Nuclear Forces at Short Distances and Superdense Nuclear Matter

Misak Sargsian

Florida International University

October 31, 2013 Texas A&M University-Commerce

Florida International University

In Miami

One of Largest Public Research University 52,000

Nuclear Group & Jefferson Lab & 21st in producing PhD in Nuclear Physics

Nuclear Forces at Short Distances

- Theory: QCD in NN Systems, High Energy Approximations

  Relativistic Bound State Problem

- Methodology Hard Nuclear Processes

- Experimentation JLab, BNL, FAIR, JPARC

- Two New Properties of High Momentum Component of Momentum Distributions in Asymmetric Nuclei

MS,arXiv:1210.3280
Phys. Rev. C

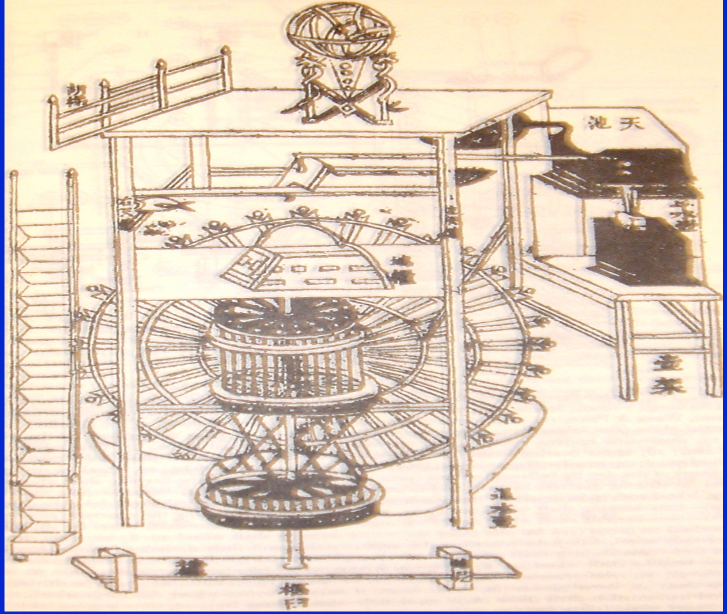
- Protons are more Energetic in Neutron Rich High Density Nuclear Matter

M. McGauley, MS
arXiv:1102.3973

- Universal Property of Asymmetric Two Component Fermi Systems

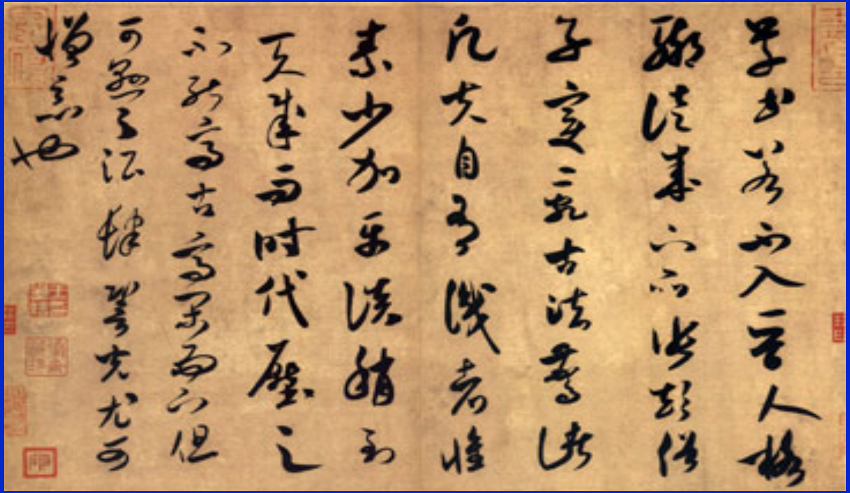
Superdense Matter $10^9\ ton/cm^3$

On July 4, 1054 A.D., Chinese astronomers noticed a "guest star" in the constellation Taurus;   This star became about 4 times brighter than Venus in its brightest light and was visible in daylight for 23 days



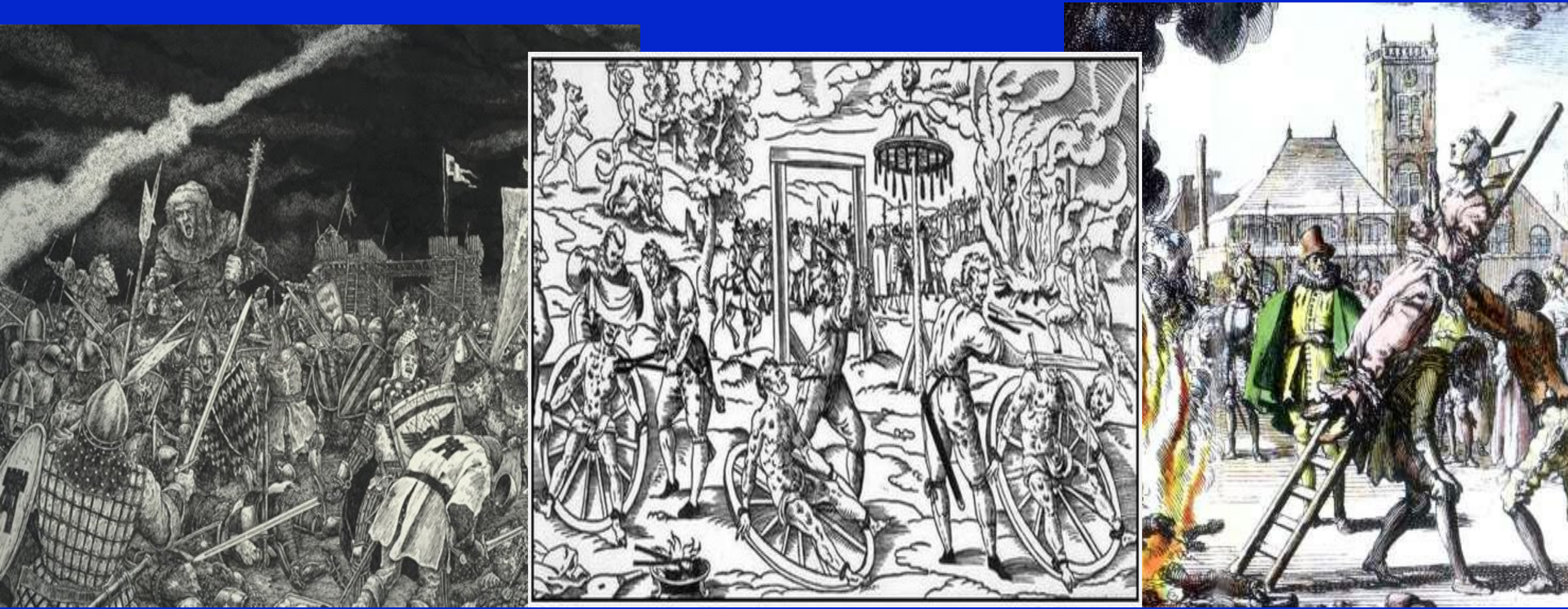
“I bow low. I have observed the apparition of a guest star. Its color was an iridescent yellow… The land will know great prosperity”

Yang Wei-T, Imperial Astronomer of
Sung Dynasty




柳陰高士寫為
高放浪形骸意
自豪設問伊人
何姓氏於唐為
李晉為陶
丁亥春月御題

Crab Supernova found Europe in the middle of the dark ages (500-1500AD)



First Universities will appear only after 34 years

Bologna
1088

Paris
1150

Oxford
1167

Crab Supernova was observed in the New World?

It was probably recorded by Anasazi Indian artists (in present-day Arizona and New Mexico), as findings in Navaho Canyon and White Mesa as well as in the Chaco Canyon National Park (NM) indicate

- Crab Supernova : by April 17 1056 it was gone

- Crab Nebula was first observed in 1731 John Devis

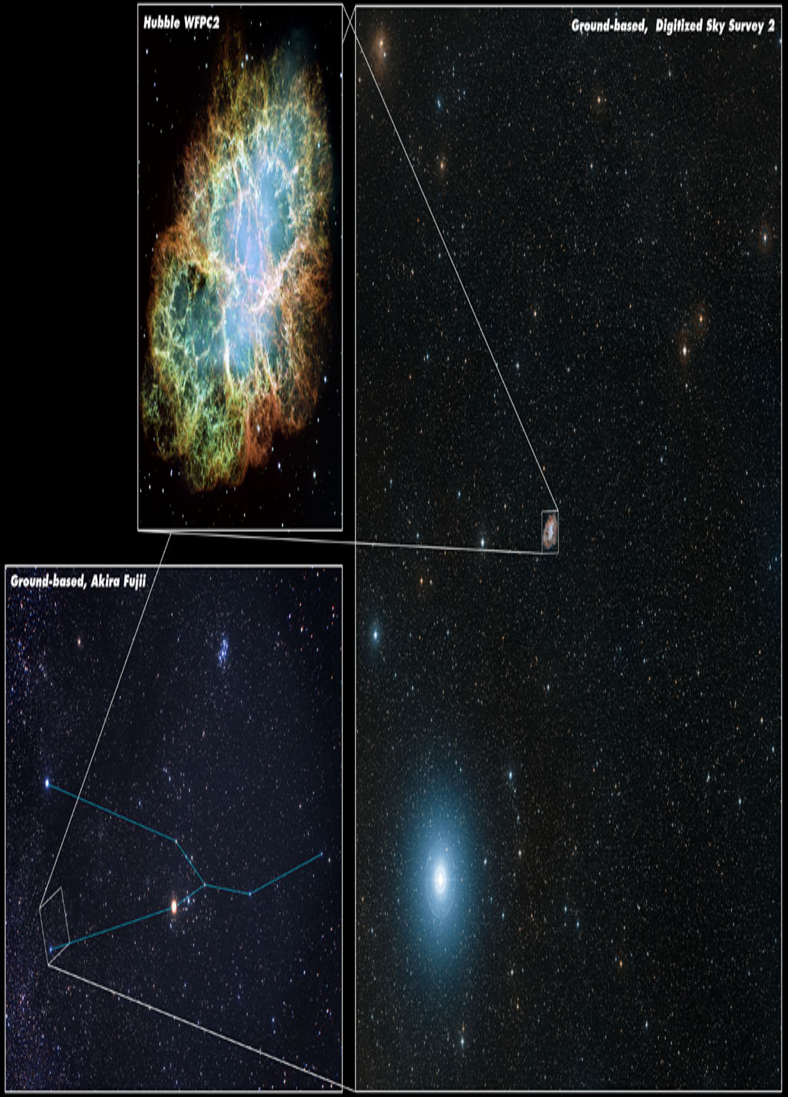
-It was rediscovered in 1758 Charles Messier – comet like object

- Named as Crab Nebula only in 1840 William Parsons (Earl of Roses)

- In 20th Century comparing pictures from the different years it was observed that nebula is expanding

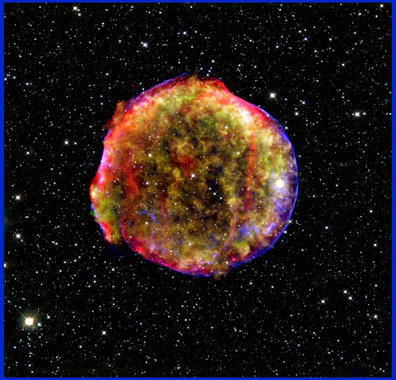
-Tracing the expansion back it was concluded that nebula must have become visible on Earth about 900 years ago

- Identified with the 1054 observations

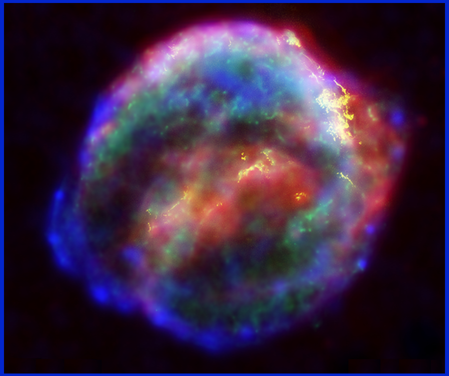


Supernova

Tycho’s Nova 1572
Cassiopea, MW

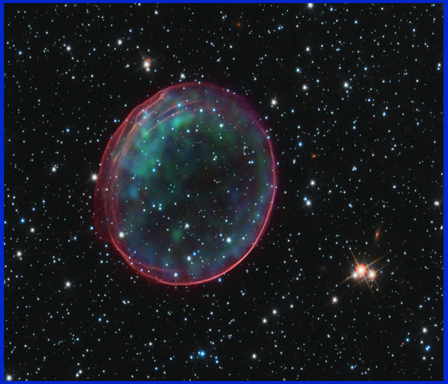


Kepler’s Nova
1604
Opiuchus MW



S Andromedae
1885

Hubble
Telescope



Fritz Zwitsky named it Supernova
1926-1931

SN’s are explosions

Advent of Mechanics and Gravity

Macroscopic Systems

Fast

Classical Mechanics

Galilean Relativity

$$t, \vec{r} \leftrightarrow t, \vec{r}'$$

Relativistic Mechanics

Special Theory of Relativity

$$t, \vec{r} \leftrightarrow t', \vec{r}'$$

Strong

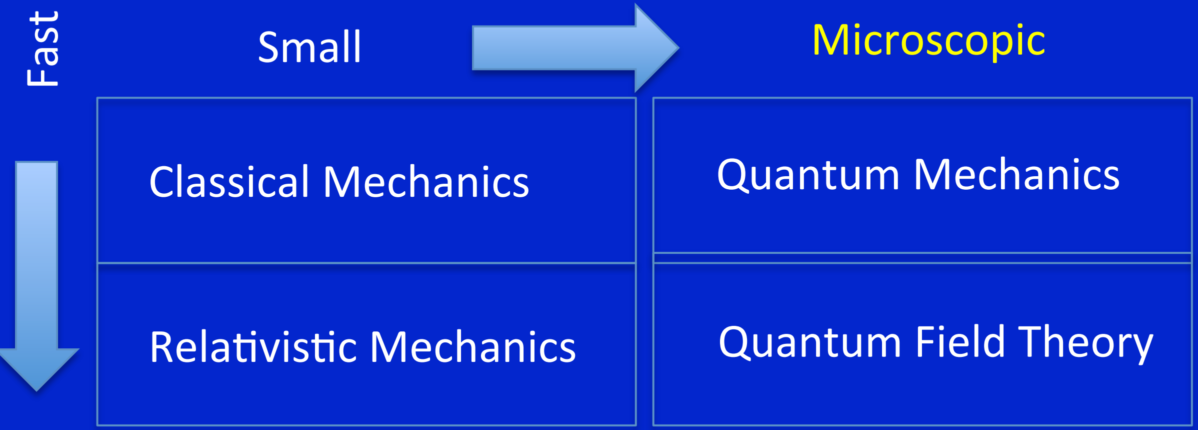
Newtonian Gravity

$$F = G\frac{m_1 m_2}{r^2}$$

General Theory of Gravitation

$$G^{\mu\nu} = -8\pi G T^{\mu\nu}$$

Advent of the Nuclear and Particle Physics



Fast

Small

Microscopic

Classical Mechanics

Quantum Mechanics

Relativistic Mechanics

Quantum Field Theory

Atom - 1805 e - 1897 Atomic Nuclei - 1911 Model of Atom 1913

Proton 1919 Neutron 1932 Neutron Stars 1933! Nuclear Forces 1934

With all reserve we advance the view that the supernovae represent the Transition from ordinary stars to neutron stars, which in their final stages consist of closely packet neutrons W.Baade and F. Zwicky, 1934 Phys. Rev. 45 (138)

Advent of the Statistical Quantum Mechanics

More

Small → Microscopic

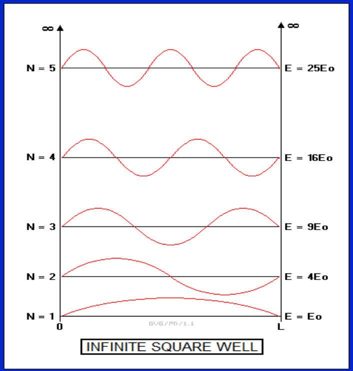
Classical Physics	Quantum Physics
Classical Statistics	Quantum Statistics

Macroscopic

Stirling's Approximation

$$ln(n!) \approx n \cdot ln(n) - n$$

Boltzmann Equation



Pauli Principle 1925

Fermi-Dirac Distributions

$$f(\epsilon) = \frac{1}{e^{\frac{(\epsilon-\mu)}{KT}} + 1}$$

$$\text{If } T \to 0$$

$$f(\epsilon) = \begin{cases} 1 & , \epsilon_k \leq \mu \equiv \epsilon_{Fermi} \\ 0 & , \epsilon_k > \epsilon_{Fermi} \end{cases}$$

Stellar Physics = General Theory of Relativity + Quantum Statistical Mechanics

Oppenheimer, Volkoff and Tolman 1939

$$\frac{dp}{dt} = -\frac{[p(r)+\epsilon(r)]G[M(r)+4\pi r^3 p(r)]}{r[r-2GM(r)]}$$

Equation of State

$$M(r) = 4\pi \int_0^r \epsilon(r) r^2 dr$$

$$\epsilon(r) = \epsilon(p(r))$$

$$\epsilon(r) = \epsilon(\rho(r))$$

$$p(r) = p(\rho(r))$$

$\epsilon(r)$ - Total Energy Density

Oppenheimer, Volkoff and Tolman 1939
Degenerate Fermi Gas Model

$$f(\epsilon) = \begin{cases} 1 & ,\epsilon_k \leq \mu \equiv \epsilon_{Fermi} \\ 0 & ,\epsilon_k > \epsilon_{Fermi} \end{cases}$$

$$\epsilon_{Fermi} \approx \frac{k_{Fermi}^2}{2m}$$

$$\epsilon = \frac{\gamma}{2\pi} \int_0^{k_{Fermi}} \sqrt{k^2 + m^2}\; k^2 dk$$

$$p = \frac{1}{3}\frac{\gamma}{2\pi} \int_0^{k_{Fermi}} \frac{k^2}{\sqrt{k^2 + m^2}}\; k^2 dk$$

