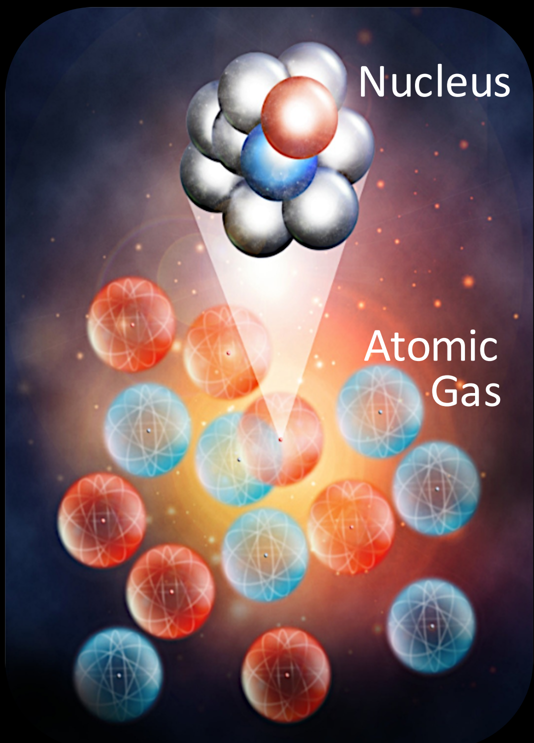
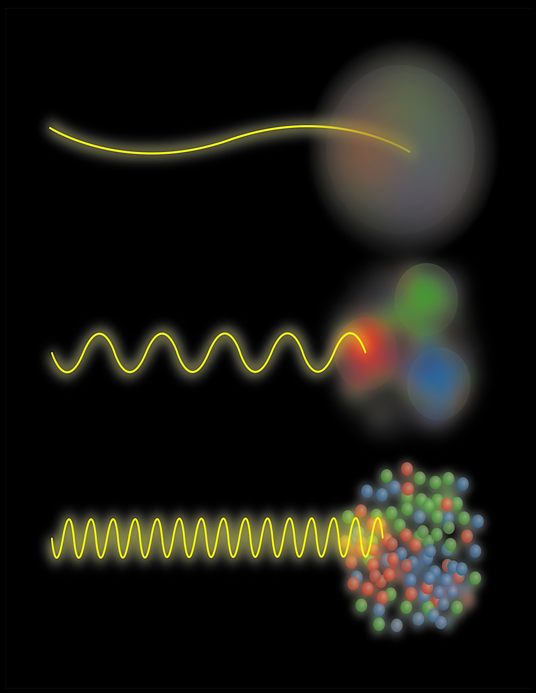
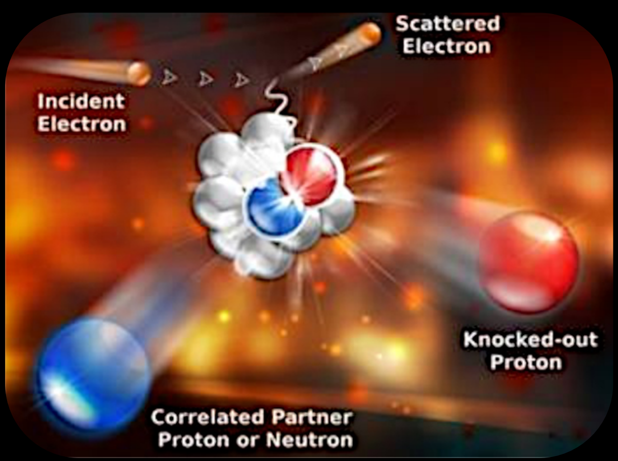
Momentum Sharing in Asymmetric Fermi-Systems



Or Hen

MIT



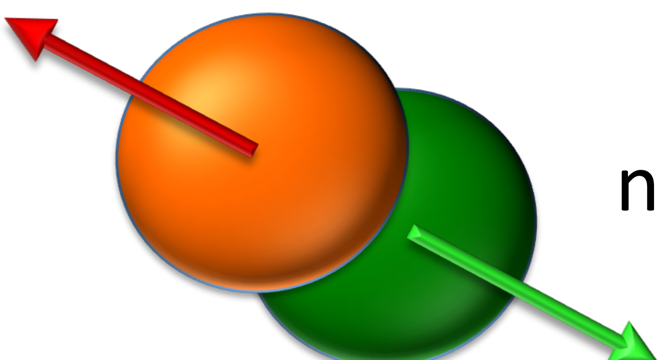


FIU FLORIDA INTERNATIONAL UNIVERSITY

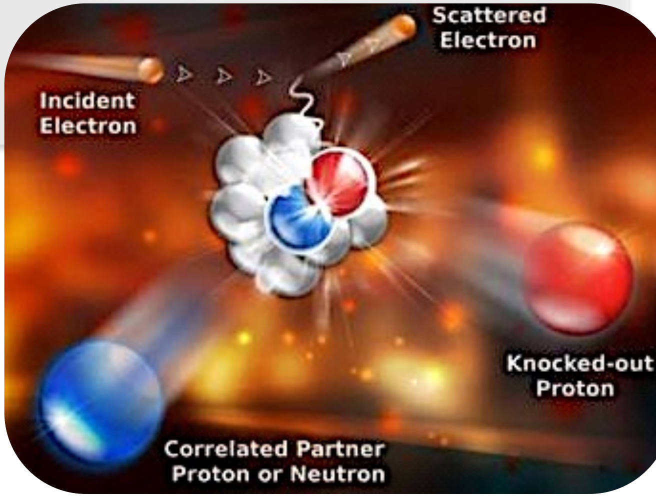
Next generation nuclear physics with JLab12 and EIC, February 11th, 2016

What are Short-Range Correlation (SRC)

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

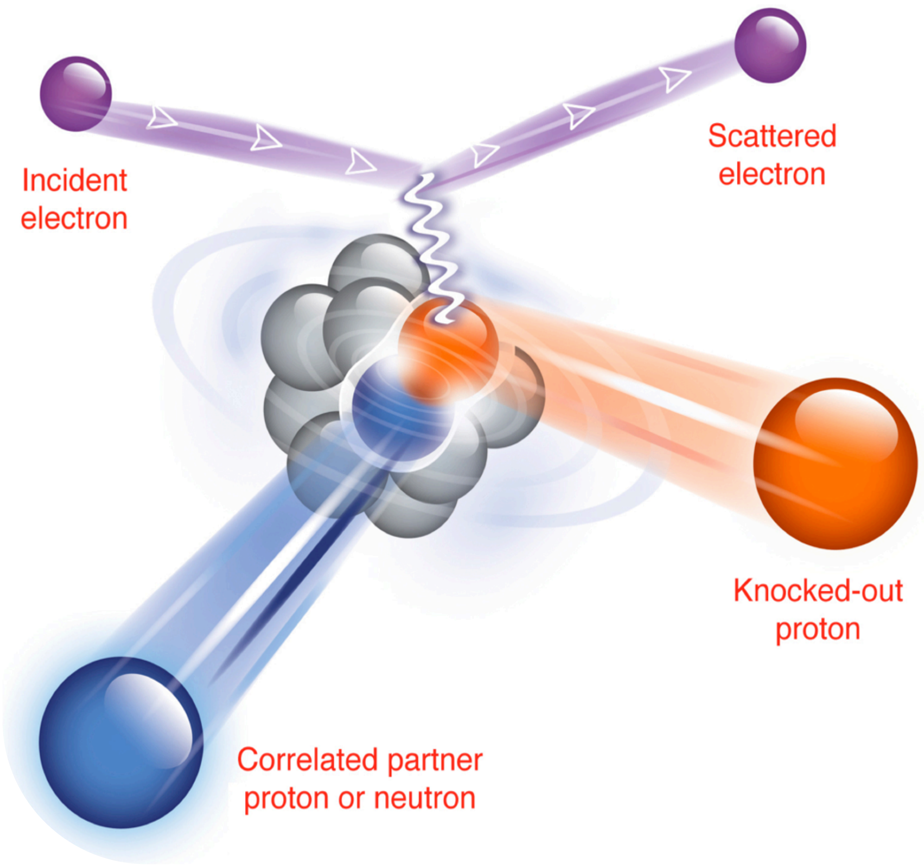


COLD dense nuclear matter

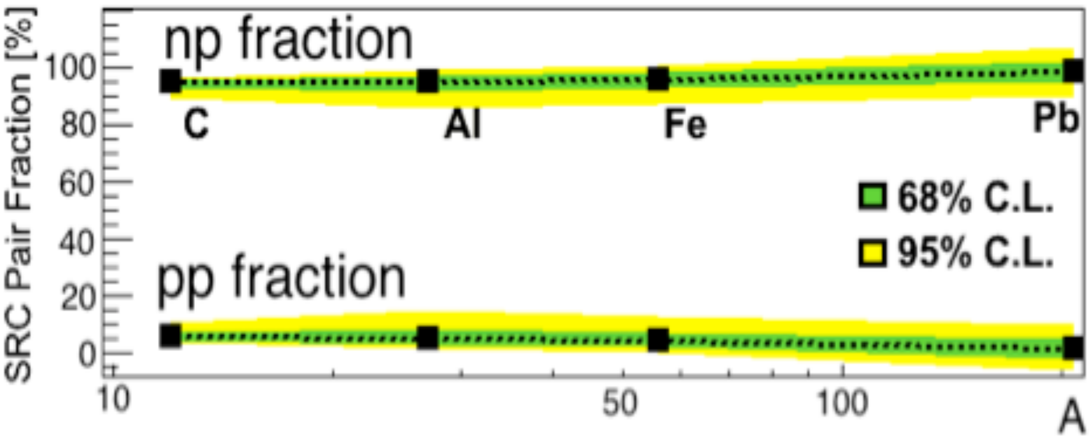


Exclusive 2N-SRC Studies

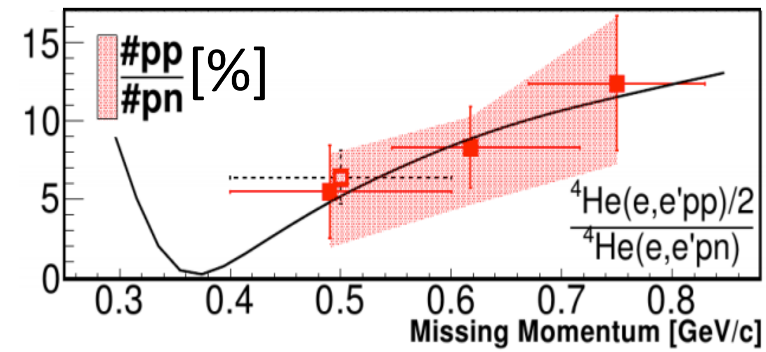
Breakup the pair =>
Detect both nucleons =>
Reconstruct 'initial' state



