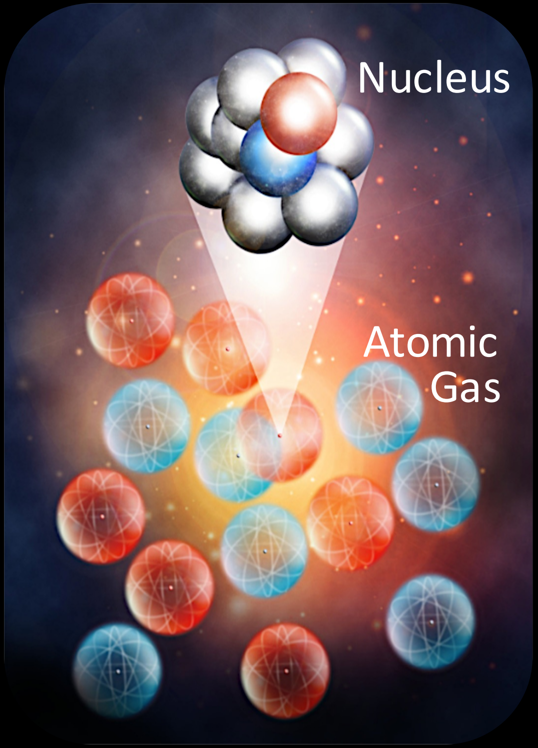
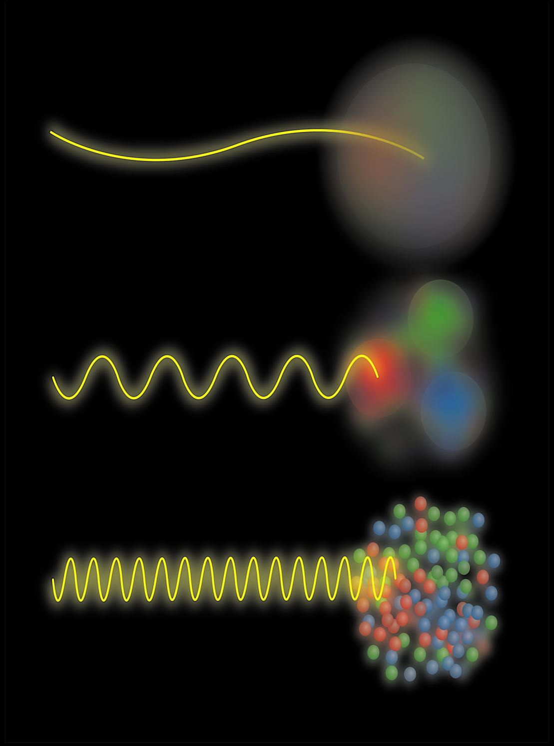
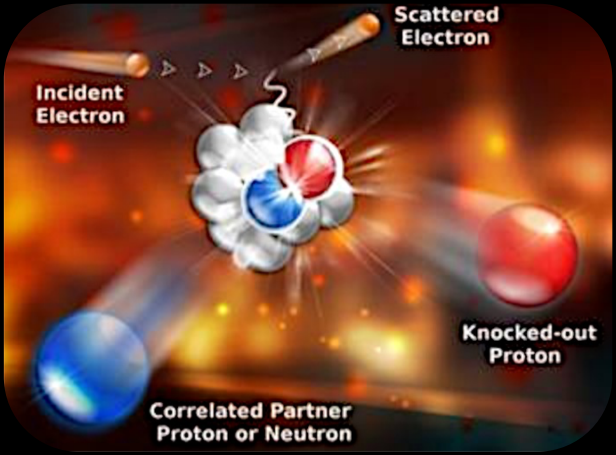
Probing Super Dense Nuclear Matter



Or Hen

MIT

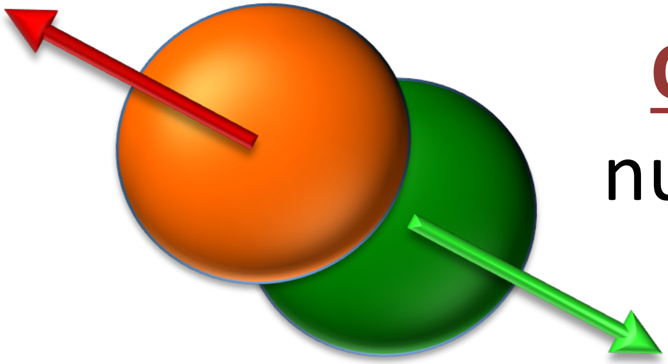




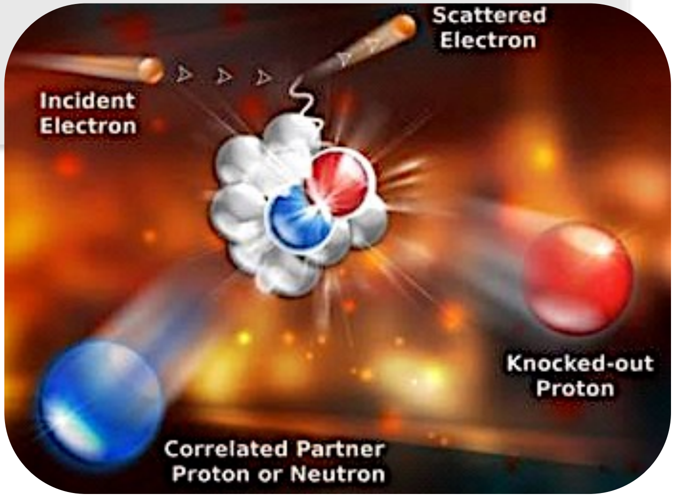
54th International Winter Meeting
on Nuclear Physics, January 29th, 2016.

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)



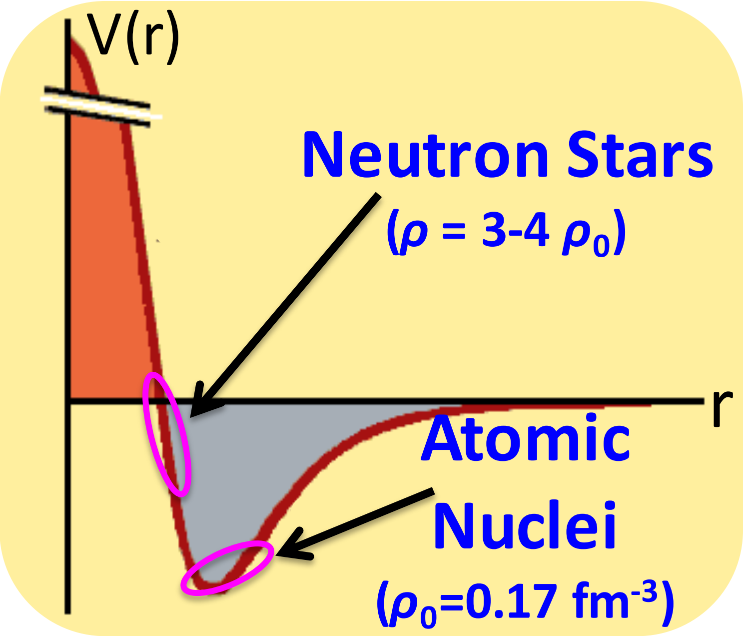
COLD dense nuclear matter



Why Study High-Momentum Nucleons?

Nuclear Physics

Better understanding of the nucleon-nucleon interaction and the nuclear momentum distribution



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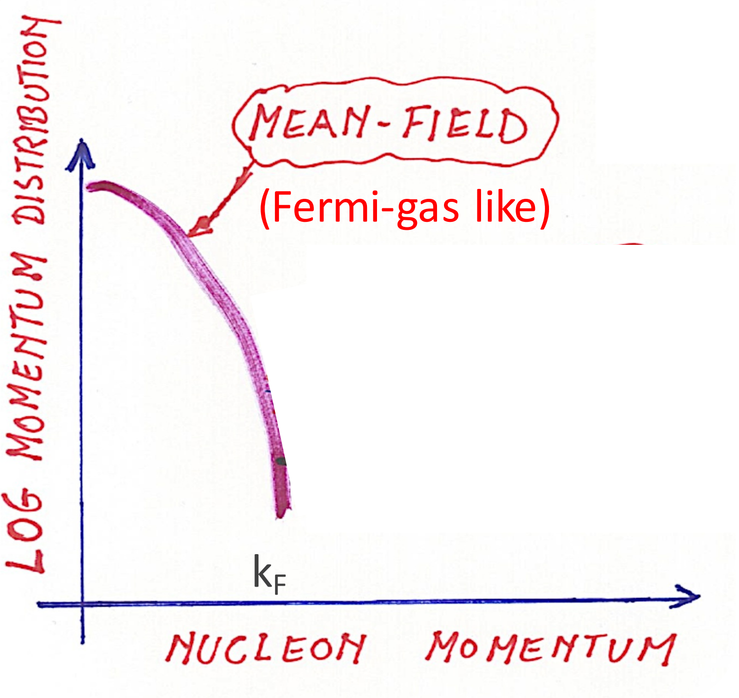

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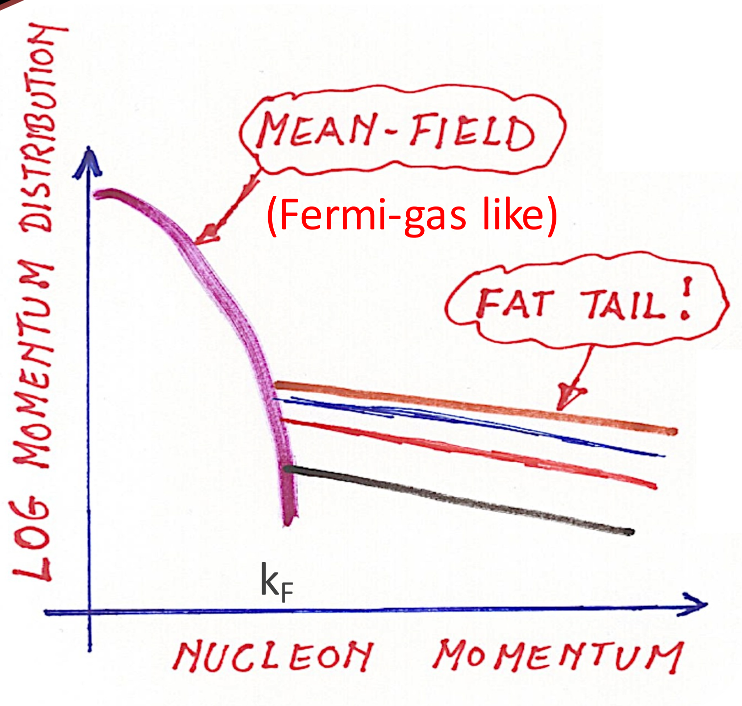
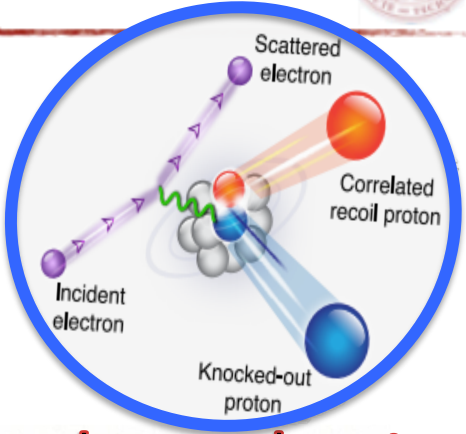


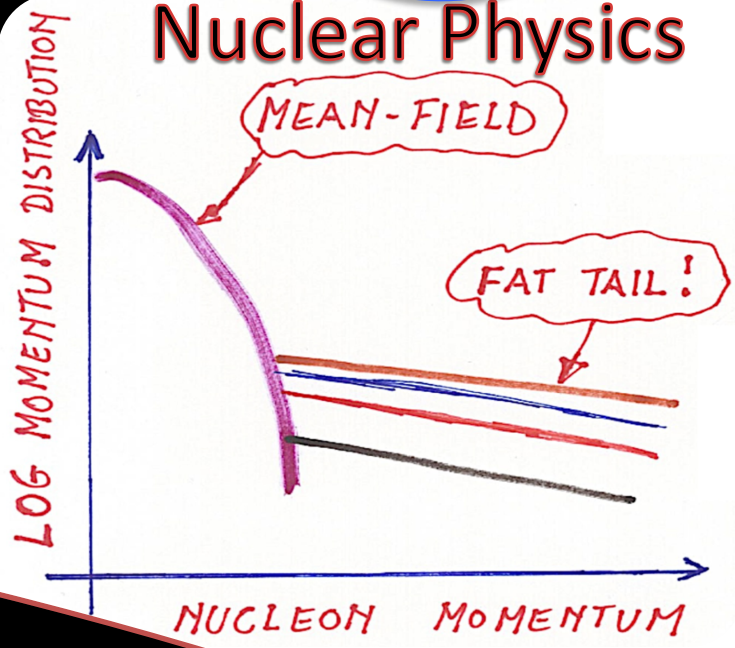
Why Study High-Momentum Nucleons?

Particle Physics

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



Nuclear Physics



Astrophysics

Neutron Stars.
Nuclear Symmetry Energy.

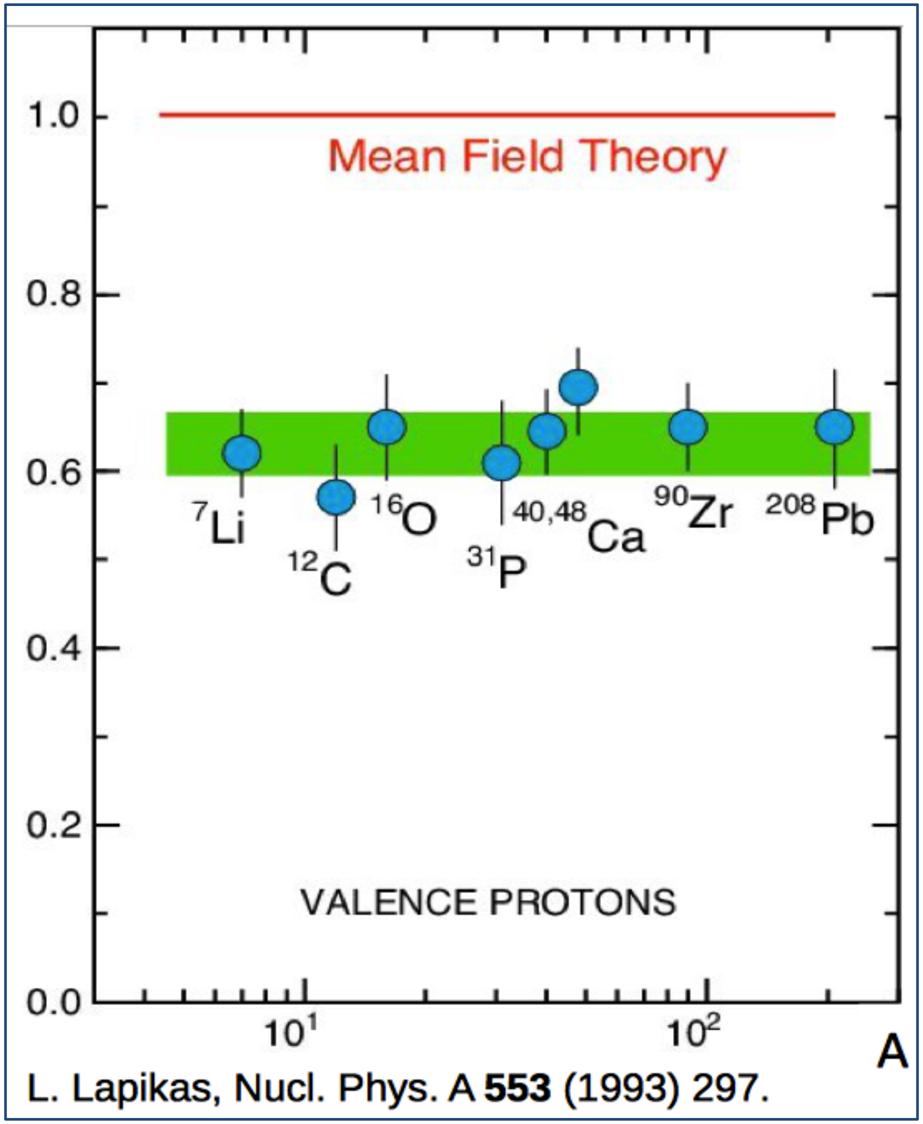
Quantum / Atomic Physics

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

Beyond the Shell-Model: NN Correlations

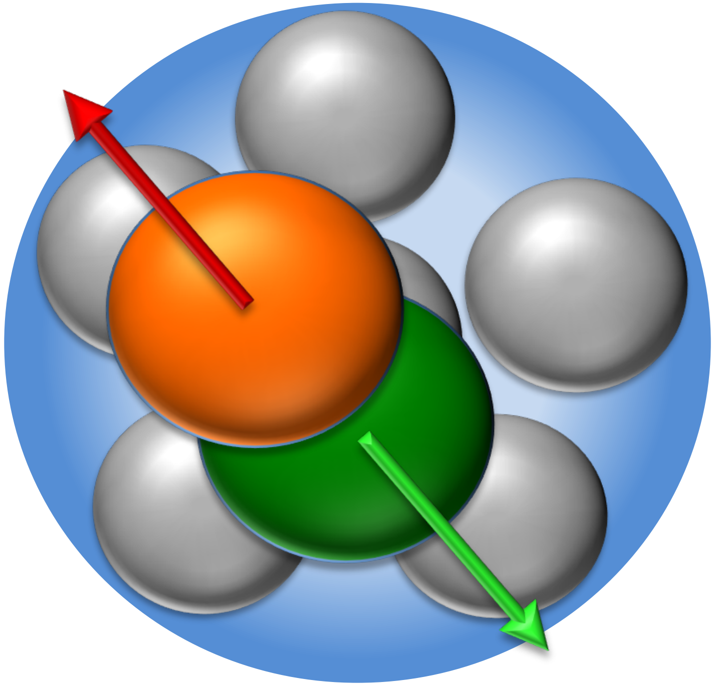
- Spectroscopic factors extracted from A(e,e'p) measurements yield only 60-70% of the expected single-particle strength

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



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

Exclusive 2N-SRC Studies



Exclusive 2N-SRC Studies

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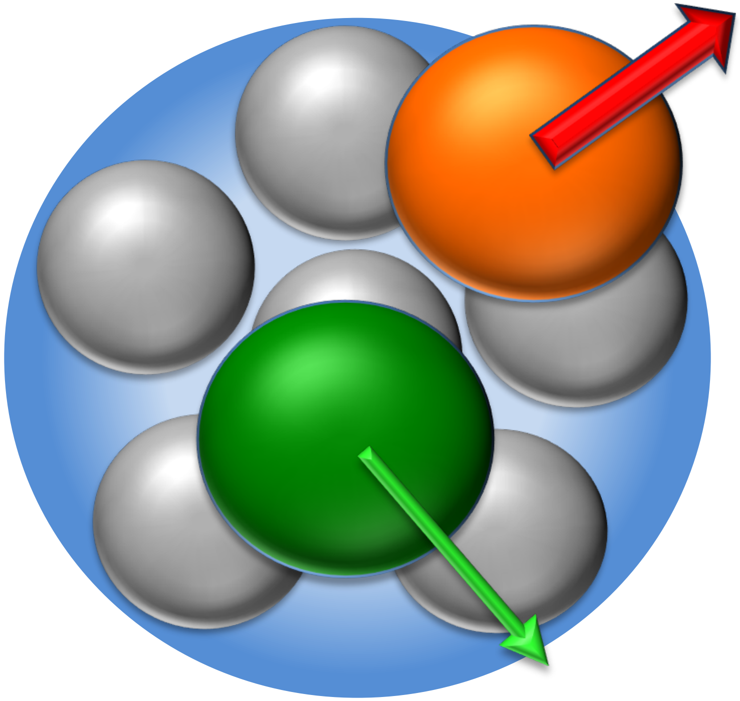
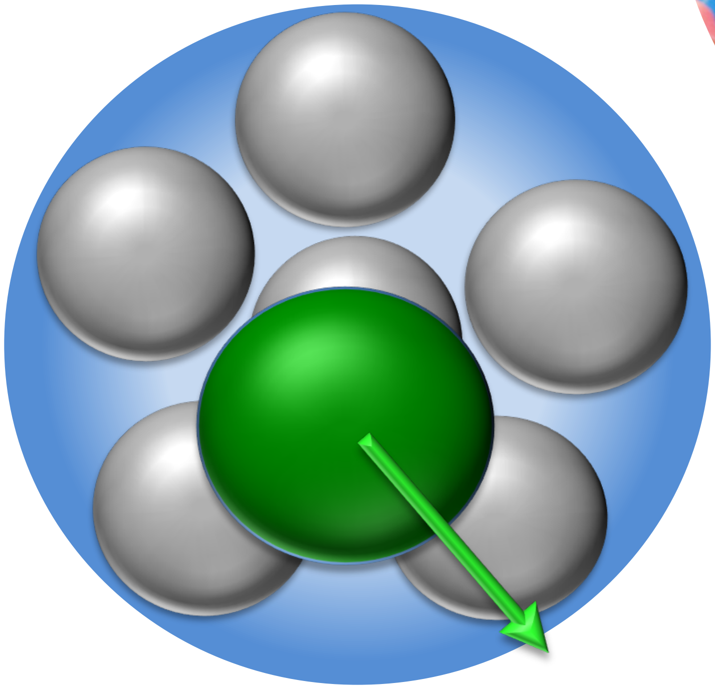


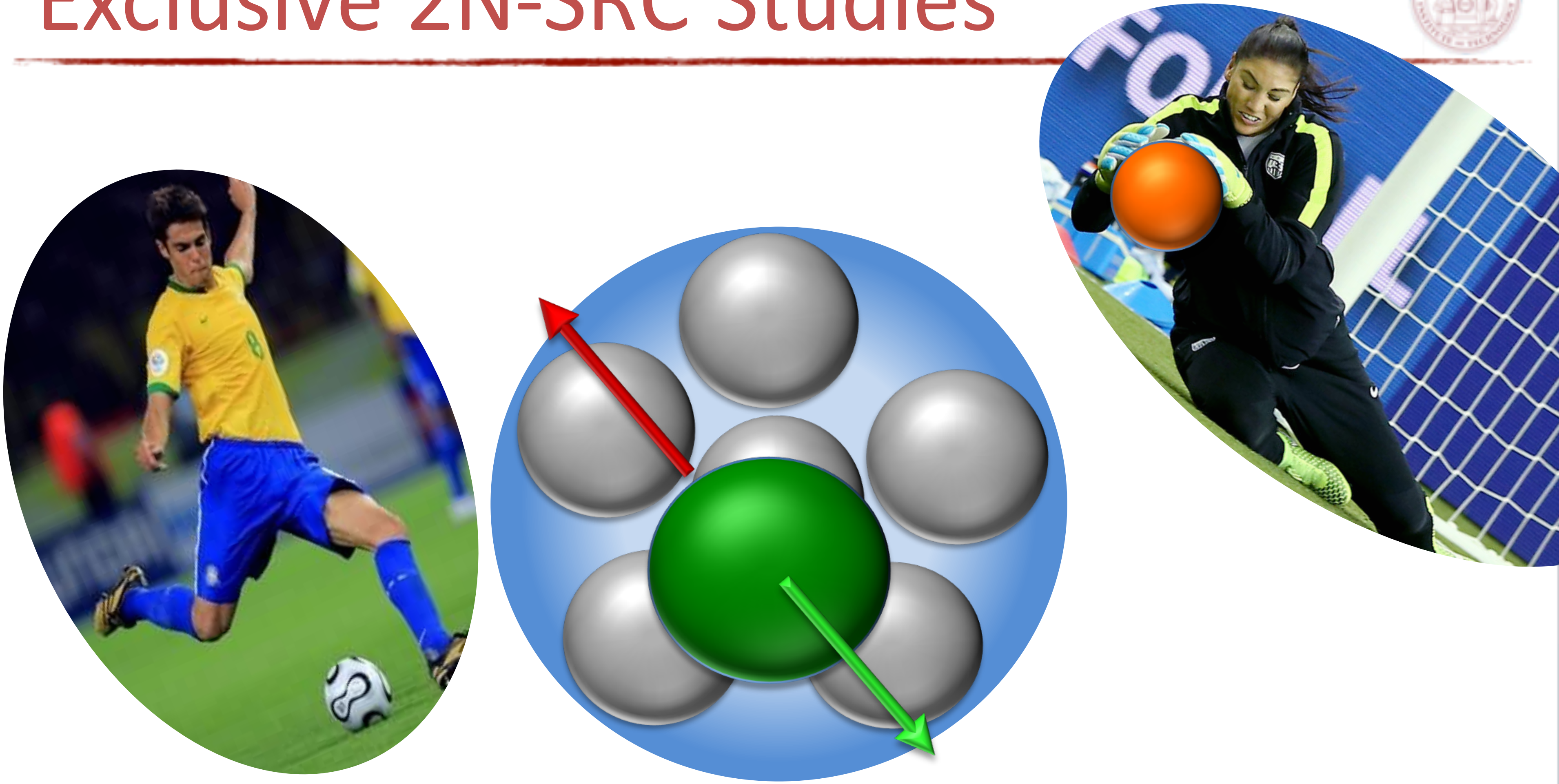
FIFA WORLD CUP
Brasil

Exclusive 2N-SRC Studies



2014
FIFA WORLD CUP
Brasil

Exclusive 2N-SRC Studies



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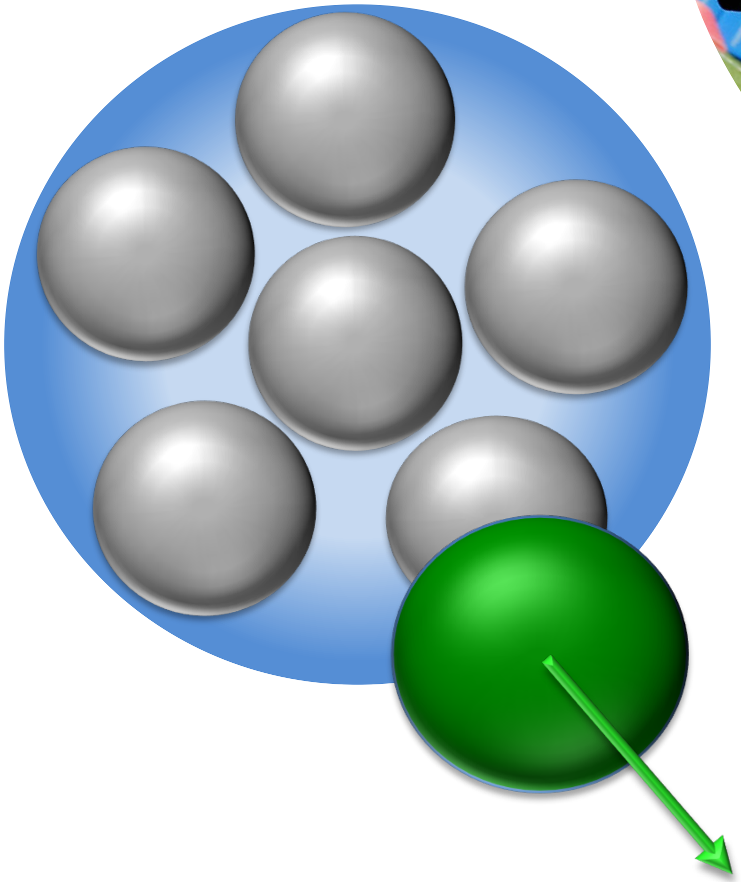

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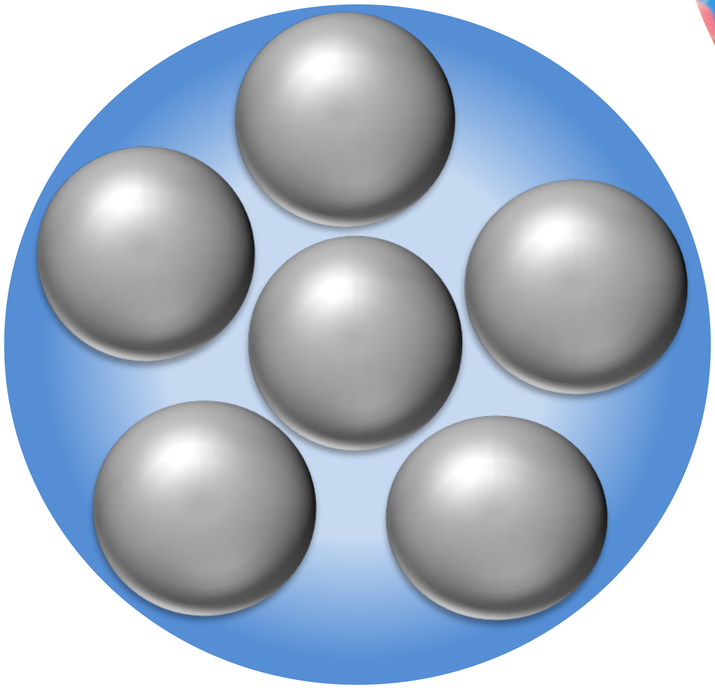

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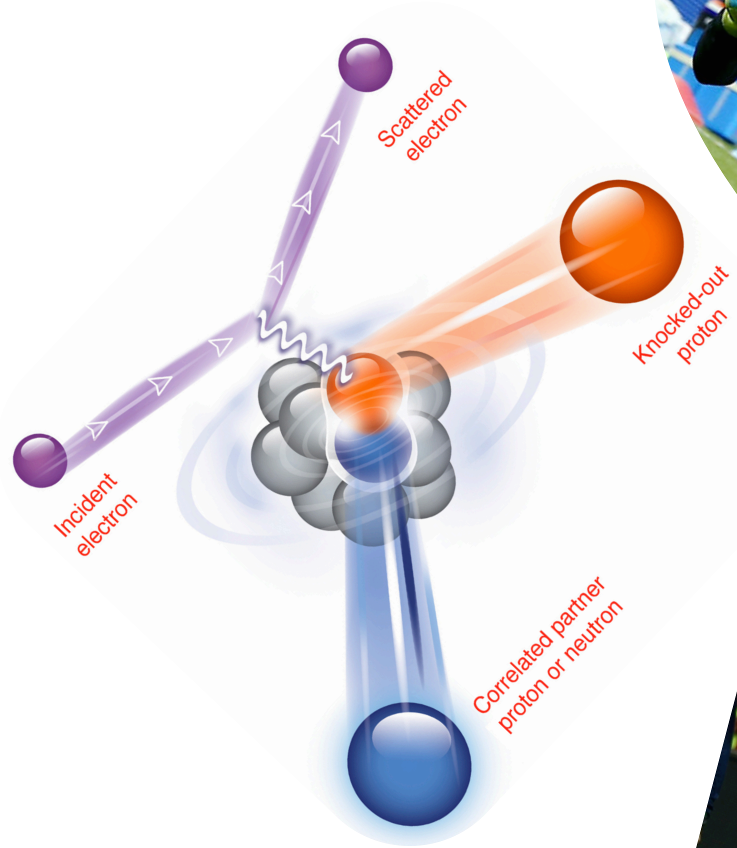
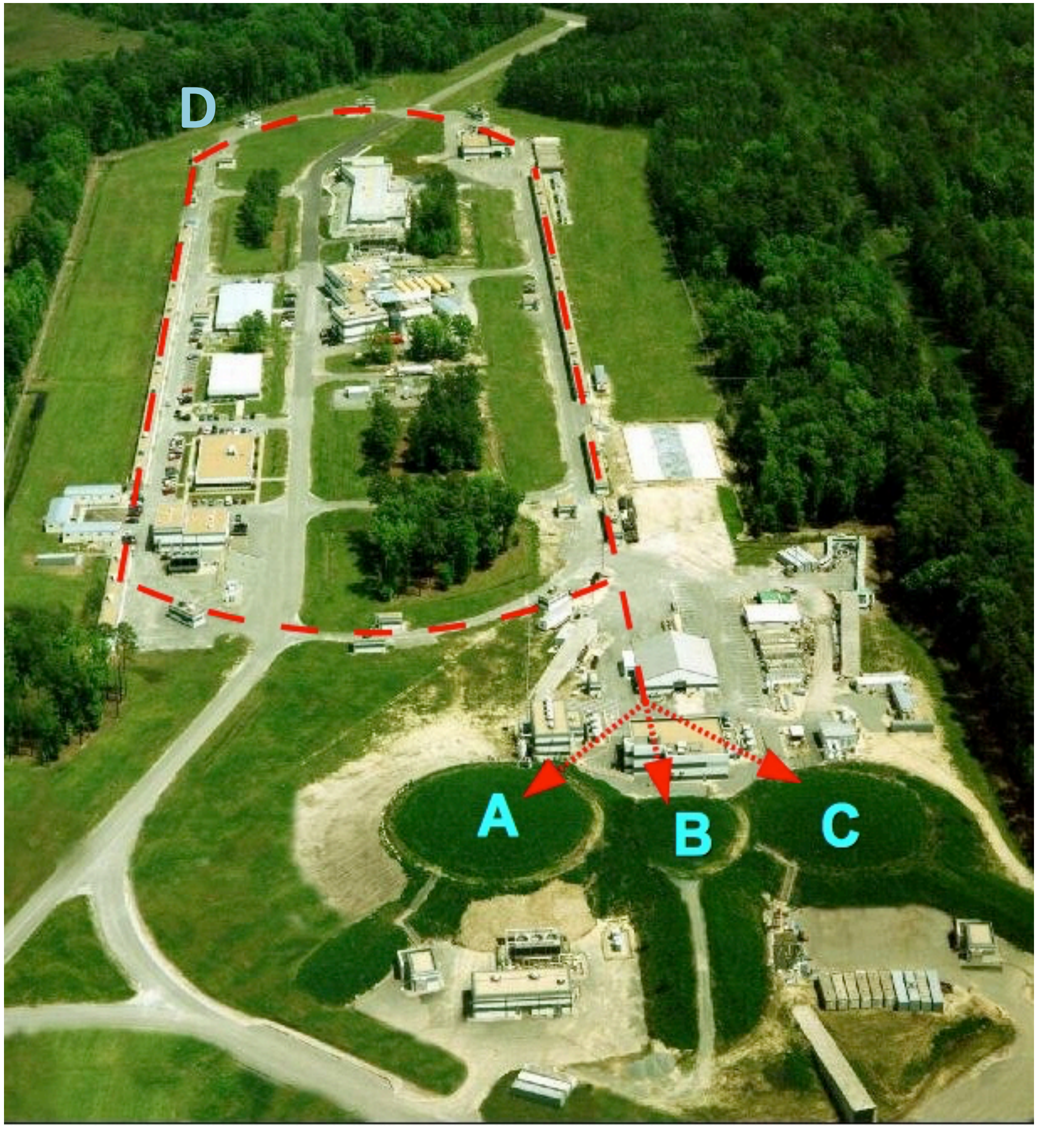


