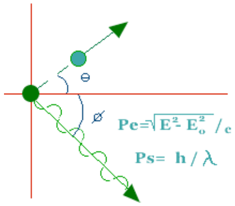
Correlations in isospin asymmetric matter and nuclei

INT 3/7/2018

Washington University in St.Louis



Wim Dickhoff

Arturo Polls

Arnau Rios

Bob Charity

Lee Sobotka

Hossein Mahzoon (Ph.D.2015)

Mack Atkinson

Natalya Calleya

Michael Keim

- Motivation (FRIB mostly)
- Green's functions/propagator method
  - vehicle for ab initio calculations —> matter
  - as a framework to link data at positive and negative energy (and to generate predictions for exotic nuclei)

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

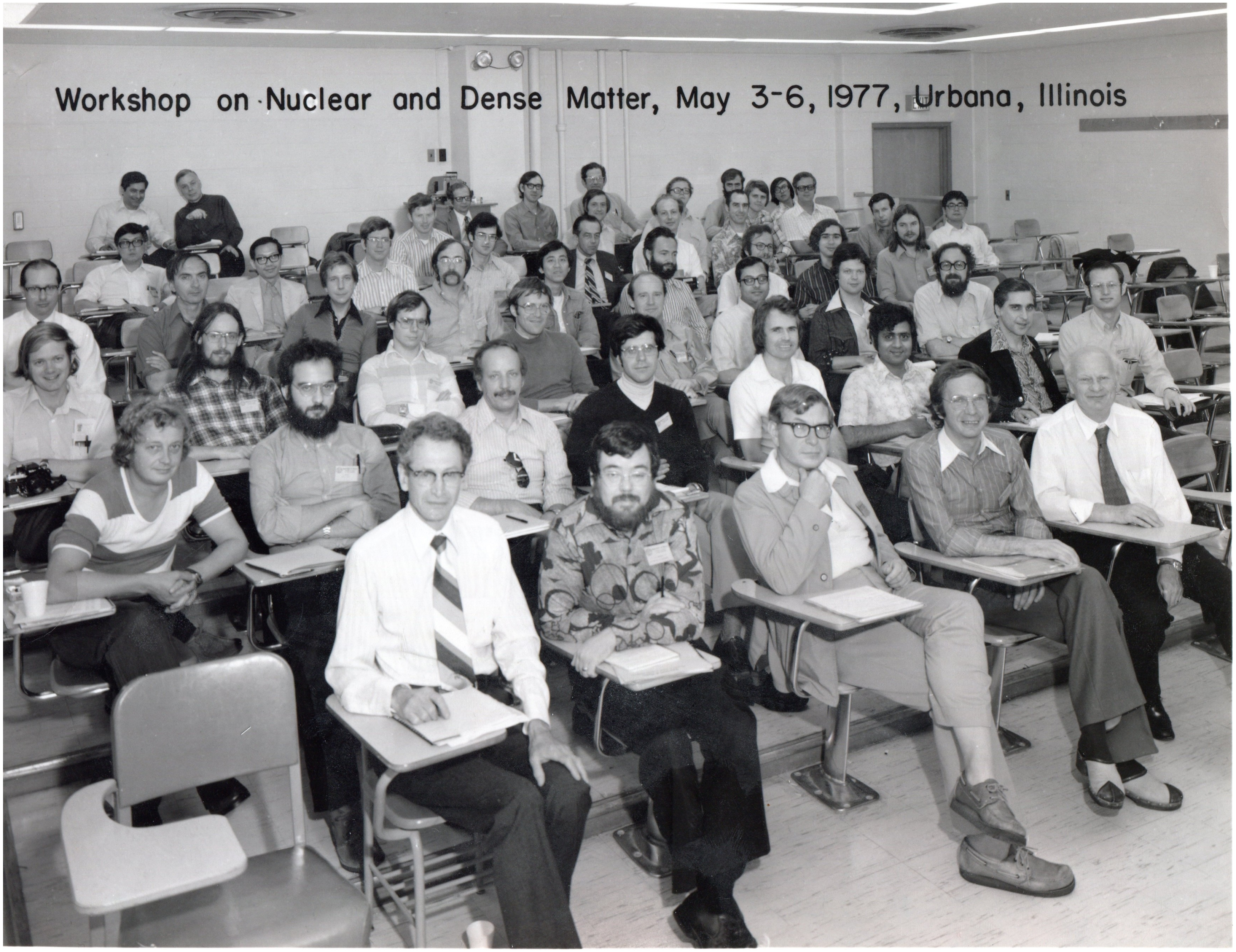
- SRC in (asymmetric) matter
- Recent DOM extension to non-local potentials
- Revisit the (e,e′p) data from NIKHEF
- Neutron skin in ^{48}Ca (importance of total xsections)
- Ongoing and future applications
- Conclusions

Recent DOM review:
WD, Bob Charity, Hossein Mahzoon
J. Phys. G: Nucl. Part. Phys. 44 (2017) 033001

reactions and structure

Those were the days…

- Precursor of many-body meetings (—> MBT-1 1978 Trieste)



Motivation

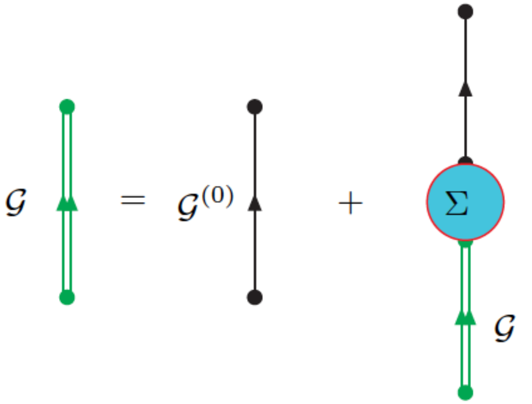
- Rare isotope physics requires a **much** stronger link between nuclear reactions and nuclear structure descriptions
- We need an ab initio approach for optical potential —> optical potentials must therefore become **nonlocal** and **dispersive**
- Current status to extract structure information from nuclear reactions involving strongly interacting probes **unsatisfactory**
- Intermediate step: dispersive optical model as originally proposed by Claude Mahaux —> some **extensions** discussed here

- Dense matter <—> nuclei: ongoing motivation <—> Jefferson Lab data
- High-momentum components <—> short-range correlations (SRC)
- Fully self-consistent Green's function treatment of SRC in matter possible at finite T for any NN interaction (except real hard core)

Self-consistent Green´s function and SRC (ladders) -> nuclear matter

Single-particle Green´s function $\mathcal{G}$

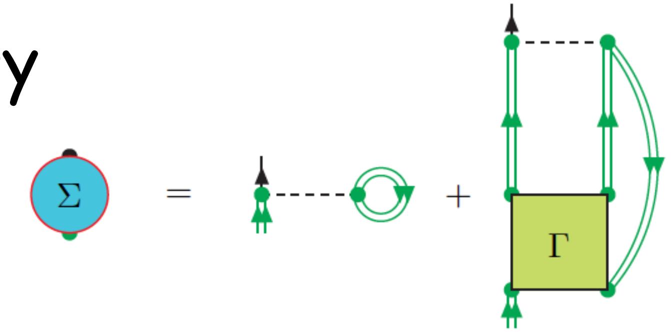
Dyson equation: $\mathcal{G} = \mathcal{G}^{(0)} + \mathcal{G}^{(0)} \Sigma\, \mathcal{G}$



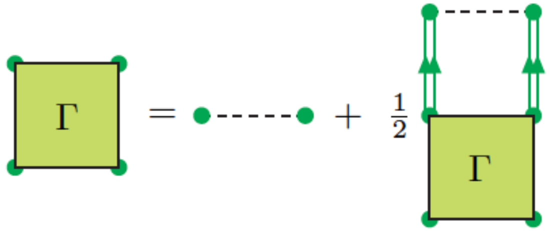
$$\mathcal{G}(k,E) = \frac{1}{E - \varepsilon_k - \Sigma(k,E)}$$

spectral function ~ $\mathrm{Im}\ \mathcal{G}(k,E)$

Self-energy



Γ-matrix



- Pairing instability possible
- Finite temperature calculation can avoid this
- T=0 extrapolation of normal self-energy OK

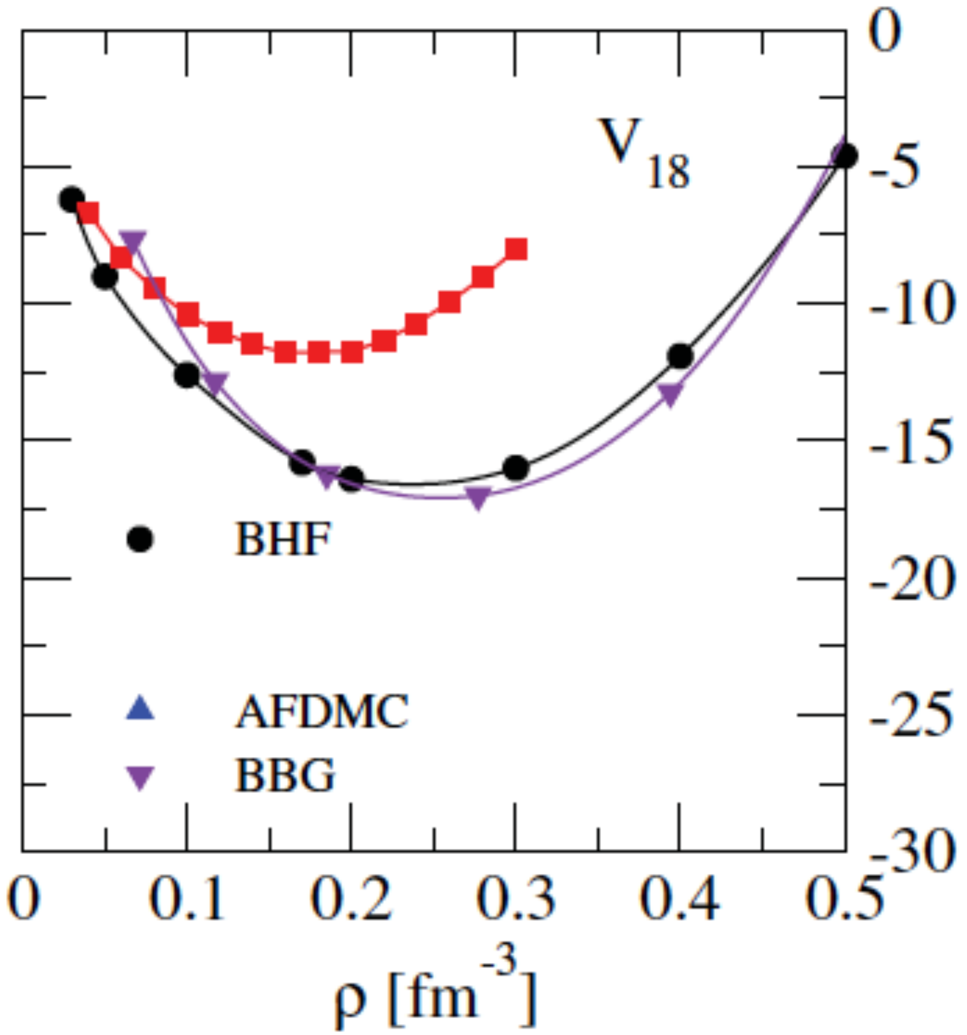
- Rios
- Polls
- WD

Recent result SCGF & SRC compared to BHF and BBG

PHYSICAL REVIEW C **86**, 064001 (2012)

Comparative study of neutron and nuclear matter with simplified Argonne nucleon-nucleon potentials

M. Baldo,[1] A. Polls,[2] A. Rios,[3] H.-J. Schulze,[1] and I. Vidaña[4]



- BBG requires a repulsive NNN at high density to improve density

nuclear matter

LRC in finite nuclei

Note:

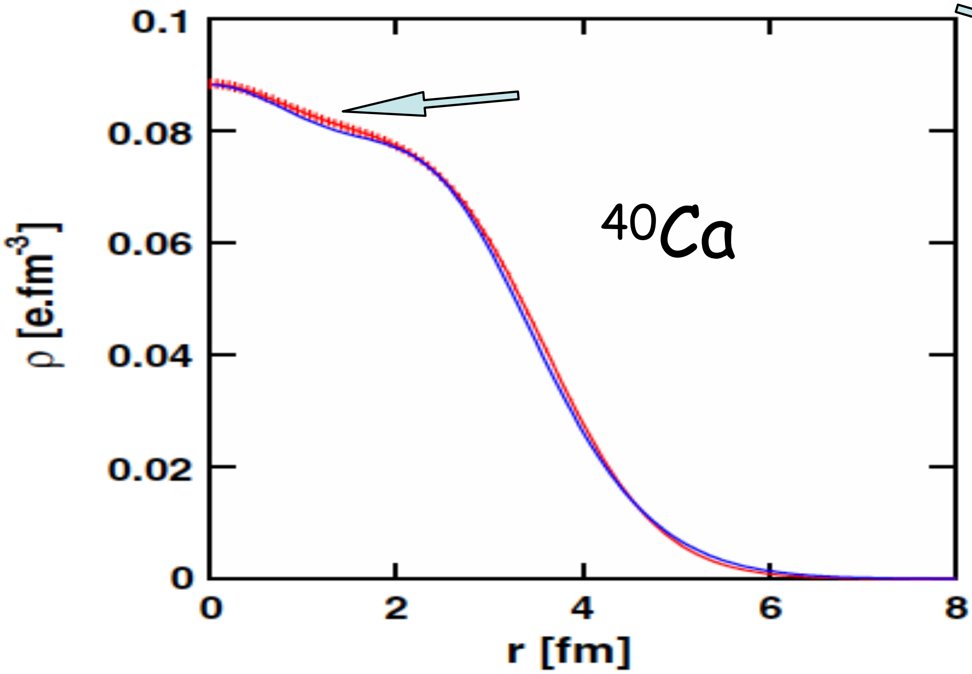
- LRC in infinite nuclear matter —> no counterpart in finite nuclei —> especially pion-like modes

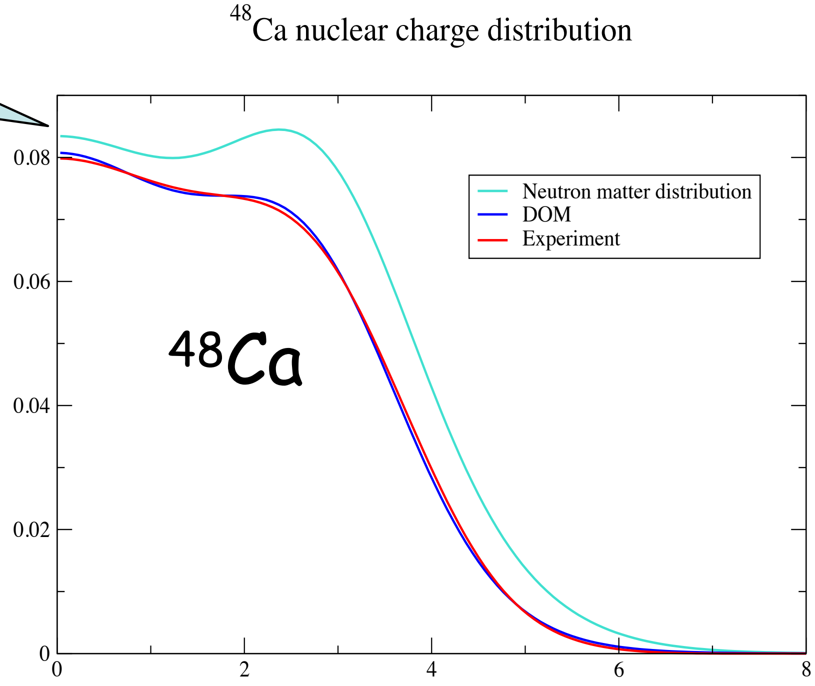
- LRC in finite nuclei —> surface excitations —> no counterpart in nuclear matter
- They will contribute some binding!

- How much?

Saturation density <—> Charge density

- Experimental results & empirical reproduction by DOM (see later)
- ^{40}Ca result: PRL 112, 162503(2014)
- ^{48}Ca result: PRL 119, 222503 (2017)

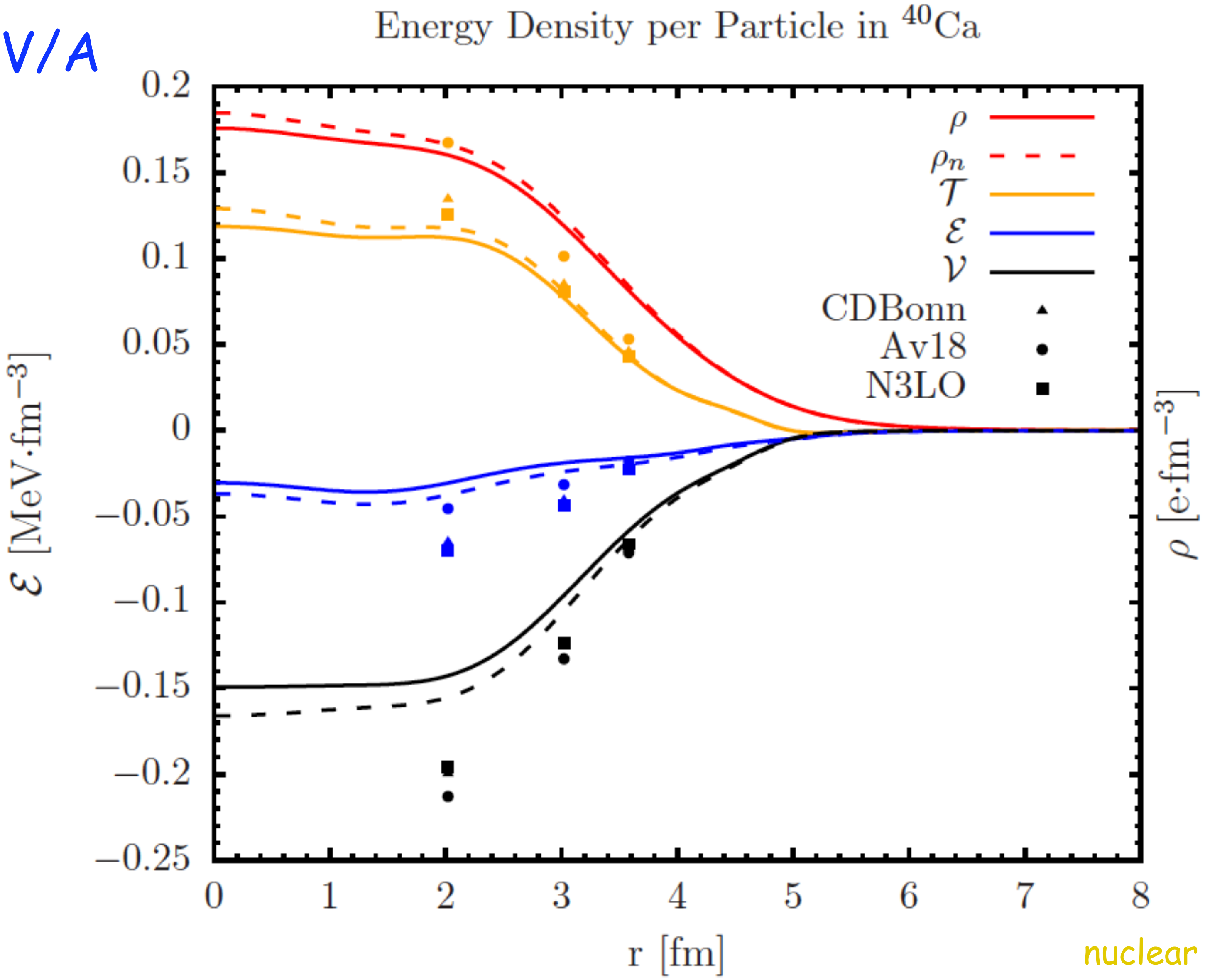




- "Explaining" nuclear matter saturation without reproducing experimental charge density is incomplete