Isospin Structure

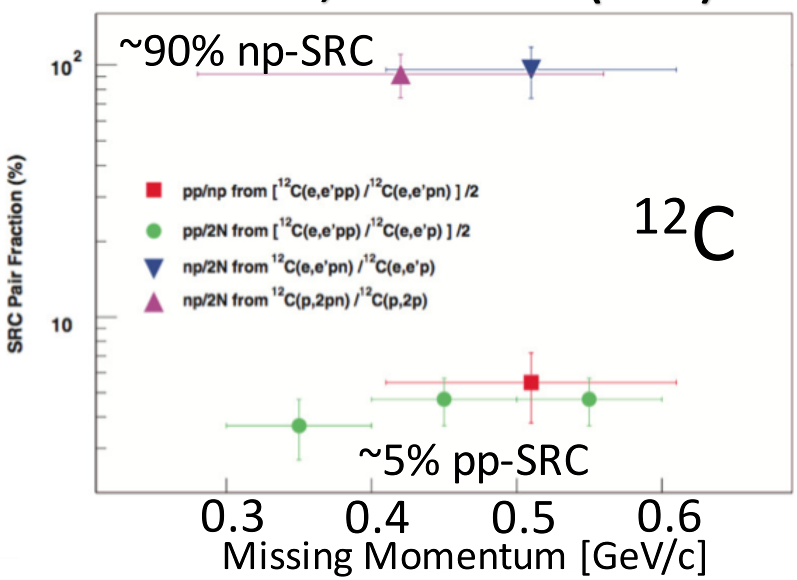


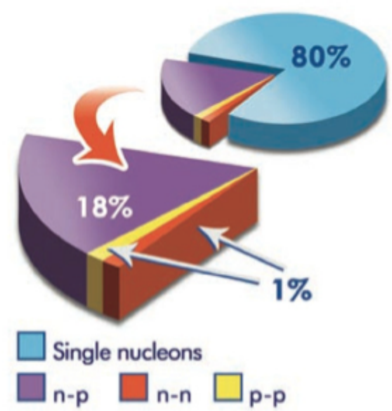
O. Hen et al., Science 364 (2014) 614

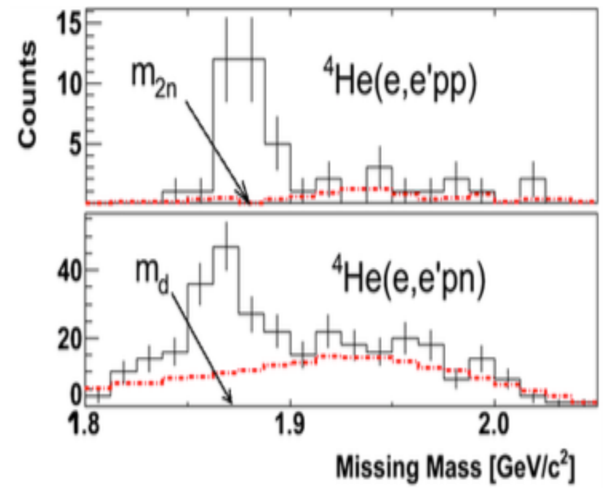


R. Subedi et al., Science 320 (2008) 1476

I. Korover et al., PRL 113 (2014) 022501

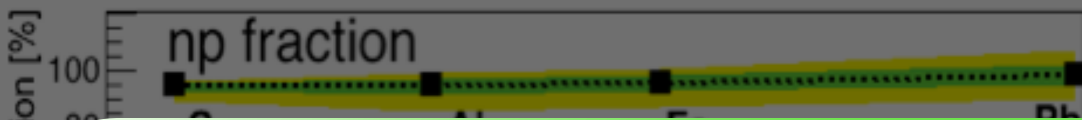






A. Tang et al., PRL (2003); E. Piasetzky et al., PRL (2006); R. Shneor et al., PRL (2007)

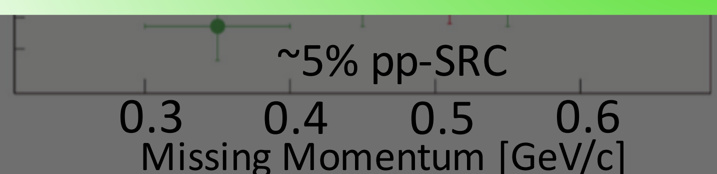
Isospin Structure



O. Hen et al., Science 364 (2014) 614

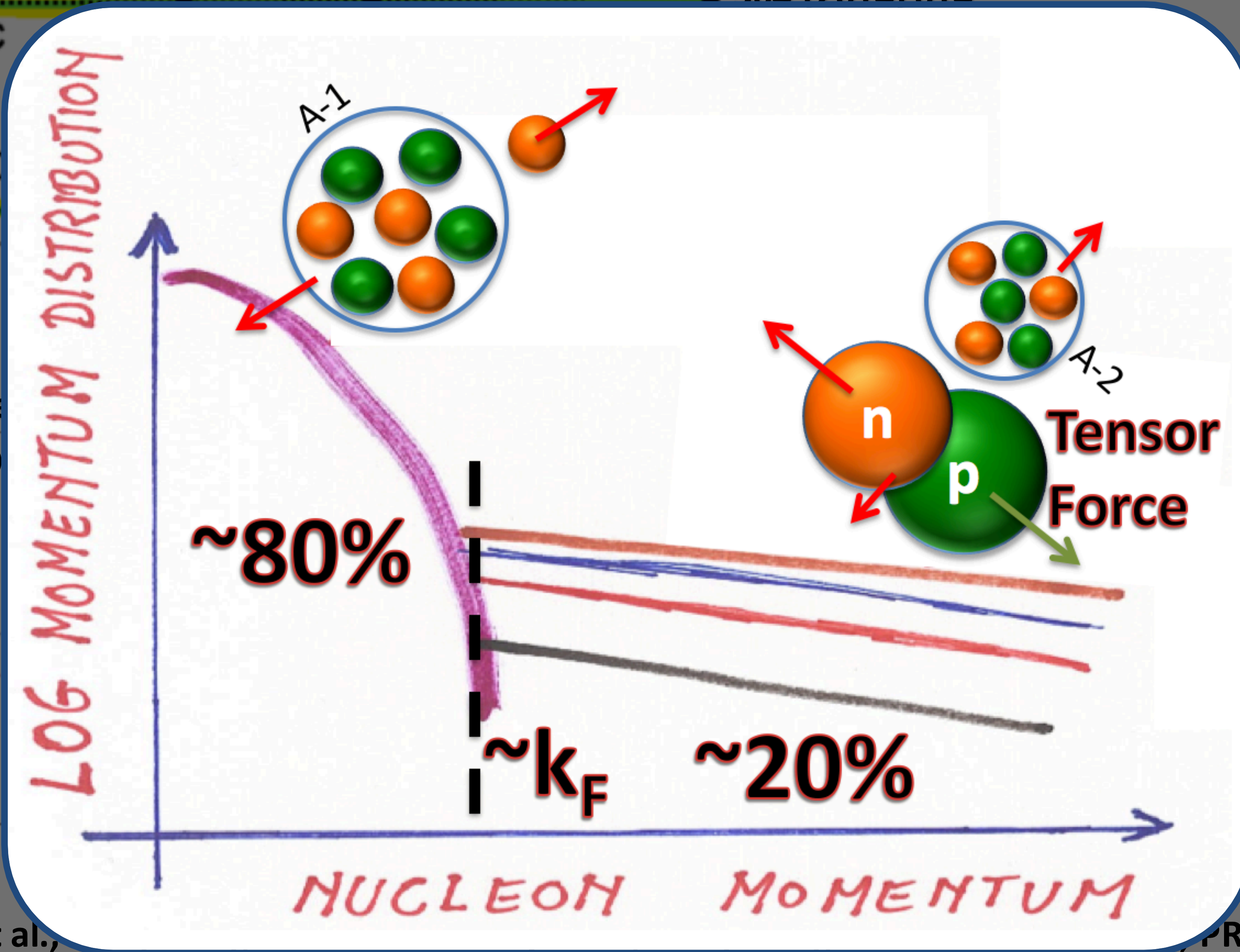
Bottom Line:

- np-SRC dominance observed in A = 4 – 208 nuclei.
- Strong indication for Tensor force dominance at short distance

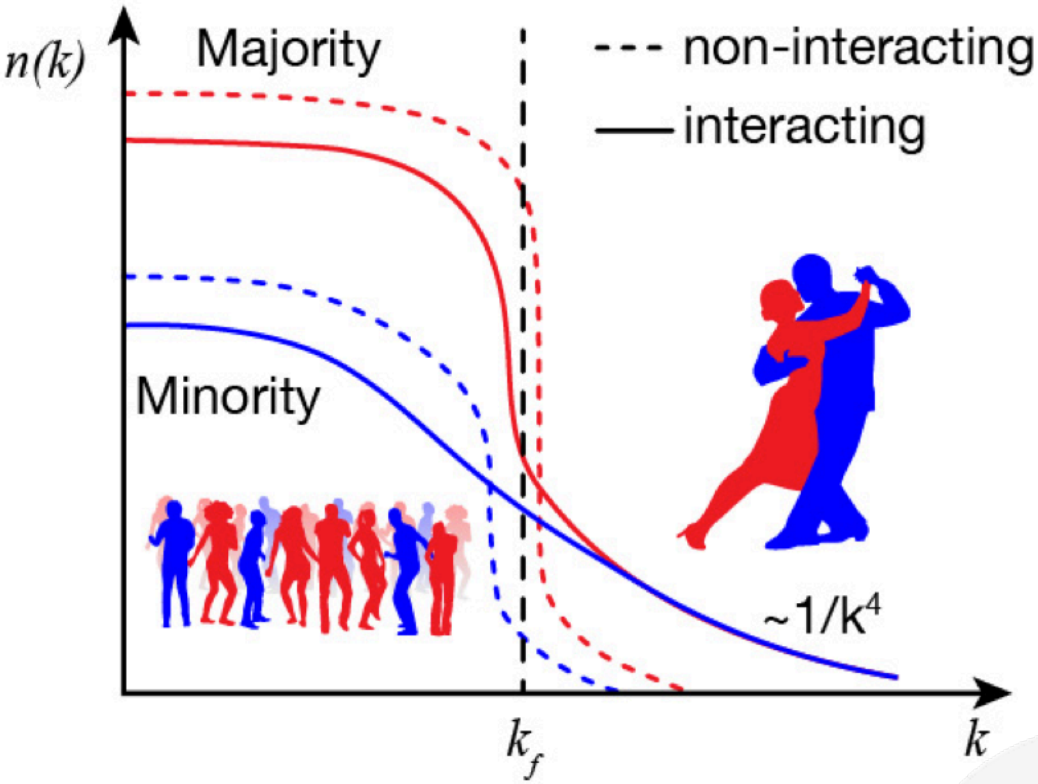


A. Tang et al., PRL (2003); E. Piasetzky et al., PRL (2006); R. Shneor et al., PRL (2007)

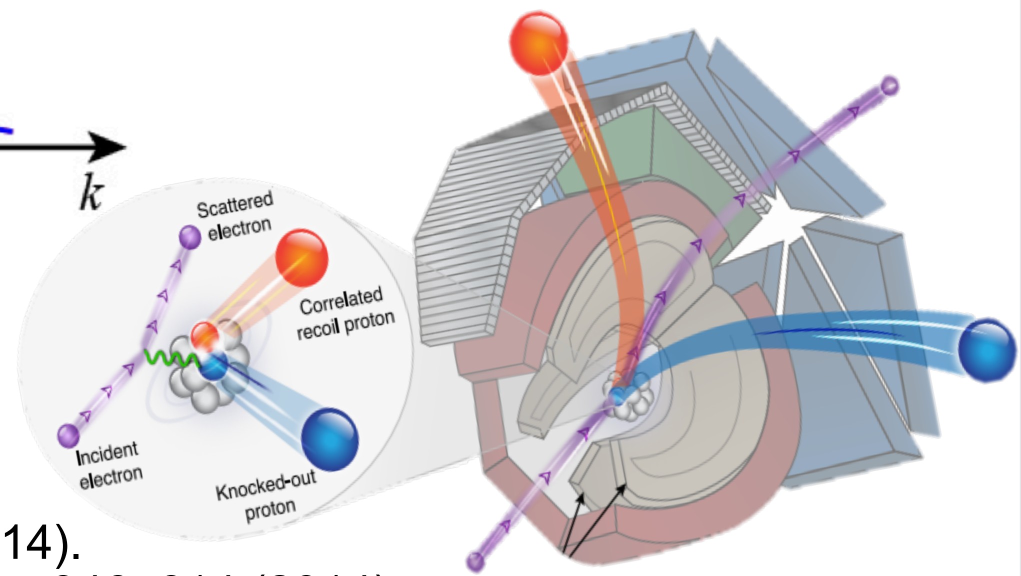
Universal structure of nuclear momentum distributions



Kinetic Energy Sharing

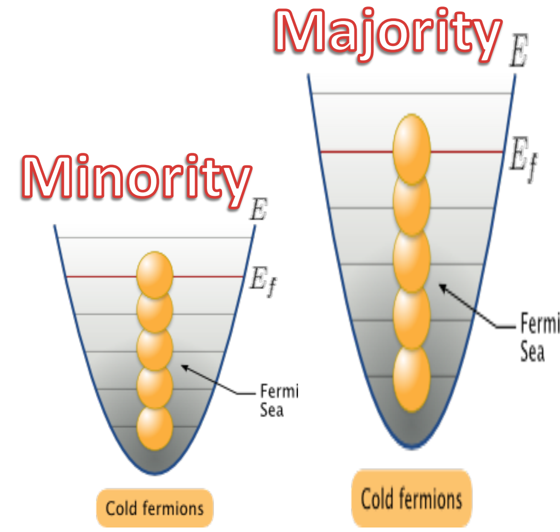


Momentum distribution of an imbalanced two-component Fermi system



M. Sargsian, Phys. Rev. C 89, 034305 (2014).
O. Hen et al. (CLAS Collaboration), Science 346, 614 (2014).

Kinetic Energy Sharing in Asymmetric Nuclei

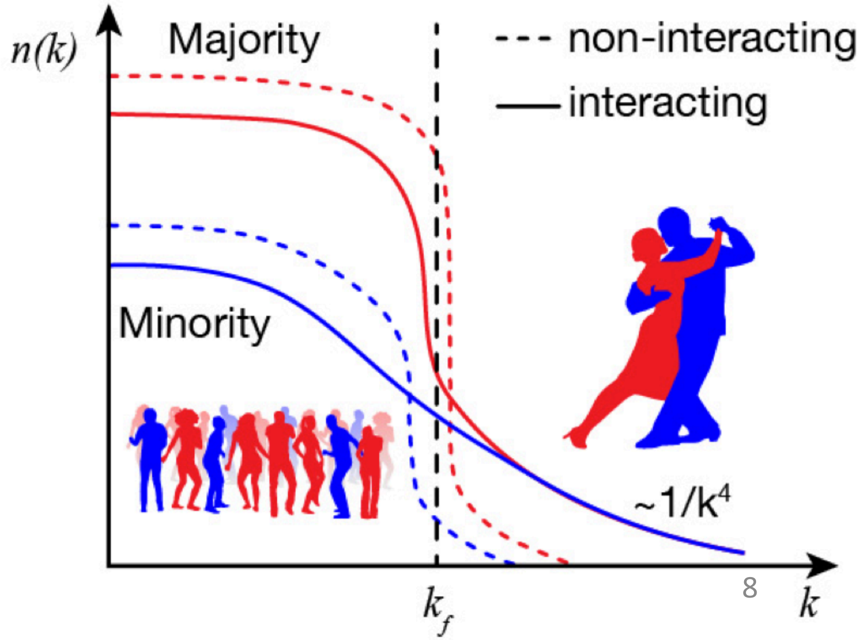


Pauli Principle:

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

np correlations:

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



Kinetic Energy Sharing in Asymmetric Nuclei

Pauli Principle:

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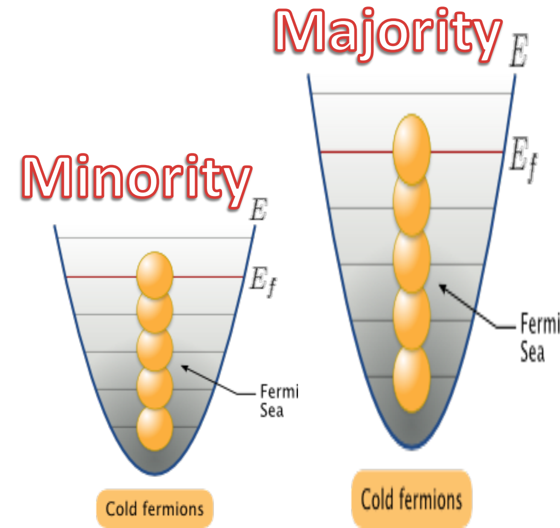

np correlations:

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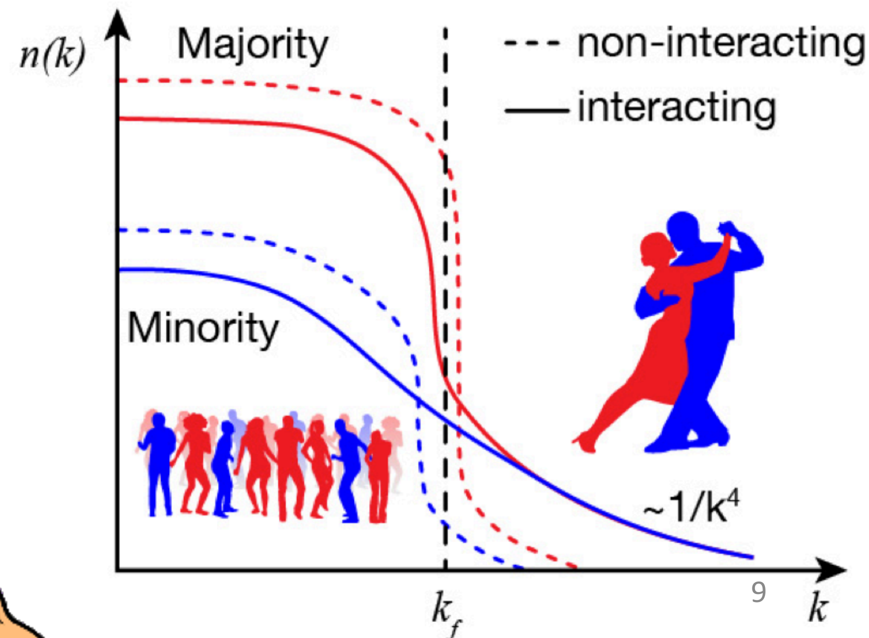
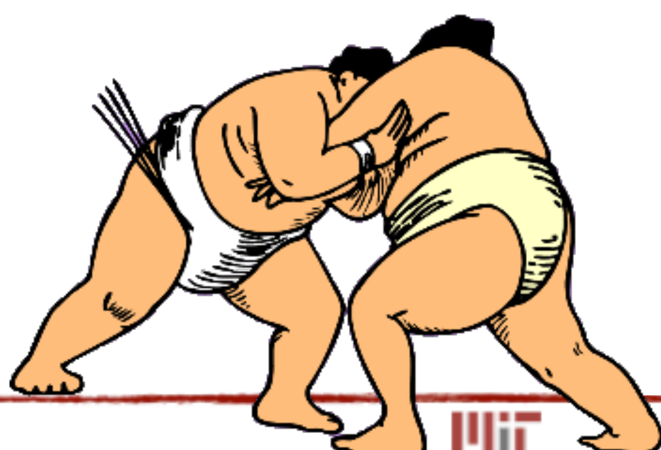
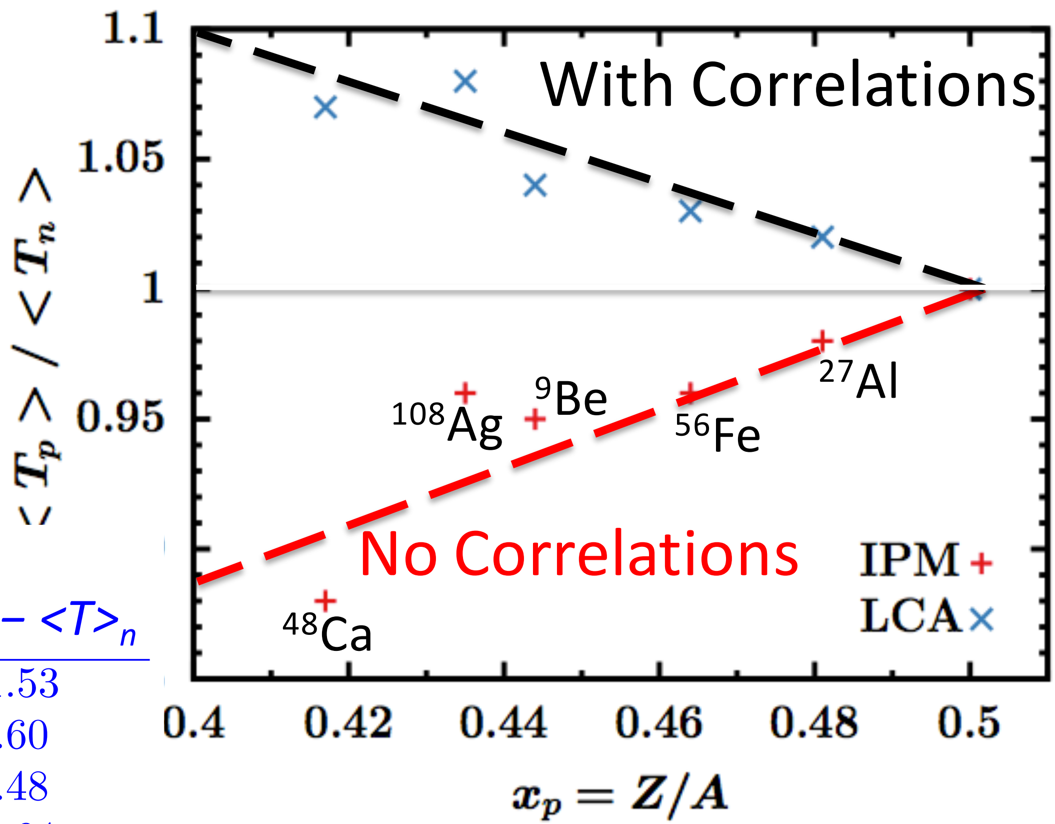


Who wins?



