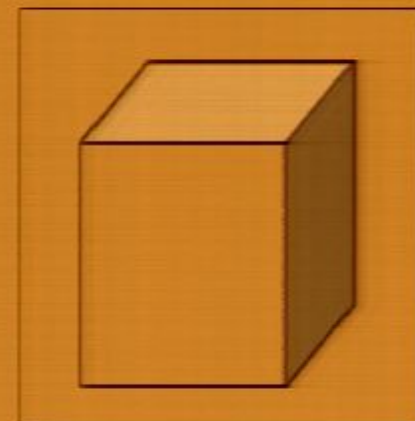


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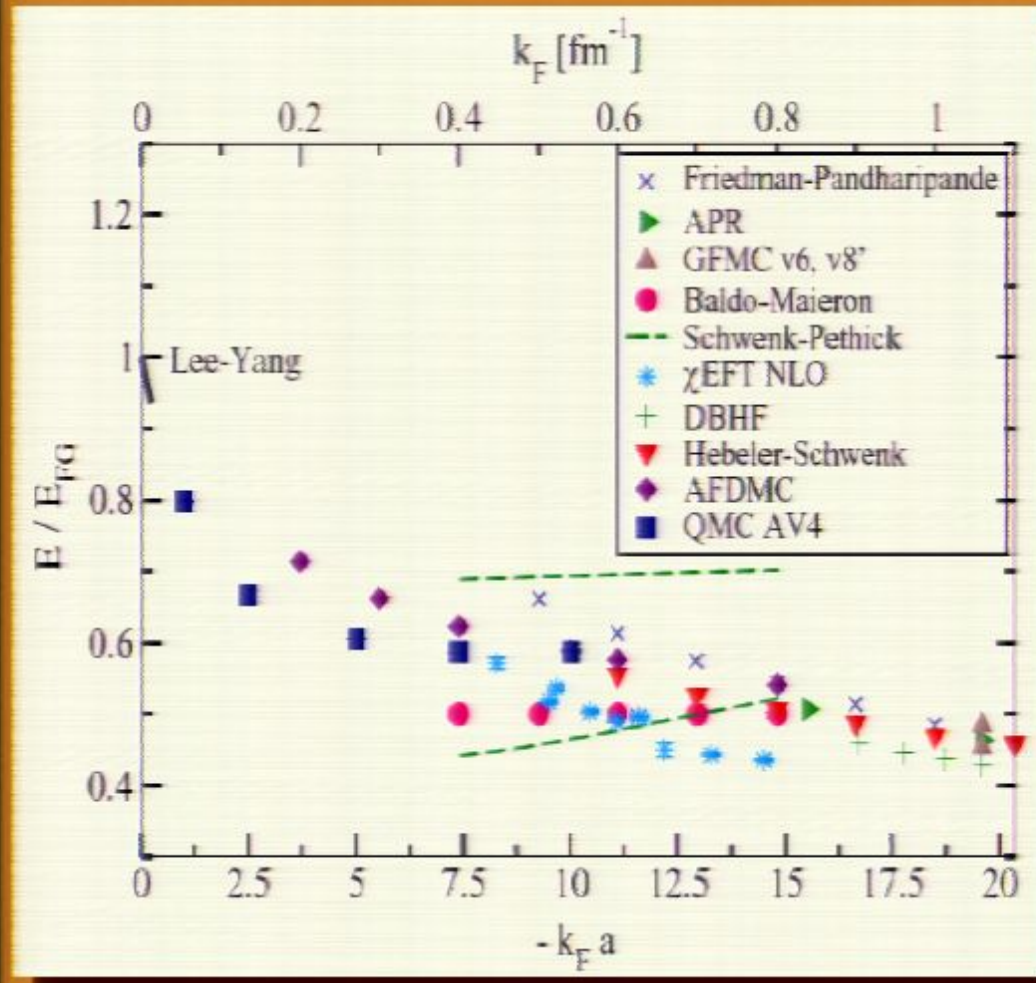
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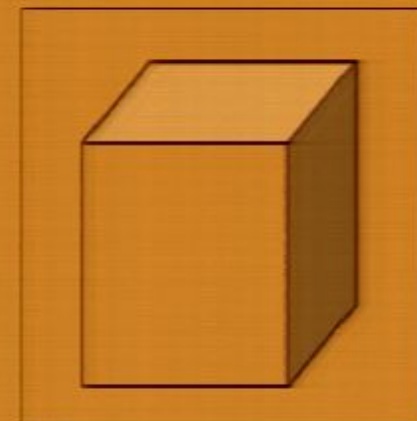
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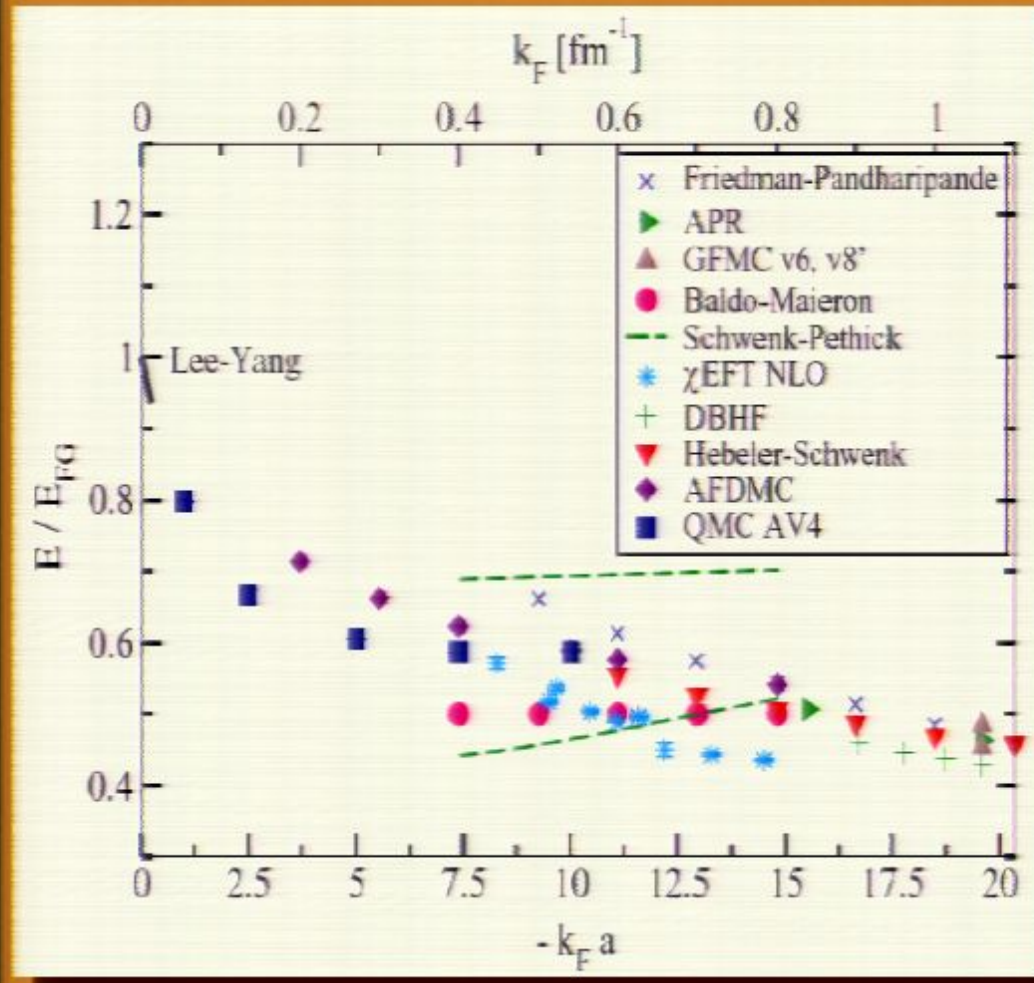


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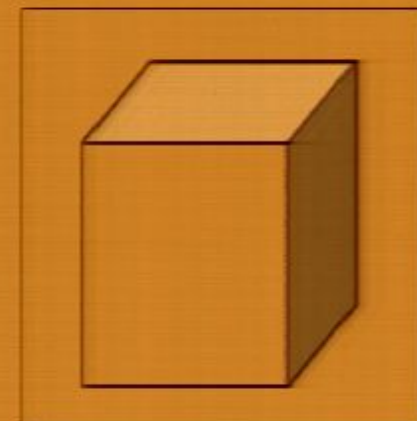


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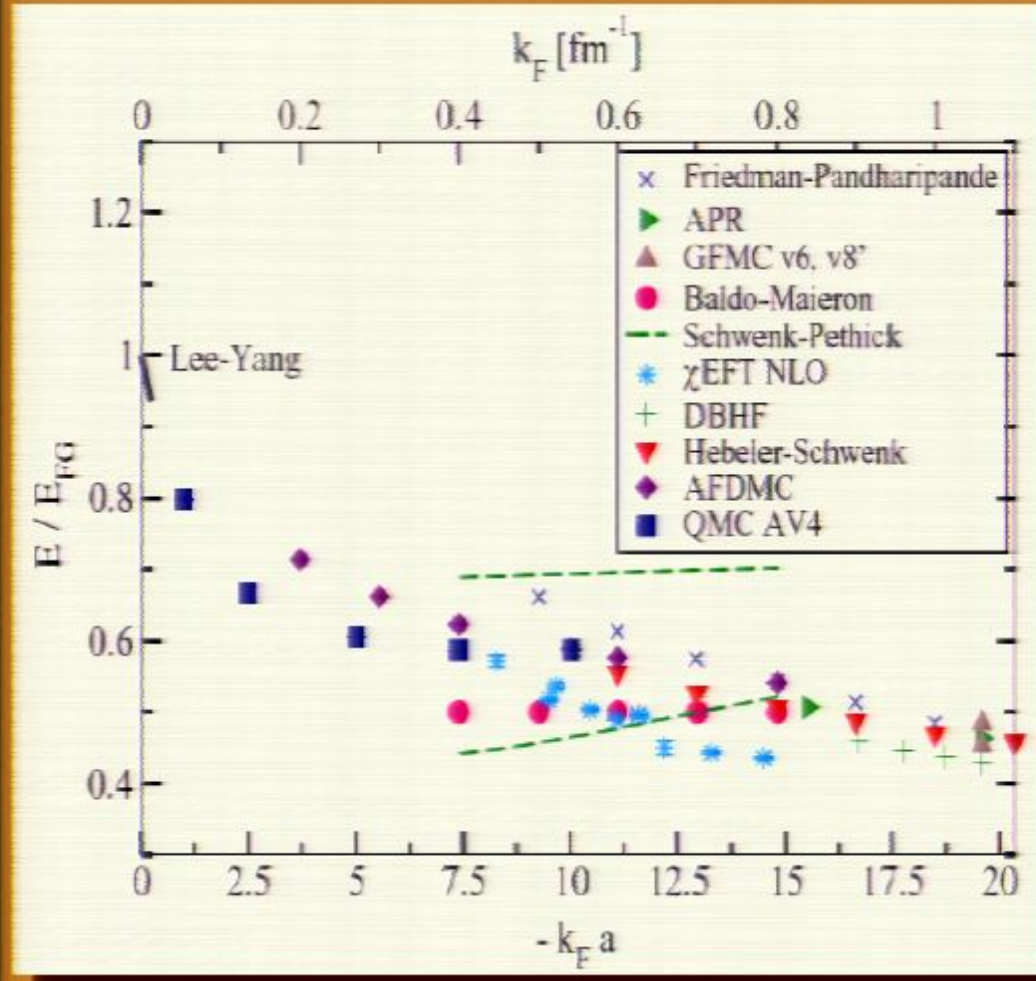


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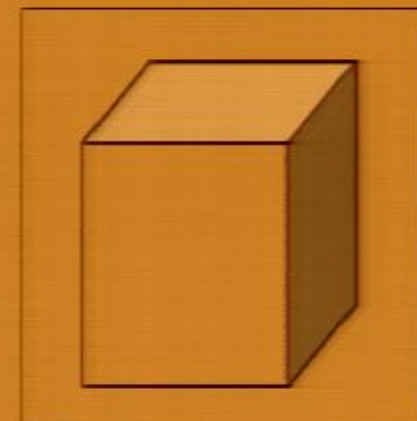


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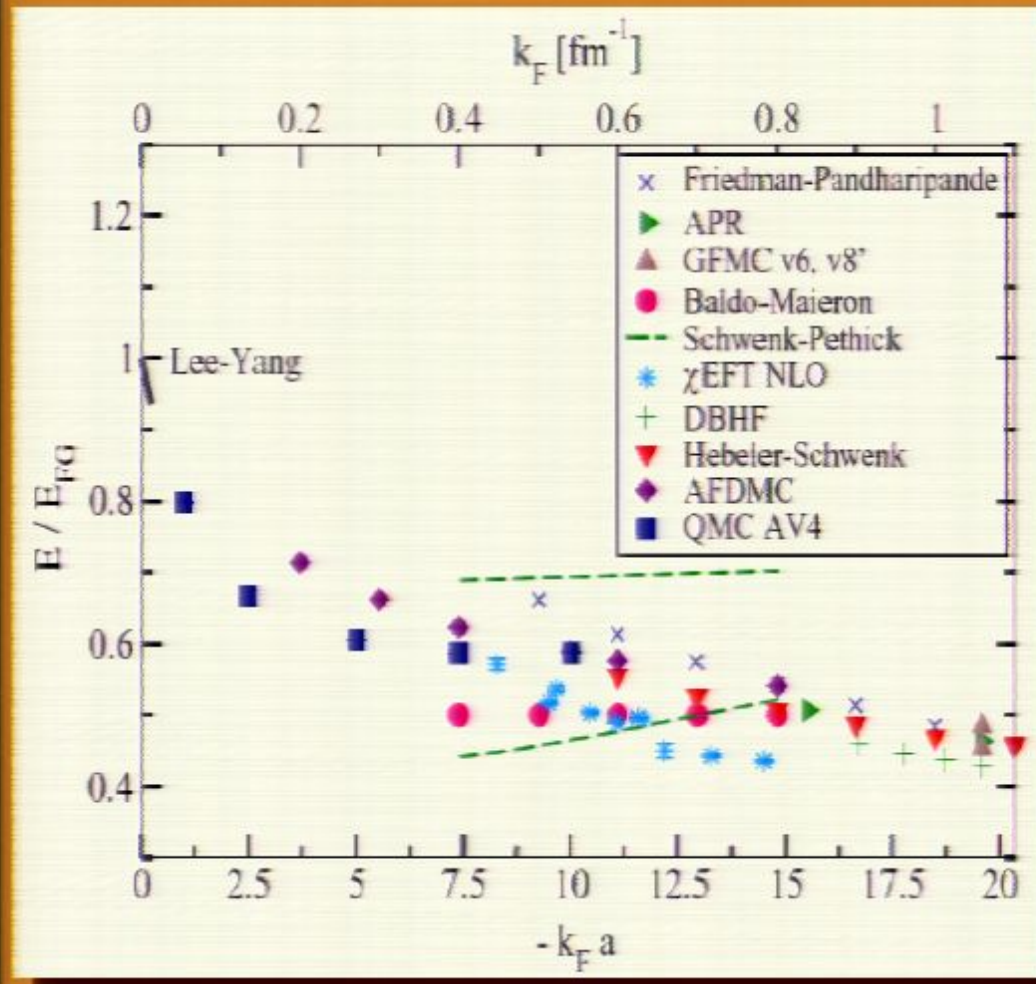


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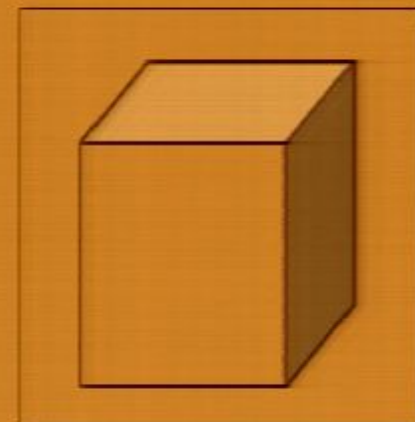


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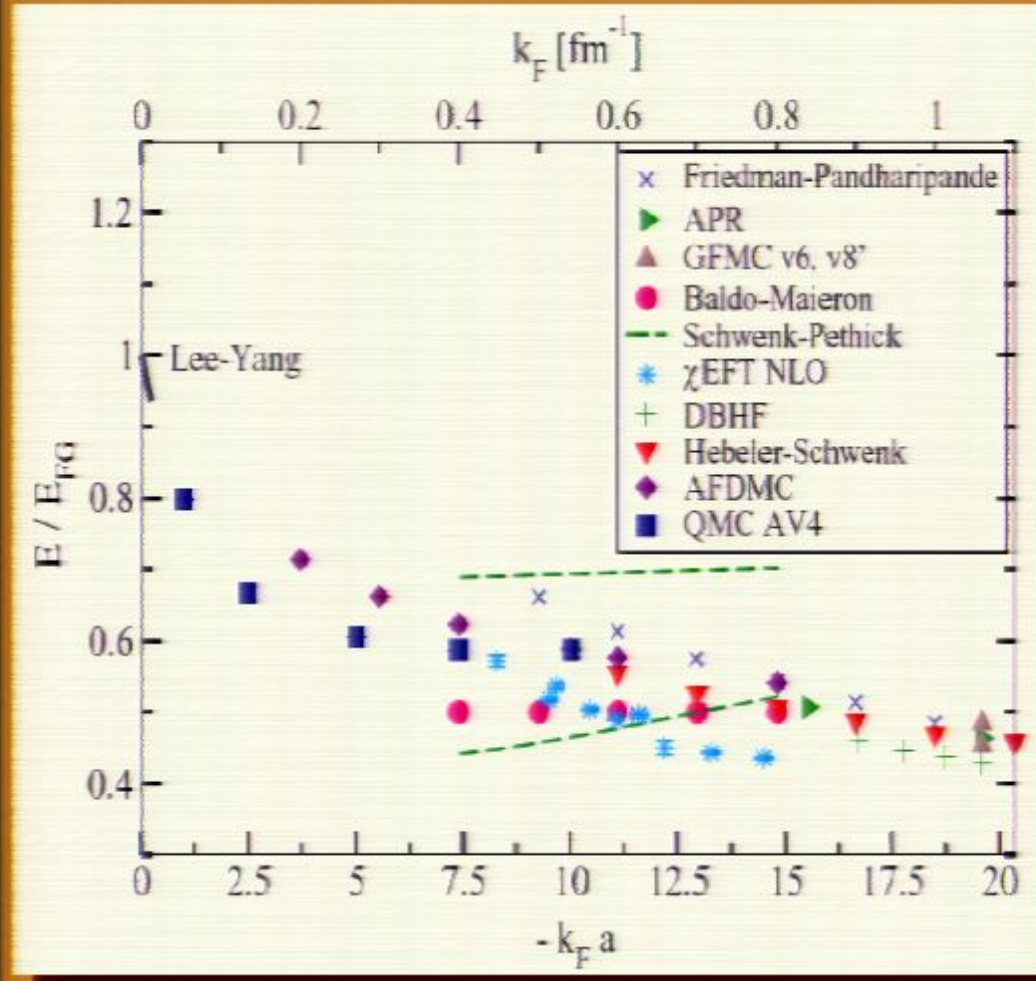


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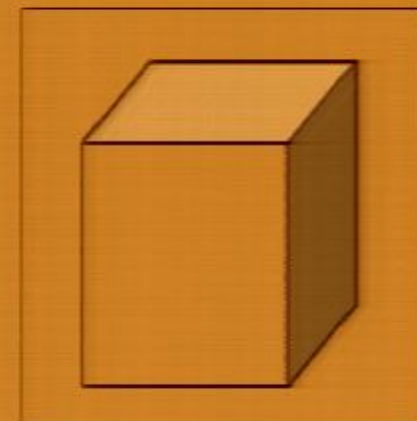


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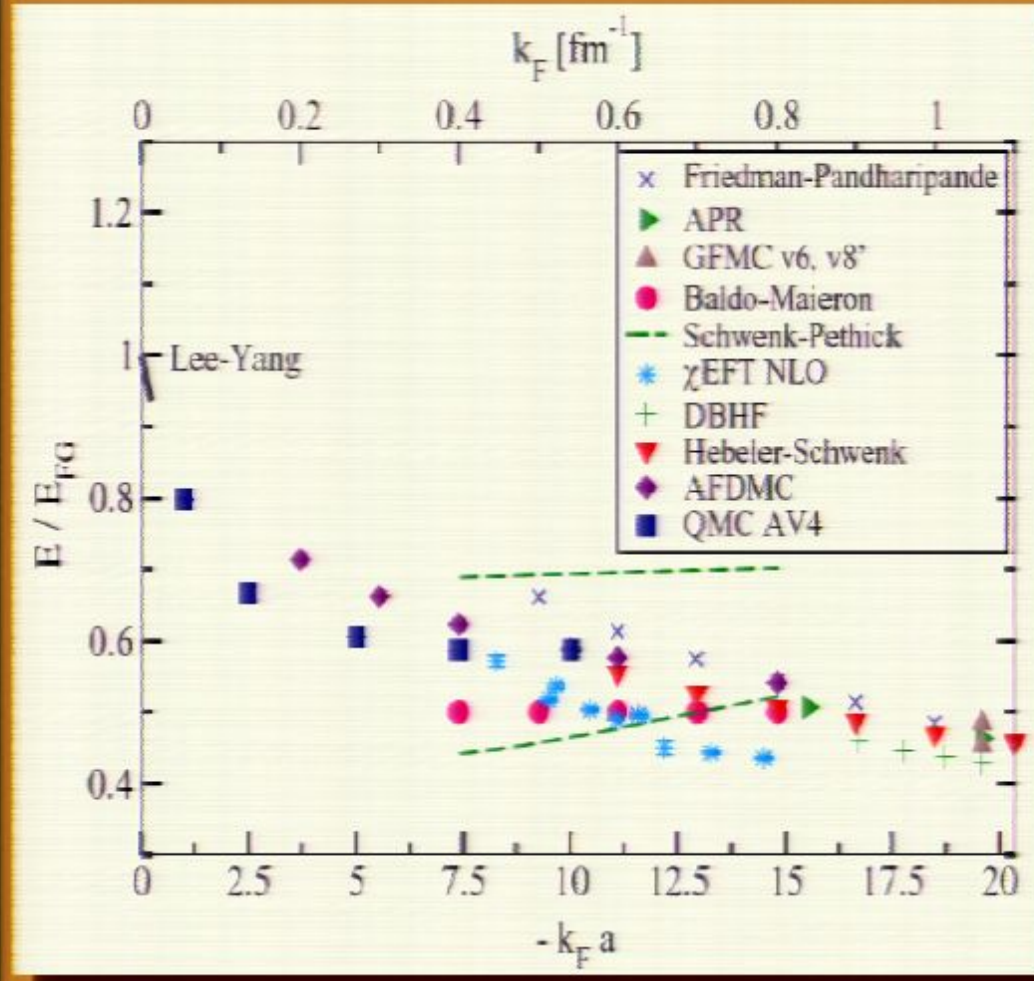


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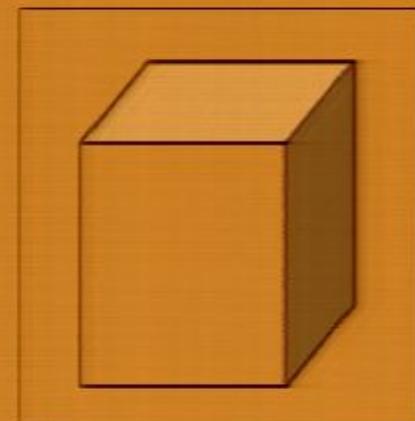


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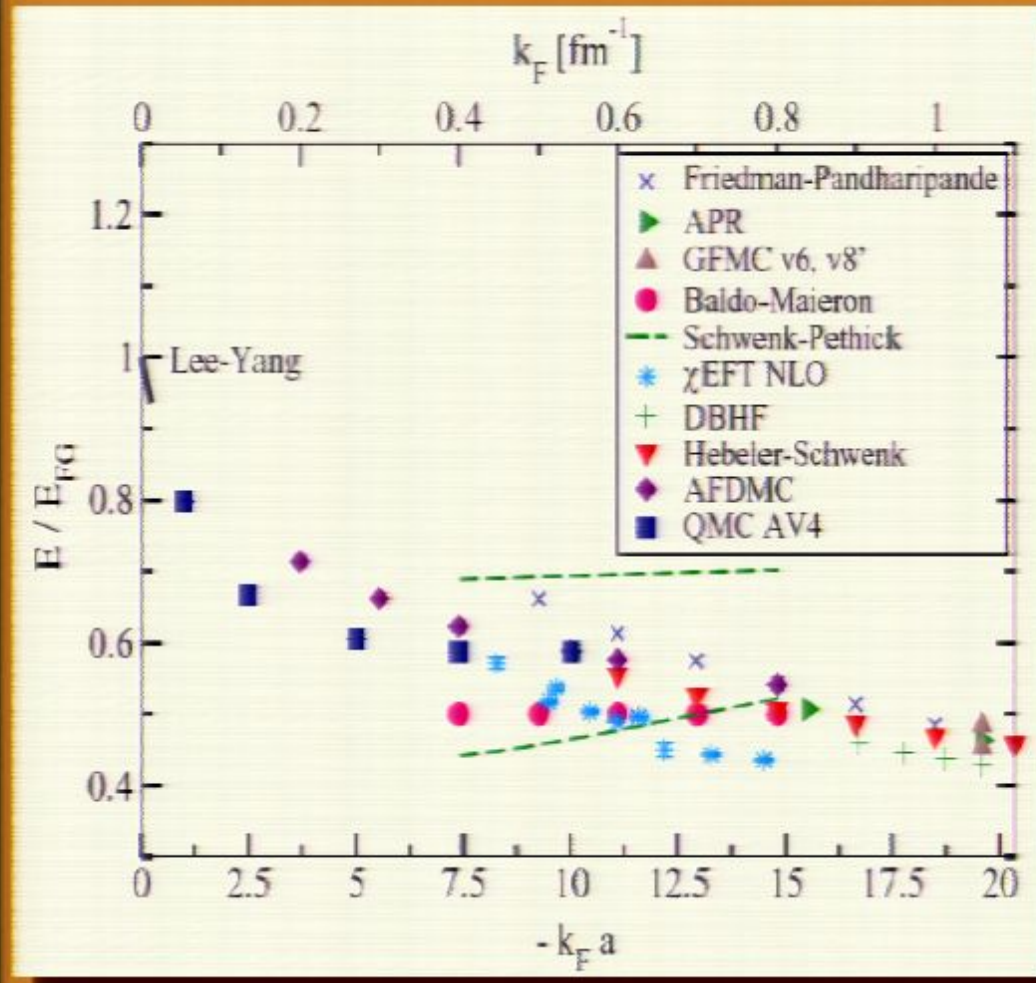


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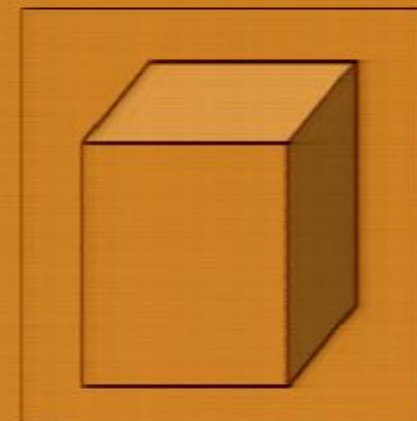


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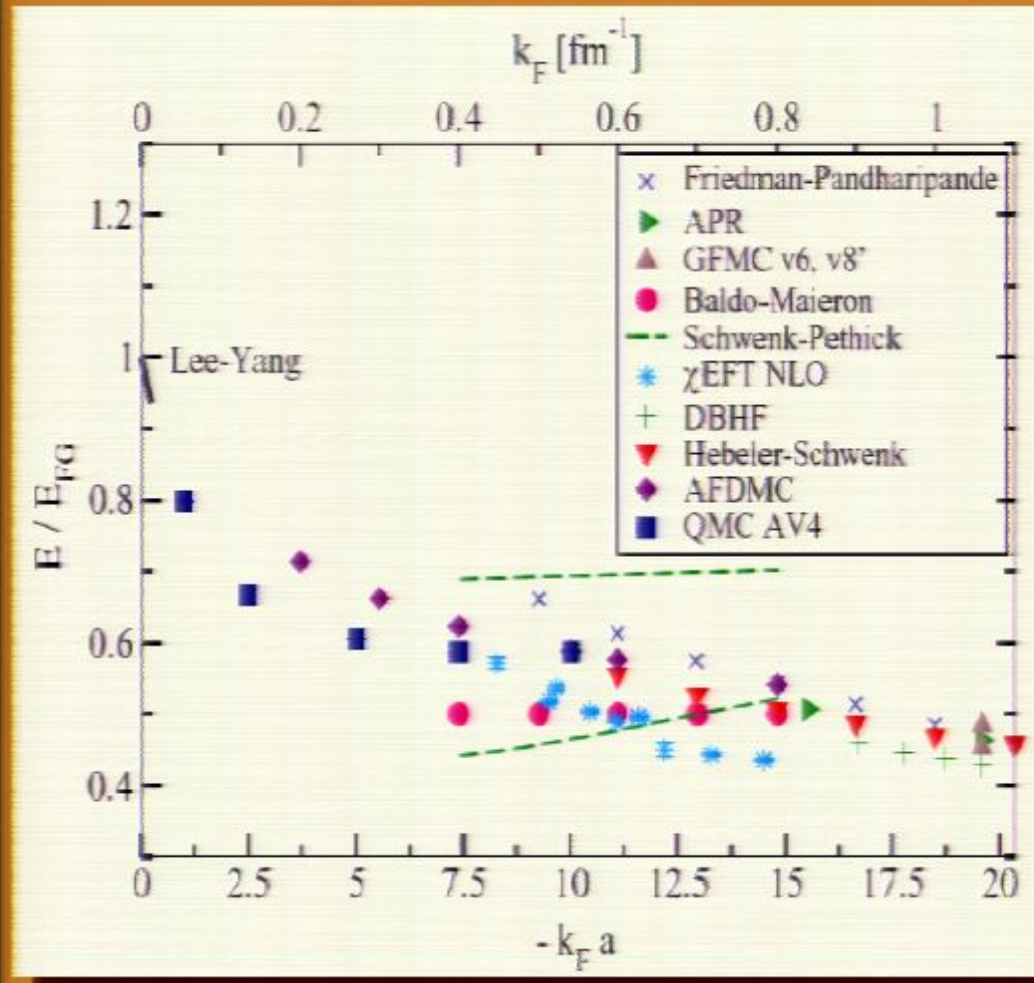


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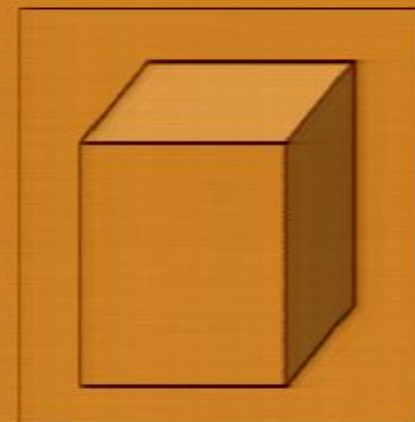


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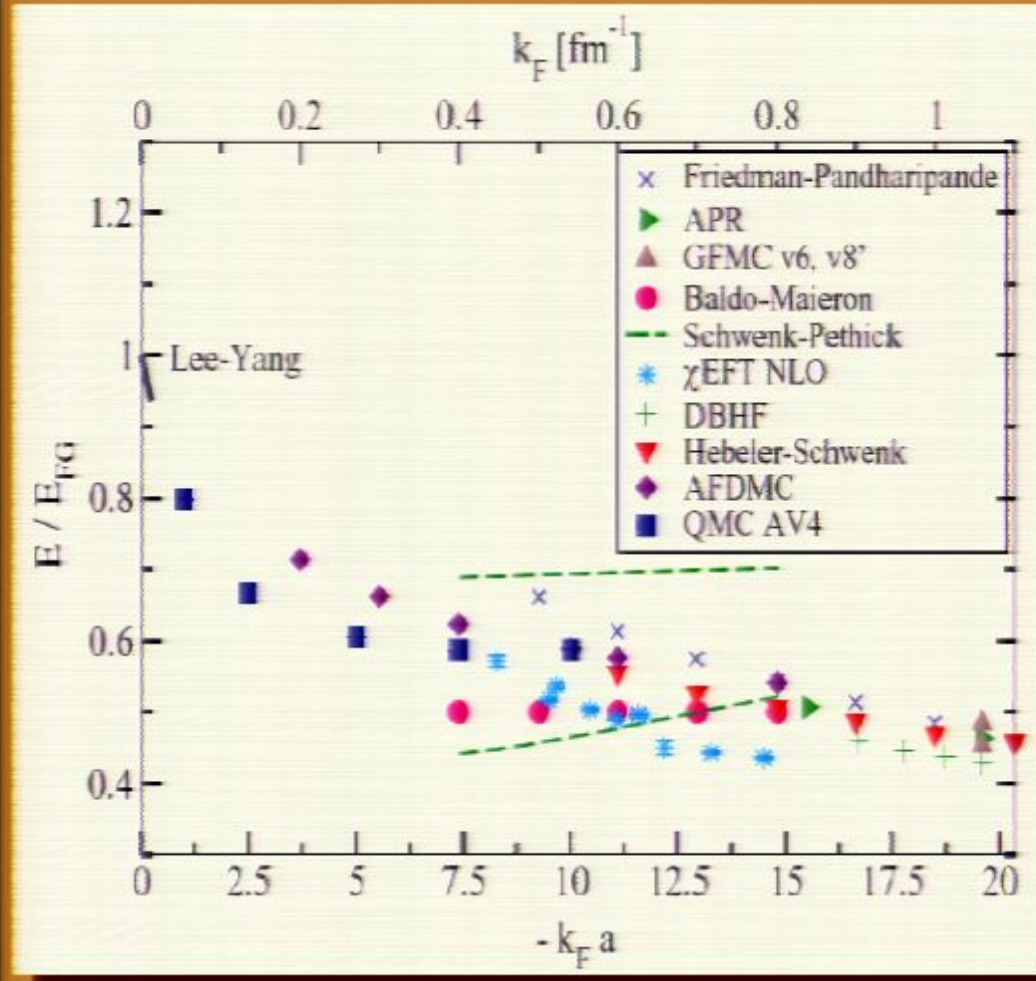


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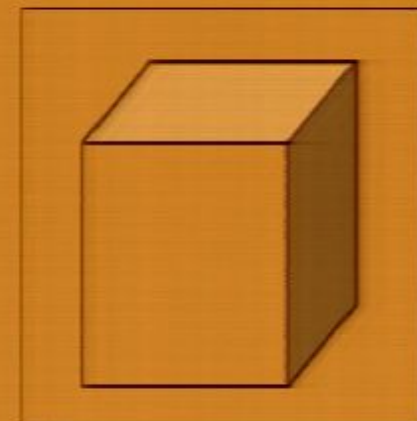