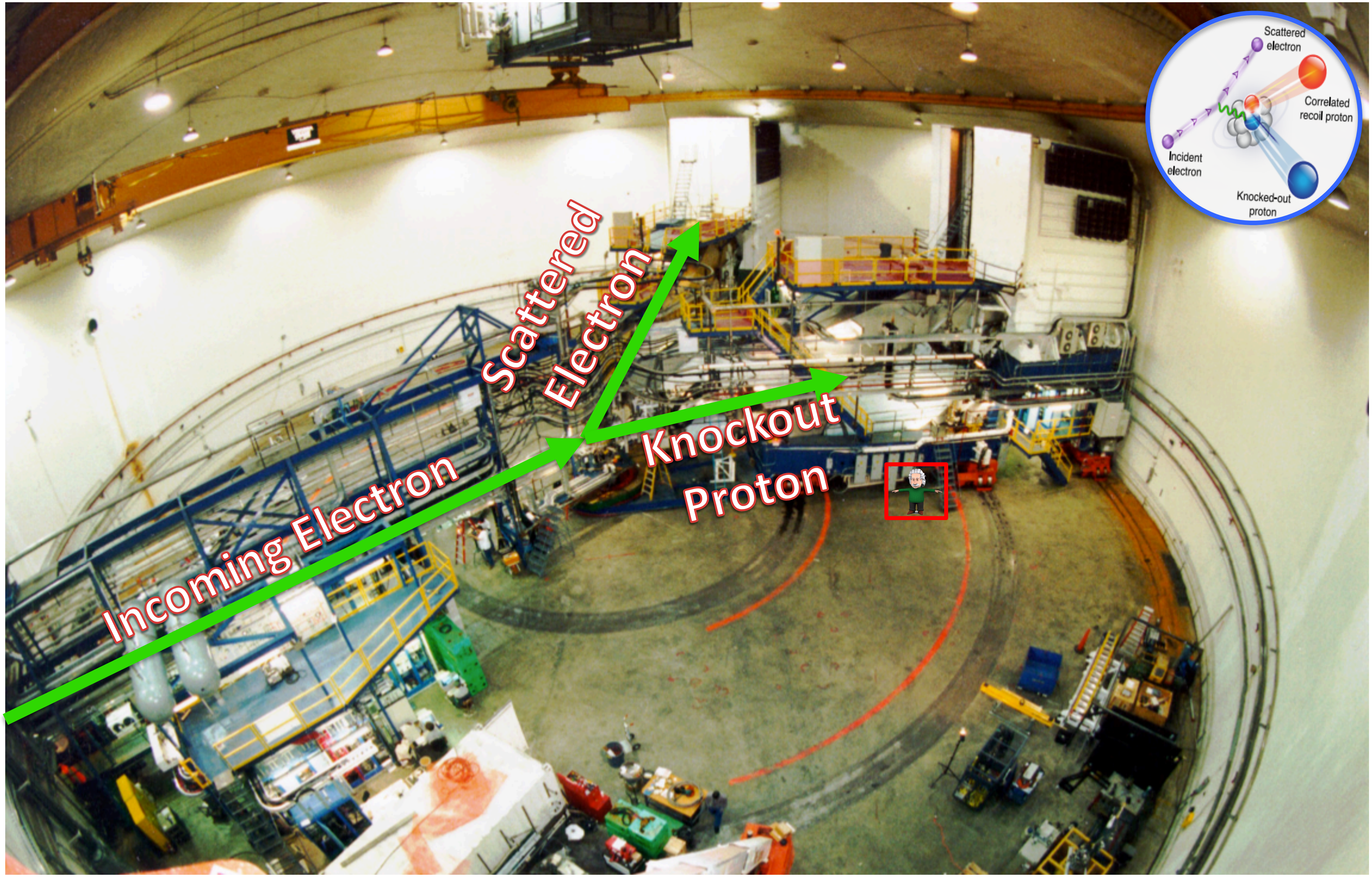
FIFA WORLD CUP
Brasil

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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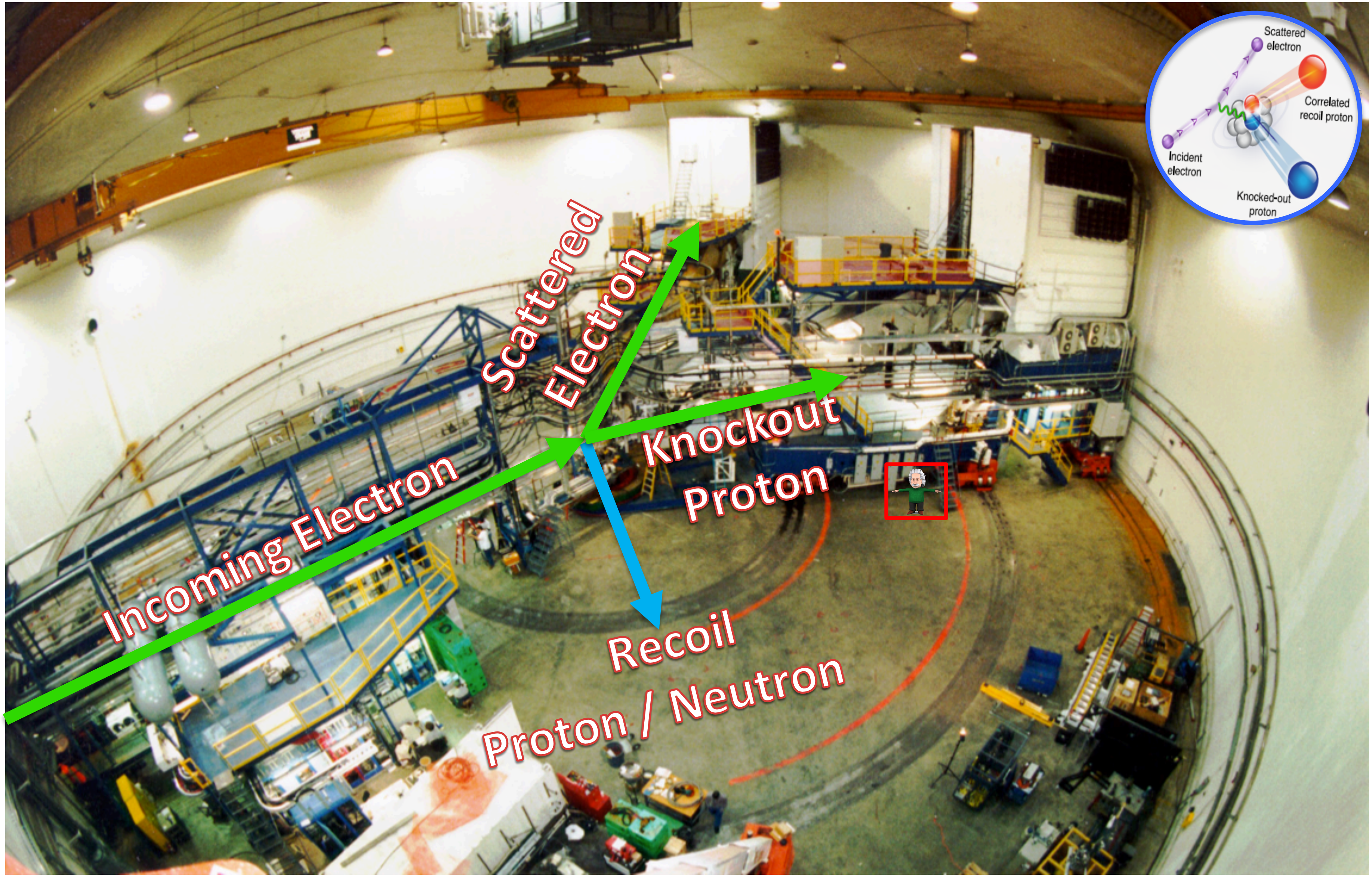

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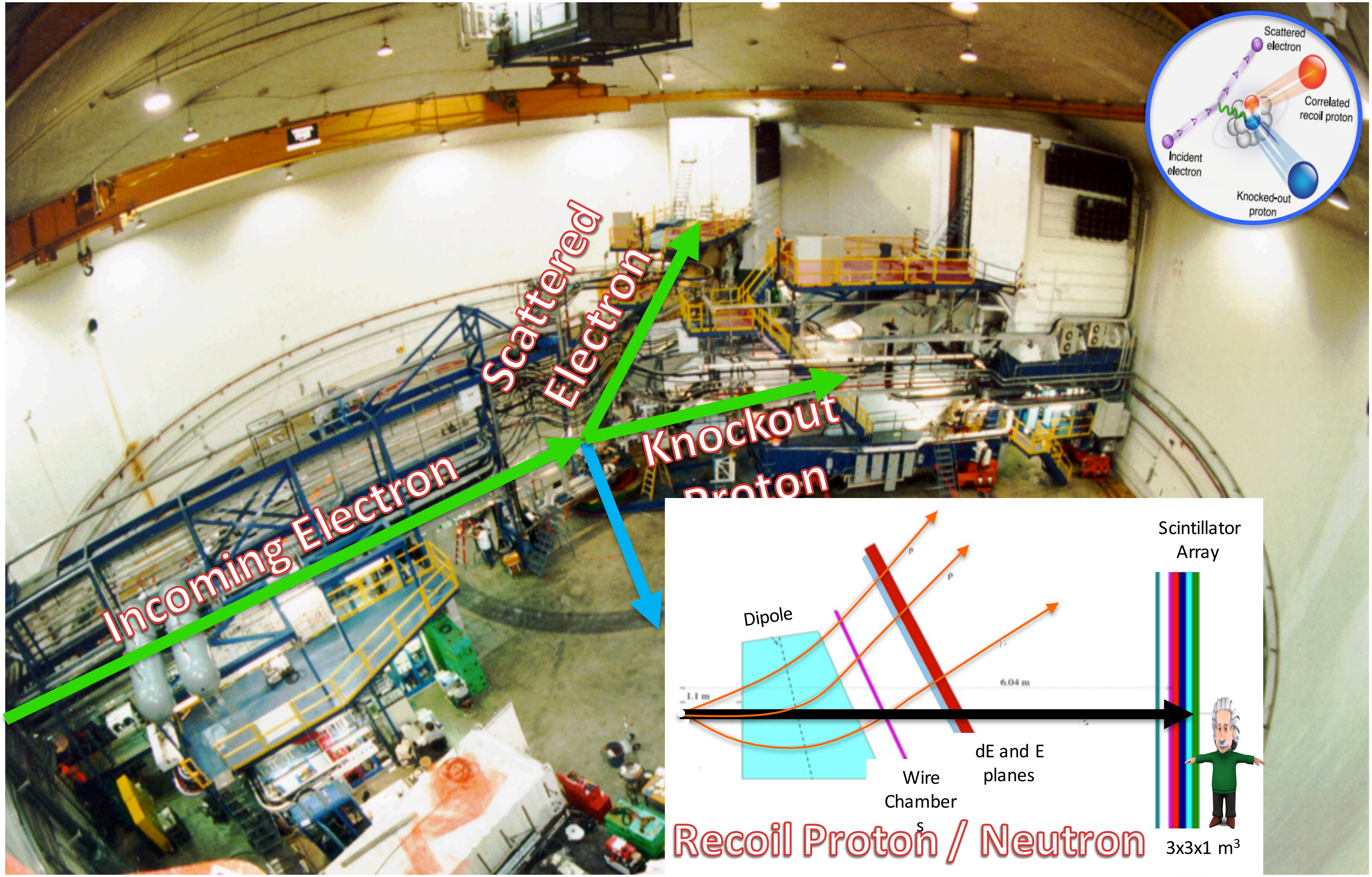
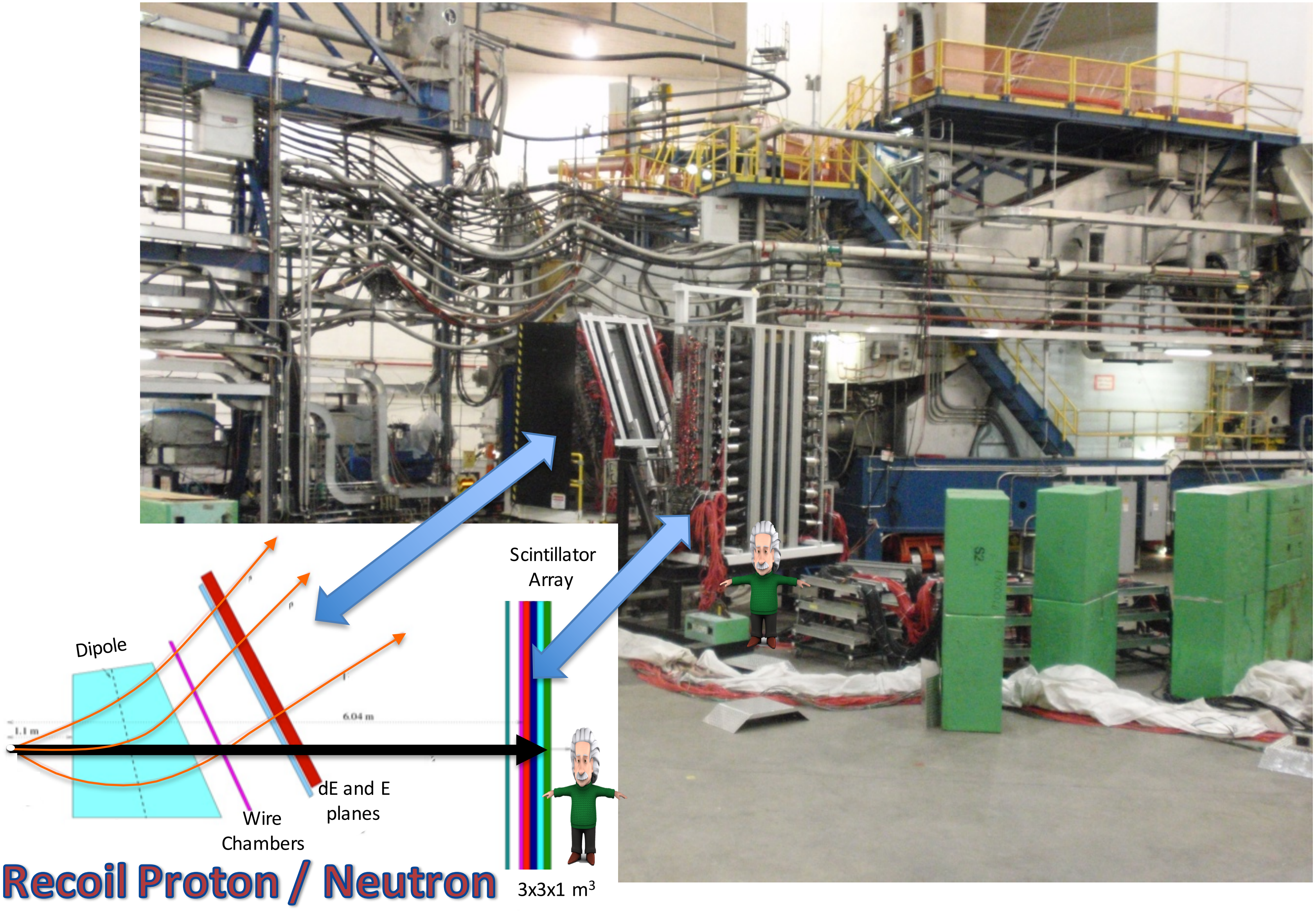


Building BigBite and HAND



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)

Award Winners - Members of Jefferson L
transfer" from the Federal Laboratory Co
improves the detection of breast cancer.

World Leader - Jefferson Lab's Free-Ele
Nature magazine. You can read the story

Breakthrough Research - Jefferson Lab
Geophysical Institution of Washington, D
House. The award is part of a $777 millio

Groundbreaking - More than 400 people
start of construction of the $310 million 1

Stimulus Dollars - The U.S. Department
receive $75 million from President Obama
project and to modernize infrastructure.

Great Job - Jefferson Science Associate
extension is based on performance score
"A" for science and technology, and an "

12 GeV Contract - A Virginia Beach com
supporting facilities at Jefferson Lab as p

Second Chance - This accelerator cavity
suffered, eventually declining below mini
beleaguered cavity and were rewarded w

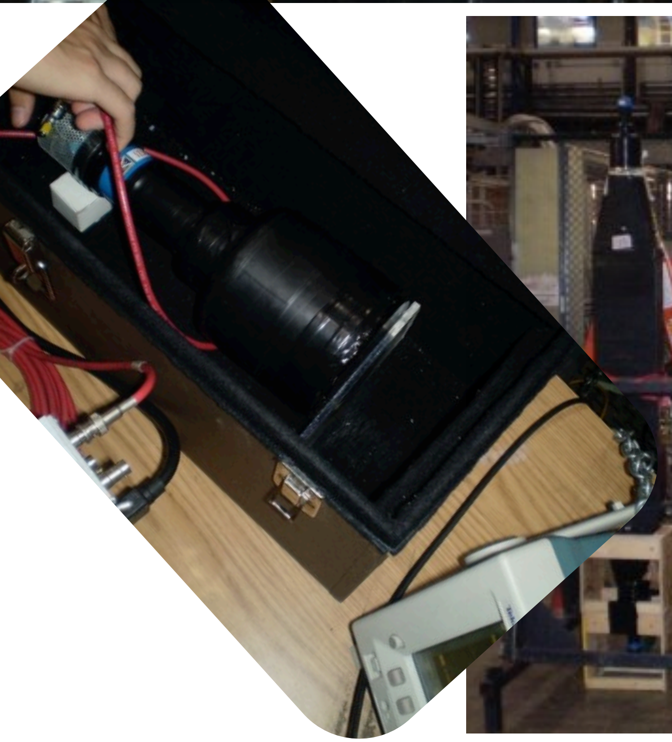
Neutron Duality - There are two ways to
overall image. This analogy applies to a
probing a phenomenon called quark-had

LAB EVENTS

DOE ACTS
July 7-31, 2009

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

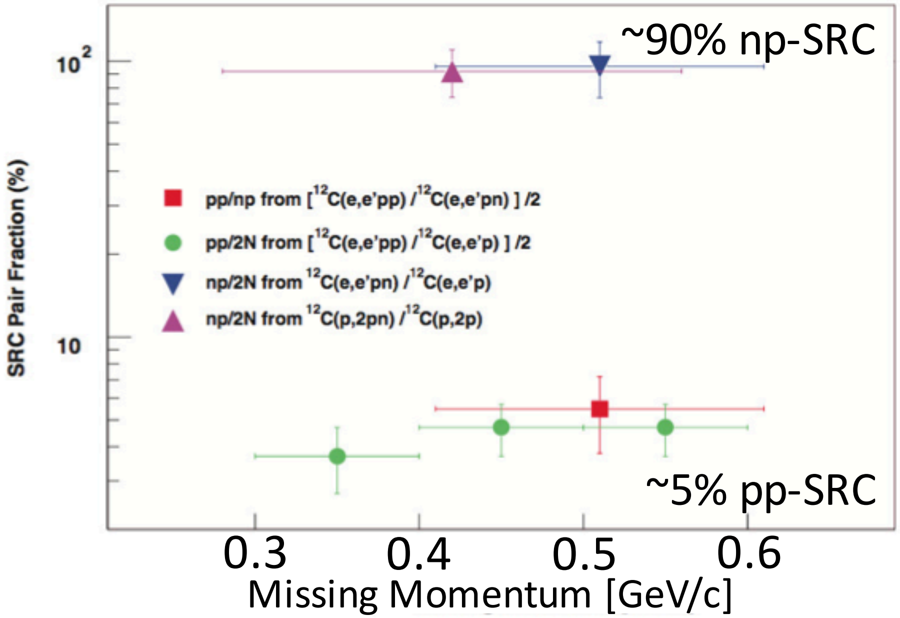
HS Summer Honors Program
June 15-July 31, 2009

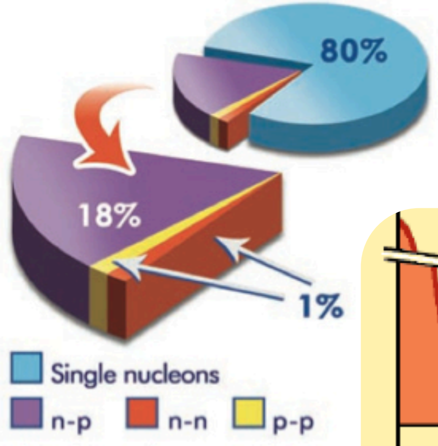


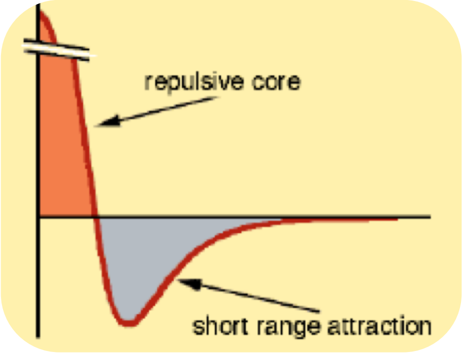

100%

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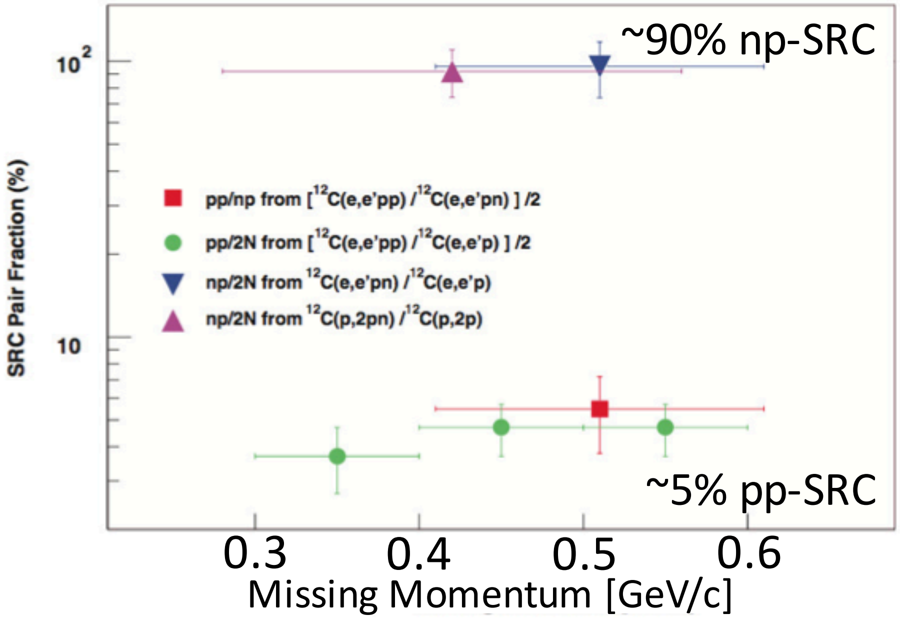

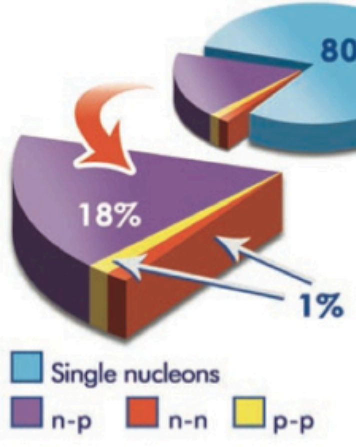

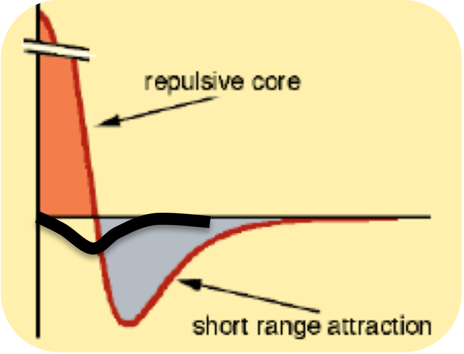

A. Tang et al., Phys. Rev. Lett. 90 (2003) 042301
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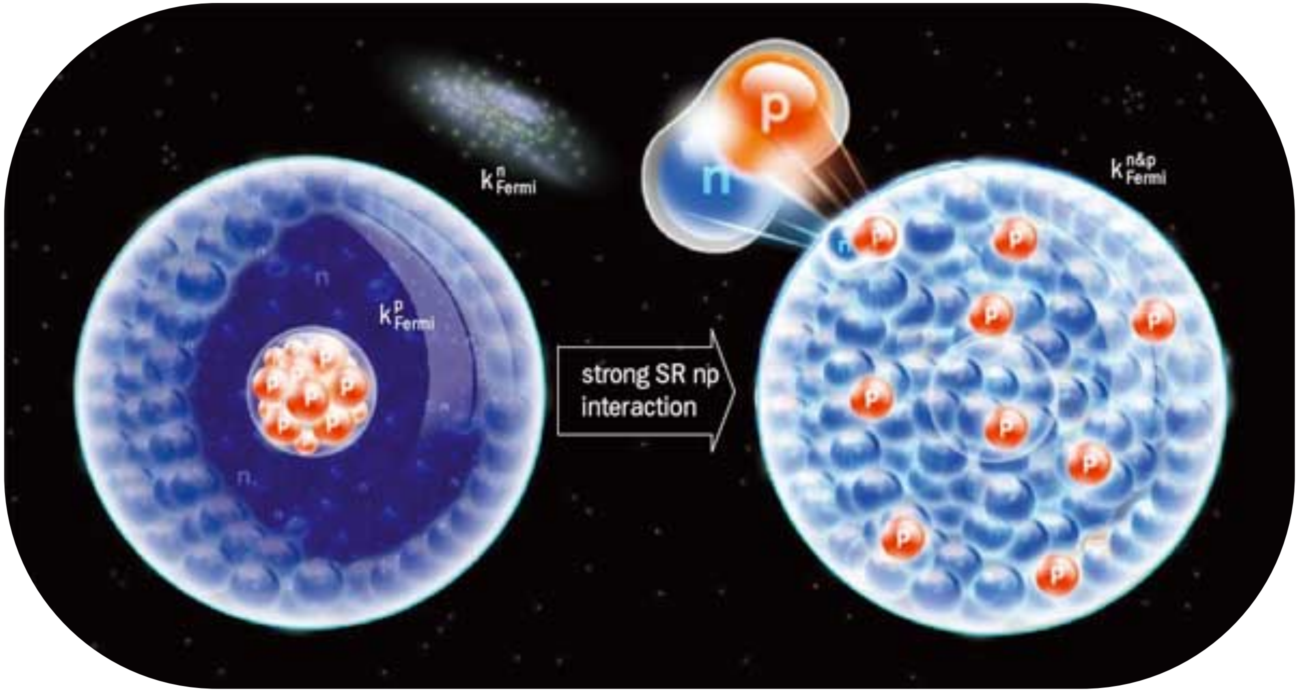
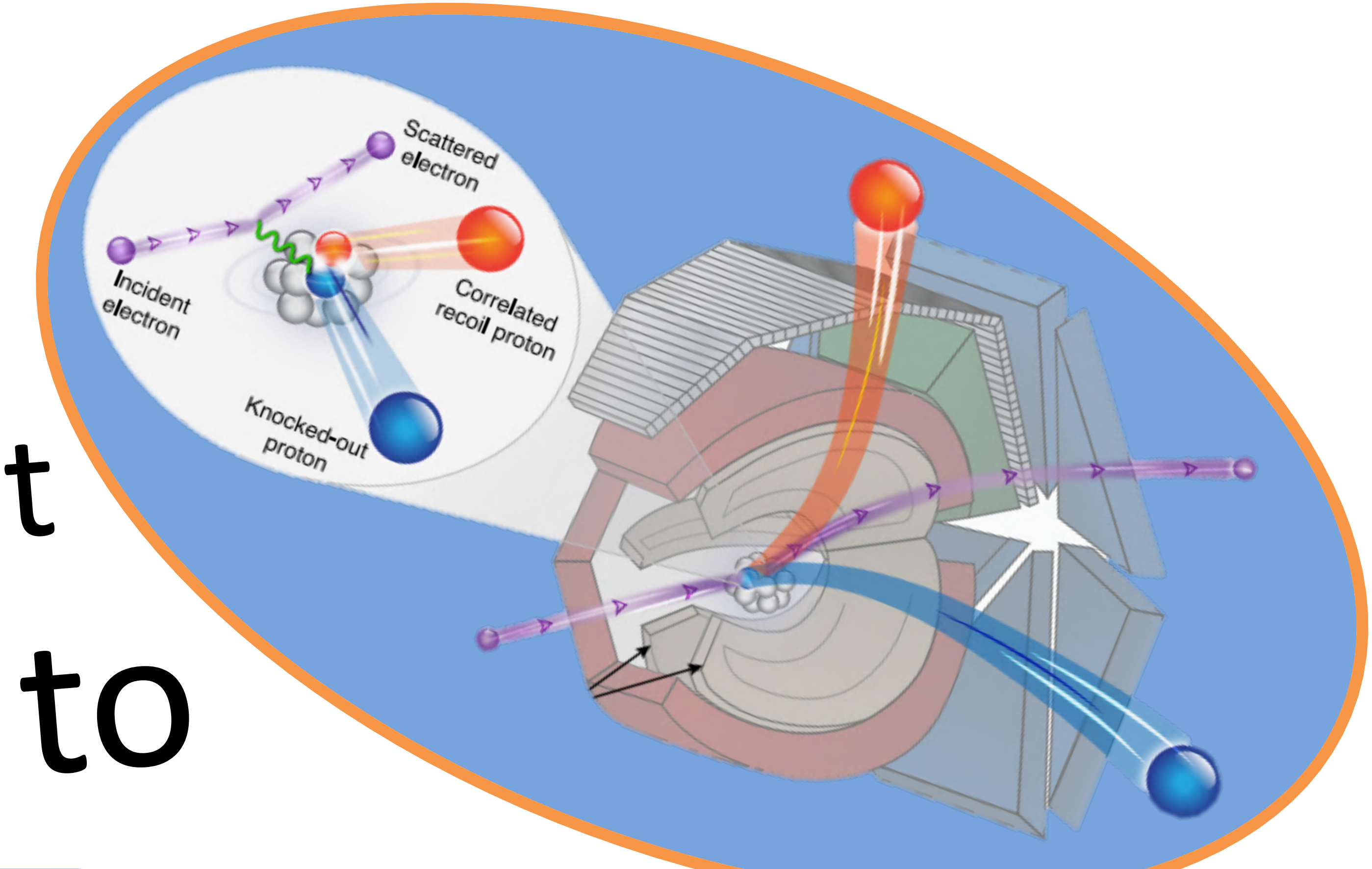
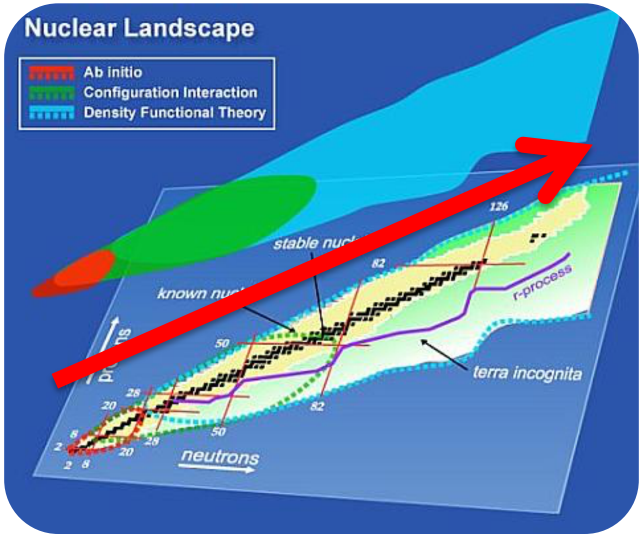


Neutrons heat protons in neutron stars?

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

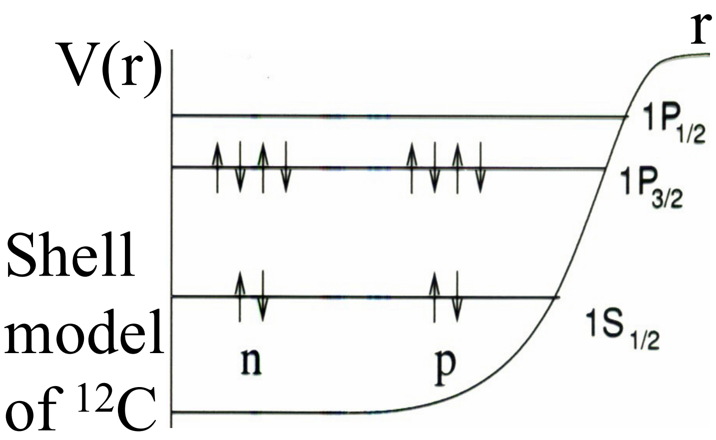
From Light to Heavy Nuclei

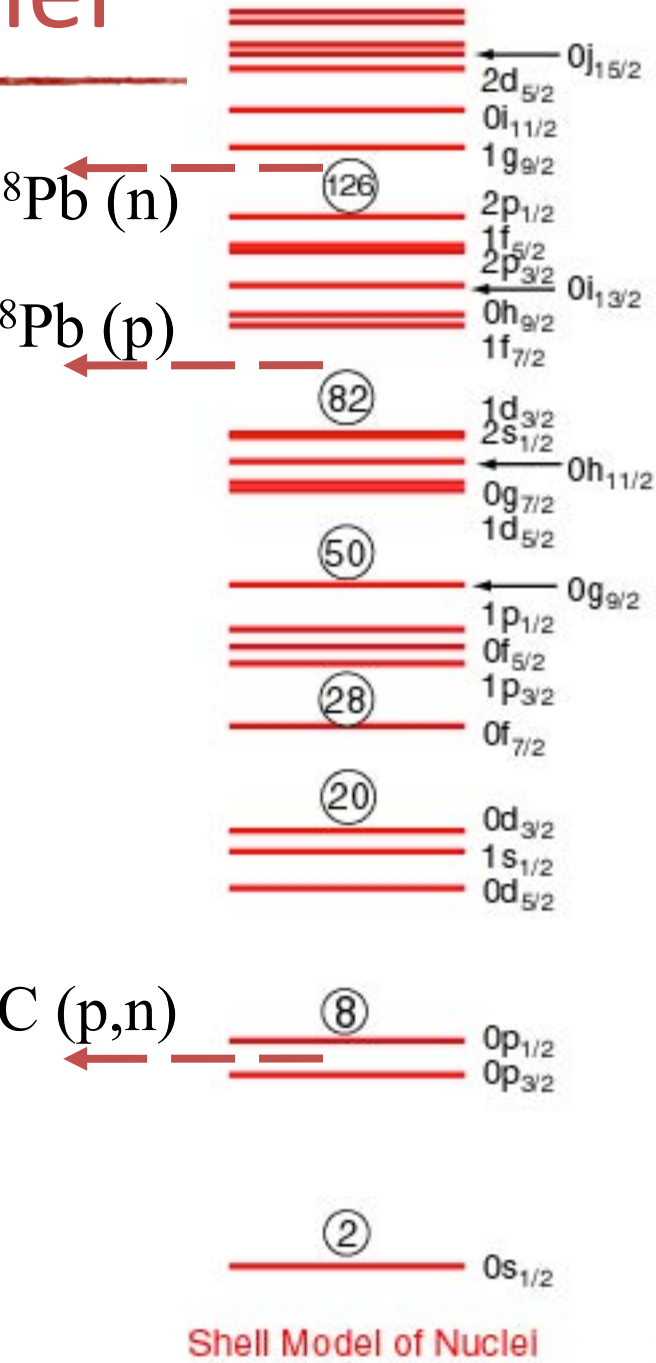


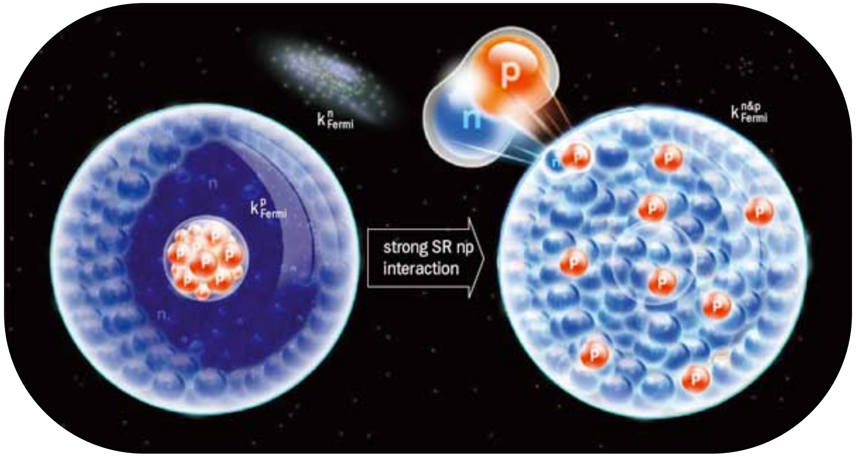


Correlations in Heavy Nuclei

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

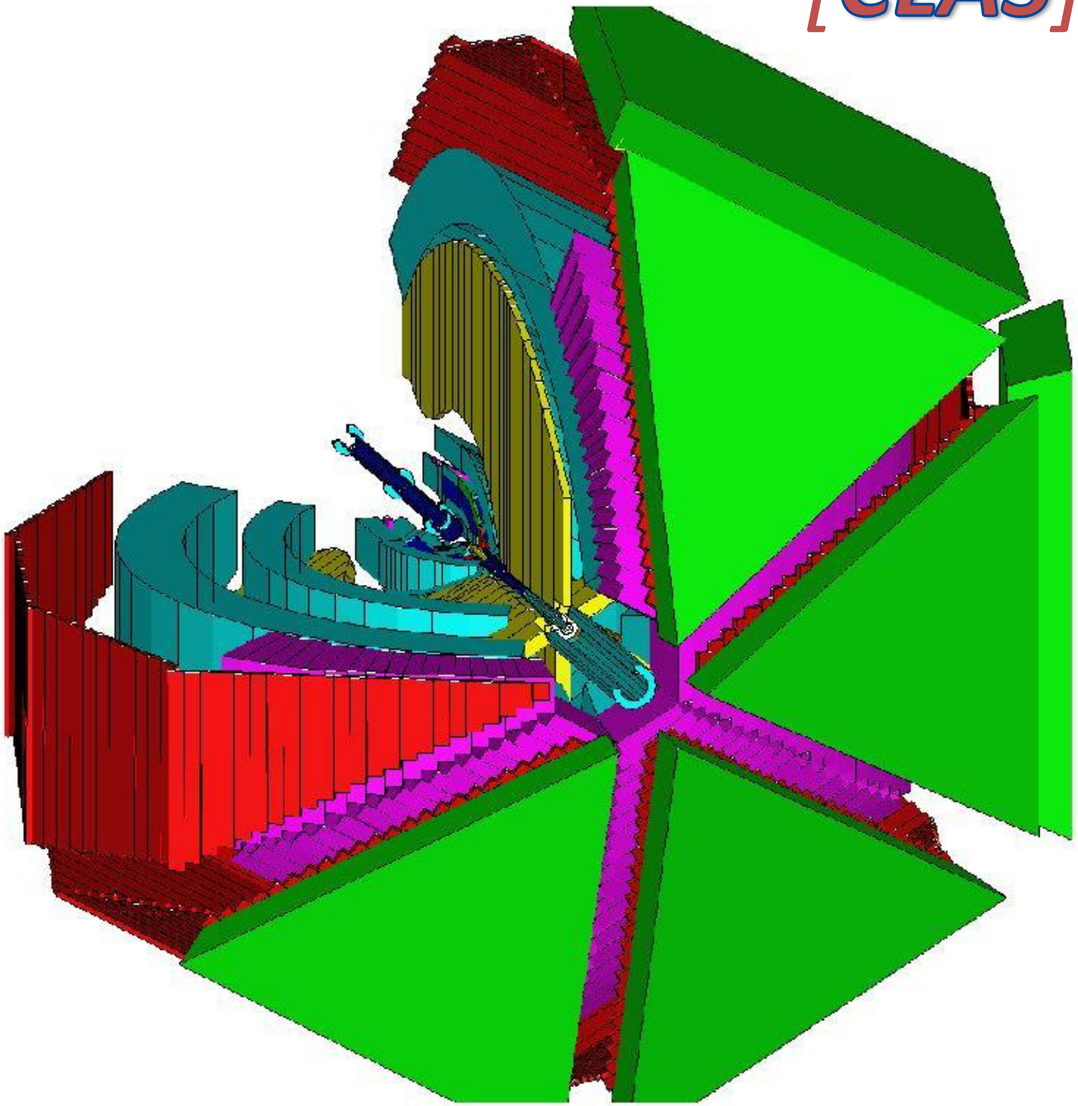


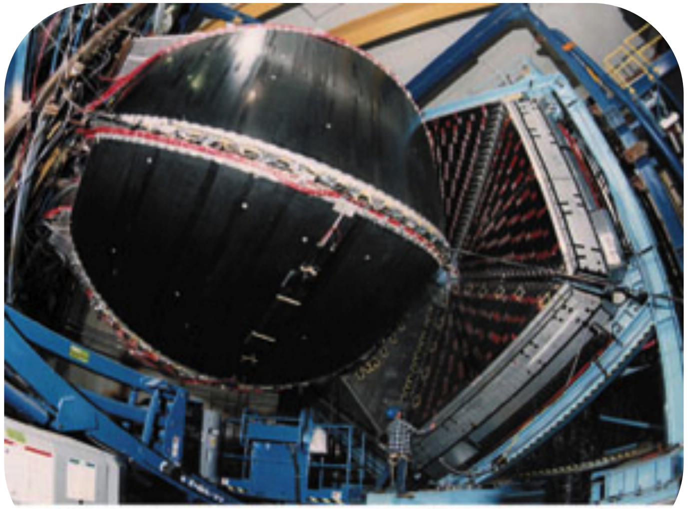




CEBAF Large Acceptance Spectrometer

[CLAS]