Calculations *Predict* Correlations wins

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



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

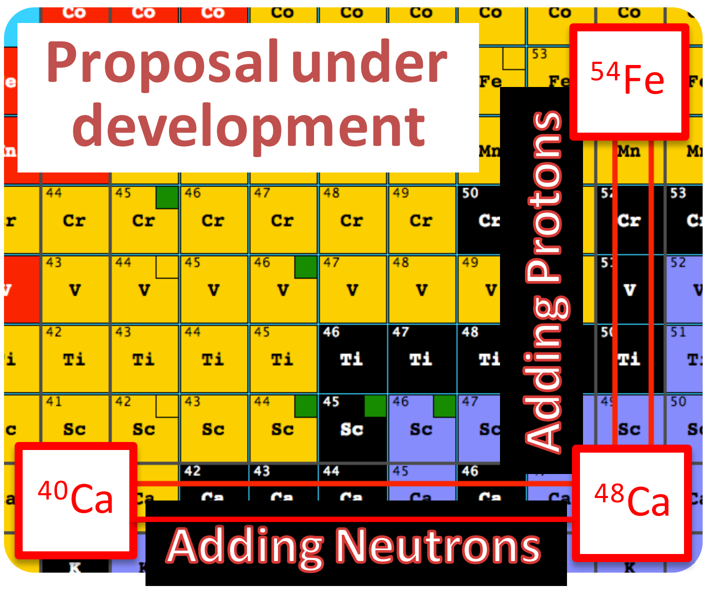
Light Nuclei (A<12)

	$\frac{\lvert N-Z \rvert}{A}$	$\langle T \rangle_p$	$\langle T \rangle_n$	$\langle T \rangle_p - \langle T \rangle_n$
^{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

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

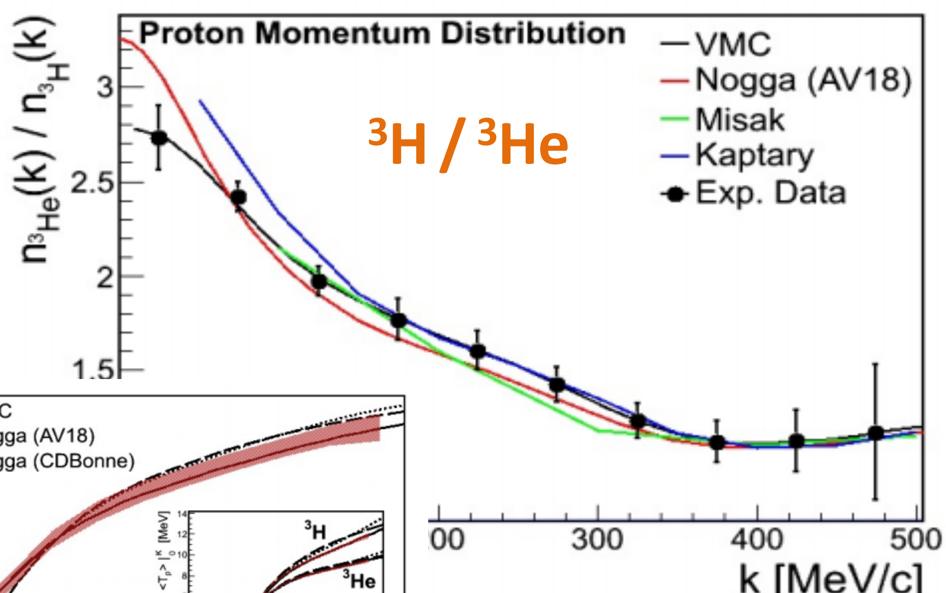
Paring in asymmetric nuclei (JLab12)

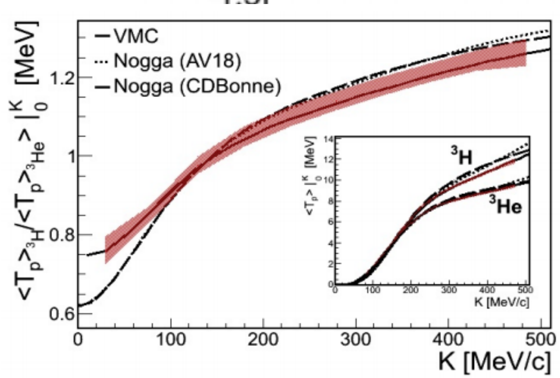
(e,e'p) studies of high-momentum nucleons



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

New targets (^{3}H, ^{48}Ca) allow studying the nuclear asymmetry dependence of the the proton (/neutron) momentum distribution.

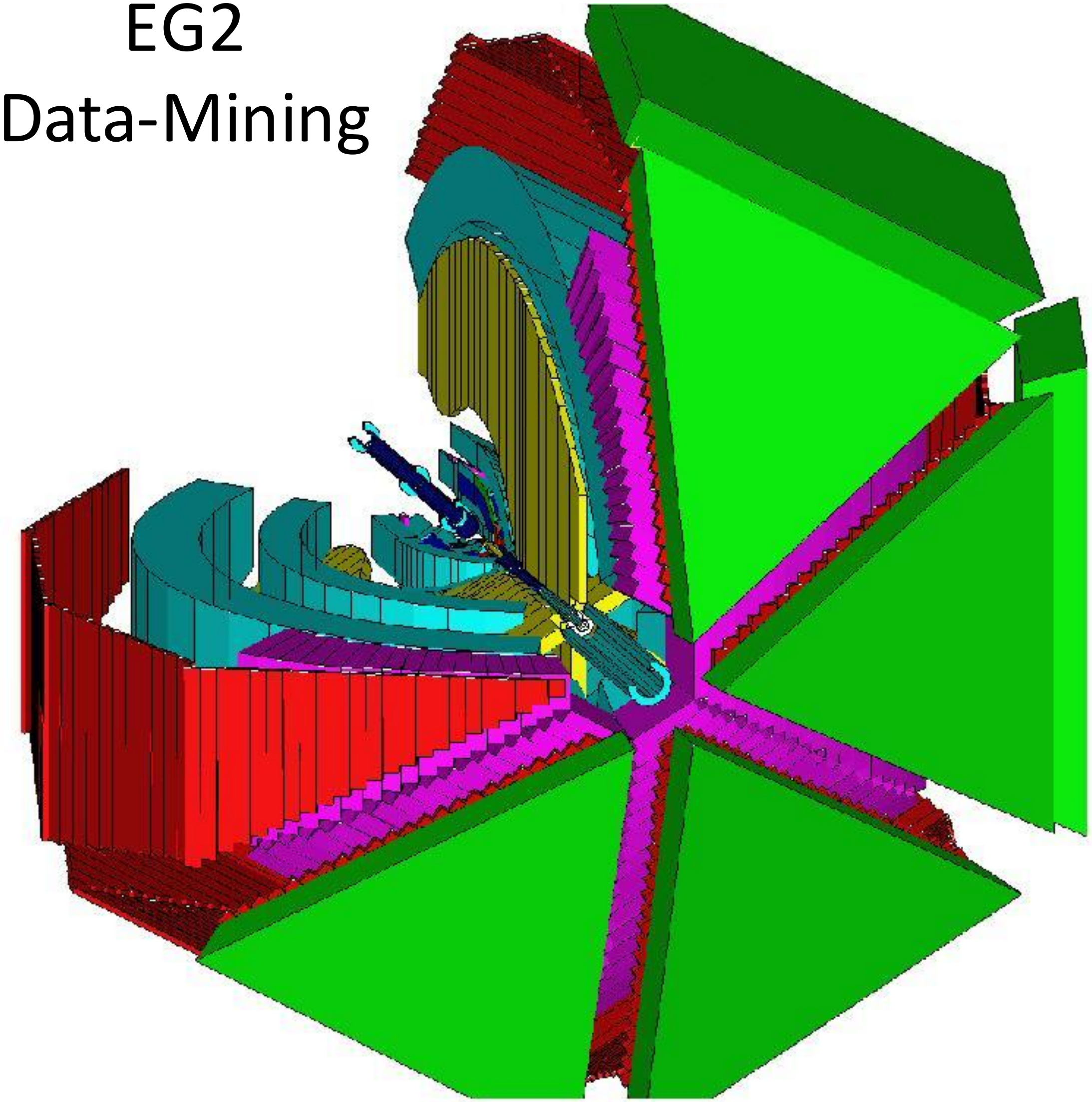


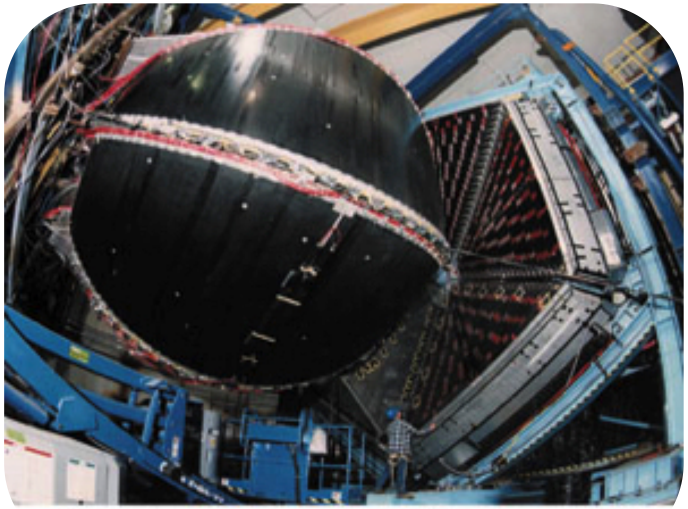


JLab E14-011 (scheduled for 2017)

New Data from CLAS (Before 12GeV)

EG2
Data-Mining



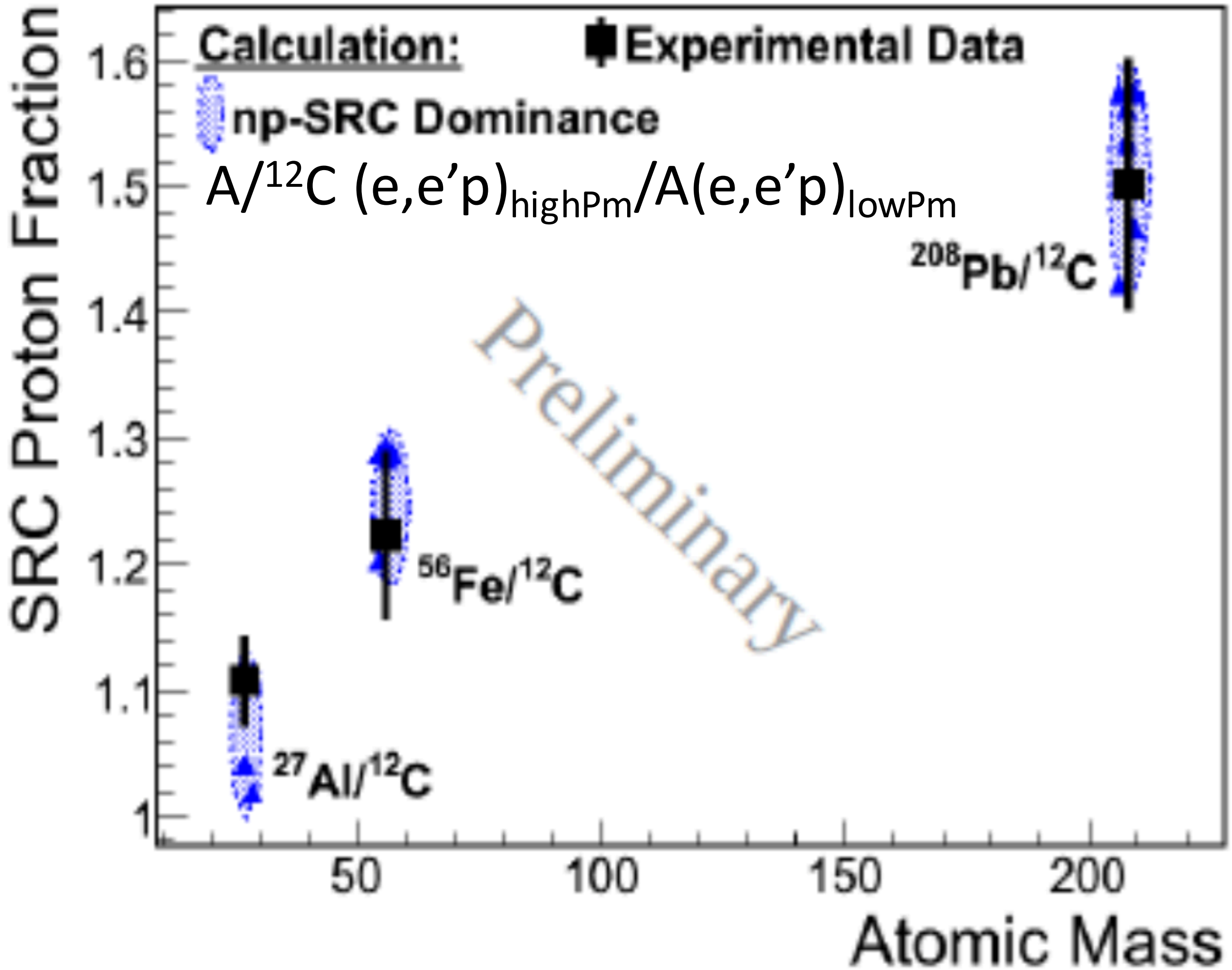


Hall B Large Acceptance Spectrometer

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

Experimental Verification?