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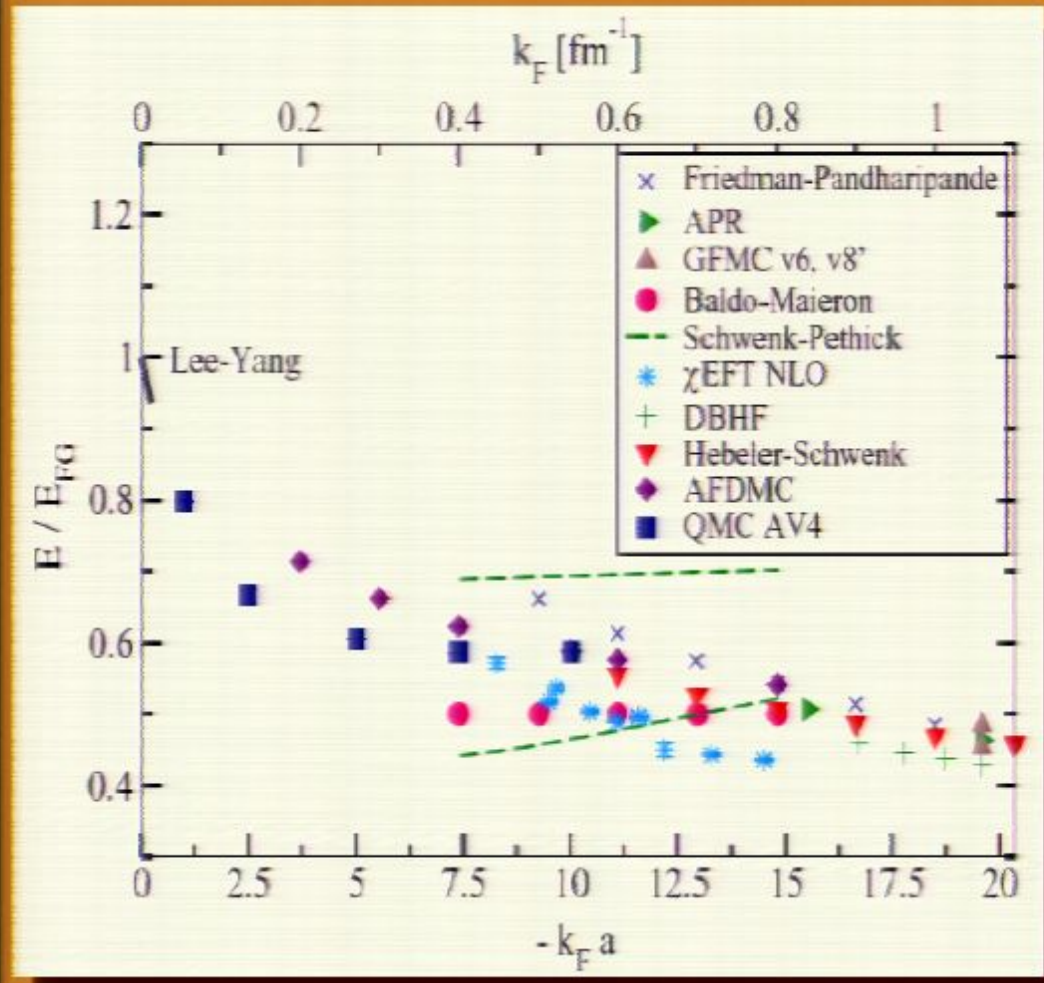


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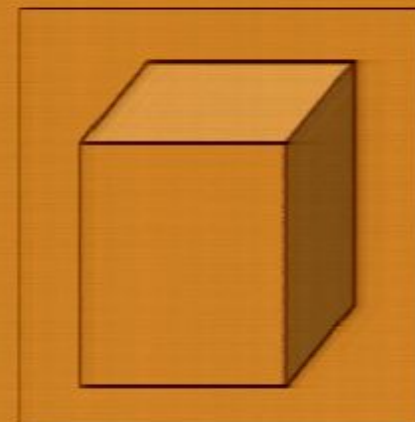


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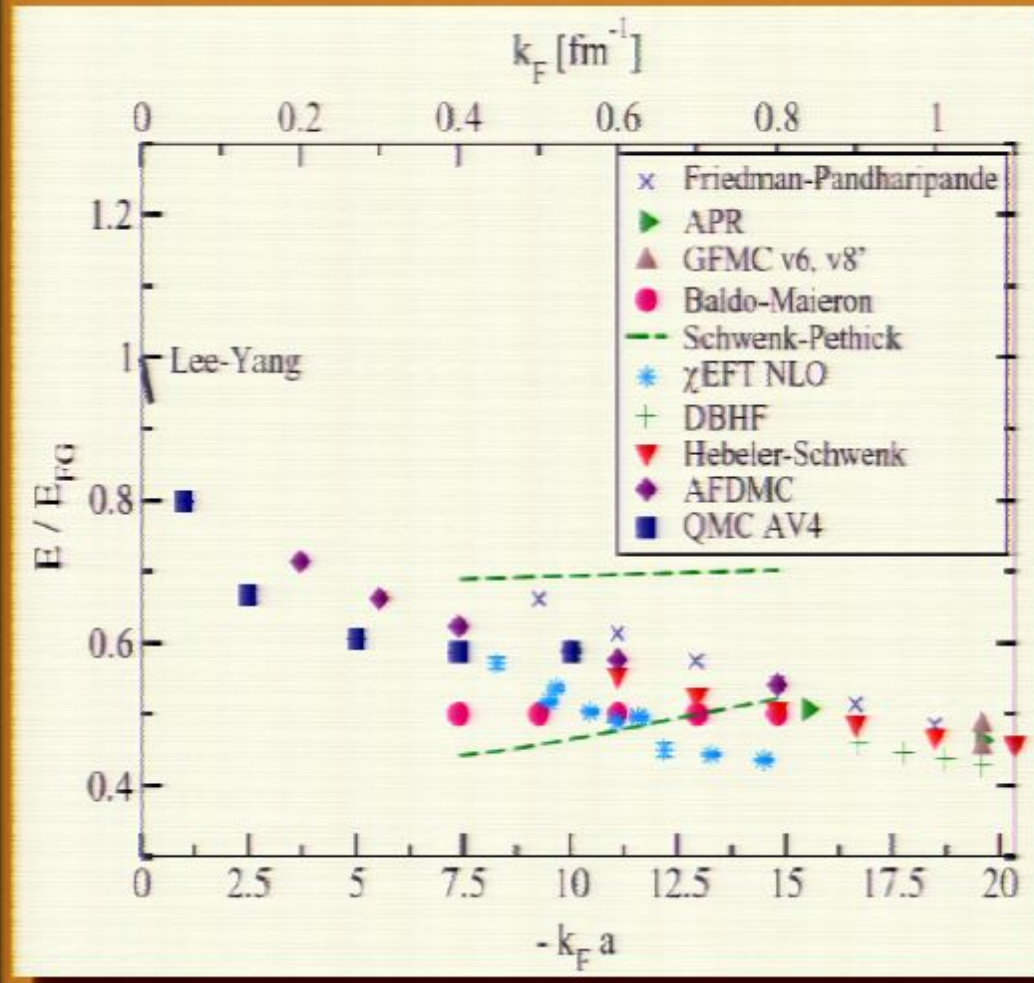


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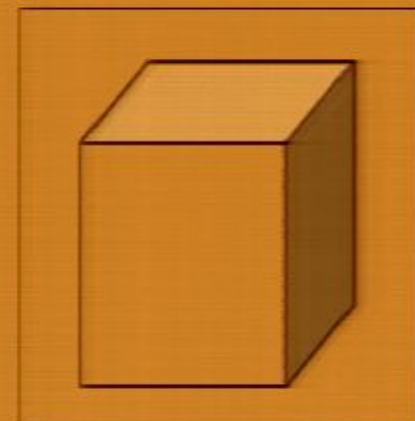


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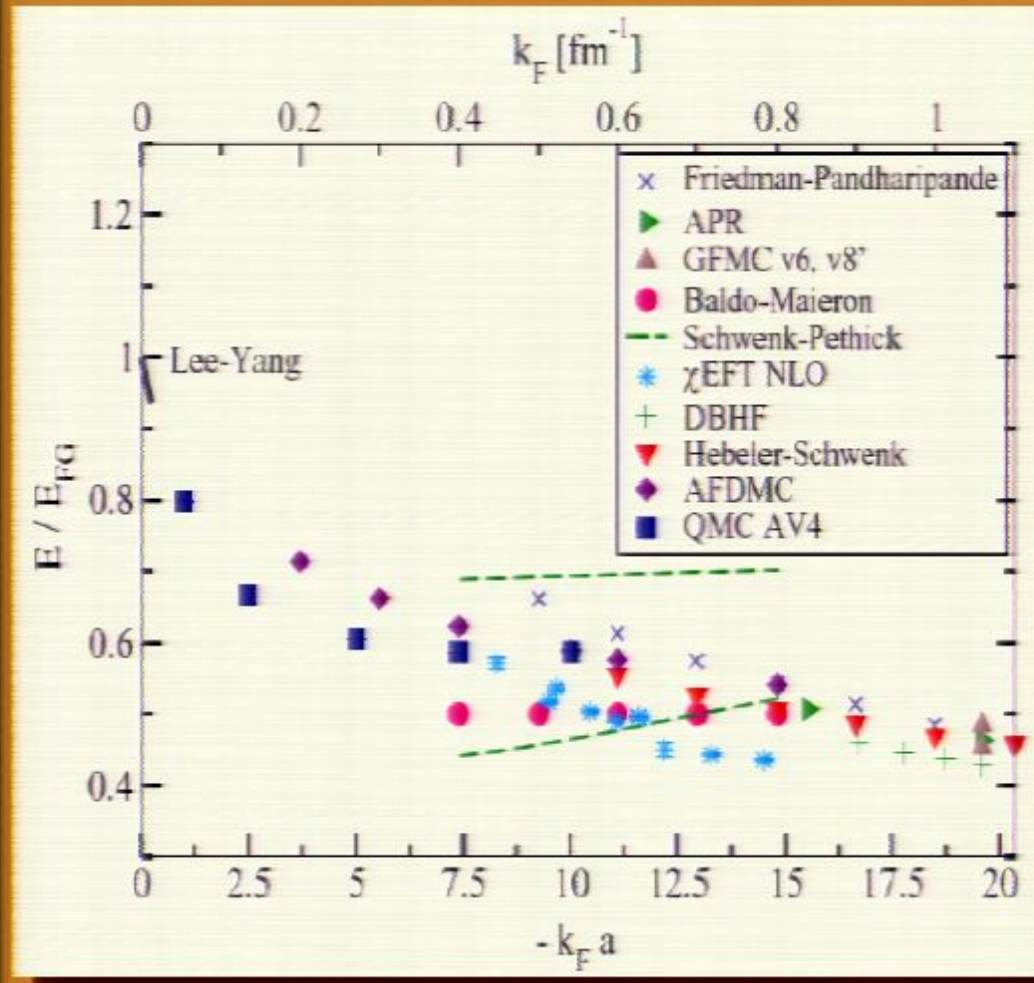
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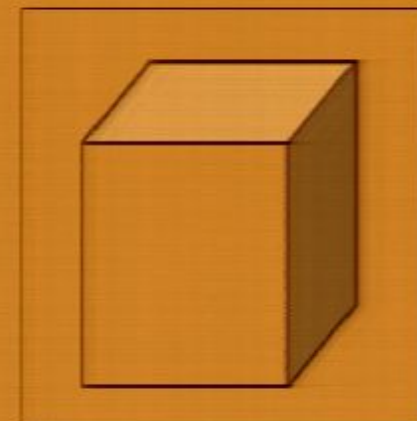
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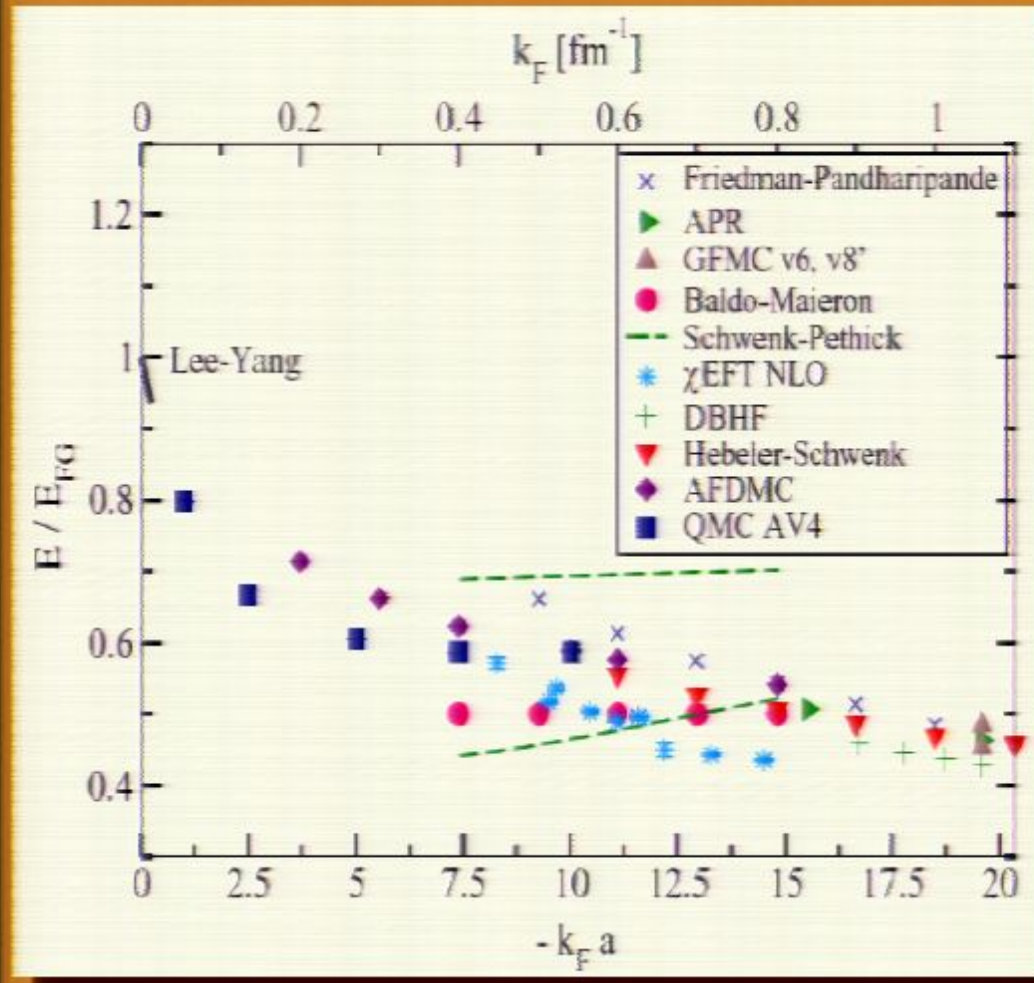


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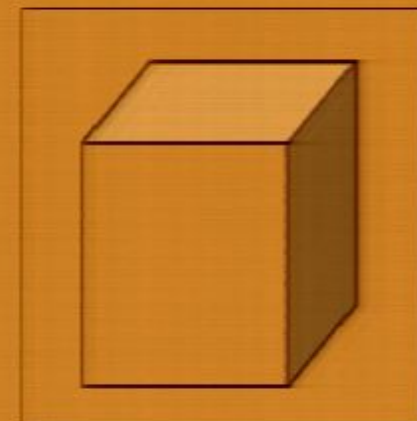


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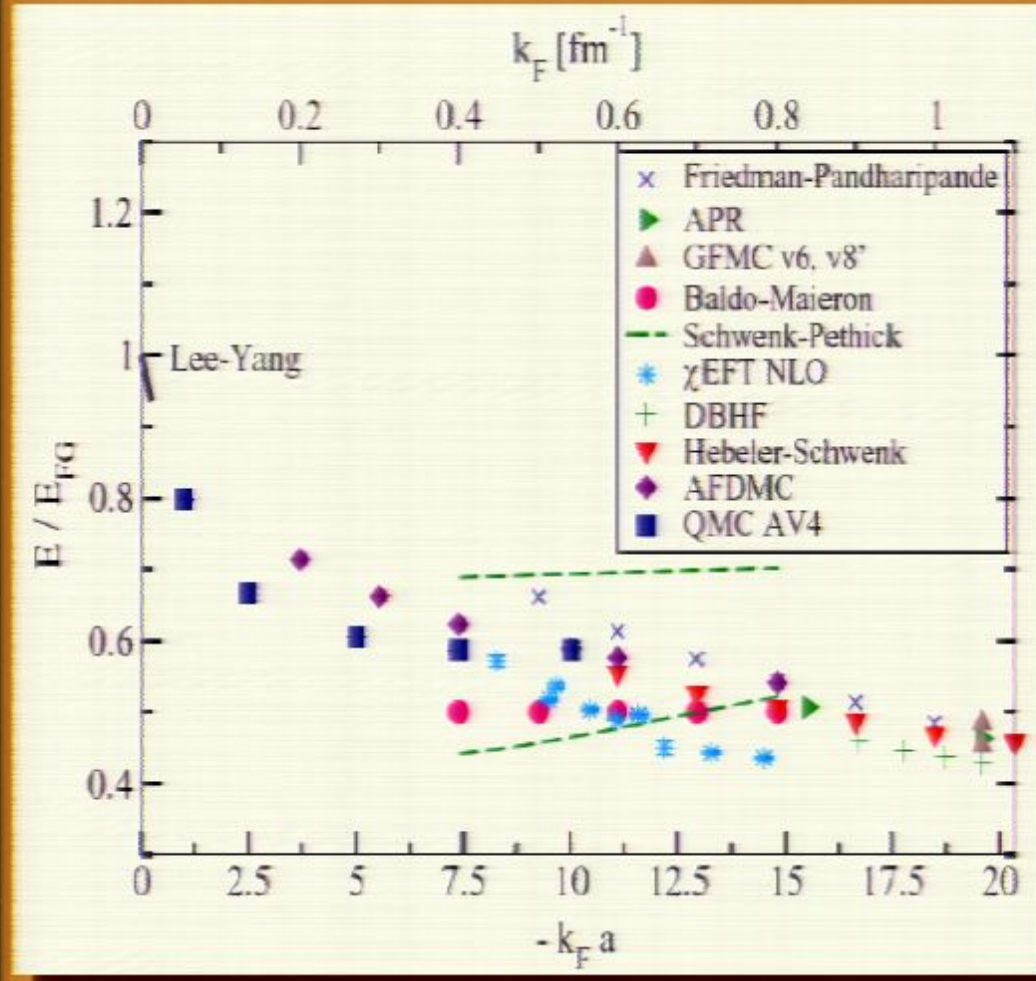


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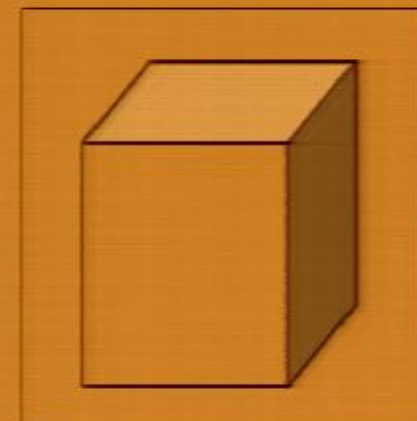


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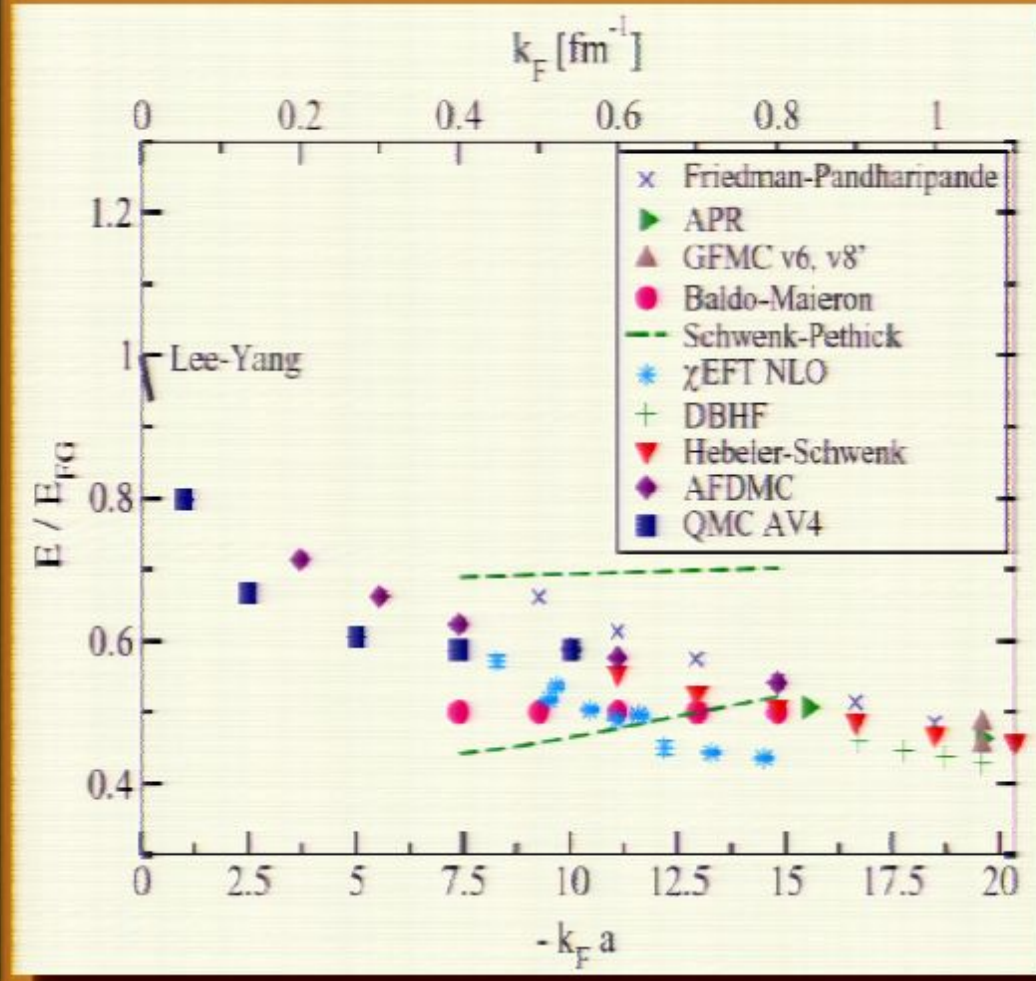


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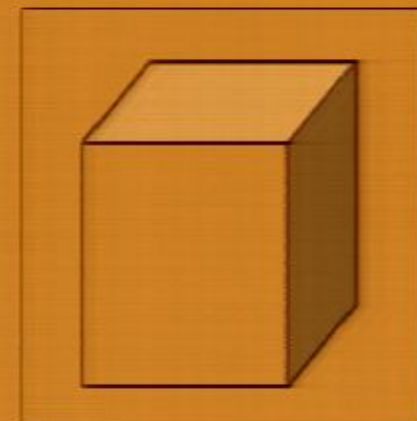


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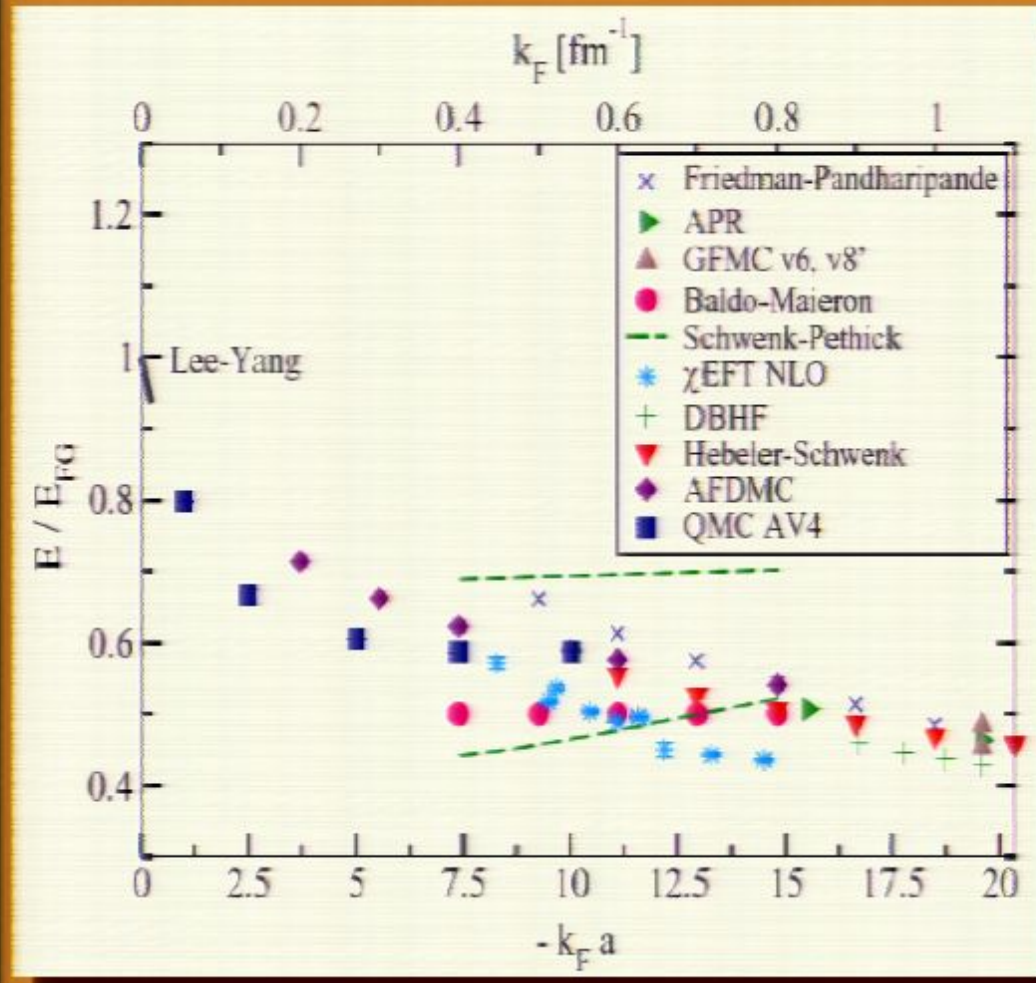


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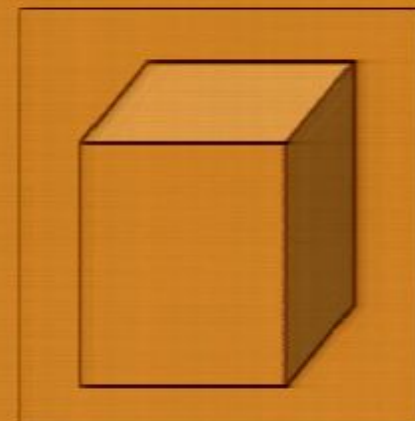


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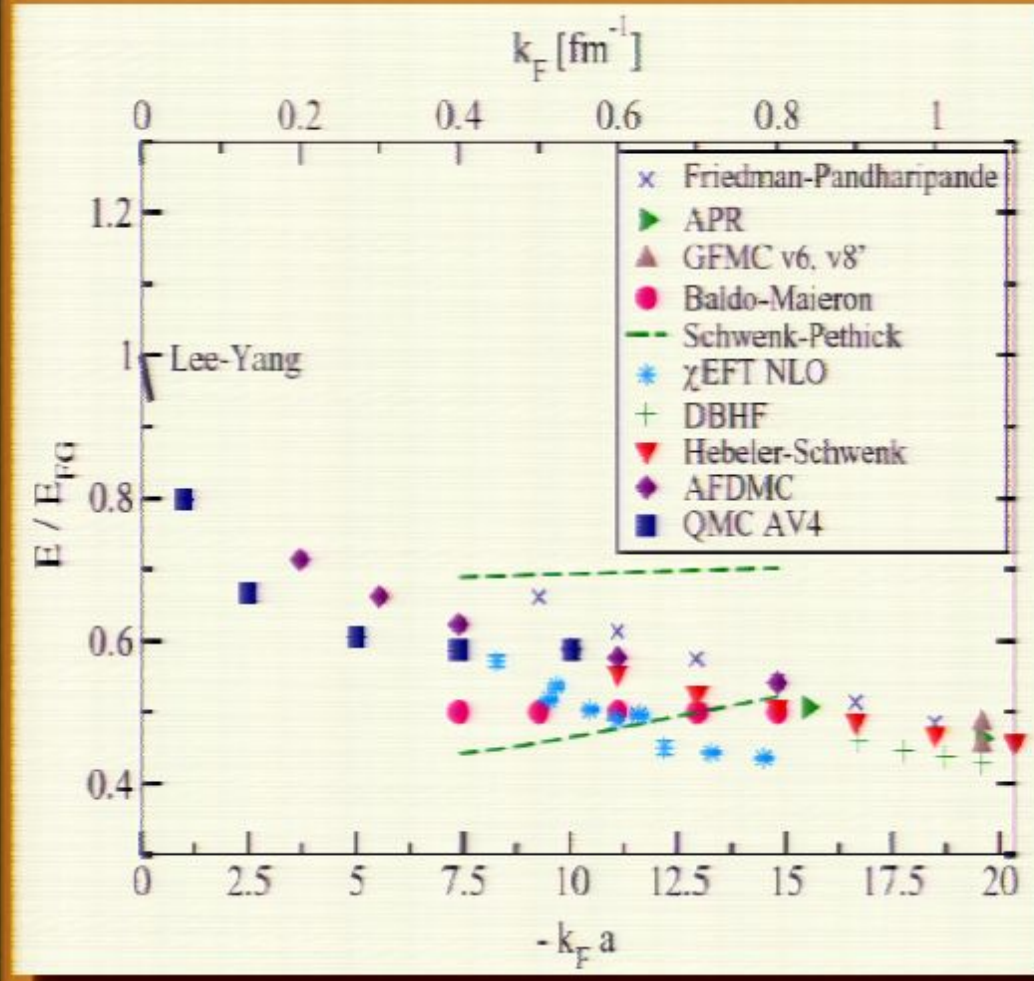


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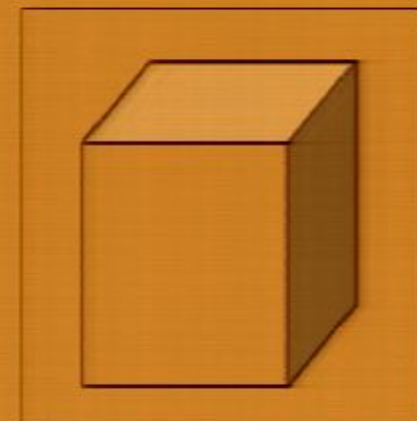


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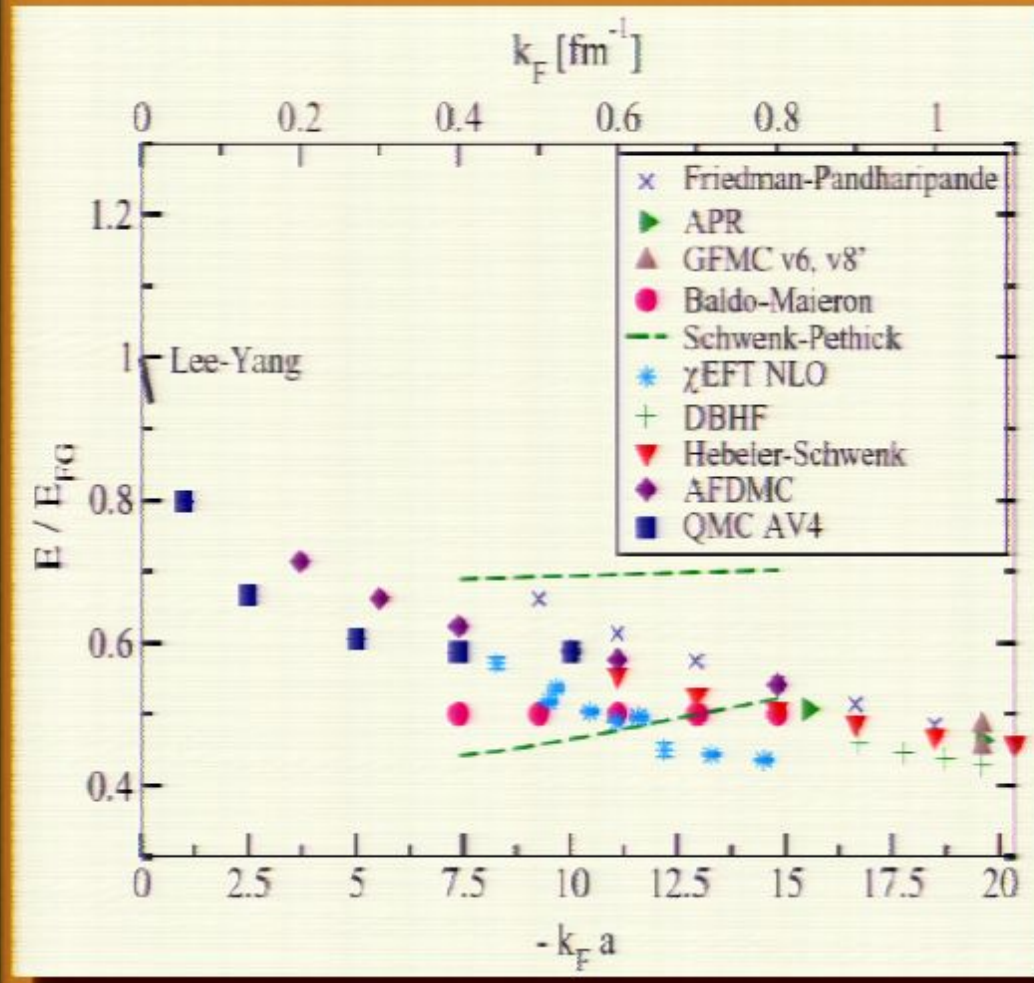


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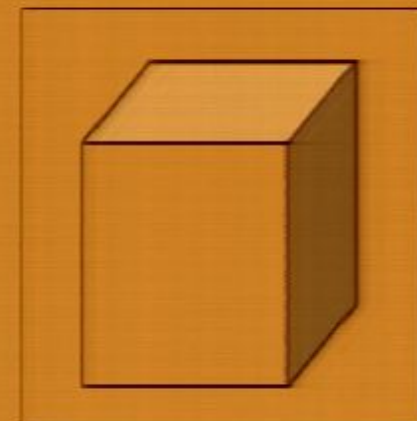


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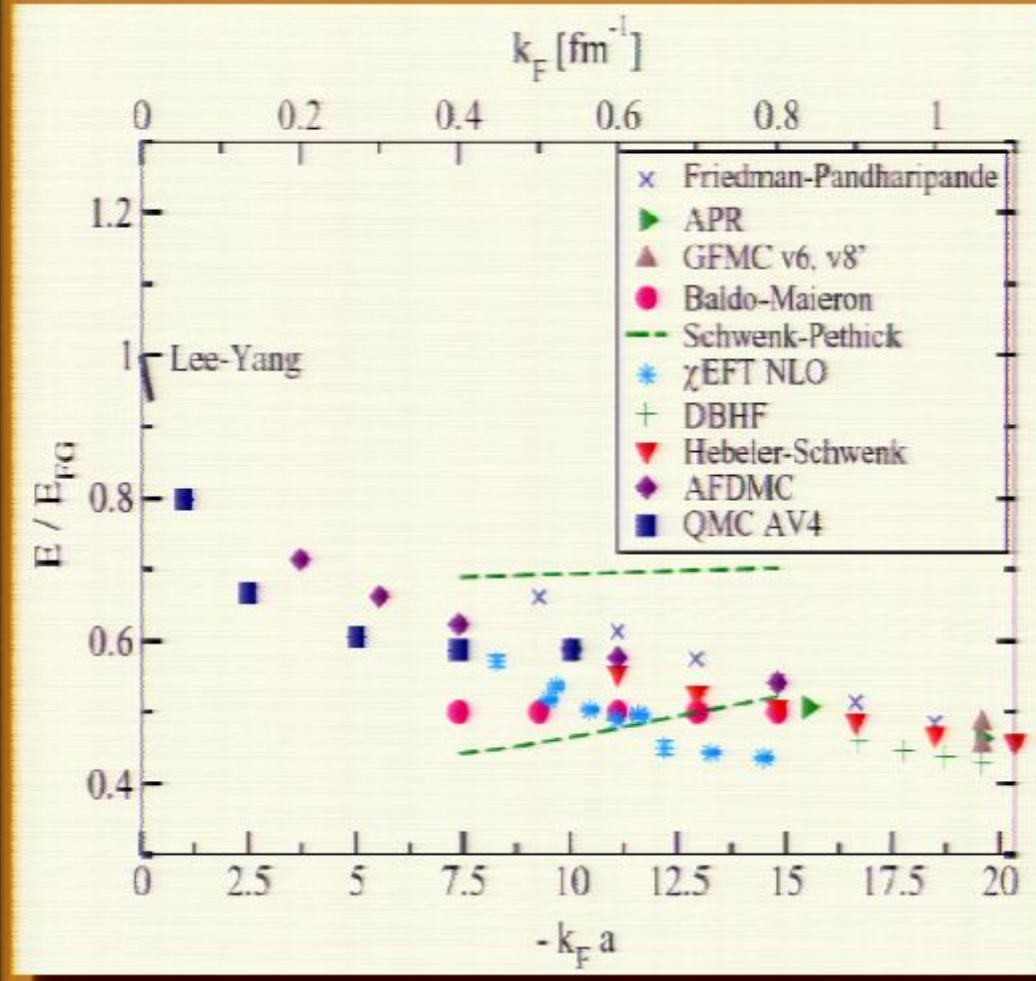


