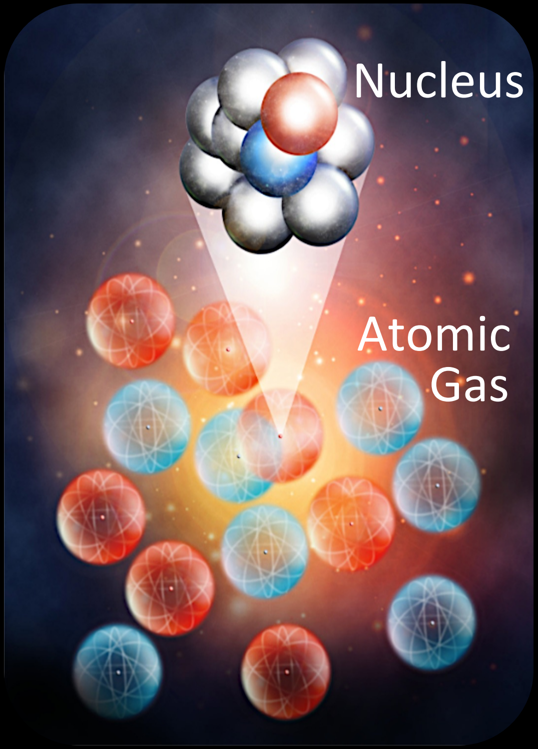
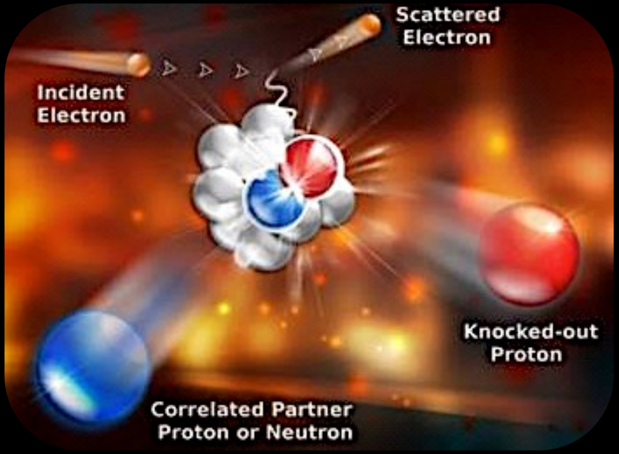
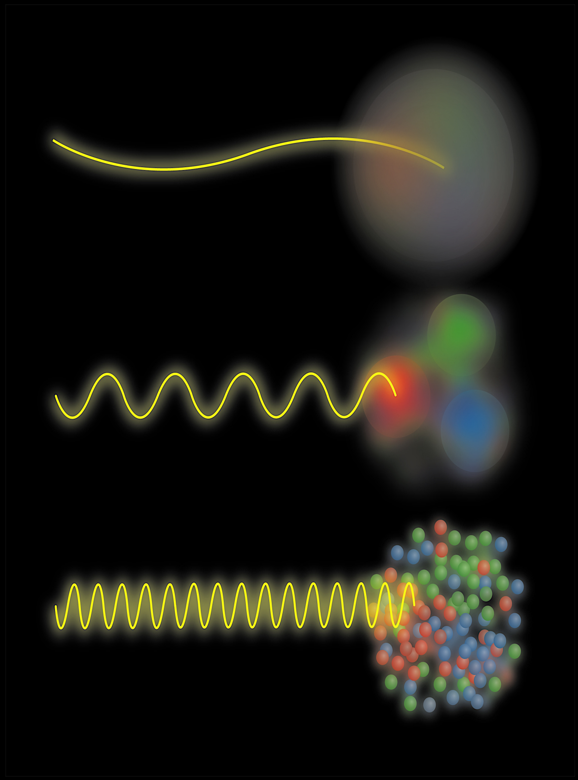
# Short-Range Structure of Nuclei

Or Hen

MIT





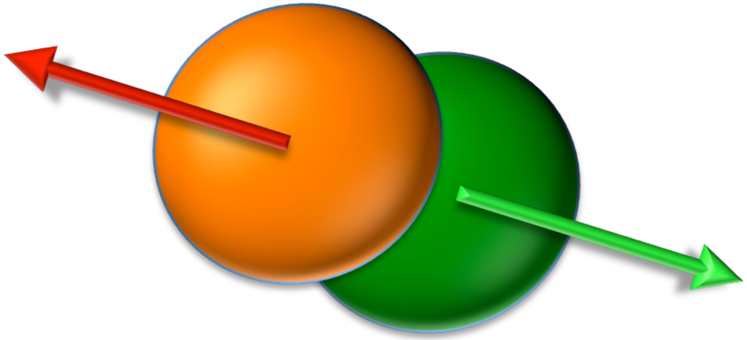


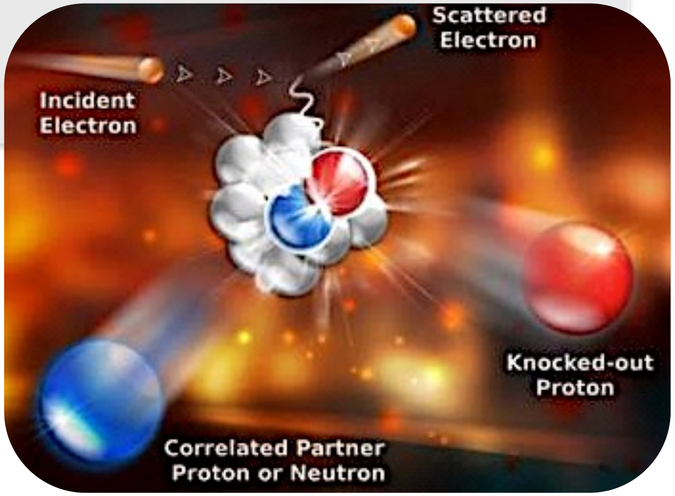
HST15 INTERNATIONAL SYMPOSIUM ON HIGH-RESOLUTION SPECTROSCOPY & TENSOR INTERACTIONS

Osaka University, Japan, November 18th 2015

# What are Short-Range Correlation (SRC)

- Are close together (wave function overlap)
- Have *high relative momentum* and *low c.m. momentum* compared to the Fermi momentum ($k_F$)

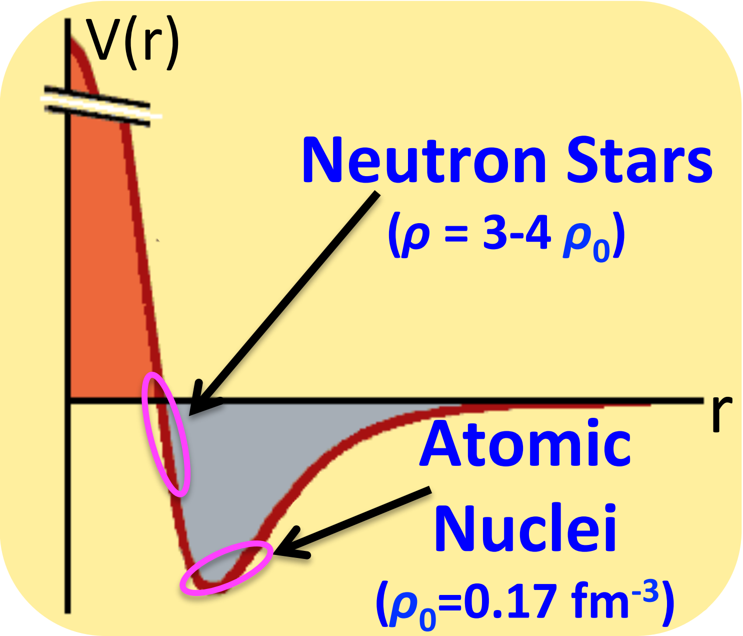




# Why Study High-Momentum Nucleons?

**Nuclear Physics**

Better understanding of the <u>*nucleon-nucleon interaction*</u> and the nuclear momentum distribution



**Neutron Stars**
**($\rho$ = 3-4 $\rho_0$)**

**Atomic Nuclei**
**($\rho_0$=0.17 fm$^{-3}$)**

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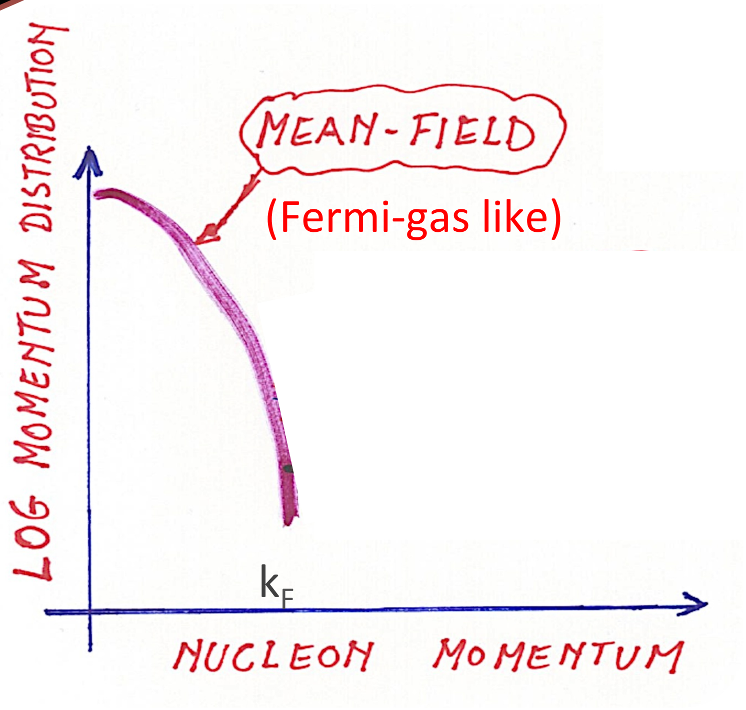

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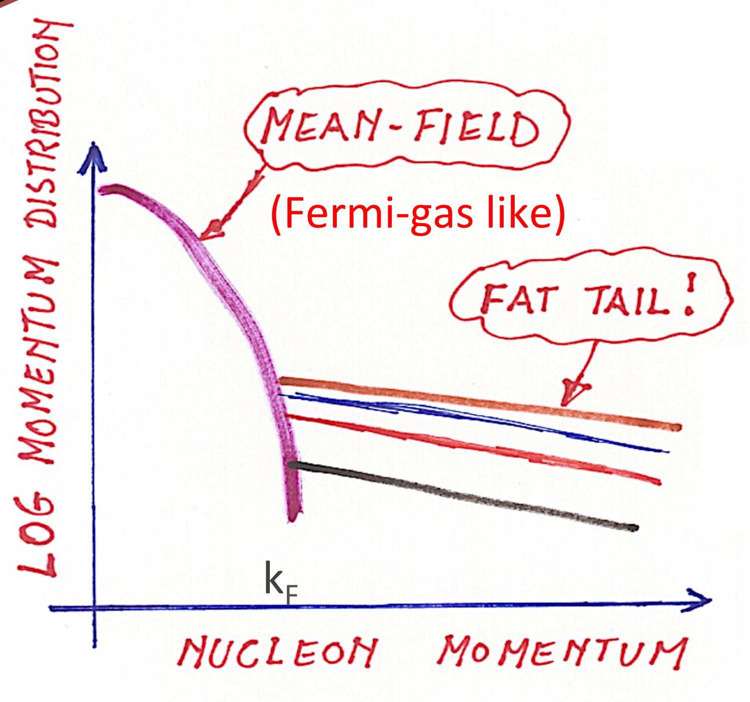
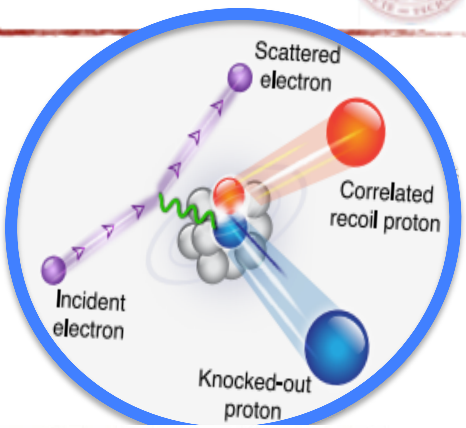


# Why Study High-Momentum Nucleons?

**Particle Physics**

The EMC Effect.
Neutrino-Nucleus Scattering.
The NuTeV Anomaly.



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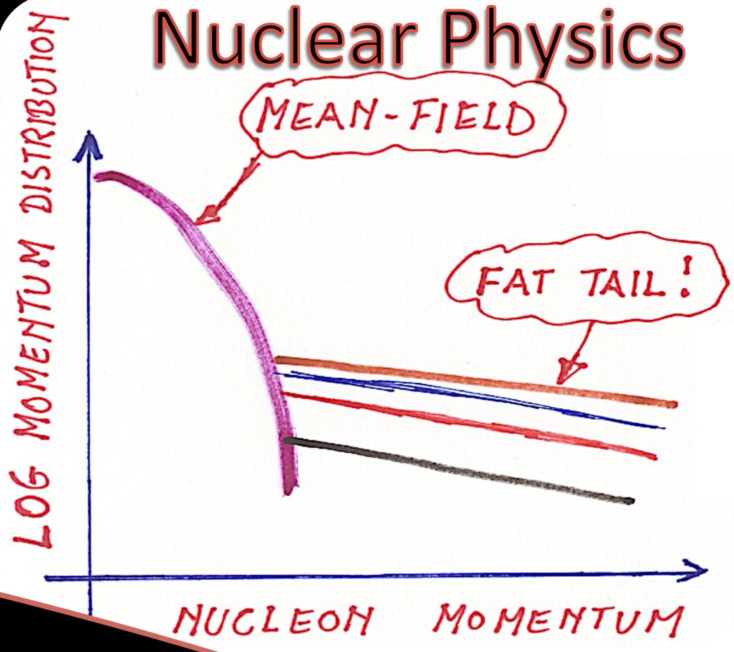


**Astrophysics**

Neutron Stars.
Nuclear Symmetry Energy.

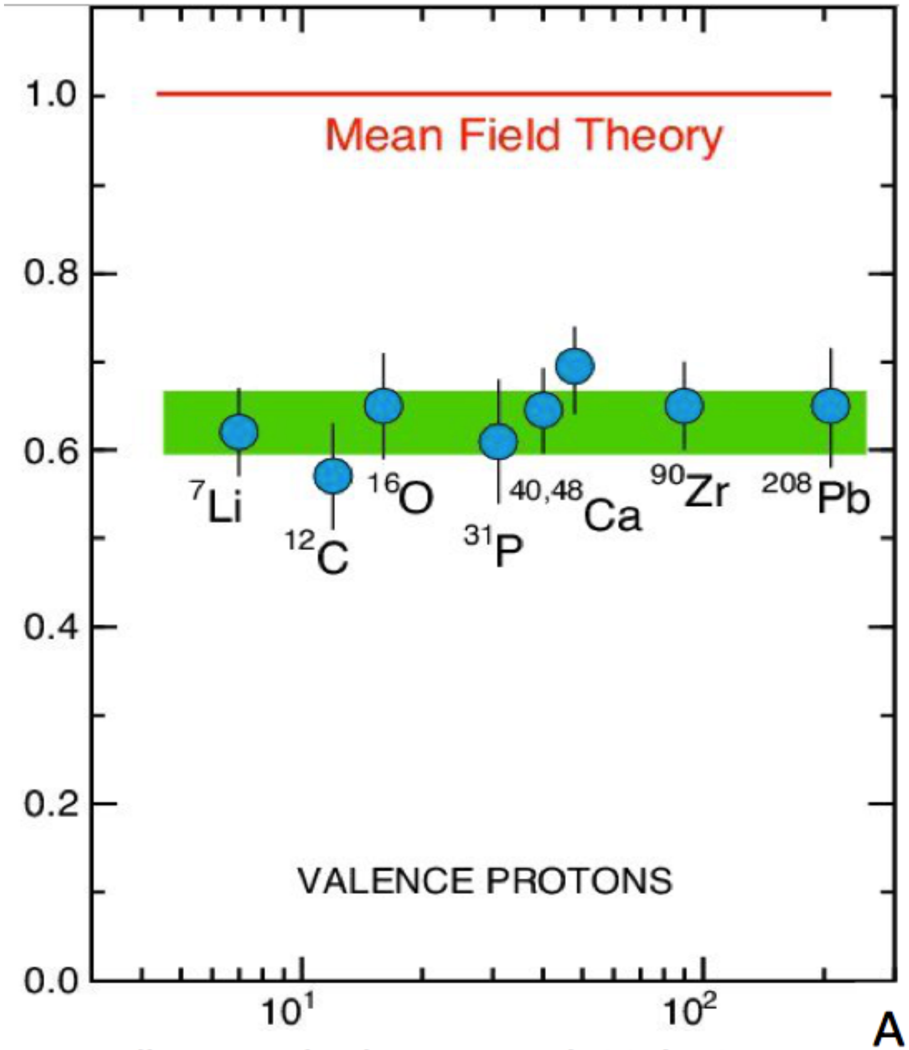
**Quantum / Atomic Physics**

Energy Sharing in Imbalanced Fermi Systems.
Contact Interaction in Universal Fermi Systems.

# Beyond the Shell-Model: NN Correlations

- Spectroscopic factors extracted from A(e,e'p) measurements yield only 60-70% of the expected single-particle strength

- **Missing:**
    - ~20%: Long-Range Correlations
    - **~20%: Short-Range Correlations (SRC)**



L. Lapikas, Nucl. Phys. A **553** (1993) 297.

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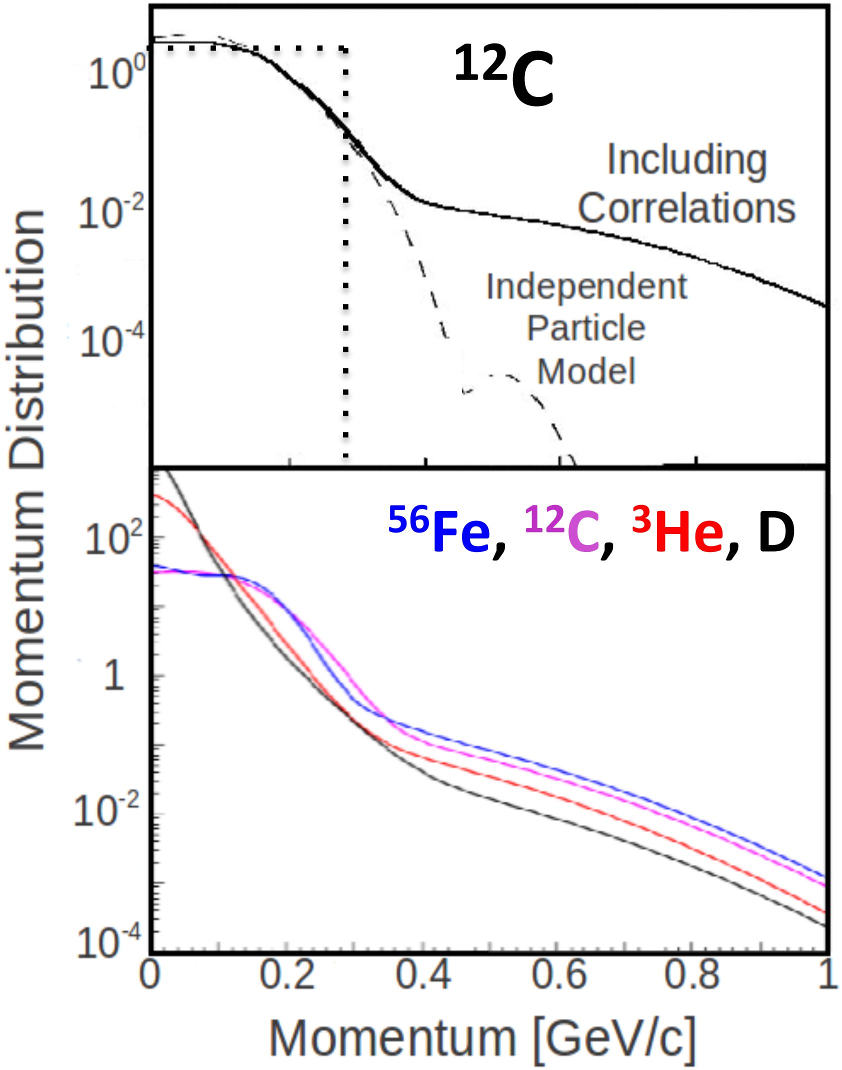

C. Ciofi degli atti et al., Phys. Rev. C **53**, 1689 (1996) O. Benhar et al., Phys. Lett. B **177**, 135 (1986)

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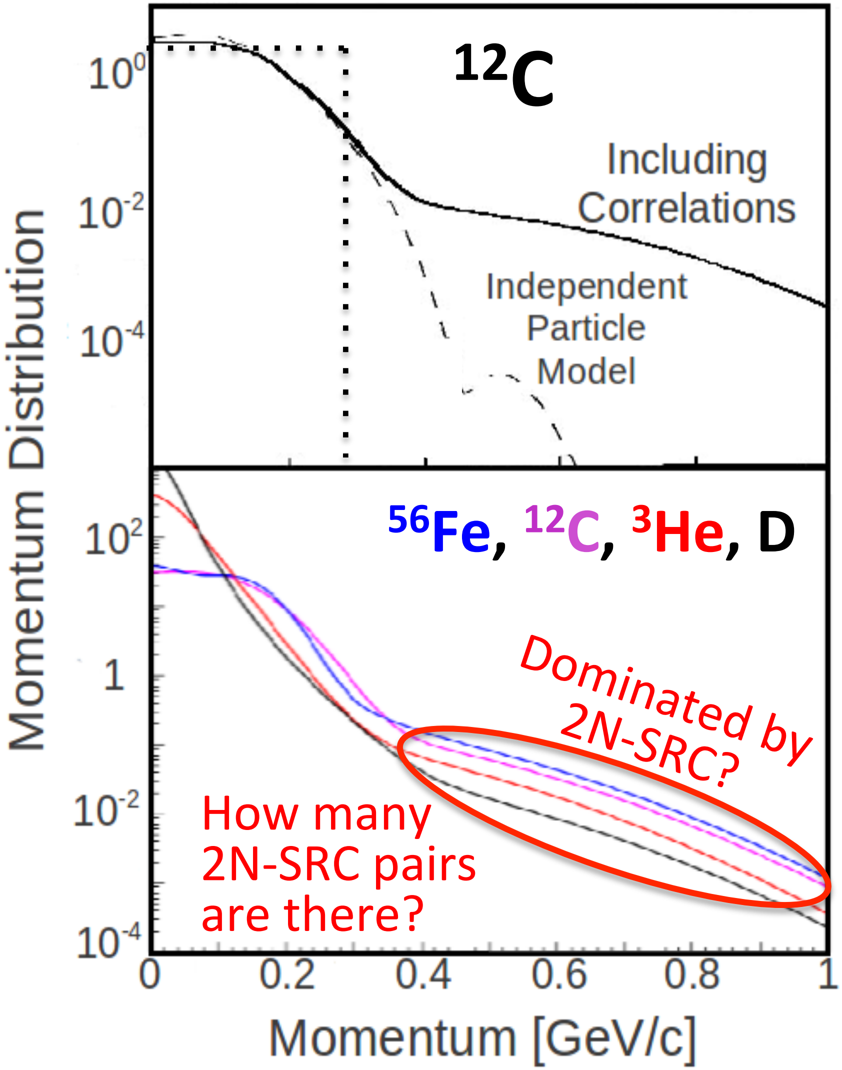

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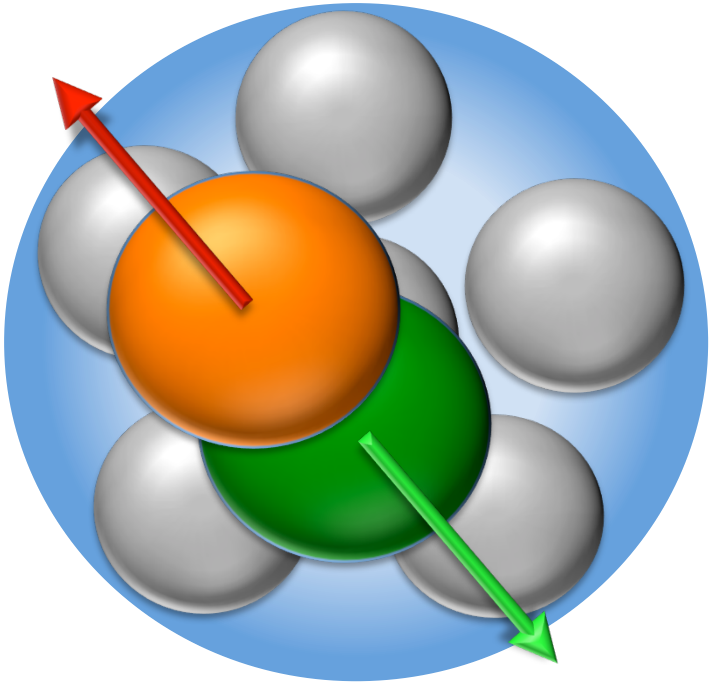
# Exclusive 2N-SRC Studies



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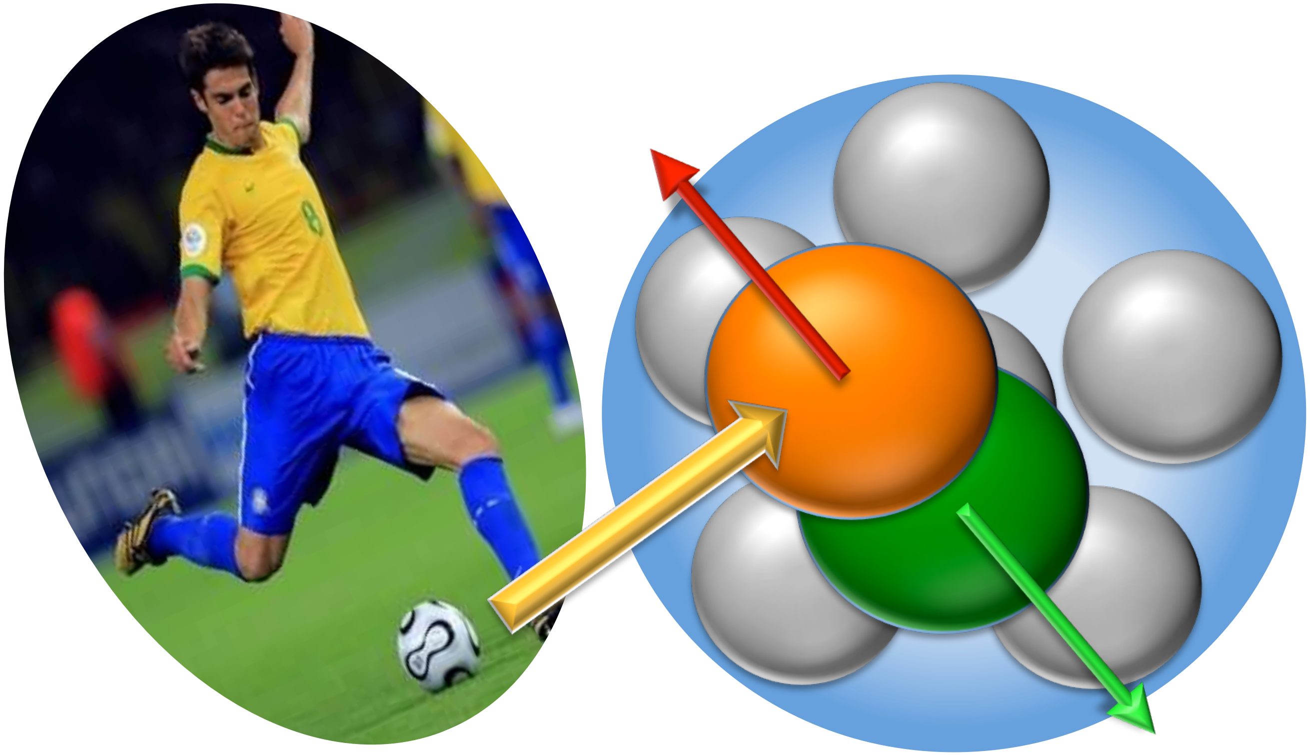

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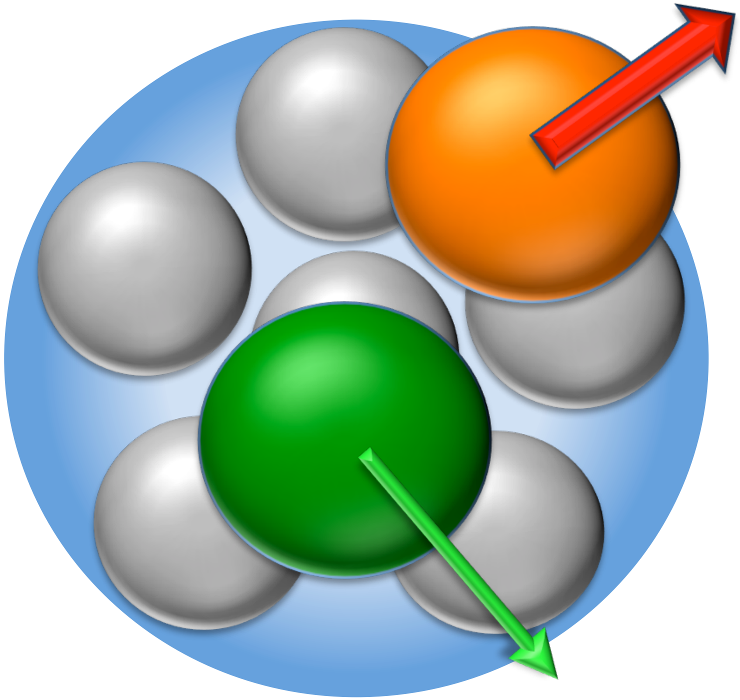
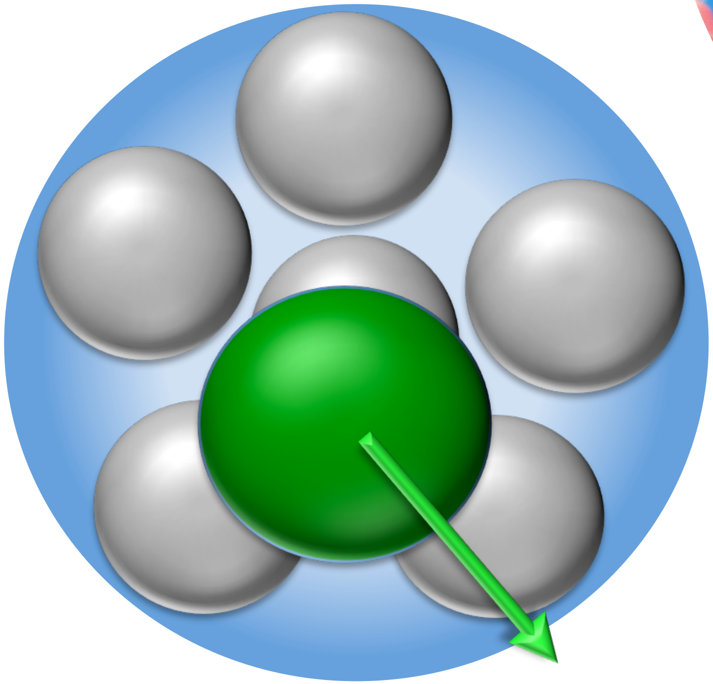


FIFA WORLD CUP
Brasil

# Exclusive 2N-SRC Studies



2014

FIFA WORLD CUP
Brasil

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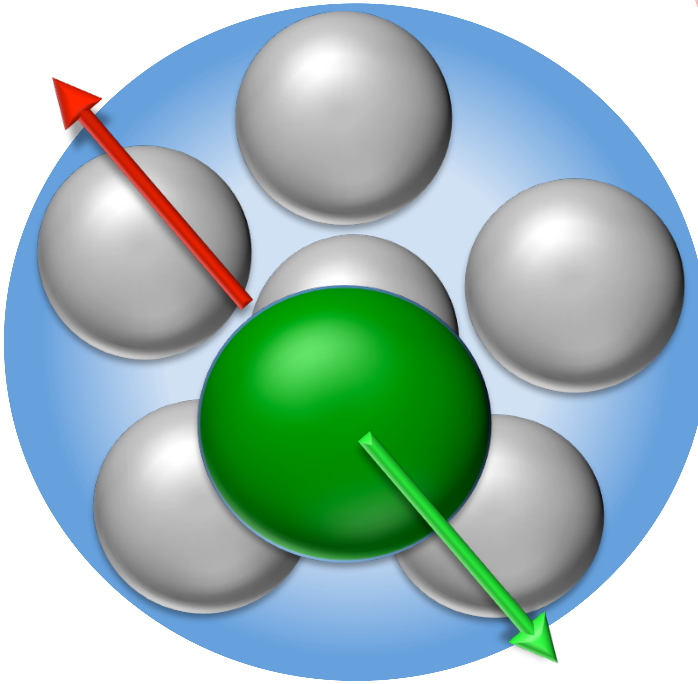

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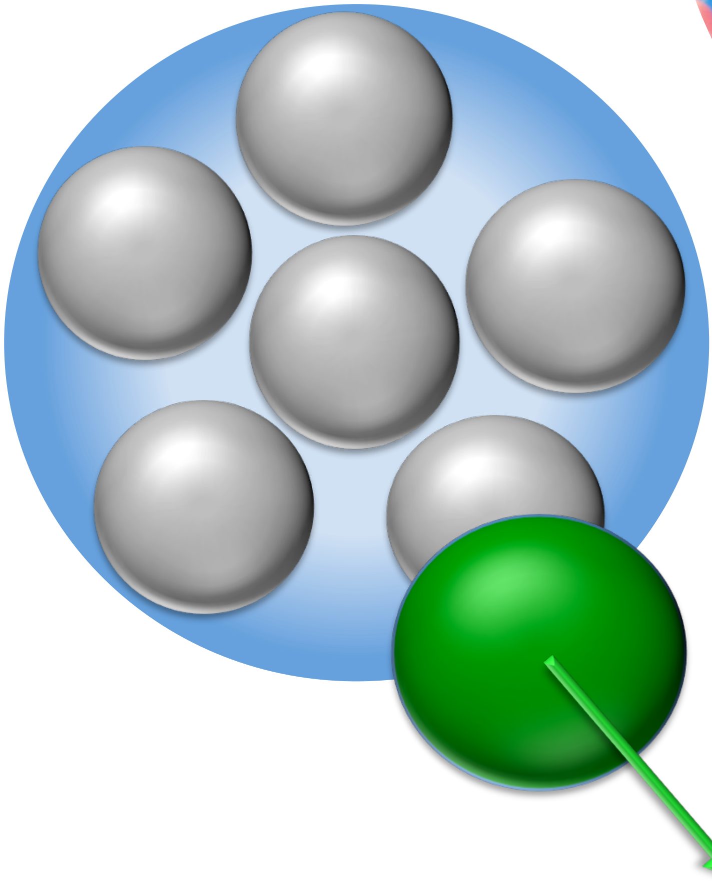

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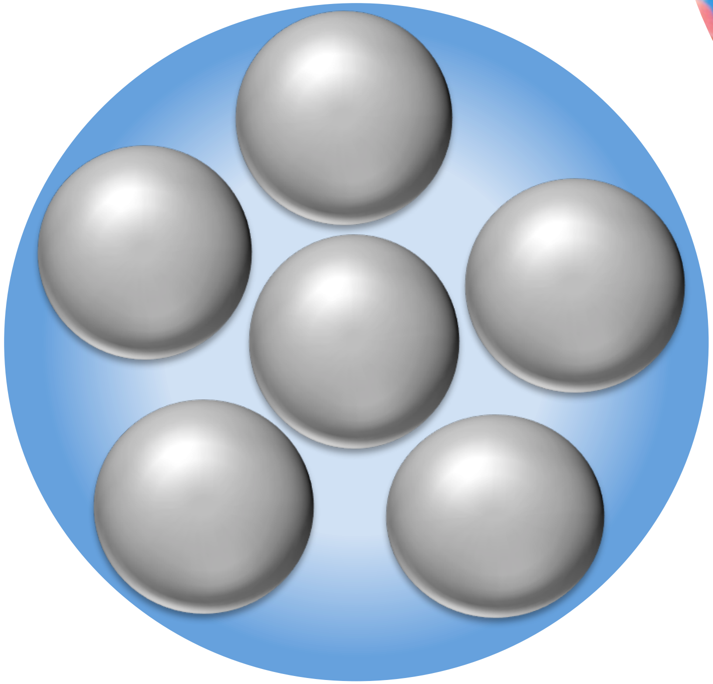

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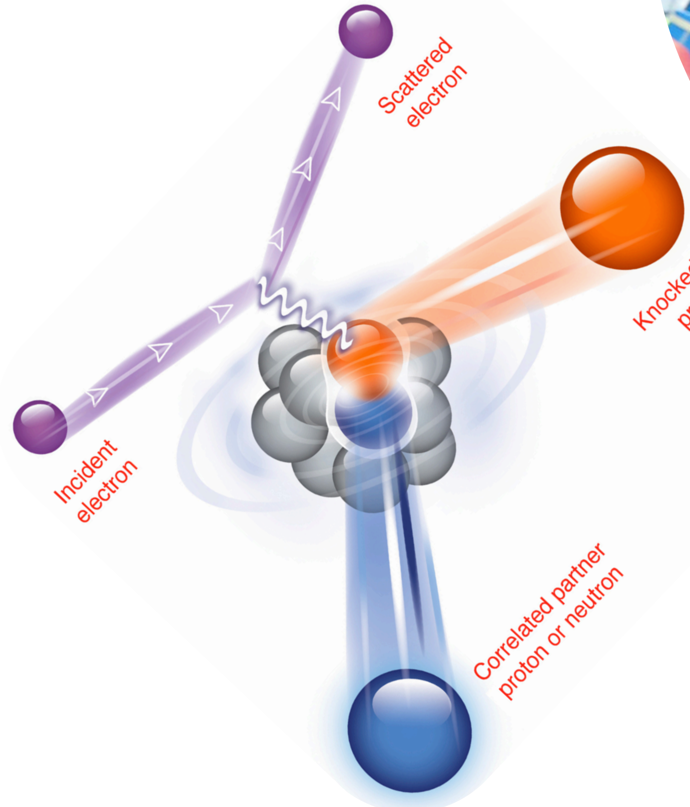

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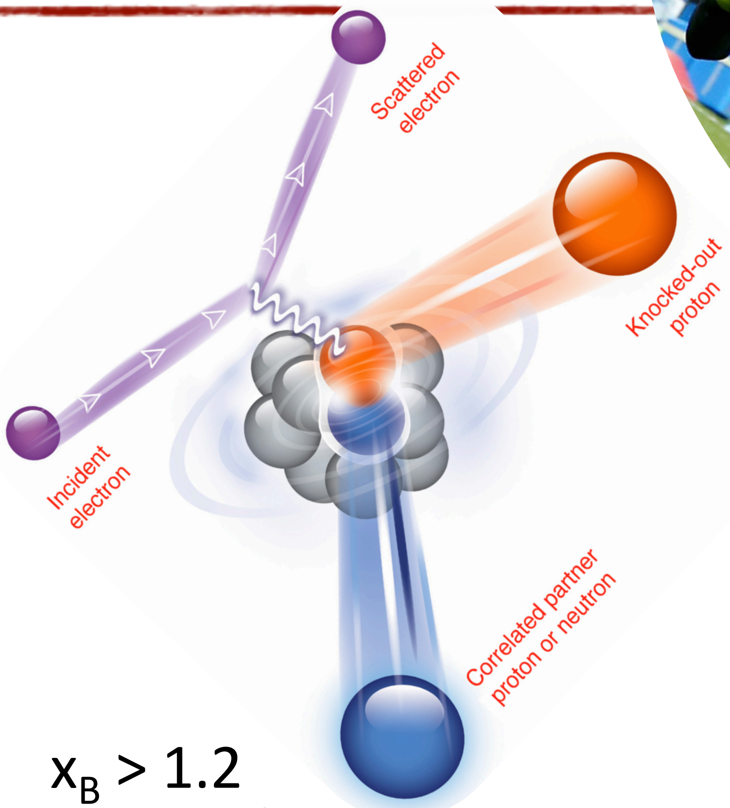
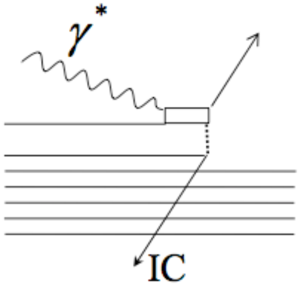
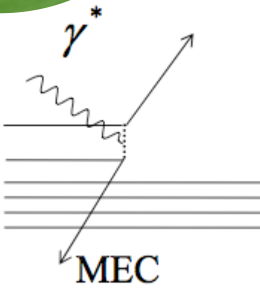


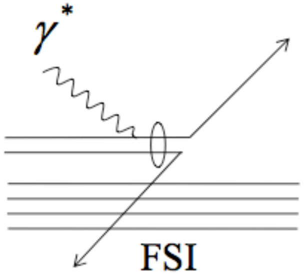
$x_B > 1.2$

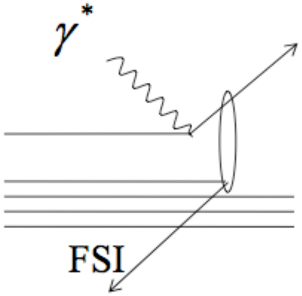
Large-$Q^2$

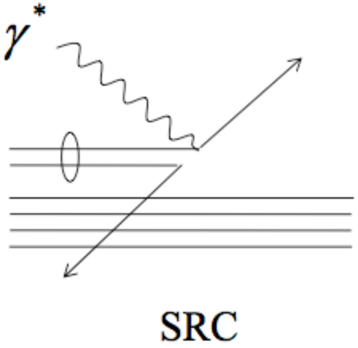
Anti-Parallel Kinematics





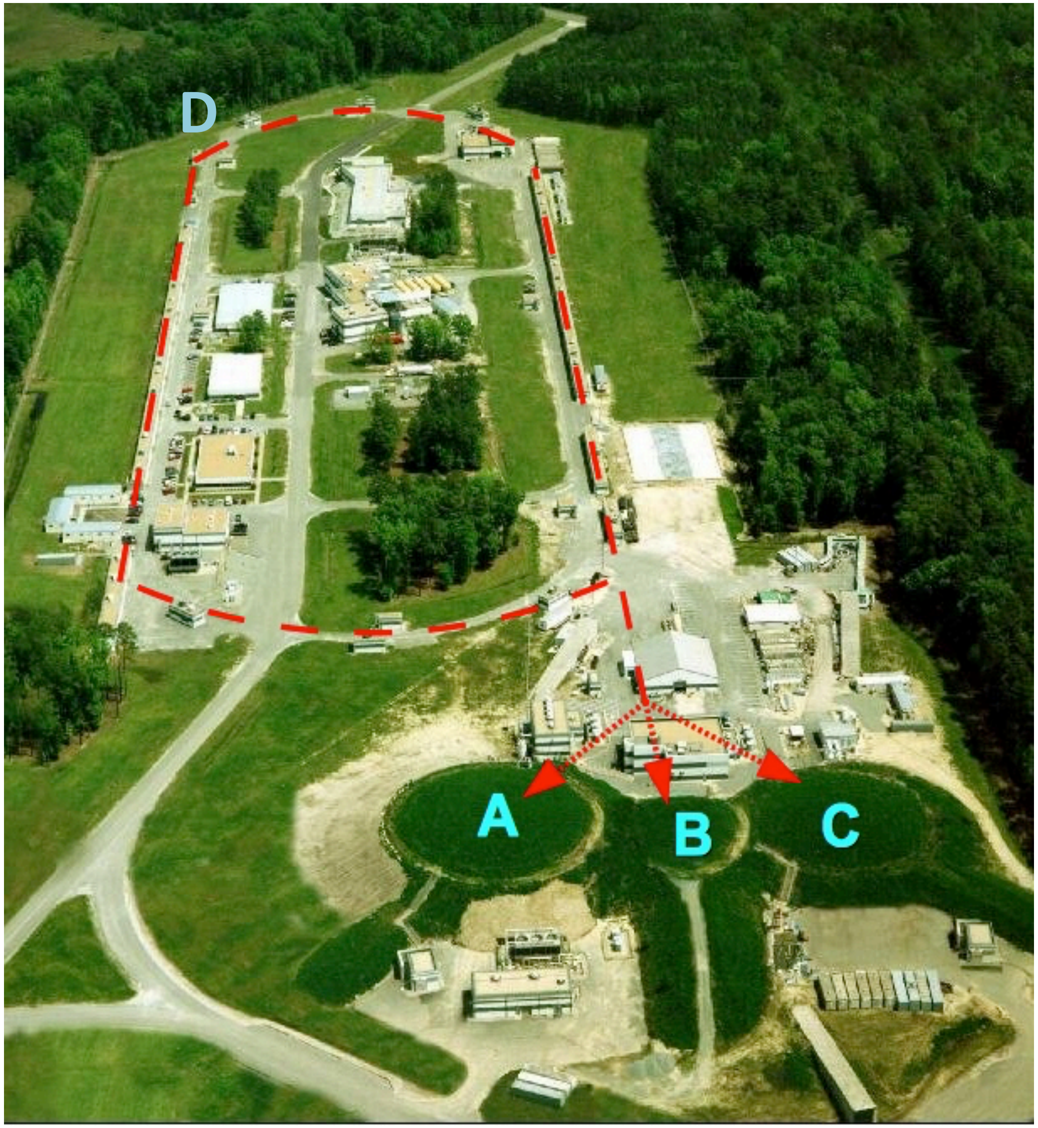




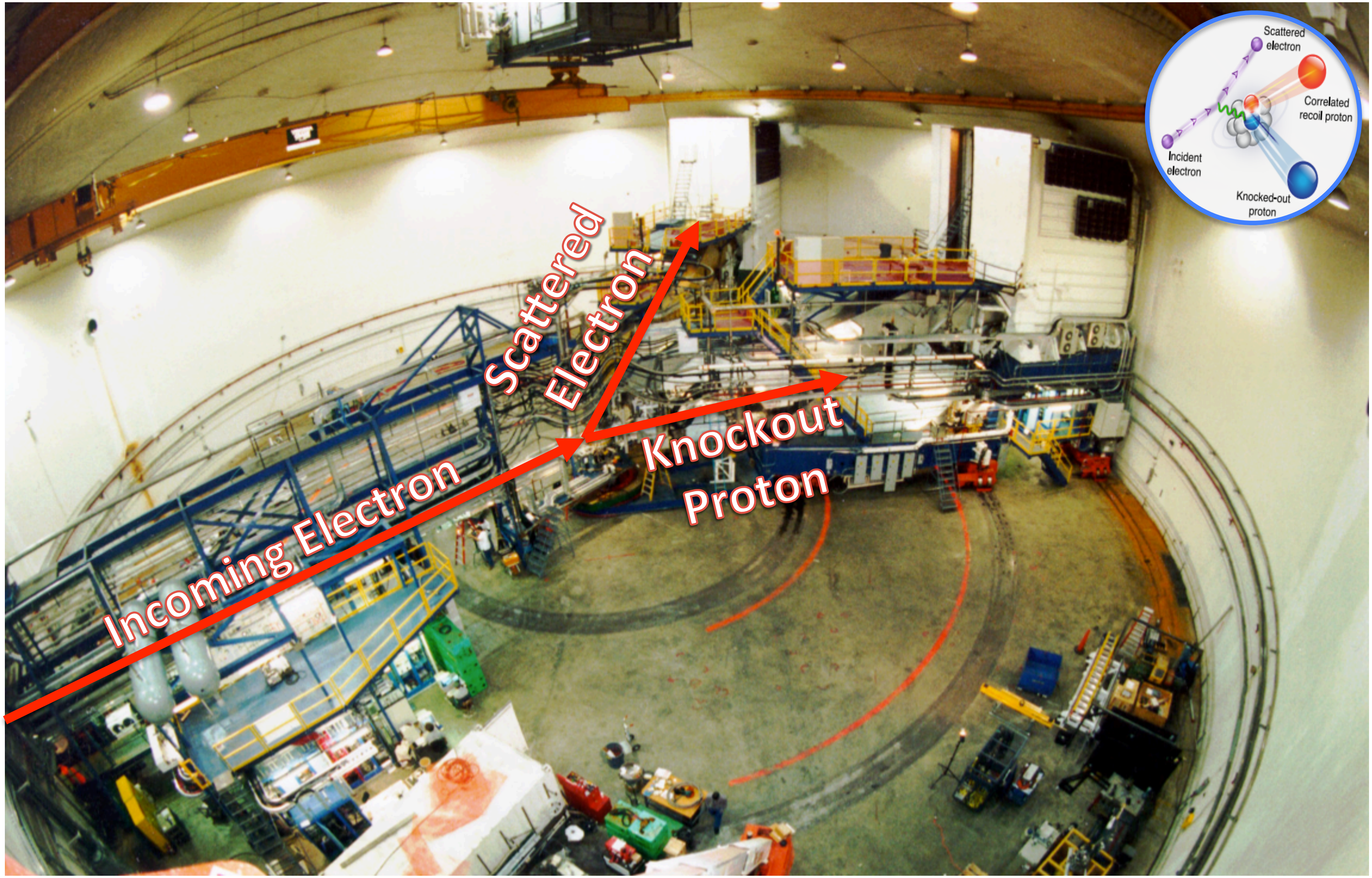


# Jefferson Lab (JLab)

- High intensity polarized electron beam.
  - 1994 – 2012: 6 GeV
  - 2015: upgraded to 12 GeV
- 3 (now 4) experimental halls.
- 7 years of 12 GeV program already approved.



