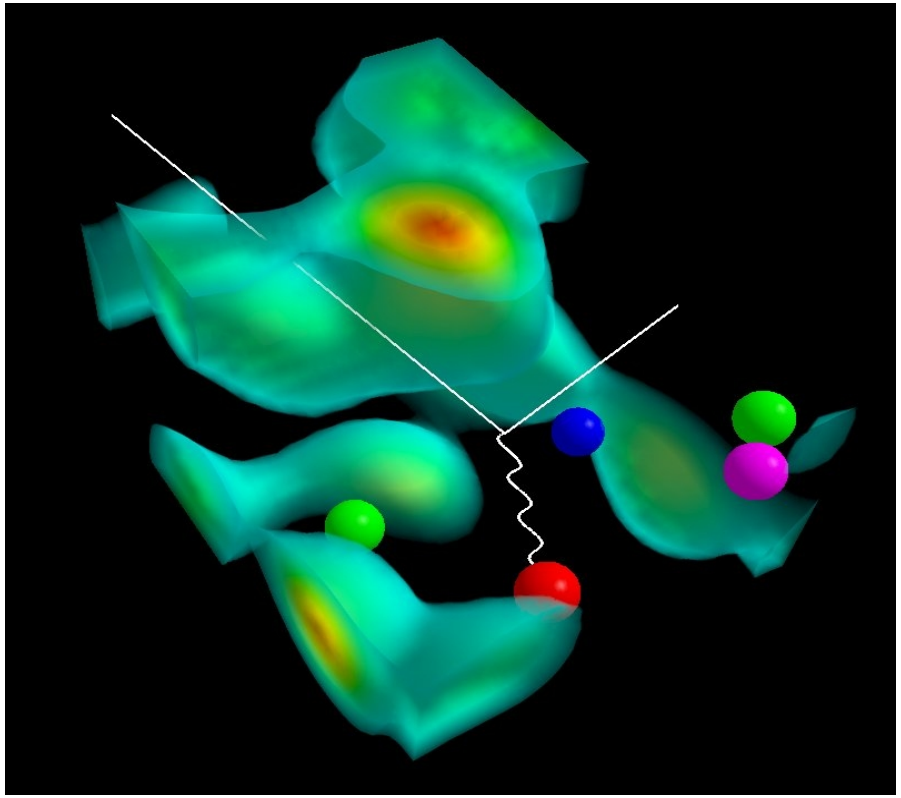
Nuclear Structure, QCD and the EMC Effect



Anthony W. Thomas

Third Proton Mass Workshop
ANL – January 15th 2021

ADELAIDE UNIVERSITY AUSTRALIA

CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Outline

I. The EMC Effect – deep-inelastic structure of nuclei is *different*

II. Recent proposal: arises from nucleons in short-range correlations

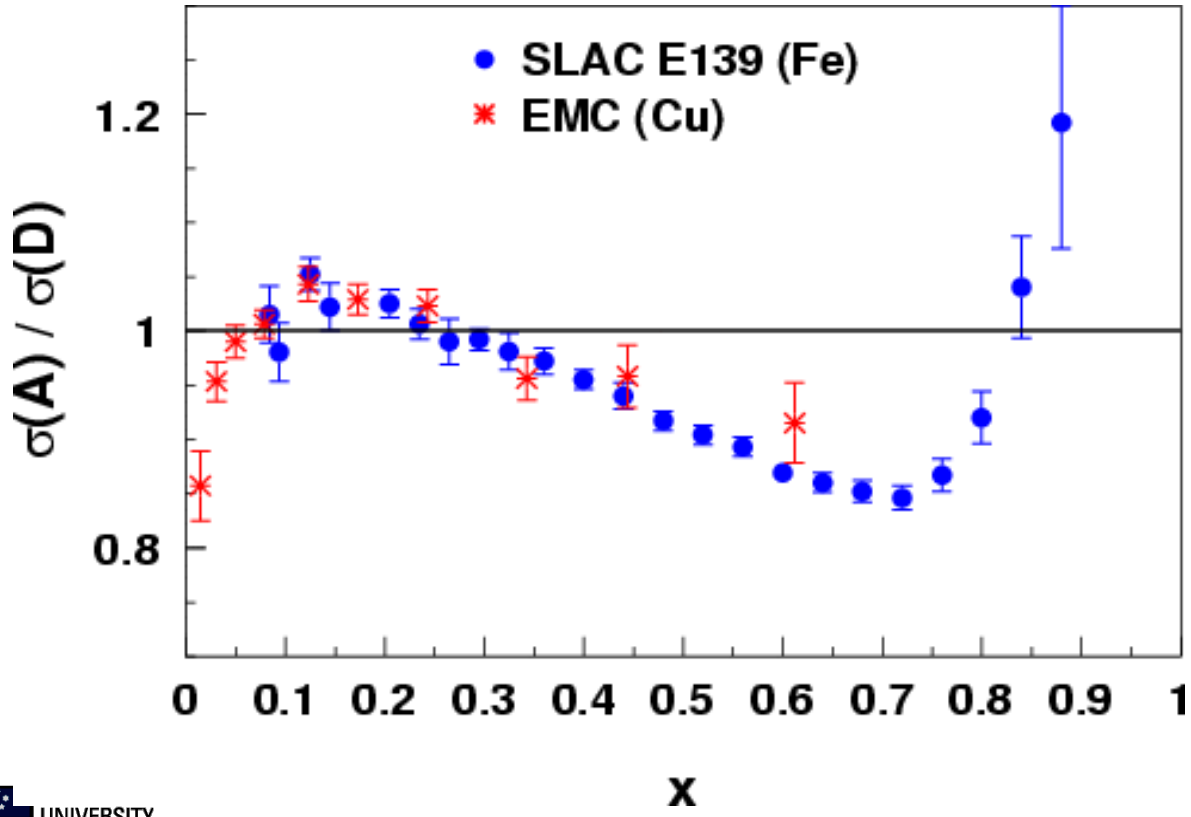
III. Alternate: It matters that nuclei are built from Quarks & Gluons
- start from a QCD-inspired model of *hadron* structure
- develop a quantitative theory of nuclear structure

IV. Test the mean-field versus SRC explanation of the EMC effect

The EMC Effect: Nuclear PDFs

- Observation **stunned and electrified** the HEP and Nuclear communities 37 years ago

- What is it that alters the quark momentum in the nucleus?



