Neutron Matter from Nuclear Interactions

J. Carlson; LANL - July 11,2022

Collaborators: Gandolfi, Gezerlis, Lonardoni, Lovato, Reddy, Tews, …

Neutron Matter and Many-Body Physics

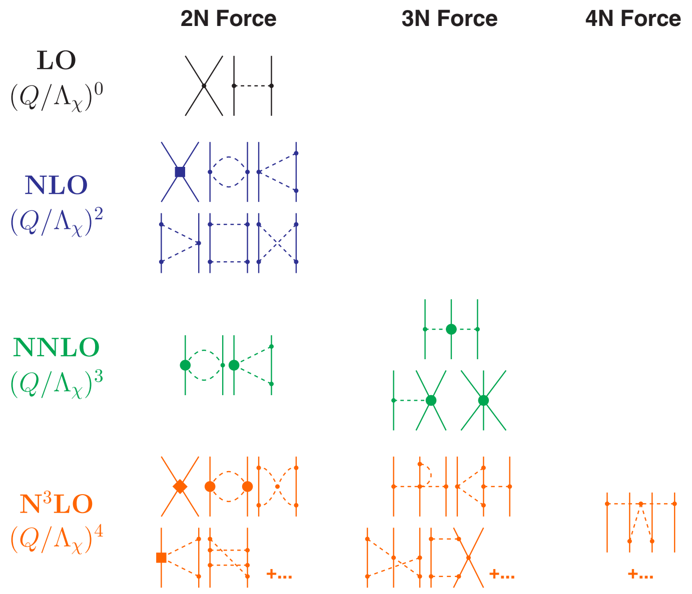
- Ideally start from QCD, particularly for studying high density/temperatures
- At modest densities and temperature, start from interacting nucleons,
  mostly (or all) neutrons
- Solve quantum Many-Body problem for (mostly) neutrons:

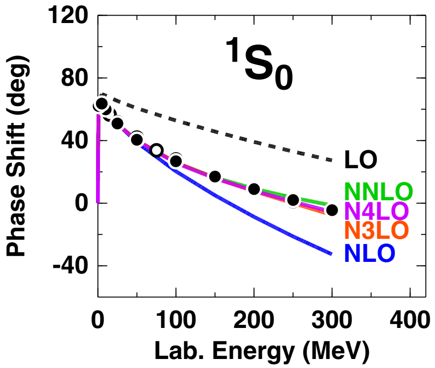
$$H = \sum_i T_i + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

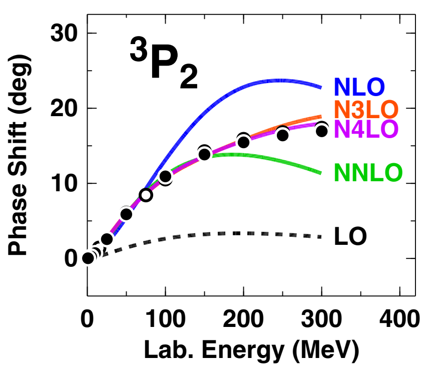
- Fit two-nucleon interaction to NN scattering data
- Fit three-neutron interaction to light nuclei, masses, beta decay, etc.
- How high in density is this appropriate? What limits are important?
  Additional degrees of freedom (pions, kaons, hyperons, deltas, ...)
  What can we reliably compute

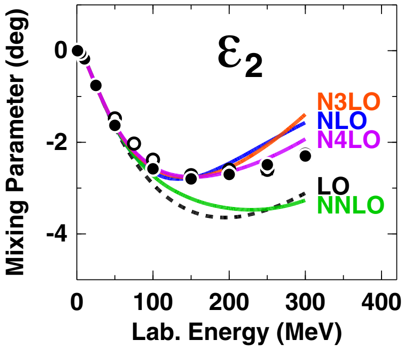
Chiral Nucleon-Nucleon Interactions

Chiral EFT potential (Entem, Machleidt; PRC 2017)





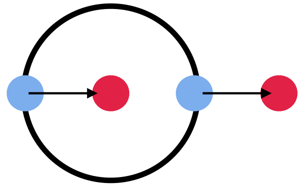




Neutron Matter Densities, Energies

Density [fm^{-3}]	k_F [fm^{-1}]	E_{lab} (2 k_F) [MeV]
0.08	1.33	138
0.16	1.67	210
0.32	2.11	320
0.48	2.42	400

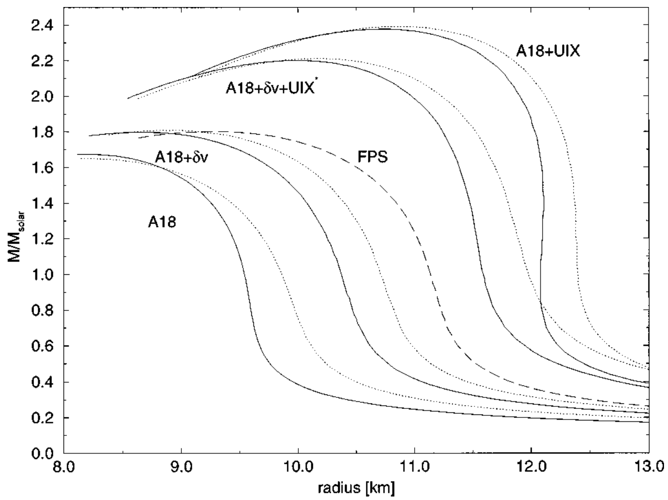
- Cutoff 450-500 MeV typically fit to NN data < 350 MeV
  Nonlocal regulator - no contribution of short-range three-nucleon interaction
- Parameters in NN fit to ~4000 pieces of NN data
- Two 3N parameters c_D and c_E fit to few-body observables



