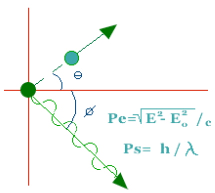
SRC and LRC in finite and infinite systems

SRC EMC workshop 3/24/2021

Washington University in St. Louis



DOM activities: Wim Dickhoff
Bob Charity
Lee Sobotka
Louk Lapikas (Nikhef, e,e'p)
Henk Blok (Nikhef, e,e'p)
Hossein Mahzoon (Ph.D.2015)
Mack Atkinson (Ph.D. April 2019)
Natalya Calleya (Grad)
Cole Pruitt (Ph.D. April 2019)
Michael Keim (BA 2018)
Blake Bordelon (BS 2019)

Recent DOM review: WD, Charity, Mahzoon
J. Phys. G: Nucl. Part. Phys. 44 (2017) 033001
Optical model review: WD, Charity
Prog. Part. Nucl. Phys. 95 (2019) 252
Quenching sp strength review: Aumann et al,
Prog. Part. Nucl. Phys. 118, 103847 (2021)

- **Dedication: Arturo Polls passed last year and I remember him fondly**
- Motivation —> where LRC where SRC
- Green's functions/propagator method
  - vehicle for ab initio calculations —> matter (see Arnau Rios talk)
  - as a framework to link data at positive and negative energy (and to generate predictions for exotic nuclei)

-> dispersive optical model (DOM <- Claude Mahaux)

- DOM with non-local potentials ^{12}C, $^{16-18}$O, ^{40,48}Ca, ^{58,64}Ni, ^{112,124}Sn, ^{208}Pb
- Revisit (e,e'p) data from NIKHEF ^{40}Ca and ^{48}Ca —> N-Z dependence
- Neutron skin in ^{48}Ca and ^{208}Pb —> PREX II
- Ground-state energy and high-momentum content
- Nuclear saturation properties revisited
- Conclusions

Propagator / Green's function and spectral functions & spectroscopic factors

- Lehmann representation

$$G_{\ell j}(k,k';E) = \sum_m \frac{\langle \Psi_0^A | a_{k\ell j} | \Psi_m^{A+1}\rangle \langle \Psi_m^{A+1} | a^\dagger_{k'\ell j} | \Psi_0^A \rangle}{E - (E_m^{A+1} - E_0^A) + i\eta} + \sum_n \frac{\langle \Psi_0^A | a^\dagger_{k'\ell j} | \Psi_n^{A-1}\rangle \langle \Psi_n^{A-1} | a_{k\ell j} | \Psi_0^A \rangle}{E - (E_0^{A} - E_n^{A-1}) - i\eta}$$

- Any other single-particle basis can be used & continuum integrals implied
- Overlap functions --> numerator   Corresponding eigenvalues --> denominator
- Spectral function

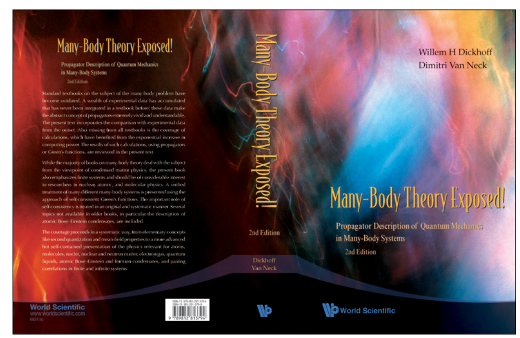
$$S_{\ell j}(k;E) = \frac{1}{\pi}\,\mathrm{Im}\, G_{\ell j}(k,k;E) \qquad E \leq \varepsilon_F^-$$

$$= \sum_n \left| \langle \Psi_n^{A-1} | a_{k\ell j} | \Psi_0^A \rangle \right|^2 \delta(E - (E_0^A - E_n^{A-1}))$$

- Discrete transitions $\sqrt{S_{\ell j}^n}\, \phi_{\ell j}^n(k) = \langle \Psi_n^{A-1} | a_{k\ell j} | \Psi_0^A \rangle$

