New results on the neutron-to-proton asymmetry dependence of short-range correlations

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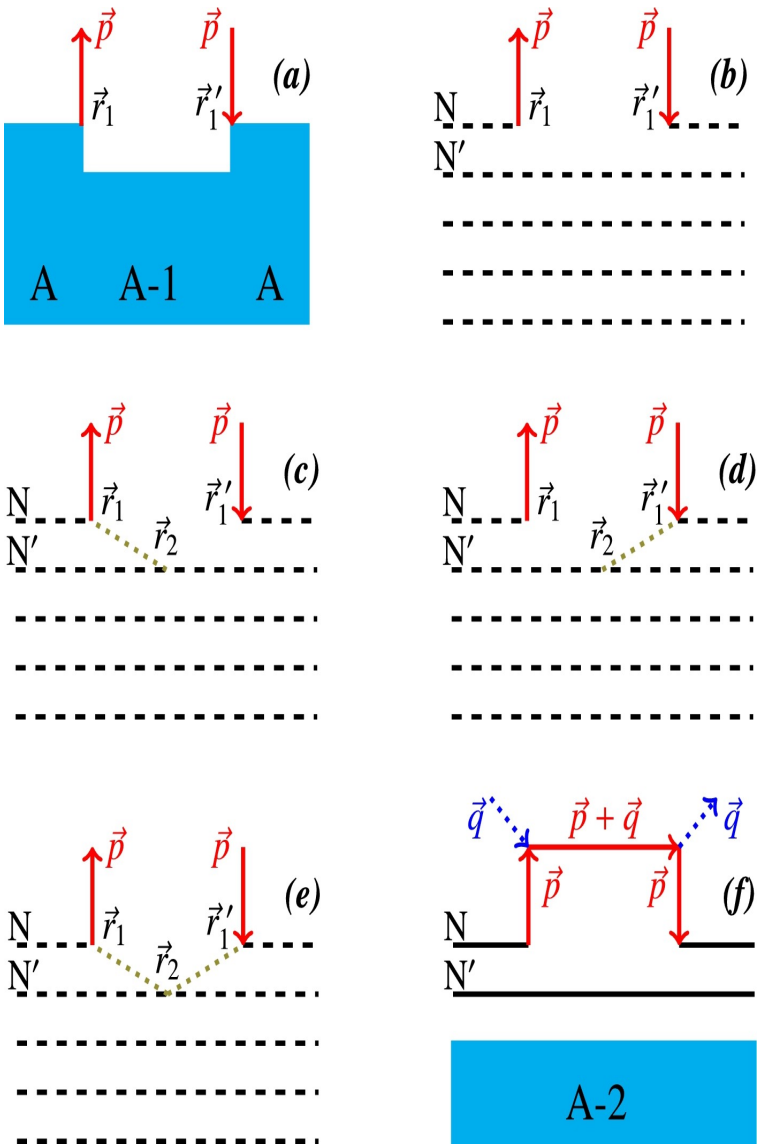
- **Is there a comprehensive picture of nuclear SRC?**
  (quest to learn about stylized facts of nuclear SRC)
- **How to forge links between nuclear-dynamics theory and A(e, e′pX) observables sensitive to nuclear SRC?**
  (forging bridges between "nuclear structure theory" and "nuclear reaction theory")

OUTLINE

1. Low-order correlation operator approximation (LCA) to compute effect of SRC—structure (this talk) & reactions (Wim Cosyn's talk)
2. Apply LCA to the computation of nuclear momentum distributions (NMDs) for selection of 14 nuclei
   $A(N,Z) : 4 \leq A \leq 208$ and $1 \leq \frac{N}{Z} \leq 1.54$
   CHECK: Compare LCA results to ab-initio ones
3. Compute aggegrated effect of SRC in LCA
   CHECK: a_2 data from $A(e,e')$
4. Compute isospin composition (pp&nn&pn) of SRC
   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. Compute 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

Single-nucleon momentum distributions in LCA



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

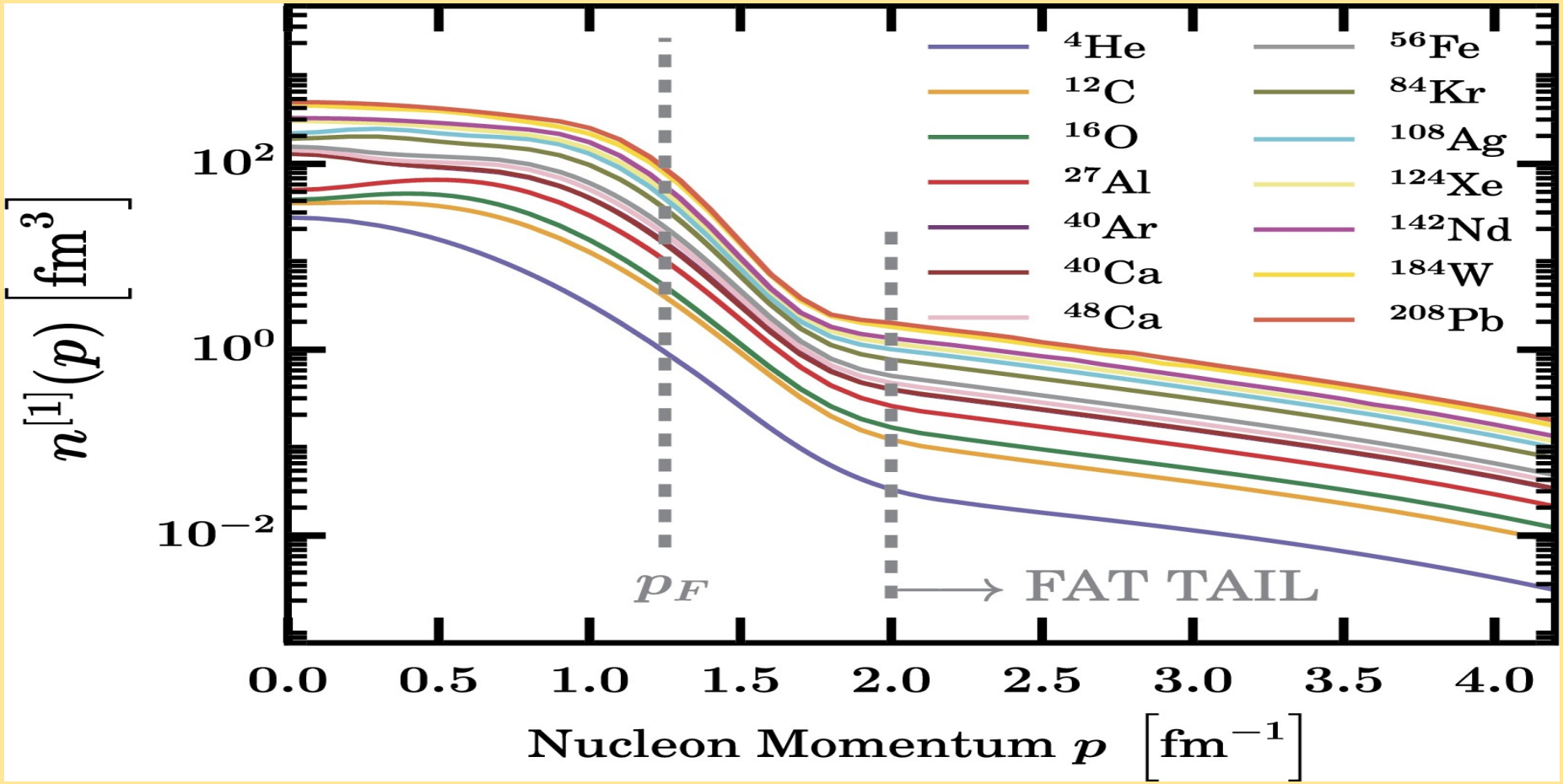
$$n^{[1]}(p) = \frac{A}{(2\pi)^3} \int d^2\Omega_p \int d^3\vec{r}_1 \; d^3\vec{r}_1' \; d^{3(A-1)}\{\vec{r}_{2-A}\}$$
$$\times \; e^{-i\vec{p}\cdot(\vec{r}_1' - \vec{r}_1)} \; \Psi^*(\vec{r}_1, \vec{r}_{2-A})\Psi(\vec{r}_1', \vec{r}_{2-A})$$