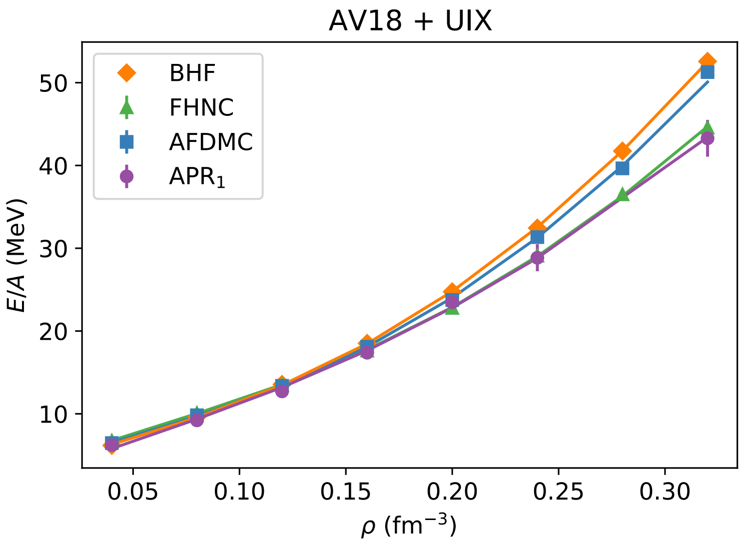
Quantum Many-Body Methods (Fermions)

No Exact General method for Many-Fermion Methods

- Integral Equations- Variational (FHNC)
- Brueckner Hartree Fock
- Quantum Monte Carlo
- Many-Body Perturbation Theory



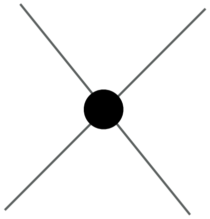
APR mass-radius curves for different interactions



Lovato, et al, PRC (2022)

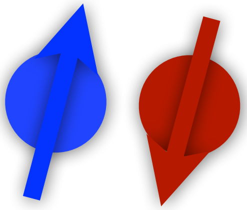
- Chiral EFT : error bars
- Pausible behavior of nucleonic matter beyond 2 x ρ_0

Similarities to Unitary Fermi Gas at (very) low density



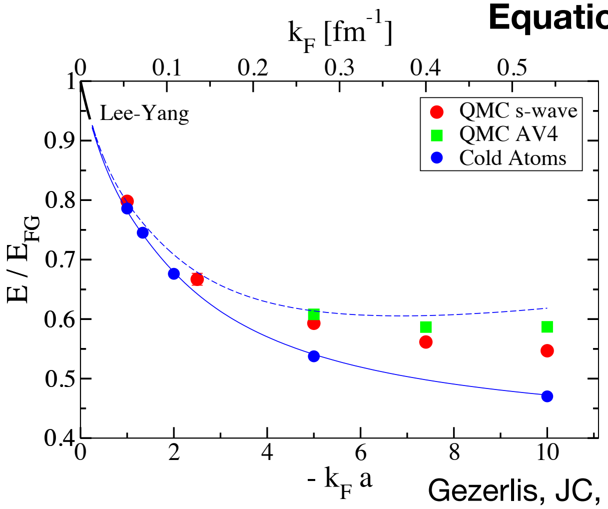
$$H = -\frac{\nabla_i^2}{2m} + \sum_{i,j} V(r_{ij})$$

$$V(r_{ij}) : a \rightarrow \infty : r_{eff} \rightarrow 0$$

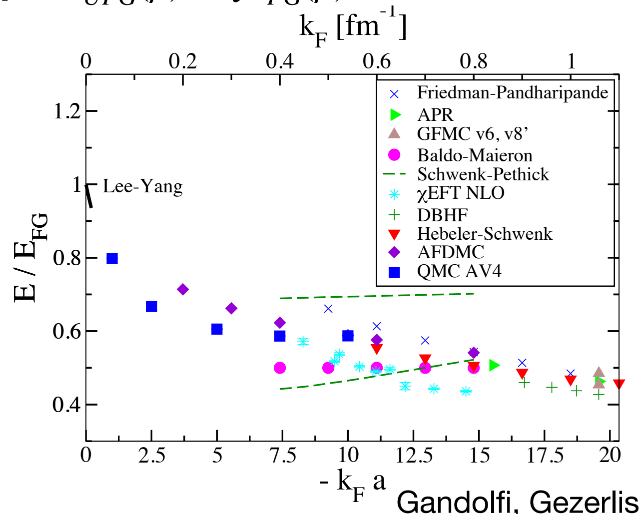


At zero temperature, all quantities are in constants times free FG quanities:

Equation of state versus density: $E_{UFG}(\rho) = \xi E_{FG}(\rho)$



Gezerlis, JC, PRC 2010



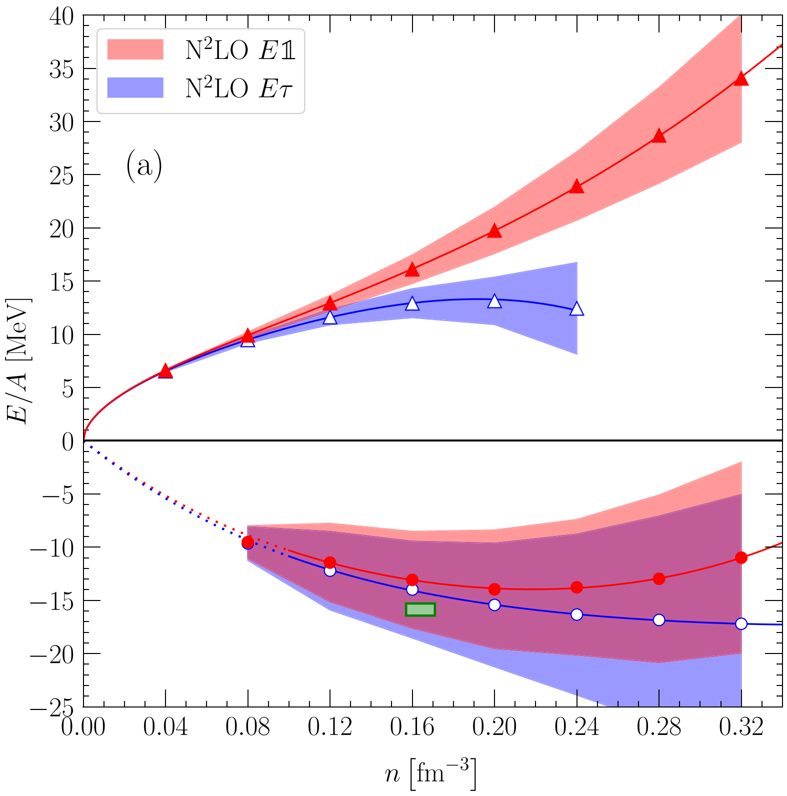
Gandolfi, Gezerlis, JC (2015)

Superfluid pairing gap at T=0 (energy to flip a spin)

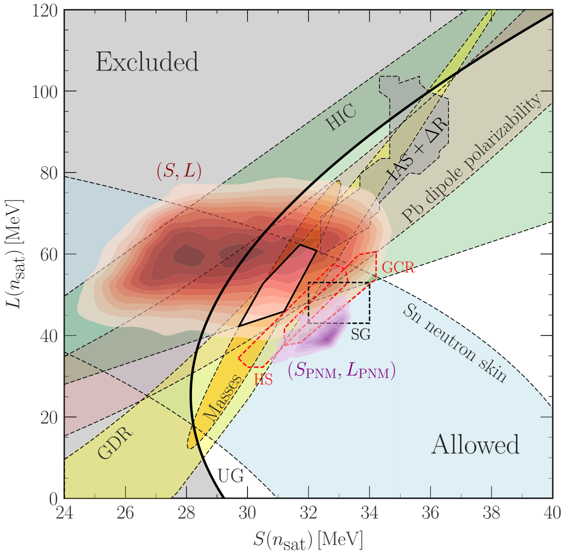
$$\Delta_{UFG} = \delta(E_F(FG)$$

Contact, Spin Response, etc.

Higher Densities



Lonardoni, Tews, Gandolfi, JC, PRR (2020)



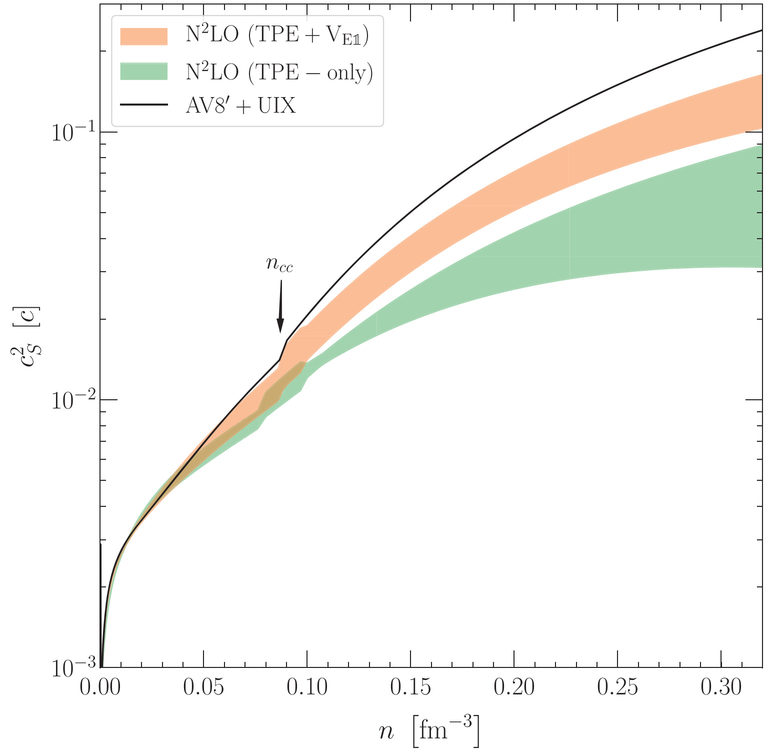
Symmetry Energy vs. Derivative (L vs S)

