Getting closer to the hard core – short-range correlations in nuclei

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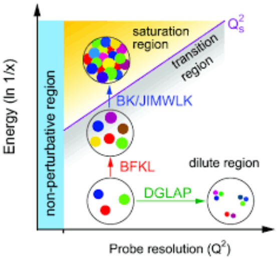
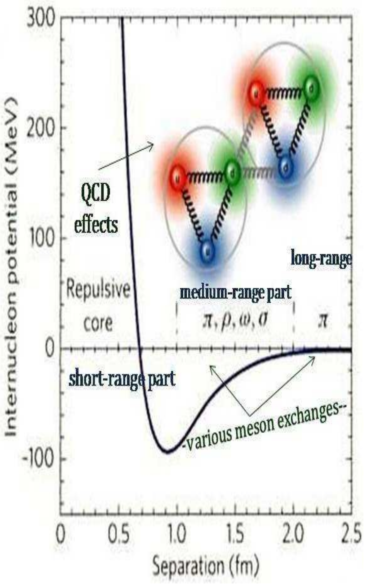
IIHE Seminar, ULB-VUB, January 2020



Embedding nucleons in an environment



- Nucleon-nucleon interaction is multifaceted
- Self-bound nuclei for a variety of (N, Z)
- Bound neutrons are "stable"
- Two-component Fermi liquids with a large ($\sim$ 50%) packing fraction
- Nuclei possess a rich dynamics
  1. "Long-range" correlations extending over size of the nucleus ("low" $(E, \vec{p})$ or Q^2)
  2. "Short-range" correlations (SRC) extending over size of the nucleon ("high" $(E, \vec{p})$ or Q^2)

SHORT-LONG: SCALE SEPARATION

Central research questions of this presentation

- **Is there a comprehensive picture of nuclear SRC? *(Quest to learn about stylized facts of SRC)***
  1. Variation with mass A
  2. Isospin (flavor) composition of SRC (pp&nn&pn)
  3. Neutron-to-proton asymmetry (N/Z) dependence of SRC
- How to forge links between nuclear models dealing with SRC and observables? Recent data from electron-nucleus scattering $(A(e,e'), A(e,e'N), A(e,e'pX))$
- Are there connections between nucleon and quark medium modifications?

After WYSIATI ("What You See Is All There Is") D. Kahneman, *"Thinking, Fast and Slow"* (2012).

Universal physics from short-distance correlations

1. **Vicszek model for understanding emergent collective motion from local interactions: neighboring particles tend to align their velocities**
2. **Competition between an aligning force and a stochastic force**
3. **Two different energy ("time") scales emerge:**
   - **Particles in high-density zones tend to align their velocities (liquid phase, SRC nucleons)**
   - **Particles in low-density zones move in a disorderly fashion (gas phase, IPM nucleons)**

OUTLINE

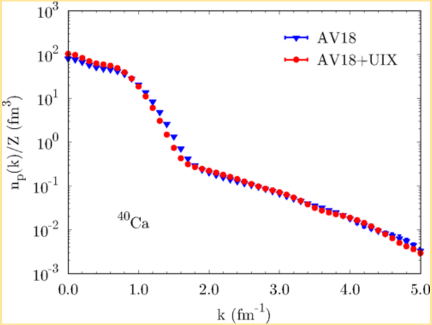
1. Low-order correlation operator approximation (LCA) to compute effect of SRC (nuclear structure & nuclear reactions)
2. Apply LCA to the computation of nuclear momentum distributions (NMDs) for 15 $A(N,Z)$: $4 \leq A \leq 208$; $1 \leq \frac{N}{Z} \leq 1.54$
   CHECK: Compare LCA results to ab-initio ones
3. Aggregated effect of SRC and its evolution with A and N/Z
   CHECK: a_2 data from $A(e,e')$
4. Isospin composition of SRC (pp&nn&pn)
   CHECK: $A(e,e'pp)$, $A(e,e'pn)$, $A(e,e'p)$ data for ^{12}C, ^{27}Al, ^{56}Fe, ^{208}Pb in "SRC" kinematics
5. N/Z asymmetry dependence of SRC
   CHECK: $A(e,e'pp)$, $A(e,e'pn)$, $A(e,e'p)$, $A(e,e'n)$ data for ^{12}C, ^{27}Al, ^{56}Fe, ^{208}Pb in "SRC" kinematics
6. Size and generative mechanisms of the EMC effect

Single-nucleon momentum distributions

- Probability to find a nucleon with momentum p

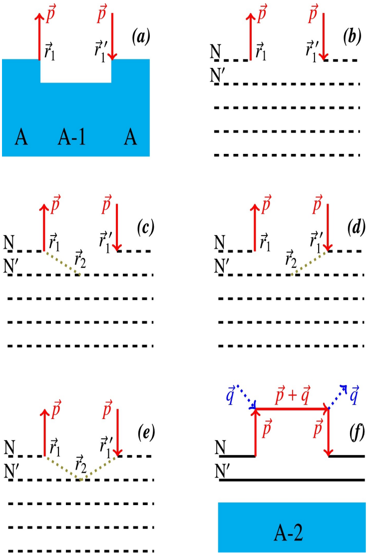
$$n^{[1]}(p) = \int \frac{d^2\Omega_p}{(2\pi)^3} \int d^3\vec{r}_1 \; d^3\vec{r}_1{}' \; d^{3(A-1)}\{\vec{r}_{2-A}\} e^{-i\vec{p}\cdot(\vec{r}_1{}'-\vec{r}_1)} \times \Psi^*(\vec{r}_1, \vec{r}_{2-A})\Psi$$

- Simplest model: Fermi gas (exclusion principle):
  $n^{[1]}(p) \sim \theta\,(p_F - p)$ $\quad p_F \approx 250$ MeV/c
- Sophisticated models: Ab-initio quantum Monte-Carlo



- Variational quantum Monte-Carlo calculations from the Argonne group: PRC96,024326 (2017); arXiv:1903.12587
- Computationally very expensive and no predictions for $A > 40$