# Hall-A: High-Resolution Spectrometers



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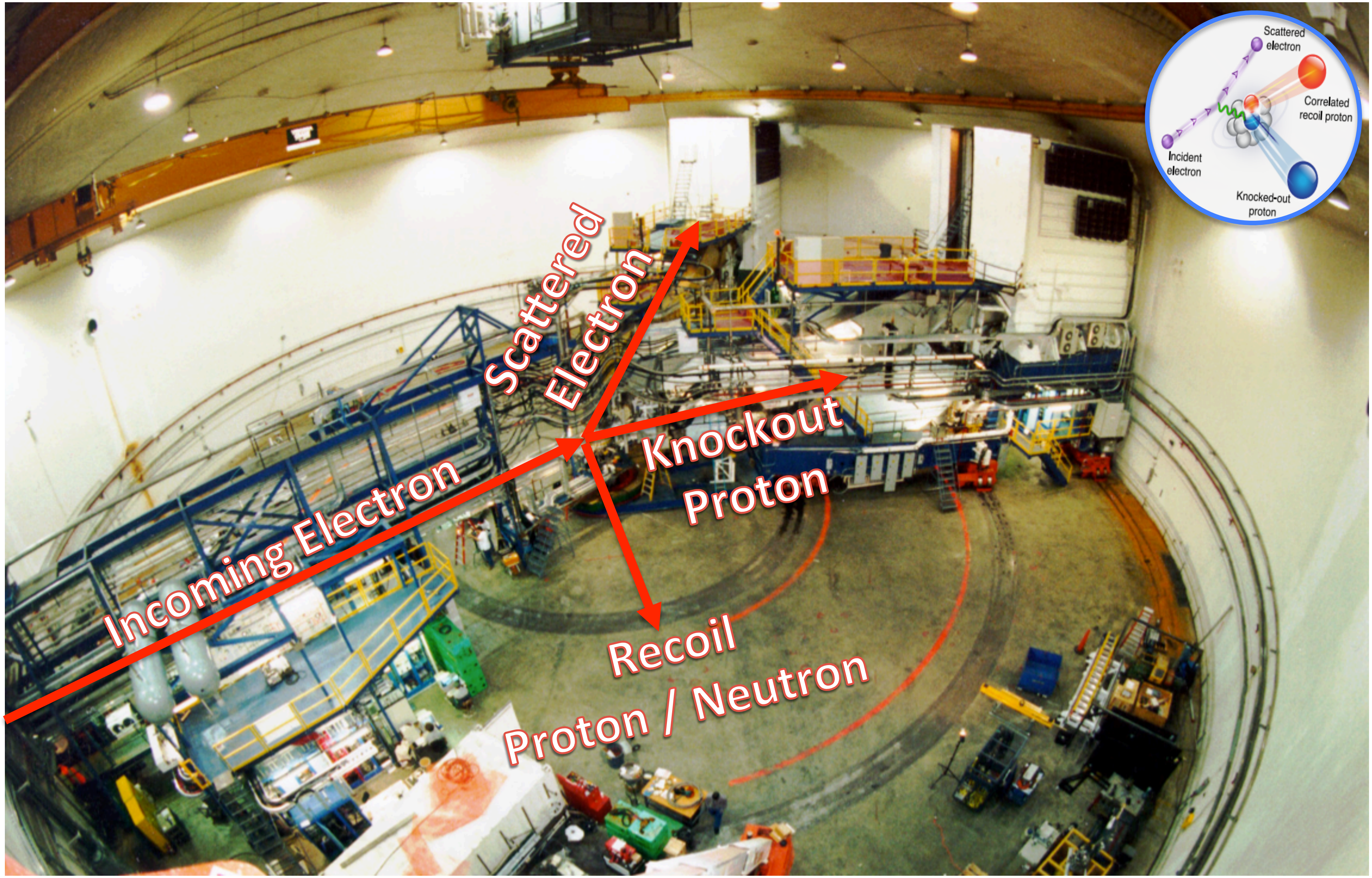

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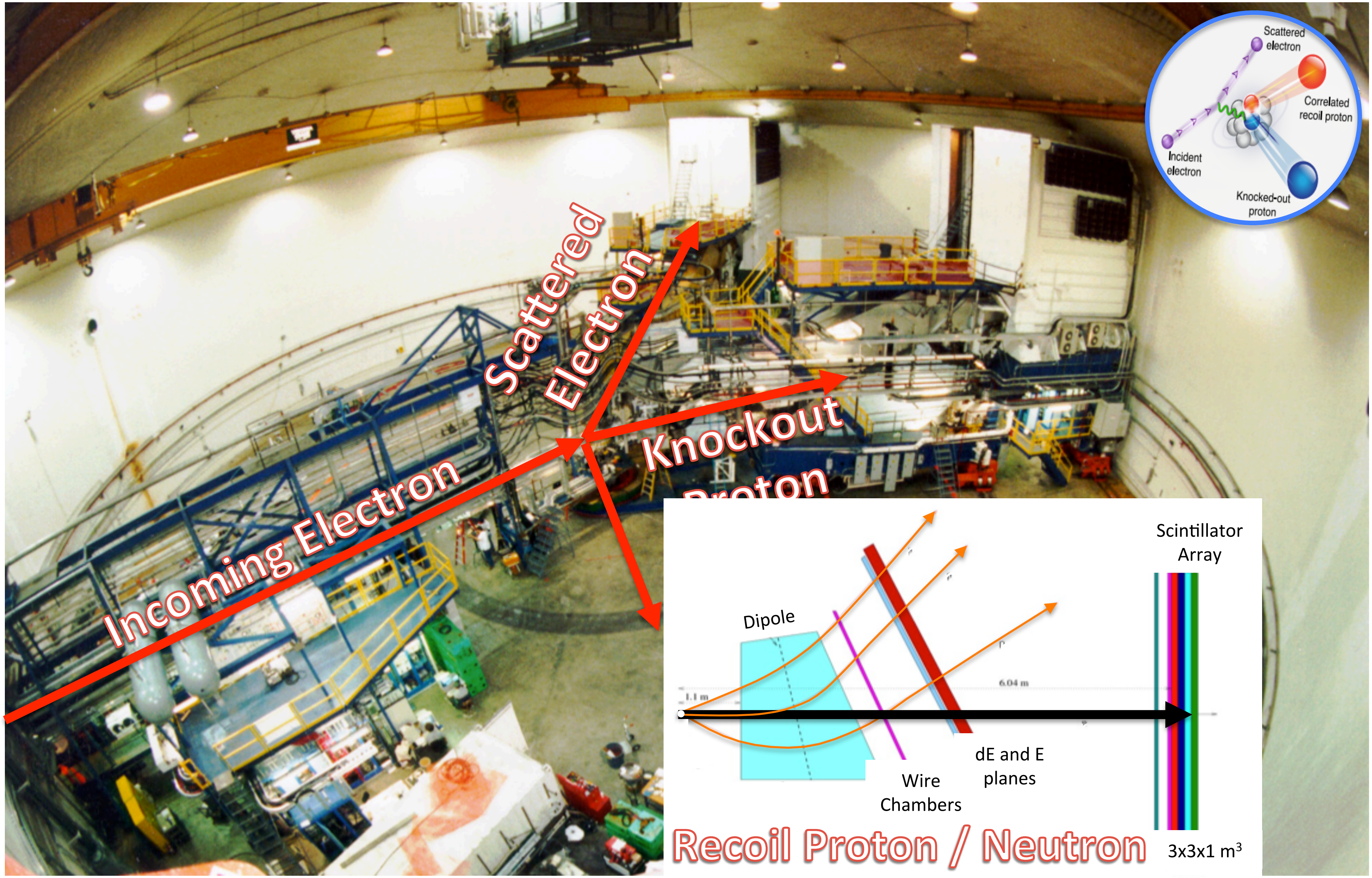
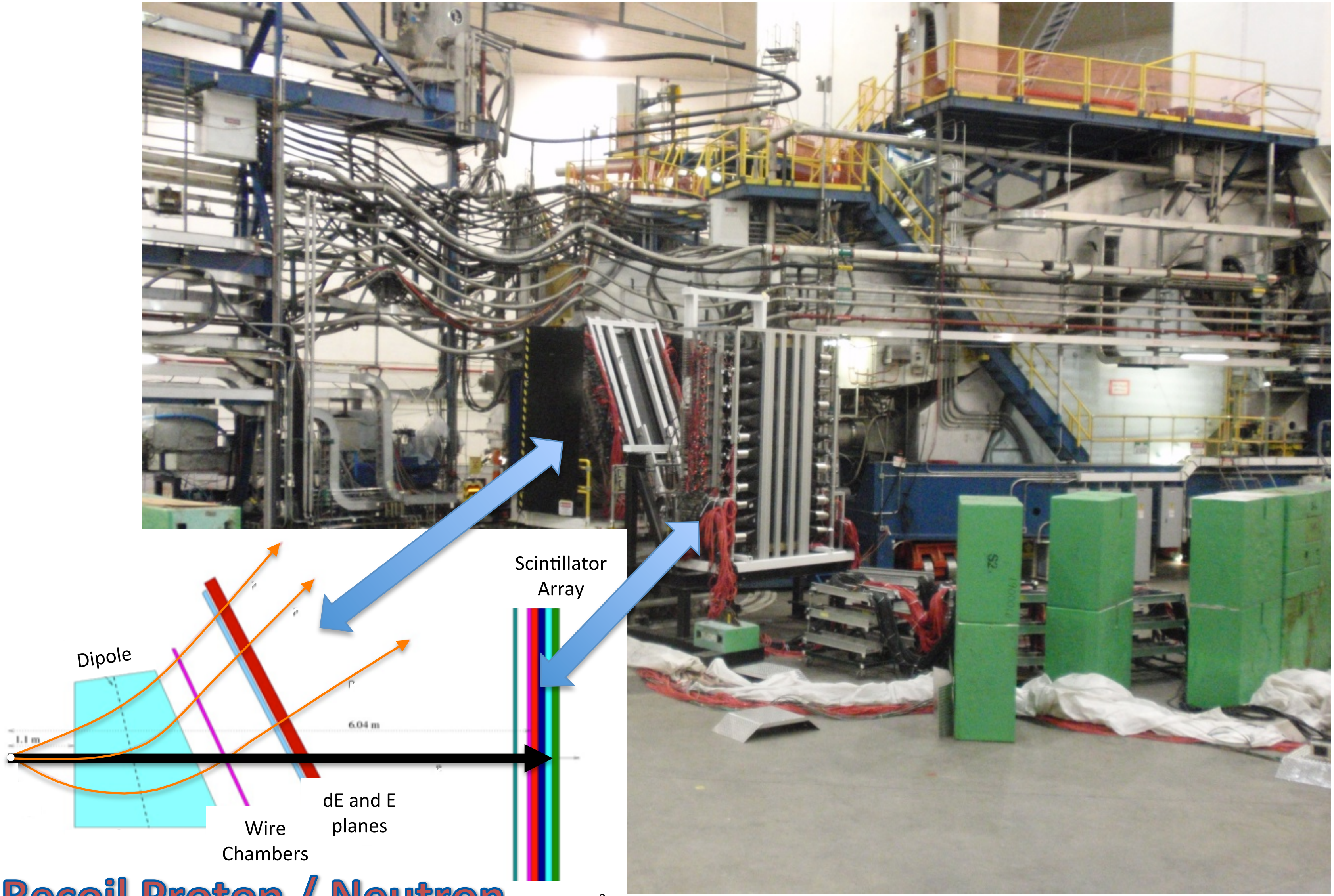


# Building BigBite and HAND



**Recoil Proton / Neutron**

Jefferson Lab

"Exploring the Nature of Matter"

**Award Winners** -

**World Leader** -

**Breakthrough Research** -

**Groundbreaking** -

**Stimulus Dollars** -

**Great Job** -

**12 GeV Contract** -

**Second Chance** -

**Neutron Duality** -

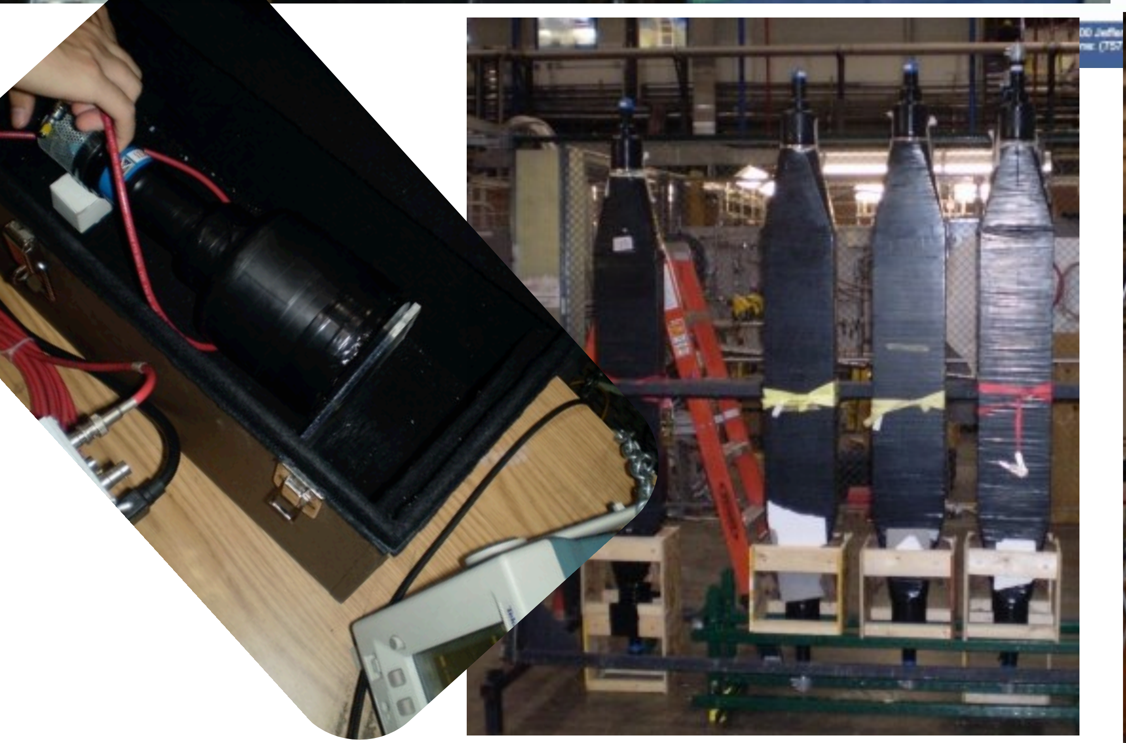
**Detector Inspectors** - Or Chen (left) and Moshe Zilka (middle), both of Tel Aviv University, prepare to assemble a neutron detector, while Dominik Wermus (right), a student from Virginia Military Institute, tests a component for the detector. The detector will be used in an upcoming experiment in Hall A. Wermus is spending the summer at JLab in the DOE's Science Undergraduate Laboratory Internships program. (Photo: Jefferson Lab)

LAB EVENTS

DOE ACTS
July 7-31, 2009

DOE Science Undergrad Lab Internship
May 26-July 31, 2009

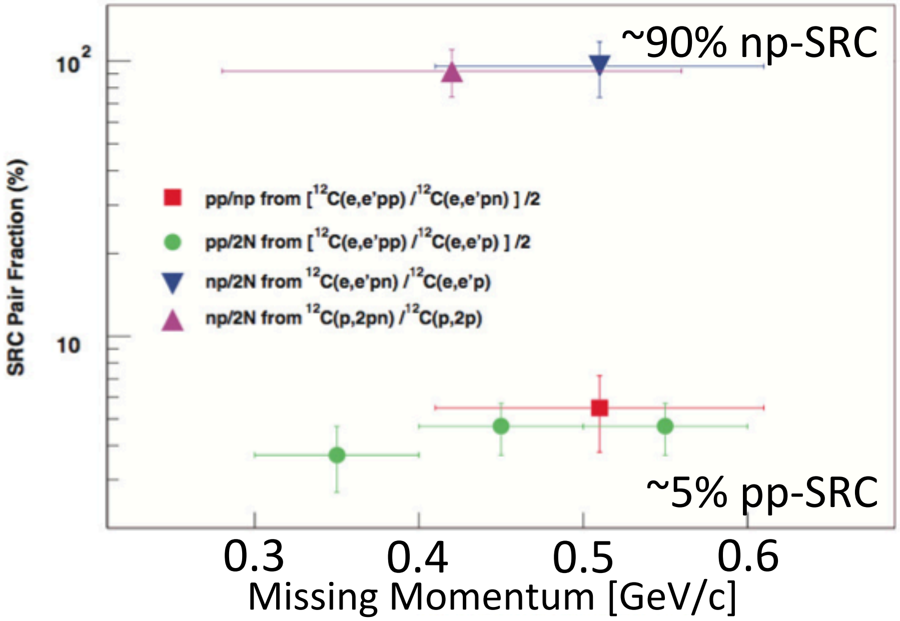
HS Summer Honors Program
June 15-July 31, 2009

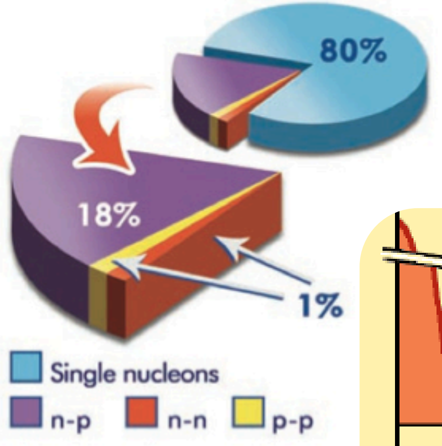


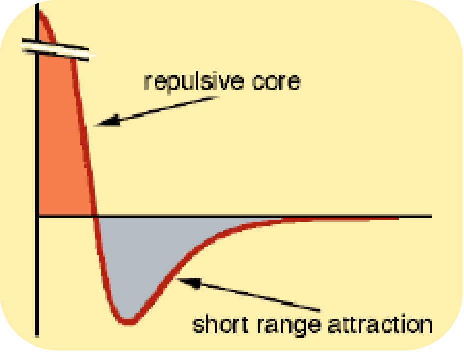
100%

# $^{12}$C(e,e'pN) Results

- Knockout high-initial-momentum proton, look for correlated nucleon partner.
- For $300 < P_{miss} < 600$ MeV/c all nucleons are part of 2N-SRC pairs: 90% np, 5% pp (nn).







A. Tang et al., Phys. Rev. Lett. 90 (2003) 042301
E. Piasetzky et al., Phys. Rev. Lett. 97 (2006) 162504
R. Shneor et al., Phys. Rev. Lett. 99 (2007) 072501
**R. Subedi et al., Science 320 (2008) 1476**

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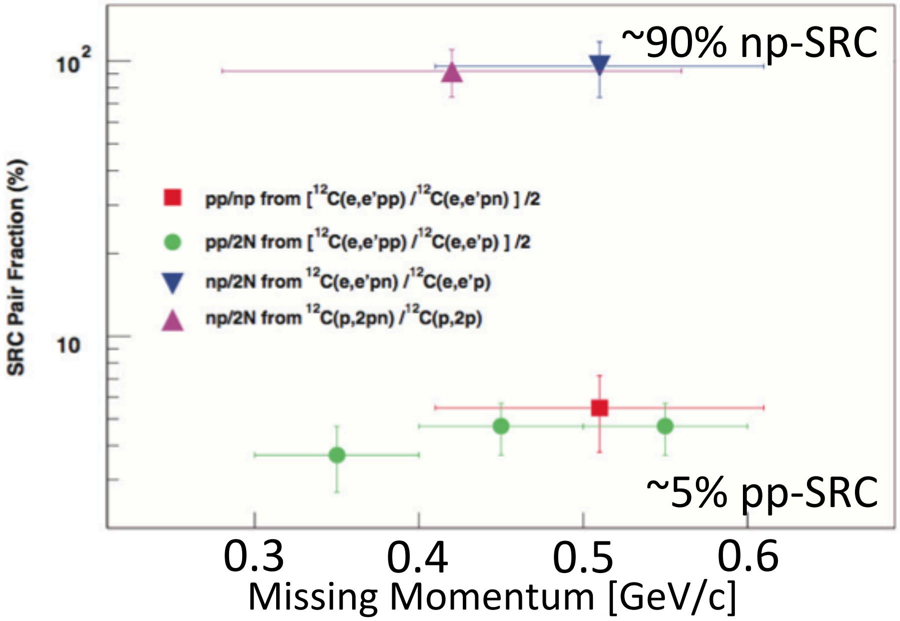

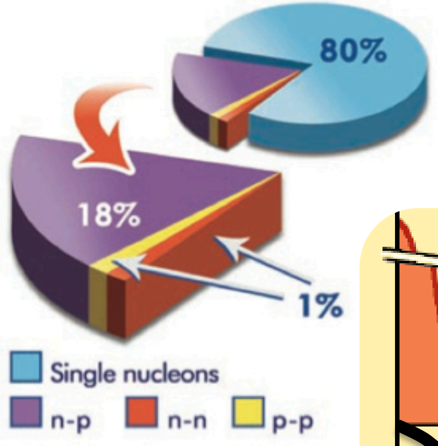

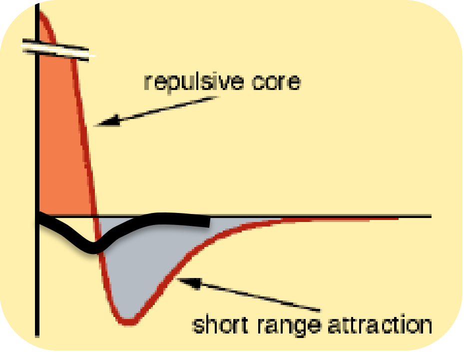

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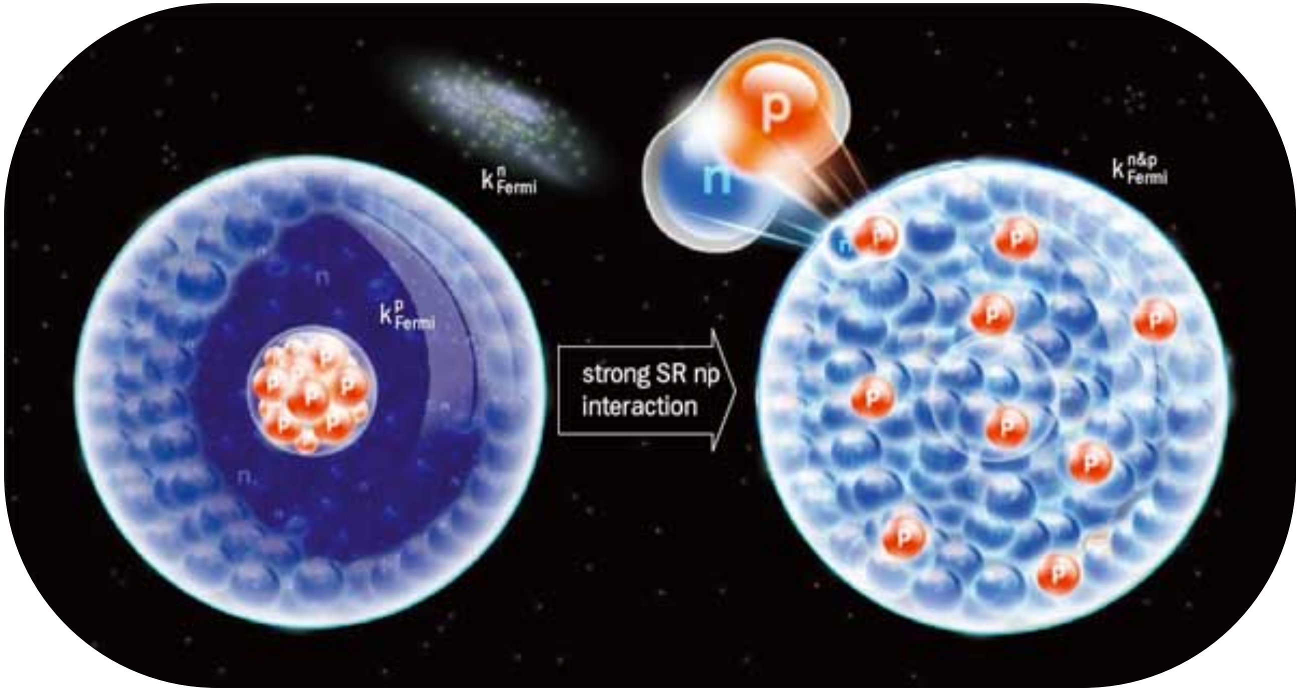
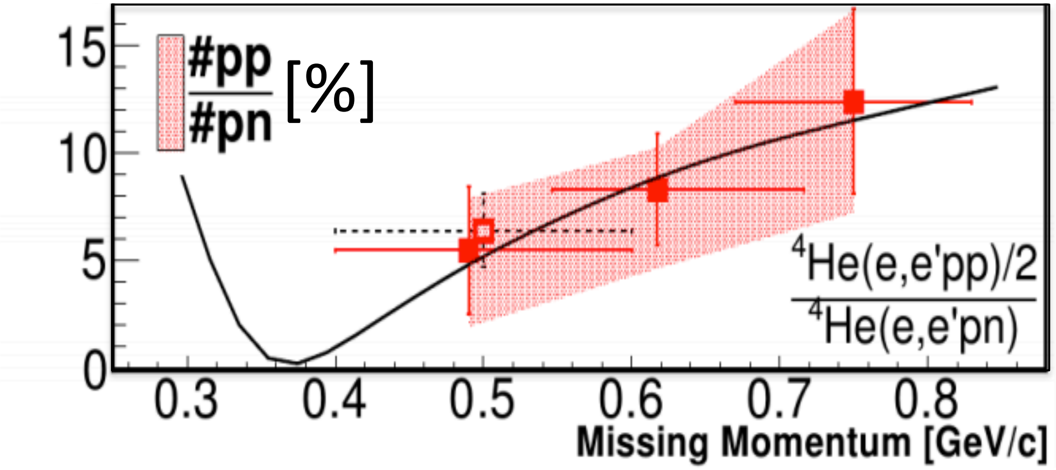


**Neutrons heat protons in neutron stars?**

A. Tang et al., Phys. Rev. Lett. 90 (2003) 042301
E. Piasetzky et al., Phys. Rev. Lett. 97 (2006) 162504

R. Shneor et al., Phys. Rev. Lett. 99 (2007) 072501
**R. Subedi et al., Science 320 (2008) 1476**

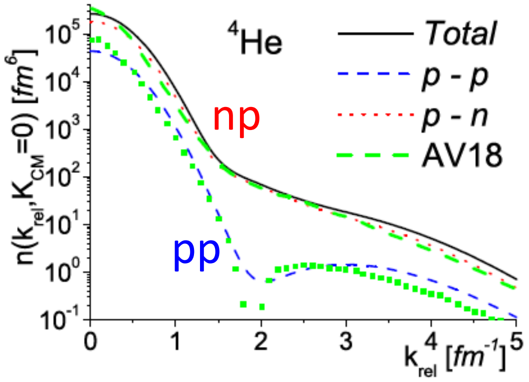
# pp/np ratio increase with $P_{miss}$

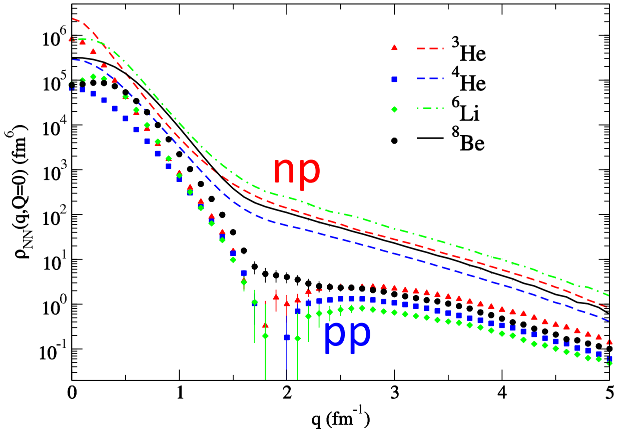


I. Korover, N. Muangma, and O. Hen et al., Phys. Rev. Lett 113, 022501 (2014).

## Pair density calculations:

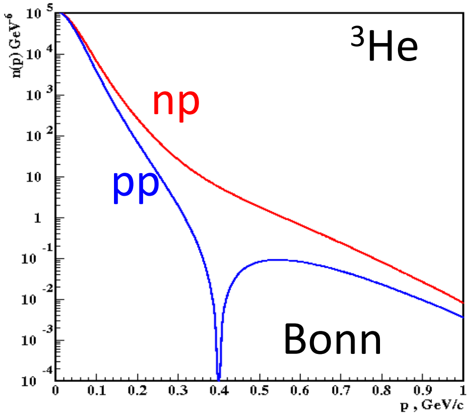
Ciofi and Alvioli PRL 100, 162503 (2008)



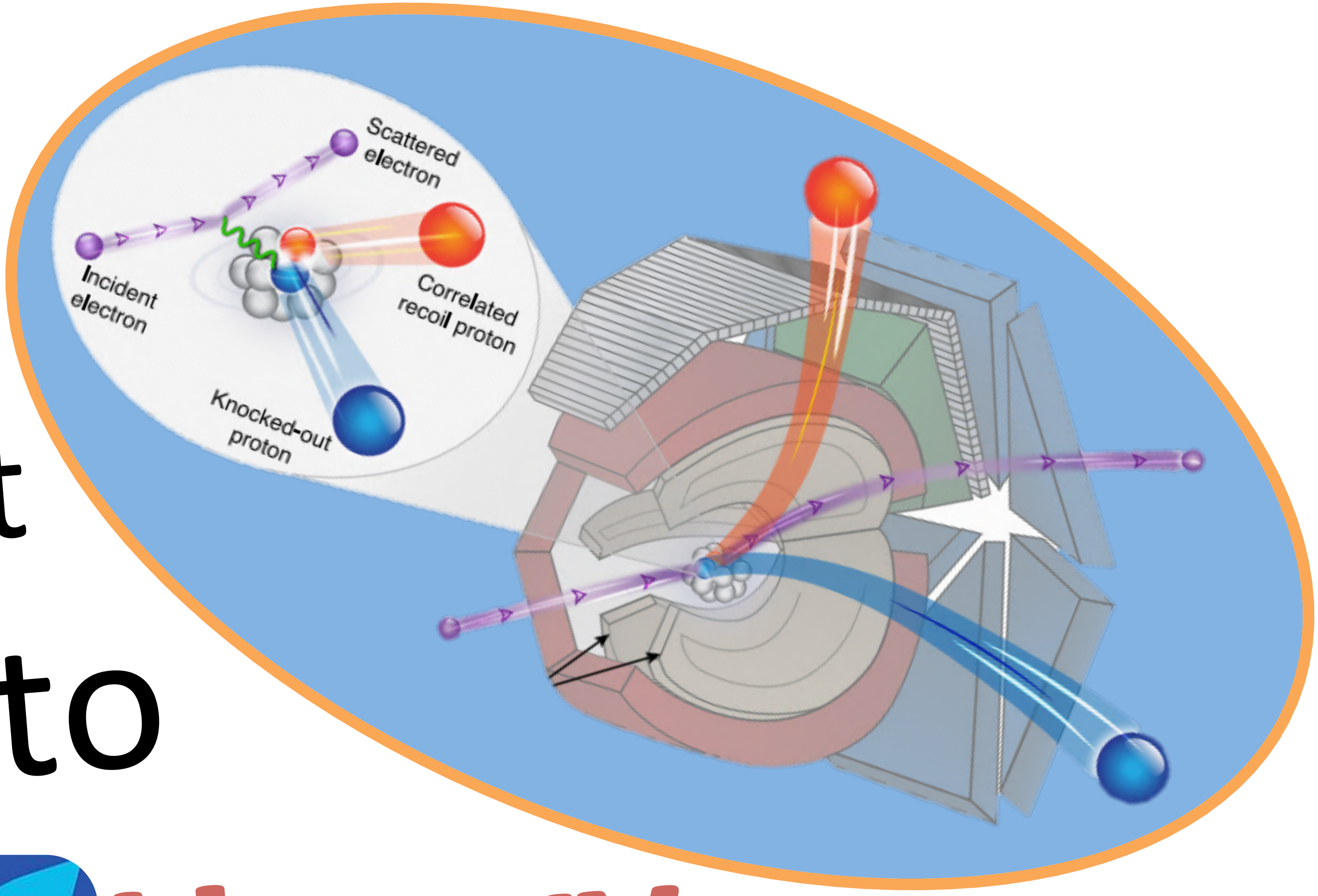


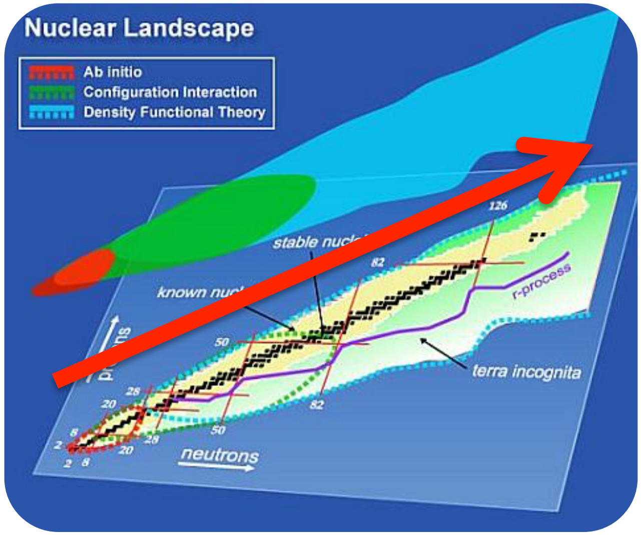
Schiavilla et al., PRL 98,132501 (2007)

Sargsian et al., PRC 71 044615 (2005)



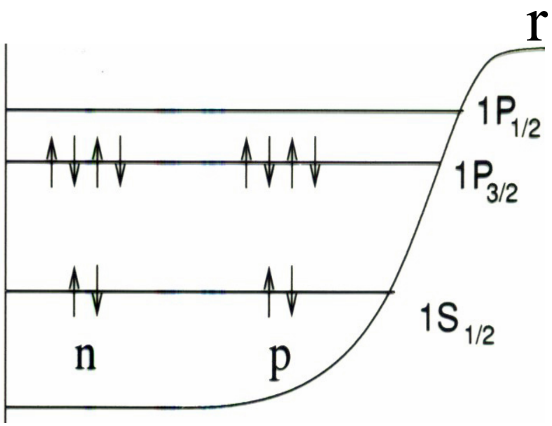
# From Light to Heavy Nuclei



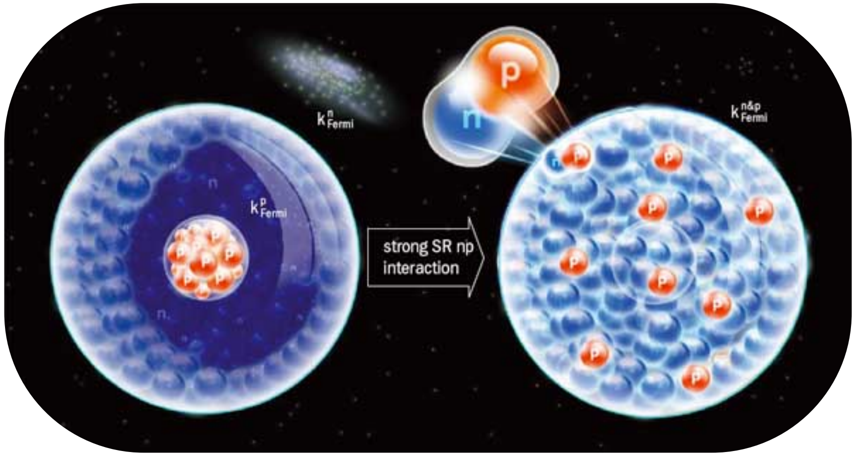


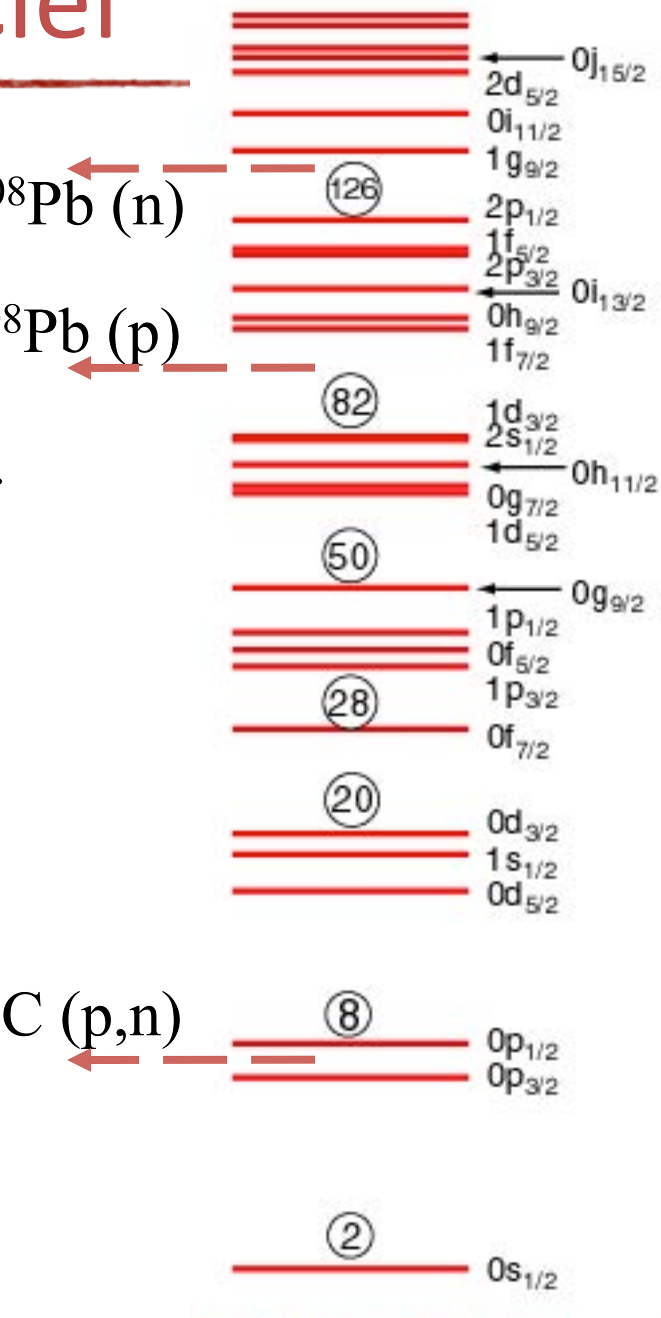
# Correlations in Heavy Nuclei

- Bridging the gap between light nuclei and neutron stars?
- General properties of Fermionic systems?



