Superfast Quarks

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A(e,e') at High Energy → **PDFs at x>1 Superfast quarks**

PN12, The Physics of Nuclei with 12 GeV Electrons Workshop, Nov. 1, 2004

"Beam in 2009 or it's free"

Superfast Quarks, Short Range Correlations and QCD at High Density

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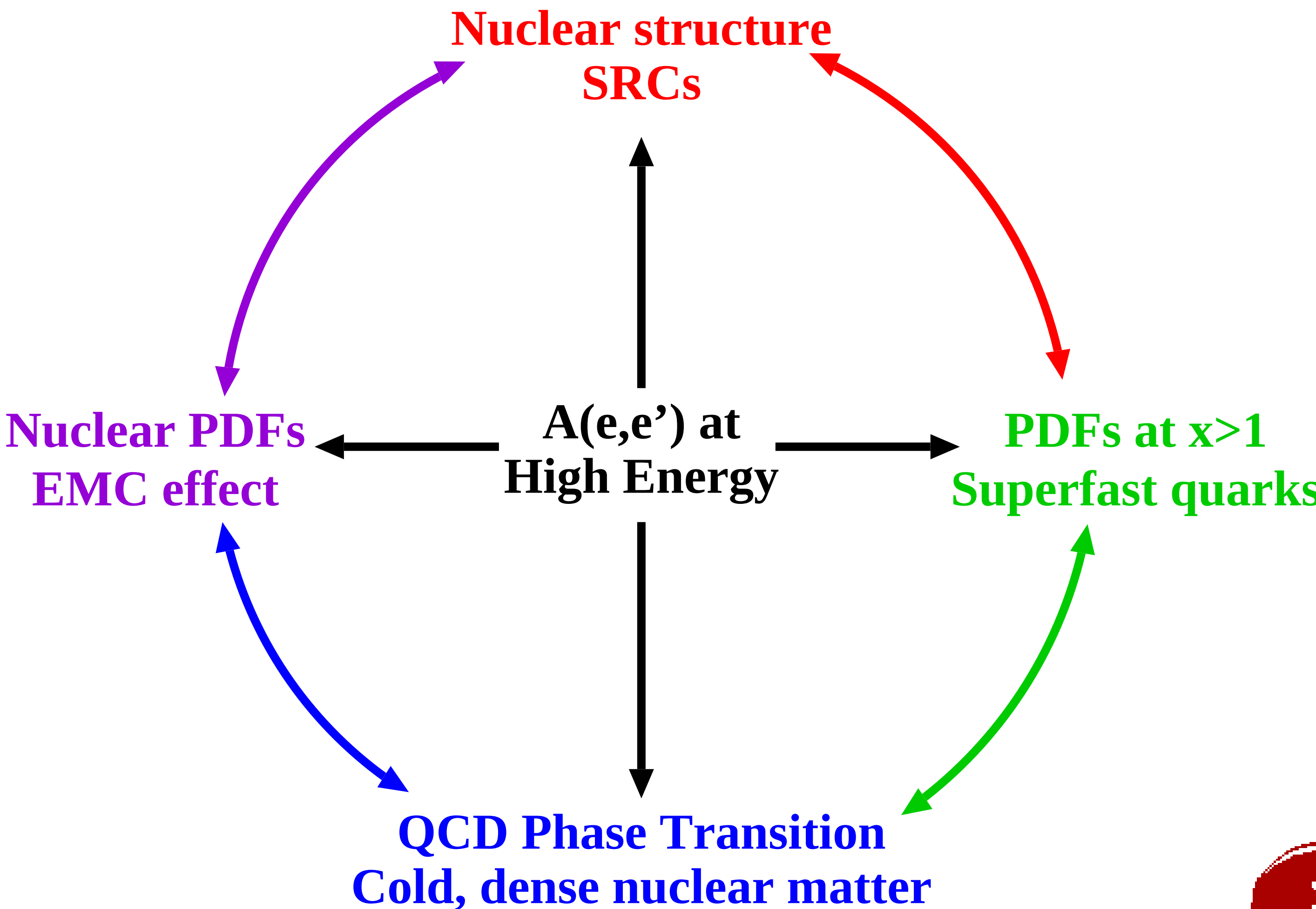

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Jeffylab-12
"Beam in 2009 or it's free"

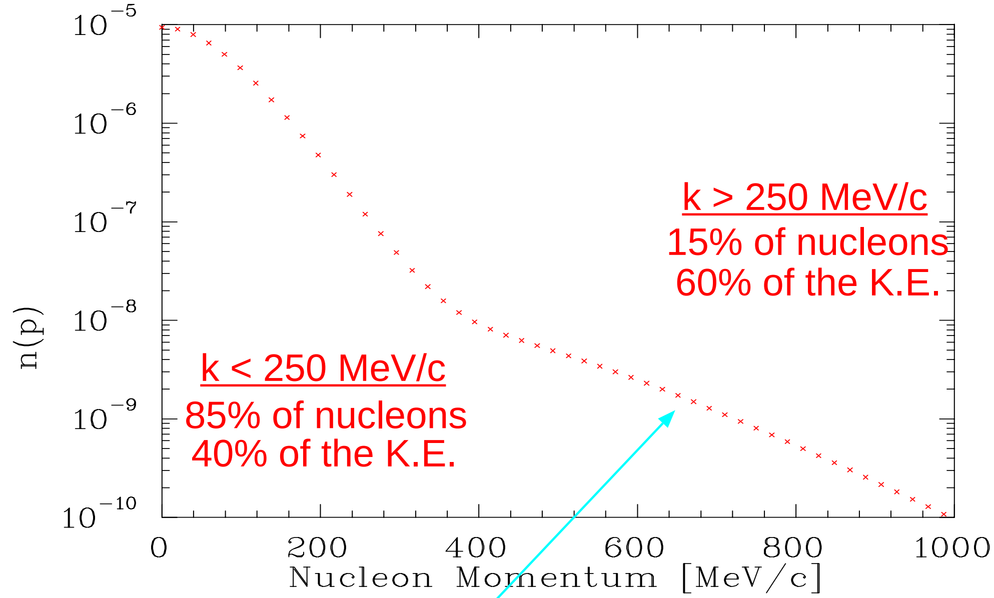
Short Range Correlations (SRCs)

Mean field contributions: $k < k_F$ — Well understood

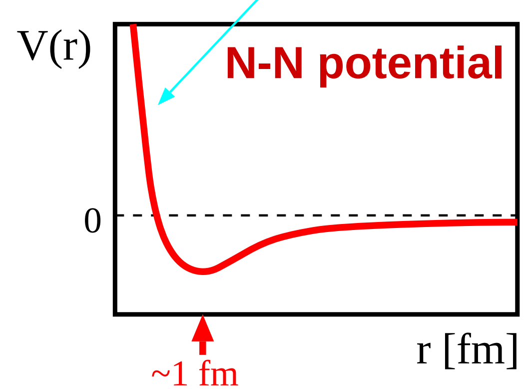
High momentum tails: $k > k_F$ — Calculable for few-body nuclei, nuclear matter. Dominated by two-nucleon short range correlations.

Calculation of proton momentum distribution in ^{4}He

Wiringa, PRC 43 1585 (1991)



Isolate short range interaction (and SRCs) by probing at high P_m ($x>1$)



Poorly understood part of nuclear structure

- Significant fraction of nucleons have $k > k_F$
- Uncertainty in short-range interaction leads to uncertainty at large momenta (>400-600 MeV/c), even for the Deuteron

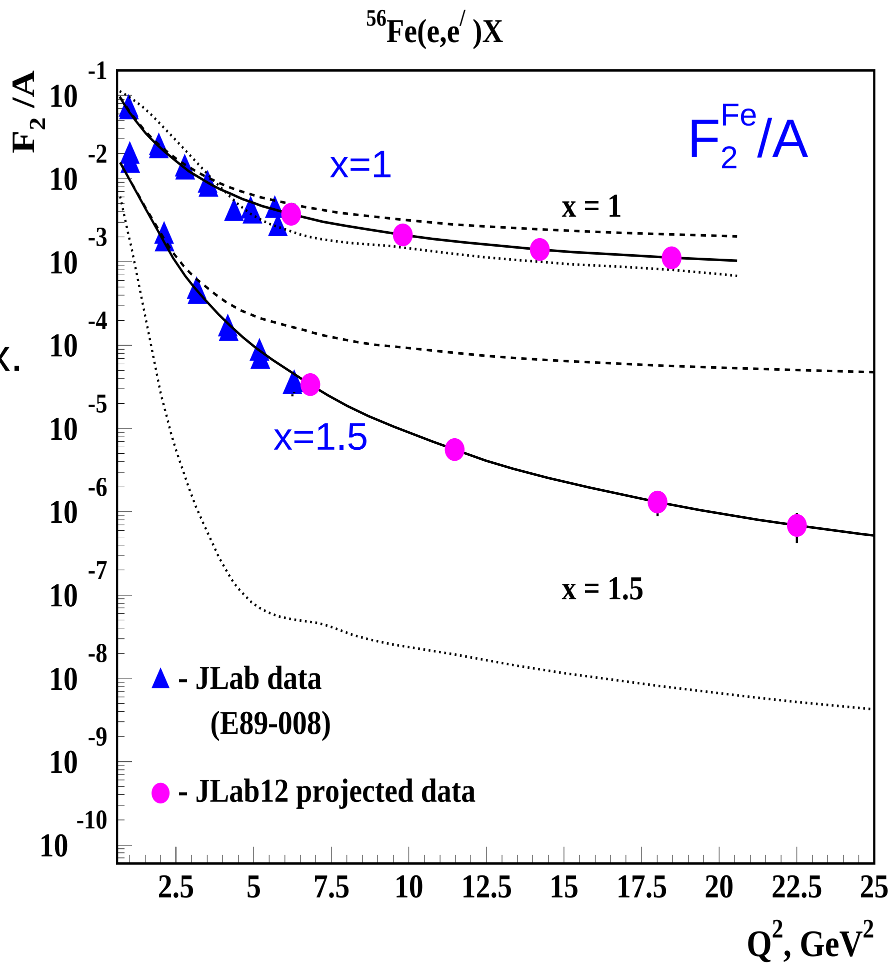
A(e,e'): Short range correlations

We want to be able to ***isolate*** and ***probe*** two-nucleon and multi-nucleon SRCs

Dotted =mean field approx.