Separate kinetic and potential energy density (DOM)

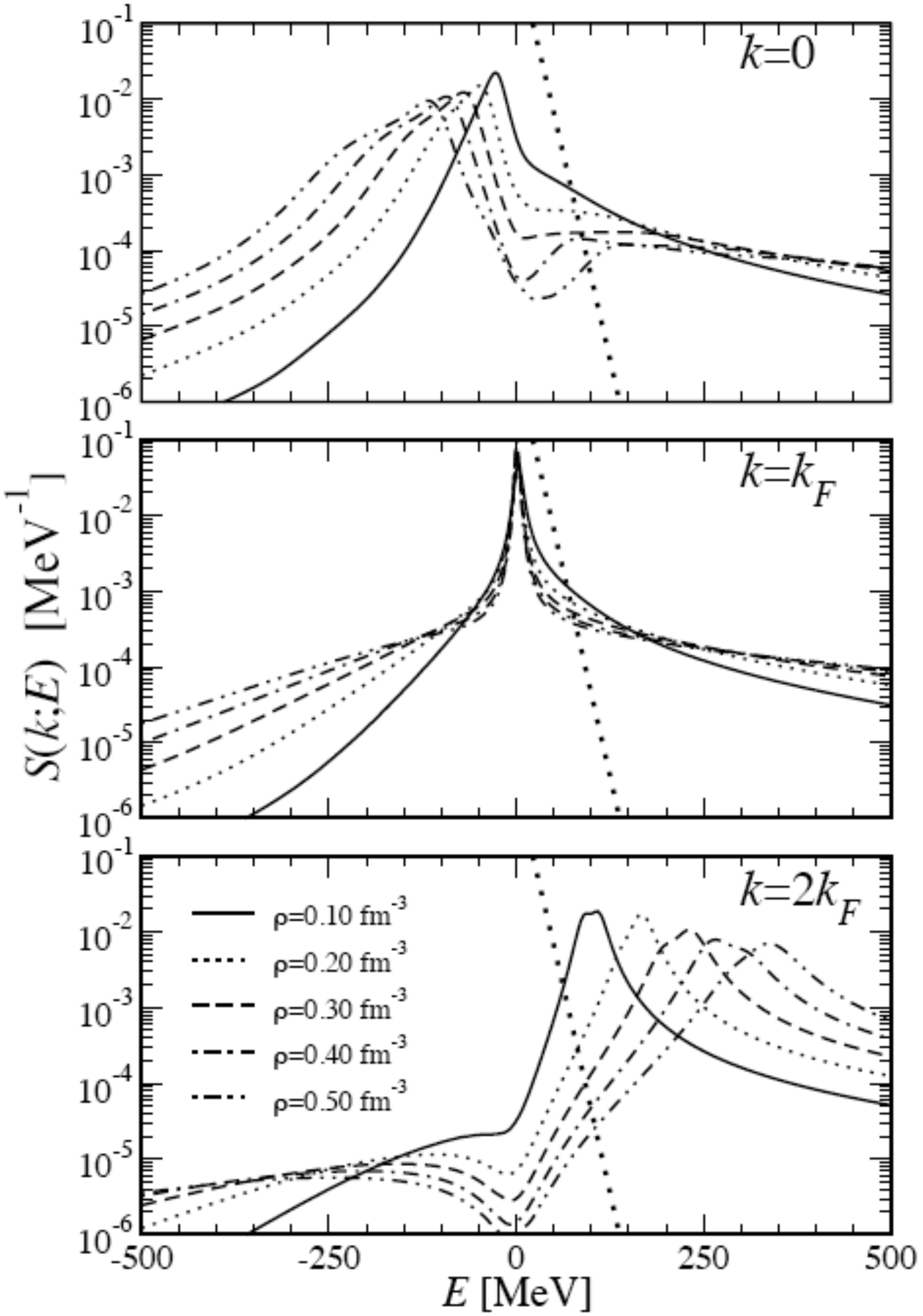
- Comparison with SCGF ladder calculations for nuclear matter by Rios (Surrey) including only SRC
- DOM ~ 8MeV/A



nuclear matter

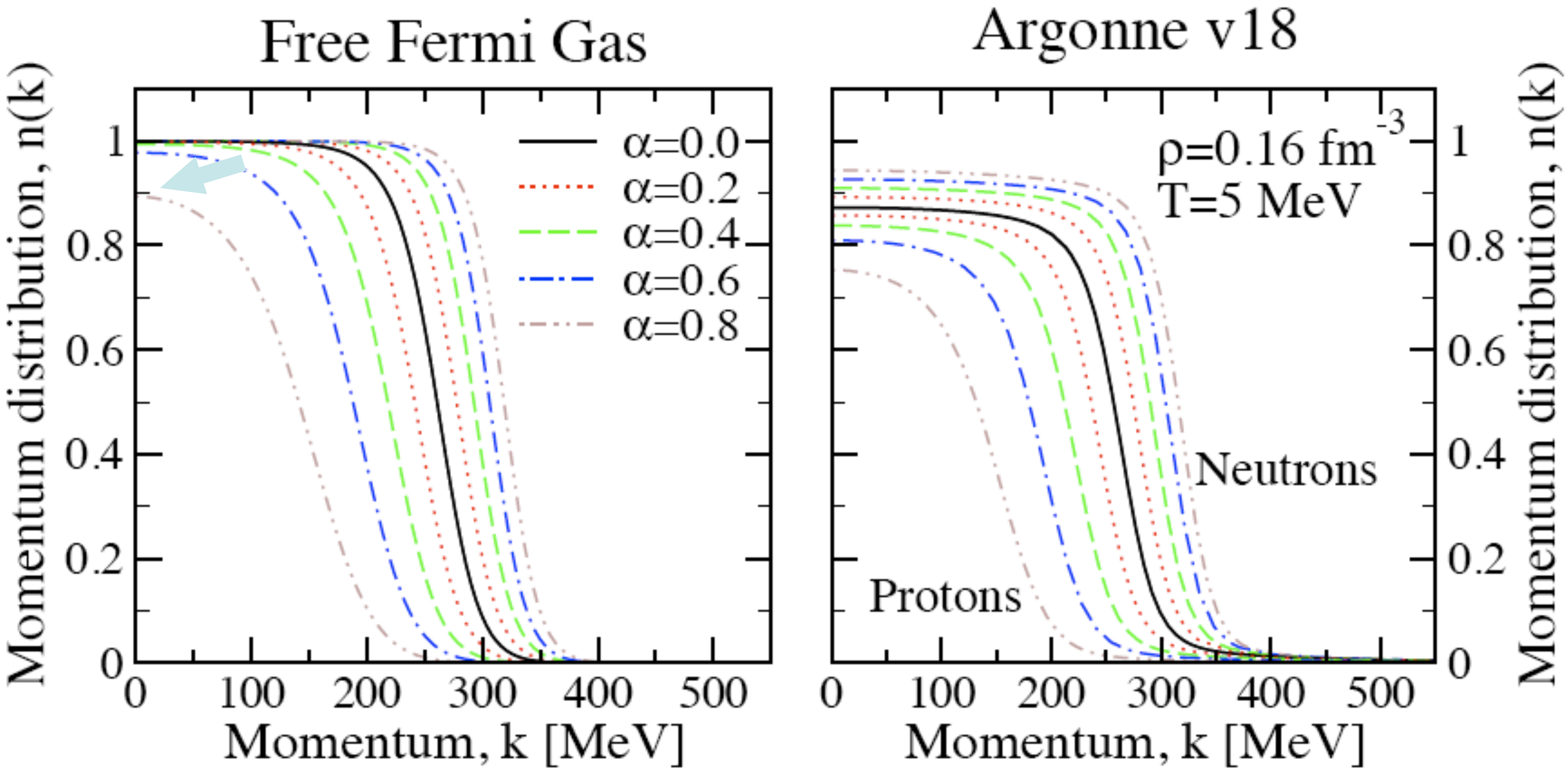
Examples for symmetric nuclear matter

- Arnau Rios thesis results (University of Barcelona 2007)
- Realistic CDBonn interaction (moderately soft)
- Spectral functions for three typical momenta--> 0, k_F, $2k_F$
- T = 10 MeV
- Dotted: Fermi function
- 5 densities
- Extra width <-> T



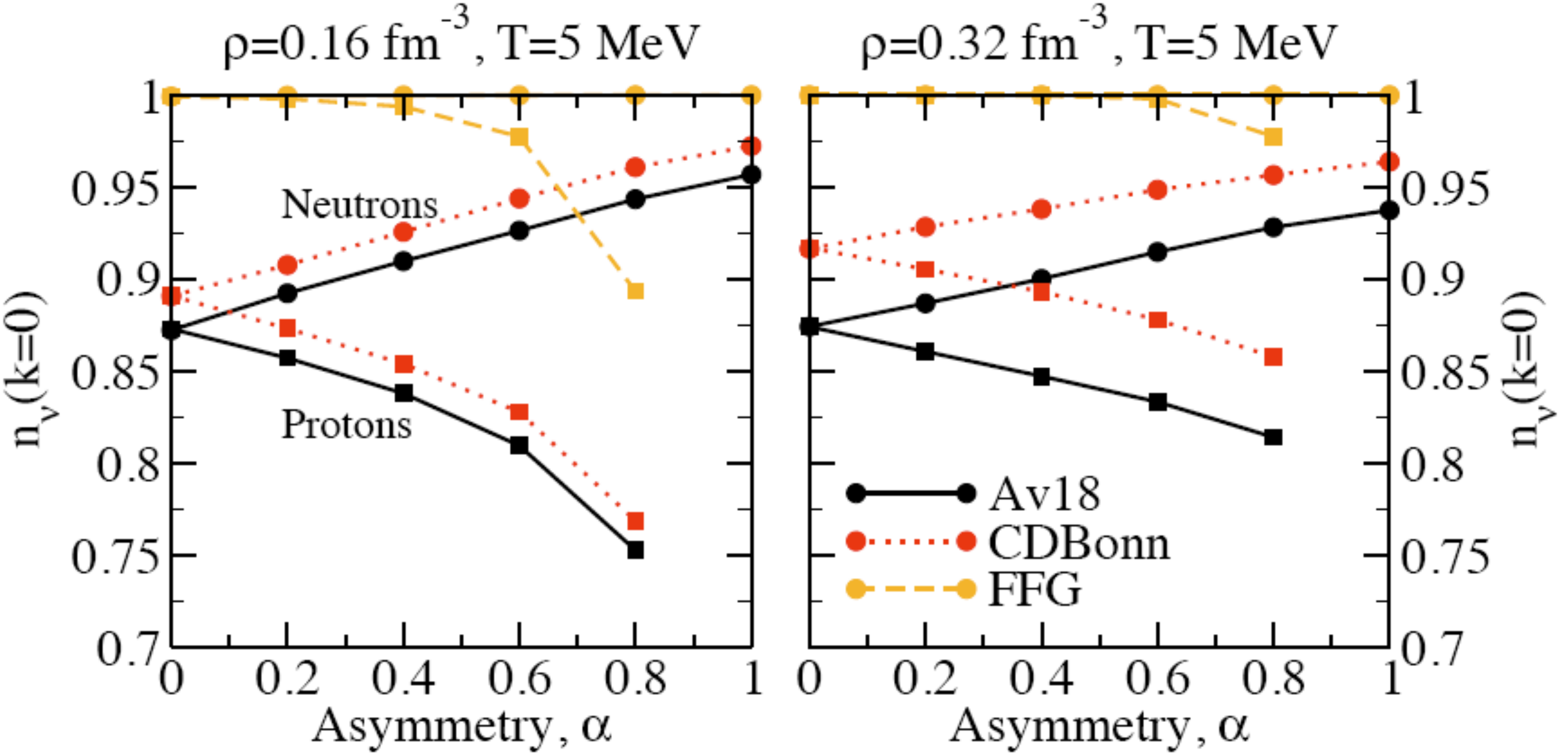
Asymmetric nuclear matter

Phys. Rev. C79, 064308 (2009)

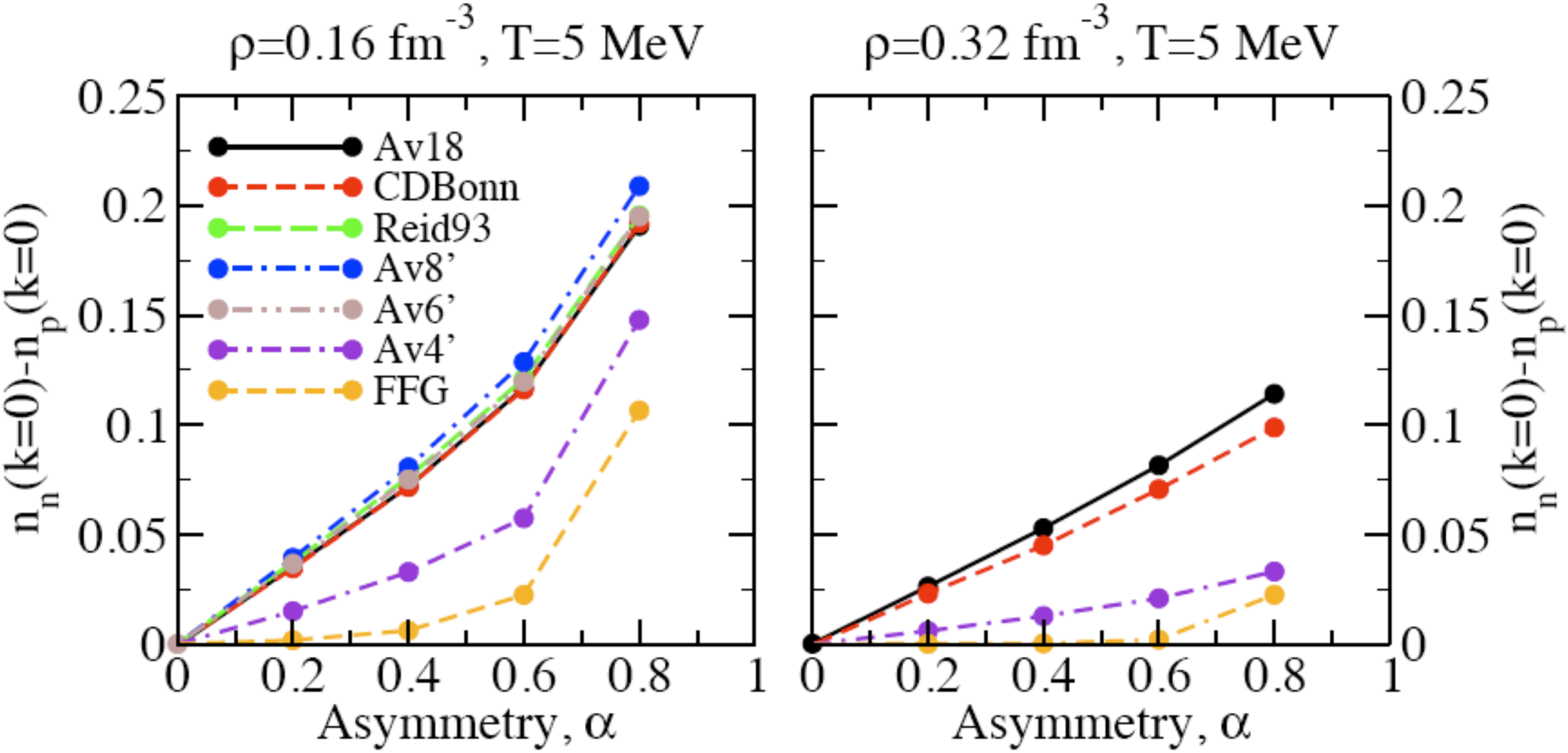


$$\alpha = \frac{N - Z}{N + Z}$$

Depletion as a function of asymmetry



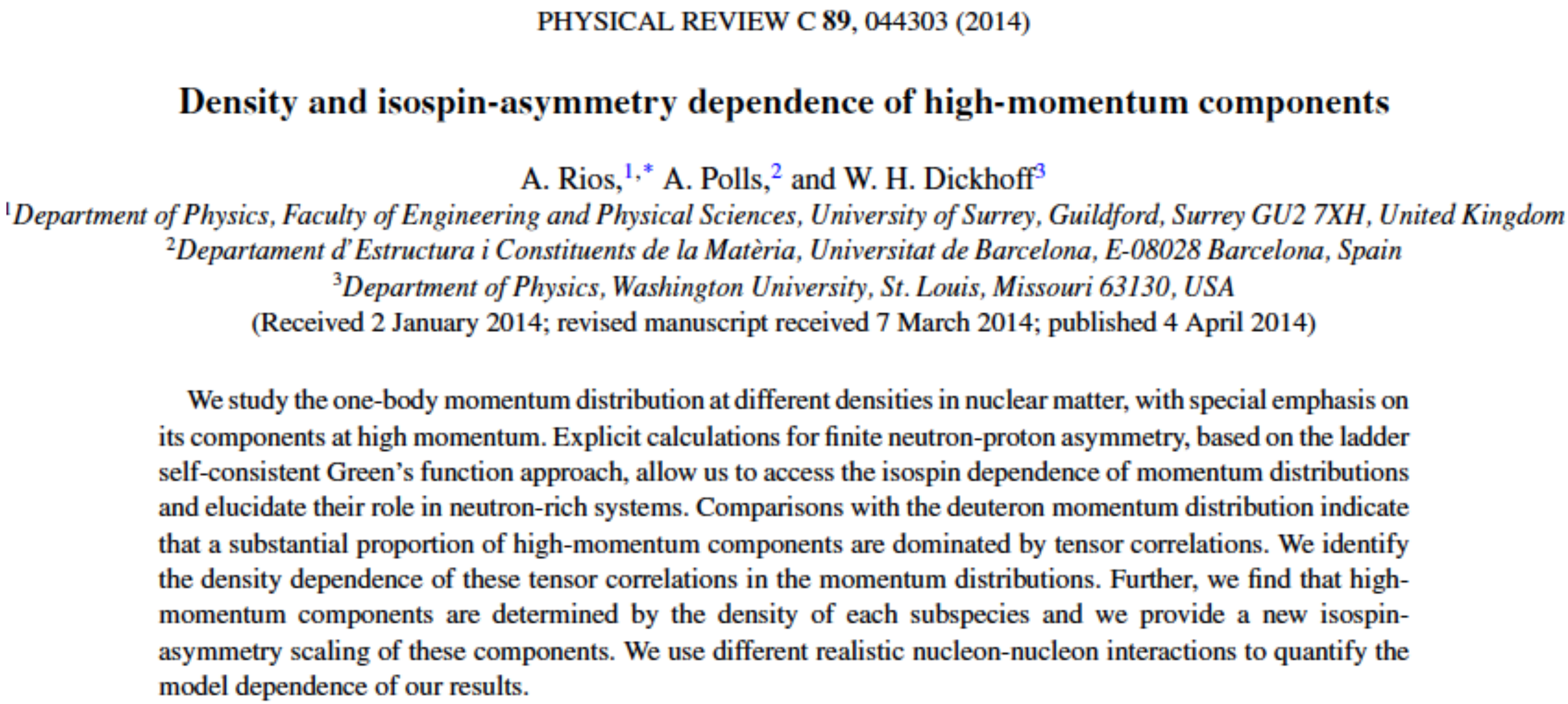
Difference $n_n(k=0)-n_p(k=0)$



Apparently determined by phase shifts!

