

# Short range correlation in nuclei:

Quarks and Nuclear Physics

× イメージを表示できません。メモリ不足のためにイメージを開くことができないか、イメージが破損している可能性があります。コンピューターを再起動して再度ファイルを開いてください。それでも赤いxが表示される場合は、イメージを削除して挿入してください。



× イメージを表示できません。メモリ不足のためにイメージを開くことができないか、イメージが破損している可能性があります。コンピューターを再起動して再度ファイルを開いてください。それでも赤いxが表示される場合は、イメージを削除して挿入してください。

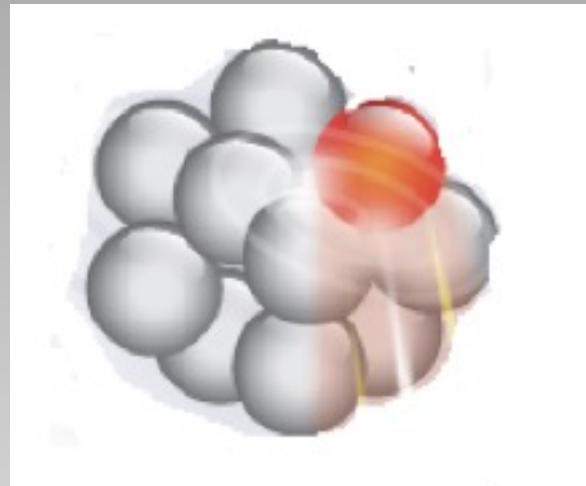
**Eli Piasetzky**  
**Tel Aviv University**

16 Nov. 2018, Tsukuba Japan



Free Neutron

$\tau \approx 15 \text{ min}$



Bound Neutron

$\tau = \infty$

Quark and gluon structure of hadrons:

- parton distribution functions, generalized parton distributions,
- transverse momentum distributions, high-energy hadron reactions, ...

**Thursday 15 November 2018**

Plenary - Hall 200 (09:00-10:30)

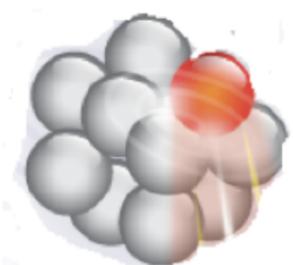
time [id]	title	presenter
09:00	[43] Hadron tomography by three-dimensional structure functions	PASQUINI, Barbara
09:30	[44] Nucleon-structure physics by lepton deep inelastic scattering	KUNNE, Fabienne
10:00	[45] Nucleon-structure physics by proton-proton collisions	LIU, Ming

Plenary - Hall 200 (11:00-12:00)

time [id]	title	presenter
11:00	[46] Nucleon structure from lattice QCD	QIU, Jianwei



Free Neutron  
 $\tau \approx 15$  min



Bound Neutron

$$\tau = \infty$$

**Is the partonic-structure of bound nucleons same as that of free nucleons ?**

**What is the connection between  
 Quarks and Nuclear Physics ?**

**Close  
 nucleons**

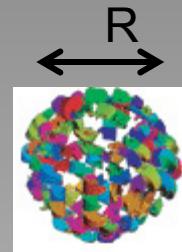


## Hard scattering :

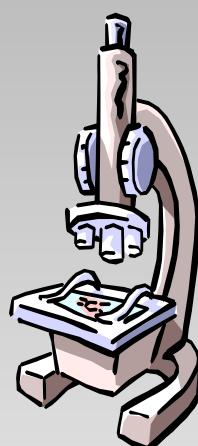
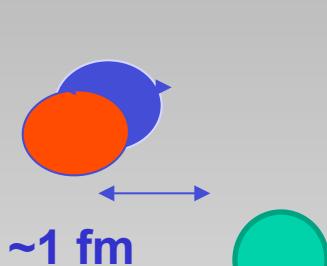
High-energy (small de Broglie wavelength  $\lambda$ )  
and large-momentum transfer  $q$ )

$$\lambda < R$$

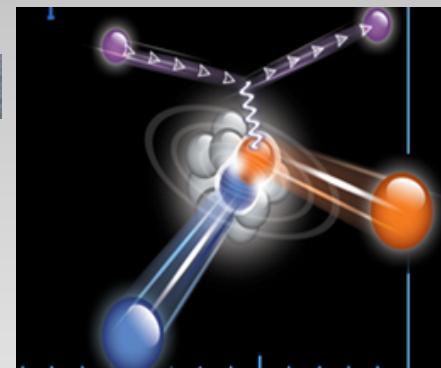
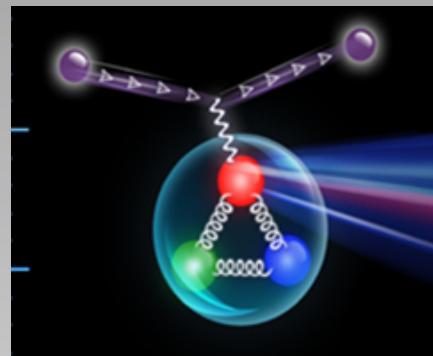
$$q \cdot R < 1$$



Hard scattering has the resolving power  
required to probe the internal (partonic)  
structure of a complex target



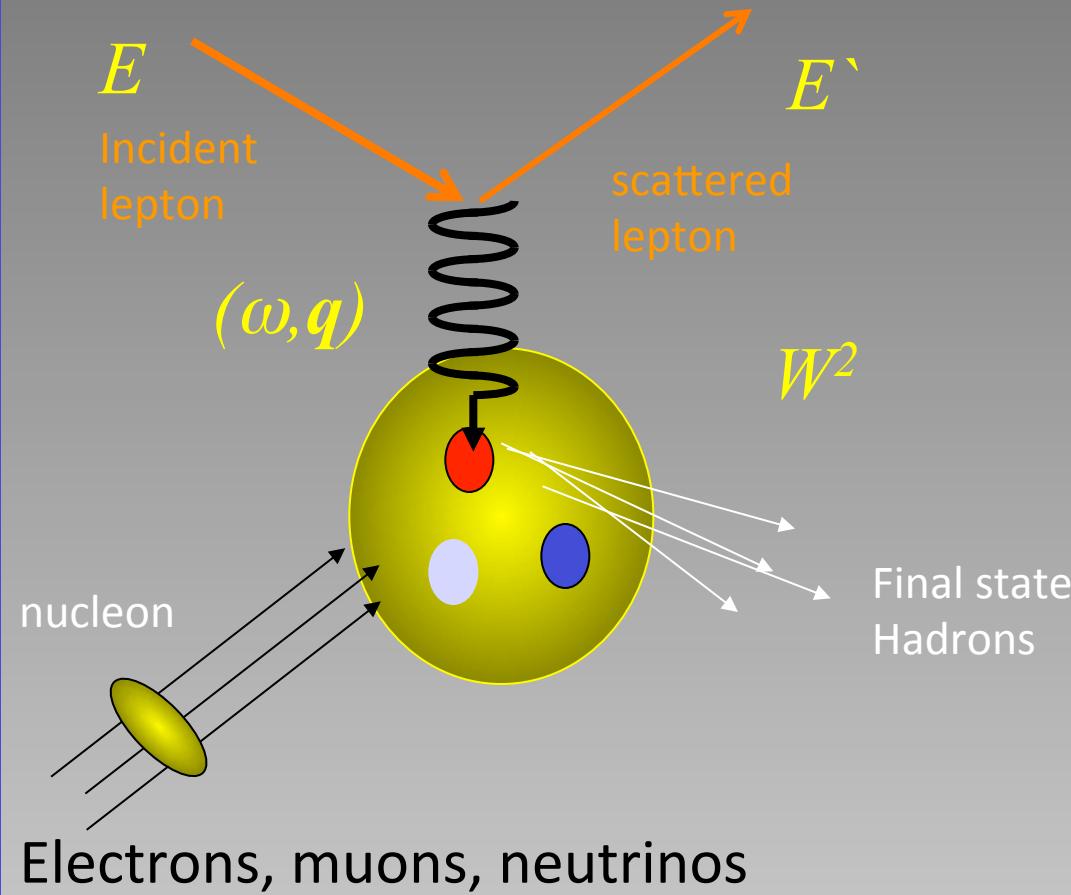
Quarks  
and  
Nuclear Physics



# Deep Inelastic Scattering (DIS)



TEL AVIV UNIVERSITY



Electrons, muons, neutrinos

SLAC, CERN, HERA, FNAL, JLAB

$E, E' 5\text{-}500 \text{ GeV}$

$Q^2 5\text{-}50 \text{ GeV}^2$

$w^2 > 4 \text{ GeV}^2$

$0 \leq x_B \leq 1$

$$Q^2 = -q_\mu q^\mu = q^2 - \omega^2$$
$$\omega = E' - E$$
$$x_B = \frac{Q^2}{2m\omega} \quad (= \frac{Q^2}{2(q \cdot p_T)})$$

$$0 \leq x_B \leq 1$$

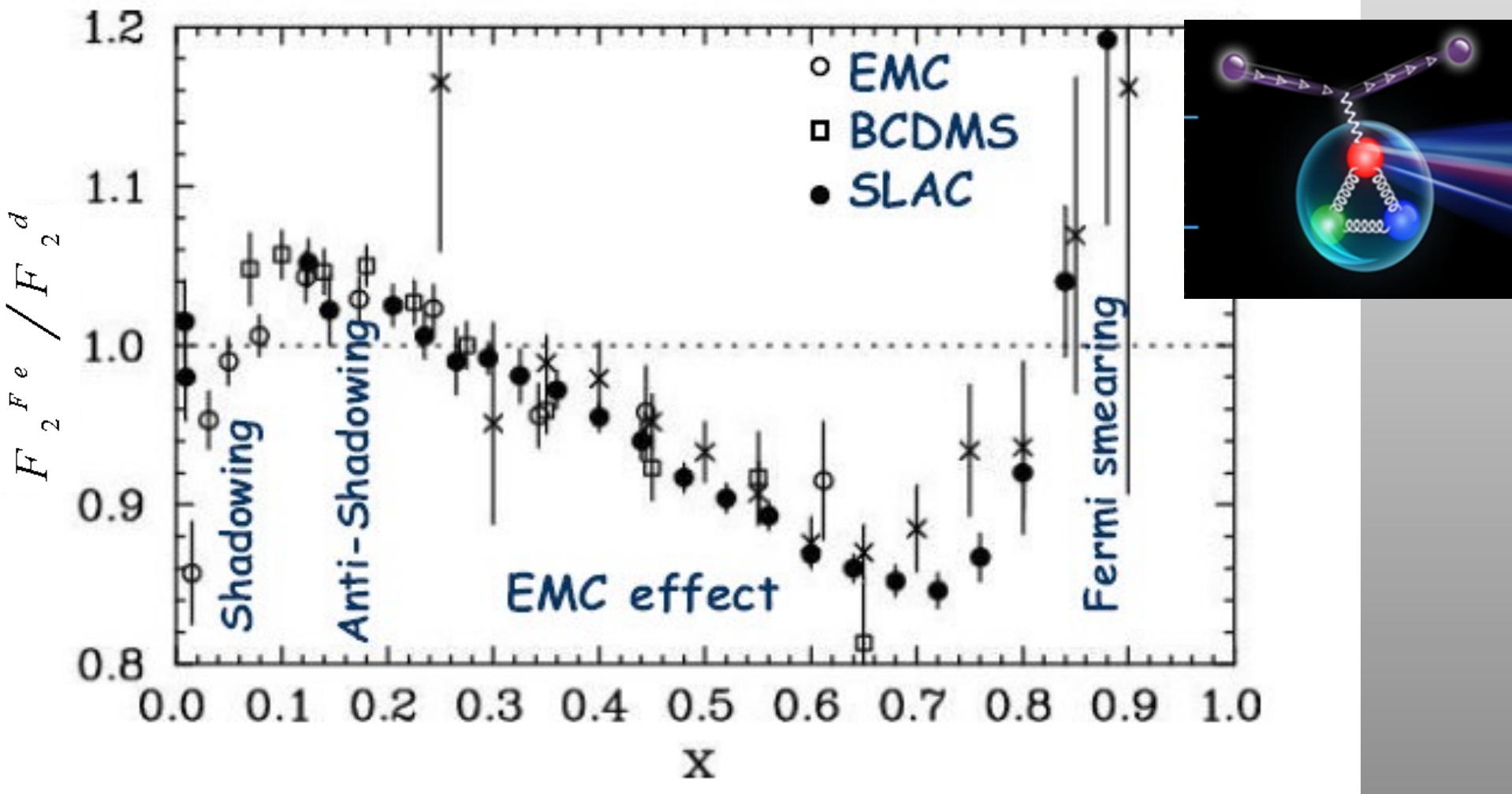
$x_B$  gives the fraction of nucleon momentum carried by the struck parton

Information about nucleon vertex is contained in  $F_1(x, Q^2)$  and  $F_2(x, Q^2)$ , the unpolarized structure functions

# The European Muon Collaboration (EMC) effect



TEL AVIV UNIVERSITY

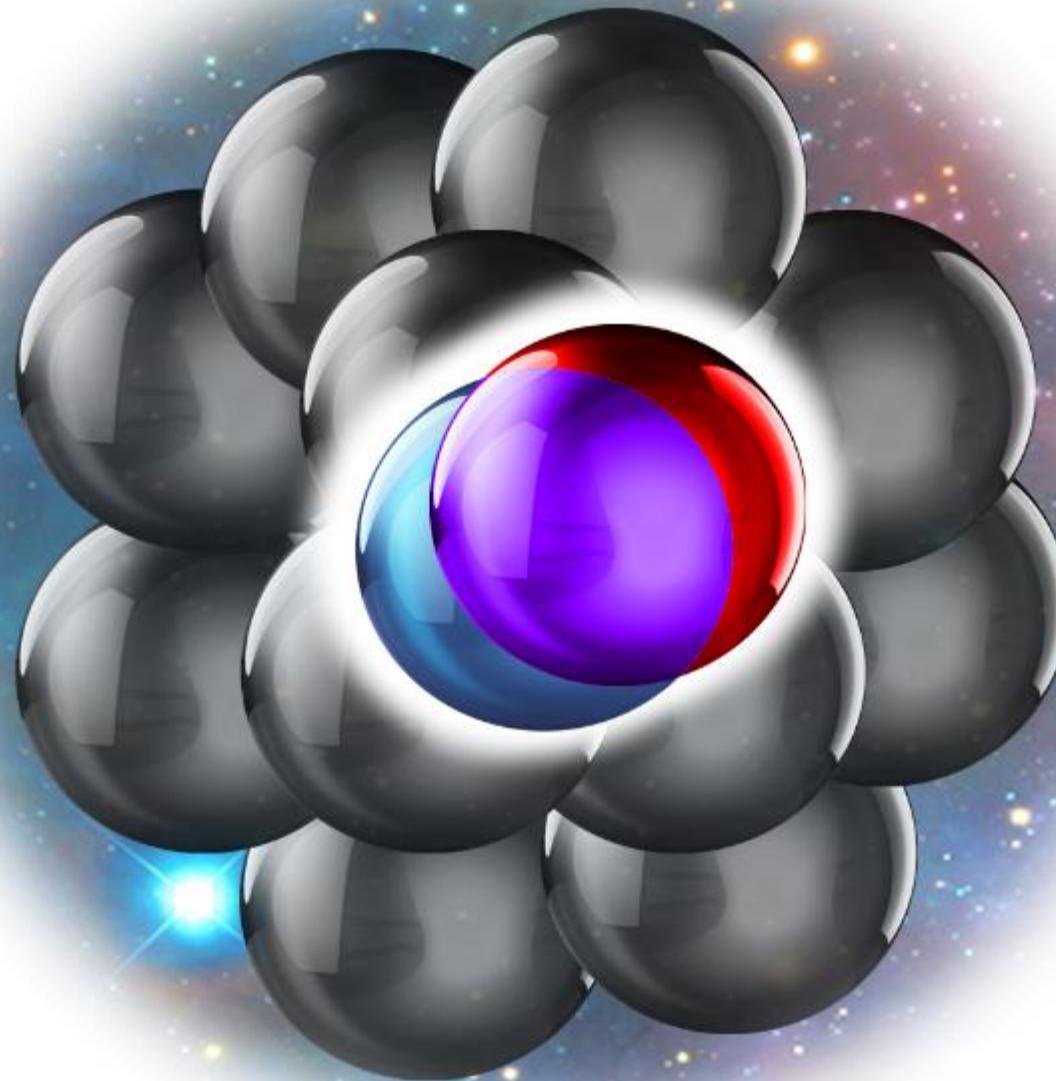


Aubert et al., PLB (1983)  
PLB (1990); Gomez et al.  $F_2^A \neq Z \cdot F_2^p + N \cdot F_2^n$  neodo et al., PLB (1988); Allasia et al., (2009); Schmookler et al., Submitted (2018)

After 30 years no consensus on cause  
Close nucleons



# Short-Range Correlations (SRC)



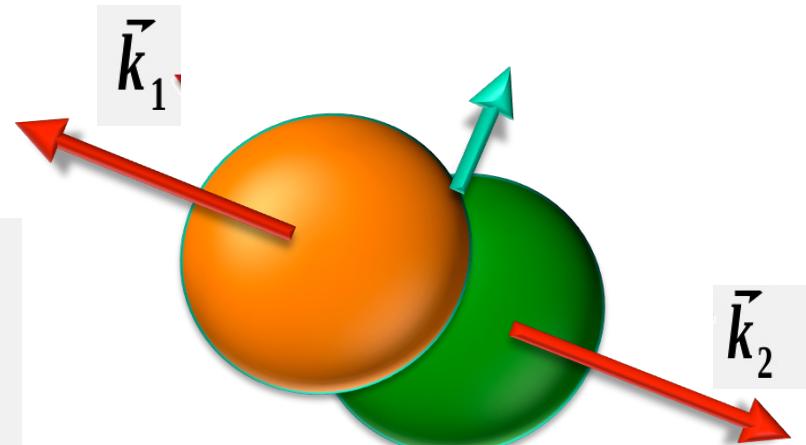
# What Do I Mean by SRCs?

Nucleon pairs that are close together in the nucleus

Momentum space: *high relative* and *low c.m. momentum*, compared to the Fermi momentum ( $k_F$ )

$$k_1 > k_F \quad k_2 > k_F \quad k_1 \approx k_2$$

$$k_F \approx 250 \text{ MeV/c}$$

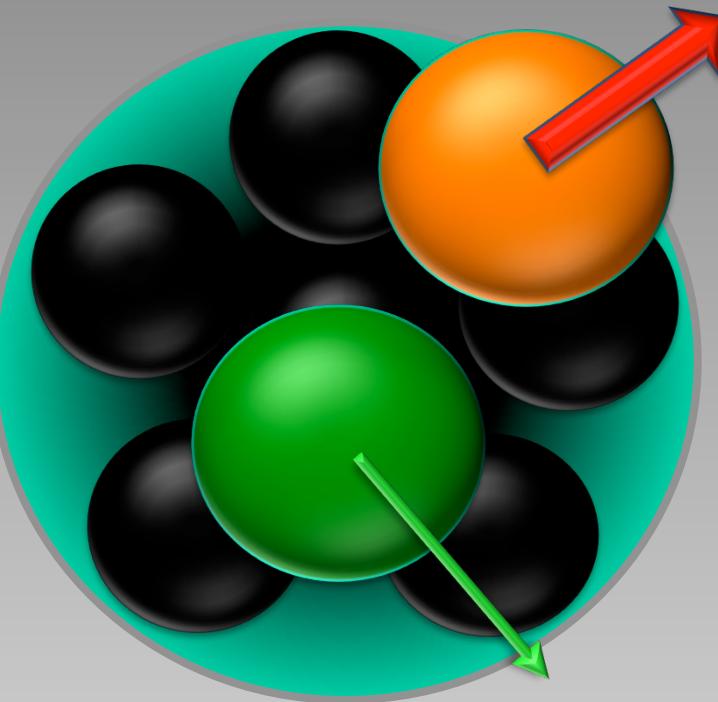


# Exclusive triple – coincidence measurements



**Quasi-Free scattering off a nucleon in a  
short range correlated pair**

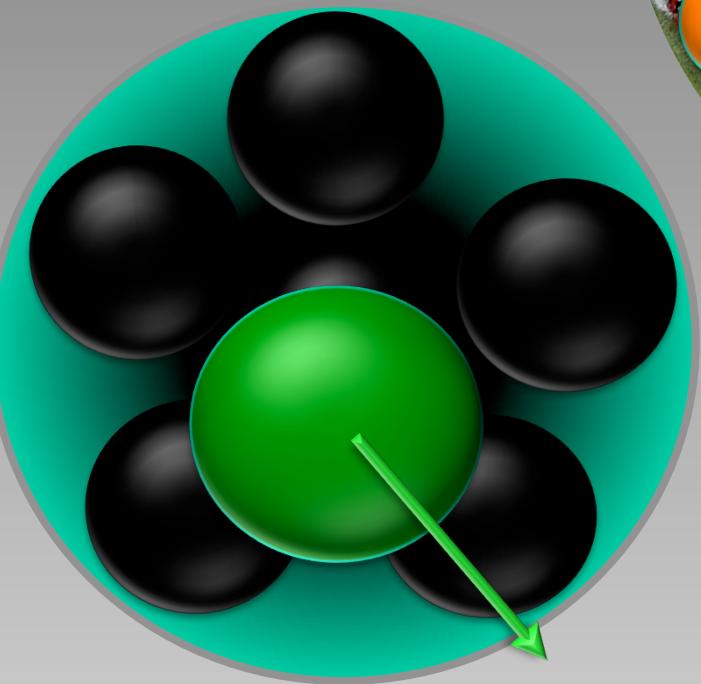
# triple – coincidence measurements



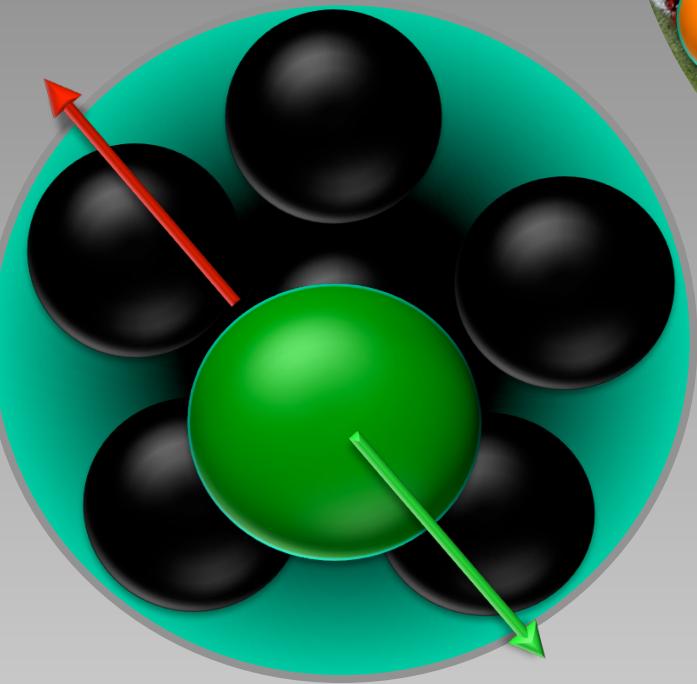
# triple – coincidence measurements



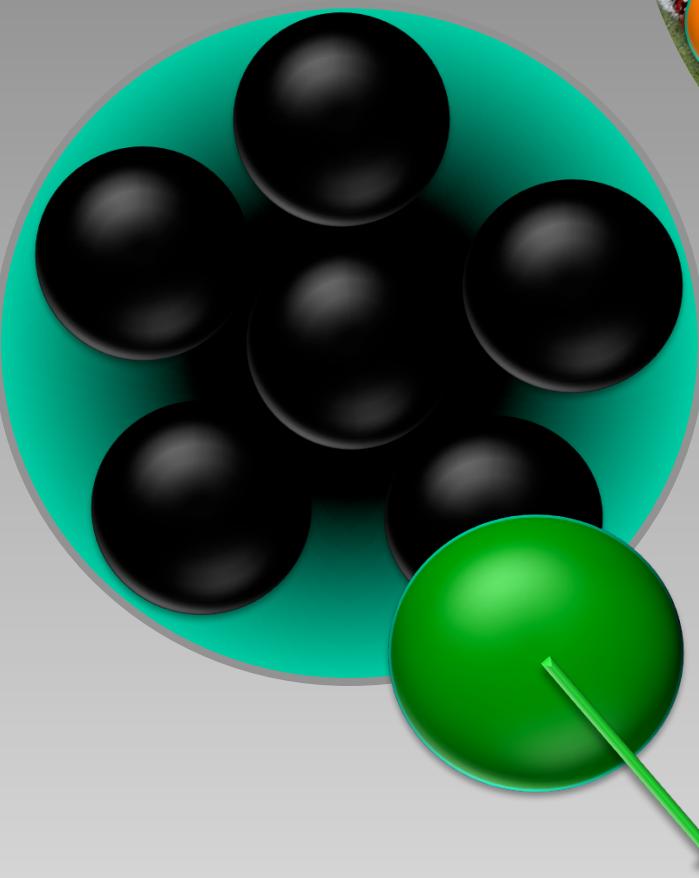
TEL AVIV UNIVERSITY



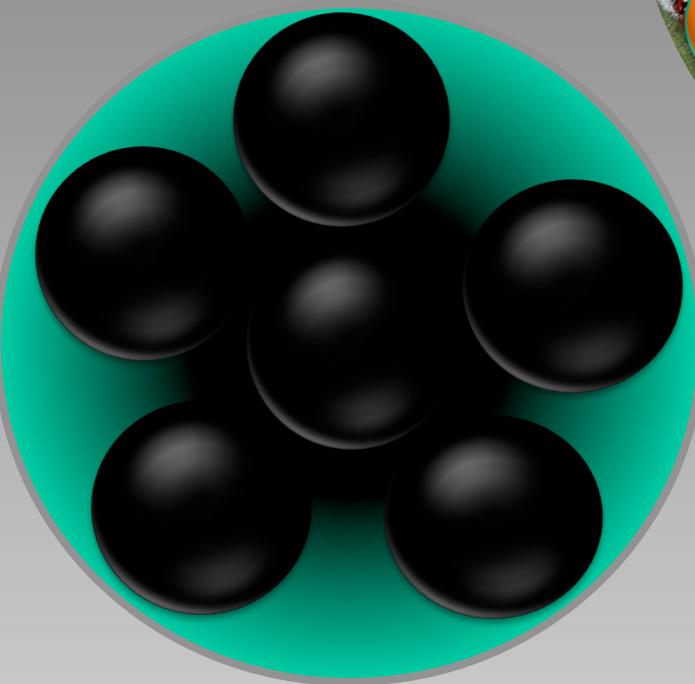
# triple – coincidence measurements



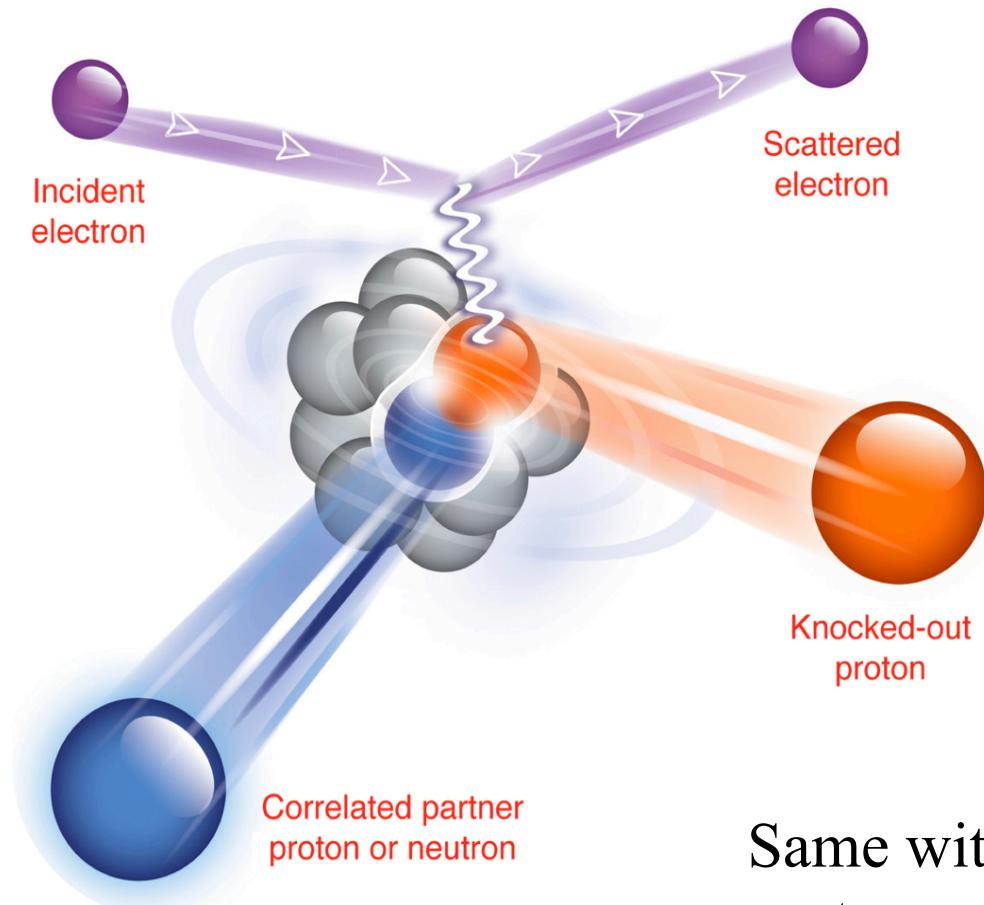
# triple – coincidence measurements



# triple – coincidence measurements



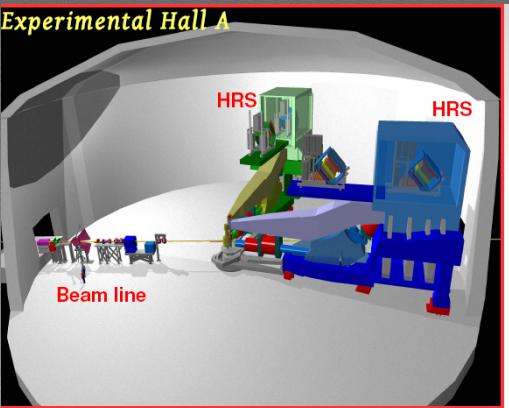
# Probing Correlations Using Hard Knockout Reactions