Shell model of $^{12}$C

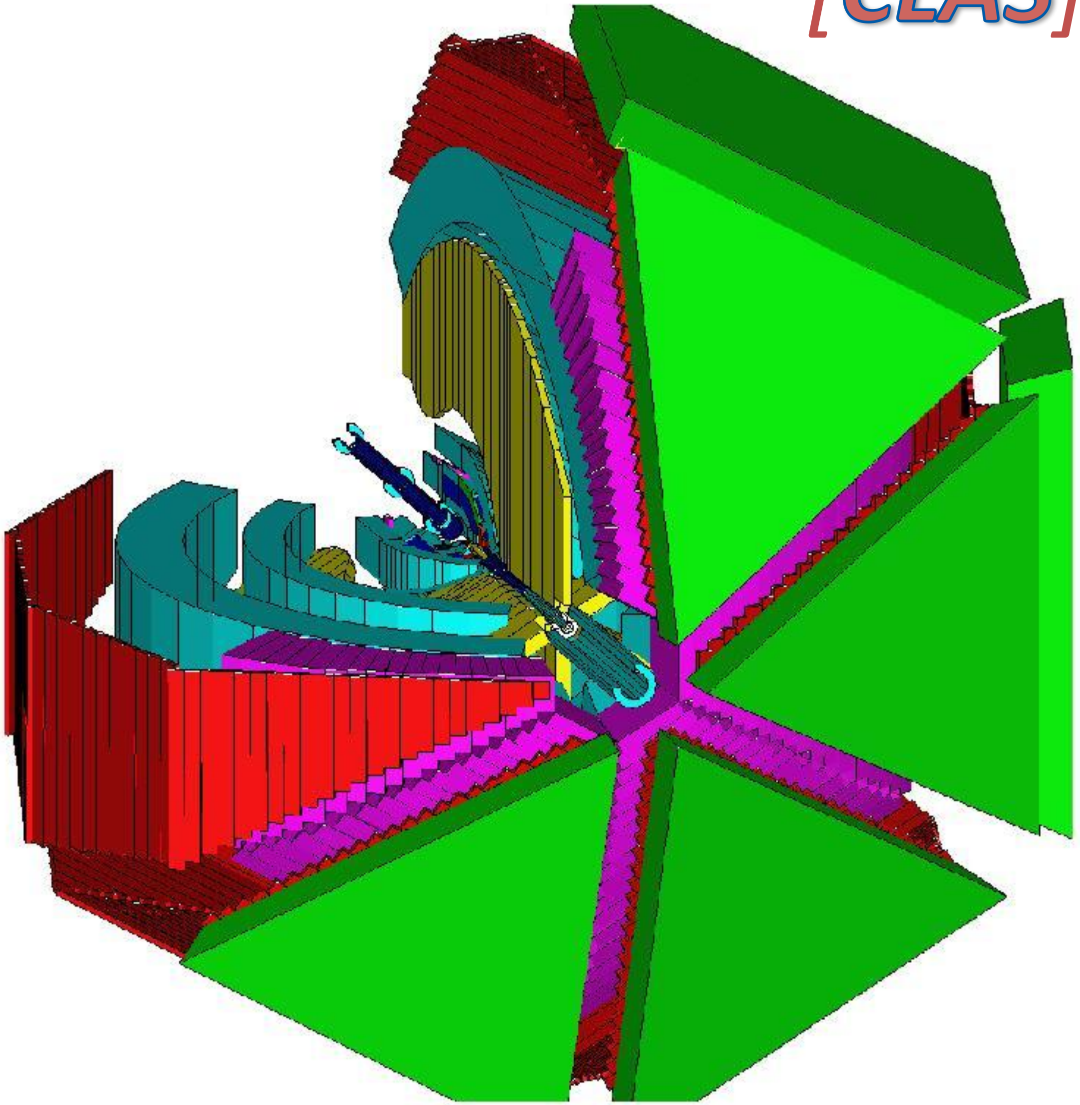


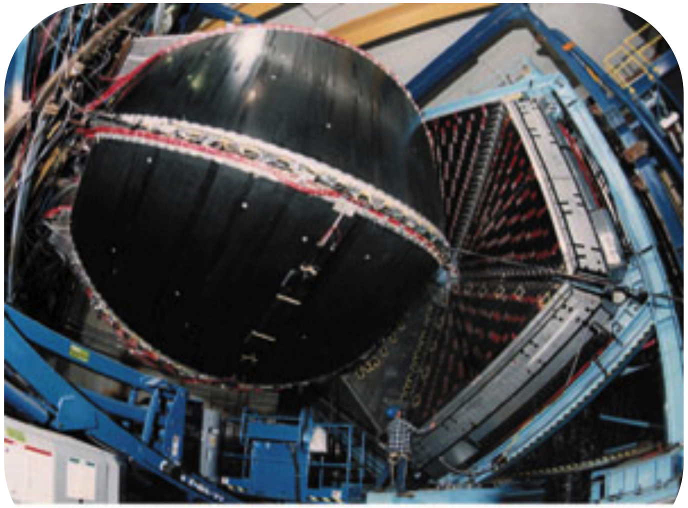


Shell Model of Nuclei

# CEBAF Large Acceptance Spectrometer

## [CLAS]





Hall B Large Acceptance Spectrometer

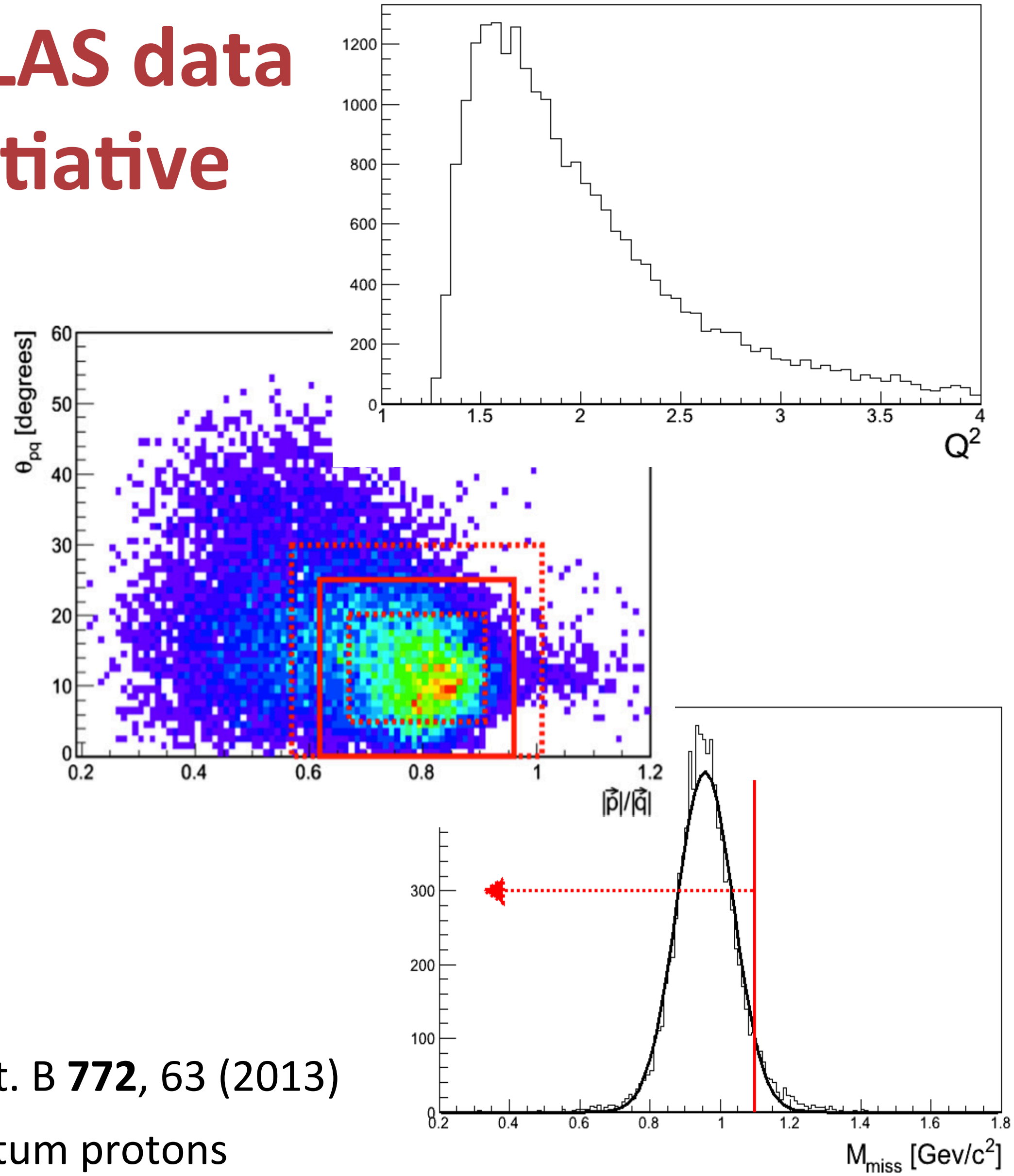
Open (e,e’) trigger, Large-Acceptance, Low luminosity (~$10^{34}$ cm$^{-2}$ sec$^{-1}$)

# Mining CLAS Data for SRCs

## Reanalyzed existing CLAS data via a data-mining initiative

5 GeV electrons on $^{12}C$, $^{27}Al$, $^{56}Fe$, and $^{208}Pb$:

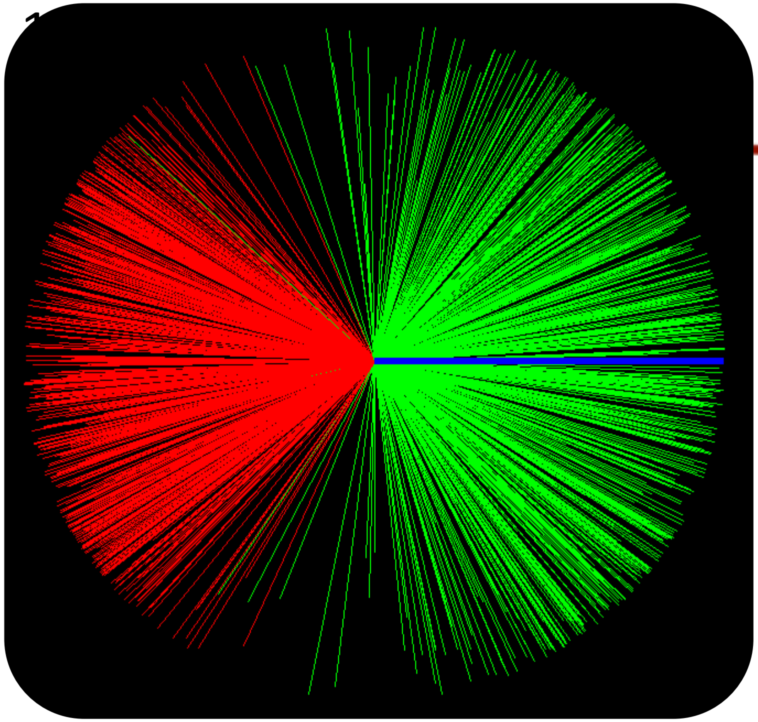
1. Cut (e,e'p) kinematics to simulate previous measurements*.
2. Look for a correlated recoil proton.

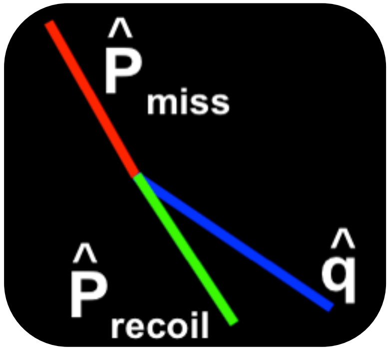


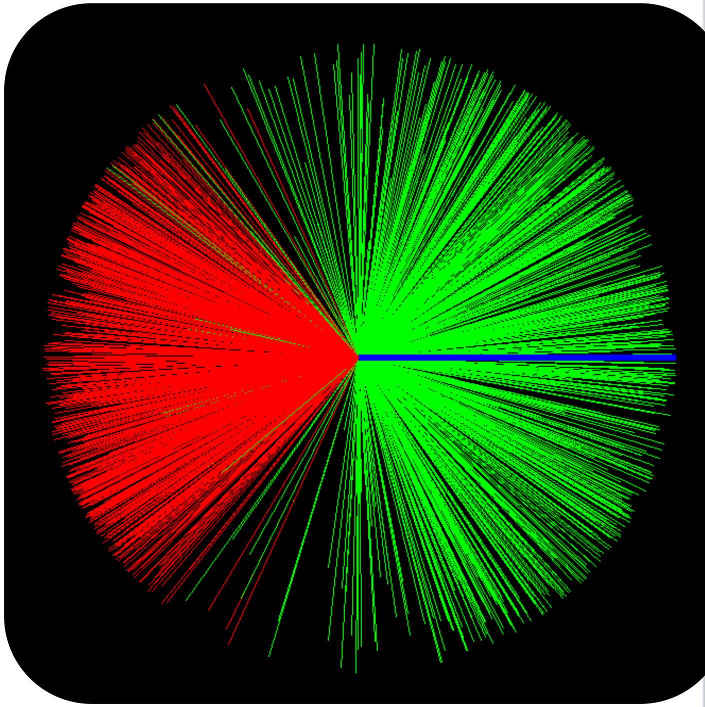
O. Hen et al. (CLAS Collaboration), Phys. Lett. B **772**, 63 (2013)

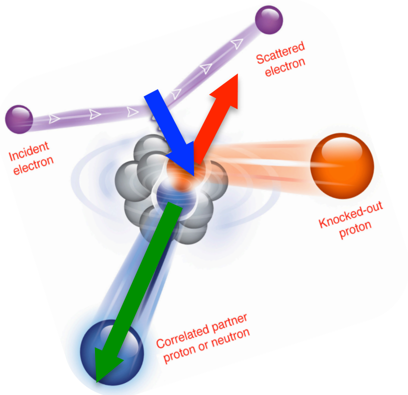
*Quasielstic knockout of high-initial-momentum protons

# 3D Reconstruction



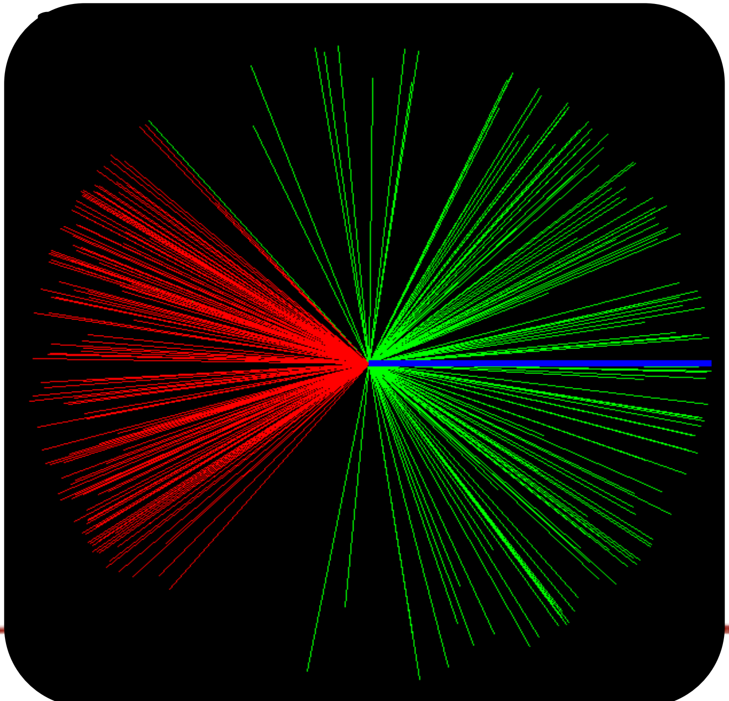


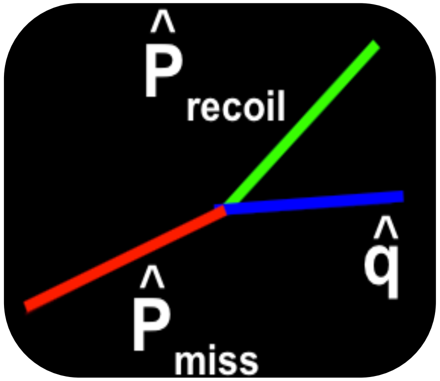




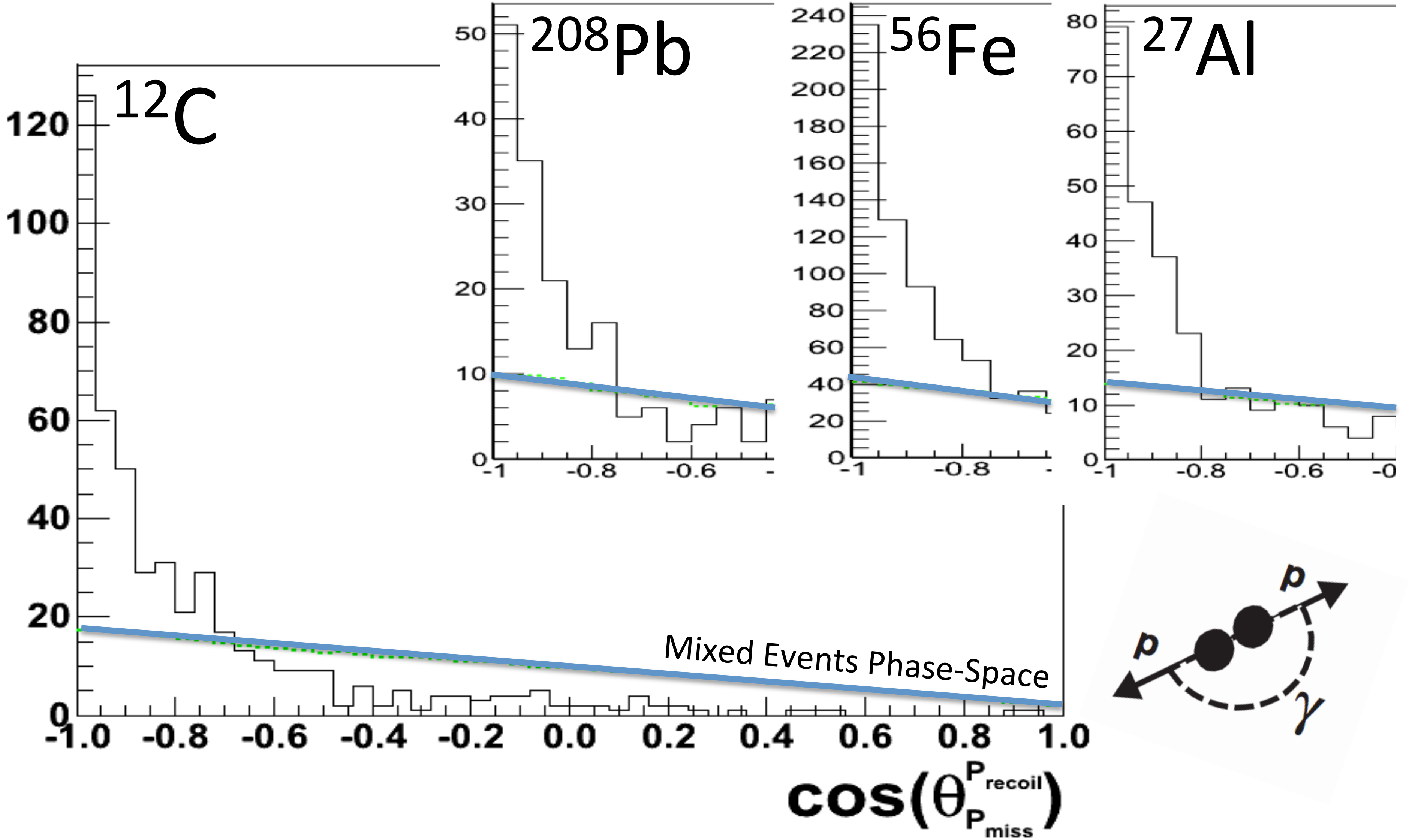
Back-to-back

= SRC pairs!





# Opening Angle



# Sensitivity to SRCs

Assuming scattering off 2N-SRC pairs:

- (e,e'p) is sensitive to *np* and *pp* pairs
- (e,e'pp) is sensitive to *pp* pairs alone

=> (e,e'pp)/(e,e'p) ratio is sensitive to the *np*/*pp* ratio

$$A\left(e,e'pp\right) \propto \# pp_A \cdot 2\sigma_p$$

$$A(e,e'p) \quad \propto \# pp_A \cdot 2\sigma_p + \# pn_A \cdot \sigma_p$$

$$= \# pp_A \cdot 2\sigma_p \left[1 + \frac{1}{2}\frac{\# pn_A}{\# pp_A}\right]$$

$$\Rightarrow \frac{\# np_A}{\# pp_A} = 2 \cdot \left[\frac{A(e,e'p)}{A\left(e,e'pp\right)} - 1\right]$$

Assuming
No FSI

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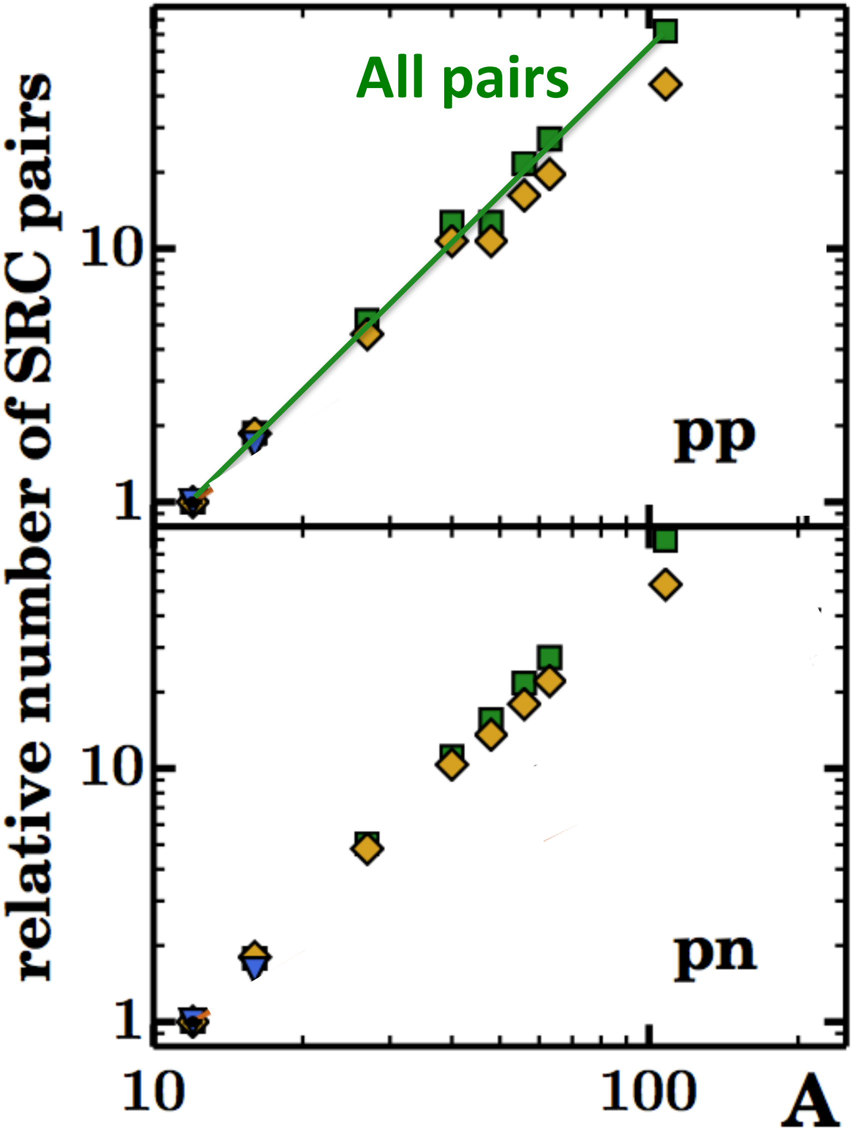
Corrected for Final-State Interactions (FSI) on the outgoing nucleon

(Attenuation and Single-Charge Exchange.)

# Selectivity of SRC Pairs

- Extract the number of pp (np) SRC pairs in nuclei relative to $^{12}C$.



C. Colle and O. Hen et al., Phys. Rev. C **92**, 024604

# Selectivity of SRC Pairs

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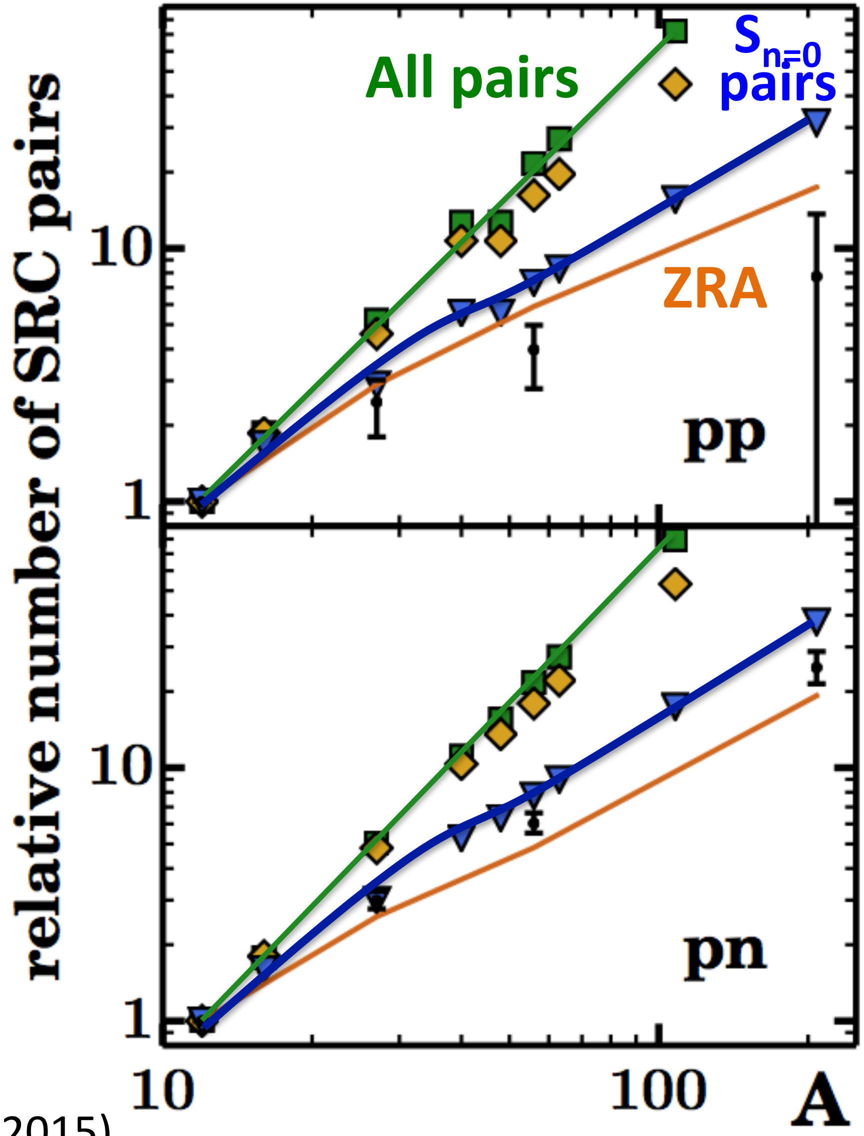
- Pair number increases very slowly with A
- consistent with $^1S_0$ ($^3S_0$) pairs creating SRCs.



C. Colle and O. Hen et al., Phys. Rev. C **92**, 024604 (2015)

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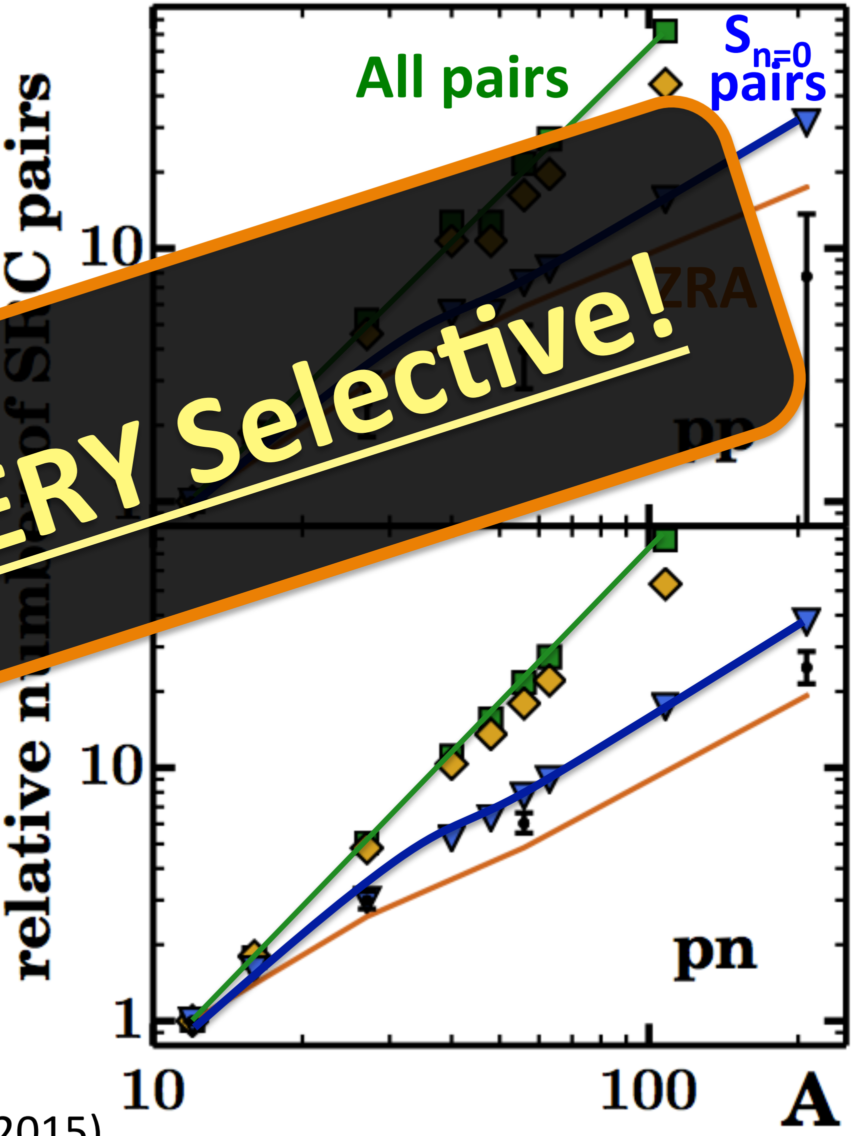
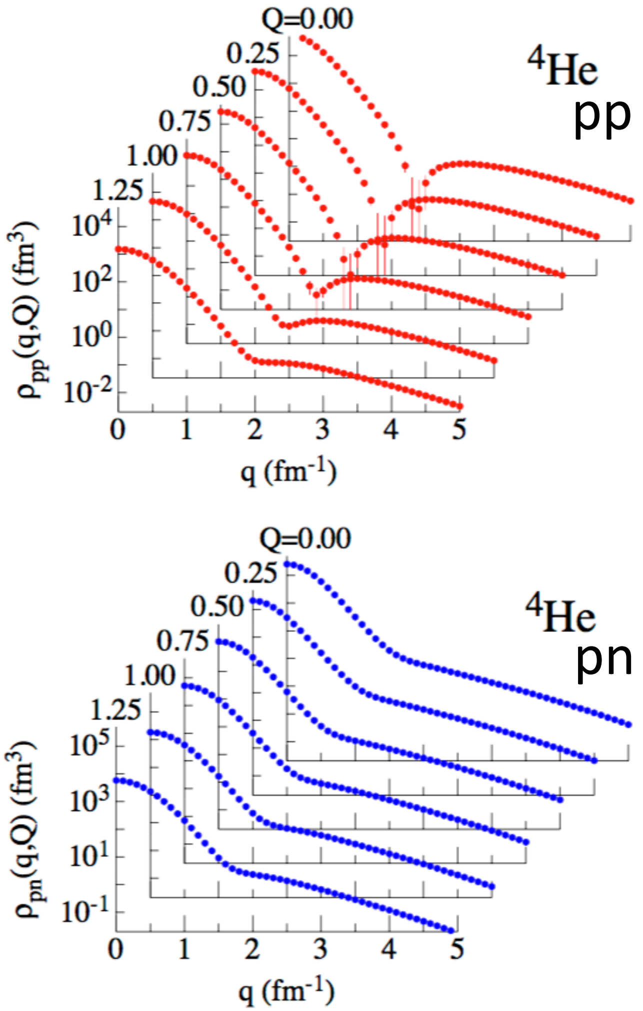
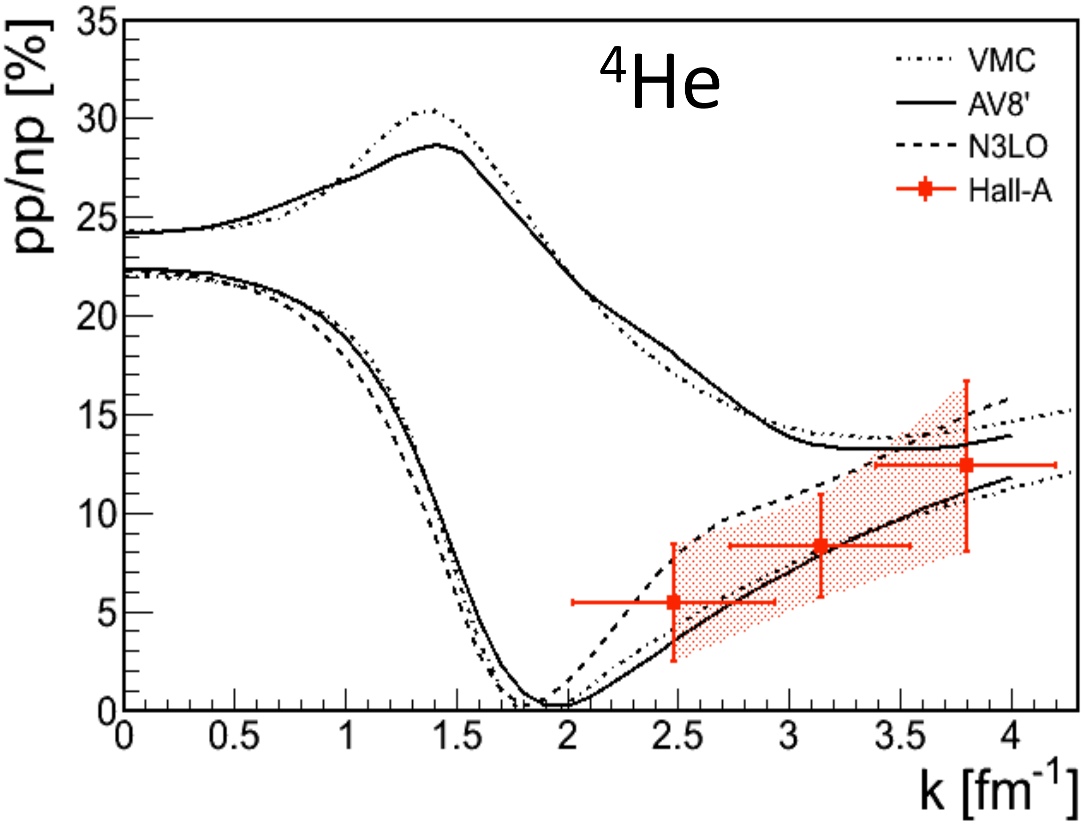
**SRC Pairs are VERY Selective!**



C. Colle and O. Hen et al., Phys. Rev. C **92**, 024604 (2015)

# Selectivity in Light Nuclei

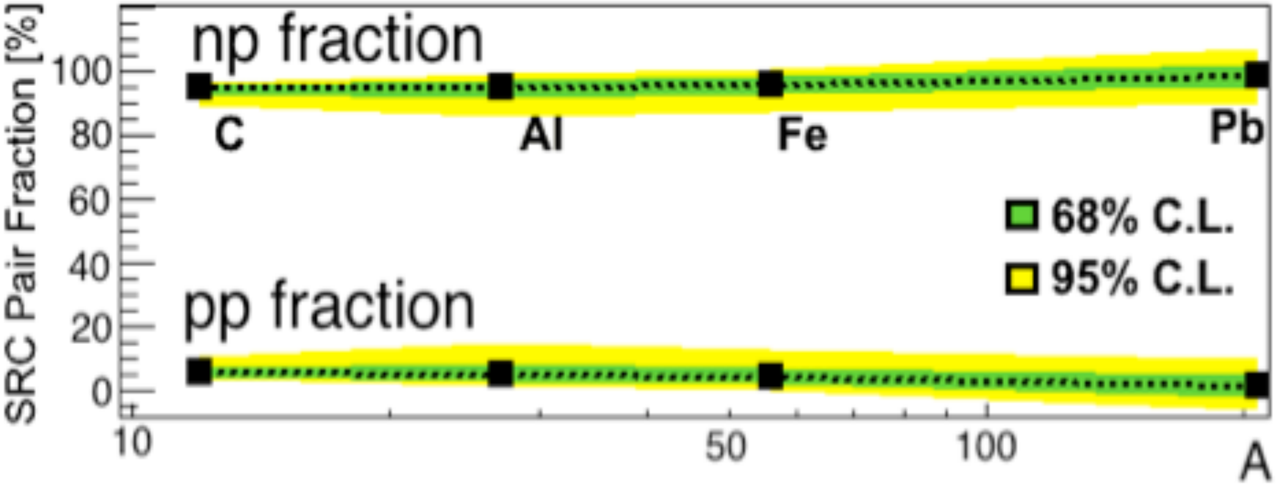


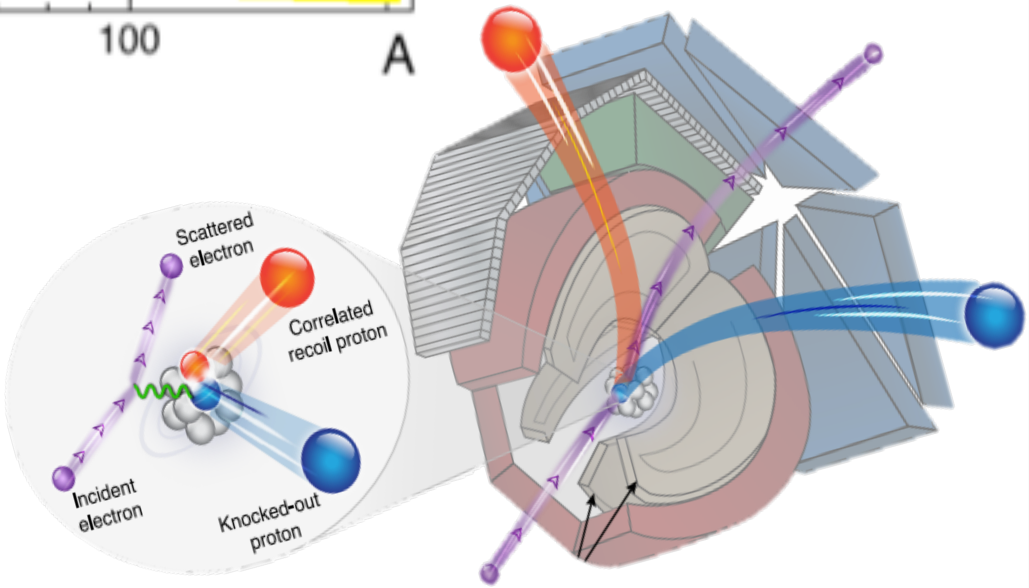


SRC pairs are consistent with Q = 0 *back-to-back* pairs

R. Wiringa et al., Phys. Rev. C 89, 024305 (2014).
T. Neff, H. Feldmeier and W. Horiuchi, Phys. Rev. C 92, 024003 (2015).
I. Korover, N. Muangma, and O. Hen et al., Phys. Rev. Lett 113, 022501 (2014).

# np-pairs dominance in *heavy* nuclei





O. Hen et al. (CLAS Collaboration),
Science 346, 614 (2014)

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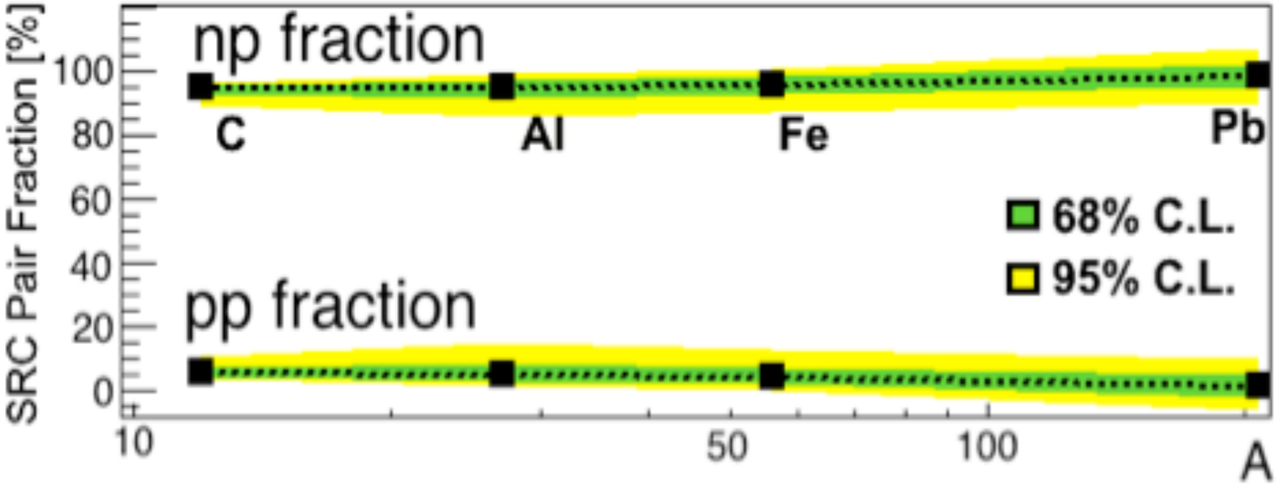
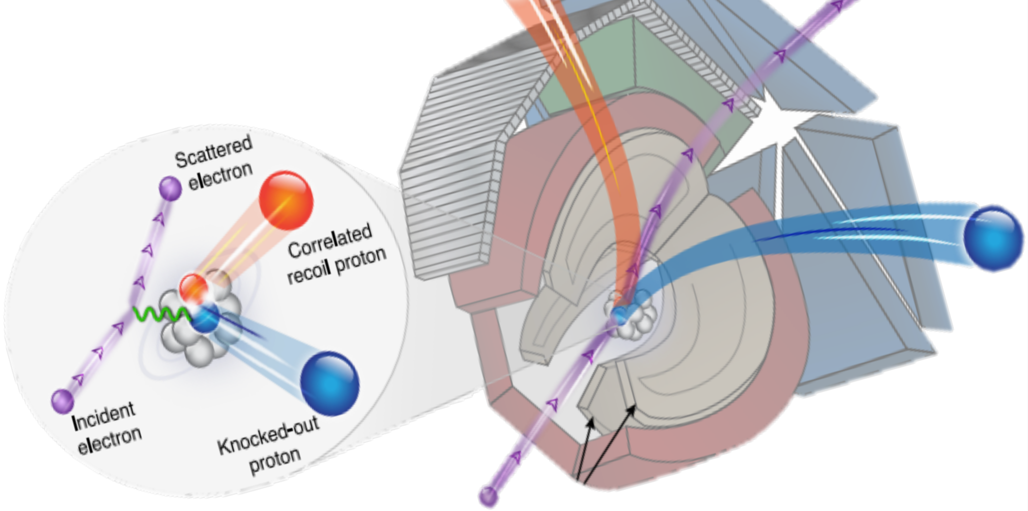
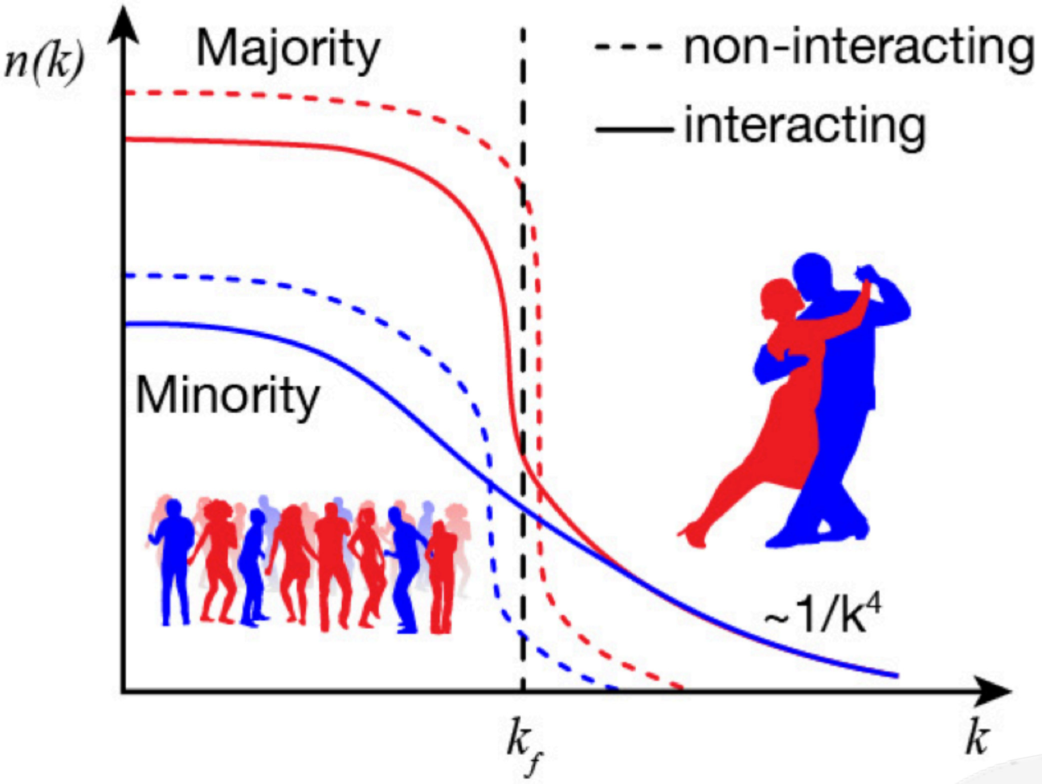




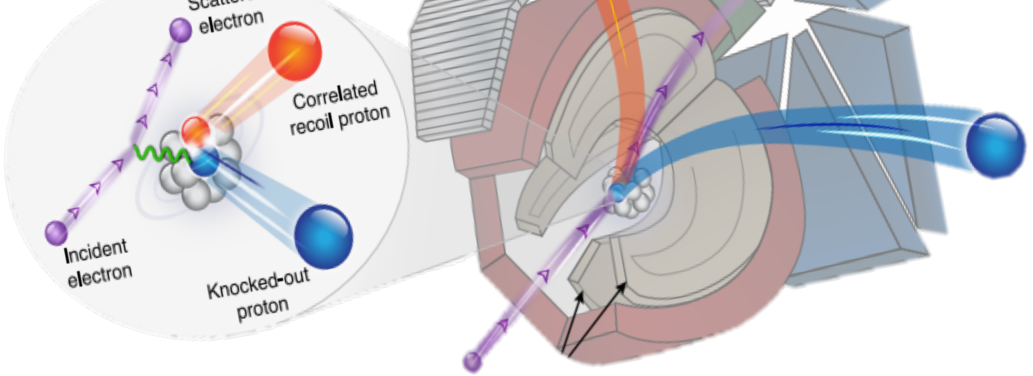
What can we learn from this result on general Fermi systems?

