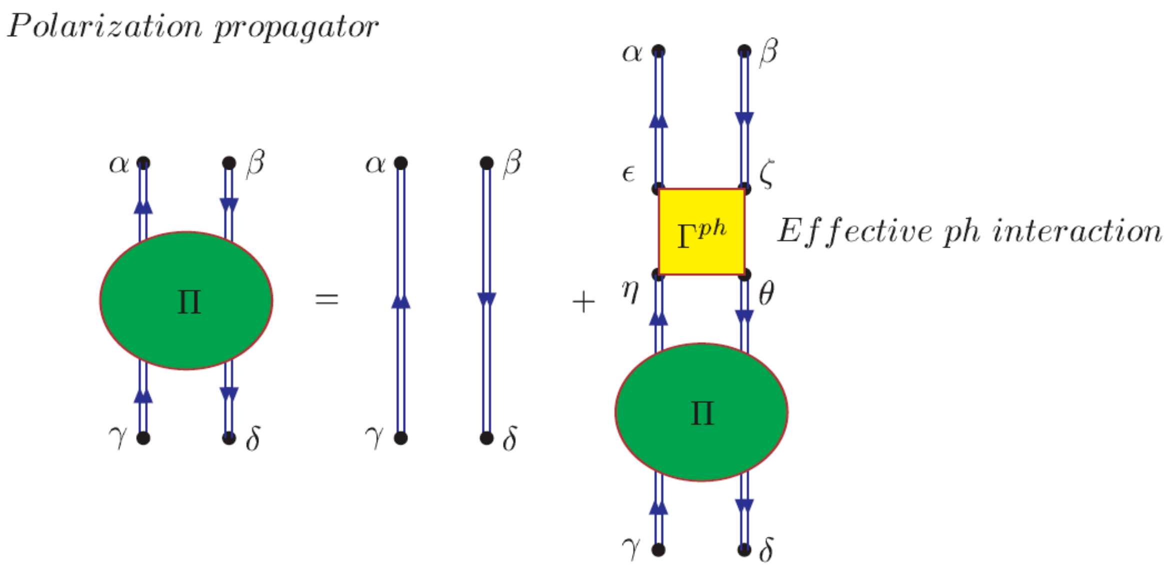
FSI and (e,e´p) ⇔ analysis

$$\hat{O} = \sum_{\alpha\beta} \langle \alpha | O | \beta \rangle a^{+}_{\alpha} a_{\beta}$$ Electron Scattering ⇒ one-body operator

$$\left| \left\langle \Psi^A_n \middle| \hat{O} \middle| \Psi^A_0 \right\rangle \right|^2 = \sum \langle \alpha | O | \beta \rangle^{*} \langle \gamma | O | \delta \rangle \left\langle \Psi^A_0 \middle| a^{+}_{\beta} a_{\alpha} \middle| \Psi^A_n \right\rangle \left\langle \Psi^A_n \middle| a^{+}_{\gamma} a_{\delta} \middle| \Psi^A_0 \right\rangle$$

Requires (imaginary part of) **exact** polarization propagator



Choose kinematics:
⇒ only first term

$$\left\langle \Psi^{A+1}_m \middle| a^{+}_{\alpha} \middle| \Psi^A_0 \right\rangle$$

⇒ Elastic scattering (phenomenology)

$$\left\langle \Psi^{A-1}_n \middle| a_{\beta} \middle| \Psi^A_0 \right\rangle$$

"Absolute" spectroscopic factors ✔ ⇒ Quasihole wave function

NSCL 7/27/05

Spectroscopic factors and the physics of the single-particle strength distribution in nuclei

Lecture 1: 7/18/05 Propagator description of single-particle motion and the link with experimental data

Lecture 2: 7/19/05 From diagrams to Hartree-Fock and spectroscopic factors < 1

Lecture 3: 7/20/05 Influence of long-range correlations and the relation to excited states

Lecture 4: 7/27/05 Role of short-range and tensor correlations associated with realistic interactions. Prospects for nuclei with N very different from Z.

Lecture 5: 7/28/05 Saturation problem of nuclear matter

Wim Dickhoff
Washington University in St. Louis

Outline

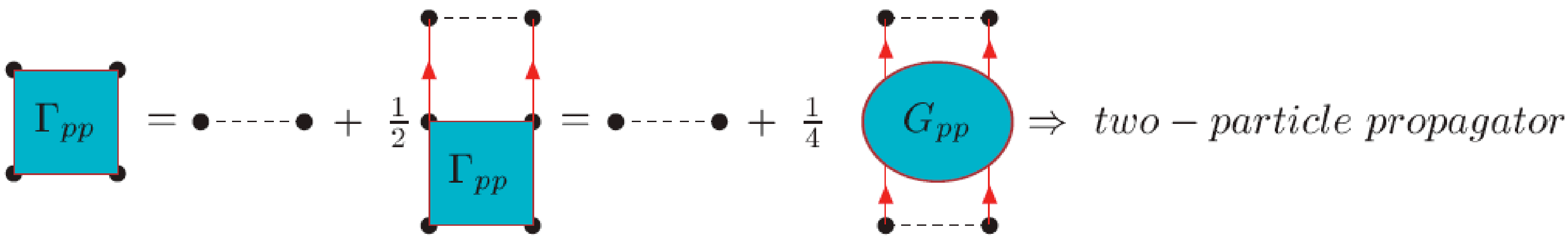
- SRC for free particles
- Ladders in the medium
- Self-energy and Dyson equation
- Nuclear matter simplifications
- Self-consistent Green's functions in nuclear matter & results
- SRC in finite nuclei: where are the high-momentum nucleons
- Summary of sp strength in closed-shell nuclei
- Other nuclei
- N very different from Z
- Nuclear matter with isospin polarization

Short-range correlations for two free particles

Solve the Schrödinger equation or the equivalent "*T*"-matrix

$$\langle k\ell|\Gamma_{pp}^{JST}(k_0)|k'\ell'\rangle = \langle k\ell|V^{JST}|k'\ell'\rangle + \frac{m}{2\hbar^2}\sum_{\ell''}\int_0^\infty \frac{dq}{(2\pi)^3} q^2 \langle k\ell|V^{JST}|q\ell''\rangle \frac{1}{k_0^2 - q^2 + i\eta}\langle q\ell''|\Gamma_{pp}^{JST}(k_0)|k'\ell'\rangle$$