J. Ashman *et al.*, Z. Phys. C57, 211 (1993)

J. Gomez *et al.*, Phys. Rev. D49, 4348 (1994)

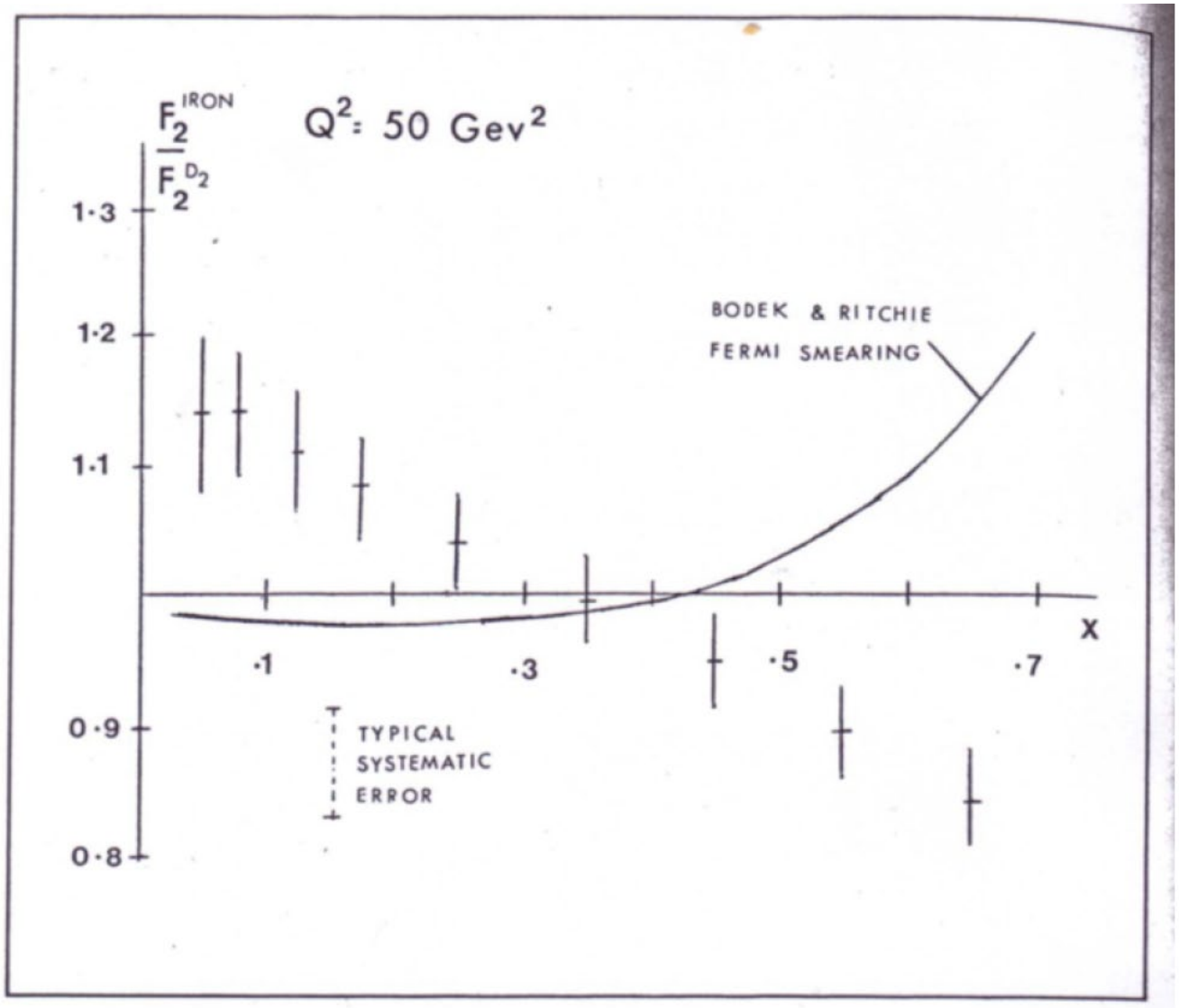


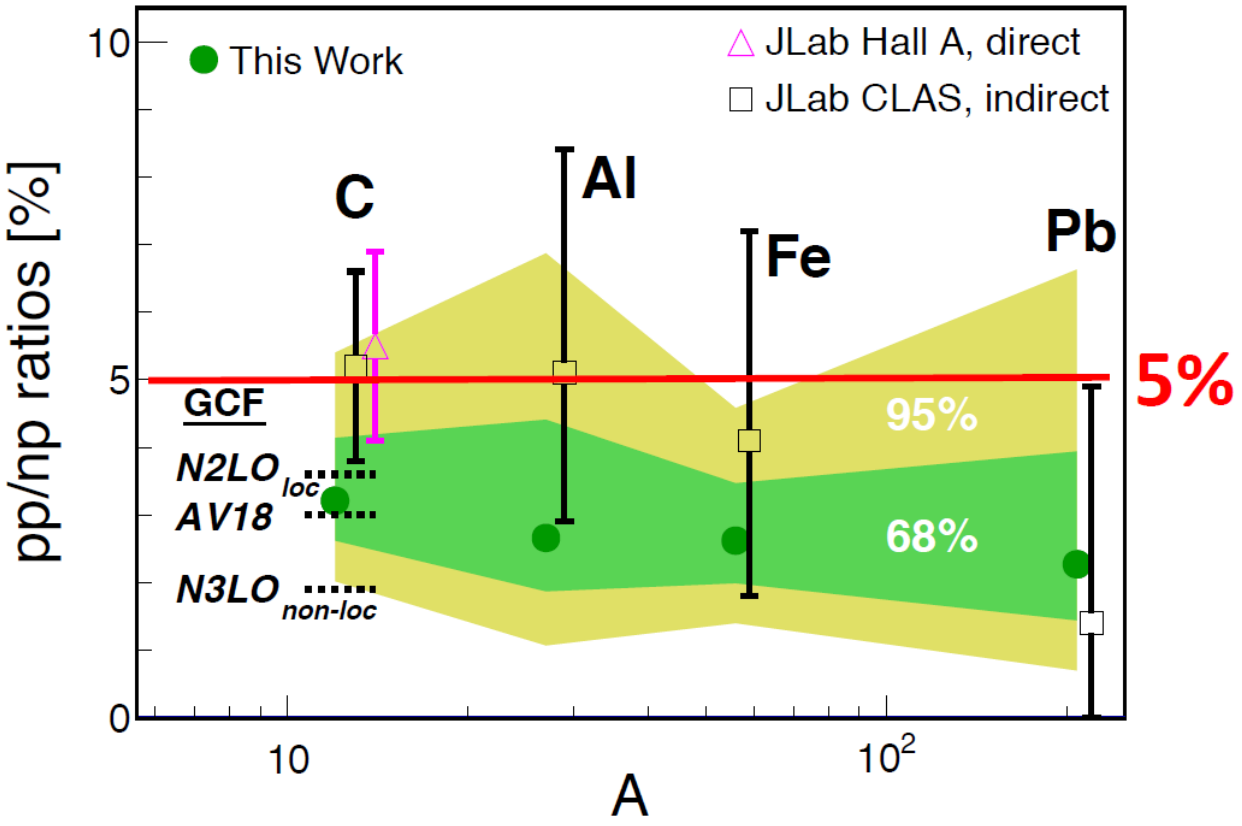
Fig. 1: Image of the EMC data as it appeared in the November 1982 issue of the CERN Courier. This image nearly derailed the highly cited refereed publication (Aubert et al., 1983), as the editor argued that the data had already been published.

Higinbotham *et al.*, CERN Courier 2013

Short-range correlations (SRC)

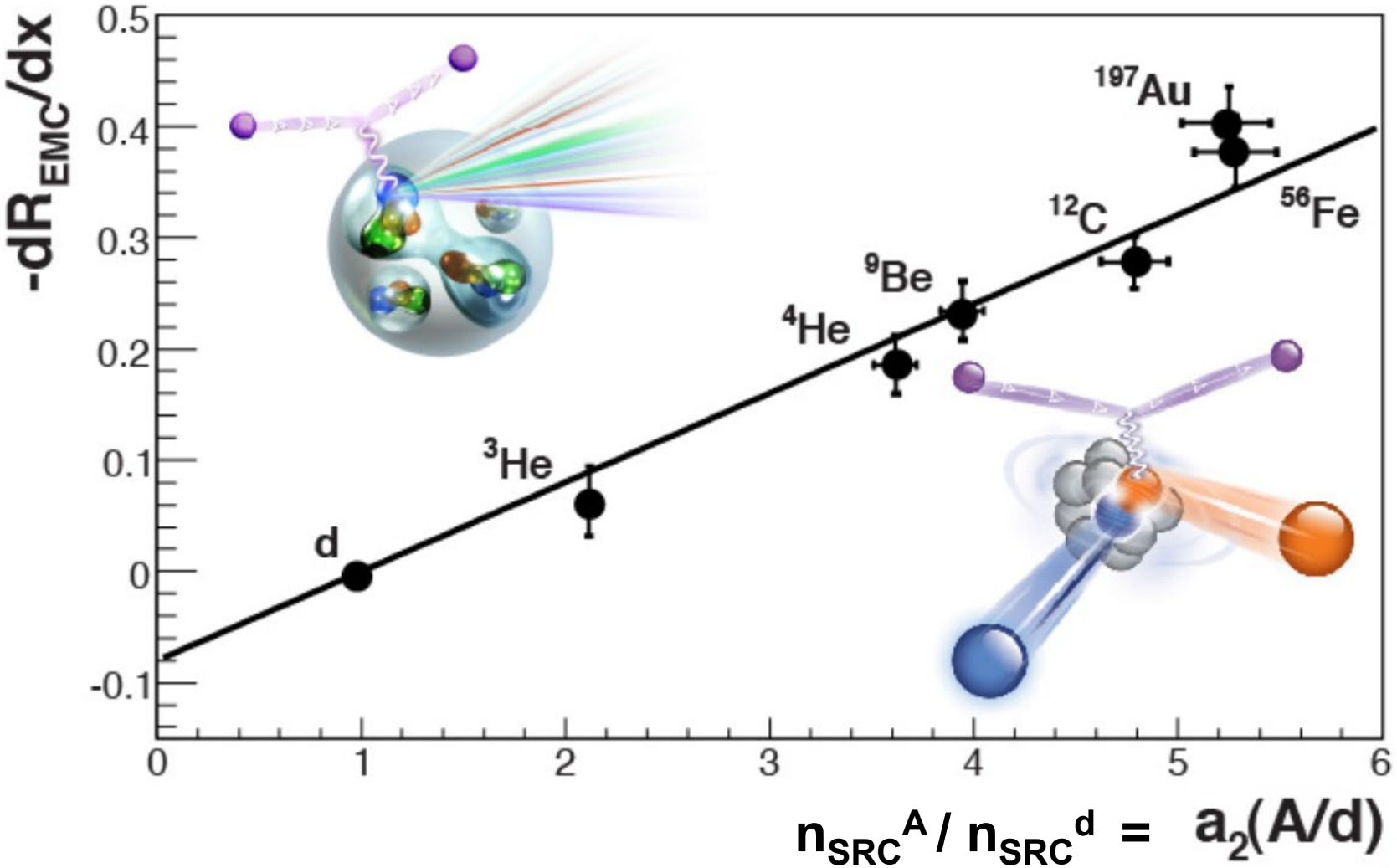
JLab established Role of the Tensor Force in SRC

