Short-Range Correlated nucleon pairs in nuclei

TECHNISCHE UNIVERSITÄT DARMSTADT

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Nucleon-nucleon interaction

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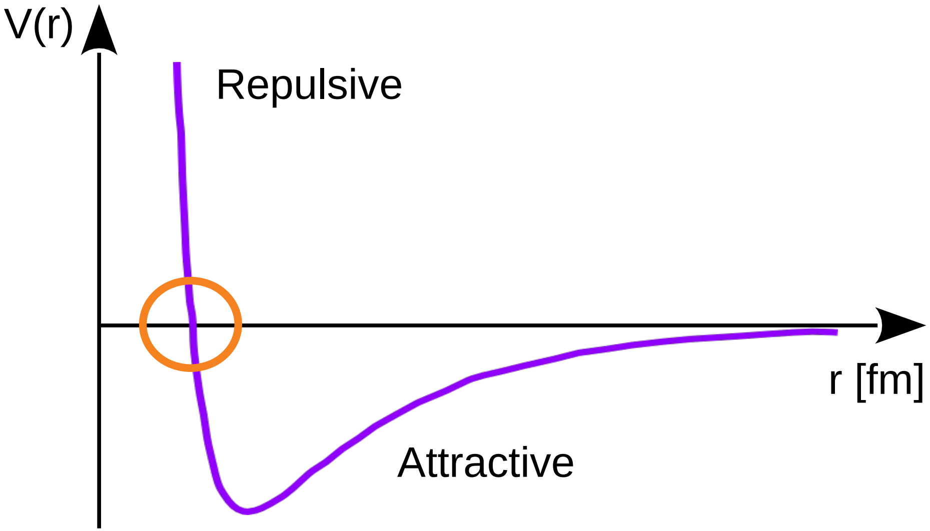
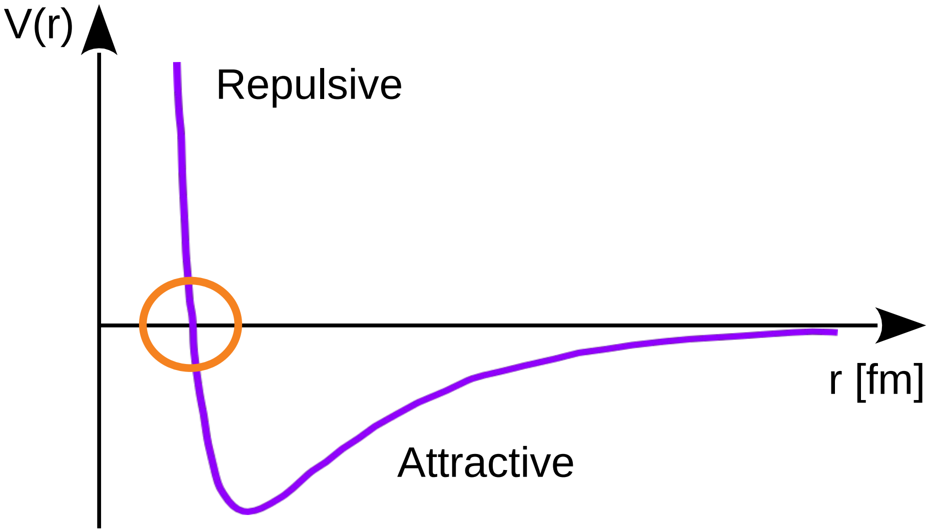


- Dominated by the **scalar interaction**
- Scalar ➜ 0: strong **tensor attraction**
  spin/isospin dependent

Nucleon-nucleon interaction



- Dominated by the **scalar interaction**
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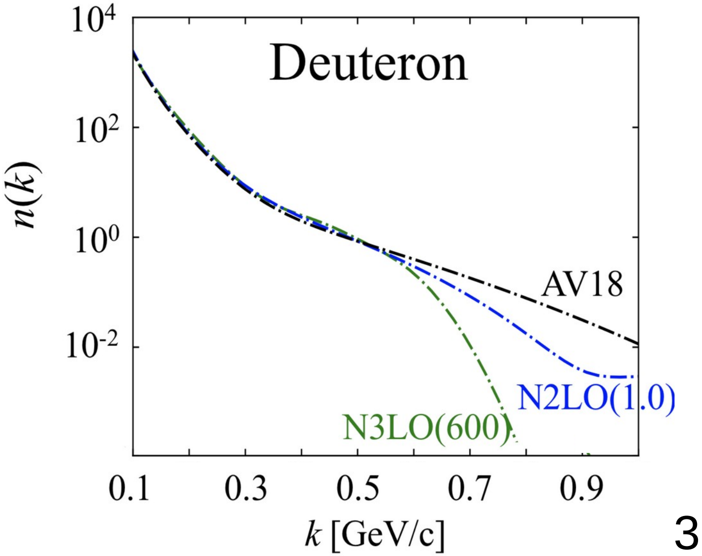
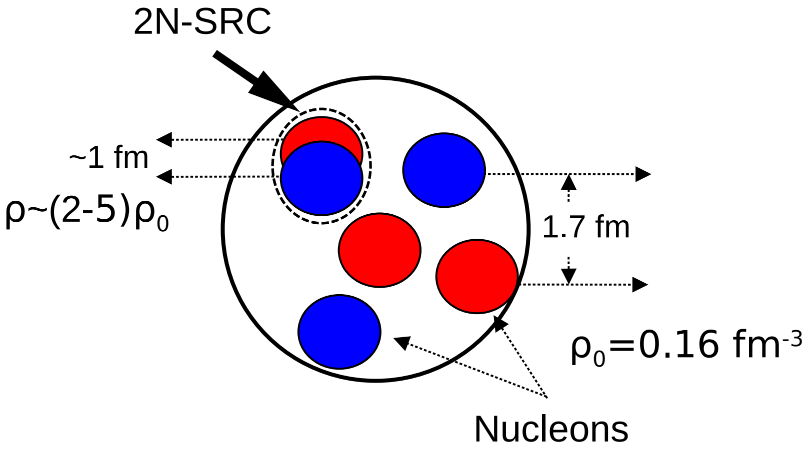
  spin/isospin dependent

- *NN* models:
  - contain experimentally determined parameters
  - large model dependence at short-distance / high-momentum



Short-Range Correlations (SRC)

- Nucleon pairs in close proximity



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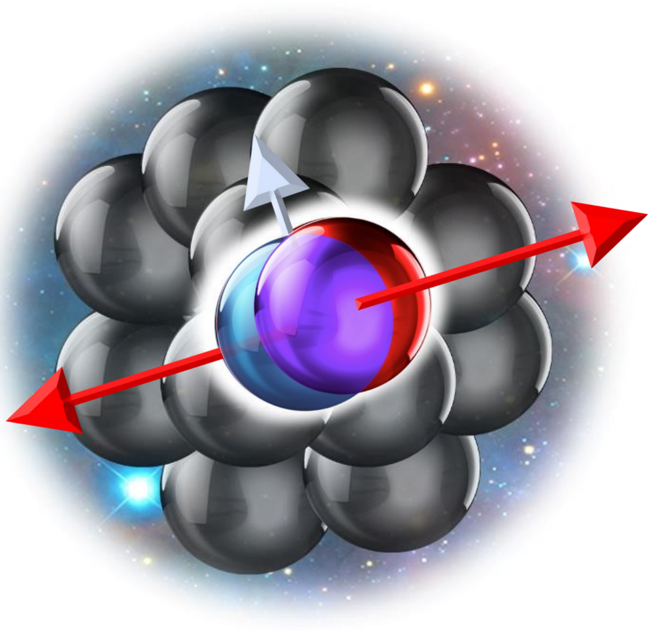

- Nucleon pairs in close proximity
- Large ***relative*** (k_{rel}>k_F) momentum and small ***center-of-mass*** ($k_{c.m.}$<k_F) motion

(relative to the Fermi momentum k_F~250 MeV/c)

$\boldsymbol{k}_{rel}=(\boldsymbol{k}_1-\boldsymbol{k}_2)/2$ $\boldsymbol{k}_{c.m.}=\boldsymbol{k}_1+\boldsymbol{k}_2$

SRC picture of nuclei

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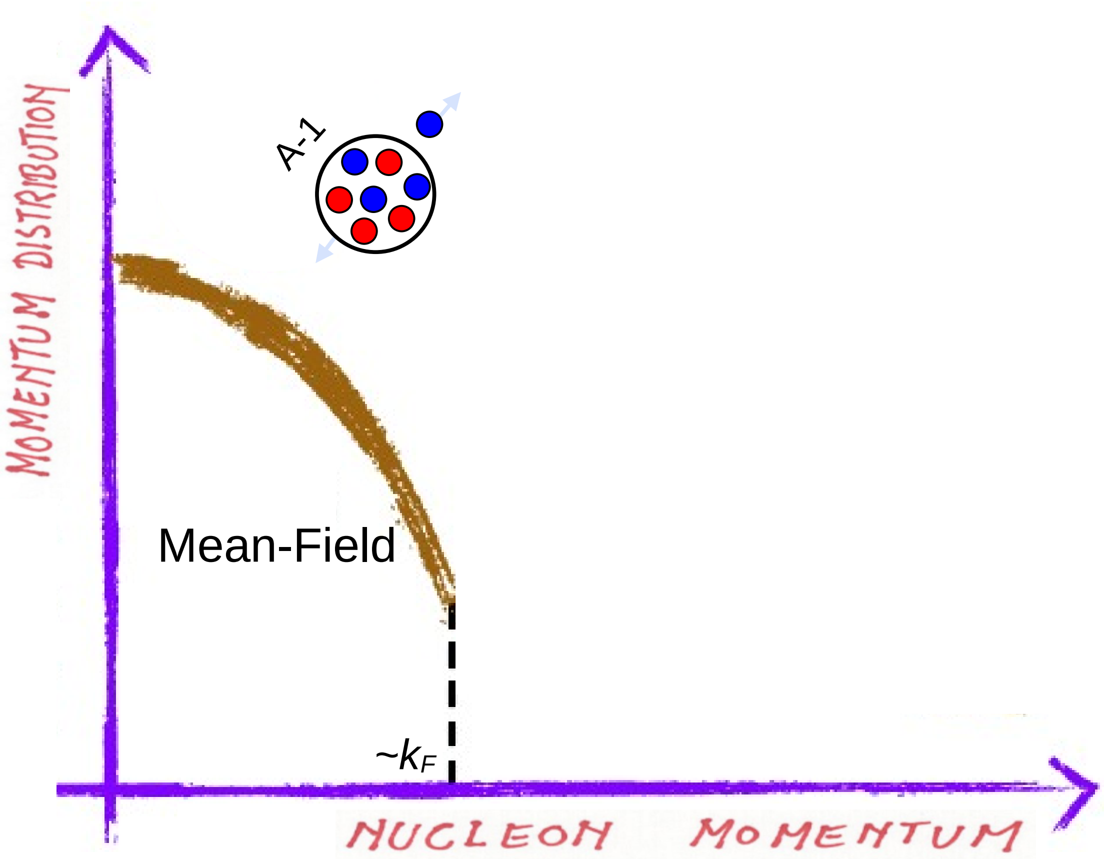
Nuclear Shell Model

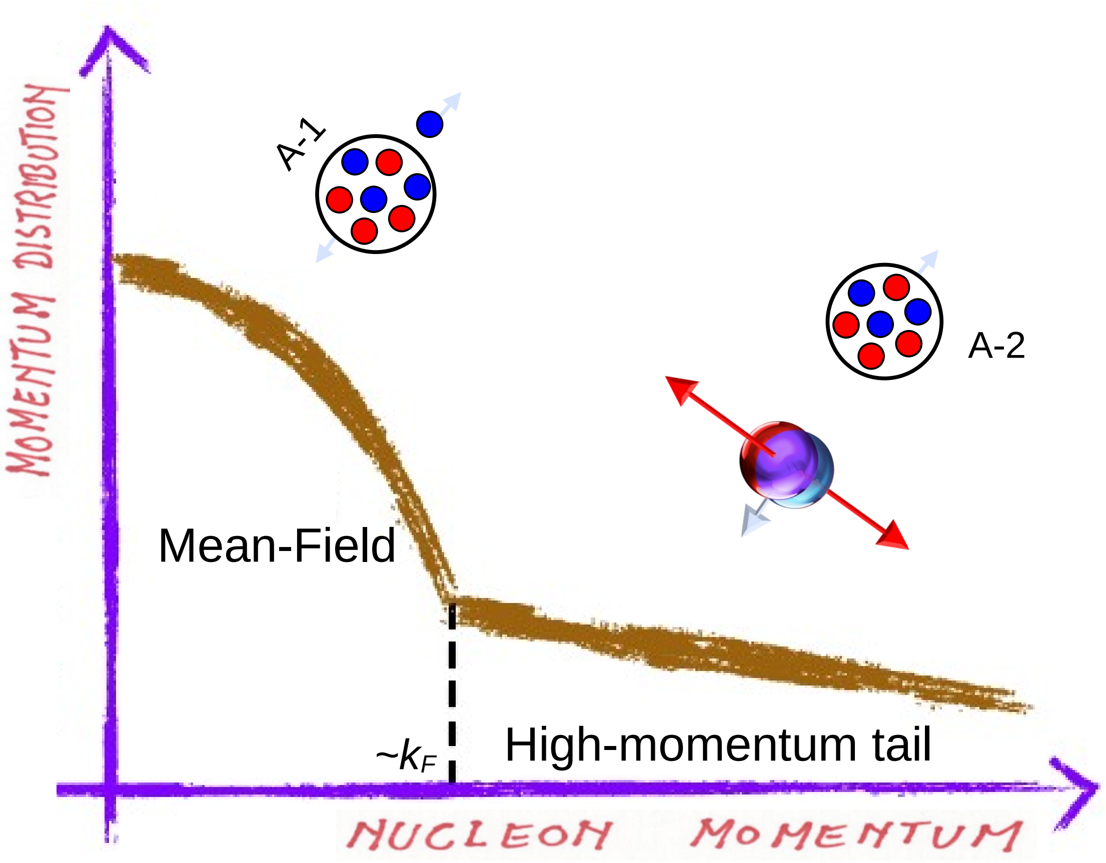
Wigner, Mayer and Jensen
1963 Nobel Prize

1st successful description

- ground-state energies
- excitation spectra
- ...