- Universal correlation operators

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

- Central $g_C(r)$, spin-isospin $f_{\sigma\tau}(r)$, tensor $f_{t\tau}(r)$ correlations
- SRC = two-body contributions!
- Quantify the *pp*, *nn*, *pn* and *np* contribution to $n^{[1]}(p)$

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

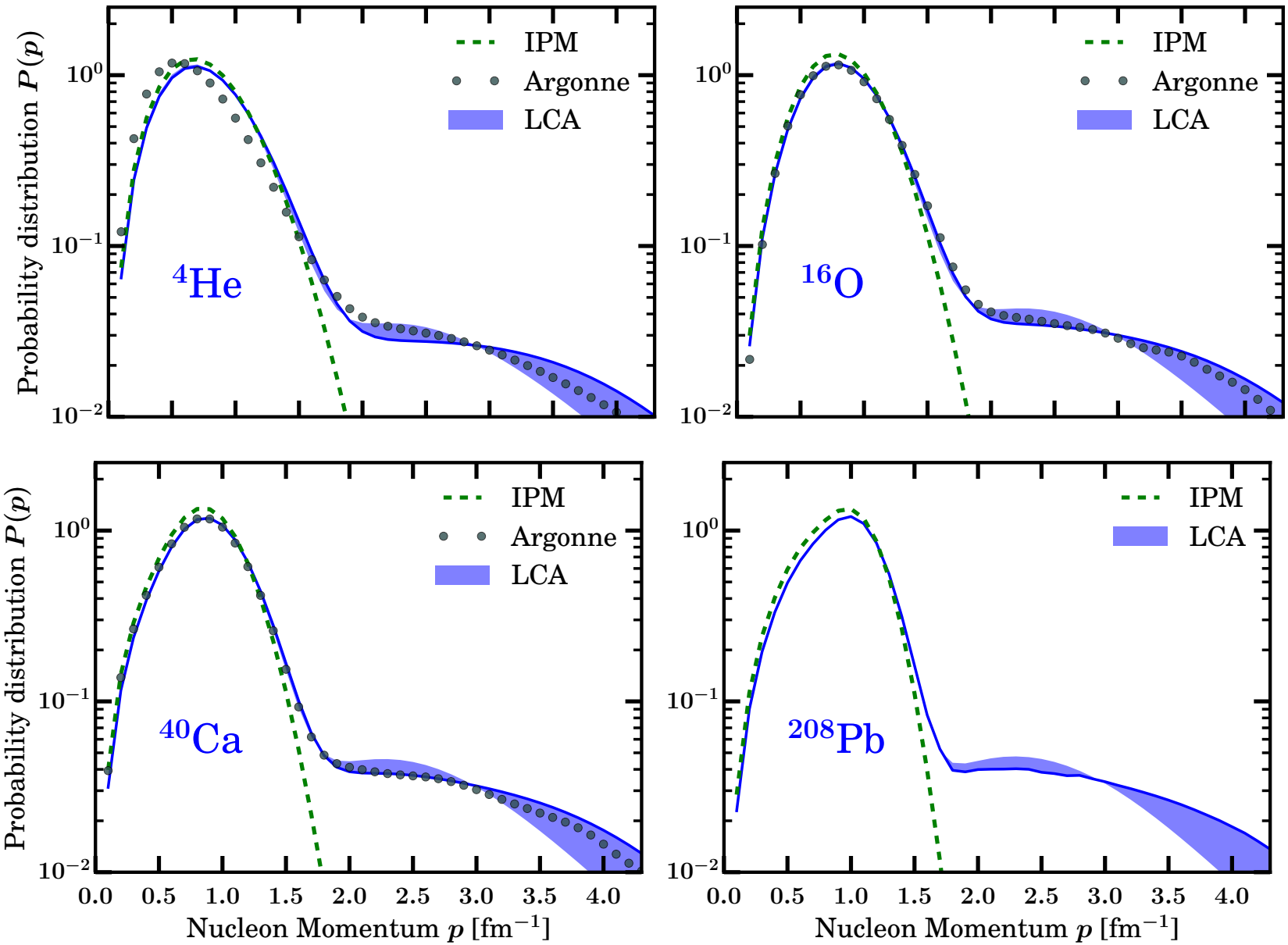


LCA: JPG42 (2015)055104 & PLB 792 (2019)21

1. Distinct momentum regimes!
2. Momentum dependence of fat tail of $n^{[1]}$ is "universal"


UCOM, FHNC, CBF,
SRG, $V_{low\ k}$, ...
MEAN-FIELD
FAT TAIL!
LOG MOMENTUM DISTRIBUTION
NUCLEON MOMENTUM

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