Solid = +2N SRCs.
-Frankfurt, Day, Sargsian, and Strikman, Phys. Rev. C (1993)

Dashed = +multi-nucleon.
-Frankfurt and Strikman, Phys. Lett. B94 (1980) 216



<u>Inclusive scattering at x>1:</u>

4 GeV data cominated by QE scattering - consistent with 2N SRCs

6 GeV can reach Q^2=11 GeV^2 - more sensitive to *multi-nucleon* contributions

JLab12 can reach Q^2=23 GeV^2 - even more sensitive, *especially at higher x values*

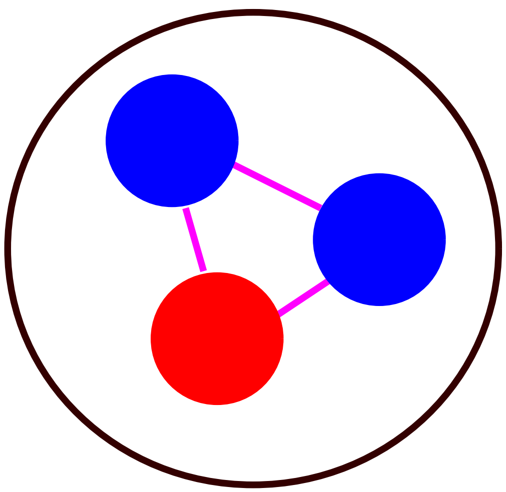
Special cases - ^{3}He and ^{3}H

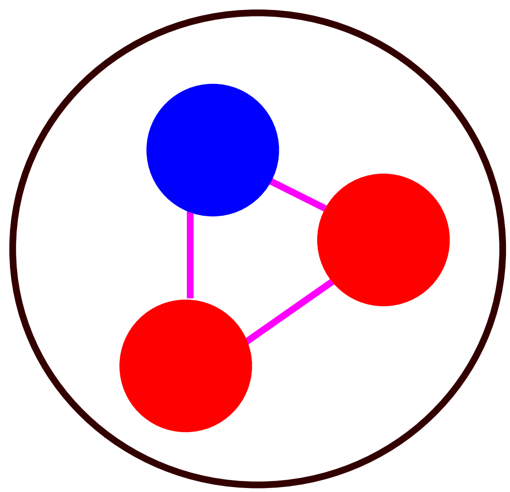
Just as comparison of A/D is sensitive to 2N SRCs, comparison of heavy nuclei to A=3 can tell us about nature, strength of 3N SRCs

A(e,e'p) and (e,e'NN) probes of ^{3}He are already able to provide more information about the nature of SRCs. 12 GeV will yield reduced FSI, MEC contributions

Comparison of ^{3}H and ^{3}He will tell us more about isospin-dependence of short range correlations (n-n vs. n-p vs. p-p pairs)

Comparison of ^{3}H and ^{3}He will allow better extraction of neutron structure than deuteron measurements





Mapping out Short Range Correlations
(nucleonic degrees of freedom, nuclear structure)

6 GeV

QE (e,e'): -Map out A-dependence of 2N SRCs

-Look for signal of multi-nucleon correlations

(e,e'p) and (e,e'NN): -Probe spectral function at high E_m, p_m - study FSIs and MECs, try to isolate spectral function

12 GeV

QE (e,e'): -Larger values of x, Q^2 should allow us to separate and map out *multi-nucleon* SRCs

(e,e'p) and (e,e'NN): -Probe spectral function at high E_m, p_m in regions where FSIs and MECs are small or calculable

-Isolate SRCs by 'tagging' the nucleon that was *not* struck

Goal: ***a complete picture of SRCs in terms of nucleonic degrees of freedom***

--> Improve for our understanding of nuclei

--> Relevant to other areas of physics

Structure of neutron stars *e.g. Burrows and Sawyer, PRC58:554(1998) S. Reddy, et al., PRC59:2888(1999)*

Sub-threshold production measurements

ν-A interactions: modeling supernovae, high-precision measurements of ν scattering (oscillations, θ_{13})

e.g. H. Nakamura, et al., hep-ph/0409300

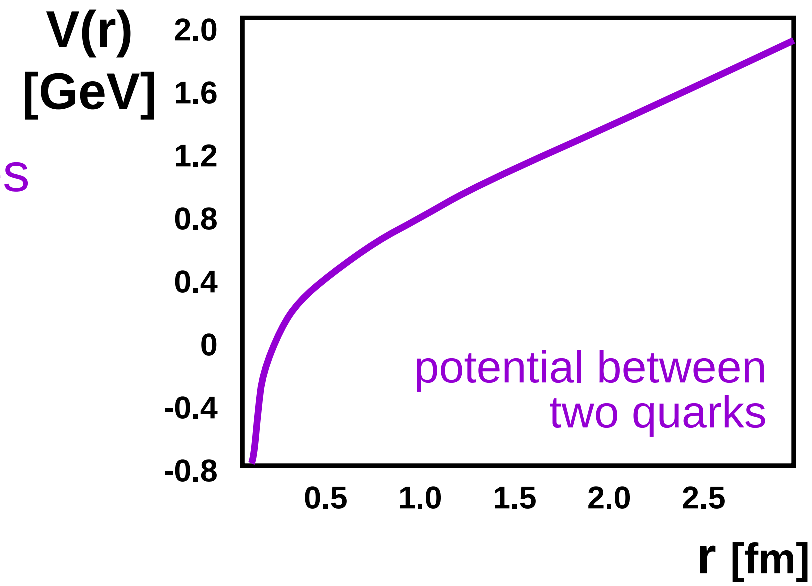
Two "Realms" of Nuclear Physics

QCD land
quarks + gluons + color

Strongly attractive at all distances

1 GeV/cm = ***18 tons***

>10^{12} times the coulomb attraction in hydrogen

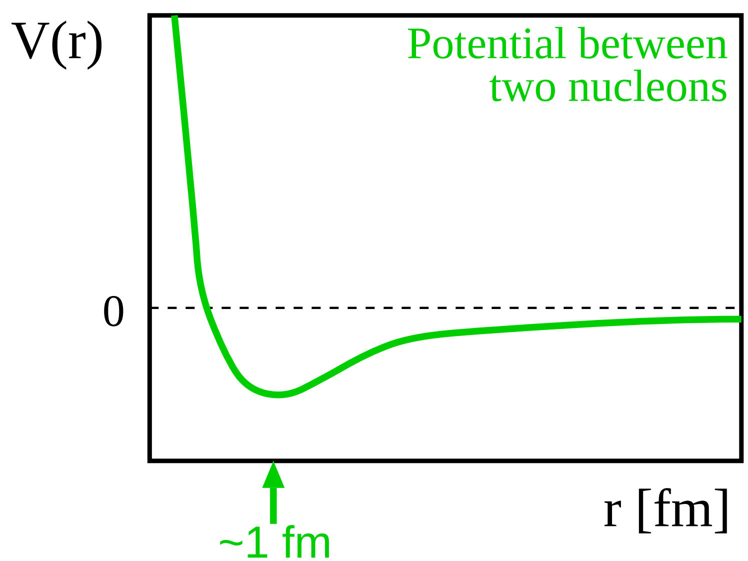


Real world
nucleons + mesons + strong interaction

Matter consists of colorless bound states of QCD

Quark interactions cancel at large distances, making the interactions of hadrons finite

Nucleons appear to be fundamental objects until we probe deeply enough to see the quark degrees of freedom