Single-nucleon momentum distributions in LCA



- Single-nucleon momentum distribution $n^{[1]}(p)$

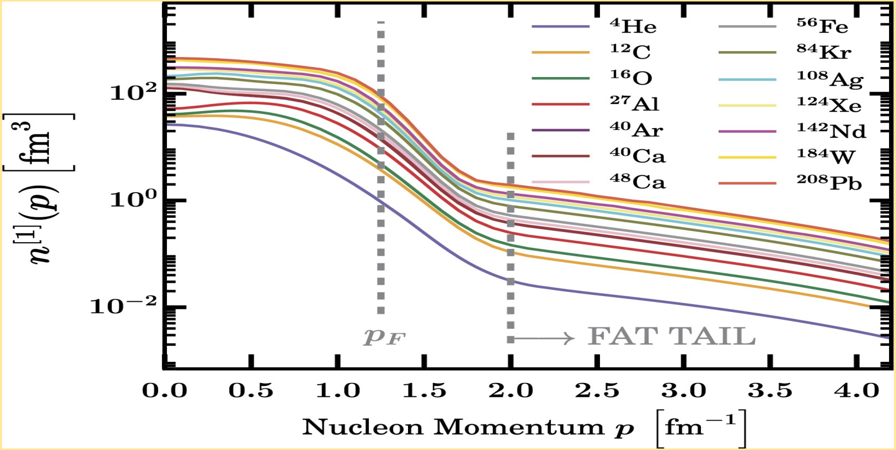
$$n^{[1]}(p) = \frac{A}{(2\pi)^3} \int d^2\Omega_p \int d^3\vec{r}_1 \; d^3\vec{r}_1{}' \; d^{3(A-1)}\{\vec{r}_{2-A}\} \times e^{-i\vec{p}\cdot(\vec{r}_1{}' - \vec{r}_1)} \; \Psi^*(\vec{r}_1, \vec{r}_{2-A})\Psi(\vec{r}_1{}', \vec{r}_{2-A})$$

- Universal correlation operators

$$|\Psi\rangle = \widehat{\mathcal{G}} \, |\Phi\rangle \, / \sqrt{\langle\Phi| \, \widehat{\mathcal{G}}^\dagger \widehat{\mathcal{G}} \, |\Phi\rangle} \; ,$$

- $\mathcal{G}$: Central $g_c(r)$, spin-isospin $f_{\sigma\tau}(r)$, tensor $f_{t_\tau}(r)$ correlations
- Truncation at $\mathcal{O}\left(\mathcal{G}^2\right)$: SRC part of $n^{[1]}(p)$ = 2-body contributions
- Quantify the *pp*, *nn*, *pn* and *np* contribution to $n^{[1]}(p)$

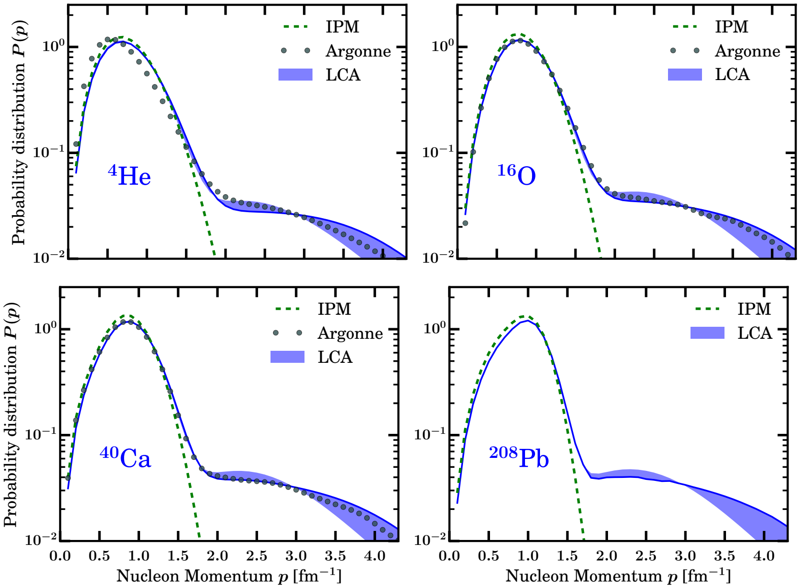
$n^{[1]}(p)$ in LCA: from light to heavy nuclei



LCA: JPG42 (2015)055104 & PLB 792 (2019)21 & arXiv:1907.07259

1. Two distinct momentum regimes ("IPM" and "SRC")
2. Momentum dependence of fat tail of $n^{[1]}$ is "universal"

Probability distribution $P(p) \sim p^2 n^{[1]}(p)$



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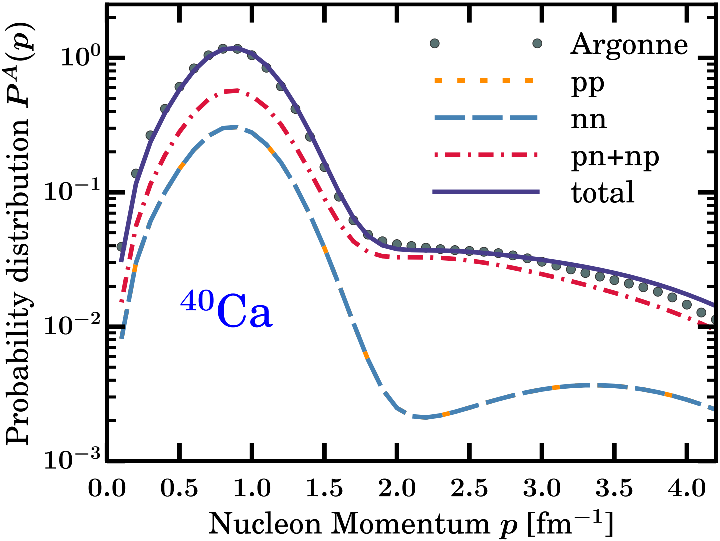