O. Hen et al. (CLAS Collaboration), Science 346, 614 (2014)

# Kinetic Energy Sharing



## Momentum distribution of an imbalanced two-component Fermi system



O. Hen et al. (CLAS Collaboration), Science 346, 614 (2014)

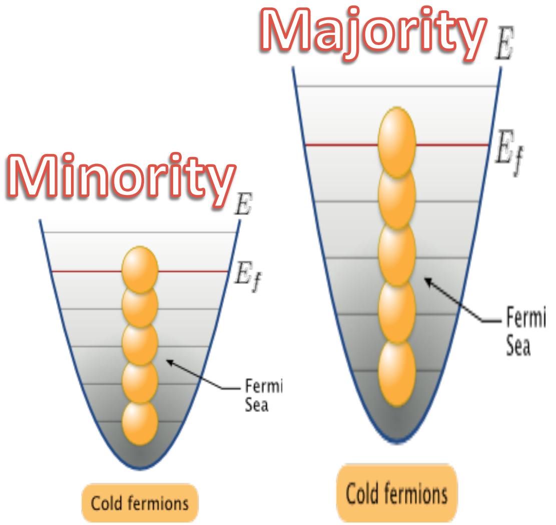
# Kinetic Energy Sharing in Asymmetric Nuclei

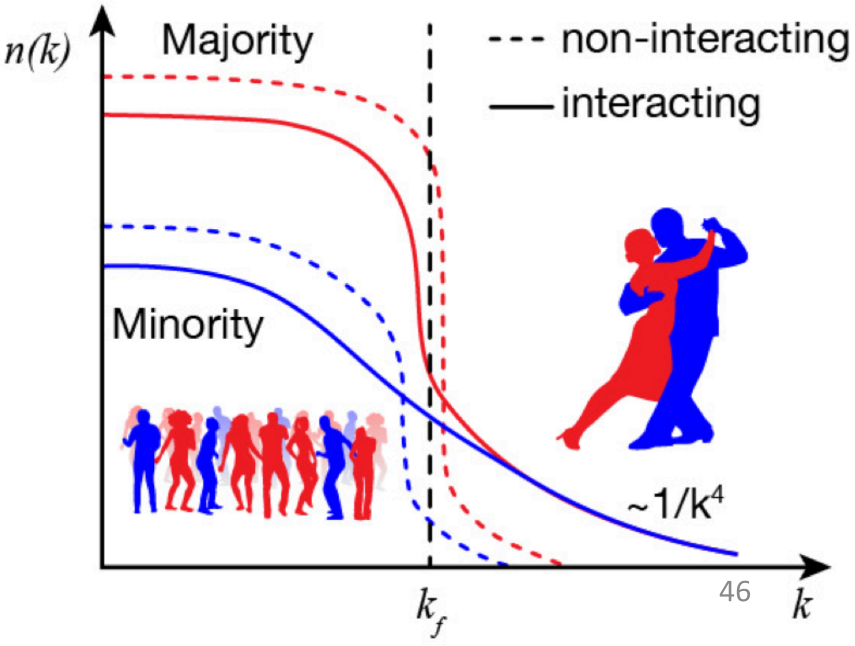
**Pauli Principle:**

*Majority (neutrons)* fermions move faster (higher Fermi momentum)

**np correlations:**

*Minority (protons)* fermions move faster (greater pairing probability)





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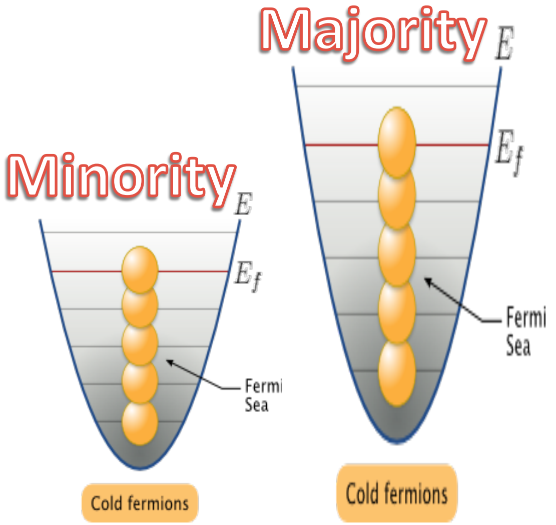

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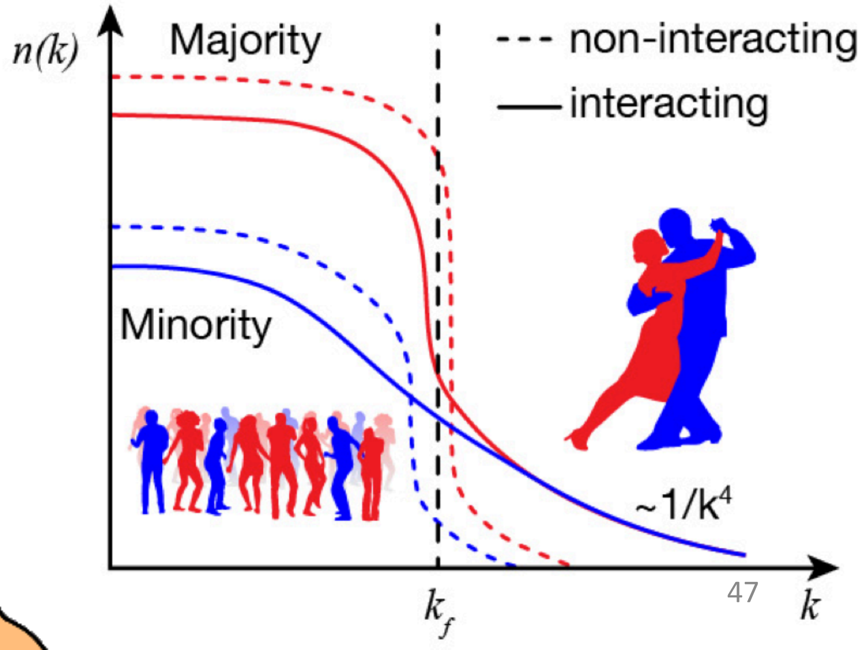
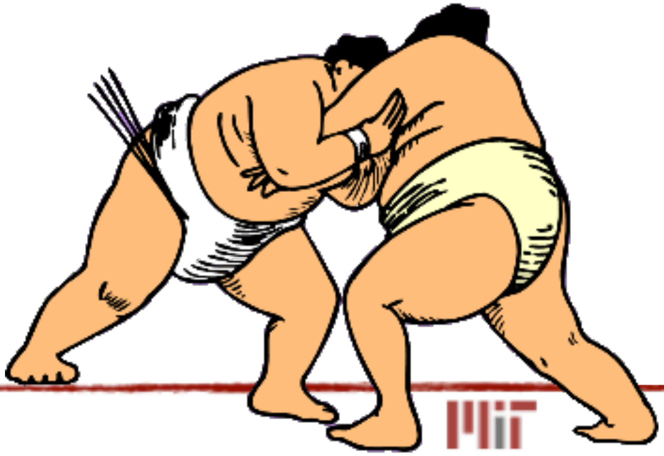
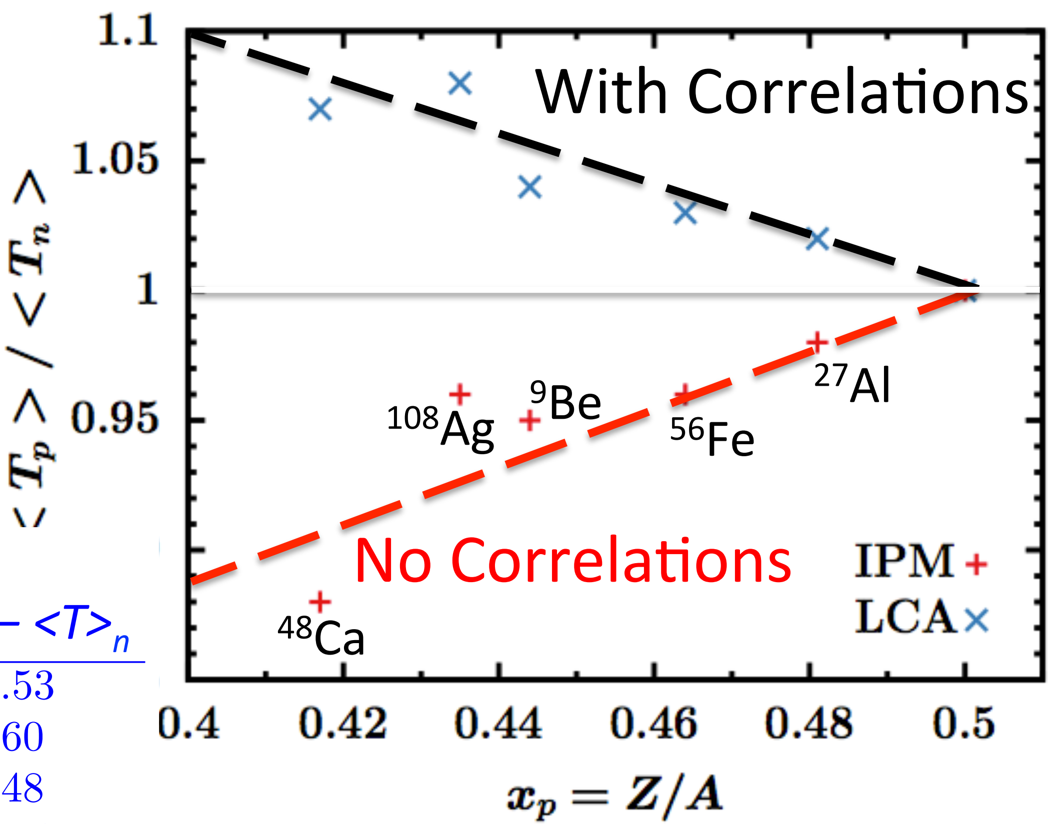


**Who wins?**



# Calculations *Predict* Correlations wins

$\langle T \rangle_{Minority} \geq \langle T \rangle_{Majority}$



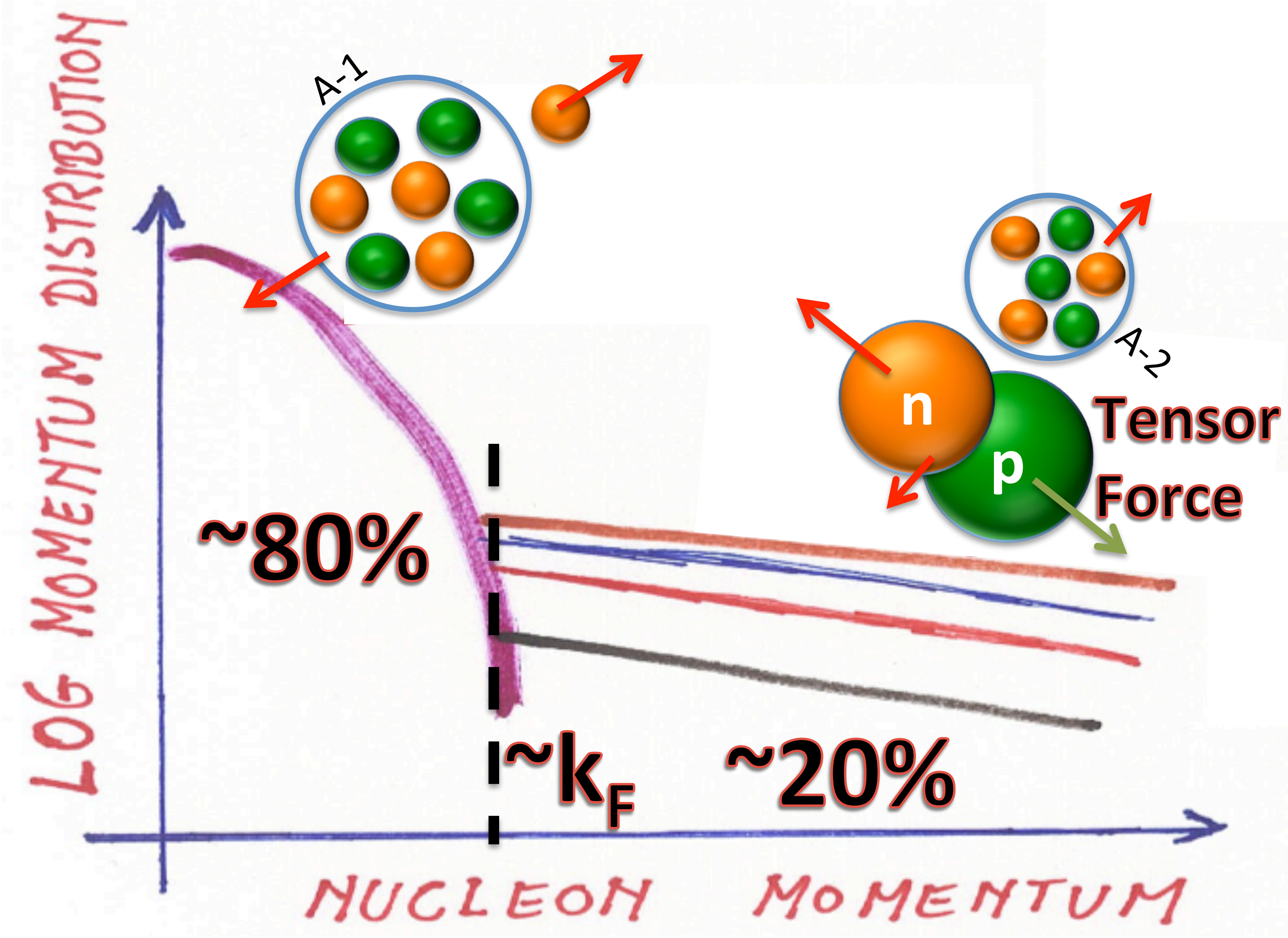
Light Nuclei (A<12)

| | $\frac{\lvert N-Z \rvert}{A}$ | $\langle T \rangle_p$ | $\langle T \rangle_n$ | $\langle T \rangle_p - \langle T \rangle_n$ |
|---|---|---|---|---|
| $^{8}$He | 0.50 | 30.13 | 18.60 | 11.53 |
| $^{6}$He | 0.33 | 27.66 | 19.06 | 8.60 |
| $^{9}$Li | 0.33 | 31.39 | 24.91 | 6.48 |
| $^{3}$He | 0.33 | 14.71 | 19.35 | -4.64 |
| $^{3}$H | 0.33 | 19.61 | 14.96 | 4.65 |
| $^{8}$Li | 0.25 | 28.95 | 23.98 | 4.97 |
| $^{10}$Be | 0.2 | 30.20 | 25.95 | 4.25 |
| $^{7}$Li | 0.14 | 26.88 | 24.54 | 2.34 |
| $^{9}$Be | 0.11 | 29.82 | 27.09 | 2.73 |
| $^{11}$B | 0.09 | 33.40 | 31.75 | 1.65 |

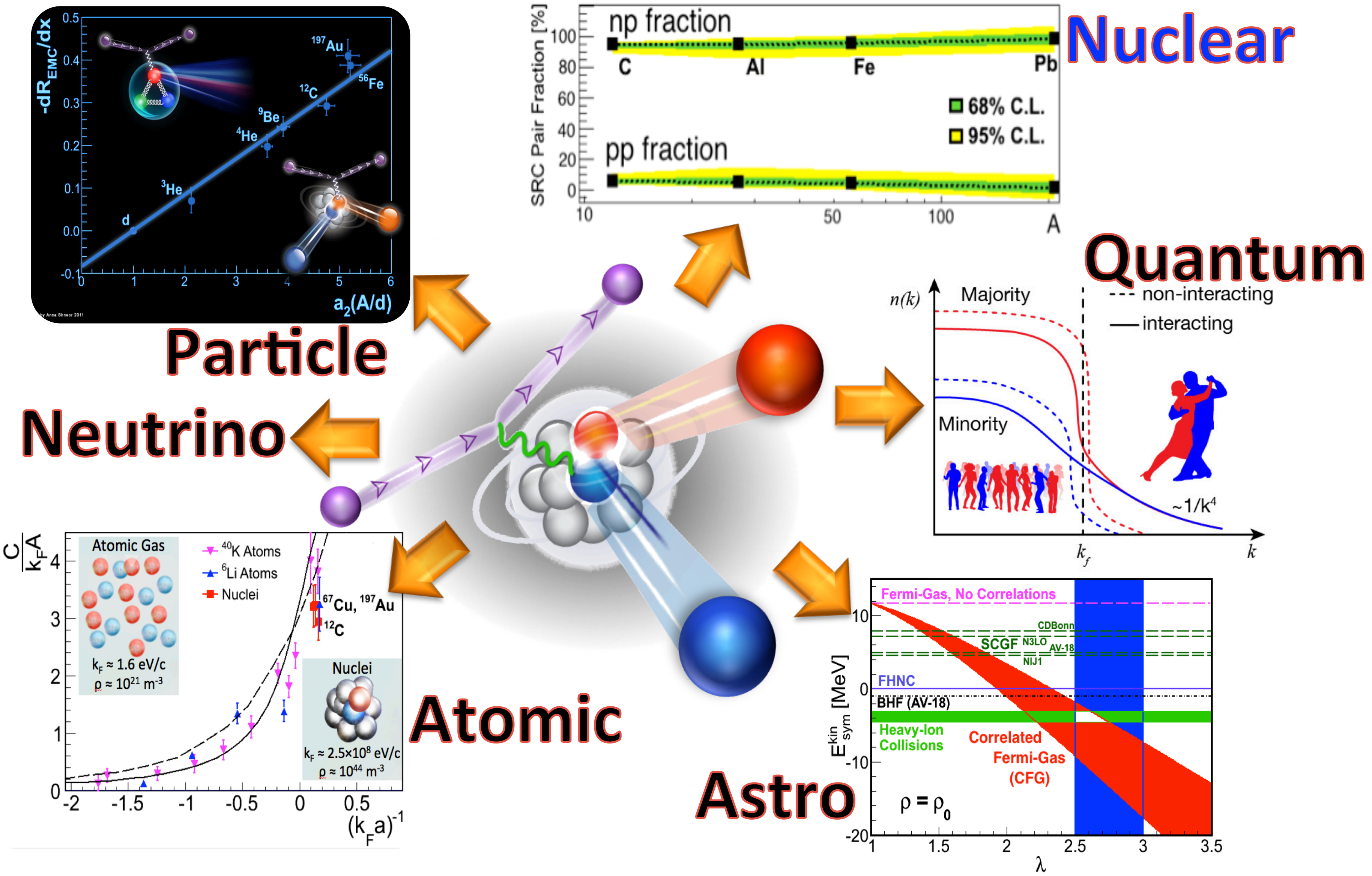
Heavy Nuclei (27<A<108):
M. Vanhalst, W. Cosyn, and J. Ryckebusch, arXiv: 1405.3814.

VMC Calculations: R. Wiringa et al., Phys. Rev. C **89**, 024305 (2013)

# Summary: Universal Structure of Nuclei



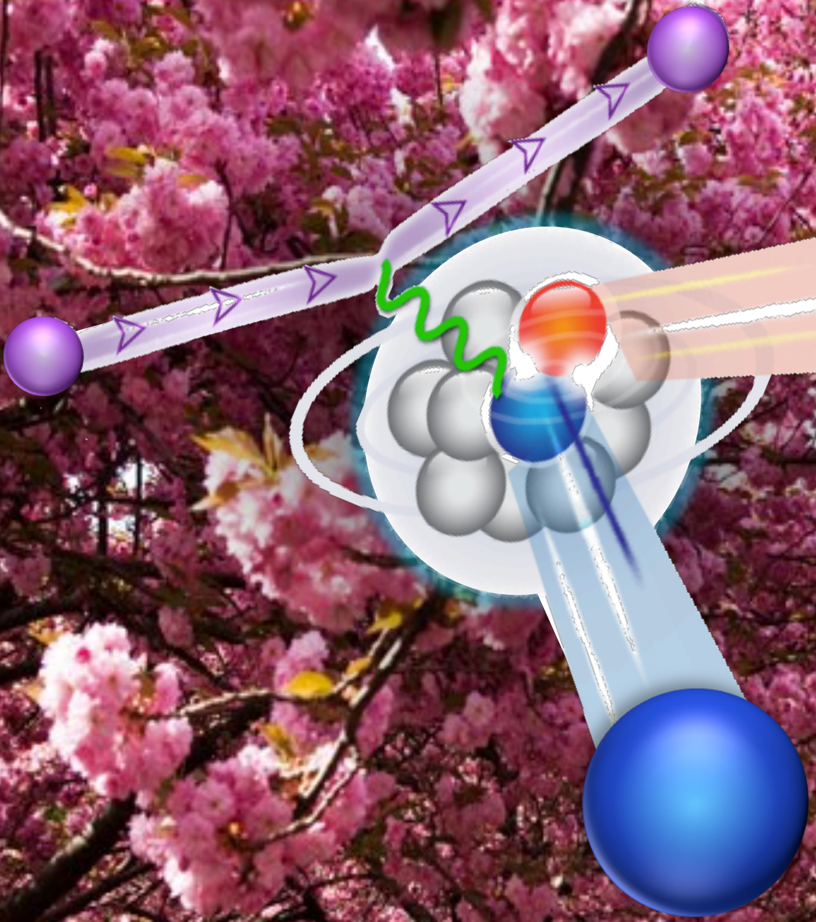
# Importance of Correlations



**Papers published in Science, PRL, PL, PRC, PRD, …**

# Personal Message:

- Next generation experiments will be much more accurate (e.g. x 10 – 100 statistics).
- Concrete *quantitative* theoretical predictions could be tested!



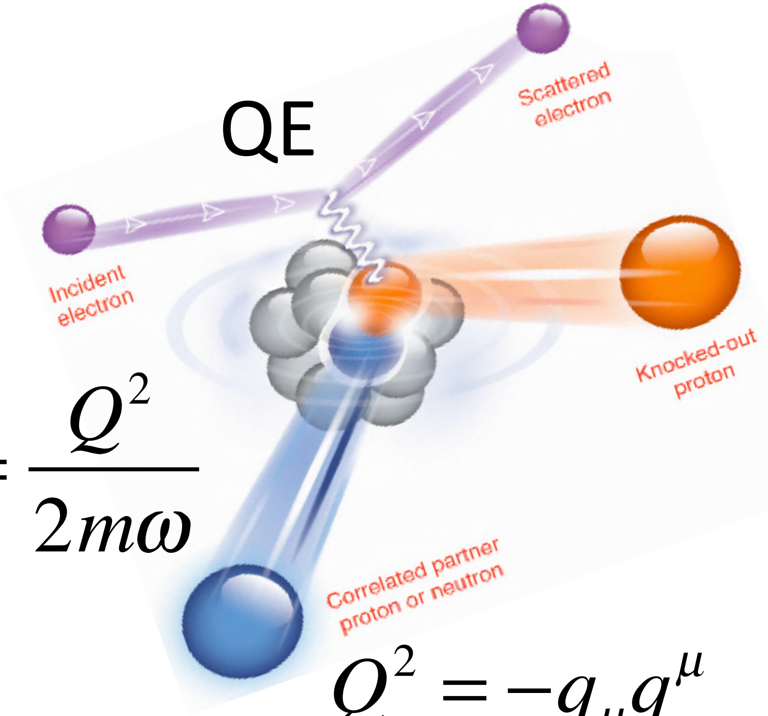
# Thank You!

# Questions?

# Quasi-Elastic Scattering

**Goal: Probe the <u>nucleonic</u> structure of the <u>nucleus</u>**

**Energy scale: several GeV**



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

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

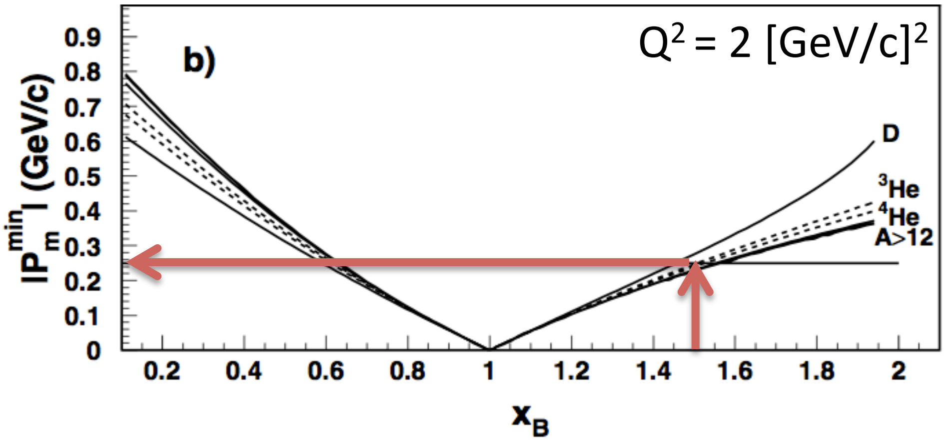
$0<x_B<A$:

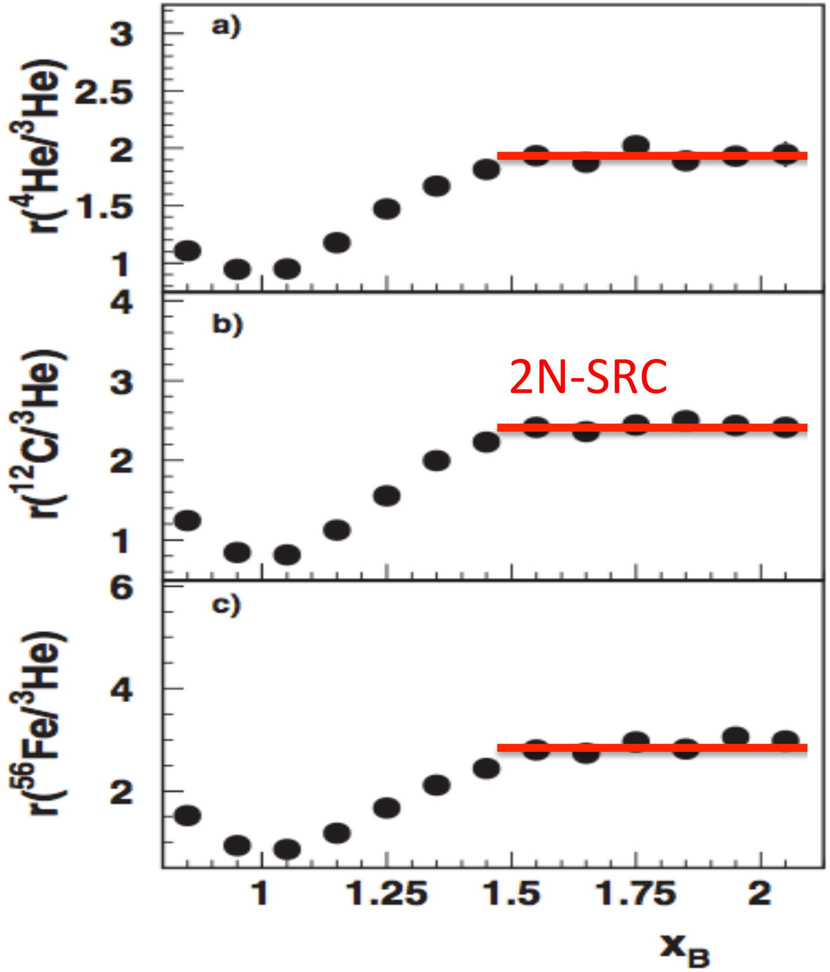
- Counts the *number of nucleons involved* in the reaction.
- Determines the *minimal initial momentum* of the scattered nucleon.

# High-Momentum Scaling

- A(e,e') cross section ratios sensitive to $n_A(k)/n_d(k)$
- Observed scaling in $\sigma_A/\sigma_d$ for $x_B \geq 1.5$:

$$n_A(k>k_F) = a_2(A) \times n_d(k)$$





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

L. Frankfurt et al. , Phys. Rev. C **48**, 2451 (1993).
K. Egiyan et al., Phys. Rev. C **68**, 014313 (2003). N. Fomin et al., Phys. Rev. Lett. **108**, 092502 (2012).

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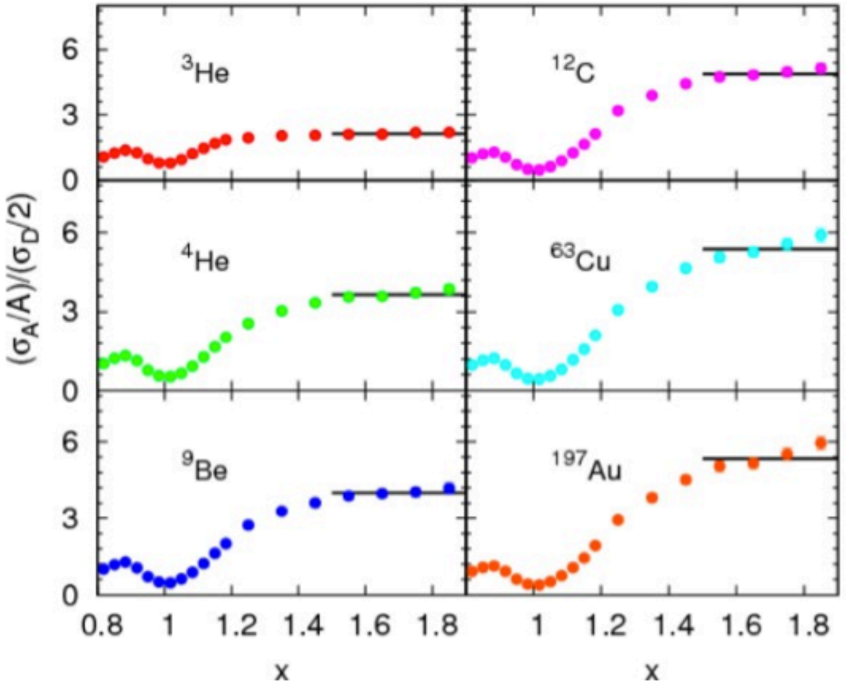

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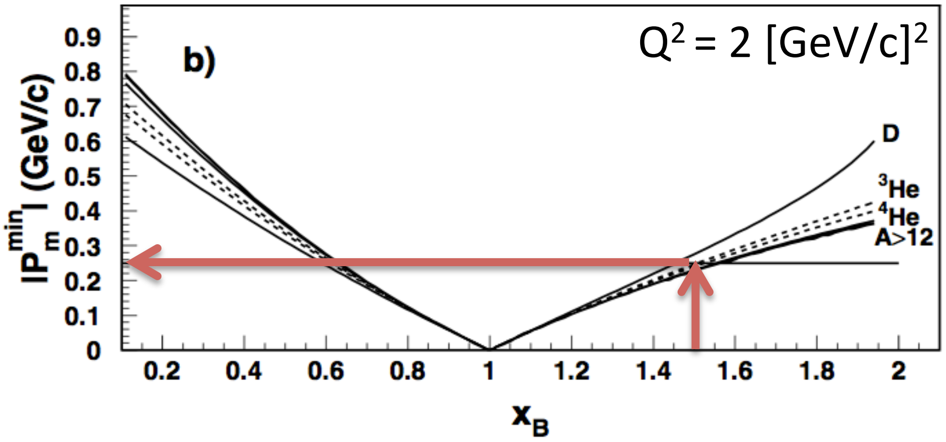

| A | $a_2(A/D)$ | A | $a_2(A/D)$ |
|---|---|---|---|
| $^3$He | **2.1 ± 0.1** | $^{12}$C | **4.7 ± 0.2** |
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O. Hen et al., PRC **85**, 047301 (2012)

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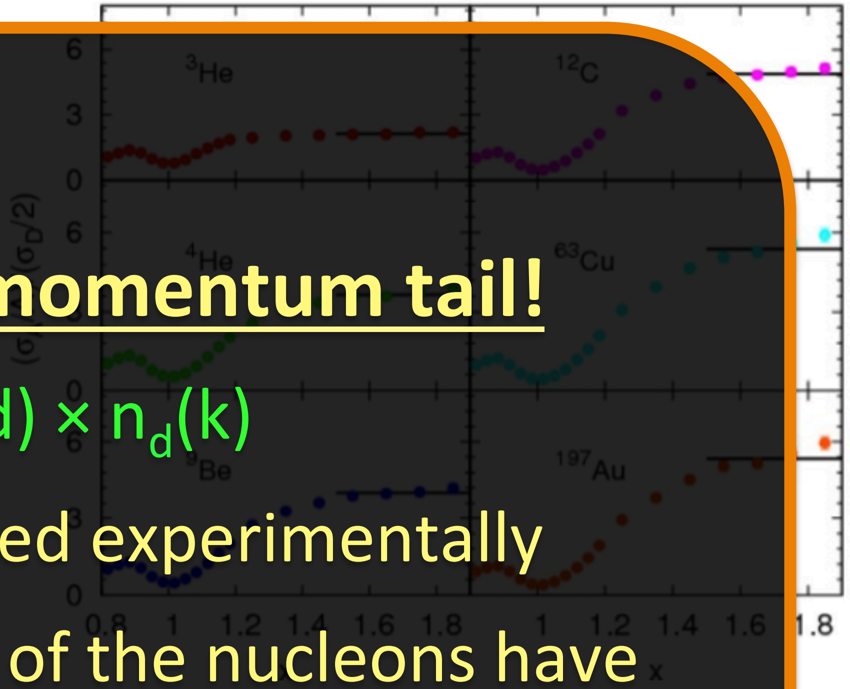
**Nuclei have a high-momentum tail!**

1. It scales: $n_A(k>k_F) = a_2(A/d) \times n_d(k)$
2. Scale factor, $a_2$, determined experimentally
3. In A ≥ 12 nuclei, 20 – 25% of the nucleons have high-momentum ($k>k_F$).



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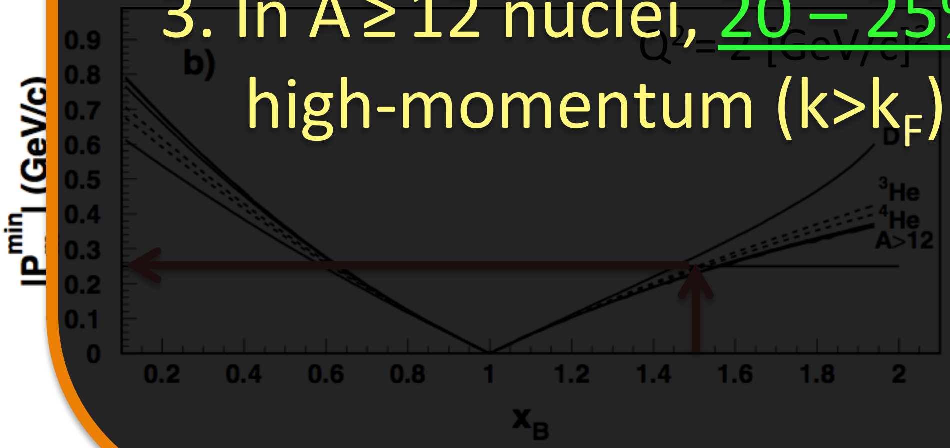

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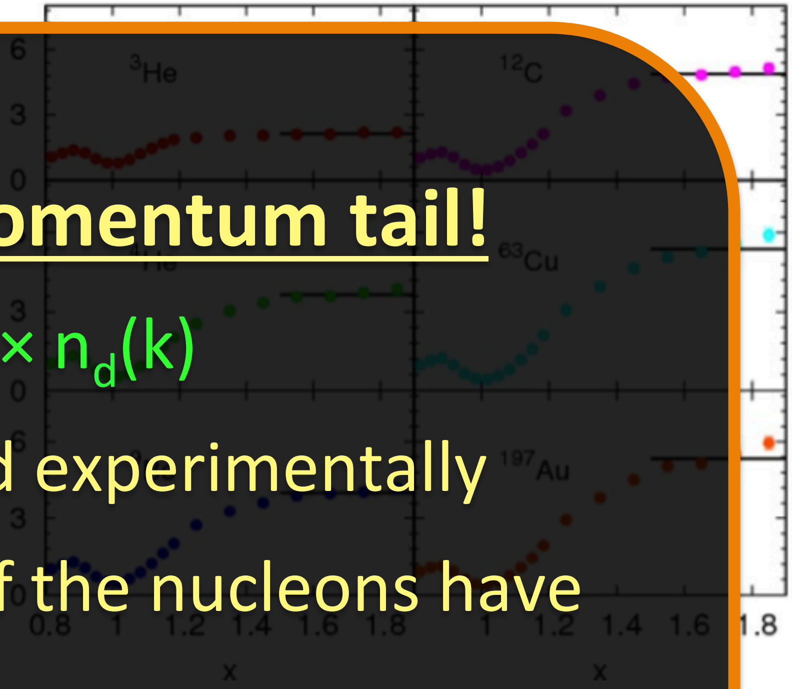

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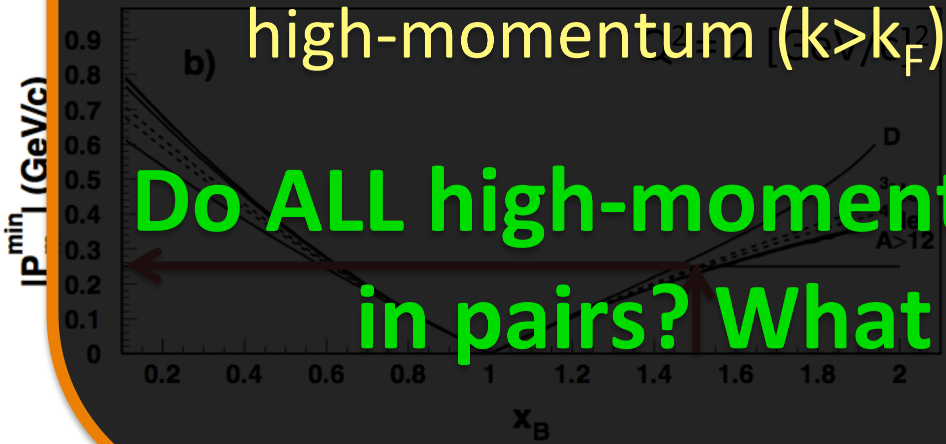

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**Do ALL high-momentum nucleons come in pairs? What kind of pairs?**

L. Frankfurt et al., Phys. Rev. C 48, 2451 (1993).
K. Egiyan et al., Phys. Rev. C **68**, 014313 (2003).
K. Egiyan et al., Phys. Rev. Lett. **96**, 082501(2006).

# Correlations in Ultracold Atomic Gases

# Two-component interacting Fermi systems

The contact term

Please forget about nuclear physics
for a moment

# The Contact and Universal Relations

A concept developed for a *dilute* two-component Fermi systems with a short-range interaction.

Scattering length

$$\text{dilute} \;\equiv\; r_{eff} << a, d$$

Distance between fermions

S. Tan Annals of Physics 323 (2008) 2952, ibid 2971, ibid 2987

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These systems have a high-momentum tail:

$$n(k) = C / k^4 \quad \text{for} \quad k > k_F$$

C is the contact term

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Tan's Contact term:

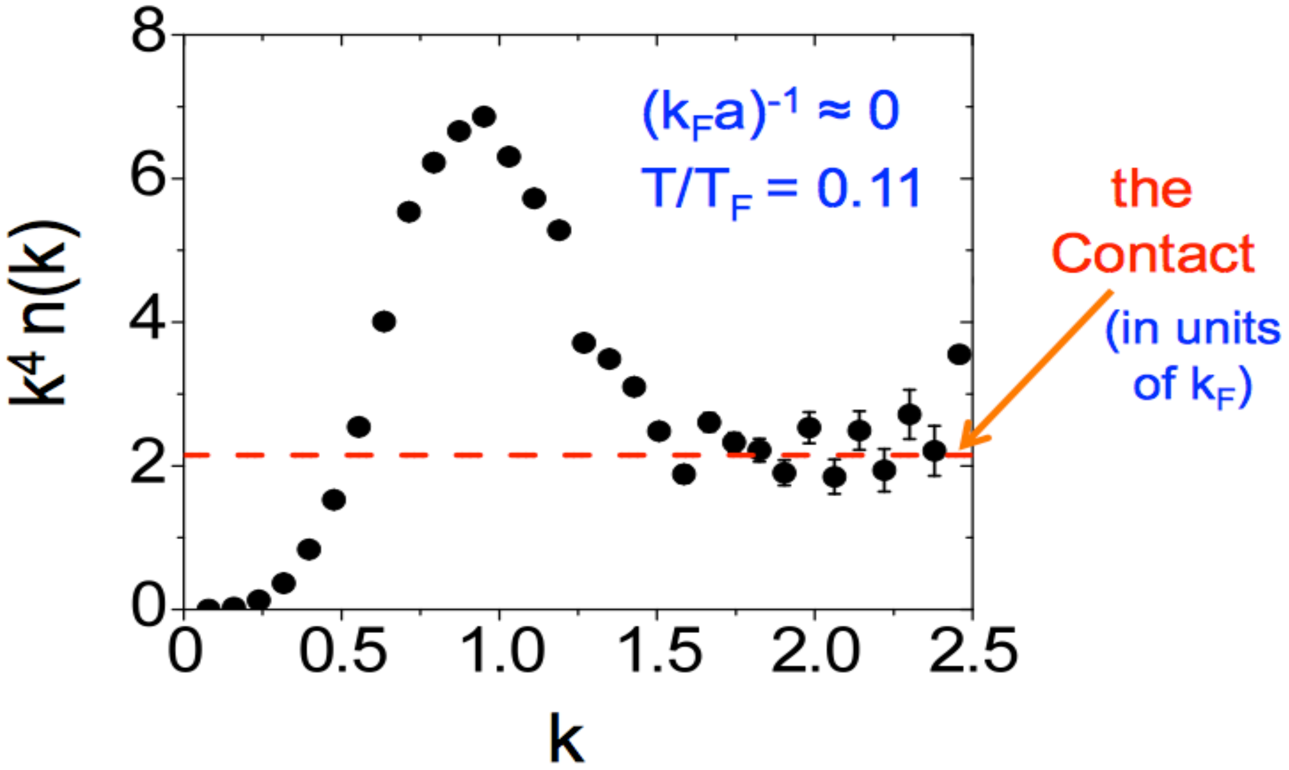
1. Measures the number of SRC different fermion pairs.
2. Determines the thermodynamics through a series of universal relations.

S. Tan Annals of Physics 323 (2008) 2952, ibid 2971, ibid 2987

# Experimental Validation

Two spin-state mixtures of ultra-cold $^{40}$K and $^{6}$Li atomic gas systems.

=> extracted the contact and verified the universal relations



Stewart et al. PRL **104**, 235301 (2010)

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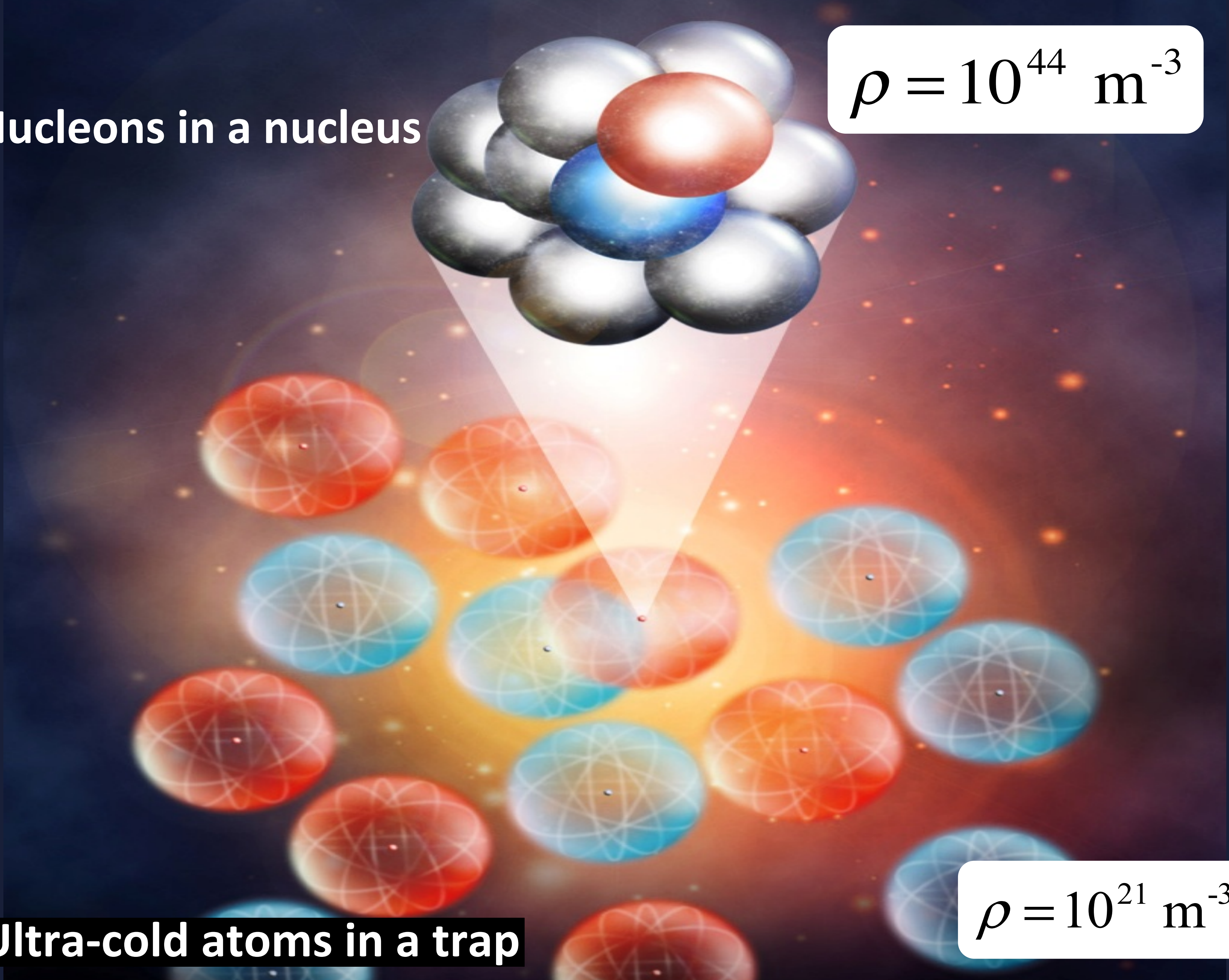
What About
a *Nuclear*
Contact ?