Extract the asymmetry dependence of the fraction of high-momentum nucleons in nuclei



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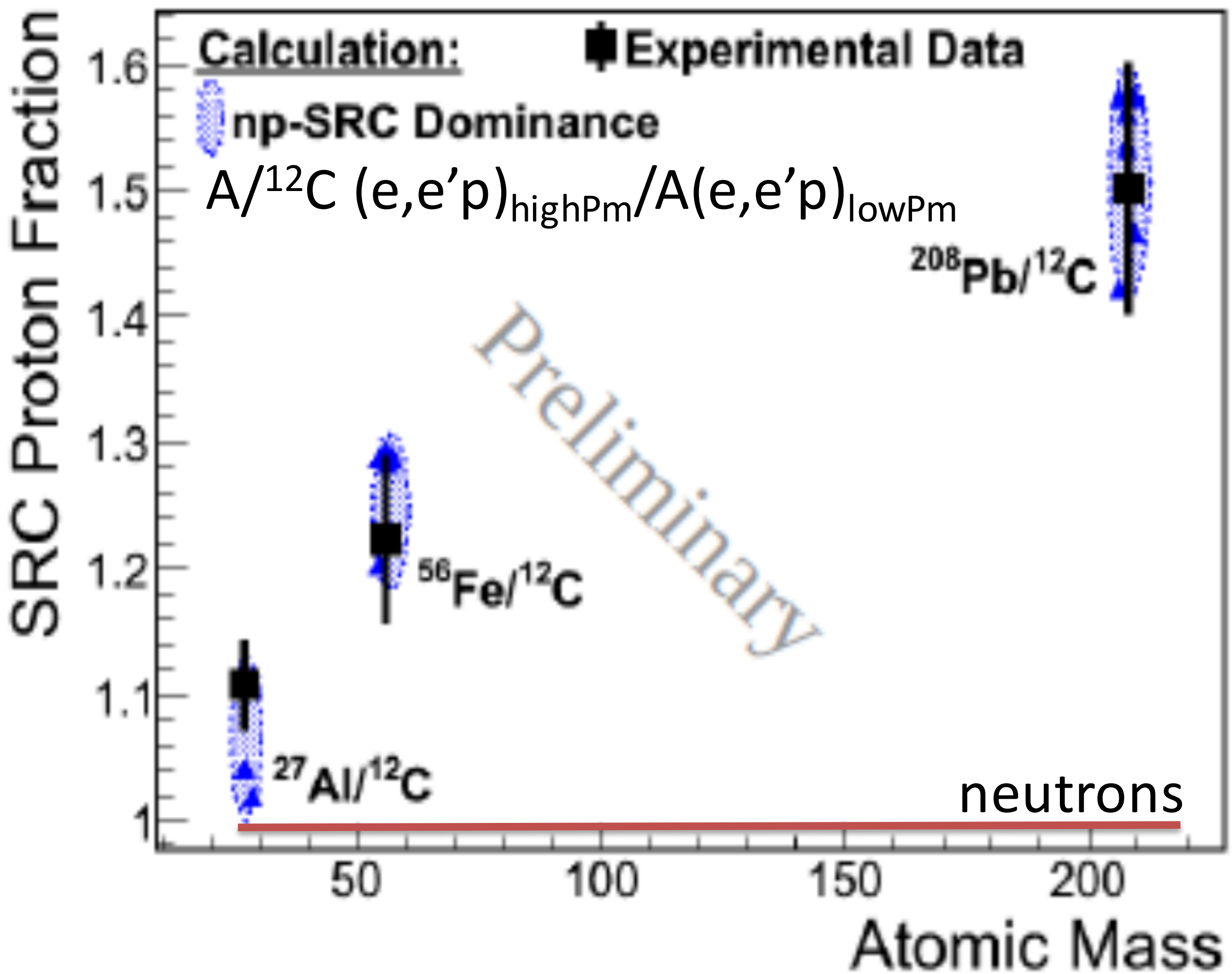

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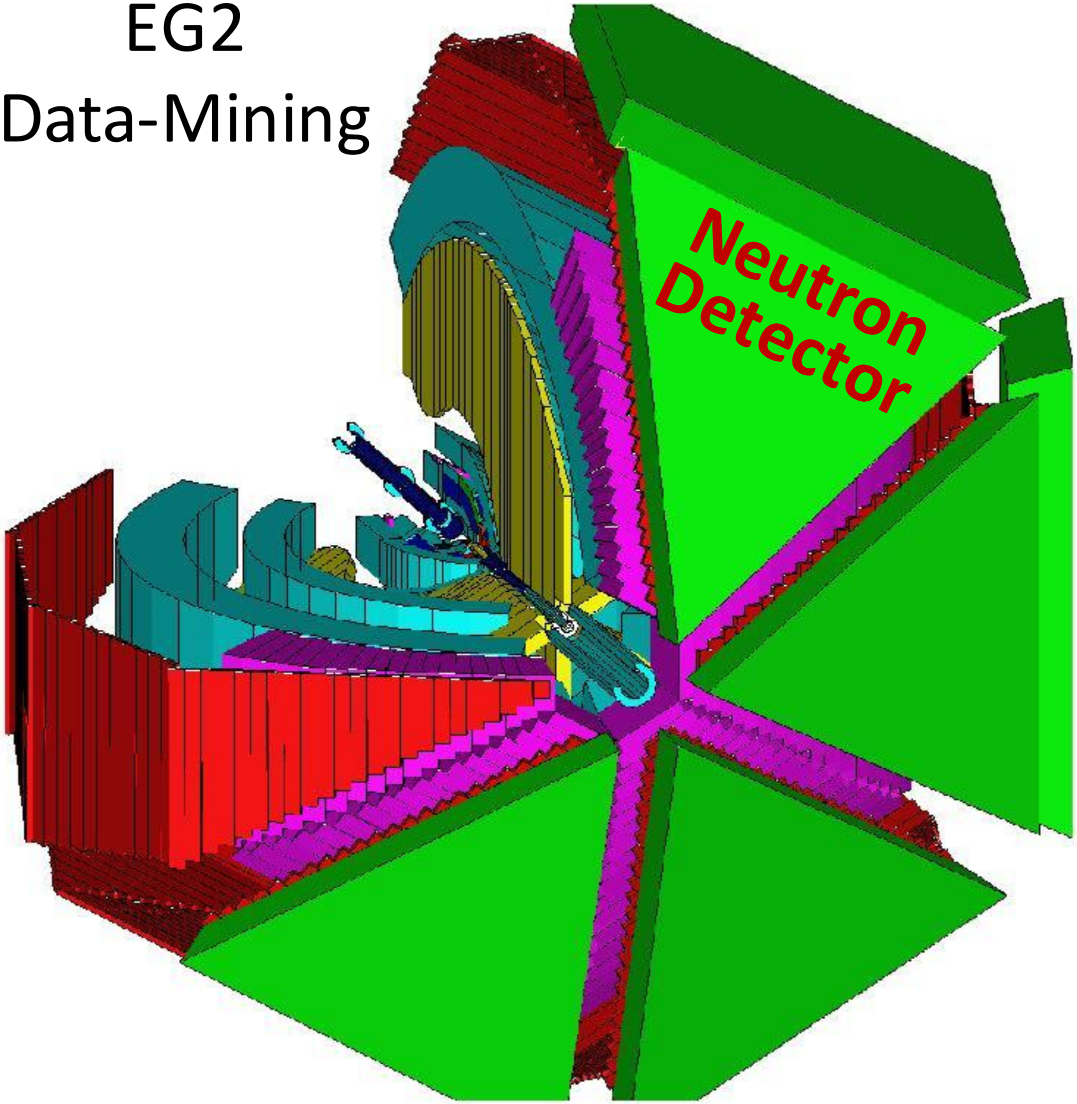
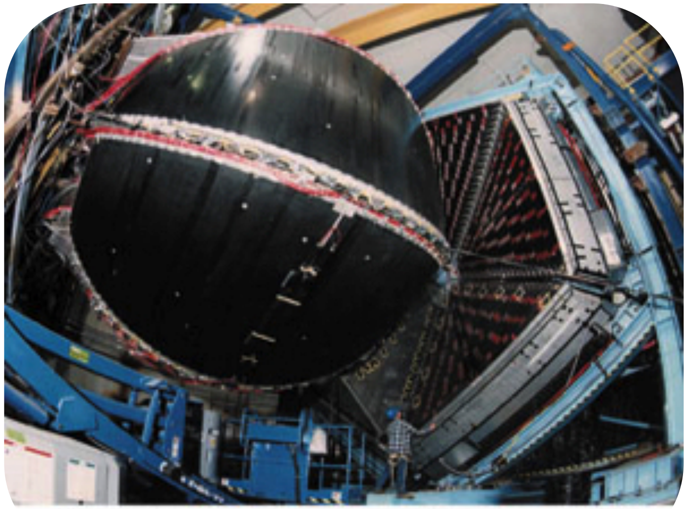


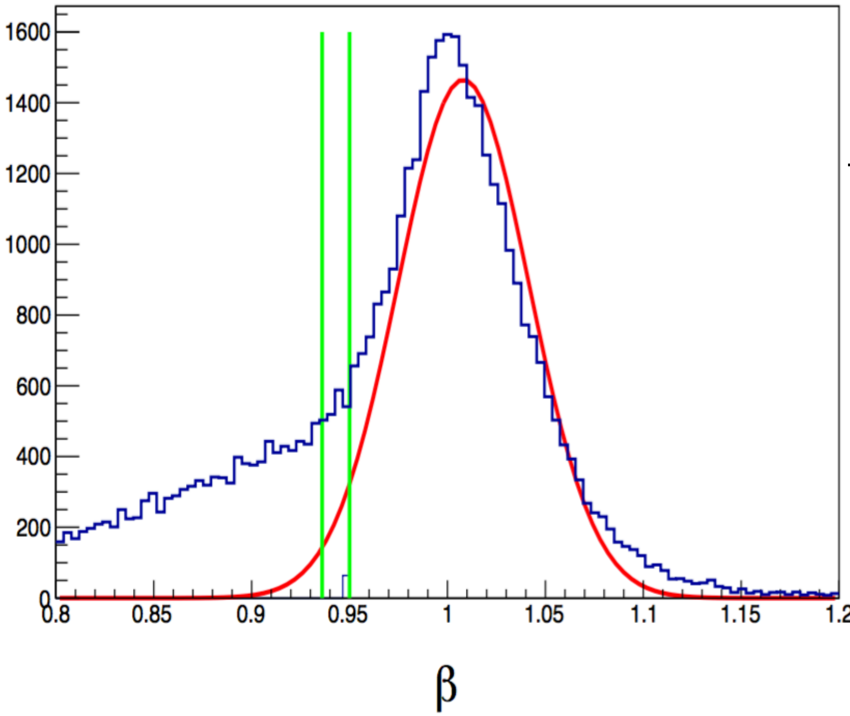


Hall B Large Acceptance Spectrometer

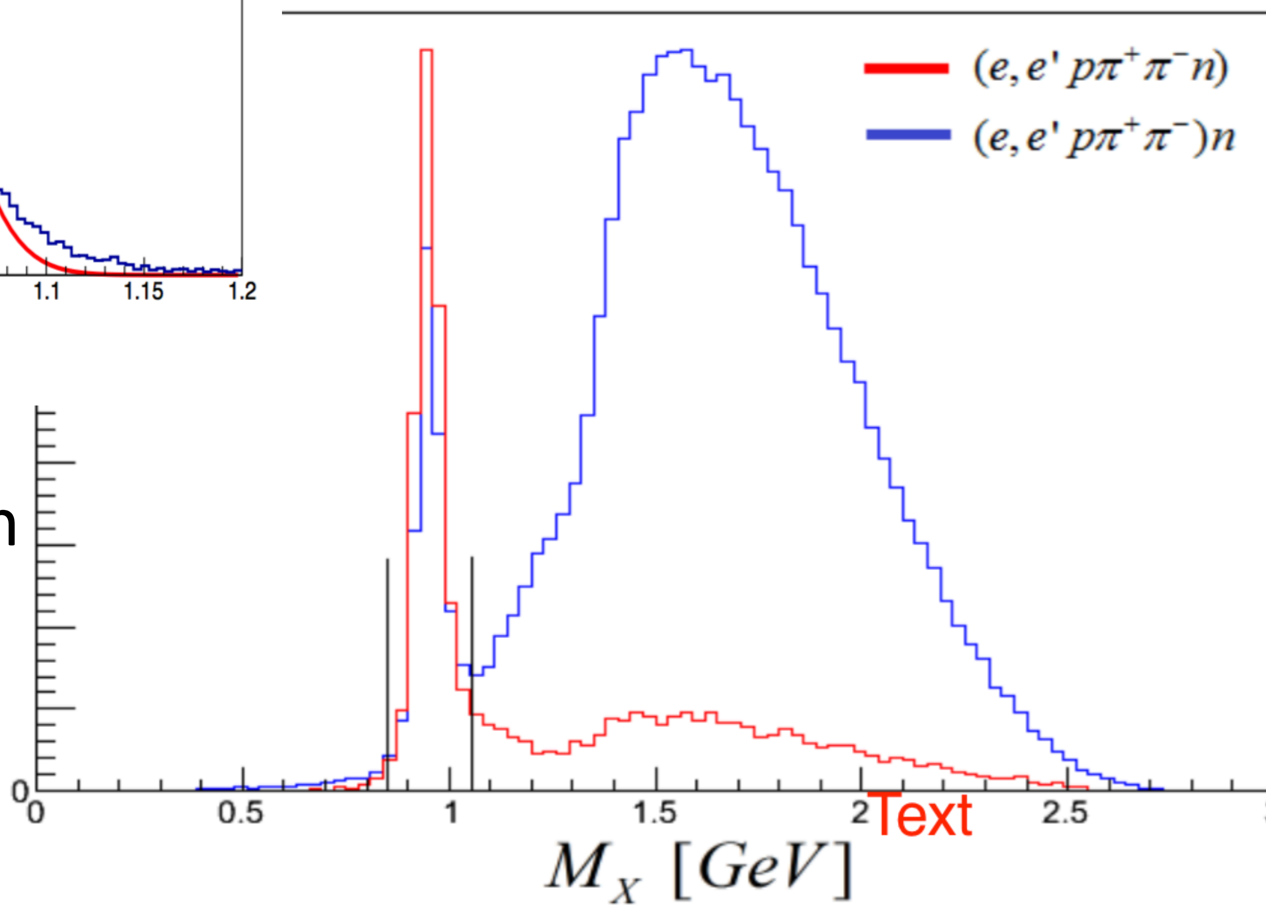
Open (e,e') trigger, Large-Acceptance, Low luminosity (~10^{34} cm^{-2} sec^{-1})