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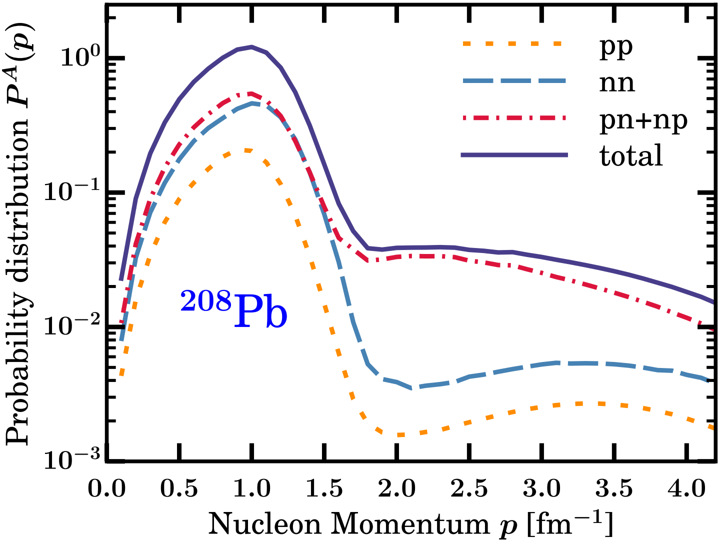
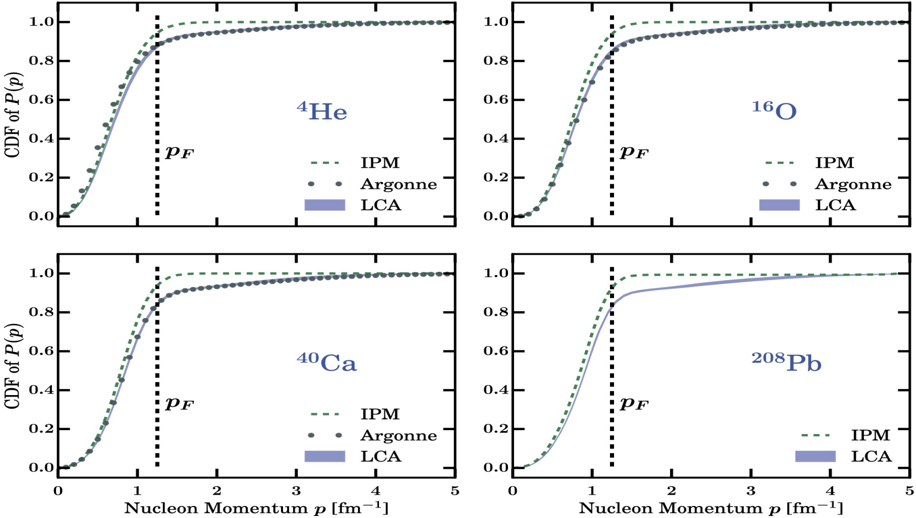


Cumulative momentum distributions



Indirect evidence of SRC: only a fraction of the nucleons are IPM like

Short-range correlations

Nuclear structure

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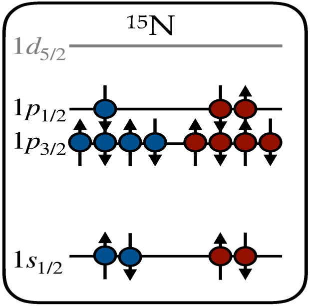
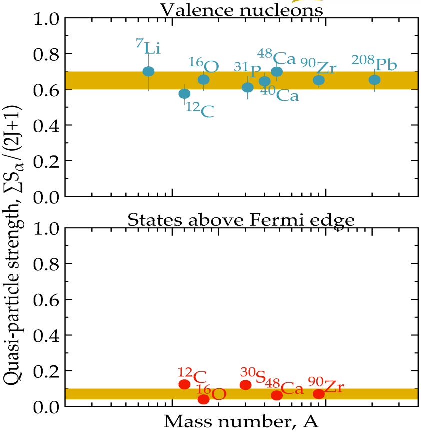
Shell model (e,e'p)



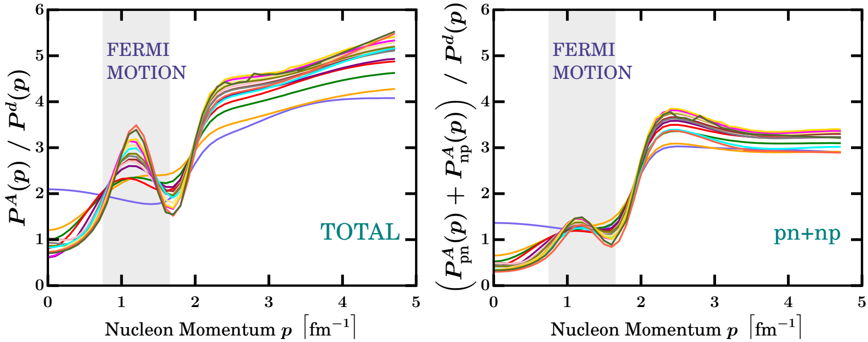


Lapikás, NPA 553 297c (1993);
Donnelly et al. *Foundations of Nuclear and Particle Physics* (Cambridge Uni Press 2017)

Slide courtesy of Arnau Rios

Ratios of probability distributions: $P^A(p)/P^d(p)$

$$P^A(p) = \underbrace{P^A_{\mathrm{pp}}(p) + P^A_{\mathrm{pn}}(p)}_{P^A_{\mathrm{p}}(p)\ \text{(proton part)}} + \underbrace{P^A_{\mathrm{nn}}(p) + P^A_{\mathrm{np}}(p)}_{P^A_{\mathrm{n}}(p)\ \text{(neutron part)}} \, .$$



N=Z: ^{4}He, ^{12}C, ^{16}O, ^{40}Ca

N≠Z: ^{9}Be, ^{27}Al, ^{40}Ar, ^{48}Ca, ^{56}Fe, ^{63}Cu, ^{84}Kr, ^{108}Ag, ^{124}Xe, ^{197}Au, ^{208}Pb