$$\rho = \frac{\gamma}{2\pi} \int_0^{k_{Fermi}} k^2 dk$$

$$M_{max} = 0.7 M_\odot$$

$$R \approx 10 km$$

$$\rho \approx 6 \times 10^9 ton/cm^3$$

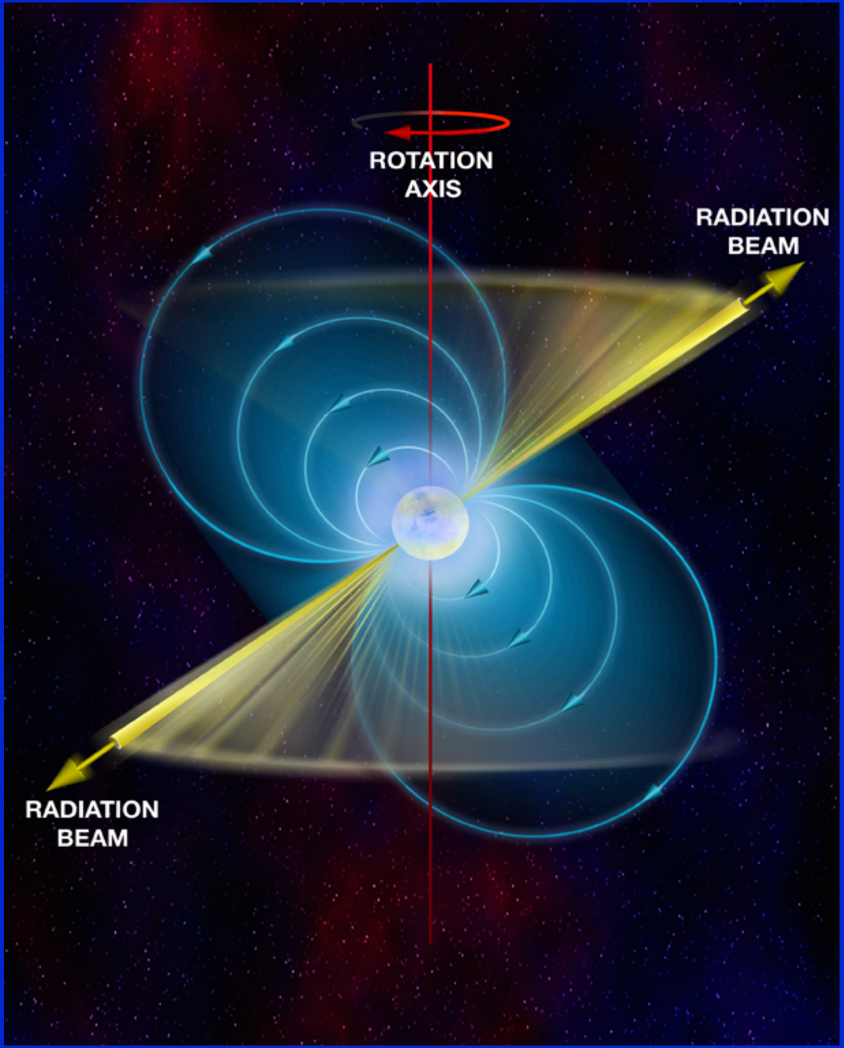
Pulsars

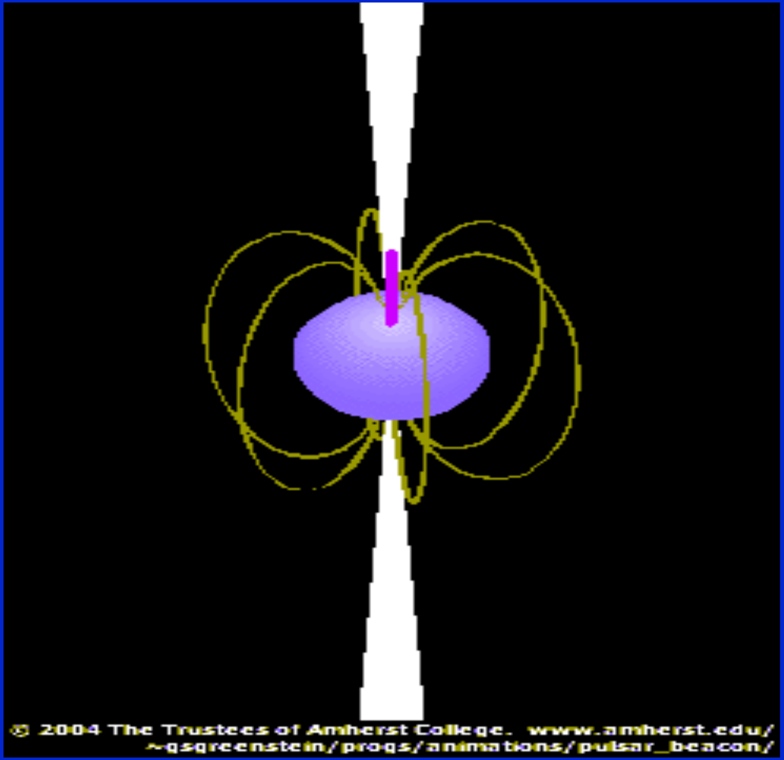
Anthony Hewish at Cambridge

Jocelin Bell
1967

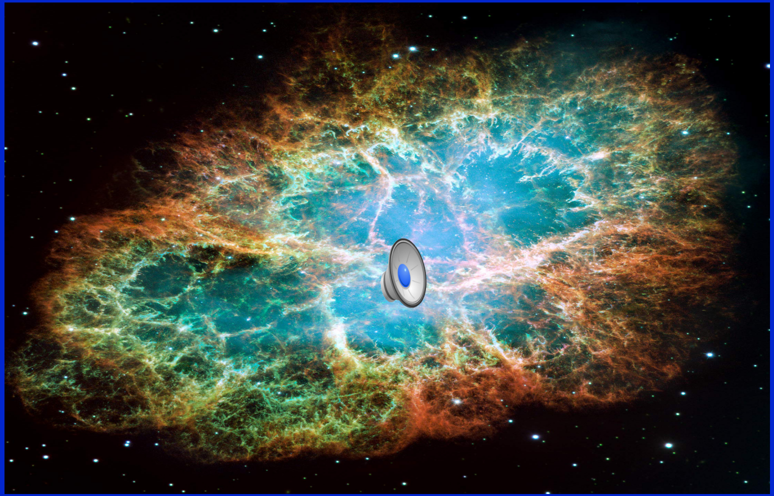
Little Green Men

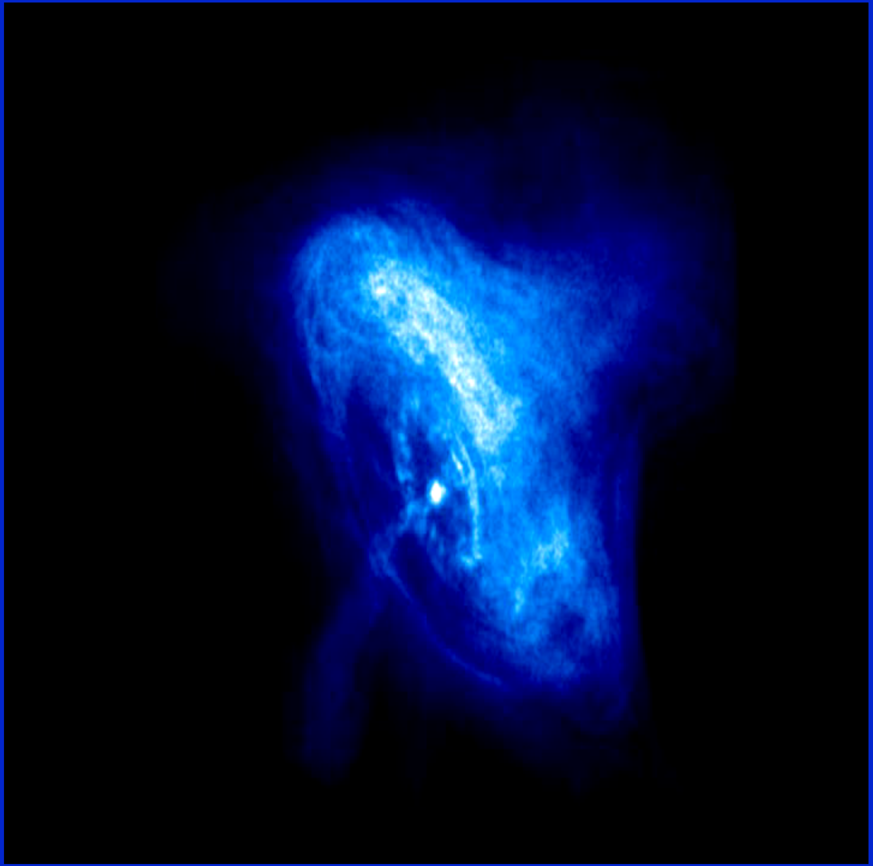
10^8 Gauss !?




© 2004 The Trustees of Amherst College. www.amherst.edu/~gsgreenstein/progs/animations/pulsar_beacon/

Back to the Crab Nebula (the pulsar found in 1968)





Chandra XRay

January 12 2011

Neutron Stars and Nuclear Physics

Limiting Conditions for Neutron Star $$\frac{MG}{R} < \frac{4}{9}$$

Causal Limit $$M = 3.14 M_\odot \quad R = 13.4 km$$

Observations $$M \approx (1.3 - 1.5) M_\odot \quad R = 10 - 12 km$$

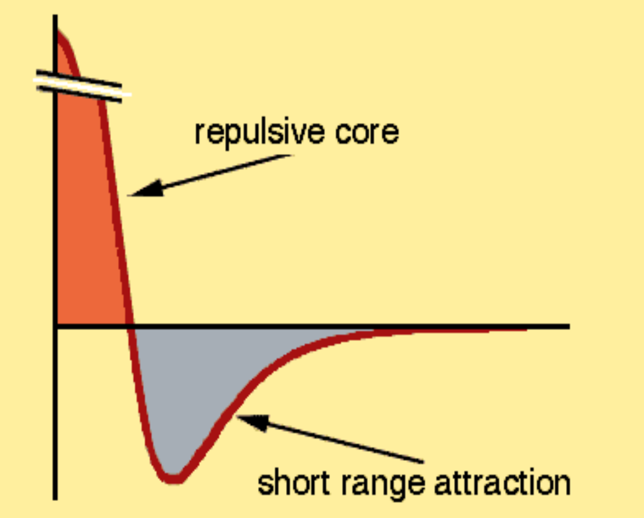
and not $$M_{max} = 0.7 M_\odot$$

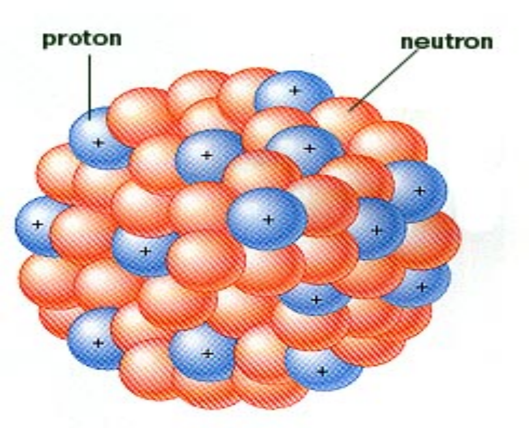
Neutron star is not a completely degenerate free Fermi Gas

Nuclear Interaction among neutrons should be taken into account

Nuclear Forces at Average Internucleon Distances

Starting with NN interaction

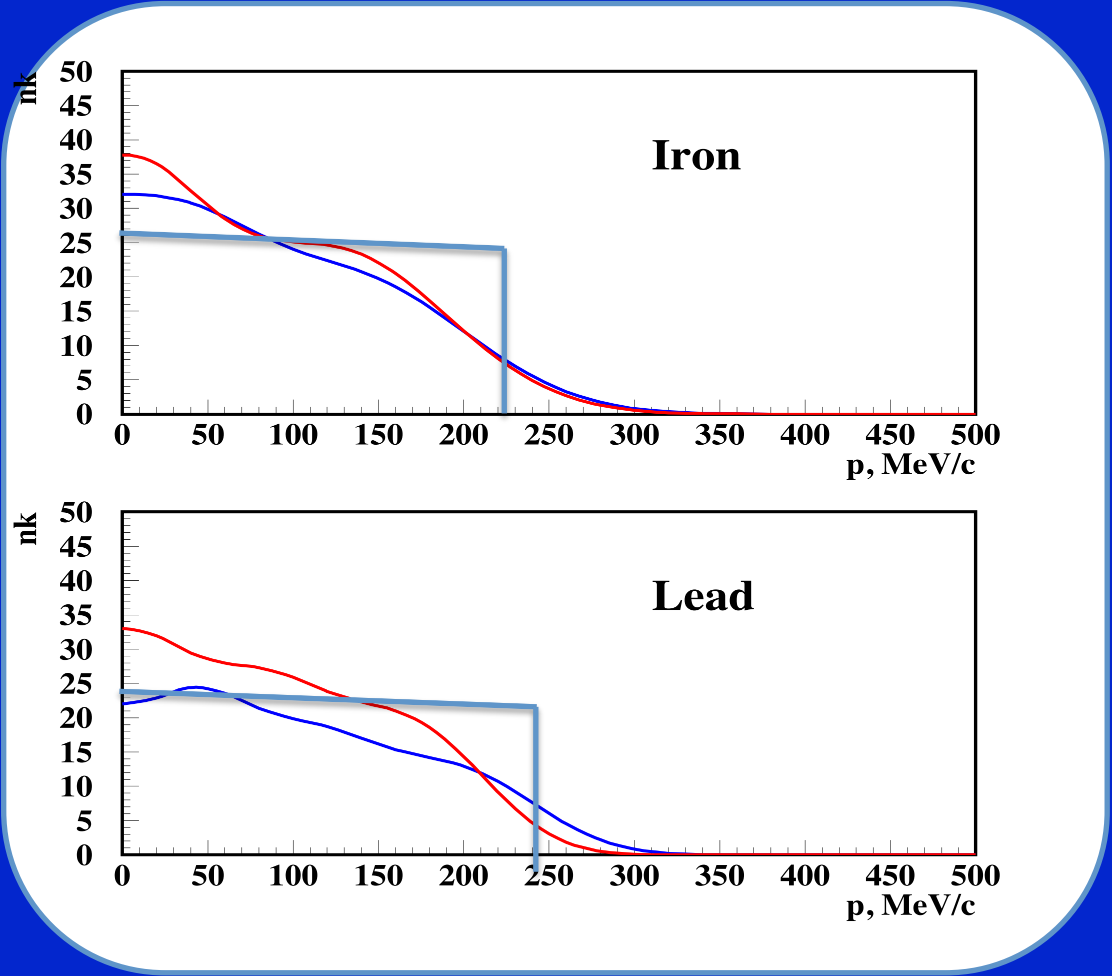




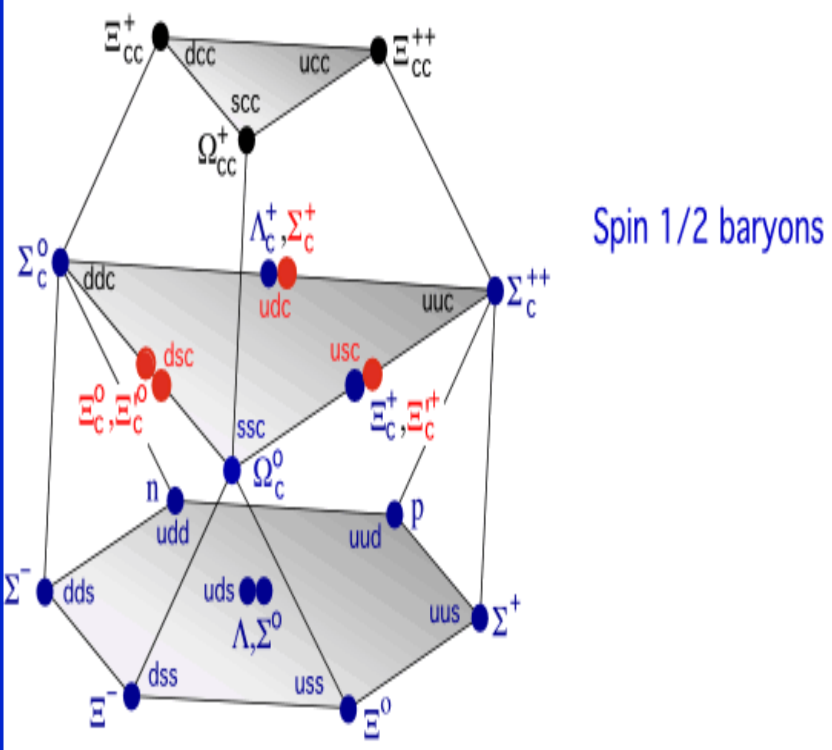
Any given nucleon feels the average nuclear field in which only total central and some LS part survived

And proton and neutron come almost identical in the nuclei

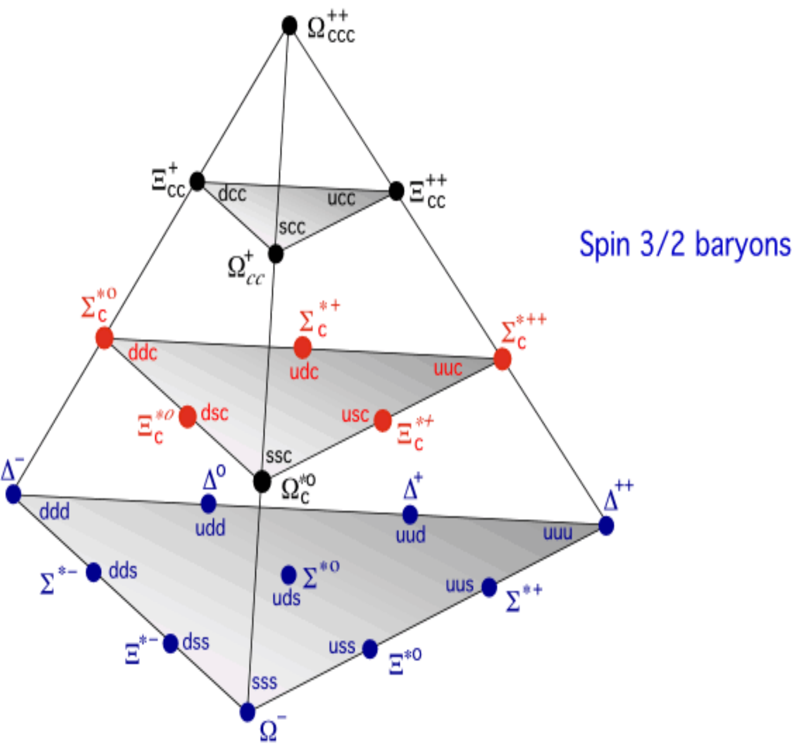
As a result average distribution of nucleons is not completely degenerate but close to it.



$$M \approx 1.3 - 1.5 M_{\odot}$$



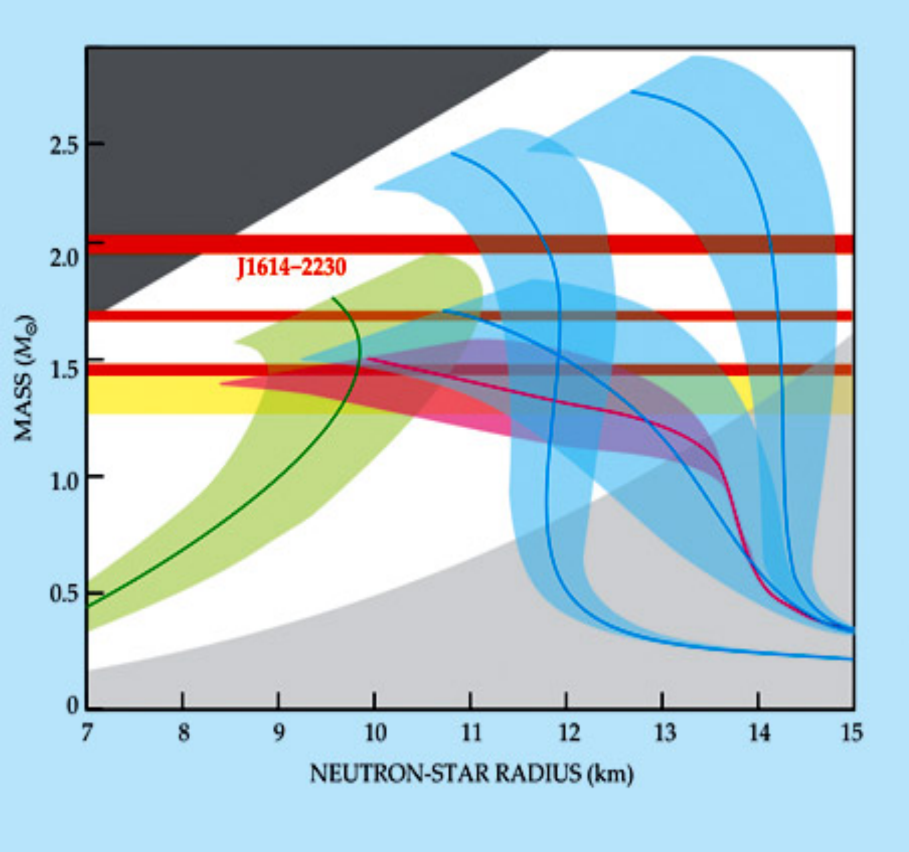
Spin 1/2 baryons



Spin 3/2 baryons

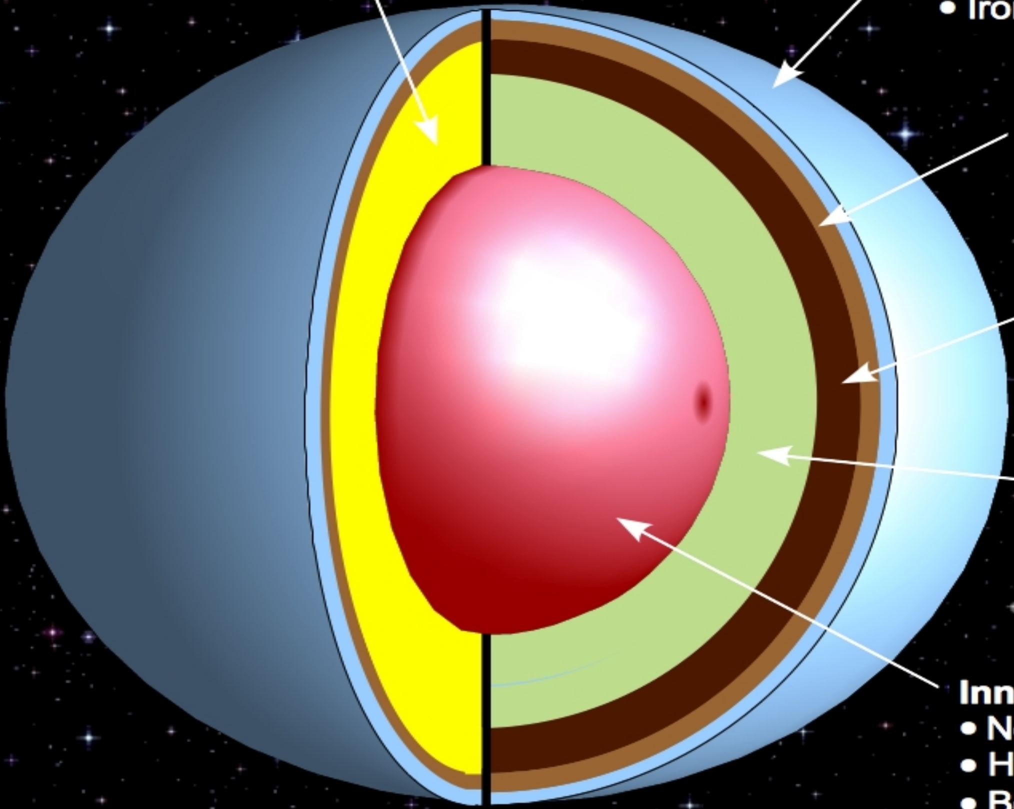
$$M_{max} \approx 1.5 - 1.7 M_\odot$$

- The Largest neutron-star mass yet recorded has broad implication
Physics Today Jan 2011



- National Radio Astronomy in Green Bank
Double Pulsar J1614-2230

"But now much of that speculation has Abruptly been laid to rest by a single astrophysical weighting".



