From atoms to neutrons and back

Alexandros Gezerlis

TECHNISCHE UNIVERSITÄT DARMSTADT

Hirschegg, Austria
Quark Gluon Plasma meets Cold Atoms - Episode III
27 August 2012

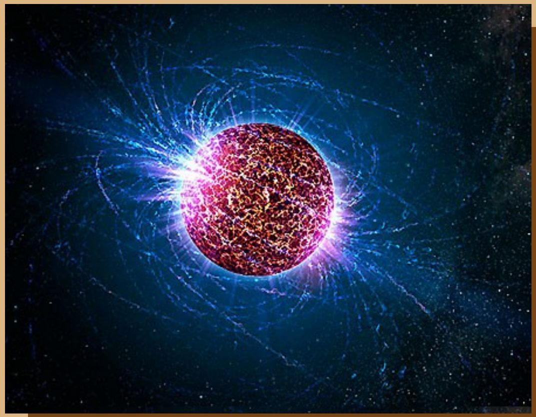
Thanks to my collaborators

- Joe Carlson (LANL)
- Michael Forbes (INT)
- Stefano Gandolfi (LANL)
- Kai Hebeler (OSU)
- Thomas Lesinski (INT)
- Achim Schwenk (Darmstadt)

Motivation: Fields

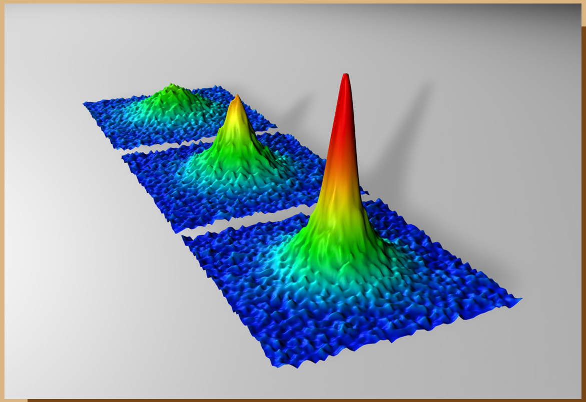
Neutron stars

- MeV scale
- $O(10^{40})$ neutrons



Cold atoms

- peV scale
- $O(10^{5})$ atoms



- Very similar E/E_{FG} and Δ/E_F
- Intermediate to strong coupling

Reminder: $E_{FG} = 3/5NE_F$, $E_F = \hbar^2 k_F^2/2m$, $\rho = g k_F^3/6\pi^2$

Motivation: Methods

Quantum Monte Carlo

- Microscopic
- Computationally demanding (3N particle coordinates + spins)
- Limited to small N

$$\Psi(\tau \to \infty) = \lim_{\tau \to \infty} e^{-(\mathcal{H}-E_T)\tau} \Psi_V$$
$$\to \alpha_0 e^{-(E_0 - E_T)\tau} \Psi_0$$

Density Functional Theory

- More phenomenological
- Easier (orbitals → density → energy density)
- Can do larger N

$$E = \int d^3r \, \{\mathcal{E}[\rho(\mathbf{r})] + \rho(\mathbf{r}) V_{\text{ext}}(\mathbf{r})\}$$