N2LO

Significant dependence on operator (Fierz) choices

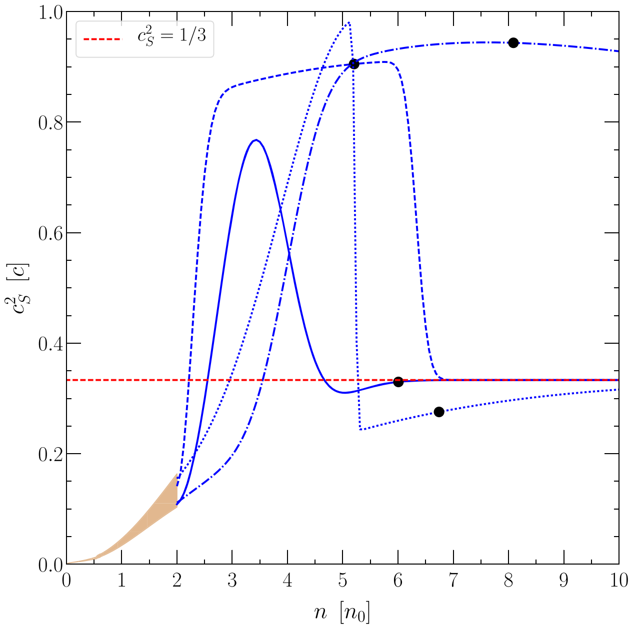
Local vs. non-local regulators…

Speed of Sound in Neutron Matter



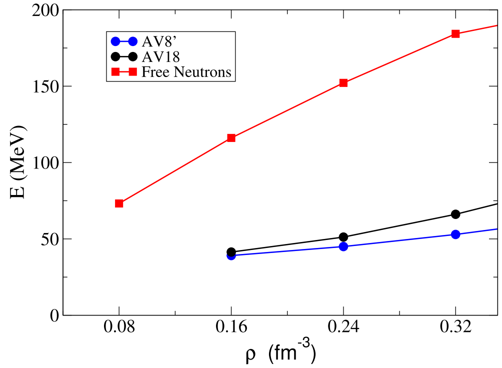
- Tess, JC, Gandolfi, Reddy (APJ - 2018)

- At extremely high densities, pQCD gives $(c_S / c)^2 = 1/3$ exactly.
- Speed of sound decreases at very high but finite density
- Related to maximum mass of neutron star
- Reconcile with few times saturation density?
- Many more degrees of freedom enter at high densities

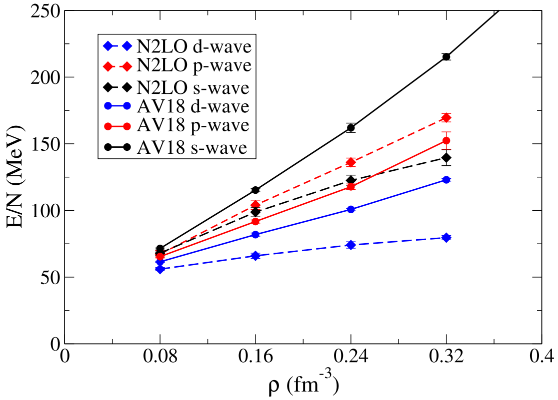


Avenues towards improvement for T=0 neutron matter

Comparisons with LQCD



ig. 1. Ground-state energies of 3 free neutrons and with AV8′ and AV18 *NN* inter-
ctions as a function of density.



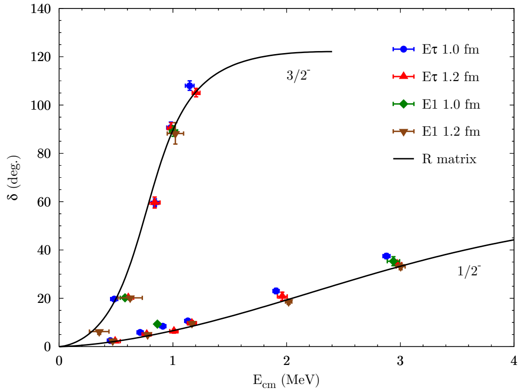
N=3 (upper figure) and N=4 results for neutrons with PBC

Gandolfi, et al, PLB (2018)

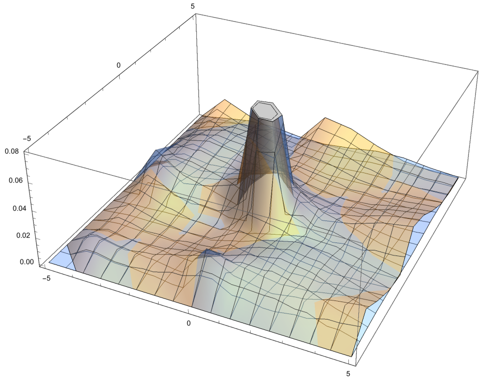
Comparisons with experimental data

- Nuclei with neutron halos (small density)

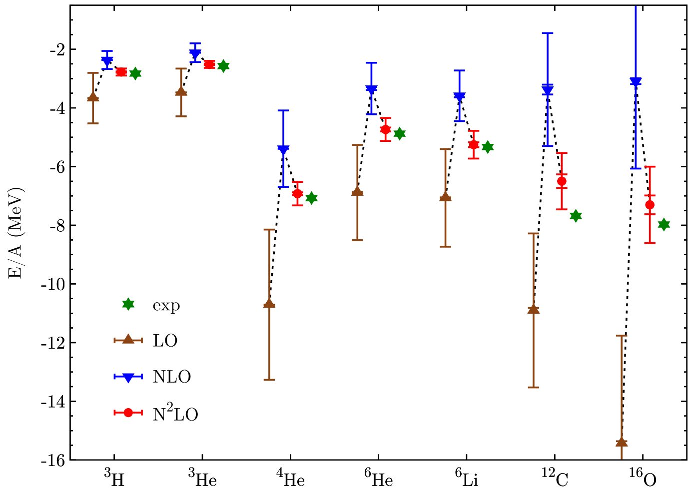
- Low-energy n-alpha scattering has some information
- N=4 scattering (p-^{3}He or n-t) well above breakup higher momenta
- Relating calculations on small lattices to asymptotic observables