- **Established in beautiful series of experiments at JLab**
- **Resolves a decades old dispute – with Arima's group as the winner**



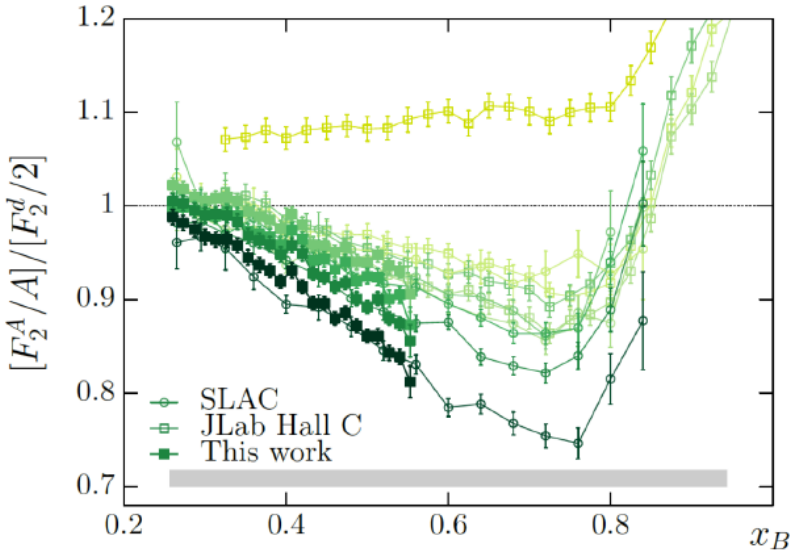
x>1 Ratios and EMC Slope Correlation

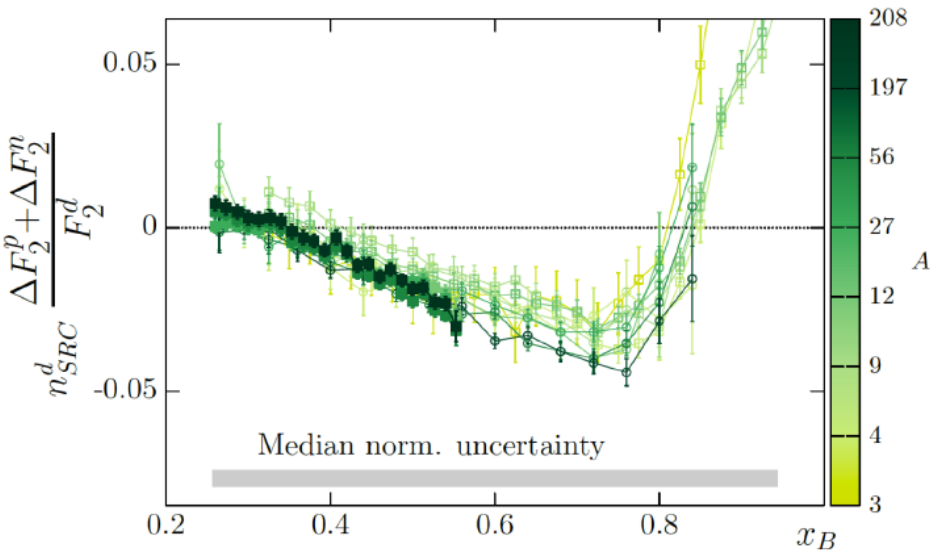
L. Weinstein *et al.*, Phys. Rev. Lett. **106** (2011) 052301.



Linear relation proposed as evidence that SRC explain the EMC effect

B. Schmookler *et al.*, Nature 566 (2019) 354-358.





$$F_2^A = (Z - n_{SRC}^A)F_2^p + (N - n_{SRC}^A)F_2^n + n_{SRC}^A(F_2^{p*} + F_2^{n*})$$
$$= ZF_2^p + NF_2^n + n_{SRC}^A(\Delta F_2^p + \Delta F_2^n),$$

Entire EMC effect from the change in SF of nucleons in SRC

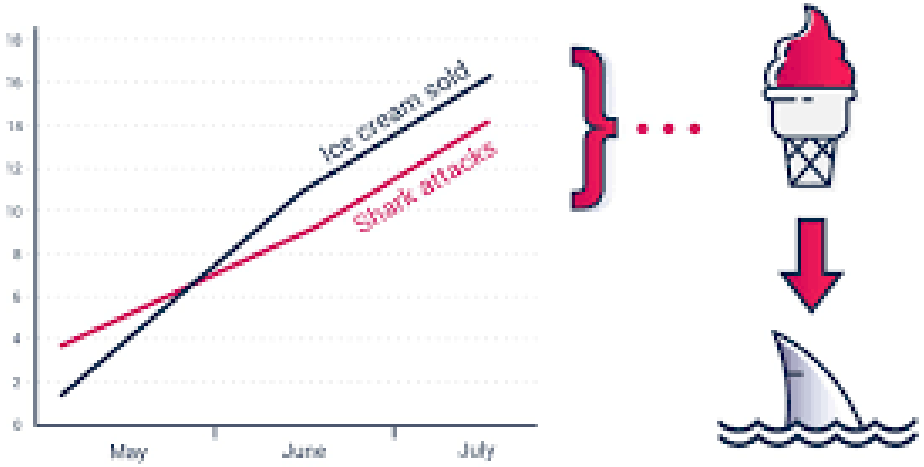
From Doug Higinbotham

"Cum hoc ergo propter hoc" is false!

- **From Wikipedia –**

  "A correlation tells you absolutely nothing about cause"

  e.g.

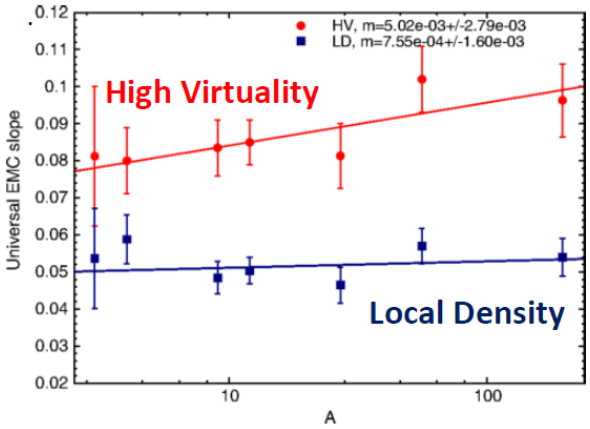


- **Yet the correlation between EMC slope and number of nucleons in short-range correlations is widely represented as proving SRC are the origin of the EMC effect**
  - **THIS IS WITHOUT LOGICAL FOUNDATION**

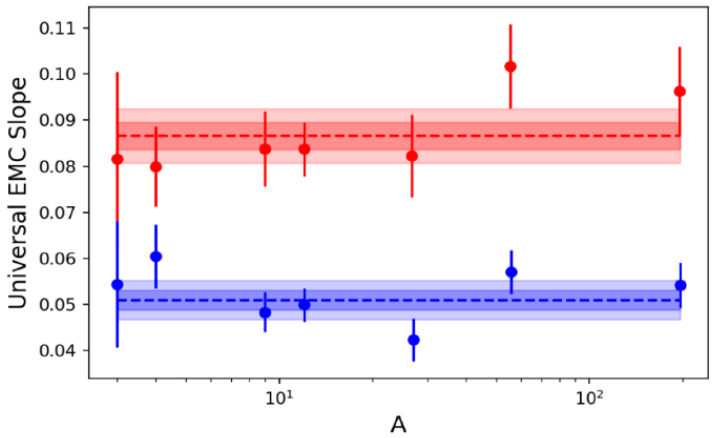
The same correlation applies to Local Density

High Virtuallity vs. Local Density

J. Arrington and N. Fomin, Phys. Rev. Lett. 123 (2019) 042501



O. Hen et al., arXiv:1905.02172.



The plots on the left and right side are exactly the same data.