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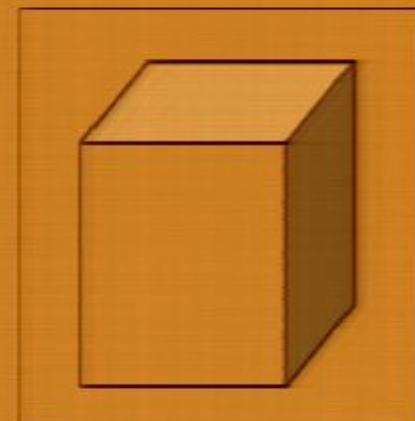


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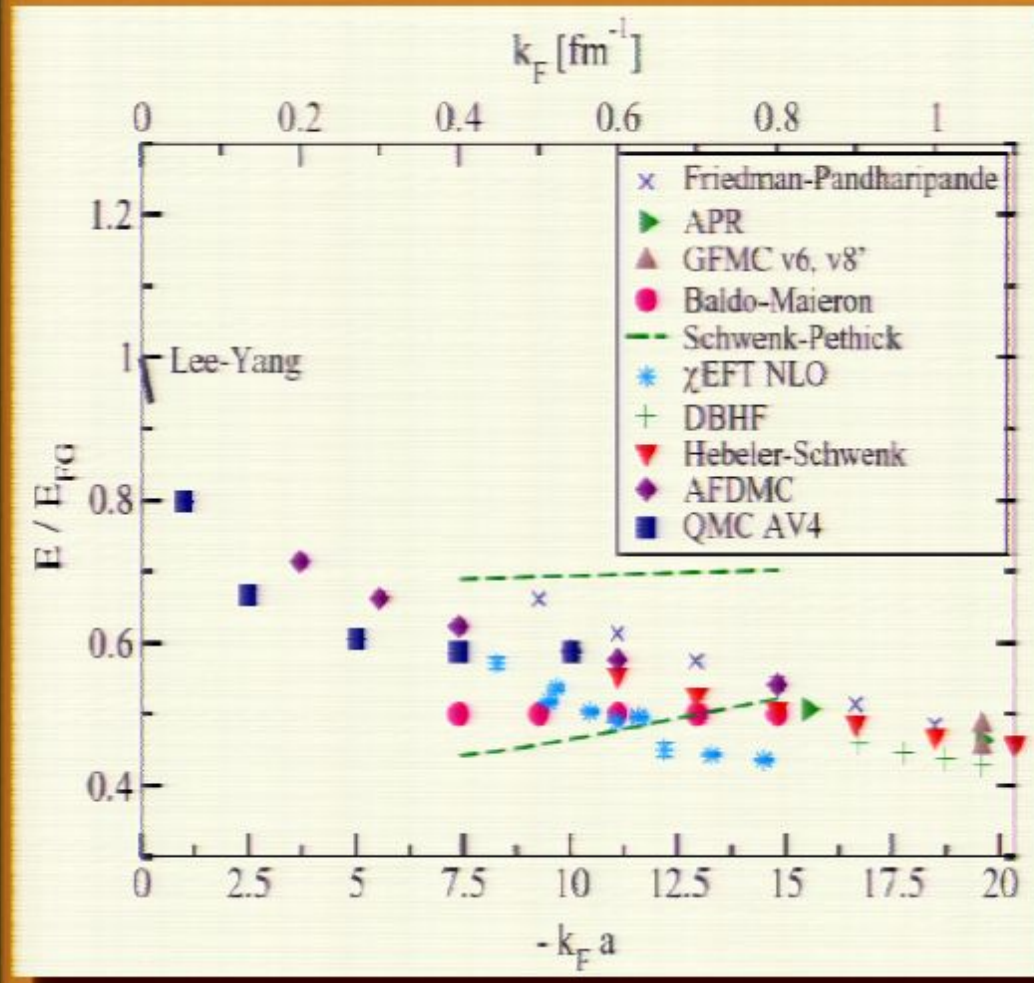


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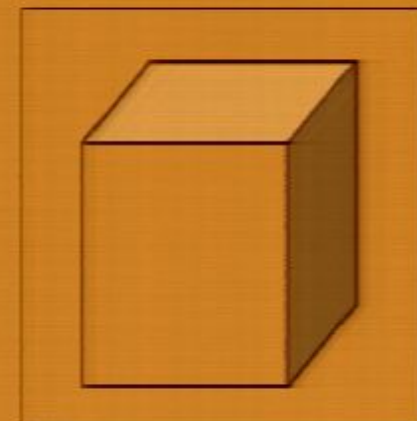


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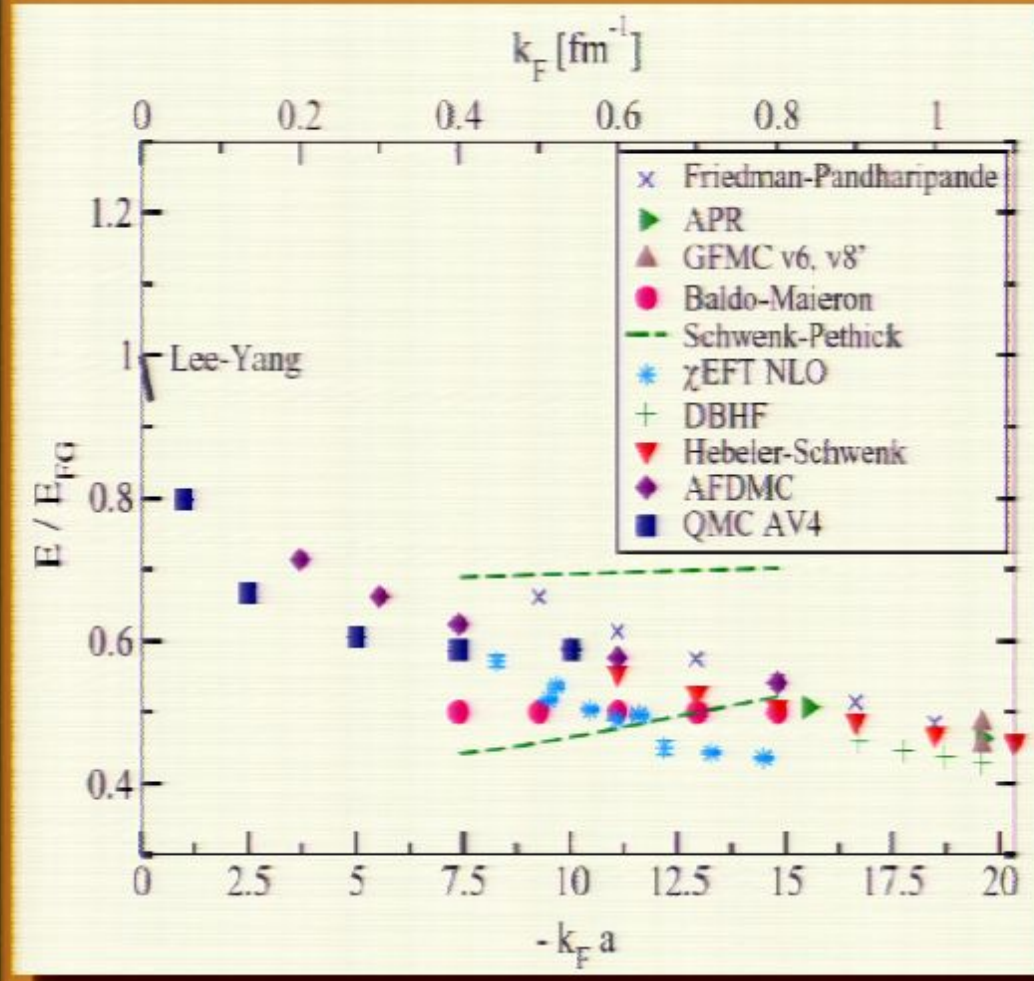


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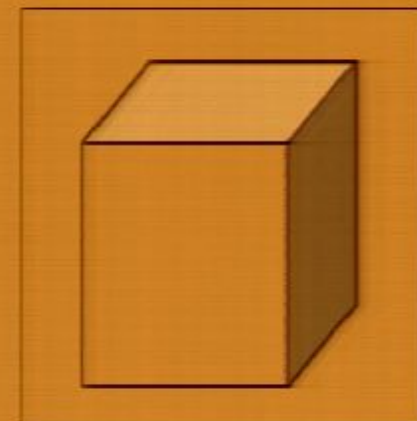


A. Gezerlis and J. Carlson, Phys. Rev. C **81**, 025803 (2010)

Equations of state: comparison

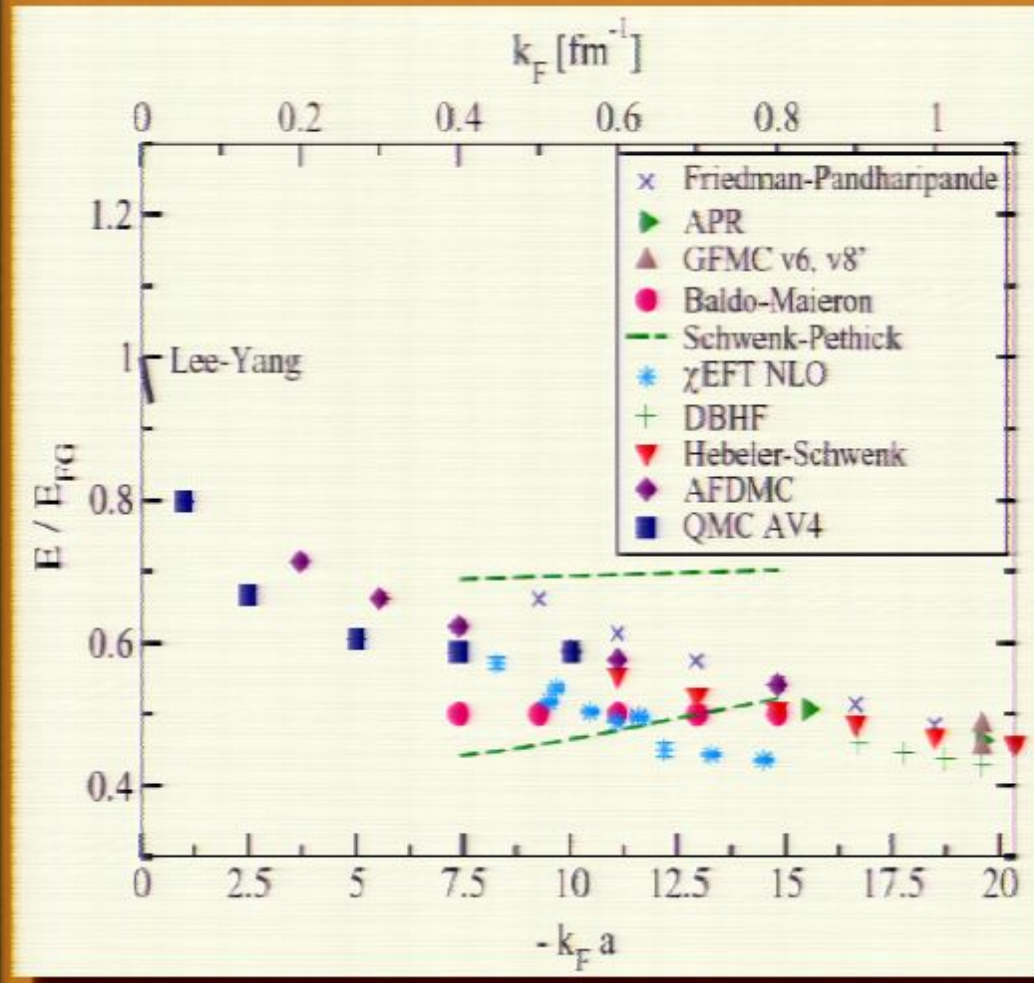


- Lowest densities on the market; agreement with Lee-Yang trend
- At higher densities all calculations are in qualitative agreement

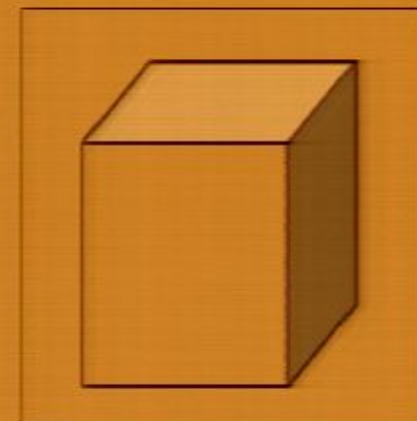


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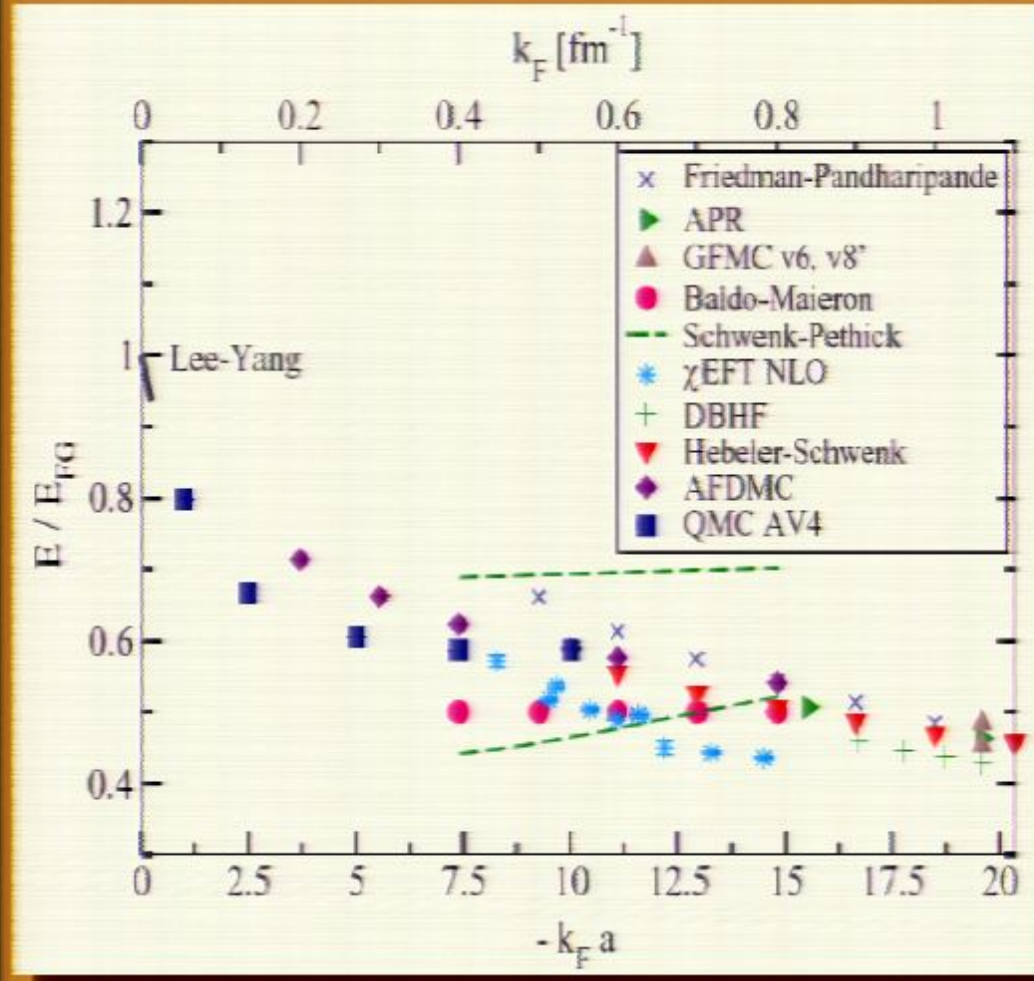


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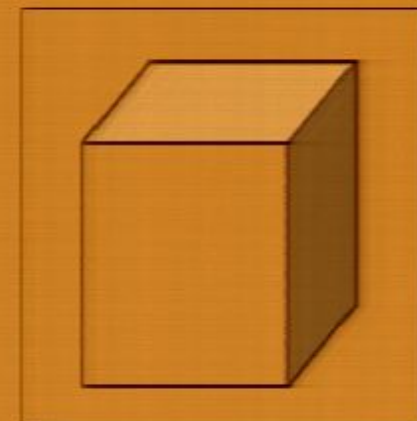


A. Gezerlis and J. Carlson, Phys. Rev. C **81**, 025803 (2010)

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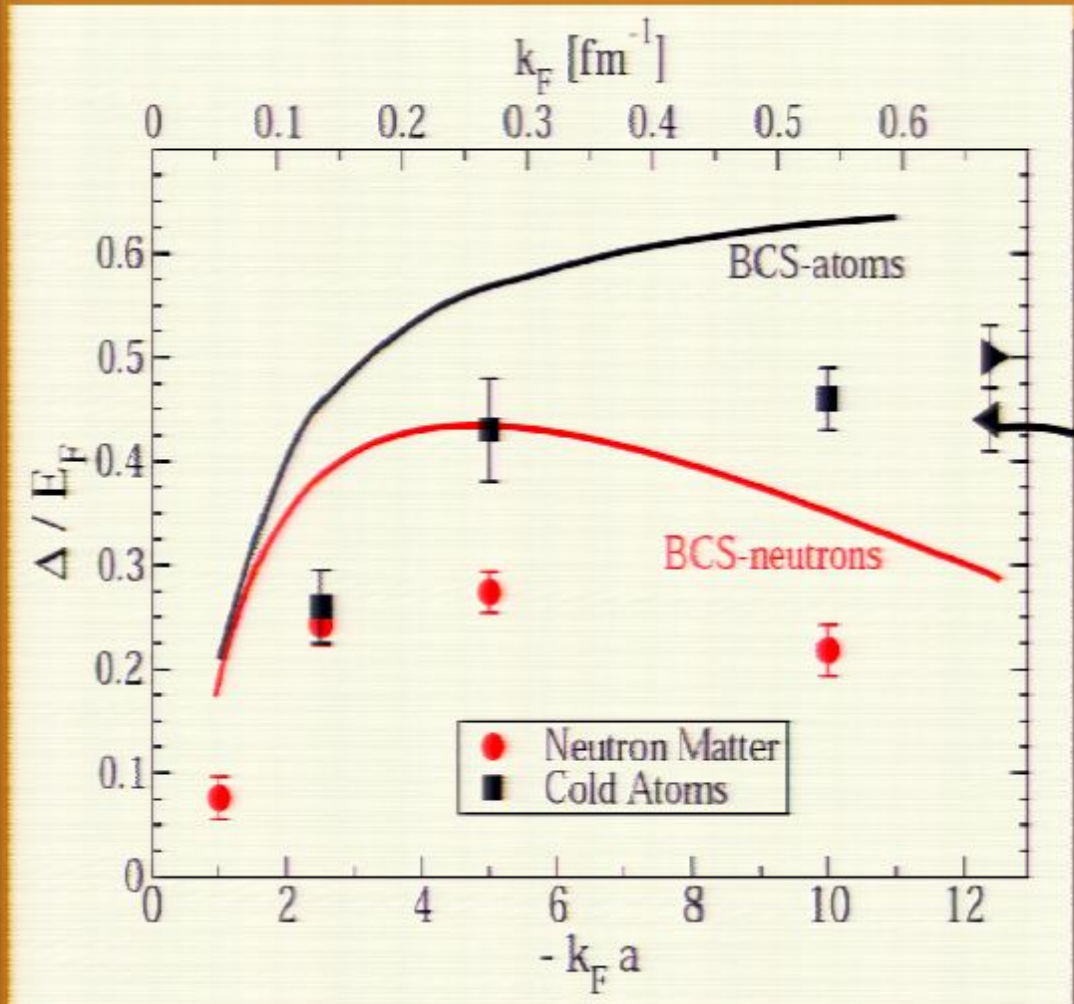
A. Gezerlis and J. Carlson, Phys. Rev. C **81**, 025803 (2010)

Odd-even staggering

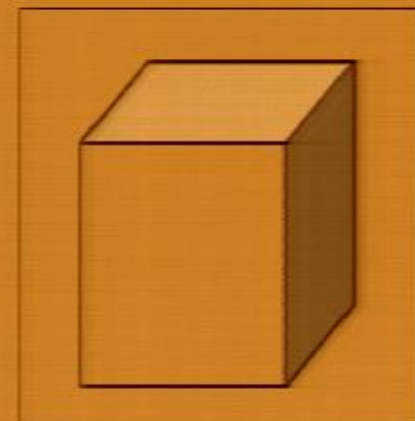
Pairing gap



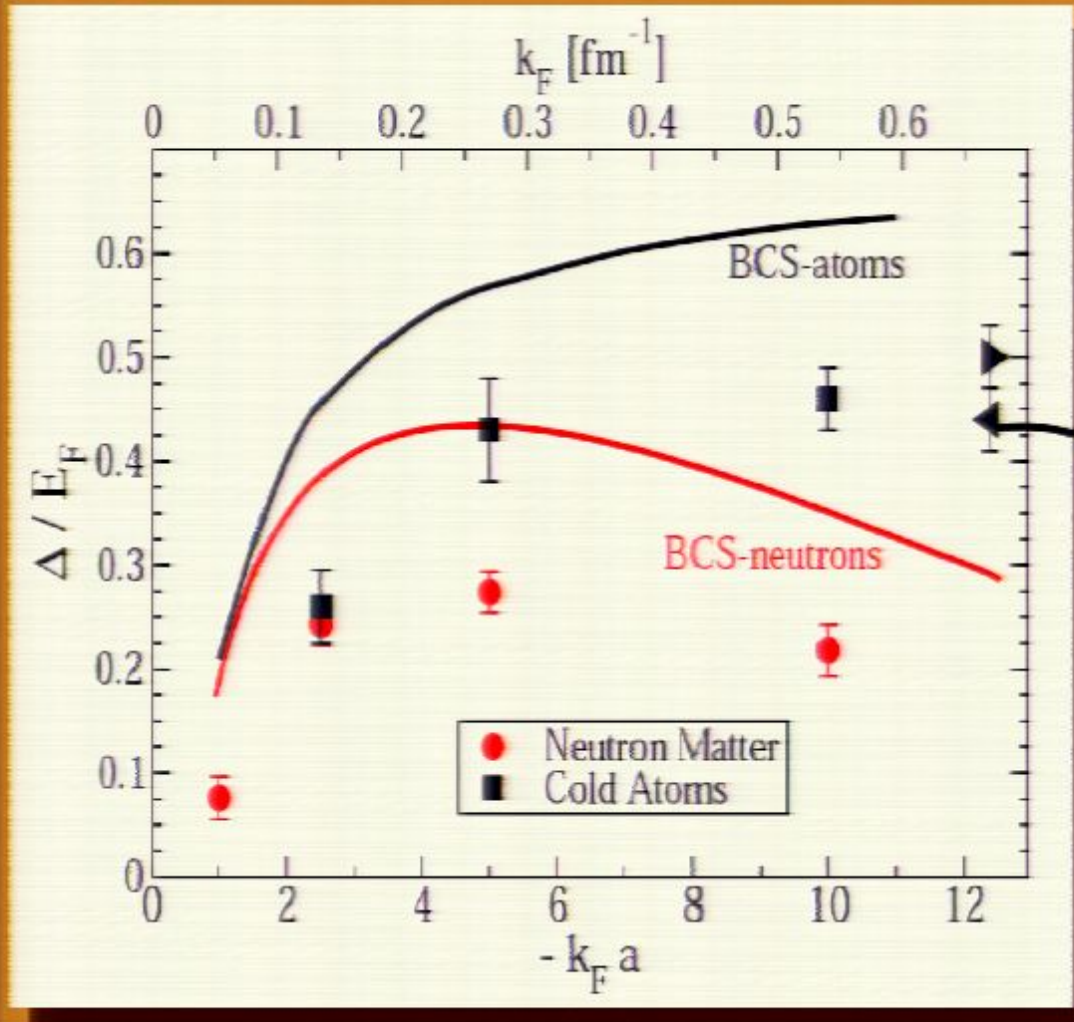
Pairing gaps: results



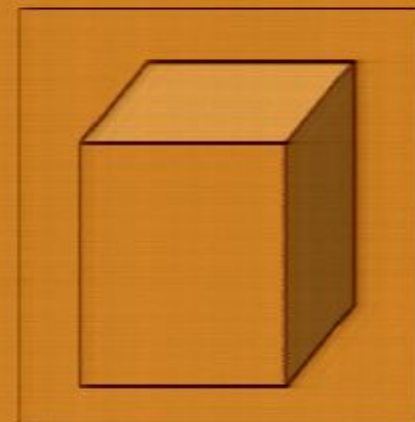
- Results identical at low density
- Range important at high density
- Two independent MIT experiments at unitarity



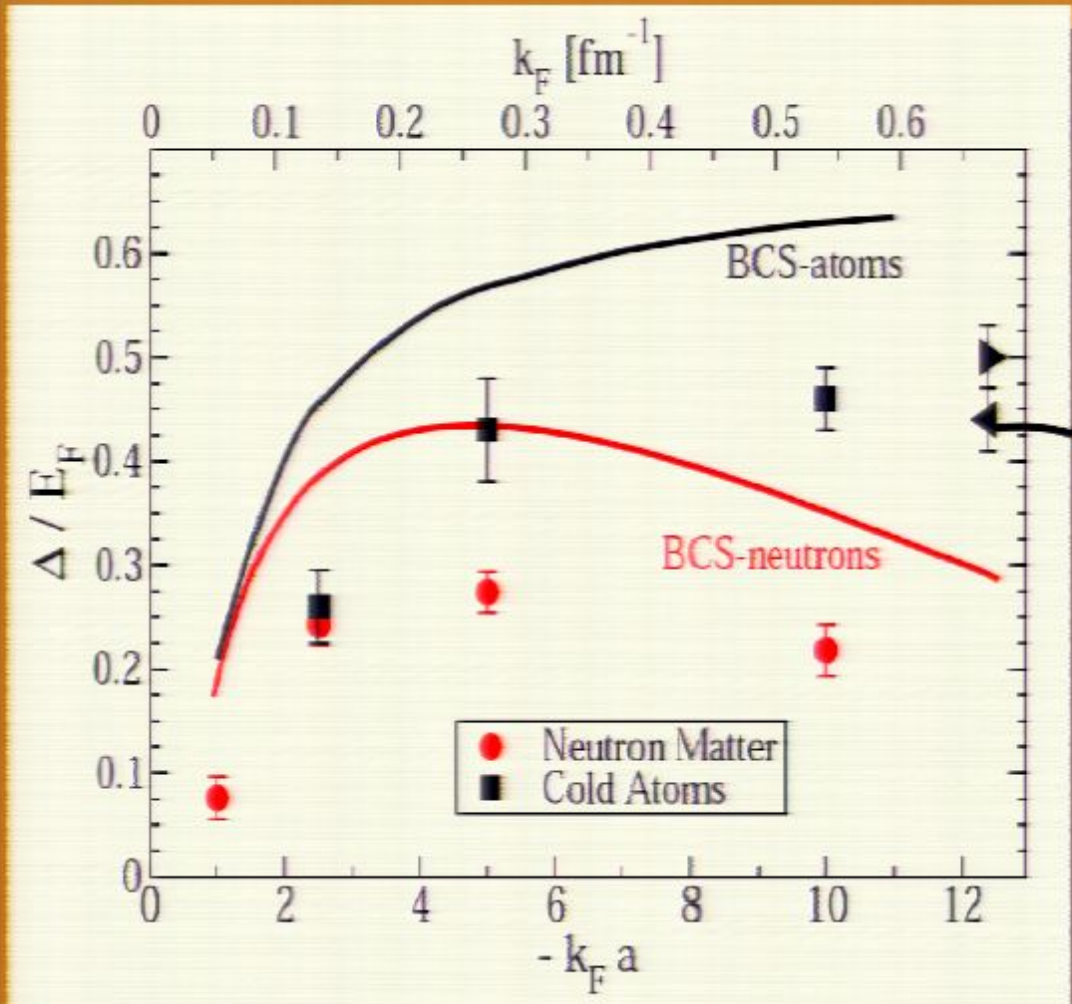
Pairing gaps: results



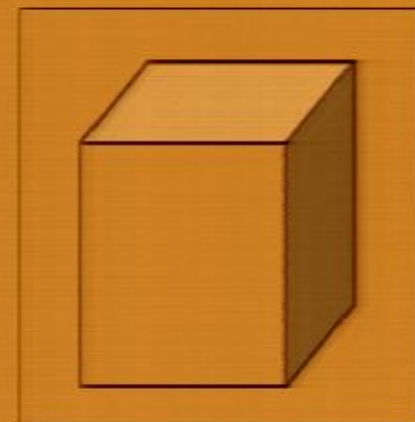
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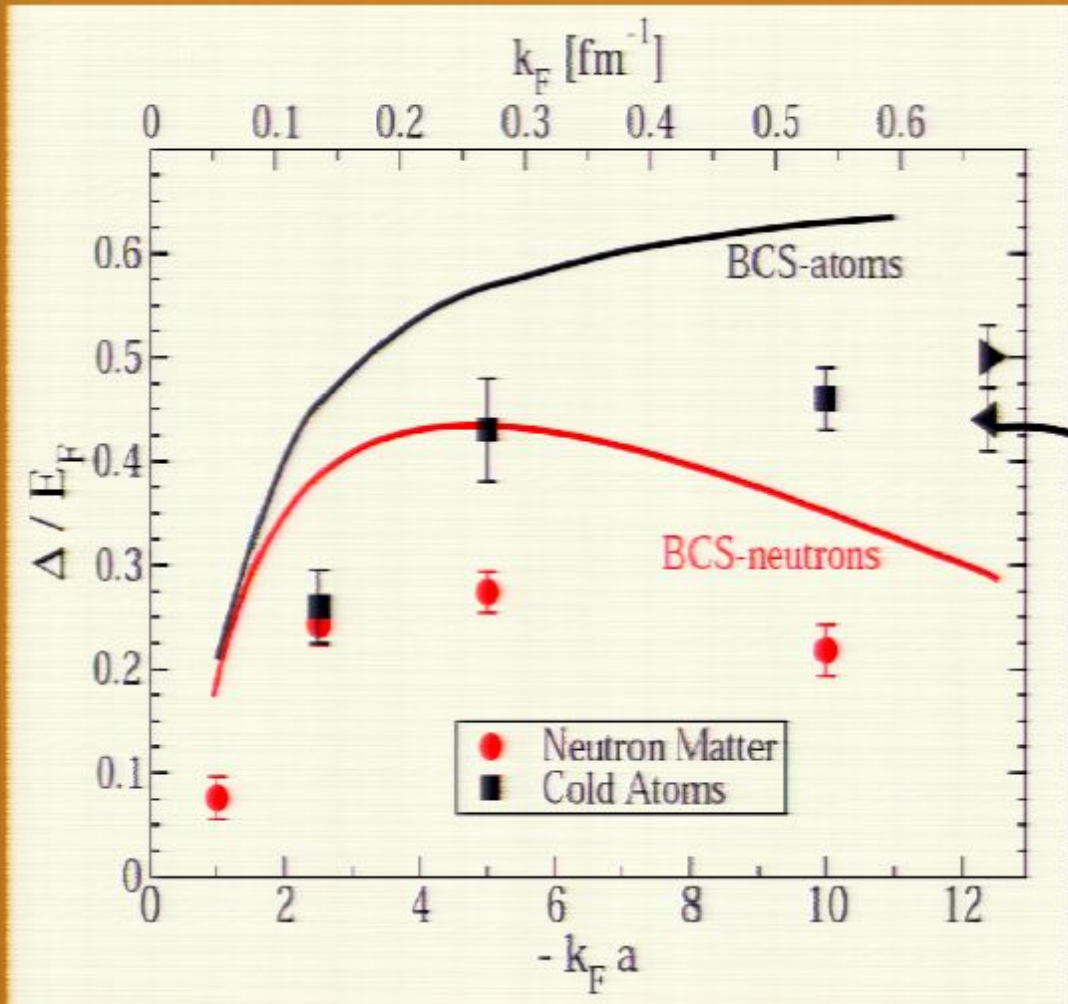
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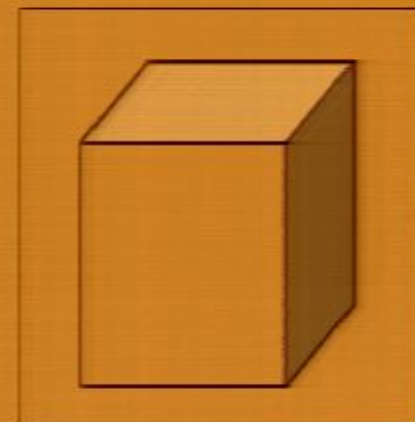
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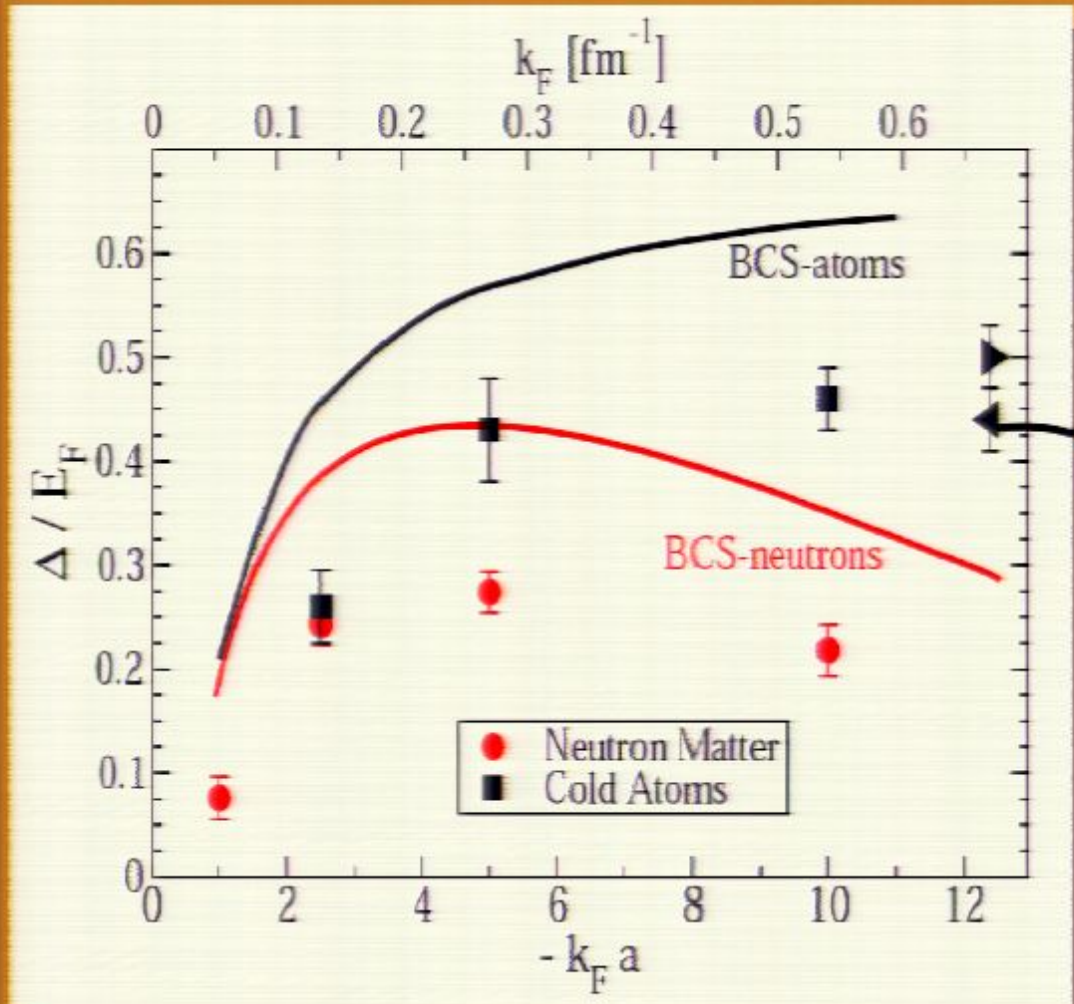
Pairing gaps: results