Isovector tensor! Note Av4'

Emphasis on high momenta



PHYSICAL REVIEW C **89**, 044303 (2014)

Density and isospin-asymmetry dependence of high-momentum components

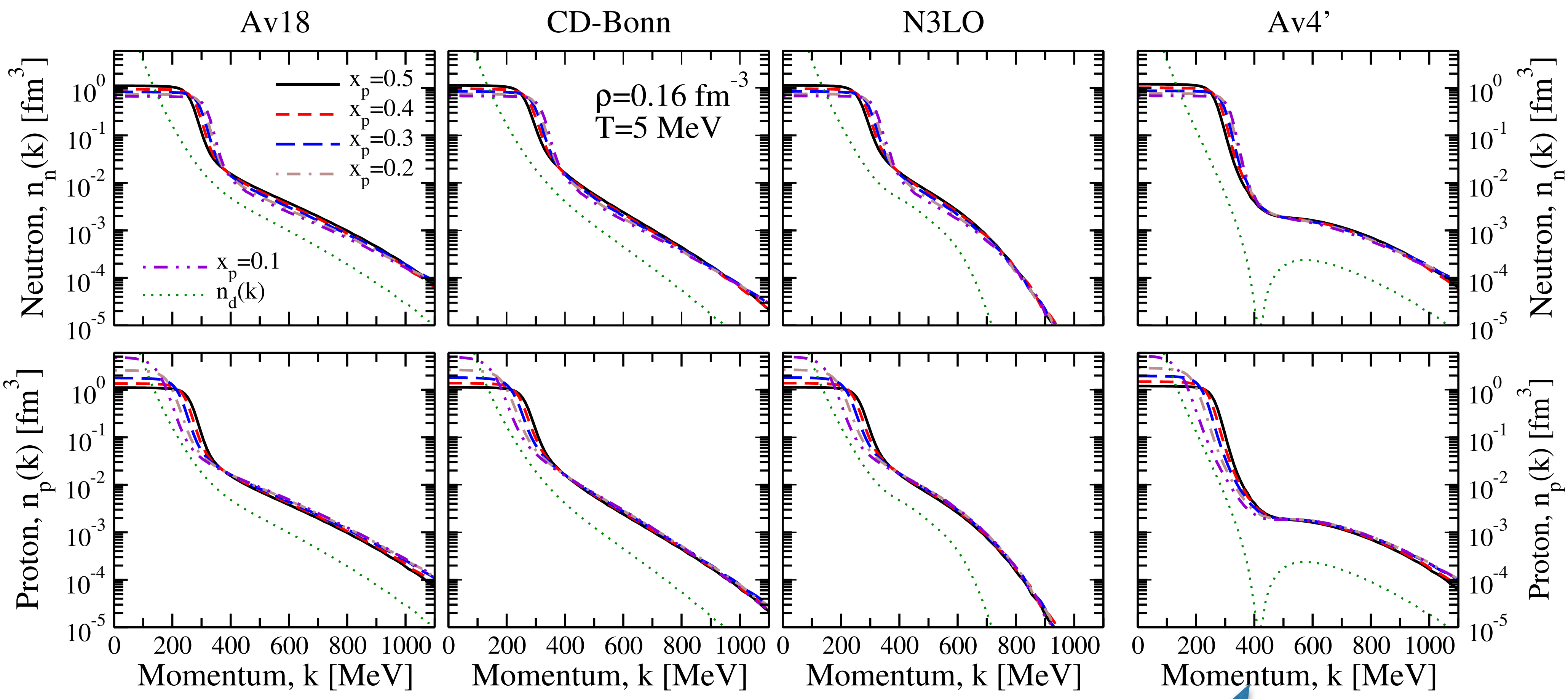
A. Rios,[1,*] A. Polls,[2] and W. H. Dickhoff[3]
[1] *Department of Physics, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom*
[2] *Departament d'Estructura i Constituents de la Matèria, Universitat de Barcelona, E-08028 Barcelona, Spain*
[3] *Department of Physics, Washington University, St. Louis, Missouri 63130, USA*
(Received 2 January 2014; revised manuscript received 7 March 2014; published 4 April 2014)

We study the one-body momentum distribution at different densities in nuclear matter, with special emphasis on its components at high momentum. Explicit calculations for finite neutron-proton asymmetry, based on the ladder self-consistent Green's function approach, allow us to access the isospin dependence of momentum distributions and elucidate their role in neutron-rich systems. Comparisons with the deuteron momentum distribution indicate that a substantial proportion of high-momentum components are dominated by tensor correlations. We identify the density dependence of these tensor correlations in the momentum distributions. Further, we find that high-momentum components are determined by the density of each subspecies and we provide a new isospin-asymmetry scaling of these components. We use different realistic nucleon-nucleon interactions to quantify the model dependence of our results.

$$\int_0^\infty dk\ k^2 n_\tau(k) = 1$$

- τ —> neutron / protons
- Allows direct comparison with finite systems
- Deuteron momentum distribution

Momentum distributions



With this normalization no strong asymmetry dependence
—> high-momenta determined by density

Deuteron —> dotted line

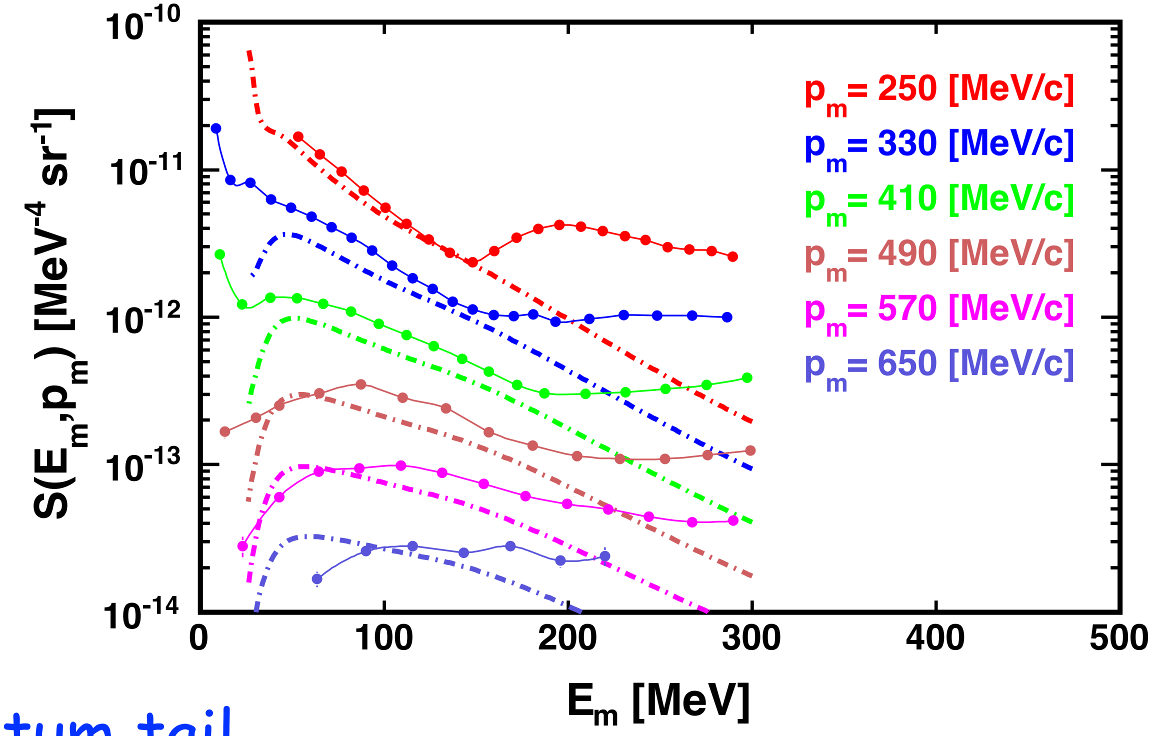
Slight dependence on proton fraction for n and p

Soft

No tensor force!

Jefferson Lab data per proton

- Pion/isobar contributions cannot be described
- Rescattering contributes some cross section (Barbieri, Lapikas)
- Jlab E97-006 Phys. Rev. Lett. 93, 182501 (2004) D. Rohe et al.



- ~**10%** high-momentum tail
- Or Hen et al.: High-momentum tail in heavy nuclei ~**20%**

Dispersive Optical Model

- Claude Mahaux 1980s
  - connect traditional optical potential to bound-state potential
  - crucial idea: use the dispersion relation for the nucleon self-energy
  - smart implementation: use it in its subtracted form
  - applied successfully e.g. to ^{40}Ca and ^{208}Pb in a limited energy window
  - employed traditional volume and surface absorption potentials and a local energy-dependent Hartree-Fock-like potential
  - Reviewed in Adv. Nucl. Phys. **20**, 1 (1991)
- Radiochemistry group at Washington University in St. Louis: Charity and Sobotka propose to use the DOM for a sequence of Ca isotopes —> data-driven extrapolations to the drip line
  - First results PRL 97, 162503 (2006)
  - Subsequently —> attention to data **below** the Fermi energy related to ground-state properties —> Dispersive Self-energy Method (**DSM**)

Propagator in principle generates

- Elastic scattering cross sections for p and n
- Including all polarization observables
- Total cross sections for n
- Reaction cross sections for p and n
- Overlap functions for adding p or n to bound states in Z+1 or N+1
- Plus normalization --> spectroscopic factor
- Overlap function for removing p or n with normalization
- Hole spectral function including high-momentum components
- One-body density matrix; occupation numbers; natural orbits
- Charge density
- Neutron distribution
- p and n distorted waves from non-local potential
- Contribution to the energy of the ground state from V_{NN}

reactions and structure

Optical potential <--> nucleon self-energy

- e.g. Bell and Squires --> elastic T-matrix = reducible self-energy
- e.g. Mahaux and Sartor Adv. Nucl. Phys. **20**, 1 (1991)
  - relate dynamic (energy-dependent) real part to imaginary part
  - employ subtracted dispersion relation
  - contributions from the hole (structure) and particle (reaction) domain

General dispersion relation for self-energy:

$$\mathrm{Re}\ \Sigma(E) = \Sigma^{HF} - \frac{1}{\pi}\mathcal{P}\int_{E_T^+}^{\infty} dE' \frac{\mathrm{Im}\ \Sigma(E')}{E-E'} + \frac{1}{\pi}\mathcal{P}\int_{-\infty}^{E_T^-} dE' \frac{\mathrm{Im}\ \Sigma(E')}{E-E'}$$

Calculated at the Fermi energy $\varepsilon_F = \frac{1}{2}\left\{(E_0^{A+1}-E_0^A)+(E_0^A-E_0^{A-1})\right\}$

$$\mathrm{Re}\ \Sigma(\varepsilon_F) = \Sigma^{HF} - \frac{1}{\pi}\mathcal{P}\int_{E_T^+}^{\infty} dE' \frac{\mathrm{Im}\ \Sigma(E')}{\varepsilon_F-E'} + \frac{1}{\pi}\mathcal{P}\int_{-\infty}^{E_T^-} dE' \frac{\mathrm{Im}\ \Sigma(E')}{\varepsilon_F-E'}$$

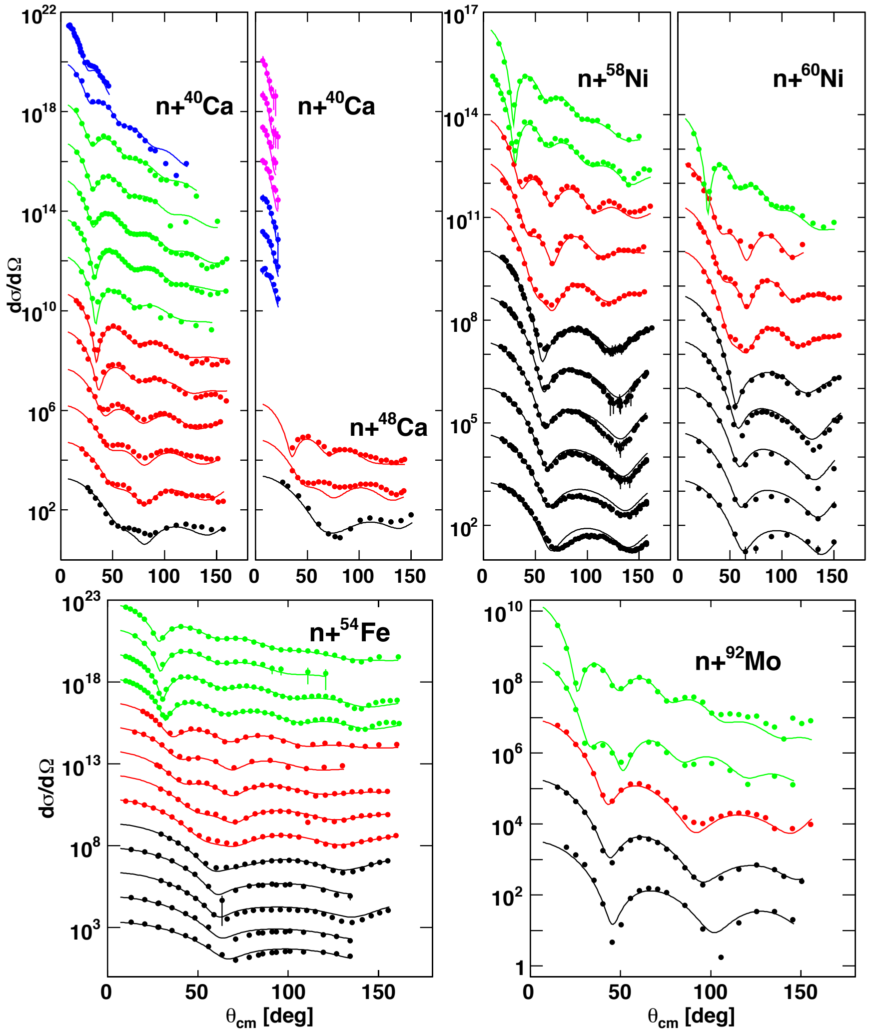
Subtract

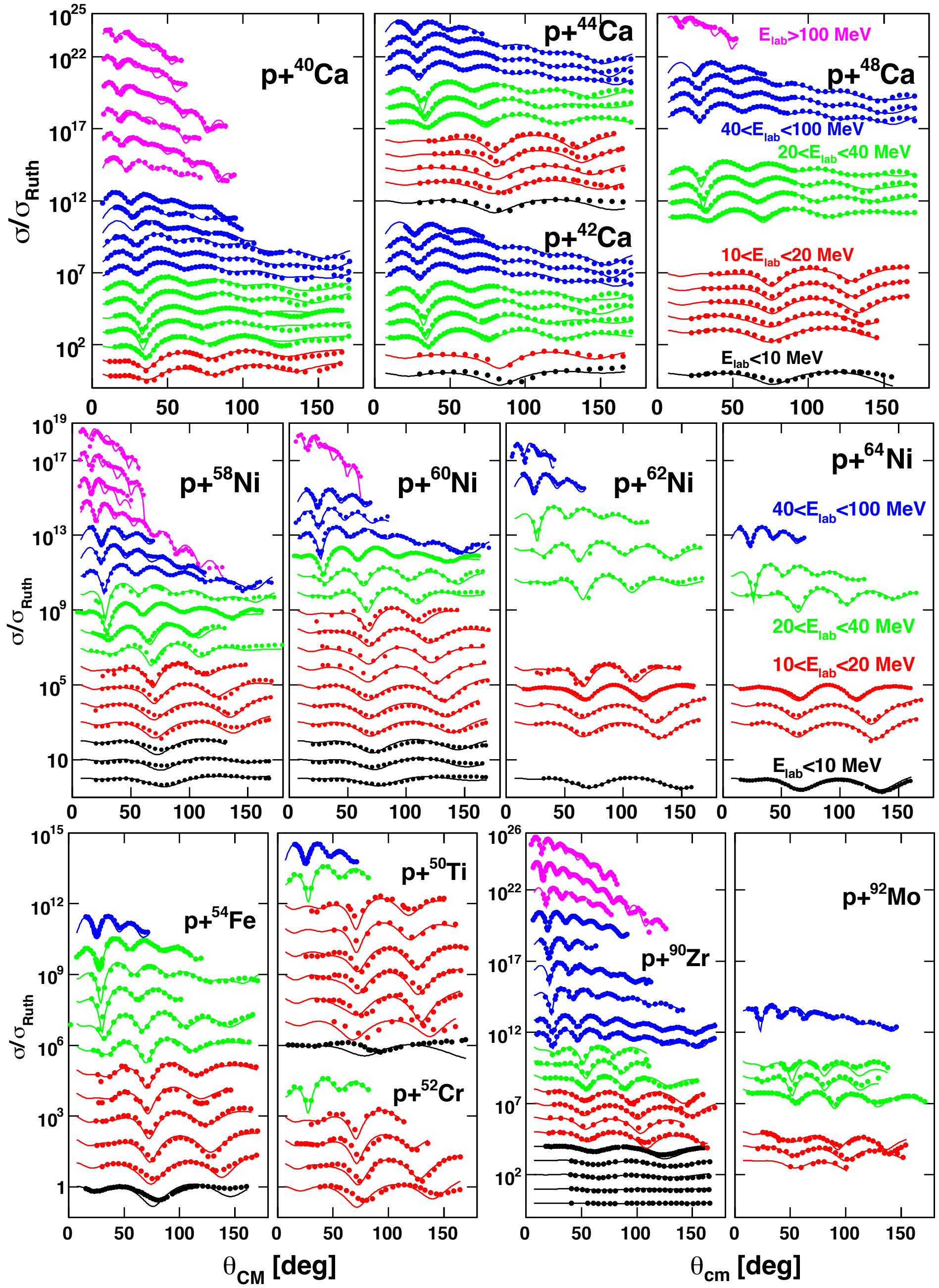
$$\mathrm{Re}\ \Sigma(E) = \mathrm{Re}\ \Sigma^{\widetilde{HF}}(\varepsilon_F)$$

$$-\ \frac{1}{\pi}(\varepsilon_F - E)\mathcal{P}\int_{E_T^+}^{\infty} dE' \frac{\mathrm{Im}\ \Sigma(E')}{(E-E')(\varepsilon_F-E')} + \frac{1}{\pi}(\varepsilon_F - E)\mathcal{P}\int_{-\infty}^{E_T^-} dE' \frac{\mathrm{Im}\ \Sigma(E')}{(E-E')(\varepsilon_F-E')}$$