The simpler model (i.e. a constant) is consistent with both universal functions.

One should define there criterion for adding parameters to a regression.
(see Higinbotham *et al.*, Phys. Rev. C. 93 (2015) 055207 for examples)

NOTE: When handled consistently, HV and LD give exactly the same 'a2' values.
https://arxiv.org/abs/1907.03658

Alternate explanation based upon the effect of local scalar and vector mean-fields (~ local density) on confined quarks

RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 46, NUMBER 6 DECEMBER 1992

Towards a microscopic understanding of nuclear structure functions

K. Saito
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(Received 10 February 1992)

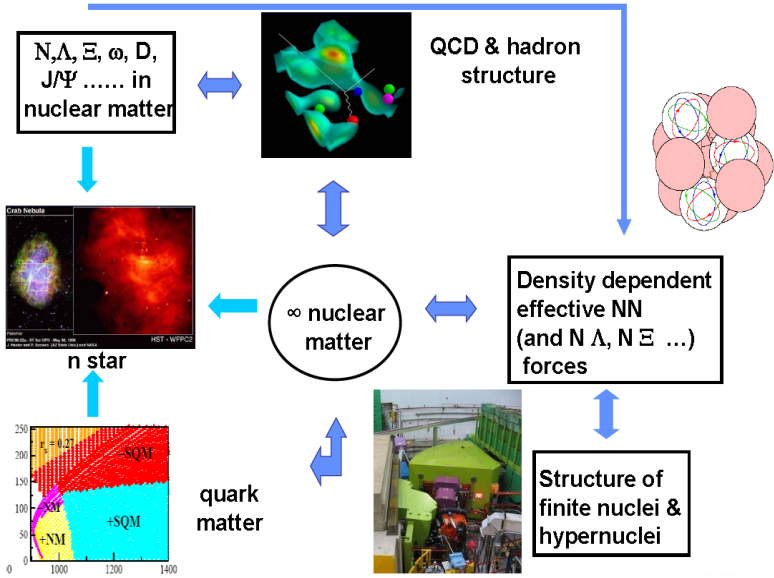
A new approach to nuclear matter: QMC Model

(Guichon, Saito, Tsushima et al., Rodionov et al., Stone
- see Saito *et al*., Prog. Part. Nucl .Phys. 58 (2007) 1 and
Guichon *et al*., Prog. Part. Nucl. Phys. 100 (2018) 262-297 for reviews)

- Start with quark model (MIT bag/NJL...) for all hadrons

- Introduce a relativistic Lagrangian with σ, ω and ρ mesons coupling to non-strange quarks

- Hence, initially only 3 parameters
  (4 if σ mass not fixed)
  - determine by fitting to:
    ρ_0 , E/A and symmetry energy
  - same in dense matter & finite nuclei



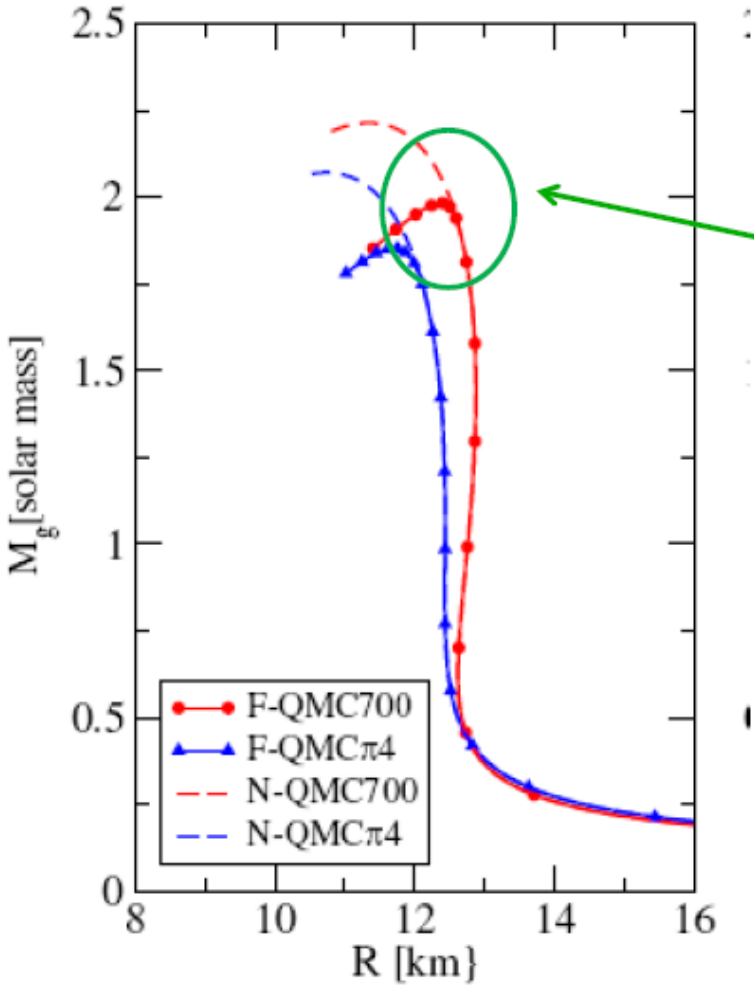
- Must solve self-consistently for the internal structure of baryons in-medium

Application to nuclear structure

and Neutron Stars – cannot be discussed here….

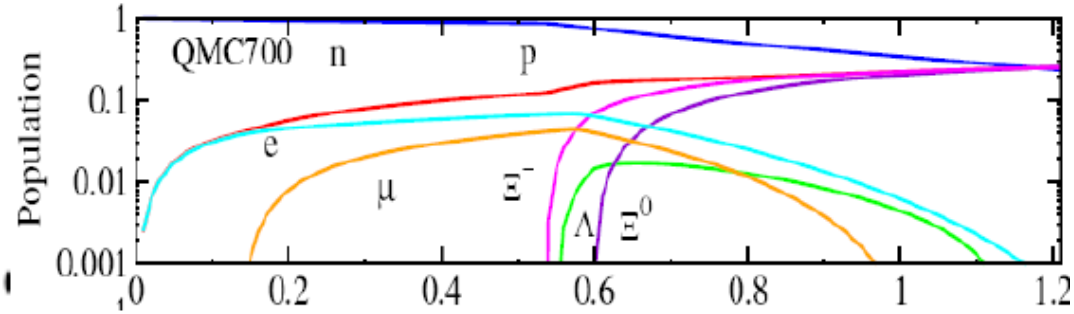
The QMC model predicted heavy neutron stars with hyperons before their discovery

Consequences of QMC for Neutron Star



Rikovska-Stone *et al.*, NP A792 (2007) 341

2 Solar mass stars predicted with hyperons present:



Predicted HNN forces crucial!

Later work: Saito et al., Whittenbury et al.....
and most recently Motta *et al.*

Derivation of Density Dependent Effective Force

Physical origin of density dependent forces of Skyrme type within the quark meson coupling model

P.A.M. Guichon [a,*], H.H. Matevosyan [b,c], N. Sandulescu [a,d,e], A.W. Thomas [b]