Effective interaction

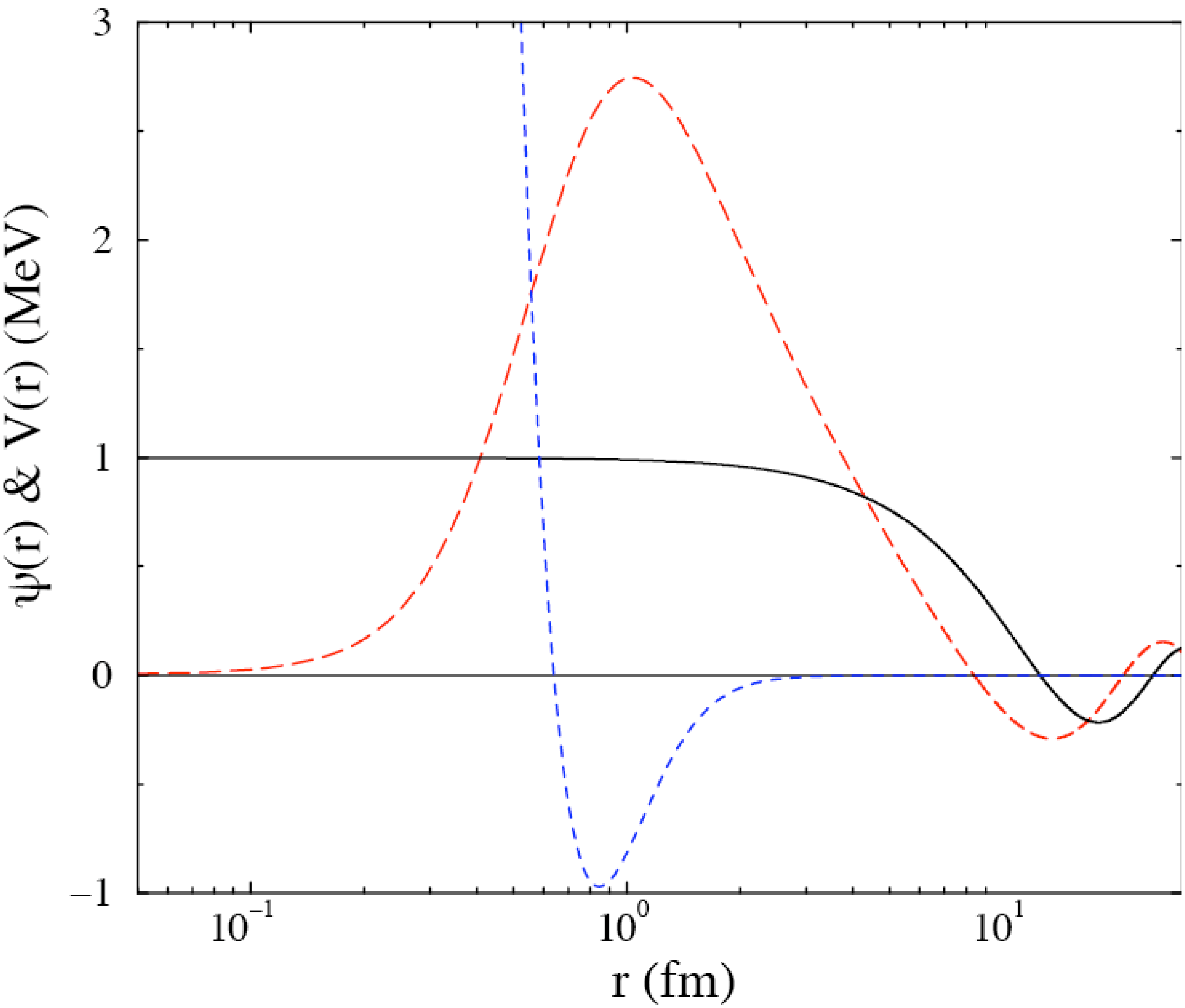


Sum of ladder diagrams

Sum of ladder diagram takes care of SRC

Also in the medium!

Relative wave function and potential



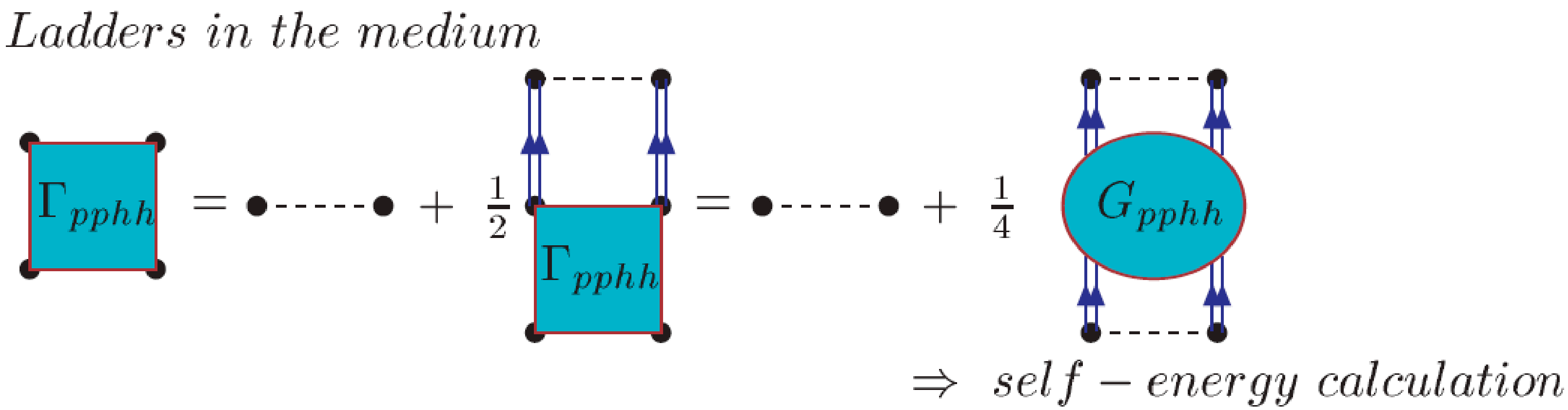
Reid $^{1}S_0$
$k_0 = 0.25\ \mathrm{fm}^{-1}$

V(r)/100

$\sin(k_0 r)/k_0 r$

correlated wf

Ladder diagrams in the medium (options)



$$\langle k\ell|\Gamma^{JST}_{pphh}(K,E)|k'\ell'\rangle = \langle k\ell|V^{JST}|k'\ell'\rangle + \frac{1}{2}\sum_{\ell''}\int_0^\infty \frac{dq}{(2\pi)^3} q^2 \langle k\ell|V^{JST}|q\ell''\rangle G^f_{pphh}(q;K,E)\langle q\ell''|\Gamma^{JST}_{pphh}(K,E)|k'\ell'\rangle$$

G^f_{pphh} has different form depending on the level of sophistication

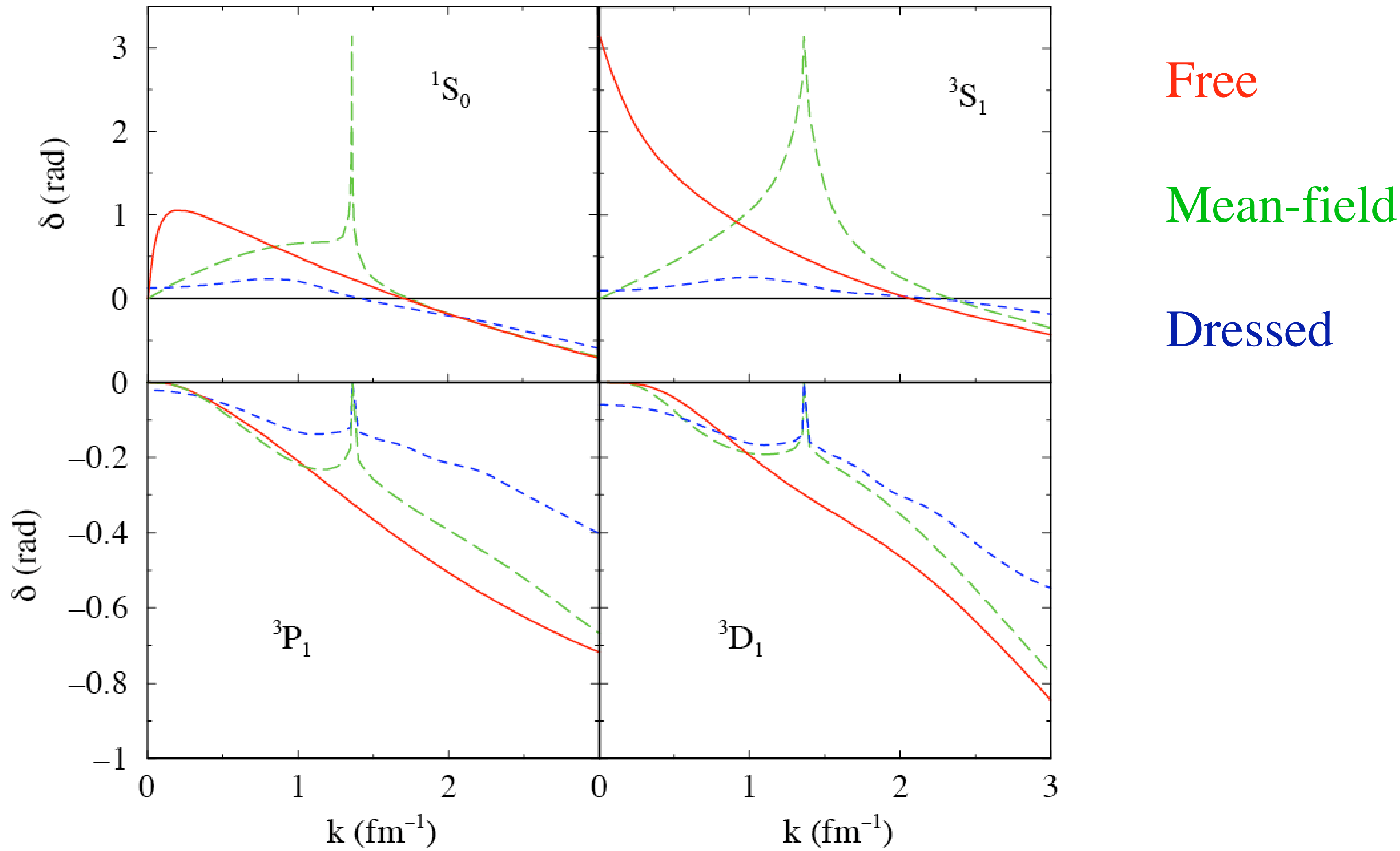
Nuclear matter:

$$G^f_{BG}(k_1,k_2;E) = \frac{\theta(k_1-k_F)\theta(k_2-k_F)}{E-\varepsilon(k_1)-\varepsilon(k_2)+i\eta}$$ Bethe-Goldstone

$$G^f_{GF}(k_1,k_2;E) = \frac{\theta(k_1-k_F)\theta(k_2-k_F)}{E-\varepsilon(k_1)-\varepsilon(k_2)+i\eta} - \frac{\theta(k_F-k_1)\theta(k_F-k_2)}{E-\varepsilon(k_1)-\varepsilon(k_2)-i\eta}$$ Galitskii-Feynman

$$G^f_{pphh}(k_1,k_2;E) = \int_{\varepsilon_F}^{\infty} dE_1 \int_{\varepsilon_F}^{\infty} dE_2 \frac{S_p(k_1;E_1)S_p(k_2;E_2)}{E-E_1-E_2+i\eta} - \int_{-\infty}^{\varepsilon_F} dE_1 \int_{-\infty}^{\varepsilon_F} dE_2 \frac{S_h(k_1;E_1)S_h(k_2;E_2)}{E-E_1-E_2-i\eta}$$ sc