- Momentum distribution: integrate spectral function to ε_F^-

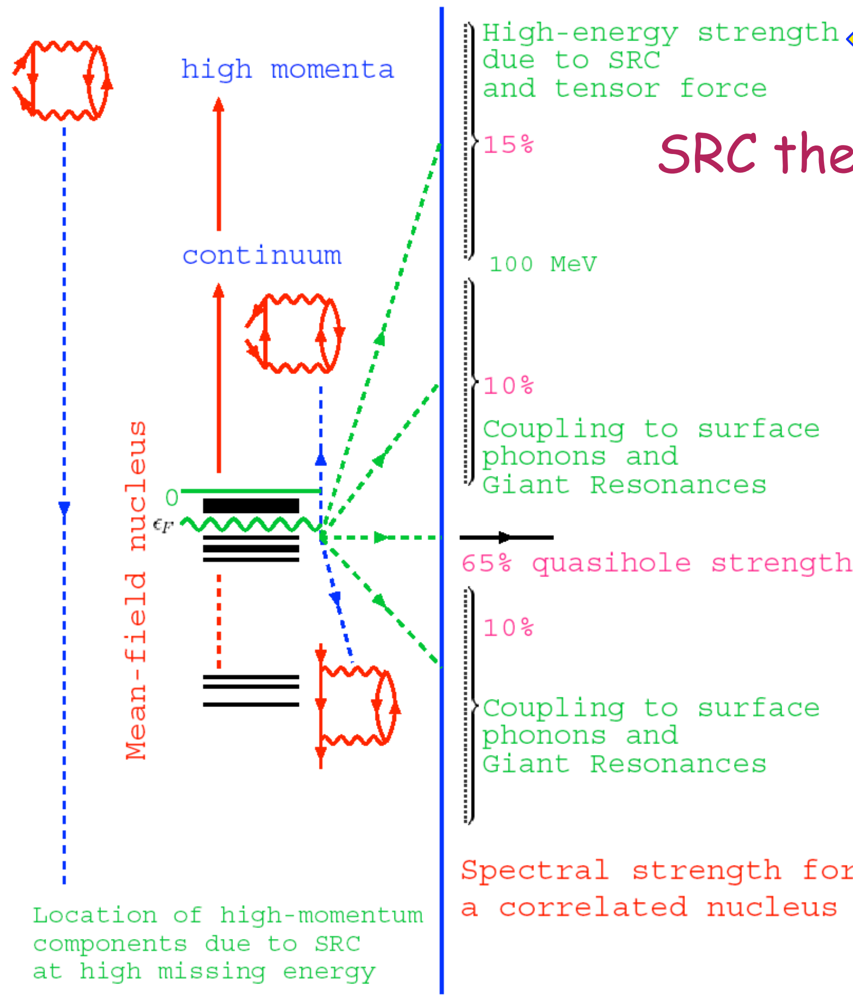
- Positive energy —> see later



SRC and LRC

Reviewed in Prog. Part. Nucl. Phys. 52 (2004) 377-496

Location of single-particle strength in closed-shell (stable) nuclei



SRC theory

Elastic nucleon scattering
PRC90, 0616O(R) (2014)

For example: protons in ^{208}Pb

Nikhef (e,e'p) data
L. Lapikas
NPA553,297c (1993)

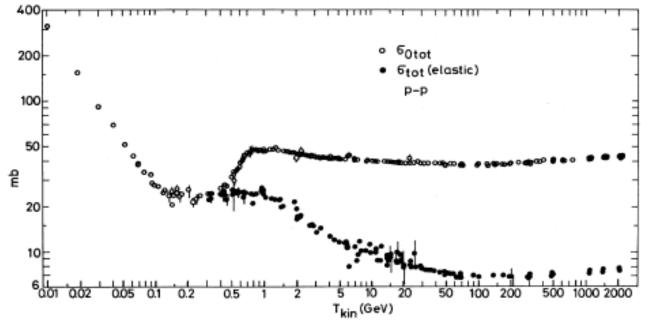
SRC

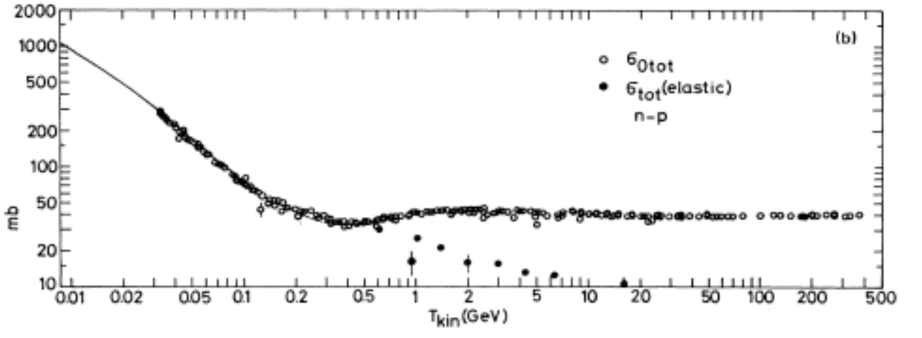
JLab E97-006

Phys. Rev. Lett. 93, 182501 (2004) D. Rohe et al.

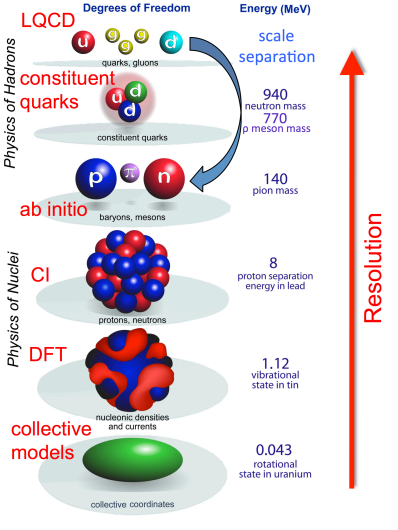
Short-range correlations

- NN total cross sections





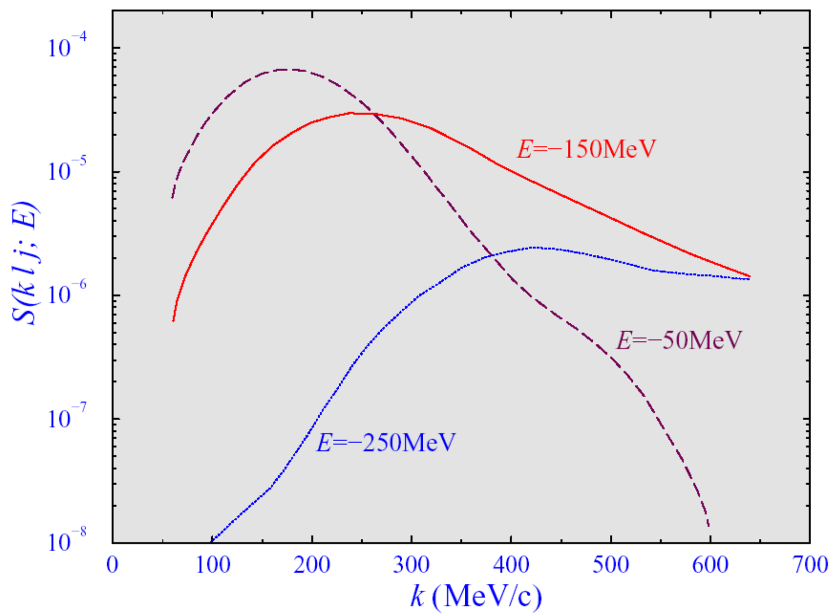
- NN —> coupled to anything at higher energy
- simulate by a strong core
- better to use dispersion relations (not much has been done)