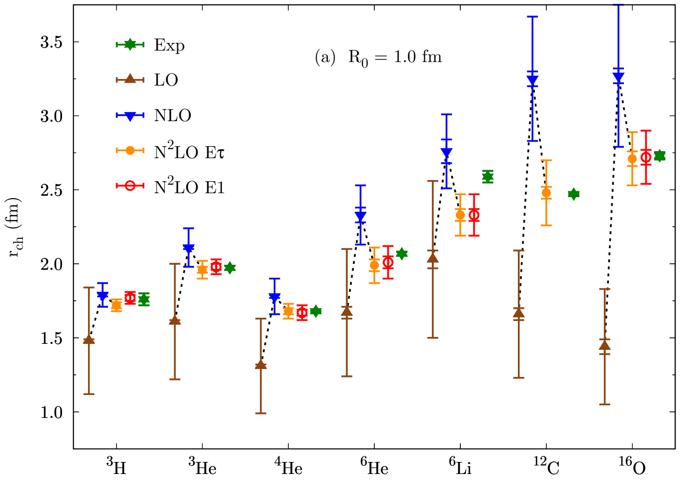
n-α scattering (Lonardoni et al, PRL 2018)



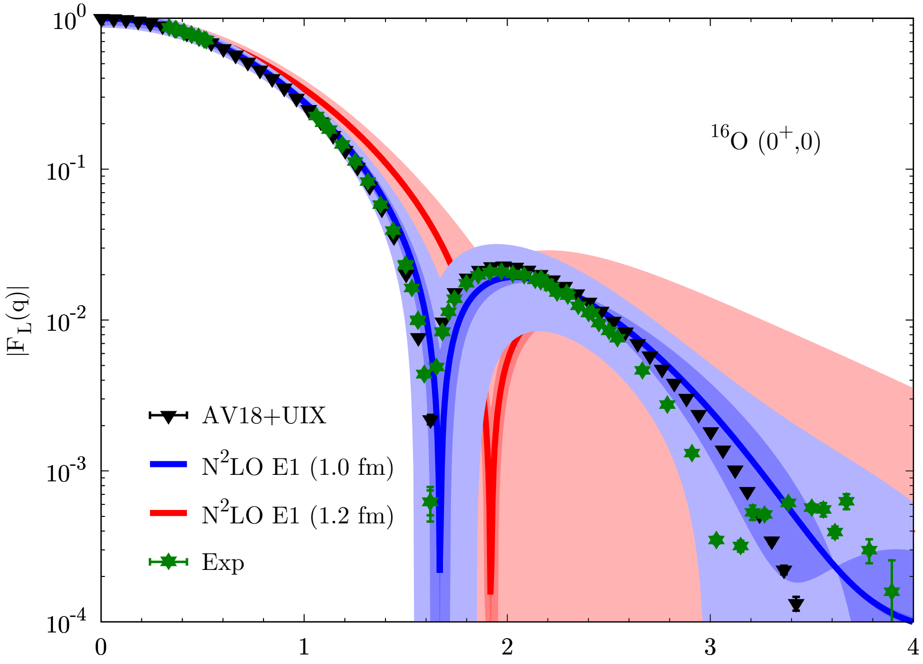
Nuclei with QMC (local regulators)



Masses



Radii

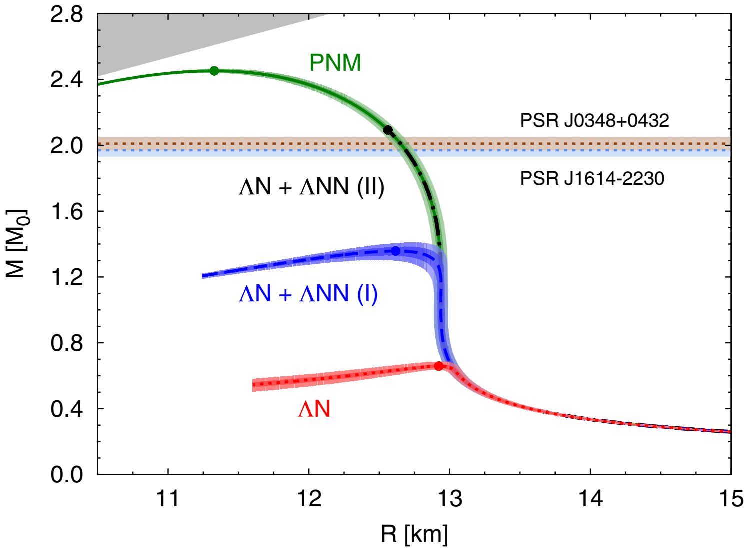


Oxygen Form Factor

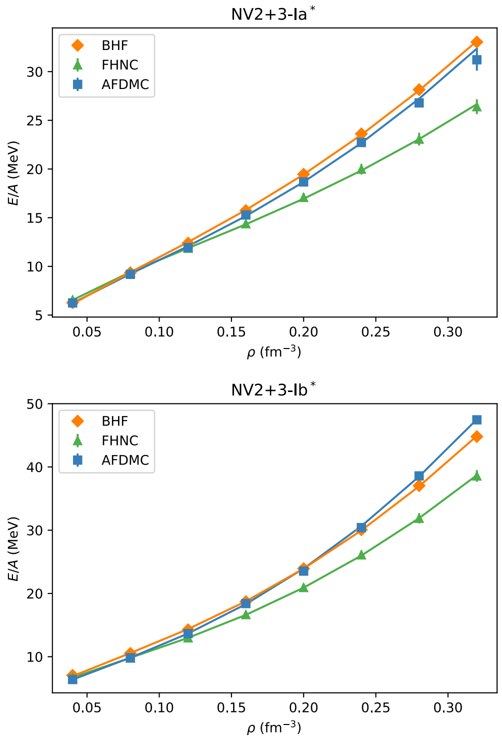
Lonardoni, JC,Gandolfi, Lynn, Schmidt, Schwenk, Wang PRL (2018)

Additional Degrees of Freedom

- Protons at ~10% at modest densities
- At higher densities, additional degrees of freedom enter
- Pion, Kaons (condensates), Hyperons, Deltas, …