SRC picture of nuclei



Correlations and High Momentum

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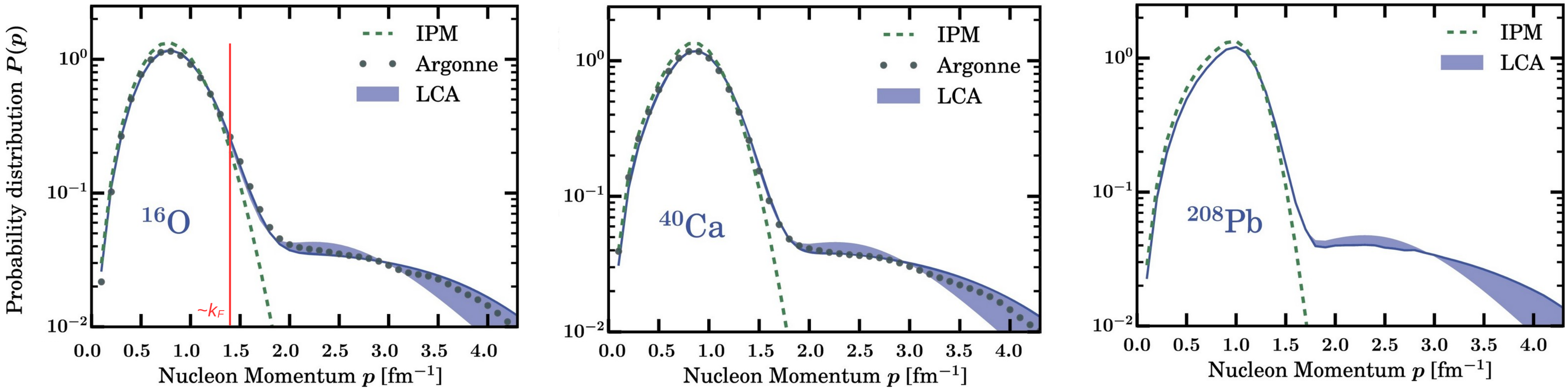
Universal!



Ryckebusch et al., Phys. Lett. B 792 (2019)

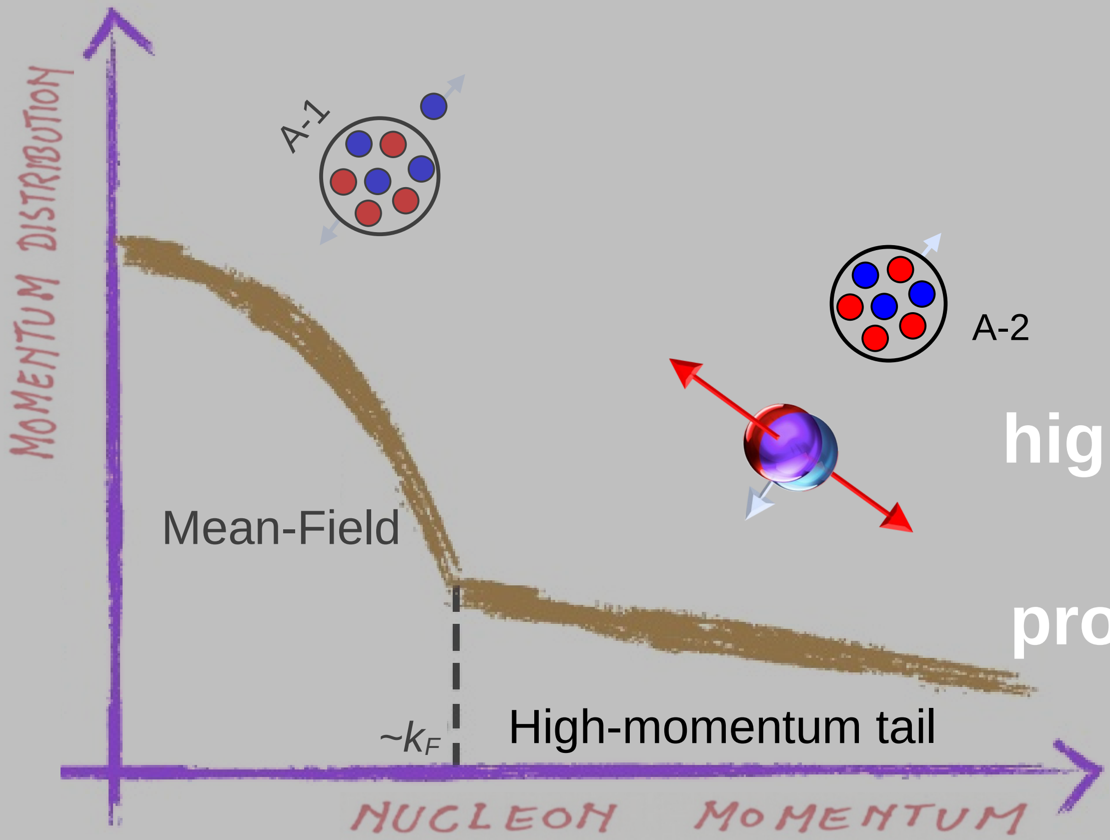
- - - IPM: Independent Particel Model

• • Argonne: QMC with AV18 nucleon-nucleon interaction

▬ LCA: Low-order Correlation operator Approximation

$$P(p) = p^2 n(p)/A$$

SRC picture of nuclei



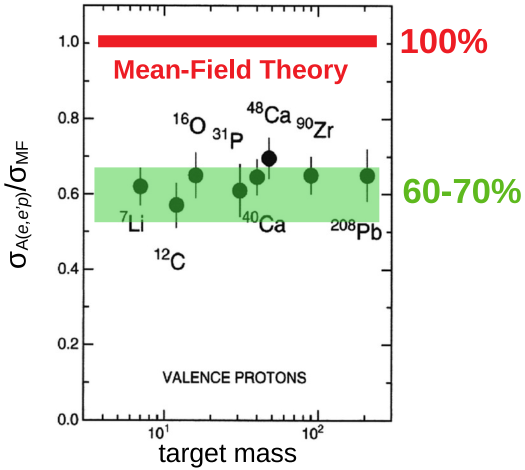
high-momenta

⟹

probing Pairs

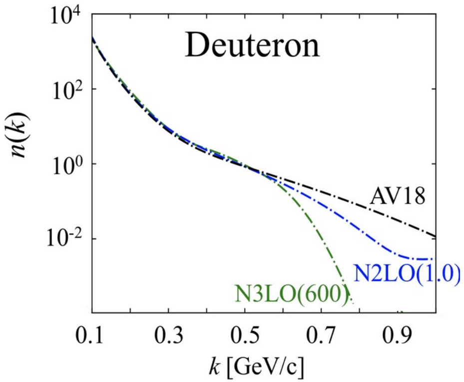
Why do we care?

nucleon-nucleon interaction



Lapikas, NPA 553 (1993)

short distance structure of nuclei



asymmetric nuclear matter

quark-gluon structure of bound nucleons (EMC effect)

Why do we care?

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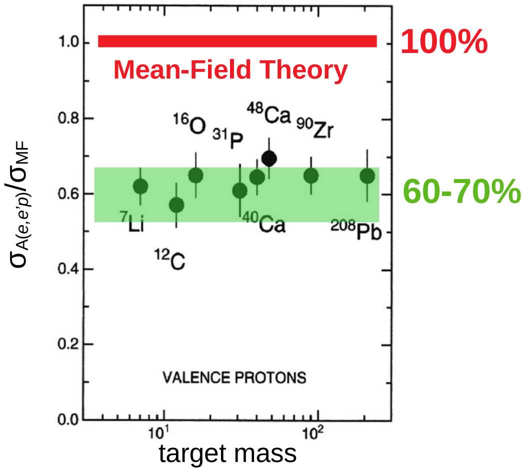

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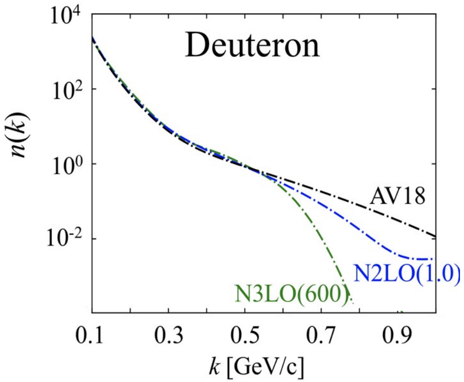

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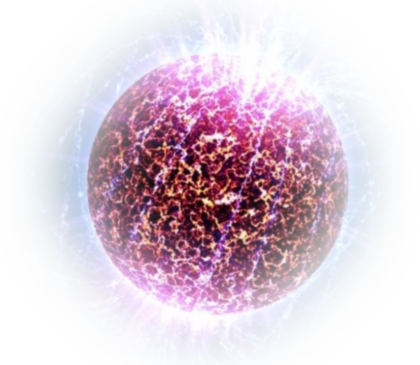

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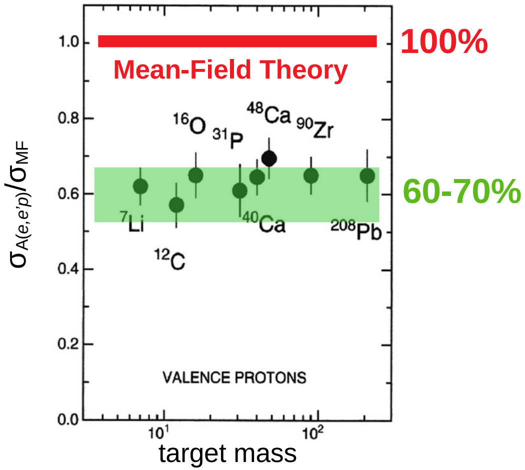

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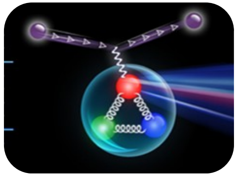
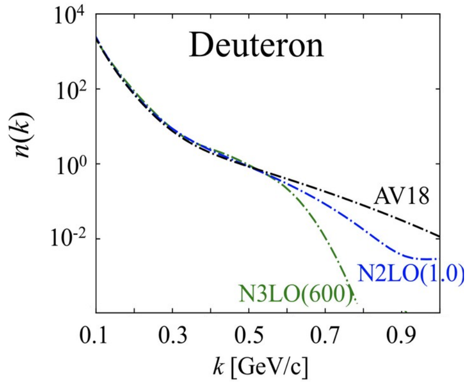
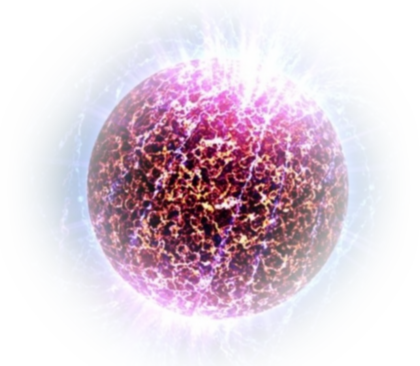


short distance structure of nuclei

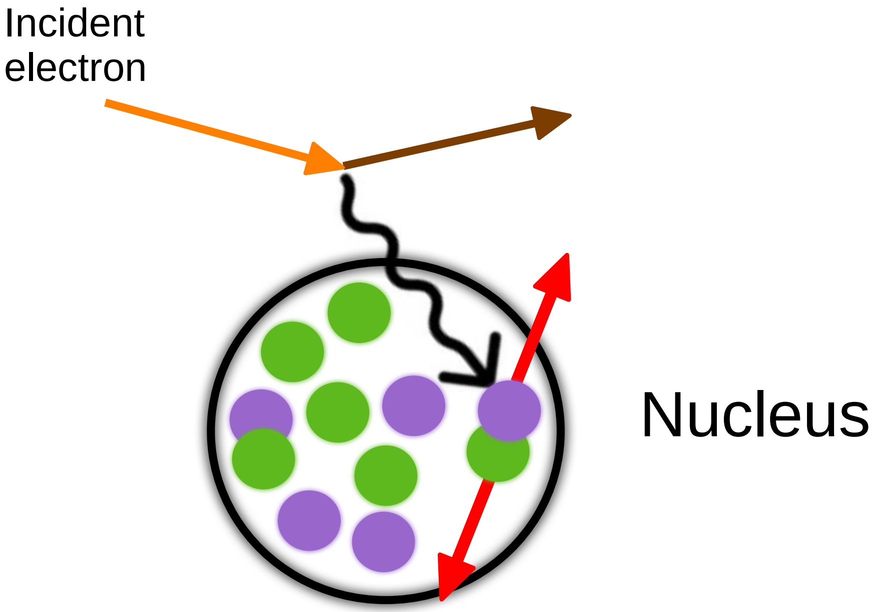


asymmetric nuclear matter



How do we study SRC?