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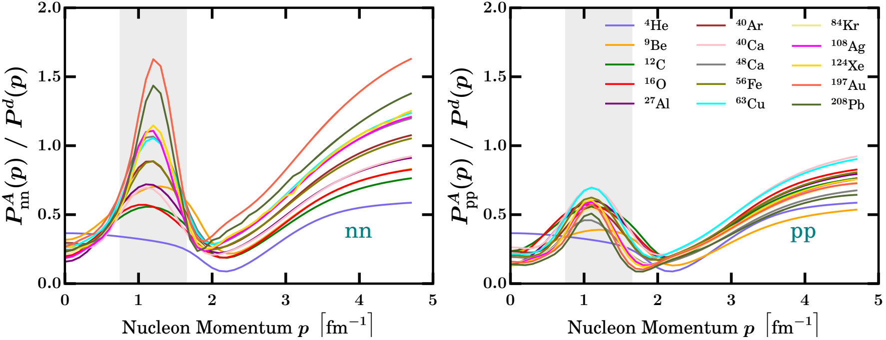
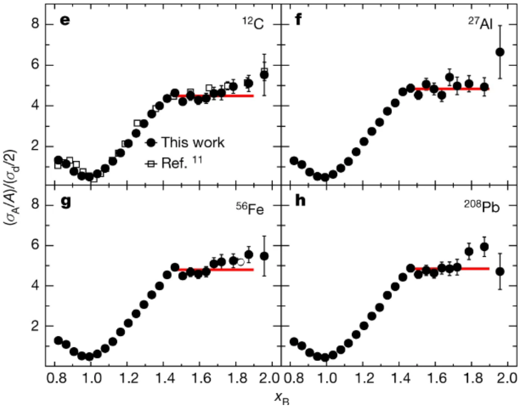


N=Z: ^{4}He, ^{12}C, ^{16}O, ^{40}Ca

N≠Z: ^{9}Be, ^{27}Al, ^{40}Ar, ^{48}Ca, ^{56}Fe, ^{63}Cu, ^{84}Kr, ^{108}Ag, ^{124}Xe, ^{197}Au, ^{208}Pb

Measurable signal of the *A*-to-*d* scaling of the momentum distributions?



In selected kinematics the A-to-d (e, e') cross sections approximately scale!

SRC SCALING FACTORS

THEORY:

$$a_2(A) = \frac{\int_{p>2\ \mathrm{fm}^{-1}} dp P^A(p)}{\int_{p>2\ \mathrm{fm}^{-1}} dp P^d(p)}$$

EXPERIMENT:

$$a_2^{exp}(A) = \frac{2}{A} \frac{\sigma^A(e,e')}{\sigma^d(e,e')}$$

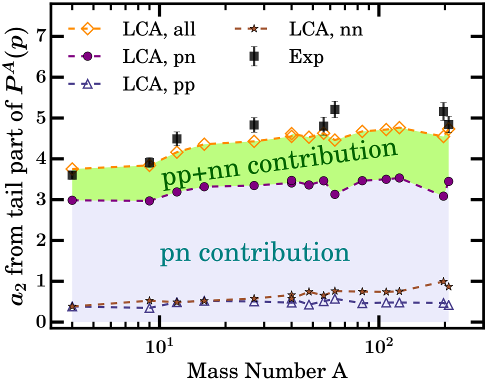
$$\left(1.5 \lesssim x \lesssim 1.9\ ;\ Q^2 \approx 2\ \mathrm{GeV}^2\right)$$

Aggregated impact of SRC on a nucleon in $A(N,Z)$ relative to the deuteron!

$a_2(A/^2\mathrm{H})$ from $A(e,e')$ at $x_B \gtrsim 1.5$ and LCA

Aggregated quantitative effect of SRC in A relative to d

$$a_2(A) = \frac{\int_{p>2\ \mathrm{fm}^{-1}} dp P^A(p)}{\int_{p>2\ \mathrm{fm}^{-1}} dp P^d(p)}\ ;\ a_2^{exp}(A) = \frac{2}{A}\frac{\sigma^A(e,e')}{\sigma^d(e,e')} \quad \left(1.5 \lesssim x \lesssim 1.9\ ;\ Q^2 \approx 2\ \mathrm{GeV}^2\right)$$



1. $A \lesssim 27$: soft A dependence
2. $A \gtrsim 27$: SATURATION
3. Ca isotopes: $a_2\,(^{40}\mathrm{Ca}) \approx a_2\,(^{48}\mathrm{Ca})$

DATA: N. Fomin *et al.*, PRL108(2012) ; B. Schmookler *et al.*, Nature566(2019)

$a_2(A/^2\mathrm{H})$ from $A(e,e')$ at $x_B \gtrsim 1.5$ and LCA

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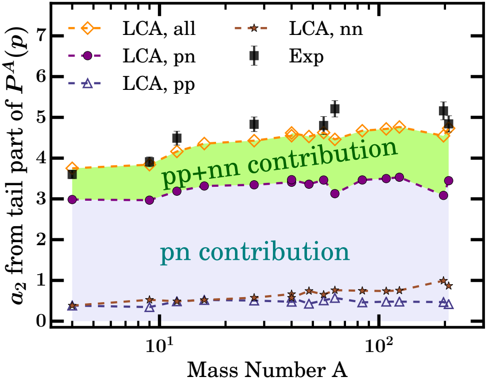
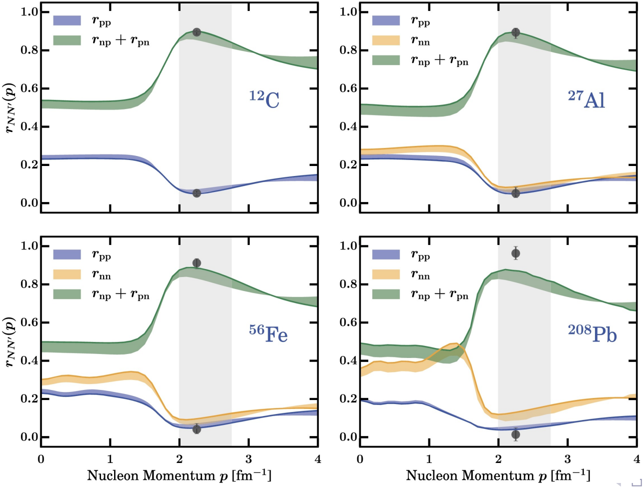


DATA: N. Fomin *et al.*, PRL108(2012) ; B. Schmookler *et al.*, Nature566(2019)

Nuclear momentum distribution: pair composition

Pair composition: $n^{[1]}(p) \equiv \underbrace{n^{[1]}_{pp}(p) + n^{[1]}_{pn}(p)}_{n^{[1]}_{p}(p) \text{ (proton part)}} + \underbrace{n^{[1]}_{nn}(p) + n^{[1]}_{np}(p)}_{n^{[1]}_{n}(p) \text{ (neutron part)}}$