Nuclear Physics A 772 (2006) 1–19

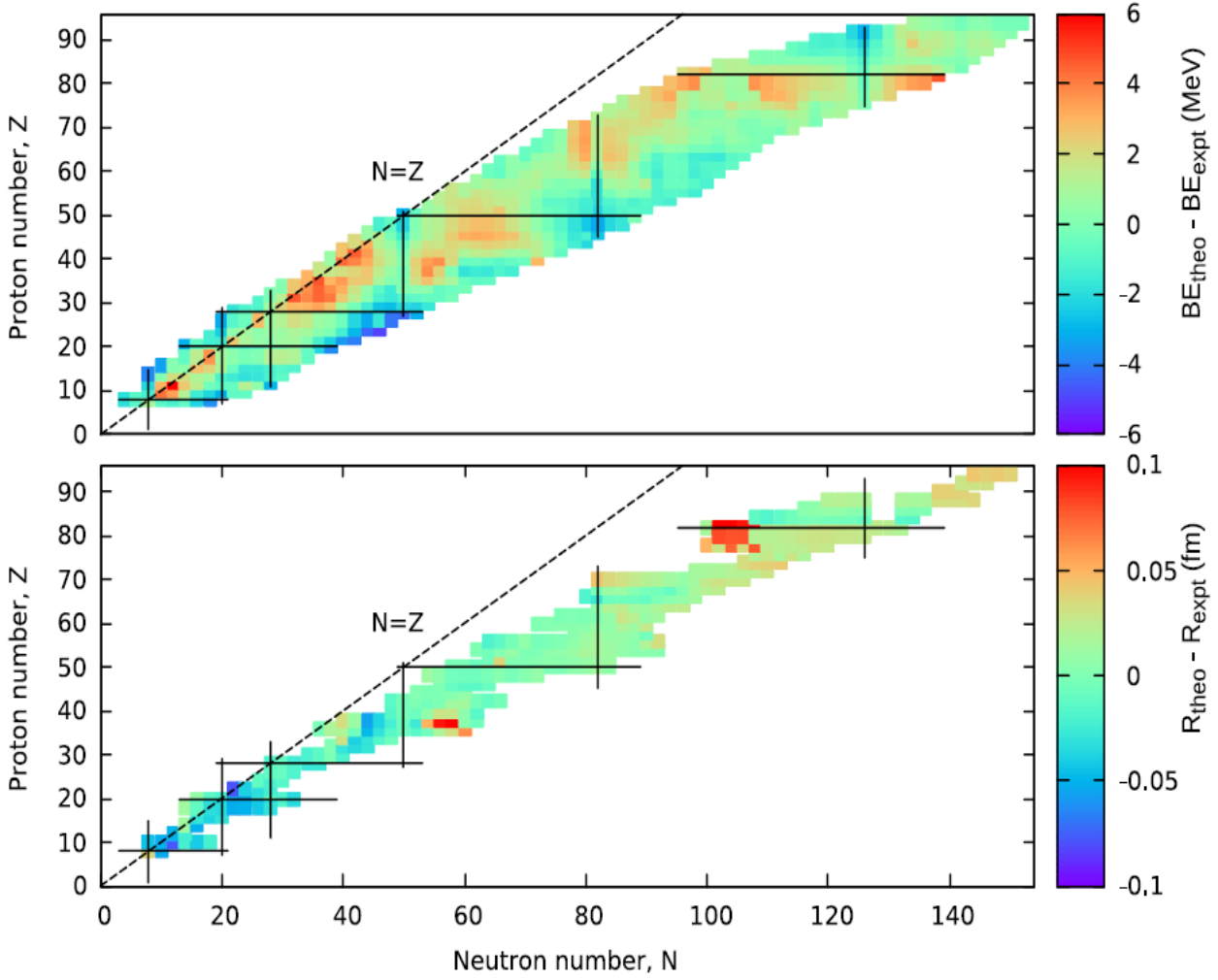
- **Start with classical theory of MIT-bag nucleons with structure modified in medium to give M_{eff} (σ).**
- **Quantise nucleon motion (non-relativistic), expand in powers of derivatives**
- **Derive equivalent, local energy functional:**

$$\langle H(\vec{r}) \rangle = \rho M + \frac{\tau}{2M} + \mathcal{H}_0 + \mathcal{H}_3 + \mathcal{H}_{\text{eff}} + \mathcal{H}_{\text{fin}} + \mathcal{H}_{\text{so}}$$

First structure calculations: Phys Rev Lett 116 (2016) 092501

Latest development: QMC pi3

- Correct to all order in nuclear density; add σ^3 term; calculate pairing
- Now just 5 parameters – cf. 15+ in typical Skyrme calculations



Martinez et al., Phys Rev C106, 034304 (2020)

Giant Monopole Resonances

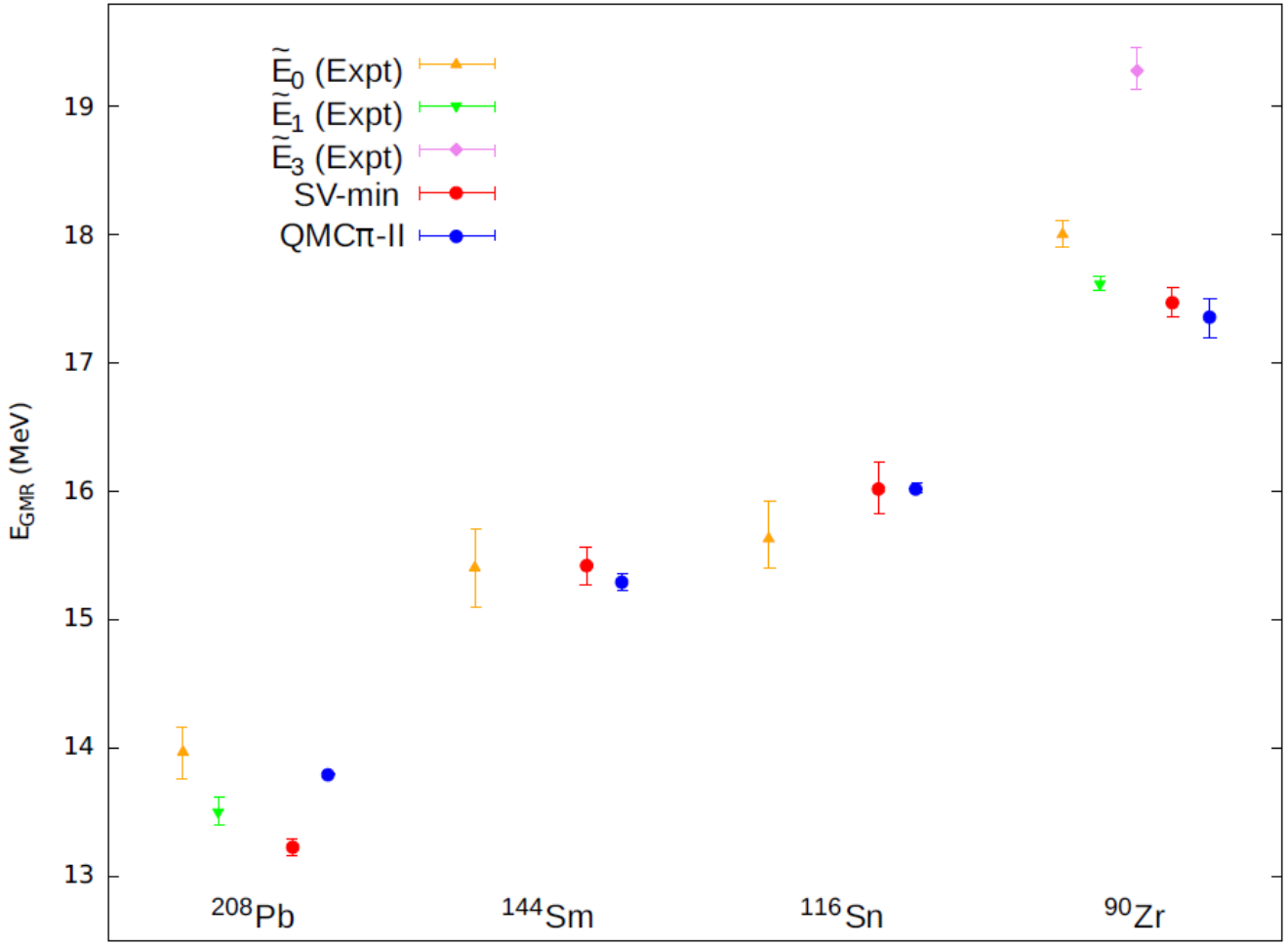
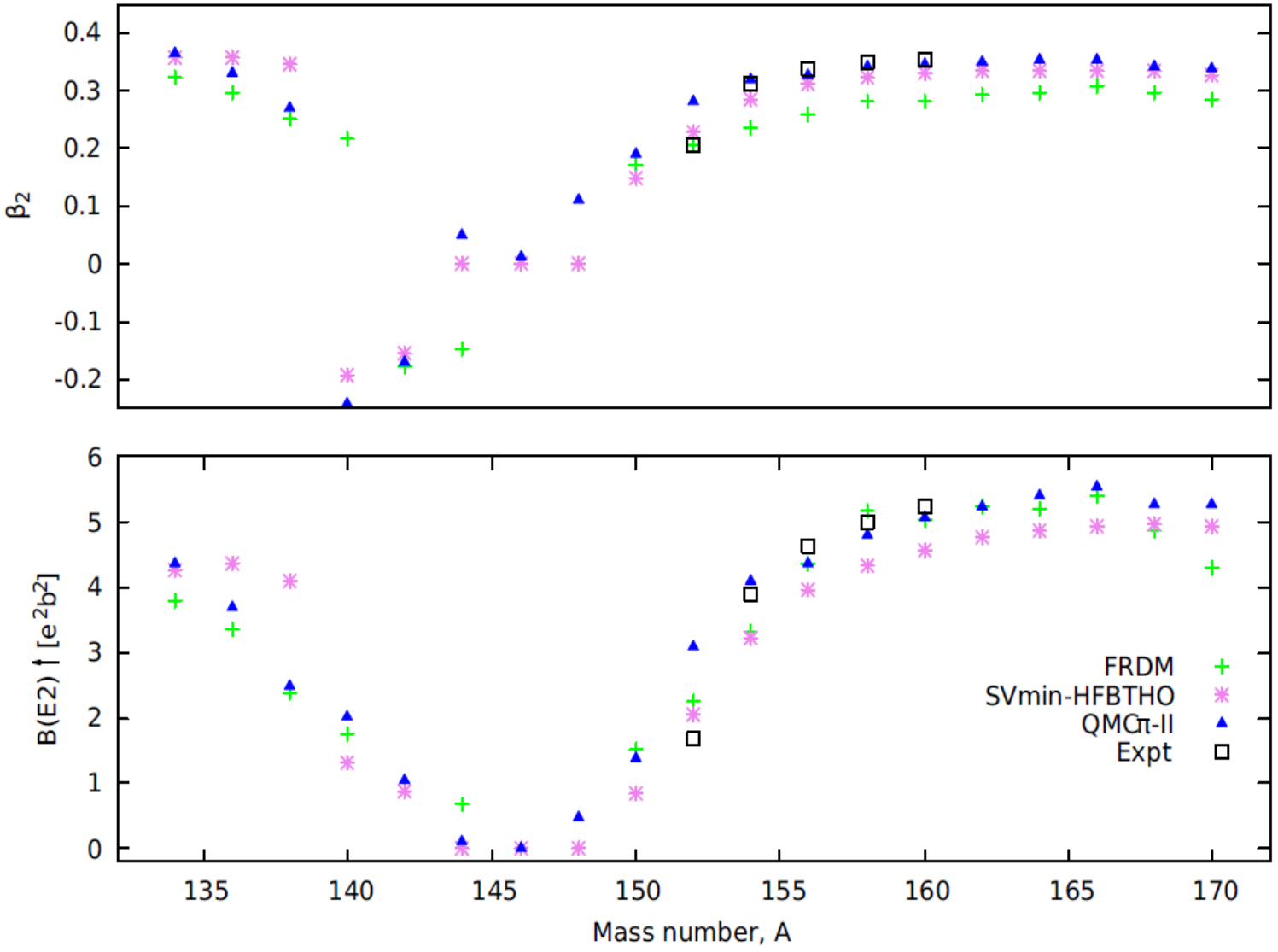