Color-superconducting strange quark matter

Surface
- Hydrogen/Helium plasma
- Iron nuclei

Outer Crust
- Atomic nuclei
- Electron gas

Inner Crust
- Heavy atomic nuclei
- Relativistic electron gas
- Superfluid neutrons

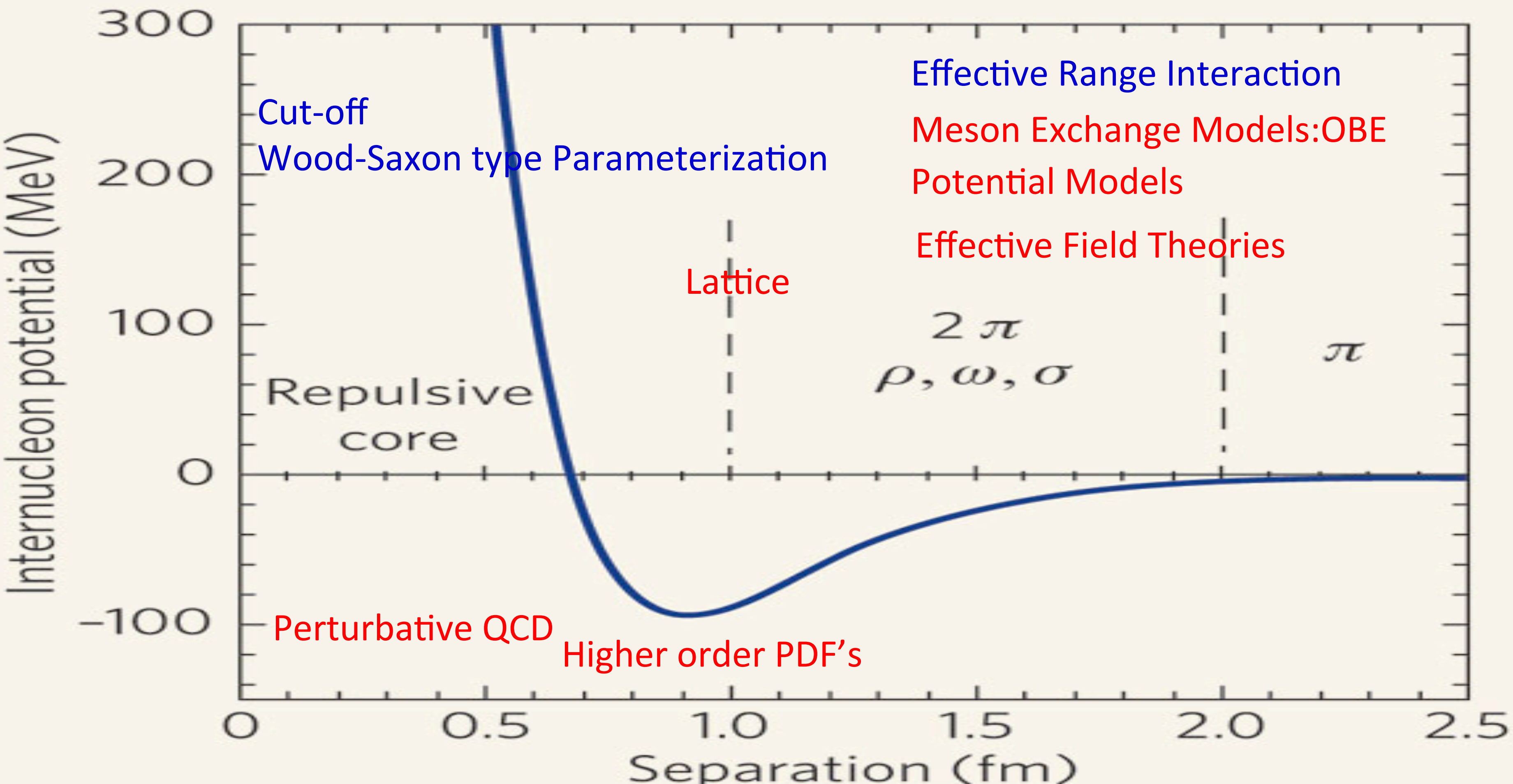
Outer Core
- Neutrons, superconducting protons
- Electrons, muons

Inner Core
- Neutrons, protons, electrons, muons
- Hyperons (Σ, Λ, Ξ)
- Boson (π, K) condensates
- Deconfined (u,d,s) quarks / color-superconducting quark matter

Radius ~ 10 to 14 km, Mass ~ 1 to 2 M_{sun}

F. Weber (SDSU, 2010)

Nuclear Forces at Short Distances :NN Interaction



Cut-off

Wood-Saxon type Parameterization

Effective Range Interaction

Meson Exchange Models:OBE

Potential Models

Effective Field Theories

Lattice

Perturbative QCD

Higher order PDF’s

Phenomenological NN Potentials

$$H = -\sum_i \frac{\nabla_i^2}{2m} + \sum_{i<j} V_{i,j}^{2N} + \sum_{i<j<k} V_{i,j,k}^{3N} + \cdots$$

$$H\Psi_A(r_1, \cdots, r_A) = E\Psi_A(r_1, \cdots, r_A)$$

$$V^{2N} = V_{EM}^{2N} + V_{\pi}^{2N} + V_R^{2N}$$

$$V_R^{2N} = V^c + V^{l2}L^2 + V^t S_{12} + V^{ls} L \cdot S + v^{ls2}(L \cdot S)^2$$

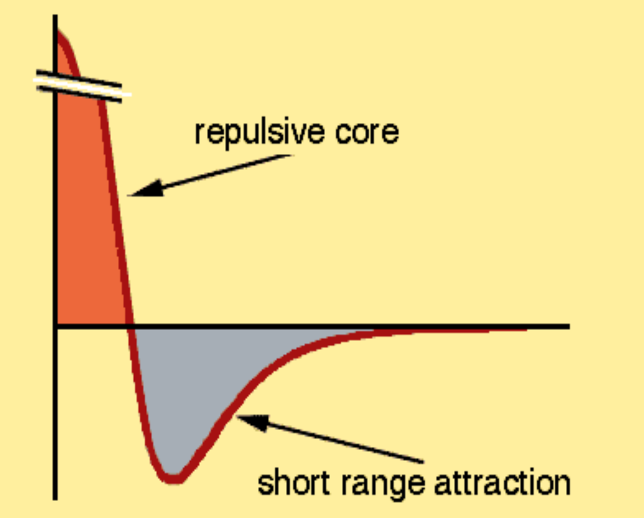
$$V^i = V_{int,R} + V_{core}$$

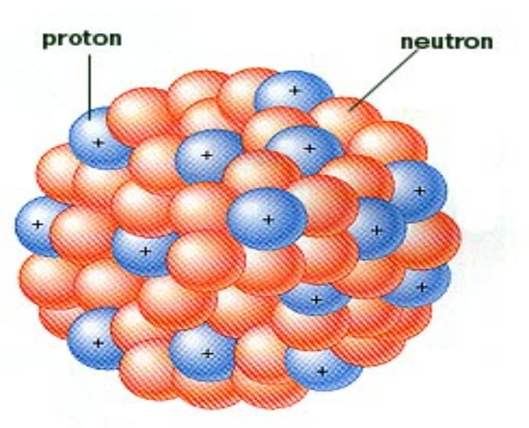
$$V_{core} = \left[1 + e^{\frac{r - r_0}{a}}\right]^{-1}$$

60's

Nuclear Forces at Average Internucleon Distances

Starting with NN interaction

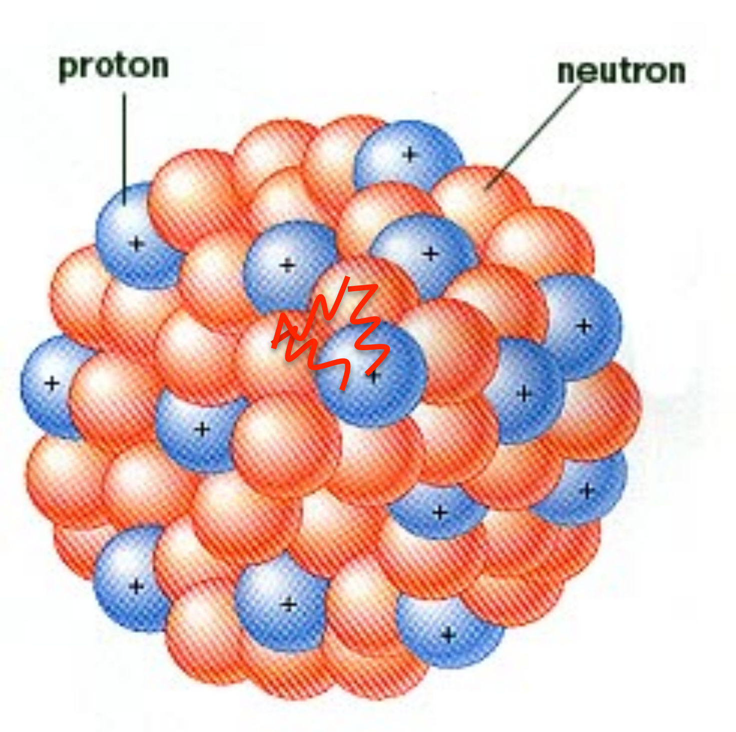




Any given nucleon feels the average nuclear field in which only total central and some LS part survived

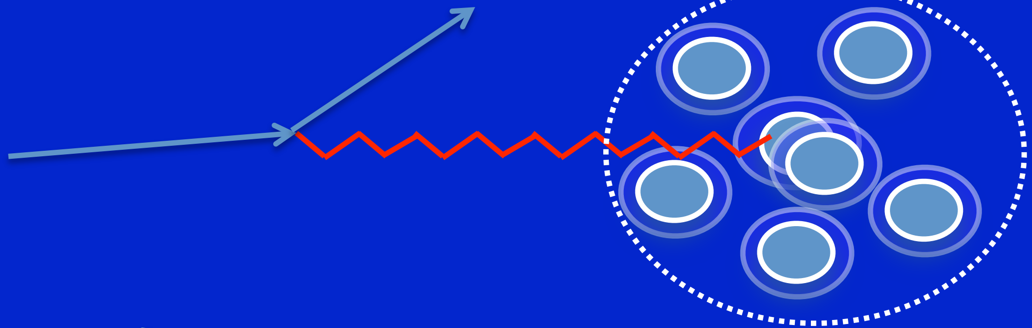
And proton and neutron come almost identical in the nuclei

High Density Fluctuations/Short Range Nucleon Correlations in Nuclei

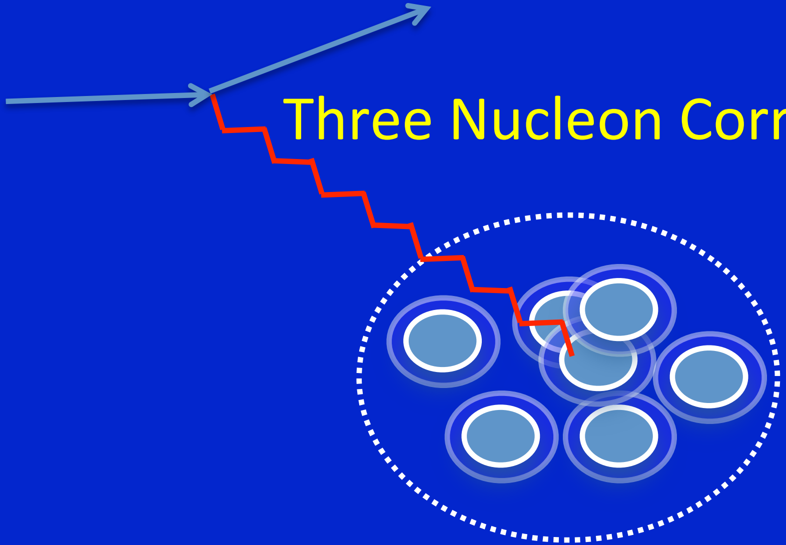


Probing Short Range Nucleon Correlations: Hard Processes

Two Nucleon Correlations

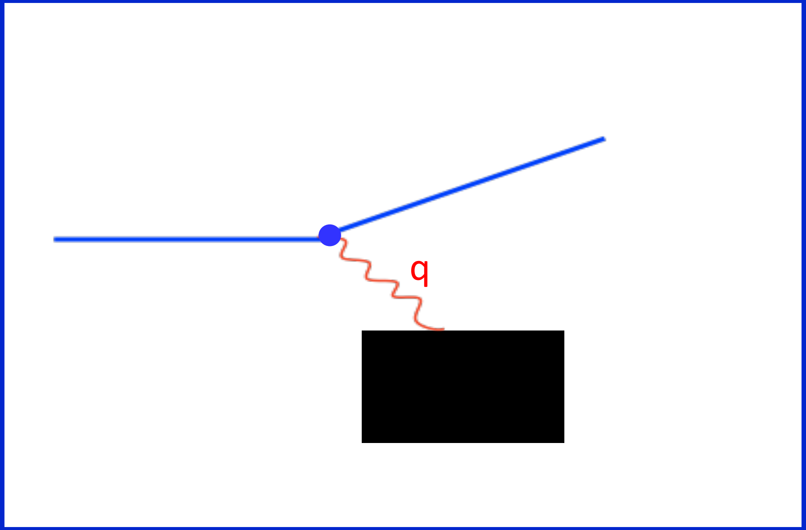


Three Nucleon Correlations



Inclusive Scattering

Inclusive Scattering From the Black Box



What we can learn
about BB without detecting it ?

- the Black Box has constituents
- the probe knocks-out one of such constituents without breaking it
- the remnant of the BB was a spectator to this action

$$p_i = P_{BB} - P_R$$

$$(q + p_i)^2 = m_c^2$$

$$-Q^2 + 2qp_i + m_i^2 = m_c^2$$

$$-Q^2 + q_+ p_{i-} + q_- p_{i+} + m_i^2 = m_c^2$$

$$\boxed{p_{i-} = \frac{Q^2}{q_+} - \frac{q_-}{q_+} p_{i+} + \frac{m_c^2 - m_i^2}{q_+}}$$

$$p_{i-} = \frac{Q^2}{q_+} = \frac{Q^2}{2q_0}$$

$$z || q$$
$$p_{i\pm} = E_i \pm p_{iz}$$
$$q_\pm = q_0 \pm q$$

$$\frac{Q^2}{q_+} = fixed$$
$$q_0 \longrightarrow \infty$$
$$q_+ \longrightarrow 2q_0$$

$$\frac{q_-}{q_+} = -\frac{fixed}{q_+} \longrightarrow 0$$

$$p_{i-} = \frac{Q^2}{q_+} = \frac{Q^2}{2q_0}$$

$$p_{i\pm} = E_i \pm p_{iz}$$

$$\boxed{p_{i-} \; =?} \xrightarrow{\quad} \frac{p_{i-}}{P_{BB-}}$$

Invariant with respect to
Lorentz transformation in z

$$\frac{p_{i-}}{P_{BB-}}\,|_{LAB} = \frac{Q^2}{2q_0 M_{BB}}$$

$$\frac{p_{i-}}{P_{BB-}}\,|_{IMF} = \left(\frac{E_i + p_i^z}{E_{BB} + P_{BB}^z}\right)_{IMF} \approx \left(\frac{p_i^z}{P_{BB}^z}\right)_{IMF}$$

$$p_{i\perp} \ll p_{iz}^{IMF}$$

If BB = nucleus

knocked out constituent is nucleon

Correlation Parameter

$$\alpha = A\frac{p_-}{p_{BB-}}$$

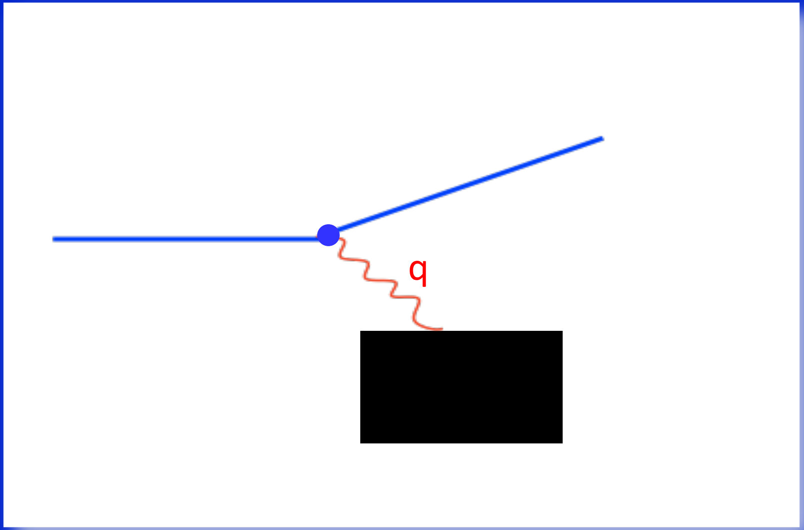
Momentum Fraction of Nucleus carried by the constituent nucleon

$\alpha > j - 1$ at least j-nucleons involved in the scattering

For sufficiently large Q2

$$\frac{p_{i-}}{P_{BB-}}|_{LAB} = \frac{Q^2}{2q_0 M_{BB}}$$

$$\alpha \approx x_{Bj} \equiv \frac{Q^2}{2m_N q_0}$$



signatures for short range correlations

$x > 1$ at least 2 nucleons are needed

$x > 2$ at least 3 nucleons are needed

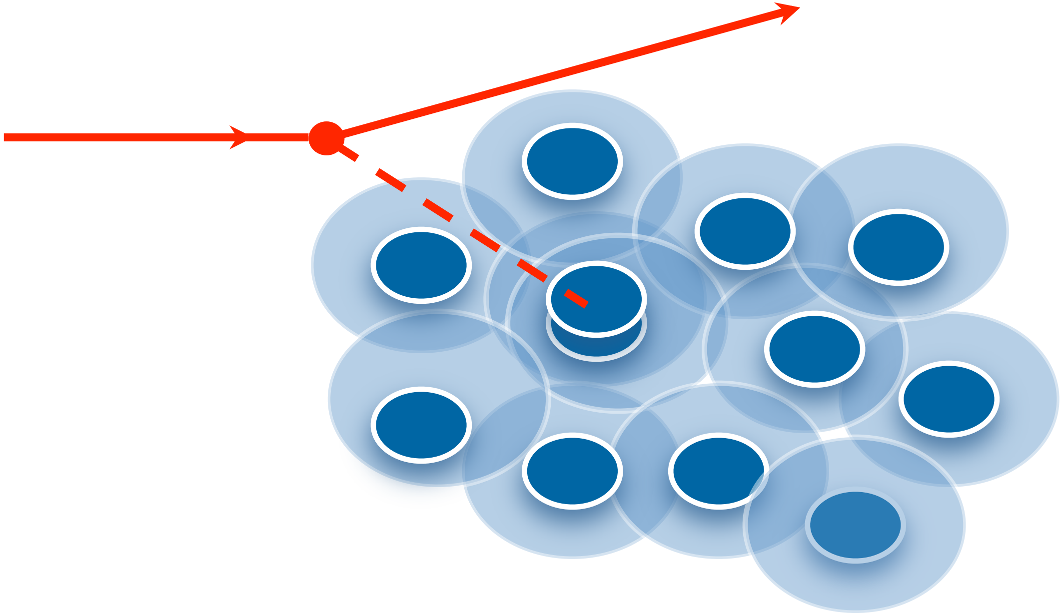
$x > j$ at least j+1 nucleons are neede

Prediction for Scaling

$x > 1$ if only 2 nucleons then $\frac{\sigma_A}{\sigma_D}$ scales

$x > 2$ if only 3 nucleons then $\frac{\sigma_A}{\sigma_{A=3}}$ scales

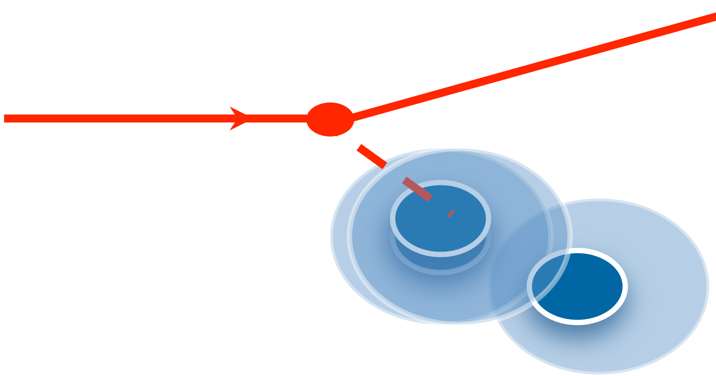
$x > j$ if only j+1 nucleons then $\frac{\sigma_A}{\sigma_{j+1}}$ scales