Hall B Large Acceptance Spectrometer

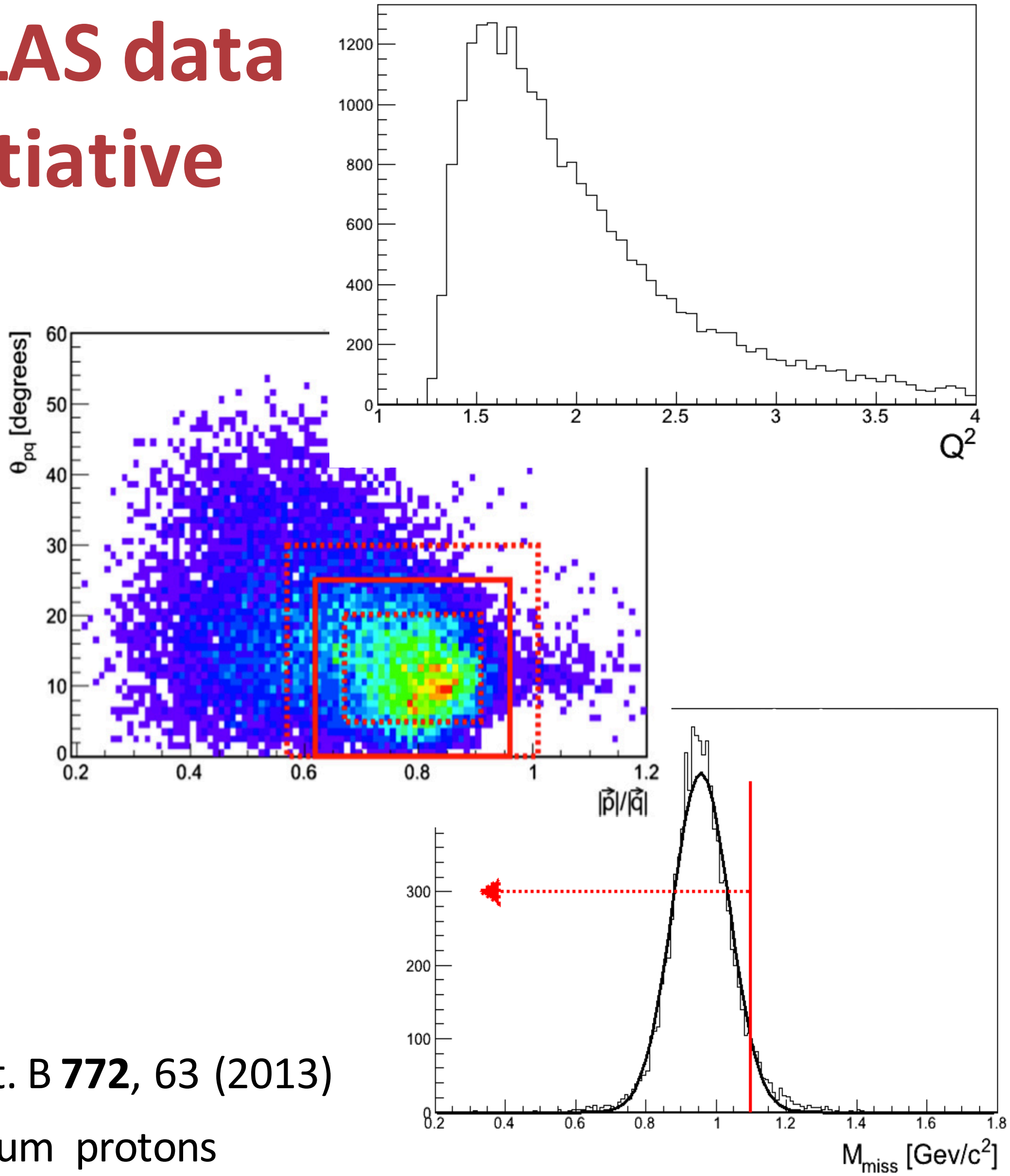
Open (e,e’) trigger, Large-Acceptance, Low luminosity (~10^{34} cm^{-2} sec^{-1})

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:

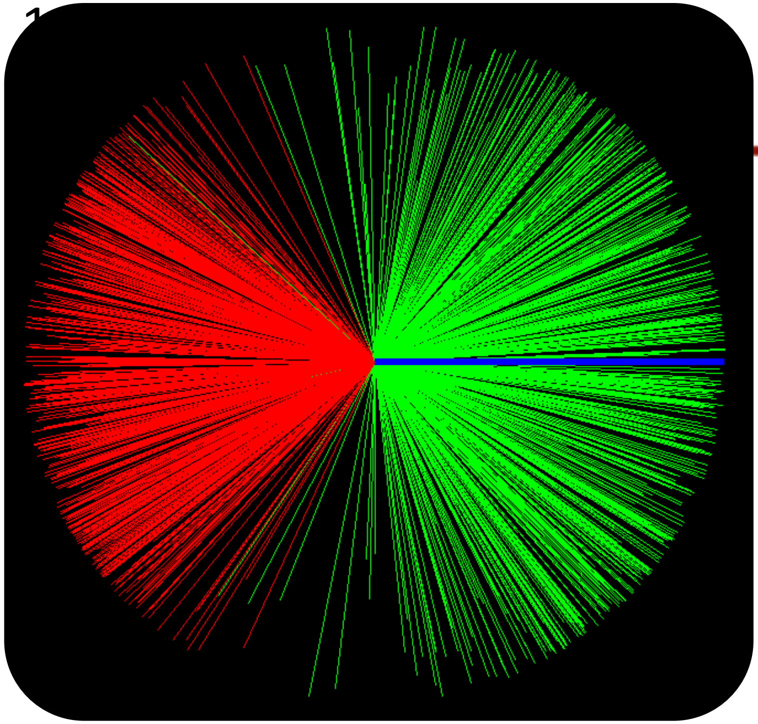
1. Cut (e,e'p) kinematics to simulate previous measurements*.
2. Look for a correlated recoil proton.

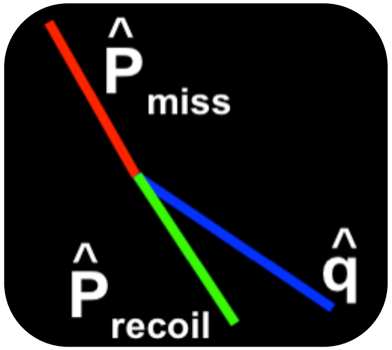


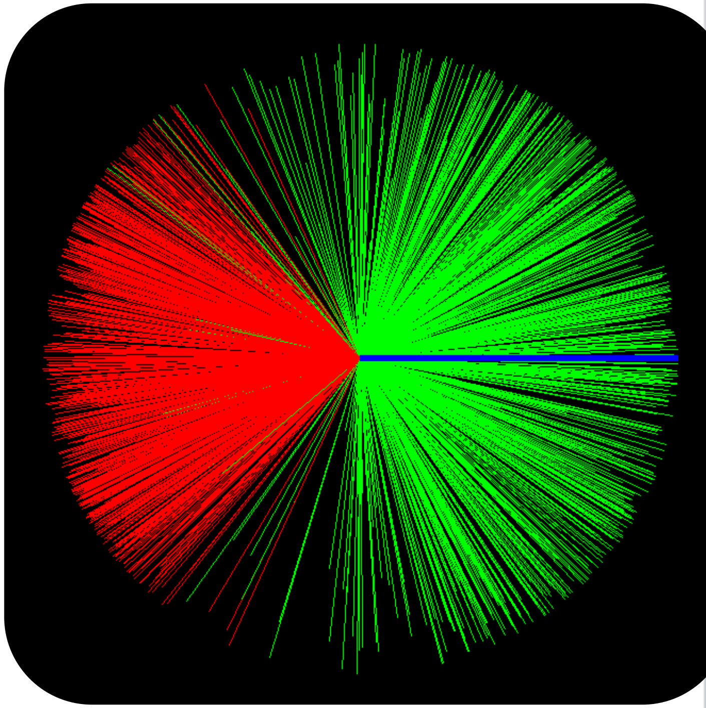
O. Hen et al. (CLAS Collaboration), Phys. Lett. B **772**, 63 (2013)

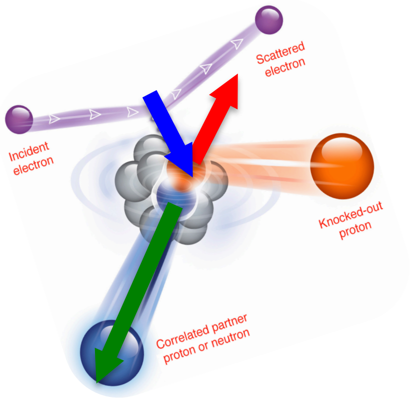
*Quasielstic knockout of high-initial-momentum protons

3D Reconstruction



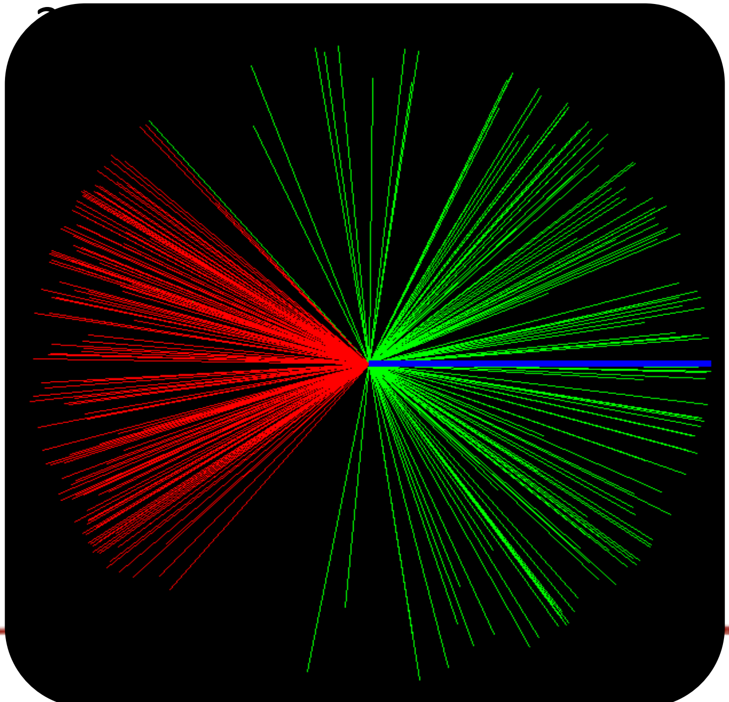


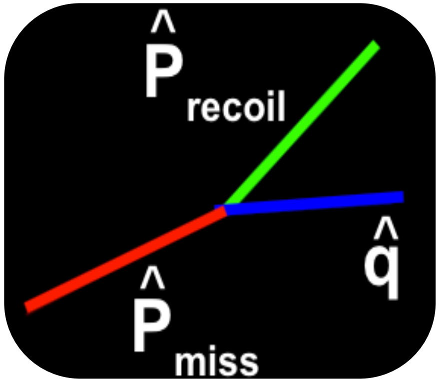




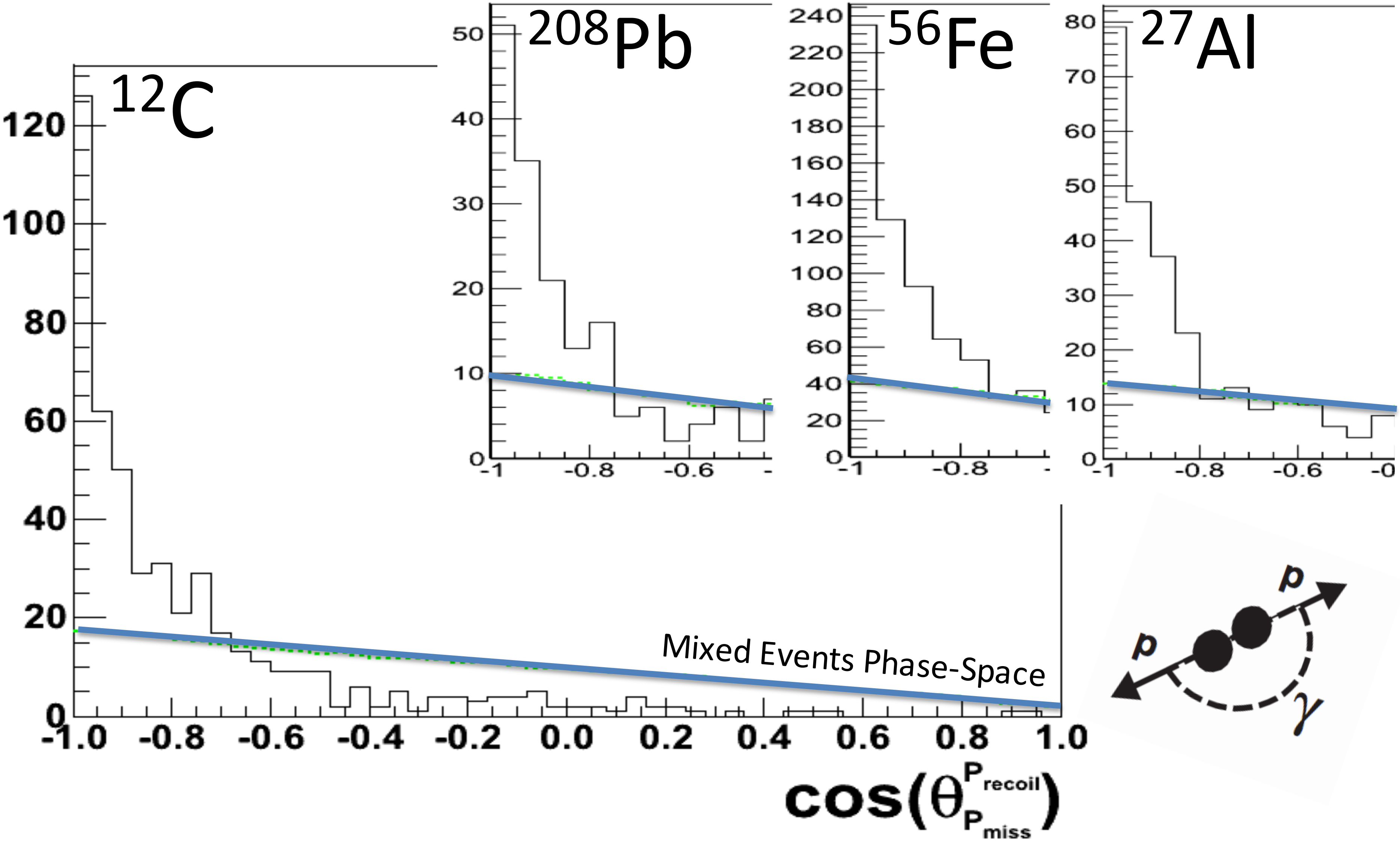
Back-to-back =

SRC pairs!





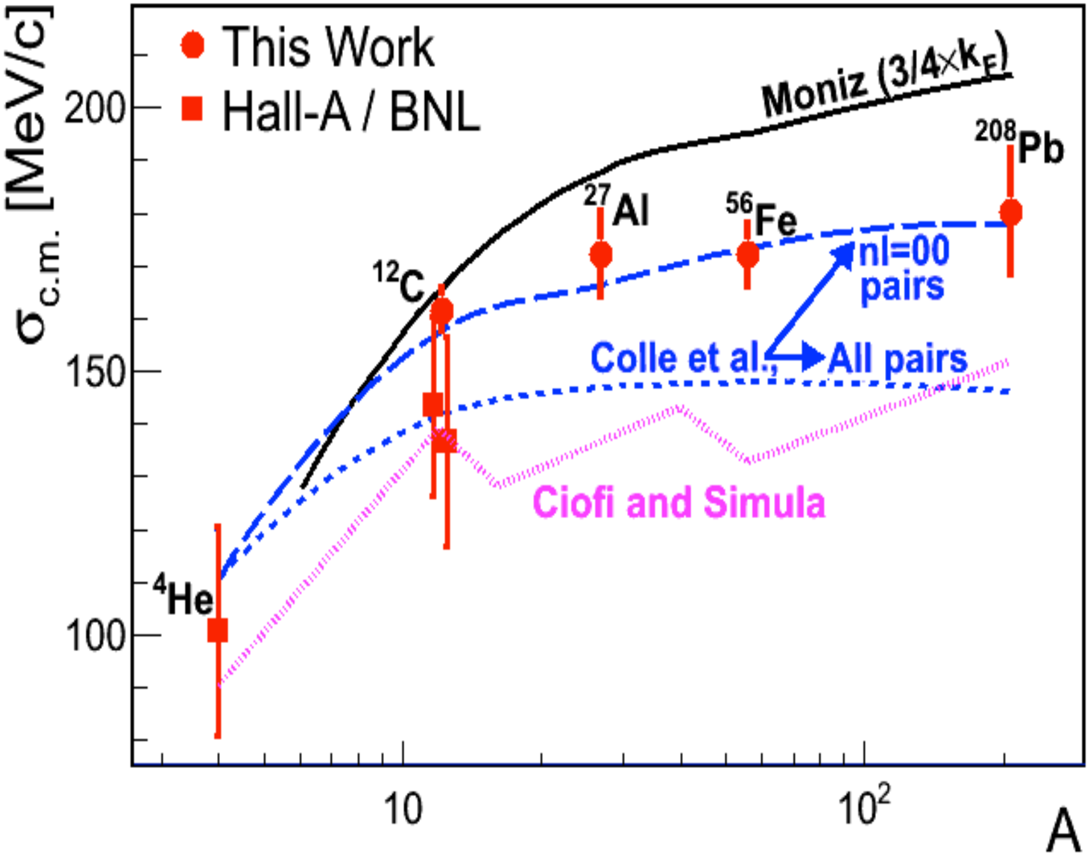
Opening Angle



Pair c.m. motion

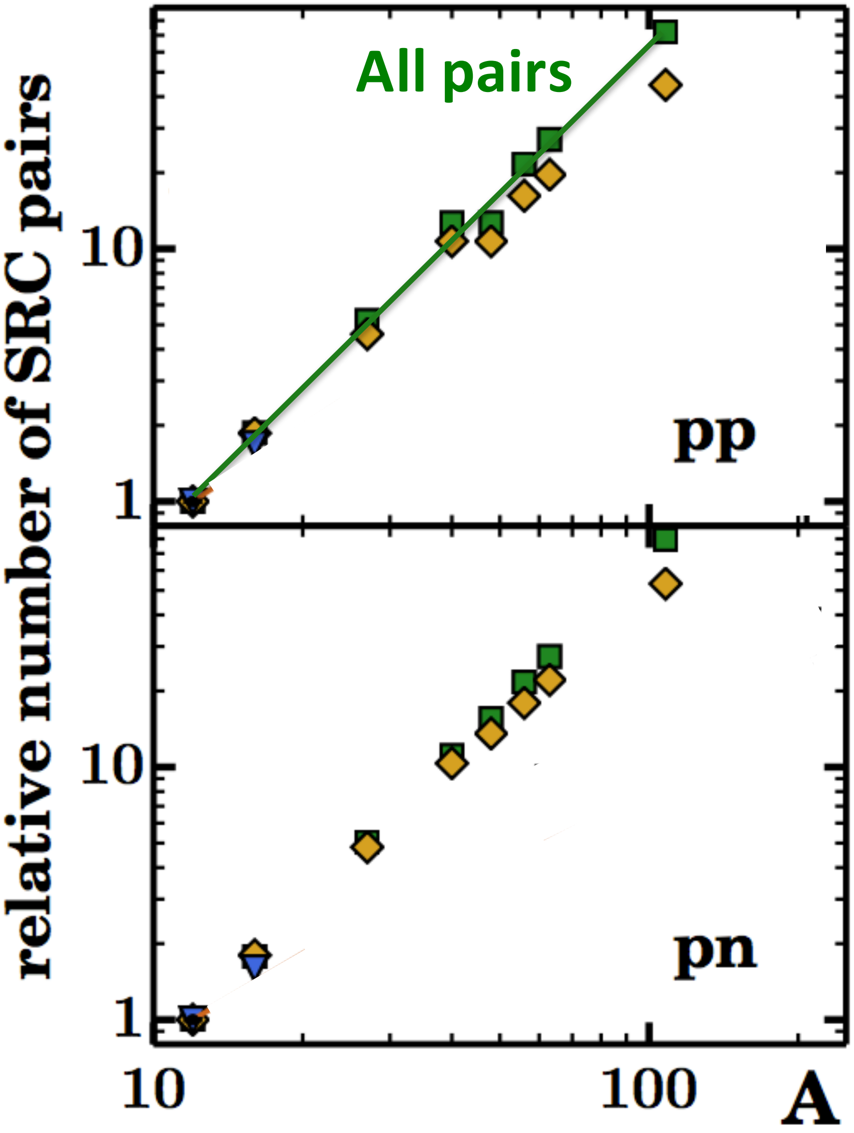
> "... *high relative momentum* and *low c.m. momentum* compared to the Fermi momentum (k_F)"

- Reconstructed total (c.m) pair momentum insensitive to FSI in the pair.
- Observed to be Gaussian in each direction.
- Small width, consistent with calculations.



Selectivity of SRC Pairs

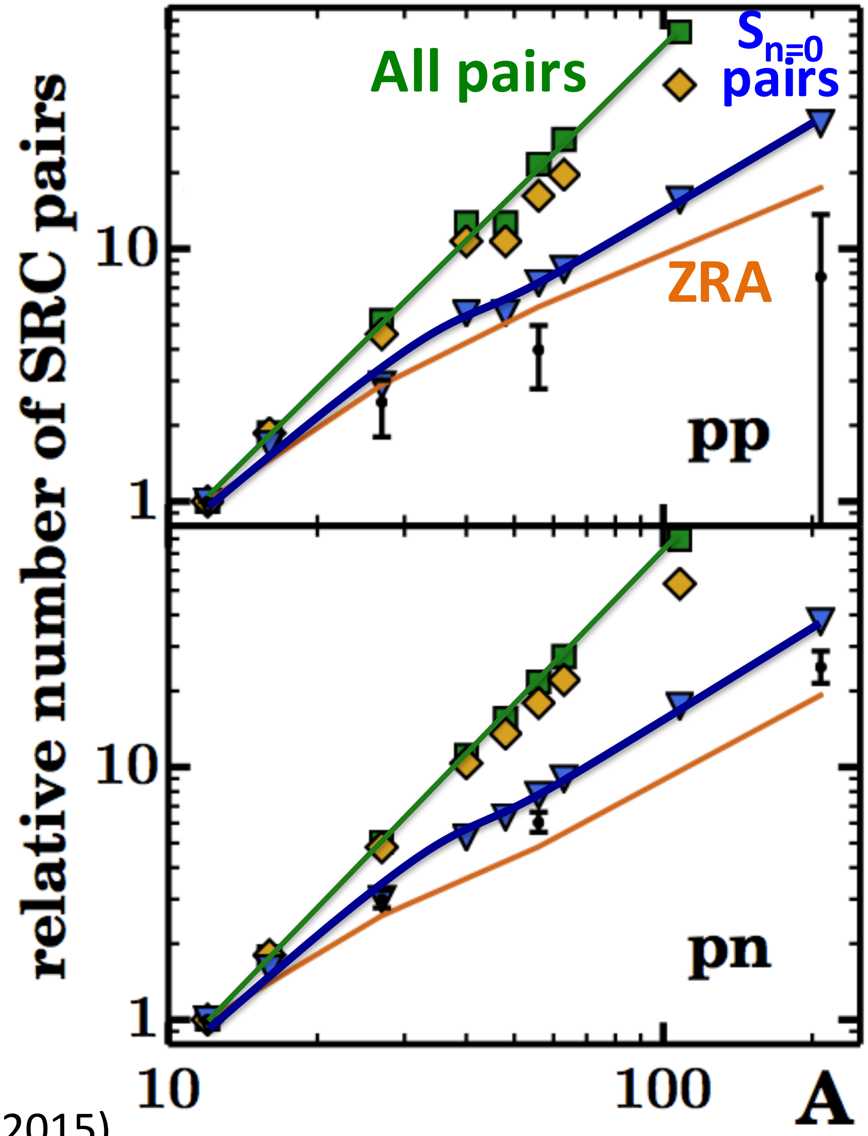
- Extract the number of pp (np) SRC pairs in nuclei relative to ^{12}C.



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

Selectivity of SRC Pairs

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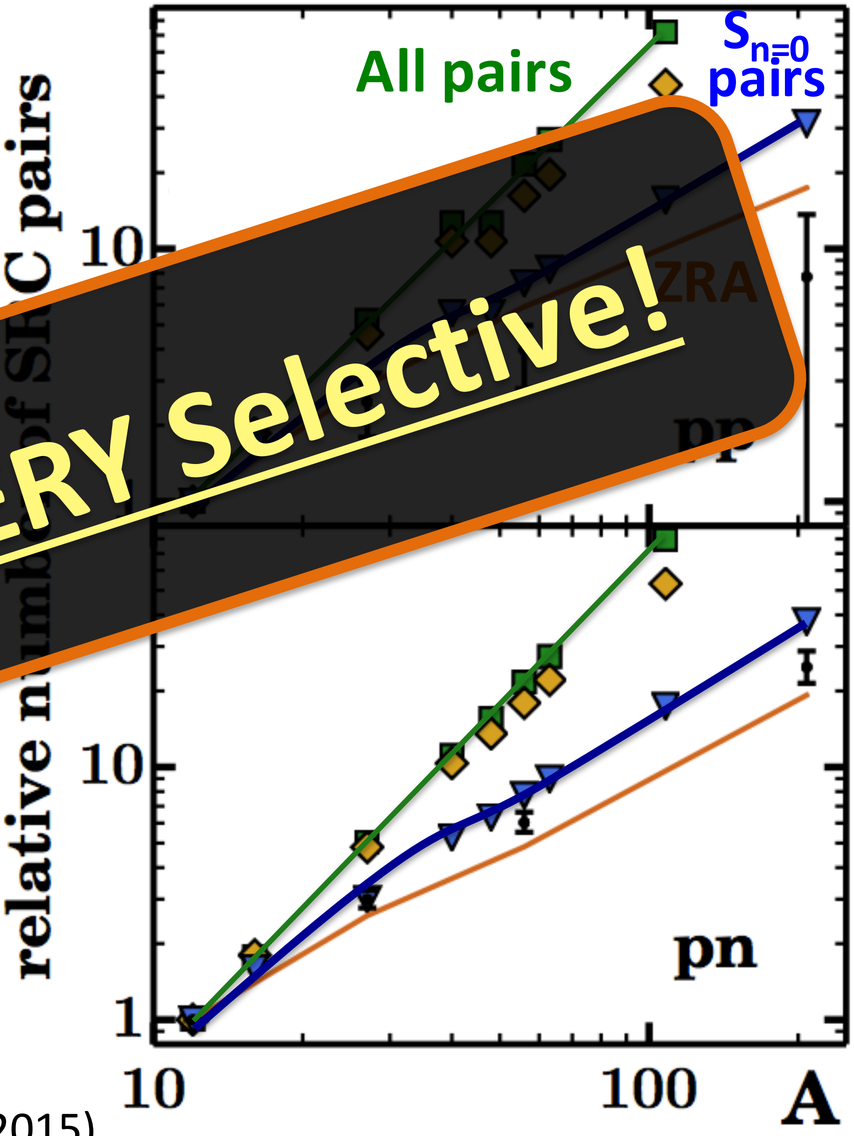
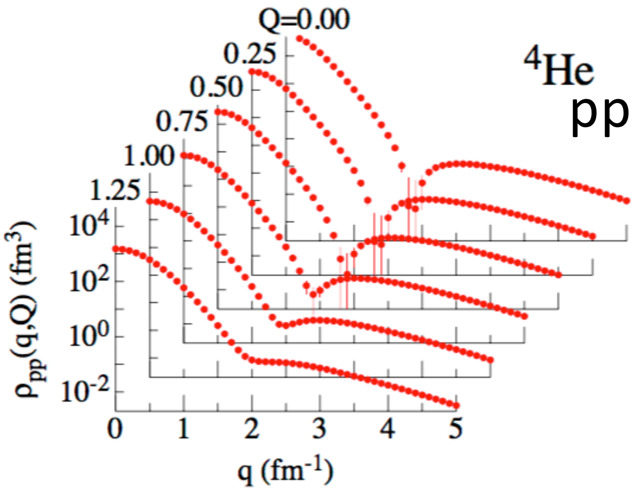
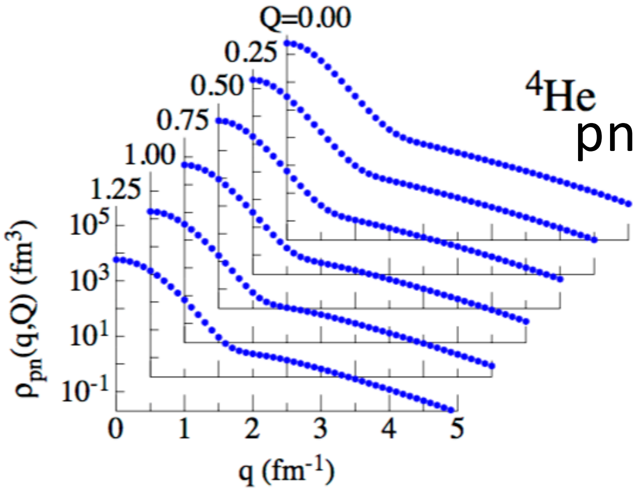


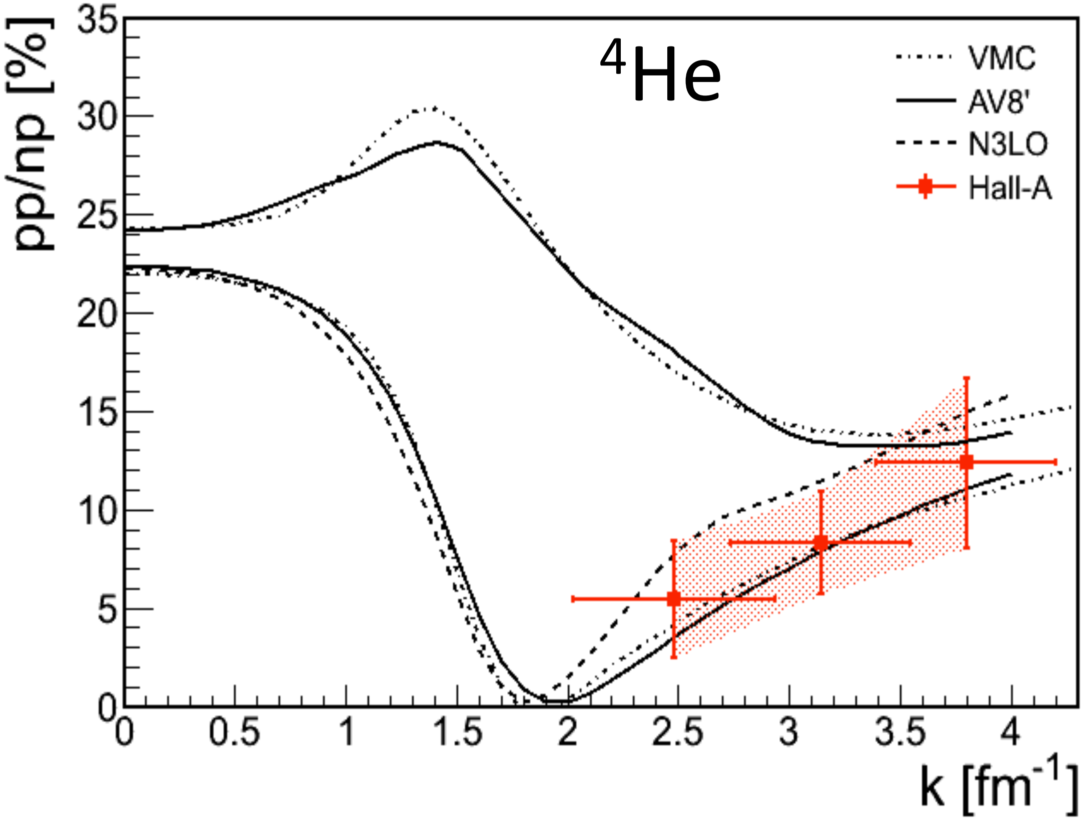
SRC Pairs are VERY Selective!

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).