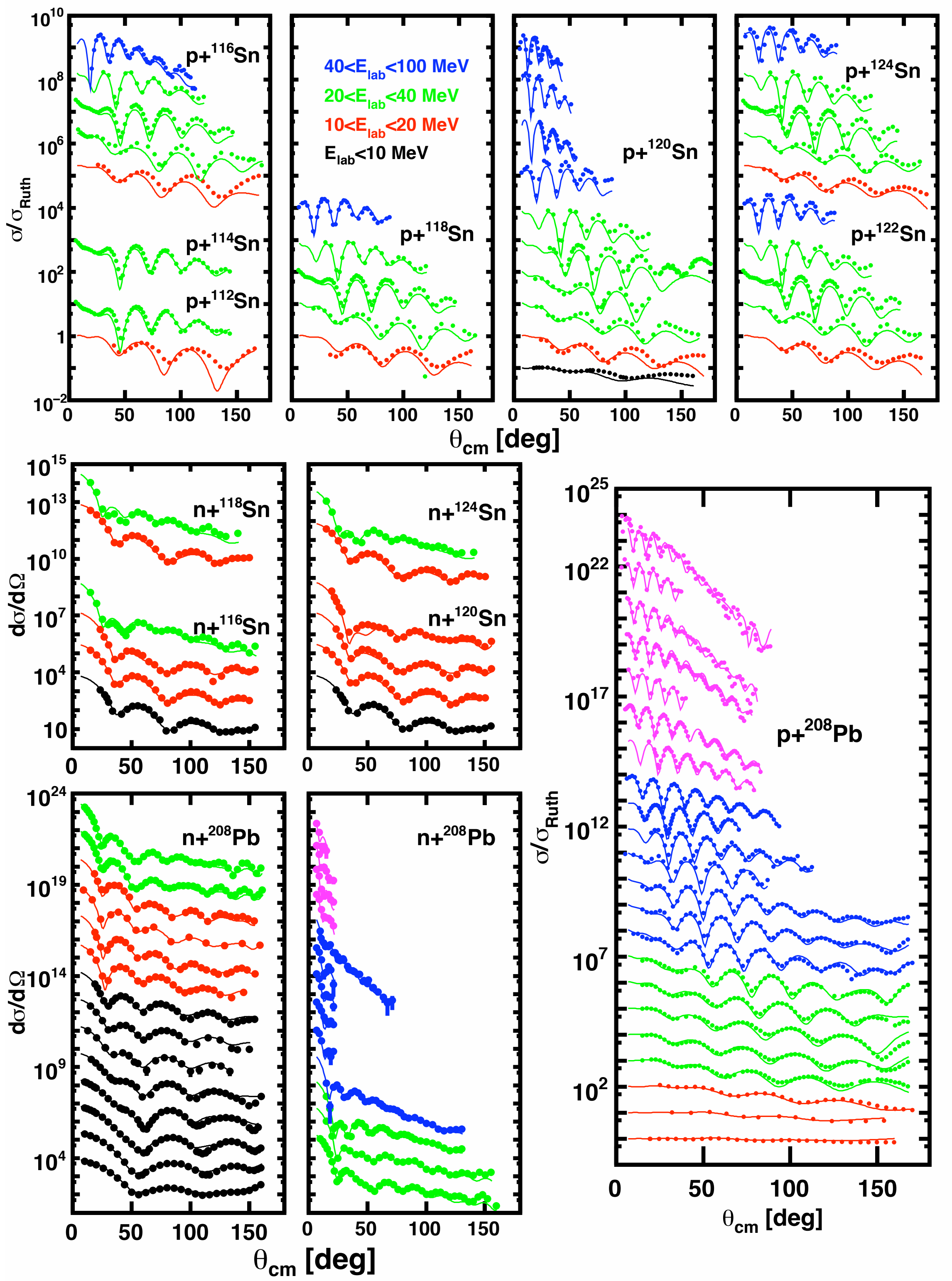
Elastic scattering data for protons and neutrons

- **Local** DOM implementation





J. Mueller et al.
PRC83,064605 (2011), 1-32



Local DOM analysis

J. Mueller et al.
PRC83,064605 (2011), 1-32

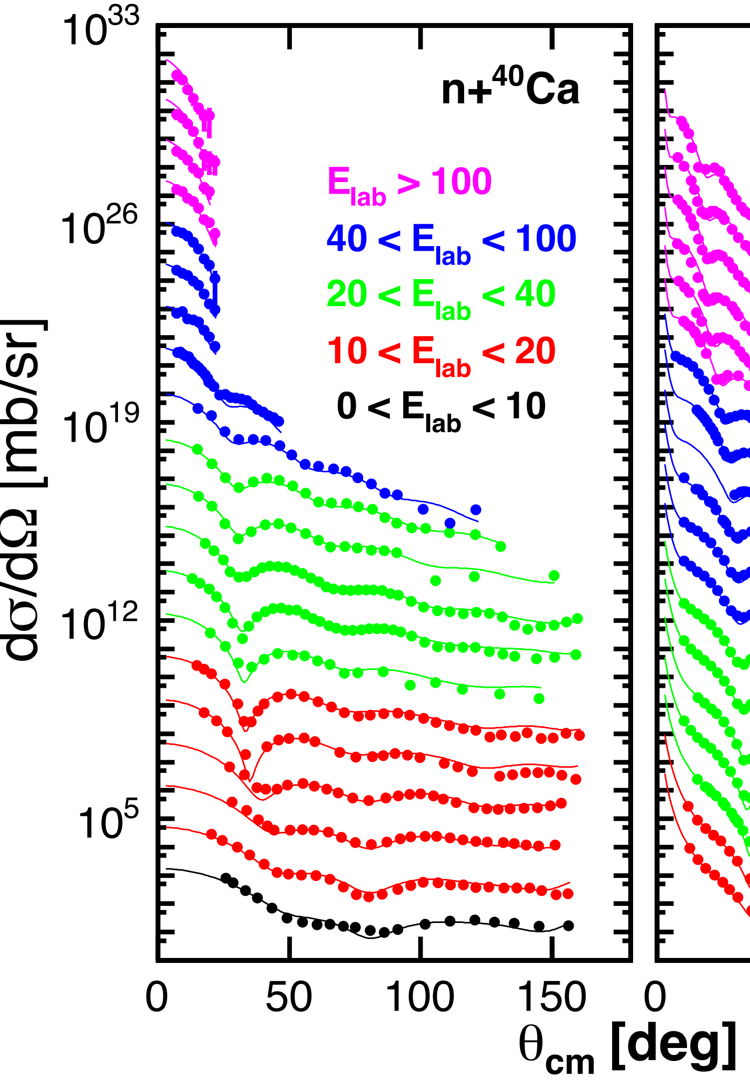
Nonlocal DOM implementation PRL112,162503(2014)

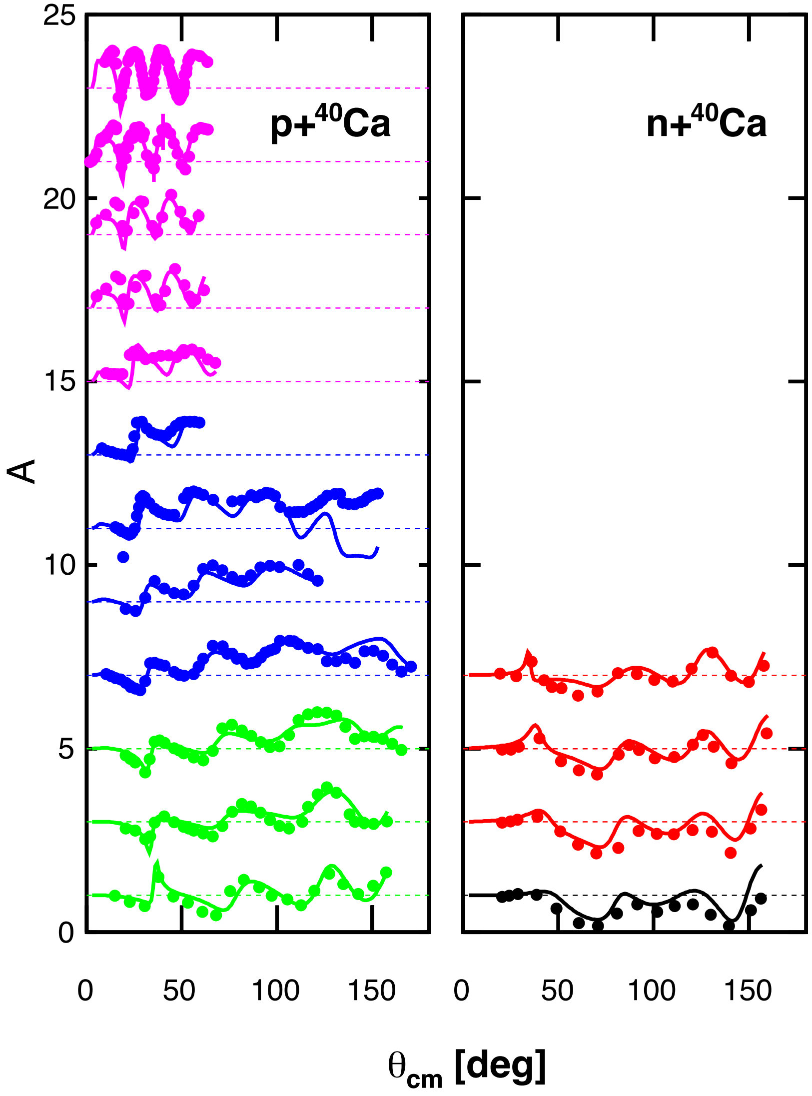
- Particle number --> **nonlocal** imaginary part
- Ab initio FRPA & SRC --> different nonlocal properties above and below the Fermi energy Phys. Rev. C84, 034616 (2011) & Phys. Rev.C84, 044319 (2011)
- Include charge density in fit
- Describe high-momentum nucleons <--> (e,e′p) data from JLab

Implications

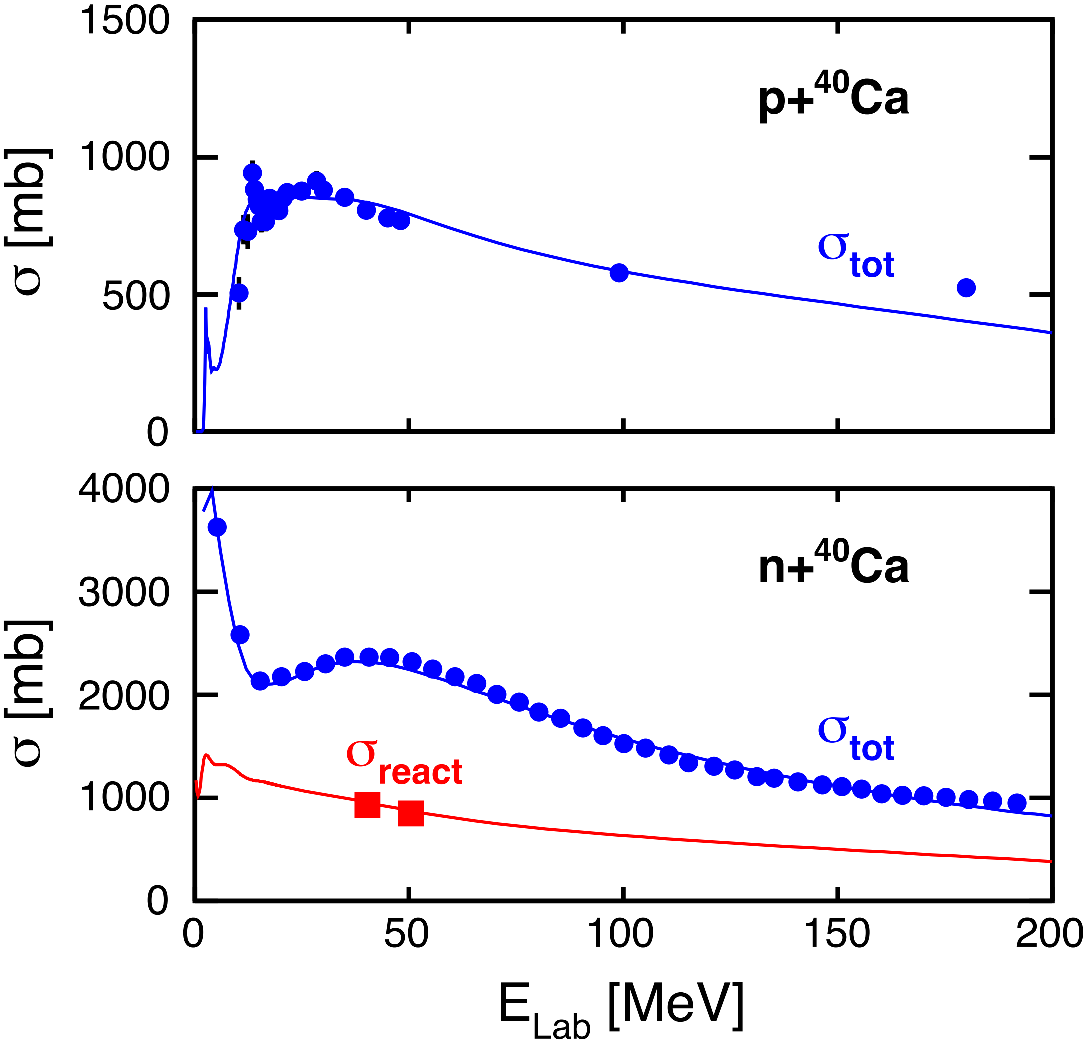
- Changes the description of hadronic reactions because interior nucleon wave functions depend on non-locality
- Consistency test of interpretation (e,e′p) reaction (see later)

Differential cross sections and analyzing powers





Reaction (p&n) and total (n) cross sections

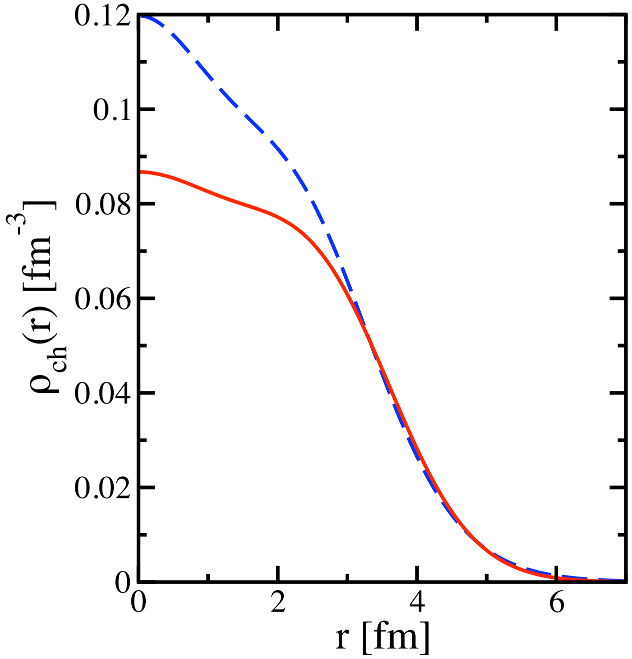


Critical experimental data—> charge density

Local version

radius correct…

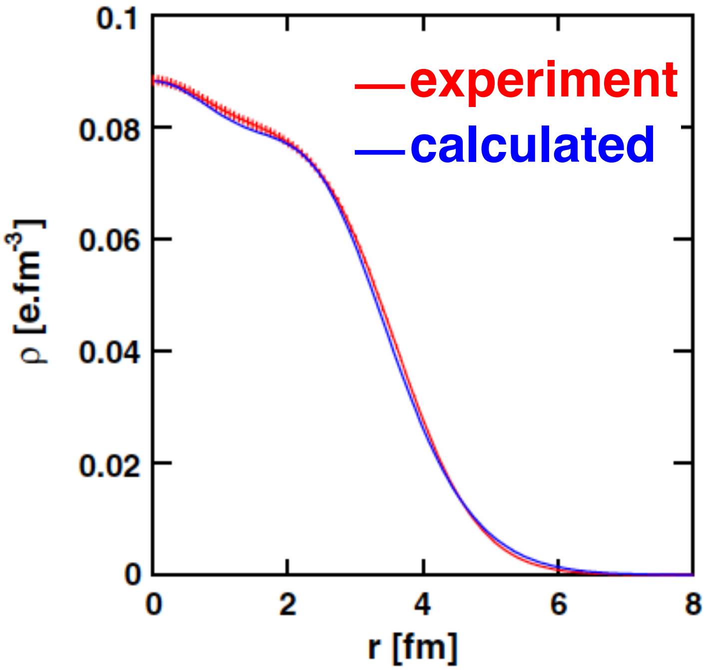
PRC82, 054306 (2010)



Charge density ^{40}Ca

Non-locality essential

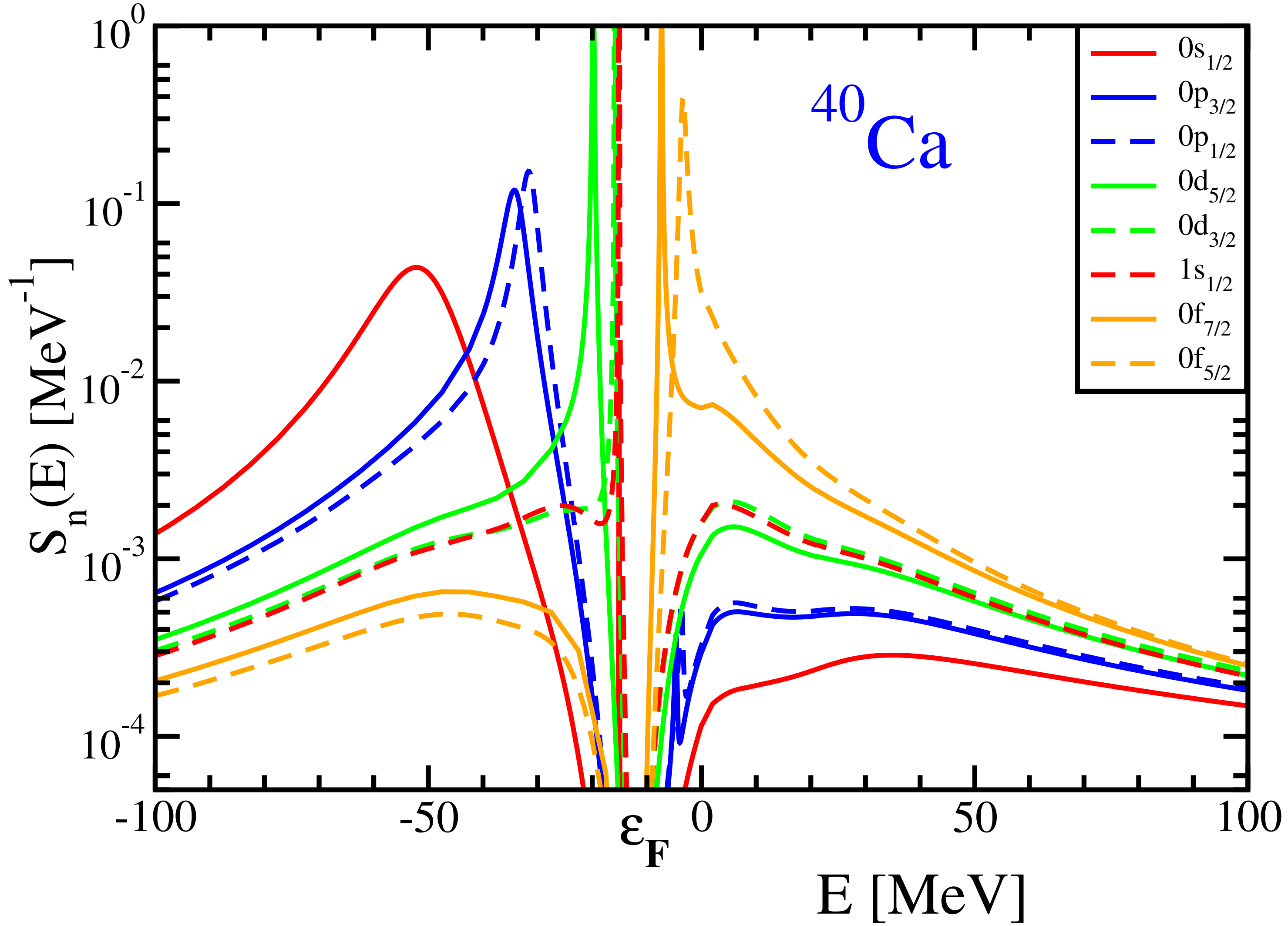
PRL 112,162503(2014)



High-momentum nucleons —> JLab can also be described —> E/A

Spectral function for bound states

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



PRC90, 061603(R) (2014)

Another look at (e,e'p) data

- collaboration with Louk Lapikás and Henk Blok
- Data published at E_p = 100 MeV Kramer thesis NIKHEF for ^{40}Ca(e,e'p)^{39}K
  Phys.Lett.B227(1989)199
  Results: S($d_{3/2}$)=0.65 and S($s_{1/2}$)=0.51…?
- More data at 70 and 135 MeV (only in a conference paper)
- What do these spectroscopic factor numbers really represent?
  - Assume DWIA for the reaction description
  - Use kinematics (momentum transfer parallel to initial proton momentum) favoring simplest part of the excitation operator (no two-body current)
  - Overlap function:
    - WS with radius adjusted to shape of cross section
    - Depth adjusted to separation energy
  - Distorted proton wave from standard "global optical potential"
  - Fit normalization of overlap function to data -> spectroscopic factor

Why go back there?