Stewart et al. PRL **104**, 235301 (2010)



**Nucleons in a nucleus**

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

**Ultra-cold atoms in a trap**

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

$$\sigma_1 \approx 1 \ \text{person/m}^2$$

$$\sigma_1 \approx 1 \text{ person/m}^2$$

$$\sigma_2 \approx 1 \text{ person/km}^2$$

$$\sigma_1 / \sigma_2 \approx 10^6$$

# A Nuclear Contact?

## Are nuclei dilute? (i.e. $r_{eff} << a,d$)

$$d = \left( {}^{\rho}\!/_{2} \right)^{-1/3} \approx 2.3 \text{ fm}$$

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

$$a\left( {}^{3}S_{1} \right) = 5.42 \text{ fm}$$

[The high-momentum tail is predominantly $^3S_1$ ($^3D_1$)]

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

$$a\left( {}^3S_1 \right) = 5.42 \text{ fm}$$

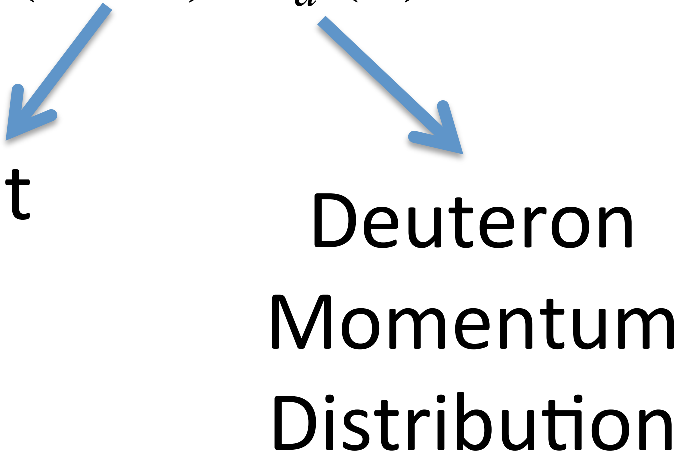
$$r_{eff}(0.7 \text{ fm}) \; < \; d(2.3 \text{ fm}), a(5.4 \text{ fm})$$

# A Nuclear Contact?

## Is there $1/k^4$ scaling regardless?

$$1.5k_F < k < 3k_F$$

$$n_A(k) = a_2(A/d) \cdot n_d(k)$$



Constant

Deuteron
Momentum
Distribution

# A Nuclear Contact?

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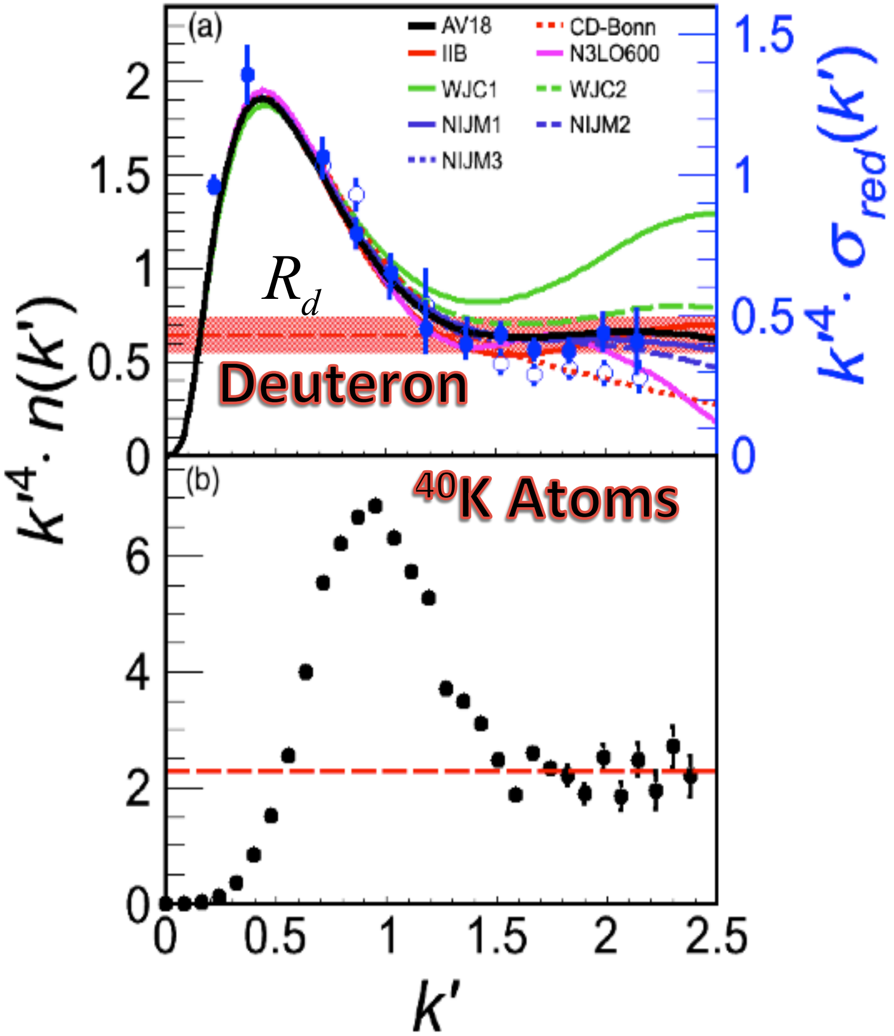

O. Hen et al. Phys. Rev. C **92**, 045205 (2015)

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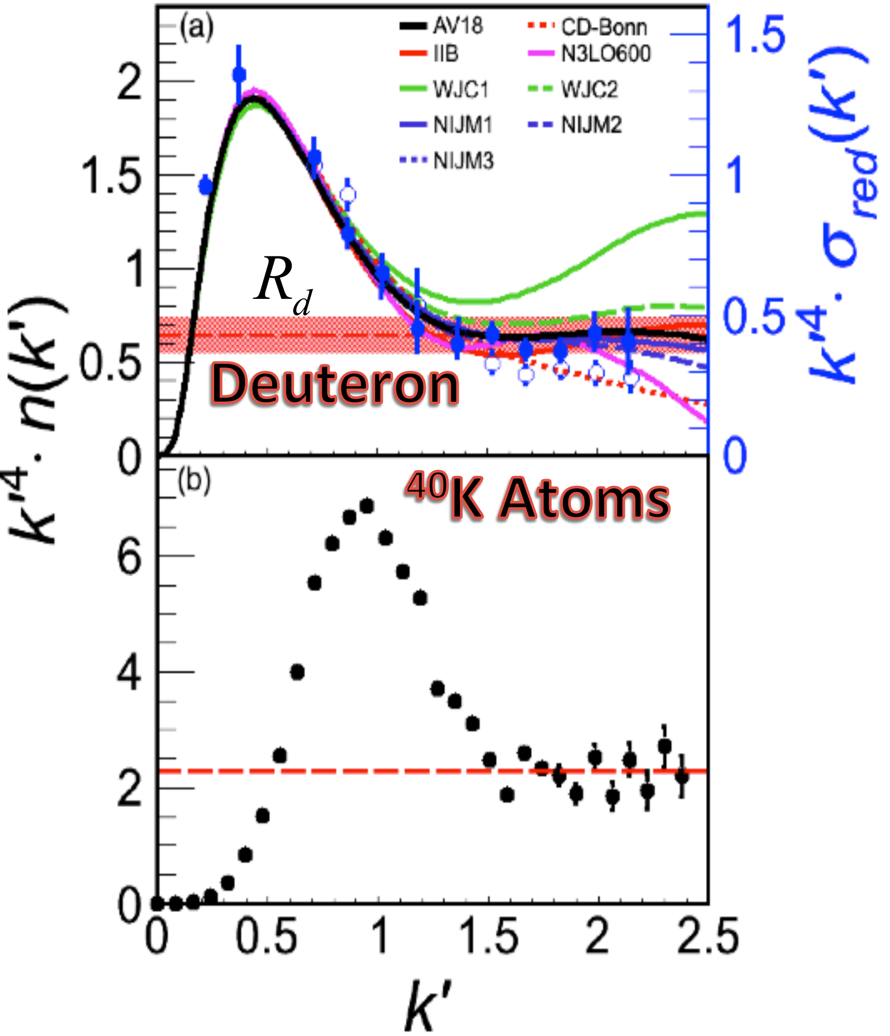
## Is there $1/k^4$ scaling regardless? YES!

$$1.5k_F < k < 3k_F$$

$$n_A(k) = a_2(A/d) \cdot n_d(k)$$



## Why $1/k^4$?

Effect of the one pion exchange (OPE) contribution to the tensor potential acting in second order

$$\left(-B-H_0\right)\left|\Psi_D\right\rangle = V_T\left|\Psi_S\right\rangle$$

$$V_{00} = V_T\left(-B-H_0\right)^{-1} V_T$$

O. Hen et al. Phys. Rev. C **92**, 045205 (2015)

# A Nuclear Contact?

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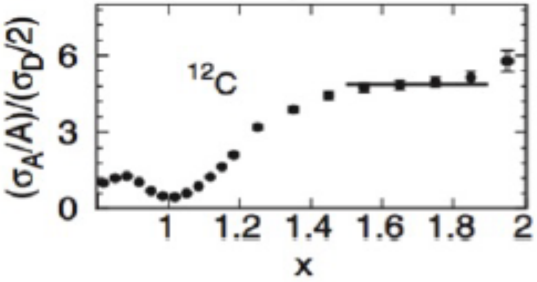

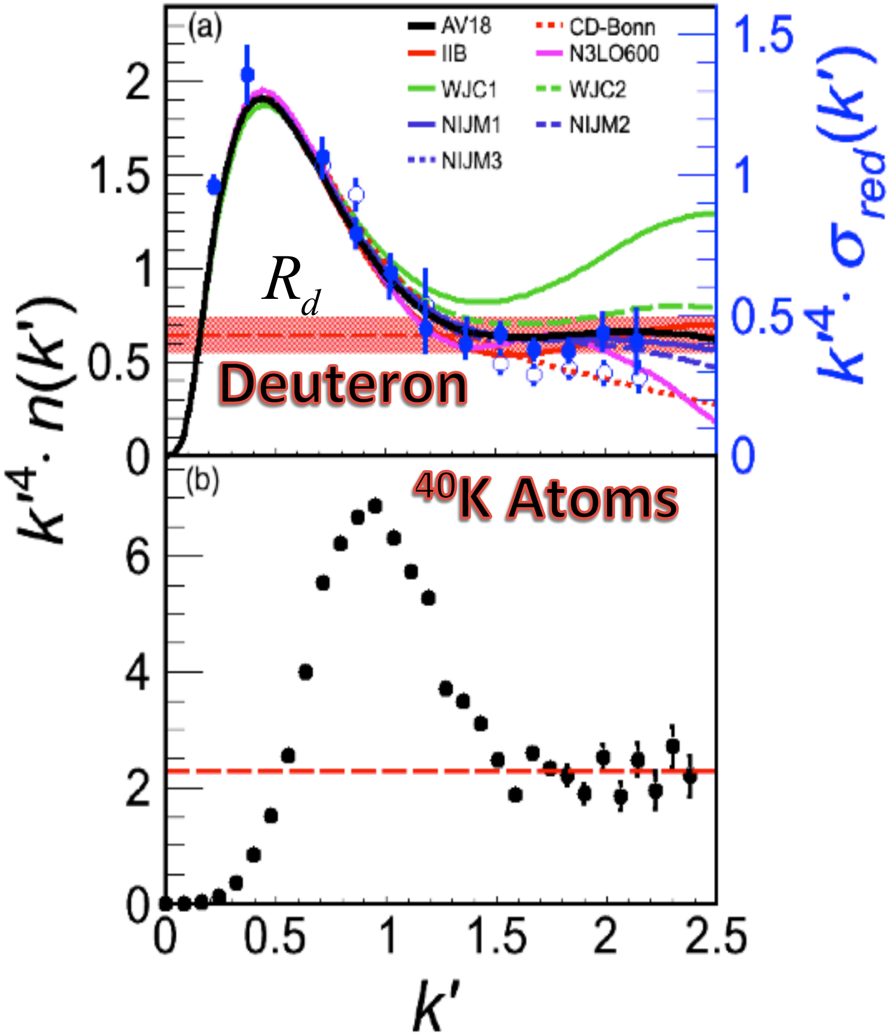

O. Hen et al. Phys. Rev. C **92**, 045205 (2015)

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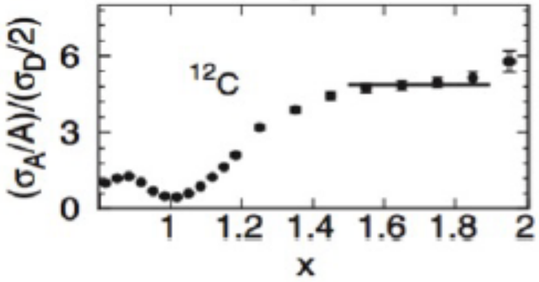
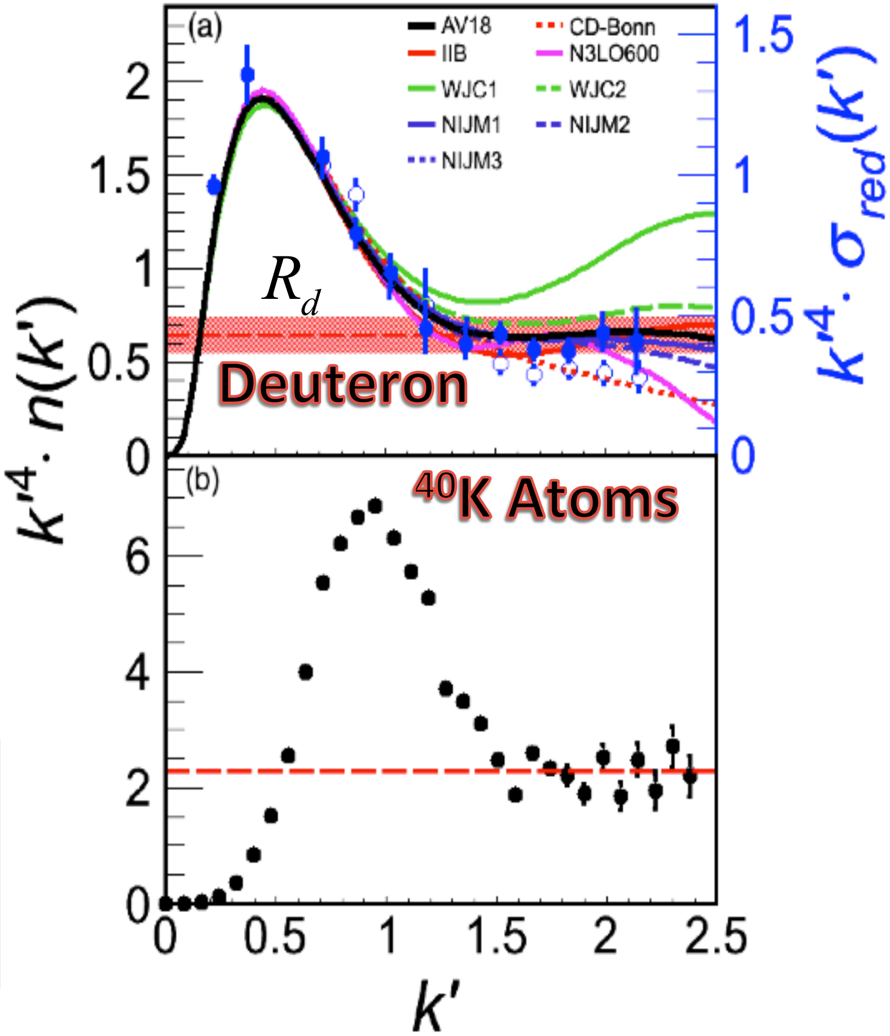




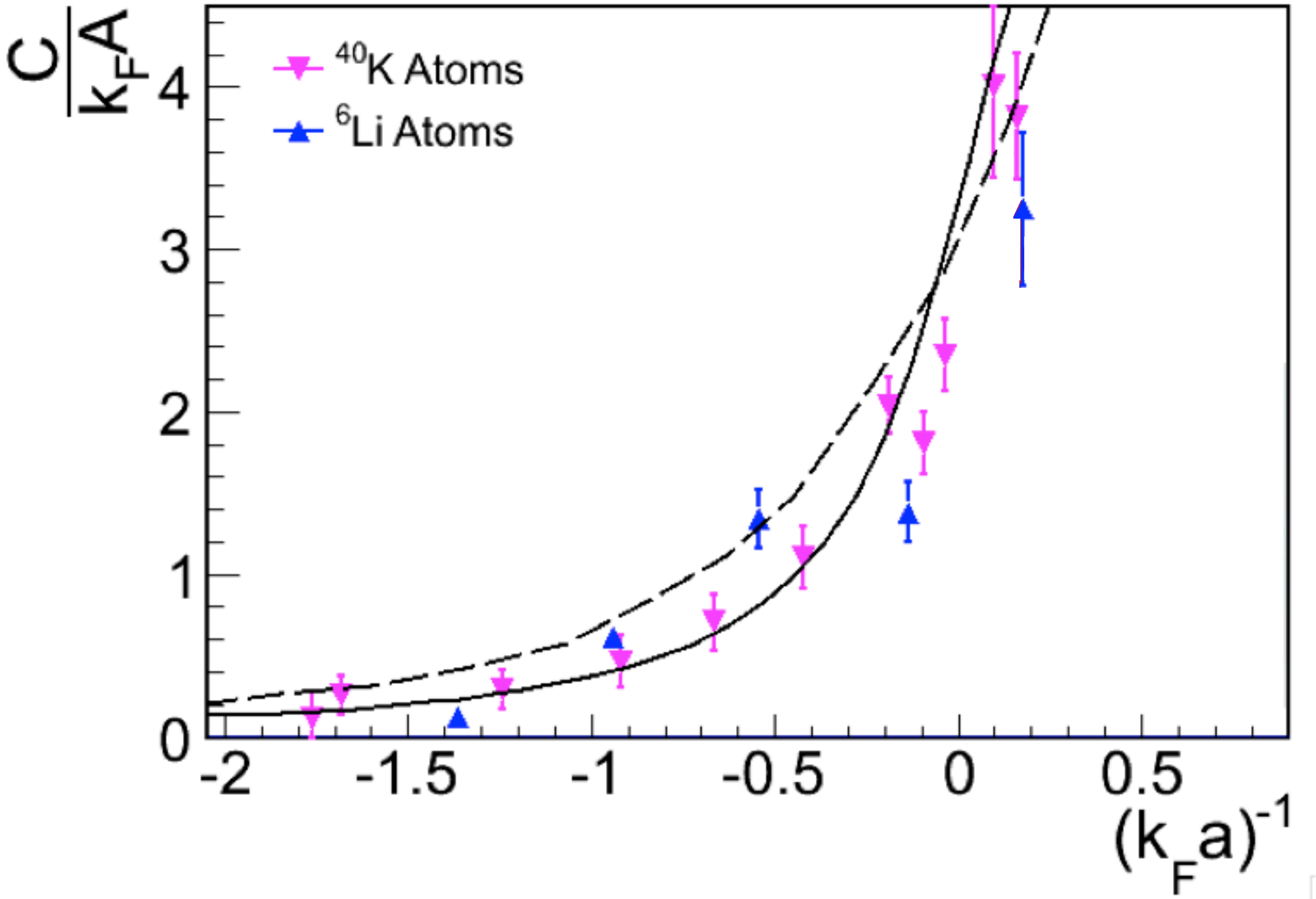
$$\frac{C}{k_F\cdot A} = a_2(A)\cdot R_d$$

| Nucleus | $a_2(A)$ | $\frac{C}{k_F A}$ |
|---|---|---|
| $^{12}$C | $4.75 \pm 0.16$ | $3.04 \pm 0.49$ |
| $^{56}$Fe | $5.21 \pm 0.20$ | $3.33 \pm 0.54$ |
| $^{197}$Au | $5.16 \pm 0.22$ | $3.30 \pm 0.53$ |

O. Hen et al. Phys. Rev. C **92**, 045205 (2015)

# Comparing with atomic systems

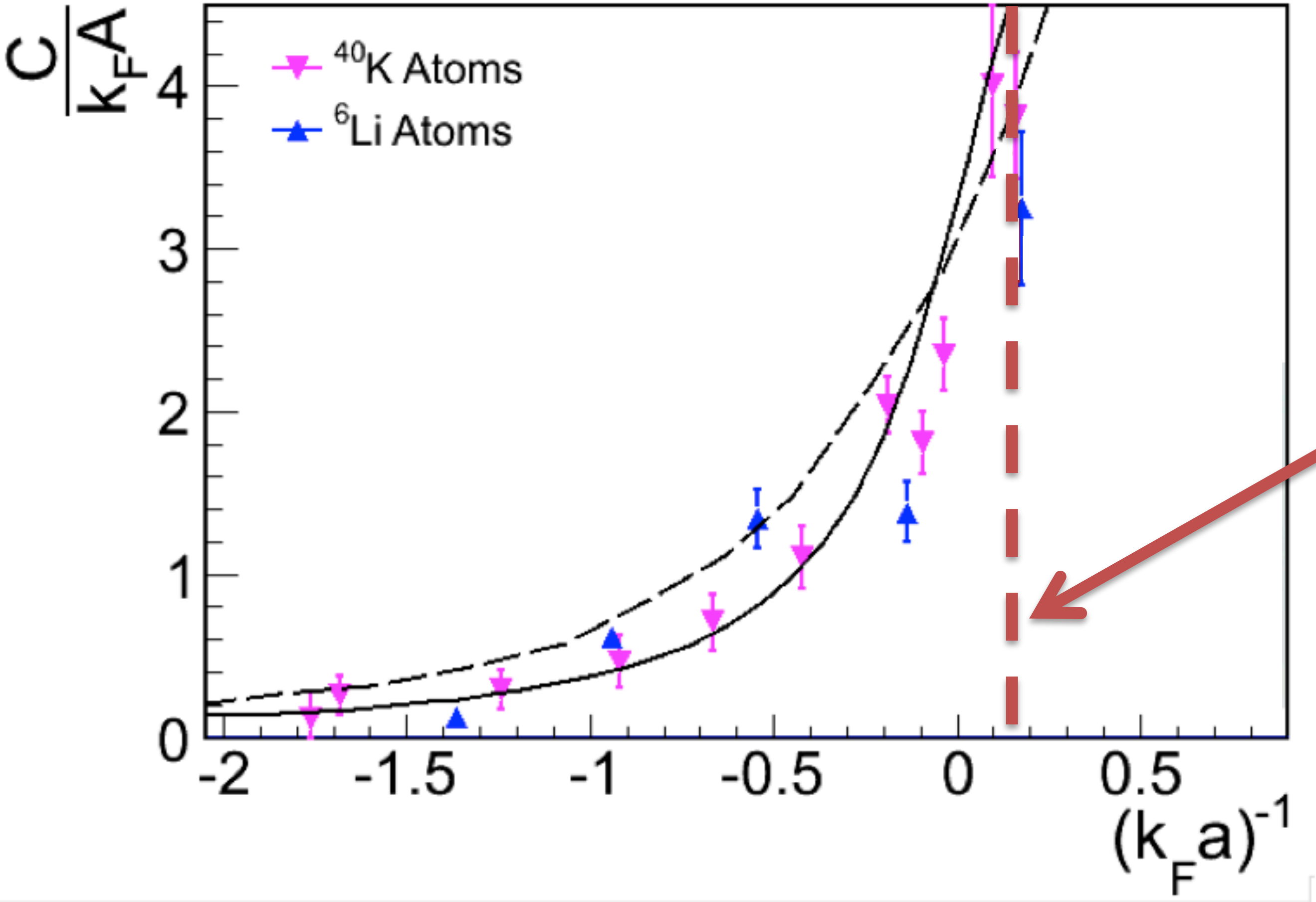
## Finding the same *dimensionless* interaction strength



Stewart et al. Phys. Rev. Lett. **104**, 235301 (2010)
Kuhnle et al. Phys. Rev. Lett. **105**, 070402 (2010)

# Comparing with atomic systems

## Finding the same *dimensionless* interaction strength



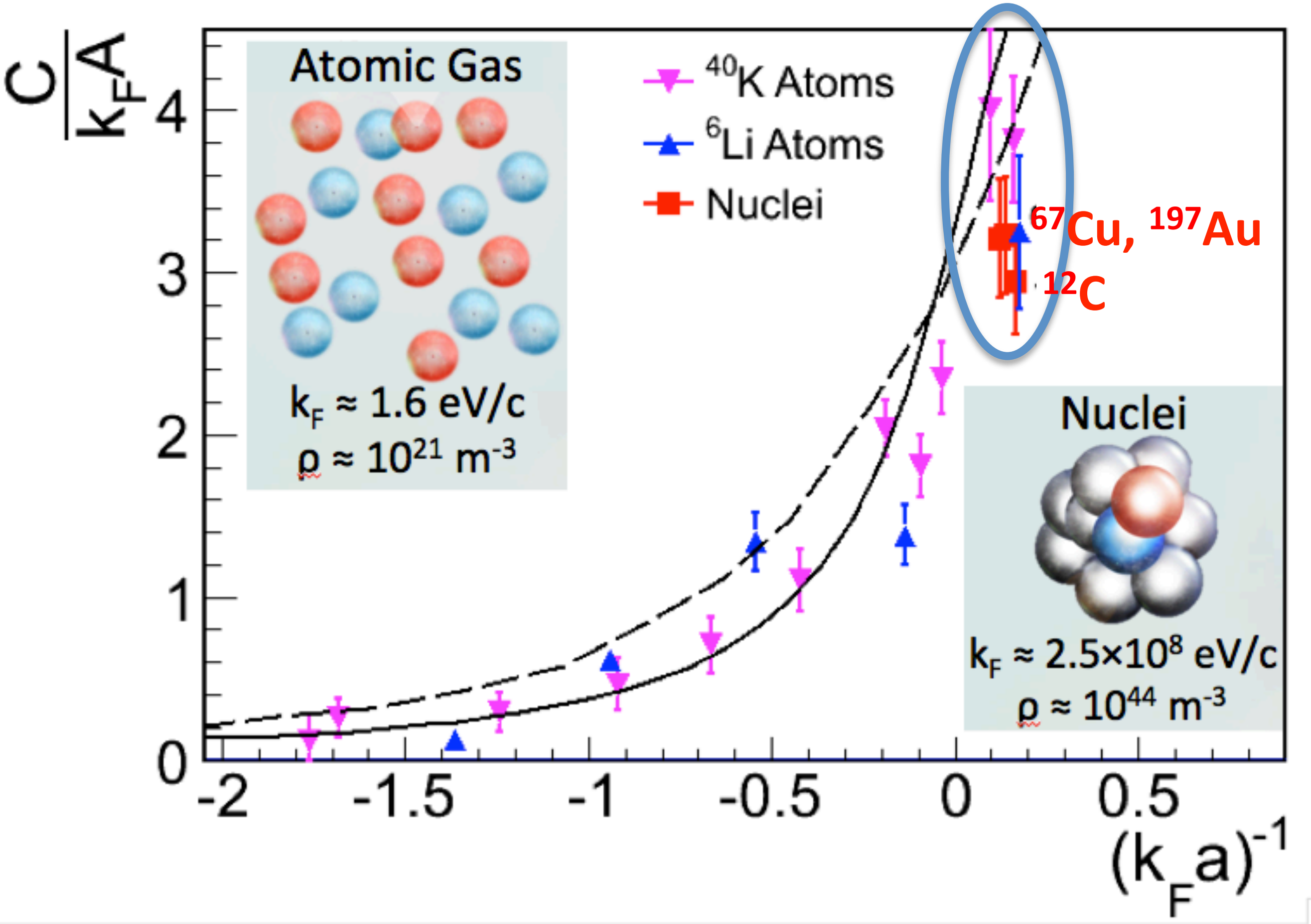
For Nuclei:

$k_F \approx 1.27$ fm$^{-1}$
$a \approx 5.4$ fm
**=> $(k_F a)^{-1} \approx 0.15$**

Stewart et al. Phys. Rev. Lett. **104**, 235301 (2010)
Kuhnle et al. Phys. Rev. Lett. **105**, 070402 (2010)

# Comparing with atomic systems

**Equal contacts** for equal interactions strength!



## For Nuclei:

$k_F \approx 1.27$ fm$^{-1}$

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|---|---|
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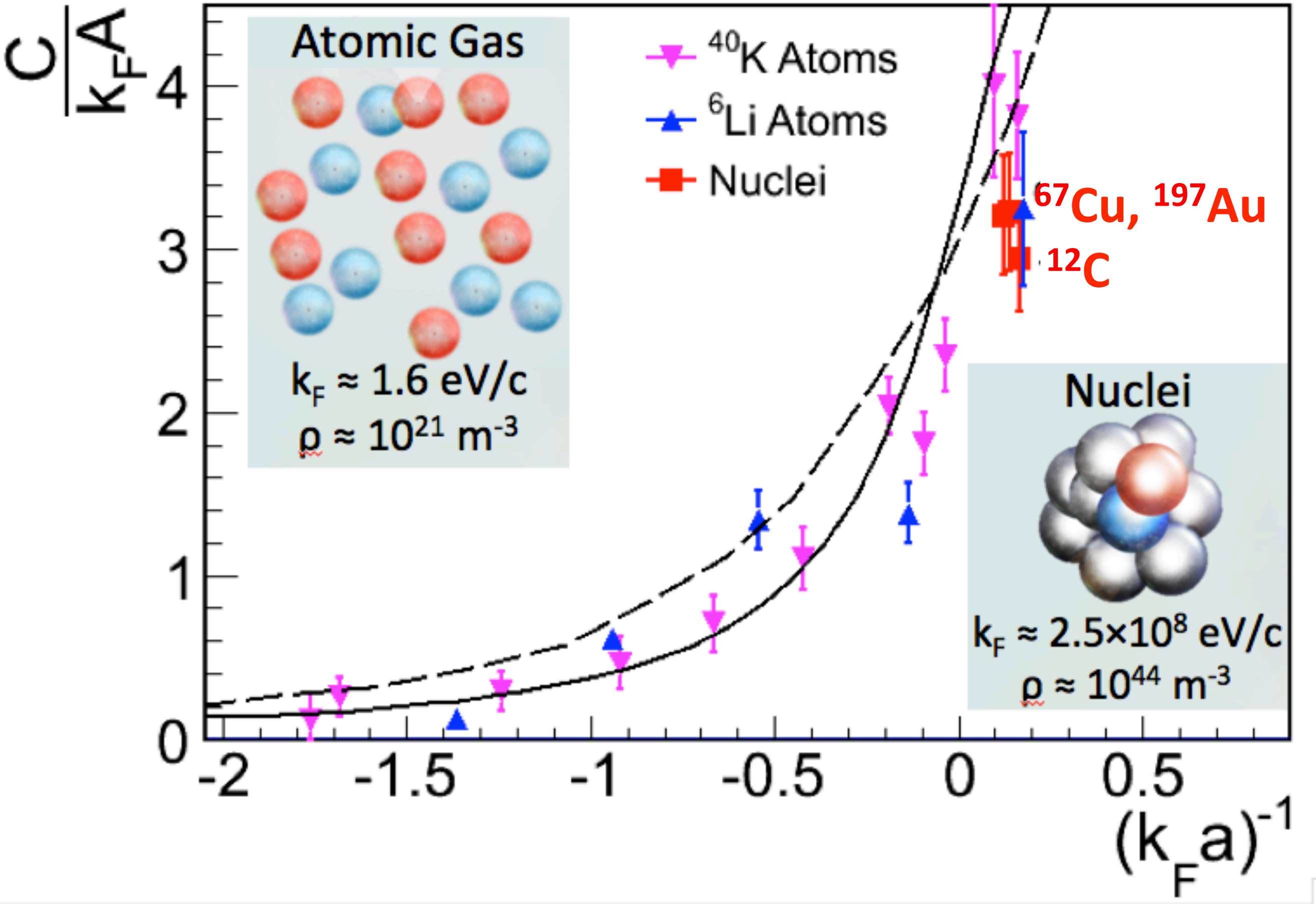
$$\frac{C}{k_F \cdot A} = a_2(A) \cdot R_d$$

O. Hen et al. Phys. Rev. C **92**, 045205 (2015)
Stewart et al. Phys. Rev. Lett. **104**, 235301 (2010)
Kuhnle et al. Phys. Rev. Lett. **105**, 070402 (2010)

# Comparing with atomic systems



At unitary (i.e. $(k_F a)^{-1} \approx 0$) the SRC probability is ~20% for both systems

O. Hen et al. Phys. Rev. C **92**, 045205 (2015)
Stewart et al. Phys. Rev. Lett. **104**, 235301 (2010)
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# Comparing with atomic systems

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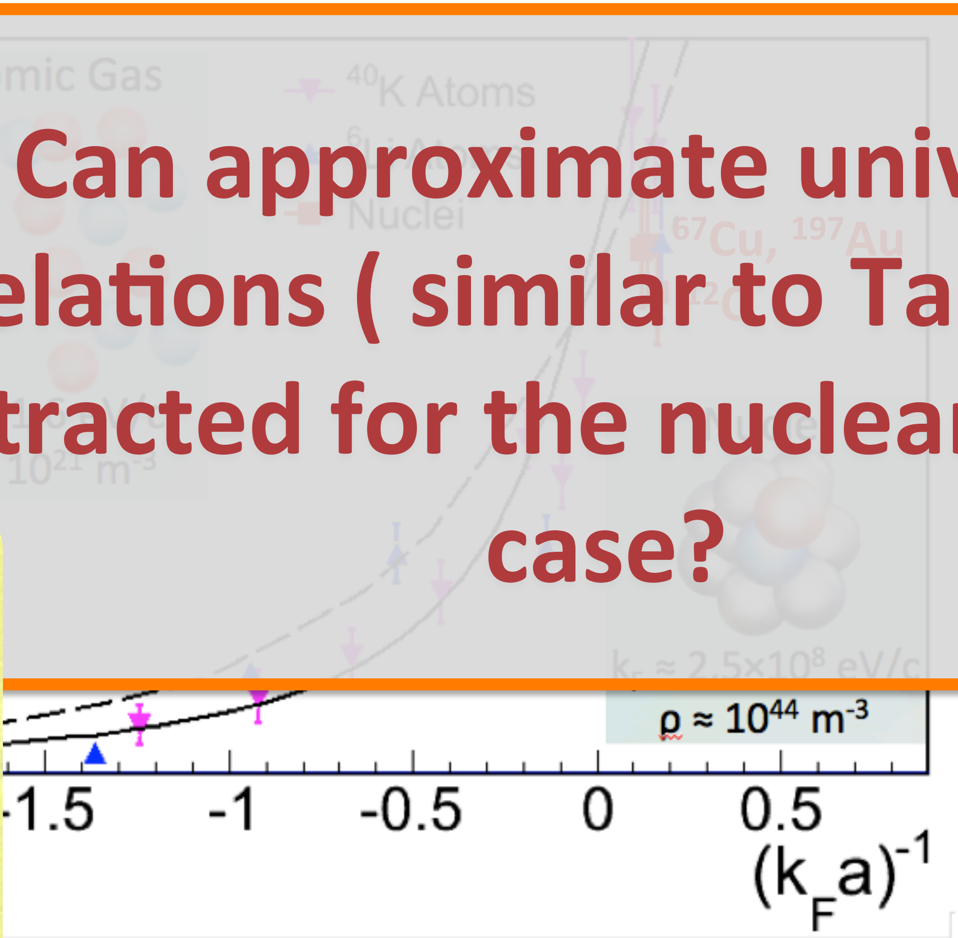
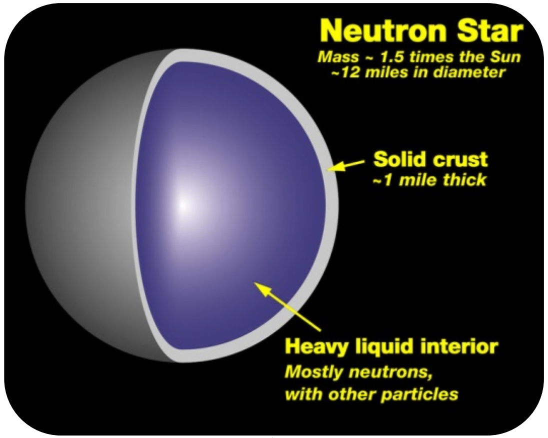


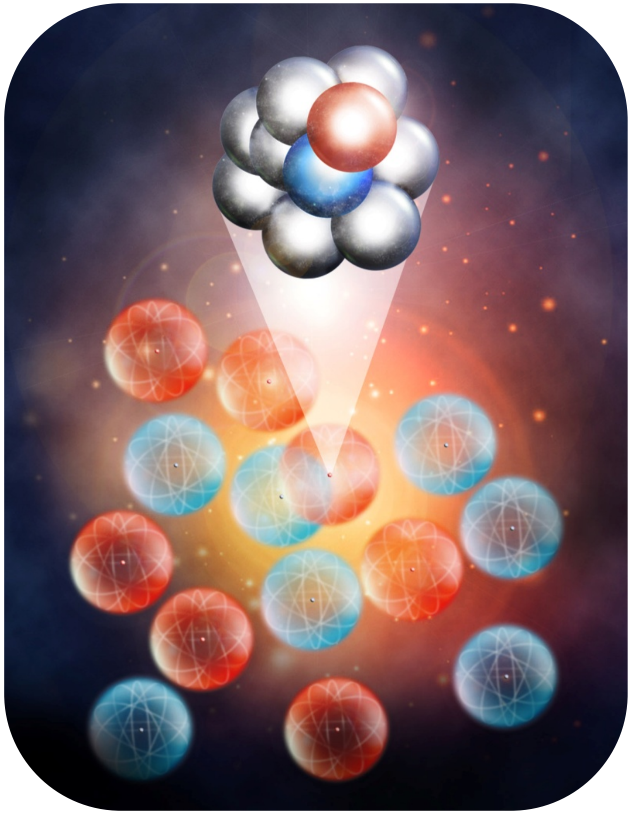
**Can approximate universal relations ( similar to Tan's ) be extracted for the nuclear physics case?**

Rev. C **92**, 045205 (2015)
Rev. Lett. **104**, 235301 (2010)
Rev. Lett. **105**, 070402 (2010)



$$(2-3)\cdot\rho_0$$

?



$$\rho_0$$

$$10^{-25}\cdot\rho_0$$

# Nuclear Symmetry Energy

# Nuclear Symmetry Energy

Energy of *asymmetric* nuclear matter:

$$E(\rho_n , \rho_p) = E_0(\rho_n = \rho_p) \quad E_{sym}(\rho)\left(\frac{\rho_n - \rho_p}{\rho}\right)^2 + O(\delta^4)$$

symmetry energy

Isospin asymmetry (δ)

Energy of *symmetric*
nuclear matter

# Nuclear Symmetry Energy

Energy of *asymmetric* nuclear matter:

$$E(\rho_n , \rho_p) \; = \; E_0 (\rho_n = \rho_p) \quad E_{sym}(\rho)\left(\frac{\rho_n - \rho_p}{\rho}\right)^2 + O(\delta^4)$$

*symmetry energy*

$$E_{sym}(\rho) \approx E(\rho)_{\mathrm{PNM}} - E(\rho)_{\mathrm{SNM}}$$

Relates to the energy change when replacing n with p

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↑

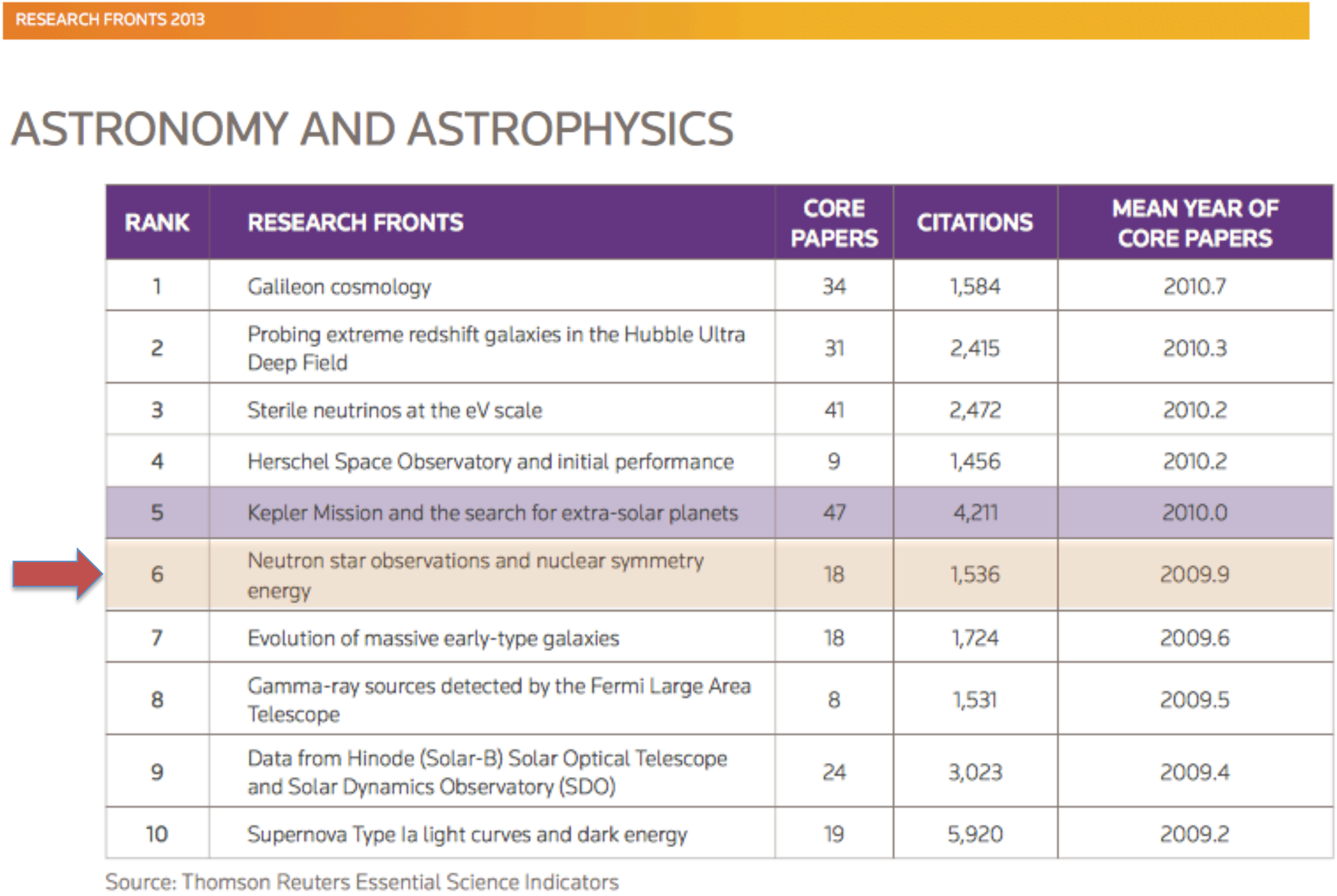
*symmetry energy*

$$E_{sym}(\rho) \approx E(\rho)_{\mathrm{PNM}} - E(\rho)_{\mathrm{SNM}}$$

Relates to the energy change when replacing n with p

- equation-of-state of neutron stars
- heavy-ion collisions
- r-process nucleosynthesis
- core-collapse supernovae
- more…

# Thomson Research Fronts 2013



RESEARCH FRONTS 2013

## ASTRONOMY AND ASTROPHYSICS

| RANK | RESEARCH FRONTS | CORE PAPERS | CITATIONS | MEAN YEAR OF CORE PAPERS |
|---|---|---|---|---|
| 1 | Galileon cosmology | 34 | 1,584 | 2010.7 |
| 2 | Probing extreme redshift galaxies in the Hubble Ultra Deep Field | 31 | 2,415 | 2010.3 |
| 3 | Sterile neutrinos at the eV scale | 41 | 2,472 | 2010.2 |
| 4 | Herschel Space Observatory and initial performance | 9 | 1,456 | 2010.2 |
| 5 | Kepler Mission and the search for extra-solar planets | 47 | 4,211 | 2010.0 |
| 6 | Neutron star observations and nuclear symmetry energy | 18 | 1,536 | 2009.9 |
| 7 | Evolution of massive early-type galaxies | 18 | 1,724 | 2009.6 |
| 8 | Gamma-ray sources detected by the Fermi Large Area Telescope | 8 | 1,531 | 2009.5 |
| 9 | Data from Hinode (Solar-B) Solar Optical Telescope and Solar Dynamics Observatory (SDO) | 24 | 3,023 | 2009.4 |
| 10 | Supernova Type Ia light curves and dark energy | 19 | 5,920 | 2009.2 |

Source: Thomson Reuters Essential Science Indicators

# Nuclear Symmetry Energy

Energy of *asymmetric* nuclear matter:

$$E(\rho_n , \rho_p) = E_0(\rho_n = \rho_p) \quad E_{sym}(\rho)\left(\frac{\rho_n - \rho_p}{\rho}\right)^2 + O(\delta^4)$$

symmetry energy

$$E_{sym}(\rho) \approx E(\rho)_{PNM} - E(\rho)_{SNM}$$

**np-SRC exist in SNM but not in PNM**

$$=> E_{sym}(\rho) = E_{PNM}(\rho) - E_{SNM}(\rho)$$

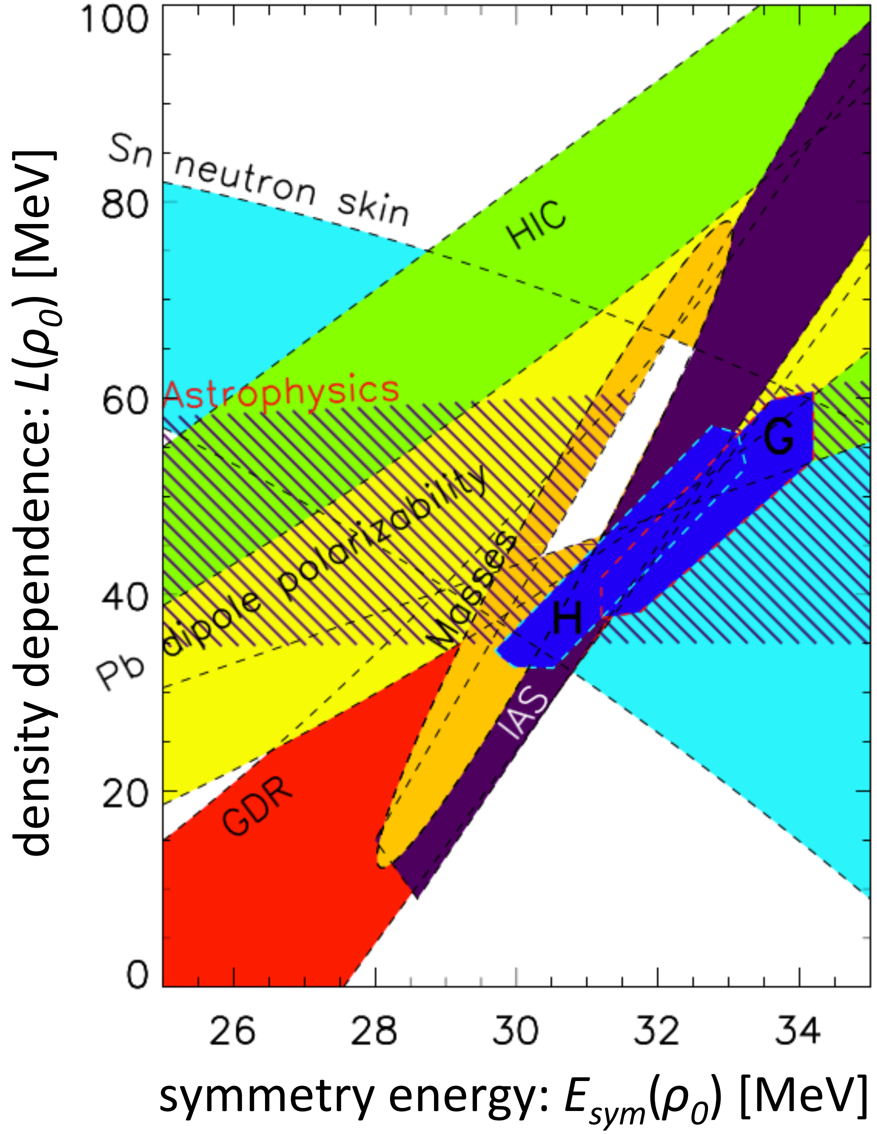
**Could change drastically**

[SNM: Symmetric Nuclear Matter, PNM: Pure Neutron Matter]

Relates to the energy change when replacing n with p

- equation of state of neutron stars
- heavy-ion collisions
- r-process nucleosynthesis
- core-collapse supernovae
- more…

# Symmetry Energy @ Saturation Density



Global analysis of world data:

$30.9 \leq E_{sym}(\rho_0) \leq 33.1$

$45 \leq L(\rho_0) \leq 67$

J. Lattimer and Y. Lim, Astrophys. J. 771, 51 (2013)
J. Lattimer and A. Steiner, Eur. Phys. J. A 50, 40 (2014)

${}^{*}L(\rho_0) = 3\rho[dE/d\rho]|_{\rho 0}$

# Constraining the Symmetry Energy

$$E_{sym}\left(\rho\right)=E_{sym}^{kin}\left(\rho_0\right)\cdot\left(\frac{\rho}{\rho_0}\right)^{\alpha}+E_{sym}^{pot}\left(\rho_0\right)\cdot\left(\frac{\rho}{\rho_0}\right)^{\gamma_i}$$

$E_{sym}(\rho)$ requires separate knowledge of the kinetic and potential parts.

**Fermi-Gas Model:** a common approximation for the kinetic term

M.B. Tsang et al., Phys. Rev. Lett **102**, 122701 (2009)
A.W. Steiner, J.M. Lattimer, and E.F. Brown, Astrophys. J. **722**, 33 (2010).