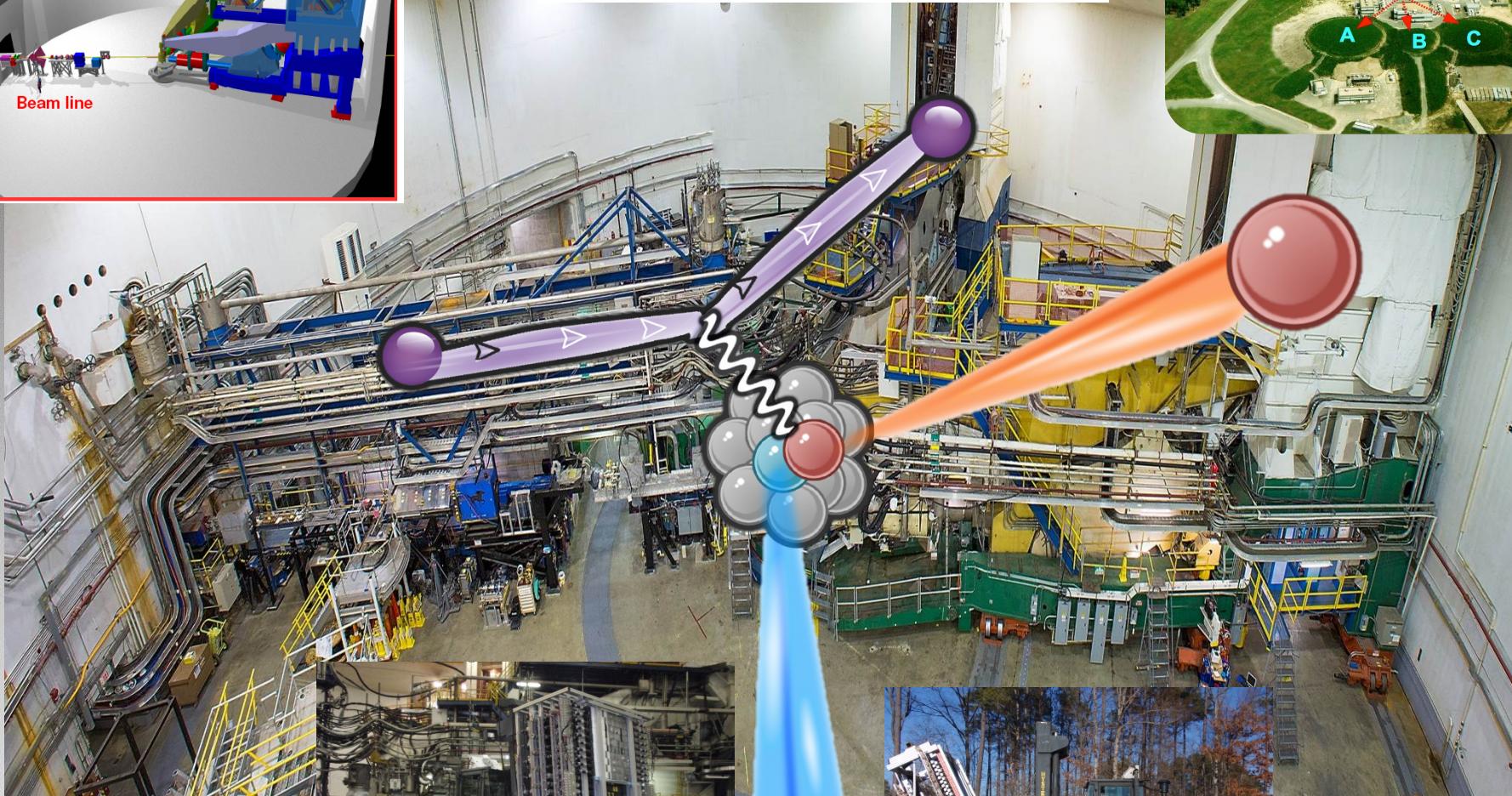
Same with high energy protons

# Exclusive SRC studies

Experimental Hall A



## Jefferson Lab Hall A



Neutron  
Detector

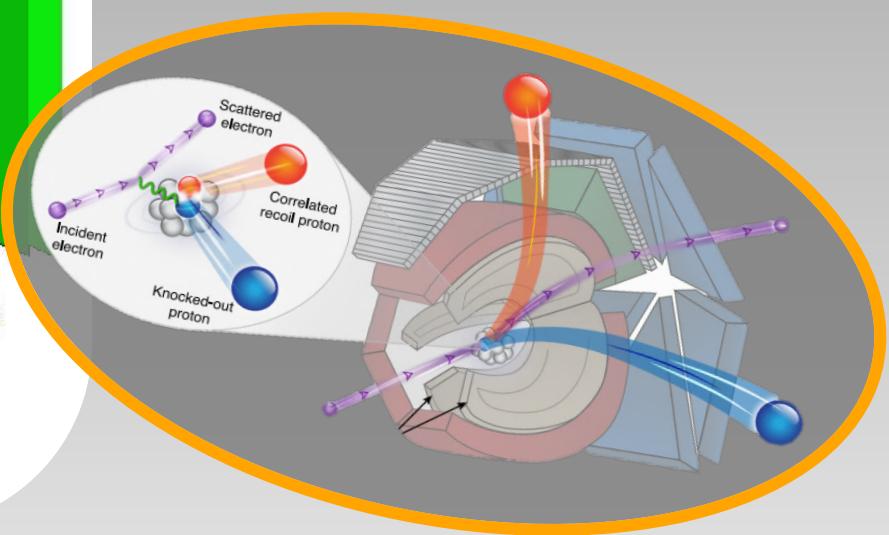
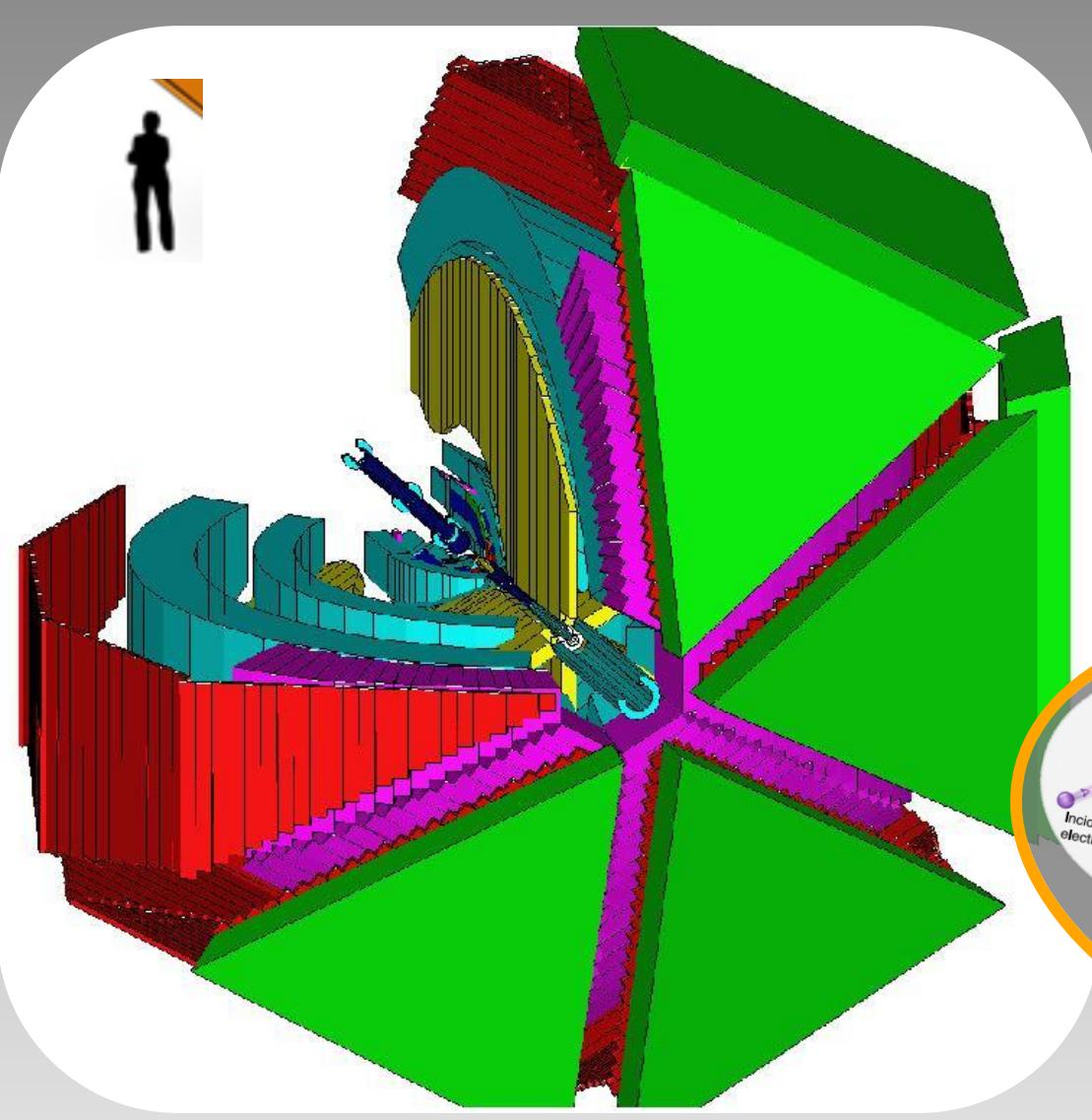


BigBite Spectrometer

# CEBAF Large Acceptance Spectrometer [CLAS]

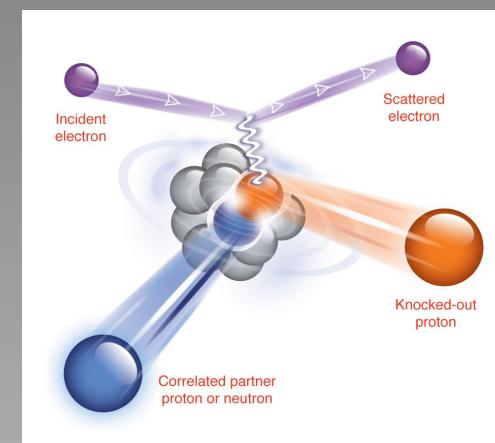
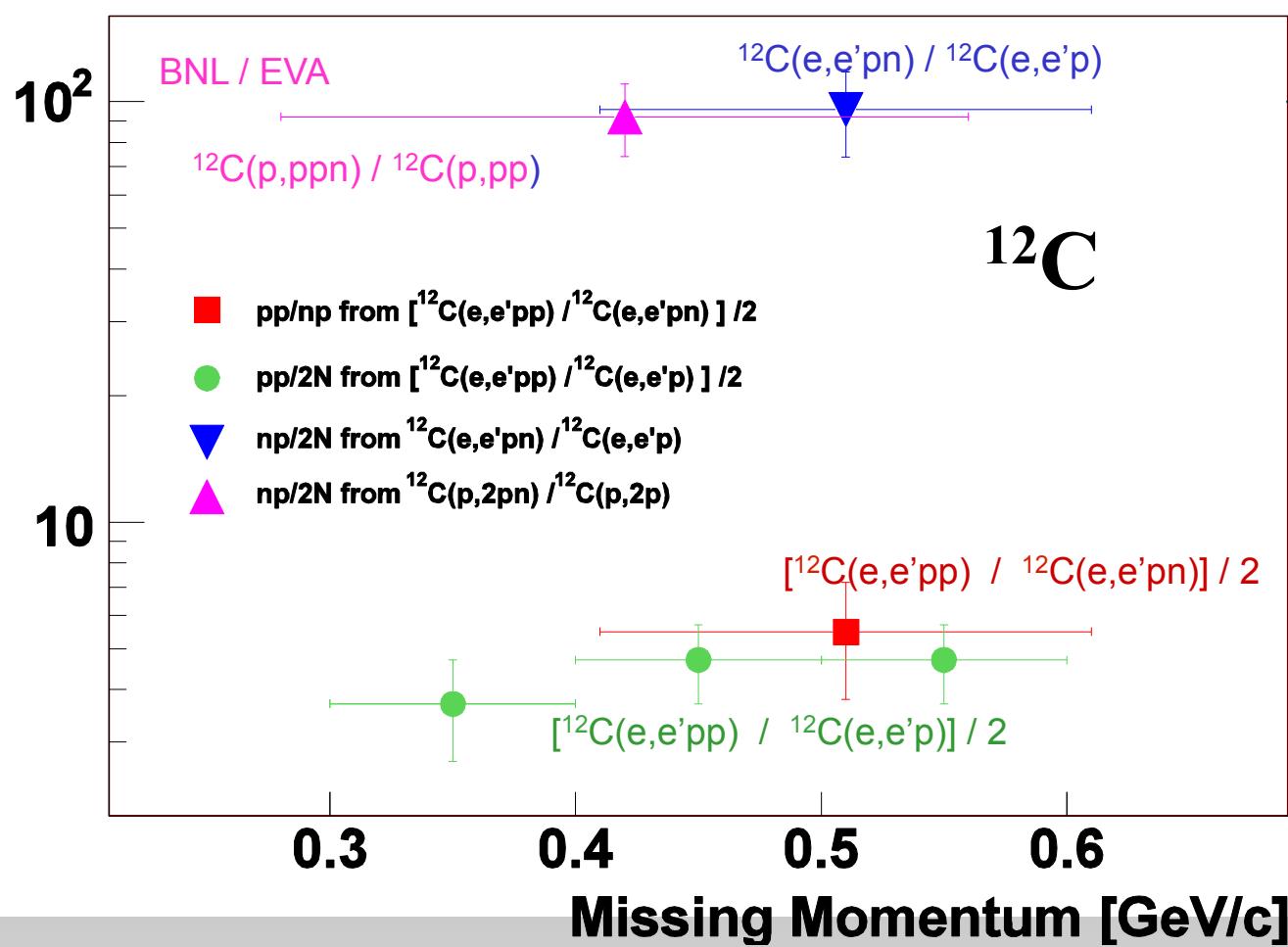


TEL AVIV UNIVERSITY



Open ( $e, e'$ ) trigger, Large-Acceptance, Low luminosity ( $\sim 10^{34} \text{ cm}^{-2}$ )

SRC Pair Fraction (%)

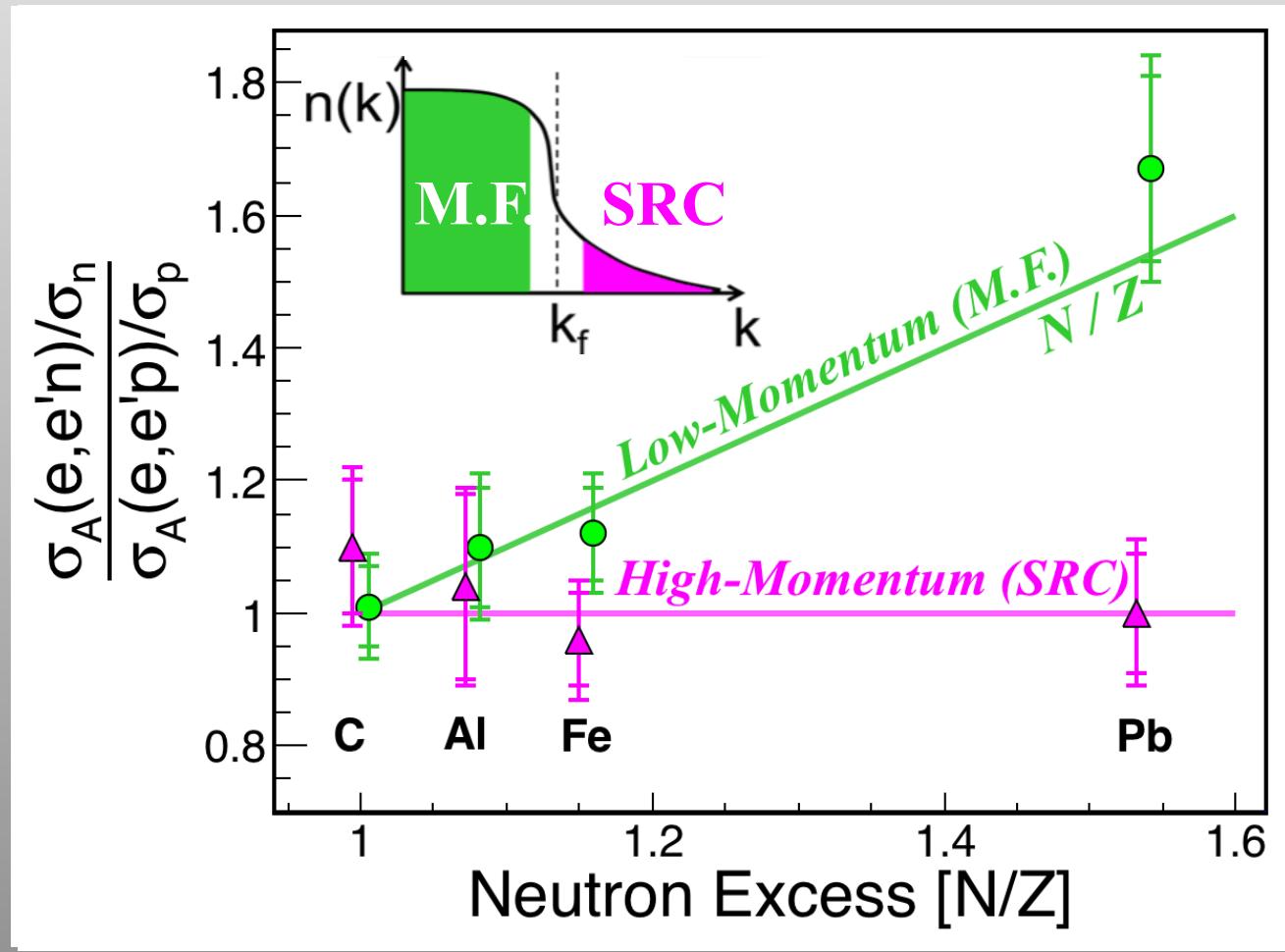


The high momentum tail in nuclei is dominated by SRC pairs

Most of the SRC pairs (90%) are np only 5% pp and 5% nn

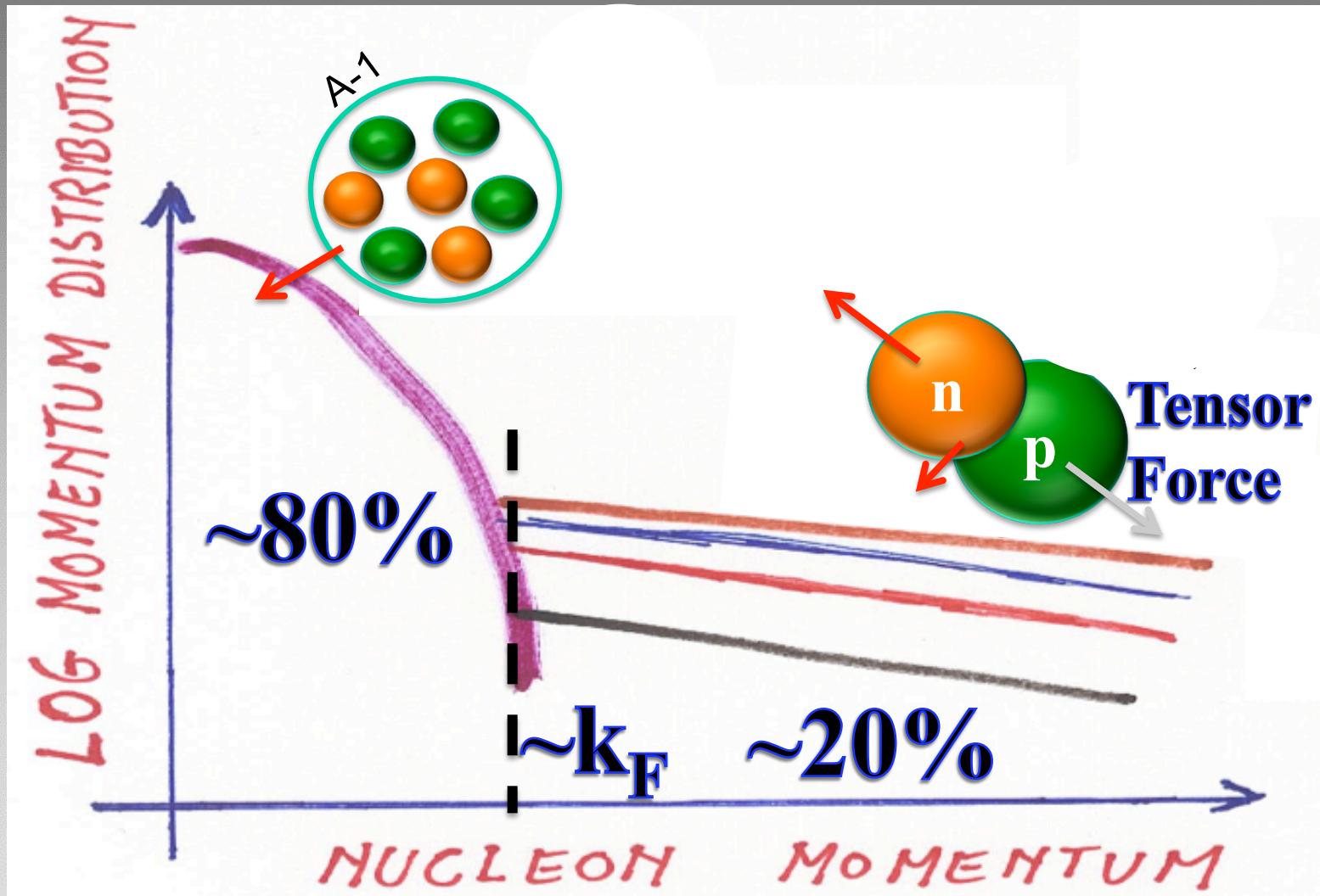
# Asymmetric nuclei

$A(e, e' p)$   $A(e, e' n)$

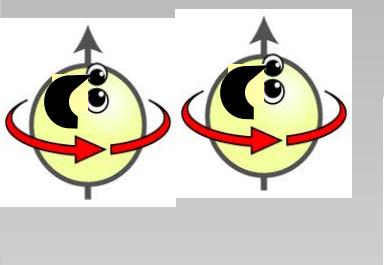
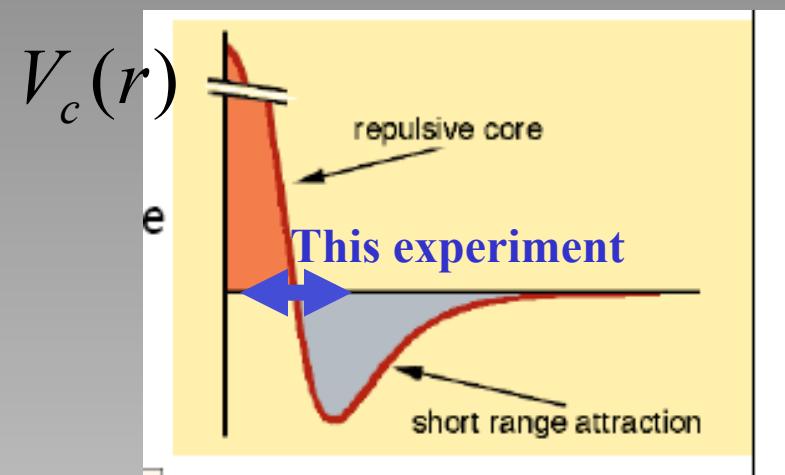
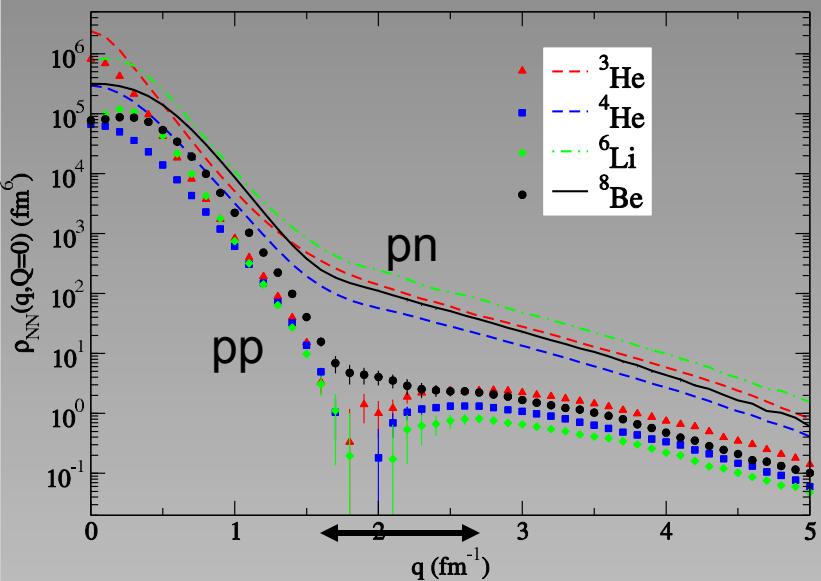


► Same # of high-momentum protons and neutrons

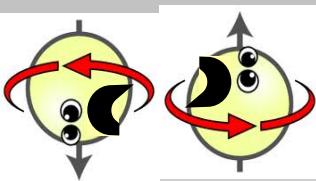
# Nucleons has Isophobia (np – dominance)



At 300-600 MeV/c there is an excess strength in the np momentum distribution due to the strong correlations induced by the tensor NN potential.



pp- nn- np- SRC



$$V_{NN}(r) = V_c(r) + V_T(r)S_{12}$$

$$S_{12} = 3(\boldsymbol{\sigma}_1 \cdot \hat{\boldsymbol{r}})(\boldsymbol{\sigma}_2 \cdot \hat{\boldsymbol{r}}) - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$$

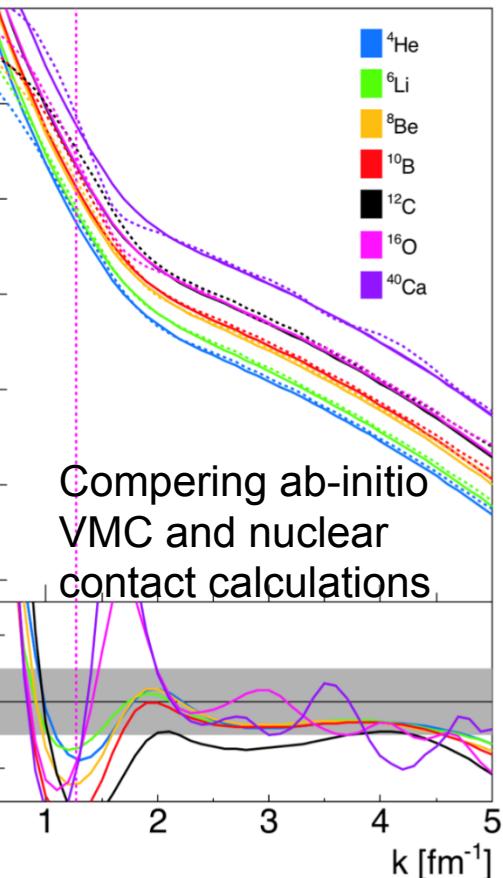
# Generalized Nuclear Contact Formalism



TEL AVIV UNIVERSITY

a factorized ansatz

Momentum Distribution



Residual

$$\Psi \xrightarrow{r_{ij} \rightarrow 0} \sum_{\alpha} \varphi_{\alpha}(\mathbf{r}_{ij}) A_{ij}^{\alpha}(\mathbf{R}_{ij}, \{\mathbf{r}\}_{k \neq ij})$$

- Universal function: the zero energy solution to the 2 body problem
- Nucleus ( $A-2$ ) specific function

The nuclear contacts and short range correlations in nuclei

R. Weiss,<sup>1</sup> R. Cruz-Torres,<sup>2</sup> N. Barnea,<sup>1</sup> E. Piasetzky,<sup>3</sup> and O. Hen<sup>2</sup>

Phys. Lett. B780 (2018) 211.

A universal description of SRC:

$$n_p(k) \xrightarrow{k \rightarrow \infty} C_{pn}^d |\varphi_{pn}^d(k)|^2 + C_{pn}^0 |\varphi_{pn}^0(k)|^2 + 2C_{pp}^0 |\varphi_{pp}^0(k)|^2$$

$l = 0, 2$   $s = 1$   $j = 1$   
np pairs

$l = s = j = 0$   
pp, nn, np pairs

# Generalized Nuclear Contact Formalism

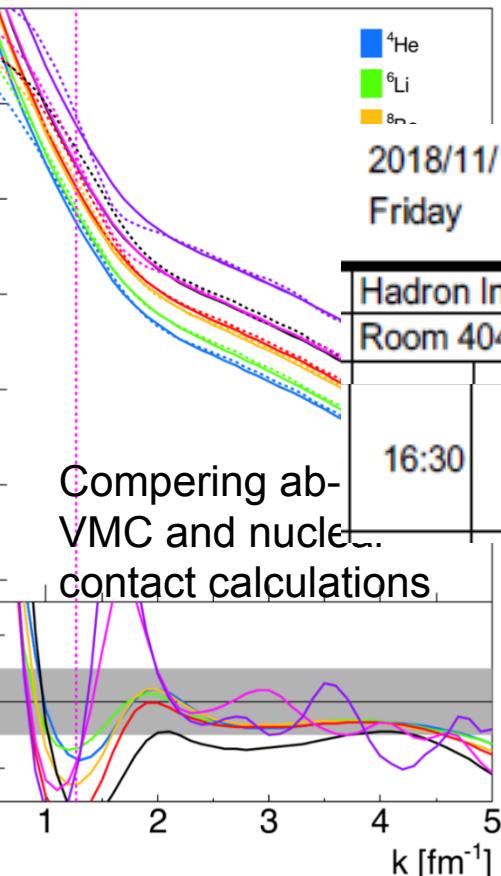


TEL AVIV UNIVERSITY

a factorized ansatz

$$\Psi \xrightarrow{r_{ij} \rightarrow 0} \sum_{\alpha} \varphi_{\alpha}(\mathbf{r}_{ij}) A_{ij}^{\alpha}(\mathbf{R}_{ij}, \{\mathbf{r}\}_{k \neq ij})$$

Momentum Distribution



Universal function: the zero energy solution to the 2-body Nucleus (A-2) specific function

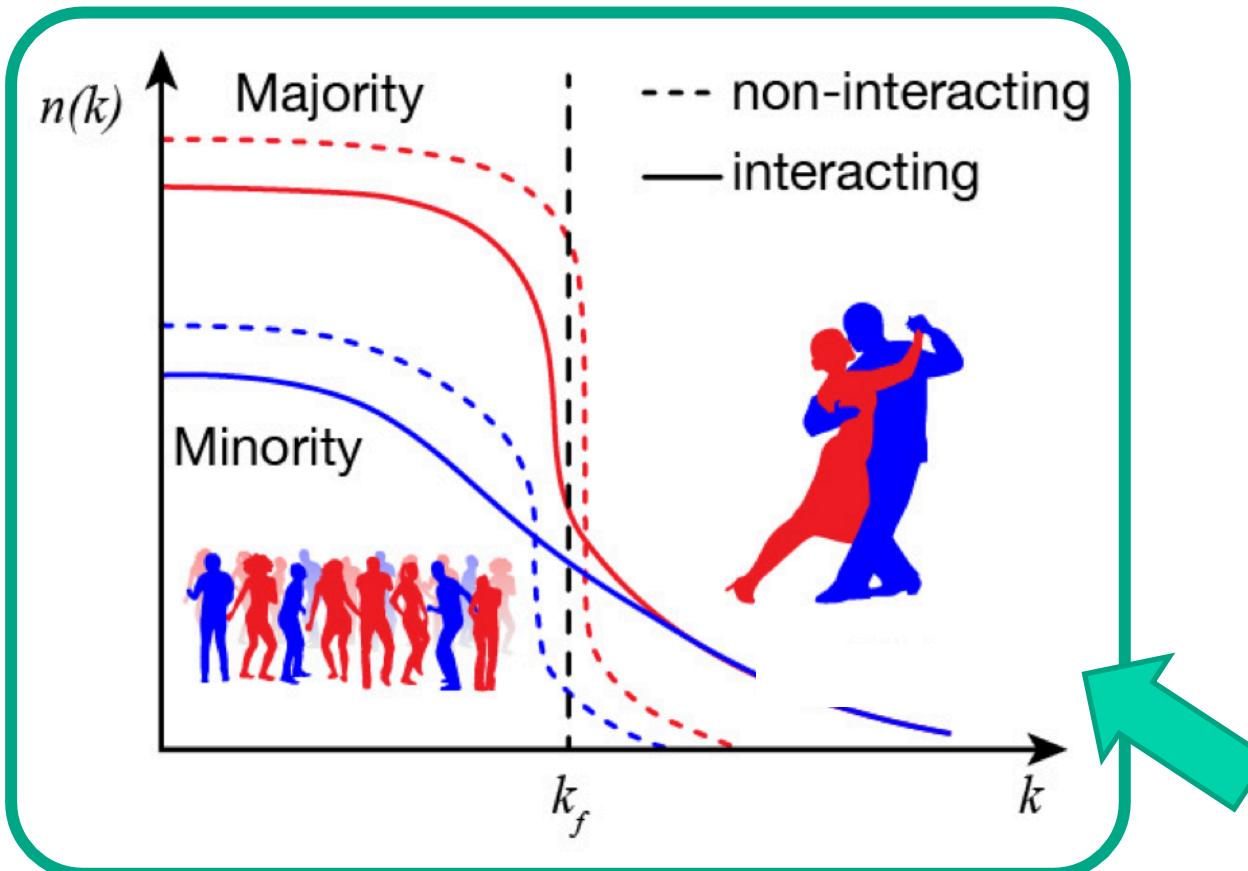
A universal description of SRC:

$$n_p(k) \xrightarrow{k \rightarrow \infty} C_{pn}^d |\varphi_{pn}^d(k)|^2 + C_{pn}^0 |\varphi_{pn}^0(k)|^2 + 2 C_{pp}^0 |\varphi_{pp}^0(k)|^2$$

$l = 0, 2$   $s = 1$   $j = 1$   
np pairs

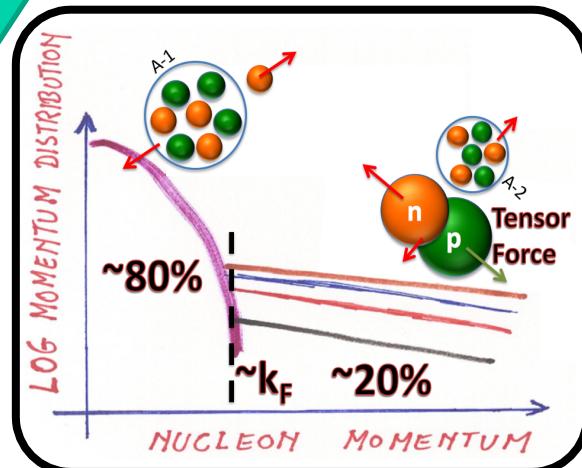
$l = s = j = 0$   
pp, nn, np pairs

# np- dominance and Asymmetric Nuclei



For nuclei with  $N > Z$ :

Protons have a greater probability than neutrons to be above the Fermi sea.