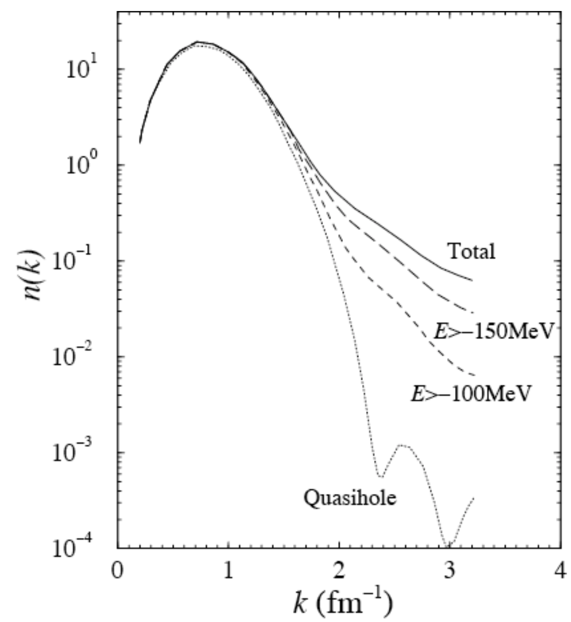
- traditional approach: deal with repulsion as in Monte Carlo
- or SCGF with ladders —> high-momentum tails & removal of strength near the Fermi energy (Arnau Rios talk)

Old prediction of high-momentum components

Spectral function ^{16}O



Momentum distribution ^{16}O



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

Phys. Rev. C49, R17 (1994)

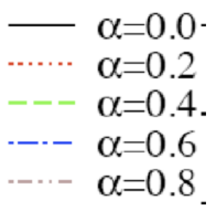
Confirms expectation:
High momentum nucleons can only be found at large negative energies

Phys. Rev. C51, 3040 (1995)

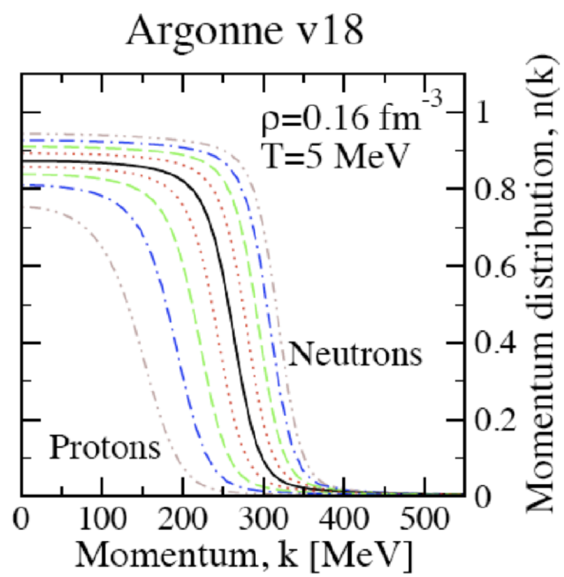
Momentum distribution SCGF asymmetric matter —> Arnau Rios talk