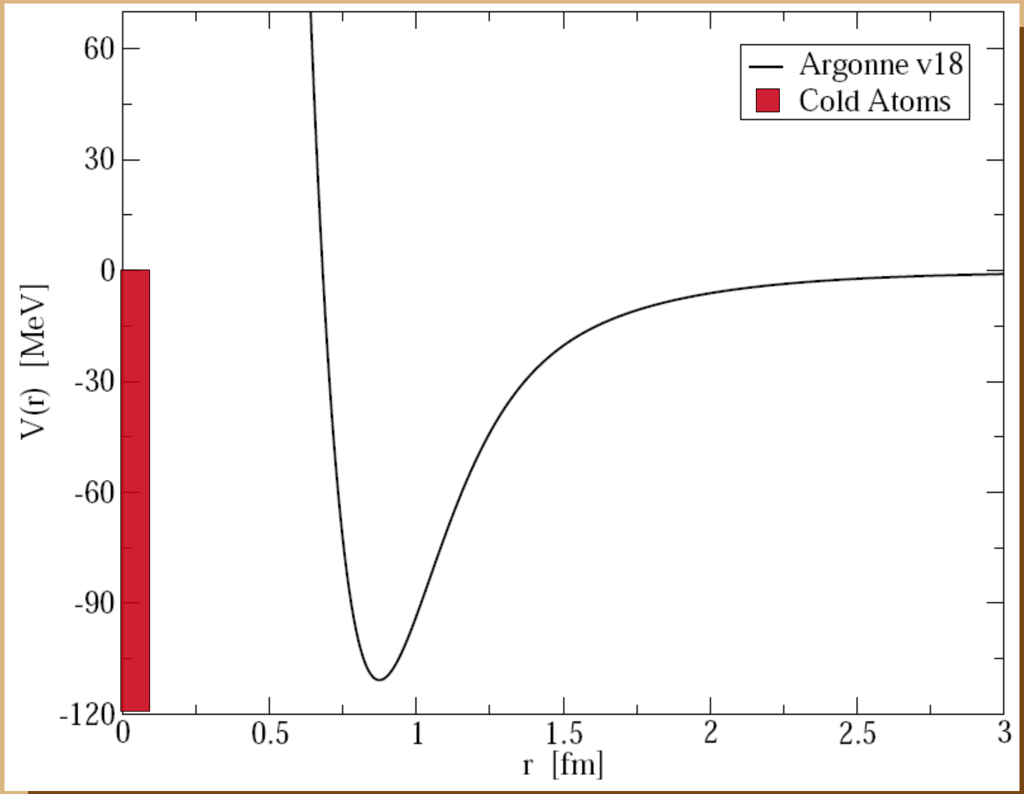
Research Strategies

i) Use QMC as a benchmark with which to compare DFT results

ii) Constrain DFT with QMC, then use DFT to make predictions

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

$^1S_0$ scattering phase shift

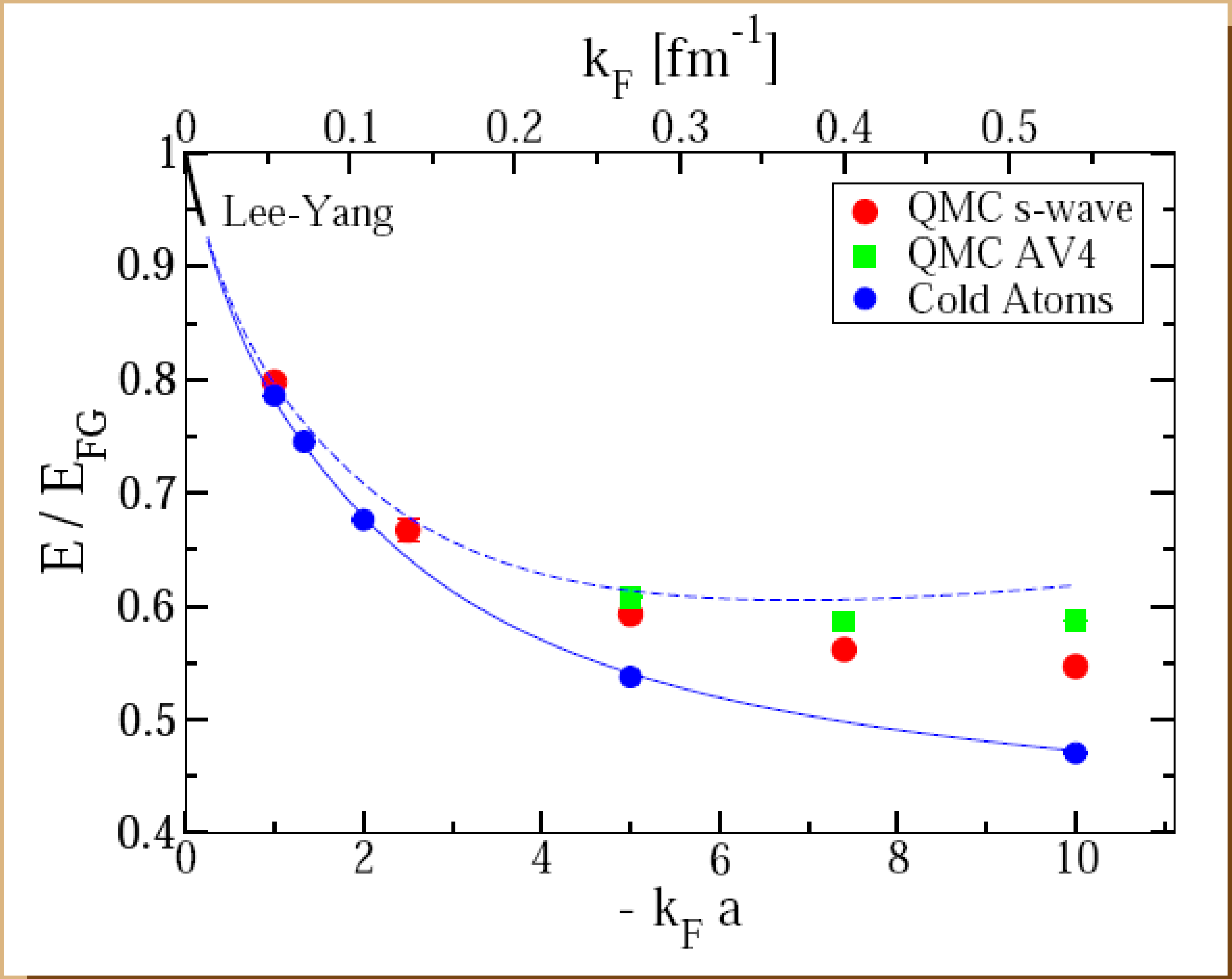
a = -18.5 fm, r_e = 2.7 fm

Cold atoms

modified Pöschl-Teller potential

a = tunable, r_e =tunable/infinitesimal

Equations of state



- Results identical at low density
- Range important at intermediate density (dashed line: linear dependence on range)
- Other channels start to matter at larger density