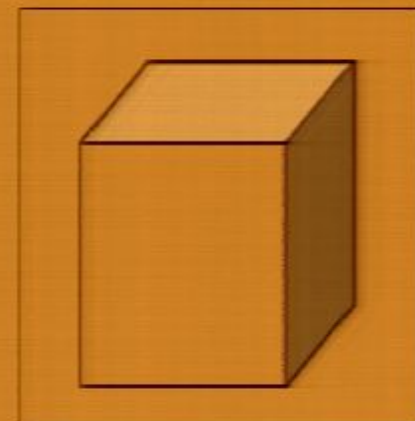
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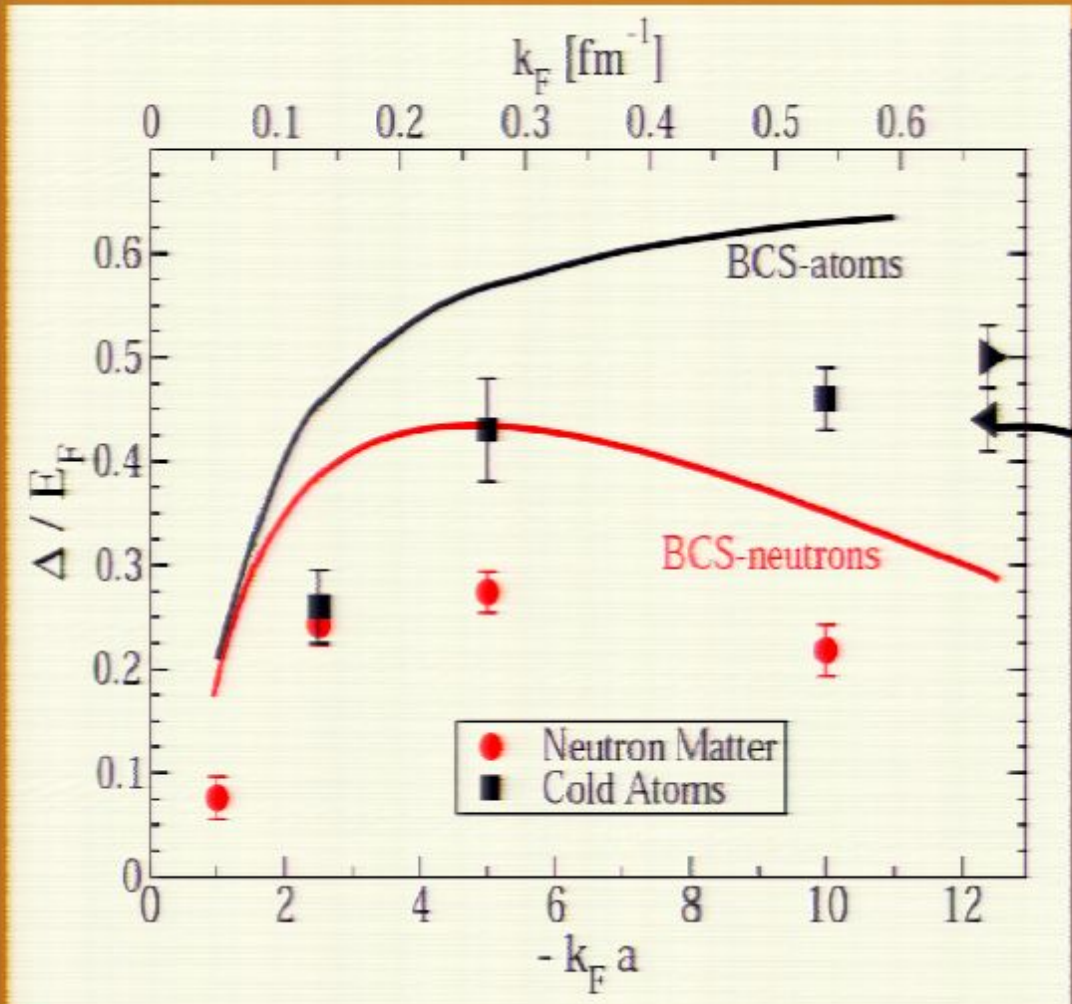
Pairing gaps: results



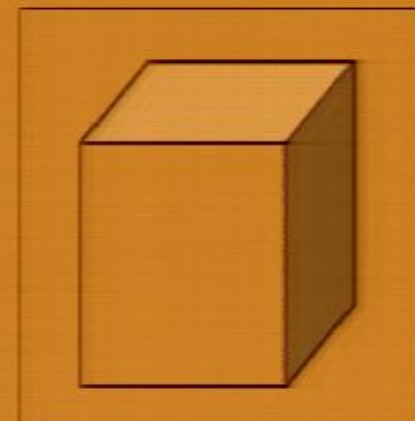
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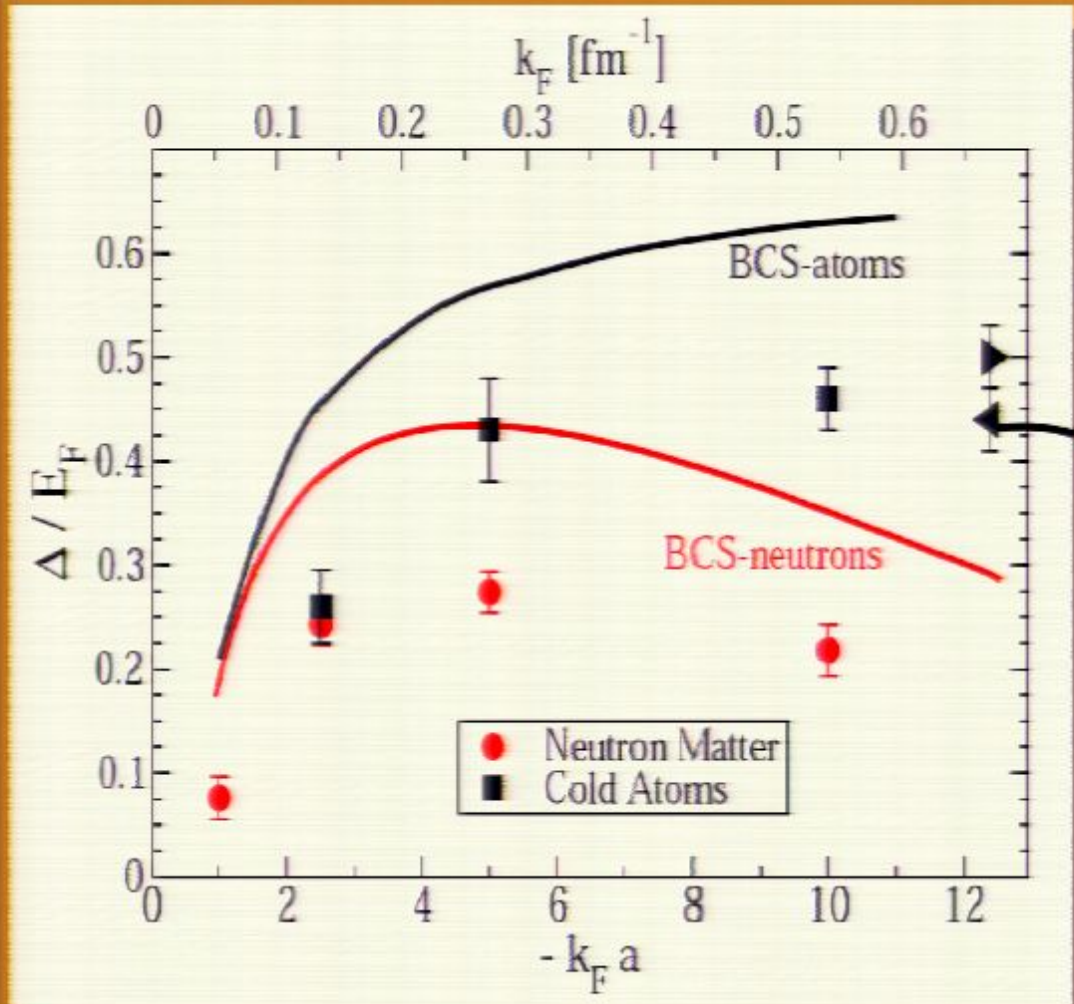
Pairing gaps: results



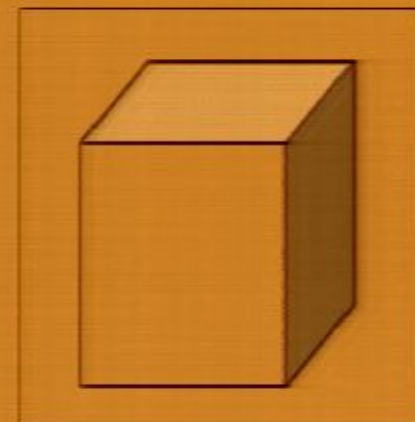
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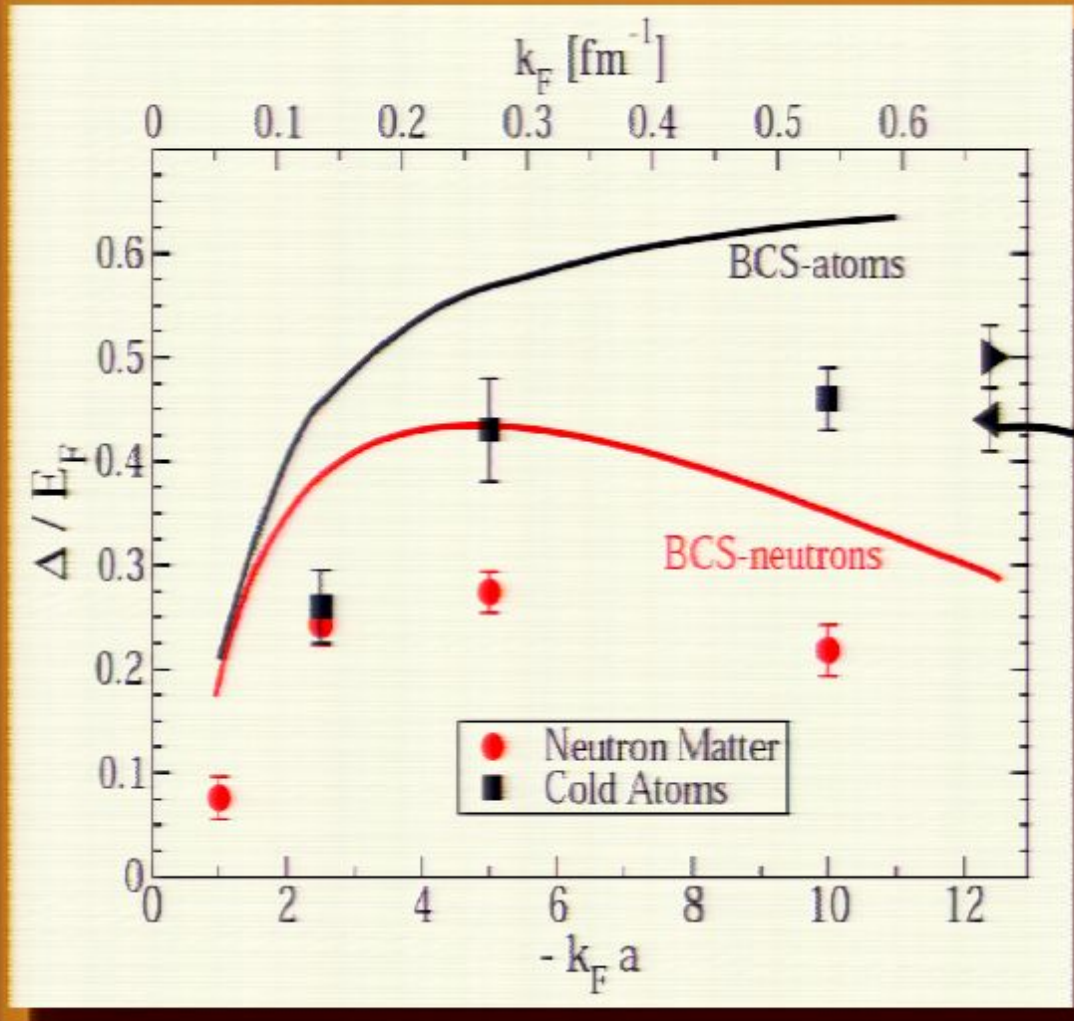
Pairing gaps: results



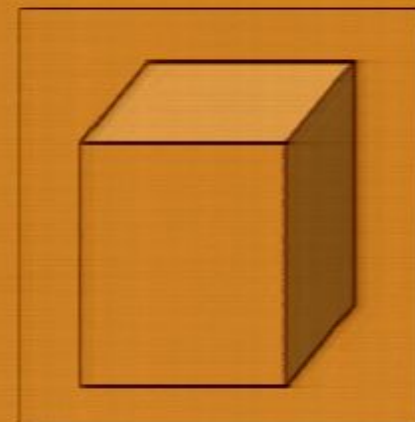
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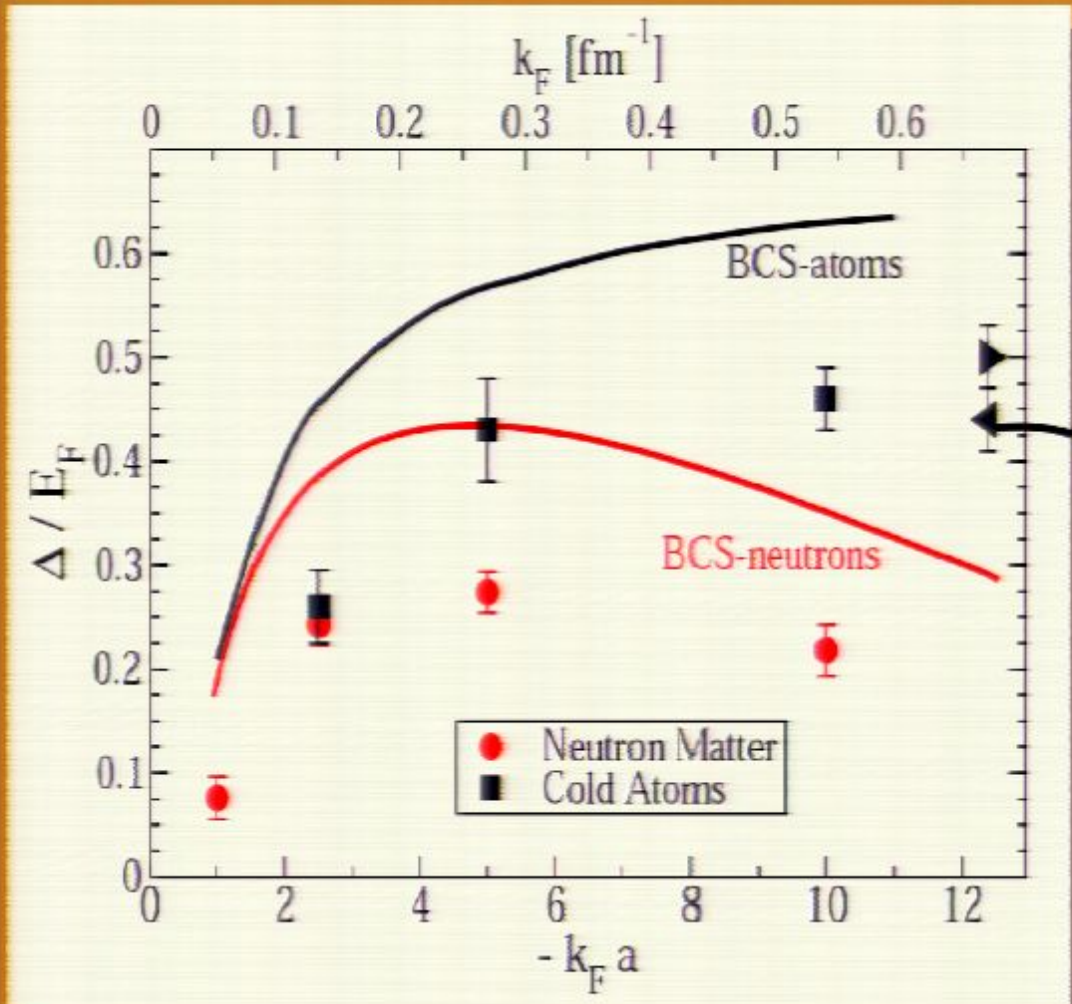
Pairing gaps: results



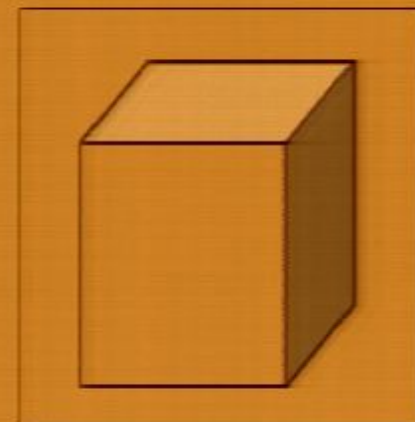
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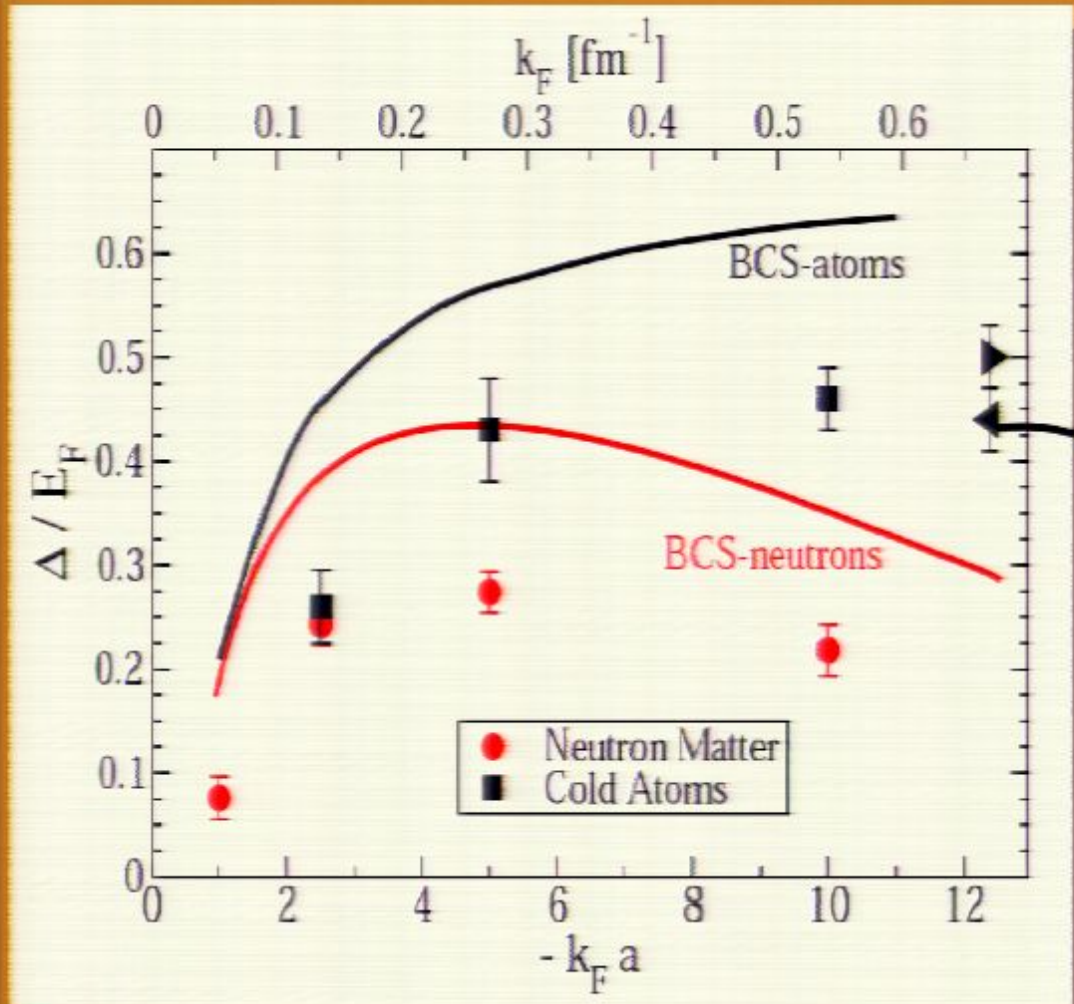
Pairing gaps: results



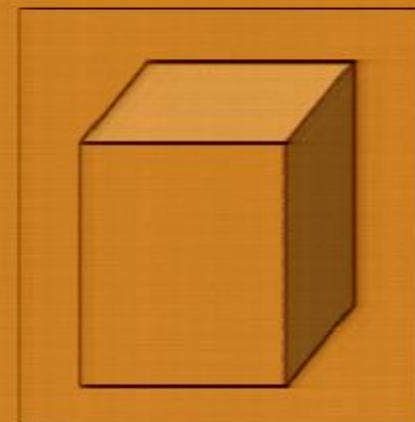
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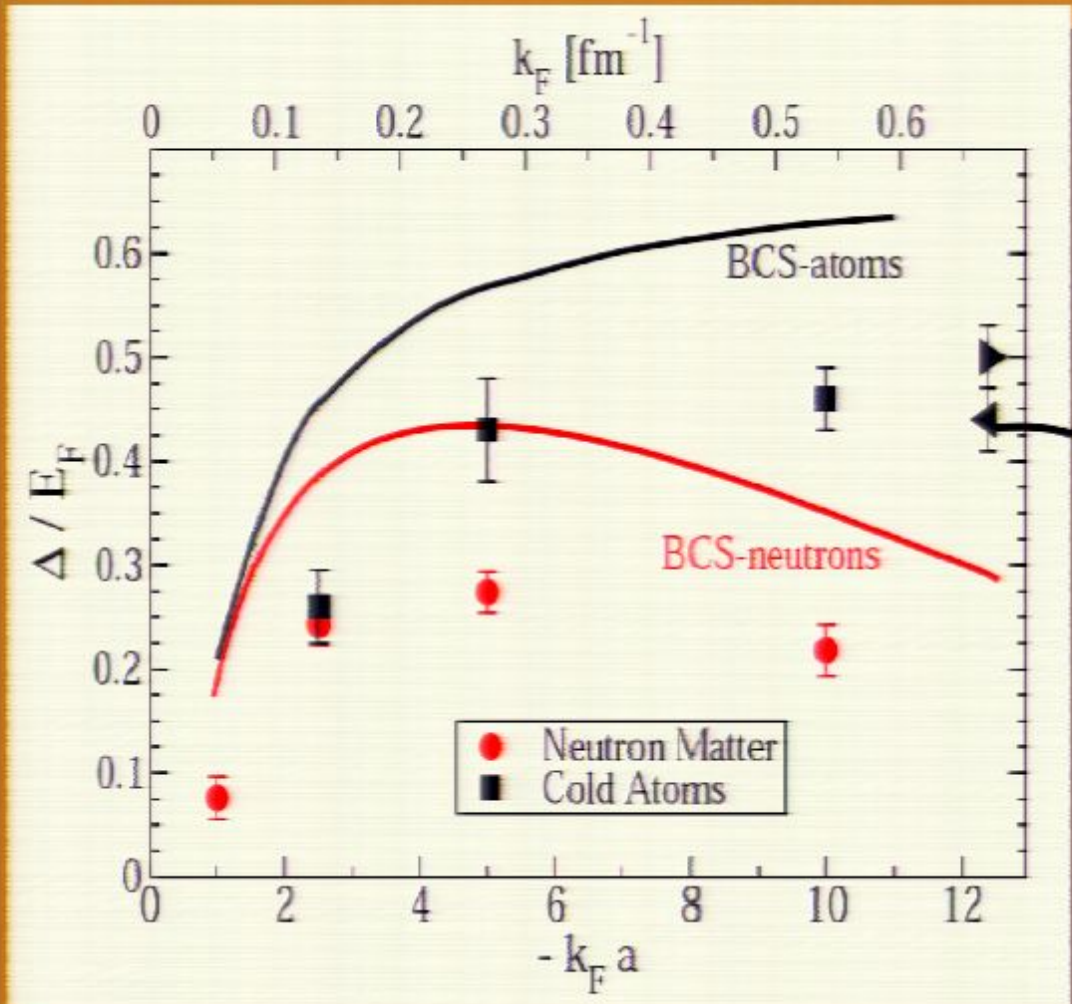
Pairing gaps: results



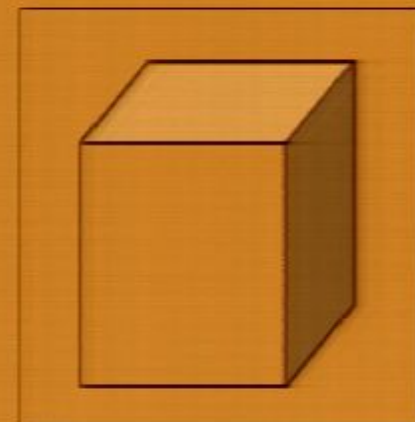
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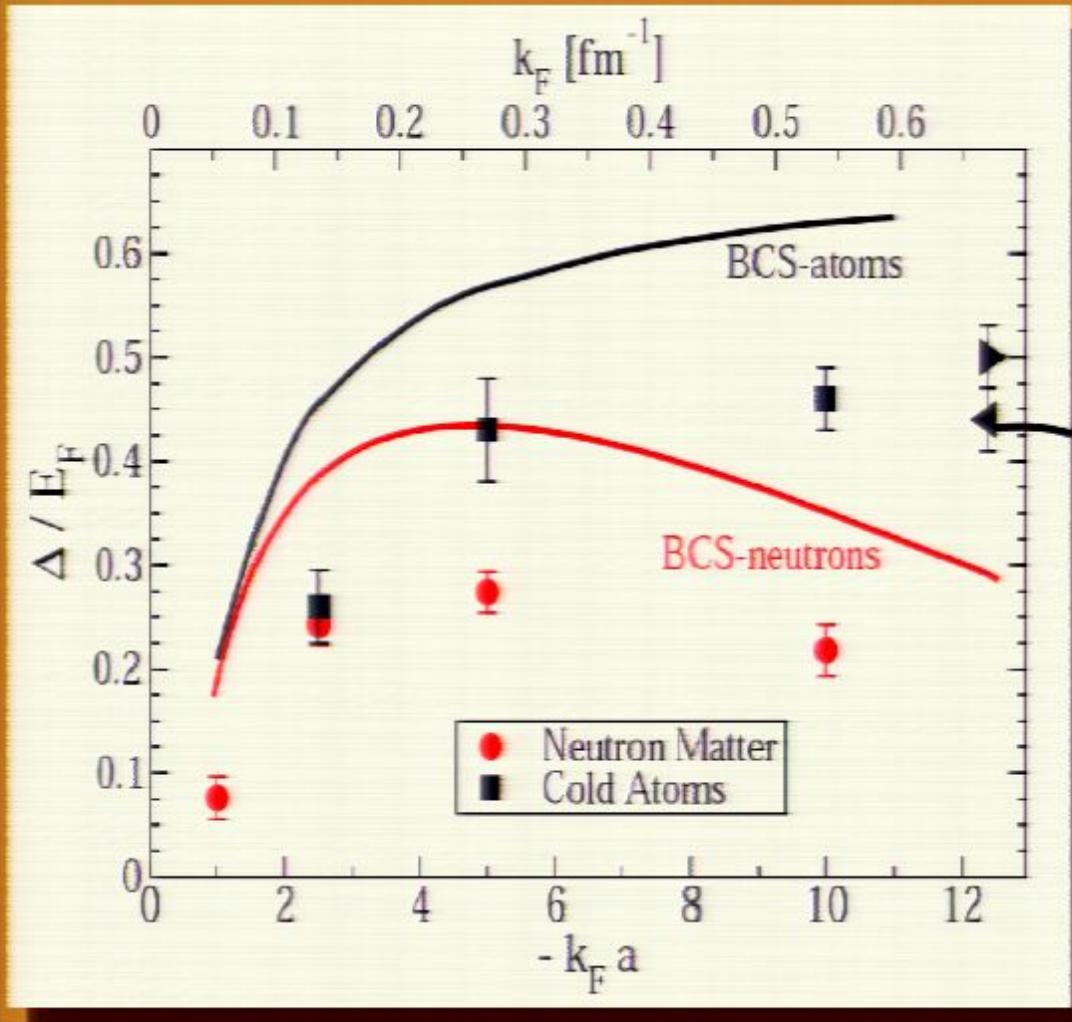
Pairing gaps: results



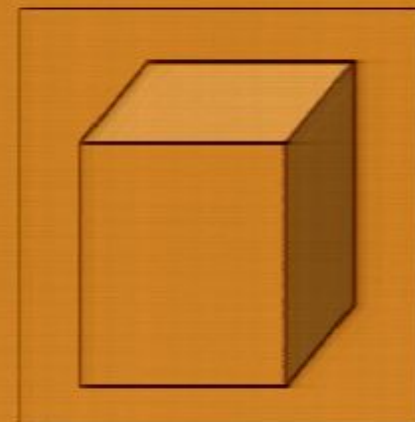
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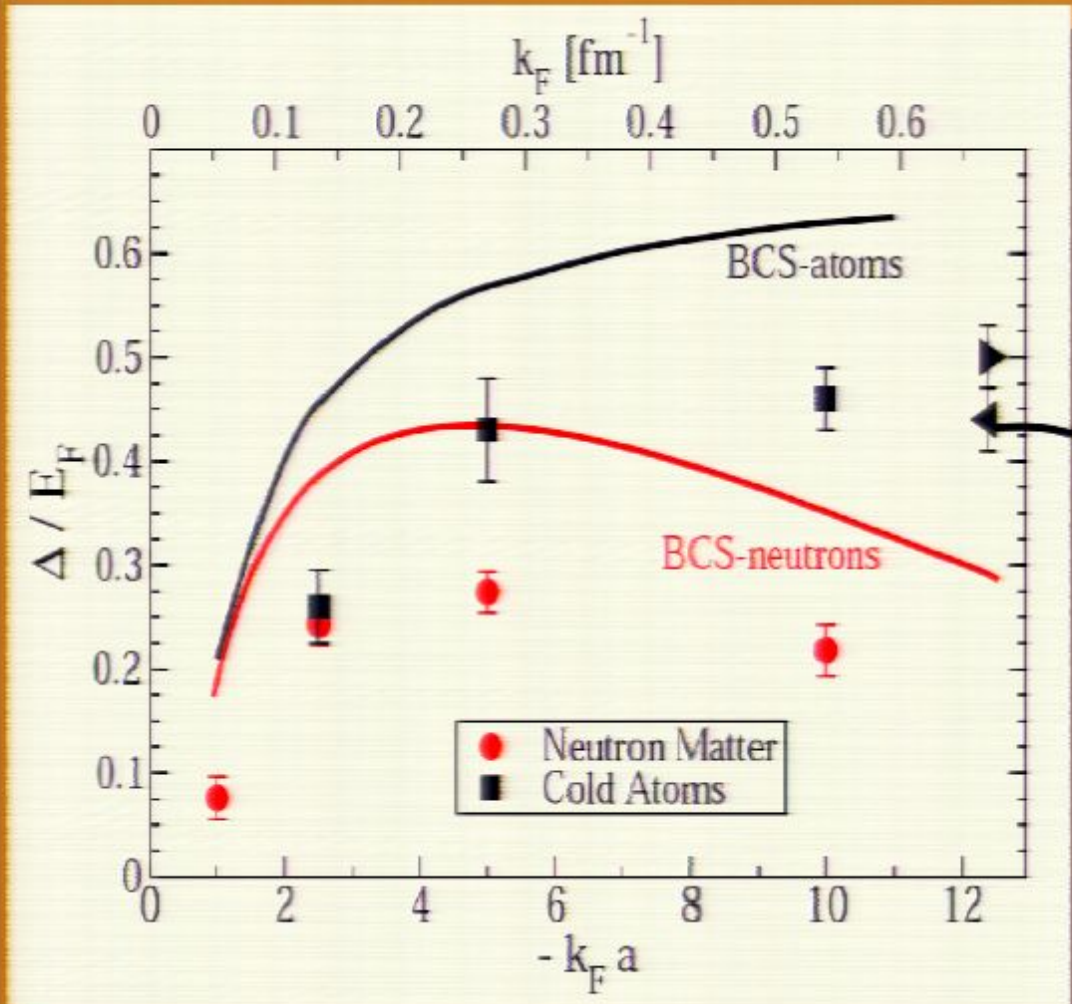
Pairing gaps: results



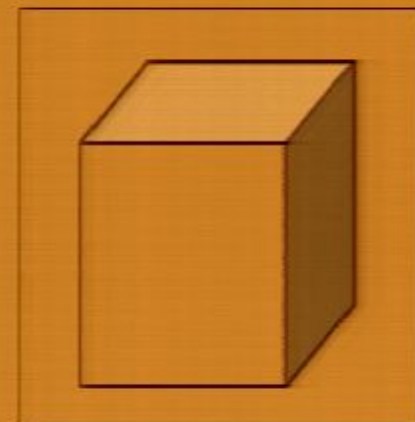
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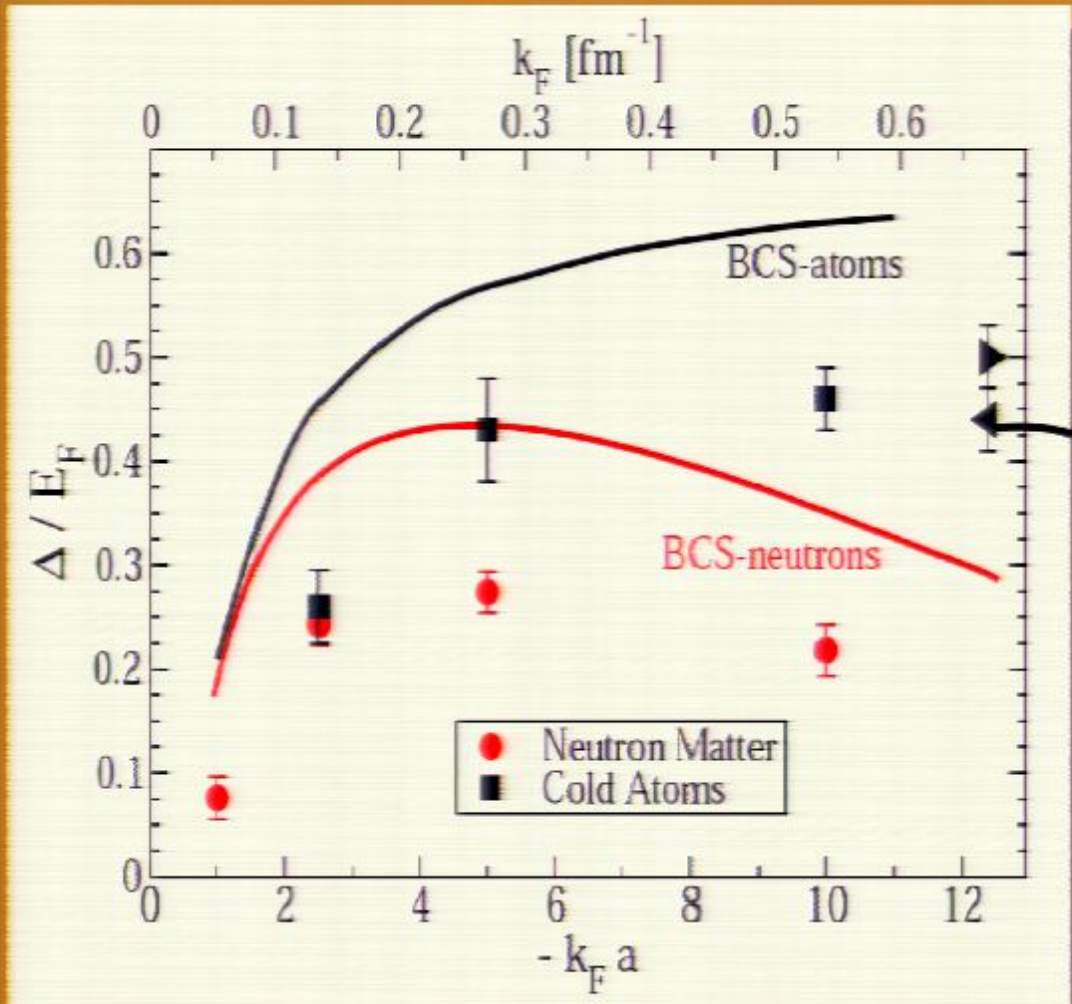
Pairing gaps: results