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

Sensitivity to SRCs

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- (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

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

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

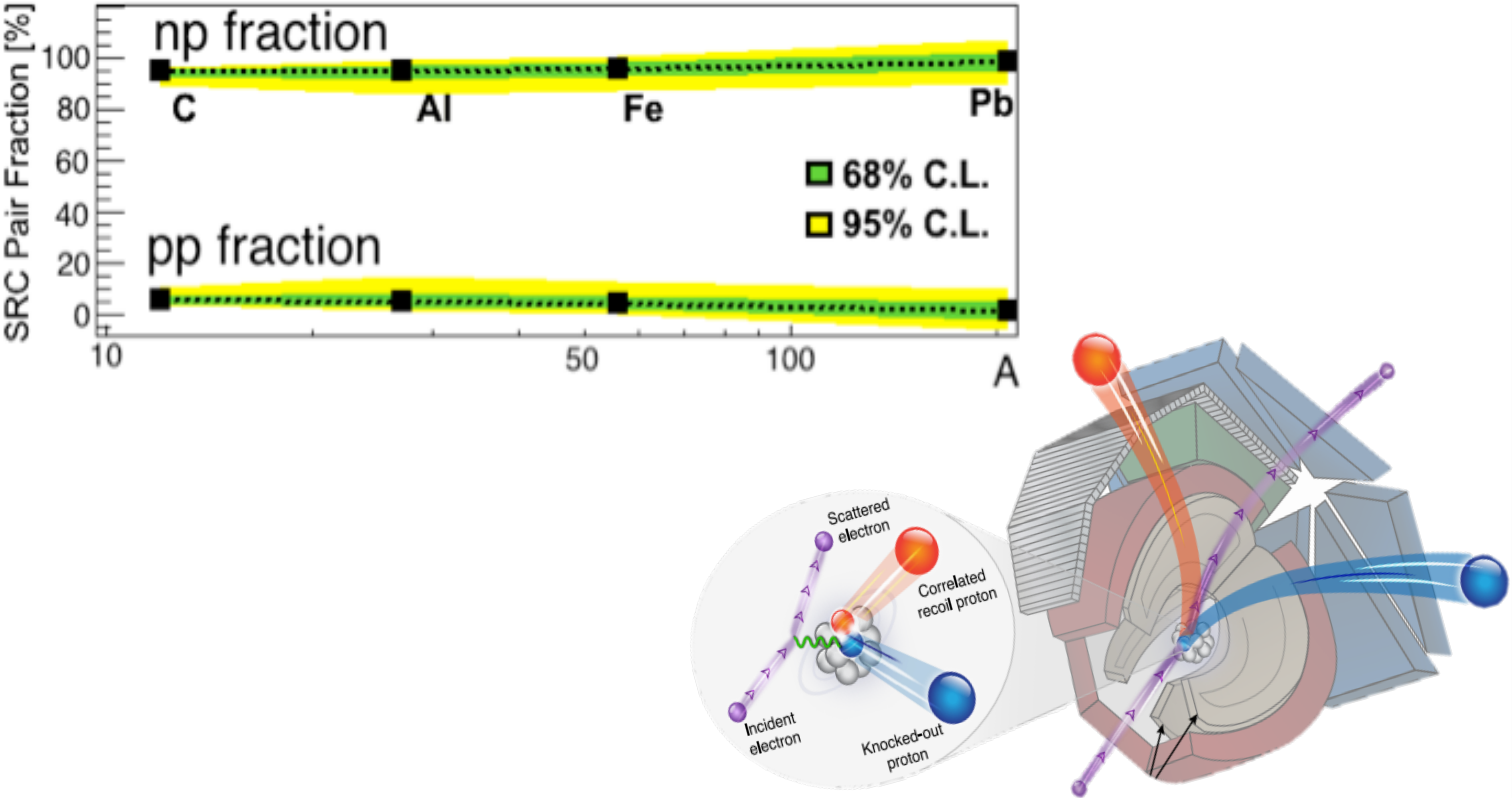
$$= \#\, pp_A \cdot 2\sigma_p \left[1 + \frac{1}{2}\frac{\#\, pn_A}{\#\, pp_A}\right]$$

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

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

(Attenuation and Single-Charge Exchange.)

np-pairs dominance in *heavy* nuclei



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

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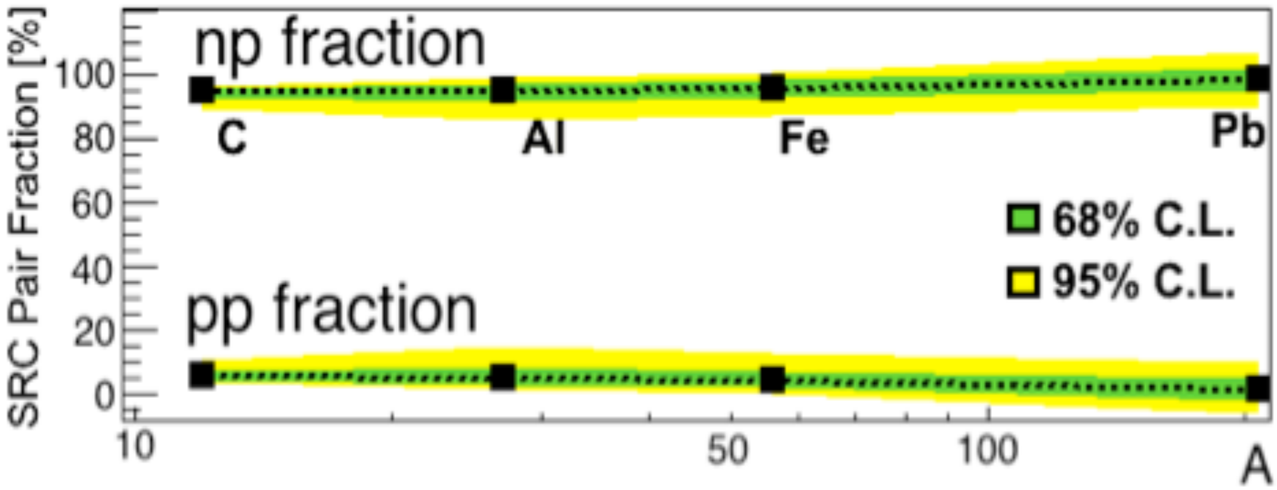
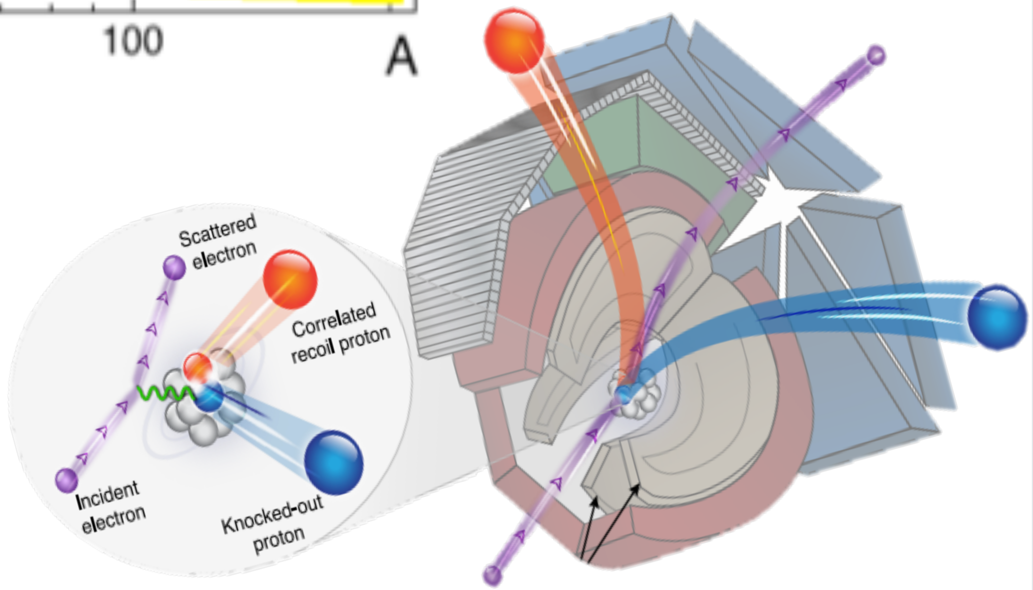
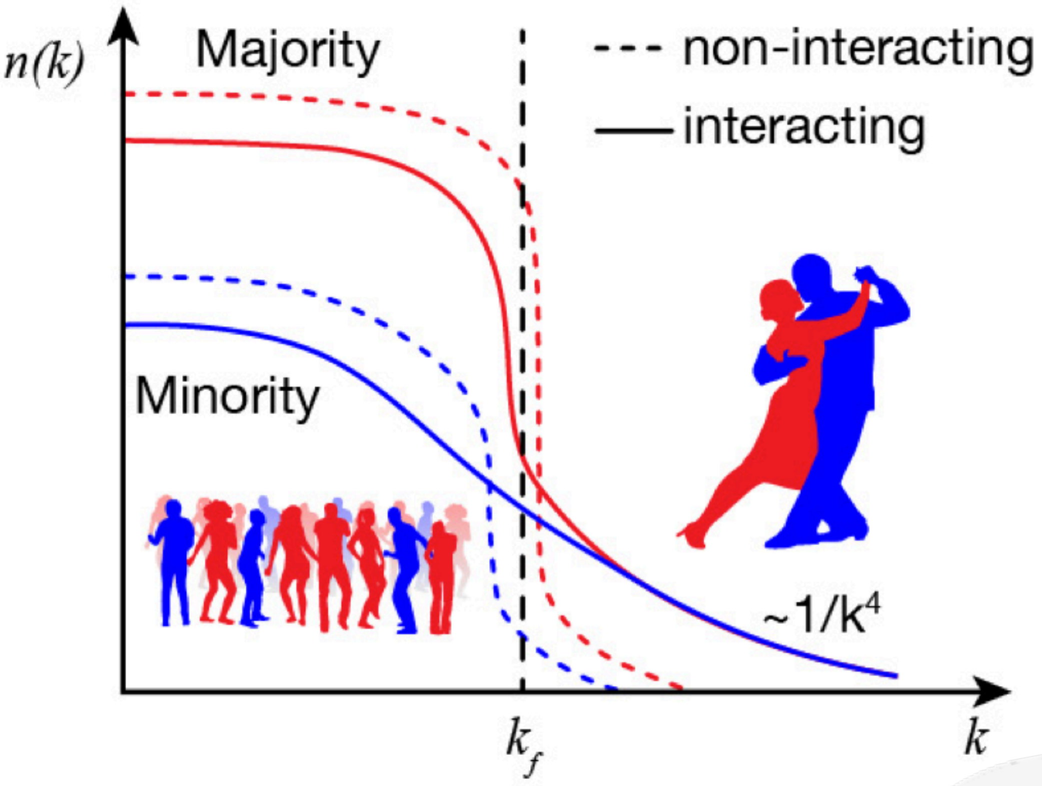


What can we learn from this result on general Fermi systems?

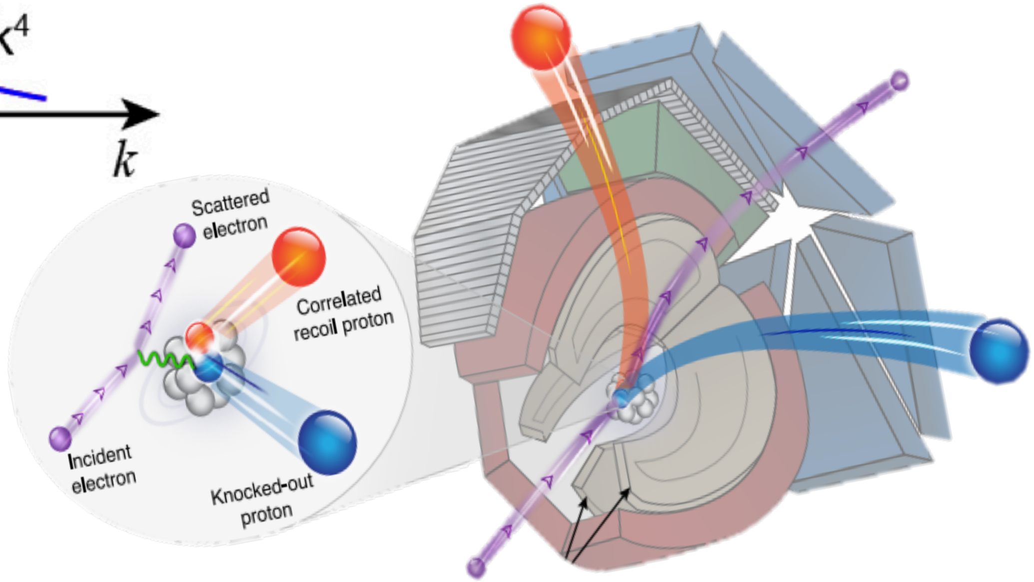


O. Hen et al. (CLAS Collaboration), Science 346, 614 (2014)

Kinetic Energy Sharing



Momentum distribution of an imbalanced two-component Fermi system



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

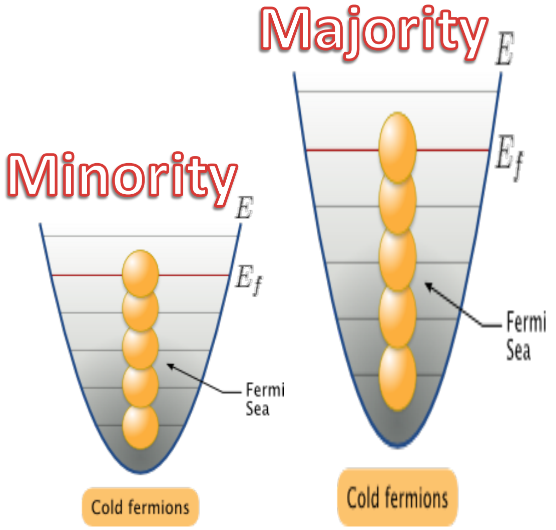
Kinetic Energy Sharing in Asymmetric Nuclei

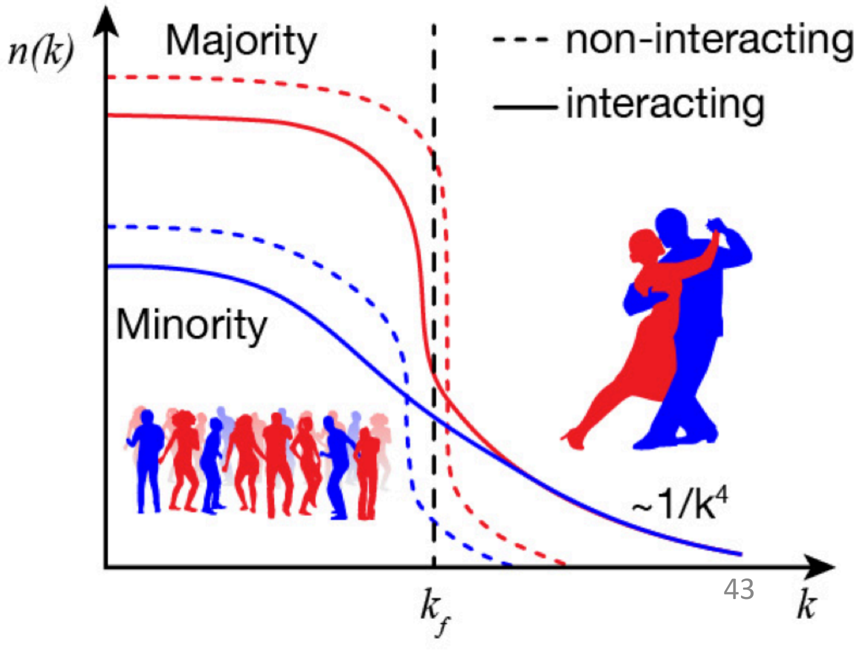
Pauli Principle:

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

np correlations:

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





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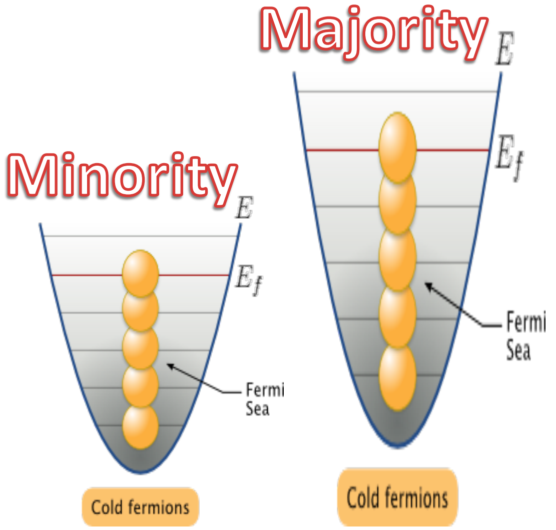
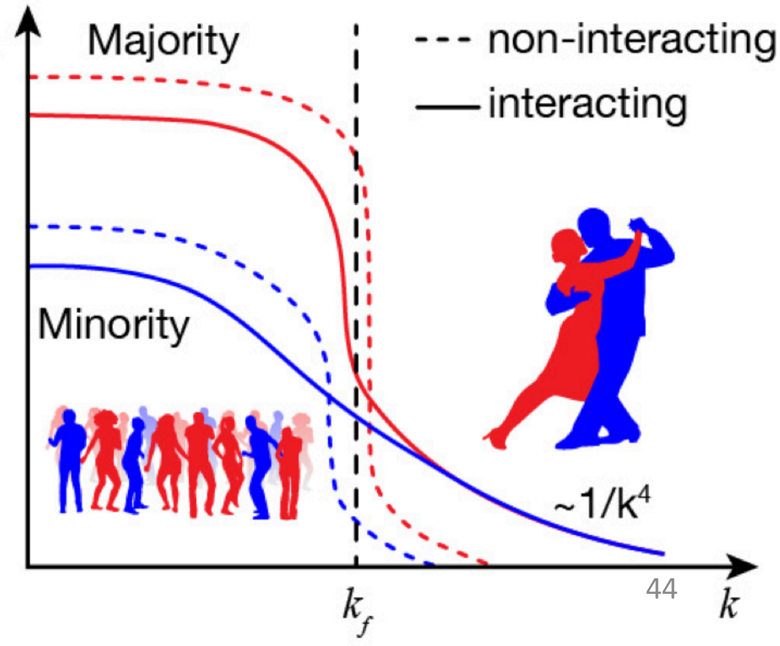
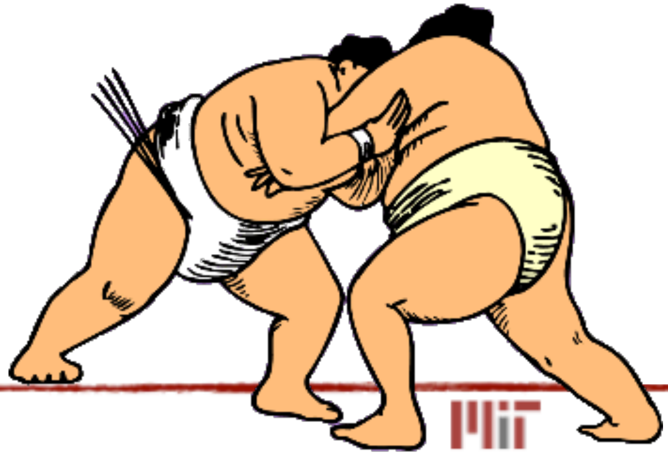
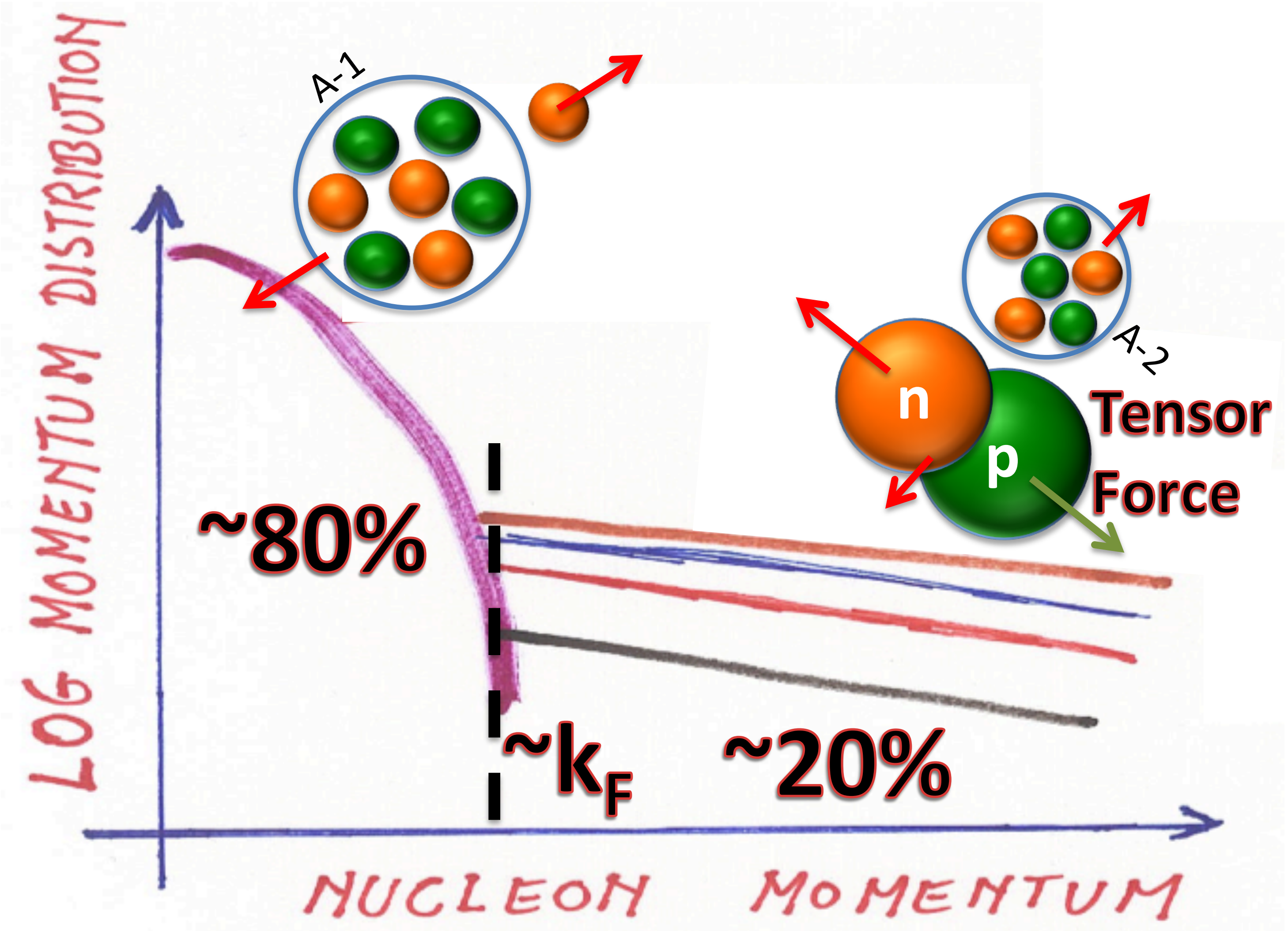


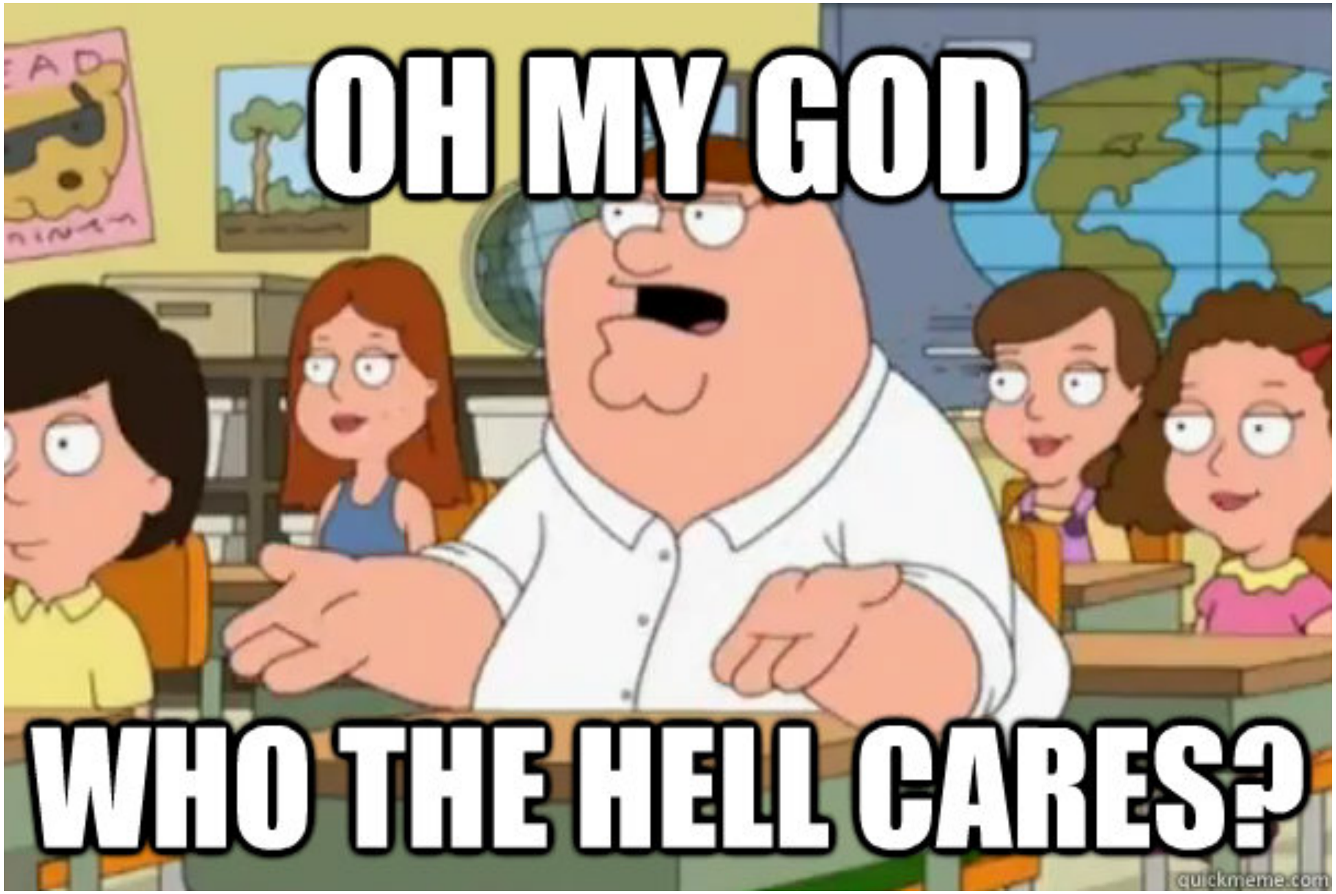


Who wins?



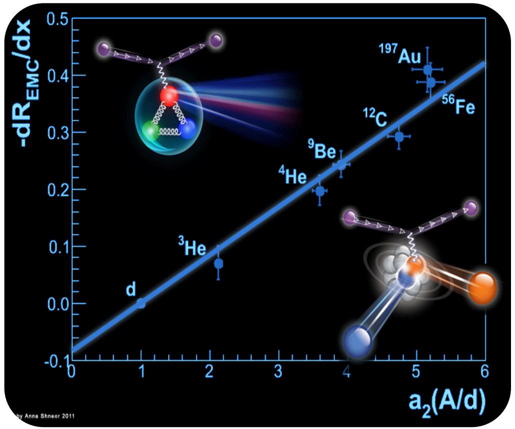
Intermediate summary: Universal structure of nuclei



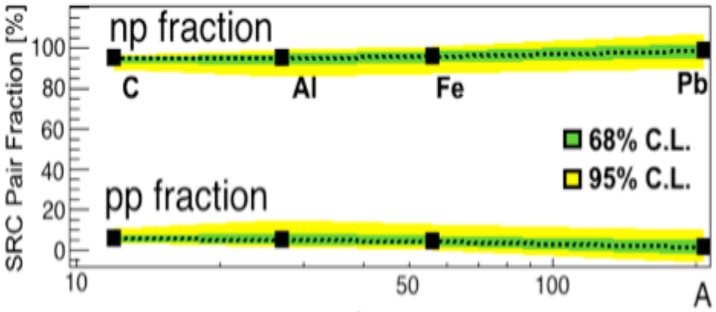


*Me at this point of the talk

Who Cares?

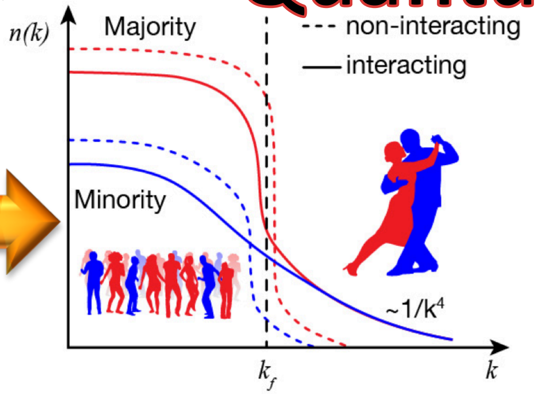


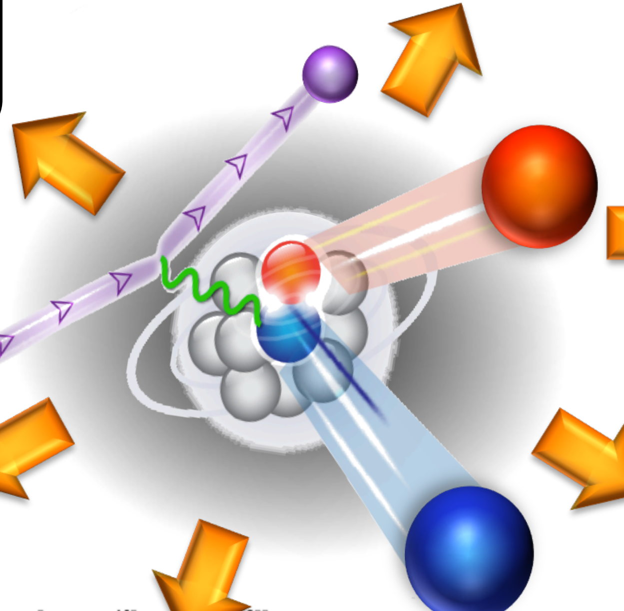
Particle

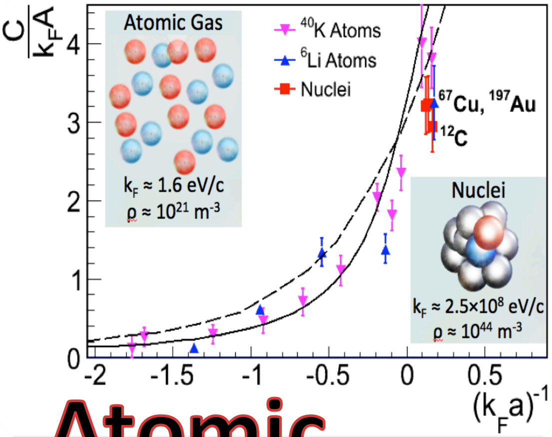


Nuclear

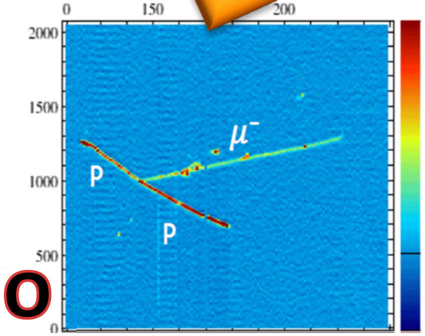
Quantum





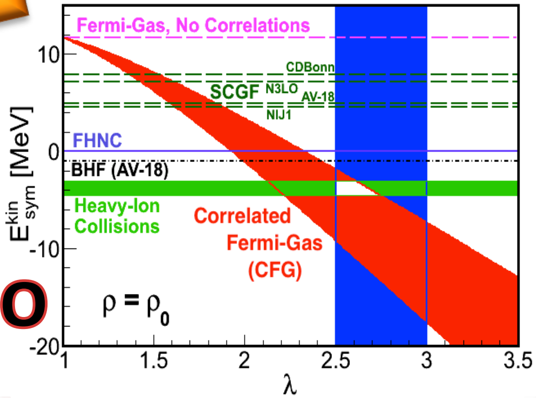


Atomic



Neutrino

Astro



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:

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

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Tan's Contact term:

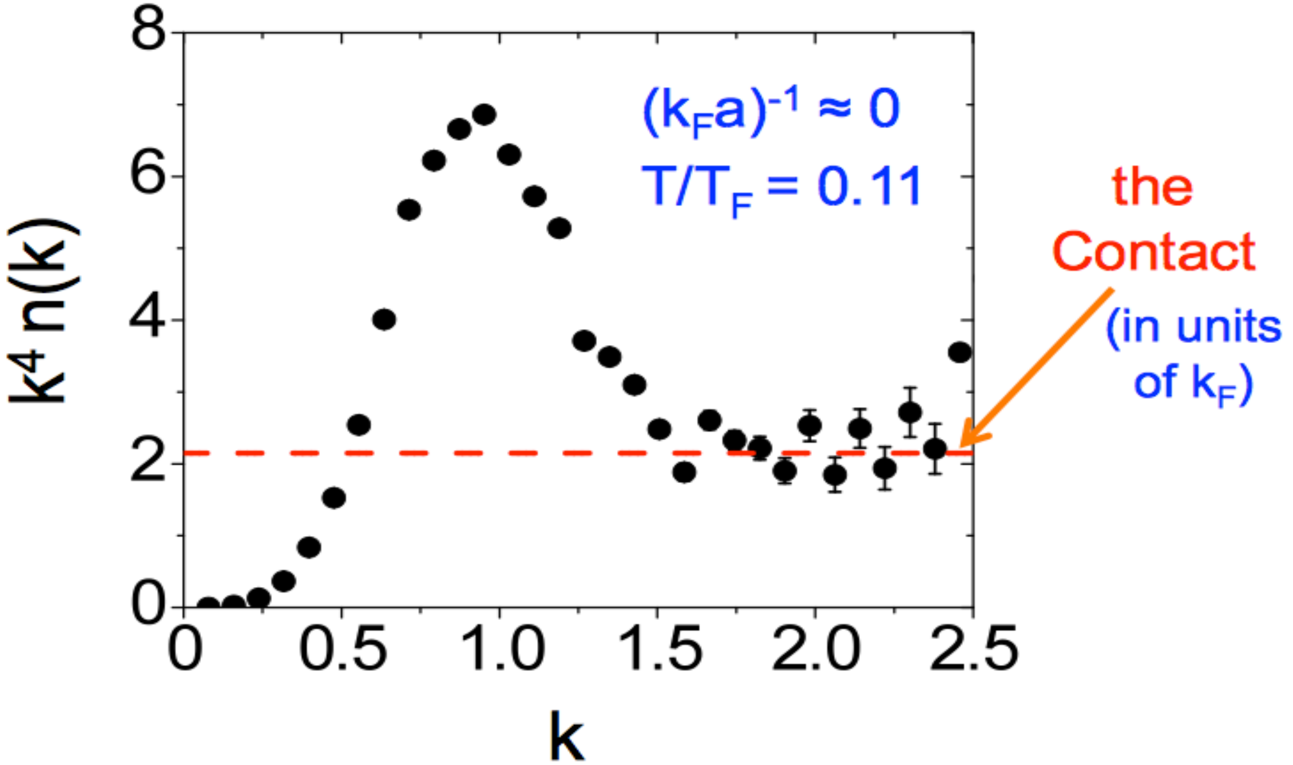
1. Measures the number of SRC different fermion pairs.
2. Determines the thermodynamics through a series of universal relations.

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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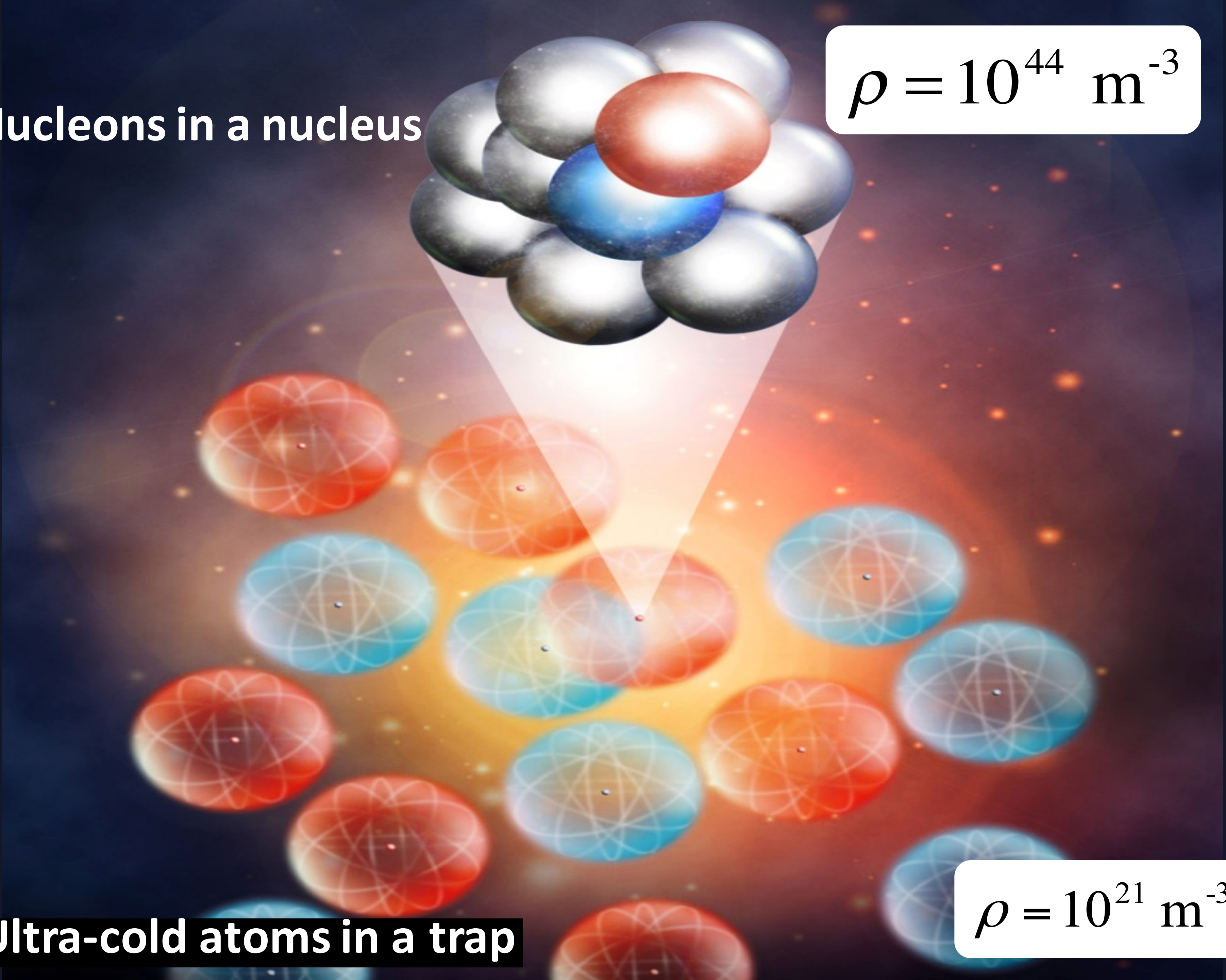
What About
a *Nuclear*
Contact ?