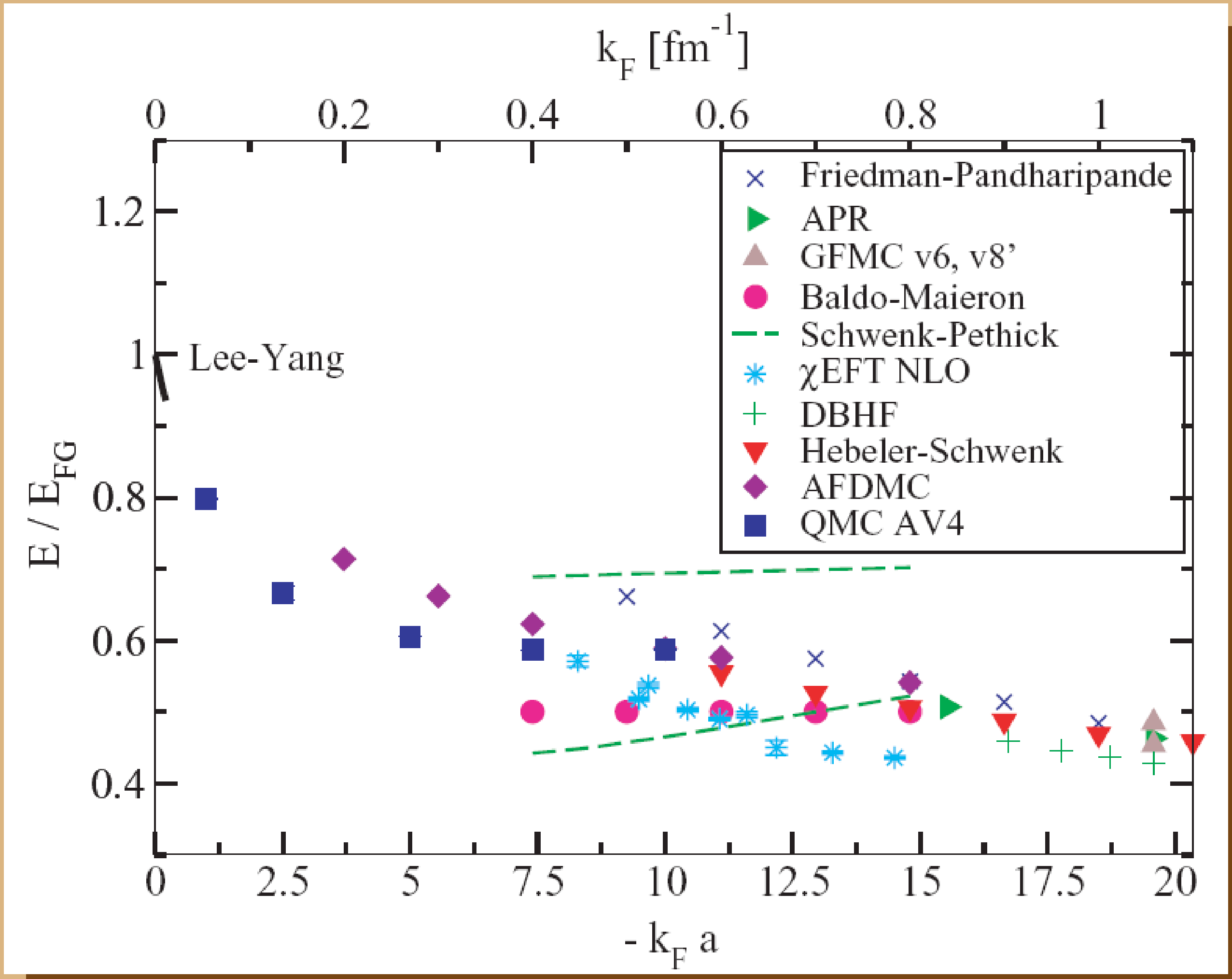
NEUTRONS

ATOMS

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

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

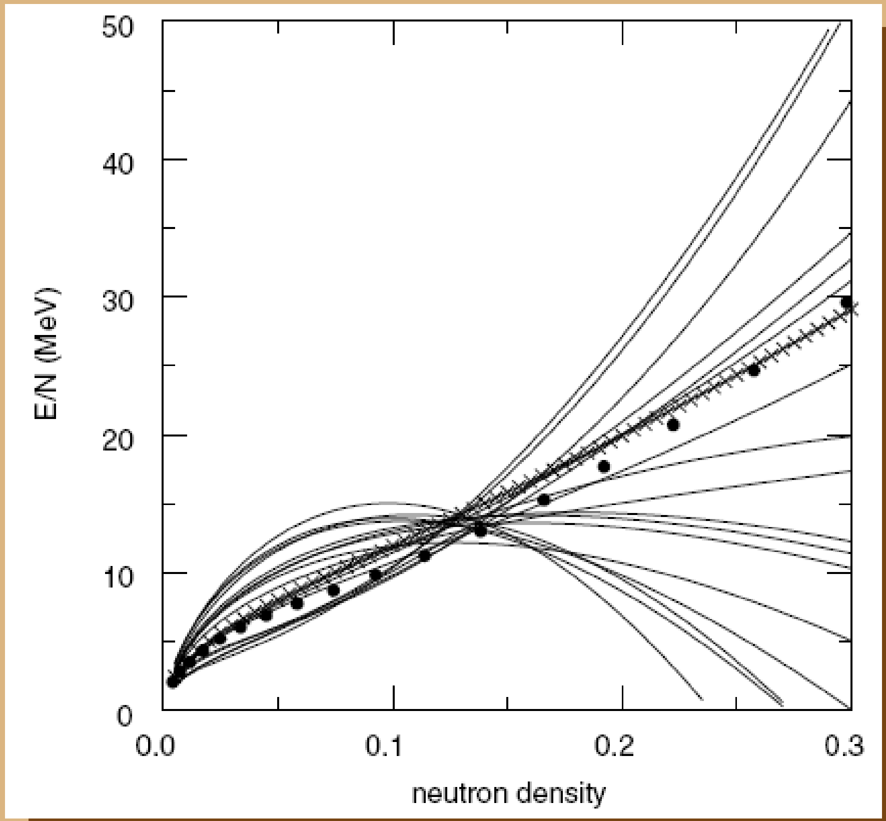
NEUTRONS

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

The DFT connection

Microscopic constraints for Skyrme functionals

- Large spread in predictions