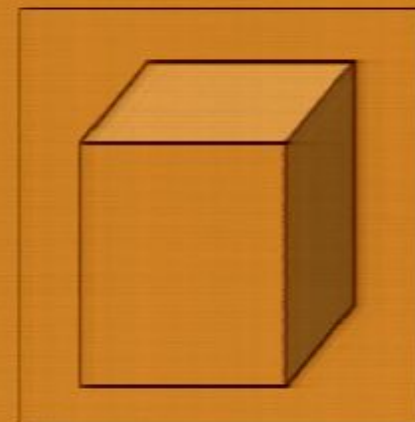
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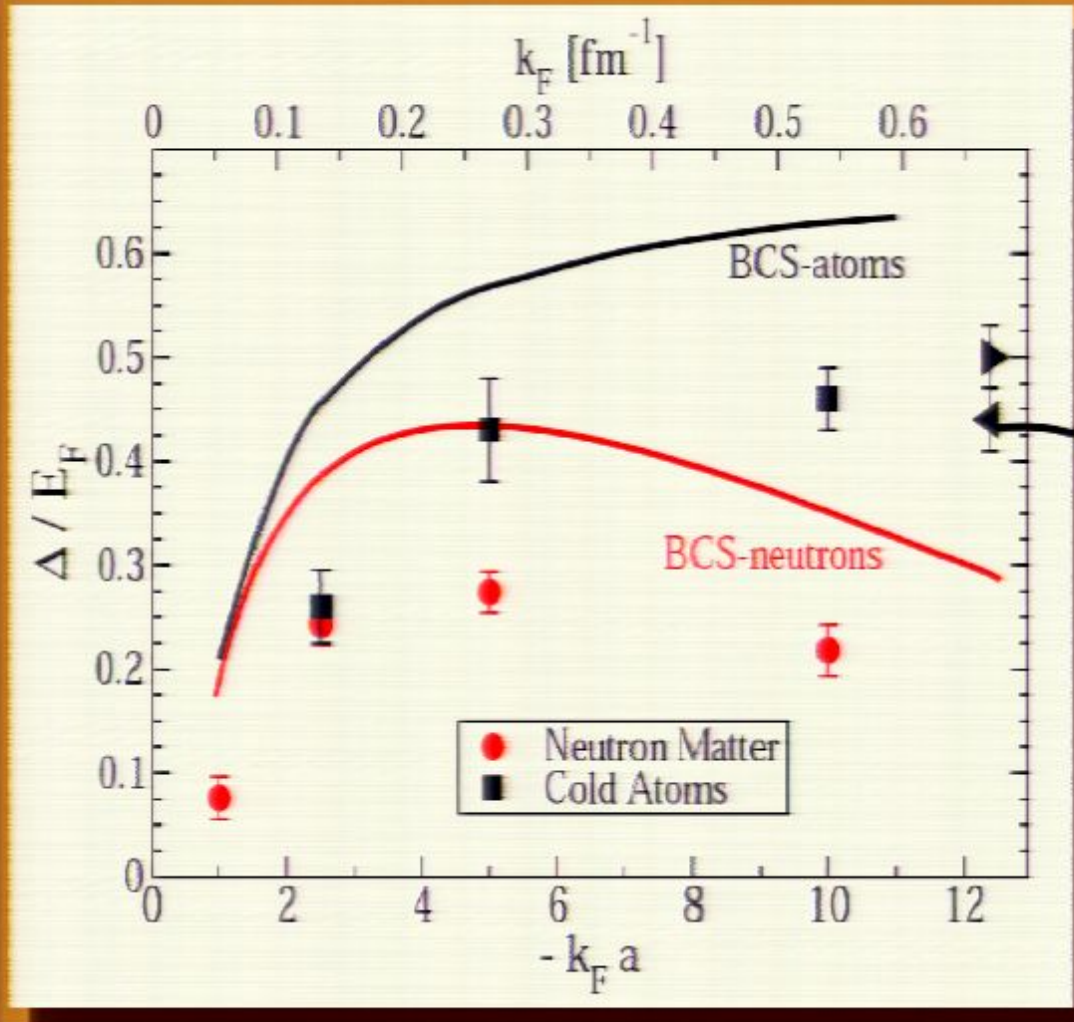
Pairing gaps: results



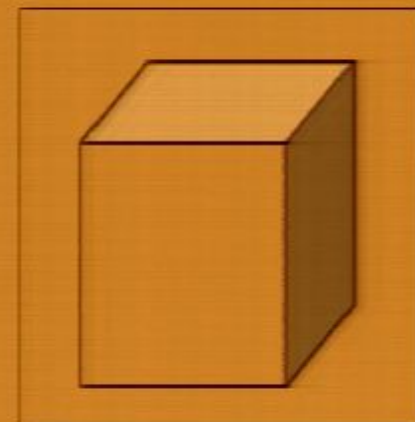
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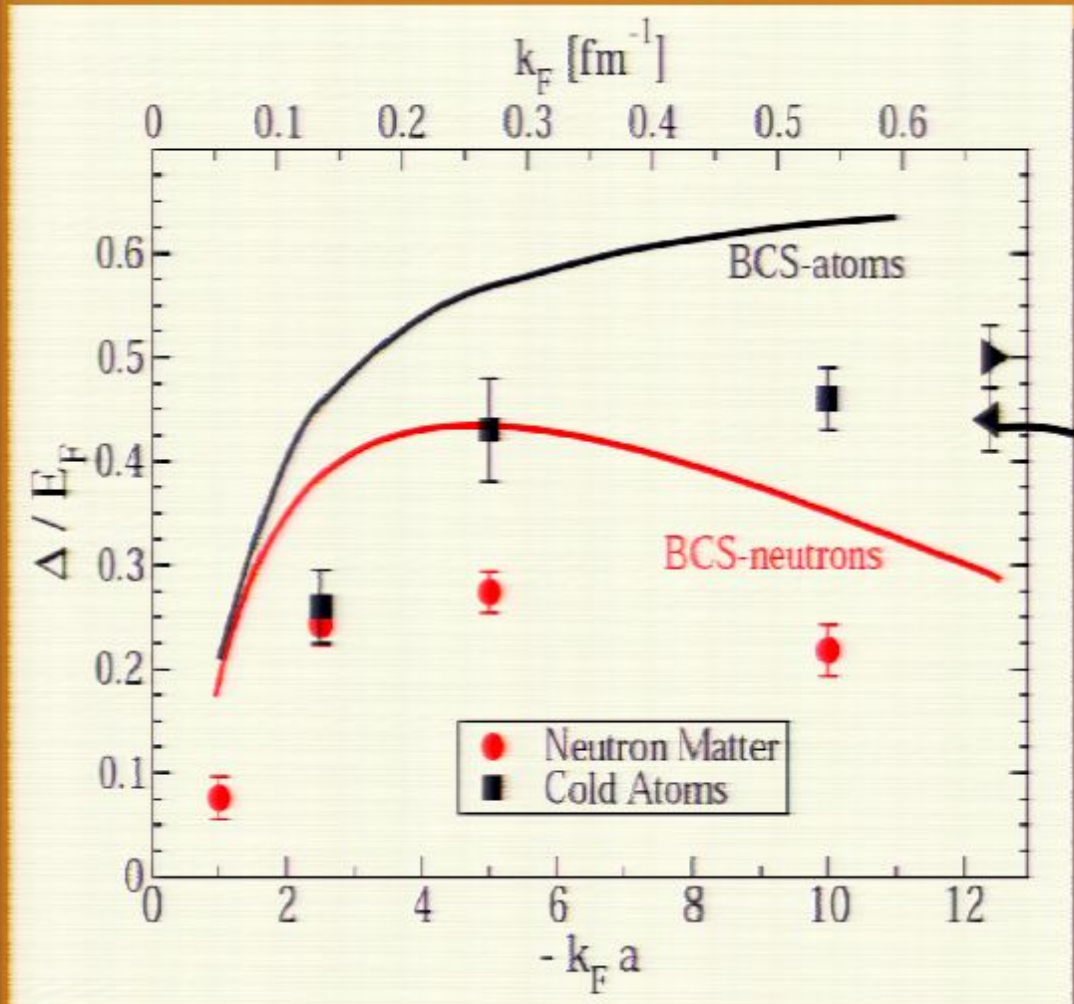
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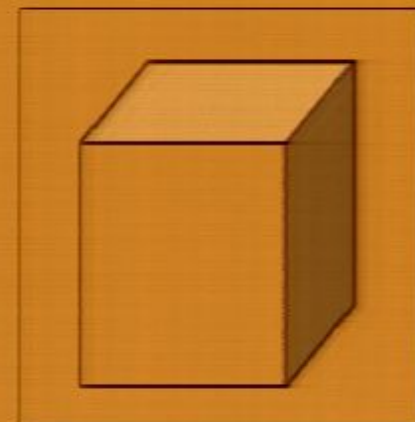
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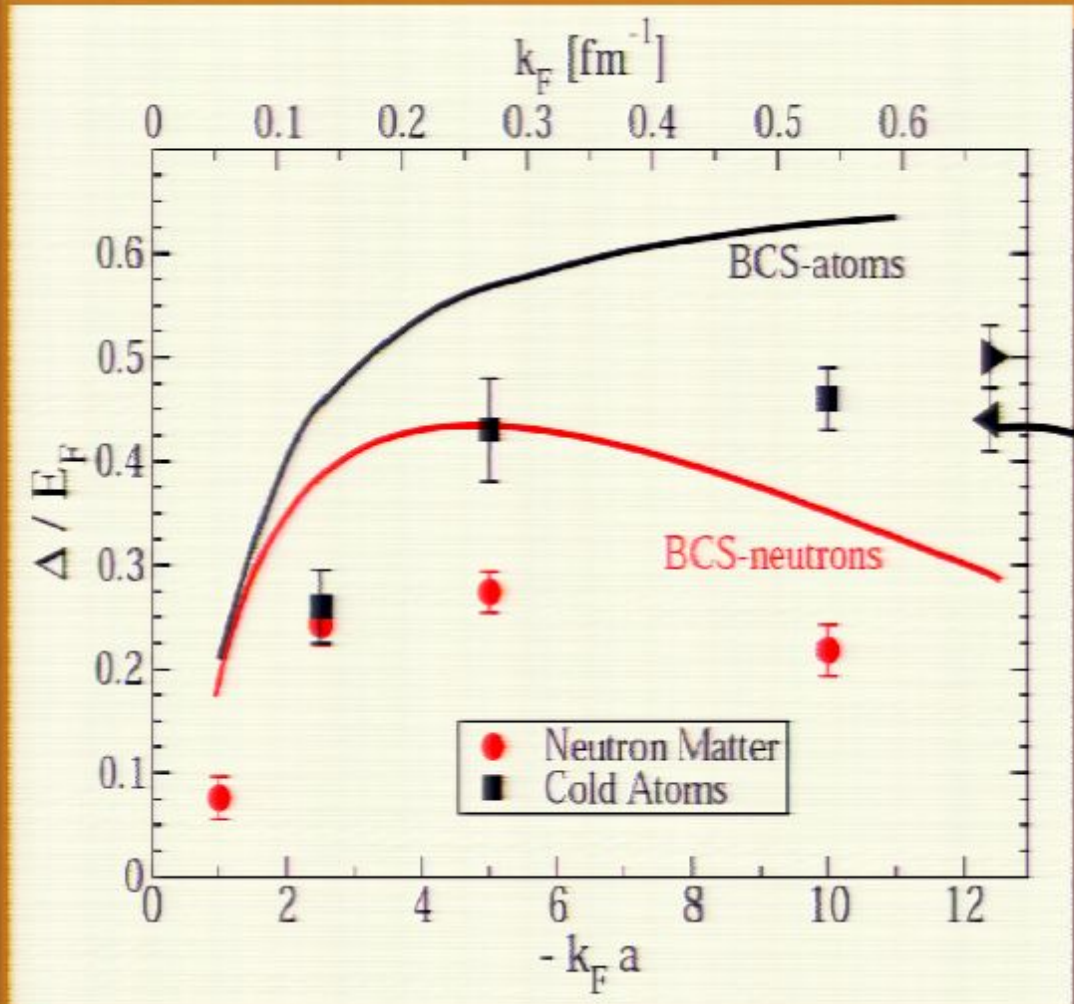
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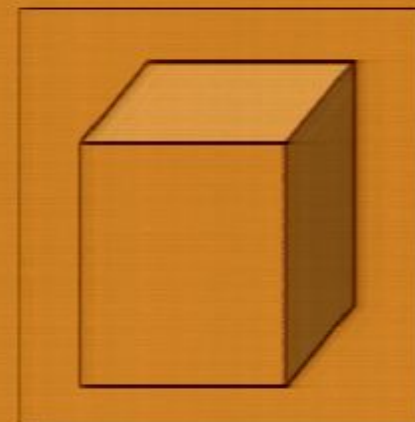
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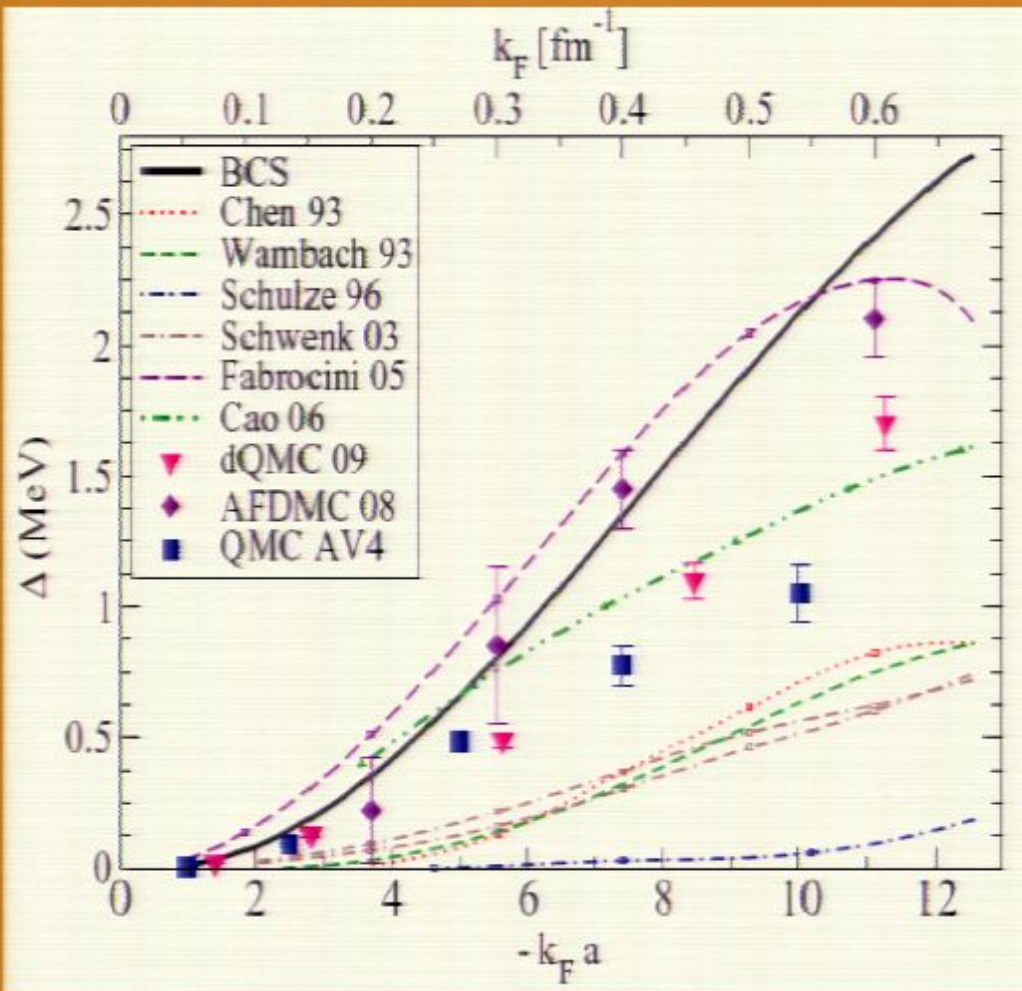
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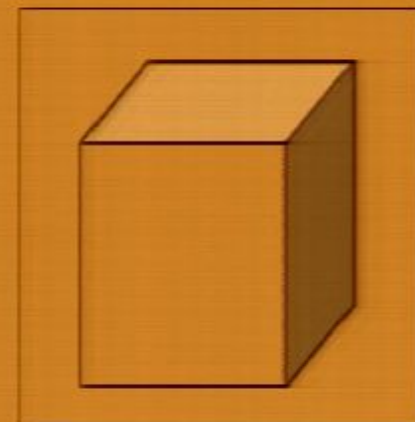
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Pairing gaps: comparison

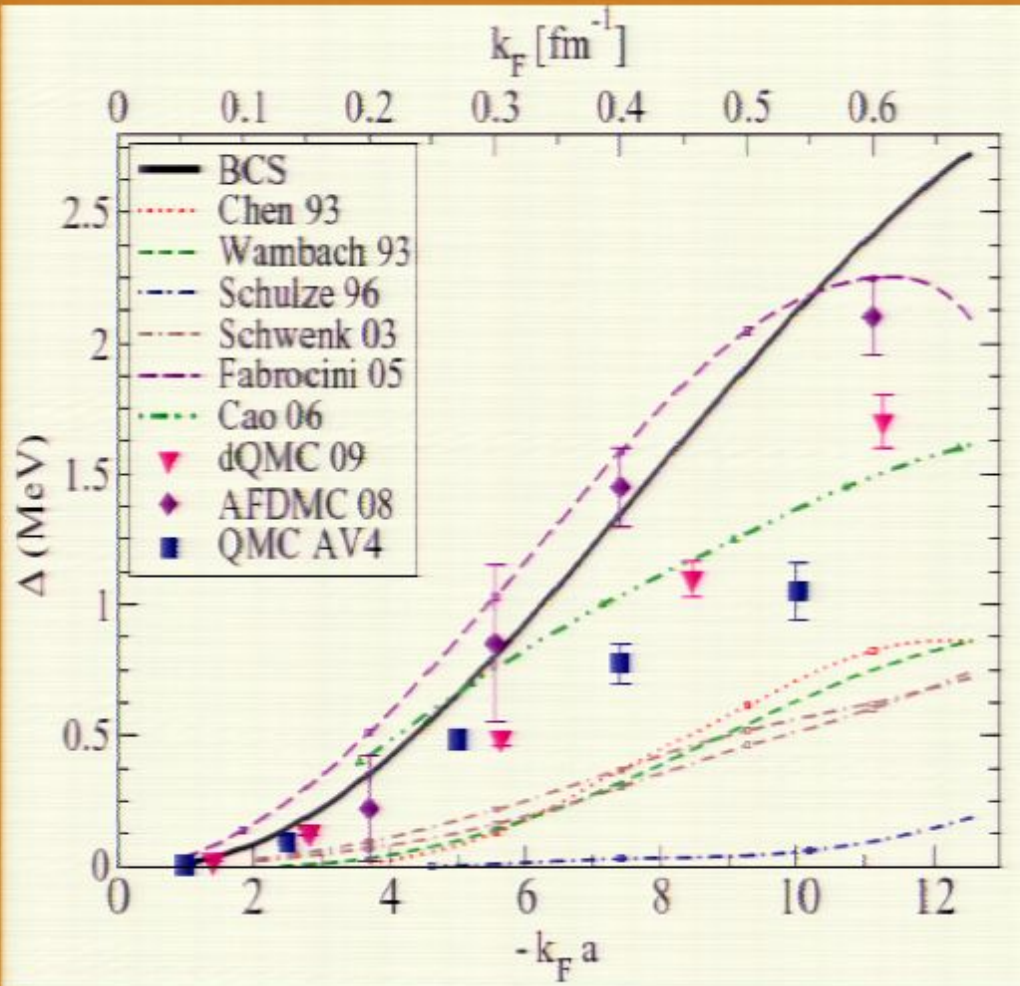


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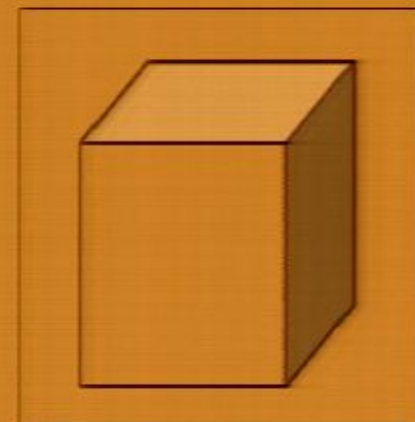


A. Gezerlis and J. Carlson, Phys. Rev. C 81, 025803 (2010)

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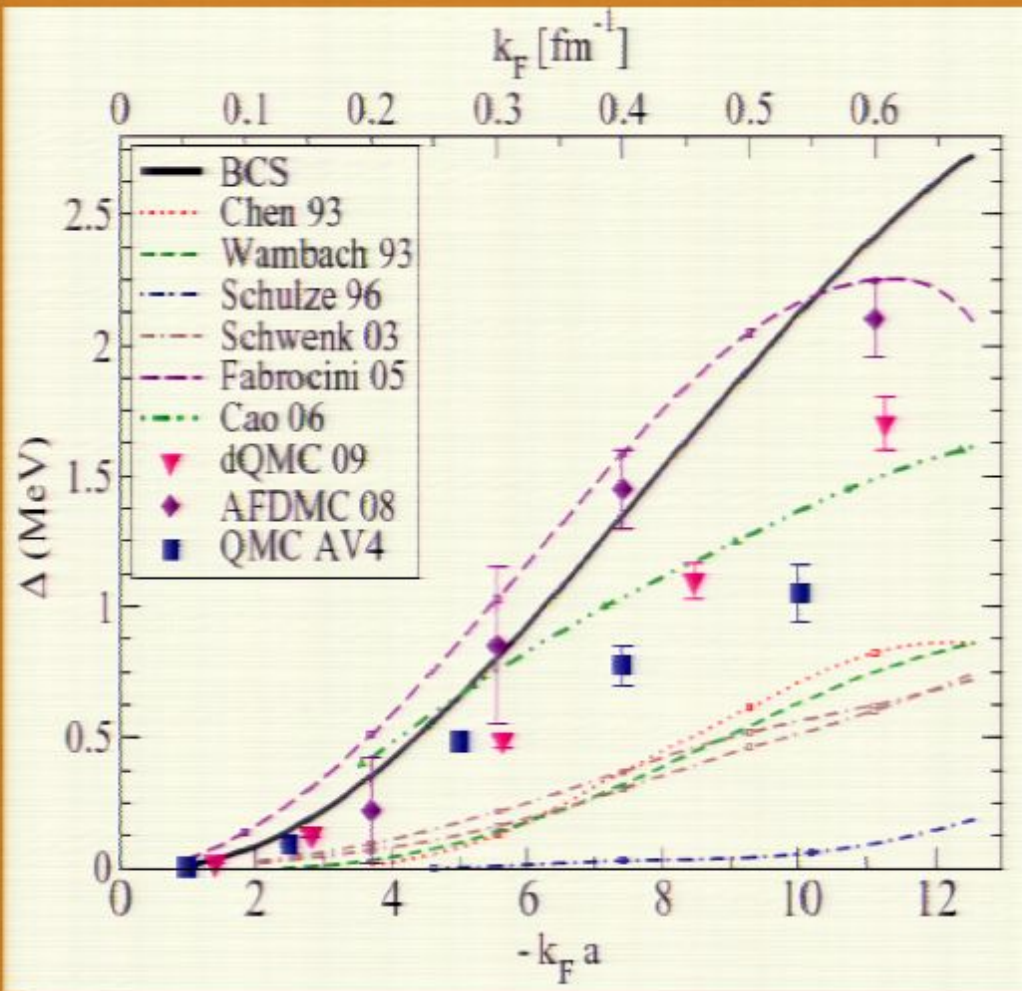


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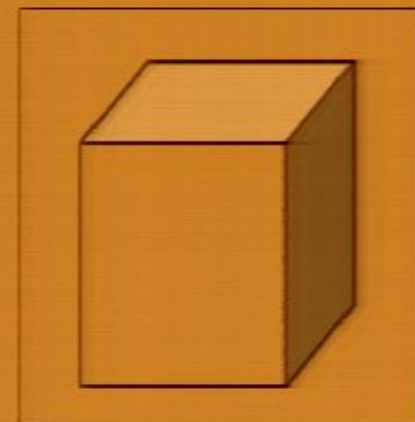


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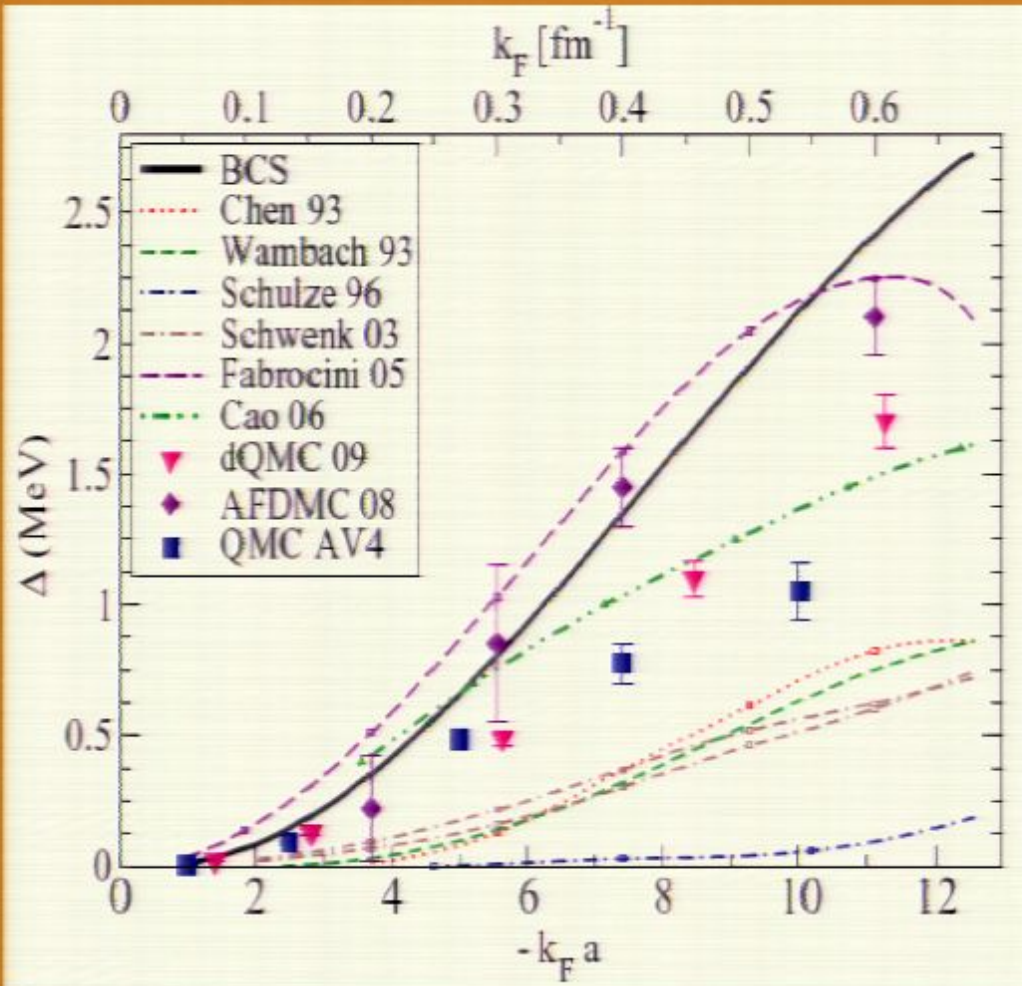
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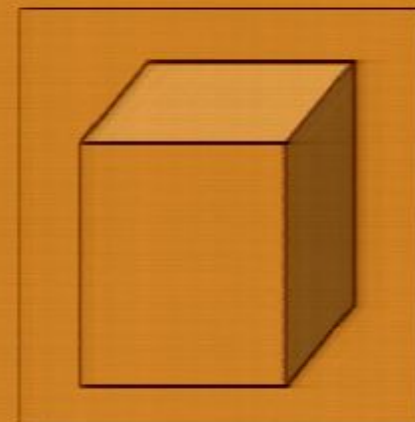
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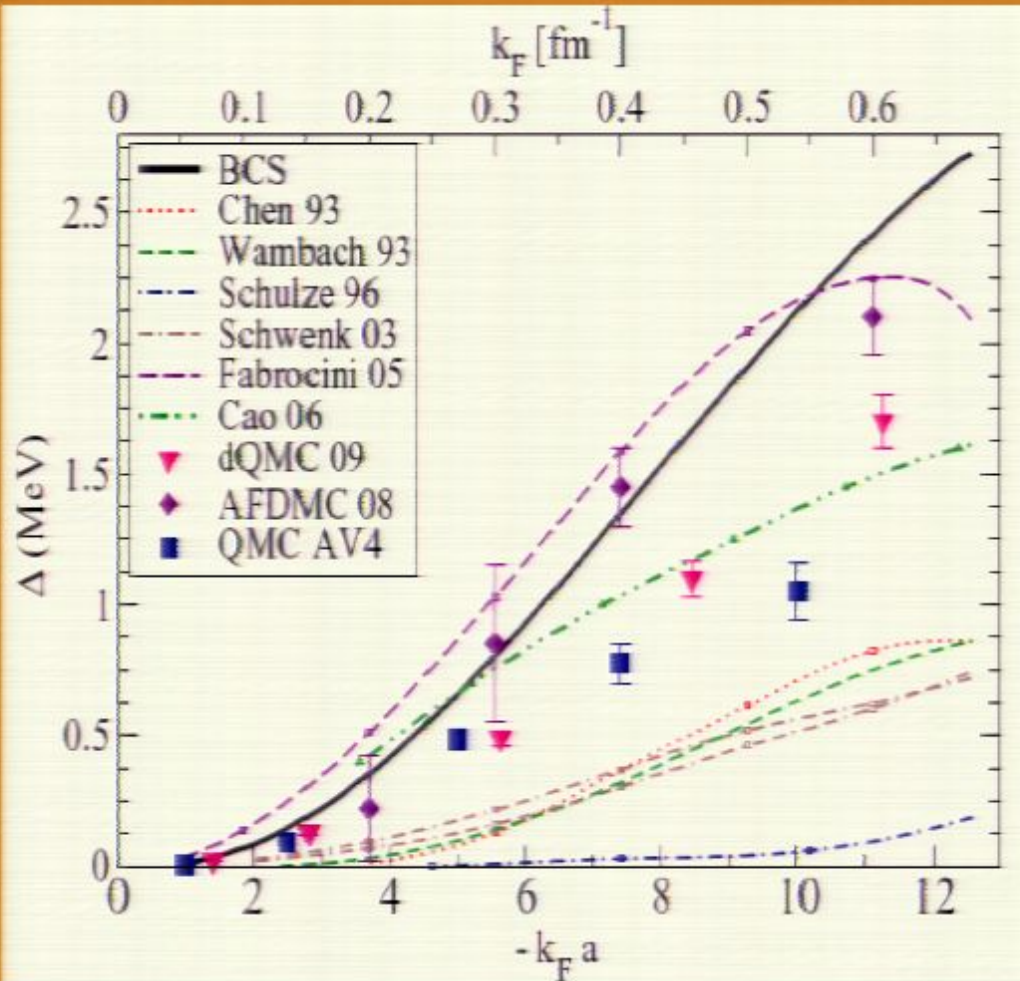


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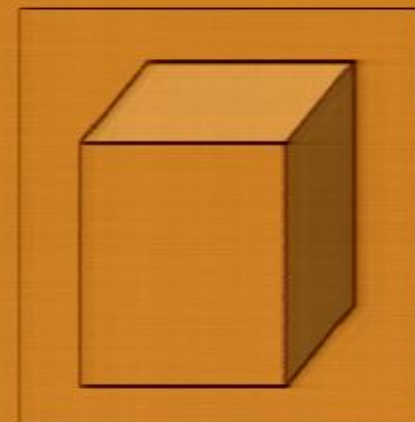


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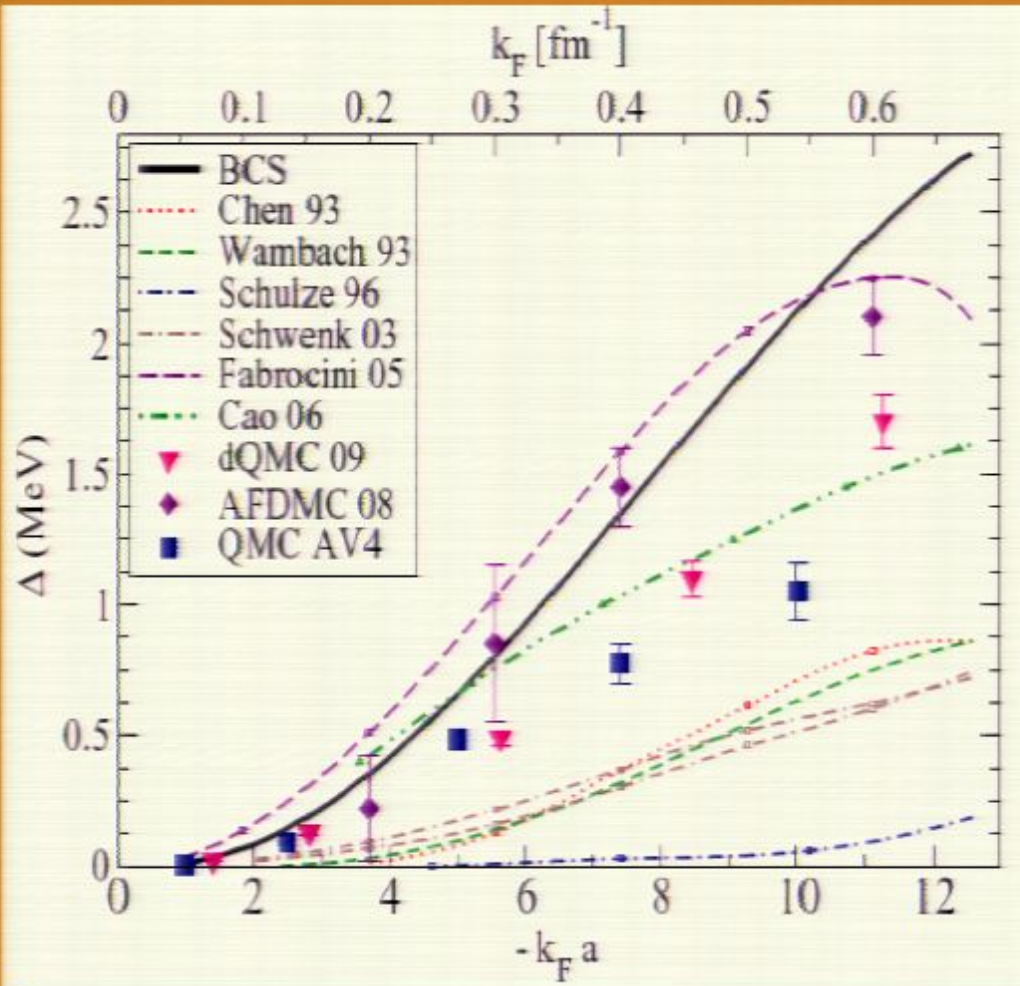


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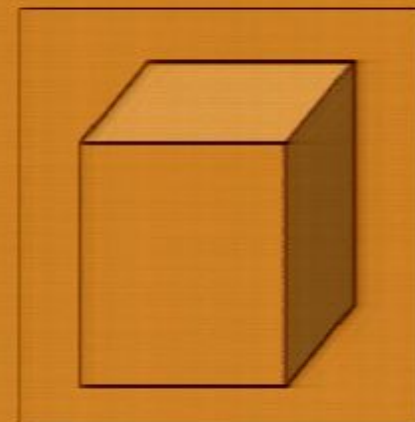