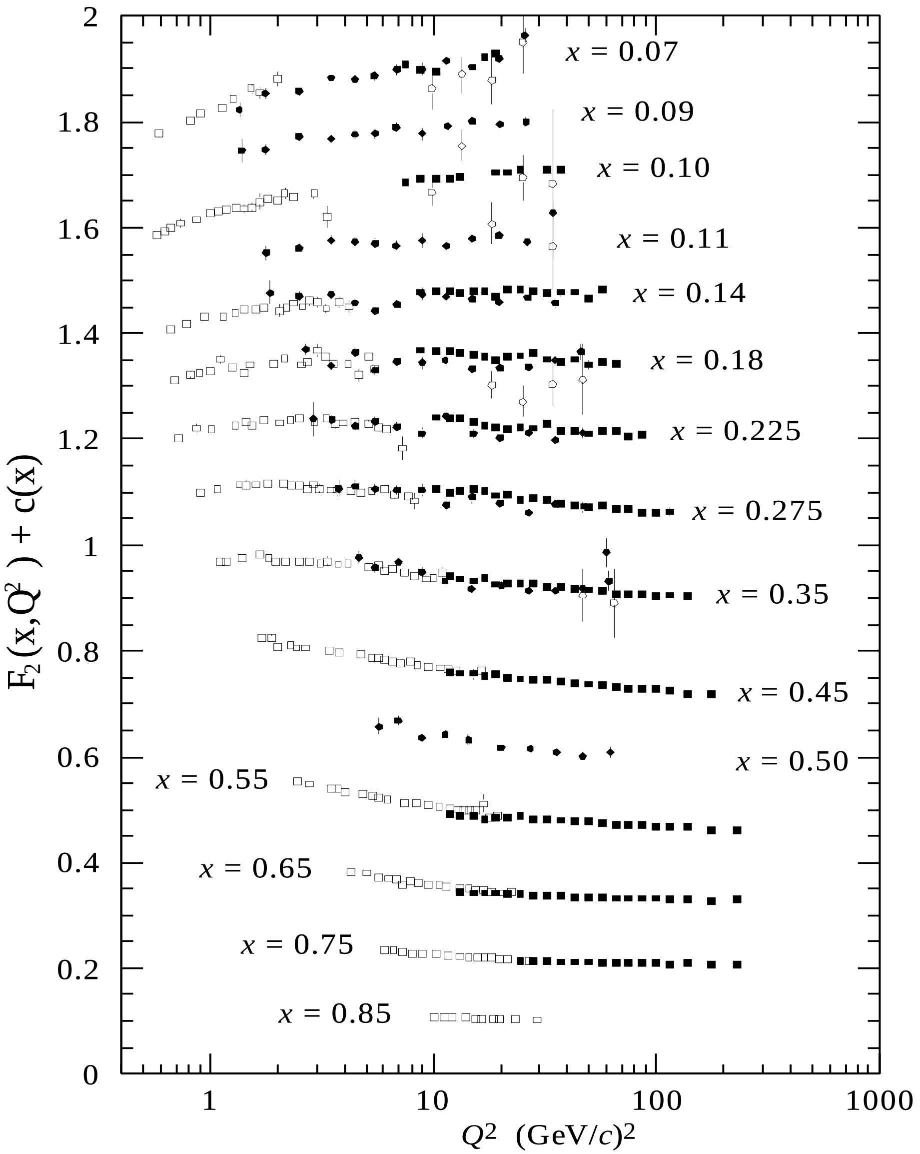
When do quarks matter?

To reveal the quarks, we need a large energy scale that can overcome the binding

High energy

Cosmic rays

SLAC, DESY, LHC...



DIS allows us to extract the quark distributions in the nucleon

Test QCD (e.g. scaling, evolution)

Map out the non-perturbative structure of hadrons

See the ***end result*** of confinement

When do quarks matter?

To reveal the quarks, we need a large energy scale that can overcome the binding

High energy

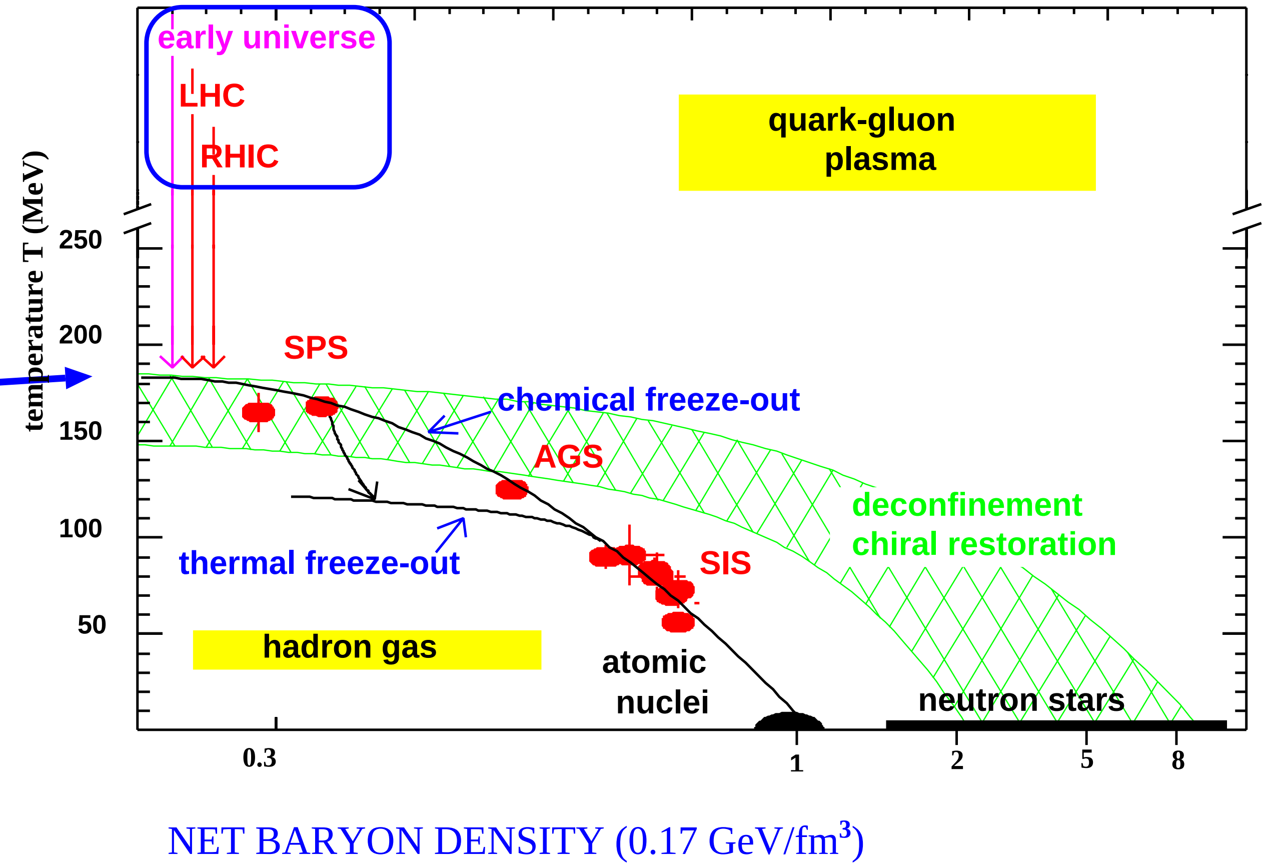
Cosmic rays

SLAC, DESY, LHC...

High temperatures

Early universe

RHIC?



RHIC: Breakdown of confinement with large ***internal*** energy scale

Study QCD phase transition from hadronic to quark-gluon phase

Study quark-gluon matter in deconfined (?) phase

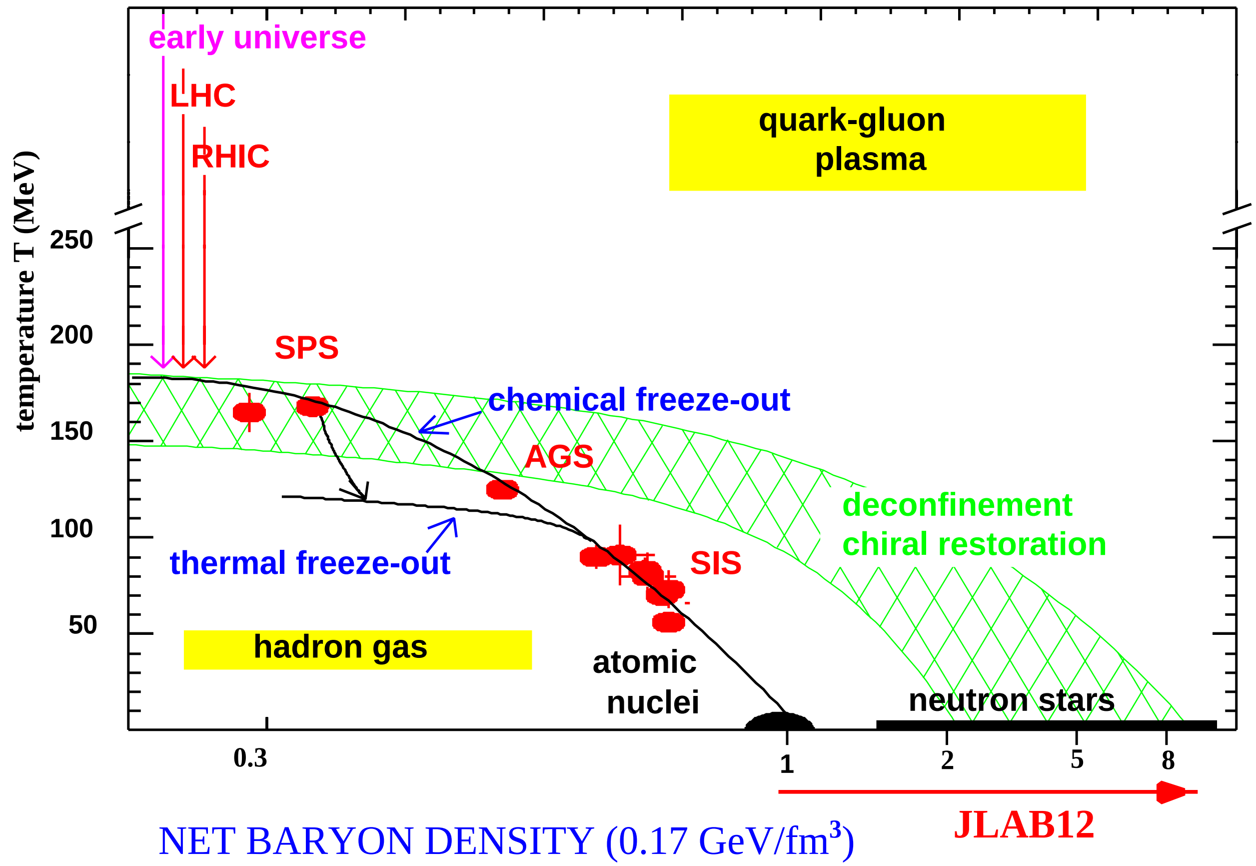
When do quarks matter?