-SRC pair fractions

$$r_{pp}(p) = \frac{n^{[1]}_{pp}(p)}{n^{[1]}(p)}$$

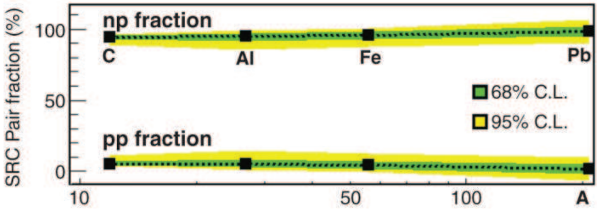
-r_{NN} are momentum dependent

-DATA: O. Hen *et al.*, Science346(2014)

Pair composition of SRC: LCA versus experiment (Science,2014)

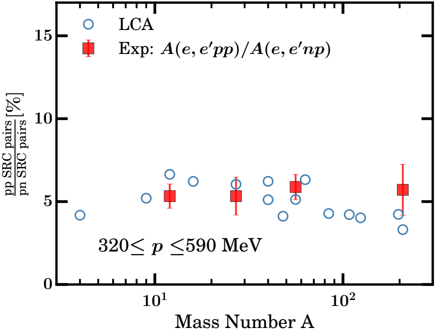
Momentum sharing in imbalanced Fermi systems

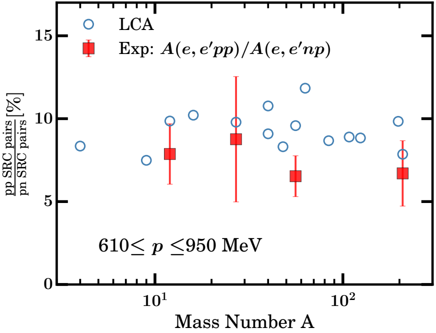
O. Hen,[1*] M. Sargsian,[2] L. B. Weinstein,[3] E. Piasetzky,[1] H. Hakobyan,[4,5] D. W. Higinbotham,[6] M



LCA predicts that ≈90% of correlated pairs is "pn", and ≈5% is "pp" (UNIVERSAL: A independent)

Pair composition of SRC: LCA versus experiment





LCA: Ratios from computed $n^{[1]}(p)$ for 15 nuclei

$$\frac{\int_{p_l}^{p_h} dp\, p^2\, n^{[1]}_{pp}(p)}{\int_{p_l}^{p_h} dp\, p^2 \left[n^{[1]}_{pn}(p) + n^{[1]}_{np}(p) \right]}$$

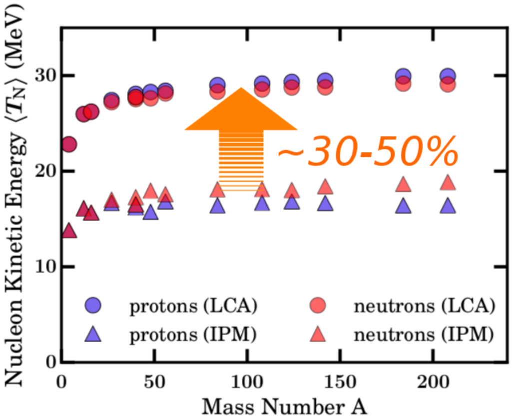
M. Duer *et al.*, PRL122(2019): Ratios from measured

$$\left. \frac{\sigma_{en}}{2\sigma_{ep}} \frac{A(e,e'pp)}{A(e,e'pn)} \right|_{p_l \leq p_m \leq p_h}$$

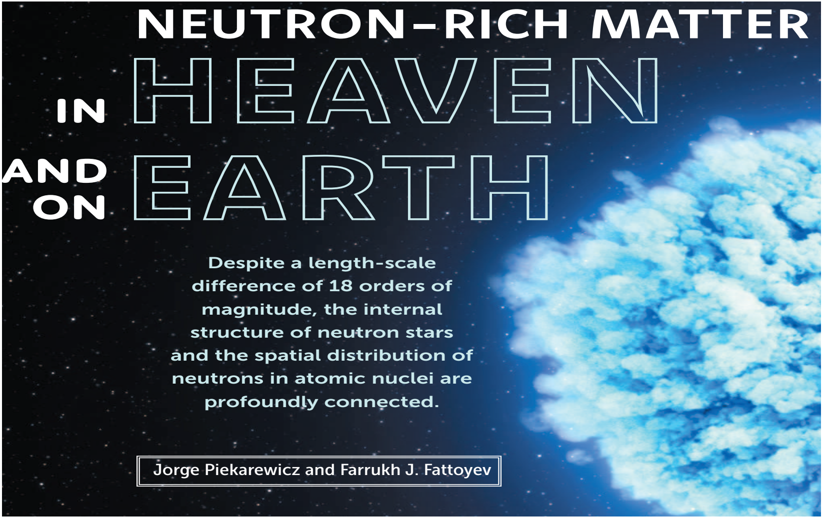
for A=^{12}C, ^{27}Al, ^{56}Fe, ^{208}Pb

Fourth moment of $n^{[1]}(p)$ from LCA

Fourth moment of $n^{[1]}(p)$: $\langle T_{\rm p} \rangle = \frac{1}{2M_p} \frac{\int_0^\Lambda dp\, p^4 \left[n^{[1]}_{pp}(p) + n^{[1]}_{pn}(p) \right]}{\int_0^\Lambda dp\, p^2 \left[n^{[1]}_{pp}(p) + n^{[1]}_{pn}(p) \right]}$



Nuclear Physics of Neutron Stars: Physics Today July 2019



Medium modifications as a function of neutron-to-proton ratio

Isospin asymmetry

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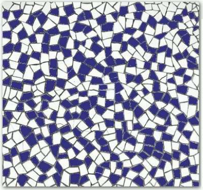
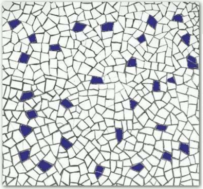
Nuclear "trencadís"