Stewart et al. PRL **104**,



Nucleons in a nucleus

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

Ultra-cold atoms in a trap

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

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

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

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

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

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]**

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

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

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

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

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

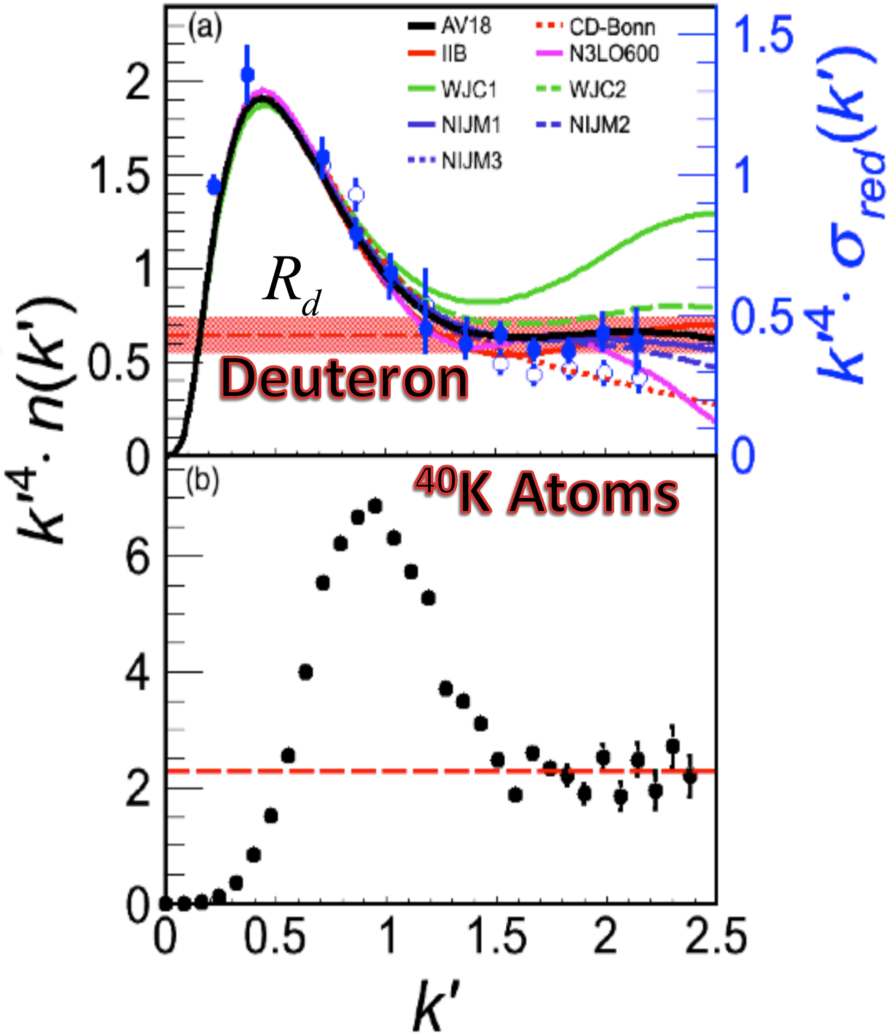
Deuteron
Momentum
Distribution

A Nuclear Contact?

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

$$1.5k_F < k < 3k_F$$

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



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

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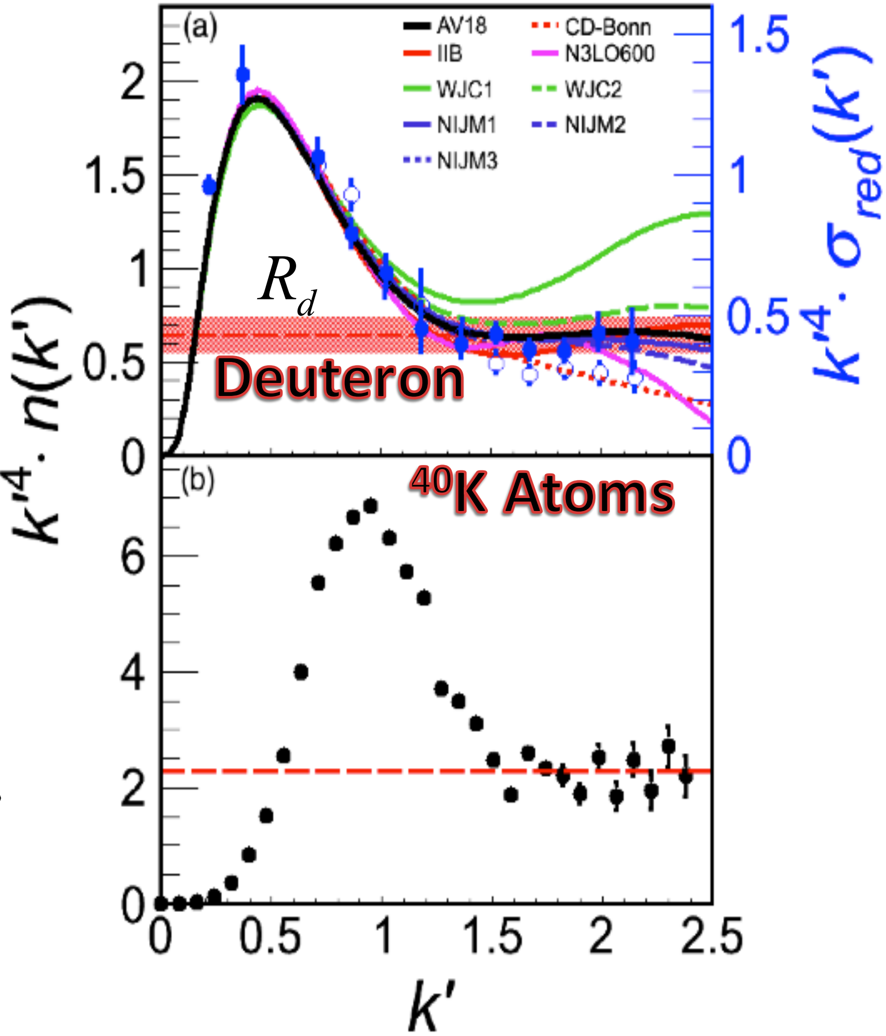

<u>Why $1/k^4$?</u>

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

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

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

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

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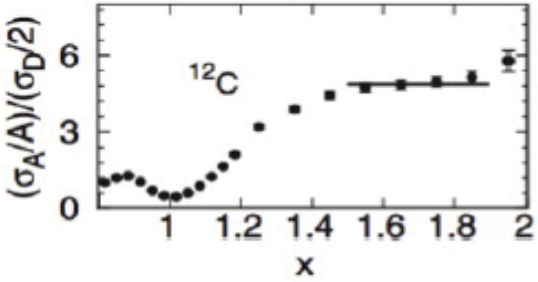

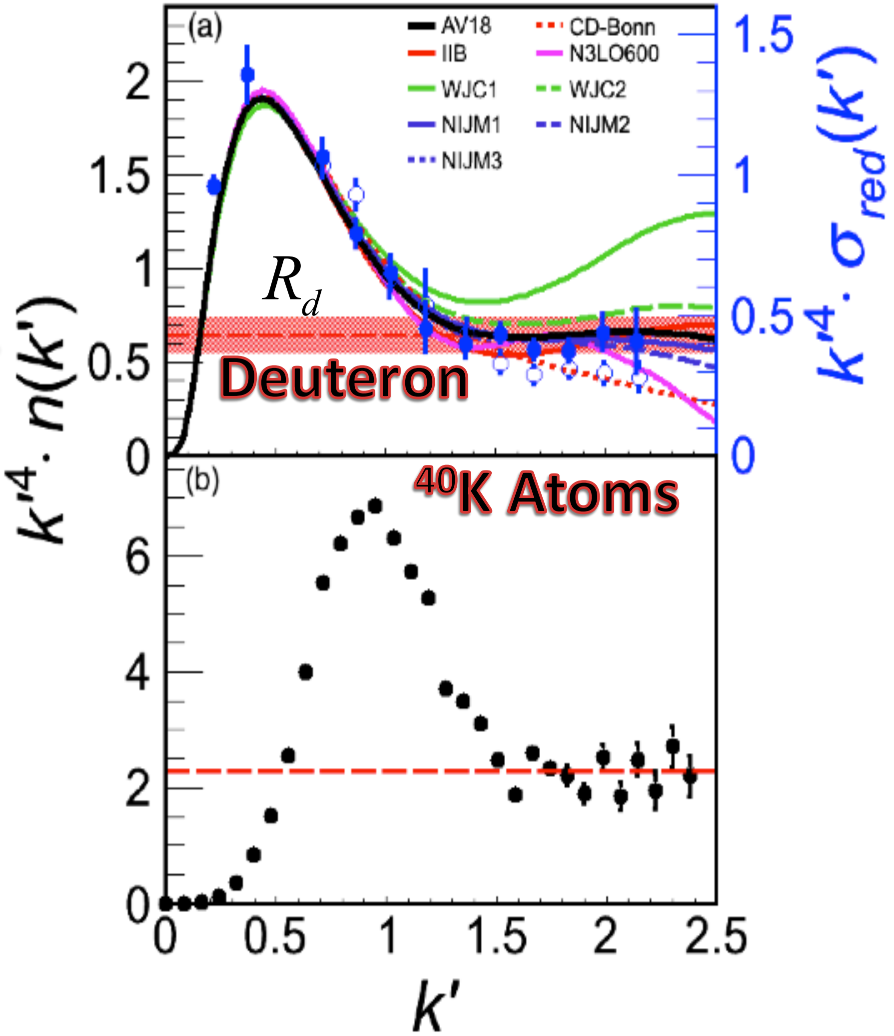

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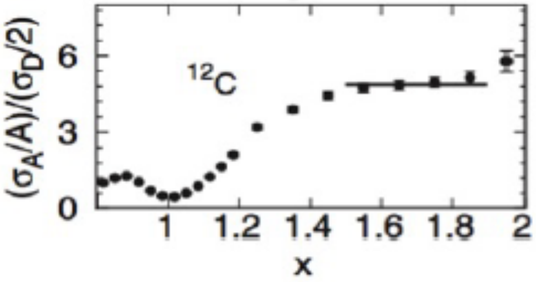
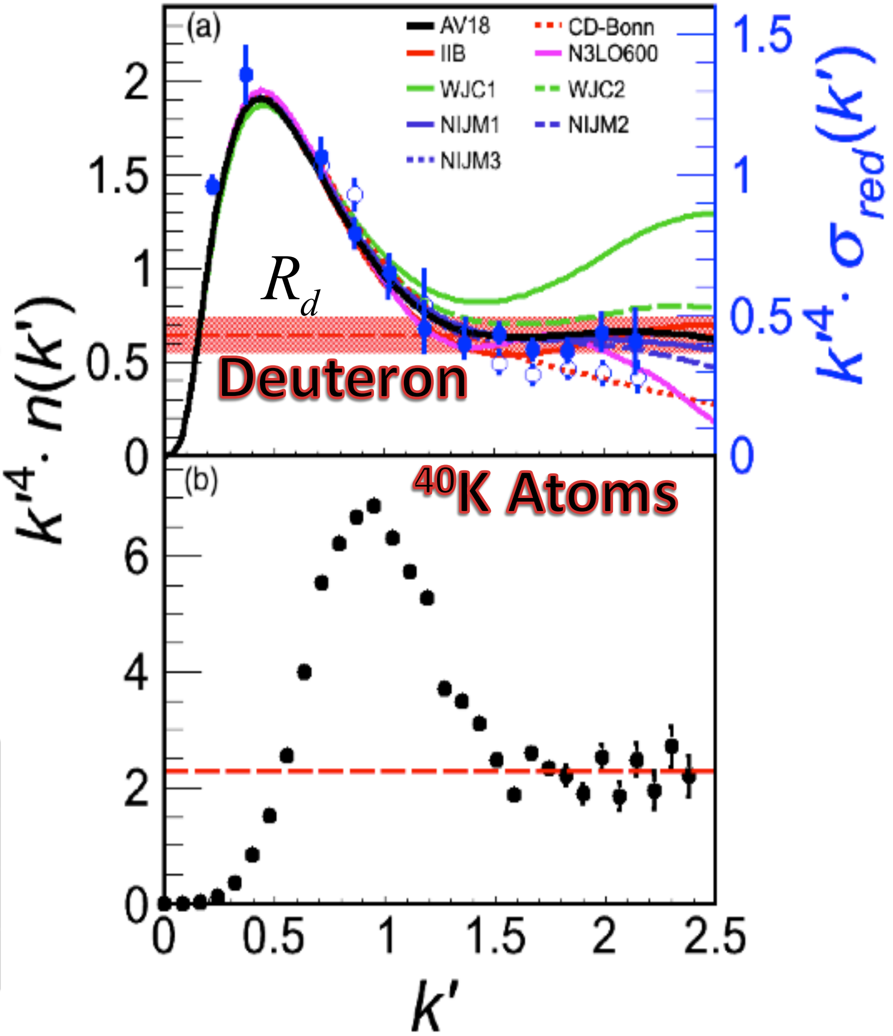


$$\frac{C}{k_F\cdot A} = a_2(A)\cdot R_d$$

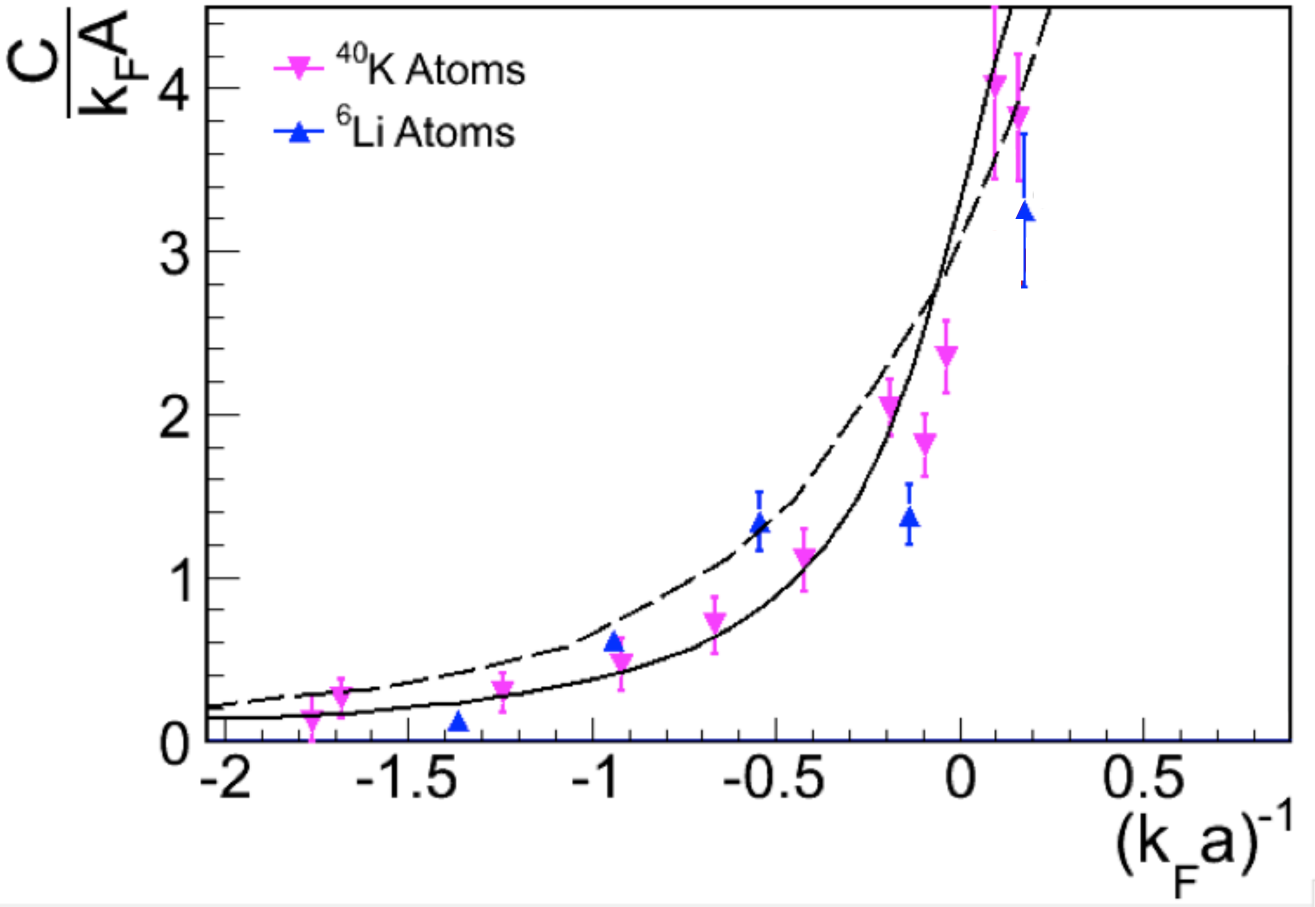
Nucleus	$a_2(A)$	$\frac{C}{k_F A}$
^{12}C	4.75 ± 0.16	3.04 ± 0.49
^{56}Fe	5.21 ± 0.20	3.33 ± 0.54
^{197}Au	5.16 ± 0.22	3.30 ± 0.53



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

Comparing with atomic systems

Finding the same *dimensionless* interaction strength



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

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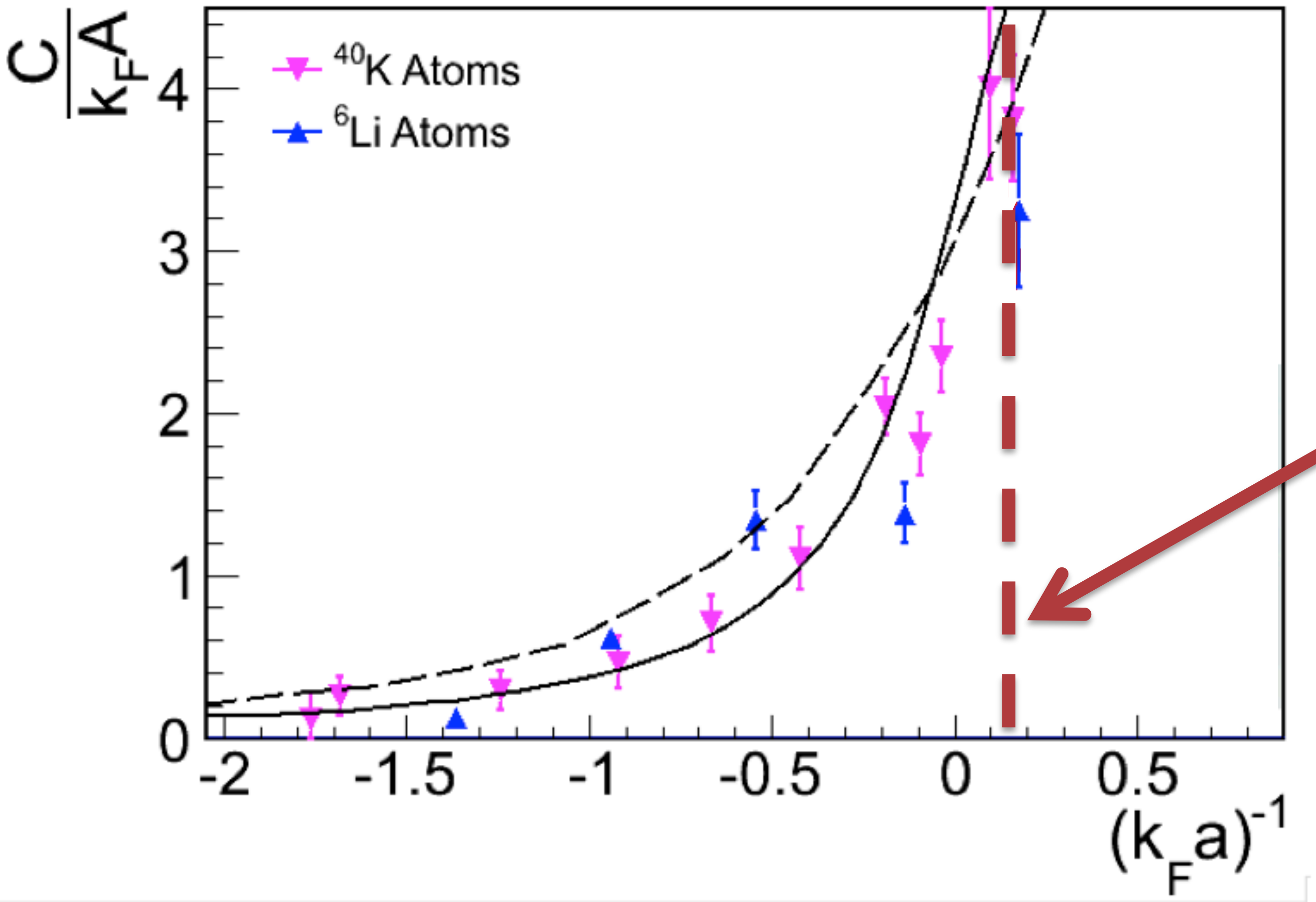

For Nuclei:

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

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

=> $(k_F a)^{-1} \approx 0.15$

Stewart et al. Phys. Rev. Lett. **104**, 235301 (2010)
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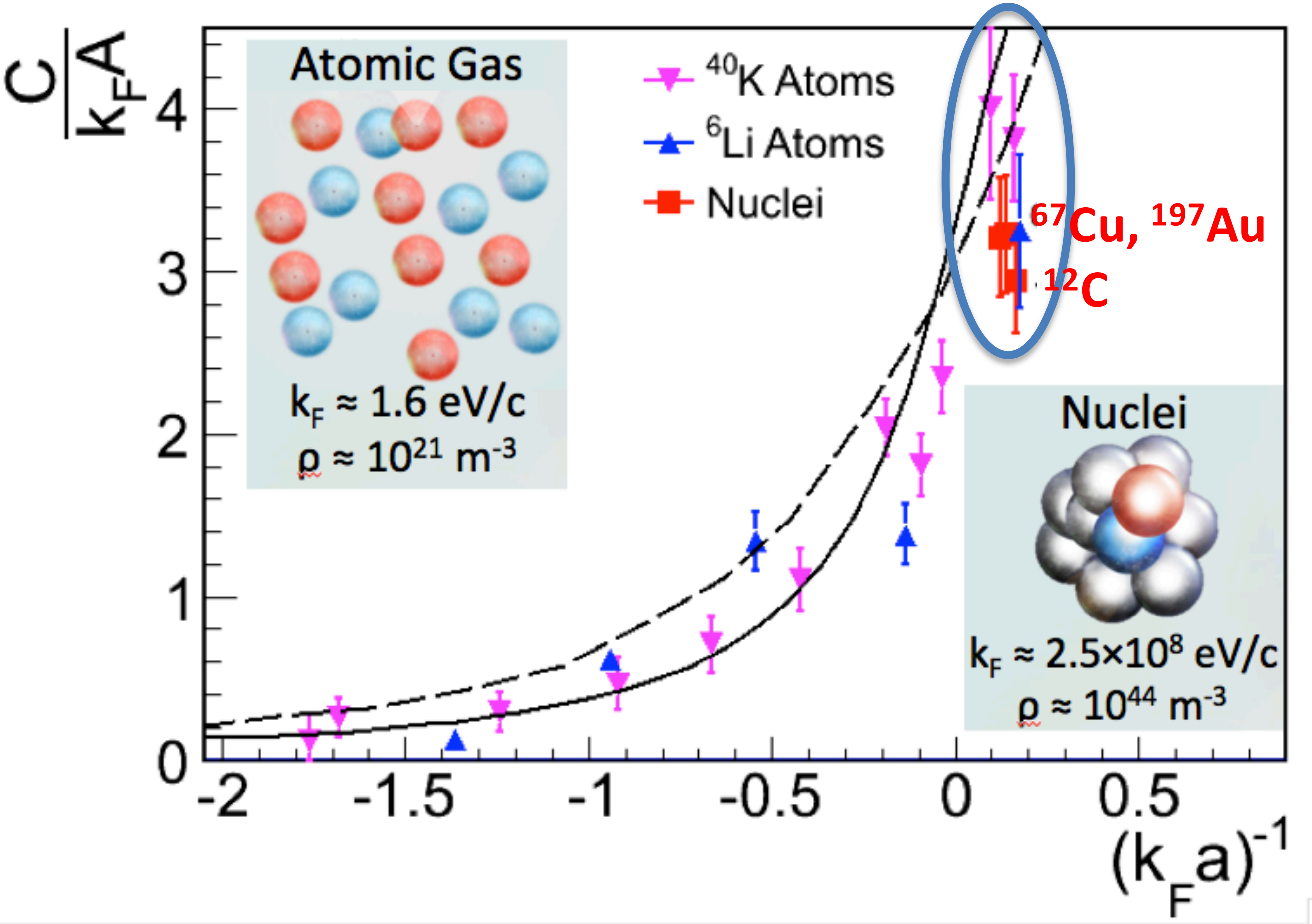
Comparing with atomic systems

Equal contacts for equal interactions strength!



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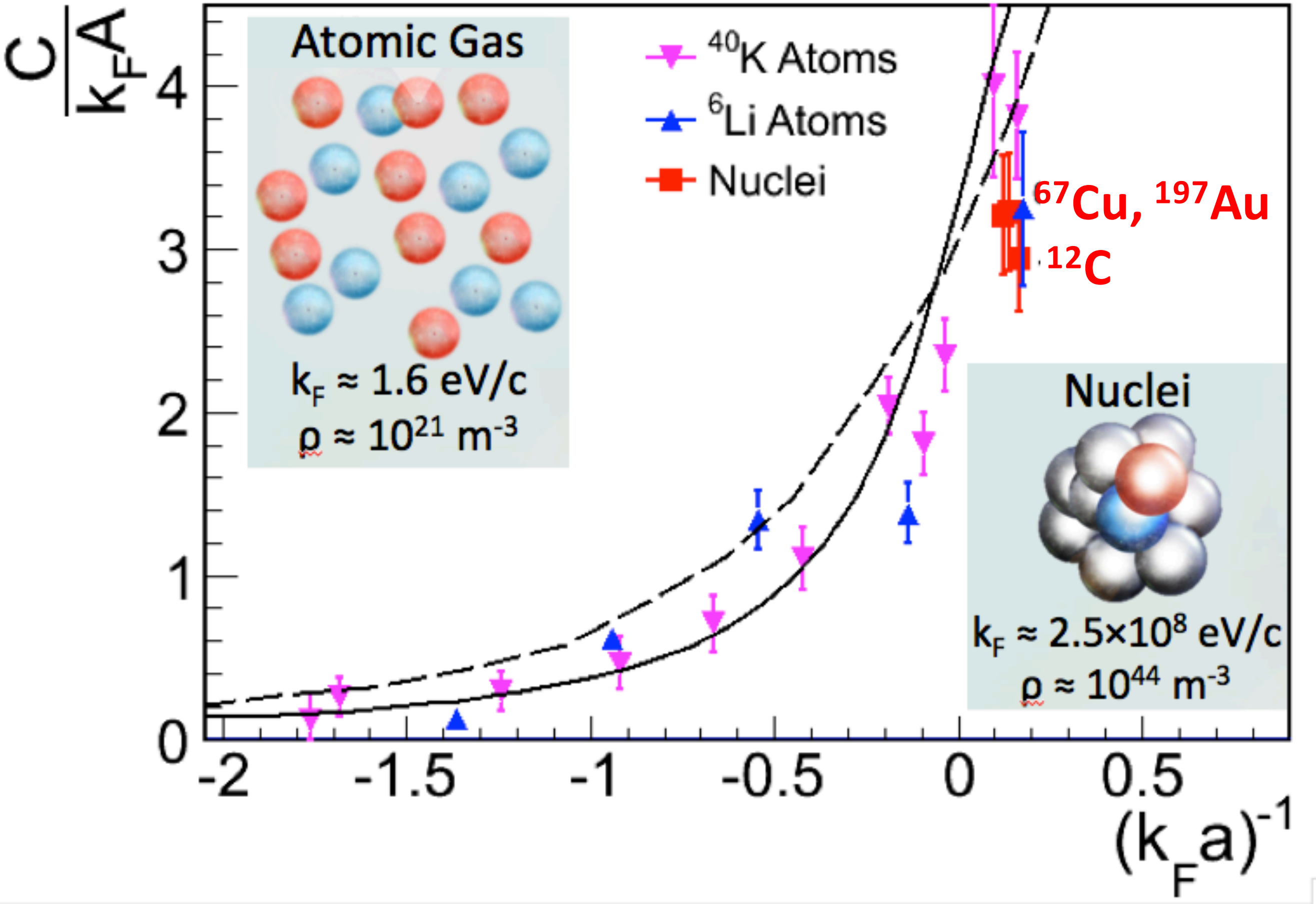

At unitary (i.e. $(k_F a)^{-1} \approx 0$) the SRC probability is ~20% for both systems

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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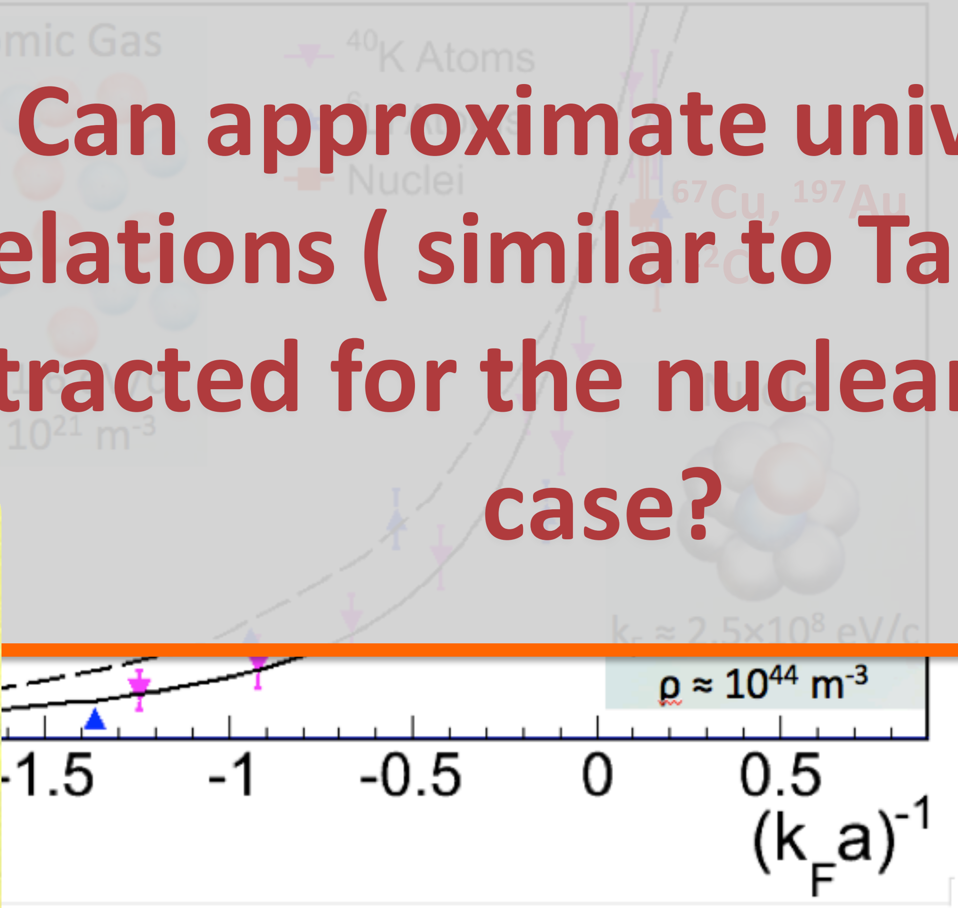
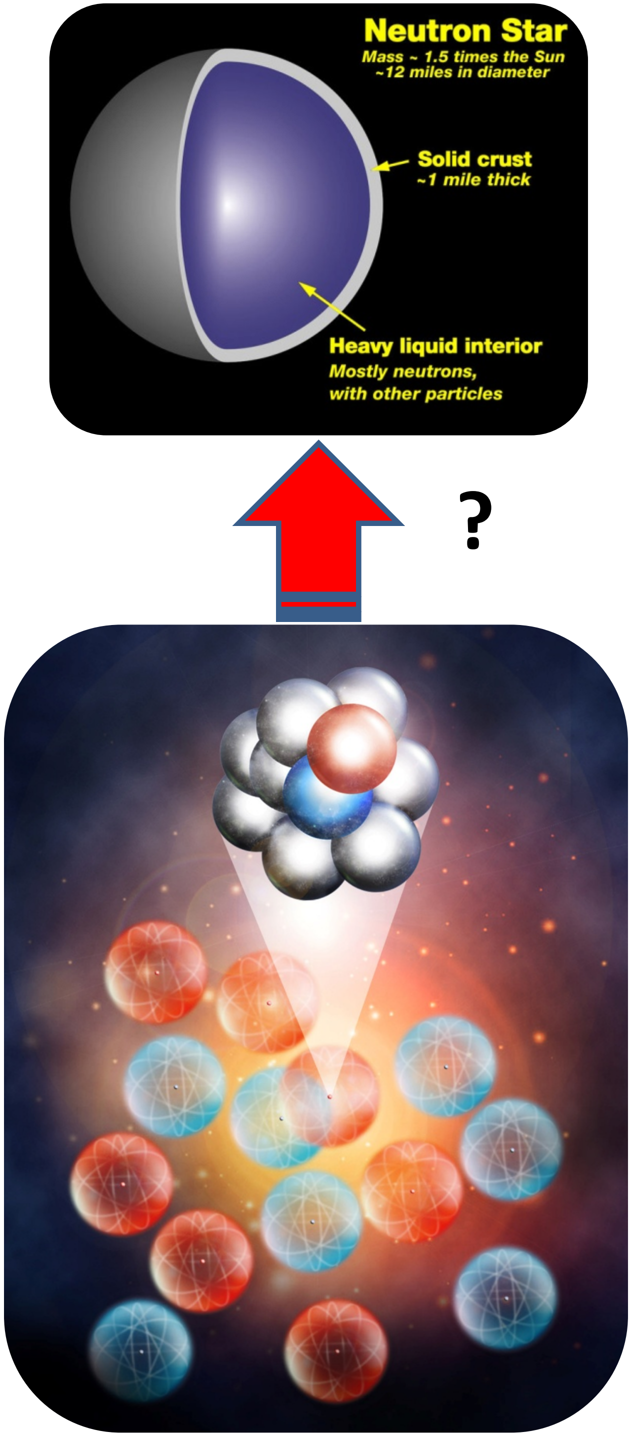


Can approximate universal relations (similar to Tan's) be extracted for the nuclear physics case?

Rev. C **92**, 045205 (2015)

Rev. Lett. **104**, 235301 (2010)

Rev. Lett. **105**, 070402 (2010)

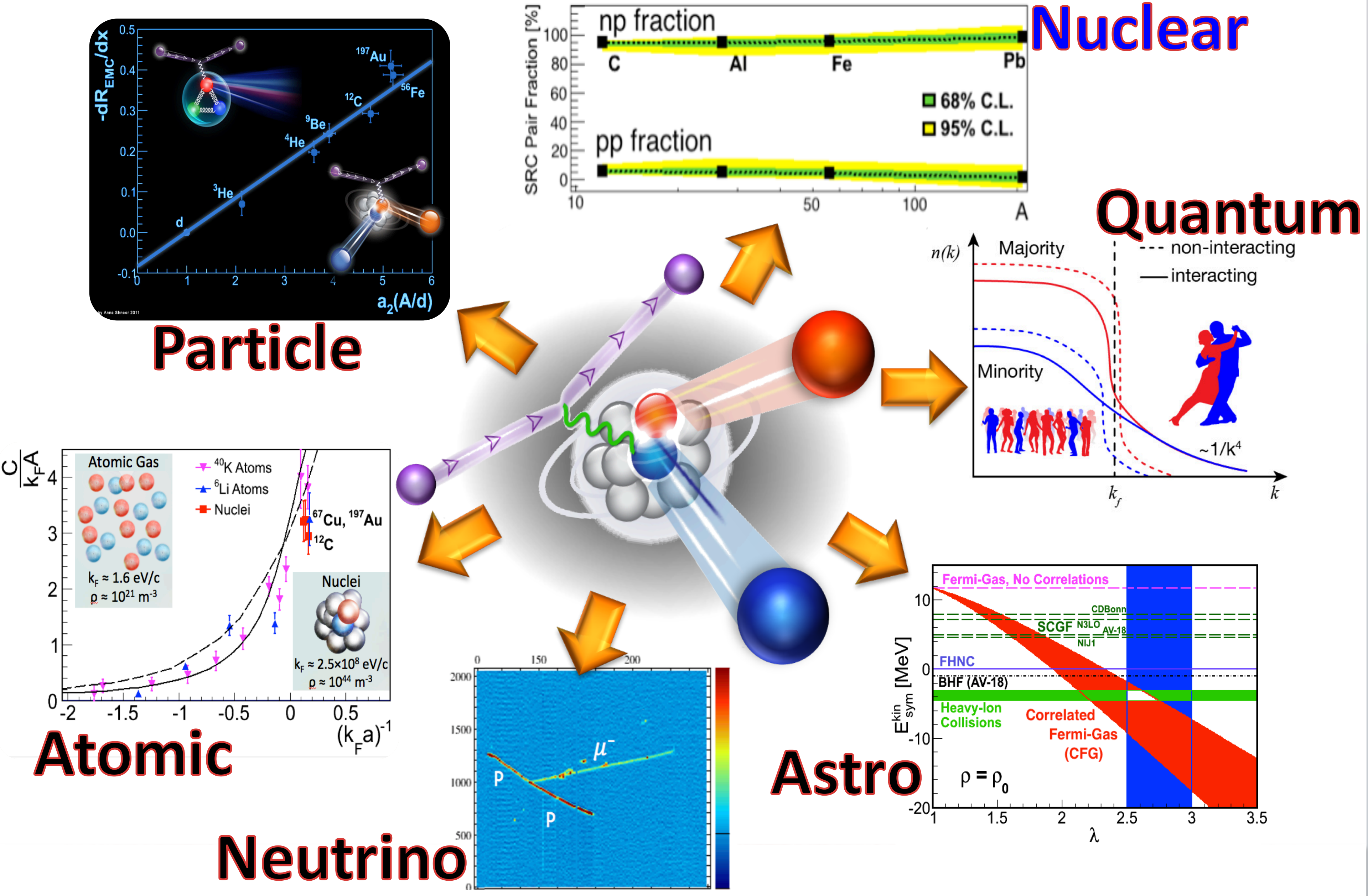


$$(2-3)\cdot\rho_0$$

$$\rho_0$$

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

Summary



Nuclear

Particle

Quantum

Atomic

Astro

Neutrino

The group

- MIT:

Barak Schmookler

Navaphon (Tai) Muangma

Reynier Torres

  - Or Hen
  - Shalev Gilad

- ODU:

Mariana Khachatryan

  - Larry Weinstein

- Tel-Aviv:

Erez Cohen

Meytal Duer

Igor Korover

  - Eli Piasetzky

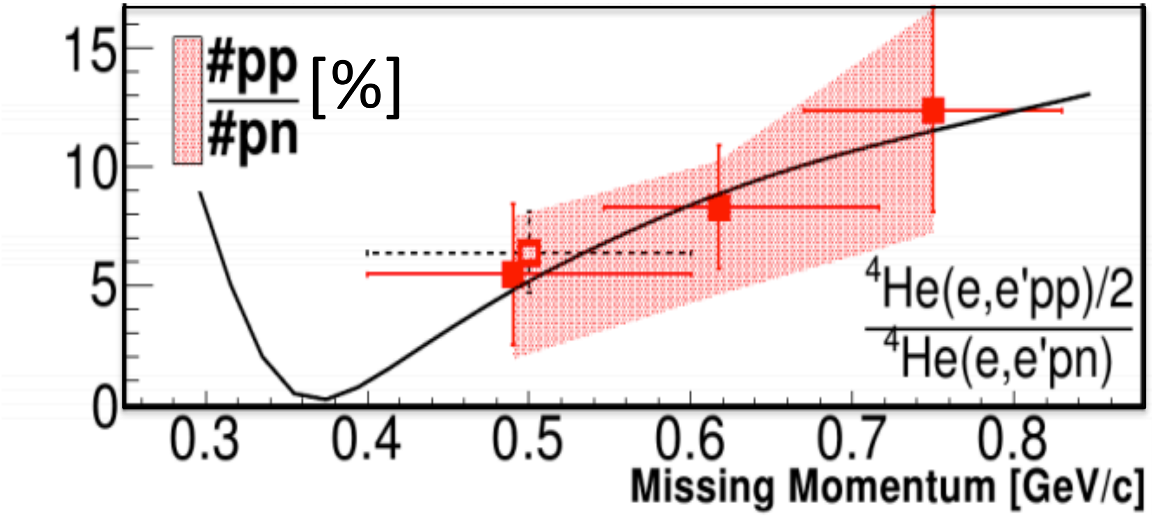
- Many theory friends ☺

+ Looking for 2 new postdocs to join the MIT group

Thank You!