To reveal the quarks, we need a large energy scale that can overcome the binding

High energy
Cosmic rays
SLAC, DESY, LHC...

High temperatures
Early universe
RHIC?

High densities
Neutron (quark?) stars
Nuclei?
JLab??



At large enough densities, confinement should break down

*Nucleons may swell or deform
*Exotic structures may form (e.g. 6-quark bag)
*Quarks may be fully deconfinded (quark stars?)

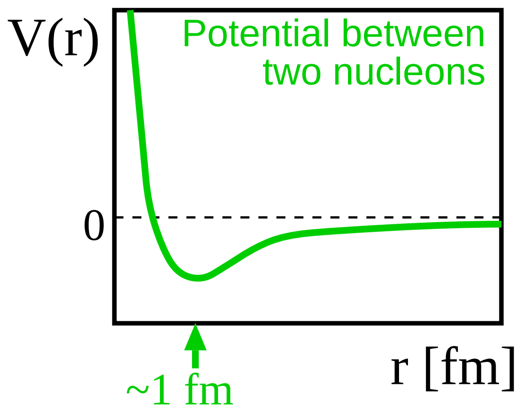
High Density Configurations

Nucleons are already closely packed in nuclei

Ave. separation ~1.7 fm in heavy nuclei

nucleon charge radius ~ 0.86 fm

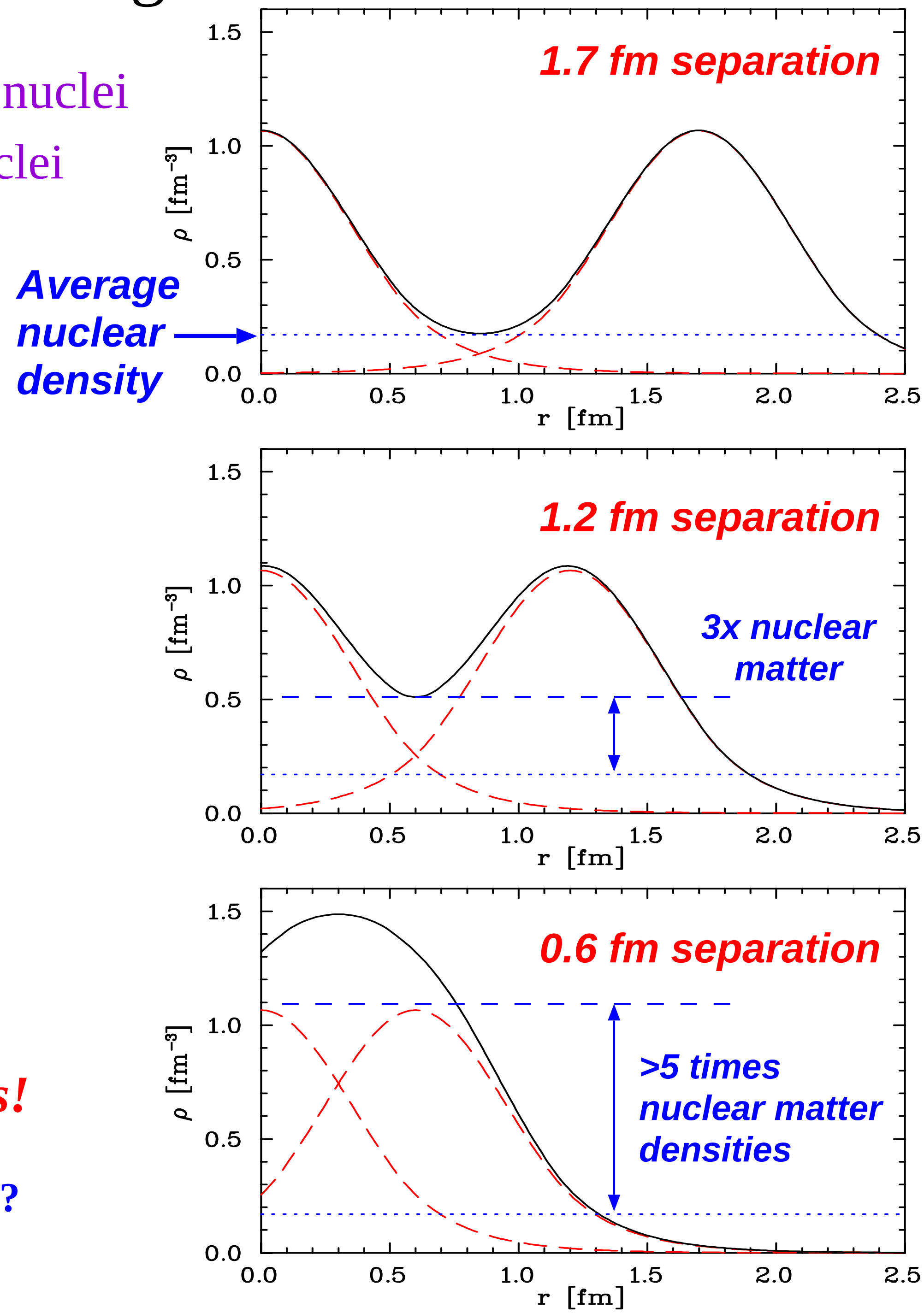
Nucleon separation is limited by the short range repulsive core



Even for a 1 fm separation, the central density is ~4x nuclear matter.

Comparable to neutron star densities!

High enough to modify nucleon structure?

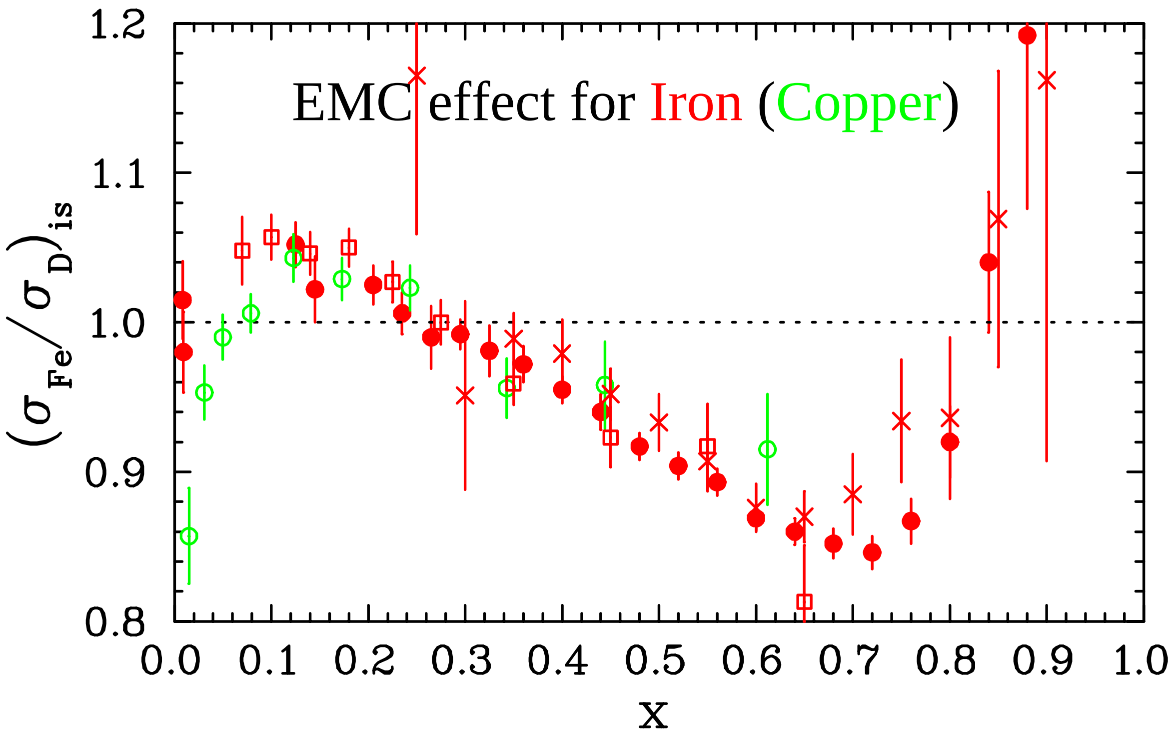


Quark structure of nuclei: EMC effect

We ***do*** see density-dependent effects in nuclear structure

Depletion of the structure function for 0.3<x<0.8

Magnitude of the depletion increases with size/density



$$q_A(x) \neq q_{p/n}(x) \otimes n_A(k)$$

It has been clear for some time that binding, Fermi motion play important roles.
Do we need something more than conventional nuclear physics?