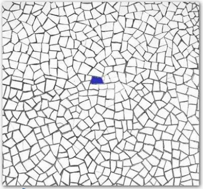
N=Z, η=0
Symmetric matter



$\eta \neq 0$
Asymmetric nuclei

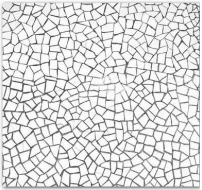


$\eta \approx 1$
Polaron



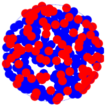
Neutron stars

$\eta = 1$
Neutron matter



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

Nuclei



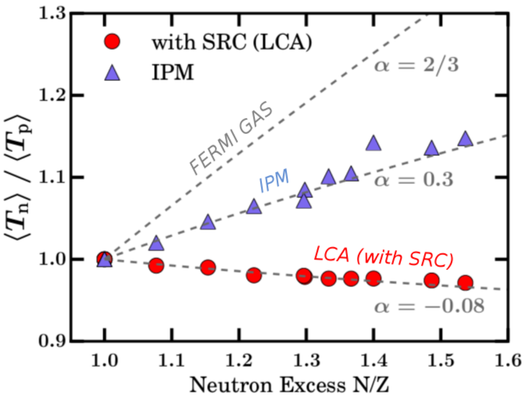
Lead 208
η =(126-82)/208=0.2

Experimentally unknown!

Slide courtesy of Arnau Rios

SRC induce inversion of kinetic energy sharing in neutron-rich nuclei

Ratio $\langle T_n = p_n^2/(2M_n) \rangle \, / \, \langle T_p = p_p^2/(2M_p) \rangle$ from computed $n^{[1]}(p)$



After correcting for SRC in LCA, minority component has largest kinetic energy (strongly depends on **N**/**Z**)

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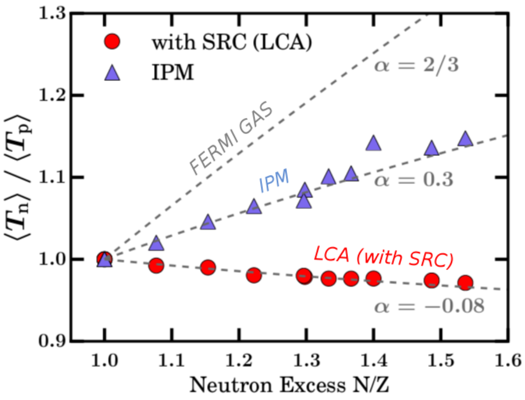
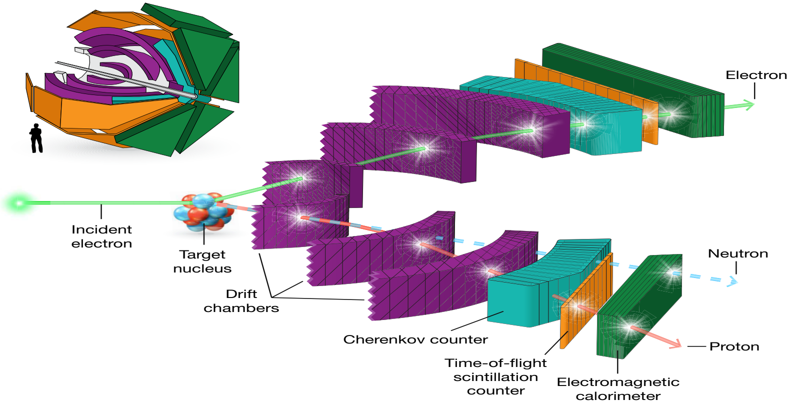


After correcting for SRC in LCA, minority component has largest kinetic energy (strongly depends on **N**/**Z**)

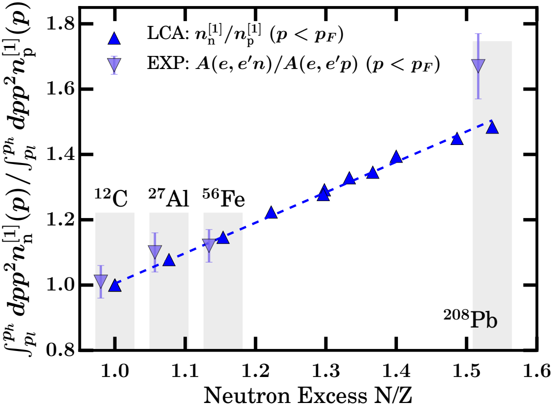
Measurable signals of kinetic energy inversion

- **Nature 560, 617-621(2018) (CLAS Collaboration, Jefferson Lab): $A(e,e'p)$ and $A(e,e'n)$ at high and low nucleon momenta**
- **$A(e,e'p)$ and $A(e,e'n)$ can be connected to probabilities to find nucleons in certain momentum ranges**



Weight of neutrons relative to protons in $n^{[1]}(p)$

$$\text{IPM:} \frac{\int_0^{p_F} dp p^2 n^{[1]}_{\mathrm{n}}(p)}{\int_0^{p_F} dp p^2 n^{[1]}_{\mathrm{p}}(p)} .$$



- DATA: M. Duer *et al.*, Nature 560 (2018) 617
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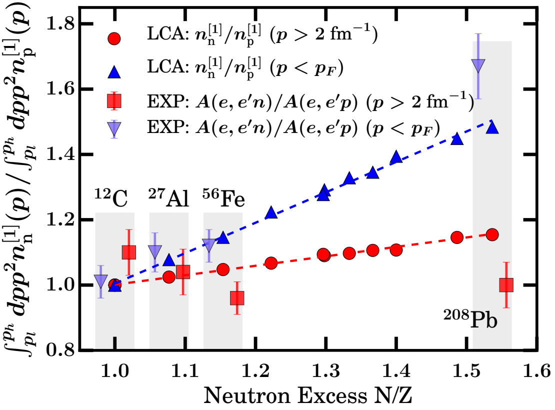
Weight of neutrons relative to protons in $n^{[1]}(p)$

$$\text{IPM:} \frac{\int_0^{p_F} dp p^2 n^{[1]}_{\text{n}}(p)}{\int_0^{p_F} dp p^2 n^{[1]}_{\text{p}}(p)} . \qquad \text{SRC :} \frac{\int_{0.4\text{ GeV}}^{1\text{ GeV}} dp p^2 n^{[1]}_{\text{n}}(p)}{\int_{0.4\text{ GeV}}^{1\text{ GeV}} dp p^2 n^{[1]}_{\text{p}}(p)} .$$