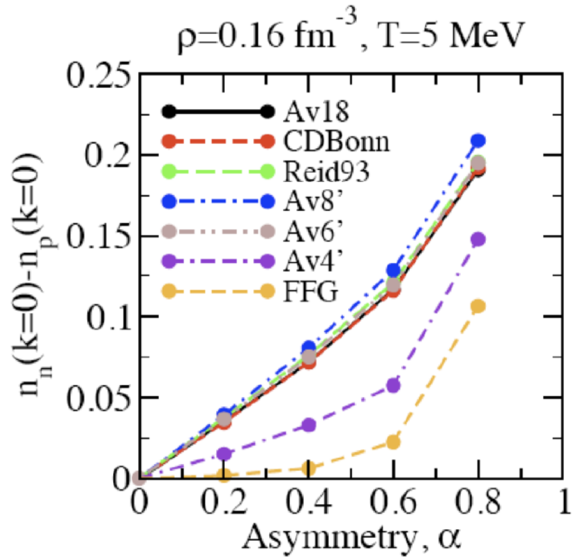
- Asymmetry dependence

$$\alpha = \frac{N-Z}{N+Z}$$



A. Rios, A. Polls, and W. H. Dickhoff
Phys. Rev. C79, 064308 (2009)

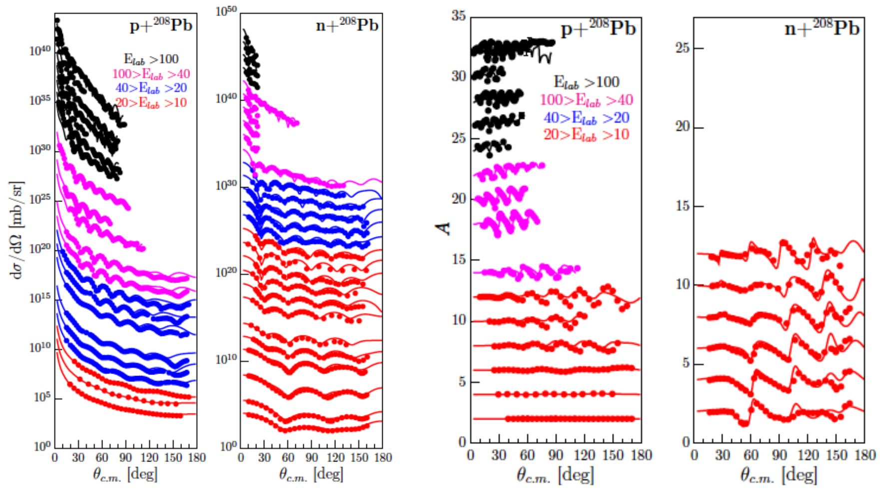


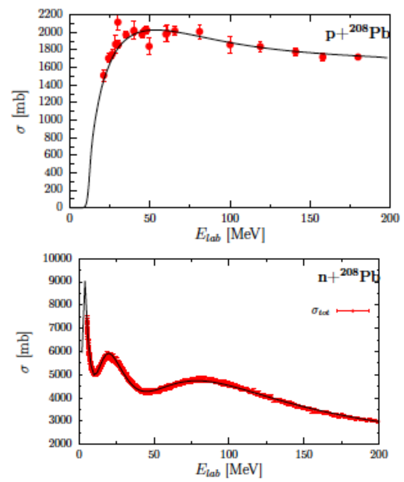


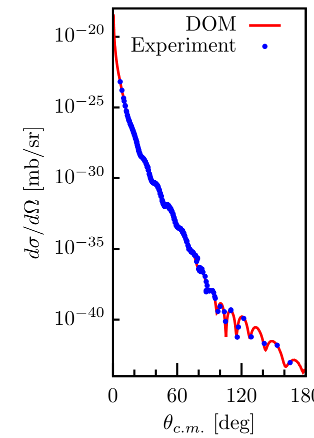
- Incorporates/represents np dominance <—> tensor force discussed by many in several talks
- So more correlations for minority species <—> other talks e.g. Alexandra Gade's

Dispersive Optical Model (St. Louis group)

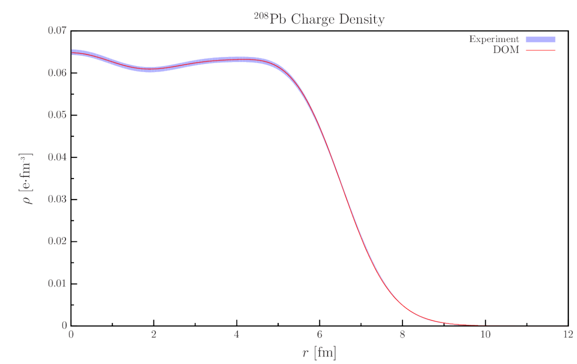
- Mahaux & Sartor 1991 —> Washington University group since 2006
- Use experimental data to constrain the nucleon self-energy while linking structure and reaction domain using dispersion relations







E<0 —>



M. C. Atkinson, M. H. Mahzoon, M. A. Keim, B. A. Bordelon, C. D. Pruitt, R. J. Charity, and W. H. Dickhoff
Phys. Rev. C 101, 044303 (2020), 1-15. [arXiv:1911.09020]

Indirectly:

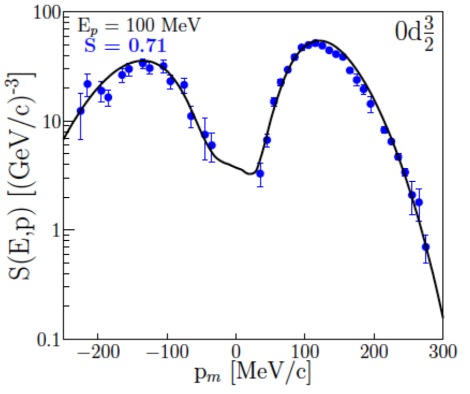
- Generates proton/neutron distorted waves
- Overlap functions with their normalization (spectroscopic factors)

Mack Atkinson thesis 2019

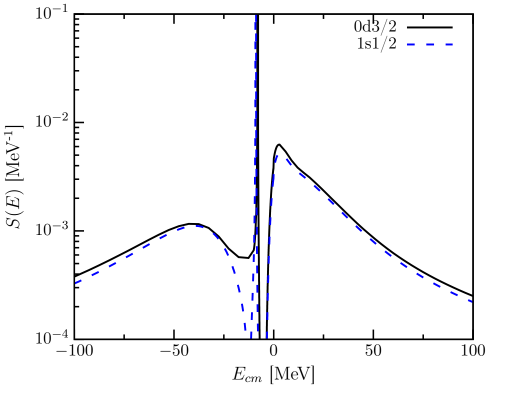
SRC and LRC

Check with (e,e'p) cross sections (Mack Atkinson)

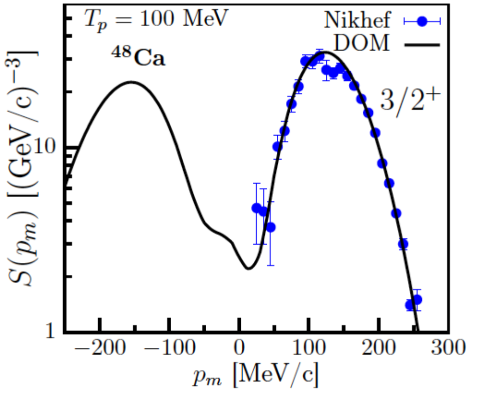
- ^{40}Ca



Phys. Rev. C98, 044627 (2018)