FIG. 13. GMR energies for ^{208}Pb, ^{144}Sm, ^{116}Sn, and ^{90}Zr from experiment and for the QMCπ-II and SVmin models. Experimental data are taken from Table 1 of Ref. [24].

Kay Martinez *et al.*, Phys Rev C100 (2019) 024333

Deformation of Gd isotopes



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DARK MATTER PARTICLE PHYSICS

Kay Martinez *et al.*, Phys Rev C100 (2019) 024333

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Nuclear DIS Structure Functions : The EMC Effect

The QMC approach is ideal as one MUST start with a theory that quantitatively describes nuclear structure and allows calculation of structure functions

– there are no other examples.....

EMC Effect for Finite Nuclei

(There is also a spin dependent EMC effect - as large as unpolarized)

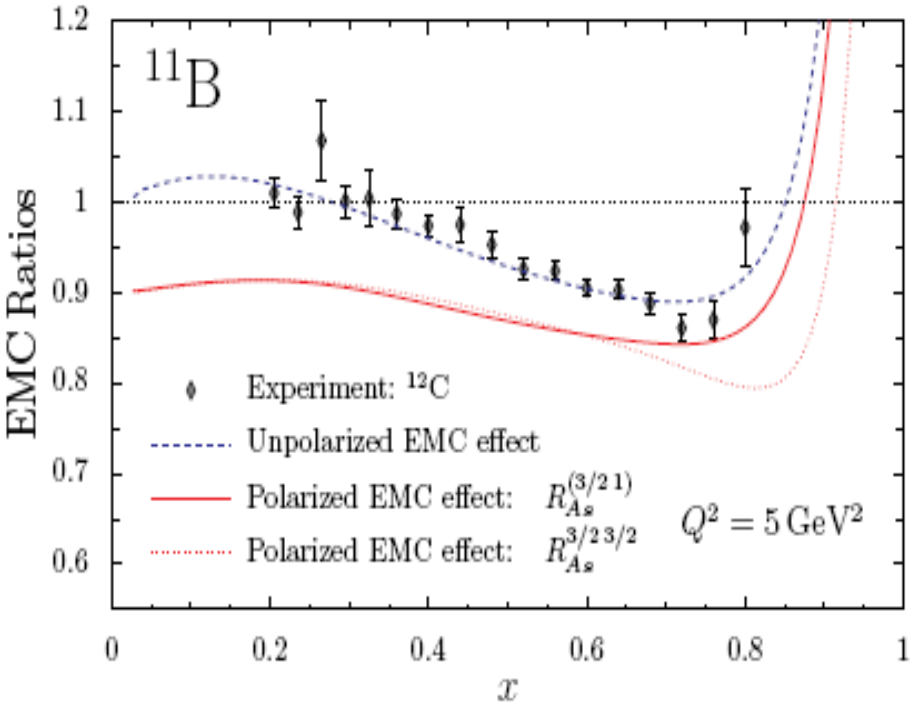


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

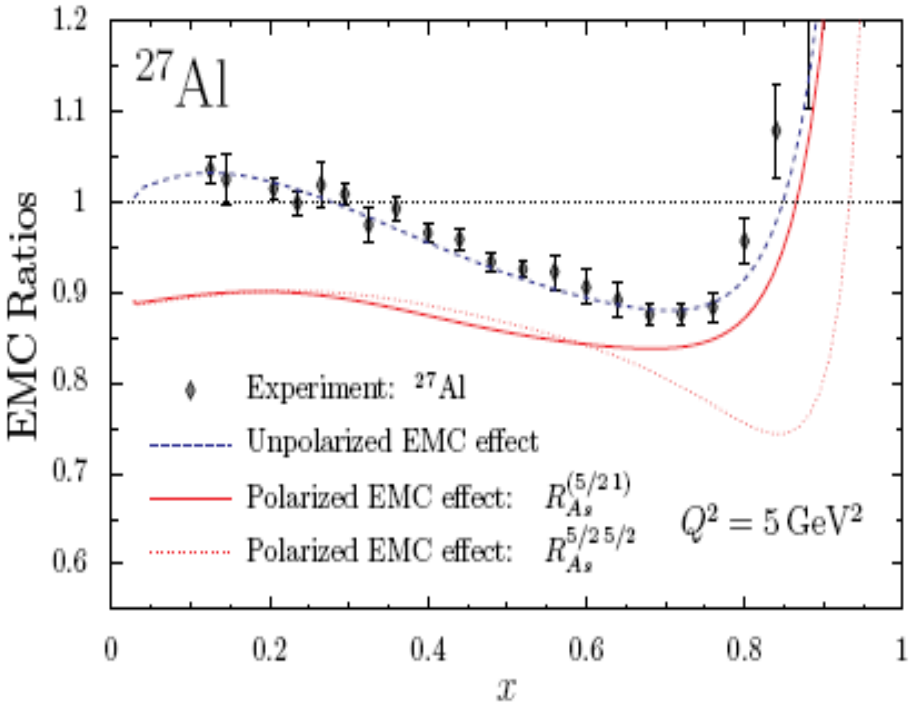
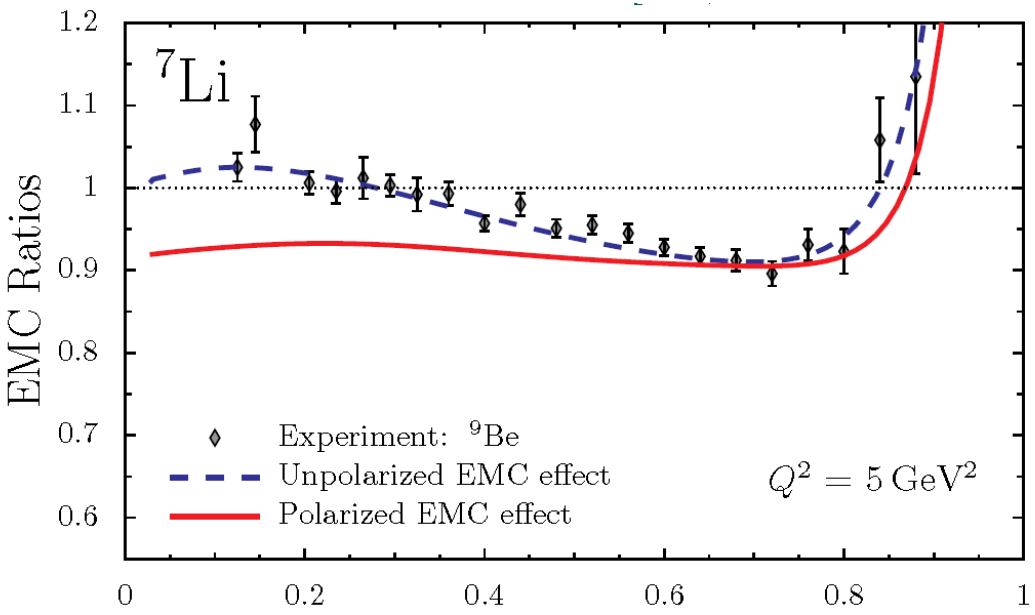