- **Hard knockout reaction**
  - high-energy (several GeV)
  - large momentum-transfer
- Breakup the SRC pair



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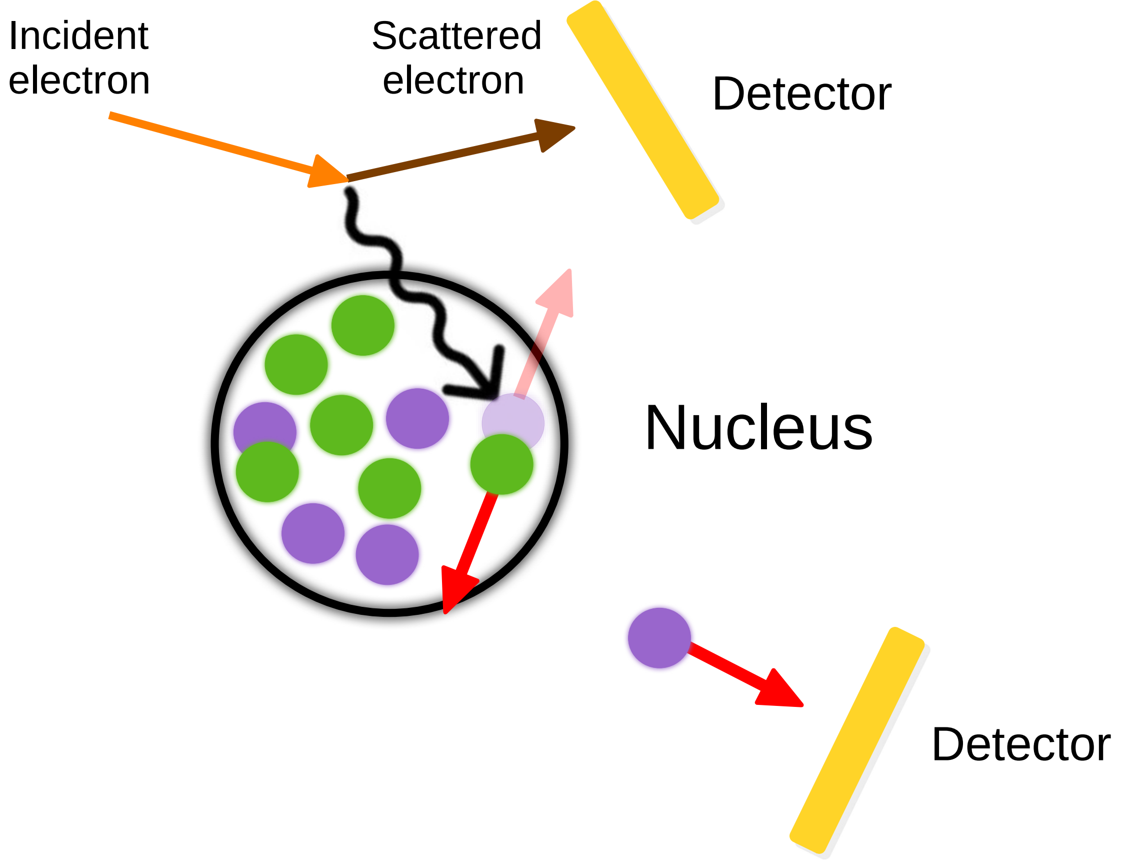

How do we study SRC?

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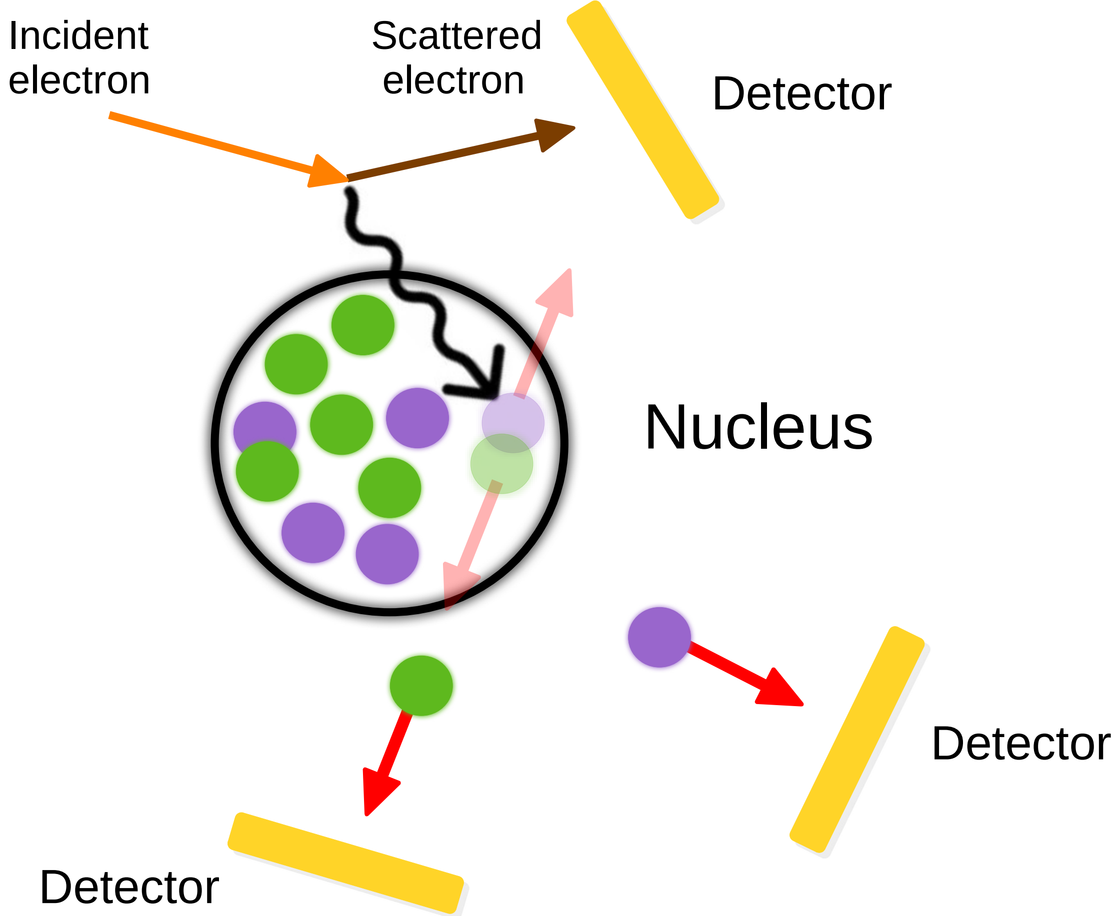
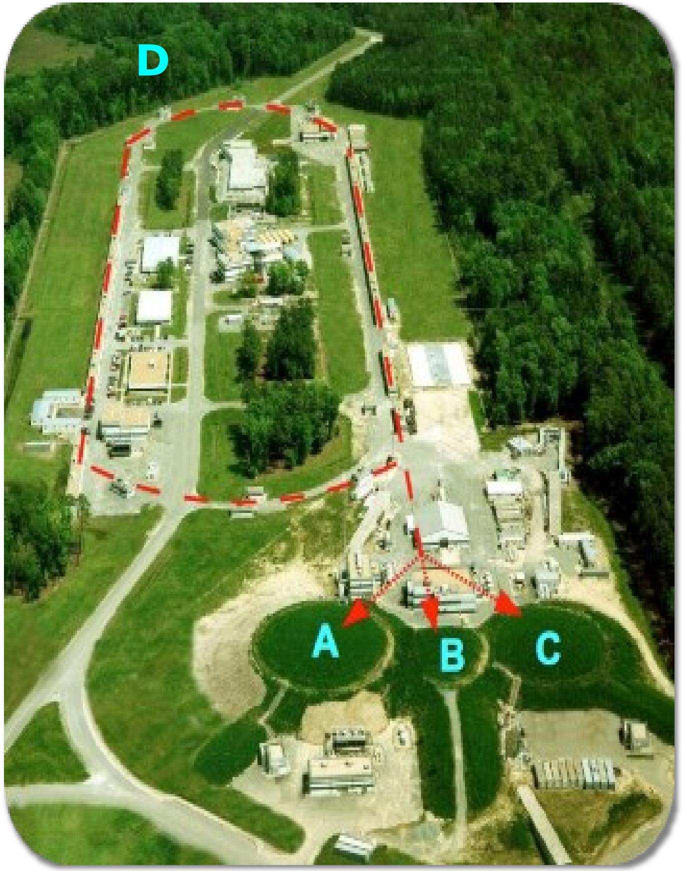
- **Hard knockout reaction**
  - high-energy (several GeV)
  - large momentum-transfer
- Breakup the SRC pair
- Triple coincidence measurement
  A(*e*,*e'NN*) *N*=*p*/*n*
- Reconstruct the initial state



SRC @ Jefferson Lab

- Located in Virginia, USA
- Electron beam (12 GeV)
- 4 experimental halls



CEBAF Large Acceptance Spectrometer

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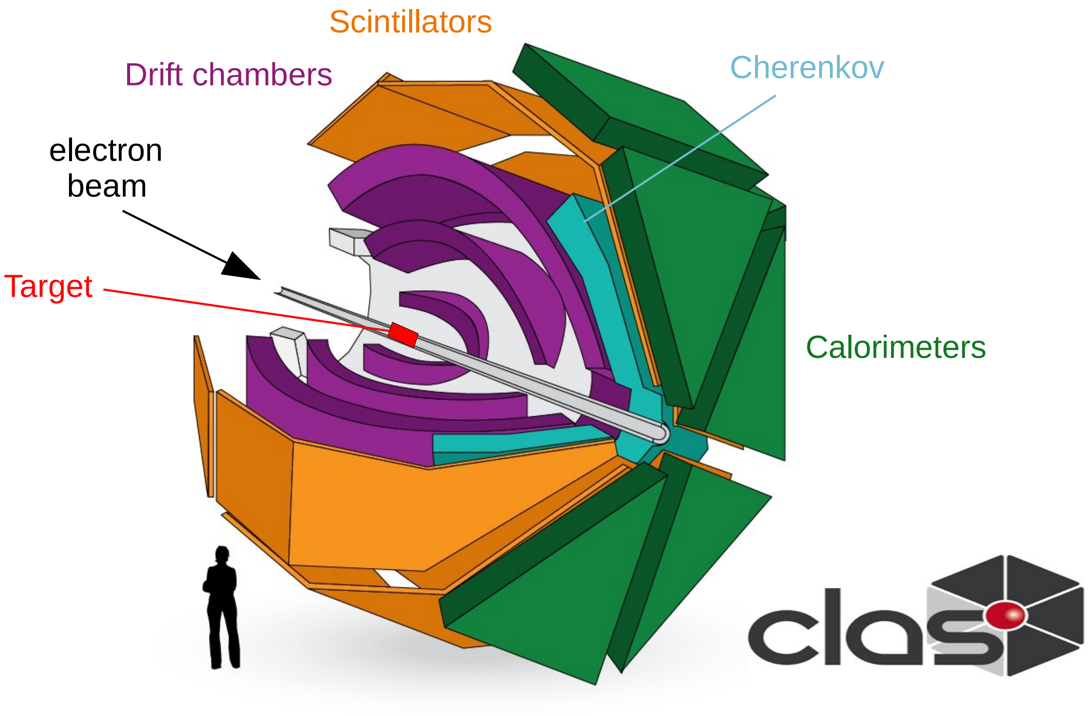
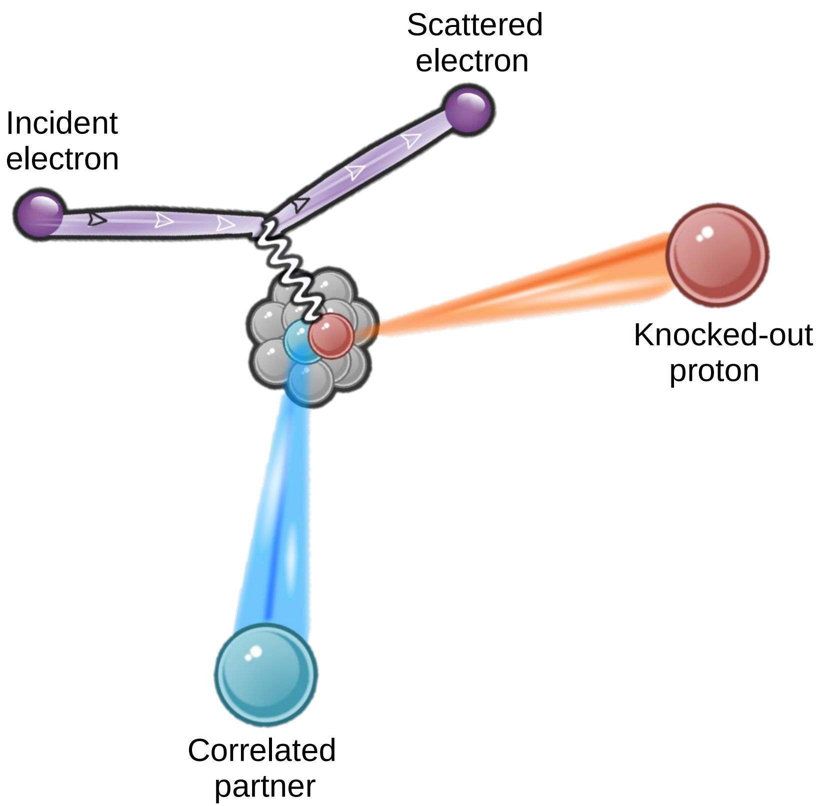