- ^{48}Ca

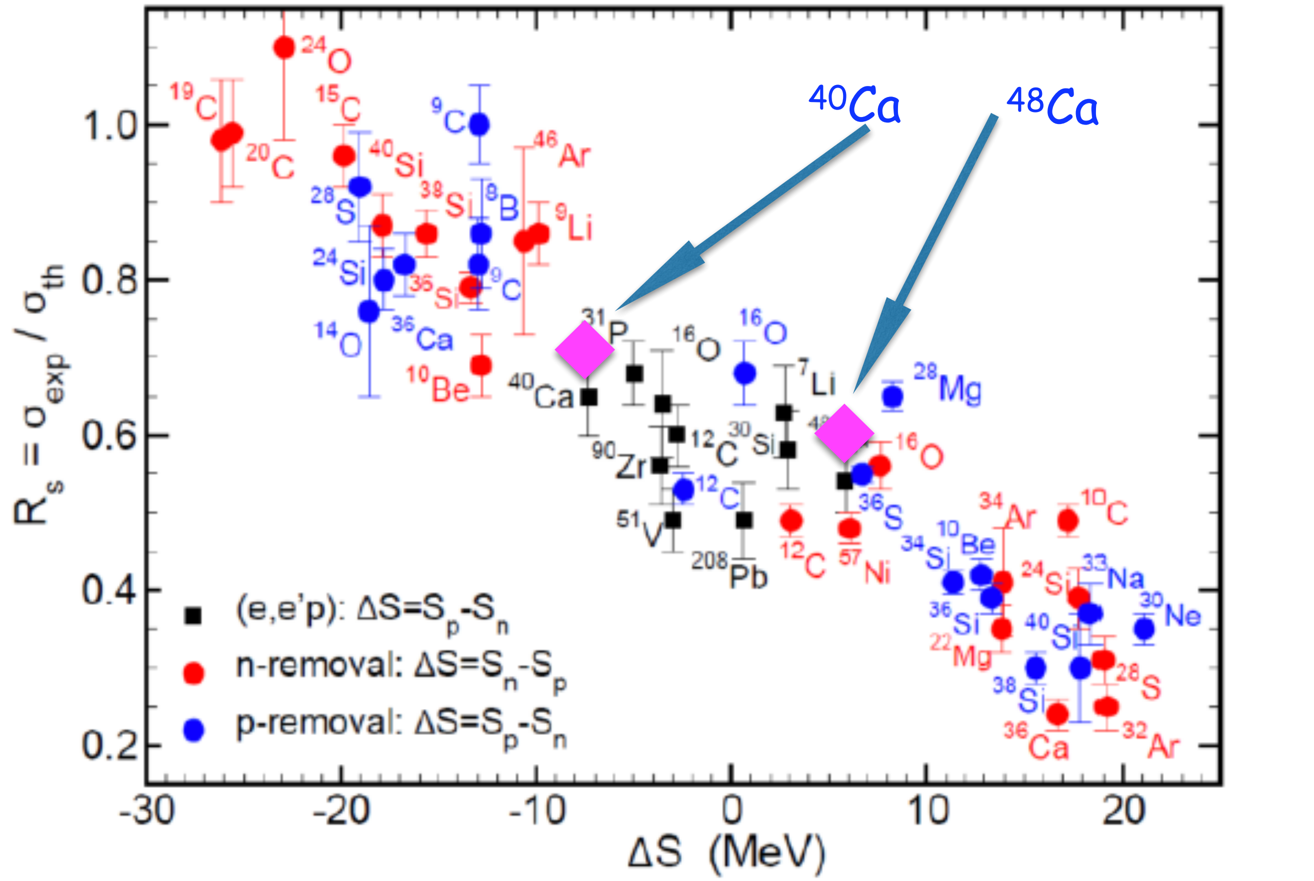


Phys. Lett. B 798, 135027 (2019)

- No further adjustments!
- **Both structure and reaction properties allowed to change**

Compare with updated Gade plot

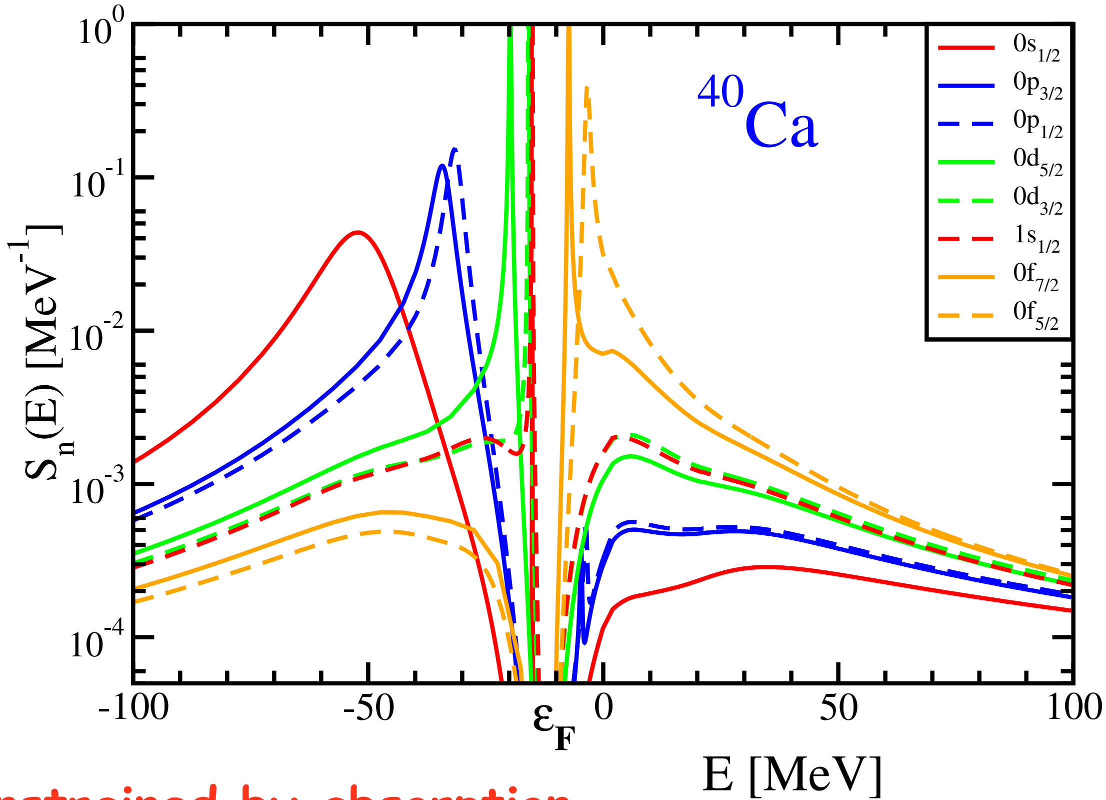
Very near the Fermi energy in ^{40}Ca and ^{48}Ca from (e,e'p) —>