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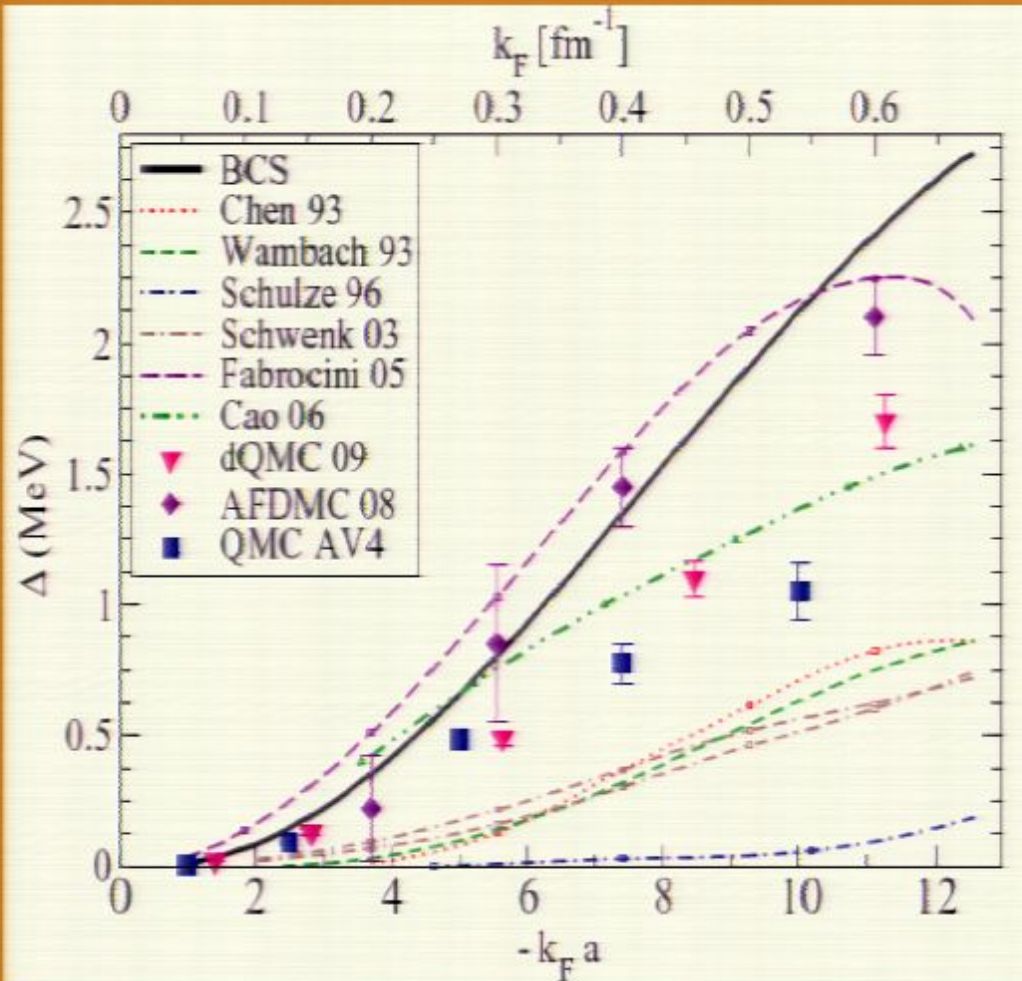


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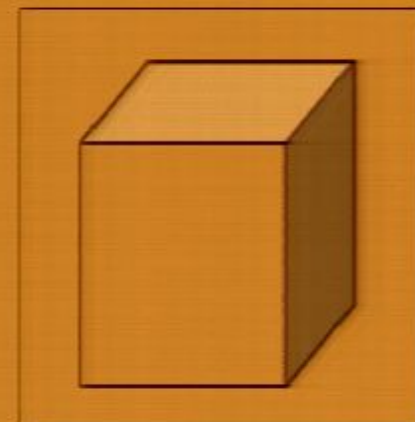


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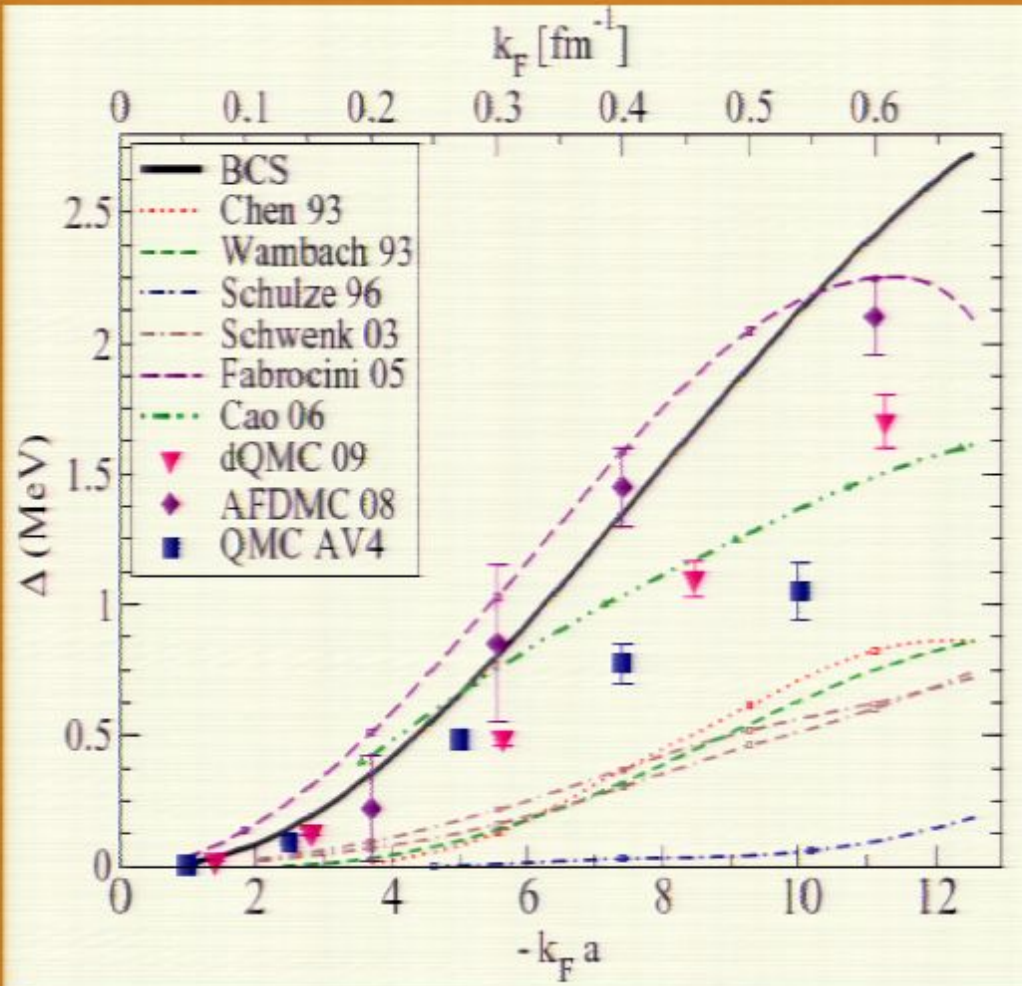
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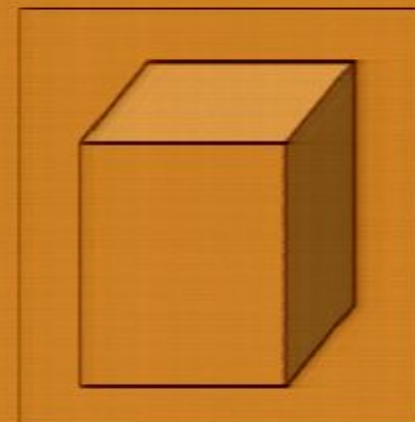
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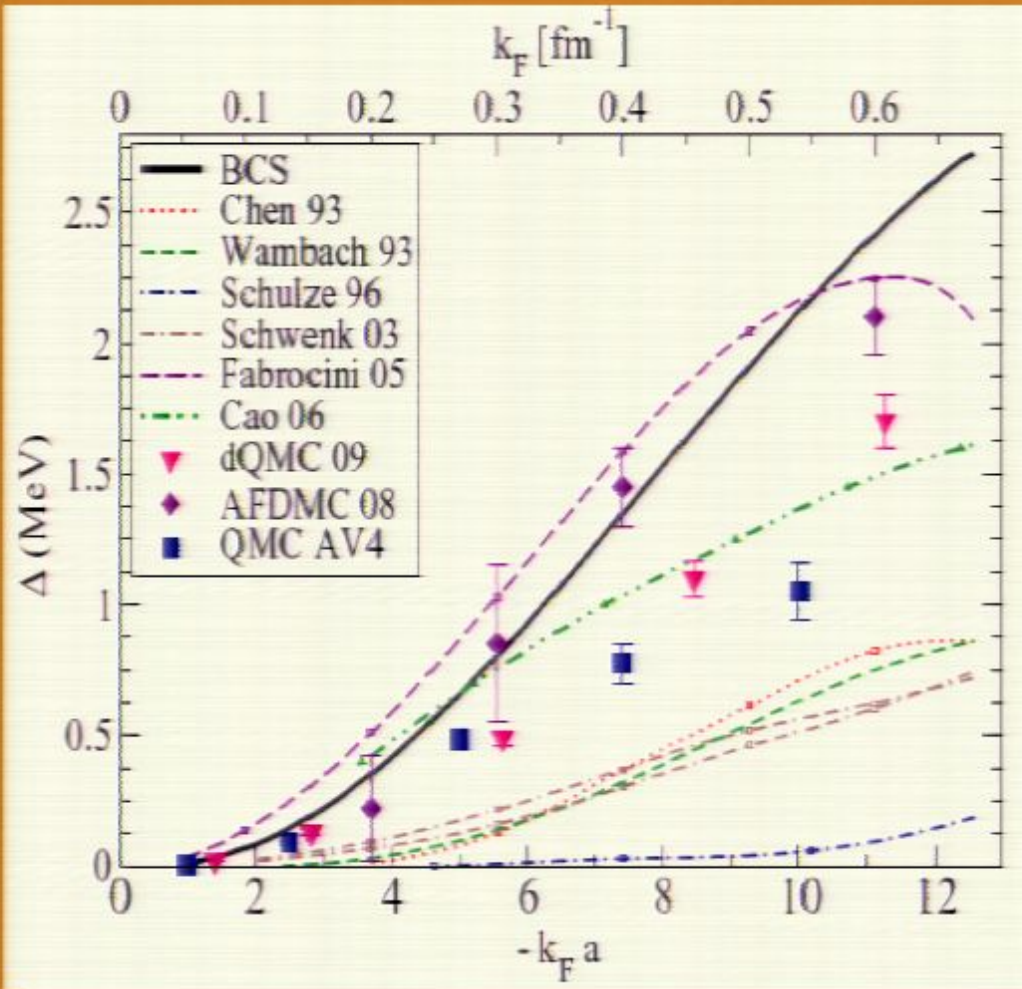


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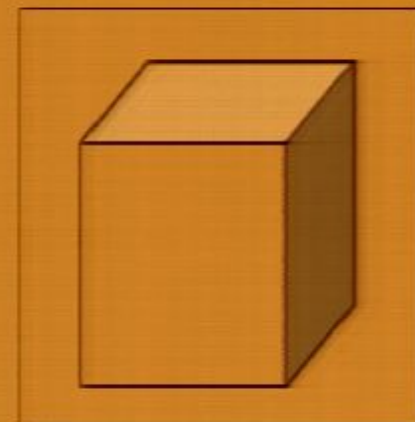


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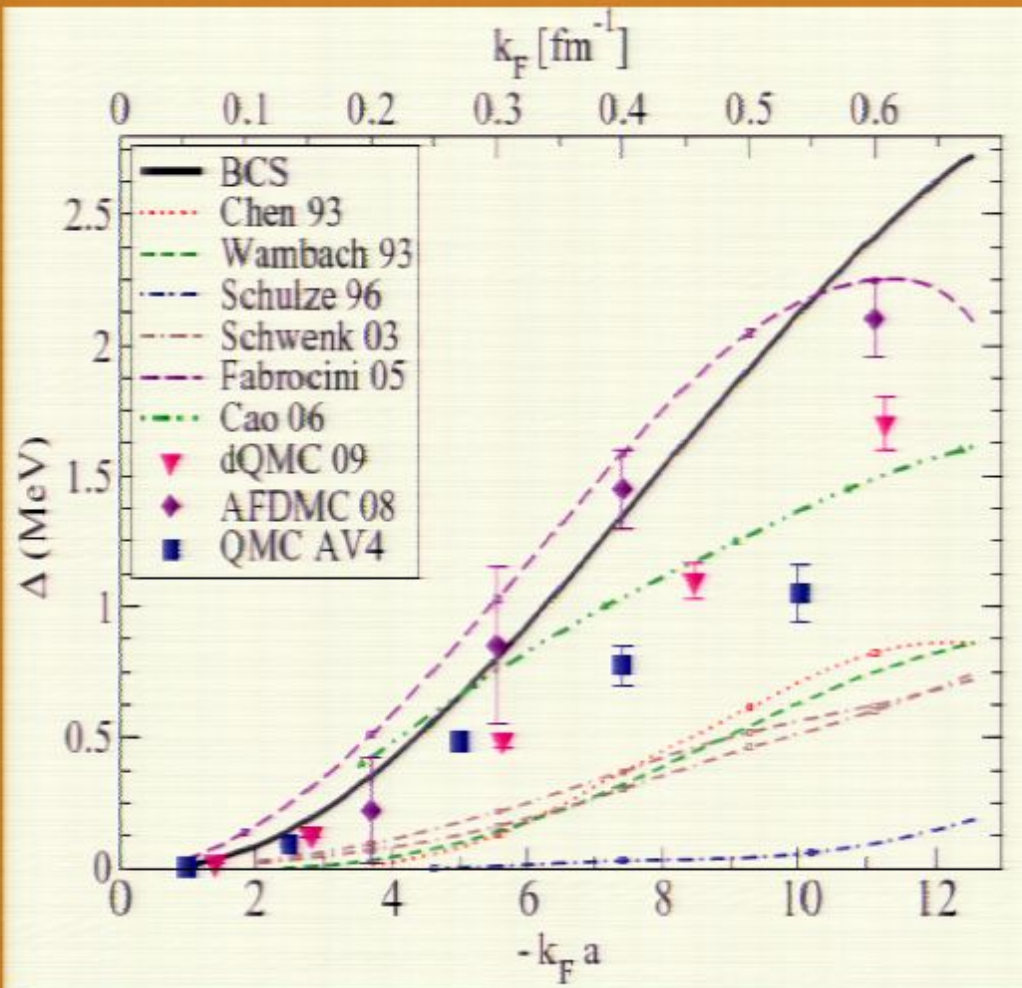


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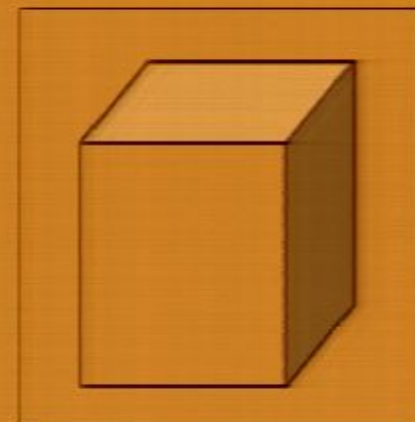


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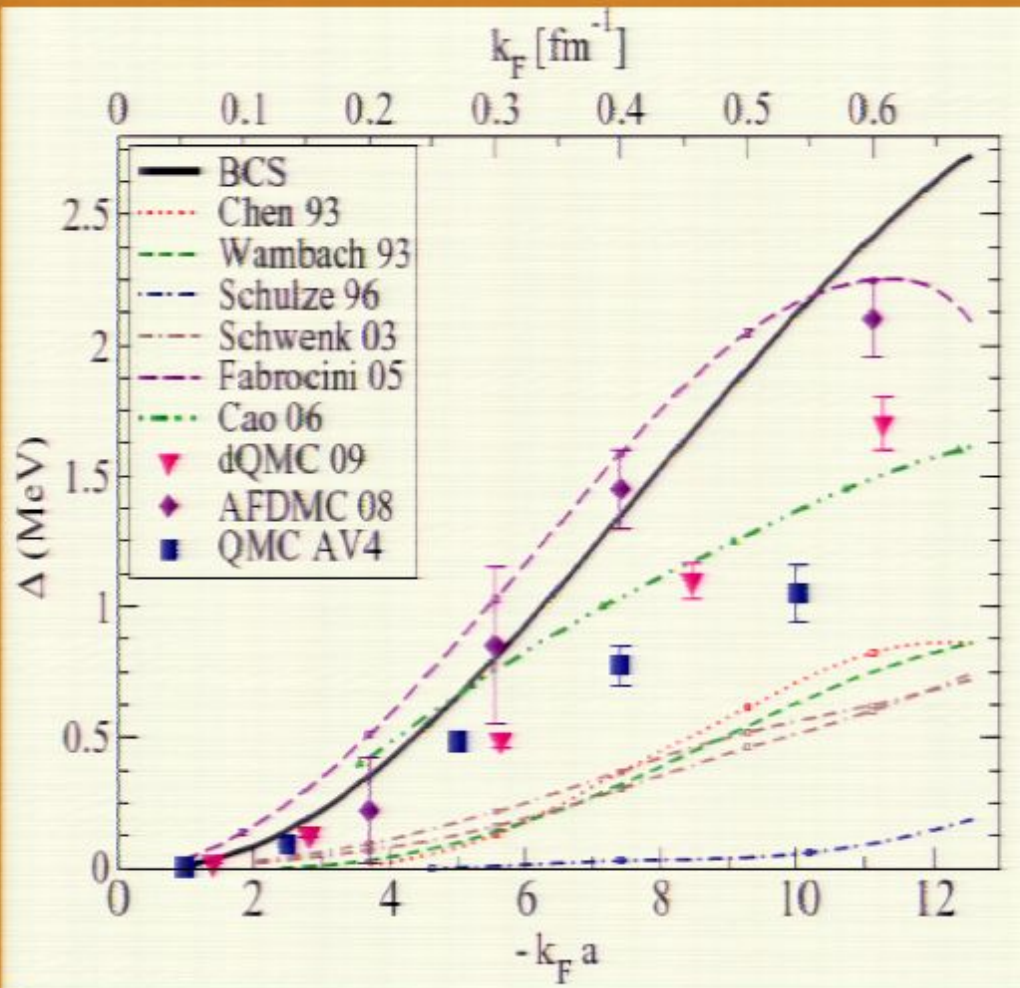


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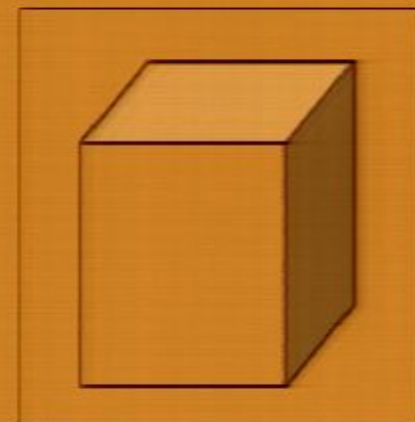


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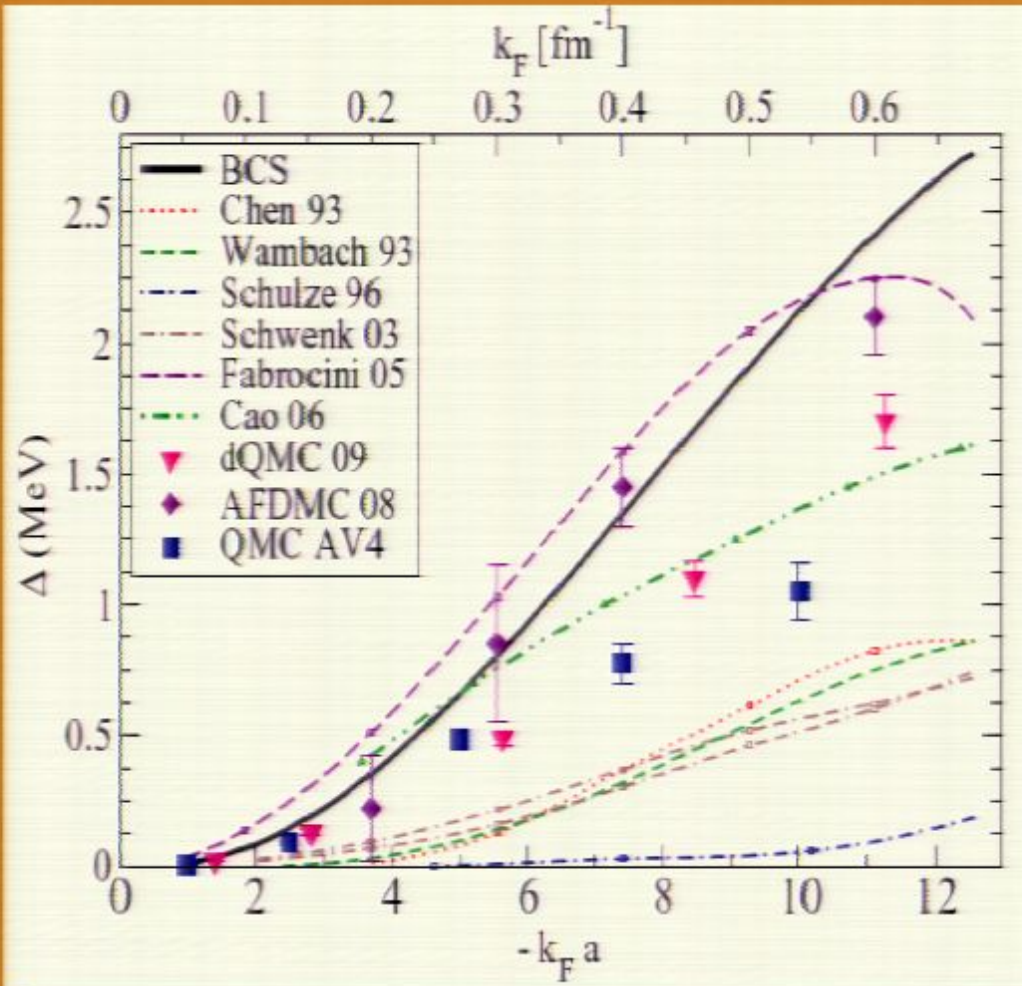


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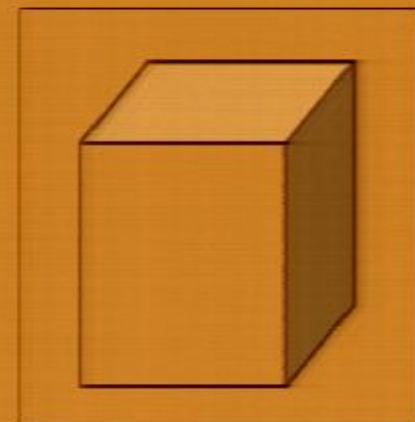


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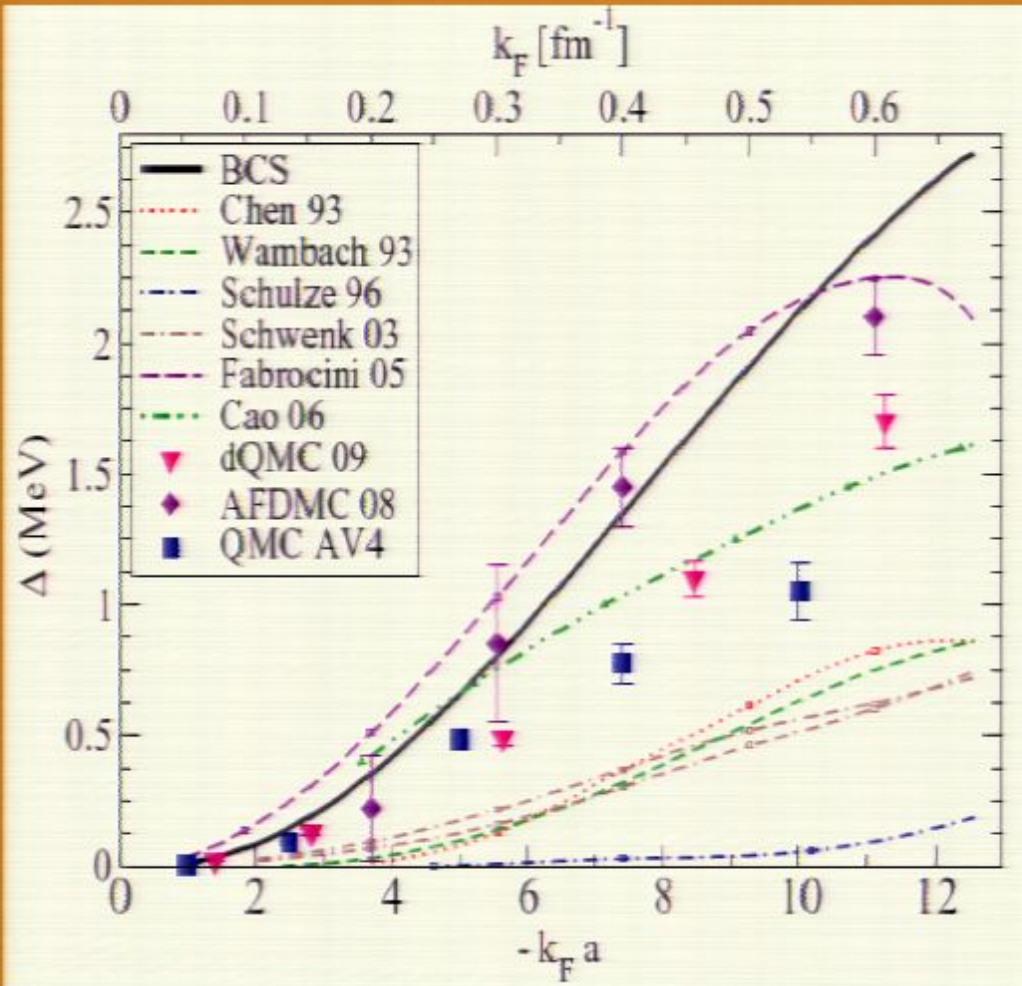


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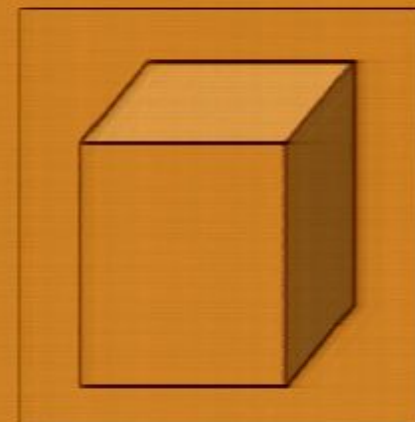


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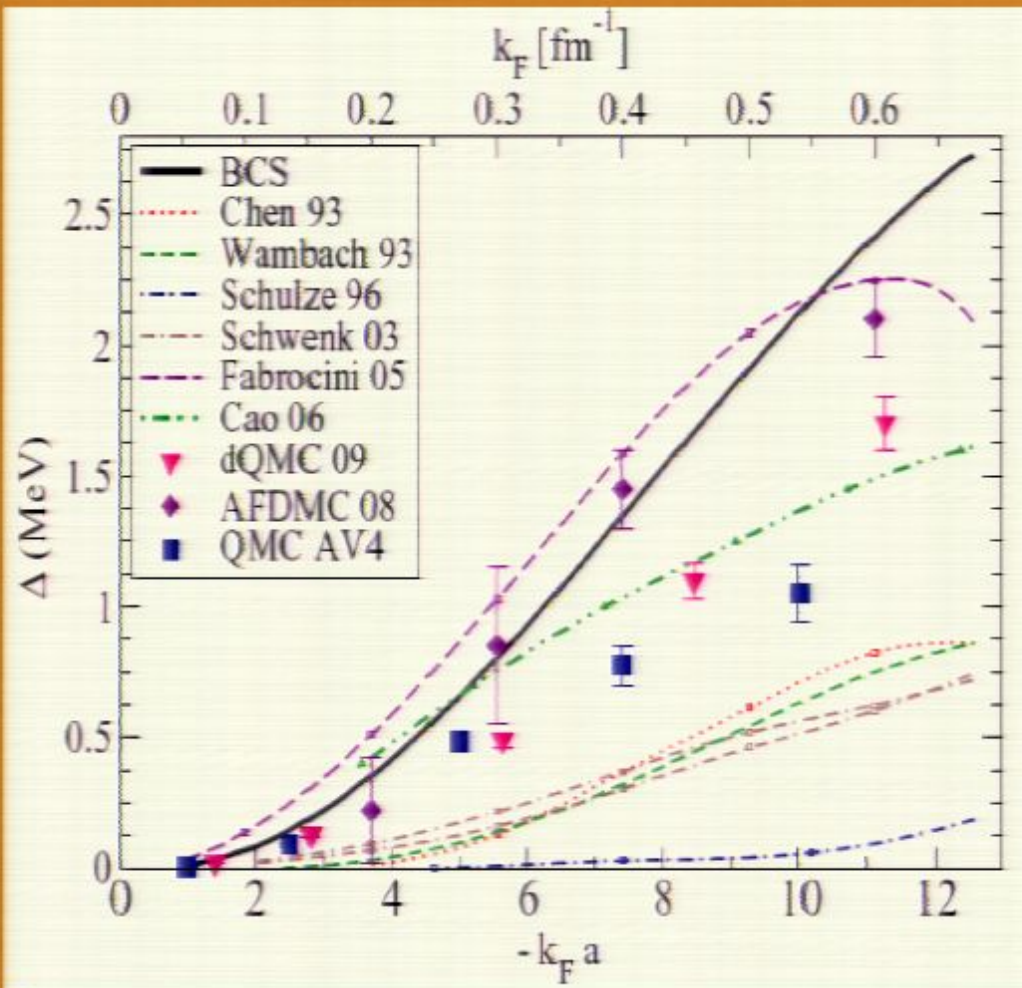


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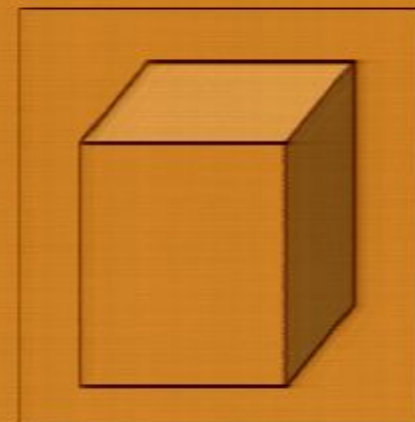


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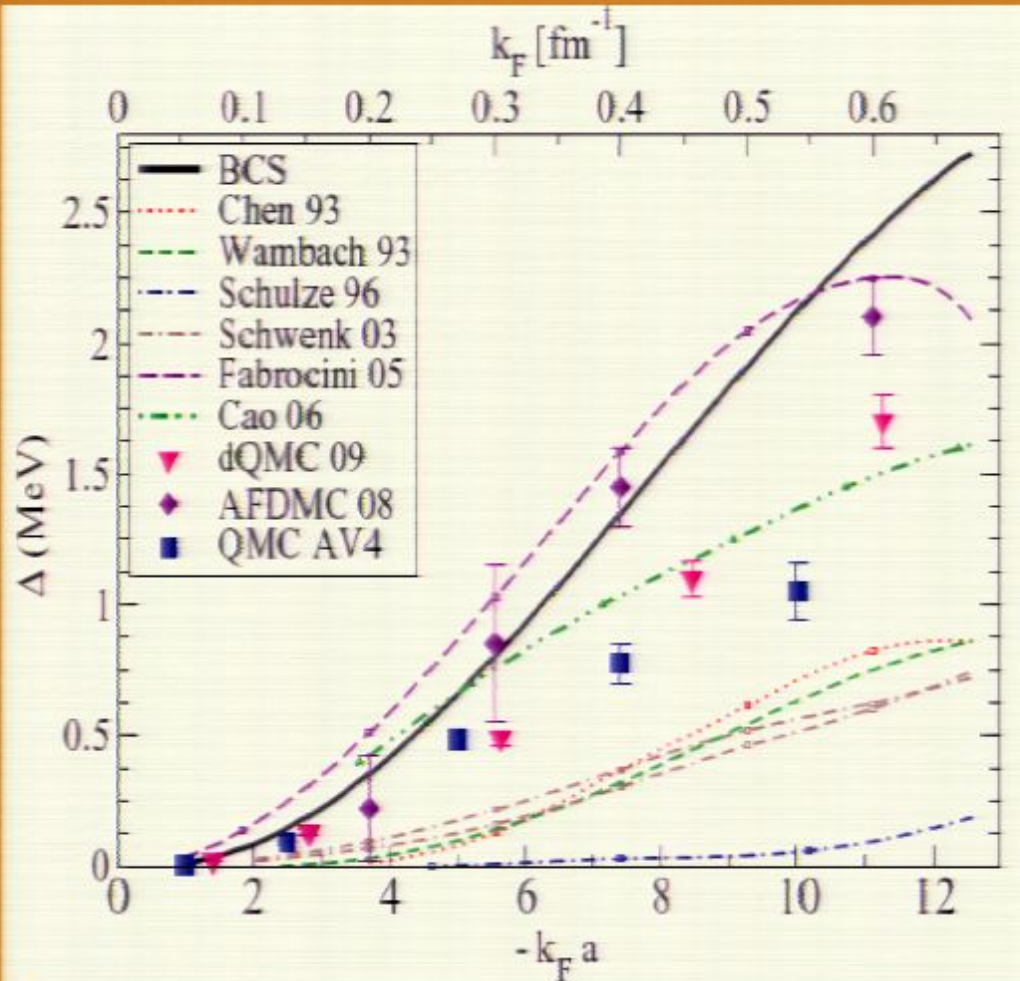


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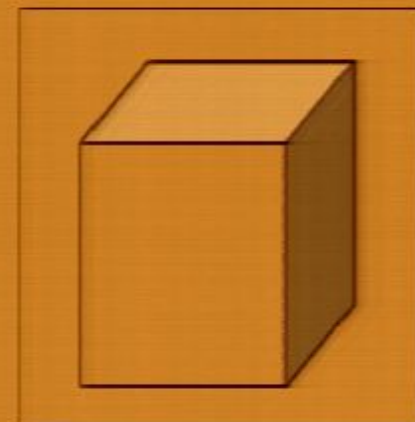


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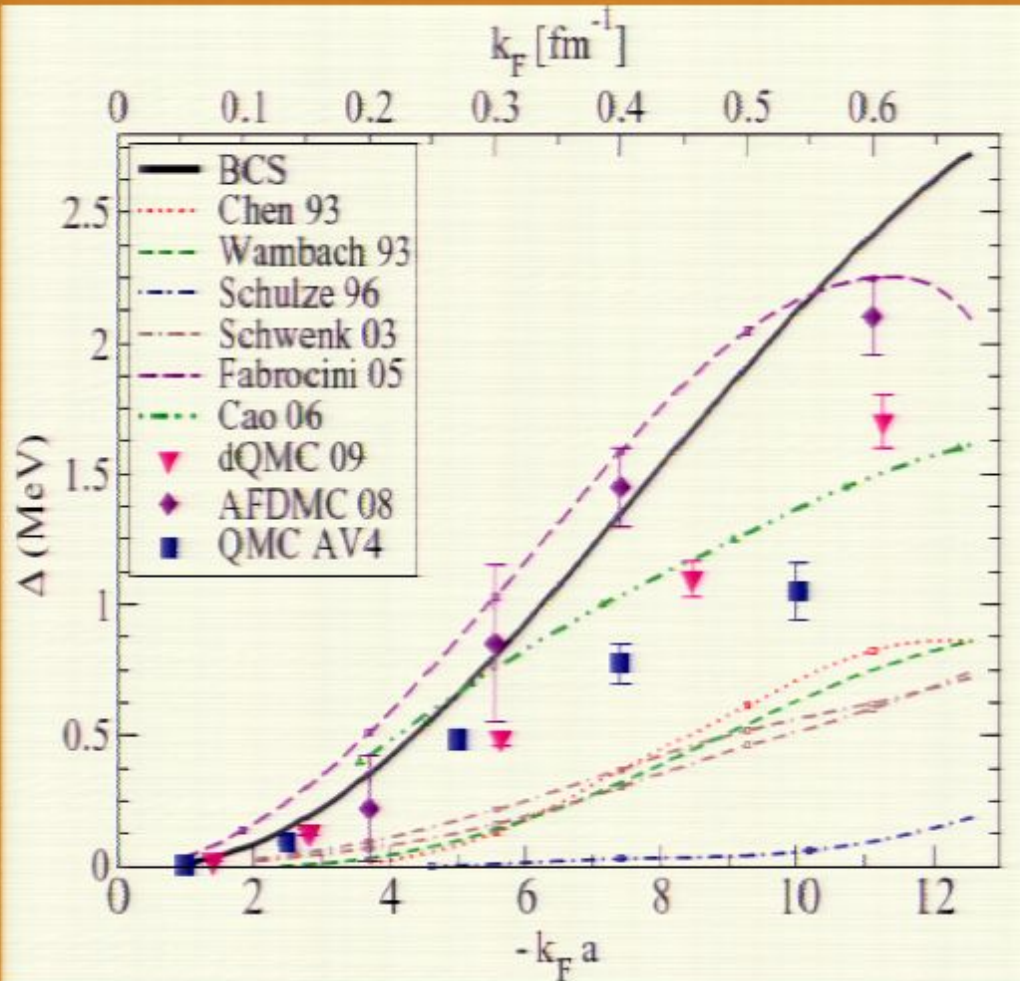