Phase shifts for dressed nucleons



PRC**60**, 064319 (1999) also PRC**58**, 2807 (1998)

Dyson equation and spectral functions in nuclear matter (some simplifications)

$$G(k;E) = G^{(0)}(k;E) + G^{(0)}(k;E)\Sigma(k;E)G(k;E)$$

Dyson equation

$$= \frac{1}{E - \varepsilon(k) - \Sigma(k;E)}$$

$$G^{(0)}(k;E) = \frac{\theta(k - k_F)}{E - \varepsilon(k) + i\eta} + \frac{\theta(k_F - k)}{E - \varepsilon(k) - i\eta}$$

Noninteracting sp propagator

$$S_p(k;E) = -\frac{1}{\pi}\frac{\mathrm{Im}\,\Sigma(k;E)}{\left(E - \varepsilon(k) - \mathrm{Re}\,\Sigma(k;E)\right)^2 + \left(\mathrm{Im}\,\Sigma(k;E)\right)^2}$$

particle spectral function

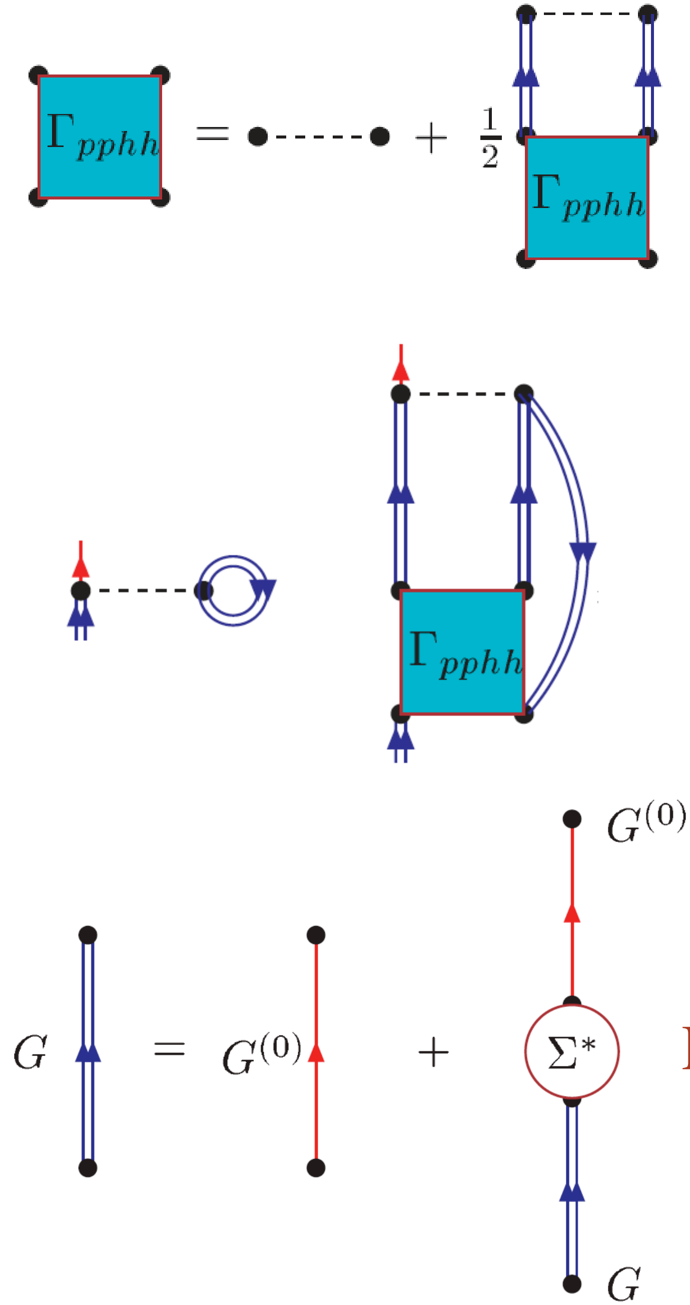
$$S_h(k;E) = \frac{1}{\pi}\frac{\mathrm{Im}\,\Sigma(k;E)}{\left(E - \varepsilon(k) - \mathrm{Re}\,\Sigma(k;E)\right)^2 + \left(\mathrm{Im}\,\Sigma(k;E)\right)^2}$$

hole spectral function

$$G(k;E) = \int_{\varepsilon_F}^{\infty} dE' \frac{S_p(k;E')}{E - E' + i\eta} + \int_{-\infty}^{\varepsilon_F} dE' \frac{S_h(k;E')}{E - E' - i\eta}$$