Quenching sp strength review: Aumann et al, Prog. Part. Nucl. Phys. 118, 103847 (2021)

Spectral function for bound states

- [0,200] MeV —> constrained by elastic scattering data



Emptiness constrained by absorption necessary to describe elastic scattering!

PRC90, 061603(R) (2014)

Updated PREX results

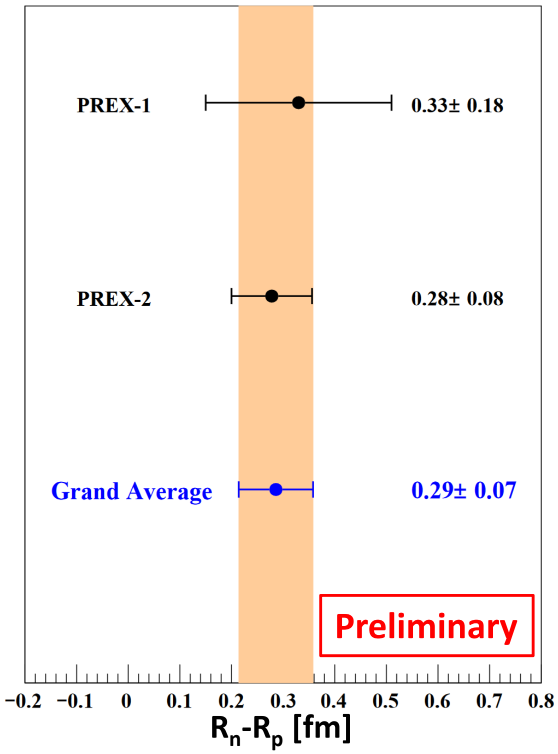
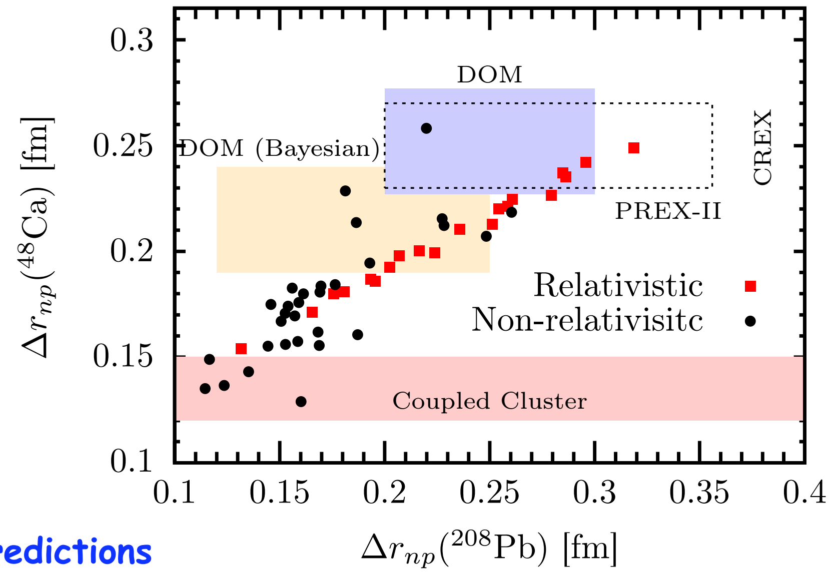


TABLE III. PREX combined experimental results for ^{208}Pb.Uncertainties include both experimental and theoretical contributions.

^{208}Pb Parameter	Value
Weak radius (R_W)	5.800 ± 0.075 fm
Interior weak density (ρ_W^0)	-0.0796 ± 0.0038 fm^{-3}
Interior baryon density (ρ_b^0)	0.1480 ± 0.0038 fm^{-3}
Neutron skin ($R_n - R_p$)	0.283 ± 0.071 fm

- <— Ciprian Gal for the PREX collaboration DNP October 2020



- **DOM predictions**
  - Phys. Rev. Lett. 119, 222503 (2017)
  - Phys. Rev. C 101, 044303 (2020)
  - Phys. Rev. Lett. 125, 102501 (2020)
  - Phys. Rev. C 102, 034601 (2020)
- <— PREX preprint ArXiv 2102.10797

High-momentum predictions & relation to ground-state energy

Ground-state energy can be included in the DOM

$$E/A = \frac{1}{2A}\sum_{\ell j}(2j+1)\int_0^\infty dk k^2 \frac{k^2}{2m} n_{\ell j}(k) + \frac{1}{2A}\sum_{\ell j}(2j+1)\int_0^\infty dk k^2 \int_{-\infty}^{\varepsilon_F} dE\, E\, S_{\ell j}(k;E)$$