Questions?

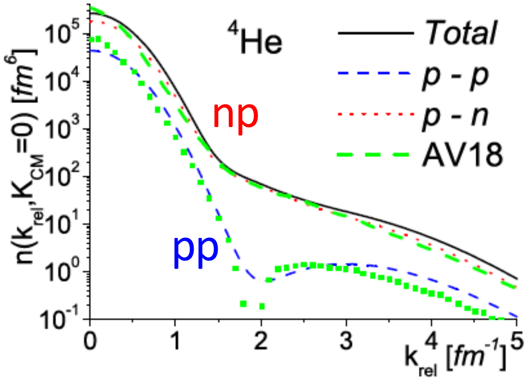
pp/np ratio increase with P_{miss}

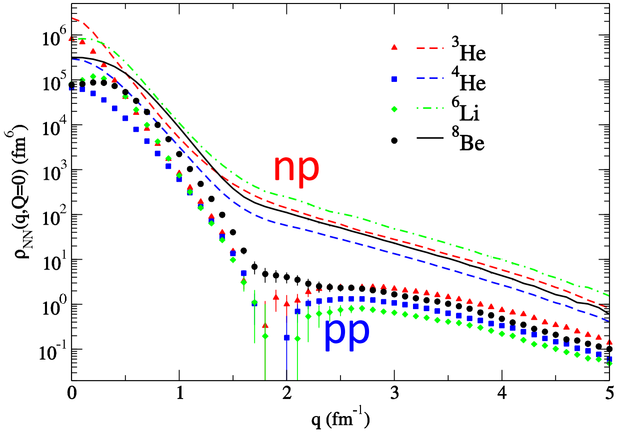


I. Korover, N. Muangma, and O. Hen et al., Phys. Rev. Lett 113, 022501 (2014).

Pair density calculations:

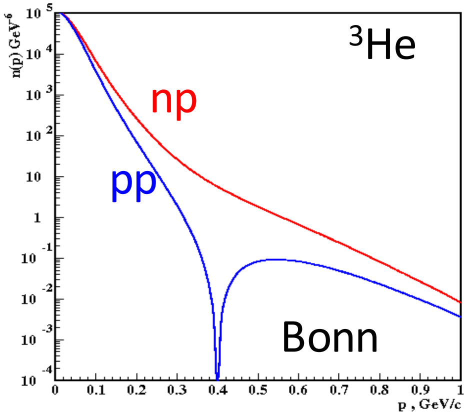
Ciofi and Alvioli PRL 100, 162503 (2008)



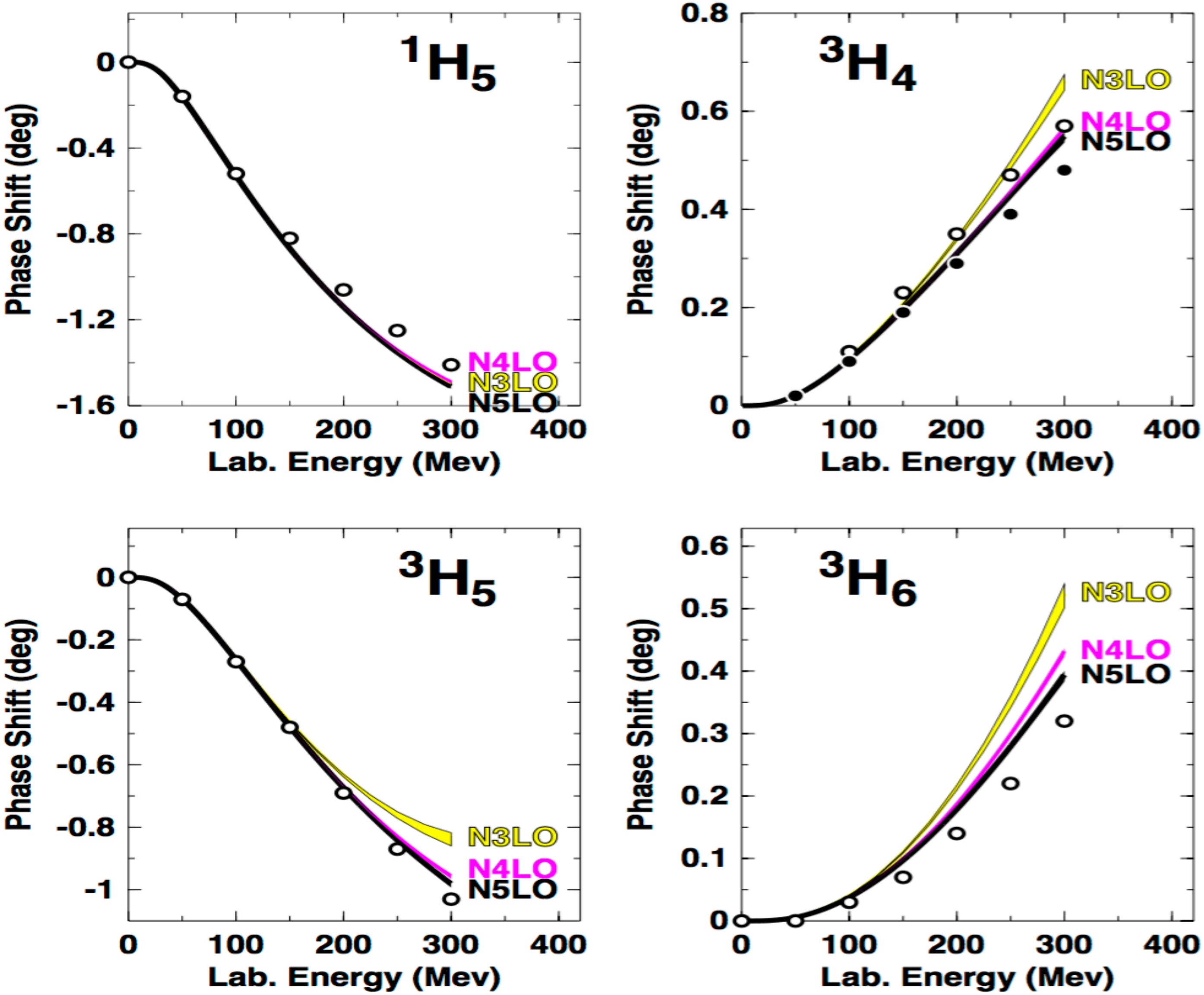


Schiavilla et al., PRL 98,132501 (2007)

Sargsian et al., PRC 71 044615 (2005)



Conversion of the Chiral Series?



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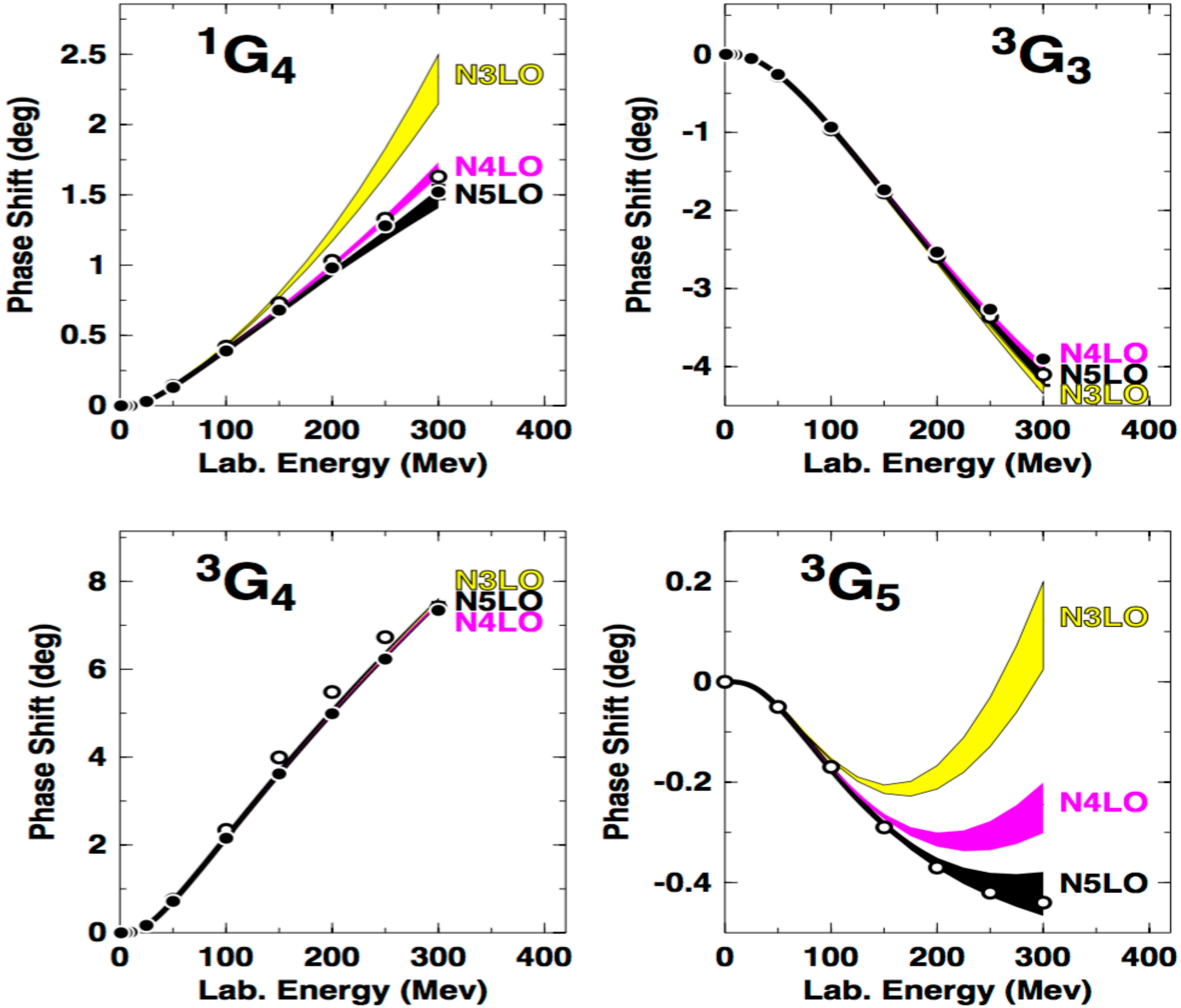

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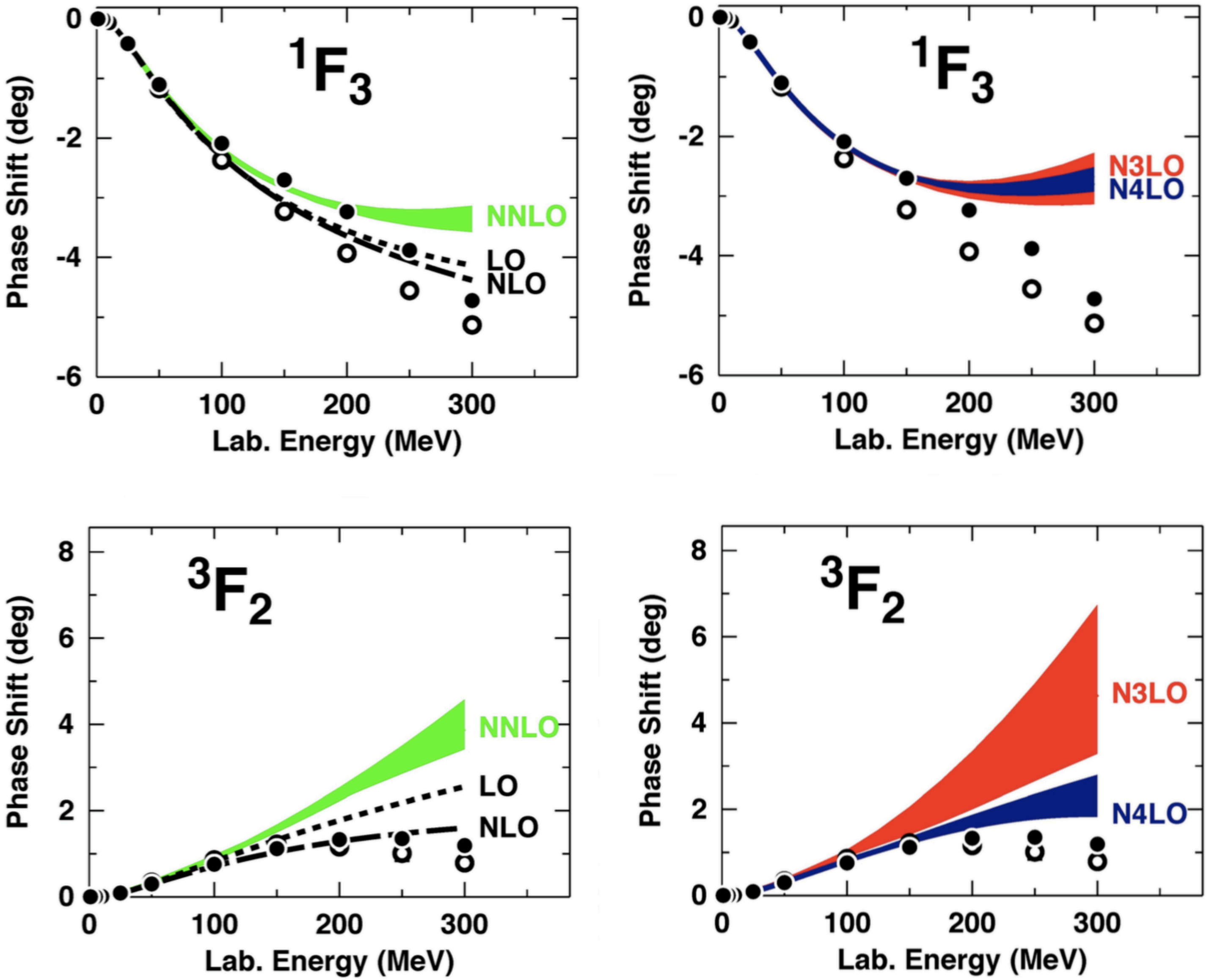

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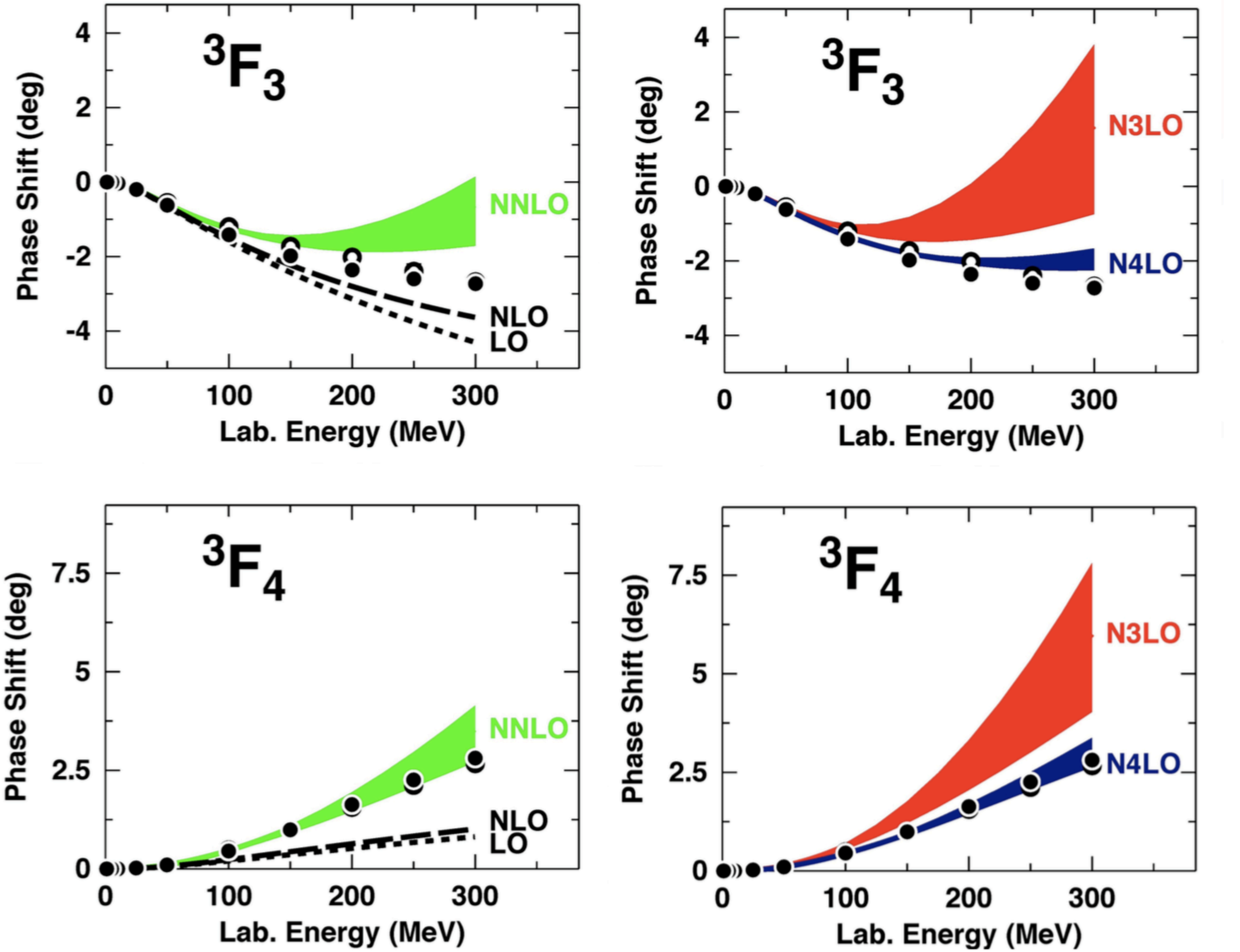

Nuclear Symmetry Energy

Energy of *asymmetric* nuclear matter:

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

Isospin asymmetry (δ)

symmetry energy

Energy of *symmetric* nuclear matter

Nuclear Symmetry Energy

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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

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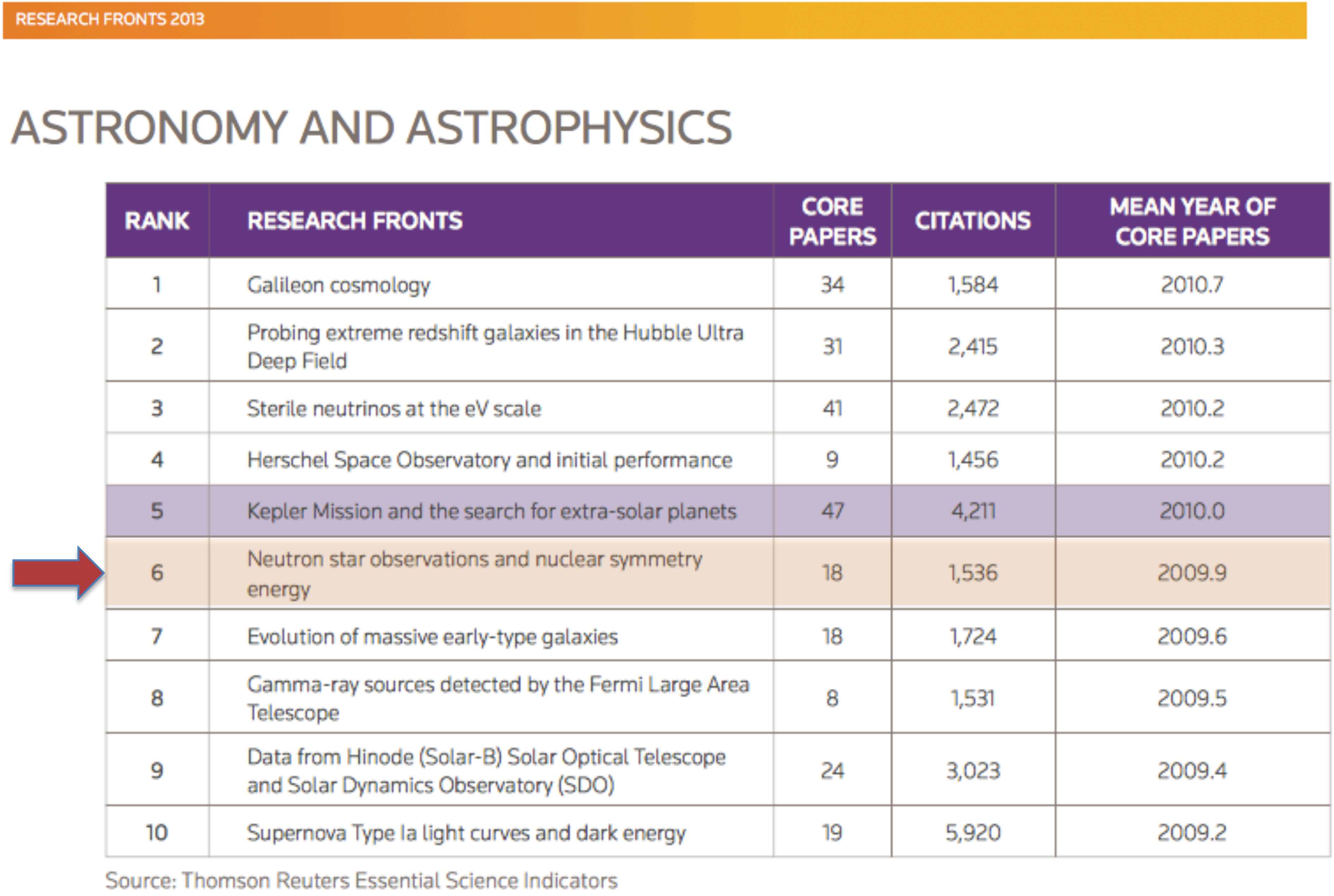
$$E_{sym}(\rho) \approx E(\rho)_{\text{PNM}} - E(\rho)_{\text{SNM}}$$

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

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

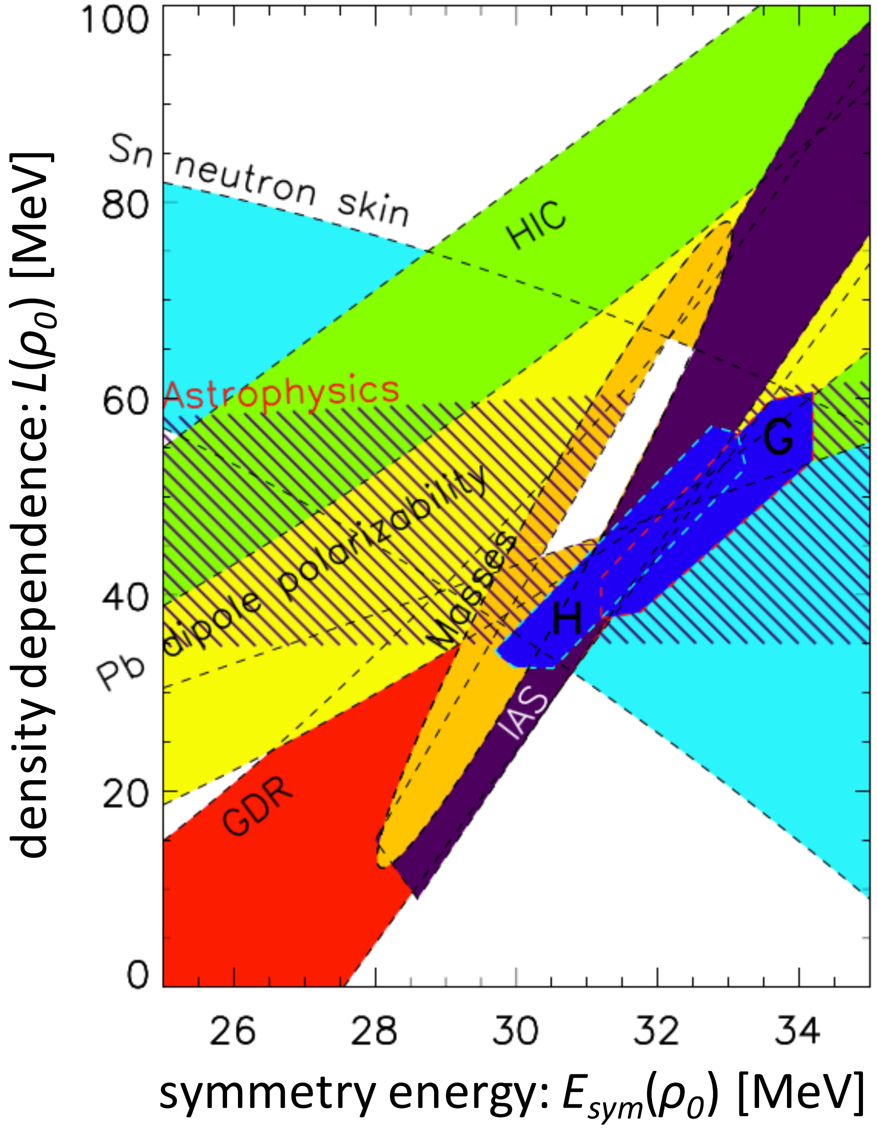
Could change drastically

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

Relates to the energy change when replacing n with p

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

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

$E_{sym}(\rho)$ 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]

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

$$\Big\Downarrow$$

<u>Fermi-Gas Model</u>

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

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

Constraining the Symmetry Energy

[Fermi-Gas Picture]

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

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

☑ $\alpha = {}^{2}\!/_{3}$

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

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

Constraining the Symmetry Energy

[Fermi-Gas Picture]

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

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

☑ $\alpha = {}^{2}\!/_{3}$

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

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

Only unknown is γ_i
probed in HI collision
measurements and
neutron stars
observations

Constraining the Symmetry Energy

[With SRCs]

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

Fermi-Gas Model + Correlations

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

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

Only unknown is γ_i

probed in HI collision measurements and neutron stars observations

Constraining the Symmetry Energy

[With SRCs]

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

+ Correlations

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

☑ $\alpha = {}^{2}\!/_{3}$

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

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

Only unknown is γ_i probed in HI collision measurements and neutron stars observations

Constraining the Symmetry Energy

[With SRCs]

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

Fermi-Gas Model + Correlations

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

☑ $\alpha = \cancel{2/3}$

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

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

Only unknown is γ_i

probed in HI collision measurements and neutron stars observations

Constraining the Symmetry Energy

[With SRCs]

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

+ Correlations

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

☑ $\alpha = \cancel{2/3}$

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

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

Only unknown is γ_i probed in HI collision measurements and neutron stars observations

Constraining the Symmetry Energy

[With SRCs]

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

+ 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 γ_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]

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

Adding np-SRCs breaks the Fermi-Gas picture

=> Need a correlated Fermi-Gas Model

Fermi-Gas Model + Correlations

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

Only unknown is γ_i

probed in HI collision measurements and neutron stars observations

☑ $\alpha = 2/3$

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

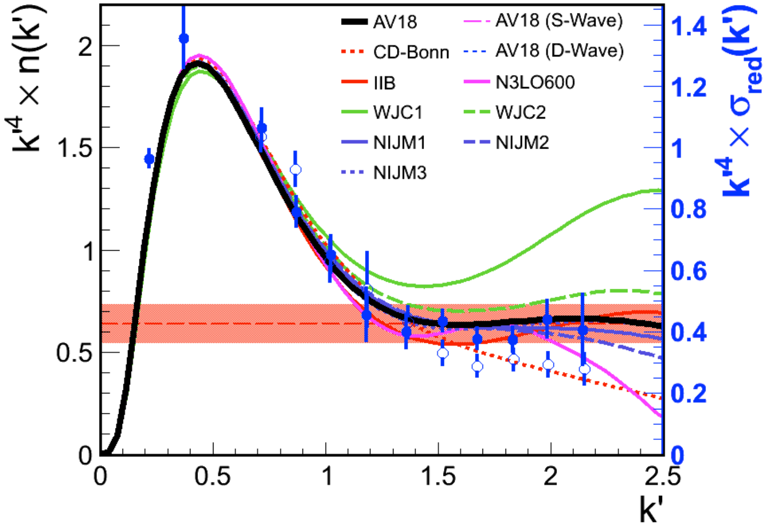
☑ $E^{pot}_{sym}(\rho_0) = E_{sym}(\rho_0) - E^{kin}_{sym}(\rho_0) \approx 18.5\ \text{MeV}$

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)

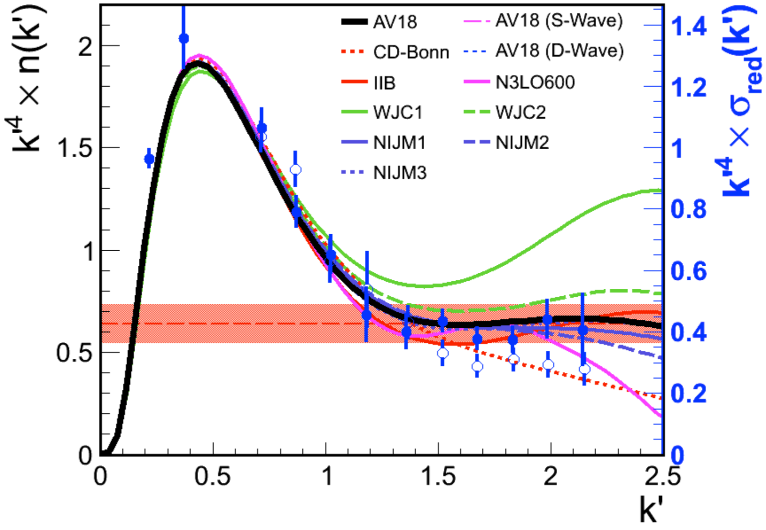
[Fermi-Gas with an SRC tail]

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

SNM Model:

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

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)

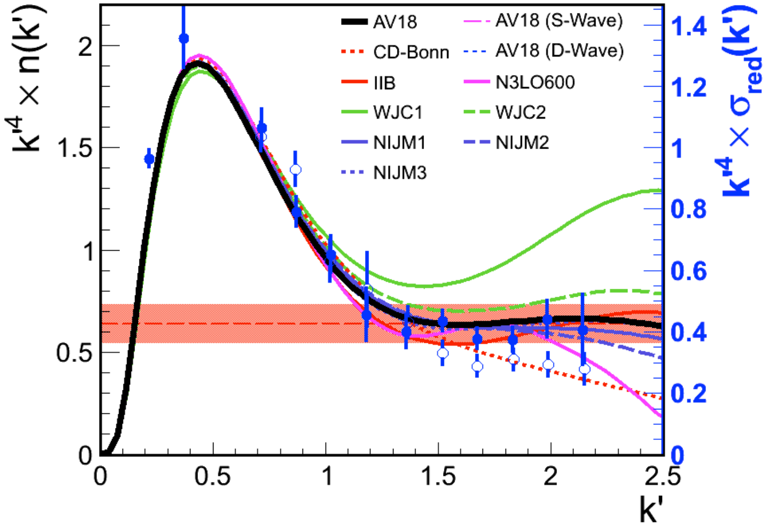
[Fermi-Gas with an SRC tail]

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

PNM Model:

- Free Fermi Gas

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

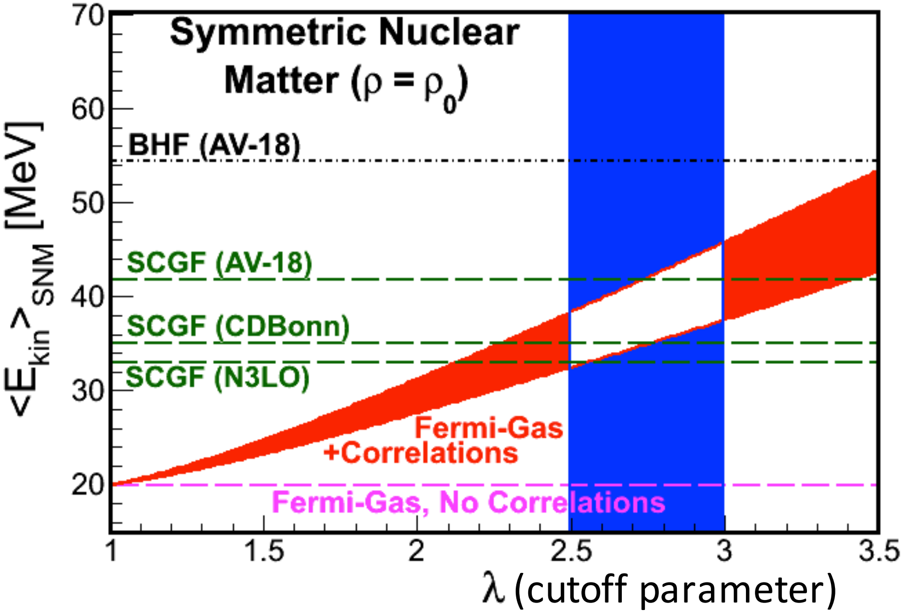


O. Hen et al., Phys. Rev. C 91, 025803 (2015).

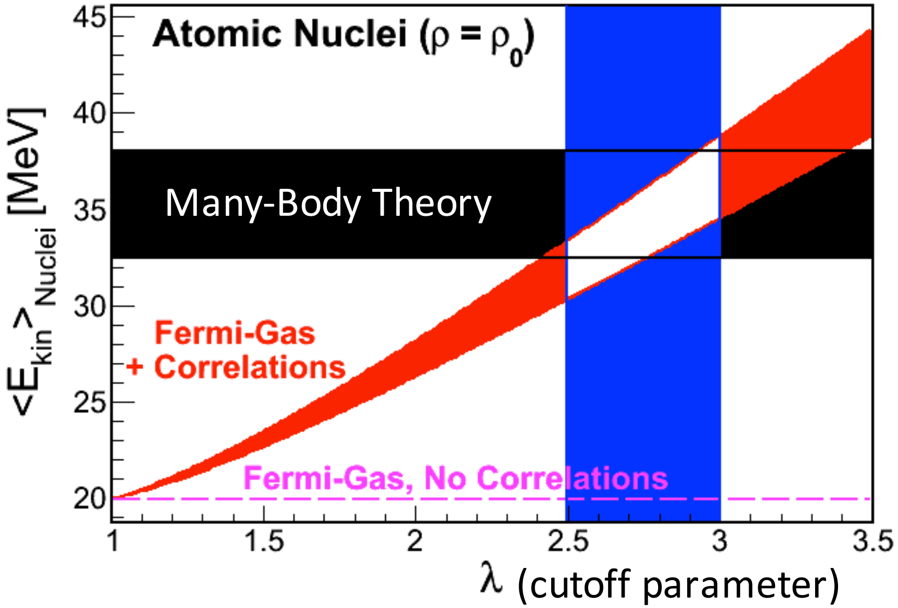
Benchmark Against Microscopic Calculations