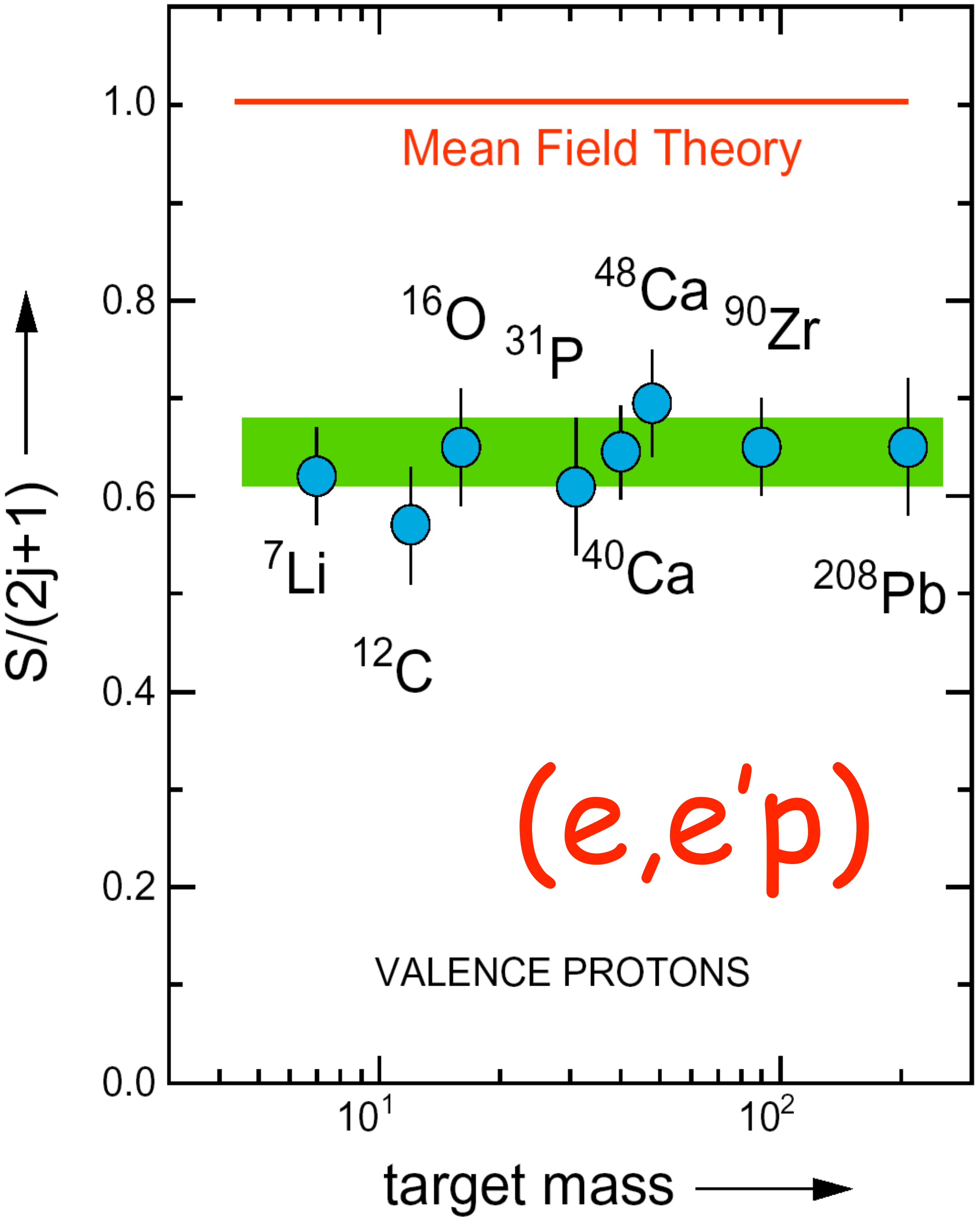
Removal probability for valence protons from NIKHEF data

L. Lapikás, Nucl. Phys. A553,297c (1993)

S ≈ 0.65 for valence protons
Reduction ⇒ both SRC and LRC

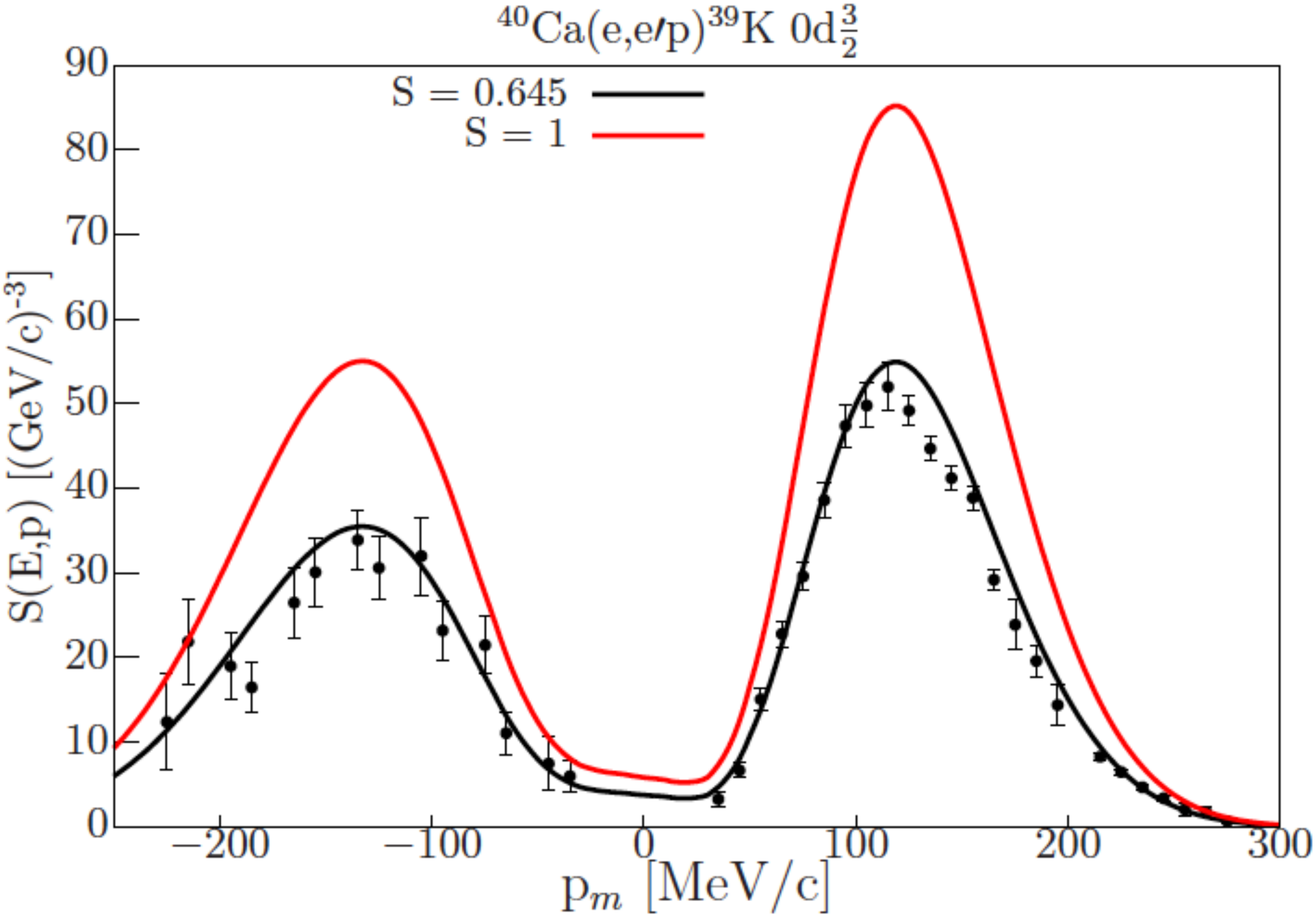
Weak probe but propagation in the nucleus of removed proton using standard optical potentials to generate distorted wave --> associated uncertainty ~ 5-15%

Why: details of the interior scattering wave function uncertain since non-locality is not constrained (so far.....)
but now available for ^{40}Ca!



NIKHEF analysis PLB227,199(1989)

- Schwandt et al. (1981) optical potential
- BSW from adjusted WS



DOM ingredients and DWIA

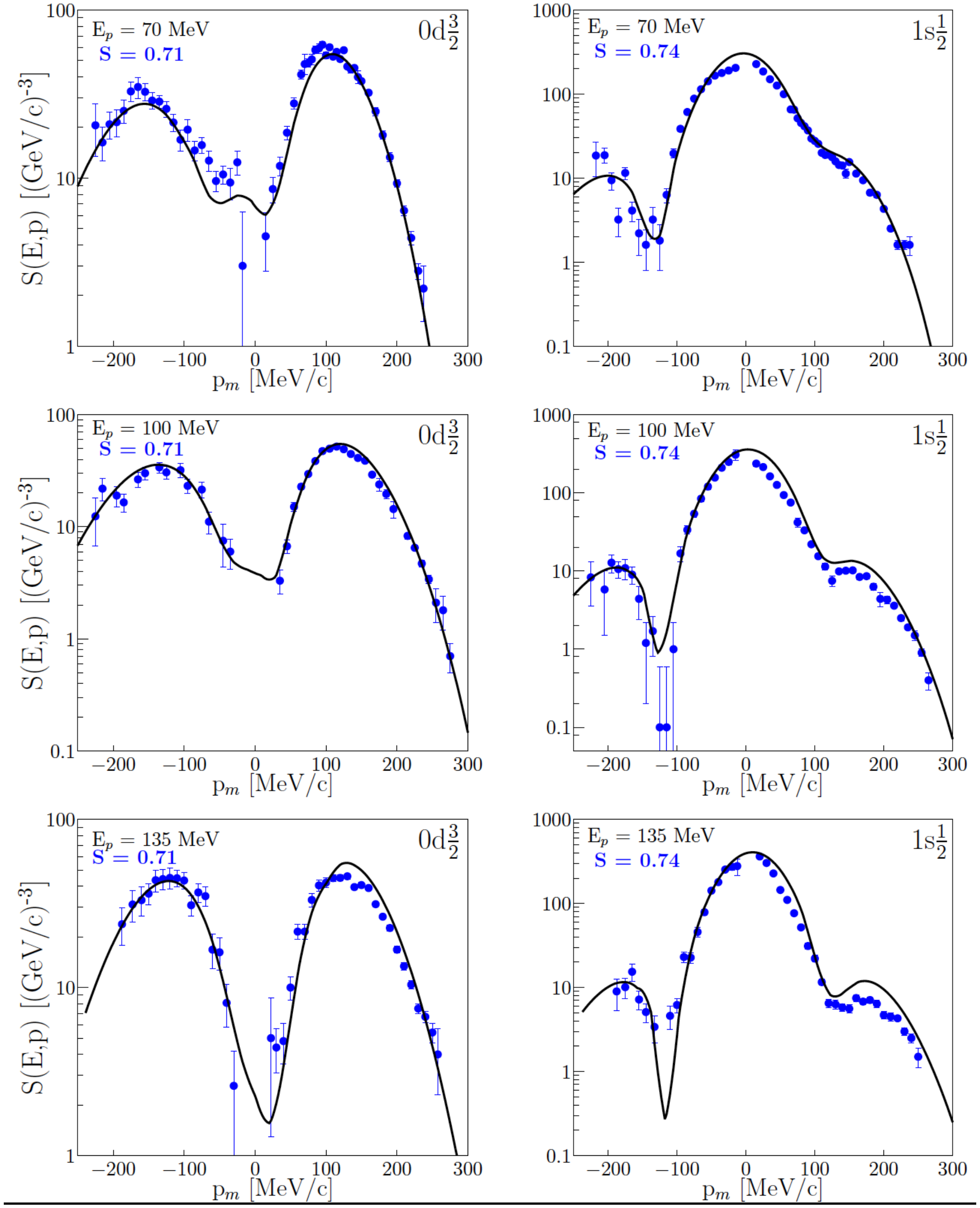
- DW non-local DOM
- Overlap functions also

Published: 100 MeV

- NIKHEF: $S(d_{3/2})=0.65\pm0.06$
- NIKHEF: $S(s_{1/2})=0.51\pm0.05$

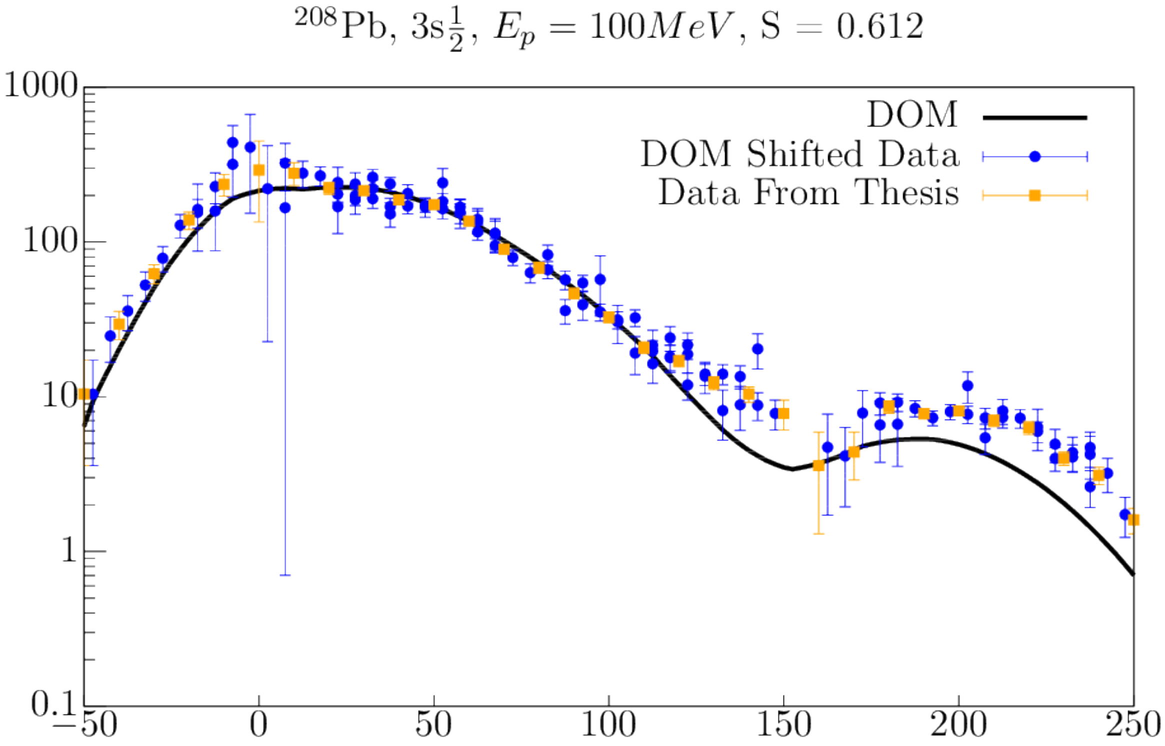
- DOM: $S(d_{3/2})=0.71$
- DOM: $S(s_{1/2})=0.74$

- DWEEPY code C. Giusti



^{208}Pb(e,e'p)

- Preliminary analysis



Inelastic electron scattering in ^{208}Pb

PHYSICAL REVIEW C VOLUME 20, NUMBER 2 AUGUST 1979

High-spin states of $J^\pi = 12^-$, 14^- in ^{208}Pb studied by (e, e')

J. Lichtenstadt, J. Heisenberg,* C. N. Papanicolas, and C. P. Sargent
Bates Linear Accelerator Center and Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

A. N. Courtemanche and J. S. McCarthy
University of Virginia, Charlottesville, Virginia 22901

(Received 2 March 1979)

Lessons from the past probably forgotten?