- Dependable calculations are useful



NEUTRONS

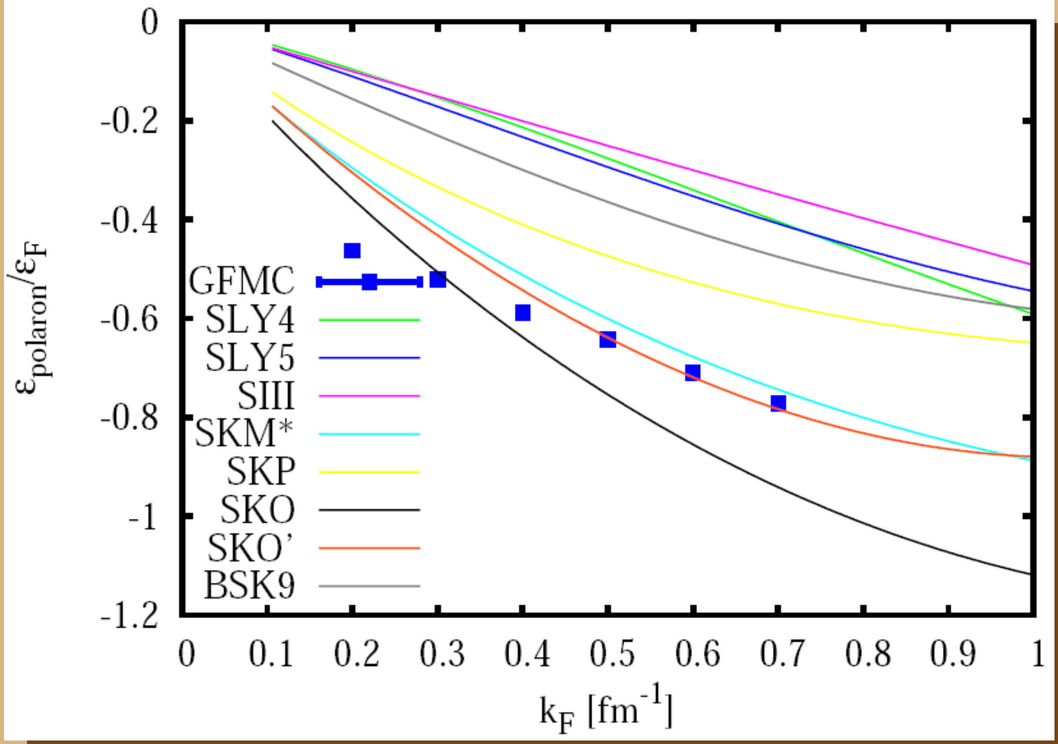
B. A. Brown, Phys. Rev. Lett. **85**, 5296 (2000).

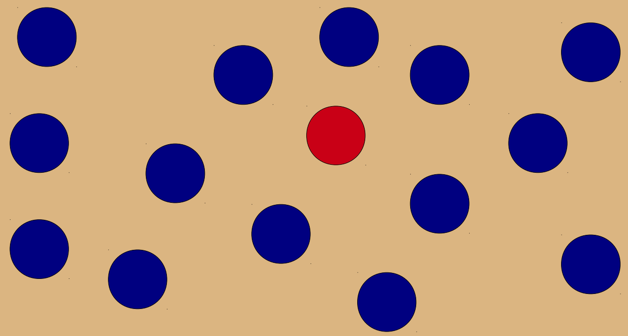
The neutron polaron

New constraint: extreme case of one impurity

Landau-Pomeranchuk $x = N_\downarrow / N_\uparrow$

$$E = \frac{3}{5} N_\uparrow E_{F\uparrow} \left(1 - Ax + \frac{m}{m*} x^{5/3} + F x^2\right)$$