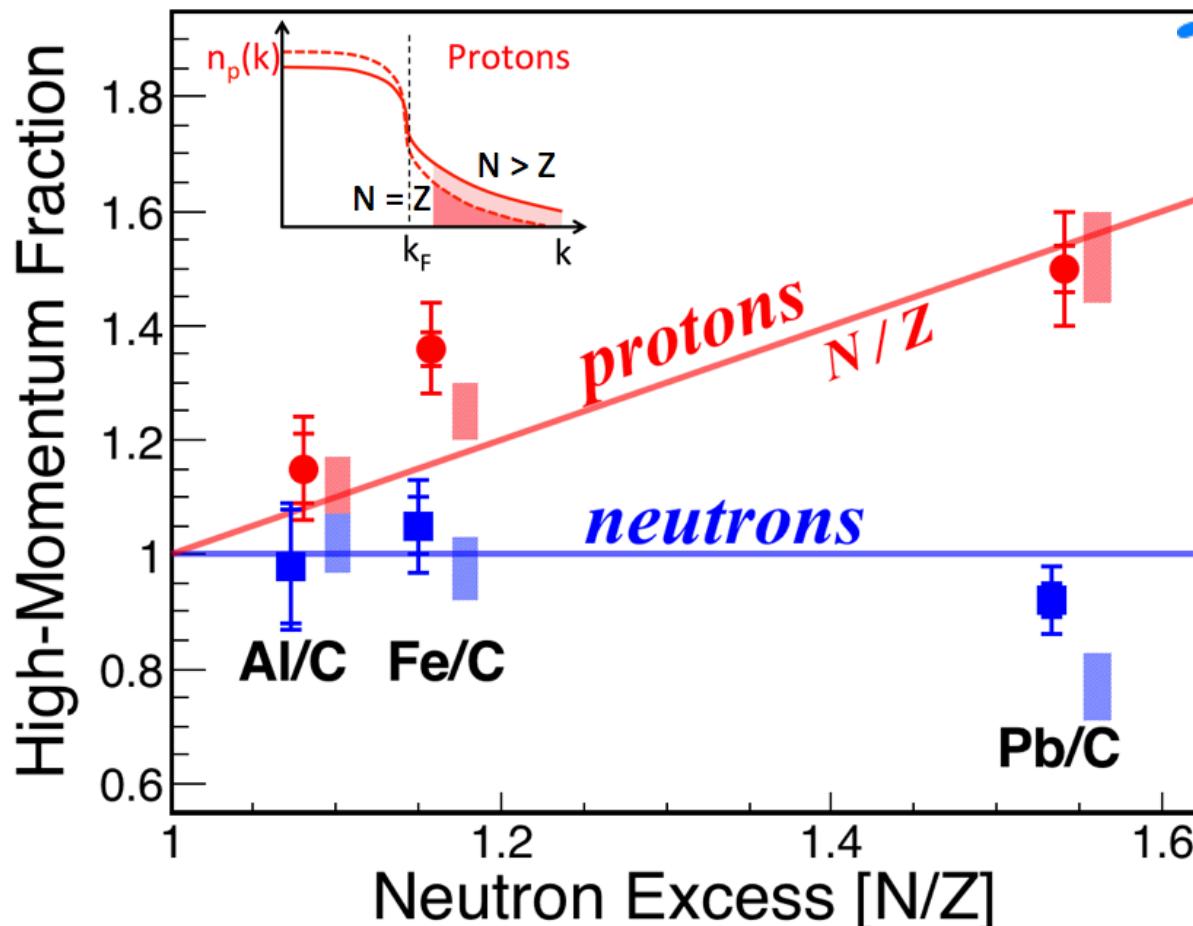
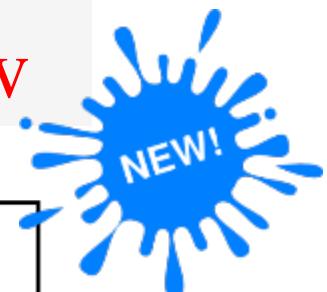


# What do the outer shell neutrons do ?

Do they produce SRC pairs  
with the inner shells protons ?



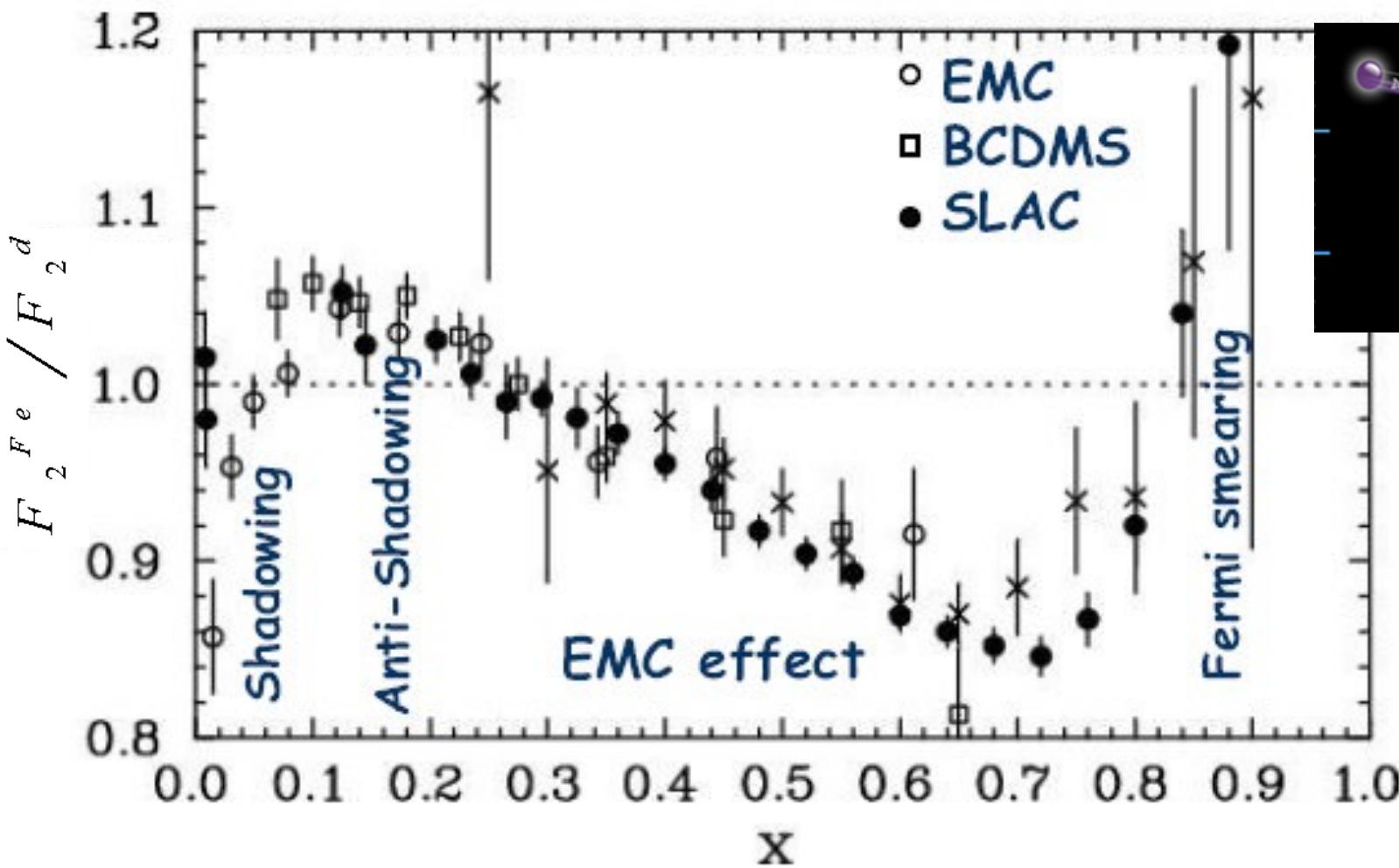
# Correlation Probability: Neutrons saturate Protons grow



# The European Muon Collaboration (EMC) effect



TEL AVIV UNIVERSITY



$$F_2^A \neq Z \cdot F_2^p + N \cdot F_2^n$$

After 30 years no consensus on cause of EMC effect

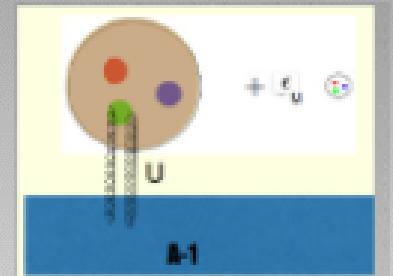
# Theory: ~1000 papers, 3 ideas

## 1. Proper treatment of “traditional” nuclear effect

Nuclear Binding, Fermi motion, Pions, Coulomb field...

DIS, DY

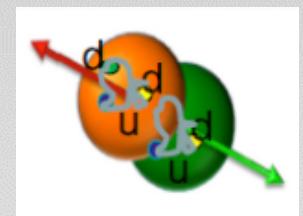
## 2. In the nuclear field, nucleons are different from free.

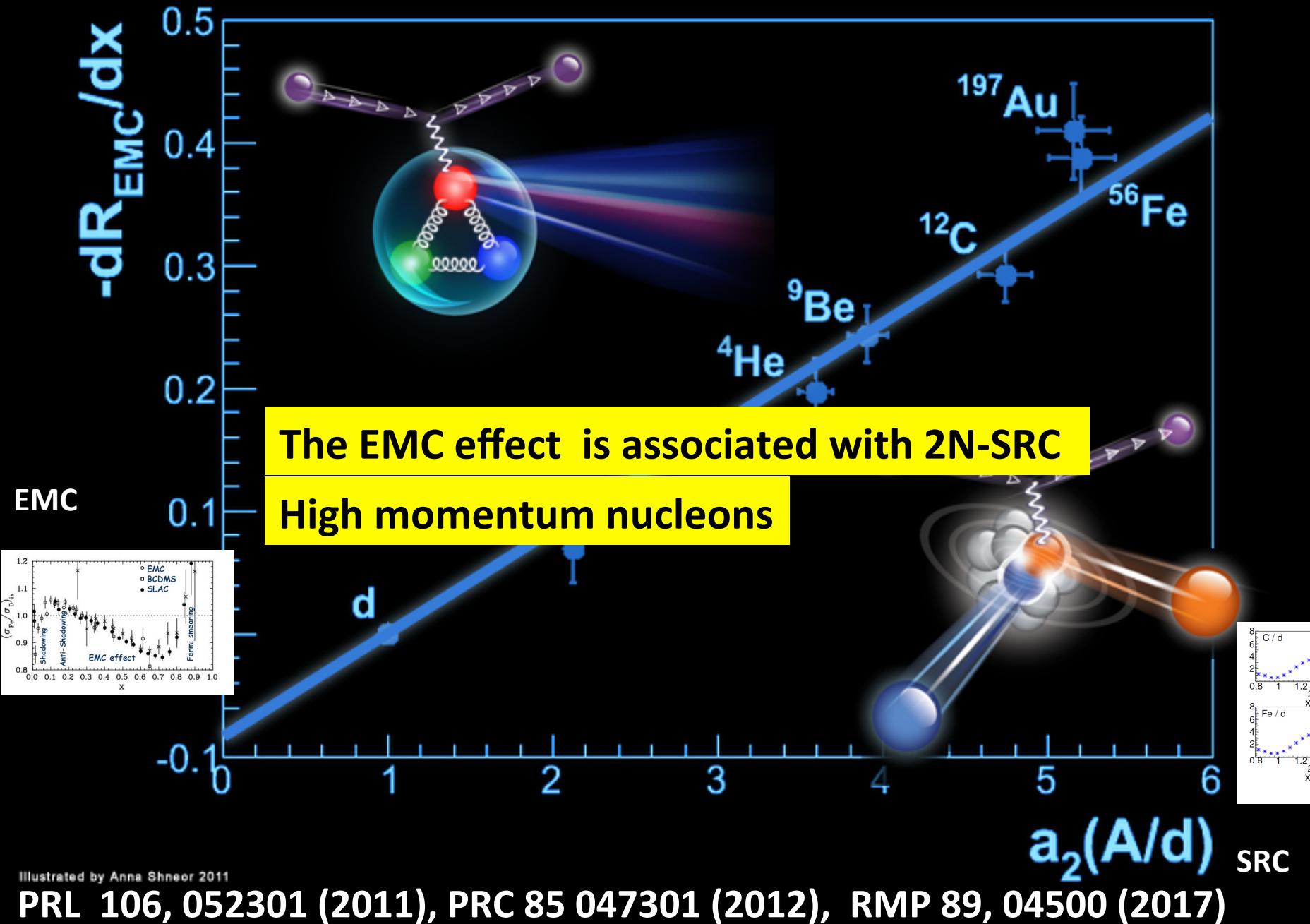


## 3. Nucleons are normally normal except when they are close to another nucleon (2N-SRC), nucleons are different from free.

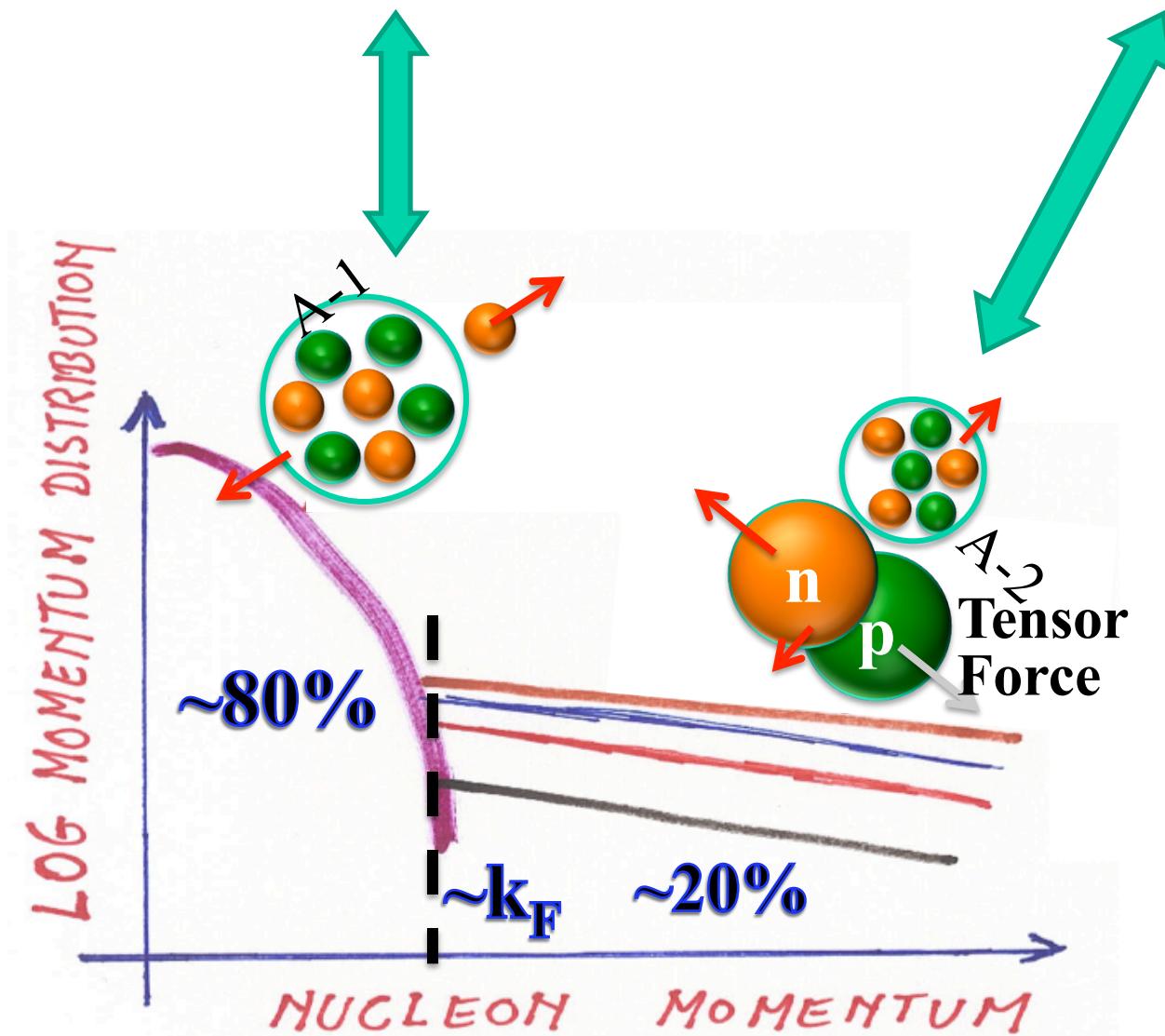
Color fluctuations in nucleons and the EMC effect

STRIKMAN, Mark





**Bound** = ‘quasi Free’ + Modified SRCs





## EMC effect is isospin dependent

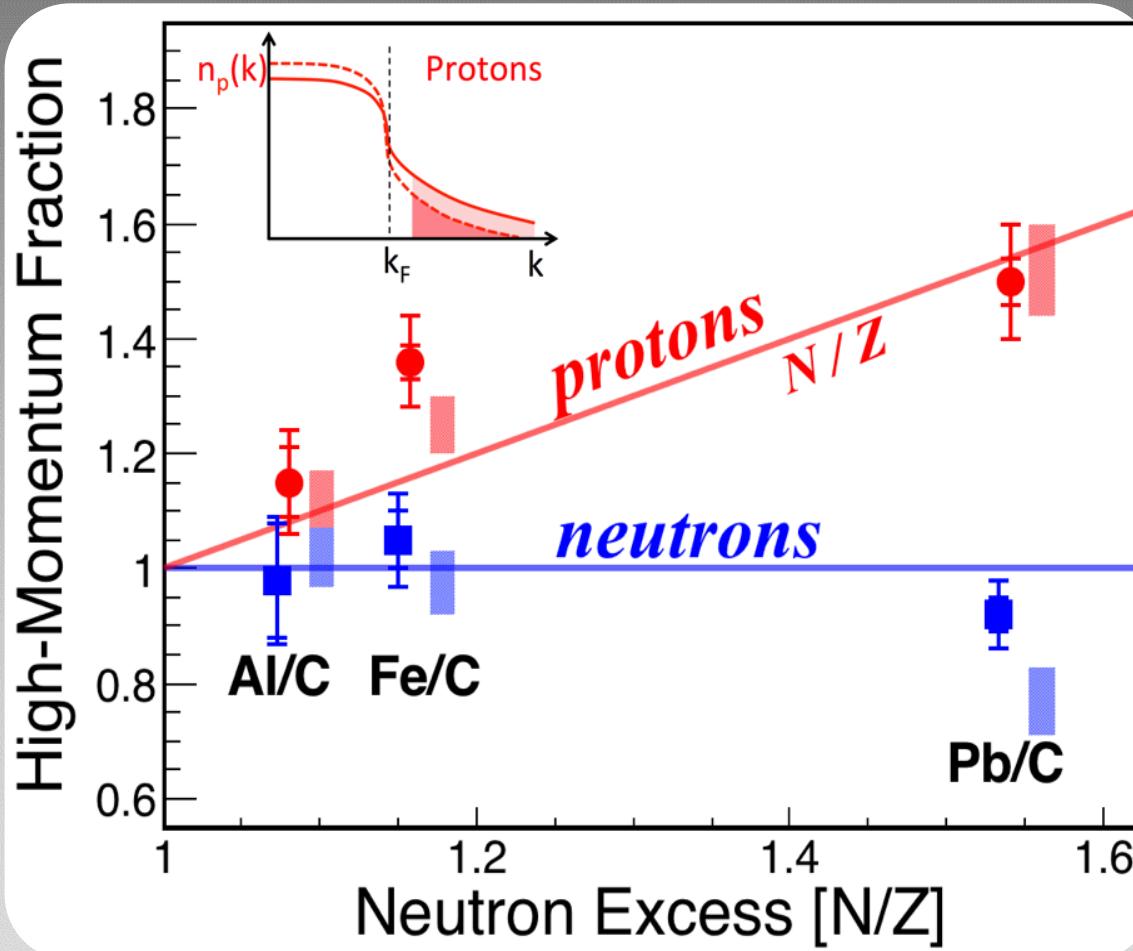
A larger fraction of the **Proton** than **neutron**  
will be modify in nuclei.

## Prediction 2:

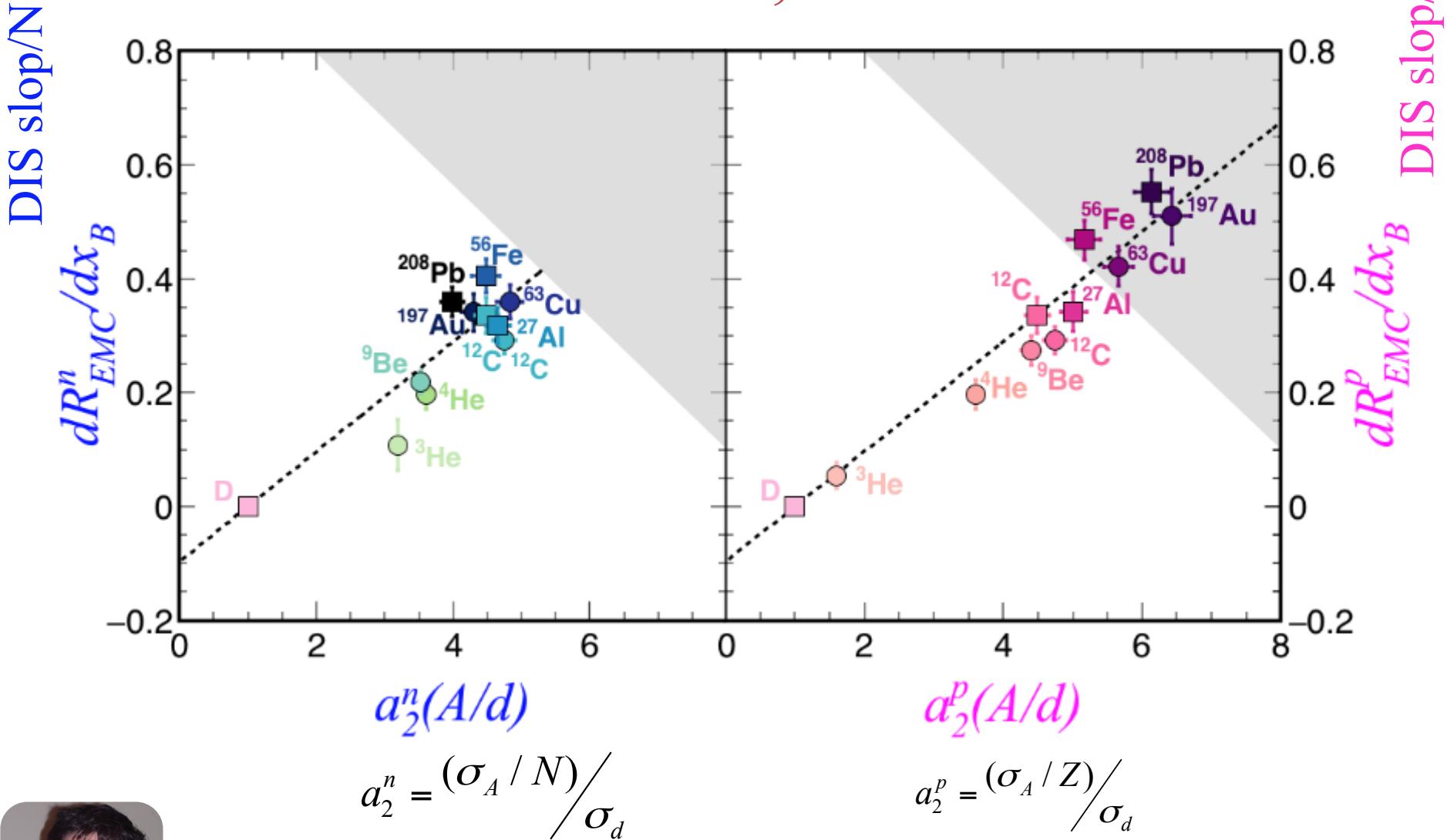


TEL AVIV UNIVERSITY

EMC effect should saturate for neutrons  
and grow for protons



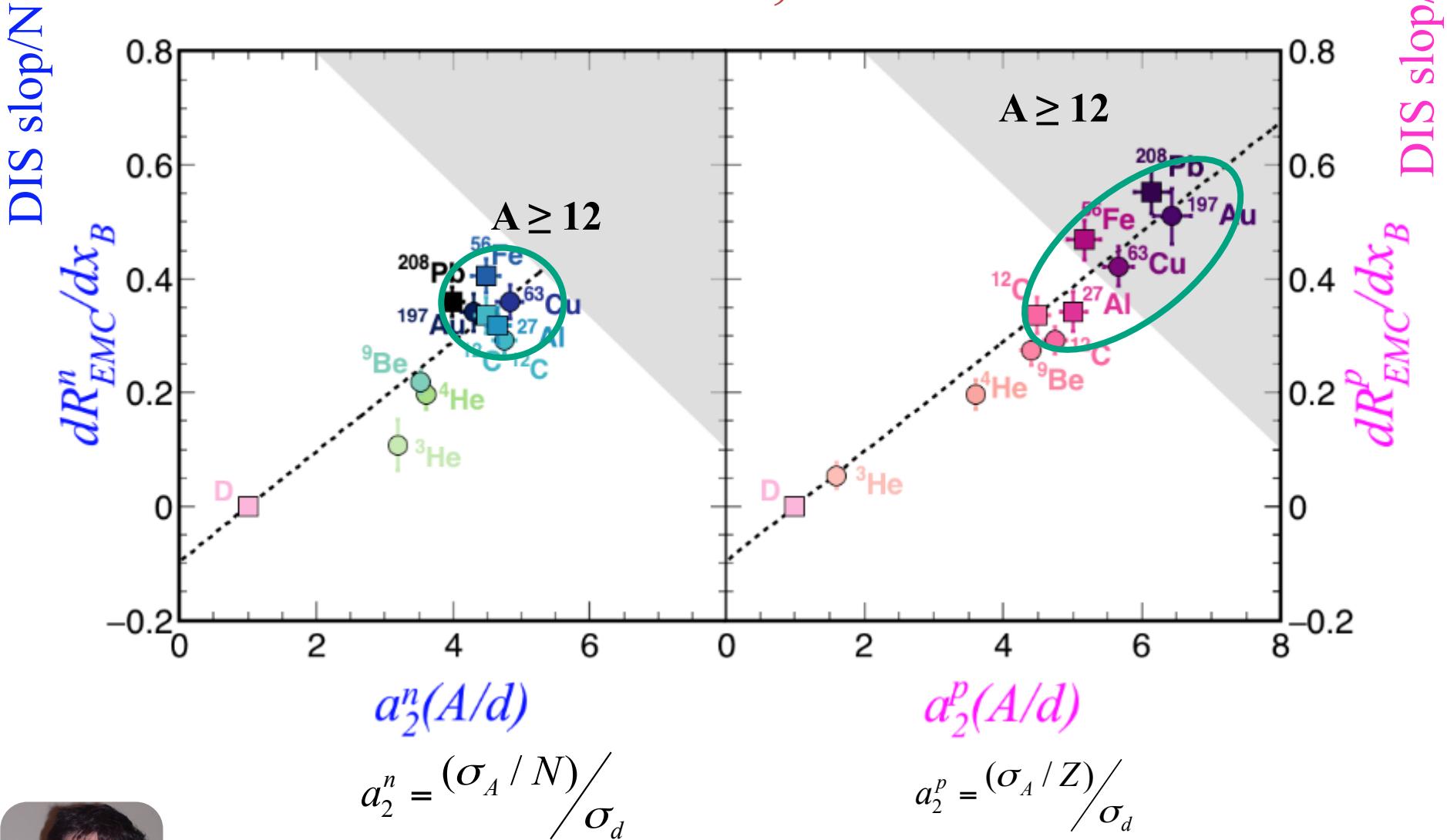
# Neutrons Saturate, Protons Grow



Schmockler, Duer, and Schmidt  
et al., submitted (2018)



# Neutrons Saturate, Protons Grow

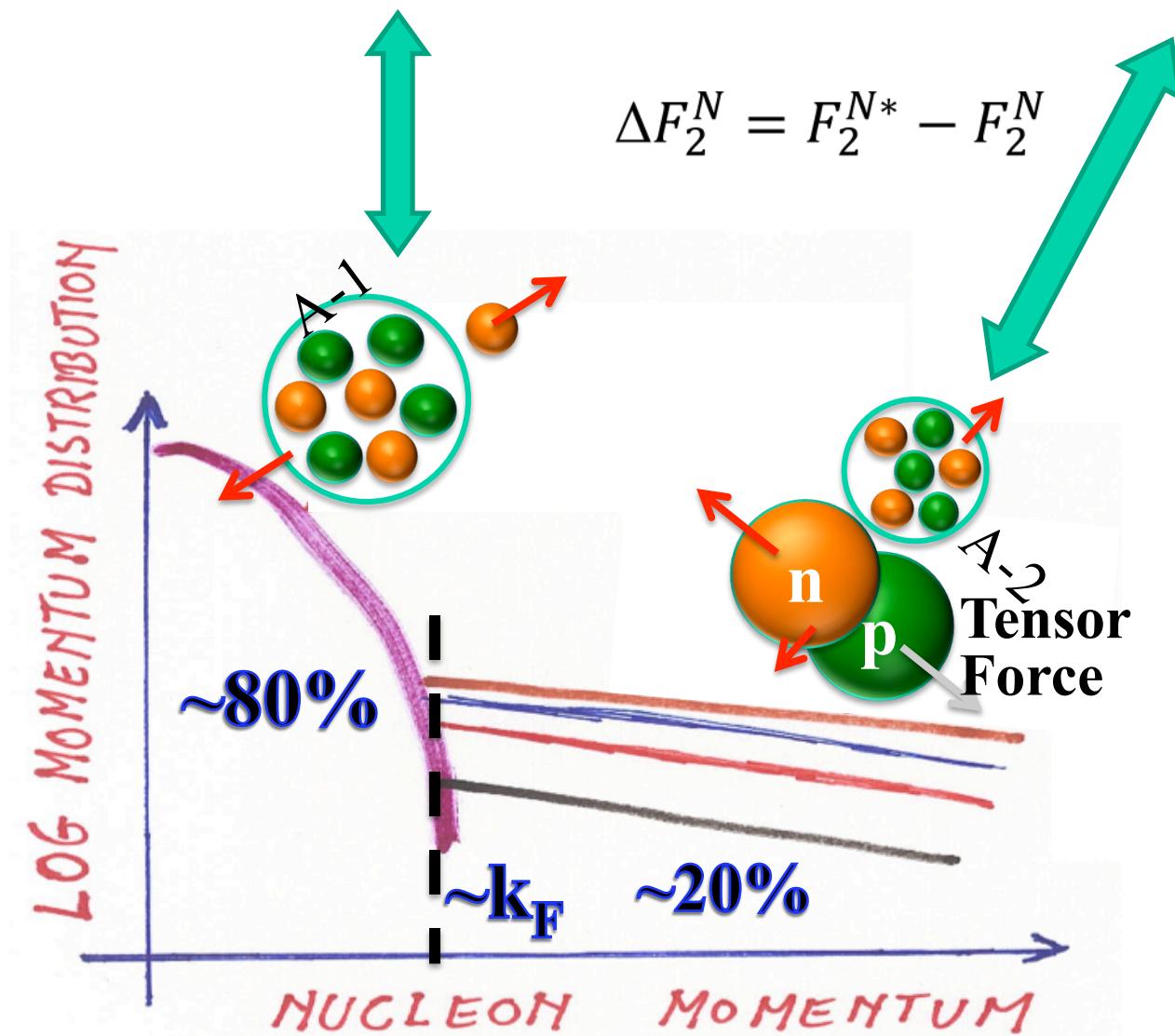


Schmookler, Duer, and Schmidt  
et al., submitted (2018)



**Bound** = ‘quasi Free’ + Modified SRCs

$$F_2^A = ZF_2^p + NF_2^n + n_{SRC}^A (\Delta F_2^p + \Delta F_2^n)$$

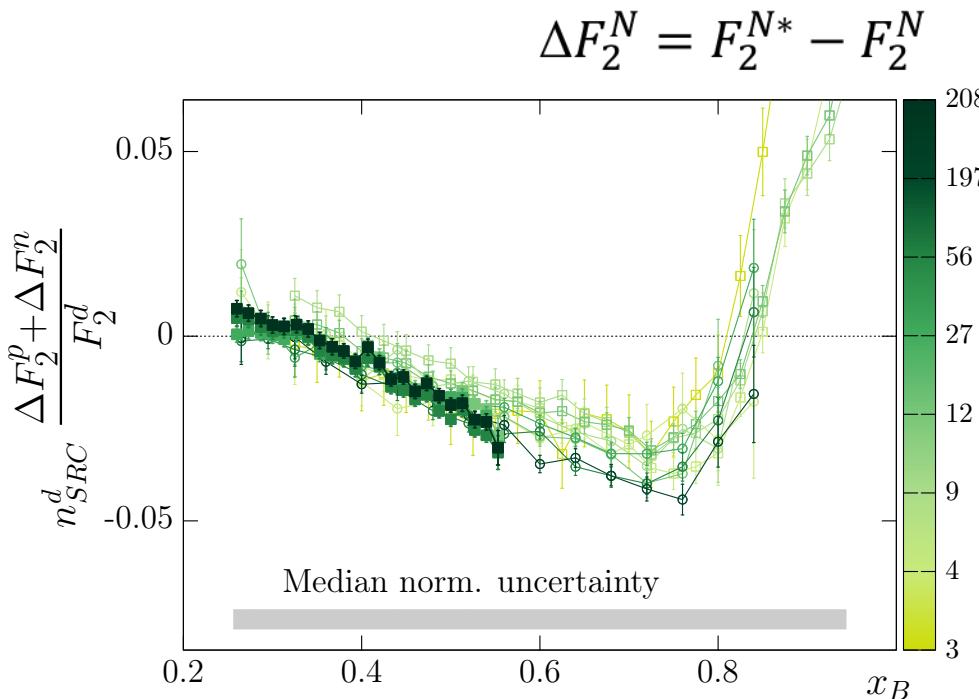
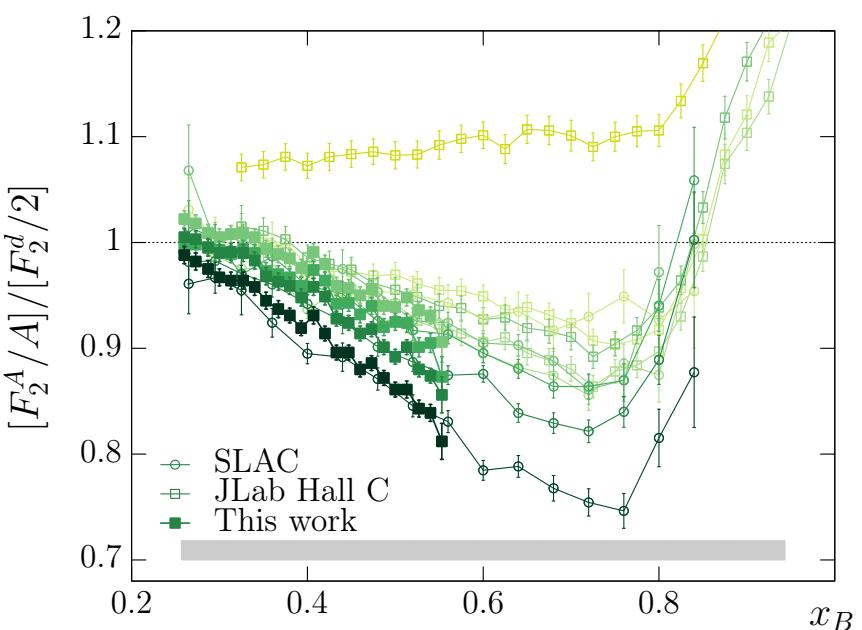


$$\frac{F_2^A}{F_2^d} = (n_{SRC}^A - N n_{SRC}^d) \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d} + (Z - N) \frac{F_2^p}{F_2^d} + N$$

A Dependent

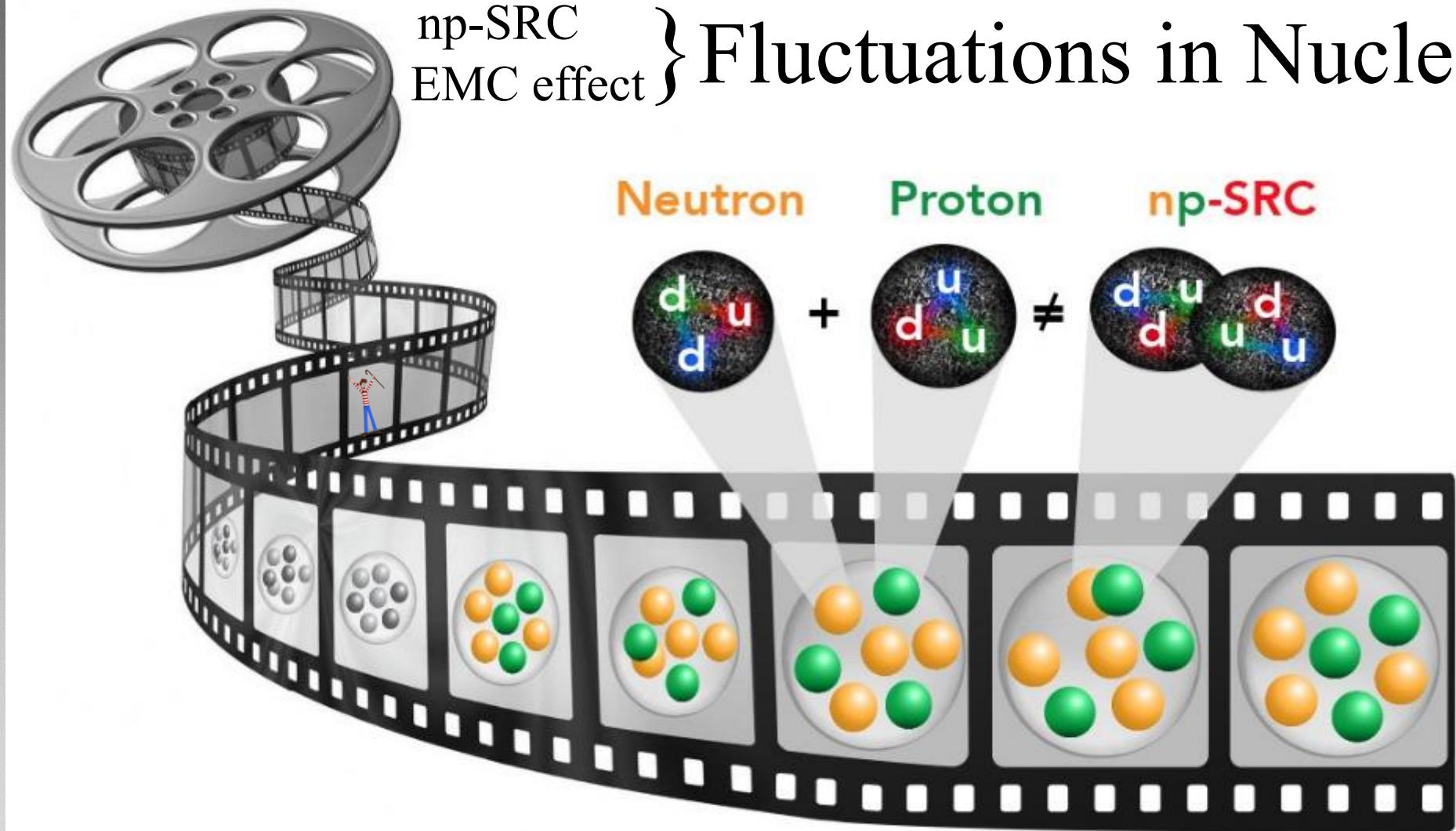
Universal!