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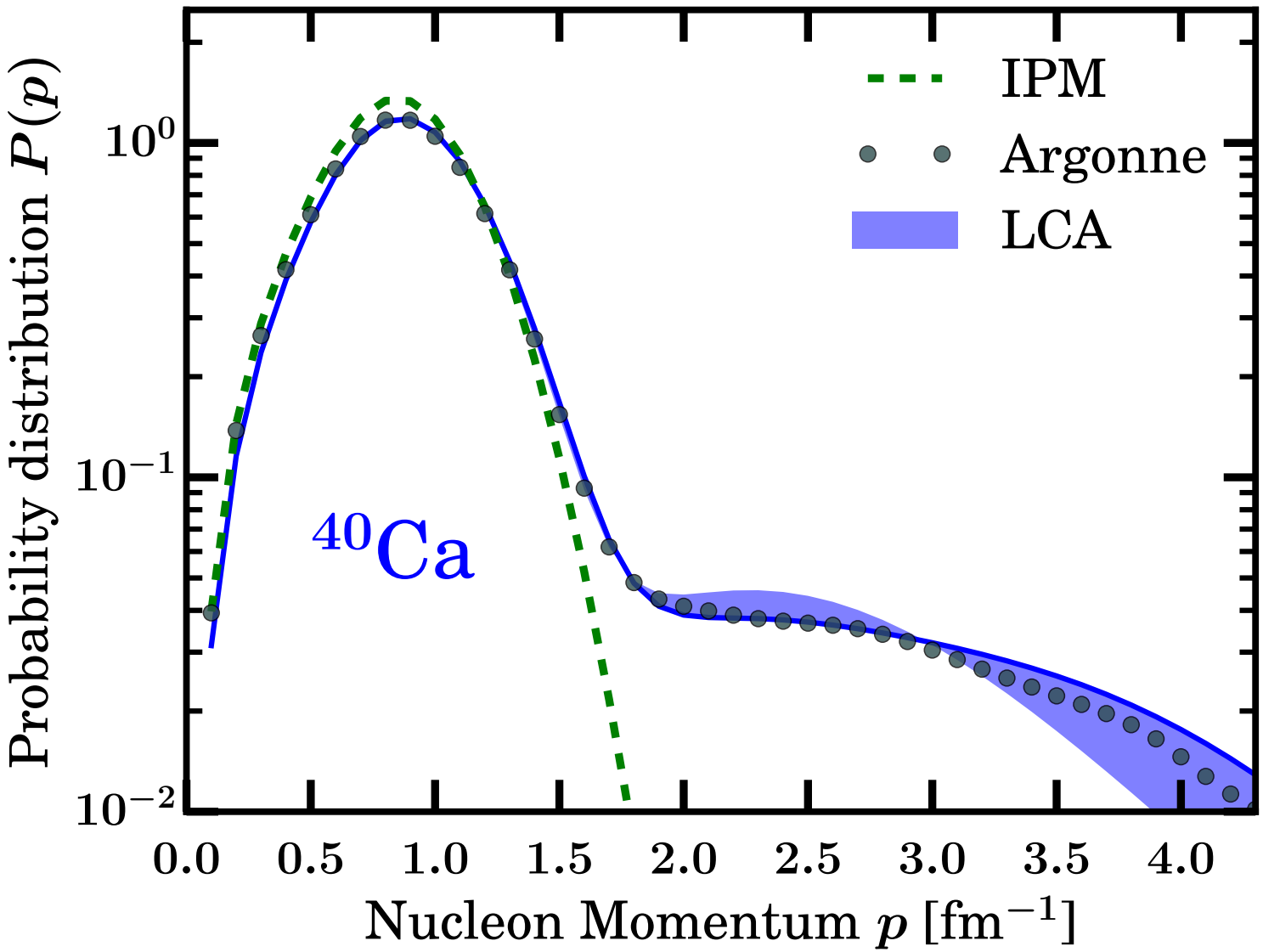
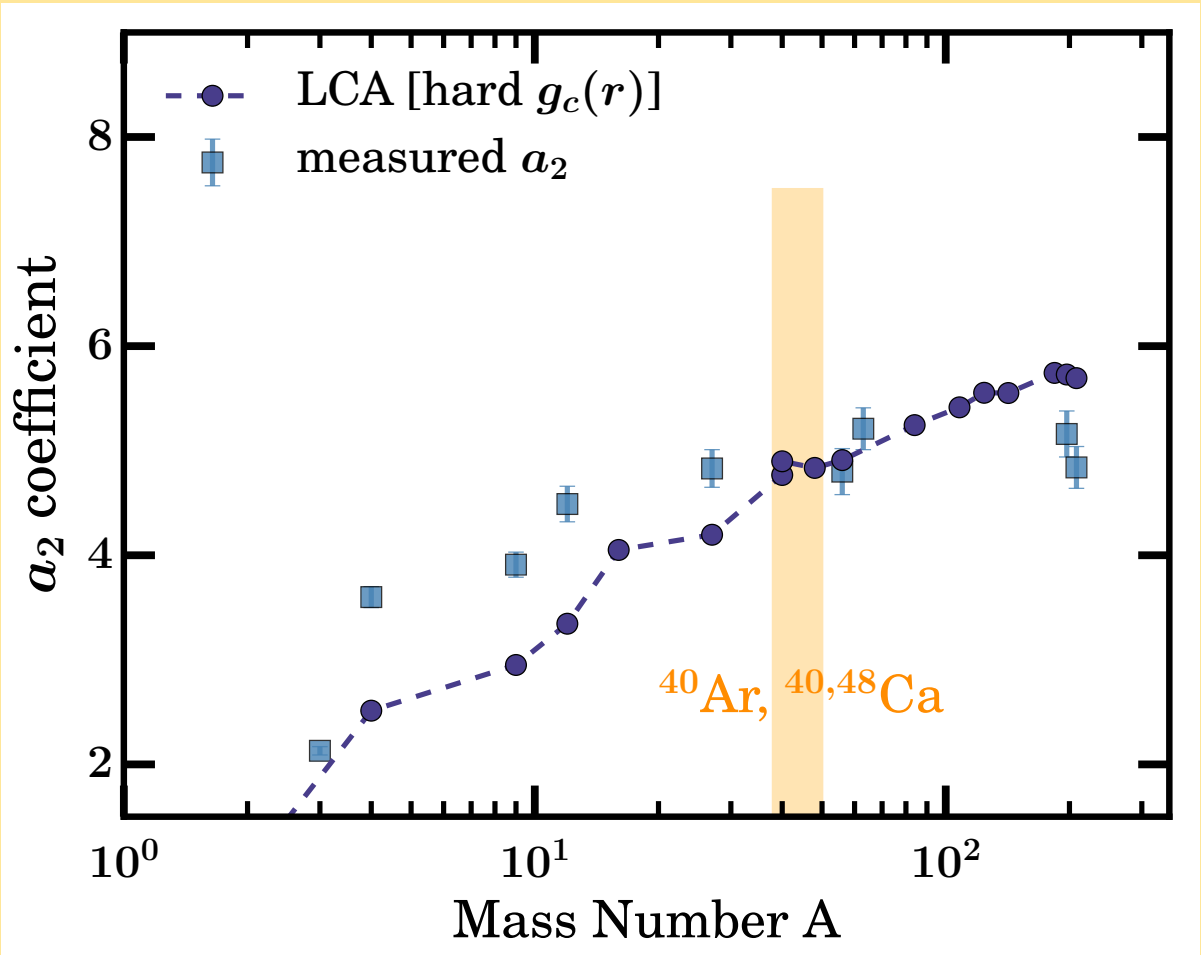


$a_2(A/^2\mathrm{H})$ from $A(e,e')$ at $x_B \gtrsim 1.5$ and LCA



- $\sim A^2$: local neighborhood gets filled
- $\sim A$: local neighborhood saturated

LCA: Aggregated quantitative effect of SRC in A relative to ^{2}H

$$\langle \Phi | \hat{\mathcal{G}}^\dagger \hat{\mathcal{G}} | \Phi \rangle - \langle \Phi \mid \Phi \rangle$$

1. $A \lesssim 40$: strong A dependence of SRC effect
2. $A \gtrsim 40$: softer A dependence of SRC effect
3. Ca isotopes: $a_2\,(^{40}\mathrm{Ca}) \approx a_2\,(^{48}\mathrm{Ca})$

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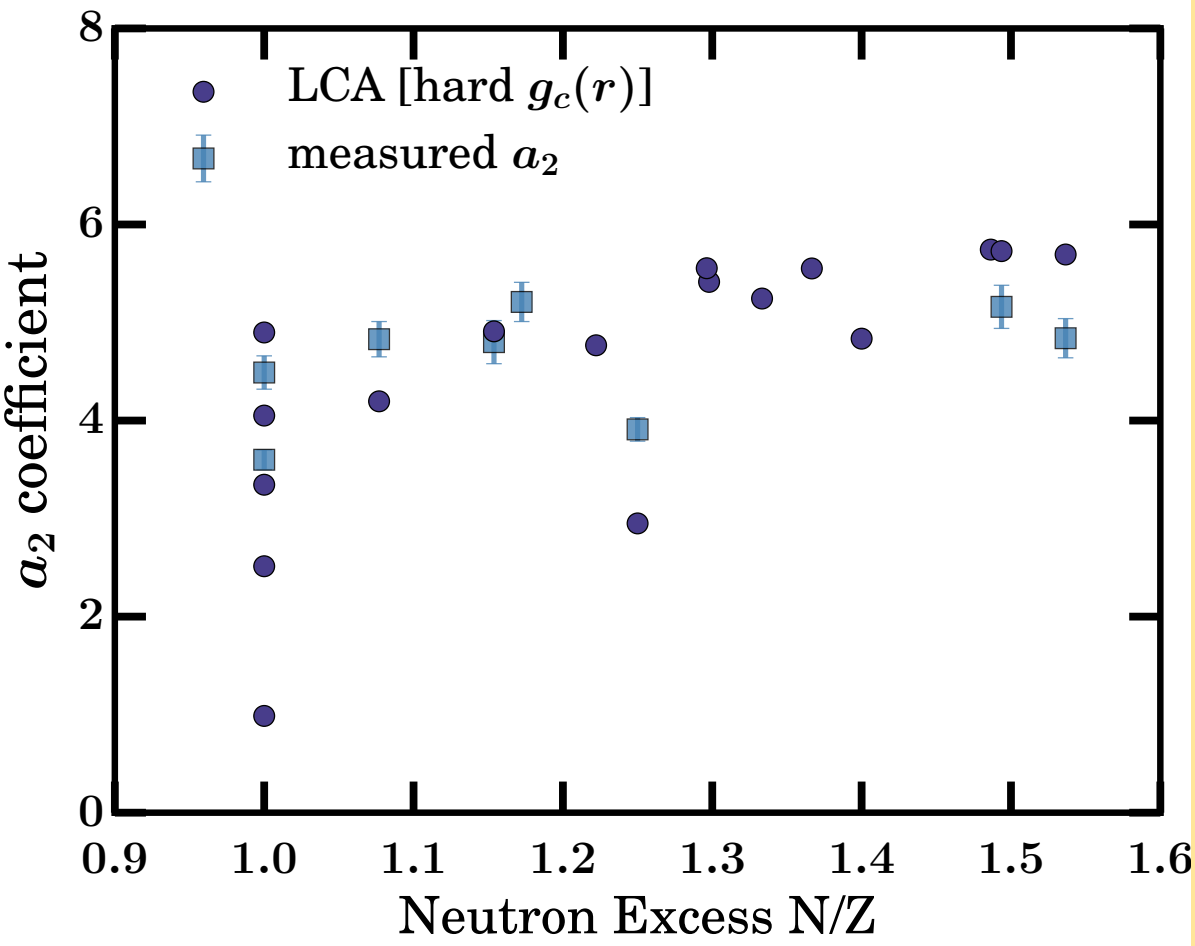