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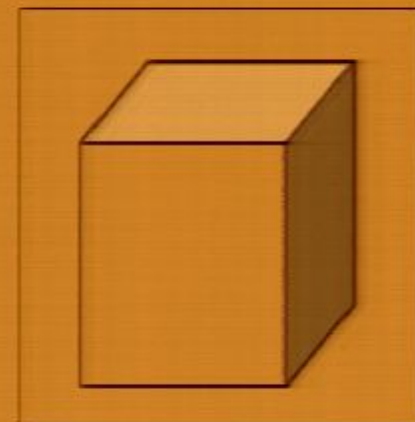


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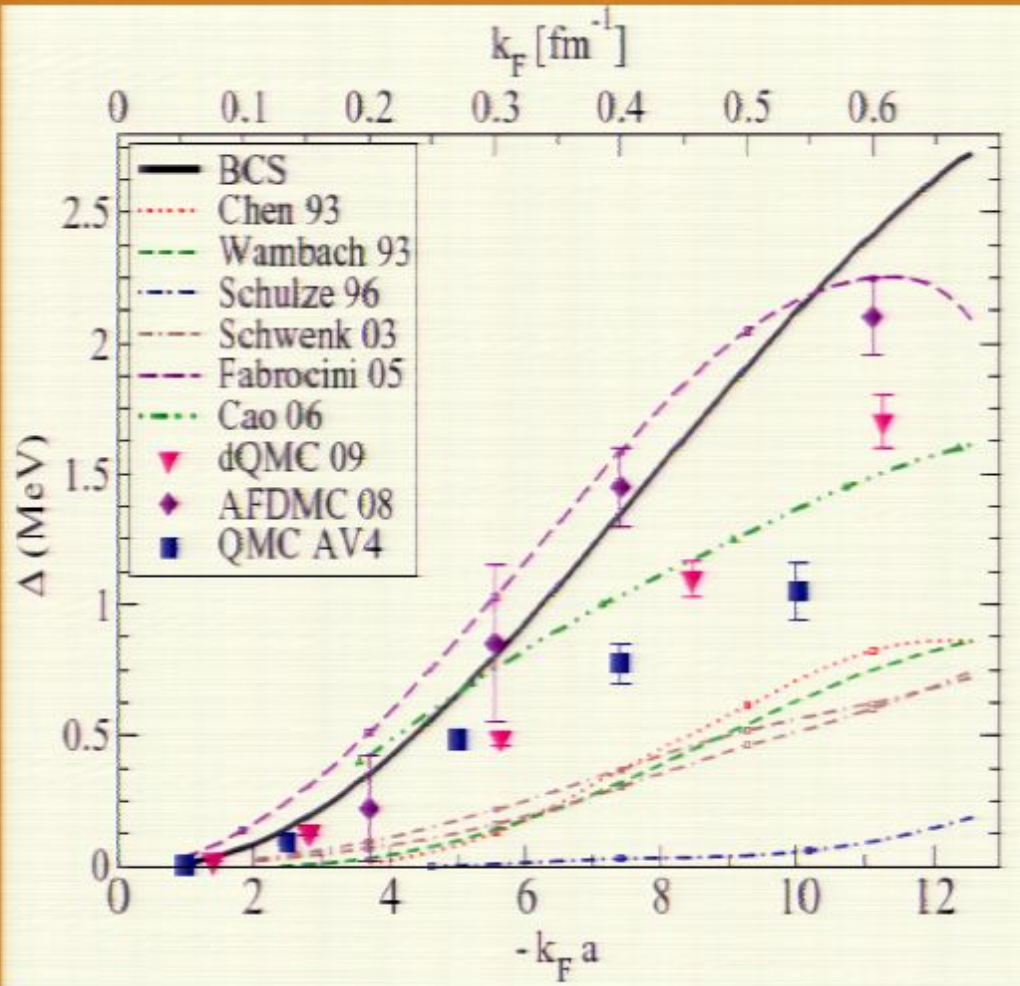
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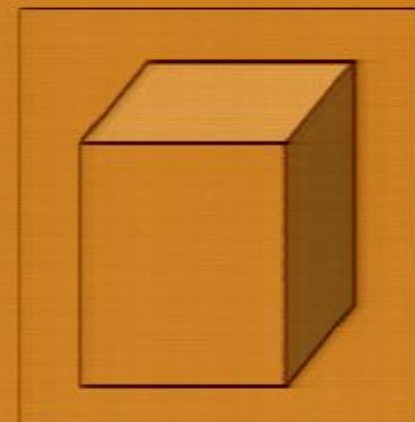
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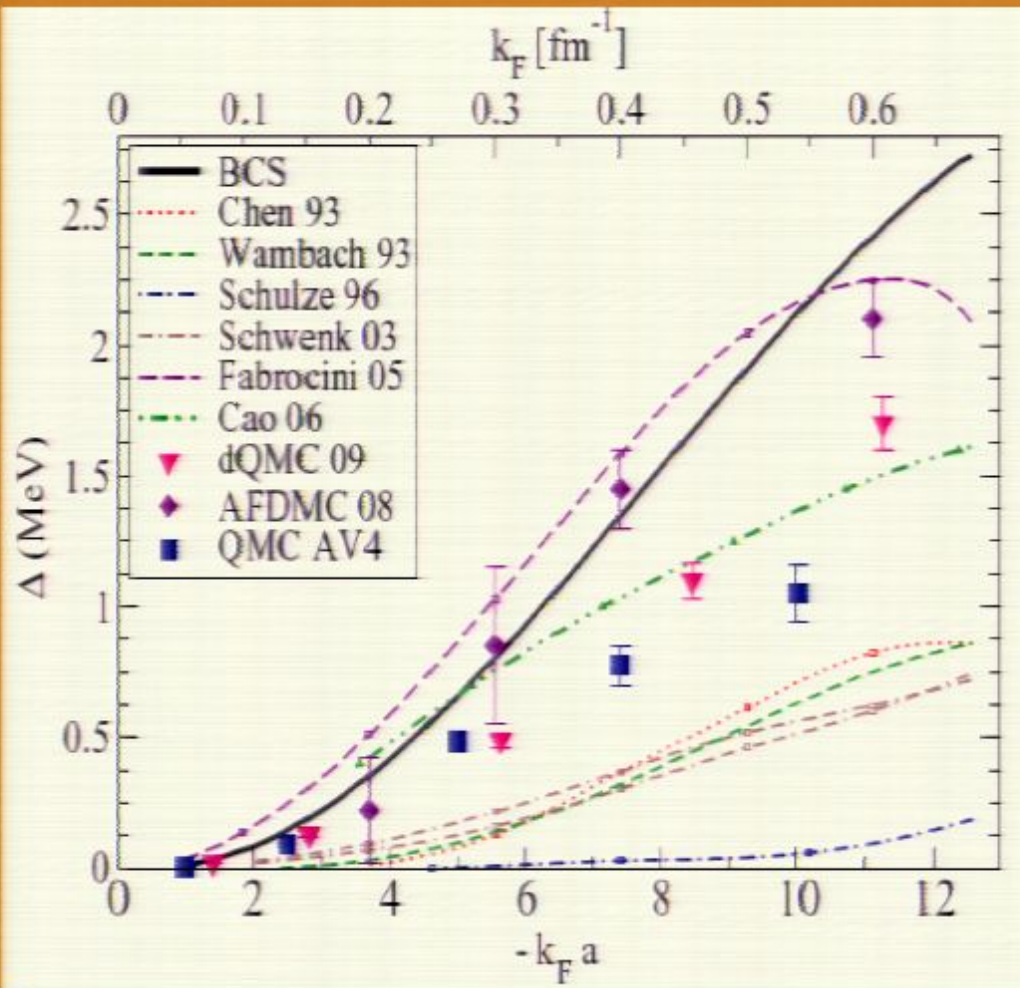


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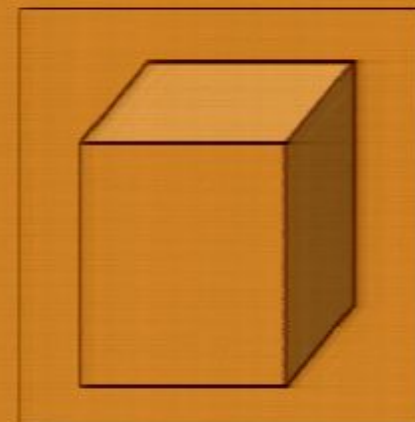


A. Gezerlis and J. Carlson, Phys. Rev. C **81**, 025803 (2010)

Pairing gaps: comparison

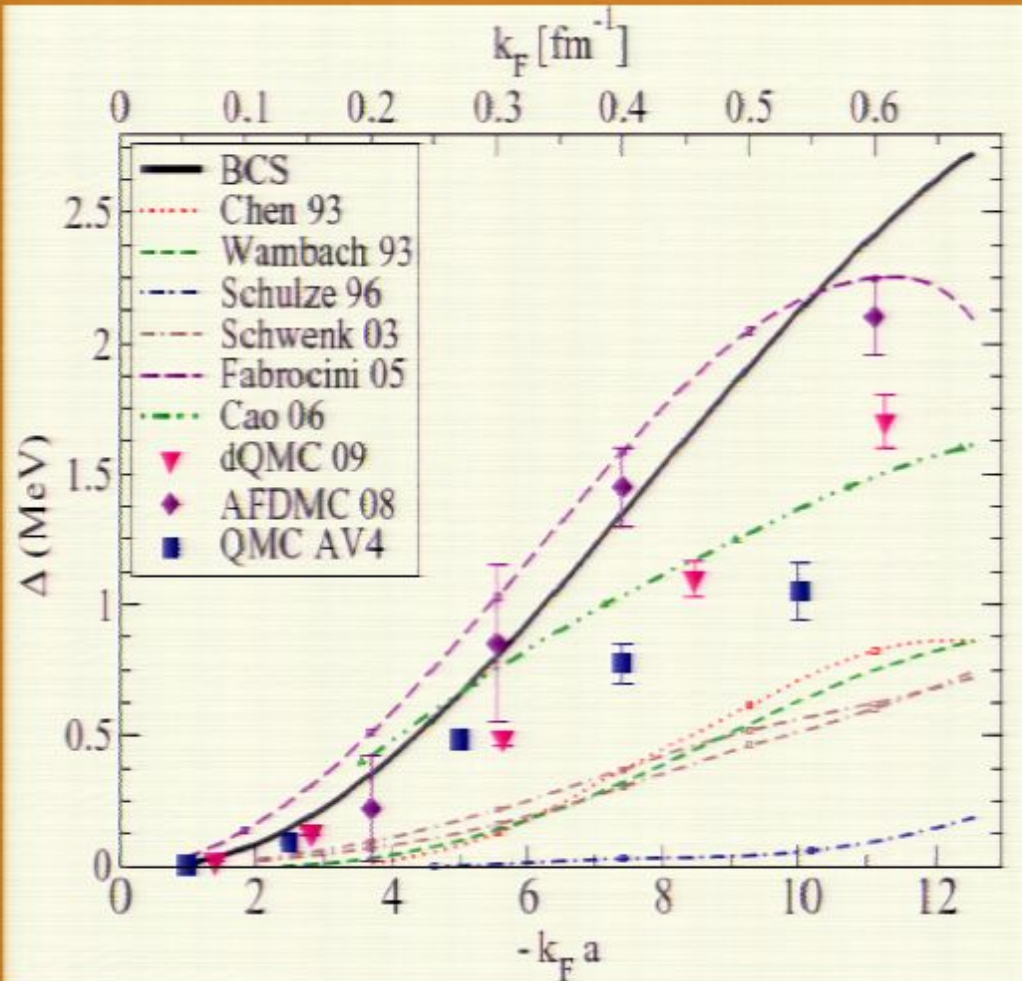


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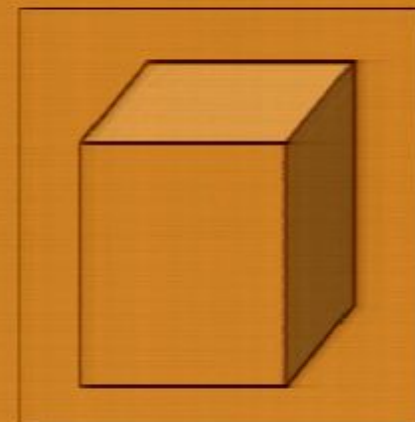


A. Gezerlis and J. Carlson, Phys. Rev. C 81, 025803 (2010)

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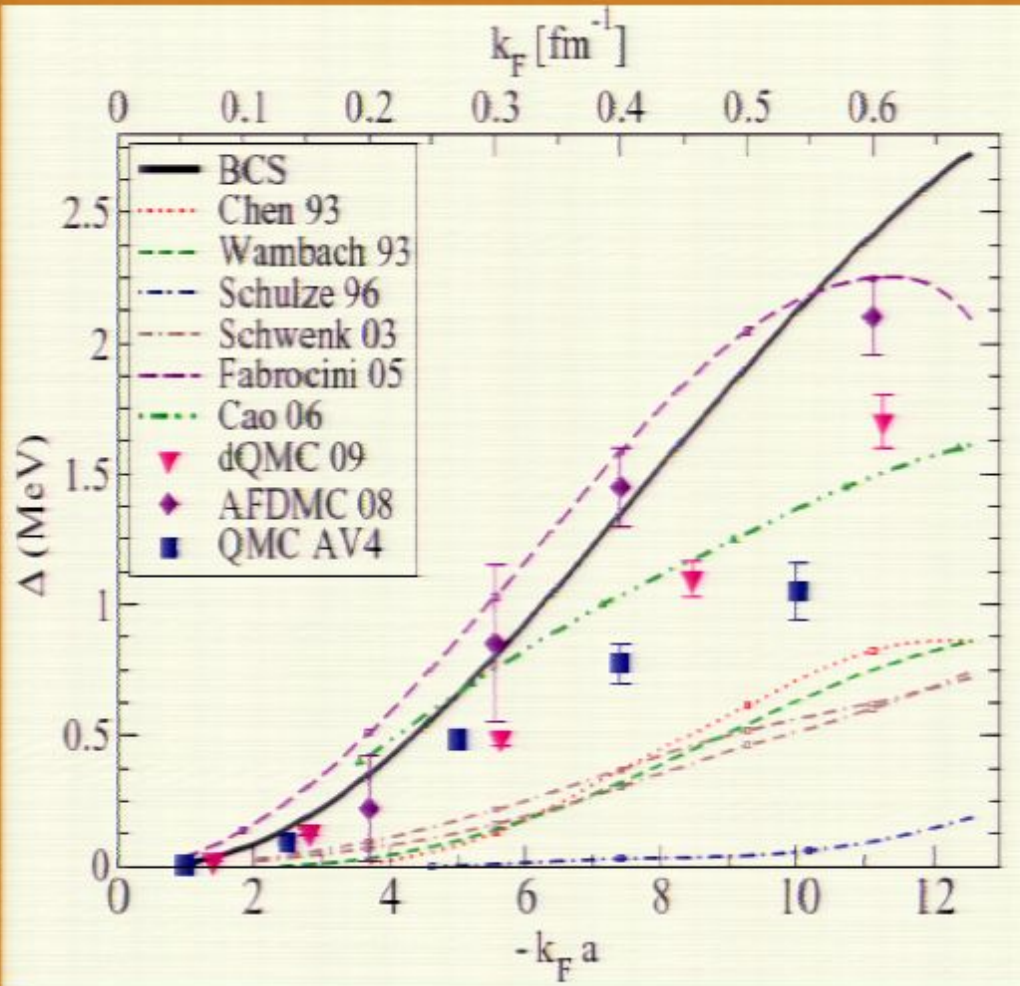


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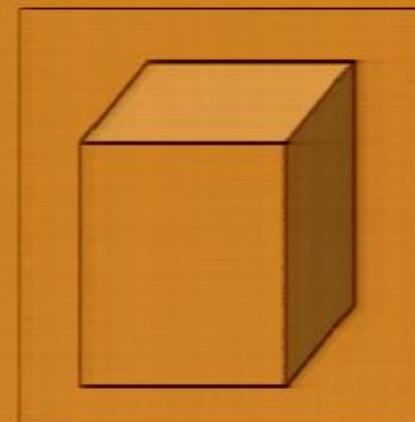


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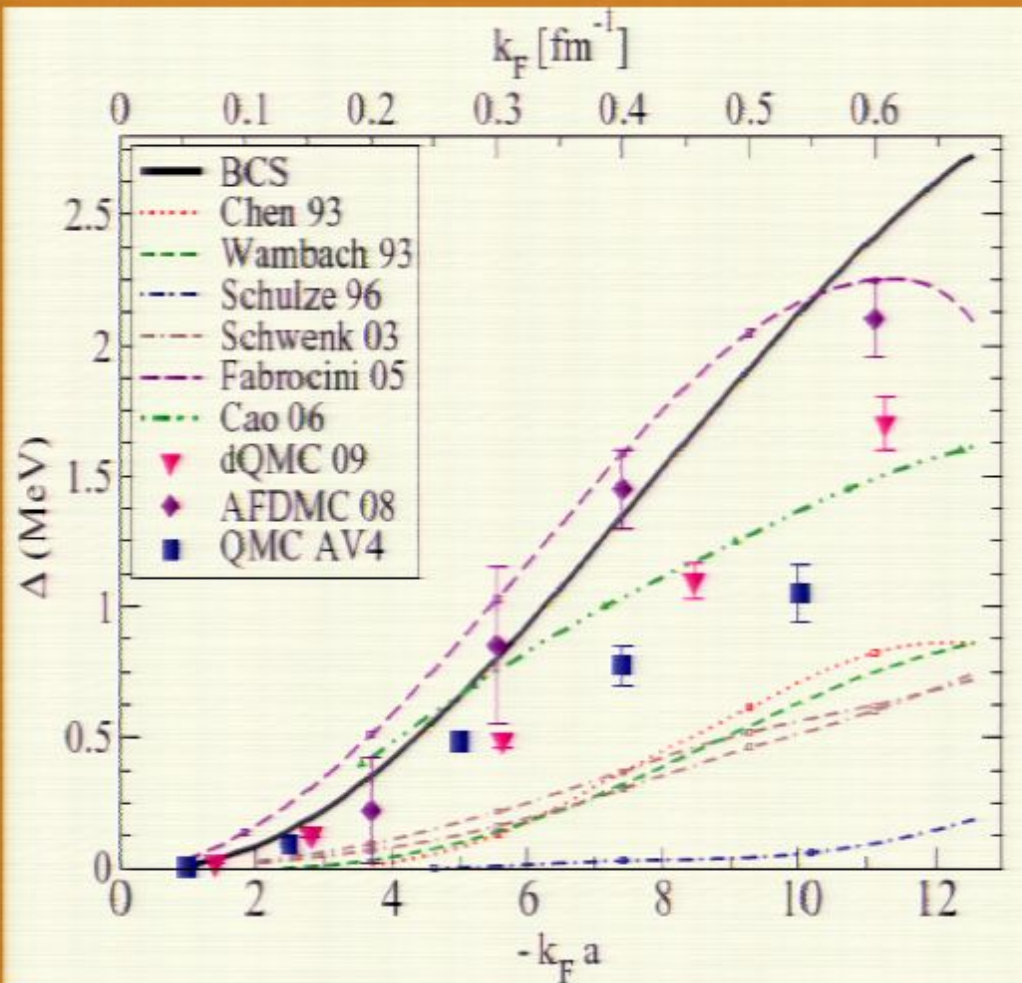


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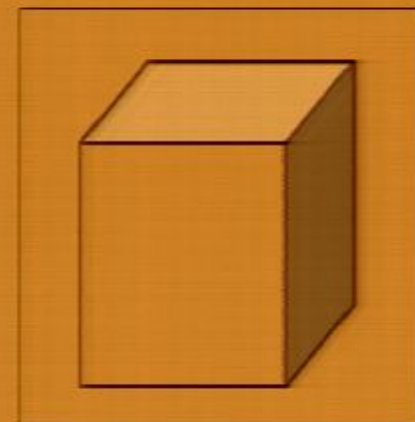


A. Gezerlis and J. Carlson, Phys. Rev. C 81, 025803 (2010)

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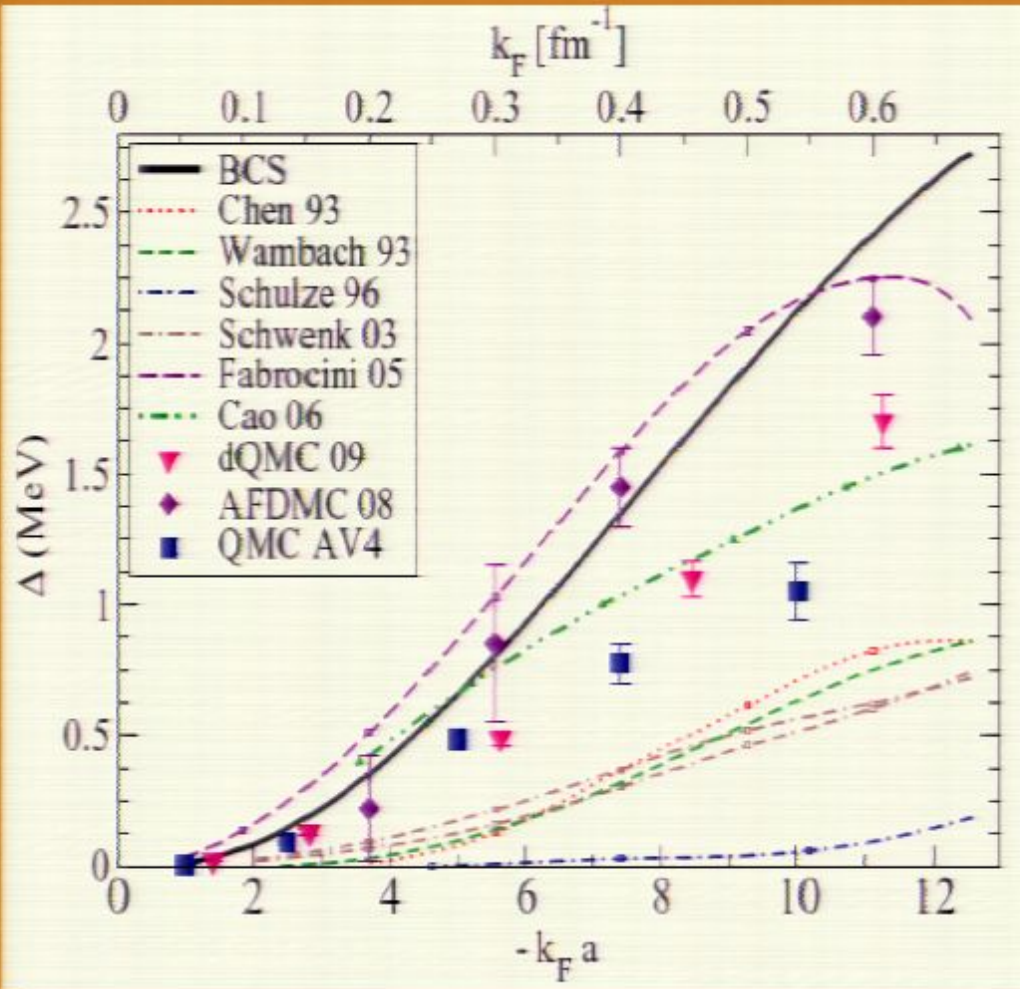


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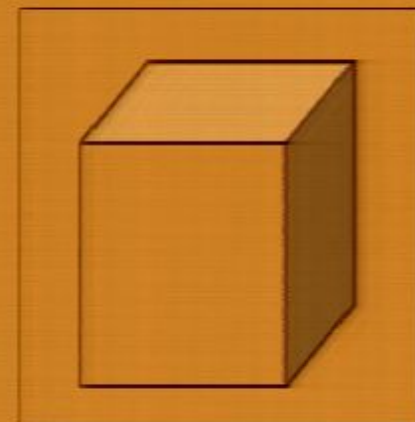


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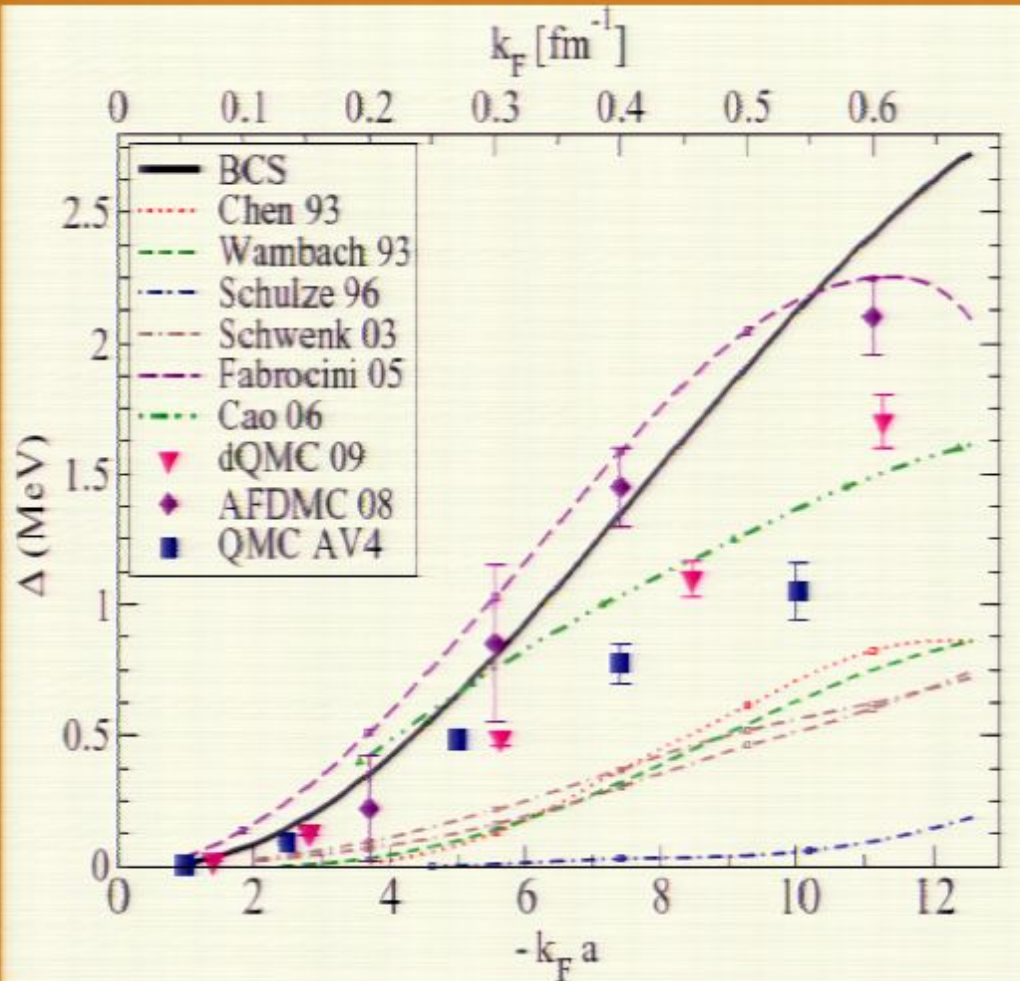


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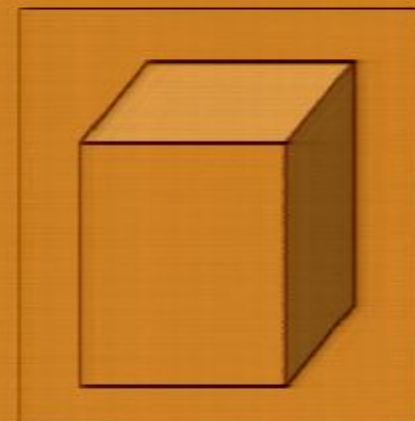


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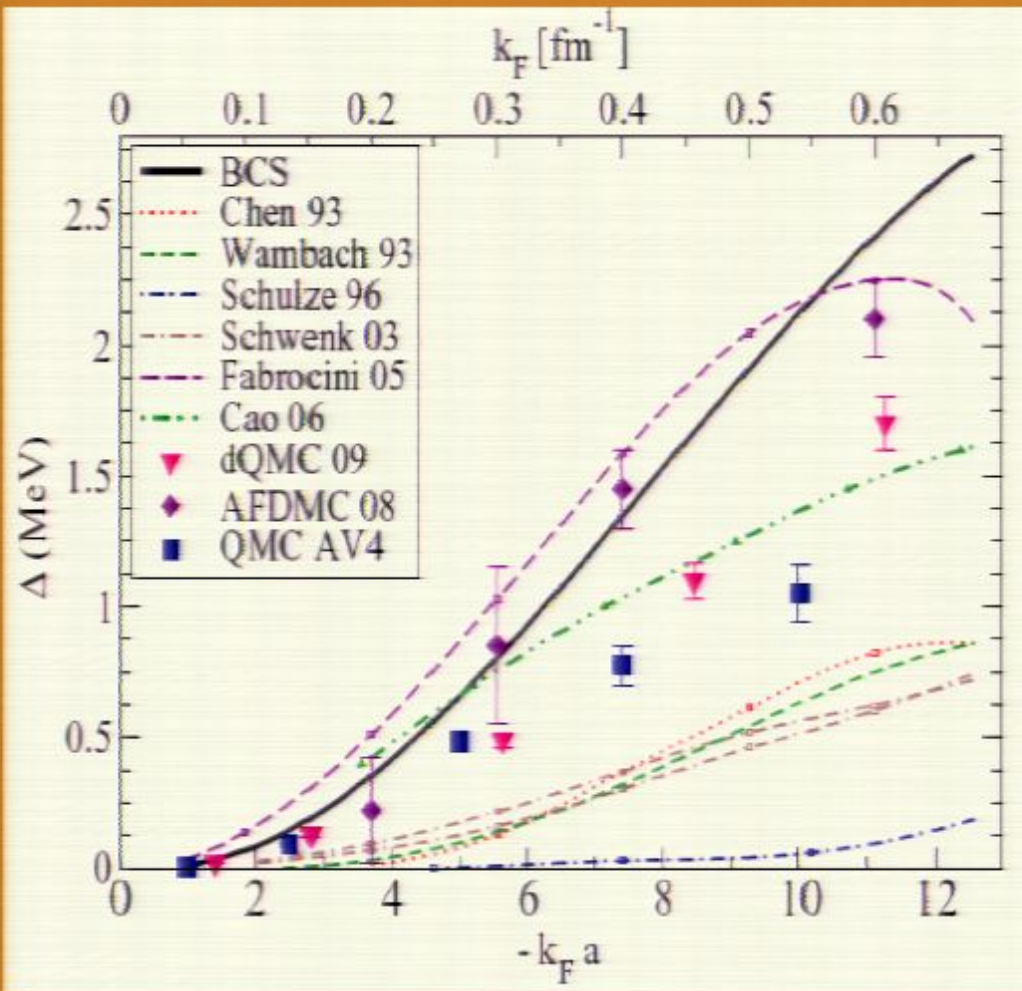


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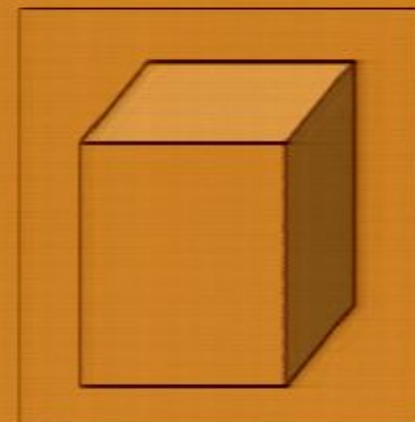


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Pairing gaps: comparison

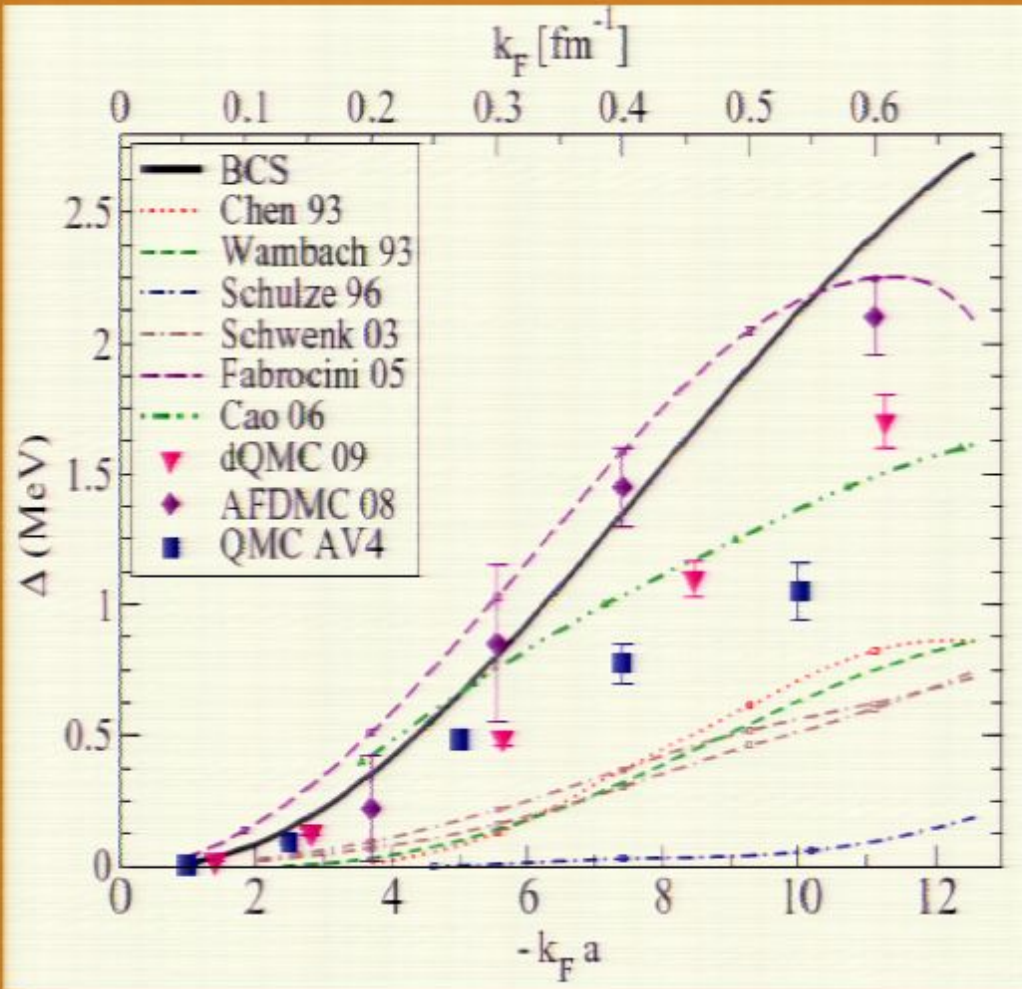


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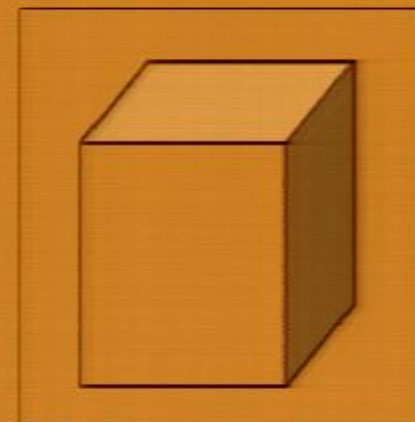