A Dependent



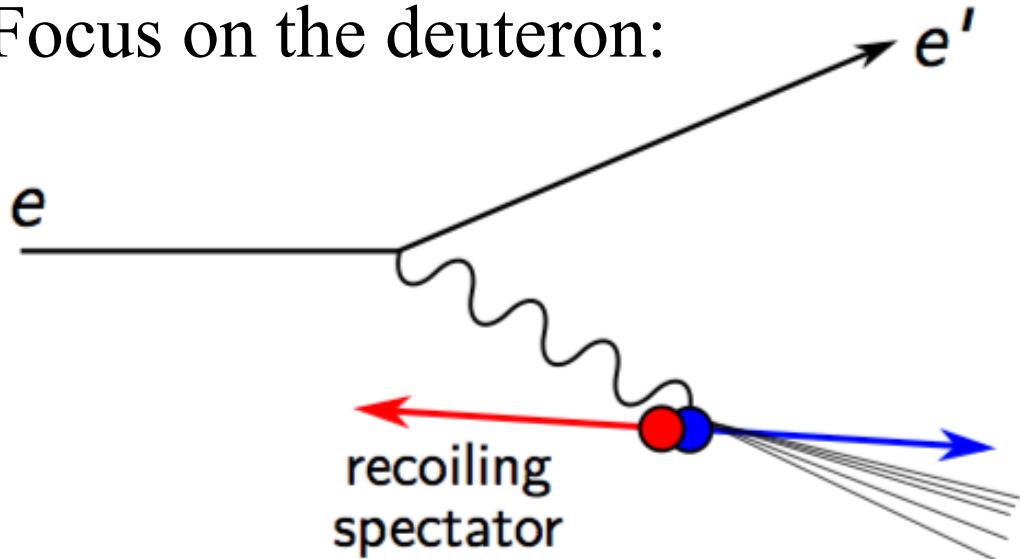
Schmookler, Duer, and Schmidt  
et al., submitted (2018)

# np-SRC EMC effect } Fluctuations in Nuclei

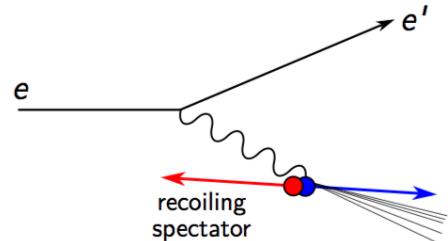
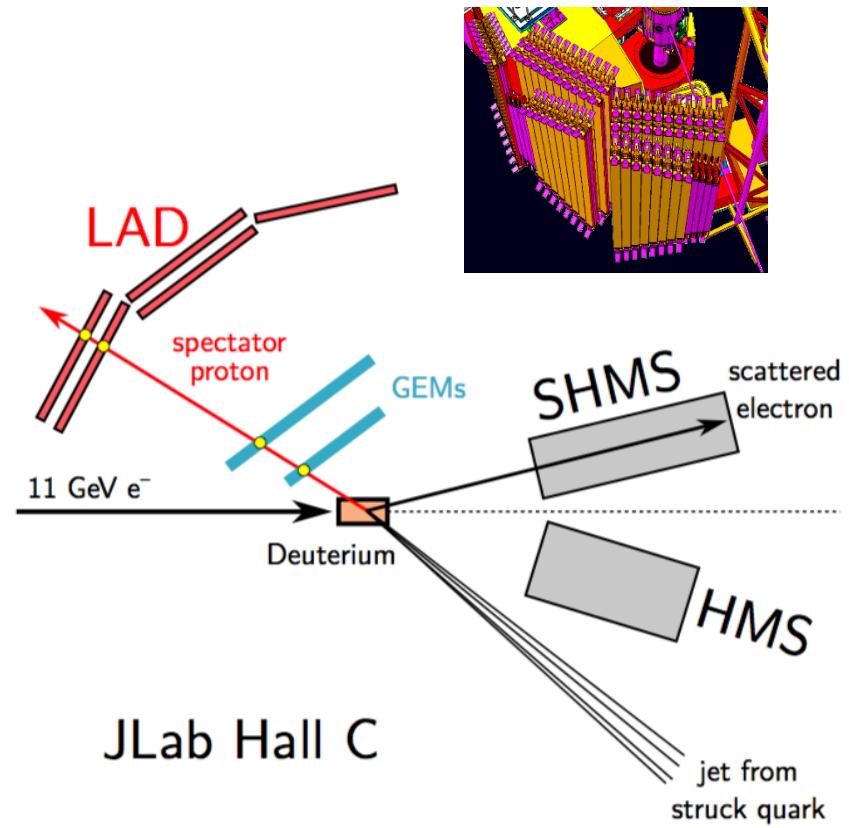
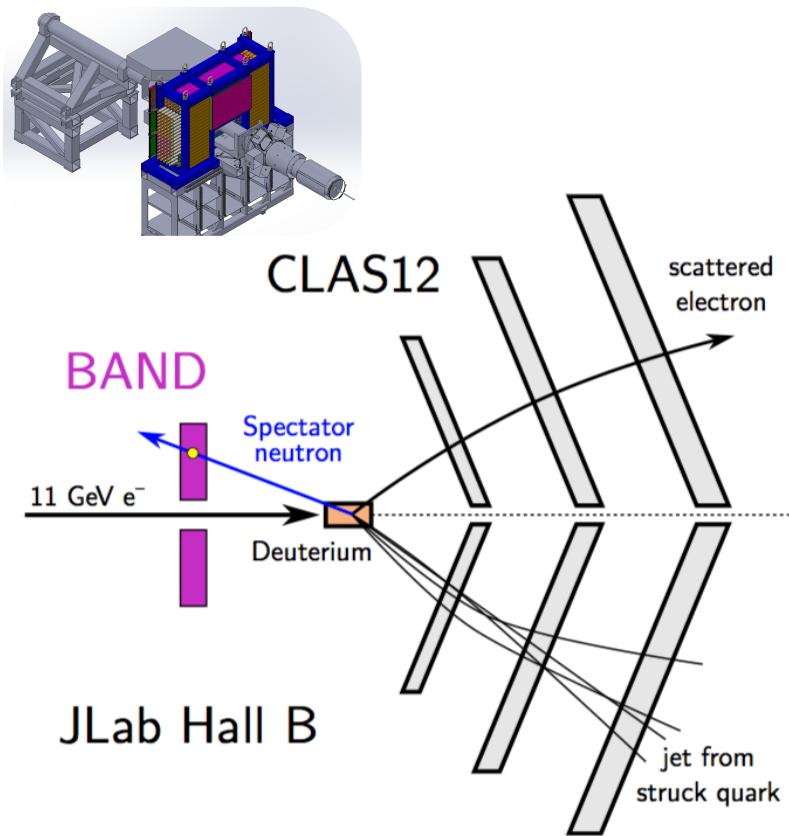


# Internal Structure of Bound Nucleons

Focus on the deuteron:



# Internal Structure of Bound Nucleons



# Summary (I)



TEL AVIV UNIVERSITY

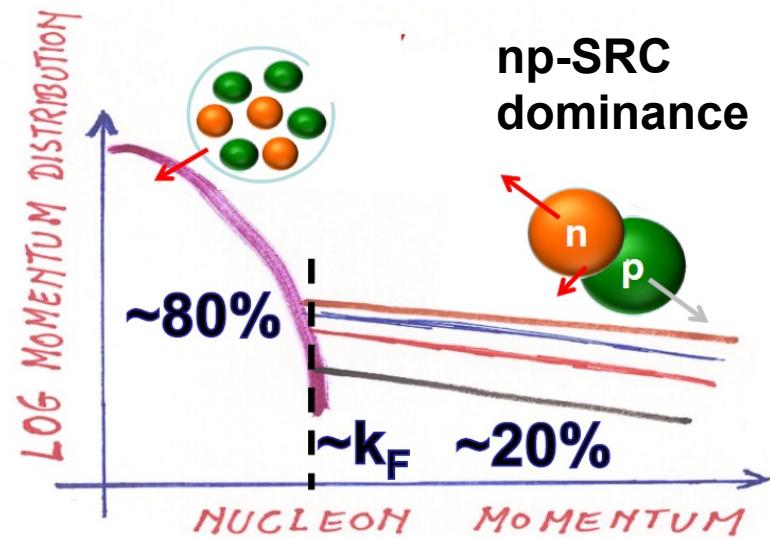
In nuclei the momentum distribution of nucleons can be divided into two distinct regions

$k < k_F$

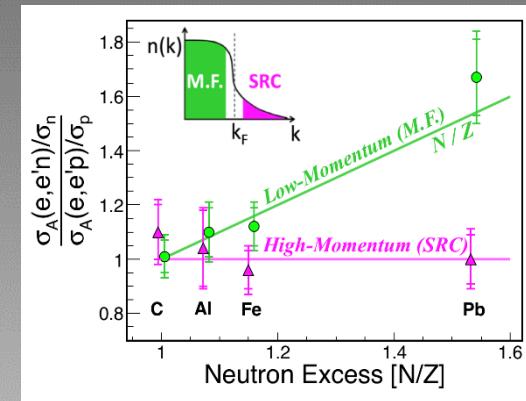
Mean field region

$k > k_F$

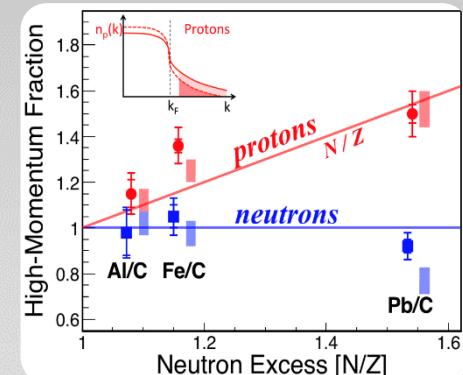
Correlated / high momentum region



The fraction of correlated **protons** / **neutrons** is **grow/constant**, as a function of neutron excess,



#protons = #neutrons,  
irrespectively of the neutron excess



**Generalized Nuclear Contact Formalism**

# Summary (II)



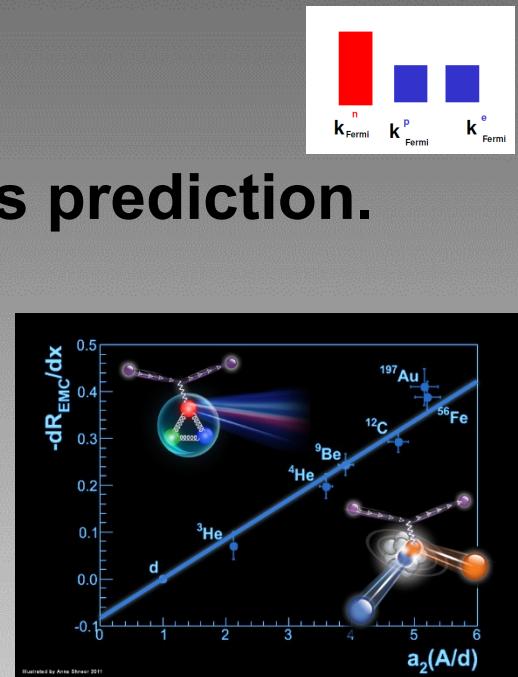
TEL AVIV UNIVERSITY

- In neutron-rich nuclei:  $\left\langle E^p_k \right\rangle > \left\langle E^n_k \right\rangle$

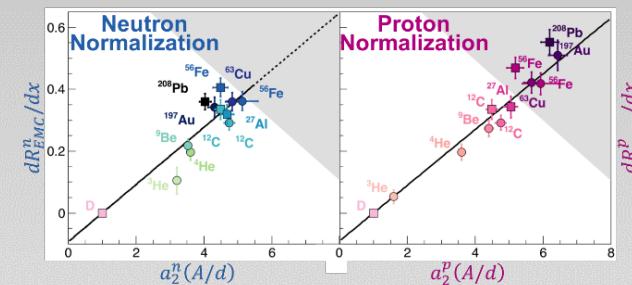
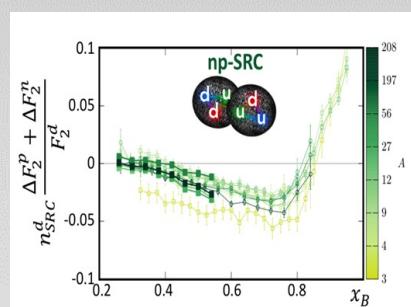
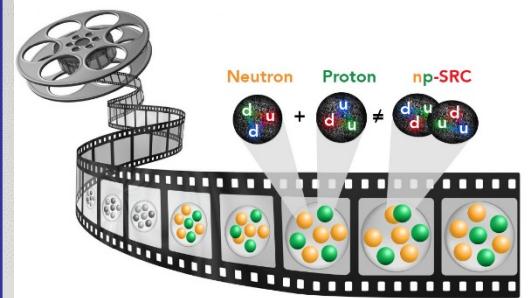
- In neutron stars  
proton momentum > Simple Fermi Gas prediction.

- EMC is associate with 2N SRC

EMC: Nucleons are normally normal except when close to others.



Proton EMC effect > neutron EMC effect.



# Related talks in this workshop



TEL AVIV UNIVERSITY

Tuesday 13 November 2018

Color fluctuations in nucleons and the EMC effect

STRIKMAN, Mark

2018/11/16

Friday

Hadron Interaction and Nuclear Structure

Room 404

16:30

16:50

I. Korover

Study the nucleon-nucleon force with short range correlation measurements

## Acknowledgment



TEL AVIV UNIVERSITY

I thank the organizers for the invitation

Shunzo Kumano

Shinya Sawada



Nov 2018

NARITASAN SHINSHO-JI TEMPLE COMPLEX, Japan

# Acknowledgment



TEL AVIV UNIVERSITY

## Collaborators



Massachusetts Institute of Technology



Or Hen



NEW!

Meytal Duer



OLD DOMINION  
UNIVERSITY



Larry  
Weinstein



Massachusetts Institute of Technology



Barak Schmookler

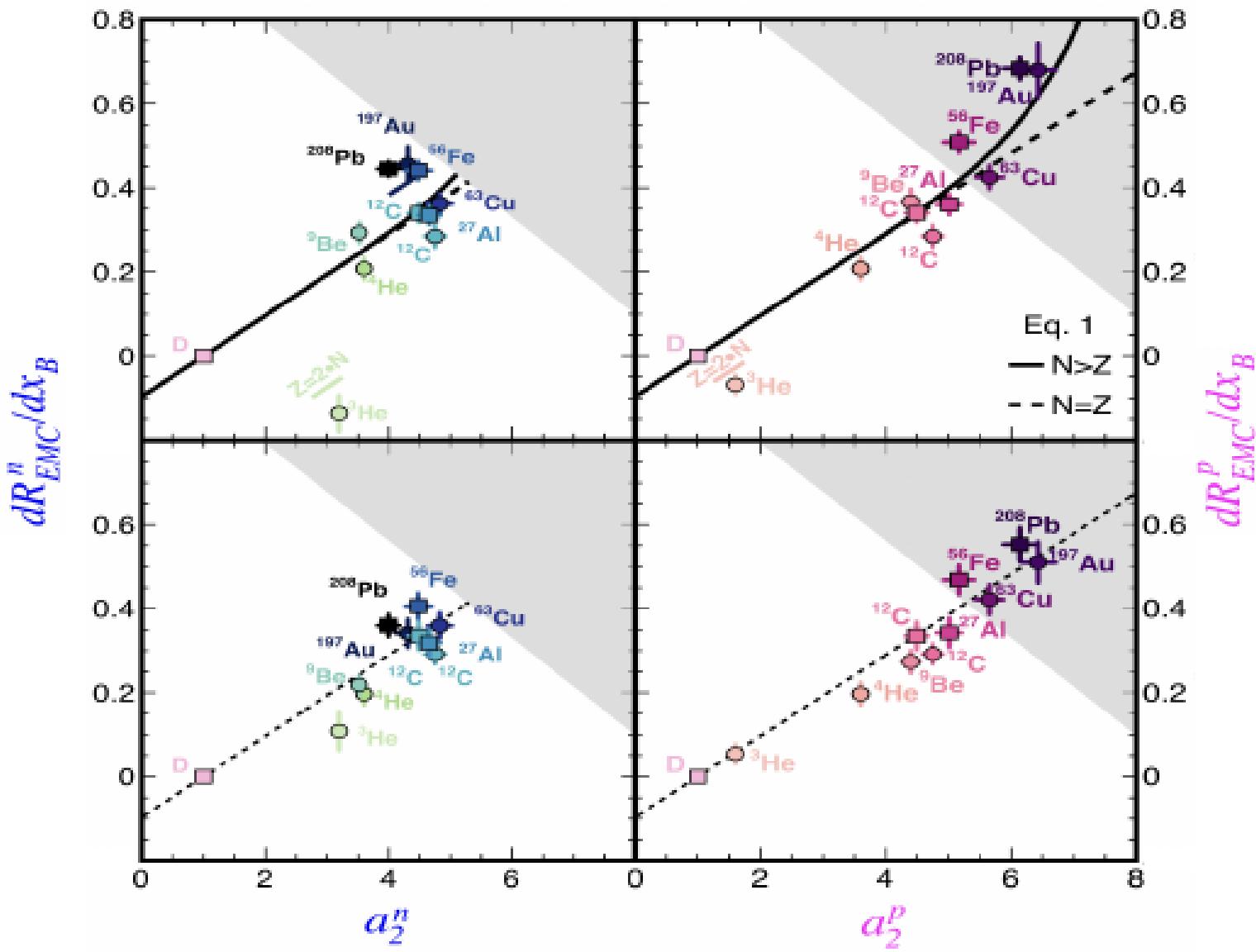
Data-Mining collaboration  
CLAS collaboration







DIS slope/N



DIS slope/Z

**Pauli principle**



$$\langle E_n^{kin} \rangle > \langle E_p^{kin} \rangle$$

~~$\langle E_n^{kin} \rangle > \langle E_p^{kin} \rangle$~~

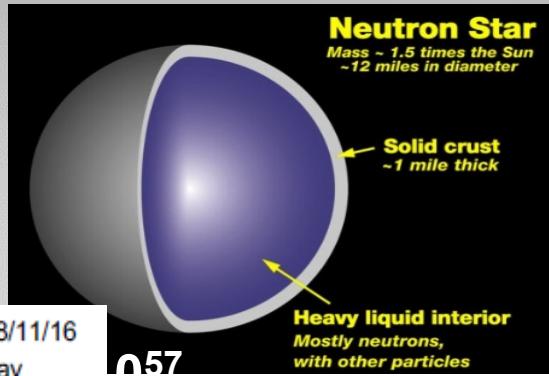
In neutron-rich nuclei ( $N > Z$ )

$$\langle E_p^{kin} \rangle > \langle E_n^{kin} \rangle$$

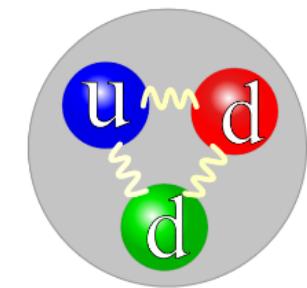
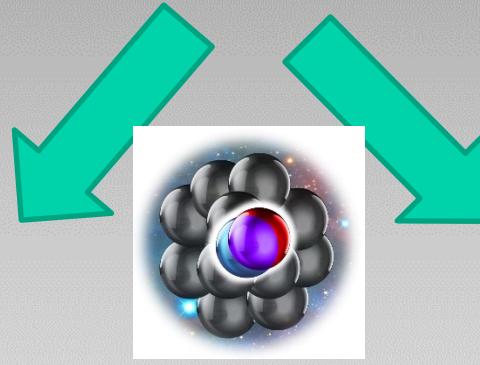
**Protons move faster than neutrons**



## Neutron Stars

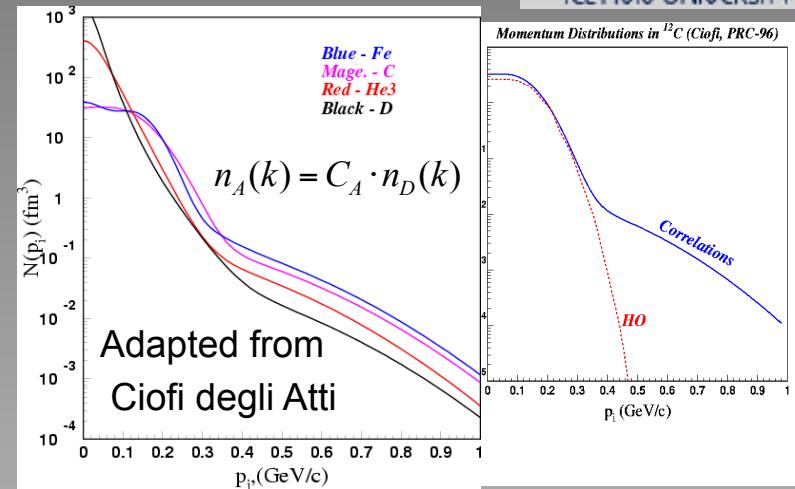
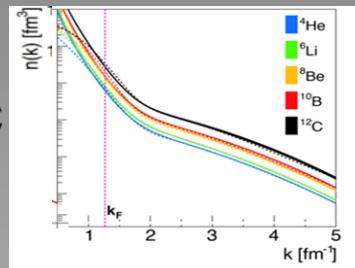


## The EMC effect



- At high nucleon momentum distributions are similar in shape for light and heavy nuclei: SCALING.

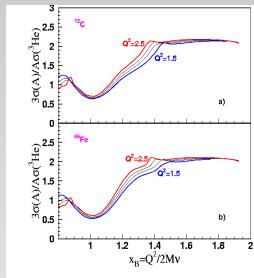
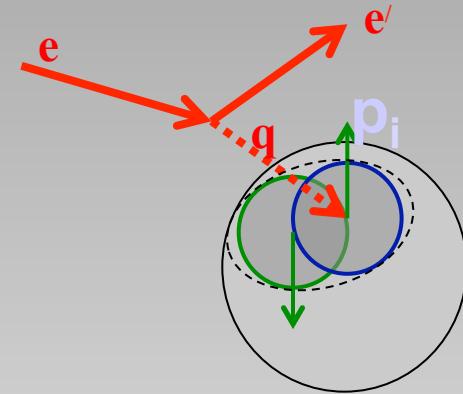
ab-initio VMC calculations



- Can be explained by 2N-SRC dominance.
- Within the 2N-SRC dominance picture one can get the probability of 2N-SRC in any nucleus, from the scaling factor.

In  $A(e, e')$  the momentum of the struck proton ( $p_i$ ) is unknown.

But: For fixed high  $Q^2$  and  $x_B > 1$ ,  $x_B$  determines a minimum  $p_i$

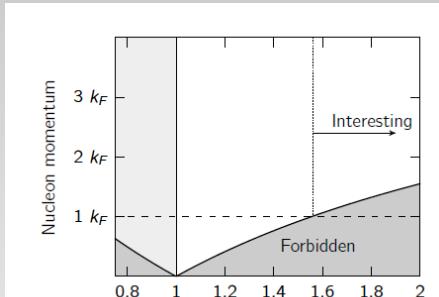


Prediction by Frankfurt, Sargsian, and Strikman:

$$Q^2 = -q_\mu q^\mu = q^2 - \omega^2$$

$$\omega = E' - E$$

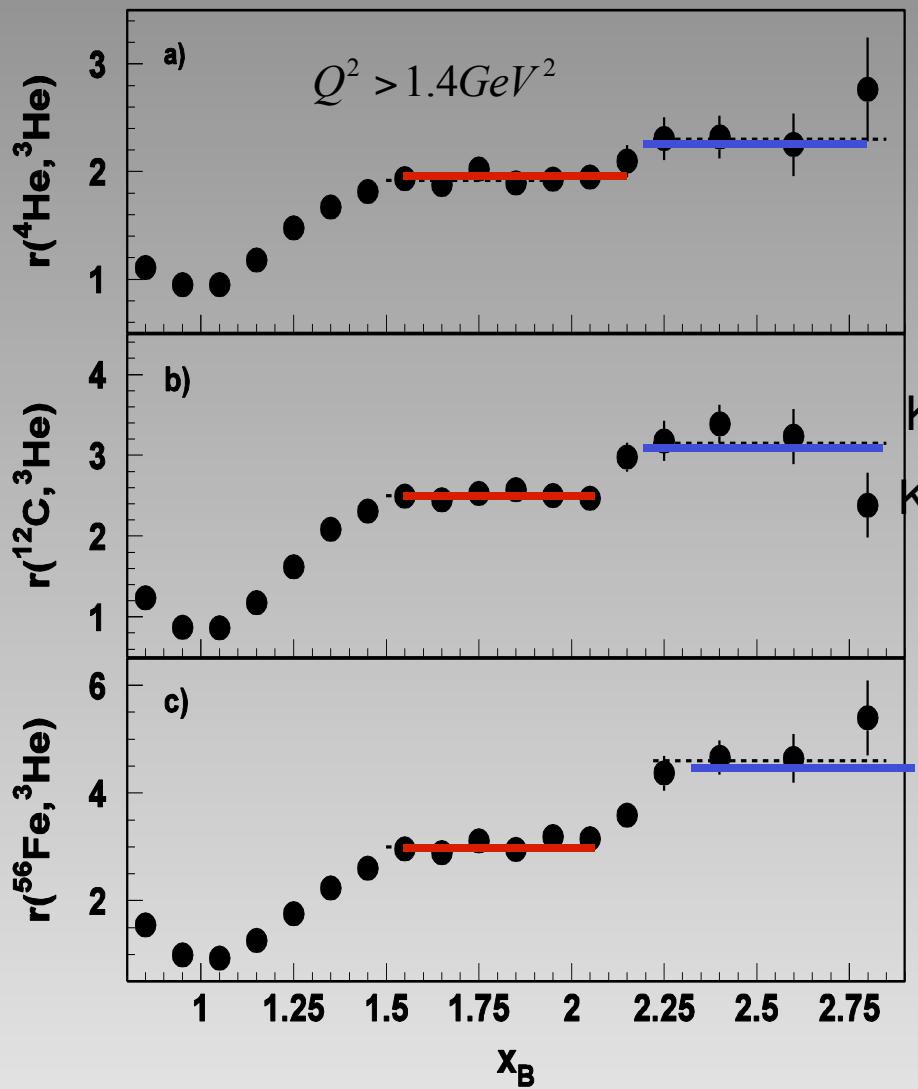
$$x_B = \frac{Q^2}{2m\omega}$$



# JLab. CLAS A(e,e') Result



TEL AVIV UNIVERSITY



K. Sh. Egiyan et al. PRL. 96, 082501 (2006)

K. Sh. Egiyan et al. PRC 68, 014313 (2003)

More  $r(A,d)$  data:

SLAC D. Day et al. PRL 59,427(1987)

JLab. Hall C E02-019

# Results from JLab Hall C (E02-019)



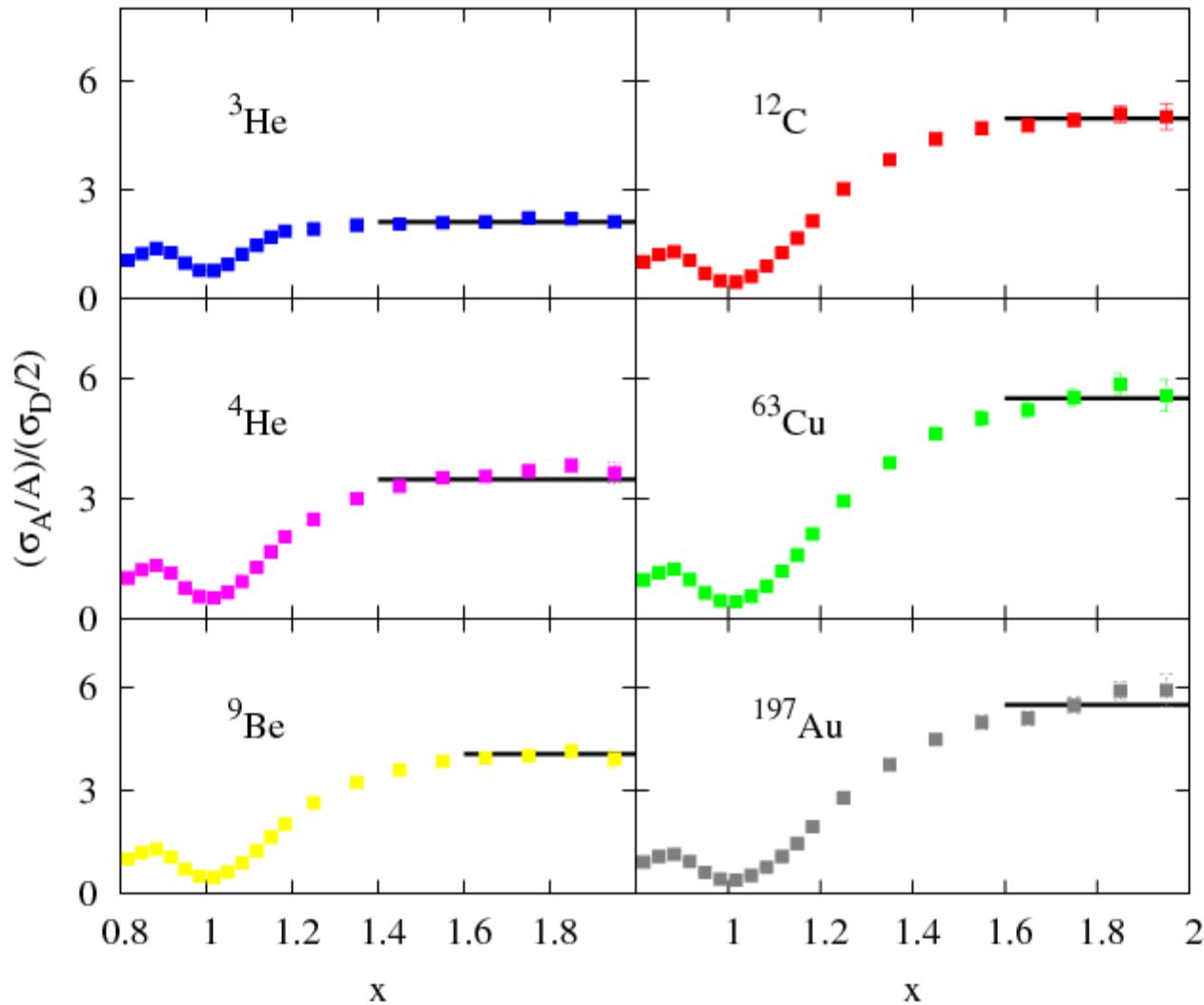
TEL AVIV UNIVERSITY

. Fomin et al. Phys. Rev. Lett. 108:092502, 2012.