Succeeds

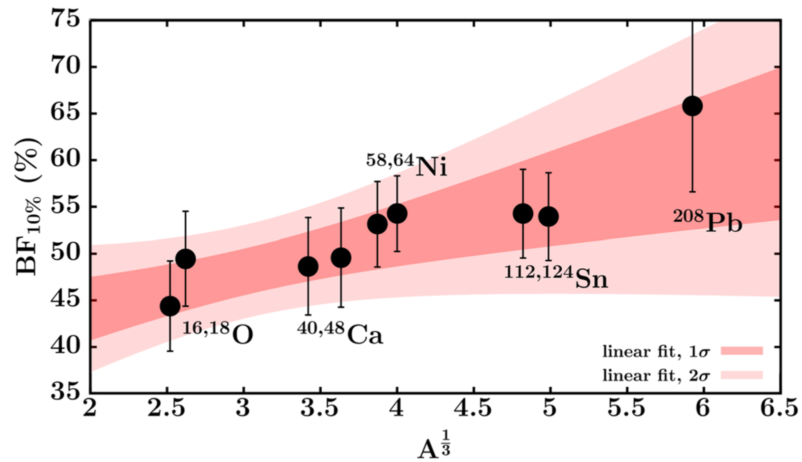
A	DOM E_0^A/A	Mass equation	Expt. E_0^A/A
^{12}C	−7.85	−7.29	−7.68
^{40}Ca	−8.46	−8.50	−8.55
^{48}Ca	−8.66	−8.59	−8.66
^{208}Pb	−7.76	−7.81	−7.87

Phys. Rev. C 102, 044333 (2020)

Because fraction of binding energy from 10% most deeply bound nucleons includes the high-momentum contribution

Phys. Rev. Lett. 125, 102501 (2020)

Predicted in Phys. Rev. C51, 3040 (1995)

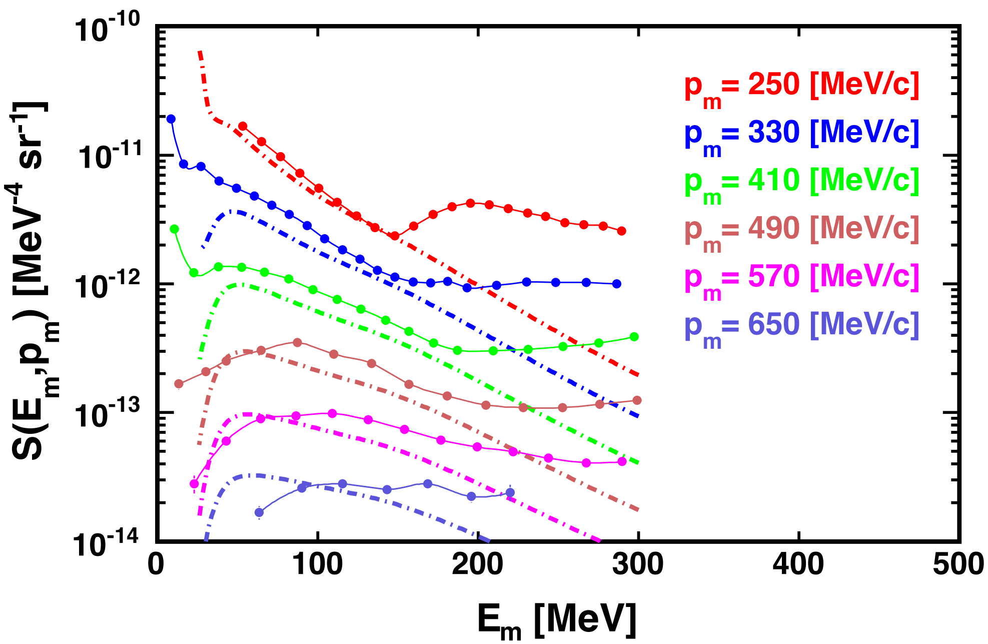


SRC and LRC

Original Jefferson Lab data per proton compared to DOM results

- Pion/isobar contributions cannot be described
- Rescattering contributes some cross section

C. Barbieri and L. Lapikás Phys. Rev. C 70, 054612 (2004)



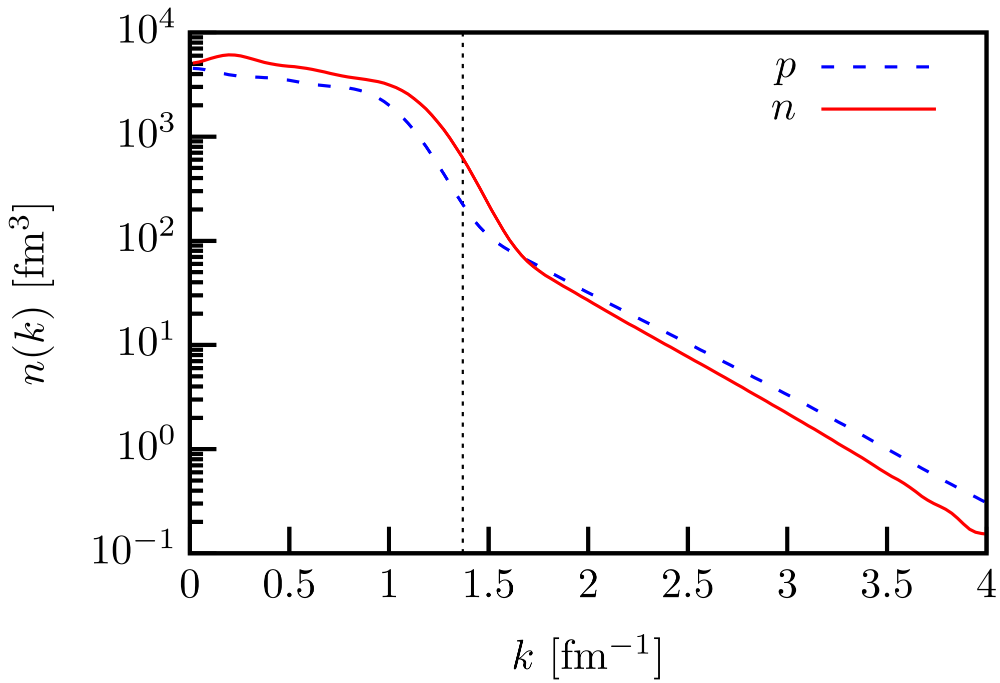
Phys. Rev. Lett. 112, 162503 (2014) DOM result

Phys. Rev. Lett. 93, 182501 (2004) Experiment D. Rohe et al.