Again:
numerator sp strength
denominator where

Self-consistency



Interaction

Self-energy

Dyson equation

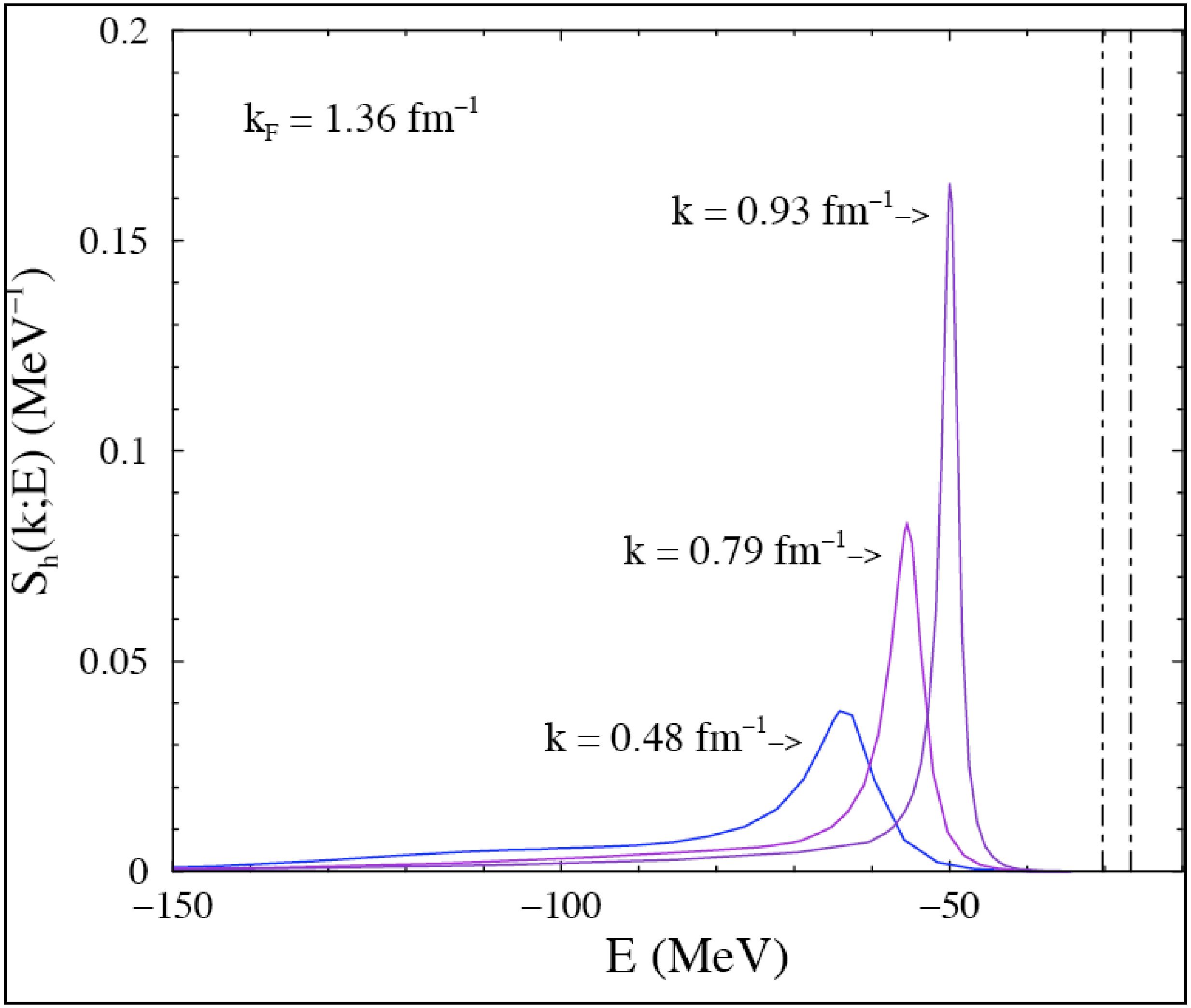
Recent developments

- St. Louis ⇒ Complete self-consistency for spectral functions

  http://wuphys.wustl.edu/~wimd/thesis1016.pdf

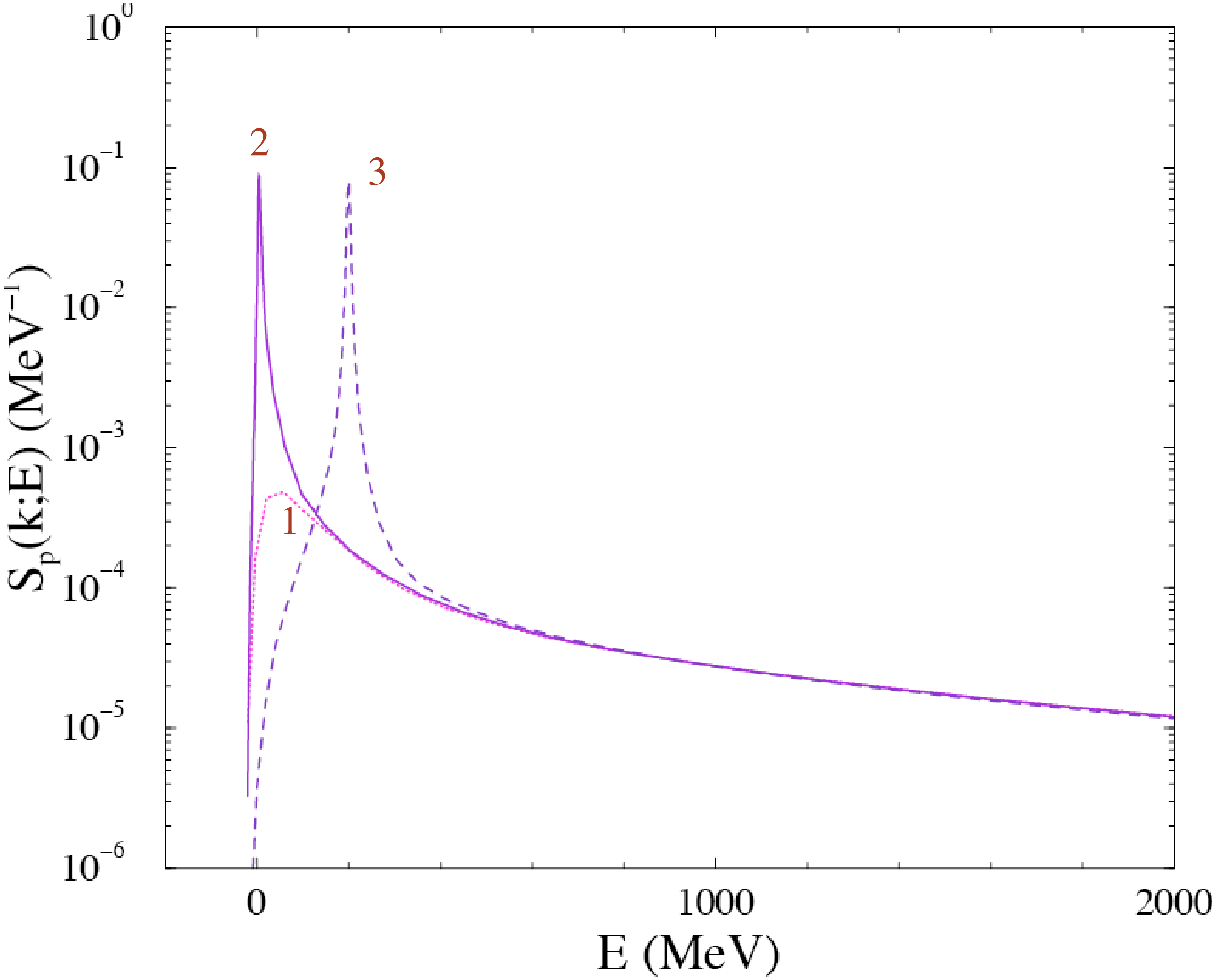
- Ghent ⇒ Discrete method
- Cracow ⇒ Separable & soft interactions
- Tübingen ⇒ Finite temperature & soft interactions
- Giessen ⇒ Interaction related to cross section

Illustrative results for mean-field input



Strength distribution as in nuclei …
peak strength +10% at lower energy + global depletion!!

Where does the strength go?



All tails the same!
$\Rightarrow$ SRC

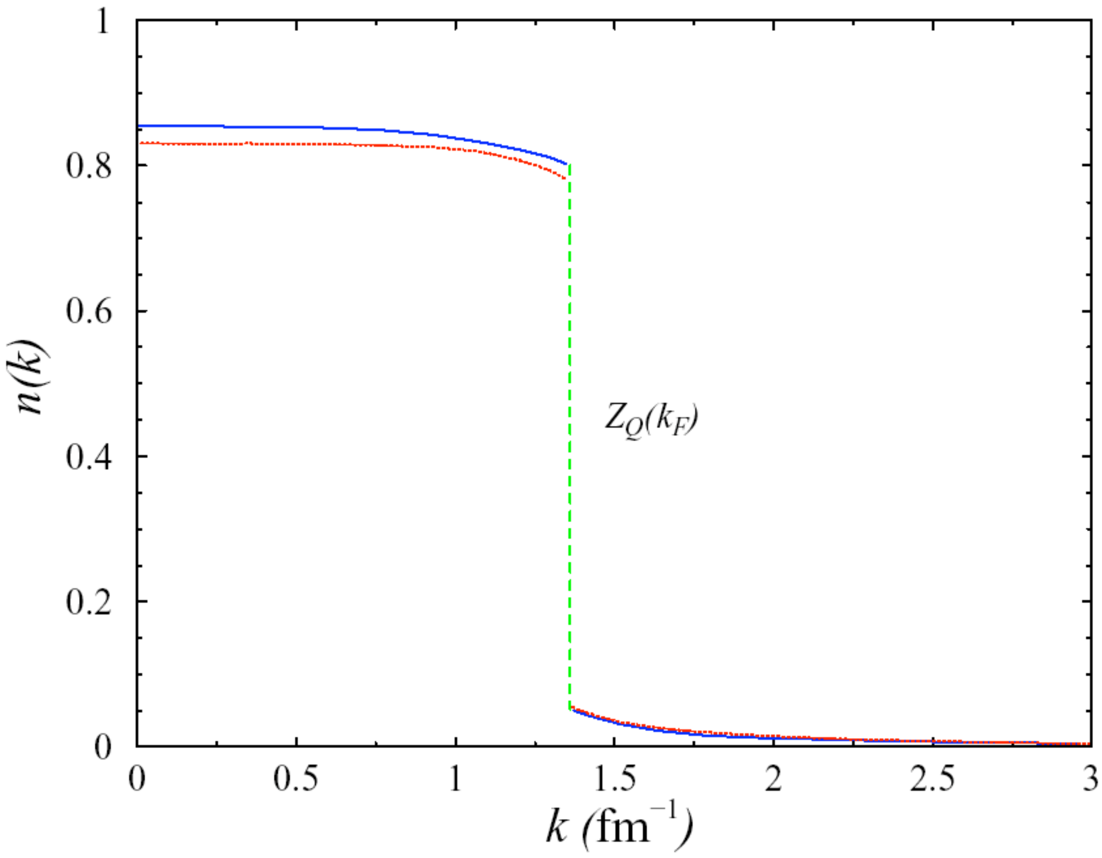
$k_1 = 0.79$ fm^{-1}
$k_2 = 1.74$ fm^{-1}
$k_3 = 3.51$ fm^{-1}

$k < k_F$: 17% > ε_F with 13% above 100 MeV (7% above 500 MeV)
Without tensor force only 10.5% above ε_F

Short-range correlations in nuclear matter and n(k)