$Q^2=2.5\text{GeV}^2$

$a_{2N}(A/d)$

Fomin et al. [ $r \rightarrow \infty$ ]	Fomin et al. [excluding the CM motion correction]
5	6
${}^3\text{He}$ $1.93 \pm 0.10$	$2.13 \pm 0.04$
${}^4\text{He}$ $3.02 \pm 0.17$	$3.60 \pm 0.09$
${}^9\text{Be}$ $3.37 \pm 0.17$	$3.91 \pm 0.12$
${}^{12}\text{C}$ $4.00 \pm 0.24$	$4.75 \pm 0.16$
${}^{56}\text{Fe}$ $4.33 \pm 0.28$	$5.21 \pm 0.19$
${}^{197}\text{Au}$ $4.26 \pm 0.29$	$5.16 \pm 0.21$



More  $r(A,d)$  data: Jlab /Hall B: K. Sh. Egiyan et al. PRC 68, 014313 (2003)

SLAC: D. Day et al. PRD 96, 082501 (2002)

K. Sh. Egiyan et al. PRD 96, 082501 (2002)

# Inclusive electron scattering $A(e,e')$



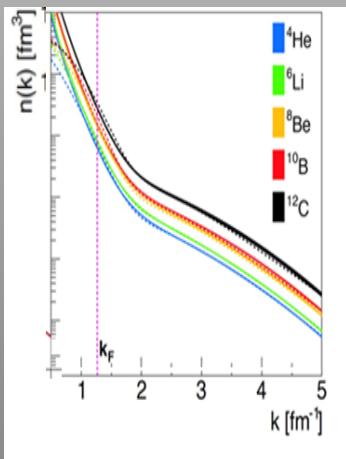
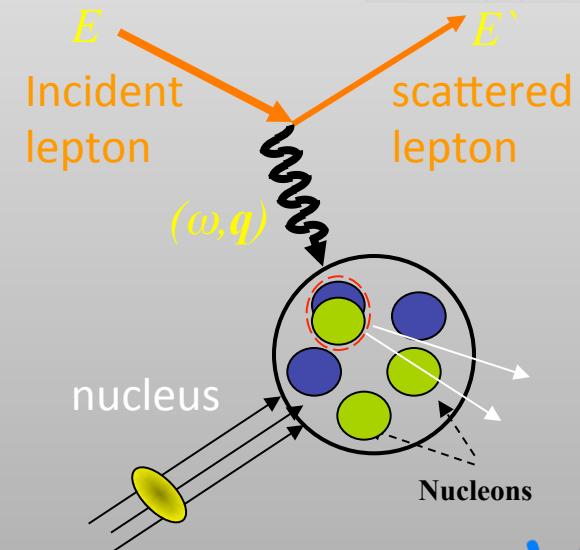
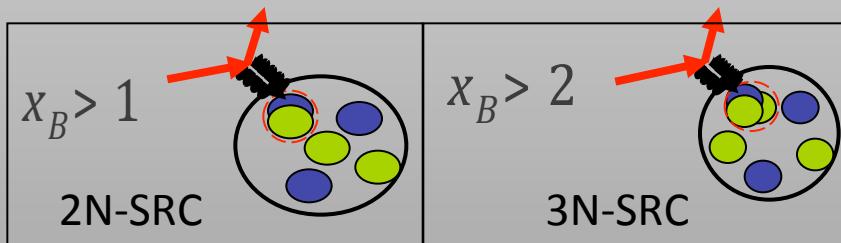
TEL AVIV UNIVERSITY

$$0 \leq x_B \leq A$$

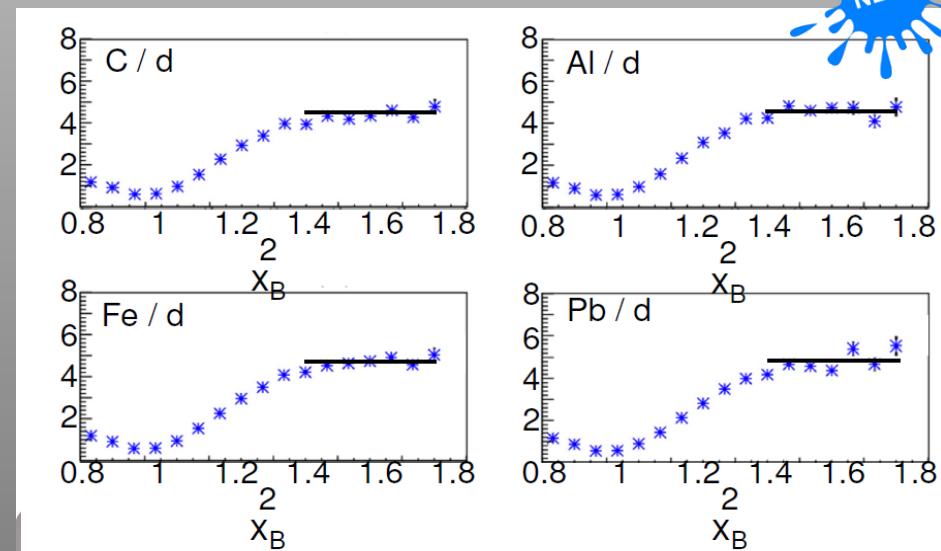
$$Q^2 = -q_\mu q^\mu = q^2 - \omega^2$$

$$\omega = E' - E$$

$$x_B = \frac{Q^2}{2m\omega} \quad (x'_B = \frac{Q^2}{2(q \cdot p_T)})$$



Momentum scaling →



→ Counts the number of SRC clusters in nuclei

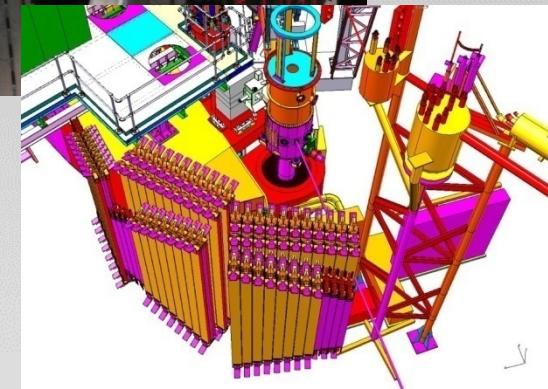
$$a_{2N}(A/d)$$

Barak Schmookler et al., submitted to Science  
Data mining (EG2c)

# Large Acceptance Detector for JLab experiment



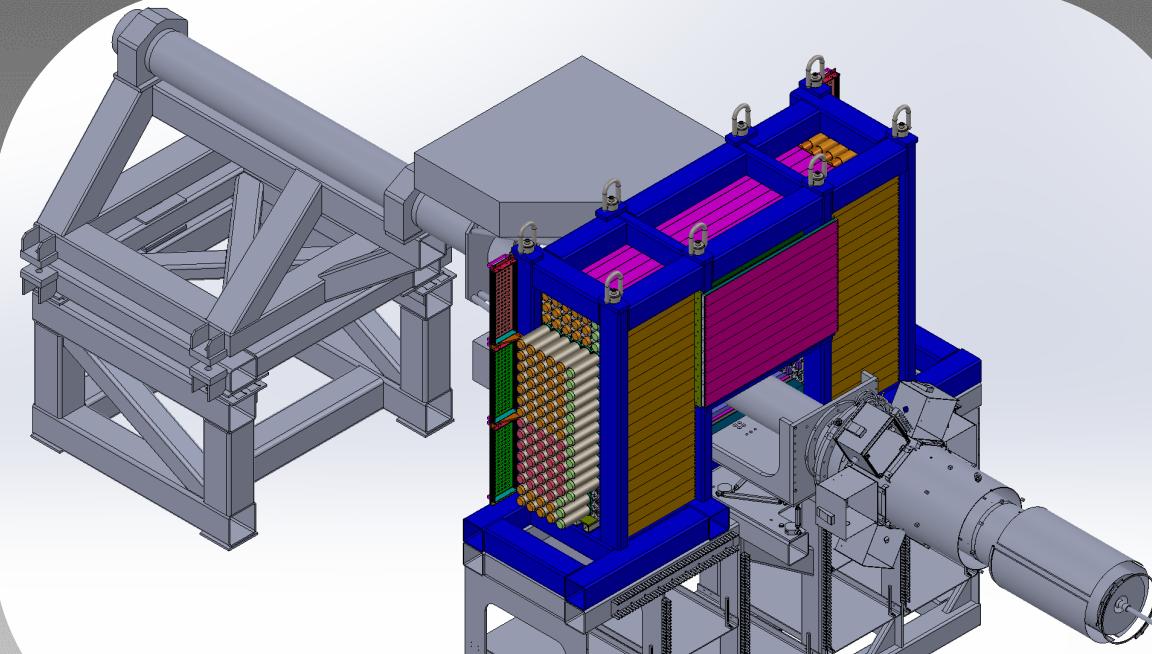
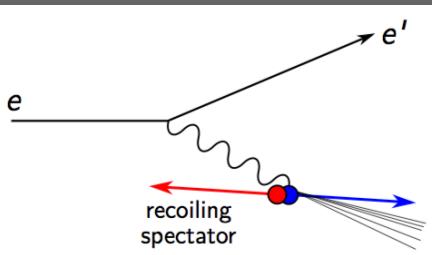
מונח לגילוי פרוטון רותע





TEL AVIV UNIVERSITY

# BackwardAngle Detector JLab experiment (Hall E)



מונה לגילוי ניוטרון רותע

האם יש אפקט EMC בדיוutrון?  
ניסוי מתוכנן ל JLAB בארה"ב

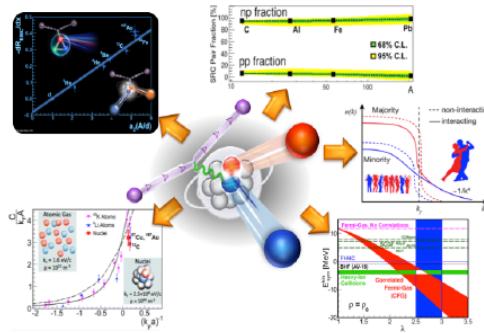
TAU / MIT/UTSM / ODU

# High-Momentum Nucleons in Nuclei

Thesis submitted towards the degree of  
Doctor of Philosophy

By

Or Hen



Submitted To The Senate of Tel-Aviv University  
November 2015

This work was carried out under the supervision of  
Professor Eli Piasetzky

Scienceexpress

Reports

## Momentum sharing in imbalanced Fermi systems

O. Hen,<sup>1</sup> M. Sargsian,<sup>2</sup> L. B. Weinstein,<sup>3</sup> E. Piasetzky,<sup>1</sup> H. Hakobyan,<sup>4,5</sup> D. W. Higinbotham,<sup>6</sup> M. Braverman,<sup>7</sup> W. K. Brooks,<sup>8</sup> S. Glad,<sup>9</sup> K. P. Arrington,<sup>10</sup> G. Asryan,<sup>9</sup> H. Avakian,<sup>9</sup> J. Ball,<sup>11</sup> N. B. Balterz,<sup>12</sup> J. Battaglieri,<sup>13</sup> S. Beck,<sup>11,14</sup> S. May-Tal Boim,<sup>15</sup> M. Beinemyer,<sup>12</sup> W. Bertozzi,<sup>12</sup> A. Biselli,<sup>13</sup> V. V. Burkhat,<sup>16</sup> F. Capo,<sup>17</sup> S. Casper,<sup>18</sup> A. Chai,<sup>19</sup> S. Chobanova,<sup>14</sup> L. Colvin,<sup>19</sup> R. P. Collins,<sup>11,18</sup> V. Cooper,<sup>19</sup> A. D'Angelo,<sup>13,20</sup> R. De Vita,<sup>11,21</sup> A. Dean,<sup>12</sup> C. Djatlow,<sup>14,22</sup> D. Drutskoy,<sup>12</sup> M. Dugay,<sup>23</sup> R. Dupre,<sup>24</sup> H. Egiyan,<sup>13</sup> A. El-Aouzi,<sup>1</sup> L. El-Fassi,<sup>1</sup> L. El-Ghoul,<sup>1</sup> Y. El-Shabani,<sup>1</sup> G. Fedotov,<sup>14,25</sup> S. Fegan,<sup>10</sup> T. Forest,<sup>17</sup> B. Goriely,<sup>24</sup> N. Gevorgyan,<sup>1</sup> Y. Ghazaryan,<sup>1</sup> G. P. Gilfoyle,<sup>26</sup> F. X. Girard,<sup>1</sup> J. T. Goetz,<sup>16</sup> R. W. Golbe,<sup>14</sup> K. A. Griffioen,<sup>27</sup> M. Guidali,<sup>24</sup> L. Guo,<sup>24</sup> K. Hafidi,<sup>1</sup> C. Hanretty,<sup>28</sup> M. Hattaway,<sup>24</sup> K. Hicks,<sup>13</sup> M. Holtrop,<sup>29</sup> C. E. Hyde,<sup>1</sup> Y. Ilieva,<sup>14,30</sup> D. G. Ireland,<sup>31</sup> B. I. Ishkanov,<sup>26</sup> E. L. Isupov,<sup>26</sup> H. Jiang,<sup>14</sup> H. S. Ju,<sup>32</sup> K. Keefer,<sup>33</sup> M. Khandaker,<sup>17,33</sup> A. Kim,<sup>34</sup> W. Kim,<sup>34</sup> F. J. Klein,<sup>19</sup> S. Koiralal,<sup>31</sup> I. Korover,<sup>1</sup> S. E. Kuhn,<sup>3</sup> V. Kubarovsky,<sup>6</sup> P. Lenisa,<sup>35</sup> W. I. Levine,<sup>36</sup> K. Livingston,<sup>37</sup> D. Lowry,<sup>9</sup> H. Y. Lu,<sup>14</sup> J. D. MacGregor,<sup>31</sup> N. Markov,<sup>32</sup> M. Mayer,<sup>1</sup> B. McKinnon,<sup>31</sup> T. Mineeva,<sup>32</sup> V. Mokeev,<sup>6,23,37</sup> A. Movsisyan,<sup>38</sup> M. Munoz Camacho,<sup>2</sup> B. Mustapha,<sup>1</sup> P. Nadel-Turanski,<sup>1</sup> S. Nicollas,<sup>24</sup> G. Niculescu,<sup>38</sup> A. Niculescu,<sup>38</sup> M. Osipenko,<sup>10</sup> L. L. Pappalardo,<sup>29</sup> R. Paremmuyan,<sup>5,23</sup> K. Park,<sup>6,34</sup> E. Pasquini,<sup>4</sup> W. Phelps,<sup>23</sup> S. Pisano,<sup>40</sup> O. Pogorelko,<sup>10</sup> J. W. Price,<sup>39</sup> S. Procureur,<sup>9</sup> Y. Prok,<sup>1,28</sup> D. Protopopescu,<sup>31</sup> A. J. R. Puckett,<sup>32</sup> D. Rimal,<sup>2</sup> M. Ripani,<sup>10</sup> B. G. Ritchie,<sup>23</sup> A. Rizzo,<sup>16</sup> G. Rosner,<sup>19</sup> P. Rossi,<sup>1</sup> F. Sabatie,<sup>9</sup> D. Schott,<sup>39</sup> R. A. Schuchmaner,<sup>16</sup> Y. G. Sharabiani,<sup>19</sup> G. D. Smith,<sup>42</sup> R. Shneor,<sup>1</sup> D. Sokhan,<sup>3</sup> S. S. Stepanyan,<sup>34</sup> S. Stepanyan,<sup>1</sup> P. Stoler,<sup>43</sup> S. Straub,<sup>43</sup> V. Syrik,<sup>4</sup> M. Tauti,<sup>44</sup> S. Tkachenko,<sup>1</sup> M. Ungaro,<sup>4</sup> V. E. Vlassov,<sup>4</sup> E. Voutier,<sup>42</sup> N. K. Walfoot,<sup>34</sup> X. Wei,<sup>1</sup> M. H. Wood,<sup>14,44</sup> S. A. Wood,<sup>1</sup> N. Zachariou,<sup>14</sup> L. Zana,<sup>39,42</sup> Z. W. Zhao,<sup>39</sup> X. Zheng,<sup>29</sup> I. Zonta,<sup>1</sup> Jefferson Lab CLAS Collaboration<sup>1</sup>

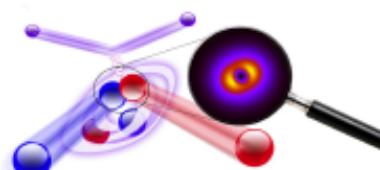
on October 16, 2014



## Study of short-range correlation in nuclei via measurement of the ${}^4\text{He}(e,e'pp)$ and ${}^4\text{He}(e,e'pn)$ reactions

Thesis submitted towards the degree of  
Doctor of Philosophy

By  
Igor Korover



Submitted to the senate of Tel-Aviv University  
April 2015

This work was carried out under the supervision of  
Professor Eli Piasetzky



## Probing repulsive core of the nucleon-nucleon interaction via the ${}^4\text{He}(e,e'pN)$ triple-coincidence reaction

- <sup>1</sup> I. Korover,<sup>1</sup> N. Muangma,<sup>2</sup> O. Hen,<sup>1</sup> R. Shneor,<sup>1</sup> V. Sulsky,<sup>2,3</sup> A. Kelleher,<sup>2</sup> S. Gilad,<sup>2</sup> D. W. Higinbotham,<sup>4</sup> E. Piasetzky,<sup>1</sup> J. W. Watson,<sup>5</sup> S. A. Wood,<sup>4</sup> Abdurahim Rakhaman,<sup>6</sup> P. Aguilar,<sup>7</sup> Z. Ahmed,<sup>6</sup> H. Albataineh,<sup>8</sup> K. Allada,<sup>9</sup> B. Anderson,<sup>5</sup> D. Anez,<sup>10</sup> K. Aniol,<sup>11</sup> J. Annand,<sup>12</sup> W. Armstrong,<sup>13</sup> J. Arrington,<sup>14</sup> T. Averett,<sup>15</sup> T. Badman,<sup>16</sup> H. Baghdasaryan,<sup>17</sup> X. Bai,<sup>18</sup> A. Beck,<sup>19</sup> S. Beck,<sup>19</sup> V. Bellini,<sup>20</sup> F. Bennokhtar,<sup>21</sup> W. Bertozzi,<sup>2</sup> J. Bittner,<sup>3</sup> W. Boeglin,<sup>22</sup> A. Camsonne,<sup>4</sup> C. Chen,<sup>23</sup> J.-P. Chen,<sup>4</sup> K. Chirapatpinol,<sup>17</sup> E. Cisbani,<sup>24</sup> M. M. Dalton,<sup>1</sup> A. Daniel,<sup>25</sup> D. Day,<sup>17</sup> C. W. de Jager,<sup>4,17</sup> R. De Leo,<sup>26</sup> W. Deconinck,<sup>2</sup> M. Defurne,<sup>27</sup> D. Flay,<sup>13</sup> N. Fomin,<sup>28</sup> M. Friend,<sup>21</sup> S. Frullani,<sup>24</sup> E. Fuchs,<sup>13</sup> F. Garibaldi,<sup>24</sup> D. Gaskell,<sup>24</sup> R. Gilman,<sup>29,4</sup> O. Glazaudin,<sup>30</sup> C. Gu,<sup>31</sup> P. Gueye,<sup>23</sup> D. Hamilton,<sup>12</sup> C. Hanretty,<sup>32</sup> J.-O. Hansen,<sup>4</sup> M. Hashemi Shabestari,<sup>17</sup> T. Holmstrom,<sup>3</sup> M. Huang,<sup>33</sup> S. Iqbal,<sup>11</sup> G. Jin,<sup>17</sup> N. Kalantarians,<sup>34</sup> H. Kang,<sup>35</sup> M. Khandaker,<sup>4</sup> J. LeRose,<sup>4</sup> J. Leckey,<sup>36</sup> R. Lindgren,<sup>17</sup> E. Long,<sup>16</sup> J. Mammei,<sup>37</sup> D. J. Margaziotis,<sup>11</sup> P. Markowitz,<sup>22</sup> A. Marti Jimenez-Arreguilo,<sup>38</sup> D. Meekins,<sup>4</sup> Z. Meziani,<sup>13</sup> R. Michaels,<sup>4</sup> M. Mihovilovic,<sup>39</sup> P. Monaghan,<sup>2,23</sup> C. Munoz Camacho,<sup>38</sup> B. Norum,<sup>17</sup> Nuruzzaman,<sup>40</sup> K. Pan,<sup>2</sup> S. Phillips,<sup>16</sup> I. Pomerantz,<sup>1,41</sup> M. Possik,<sup>13</sup> V. Punjabi,<sup>42</sup> X. Qian,<sup>33</sup> Y. Qiang,<sup>33</sup> X. Qiu,<sup>43</sup> P. E. Reimer,<sup>14</sup> S. Riordan,<sup>17,44</sup> G. Ron,<sup>45</sup> O. Rondon-Aramayo,<sup>4</sup> A. Saha,<sup>4,\*</sup> E. Schulte,<sup>29</sup> L. Selvy,<sup>5</sup> A. Shahinyan,<sup>46</sup> S. Sireca,<sup>47</sup> J. Sjoegren,<sup>12</sup> K. Slifer,<sup>16</sup> P. Solvignon,<sup>4</sup> N. Sparveris,<sup>13</sup> R. Subedi,<sup>17</sup> W. Tireman,<sup>48</sup> D. Wang,<sup>17</sup> L. B. Weinstein,<sup>8</sup> B. Wojtsekhowski,<sup>4</sup> W. Yan,<sup>49</sup> I. Yaron,<sup>1</sup> Z. Ye,<sup>17</sup> X. Zhan,<sup>2</sup> J. Zhang,<sup>4</sup> Y. Zhang,<sup>29</sup> B. Zhao,<sup>15</sup> Z. Zhao,<sup>17</sup> X. Zheng,<sup>17</sup> P. Zhu,<sup>49</sup> and R. Zielinski<sup>16</sup>

(The Jefferson Lab Hall A Collaboration)

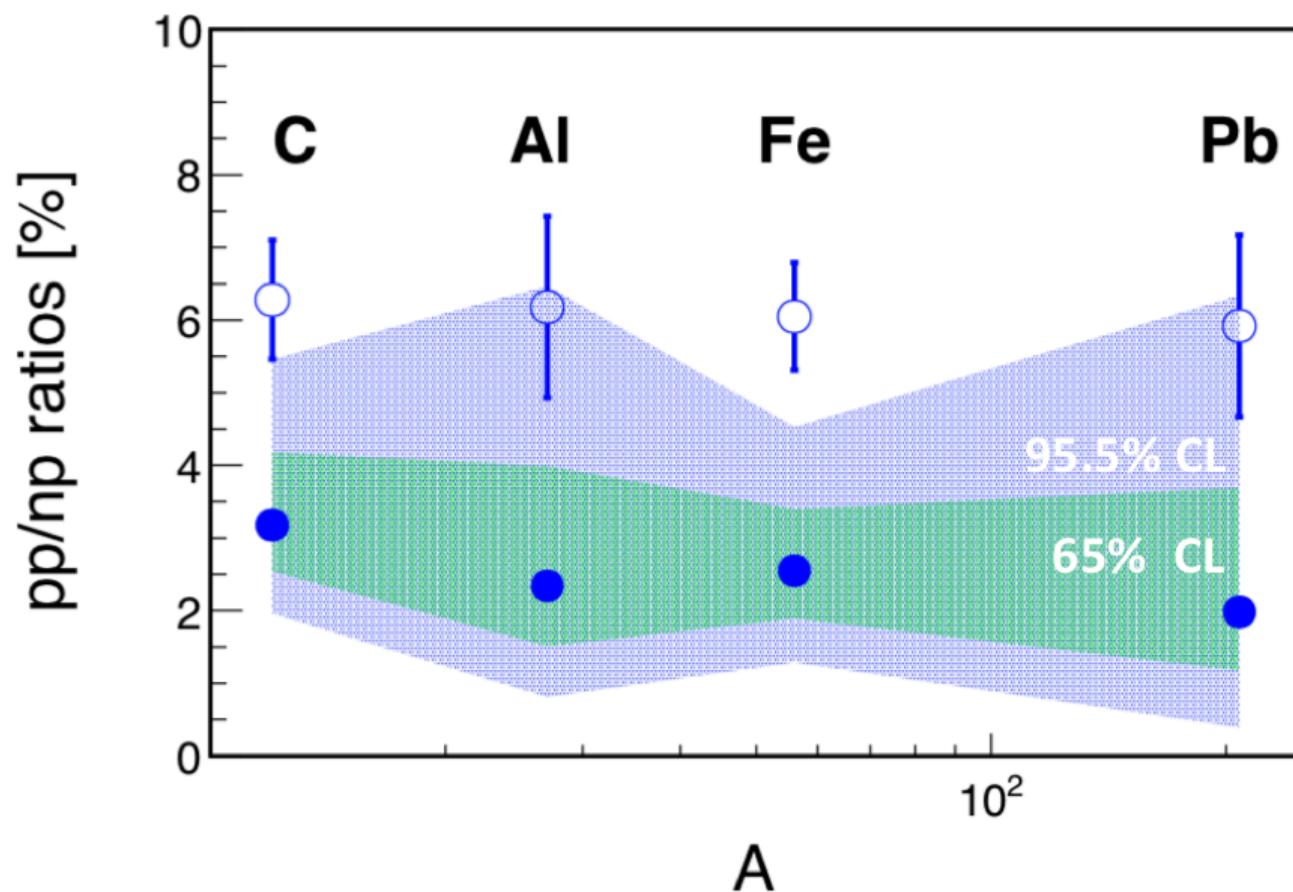
# Our SRC Worldwide Program



# Our SRC Worldwide Program



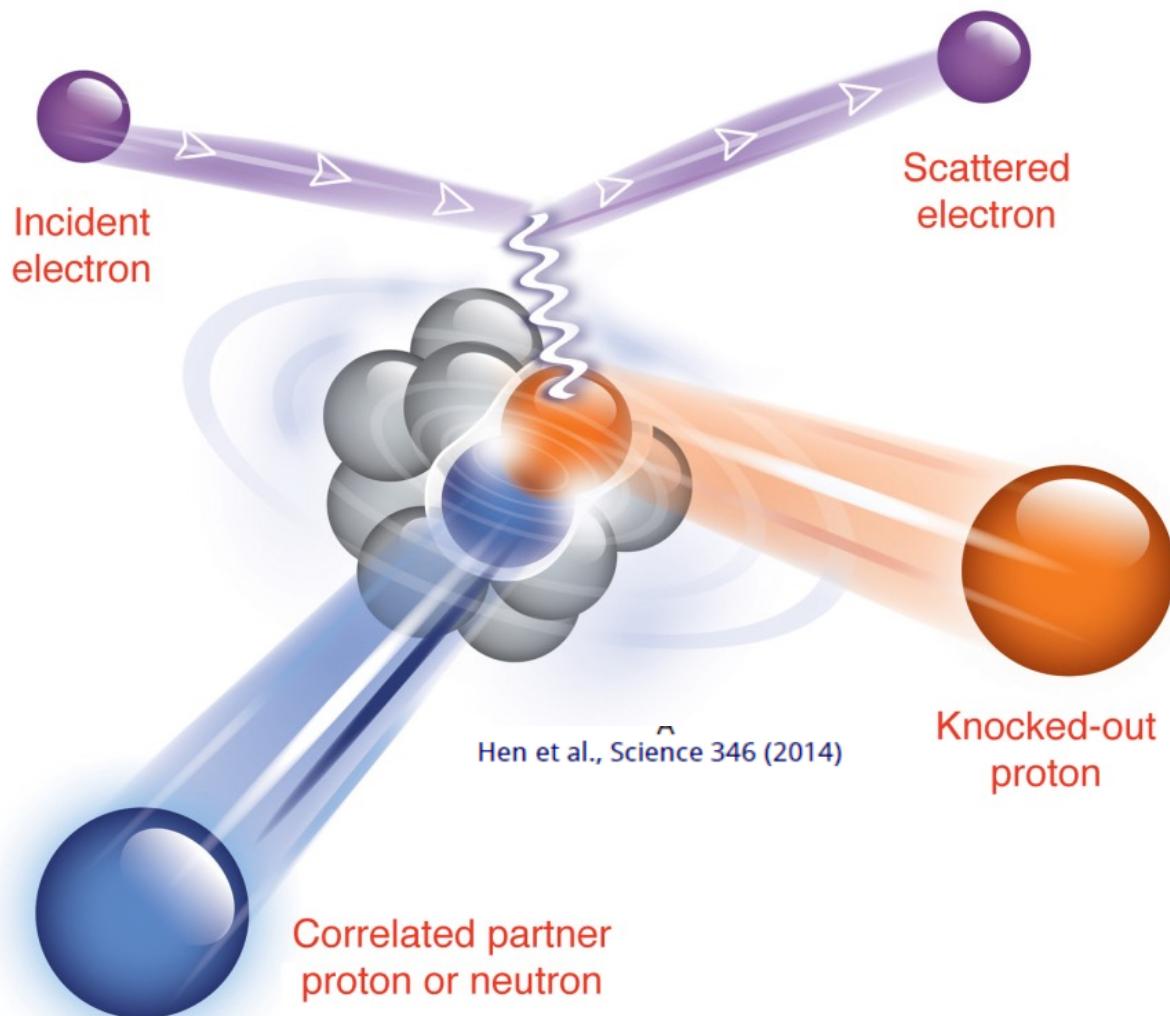




# ניסויים שבוצעו במעבדת המאיצ' זפרסון בארץ"ב



TEL AVIV UNIVERSITY

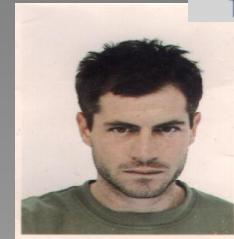


Phys Review Letter 99, 072501 (2007)

Science 320,1476 (2008)

Science 346 (2014)

60



רן שניאור (2008)



איגור קורוב (2015)