$$x_{Bj} > 1.5 \quad Q^2 \geq 1.4 GeV^2$$

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

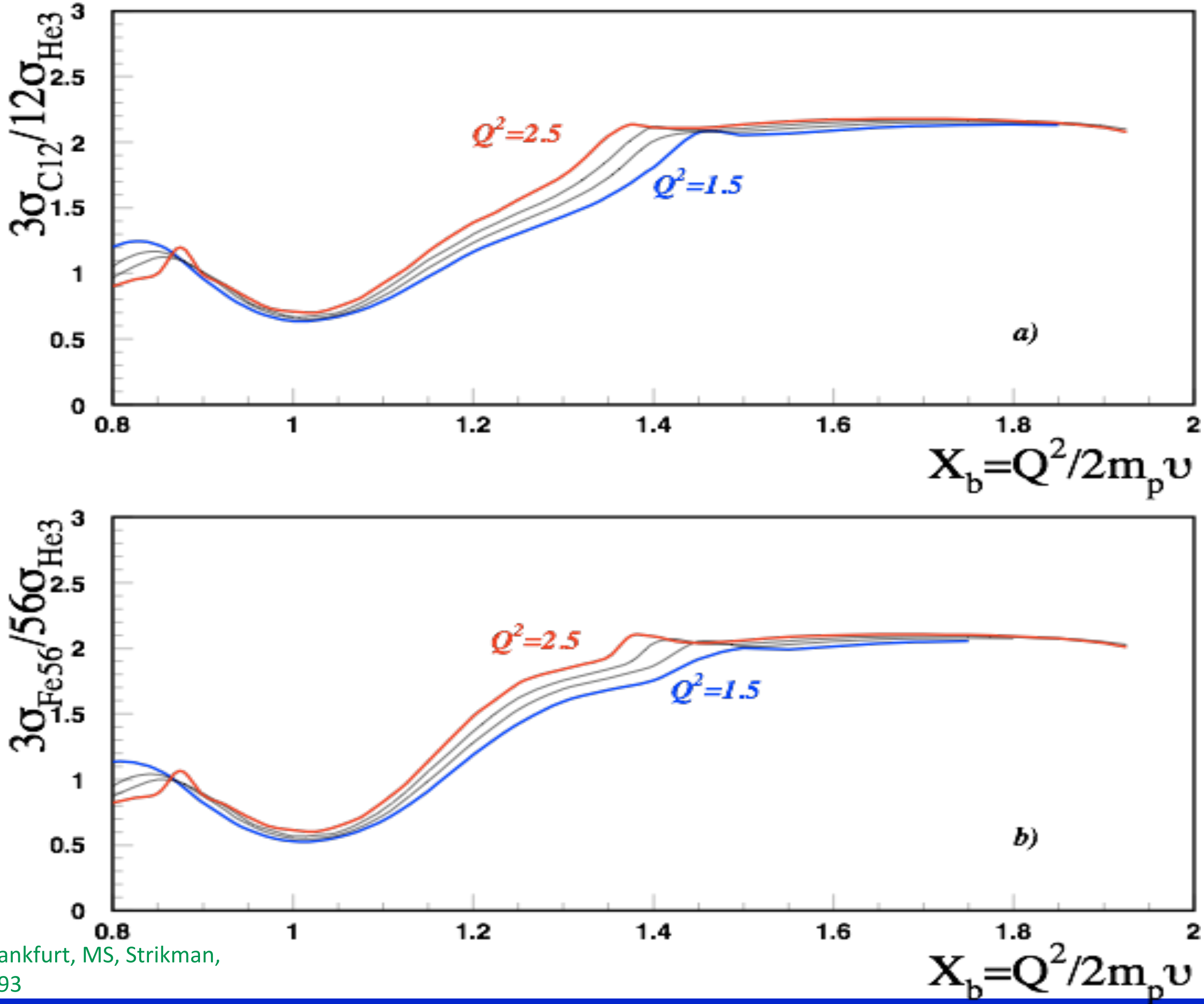
$$\frac{\sigma_{^{12}C}}{12}$$



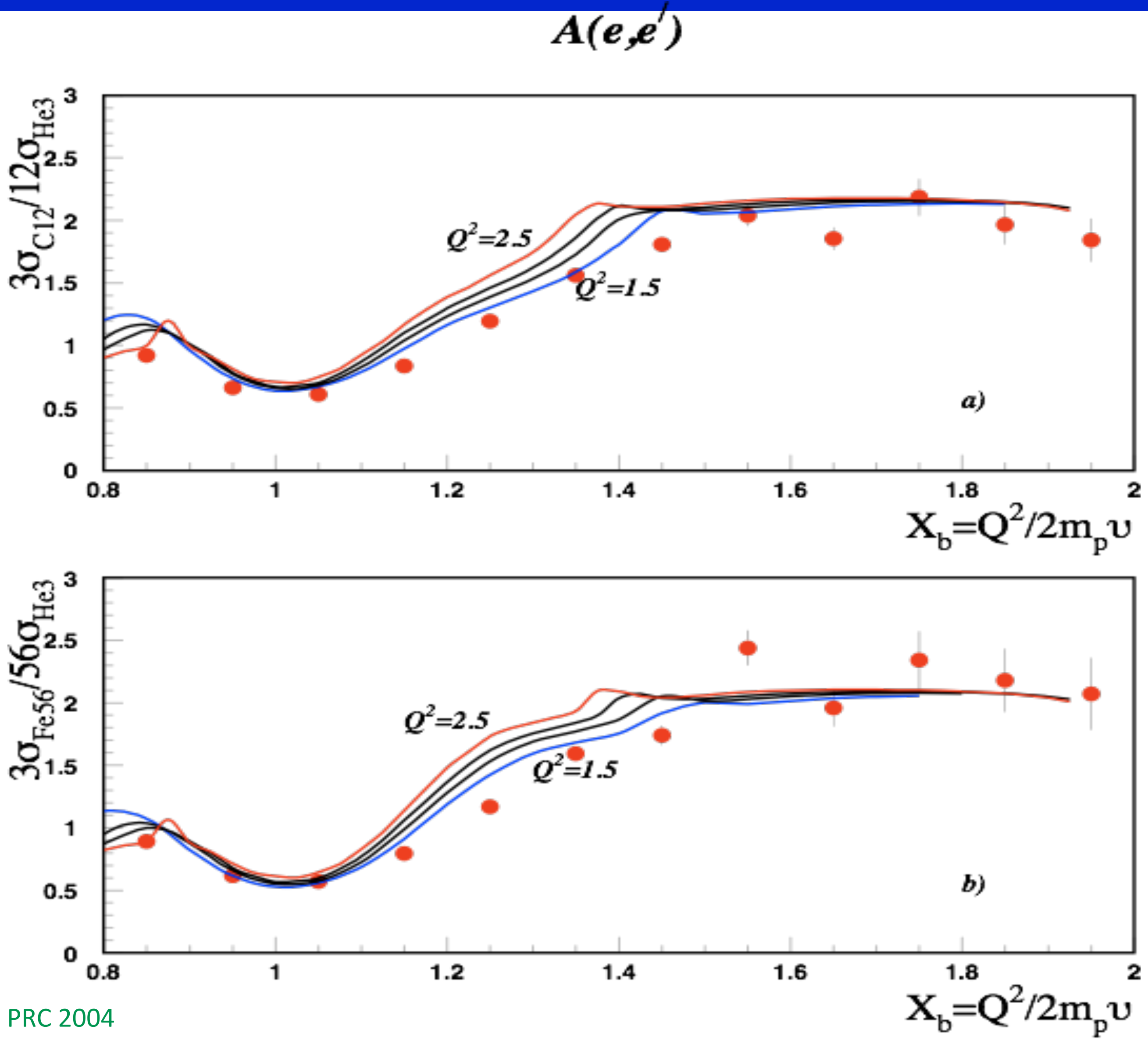
$$^{3}He(e,e')X$$

$$\frac{\sigma_{^{3}He}}{3}$$

$A(e,e')$

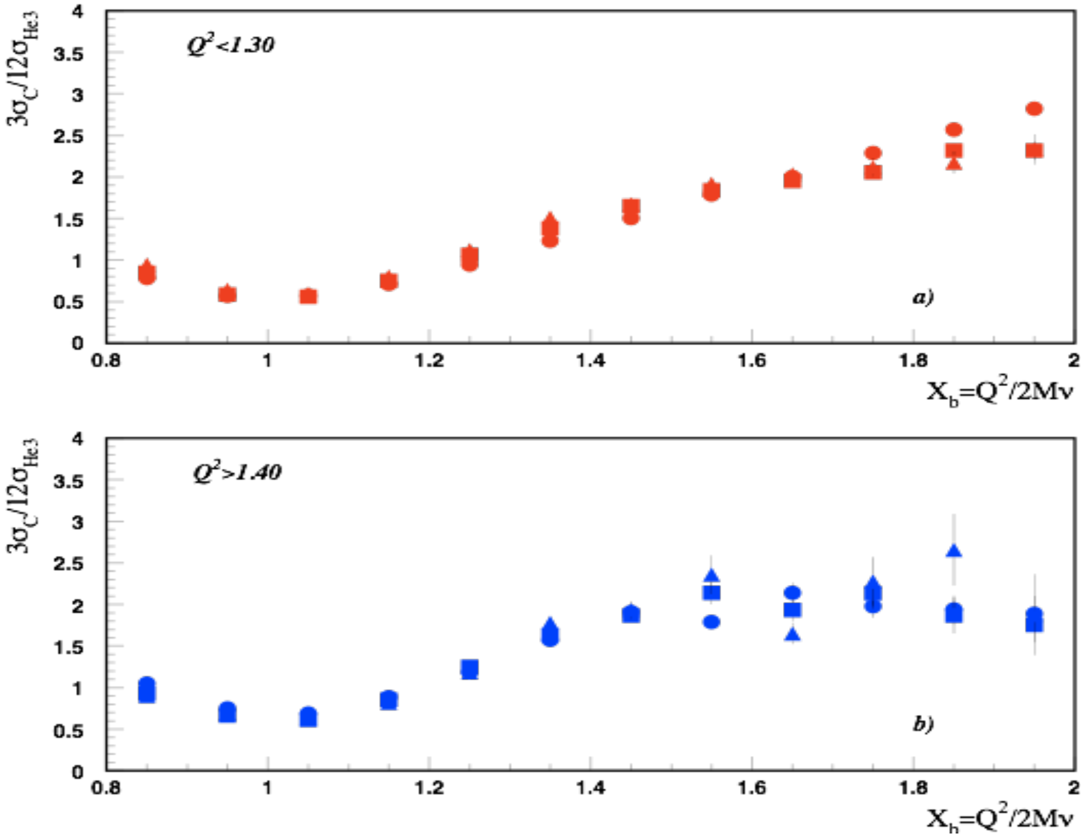


Day, Frankfurt, MS, Strikman,
PRC 1993



Egiyan, et al PRC 2004

$A(e,e^{/})$


$3\sigma_C/12\sigma_{He3}$
$Q^2<1.30$
a)
$X_b=Q^2/2M\nu$
0
0.5
1
1.5
2
2.5
3
3.5
4
0.8
1
1.2
1.4
1.6
1.8
2
$3\sigma_C/12\sigma_{He3}$
$Q^2>1.40$
b)
$X_b=Q^2/2M\nu$

signatures for short range correlations

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$x > 2$ at least 3 nucleons are needed

$x > j$ at least j+1 nucleons are neede

Prediction for Scaling

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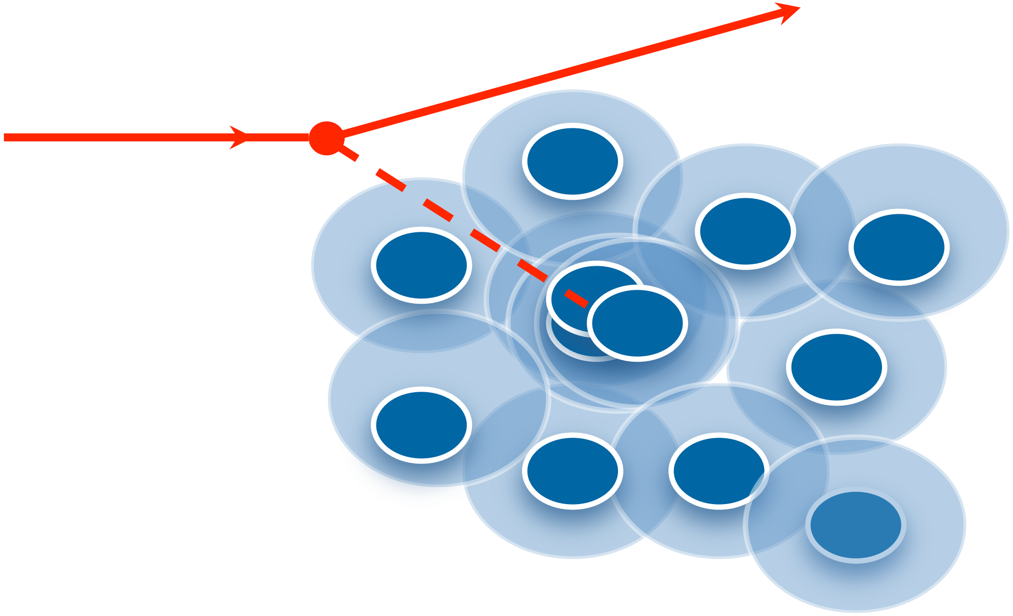
$x > 2$ if only 3 nucleons then $\frac{\sigma_A}{\sigma_{A=3}}$ scales

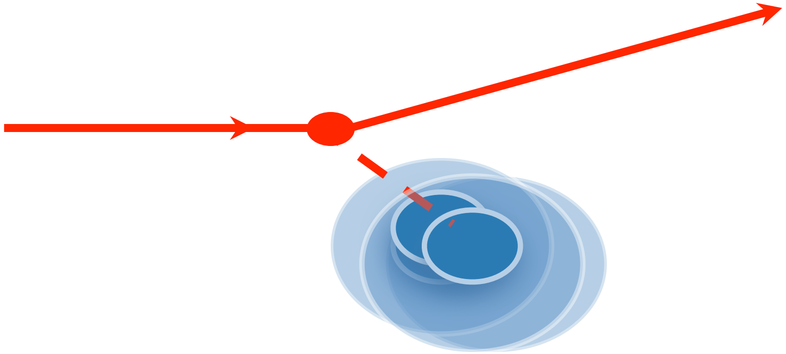
$x > j$ if only j+1 nucleons then $\frac{\sigma_A}{\sigma_{j+1}}$ scales

$$\boxed{x_{Bj} > 2}$$



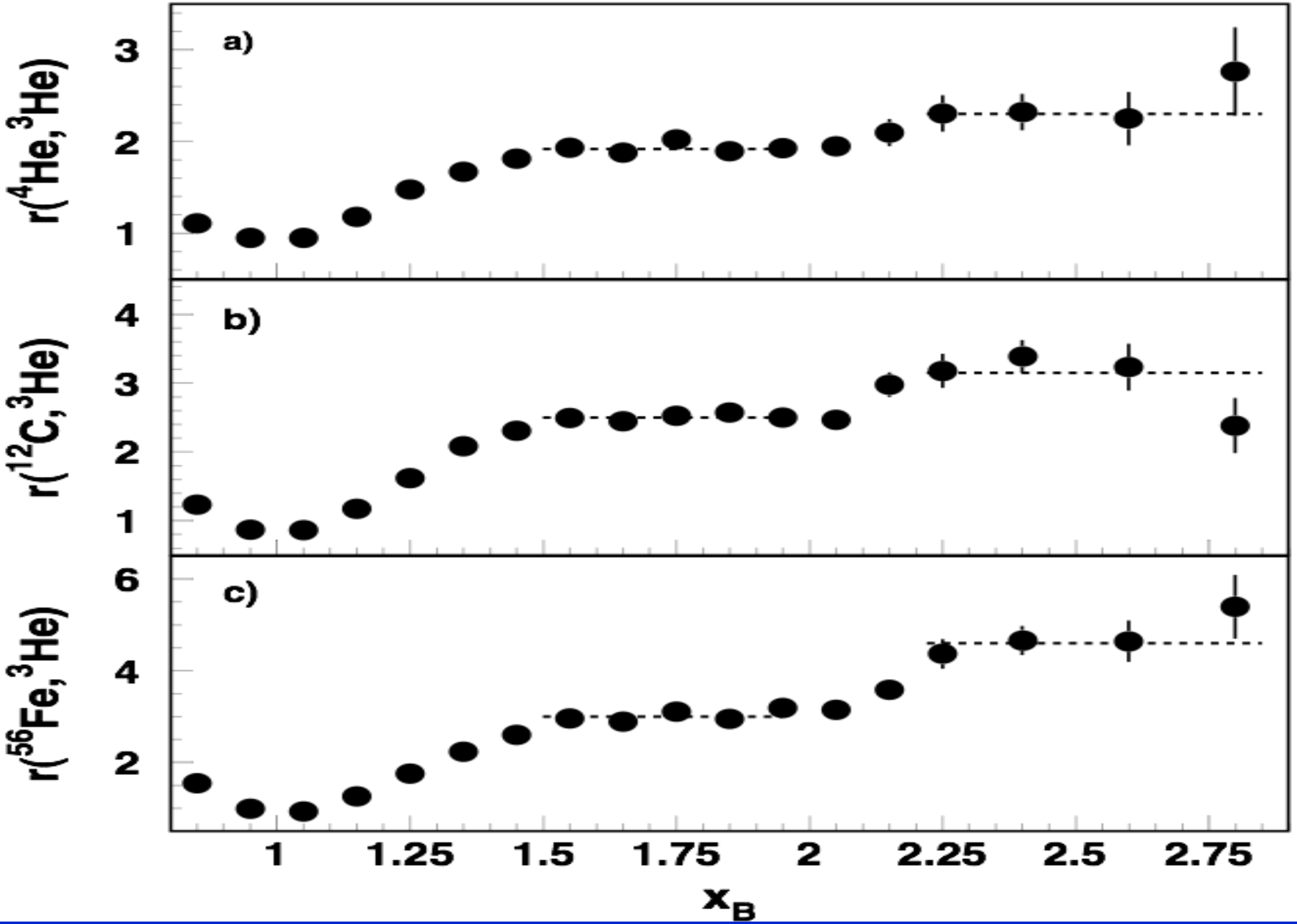
$$^{12}C(e,e')X$$

$$\frac{\sigma_{^{12}C}}{12}$$



$$^{3}He(e,e')X$$

$$\frac{\sigma_{^{3}He}}{3}$$


a)
b)
c)
r(⁴He,³He)
r(¹²C,³He)
r(⁵⁶Fe,³He)
1
2
3
4
6
1
1.25
1.5
1.75
2
2.25
2.5
2.75
x_B

Meaning of the scaling values

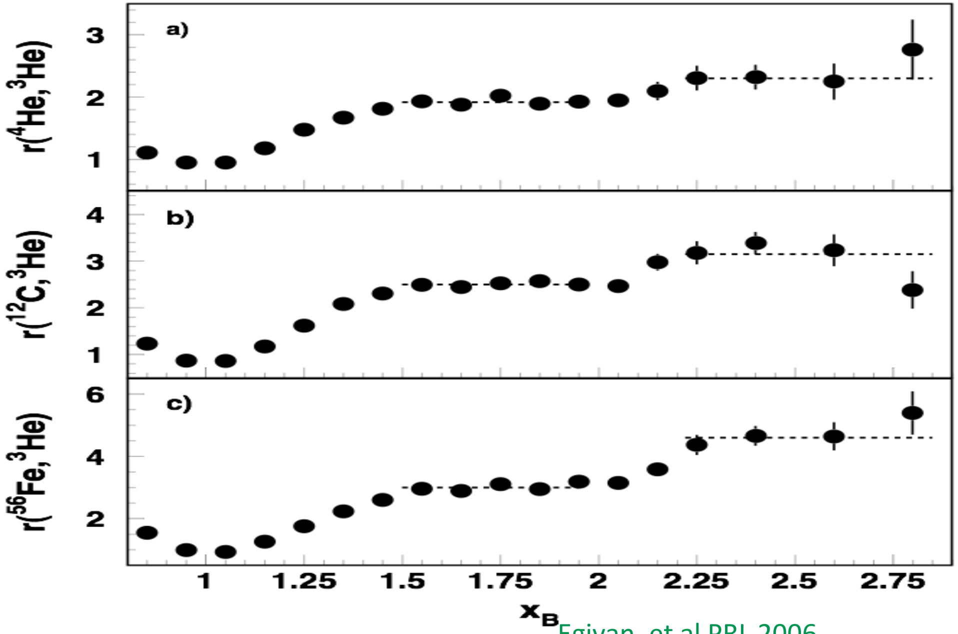
Day, Frankfurt, MS,
Strikman, PRC 1993

Frankfurt, MS, Strikman,
IJMP A 2008

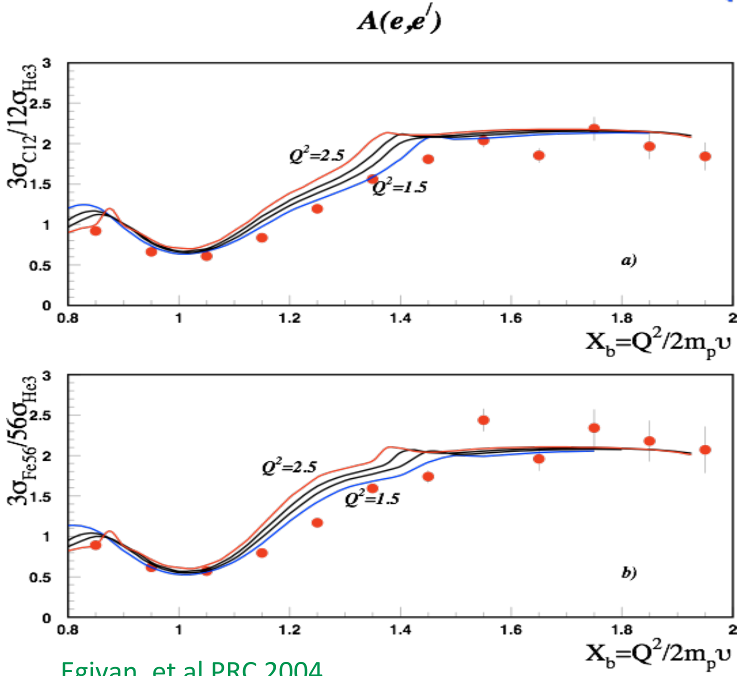
$$\boxed{R = \frac{A_2\sigma[A_1(e,e')X]}{A_1\sigma[A_2(e,e')X]}}$$

For $2 < x < 3$ $R \approx \frac{a_3(A_1)}{a_3(A_2)}$

For $1 < x < 2$ $R \approx \frac{a_2(A_1)}{a_2(A_2)}$

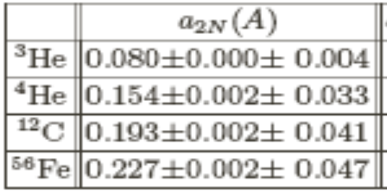


Egiyan, et al PRL 2006

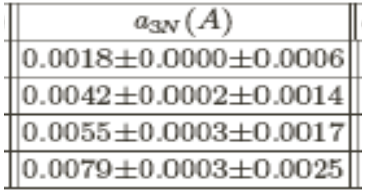


Egiyan, et al PRC 2004

What we Learned from A(e,e’)X Reactions



	$a_{2N}(A)$
^{3}He	0.080±0.000± 0.004
^{4}He	0.154±0.002± 0.033
^{12}C	0.193±0.002± 0.041
^{56}Fe	0.227±0.002± 0.047



$a_{3N}(A)$
0.0018±0.0000±0.0006
0.0042±0.0002±0.0014
0.0055±0.0003±0.0017
0.0079±0.0003±0.0025

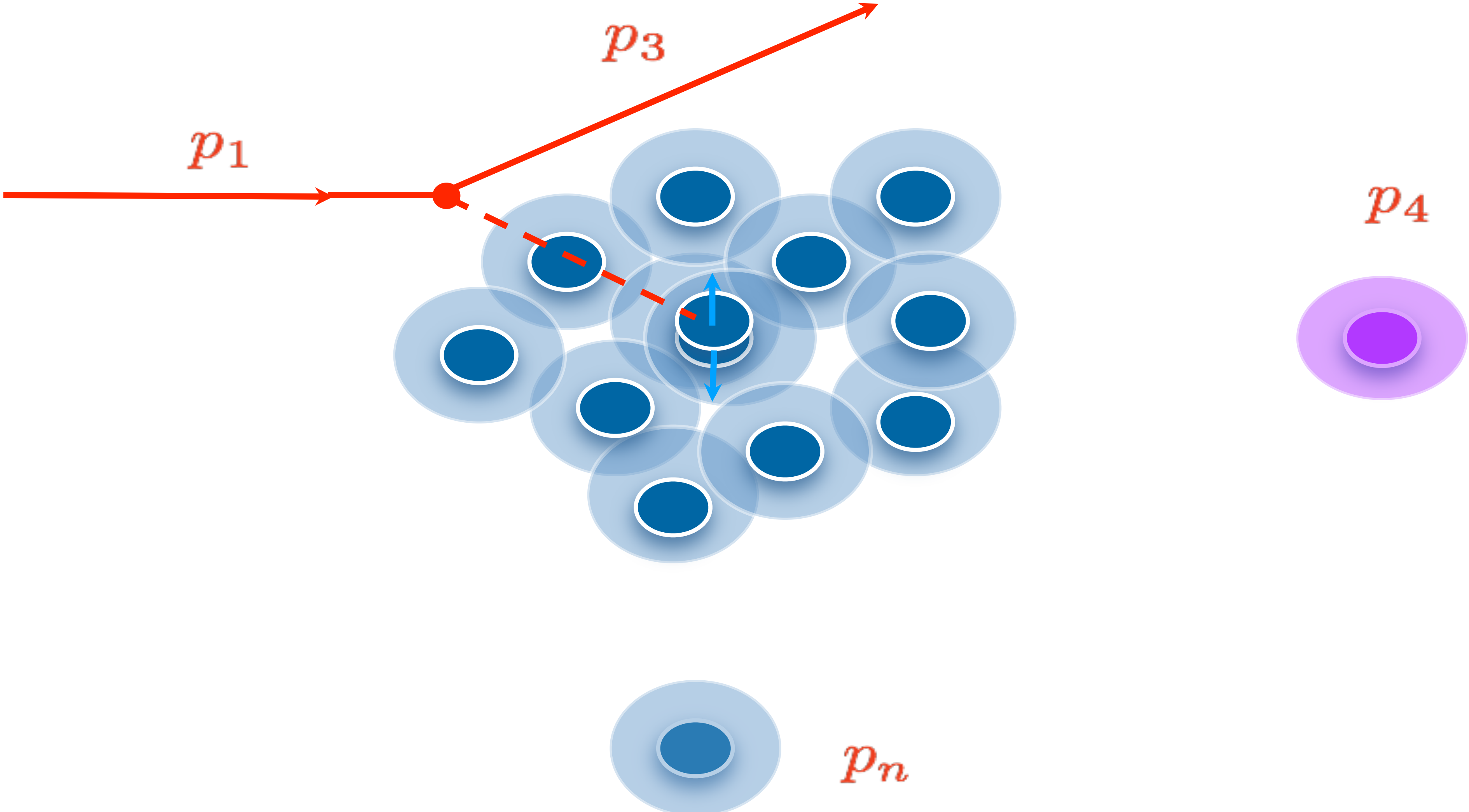
$$a_2(^{12}C) = 0.194\%$$
$$a_3(^{12}C) = 0.0055\%$$