Large-acceptance

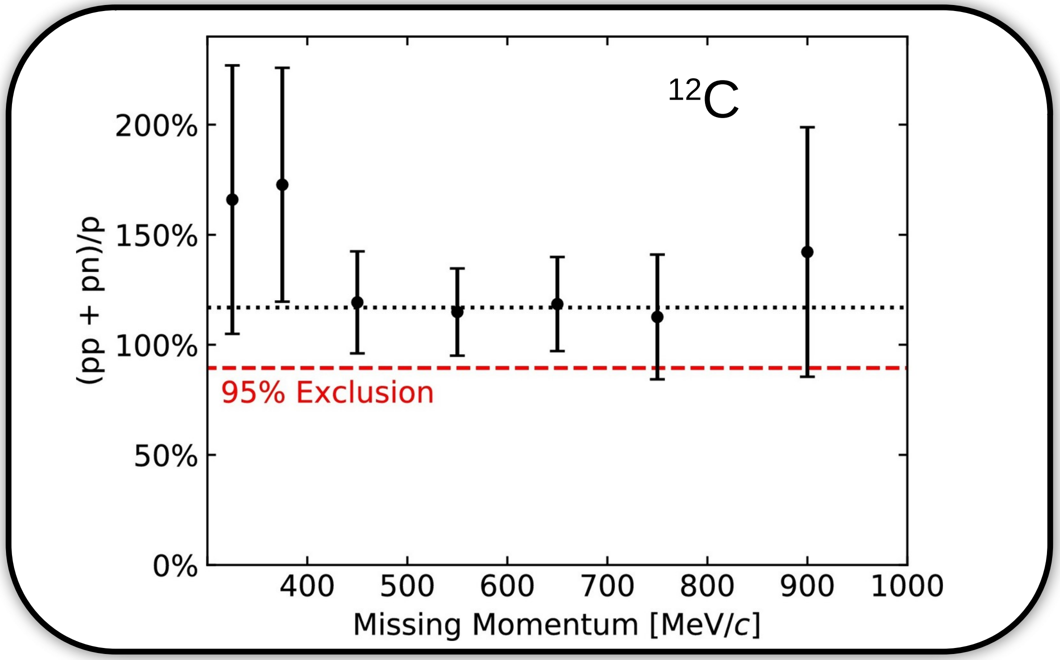
Open (*e*,*e*') trigger

Low luminosity

Do high-momentum nucleons come in pairs?



Yes!



I. Korover et al., PLB (2021)

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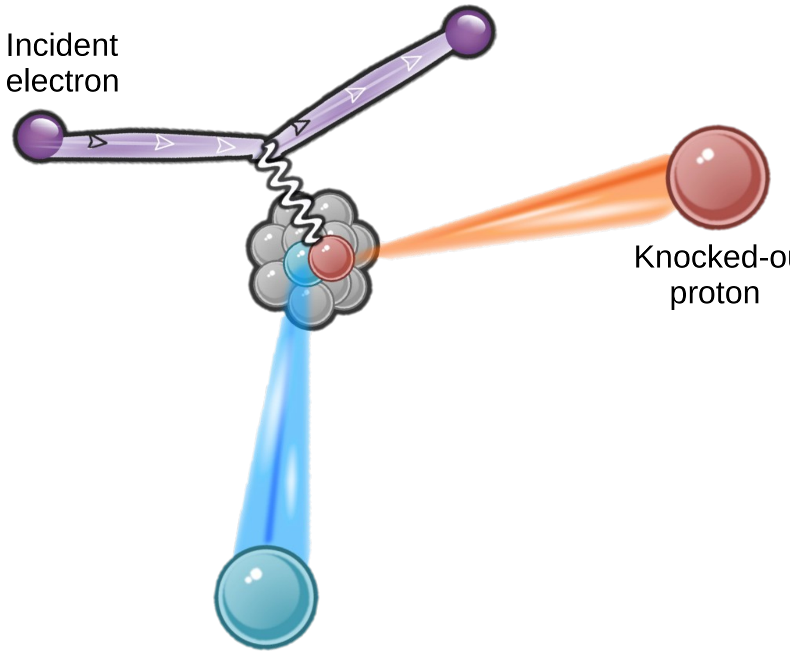
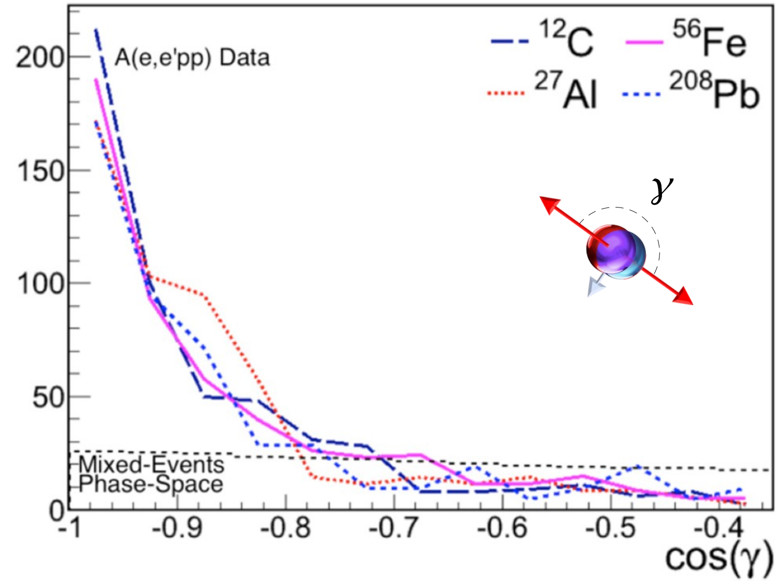


Back-to-back = SRC pairs



O. Hen et al., Science (2014)

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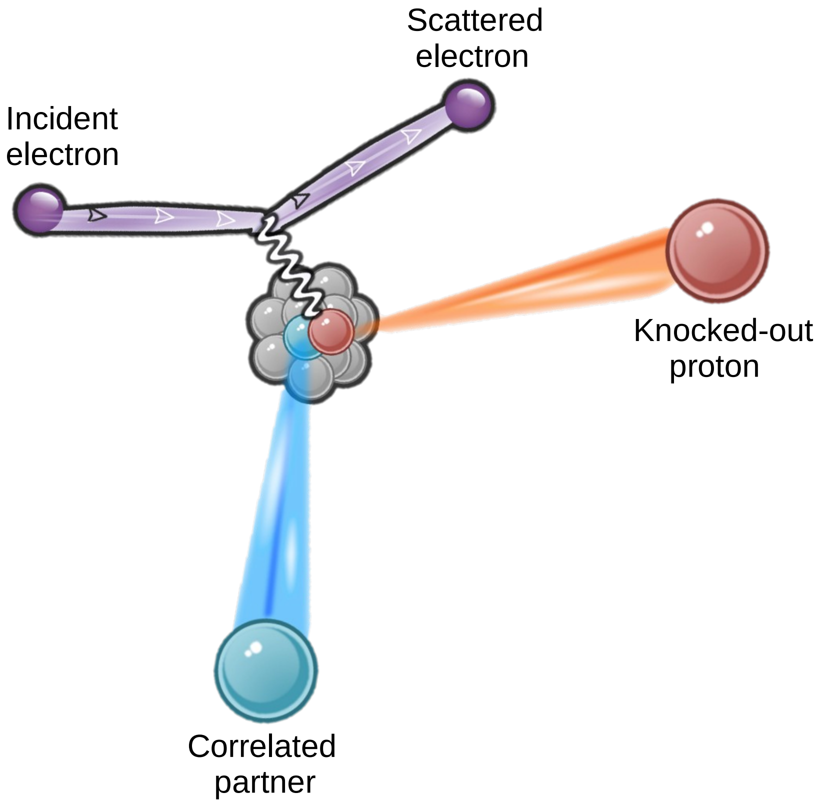
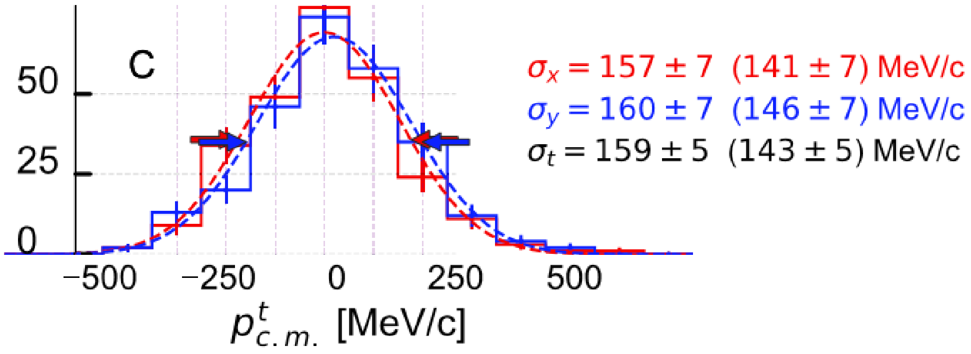


"large relative and
small center-of-mass motion"



E. Cohen et al., PRL (2018)

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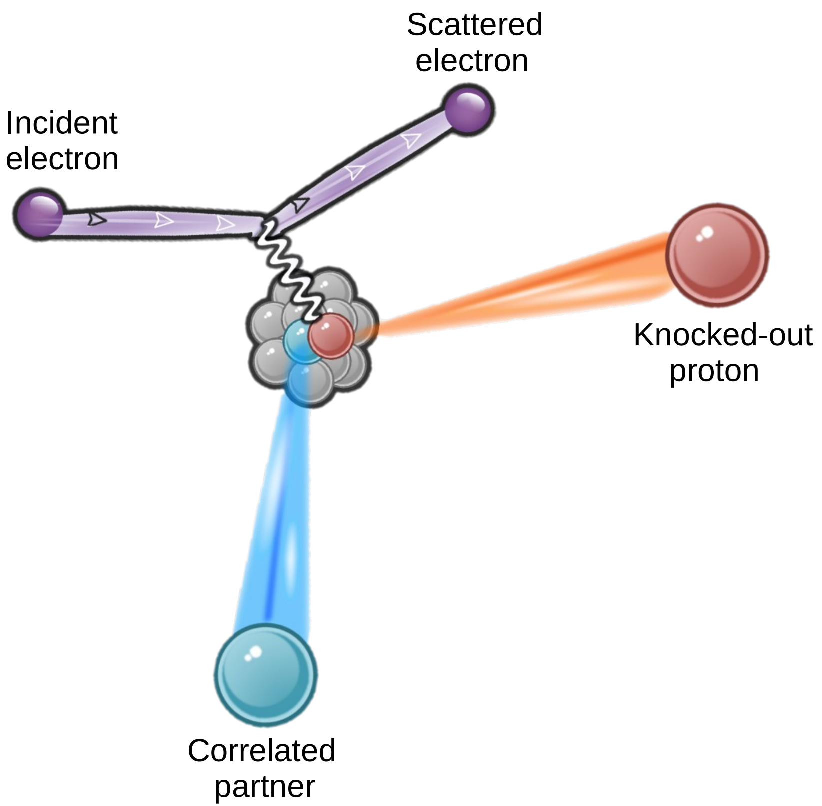
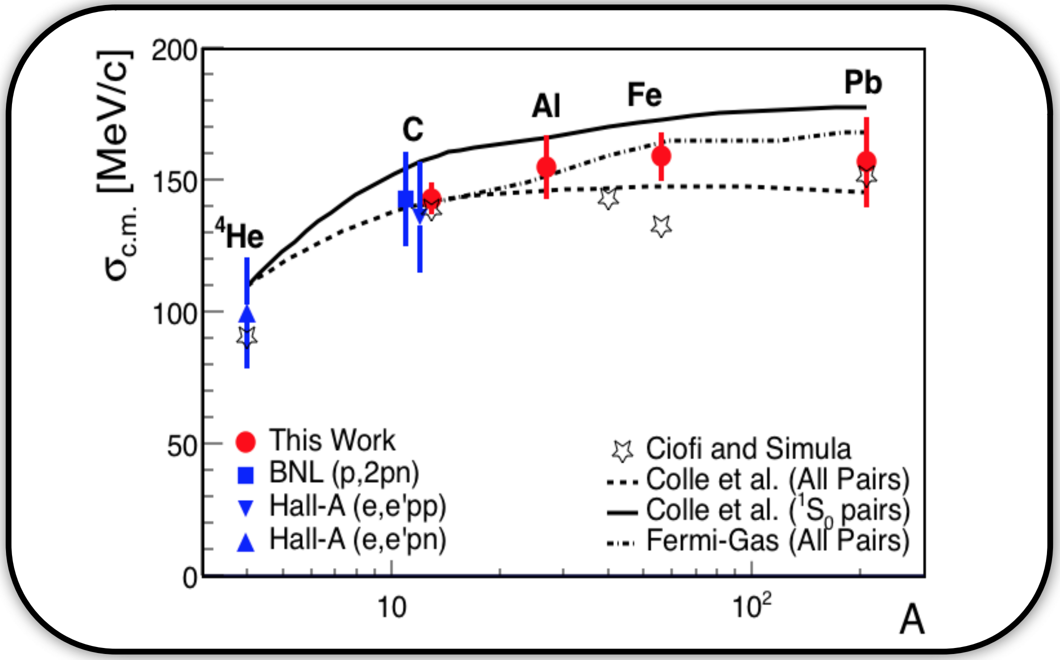