$n(k=0) = 0.83 \,/\, 0.85 \;\Rightarrow$ finite nuclei

$$n(k) = \int_{-\infty}^{\varepsilon_F} dE\, S_h(k;E)$$



Reid soft core
$k_F = 1.36$ fm^{-1}

Old prediction!
New result

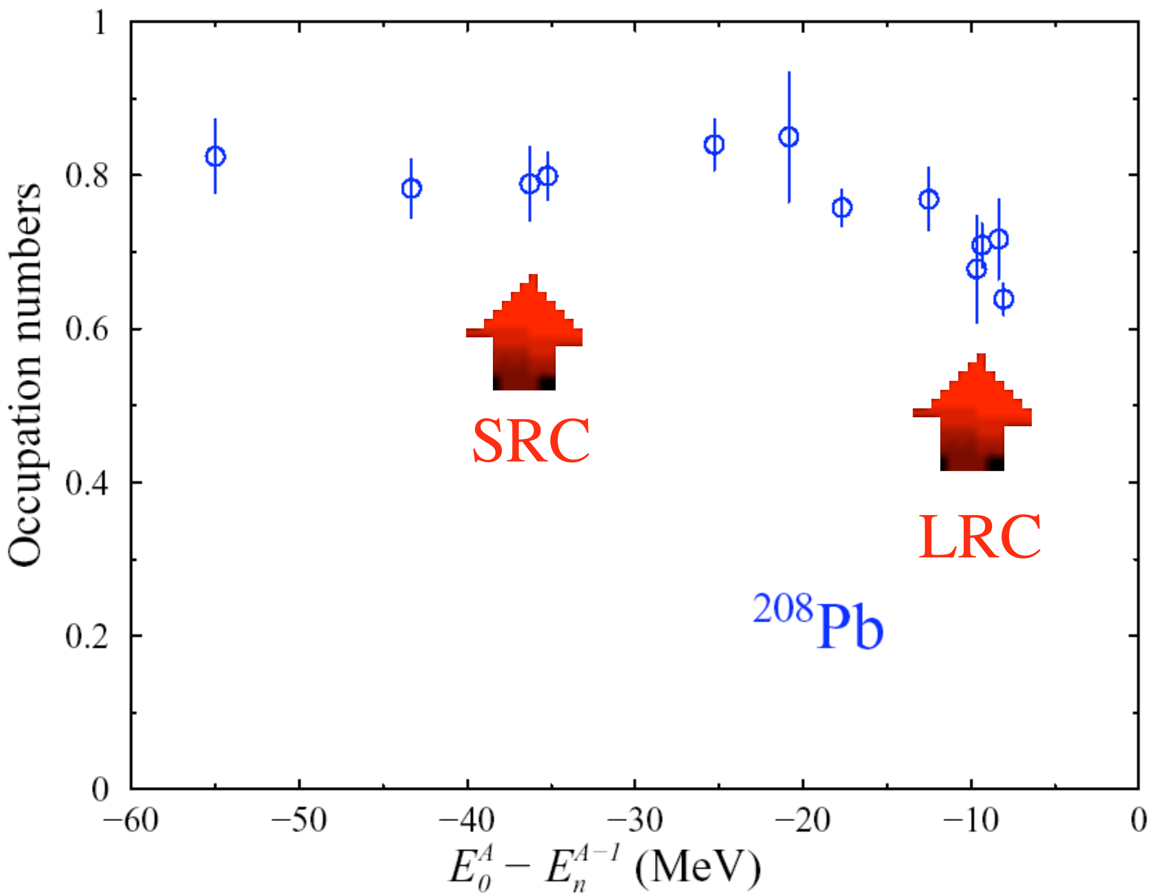
$Z_Q(k_F)$=0.72

$Z_Q(k_F)$=0.75

B.E.Vonderfecht et al. Nucl. Phys. A555, 1 (1993)
E.R.Stoddard, thesis (self-consistent ladders)

M. van Batenburg (thesis, 2001) & L. Lapikás from ^{208}Pb (e,e´p) ^{207}Tl

Occupation of deeply-bound proton levels from **EXPERIMENT**



Up to 100 MeV
missing energy
and
270 MeV/c
missing momentum

Covers the whole
mean-field domain
for the FIRST time!!

Confirmation of theory

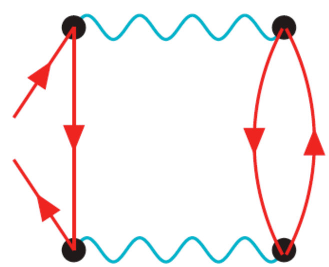
Two effects associated with short-range correlations

- Depletion of the Fermi sea

- Admixture of high-momentum components
  to replace depleted strength

Location of high-momentum components

high momenta

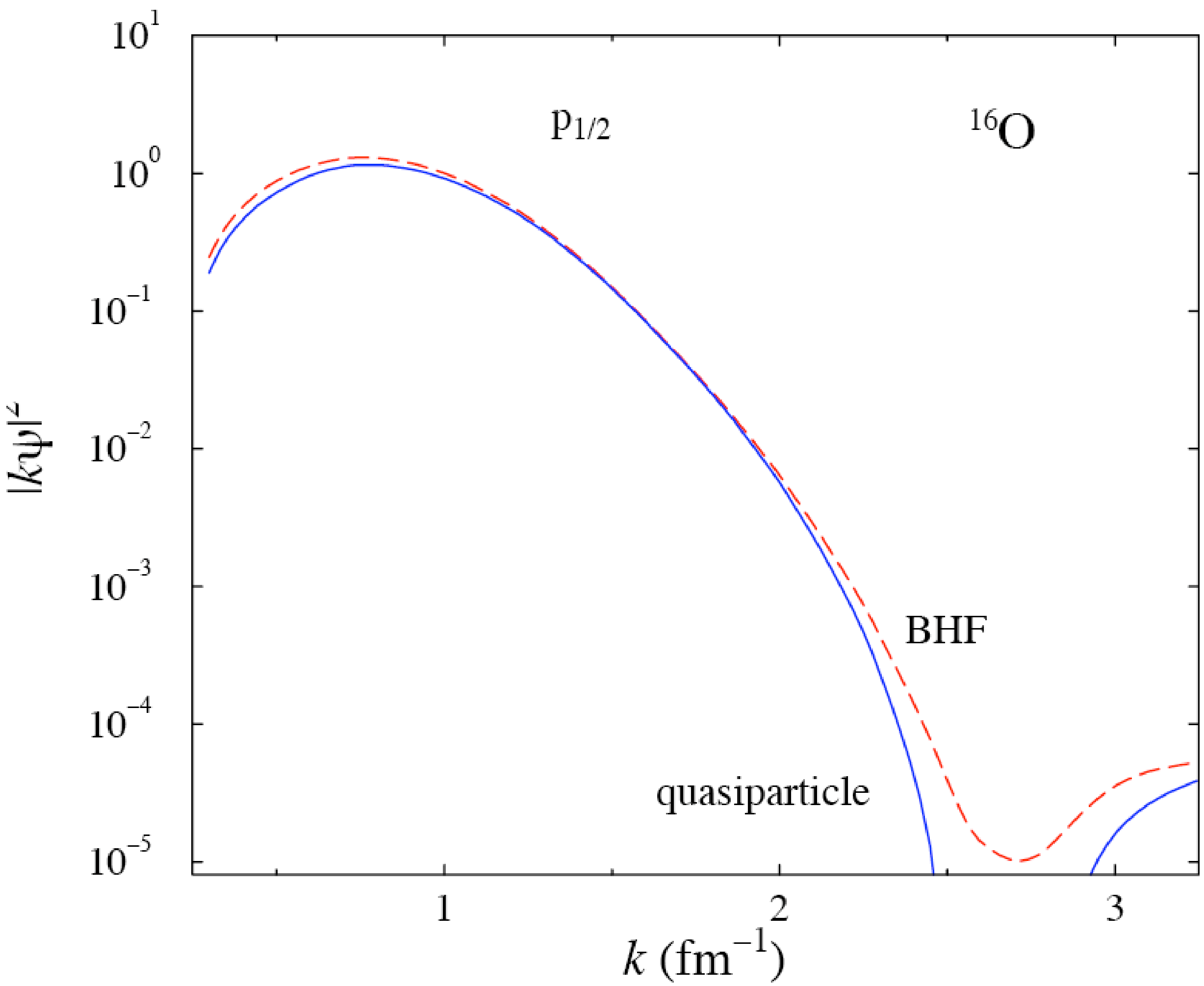


require specific intermediate states

External line $\boldsymbol{k}$ (large).
Intermediate holes < k_F, say total momentum ~ 0.
Momentum conservation: intermediate particle -$\boldsymbol{k}$

⇒ Energy intermediate state ~ $\langle \varepsilon_{2h} \rangle - \varepsilon(\boldsymbol{k})$
⇒ the higher k the more negative the location of its strength
⇒ no high-momentum components near ε_F