# Constraining the Symmetry Energy

## [Fermi-Gas Picture]

$$E_{sym}(\rho) = \underbrace{E_{sym}^{kin}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\alpha}}_{\Big\downarrow\ \underline{\text{Fermi-Gas Model}}} + E_{sym}^{pot}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\gamma_i}$$

$$E_{sym}^{kin}(\rho) = \frac{1}{3}E_F(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{2/3}$$

# Constraining the Symmetry Energy

## [Fermi-Gas Picture]

$$E_{sym}(\rho)=\underbrace{E_{sym}^{kin\,\checkmark}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\alpha\,\checkmark}}_{\Big\Downarrow}+E_{sym}^{pot}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\gamma_i}$$

**Fermi-Gas Model**

$$E_{sym}^{kin}(\rho)=\frac{1}{3}E_F(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{2/3}$$

☑ $\alpha = {}^{2}\!/_{3}$

☑ $E_{sym}^{kin}(\rho_0)=12.5\ \text{MeV}$

# Constraining the Symmetry Energy

## [Fermi-Gas Picture]

$$E_{sym}(\rho) = \underbrace{E_{sym}^{kin\,\checkmark}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\alpha\,\checkmark}}_{\Big\Downarrow\ \underline{\text{Fermi-Gas Model}}} + E_{sym}^{pot\,\checkmark}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\gamma_i}$$

$$E_{sym}^{kin}(\rho) = \frac{1}{3}E_F(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{2/3}$$

- ☑ $\alpha = {}^{2}\!/_{3}$
- ☑ $E_{sym}^{kin}(\rho_0) = 12.5\ \text{MeV}$
- ☑ $E_{sym}^{pot}(\rho_0) = E_{sym}(\rho_0) - E_{sym}^{kin}(\rho_0) \approx 18.5\ \text{MeV}$

# Constraining the Symmetry Energy

## [Fermi-Gas Picture]

$$E_{sym}(\rho) = \underbrace{\overset{\checkmark}{E^{kin}_{sym}}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\alpha\checkmark}} + \overset{\checkmark}{E^{pot}_{sym}}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\gamma_i}$$

**Fermi-Gas Model**

$$E^{kin}_{sym}(\rho) = \frac{1}{3}E_F(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{2/3}$$

☑ $\alpha = {}^{2}\!/_{3}$

☑ $E^{kin}_{sym}(\rho_0) = 12.5\ \mathrm{MeV}$

☑ $E^{pot}_{sym}(\rho_0) = E_{sym}(\rho_0) - E^{kin}_{sym}(\rho_0) \approx 18.5\ \mathrm{MeV}$

**Only unknown is $\gamma_i$**

probed in HI collision measurements and neutron stars observations

# Constraining the Symmetry Energy

## [With SRCs]

$$E_{sym}(\rho)=\underbrace{E_{sym}^{kin\,\checkmark}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\alpha\,\checkmark}}+E_{sym}^{pot\,\checkmark}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\boxed{\gamma_i}}$$

Fermi-Gas Model + Correlations

$$E_{sym}^{kin}(\rho)=\frac{1}{3}E_F(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{2/3}+\Delta_{SRC}(\rho)$$

**Only unknown is $\gamma_i$**

probed in HI collision measurements and neutron stars observations

☑ $\alpha = {}^{2}\!/_{3}$

☑ $E_{sym}^{kin}(\rho_0)=12.5\ \mathrm{MeV}$

☑ $E_{sym}^{pot}(\rho_0)=E_{sym}(\rho_0)-E_{sym}^{kin}(\rho_0)\approx 18.5\ \mathrm{MeV}$

# Constraining the Symmetry Energy

## [With SRCs]

$$E_{sym}(\rho) = \underbrace{E_{sym}^{kin\,\times}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\alpha\,\checkmark}}_{\text{Fermi-Gas Model}} + E_{sym}^{pot\,\checkmark}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\boxed{\gamma_i}}$$

**Fermi-Gas Model** + Correlations

$$E_{sym}^{kin}(\rho) = \frac{1}{3}E_F(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{2/3} + \Delta_{SRC}(\rho)$$

☑ $\alpha = 2/3$

☑ $E_{sym}^{kin}(\rho_0) = \cancel{12.5}\ \text{MeV}$

☑ $E_{sym}^{pot}(\rho_0) = E_{sym}(\rho_0) - E_{sym}^{kin}(\rho_0) \approx 18.5\ \text{MeV}$

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# Constraining the Symmetry Energy

## [With SRCs]

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**+ Correlations**

$$E_{sym}^{kin}(\rho) = \frac{1}{3}E_F(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{2/3} + \Delta_{SRC}(\rho)$$

☑ $\alpha = \cancel{2/3}$

☑ $E_{sym}^{kin}(\rho_0) = \cancel{12.5}\ \text{MeV}$

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# Constraining the Symmetry Energy

## [With SRCs]

$$E_{sym}(\rho) = \underbrace{E^{kin\,\text{✗}}_{sym}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\alpha\,\text{✗}}}_{\text{Fermi-Gas Model}} + E^{pot\,\text{✗}}_{sym}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\bigcirc\!\!\!\gamma_i}$$

<u>Fermi-Gas Model</u> **+ Correlations**

$$E^{kin}_{sym}(\rho) = \frac{1}{3}E_F(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{2/3} + \Delta_{SRC}(\rho)$$

- ☑ $\alpha = \xcancel{2/3}$
- ☑ $E^{kin}_{sym}(\rho_0) = \xcancel{12.5}\ \text{MeV}$
- ☑ $E^{pot}_{sym}(\rho_0) = E_{sym}(\rho_0) - E^{kin}_{sym}(\rho_0) \approx \xcancel{18.5}\ \text{MeV}$

**<u>Only unknown is $\gamma_i$</u>**

probed in HI collision measurements and neutron stars observations

# Constraining the Symmetry Energy

## [With SRCs]

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**+ Correlations**

$$E_{sym}^{kin}(\rho) = \frac{1}{3}E_F(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{2/3} + \Delta_{SRC}(\rho)$$

~~**Only unknown is $\gamma_i$** probed in HI collision measurements and neutron stars observations~~

☑ $\alpha = \cancel{2/3}$

☑ $E_{sym}^{kin}(\rho_0) = \cancel{12.5}\ \text{MeV}$

☑ $E_{sym}^{pot}(\rho_0) = E_{sym}(\rho_0) - E_{sym}^{kin}(\rho_0) \approx \cancel{18.5}\ \text{MeV}$

# Constraining the Symmetry Energy

## [With SRCs]

**Adding np-SRCs breaks the Fermi-Gas picture**

**=> Need a correlated Fermi-Gas Model**

$$E_{sym}(\rho) = \underbrace{E_{sym}^{kin}(\rho_0)\left(\frac{\rho}{\rho_0}\right)^{\alpha}}_{\text{Fermi-Gas Model}} + E_{sym}^{pot}(\rho_0)\left(\frac{\rho}{\rho_0}\right)^{\gamma_i}$$

Fermi-Gas Model + Correlations

$$E_{sym}^{kin}(\rho) = \frac{1}{3}E_F(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{2/3} + \Delta_{SRC}(\rho)$$

~~Only unknown is $\gamma_i$ probed in HI collision measurements and neutron stars observations~~

☑ $\alpha = \cancel{2/3}$

☑ $E_{sym}^{kin}(\rho_0) = \cancel{12.5}\ \mathrm{MeV}$

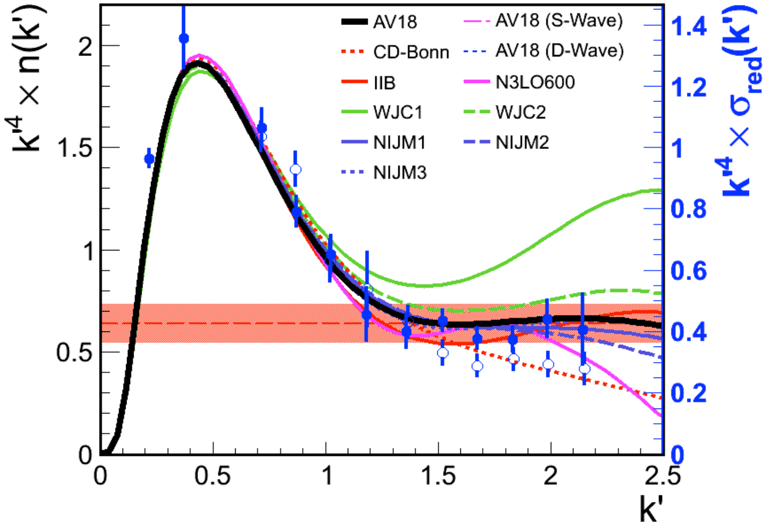
☑ $E_{sym}^{pot}(\rho_0) = E_{sym}(\rho_0) - E_{sym}^{kin}(\rho_0) \approx \cancel{18.5}\ \mathrm{MeV}$

# Correlated Fermi-Gas Model (CFG)

## [Fermi-Gas with an SRC tail]

$$
\begin{array}{cccccc}
 & & \text{SNM} & & \text{PNM} & \\
n_{CFG}(k) & = & \left\{ \begin{array}{c} A_0 \\ C_\infty / k^4 \\ 0 \end{array} \right. & \begin{array}{c} , \\ , \\ , \end{array} & \begin{array}{c} A_1 \\ 0 \\ 0 \end{array} & \begin{array}{c} k < k_F \\ k_F < k < \lambda k_F^0 \\ 0k > \lambda k_F^0 \end{array}
\end{array}
$$

C/k$^4$ is a good parameterization of the high-momentum tail:



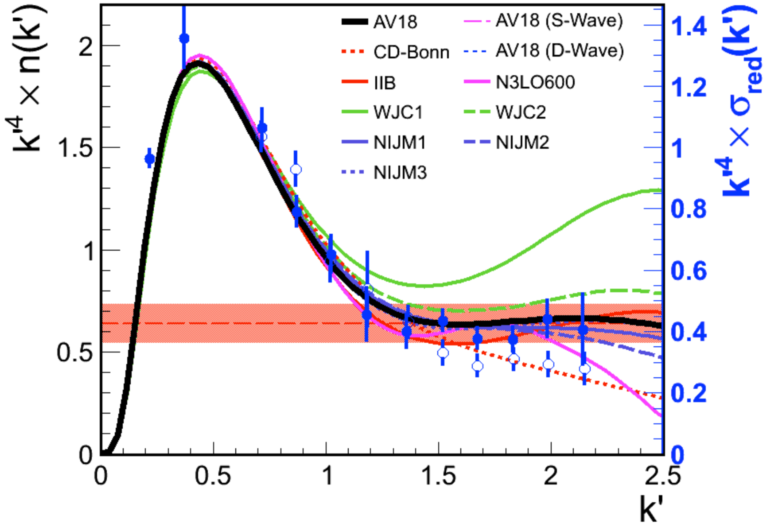
O. Hen et al., Phys. Rev. C 91, 025803 (2015).

# Correlated Fermi-Gas Model (CFG)

## [Fermi-Gas with an SRC tail]

$$n_{CFG}(k) = \left\{ \begin{array}{ccccc} \text{SNM} & & \text{PNM} & & \\ A_0 & , & A_1 & & k<k_F \\ C_\infty/k^4 & , & 0 & & k_F<k<\lambda k_F^0 \\ 0 & , & 0 & & 0k>\lambda k_F^0 \end{array} \right.$$

C/k$^4$ is a good parameterization of the high-momentum tail:



SNM Model:

- Depleted Fermi Distribution ($A_0$)
- High-Momentum tail (C/k$^4$)
- Momentum cutoff (λ)

O. Hen et al., Phys. Rev. C 91, 025803 (2015).

# Correlated Fermi-Gas Model (CFG)

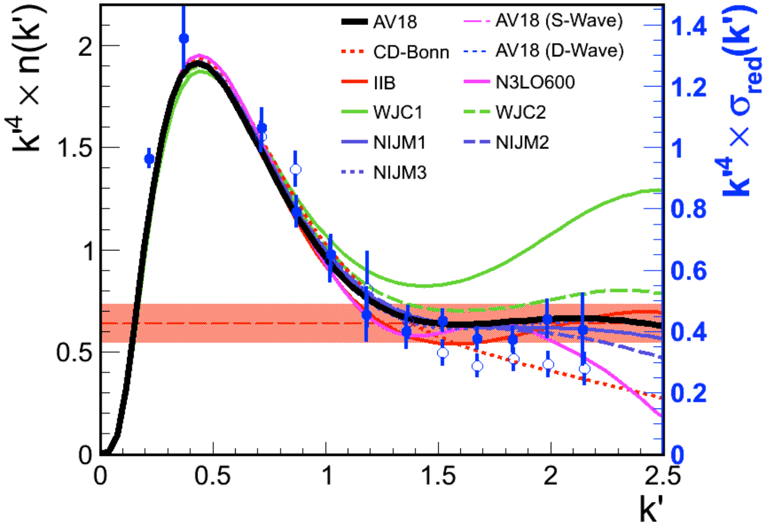
## [Fermi-Gas with an SRC tail]

$$n_{CFG}(k) = \left\{ \begin{array}{ccccc} \text{SNM} & & \boxed{\text{PNM}} & & \\ A_0 & , & A_1 & & k < k_F \\ C_\infty / k^4 & , & 0 & & k_F < k < \lambda k_F^0 \\ 0 & , & 0 & & 0k > \lambda k_F^0 \end{array} \right.$$

PNM Model:

- Free Fermi Gas

C/k⁴ is a good parameterization of the high-momentum tail:

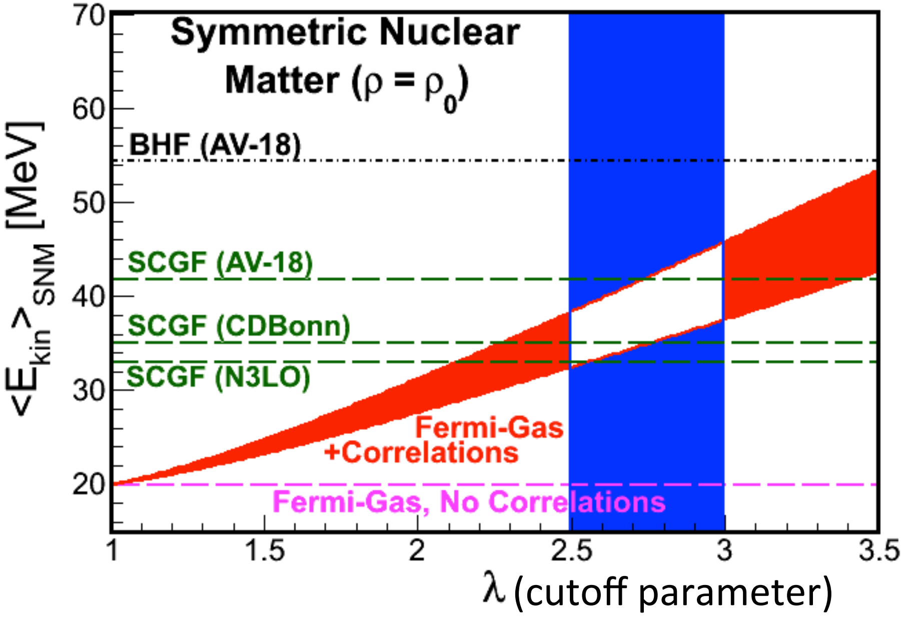


O. Hen et al., Phys. Rev. C 91, 025803 (2015).

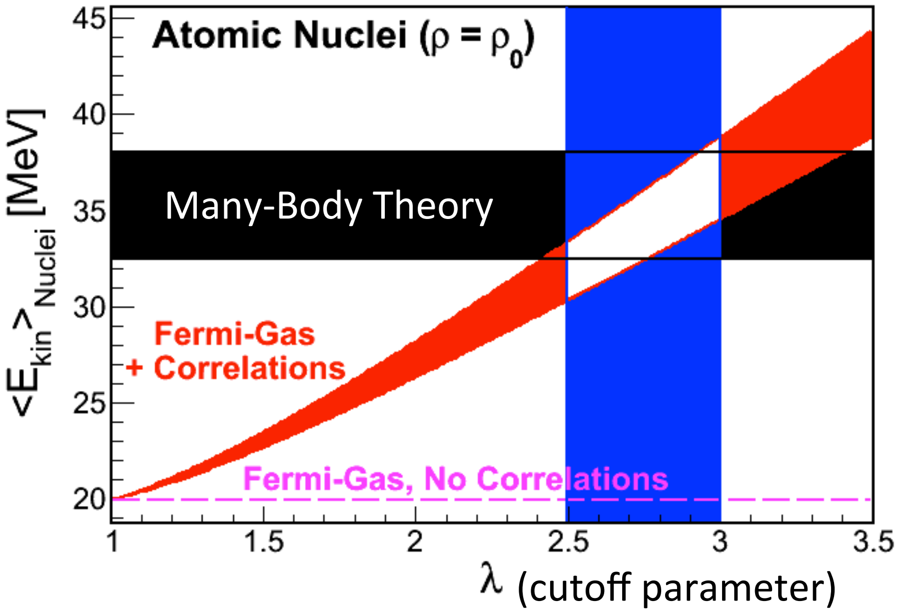
# Benchmark Against Microscopic Calculations

$$E_{kin} = \frac{4\pi}{(2\pi)^3}\int_0^\infty \frac{\hbar^2 k^2}{2m} n(k) k^2 dk.$$

Average kinetic energy – SNM



Average kinetic energy - Nuclei



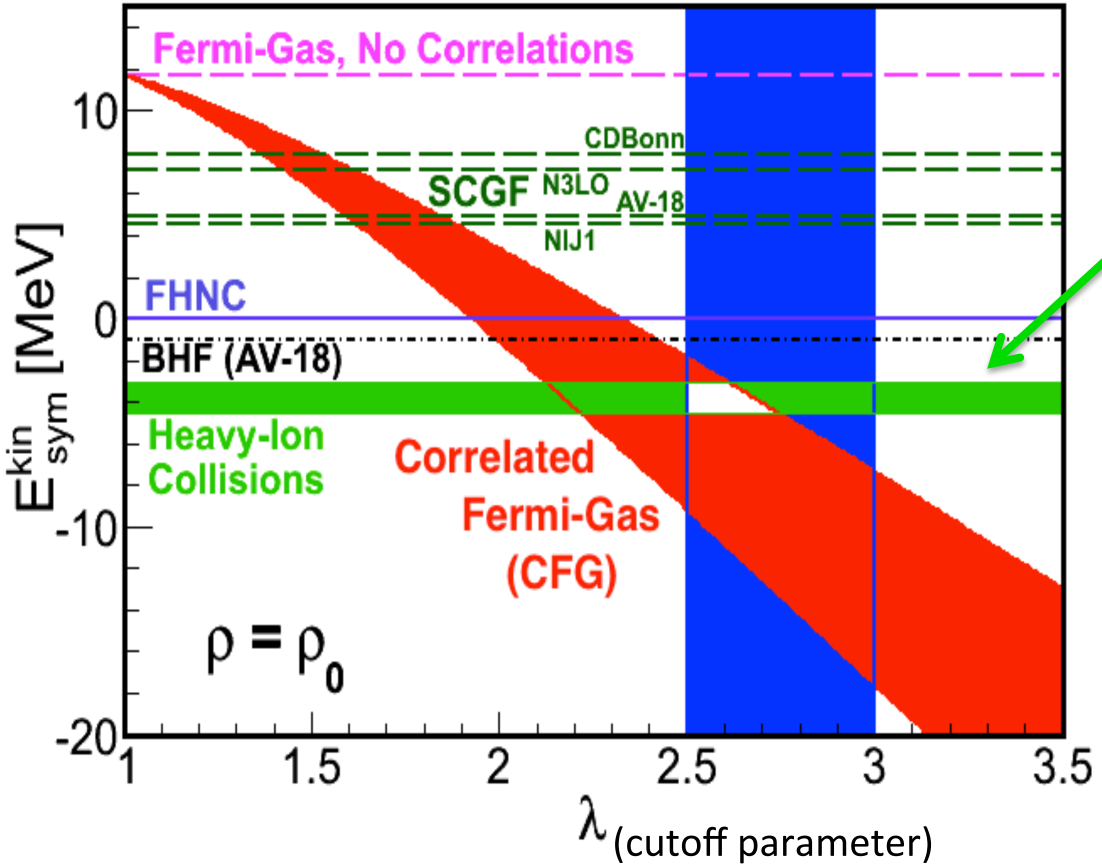
$a_2(A) = 5.0 \pm 0.3$

$a_2(\infty) = 7.0 \pm 1.0$

O. Hen et al., Phys. Rev. C 91, 025803 (2015).

# Extracting the Kinetic Symmetry Energy

Kinetic symmetry energy

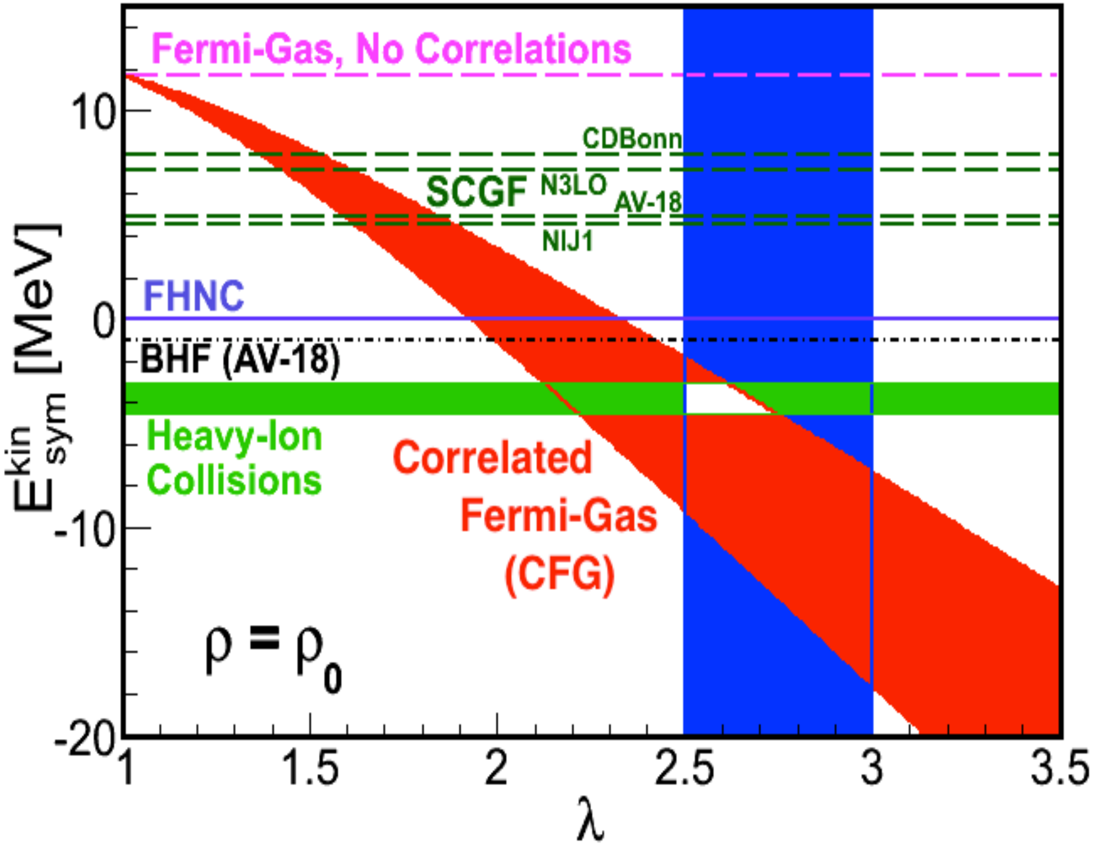


Transport calculation of $^{124}Sn+^{124}Sn$ and $^{112}Sn+^{112}Sn$ collisions also yield reduced kinetic symmetry energy

O. Hen et al., Phys. Rev. C 91, 025803 (2015).

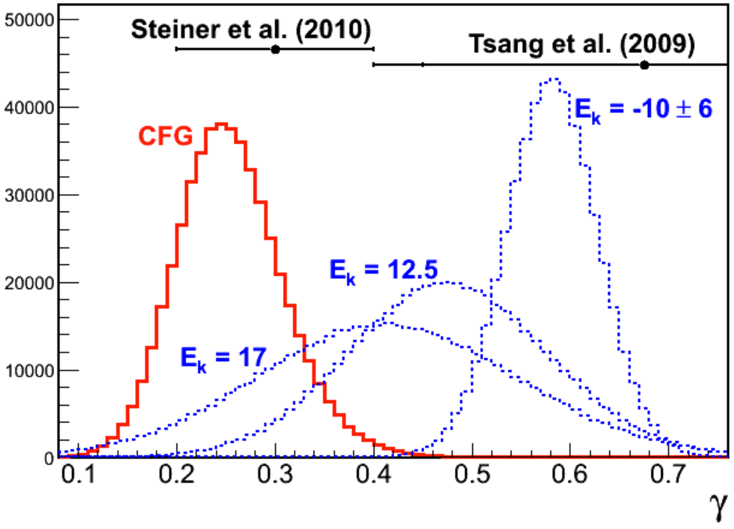
# Extracting the Kinetic Symmetry Energy

Kinetic symmetry energy



**SRCs reduce the kinetic symmetry energy**

**[Enhance the potential symmetry energy and alter its density dependence]**



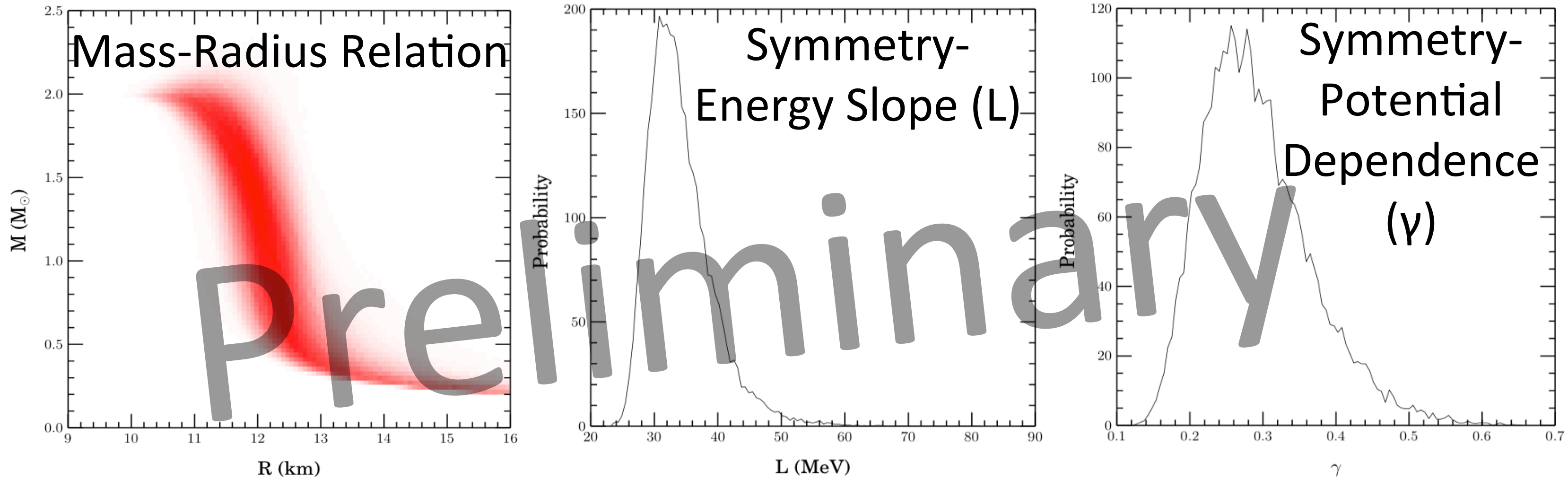
O. Hen et al., Phys. Rev. C 91, 025803 (2015).

## Next Step – Incorporating CFG model into:

- neutron stars equation-of-state fits
- Transport models for HI collision analysis

# Next (*ongoing*) Step – Incorporating CFG model into:

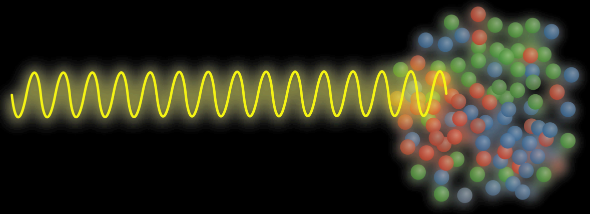
- **neutron stars equation-of-state fits**
- **Transport models for HI collision analysis**

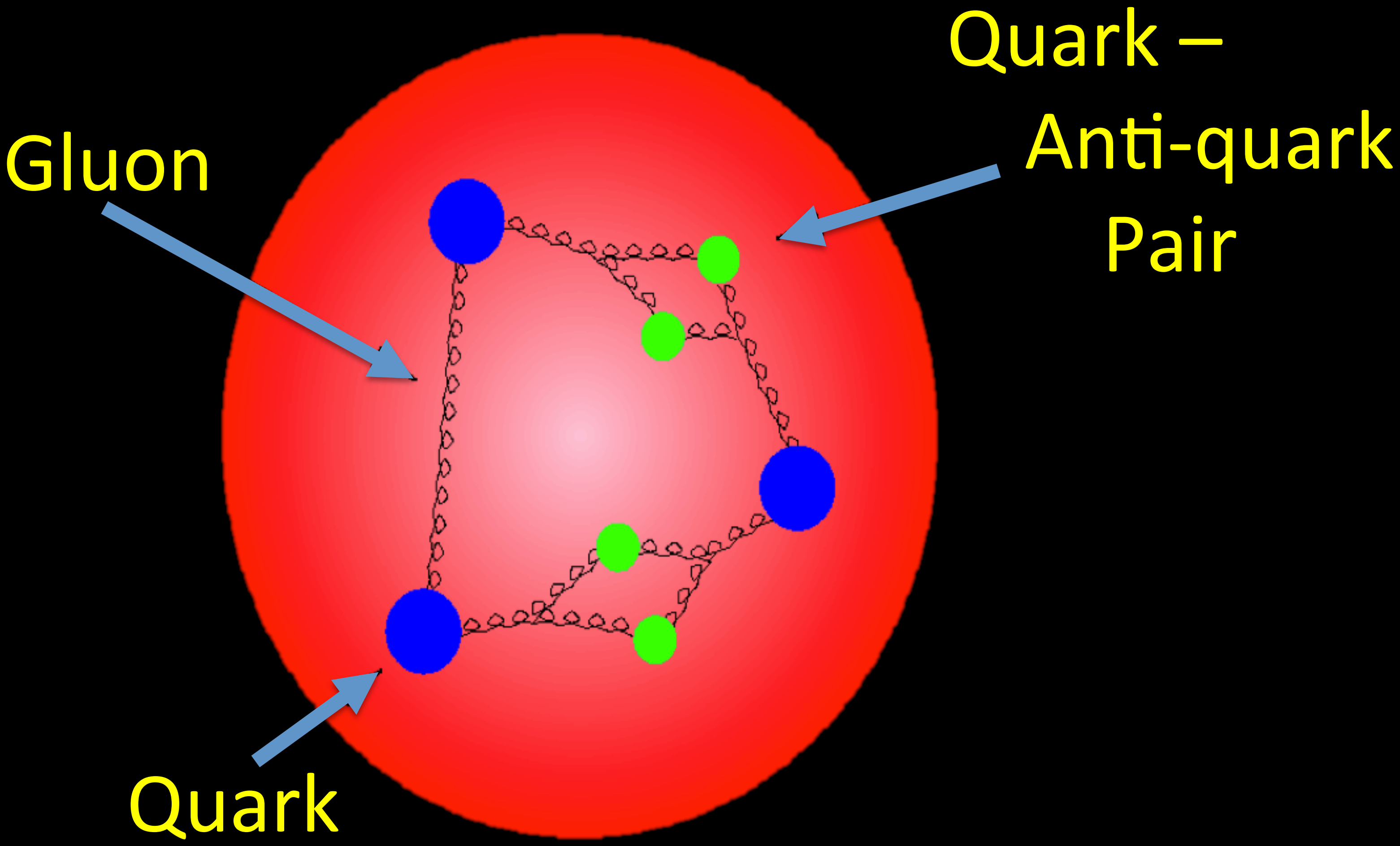


O. Hen, A.W. Steiner, and E. Piasetzky, In-Preparation (2015)

# Inelastic Structure of Nucleons

# Looking Inside the Proton



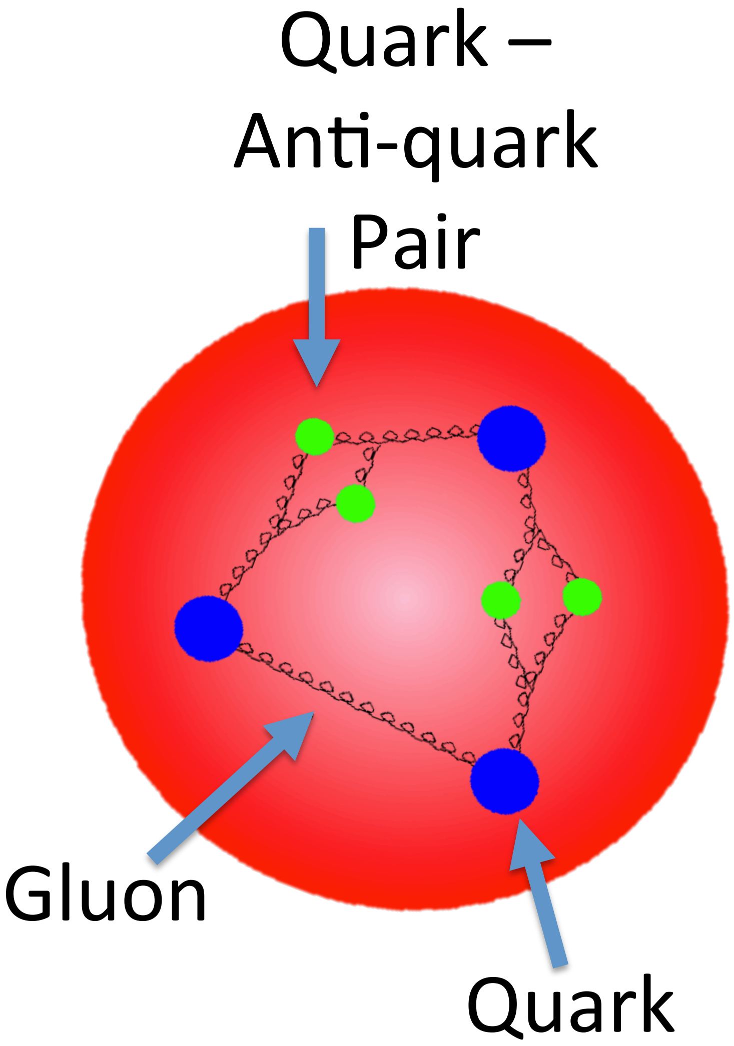


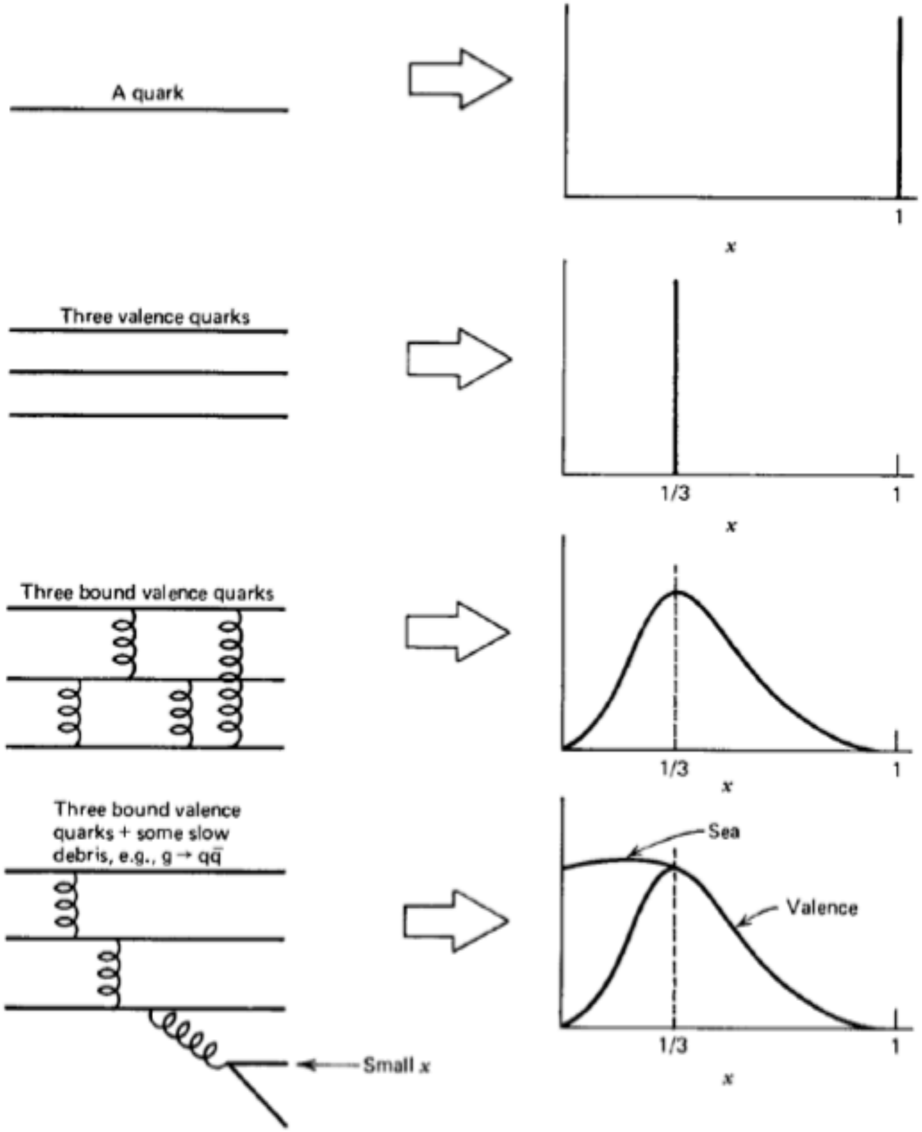
Gluon

Quark – Anti-quark Pair

Quark

# Deep-Inelastic Structure Functions

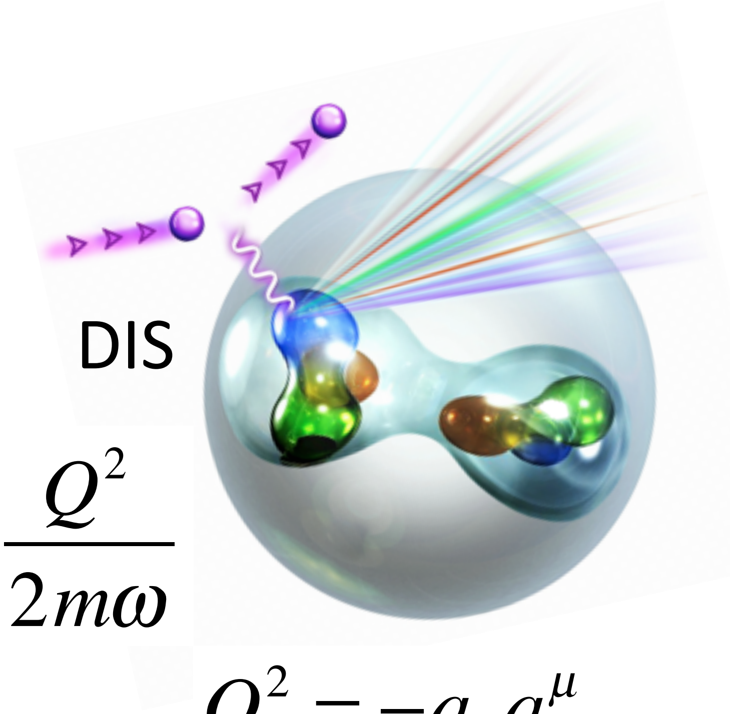




# Deep Inelastic Scattering

**DIS: Study of the partonic structure of the nucleon**

**DIS scale: several tens of GeV**



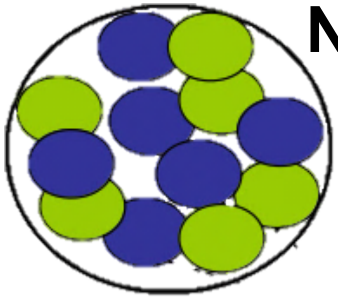
$$x_B = \frac{Q^2}{2m\omega}$$

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

$0<x_B<1$:
equals the fraction of nucleon momentum carried by the struck parton (in the infinite momentum frame).

# Deep Inelastic Scattering *Off-Nuclei*

**DIS scale: several tens of GeV**



**Nucleon in nuclei are bound by a few MeV**

**Naive expectation :**

DIS off a bound nucleon = DIS off a free nucleon

(Except some small Fermi momentum correction)

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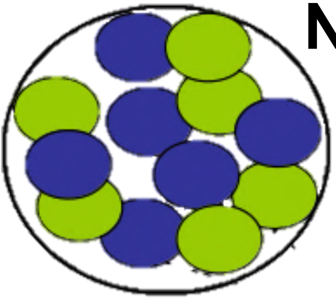

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**Average nucleons separation ~2 fm**

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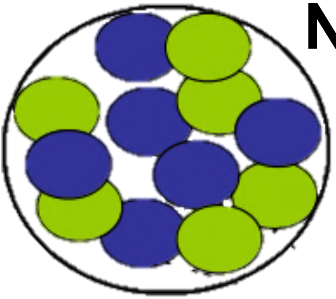

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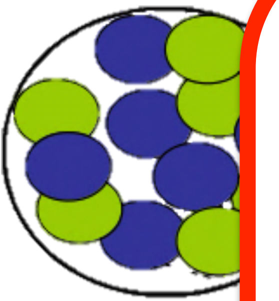
## General Naive Expectation :

**DIS off nucleons in *nuclei***
**= DIS off nucleons in *deuterium***

# Deep Inelastic Scattering *Off-Nuclei*

**DIS sc**

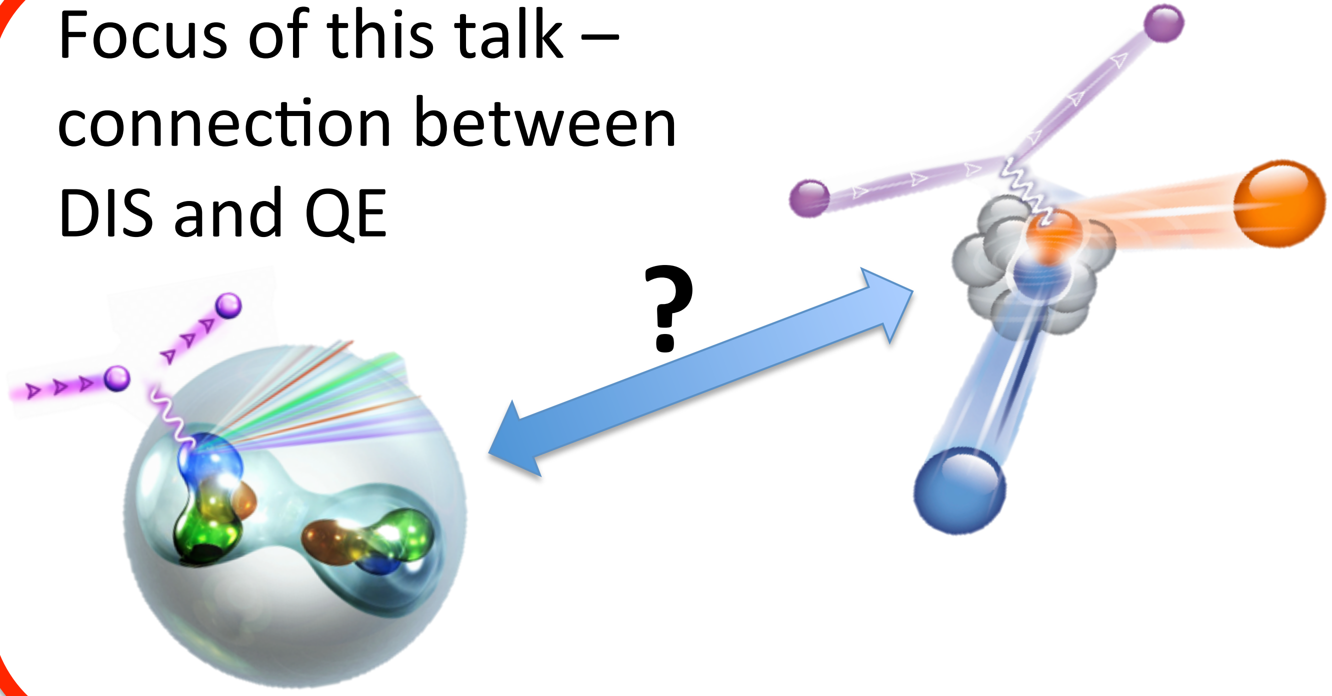


eon

**Deu**

eutron pair

Focus of this talk – connection between DIS and QE



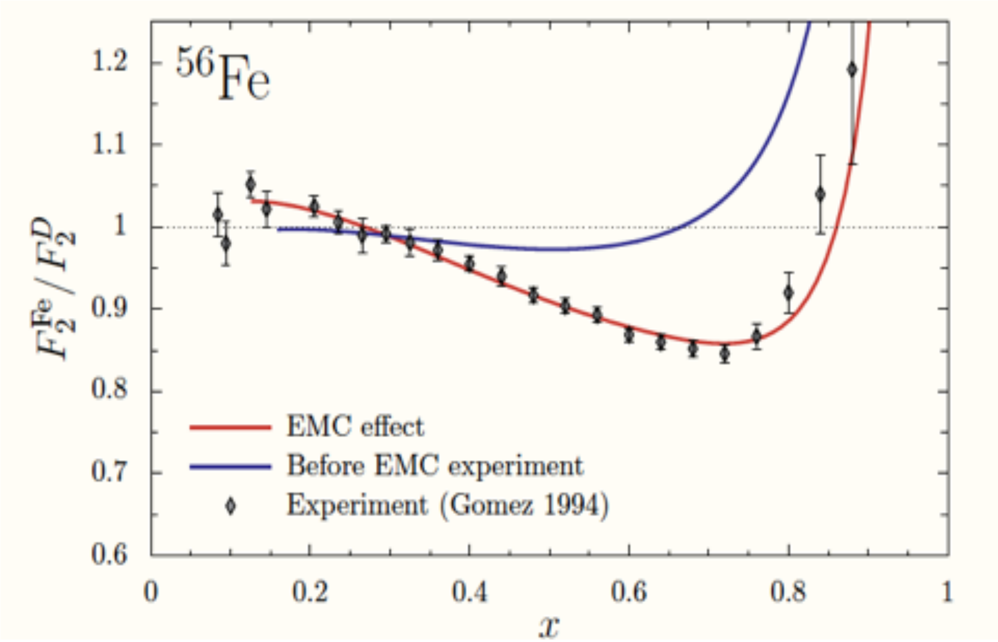
**General Naive Expectation :**

**DIS off nucleons in *nuclei***

**= DIS off nucleons in *deuterium***

# EMC Effect

- Deviation of the per-nucleon DIS cross section ratio of nuclei relative to deuterium from unity.
- Universal shape for 0.3<x<0.7 and 3<A<197.
- ~Independent of $Q^2$.
- Overall increasing as a function of A.
- No fully accepted theoretical explanation.