Consistent with Mean-Field calculations



E. Cohen et al., PRL (2018)

What kind? Predominantly neutron-proton pairs

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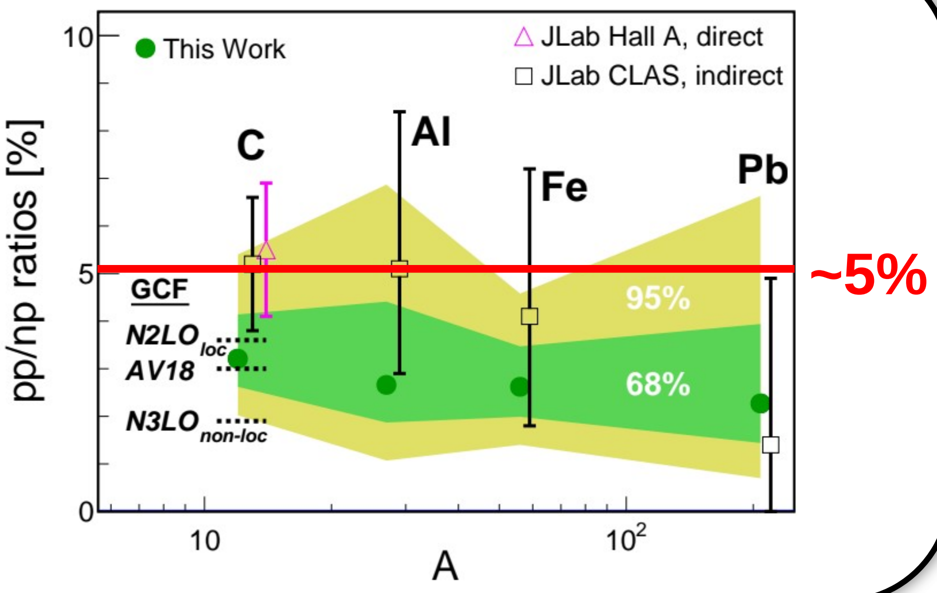
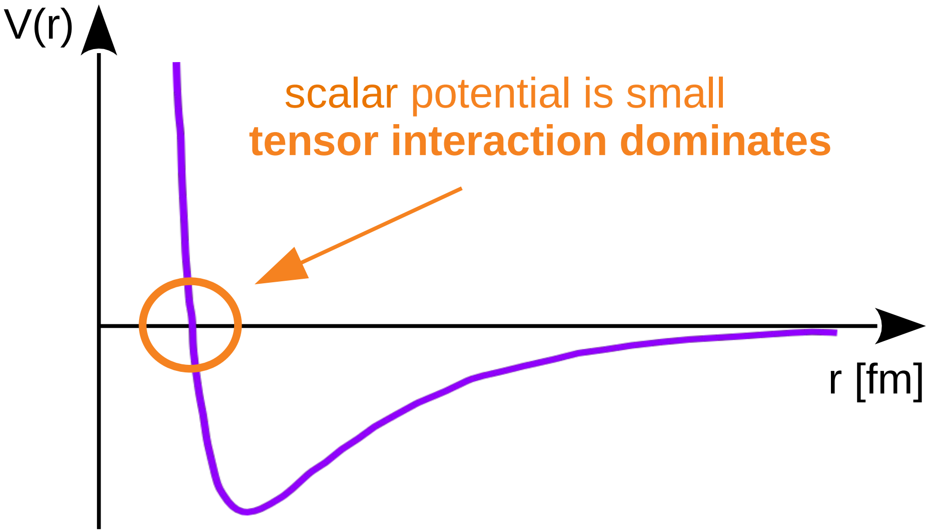
No A dependence -> Universal!





MD, PRL (2019); MD, Nature (2018); Hen, Science (2014); Korover, PRL (2014); Subedi, Science (2008); Shneor, PRL (2007); Piasetzky, PRL (2006); Tang, PRL (2003);

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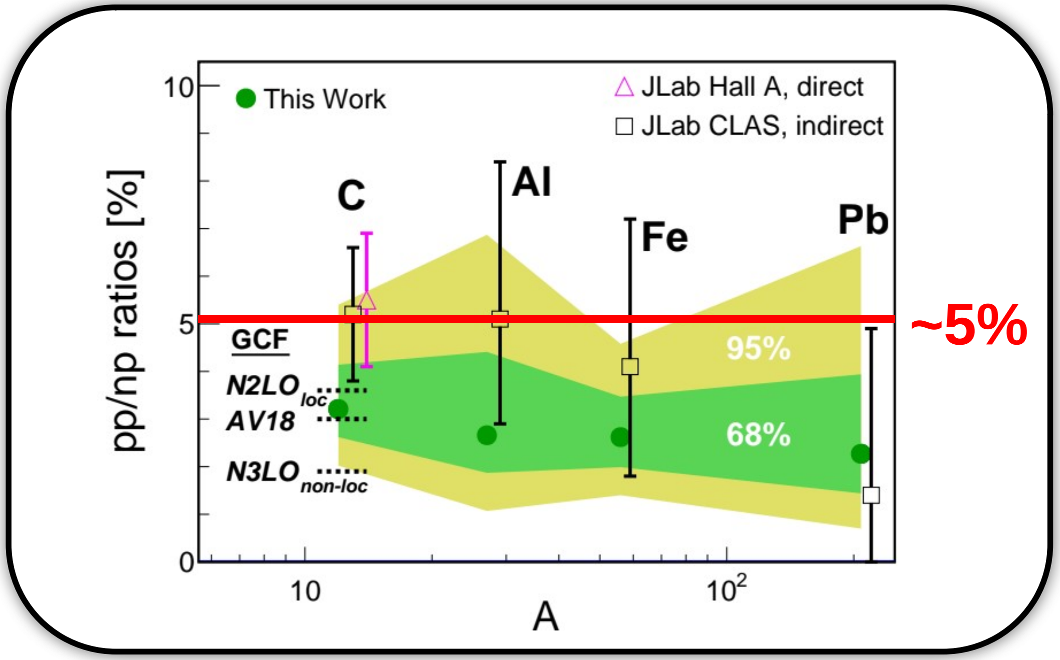

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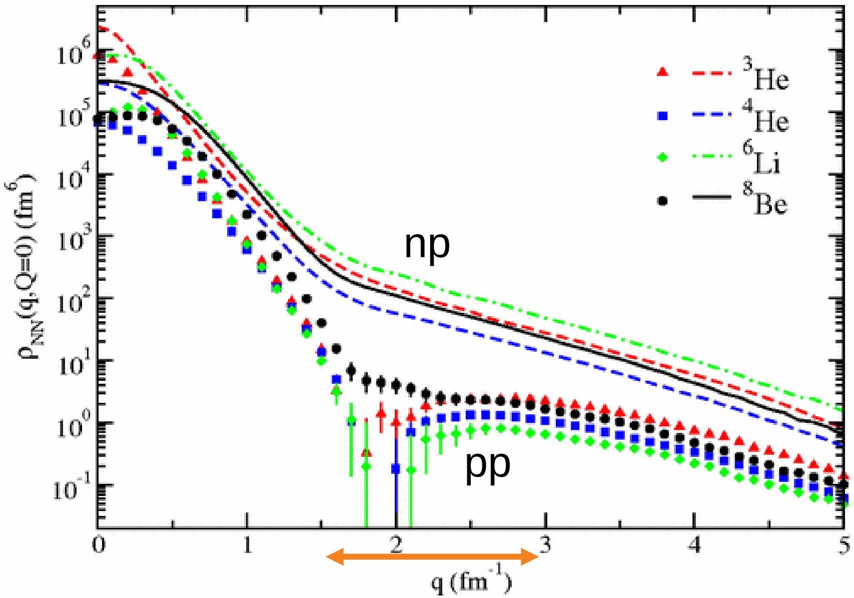
Also seen in ab-initio pair distributions



Schiavilla et al., PRL 98 (2007)

Sargsian et al., PRC 71 (2005); Ciofi and Alvioli, PRL 100 (2008)

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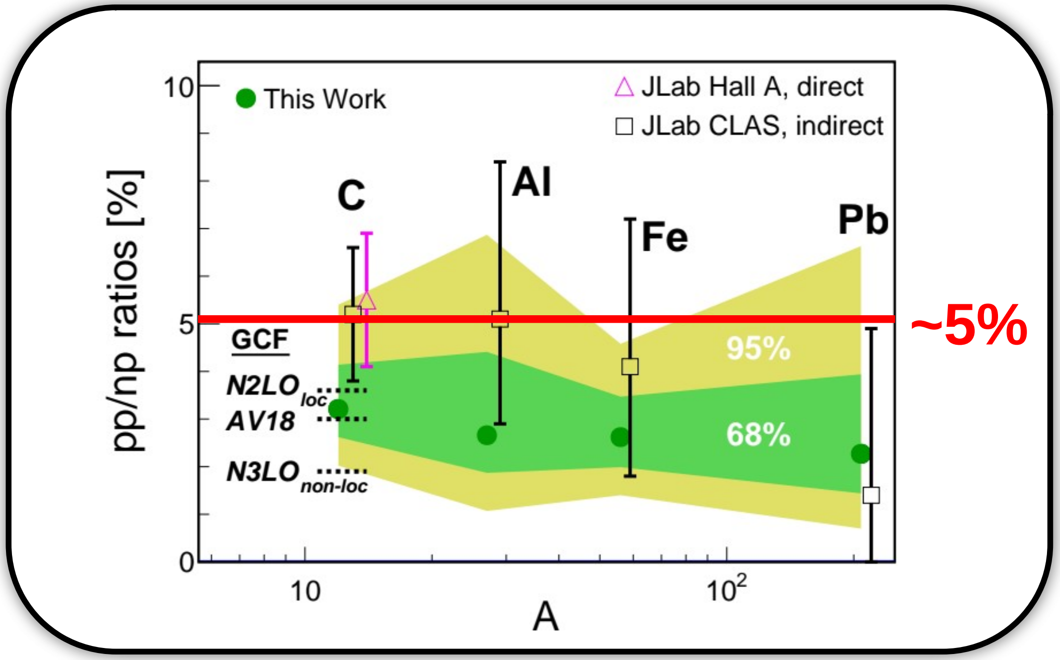

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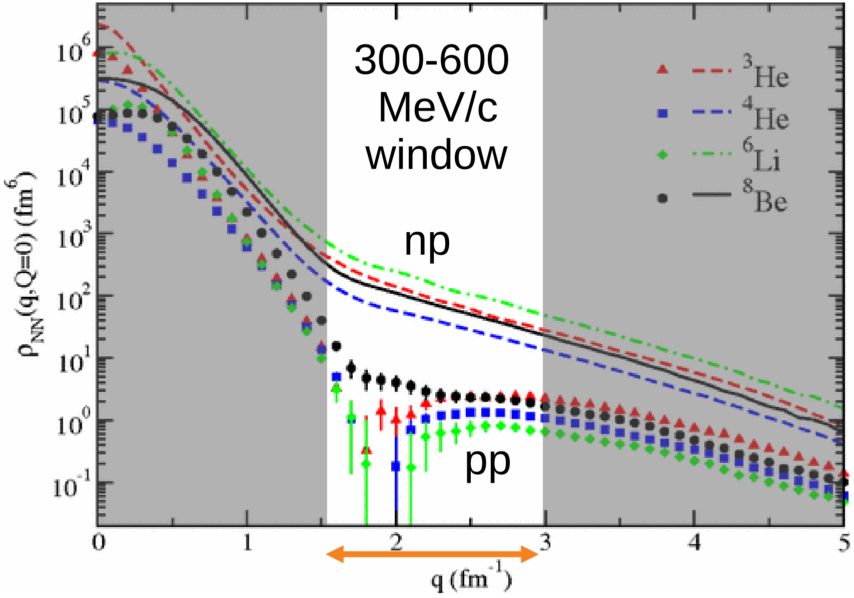

Schiavilla et al., PRL 98 (2007)

Sargsian et al., PRC 71 (2005); Ciofi and Alvioli, PRL 100 (2008)

What do excess neutrons do?

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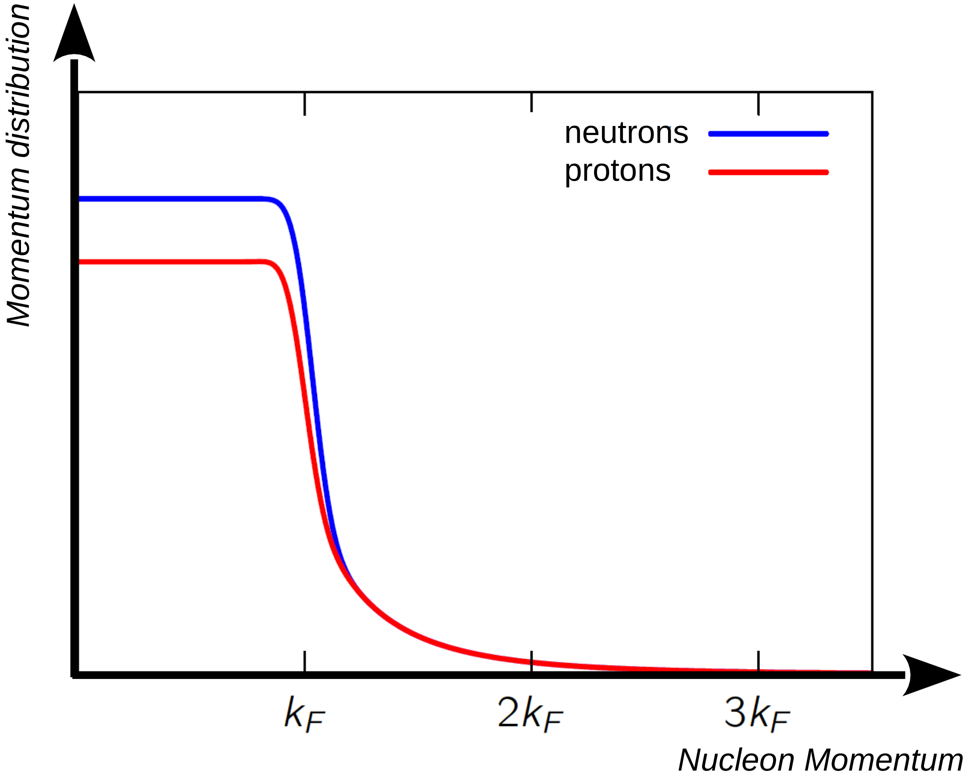

don't correlate?

correlate with core protons?

correlate with each other?