$$a_2(^{56}Fe) = 0.227\%$$
$$a_3(^{56}Fe) = 0.0079\%$$

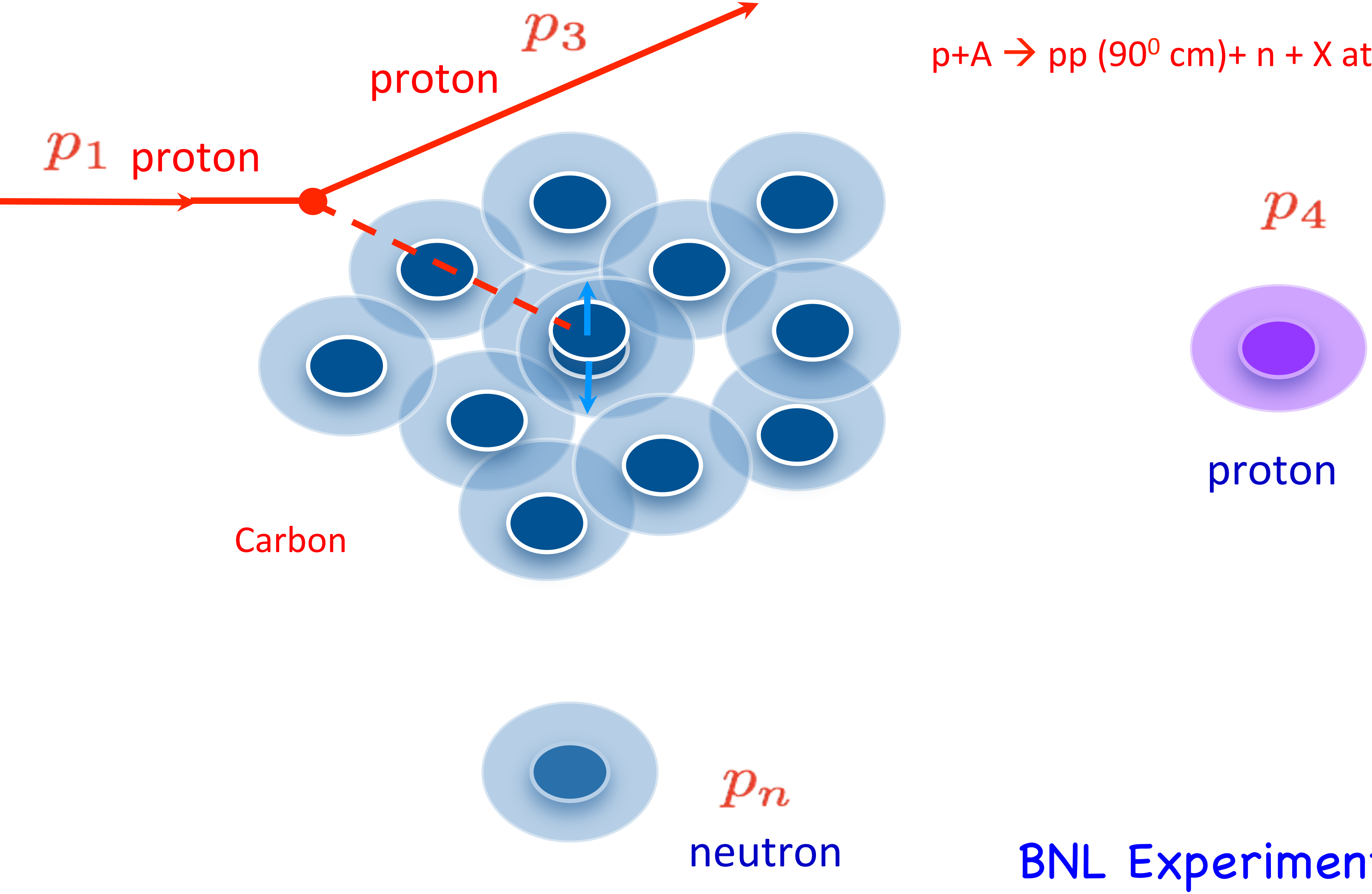
- high energy inclusive probe at x>1 and large Q2 can detect high density fluctuations

- and measure their probabilities $a_2(A)$ $a_3(A)$

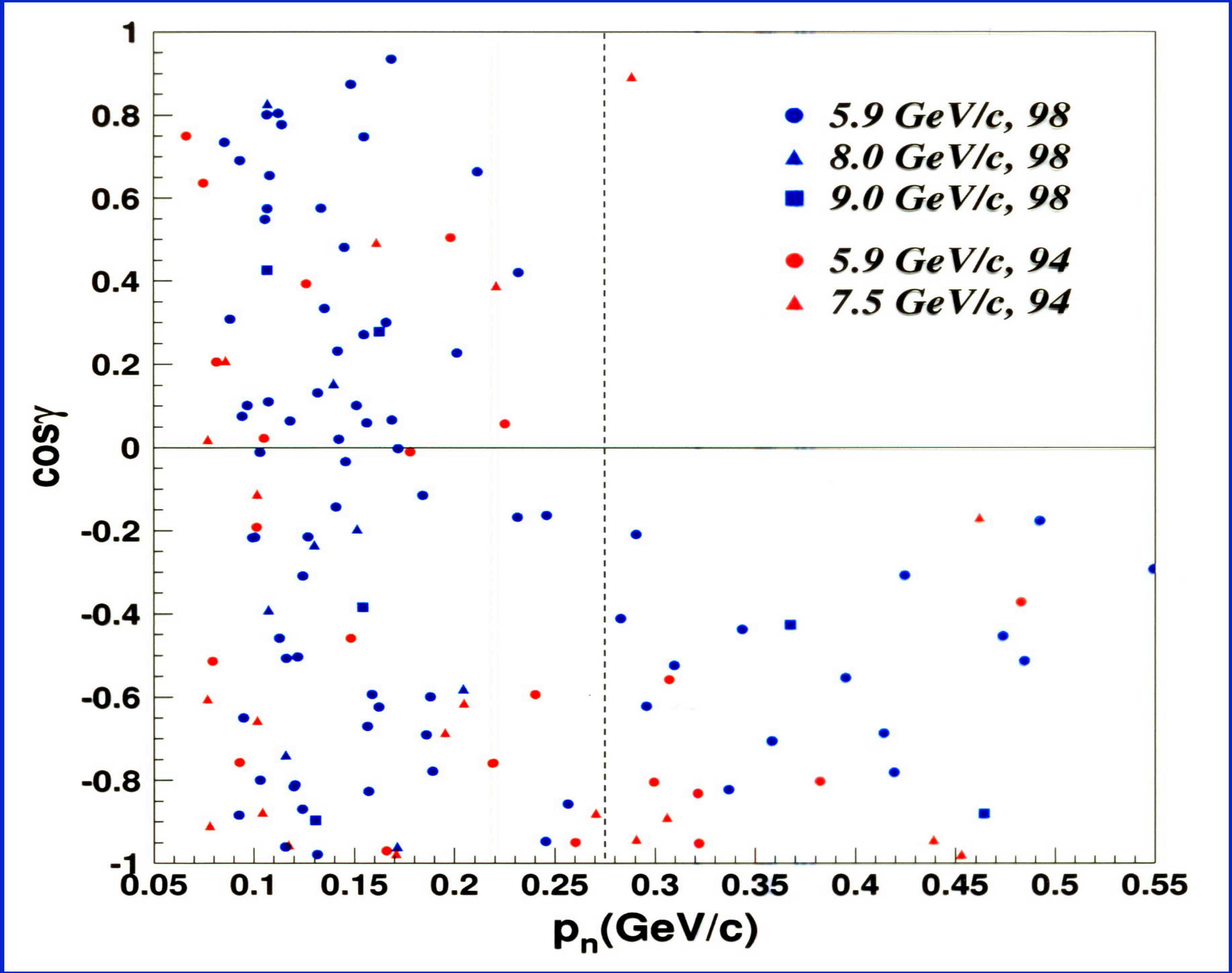
Structure of these correlations/high density fluctuations

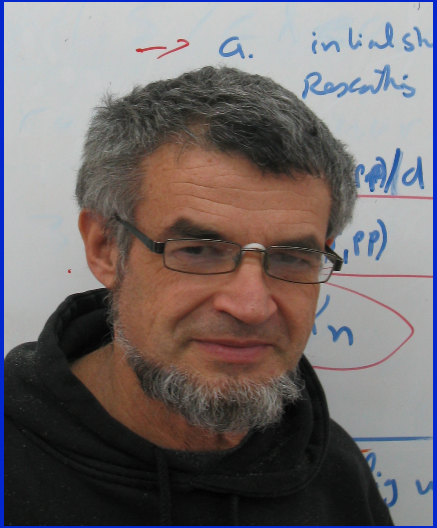


p+A → pp (90^0 cm)+ n + X at BNL



BNL Experiment





Eli Pasetzky
TAU

A. Tang et al, PRL 2003

Brookhaven Experiment

A. Tang et al, PRL 2003

$$F = \frac{\text{Number of (p,ppn) events } (p_i, p_n > k_F)}{\text{Number of (p,pp) events } (p_i > k_F)},$$

$$F = 0.43^{+0.11}_{-0.07} \qquad \text{for } 275 \le p_i, p_n \le 550 \text{ MeV/c}$$

Theoretical Analysis

Piasetzky, Sargsian, Frankfurt,
Strikman, Watson PRL 2007

$$P_{pn/pX} = \frac{F}{T_n R}$$

relative probability of finding pn SRC in the "pX" configuration that contains a proton with $p_i > k_F$.

$$R \equiv \frac{\int\limits_{\alpha_i^{min}}^{\alpha_i^{max}} \int\limits_{p_{ti}^{min}}^{p_{ti}^{max}} \int\limits_{\alpha_n^{min}}^{\alpha_n^{max}} \int\limits_{p_{tn}^{min}}^{p_{tn}^{max}} D^{pn}(\alpha_i, p_{ti}, \alpha_n, p_{nt}, P_{R+}) \frac{d\alpha}{\alpha} d^2p_t \frac{d\alpha_n}{\alpha_n} d^2p_{tn} dP_{R+}}{\int\limits_{\alpha_i^{min}}^{\alpha_i^{max}} \int\limits_{p_{ti}^{min}}^{p_{ti}^{max}} S^{pn}((\alpha_i, p_{ti}, P_{R+}) \frac{d\alpha}{\alpha} d^2p_t dP_{R+}}.$$

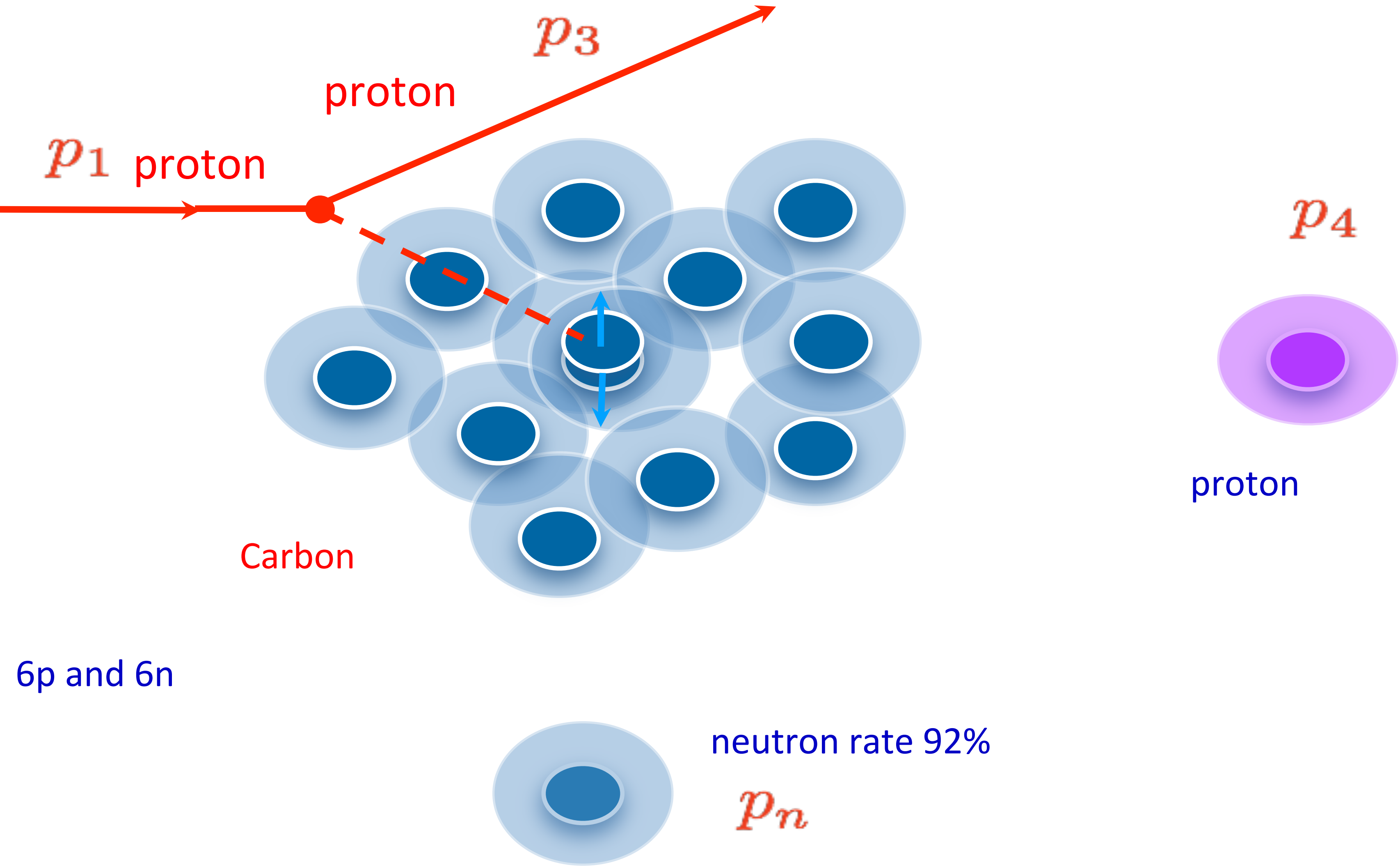
$$P_{pn/pX} = 0.92^{+0.08}_{-0.18}$$

Expected: (Wigner counting)
pn = 2/3, pp = 1/3

$$\frac{P_{pp}}{P_{pn}} \leq \frac{1}{2}(1 - P_{pn/pX}) = 0.04^{+0.09}_{-0.04}.$$

- 92% of the time two-nucleon correlations are proton and neutron

- at most 4% of the time proton-proton or neutron-neutron



p_3

proton

p_1 proton

p_4

proton

Carbon

6p and 6n

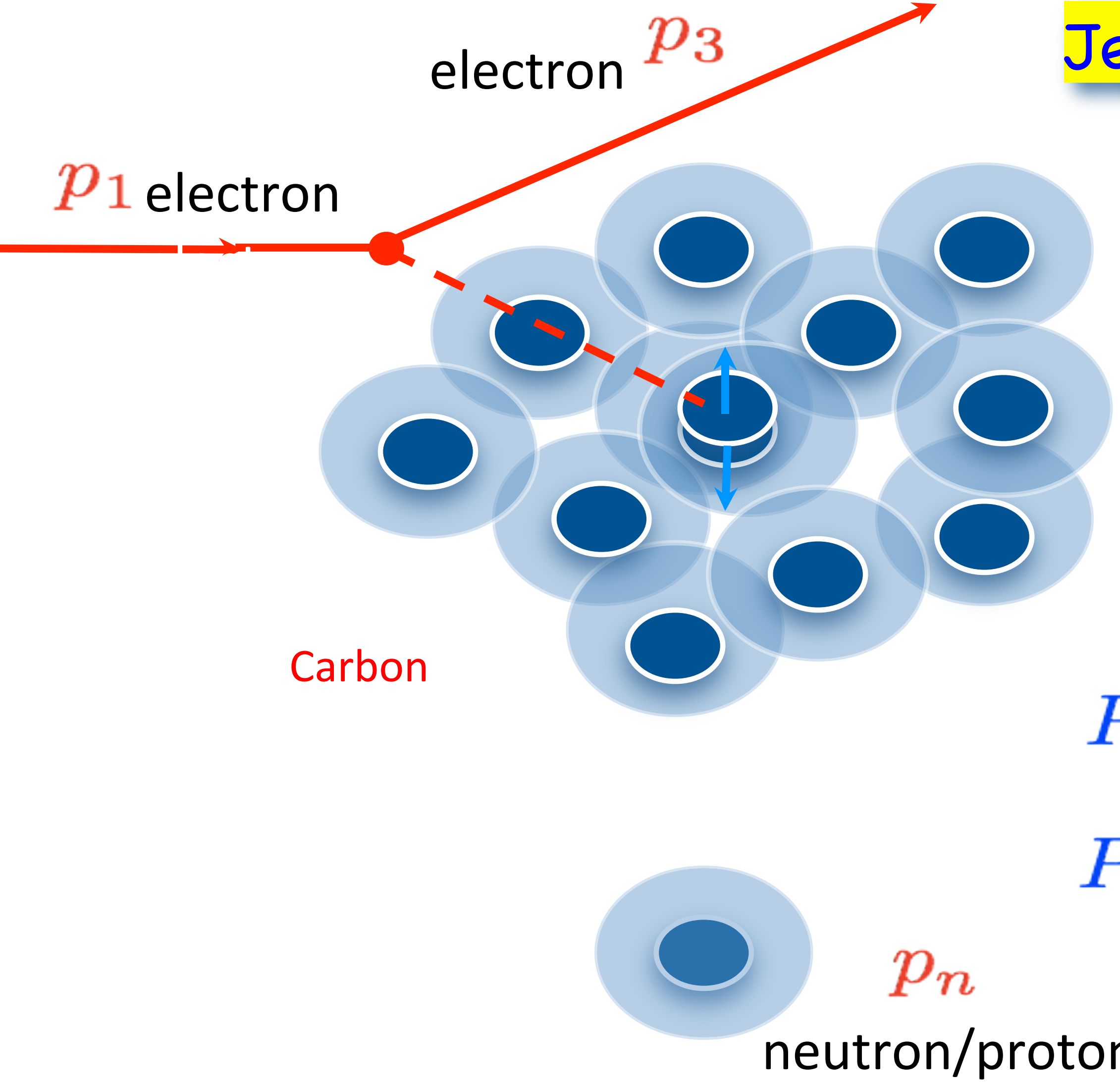
neutron rate 92%

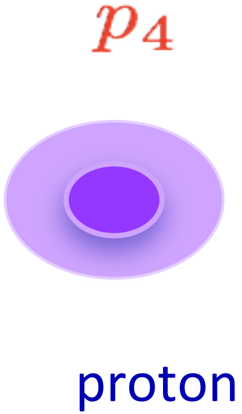
p_n

calculated upper limit of proton rate 4%

Jeferson Lab Experiment

R. Shneor et al. PRL 07



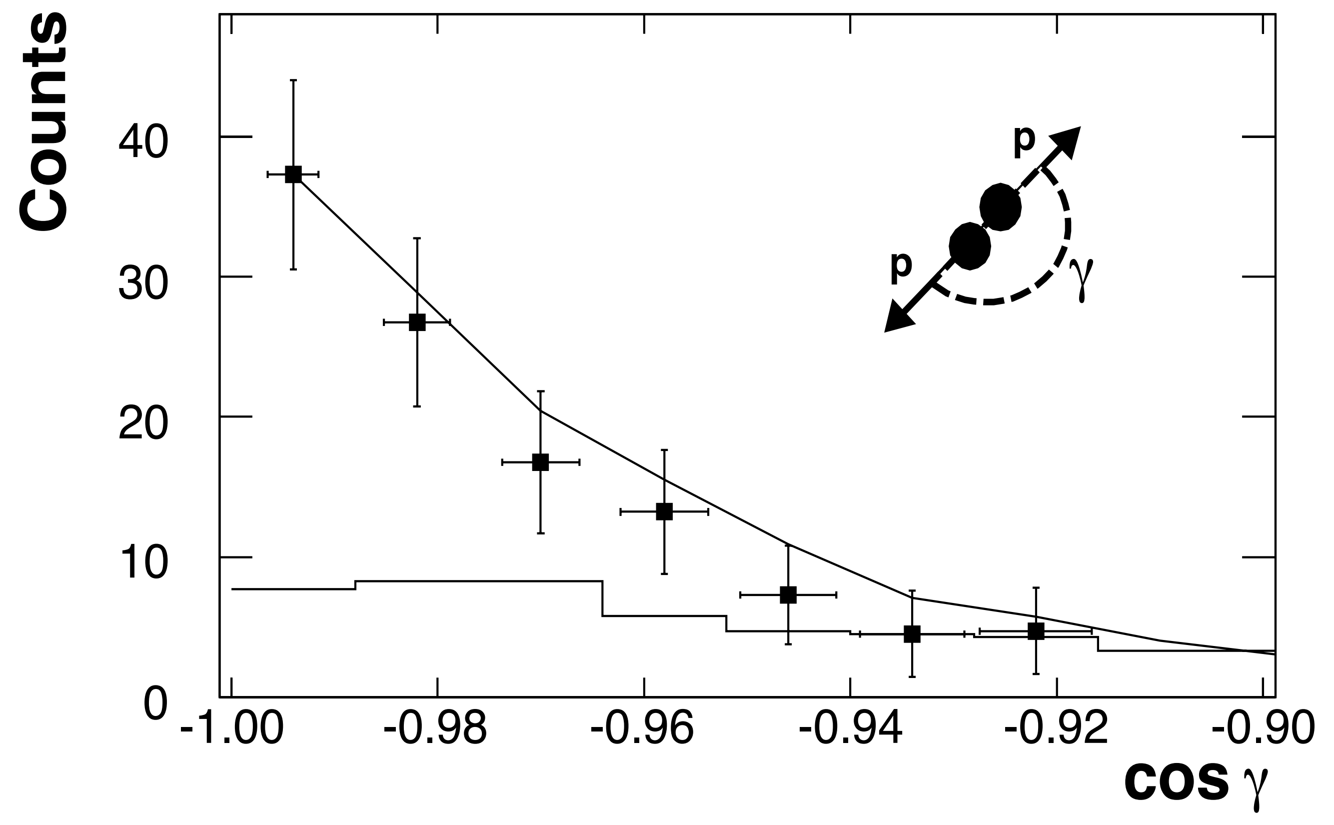


$$P_{pn/pX} = 0.96{\pm}0.22$$

$$P_{pp/pn} = 0.056{\pm}0.018$$

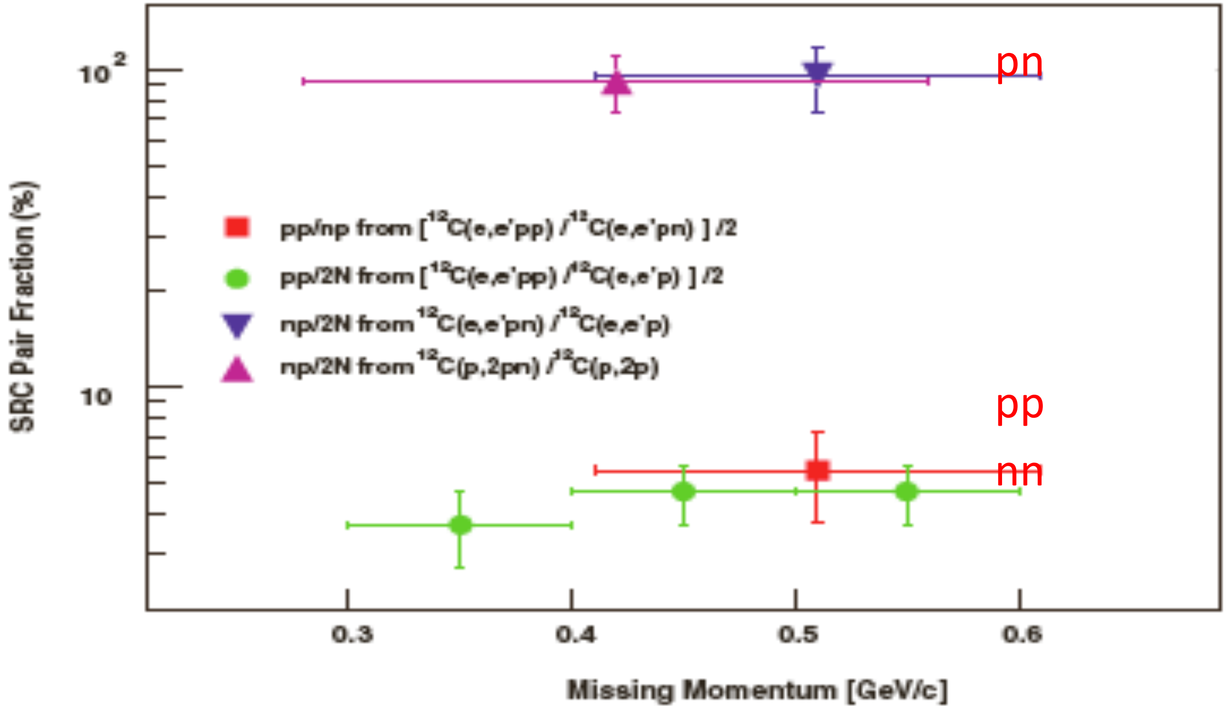
e + A → e' + p (> GeV)+ n/p (300-600MeV) + X