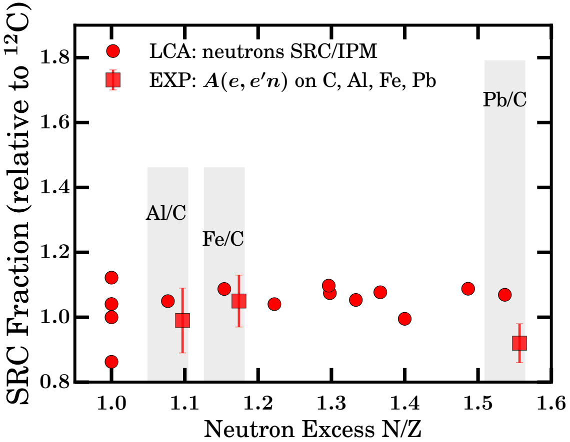


- DATA: M. Duer *et al.*, Nature 560 (2018) 617
- Relative weight of the protons and neutrons is very different in "IPM" and "SRC" regions!
  1. IPM: $0.93\frac{N}{Z} + 0.07$
  2. SRC: $0.29\frac{N}{Z} + 0.71$

N/Z asymmetry dependence of the SRC?

Superratio of $A(e,e'\text{N})$ for A=Al, Fe, Pb relative to $\text{C}(e,e'\text{N})$

$$\mathcal{R}_{\text{N}}^{\text{SRC/IPM}}(A) \equiv \frac{\int_{0.4\text{ GeV}}^{1.\text{ GeV}} dp p^2 n_{\text{N}}^{[1]}(p)}{\int_0^{p_F} dp p^2 n_{\text{N}}^{[1]}(p)} \quad (\text{N} \equiv \text{p,n})$$



- DATA: M. Duer *et al.*, Nature 560 (2018) 617
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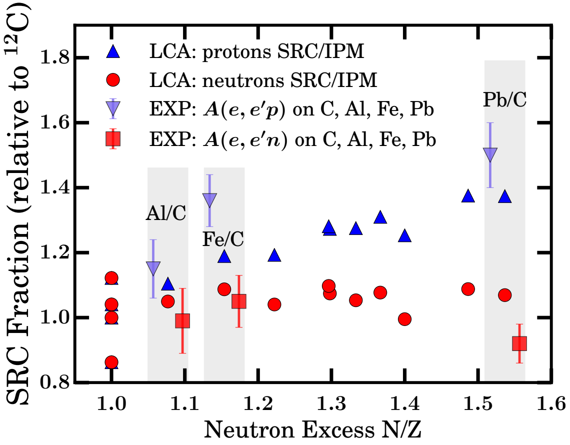
N/Z asymmetry dependence of the SRC?

Superratio of $A(e,e'N)$ for A=Al, Fe, Pb relative to $C(e,e'N)$

$$\mathcal{R}_{N}^{SRC/IPM}(A) \equiv \frac{\int_{0.4\text{ GeV}}^{1.\text{ GeV}} dp p^2 n_N^{[1]}(p)}{\int_0^{p_F} dp p^2 n_N^{[1]}(p)} \quad (N \equiv p,n)$$



- DATA: M. Duer *et al.*, Nature 560 (2018) 617
- Weight of the minority component in the tail (SRC) part of $n^{[1]}(p)$ increases with the asymmetry N/Z

Quark-gluon structure of a bound nucleon

- EMC effect (1980s, CERN): quarks work differently in nucleus
- Is the quark-gluon structure of protons and neutrons equally modified?
- Variations across nuclei? Asymmetric matter?
- Generative mechanism for the medium modifications of the quark structure?
- Recent suggestion: EMC effect is connected to "SRC pairs"

nature

Letter | Published: 20 February 2019

Modified structure of protons and neutrons in correlated pairs

The CLAS Collaboration

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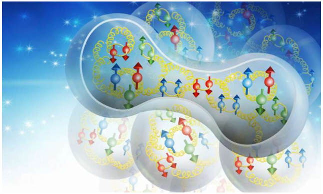
Quark modification & nucleon pairs

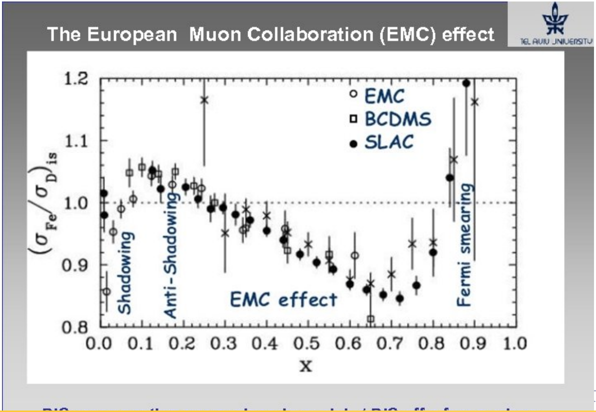


DIS $A(e,e')$ & $d(e,e')$ at $0.2 \lesssim x \lesssim 0.7$

$$-\frac{dR_{EMC}(A,x)}{dx} = -\frac{d\left(\frac{2F_2^A(x,Q^2)}{AF_2^d(x,Q^2)}\right)}{dx}$$

Short-distance neutron-proton pairs may be responsible for the bulk of the EMC effect

Alternate views: PRL **123**, 042501 (2019)



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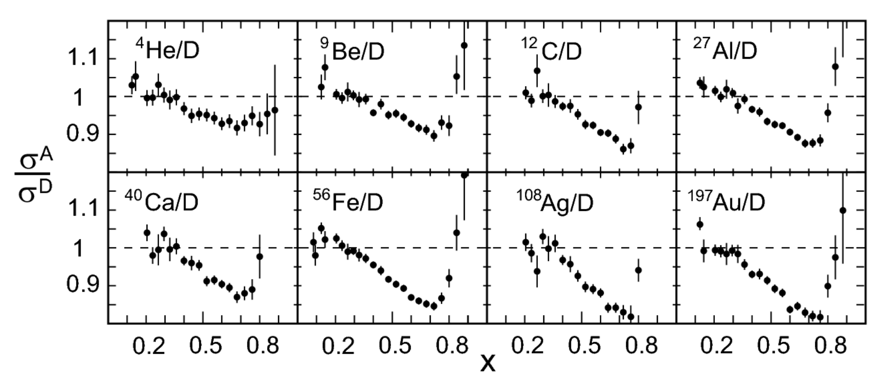
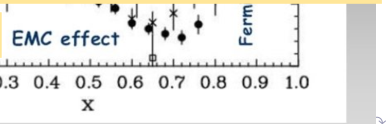


Size of EMC effect depends on A(N, Z)

Isospin dependence of EMC effect?