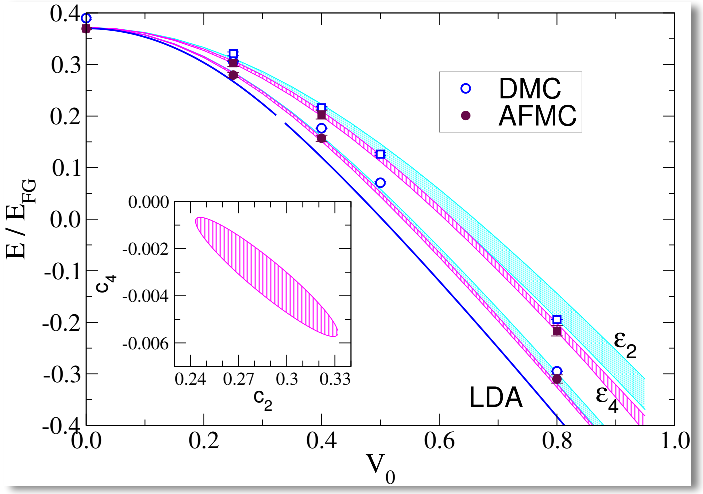
Lonardoni, Lovato, Gandolfi, Pederiva (2015)



Delta-full chiral interactions;
Lovato, et al, 2022

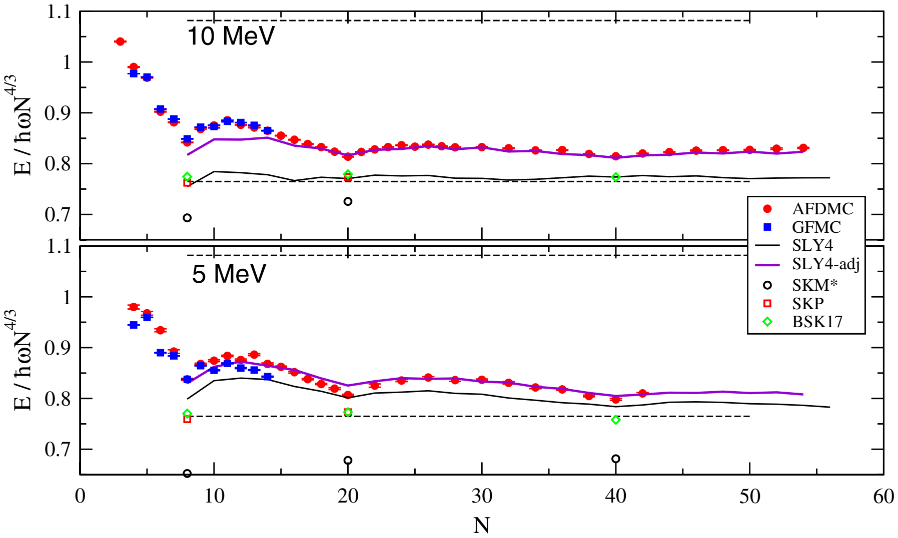
Inhomogeneous Matter: Connection to Density Functionals

Inhomogeneous Matter: Cold Atoms



JC, Gandolfi, PRA 2014

Neutrons trapped in Harmonic Oscillator Potential



Gandolfi, JC, Pieper (PRL 2011)

- Probes shell closure, spin-orbit interactions, pairing, ...
- Density Functionals fit to Nuclei (N~Z), near saturation density
- Much more could be done at finite asymmetry, inhomogeneous potentials (surface)
- Enables additional constraints from experiments

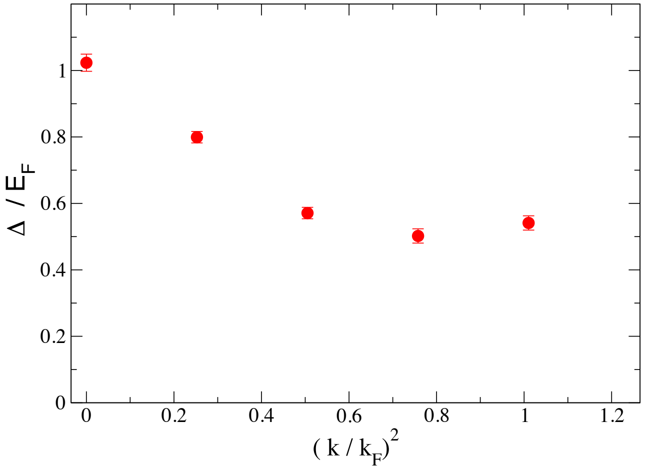
Other Properties

Many other properties are important in various contexts: transport

- Finite Temperature
- Superfluid Gap
- Spin Response (Neutrino Opacity)

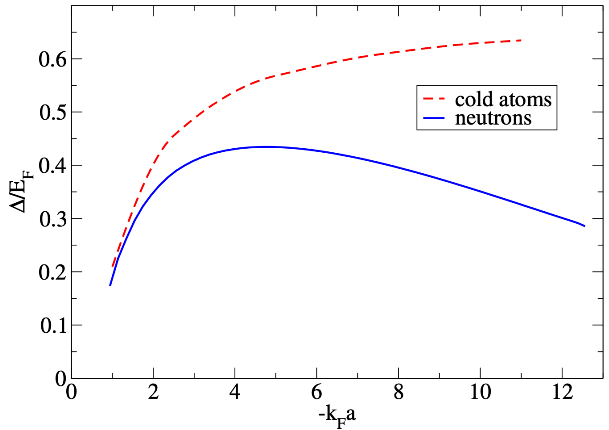
Dispersion Relation and Superfluid Gap: $^1S_0$