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

Cloët, Bentz &Thomas, Phys. Lett. B642 (2006) 210 (nucl-th/0605061)

Approved JLab Experiment

- Effect in ^{7}Li is slightly suppressed because it is a light nucleus and proton does not carry all the spin (simple WF: $P_p = 13/15$ & $P_n = 2/15$)
- Experiment now approved at JLab [E12-14-001] to measure spin structure functions of ^{7}Li (GFMC: $P_p = 0.86$ & $P_n = 0.04$)
- *Everyone with their favourite explanation for the EMC effect should make a prediction for the polarized EMC effect in ^{7}Li*



Other tests (e.g. Isovector EMC effect)

SRC versus QMC - tests

Spin-EMC Effect is a crucial test

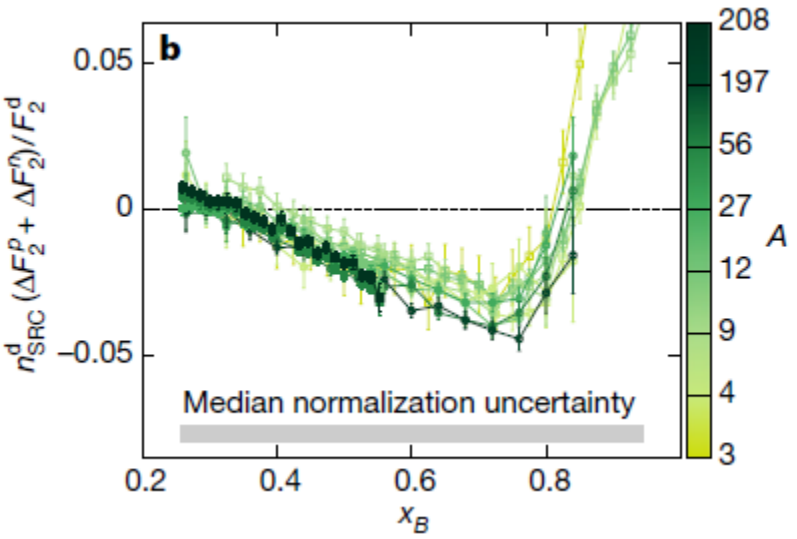
- **Tensor correlations leading to high momentum components in nuclear wave function have been proposed as an alternate explanation of the EMC effect**

- **The tensor force scatters $^3S_1$ pairs almost entirely into $^3D_1$ at high momentum (~84% at p > 400 MeV/c)**

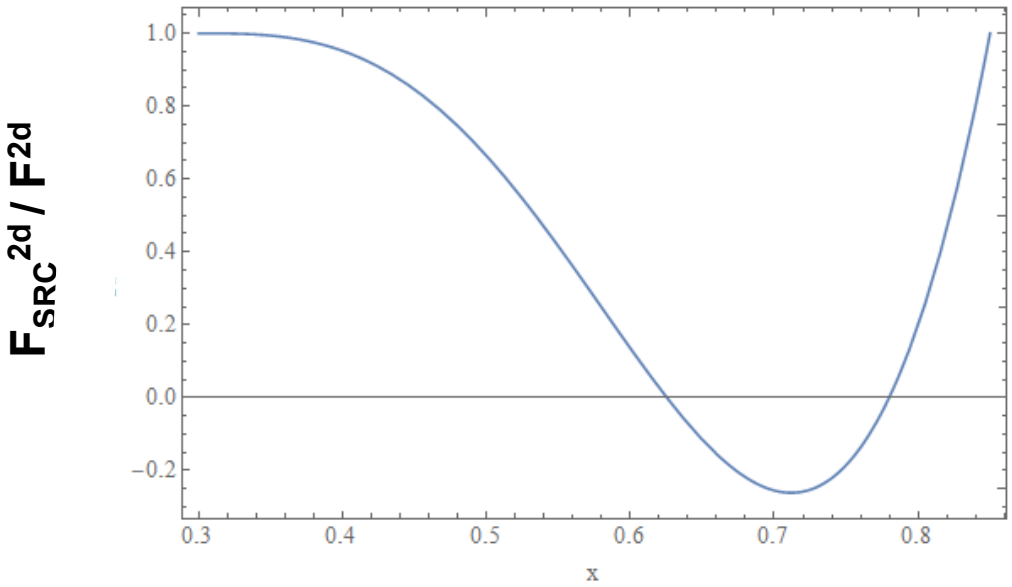
- **Nucleons in SRC are depolarized – simple Clebsch-Gordan coefficients - and cannot contribute to spin-EMC effect**

- **That is, SRC idea gives essentially NO spin-EMC effect**

Further: change in F_2 is dramatic in SRC approach



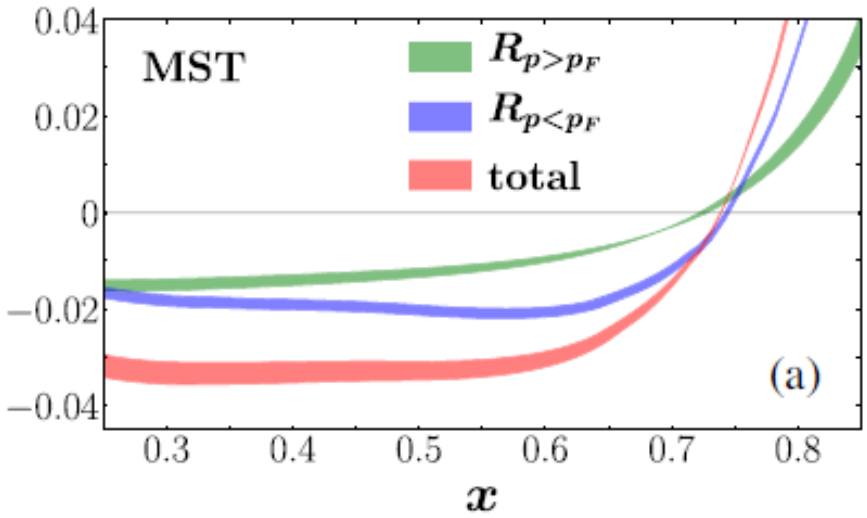
- Does not look so bad but n^d_{SRC} is of order 0.03
  (p> 0.3 GeV: only ~80 MeV off-shell))
- Hence suppression of structure of correlated nucleons is more than 100% in the valence region