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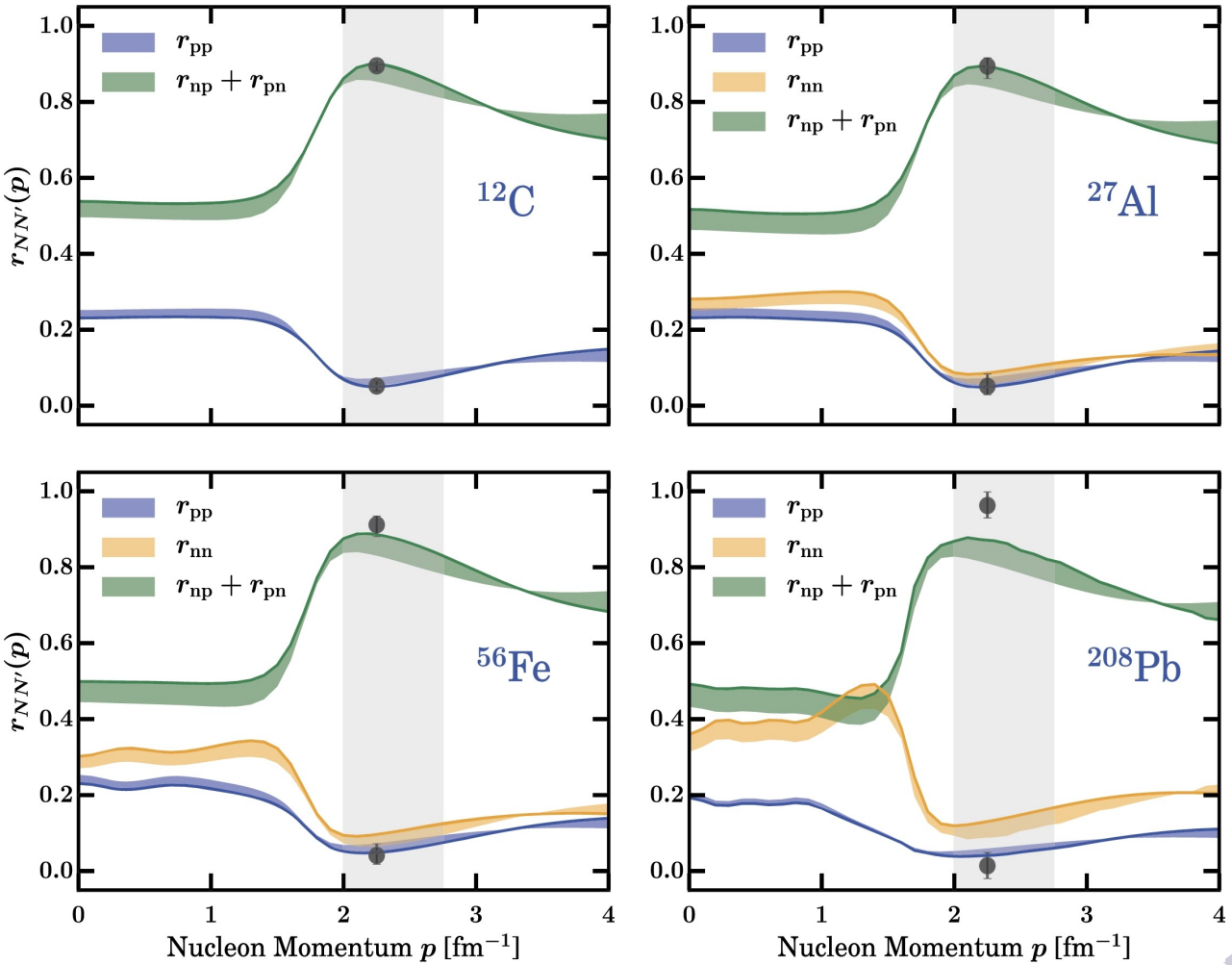
Nuclear momentum distribution: pair composition

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



-The pp and pn SRC pair fractions are momentum dependent

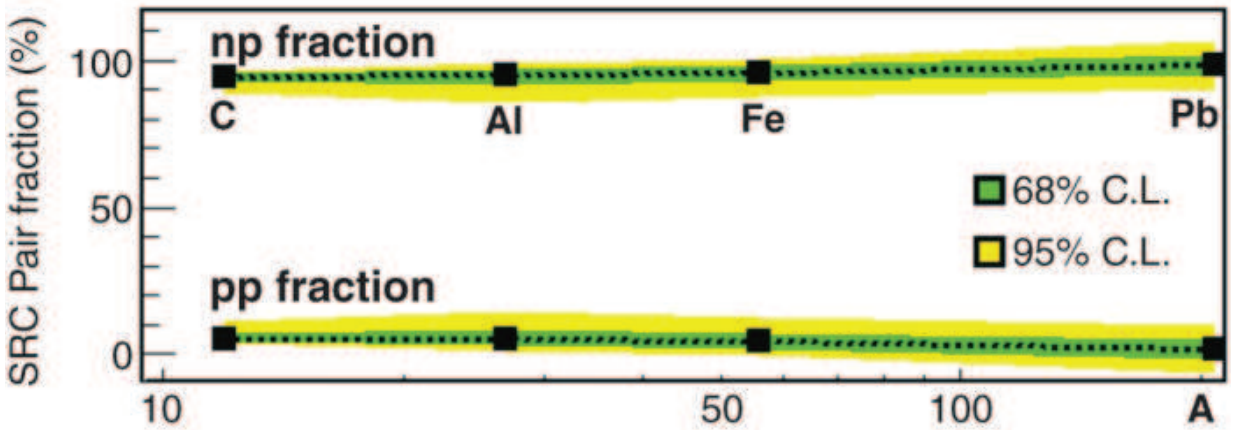
-Semi-exclusive $A(e, e'pN)$ mainly probe the low p part of the SRC region:

$r_{np} \sim 90\%$ and $r_{nn} + r_{pp} \sim 10\%$

Pair composition of SRC: LCA versus experiment

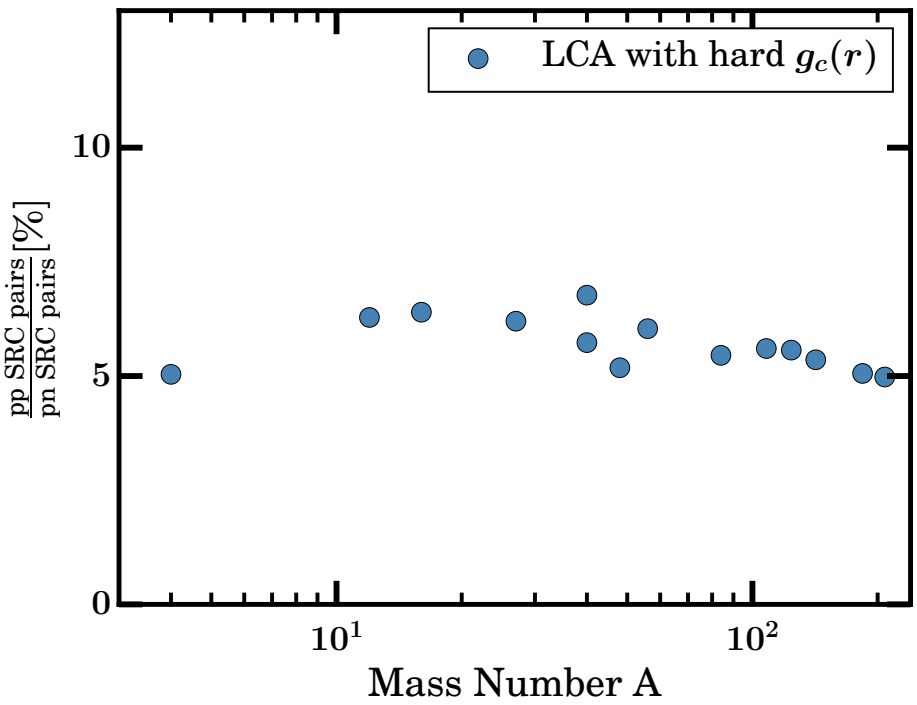
Momentum sharing in imbalanced Fermi systems

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)

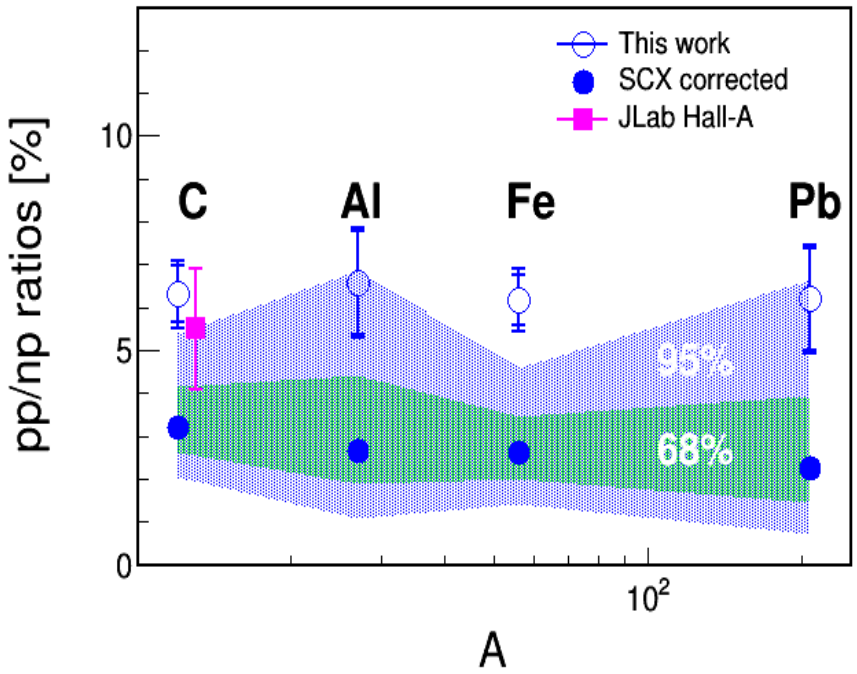
Pair composition of SRC: LCA versus experiment



Ratios from computed $n^{[1]}(p)$

$$\frac{\int_{0.40\ \text{GeV}}^{1.00\ \text{GeV}} dp\, p^2\, n^{[1]}_{\text{pp}}(p)}{\int_{0.40\ \text{GeV}}^{1.00\ \text{GeV}} dp\, p^2 \left[n^{[1]}_{\text{pn}}(p) + n^{[1]}_{\text{np}}(p) \right]}$$

for 14 nuclei



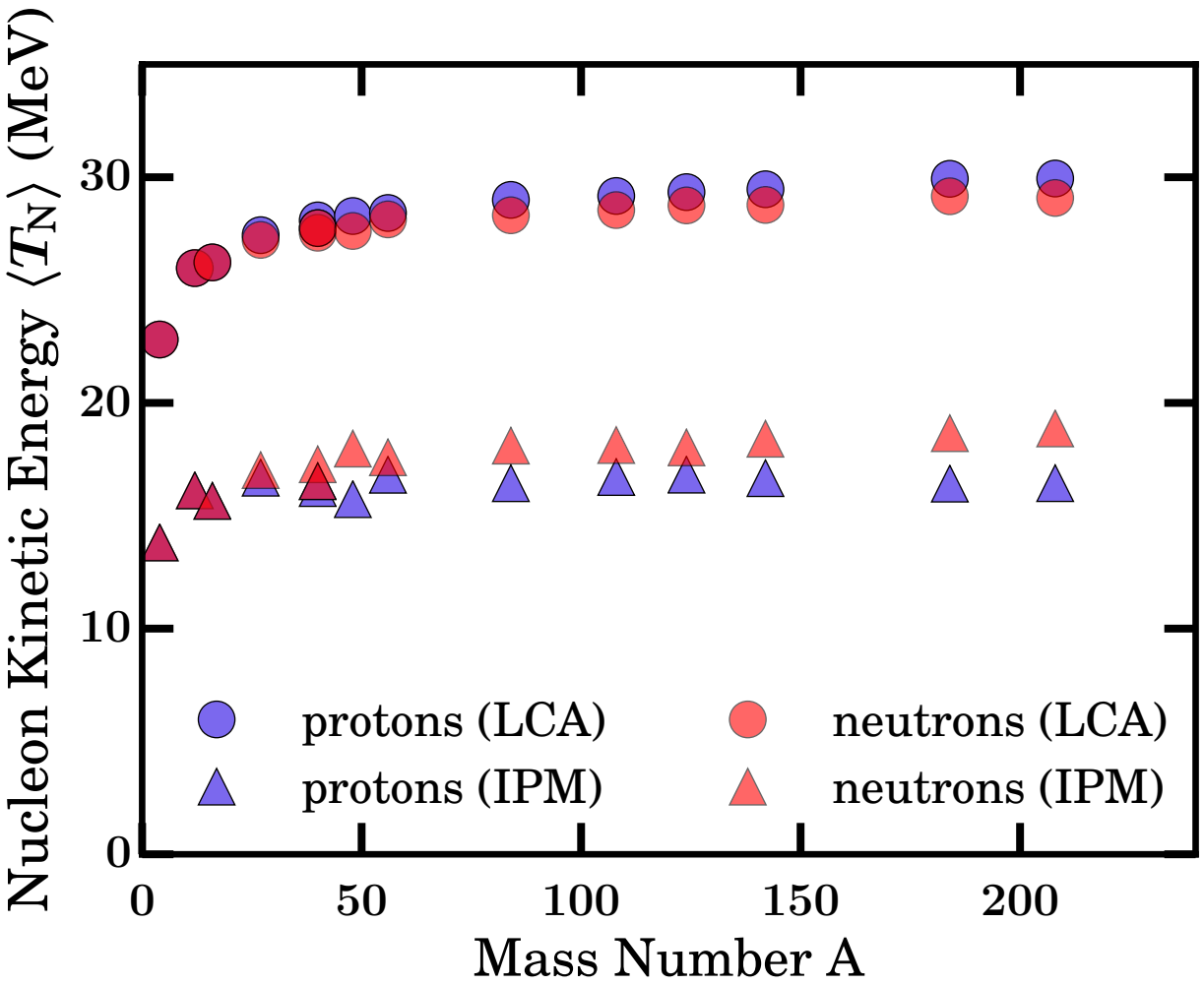
M. Duer *et al.*, arXiv:1810.05343:
Ratios from measured