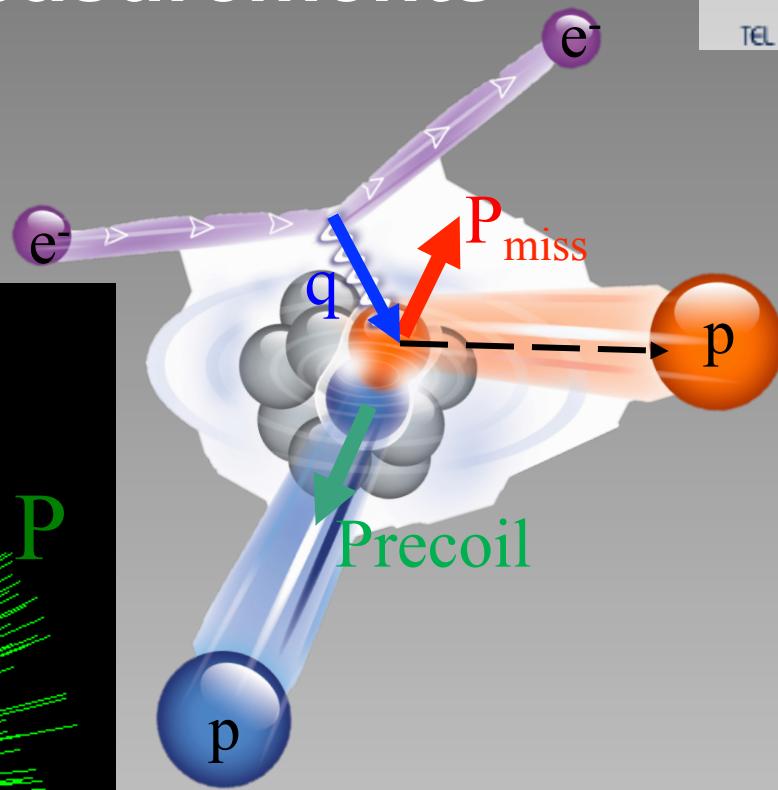
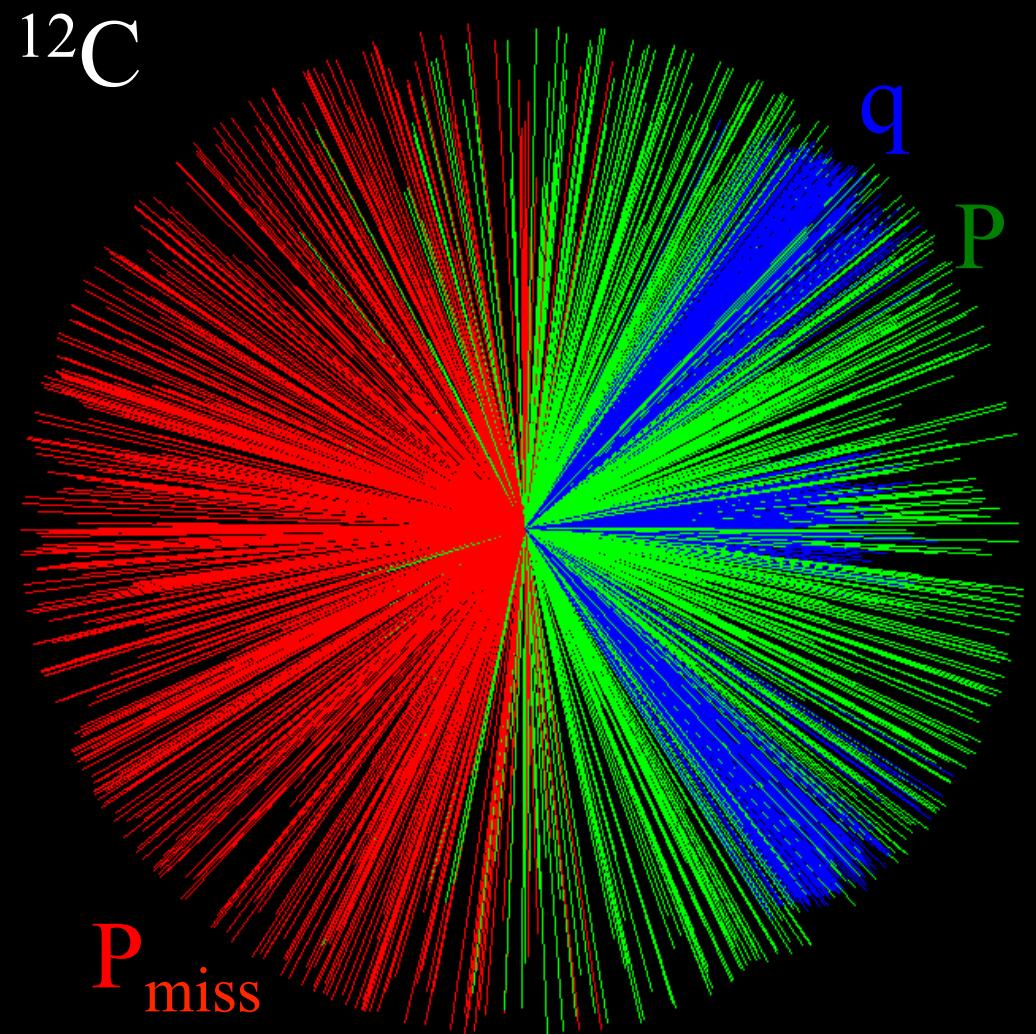
אור חנן (2015)

# triple – coincidence measurements

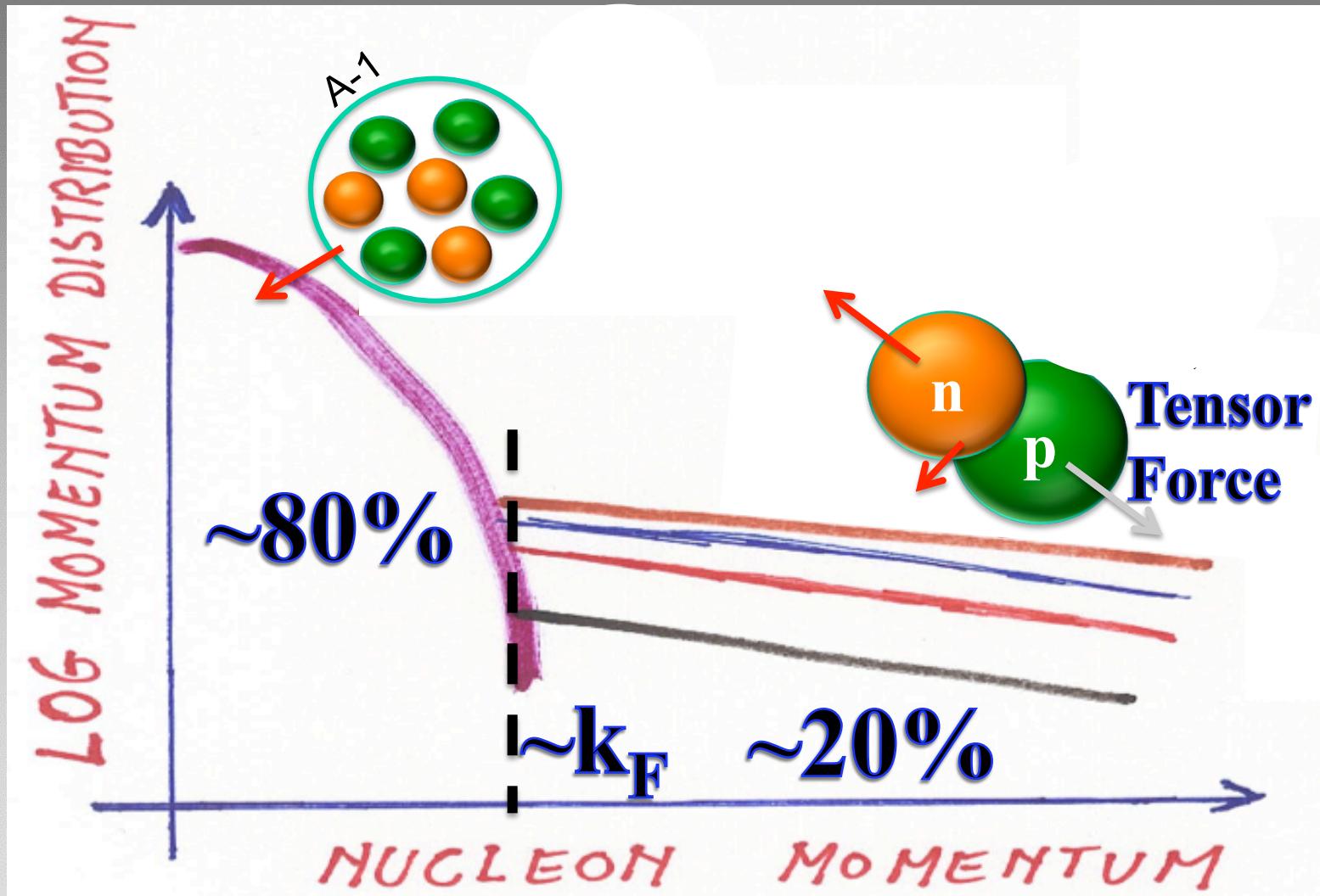


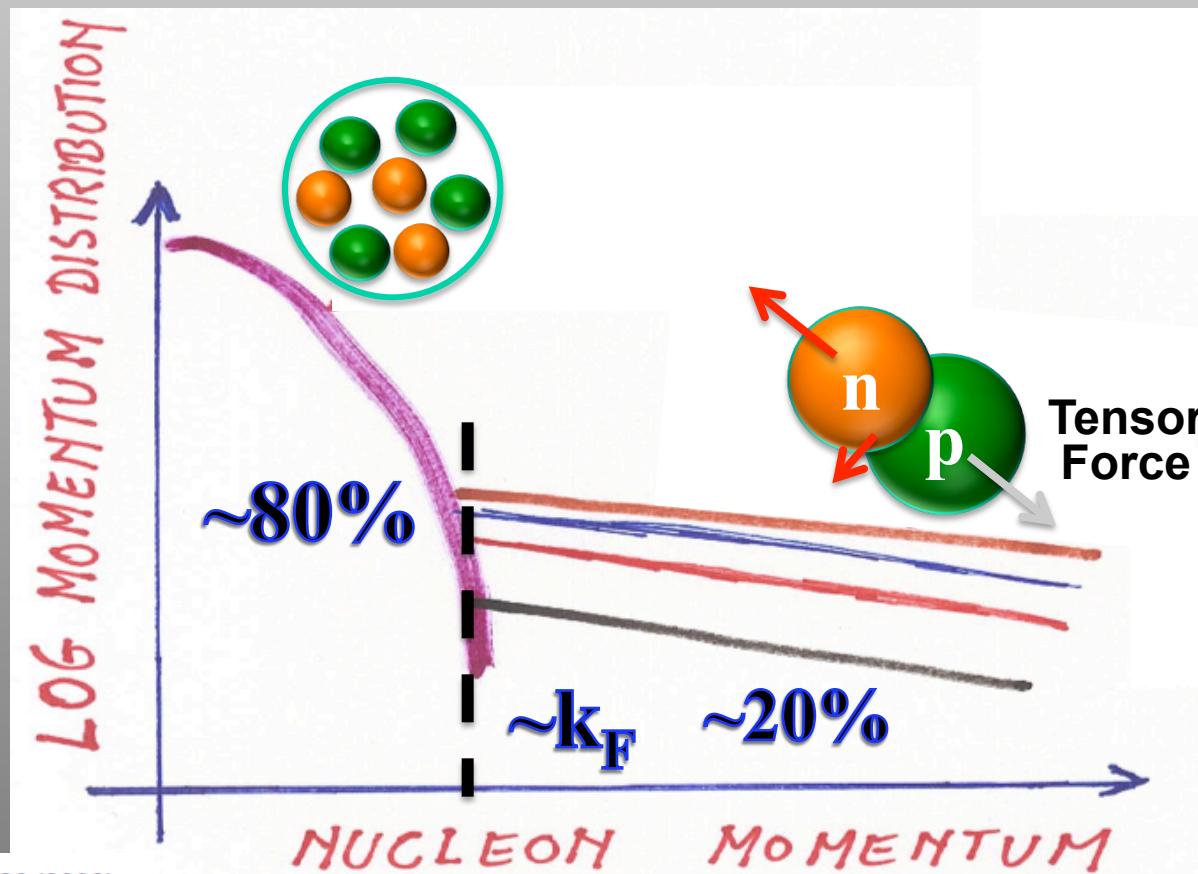
TEL AVIV UNIVERSITY

## 3D Reconstruction



# Nucleons has Isophobia (np – dominance)



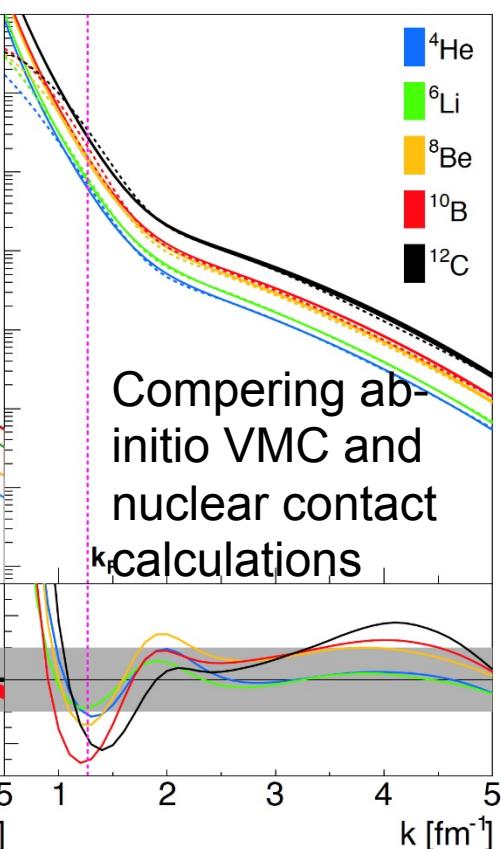


# Generalized Nuclear Contact Formalism



TEL AVIV UNIVERSITY

A universal description of SRC without many-body calculations



$$n_p(k) \xrightarrow{k \rightarrow \infty} C_{pn}^d |\varphi_{pn}^d(k)|^2 + C_{pn}^0 |\varphi_{pn}^0(k)|^2 + 2C_{pp}^0 |\varphi_{pp}^0(k)|^2$$

$l = 0, 2$   $s = 1$   $j = 1$   
np pairs

$l = s = j = 0$   
pp, nn, np pairs

The nuclear contacts and short range correlations in nuclei

R. Weiss,<sup>1</sup> R. Cruz-Torres,<sup>2</sup> N. Barnea,<sup>1</sup> E. Piasetzky,<sup>3</sup> and O. Hen<sup>2</sup>

arXiv:1612.00923

$$\Psi \xrightarrow{r_{ij} \rightarrow 0} \sum_{\alpha} \varphi_{\alpha}(\mathbf{r}_{ij}) A_{ij}^{\alpha}(\mathbf{R}_{ij}, \{\mathbf{r}\}_{k \neq ij})$$

a factorized ansatz

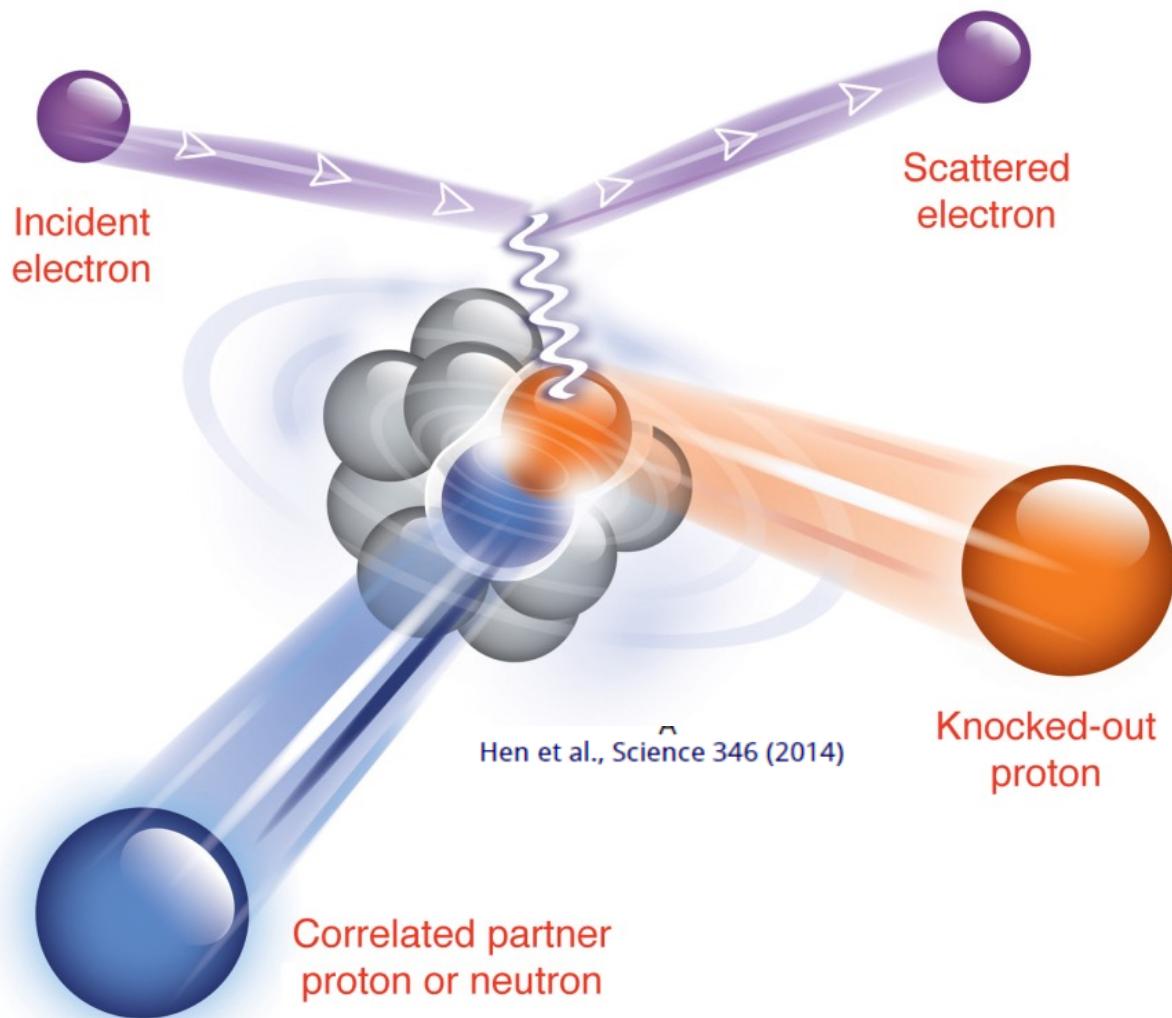
- Nucleus ( $A=2$ ) specific function

- Universal function: the zero energy solution to the 2 body problem

# ניסוי שבוצע במעבדת המאיצ' זפרסון בארץ"ב



TEL AVIV UNIVERSITY



Phys Review Letter 99, 072501 (2007)

Science 320,1476 (2008)

Science 346 (2014)



רן שניאור (2008)



איגור קורובר (2015)

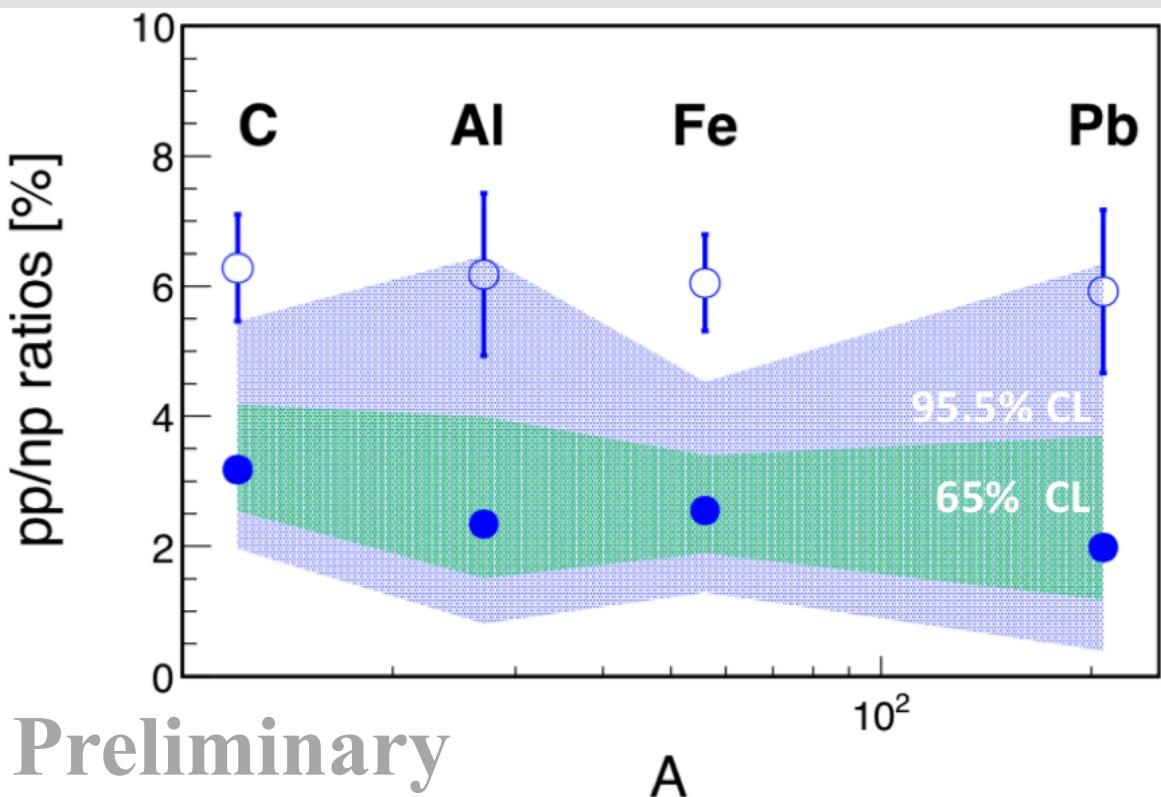


אור חן (2015)



ארץ כהן

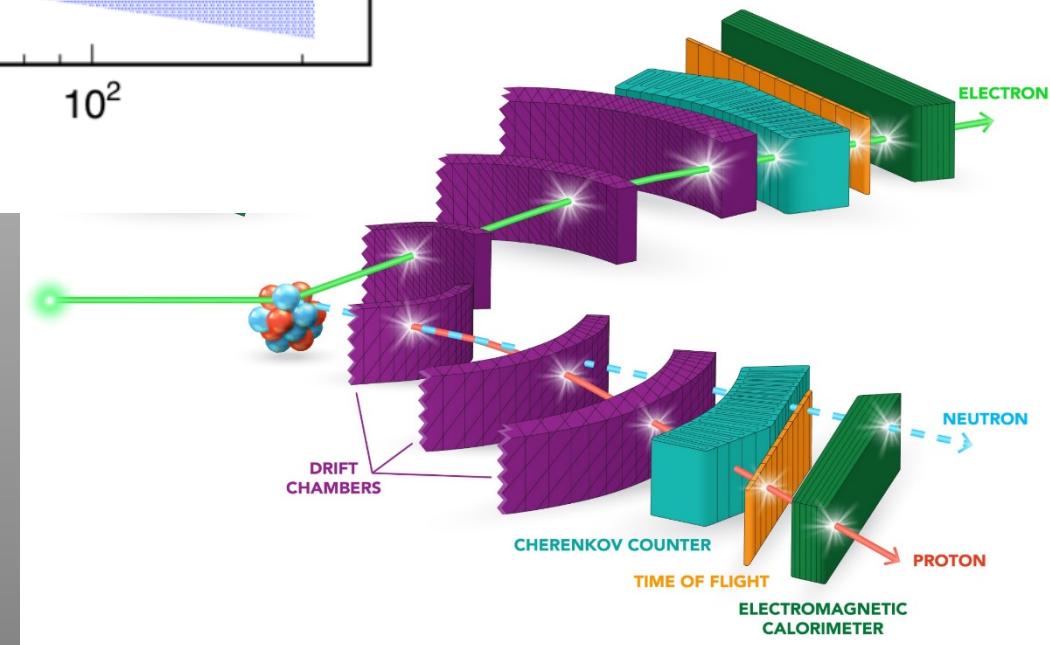
מיטל דוואר



Preliminary

A

$$A(e, e' np)$$
$$A(e, e' pp)$$



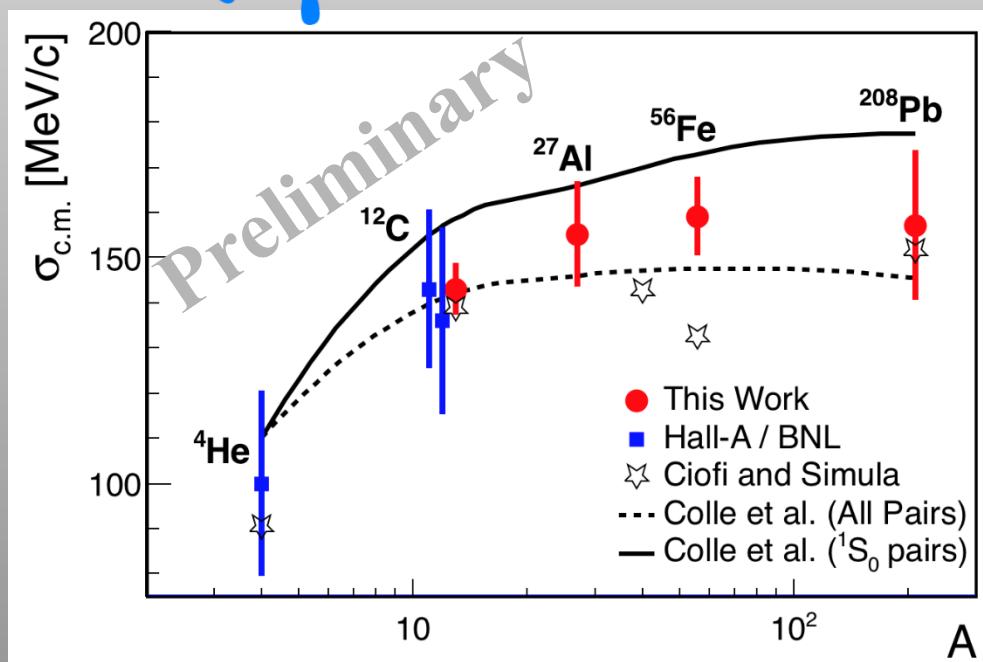
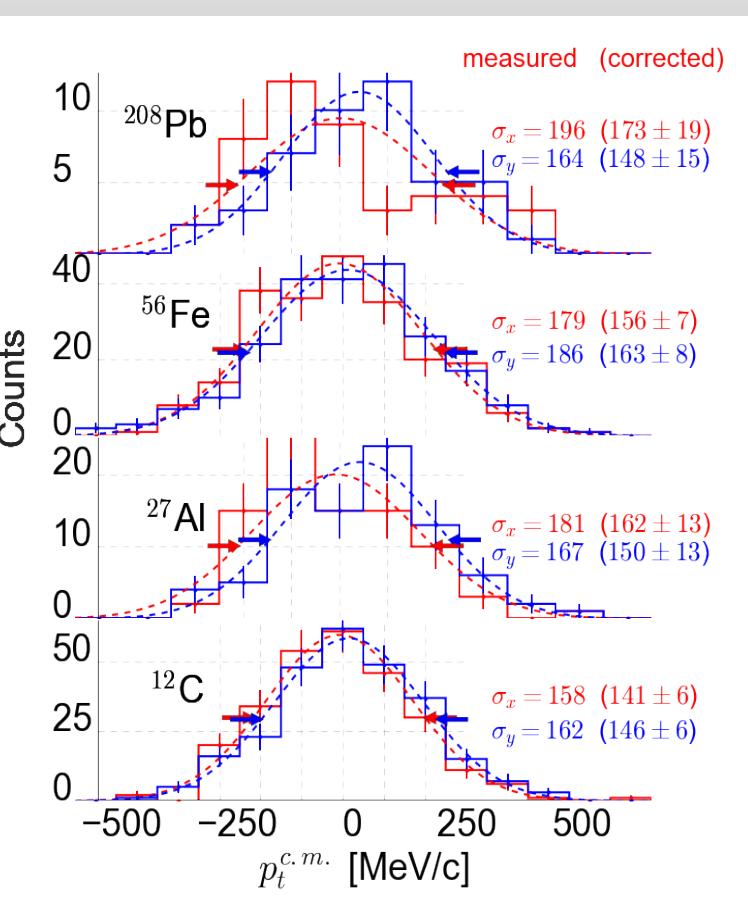
M. Duer (TAU)

# C.M. Motion of the SRC pairs

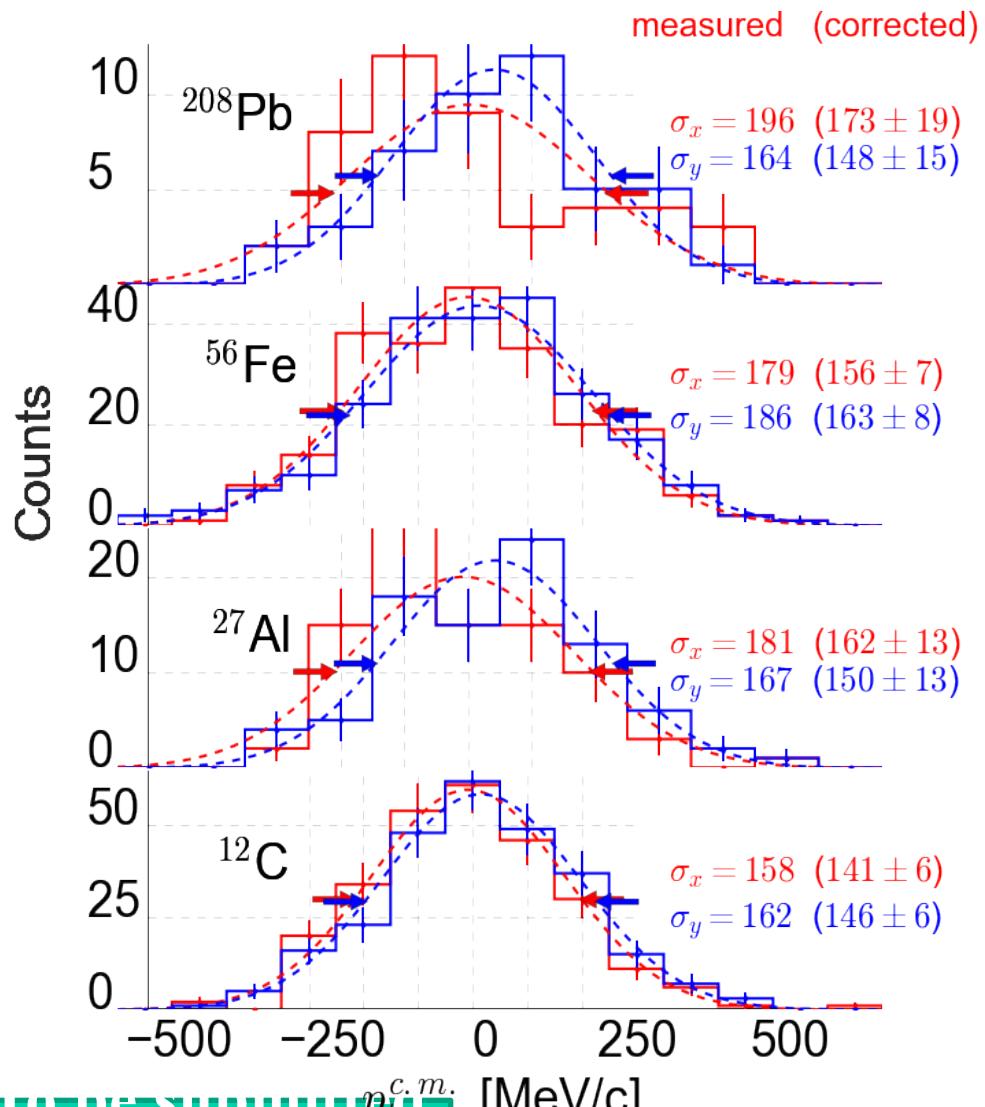


TEL AVIV UNIVERSITY

$A(e, e' pp)$



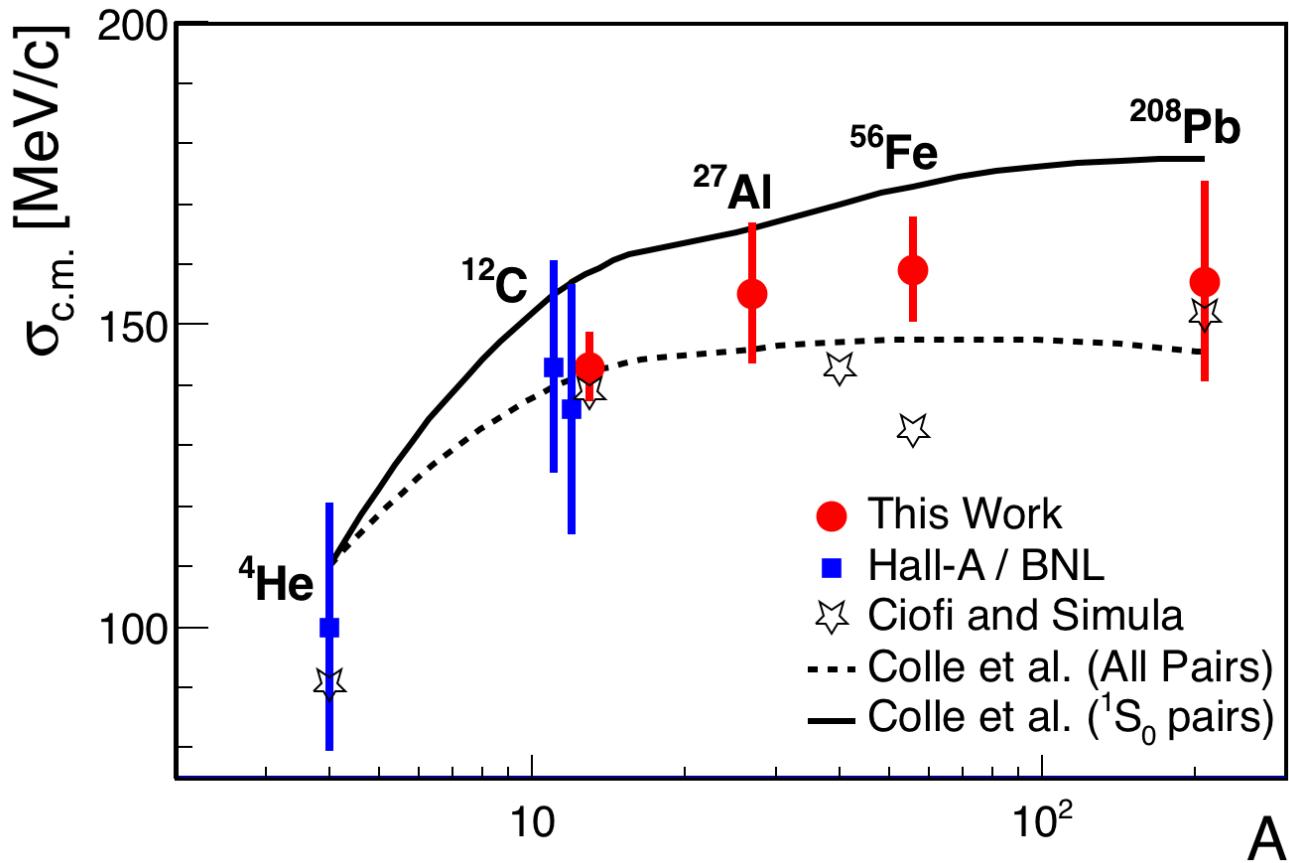
Erez Cohen (TAU)