SRC (only) calculated in ^{16}O

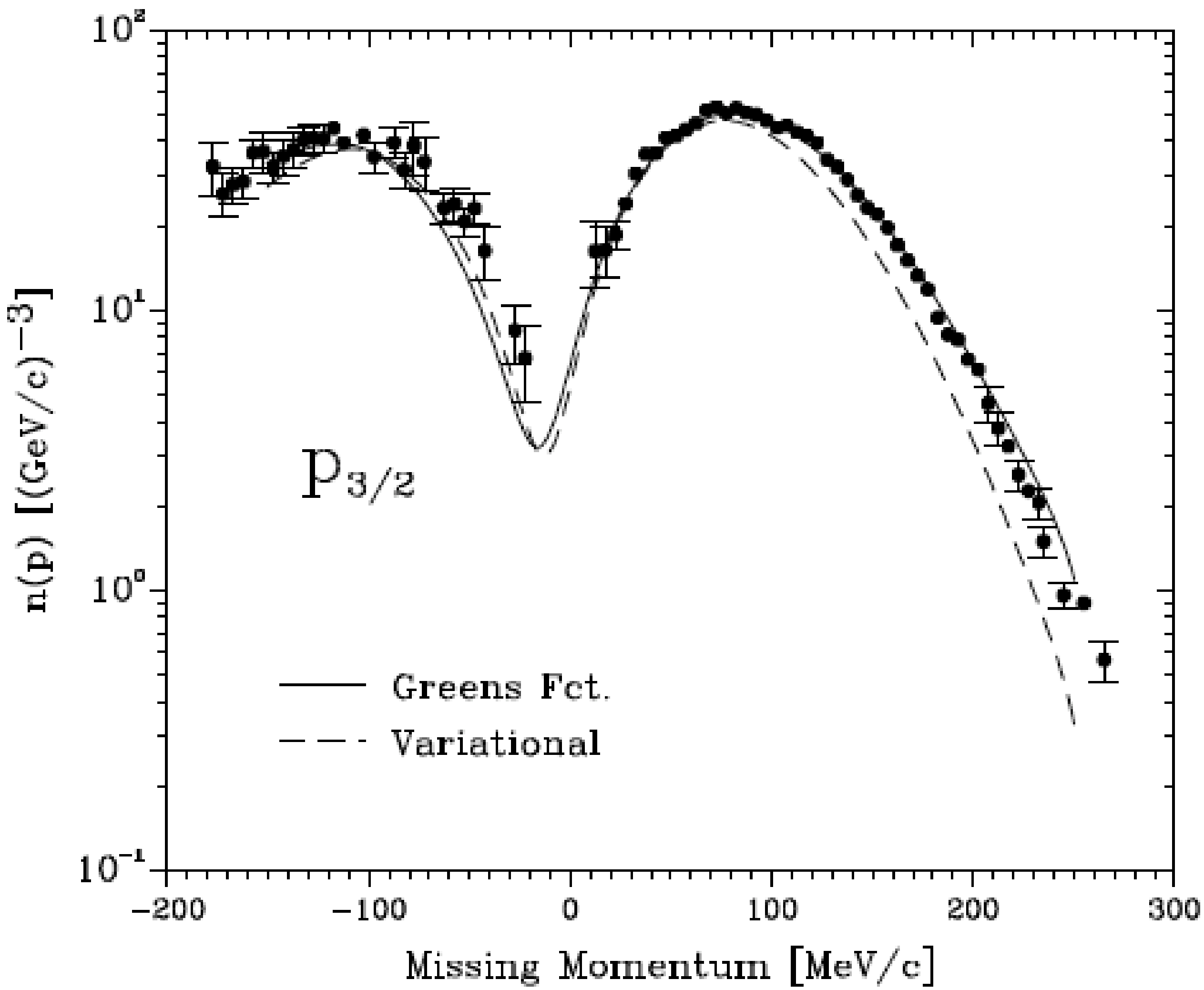


No enhancement of high k near ε_F

Not observed experimentally either!
PRL**73**,2684(1994)
PLB**344**,85(1995)

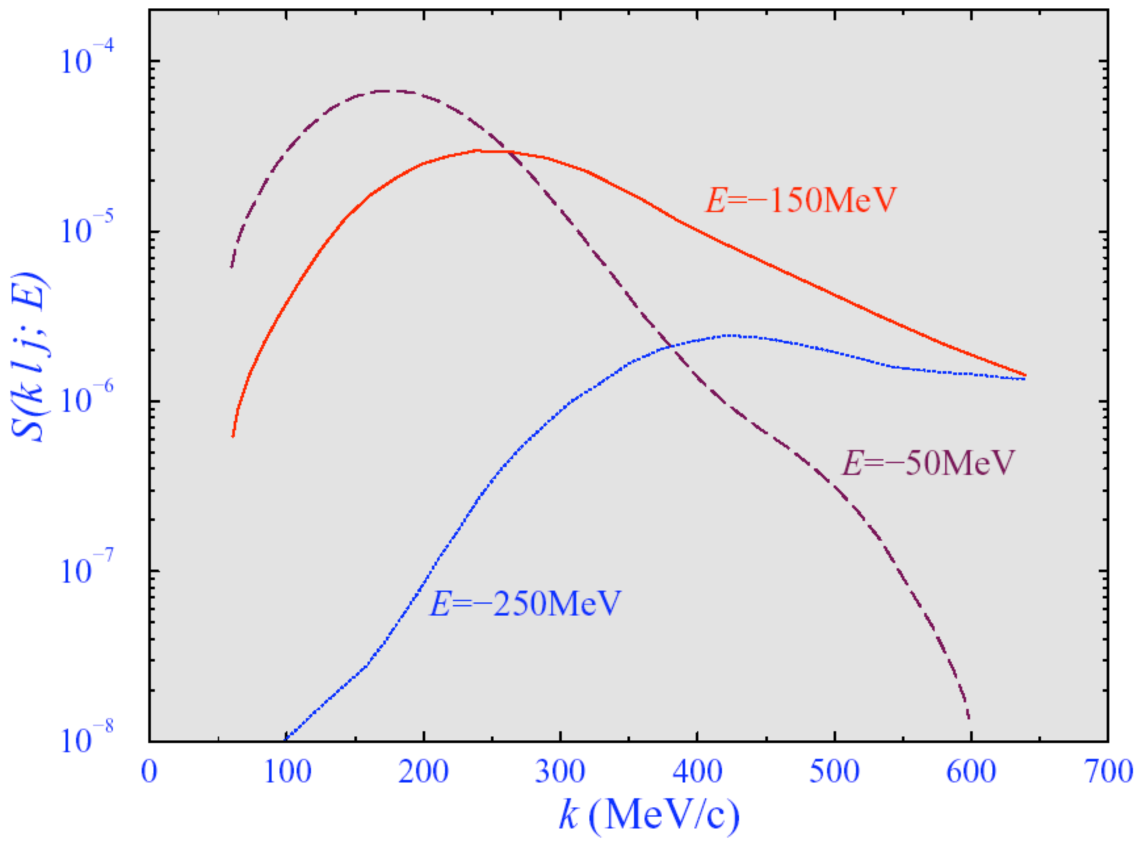
Strength depleted by 10% due to SRC

Quality of quasihole wave function



PRC**55**, 810 (1997)

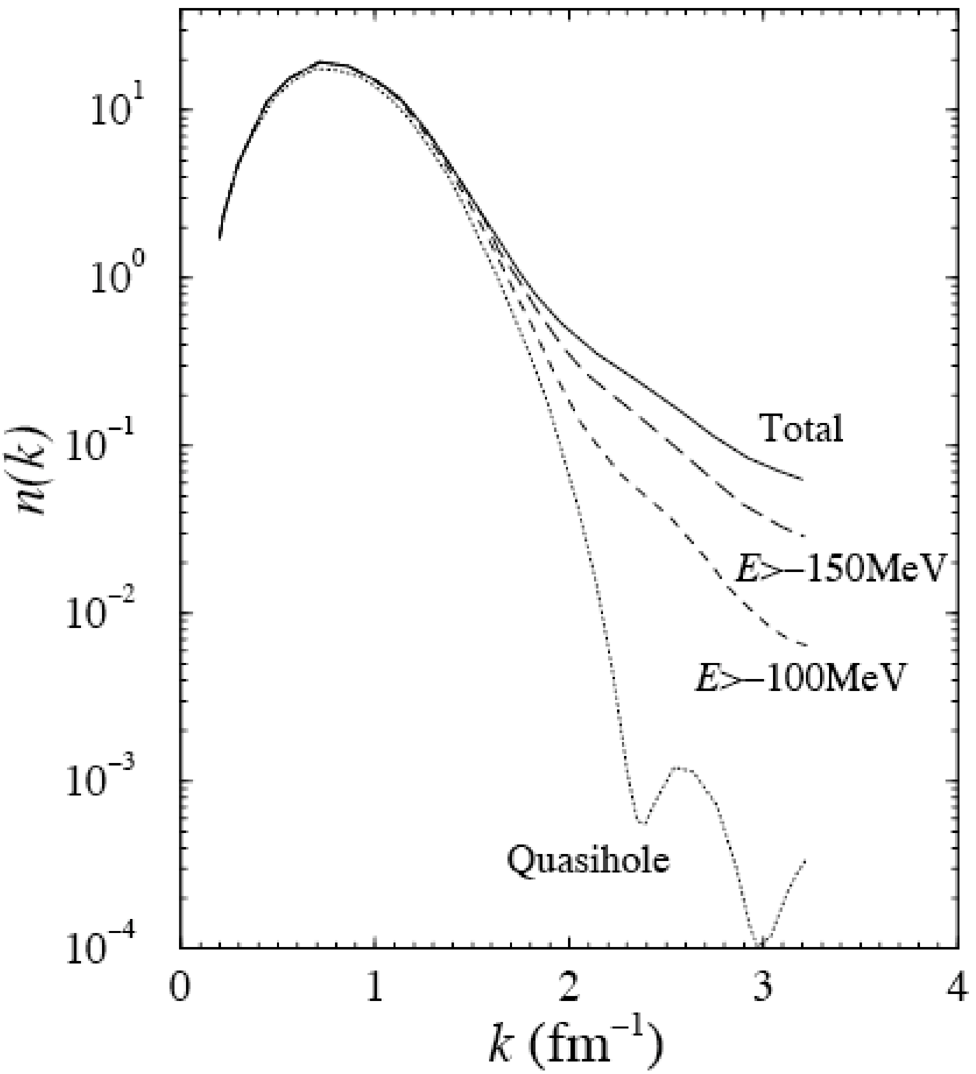
Prediction of high-momentum components



$p_{1/2}$ spectral function at fixed energies in ^{16}O

Phys. Rev. C49, R17 (1994)