$$\frac{\sigma_{en}}{2\sigma_{ep}} \frac{A(e,e'pp)}{A(e,e'pn)}$$

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

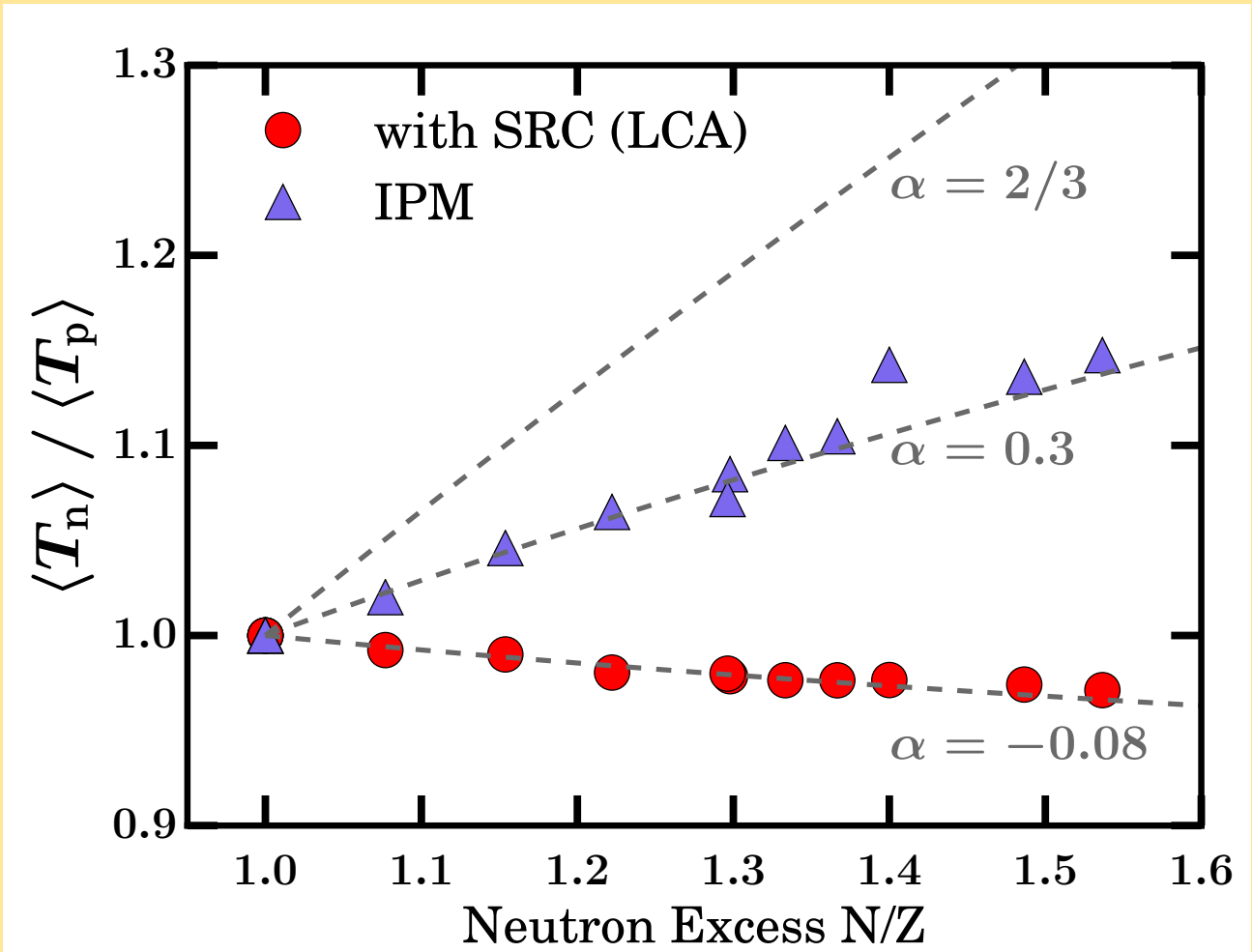
Second moment of $n^{[1]}(p)$ from LCA

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



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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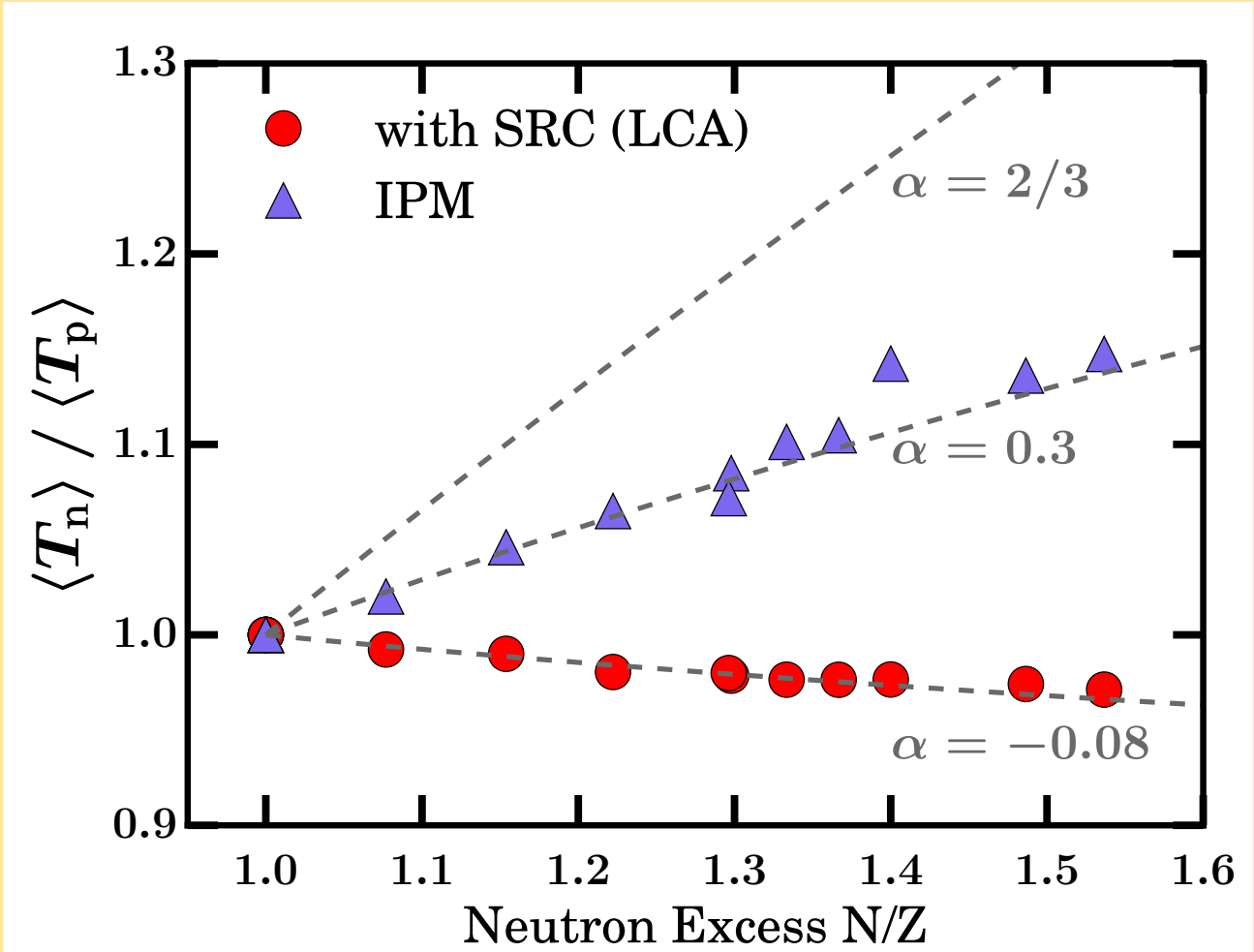