$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_A = \frac{4\alpha^2 E'^2}{Q^4}\left[2\frac{F_1}{M}\sin^2\left(\frac{\theta}{2}\right) + \frac{F_2}{\nu}\cos^2\left(\frac{\theta}{2}\right)\right]$$

$$F_2\left(x,Q^2\right) = \sum_i e_i^2 \cdot x \cdot f_i\left(x\right)$$

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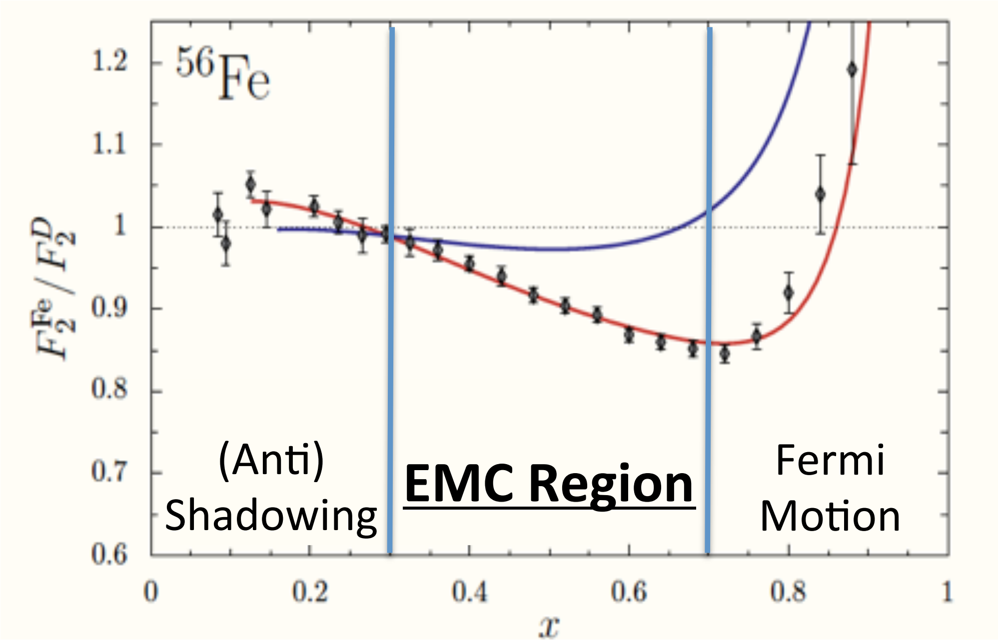

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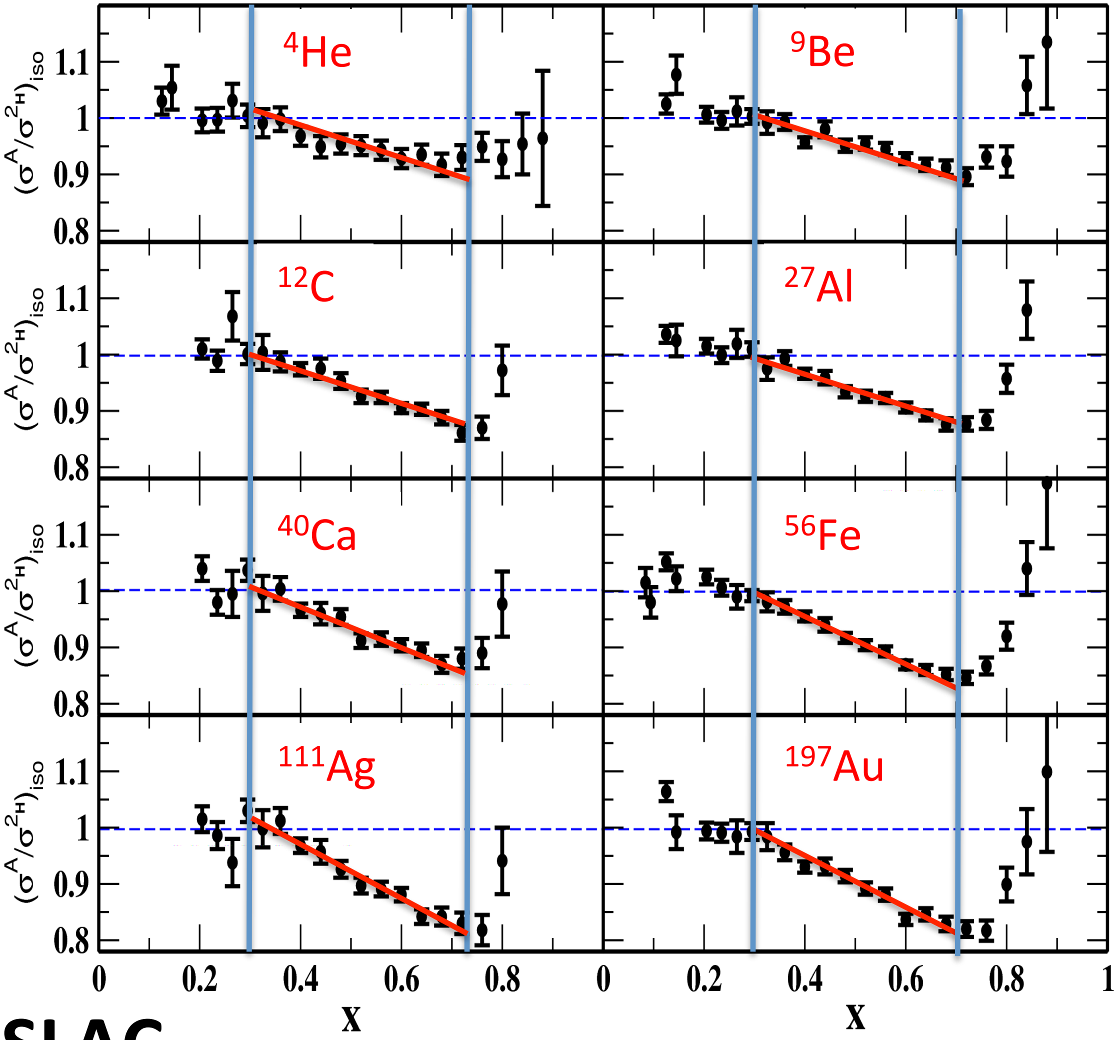
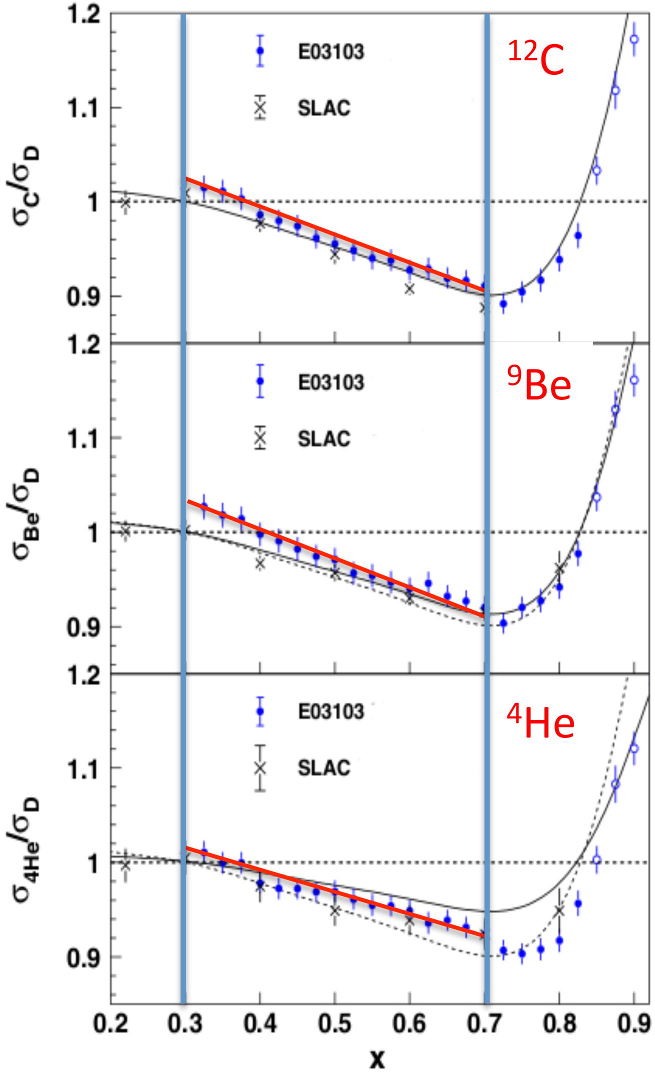
# Universality of the EMC Effect



**SLAC**

J. Gomez et al., Phys. Rev. D **49**, 4348 (1994).

**JLab**



J. Seely et al., Phys. Rev. Lett. **103**, 202301 (2009).

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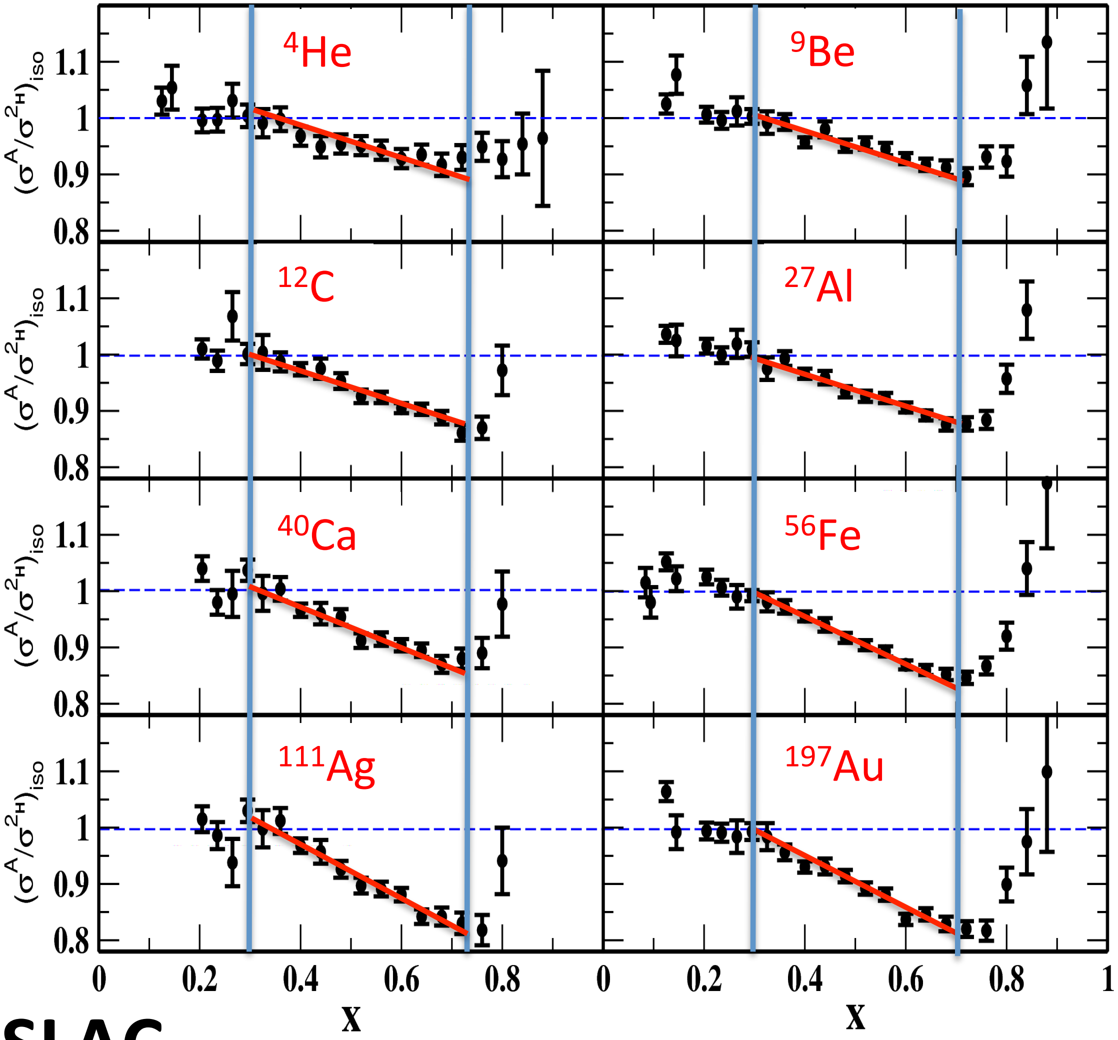

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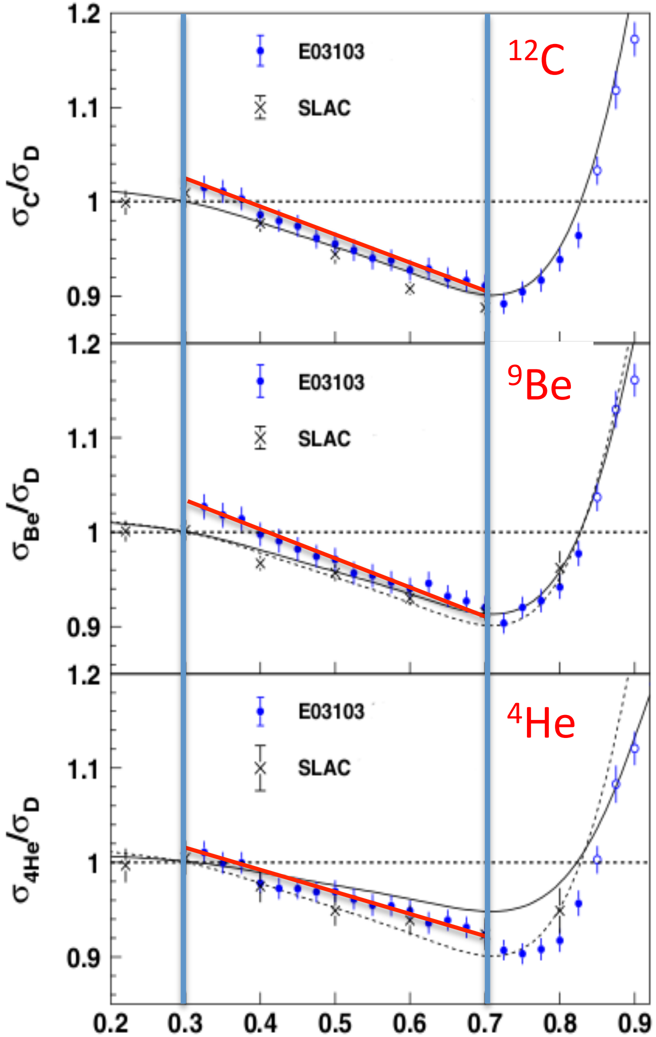
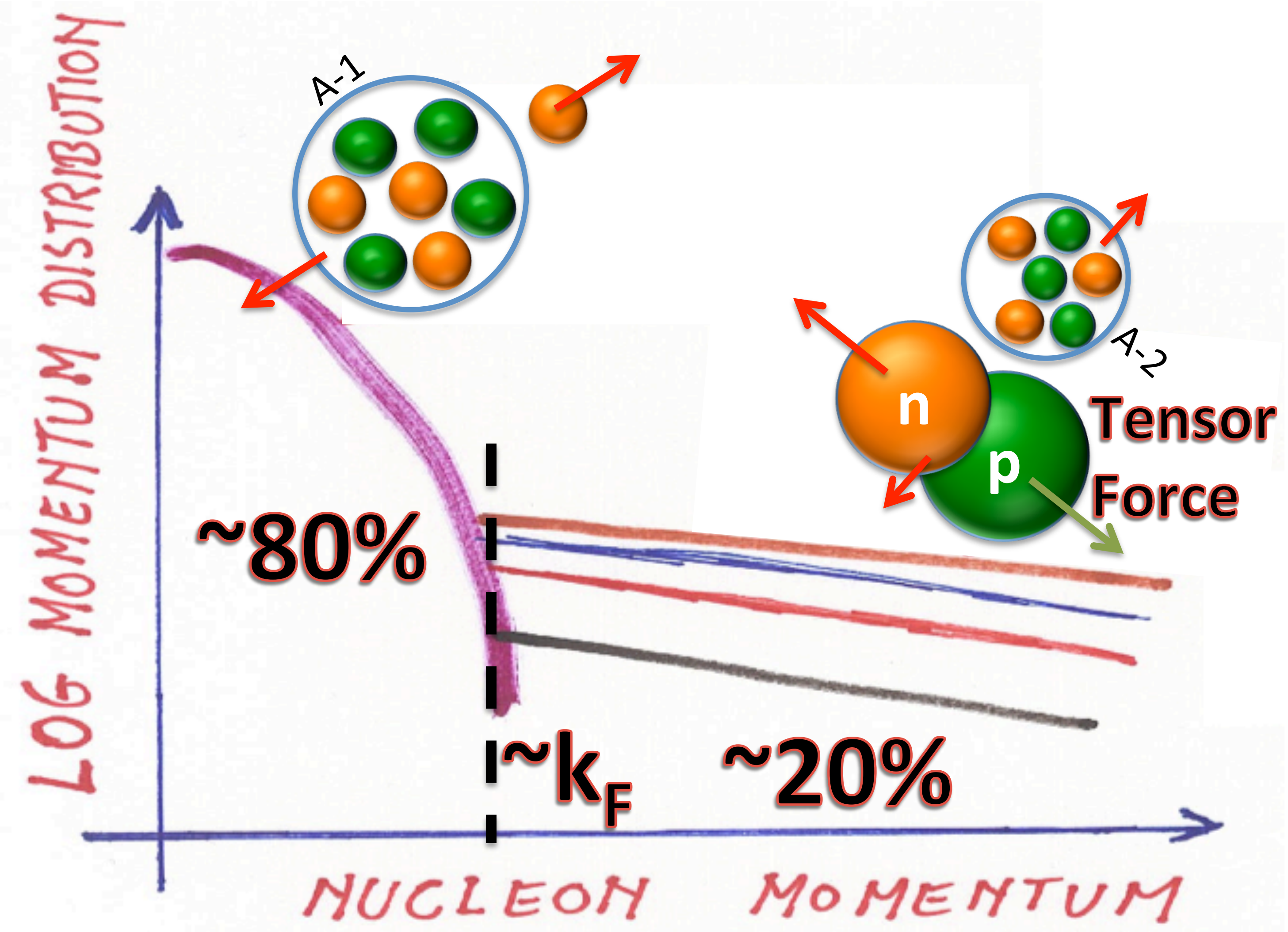
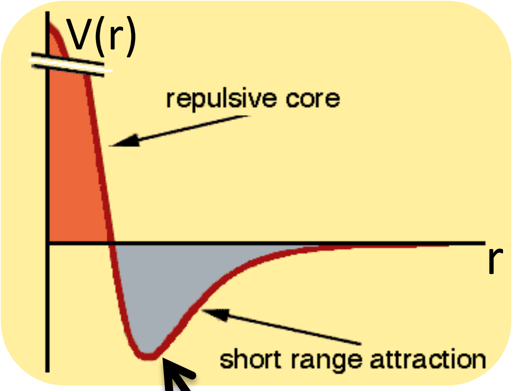


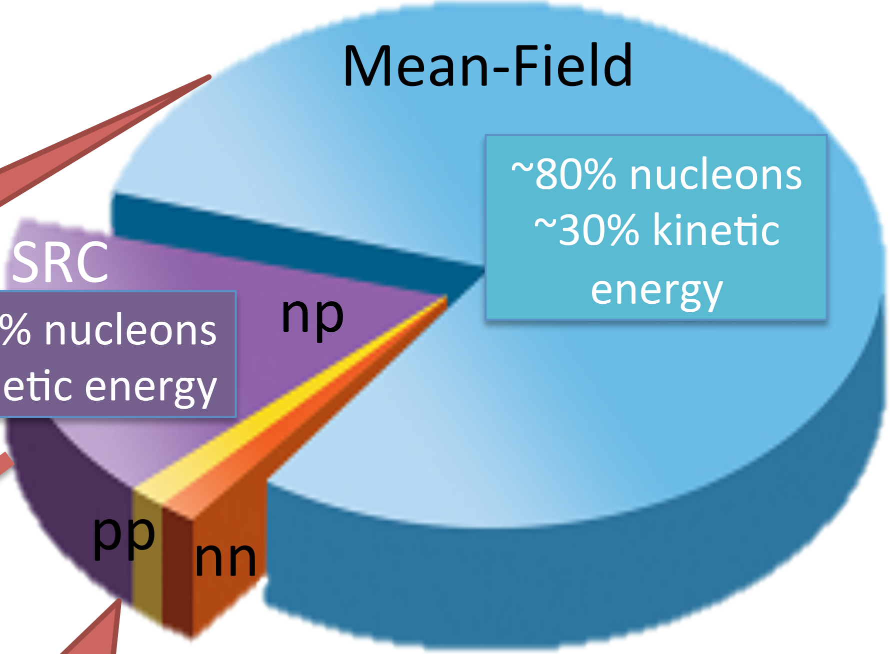
## + In-Medium Form-Factor Measurements Program

# Nuclear Structure



# Where is the EMC Effect?





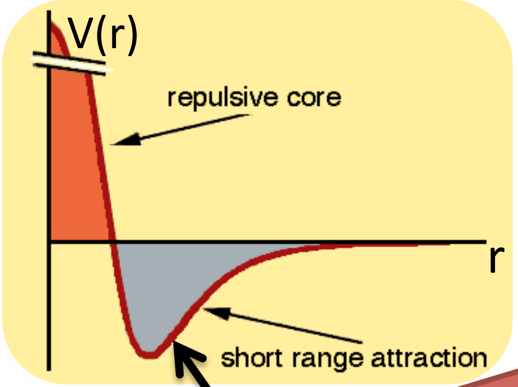
~80% nucleons
~30% kinetic energy

~20% nucleons
~70% kinetic energy

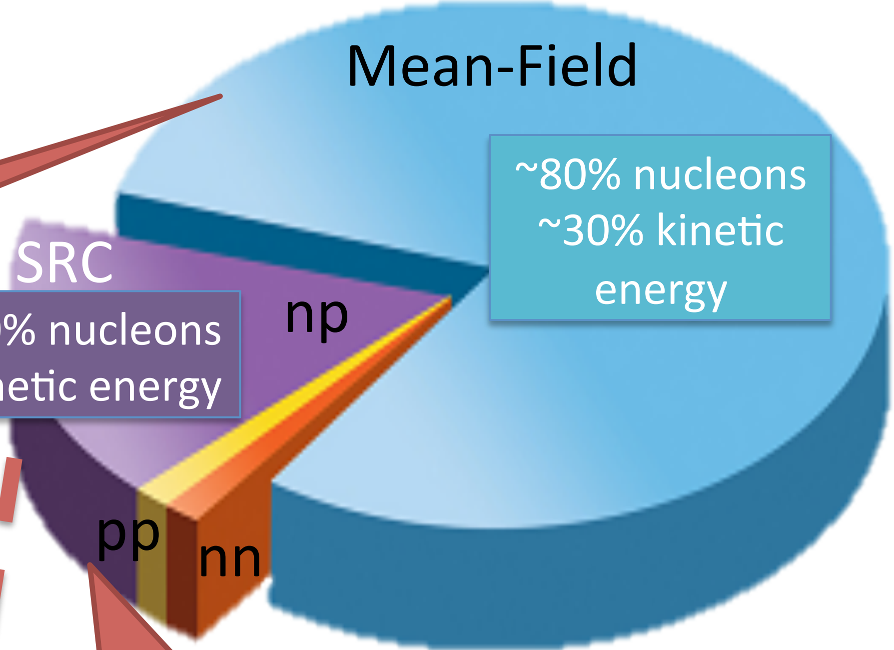
Largest attractive force

High local nuclear matter density, large momentum, large off shell, large virtuality ($v = p^{\mu 2} - m^2$)

# Where is the EMC Effect?



Largest attractive force



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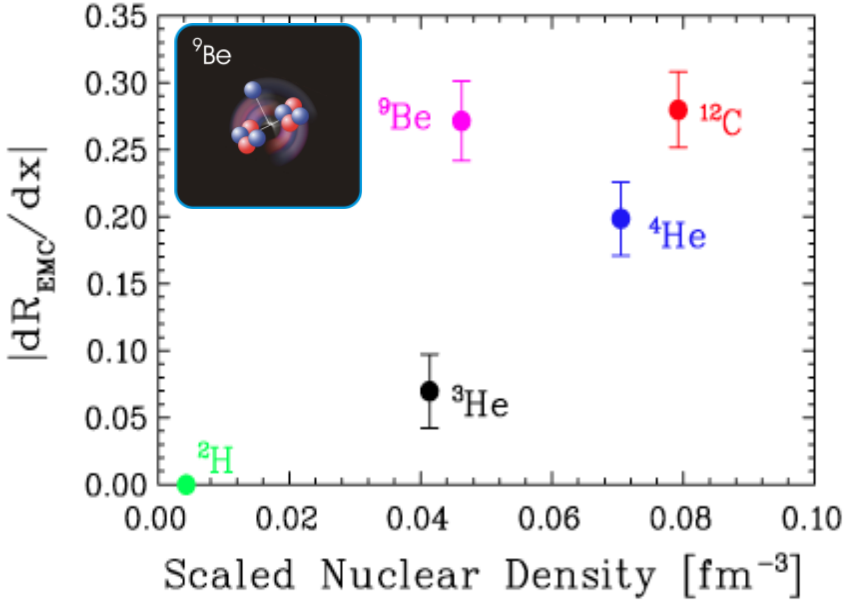
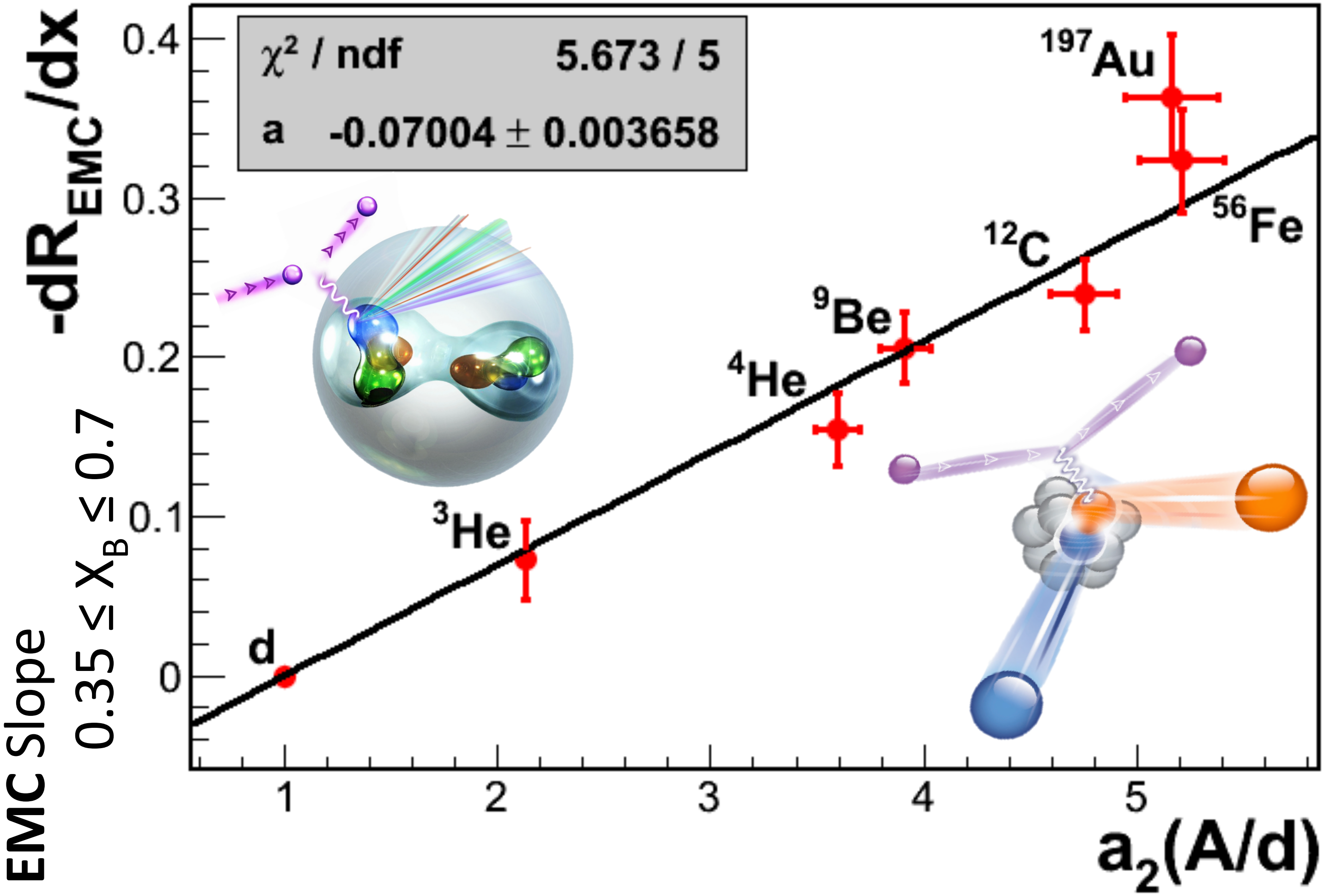


J. Seely et al., Phys. Rev. Lett. **103**, 202301 (2009)

High local nuclear matter density, large momentum, large off shell, large virtuality ($v = p^{\mu 2} - m^2$)

# EMC-SRC Correlation

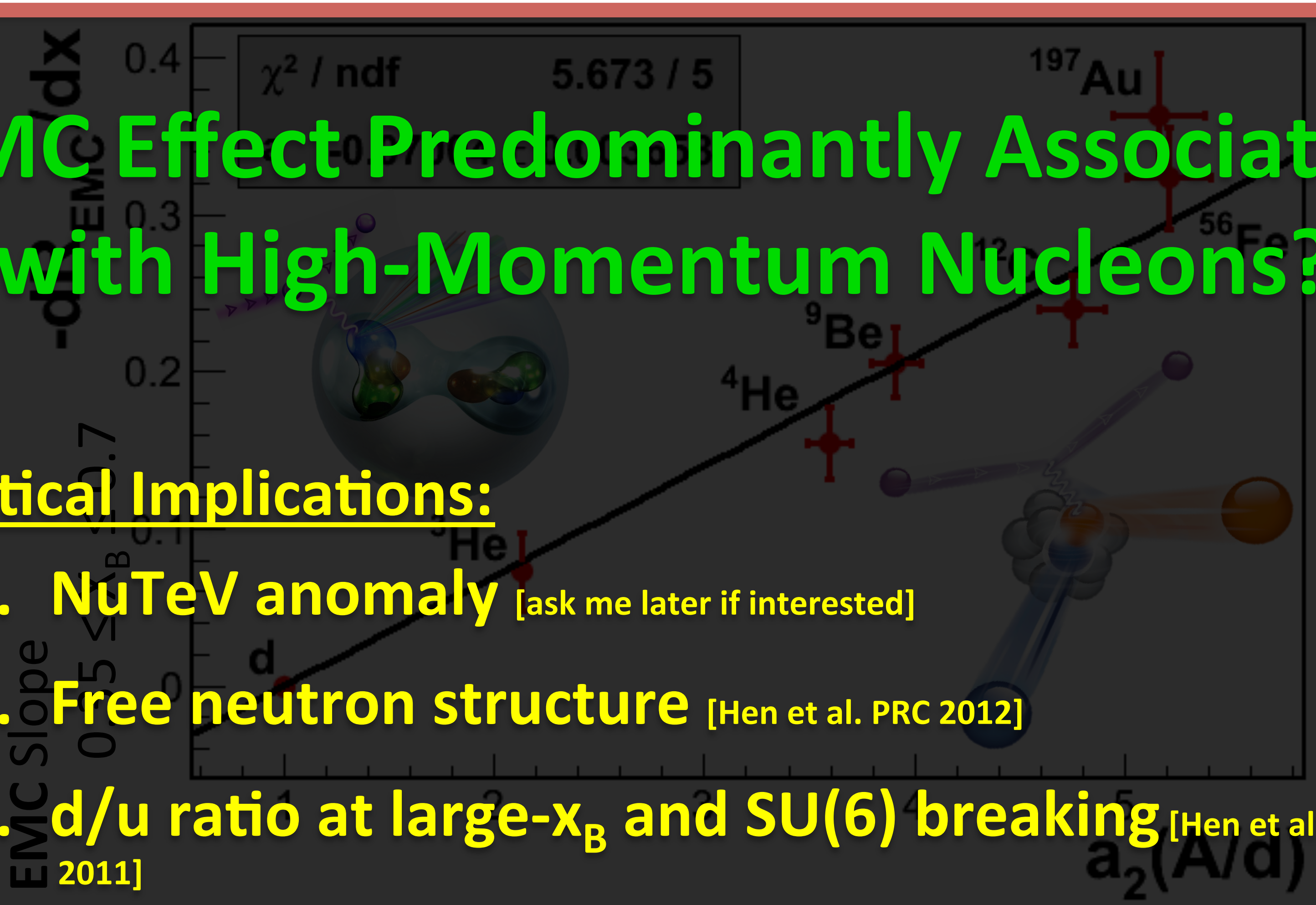


O. Hen et al., Int. J. Mod. Phys. E. **22**, 1330017 (2013).

O. Hen et al., Phys. Rev. C **85** (2012) 047301.

L. B. Weinstein, E. Piasetzky, D. W. Higinbotham, J. Gomez, O. Hen, R. Shneor, Phys. Rev. Lett. **106** (2011) 052301.

# EMC-SRC Correlation



## EMC Effect Predominantly Associated with High-Momentum Nucleons?

**Practical Implications:**

1. **NuTeV anomaly** [ask me later if interested]
2. **Free neutron structure** [Hen et al. PRC 2012]
3. **d/u ratio at large-$x_B$ and SU(6) breaking** [Hen et al. PRD 2011]

O. Hen et al., Int. J. Mod. Phys. E. **22**, 1330017 (2013).

O. Hen et al., Phys. Rev. C **85** (2012) 047301.

L. B. Weinstein, E. Piasetzky, D. W. Higinbotham, J. Gomez, O. Hen, R. Shneor, Phys. Rev. Lett. **106** (2011) 052301.

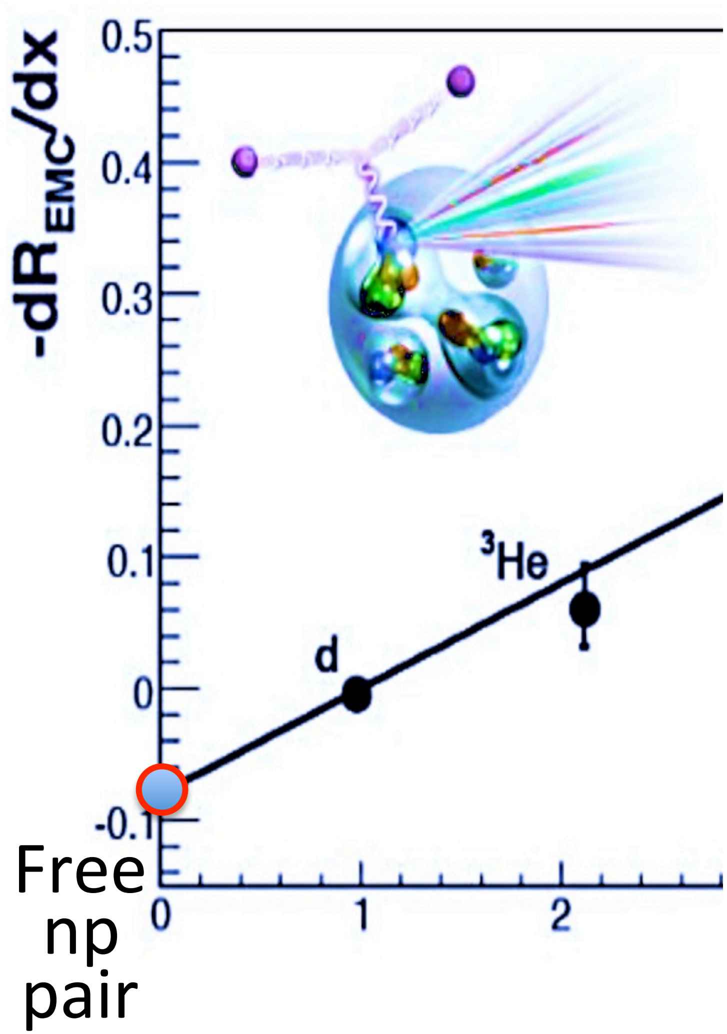
# Probing the Free Neutron

- $a_2 \rightarrow 0$ is the limit of a free proton-neutron pair with no interaction

- Extrapolating the EMC-SRC correlation to $a_2=0$ gives EMC (IMC) effect for the free p+n:

$$\frac{\sigma_d}{\sigma_p+\boxed{\sigma_n}} = 1 - a(x_p - b) \quad \text{for } 0.3 \le x_p \le 0.7,$$

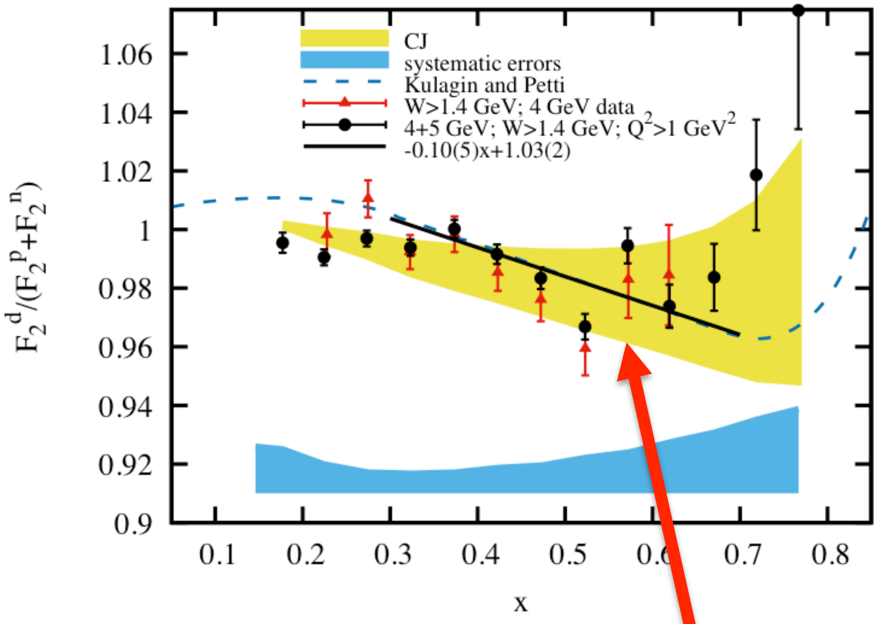
➔ the free neutron cross-section

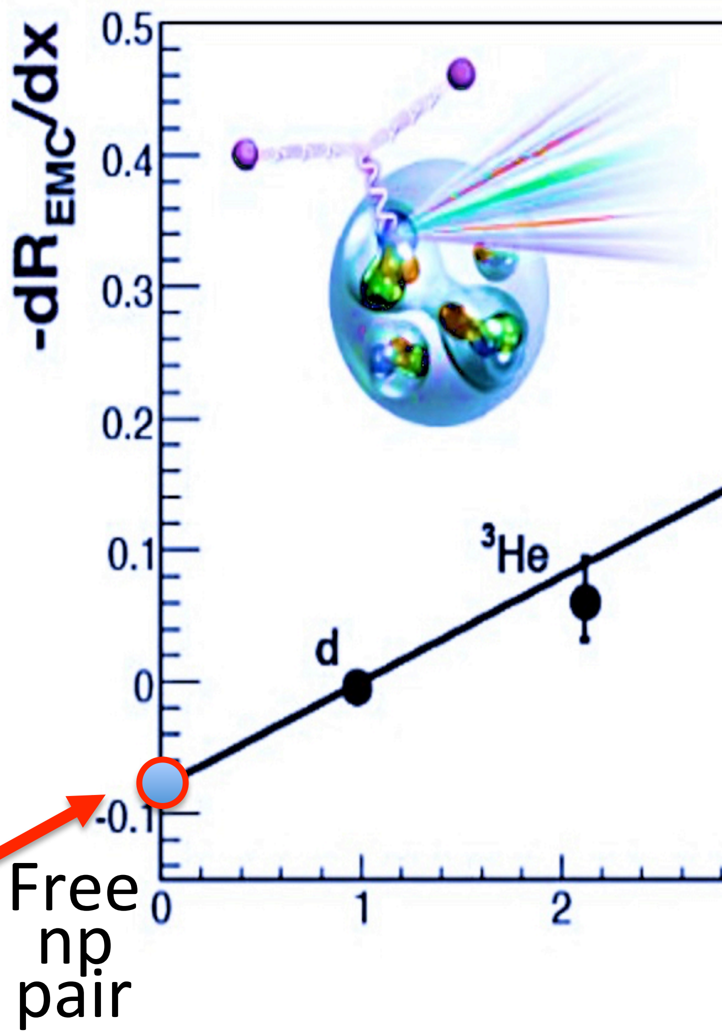


L.B.Weinstein et al., Phys. Rev. Lett. 106 (2011) 052301
O. Hen et al., Phys. Rev. C 85 (2012) 047301; O. Hen et al., Phys. Rev. D 84 (2011) 117501

# Comparing with the BONUS Experiment

BONUS IMC measurement (d/p+n)





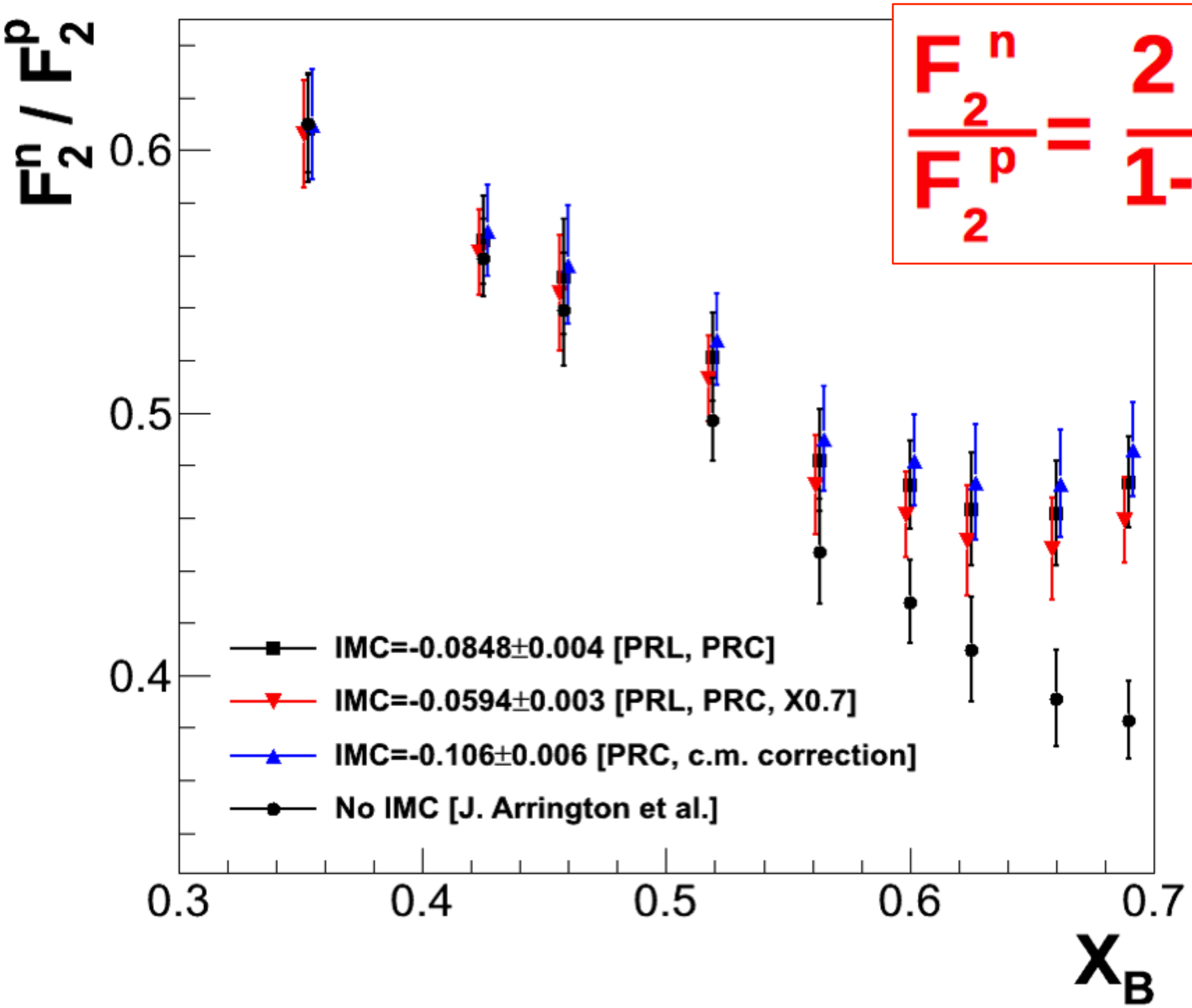
**IMC Effect Slope**

BONUS (2015): -0.10(5)

EMC/SRC (2011): -0.09(1)

O. Hen et al., Phys. Rev. C 85, 047301 (2012); K. Griffioen et al., arXiv: 1506.00871 (2015).

# Extracting $F_2^n/F_2^p$



$$\boxed{\frac{F_2^n}{F_2^p} = \frac{2\,F_2^d/F_2^p}{1-a(x_B-b)} - 1}$$

Large $x_B$ Approximation: $\frac{d_v}{u_v} \approx \frac{4F_2^n/F_2^p - 1}{4 - F_2^n/F_2^p}$

# Proton Wave-Function in QCD ($x_B \rightarrow 1$)

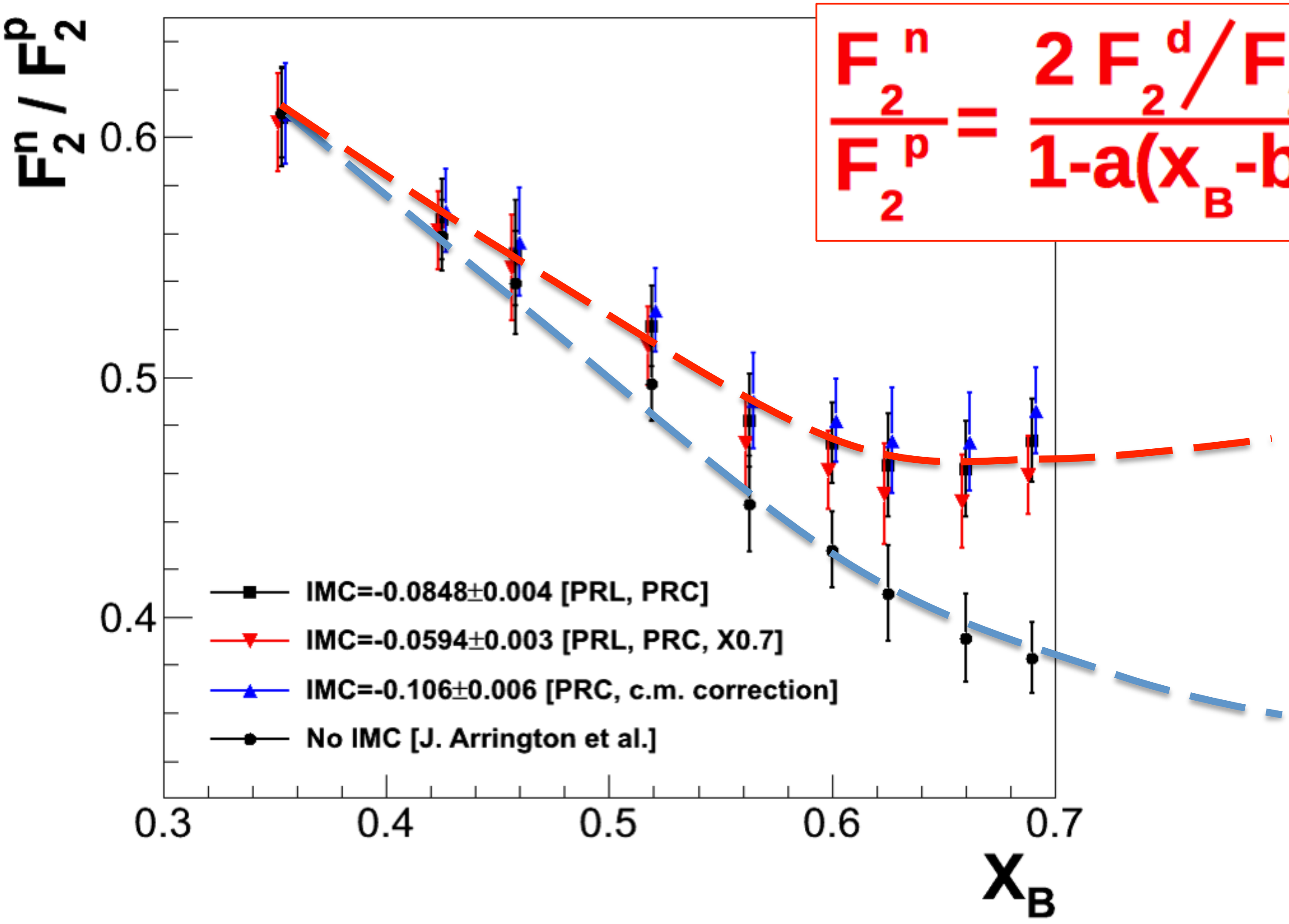
$$|p\uparrow\rangle = \boxed{\frac{1}{\sqrt{2}}|u\uparrow(ud)_{S=0}\rangle} + \frac{1}{\sqrt{18}}|u\uparrow(ud)_{S=1}\rangle - \frac{1}{3}|u\downarrow(ud)_{S=1}\rangle$$
$$-\frac{1}{3}|d\uparrow(uu)_{S=1}\rangle + \frac{\sqrt{2}}{3}|d\downarrow(uu)_{S=1}\rangle$$

- SU(6) predict
  - ✧ N - Δ mass difference implies SU(6) is broken
- Diquark dominance with $S_z$=0 predict d/u = 0.2
- Scalar (S=0) diquark dominance predict d/u = 0

| Nucleon Model | F2n / F2p | d / u |
|---|---|---|
| SU(6) | 2 / 3 | 0.5 |
| pQCD ($S_z$=0) | 3 / 7 | 0.2 |
| Scalar Diquark | 1 / 4 | 0 |

Brodsky et al., Nucl. Phys. B441, 197 (1995); Melnitchouk and Thomas, Phys. Lett. B377, 11 (1996)

# Extracting $F_2^n/F_2^p$



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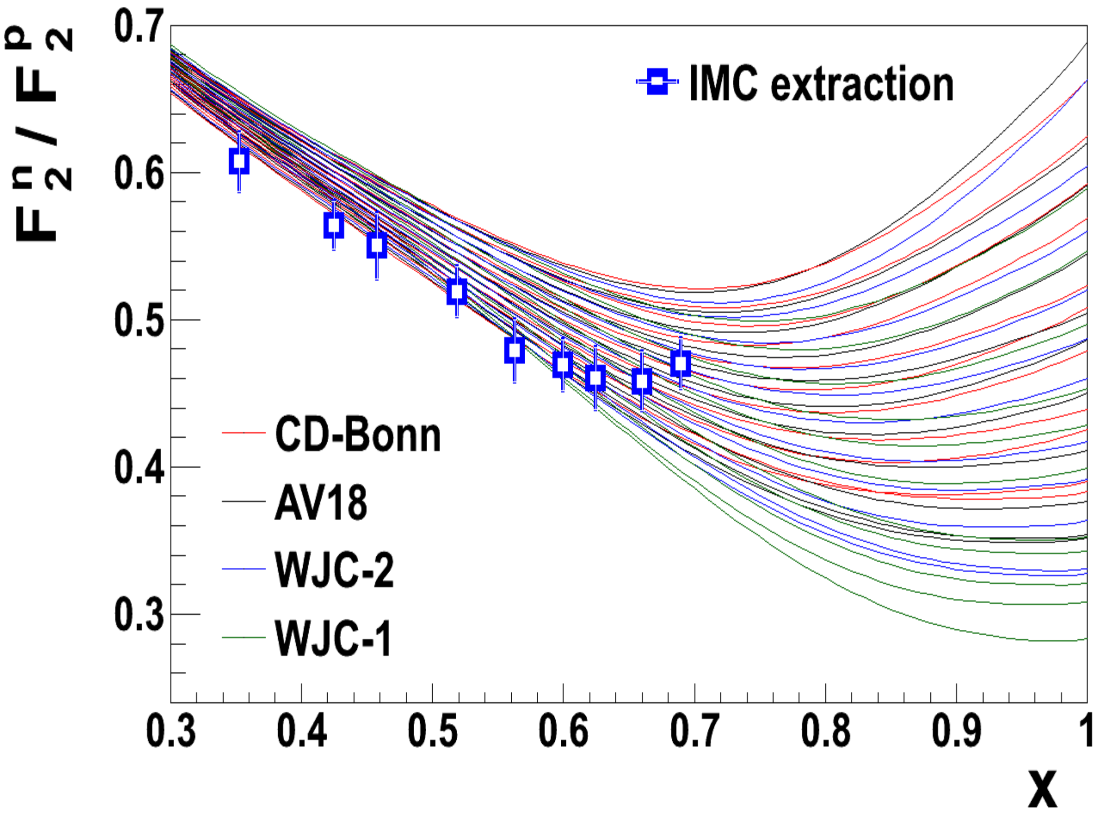
# Comparing with CTEQ-JLab Analysis



$$\lambda = \frac{\partial \Lambda^2}{\partial \log p^2}\bigg|_{p^2=M^2} = -2\frac{\delta R_N}{R_N}\frac{\delta p^2}{M^2},$$

Swelling Level

Average Nucleon Virtuality

Smearing Function

Free Nucleon S.F.