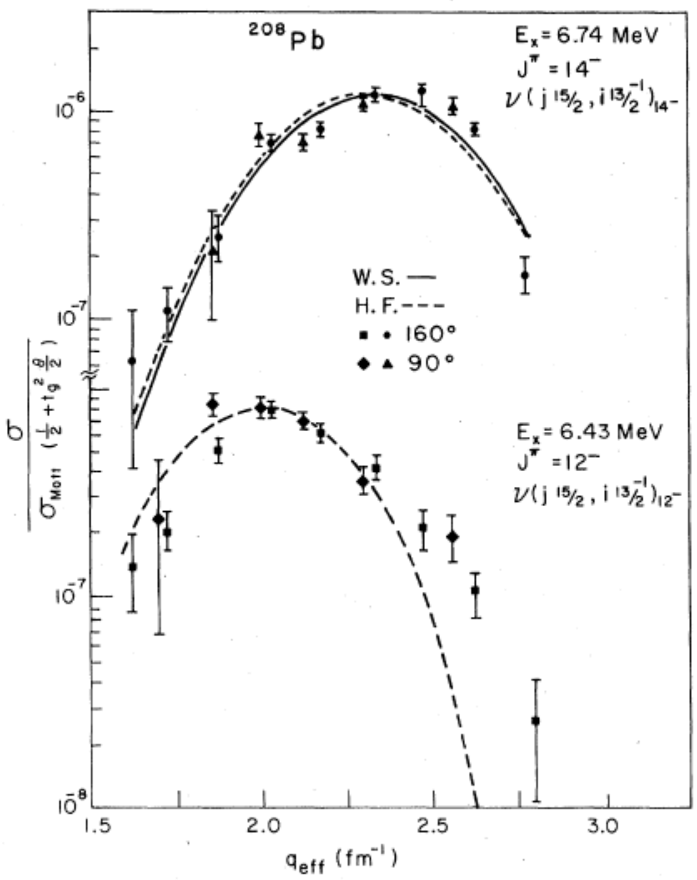
All these high spin cross sections
must be multiplied by 50±3.5%

Spectroscopic factors (DOM)

$\nu j_{15/2}$ 0.72

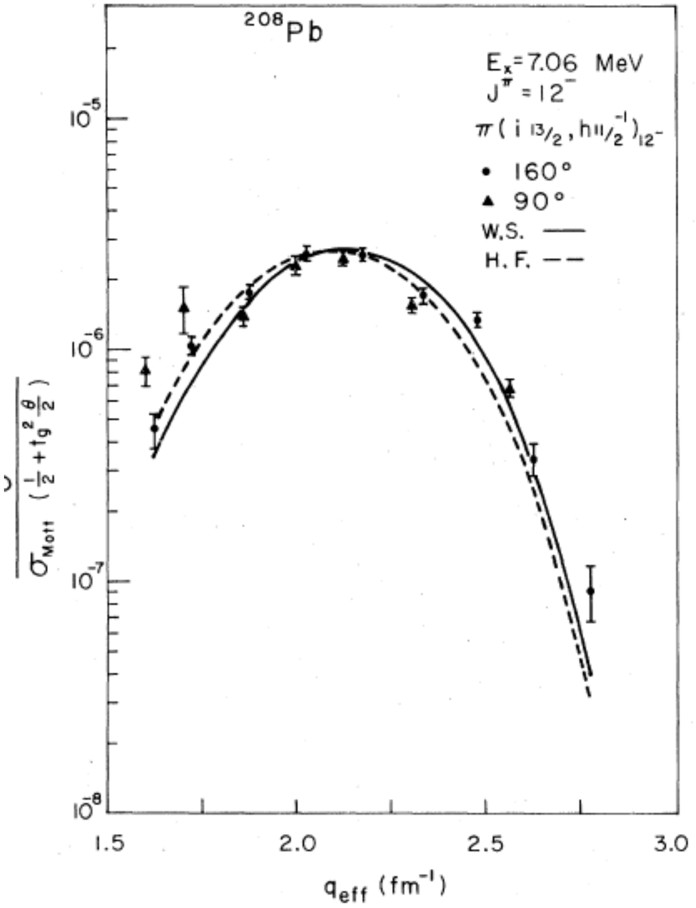
$\nu i_{13/2}$ 0.71

$\nu i_{11/2}$ 0.73



$\pi i_{13/2}$ 0.68

$\pi h_{11/2}$ 0.65



reactions and structure

Message

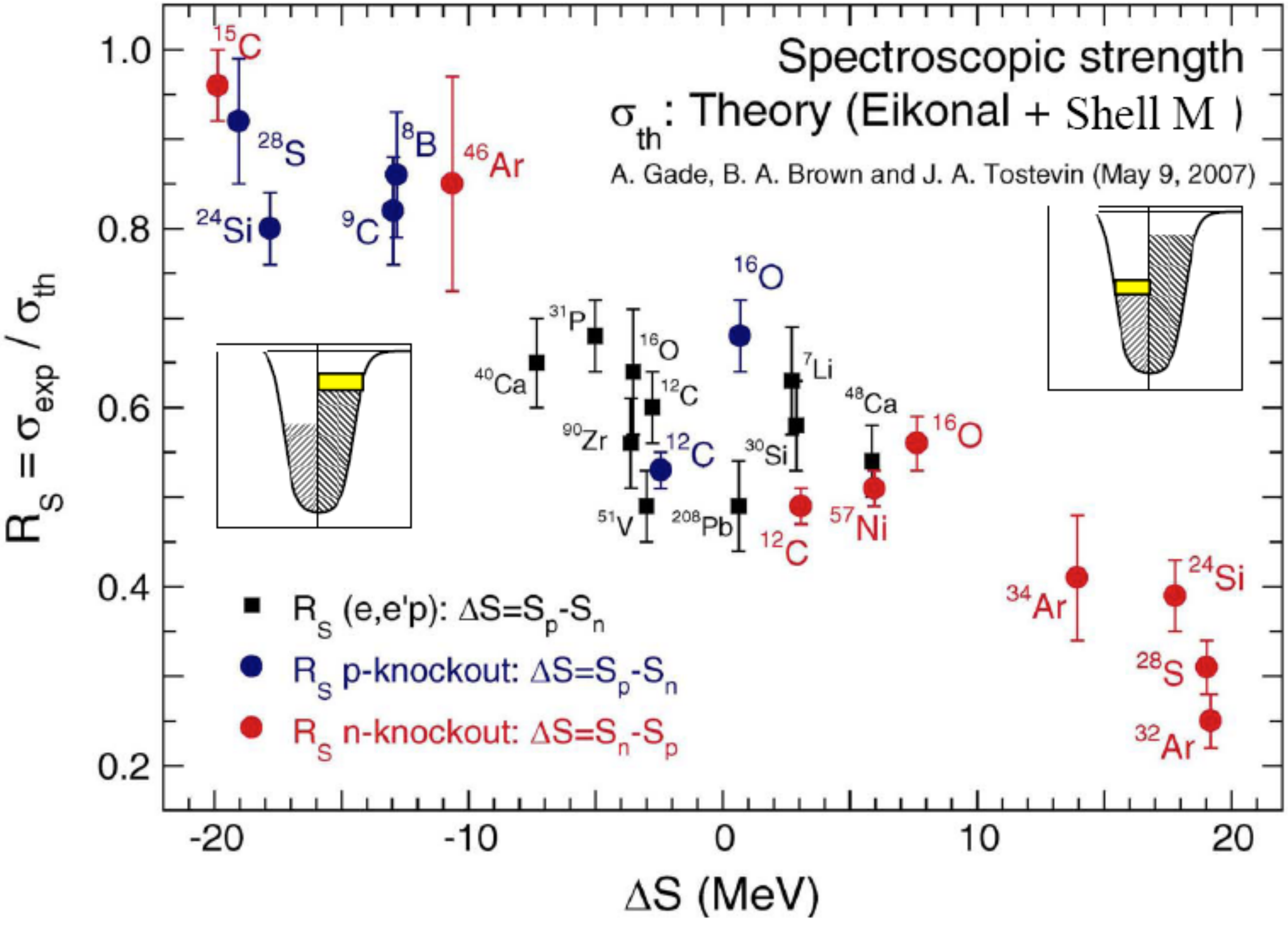
- Nonlocal dispersive potentials yield consistent results with DWIA interpretation of (e,e′p) data in parallel kinematics

- Constraints from other data generate spectroscopic factors ~ 0.7-0.75 in ^{40}Ca

- Similar reduction consistent with high-spin inelastic electron scattering data from ^{208}Pb

Gade et al. Phys Rev C77, 044396 (2008)

Deeply-bound systems



$R_S \neq$ not spectroscopic factor

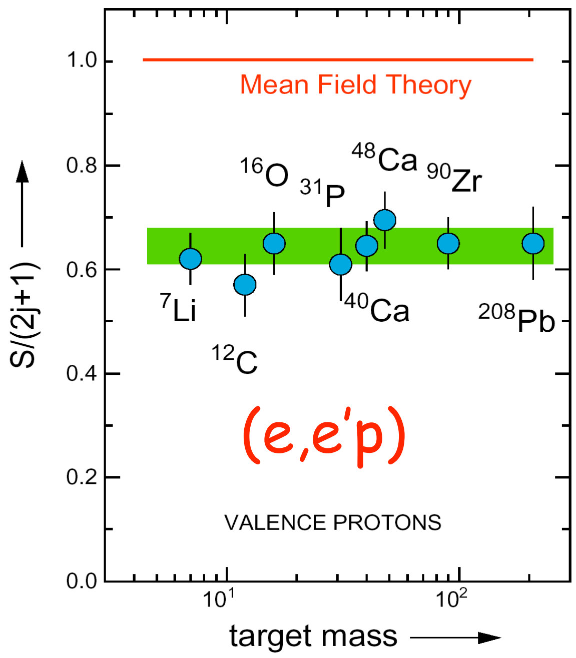
Reduction w.r.t. shell model

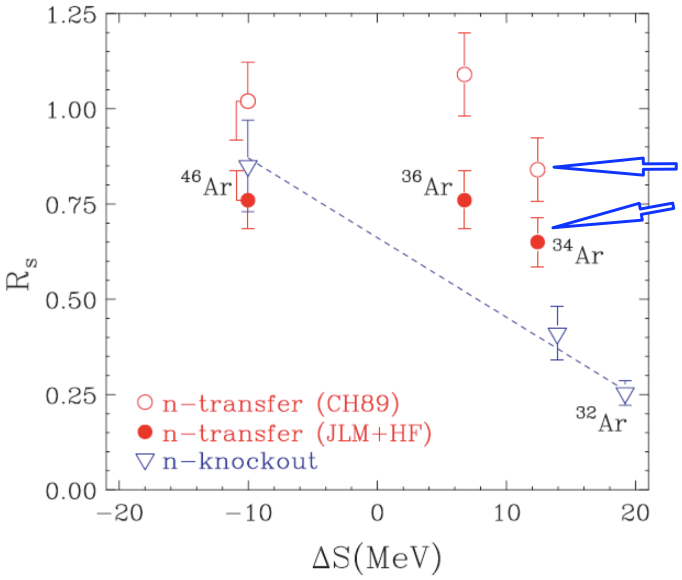
neutrons more correlated with
increasing proton number
and accompanying increasing
separation energy & vice versa

⇒ Spectroscopic factors become very small; way too small?

Linking nuclear reactions and nuclear structure —> DOM

Correlations from nuclear reactions





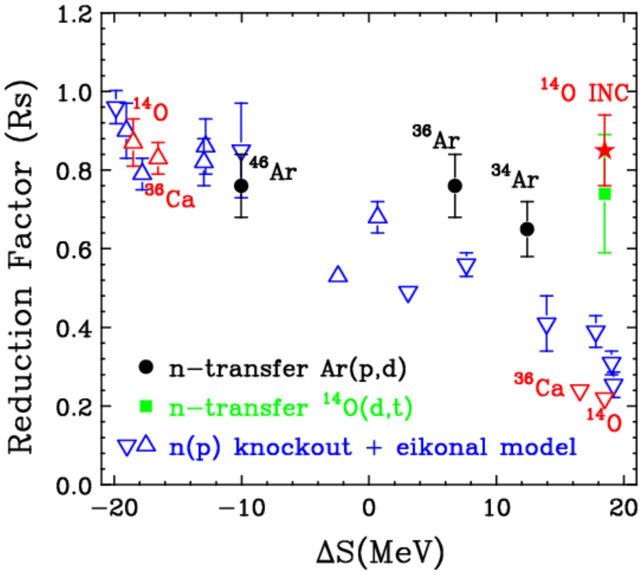
Different optical potentials --> different reduction factors for transfer reactions

Spectroscopic factors > 1

???

PRL 93, 042501 (2004) HI

PRL 104, 112701 (2010) Transfer



In (e,e'p) proton still has to get out of the nucleus —> optical potential

Nucl. Phys. A553,297c (1993)

Appears more or less consistent with DOM analysis!

Recent summary —> Jenny Lee

Different reactions different results???

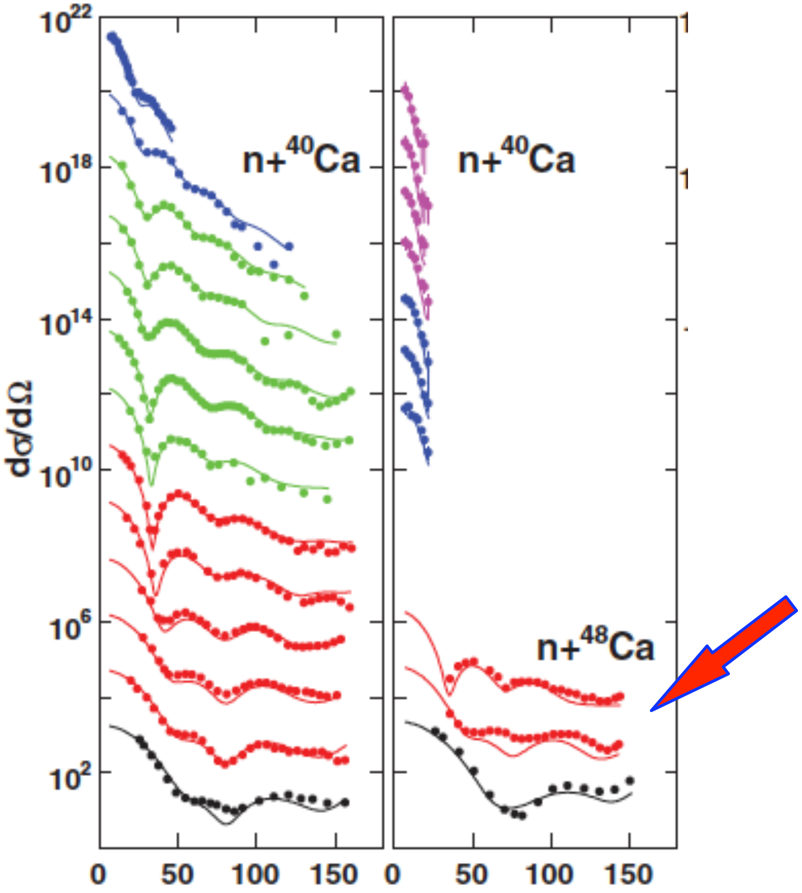
DOM results for ^{48}Ca

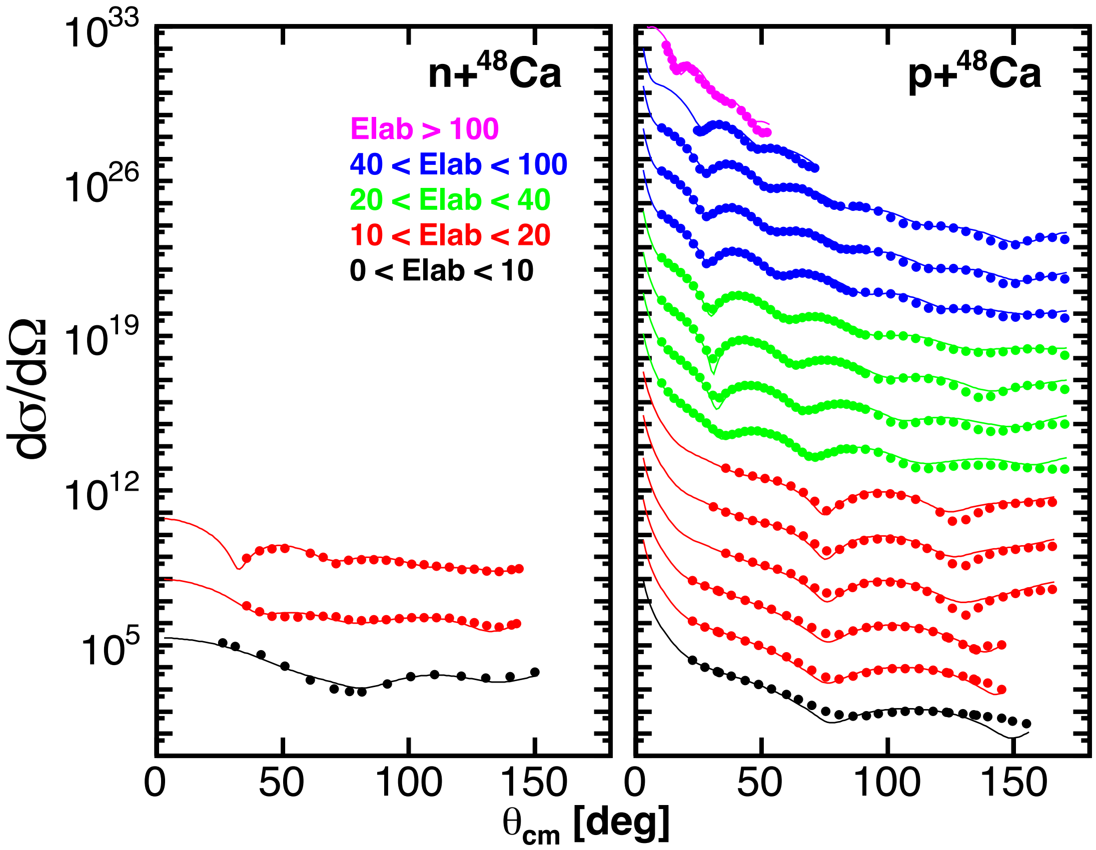
- Change of proton properties when 8 neutrons are added to ^{40}Ca?
- Change of neutron properties?
- Can hard to measure quantities be indirectly constrained?

reactions and structure

What about neutrons?

- ^{48}Ca —> charge density has been measured
- Recent neutron elastic scattering **data** —> PRC83,064605(2011)
- Local DOM **OLD** Nonlocal DOM **NEW**