Predict size of EMC effect and learn about generative mechanisms

- Per-proton probability to find a high-momentum proton in $A(N,Z)$ relative to D: A-to-D medium modifications

$$a_2^p(A) = \lim_{\text{high } p} \frac{A\, P_p^A(p)}{Z\, P_p^D(p)}$$

Can be computed in LCA!

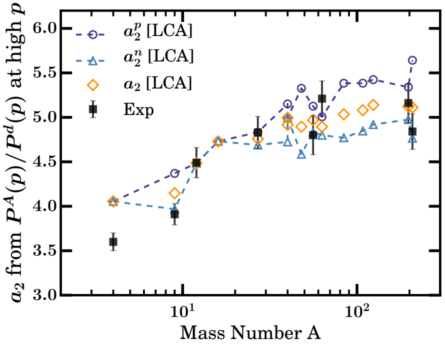
- Size of EMC effect is connected to "SRC" nucleons

$$\frac{dR_{EMC}(A,x)}{dx} = m_1 \left(\underbrace{\frac{Z a_2^p(A) + N a_2^n(A)}{A}}_{\text{ISOSCALAR}} - 1 \right) + m_2 \left(\underbrace{\frac{Z a_2^p(A) - N a_2^n(A)}{A}}_{\text{ISOVECTOR}} \right)$$

Connects measured size of EMC effect to computed SRC scaling factors!

Proton and neutron modifications in nuclei

Proton & neutron SRC scaling factors

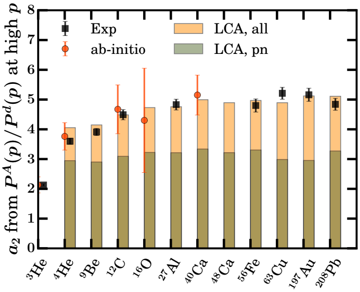


Measured SRC scaling factors from:

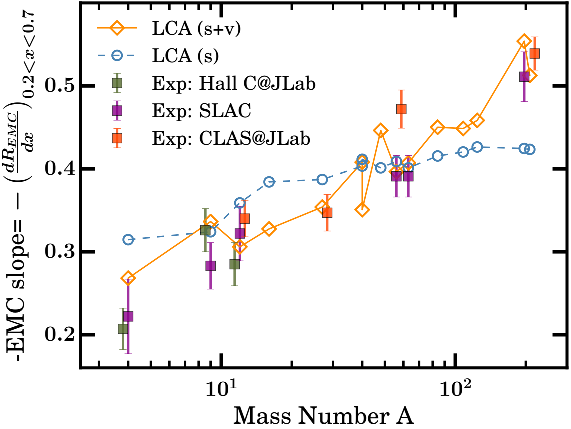
$$a_2^{exp}(A) = \frac{2}{A}\frac{\sigma^A(e,e')}{\sigma^d(e,e')}(1.5 \lesssim x \lesssim 1.9)$$

for $Q^2 \approx 2$ GeV^2

- Per-proton dynamical modification is larger than the per-neutron one for $N > Z$
- SRC scaling factor $a_2(A)$: $(Za_2^p(A) + Na_2^n(A))/A$



Size of the EMC effect



Meausured size of the EMC effect displays stronger variations across $A(N,Z)$ than SRC scaling factors!

- LCA (s): isospin blind generative mechanisms
- LCA (s+v): also isospin-dependent generative mechanisms
- flavor dependent nuclear effects influence the size of the EMC effect
- *u* and *d* quark distributions are affected differently by the medium

SUMMARY

- **SRC induced spatio-temporal fluctuations in nuclei are measurable, are significant and are quantifiable**
- **LCA: suited for systematic studies of SRC contributions to $n^{[1]}(p)$ and SRC-sensitive reactions**
  1. **Reasonable predictions for a_2 factors**
  2. $A \leq 40$: **LCA predictions for fat tails in line with QMC ones**
  3. **Natural explanation for the "universal" behavior of the fat tails of NMD**
- **Distinct isospin and N/Z SRC effects: in line with $A(e, e'pN)$ findings**
- **EMC effect: connections between nucleon SRC and quark medium modifications**


THANK YOU!

Selected publications

- JR, W. Cosyn, T. Vieijra, C. Casert *"Isospin composition of the high-momentum fluctuations in nuclei from asymptotic momentum distributions"* arXiv:1907.07259 and PRC **100** (2019), 054620.
- JR, W. Cosyn, S. Stevens, C. Casert, J. Nys *"The isospin and neutron-to-proton excess dependence of short-range correlations"* arXiv:1808.09859 and PLB **B792** (2019), 21.
- S. Stevens, JR, W. Cosyn, A. Waets *"Probing short-range correlations in asymmetric nuclei with quasi-free pair knockout reactions"* arXiv:1707.05542 and PLB **B777** (2018), 374.
- C. Colle, W. Cosyn, JR *"Final-state interactions in two-nucleon knockout reactions"* arXiv:1512.07841 and PRC **93** (2016) 034608.
- JR, M. Vanhalst, W. Cosyn *"Stylized features of single-nucleon momentum distributions"* arXiv:1405.3814 and JPG **42** (2015) 055104.
- C. Colle, O. Hen, W. Cosyn, I. Korover, E. Piasetzky, JR, L.B. Weinstein *"Extracting the Mass Dependence and Quantum Numbers of Short-Range Correlated Pairs from $A(e,e'p)$ and $A(e,e'pp)$ Scattering"* arXiv:1503.06050 and PRC **92** (2015), 024604.