^{208}Pb enhancement of p over n

high-momentum content automatically

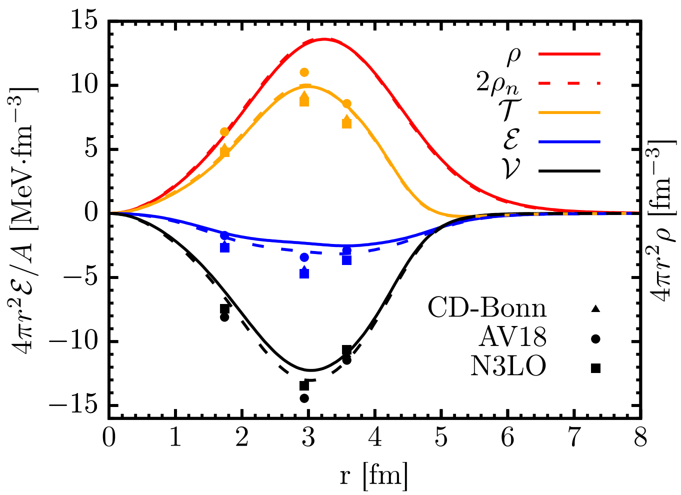
Phys. Rev. C 101, 044303 (2020)

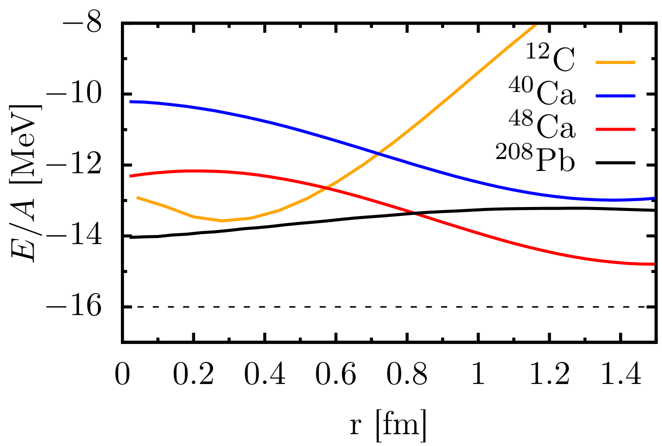


SRC and LRC

Consequence

- Maybe 16 MeV binding is not needed!



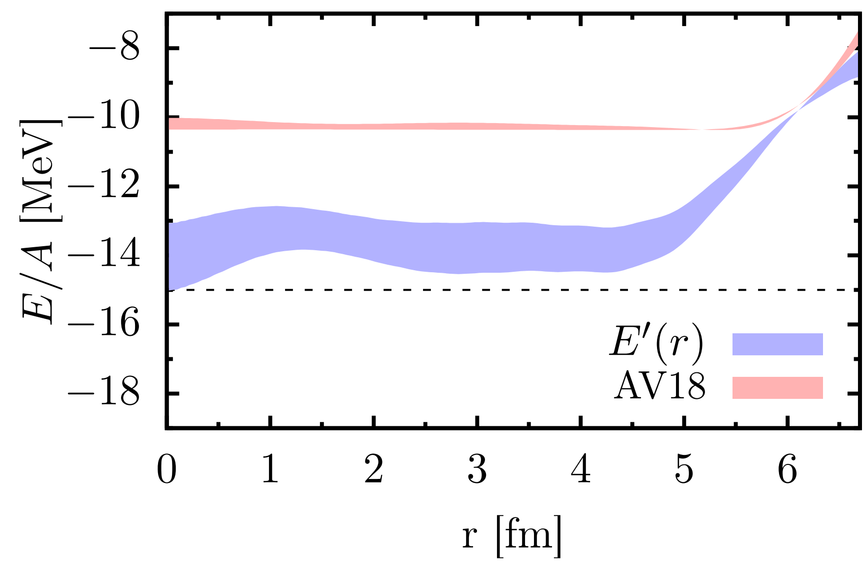


PHYSICAL REVIEW C **102**, 044333 (2020)

Editors' Suggestion

Reexamining the relation between the binding energy of finite nuclei and the equation of state of infinite nuclear matter

M. C. Atkinson,[1,2,*] W. H. Dickhoff,[1] M. Piarulli,[1] A. Rios,[3] and R. B. Wiringa[4]



LRC in finite nuclei and infinite matter

Comment:

- LRC or low-energy excitations in infinite nuclear matter —> no counterpart in finite nuclei
- BUT: LRC in finite nuclei —> no counterpart in nuclear matter
- They will contribute some binding!
- How much: nobody has really looked into this
- Extrapolations from nuclei to matter should deal with this in more detail

Conclusions

- DOM can describe many experimental data by simultaneously describing structure and reaction energy domain
- DOM can predict hard to access experimental data —> neutron skin
- DOM can be constrained by energy of the ground state and then automatically requires the inclusion of high-momentum components yielding more correlated protons when neutrons are in the majority
- DOM suggests that some reexamining of nuclear saturation properties might be in order: 16 MeV at saturation may be too large

- For rare isotopes use (p,2p) in inverse kinematics
- Outlook: (p,2p) analysis with DOM ingredients that yield precise (e,e'p) cross sections, exhibits some issues suggesting that the effective interaction is not sufficiently accurate (RCNP-St. Louis collaboration)