R.Shneor, et al PRL , 2007



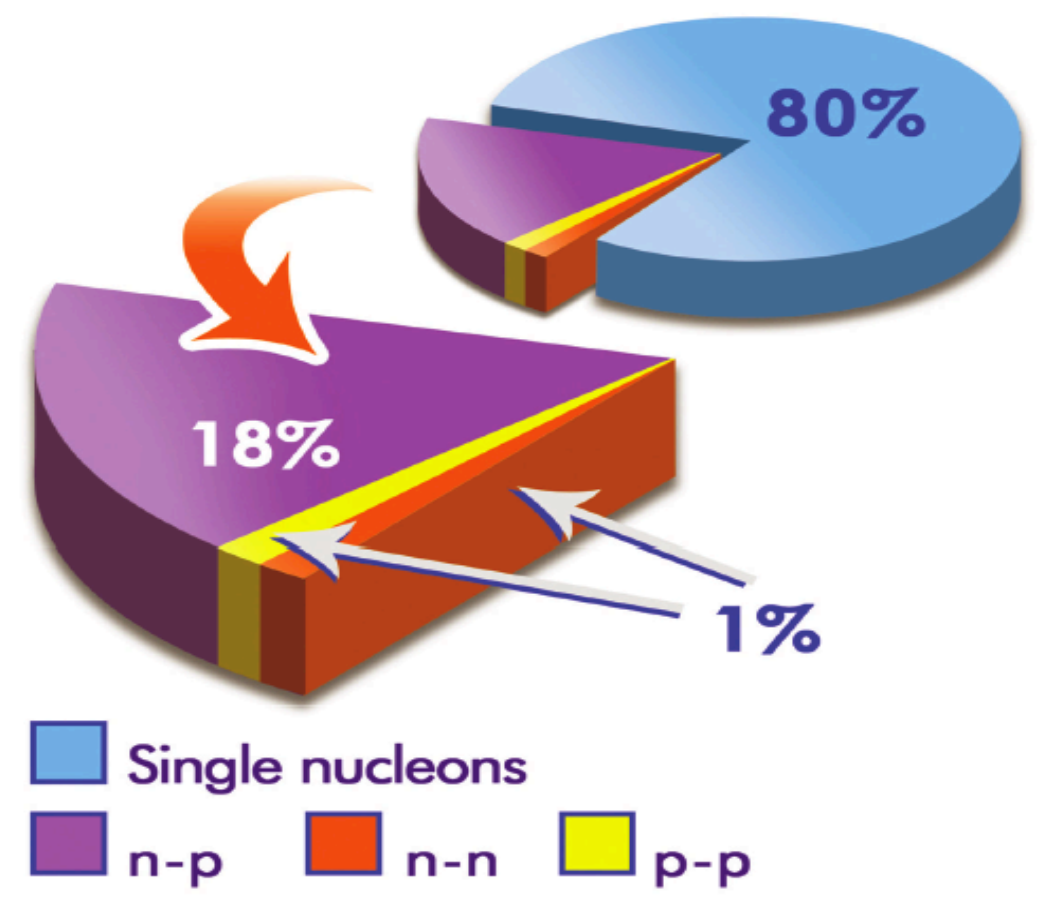
Combined Analysis

R.Subdei, et al Science , 2008



Combined Analysis

R.Subdei, et al Science , 2008



$$P_{pn/pX} = 0.92^{+0.08}_{-0.18}$$

BNL data on A(p,2pn)X

Piasetzky, MS, Frankfurt,
Strikman, Watson PRL 2007

$$\frac{P_{pp}}{P_{pX}} \leq \frac{1}{2}(1 - P_{pn/pX}) = 0.04^{+0.09}_{-0.04}$$

- 92% of the time two-nucleon high density fluctuations are proton and neutron
- at most 4% of the time proton-proton or neutron-neutron

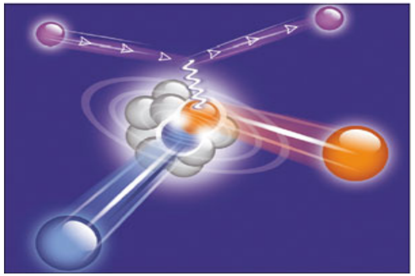
JLAB data A(e,e’pn)X

$$P_{pn/pX} = 0.96 \pm 0.22$$

R. Shneor et al. PRL 07

$$P_{pp/pX} = 0.056 \pm 0.018$$

- short range correlations in the range of 250-600 MeV/c are pn SRCs



Press releases on SRC:

protonSRCfinal.pdf
EVA-SRC-discoverbnl.pdf
Protons Pair Up with Neutrons (from BNL News, pdf)
Science Magazine: Probing Cold Dense Nuclear Matter (pdf)
Nature Physics (Research Highlights: Unequal pairs (pdf))
Protons Pair Up With Neutrons, EurekAlert, May 29, 2008
Jefferson Lab in the News: Nuclear Pairs
Brookhaven National News: Protons Pair Up with Neutrons
Press release from Kent State University
ScienceDaily (Penn State University)
ScienceDaily (Penn State University)
ScientistLive (Penn State University)
On Target
Physics Today (July, 2008)
PHYSORG.com
NFC (in hebrew)
Tel Aviv University Press (in hebrew)
CERN Courier article: "Protons and neutrons certainly prefer each other's company" (July, 2008)

R&D magazine
The A to Z of Nanotechnology
analitica-world
Matter News
Softpedia
News @ Old Dominion

from http://tauphy.tau.ac.il/eip

Some Conclusions

- We learned to how to probe directly the short range correlations in nuclei with relative momenta 250- 600 MeV/c

- SRC’s are dynamically high-density fluctuations with strong angular correlations

- There is a strong suppression (factor of 20) of pp and nn SRCs as compared to pn SRCs

- this disparity is related to the dominance of the strong tensor force at intermediate to short distances

Explanation lies in the dominance of the tensor part in the NN interaction

$$V_{NN}(r) \approx V_c(r) + V_t(r) \cdot S_{12}(r) + V_{LS} \cdot \vec{L}\vec{S}$$

$$S_{12} = 3(\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) - \sigma_1\sigma_2$$

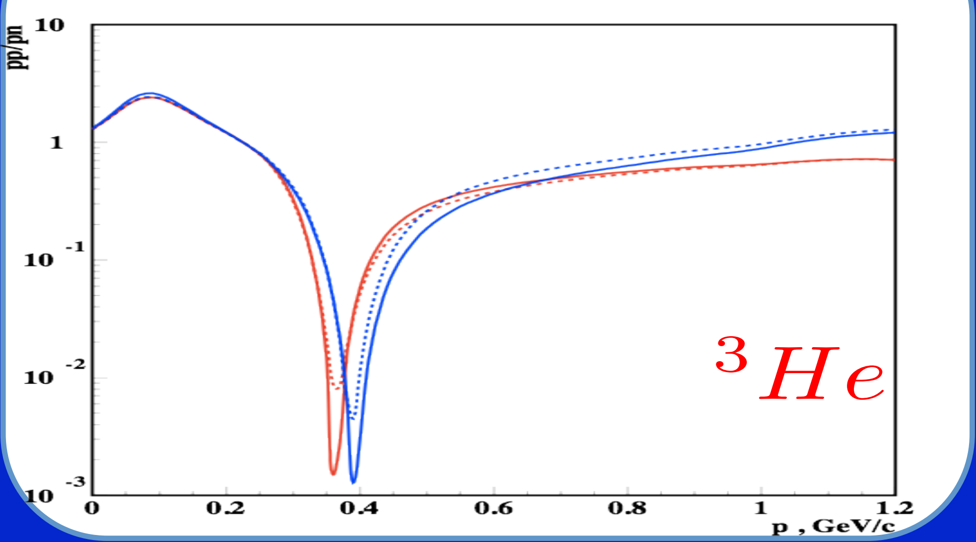
$$S_{12}|pp\rangle = 0$$

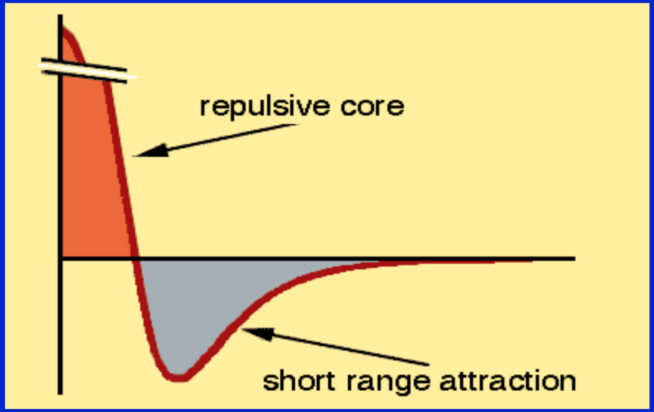
$$S_{12}|nn\rangle = 0$$ Isospin 1 states

$$S_{12}|pn\rangle = 0$$

$$S_{12}|pn\rangle \neq 0$$ Isospin 0 states

M.S, Abrahamyan, Frankfurt,Strikman PRC,2005



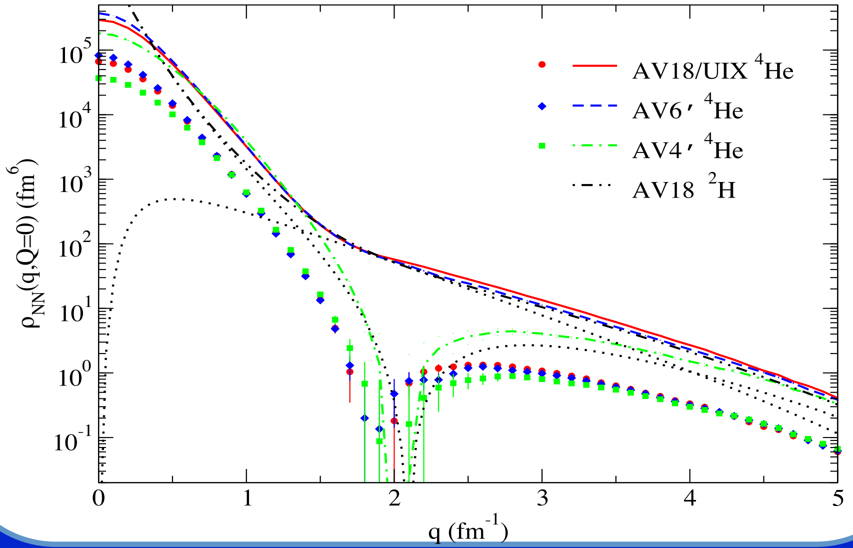


Explanation lies in the dominance of the <u>tensor</u> part in the NN interaction

$$V_{NN}(r) \approx V_c(r) + V_t(r) \cdot S_{12}(r) + V_{LS} \cdot \vec{L}\vec{S}$$

$$S_{12} = 3(\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) - \sigma_1 \sigma_2$$

Sciavilla, Wiringa, Pieper, Carlson PRL,2007



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Isospin 1 states

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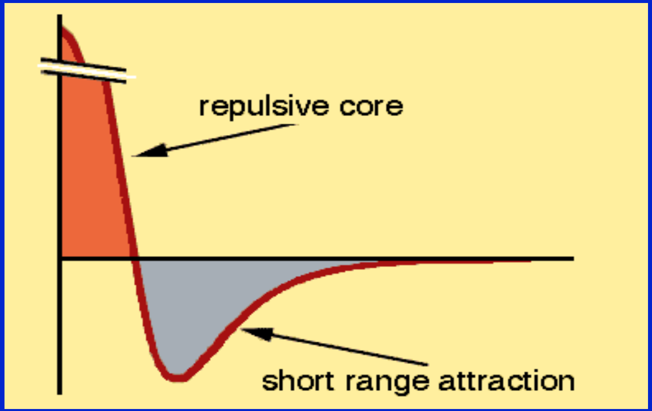
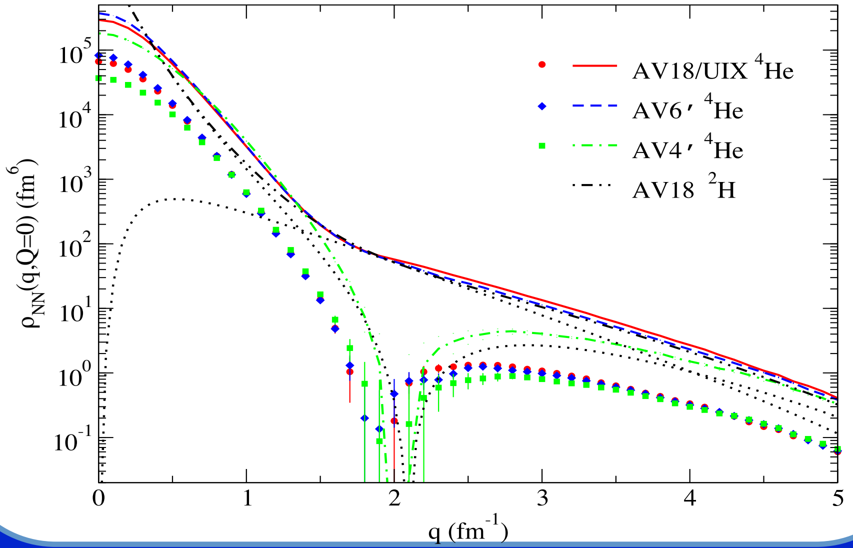


- Nuclear momentum distribution at $k > k_F$ should reflect the dynamics of V_{NN} rather than V_{Nucl}

$$V_{NN}(r) \approx V_c(r) + V_t(r) \cdot S_{12}(r) + V_{LS} \cdot \vec{L}\vec{S}$$

$$S_{12} = 3(\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) - \sigma_1\sigma_2$$


Sciavilla, Wiringa, Pieper, Carlson PRL,2007

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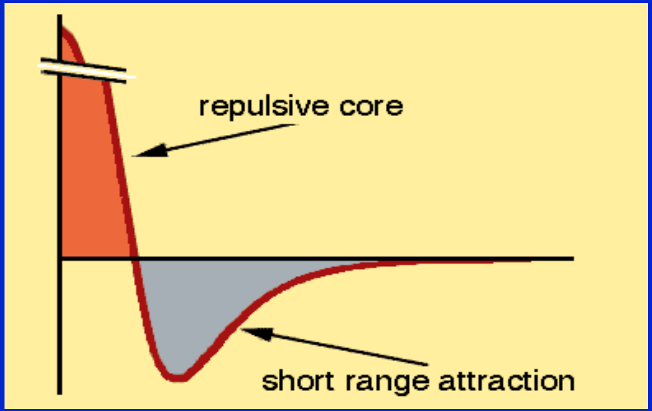


- Dominance of pn short range correlations as compared to pp and nn SRCs

2006-2008s

- Dominance of NN Tensor as compared to the NN Central Forces at <= 1fm

- Two New Properties of High Momentum Component

- Energetic Protons in Neutron Rich Nuclei

- Implications

EMC-SRC - correlation

Neutrino-Nuclei Interactions: NuTeV anomaly

Protons in the Neutron Stars

Short-Range NN Correlations in Nuclei: Theory

- Dominance of NN Correlations

(Lippmann-Schwinger Equation)

$$\begin{aligned}(E_B - \frac{k^2}{2m} - \sum_{i=2,..A} T_i)\psi_A &= \sum_{i=2,...A} \int V(k-k_i')\psi_A(k,k_i',...k_j,...k_A)\frac{d^3k_i'}{(2\pi)^3} \\ &+ \sum_{i=2,...A} \int V(k_i-k_i')\psi_A(k,k_i',...k_j,...,k_A)\frac{d^3k_i'}{(2\pi)^3},\end{aligned}$$

-if the potential decreases at large k, like $V(k) \sim \frac{1}{k^n}$ and $n > 1$

- then the k dependence of the wave function for $k^2/2m_N \gg |E_B|$

$$\psi_A \sim \frac{V_{NN}(k)}{k^2} f(k_3, \ldots k_A)$$

- The same is true for relativistic equations as:

  Bethe-Salpeter or Weinberg Light Cone Equations

- From $\psi_A \sim \frac{V_{NN}(k)}{k^2} f(k_3, \ldots k_A)$ follows

$\text{at } p > k_F$

$$n^A(p) \sim a_{NN}(A) \cdot n_{NN}(p)$$

Frankfurt, Strikman Phys. Rep, 1988
Day,Frankfurt, Strikman, MS, Phys. Rev. C 1993

- Experimental observations

Egiyan et al, 2002,2006
Fomin et al, 2011

- Isospin composition ?

- From $\psi_A \sim \frac{V_{NN}(k)}{k^2} f(k_3, \ldots k_A)$ follows

at $p > k_F$

$$n^A(p) \sim a_{NN}(A) \cdot n_{NN}(p) \qquad (1)$$

- Dominance of pn Correlations
(neglecting pp and nn SRCs)

$$n_{NN}(p) \approx n_{pn}(p) \approx n_{(d)}(p) \qquad (2)$$

- Define momentum distribution of proton & neutron

$$n^A(p) = \frac{Z}{A} n_p^A(p) + \frac{A-Z}{A} n_n^A(p) \qquad (3)$$

$$\int n_{p/n}^A(p) d^3p = 1$$

- Now define

$$I_p = \frac{Z}{A} \int_{k_F}^{600} n_p^A(p) d^3p \qquad I_n = \frac{A-Z}{A} \int_{k_F}^{600} n_n^A(p) d^3p$$

- and observe that in the limit of no pp and nn SRCs

$$I_p = I_n$$

- Neglecting CM motion of SRCs

$$\frac{Z}{A} n_p^A(p) \approx \frac{A-Z}{A} n_n^A(p)$$

First Property: Approximate Scaling Relation

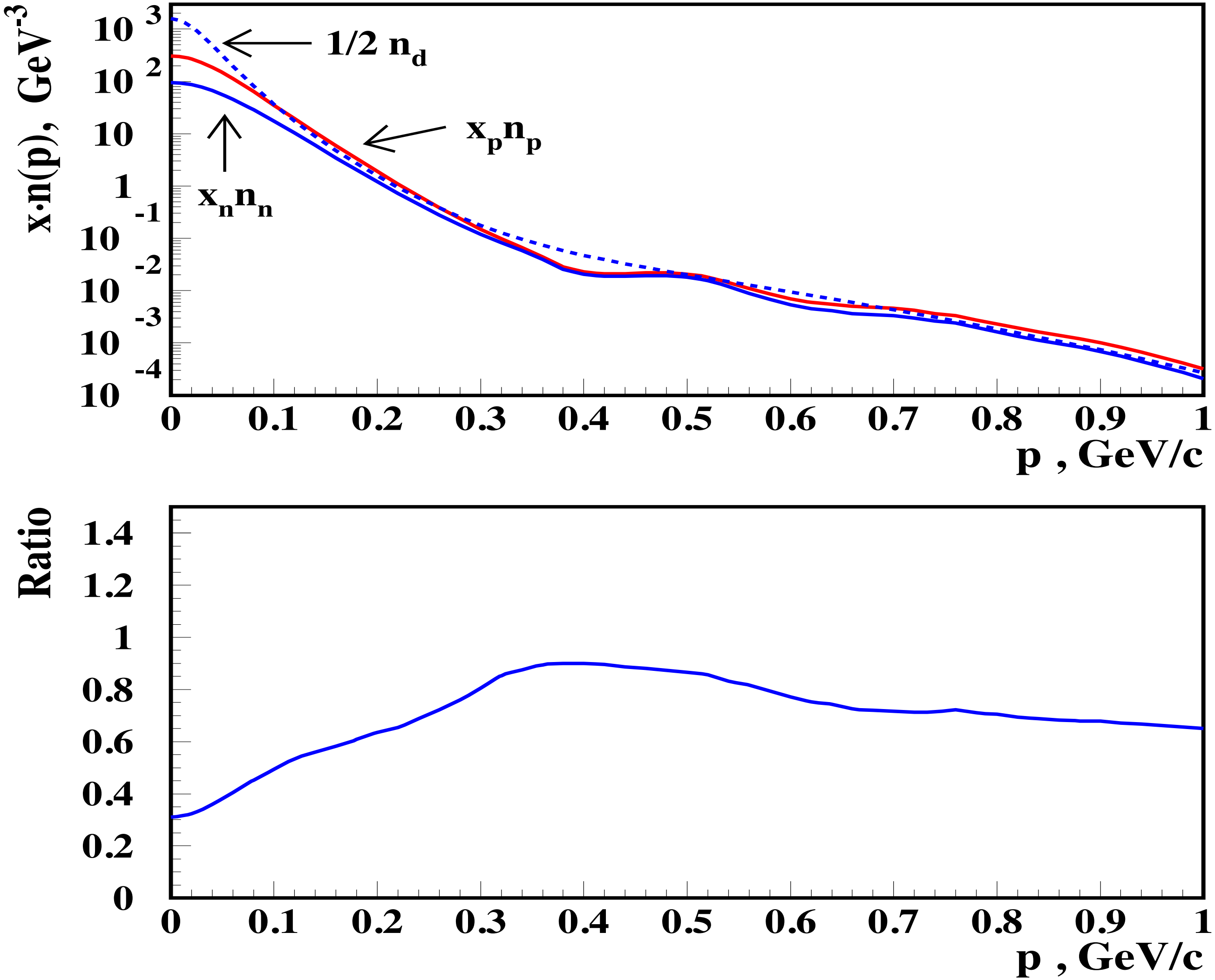
-if contributions by pp and nn SRCs are neglected and the pn SRC is assumed at rest

- for $\sim k_F - 600$ MeV/c region:

$$\boxed{x_p \cdot n_p^A(p) \approx x_n \cdot n_n^A(p)}$$

where $x_p = \frac{Z}{A}$ and $x_n = \frac{A-Z}{A}$.