E. Conesa et al., to be submitted to  $p_t^{c.m.}$   
next month

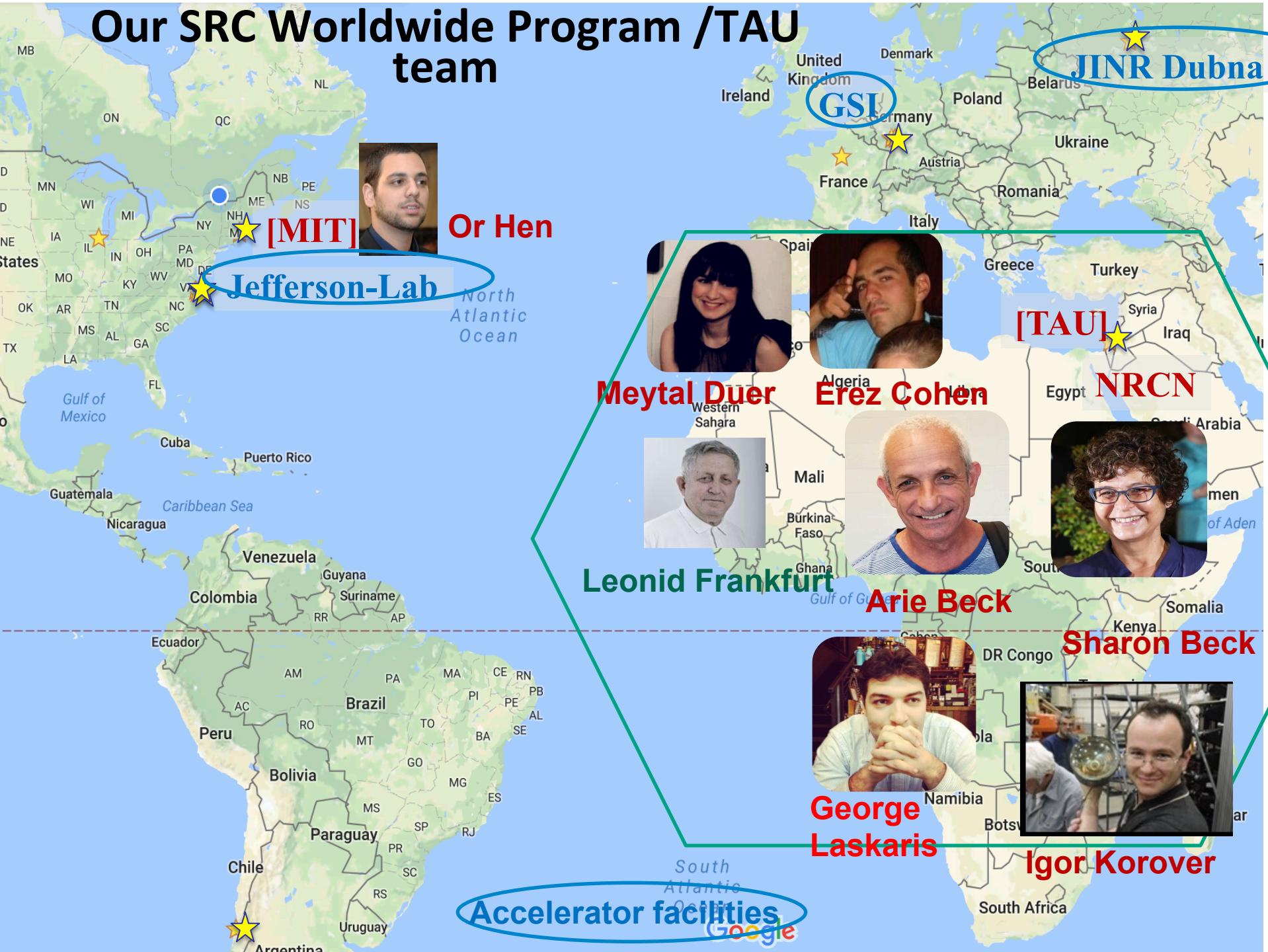


# New Results (1): C.M. Motion

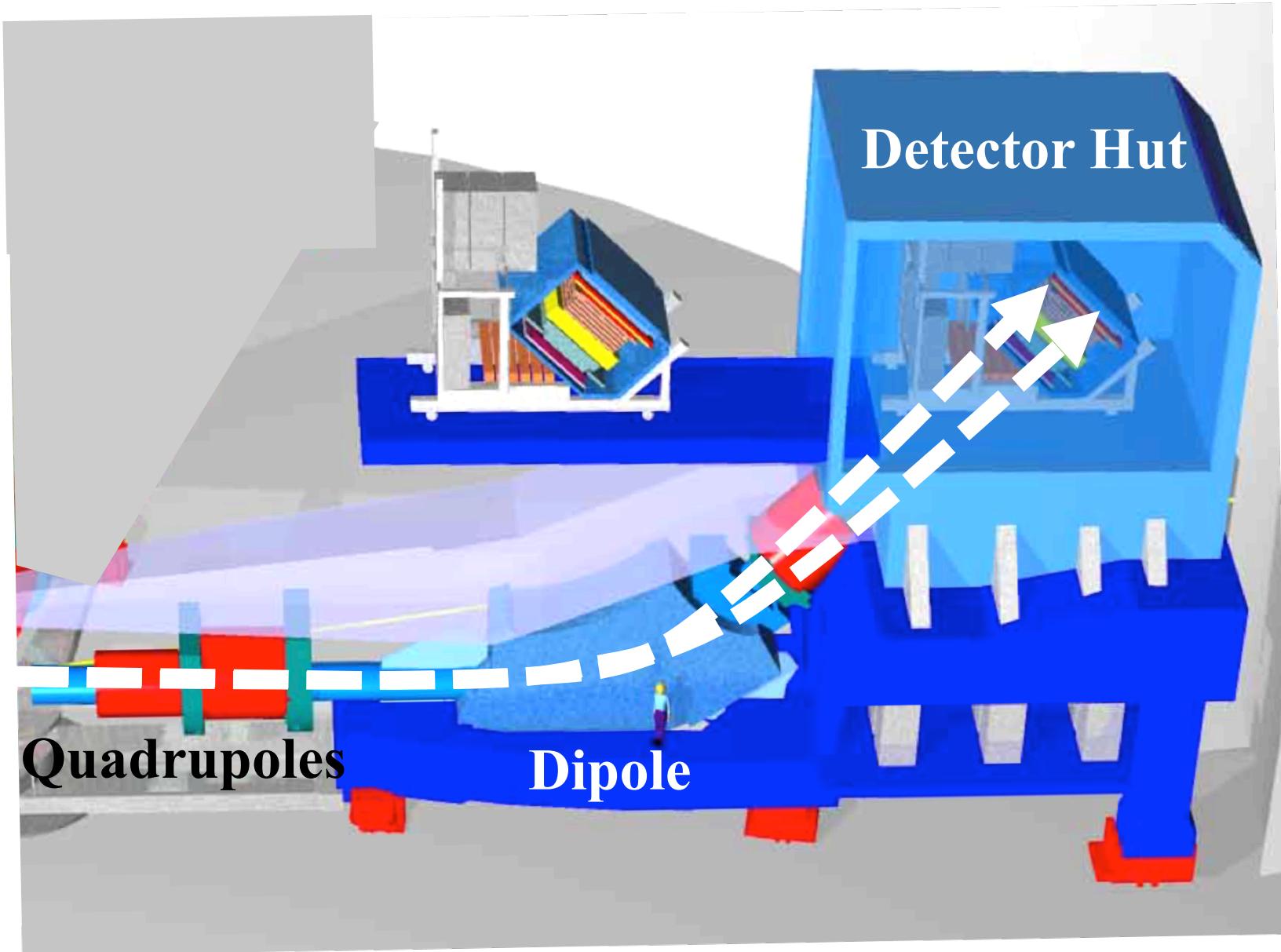


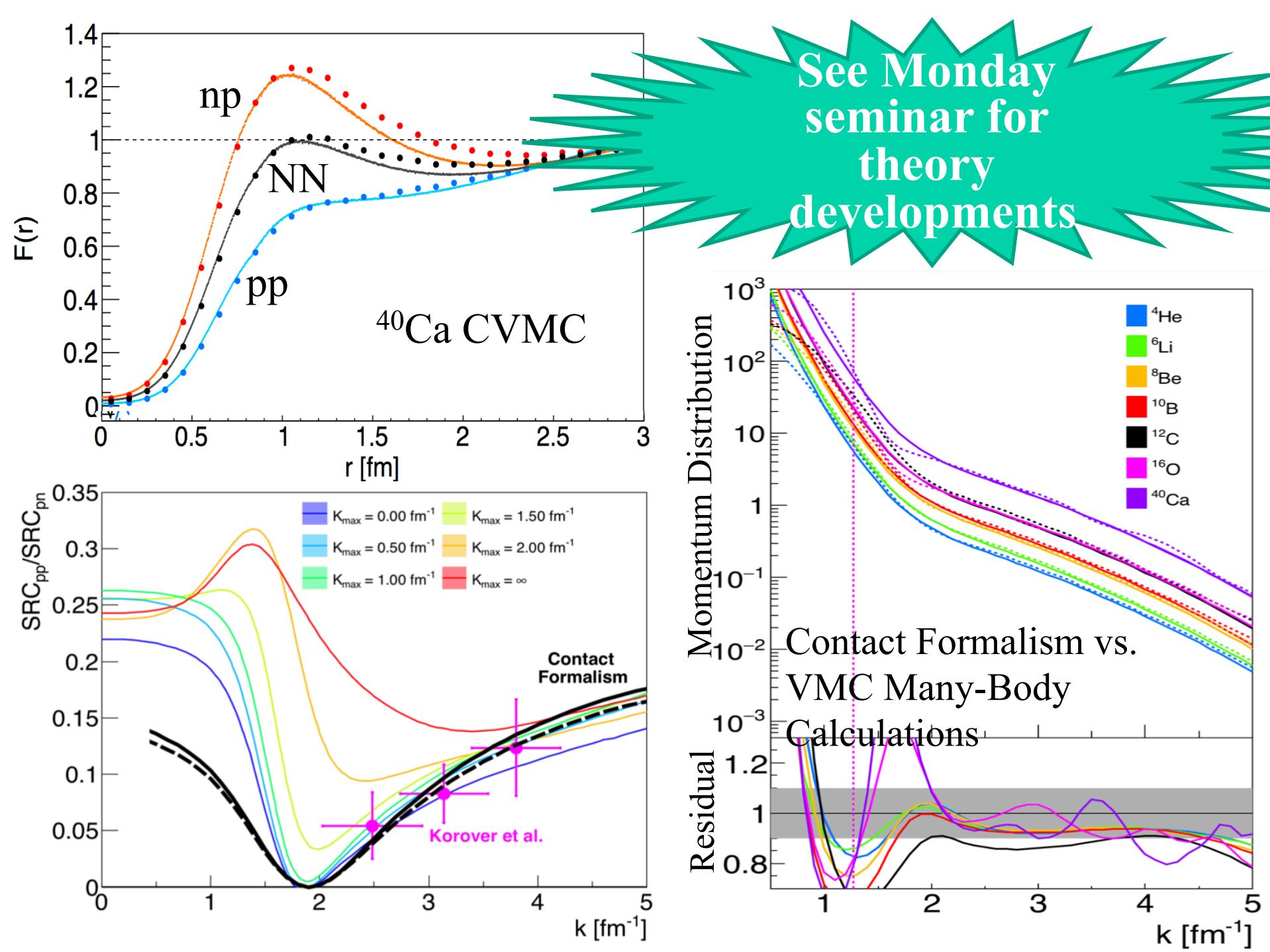
E. Colle et al., to be submitted  
next month

# Our SRC Worldwide Program /TAU team



# Hall-A: High-Resolution Spectrometers





# Scale-Separated Nuclear Structure

1. Use a factorized ansatz for the short-distance (high-momentum) part of the many-body wave function:

$$\Psi \xrightarrow{r_{ij} \rightarrow 0} \sum_{\alpha} \varphi_{\alpha}(\mathbf{r}_{ij}) A_{ij}^{\alpha}(\mathbf{R}_{ij}, \{\mathbf{r}\}_{k \neq ij})$$

- Universal function of the NN interaction.
- Taken as the zero energy solution to the 2 body problem
- Nucleus (/ system) specific function
- Depends on all nucleons except the SRC pair (primarily mean-field)

2. Test by comparing to many-body calculations *and* data from hard knockout measurements

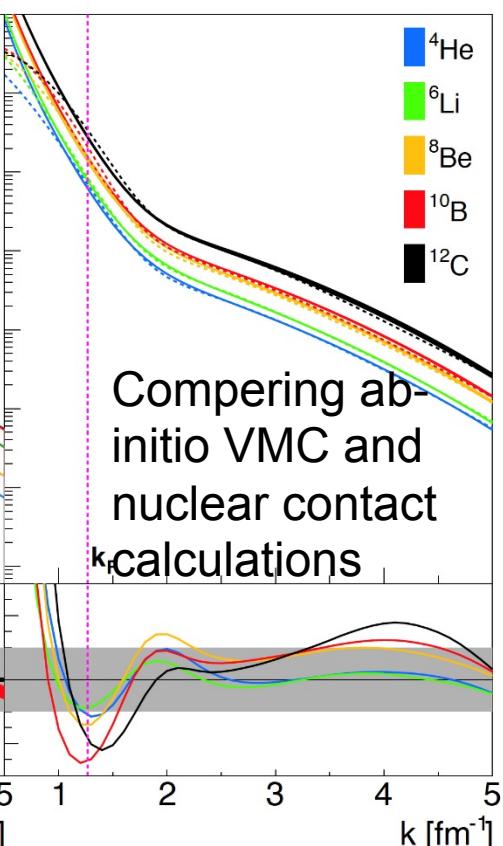


# Generalized Nuclear Contact Formalism



TEL AVIV UNIVERSITY

a factorized ansatz



$$\Psi \xrightarrow{r_{ij} \rightarrow 0} \sum_{\alpha} \varphi_{\alpha}(\mathbf{r}_{ij}) A_{ij}^{\alpha}(\mathbf{R}_{ij}, \{\mathbf{r}\}_{k \neq ij})$$

- Universal function: the zero energy solution to the 2 body problem
- Nucleus ( $A-2$ ) specific function

The nuclear contacts and short range correlations in nuclei

R. Weiss,<sup>1</sup> R. Cruz-Torres,<sup>2</sup> N. Barnea,<sup>1</sup> E. Piasetzky,<sup>3</sup> and O. Hen<sup>2</sup>

Phys. Lett. B780 (2018) 211.

A universal description of SRC:

$$n_p(k) \xrightarrow{k \rightarrow \infty} C_{pn}^d |\varphi_{pn}^d(k)|^2 + C_{pn}^0 |\varphi_{pn}^0(k)|^2 + 2 C_{pp}^0 |\varphi_{pp}^0(k)|^2$$

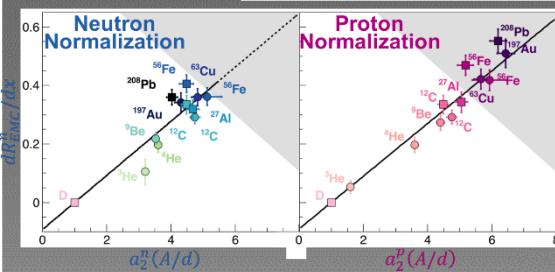
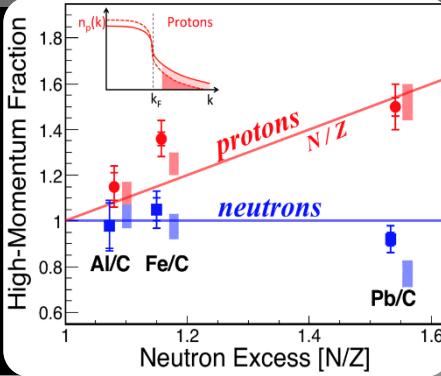
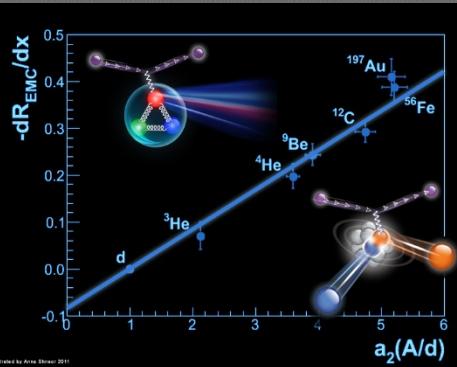
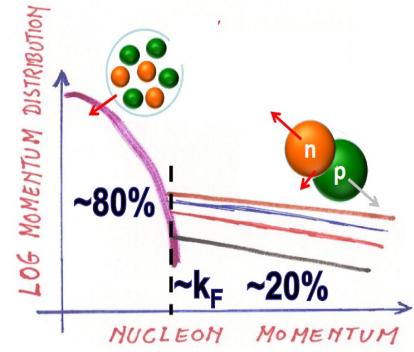
$l = 0, 2$   $s = 1$   $j = 1$   
np pairs

$l = s = j = 0$   
pp, nn, np pairs

# Summary



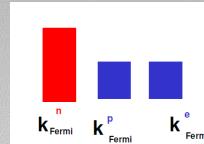
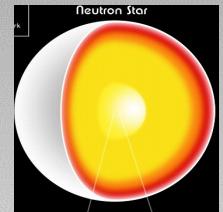
TEL AVIV UNIVERSITY



## np-SRC dominance

- In neutron-rich nuclei:
- In neutron stars  
proton momentum > SFG prediction.

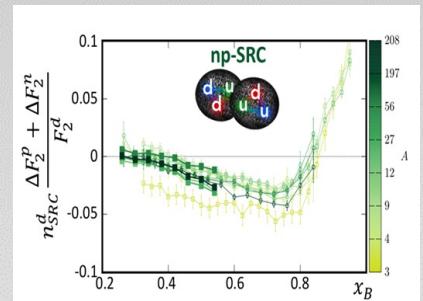
$$\left\langle E^p_k \right\rangle > \left\langle E^n_k \right\rangle$$



$$N/Z \approx 95\% / 5\% = 20$$

## EMC is associated 2N SRC

- EMC: Nucleons are normally normal except when close to others.  
Proton EMC effect > neutron EMC effect.



# Two-component interacting Fermi systems

For ultra-cold atomic gas systems of two different type of fermions with short-range interaction

$$a \gg d \gg r_{eff}$$

Thermodynamics can be describe by a single parameter: ‘contact’

The contact measure the number of close different –fermions pairs



Adapted from Debora Jin (JILA).

# Two-component interacting Fermi systems

## The contact term

Please forget about nuclear physics for a moment



Adapted from Debora Jin (JILA).

# The contact and universal relations

$$a \gg d \gg r_{\text{eff}}$$

For systems of two different type of fermions

With short-range interaction and large scattering length  
between different fermions

Thermodynamics can be describe by a single parameter: ‘contact’

The contact measure the number of close different –fermions pairs

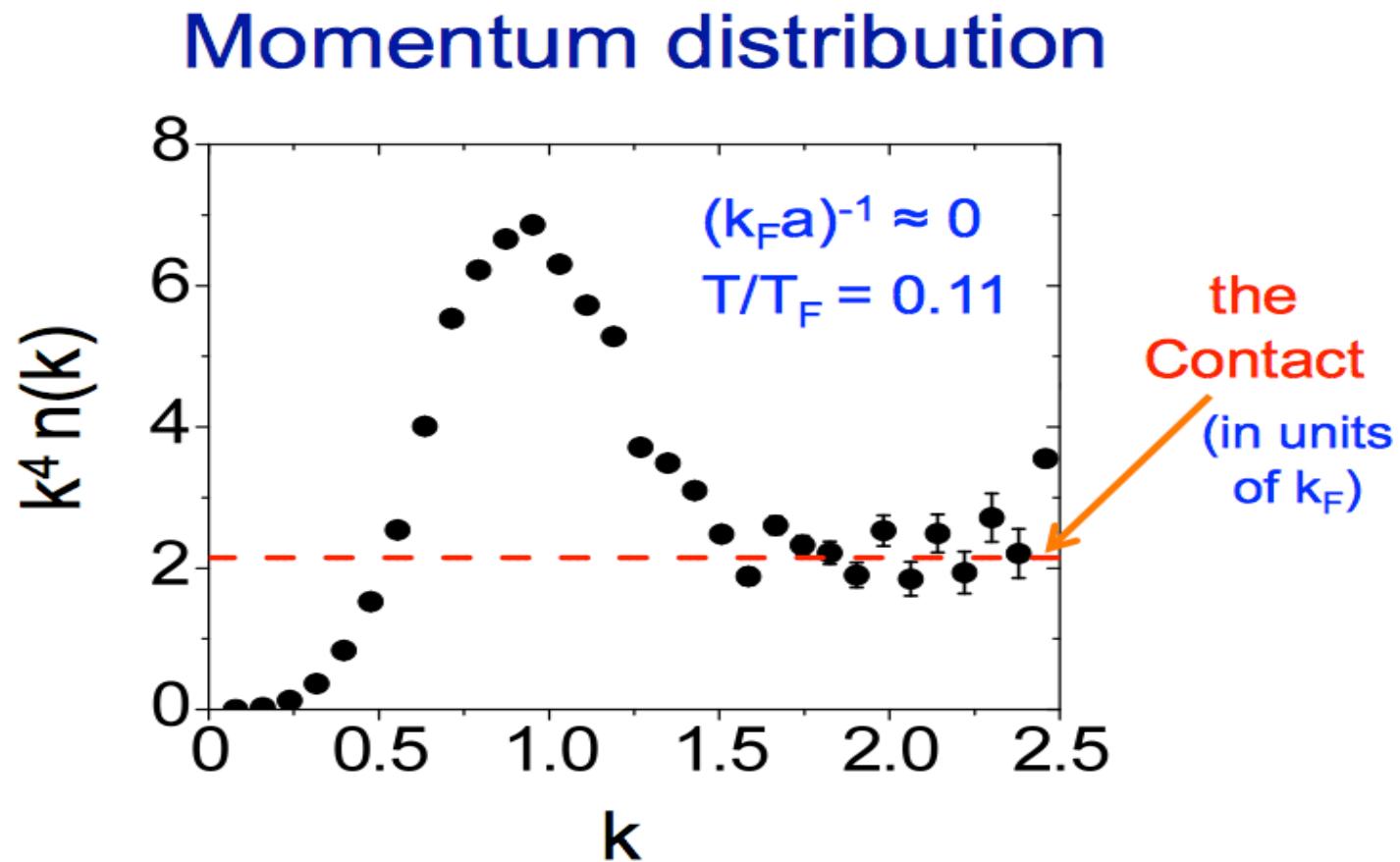
S. Tan Annals of Physics 323 (2008) 2952, ibid 2971,

In these systems there is high- momentum tail:  $n(k) = C / k^4$

C is the contact term

Units: (length)<sup>-1</sup>

Experiments with two spin-state mixtures of ultra-cold  $^{40}\text{K}$  and  $^6\text{Li}$  atomic gas systems extracted the contact term and verified the universal relations

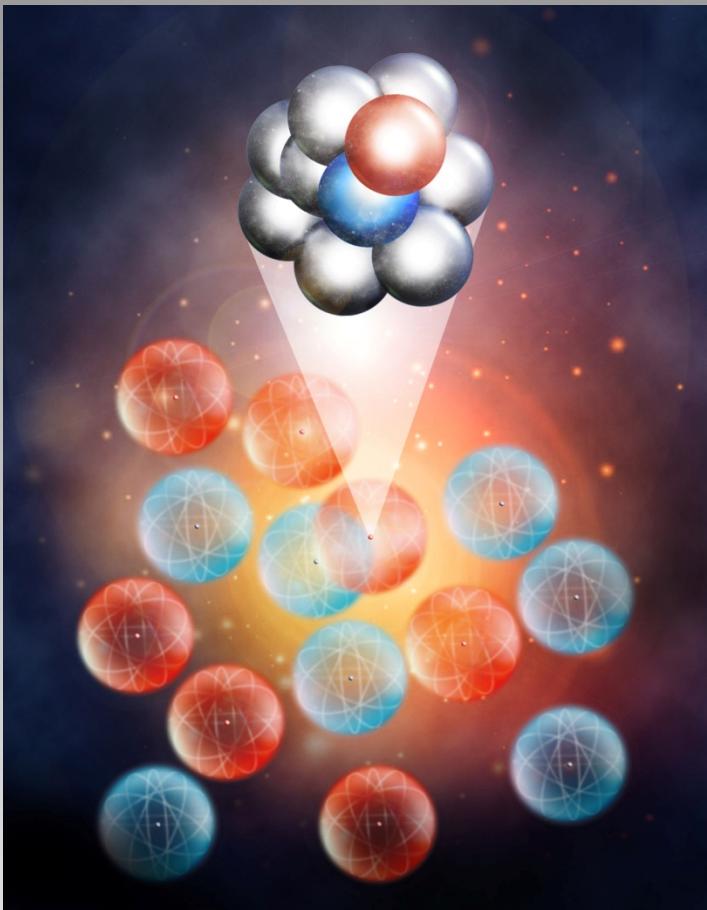


# Is this relevant to the only Gordon conference in nuclear physics ?

$$\rho = 10^{44} \text{ m}^{-3}$$

$$k_F \approx 2.5 \cdot 10^8 \text{ eV/c}$$

strong NN interaction  
(tensor)  
Self Bound



$$\rho = 10^{21} \text{ m}^{-3}$$

$$k_F \approx 1.6 \text{ eV/c}$$

atom-atom interaction  
(S-wave )  
Confined in external potential



Adapted from Debora Jin (JILA).

# What about nuclear contact ?

$$a \gg d \gg r_{eff} \quad ?$$

$$d = \rho^{-1/3} \approx 1.8 \text{ fm}$$

$$r_{eff} \approx \frac{\hbar}{2 \cdot m_\pi \cdot c} \approx 0.7 \text{ fm} \quad \text{Tensor force}$$

The high-momentum tail is predominantly:

J=1 S and D pairs :

$$T=0 \text{ S=1 L=0 } {}^3S_1$$

$$T=0 \text{ S=1 L=0 } {}^3D_1$$

$$a({}^3S_1) = 5.424 \pm 0.003 \text{ fm}$$

$$a(\approx 5.4 \text{ fm}) > d(1.8 \text{ fm}) > r_{eff}(0.7 \text{ fm})$$

# Another (same) way to look at it

$$ka \gg 1$$

$$kr_0 \ll 1$$

$$k \geq 250 \text{ MeV/c}/197 = 1.3 \text{ fm}^{-1}$$

$$a = 5.4 \text{ fm}$$

$$(ka) \approx 7 \gg 1$$

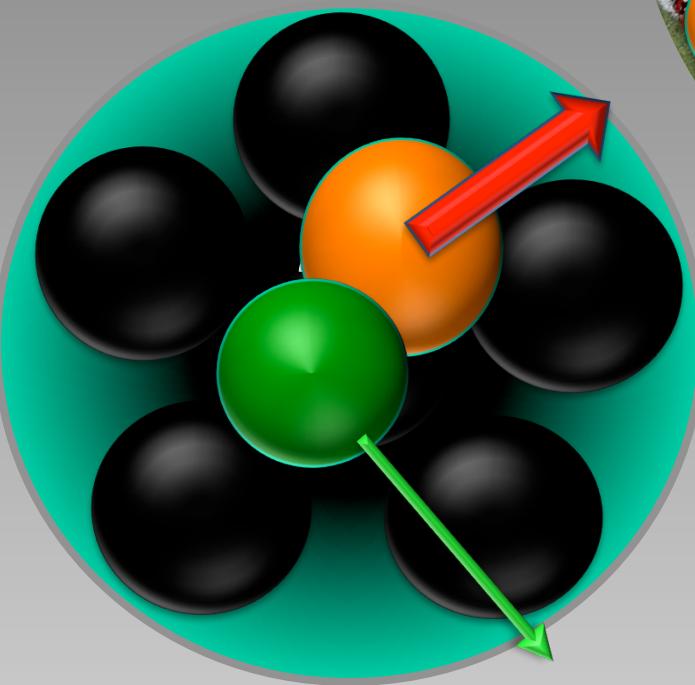


$$(ka)^{-1} \approx 0.1$$

$$r_0 = 0.7 \text{ fm}$$

$$kr_0 \approx 1$$

# triple – coincidence measurements



# קינמטיקה הפוכה



TEL AVIV UNIVERSITY



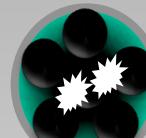
nuclear beam



leading protons



target proton



A-2



recoil proton

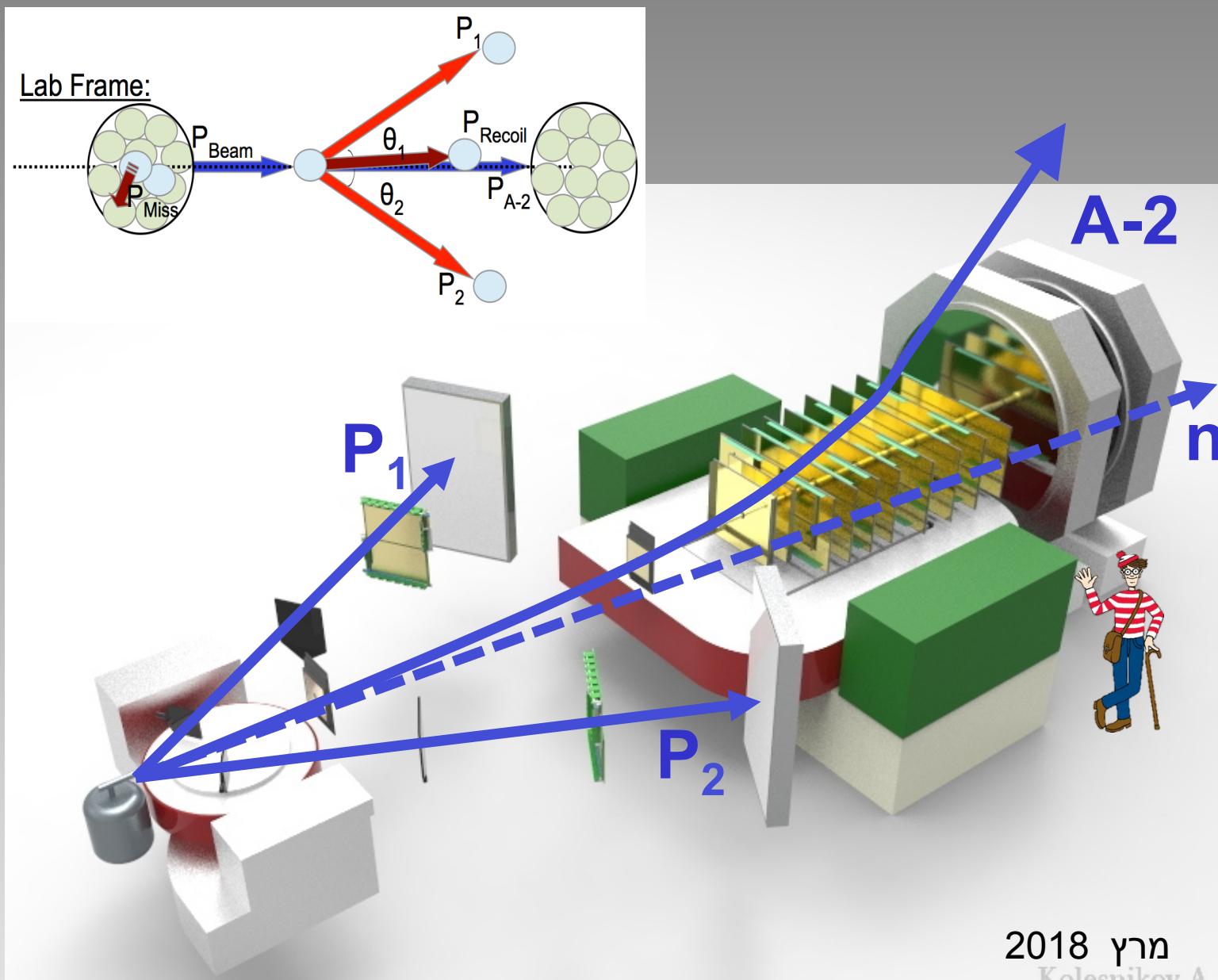




-15° +25cm snow

Dubna, Rusia, March 2018

# רוסיהJINR מערך הניסוי ב



# **QNP2018**

**8th International Conference on  
Quarks and Nuclear Physics**

**November 13(Tue) – 17(Sat), 2018  
Tsukuba, Ibaraki, JAPAN**

Pauli principle



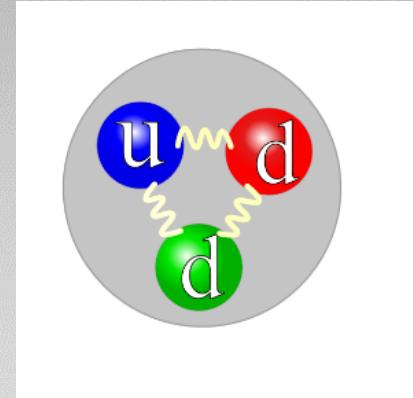
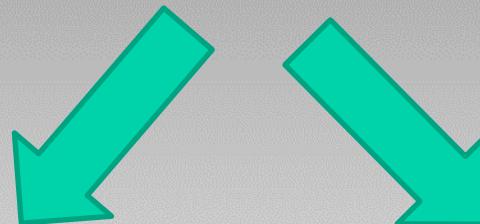
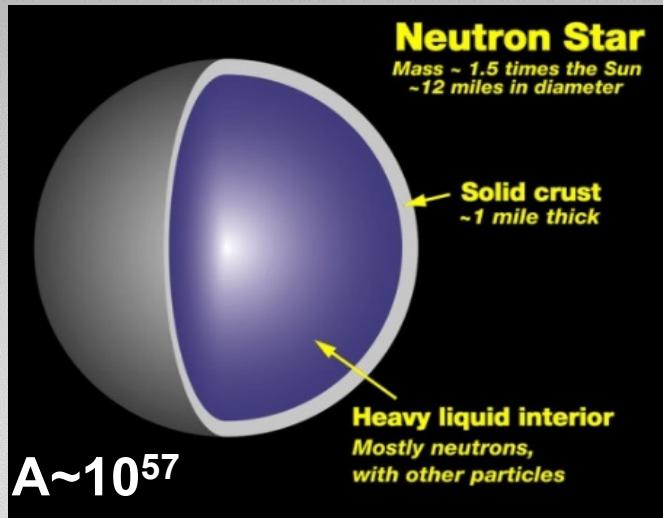
$$\langle E_n^{kin} \rangle > \langle E_p^{kin} \rangle$$

~~$\langle E_n^{kin} \rangle > \langle E_p^{kin} \rangle$~~

In neutron-rich nuclei ( $N > Z$ )

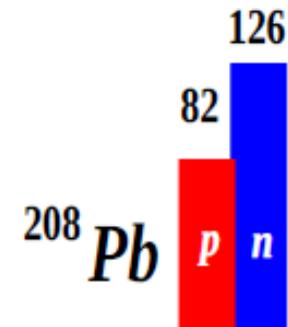
$$\langle E_p^{kin} \rangle > \langle E_n^{kin} \rangle$$

Protons move faster than neutrons



The EMC effect

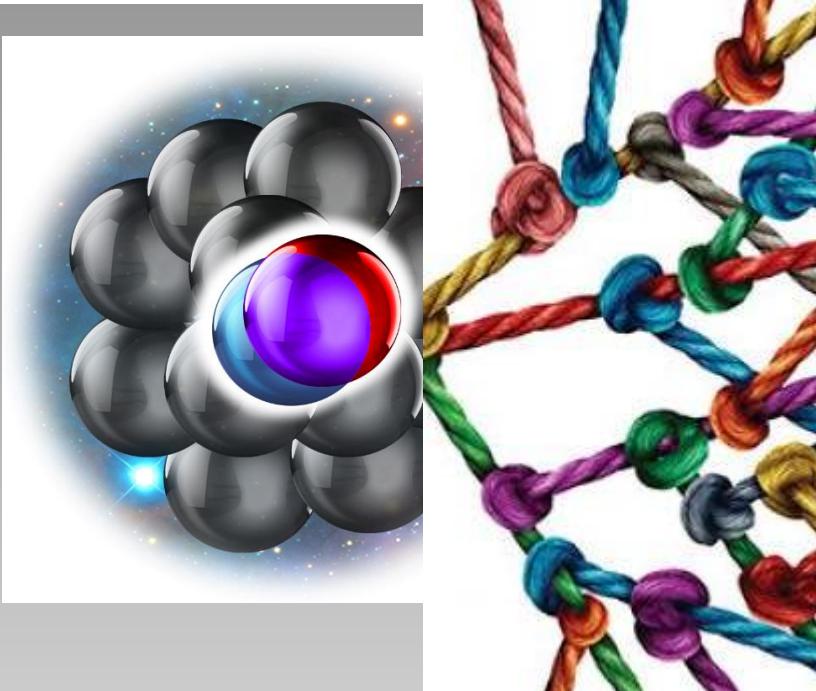
Neutron Stars



# QNP2018

Quark and gluon structure of hadrons:

- parton distribution functions, generalized parton distributions,
- transverse momentum distributions, high-energy hadron reactions, ...