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

Average kinetic energy – SNM



Average kinetic energy - Nuclei



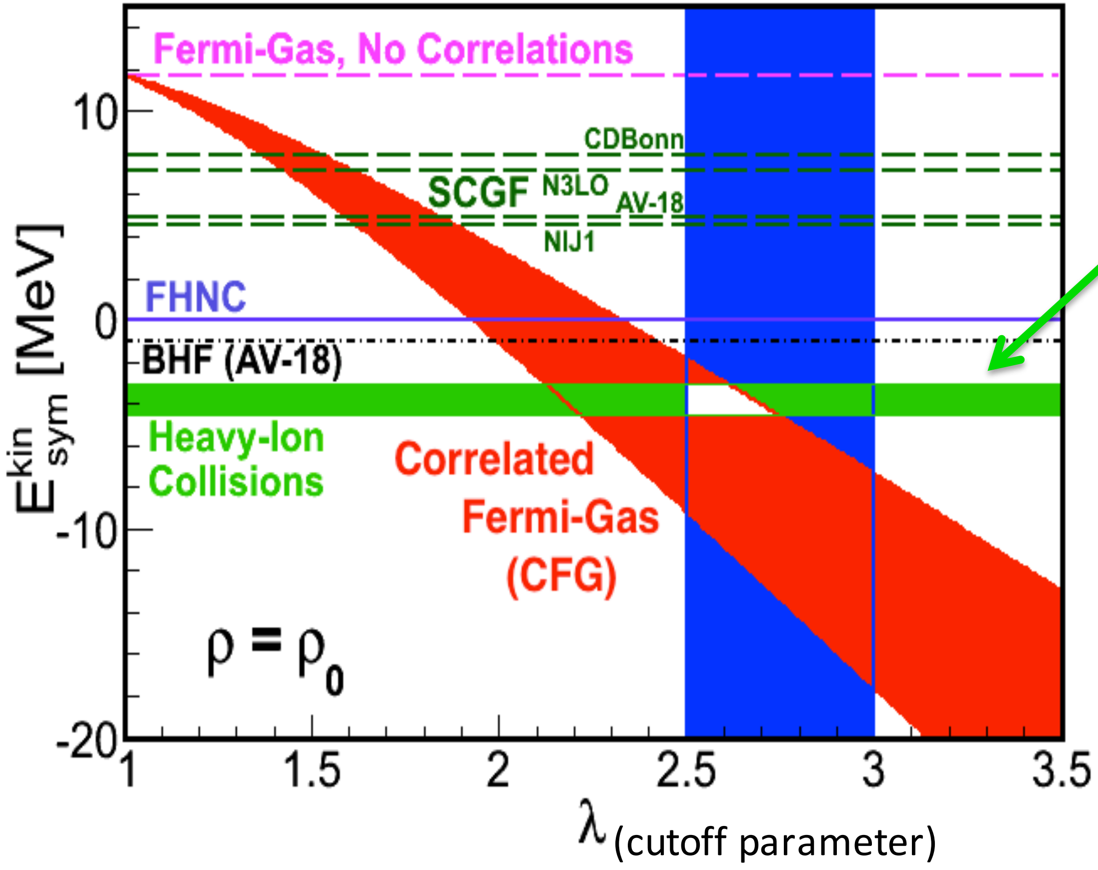
$a_2(A) = 5.0 \pm 0.3$

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

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

Extracting the Kinetic Symmetry Energy

Kinetic symmetry energy

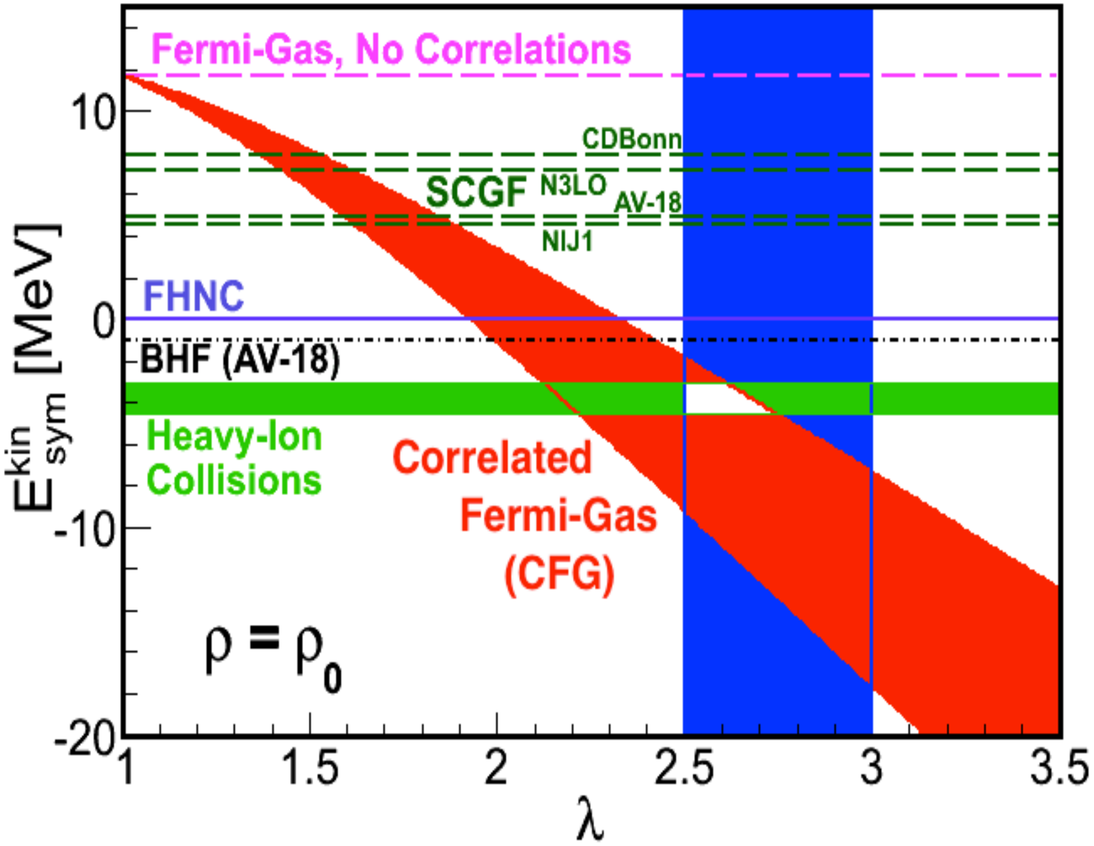


Transport calculation of ^{124}Sn+^{124}Sn and ^{112}Sn+^{112}Sn collisions also yield reduced kinetic symmetry energy

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

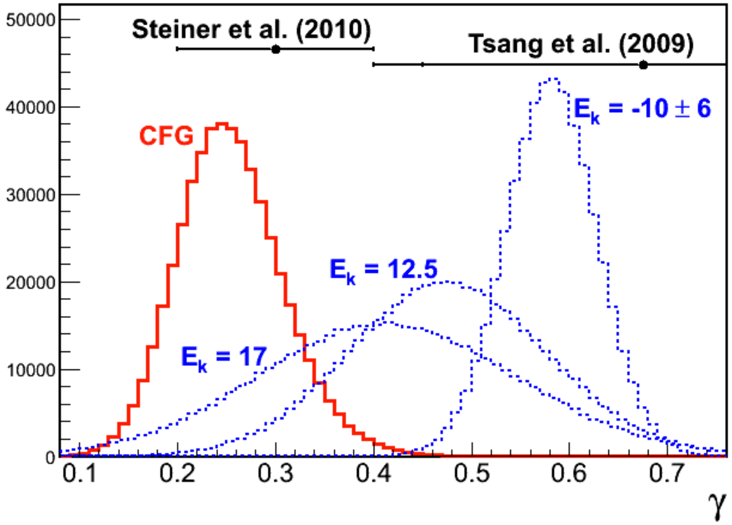
Extracting the Kinetic Symmetry Energy

Kinetic symmetry energy



SRCs reduce the kinetic symmetry energy

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



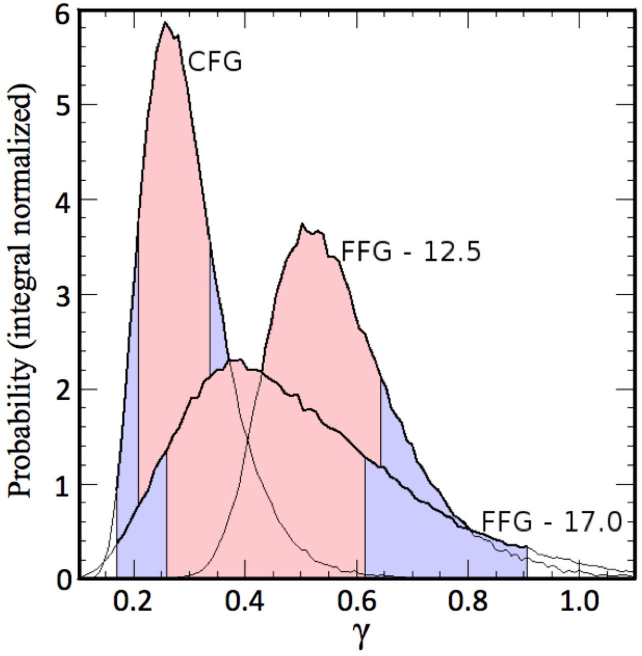
O. Hen et al., Phys. Rev. C 91, 025803 (2015).

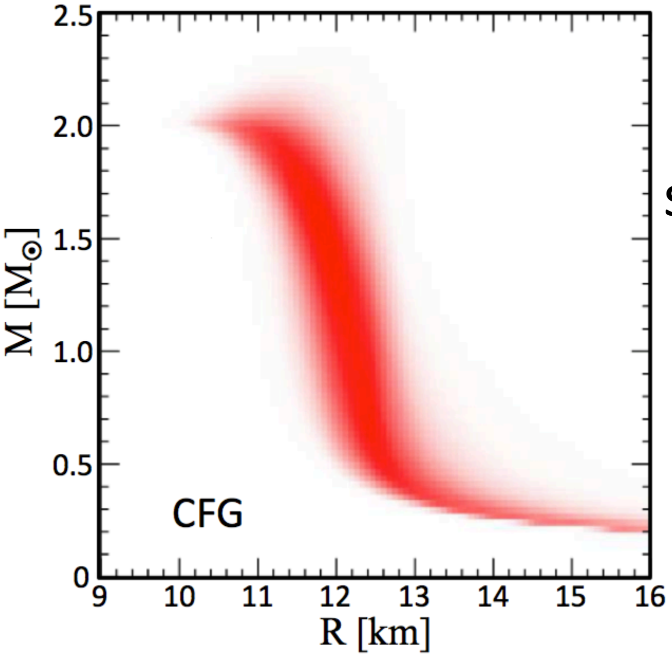
Next Step – Incorporating CFG model into:

- 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**



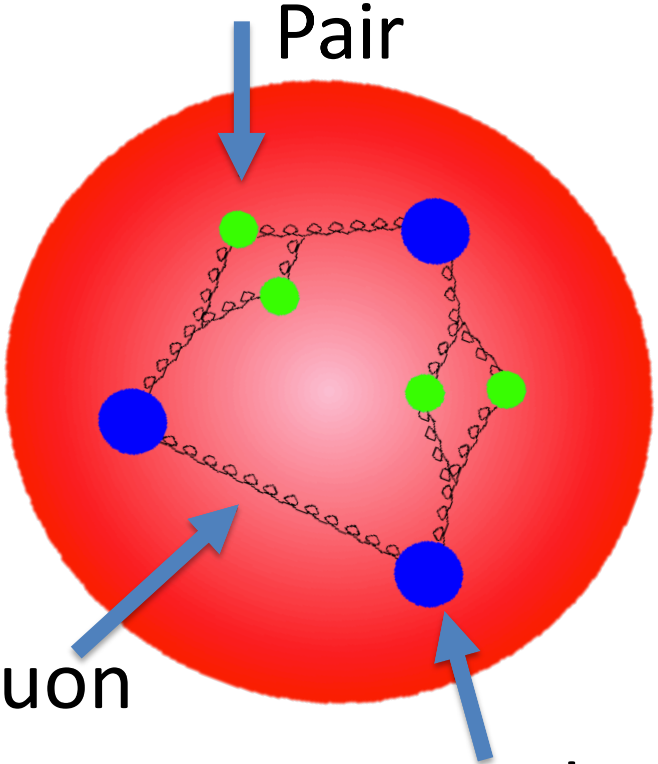


Bayesian analysis of n. star observables show large difference in the extracted γ parameter.

CFG model supports a two solar-mass neutron star

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

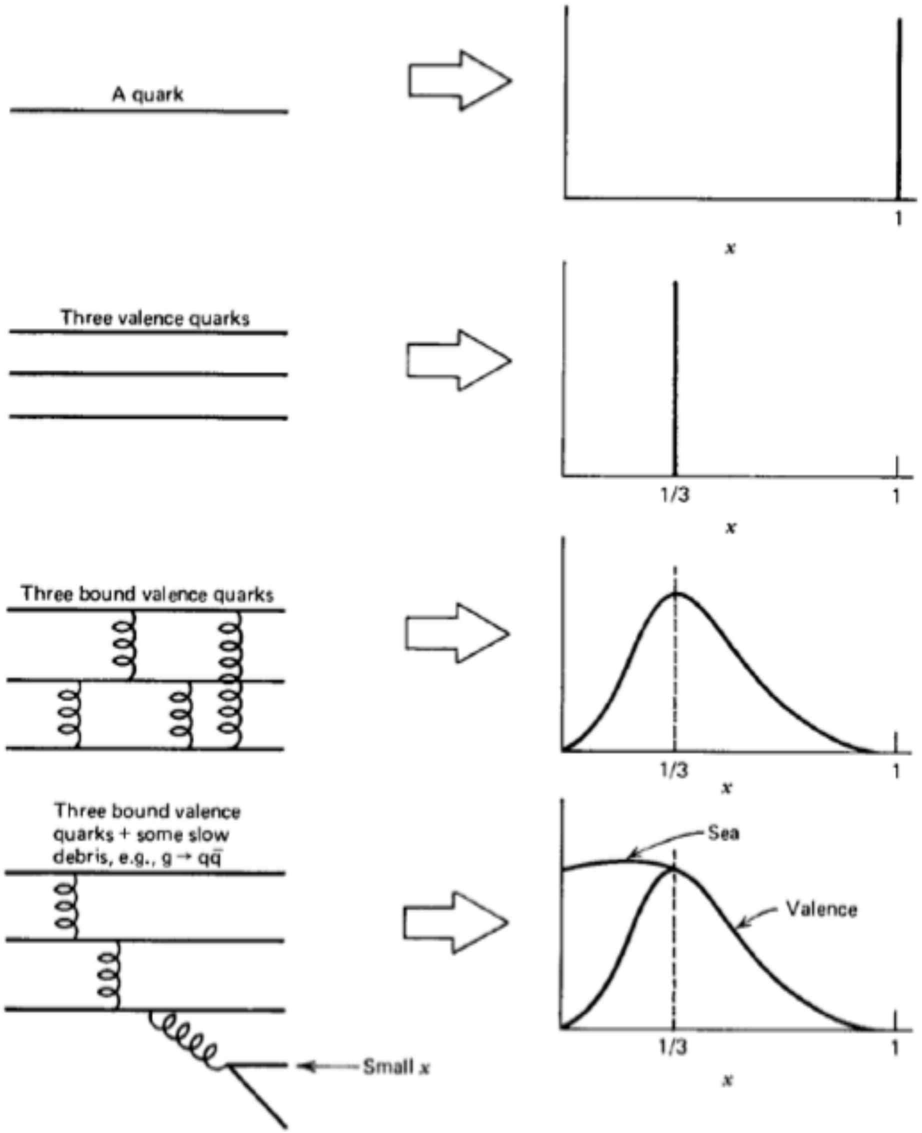
Deep-Inelastic Structure Functions



Quark –
Anti-quark
Pair

Gluon

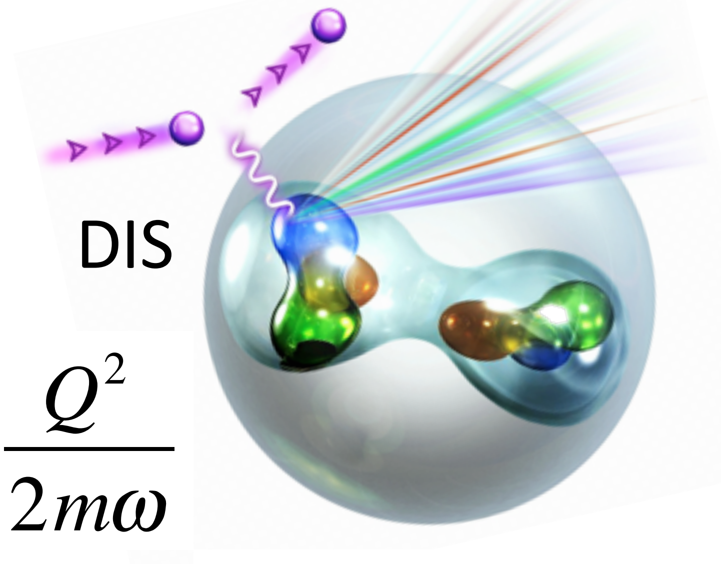
Quark



Deep Inelastic Scattering

DIS: Study of the partonic structure of the nucleon

DIS scale: several tens of GeV



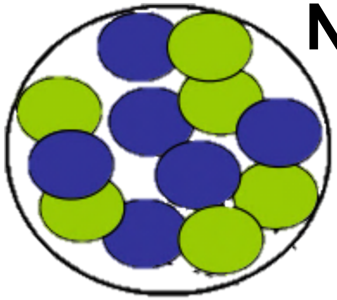
$$x_B = \frac{Q^2}{2m\omega}$$

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

$0<x_B<1$:
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

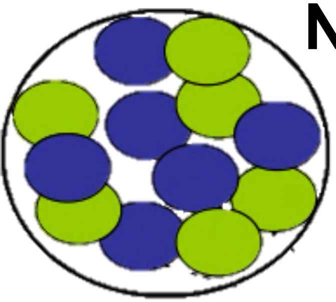
Naive expectation :

DIS off a bound nucleon = DIS off a free nucleon

(Except some small Fermi momentum correction)

Deep Inelastic Scattering *Off-Nuclei*

DIS scale: several tens of GeV



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Deuteron: binding energy ~2 MeV

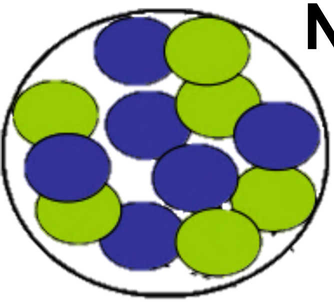
Average nucleons separation ~2 fm

Naive expectation :

DIS off a deuteron = DIS off a free proton neutron pair

Deep Inelastic Scattering *Off-Nuclei*

DIS scale: several tens of GeV



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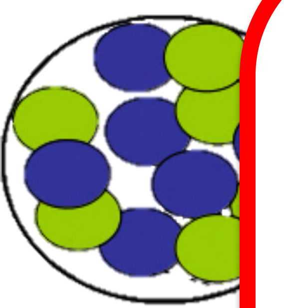
General Naive Expectation :

DIS off nucleons in *nuclei*

= DIS off nucleons in *deuterium*

Deep Inelastic Scattering *Off-Nuclei*

DIS sc

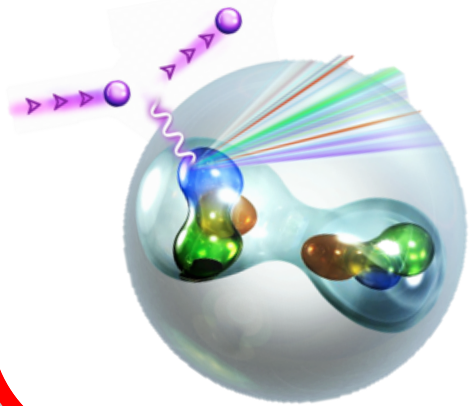


eon

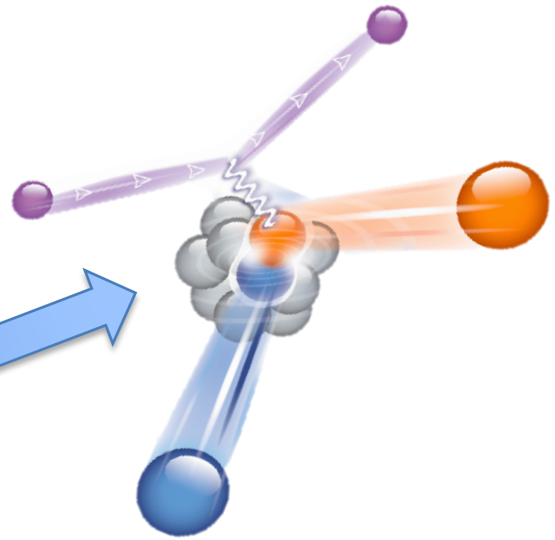
Deu

eutron pair

Focus of this talk – connection between DIS and QE



?

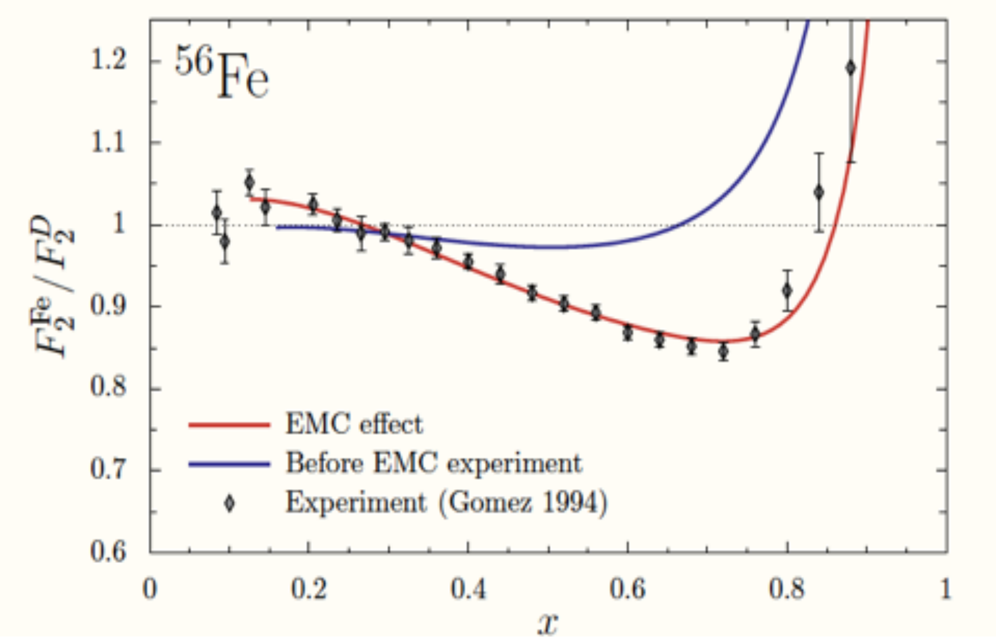


General Naive Expectation :

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.



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

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

EMC Effect

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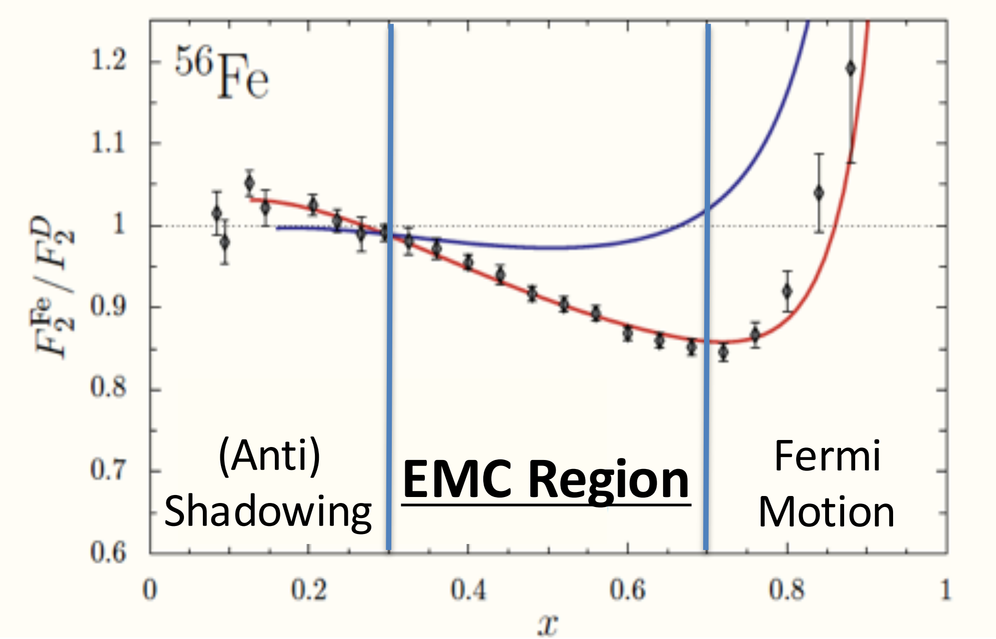
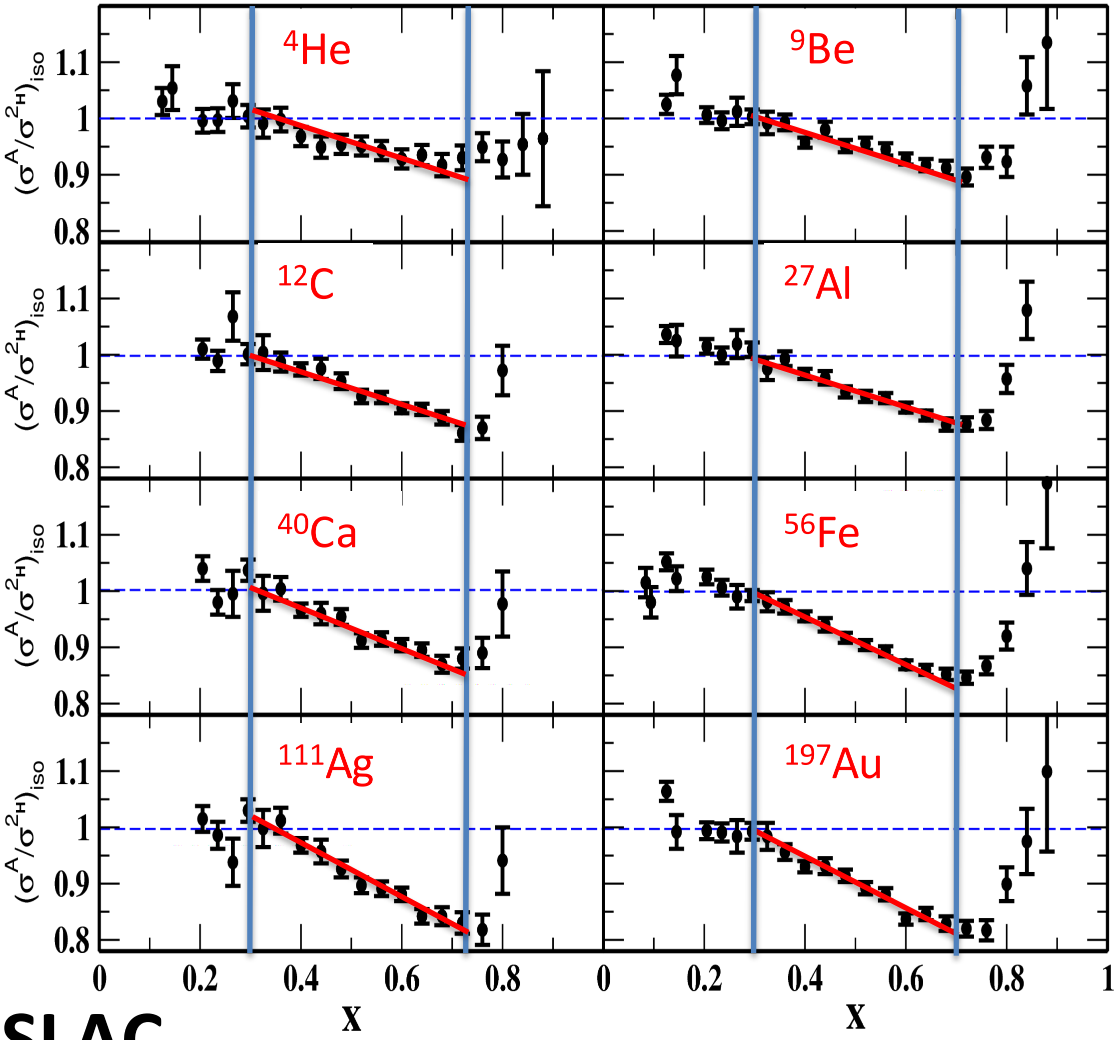


$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_A = \frac{4\alpha^2 E'^2}{Q^4}\left[2\frac{F_1}{M}\sin^2\left(\frac{\theta}{2}\right) + \frac{F_2}{\nu}\cos^2\left(\frac{\theta}{2}\right)\right] \qquad F_2\left(x,Q^2\right) = \sum_i e_i^2 \cdot x \cdot f_i\left(x\right)$$

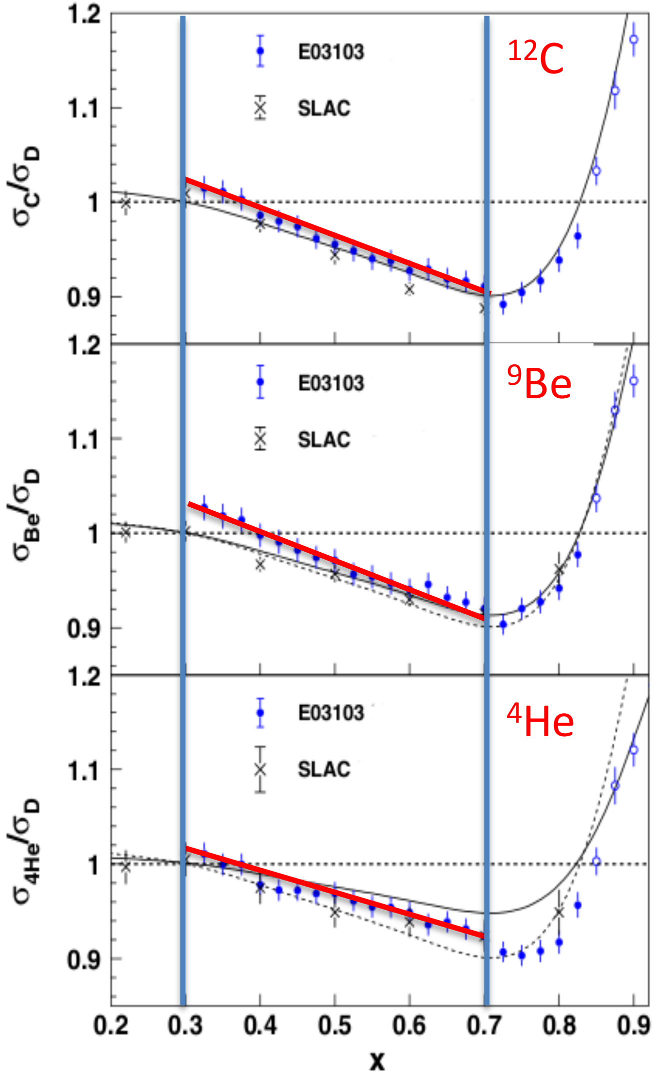
Universality of the EMC Effect



SLAC

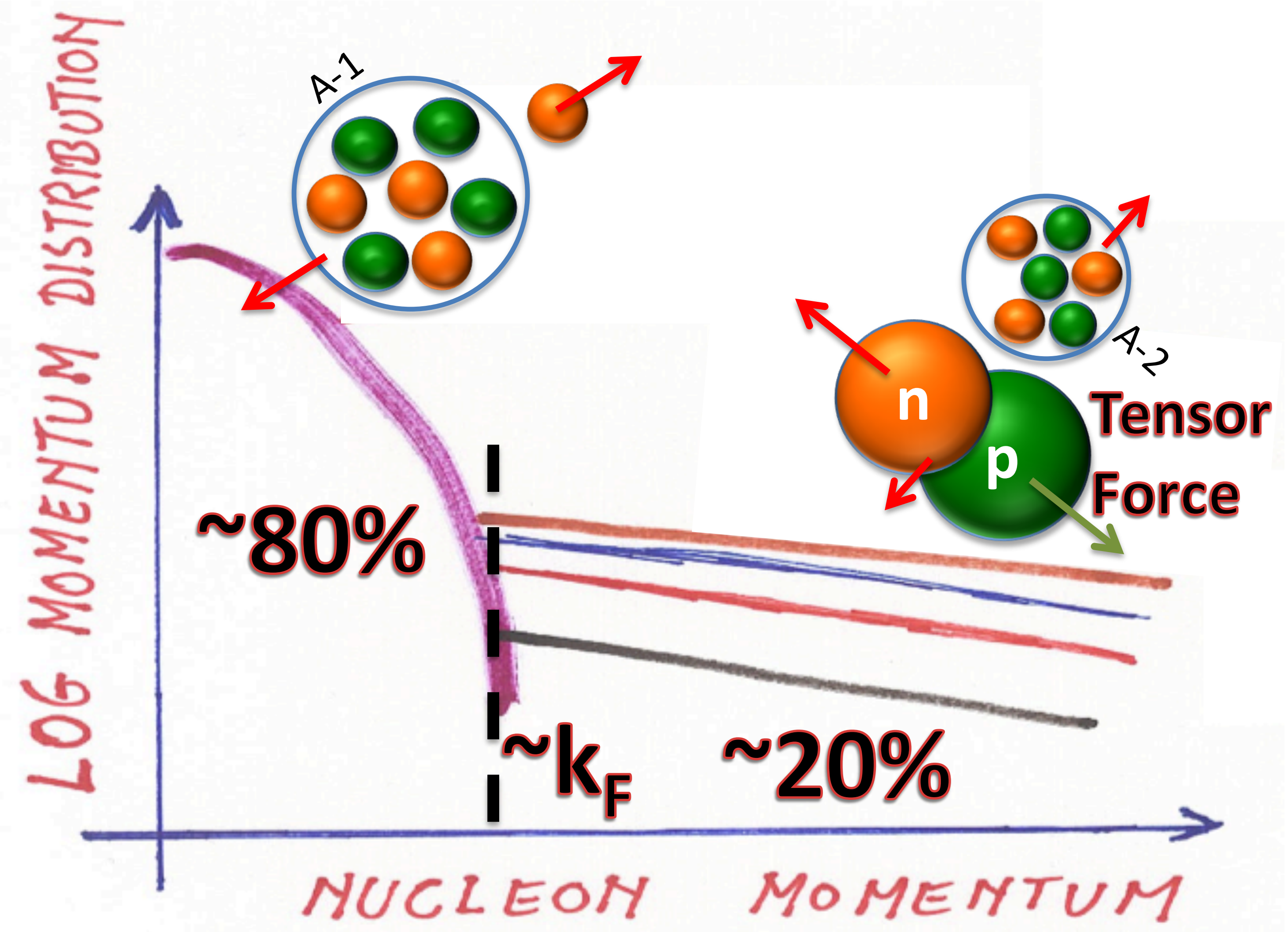
J. Gomez et al., Phys. Rev. D **49**, 4348 (1994).

JLab

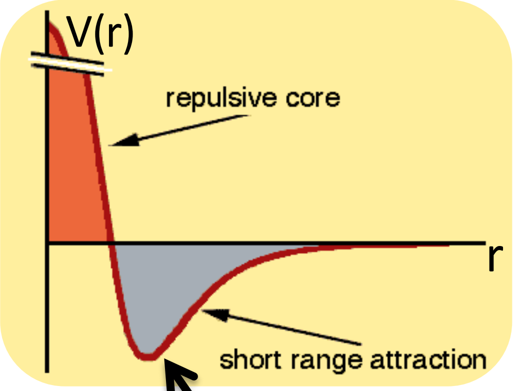


J. Seely et al., Phys. Rev. Lett. **103**, 202301 (2009).

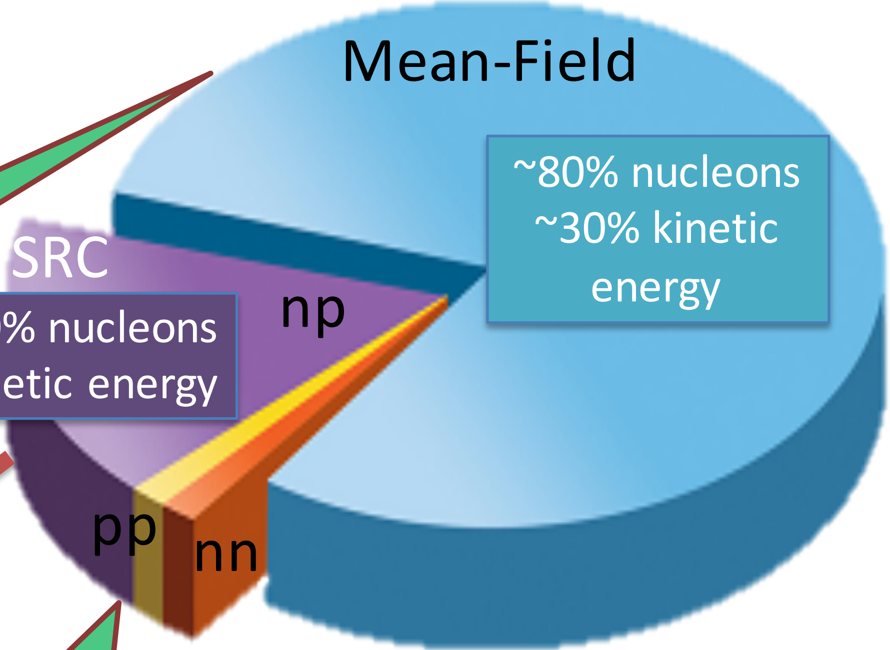
Nuclear Structure



Where is the EMC Effect?