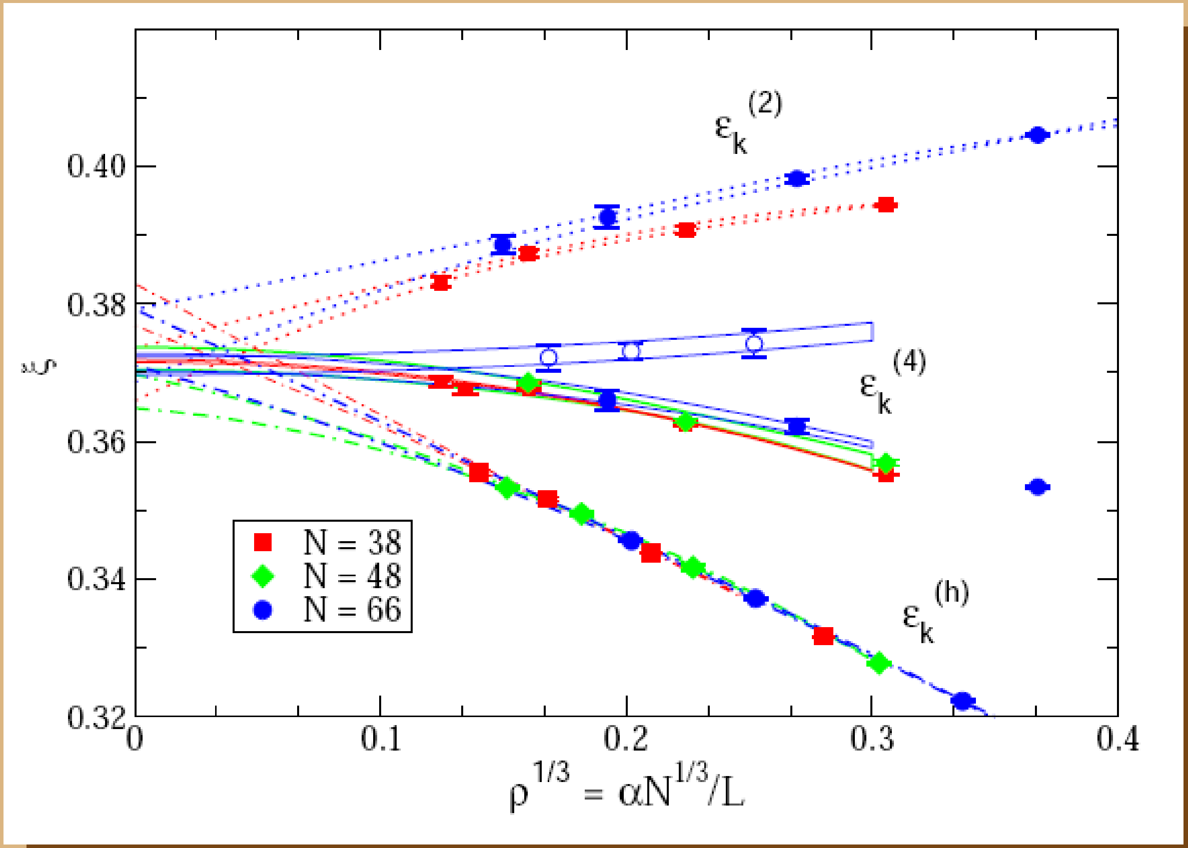
- Microscopic benchmark
- New functional needed

NEUTRONS

M. M. Forbes, A. Gezerlis, K. Hebeler,
T. Lesinski, A. Schwenk, *in preparation* (2012)

Unbiased lattice results

All curves point to 0.372(5)



- No fermion-sign problem
- Different kinetic dispersions all consistent
- Lattices up to 24^3 & 27^3
- Agrees with Zwierlein group measurement