JLab12: Extend traditional EMC measurements

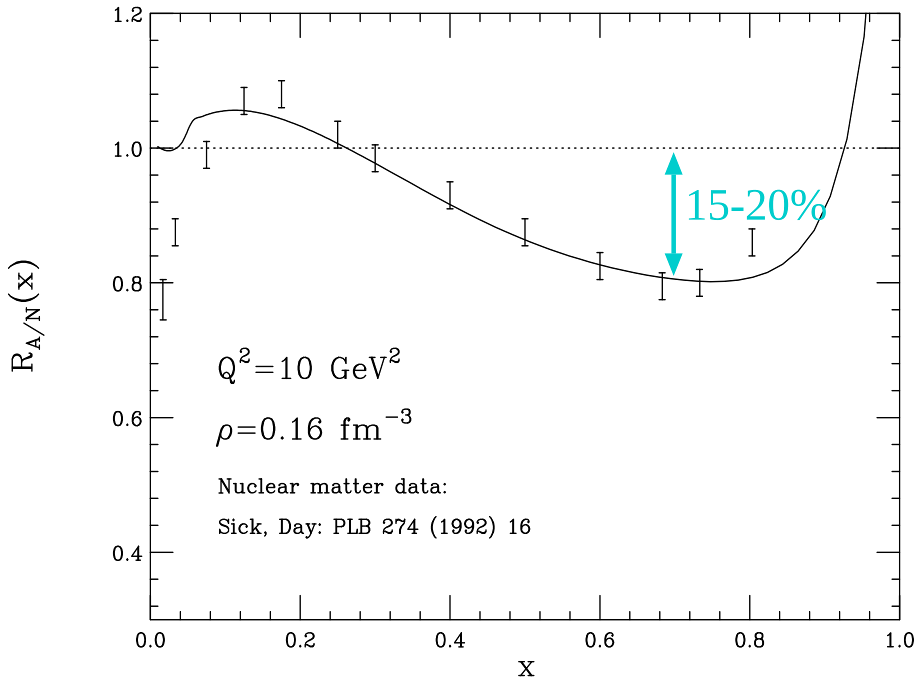
Improved data on large-x ratios and the A-dependence of the EMC effect

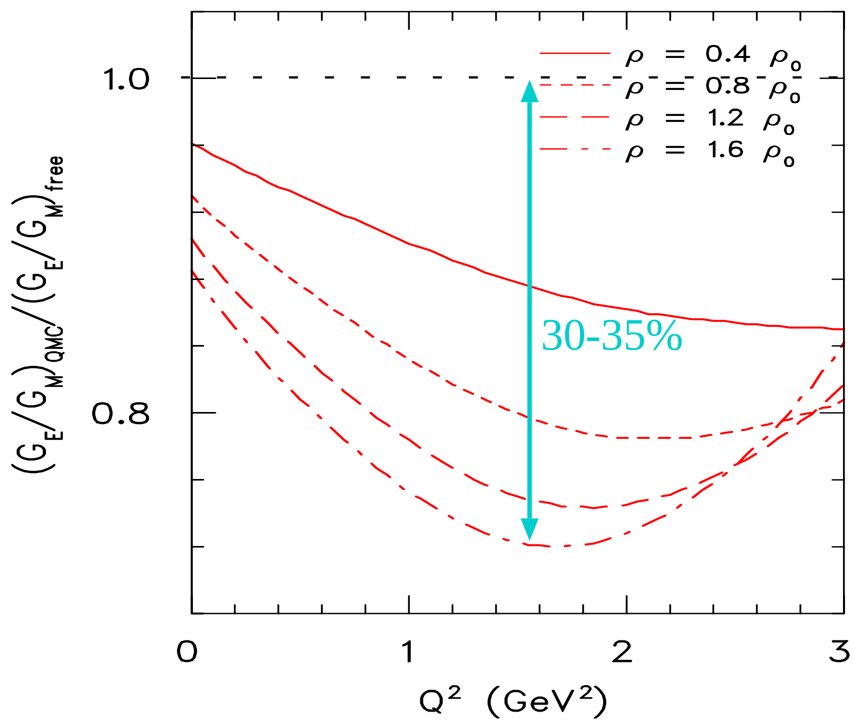
EMC effect for separated structure functions

Flavor dependence, quark vs. antiquark (Drell-Yan, ν-A DIS, Semi-inclusive DIS)

Beyond "The EMC Effect"

Some models, e.g. Quark-Meson Coupling model (Thomas, et al.), predict modified *nucleon form factors* as a consequence (or cause) of the EMC effect





If nucleon modification explains the EMC effect, why probe nuclei? ***Probe nucleons!***

Previous attempts to look for nucleon form factor modification had mixed results

- Nuclear effects large for quasielastic cross section measurements
- Almost no sensitivity to G_E at large Q^2 (e.g. y-scaling limits)

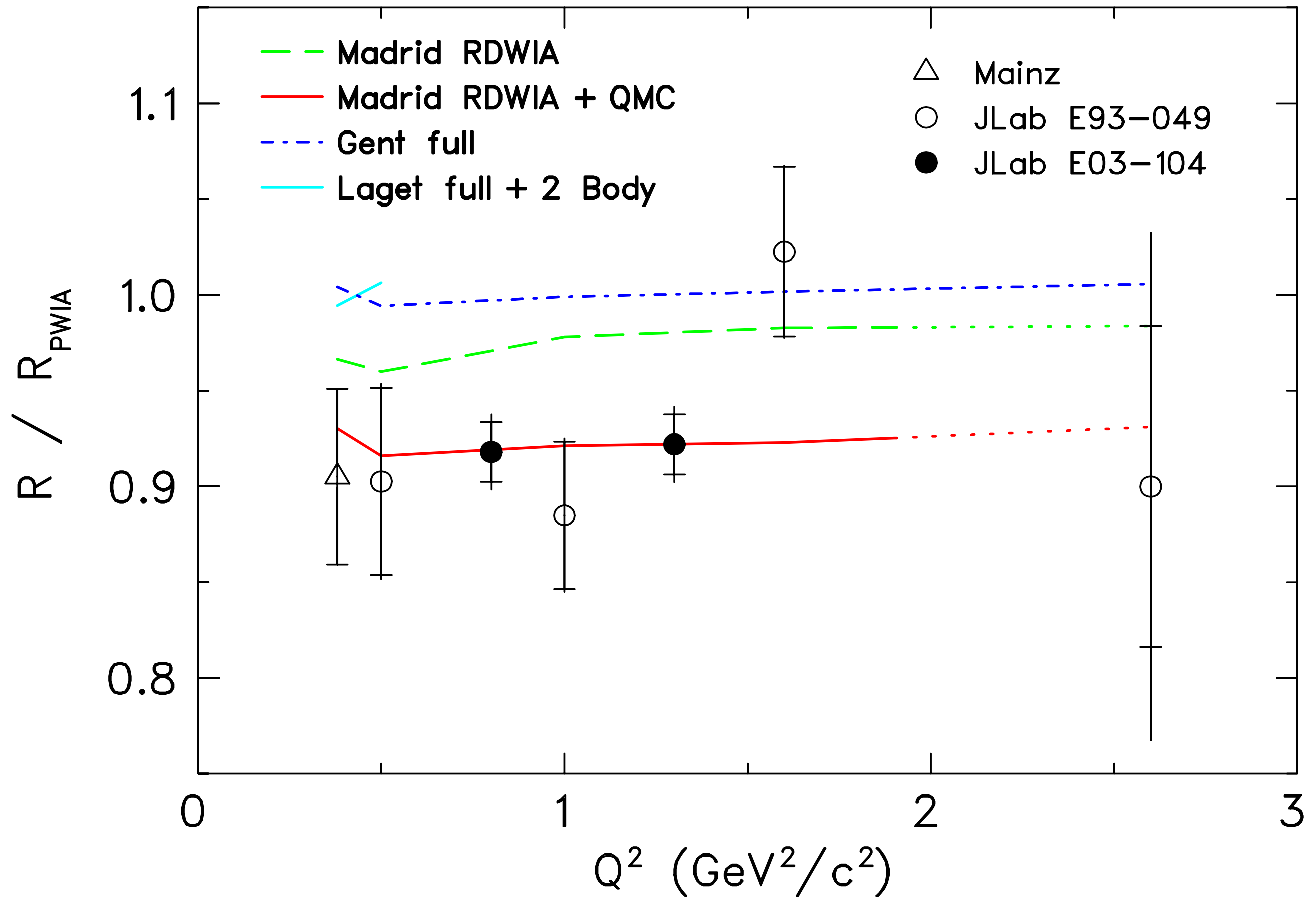
JLab luminosity, polarization, polarimetry --> Study in-medium form factors using the ***polarization transfer*** technique