Such a dramatic change is not viable

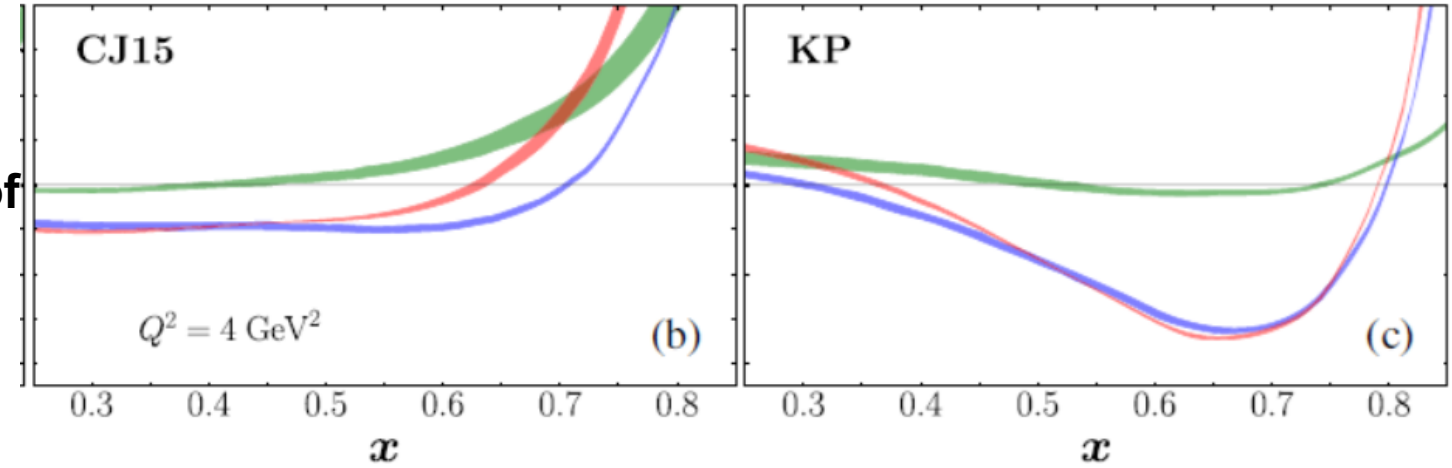
Wang *et al.*, Phys Rev Lett 125 (2000) 262002

Careful study of the EMC effect in the deuteron



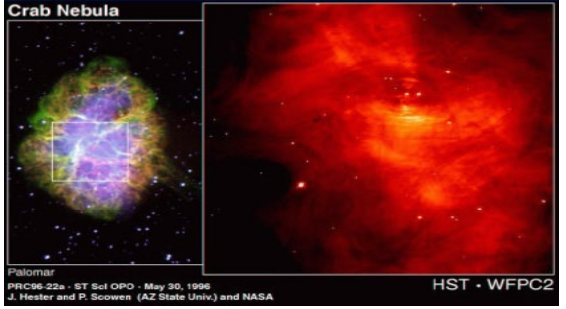
Microscopic model of Melnitchouk et al., shows little of valence EMC effect in D arises from nucleons in SRC

Even more emphatic in off-shell models of Kulagin-Petti and CTEQ-JLab



Wang *et al.*, Phys Rev Lett 125 (2020) 262002

Summary



- The EMC effect contains fundamental information about the structure of atomic nuclei

- The QMC approach is based upon the change in nucleon structure because of STRONG Lorentz scalar mean field

- Initial systematic study of finite nuclei very promising
  - Binding energies typically within 0.3%

- Naturally generates effective HN and HNN forces with no new parameters and predicts heavy neutron stars

- Model describes the EMC effect very well, and in addition:
  - Predicts isovector EMC effect (>1σ of the NuTeV anomaly)
  - Predicts significant spin-EMC effect

- SRC explanation implies a HUGE/unphysical suppression of F_2 for correlated nucleons
  - SRC proposal predicts NO spin-EMC effect
  -- SRC produce little of EMC effect in the deuteron

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To understand this approach we need:

Insights into nuclear structure

– what is the atomic nucleus?

There are two very different extremes….

Quark Structure matters/doesn't matter

1. **Nuclear femtography: the science of mapping the quark and gluon structure of *atomic nuclei* is just beginning**

   OR

2. **"Considering quarks is in contrast to our modern understanding of nuclear physics… the basic degrees of freedom of QCD (quarks and gluons) have to be considered only at higher energies. The *energies relevant for nuclear physics are only a few* MeV"**

What do we know?

- **Since 1970s: Dispersion relations → intermediate range NN attraction is a strong Lorentz scalar**

- **In relativistic treatments (RHF, RBHF, QHD…) this leads to mean scalar field on a nucleon ~300 to 500 MeV!!**

- ***This is not small* – up to half the nucleon mass**
  - death of "wrong energy scale" arguments

- **Largely cancelled by large vector mean field BUT these have totally different dynamics: ω^0 just shifts energies, σ seriously modifies internal hadron dynamics**

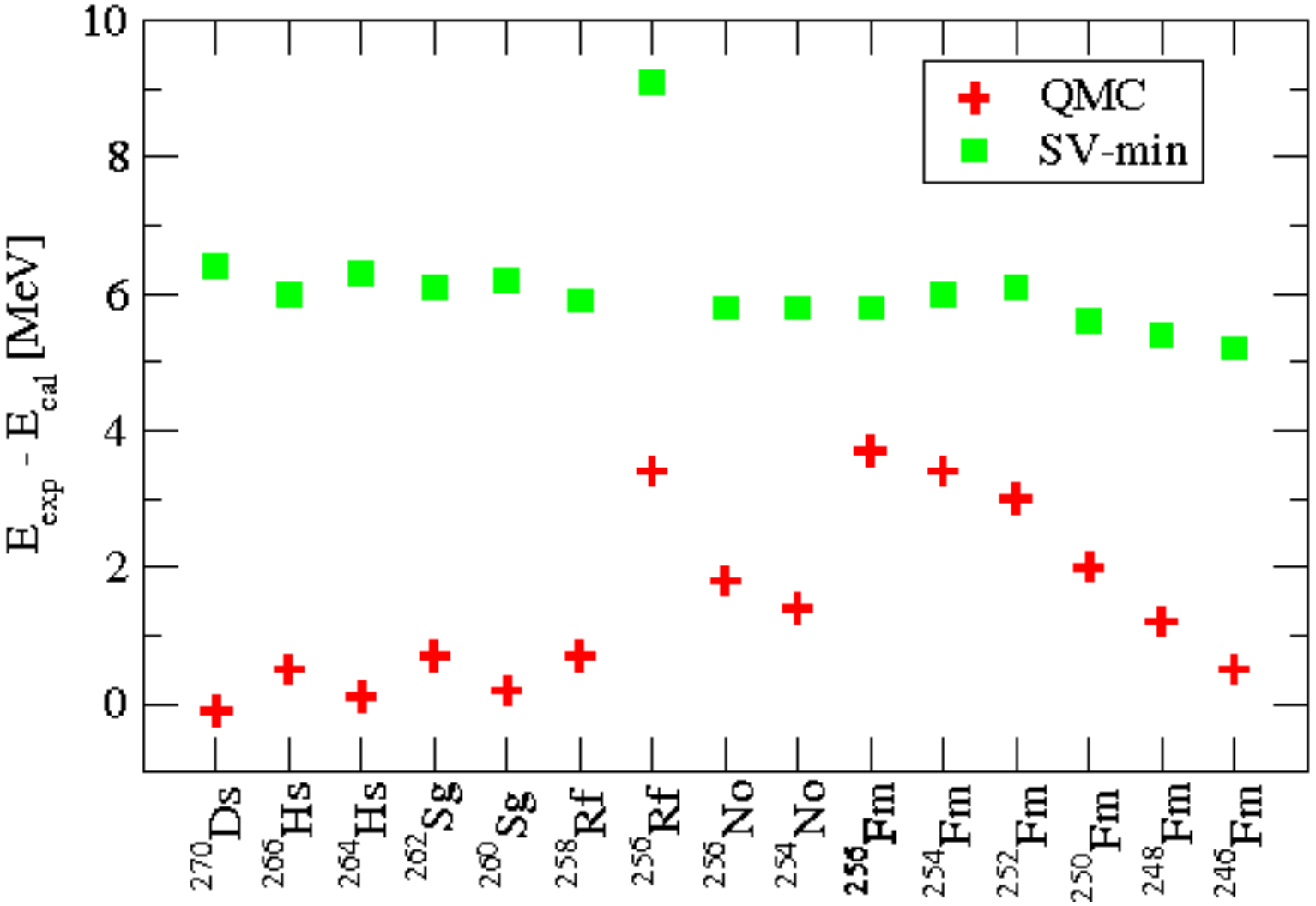
- **Latter cannot be accurately captured by EFT with N and π**

Overview: 4 parameters vs 10

data	rms error %	
	QMC	SV-min
fit nuclei: ~ 70 nuclei across the periodic table		
binding energies	0.36	0.24
diffraction radii	1.62	0.91
surface thickness	10.9	2.9
rms radii	0.71	0.52
pairing gap (n)	57.6	17.6
pairing gap (p)	25.3	15.5
ls splitting: proton	15.8	18.5
ls splitting: neutron	20.3	16.3
superheavy nuclei:	0.1	0.3
N=Z nuclei	1.17	0.75
mirror nuclei	1.50	1.00
other	0.35	0.26

Stone et al., PRL 116 (2016) 092501

Superheavies (not fit) : 0.1% accuracy



Stone et al., PRL 116 (2016) 092501

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