Momentum distribution ^{16}O



Confirms expectation:

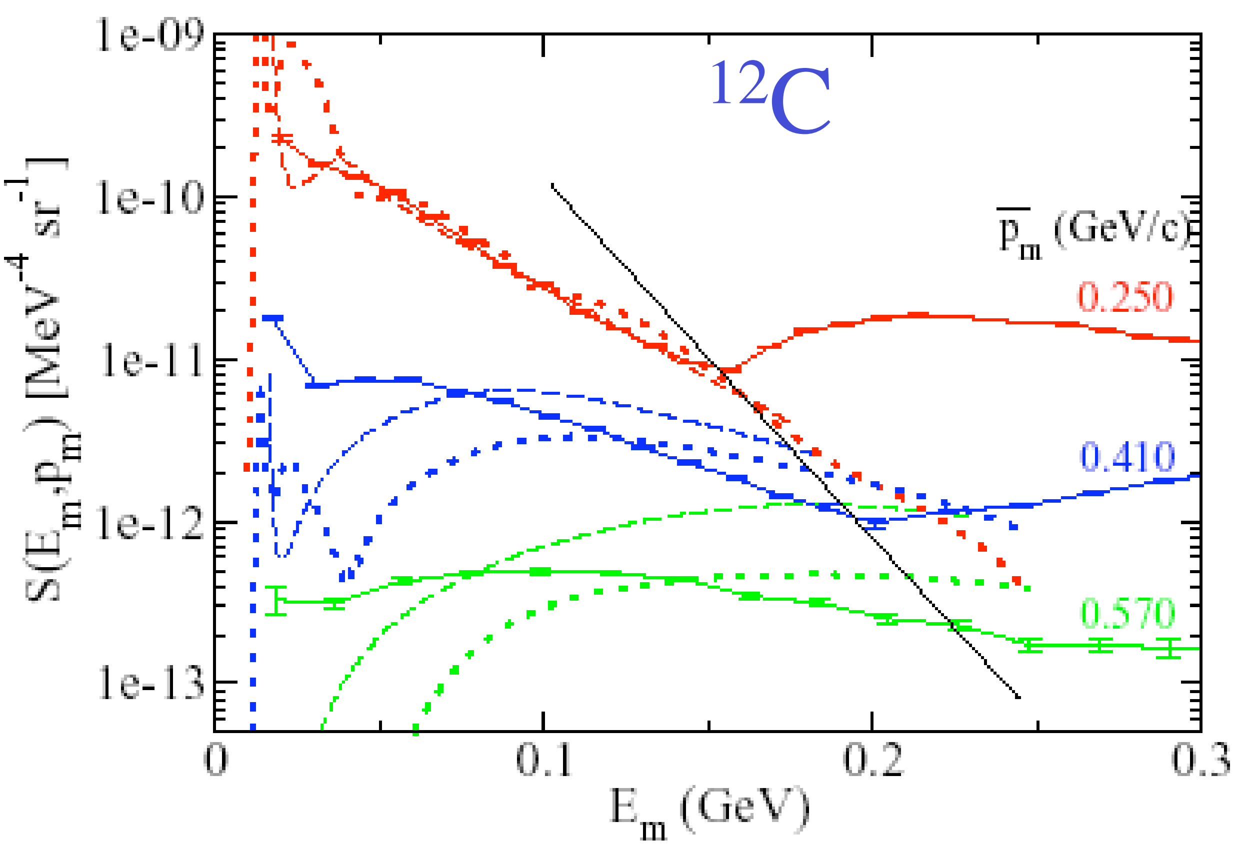
High momentum nucleons can be found at large negative energies

Where are the last protons?
Answer is coming!

JLab data
PRL**93**,182501 (2004)
Rohe et al.

Location of high-momentum components

Integrated strength ✓

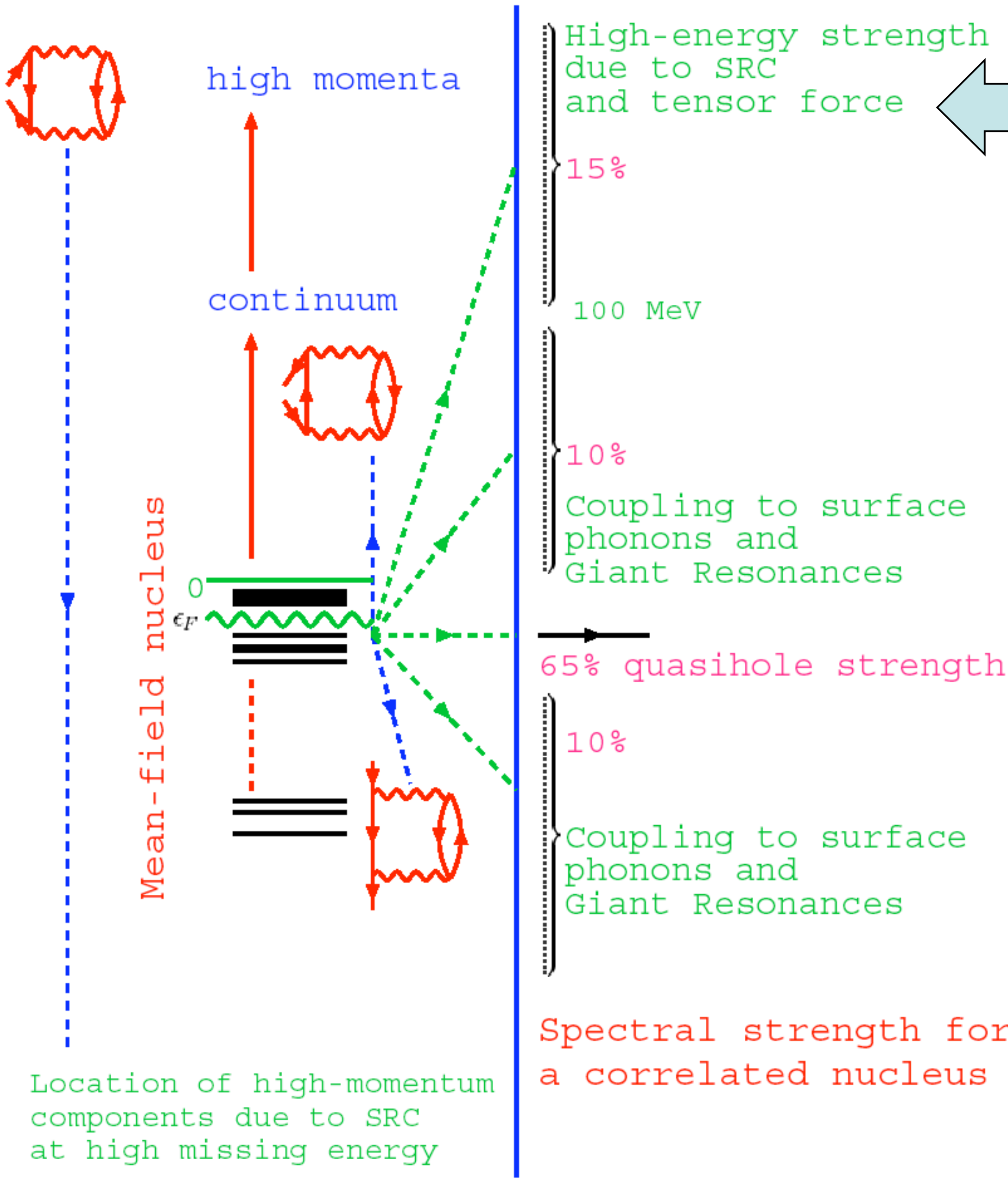


We now essentially know what all the protons are doing in a "closed-shell" nucleus !!!