Polarization transfer in $^4He(\vec{e},e'\vec{p})^3He$

E93-049 (Hall A): Compare $R=G_E/G_M$ of a bound proton to G_E/G_M of a free proton

Nuclear effects are small
(dotted and dashed lines)

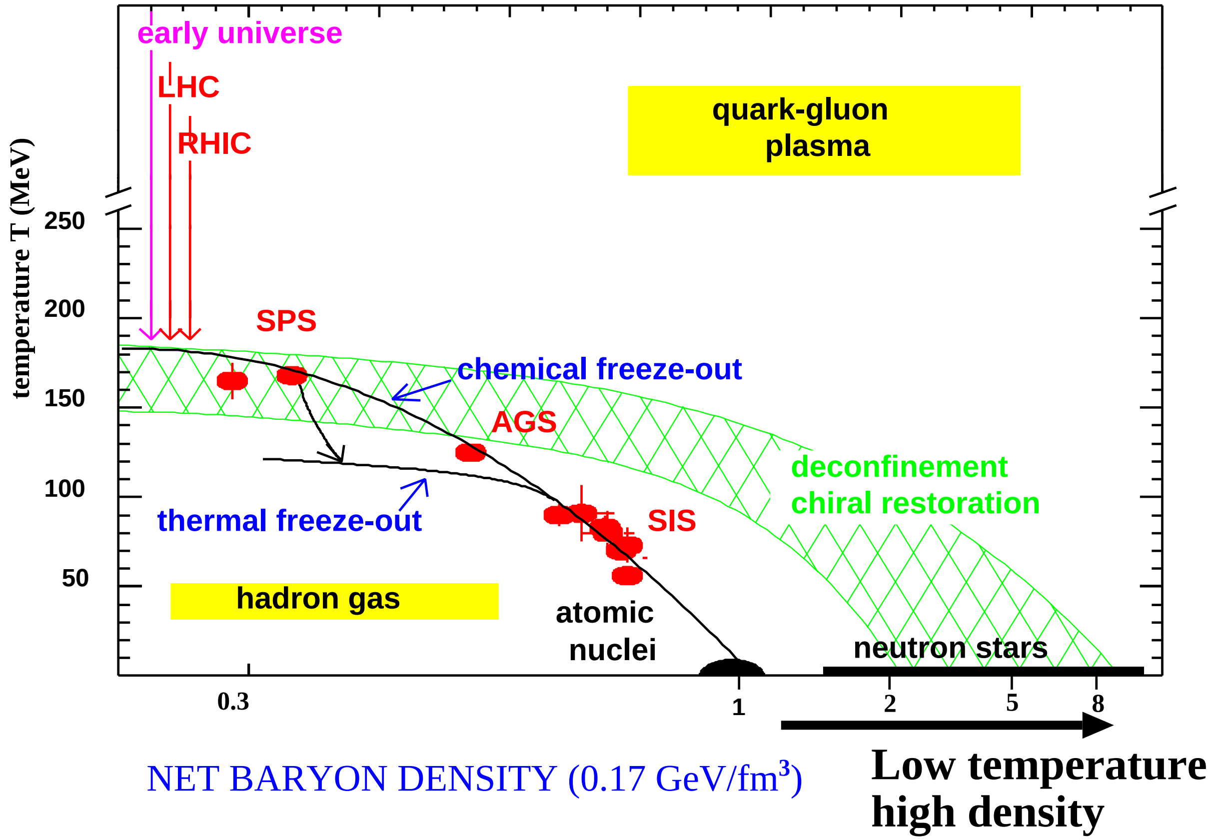
Data are systematically
~10% below calculations
without modification



Indication of modified form factors in a nucleus

Additional data to come...

Another idea: Probe even higher densities



Average nuclear density is a few times smaller than the critical density

A nucleus is a dynamic system, with local fluctuations in density

These fluctuations provide a small high-density component (short-range correlations)

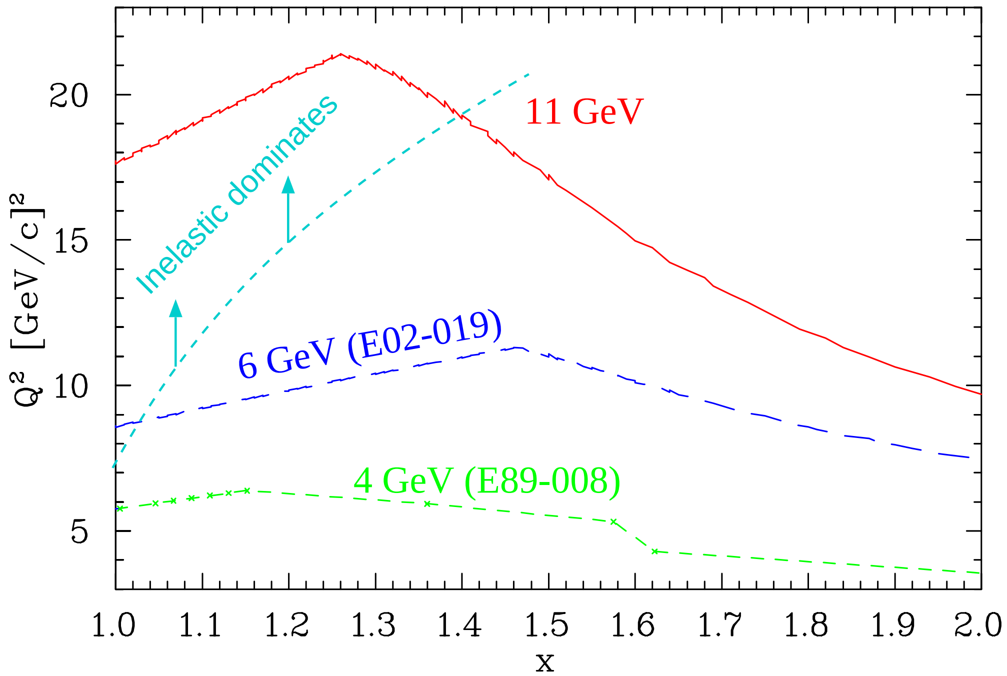
- * This may be origin of EMC effect, medium modifications
- * We can try to isolate SRCs to probe <u>high density matter</u>

If SRCs are the source of the EMC effect, why probe nuclei? ***Probe SRCs instead!***

Quark distributions at x>1

With 11 GeV beam, we should be in the scaling ("DIS") region up to x~1.4

Existing measurements of duality in nuclei suggest we may be able to reach larger x



--> Extract the distribution of '***super-fast***' quarks

Two measurements (very high Q^2) exist so far:

CCFR (ν-C): $F_2(x) \sim \mathbf{e^{-8x}}$ **Limited x range, poor resolution**

BCDMS (μ-Fe): $F_2(x) \sim \mathbf{e^{-16x}}$ **Limited x range, low statistics**

JLab@12 GeV will allow high precision measurements for x>1

High-density configurations: quark distributions at x>1

The EMC effect compares light nuclei to heavy nuclei in order to see the effect of changing the ***average*** density (0.06-0.15 nucleons/fm^{-3})

Probing the quark structure of SRCs allows us to see the effect of changing ***local*** density. Densities can be several times larger in the region where nucleons overlap

Need the following:

* A way to isolate high density configurations
* Understanding of SRCs in terms of nucleonic degrees of freedom

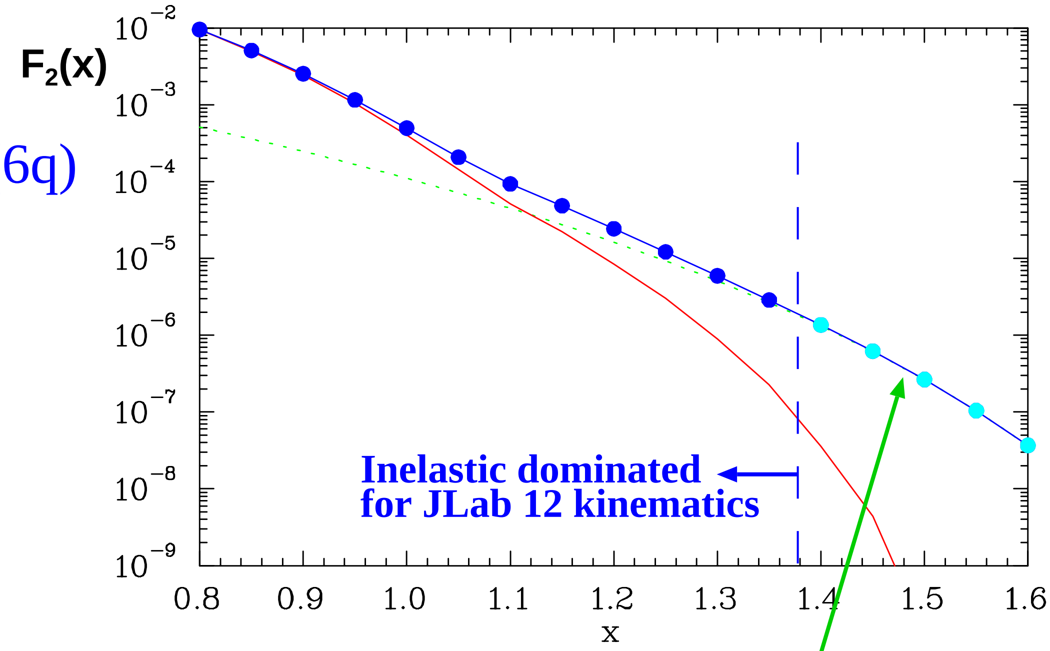
* DIS (e,e'):   Measure *quark* distributions at x>1.
  - Structure of SRCs: Superfast quarks
    At x>1, contributions from mean-field momentum distributions are negligible, and we probe the distribution of SRCs
  - Look for deviations from simple convolution model

$$q_A(x) = q_{p/n}(x) \otimes n_A(k)$$

10-20% for EMC effect measurements
Possibly much higher when probing high-density configurations