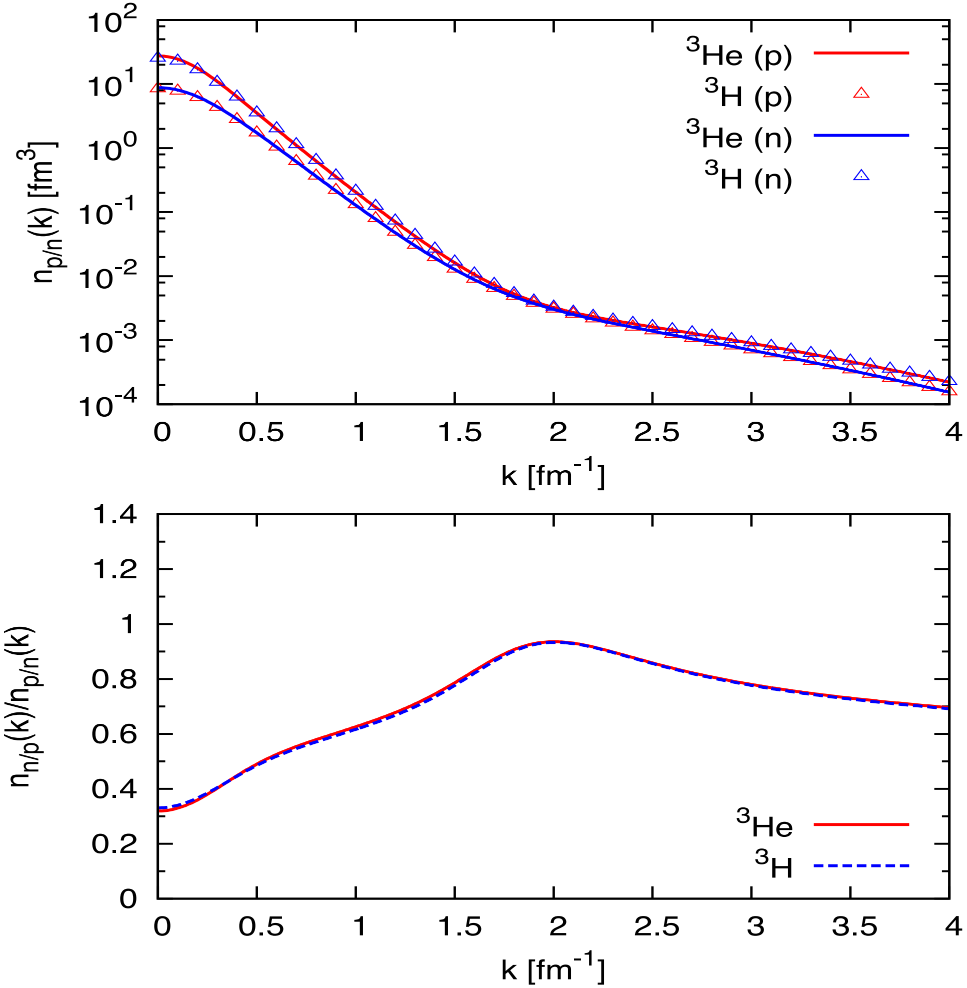
Realistic 3He Wave Function: Faddeev Equation



MS,arXiv:1210.3280

Realistic 3He Wave Function: Correlated Gaussian Basis

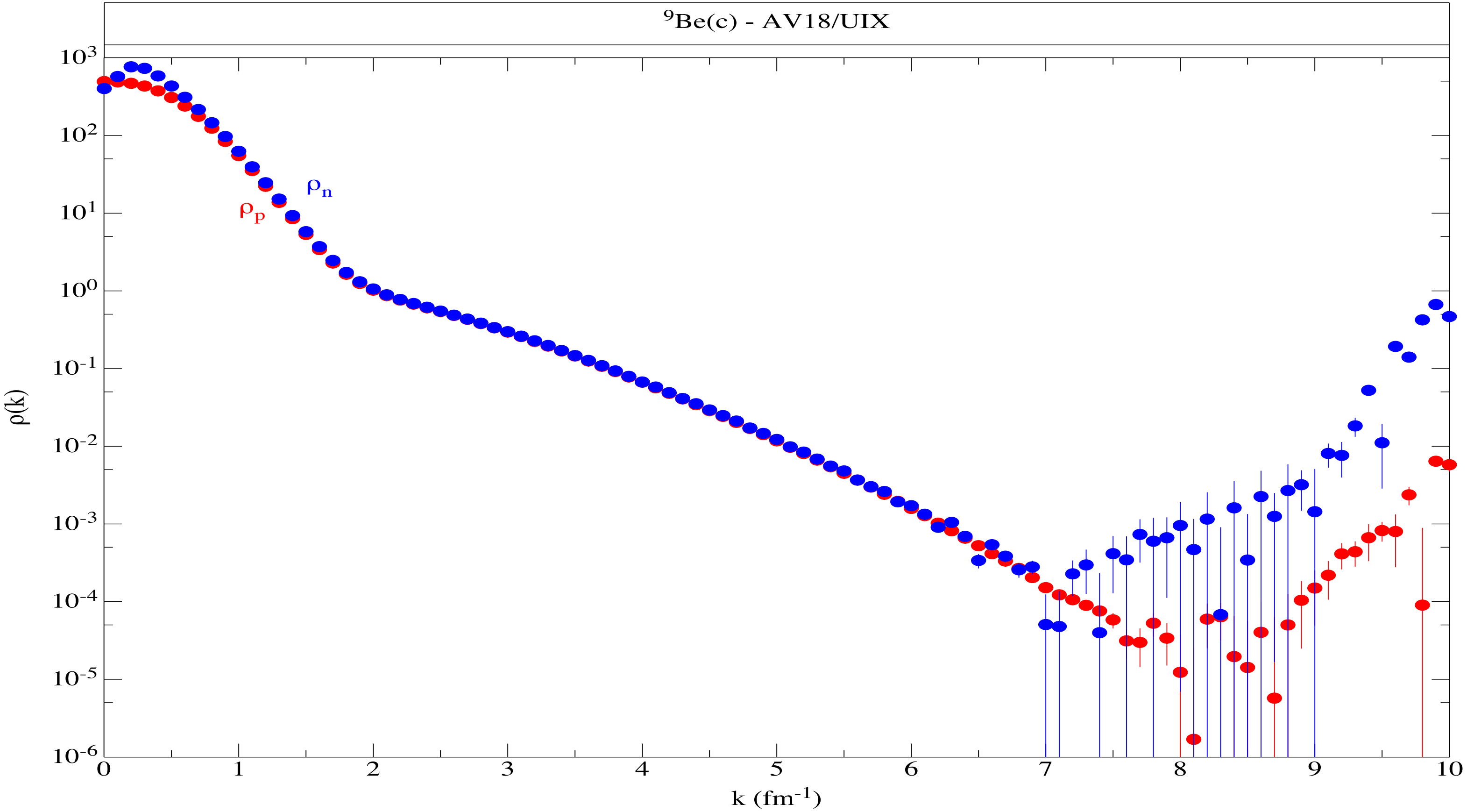
T.Neff & W. Horiuchi



April 2013

Be9 Variational Monte Carlo Calculation:

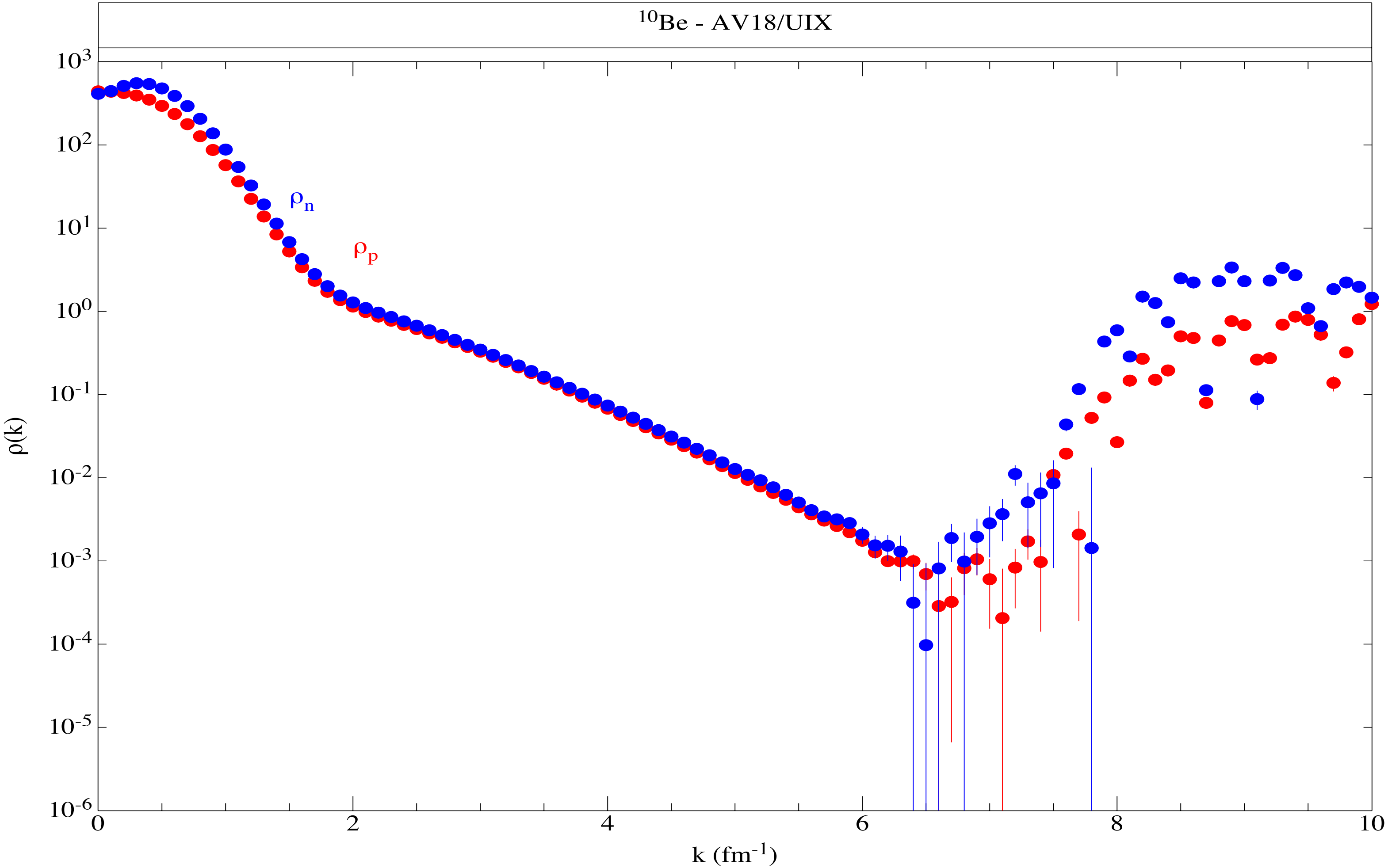
Robert Wiringa http://www.phy.anl.gov/theory/research/momenta/



Tanks to S. Pastore

Be10 Variational Monte Carlo Calculation:

Robert Wiringa



Second Property:

Using Definition: $n^A(p) = \frac{Z}{A} n_p^A(p) + \frac{A-Z}{A} n_n^A(p)$

Approximations: $n^A(p) \sim a_{NN}(A) \cdot n_{NN}(p)$

$n_{NN}(p) \approx n_{pn}(p) \approx n_{(d)}(p)$

One Obtains

$$x_p \cdot n_p^A(p) \approx x_n \cdot n_n^A(p) \quad \approx \frac{1}{2} a_{NN}(A, y) n_d(p)$$

where $y = |1 - 2x_p| = |x_n - x_p|$

- $a_{NN}(A, 0)$ corresponds to the probability of pn SRC in symmetric nuclei
- $a_{NN}(A, 1) = 0$ according to our approximation of neglecting pp/nn SRCs

Second Property: Fractional Dependence of High Momentum Component

$$a_{NN}(A,y) \approx a_{NN}(A,0) \cdot f(y)$$ with $f(0) = 1 \text{ and } f(1) = 0$

$$f(|x_p - x_n|) = 1 - \sum_{j=1}^{n} b_i |x_p - x_x|^i \text{ with } \sum_{j=1}^{n} b_i = 0$$

In the limit $\sum_{j=1}^{n} b_i |x_p - x_x|^i \ll 1$ Momentum distributions of p & n are inverse proportional to their fractions

$$\boxed{n^A_{p/n}(p) \approx \frac{1}{2x_{p/n}} a_2(A,y) \cdot n_d(p)}$$

Observations: High Momentum Fractions

if $n^{A}_{p/n}(p) \approx \frac{1}{2x_{p/n}} a_2(A,y) \cdot n_d(p)$

$$P_{p/n}(A,y) = \frac{1}{2x_{p/n}} a_2(A,y) \int\limits_{k_F}^{\infty} n_d(p) d^3p$$

A	Pp(%)	Pn(%)
12	20	20
27	23	22
56	27	23
197	31	20

M.S. 2012, Nucl-Th

Observations: High Momentum Fractions

$$P_{p/n}(A,y) = \frac{1}{2x_{p/n}} a_2(A,y) \int_{k_F}^{\infty} n_d(p) d^3p$$

Checking for He3

Energetic Neutron

$E^{p}_{kin} = 14$ MeV (p= 157 MeV/c)

$E^{n}_{kin} = 19$ MeV (p= 182 MeV/c)

Energetic Neutron
(Neff & Horiuchi)

$E^{p}_{kin} = 13.97$ MeV

$E^{n}_{kin} = 18.74$ MeV

VMC Estimates: Robert Wiringa

Table 1: Kinetic energies (in MeV) of proton and neutron

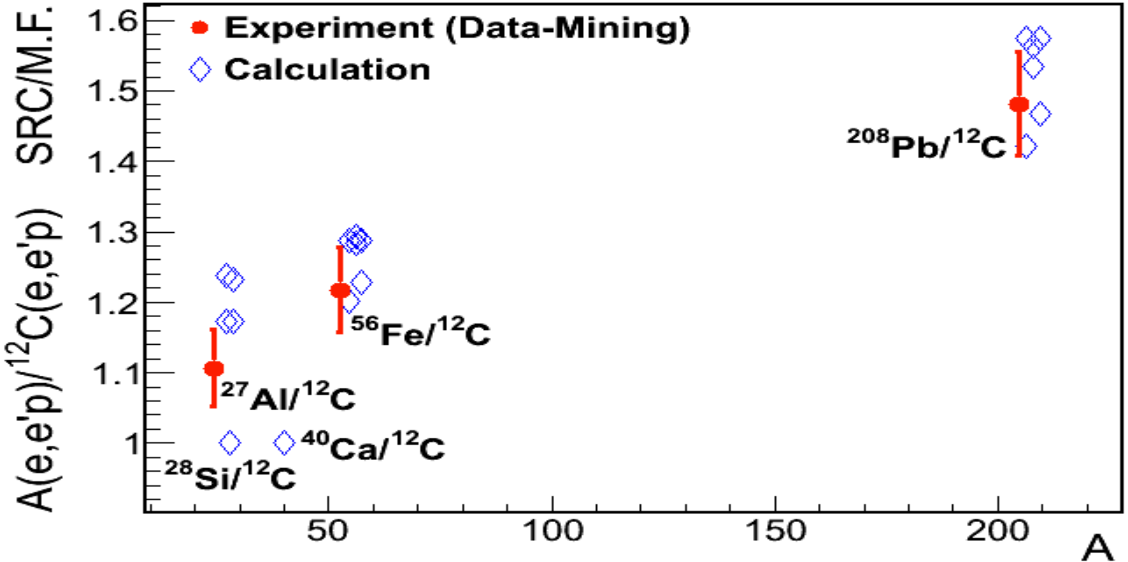
A	y	E^p_{kin}	E^n_{kin}	$E^p_{kin} - E^n_{kin}$
^{8}He	0.50	30.13	18.60	11.53
^{6}He	0.33	27.66	19.06	8.60
^{9}Li	0.33	31.39	24.91	6.48
^{3}He	0.33	14.71	19.35	-4.64
^{3}H	0.33	19.61	14.96	4.65
^{8}Li	0.25	28.95	23.98	4.97
^{10}Be	0.2	30.20	25.95	4.25
^{7}Li	0.14	26.88	24.54	2.34
^{9}Be	0.11	29.82	27.09	2.73
^{11}B	0.09	33.40	31.75	1.65

Implications: Protons are more energetic in neutron reach Nuclei

- Can be checked in A(e,e'p) Reactiosn (Or Hen & Eli Piasetzky)

$$R_A = \frac{\int_{k_F}^{\infty} \sigma_A(p_{in}) d^3 p_{in}}{\int_{0}^{k_F} \sigma_A(p_{in}) d^3 p_{in}}$$

$$R = \frac{R_A}{R_{C12}}$$



Implications: Energetic Protons in neutron rich Nuclei

Implications: Protons are more modified in neutron rich nuclei

u-quarks are more modified then d-quarks in Large A Nuclei

- Flavor Dependence of EMC effect
- Different explanation of NuTev Anomaly
- Can be checked in neutrino-nuclei or in pvDIS processes

What these studies can tell us about structure of Neutron Stars ?

Number of nucleons beyond the Fermi Energy

$$P_{p/n}(A,y) = \frac{1}{2x_{p/n}} a_2(A,y) \int\limits_{k_F}^{\infty} n_d(p) d^3p$$

$$a_2(A,y) = a_2(\rho,y)$$

$$a_2(\rho,y) \mid_{\rho\to\infty} = ?$$

Implications: For Nuclear Matter

$$P_{p/n}(A,y) = \frac{1}{2x_{p/n}} a_2(A,y) \int\limits_{k_F}^{\infty} n_d(p) d^3p$$

Table 1: The results for $a_2(A,y)$

A	y	This Work	Frankfurt et al	Egiyan et al	Famin et al
^{3}He	0.33	2.07±0.08	1.7±0.3		2.13±0.04
^{4}He	0	3.51±0.03	3.3±0.5	3.38±0.2	3.60±0.10
^{9}Be	0.11	3.92±0.03			3.91±0.12
^{12}C	0	4.19±0.02	5.0±0.5	4.32±0.4	4.75±0.16
^{27}Al	0.037	4.50±0.12	5.3±0.6		
^{56}Fe	0.071	4.95±0.07	5.6±0.9	4.99±0.5	
^{64}Cu	0.094	5.02±0.04			5.21±0.20
^{197}Au	0.198	4.56±0.03	4.8±0.7		5.16±0.22

$$a_2(A,y) \equiv a_2(\rho,y)\,,\; y = |1-2x_p|\,,\; x_p \equiv \frac{Z}{A}$$

(1) $$\boxed{a_2(A,y) = a_2^{sym}(A)\cdot f(y)}$$

Parametric Form

(2) For $a_2^{sym}(A)$ we analyze data for symmetric nuclei

and for other A's use the relation $$\boxed{a_2^{sym}(A) = C\cdot\langle\rho^2_{A,sym}\rangle}$$

where

$$\langle\rho^2_{A,sym}\rangle = \frac{1}{A}\int\rho_{A,sym}(r)^2 d^3r$$

(3) Neglecting contributions due to pp and nn SRCs one obtains boundary conditions