- Unique for a correlated many-body system
- Information available for electrons in atoms (Hartree-Fock)
- Not for electrons in solids
- Not for atoms in quantum liquids
- Not for quarks in nucleons

⇒ **Study the nucleus for its intrinsic interest as a quantum many-body problem!**

Location of single-particle strength in nuclei

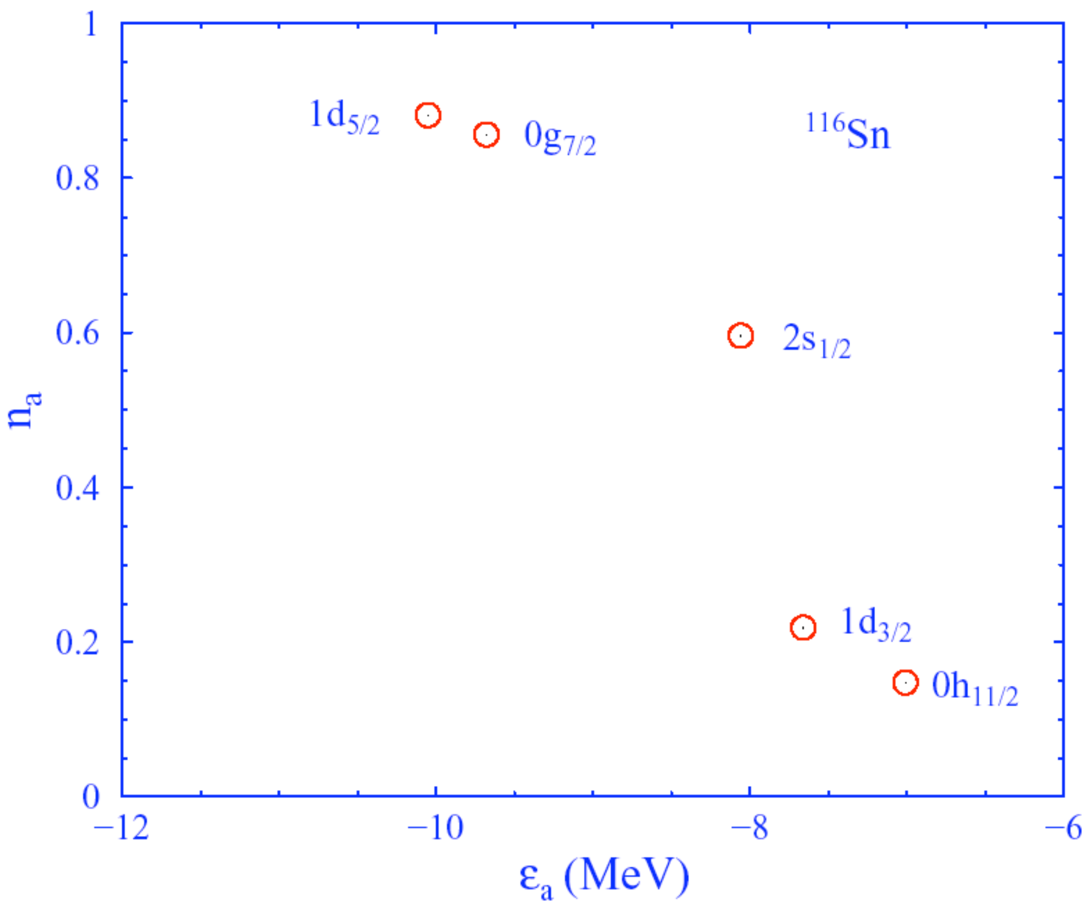


SRC

SRC

What about open-shell systems?

Semi-magic nuclei
Green's function calculation



SRC the same
GRs similar

only difference near ε_F

removal & addition probabilities similar size for $2s_{1/2}$!!

⇒ pairing

Deformation?

^{142}Nd(e,e´p) Z=60; N=82 compare with ^{146}Nd(e,e ´p) Z=60; N=86
Nucl. Phys. **A560**, 811 (1993)

E_x ^{141}Pr	J^{π}	S_{exp}
0.000	$5/2^+$	0.23
0.145	$7/2^+$	0.39
1.118	$11/2^-$	0.05
1.298	$1/2^+$	0.03

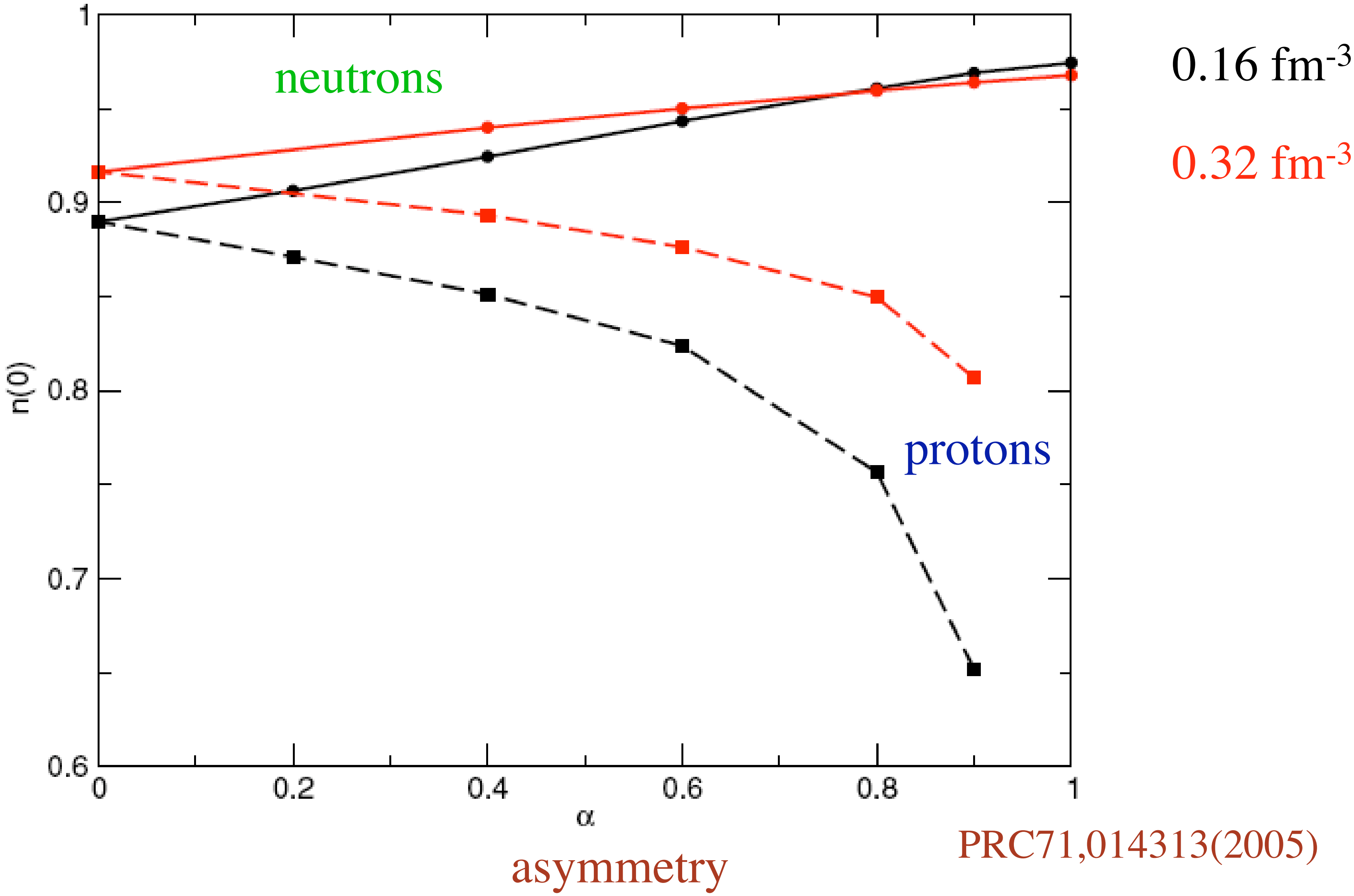
E_x ^{145}Pr	J^{π}	S_{exp}
0.000	$7/2^+$	0.19
0.063	$5/2^+$	0.17
0.189	$5/2^+$	0.03
0.348	$3/2^+$	0.02
0.555	$7/2^+$	0.03

Wave functions in both nuclei are the same!

Systems with N very different from Z?

- SRC still the same (tensor force disappears for n and "increases" for p for N>Z) (see PRC71,014313(2005))
- Collectivity of excited states is reduced
  So less fragmentation
    and removal of sp strength becomes
    more like mean-field (+ SRC+ whatever is left of tensor force for n but perhaps strong effect for p)
- Continuum effects (soft dipoles …)

SCGF for isospin-polarized nuclear matter



PRC71,014313(2005)