Quark distributions at x>1

Red curve: $^2H = p + n$
Blue curve: $^2H = 0.95(p+n) + 0.05(6q)$



Deuteron provides ***cleanest*** signature
(we understand deuteron as p+n)

Heavy nuclei may yield ***larger*** signals, but need better understanding of SRCs for hadronic 'baseline'

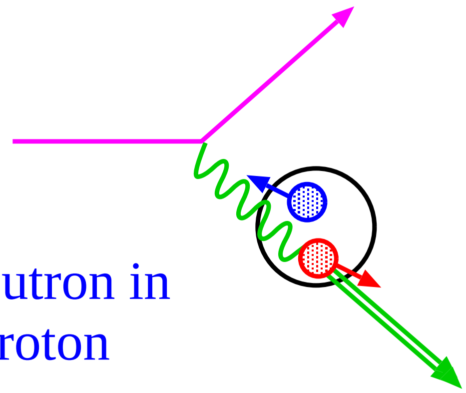
Such a signal would provide *clear signature of deviation from a purely hadronic picture*

Expect any 'quark-mixing' between nucleons to increase strength at large x

Improved nuclear PDFs provides important input to other experiments

- Hard processes in hadron-hadron collisions
- Sub-threshold particle production measurements

Further extensions: Tagged EMC effect



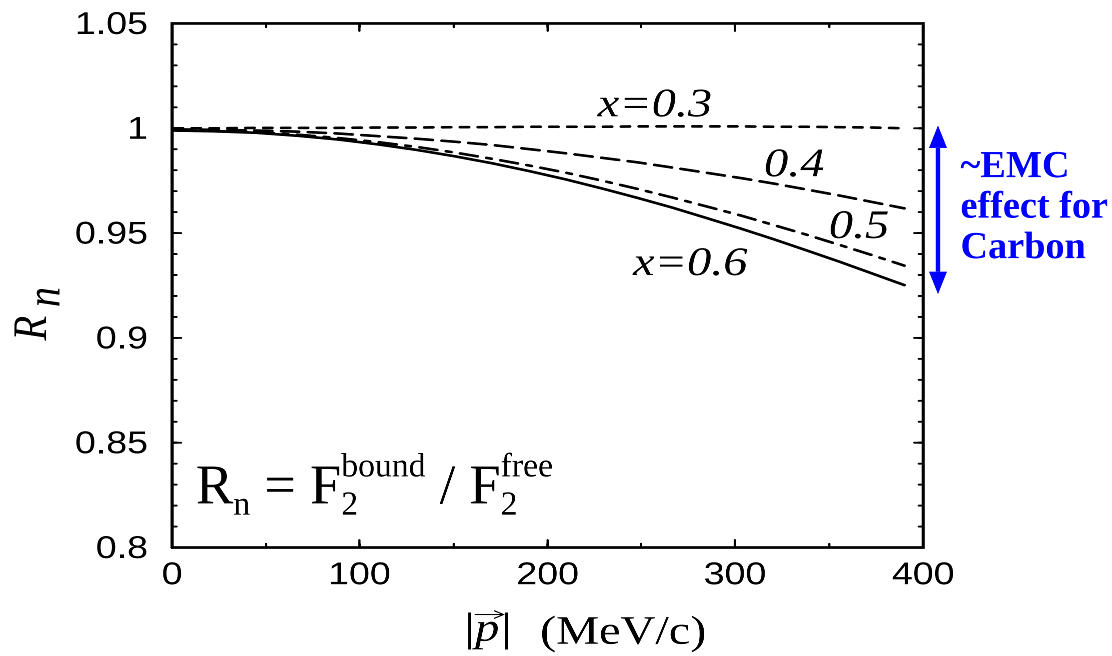
Strike neutron in ^{2}H, tag proton

Proton at θ≅180° --> spectator
(reconstruct initial nucleon)

Proton at low momentum -->
suppress FSI, off-shell effects

Small P_S --> ~free neutron

Large P_S --> Isolate SRCs
(high-density configuration)



Spectator proton acts as a 'knob' we can use to vary the density of the pair

EMC effect: structure of a nucleus as a function of ***average*** nuclear density

Tagged EMC effect: structure of a SRC as a function of ***local*** density

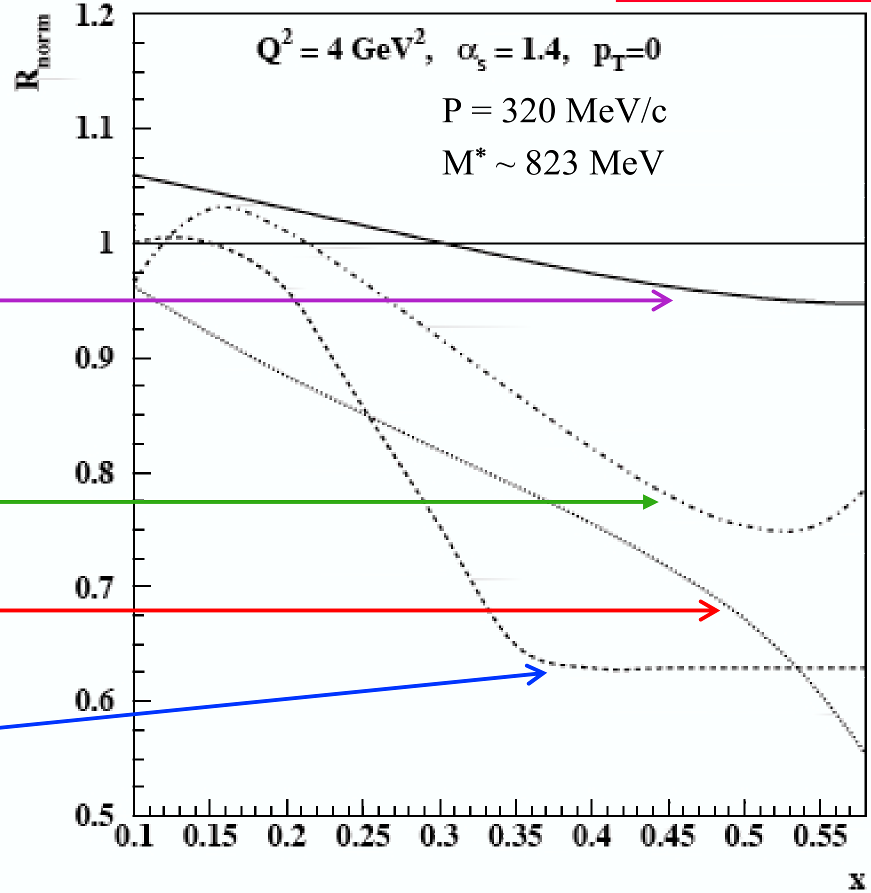
Models of the EMC effect yield very different predictions for this experiment

Tagged Structure Functions

Goal: Tag nucleon (here, neutron) participating in SRC directly

D(e,e'p_s)n

$$\frac{F_{2N}^{eff}(x,Q^2,\alpha)}{F_{2N}^{free}(x,Q^2,\alpha)}$$



Modification of the off-shell scattering amplitude (Thomas, Melnitchouk)