Dispersion Relations in Unitary Fermi Gas

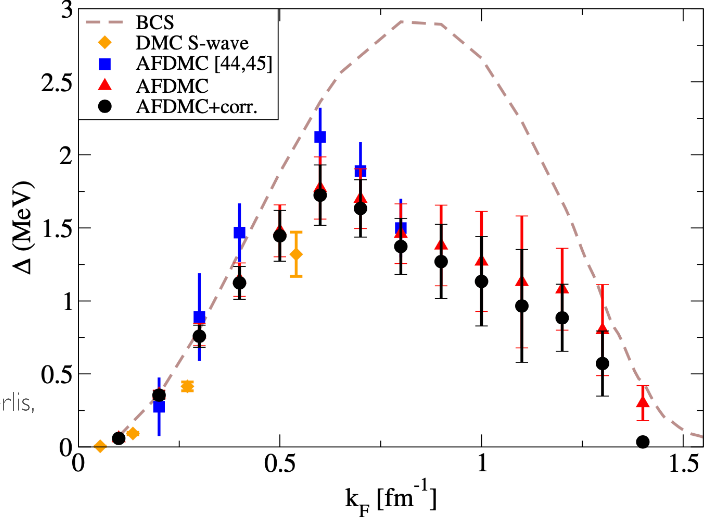


- Pairing gap very large in unitary Fermi Gas (~0.45 E_F)
- Different QMC methods agree for singlet-S gap
  Some suppression from BCS treatment
- Dispersion relation related to finite temperature
- A lot of interest in p-wave superfluidity

Comparison of neutron matter with cold Atoms



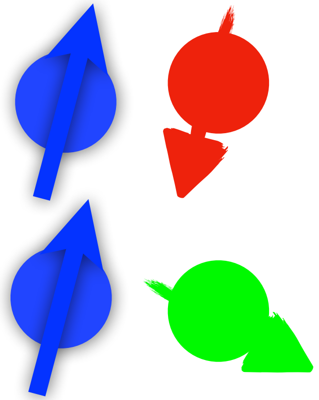
Pairing Gap in neutron matter versus BCS



Gandolfi, Palkanoglou, JC, Gezerlis, Schmidt (2022)

Recent Review of RF and Bragg Spectroscopy:

Spectroscopic probes of quantum gases
Chris J. Vale and Martin Zwierlein, Nature Physics17, 1305–1315 (2021)



RF response: spin flip, essentially zero momentum transfer
high frequency tail gives contact
beautiful measurements at different T

NP analogs to neutrino emissivity of neutron matter
spin flip response (to leading order)
q small (astrophysical energies) but not zero
But Hamiltonian flips/exchanges spins
in general, low E collective excitations (EW transitions, …)

Dynamic Response Functions:

$$S(q,\omega) = \int dt \langle 0 | O^\dagger \exp[-i(H-E_0)t] O | 0 \rangle \delta((\omega - E_0)t)$$

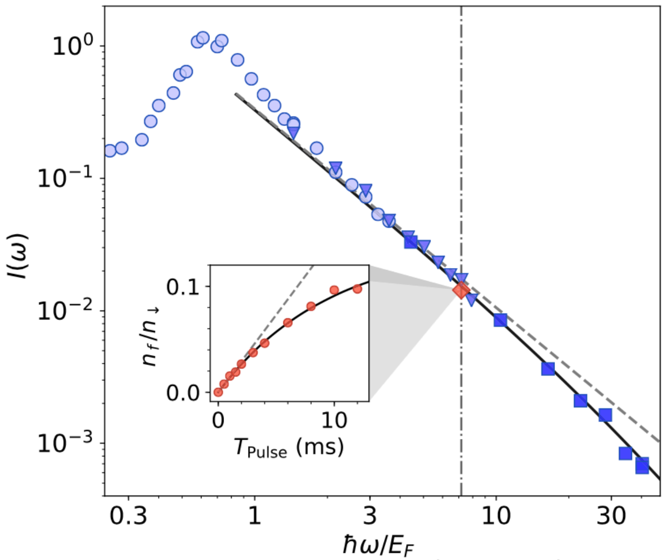
Sum Rules: $$S^N(q) = \langle 0 | O^\dagger (H-E_0)^N O | 0 \rangle$$

Imaginary Time Response: $$S(q,\tau) = \int d\omega \langle 0 | O^\dagger \exp[-(H-E_0)\tau] O | 0 \rangle$$

Spin Response at low momentum transfer

- Both Unitary Fermi Gas and Neutron Matter have large strength at energies near EF
- Mechanisms somewhat different: high momentum components versus spin-dependent interac

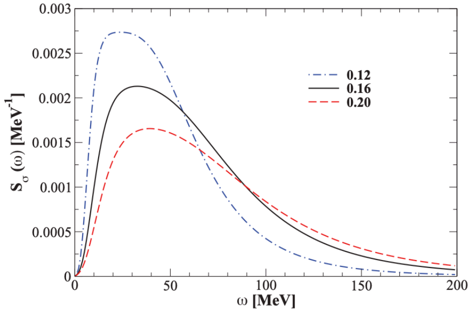
Cold Atoms (RF response)



Want strength at high energy (contact)
RF response vs. temperature
(Single Peak near E_F: Narrow at low T**)**

Zwierlein et al, PRL (2019)

Neutron Matter



$$Q = \frac{C_A^2 G_F^2 n}{20\pi^3}\int_0^\infty d\omega\,\omega^6 e^{-\omega/T} S_\sigma(\omega),$$