Extracting NEUTRONS from CLAS

(1) Identify neutrons as 'slow' neutral hits in the EC

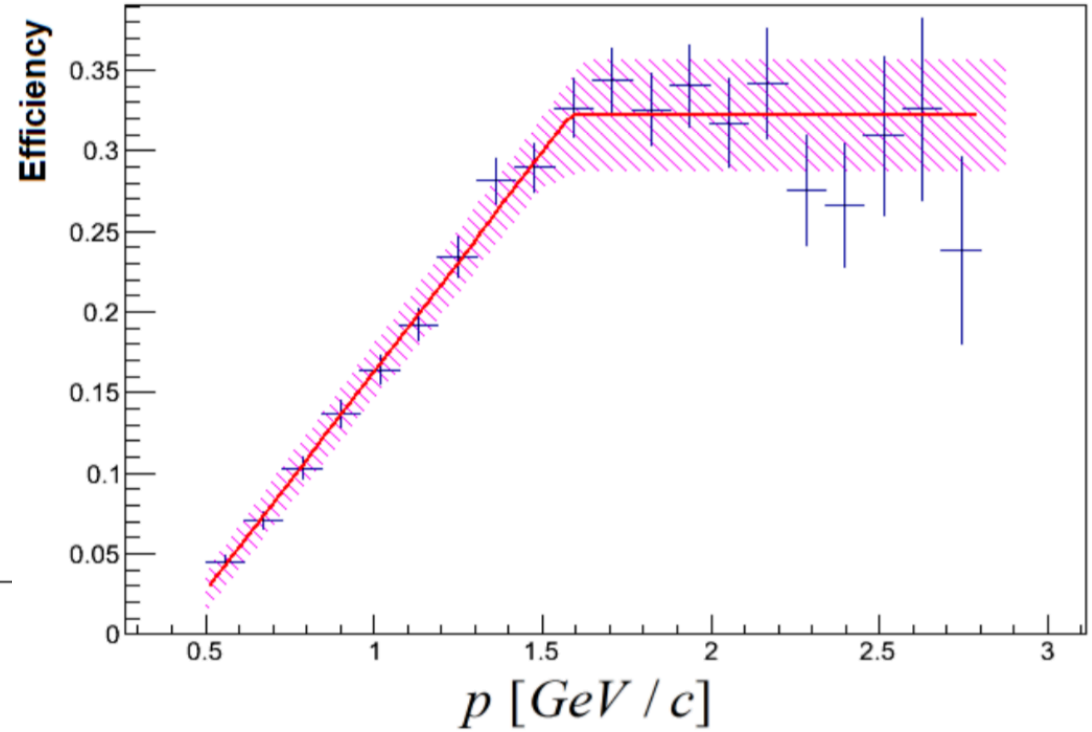


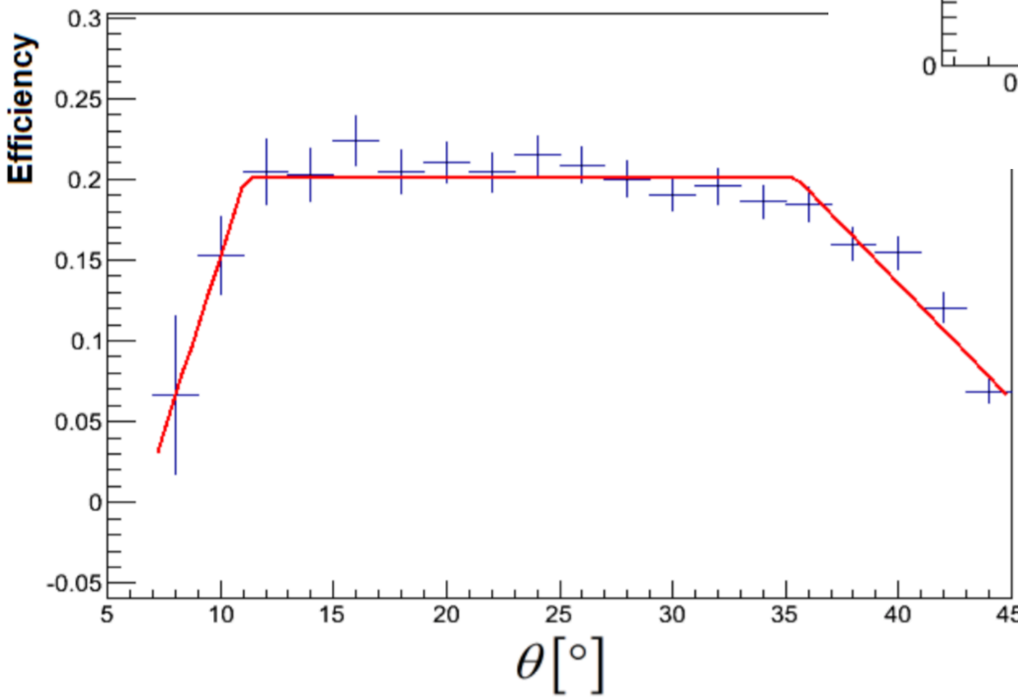
(2) Extract detection efficiency and TOF resolution using exclusive events.



New (Forthcoming) Data from CLAS

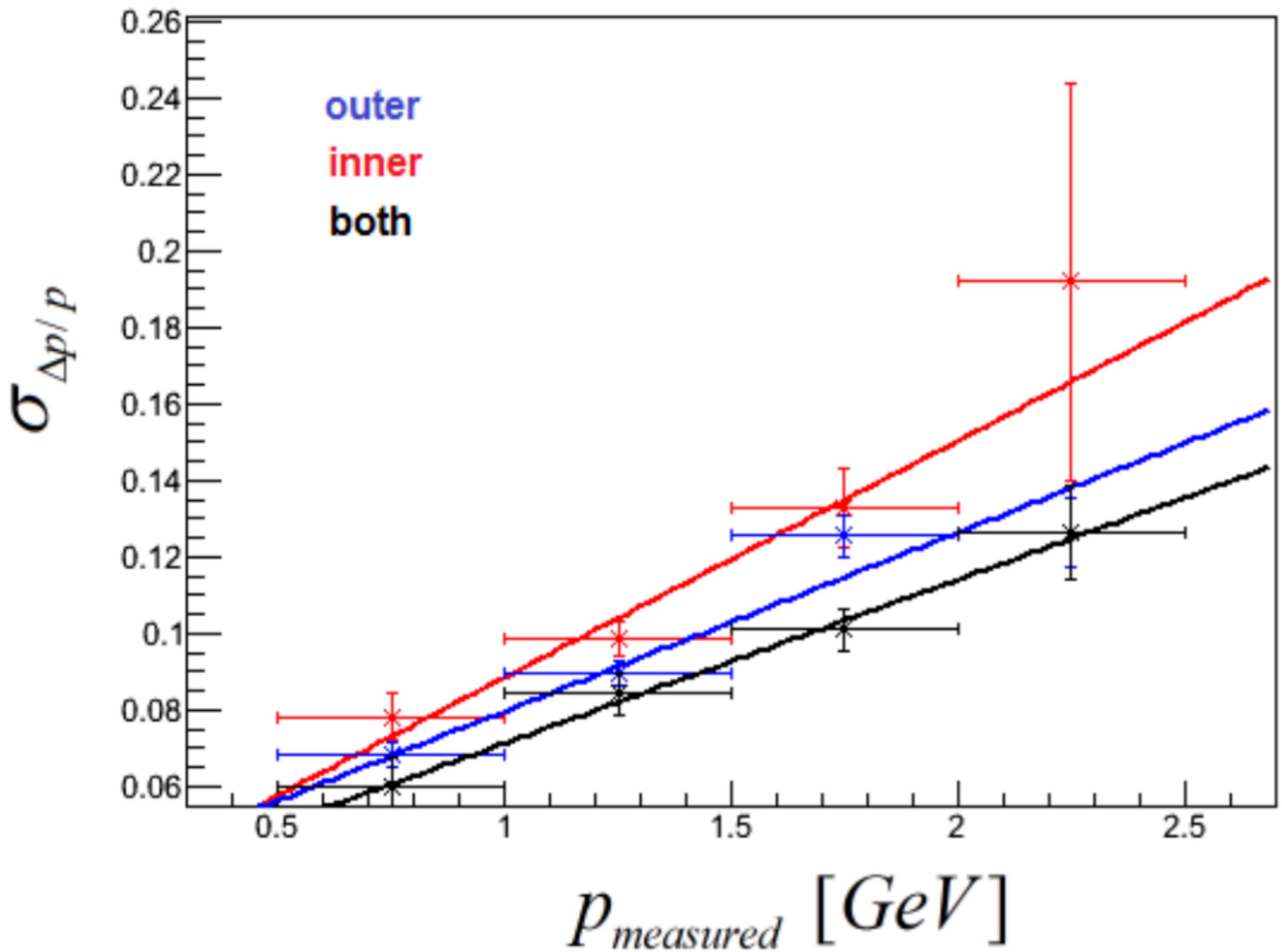
Extract Detection Efficiency





New (Forthcoming) Data from CLAS

Extract TOF Resolution



New (Forthcoming) Data from CLAS

Calculating different ratios for ^{12}C:

low

$$\left.\frac{^{12}C(e,e'p)/\sigma_p}{^{12}C(e,e'n)/\sigma_n}\right|_{P_{miss}<0.25} = 1.09 \pm 0.12$$

high

$$\left.\frac{^{12}C(e,e'p)/\sigma_p}{^{12}C(e,e'n)/\sigma_n}\right|_{0.35<P_{miss}<1} = 1.06 \pm 0.14$$

Current Status: Finalizing analysis for ^{12}C.
Doing a ‘blind’ analysis of the heavy nuclei

New (Forthcoming) Data from CLAS

What's Coming?

- A(e,e'n) Low and High P_{miss}
- A(e,e'np) and A(e,e'pn)
- A(e,e'ppp) and (e,e'npp)

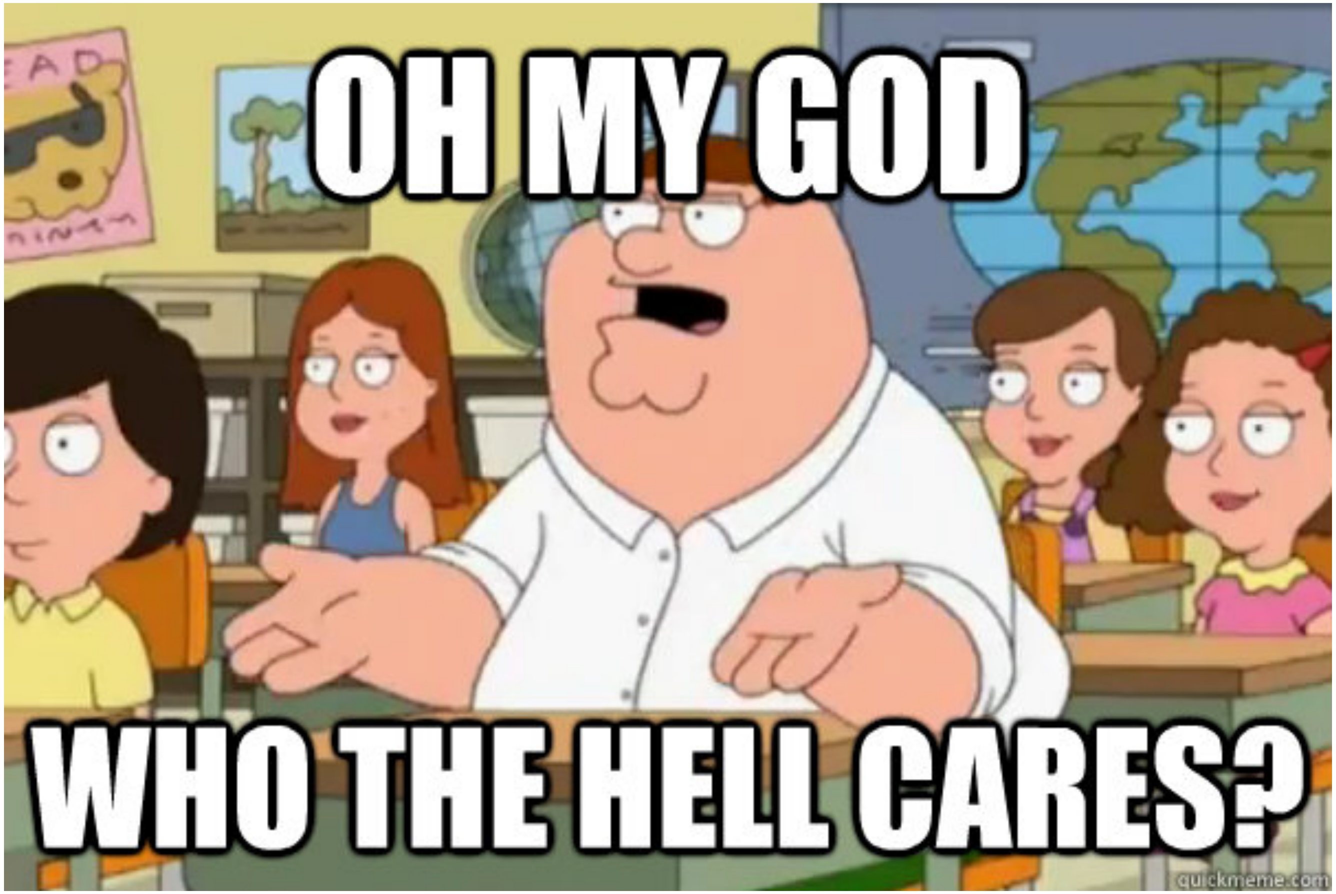
  [See Erez's talk]