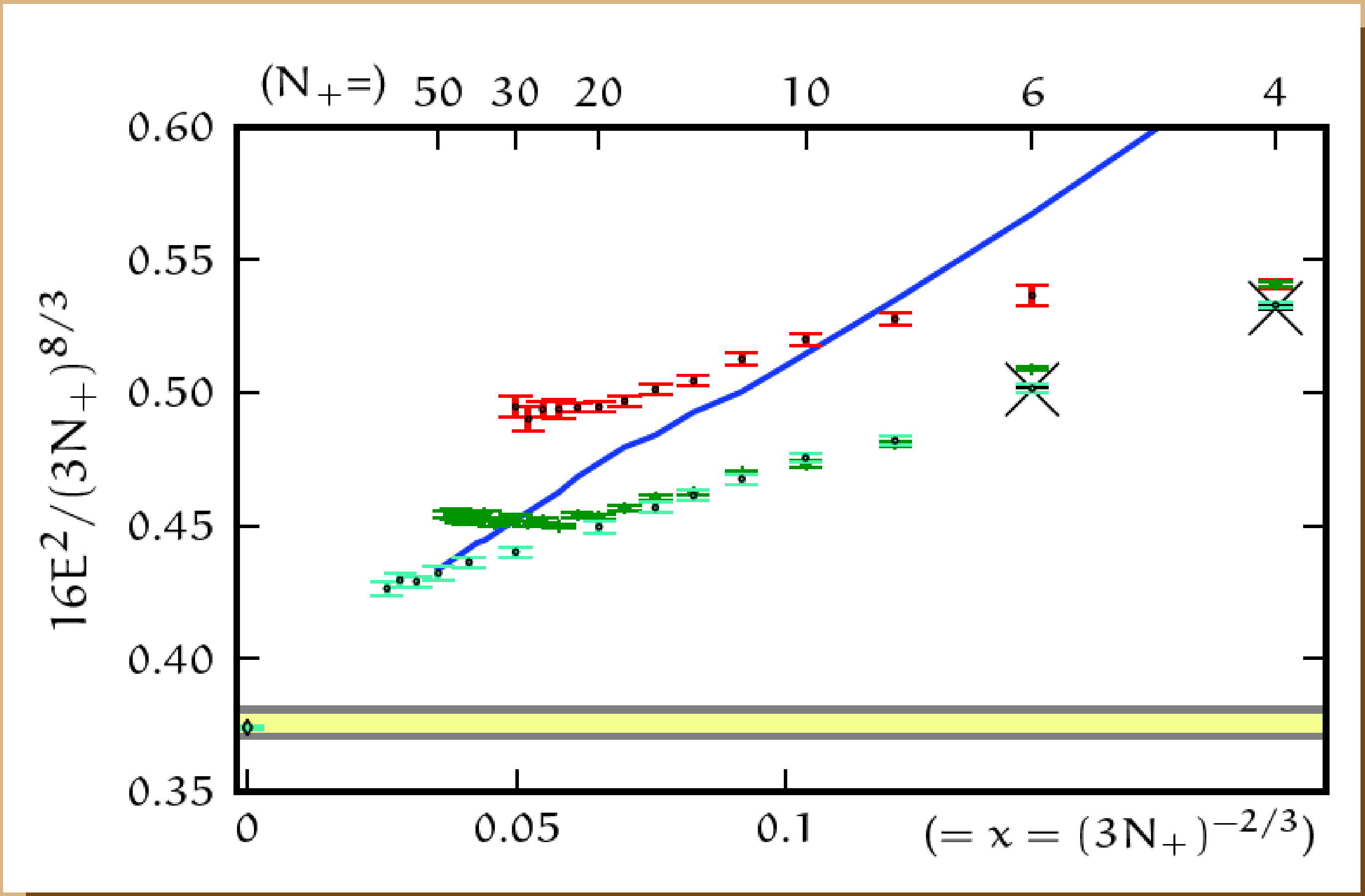
ATOMS

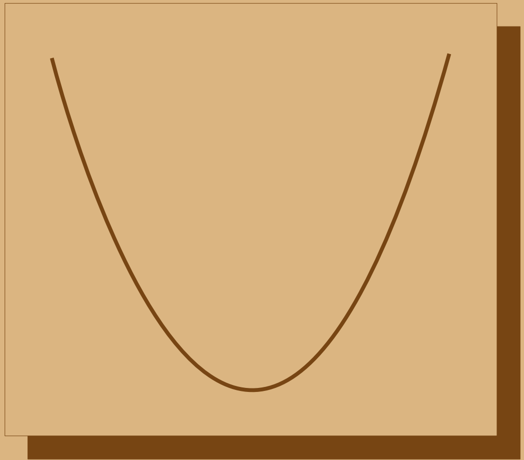
J. Carlson, S. Gandolfi, K. E. Schmidt, S. Zhang, Phys. Rev. A **84**, 061602 (2011)

J. Carlson, S. Gandolfi, A. Gezerlis, Prog. Theor. Exp. Phys. **2012**, 01A???

Newer QMC in a trap

$$\frac{16E^2}{\hbar^2\omega^2(3N_+)^{8/3}} = \xi + cx + \ldots$$





Both SLDA (blue line) and latest QMC (cyan dots) are consistent with Son-Wingate / Rupak-Schaefer effective theory

ATOMS

M. M. Forbes, S. Gandolfi, A. Gezerlis, arXiv:1205.4815, submitted to Phys. Rev. A (2012)

Conclusions

- Cold-atom experiments can constrain nuclear theory
- Neutron matter calculations impact both neutron-star phenomenology and heavy nuclei fits
- Phenomenology (DFT) and *ab initio* (QMC) are mutually beneficial