Comparing proton & neutron dynamics

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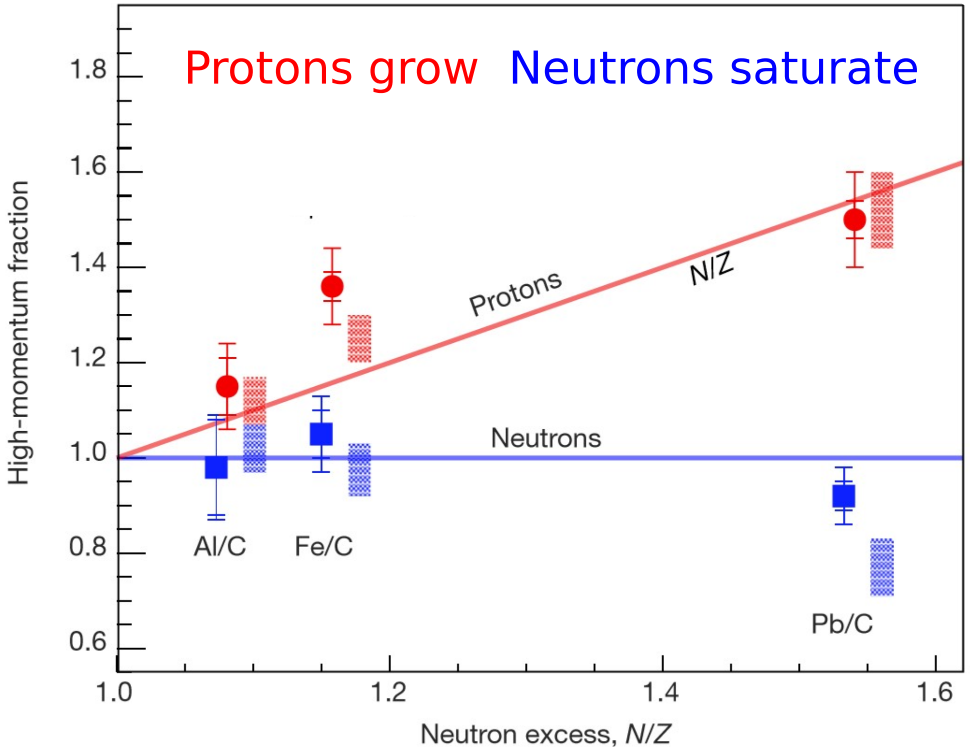
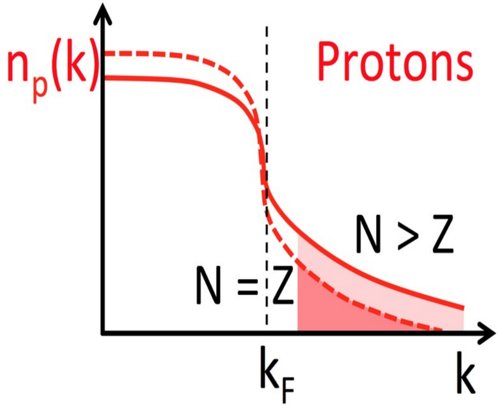
Correlation probability



MD et al., Nature 560 (2018)



Protons 'Speed-Up' in neutron-rich nuclei

Comparing proton & neutron dynamics

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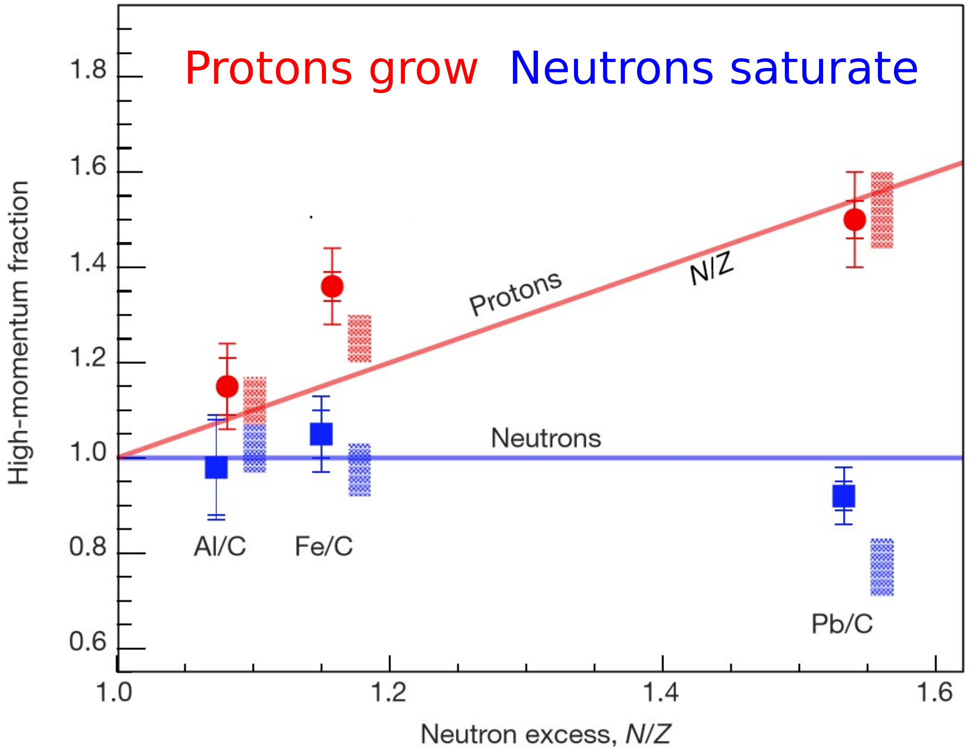
Correlation probability



MD et al., Nature 560 (2018)

Daily Press
Jefferson Lab breaks new ground, from nucleons to neutron stars

PHYS.ORG
Protons may have an outsize influence on the properties of neutron stars and other neutron-rich objects

Space Answers
Protons strongly influence the behaviour of neutron stars

Astronomy Now

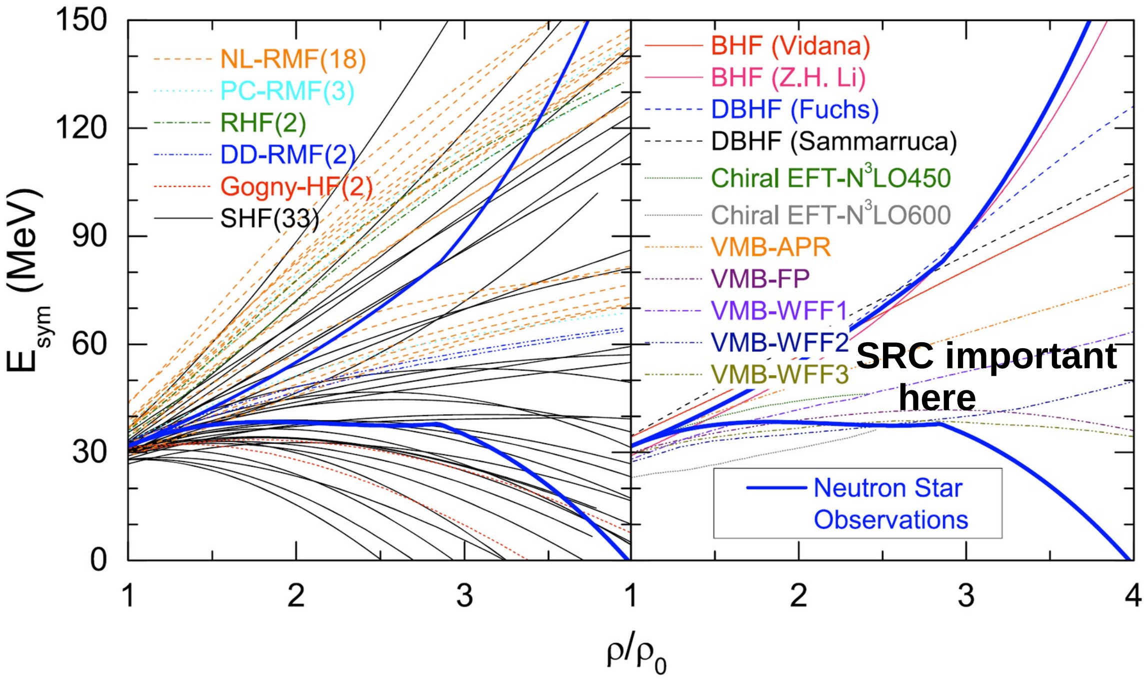
physicsworld

GIZMODO
Surprising Accelerator Finding Could Change the Way We Think About Neutron Stars

Nuclear symmetry energy

Phenomenological models
60 examples

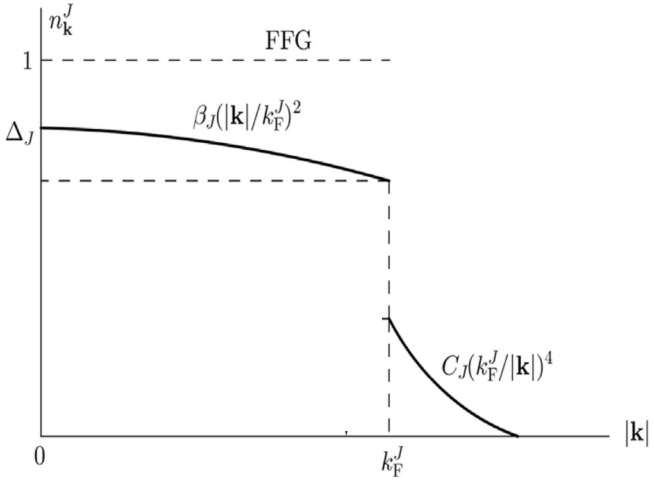
Microscopic & ab initio theories
11 examples



N.-B. Zhang & B.-A. Li, APJ 902 (2020)

SRC effects on nuclear symmetry energy

Phenomenological nucleon momentum distribution n^J_k *(J=p/n)* guided by microscopic theories & experimental findings



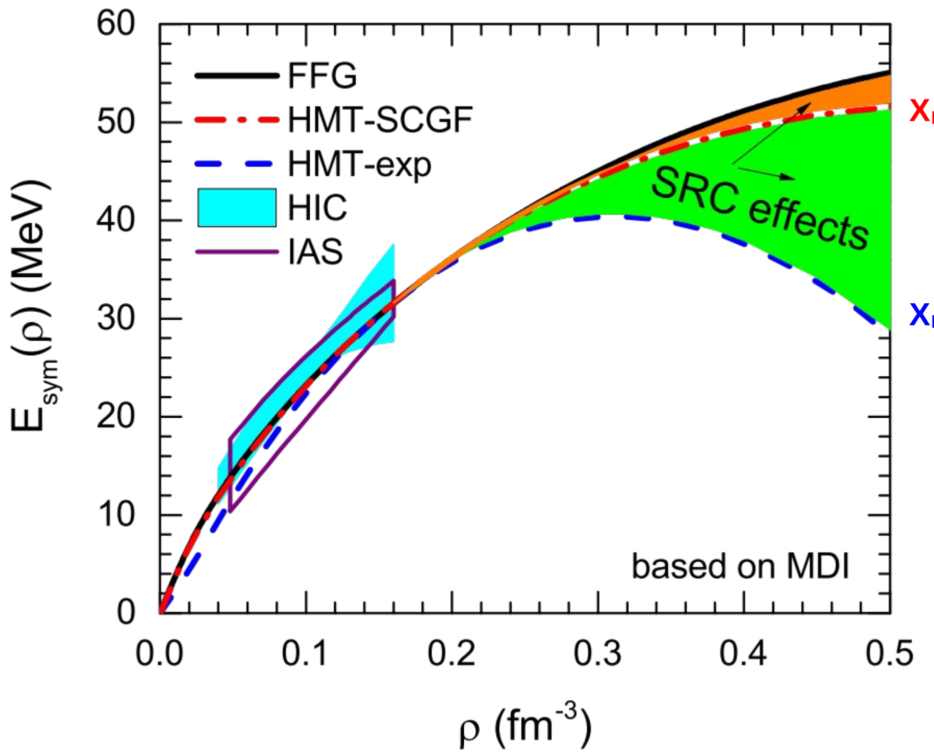
FFG = free Fermi gas

$$n^J_{\mathbf{k}}(\rho,\delta) \equiv n_J(\rho,|\mathbf{k}|,\delta) = \begin{cases} \Delta_J + \beta_J I\left(\frac{|\mathbf{k}|}{k_F^J}\right), & 0 < |\mathbf{k}| < k_F^J, \\ C_J\left(\frac{k_F^J}{|\mathbf{k}|}\right)^4, & k_F^J < |\mathbf{k}| < \phi_J k_F^J. \end{cases}$$

***** parameters assumed to have linear isospin-asymmetry dependence based on predictions from self-consistent Green's function (SCGF)

B.-A. Li et al., Prog. Part. Nucl. Phys. 99 (2018)