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

New A … CLAS

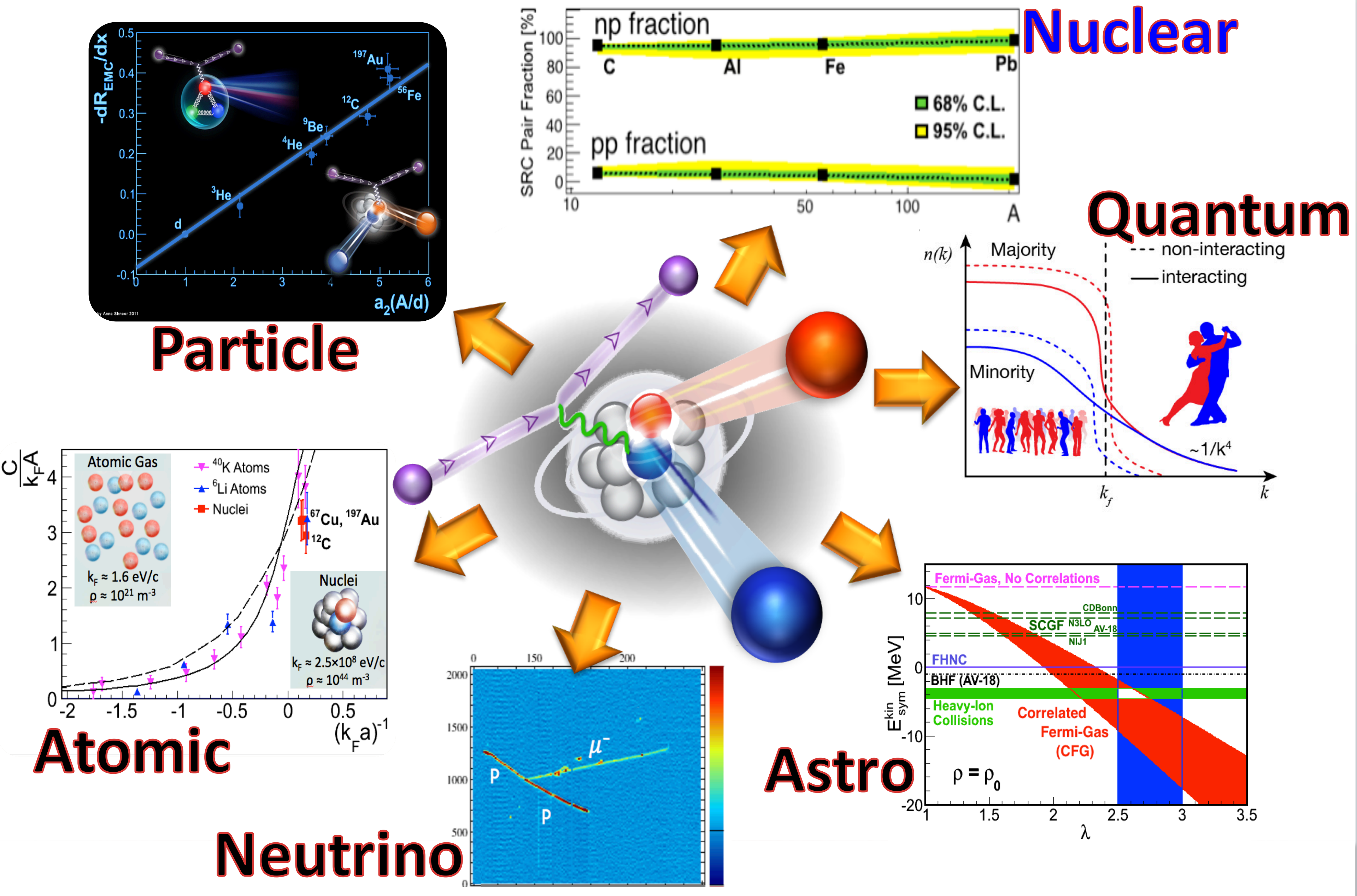
- A(e,e
- A(e,e
- A(e,e

[See E

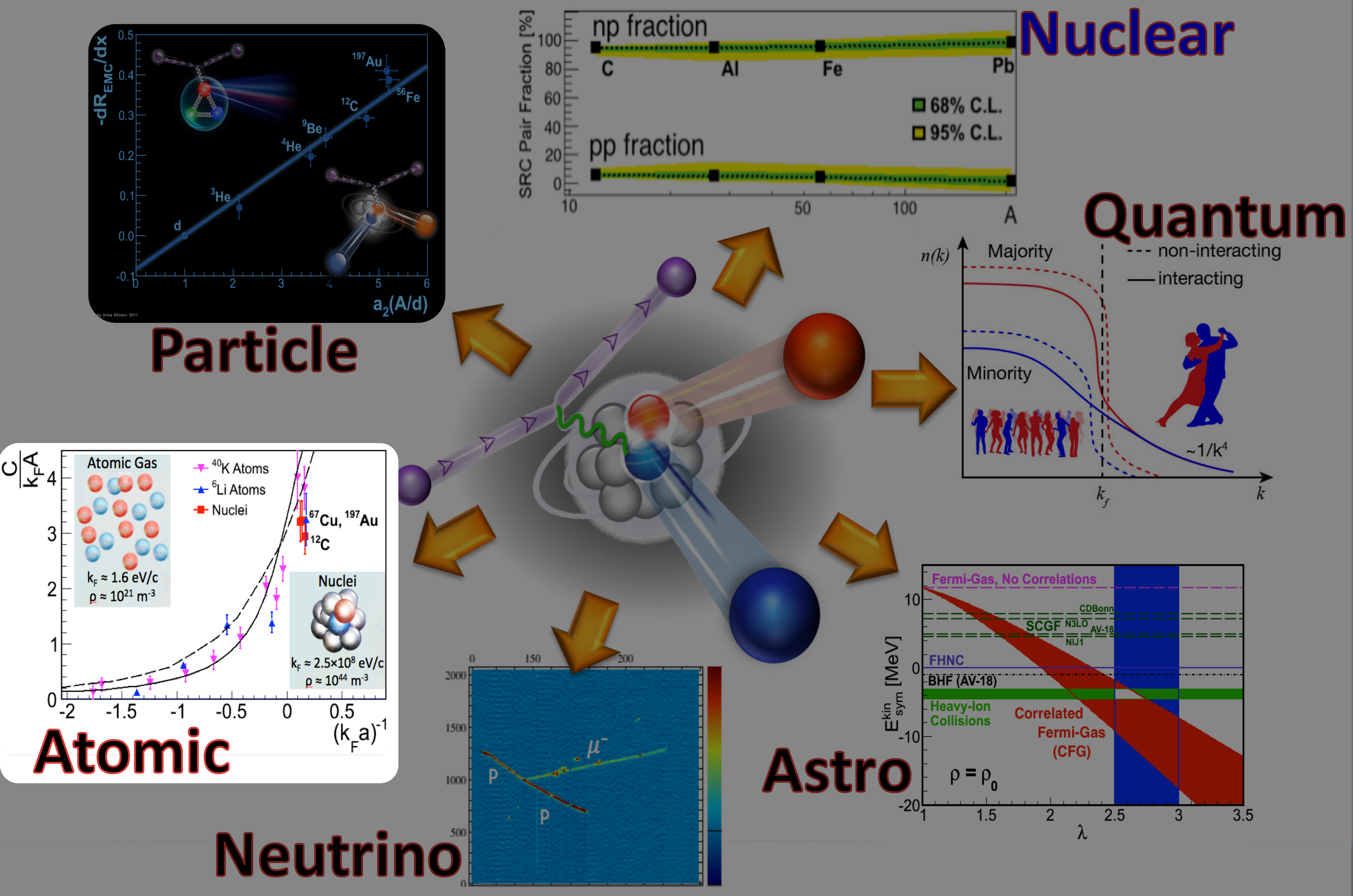


*Me at this point of the talk

Who Cares?


Nuclear
np fraction
pp fraction
C
Al
Fe
Pb
68% C.L.
95% C.L.
SRC Pair Fraction [%]
A
Quantum
n(k)
Majority
Minority
non-interacting
interacting
~1/k⁴
k_f
k
Particle
-dR_EMC/dx
a_2(A/d)
d
³He
⁴He
⁹Be
¹²C
⁵⁶Fe
¹⁹⁷Au
Atomic
Atomic Gas
k_F ≈ 1.6 eV/c
ρ ≈ 10²¹ m⁻³
Nuclei
k_F ≈ 2.5×10⁸ eV/c
ρ ≈ 10⁴⁴ m⁻³
⁴⁰K Atoms
⁶Li Atoms
Nuclei
⁶⁷Cu, ¹⁹⁷Au
¹²C
C/(k_F A)
(k_F a)⁻¹
Neutrino
μ⁻
p
p
Astro
Fermi-Gas, No Correlations
CDBonn
SCGF
N3LO
AV-18
NIJ1
FHNC
BHF (AV-18)
Heavy-Ion Collisions
Correlated Fermi-Gas (CFG)
ρ = ρ₀
E^kin_sym [MeV]
λ

Who Cares?


Nuclear
np fraction
pp fraction
C
Al
Fe
Pb
68% C.L.
95% C.L.
SRC Pair Fraction [%]
A
Quantum
Majority
Minority
non-interacting
interacting
~1/k^4
n(k)
k_f
k
Particle
-dR_EMC/dx
a_2(A/d)
197Au
56Fe
12C
9Be
4He
3He
d
Atomic
Atomic Gas
k_F ≈ 1.6 eV/c
ρ ≈ 10^21 m^-3
Nuclei
k_F ≈ 2.5×10^8 eV/c
ρ ≈ 10^44 m^-3
40K Atoms
6Li Atoms
Nuclei
67Cu, 197Au
12C
C/(k_F A)
(k_F a)^-1
Neutrino
μ-
P
P
Astro
Fermi-Gas, No Correlations
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BHF (AV-18)
Heavy-Ion Collisions
Correlated Fermi-Gas (CFG)
ρ = ρ_0
E^kin_sym [MeV]
λ

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

The Contact and Universal Relations

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

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

Scattering length (→ a)

Distance between fermions (→ d)

These systems have a high-momentum tail:

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

C is the contact term

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

The Contact and Universal Relations

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Tan's Contact term:

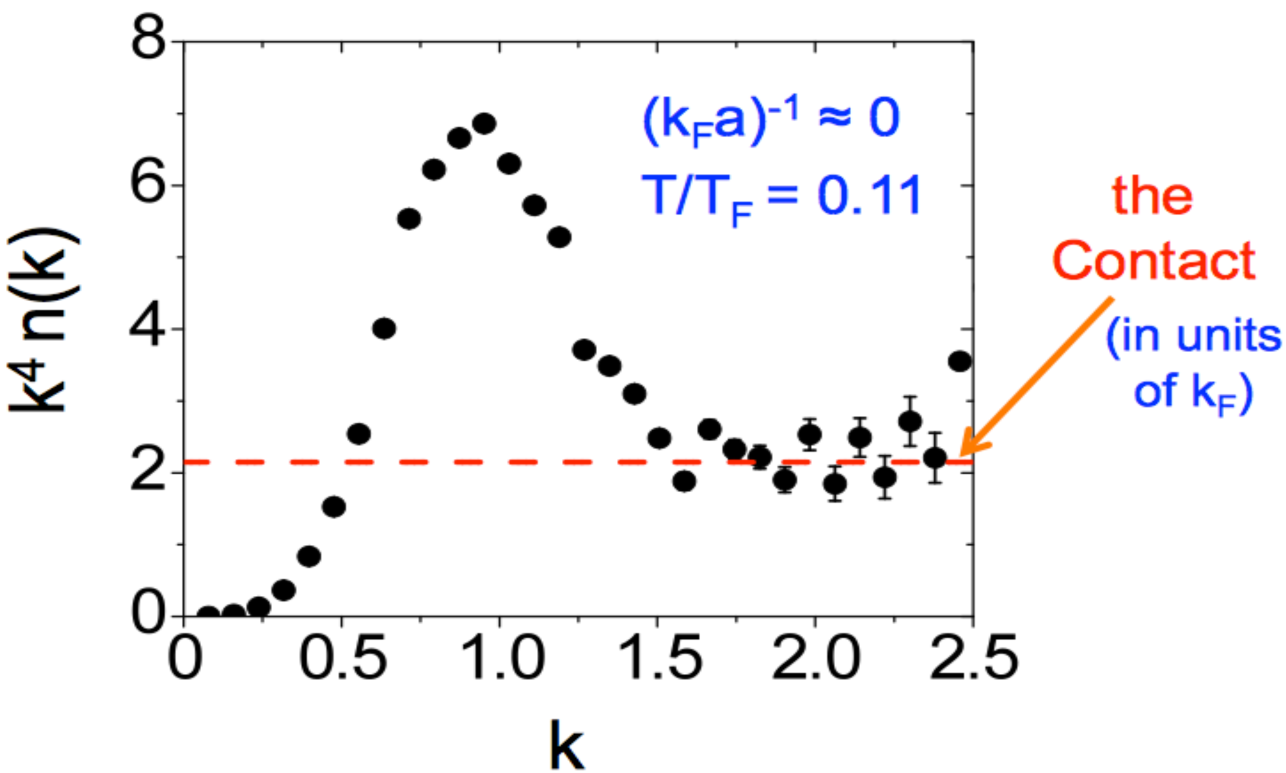
1. Measures the number of SRC different fermion pairs.
2. Determines the thermodynamics through a series of universal relations.

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)

Experimental Validation

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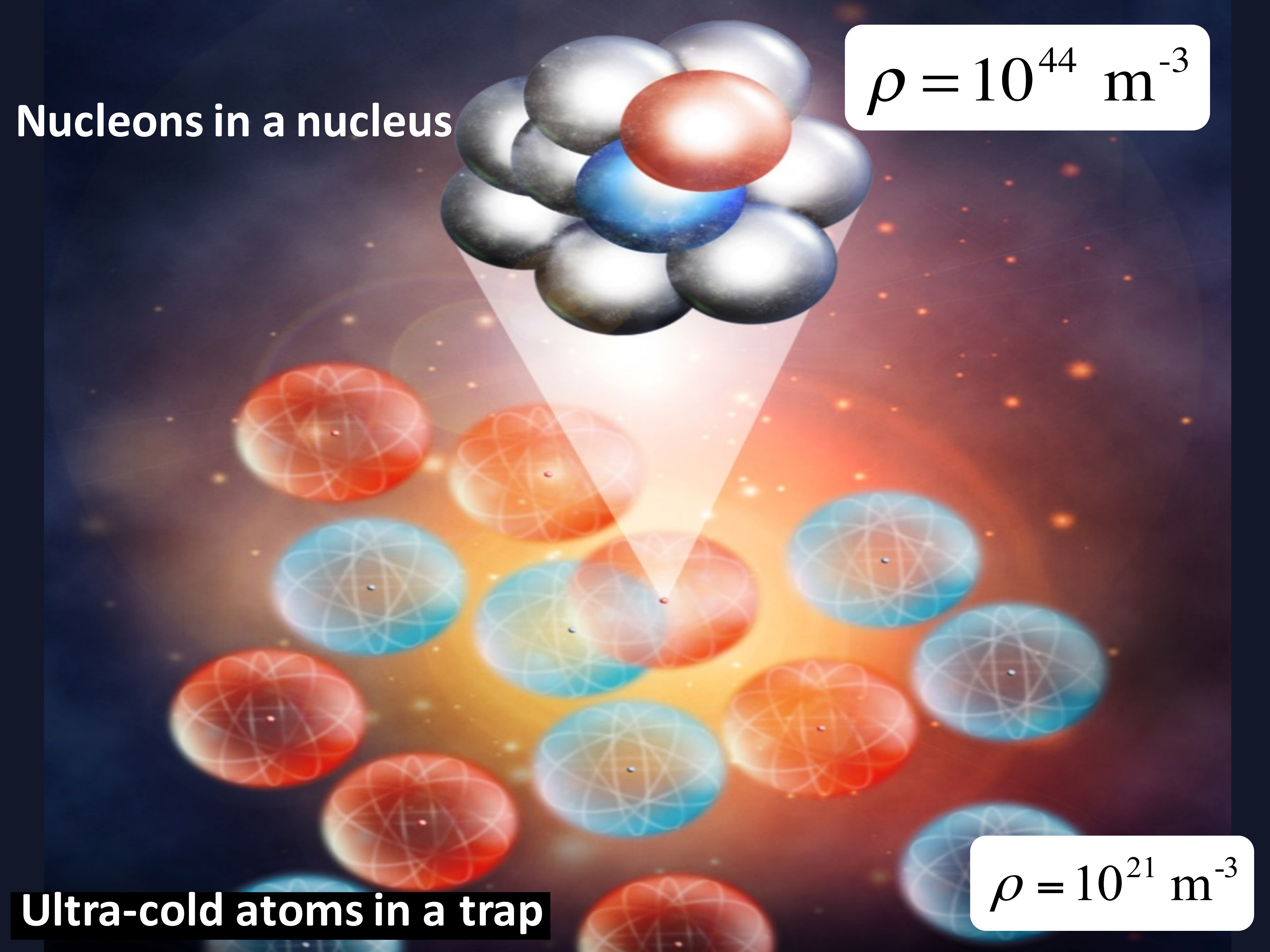
=> extracted the contact and verified the universal relations

What About a *Nuclear* Contact ?