Largest attractive force

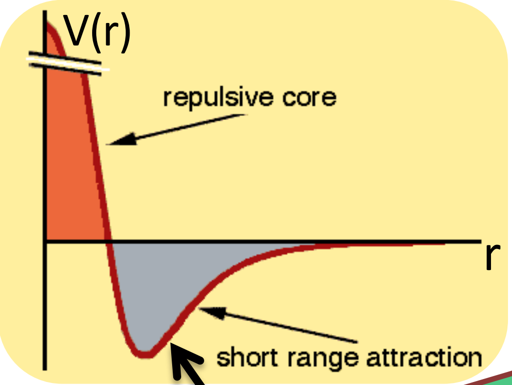


~80% nucleons
~30% kinetic energy

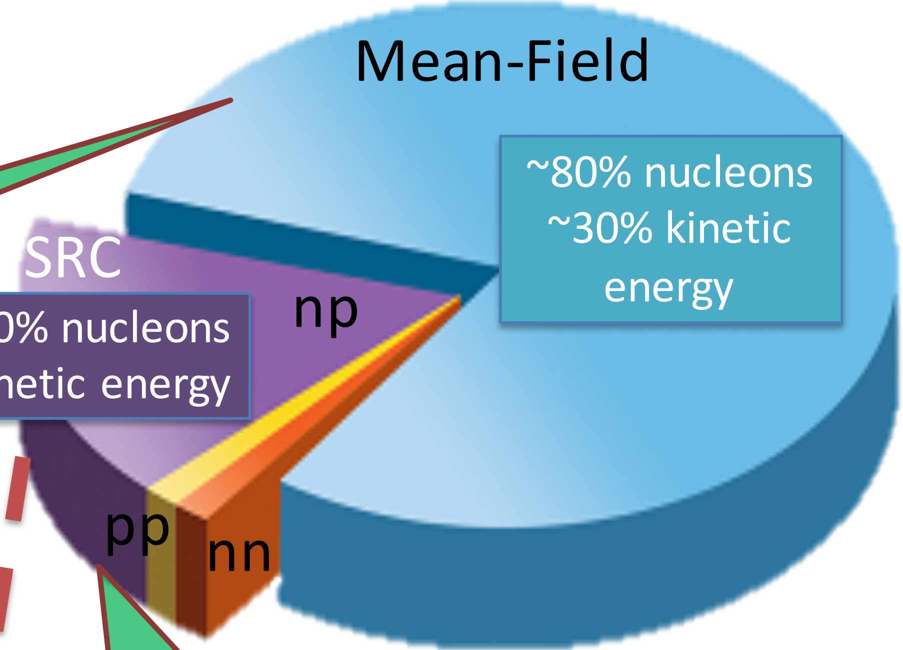
~20% nucleons
~70% kinetic energy

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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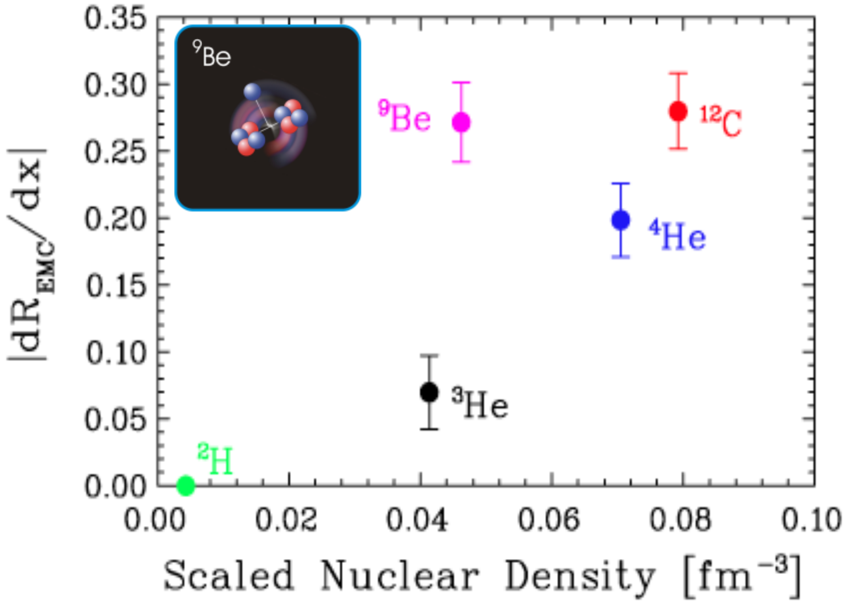

J. Seely et al., Phys. Rev. Lett. **103**, 202301 (2009).

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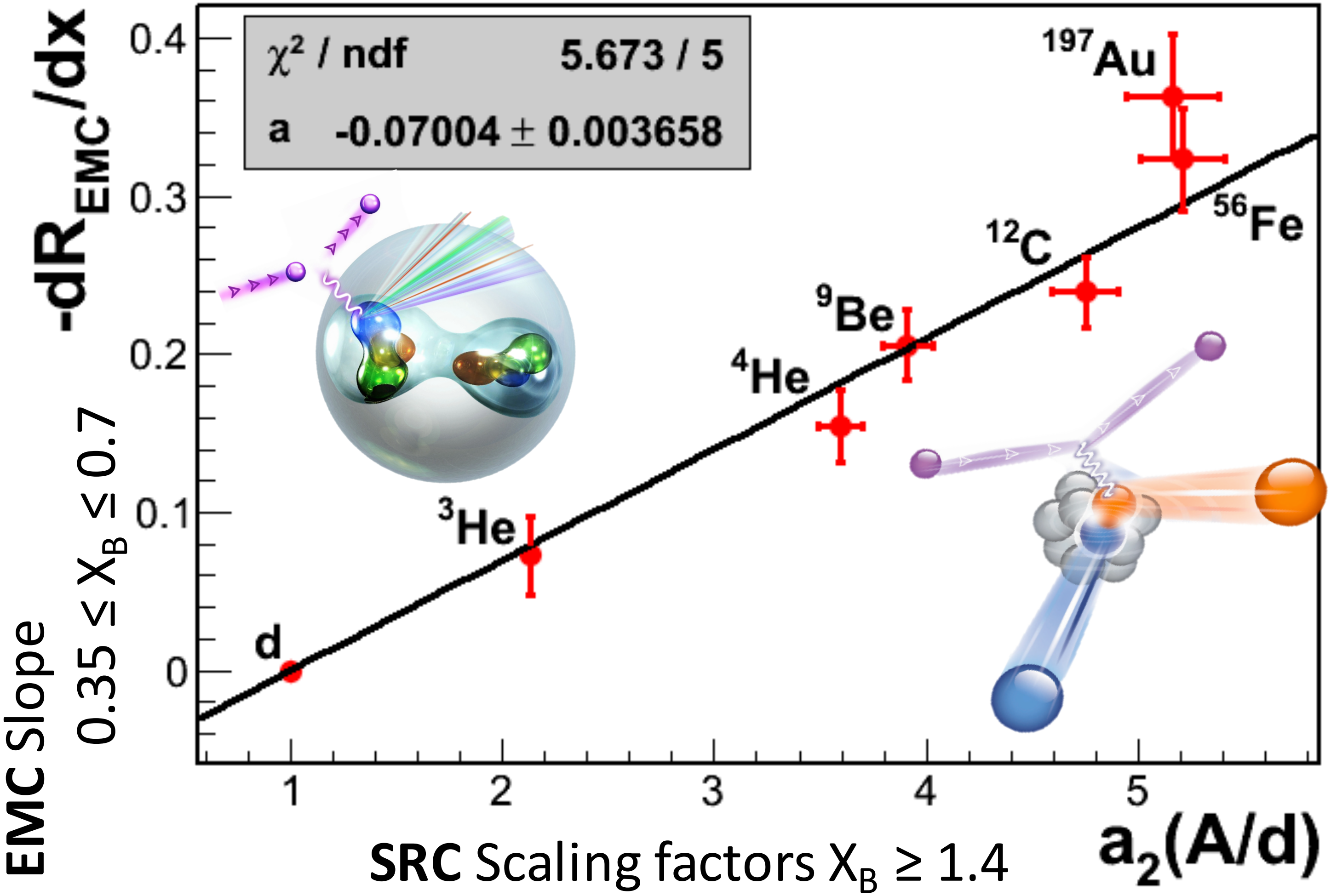
EMC-SRC Correlation



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.

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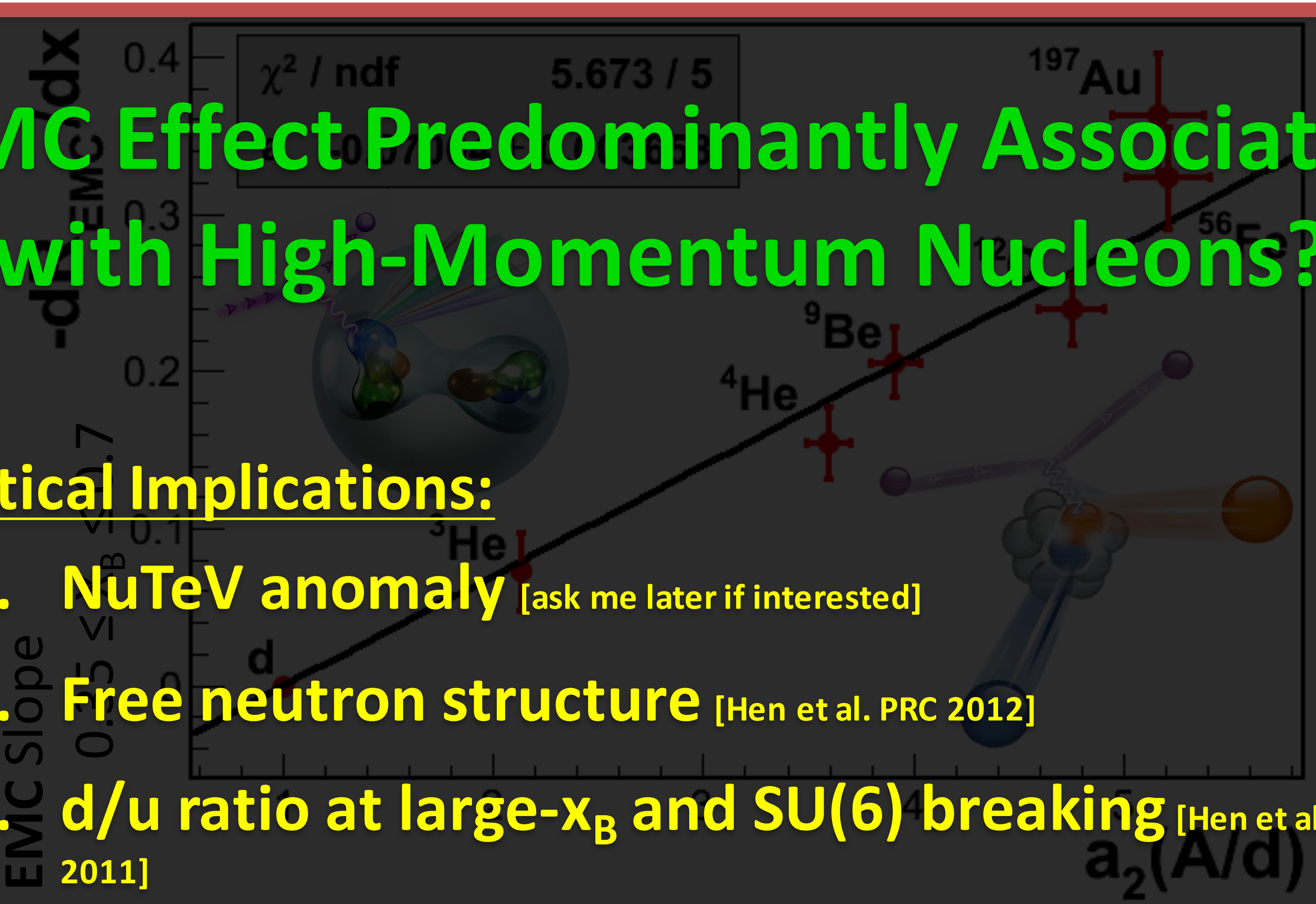

EMC Effect Predominantly Associated with High-Momentum Nucleons?

Practical Implications:

1. **NuTeV anomaly** [ask me later if interested]

2. **Free neutron structure** [Hen et al. PRC 2012]

1. **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).

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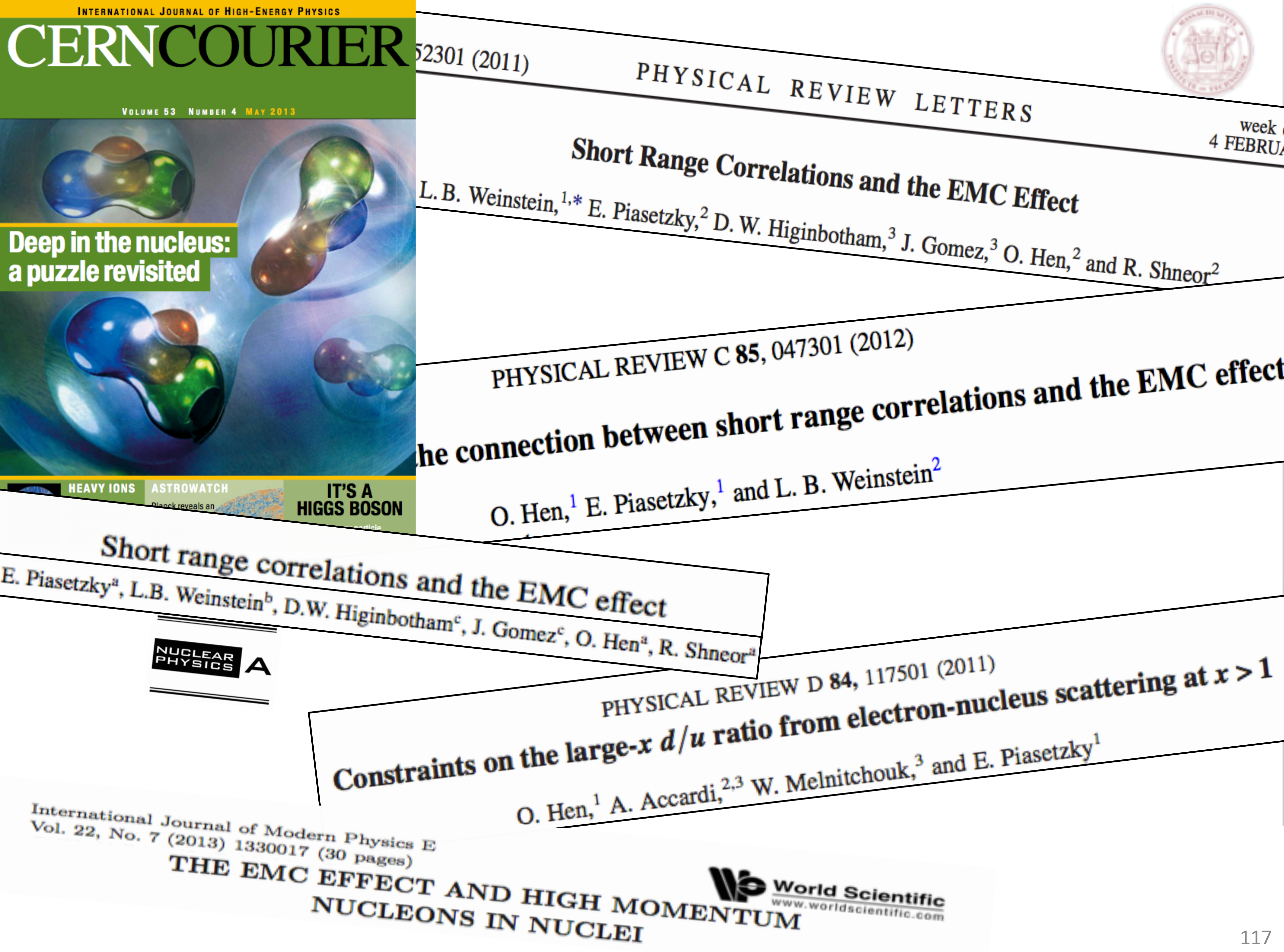

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

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PHYSICAL REVIEW LETTERS

week
4 FEBRU

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NUCLEAR PHYSICS A

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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]

International Journal of Modern Physics E
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THE EMC EFFECT AND HIGH MOMENTUM NUCLEONS IN NUCLEI

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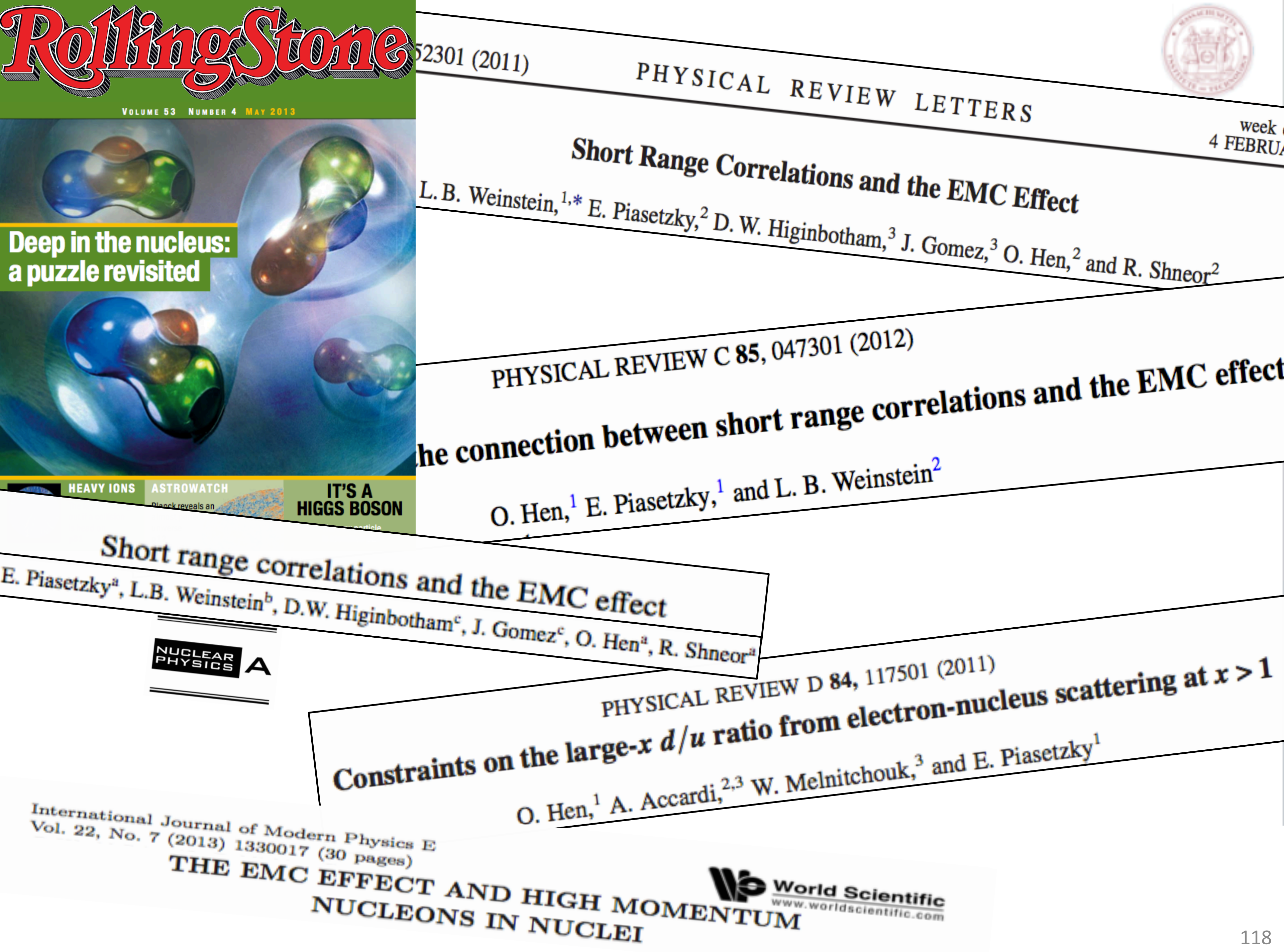

Rolling Stone

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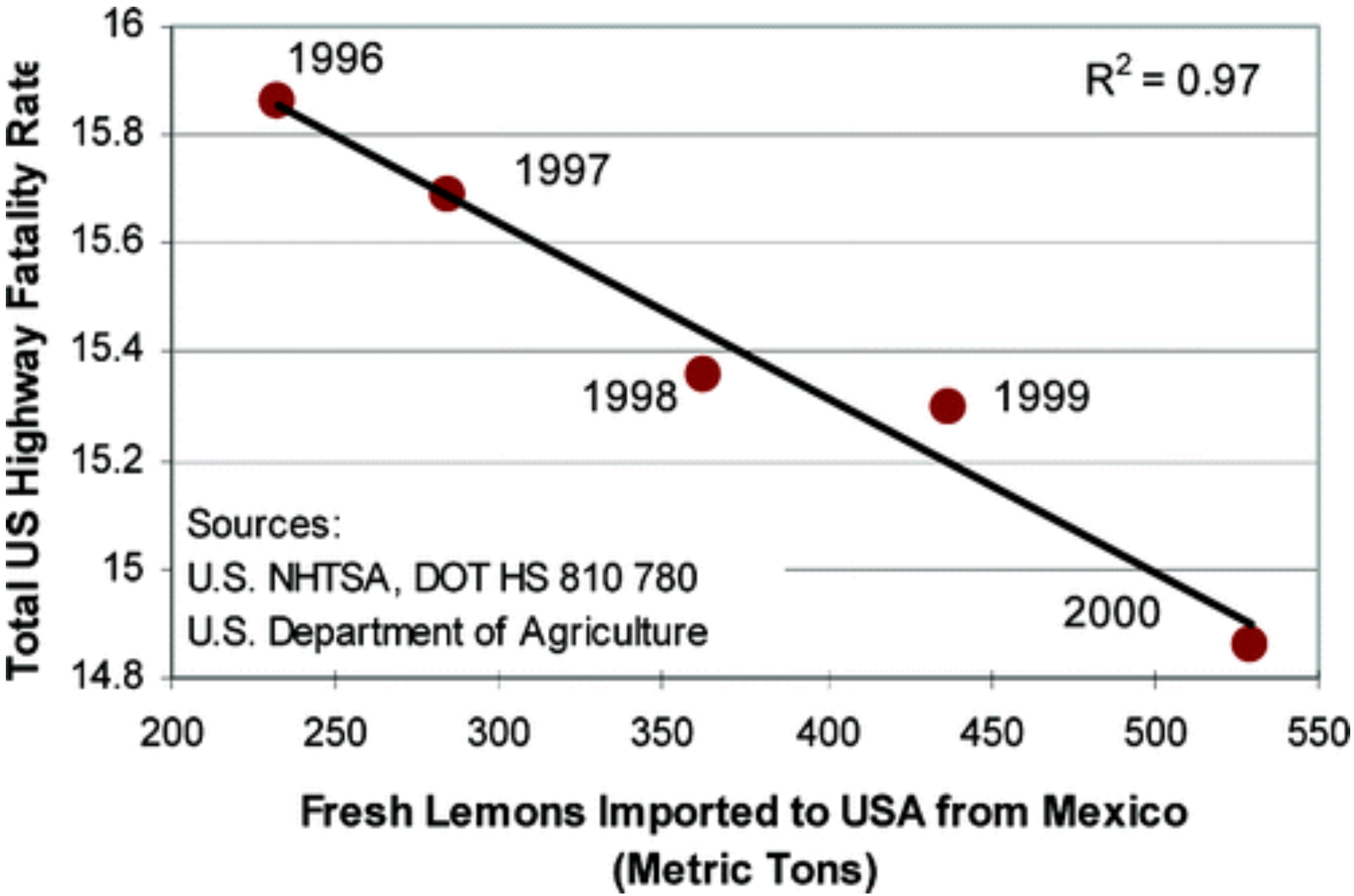
Other Correlations…



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

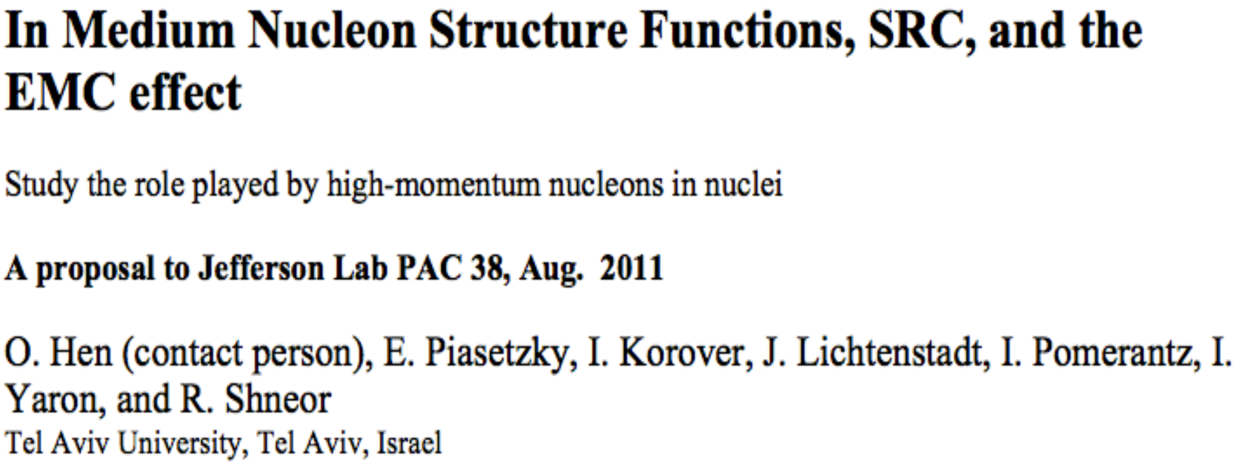
- Models suggested that the EMC effect depends on the average kinetic energy, <T>, carried by nucleons in the nucleus
  - <T> is dominated by 2N-SRC

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

Experimental Tests ?

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

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

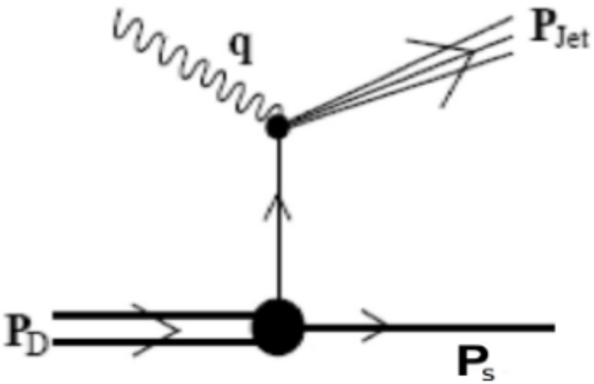


In Medium Nucleon Structure Functions, SRC, and the EMC effect

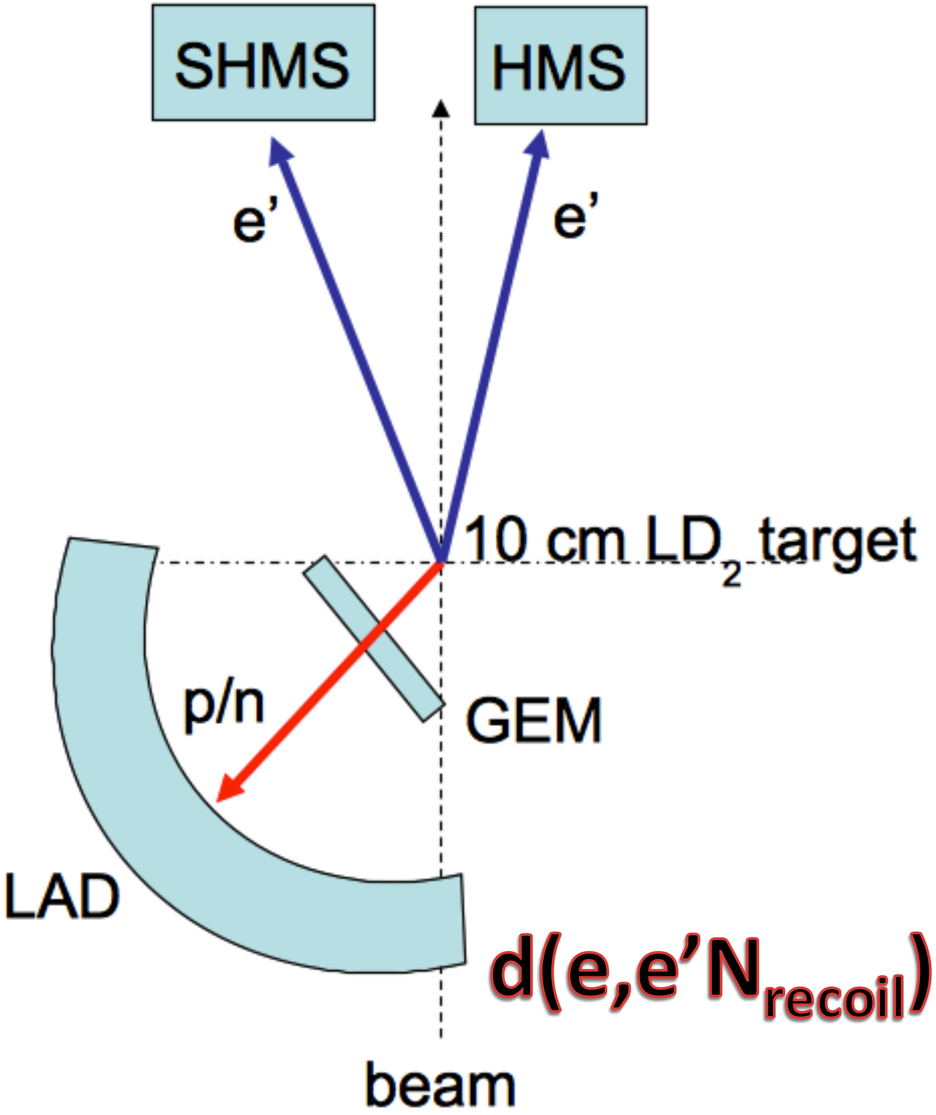
Study the role played by high-momentum nucleons in nuclei

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



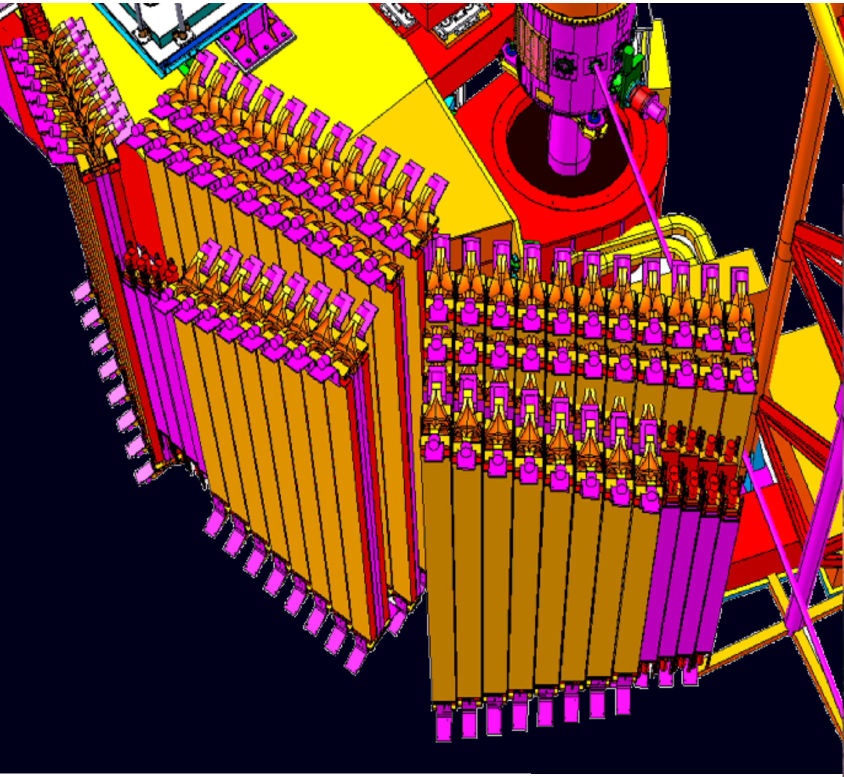
Our Concept…



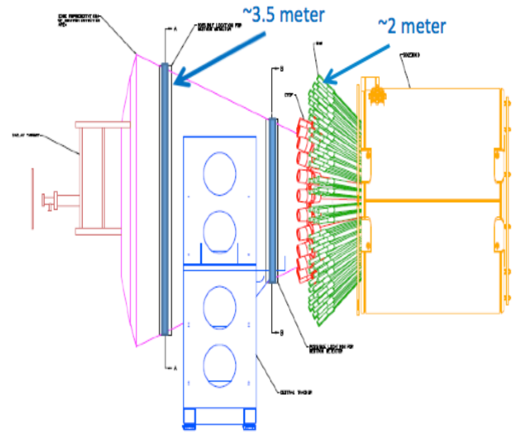
$d(e,e'N_{recoil})$

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

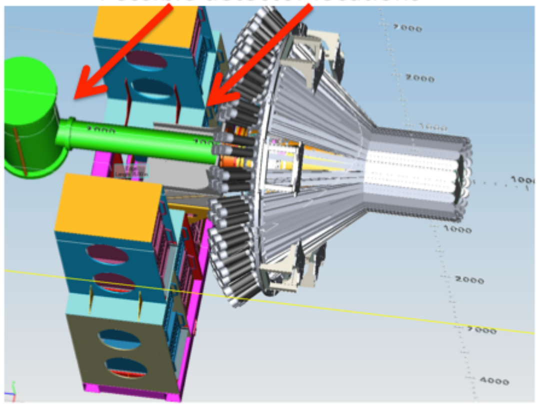
…Its realization (LAD / BAND)



Large Acceptance Detector (LAD@Hall-C)



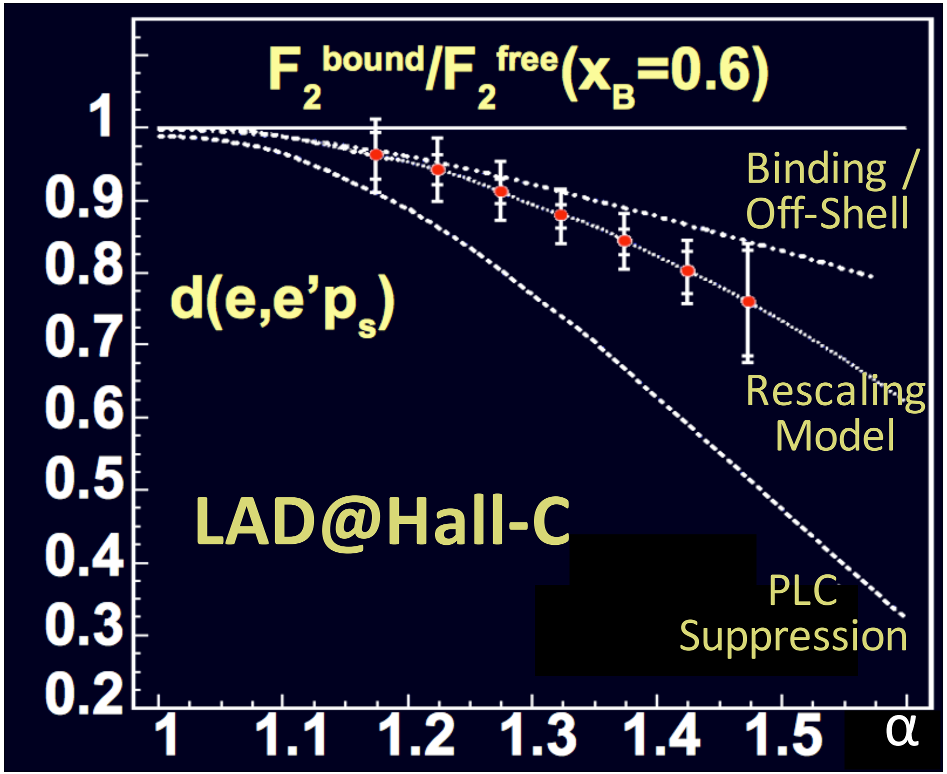
Possible detector locations



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) @ $W^2 > 4\ [\text{GeV/c}]^2$



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