SRC effects on nuclear symmetry energy



X_{HMT}^{SNM}=12%, X_{HMT}^{PNM}=4%

X_{HMT}^{SNM}=25%, X_{HMT}^{PNM}=1.5%

FFG = free Fermi gas

HMT = high-momentum tail

SCGF = self-consistent Green's function

SNM = symmetric nuclear matter

PNM = pure neutron matter

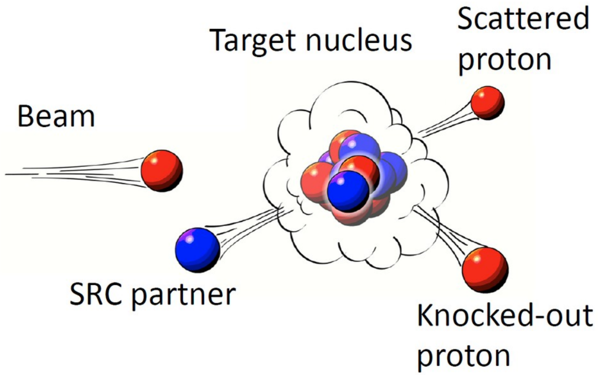
ρ_0=0.16 fm^{-3}

Consequence: symmetry energy gets softened

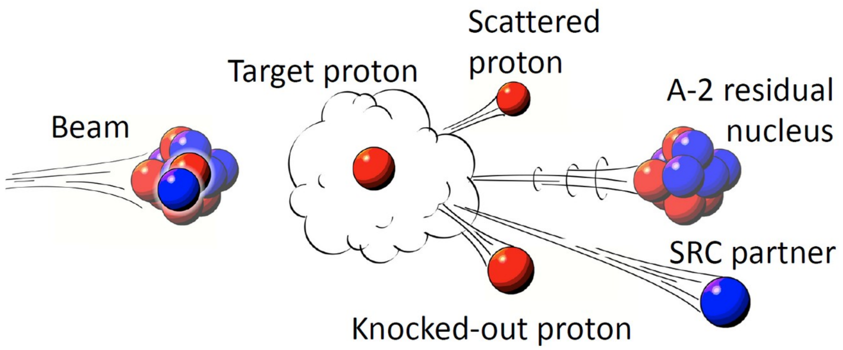
B.-A. Li et al., Prog. Part. Nucl. Phys. 99 (2018)

Going more neutron-rich

Direct kinematics



Inverse kinematics



- Limited to stable nuclei $N/Z \leq 1.5$

- Radioactive-ion beams
  - larger N/Z asymmetry
  - systematics of isospin-asymmetry
- Kinematically complete measurement A(p,2pN)**A-2**

1st measurement in inverse kinematics

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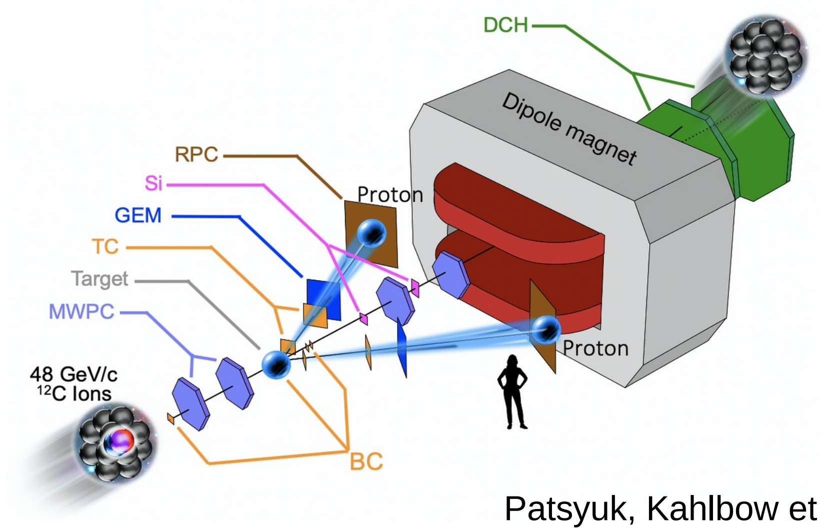
- BM@N setup, JINR (2018)
- Well known system: ^{12}C
- High-energy: 3 GeV/nucleon

➜ **Identify SRC signal in inverse kinematics**



Patsyuk, Kahlbow et al., Nature Physics 17 (2021)

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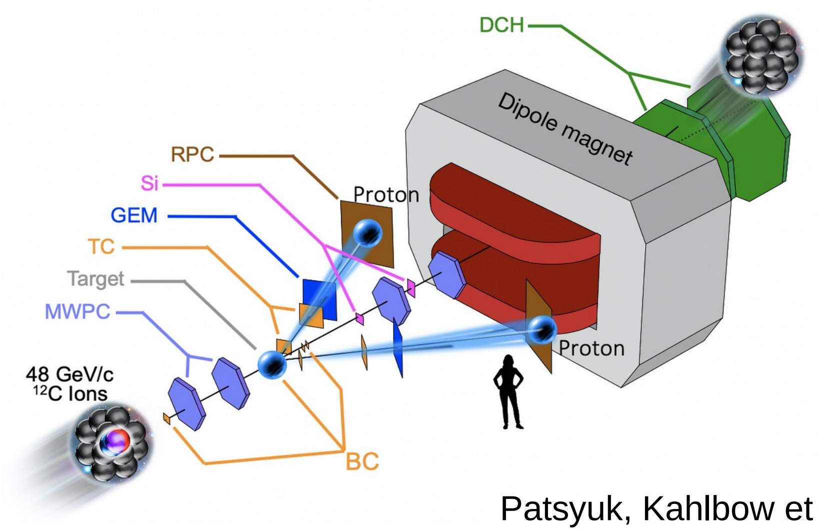


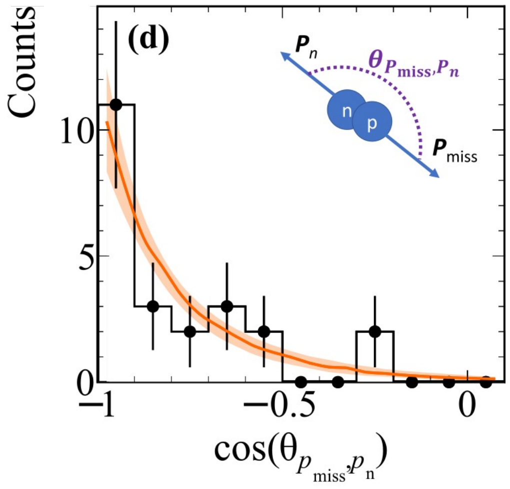
np-pairs: $^{12}C(p,2p)^{10}B$ – 23 events

pp-pairs: $^{12}C(p,2p)^{10}Be$ – 2 events

➜ np-dominance

* correlated partner not measured

Back-to-back correlation!



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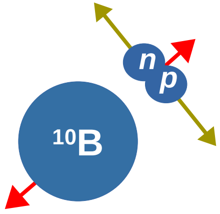
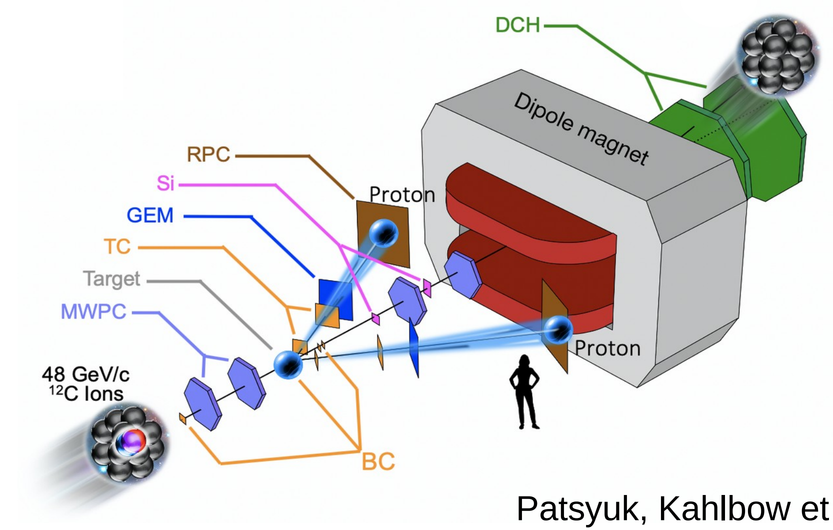
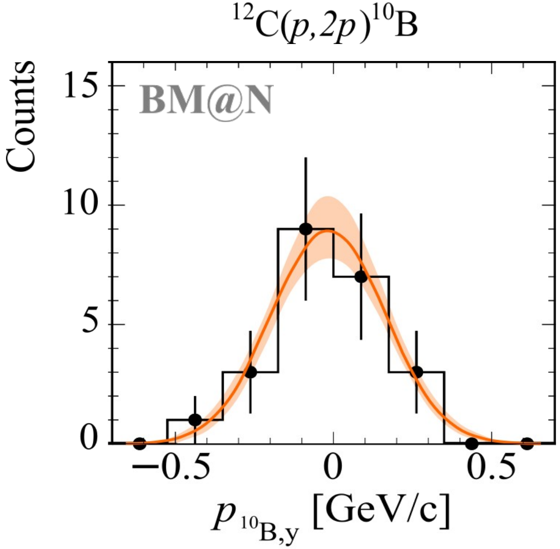
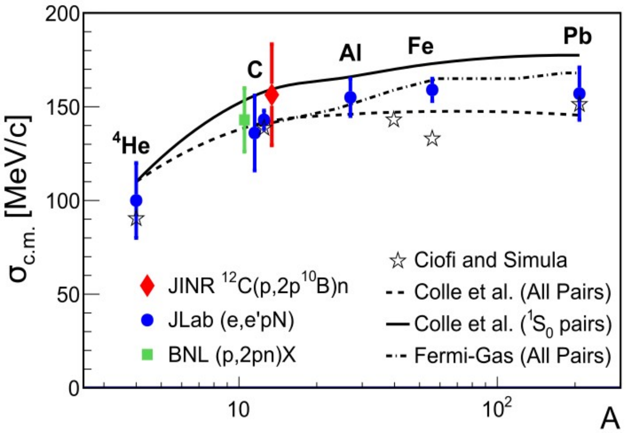
fragment momentum -> c.m. motion









Cohen et al., PRL 121 (2018)

Patsyuk, Kahlbow et al., Nature Physics 17 (2021)

SRC @ R³B/GSI

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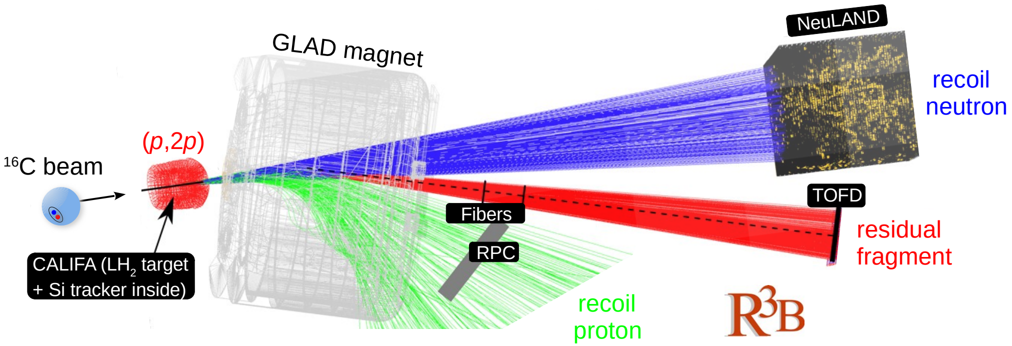

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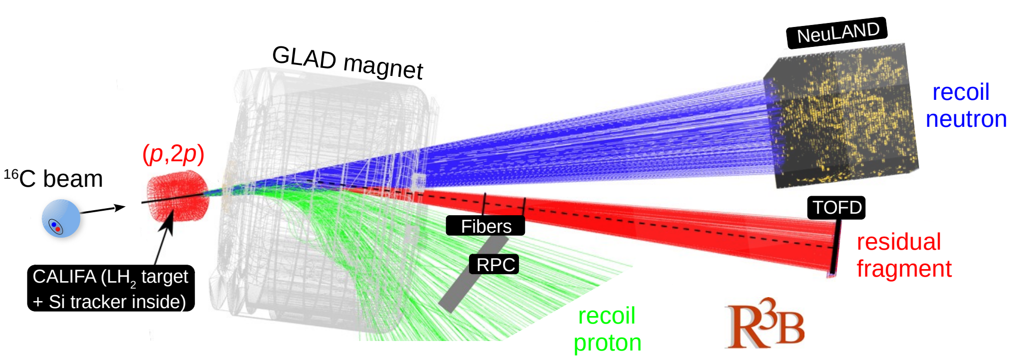

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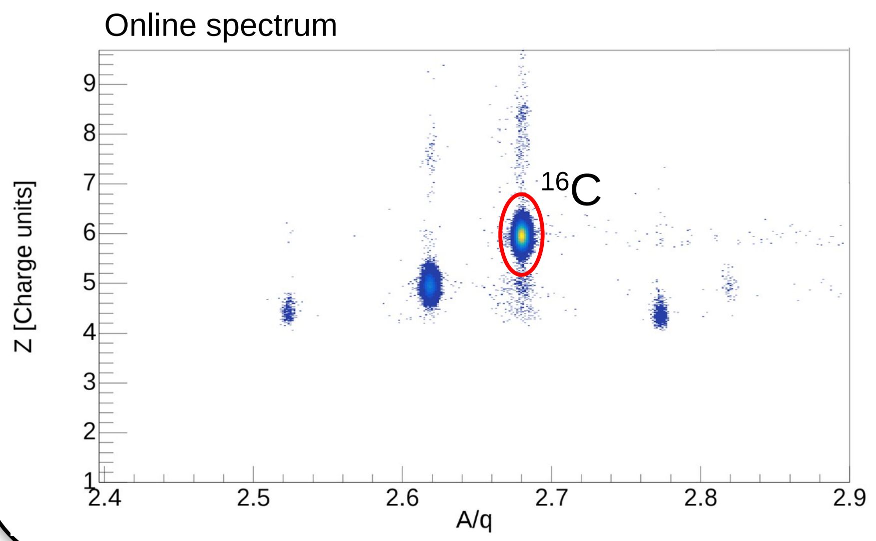