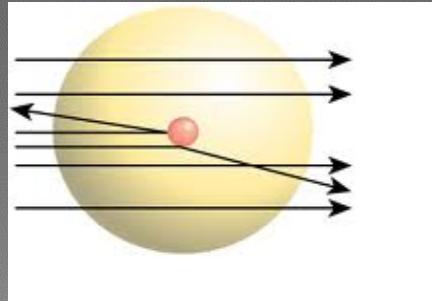
Hot and cold dense matter:

- quark-gluon plasma, color glass condensate, dense stars,
- strong magnetic field, mesons in nuclear medium, hadronization



TEL AVIV UNIVERSITY

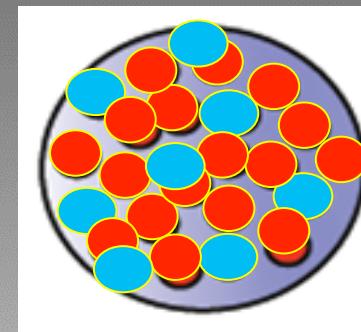
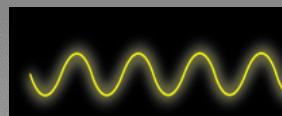
# Physicists view nuclei with different resolution



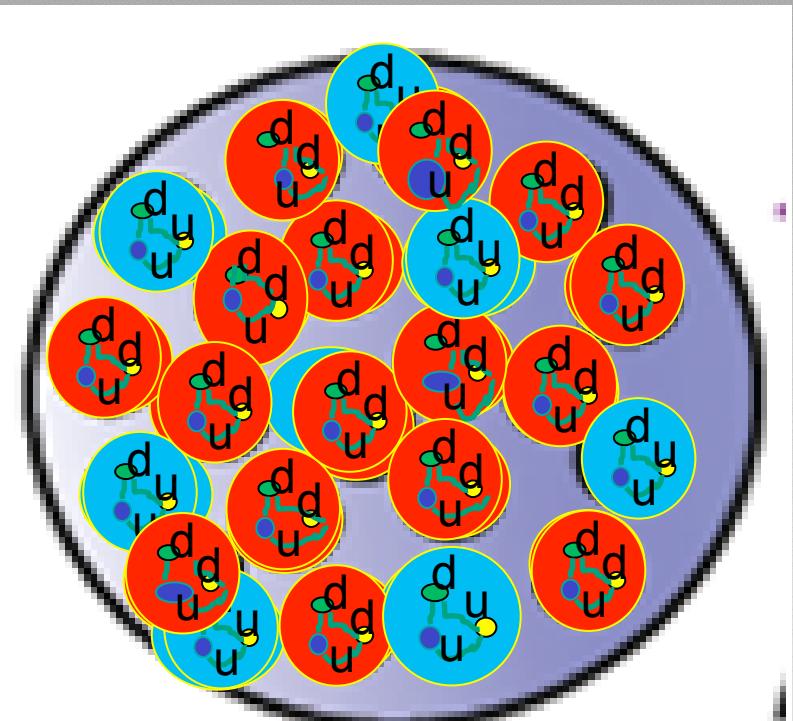
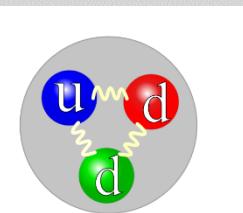
Rutherford scattering



**Nucleons in the Nucleus**



**Quarks  
in Nucleons  
in the Nucleus**



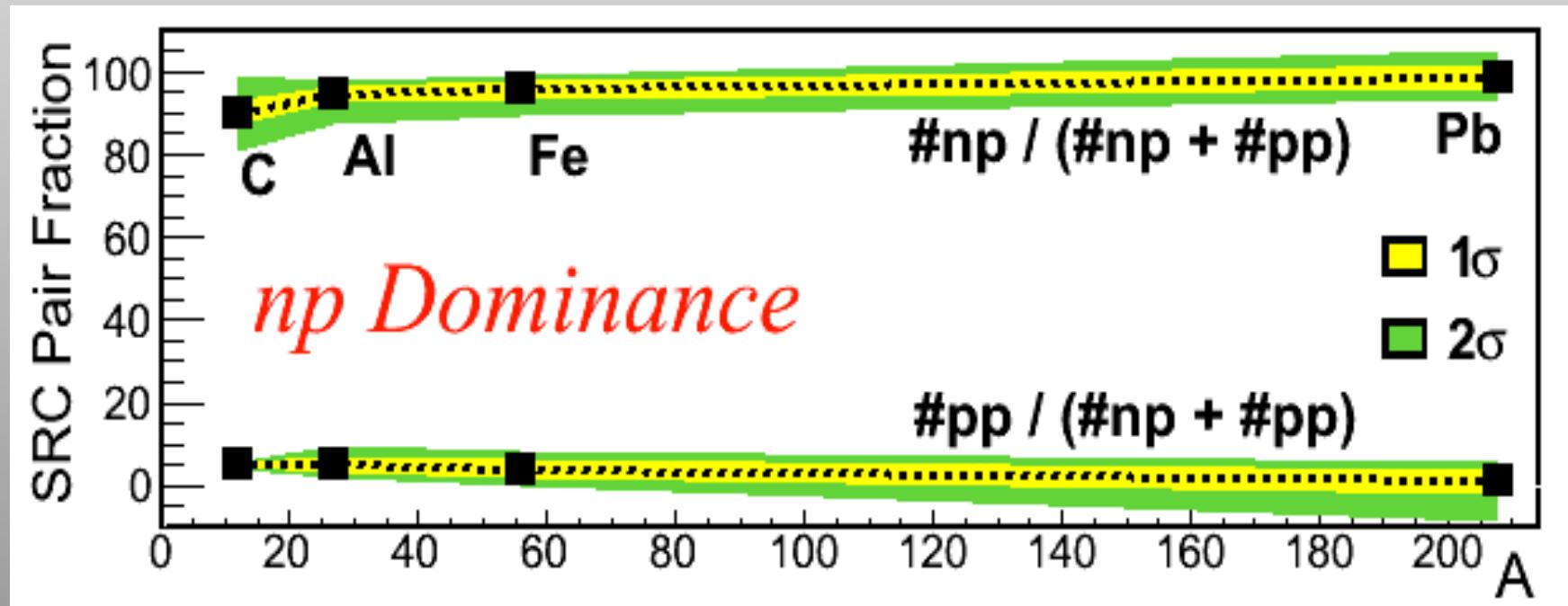
**Close  
nucleons**



**Quarks and Nuclear Physics**



$A(e, e' p)$  and  $A(e, e' pp)$



**Pauli principle**



$$\langle E_n^{kin} \rangle > \langle E_p^{kin} \rangle$$

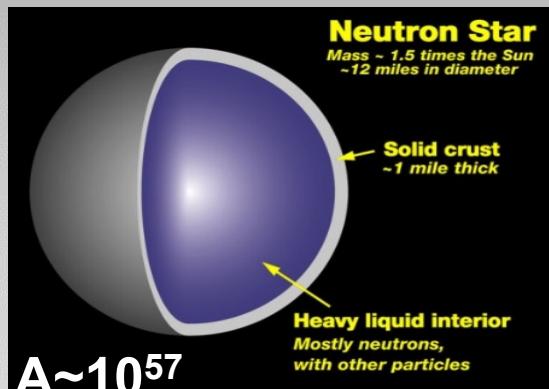
In neutron-rich nuclei ( $N > Z$ )

$$\langle E_p^{kin} \rangle > \langle E_n^{kin} \rangle$$

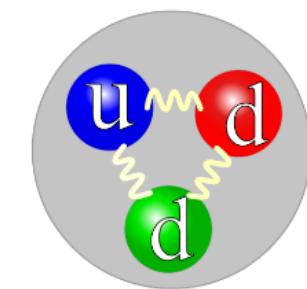
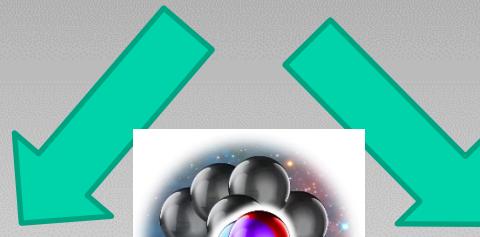
**Protons move faster than neutrons**



## Neutron Stars



## The EMC effect

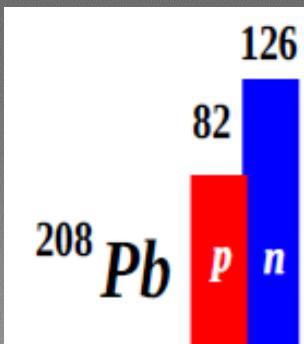


Hot and cold dense matter:

- quark-gluon plasma, color glass condensate, dense stars,
- strong magnetic field, mesons in nuclear medium, hadronization, ...

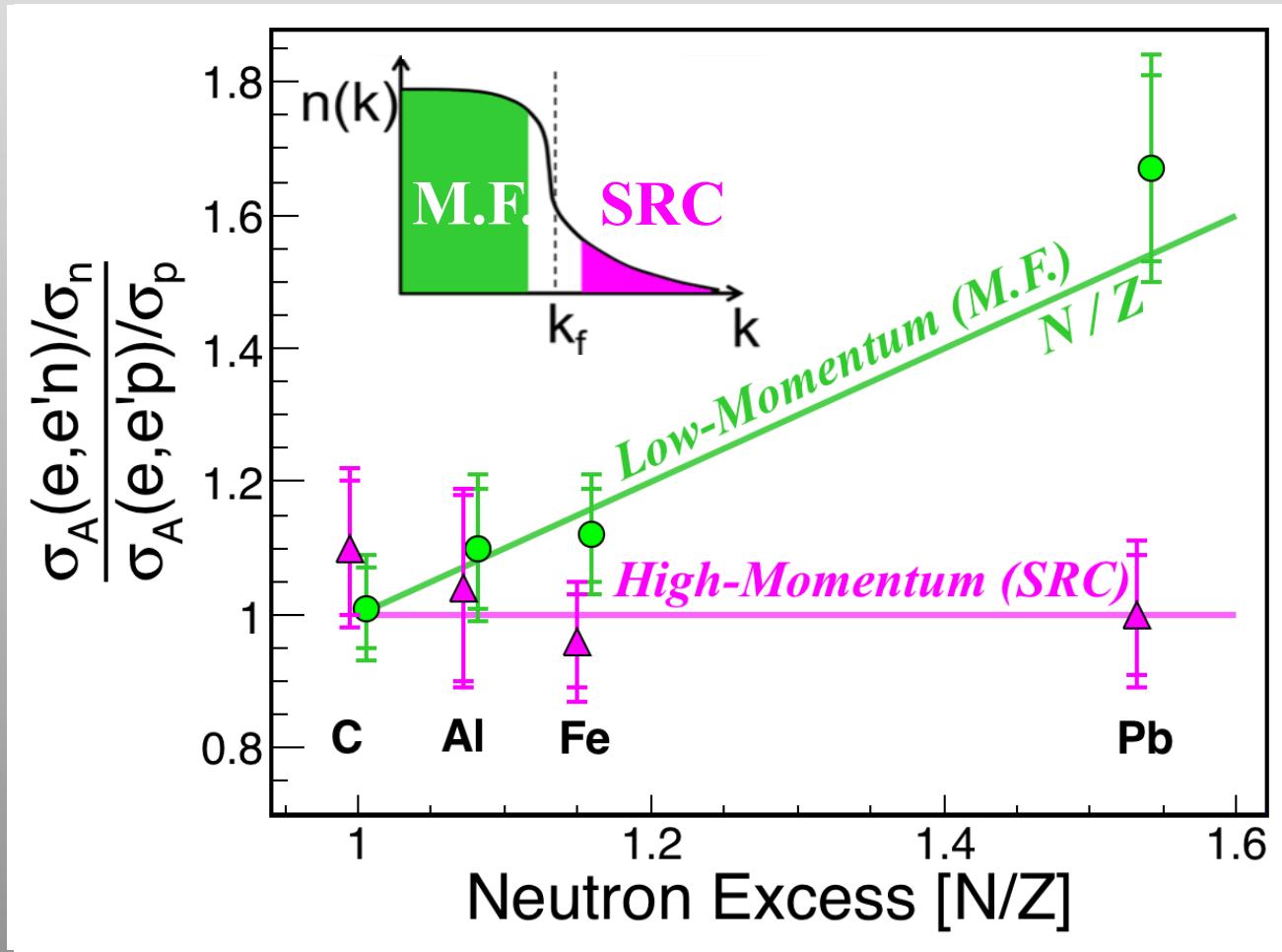
Quark and gluon structure of hadrons:

- parton distribution functions, generalized parton distributions,
- transverse momentum distributions, high-energy hadron reactions,

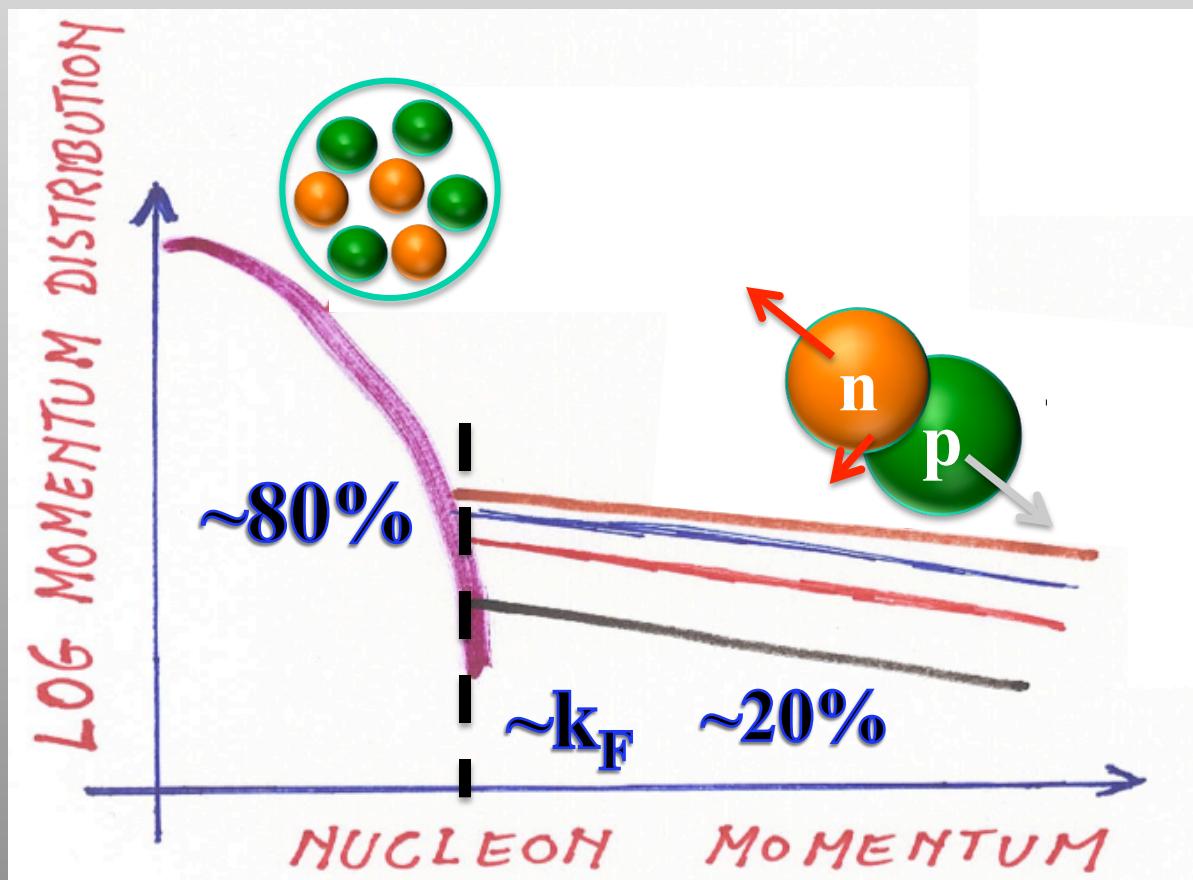


# Proton vs. Neutron Knockout

$A(e, e' p)$   $A(e, e' n)$

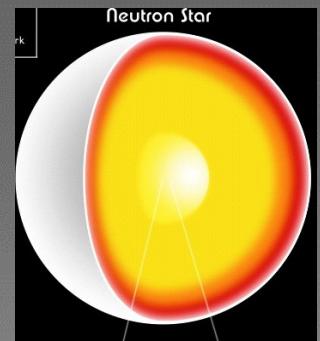


► Same # of high-momentum protons and neutrons



Subedi et al., Science 320 (2008)

What about np-dominance in asymmetric nuclei ?



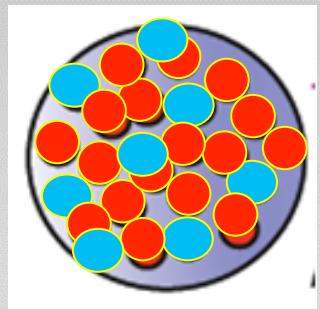
# Nuclear density

## Asymmetry

$$A \approx \frac{M_e}{M_p} \approx 10^{57}$$

$$N/Z \approx 95\% / 5\% = 20$$

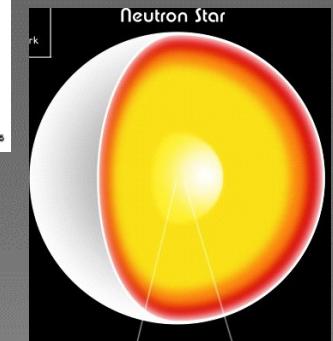
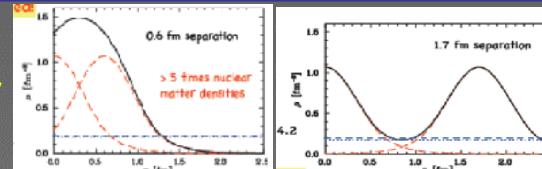
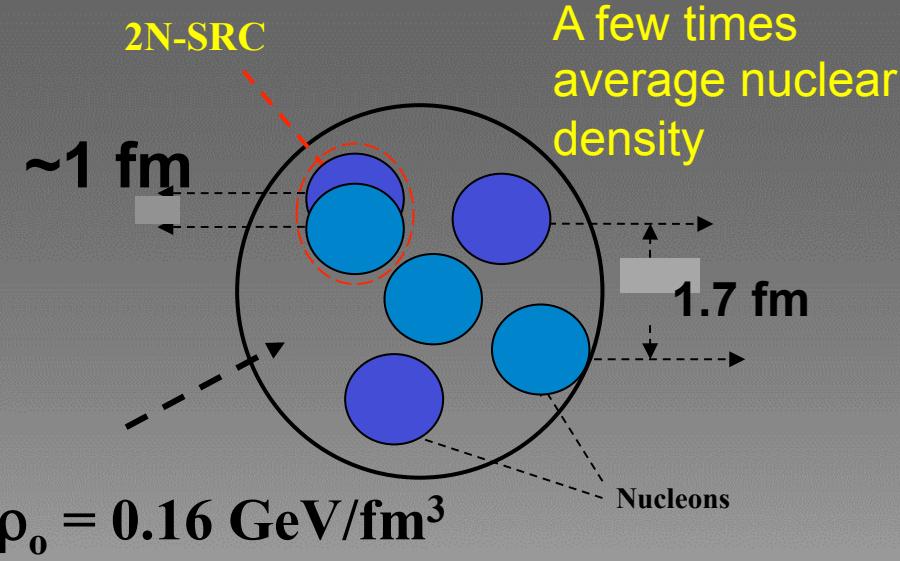
$$\rho_0 = 2 - 5 \rho_0$$



$$A < 200 \text{ (300)}$$

$$N/Z < 1.5 \text{ (2.5)}$$

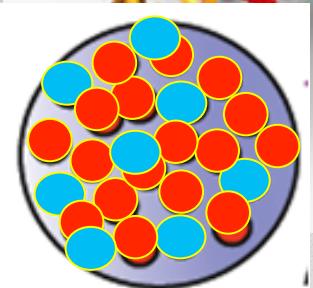
$$\rho_0 = 0.17 N/fm^3 = 0.16 GeV/fm^3$$



$$A \approx \frac{M_e}{M_p} \approx 10^{57}$$

$$N/Z \approx 95\% / 5\% = 20$$

$$\rho_0 = 2 - 5 \rho_0$$



$$A < 200 \text{ (300)}$$

$$N/Z < 1.5 \text{ (2.5)}$$

$$\rho_0 = 0.17 N / fm^3$$

2N-SRCs: pairs of nucleons close together in the nucleus (wave functions overlap)

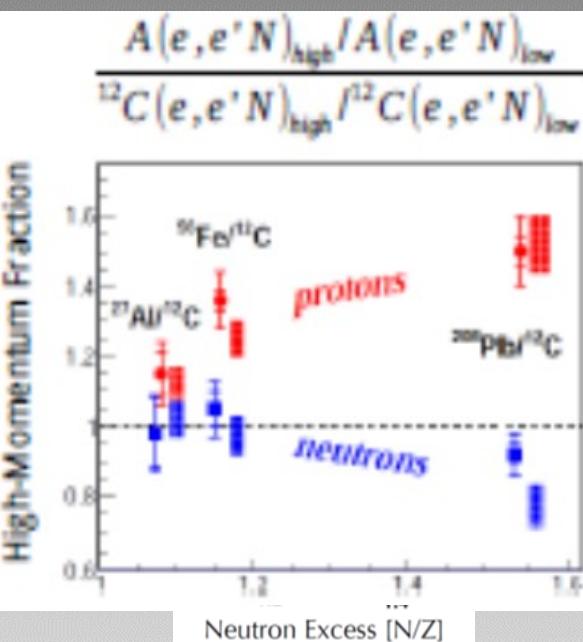
**Pauli principle**



$$\langle E_n^{kin} \rangle > \langle E_p^{kin} \rangle$$

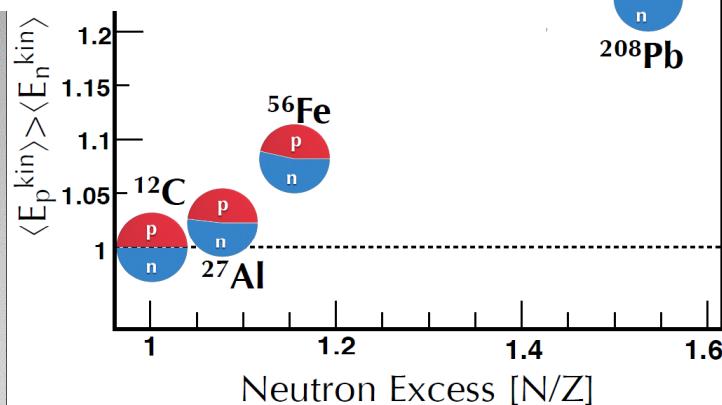
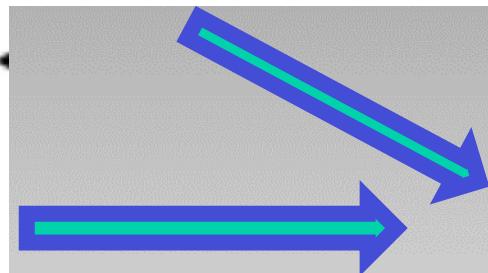
~~$\langle E_n^{kin} \rangle > \langle E_p^{kin} \rangle$~~

In neutron-rich nuclei ( $N>Z$ )



**Simple np-dominance model**

$$n_p(k) = \begin{cases} \eta \cdot n_p^{M.F.}(k) & k < k_0 \\ \frac{A}{2Z} \cdot a_2(A/d) \cdot n_d(k) & k > k_0 \end{cases} \quad (\text{for neutrons: } Z \rightarrow N)$$



**Inversion of the momentum sharing:**

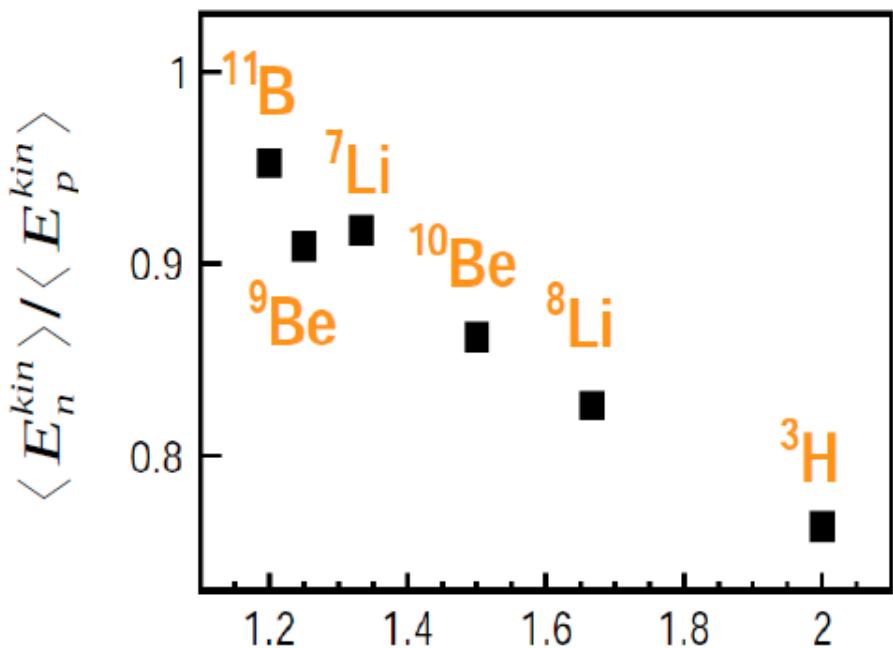
$$\langle E_p^{kin} \rangle > \langle E_n^{kin} \rangle$$

**Protons move faster than neutrons**

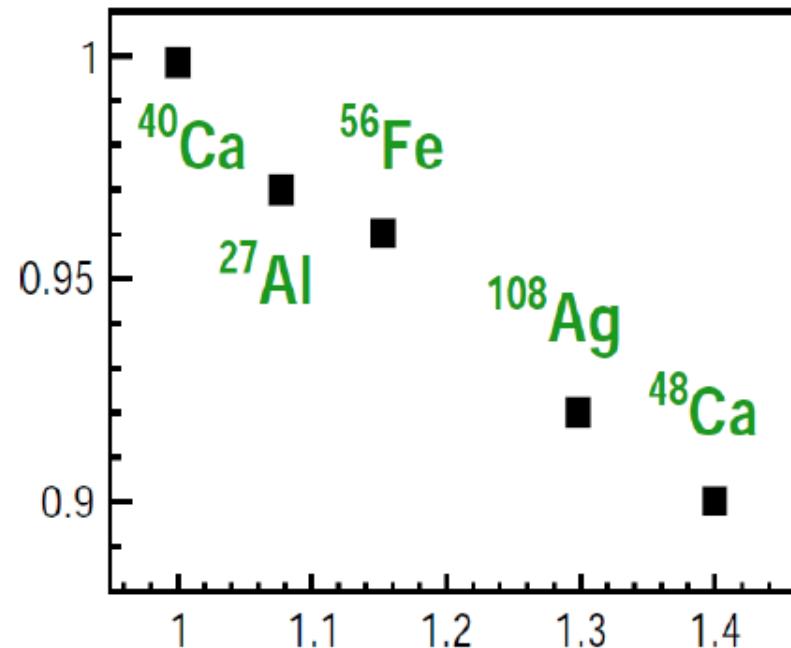


# Theoretical predictions (N>Z)

## Light nuclei (A<12)



## Heavy nuclei (A>12)



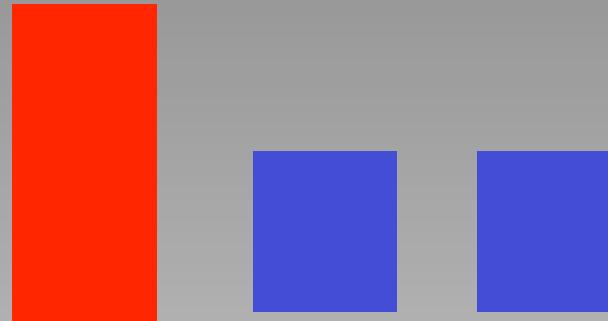
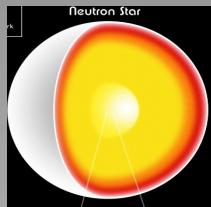
Z>N:

$$^3\text{He} \quad \text{N/Z} = 1/2 \quad \langle E_n^{kin} \rangle / \langle E_p^{kin} \rangle = 1.31$$

Wiringa, Phys. Rev. C89, 024305 (2014)

Ryckebusch, J. Phys G42 (2015)

- ~95% neutrons, ~5% protons ~5% electrons ( $\beta$ -stability).
- three separate Fermi gases (n, p, e).



$$N/Z \approx 95\% / 5\% = 20$$

$$\frac{\langle E_k^p \rangle}{\langle E_k^n \rangle} = \frac{k_F^p}{k_F^n} = \left( \frac{n_p}{n_n} \right)^{2/3} = \left( \frac{5 - 10\%}{90 - 95\%} \right)^{2/3} \approx \frac{1}{5 - 10}$$

$$\frac{\langle E_k^p \rangle}{\langle E_k^n \rangle} > 1$$

SRC in neutron rich nuclei

in neutron stars



# Acknowledgment



## Collaborators



Massachusetts Institute of Technology



Or Hen



Meytal Duer



OLD DOMINION  
UNIVERSITY



Larry  
Weinstein



Massachusetts Institute of Technology



Barak Schmookler

Data-Mining collaboration  
CLAS collaboration



# Asymmetric nuclei



TEL AVIV UNIVERSITY

$A(e, e' pp)$  and  $A(e, e' pn)$