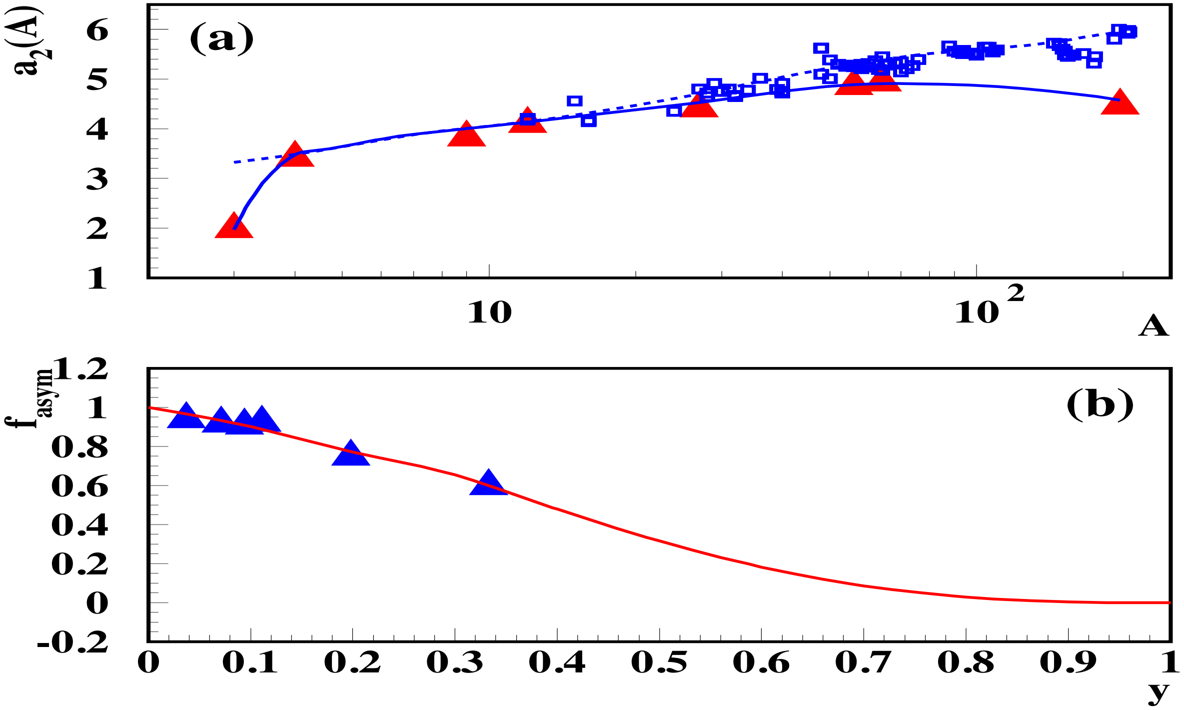
$$f(0) = 1 \text{ and } f(1) = 0$$

M. McGauley, MS Feb. 2011
arxiv 1102.3973

Implications: For Nuclear Matter

$$a_2(A, y) = a_2(A, 0) f(y)$$

$$a_2(A, 0) = C \int \rho_A^2(r) d^3r$$

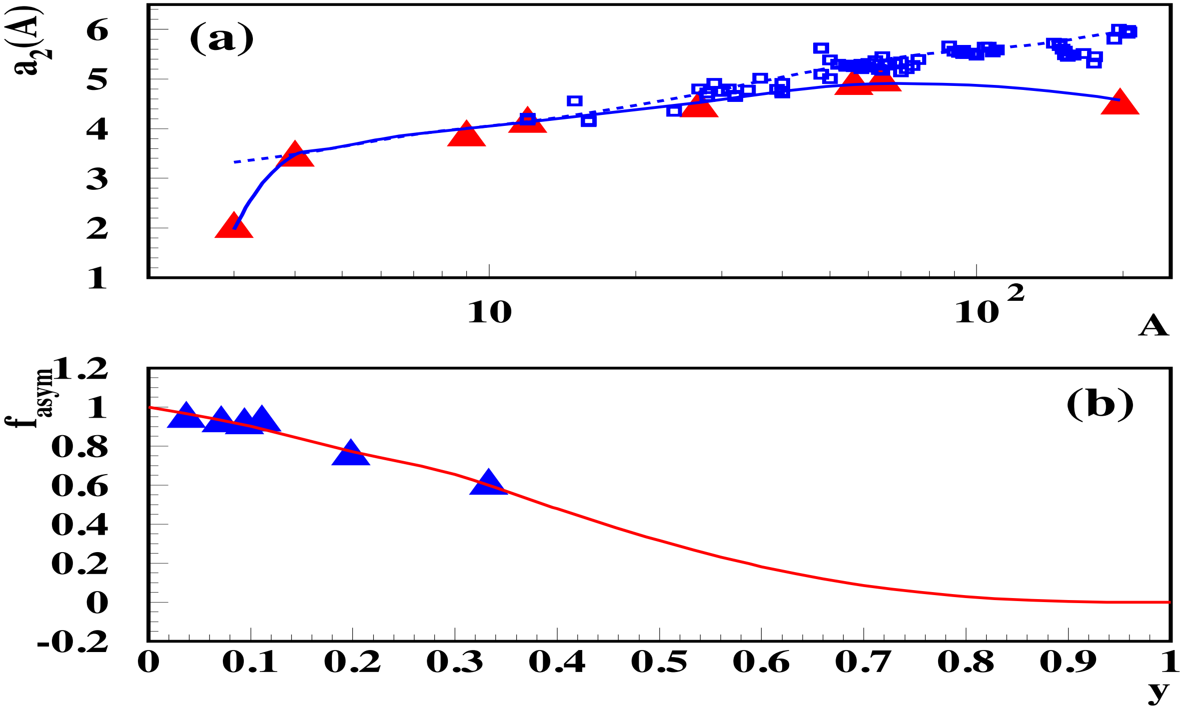


$$C = 49.1 \pm 2.6$$

Implications: For Nuclear Matter

$$a_2(A,y) = a_2(A,0)f(y)$$

Fitting $f(y)$



- *6 data points*
- *2 boundary conditions due to the neglection of pp/nn SRCs*

  $f(0) = 1$ and $\mathrm{f}(1) = 0$

- *2 more boundary conditions due to*

  $y \to 1$ and $y \to 0$ corresponds to $A \to \infty$

  $f'(0) = f'(1) = 0$

- *1 more positiveness of f(y)*

$$f(y) \approx (1 + (b-3)y^2 + 2(1-b)y^3 + by^4) \qquad b \approx 3$$

Extrapolation to infinite and superdense nuclear matter

$$a_2(A, y) = a_2^{sym}(A) \cdot f(y)$$ with $$a_2^{sym}(A) = C \cdot \langle \rho^2_{A,sym} \rangle$$

For the symmetric nuclear matter at saturation densities ρ_0
using: $R = r_0 \cdot A^{\frac{1}{3}}$ we obtain:

$$\langle \rho^2 \rangle^{INM}_{sym} = \frac{1}{A} \int \rho^2_{A,sym}(r) d^3 r = \frac{4\pi}{3} \rho_0^2 r_0^3 \approx 0.143 \ fm^{-3}$$

$$\boxed{a_2(\rho_0, 0) \approx 7.03 \pm 0.41}$$

compare

$$a_2(\rho_0, 0) \approx 8 \pm 1.24$$

C.Ciofi degli Atti, E. Pace, G.Salme, PRC 1991

Asymmetric and superdense nuclear matter:

$$a_2(\rho, y) = \langle \rho^2 \rangle_{sym}^{INM} \cdot f(y)$$

Consider β equilibrium $e - p - n$ superdense asymmetric nuclear matter at the threshold of URCA processes $x_p = \frac{1}{9}$ $(y = \frac{7}{9})$.

At $x_p < \frac{1}{9}$ the URCA processes

$$n \to p + e^- + \bar{\nu}_e, \qquad p + e^- \to n + \nu_e$$

will stop in the standard model of superdense nuclear matter consisting of degenerate protons and neutrons.

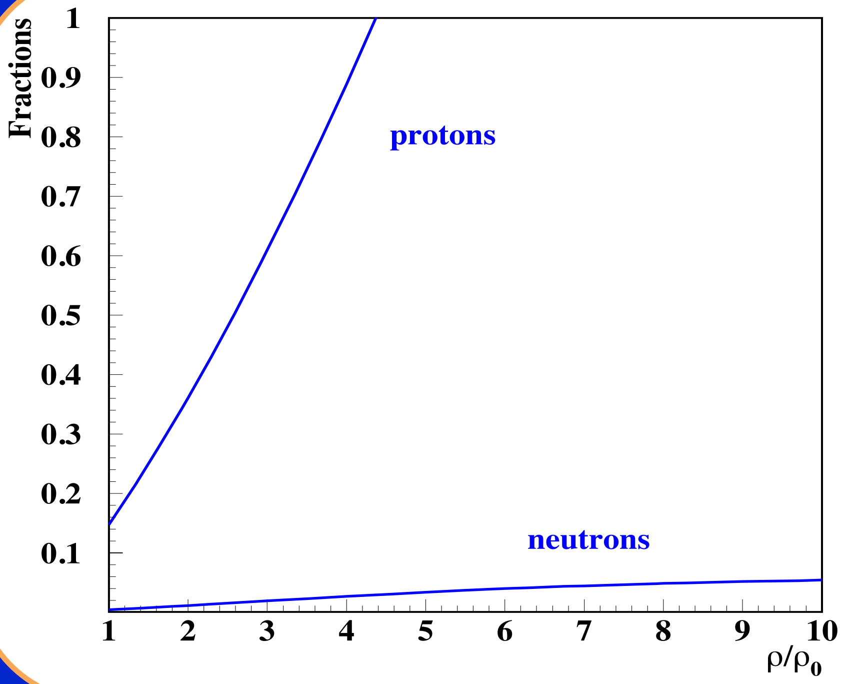
Implications: For Nuclear Matter

$$P_{p/n}(A,y) = \frac{1}{2x_{p/n}} a_2(A,y) \int_{k_F}^{\infty} n_d(p) d^3p$$

For $x_p = \frac{1}{9}$ and $y = \frac{7}{9}$
and using $k_{F,N} = (3\pi^2 x_N \rho)^{\frac{1}{3}}$

For $x_p = \frac{1}{9}$ and $y = \frac{7}{9}$
and using $k_{F,N} = (3\pi^2 x_N \rho)^{\frac{1}{3}}$

$$P_{p/n}(\rho, y) = \frac{a_2(\rho,y)}{2x_{p/n}} \int_{k_F} n_d(k) d^3k$$



Some Possible Implication of our Results

Cooling of Neutron Star:

Large concentration of the protons above the Fermi momentum will allow the condition for Direct URCA processes $p_p + p_e > p_n$ to be satisfied even if $x_p < \frac{1}{9}$. This will allow a situation in which intensive cooling of the neutron stars will be continued well beyond the critical point $x_p = \frac{1}{9}$.

Superfluidity of Protons in the Neutron Stars:

Transition of protons to the high momentum spectrum will smear out the energy gap which will remove the superfluidity condition for the protons. This will also result in significant changes in the mechanism of generation of neutron star magnetic fields.

Protons in the Neutron Star Cores:

The concentration of protons in the high momentum tail will result in proton densities $\rho_p \sim p_p^3 \gg k_{F,p}^3$. This will result in an equilibrium condition with ”neutron skin” effect in which large concentration of protons will populate the core rather than the crust of the neutron star. This situation may provide very different dynamical conditions for generation of magnetic fields of the stars.

Isospin Locking and Large Masses of Neutron Stars

With an increase of the densities more and more protons move to the high momentum tail where they are in short range tensor correlations with neutrons. In this case on will expect that high density nuclear matter will be dominated by configurations with quantum numbers of tensor correlations $S = 1$ and $I = 0$. In such scenario protons and neutrons at large densities will be locked in the NN iso-singlet state. Such situation will double the threshold of inelastic excitation from $NN \rightarrow N\Delta$ to $NN \rightarrow \Delta\Delta(NN^*)$ transition thereby stiffening the equation of the state. This situation my explain the observed neutron star masses in Ref.[?] which are in agreement with the calculation of equation state that include only nucleonic degrees of freedom

Limitation of the Model

- pp/nn Correlations are neglected

- pn SRC is at Rest

- 3N SRCS

- non-nucleonic component of SRCs

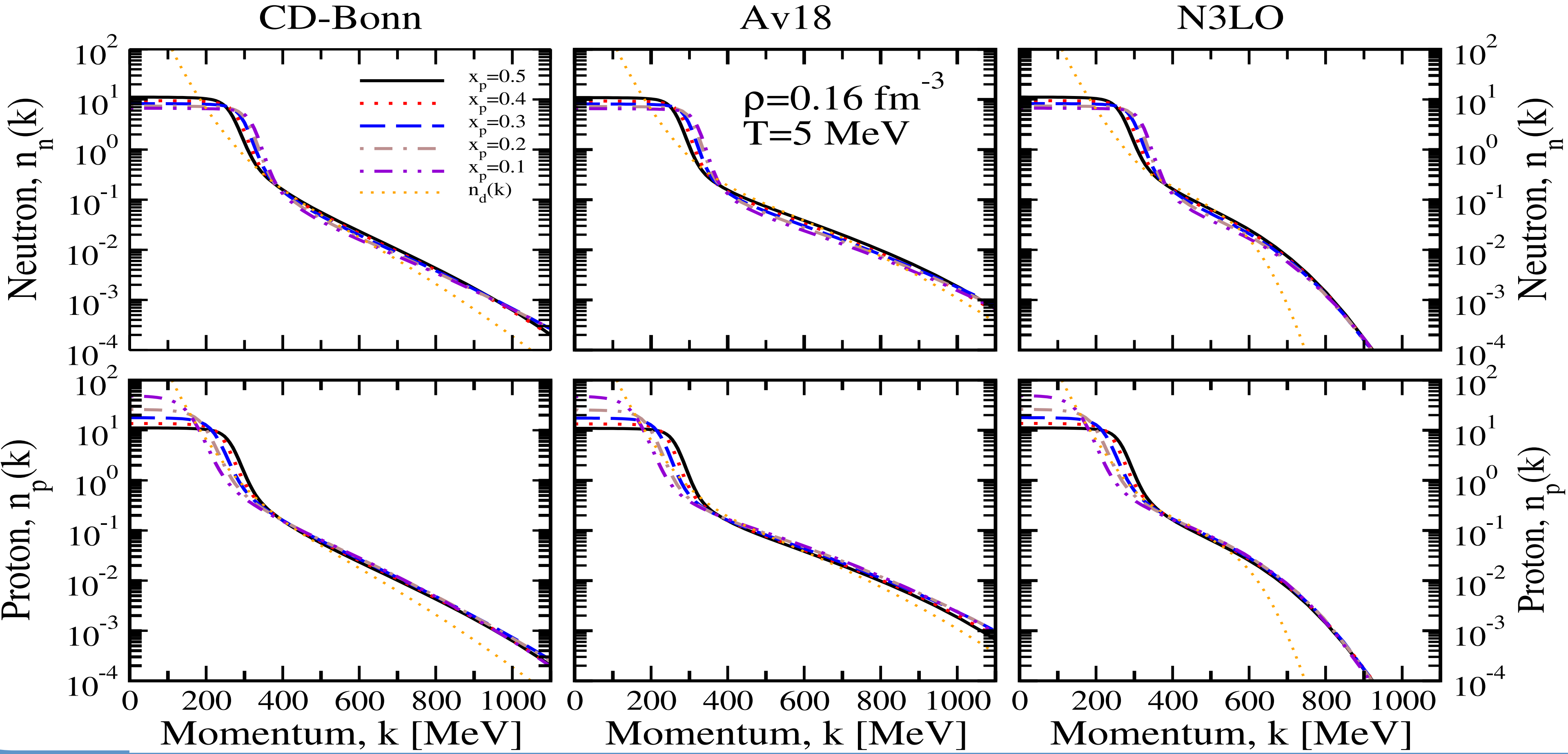
Identical Effects on proton and neutron distributions?

$$x_p^\gamma \cdot n_p^A(p) \approx x_n^\gamma \cdot n_n^A(p)$$

$$\gamma < 1$$

$$n_{p/n}^A(p) \approx \frac{1}{2x_{p/n}^\gamma} a_2(A,y) \cdot n_d(p)$$

A.Rios, A. Polls and W. H. Dickhoff,
PRC 79, 064308 (2009).
Private Communication



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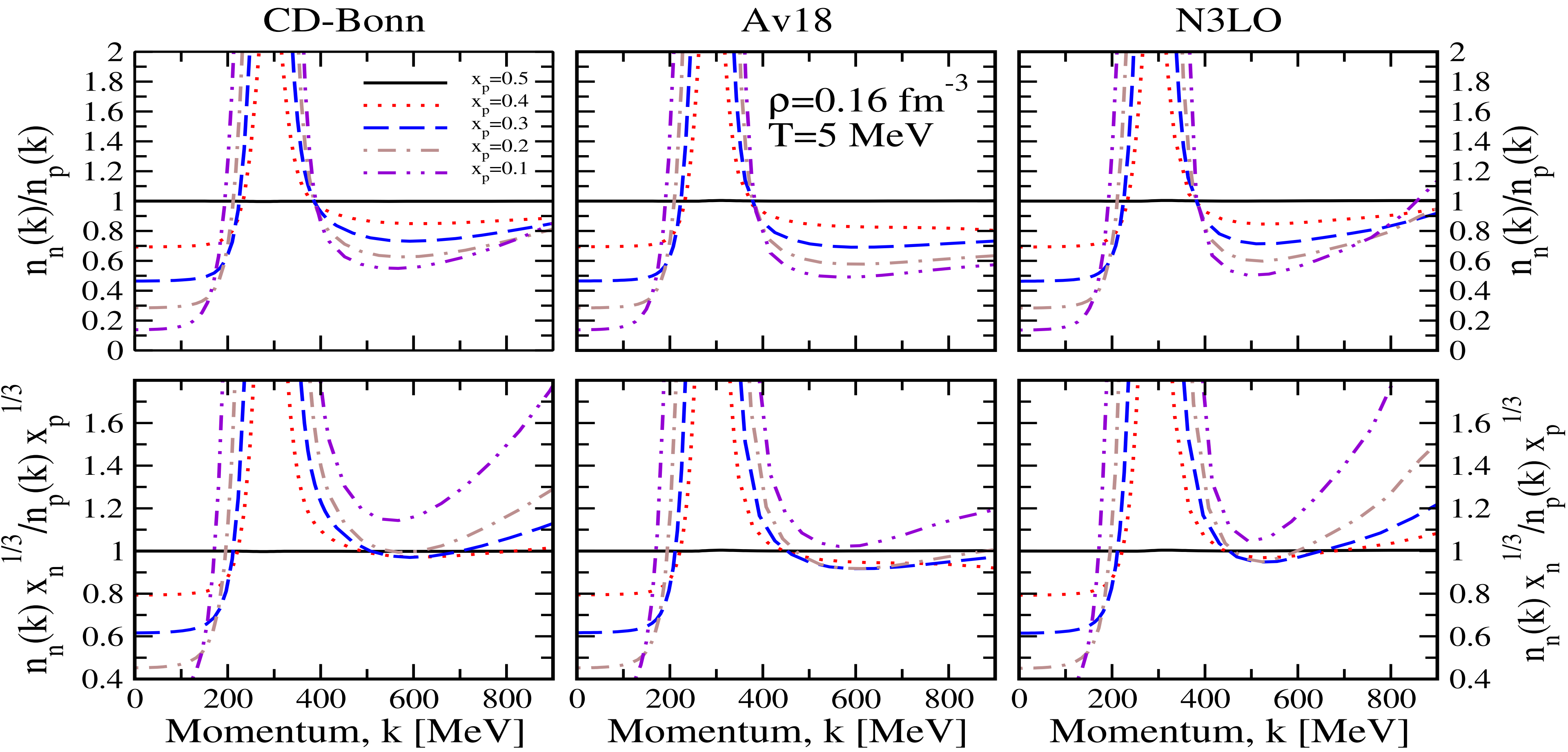


Is the Observed Effects Universal for Two Component Asymmetric Fermi Systems?

- Start with Two Component Asymmetric Degenerate Fermi Gas

- Asymmetric: $\rho_1 << \rho_2$

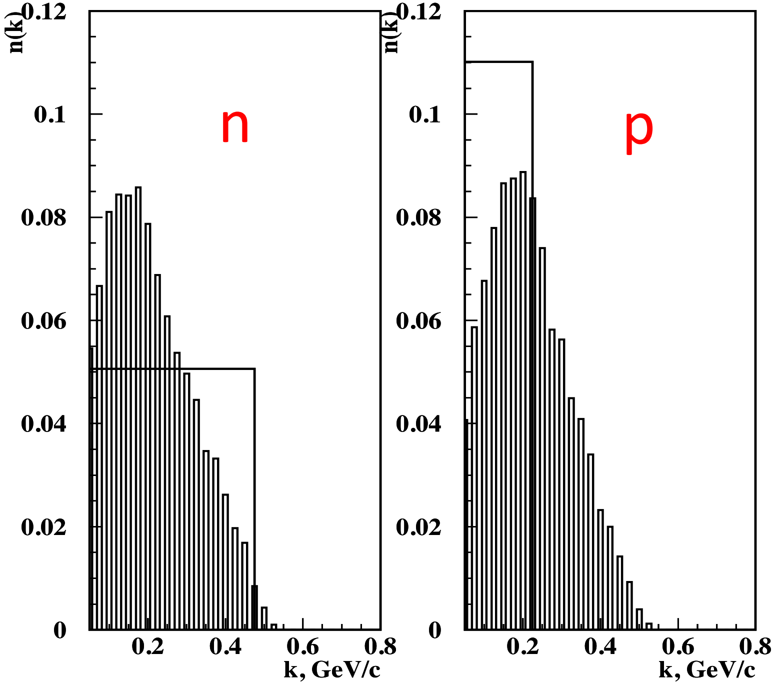
- Switch on the short-range interaction between two-component

- While interaction between each components is weak

- Spectrum of the small component gas will strongly deforme

Cold Atoms

Is the Observed Effect Universal to Two Component Asymmetric Fermi Systems?

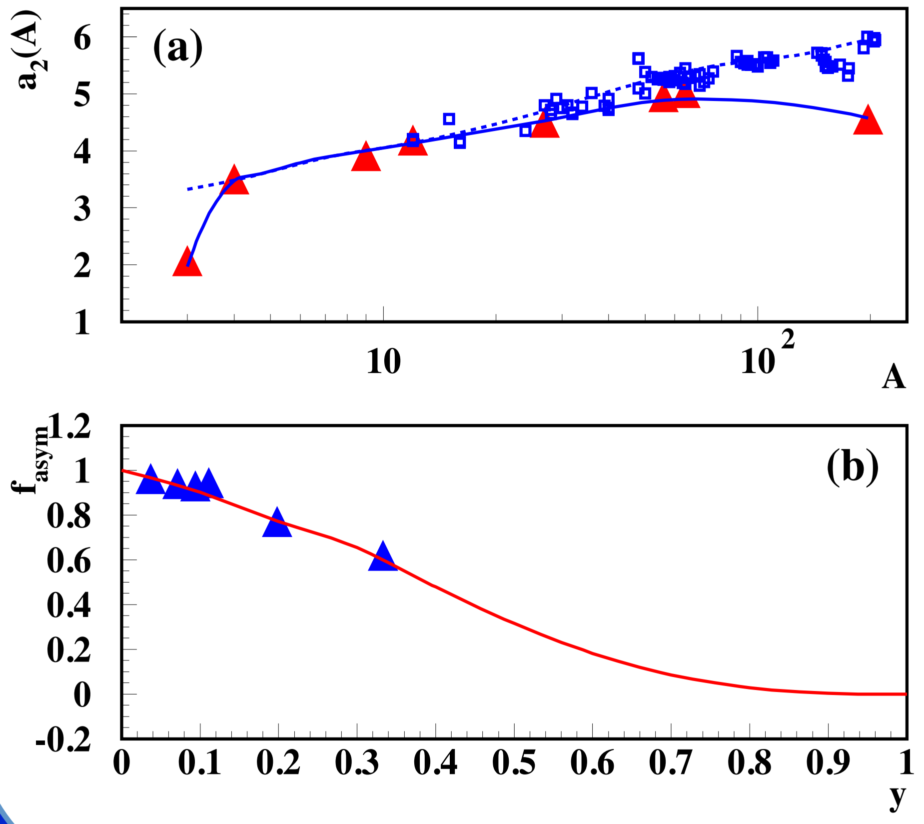


Conclusions and Outlook

- We observe two new properties of high momentum distribution of proton and neutron in nuclei
- Predicting more energetic/virtual protons in neutron reach matter

- Explains the form of the EMC-SRC correlation *(preliminary)*
- Explains NuTeV anomaly *(preliminary)*
- May have strong implication for protons in neutron stars *Cooling & Magnetic Fields*

Some Outlook



- *More Symmetric Nuclei*
- *Measurements of pp/nn*
  - *3N SRCS*
- *Nuclei with large asymmetry parameters*
- *Break-down of nucleon framework*