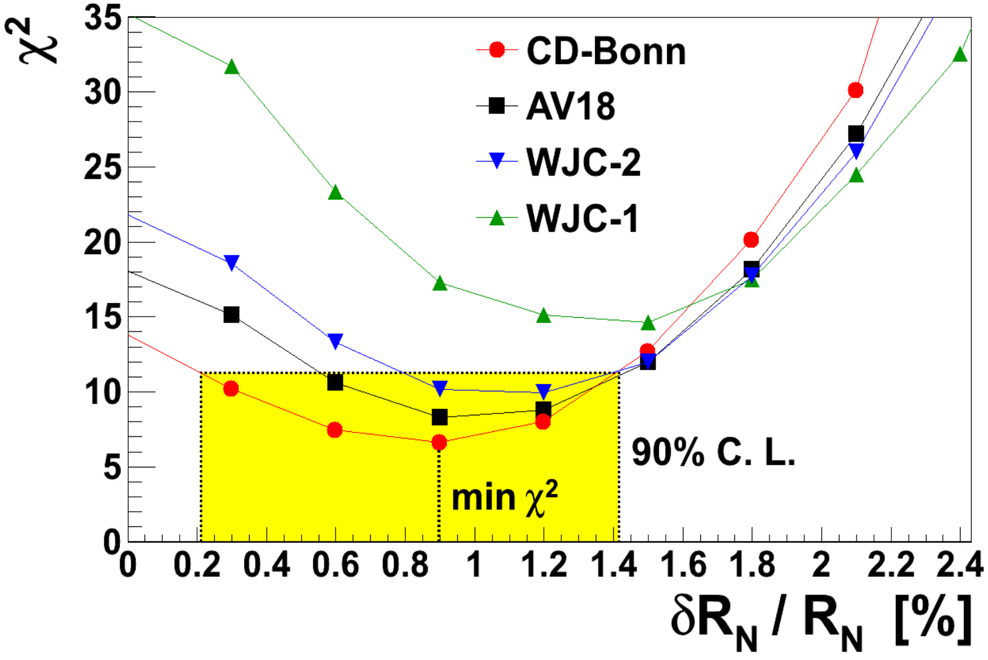
Off-Shell Correction

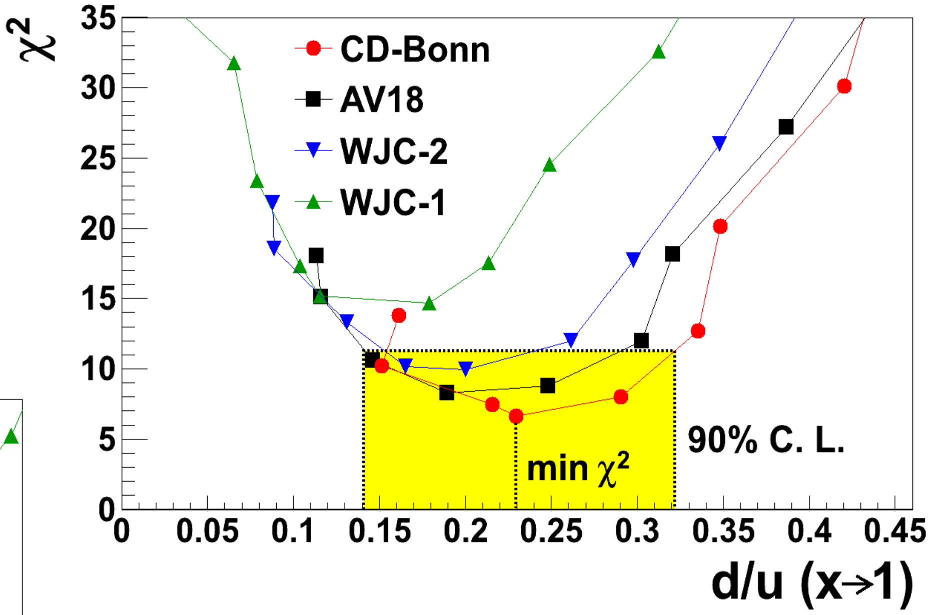
$$F_{2d}(x_B) = \int_{x_B}^{A} dy S_A(y,\gamma,x_B) F_2^{TMC+HT}(x_B/y,Q^2)\left(1+\frac{\delta^{\rm off}F_2(x)}{F_2(x)}\right)$$

O. Hen, A. Accardi, W. Melnitchouk, and E. Piasetzky, Phys. Rev. D 84, 117501 (2011).

# Comparing with CTEQ-JLab Analysis

Constraining nuclear off-shell parameters and the d/u ratio at x ➔ 1





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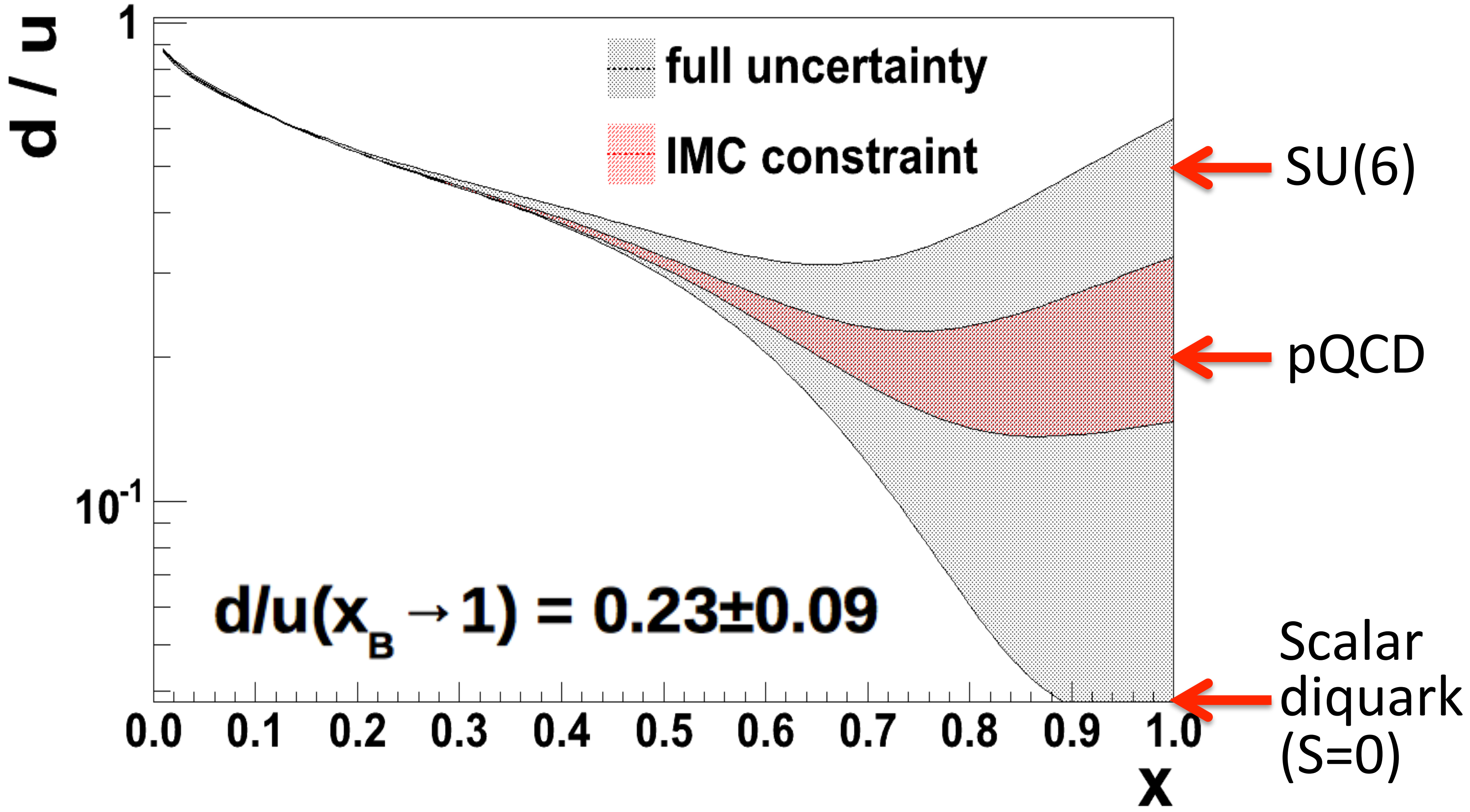

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INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERN COURIER

VOLUME 53 NUMBER 4 MAY 2013

Deep in the nucleus: a puzzle revisited

52301 (2011) PHYSICAL REVIEW LETTERS week
4 FEBRU

## Short Range Correlations and the EMC Effect

L. B. Weinstein,[1,*] E. Piasetzky,[2] D. W. Higinbotham,[3] J. Gomez,[3] O. Hen,[2] and R. Shneor[2]

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PHYSICAL REVIEW C **85**, 047301 (2012)

## he connection between short range correlations and the EMC effect

O. Hen,[1] E. Piasetzky,[1] and L. B. Weinstein[2]

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## Short range correlations and the EMC effect

E. Piasetzky[a], L.B. Weinstein[b], D.W. Higinbotham[c], J. Gomez[c], O. Hen[a], R. Shneor[a]

NUCLEAR PHYSICS A

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PHYSICAL REVIEW D **84**, 117501 (2011)

## Constraints on the large-$x$ $d/u$ ratio from electron-nucleus scattering at $x > 1$

O. Hen,[1] A. Accardi,[2,3] W. Melnitchouk,[3] and E. Piasetzky[1]

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International Journal of Modern Physics E
Vol. 22, No. 7 (2013) 1330017 (30 pages)

## THE EMC EFFECT AND HIGH MOMENTUM NUCLEONS IN NUCLEI

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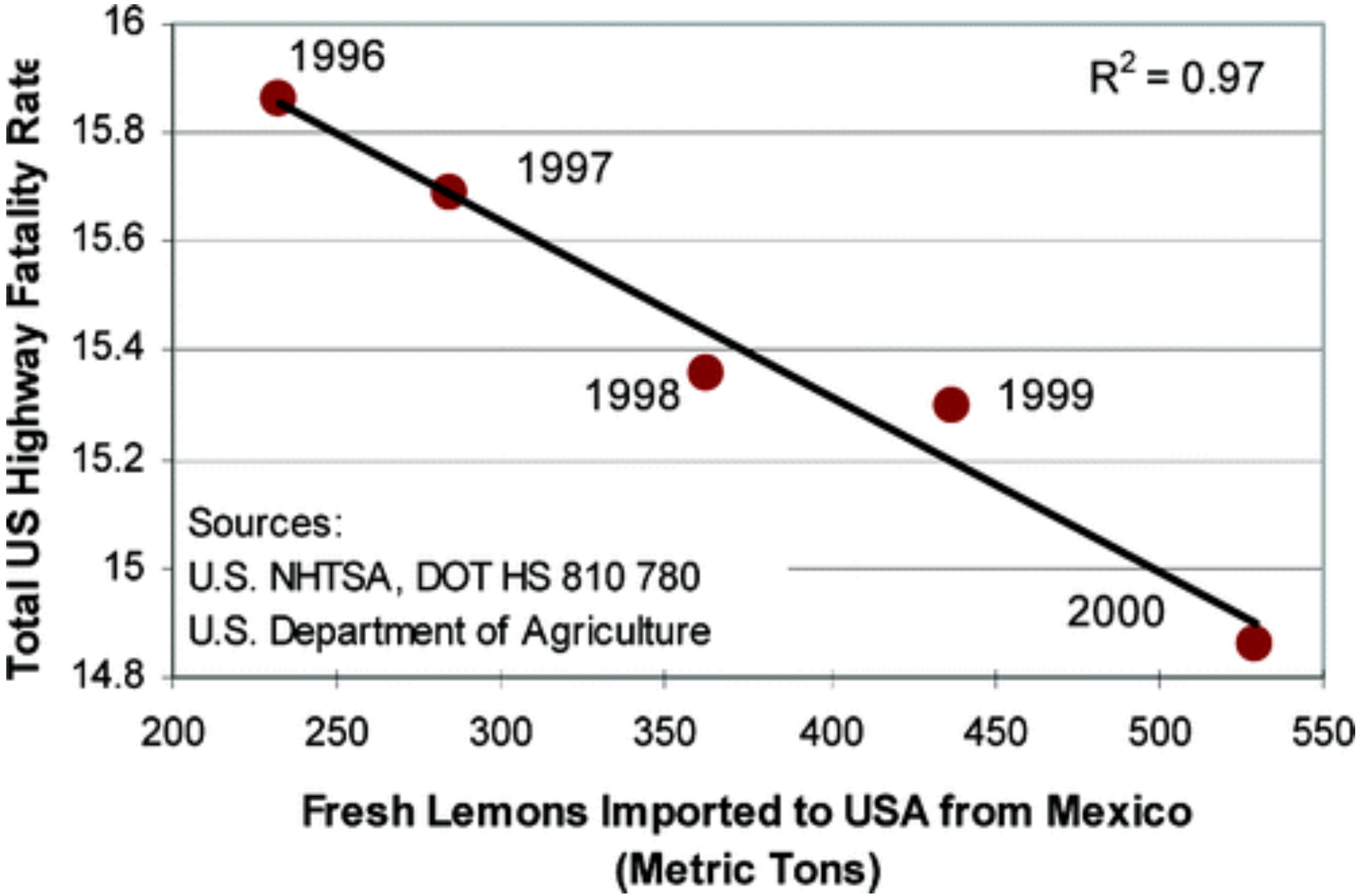
## THE EMC EFFECT AND HIGH MOMENTUM NUCLEONS IN NUCLEI

# Other Correlations…



Sources:
U.S. NHTSA, DOT HS 810 780
U.S. Department of Agriculture

# Other Correlations

## Mexican Lemonade Saves Lives!

# Physics Behind the Correlation?

- The EMC-SRC Correlation is robust.
  - Independent of different experimental and theoretical corrections applied to the SRC scaling data
- Models suggested that the EMC effect depends on the average kinetic energy, <T>, carried by nucleons in the nucleus
  - <T> is dominated by 2N-SRC

O. Hen et al., Phys. Rev. C 85 (2012) 047301 J. Arrington et al., Phys.Rev. C 86 (2012) 065204

# Can We Test It? (Yes! Partially…)

- 2N-SRC pairs are universal
- Their interaction is largely independent of the (spectator) A-2 system
  - – Depends mainly on the basic nucleon-nucleon interaction
- If SRC nucleons are modified – it should be a universal modification, independent of A

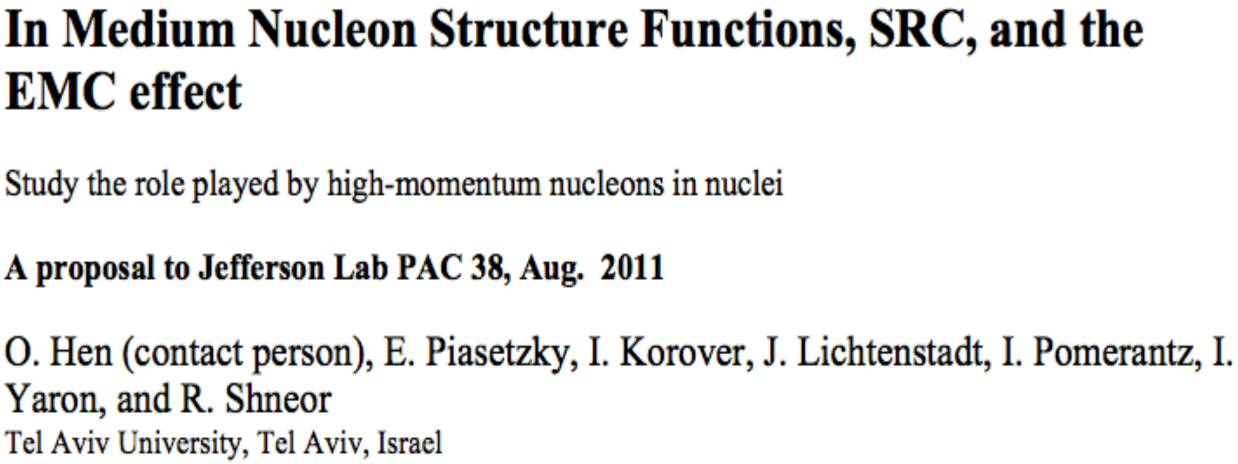
Can we incorporate a universal SRC modification with a simple EMC convolution model to explain the data? YES….

O. Hen et al., Int. J. Mod. Phys. E **22,** 1330017 (2013).

# Experimental Tests ?

- Goal: measure the virtuality (nuclear density) dependence of the structure function
- (our) Method: tagged DIS using $d(e,e'N_{\text{recoil}})$ reactions

Deuterium is the only system in which the momentum of the struck nucleon equals that of the recoil (Assuming no FSI)

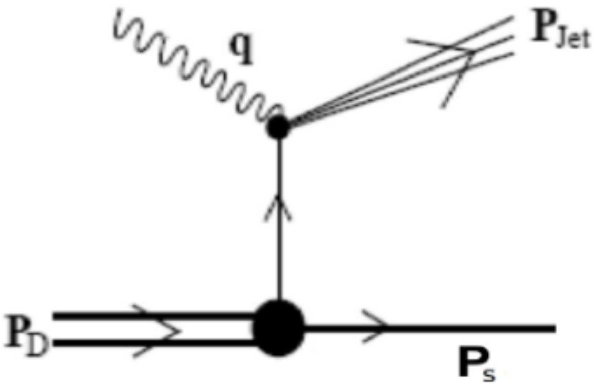


**In Medium Nucleon Structure Functions, SRC, and the EMC effect**

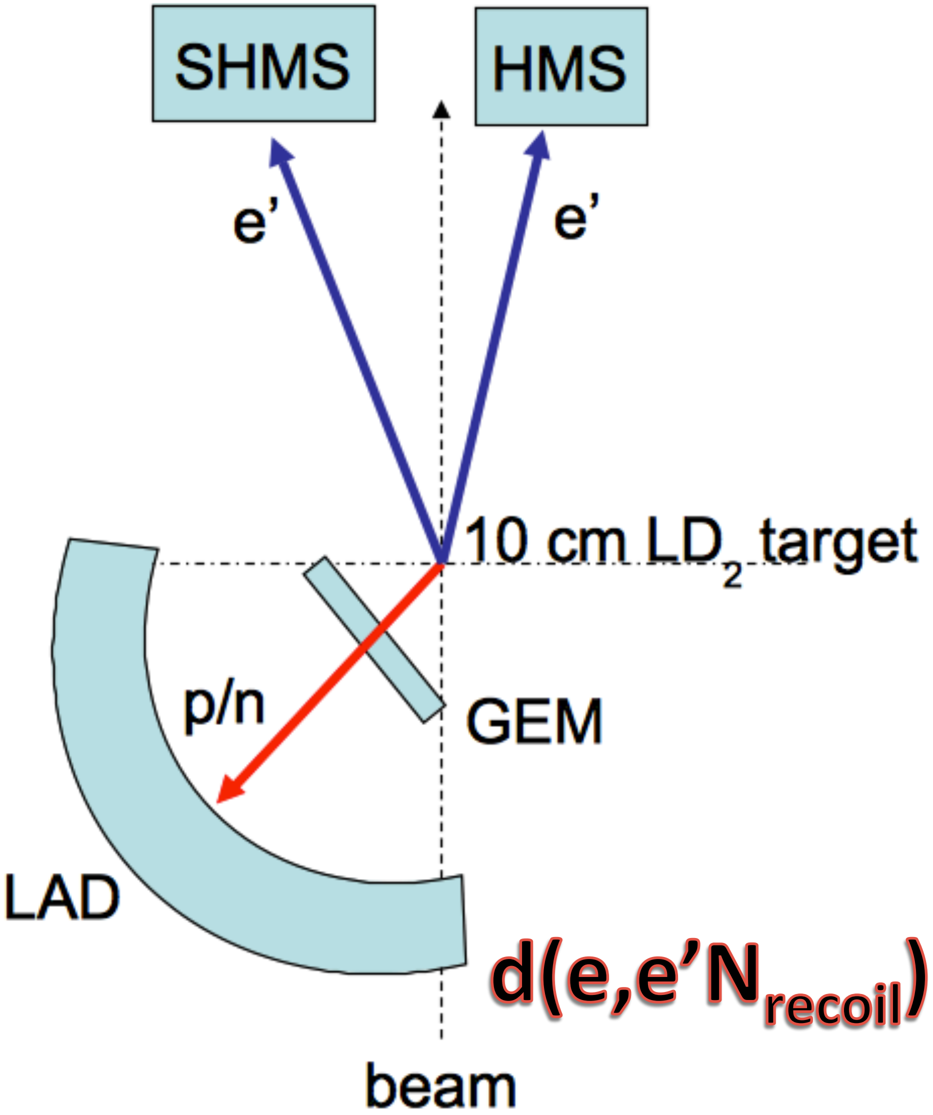
Study the role played by high-momentum nucleons in nuclei

**A proposal to Jefferson Lab PAC 38, Aug. 2011**

O. Hen (contact person), E. Piasetzky, I. Korover, J. Lichtenstadt, I. Pomerantz, I. Yaron, and R. Shneor
Tel Aviv University, Tel Aviv, Israel



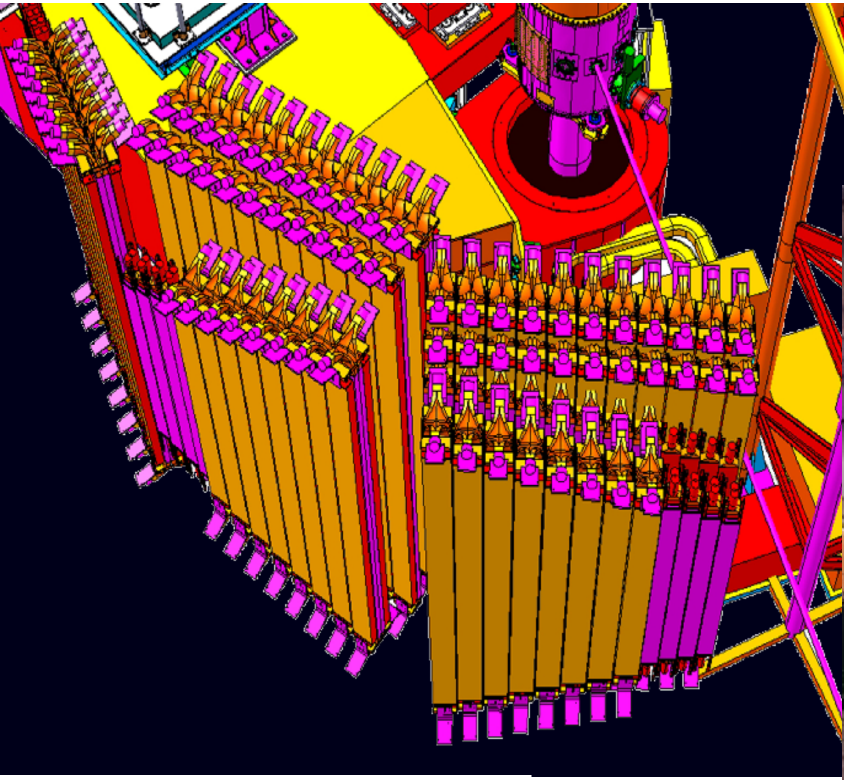
# Our Concept…



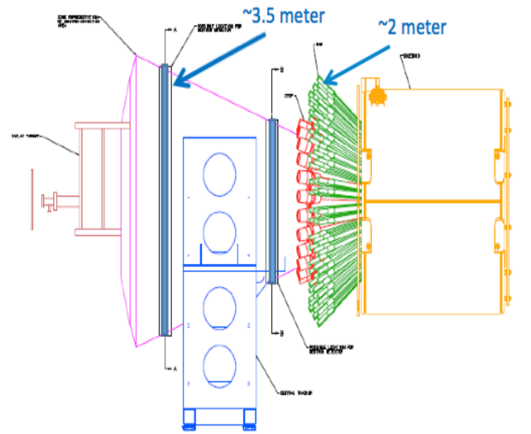
**$d(e,e'N_{recoil})$**

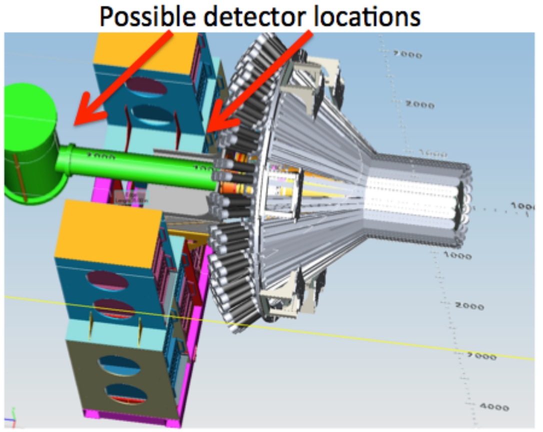
- High resolution spectrometers for (e,e’) measurement in DIS kinematics
- Large acceptance recoil proton \ neutron detector
- Long target + GEM detector – reduce random coincidence

# …Its realization (LAD / BAND)



Large Acceptance Detector (LAD@Hall-C)

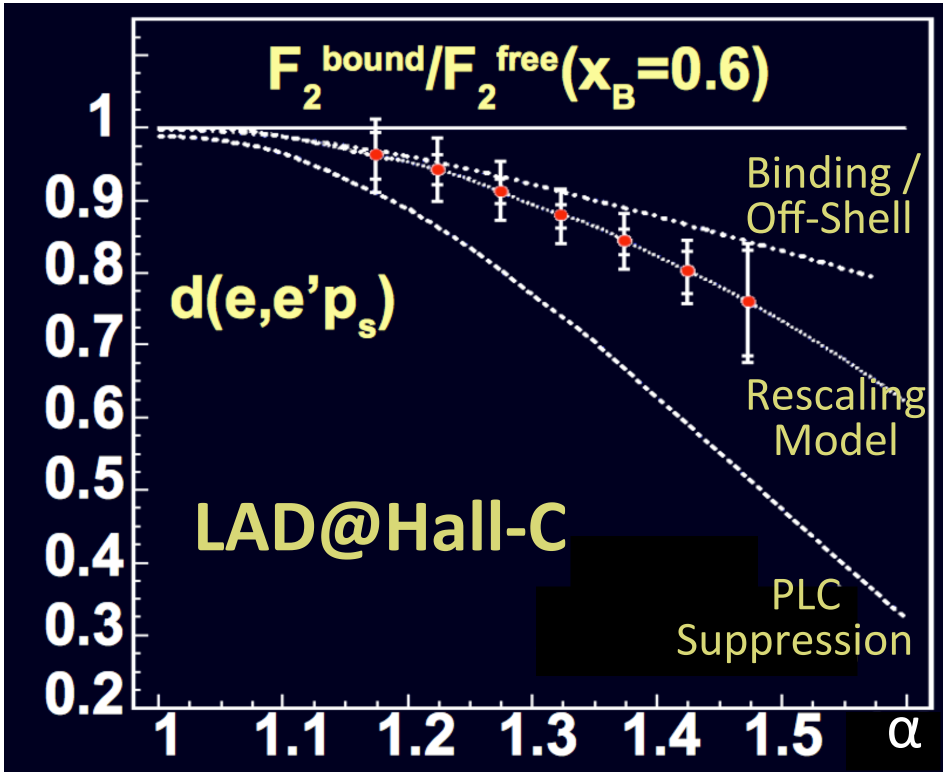




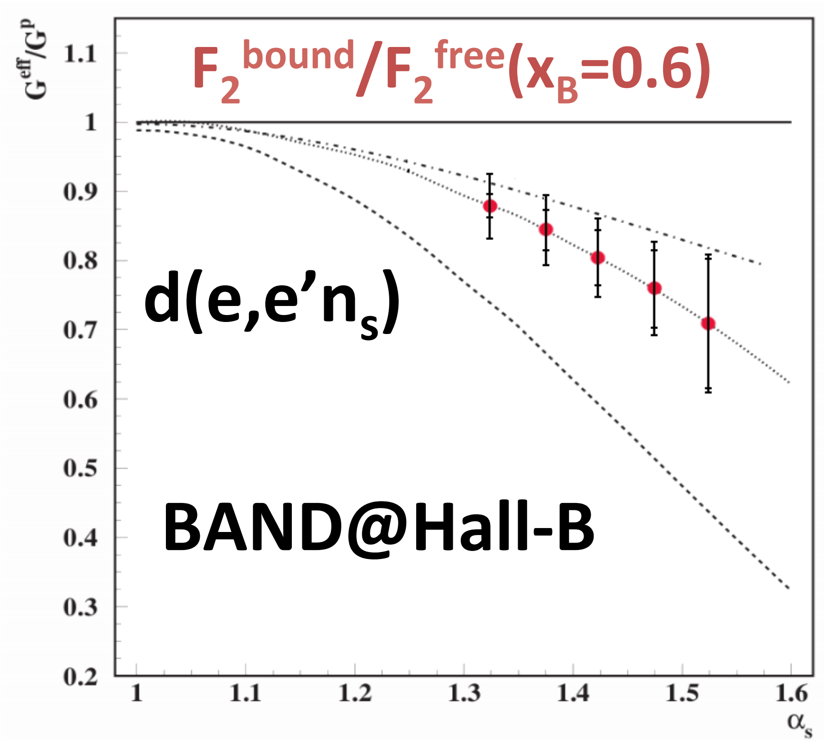
Backward Angle Neutron Detector (BAND@Hall-B)

# Kinematics and Uncertainties

- Tagging allows to extract the structure function in the nucleon reference frame: $x' = \frac{Q^2}{2(\bar{q} \cdot \bar{p})}$
- Expected coverage: x’ ~ 0.3 & 0.45(0.5) < x’ < 0.55(0.7) @ $W^2 > 4\ [\mathrm{GeV}/c]^2$



Melnitchouk et al., Z. Phys. A **359**, 99-109 (1997)



# Questions for Next Generation

## Properties of SRC Pairs

Quantum numbers?
Central vs. tensor correlations?
Mean-field to SRC transition (Migdal jump)?
c.m. and relative motion?
Nuclei far from stability?

## Structure of SRC nucleons

Structure of SRC nucleons?
Explaining the EMC effect?

## Imbalanced systems

Minority move faster?
Minority have larger pairing probability?
Dynamics of pairing with symmetry?

## Effect of SRC on…

Neutrino-nucleus interactions?
Neutron stars structure and cooling rate?
Universality of contact interactions?
Atomic traps studies of asymmetric systems?

# Questions for Next Generation

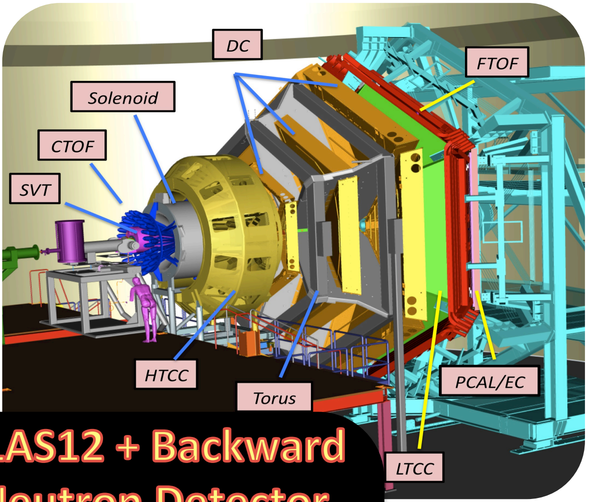
**Structure of SRC nucleons**

Tagged structure function measurements allows accessing the internal structure functions of SRC nucleons. [JLab 12GeV / EIC]

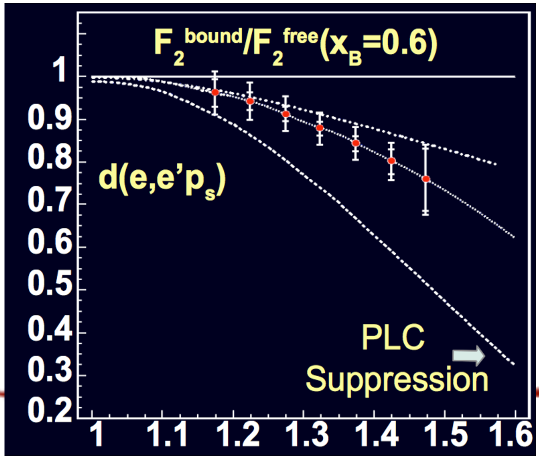
Structure of SRC nucleons?

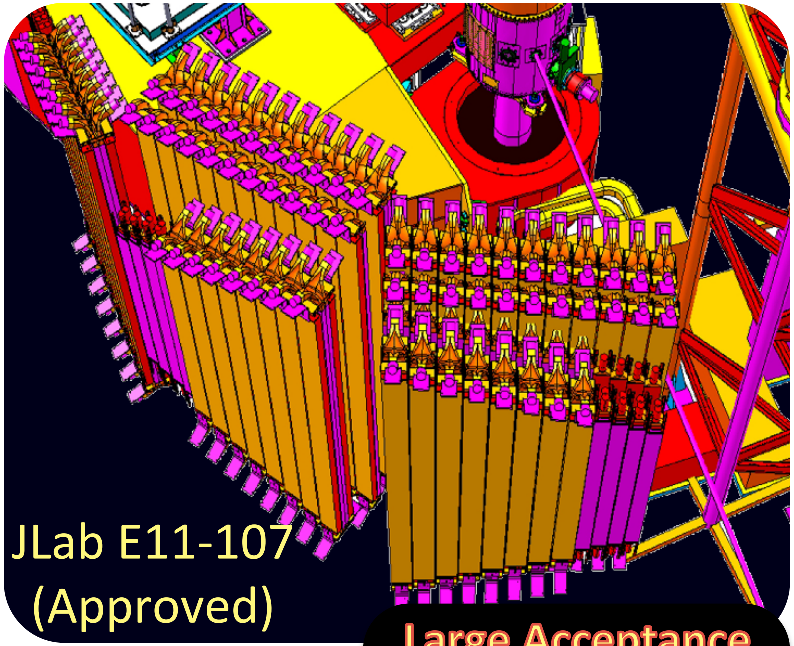
Proton vs. neutron modification?

Explaining the EMC effect?



**CLAS12 + Backward Neutron Detector (BND)**





JLab E11-107 (Approved)

**Large Acceptance Detector (LAD)**

# Questions for Next Generation

## Properties of SRC Pairs

New high-intensity, few-GeV, Hadron beams allow high-statistics exclusive 2N-SRC measurements. [GSI / Dubna / Lanzhou]

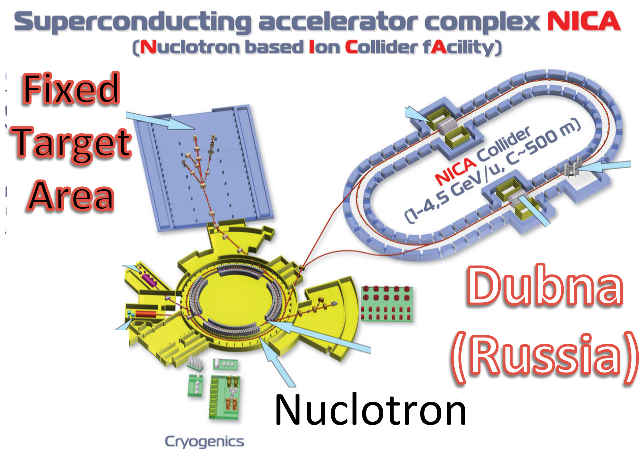
Quantum numbers?

Central vs. tensor correlations?

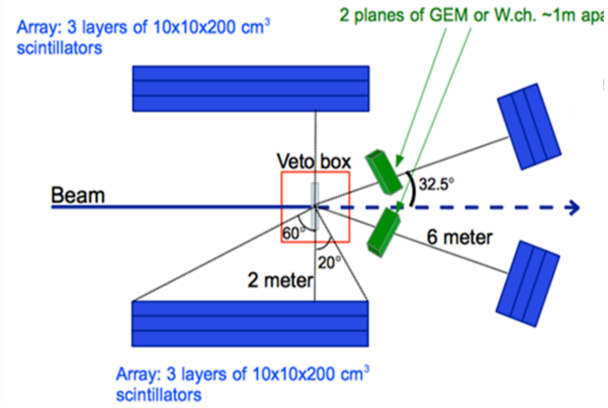
Mean-field to SRC transition (Migdal jump)?

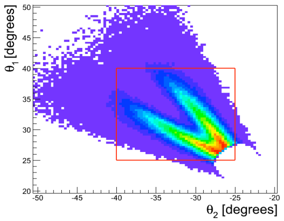
c.m. and relative motion?

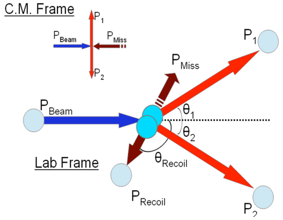
Nuclei far from stability? (FRIB)



Proposal submitted to Lanzhou:





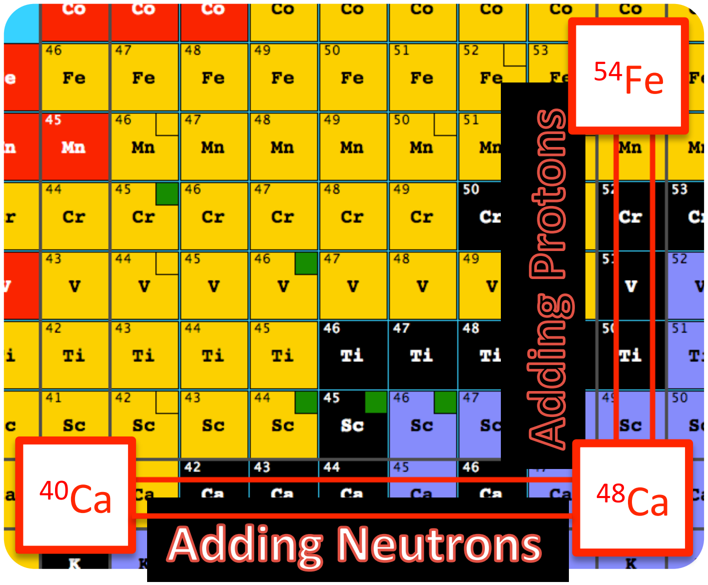


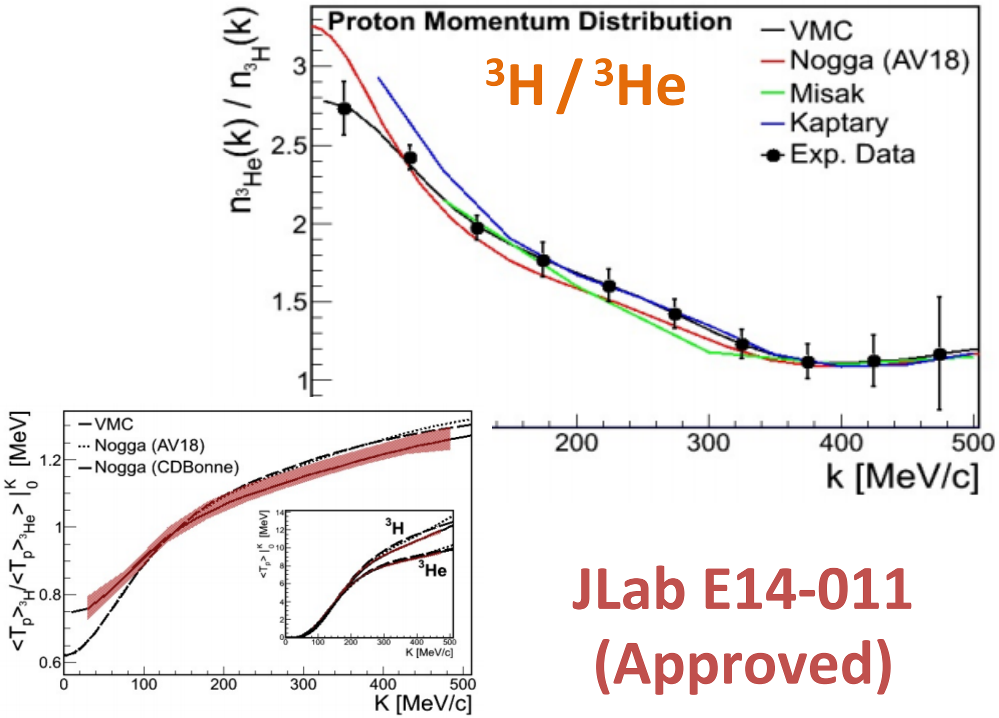
# Questions for Next Generation

## Imbalanced Systems

Minority move faster?
Minority have larger pairing probability?
Dynamics of pairing with symmetry?

New targets (e.g $^{3}$H, $^{48}$Ca) allow studying the momentum distribution of protons and neutrons and Isospin dynamics of SRC with change of nuclear asymmetry.





**JLab E14-011 (Approved)**