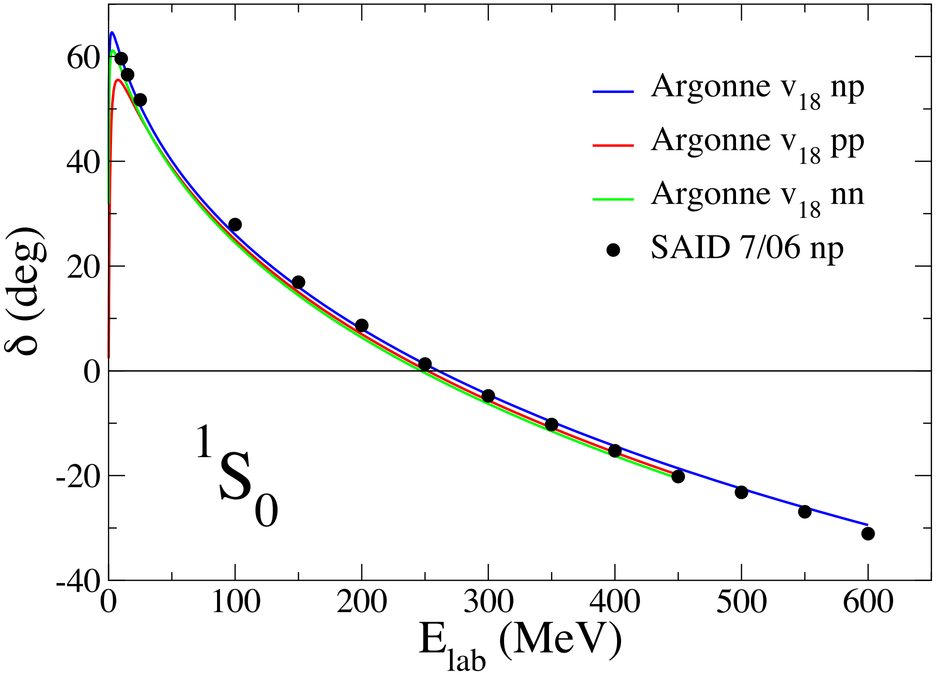
Want strength < 50 MeV
E_F at saturation density = 60 MeV

Shen, Gandolfi, Reddy, JC; PRC 2013

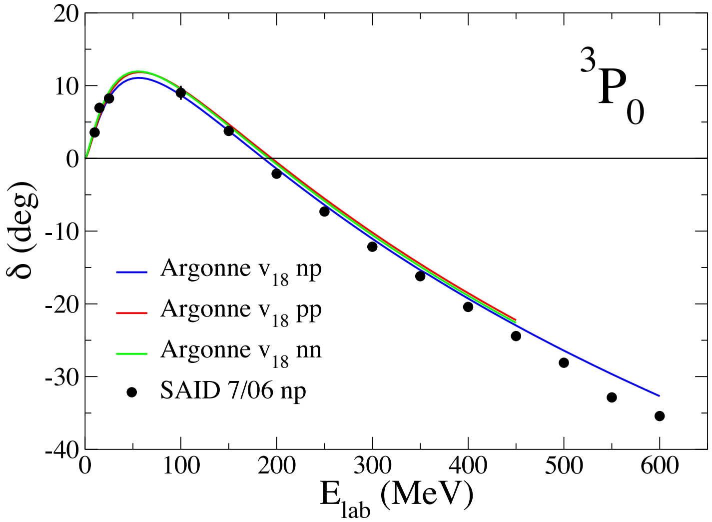
Conclusions and Outlook

- *Ab initial approaches can bring valuable insight into dense nucleonic matter*
- *Static properties near T=0 are in reasonably good agreement with NP experiments and astrophysical observation*
- *Improvements possible by higher order calculations (interaction and many-body) and more constraints on three-nucleon interactions (scattering, halo nuclei)*
- *Finite Temperature and dynamic response are important challenges for the present and future*
- *Monte Carlo methods have some unique strengths - and of course some challenges…. (QC?)*

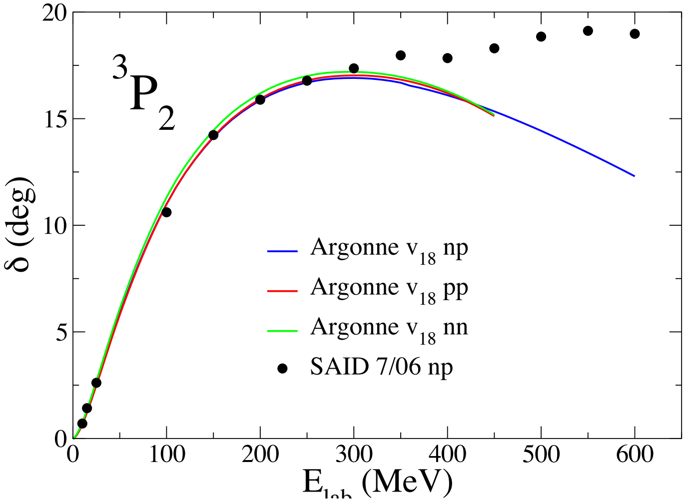
Backup Slides



$^1S_0$
δ (deg)
60
40
20
0
-20
-40
0
100
200
300
400
500
600
E_{lab} (MeV)
Argonne v_{18} np
Argonne v_{18} pp
Argonne v_{18} nn
SAID 7/06 np



$^3P_0$
δ (deg)
20
10
0
-10
-20
-30
-40
0
100
200
300
400
500
600
E_{lab} (MeV)
Argonne v_{18} np
Argonne v_{18} pp
Argonne v_{18} nn
SAID 7/06 np



$^3P_2$
δ (deg)
20
15
10
5
0
0
100
200
300
400
500
600
E_{lab} (MeV)
Argonne v_{18} np
Argonne v_{18} pp
Argonne v_{18} nn
SAID 7/06 np