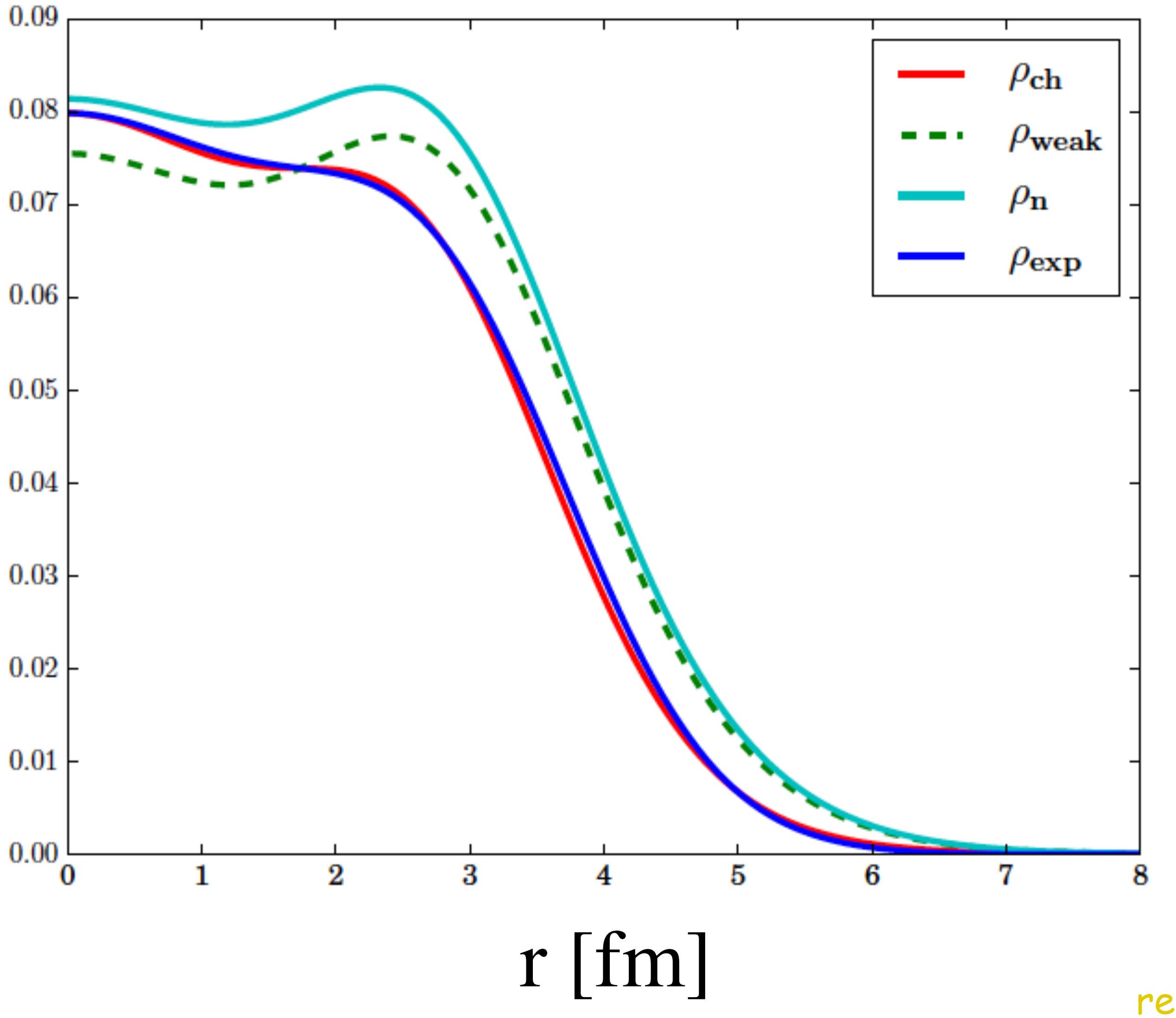




reactions and structure

Results ^{48}Ca

- Density distributions
- DOM —> neutron distribution —> R_n-R_p

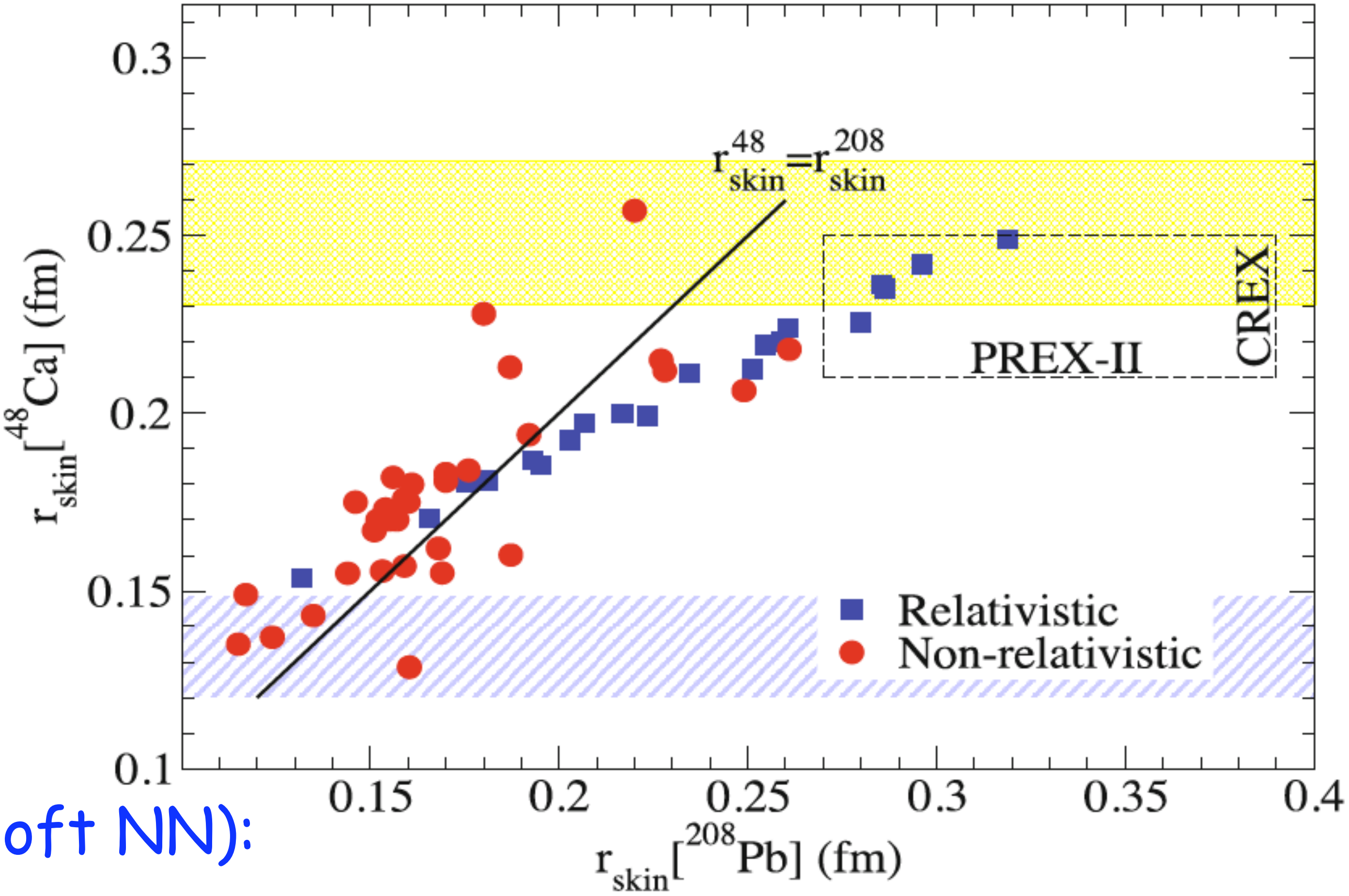


reactions and structure

Comparison of neutron skin with other calculations and future experiments…

- Figure adapted from

C.J. Horowitz, K.S. Kumar, and R. Michaels, Eur. Phys. J. A (2014)



DOM

ab initio

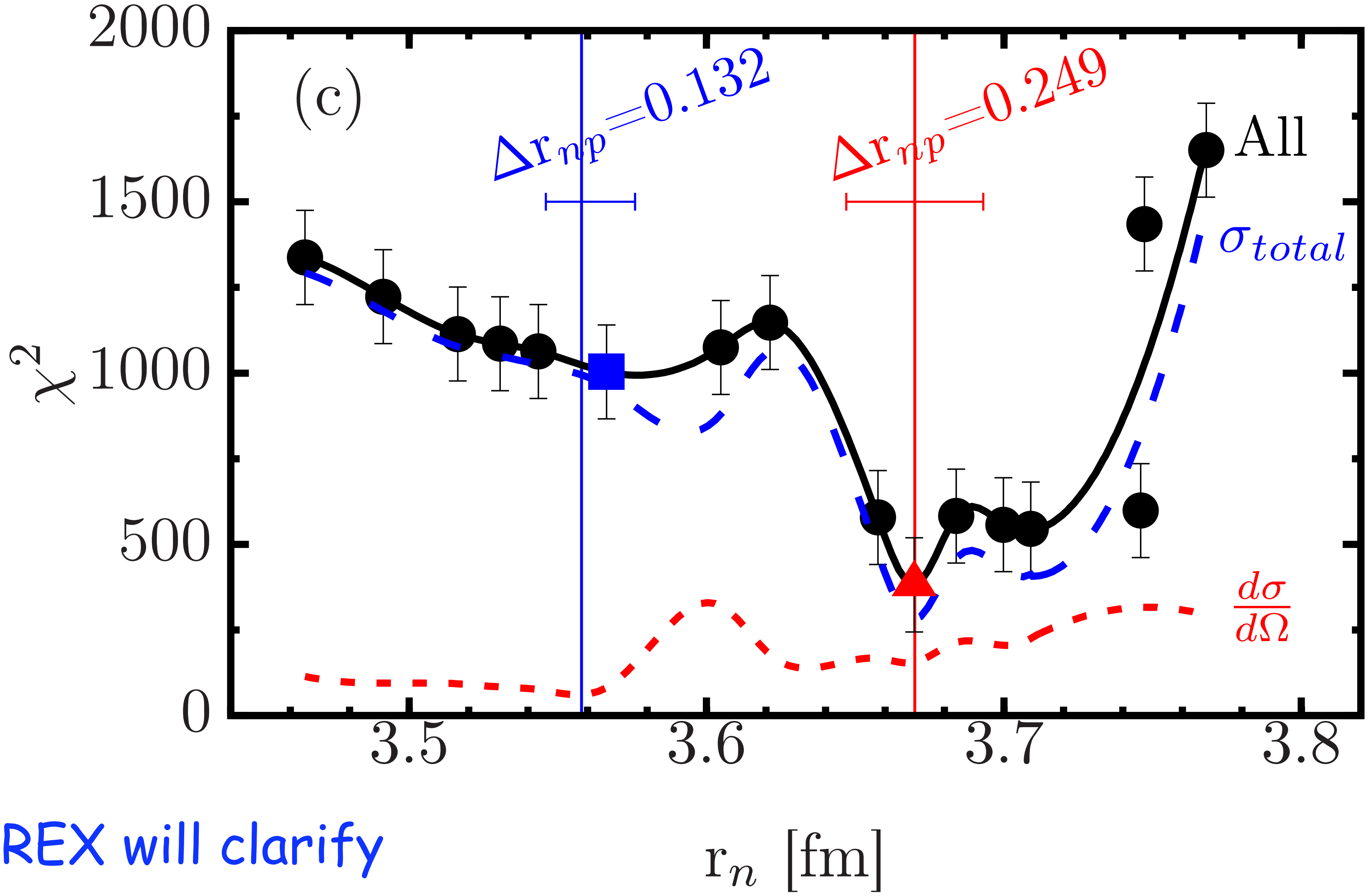
- Ab initio (soft NN):

G. Hagen et al., Nature Phys. 12, 186 (2016)

--> drip line

Comparison with small neutron skin

- Data sensitivity and error

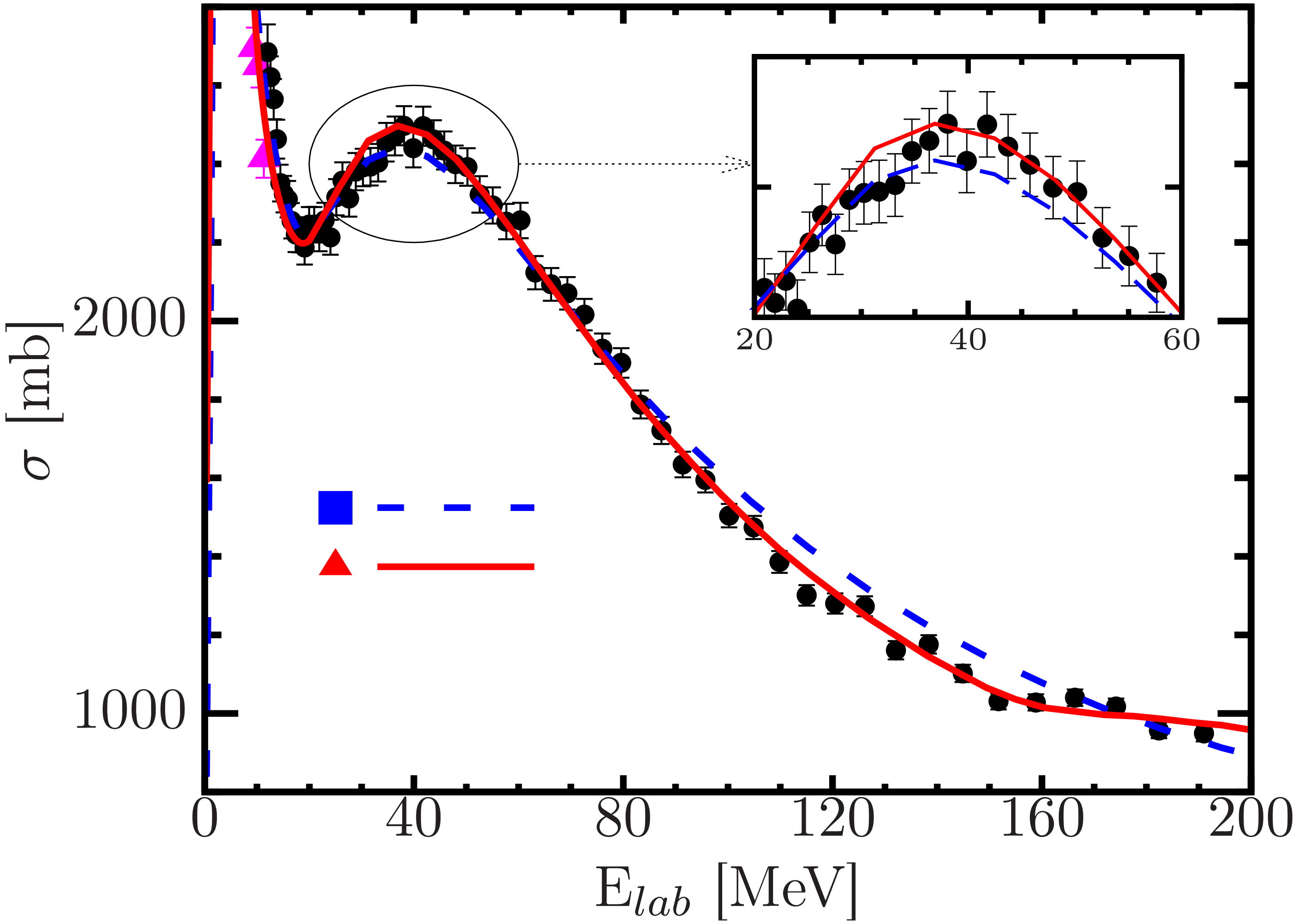


- CREX will clarify

--> drip line

Constraining the neutron radius

- Using total neutron cross sections



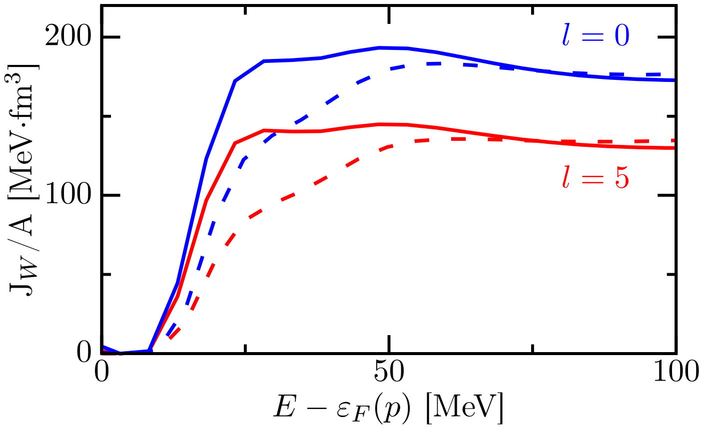
M.H. Mahzoon, M.C. Atkinson, R.J. Charity, W.D.

Phys. Rev. Lett. **119**, 222503 (2017)

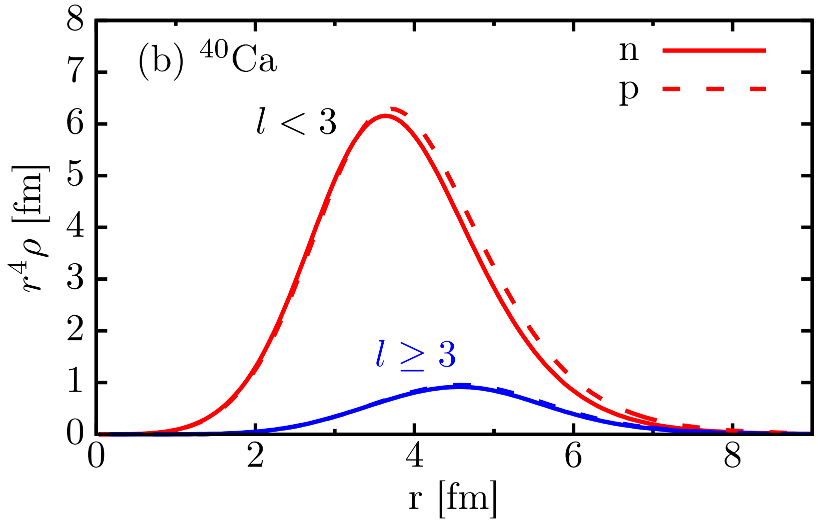
--> drip line

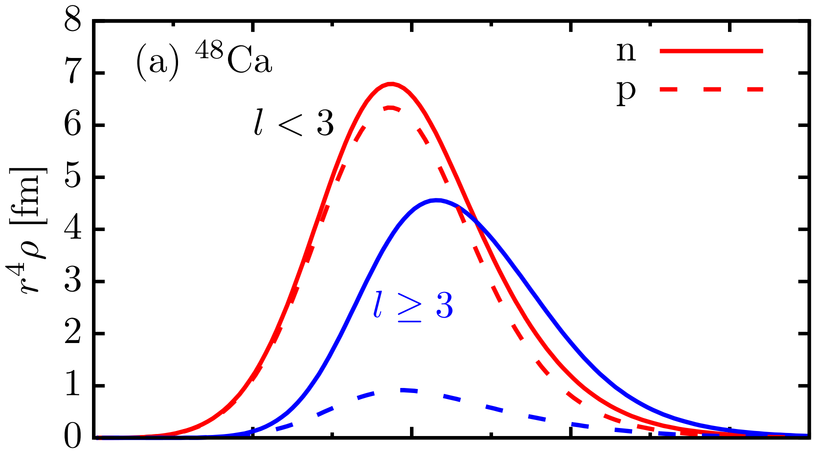
Arguments to support a large skin?

- Volume integrals for proton absorption in ^{40}Ca and ^{48}Ca



- Where would you put 8 mostly $f_{7/2}$ neutrons in ^{48}Ca

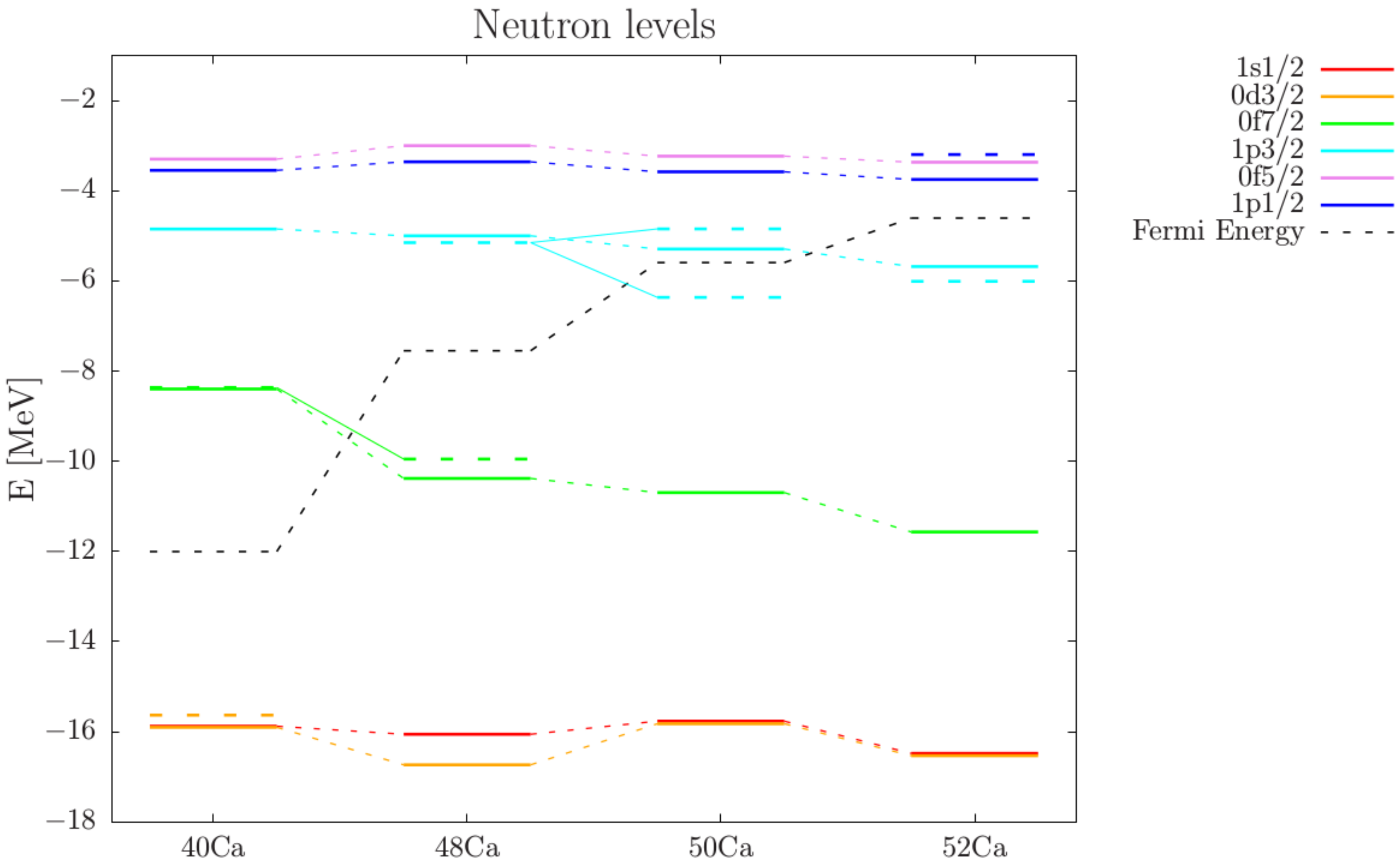




--> drip line

Extrapolation towards the drip line for nonlocal DOM

- Ca isotopes: for a correct description of neutron particle number a proper inclusion of pairing is required (Natalia Calleya)