Stewart et al. PRL **104**, …


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 $^{3}S_{1}$ ($^{3}D_{1}$)]

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]**

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

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

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

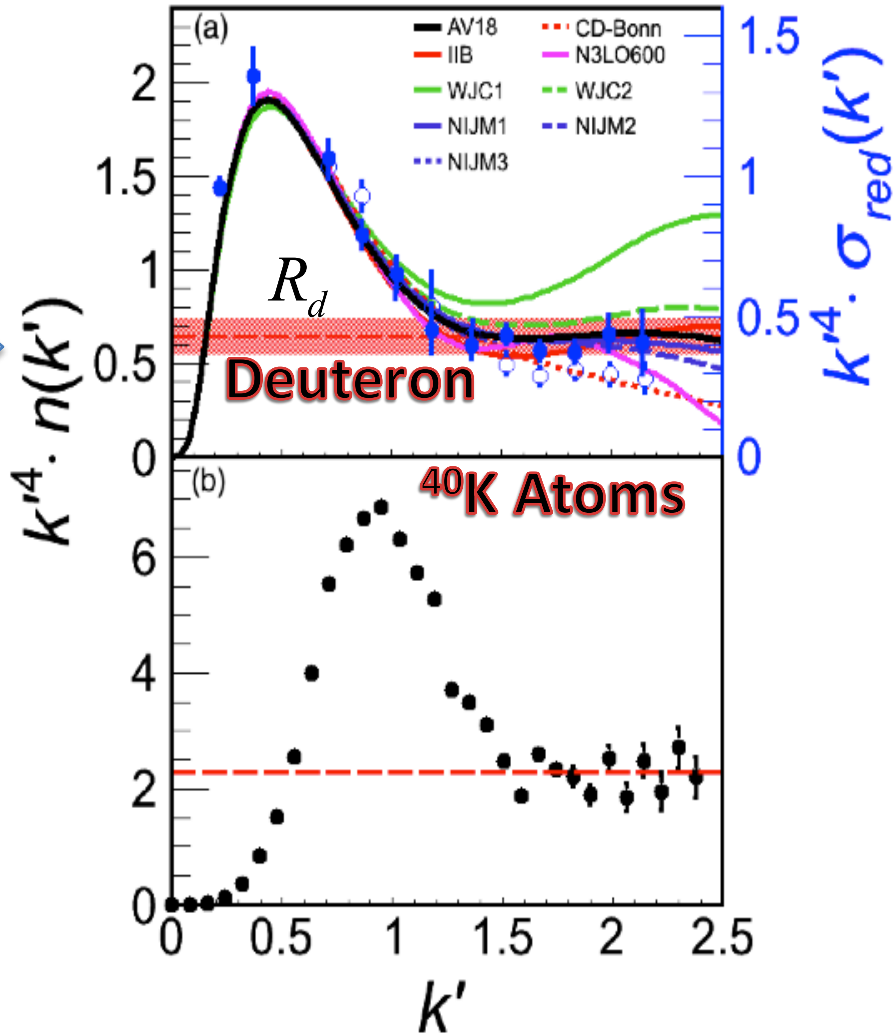
Deuteron Momentum Distribution

A Nuclear Contact?

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

$$1.5k_F < k < 3k_F$$

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



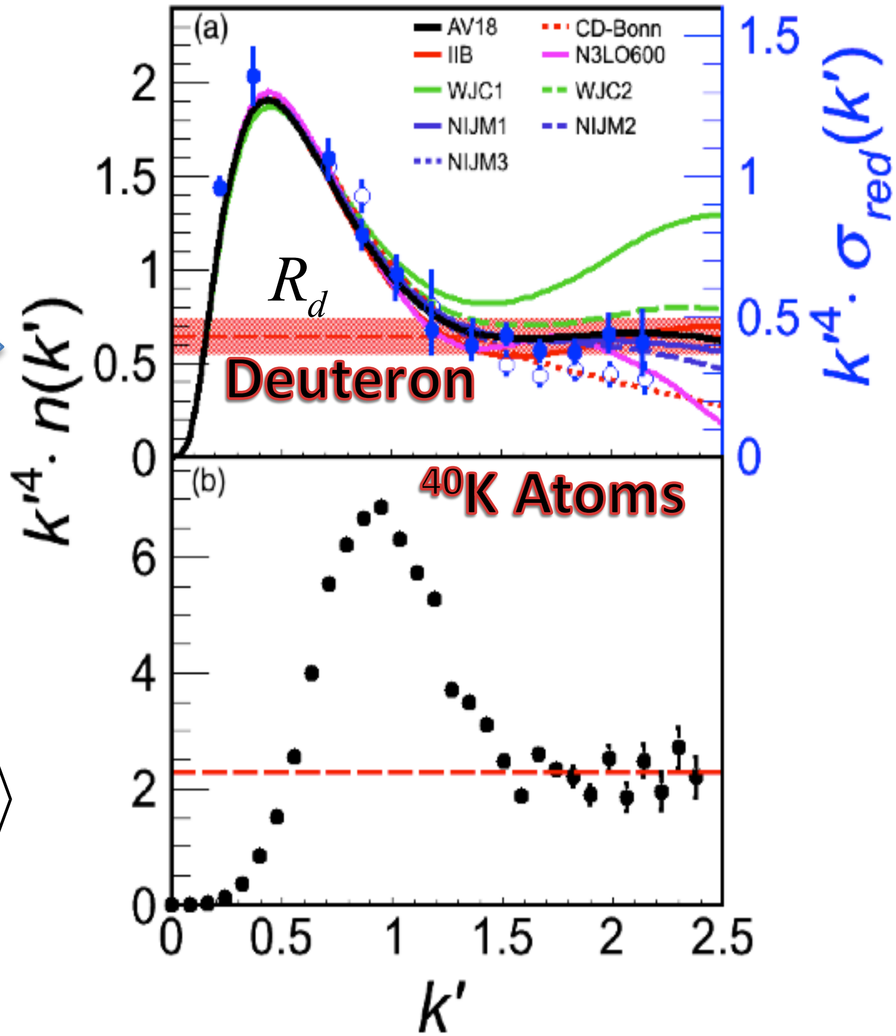
O. Hen et al. Phys. Rev. C **92**, 045205 (2015)

A Nuclear Contact?

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

$$1.5k_F < k < 3k_F$$

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



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

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?

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

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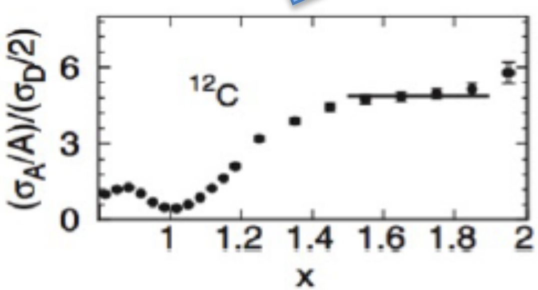

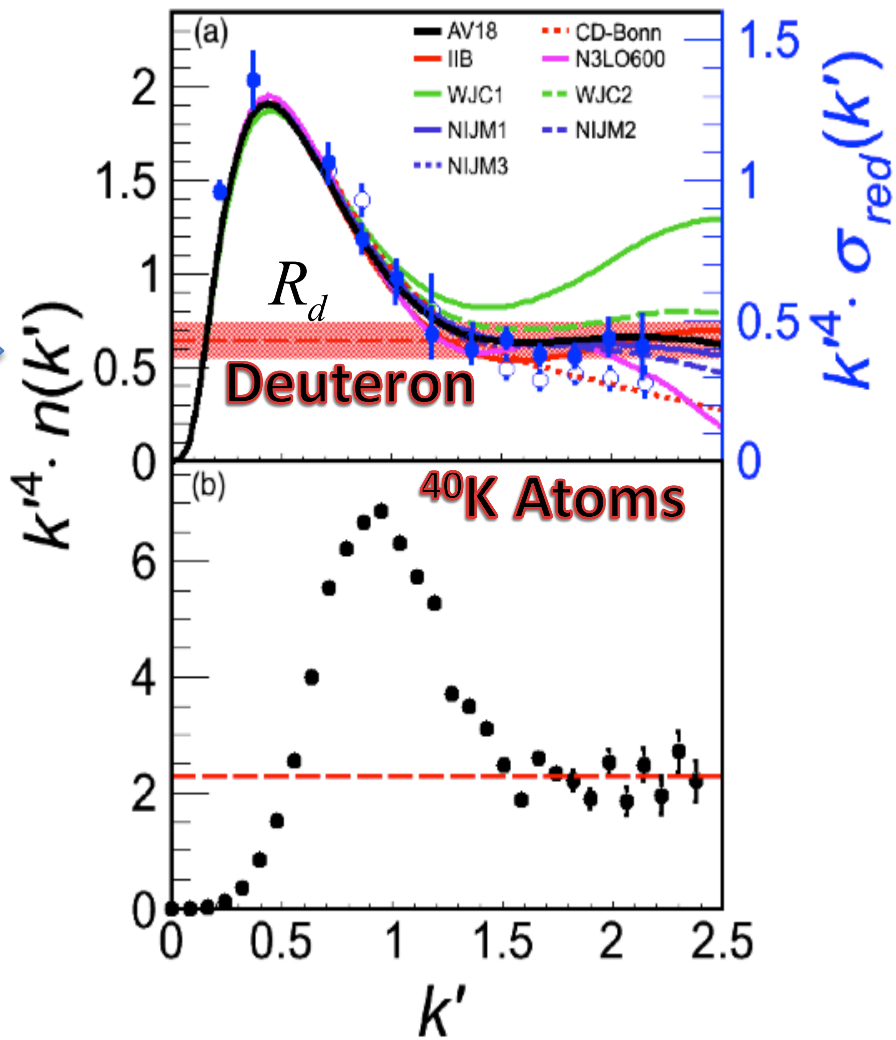

O. Hen et al. Phys. Rev. C **92**, 045205 (2015)

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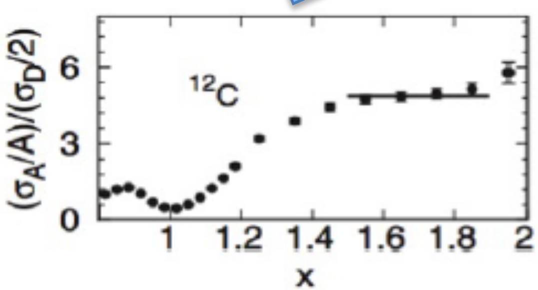
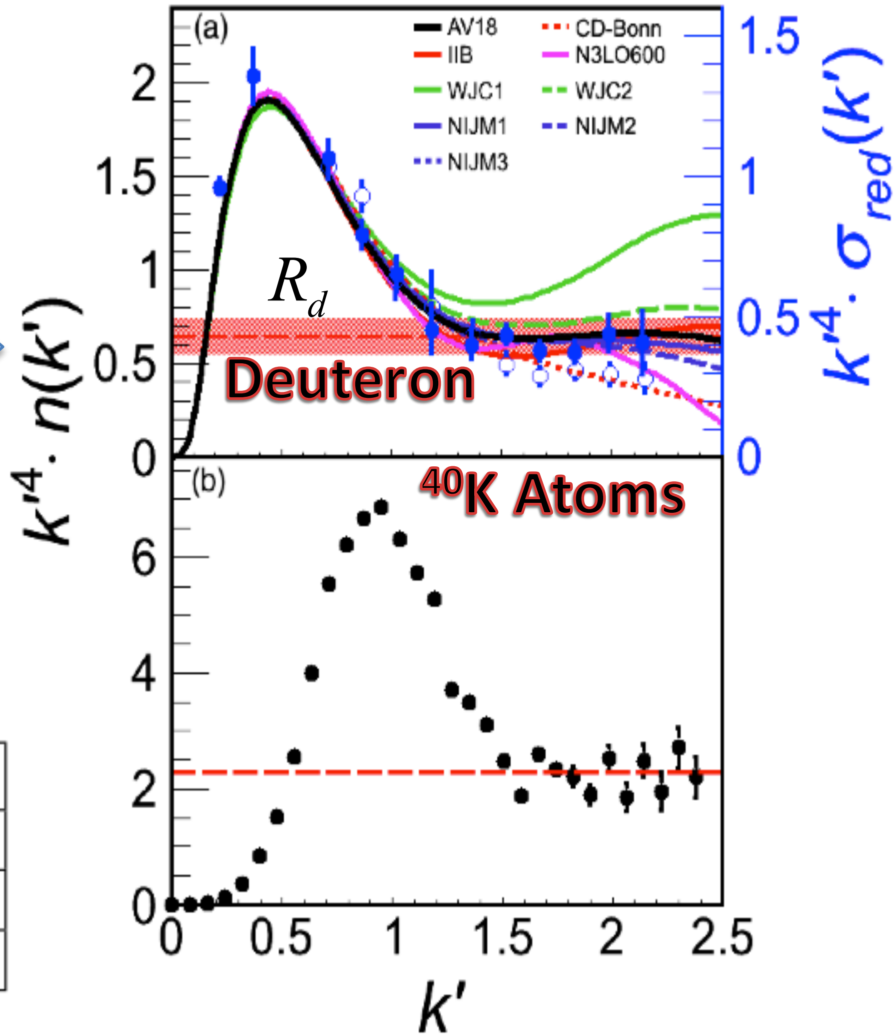


$$\frac{C}{k_F \cdot A} = a_2(A) \cdot R_d$$

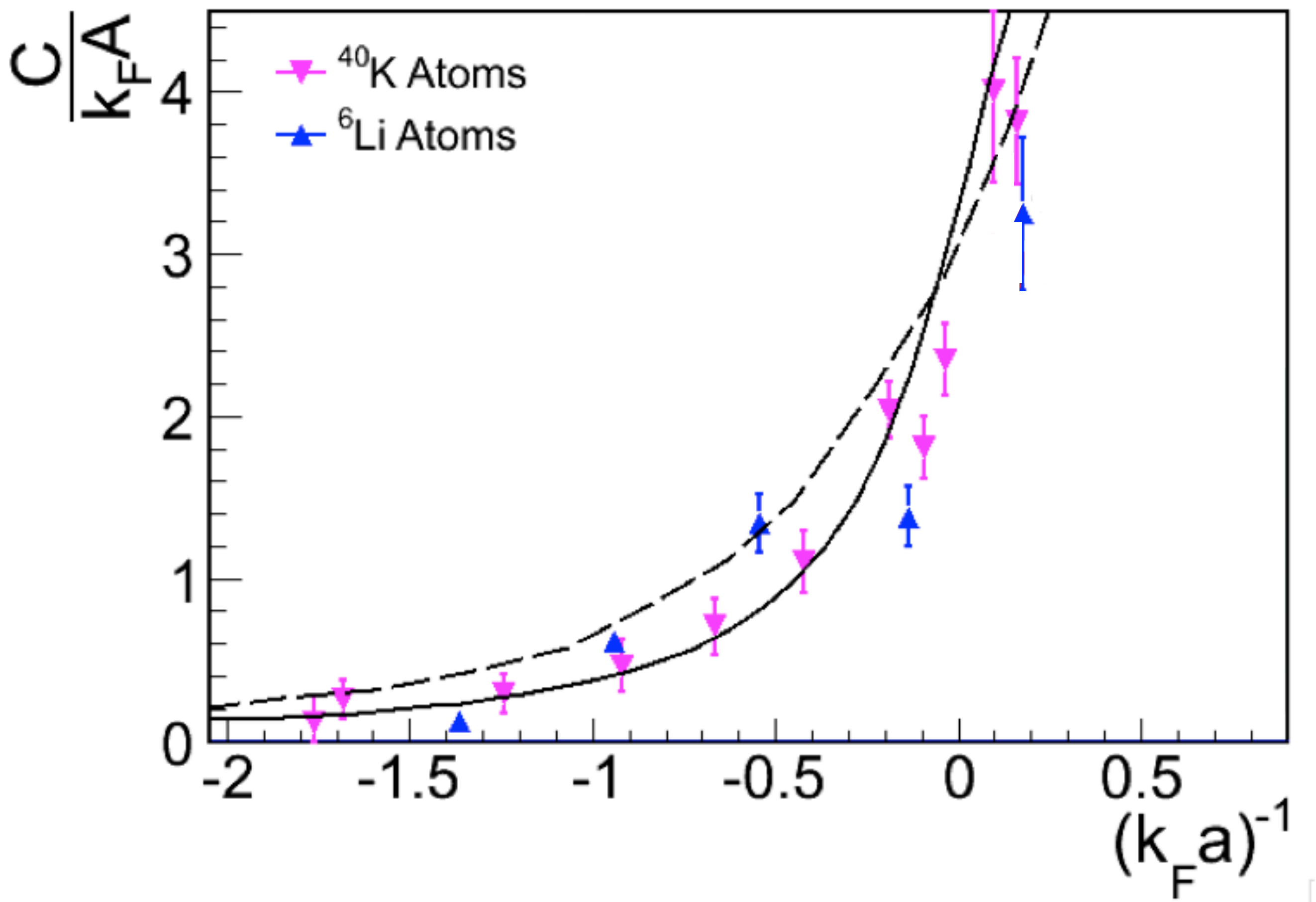
Nucleus	$a_2(A)$	$\frac{C}{k_F A}$
^{12}C	4.75 ± 0.16	3.04 ± 0.49
^{56}Fe	5.21 ± 0.20	3.33 ± 0.54
^{197}Au	5.16 ± 0.22	3.30 ± 0.53