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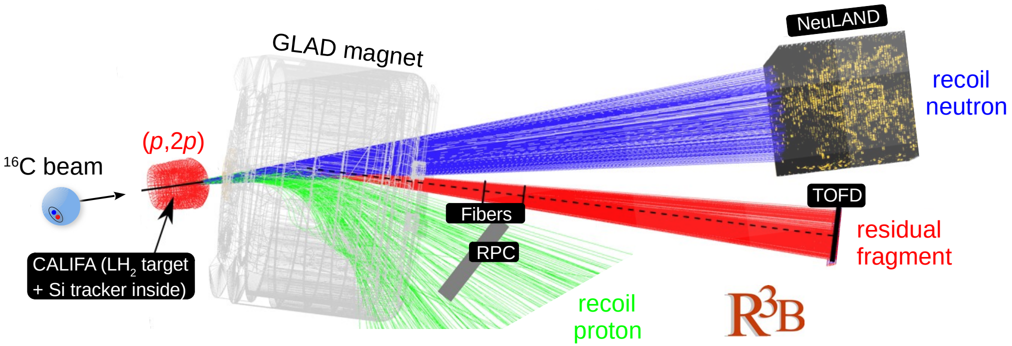

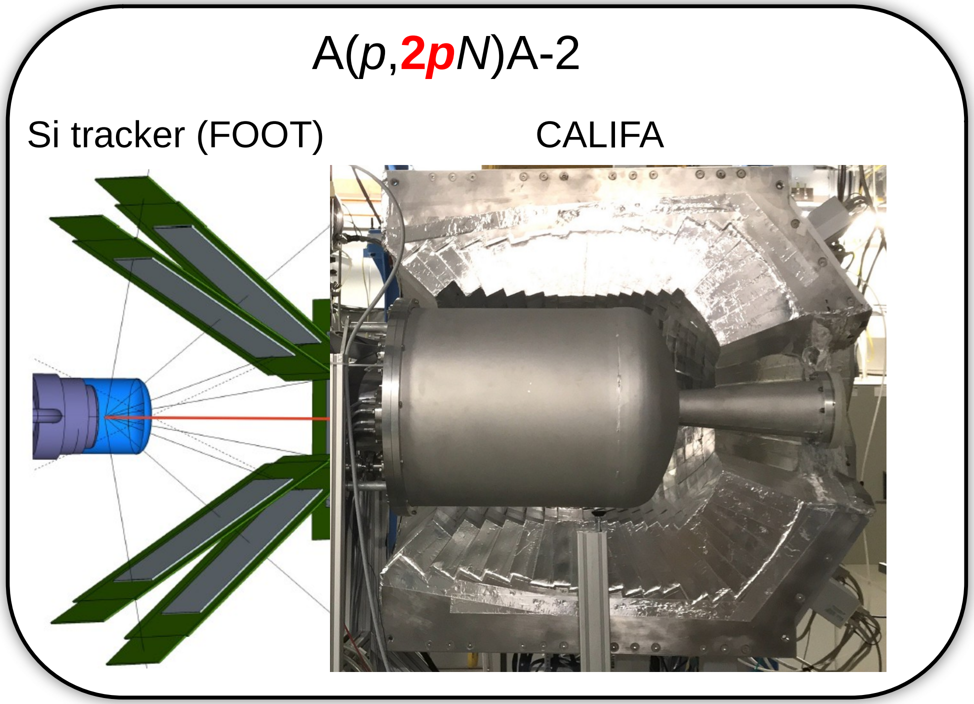

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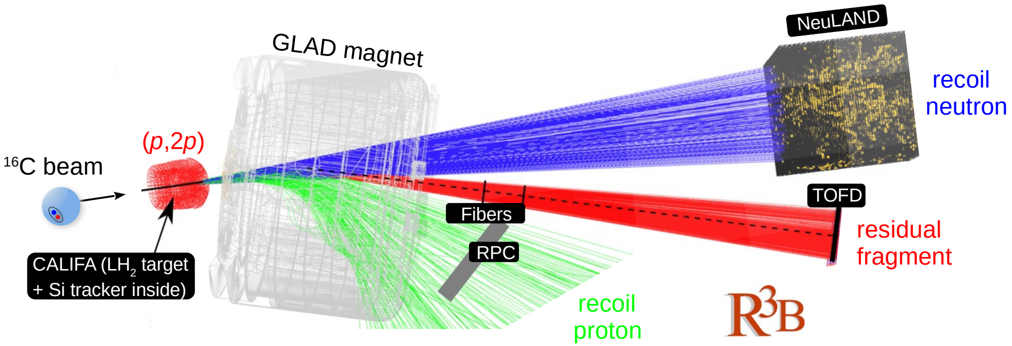
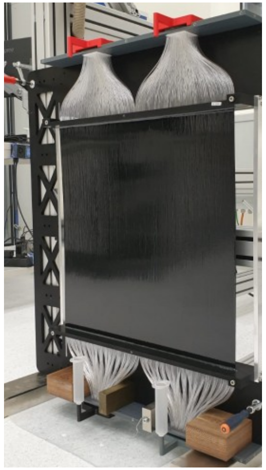
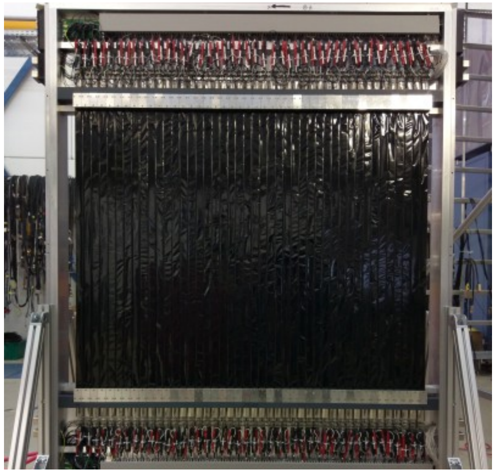


A(p,2pN)**A-2**

Fiber detectors



Time-of-flight wall



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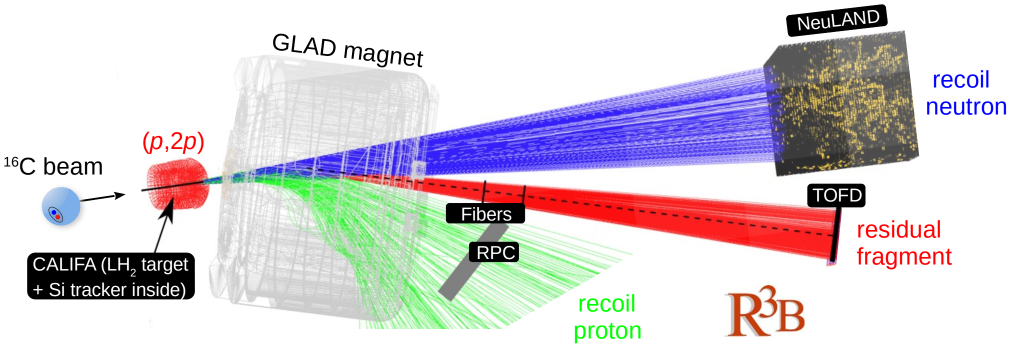

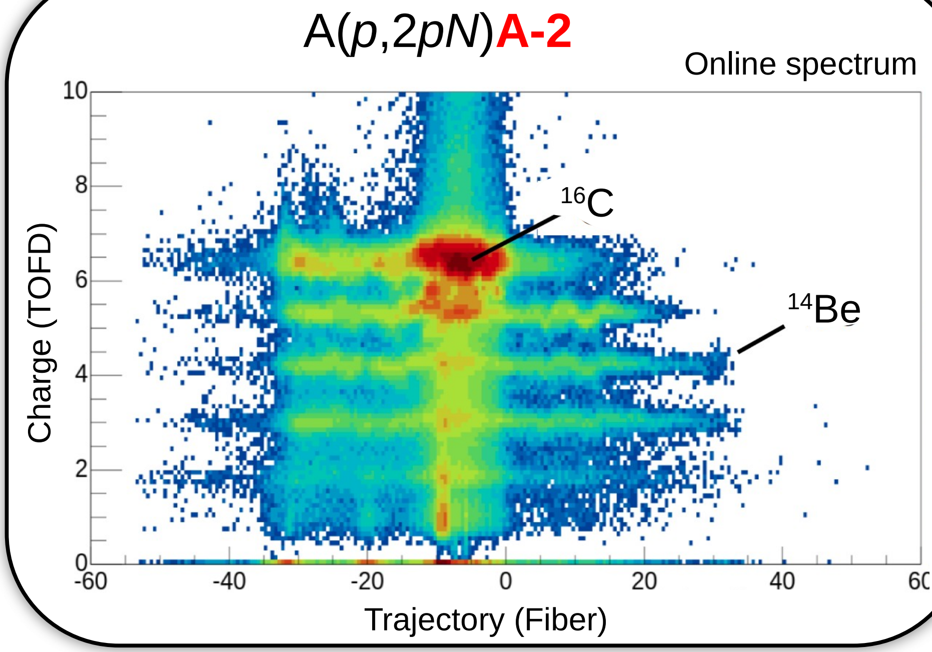

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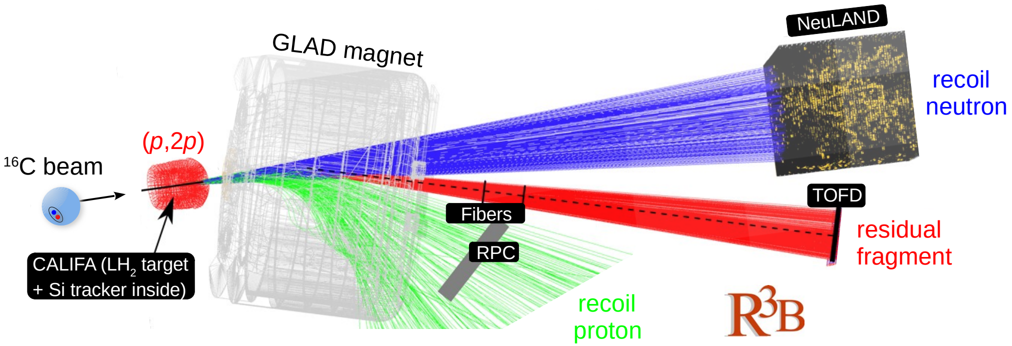
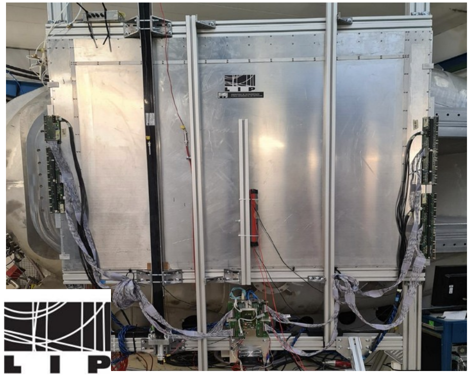


A(*p*,2*p**N***)A-2

Resistive Plate Chamber



NeuLAND

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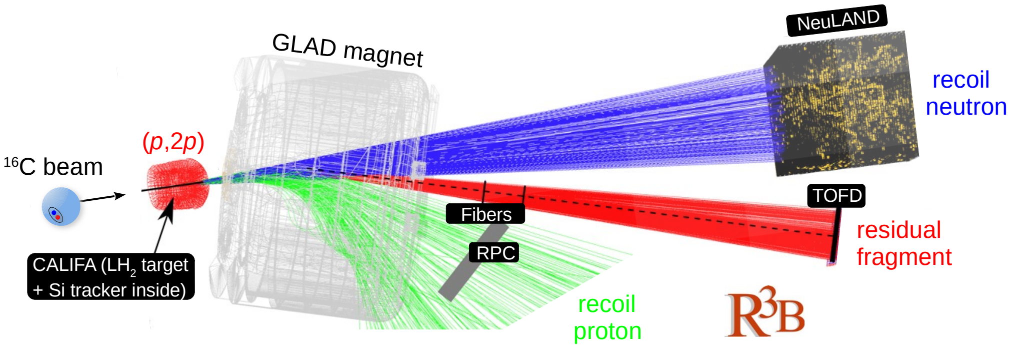
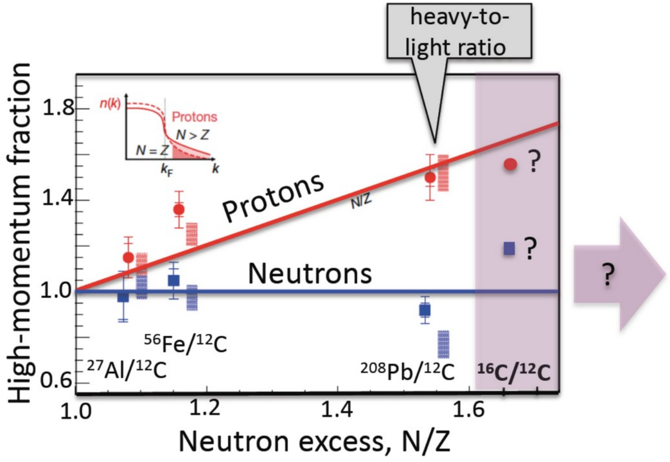


- Main reactions of interest:

  ^{16}C(*p*,2*pn*)^{14}B (np-pairs)
  ^{16}C(*p*,2*pp*)^{14}Be (pp-pairs)

- Correlation probability



Thank you !