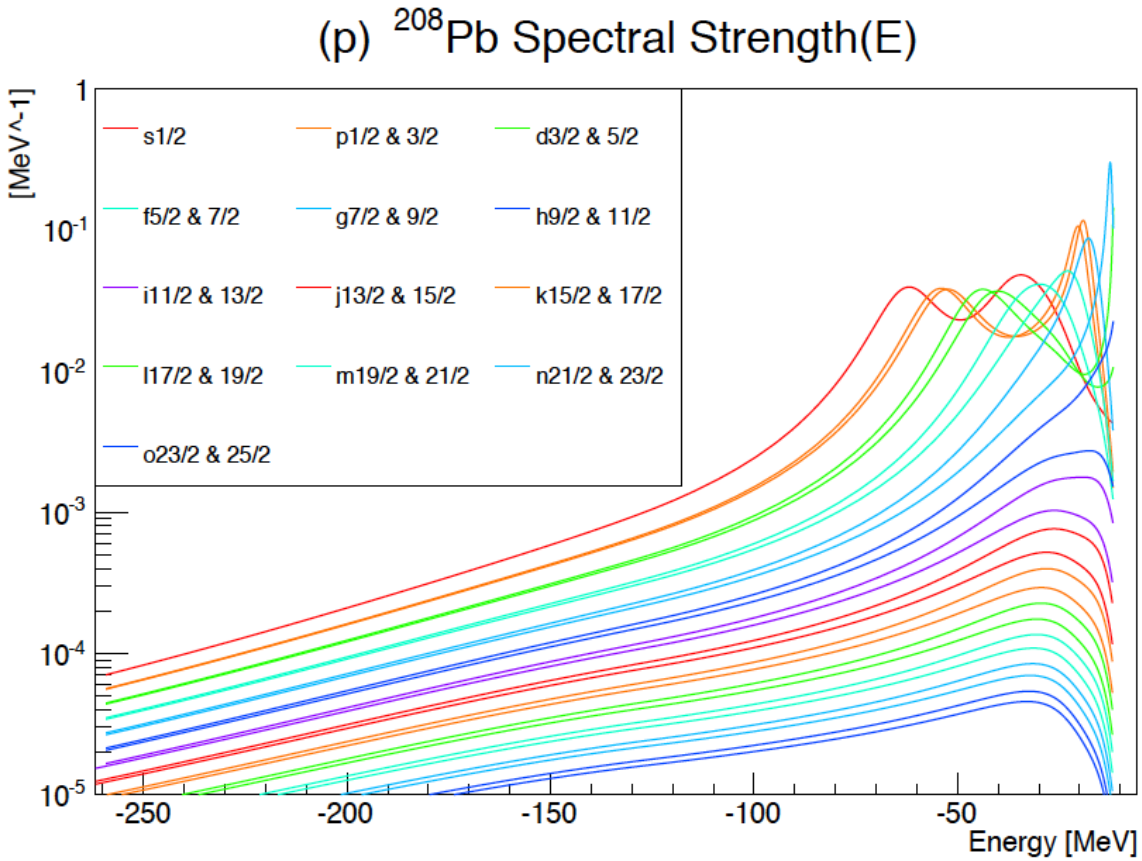


- Spectral function for ^{40}Ar can be generated

--> drip line

Neutron skin in ^{208}Pb under way (Michael Keim)

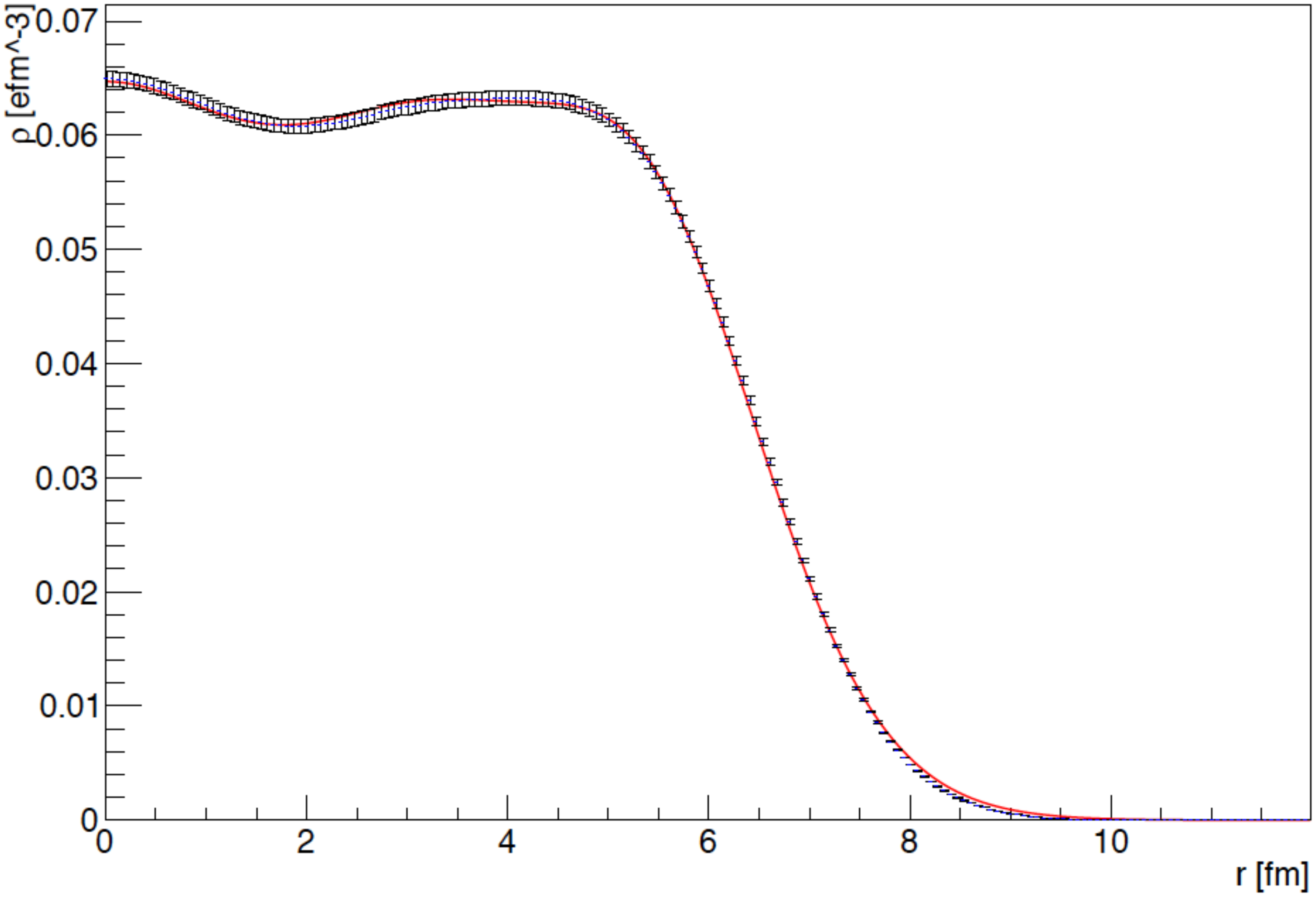
- Good inventory of elastic neutron scattering data including total cross sections
- Charge density well determined
- More angular momentum contributions for the ground state



--> drip line

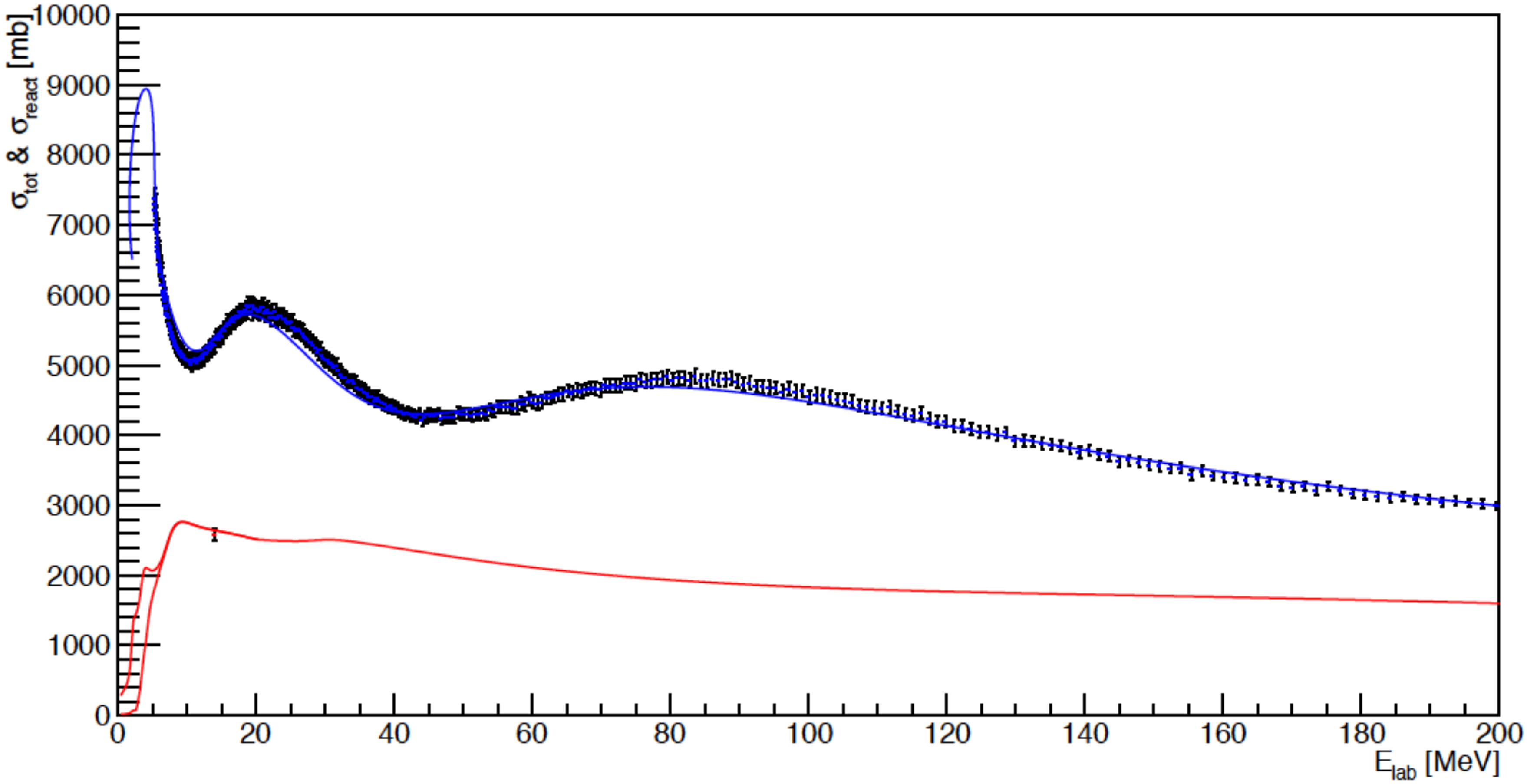
^{208}Pb Charge density

- Possible to get an excellent charge density

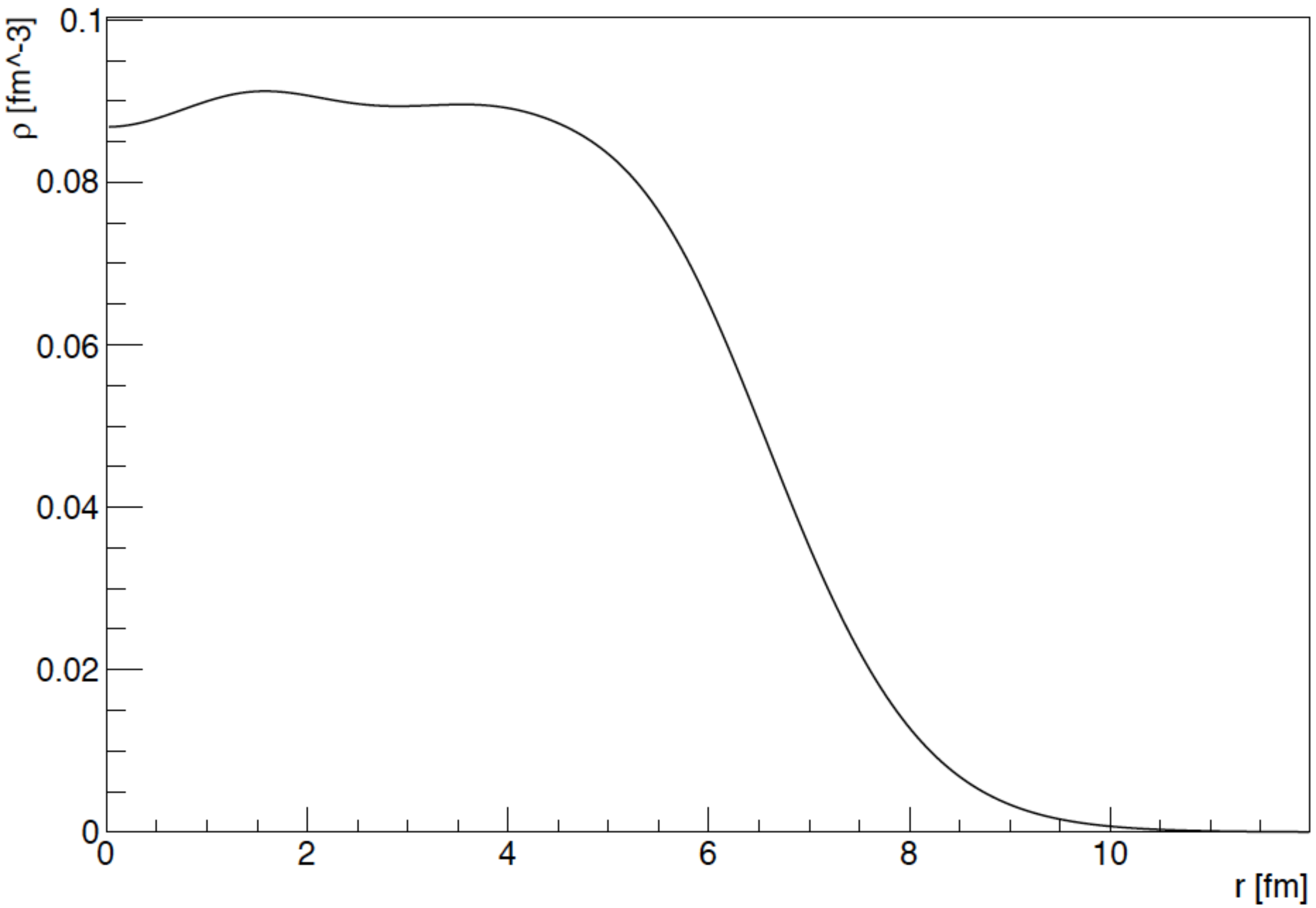


^{208}Pb (not finished)

- Total neutron cross section

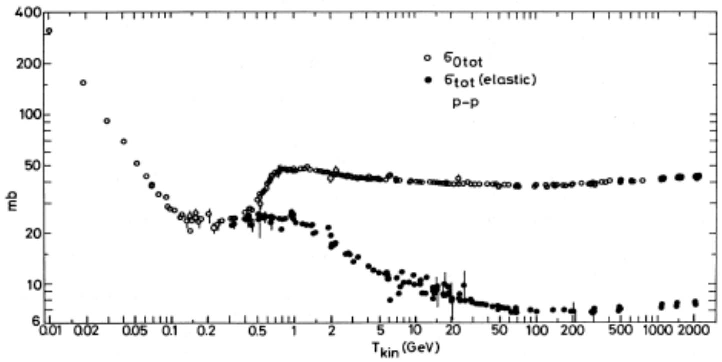


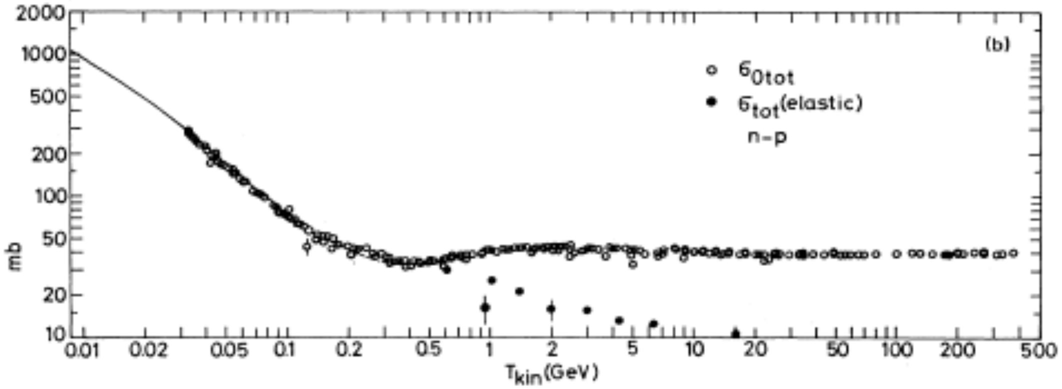
Preliminary neutron distribution



Some future plans

- Include higher energy data (proton elastic scattering) using a Dirac formulation (Dr. Chen Hefei University)





- (p,2p) and (p,pn) reactions
- extend DOM to deuteron
- Construct functional derivative of DOM self-energy —> excited states

- Improve functional form of self-energy (computationally expensive)

Ongoing work

- ^{208}Pb fit —> neutron skin prediction
- ^{48}Ca(e,e′p)
- ^{112}Sn and ^{124}Sn total neutron cross sections being analyzed
- ^{64}Ni measurement of total neutron cross section just completed
- Local then nonlocal fit to Sn, and Ni isotopes
- Integrate DOM ingredients with (d,p) - (n,γ) surrogate- and (p,d) codes
- Insert correlated Hartree-Fock contribution from realistic NN interactions in DOM self-energy—> tensor force included in mean field
- Extrapolations to the respective drip lines becoming available necessitating inclusion of pairing in the DOM
- Analyze energy density as a function of density and nucleon asymmetry
- **Ab initio optical potential calculations initiated using Green's function method**

reactions and structure

Conclusions

- It is possible to link nuclear reactions & nuclear structure (DOM)
- Can be used as input for analyzing nuclear reactions, predict properties of exotic nuclei, and is consistent with (e,e′p) data (~spectroscopic factors)
- Can describe ground-state properties
    - charge density & momentum distribution
    - spectral properties including high-momentum Jefferson Lab data
- Elastic scattering determines depletion of bound orbitals
- For N $\gtreqless$ Z sensitive to properties of neutrons —> weak charge prediction, **neutron skin**, perhaps more…
- Green's function method ideal to include SRC completely in matter for any interaction and asymmetry <—> Jefferson Lab data
- Link between saturation properties and nuclei more subtle