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

Comparing with atomic systems

Finding the same *dimensionless* interaction strength



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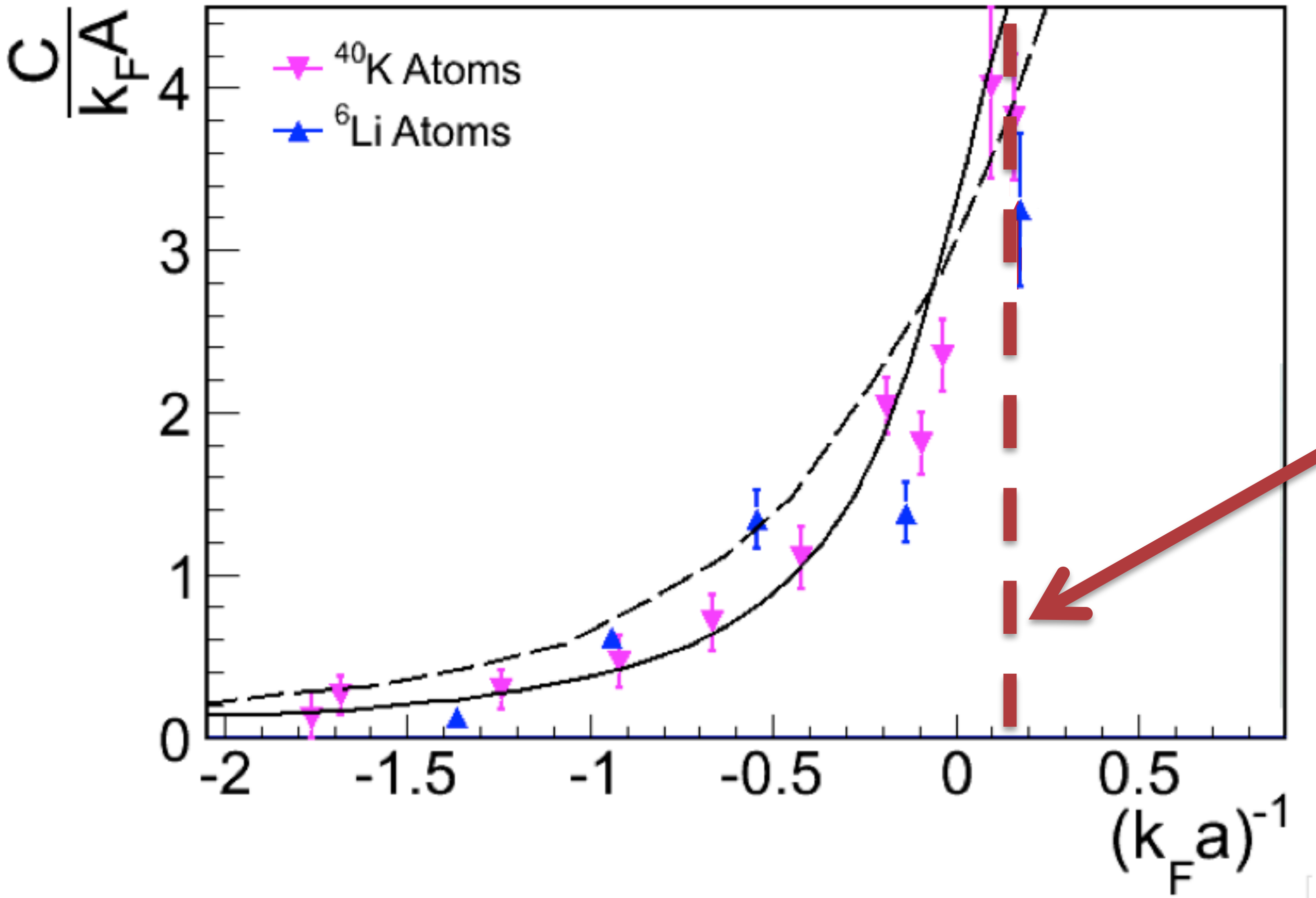

For Nuclei:

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

$a \approx 5.4$ fm

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

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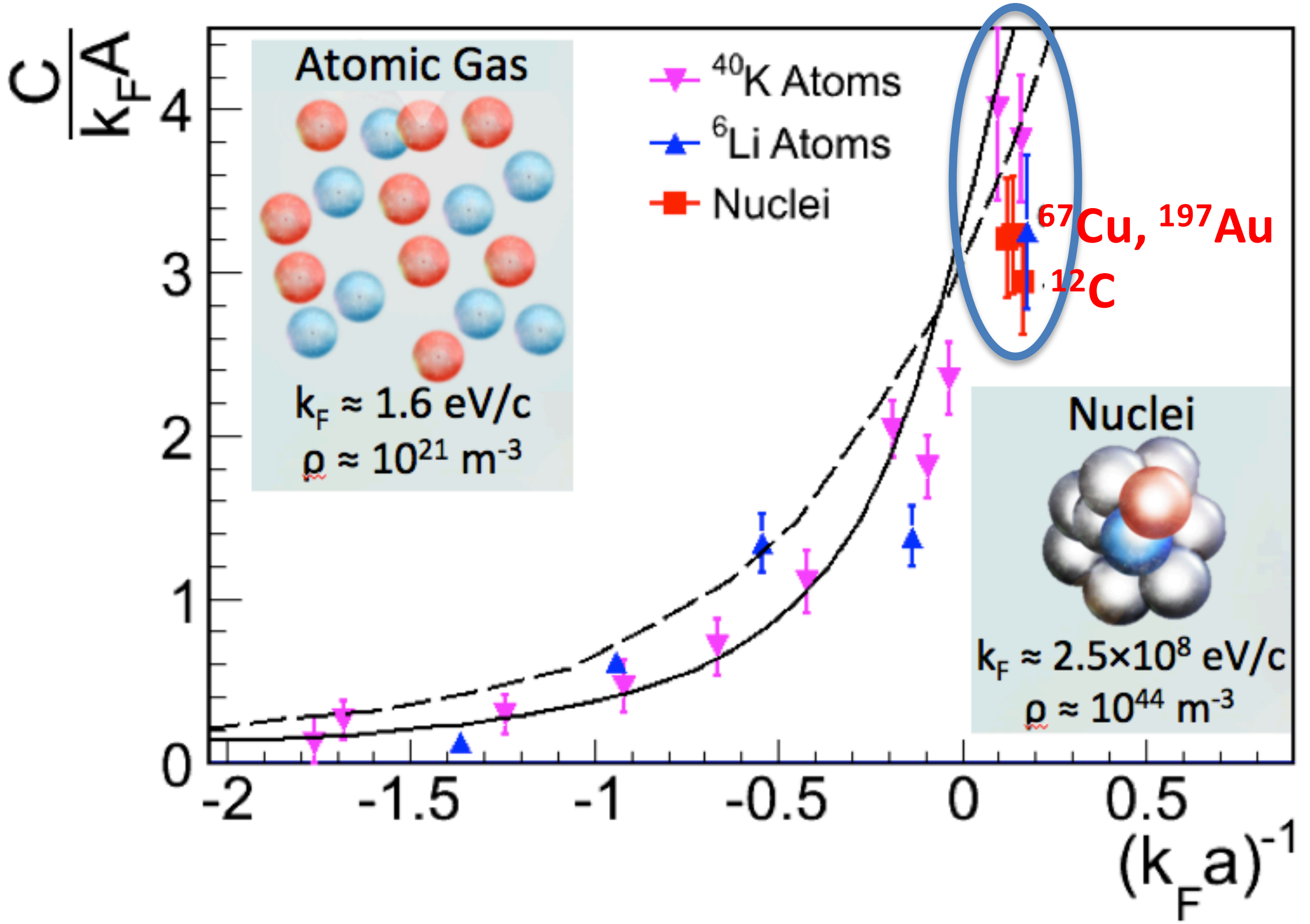
Comparing with atomic systems

Equal contacts for equal interactions strength!



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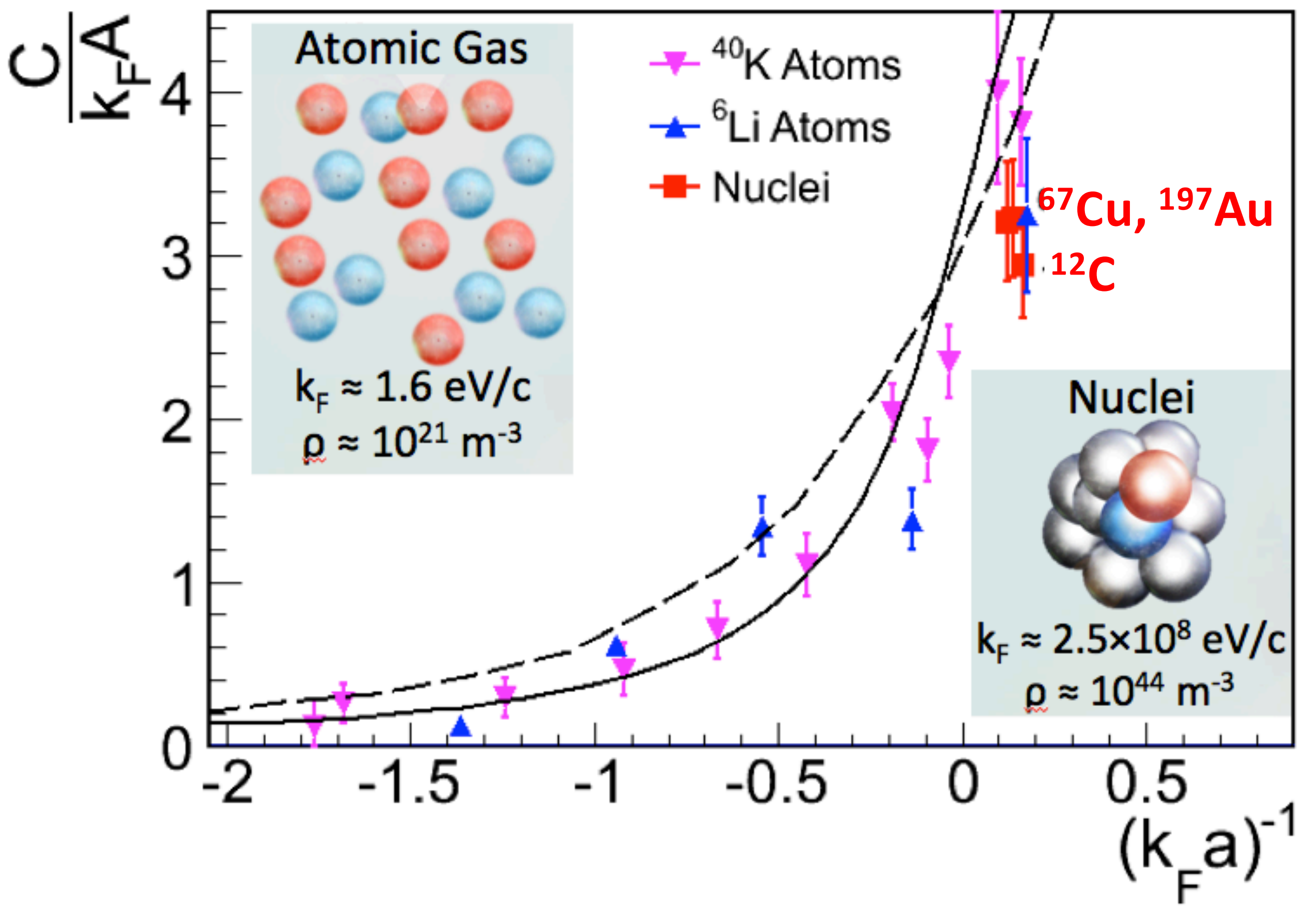
Comparing with atomic systems



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)
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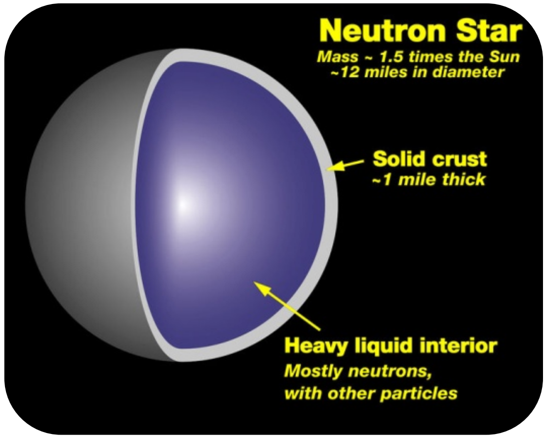
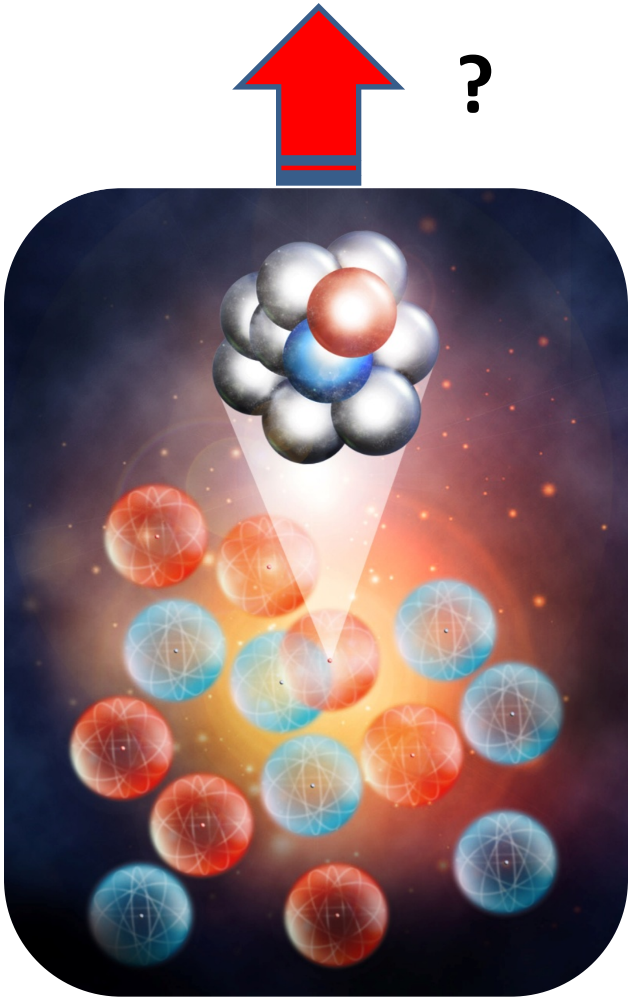


$$(2-3)\cdot\rho_0$$

?



$$\rho_0$$

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

The group

- <u>MIT:</u>

Barak Schmookler

Navaphon (Tai) Muangma

Reynier Torres

  – Or Hen
  – Shalev Gilad

<u>+ Looking for two new postdocs!</u>

- <u>Tel-Aviv:</u>

Erez Cohen

Meytal Duer

Igor Korover

  – Eli Piasetzky

- <u>ODU:</u>

Mariana Khachatryan

  – Larry Weinstein

- Many theory friends ☺

Thank You!

Questions?


Thank You!
Questions?
*What I would be doing today if I was in Boston....