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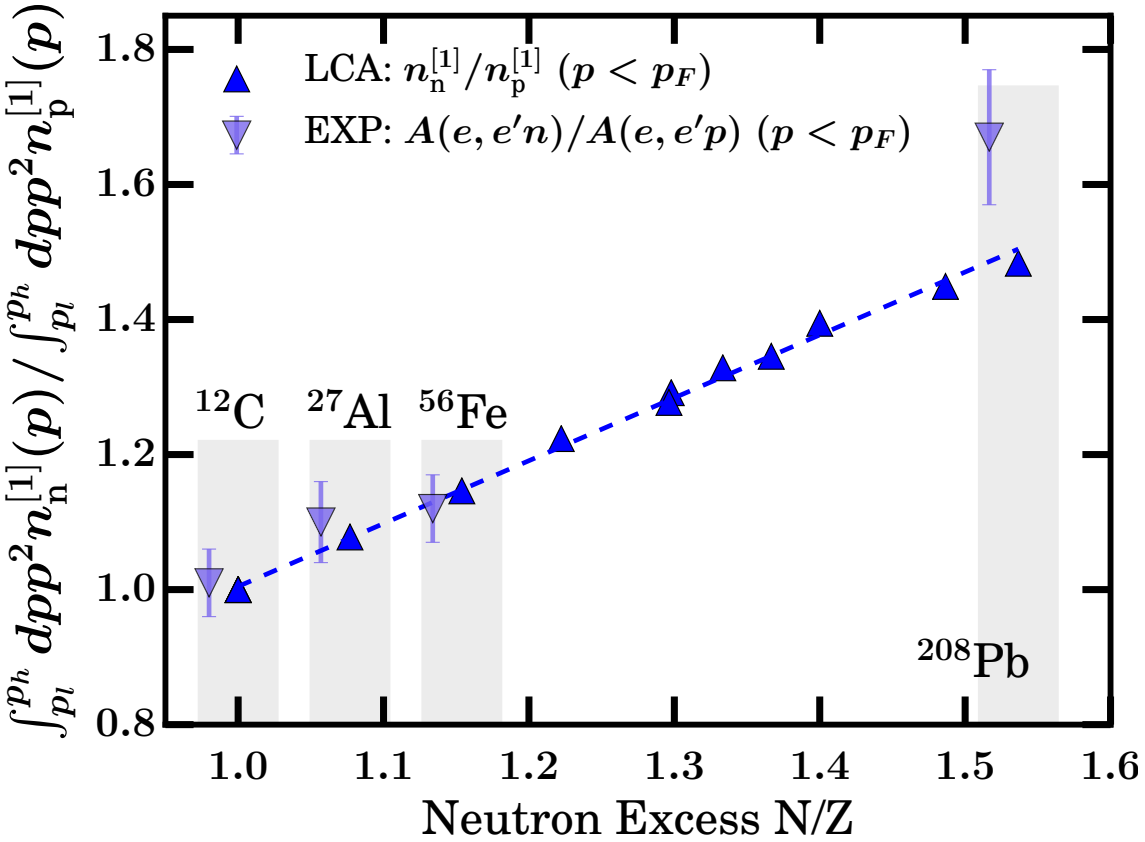
Weight of neutrons relative to protons in $n^{[1]}(p)$

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



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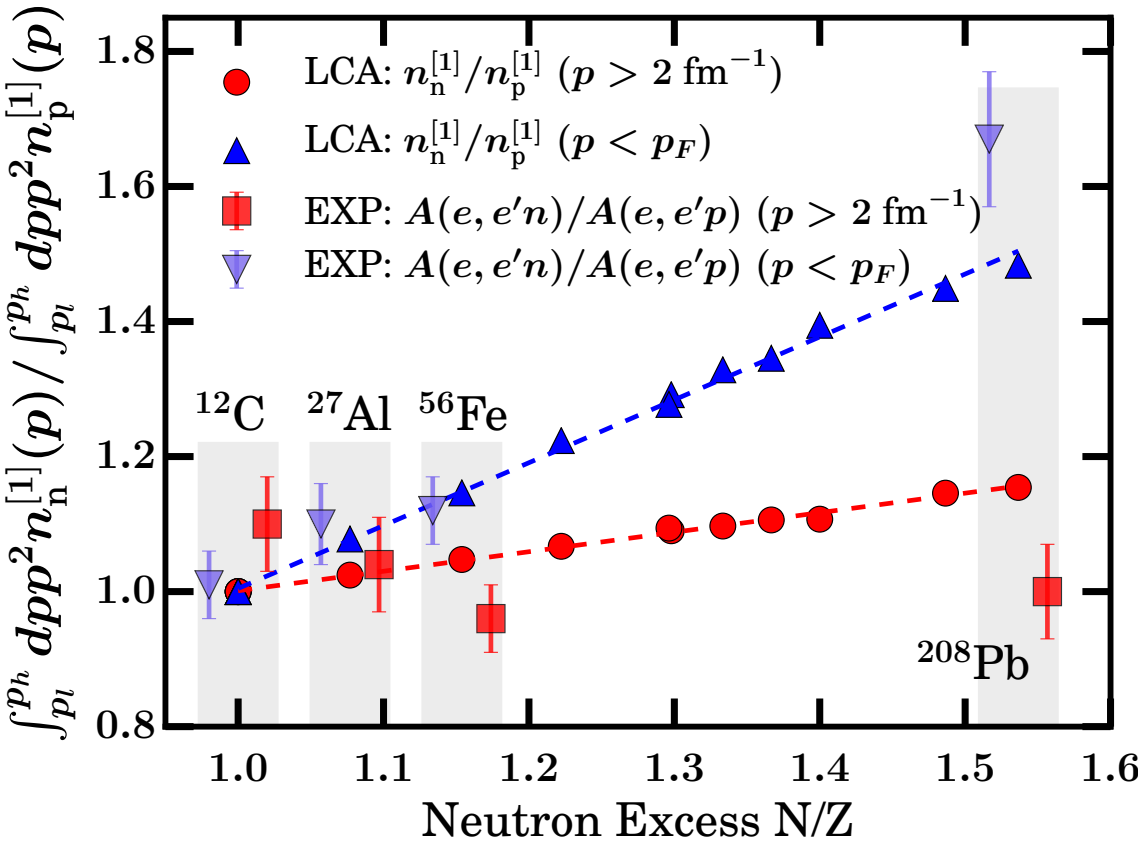
- DATA: Nature 560 (2018) 617