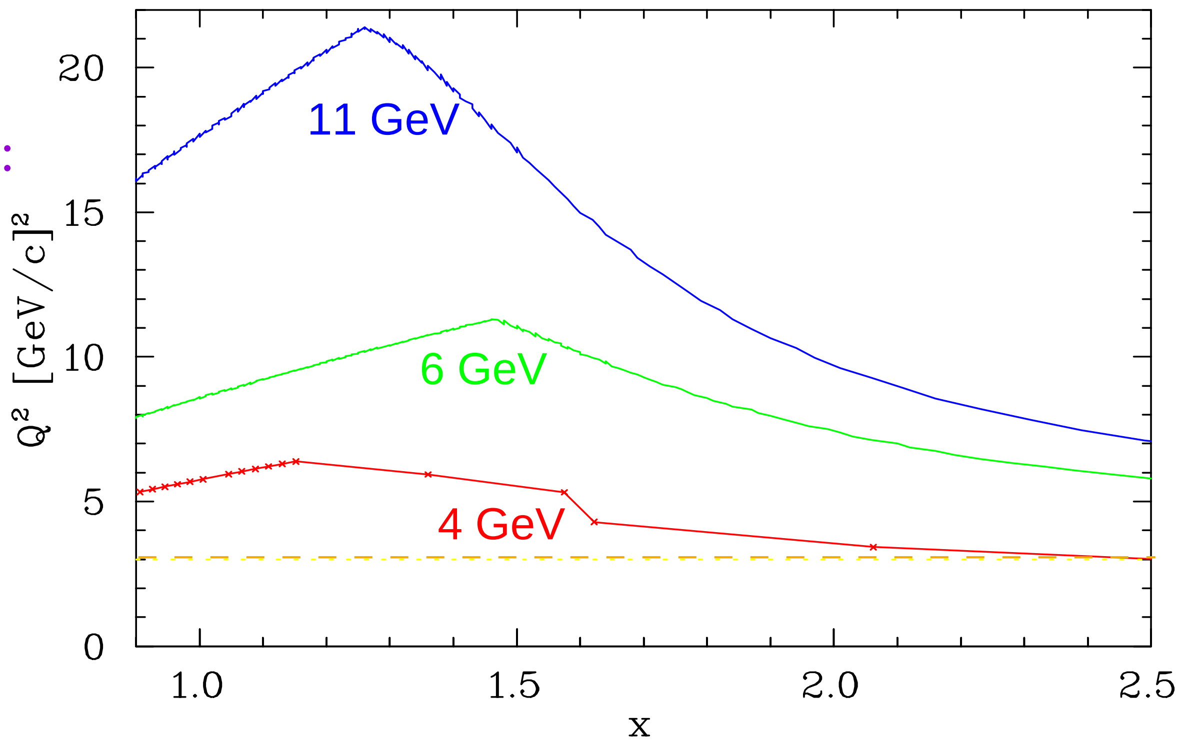
6-quark bags (C. Carlson et al.)

Color delocalization

Suppression of "point-like configurations"

Already measured in CLAS for 300 < P < 600 MeV/c (proton angles > 107°)

Summary I: Nuclear Structure



1) A(e,e'): x>1.5, Q^2~ 5-10 GeV^2:

A-dependence of 2N SRCs

Isolate multi-nucleon SRCs

⇨ Map out size of 2N, 3N SRCs in nuclei

2) Exclusive A(e,e'p) and A(e,e'NN) reactions, 'tagged' SRCs

Provide much more detailed information on SRCs, but with reduced kinematic range, larger issues with reaction mechanism (FSIs, MECs,...)

3) x ~ 1.0-1.5, Q^2 > 15 GeV^2:

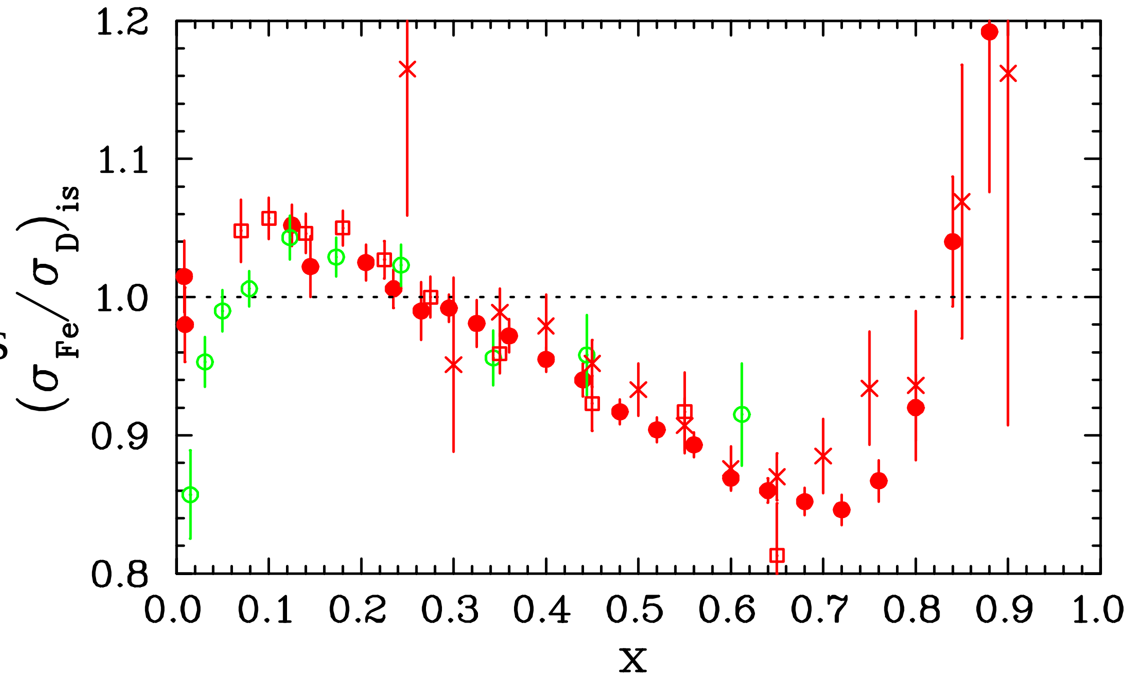
Measure PDFs for x>1

Look for excess superfast quarks - beyond contribution from quarks in ordinary (but high momentum) nucleons

⇨ Isolate and identify non-hadronic contributions to nuclear structure

Summary II: EMC effect

Average nuclear densities are quite low - well below expected phase transition



Extend traditional measurements of the EMC effect

- Measure at larger x values
- Separated structure functions
- Flavor dependence
- ^3H vs. ^3He to separate nuclear effect, neutron excess

Test models that assume non-hadronic explanation more directly

- Modified in-medium nucleon form factors
- Probe SRCs to look for non-hadronic componenets in SRCs

*** SRCs provide a small high-density component in nuclei**

*** Several times higher than average nuclear densities**

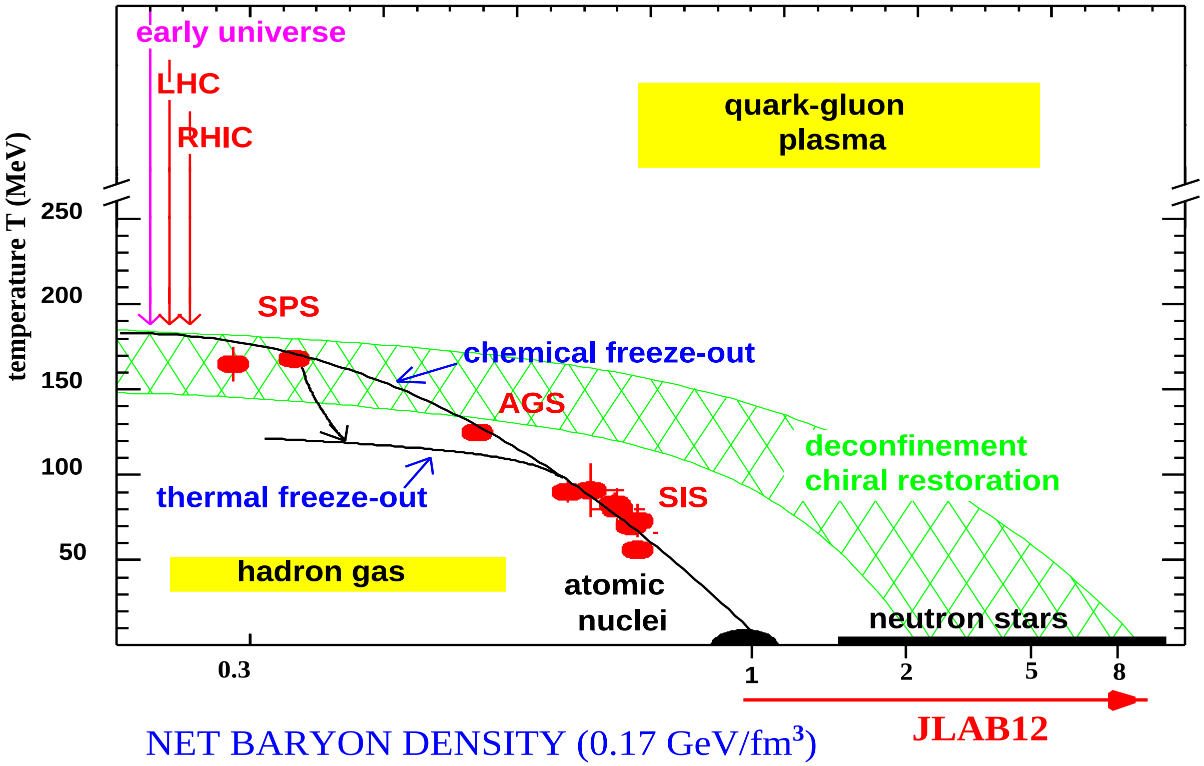
*** Tightly packed nucleons could deform, swell, or even merge**

*** May be origin of EMC effect, medium modifications**

Summary III: Cold, Dense Nuclear Matter

SRCs represent high density configuration of hadronic matter

Dense nuclear matter may differ from a system of densely packed nucleons



SRCs provide the only way to study matter at these densities in the lab

Examine the *approach* to deconfinement at very high density

Complements RHIC studies of QCD at high temperature

Implications for astrophysics (cold, dense matter)

Input to equation-of-state of cold, dense hadronic matter