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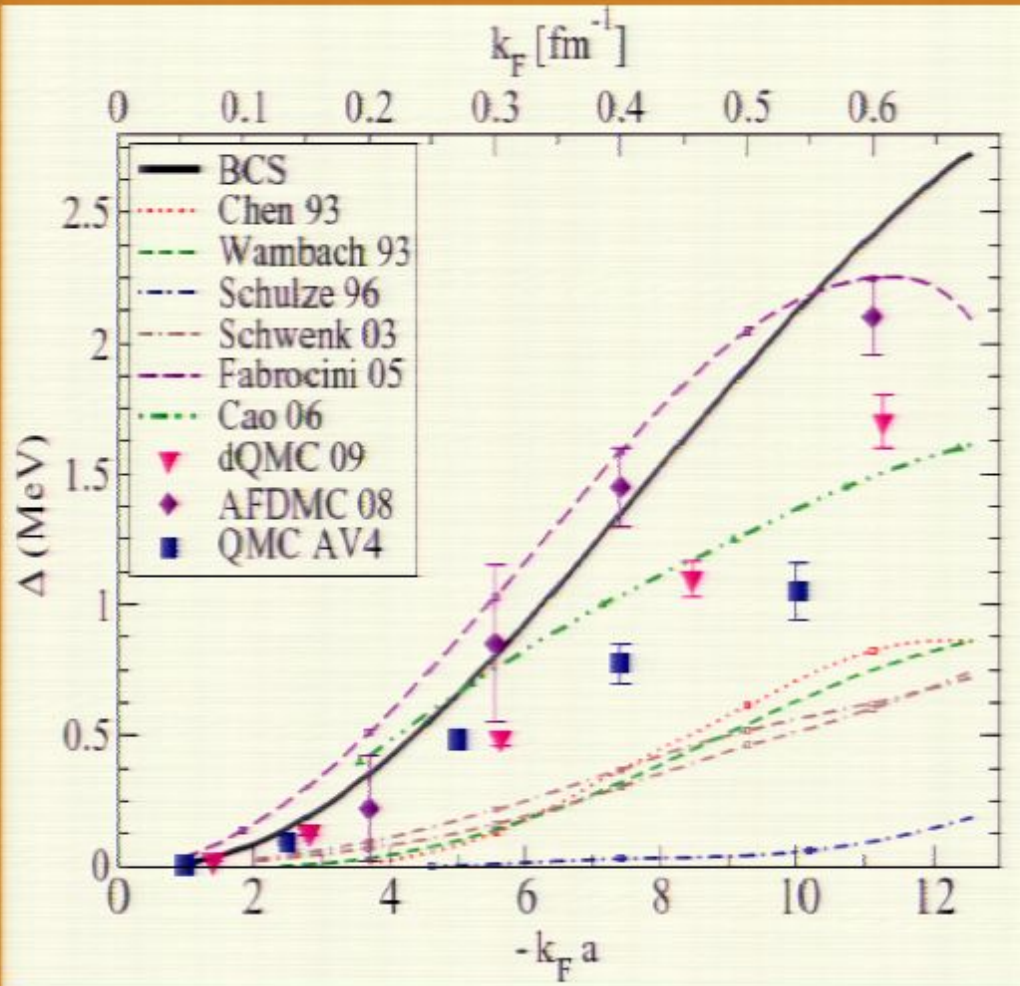


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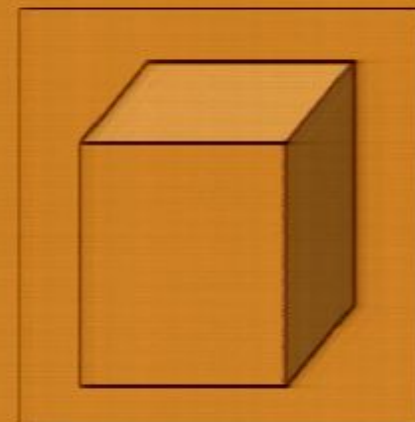


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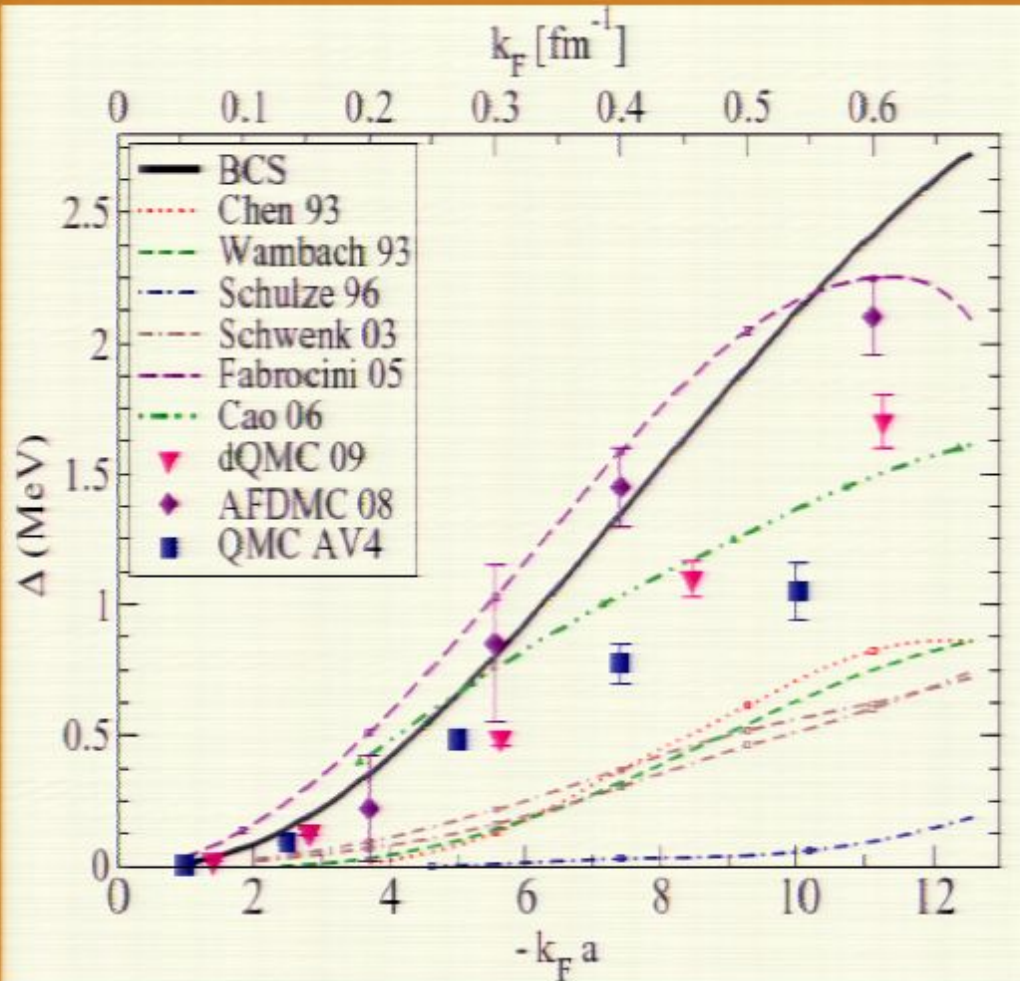


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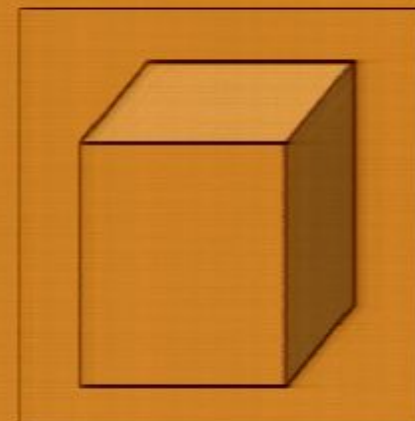


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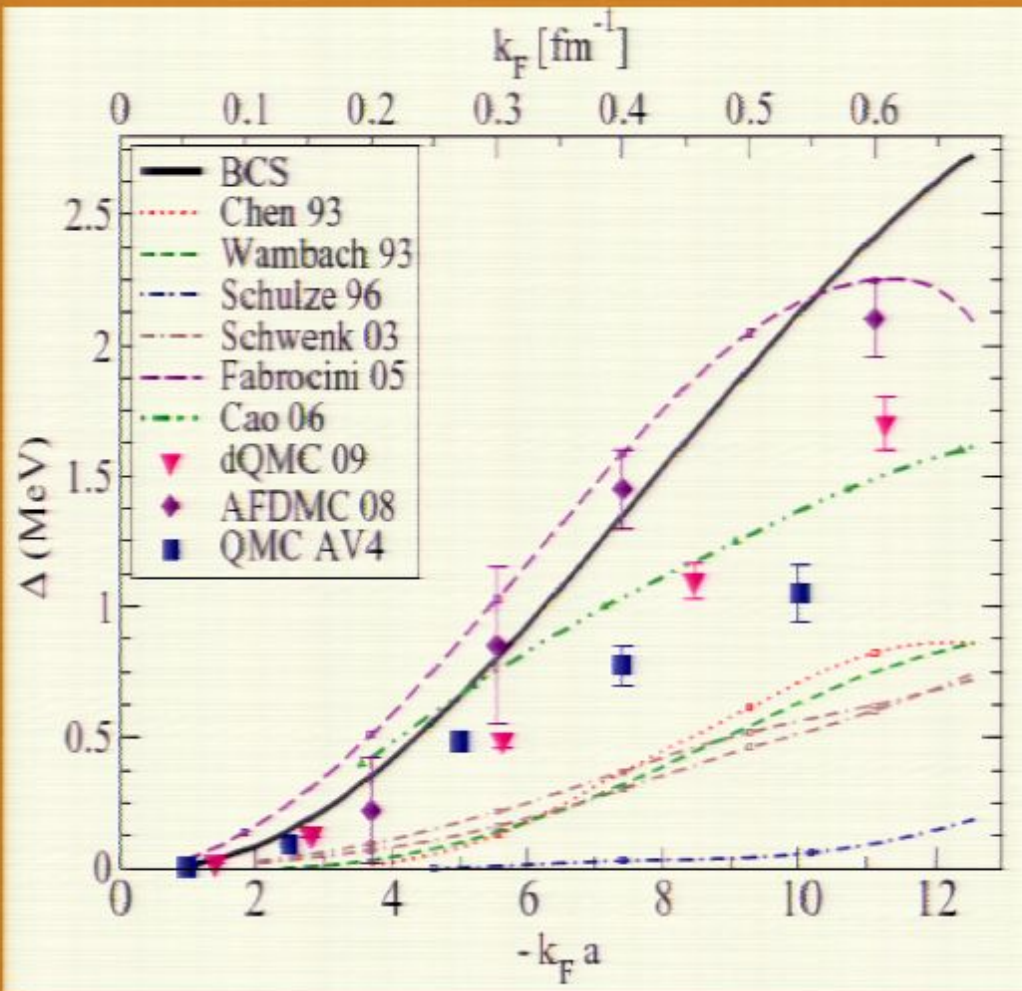


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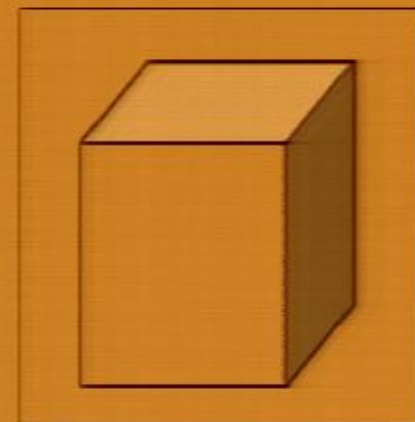


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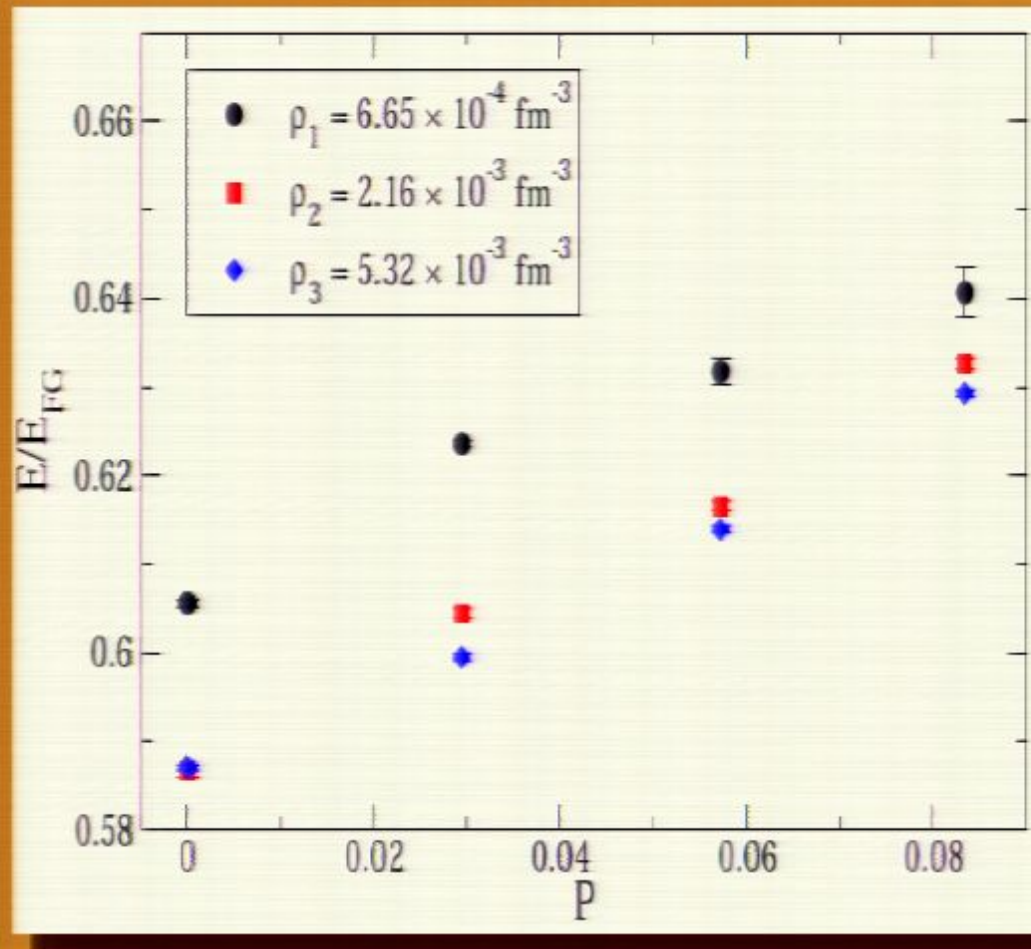
A. Gezerlis and J. Carlson, Phys. Rev. C 81, 025803 (2010)

Unequal Populations

Energy versus polarization

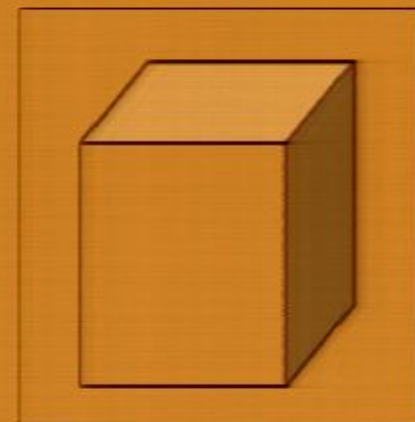


Polarized neutron matter: energy

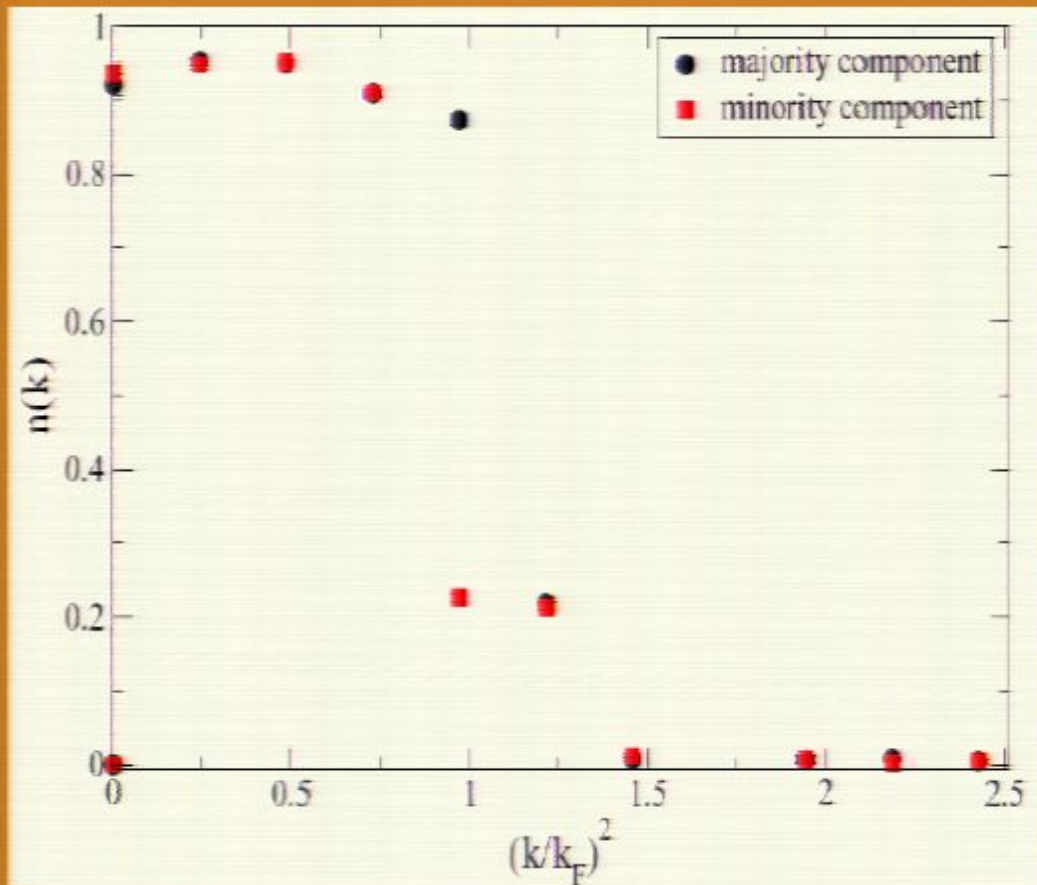


- Possibly relevant to magnetars and nuclear functionals
- Linear with respect to polarization:

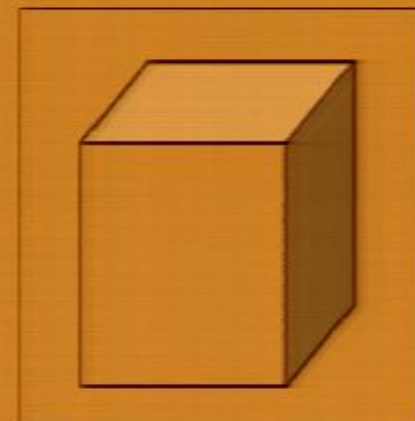
$$P = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}}$$



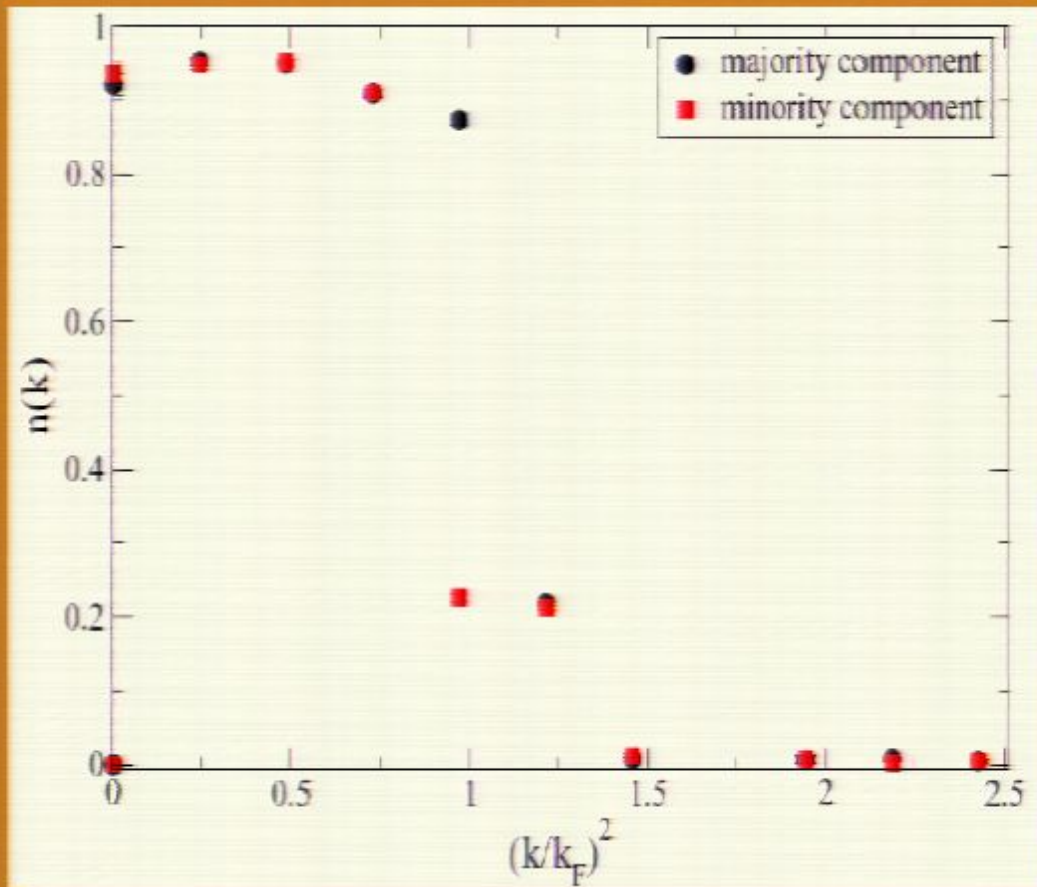
Polarized neutron matter: momentum distribution



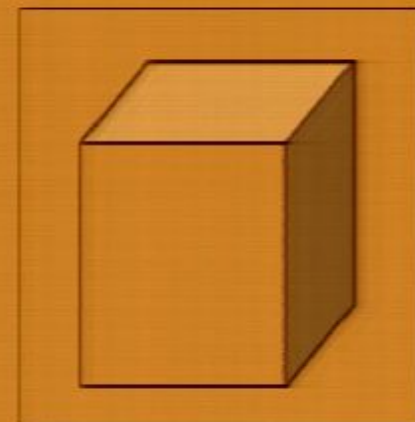
- Spread around k_F noticeable
- Known as “Fermi surface mismatch”



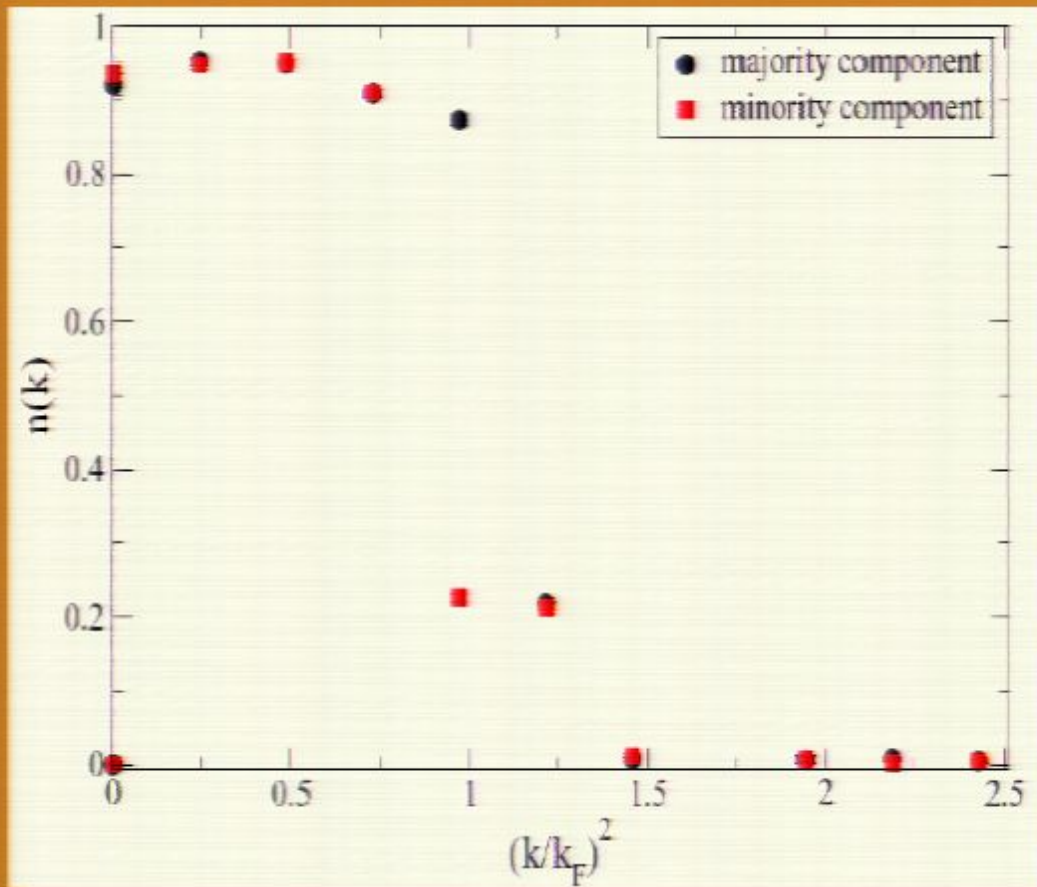
Polarized neutron matter: momentum distribution



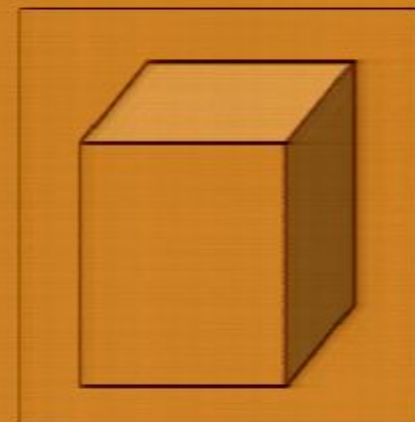
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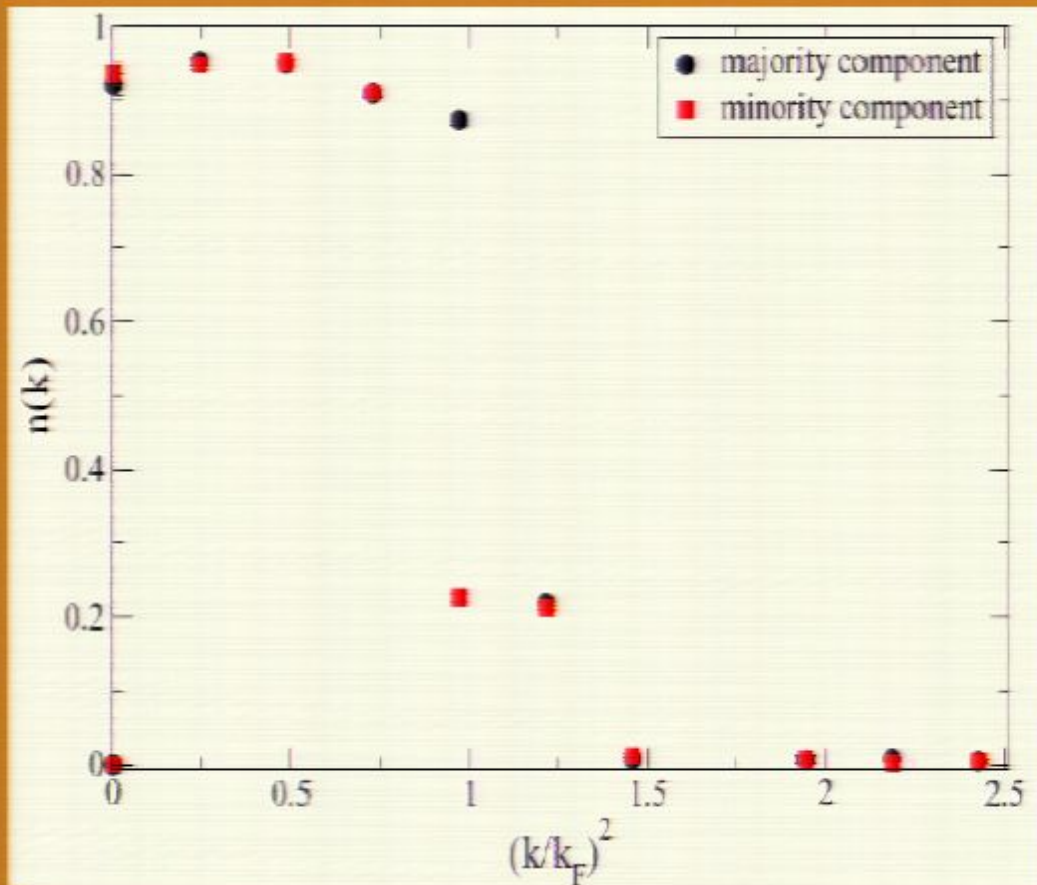
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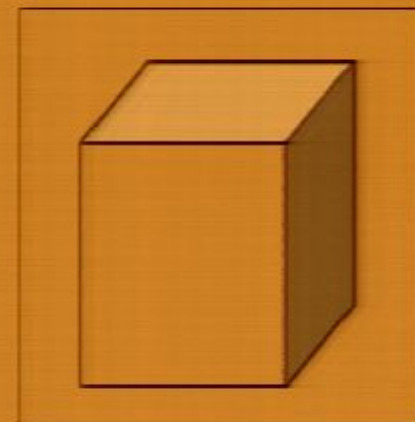
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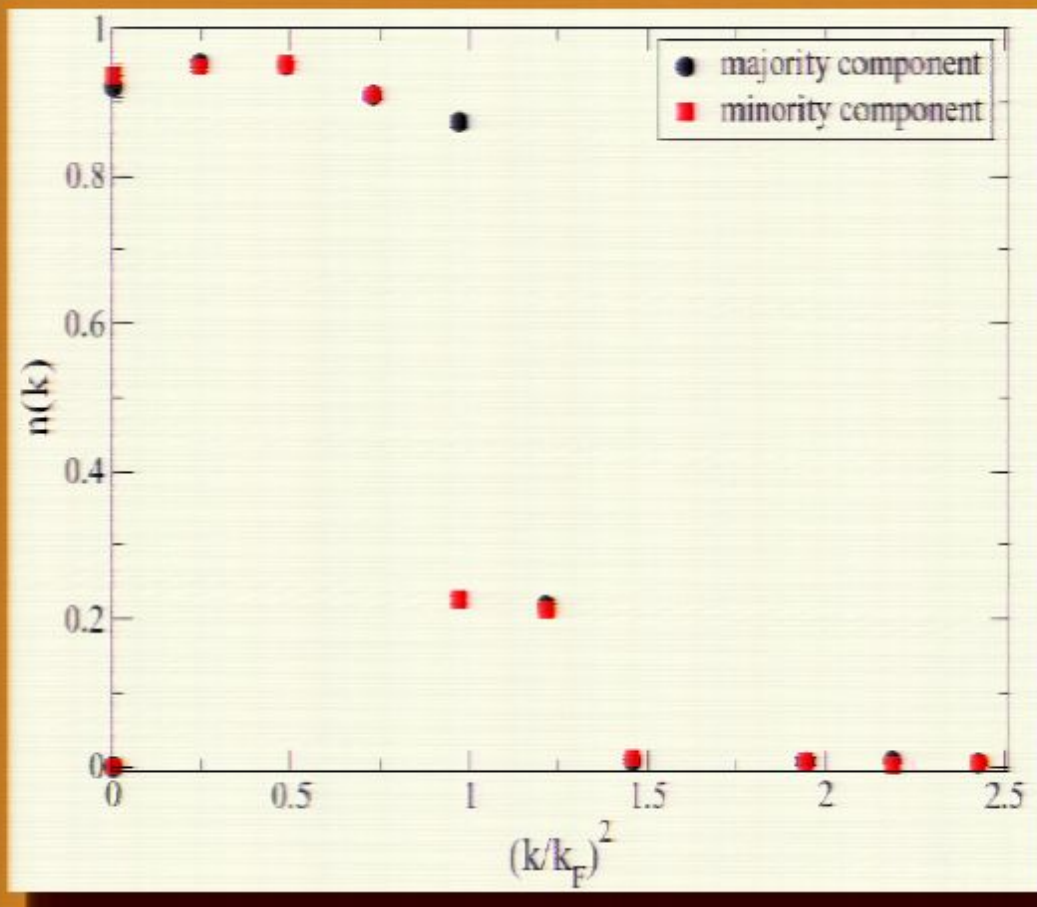
Polarized neutron matter: momentum distribution



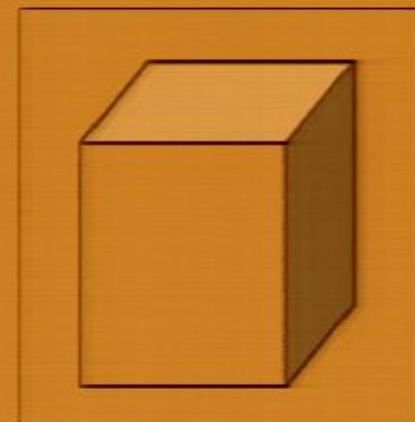
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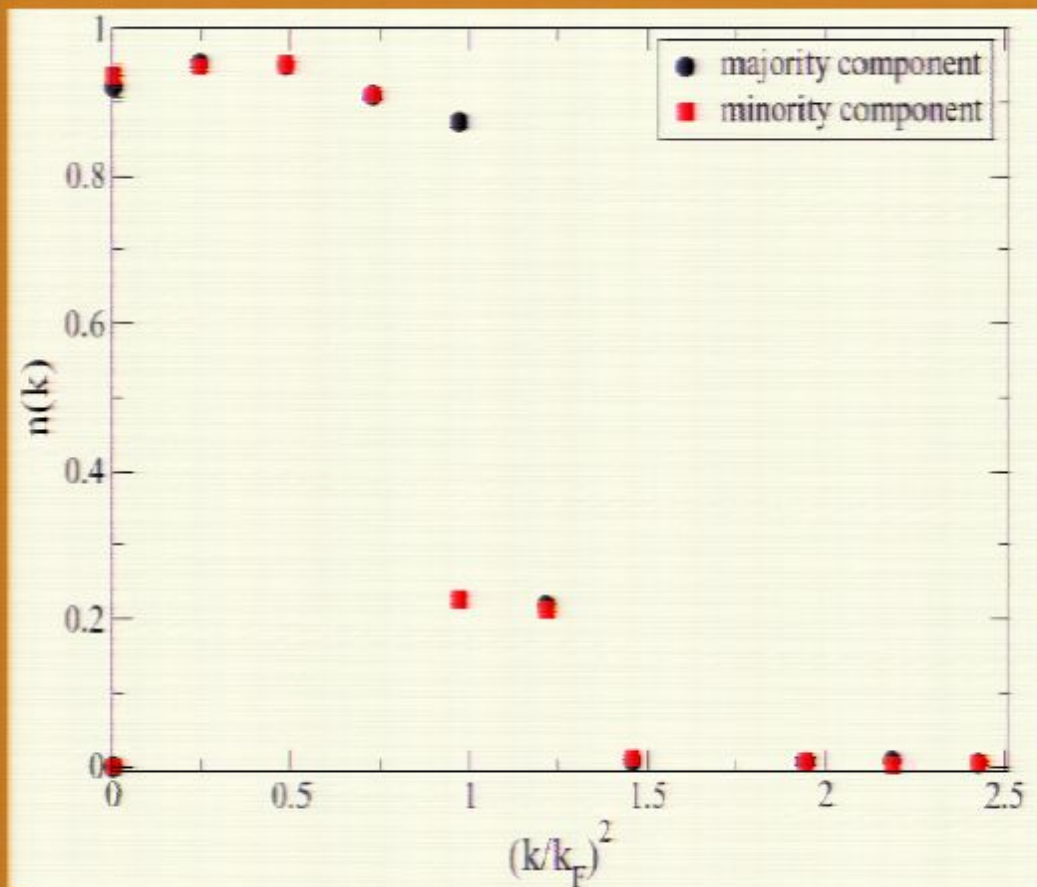
Polarized neutron matter: momentum distribution



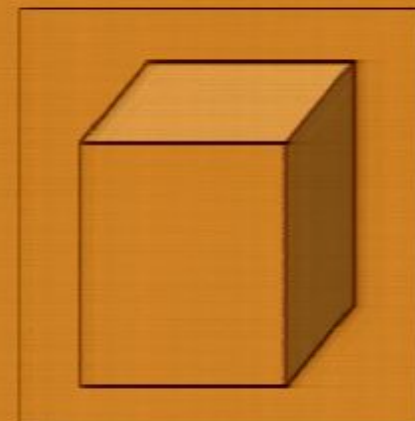
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Polarized neutron matter: momentum distribution



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- Known as “Fermi surface mismatch”



Conclusions

- Qualitative agreement on equation of state:
benchmarking
- Emerging consensus (?) regarding the
pairing gap
- Energy versus polarization is linear:
benchmarking

The Present Future

- Extreme polarizations: the polaron problem
- Highly asymmetric nuclear matter
- Static response of neutron matter

No Signal

VGA-1

No Signal

VGA-1

The Present Future

- Extreme polarizations: the polaron problem
- Highly asymmetric nuclear matter
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