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

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

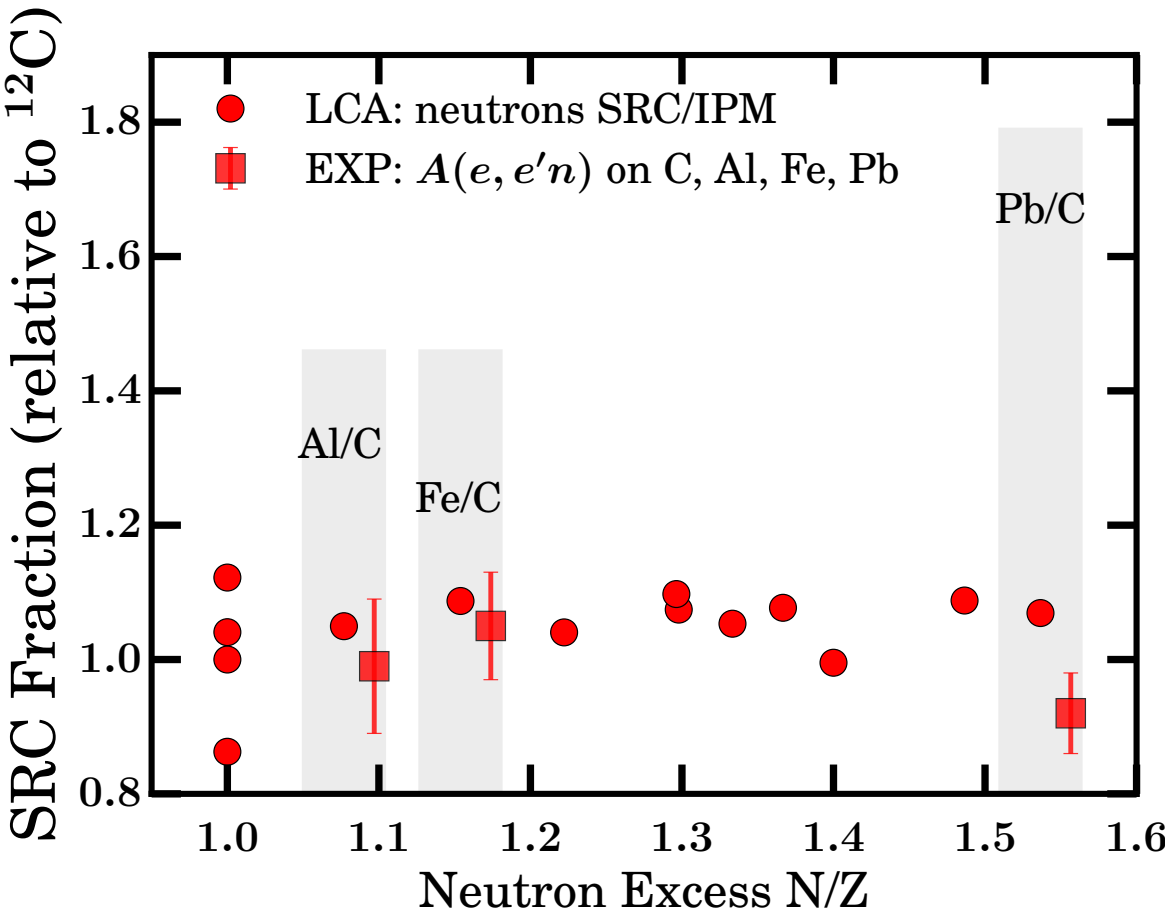


- Relative weight of the protons and neutrons is very different in "IPM" and "SRC" regions!
  1. IPM: $0.93\frac{N}{Z} + 0.07$
  2. SRC: $0.29\frac{N}{Z} + 0.71$
- DATA: Nature 560 (2018) 617

N/Z asymmetry dependence of the SRC?

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

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



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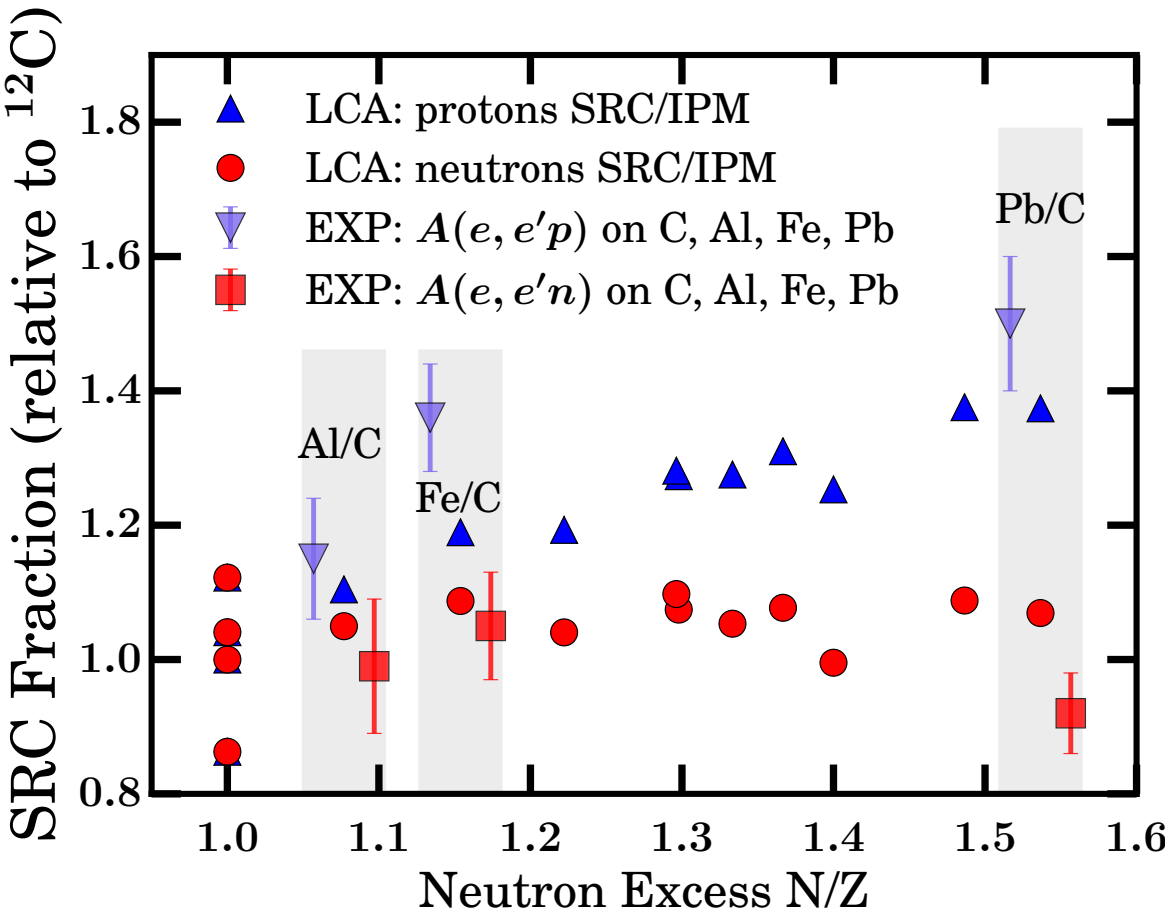

- Weight of the minority component in the tail (SRC) part of $n^{[1]}(p)$ increases with the asymmetry N/Z
- DATA: Nature 560 (2018) 617

SUMMARY

- **LCA: suited for systematic studies of SRC contributions to $n^{[1]}(p)$ and SRC sensitive reactions (Wim Cosyn's talk)**
  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 NMD tails**
- **Distinct isospin and N/Z SRC effects: in line with $A(e, e'pN)$ findings**
- **Neutron rich nuclei in SRC regime: protons are punching above their weight ($\approx 35\%$ in Pb)**
- **SRC induced spatio-temporal fluctuations in nuclei are measurable, are significant and are quantifiable**


THANK YOU!

Selected publications

- J. Ryckebusch, 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, J. Ryckebusch, 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, J. Ryckebusch *"Final-state interactions in two-nucleon knockout reactions"* arXiv:1512.07841 and PRC **93** (2016) 034608.
- J. Ryckebusch, 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, J. Ryckebusch, 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.